

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α , β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s -mixing well beyond the largest conceivable values of x_s . LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

Members of the LHC-B Collaboration

University of Aarhus - Institute for Synchrotron Radiation, Aarhus, Denmark

K. Kirsebom, S.P. Møller, E. Uggerhøj

Cukurova University, Adana, Turkey

A. Kuzucu-Polatoç, G. Onengüt, N. Özdes-Koca

University of Massachusetts, Amherst, MA, U.S.A.

E.P. Hartouni, M. Kreisler

NIKHEF, Amsterdam, The Netherlands

¹University of Amsterdam, ²University of Utrecht, ³Foundation for Fundamental Research of Matter in the Netherlands

G. v. Apeldoorn¹, Th.S. Bauer^{2,3}, A. Buijs², B. Koene³, P.M. Kooijman¹, M. Merk³, W. Ruckstuhl³, J. Timmermans³, J. Visschers³

Humboldt University, Berlin, Germany

T. Lohse, R. Mankel

University of Bologna and INFN, Bologna, Italy

A. Bertin, M. Bruschi, M. Capponi, I. D'Antone, S. De Castro, A. Ferretti, D. Galli, B. Giacobbe, U. Marconi, I. Massa, M. Piccinini, M. Poli, N. Semprini-Cesari, R. Spighi, S. Vecchi, A. Vezzani, F. Vigotti, M. Villa, A. Vitale, A. Zoccoli

Cambridge University, Cambridge, U.K.

V. Gibson, C.P. Ward

University of Virginia, Charlottesville, VA, U.S.A.

M. Arenton, B. Cox, S. Conetti, G. Corti, C. Dukes, A. Mcmanus, K. Nelson, B. Norum, I. Tzamouranis

JINR, Dubna, Russia

E.N. Kozarenko, I.E. Kreslo

Northwestern University, Evanston, IL, U.S.A.

J. Marques, J. Rosen, K. Seth

University of Freiburg, Freiburg, Germany

H. Fischer, J. Franz, K. Königsmann, H. Schmitt

CERN, Geneva, Switzerland

H. Dijkstra, G. Fidecaro, M. Fidecaro, R. Forty, W. Hoogland¹, J. May, T. Ruf, A. Schopper

DAPNIA, CE-Saclay, Gif-sur-Yvette, France

J. Zsembery

University of Glasgow, Glasgow, UK

N.H. Brook, A.W. Halley

University of Science and Technology of China, Hefei 230026, P.R.C.

X.-Q. Yu, G. Jin, X.-S. Lin, T.-K. Liu, X.-Y. Wu

Physikalisches Institut, University of Heidelberg, Heidelberg, Germany

P. Bock, F. Eisele, P. Igo-Kemenes, J. von Krogh

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

T. Knöpfle, W. Hofmann

Rice University, Houston, TX, U.S.A.

D. Crosetto

¹permanent address: NIKHEF, Amsterdam

Institute of Physics and Techniques, Kharkov, Ukraine

Yu.N. Ranjuk, P.V. Sorokin

Institute for Nuclear Research, Kiev, Ukraine

V.E. Aushev, A.A. Klipenstein, I.N. Kolomiets, V.I. Medvedev, Yu.N. Pavlenko, V.M. Pugatch, N.M. Tkatch, V.V. Zerkov

University of Lausanne, Lausanne, Switzerland

C. Joseph, N. Leros, J.P. Perroud, M.T. Tran, M. Werlen

University of Lodz, Poland

J. Kempa, J. Wdowczyk, T. Wibig, Inz.J. Zabierowski

Imperial College, London, U.K.

N.C. Brümmer, S. Margetides, J.G. McEwen², D. Websdale

University of California, Los Angeles, CA, U.S.A.

S. Erhan, M. Medinnis, P. Schlein, J.G. Zweizig

Institute for Nuclear Research, Moscow, Russia

B. Bakhtin, A. Dement'ev, R. Dzhilkibaev, A. Kovzelev, L. Kravchuk, V. Postoev, S. Volkov, G. Atoyanyan, M. Akopyan

Institute of Theoretical and Experimental Physics, Moscow, Russia

V. Balagura, S. Semenov, A. Snizhko, Yu. Zaitsev

Lebedev Physical Institute, Moscow, Russia

Yu. Alexandrov, V. Biaskov, L. Gorbov, B. Govorkov, V. Kim, P. Netchaeva, V. Polyansky, L. Shtarkov, A. Verdi, M. Zavertiaev

Nanjing University, Nanjing 210008, P.R.C.

T.-Y. Chen, D. Gao, Z.-X. Sha, D. Xi, Z.-W. Zhang

University of Oxford, Oxford, U.K.

N. Harnew, G. Wilkinson

Collège de France, Paris, France

J. Seguinot, T. Ypsilantis

IHEP-Serpukhov, Protvino, Russia

G.V. Borissov, R.I. Dzhelyadin, S.V. Golovkin, Y.P. Guz, A.K. Konoplyannikov, V.D. Matveev, A.P. Ostankov, V.I. Rykalin

University of Rome - “La Sapienza” and INFN, Rome, Italy

A. Frenkel, G. Martellotti, G. Penso

University of Rome - “Tor Vergata” and INFN, Rome, Italy

G. Carboni

University of Santiago de Compostela, Spain

B. Adeva, A. Gallas, F. Gomez, A. Lopez-Aguera, M. Plo

Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, Russia

A. Krivshich, G. Obrant, V. Samsonov, V. Sarantsev, I. Tkach, A. Tsaregorodtsev, L. Uvarov, S. Volkov, A. Vorobyov, N. Zaitsev, Yu. Zalite

Paul Scherrer Institute, Villigen, Switzerland

J. Egger, T. Nakada

Contactpersons: T. Nakada (nakada@cvax.psi.ch) and P. Schlein (schlein@uxucla.cern.ch)

Collaboration Board Chair: W. Hofmann (wh@eu12.mpi-hd.mpg.de)

²permanent address: University of Southampton

Contents

1	Introduction & Overview	1	5	Tracking System	37
1.1	Historical background	1	5.1	Inner tracking system options	37
1.2	Aperture considerations	3	5.1.1	Micro-cathode strip chambers	37
1.3	Overview of detector	4	5.1.2	Micro-strip gas counters	41
1.3.1	Beam pipe	5	5.2	Outer tracking system	42
1.3.2	Dipole magnet	5	6	Ring Imaging Cerenkov Detectors	47
1.3.3	Microvertex detector	5	6.1	Mirror-focused aerogel	47
1.3.4	Tracking system	5	6.2	Mirror-focused gas counters	50
1.3.5	RICH counters	5	6.3	Total channel and HPD counts	51
1.3.6	Calorimeter systems	6	6.4	R&D program	51
1.3.7	Muon system	6	6.5	Alternative technologies	51
1.3.8	Roman-pot detectors	7	7	Calorimetry	53
1.4	Particle densities	7	7.1	Performance requirements	53
1.5	Running conditions	7	7.2	Electromagnetic calorimeter	53
1.6	Triggering overview	8	7.2.1	Outer EM calorimeter	53
1.7	Performance overview	8	7.2.2	Inner EM calorimeter	54
1.8	Other physics	9	7.2.3	Preshower detector	54
2	B-Physics Objectives	11	7.3	Hadron calorimeter	55
2.1	CKM matrix & unitarity triangle	11	7.3.1	Outer hadron calorimeter	56
2.2	B_s^0 - \bar{B}_s^0 mixing	12	7.3.2	Inner hadron calorimeter	57
2.3	CP violation in B -decays	13	7.4	Calibration and monitoring	58
2.4	Desired precision in CP angle measurements	17	8	Muon System	61
2.5	Search for non-CKM physics	17	8.1	Design criteria	61
2.6	Rare B-decays	17	8.2	The muon shield	62
2.7	Heavy flavor spectroscopy	18	8.3	Muon detectors	64
3	Other Physics	22	8.3.1	2-D projective pad geometry	64
3.1	Prospects for mixing and direct CP-violation in D-decays	22	8.3.2	Muon chamber technologies	65
3.2	Search for lepton-number violation in $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$	24	8.3.3	Proportional drift tubes	67
3.3	Tagged Pomeron-beam experiments (Diffraction)	24	9	Roman-Pot Detectors	68
3.4	Cosmic ray phenomena in pp and ion-ion collisions	27	9.1	Measurement of beam-like outgoing protons	68
3.5	J/ψ and Υ production in ion-ion collisions	27	10	Triggering	70
4	Silicon Microvertex Detector	30	10.1	High- p_t muon trigger (Level-1)	71
4.1	Design requirements	30	10.1.1	Projective-pad-plane technique	71
4.2	P238 R&D project	31	10.1.2	Cathode-strip-chamber technique	73
4.3	Detector layout and performance	32	10.2	High- p_t electron trigger (Level-1)	75
4.4	Readout electronics	33	10.3	High- p_t hadron trigger (Level-1)	79
4.5	Radiation damage	34	10.4	Pileup tag (Level-1)	82
4.6	Mechanics and engineering	35	10.5	Level-1 hardware implementation	83
4.7	Scintillating capillary option for vertex detector	35	10.6	Level-1 summary	84
			10.7	Level-2 trigger	84
			10.7.1	Vertex-topology trigger	85
			10.8	Level-3 trigger	87
			10.9	Trigger summary	89

11 Data Acquisition	91	13.6 Installation time	120
11.1 Comparison with the other LHC experiments	91	13.7 Experimental area costs	120
11.2 LHC-B data flow	91	A Detector Option: Liquid-Scintillator-Filled Capillaries	123
11.3 Front-end electronics	92	A.1 Vertex detector layout	123
11.3.1 Analog signal processing	92	A.2 Readout system	124
11.3.2 Level-1 storage	92	A.3 Spatial resolution	125
11.3.3 Synchronization and trigger distribution	92	A.4 Radiation resistance	125
11.4 Detector readout	92	A.5 Costs	126
11.4.1 Readout units	92	A.6 Inner tracking system based on capillary layers	126
11.4.2 Readout links	93		
11.4.3 Level-2 buffers & trigger interface	93		
11.4.4 Rate limitations	93		
11.5 Event building	93		
11.5.1 Detector pre-processors	93		
11.5.2 Event builder network	94		
11.5.3 The event builder output node	94		
11.6 Level-3 processing	94		
11.6.1 Sub-farm structure	94		
11.6.2 Level-3 sub-farm interconnect .	94		
11.6.3 Sub-farm controller	95		
11.6.4 Level-3 processors	95		
11.6.5 I/O processor unit	95		
12 Physics Performance	96		
12.1 LHC-B simulation programme	96		
12.2 Reconstruction of final states	97		
12.2.1 The $B^0(\pi^+\pi^-)$ final state	97		
12.2.2 The $B^0(J/\psi K_S)$ final state	101		
12.2.3 The $B_s(J/\psi\phi)$ and $B_d(J/\psi K^{*0})$ final states	103		
12.2.4 The $B_s(D_s\pi)$ and $B_s(D_sK)$ final state	104		
12.2.5 The $B^0(\overline{D}^0 K^{*0})$ Final State	106		
12.3 Flavour Tagging	107		
12.4 Control Channels and Systematics	109		
12.5 The $B_s\text{-}\overline{B}_s$ Oscillations	110		
12.5.1 Introduction	110		
12.5.2 Determination of x_s , τ_s and y_s	110		
12.6 CP Sensitivities	111		
12.6.1 The angle α	111		
12.6.2 The angle β	112		
12.6.3 The angle γ Method-1	112		
12.6.4 The angle γ Method-2	113		
12.6.5 CP violation in $B_s \rightarrow J/\psi\phi$	114		
12.7 $B_s \rightarrow \mu^+\mu^-$	115		
12.7.1 Reconstruction Simulation	116		
13 Costs & Experimental Area	119		
13.1 Detector costs	119		
13.2 Machine constraints	119		
13.3 Underground cavern	119		
13.4 Displaced crossing point	120		
13.5 Surface zones and services	120		

1 Introduction & Overview

The LHC offers a unique opportunity to study the physics of b-quarks. The expected $b\bar{b}$ production cross section of $500 \mu\text{barn}$ leads to a production rate of almost $10^{12} b\bar{b}$ per 10^7 second year already with a modest luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. With the present Letter-of-Intent, we propose an optimised open-geometry forward collider detector which we believe will be able to *fully* exploit the B-physics potential of the LHC.

The forward peaking of beauty production in high energy hadron collisions offers several important advantages:

- The produced b and \bar{b} are typically correlated in one unit of rapidity. Therefore, the geometric efficiency to detect all B-decay tracks *plus* a tagging particle from the accompanying \bar{B} is large.
- The large Lorentz boost of accepted B-mesons (corresponding to about 7 mm mean decay distance) allows proper-time measurements to be made with a few percent uncertainty, permitting time-dependent B_s -mixing analyses well beyond the largest conceivable values of x_s .
- The observed particle momentum distributions match the particle identification capabilities of Ring-Imaging Cerenkov Counters. The possibility for π/K separation is an important feature of the LHC-B experiment.
- The forward approach facilitates the construction of multiple efficient triggers.
- Muon triggers are inherently more efficient in the forward direction because of the large longitudinal momenta of muons. p_t cuts can be decided on the basis of physics (background suppression) and not on the muon's penetration.
- Forward planar detector systems, quite similar to those used in fixed target experiments, are less expensive, easier to maintain and can be optimized for best resolution.

In acquiring the data, we plan to include the maximum possible redundant information from different decays and triggering modes. In this way, we hope to adequately understand and minimize the systematic uncertainties of the experiment.

We take the point of view that the ultimate measurements of CP-violation and rare B-decays will take several years of dedicated experimentation with a continual learning process to achieve optimal running conditions. Therefore, we do not see LHC-B as a

“frozen” setup but rather as a detector which may, to some extent, evolve with time and experience. We believe that the open geometry detector configuration proposed here will provide the necessary flexibility for possible future developments.

We expect LHC-B to be fully operational at the startup of LHC. It is a relatively simple setup compared with the other LHC experiments, and there will be significant experience constructing a similar detector, HERA-B, in which part of our LHC-B collaboration also participates.

The actual detector construction will start in a couple of years, during which time the optimization of the system will continue. While we do not expect the basic layout of the detector to change significantly, the choices for individual detector technologies given here are meant to demonstrate that viable solutions exist, but will not necessarily coincide with the final solution.

In the remainder of this chapter, we present an overview of the experiment, its historical background and “CP-violation Reach”. Our B-physics goals are discussed in Chapt. 2. Some of the non-B-physics topics which LHC-B will address are described in Chapt. 3. The detector components are covered in Chaps. 4-9. Triggering, Data Acquisition and Physics Performance are described in Chaps. 10-12, respectively. The anticipated costs and issues connected with the installation of LHC-B in the experimental area are covered in Chapt. 13. And, finally, Appendix A contains a discussion of liquid-scintillator-filled capillaries, which, because of their radiation hardness and “pointing” capabilities, may be useful as tracking detectors at small polar angles.

1.1 Historical background

In the minutes of the LHCC meeting on 7-8 June, 1994, the proponents of three dedicated B experiments for the LHC (COBEX, GAJET and LHB), were encouraged to “join together to prepare a new letter of intent for a new collider mode b experiment to be submitted to the LHCC”.

With regard to the original COBEX forward collider proposal, it was stated that, “Whilst the LHCC considers that a very close vertex detector in a Roman pot is a very desirable feature for a collider b-experiment it has not yet seen an adequately optimised spectrometer. A new design for the spectrometer should contain a trigger system capable of effectively exploiting the high b-rate at the collider.”

The committee also wrote that they “would welcome a report of the progress made to form this collaboration at the 31 August meeting of the LHCC,

at which a time scale for the future would be established". Our new collaboration responded to that request with a memo (CERN/LHCC/94-34) in which we reported that COBEX, GAJET and LHB had merged with the new name LHC-B and that we were proceeding with a new study of a forward collider experiment. We also reported that a number of institutions had joined our new LHC-B collaboration that were not in any of the three original collaborations.

In arriving at our new proposed detector layout, we have taken into consideration the "Guidelines for the New Letter of Intent" which were set by the LHCC at their June 1994 meeting. We were asked to address the following issues (comments in *italics* at the end of each topic briefly summarize the steps taken):

- "The viability of the triggering scheme, at levels 1, 2 and 3 for luminosities between 10^{31} and 10^{33} . Single particle electron, muon and hadron triggers and two particle triggers should be considered. The effectiveness of topological triggers as a function of luminosity should be assessed. The requirements of the technology assumed at all levels should be made clear". *As is discussed in Chapt. 10, the trigger system is now designed to be very flexible and facilitates the study of many different channels with redundant triggers which will allow for checks of systematic uncertainties. We give an example of an existing processor development which could satisfy the hardware needs of our Level-1 trigger.*
- "The steps to be taken to minimise the effects of performance deterioration arising from the high levels of radiation, particularly for the vertex detectors". *As mentioned below and in Chapt. 4, the LHC-B silicon microvertex system is designed to run further from the beam than in COBEX. In addition, the improved LHC-B trigger efficiencies allow us to obtain large event yields while running with lower luminosity.*
- "Evidence that tracking devices in the spectrometer can handle the proposed rates, particularly those very close to the beam pipe". *We have profited significantly from the extensive R&D and Monte Carlo calculations done for the HERA-B experiment at DESY. HERA-B has particle densities similar to those expected in LHC-B. In designing our tracking system, it is shown in Chapt. 5 that occupancies can be held to an acceptable level.*
- "A justification for the performance claimed for the particle identification devices. A justification for the performance of the calorimeters".

The performance of the RICH counters depends on the development of Hybrid Photo-Diodes with silicon-pad pixels, as described in Chapt. 6. The calorimeter technologies are based on R&D carried out for ATLAS & CMS and should present no particular difficulties. See the discussion in Chapt. 7

- "The trade-off between the physics benefits and the consequent increase in cost of enlarging the aperture of the spectrometer". *The 400 mrad aperture we propose for LHC-B is reduced compared to the previous collider design and offers, in our opinion, the best compromise between acceptance and cost. As shown in Sect. 1.2, 400 mrad has only a modest acceptance loss below the 600 mrad proposed earlier. With the present cost estimates for LHC-B (see Chapt. 13), we believe it is impractical to consider any larger aperture.*
- "A discussion of non-CP-violating physics which could be attempted with such an apparatus". *In addition to the study of rare FCNC decays of B-mesons (see Chaps. 2 and 12), the acceptance of LHC-B allows the coverage of a wide range of forward collider physics topics. In Chapt. 3, we discuss a number of topics, for example, mixing and CP-violation in D-decay, search for lepton number violation in τ decay, tagged Pomeron beam experiments, cosmic-ray phenomena. We also comment (briefly) on the study of J/ψ and Υ production in ion collisions, which we were specifically asked about by our LHCC Referees.*
- "The advantages of a special insertion for such an experiment should be addressed". *Our optimal running conditions are discussed in Sect. 1.5. We propose to record most of our data at the rather modest luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This will be possible, as long as ATLAS & CMS are running with a luminosity less than thirty times this value (the available tuning range). Thus, when the machine luminosity exceeds about $\mathcal{L} = 4.5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, a special insertion would be required for LHC-B..*
- "The emerging collaboration must have the organisation and resources commensurate with the magnitude of the proposed experiment". *In addition to the combined COBEX-GAJET-LHB collaborations, a growing number of additional groups have joined the LHC-B collaboration. We now number 37 institutions. We anticipate additional growth by the time we submit the Technical Proposal.*

In the text of this Letter-of-Intent, we address these issues and present a new design of a forward collider B detector.

Compared to the previous proposal for a colliding-beam B experiment (COBEX), the present LOI contains a number of essential improvements, and has also benefited considerably from concepts contained in the previous fixed-target proposals (GAJET and LHB):

1. The Quadrupole magnet was eliminated and the dipole magnet (enlarged) moved forward. This simplifies the detector considerably and is made possible by maintaining small angle acceptance with the use of a 25 mm diameter vacuum pipe at the exit of the large vacuum window at $z = 1$ meter.
2. In order to decrease radiation damage to the silicon system, it is designed to run further from the beam (10 mm). Consequently, the silicon system has been lengthened, in order to maintain small angle acceptance.
3. To allow triggers based on high- p_t hadrons, a hadron calorimeter was added.
4. An electron trigger was added.
5. The aperture of the muon system has been enlarged from 100 mrad to 300 mrad (made possible by the elimination of the quadrupole magnet). The rate calculations for the muon triggers, like the electron and hadron trigger rates, are based on detailed GEANT[9] simulations and are more reliable than the rate estimates given previously.

1.2 Aperture considerations

Fig. 1.1 shows the laboratory angular distributions of the B-meson and \bar{B} -meson momentum vectors expected at the LHC, calculated using the PYTHIA 5.7 Monte-Carlo event generator[1].

The parton-parton interactions for production of relatively low-mass $b\bar{b}$ -quarks at collider energies are inherently asymmetric in momentum and therefore lead to the rather conspicuous forward-backward peaking seen in the figure. The strong correlations between B and \bar{B} production are evident.

Fig. 1.2 shows the expected distribution of all B-momenta at LHC; the shaded events are those whose decay products are contained in the aperture *and* have momentum measurements in the LHC-B tracking system. For the purpose of this plot, in order to illustrate the effectiveness of the forward direction,

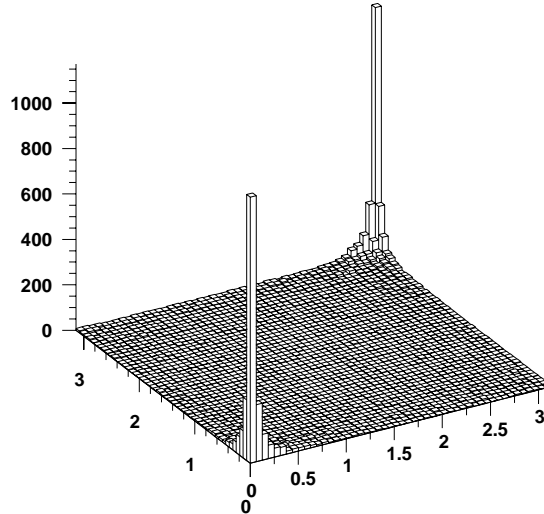


Figure 1.1: Production angle of B vs. angle of \bar{B} in the laboratory (in units of rad.), calculated using PYTHIA. The peaks in the forward directions shows the correlation between their respective production directions.

the aperture is assumed to exist on both arms. The area of the shaded events is 24% of the total; that is, the average LHC-B single-arm acceptance is 12% for generic B-mesons, which is typical for this detector (see Table 8.12 in Chapt. 10).

The difference in shape between all events and the “accepted” events at large momenta is due to the conservative small angle requirement that all B-decay tracks must have hits in at least three silicon detector planes (see Chapt. 4). The momentum distributions of reconstructed event samples are similar to the shaded distribution in Fig. 1.2 with a mean B-momentum of about 80 GeV. This corresponds to a mean flight path³ of about 7 mm.

We now consider the optimal acceptance aperture for a forward spectrometer experiment. B-mesons are generated with PYTHIA via the gluon-gluon fusion mechanism. Two decay modes, $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$, are chosen as representative low and high multiplicity B-meson decay modes.

We consider three different definitions of geometric

³As discussed in Chapt. 12, this distance will be measured in LHC-B with an uncertainty of about 0.16 mm, leading to a B-meson proper time measurement with $\approx 3.5\%$ accuracy.

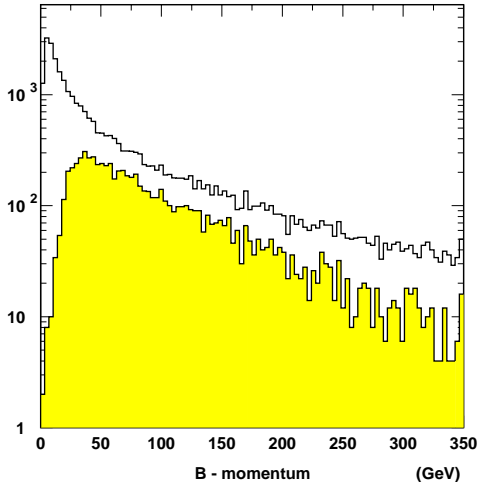


Figure 1.2: Total momentum of generic B-mesons produced at the LHC, calculated using PYTHIA. The shaded events are those (averaged over all decay modes), whose decay products would be accepted in a 2-arm LHC-B. With our proposed 1-arm spectrometer, 50% of the shaded events are accepted. See discussion in text.

acceptance. Our first definition requires that all B-meson decay tracks are contained between two cones defined by the detector minimum (θ_{min}) and maximum (θ_{max}) angles, defined with respect to the beam line. Figs. 1.3(a,b) shows the resulting acceptance function for the two representative decay modes as a function of θ_{max} , for various choices of θ_{min} : 0, 10 and 20 mrad.

When the geometric acceptance definition is extended to require that a trigger/tag muon from the accompanying \bar{B} decay be within the same cone, we obtain the curves plotted in Figs. 1.3(c,d). To obtain these curves, a muonic decay of the accompanying \bar{B} meson is “forced”, and an event is considered accepted if the decay muon is found to be within the aperture.

Our final definition of acceptance makes the additional requirements that: (i) all decay tracks from a B-meson have momentum larger than 500 MeV and (ii) The tagging muons have momentum larger than 10 GeV and transverse momentum $p_t > 1.5$ GeV. The resulting curves are plotted in Figs. 1.3(e,f).

As seen in Fig: 1.3, the geometric acceptance function increases monotonically with θ_{max} , but with de-

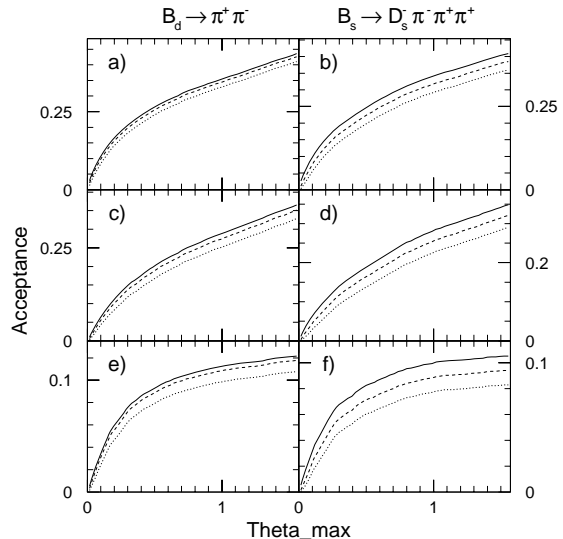


Figure 1.3: The geometric acceptance as a function of θ_{max} (radians) for two decay modes. On each plot, the curves are for $\theta_{min} = 0, 10$ and 20 mrad, (from top to bottom, respectively). (a,b) are for the acceptance of the B-meson decay tracks only; (c,d) include, in addition, a trigger/tag muon within the same acceptance cone; (e,f) have the additional requirements that all decay tracks from the B-meson have $p > 500$ MeV and that the muon from the \bar{B} -meson have $p > 10$ GeV and $p_t > 1.5$ GeV.

creasing slope at larger angles. This plateauing becomes much more pronounced when the momentum cuts are imposed on the decay particles and the trigger/tag muon. We find as well that the height of the plateau depends on the values of the momentum cuts, but the position of the shoulder is not very sensitive to actual cut values.

We conclude that an aperture of about 400 mrad would be optimal. We see no physics justification for the additional expense and effort required for even a modest increase in aperture (very large increases would require a departure from planar geometry of the detector)

1.3 Overview of detector

Fig. 1.4 shows the resulting layout of the LHC-B detector. As discussed in Chapt. 13, it is expected to be installed in pit IP-8, currently occupied by the DELPHI experiment.

LHC-B is a forward single-dipole spectrometer,

with the LHC storage ring beam pipe passing through the apparatus. The detector consists of a microvertex detector, a tracking system, aerogel and gas RICH counters, electromagnetic and hadronic calorimeters and a muon filter. In the following subsections, we briefly describe each spectrometer element. Chapters 4-9 contain more detailed descriptions of the different elements.

1.3.1 Beam pipe

At the center of the interaction region, there is a large vacuum tank which flares out to a diameter of 80 cm at $z = 1$ m, to accommodate the 400 mrad acceptance of the spectrometer. It is followed by a conical vacuum pipe with an angle of 13 mrad. A second vacuum window at about $z = 5.4$ meters will allow tracks with polar angles as small as 5 mrad to emerge. Such tracks, although they will not be detected in the microvertex detector system, will be useful for reconstructing certain types of events.

1.3.2 Dipole magnet

In order to keep the size of the magnet reasonable for the proposed acceptance, the dipole magnet is positioned just after the first gas RICH counter, with the pole pieces covering $z = 3$ m to 6 m. For all Monte-Carlo simulations reported in this document, a “box-field” has been assumed over this region with a field of 1.2 Tesla. As shown in Chapt. 12, The 3.6 Tm field integral, combined with the proposed LHC-B tracking system, provides good invariant mass resolution and background suppression.

LHC-B has reserved 4.6 m along the beam for the magnet. The magnet proposed as the preferred option for GAJET[2] almost fits these requirements. The conceptual design of the GAJET magnet was approved by the LHCC Magnet committee. The GAJET magnet has a free aperture of 3.5×3.5 m², a superconducting coil length of 4.3 m along the beam and a field integral of 4 Tm. The weight would be 950 tonnes for the iron and 35 tonnes for the coil. A magnet of this type would satisfy the needs of LHC-B.

In order to limit the Level-2 topology trigger algorithm to the reconstruction of straight tracks (see Chapt. 10), conventional shielding plates would be used to minimize the stray field at the vertex detector.

1.3.3 Microvertex detector

The silicon microvertex detector (see Chapt. 4) is installed inside the vacuum tank at the center of the

interaction region. The silicon planes are perpendicular to the circulating beams, operate at about 10 mm from the beams and will accept particles in the angular range from about 13-400 mrad. The silicon detectors are shielded from RF pickup of the passing beam bunches by 100 μ m-thick aluminum windows. In order to avoid collapse of the windows, the silicon detectors operate in a secondary vacuum.

Alternative possibilities, such as the use of GaAs[3], Diamond[4, 5] and Scintillator-filled capillaries[6] (see Appendix A), are also under consideration because of their improved tolerance to radiation damage. All of these devices are also candidates for use as part of the inner tracker system discussed in Chapt. 5. An additional advantage of capillary detectors is that each measurement station provides a track slope, which could simplify pattern recognition. A recent interesting silicon development[7] is that oxygen-doped silicon may also reduce radiation damage.

1.3.4 Tracking system

The tracking system is described in Chapt. 5. There will be independent inner and outer tracking systems, similar to what is planned for the HERA-B experiment at DESY. The inner tracking chambers have dimensions of ± 20 cm.

There are two tracking stations in front of the magnet, one just before and one just after the aerogel RICH counter system. The angular coverage of these stations matches that of the silicon system and will permit reliable matching of tracks in the silicon with those in the chamber system.

Tracks with polar angles less than 300 mrad emerge from the magnet in the non-bending y -view, and will be measured by a total of 11 chamber stations, in addition to the two stations before the magnet. Those with angles between 300 and 400 mrad only reach the center of the magnet and are measured by a total of 6 chambers.

As described in Chapt. 5, we consider Honeycomb strip chambers as a candidate for the outer tracking system, similar to the HERA-B system. For the inner trackers where the highest particle densities will be found, two possible options are discussed in that chapter (Micro-Cathode-Strip chambers and the Micro-Strip Gas Counters). Micro-Gap chambers will also be considered.

1.3.5 RICH counters

Acceptance for B-mesons turns on at a B-meson momentum of about 30 GeV and extends to several hundred GeV, as seen in Fig. 1.2. The momentum range

LHC-B

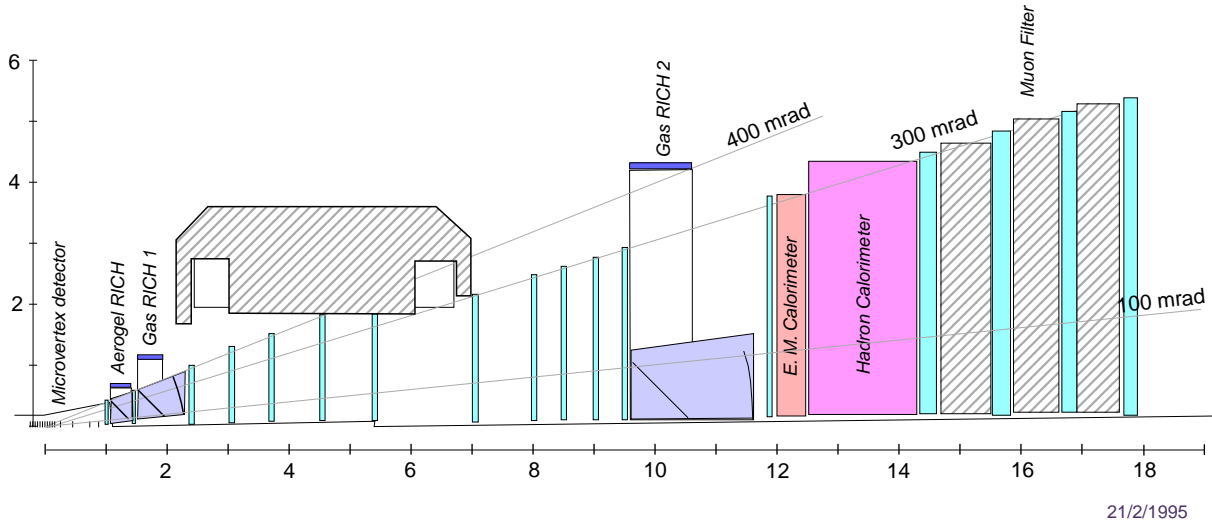


Figure 1.4: Side View of LHC-B layout (scales in meters):

The silicon microvertex detector is installed inside the collider vacuum pipe at the center of the interaction region (on the left-hand side of the drawing at $z = 0$). The two vacuum windows, at 100 cm and 540 cm, respectively, are connected by a 13 mrad conical vacuum pipe section. There are 13 tracking stations, positioned before, inside and after the dipole magnet (the 13th station is identical to μ_2 in Chapt. 8). There are also Roman-pot detectors installed downstream in both arms as described in Chapt.9.

of the decay products from accepted B-mesons extends from about 1 GeV to 150 GeV (see Fig. 6.1). Particle identification coverage of the full momentum range requires a combination of aerogel and two gas-RICH counter systems.

As shown in Fig. 1.4, the spectrometer utilizes two gas RICH counters, one before the magnet which covers angles between 100-400 mrad and one after the magnet which covers 10-120 mrad. In addition, there is an aerogel RICH counter before the magnet which covers the angular range from about 100-400 mrad. In all counters, the photon detectors are positioned outside the spectrometer aperture. Chapt. 6 contains further details of the counters.

1.3.6 Calorimeter systems

The proposed electromagnetic calorimetry will be used to:

- provide electron identification over the full energy range,
- provide a high- p_t electron trigger,

A medium resolution electromagnetic calorimeter based on the Shashlik design would be sufficient for the particle identification and the high- p_t electron triggers. The hadron calorimeter, whose primary purpose is for the high- p_t hadron trigger discussed in Chapt. 7, also serves as the initial part of the muon filter system, as described in Chapt. 8. We are considering a scintillating tile design for the hadron calorimeter. The inner sections of both calorimeters will use different technologies in order to minimize difficulties due to radiation damage.

It has been demonstrated that certain types of B-decays involving γ 's and π^0 's in the final state can be reconstructed if a higher resolution (e.g., crystal) e.m. calorimeter is used. This would be considered as a possible upgrade.

1.3.7 Muon system

The LHC-B muon detection system described in Chapt. 8 serves two purposes:

- It provides muon identification,
- It provides a high p_t muon trigger.

The system covers a 300 mrad aperture in both non-bending and bending views and has four wire chamber stations imbedded in the calorimeter and muon-shield system. Two possible muon trigger algorithms are described in Chapt. 10, both of which lead to a very efficient high- p_t muon trigger. Cathode-Strip Chambers are described as an example of a system that could satisfy the requirements of the muon system.

1.3.8 Roman-pot detectors

Detectors will be installed in Roman-pots[8] along both of the spectrometer arms. This is a standard technology which allows particles which are outside the circulating-beam envelopes to be measured by detectors installed in moveable devices, such that the pots can be retracted during beam manipulations.

As described in Chapt. 9, the installation of pot systems at varying distances from the LHC-B installation will allow particles emitted at small polar angles to be measured over a large range of momenta. Measurement of outgoing beam-like particles allows the study of diffractive phenomena, which have experienced a recent renewal of interest, because of the observation of hard-scattering processes in such reactions. See the discussion in Chapt. 3.

1.4 Particle densities

The particle density (per interaction) can be described to a good approximation as a function of the radial distance, r , from the beam:

$$\frac{dn}{dA} = \frac{a(z)}{r^2} \quad (1)$$

The parameter $a(z)$ has been evaluated at the z -positions of all tracking stations with the use of the PYTHIA event generator (used together with JETSET 7.4[1]) and GEANT[9] to model the interactions of particles traversing the beam pipe and the detector elements.

The results are given in Fig. 1.5. The effects of the secondary interactions are clearly visible. Since the differences of the particle fluxes in planes parallel and perpendicular to the magnetic field are less than 10%, Fig. 1.5 shows the average over all azimuthal angles.

The HERA-B experiment has to deal with similar particle densities ($a(z) \approx 3$ particles per bunch crossing). Therefore, the final design of our tracking system will be aided by the experience and detailed Monte Carlo studies for HERA-B [10].

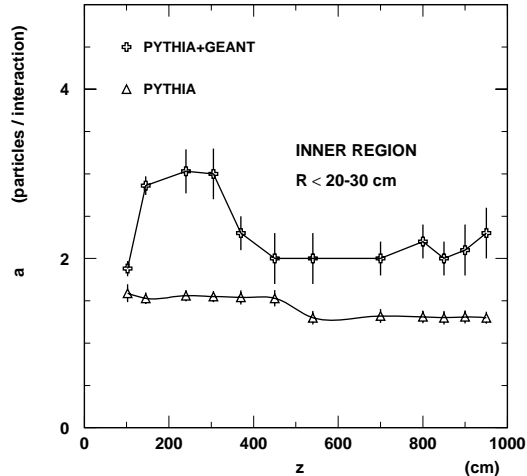


Figure 1.5: $a(z)$ -parameter (particles per interaction) versus z -position of the measuring stations, as defined in Eq. 1. The raw generated PYTHIA points are triangles and the yields after secondary interactions in the beam pipe and detector elements are crosses.

1.5 Running conditions

We propose a nominal running scenario in which a constant luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is maintained during a run⁴. All yield estimates in this LOI are given for this luminosity.

The ability to run with this rather modest luminosity is made possible by our proposed efficient and versatile Level-1 trigger system (see next section and Chapt. 10). There will be about 0.25 interactions per bunch crossing and pileup (multiple interactions in a bunch crossing) will be negligible.

The Level-1 triggering scheme described in Chapt. 10 leads to a Level-1 output rate of about 230 kHz, significantly below our design value of 400 kHz (see Chapt. 11).

A Level-2 suppression of about 20 will lead to a Level-2 output rate of 10 kHz. The final stage of triggering (Level-3), as described in Chapt. 10, will reduce the recorded event rate to a few times 100 Hz.

⁴In the detector and data-acquisition designs, we plan to allow for running up to a maximum luminosity of $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, which would be useful for certain dedicated runs, such as for the rare mode $B_s \rightarrow \mu^+ \mu^-$ (see Chapt. 12).

1.6 Triggering overview

This subject is covered in detail in Chapt. 10. Here we summarize the main features of the triggering approach. There will be three basic trigger types at Level-1:

- High- p_t single- and di-Muon triggers
- High- p_t single- and di-Electron triggers
- High- p_t Hadron trigger

Level-2 will contain refined versions of all components of the Level-1 trigger, in addition to a vertex topology trigger using data from the microvertex detector. In this document, we only discuss the Level-2 topology trigger in detail, as it alone gives us sufficient additional suppression to demonstrate the feasibility of the entire triggering scheme.

One purpose of the high- p_t Hadron trigger is to supplement the yield of those final states which do not have a lepton in them. In particular, as will be shown in Chapt. 10, this trigger significantly enhances the yield for $B_d \rightarrow \pi^+ \pi^-$ over what can be obtained from a muon trigger alone.

The larger variety of triggering sources for our final data samples will make for a sounder experiment and lead to a greater understanding of trigger and other biases.

Table 1.1 summarizes the trigger simulation results in Chapt. 10. For the assumed luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and the calculated Level-1 and Level-2 trigger efficiencies, the table shows the expected annual number of accepted and triggered “Events on Tape” (assuming no further losses in the Level-3 trigger). The results of reconstruction and flavour-tagging on these events are discussed in Chapt. 12 and partially summarized in the next section.

1.7 Performance overview

Very detailed but, to some extent, still preliminary results on event reconstruction, tagging and “CP-Reach” are given in Chapt. 12. The greatest uncertainties lie in the area of background suppression, a topic which is the subject of ongoing work. In addition, we have not yet studied all possible methods for the determination of the angles in the unitarity triangle.

Table 1.2 shows the LHC-B “CP-Reach” expected annually for $\sin(2\alpha)$ and $\sin(2\beta)$, when we run with $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. Only the statistical errors are shown - see Chapt. 12 for discussions of the systematic uncertainties. The event yields are also given

Event Sample	Visible B.R.	Events On Tape
$B_d \rightarrow \pi^+ \pi^-$	$2.0 \cdot 10^{-5}$	110k
$B_d \rightarrow J/\psi K_s^0 (\mu\mu)$	$2.1 \cdot 10^{-5}$	340k
$B_d \rightarrow J/\psi K_s^0 (ee)$	$2.1 \cdot 10^{-5}$	183k
$B_d \rightarrow J/\psi K^* (\mu\mu)$	$6.3 \cdot 10^{-5}$	1,270k
$B_d \rightarrow J/\psi K^* (ee)$	$6.3 \cdot 10^{-5}$	679k
$B_d \rightarrow \bar{D}^0 K^* (K\pi K\pi)$	$8.0 \cdot 10^{-7}$	3k
$B_s \rightarrow D_s^- \pi^+$	$1.4 \cdot 10^{-4}$	171k
$B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$	$3.5 \cdot 10^{-4}$	277k
$B_s \rightarrow D_s^- K^+$	$1.1 \cdot 10^{-5}$	13k
$B_s \rightarrow D_s^+ K^-$	$5.3 \cdot 10^{-6}$	6k
$B_s \rightarrow J/\psi \phi (\mu\mu)$	$4.2 \cdot 10^{-5}$	246k
$B_s \rightarrow J/\psi \phi (ee)$	$4.2 \cdot 10^{-5}$	133k
$B_s \rightarrow \mu^+ \mu^-$	$4.0 \cdot 10^{-9}$	30
$B_d \rightarrow \mu^+ \mu^- K^*$	$2.9 \cdot 10^{-6}$	17k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi)$	$1.5 \cdot 10^{-5}$	76k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi\pi\pi)$	$3.1 \cdot 10^{-5}$	117k

Table 1.1: The calculated number of “Events on Tape” in single-interaction bunch crossings, using the Level-1 and Level-2 trigger efficiencies from Chapt. 10 $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, and assuming no losses in Level-3. Note that reconstruction and tagging efficiencies are not included in this table. For $B_d \rightarrow \pi^+ \pi^-$ the branching fraction, 2×10^{-5} , is used, as it has become the “standard” for comparing different experiments. Recent measurements[11] indicate that the actual value may be smaller. The predicted branching fraction for $B_s \rightarrow \mu^+ \mu^-$ is from Ref. [12].

for the modes used in the two γ analysis methods which are described in Chapt. 12. The following paragraph contains a short description of the methods and gives a typical result for γ .

The third angle γ is studied in two different ways. Method-1 uses the time-dependent rates of $B_s \rightarrow D_s^\pm K^\mp$. Method-2 requires time-integrated decay rates for $B_d \rightarrow \bar{D}^0 K^*$. Since the two methods use different techniques, systematics can be well understood. Furthermore, Method-1 measures $\sin(\gamma)$ and Method-2 measures $\sin(2\gamma)$. Thus, even for the case of $\gamma = 90^\circ$, we will observe a positive signal for CP violation. As an example of the “CP-reach” in this sector, if the difference in the strong interaction phases between the two relevant quark diagrams is small, γ can be measured with a precision of $\sigma \approx 10^\circ$ for $x_s = 20$ and $\gamma \approx 80^\circ$.

We also show in Chapt. 12 that mixing in B_s decay can be measured for values as large as $x_s = 55$, with errors less than 0.1.

Finally, in the area of FCNC decays, we summarize the result for $B_s \rightarrow \mu^+ \mu^-$. A detailed GEANT analysis of this decay, and the dominant background from

	$\sin(2\alpha)$ from $B_d \rightarrow \pi^+ \pi^-$	$\sin(2\beta)$ from $B_d \rightarrow J/\psi K_s^0$		$\sin(\gamma)$ from $B_s \rightarrow D_s^\pm K^\mp$	$\sin(2\gamma)$ from $B_d \rightarrow \bar{D}^0 K^*$
Number Events	110k	340k ($\mu\mu$)	183k (ee)	19k	3k
Reconstruction efficiency	0.29	0.38	0.10	0.36	0.20
Tagging efficiency	0.44	0.37	0.37	0.49	–
N(Reconst. & Tagged)	14k	48k	7k	3.3k	600
$\delta \sin(2\phi_i)$	0.030	0.017		see text	see text

Table 1.2: “CP-Reach” for angles α and β for one year of running with the luminosity, $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. Errors are statistical only. See Chapt. 12 for a discussion of the systematic uncertainties.

two semi-leptonic B-decays, shows that a 3σ signal of the Standard Model decay could be seen in 2-years, running with a luminosity of $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. We believe that, with continued analysis of the decay and its background, it should be possible to improve on this result. It may also be possible, if desired, to have a dedicated run with higher luminosity than $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

1.8 Other physics

The LHC-B spectrometer is a general purpose detector for the forward direction and, as such, can be used for many physics topics in addition to CP-violation in B-decay. Chapt. 3 outlines a partial list of additional physics topics which can be addressed by the LHC-B collaboration.

Some of these topics are direct “fall-out” from our primary B-physics program. They require no special triggers or additional detectors. Examples of this class of physics are focussed studies of special B-final-states:

- Mixing & direct CP-violation in D-decays;
- Search for lepton-number violation in $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$.

It is evident from the Monte-Carlo work we have already done that the useful D-event yields are about an order-of-magnitude better than expectations at the proposed Tau-Charm factory[13]. For τ -decay studies, our yields are perhaps two or three times larger than expected event samples at a future e^+e^- “B-factory” running with design luminosity. It appears that LHC-B will be an interesting “Tau-Charm factory”.

Other topics include “center stage” strong interaction physics items to which LHC-B can make important contributions:

- Tagged Pomeron beam experiments (Diffraction);

- Cosmic ray phenomena in pp and ion-ion collisions;
- Production of J/ψ and Υ production in ion-ion collisions.

The first two strong-interaction topics can be studied parasitically, while the last would require rebuilding the detector with appropriate shielding. It could therefore only be carried out after the primary B-physics program was completed.

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2 B-Physics Objectives

The physics topics described in this chapter which allow stringent tests of the Standard Model are those which will have our absolutely highest priorities during the life of LHC-B.

2.1 CKM matrix & unitarity triangle

Within the Standard Model, quark mixing is described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix. This matrix has 9 complex elements, but only 4 independent variables. Eq. 2 shows the matrix in the parameterization of Wolfenstein[1]:

$$\begin{aligned}
 V &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
 &= \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}
 \end{aligned} \tag{2}$$

It is important to note that the CKM matrix is not simply an arbitrary parameterisation of physical observables, but appears in the Standard Model Lagrangian. *Hence its parameters are of equal importance in the theory as, say, G_F or the masses of the Z^0 and the top quark.* There has been much experimental effort expended recently[2] on measuring the latter two quantities, the first of which is now known with startling precision, and the second of which is now known to better than 10% [3].

In contrast however, two of the CKM parameters, ρ and η , are very poorly determined. A major goal of this experiment is a precise determination, and in fact an over-determination of these two quantities as a sensitive test of the Standard Model description of quark mixing. In conjunction with measurements already made, this can be accomplished by the measurement of $B_s^0-\bar{B}_s^0$ mixing, CP violation in various decays of B mesons, and rare decays of B mesons.

In order to appreciate the full significance of these measurements, it is necessary to consider the information currently available on the elements of the CKM matrix, and its limitations.

So far, $|V_{ud}|$ has been determined precisely in nuclear beta decay and $|V_{us}|$ from $K \rightarrow \pi l \nu$ decays. These give a precise measurement of λ ($\simeq 0.22$) to about 1 %. $|V_{cb}|$, and thus A , is determined from semileptonic B decays, A being found to be 0.84 ± 0.06 [4]. With the increased statistics which will become available at CLEO II over the next few years, and later at BaBar, the techniques[5] of heavy quark symmetry applied to exclusive semi-leptonic decays

will probably enable the eventual extraction of $|V_{cb}|$ with a precision of around 2 %.

Three present measurements provide limited information on the remaining two variables, ρ and η . One is the determination of $|V_{ub}/V_{cb}|$ from the measurement of the ratio of charmless to charmed semi-leptonic B decays at CLEO. From Eq. 2 it can be seen that this combination fixes the value of $\sqrt{\rho^2 + \eta^2}$ (as λ is known). This results in an annulus in the $\rho - \eta$ plane, centered on the origin (Fig. 2.1). It is

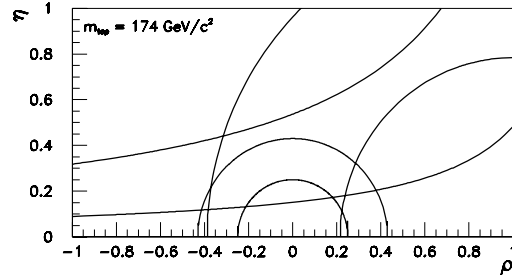


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for $m_t = 174$ GeV. The annular region centered at the origin is the region allowed by the measurements of $|V_{ub}/V_{cb}|$. The annular region centered on the point (1,0) is that allowed by measurements of $B_d^0-\bar{B}_d^0$ mixing. The approximately hyperbolic band is the region allowed by the measurements of the CP-violation parameter ϵ in kaon decays.

again likely that this measurement will improve over the next few years, as statistics increase. At present however, the errors which determine the width of the annulus are dominated by model dependence. A program is underway[6] to try to gather enough data to distinguish between the models. It is expected that the width of the annulus will eventually be reduced by a factor of 2 which will help considerably to constrain the allowed region of the $\rho - \eta$ plane.

The other two relevant measurements are those of $B_d^0-\bar{B}_d^0$ mixing and the CP-violation parameter, ϵ , in K decays. Although both are well-measured, their interpretations in terms of CKM parameters are dogged by theoretical uncertainties and a dependence on the imperfectly-measured top-quark mass. $B_d^0-\bar{B}_d^0$ mixing depends on the combination $|V_{td}V_{tb}^*|^2$ which can be seen to fix the quantity $(1-\rho)^2 + \eta^2$ (A and λ being known), thereby defining an annulus in the $\rho-\eta$ plane centered on the point (1,0). ϵ depends approximately on the quantity $(1-\rho)\eta$, measurements thereby providing constraints which form hyperbolae in the $\rho-\eta$

plane. The constraints provided by all the above measurements are shown in Fig. 2.1 for a top-quark mass of 174 GeV. For each constraint, the theoretical errors dominate the width of the allowed regions shown.

The above measurements are usually discussed with reference to the so-called ‘‘Unitarity Triangle’’, (Fig. 2.2) whose vertices are formed by the origin, the point (1,0) and the point (ρ,η) . The inside angles of

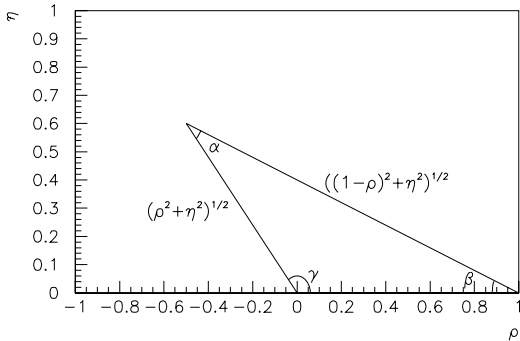


Figure 2.2: The Unitarity Triangle

the triangle can be determined rather well by measurements of CP-violation in B decays. The following notation will be used for them:

- α is the inside angle at the point (ρ,η) ,
- β is the inside angle at the point (1,0),
- γ is the inside angle at the origin.

In total, there exist 5 other triangles, corresponding to the unitarity conditions of the CKM matrix. All 6 triangles can be determined by the measurement of their sides, four sides being independent. As shown above, this leads to some limited knowledge about the shape of the triangles already today. The goal of CP-violation experiments is the precise measurements of the angles inside the triangles. Again there are four independent angles (α, β, γ are three of them). Their measurement would also completely determine the CKM matrix, independently of any measurement of side lengths.

In the LHC-B experiment, we hope to determine the unitarity triangle completely, without using previous measurements. All angles, one side and the height of the triangle can be measured independently. This allows a thorough test of the internal consistency of the Standard Model.

The general strategy might look as follows:

1. From the precise measurement of CP violation in the decay $B^0 \rightarrow J/\psi K_S^0$ and similar channels we will obtain a clean and precise measurement of the angle β . The measurement of B_s -mixing determines the length of the side opposite to the angle γ . Thus, assuming the validity of the CKM description, the whole unitarity triangle is completely determined with high accuracy.
2. Additional decay channels, mostly exhibiting CP violation, are used to check the internal consistency of the CKM description of the unitarity triangle. These measurements are in general less clean or precise than those in step 1: The measurement of the angle α may suffer from possible penguin contributions. The measurement of the angle γ is limited in precision because strong phases have to be experimentally determined together with the weak phase and there are fewer events. The increased number of fit parameters reduces the statistical power of the method. Also, the measurement of the triangle height using the small CP-violating decay $B_s^0 \rightarrow J/\psi \phi$ is limited in statistical precision. Nevertheless, these three classes of decays should together allow a stringent test of the internal consistency of the unitarity triangle.
3. Beyond the detailed test of the CKM description of CP violation, a wide spectrum of rare B decays can be studied, yielding independent information on the CKM parameters.

In the following sections, we discuss the formalism behind this experimental program in more detail.

2.2 B_s^0 - \bar{B}_s^0 mixing.

The general formalism of $B^0 - \bar{B}^0$ -mixing has been described many times and is reviewed in Ref. [7]. Allowing for $B^0 \leftrightarrow \bar{B}^0$ transitions, the time-evolved state for an initial B^0 (\bar{B}^0) may be written:

$$|\overline{\psi}^0\rangle(t) \propto e^{-im_1 t - \frac{\Gamma_1}{2}t} \cdot |B_1\rangle \pm e^{-im_2 t - \frac{\Gamma_2}{2}t} |B_2\rangle \quad (3)$$

where $|B_1\rangle$ and $|B_2\rangle$ are the two eigenstates of the B meson mass matrix. Then the probability of the state to decay as a B^0 (\bar{B}^0) meson is given by

$$|\langle B^0 | \overline{\psi}^0(t) \rangle|^2 \propto e^{-\Gamma t} [1 \pm \cos(\Delta m t)] \quad (4)$$

$$|\langle \bar{B}^0 | \overline{\psi}^0(t) \rangle|^2 \propto e^{-\Gamma t} [1 \mp \cos(\Delta m t)] \quad (5)$$

where $\Delta m = m_2 - m_1$ and $\Gamma \equiv \Gamma_1 \approx \Gamma_2$. Dilution effects, or mis-tagging of a B meson’s initial flavor (see Chapt. 12), have the consequence that what is

observed in the four data samples are linear combinations of the two functions in Eqs. 4 and 5. Observation of the time dependences in any of the 4 data samples (i.e., the 4 combinations of initial and final state flavours) enables the mass difference Δm_α and a “dilution factor” to be determined. From this, the mixing parameter $x_\alpha = \Delta m_\alpha/\Gamma_\alpha$, the number of oscillations per lifetime, can be derived.

Let us see how a measurement of $B_s^0 - \overline{B}_s^0$ mixing can improve the determination of the quantity $(1 - \rho)^2 + \eta^2$ (ie. the distance from the apex to the point (1,0)). In the Standard Model, the mixing frequency Δm_α , where α stands for the flavour of the light quark in the B meson, is given by [7]:

$$\Delta m_\alpha = \frac{G_F^2}{6\pi^2} m_{B_\alpha} \eta_{QCD} (B_{B_\alpha} f_{B_\alpha}^2) F m_t^2 |V_{t\alpha} V_{tb}^*|^2. \quad (6)$$

The masses m_{B_α} are measured, while η_{QCD} , B_{B_α} and f_{B_α} are all calculated, their uncertainties accounting for the widths of the relevant annular bands in Fig. 2.1. $F(m_t^2/M_W^2)$ is an analytic and slowly varying function of m_t , the top-quark mass. If we now consider the ratio $\Delta m_d/\Delta m_s$, we see that the top-quark mass dependence is canceled completely while all the calculated quantities appear as ratios which are expected to be close to unity and to have small uncertainties. In fact we get⁵

$$(\rho-1)^2 + \eta^2 = \left(\frac{\Delta m_d}{\Delta m_s}\right) \left(\frac{1}{\lambda^2}\right) \left(\frac{B_{B_s}}{B_{B_d}}\right) \left(\frac{f_{B_s}}{f_{B_d}}\right)^2 \quad (7)$$

where the last three factors are all known with small uncertainties, giving a much improved constraint for $(\rho - 1)^2 + \eta^2$.

It should be noted that, as the parameter $|V_{ts} V_{tb}^*|^2$ which governs $B_s^0 - \overline{B}_s^0$ mixing depends only on A and λ , the measurement of this quantity provides no direct information on ρ and η . Rather it provides the combination $\eta_{QCD} (B_{B_s} f_{B_s}^2) F(m_t^2/M_W^2) m_t^2$ in Eq. 6. Assuming this to be similar to the equivalent combination for the B_d^0 , as expected, one is then able to extract the combination $(\rho - 1)^2 + \eta^2$ from $B_d^0 - \overline{B}_d^0$ mixing.

It is of interest to know what the current experimental and theoretical limits are on the parameter x_s . The time-integrated B^0 mixing observed at the $\Upsilon(4S)$ machines[8] is pure $B_d^0 - \overline{B}_d^0$ mixing, while that observed at UA1, CDF and LEP is due to a mixture of B_d^0 and B_s^0 mesons. While this provides a clear proof of the existence of $B_s^0 - \overline{B}_s^0$ mixing, the time dependence could not yet be resolved

⁵Historically, the ratio $x_d/x_s = (\Delta m_d \tau_{B_d})/(\Delta m_s \tau_{B_s})$ was used rather than $\Delta m_d/\Delta m_s$. We prefer to express the whole argument in term of mass difference parameters since these are directly measured in time dependent mixing experiments.

experimentally. First time-dependent mixing measurements have been made at LEP, but fitting them with two frequency components, only enables to set a lower limit for the frequency of $B_s^0 - \overline{B}_s^0$ mixing at $x_s > 8.5$ [9].

Theoretical predictions of the rate of B_s^0 mixing may be obtained from the Standard Model, Eq. 6 above. Allowing the ranges $158 \text{ GeV} < m_t < 190 \text{ GeV}$ [3] and $0.12 \text{ GeV} < \sqrt{B_{B_s}} f_{B_s} < 0.25 \text{ GeV}$ [10], this predicts $4 < x_s < 32$. In principle, another constraint is available for x_s : the determination of $|V_{ub}/V_{cb}|$ by CLEO may be combined with the measured value of ϵ to constrain the position of the point (ρ, η) . The argument may then be reversed to determine x_s from Eq. 7 using the measured value of x_d . We find $0.5 < (\rho - 1)^2 + \eta^2 < 2.0$, giving $7 < x_s < 59$, where we have used $x_d = 0.78 \pm 0.05$ [11] and $f_{B_s} \sqrt{B_{B_s}}/f_{B_d} \sqrt{B_{B_d}} = 1.16 \pm 0.1$ [10]. The fact that this method gives similar information to the previous direct method of calculation is related to the internal consistency of the allowed regions in Fig. 2.1.

As shown in Chapt. 12, the above range of x_s is well within the reach of LHC-B. It is quite possible that, in the meantime, improved measurements of the ratio $|V_{ub}/V_{cb}|$ will become available. Such a development will serve to constrain further the theoretically allowed range of values of x_s . Failure to find $B_s^0 - \overline{B}_s^0$ mixing frequencies in the allowed range will immediately signal a failure of the Standard Model description of quark mixing in weak interactions.

With the ratio $\Delta m_d/\Delta m_s$, or equivalently x_d/x_s , measured as discussed above, and with the anticipated improved bounds on the ratio $|V_{ub}/V_{cb}|$, the intersection of the two resulting (relatively narrow) bands defining the sides of the unitarity triangle should be quite well determined. The constraint from ϵ will provide a non-trivial cross-check. Then the latter, in conjunction with the x_s measurement, will provide a “measurement” of the quantity $\sqrt{B_{B_s}} f_{B_s}$ for comparison with lattice QCD calculations[12].

2.3 CP violation in B -decays

CP-violation is not yet fully understood in the Standard Model. It is put-in for empirical reasons, by allowing the Yukawa couplings of the Higgs to the quarks to be complex. In the case of 3-or-more generations, this results in an imaginary component in the CKM matrix which, in turn, gives rise to CP violating observables in weak interactions. This origin of CP violation is intimately related to both the mass problem (the quark masses also arise from the Higgs-quark Yukawa couplings) and the generation problem (as the effect would be absent with less than

three generations). On a larger scale, CP violation is thought to be a necessary precondition for the origin of the baryon asymmetry of the universe. All these facts make the study of CP violation a compelling one.

As we have argued in the above sections, despite the fact that CP violation is well-measured in the neutral Kaon system, this has only a limited impact on our knowledge of the size of the fundamental imaginary quantity, $|\eta|$, in the CKM matrix, both because of the uncertainties in the top-quark mass, and because of incalculable (to date) hadronic factors. On the other hand, many CP-violating observables in the decays of B mesons are expected to provide highly constraining information, owing to a complete absence of hadronic uncertainties. These will not only tightly fix the unitarity triangle but also highly over-constrain it. Thus we can perform very precise tests on its internal consistency using measurements of such observables, as a test of the Standard Model description of quark mixing in weak interactions. There are three types of such measurements:

- Decays of neutral B mesons to final states which are CP-eigenstates.
- Decays of neutral B mesons to final states which are not CP-eigenstates.
- Decays of charged B mesons.

The general features of the above types of measurements are discussed below in turn:

General description of decays of B_d , B_s -mesons:

In the case of neutral B mesons, CP-violation is entwined with the phenomenon of $B^0 - \bar{B}^0$ mixing. The general formalism has been described many times and may be found for example in the review of Ref. [13]. In this formalism, the two eigenstates of the neutral B meson mass matrix, $|B_1\rangle$ and $|B_2\rangle$, may be written in terms of the beauty eigenstates:

$$|B_{1(2)}\rangle = p|B^0\rangle + (-)q|\bar{B}^0\rangle \quad (8)$$

where p and q are complex numbers with $|p|^2 + |q|^2 = 1$. Within the Standard Model, the ratio q/p is given by the CKM phases

$$(q/p)_{B_d} \simeq 2 \arg(V_{td}V_{tb}^*), (q/p)_{B_s} \simeq 2 \arg(V_{ts}V_{tb}^*) \quad (9)$$

for the two types of neutral B mesons respectively. Considering a final state f and its CP conjugate \bar{f} , we can define the decay amplitudes for pure beauty

eigenstates:

$$\begin{aligned} M_f &= \langle f|B^0\rangle & \bar{M}_f &= \langle f|\bar{B}^0\rangle \\ M_{\bar{f}} &= \langle \bar{f}|B^0\rangle & \bar{M}_{\bar{f}} &= \langle \bar{f}|\bar{B}^0\rangle \end{aligned} \quad (10)$$

and the quantities:

$$\lambda = \frac{q}{p} \frac{\bar{M}_f}{M_f} \quad \bar{\lambda} = \frac{q}{p} \frac{\bar{M}_{\bar{f}}}{M_{\bar{f}}} \quad (11)$$

(these should not be confused with the CKM parameter λ). Then the time-dependent rates, $(\bar{\Gamma}_f)(\bar{B}^0 \rightarrow f)$ and $(\bar{\Gamma}_{\bar{f}})(\bar{B}^0 \rightarrow \bar{f})$, for the decays of states which are initially in a pure B^0 or \bar{B}^0 state (they may oscillate into the charge-conjugate state before decaying) into the final states f and \bar{f} are given by

$$\begin{aligned} (\bar{\Gamma}_f)(t) &= A \cdot e^{-\Gamma t} \cdot \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \frac{2|\lambda| \cos\Theta_\lambda}{1+|\lambda|^2} \sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm I(t) \right] \\ (\bar{\Gamma}_{\bar{f}})(t) &= \bar{A} \cdot e^{-\Gamma t} \cdot \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \frac{2|\bar{\lambda}| \cos\Theta_{\bar{\lambda}}}{1+|\bar{\lambda}|^2} \sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm \bar{I}(t) \right] \end{aligned} \quad (12)$$

where I, \bar{I} are the $B_1 - B_2$ interference terms due to mixing:

$$\begin{aligned} I(t) &= \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m t) - \frac{2|\lambda| \sin\Theta_\lambda}{1+|\lambda|^2} \sin(\Delta m t) \\ \bar{I}(t) &= \frac{1-|\bar{\lambda}|^2}{1+|\bar{\lambda}|^2} \cos(\Delta m t) - \frac{2|\bar{\lambda}| \sin\Theta_{\bar{\lambda}}}{1+|\bar{\lambda}|^2} \sin(\Delta m t) \end{aligned} \quad (13)$$

and where we introduced

$$A = \frac{1}{2} (|M_f|^2 + |\bar{M}_f|^2) \quad (14)$$

$$\bar{A} = \frac{1}{2} (|M_{\bar{f}}|^2 + |\bar{M}_{\bar{f}}|^2) \quad (15)$$

$$\Gamma = \frac{1}{2} (\Gamma_1 + \Gamma_2) \quad (16)$$

$$\Delta\Gamma = \Gamma_1 - \Gamma_2 \quad (17)$$

$$\Delta m = m_2 - m_1 \quad (18)$$

$$\theta_\lambda = \arg(\lambda) \quad (19)$$

$$\theta_{\bar{\lambda}} = \arg(\bar{\lambda}) \quad (20)$$

If decays of B_d^0 mesons are considered, $\Delta\Gamma$ is very small compared to Γ and can be set to zero in these expressions.

Of special interest is the case, where only a single diagram and therefore only a single CKM phase and

hadronic matrix element contributes to the decay. In this case, λ and $\bar{\lambda}$ are connected via

$$|\lambda| = \frac{1}{|\bar{\lambda}|} . \quad (21)$$

Decays of B_d , B_s -mesons to CP-eigenstates:

If the neutral B meson decays into a CP eigenstate ($|\bar{f}\rangle = \pm CP|f\rangle$), like in the decays⁶

$$\begin{aligned} B_d^0 &\rightarrow J/\psi K_S^0 \\ B_d^0 &\rightarrow \pi^+ \pi^- \\ B_s^0 &\rightarrow \rho K_S^0 , \end{aligned}$$

λ and $\bar{\lambda}$ are identical,

$$\lambda = \bar{\lambda} , \quad (22)$$

and one is left with only two independent decay rates, Γ_f and $\bar{\Gamma}_f$.

If in addition only a single diagram contributes to the decay, Eqs. (21),(22) imply $|\lambda| = |\bar{\lambda}| = 1$ and the decay rates simplify considerably. For the decay of B_d^0 mesons one finds

$$\langle \bar{\Gamma}_f(t) \rangle = A \cdot e^{-\Gamma t} \cdot [1 \mp \sin(2\phi_f) \sin(\Delta m t)] , \quad (23)$$

where $2\phi_f = \Theta_\lambda$ is given by the CKM phases and is thus directly connected to the angles of the unitarity triangle. In this case, all hadronic matrix elements cancel in the CP asymmetry

$$A_f(t) = \frac{\Gamma_f(t) - \bar{\Gamma}_f(t)}{\Gamma_f(t) + \bar{\Gamma}_f(t)} = \sin(2\phi_f) \cdot \sin(\Delta m t) \quad (24)$$

which therefore provides a direct measure of the CKM phase ϕ_f .

The most important channel where this scenario applies is the decay $B_d^0 \rightarrow J/\psi K_S^0$, which is governed by the angle β . This channel is also very attractive experimentally, because of its dilepton signature.

If more than a single diagram contributes to the decays, several CKM phases and hadronic matrix elements appear and therefore there is no longer a perfect cancellation of the hadronic matrix elements in the CP asymmetry. An important example is the case $B_d^0 \rightarrow \pi^+ \pi^-$ whose asymmetry is in lowest order governed by the angle α . Penguin diagrams may however also contribute significantly, in which case the measurement of α becomes more difficult. The unknown hadronic contributions can in principle still be eliminated by performing an isospin analysis which would

⁶The small deviation of $|K_S^0\rangle$ from the CP eigenstate can be neglected.

however necessitate reconstruction of the experimentally daunting $\pi^0 \pi^0$ final state.

Another channel suffering from additional hadronic contributions is that of $B_s^0 \rightarrow \rho K_S^0$ whose asymmetry is governed by γ . It is also thought to have a very low branching fraction, making measurements difficult. However there are alternative channels and methods for all these angles.

LHC-B will be sensitive to $\sin 2\beta$ in several decay channels, including $B_d^0 \rightarrow J/\psi K_S^0$, $B_d^0 \rightarrow \psi(2S) K_S^0$ and $B_d^0 \rightarrow J/\psi K^{0*}$. The CP-reach in these channels will be summarised in Chapt. 12.

Decays of B_s -mesons to non-CP-eigenstates:

These decays can be used for a measurement of the angle γ in the unitarity triangle. The unknown hadronic phases can be extracted experimentally, if the time dependence of the decays

$$\begin{aligned} B_s^0 &\rightarrow f & B_s^0 &\rightarrow \bar{f} \\ \bar{B}_s^0 &\rightarrow f & \bar{B}_s^0 &\rightarrow \bar{f} \end{aligned}$$

are measured independently.

Considering again the case where only a single tree diagram contributes to the decays ($r = |\lambda| = 1/|\bar{\lambda}|$) and denoting by ϕ_f the weak phase difference and by δ_s the strong phase difference between $\langle f|B_s^0\rangle$ and $\langle f|\bar{B}_s^0\rangle$, the time dependent rates read

$$\langle \bar{\Gamma}_f(t) \rangle = A \cdot e^{-\Gamma t} \cdot \left[\cosh\left(\frac{\Delta\Gamma}{2} t\right) - \frac{2r \cos(\phi_f + \delta_s)}{1+r^2} \sinh\left(\frac{\Delta\Gamma}{2} t\right) \pm I(t) \right] \quad (25)$$

$$\langle \bar{\Gamma}_f(t) \rangle = A \cdot e^{-\Gamma t} \cdot \left[\cosh\left(\frac{\Delta\Gamma}{2} t\right) - \frac{2r \cos(\phi_f - \delta_s)}{1+r^2} \sinh\left(\frac{\Delta\Gamma}{2} t\right) \pm \bar{I}(t) \right] \quad (26)$$

with the interference terms

$$I(t) = +\frac{1-r^2}{1+r^2} \cos(\Delta m t) - \frac{2r}{1+r^2} \sin(\phi_f + \delta_s) \sin(\Delta m t) \quad (27)$$

$$\bar{I}(t) = -\frac{1-r^2}{1+r^2} \cos(\Delta m t) - \frac{2r}{1+r^2} \sin(\phi_f - \delta_s) \sin(\Delta m t) . \quad (28)$$

The standard model predicts $\Delta\Gamma/\Gamma \approx 0.1$.

An illustration of the forms of the above functions for typical values of the parameters is shown in Fig. 2.3. Fitting Eqs. 25 and 26 to the observed time-dependences yields the quantities r , $\sin(\phi_f + \delta_s)$

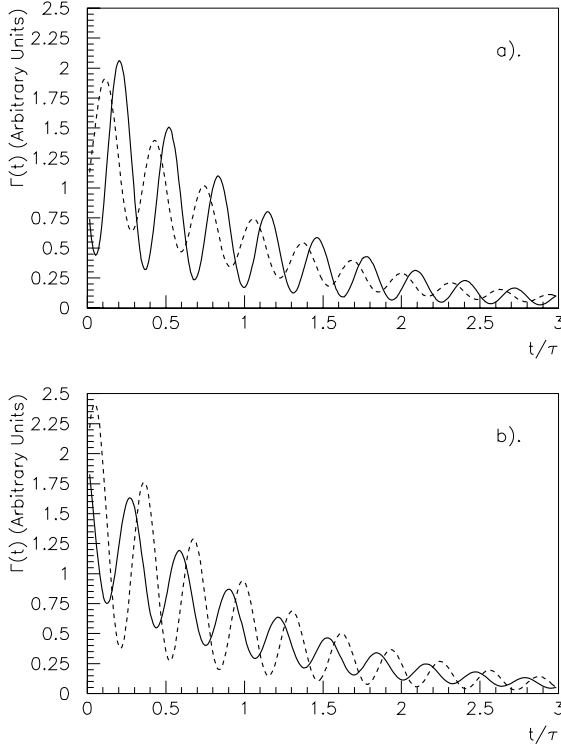


Figure 2.3: Examples of proper time distributions for decays of neutral B mesons to final non-CP-eigenstates. The examples shown are for B_s mesons with $x_s = 20$, $\phi_f = 0.5$, $\delta_s = 0.2$ and $\overline{M}/M = 1/\sqrt{2}$, neglecting $\Delta\Gamma$. The solid and dashed curves are for B_s mesons and \overline{B}_s mesons respectively for Eq. 25 in a). and Eq. 26 in b).

and $\sin(\phi_f - \delta_s)$, from which both the weak and the strong phase may be obtained.

This method can be applied to measure γ at LHC-B, by using the following B_s decays to non-CP-eigenstates:

- $B_s^0 \rightarrow D_s^\pm K^\mp$,
- $B_s^0 \rightarrow D_s^{*\pm} K^\mp$

In all cases, the weak phase is given by $\phi_f = 2(\pi - \gamma)$.

Decays to self-tagging final states

A second method of measuring γ consists of measuring the exclusive decay rates in the following 3 channels:

- $B^+ \rightarrow D_1^0 K^+$
- $B^+ \rightarrow \overline{D}^0 K^+$

- $B^+ \rightarrow D^0 K^+$

and their CP-conjugates. As $D_1^0 = (D^0 + \overline{D}^0)/\sqrt{2}$,

$$A(B^+ \rightarrow D_1^0 K^+) = \frac{1}{\sqrt{2}} [A(B^+ \rightarrow D^0 K^+) + A(B^+ \rightarrow \overline{D}^0 K^+)] \quad (29)$$

and

$$A(B^- \rightarrow D_1^0 K^-) = \frac{1}{\sqrt{2}} [A(B^- \rightarrow D^0 K^-) + A(B^- \rightarrow \overline{D}^0 K^-)] \quad (30)$$

Gronau and Wyler[14] have shown that the amplitudes are related by:

$$A(B^+ \rightarrow \overline{D}^0 K^+) = A(B^- \rightarrow D^0 K^-) \quad (31)$$

$$A(B^+ \rightarrow D^0 K^+) = \exp(2i\gamma) A(B^- \rightarrow \overline{D}^0 K^-) \quad (32)$$

where γ is the CKM phase to be measured. Then, Eqs. 29 and 30 may be described by two triangles in the complex plane, as shown in Fig. 2.4.

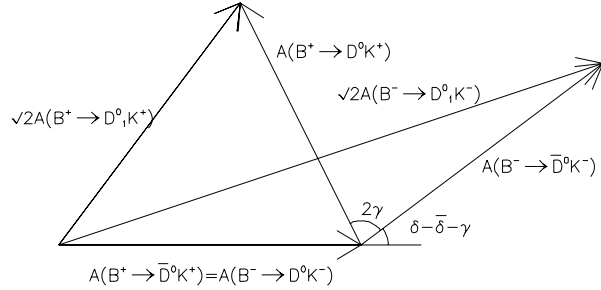


Figure 2.4: Complex triangles of Eqs. 29 and 30

In these channels, the charged B meson is self-tagging (by the charge of the kaon in the final state). Measurement of all six amplitudes (in fact, only four are independent) enables the angle γ to be extracted up to a two-fold ambiguity. As described in Ref. [14], the ambiguity may be removed by comparison of several different channels, eg. the ones above with D_1^0 replaced by D_2^0 , and both of these channels with the K^\pm replaced by other states with similar quantum numbers, eg. $K^0 \pi^\pm$, $K^\pm \pi^0$, $K^0 \pi^\pm K^\mp$, etc. These have the same CKM dependence, but different final state phases in each case, allowing the common CKM phase to be extracted from the analyses. In fact, this procedure alone provides a test of the Standard

Model, namely the requirement of a common CKM solution between all channels.

Analogous channels exist for B^0 decays[15], which are studied in Chapt. 12.

This method has the advantage of simplicity, in the sense that only the rates are required to be measured. On the other hand, not observing a time dependence, it may be difficult to prove that what one sees is really CP violation. The many channels approach should however increase confidence in the results.

LHC-B will be able to reconstruct all the above channels, and in view of its large cross-section \times Luminosity \times acceptance, will have unrivalled statistical precision.

2.4 Desired precision in CP angle measurements

In a talk at the 1994 La Thuile meeting, Bigi[16] quoted a comprehensive study by Ramond, Ross and Roberts of different classes of models with conditions (so-called “texture zeros”) postulated for the quark mass matrices at the GUT scale and then evolved down to the hadronic scales probed in B decay.

Bigi summarized these results in a simplified way in Table 2.1 for five classes of mass matrices with texture zeros in different positions. Although considerable theoretical progress is anticipated in this field over the next five years or so, the table is interesting because it provides us with a guide of how well the CP-violation angles would have to be measured in order to discriminate between these classes of models.

	A	B	C	D	E
$ V_{ub} / V_{cb} $	0.06	0.062	0.068	0.059	0.089
x_s/x_d	23	23	21	28	34
$\sin 2\alpha$	-0.17	-0.22	0.31	-0.39	-0.61
$\sin 2\beta$	0.52	0.54	0.58	0.51	0.72
$\sin 2\gamma$	0.66	0.71	0.31	0.81	0.99
$\sin \gamma$	0.94	0.92	0.99	0.89	0.75

Table 2.1: Predictions for CP-violation and mixing parameters for five classes of quark mass matrix models. A top mass of 180 GeV is assumed. Also assumed is $(f(B_s)/f(B_d))^2 = 1.1$, in order to translate $|V(ts)/V(td)|^2$ into x_s/x_d .

Fritzsch and Xing[17] have recently shown that a simple pattern for the generation of masses for the first family of leptons and quarks leads to an interesting and predictive pattern for the violation of CP symmetry. The observed magnitude of the Cabibbo angle requires CP violation to be maximal or at least near its maximal strength. The unitarity triangle is

approximately rectangular with $\alpha \approx 90^\circ$ and β in the range 13° to 18° . Then $\sin 2\alpha \approx \sin 2\gamma \approx 0.45$ to 0.59 .

2.5 Search for non-CKM physics

The decay mode

$$B_s \rightarrow J/\psi \phi \quad (33)$$

offers us the possibility to search for new (i.e., non-CKM matrix) physics[16]. We quote from Ref. [16]: “..in the transitions, quarks of only the 2nd and 3rd families contribute. Thus, there can be no observable CP violation, apart from violations of weak universality. CP asymmetries are then suppressed by λ^2 . However, once New Physics intervenes in the $\Delta B = 2$ sector driving $B^0 - \bar{B}^0$ oscillations, it will in general generate a CP asymmetry that in $B_s \rightarrow J/\psi \phi$ decays has a practically zero SM background - in contrast to $B_d \rightarrow J/\psi K_S$.”

The standard model prediction for the time-dependent decay distribution for React. 33 is Ref. [18]:

$$e^{-\Gamma_s t} [1 \pm 2\lambda^2 \eta \sin(\Delta m_s t)] \quad (34)$$

With $\lambda = 0.22$, and assuming that $\eta = 0.3$, we find $2\lambda^2 \eta \approx 0.03$ for the CP-violation coefficient. Since, as shown in Chapt. 12, we may expect to measure this coefficient with an annual statistical uncertainty of about 0.01, LHC-B should be in a very good position to detect larger values that could result from new physics (i.e. non-CKM physics).

It is also interesting to note that, with the small expected statistical uncertainty, a multi-year measurement of the CP-violation coefficient in React. 34 might be useful in its own right, since it yields η , the height of the unitarity triangle in Fig. 2.1. Of course, the limiting uncertainty in a measurement of $2\lambda^2 \eta$ will ultimately come from the determination of the multiplicative dilution factor.

2.6 Rare B-decays

Flavor-Changing-Neutral-Current B -decays are of great interest because of their role in providing quantitative information on the CKM matrix-elements, V_{td} , V_{ts} and V_{tb} . When combined with other available CKM matrix-elements information, as outlined earlier in this chapter, precision tests of the Standard Model can be made. This may provide one of the earliest routes to the discovery of a new physics sector beyond the Standard Model.

In the interest of brevity, we only discuss two classes of reactions for which LHC-B has particularly good sensitivity (see Chapt. 12), FCNC semilep-

tonic and purely leptonic B decays. They can be further classified as CKM-allowed and CKM-suppressed transitions involving the matrix element V_{ts} and V_{td} , respectively.

Inclusive semileptonic FCNC B -decays:

Ali et al.[19] have calculated both the long and short-distance contributions to inclusive FCNC $B \rightarrow (X_s, X_d) + \ell^+ \ell^-$ decays. For example, the short distance contributions (when the dilepton mass is away from the J/ψ and ψ' resonance regions) to the branching fractions are (for $m_t = 150$ GeV):

$$\begin{aligned} BR(B \rightarrow X_s + e^+ e^-) &= 1.5 \cdot 10^{-5} \\ BR(B \rightarrow X_s + \mu^+ \mu^-) &= 8.5 \cdot 10^{-6} \end{aligned}$$

Ref. [19] also calculate the (experimentally observable) forward-backward asymmetry for the dileptons in their center-of-mass system. This asymmetry in the Standard Model is proportional only to the Z and $W^+ W^-$ exchange diagrams, with the virtual Z contribution numerically dominating. Thus, it is sensitive to any enhancement in the effective bsZ and bdZ couplings. Likewise, all non-SM scenarios, which inherently have a chiral structure different from that of the Standard Model, will yield unmistakable distortion effects on the B -decay distributions.

Exclusive semileptonic FCNC B -decays:

We now discuss the exclusive semileptonic rare decays, $B \rightarrow (K, K^*) + \ell^+ \ell^-$ and $B \rightarrow (\pi, \rho, \omega) + \ell^+ \ell^-$ (also for them, the short distance pieces are measurable only away from the J/ψ and ψ' resonant regions).

Ali et al.[20, 21] have calculated the branching fractions of the exclusive semileptonic rare decays, as shown in Table 2.2. The corresponding CKM-suppressed exclusive decays $B \rightarrow (\pi, \rho, \omega) \ell^+ \ell^-$ are obtained by the appropriate CKM-matrix element ratio. The heavy quark symmetries of heavy to light transitions are exploited to obtain relations between the CC semileptonic heavy to light decays and the FCNC rare B decays. Their estimates are based on different assumed parametrizations of the Isgur-Wise function, fitted to the semileptonic D decays.

Leptonic FCNC B -decays:

The decay rates for $(B_s^0, B_d^0) \rightarrow \ell^+ \ell^-$ were discussed some time ago by Campbell & O'Donnell [22] to lowest (1 loop) order. More recently, next-to-leading-order calculations have been reported by Buchalla & Buras [23]. These calculations yield:

$$BR(B_s \rightarrow \mu^+ \mu^-) = 4.10 \cdot 10^{-9} \times$$

Parameterization	A	B
$BR(B \rightarrow K \ell^+ \ell^-)$	$6.0 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$
$R(B \rightarrow K e^+ e^-)$	4%	2%
$R(B \rightarrow K \mu^+ \mu^-)$	7%	3%
$BR(B \rightarrow K^* e^+ e^-)$	$5.6 \cdot 10^{-6}$	$4.1 \cdot 10^{-6}$
$R(B \rightarrow K^* e^+ e^-)$	37%	28%
$BR(B \rightarrow K^* \mu^+ \mu^-)$	$2.9 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$
$R(B \rightarrow K^* \mu^+ \mu^-)$	34%	29%

Table 2.2: Rates and branching fractions[19, 20, 21] for the decays $B \rightarrow K \ell^+ \ell^-$, and $B \rightarrow K^* \ell^+ \ell^-$ with $m_t = 150$ GeV. A and B are two different parametrizations of the Isgur-Wise function used in the calculation. The quantity R is the ratio of the rate of each channel to that of its corresponding inclusive strangeness channel.

$$\left(\frac{F_{B_s}}{230 M e V}\right)^2 \left(\frac{\bar{m}_t(m_t)}{170 G e V}\right)^{3.12} \left(\frac{|V_{ts}|}{0.040}\right)^2 \left(\frac{\tau_{B_s}}{1.6 p s}\right).$$

Ref. [23] also point out a very impressive reduction in the scale uncertainties going from leading order to next-to-leading order. The uncertainty in the branching fraction value, 4.10, decreases from 0.50 to 0.05.

The rate for $B_d \rightarrow \mu^+ \mu^-$ is expected to be smaller by about a factor or 20 and we do not discuss it here.

The purely leptonic decays of B_d^0 and B_s^0 mesons are of considerable interest in theories with leptoquarks[24]. In the leptoquark scenario, the effective four-fermi operators involving the $(\bar{s} \Gamma_i b)(\ell^+ \Gamma_i \ell^-)$ couplings can be enormously enhanced. This allows for searches for induced effects of leptoquarks which would go much beyond their direct searches.

2.7 Heavy flavor spectroscopy

As a useful by-product of the search for CP-violation in the beauty sector, the very large samples of data containing heavy flavour particles which will be accrued may be used for the study of heavy flavor spectroscopy[25].

There are two interesting areas of heavy flavour spectroscopy:

- Open flavor states, i.e. B_d , B_s , B_c , D_s and D meson systems and Charm- and Beauty-flavored baryons.
- Hidden flavor states, i.e. $c\bar{c}$ and $b\bar{b}$ onium states.

There are many missing (undiscovered) states in both categories — states which are not readily produced exclusively, due to quantum number preferences, or states which are not observed inclusively,

due to experimentally difficult decay channels. With LHC-B, it may be possible to fill in some of the holes in the present listings of heavy flavor states. Of particular interest would be the identification of heavy flavor mesons which are not easily explained in terms of a $q\bar{q}$ paradigm but rather may be evidence for hadro-molecular states.

There is some interest in whether useful self-tagging schemes might be possible, using the hadronic or electromagnetic cascade decays of excited B mesons, some of which have already been found (see next paragraphs). Whether or not such B meson flavor-tagging will prove to be competitive with traditional methods based on the partner \bar{B} decay remains to be seen.

Excited heavy flavor states:

Within the quark model, the ground state B mesons consist of the B^+ ($\bar{b}u$), the B^0 ($\bar{b}d$), the B_s^0 ($\bar{b}s$) and the B_c^+ ($\bar{b}c$) mesons. An excited vector partner, B^* , of the pseudoscalar B meson has also been observed[26]. The mass difference between the B and B^* is approximately 46 MeV and hence the B^* meson always decays via an electromagnetic transition to the ground state. Unfortunately the maximum energy of a photon produced in this decay will be ~ 1.5 GeV at LHC energies and will be difficult to detect with the current LHC-B calorimeter design.

Resonant P-wave states have been observed in the charm system and most recently similar excited meson production has been observed in beauty hadronization[27]. The observed states, generically called D^{**} and B^{**} , are consistent with calculations based on heavy quark effective theory[28]. Two of the states, the 3P_2 (D_2^* , B_2^*) and a mixture of the 1P_1 and 3P_1 states (D_1 , B_1), have intrinsic widths of ~ 20 MeV. The two remaining states, the 3P_0 and the other mixture of the 1P_1 and 3P_1 states, are expected to have large widths and therefore not to be observed. Results from LEP show that the production of B mesons in $Z^0 \rightarrow b\bar{b}$ decays proceeds via a B^{**} more than 20% of the time, however these results may not necessarily be indicative of hadro-production trends. It is expected that LHC-B will be able to shed considerable light on this field.

Excited P-wave beauty mesons decay to the lowest lying ground states through a combination of radiative transitions and strong decays. As such, their secondaries come from the primary interaction vertex. Due to parity conservation the B_1 state cannot decay directly by pion emission to the ground state but goes through the B^* , $B_1 \rightarrow B^*\pi$. The B_2^* state can decay by single pion emission, $B_2^* \rightarrow B\pi$ or $B^*\pi$.

The identification of a B^{**} therefore involves identifying a charged pion whose direction vector is close to the B meson vector and whose $B\pi$ invariant mass is close to the B^{**} .

The charge correlation between the B meson and the charged pions produced in fragmentation should provide a method to tag the initial flavor of neutral B mesons. The presence of B^{**} states will enhance the performance of such a tagging technique. For example, the presence of a d -quark in a B^0 meson implies the production of a \bar{d} nearby in phase space. Ignoring strange hadron and baryon production, this \bar{d} will give rise to a π^+ ; the remainder of the fragmentation chain is charge symmetric and hence will give equal production rates and kinematic properties for the π^\pm produced there. However, we note that this type of flavor self-tag could be complicated for a several reasons. Although the production of P-wave states may be large, only a restricted number of decays are relevant for tagging the flavor of neutral B mesons. For example, given equal initial populations of the charged and neutral B_1 and B_2^* states, only one third of the strong decays will lead to the desired final state. Also, contributions from decays such as $B^{**0} \rightarrow \rho, \omega B^0$ with $\rho, \omega \rightarrow \pi^+\pi^-$ in which one of the pions is soft and missed and the other appears to resonate with the B^0 will result in the dilution of the flavor tag.

Excited B_s^{0**} states decay to $B_s^{0(*)}\gamma$ or $B^{(*)}K$ depending on the mass of the $\bar{b}s$ state. The masses of the P-wave $\bar{b}s$ states are expected to be close to the $m_B + m_K$ threshold. Above this threshold B_s^0 excited states will fall apart into $B + K$ (or $B + K\pi$) and consequently short circuit the B_s^0 . This is directly analogous to the more familiar situation in charmonium where transitions to low lying states are effectively quenched above the open charm thresholds, $2m_D$ and $m_D + m_{D^*}$. In addition, the flavor self-tagging will not work for B_s^0 since the $\bar{b} - s$ system has no transitions involving single charged pions and hence the pion charge symmetry no longer holds.

Excited heavy flavor production is a rich field of spectroscopy to be mined. Not only is it interesting in its own right, but it can clarify outstanding issues in light quark spectroscopy as well as serve as a technical basis for symmetry studies such as CP violation.

B_c physics:

Bound states of a b and \bar{c} quark pair (the B_c mesons) have never been observed. The study of bound states of heavy quarks with different flavours, such as B_c ($\bar{b}c$) and \bar{B}_c ($b\bar{c}$), is of great interest for several reasons. Firstly, this interest is related to heavy meson spectroscopy and its description in the frame-

work of potential models. Secondly, the study of weak decays of such mesons implies the possibility of determining some parameters of the Standard Model.

The current theoretical status of B_c physics, both production and decay, is summarized by Likhoded et al.[29] (see also Refs. [30, 31, 32]). One can expect B_c production rates at LHC which are nearly 1% of those for B_d mesons. Because of the existence of one c quark already in the meson, branching fractions to final states which contain J/ψ are expected to be very large.

Heavy flavor onium states:

The observed $b\bar{b}$ onium states, consist of six 3S_1 and six $^3P_{J=0,1,2}$ states. Conspicuous in their absence are D-wave states, singlet P-wave states, and the 1S_0 's. Potential model predictions for some of these states exist. The reasons for this pattern are well known: much of the world's sample of beauty particles (hidden and open) comes from e^+e^- machines where the $b\bar{b}$ pair has the quantum numbers of the virtual annihilation photon, 1^{--} . Triplet P-wave states are subsequently populated through radiative decays of higher-lying 3S_1 states. By contrast however, inclusive production at hadron colliders might lead to a more democratic population of quantum levels. The excited states produced will decay radiatively to the ground state which will, at least in some cases, decay to dimuon pairs which will satisfy the LHC-B muon trigger. The problem of identifying the excited states then becomes one of identifying the transitions to the ground state through small and experimentally difficult decay modes. But, this might well be possible in some cases at LHC-B.

Generally the spacings between bottomonium states are reasonably well described by potential models. Thus, on the whole, potential model predictions should serve as useful guides to undiscovered states.

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3 Other Physics

The LHC-B spectrometer is a general purpose detector for the forward direction. As such, it can be used for many physics topics other than CP-violation in B-decay. We briefly discuss a few of these topics in order to indicate the breadth of the physics program which will be possible with the LHC-B apparatus.

Some of the topics are direct “fall-out” from our primary B-physics program. They require no special triggers or additional detectors. Examples of this class of physics are focussed studies of special B-final-states, such as a search for mixing & direct CP-violation in D-decays, or a search for lepton-number violation in $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$.

Although we have not yet carried out specific Monte-Carlo studies for either of these two cases, it is evident from the work we have already done that the useful D-event yields are more than an order-of-magnitude better than expectations at the proposed Tau-Charm factory[1]. For τ -decay studies, our yields are perhaps two or three times larger than expected event samples at a future e^+e^- “B-factory” running with design luminosity. It appears that LHC-B will be an interesting “Tau-Charm factory”.

There are also several types of “center-stage” strong-interaction experiments to which LHC-B can make important contributions. As will be discussed, these require varying degrees of additional equipment and/or perturbation to the B-physics program.

Experiment UA8 demonstrated[2] the value of tagging final state particles with the same identity as a beam particle in a large collider experiment. As discussed below, these are in effect, “Tagged Pomeron-beam Experiments”. With the installation of detectors in Roman-pots in both outgoing arms, as described in Chapt. 9, an analogous rich program can be run parasitically with B-mesons.

Measurements of forward large- x_F systems at the highest energy pp collider will add important information to the understanding of cosmic-ray phenomena. Some members of our collaboration are very interested in these possibilities. This work can also be done parasitically, but would require the addition of small angle downstream charged and neutral particle detectors to the LHC-B spectrometer.

The observation of the “melting” of onium-states produced in ion collisions with low p_t in the forward direction with increasing nuclear temperature could lead to an understanding of the quark-gluon plasma. Although the properties of our muon spectrometer make it ideal for such measurements, a rebuilding of the LHC-B spectrometer would be required and therefore could not happen until the B-physics pro-

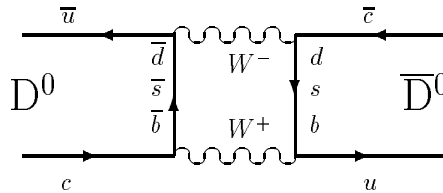


Figure 3.1: Box Diagram describing $D^0 \bar{D}^0$ Mixing.

gram was rather mature.

In the following sections, we briefly discuss these topics in more detail and demonstrate that LHC-B will have a very rich physics program ahead of it. Of course, it may turn out that the greatest riches will be in areas that have not yet been thought of.

3.1 Prospects for mixing and direct CP-violation in D-decays

LHC-B will produce a very large number of D-mesons from B-meson decay. Since the B-decay vertices are displaced downstream from the primary pp interaction vertices, the D-mesons can be analyzed in a rather straight-forward manner. This should enable a comprehensive study of direct CP violation to be made which could test the standard model in ways complementary to those from B experiments.

Direct CP violation, crucial in testing the standard model and ruling out the super-weak alternative, will be probed with a sensitivity of 2 or 3×10^{-4} in asymmetry, which is well within the range of theoretical expectations. Particle-antiparticle oscillations, so far only observed for neutral kaons and B-mesons and expected to be very small for charm, can be tested to the level of 1 oscillation in 10^7 decays.

Mixing between the two neutral mesons of opposite flavour (e.g. D^0 and \bar{D}^0) arises from both short-range and long-range contributions. The former, usually exemplified by box diagrams (Fig. 3.1), is expected to be extremely small for the D^0 system, since the GIM cancellation is almost perfect because of the small quark masses in the loop compared with the W mass. Thus, the long-range interactions are expected to dominate. But they are more problematic to calculate. New calculations yield much smaller contributions than previously estimated, due to cancellations between different classes of intermediate mesonic states[3]. Any rate of D^0 - \bar{D}^0 mixing exceeding one oscillation in 10^7 D^0 decays would imply the existence of new physics beyond the Standard Model[4].

Observable CP violating effects are only generated when (at least) two different amplitudes, having a difference in phase, contribute to the same physical

transition. Without loss of generality, we can write the decay transitions as:

$$\begin{aligned} A_{D \rightarrow f} &= g_1 M_1 e^{i\alpha_1} + g_2 M_2 e^{i\alpha_2} \\ A_{\bar{D} \rightarrow \bar{f}} &= g_1^* M_1 e^{i\alpha_1} + g_2^* M_2 e^{i\alpha_2} \end{aligned} \quad (35)$$

where g_1 and g_2 denote the weak couplings, α_1 and α_2 the strong final-state phases, and M_1 and M_2 the moduli of the matrix elements. The difference in decay rates is then proportional to:

$$\Gamma_{D \rightarrow f} - \Gamma_{\bar{D} \rightarrow \bar{f}} \sim \Im m (g_1^* g_2) \sin(\alpha_1 - \alpha_2) M_1 M_2$$

Thus, the two interfering amplitudes must have different weak and strong phases in order for the CP-violating effect to be observable.

In the case of mixing, this occurs through the complex CKM couplings of the different quarks in the box diagram contribution. Final state interactions can also introduce a phase shift between different weak amplitudes, and this is of particular importance for CP violation in D-decays, where we know from the lifetime differences between the neutral and charged D that final state interactions are very strong. The CP-violating contribution to the mixing amplitude is expected to be small within the standard model, as can be seen from the following semi-quantitative argument. It is given by the imaginary part of the box diagram, and hence the ratio of CP-violating to CP-conserving amplitudes is given approximately by:

$$A_f = \frac{A_{CP \text{ Viol}}}{A_{CP \text{ Con}}} \approx \frac{\Im m (V_{us} V_{cb} V_{ub}^* V_{cs}^*)}{\Re e (V_{cs} V_{us}^*)^2} \approx \frac{\lambda^6 \eta}{\lambda^2} \approx 10^{-3}$$

Indirect ($\Delta C = 2$) CP-violation is therefore expected to make an extremely small contribution to the dominantly CP-conserving amplitude in D^0 decay because of the additional mixing suppression discussed above.

Recent calculations[5] for charged and neutral D mesons indicate that direct CP-violation within the Standard Model should give rise to asymmetries of the order of 10^{-3} for several final states accessible at LHC-B. It therefore appears that the D system is unique in its sensitivity to direct CP-violation ($\Delta C = 1$) in the decay - and also to enhanced CP-violating amplitudes originating from non standard model processes[6].

Although complete Monte-Carlo calculations have not yet been performed on these decays, it is evident from the calculations we have already done for other B-decays that the situation will be very favorable.

With our planned operating luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, a total of 1.2×10^{12} B_u and B_d and 1.8×10^{11} B_s mesons (including antiparticles) will be produced in 10^7 s. As shown in Chapt. 10 for

many different final states, the rule-of-thumb acceptance is that about 15% are contained in the forward LHC-B spectrometer. Based on measured branching ratios $B \rightarrow D$ [7], and assuming $\mathcal{B}(B_s \rightarrow D_s^-) \approx 100\%$, we expect the following annual number of accepted D-mesons:

$$\begin{array}{ll} D^+ + D^- & 3.1 \times 10^{11} \\ D^0 + \bar{D}^0 & 6.5 \times 10^{11} \\ (D^0 + \bar{D}^0)_{\text{tagged}} & 0.8 \times 10^{11} \\ D_s^- & 2.9 \times 10^{11} \end{array}$$

Flavor-tagged D^0 -mesons are obtained e.g. from $\bar{B} \rightarrow D^0 \mu^- X$. Directly-produced D-mesons are much more difficult to trigger on and reconstruct (perhaps impossible at LHC) and have been neglected for now. The trigger efficiency of the desired final states is expected to be about 6% for events with no muons and 28% for events with a muon. We assume a 13% reconstruction efficiency for a 3-body final state of a D-meson, including a vertex cut (an appropriate Δz cut on the B-decay length retains about one-third of the B-mesons and the reconstruction efficiency for these events should be $\approx 40\%$).

Mixing: Conceptually, a measurement of the mixing rate is straightforward. It involves tagging a D^0 (for example) on production and identifying whether it decays as a D^0 or as a \bar{D}^0 , assuming that no other process overwhelmingly fakes the mixed decay. The mixing rate is then defined as:

$$r_D \equiv \frac{N(D^0 \text{ decaying as } \bar{D}^0)}{N(D^0 \text{ decaying as } D^0)} \simeq \frac{x^2 + y^2}{2}$$

where: $x = \frac{\Delta m}{\Gamma}$; $y = \frac{\Delta \Gamma}{2\Gamma}$. Using the decay chain, $\bar{B} \rightarrow D^0 \mu^- X$, $D^0 \rightarrow \mu^+ Y$, we tag the flavor of the neutral D-meson at the time of production and decay. The observation of like sign muon pairs would establish D^0 mixing. Unfortunately, this method suffers from a large background due to the partial reconstruction of the event. For example, it is very difficult to reject the background from semileptonic charged D decays.

The second method also uses tagged neutral D-mesons from B-decays, with the exclusive final state $K^- \pi^+$. A clean tagged sample can be selected by demanding, in addition, a $D^{*\pm}$ -meson in an intermediate state. The distinction between D-mixing and Double-Cabibbo-Suppressed-Decays (DCSD) is done by measuring the D^0 lifetime distribution. The time-dependent decay rate for $D^0 \rightarrow K^+ \pi^-$ is given (approximately) by:

$$\begin{aligned} R(t) &\propto e^{-\Gamma t} \left(\frac{1}{2} r_D (\Gamma t)^2 + 4 |A_{DCSD}|^2 \right) \\ &+ e^{-\Gamma t} \Gamma t (y \Re e A_{DCSD} + x \Im m A_{DCSD}) \end{aligned}$$

where A_{DCSD} is defined as the ratio of the DCSD amplitude ($D^0 \rightarrow K^+\pi^-$) to the unsuppressed amplitude ($D^0 \rightarrow K^-\pi^+$), and x , y and r_D were defined above. From (approximately) 1000 decays, E-691 saw no evidence of mixing, and put an upper limit on r_D of $3.7 \cdot 10^{-3}$ (90% confidence level). The CLEO collaboration has observed a signal for $D^0 \rightarrow K^+\pi^-$ with a branching ratio of $\mathcal{B}(D^0 \rightarrow K^+\pi^-)/\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (7.7 \pm 2.5 \pm 2.5) \times 10^{-3}$. CLEO is unable to distinguish if this signal arises from mixing or DCSD.

At LHC-B, we expect to reconstruct 1.2×10^8 dilepton events and 1×10^7 hadronic decays $D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^-\pi^+$. Even with additional cuts to remove possible background events, one remains with a sensitivity of $\approx 10^{-5} - 10^{-6}$ for r_D . Other experiments at e^+e^- B-factories[8], will reach a sensitivity in an optimistic case of $\approx 10^{-5}$.

CP-Violation: Since indirect CP-violation ($\Delta C = 2$) is expected to be very small, the dominant theoretical interest is in direct CP-violation ($\Delta C = 1$). An unambiguous signature for direct CP-violation is an observed difference in the rates for the decay $D \rightarrow f$ and its charge conjugate decay $\bar{D} \rightarrow \bar{f}$, where the final state f and \bar{f} are different and hence the decays are self-tagged. In a study by Bucella et al.[5], predictions based on the standard model indicate rate-differences of the order of a few parts in 10^3 for several final states. The measured quantity used is the time integrated CP asymmetry:

$$A = \frac{R(D \rightarrow f) - R(\bar{D} \rightarrow \bar{f})}{R(D \rightarrow f) + R(\bar{D} \rightarrow \bar{f})}$$

The 2-body decays (Table 3.1) are easy to reconstruct with small background because of the well-defined D^+ mass peak, and the fact that their production point is at the detached downstream B-vertex. Particle identification is crucial.

Estimates of the expected numbers of reconstructed events and the resulting significance for the rate-integrated asymmetries in a search for direct CP-violation are shown in Table 3.1 for a one-year run of LHC-B with an average luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The difficulty in measurements of the type discussed here is to ensure a symmetric reconstruction efficiency for charged-conjugate final states to the level of better than 10^{-4} . Therefore, reference channels with an expected asymmetry of zero are useful to calibrate the reconstruction efficiencies.

The measurement of direct CP-violation at the level currently predicted by the standard model is clearly feasible. The importance of such measurements in testing the consistency of the standard model and searching for new physics cannot be

stressed too highly. Every effort should be made to make these measurements and refine the accompanying theoretical calculations.

3.2 Search for lepton-number violation in $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$

The expected annual production of $\sim 10^{12}$ B and \bar{B} mesons, together with a 5% branching ratio, $B \rightarrow \tau$, corresponds to $5 \times 10^{10} \tau$ per year. The same efficiencies apply as for the D-meson analysis in the previous section. About $\sim 15\%$ will be accepted in the LHC-B spectrometer, $\sim 33\%$ survive a Δz cut on the B-decay vertex and $\sim 40\%$ are reconstructed (the muon trigger for this 3-muon final state is very large - see Chapt. 10). We arrive at the following number of observed τ -decays:

$$N(\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-) = 10^8 \cdot \mathcal{B}(\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-) \quad (36)$$

where $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-)$ is the unknown branching fraction for this final state. The number expected at an e^+e^- B-factory running at design luminosity is about a factor 2-3 smaller than this.

Of course, the number of events required to establish a signal at LHC-B will depend on detailed Monte-Carlo calculations and background estimates, which are still to be done. Of course, a dedicated run at higher luminosity with a more radiation-resistant microvertex-detector would increase the sensitivity to smaller Branching fractions.

3.3 Tagged Pomeron-beam experiments (Diffraction)

Reactions with beam-like particles in the final state are well known to be dominated by interactions involving a component in the proton called the Pomeron. The Pomeron, with momentum fraction of the beam proton, $\xi = 1 - x_p$ (x_p is the Feynman- x of the final state proton), interacts with the other beam proton as indicated in Fig. 3.2. The Pomeron has been observed[2] to exhibit partonic structure and participate in hard (jet-producing) interactions.

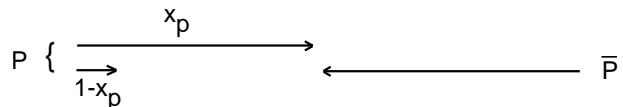


Figure 3.2: Incident proton from right interacts with $(1 - x_p)$ object in incident proton from left.

At small values of momentum transfer, the probability to find a Pomeron with momentum fraction ξ

$[10^{-3}]$	A (expected) $[10^{-3}]$	Events reconstructed in one year $[10^6]$	σ_A $[10^{-3}]$
$D^0 \rightarrow \bar{K}^0 K^{*0}, K^0 \bar{K}^{*0}$	0.67 ± 0.39	0.7	1.2
$D^0 \rightarrow K^+ K^-$	0.13 ± 0.8	3.6	0.5
$D^0 \rightarrow \pi^+ \pi^-$	0.02 ± 0.01	1.3	0.9
$D^+ \rightarrow \bar{K}^{*0} K^+$	2.8 ± 0.8	3.2	0.6
$D^+ \rightarrow \rho^0 \pi^+$	-1.17 ± 0.68	1.0	1.0
$D^+ \rightarrow \phi \pi^+$	0	3.1	0.6
$D_s^- \rightarrow K^{*0} \pi^-$	-2.6 ± 0.8	1.9	0.7
$D_s^- \rightarrow K^0 \pi^-$	-1.5 ± 0.5	2.5	0.6
$D_s^- \rightarrow \rho^0 K^-$	1.0 ± 0.3	1.3	0.9

Table 3.1: Preliminary estimates of LHC-B sensitivity to Direct CP-violation in D-decays in one year with luminosity, $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

goes roughly as $1/\xi$. Thus, the most likely value of ξ is near zero and the most likely momentum fraction of the final state proton, x_p , is therefore near unity, as is observed experimentally.

With the addition of Roman-pot spectrometers in both arms to measure outgoing protons, LHC-B will be in a position to make fundamental contributions to our understanding of the Pomeron and of high energy interactions in general.

First, let us consider the kinematics. The interacting Pomeron-proton system in Fig. 3.2 has squared-energy in its center-of-mass, $s' = \xi s$, where s is the total squared-energy of the LHC. The Pomeron-proton system has $(\beta\gamma) = P/\sqrt{s'}$, where $P = (1-\xi)P_{beam}$ is the total momentum of the system. It follows that a (massless) particle emerging from the Pomeron-proton interaction at 90° in their center-of-mass, appears in the laboratory with angle:

$$\tan \theta = \frac{2\sqrt{\xi}}{1-\xi} \quad (37)$$

Eq. 37 is evaluated in Table 3.2 for several interesting values of ξ . $\xi = 0.1$ is the largest value of ξ at which the Pomeron shows evidence of contributing significantly and $\xi = 0.001$ is the smallest value for which the proton is measurable in the Roman pots, as explained in Chapt. 9. $\xi = 0.05$ is the largest value at which the Pomeron is the dominant contributor.

The vectors along which the 90° c.m. particles emerge in the laboratory for these values on ξ are shown in Fig. 3.3. From this drawing, several conclusions can be drawn:

- If the observed proton is opposite the LHC-B

$\xi = 1 - x_p$	$\sqrt{s'} = \sqrt{\xi s}$	θ
0.001	443 GeV	4°
0.01	1400 GeV	11°
0.05	3131 GeV	25°
0.1	4427 GeV	35°

Table 3.2: ξ is the fractional momentum of the beam proton possessed by the Pomeron. $\sqrt{s'}$ is the invariant mass of the diffractive or Pomeron-proton interacting system. θ is the polar angle in the hemisphere opposite the detected proton at which a particle at 90° in the Pomeron-proton system emerges in the laboratory.

spectrometer, the spectrometer sees all the the particles in the proton hemisphere (in the Pomeron-proton system).

- if the observed proton is in the LHC-B arm, the spectrometer “sees” the extremity of the Pomeron hemisphere (in the Proton-proton system).

The physics interests in these two regions are rather different. Consider first the case where the proton is measured in the arm opposite the spectrometer. In that case, the entire proton hemisphere in the Pomeron-proton c.m. is boosted into the LHC-B spectrometer aperture, up to the largest mass, $\sqrt{s'} = 4.4 \text{ TeV}$. It will be possible to study these events in the LHC-B calorimeter system. There are several interesting topics. One is the search for anomalous electromagnetic energy content in the system, as discussed in the following section. Another is the study

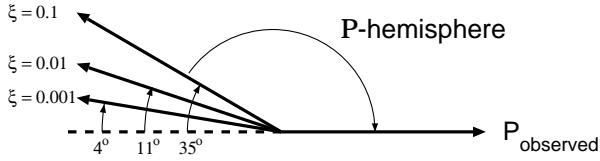


Figure 3.3: In the laboratory, the observed proton is shown on the right side. The vectors on the left side show the angles at which particles produced at 90° in the Pomeron-proton center-of-mass emerge in the laboratory. In each case, all lab angles to the left of the vector correspond to the proton hemisphere and all angles to the right correspond to the Pomeron hemisphere.

of jet production in the proton system and in the 90° region of the Pomeron-proton c.m. These jets result from hard scattering in the Pomeron-proton interaction and provide information on the Pomeron structure which is complementary to what has been studied in Experiment UA8[2]. For example, Jets in the proton hemisphere probe the soft structure of the Pomeron.

In the case where the detected proton is in the LHC-B spectrometer direction, the spectrometer “sees” the Pomeron direction. For the ξ values in Table. 3.2, the Pomeron momentum spans the range 7-700 GeV. In this case, $b\bar{b}$ production arises from the interaction of the Pomeron with a gluon in the other proton. The special interest in this situation is that Experiment UA8 observed that, in hard scattering, the Pomeron gives up its entire momentum in the interaction about 30% or the time, analogous to “direct” γp interactions. The produced B-mesons will then have large momentum and good acceptance. The study of these events, as well as possible W^\pm and Z^0 production, should lead to further understanding of the quark and gluon content of the Pomeron.

Finally, we comment on a further aspect of Pomeron interactions that could be of great interest. It is the study of possible production of “glueballs” (bound gluonic systems) or hybrid systems in Pomeron-Pomeron interactions. This type of interaction occurs when Pomerons from both of the incident protons interact. Depending on the relative momenta of the two Pomerons, such interactions may be asymmetric and the resulting system could be accepted by the LHC-B spectrometer. Fig. 3.4 shows the relevant kinematics. The momentum and mass of the system produced in the Pomeron-Pomeron interaction are related to ξ_1 and ξ_2 of the interacting Pomerons

by:

$$\begin{aligned} P_x &= (\xi_2 - \xi_1) \cdot 7 TeV \\ M_x &= \sqrt{\xi_1 \cdot \xi_2} \cdot 14 TeV \end{aligned} \quad (38)$$

It is evident in Fig. 3.4 that the values of ξ_1 are un-

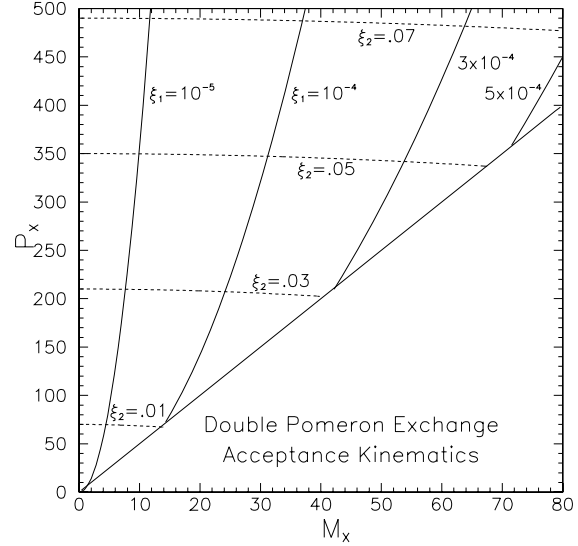


Figure 3.4: Acceptance kinematics for double-Pomeron-exchange process at LHC-B (units of P_x and M_x in GeV). The diagonal line is the approximate acceptance limit, corresponding to the requirement that $P_x > 5M_x$. The solid and dashed curves show lines of constant ξ_1 and ξ_2 , respectively.

measurably small. That should not cause problems, because Pomeron exchange (diffraction) is dominant when a rapidity gap is imposed. In fact, with rapidity gaps in both arms, neither proton need be seen. This can be achieved with veto counters downstream in both arms, each of which cover a rapidity range of 1-2. Experiment UA8 demonstrated[9] the validity of this point at the SPS-Collider. In this case, an outgoing proton opposite the LHC-B takes on its “natural values”, near momentum transfer of zero and Feynman- x near unity.

The kinematics of the interesting events are the following. There are no particles outside the spectrometer aperture. A simple veto system can insure this in the trigger. The total energy seen in the LHC-B calorimeter system must be relatively small, corresponding to the interesting range on the ordinate axis of Fig. 3.4. It is seen, for example, that with values of $\xi_2 = .002$ and $\xi_1 = .00001$, $M_x = 2$ GeV, while P_x

= 14 GeV. Data recorded with the rapidity gap and calorimeter energy conditions outlined here will result in low mass systems with moderate energies entering the spectrometer, where their invariant masses may be calculated and searches for glueballs can be carried out. Naturally, a high resolution electromagnetic calorimeter would be very valuable for such studies. That might provide one of the arguments for a later upgrade of LHC-B.

3.4 Cosmic ray phenomena in pp and ion-ion collisions

Proton-proton collisions at the LHC correspond to 10^{17} eV fixed-target collisions, well into the domain of interesting primary cosmic-ray energies[10, 11]. Since the common “beam-jet” (forward) particles dominate cosmic-ray observations, it is evident that LHC-B, modestly supplemented by additional smaller angle detectors (as summarized in Chapt. 9), can contribute significantly to the understanding of cosmic-ray phenomena. In this section, we briefly outline some of the outstanding problems in the field of cosmic-ray physics and the types of relevant measurements which LHC-B can make.

The primary cosmic-ray energy spectrum and its particle composition is essentially unknown for energies larger than about 10^{15} eV, although its knowledge would be very important from an astrophysical point of view. Extensive-Air-Shower (EAS) data lead to ambiguous conclusions. Either the primary particles are predominantly heavy nuclei (around iron), or at those energies the energy spectra of the secondary particles produced in high energy proton-air nucleus collisions are different than expected from the current model of high energy interactions deduced from accelerator data[10]. Extraction of information on primary particle composition from the observed EAS data relies on the very meager knowledge of the energy spectra of secondary particles from high energy interactions at collider energies. Except for some UA5 data[12] and measured cross sections for diffractive protons and large- x Δ^{++} production[13] at the CERN and Fermilab colliders, the data is essentially non-existent in the large Feynman- x region ($x \geq 0.1$, or so).

Unusual or surprising phenomena in cosmic-ray observations is another area where LHC-B can make important contributions. Much of the most relevant observational information comes from the Pamir-Chacaltaya emulsion chambers (fine-grained lead-emulsion e.m. calorimeter and carbon sandwich) and is reviewed in Ref. [14]. Bjorken[11], in his Proposal for the Full-Acceptance Detector for the SSC, sum-

marized some of these emulsion results as follows:

- “Difficulty in accounting for the yield and x -distribution of gammas (π^0 's) using smooth extrapolation of collider data to higher energies. Quite strong violation of Feynman scaling is indicated, but no one as yet has a good model.”
- “An excess of hadron (non- π^0) energy fraction relative to what is obtained in simulations; i.e. there is a tendency toward Centauro behavior in a statistical sense, although no more smoking-gun Centauro candidates have been exhibited.”
- “At the highest energies, a class of penetrating shower-clusters (hadron-like, not pure electromagnetic) are seen, with estimated relative p_t 's in the tens of MeV - too large to be electromagnetic and too small to be conventional hadronic. These clusters dominate the total energy of the event (they “lead”). It is claimed that there are too many of them to be explained as events originating at low altitude above their detector.”

Ref. [11] also refers to other unusual event structures that have been discussed. For example, “bands of high density at a fixed η of rings of high density in the lego plot (η vs. ϕ) caused by Cerenkov-like radiation of gluons by partons moving through the collision debris[15]; There have been hints in cosmic ray data of multijet final states where all the jets lie in a single plane containing the beam axis, and there is a tendency toward coplanarity in QCD calculations as well[16]”, as well as many other intriguing suggestions.

These are all possible phenomena that may be studied in LHC-B. Our electromagnetic and hadronic calorimetry will permit us to look for unusual e.m./total energy ratios (“Centauro” or “anti-Centauro” behavior) on an event-by-event basis. This will be possible in the general minimum-bias data sample and also in diffractive events (see last section). Possible correlations with other phenomena in the same events (muons, jets, etc.) can also be looked for.

The point is that a systematic study of minimum bias events at the LHC energy, looking for unusual or unexpected phenomena, might turn out to yield a new understanding of high-energy strong interactions and shed light on many of the existing cosmic-ray physics puzzles.

3.5 J/ψ and Υ production in ion-ion collisions

There has been sufficient interest in measurements

of J/ψ and Υ production with low- p_t in ion-ion collisions that we need not dwell on this matter here. The idea of Matsui & Satz[17] was that “melting” or suppression of their production with increasing nuclear temperature would be a signature for the deconfining medium of the quark-gluon plasma.

We are, of course, aware that the ALICE collaboration has proposed the addition of a forward muon arm to perform such measurements[18]. Although we have not yet performed the same level of Monte-Carlo calculations as has ALICE, in view of the limited resources available to LHC experiments and the fact that LHC-B already has a rather powerful intrinsic muon system, it may be useful for us to offer some comments on the subject.

The LHC-B magnet discussed in Chapt. 1 has an aperture of 23° and a field integral of 4 Tm. Figs. 3.5 and 3.6 show the fractional acceptance for J/ψ and Υ as a function of rapidity, y , and p_t . Production of these particles is expected to be relatively flat beyond $y = 4$ [19]. Thus, we have quite good acceptance which extends down to $p_t = 0$.

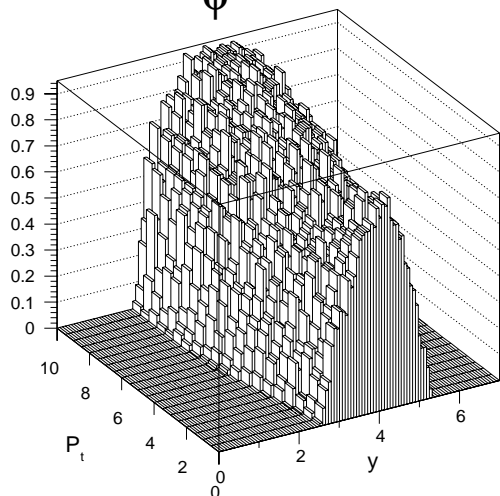


Figure 3.5: Geometric Acceptance in the LHC-B Spectrometer of $J/\psi \rightarrow \mu^+ \mu^-$ vs. J/ψ Rapidity and Transverse Momentum.

As has been demonstrated by the ALICE Collaboration[18], considerable shielding is required in order to obtain a sufficiently low particle density in the chamber system. For this reason, the LHC-B detector would have to experience major modifications in order to perform such measurements. The silicon and RICH systems would have to be removed and major positional and perhaps other changes would be necessary for the chamber system. Thus, it is obvious that such measurements would only be possible for the LHC-B collaboration to undertake, after the major part of its B-physics program were completed.

Upsilon

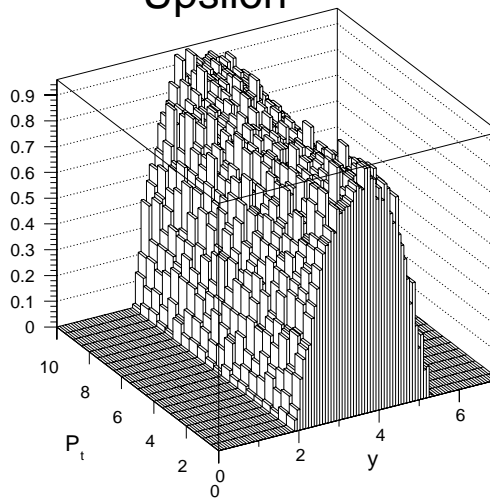


Figure 3.6: Geometric Acceptance in the LHC-B Spectrometer of $\Upsilon \rightarrow \mu^+ \mu^-$ vs. Υ Rapidity and Transverse Momentum.

Nonetheless, if it should turn out that such measurements were still of interest on the time scale which would be possible for us, we do wish to express our willingness to collaborate in doing them with any other interested parties.

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4 Silicon Microvertex Detector

The LHC-B vertex detector is shown installed inside the vacuum pipe at the centre of the interaction region in Fig. 1.4. In the following sections we describe its essential design requirements and the features of the P238 test-experiment at the Sp \bar{p} S-Collider which has provided much of the R&D work for this project. Then we describe the detector parameters used in our baseline LHC-B Monte Carlo simulation, a possible scheme for the readout electronics, and an assessment of the expected performance. Most of the requirements (fast readout and pipelining of many channels of silicon detector signals, ability to survive in a hostile radiation environment, etc.) are common to those in collider central detectors.

We have been conservative in our approach to the design, using technology already available and profiting from prototypes already proven in the R&D programmes for LHC/SSC detectors. We have attempted to choose running conditions and silicon configuration such that detectors survive for at least one year.

Alternate possibilities, such as the use of GaAs[1], Diamond[2, 3] and Scintillator-filled capillaries[4] (see Appendix A), are also under consideration because of their superior tolerance to radiation damage. A recent interesting development[5] is that oxygen-doped silicon may also offer improved tolerance to radiation damage. Capillaries have an additional advantage that each measurement station provides a track slope, which could simplify pattern recognition.

4.1 Design requirements

The microvertex detector has two principal functions:

- To provide an accurate measurement of the flight time of B-decays. This is achieved by precise tracking of charged particles close to the beam crossing such that primary tracks and the products of secondary decays can be assigned to their vertices of origin.
- To provide information to the Level-2 trigger which will enrich the B-decay content of the data (see Chapt. 10).

The design of the LHC-B vertex detector has been strongly influenced by two related programmes, both of which involved members of our collaboration. Firstly, the experience gained by the P238 Collaboration[6] in which a novel configuration of microvertex detector was successfully operated inside the vacuum pipe at the Sp \bar{p} S collider. Secondly, the recently approved HERA-B[7] experiment, which has

undertaken a thorough engineering study for a vertex detector with similar requirements and which needs to work with comparable particle densities and event rates to those expected at LHC-B.

The P238 R&D programme established that a silicon microvertex detector can be added to any forward detector through which a storage ring beam pipe passes; the interactions could be beam-beam, as in LHC-B, beam-wire[7] or beam-gas jet[8].

For a forward detector, the design of the silicon microvertex detector should satisfy the following requirements:

- Detectors should be perpendicular to the direction of traversing particles. Effectively this implies silicon planes perpendicular to the circulating beams.
- A gap or hole in the detector planes is needed, through which the circulating beams can pass. Fig. 4.1 shows the shape of silicon planes that will be used in LHC-B.

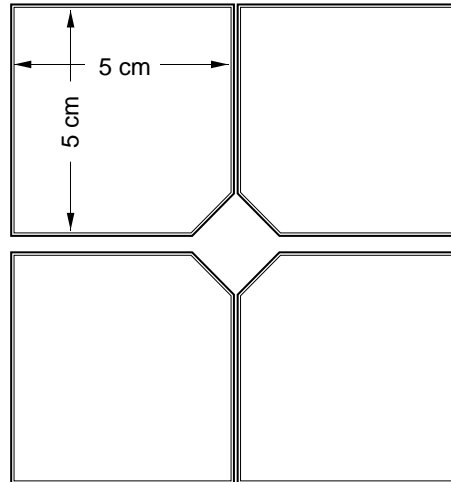


Figure 4.1: The proposed shapes of the silicon quadrant detectors ($5 \times 5 \text{ cm}^2$ each). The silicon masks are designed with the guard rings following the "clipped" corners. The circulating beams are perpendicular to the page at the centre of the sketch.

- The planes must be mounted inside the machine vacuum, on Roman pot devices, so that they can be positioned an appropriate distance from the beam to achieve the desired minimum angle coverage, and be retracted during beam manipulation.
- The silicon detectors need to be protected against RF pickup from circulating charge

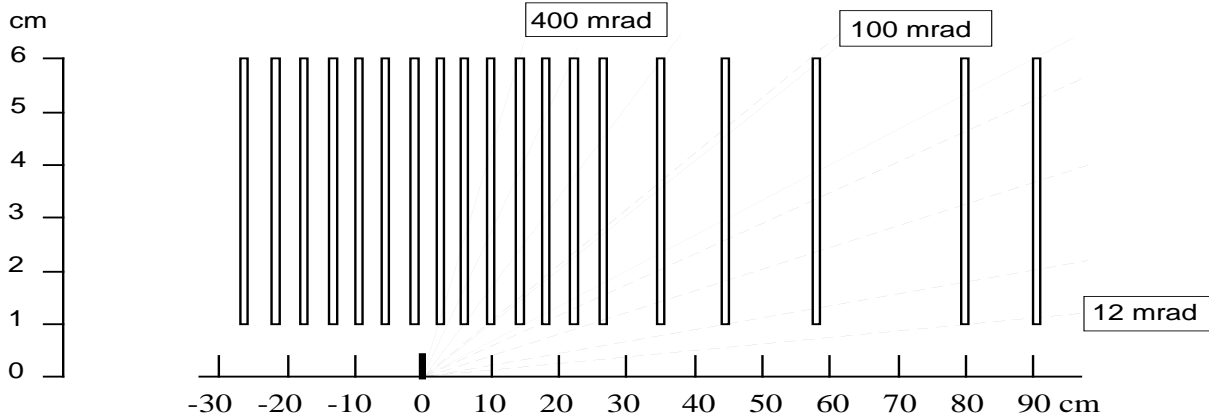


Figure 4.2: Side-view of the LHC-B silicon microvertex detector: layout of the upper silicon planes. The lower half system below the beam-line is not shown. The r.m.s. length of the bunch-crossing region is 5 cm. Note comment in the text concerning the 1 cm beam-silicon distance shown.

bunches, by a thin aluminum window. To avoid destruction of the windows, the silicon detectors are operated in a secondary vacuum.

- In order to minimize the extrapolation distance to all possible interaction vertices, the silicon system is positioned straddling the centre of the interaction region and, in the vicinity of the bunch crossings, the horizontal distance between planes is about 4 cm. Silicon planes are also distributed beyond the source region, in order to provide the required minimum angle acceptance. A sketch of the upper-half system is shown in Fig. 4.2.
- The angular acceptance should match, as far as is possible, that of the spectrometer tracking system. The system shown has forward angular coverage from 12 to 400 mrad.

4.2 P238 R&D project

A brief description of this prototype system[6] and its properties will serve to illustrate that, despite its unorthodox nature, an LHC-B silicon system based on the same ideas should satisfy the needs of the experiment.

Fig. 4.3 is an installation sketch of the 6-plane P238 silicon microvertex detector in its Roman-pot system, that was run at the $Spp\bar{S}$ -Collider in 1990.

The pot bottoms (sides closest to the circulating beams) were closed by the undulating 200 μm thick aluminum window, shown by the thin lines in the figure. The reason for using an undulating window of this type, rather than simply a square box bottom,

is that it minimizes the material closest to the beam and therefore reduces the interactions of small angle tracks.

The outer edge of the aluminum window was routinely positioned 1.5 mm from the center of the circulating beams. There was an additional 1.6 mm “dead space” from that point to the first sensitive silicon strip⁷.

The following points summarize the P238 operating features and properties that we can also expect in LHC-B:

- Fig. 4.4 shows a side view of a typically clean P238 event. Essentially all hits in the silicon detectors were track related.
- Tracks were seen in both hemispheres and aided in the primary vertex determination
- Because the silicon detectors are in a field-free region, straight line tracks are easily found in real time, and extrapolated to $x = y = 0$ to obtain a fast online determination of the longitudinal (z) vertex position (see Chapt. 10). Analysis of the P238 data showed that x, y, z of the primary vertex can be determined online with uncertainties $(\sigma_x, \sigma_y, \sigma_z) = (25, 25, 210) \mu\text{m}$, respectively. This would allow a very effective trigger algorithm to be implemented in real time.

⁷This dead space consisted of the 200 μm aluminum thickness, 900 μm gap between inner aluminum wall and edge of silicon plus an additional 500 μm in the silicon. In LHC-B, we expect to be able to reduce the total dead space by nearly a factor of two.

Figure 4.4: Side view of a typical P238 event showing tracks in both hemispheres.

mine online where the beam is with respect to the detector, periodically during the course of a run. These constants can be easily input to a trigger processor for on-line use.

- Since the silicon detectors operate in a secondary vacuum, separated from the main machine vacuum (and the circulating beams) by the thin aluminum RF shield, the extraction of signals from the large silicon system proved to be relatively simple, as there were minimal requirements on the feed-throughs.
- The events were visually very clean, The worst-case run had one halo track per 100 interactions.
- The P238 minimum bias silicon data were modeled using the event generator PYTHIA 5.3[9] and GEANT 3.14[10]. The reliability of the Monte Carlo simulations were then tested by comparing Monte Carlo events with the real data. Excellent agreement was found, implying that we may have confidence in our simulations for LHC-B.

4.3 Detector layout and performance

The LHC-B vertex detector shown in Fig. 4.2 comprises 19 planes of silicon microstrips and is situated between $z = -26$ cm and $z = +90$ cm. Close to the

interaction region (the rms bunch-crossing length is 5 cm), the detector planes are separated by 4 cm in both forward and backward hemispheres. Further forward, the plane spacing is increased, so as to extend the polar angle acceptance down to about 12 mrad, in order to match the acceptance of the first chambers in the tracking system (tracking quality is improved even if small angle tracks pass through only one or two silicon planes). The closest distance of active silicon to the beam is 1 cm. As seen in Fig. 4.1, this applies only along the 45°-diagonal.

For simplicity the detectors have single-sided readout. The strip pitch is 25 μm and readout pitch is 50 μm . Two detectors, 50 \times 50 $\text{mm}^2 \times$ 150 μm thick, placed back-to-back, provide x and y coordinates with a precision $<$ 10 μm .

The parameters of the silicon detectors as currently modelled in our Monte Carlo simulation are summarised in Table 4.1.

On average, five charged tracks cross each quadrant per interaction and the strip occupancy never exceeds 1%. Pattern recognition in the vertex detector requires the matching of tracks in projection; this can be provided using (additional) inclined planes or, more effectively, using pixel detectors. A plane of 1 \times 1 mm^2 pixels at the downstream end of the silicon system would clearly aid in pattern recognition of the denser small-angle tracks. Another possibility is the hybrid “strip/pixel” pattern for the LHC-B detectors similar to that proposed as an option for the HERA-B vertex detector[14]. The pixel dimensions are 1.6 \times 1.6 mm^2 , the same area as the strips, which would allow uniform integration of the readout of both pixels and strips.

The ultimate performance of the vertex detector is limited by Coulomb scattering in the material of the first silicon detector. With a P238-type RF-shield configuration, the impact parameter precision for a track of transverse momentum p_T is

$$\sigma_{\text{imp}}^2 = \left(\frac{21 \text{ MeV}}{p_T} \sqrt{\frac{X}{X_0}} r \right)^2 + \sigma_{\text{detector}}^2$$

where r is the transverse distance from the beam of the first measured point. With the $X/X_0 \sim 0.5\%$ (radiation length of the aluminum windows and silicon of a single silicon measuring station), the impact parameter precision of a track with $p_T \sim 1 \text{ GeV}/c$ is $\sim 25 \mu\text{m}$, approximately independent of polar angle. With this precision, the primary interaction vertex is reconstructed with an rms error $\sigma_z \sim 70 \mu\text{m}$.

Pattern recognition and track reconstruction quality are, however, dependent on the polar angle. Fig. 4.5 shows the number of silicon planes traversed as a function of the track’s polar angle. There is

an acceptable number in the range $15 \text{ mrad} < \theta < 400 \text{ mrad}$.

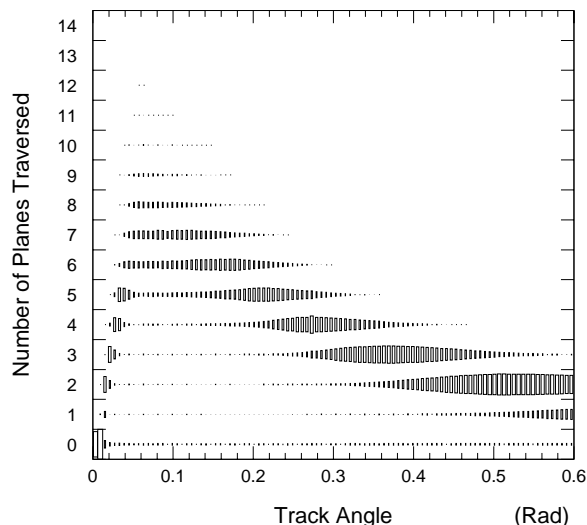


Figure 4.5: The mean number of silicon planes traversed as a function of a track’s polar angle.

Overall performance figures are presented in Chapter 12, where the efficiency and precision in reconstruction of B-decay vertices have been evaluated using the full GEANT[10] Monte Carlo simulations.

4.4 Readout electronics

The requirements of the LHC-B microvertex detector readout are similar to those of the ATLAS or CMS vertex/tracking detectors (although our total number of channels, $\sim 150\,000$, (see Chapt. 11) is about two orders of magnitude less). We aim to follow and, where appropriate, participate in current R&D to choose the most appropriate system for our application. From the developments currently in progress the system designed by the RD20/RD23 groups and adopted as the baseline by CMS[11] appears most attractive, in that the analogue signals are transmitted to the remote receiver modules. This solution permits flexibility in coping with changing detector characteristics resulting from radiation damage.

The first requirement of the readout is to provide a time resolution of 25 ns to allow “time-stamping” of the LHC beam crossing. At the same time the amplifier noise should be low ($<$ 10%) compared with the signal from a minimum ionising particle (mip) in the silicon (14000 e). The RD20 solution uses a “slow” amplifier with 70 ns shaping time and low noise characteristics. The analogue signal is sampled at 40MHz

Silicon Strip Detectors	
Detector type	150 μm thick single-sided silicon strip detector
Number of planes	18 (May be increased to 19)
Number of quadrants per plane	4
Number of detector planes per quadrant	2 (x and y)
Total number of detectors	$2 \times 4 \times 18 = 144$ (152 with 19 planes)
Detector dimensions	$5 \times 5 \text{ cm}^2$, with one corner clipped
Diode pitch	25 μm
Readout pitch	50 μm
Gaps between quadrant detectors:	
	$\Delta x = 0.1 \text{ mm}$
	$\Delta y = 4.0 \text{ mm}$
	$\Delta z = 1.0 \text{ mm}$
Minimum distance active area to beam	1.0 cm
z -positions of planes	14 planes every 4 cm from -26 cm to +26 cm. thereafter, planes at 34, (44), 58, 80 and 90 cm.
RF shield	100 μm Aluminium
RF shield to beam distance	1.5 mm height

Table 4.1: LHC-B Silicon Microvertex Detector Geometry constants used in the Monte-Carlo. The bracketed plane at $z = 44 \text{ cm}$ is optional.

and pipelined until the Level-1 trigger arrives. At this stage a weighted sum is formed from three consecutive samples resulting in a deconvolution corresponding to the amplifier input pulse. The effective time resolution is 25 ns, the amplifier noise increases by 60% consistent with this improved timing, and the filter provides an effective suppression of pile-up[12]. An additional advantage of this scheme is the low power of the readout chip partly due to the employment of the slow amplifier.

We show in Fig. 4.6 a schematic of the proposed RD20 system. The front-end chip [APVn] processes 128 channels. Its physical dimensions match the 50 μm readout pitch of the LHC-B vertex detector and it is made using the Harris rad-hard process. Following amplification the 40 MHz analogue samples are stored in a pipeline for 128 cycles (3.2 μs). In the event of a Level-1 trigger, the appropriate samples are filtered to provide the deconvoluted signal which is multiplexed ($\times 128$) on to a serial output line (an optical fibre). This output is processed by a Flash ADC at 40 MHz and stored in a buffer during the Level-2 latency period. Employing the RD20 design at LHC-B implies a delay of 6.4 μs (trigger wait time and read out) before the data are available to the Level-2 impact parameter trigger. This is not a problem. However, the bandwidth of the system should permit a Level-1 trigger rate of up to 400 kHz (the “nominal” rate is 230 kHz) and this requires a reduction in the level of multiplexing from 128 to 64. This is a minor design modification but doubles the number of (costly) fibre links.

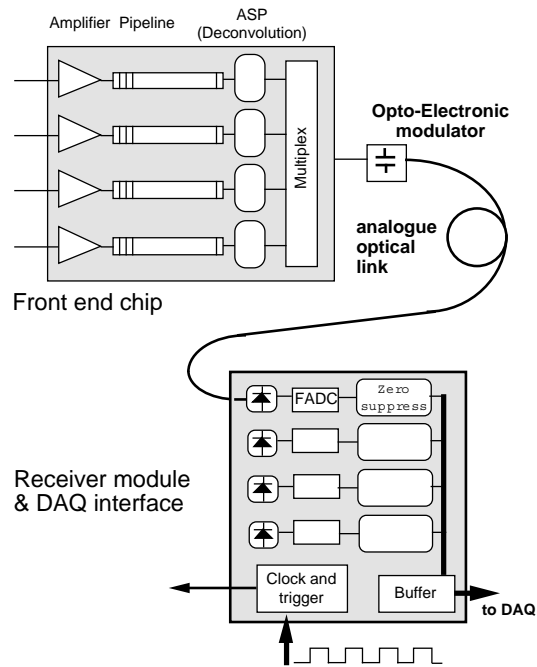


Figure 4.6: Schematic of the RD20 readout

4.5 Radiation damage

Radiation damage and the performance of silicon detectors has been studied in R&D programmes both for LHC and SSC. The main effects of damage are established and performance can be degraded due to

the following:

- Increased leakage currents: increases shot noise in readout electronics.
- Modifications to doping: leads to type inversion of substrate, and subsequently increases the depletion voltage.
- Reduced interstrip isolation: leads to loss of precision.
- Reduced charge collection: decreases signal amplitude.

Results reported by the RD20 group[13] indicate that single-sided detectors can be designed to tolerate up to 10 Mrad (a fluence $\sim 4 \times 10^{14}$ particles/cm²). The front-end readout electronics have been similarly tested up to 5 Mrad with no deterioration in the signal/noise performance.

As shown in Fig. 1.5, the density of charged particles per interaction (including secondary interaction products) traversing the silicon detectors is:

$$\frac{dN}{dA} \simeq \frac{2}{r^2}$$

where r is the radial distance to the beam line. The particle density is approximately independent of z . It is clear that regions of the silicon detectors closest to the beam are most critical. At the “nominal” LHC-B luminosity of 1.5×10^{32} cm⁻² s⁻¹ (11 MHz interaction rate) the fluence of particles in one year of operation is 3×10^{14} cm⁻² at $r = 1$ cm, leakage currents will increase to $\sim 3 \mu\text{A}$, with a corresponding increase in noise at readout of 700e (5% of the mip signal from a fully depleted detector). As the bulk damage increases, the bias voltage necessary to achieve full depletion will also increase. A survey of measurements reported by the HERA-B collaboration[14] indicate that, following this fluence, a bias of at least 250 V will be required for a 280 μm thick detector. Since the depletion bias varies as (thickness)⁻² we expect to maintain our 150 μm detectors fully biased throughout the 10⁷ seconds annual running period.

The front-end readout electronics will, accidents notwithstanding, experience less than 2 Mrad during ten years of operation. Since the silicon detectors will need replacement annually, the possibility of recycling the electronics will be studied in the interest of reducing the replacement costs.

4.6 Mechanics and engineering

The major engineering problem which has been solved by HERA-B was to design a system which possessed extended, relatively low-mass support structures to allow track clearance up to 250 mrad. The

vacuum tank which contains the silicon detectors has a 1 m diameter window at $z = 2$ m. Individual Roman pots protrude through the vacuum vessel. The LHC-B design will be similar, except that the window will be at $z = 1$ m and have an 80 cm diameter. Since the silicon detectors will be, on the average, closer together in z than in HERA-B, there will have to be some significant differences in pot design. These will be detailed in the LHC-B Technical Proposal.

For LHC-B, improvements can be foreseen which reduce the dead space required to allow beam traversal from that used in P238. The layout shown in Fig. 4.1 uses 100 μm thick RF shields which extend to $y = \pm 1.5$ mm from the beam height. The first active strips of the detectors are then at $y = \pm 2.5$ mm. The dead regions are included in the GEANT simulations used in evaluating the performance in Chaps. 10 and 12 (After carrying out the Monte-Carlo simulation for this LOI, we realized that it will be possible to “clip” the corners of the RF shields as are the detector corners in Fig. 4.1. Thus, multiple scattering of small angle tracks will be less than in the results presented in Chapt. 12.

Eventually, a full engineering study for LHC-B of the mechanical mounting of the detectors in the Roman pots, their alignment and cooling, design of signal feed-throughs, etc., will be undertaken. For this LoI we justify our confidence that such a system is feasible from the success of P238 and from the HERA-B engineering design. Experience from HERA-B will be gained early enough (already in 1996) to influence the LHC-B Technical Proposal.

4.7 Scintillating capillary option for vertex detector

The precision in vertex reconstruction improves when the transverse distance of the vertex detector from the beam is reduced (permitting a shorter lever arm for tracks produced at a given angle). To do so requires a detector capable of withstanding higher radiation doses than silicon.

The collaboration is studying different options exploiting the capabilities of a capillary detector, filled with liquid scintillator. This could be used as an alternative to, or in conjunction with, the silicon microstrip vertex detector. It could also serve as a component of the inner tracker.

The high radiation resistance of glass capillaries and liquid scintillator permits the operation of the detector for long running periods at a distance from the beam as low as 2mm. As a consequence of the high detected hit density it is possible to measure, in a thin capillary layer, not only the track coordinates but

also the track vector (direction) of a traversing particle. This improves track reconstruction efficiency.

Details of the properties of these detectors, their readout, and performance within the context of an LHC-B option are described in the Appendix to this LoI.

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5 Tracking System

The tracking system comprises twelve tracking stations distributed more or less uniformly between the vertex detector vessel and the second gas RICH counter. A thirteenth station right in front of the calorimeter serves specifically for muon triggering purposes, together with one of the stations near the exit of the magnet. Their positions are shown in the layout of the detector, Fig. 1.4, in Chapt. 1. The size of the stations ranges from $1 \times 1 \text{ m}^2$ to $8 \times 11 \text{ m}^2$. The choice of the detector types is driven by the following requirements:

- resolution per station well below $100 \mu\text{m}$ in the bending plane
- fast response and readout in order to minimize pileup of signals from several bunch crossings
- occupancy per cell below 10%
- capability to withstand the radiation levels without significant aging problems over a lifetime of 10 years
- minimal amount of material in the spectrometer
- manageable number of read-out channels

The Monte Carlo simulations of occupancies and aging effects presented in this chapter are based on a maximum LHC-B luminosity of $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, which corresponds to an average of nearly one interaction per bunch crossing. Our nominal running luminosity will be $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The particle flux per interaction is given by Eq. 1 with the constant plotted in Fig. 1.5, as a function of the distance z from the interaction point.

The geometry and the choice of techniques is mainly governed by the requirement of low occupancies. The required resolutions are naturally satisfied. The LHC-B experiment has to deal with similar particle densities as HERA-B. The design of the tracking system is therefore largely based on the detailed Monte Carlo studies for HERA-B [1]. These studies show that efficient and robust track finding is possible if the maximum occupancy is less than 10-15%. The tracking system provides precise particle trajectories in the bending plane of the spectrometer. Three dimensional track reconstruction is achieved with stereo views. Following the HERA-B studies small stereo angles of $\pm 5^\circ$ are chosen. Additional planes for measurements in the non-bending plane may be implemented to help track finding and to resolve multi-track ambiguities.

In the major part of the detector acceptance the particle density is such that it allows the use of drift chambers with small cells. In this region (Outer Tracking System) we propose stations composed of honeycomb chambers of varying sizes. The Inner Tracking System covers in all stations an area of $40 \times 40 \text{ cm}^2$ around the beampipe, where a much finer granularity is necessary. For this region several technologies are available.

It appears very difficult to assemble the large tracker stations from different segments with a precision below $100 \mu\text{m}$ and to guarantee the required stability in time. Instead we foresee accurate displacement monitoring by means of an optical alignment system. Two such systems are developed for the ATLAS muon spectrometer [2]: RASNIK consists of LED's with masks, lenses and CCD's. The second system uses infrared lasers and semitransparent silicon strip photo-diodes. Both systems are fully adequate for the alignment of the LHC-B tracker.

5.1 Inner tracking system options

Here we discuss two promising detector types which seem to be able to meet the requirements: Micro-Cathode-Strip Chambers (MCSC) and Micro-Strip-Gas Counters (MSGC). On the time scale of LHC, the Micro-Gap Chambers [3] might also be a very promising alternative. At present however, there are too many open questions for a detailed design of an Inner Tracker System based on such chambers.

The particle flux is particularly high in the innermost part of the tracker in the stations closest to the interaction point. Here, the finer granularity of a conventional Silicon Microstrip Detector is required. We foresee the use of such a detector with $80 \mu\text{m}$ pitch in the region of $5 \times 5 \text{ cm}^2$ of stations 1 and 2. If necessary, this can also be done in other stations. Silicon Microstrip detectors provide also a backup solution for the whole inner tracker area. Of course, any technique used for the micro vertex detector is also suited for the innermost part of the tracking system, e.g. the scintillator filled capillaries described in the appendix.

The dimensions of the inner tracker stations are summarized in Table 5.1.

5.1.1 Micro-cathode strip chambers

The Micro Cathode Strip Chambers (MCSC) use the analog signals which are induced on narrow cathode strips orthogonal to the wires. In order to get low occupancies, the distance between the cathode and the wires is only 0.6 mm, and the width of the cathode strips is $\leq 1 \text{ mm}$.

station	z [cm]	$R_{beam\ pipe}$ [cm]	$x_{min} = y_{min}$ [cm]	Θ_{min} [mrad]	Θ_{max} [mrad]
1	102	1.4	1.9	18.6	193
2	145	1.9	2.4	16.5	137
3	240	3.1	3.6	15.0	83
4	305	4.0	4.5	14.8	65
5	370	4.7	5.2	14.0	54
6	450	5.7	6.2	13.8	44
7	540	6.9	7.4	13.7	37
8	700	3.5	4.9	7.0	28
9	800	4.0	5.6	7.0	25
10	850	4.3	6.0	7.0	24
11	900	4.5	6.3	7.0	22
12	950	4.7	6.7	7.0	21
13	1160	5.7	8.1	7.0	18

Table 5.1: Inner Tracking System dimensions. All stations have maximum dimension of $x_{max} = y_{max} = 20$ cm. Station 13 is the muon station “ μ_2 ” in Chapt. 8.

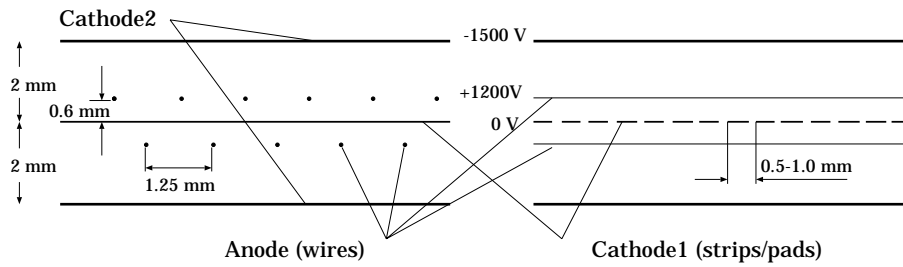


Figure 5.1: Schematic cross cut of MCSC

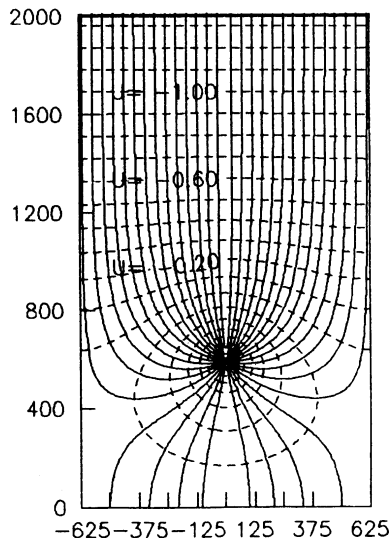


Figure 5.2: Typical field map of MCSC

Detector layout

The geometry of the MCSC that we propose to use in this project is shown in Fig. 5.1. An essential feature of the design is the back-to-back structure where the charge is induced on the cathode strips simultaneously from two anode planes. This yields a charge distribution along the anode wires which is symmetric around the crossing point of the track with the cathode strips plane. Therefore, the track inclination and the Lorentz shift of the electrons drifting in a magnetic field do not produce any systematic shifts in the measured coordinates but lead only to a small increase in the signal width.

Cathode 1 is on electrical ground. The voltage on Cathode 2 can be varied down to -1.5 kV and on the Anode up to +1.2 kV. A typical field map is shown in Fig. 5.2. The electric field in the main drift region is around 10 kV/cm and that at the surface of Cathode 1 varies from 2 kV/cm to 5 kV/cm. The chambers are filled with a fast gas mixture $CO_2/Ar/CF_4$. For this gas, the electron drift velocity is about 100 $\mu\text{m}/\text{ns}$ and the total collection time is less than 15 ns thus avoiding pile-up of signals from subsequent bunches. With maximal high voltages, the gas gain can reach $2 \cdot 10^5$ or more. The nominal value of the gas gain should be around $5 \cdot 10^4$.

The counting efficiency of the MCSCs is high ($\geq 99\%$). However, it may be necessary to reject a few percent of the signals with the highest (Landau tail) and lowest amplitudes as such signals provide less precise measurements of the coordinate. The overall efficiency per station will still be close to 100%

as there are three layers of the MCSCs in each station.

On average a minimum ionizing particle produces 20 ionization electrons in each half of the MCSC. With the gas gain of $5 \cdot 10^4$ this gives 10^6 electrons in the avalanche around one anode wire. Approximately 25% of the charge is integrated during the 20 ns integration time, and 70% of the integrated charge will be induced on Cathode 1. This gives a total charge on the cathode of $Q_{cath} \simeq 350000 \text{ e}$.

The x -coordinate can be determined using, for example, the following algorithm [4]:

$$\langle x \rangle = \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_2 + Q_3 - Q_1 - Q_4} \frac{W}{2},$$

where Q_i are the induced charges on the neighboring strips and W is the strip width. The advantage of this algorithm is that the systematic bias of the measured coordinates which it introduces does not exceed 10 μm (σ) for our MCSC geometry. Assuming electronics noise at the level of σ_N of 3000 e, the contribution of the noise to the spatial resolution is $\simeq 10 \mu\text{m}$.

Several types of the MCSCs have been tested and described in the literature [5],[6],[7]. A resolution of 27 μm was observed in the tests of the Cathode Strip Chambers [8] designed for the GEM Muon System. In those chambers the strip size was much larger ($5 \times 500 \text{ mm}^2$) but also the integration time was larger (300 ns). A 15 μm resolution was reported for a MCSC with 1 mm strips but again with large integration time [9].

Recently several MCSCs have been designed at PNPI for the E781 experiment at FNAL. These chambers have the same geometry and integration time as those proposed for LHC-B. The final figures for the spatial resolution will be obtained from tests of these chambers. It seems safe to assume though that a resolution of $\sigma_x \leq 50 \mu\text{m}$ per plane and $\sigma_x \leq 40 \mu\text{m}$ per station will be obtainable, taking into account the difficult conditions at the LHC-B experiment due to the high counting rates.

Some of the chambers will operate inside the magnet at $B \leq 1.2 \text{ T}$. In such a field, the Lorentz angle should be $\leq 6^\circ$. The deflection of the electrons in the magnetic field leads to $\leq 300 \mu\text{m}$ (full width) spread of the avalanche charge along the anode wires. However, the center-of-gravity of this distribution fluctuates by less than 20 μm (σ). The compensation for the effects of the magnetic field by rotation of the MCSC by the Lorentz angle is therefore not needed. A similar spread can be produced by tracks which are inclined along the anode wires but once again it can be neglected in the angular range where the Inner

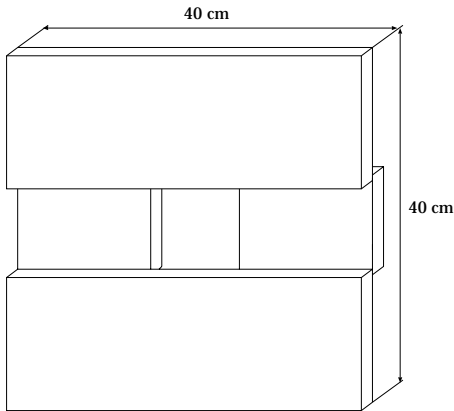


Figure 5.3: MCSC station assembly

Tracking System operates.

Geometry of inner tracker stations

To reduce the occupancy the inner tracker stations are divided into several modules of MCSCs. The strip widths will be 1.0 mm, although those closest to the beam pipe will have 0.5 mm width. In principle, some strips may be cut in half to reduce the occupancy, if needed; in this case the MCSC would be read out on both sides.

The stations are built from the modules with some overlap as shown in Fig. 5.3. The dimensions of the stations are summarized in Table 5.1.

The MCSC multilayer modules are assembled as indicated in Fig. 5.4. A four-layer module contains 9 cathode planes and 8 planes of wires. One of the layers has vertical strips and two have stereo angles of $\pm 5^\circ$. In the optional fourth layer the strips are replaced by pads for trigger purposes. The size of the pads can be varied to suit the reconstruction requirements from $5 \times 5 \text{ mm}^2$ near the inner edge of the chamber to $20 \times 20 \text{ mm}^2$ near the outer edge. In this case one such layer contains 800 pads. It has not yet been decided how many pad layers will be incorporated in the Inner Tracker System. The estimated amount of material is about $1.5\% X_0$ for one module. This value contains only the contribution from the sensitive area of the chambers, frames and the necessary connections are not taken into account here. The mechanical design of the modules aims at reducing the amount of material as much as possible. It will be based on the experience gained with the chambers of the E781 experiment.

Readout

For a precision coordinate measurement in the high particle flux a fast, low-noise front-end preamplifier/shaper is necessary. The readout should contain

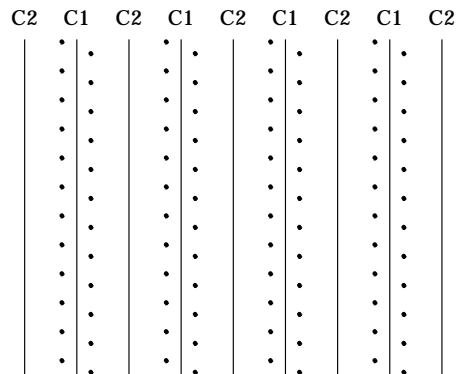


Figure 5.4: Arrangement of a MCSC module with four layers

an analogue pipe-line suitable for storing the signals until the Level-1 trigger decision. The readout requirements for MCSCs are to a large extent similar to those of the ATLAS and CMS Cathode Strip Chamber based muon systems. Our intention is to profit from developments made by these collaborations. The final design of the readout system however requires an R&D effort for the features that are specific to LHC-B. The goal is to use a very short pulse width of $< 25 \text{ ns}$ at the base in order to avoid pileup from neighboring bunches. Each inner tracker layer contains 2100 strips. This gives 6300 strip read-out channels per station and 81900 channels in total.

Occupancy and integrated charge

The cell occupancy is calculated for all stations using full GEANT event simulation.

Based on the width of the induced signals, two tracks are resolved if they are separated by half a strip-width; even then, the space resolution is not worse than 10% of the strip-width or $70 \mu\text{m}$ [10]. To calculate occupancies we use a conservative effective cluster size of two strips. The results are shown in Fig. 5.5 for the hottest strip in each station. All strips have occupancies well below 10%.

The effect of space charge on the gas gain in the MCSCs is studied in [6] and [11]. The measurements are performed with mean avalanche charges of $(0.5-2.0) \cdot 10^6 \text{ e}$. The gain remains stable up to fluxes of $(1-2) \cdot 10^7 \text{ part/cm}^2 \cdot \text{s}$. At a maximum LHC-B luminosity of $5 \cdot 10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$, the flux on the wires closest to the beam pipe is highest in station 3 at $1.0 \cdot 10^7 \text{ part/cm}^2 \cdot \text{s}$, whereas in the other stations it is below $0.4 \cdot 10^7 \text{ part/cm}^2 \cdot \text{s}$. We therefore expect no severe space charge problems in the MCSCs.

In all stations except station 3, the wires that receive maximum irradiation accumulate a

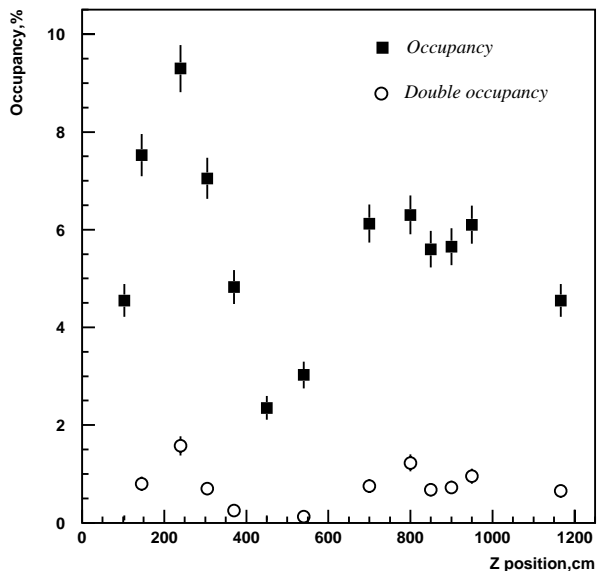


Figure 5.5: Single-hit and double-hit occupancy in the different stations of the MCSC-based Inner Tracker.

charge of less than 0.5 C/cm in one year of operation at the maximum LHC-B luminosity of $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. In station 3 the charge accumulation can reach 1.1 C/cm. It has been shown in a number of publications [12],[13] that MWPCs with a similar gas filling can collect more than 2.0 C/cm without degradation of the gas gain. A careful design and test of MCSCs should therefore allow to build chambers able to operate in the LHC-B environment. If necessary, the gas gain can be reduced in the most critical regions of the inner tracker.

5.1.2 Micro-strip gas counters

Microstrip Gas Chambers (MSGC), first proposed by Oed [15], are another technology which may provide a viable and cost-effective system for the inner tracker of LHC-B. They can withstand high rates because of a short drift time in a small gas gap and to an excellent granularity, which enables a good spatial resolution. In view of its possible application in LHC detectors the MSGC technique has undergone extensive tests and developments at several laboratories (Pisa [16], RD28 collaboration at CERN [17] and others).

Detector layout

As basic detector element we propose (following the HERA-B approach [1]) an L-shaped chamber. Each individual detector is manufactured on a single substrate (DESAG D263 with bulk resistivity $10^{19} \Omega\text{cm}$) having 300 μm thickness (0.24% X_0) for large areas.

On this substrate 8 μm metal anode strips are implanted, alternating with 90 μm cathode strips with a 200 μm anode-to-anode pitch. Detector sizes up to 25 cm strip length have been manufactured, and their performance in terms of capacitance and attenuation will be tested in the near future. Coating the substrate with a thin layer of lower surface resistivity of about $10^{11} \Omega/\square$ in order to avoid charge attachment to the substrate improves the rate tolerance and probably also the aging properties of the detectors. Several promising techniques are presently tested like lead silicate, diamond and coating with S8900 electron conducting glass, but long term tests on the stability have still to be carried out.

A glass frame encloses a 3 mm gap of a $DME - CO_2$ (60:40) gas mixture [18] which provides a high drift velocity of 60 $\mu\text{m}/\text{ns}$ and about 40 primary electrons. The gap is closed with a drift electrode made of a 100 μm thick metallized glass. With this configuration an amplification of $1-2 \times 10^3$ can be easily obtained. Local space-charge effects are not expected up to rates of $10^6 \text{ mm}^{-2}\text{s}^{-1}$.

Using analog readout on either cathode or anode strip signals, a single-hit resolution of 40 μm at 98% efficiency has been demonstrated by several groups. Tests have been performed to investigate the effects of a magnetic field of 2.24 T [19]. By compensating for the Lorentz angle by rotation of the chamber by 10 degrees a 40 μm resolution was again obtained. The same compensation procedure can be applied in LHC-B for stations 3 to 7 which are located inside the magnet.

Geometry of inner tracker stations

Four of the L-shaped chambers can be combined to provide detection in one plane, up to 20 cm distance from the beam in both x and y , as indicated in Fig. 5.6. Each of these chambers has independent front-end electronics readout and gas supplies. They are assembled with an overlap of 5 mm, as shown in Fig. 5.6, in order to avoid gaps and to facilitate alignment.

Several detector planes are combined in groups, mounted very close in z and at different angles in the xy plane. Such a module is illustrated in Fig. 5.7. In addition to vertical strips and the stereo planes rotated by $\pm 5^\circ$, the figure also includes a plane with horizontal strips that may be needed to resolve multi-particle ambiguities.

The total amount of material traversed by a particle passing through all detector planes in front of gas RICH 2 is $4 \times 12 \times 0.32\% X_0$. Here the material increase due to the small overlap region between detectors in the same plane (about 0.5% of the total area) is neglected. The front-end electronics can be

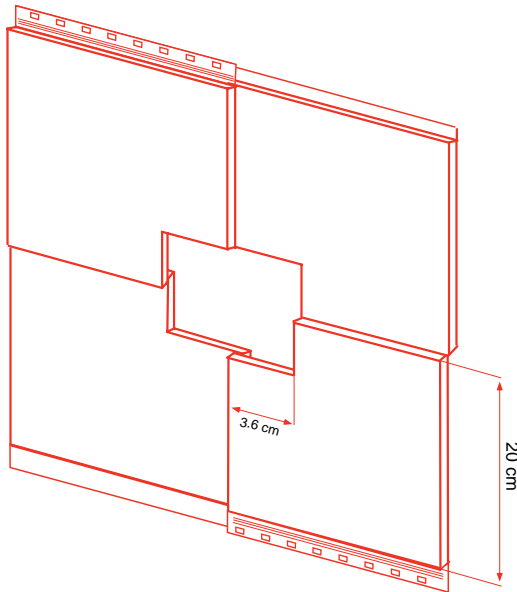


Figure 5.6: Layout of an individual MSGC detector element, corresponding to plane number 3. Four of them are grouped into one module.

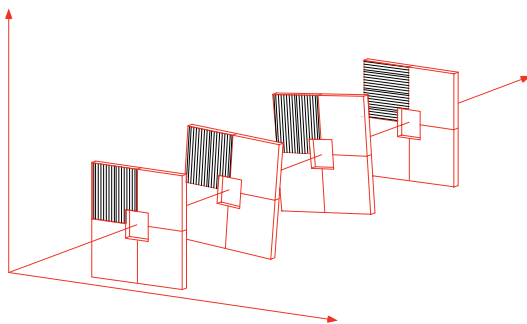


Figure 5.7: Orientation of MSGC detector elements making part of one module

mounted on a 2 cm board along the detector edge on a low density material, as shown in Fig. 5.6.

Readout

The VLSI readout electronics should have a fast front-end low noise preamplifier [17],[20]. In order to wait for the trigger decision of the experiment, the preamplifier will be followed by an analogue memory clocked at 40 MHz. The LHC-B requirements are quite similar to those of other LHC collaborations such as CMS [21] where solutions are now being worked out for systems with analog readout and a similar frequency [22], [23].

Recently, MSGC readout with an analogue pipeline has been successfully performed [24]. Due to the low gas gain and small primary ionization a relatively long integration time of 50 ns is required. The resolution will thus be at least 2 bunch crossings [17],[25], [26].

The number of readout channels per 3-layer station is 12,600. This amounts to a total of 163,800 for the MSGC region and 20,000 for the Silicon Strip detectors in the central part of stations 1 and 2.

Occupancy and integrated charge

The occupancy is calculated by overlaying two interactions from a full GEANT event simulation. The average cluster size is 2 strips. The results are shown in Fig. 5.8. The occupancy for the strips located at the hottest place in every station is indicated, and also the probability to have two or more particles firing the same strip (double occupancy), giving rise to ambiguities that can be resolved by the use of rotated planes.

Since long-term aging effects may become critical for MSGC's, we have plotted in Fig. 5.8 the total accumulated charge in the most irradiated channel of each plane. In the worst case this does not exceed 20 mC/cm/year. Aging and long-term stability of MSGC's is being studied in many laboratories. Encouraging results have been obtained by groups at CERN and Pisa [16] showing that aging effects can be controlled with special care in the selection of material and clean gases.

5.2 Outer tracking system

The basic elements for the outer tracking system are honeycomb chambers [27],[28]. They provide a cost-effective way to manufacture "straw tube" like drift chambers with a minimum amount of material.

Detector layout

The cathodes are made of conductive folded foils. A pair of such foils together with an insulating planar foil are combined into one monolayer of hexagonal cells. Two staggered monolayers arranged as shown

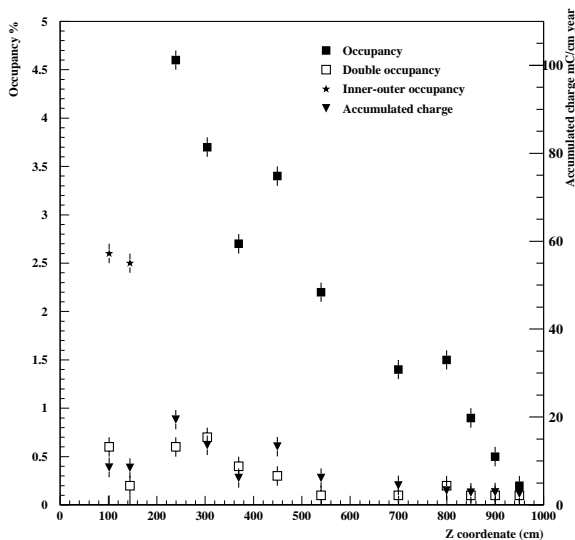


Figure 5.8: Occupancy and maximum accumulated charge distribution in the different planes of the tracker. Blank stars show the estimated occupancy for a $80\mu\text{m}$ pitch detector covering the innermost region of the planes 1 and 2.

in Fig. 5.9 provide full geometrical coverage. This arrangement with a flat foil between two staggered layers forms a stiff, self-supporting block. A more compact, but less rigid arrangement with “full honeycomb structure” as used in the HERA-B tracking system will also be studied.

The drift cells in the outer tracker must be small in order to cope with the high particle flux. Due to high voltage stability and resolution deterioration near the sense wire the smallest cell diameter is chosen to be 5 mm. The chambers are built from $75\mu\text{m}$ thick conductive Pocalon C foil. A fast drift gas (Ar-CO_2) is necessary to minimize the pileup of hits from several bunch crossings.

For trigger purposes pad chambers are included in some of the tracking stations. It is possible to divide the cathodes of the first and the last foil of the outer tracker stations into pads with the required dimensions. Here, kapton or mylar foils with sputtered copper pads can be used. This does not affect the performance of the chambers for the offline tracking. The read-out of the pads has to be studied in more detail.

In principle honeycomb chambers allow two dimensional high-precision readout of a single plane using the drift time to the wire and the charge distribution on cathode strips. However, a precise charge measurement needs relatively long electronic integration

times resulting in pile-up of signals from many bunch crossings. This pile-up has not yet been studied in detail. The proposed outer tracker relies therefore on drift time measurements only, and the strip readout is kept as an option requiring dedicated R&D efforts.

Prototypes of honeycomb chambers have been tested extensively over the past years with cosmic rays at NIKHEF and by the HERA-B collaboration, as well as in test beams at CERN by the RD5 collaboration [29]. The RD5 results include wire and strip readout. One type of chamber tested in RD5 has a size of $100\text{ cm (wires)} \times 325\text{ cm (strips)}$ and consists of 8 monolayers. The outer cell diameter is 11.6 mm. The resolution in the position determined from the drift time is around $70\mu\text{m}$ for tracks passing not too close to the wires. The performance of the chambers does not change significantly in magnetic fields up to 3 Tesla. The largest honeycomb chambers built so far have 5.6 m long anode wires and 24 mm cell diameter. They are tested with cosmic rays and no degradation of performance is found as compared to the RD5 chambers. The HERA-B collaboration has tested chambers with 5 mm cell diameter. The prototypes consist of kapton or mylar foils with sputtered copper strips. Chambers have also been made with conductive Pocalon and aluminium foils.

The performance of the outer tracker chambers is studied with a detailed simulation program [30], which reproduces the RD5 results to a good precision. With an Ar-CO_2 gas mixture the maximum drift time is below 50 ns, and the resolution per layer varies between $70\mu\text{m}$ and $230\mu\text{m}$ depending on the distance of the tracks to the wire. For tracks traversing an eight layer station with angles between 0 mrad and 300 mrad an average of 6.2 hits are recorded, and the overall spatial resolution is $48\mu\text{m}$.

Geometry of outer tracker stations

The layout of the outer tracker stations is similar to the one of HERA-B [1]. All wires are oriented essentially in vertical direction. The stations are comprised of eight monolayers, out of which two are tilted by $+5^\circ$ and two by -5° . In order to keep occupancies low, each outer tracker station is divided into different segments as shown schematically in Fig. 5.10. The segments are built as independent modules of chambers and overlap with each other. The outer cell diameter is 5 mm and 10 mm (wire pitch 6 mm and 11 mm) for the segments close and far from the beam, respectively. Since the particle density does not depend strongly on the distance z from the collision point, all stations have the same segment structure, except for the four small stations before the magnet which are fully covered by segments with 5 mm cells. The dimensions are summarized in Table 5.2.

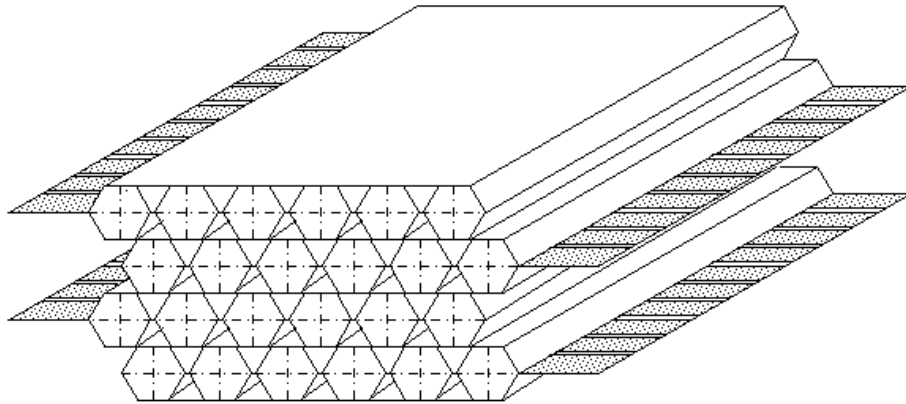


Figure 5.9: Layout of the cell arrangement in Honeycomb Chambers

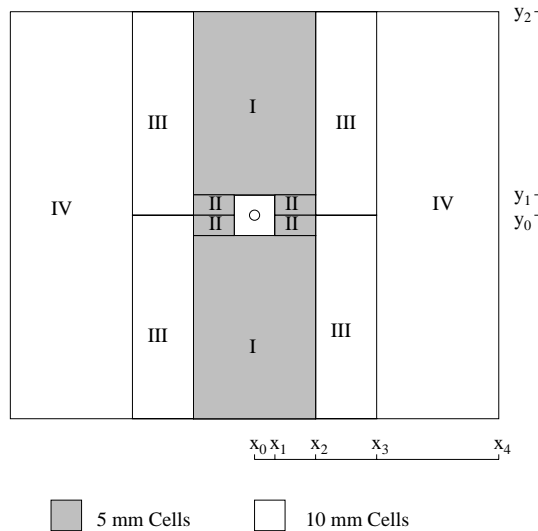


Figure 5.10: Segmentation of the stations

The total material per station amounts to 0.5% of a radiation length.

Readout

The requirements on the readout electronics are quite similar to those of any straw-tube-like detector operated at LHC. An example of such a detector is the TRT for ATLAS where solutions for the readout including a pipeline are being worked out [2]. The number of readout channels for each station is given in Table 5.2. For the whole outer tracker the number of channels amounts to a total of 183290.

Occupancy and integrated charge

The expected occupancy of the cells is studied with the full GEANT simulation of the LHC-B detector. Here, bunch crossings with one interaction are simulated, i.e. pile-up from multiple interactions in one crossing or neighboring crossings is not included. The results are shown in Fig. 5.11 for the four segment

Station	X2 [cm]	X3 [cm]	X4 [cm]	Y4 [cm]	Channels
1	43	43	43	43	4224
2	61	61	61	61	6528
3	102	102	102	102	11712
4	129	129	129	129	15232
5	65	96	157	157	9008
6	80	118	190	180	11328
7	95	142	228	180	13760
8	125	184	296	217	18400
9	143	210	338	248	21216
10	151	224	359	263	22544
11	160	237	380	278	23968
12	169	250	402	294	25376

Table 5.2: Characteristics of the Outer Tracker Segments. The radii X1, X2, X3, X4, Y1 and Y4 are defined in the figure. X1 and Y1 are 20 cm for all stations. As shown in Table 5.1, the muon chamber-station “ μ_2 ” (see Chapt. 8) will also provide tracking information as “station 13”.

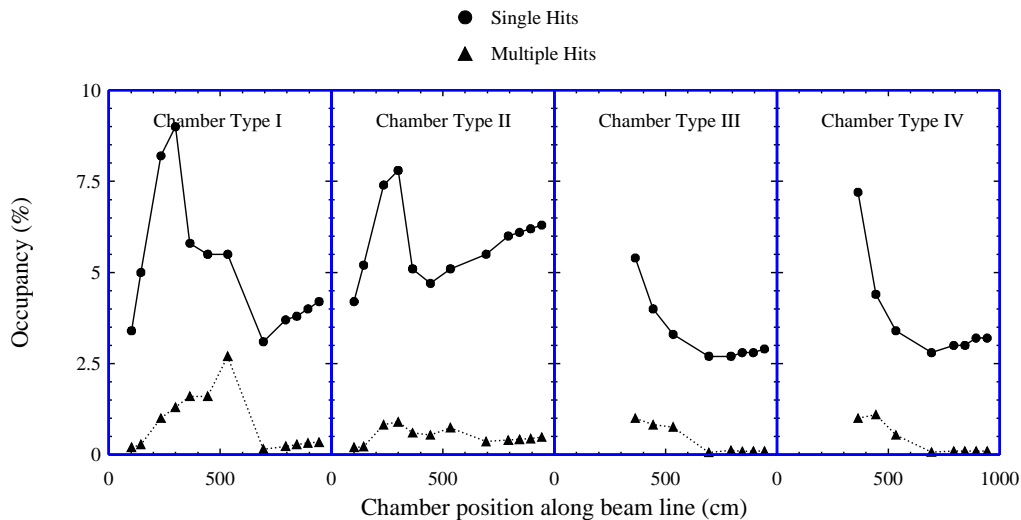


Figure 5.11: Maximum occupancy and fraction of double hits for the four segment types.

types. All cells of the outer tracker have occupancies below 10%.

The occupancy in bunch crossings with more than one interaction is obtained by scaling the numbers shown in Fig. 5.11. The effect from pile-up due to neighboring crossings is more difficult to estimate. The chambers are “self-timing” in the staggered arrangement shown in Fig. 5.9: The t_0 (and hence the bunch crossing) of each detected particle can be determined without external information by comparing the measured drift times in two adjacent layers. Hits originating from earlier crossings can thus be removed before the track finding algorithm is applied. However, overlaps of a particle in the triggering crossing with a particle in the earlier crossing lead to an effective inefficiency of the chambers. This inefficiency corresponds to the cell occupancy in the early crossing, and is therefore below 10% for all cells.

One year of operation with a gas amplification of $5 \cdot 10^4$ leads to an accumulated charge of 0.9 C/cm in the outer tracker regions closest to the beam. At these charge deposits the aging properties of the system have to be carefully studied and checked. A program of systematic aging tests with honeycomb chambers has been started in the HERA-B collaboration. The experiences with straw tubes at similar rates give us the confidence that a viable solution can be found. In the study of the TRT in ATLAS, straw tubes have been irradiated with a total dose corresponding to 5 C/cm. No aging or other changes in the straw properties are observed [2].

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6 Ring Imaging Cerenkov Detectors

The layout of the RICH detector system is shown in Fig. 1.4 of Chapt. 1. A mirror-focused aerogel radiator is followed by a mirror-focused gas radiator, both placed before the dipole magnet. A second mirror-focused gas radiator, needed to measure the small angle, high energy particles, is placed after the dipole magnet. Two types of Aerogel radiators are under consideration, and are referred to as Aerogel-A and Aerogel-B throughout this section. Tables 6.1 and 6.2 contain the parameters of the RICH counters and their detectors. The optics of these counters has been previously developed[1].

Cerenkov photons from each of the radiators will be detected by Hybrid Photo-Diodes[2] (HPD's) placed outside of the beam aperture in order to reduce particle interactions and multiple scattering. In each counter, a ring image is transferred without aberration, to its HPD detector plane, by reflection from a flat mirror placed at 45° to the beam axis (z), as shown in Fig. 1.4. The HPD's are sensitive to visible and near-UV light and have small silicon-pad pixels which give unambiguous 2-D space points.

The integral track momentum distributions, shown in Fig. 6.1 for representative low and high multiplicity B-decay modes, allow us to define the requirements of the LHC-B RICH system. In the large-angle region before the dipole ($100 \leq \theta \leq 400$ mrad), particles between 1 and 65 GeV must be identified, whereas after the dipole ($10 \leq \theta \leq 120$ mrad), the required range is from 10 to 150 GeV. Particle identification (ID) in the low-momentum range ($p < 10$ GeV) is important because it contains a large fraction of the tracks. A counter to identify these particles must be placed before the dipole since a substantial fraction of them do not exit the dipole for subsequent measurement. Obviously, all charged tracks from B-mesons must be measured and positively identified, in order to determine the correct invariant mass.

The highest index NTP-gas radiator available, C_5F_{12} has threshold $\gamma_t \approx 17$ which permits positive π/K ID only above 8 GeV. This radiator alone would result in unacceptably low values for the B^0 reconstruction efficiency. The event loss would considerably exceed the fraction of low energy particles, because many B^0 decays have one or more such particles and all are needed to reconstruct the B^0 mass. For example, Fig. 6.1 shows that, for the high multiplicity case, the loss factor is 4 if the minimum momentum for positive π/K ID is 8 GeV. Even though the loss for the $\pi\pi$ mode is only $\approx 30\%$, this factor is also recovered if we instrument for the $D_s \pi\pi\pi$ mode.

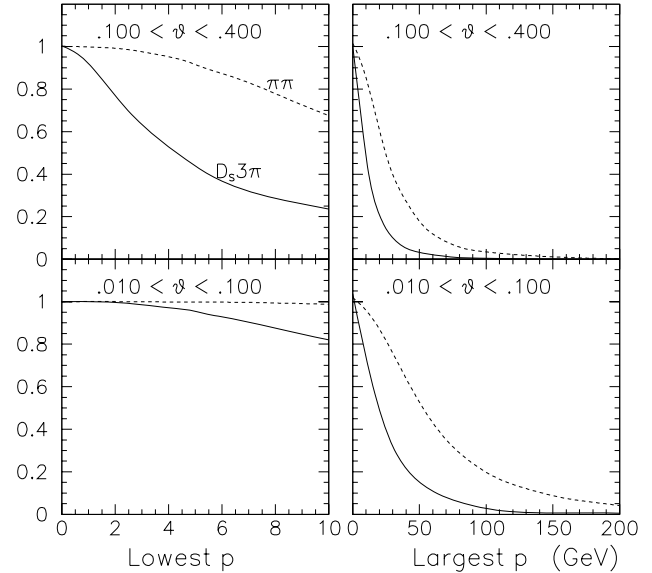


Figure 6.1: Integral momentum distributions for the representative low and high multiplicity decay modes, $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$, in the two indicated angular regions. In each plot, the upper curve is for the former reaction and the lower curve is for the latter. The curves labeled “largest p” show the fraction of events for which the largest momentum track in the final state is greater than the abscissa value. The curves labeled “lowest p” show the fraction of events for which the lowest momentum track in the final state is greater than the abscissa value.

As shown in Table 6.2, a mirror-focused aerogel[3] radiator (“Aerogel-A”) can cover the low-momentum region and provide positive π/K ID for momenta from 1.4 to 12 GeV (3σ upper limit). Since the mirror-focused C_5F_{12} gas radiator allows positive π/K ID above 8 GeV, the combination allows positive π/K ID in the large angle region ($100 < \theta < 400$ mrad) from 1 to 60 GeV.

A convenient low-index NTP-gas radiator CF_4 has $\gamma_t \approx 33$. When used in the counter positioned after the dipole magnet, it will allow positive π/K ID in the small angle region ($10 \leq \theta \leq 120$ mrad) for particles between 16 and 150 GeV.

6.1 Mirror-focused aerogel

The mirror-focused aerogel radiator is shown schematically in Fig. 6.2. A summary of the mir-

Radiator				Mirror		Detector		
Medium (radians)	γ_t	index n	length L	radius r_m	position z_m	relative position z_{dr}	absolute position z_{da}	window
Aerogel-A (0.1-0.4)	3	1.06	50	2000	1650	1150	800	glass
Aerogel-B (0.1-0.4)	4.2	1.03	50	2000	1650	1080	730	glass
C_5F_{12} (0.1-0.4)	17	1.00175	290-620	2300	2300	1150	1150	UV glass
CF_4 (0.01-0.12)	33	1.00046	1110-2120	12000	11600	6000	5600	UV glass

Table 6.1: Radiator, Mirror and Detector Geometry. All lengths are mm. Aerogel-A and Aerogel-B are alternative solutions.

Counter	(GeV) π/K ID Range	(eV) q_{int}	(eV) \bar{E}	(mrad) $\sigma_\theta(total)$	(mm) pixel size $\Delta x, \Delta y$	Photo- electrons n_{pe}	(m ²) Detector area A	(10 ³) No. pixels P	No. HPD's N
Aerogel-A	1.4-12	0.081	$2.72 \pm .38$	2.28-2.42	5	10	1.66	49	191
Aerogel-B	2-17	0.194	$2.72 \pm .38$	1.81-1.89	4	12.5	1.30	60	150
C_5F_{12}	8-60	0.785	$3.82 \pm .92$	0.79-1.13	2	18-38	0.96	177	111
CF_4	16-140	0.785	$3.82 \pm .92$	0.28	4	18-34	2.57	76	297

Table 6.2: HPD Detector Parameters. See text for definitions. Photoelectron yields include losses for geometrical coverage (0.73) and mirror reflectivities (0.95)². All counters will have tri-alkali photocathodes sealed in high vacuum. In all cases, the 3σ momentum upper limit for K/proton ID is 1.69 times higher than for π/K .

ror, detector and radiator geometries may be found in Table 6.1 and the detector parameters in Table 6.2.

The 5 cm thick aerogel radiator would be pre-molded between two spherical surfaces and then placed flush against a 3 mm thick Be (or Al) spherical mirror⁸ with radius-of-curvature, r_m .

The radiator and mirror ensemble is oriented normal to the beam axis (z) at position, z_m , from the LHC collision point at $z = 0$. The virtual image plane is also normal to the beam axis at the optimal focal distance, z_{dr} , relative to the mirror center-of-curvature. Its absolute position is given by: $z_{da} = z_{dr} + z_m - r_m$. The most important feature of this geometry is that the mirror center-of-curvature is located near the beam-crossing point so that all secondary particles have small impact parameter $x_e = (z_m - r_m) \sin \theta_p$ (here θ_p is the particle polar angle). This minimizes a major error source (coma) of the ring image and thus allows large an-

gular acceptance ($100 \leq \theta_p \leq 400$ mrad) with good resolution⁹.

Particle deflection in a magnetic field can also generate a non-zero impact parameter. The integrated magnetic field which reduces the momentum limit for π/K ID by 10% is $\int B dl = 0.25$ Tm for the aerogel counter. Since the counter is only 5 cm thick, we require $\bar{B} < 5$ T, a condition that is always satisfied.

For the first possible type of aerogel discussed below (referred to as Aerogel-A in Tables 6.1 and 6.2), the average chromatic error of the radiator is $\sigma_\theta(E) = 1.78$ mrad, over the flat Cerenkov spectrum interval 2 to 3.5 eV ($\bar{E} = 2.71 \pm 0.38$ eV). The pixel error for 5×5 mm² pads will be $\sigma_\theta(x, y) = \sqrt{\sigma_\theta(x)^2 + \sigma_\theta(y)^2} = 1.5$ mrad. The total angular error for the ring image, $\sigma_\theta(total)$ is thus given by the quadratic sum of these two errors, plus those for impact parameter and radiator thickness. The small dependence on incident angle leads to the range for this parameter given in Table 6.2.

⁸To reduce the material mass in the beam aperture, we will try to form a thin-film reflective mirror on the back surface of the aerogel radiator by vacuum deposition of a 200 nm film of quartz followed by a 150 nm film of Al and again a 200 nm film of quartz-to protect the Al film.

⁹Even better resolution would be obtained if the detector surface were constructed to follow the spherical focal surface. However, this complication is unnecessary, since the acceptance aperture is not so large.

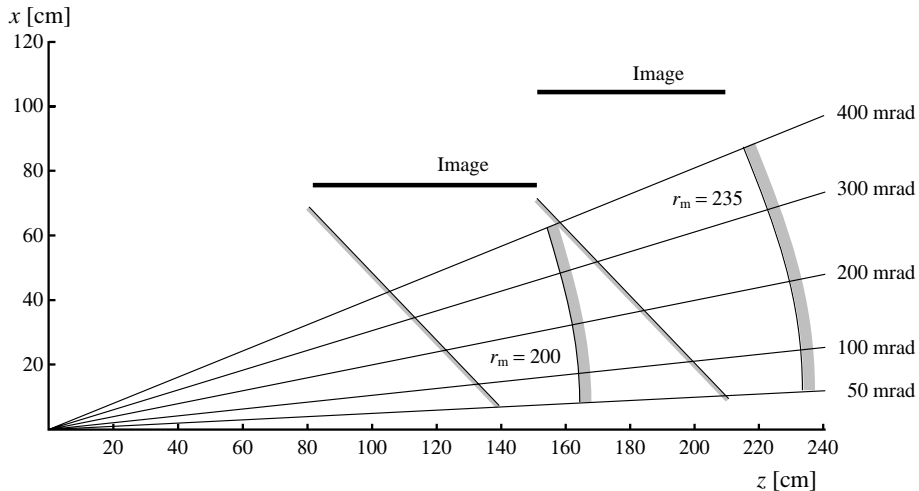


Figure 6.2: Preliminary geometry of the aerogel counter and the C_5F_{12} gas counter. The final system may have to be displaced downstream by 10 cm or so, to accommodate the vacuum window at $z = 1$ m and parts of the tracking system

Fields et al.[3] have recently demonstrated fine ring images by focusing the (Rayleigh) unscattered photons from $n = 1.03$ aerogel. Because the Rayleigh scattering cross section goes like λ^{-4} , selection of mostly visible photons (using HPD's with glass windows) largely enhances the ratio of imaged to background photons[3]. Since the Rayleigh scattering cross section $\sigma = \sigma_R/\lambda^4$, we evaluate the rms scattering length $\ell_0 = 1/n\sigma = \lambda^4/n\sigma_R$ (where $\ell_0 = t/[-\ln T]$, for a sample of thickness t and transmission T at wavelength λ).

Comparison of various aerogels is made by plotting the density- and λ^4 -independent coefficient $c = \lambda^4/[\ell_0 \cdot (\rho/\rho_0)]$. The best aerogel¹⁰ of Ref. [3] had $c = 0.0183 \mu\text{m}^4/\text{cm}$. The probability for no scattering in length x is $P(x) = e^{-x/\ell_0}$. Thus, for Cerenkov light produced uniformly in a radiator of length L , the unscattered probability $\overline{P} = (1 - e^{-L/\ell_0})/(L/\ell_0)$. For mirror focusing in the present geometry, the average pathlength $L = 3t/2$.

Including this factor, \overline{P} , evaluated for their “best future aerogel” (i.e. for $c = 0.01 \mu\text{m}^4/\text{cm}$), the quantum-response of an HPD photocathode averaged over the spectrum (2 to 3.5 eV) from a 50 mm thick Aerogel-A radiator is:

$$q_{int} \equiv \int Q dE = 0.081 \text{ eV}, \quad (39)$$

counting only unscattered photons. We have recently obtained an aerogel sample from CalTech[4]

¹⁰for $\rho = \rho_0 = 0.14 \text{ g/cm}^3$ and $n = 1 + 0.214\rho_0 = 1.03$.

with index $n = 1.06$ (i.e. $\rho = 0.28$) and measured $c \approx 0.012 \mu\text{m}^4/\text{cm}$ (see Fig. 6.3). Hence, their ‘best future aerogel’ is almost achieved.

The number of photoelectrons in the image n_{pe} is obtained after accounting for mirror reflectivities $(0.95)^2$ and window reflectivities with negligible bulk absorption loss. A detector coverage factor of 0.907 is obtained for hexagonal close packing of the HPD cylinders. An additional reduction factor of $(0.9)^2$ accounts for photocathode coverage of 90 mm within the 100 mm diameter HPD cylinder. Hence, the total geometric coverage factor is 0.735. With these factors, the average number of imaged photons from Aerogel-A ($n=1.06$, $c = 0.01 \mu\text{m}^4/\text{cm}$, $t = 50$ mm, $q_{int} = 0.081$ eV) is $\overline{n}_{pe} = 10$. The 3σ upper momentum limit for $p_{\pi/K}$ ID is plotted vs. θ_p in Fig. 6.4 and shows that the Aerogel-A counter will satisfy our needs.

With further advances, we expect to be able to achieve an improved aerogel with $c = 0.005 \mu\text{m}^4/\text{cm}$. A counter with $n = 1.06$, $t = 50$ mm, $q_{int} = 0.134$ eV. would give $\overline{n}_{pe} \approx 16$ and $p_{\pi/K}(3\sigma) \approx 13.5$ GeV.

A better choice would be “Aerogel-B” with ($n=1.03$, $c = 0.005 \mu\text{m}^4/\text{cm}$, $t = 50$ mm and $q_{int} = 0.194$ eV), giving $\overline{n}_{pe} \approx 12.5$ and $p_{\pi/K}(3\sigma) \approx 17$ GeV. Although the presently available Aerogel-A is already good enough for LHC-B, Aerogel-B would have even better performance.

For Aerogel-A the image centers are contained inside a disk of 406 mm radius. Thus, for image radii $R \leq 320$ mm ($\beta \leq 1$), the detector must extend to $406 + R \approx 726$ mm and cover an area of 1.66 m^2 .

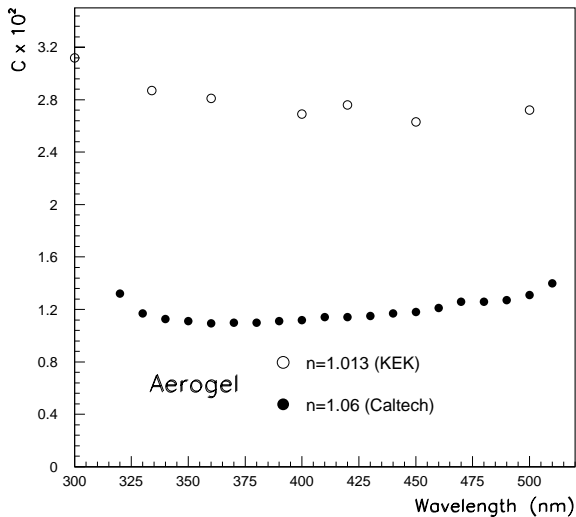


Figure 6.3: Comparison of different aerogels via the density- and λ^4 -independent coefficient “c” (see text for definition), for a sample of thickness t with transmission T at wavelength λ . The reference density $\rho_0 = 0.14 \text{ g/cm}^3$ and index $n = 1 + 0.214\rho_0$ are as given in Ref. [3]: they find $c = \text{constant} = 0.0183 \mu\text{m}^4/\text{cm}$.

With 73.5% surface coverage, we require 1.2 m^2 of silicon with 49k pixels of $5 \times 5 \text{ mm}^2$ contained in 191 HPDs of 100 mm diameter.

For Aerogel-B the image centers are inside a disk of 408 mm radius with image radii $R \leq 236 \text{ mm}$ ($\beta \leq 1$). Hence, the detector must extend to $236 + R \approx 644 \text{ mm}$ and cover an area of 1.3 m^2 . With 73.5% surface coverage, the silicon area is 0.96 m^2 with 60k pixels of $4 \times 4 \text{ mm}^2$ contained in 150 HPDs.

The two Be mirrors total 2.1% X_0 ; 50 mm of Aerogel-A to 5.2% X_0 (or 2.6% for Aerogel-B). Thus, the total is 7.3% X_0 (or 4.7% X_0). This material represents 2.4% (or 1.5%) of an interaction length λ_I .

6.2 Mirror-focused gas counters

The two mirror-focused, NTP-gas radiators are shown schematically in Figs. 6.2 and 6.5. Because of their similarity, we discuss them in common and then point out any specific differences.

The downstream end of each counter has a 3 mm thick Be (or Al) spherical mirror, with a radius-of-curvature, r_m , and is positioned normal to the beam axis at distance, z_m , from the LHC collision point at $z = 0$. In each case, the virtual image plane is also normal to the beam axis at the optimal focal

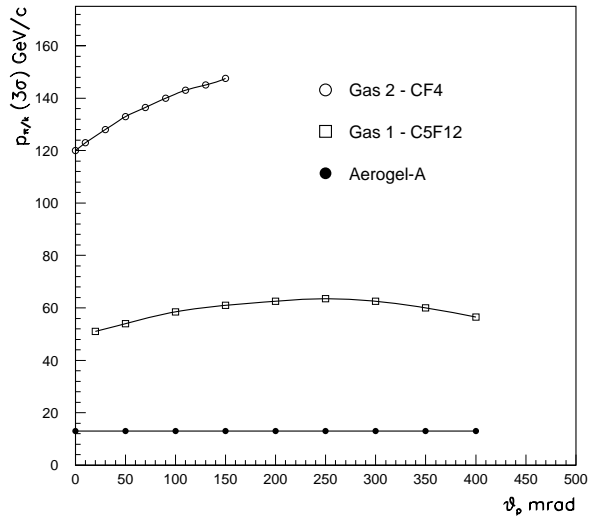


Figure 6.4: The 3σ upper momentum limit for π/K ID: p vs θ_p for the aerogel counter - Type A; the C_5F_{12} gas counter; for the CF_4 gas counter.

distance $z_{dr} = r_m/2$. Thus, its absolute position is at $z_{da} = z_{dr} + z_m - r_m \approx z_m - r_m/2$. As for the aerogel counter, the mirror center-of-curvature for the first counter is located exactly at the average beam-crossing point. Thus, all secondaries have zero impact parameter (*i.e.* $x_e = (z_m - r_m) \sin \theta_p \approx 0$), and we have good resolution over the large aperture. In the second counter, the mirror center-of-curvature is near the particle source and x_e is small enough to ensure good resolution over its (smaller) aperture.

Particle deflection by a magnetic field in the radiator could generate non-zero impact parameters which would diminish the resolution. However, the fields are sufficiently small that this is not a problem. The integrated magnetic field which reduces the momentum limit for π/K ID by 10% is $\int B dl = 0.57$ (0.53) Tm for the C_5F_{12} (CF_4) counters, respectively[1]. Since the counters have average lengths of 0.5 m (1.5 m), the average magnetic fields are required to be $\bar{B} < 1.14$ (0.35) T, respectively. This condition is readily satisfied for both cases, especially since the CF_4 counter is $\approx 3 \text{ m}$ downstream of the dipole.

The upstream 45° mirror, which transfers the images to the HPD detector plane, reduces the particle path length in the radiator at the smallest angles to about half of what it is at the largest angles. This loss, however, is acceptable because the HPD quantum-response is large enough ($q_{int} = 0.79 \text{ eV}$ for photons between 2 and 5.5 eV) to compensate the reduced pathlength. With Corning 7941 UV

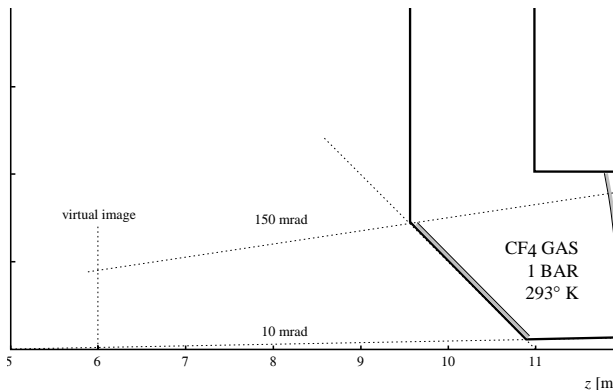


Figure 6.5: Geometry of the CF_4 gas counter 2.

glass as the HPD window, sufficient UV transmission will be provided. In this energy interval, ($\bar{E} = 3.82 \pm 0.92$ eV), the C_5F_{12} counter will have a chromatic error of $\sigma_\theta(E) = 0.60$ mrad, as compared to the pixel error $\sigma_\theta(x, y) = 0.50$ mrad for 2×2 mm² pads, while the CF_4 counter will have $\sigma_\theta(E) = 0.28$ mrad compared to the pixel error $\sigma_\theta(x, y) = 0.24$ mrad for 4×4 mm² pads,

The number of photoelectrons in the image is obtained after accounting for mirror reflectivities, window reflectivities, absorption in the windows and geometric coverage in the same way as for the aerogel counter. With these factors, the number of imaged photons is given in Table 6.2 for the lower and upper angular limits. The 3σ upper momentum limits for π/K identification are shown in Fig. 6.4 and in Table 6.2.

C_5F_{12} Counter: The image centers are contained inside a disk of 486 mm radius. Therefore, for image $R \leq 68$ mm ($\beta \leq 1$), the detector must extend to $460 + R \approx 554$ mm and cover an area of 0.96 m². With 73.5% surface coverage, this requires 0.71 m² of silicon with ≈ 177 k pixels of 2×2 mm². To cover this surface in hexagonal close pack will require 111 HPDs of 100 mm diameter.

The two Be mirrors have 2.1% X_0 thickness and the 0.5 m of C_5F_{12} gas to 1.7% X_0 . The combined material is 3.8% X_0 and 2.5% λ_I .

CF_4 Counter: The image centers are contained inside a 723 mm radius disk so, for image radii $R \leq 182$ mm ($\beta \leq 1$) the detector must extend to $723 + R \approx 905$ mm and cover an area of 2.57 m². With 73.5% surface coverage, we require 1.89 m² of silicon with 76k pixels of 4×4 mm². To cover this

surface in hexagonal close pack will require 297 HPDs of 100 mm diameter.

The two Be mirrors total 2.1% X_0 and 2 m of CF_4 gas to 2.2% X_0 , for a total 4.3% X_0 and 2.6% λ_I .

6.3 Total channel and HPD counts

The total channel count for the three RICH counters is $49 + 177 + 76 = 302$ k pixels and the HPD count is $191 + 111 + 297 = 599$. The present cost estimate of an HPD is about 5 kCHF (independent of pixel number), for a total detector cost of 3.6 MCHF. Another way of estimating is 10 CHF per pixel, for a total of 3 MCHF. We tentatively budget 5 MCHF for the photodetector cost.

6.4 R&D program

We have started an R&D program to make 100 mm diameter HPD's initially with quartz windows and transmissive CsI photocathodes¹¹. After achieving this first milestone, we will attempt to enlist commercial companies to produce our design with visible tri-alkali photocathodes sealed in high vacuum. In parallel, we will acquire and test aerogel samples in preparation for a test of a focusing aerogel counter, once the HPD becomes operational.

The next R&D goal would be to demonstrate focused C_5F_{12} and CF_4 gas images and to demonstrate positive π/K separation up to 65 and 150 GeV respectively. This should be straightforward, once successful operation of the HPD's is demonstrated.

All pads may be read out with the electronics used for the silicon strip detectors or with our already developed and tested VLSI electronics[5]. We are currently upgrading the analog and digital chips for lower noise, lower power consumption and a longer pipeline (128 crossings, rather than 64). The test structures are now available and, if test results are positive, we may make a production run (of 20 k channels) before the end of the year.

6.5 Alternative technologies

We note from Table 6.2 that the number of imaged points expected from the aerogel radiator, $n_{pe} \approx 10 - 12$ is adequate. But, if the HPD efficiency is less than expected, there would be a problem. This could be compensated with higher quality aerogel. However, it is not expected that $c < .005 \mu\text{m}^4/\text{cm}$ can be

¹¹J. Seguinot, P. Weilhammer and T. Ypsilantis are proposing this project to the LHCC. We have begun to acquire the glass envelopes and pixelated silicon detectors. Each HPD will contain 256 pixels and be read out initially with the Viking-2 chip.

readily attained. The only alternative would be to increase the detector quantum efficiency. Recently, Visible Light Photon Counters (VLPCs) have been developed with extremely high quantum efficiency ($\approx 80\%$ between 1.5 and 3 eV) and with excellent single-electron efficiency[6].

The detection element is a doped SiAs crystal, operating at 7 K to reduce the dark current. A possible implementation would require that an imaged Cerenkov photon enter clear glass fibers (≈ 5 mm diameter) for delivery to a liquid-He dewar in which the VLPC detector is housed. The clear glass fibers would be coupled to glass fibers that are interfaced to the VLPC. This could, in principle, double or triple n_{pe} , thus giving a more than adequate level of security. These detectors are being developed for fiber trackers in the CDF and D0 upgrades at Fermilab[7]. We propose to keep abreast of these developments, in order to use the technology, should it become available. At the present time, the cost is very high (estimated as 60 CHF/pixel[7]). Thus, the VLPCs could only be used for the aerogel counter ($\approx 40k$ pixels ≈ 2.4 MCHF). However, this is just where it might be needed.

With regard to the C_5F_{12} and CF_4 gas counters, the only alternative technology available would be the Fast-RICH photodetectors based on the photosensor TEA with MWC gas amplification, as proposed earlier for COBEX[8]. However, the quantum-response of the TEA-Fast-RICH counter ($q_{int} \approx 0.35$ eV) is not sufficient to allow the use of the 45° transfer geometry (see Figs. 6.2 and 6.5), and this fallback solution would thus require significantly more material in the aperture ($\approx 20\%X_0$). In addition, the C_5F_{12} gas which is not transparent in the TEA response region (7.5-9 eV) would have to be replaced by C_2F_6 at 2.2 bar, thus further increasing material in the aperture.

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7 Calorimetry

7.1 Performance requirements

The calorimeter system comprises electromagnetic and hadronic components. The goal of the calorimeter system is to provide data for the trigger as well as to allow background suppression of B-decays at the reconstruction stage. There are three areas where the calorimeters are used in triggering:

- To provide an electron energy and position measurement to be used in electron identification,
- To provide a hadron transverse energy measurement for selection of high- p_t pions,
- To improve particle identification by using longitudinal segmentation of the hadron calorimeter.

The performance requirements of the LHC-B calorimeters are summarized in Table 7.1. The trigger requires fine granularity of the calorimeter system over the full coverage of detector acceptance. We have chosen to segment the calorimeters into inner and outer parts because of the hostile radiation conditions close to the beampipe. This implies different detector technologies for each.

Typical of forward collider experiments, longitudinal space is at a premium. We are therefore constrained to minimize the lengths of calorimetry and readout.

7.2 Electromagnetic calorimeter

The Electromagnetic Calorimeter (ECAL) is divided into an inner and outer part. A viable option for the outer part is a Shashlik-type lead/scintillator-plate sandwich with wavelength shifter (WLS) fiber readout. This detector has been extensively studied in the CERN RD-36 project[1, 2, 3]. In contrast, the inner part of the ECAL has to be made of more radiation-hard material than plastic scintillator and moreover it should have finer granularity and less Moliere radius than conventional Shashlik. The recently developed $PbWO_4$ scintillating crystal[4, 5] is considered a possible option.

The ECAL detector layout is shown in Fig. 7.1. The ECAL is designed to allow electron selection from copiously produced gammas and hadrons. A preshower detector is placed in front of the ECAL to reject neutrals and for use in the trigger. Its granularity will match the ECAL cells. The main features of the Inner and Outer parts of the Electromagnetic Calorimeter are summarized in Table 7.2.

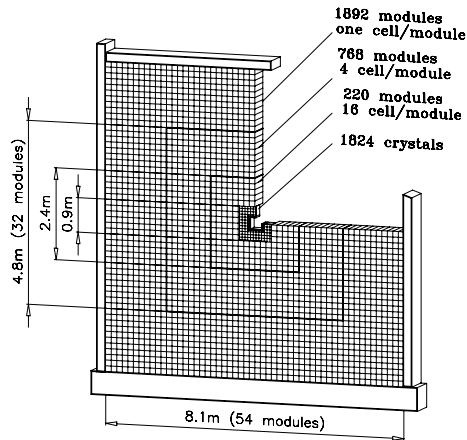


Figure 7.1: The Electromagnetic Calorimeter layout.

7.2.1 Outer EM calorimeter

For the outer part of the ECAL, the Shashlik-type structure has many advantages. It has uniform response, good energy resolution and is cheap and simple in production. We propose to segment it into identical modules of external dimensions $15 \times 15 \times 50$ cm. Within a module, the cell segmentation can be determined by the different grouping of fibers onto the photoreceiver. A module consists of 125 plates of 1 mm lead interspersed by 2 mm plastic scintillator surrounded by white paper. Each plate has 20×20 1.2 mm diameter holes with WLS fiber of 1 mm in diameter fed through to the back side, where the photomultiplier tubes (PMTs) are housed. Three type of modules differ by the fiber grouping scheme:

- 4×4 cells of 3.75×3.75 cm²,
- 2×2 cells of 7.5×7.5 cm²,
- a single cell of 15×15 cm².

A schematic view of the module is illustrated in Fig. 7.2. The fine sampling structure can provide an energy resolution up to $0.07/\sqrt{E}$ and a fiber density of ~ 1.8 cm⁻² allows a uniformity of response with a $\sim 1\%$ constant term[6].

For a photosensitive detector, the recently developed Hamamatsu R5600 PMT with very short (17 mm) dynode system offers a viable possibility for the central part of the ECAL. At the periphery, the detector thickness is less critical and can be shorter ($\sim 19X_0$). For example the FEU-115M photomultiplier[7] could be used in this region. It is fast enough with less than 10 ns signal duration base-to-base, sufficient linearity ($\sim 1\%$ for currents up to 50 mA), has small dark current (2 nA or less) and is

Calorimeter feature	ECAL	HCAL
	<i>Inner</i>	
Beampipe hole, mrad	~ 15	~ 15
Angular coverage, mrad	~ 30	~ 30
Energy to be measured, GeV	$0.1 \div 500$	$0.5 \div 1000$
Depth	$\sim 25X_0$,	$\sim 10\lambda_I$
Two shower separation	2 mrad	5 mrad
Radiation resistance	3 MRad/y	5 MRad/y
	<i>Outer</i>	
Angular coverage, mrad	~ 300	~ 300
Energy to be measured, GeV	$0.05 \div 150$	$0.2 \div 250$
Depth	$22 X_0$,	$\sim 7\lambda_I$
Two shower separation	5 mrad	15 mrad
Radiation resistance	100 KRad/y	200 KRad/y
Energy resolution, $\sigma(E)/E$	$0.1/\sqrt{E} \oplus 0.02$	$0.6/\sqrt{E} \oplus 0.05$

Table 7.1: Calorimeter design requirements. Radiation doses correspond to annual integrated luminosity of $3 \cdot 10^3 \text{ pb}^{-1}$ ($3 \cdot 10^{32}$ luminosity for 10^7 s).

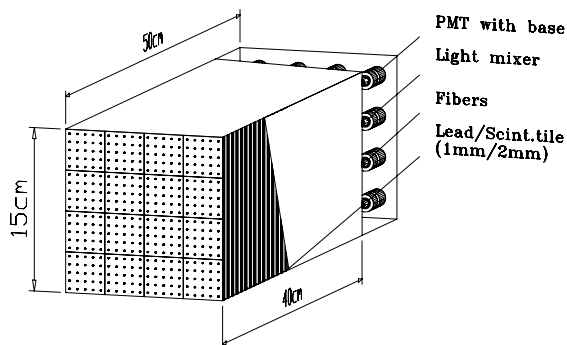


Figure 7.2: Shashlik type module, schematic drawing.

moderately priced.

7.2.2 Inner EM calorimeter

The heavy radiation environment of the very forward region implies that a greater radiation tolerance is necessary for the inner part of the calorimeter. An option for this region is $PbWO_4$ scintillating crystal. This crystal is known to be radiation resistant up to 10 MRad without significant damage[8, 9]. An additional advantage is its relatively small radiation length of $\sim 9 \text{ mm}$ and hence a small Moliere radius ($\sim 2 \text{ cm}$). It is known to be fast enough with decay time components of 2, 10 and 30 ns.

The central part of the inner calorimeter has a $30 \times 30 \text{ cm}^2$ window for the beam pipe. Tungsten alloy shielding surrounds the beam pipe inside the inner ECAL up to $45 \times 37.5 \text{ cm}^2$ to screen from irradiation caused by interactions in the beam-pipe due to particles bent by the magnet. The inner calorimeter itself has external dimensions of $90 \times 90 \text{ cm}^2$ and consists of a matrix of $PbWO_4$ crystals of size $1.875 \times 1.875 \times 22.5 \text{ cm}^3$. These crystals have been chosen as a base option for CMS[10] and the technology of mass production has been intensively studied. The light is collected from the back side of the crystals by PMTs. Possible photodetectors are small Hamamatsu R5600 PMTs, R5189 phototriodes or FEU-68 10-stage PMTs. Shorter crystals, with about $20 X_0$, could be chosen in our case without significant degradation in performance. The dependence of energy resolution on crystal length was studied by Monte-Carlo[11]. One can expect $\sigma(E)/E = 0.05/\sqrt{E} + 0.02$ for 18 cm long pieces.

7.2.3 Preshower detector

The preshower detector is used to reject gammas and hadrons in the electron trigger and also used to form pre-clusters in the hadron trigger. A viable option is a preshower detector constructed from two layers of scintillating tiles with a 1 cm thick lead converter between them. The total number of cells should match the ECAL. A problem is how to minimize the overall cost of the system and the availability of multianode PMTs opens an encouraging possibility. A WLS fiber is embedded into the tile

Radiator	<i>Inner</i> <i>PbWO₄</i> crystal
Dimensions, cm	80 × 80 × 40
Beampipe hole, cm	30 × 30
Shielding, cm	space between 30 × 30 and 45 × 37.5 is filled by heavy metal alloy
Average thickness	25 X_0 , 1.08 λ_I
Moliere radius, cm	2
Module size, cm	7.5 × 7.5 × 40
Channels per module	16
Number of modules	128
Crystal size, mm	18.75 × 18.75 × 225.0
Photomultiplier	Hamamatsu R5189 or FEU-68 with amplifier
Number of channels	1824
	<i>Outer</i>
Dimensions, m	8.1 × 8.1 × 0.5
Average thickness	22.5 X_0 , 1.06 λ_I
Moliere radius, mm	34 (separate tiles), ~ 40 (multibundle)
Module size, cm	15 × 15 × 50
Sampling structure	125 layer (1 mm Pb + 2 mm Scint. + 0.2 mm paper)
Holes per module	20 × 20, 7.5 mm spacing, 1.2 mm diam, 2.9%
Fiber per module, m	~ 200
Module weight, kg	42.4
16-cell modules	220 (3520 cells)
4-cell modules	768 (3072 cells)
1-cell modules	1892 (1892 cells)
Photomultiplier possibility	Hamamatsu R5600 or FEU-115M
Number of channels	8484
Total number of channels	10308

Table 7.2: Electromagnetic calorimeter summary.

in the form of a so-called ‘sigma path’ which yields $\sim 4 \div 8$ photoelectrons for a 4 mm tile thickness[12]. Light is transported from tile to photocathode by a 5 m-long transparent fiber. The rejection power of the preshower detector is determined by the gamma-conversion probability prior to the scintillator and also by system inefficiencies. A gamma rejection factor of the order of 10 could be expected at the Level-1 trigger.

Further improvement in signal gain could be obtained by the use of small tube-diameter PMTs. Here the photocathode is coated on the inner cylindrical surface of a tube which is $\sim 5 \div 15$ mm in diameter and $3 \div 8$ cm long. This type of PMT could be directly joined to the tile or embedded into a hole in it. These PMTs are now being developed at IHEP in collaboration with the MELS plant in Moscow.

7.3 Hadron calorimeter

A schematic view of the Hadron Calorimeter (HCAL) is shown in Fig. 7.3. Like the ECAL, the HCAL consists of an inner and outer part. For the outer part we propose a scintillating tile calorimeter. This has a sampling structure with the scintillating tiles parallel to the beam axis and with passive radiator made of steel plates. Tiles produced by injection-molding techniques are sandwiched between the steel plates which are separated by passive spacers made of steel, lead or copper. Two options for light collection are considered. The first is an already tested ATLAS solution which has WLS fibers running along the shower direction to the back side of the detector. The second option is more compact and uses photoreceivers embedded inside calorimeter cells.

The inner part of the HCAL needs to be more radiation hard than plastic tile allows ($\sim 1 \div 3$ MRad[14]). We suggest as an alternative option the use of tungsten or copper plates interspaced by quartz glass as

an active media. Quartz is preferred because it has good radiation hardness[16]. This type of calorimeter will detect Cerenkov light and since the angular acceptance of the emitted light is concentrated in the forward direction, there is good sensitivity to the shower core. This feature will allow good two-shower separation in the very forward region.

The design parameters of the HCAL are summarized in Table 7.3.

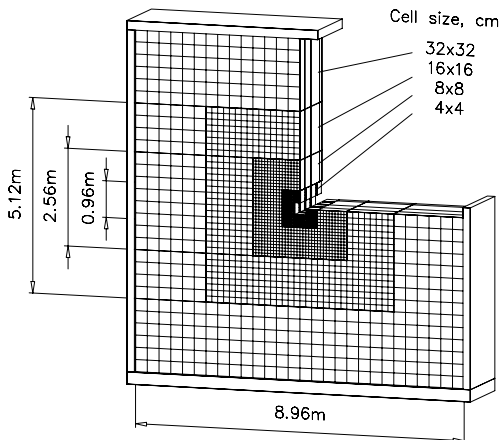


Figure 7.3: The Hadron Calorimeter layout

7.3.1 Outer hadron calorimeter

The outer Hadron Calorimeter has external dimensions of $8.64\text{ m} \times 8.64\text{ m}$ and 1.8 m in depth, giving a 300 mrad angular acceptance. The sampling structure looks similar to the ATLAS hadron tile calorimeter with a 3-fold segmentation in depth[13]. Here a resolution of $\sigma(E)/E = 0.5/\sqrt{E} \oplus 0.02$ has been achieved in a beam test (without an ECAL in front)[15].

The lateral cell segmentation has to satisfy the following criteria:

- it must allow precise shower position measurement to yield a small contribution to the p_t error measurement of single hadrons,
- it must allow good two-hadron separation,
- it must provide a good segmentation match to the ECAL for combined energy reconstruction at the trigger level,
- it must have a relatively low channel count to minimize cost.

We have chosen a four to one cell correspondence between the HCAL and ECAL throughout the detector. Hence the cell sizes range from 8×8 in the central region to 16×16 and $32 \times 32\text{ cm}^2$ at the periphery, approximately 6% larger than the ECAL cell sizes to maintain projectivity. Estimates show that the error in the transverse momentum measurement due to the uncertainty in the shower position will be 10 times less than from the energy resolution term at $p_t \sim 5\text{ GeV}/c$.

Two options are considered for the light collection:

(i) Fiber option. Light collection is achieved using 1 mm diameter WLS fibers with double cladding, fed through to the back side of the calorimeter wall, as shown in Fig. 7.4. A calorimeter cell is constructed of 160 cm long, 5 mm thick steel plates, interspaced by polystyrene scintillating tiles which alternate longitudinally with additional absorber (“spacers”). Three-fold longitudinal segmentation is foreseen for better muon identification, e/π and two shower separation. On the back side of the detector, fibers are connected to PMT’s. The details of assembly technology as well as choice of material for the spacers between the steel plates (*e.g.* iron, lead or copper) will be performed at a later stage.

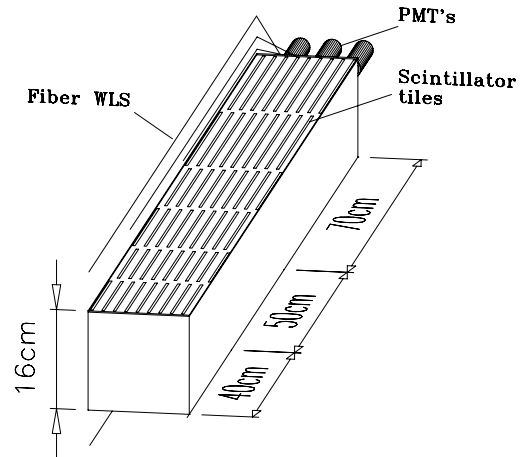


Figure 7.4: The Hadron Calorimeter fiber option, schematic view.

(ii) Embedded option. An alternative option is to embed the photoreceivers inside the calorimeter cell. In this option there exists a cylindrical hole in the middle of each cell in which the wavelength shifter and PMT are housed. A schematic view is shown in Fig. 7.5. The advantage of this option is that light attenuation in the long WLS fiber is excluded and hence the nonuniformity in response from this source is eliminated. The existence of the hole

	<i>Inner</i>
Dimensions, cm	$96 \times 96 \times 180$
Average thickness of 4 blocks tungsten radiator	$77.5 \times 4 = 310X_0, \quad 2.8 \times 4 = 11.2\lambda_I$
copper radiator	$19.0 \times 4 = 76X_0, \quad 2.0 \times 4 = 7.9\lambda_I$
Cell size, cm	4×4 upstream 2 blocks, 8×8 downstream blocks
Depth segmentation	4-fold
Radiator/quartz ratio	3.9 : 1
Quartz plate, mm	$2.2 \times 17.5 \times 350$
Photomultiplier possibility	Hamamatsu R5900
Number of channels	1280
	<i>Outer</i>
Dimensions, m	$8.96 \times 8.96 \times 1.8$
Average thickness	$68 X_0, \quad 7.2 \lambda_I$
Cell size, cm	8×8 within 2.56 m square 16×16 within 5.12 m square 32×32 outside
Sampling structure	5 mm steel plate + 4 mm spacer + 3 mm Scint.
Total weight, t	946
Longitudinal segmentation	3-fold in depth
Number of cells:	
— with 8×8 cm	2640 cells
— with 16×16 cm	2304 cells
— with 32×32 cm	1474 cells
Number of channels	6418
Photomultiplier possibility	Hamamatsu R5600 or FEU-115M
Total number of channels	7698

Table 7.3: Hadron Calorimeter summary

inside each calorimeter cell is compensated by the increase in light yield in the vicinity of the PMT. Measurements of the signal output from an embedded phototube have been compared with the fiber option at IHEP and a gain of $2 \div 3$ times in the response has been observed.

7.3.2 Inner hadron calorimeter

A quartz-tungsten arrangement provides a preferable option for the inner HCAL, however at the present time this choice appears too expensive. Hereafter, when we refer to tungsten, we assume that most of the radiator could be made of a cheaper material, *e.g.* tungsten containing alloy or copper. A schematic diagram showing a proposed module is shown in Fig. 7.6. Parallel tungsten plates of 16×35 cm and 2.5 mm thickness are interspaced by tungsten spacers with a gap for the flat quartz-glass radiators. Four such modules are arranged longitudinally along the beam direction. The quartz sandwich orientation will be alternated from vertical to horizontal for each con-

secutive block to minimize the punch-through probability.

Flat quartz glass plates, 2.2 mm thick and arranged parallel to the beam direction, can be used as an active medium for Cerenkov light. The granularity of the first two blocks is 4×4 cm and corresponds to the expected shower dimensions. Two downstream blocks have an 8×8 cm cell size. Each block is 35 cm in length and will be followed by a short PMT, a possibility is the Hamamatsu R5900.

The typical attenuation length of quartz-glass is greater than 2 m. The light collection to the PMT will be performed through air via a metal foil cone-mirror. Estimates of the light output indicate the order of 15 photo-electrons per GeV, however the registration of a muon signal could be a problem at these very small angles.

The flat quartz plates have a maximum angular acceptance for Cerenkov light along the general shower direction. This is illustrated in Fig. 7.7, which shows the collected Cerenkov light yield as a function of the angle between the emitting particle and the quartz

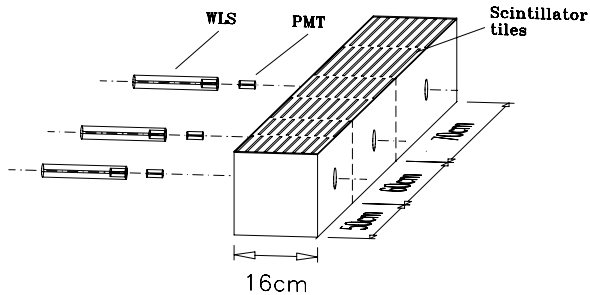


Figure 7.5: The Hadron Calorimeter option with embedded photoreceiver.

plate longitudinal direction. The dashed histogram demonstrates what kind of improvement could be expected if the front surface of the quartz were to be coated with an aluminium mirror (assuming a 90% reflectivity).

The advantage of the proposed design is that the lateral shower dimensions for such Cerenkov light detectors are expected to be much less than for corresponding scintillation or other ionization-based calorimeters. With this design, we expect the energy resolution of the inner HCAL will be comparatively poor, $\sim (1.5 \div 2)/\sqrt{E} \oplus (0.1 \div 0.2)$. However, this is compensated by good spacial resolution (~ 1 cm) and a good (few cm) two-hadron separation.

Recently, studies have been made on quartz fibers as an active media. In one such study it has been proposed to bend *cladded* fibers at a 45° angle to the general shower direction for better light capture. The hadron shower lateral dimension has been estimated from a module edge scan to be ~ 2.5 cm FWHM[17]. In a second study, 0° oriented fibers were used and larger values (7 cm) were obtained for the shower lateral size. This is because the emitted Cerenkov light is captured in the fiber predominantly for shower particles which travel at $\sim 60^\circ$ to the general shower direction[18].

Further GEANT calculations and beam test measurements will be performed to achieve a final solution. The use of radiation-hard glass (up to 30 MRad) as a sensitive medium and the use of a copper radiator can be considered as cheaper options.

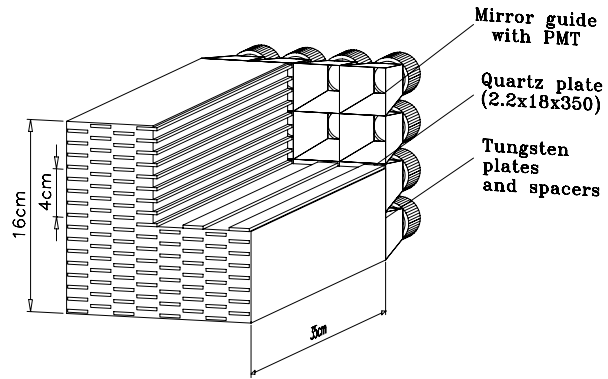


Figure 7.6: The Inner Hadron Calorimeter module view.

7.4 Calibration and monitoring

It is expected that all the calorimeter modules will be calibrated individually in a test beam prior to installation. Calibration *in situ* can be performed both for the ECAL and HCAL by comparing the energy deposited in the calorimeter with charged particle momenta measured using the magnetic spectrometer. For the ECAL calibration the possibility exists to use electrons from gamma conversions which occur before the first tracking station. It may be practical to introduce a few millimeter lead convertor for a short period of time to increase the electron flux on the peripheral part of the ECAL.

During data-taking the ECAL calibration can be tuned by constraining the effective mass of $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, and $J/\psi \rightarrow e^+e^-$ decays associated with isolated showers. This will provide a cross-check of the relative cell response and the absolute calibration. A special low-rate scaled trigger could be used to allow a uniform illumination of the whole ECAL.

Each calorimeter cell will need to be monitored for short-term stability (*e.g.* over the timescale of a few weeks). A light pulsing system can be used for the ECAL, distributed by fibers either from light emitting diodes (LEDs) or a laser source. The outer HCAL can be monitored by a radioactive source (*e.g.* ^{137}Cs) moved inside small diameter tubes running through the calorimeter in the transverse direction to the beam line. Measurement of the current recorded in the PMTs as a function of the γ -source position will allow a stability check of individual tiles. Both the LED system or Cerenkov light produced by a

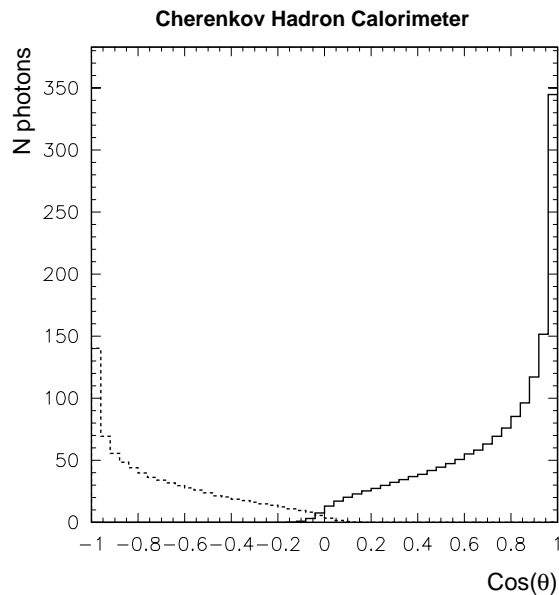


Figure 7.7: The Cherenkov light yield collected at the rear side of the quartz plate as a function of angle between the emitting particle and the plate longitudinal direction. The dashed line represents the light increase resulting from a mirror placed on the front surface of the quartz.

^{90}Sr β -source could be used for monitoring the inner HCAL.

The technical details of the monitoring system and the calibration procedure will be finalized after prototype studies.

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8 Muon System

8.1 Design criteria

The LHC-B muon detector serves the purpose of both muon identification and trigger device to the maximum luminosity contemplated for the LHC-B experiment, $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. In addition, it must cope with the large hadronic particle densities of 10-14 TeV interactions in the forward region between 10 and 300 mrad. In that regime and at these rates, the LHC-B muon detector must be optimized for good efficiency for B-signals (e.g. $B_d \rightarrow \pi^+ \pi^-$ with semi-inclusive $\bar{B} \rightarrow \mu$), while minimizing the trigger rate due to $\pi/K \rightarrow \mu$, charm $\rightarrow \mu$ decays and hadronic punchthrough.

The design goal is to reduce the single muon trigger rate from all background sources by a factor of 100 while maintaining the highest possible $B \rightarrow \mu$ efficiency.

The configuration of the muon detector is specified by:

- the thickness of the muon-shield
- the number and types of detector planes
- the angular coverage

The choices that best optimize signal efficiencies and minimize trigger rate have been studied. The angular range covered by the muon detector has been determined to be $10 \leq \theta_\mu \leq 300$ mrad from studies of signal loss and the dependence of the trigger rate on angular coverage. Very little increase in $B \rightarrow \mu$ rate is seen if the minimum angle is decreased to 5 mrad. The maximum practical angular coverage is chosen to be 300 mrad. Although only about 10% of the $B \rightarrow \mu$ triggers are contributed by the region between 200 and 300 mrad, this aperture offers excellent acceptance for the higher p_t muons from the FCNC di-muon decay of B-mesons and very clean muons with which to evaluate the effect of track density on more cluttered regions.

The thickness of the shield is determined by the dual requirements of elimination of the low momentum muons from π/K semi-muonic decays by dE/dx and the elimination of hadronic punchthrough. The thickness discussed below is enough to substantially decrease the light meson semi-muonic decays even before a muon p_t cut and to make the hadronic punchthrough negligible ($\leq 0.05\%$ of all hadronic interactions generate a punchthrough trigger). The energy attenuation produced by the thickness of the muon-steel plus the electromagnetic and the hadron calorimeters (19 absorption lengths) is approximately

5.9 GeV.

Hereafter, when the muon-shield is referred to, it will be taken to mean the total shield formed by the combination of the electromagnetic calorimeter, the hadron calorimeter, and the three segments of muon-steel shielding shown in Fig. 8.1. Several different muon absorber and detector configurations have been studied using full GEANT simulations before arriving at this configuration. Additional sophistications, such as "sculpting" of the shield thickness, have been considered, but have been deemed unnecessary for the purposes of this LOI.

In this chapter, the six "Muon Chamber" stations which are used in the muon trigger are labeled $\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6$, as shown in Fig. 8.1. μ_1 is just after the magnet. μ_2 is just in front of the electromagnetic calorimeter and $\mu_3 - \mu_6$ are "buried" in the muon-steel. Two chamber stations of the main tracking system serve as μ_1 and μ_2 , possibly upgraded with a pad readout.

Coincidences between various combinations of hits in μ_3 through μ_6 due to penetrating particles provide the first stage of the Level-1 muon trigger. Muon candidates are then followed back through the stations μ_2 and μ_1 in front of the shield. We have studied two alternate approaches to the Level-1 muon trigger, in which a minimum p_t is required of the penetrating particle. In the first approach, muon candidates are identified as coincidences between cathode pads in the various layers of the muon systems; this strategy is similar to the one employed in the FERMILAB experiment E771. Compared to this first method, which defines tracks in space, the second technique searches for track candidates in the $x - z$ and $y - z$ projections, but uses the higher-precision information from wires and narrow cathode strips. Here, the last muon station is separated into two layers spaced by about 0.5 m, which provide not only a starting position, but also a direction of track candidates. Tracks are then propagated to the earlier layers, somewhat in analogy to the strategy of the HERA-B Level-1 trigger.

In both cases, the candidate muon trajectory in the y projection (the non-bend plane) is required to point close to $y = 0$ at $z = 0$, the center of the LHCB interaction region. The choice of search region in the bend-plane (x -projection) limits the allowed bending of the candidate muons and hence imposes a momentum (and p_t) cut. The sizes of the search windows in the y -projection also place some restrictions on the allowed muon momenta by restricting the Coulomb multiple scattering that can take place.

Both methods are discussed more fully in Chapt. 10, where the results of all simulations of trigger rates and efficiencies are presented. Calculations

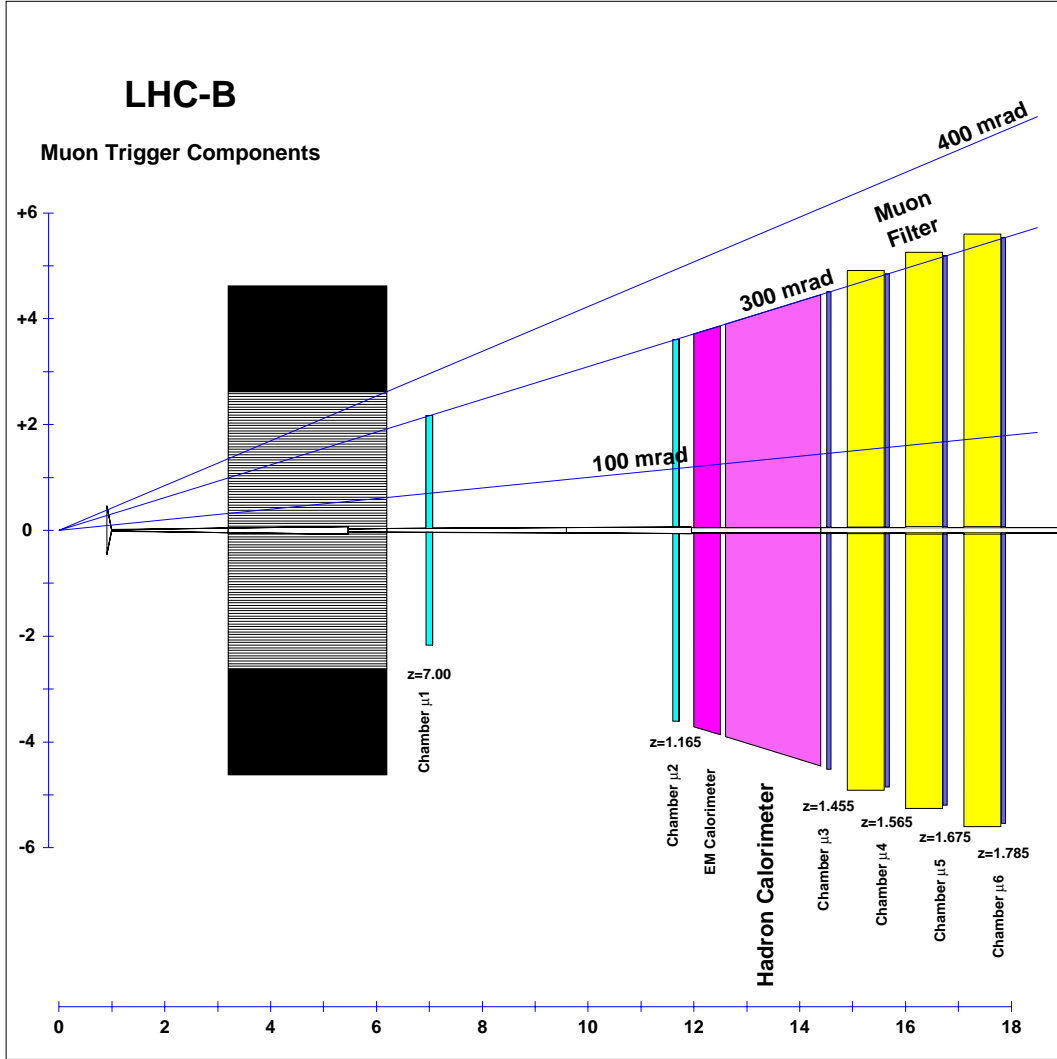


Figure 8.1: Components of the LHC-B Muon System

are performed assuming a box magnetic field with a p_t kick of $\Delta p_t = 1.08$ GeV for a 0° incident particle.

8.2 The muon shield

In optimizing the LHC-B muon trigger and shield, the effectiveness of a p_t cut on the muon in suppressing the trigger rates due to π/K and charm decay into single muons as well as hadronic punchthrough has been recognized. This effectiveness is illustrated in Fig. 8.2(a-c), where the energy of the muon from the various trigger sources in 14 TeV pp interactions is plotted vs. the production angle of the muon. The two curves superimposed on the scatter-plots are for p_t cuts of 1.0 and 1.5 GeV. As can be seen, a cut on muon p_t should significantly reduce the trigger

rates due to u,d,s and c quark semi-leptonic decays, while maintaining reasonable efficiencies for b quark semi-muonic decays. For the ideal case of perfect p_t resolution, only 1.6% of the $D \rightarrow \mu$ and 0.7% of the $\pi/K \rightarrow \mu$ survive a $p_t \geq 1.5$ GeV cut, while 43.7% of the $B \rightarrow \mu$ decays are retained. We have optimized the muon detector for the fraction of the $B \rightarrow \mu$ decays having a muon with $p_t \geq 1.0$ GeV.

In considering what muon-shield thickness will optimize the trigger acceptance for muons with $p_t \geq 1.0$ GeV, the LHC-B muon detector has been divided into two angular regions; Region I covers 10 to 200 mrad; Region II covers the 200 to 300 mrad. Fig. 8.3 schematically shows the relationship of the shield attenuation in the two different regions for B semi-muonic decays. Because the momenta of the B-decay

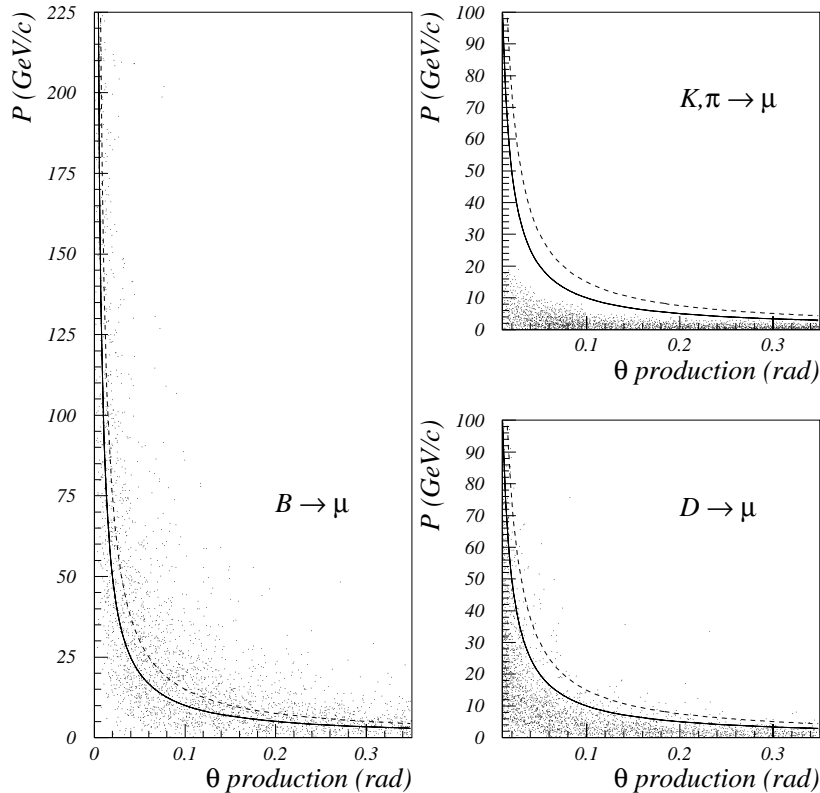


Figure 8.2: Muon Momentum vs. Production Angle for: (a) Muons from $B \rightarrow \mu$ Decays; (b) Muons from π and K Decays; (c) Muons from D-Meson Decays. In each case, the upper (lower) curve is for $p_t > 1.5$ (1.0) GeV.

muons in Region II are relatively low, it may be optimal to require penetration only to the μ_5 chamber rather than to μ_6 , as is the criterion for Region I. As indicated in Fig. 8.3, the choice will depend on the p_t threshold at which LHC-B operates. In addition, in Region I, the shield thickness can only be relied on to do part of the job of reducing the Level-1 muon trigger rates. As described below, an active p_t cut must be included in the Level-1 trigger to reduce the Level-1 rates to an acceptable level.

While a final optimization of the muon detector of Fig. 8.1 might involve more detailed sculpting to match the p_t curves more precisely, the configuration of Fig. 8.3, when taken in combination with the electromagnetic and hadronic detectors, represents a reasonable initial choice for shield thickness and positioning of the various chamber planes. The various parameters for the LHC-B muon-shield together with similar parameters for the LHC-B electromagnetic

and hadronic calorimeters are given in Table 8.1.

The dE/dx energy attenuation quoted for the various components is appropriate for a 10 GeV muon. The densities and other parameters quoted are those for the various mixtures of materials composing a given component.

The r.m.s. multiple scattering for muons from $B \rightarrow \mu$ which penetrate the shield and satisfy the criterion, $p_t \geq 1.5$ GeV, has been determined from a GEANT simulation of the LHC-B detector. The dependence on production angle, θ_μ , of the r.m.s. deviation of the unscattered muon entering the electromagnetic calorimeter to the μ_6 plane, $y_{r.m.s.}$, is shown in Fig. 8.4. This distribution, together with the requirement of a p_t resolution of order $\sigma_{p_t} \approx 250$ MeV, has been used to guide the choice of pad size for the chambers.

Shield Element	Composition ($\approx 80\%/20\%$)	ρ g/cm^3	X_o cm	λ_a cm	dE/dx MeV/cm	Length			
						m	GeV	z/X_o	λ_a
EM Cal.	Pb/Scint.	3.10	2.17	47.2	5.34	0.50	0.27	23.0	1.06
Had Cal.	Fe/Scint.	6.85	2.65	25.0	13.19	1.80	2.37	68.0	7.20
μ_3 Chamber						0.40			
Shield-1	Fe	7.80	1.78	19.2	15.50	0.70	1.08	39.3	3.65
μ_4 Chamber						0.40			
Shield-2	Fe	7.80	1.78	19.2	15.50	0.70	1.08	39.3	3.65
μ_5 Chamber						0.40			
Shield-3	Fe	7.80	1.78	19.2	15.50	0.70	1.08	39.3	3.65
μ_6 Chamber						0.40			
Total Shield Thickness (including space for chambers)						6.00	5.88	209.9	19.21

Table 8.1: The components of the muon-shield including the electromagnetic and hadronic calorimeters

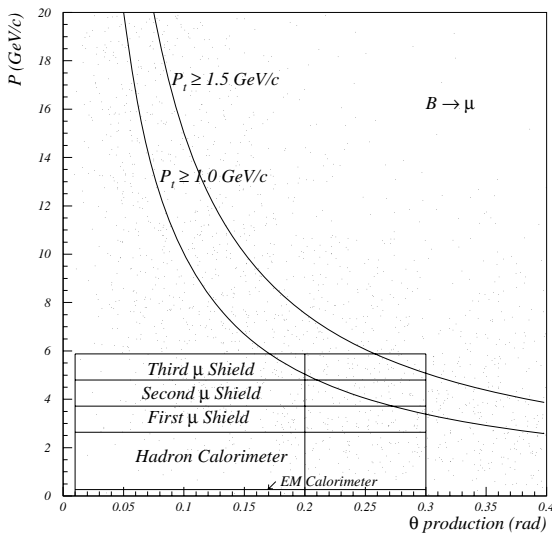


Figure 8.3: Relationship of LHC-B muon-shield configuration and θ_μ of μ 's from Semi-muonic B Decays.

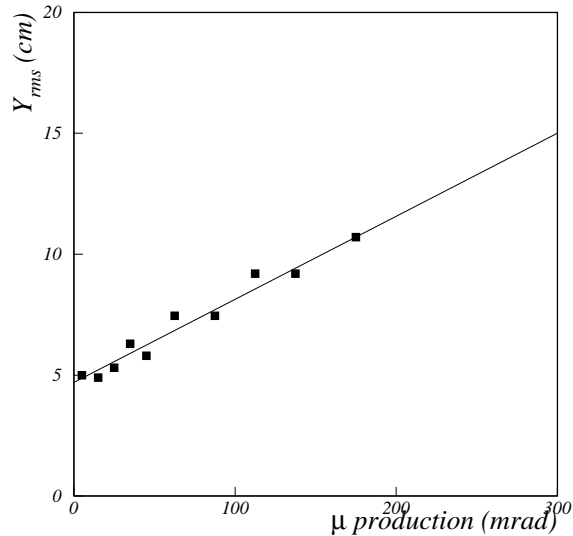


Figure 8.4: $y_{r.m.s.}$ deviation of muon trajectory from entrance to electromagnetic calorimeter to μ_6 -chamber, vs θ_μ

8.3 Muon detectors

In this section, we first describe the details of a projective pad geometry which would be adequate for the first of the muon track-finding algorithms referred to above. We then discuss possible muon chamber technologies.

8.3.1 2-D projective pad geometry

The pad structure required for the pad trigger has been designed to be projective in both bend and non-bend planes in order to simplify the search algorithms and the Level-1 determination of the muon p_t . Each

chamber, whether upstream of the shield or embedded in the muon-steel, has the same pad layout, as is shown in Figs. 8.5 and 8.6. Fig. 8.5 shows the general overall view of a pad plane with the five regions and the beam hole displayed. Fig. 8.6 gives the general pad configuration for the first quadrant of any of the chambers.

The pad strategy obviously requires at least one such cathode pad structure be included in each chamber. In addition, in order to minimize the inefficiencies (which are of order ϵ_μ^6 if triple coincidences of μ_4 , μ_5 and μ_6 are required to define a muon), each

chamber may require two cathode pad planes with overlapping pad structures to minimize inefficiencies due to cracks between pads.

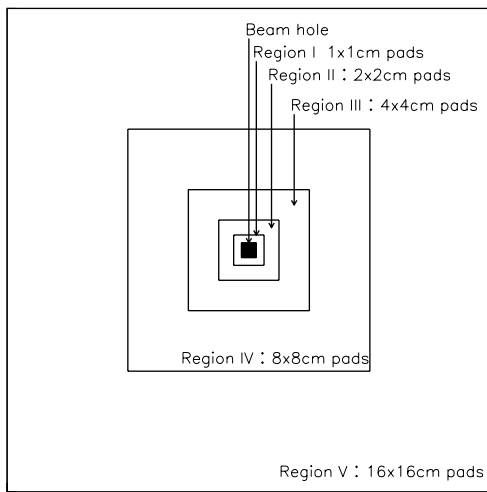


Figure 8.5: Five Muon Pad Plane Regions

The general pad configuration shown in Fig.8.6 for the first quadrant of μ_2 is quadrant-symmetric and is the same for all six muon pad planes. As shown in Fig. 8.5, there are five nested regions with different pad sizes which, for μ_2 , are 1×1 , 2×2 , 4×4 , 8×8 and 16×16 cm^2 , for Regions I-V, respectively. There are 1,200 pads per region and 6,000 pads per plane, making a total number of 36,000 pads for the muon system.

8.3.2 Muon chamber technologies

We have not yet chosen a particular technology for our muon system. The eventual choice of chamber technology for a given muon station will be dictated by many factors: dead time, time and spatial resolutions of the chambers, as well as cost considerations.

Several technologies are under consideration:

- Cathode-Strip-Chambers (CSC), described in this section;
- Honeycomb Chambers, described in Chapt. 5;
- Proportional Drift Tubes (PDT), described in the next section.

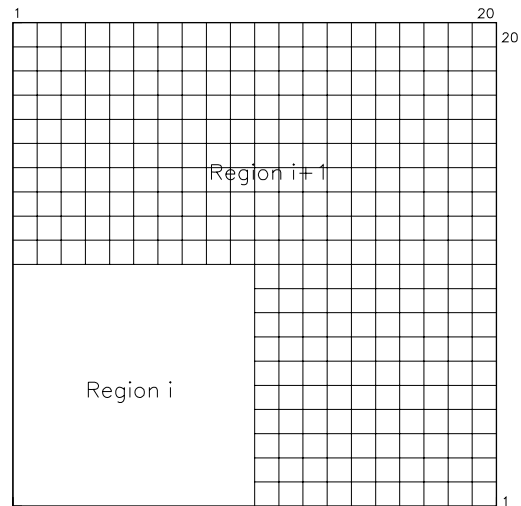


Figure 8.6: Muon Chamber General Pad Configuration for First Quadrant

The first two types can support a pad system similar to the one described in the previous section. Other pad chamber technologies have also been developed[1, 2] which would meet the requirements for the task at hand, should either of these technologies prove inadequate for some reason.

Although the third type, PDT chambers, do not support a pad structure as such, they do allow a 2-dimensional readout which, for the low particle densities in the periphery of the muon system, may be appropriate because of their low cost.

We now discuss Cathode Strip Chambers (CSC) in more detail. These chambers have good time and spatial resolutions and can operate in high radiation environments, In addition, they can accomodate any desired cathode pad structure.

Fig. 8.7 shows an example of the possible geometry of one muon station. The dimensions, parameters and quantities of the different modules (sensitive areas) are given in Table 8.2.

There would be three types of various size modules which cover the 9×9 m^2 area shown (with some overlap possible). There is a 30×30 cm^2 hole at the center. Each module would contain four layers of CSC's.

This model of the chamber stations leads to a total channel count of approximately 220,000 (120,000 cathode and 100,000 anode channels). In addition, 36,000 pad channels would be required to implement

Module Type	Module Size (m ²)	Quantity	Cathode Strips		Anode Strips	
			width (mm)	channels	width (mm)	channels
A	3.0 x 1.1	24	10	100 x 4	30	100 x 4
B	1.2 x 0.6	16	5	120 x 4	15	digital readout 80 x 4
C	0.6 x 0.36	8	3	120 x 4	7.5	analog/dig readout 80 x 4 analog readout

Table 8.2: CSC module parameters and quantity of each in plane shown in Fig. 8.7

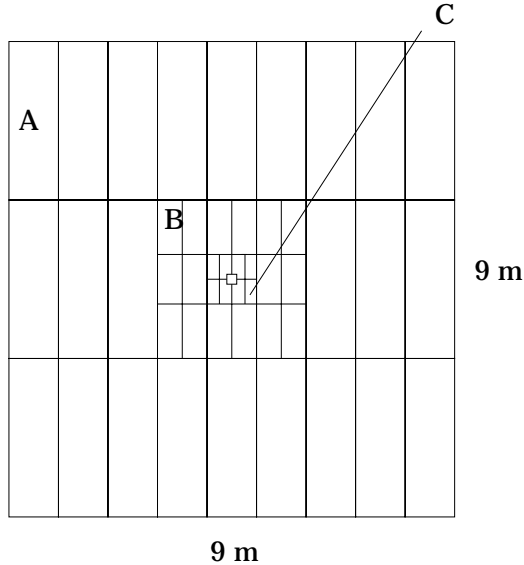


Figure 8.7: One cathode-strip-chamber plane at $z = 15$ m.

the pad strategy.

The CSC technology has been developed in the GEM R&D programs[3, 4] and has been chosen for the end caps in the CMS detector[5], the forward muon system in ATLAS[6] and in the muon system of PHENIX. Several prototypes of CSC's have been studied in the course of the GEM and CMS tests. These include the PNPI (4 layers, size 0.5×0.5 m²), BNL/PNPI (4 layers, size 0.5×0.5 m²) and Dubna (4 layers, size 1×3 m²) prototypes. The resolution properties of these chambers are well documented[7]-[13].

Each CSC muon chamber would consist of four layers. Each layer is formed using 23 mm thick, flat, rigid panels of "nome" honeycomb covered with 1 mm thick laminates with 17 μ m copper cladding which forms the cathode planes. The gap between the cath-

ode planes would be 5 mm. The anode planes are wire planes with 2.5 mm wire spacing with a horizontal orientation (possibly stereo orientation in some planes) placed halfway between the cathode planes. The cathode strips from which these chambers derive their name would be etched on one of the cathodes in each layer with a vertical orientation. The other cathode plane would be etched with the pad configuration required for the pad trigger. The pad and strip sizes can be varied over a wide range.

The gas mixture contemplated for each chamber is a mixture of 50% CO₂, 30% Ar and 20% CF₄. Using this mixture, a drift velocity of $\approx 90 \mu\text{m/ns}$ can be achieved with an electric field of $\approx 6 \text{ kV/cm}$. For the chamber configuration described above, the total drift time would be 30 ns. The CSC time resolution as measured with the PNPI prototype is $\sigma \approx 3.2$ ns.

The precision x -position information required for second muon trigger technique is obtained from the center of gravity of the set of analog signals from the cathode strips that fire when a muon passes through the chamber layer. Fast signals are available from each cathode strip that, in coincidence with the corresponding fast anode signal, can tag the set of cathode wires in which the signal originated.

The y -position information is obtained from fast signals from anode wires joined together in sets of 2 to 20 wires, matched to the required resolution as a function of angle. Since each chamber consists of four such anode planes, coincidence requirements between anode planes within a given chamber set can be used as a muon pretrigger and to reject accidental background. Majority logic between the four layers will also insure good efficiency. In addition, the vulnerability of the CSC chambers to neutrons is low. The neutron efficiency as measured at PNPI using a time-of-flight neutron spectrometer was of order 0.008% over a range of neutron energies from 1 eV to 10 MeV and was mainly a function of gap thickness. The sensitivity to gammas was somewhat larger, ranging between 0.1% to 1% for gammas with energy between 10 eV and 3 KeV.

Excellent spatial resolution of less than 100 μ m has

been achieved in all CSC prototypes. While the muon chamber resolution need not be so good, in the region near the beam a resolution below 1 mm should be aimed at for the second (cathode-strip) muon trigger technique (the Monte-Carlo simulations use 300 μm). For the innermost region, one may consider analog readout, given that these requirements are near the limits of a purely digital readout. In most regions, digital rather than analog read-out can be used.

8.3.3 Proportional drift tubes

Finally, we briefly mention Proportional Drift Tube (PDT) chambers which provide an alternative technology for covering the large area on the periphery of the muon detector. Some of our collaborators have recently tested such devices at IHEP[14].

PDTs are relatively simple and inexpensive devices which have been used in many experiments. A track's location is measured simultaneously in both x and y coordinates by arrival-timing of the drift-signal and by charge division on the resistive anode wire. A resolution of ~ 0.2 mm can be achieved transverse to the wire direction and ~ 15 -25 mm along the wire, for tube lengths up to ~ 1 m. With special shapers developed at IHEP, the trailing edge of the drift signal achieves a timing resolution of ~ 15 ns. Use of PDT's in the low-occupancy region of the muon detector could therefore avoid the timing problems that occur with signals from large area pads and provide wide angle coverage for the muon system.

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9 Roman-Pot Detectors

In addition to the measurement of beam-like protons for the purpose of “tagged Pomeron-beam” experiments, Chapt. 3 also discusses the interest in measuring small angle tracks with momenta much smaller than the beam momentum (e.g. $x \sim 0.1$). This requires other sets of Roman-pot detectors which are much closer to the interaction region. For example, note that all particles that pass through the LHC-B magnet receive a p_t “kick” of almost 1 GeV. Thus, an $x = 0.1$ particle will have a transverse displacement of about 2 cm at $z = 15$ m, which is well outside the beam envelope. Measurement of only the track’s direction between $z = 15$ m and 20 m with small precise Roman-pot installations (together with other installations further downstream which employ bending in LHC machine magnets) should permit the determination of the complete Feynman- x distribution of LHC interactions.

It will be valuable to also measure forward, small angle, neutral particles. Thus, we envisage the installation of small 0° calorimeters to complement the small angle charged-particle measurements.

9.1 Measurement of beam-like outgoing protons

As discussed in Chapt. 3, the “tagged Pomeron beam” experiments possible with the LHC-B apparatus require the downstream measurement of beam-like outgoing protons with detectors installed in a series of Roman-pots[1]. For the physics reasons described in Chapt. 3, we propose to install two such spectrometers, one in each arm.

Eggert and Morsch[2] have presented a preliminary design of a Roman pot spectrometer for the LHC. Its properties are briefly summarized in this section. Ref. [3] contains all equations involving machine optical functions.

Momentum measurement using the existing accelerator optics is based on the dispersion $D(s)$ of the machine, where s is the distance to the interaction point along the beam, and $D(s)$ is a particle’s transverse displacement in the bending plane from the central beam orbit, per fractional difference of its momentum from the central momentum. The transverse displacement is then given by:

$$x = \xi D(s) \quad (40)$$

where $\xi = \Delta p/p_0$. ξ is, of course, related to Feynman- x_p of the outgoing measured proton by $\xi = 1 - x_p$ and is also, interestingly, the Pomeron’s momentum fraction of the beam particle.

With Eq. 40, ξ is obtained from a measurement of the transverse displacement, x , of a particle. The range of ξ which can be covered is, however, limited on the low side by the necessity for the detectors to be at least 10 beam σ from the beam center and, on the high side, by the requirement that the particle not touch the vacuum chamber wall:

$$\frac{10\sigma_x(s)}{D(s)} < \xi < \frac{R}{D_{max}(s)} \quad (41)$$

where σ_x is the transverse dimension of the beam at the point where the measurement is performed, and R is the radius of the beam pipe. D_{max} denotes the maximal dispersion the particle has passed before reaching the point s .

$\sigma_x(s)$, has two components, one given by the beam emittance, ε , and the β -value and the second given by the natural beam momentum spread, $\xi_0 \sim 10^{-4}$, and the dispersion:

$$\sigma_x(s) = \sigma_\beta \oplus \sigma_\xi = \sqrt{\varepsilon\beta_x} \oplus \xi_0 D(s) \quad (42)$$

Fig. 9.1 shows the 10σ beam profile together with the scattered proton profile for $\xi = 0.005$ versus the distance to the intersection point. The magnet configuration for a standard insertion and the phase advance are also drawn. The dips correspond to the phase advances where either the effective length or the magnification become zero.

If the free space at a phase advance $\Delta\mu = 495^\circ$ relative to the interaction point is used for a Roman pot installation, protons with momentum loss in the range $0.002 < \xi < 0.01$ can be measured, but protons with smaller momenta are lost in the beam pipe. However, they can be seen at $\Delta\mu = 180^\circ$. This is demonstrated in Fig. 9.2, where ξ_{min} and the error on ξ are plotted. The measurement precision is of the order of 10%.

The proton acceptance versus the relative momentum loss, ξ , is given in Fig. 9.3, demonstrating the almost full acceptance for $0.002 < \xi < 0.1$.

References

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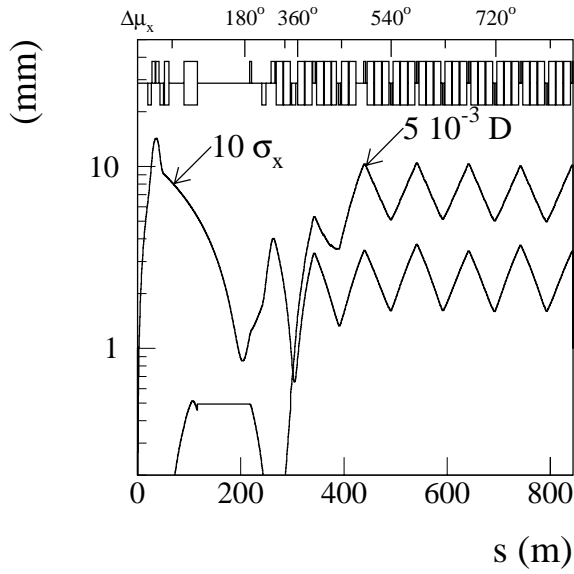


Figure 9.1: The 10σ beam profile as compared to the excursion of a particle with momentum deviation, $\xi = 5 \cdot 10^{-3}$, vs. the distance to the intersection point.

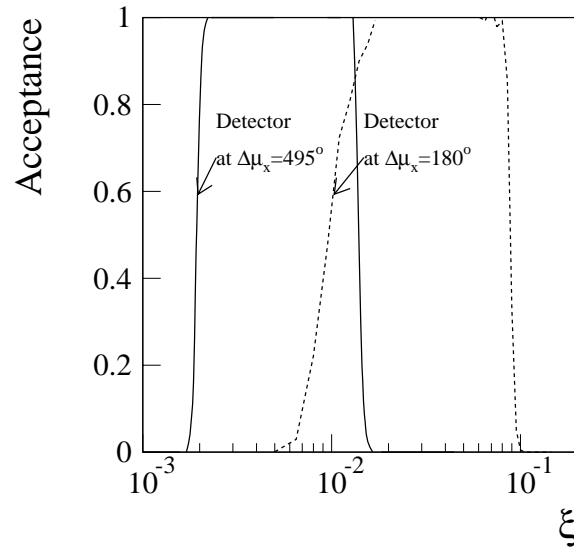


Figure 9.3: Proton acceptance vs. ξ for detectors at 495° and 180° .

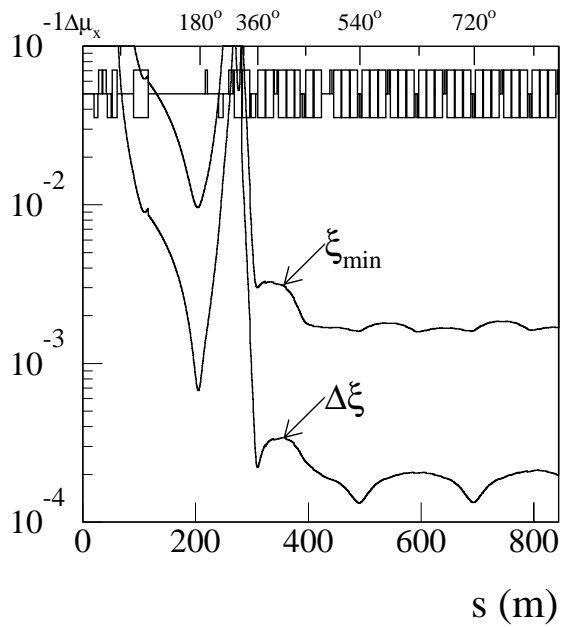


Figure 9.2: The minimum measurable ξ_{min} and its error, vs. distance from interaction center and phase advance.

10 Triggering

At LHC energies, $B\bar{B}$ events look very much like minimum-bias events, apart from having detached secondary and possibly tertiary vertices and a somewhat higher transverse momentum for the B-hadron decay products. Moreover, the interesting $B\bar{B}$ final states are a small fraction of the $B\bar{B}$ events produced, due to the small branching ratios involved, a limited detector acceptance and the need to identify (tag) the initial flavor of the reconstructed B-mesons. Therefore the overall trigger scheme should be both selective and efficient in extracting the small number of interesting events from the large number of $B\bar{B}$ and minimum-bias events.

Fig. 10.1 shows a block diagram of the proposed triggers and their interconnections. The high interaction rates necessitate a multi-level trigger scheme. We propose to have three trigger levels, each running several parallel trigger algorithms. The overall yield of recorded $B\bar{B}$ events is maximized, while the independently triggered samples will provide a better control of systematic uncertainties.

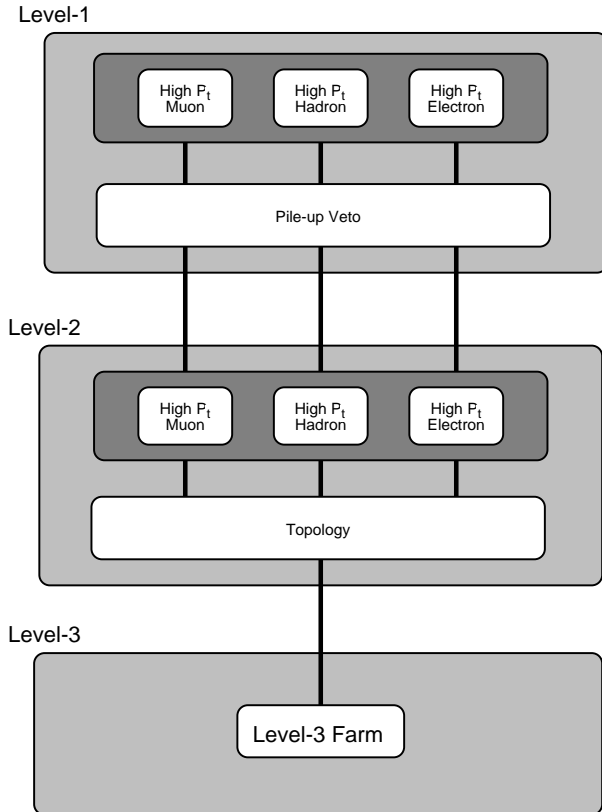


Figure 10.1: Block diagram of multiple triggers and their interconnections in each trigger level.

The Level-1 trigger exploits the relatively high transverse momentum of the B-hadron decay products. There will be three high- p_t triggers running in parallel on muons, electrons and hadrons, respectively.

The high- p_t lepton triggers will be most effective in selecting B-meson decays which have leptons in the final state, such as $B_d \rightarrow J/\psi K_s^0$. Frequently the trigger lepton will be from a semi-leptonic decay of a B-meson, in which case the strong rapidity correlations between b and \bar{b} quarks (typically less than one unit of rapidity) make it likely that its accompanying \bar{B} -meson will also be accepted in the spectrometer. In this case, the trigger increases the probability of simultaneous reconstruction and tagging of the B-mesons under study.

The high- p_t hadron trigger is more effective for low multiplicity purely hadronic decay modes such as $B_d \rightarrow \pi^+ \pi^-$ and the trigger is optimized for this decay mode. Once again the tagging probability is enhanced by the $b\bar{b}$ rapidity correlation.

The Level-1 trigger will be the OR of the three high- p_t triggers and will be followed by a pileup veto which will suppress bunches which have more than one interaction.

The choice of the rejection-level demanded of the Level-1 trigger OR is determined by the constraints on the running luminosity and the capability of the DAQ system to handle the Level-1 output rate. Another parameter is the rejection-level desired for the multiple-interaction bunches. Even though our DAQ system will be designed to handle a Level-1 output rate of 400 kHz (see Chapt. 11), our yield projections will be based on a very conservative Level-1 rate around 200 KHz. A luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to an interaction rate of about 7 MHz, would then require, in order to meet the 200 KHz goal, a 3% retention of minimum-bias events. The inclusion of a pile-up veto would allow a slightly higher luminosity, while maintaining the 3% minimum-bias Level-1 trigger efficiency.

In the following, we quote all yields for the conservative running luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, which corresponds to about 0.25 interactions per bunch crossing. At this luminosity, 76% percent of all interactions will happen in single-interaction bunch crossings. For the purpose of the LOI, the corresponding 3% Level-1 required performance will be achieved by approximately allocating to each of the three high- p_t triggers 1/3 of the total bandwidth. Even though this choice might not represent the best optimization of event yields for any given B-decay mode, it makes it easier to compare the performance of the various triggers, and it allows the

collection of comparable samples of events from the three independent triggers, with obvious advantages of cross-calibration .

The Level-2 trigger will also consist of parallel triggers and will have a maximum output rate of 10 kHz. In addition to improving the Level-1 decision, Level-2 will detect the presence of a detached vertex using the silicon information. This will be accomplished either by rejecting events which are consistent with having a single vertex or by requiring that the Level-1 trigger particles have a large impact parameter with respect to the primary vertex.

The Level-3 trigger will select a sub-class of events which are reconstructable and of physics interest. Most of the reconstruction and the selection done at Level-3 can be thought of as part of the off-line reconstruction, albeit done online. Therefore, it will require a considerable computing power. This part of the trigger will run on a processor farm, as discussed in Chapt. 11.

The following three sections describe the details of the high- p_t muon, electron and hadron triggers, respectively. The ‘‘Pile-up’’ tag is discussed in Sec. 10.4. The details of the ‘‘Topology’’ trigger are given in Sec. 10.7.1. The trigger strategy employed in Level-3 will be explained in Sec. 10.8. A detailed summary of the Level-1 and Level-2 trigger efficiencies is given in Sect. 10.9.

10.1 High- p_t muon trigger (Level-1)

The muon trigger should efficiently select B-hadron decays into one or more muons, while minimizing contributions from $\pi/K \rightarrow \mu$, charm $\rightarrow \mu$ decays and hadronic punch-through. The selection is made progressively with the following three trigger levels:

Level-1: Detects the presence of one or more muons which penetrate the EM and hadron calorimeters and the muon shield. For muons which satisfy this condition, we have investigated two alternative methods to impose an effective p_t cut, using either pad chambers with projective geometry or Cathode-Strip-Chambers. Results are presented for the two methods in Sections 10.1.1 and 10.1.2, respectively.

Level-2: The determination of the muon p_t is refined. The muon track is associated with a track segment upstream of the magnet, with the ultimate objective of using the silicon detector segment of that track to impose an impact parameter cut.

Level-3: Further event reconstruction will be performed, using the muon(s) from Level-2 as seed(s).

The Level-1 efficiencies and trigger rates given below have been calculated using a GEANT simulation of the LHC-B spectrometer including the muon de-

tor, magnetic bending using a 3.6 Tm uniform box field, and energy attenuation and multiple scattering in the shield. For both Level-1 muon-trigger techniques, full pattern recognition starting from chamber hits is performed. The efficiencies given include the pattern recognition losses. A 100% efficiency has been assumed for the chambers used in the trigger simulations.

The muon trigger for LHC-B is critical and merits more than one approach. We have pursued the two quite different avenues which are conceptually different and have very different implementations. Similar studies and simulations were performed for both techniques. We show in the following sections, that both methods are successful in retaining comparable and significant fractions of B-events in which one of the B-hadrons decays into final states containing one or two muons, while they reject by more than a factor of 100 the major trigger background due to $\pi/K \rightarrow \mu$ decays. We report results from both algorithms for inclusive $B \rightarrow \mu + X$ events but, for the exclusive B-decay yields, since the results are comparable, only one set is given.

10.1.1 Projective-pad-plane technique

The first step in the projective pad chamber Level-1 trigger involves detection of all triple coincidences in μ_4 , μ_5 , and μ_6 planes that are consistent with a muon from the interaction region. The projective pad structure of $\mu_1 - \mu_6$ described in Chapt. 8 makes this process relatively simple. An infinite-momentum muon passing through a given pad in μ_4 will pass through pads with the same indices in all six planes $\mu_1 - \mu_6$. The μ_4 plane has been chosen to be the ‘‘index plane’’ on which to base the search for the muon triple coincidences. All hit pads in μ_4 are taken as seed pads in the search for triple coincidences.

Search windows centered on the index of the μ_4 seed pad are opened in μ_5 and μ_6 . The size of the search window in the x -projection is set by the expected bend of a muon at the trigger p_t threshold at that angle (the minimum momentum muon of interest at that angle). Multiple scattering in the muon absorber also contributes to the size of the search window in x and sets the size of the search window in y . We are presently using a search window of ± 7 pads in x and ± 2 pads in y . Since the pad size varies roughly linearly with angle, the p_t resolution is maintained over the aperture of the muon detector. If at least one hit is found within the search regions in both μ_5 and μ_6 , a triple coincidence is said to be formed. Similar techniques have been used successfully for Level-1 μ triggers in previous experiments[1, 2].

Once a triple coincidence of μ_4 , μ_5 , and μ_6 has

been found, search windows are opened in the x and y projection in μ_1 and μ_2 , based on the index pad in μ_4 . Once again, the size of the search windows is determined by a combination of maximum-bend angle (lowest momentum) and multiple scattering of the muon. For the efficiencies and trigger rates tabulated below, we have used search windows of ± 30 pads in x and ± 3 pads in y for μ_1 and μ_2 . If one or more pairs of hits are found in the μ_1 and μ_2 search regions, then all possible μ trajectories are formed from combinations of the μ_1 and μ_2 hits. The cuts against spurious $\mu_1 \cdot \mu_2$ combination presently used include the following requirements:

- the $\mu_1 \cdot \mu_2$ combination points to the interaction point in the y projection (± 1 cm),
- the $\mu_1 \cdot \mu_2$ combination has a x -slope and a y -slope consistent with the slopes of the muon triple coincidence (as determined from $\mu_4 \cdot \mu_5$ combination) within ± 100 and ± 50 mrad, respectively,
- the $\mu_1 \cdot \mu_2$ combination points to the hit pad in μ_4 to within ± 2 pads.

A value of p_t is calculated for the combinations that survive all the cuts under the assumptions that they are due to a muon which originated at $x = y = z = 0$. If any combination which passes all the cuts has a p_t greater than the trigger threshold of 1.25 GeV, the event is accepted into the trigger sample.

Our simulations showed that for complete $B \rightarrow \mu + X$ events, including all B products as well as all other tracks, 1.08 muon triples are found per event. The average number of $\mu_1 \cdot \mu_2$ combinations per triple coincidence is then found to be 1.14. The number of spurious triple coincidences per event could be decreased even further if local adjacency suppression is introduced into the trigger to eliminate events in which a single muon produces a hit in two adjacent pad in μ_4 .

The trigger p_t resolution is important in achieving the desired rejection of π/K decays. There are several contributions to the p_t resolution, viz. the finite size of the pads and the finite extent of the interaction region. The p_t formed as described above is accurate only to the extent that the decay muon points at the center of the interaction region. The difference between the pad chamber trigger p_t and the true p_t of the trigger muon for $B \rightarrow \mu + X$ events is shown in Fig. 10.2, which shows that a p_t resolution of ~ 350 MeV is achieved with our choice of pad size. The muon trigger rates are not changed appreciably by increasing the precision with which the muon trajectory is measured in the pad planes downstream of the

analysis magnet, due to the other factors contributing to the p_t resolution.

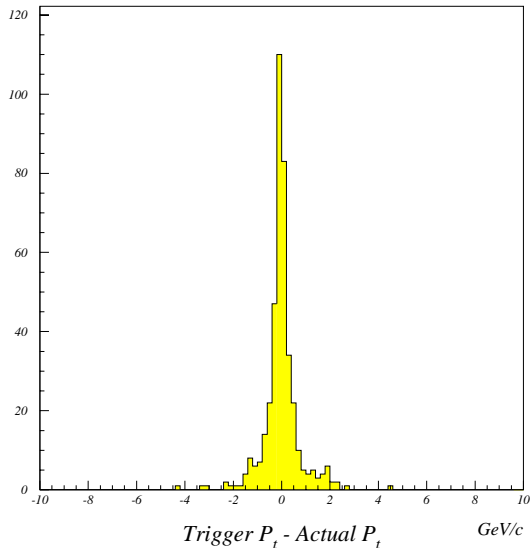


Figure 10.2: Muon P_t Resolution of the LHC-B Pad Trigger for $B \rightarrow \mu$ Decays

We have evaluated the performance of the pad strategy for minimum-bias, for 2-fold pile-up events surviving the pile-up veto, for $B \rightarrow \mu + X$ and for inclusive $B\bar{B}$ events, all of them generated over 4π . The results are given in Table 10.1 at each stage of the Level-1 μ trigger. The sources of the trigger muons shown in the bottom section of the table demonstrate that, for $B \rightarrow \mu + X$ decays where the muon is contained within the spectrometer aperture, the majority of the triggers selected by this technique is in fact due to the direct muons from the B.

The trigger rate due to charm events was estimated by selecting Monte-Carlo events containing at least one $c\bar{c}$ pair. Such events are present in about 15% of the interactions (estimated total charm cross section is 20 mb, vs. 70 mb total cross section), but the simulations showed that their likelihood to produce a muon satisfying the trigger was only slightly larger than the average minimum-bias event. This is reflected in the fact that for $c\bar{c}$ events generating a trigger, only 15% of the triggering muons came from the actual charm decay, the remainder coming from ordinary light quark decays. Therefore, to a large extent, the overall trigger rate is insensitive to charm production.

We estimate the Level-1 punch-through trigger rate to be less than 3% of the trigger rate due to π/K

Level 1 Muon Trigger Conditions	Minimum Bias	Pile-up	$B \rightarrow \mu + X$ + other	$B\bar{B}$ inclusive
In Acceptance (≤ 400 mrad)	-	-	33.4%	-
Muons Penetrating Shield	15.7%	28.2%	26.9%	21.6%
$\mu_4 \cdot \mu_5 \cdot \mu_6$ Triple Found	15.0%	27.8%	25.2%	20.6%
“Good” $\mu_1 \cdot \mu_2$ muons	6.0%	23.0%	18.2%	10.0%
Trigger $p_t \geq 1.25$ GeV	0.9%	2.9%	12.1%	3.4%
Sources of Trigger Muons				
Direct $B \rightarrow \mu + X$	-	-	91.2%	47.8%
$B \rightarrow D \rightarrow \mu$	-	-	2.7%	21.7%
$\pi/K \rightarrow \mu$	-	-	6.1%	29.0%
$c \rightarrow \mu$	-	-	0.0%	1.5%

Table 10.1: Level-1 Muon trigger efficiency for minimum-bias , 2-event pile-up , inclusive $B \rightarrow \mu + X$ and inclusive $B\bar{B}$ events, plus the sources of the trigger muons. Percentages in the upper section are cumulative. All percentages are given with respect to the total number of events generated over 4π steradians.

decays, in accordance with the parameterization of hadronic punch-through data by Green & Hedlin[3]. Thus, it is negligible.

We have varied the p_t cut to study the behavior of both the π/K retention rate and the various $B \rightarrow \mu$ efficiencies. Fig. 10.3 shows the variation of retention of $\pi/K \rightarrow \mu$ vs. $B \rightarrow \mu$ and inclusive $B\bar{B}$.

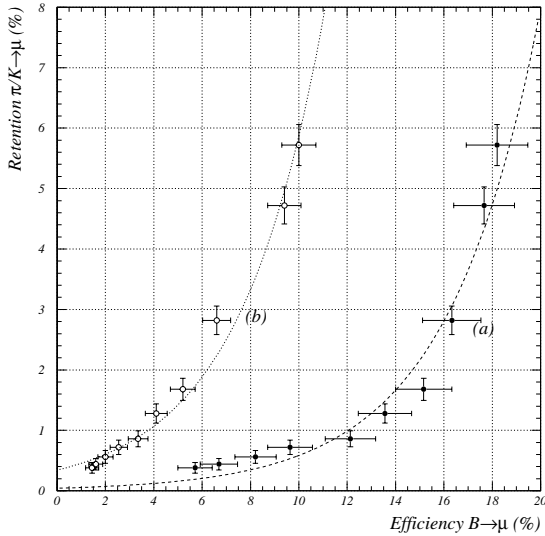


Figure 10.3: Retention of $\pi/K \rightarrow \mu$ vs. Efficiency for B's. (a) $B \rightarrow \mu + X$; (b) inclusive $B\bar{B}$

As an example of the muon-trigger efficiency for specific exclusive decay channels interesting for CP studies, we give the acceptances and the efficiencies for $B_d \rightarrow J/\psi K_s^0$ exclusive decays in Table 10.2. The

acceptance criteria for $B_d \rightarrow J/\psi K_s^0$ are that the two muons and the K_s^0 be inside 400 mrad and that the K_s^0 decays into two pions before the magnet. The acceptance and trigger efficiency are given for three different trigger requirements. The first trigger requires at least two muons which satisfy all the track finding criteria defined for the single-muon trigger, but with a lower p_t cut set at 0.75 GeV. The second trigger requires both muons to satisfy all the criteria for good muons except no p_t cut is imposed on either muon. The third trigger requires the leading muon to satisfy the criteria of the single muon trigger while the second muon is only required to be in the acceptance. The percentages quoted in Table 10.2 are appropriate for event samples generated over 4π .

The corresponding minimum-bias retention rates are also reported in Table 10.2 showing that the di-muon trigger will not appreciably affect the overall trigger rate.

10.1.2 Cathode-strip-chamber technique

This method makes use of hit information from chambers $\mu_2 - \mu_6$. The strategy emphasizes the use of relatively precise measurements in the x and y projections from muon-chamber planes within the muon shield.

As described in Chapt. 8, the muon chambers are assumed to have four quadrant segmentation with subdivision into 4 regions in radius. The algorithm assumes that the chambers have strip-type layout both in x - and y -views. There will be also some additional layers with pads to help view-matching. The measurement resolutions for chamber μ_2 are assumed to be consistent with the drift-tube diameter for the Outer Tracker and strip-pitch for the Inner Tracker. The resolutions for the chambers $\mu_3 - \mu_6$

Muon Criteria	$B_d \rightarrow J/\psi K_s^0$	Minimum-Bias
Accepted (≤ 400 mrad)	20.6%	-
$\mu_1 \cdot \mu_2 \cdot \mu$ triple(s)	14.6%	-
Good $\mu_1 \cdot \mu_2$ triple(s)	8.3%	-
Two muons- $p_t \geq 0.75$ GeV	6.6%	0.04%
Two muons-no p_t cut	8.3%	0.36%
One muon - $p_t \geq 1.25$ GeV (no second-muon required)	14.7%	0.9%

Table 10.2: Acceptances and muon trigger efficiencies for $B_d \rightarrow J/\psi K_s^0 \rightarrow (\mu\mu)(\pi\pi)$ exclusive decays.

are chosen to be $\sigma = 1.0$ mm at $\theta = 10$ mrad in both views, increasing gradually up to $\sigma = 6.0$ mm and 18.0 mm at $\theta = 300$ mrad in the x - and y -views, respectively. The μ_6 chamber station is assumed to have the additional capability to measure angles with a resolution in the range 6 to 12 mrad in the x -view and 4 to 8 mrad in the y -view. These resolutions are easily achieved with Cathode-Strip-Chamber technology using cathode-strip read-out for the x -measurement and anode-wire read-out for the y measurement, without sophisticated centre-of-gravity procedures. The same technology can also be used to implement a pad-type layout.

To select the high- p_t muon candidates, the muon track is required to be contained entirely in a road consistent with a muon coming from the interaction point (IP) at $x = y = z = 0$ with high p_t . The first part of the algorithm is to find the muon-candidate track segment and consists of the following steps (see Fig. 10.4 for an illustration of the regions of interest):

- Find a hit in μ_6 , both in x and y views. Using the hit in μ_6 , define a region of interest in all muon chambers $\mu_5 - \mu_2$ consistent with a high- p_t track from the IP. Find hits in μ_5 .
- In the y -view, find hits in μ_3 , μ_4 and μ_5 lying in the defined region of interest. Redefine the region of interest in μ_2 using the hit found in μ_3 , assuming the muon to originate at the interaction point (IP).
- In the x -view, use a hit found in μ_5 to define a region of interest in μ_4 , by projecting to the IP. Repeat this step to find a hit in μ_3 . Use the hits found in μ_3 and μ_4 to find a prediction for a hit in μ_2 by linear extrapolation.
- The candidate muon track segments are required to have hits in all 5 chambers $\mu_2 - \mu_6$ and in both views.

If, in any step, more than one candidate hit is found in the region of interest, the one nearest to the predic-

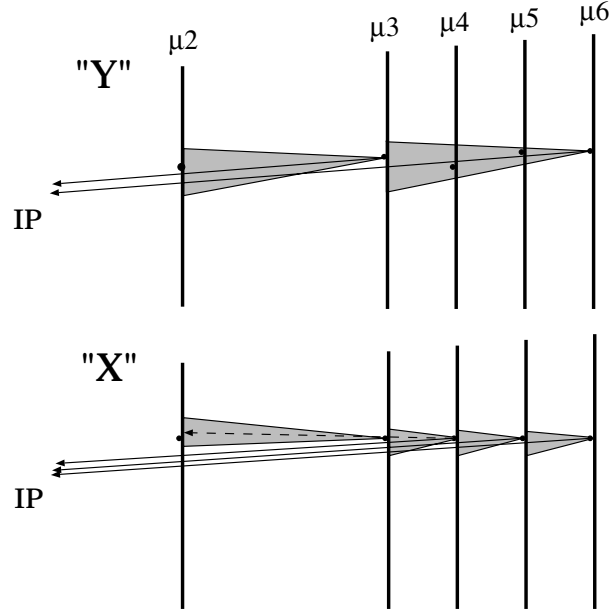


Figure 10.4: Muon track finding algorithm

tion is retained for later stages. The muon segment search is done independently in the x - and y -views.

In the second part of the algorithm, the p_t of a candidate muon is calculated using the trajectories found in chambers μ_2 and μ_3 , and the high- p_t muons are selected. In selecting the good candidates, cuts are made on the following quantities calculated from the chamber hits on the track segment:

- ϕ_x - difference of the track slope as measured by μ_2 and μ_3 , and by μ_6 alone in the x -view;
- ϕ_y - difference of the track slopes as measured by μ_2 (assuming a straight line connecting the point to $x = y = z = 0$), and by μ_6 alone.
- p_t as calculated from measurements in μ_2 and μ_3 .

Table 10.3 shows the fraction of events retained after various steps of the algorithm for four event samples. About 1/3 of the minimum-bias events have at least one hit in the last muon chamber. For the B-event sample, the fraction of events with a hit in the last muon chamber is larger due to the semi-leptonic B decays. More than half of the muons in the B sample are actually decay products of light mesons. The second and third rows of Table 10.3 show the fraction of events surviving after the track segment is found in $\mu_3 - \mu_6$, and $\mu_2 - \mu_6$, respectively. The sources of the muon triggers are shown in the bottom section of the table.

The p_t plots for selected events from the $B \rightarrow \mu + X$ and minimum-bias samples are shown in Fig. 10.5. The unshaded histogram shows the true p_t of muons from the $B \rightarrow \mu + X$ sample, the shaded histogram corresponds to muons from minimum-bias events. The resulting plot of minimum-bias rejection vs. $B \rightarrow \mu + X$ efficiency is shown in Fig. 10.6. This plot gives the efficiency of the complete $B \rightarrow \mu + X$ sample (solid line) and $B \rightarrow \mu + X$ events excluding those triggered by muons from underlying π/K decays (dashed line).

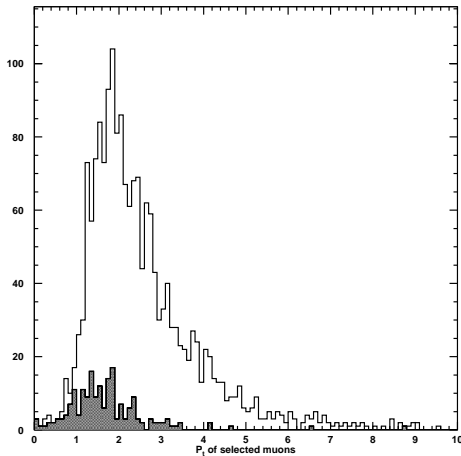


Figure 10.5: p_t -distribution of selected muons from the $B \rightarrow \mu + X$ and minimum-bias samples.

It is important that the number of hit candidates in the regions of interest should be low enough to not deteriorate track finding. The chamber segmentation described above results in an average of 1.25 hits in the regions of interest in chamber μ_2 . 19% of the found tracks contain at least one hit either in the x or y view that does not belong to the muon track.

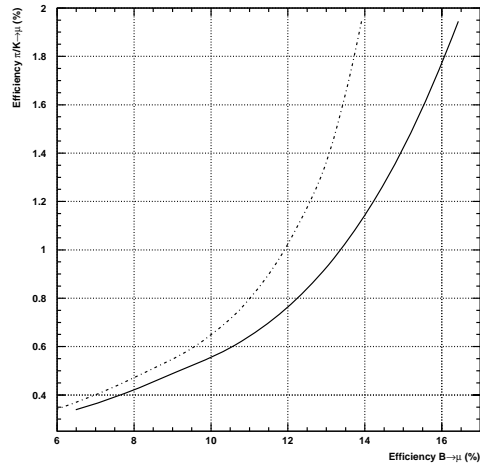


Figure 10.6: Minimum-bias efficiency vs. $B \rightarrow \mu + X$ efficiency. Solid line is for $B \rightarrow \mu + X$ events where any muon could trigger the event. Dashed line is for $B \rightarrow \mu + X$ events where only muons from B-decay can contribute to the trigger.

13% of the tracks contain one fake hit in the x view alone. The number of fake tracks can be decreased using finer segmentation for the μ_2 chamber.

10.2 High- p_t electron trigger (Level-1)

Compared to the muon trigger, a high- p_t electron trigger is expected to be very similar in terms of B-event yields (rates and kinematic distributions are the same for either leptonic decay), but completely different in terms of the environment in which it has to operate. While the muon detectors operate in a relatively quiet environment, the detection of isolated high p_t electrons has to take place in the presence of the full multiplicity of hadrons, photons and the most treacherous hadron-photon overlaps. Fortunately, however, real electrons differ from the background in several independent ways, so that real-time electron identification can be attempted by combining several, fairly uncorrelated, pieces of information. The strategy obviously has to be quite different from muon triggering, where the actual track rate in the muon detectors is effectively dominated by real muons, and the only parameter at one's disposal to control the trigger rate is the p_t threshold.

The Level-1 electron trigger should effectively eliminate most of the hadron and hadron/photon background, getting close to the irreducible background of real electrons, which mainly come from γ conversion

Requirement	Min.bias	Pile-up	$B \rightarrow \mu + X$	$B\bar{B}$ incl.
hit in μ_6	29.8%	50.7%	54.6%	37.3%
segment in $\mu_3 - \mu_6$	7.6%	14.8%	25.7%	12.8%
segment in $\mu_2 - \mu_6$	6.4%	12.7%	23.6%	11.2%
$\phi_x \times \phi_y$	3.9%	7.5%	19.1%	8.0%
$p_t > 1.1$ GeV	1.0%	2.1%	13.5%	4.1%
Sources of Trigger Muons				
Direct $B \rightarrow \mu + X$	-	-	88.9%	58.5%
$B \rightarrow D \rightarrow \mu$	-	-	3.7%	14.8%
$\pi/K \rightarrow \mu$	-	-	7.4%	26.2%

Table 10.3: Percentage of events satisfying Level-1 Muon Trigger requirements.

All percentages are given with respect to the total number of events generated into 4π steradians. The bottom section shows the sources of the muon triggers.

in the spectrometer. At Level-2, residual background should be eliminated by verifying that a real track is present with the right momentum, which traces back to the interaction point.

The electron trigger will have to exploit, as early as Level-1, all pieces of information that can reasonably be made available. Accordingly, in our studies of the electron trigger, we utilize the information from the following sequential detectors.

1. A plane of pads, P1, located at the exit of the analyzing magnet.
2. The front and rear scintillator tiles of the pre-shower detector, PS1 and PS2.
3. The electromagnetic calorimeter, EMcal.
4. The hadron calorimeter, Hcal.

The Level-1 algorithm implemented in the simulation package is the following:

- Look for 3×3 clusters of energy deposition in the electromagnetic calorimeter.
- Keep clusters whose energy-sum is greater than 5 GeV.
- Look for an electron signature (PS1 \sim minimum ionizing, PS2 $\gtrsim 3$ times minimum-ionizing) in the pre-shower element corresponding to the cluster center.
- Demand that the hadron calorimeter cell behind the cluster center has some minimal energy.
- Finally, cut on the p_t calculated from the total electromagnetic energy of the 3×3 cells and the position of the cluster center.

Two different approaches were tried for the p_t calculation. The simpler solution, used the so-called “non-bend algorithm”, in which p_t was simply estimated from the cluster position and energy, ignoring the bend in the magnetic field. A more sophisticated alternative, the “bend” approach, computed the two possible solutions for p_t one for each sign of the incoming particle, and predicted where the particle would have crossed the pad chamber at the magnet’s exit. The appropriate region in the pad chamber was then searched for a confirming hit. The p_t resolution attainable within the “bend” algorithm is shown in Fig. 10.7, which contains, for electrons from $B(\bar{B}) \rightarrow e + X$ decays, the ratio between the p_t inferred from the energy in the 3×3 array and the original p_t of the electron at the decay point. Apart from the contributions due to the intrinsic resolution of the calorimeter, further degradation of the resolution is caused by electron bremsstrahlung as well as spurious energy in the 3×3 array from other showering particles.

The simulations showed that the bend and non-bend approaches have similar properties in terms of $B(\bar{B}) \rightarrow e + X$ acceptance, but different responses to the several backgrounds. In the end, it was found that the best performance was reached when both p_t conditions were satisfied simultaneously. The p_t spectra for signal and background events is illustrated in Fig. 10.8, showing the p_t spectrum of candidate electron clusters, i.e. after applying the pre-shower and Hcal cuts, for both minimum-bias and $B(\bar{B}) \rightarrow e + X$ events. In the figure, p_t is estimated using the non-bend approximation.

The complete algorithms described above were programmed into a full GEANT simulation.

In the first Monte-Carlo studies of the algorithms, performed with limited statistics, particles were allowed to shower in EMcal according to the full GEANT simulation. Later, higher statistics runs

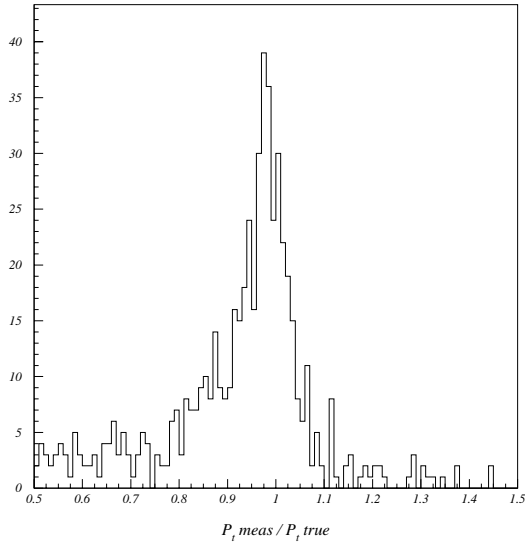


Figure 10.7: Ratio between the B electron p_t as inferred from the calorimeter and the original p_t .

were executed where the energy depositions in the calorimeter blocks were derived from random sampling of shower parametrizations. The two procedures were found to be consistent.

The summary of the electron trigger performance is given in Table 10.4 where $B(\bar{B}) \rightarrow e + X$ acceptance and background rejections, both for single interactions as well as pile-up events, are given at each stage of the selection criteria. The choice of cut parameters gives a 1/100 global rejection of minimum-bias, single interaction events. In the table, the p_t cut is applied first, in order to show better the effect of the pre-shower and Hcal cuts when applied to high p_t clusters.

Fig 10.9 shows the global acceptance vs. rejection curve. The curve, certainly not optimized, was produced by freezing all cuts except p_t and studying the acceptance vs. rejection response as a function of the p_t cut. The B acceptance values refer to $B(\bar{B}) \rightarrow e + X$ events generated over 4π , and therefore include the geometric acceptance.

The performance of the electron trigger with respect to specific B exclusive decays is given in Table 10.7, section 10.6. The entries in this table were produced at an earlier stage of the simulation employing the “non-bend” algorithm only, and therefore they don’t fully represent the best trigger performance we were able to obtain from further studies. Table 10.7 also contains performance values for B-

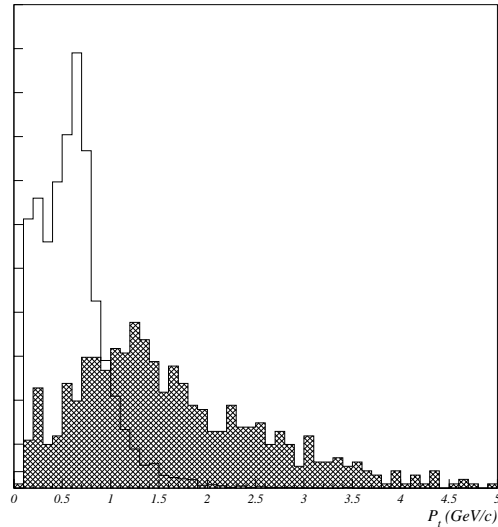


Figure 10.8: p_t spectra for candidate electrons for B (dark histogram) and minimum-bias (light histogram) events. The plots are arbitrarily normalized to the same number of entries.

decays containing J/ψ . Such figures refer to events collected by running the single electron p_t trigger, with $p_t > 1.5$ GeV. If necessary, J/ψ yields could be enhanced by running a di-electron trigger, with milder p_t requirements on both electrons. Such a trigger would access a different region of decay kinematics, and would have a negligible contribution to the trigger rate, compared to the single-lepton rates.

While keeping in mind the limitations mentioned above, the following conclusions can be drawn from the best set of results obtained:

- In spite of the much more severe environment, an electron trigger with a performance approaching that of the more conventional muon trigger (roughly 6% vs. 10% global trigger acceptance for direct B semi-leptonic decays) can be devised.
- The main Level-1 background contribution is found to be due to real electrons from γ conversions. Fig. 10.10 shows the z vs. r distribution (and its projection onto the z axis) of such electrons detected in the calorimeter and contributing to the background triggers. The structure of the beam pipe and the material associated with the chambers are clearly visible. It is clear from this picture that improved electron trigger performance could be obtained more from

Requirement	Min Bias	Pile-up	Inclusive $B(\bar{B}) \rightarrow e + X$ All Clusters	e^\pm from direct $B(\bar{B}) \rightarrow e + X$
B-electron inside calorimeter	-	-	-	.25
Energy in EMcal (3×3) > 5 GeV	16.0	31.6	16.6	0.19
$p_t > 1.4$ GeV	0.079	0.25	0.16	0.075
Pre-Shower selection	0.029	0.065	0.082	0.062
Energy in Hcal < 100 MeV	0.010	0.027	0.067	0.058

Table 10.4: Number of clusters per generated event, after each step of the electron-trigger algorithm for Minimum-Bias, Pile-up and inclusive $B(\bar{B}) \rightarrow e + X$ events. The first row gives the geometric acceptance for direct $B(\bar{B}) \rightarrow e + X$ decays. The difference between the third ($B(\bar{B}) \rightarrow e + X$ All Clusters) and the fourth (e^\pm direct) columns, has contributions from both $b \rightarrow c \rightarrow e$ decays as well as from clusters not associated with the B-decay products.

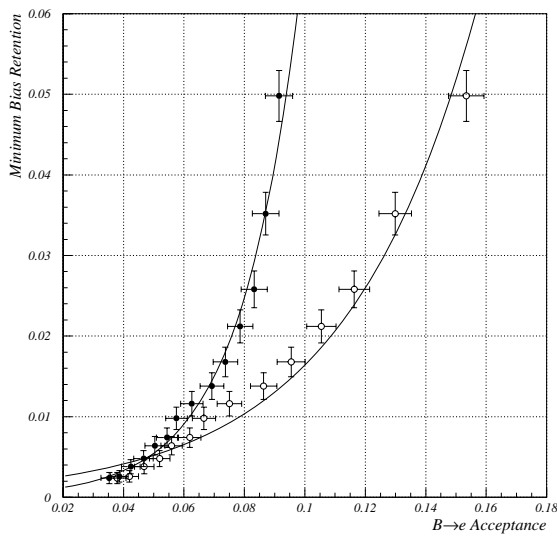


Figure 10.9: $B(\bar{B}) \rightarrow e + X$ acceptance vs. minimum-bias retention. Solid points: the triggering particle for the B-events is the actual electron from B decay. Open points: B-events triggered by any particle

reduced material encountered by the secondary particles, than from modifications to the algorithm. But even with the current configuration, Level-2 tracking should yield significant suppression of backgrounds from conversion electrons. In this respect, the Level-2 electron trigger has the potential of providing a more straightforward background rejection than will be achievable for the muon or hadron triggers.

- Despite the necessary sophistication of the fore-

seen electron trigger Level-1 algorithm, its hardware realization is very much within the realm of existing technology, as discussed in Section 10.5.

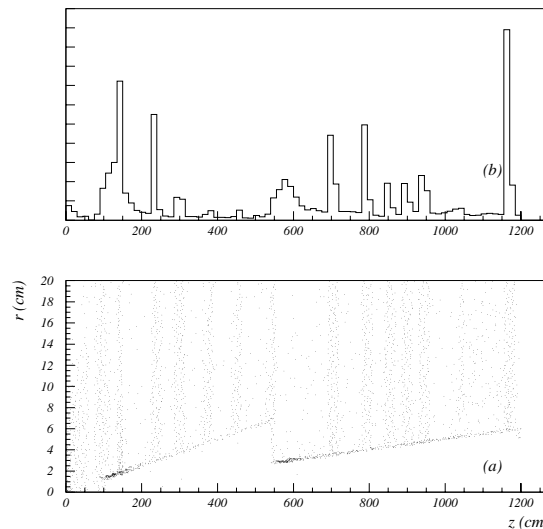


Figure 10.10: Longitudinal distribution of the origin of e^+e^- pairs from γ conversion. (a) : z vs. r scatter plot. (b) : projection onto the z axis.

It should be pointed out that, even though a reasonable performance was achieved in the simulations, many of the algorithm details, the cuts used and even the properties of the calorimeter itself have not been optimized. Continuing optimization of the electron trigger and the calorimeter design will form a natural part of our work on the LHC-B Technical Proposal.

10.3 High- p_t hadron trigger (Level-1)

Few-body, non-leptonic B decays have a characteristic hadron p_t spectrum which is substantially harder than that of minimum-bias background. In this class of events, $B_d \rightarrow \pi^+ \pi^-$ is one of the decay channels that has the greatest physics interest. A calorimeter-based algorithm can recognise the kinematic signature of $B_d \rightarrow \pi^+ \pi^-$ decays and provide a fast trigger with good discrimination against minimum-bias.

A fast simulation was used to evaluate the performance of such a trigger. The simulation modelled in detail the response of the preshower detector, electromagnetic and hadron calorimeters to the incident particles. An empirical parametrisation was used to represent the longitudinal development and lateral profiles of the hadronic showers [4].

Most of our performance studies of the high- p_t hadron trigger were carried out assuming a uniform granularity of 4×4 cm for both the EMcal and the Hcal. An EMcal energy resolution of $2 \oplus 10/\sqrt{E}$ % and a Moliere radius of 3 cm was assumed. For Hcal, the energy resolution was $5 \oplus 60/\sqrt{E}$ %. The trigger performance was re-evaluated using the calorimeter parameters of Chapt. 7. Since we found that the trigger performance was relatively insensitive to the assumed granularity and resolution, all results presented below are for the uniform granularity calorimeters specified above.

Algorithm: A di-hadron algorithm was devised and optimized to select $B_d \rightarrow \pi^+ \pi^-$ events. At the event-generator level, a requirement on the p_t of the two leading hadrons gives no better performance in signal-background separation than a cut placed only on a single hadron. Practically, however, the di-hadron approach gives improved protection against false triggers from overlapping showers and allows for additional cuts to be made, for instance in invariant mass. Furthermore the di-hadron trigger is found to select a greater fraction of $B_d \rightarrow \pi^+ \pi^-$ events which survive the reconstruction cuts. Finally, moderate demands on the p_t of two hadrons is more effective in selecting higher-multiplicity purely hadronic B-decays, than is a higher threshold on a single particle. In constructing a robust low-rate trigger, which selects events more favourable for the reconstruction, the di-hadron trigger is to be preferred.

The important steps in the algorithm are as follows:

- The preshower is used to identify potential charged hadron candidates, by looking for MIP signals in both scintillator planes.
- Candidates with an excess of signal in the

preshower planes, or with activity in nearby preshower cells are vetoed, to reduce the risk of overlapping showers in the calorimeters.

- The preshower cells of interest are used to seed the clustering in the EMcal and the Hcal. A 3×3 cluster is formed in the EMcal and behind this a 3×3 cluster in the Hcal. The energies in these clusters are summed, and from this the transverse momentum of the incident particle calculated, assuming a straight trajectory from the interaction region to the centre of the preshower seed cell, neglecting the bend of the magnet.
- Those two hadrons with highest reconstructed transverse momentum are taken, and a leading p_t and second p_t cut applied.
- For those events passing the p_t cuts, the invariant mass of the candidate pair is calculated, using the calorimeter information alone and again assuming straight line trajectories through the magnet. A loose cut is placed on this mass.
- The total energy of the event seen in the calorimetry is required to be less than some cutoff. The motivation for this condition is described below.

The reconstructed p_t distribution of the leading two hadron candidates for $B_d \rightarrow \pi^+ \pi^-$ events and for minimum-bias events are given in Fig. 10.11 (because the cluster size is smaller than the typical lateral shower profile, the reconstructed energy, and in turn p_t , is on average an underestimate of the true value by $\sim 30\%$). There is a good separation between the two categories – it is from this, and the highest p_t cut in particular, that the power of the algorithm comes. Also shown in Fig. 10.12 is the calorimeter invariant mass distribution, which, for a suitably placed cut, enables the background to be further reduced by up to 30% with a negligible loss of signal.

The zero-field approximation, made in the p_t calculation, is a reasonable assumption for this trigger. Typically the cuts are placed high and, in this kinematic regime, the kick of the magnet (~ 1 GeV) has little effect on the reconstructed p_t , mostly because of the limited energy resolution available from the hadron calorimeter. (Algorithms which preferentially weight the non-bending component of the p_t were tried and found to be no better.)

Table 10.5 shows the performance of the di-hadron trigger on $B_d \rightarrow \pi^+ \pi^-$ events for cuts of ~ 3 GeV and ~ 2 GeV placed on the reconstructed p_t of the leading two hadrons, a requirement that the calorimeter

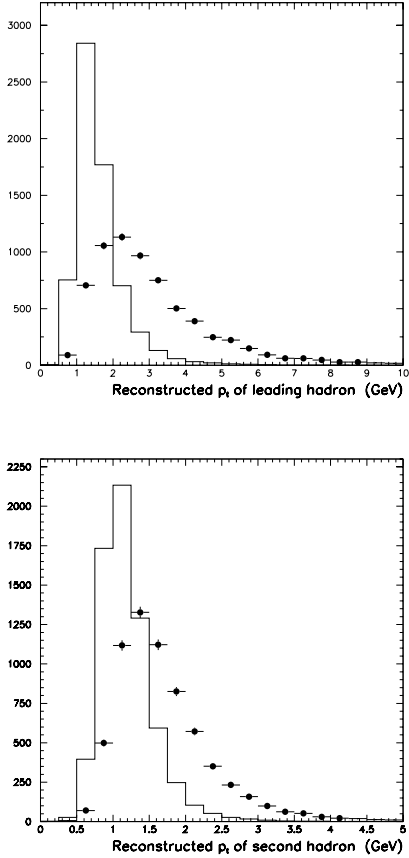


Figure 10.11: Top: distribution of highest reconstructed p_t in $B_d \rightarrow \pi^+ \pi^-$ events (points) and minimum-bias events (solid line). Bottom: distribution of second highest reconstructed p_t in $B_d \rightarrow \pi^+ \pi^-$ events (points) and minimum-bias events (solid line). The B_d events decay within the acceptance and the minimum-bias is generated over 4π .

formed invariant mass be above 2 GeV and a demand that the total seen energy in the event be less than 2200 GeV. The efficiency is given after each successive cut and is normalised to those events where both pions are found within the spectrometer. (As the total spectrometer acceptance is somewhat larger than that of the calorimeter, there is some residual geometric loss included in the numbers.) Also shown is the efficiency for $B_s \rightarrow D_s^- K^+$, $D_s^- \rightarrow \phi \pi$ decays, again for events where all the B decay products are within the spectrometer. Even in this higher multiplicity decay mode there is a significant sensitivity, largely on account of the leading kaon. Note though that this sensitivity is no longer present in B decays with

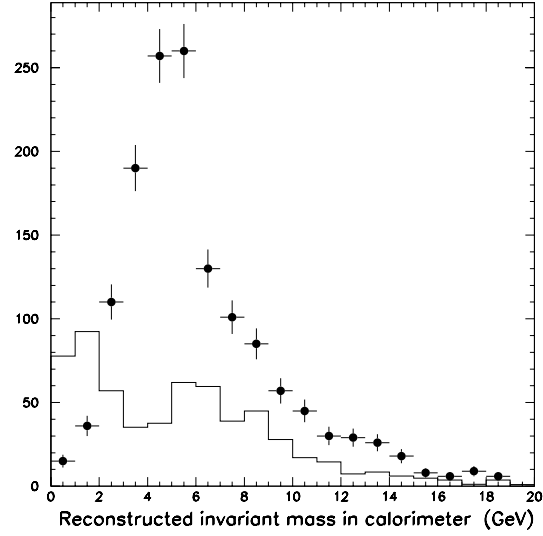


Figure 10.12: Calorimeter reconstructed invariant mass of hadron candidates passing p_t cuts in $B_d \rightarrow \pi^+ \pi^-$ events (points) and minimum-bias events (solid line). The normalisation is arbitrary.

a final state lepton: the response to $B_d \rightarrow J/\psi K_s^0$ is almost indistinguishable from background.

Table 10.6 shows the misidentification efficiency for minimum-bias events generated over the full solid angle. Again the effect of each cut is given. It is seen that for the above signal efficiencies, the background is suppressed by a factor of 100.

This background suppression of 100 is of course only one possible working point of the trigger. Fig. 10.13 shows the variation of signal vs. background efficiency for $B_d \rightarrow \pi^+ \pi^-$ efficiencies up to 30%, arrived at by changing the p_t requirements of the algorithm. Observe that this signal vs. background relationship is continuous and well-behaved and therefore offers a choice of running conditions.

The nature of those signal events satisfying the trigger was studied. By taking precautions against possible overlapping showers, the algorithm naturally biases the $B_d \rightarrow \pi^+ \pi^-$ selection in favour of those events with wide angle, lower momentum pions. This correlation constitutes a useful bonus of the trigger as such decays are in general easier to reconstruct than those in the low angle, high-momentum class. Note though, that it is not only the two pions from the B_d decay which form the leading p_t pair in triggers. These ‘pure’ combinations occur $\sim 40\%$ of the time; otherwise it is one pion from the B_d and one track

Event Sample	$B_d \rightarrow \pi^+ \pi^-$	$B_s \rightarrow D_s^- K^+$
p_t cut 1	46.2%	31.5%
p_t cut 2	21.6%	16.8%
mass cut	20.8%	13.8%
total energy cut	15.7%	9.1%

Table 10.5: The hadron trigger efficiency for $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow D_s^- K^+$, $D_s^- \rightarrow \phi \pi$ exclusive decays. The \bar{B} meson is decayed inclusively for both channels. All efficiencies are for events where the B-decay products are within the calorimeter acceptance. They are calculated from samples of 6600 ($B_d \rightarrow \pi^+ \pi^-$) and 3200 ($B_s \rightarrow D_s^- K^+$) such accepted events. The efficiencies are shown after each successive cut. The bottom row holds the final efficiencies.

Event Sample	Minimum-Bias	Pileup
p_t cut 1	5.53%	10.98%
p_t cut 2	2.10%	5.48%
mass cut	1.51%	4.32%
total energy cut	0.97%	0.28%

Table 10.6: The hadron trigger efficiency for minimum-bias and two superimposed (pileup) events. All efficiencies are for events samples generated over 4π and are calculated from samples of 24k (minimum-bias) and 5k (pileup) events. The efficiencies are shown after each successive cut. The bottom row holds the final efficiencies.

from the underlying event (usually the accompanying B) which satisfy the criteria. A Level-2 refinement to the trigger is conceivable, in which not only the two highest p_t candidates, but also the four or five leading clusters would be considered as pions from the B. If some tracking information associated with these clusters were available, an invariant mass cut could be made on that combination closest to the B-mass. A resolution of ~ 500 MeV would retain approximately 90% of the signal while suppressing the background by a factor 3. By using only the leading two clusters, much higher background suppression is achievable, but at a reduced signal efficiency. Of course, such strategies are only useful in a dedicated $B_d \rightarrow \pi^+ \pi^-$ trigger.

Examination of minimum-bias triggers showed that, in general, it is genuine high p_t activity from the interaction region which pass the cuts, rather than overlapping showers faking single high energy hadrons, or high angle particles from downstream secondary interactions. It was concluded that there was no significant gain to be won in augmenting the algorithm with track information from, for instance, pad chambers. Further studies are needed to fully quan-

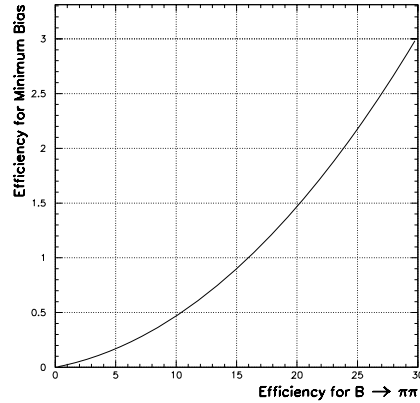


Figure 10.13: Variation in $B_d \rightarrow \pi^+ \pi^-$ efficiency with background efficiency for the hadron trigger. The $B_d \rightarrow \pi^+ \pi^-$ efficiency is for accepted events.

tify this statement, but at this stage the technical simplicity of a standalone calorimeter trigger is considered a strong additional argument. (Note that the pad chambers already proposed for the muon trigger provides a ready system which can be exploited if necessary.)

The behaviour of the trigger was studied in the pileup environment. The rate was evaluated for superimposed, double minimum-bias events; after the p_t and invariant mass cuts this was found to increase by a factor of 3 compared with the single interaction value (see Table 10.6). The doubling of the track multiplicity more than doubles the trigger rate because of the dual p_t cut strategy with thresholds tuned for single interactions. Also, the contribution of overlapping showers starts to become more important.

This increase in background triggers for double events is potentially worrying, as it might threaten to saturate the available rate. However there exists a strong correlation between the pileup veto (see Sect. 10.4) and the hadron trigger which contains the problem. The veto identifies and rejects 79% of bunches with more than one interaction in them. Therefore, one need only consider the trigger misidentification rate on the residual $\sim 21\%$. In fact, these events have a much reduced chance of firing the hadron trigger for the very reason that they have passed the pileup veto. By definition, they have relatively little energy seen in the calorimeters and are consequently depleted in high p_t hadrons. This is clear from Fig. 10.14 which shows the total reconstructed energy in all double pileup events and the total energy for those events which satisfy the p_t and

mass cuts of the hadron trigger. The latter class is concentrated in that region of the distribution removed by the veto. It is found that the efficiency for these cuts of pileup events which pass the veto is essentially the same as that of single events.

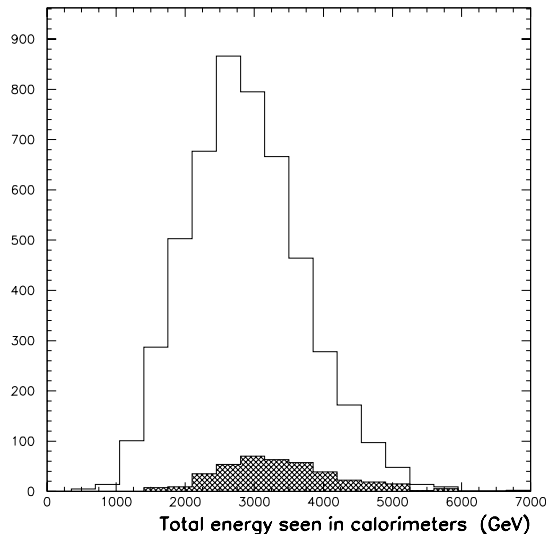


Figure 10.14: Total energy seen in the calorimeters for double minimum-bias pileup events. Superimposed (shaded) is the total energy distribution of those events which pass the p_t and mass cuts of the hadron trigger (with an arbitrary normalisation). Those events with low total energy have a reduced proportion of occasions where these trigger conditions are satisfied.

For the same reason, those single $B_d \rightarrow \pi^+ \pi^-$ events which pass the pileup veto have a reduced efficiency for firing the hadron trigger. Nonetheless, by loosening the criteria, and giving emphasis to the wide angle, low momentum decays, the loss of signal events from this effect and from the pileup veto itself may be reclaimed. In conclusion, a pileup veto is a desirable condition to impose for the hadron trigger, as it guarantees a stable rate without inhibiting the event yield.

We have investigated whether further optimization of the trigger algorithm is possible. Studies were made with clustering algorithms which integrated over larger areas in the outer calorimeter regions, where the risk of shower overlaps is small. In addition, more stringent preshower vetoes on possible overlaps in the innermost region were imposed. An improved signal to background discrimination re-

sulted, yielding an effective increase in signal efficiency of 20 – 30% for a given trigger rate. Presumably, further optimisation will further improve these numbers. Certainly, the results shown in Tables 10.5 and 10.6 do not represent the best performance achievable. The improvements described were not included in the analysis chain leading to the final reconstruction estimates because of time constraints.

To assess the effects of calorimeter energy resolution on the trigger, the outer Hcal stochastic resolution term was varied between 40% and 80%. The background rate changed by 0.93 and 1.11 respectively with respect to that obtained with the proposed resolution of 60%. The indication is that energy resolution is not a critical parameter in the trigger performance, although more detailed studies are necessary.

Ideally, the hardware implementation of a di-hadron algorithm would be one task of a global calorimeter trigger system, also performing electron trigger and pileup veto processing. Section 10.5 gives one example of a technology which could meet this need.

10.4 Pileup tag (Level-1)

With luminosity, $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, about 25% of all bunch crossings have a single interaction in them, while about 5% have multiple interactions. Therefore, almost 75% of all interactions occur in the single-interaction crossings. This significantly lessens the demands on the efficiency of a Level-1 pile-up veto.

Indeed, our Monte-Carlo studies show that rather efficient and straightforward pile-up rejection can be achieved by discriminating on the basis of the energy deposit in the LHC-B calorimeters. Fig. 10.15 shows the total energy measured by the LHC-B calorimeters for single events and double events. Setting an upper limit of 2.2 TeV on the energy detected in the calorimeters would reject pile-up events with an efficiency of $\approx 79\%$ while keeping $\approx 90\%$ of the single events ($\approx 80\%$ for B-events).

The resulting Level-1 trigger rate after pileup rejection is shown in Fig. 10.16, together with rate of single-interaction bunches. It illustrates that, with the pileup veto, a much more efficient use is made of the available bandwidth. Without the veto, the rate increases linearly with luminosity and reaches 315 kHz at our nominal luminosity, $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, compared with our nominal Level-1 output rate of 230 kHz.

The Level-1 trigger efficiencies given in the previous sections are for events in single-interaction bunch

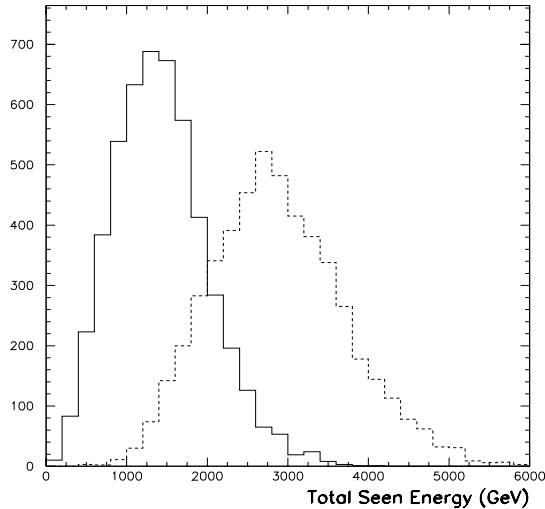


Figure 10.15: Energy [GeV] in the Electro-magnetic and Hadron Calorimeters for single interactions (solid line) and double interactions (dashed line)

crossings. The calorimeter-based triggers are especially sensitive to the presence of a second event in the same bunch crossings. Therefore, our nominal minimum-bias trigger rate of 230 KHz is most effective with the inclusion of a pile-up veto in the Level-1 trigger.

For reasons given above, at least for the main elements of the LHC-B physics programme, the Level-1 trigger will include a pile-up rejection. The trigger efficiencies and the event yields given at the end of this chapter include losses from the pile-up veto discussed above.

10.5 Level-1 hardware implementation

From the descriptions of the various trigger algorithms, it is clear that the corresponding hardware should provide a high level of performance, both in terms of speed and sophistication. The main obstacles to be surmounted are the need to sustain a 40 MHz input rate in a pipelined mode with a rather large amount of inter-communication between detector elements.

In view of the extremely critical role that the trigger plays in LHC-B and of the natural expectation that, at the time of running, unanticipated conditions might have to be met, the chosen trigger hardware should allow a good degree of flexibility and possibil-

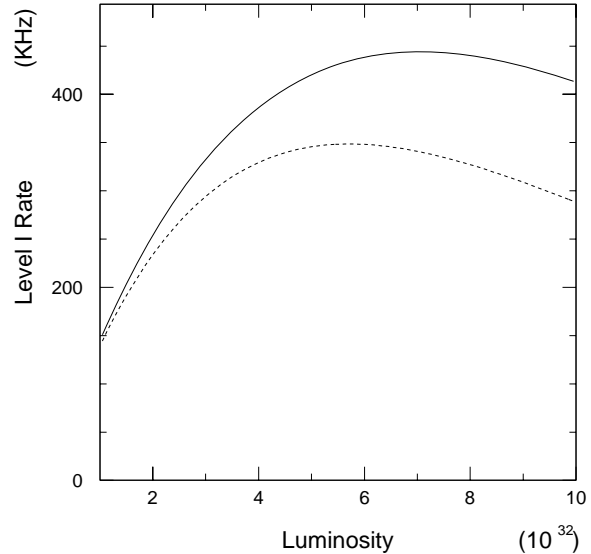


Figure 10.16: Full “OR’ed” Level-1 trigger rate as a function of luminosity, including pile-up veto. The dashed curve shows the component of the full Level-1 trigger rate for bunches which contain single-interactions.

ity of expansion. Moreover, given the rapid advances in the performance attainable from digital systems, it is felt that, even for the handling of the calorimeter information, a digital system is preferred to an analogue one. Such requirements point to a choice of a programmable, very high-performance system of parallel processors, capable of very fast data switching.

We wish to point out that a possible solution, meeting all of the demanding requirements, could already be found within the realm of existing developments. As an “existence proof” we note that the system called “3D-Flow”, originally designed to provide Level-1 triggering for the high- p_t SSC detectors[5], could satisfy these needs.

The “3D-Flow” consists essentially of a parallel-processing architecture built around an ASIC containing four identical processors. Each processor, highly optimized for fast, parallel communication, contains six communication channels, which can all operate concurrently. In a typical application, an individual processor would be connected as sketched in Fig. 10.17, where in the planar structures each processor is associated directly with individual detector elements or some set of them, and the stack of

planes in the “third dimension” is exploited to achieve pipelined operation.

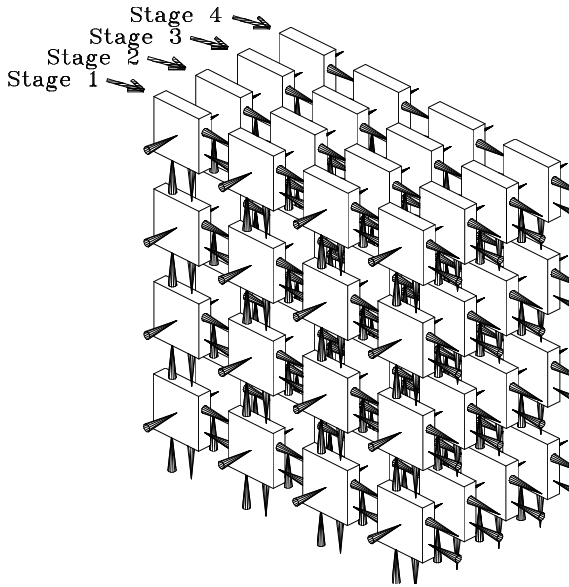


Figure 10.17: General scheme of the 3D-Flow pipelined parallel-processing architecture

Detailed studies[6] have shown that a suitable architecture of 3D-Flow processors operating at 200 MHz can easily execute the envisaged muon, electron and hadron algorithms within the allowed time limit of 2 μ sec, while providing an environment suitable for expansion or algorithm re-definition.

10.6 Level-1 summary

Here we summarize the combined Level-1 trigger efficiencies and pile-up veto for some of the interesting exclusive decay modes. The individual trigger efficiencies for each component of the Level-1 trigger and their “OR” for accepted events are shown in Table 10.7. The numbers given in the table are obtained from event samples in which the B-mesons are forced to decay to a specific exclusive channel given in the table, while their accompanying \bar{B} -mesons are allowed to decay into all possible final states with their natural branching ratios. The Level-1 trigger efficiency is specified for events which are “accepted”. Accepted events have all their B-meson decay products detected and momentum-analyzed in the spectrometer.

The trigger efficiency for the high- p_t triggers is shown in the first three columns where each Level-1 trigger is “tuned” to give a $\sim 1\%$ efficiency for

minimum-bias events. As mentioned earlier, the performance figures for the electron and hadron trigger do not reflect the best possible results that were obtained from such triggers simulations, but, because of the need to generate a large sample of “triggered” events for reconstruction studies, were obtained at an earlier stage of the trigger studies and simulations.

The final column contains the 3-fold OR’ed Level-1 trigger. Both individual and OR’ed trigger efficiencies include the losses due to the pile-up veto on single interaction bunch crossings. The 3-fold OR’ed Level-1 trigger including the pile-up veto has a 2.5% efficiency for minimum-bias events. In each case, the OR of the three triggers contains very few events where more than one trigger is satisfied. In the minimum-bias events, only 4% are selected by more than one trigger.

10.7 Level-2 trigger

The Level-2 trigger envisioned for LHC-B consists of two parts running in parallel and providing the required Level-2 suppression, when the two parts are AND’ed together. The first part consist of improving the Level-1 trigger decisions using information from additional sub-systems. Using the Level-1 trigger track candidates as seeds, track finding in the spectrometer will be carried out, ultimately matching them to the ones found upstream of the magnet and in the silicon. Tracking of the trigger particles to the silicon will decrease the contamination from “ghost” tracks and gamma conversions and, to some extent, from K/π decays. A similar Level-2 algorithm is being developed for the HERA-B experiment[7] using Digital Signal Processors.

The second part of the Level-2 trigger will perform a selection based on the event topology. The topology trigger employed will depend on the trigger satisfied in Level-1. For example for single lepton triggers, this could be the requirement that the trigger muon or electron has a large impact parameter to the primary vertex or the two trigger tracks for di-lepton and di-hadron triggers form a detached vertex and possibly satisfy a mass constraint. Alternatively, we can perform a “Topology” trigger similar to that proposed by the COBEX collaboration, where events consistent with a single vertex hypothesis are rejected.

In principle, the load of the Level-2 trigger should be divided between the two parts, each providing a factor of ≈ 4.5 reduction. With the resulting factor of 20 reduction, the expected Level-2 output rate will be 10kHz. But the performance numbers for the Level-2 trigger, especially the tracking part, require the detailed description of the detector elements and full

Event Sample	Level-1 Trigger Efficiencies			
	Muon	Electron	Hadron	OR'ed
Minimum-Bias	0.8%	0.8%	1.0%	2.5%
$B_d \rightarrow \pi^+ \pi^-$	4.8%	2.0%	15.3%	20.6%
$B_d \rightarrow J/\psi K_s^0 (\mu\mu)$	73.0%	1.9%	2.2%	73.5%
$B_d \rightarrow J/\psi K_s^0 (ee)$	4.7%	41.0%	2.4%	44.6%
$B_d \rightarrow J/\psi K^* (\mu\mu)$	75.2%	1.6%	3.1%	75.3%
$B_d \rightarrow J/\psi K^* (ee)$	5.0%	42.6%	3.2%	45.5%
$B_d \rightarrow \bar{D}^0 K^* (K\pi)$	5.2%	1.6%	9.5%	15.4%
$B_s \rightarrow D_s^- \pi^+$	3.7%	2.3%	9.9%	14.7%
$B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$	5.2%	1.9%	5.6%	12.0%
$B_s \rightarrow D_s^- K^+$	4.6%	1.4%	9.5%	14.6%
$B_s \rightarrow J/\psi \phi (\mu\mu)$	71.3%	1.7%	2.0%	71.8%
$B_s \rightarrow J/\psi \phi (ee)$	3.7%	41.3%	2.8%	44.0%
$B_s \rightarrow \mu^+ \mu^-$	84.1%	2.1%	1.5%	84.3%
$B_d \rightarrow \mu^+ \mu^- K^*$	69.1%	1.8%	2.9%	70.0%
$B_u \rightarrow \bar{D}^0 K^+ (K\pi)$	5.9%	2.2%	11.7%	18.5%
$B_u \rightarrow \bar{D}^0 K^+ (K\pi\pi\pi)$	5.2%	2.0%	8.6%	14.2%

Table 10.7: Summary of the Level-1 high- p_t trigger efficiencies for the indicated exclusive decay modes. In the event generation, the accompanying \bar{B} -meson is decayed inclusively. The trigger efficiencies quoted are the fraction of “accepted” events in which the trigger particle(s) are accepted by their appropriate detectors and the trigger algorithm is satisfied. Column 4, labeled OR’ed, contains the percentage of accepted events which satisfy one or more of the three Level-1 triggers.

pattern recognition programs running online. Therefore, in this document we will assume a pessimistic scenario and give the details only of the COBEX type topology trigger which will reduce by a factor of 10 the events coming out of Level-1, and assume that the remaining factor of 2 reduction can be obtained from tracking in the spectrometer.

10.7.1 Vertex-topology trigger

The algorithm: The vertex detector will be an important part of the Level-2 trigger and will be used to fulfill the following tasks:

- Classify events according to the number of primary interactions that occurred.
- Determine the position of the interaction point(s).
- Enrich the sample with those valuable events that contain B decays with a non-zero lifetime.
- Provide precise information about tracks near the interaction point(s) to be combined with the information from other detectors in the final Level-2 trigger.

The strategy of the vertex topology trigger is to use digitized silicon hit information to locate the primary

vertices in the event and to select events which are inconsistent with having a single vertex, while rejecting events with multiple primary interactions.

The LHC-B vertex topology algorithm consists of the following steps:

- **Point Finding:** The raw silicon hit information is transformed into points independently in the x - z and y - z planes. A point is defined as the geometrical center of a cluster (contiguous hit strips). The average cluster width is 1.6 strips. A comparison of the points found in this way with the original track coordinates indicates a resolution of $10 \mu\text{m}$ (FWHM). Although the total event charged track multiplicity is high, one quadrant sees on average, less than 1/8 of the total, resulting in the rather modest mean multiplicity of 3.5 points per quadrant.
- **Track Finding:** Next, straight lines which traverse at least three planes of silicon, are found independently in both hemispheres in their x - z and y - z projections, using a road width of one silicon strip or ($25 \mu\text{m}$). This rather stringent collinearity cut corresponds to the multiple scattering of a 2 GeV track and thus tends to reject tracks with lower momentum which degrade the vertex algorithm. It also tends to reduce the number of ghost tracks. No attempt is made to match the views online.

- **Duplicate Rejection:** The track-finding algorithm tends to find several segments of the same track with different hit combinations. Moreover, due to the narrow road width, tracks which suffer from large multiple scattering can be found in more than one non-overlapping segment. The duplicate rejection process attempts to remove all segments but the one with a hit closest to the beam.
- **Primary Vertex Approximation:** In order to define the subset of found tracks whose origins are near the primary vertex, we need to have a first estimate of this vertex position in the longitudinal coordinate, z . This estimate is made by histogramming in 5 mm bins, the z -intercepts of all the found x - z and y - z track projections (only the two hits closest to the beam on each track are used to define the track parameters). The two adjacent bins which contain the most hits are then found and their average position, weighted by the number of hits in each bin, is taken as the preliminary primary vertex z coordinate. This procedure yields a z -position with an accuracy better than 1 mm. The vertex transverse positions, x and y , are assumed to be zero.
- **Exclude Tracks with Projected Impact Parameters > 1 mm:** Most tracks from strange particle decays as well as remaining badly-scattered and ghost tracks are removed by eliminating all tracks with projected impact parameter larger than 1 mm at the estimated primary vertex position (almost all tracks from beauty or charm decays have much smaller impact parameters).
- **χ^2 Calculation:** An improved primary vertex position is calculated from the remaining tracks by minimizing the following χ^2 for a single vertex hypothesis, using the projected track impact parameters and slope dependent weights. A large χ^2 results if the event topology is inconsistent with a single vertex hypothesis, and is therefore evidence of heavy flavor production.

$$\chi^2 = \left[\sum_{i=1}^{N_x} \frac{b_{xi}^2}{\sigma_{xi}^2} \right] + \left[\sum_{j=1}^{N_y} \frac{b_{yj}^2}{\sigma_{yj}^2} \right] \quad (43)$$

This equation contains independent sums over x and y view tracks. b_{xi} (b_{yj}) is the projected impact parameter of the i 'th (j 'th) track in the x (y) view. Here, the primary vertex point, which is used to evaluate the projected impact parameter, is no longer constrained to be at $x = y = 0$.

A weight, σ_{xi} (or σ_{yj}) is assigned to each impact parameter based on the tracks slope (which gives a very rough indication of the tracks momentum) and the extrapolation distance between the vertex and the closest measured point on the track.

- **Iteration:** Despite the care taken to eliminate bad tracks and tracks from strange particle decays, minimum-bias events often retain one or two such tracks with large impact parameters. Since usually many more large impact parameter tracks are contained in a $\overline{B}\overline{B}$ event, discarding the track with the largest contribution to the χ^2 and repeating the vertex fit, yields a larger minimum-bias suppression with acceptable B efficiency. Simulation shows that the trigger selectivity is maximized after two such iterations.
- **Trigger selection:** At the end of the second iteration, vertex χ^2 's formed separately by forward and backward tracks are compared. Event which have large forward χ^2 's are kept as multiple vertex event candidates.

Simulation of the vertex topology trigger:

In chapter 4, it was pointed out that the P238 test-experiment demonstrated that it is possible to make reliable Monte-Carlo predictions of triggering efficiencies. Here we calculate the trigger efficiency of minimum-bias events and some B-meson decays for a full vertex detector system.

Complete GEANT simulations have been made of the silicon detector response to PYTHIA-generated events and the response of the proposed Level-2 topology trigger algorithm was obtained using these events. Fig. 10.18 shows the difference between the z of the vertex found by the "First Vertex" by histogramming method and the true primary vertex. Even though the primary interactions occur over an extended z region, it is possible to locate the interaction point with good accuracy, $\sigma_z = 537\mu$, with a simple histogramming method.

The performance of the vertex topology algorithm is summarized in Fig. 10.19 which shows the fraction of events retained for minimum-bias events vs. two different B-meson decay modes as the χ^2 cut used varies. This algorithm provides a minimum-bias suppression of 1/10 with a B-Meson efficiency of 30-50% (depending on final-state multiplicity). Decay modes with larger multiplicity have somewhat larger efficiencies, while decay modes such as $B_d \rightarrow \pi^+ \pi^-$ have, understandably, smaller efficiencies. The Level-2 trigger efficiencies for different decay modes are summarized in Table 10.12, section 10.9.

The algorithm is sufficiently concise to allow implementation in a pipelined data-driven trigger

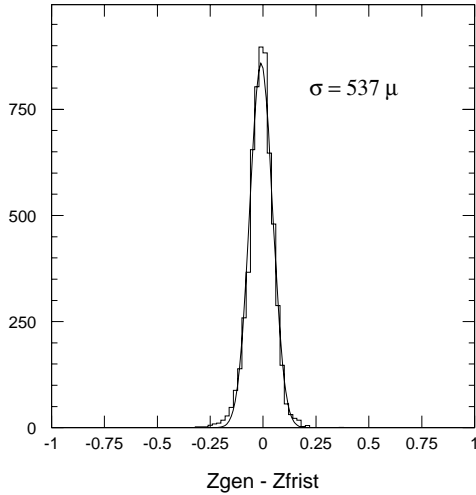


Figure 10.18: Difference of first vertex estimate from generated primary vertex

processor[9]. The suppression of minimum-bias background is sufficient to allow efficient transfer of accepted events to a Level-3 trigger processor farm for further filtering.

10.8 Level-3 trigger

The final stage of triggering will reduce the event rate from the ≤ 10 kHz passed by Level-2 to about 100-200 Hz. The output rate requirement was chosen to keep the off-line analysis and tape handling tasks to a manageable level. It should be noted that, at an average luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, the $b\bar{b}$ production rate will be about 75 kHz. With combined acceptance and Level-1/2 efficiencies greater than 1%, more than 750 B-events will be passed to Level-3 every second. Thus, it is not sufficient merely to collect a pure sample of $b\bar{b}$ events. Instead, the Level-3 algorithm must select the most promising B-events, in addition to removing practically all the minimum-bias background.

The Level-3 processing and selection will be performed by an extensive farm of commercial microprocessors, as discussed in Sect. 11.6.

The Level-3 algorithm has not yet been studied in detail, but general ideas are emerging about how the Level-3 selection will be made. The Level-3 algorithm can be decomposed into three logical phases: trigger refinement, event reconstruction, and event selection.

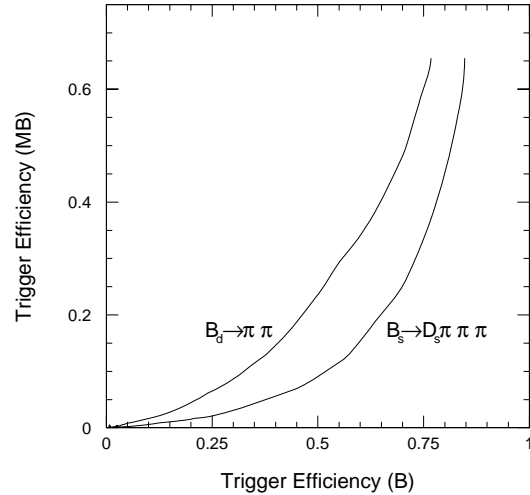


Figure 10.19: Topology trigger efficiency of minimum-bias vs. $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$ events.

Trigger Refinement: The trigger refinement phase attempts a rapid rejection of events for which the trigger resulted from an obvious background source. The original trigger criterion is examined in detail, using all appropriate data. For example, events passing the topology trigger will be searched for evidence of pile-up or strange particle decays which could have caused a false trigger. Tracks with large χ^2 contributions to the vertex fit will be momentum analyzed to give a better estimate of the total single vertex hypothesis χ^2 . An event is rejected if it does not pass the improved trigger requirements.

Similar reanalysis can be performed for high p_T lepton triggers. The candidate lepton track can be traced through the spectrometer and, in many cases, through the silicon. The χ^2 of a fit of the track to all the measurements in the spectrometer will be large if there is a kink in the track resulting from a particle decay. The track must also point to within a few millimeters of the interaction position. In addition, the information from the RICH and EM calorimeter must be consistent with the identification of the particle as a lepton. In most cases the RICH will show a $\beta \approx 1$ track. There will be little or no energy in the calorimetry where a muon passes through, or a cluster in the EM calorimeter with energy and centroid consistent with an electron track momentum and extrapolated position. Chamber drift times can

be used as an additional verification that the track belongs to the correct event.

In most cases, only a limited amount of event data will be needed to perform the trigger refinement. Where necessary, partial reconstruction will be performed within a region of interest using the mechanism described below.

Event Reconstruction: In the second phase, remaining events will be completely reconstructed. All tracks will be found, momentum analyzed, and identified. Rough vertexing will also be performed including finding the primary vertex, searching for pile-up vertices, and finding Λ and K_S^0 Vees. To reduce the processing requirements, the reconstruction phase can be designed such that it is performed on a demand basis. In this case, tracks are reconstructed, fitted, and identified as they are required by other phases of the algorithm. Remaining tracks or regions in accepted events are processed before they are written to tape.

Event Selection: The third phase will select events to be written to tape. Table 10.8 gives some suggested criteria along with their expected rates and examples of the physics to be explored with each resulting data sample.

Criterion	Rate (Hz)	Examples of Targeted Physics
$m(+ -) > 5 \text{ GeV}$ ·vertexing	5	$B_d \rightarrow \pi^+ \pi^-$, $B_s \rightarrow K \pi$ $B \rightarrow \rho \pi$, $\Lambda_b \rightarrow p^+ K^-$
$\ell^+ \ell^+$ ·vertex	50	$B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow J/\psi + X$, etc.
Reconstructed D^0, D^+, D_s^+	60	$B_d \rightarrow DD$, $B_s \rightarrow D_s + n\pi$, other $b \rightarrow c$ physics.

Table 10.8: Level-3 criteria and rates

It is at this stage that the Level-3 algorithm must choose the most promising B-decays. In general, the filter criteria will attempt to select classes of B decays which can be used for the most interesting physics topics (CKM measurements, etc.). By limiting selection to classes of decay modes, and keeping the cuts fairly loose, we can retain enough data to help assess systematic errors and avoid causing additional biases.

Two particle sub-mass: The first criterion selects events with a pair of particles of opposite charge which have mass greater than some minimum (nominally 5 GeV), and which form a good vertex away from the primary interaction point. This filter selects 2- and occasional 3-particle final states. The study of $B \rightarrow \pi^+ \pi^-$ shows that such high-mass pairs

occur with a frequency of $1/1000 \text{ } b\bar{b}$. A factor of 2 is included in Table 10.8 to compensate for the lack of the pion identification requirement.

Di-leptons: The di-lepton criterion selects the J/ψ decay modes and the rare Flavor Changing Neutral Current decay modes. It requires that two leptons of the same flavor, but opposite charge form a good vertex downstream of the interaction point. Studies of $B_s \rightarrow \mu^+ \mu^-$ indicate that the background to this filter will be shared between J/ψ decays, and background from events with two semi-leptonic decays, in which the decay leptons accidentally form a good vertex. Table 10.9 shows the rate of the di-lepton filter broken down by component. A relatively low-mass cut may be necessary to suppress events with two semi-leptonic decays in the same decay chain, *e.g.* $B \rightarrow \mu^+ \nu (\bar{D} \rightarrow K \mu^- \bar{\nu})$.

Mode	$B \rightarrow J/\psi + X$	$b\bar{b} \rightarrow \mu^+ \mu^-$
$b\bar{b}$ / sec	$7.5 \cdot 10^4$	$7.5 \cdot 10^4$
BR	$2 \cdot 0.011 \cdot 0.06$	0.029
Accept	0.20	0.20
Trigger	0.50	0.50
Recon.	0.80	0.05
Rate (Hz)	12 Hz	36 Hz

Table 10.9: Di-lepton rates

Reconstructed D-mesons: The third selection criterion is that a fully reconstructed D-meson be found in the event. This sample should be rich in reconstructable high-BR decay modes (*e.g.* $B \rightarrow \bar{D} n \pi$) which will be useful for production studies, calibration, monitoring systematic errors, and normalization. Several specific modes useful for CP violation (*e.g.* $B_d \rightarrow D \bar{D}$) or B_s -mixing studies (*e.g.* $B_s \rightarrow D_s^\pm (n\pi)^\mp$) will also be found in this sample.

Table 10.10 shows the currently measured charged decay modes for the D^\pm, D^0 , and D_s^\pm . The individual rate calculations for the three D-flavors are presented in Table 10.11. The fragmentation factors ($b\bar{b} \rightarrow D$) are derived from JETSET V7.401[11] and are consistent with the measured branching fractions of B mesons. The total selection rate given in Table 10.8 contains a factor of 1.5 to account for background.

The rates given in Table 10.11 use very rough estimates of the acceptance and reconstruction efficiencies. Nevertheless, these estimates are consistent with a simulation of the reconstruction of $D^0 \rightarrow K^- \pi^+$ decays. The simulation uses 50000 $pp \rightarrow b\bar{b}$ events generated and propagated through a forward spectrometer with a fast Monte-Carlo. The simulated acceptance \times reconstruction efficiency was 6.1% (132

D^0 s were reconstructed). Furthermore, 3.0% of the reconstructed Ds were accompanied by a small angle, high- p_T muon, consistent with the trigger factor. The combinatoric background under the reconstructed D^0 peak was about 1.7 events/MeV. This corresponds to a 50% background over a 40 MeV mass bin. Since the cuts have not been optimized, it should be possible to reduce this background figure with minimal deterioration of the reconstruction efficiency.

D-meson	Mode	BR (%)
$D^+ \rightarrow$	$K^- \pi^+ \pi^+$	9.1
	$K_S^0 \pi^+ \pi^+ \pi^-$	2.4
	$\pi^+ \pi^+ \pi^-$	0.3
	$K^+ K^- \pi^+$	1.1
	Total charged	12.9
$D^0 \rightarrow$	$K^- \pi^+ \pi^+ \pi^-$	8.1
	$K^- \pi^+$	4.0
	$K_S^0 \pi^+ \pi^-$	1.8
	$K^+ K^-$	0.4
	$\pi^+ \pi^-$	0.2
	Total charged	14.5
$D_s^+ \rightarrow$	$K^+ K^- \pi^+$	4.8
	$K_S^0 K^- \pi^+ \pi^+$	1.4
	$\pi^+ \pi^+ \pi^-$	1.4
	Total charged	7.6
$b\bar{b} \rightarrow$	D→charged	27.9

Table 10.10: Reconstructible D-Meson Branching Ratios from Ref. [10]. K_S^0 branching ratios include a factor of 0.34 for $BR(K^0 \rightarrow K_S^0 \rightarrow \pi^+ \pi^-)$

Mode	D^+	D^0	D_s^+
$b\bar{b}$ (kHz)	75	75	75
$b\bar{b} \rightarrow D$	0.48	1.29	0.39
BR	0.129	0.145	0.076
Accept	0.20	0.20	0.20
Recon.	0.30	0.30	0.30
Trigger	0.03	0.03	0.03
Rate (Hz)	8	25	4

Table 10.11: Reconstructed D selection rates

Other criteria: Although the criteria listed above cover most of the interesting B-physics, they are blind to many classes of B-decays which could have some future interest. Such decay modes will still be included in the data sample indirectly *e.g.* accompanying a B decaying to a reconstructible D-meson, but this implies at best a few percent efficiency for the

untriggered modes. An example of modes that will not be triggered by the Level-3 criteria listed above are: most Cabibbo-suppressed $b \rightarrow u$ decays, Penguins *e.g.* $b \rightarrow s \gamma$, and rare decays such as ϕK_S^0 . Some additional filter criteria should be added to snare these and other more unusual decay modes. The listed criteria also neglect the non-B physics (precision charm physics, diffraction, or other forward physics), as well as the obligatory monitoring and calibration events.

10.9 Trigger summary

In this section, we give the combined Level-1 and Level-2 trigger efficiencies along with the number of events at the input to Level-3 (or “written to tape”, assuming no loss in Level-3).

Table 10.12 shows the assumed total branching ratios, the geometric acceptance, the Level-1 and the Level-2 trigger efficiencies which are used in calculating the expected event yields going into the Level-3 trigger. The “visible” branching ratio includes only charged decay modes of the secondary decays. For B_s decays, only the $D_s \rightarrow K^+ K^- \pi^-$ decay mode is considered. The decay modes assumed for $J/\psi K_S^0$ and \bar{D}^0 are shown in parenthesis in the first column. The “Decay Acceptance” column shows the fraction of events, generated by PYTHIA over 4π steradians, in which all decay products are detected and momentum-analyzed in the spectrometer. The quoted trigger efficiencies are for these accepted events only.

The event yields are calculated assuming $7.5 \cdot 10^{11}$ $b\bar{b}$ ’s produced per year (from luminosity, $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, 10^7 s and $500 \mu\text{b}$ $b\bar{b}$ cross section). The expected events also include factors for B_d , B_u and B_s hadronization, 2×0.4 , 2×0.4 and 2×0.12 respectively, and 0.76 for those events that occur in single-interaction bunches.

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Event Sample	Visible B.R.	Decay Acceptance	Efficiency		Events On Tape
			Level-1	Level-2	
$B_d \rightarrow \pi^+ \pi^-$	$2.0 \cdot 10^{-5}$	17.8%	20.6%	33.1%	110k
$B_d \rightarrow J/\psi K_s^0 (\mu\mu)$	$2.1 \cdot 10^{-5}$	14.0%	73.5%	34.5%	340k
$B_d \rightarrow J/\psi K_s^0 (ee)$	$2.1 \cdot 10^{-5}$	12.4%	44.6%	34.5%	183k
$B_d \rightarrow J/\psi K^* (\mu\mu)$	$6.3 \cdot 10^{-5}$	13.7%	75.3%	42.8%	1270k
$B_d \rightarrow J/\psi K^* (ee)$	$6.3 \cdot 10^{-5}$	12.1%	45.5%	42.8%	679k
$B_d \rightarrow \bar{D}^0 K^* (K\pi K\pi)$	$8.0 \cdot 10^{-7}$	12.8%	15.4%	43.3%	3k
$B_s \rightarrow D_s^- \pi^+$	$1.4 \cdot 10^{-4}$	13.0%	14.7%	46.8%	171k
$B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$	$3.5 \cdot 10^{-4}$	9.6%	12.0%	50.8%	277k
$B_s \rightarrow D_s^- K^+$	$1.1 \cdot 10^{-5}$	12.6%	14.6%	47.5%	13k
$B_s \rightarrow D_s^+ K^-$	$5.3 \cdot 10^{-6}$	12.6%	14.6%	47.5%	6k
$B_s \rightarrow J/\psi \phi (\mu\mu)$	$4.2 \cdot 10^{-5}$	14.2%	71.8%	42.0%	246k
$B_s \rightarrow J/\psi \phi (ee)$	$4.2 \cdot 10^{-5}$	12.5%	44.0%	42.0%	133k
$B_s \rightarrow \mu^+ \mu^-$	$4.0 \cdot 10^{-9}$	19.2%	84.3%	33.5%	30
$B_d \rightarrow \mu^+ \mu^- K^*$	$2.9 \cdot 10^{-6}$	14.3%	70.0%	42.2%	17k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi)$	$1.5 \cdot 10^{-5}$	14.4%	18.5%	41.9%	76k
$B_u \rightarrow \bar{D}^0 K^+ (K\pi\pi\pi)$	$3.1 \cdot 10^{-5}$	11.9%	14.2%	49.0%	117k

Table 10.12: Events accepted and triggered which are written to tape each year (assuming no loss in Level-3). See text for description. The yields are calculated for a constant luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

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11 Data Acquisition

The LHC-B data rates are determined by the channel counts and occupancies of the LHC-B detectors and by the trigger rates. The channel counts are summarized in table 11.1.

Detector	Channels	Occupancy
Silicon	147,456	2%
Inner Tracker	196,608	2%
Outer Tracker	183,290	5%
RICH	302,000	1%
ECal	10,000	100%
HCal	11,500	100%
Muon System	256,000	1%
Total	1,106,854	3.9%

Table 11.1: LHC-B channel counts and occupancies

11.1 Comparison with the other LHC experiments

The LHC-B data acquisition system (hereafter referred to as DAQ) will be similar to those of ATLAS[1] and CMS[2]. The problems of sampling detectors every 25 nsec and the technique of reducing the data rates using a multi-level trigger scheme are identical in LHC-B and the large central detectors. This allows LHC-B to exploit much of the R&D work already performed for the larger experiments.

Table 11.2 compares the DAQ parameters for LHC-B and ATLAS.

Parameter	LHC-B	ATLAS
Number of channels	$1.1 \cdot 10^6$	$1.5 \cdot 10^8$
Channels (ex. pixels)	$1.1 \cdot 10^6$	$7.1 \cdot 10^6$
Max. Level-1 Rate (kHz)	400	100
Readout bandwidth (Gby/s)	35	128
Max. Level-2 Rate (kHz)	10	1
Compressed event size (kby)	100	1280
Event building rate (Mby/s)	1000	1280
Max. Level-3 Event rate (Hz)	200	100
Max. archival rate (Mby/s)	20	100

Table 11.2: Comparison of DAQ parameters for LHC-B and ATLAS

Two differences stand out between LHC-B and its sister experiments. The first major difference is that LHC-B requires many fewer channels and has a much lower raw data rate. This is most noticeable in the

raw channel counts (with the pixels included), but is even obvious when the ATLAS pixel detectors are ignored. The large discrepancy in channel counts follows from the lower luminosity and smaller pseudo-rapidity coverage requirements of LHC-B. ATLAS and CMS expect to operate at the design Luminosity of the LHC, above $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. At these luminosities, ≈ 20 interactions will result from each bunch crossing. Extensive pixel arrays are needed to resist the high radiation environment and to avoid confusion in reconstructing the dense particle flux. Because we plan to limit the LHC-B luminosity to less than $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and to suppress the remaining pileup (multi-interaction bunches), the data rates produced by our apparatus will be at least 10 times less than those of the larger experiments.

The second difference is that LHC-B has a lower Level-1 trigger rejection. The inability of Level-1 to efficiently reduce the interaction rate by more than a factor of ≈ 100 is correlated to the large B production cross section at the LHC. The B features used as Level-1 trigger criteria in LHC-B (*e.g.* leptons or hadrons with modest p_t cuts - see Chapt. 10) are commonly produced in LHC minimum-bias events. Those features which can most effectively distinguish B events from the minimum bias background (*e.g.* B-lifetime and narrow mass) are less accessible at Level-1.

These two differences tend to counteract one another. The large LHC-B advantage in channel count is partially reversed at the readout level by the need to increase the number of parallel data paths to increase rates. This advantage almost vanishes at Level-3 where the event building and processing requirements are comparable to those of ATLAS. Thus, the LHC-B DAQ system can be interpolated from those of the high- p_t experiments at all stages. The only issue is the tradeoff of readout cost and complexity with the desire to accept higher Level-1 rates. We believe that a maximum Level-1 trigger rate of 400 kHz is possible at an acceptable cost.

11.2 LHC-B data flow

The data flow in the LHC-B DAQ system is illustrated in figure 11.1. Detector signals undergo analog processing in the front-end electronics. The data are stored in analog or digital pipelines (as appropriate) for 128 bunch-crossings pending the Level-1 trigger decision. The resulting $3.2 \mu\text{s}$ delay allows approximately $2 \mu\text{s}$ for the trigger formation with the rest going to data gathering and trigger dispersal. Level-1 trigger decisions are made based on low granularity data transferred to the Level-1 trigger processors over

dedicated channels.

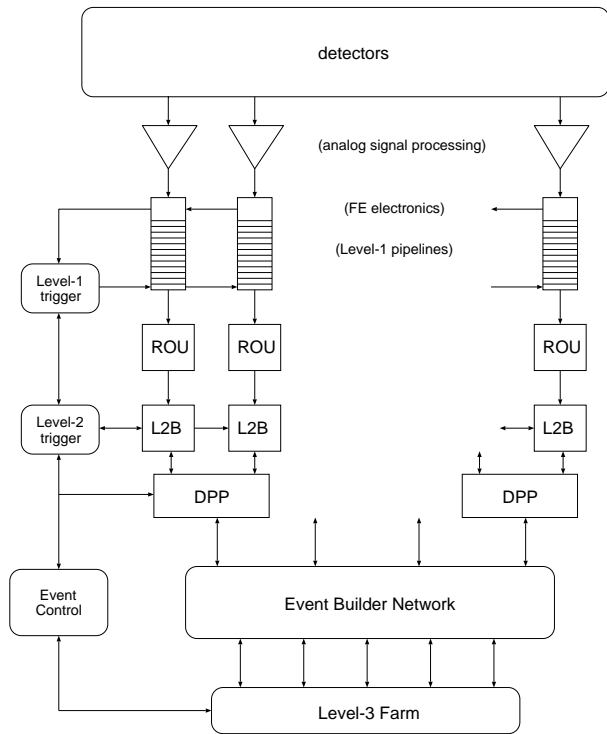


Figure 11.1: Data flow through the LHC-B DAQ system

Events selected by the Level-1 trigger are read out into Level-2 digital buffers interfaced by and under the control of the Readout Units (ROUs of figure 11.1). Data flow between the front-end interfaces and the Level-2 buffer system will be data-driven, and pass over high-speed optical fibers. Data in the Level-2 buffers may be accessed by Level-2 trigger processor as needed, and are stored until the Level-2 trigger decision has been made.

Events selected by the Level-2 trigger are sent to the event builder by way of a layer of detector preprocessors (DPP). The detector preprocessors gather data from all or part of a detector and perform local pre-processing of data before the event builder from events that have passed the Level-2 trigger requirements. This pre-processing may include zero-suppression or other concentration of the detector data. The event builder architecture isn't yet defined, but the requirements of about 1 Gby/s may be met by several possible scenarios as described in Sect. 11.5.

Final selection and processing of the event data are performed in a farm of high performance micro-processors.

11.3 Front-end electronics

11.3.1 Analog signal processing

The front-end electronics requirements for LHC-B are similar to those for the other LHC experiments. The electronics must be sufficiently fast to discriminate between successive LHC bunches. The bunch discrimination may be accomplished either directly, by using electronics with shaping times less than the interbunch time, or indirectly, by interpolating between several successive measurements from a single channel. The latter choice is most appropriate for the readout of channels for which some analog information is necessary. The RD-20[3] silicon readout is an example of this option.

11.3.2 Level-1 storage

After front-end signal processing, the data must be stored for up to 128 bunch-crossings ($3.2 \mu s$) while waiting for the results of the Level-1 trigger calculation. Several architectures have been proposed for this step, any of which could be appropriate for use by LHC-B. The storage techniques include:

- storage of analog information in an analog pipeline (an example is the RD-20 silicon system[3])
- storage of digital information in a digital pipeline (shift register).
- storage of sparsified digital data in RAM with a Bx code.
- storage of digitized data in RAM under external control (an example is the Fermi calorimeter readout[4]).

The most appropriate storage technique will be used for each detector.

11.3.3 Synchronization and trigger distribution

The front-end electronics will be synchronized to the LHC bunch structure, and the Level-1 event accepts will be distributed to the various front-end nodes by a global trigger and timing subsystem. The system under development by RD-12 and RD-27[5] should meet all the requirements for LHC-B.

11.4 Detector readout

11.4.1 Readout units

The Readout Units supply control and sequencing signals to the front-end electronics (predominately

ASICs), and optionally digitize and sparsify the front-end data. They will also provide an interface between the front-end electronics and the readout links which carry data to the Level-2 buffers. These units are located near the detectors in the experimental hall.

11.4.2 Readout links

Data from the readout units will be passed to a bank of Level-2 storage units over fiber optic links with a bandwidth of $> 1 \text{ Gbit/s}$. This allows the transfer of an average of 250 bytes per link per event, requiring about 400-500 links for the entire detector. Because of the large number of small blocks to be sent over these links, an efficient (probably data-driven) protocol must be used.

11.4.3 Level-2 buffers & trigger interface

The Level-2 buffers will hold the data from all or part of a given subdetector while the Level-2 decision is being made. The buffer modules will also enable the Level-2 trigger to access the data, and will ultimately pass accepted event data to the event builder.

Given a maximum sustained Level-1 trigger rate of 400 kHz and an average Level-2 decision latency of 10 ms, the Level-2 buffers must each hold about 4000 events. This places a reasonable requirement of 400 Mby of storage distributed through the Level-2 buffer subsystem. The most obvious implementation, in which a Level-2 buffer module services a single readout link, would require about 400-500 modules, each with $\sim 1 \text{ Mby}$ of buffer memory.

Access of the silicon data by the Level-2 trigger will provide the most challenging requirement for the Level-2 buffer. In the worst-case scenario, in which no significant suppression is provided by other Level-2 criteria, the buffers will have to send all of the silicon data to the Level-2 topology trigger. This data rate corresponds to $\sim 15 \text{ Mby/s}$ per silicon detector. This rate could be handled if each buffer module services a single detector, and a dedicated Level-2 trigger interface is provided on each module.

It is likely that significant Level-2 trigger suppression may be provided by tracking the trigger particle(s) through the chambers. This would require much less data and the data would be distributed through several buffers. In this case, an intelligent, lower bandwidth interface may be used which would provide a limited amount of data from a region of interest to the Level-2 processor(s) through a bus or ring-based network. Thus, although detailed Level-2 simulations have not yet determined the Level-2 trigger interface requirements, we are confident that

an appropriate Level-2 buffer system can be designed and built.

11.4.4 Rate limitations

The upper limit on the readout rate comes from the maximum rate at which data can be read out from the front-end electronics. Although, in principle, this rate can be increased by sparsifying the data at the front-end or by using faster electronics we will likely be constrained to use front-end electronics already developed for the other experiments or simple modifications thereof.

To date the slowest constraints come from the 128-way multiplexing of analog channels to a single flash ADC. If the multiplexer is run at the Bx frequency (this seems to be the standard solution now), the full readout cycle will take $3.2 \mu\text{s}$ plus any per-event overhead and limit the Level-1 trigger rate to no more than 300 kHz. This limit may be reduced by modifying the front-end ASICs to multiplex fewer channels (e.g. 32) to a single FADC. This is thought to be a relatively minor change, although it will necessitate the use of a larger number of analog readout channels, at additional cost.

11.5 Event building

Event building proceeds through three logical phases. Data from events selected by the Level-2 trigger are first collected, and preprocessed on a detector (or partial detector) basis. The detector data packets are then passed through a passive switch network to an output node. The output node collects all the packets from a given event and merges them together before passing them on to the Level-3 trigger farm. The choice of interconnects carrying data to, from and internal to the event builder will depend on which event builder architecture is selected. As described below, a wide variety of event builder architectures are possible. Each would have a preferred interconnection that would minimize the number of interfaces needed.

11.5.1 Detector pre-processors

The detector pre-processors (DPPs) collect the data for a given event from the Level-2 buffers for a single detector or part of a detector. The data are then preprocessed and condensed with a view to

- reducing the amount of data that must be passed through the event builder and
- minimizing the processing necessary by the Level-3 farm.

Finally, the data are formatted into a suitable packet with the appropriate destination address and sent to the event builder network.

11.5.2 Event builder network

The event builder network is a passive, data-driven packet switching network. All data packets from a given event are received from the DPPs with the same destination address. The packets are then routed independently within the event builder network to the specified output node. The event builder output node will assemble the various packets from a single event and sends them to the associated Level-3 sub-farm.

Several switching network implementations are, or will be, available in time for the running of LHC-B. These possibilities range from ring structures such as SCI[6] or Quickring to switching fabrics such as ATM or the InMos C104 to a network of DSPs ('C40s or AMD21060s) connected via their data-links. All of these switch implementations are driven by commercial applications and are developing rapidly. This assures us that a scalable, cost-effective solution can be found for LHC-B.

11.5.3 The event builder output node

The function of the output node, the final merging and checking of the complete event, may require an independent unit, or could be incorporated into either the event builder network or the I/O and control section of the Level-3 Farm. For this reason, explicit output units were omitted from figure 11.1. For instance, in a routing network built from DSPs, some or all of the packet merging and error detection and reporting functions could be handled by the DSPs.

11.6 Level-3 processing

The Level-3 processor farm performs the processing and final selection of the events which pass the Level-2 trigger. In addition to performing this processing, the farm must provide access to the data for all aspects of experimental monitoring.

At present, the calculational complexity needed for the Level-3 algorithm can be estimated only roughly. We assume that the filtering and reconstruction of the events will take at most a similar amount of time to execute as our fast Monte Carlo¹² which uses about 1 s of CPU time on the Cern/SP-2 machine. This

¹²The fast Monte Carlo doesn't perform pattern recognition in the spectrometer, but it does perform complete pattern recognition and fitting of tracks in the silicon detector, and fits the perfectly reconstructed spectrometer tracks. The Monte Carlo track propagation code is assumed to take about the same time as a Kalman reconstruction algorithm.

implies that $\sim 10^8$ instructions are required to perform the reconstruction of each event. Since the input event rate to the Level-3 farm is 10 kHz, the farm must provide a 10^6 -MIPS processing capability.

Because the constituents of the farm belong to one of the most rapidly changing classes of technology, the final details of the farm will be best decided at a future time. It is quite possible that by the time LHC-B starts to take data a commercial solution may exist which will satisfy the Level-3 processing requirements, and provide in addition most of the communications and system software. We now see several lines of commercial development which may result in an appropriate system for our use. On the one hand there are several massively parallel systems being offered which should in the future have sufficient processing power to satisfy our needs. On the other hand, a partnership to develop clusters of PCs was recently announced, which would bring with it the cost benefits of the PC revolution. The decision whether to use a commercial device, if one exists, or to produce a home-made system as described below, will depend on the total cost, including both hardware and software development costs.

In the remainder of this section, we describe a model of the Level-3 farm in order to define the functionality and to demonstrate that it can be built from available components with little difficulty.

11.6.1 Sub-farm structure

The Level-3 Farm structure is illustrated in figure 11.2. The Level-3 processor farm is organized in up to 32 sub-farms, each of which is controlled locally by an intelligent sub-farm controller. This sub-farm structure has been shown by traffic simulation[7] to be preferable to a single, centrally controlled farm. This is because the sub-farm structure facilitates the allocation of processors and decreases the control latency. In doing so, it helps optimize the duty cycle of the processors.

For the purpose of this discussion, we assume a baseline sub-farm structure of 32 sub-farms, each containing 32 1000-MIPS processors to give the required processing power. In this case, data from about 320 events per second (30 Mby/s) will be passing through each sub-farm and each processor will have an average of 100 ms to complete its calculations.

11.6.2 Level-3 sub-farm interconnect

The Sub-Farm Controller (SFC) and Level-3 Processors (L3Ps) in a given sub-farm are joined by a common interconnect. This is used both for passing

control messages and for transferring event data between the units of the sub-farm. The interconnect can be either a bus (e.g. VME) or some ring interconnect (e.g. SCI or Quickring). It must only have a reasonable bandwidth (> 40 Mby/s) and an efficient means of transferring large (100 kby - 1 Mby) data blocks. The bandwidth of the interconnect chosen will influence the number of sub-farms and the number of processors in each farm. The relatively modest (30 Mby/s) data rates needed by the baseline configuration would allow the use of simple bus interconnect such as VME-D64.

11.6.3 Sub-farm controller

Each Level-3 sub-farm will contain a sub-farm controller (SFC) to collect data from the event builder and distribute the events to the processors in the sub-farm. The SFC will also provide a slow interface to allow the physicists to monitor the results of the run and to diagnose hardware or software malfunctions of the processor units. The SFC can be constructed from a general purpose processor board with an additional high speed data interface to connect to the event builder, and a network connection to provide for communication with the physicists' work-stations.

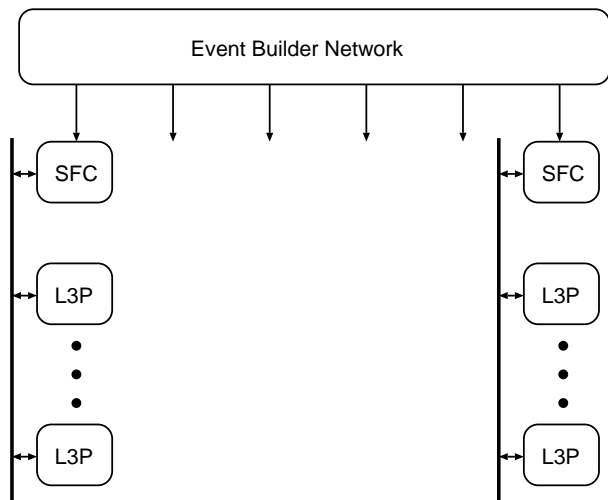


Figure 11.2: Level-3 farm structure. The Level-3 farm is divided into several (up to 32) autonomous sub-farms. Each sub-farm consists of a Sub-Farm Controller (SFC) and several Level-3 Processor (L3P) modules.

Software on the SFC will keep a workload table for each processor to be used in allocating a processor for each event received. It will also provide a message transfer system to enable communication between the

control workstations and the farm processors and a file system interface.

11.6.4 Level-3 processors

The Level-3 Processors (L3Ps) are general purpose microprocessors which perform the reconstruction and selection of events which pass the Level-2 trigger. A discussion of the Level-3 selection algorithm appears in Chapt. 10. Since the I/O rates for a single processor are modest (1 Mby/s), the configuration of multiple processors in a single module with a shared I/O interface and communication memory could be compelling. Although it is not likely to be advantageous to divide the processing of one event among several processors, sharing an input queue among several processors will tend to average out the time between events and reduce the bulk of communication necessary between the processor modules and the sub-farm controller.

11.6.5 I/O processor unit

Each sub-farm contains an I/O processor unit to perform final histogramming and archiving of accepted events.

References

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12 Physics Performance

In this chapter, we present the results of the simulation work. This is to demonstrate the performance of the LHC-B detector for investigating the physics of CP violation. The chapter is structured as follows: After a short description of the simulation program, the reconstruction of the selected channels used to measure CP violation later is discussed. A detailed description is given for the reconstruction of the $B \rightarrow \pi^+\pi^-$ decay. For other channels, the description has been kept brief. Discussions on the tagging and the source of systematic errors are also given. Based on these results, the measurement sensitivity for the B_s - \bar{B}_s oscillations and the three angles of the unitarity triangle, α , β and γ are presented. Lastly, the $B_s \rightarrow \mu^+\mu^-$ decay mode is discussed as an example of the capability of the LHC-B detector to study rare decays.

The major difficulty in the analysis was the background estimation. All the interesting decay modes studied have very small branching fractions (see table 10.12). Therefore, the large number of events required for a direct study of the background could not be generated. The background estimates presented here rely on an extrapolation from the results obtained with a set of looser cuts. This prevented us from fully optimising the cuts for the signal. Although the background estimation has a considerable uncertainty, our study shows clearly the potential of the LHC-B detector in measuring CP violation in many different decay modes. This allows us to determine all three angles of the unitarity triangle as discussed in this chapter.

12.1 LHC-B simulation programme

Pythia 5.7 and JETSET 7.3 [1] are used as the event generators for all data samples. The primary interaction vertices are distributed with the expected LHC interaction region length ($\sigma_x = \sigma_y = 70\mu\text{m}$ and $\sigma_z = 5.3\text{ cm}$).

In the study of exclusive decays, B-mesons are forced to decay into a specific final state. For the neutral B-mesons, oscillations are also included in the event generation with $x_d = 0.7$ and $x_s = 10$. In the generation of events for the inclusive channels which provide data samples for background studies, JETSET is used for all particle decays.

Particles from the generated events are passed through the GEANT [2] based LHC-B detector simulation software and digitised events are written out as raw data tapes. The detector simulation includes all elements discussed in Chaps. 8, 4 and 6, with multiple scattering, gamma conversions, secondary inter-

actions and energy loss. The secondary particles produced in the hadronic interactions are also accounted for in the GEANT tracking using the GHEISHA method [3]. In the calorimeters and muon filter, a simplified parameterization of the shower is used. Decays in flight of π^\pm 's and K^\pm 's are also included.

Particles are tracked through the dipole spectrometer assuming a simple box-type field of 3.6 Tm. The particle coordinates at each chamber position are smeared with the expected resolution and then recorded for use in the track reconstruction. For the calculation of the geometric acceptance, we demand that tracks have sufficient numbers of chamber hits so that their momenta can be reconstructed. Full pattern recognition is performed only in the vertex detector. Track parameters are obtained by fitting a charged particle trajectory through the dipole field to the measured points. All available chamber points on a track and the track segments found in the silicon detector are used in the fit.

For the mass identification of charged particles in the RICH counters, smeared Cherenkov angles are generated based on the numbers of detected photons. A likelihood method is used to assign probabilities to various mass hypotheses. These probabilities are available for the decay reconstruction. Electrons reaching the electromagnetic calorimeter are identified as electrons with an efficiency of 95%. Hadrons reaching the electromagnetic calorimeter are misidentified as electrons with a probability of 0.2%. When a muon penetrates up to the middle of the muon system, the likelihood for the muon hypothesis is increased by a factor of ten. Pion punch through is negligible. The positively identified mass hypothesis is the one with the highest probability. Any mass hypothesis with a probability of larger than 5% is called compatible.

The primary vertex of each event is found by minimising a χ^2 using tracks reconstructed by the vertex detector. The χ^2 of the vertex is formed from the impact parameters of all the tracks. We then look for the track giving the largest contribution to the χ^2 of the vertex fit. If the contribution from this track is too high (> 4), the track is removed and a new vertex fit is performed. This process is repeated until either the largest contribution to the vertex χ^2 becomes acceptable, or fewer than four tracks remain in the track list. The longitudinal resolution of the primary vertex is $\sigma_s = 65\mu\text{m}$. If a primary vertex is found, the discarded tracks are used to reconstruct B-meson decays as described in the following sections.

12.2 Reconstruction of final states

12.2.1 The $B^0(\pi^+\pi^-)$ final state

The channel $B_d \rightarrow \pi^+\pi^-$ is a very demanding decay mode to reconstruct. The low branching ratio (of order 10^{-5}) and no sub-mass constraint means that the background problems are daunting. LHC-B has several unique features which are exploited in this challenge:

- The particle identification capability of the RICH system enables $B_d \rightarrow \pi^+\pi^-$ to be cleanly isolated from similar topologies, such as $B_d \rightarrow K^\pm\pi^\mp$;
- The microvertex detector close to the interaction point gives good impact parameter resolution and allows selection of tracks not originating from the primary vertex;
- The excellent mass resolution permits tight cuts to be placed around the B peak.

For the signal studies an equivalent of $\sim 150K$ $B_d \rightarrow \pi^+\pi^-$ events generated over the full solid angle were processed; of these 17.8% entered the geometric acceptance of LHC-B. In order to understand the effects of correlations, the reconstruction was first performed without the trigger selection in place, and then the trigger was added.

For the background a sample of 500K generic $b\bar{b}$ events was used; in addition smaller samples of specific decay modes were studied. Unless stated otherwise, ‘background’ refers to the former category.

The event selection was made in three stages. First a preselection was made to eliminate manifestly harmless background, and badly reconstructed signal events. Then event cuts were devised to achieve the necessary suppression. Finally a severe mass cut was applied. (The mass cut was separated from the other ‘event cuts’ to help in the background estimates, as will be explained.)

The preselection looked for well measured, potentially interesting pions in the event using the following criteria:

- At least 2 associated hits in the microvertex detector;
- Momentum of at least 200 MeV/c;
- Impact parameter with respect to the primary vertex measured with an error of less than 200 μm ;
- χ^2 per degree of freedom of track fit less than 5;

- RICH information consistent with the pion hypothesis (loose RICH).

All unlike-sign combinations of candidates surviving these demands were taken, and secondary vertices formed. Those pairs with an invariant mass lying within the window 5 to 5.5 GeV/c² were retained; if more than one such vertex was present, that combination with best χ^2 was chosen. Events without a high mass vertex were discarded. This preselection was found to have an efficiency of 68.6% for $B_d \rightarrow \pi^+\pi^-$ events within the acceptance, and 5.4% for the background events over 4π .

After this preselection, the following tight event cuts were applied:

- The χ^2 of the secondary vertex fit to be below 5;
- $\delta z/\sigma_{\delta z}$, the separation in z between the primary and secondary vertices normalised by the assigned error to be above 3, and the absolute value of δz to be at least 1.5 mm;
- The impact parameter to the primary vertex of *both* pions, normalised by the assigned errors, IP/σ_{IP} , to exceed 4 units of significance;
- The transverse momentum of both pions to be above 1.5 GeV/c, and the transverse momentum of at least one pion to be above 2.0 GeV/c ($p_t^{\pi^1} > 1.5, p_t^{\pi^2} > 2.0$);
- The polar angle of the pions, θ_π , in the B rest frame to be such that $|\cos\theta_\pi| < 0.8$;
- The transverse momentum of the reconstructed B, p_t^B , to exceed 3 GeV/c;
- The momentum vector of the reconstructed B to be consistent with the flight path from the primary to the secondary vertex, such that $\cos\theta_B > 0.95$, where θ_B is the opening angle between these two vectors.

The selection power of some of these cuts can be seen in figure 12.1 where distributions of the variables used in the selection are shown for the signal and $b\bar{b}$ generic background events. The actual efficiencies are given in table 12.1. For the background, the cuts are largely independent. Recall that all these numbers are given without the trigger selection having been applied.

The B mass peak obtained after this selection is shown in figure 12.2. It has a width of 13.6 MeV/c². The final cut was to accept only events within 25 MeV/c² of the B_d mass. This removed 7.6% of the signal. The final selection efficiency, relative to

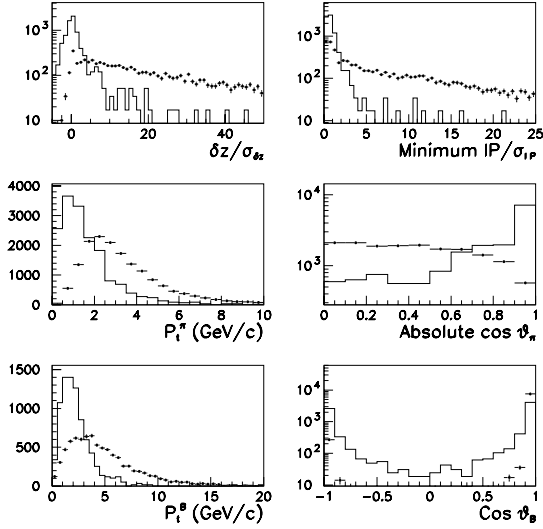


Figure 12.1: Distribution in the key discriminating quantities for $B_d \rightarrow \pi^+ \pi^-$ events (points) and generic $b\bar{b}$ background (solid line). The plots are normalised to the number of preselected events and are made without the trigger selection having been applied.

Cut	$B_d \rightarrow \pi^+ \pi^-$	Generic $b\bar{b}$
Preselection	68.6%	5.4%
Vertex χ^2	88.7%	74.6%
δz	71.0%	8.3%
IP/σ_{IP}	62.3%	2.9%
p_t^π	76.0%	10.5%
$\cos \theta_\pi$	89.7%	43.4%
p_t^B	67.4%	23.4%
$\cos \theta_B$	94.1%	37.4%

Table 12.1: The efficiency of the event cuts on preselected $B_d \rightarrow \pi^+ \pi^-$ events and generic $b\bar{b}$ background. These numbers are given without the trigger selection applied. Also shown is the efficiency of the preselection itself. For the signal this is quoted relative to the geometric acceptance, whereas for the background it is quoted relative to 4π .

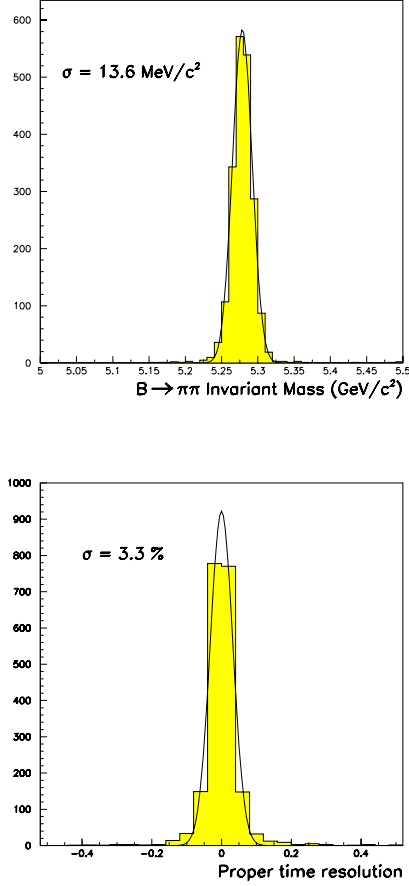


Figure 12.2: Top: $B_d \rightarrow \pi^+ \pi^-$ mass peak after the reconstruction. Bottom: proper time resolution of $B_d \rightarrow \pi^+ \pi^-$ events normalised to the average b lifetime after the reconstruction. The average b -lifetime is taken to be 1.3 ps.

Event class	$\epsilon_{\text{Rec.}}$	$R_{B/S}$
Accepted(loose RICH)	15.6%	-
Triggered(loose RICH)	28.5%	0.59
Triggered(tight RICH)	21.1%	0.38

Table 12.2: The reconstruction efficiency on $B_d \rightarrow \pi^+ \pi^-$ events ($\epsilon_{\text{Rec.}}$) for accepted events, accepted and triggered events, and accepted and triggered events, reconstructed with the tight RICH identification. It also shows the background over signal ratios ($R_{B/S}$).

accepted events, was 15.6%, as is summarised in table 12.2.

Figure 12.2 also shows the proper time resolution of 3.3% obtained on the $B_d \rightarrow \pi^+ \pi^-$ candidates; the corresponding resolution in z on the secondary vertex position is $90 \mu\text{m}$.

In a real experiment, only events triggered can be reconstructed. The reconstruction was rerun on those accepted events satisfying both the Level-1 and Level-2 criteria. On this sample the reconstruction efficiency was determined to be 28.5%. There is a strong positive correlation between the triggers and the reconstruction, given by factors of about 1.6 at Level-1 and 1.3 at Level-2. The effective requirement to have well separated secondary vertices is responsible for the correlation at Level-2. The correlation from Level-1 is dominated by the hadron trigger and arises primarily from the p_t cuts, but also from the tendency of both the trigger and the reconstruction to favour wider angle decays.

Table 12.3 shows the contribution of each trigger to the total sum of triggers for both accepted events, and accepted and triggered events. In the latter category the hadron trigger is present in almost 90% of occasions. It should be remembered however, that these additional events yielded by the hadron trigger do not have the same weight as the events obtained through the lepton triggers. Events triggered by the hadron trigger alone give 30% less tags than events where there is a muon or electron trigger present. The occurrence of wrong tags is also 1.4 times more frequent. This is because of the greater reliance placed on the kaon tag. Detailed discussions on the flavour tag can be found in section 12.3.

Trigger	Accepted	Reconstructed
Muon	23.3%	15.0%
Electron	9.7%	7.9%
Hadron	74.3%	86.9%

Table 12.3: The contribution of each trigger to the total sum of triggers for $B \rightarrow \pi^+ \pi^-$ accepted events and for accepted and reconstructed events. More than one component may contribute to each trigger.

The effect of more stringent particle identification strategies was also investigated. By using particles which are *positively identified* as pions by RICH (tight RICH), the signal efficiency decreased to 21.1% for accepted and triggered events. Even stricter options are available, such as accepting only those tracks which are *inconsistent* with a kaon hypothesis. The additional loss in efficiency makes this approach unattractive, but further studies are necessary.

In figure 12.3 is the reconstructed proper time distribution for the preselected events, the triggered events and the triggered and reconstructed events. Also shown is the acceptance curve against proper time for triggered and reconstructed events with respect to the initial generated events. This has been fitted to a function of the form

$$A(t) \propto \frac{(at)^3}{1 + (at)^3} \quad (44)$$

with $a = 1.10 \pm 0.06 \text{ps}^{-1}$. Above 1.6 ps the acceptance appears flat.

Figure 12.4 shows the momentum and angular distributions of the pions from the selected candidates. The broad momentum spectrum justifies the proposed RICH system of LHC-B.

It is expected that the dominant sources of background for $B_d \rightarrow \pi^+ \pi^-$ will be other rare B decays of the same or similar topology, such as $B_d \rightarrow K^\pm \pi^\mp$ or $B_s \rightarrow K^+ K^-$ and random associations of pairs of tracks in generic $b\bar{b}$ events. Background from non-b events is expected to be small due to the trigger and reconstruction requirements.

Three specific rare modes were investigated: $B_d \rightarrow K^\pm \pi^\mp$, $B_s \rightarrow K^- \pi^+$ and $B_s \rightarrow K^+ K^-$. These were passed through the reconstruction chain. From these results and from assumptions on their branching ratios relative to $B_d \rightarrow \pi^+ \pi^-$ (taken to be 2×10^{-5}) the results in table 12.4 were obtained. The particle identification capabilities of LHC-B, and the good mass resolution, allows the contamination from these channels to be restricted to below 20%. This is clear from figure 12.5 which shows the invariant mass distributions prior to the mass cut for $B_d \rightarrow K^\pm \pi^\mp$ and $B_d \rightarrow \pi^+ \pi^-$. When the alternative, tighter RICH strategy was imposed the contamination level dropped to below 10%. Additional background from other specific decay channels to the three considered have been shown to be negligible in comparison [4].

Because suppression of better than 10^{-6} is required, it is very difficult to directly determine the expected contamination from random associations in generic $b\bar{b}$ events. Indirect means were used to estimate this background.

A sample of 500,000 generic $b\bar{b}$ events was processed through the preselection and event cuts. The mass cut was not applied, but the surviving candidates counted within the wide $5 - 5.5 \text{GeV}/c^2$ mass window. As the background distribution is relatively flat within this interval, extrapolating from here into the narrow $50 \text{MeV}/c^2$ window of the final selection simulated an effective sample of five million events. Again, because of the available statistics, the trigger, apart from the pileup veto, was not applied to the

Channel	BR Relative to Signal	Hadronisation Relative to B_d	Contamination (loose RICH)	Contamination (tight RICH)
$B_d \rightarrow K^\pm \pi^\mp$	1	1	9.6%	5.7%
$B_s \rightarrow K^- \pi^+$	0.5	0.3	0.5%	0.1%
$B_s \rightarrow K^+ K^-$	1	0.3	6.9%	2.4%

Table 12.4: The contamination to the $B_d \rightarrow \pi^+ \pi^-$ reconstruction from the three most important decay modes. The assumed relative branching ratios are stated. The contamination is given for two alternative RICH strategies. (The statistical uncertainty on the $B_s \rightarrow K^- \pi^+$ values are large, and the apparent five fold reduction in contamination for this channel between the strategies is not significant.)

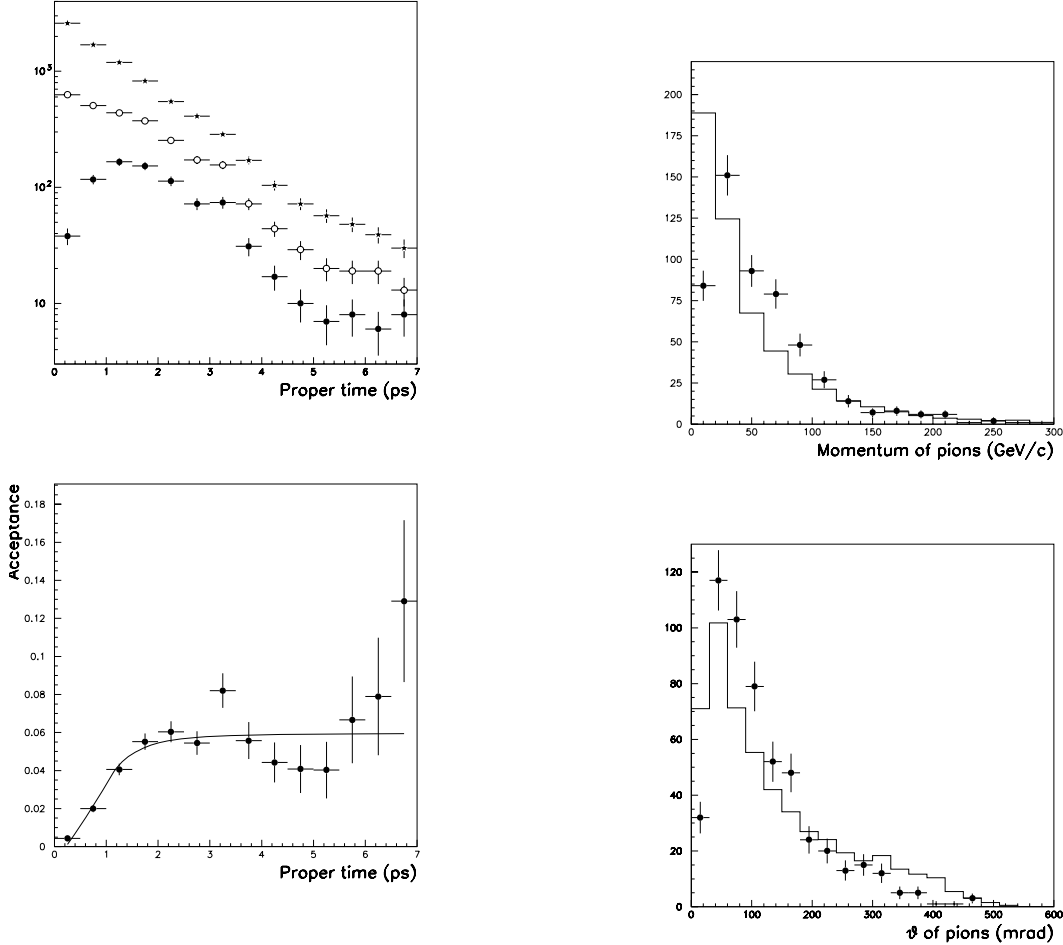


Figure 12.3: Top: reconstructed proper time for $B_d \rightarrow \pi^+ \pi^-$ events at different stages in the selection. Shown is the distribution for preselected events (stars), triggered events (open circles) and triggered and reconstructed events (closed circles). The effect of the topology trigger and of the reconstruction cuts at low proper times can be seen. Bottom: acceptance with proper time of triggered and reconstructed events surviving from all events generated within 600 mrad.

Figure 12.4: The momentum (top) and angular (bottom) distributions of the pions from the final sample of triggered and reconstructed $B_d \rightarrow \pi^+ \pi^-$ events (points). Also shown are the equivalent distributions from the sample of all initial events within the acceptance (solid line). The normalisation is arbitrary.

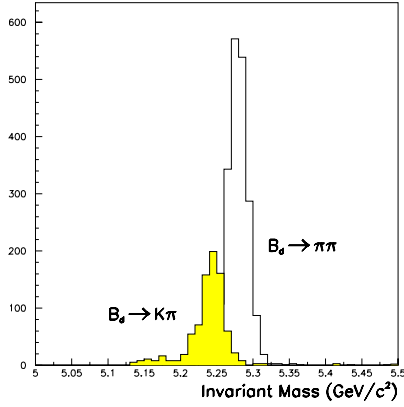


Figure 12.5: The mass peaks for the channels $B_d \rightarrow \pi^+\pi^-$ and $B_d \rightarrow K^\pm\pi^\mp$ reconstructed under the $B_d \rightarrow \pi^+\pi^-$ hypothesis. The $B_d \rightarrow K^\pm\pi^\mp$ contribution has been suppressed by the particle identification requirements. A cut on the invariant mass gives substantial additional rejection.

sample. It was assumed that the correlation between the individual triggers and the reconstruction would be the same for the background as for signal events. The Level-1 trigger efficiency on preselected events was measured, and found to be 6.0%, 2.9% and 3.3% for the muon, electron and hadron triggers respectively, and 11.5% in total – that is about half the efficiency of that obtained on the signal events, a factor essentially due to the hadron trigger. There was no significant difference between the Level-2 performance on these events and on accepted $B_d \rightarrow \pi^+\pi^-$. From this it was calculated that the signal enrichment coming from the trigger was 2.2.

After the reconstruction only 2 events remained within the wide mass window, corresponding to an efficiency for the background of 0.4×10^{-6} . This yields a signal to (generic) background ratio of 2.5. Including the contribution from the specific B modes mentioned before gives signal to background of 1.7.

When the stricter RICH identification was imposed, no background events remained. This implies a signal to (generic) background ratio of better than 3.5, and signal to all background of better than 2.6. The background over signal ratios and reconstruction efficiencies are summarised in table 12.2

Because of the limited statistics, proper optimisation of the cuts was not feasible and other potentially powerful cuts could not be investigated; for instance the requirement that the pions not be associated to another vertex, in addition to the candidate

B_d . Therefore, the above estimates are conservative.

12.2.2 The $B^0(J/\psi K_S)$ final state

The reconstruction of $B \rightarrow J/\psi K_S$ decays proceeds as follows. Firstly, J/ψ is reconstructed from lepton pairs. When J/ψ candidates are present, we look for K_S decays. Finally, they are combined to make B-mesons. Fig. 12.6 shows distributions of some variables used to select candidates for real signals and backgrounds. They demonstrate the selection power of the cuts used in the following steps.

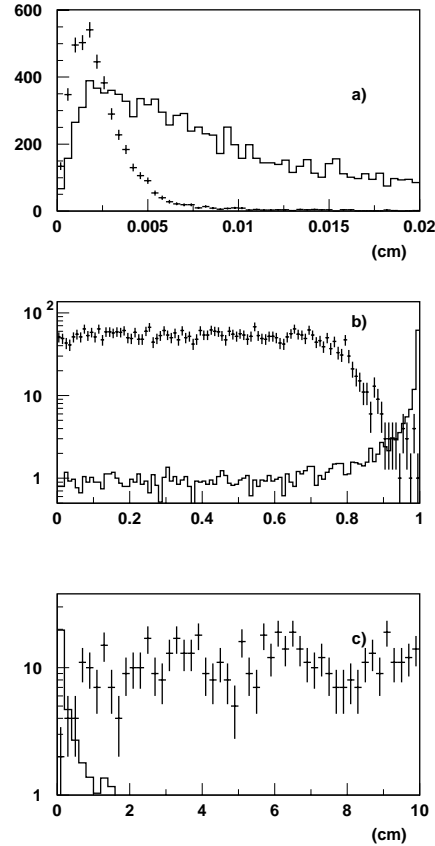


Figure 12.6: Distributions of three variables used to select $B_d \rightarrow J/\psi K_S$ decays: (a) B impact parameter, (b) $|(I_1 - I_2)/(I_1 + I_2)|$ where I 's are the impact parameters of two pions which form the K_S^0 and (c) decay distance of K_S^0 . Signal events are shown by the points with error bars and the background events are by the histograms.

For J/ψ reconstruction, two oppositely charged muons or electrons are combined. In order to ensure a good vertex resolution, both leptons have to

be reconstructed in the silicon vertex detector and the χ^2 of the vertex fit has to be less than 4. The J/ψ produced at the primary vertex is rejected by requiring the longitudinal distance between the primary and J/ψ vertices to be $> 500 \mu\text{m}$. Figure 12.7 shows the invariant mass distributions for $\mu^+\mu^-$ pairs (a) and e^+e^- (b) pairs before and after all the cuts. For the muon pairs, the mass resolution of the J/ψ peak is $8.1 \text{ MeV}/c^2$. The muon pairs having invariant masses within $\pm 23 \text{ MeV}/c^2$ of the nominal J/ψ mass are accepted to make B-mesons. The J/ψ signal reconstructed from e^+e^- has a long tail to the lower mass region due to energy losses. The mass window for this decay mode is $+23 \text{ MeV}/c^2$ and $-50 \text{ MeV}/c^2$ from the nominal J/ψ mass.

For the reconstruction of K_S , two oppositely charged particles compatible with pions are combined. In order to reject pions from the primary vertex, a cut is applied

$$\left| \frac{I_1 - I_2}{I_1 + I_2} \right| < 0.85$$

where I_1 and I_2 are the impact parameters of the two pions. The distance between the primary and K_S decay vertices is required to be $> 5 \text{ cm}$. Since the momentum measurement is needed, the decay volume of the K_S ends at the middle plane of the spectrometer dipole (4.2 m from the interaction point). Figure 12.7 shows the invariant mass plot for selected K_S candidates. The mass resolution is $4.3 \text{ MeV}/c^2$. We accept candidates with masses $\pm 12 \text{ MeV}/c^2$ from the nominal K_S mass.

After combining the J/ψ and K_S , the J/ψ decay vertex is considered as the B decay vertex. Since B-mesons come from the primary vertex, the impact parameter of the reconstructed B is required to be $< 100 \mu\text{m}$. Figure 12.7-d shows the mass distribution for B-mesons where J/ψ is reconstructed from muons. The mass resolution is $7 \text{ MeV}/c^2$. Figure 12.7-e shows the mass distribution for B-mesons with a mass resolution of $9 \text{ MeV}/c^2$ where J/ψ is reconstructed from e^+e^- .

We accept only those B-mesons with their masses $\pm 20 \text{ MeV}/c^2$ from the nominal B-meson mass. After all the cuts, 38% of geometrically accepted and triggered $B \rightarrow J/\psi K_S$ events with $J/\psi \rightarrow \mu^+\mu^-$ remained and 10% for $J/\psi \rightarrow e^+e^-$.

Let us summarise the cuts applied;

- Lepton pair required to be measured by the vertex detector.
- $\chi^2(\text{J}/\psi \text{ vertex}) < 4$.
- $z(\text{primary}) - z(\text{J}/\psi) > 500 \mu\text{m}$.

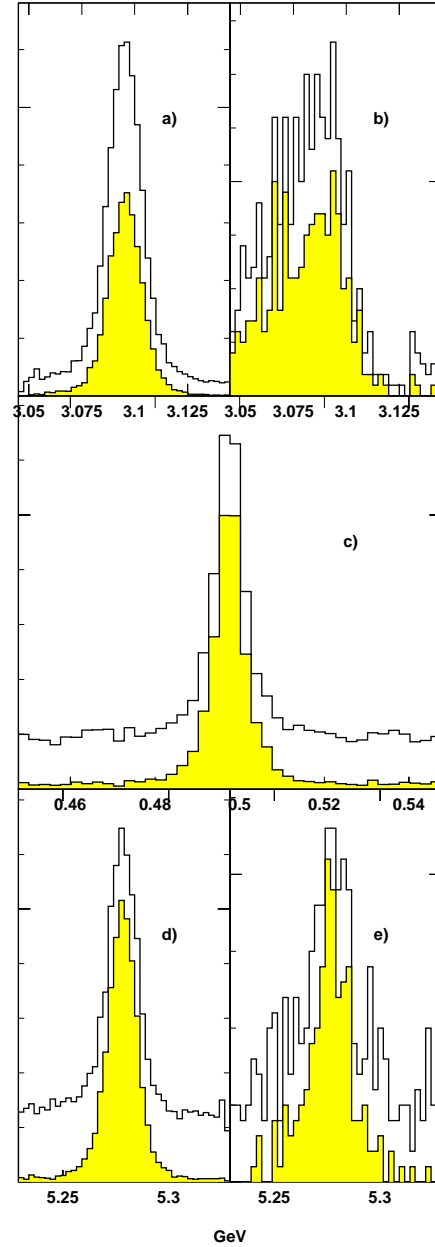


Figure 12.7: Invariant mass distributions for reconstructed J/ψ from $\mu^+\mu^-$ (a) and e^+e^- (b), K_S (c) and B-mesons with $J/\psi(\mu^+\mu^-)$ (d) and with $J/\psi(e^+e^-)$ (e) in $2.5 \text{ MeV}/c^2$ mass bin before and after the cuts described in the text.

- mass window(J/ψ) = ± 23 MeV/ c^2 for $\mu^+\mu^-$ and $+23$ MeV/ c^2 and -50 MeV/ c^2 for e^+e^- .
- pion impact parameter cut $\left| \frac{I_1 - I_2}{I_1 + I_2} \right| < 0.85$.
- decay length(K_S^0) > 5 cm.
- mass window(K_S^0) = ± 12 MeV/ c^2 .
- Impact parameter(B) < 100 μm .
- mass window(B) = ± 20 MeV/ c^2 .

The B decay vertex resolution is determined to be 123 μm . Figure 12.8 shows the B decay time resolution as a function of the B decay time. The average is $\sigma(t_B) = 0.045$ ps.

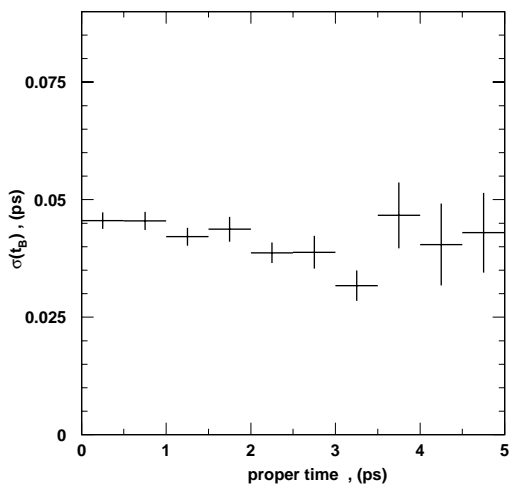


Figure 12.8: Decay time resolutions for the reconstructed $B \rightarrow J/\psi K_S$ as a function of the decay time.

Figure 12.9 shows the ratios for the reconstructed number of $B \rightarrow J/\psi K_S$ over the number of generated events as a function of the proper time. The proper time dependence can be parameterized by equation 44 with $a = 1.65 \pm 0.13$ ps $^{-1}$.

The major source of background is an accidental combination of a real J/ψ with a real K_S . These J/ψ 's produced at the primary vertex are largely rejected by the cut in the longitudinal distance between the primary and J/ψ vertices. Therefore, the background was studied using the $B \rightarrow J/\psi K_S$ events, where J/ψ was combined with other K_S candidates in the event. The number of background events in this analysis is

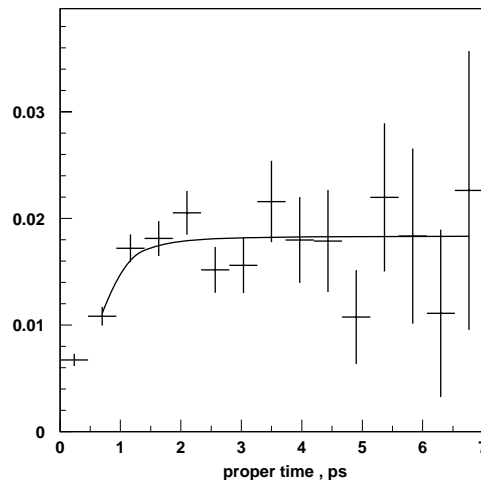


Figure 12.9: Ratios of the reconstructed $B \rightarrow J/\psi K_S$ over generated events as a function of the decay time.

then multiplied by the ratio of the branching fraction for $B \rightarrow J/\psi + \text{anything}$ over that for $B \rightarrow J/\psi K_S$ and compared with the number of reconstructed real $B \rightarrow J/\psi K_S$ decays. In this way, we obtain for both $J/\psi \rightarrow \mu^+\mu^-$ and $\rightarrow e^+e^-$ a background over signal ratio, $R_{B/S}$, of 0.3. In table 12.5, the conclusions of this reconstruction study are summarised.

12.2.3 The $B_s(J/\psi\phi)$ and $B_d(J/\psi K^{*0})$ final states

Reconstruction of the $B_s \rightarrow J/\psi\phi$ decay is very similar to that of the $B^0(J/\psi K_S)$ decay. The J/ψ is first reconstructed from the lepton pair using similar selection criteria. Since four charged tracks originate from the B vertex, the leptons are not required to have a good measurement in the silicon vertex detector. For the ϕ reconstruction, two oppositely charged particles, identified by the RICH as being consistent with kaons, are combined. The following cuts are applied for rejecting kaons from the primary vertex and selecting ϕ :

- Kaon impact parameter cut $\left| \frac{I_1 - I_2}{I_1 + I_2} \right| < 0.9$.
- Distance between primary and ϕ decay vertices $> 500\mu\text{m}$.
- Mass window (ϕ) = ± 12 MeV/ c^2 .

K_S	
eff.(K_S)	0.67
$\sigma(m_{K_S})$	4.3 MeV/ c^2
$\mu^+\mu^-$	
eff.(J/ψ)	0.63
$\sigma(m_{J/\psi})$	8.1 MeV/ c^2
eff.(B total)	0.38
$\sigma(m_B)$	7 MeV/ c^2
e^+e^-	
eff.(J/ψ)	0.18
$\sigma(m_{J/\psi})$	12 MeV/ c^2
eff.(B total)	0.1
$\sigma(m_B)$	9 MeV/ c^2
$\sigma(t_B)$	0.045 ps
$R_{B/S}$	0.3

Table 12.5: Summary of the reconstruction quality; reconstruction efficiencies relative to the accepted and triggered events, mass resolutions, B-meson proper time resolution and background over signal ratio for the B-meson.

Finally, the B_s meson is found by combining J/ψ and ϕ . The mass window is set to ± 20 MeV/ c^2 and B_s impact parameter $< 100\mu\text{m}$. At least two of four particles in the final state are required to be detected in the silicon vertex detector. The reconstruction quality is summarized in table 12.6. Since four charged tracks form the B_s decay vertex, the longitudinal vertex resolution is better than that for the $J/\psi K_S$ final state ($115\mu\text{m}$). The decay time resolution is $\sigma(t_B) = 0.036$ ps.

The proper time dependence for the ratio of the number of reconstructed events over the number of generated events can be parameterized by equation 44 with $a = 1.24 \pm 0.07$ ps $^{-1}$.

Assuming that most of the background arises from accidental combinations of real J/ψ and ϕ , the background to signal ratio can be estimated by studying the $B_s \rightarrow J/\psi\phi$ event sample. This gives $R_{B/S}$ of 0.04 for both $J/\psi \rightarrow \mu^+\mu^-$ and e^+e^- decay modes.

The $B_d \rightarrow J/\psi K^{*0}$ final state has an identical topological structure to $B_s \rightarrow J/\psi\phi$ with four charged tracks from the B-meson decay vertex. However, the sub-mass constraint on K^{*0} is not as good as for ϕ due to the wide K^{*0} natural width. The background is also worse for $B_d \rightarrow J/\psi K^{*0}$, since there are many more $K\pi$ combinations which satisfy the cuts than KK combinations do. The simulation study shows that for the same reconstruction efficiencies as $B_s \rightarrow J/\psi\phi$, we obtain a background to signal ratio of 0.5.

ϕ	
eff.(ϕ)	0.70
$\sigma(m_\phi)$	3.3 MeV/ c^2
$\mu^+\mu^-$	
eff.(J/ψ)	0.68
$\sigma(m_{J/\psi})$	8.1 MeV/ c^2
eff.(B total)	0.42
$\sigma(m_B)$	5.8 MeV/ c^2
e^+e^-	
eff.(J/ψ)	0.21
$\sigma(m_{J/\psi})$	11.2 MeV/ c^2
eff.(B total)	0.12
$\sigma(m_B)$	7.4 MeV/ c^2
$\sigma(t_B)$	0.036 ps
$R_{B/S}$	0.04

Table 12.6: Summary of the reconstruction quality; reconstruction efficiencies relative to the accepted and triggered events, mass resolutions, B-meson proper time resolution and signal over background ratio for the B-meson.

12.2.4 The $B_s(D_s\pi)$ and $B_s(D_sK)$ final state

The channel $B_s \rightarrow D_s\pi$ was chosen for a study of B_s - \bar{B}_s oscillations. The reactions in which the D_s decays into all-charged final states:

$$D_s^\pm \rightarrow \phi\pi^\pm \quad ; \quad \phi \rightarrow K^+K^- \quad (45)$$

$$D_s^\pm \rightarrow K^*K^\mp \quad ; \quad K^* \rightarrow K^+\pi^- \quad (46)$$

are readily accessible in LHC-B.

The topologically similar decays $B_s \rightarrow D_s^\pm K^\mp$, together with their charge conjugate processes, provide a method of measuring the angle γ . Although the physics motivation is different, the reconstruction strategies are similar and we describe both $B_s \rightarrow D_s\pi$ and $B_s \rightarrow D_sK$ together in this section.

Full simulation studies of the production and decay chains:

$$B_s \rightarrow D_s^- K^+ / D_s^- \pi^+ \quad ; \quad D_s^- \rightarrow \phi\pi^- \quad ; \quad \phi \rightarrow K^+K^-$$

were performed. Samples of ~ 30000 events were generated for both decay modes. Events, within the geometrical acceptance and satisfying the Level-1 and Level-2 trigger conditions, were subjected to reconstruction cuts, designed to remove backgrounds.

The rms precision obtained in reconstruction of the sub-masses was 4 MeV/ c^2 (ϕ), 6 MeV/ c^2 (D_s) and 8.5 MeV/ c^2 (B_s). The rms precision in measurement of the vertex z -coordinates was 70 μm for the primary vertex and 160 μm for the B_s vertex. These values

provide a resolution of 0.042 ps for the B_s proper time (see Fig. 12.10).

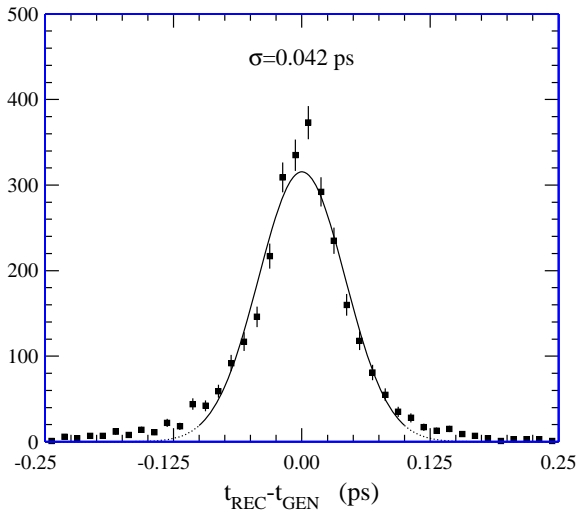


Figure 12.10: Reconstructed proper time resolutions of the observed B_s decay.

The method of the event selection used for the two channels was, in principle, the same, though the precise details differ. Cuts were applied (at $\pm 3\sigma$) to the ϕ , D_s and B_s mass distributions, on the quality of vertex reconstruction and on good separation between primary and secondary vertices. All final-state K's were required to be positively identified by the RICH detectors.

After applying these cuts we determine a reconstruction efficiency (relative to the number of events within the LHC-B acceptance and satisfying the trigger) of 0.42 for $B_s \rightarrow D_s\pi$ and 0.36 for $B_s \rightarrow D_sK$. The values differ since the cuts were not identical: for the $B_s \rightarrow D_sK$ channel one additional kaon requires a RICH identity and a B_s mass window of $\pm 10 \text{ MeV}/c^2$ is used ($\pm 25 \text{ MeV}/c^2$ for the $B_s \rightarrow D_s\pi$). This last cut improves the background rejection, which is more critical in D_sK than in $D_s\pi$, as described below.

The time dependence of the reconstruction efficiency is given by the acceptance function $A(t)$ defined by equation 44 with $2.34 \pm 0.18 \text{ ps}^{-1}$.

Two sources of background are common to both channels: combinatoric background, from the same event, and background from generic $b\bar{b}$ -events. In the combinatoric, same-event, background a B_s is reconstructed using the wrong track combination from a good event. The simulation indicated this to be small ($< 1\%$ of the signal).

Due to the small branching fractions of the signal decay channels a very large sample of simulated generic $b\bar{b}$ -events is required before a reliable esti-

mate of background is possible. By relaxing the trigger requirements (but not the pile-up veto), and accepting “ B_s ” in a wide mass window we used “effective” samples of 2.5×10^7 and 6×10^7 events, respectively for the background studies of the $D_s\pi$ and D_sK channels. Assuming that the background is uniform within the wide B_s mass windows, and taking into account the branching fractions, acceptances and reconstruction efficiencies, we obtain no background events compared with 6 $D_s\pi$ signal events and 1.1 D_sK signal events. This means that our current estimates of backgrounds are respectively, $< 16\%$ and $< 90\%$ compared with the signals in the $D_s\pi$ and D_sK channels. These backgrounds can surely be further reduced, by using cuts on individual track impact parameter, and on pointing constraints, similar to those used in the $B \rightarrow \pi\pi$ analysis. Since no events survive the existing cuts we need to increase our simulated sample before these can be exploited.

A potential source of background to $B_s \rightarrow D_sK$ arises from the $B_s \rightarrow D_s\pi$ decay when the π is taken as a K. This is illustrated in Fig. 12.11. The latter channel has a branching fraction $\times 10$ that of the signal channel and the importance of the RICH is evident. Combinations misidentified by the RICH are further reduced to an insignificant level by the $\pm 10 \text{ MeV}/c^2$ mass window applied in the B_s selection.

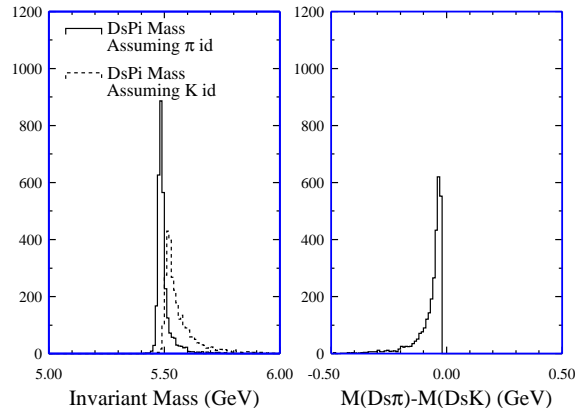


Figure 12.11: a) A comparison of the invariant mass distribution of a $D_s\pi$ in the case that the pion is correctly identified and in the case where the pion is assumed to be a kaon. b) The mass difference between the two assumptions.

The numbers used for calculating the physics “reach” in measurements of x_s and of $\sin \gamma$ are summarised in table 12.7.

	$B_s \rightarrow D_s \pi$	$B_s \rightarrow D_s K$
$\epsilon_{\text{Rec.}}$	0.42	0.36
$\sigma(m_{D_s})$	5.5 MeV/c ²	6.6 MeV/c ²
$\sigma(m_{B_s})$	8.4 MeV/c ²	8.5 MeV/c ²
$\sigma(t_{B_s})$	0.042 ps	0.036 ps
$R_{B/S}$	< 0.16	< 0.9

Table 12.7: Summary information on $B_s \rightarrow D_s \pi$ and $B_s \rightarrow D_s K$ reconstruction qualities. The reconstruction efficiency is calculated with respect to the accepted and triggered events.

12.2.5 The $B^0(\bar{D}^0 K^{*0})$ Final State

In this section, the decay channels

$$\begin{aligned} B^0 &\rightarrow \bar{D}^0 K^{*0}(892) \\ B^0 &\rightarrow D^0 K^{*0}(892) \\ B^0 &\rightarrow D_1^0 K^{*0}(892) \end{aligned}$$

used to extract γ are studied.

The D and K^{*0} decays that have been considered so far are \bar{D}^0 and $K^{*0}(892)$ decay into $K^+ \pi^-$ and D_1^0 into $\pi^+ \pi^-$ or $K^+ K^-$.

The track set found by the reconstruction program is searched to find the decays of interest. The criteria imposed on the accepted and triggered events are:

- the events must contain a primary vertex
- the events must contain a good $\bar{D}^0 \rightarrow K^+ \pi^-$ (or $D_1^0 \rightarrow \pi^+ \pi^-$ or $K^+ K^-$). The K and π must be positively identified and the reconstructed $K\pi$ mass has to be within 11 MeV/c² of the D^0 mass. The $K\pi$ tracks must form a good vertex with $\chi^2 \leq 10$.
- the events must contain a good $K^{*0} \rightarrow K^+ \pi^-$ where the K and π must be positively identified, the $K\pi$ combination must have a mass within 33 MeV/c² of the $K^*(892)$ mass and the $K\pi$ tracks form a good vertex with $\chi^2 \leq 10$.
- the $K^{*0} \bar{D}^0$ mass combination must be within 18 MeV/c² of the B^0 mass and the K , π and D tracks must form a good vertex with $\chi^2 \leq 10$ well separated from the primary vertex.
- the B , D and primary vertices must be separated from each other according to the following criteria;

$$\begin{aligned} z_B - z_{\text{primary}} &\geq 0.05 \text{ cm}, \\ 0 \text{ cm} &\leq z_D - z_B \leq 3 \text{ cm}, \\ 0.05 \text{ cm} &\leq \Lambda_B \leq 3.0 \text{ cm} \end{aligned}$$
 where Λ_B is the B decay length.

The $\bar{D}^0 K^+ \pi^-$ mass distribution for events containing a $B^0 \rightarrow \bar{D}^0 K^{*0}(892)$ decay is shown in Fig. 12.12. The \bar{D}^0 is required to meet all the criteria listed above. The upper histogram shows all $\bar{D}^0 K^+ \pi^-$ combinations whereas the shaded histogram shows the effect of demanding that the $K^+ \pi^-$ be in the $K^{*0}(892)$ mass region and form a good vertex. No vertex separation cuts have yet been imposed on the events shown.

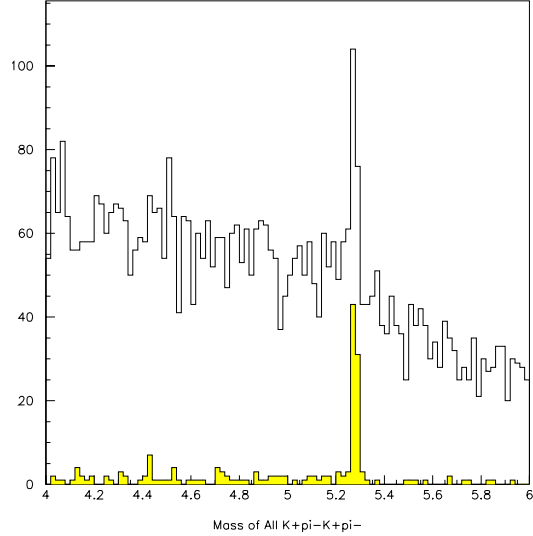


Figure 12.12: The upper histogram shows the invariant mass distribution of $\bar{D}^0 K^+ \pi^-$. The invariant mass distribution of $\bar{D}^0 K^{*0}$ is given by the shaded one.

The mass resolutions are summarized in Table 12.8 below.

Meson	Mass Resolution
$K^{*0}(892)$	3.3 MeV/c ²
\bar{D}^0	7.0 MeV/c ²
B^0	12.0 MeV/c ²

Table 12.8: Mass Resolutions for $K^{*0}(892)$, \bar{D}^0 and B^0 Mesons

The top left and the top right of fig. 12.13 show the reconstructed $\bar{D}^0 \rightarrow K^+ \pi^-$ and $B^0 \rightarrow \bar{D}^0 K^{*0}(892)$ decay length distributions.

Table 12.9 gives the percentage of these events that contain the D , K^{*0} and B mesons which survive the various reconstruction criteria. We have processed 15 k, 15 k and 13.5 k decays of the three topologies $B \rightarrow K^{*0} \bar{D}(D_1)$ where the $\bar{D}(D_1)$ decays to

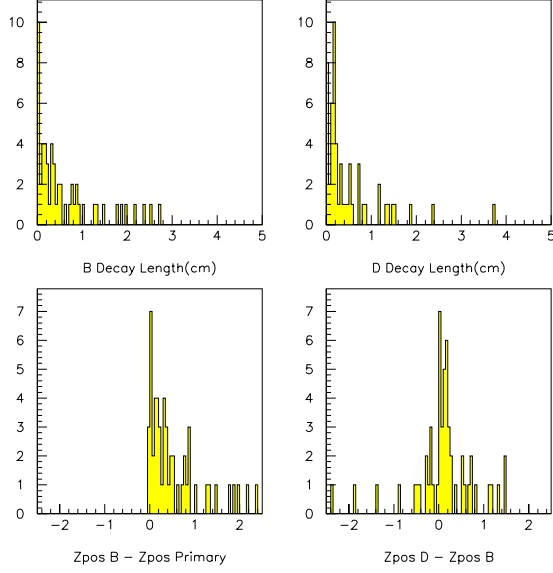


Figure 12.13: The top left and top right show B^0 and \bar{D}^0 reconstructed decay length distributions and the bottom left and bottom right z separation of B and primary vertices and z separation of D and B vertices.

$K^+\pi^-$ ($\pi^+\pi^-$ or K^+K^-) to obtain these efficiencies. The efficiencies are quoted for the subset of the three event topologies which survive the acceptance and first and second level trigger requirements imposed by the LHCb spectrometer.

The backgrounds to the B decays of interest are expected to come mainly from other b hadron decays. We have studied these backgrounds by processing 86.6 k “generic” $b\bar{b}$ events through the same trigger and reconstruction process. In order to increase the sensitivity of the background search for these rare B decay modes, we have loosened the mass windows for the $K^{*0}(892)$ to ± 200 MeV/ c^2 and for the D to ± 400 MeV/ c^2 . With these loosened mass windows, we reconstruct no background B events meeting the criteria for the interesting decay chains types in a mass region within -0.5 GeV/ c^2 and $+1.0$ GeV/ c^2 of the B mass from the 86.6 k generic $b\bar{b}$ events. Under the hypothesis that events this far from the K^{*0} , D^0 and B^0 masses have the same probability for surviving the trigger and reconstruction process as the real decay chains, we have, thus far, been able to establish the upper limits on background over signal ratios given in Table 12.10. The background study is still ongoing and we expect to be able to achieve limits of ≤ 1 .

B Decay Mode	Assumed BR's	$R_{B/S}$
$B^0 \rightarrow \bar{D}^0 K^{*0}(892)$	$3.0 \cdot 10^{-5}$	$\leq 7/1$
$\bar{D}^0 \rightarrow K^+ \pi^-$	$4.0 \cdot 10^{-2}$	
$K^{*0}(892) \rightarrow K^+ \pi^-$	$6.7 \cdot 10^{-1}$	
Cumulative BR	$8.0 \cdot 10^{-7}$	
$B^0 \rightarrow D^0 K^{*0}(892)$	$1.0 \cdot 10^{-5}$	$\leq 20/1$
$D^0 \rightarrow K^- \pi^+$	$4.0 \cdot 10^{-2}$	
$K^{*0}(892) \rightarrow K^- \pi^+$	$6.7 \cdot 10^{-1}$	
Cumulative BR	$2.7 \cdot 10^{-7}$	
$B^0 \rightarrow D_1^0 K^{*0}(892)$	$3.5 \cdot 10^{-5}$	$\leq 630/1$
$D_1^0 \rightarrow \pi^+ \pi^-$	$1.6 \cdot 10^{-3}$	
$K^{*0}(892) \rightarrow K^+ \pi^-$	$6.7 \cdot 10^{-1}$	
Cumulative BR	$3.8 \cdot 10^{-8}$	
$B^0 \rightarrow D_1^0 K^{*0}(892)$	$3.5 \cdot 10^{-5}$	$\leq 40/1$
$D_1^0 \rightarrow K^+ K^-$	$4.4 \cdot 10^{-3}$	
$K^{*0}(892) \rightarrow K^+ \pi^-$	$6.7 \cdot 10^{-1}$	
Cumulative BR	$1.0 \cdot 10^{-7}$	

Table 12.10: Estimated background over signal ratio ($R_{B/S}$) for $B \rightarrow K^{*0}(892)$, $K^{*0}(892)\bar{D}^0$ and D_1^0 Modes based on presently available number of processed Monte Carlo events. For the branching fractions of $B \rightarrow D_1 K^{*0}$, $\gamma = 20^\circ$ and $\Delta = 10^\circ$ are assumed.

The branching ratios quoted for the B decays in Table 12.10 are those appropriate to $\gamma=20$ degrees and $\Delta=10$ degrees. The branching ratio for the decay $\bar{D}^0 \rightarrow D_1^0 \bar{K}^{*0}(892)$ differs by only five percent from the the branching ratio for $B^0 \rightarrow D_1^0 K^{*0}(892)$ at this γ and Δ so the background to signal ratios for decays into $D_1^0 \bar{K}^{*0}$ are very similar to those for $D_1^0 K^{*0}$ decays.

12.3 Flavour Tagging

Knowledge of the initial state flavour of the neutral B-meson is required for a large class of physics topics. If the neutral B-meson is a decay product of an excited state such as $B^{**\pm}$, the charge sign of the accompanying pion can be used as a tag. Although this may provide a very high tagging efficiency, the $B^{**\pm}$ production rate is completely unknown and no reliable estimate can be made. Therefore, we study a conventional method of using the flavour of the accompanying b-hadron to tag the initial flavour of the neutral B-meson under the consideration.

The tagging of the flavour by a full or even partial reconstruction of the b-hadron will be prohibitively inefficient due to small reconstructible branching ratios, geometric acceptance and reconstruction efficiency. Instead, one could rely on the correlation between the charge of the decay leptons and kaons and the flavour of the parent b-hadron. This results

Reconstruction Criteria	Fraction of surviving events with		
	$\bar{D}^0 \rightarrow K^+ \pi^-$	$D_1^0 \rightarrow \pi^+ \pi^-$	$D_1^0 \rightarrow K^+ K^-$
with a good primary vertex	99.1%	99.0%	98.9%
with a good \bar{D}^0 or D_1^0	60.6%	80.0%	69.1%
with \bar{D}^0 or D_1^0 and $K^{*0}(892) \rightarrow K^+ \pi^-$	49.6%	63.3%	54.5%
with a $B^0 \rightarrow \bar{D}^0 K^{*0}$ or $D_1^0 K^{*0}$	28.2%	25.8%	26.4%
Surviving vertex-topology cuts	19.6%	21.1%	17.6%

Table 12.9: Summary of the percentages of accepted and triggered events satisfying the $B \rightarrow DK^*$ criteria

in large tagging efficiencies, but sometimes leads to erroneous tags.

Leptons from direct b-hadron decay are most easily distinguished from other leptons with a p_t -cut while the most effective method to select kaons from b-hadron decays is an impact parameter cut. Tracks from the reconstructed primary vertex and the reconstructed B-mesons are excluded from tag considerations.

The fractions of events tagged by leptons and kaons (tagging efficiency ϵ_{tag}) depend on the Level-1 trigger condition being satisfied and the decay mode under investigation. For example, a large fraction of events is tagged by leptons when the events are triggered by a high- p_t lepton and the B-mesons which are being reconstructed do not produce any lepton.

The initial flavour of the reconstructed B-meson can not be determined perfectly due to various reasons. There are numerous leptons from K and π decays and semi-leptonic charm decays giving wrong sign leptons. $B \rightarrow D_s + X$ decays in general produce two oppositely charge kaons. If the b-hadron providing the tag is B_d or B_s , it can oscillate before it decays, therefore giving a wrong tag. Some of these introduce an irreducible wrong tag rate.

In order to optimise the cut, the tagging efficiency ϵ_{tag} (solid point), the fraction of wrong tag ω (dashed point) and a quality factor defined as $(1 - 2\omega)\sqrt{\epsilon_{tag}}$ (histogram) for events tagged by high- p_t muons were studied. This is shown in Fig 12.14 as a function of muon p_t . In the simulation, the wrong tags due to neutral B-meson oscillations with $x_d = 0.7$ and $x_s = 10$ are included. Based on similar plots for other tagging categories, we conclude that a p_t cut of 1.25 GeV/c for leptons and a 3σ separation of kaons from the primary vertex give the best quality tagged events.

Lepton tags give smaller ω than the kaon tag, we first look for muon tags. Therefore, no muon tag is found then electron tags are searched for. Kaon tags are used only if there is no lepton tag present. The sum of charges of the particles passing the selection cuts is used to tag the flavour.

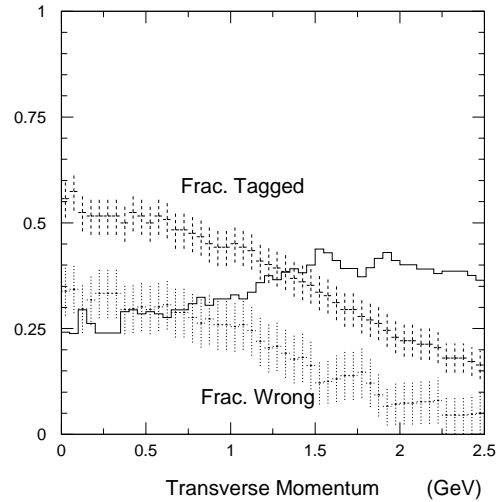


Figure 12.14: The muon tagging efficiency, the wrong tag fraction and tagging quality as a function of p_t for high- p_t muon triggered events.

Table 12.11 shows the tagging efficiencies and wrong tag fractions for events which pass all Level-1 and Level-2 trigger selection and pile-up veto cuts.

Decay mode	$\mu+e+K$ tag	Wrong tag (ω)
$B_d \rightarrow \pi^+ \pi^-$	0.44	0.26
$B_d \rightarrow J/\psi K_s^0$	0.37	0.29
$B_s \rightarrow D_s^- \pi^+$	0.49	0.28

Table 12.11: Tagging efficiencies and fraction of wrong tags for accepted and triggered $B_d \rightarrow \pi^+ \pi^-$, $B_d \rightarrow J/\psi K_s^0$ and $B_s \rightarrow D_s^- \pi^+$ exclusive decay events. Due to the limited statistics of the simulated events, tagging efficiencies and wrong tag fractions have uncertainties of ~ 0.02 .

Due to differences in the Level-1 trigger composition for the signal and control channels, the tagging efficiency and the fraction of the wrong tag for each tag category and trigger has to be evaluated separately. Combining the separately measured CP violation effects for each trigger and tag category leads to a smaller statistical error. However, we use the combined tagging efficiencies and the wrong tag fractions given above in the performance section.

In practice, the fraction of wrong tags has to be determined from control channels which are flavour specific decay modes such as $J/\psi K^{*0}$. Details are discussed in the following section. The wrong tag fraction is also determined in the study of $B_s\text{-}\bar{B}_s$ oscillations as discussed there.

12.4 Control Channels and Systematics

In the extraction of CP violation parameters, if there exists a difference in the production rates between B^0 and \bar{B}^0 , a fake CP violating effect can be introduced. A similar effect can be introduced if there is a difference in tagging efficiencies between b and \bar{b} . As discussed in the previous section, the wrong tag fraction must be known for determination of the CP violation parameters from the measured observable. Additional complications are introduced in the determination if there is a difference in the wrong tag fractions for b and \bar{b} .

Let us define the following quantities;

- n (\bar{n}): number of produced B^0 (\bar{B}^0)
- ϵ_b ($\epsilon_{\bar{b}}$): tagging efficiency for b - (\bar{b})-hadrons.
- ω ($\bar{\omega}$): wrong tag fraction when tagged with b - (\bar{b}) hadrons.

We assume that differences in these quantities for b and \bar{b} are small, i.e. $|\delta_B| \ll 1$, $|\delta_\epsilon| \ll 1$ and $|\delta_\omega| \ll 1$ where

$$\frac{\epsilon_{\bar{b}}}{\epsilon_b} = 1 + \delta_\epsilon, \quad \frac{\omega_{\bar{b}}}{\omega_b} = 1 + \delta_\omega, \quad \frac{\bar{n}}{n} = 1 + \delta_B.$$

Among these quantities, the $B^0\text{-}\bar{B}^0$ normalisation factor, $r_B = (\bar{n} \epsilon_{\bar{b}})/(n \epsilon_b)$, ω and δ_ω are needed for the CP violation studies. The normalisation factor, r_B , can be included as one of the free parameters in the fit when the CP violation parameters are determined. However, this leads to increased statistical uncertainties for the CP parameters. Furthermore, no information on the wrong tag fraction can be obtained from the fit.

Therefore, we intend to use flavour specific final states of the neutral B-meson such as $J/\psi K^{*0}$ and $J/\psi \bar{K}^{*0}$ which indicate whether it was B^0 or \bar{B}^0 at the moment of the decay. Note that those are the decay modes used to study $B\text{-}\bar{B}$ oscillations and no CP violation is expected. For B_d , the study can be done in a decay time integrated way as discussed here. However, a decay time dependent study discussed in the $B_s\text{-}\bar{B}_s$ oscillation section is necessary for B_s due to its rapid oscillation.

The charged B-meson can also be used for studying the wrong tag fraction, the differences in wrong tag fractions and the difference in tagging efficiencies between b - and \bar{b} -hadrons. This is a simpler analysis since the charged B-meson does not oscillate. However, we present here an analysis based on the neutral B-meson in order to keep a similar experimental environment to that for the CP violating decay modes.

We use the following measurements;

- N_b : number of $J/\psi K^{*0}$ events with b -tag
- $N_{\bar{b}}$: number of $J/\psi K^{*0}$ events with \bar{b} -tag
- \bar{N}_b : number of $J/\psi \bar{K}^{*0}$ events with b -tag
- $\bar{N}_{\bar{b}}$: number of $J/\psi \bar{K}^{*0}$ events with \bar{b} -tag

It can be shown that

$$\begin{aligned} r_B &= 1 + \delta_B + \delta_\epsilon \\ &= 1 + (1 + x^2) \left(\frac{\bar{N}_{\bar{b}} + \bar{N}_b}{N_b + N_{\bar{b}}} - 1 \right) \end{aligned}$$

where $x = \Delta m/\Gamma$. In order to simplify the discussion, we obtain

$$\omega = \frac{1}{2} \left[1 - (1 + x^2) \frac{(N_b + \bar{N}_{\bar{b}}) - (\bar{N}_b + N_{\bar{b}})}{(N_b + \bar{N}_{\bar{b}}) + (\bar{N}_b + N_{\bar{b}})} \right]$$

by assuming $\omega = \bar{\omega}$. We also assume that x will be measured much better than now and its error is not taken into account.

Using the expected event yields summarised in table 12.12, we can measure r_B with a statistical accuracy of

$$\sigma_{r_B} = 0.008 \quad (47)$$

and ω with

$$\sigma_\omega = 0.0018 \quad (48)$$

for $\omega = 0.29$.

It must be noted that tagging efficiencies and wrong tag fractions may depend on the trigger. Therefore, they must be studied separately for events triggered by the muon, electron and hadron. Studies with different final states, such as $D^\pm \pi^\mp$, will also be performed to allow further understanding of systematics.

No. of $J/\psi K^{*0} + \text{c.c.}$ produced	$7.1 \cdot 10^8$
$e^+e^- K^\pm \pi^\mp$ accepted and triggered	679 k
$\mu^+\mu^- K^\pm \pi^\mp$ accepted and triggered	1270 k
$e^+e^- K^\pm \pi^\mp$ reconstructed	81 k
$\mu^+\mu^- K^\pm \pi^\mp$ reconstructed	533 k
$\ell^+\ell^- K^\pm \pi^\mp$ tagged	227 k
$R_{B/S}$	0.5

Table 12.12: Expected numbers of $J/\psi K^{*0}$ and $J/\psi \bar{K}^{*0}$ final states in one year and the background over signal ratio $R_{B/S}$

12.5 The B_s - \bar{B}_s Oscillations

12.5.1 Introduction

The channel studied here for the B_s - \bar{B}_s oscillations is $B_s^0 \rightarrow D_s^- \pi^+$. The reactions in which the D_s decays into all-charged final states $D_s^\pm \rightarrow K^\pm K^\mp \pi^\pm$ with a branching fraction of 4.8% are readily accessible in LHC-B. Note that decays proceed mainly through ϕ or K^* .

Assuming that the flavour of the initially produced B_s can be determined through a charge tag on the other B , the decay rate is given as:

$$R_\pm = A(t) \exp(-t/\tau_s) \left[\cosh(y_s t/2\tau_s) \pm (1 - 2\omega) \cos(x_s t/\tau_s) \right] \quad (49)$$

where ω is the wrong tag fraction and τ_s is the B_s -meson lifetime. The acceptance term $A(t)$ reflects a proper time dependent efficiency for triggering and reconstructing the B_s . The term $\cosh(y_s t/2\tau_s)$ represents a possible difference in the lifetime of a heavy and light B_s mass eigenstate, by means of the quantity $y_s = \Delta\Gamma_s/\Gamma_s$, which is expected to be ~ 0.1 in

the standard model. The last term includes the oscillation frequency $x_s = \Delta m_s/\Gamma_s$.

The sensitivity for both x_s and y_s in LHC-B is discussed below. Expected event yields for one year are given in table 12.13.

No. of $B_s \rightarrow D_s^\pm \pi^\mp + \text{c.c.}$	$4 \cdot 10^8$
Accepted and triggered $(K^\pm K^\mp \pi^\pm) \pi^\mp$	171 k
Reconstructed $(K^\pm K^\mp \pi^\pm) \pi^\mp$	72 k
And tagged	35 k
$R_{B/S}$	< 0.16
ω	0.28

Table 12.13: Event yields for $B_s \rightarrow D_s^\mp \pi^\pm$ and $\bar{B}_s \rightarrow D_s^\pm \pi^\mp (\text{c.c.})$ in one year (10^7 s) with a luminosity of $1.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

12.5.2 Determination of x_s , τ_s and y_s

The fits of the decay-time distributions are based on minimizing the negative log likelihood defined as

$$-\mathcal{L} = \sum_{i=1}^N -\log \mathcal{P}_i(x_s, y_s, \tau_s) \quad (50)$$

where the sum runs over all generated events. The quantity $\mathcal{P}_i(x_s, y_s, \tau_s)$ is the probability for a given event i to be observed with parameters x_s, y_s, τ_s . It takes into account the individual proper time error of each event by assigning each event a weight inversely proportional to the error on the reconstructed B_s decay time.

The parameter y_s and the B_s lifetime τ_s are obtained simultaneously by fitting

$$R_u = A(t) \exp(-t/\tau_s) \cosh(y_s t/2\tau_s) \quad (51)$$

to untagged $B_s \rightarrow D_s^\pm \pi^\mp$ events. This fit is also used to study the acceptance function $A(t)$.

In table 12.14, errors on y_s and τ_s obtained from the fits using various input values are shown. Fits were done using 100 k untagged events corresponding to roughly one year of data taking.

For the x_s measurement, a sample of 35 k flavour tagged events expected in one year of data taking is used. The weighted likelihood fit of the decay rate according to equation 49 is done with x_s , the wrong tag fraction ω and the background over signal ratio as free parameters. The background is assumed to be produced by B_d decays. The acceptance function, B_s lifetime and y_s are assumed to be well measured from the first measurement and are kept fixed. Events are generated with a wrong tag fraction of $\omega = 0.25$ and

y_s input value	$\sigma(y_s)$	$\sigma(\tau_s)$ ps
0.40	0.03	0.011
0.20	0.03	0.007
0.15	0.05	0.009
0.10	0.08	0.009

Table 12.14: Errors on $y_s = \Delta\Gamma_s/\Gamma_s$ and τ_s obtained from the fit using 100 k untagged events equivalent to one years of data taking.

x_s input	$\sigma(x_s)$	$\sigma(\omega)$	$\sigma(R_{B/S})$
25	0.016	0.007	0.016
35	0.021	0.008	0.017
45	0.028	0.012	0.017
55	0.049	0.016	0.020

Table 12.15: Errors on x_s , ω and $R_{B/S}$ obtained from the fit for various values of x_s using 35 k events expected in one year of data taking. Events are generated with $\omega = 0.25$ and $R_{B/S} = 0.1$.

a background over signal ratio of $R_{B/S} = 0.1$ close to the values given in table 12.13.

The decay time distributions of the reconstructed events are shown in fig 12.15 for $x_s=25$. The likelihood distributions for the fits using 35 k events are shown in fig 12.16 for input values of $x_s = 25, 35, 45$ and 55. In all cases, a clear minimum at the correct position indicates the validity of the fit. The errors of the three parameters are listed in table 12.15. The errors on x_s depend little on the values of ω and $R_{B/S}$ used in the event generation.

12.6 CP Sensitivities

12.6.1 The angle α

The measured decay time distributions for tagged initial B^0 and \bar{B}^0 into $\pi^+\pi^-$ can be expressed by

$$\begin{aligned} R_{\text{exp}}(t) &= NA(t)e^{-\Gamma_s t} [1 + D_\omega I] \\ \bar{R}_{\text{exp}}(t) &= \bar{N}A(t)e^{-\Gamma_s t} [1 - D_\omega I] \end{aligned}$$

where $D_\omega = 1 - 2\omega$. The wrong tag rate ω and the decay time acceptance for the final state π^+ and π^- , $A(t)$ are assumed to be identical for $R_{\text{exp}}(t)$ and $\bar{R}_{\text{exp}}(t)$. They must be obtained using simulation or(and) data. The term I is given by

$$I = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos \Delta mt - \frac{2Im\lambda}{1 + |\lambda|^2} \sin \Delta mt.$$

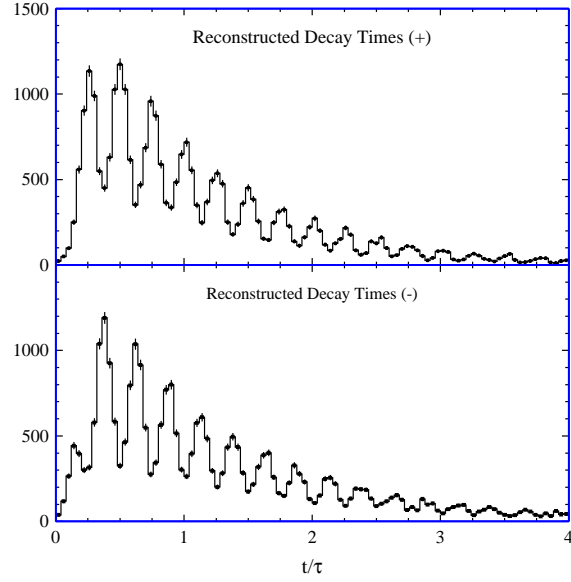


Figure 12.15: Proper time distribution for reconstructed $D^-\pi^+$ with b-tag (top) and for reconstructed $D^-\pi^+$ with \bar{b} -tag (bottom). Events are generated with $x_s = 25$ and $\omega = 0.25$.

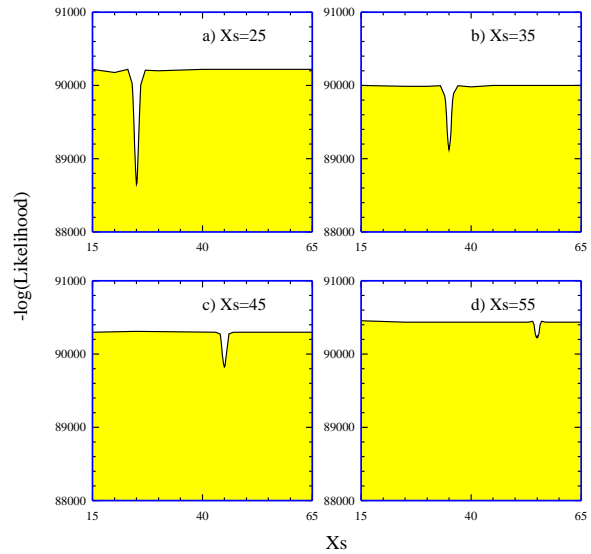


Figure 12.16: The likelihood distribution for x_s input values of a) 25 b) 35 c) 45 d) 55 . Each distribution shows a minimum at the correct x_s value.

In the CP asymmetry defined as

$$A_{\text{CP}}(t) = \frac{R_{\text{exp}}(t) - r_{\text{B}} \overline{R}_{\text{exp}}(t)}{R_{\text{exp}}(t) + r_{\text{B}} \overline{R}_{\text{exp}}(t)} \quad (52)$$

the final state acceptance cancels and the CP violating interference term is isolated. The CP parameter λ can be obtained by fitting a function

$$D_{\omega} \left(\frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos \Delta mt - \frac{2 \text{Im} \lambda}{1 + |\lambda|^2} \sin \Delta mt \right)$$

to the observed CP asymmetry. The normalisation parameter r_{B} can be left free in the fit. However, we constrain it to a value obtained from the control channels as explained in the previous section.

Using the trigger, reconstruction and tagging efficiencies as stated earlier, expected event yields in one year (10^7 s) are summarised in table 12.16.

No. of $\text{B}^0 \rightarrow \pi^+ \pi^- + \text{c.c.}$	$9 \cdot 10^6$
And accepted and triggered	110 k
And reconstructed	31 k
And tagged	14 k
$R_{\text{B}/s}$	0.59
ω	0.26

Table 12.16: Event yields for B^0 and $\overline{\text{B}}^0 \rightarrow \pi^+ \pi^-$ in one year (10^7 s) with a luminosity of $1.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

From the fit, we obtain errors of 0.038 for $|\lambda|$ and 0.041 for $\text{Im} \lambda$ where events are generated with no CP violation. The errors include statistical errors coming from $\text{B} \rightarrow \pi^+ \pi^-$ sample (0.038 for $|\lambda|$ and 0.035 for $\text{Im} \lambda$) and from the relative normalisation obtained with the control sample. They include also the statistical fluctuation of the background. The uncertainty in the wrong tag fraction, obtained from the control sample, introduces an additional fractional error of 0.9% to both $|\lambda|$ and $\text{Im} \lambda$. Contributions from the other sources of systematic error such as the decay time resolution are found to be negligible. In conclusion, we obtain

$$\begin{aligned} \sigma_{|\lambda|} &= 0.038 \oplus 0.009 \times |\lambda| \\ \sigma_{\text{Im} \lambda} &= 0.041 \oplus 0.009 \times \text{Im} \lambda \end{aligned}$$

where the two error contributions have to be added in quadrature.

If the penguin diagram can be neglected in the $\text{B} \rightarrow \pi^+ \pi^-$ decay amplitude, it follows that $|\lambda| = 1$ and $\text{Im} \lambda = \sin 2\alpha$. By fixing the value of $|\lambda|$ to 1 in the fit, we obtain

$$\sigma_{\sin 2\alpha} \equiv \sigma_{\text{Im} \lambda} = 0.039 \oplus 0.005 \times \sin 2\alpha. \quad (53)$$

The statistical error for the $\text{B} \rightarrow \pi^+ \pi^-$ sample alone is 0.03. Again the second term is due to the uncertainty in the wrong tag fraction.

12.6.2 The angle β

Using the already stated trigger, reconstruction and tagging efficiencies, event yields for $\text{B} \rightarrow \text{J}/\psi \text{K}_S$ are summarised in table 12.17.

No. of $\text{B}^0 \rightarrow \text{J}/\psi \text{K}_S + \text{c.c.}$	$2.3 \cdot 10^8$
$e^+ e^- \pi^+ \pi^-$ accepted and triggered	183 k
$\mu^+ \mu^- \pi^+ \pi^-$ accepted and triggered	340 k
$e^+ e^- \pi^+ \pi^-$ reconstructed	18 k
$\mu^+ \mu^- \pi^+ \pi^-$ reconstructed	130 k
$\ell^+ \ell^- \pi^+ \pi^-$ tagged	55 k
$R_{\text{B}/s}$	0.3
ω	0.29

Table 12.17: Event yields for B^0 and $\overline{\text{B}}^0 \rightarrow \text{J}/\psi \text{K}_S$ in one year (10^7 s) with a luminosity of $1.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

Since the contribution from the penguin diagram is expected to be very small in the $\text{B} \rightarrow \text{J}/\psi \text{K}_S$ decay amplitude, we assume $|\lambda| = 1$ and $\text{Im} \lambda = \sin 2\beta$. From the fit of

$$D_{\omega} \sin 2\beta \sin \Delta mt$$

to the observed CP asymmetry with $\text{B} \rightarrow \text{J}/\psi \text{K}_S$ events, we obtain

$$\sigma_{\sin 2\beta} = 0.023 \oplus 0.009 \times \sin 2\beta. \quad (54)$$

The statistical error due to $\text{B} \rightarrow \text{J}/\psi \text{K}_S$ sample alone is 0.017 and the second term is due to the uncertainty of the wrong tag fraction.

12.6.3 The angle γ Method-1

One way to measure the angle γ is to use B_s decays into $\text{D}_s^{\pm} \text{K}^{\mp}$. In this study, we use the same maximum likelihood method used for the $\text{B}_s - \overline{\text{B}}_s$ oscillation measurement where the detail of the fit can be found.

For the measured decay time distributions of the initial B_s and $\overline{\text{B}}_s$ decaying into $\text{D}_s^- \text{K}^+$, the following probability distributions are used for the fit;

$$\begin{aligned} P_{\text{D}_s^- \text{K}^+}(t) &= N A(t) e^{-\Gamma_s t} \left(\cosh \frac{y_s}{2} \Gamma_s t \right. \\ &\quad \left. + \frac{2|\lambda| \cos \theta_{\lambda}}{1 + |\lambda|^2} \sinh \frac{y_s}{2} \Gamma_s t + D_{\omega} I \right) \\ \overline{P}_{\text{D}_s^- \text{K}^+}(t) &= \overline{N} A(t) e^{-\Gamma_s t} \left(\cosh \frac{y_s}{2} \Gamma_s t \right. \\ &\quad \left. + \frac{2|\lambda| \cos \theta_{\lambda}}{1 + |\lambda|^2} \sinh \frac{y_s}{2} \Gamma_s t - D_{\omega} I \right) \end{aligned}$$

where the interference term is given by

$$I = \left(\frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos x_s \Gamma_s t - \frac{2|\lambda| \sin \theta_\lambda}{1 + |\lambda|^2} \sin x_s \Gamma_s t \right)$$

The variable Γ_s is the average decay width of the B_s meson, and $y_s = \Delta\Gamma_s/\Gamma_s$ and $x_s = \Delta m_s/\Gamma_s$, where $\Delta\Gamma_s$ and Δm_s are, respectively, the mass and decay width differences of the B_s meson mass eigenstates. The function $A(t)$ describes the acceptance of the reconstructed events. Events are generated with $y_s = 0.1$ and $|\lambda| = 0.71$ for various values of x_s and θ_λ , and λ and $\theta_\lambda = \arg \lambda$ are treated as free parameters in the fit. Since x_s , y_s , ω and the background fractions can be well measured also by LHC-B, they are fixed to the values used for the event generation.

No. of $B_s \rightarrow D_s^\pm K^\mp + c.c.$	$4.4 \cdot 10^7$
Acc. and trig. $(K^\pm K^\mp \pi^\pm)_D K^\mp$	19 k
Reconst. $(K^\pm K^\mp \pi^\pm)_D K^\mp$	6.8 k
Tagged $(K^\pm K^\mp \pi^\pm)_D K^\mp$	3.3 k
$R_{B/s}$	< 0.9
ω	0.25

Table 12.18: Event yields for $B_s \rightarrow D_s^\mp K^\pm$ and $\bar{B}_s \rightarrow D_s^\pm K^\mp$ (c.c.) in one year (10^7 sec) with a luminosity of $1.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

The decay time probability distributions of the initial B_s and \bar{B}_s into $D_s^+ K^-$ are given by

$$P_{D_s^+ K^-}(t) = N' A(t) e^{-\Gamma_s t} \left(\cosh \frac{y_s}{2} \Gamma_s t + \frac{2|\lambda| \cos \theta_\lambda}{1 + |\lambda|^2} \sinh \frac{y_s}{2} \Gamma_s t - D_\omega \bar{I} \right)$$

$$\bar{P}_{D_s^+ K^-}(t) = \bar{N}' A(t) e^{-\Gamma_s t} \left(\cosh \frac{y_s}{2} \Gamma_s t + \frac{2|\lambda| \cos \theta_\lambda}{1 + |\lambda|^2} \sinh \frac{y_s}{2} \Gamma_s t + D_\omega \bar{I} \right)$$

where the interference term is defined as

$$\bar{I} = \left(\frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos x_s \Gamma_s t + \frac{2|\lambda| \sin \theta_\lambda}{1 + |\lambda|^2} \sin x_s \Gamma_s t \right)$$

and $|\lambda|$ and θ_λ are treated as free parameters in the fit.

It must be noted that θ_λ and θ_λ have twofold ambiguities without the term proportional to $\sinh[(y_s/2)\Gamma_s t]$. By having this additional term, we can resolve the ambiguity. Figure 12.17 shows the negative log likelihood distribution of the fit as a function of θ_λ obtained with 10000 events and $x_s = 30$.

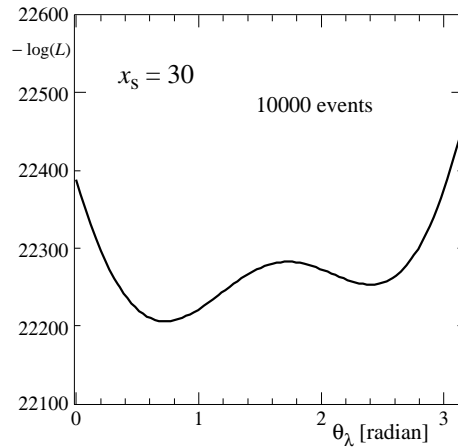


Figure 12.17: The distribution of negative log likelihood as a function of θ_λ for the CP fit with 1000 events with $x_s = 30$.

Although there are two minima, one solution (the correct one) is clearly favoured.

As explained in the chapter describing our physics objective, θ_λ and θ_λ are related to the angle γ as

$$\gamma = \frac{\theta_\lambda - \theta_\lambda}{2}$$

The difference in the strong interaction phase, Δ is given by

$$\Delta = \frac{\theta_\lambda + \theta_\lambda}{2}$$

Table 12.18 summarises the expected event yields for one year of data taking. Although the decay amplitude ratio $|A(B_s \rightarrow D_s^+ K^-)/A(B_s \rightarrow D_s^- K^+)|$ is predicted to be ~ 0.71 , the decay rates for the initial B_s into $D_s^+ K^-$ and into $D_s^- K^+$ are almost identical due to the rapid oscillations.

Clearly we can determine both the unitarity angle γ and the strong interaction phase difference Δ from the data. However, a particular value of Δ must be assumed for giving a sensitivity on γ . At the energy region of the B-meson mass, the strong interaction phase shift is very likely to be small. Thus by assuming $\Delta = 0$, we obtain the errors on γ given in table 12.19 for different values of x_s and γ .

The effect of background to the fit is found to be negligible once the background is known to better than 90%.

12.6.4 The angle γ Method-2

An alternative way of extracting the angle γ from B decays is to compare the branching ratios for decays

	$x_s = 10$	$x_s = 20$	$x_s = 30$
$\gamma = 10^\circ$	$\pm 3.7^\circ$	$\pm 4.4^\circ$	$\pm 5.9^\circ$
$\gamma = 45^\circ$	$\pm 4.2^\circ$	$\pm 5.4^\circ$	$\pm 7.4^\circ$
$\gamma = 80^\circ$	$+9.8^\circ$ -8.1°	$+12.1^\circ$ -10.3°	$+16.2^\circ$ -13.3°

Table 12.19: Expected error on γ for one year of data taking. The value of the difference in the strong interaction phases is assumed to be 0. See Fig. 2.4

of the type (a), (b) or (c), and their CP conjugates (d), (e) and (f):

$$\begin{aligned}
B^0 &\rightarrow \bar{D}^0 X & (a) \\
&\rightarrow D^0 X & (b) \\
&\rightarrow D_{1,2} X & (c) \\
\bar{B}^0 &\rightarrow D^0 \bar{X} & (d) \\
&\rightarrow \bar{D}^0 \bar{X} & (e) \\
&\rightarrow D_{1,2} \bar{X} & (f)
\end{aligned} \tag{55}$$

as explained in physics chapter.

In these reactions, X is different from \bar{X} and $D_{1,2}^0 = (\bar{D} \pm D)/\sqrt{2}$ are CP eigenstates of the D meson. We use the decays

$$B^0 \rightarrow \bar{D}^0 K^{*0}, \quad B^0 \rightarrow D^0 K^{*0}, \quad B^0 \rightarrow D_{1,2} K^{*0}$$

and their charge conjugates. Table 12.20 summarises expected event yields for one year of data taking. The branching fractions for $B^0 \rightarrow D_1 K^{*0}$ and $\bar{B}^0 \rightarrow D_1 \bar{K}^{*0}$ depend on the angle γ and the strong phase difference Δ . We assume $\gamma = 40^\circ$ and $\Delta = 10^\circ$. Note that the branching fractions for $B \rightarrow D_1 K^{*0}$ and $\bar{B} \rightarrow D_1 \bar{K}^{*0}$ depend on γ and the strong interaction phase difference, Δ .

From the measured six decay rates, relative branching ratios must be calculated. We assume that differences in the reconstruction efficiencies for the six decay modes can be well understood and they do not introduce any error. Using the six relative branching fractions, we form the two triangles explained in the physics chapter. Assuming $\Delta = 10^\circ$, the errors on $\sin 2\gamma$ are given in table 12.21

12.6.5 CP violation in $B_s \rightarrow J/\psi\phi$

As discussed in Chapt. 2, CP violation in the decay, $B_s \rightarrow J/\psi\phi$ is expected to be very small in the standard model. By assuming that one CP eigenstate

Produced $B \rightarrow \bar{D}^0 K^{*0} + c.c.$	$1.4 \cdot 10^7$
Acc. + trig. $(K^+ \pi^-)(K^+ \pi^-) + c.c.$	3.2 K
Recon. $(K^+ \pi^-)(K^+ \pi^-) + c.c.$	604
Produced $B \rightarrow D^0 K^{*0} + c.c.$	$4.5 \cdot 10^6$
Acc. + trig. $(K^- \pi^+)(K^+ \pi^-) + c.c.$	1.0 K
Recon. $(K^- \pi^+)(K^+ \pi^-) + c.c.$	201
Produced $B^0 \rightarrow D_1 K^{*0}$	$7.0 \cdot 10^6$
Acc. + trig. $(KK + \pi\pi)(K^+ \pi^-)$	244
Rec. $(KK + \pi\pi)(K^+ \pi^-)$	49
Produced $\bar{B}^0 \rightarrow D_1 \bar{K}^{*0}$	$7.9 \cdot 10^6$
Acc. + trig. $(KK + \pi\pi)(K^- \pi^+)$	276
Recon. $(KK + \pi\pi)(K^- \pi^+)$	51

Table 12.20: Summary of event yields for $B \rightarrow \bar{D}^0 K^{*0}$, $B \rightarrow D^0 K^{*0}$ and their charge conjugate states and $B \rightarrow D_1 K^{*0}$ and $\bar{B} \rightarrow D_1 \bar{K}^{*0}$ for one year of data taking. We assume $\gamma = 40^\circ$ and $\Delta = 10^\circ$.

γ	$\sigma(\sin 2\gamma)$
20°	0.14
30°	0.19
40°	0.24

Table 12.21: The expected errors on $\sin 2\gamma$ for three different values of γ with $\Delta = 10^\circ$ with one year of data taking.

dominates in the $J/\psi\phi$ final state, the time dependent decay rates for measured initial B_s and \bar{B}_s are given by

$$\begin{aligned}
P(t) &= NA(t)e^{-\Gamma_s t} \left(\cosh \frac{y}{2} \Gamma_s t \right. \\
&\quad \left. + \cos \theta_\lambda \sinh \frac{y}{2} \Gamma_s t - D_\omega I \right) \\
\bar{P}(t) &= \bar{N}A(t)e^{-\Gamma_s t} \left(\cosh \frac{y}{2} \Gamma_s t \right. \\
&\quad \left. + \cos \theta_\lambda \sinh \frac{y}{2} \Gamma_s t + D_\omega I \right)
\end{aligned}$$

where the interference term is given by

$$I = \sin \theta_\lambda \sin x_s \Gamma_s t$$

The CP violation parameter θ_λ is extracted with the maximum likelihood method used for x_s and γ measurements. We assume that all the other variables, such as ω , y_s and τ_s are well measured as discussed in the previous sections. Thus, they are fixed in the fit to the values used in the event generation. Table 12.22 summarises the expected event yields for one year of running.

No. of $B_s^0 \rightarrow J/\psi \phi + \text{c.c.}$	$1.4 \cdot 10^8$
$e^+e^-K^+K^-$ accepted and triggered	133 k
$\mu^+\mu^-K^+K^-$ accepted and triggered	246 k
$e^+e^-K^+K^-$ reconstructed	16 k
$\mu^+\mu^-K^+K^-$ reconstructed	103 k
$\ell^+\ell^-K^+K^-$ tagged	44 k
$R_{B/s}$	0.04
ω	0.29

Table 12.22: Event yields for B_s^0 and $\bar{B}_s^0 \rightarrow J/\psi \phi$ in one year (10^7 s) with a luminosity of 1.5×10^{32} $\text{cm}^{-2}\text{sec}^{-1}$.

Errors on θ_λ determined from the fit with 44 k events expected in one year of data taking are given in table 12.23. Obtained errors are comparable to the value of $\sin \theta_\lambda$ predicted by the standard model. Similar to the case for the γ study using $B_s \rightarrow D_s K$, background does not introduce any additional error if it is known to better than 90%.

x_s	10	20	30
$\sigma(\theta_\lambda)$	0.014	0.016	0.020

Table 12.23: CP violation measurement for $B_s \rightarrow J/\psi \phi$ decays in one year of data taking

12.7 $B_s \rightarrow \mu^+ \mu^-$

The Standard Model predicts a strong suppression of the flavor-changing neutral-current mode $B_s \rightarrow \mu^+ \mu^-$. A deviation from the predicted branching ratio ($BR(B_s \rightarrow \mu^+ \mu^-) \approx 4 \times 10^{-9}$) would be a signal of new physics.

Properties of LHC-B which are favorable for measuring this mode are:

- Efficient trigger. The LHC-B muon trigger is $\sim 80\%$ efficient for $B_s \rightarrow \mu^+ \mu^-$ decays within the spectrometer aperture.
- High detection efficiency. Because the forward muons have high momentum (the average momentum of the accepted $B_s \rightarrow \mu^+ \mu^-$ muons is 40 GeV/c) and the $B_s \rightarrow \mu^+ \mu^-$ decays can be measured down to $p_t = 0$, the detection efficiency (geometric acceptance \times trigger efficiency \times track reconstruction efficiency) is about 12%.
- Good particle Identification. Muons are identified across the spectrometer aperture and along

the particle trajectory by a combination of the muon detector and the RICH system.

- Mass resolution. The $\mu^+ \mu^-$ invariant mass resolution is $12.4 \text{ MeV}/c^2$, so most reconstructed B_s are contained in a narrow ($36 \text{ MeV}/c^2$) mass window.
- Vertex resolution. The high LHC-B vertex resolution allows the rejection of most accidental combinations of muons from different vertices.
- Clean operating environment. Although the choice of a low luminosity operating point limits the number of $B_s \rightarrow \mu^+ \mu^-$ decays produced, this sacrifice should be compensated in part by the cleanliness of the interactions, and the resulting ease of reconstructing the events. This also leads to confidence in the reconstruction simulation.

There are two background sources which will make it difficult to measure this branching ratio. The first background source is two semi-muonic decays of a B and \bar{B} which by chance extrapolate to a common vertex with the correct mass. The second type of background results from the incorrect identification of hadrons in two body decays, such as $B_s \rightarrow K^- \pi^+$, or $\Lambda_b \rightarrow p K^-$.

The combinatoric background can be eliminated in the following ways:

- Track quality: The tracks used in the reconstruction were required to be identified as a muon, with an additional requirement that the Confidence Level for the identification $\geq 60\%$. Muons selected in this way have a $\sim 20\%$ π contamination while maintaining a $\sim 96\%$ efficiency for the $B_s \rightarrow \mu^+ \mu^-$ decay muons. The tracks are also required to have an impact parameter error of $\sigma_b < 40 \mu\text{m}$ when extrapolated to the z -position of the interaction vertex.
- Mass cut: The two muons should have an invariant mass equal to the B_s mass. A $\pm 18 \text{ MeV}/c^2$ bin around the B_s mass contains 84% of the signal.
- Vertex cuts: The two muon trajectories must extrapolate to a common vertex point which is well separated from the primary vertex. Two cuts are made in the reconstruction. First, the di-muon vertex is required to have $\chi^2 < 1.5$, and the z -position of the di-muon vertex is required to be at least 0.10 cm downstream of the primary vertex ($\Delta z > 0.10$).
- Kinematics cuts: The candidate B_s momentum must point from the primary vertex to the $\mu^+ \mu^-$

vertex. This requirement is imposed by measuring the impact parameter ($b_{\mu\mu}$) of the reconstructed B_s track relative to the primary vertex. The error-weighted square of this quantity is cut at $b_{\mu\mu}^2/\sigma_b^2 < 6$.

- Cleanliness cut: The muon tracks should not form a good vertex downstream of the primary with any of the other tracks in the event. This is tested by requiring the minimum vertex chi-square between one of the candidate muons and any other non-primary track in the event, $\chi_{min}^2 \geq 3$.

Track misidentification should be a lesser problem, mostly because the two-body decay modes have low branching ratios (of order 10^{-5}), and therefore need to be suppressed by only 10^{-4} . This can be accomplished, if necessary, by tightening the identification cuts for one or both of the muons at a small cost in efficiency.

12.7.1 Reconstruction Simulation

Three data samples were used to study the reconstruction of this decay mode. A $B_s \rightarrow \mu^+ \mu^-$ data sample was used to measure the reconstruction efficiency and a $b\bar{b} \rightarrow \mu + X$ sample was used for measuring the combinatorial background. Finally, a $B_d \rightarrow \pi^+ \pi^-$ sample was used to evaluate the contamination from two-particle decay modes in which the daughters are mis-identified as muons. Although the Level-1 trigger was simulated exactly, Level-2 simulation was omitted. It is assumed that the di-muon topology is sufficiently easily identified that a special Level-2 trigger can be implemented.

Table 12.24 shows the number of events in the signal sample at various points in the reconstruction process. The distributions of the four cut quantities are shown for $B_s \rightarrow \mu^+ \mu^-$ events in fig 12.18(a-d). The total efficiency for detection and reconstruction of $B_s \rightarrow \mu^+ \mu^-$ events is 4.2%, leading to a signal of $1.1 \cdot 10^{-2} \times \text{BR}$ per $b\bar{b}$ event.

A sample of 34 k $b\bar{b} \rightarrow \mu + X$ events was used to estimate the background. Approximately 13% of these events passed the Level-1 trigger, leading to 113 $\mu^+ \mu^-$ combinations in a 3 GeV/ c^2 window centered around the B_s mass. The distribution of the cut quantities for the accidental combinations are shown in figures 12.18(e-h).

Because of the limited statistics available to estimate the large background suppression needed to reveal a $B_s \rightarrow \mu^+ \mu^-$ signal, it is necessary to assume that there is limited correlation between the cuts. This has been verified to be the case, except for a

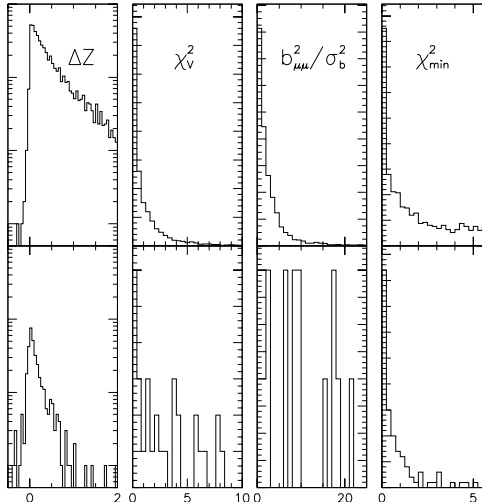


Figure 12.18: Distributions of the quantities used for isolation of $B_s \rightarrow \mu^+ \mu^-$. The upper row contains events from the $B_s \rightarrow \mu^+ \mu^-$ signal sample, and the lower row contains the same distributions from the background samples.

Cut	events	Efficiency
$b\bar{b}$ events	200000	1.000
$b\bar{b} \rightarrow B_s \rightarrow \mu^+ \mu^- + cc$	50000	0.250
$\theta_B < 0.600$	20000	0.400
L1 Trigger	14092	0.699
Tracks reconstructed	6051	0.429
ID, track quality cuts	5467	0.904
Vertex $\chi^2 < 1.5$	3978	0.728
$\Delta z > 0.10 \text{ cm}$	3166	0.796
$b_{\mu\mu}^2/\sigma_b^2 < 6$	2897	0.915
$\chi_{min}^2 < 3$	2502	0.864
$ m_{\mu\mu} - m_B < 18 \text{ MeV}/c^2$	2091	0.836
Sensitivity per $b\bar{b}$		0.0105

Table 12.24: Reconstruction efficiencies for $B_s \rightarrow \mu^+ \mu^-$.

noticeable correlation between the Δz cut and the other cuts. This correlation is expected since the Δz cut removes the events near the primary vertex where the other cuts are less sensitive, or swamped by misidentified primary tracks. Thus, the Δz cut suppression is measured with all combinations passing the track quality cuts, and the remaining cuts use only those combinations that have first passed the Δz cut. The numbers of events at various stages of the reconstruction process (and the associated suppression) are listed in table 12.25.

The $B_s \rightarrow \mu^+ \mu^-$ sample also contains numerous false di-muon combinations. These false combinations should have similar characteristics to the background events, although the proper normalization of these combinations to the total $b\bar{b}$ sample is difficult. The false combinations in the $B_s \rightarrow \mu^+ \mu^-$ sample are included in table 12.25 in the column headed $b\bar{b} \rightarrow \mu\mu$. The total number of triggered combinations is normalized to the $b\bar{b} \rightarrow \mu + X$ sample to obtain the total suppression of $b\bar{b}$ events. The suppression of the false combinations is very similar to that of the $b\bar{b} \rightarrow \mu + X$ sample, giving additional support to the suppression conclusions.

The results in tables 12.24 and 12.25 indicate that the overall signal to noise ratio will be $1.2 \cdot 10^7 \text{ BR}(B_s \rightarrow \mu^+ \mu^-)$. A year's running at $1.5 \cdot 10^{32}$ will produce about $7.5 \cdot 10^{11}$ $b\bar{b}$ events. With a noise rejection of $8.8 \cdot 10^{-10}$, 660 background events will be produced in the B_s mass bin. A 3σ effect requires a 77-event signal, corresponding to a branching ratio of $9.8 \cdot 10^{-9}$, or about 2.5 times larger than the Standard Model prediction.

Thus, a 3σ -signal SM signal could be seen in 1-year, running with about 10^{33} luminosity, or in 2-years with $\mathcal{L} = 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. However, tuning of the cuts is not yet finalized and we therefore believe that, with some additional effort, significant improvements on this result can be expected.

The limitations on running with 10^{33} luminosity would be the radiation damage to the vertex detectors and charge pileup in the tracking chambers. Event pileup would reduce the reconstruction efficiency somewhat, but this should be limited to events with two nearby interaction vertices.

The susceptibility to di-hadron background was tested using a sample of 5000 $B_d \rightarrow \pi^+ \pi^-$ events (equivalent to $7.8 \cdot 10^8$ $b\bar{b}$ events assuming $\text{BR}(B_d \rightarrow \pi^+ \pi^-) = 2 \cdot 10^{-5}$). Even with the trigger, track quality and muon identification requirements relaxed, no $\pi^+ \pi^-$ events passed all the reconstruction requirements. Since the trigger efficiency for $B_d \rightarrow \pi^+ \pi^-$ is $\sim 5\%$ compared to $\sim 80\%$ for the $\mu\mu$ channel, this places an upper limit on the

di-hadron background of $6.4 \cdot 10^{-11}$ per $b\bar{b}$, well below the combinatoric background.

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Cut	$b\bar{b} \rightarrow \mu$	$b\bar{b} \rightarrow \mu\mu$
$b\bar{b}$ events	176000 (1.000)	
B or $\bar{B} \rightarrow \mu + X$	34300 (0.195)	
L1 Trigger	4467 (0.130)	
Combinations, $ m_{\mu\mu} - m_B < 1.5\text{GeV}/c$	113 (0.025)	879 (1.000)
ID, track quality cuts	54 (0.478)	297 (0.338)
$\Delta z > 0.10$ cm	29 (0.537)	121 (0.407)
Normalized to $\Delta z > 0.10$ cm		
Vertex $\chi^2 < 1.5$	2 (0.069)	10 (0.083)
$b_{\mu\mu}^2 / \sigma_b^2 < 6$	0 (< .035)	4 (0.033)
$\chi_{min}^2 > 3$	8 (0.276)	49 (0.405)
Ratio of bin widths		
$ m_{\mu\mu} - m_B < 18\text{MeV}/c^2$	(0.009)	(0.009)
Total	$1 \cdot 10^{-9}$	$8.8 \cdot 10^{-10}$

Table 12.25: Suppression of $b\bar{b} \rightarrow \mu + X$ background. The second column documents the suppression of the false combinations in the $B_s \rightarrow \mu^+ \mu^-$ sample. When normalized to the number of triggered $\mu^+ \mu^-$ combinations, the two samples give compatible results.

13 Costs & Experimental Area

13.1 Detector costs

A summary of the cost estimates for the individual detector components is given in Table 13.1. They are based on figures previously presented to the Cost Review Committee (CORE) of the LHCC by the COBEX, GAJET and LHCb collaborations, taking into account comments by CORE. In addition, use has been made of the latest cost estimates of ATLAS and CMS. At this early stage of the LHC-B detector design, our costs are inevitably preliminary. Cost optimization will be an important consideration in preparation of the LHC-B Technical Proposal.

Detector Subsystem	Cost (kCHF)
Micro Vertex Detector	5,000
Magnet	15,000
Tracking System	9,000
Muon Detector	9,000
EM Calorim. & Preshower	10,000
Hadron Calorim.	7,000
RICH	9,000
Trigger, DAQ & Offline	17,000
Infrastructure	5,000
Total	86,000

Table 13.1: Summary of Detector Costs

13.2 Machine constraints

In the present lay-out of the LHC, LHC-B has been assigned to IP-8. In this scheme an even number of (four) crossing points is arranged in a symmetric pattern around the LHC ring as shown in Fig. 13.1.

LHC-B will be a colliding beam experiment. As discussed in Chaps. 1 and 10, we propose to record most of our data at the rather modest luminosity of $\mathcal{L} = 1.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This will be possible with a standard low- β insertion, as long as ATLAS & CMS are running with a luminosity less than thirty times this value (the available dynamic range). Thus, when the machine luminosity exceeds about $\mathcal{L} = 4.5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, a modified insertion will be required for LHC-B.

When the LHC is operating at its design performance, the β^* -value at the LHC-B IP will be of the order of 10 m to 30 m (compared to the minimum value of 0.5 m). For these β^* values the beam will have a r.m.s. radius of $\simeq 75 - 100 \mu\text{m}$ at the IP, a value which increases slowly with increasing distance, $s[\text{m}]$, to the crossing point (i.e. like $\sqrt{1 + s^2/100}$). The microvertex detector will, in all cases, be at a

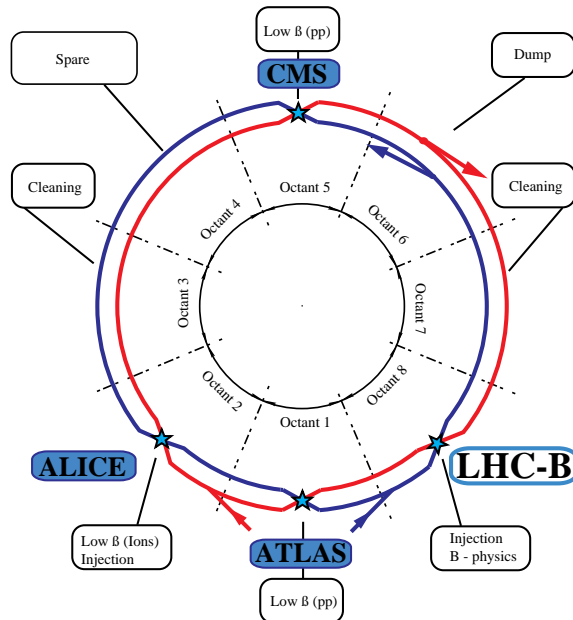


Figure 13.1: LHC experiments lay-out

comfortably safe distance of more than 100σ from the beam centre.

The free space at the even IP-8 amounts to $L^* = 21\text{m}$ (CERN SL/95-06). For a luminosity of less than $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, there is no need for a Cu/W collimator block in front of Q1 as foreseen in points 1 and 5 to protect the magnet against secondary particles from the crossing point. Since almost 2.0 m, however, is required for the cold/warm transition of the superconducting magnets, the effective free space for the detector is only 19 m. Moreover, a shield may have to be placed in between Q1 and the last μ -chamber to protect the latter against neutrons and other secondaries produced in machine components up till and including Q1.

The total deflection contributed by the spectrometer dipole ($\int B dl \leq 4.0 \text{ Tm}$) is small at the nominal beam energy of the LHC and will require only modest adjustments to the final machine dipole magnets[1]. During injection the magnet is switched off, or will run at low current. The possibility to ramp the field fast to its nominal value is part of the design requirements.

13.3 Underground cavern

The standard LEP cavern has a width of 21 m. If the crossing point were at its nominal position at the centre of the cavern, the tunnel would have to be

enlarged over a length of about 10 m to make room for the detector. Civil engineering considerations require the diameter of this alcove to be at most 14.5 m. This would be just sufficient for a forward angular coverage of the detector of up to 250 mrad. Installation of the detector and later access to the detector components inside the alcove would require the detector to be put on rails so that it could be moved under the span of the overhead crane in the existing cavern. Although an acceptable solution, it clearly would impede the accessibility of the detector. Moreover, the alcove would entail civil engineering costs estimated to be of the order of 5-8 MCHF.

13.4 Displaced crossing point

A displacement of the crossing point by about 11.25 m (one and a half times the bunch distance) would allow the experimental area to be used without any additional costly civil engineering work. It would also significantly improve the accessibility of the detector.

A preliminary study[2] suggests that the machine optics for such a displacement are perfectly feasible and should not entail any special requirements implying extra cost. This scheme is therefore proposed as the baseline lay-out for the LHC-B experimental area and is shown in Figs. 13.2 and 13.3.

The fact that a few leading and trailing bunches of each bunch-train will not have collision partners at such an offset collision point, means that they will suffer a different tune shift and hence the machine will be required to accommodate a larger overall tune spread. This concern requires further study, but it is not expected to have a large effect on general machine performance when the LHC is operated with three collision points at luminosities below the maximum.

13.5 Surface zones and services

For installation in point 8, the existing surface zones could be used without modification. Since the size of the LHC-B detector is comparable to the LEP detectors, existing facilities such as counting rooms, electrical power distribution, cooling and ventilation and gas installations are expected to be adequate. Similarly, the SX assembly hall and crane will be sufficient for preassembly and testing and the PX access shaft will be large enough for installation underground. Electronics could be installed behind the shielding wall in the US area, and therefore could be accessed during collider operation.

13.6 Installation time

From a total shut-down period of 3 years before the commissioning of the LHC, about 6 months will be required for the removal of the DELPHI detector. The civil engineering work associated with the excavation of an alcove (should it be necessary) would take about 12 months and would leave 18 months for the assembly of the magnet and the installation of the detector.

13.7 Experimental area costs

Assuming a displacement of the crossing point by 11.25 m no major civil engineering costs are expected. The experimental area costs are therefore limited to the standard cost items i.e. Intersection Elements and Technical Services which in the LHC costing are estimated at about 10 MCHF and 3 MCHF respectively.

References

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LHC-B

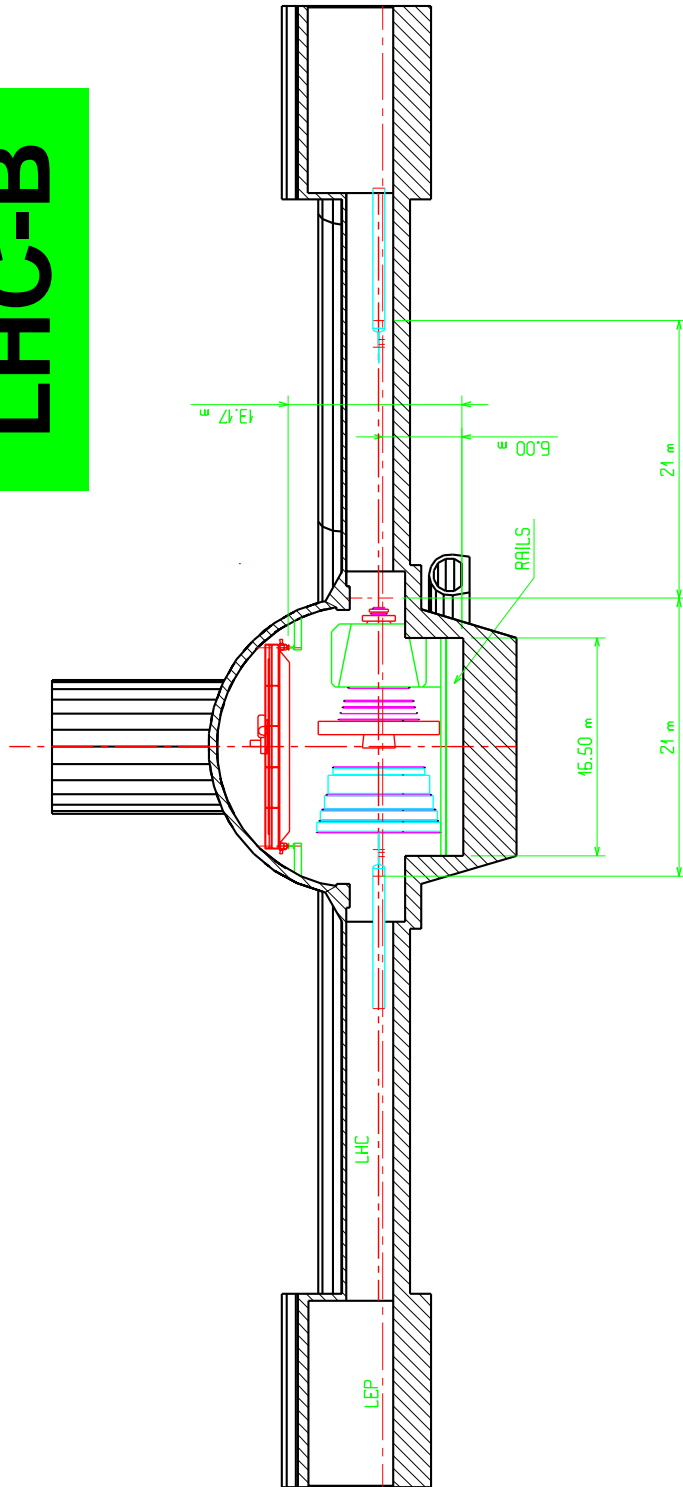


Figure 13.2: Side view of the experimental area with the detector in place. The crossing point is displaced by about 11.25 m with respect to the center of the cave.

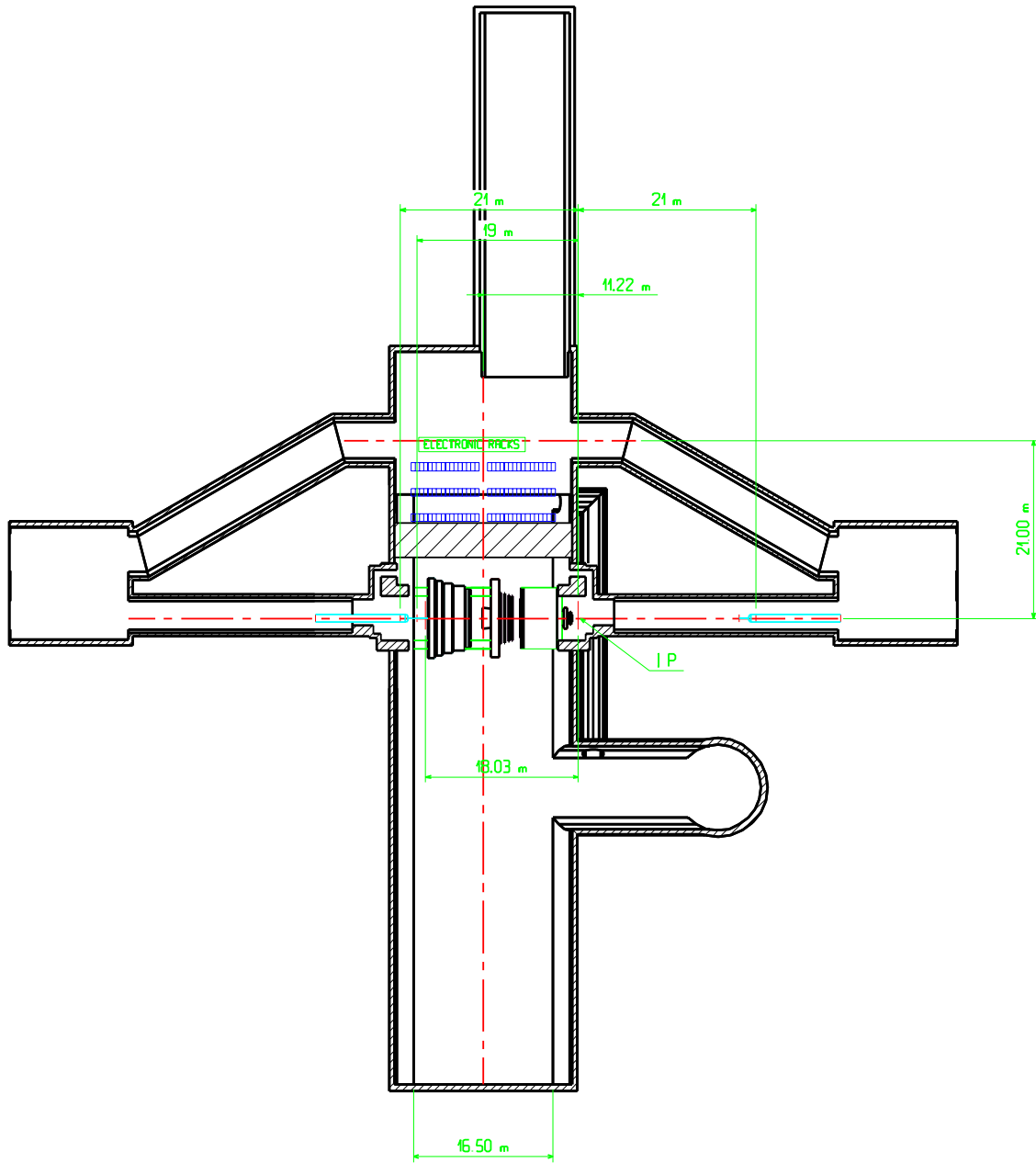


Figure 13.3: Top view of the experimental area with the detector in place. The crossing point is displaced by about 11.25 m with respect to the center of the cave.

A Detector Option: Liquid-Scintillator-Filled Capillaries

The collaboration is studying different options exploiting the tracking capabilities and the radiation resistance of a capillary detector. This could be used as an alternative to, or in conjunction with, the silicon microstrip vertex detector. It could also serve as a component of the inner tracker. In this appendix we describe possible configurations for a capillary vertex detector and for an inner tracker which could replace the baseline LHC-B detectors.

Tracking detectors based on a new type of scintillating fibre, glass capillaries filled with liquid scintillator (LS)[1]-[6], have many advantages. The following performance has been achieved:

- 10 hits detected per mm (for normal incidence),
- light attenuation length of the order of 1 m for capillaries of 16 μm diameter,
- spatial resolution of 14 μm per hit,
- two-track resolution of 33 μm ,
- excellent radiation resistance,
- small number of output channels due to the high integration level of CCD readout.

The high radiation resistance of glass capillaries filled with LS permits the operation of such a detector for a long running period at a few mm distance from the beam line, thus increasing the small-angle acceptance of the apparatus.

As a consequence of the high detected hit density it is possible to measure in a thin capillary layer not only the track coordinates but also the track vector (direction) of a passing particle. Fig. A.1 shows Monte Carlo simulated images of tracks detected in two capillary layers compared with the same tracks in two layers of a silicon microstrip detector (having a comparable amount of radiating material). This figure clearly demonstrates the reconstruction capabilities of the capillary detector.

In the following we describe a capillary vertex detector (VD), with a layout as shown in Fig. A.2. Compared to the silicon microvertex detector (SMD), a capillary VD operating at a distance of 2 mm from the beam line, covers larger angular range (5-560 mrad), and has a better spatial resolution (5 $\mu\text{m}/\text{layer}$). The very large average number of hits per track (order of 100) and the possibility of reconstructing a track vector in each layer ensure a high reconstruction efficiency.

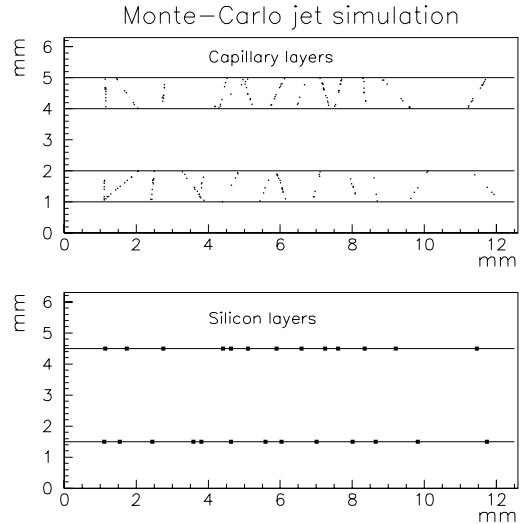


Figure A.1: Monte Carlo simulated track images in two 1 mm thick capillary layers and the same tracks in two layers of a silicon microstrip detector.

The VD readout system is based on an Electron-Bombarded CCD (EBCCD). It has fewer output channels than are required by the SMD but this readout is too slow to permit its use for triggering. Another, faster, read-out option for the VD is under study and is briefly described below.

We also describe a possible configuration for the inner tracking system based on capillaries.

A.1 Vertex detector layout

Fig. A.3 shows the array of capillaries, constructed from rectangular bundles, which are used to form a detector layer. The central part of the VD shown in Fig. A.2 covering the angular range of 14-560 mrad, consists of 16 plane layers of capillary bundles with a thickness of 1 mm and transverse dimensions of $12 \times 12 \text{ cm}^2$ placed perpendicular to the beam. The diameter of the capillaries is 16 μm .

Layers are arranged alternately along the x and y directions. Each layer is divided in two parts, 2 mm distant from the beam line (see Fig. A.4). The distance between layers is 2.4 cm, and the total length of the central part of the VD is 36 cm, with the central point of the interaction region near the 7th layer. To cover very small angles (5-20 mrad), 6 capillary layers ($3x$ and $3y$, $3 \times 3 \text{ cm}^2$), are added at 40, 55 and 70 cm from the central point of the interaction region (the forward part of the VD shown in Fig. A.2).

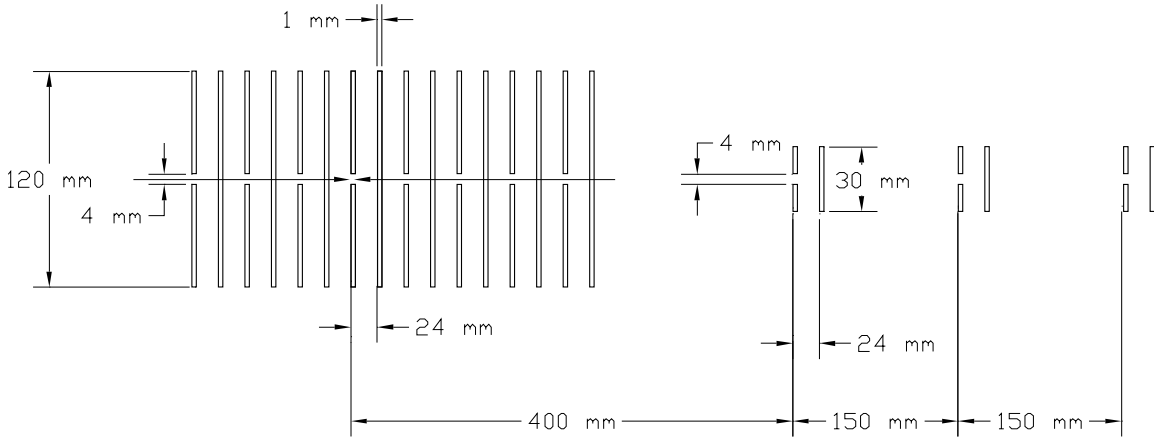


Figure A.2: Capillary VD layout.

A special window separating the beam and the capillary layers can be constructed, similar to the one of the SMD. RF shielding is not required and a window made of material with low X_0 (for example Be) could be used. The average total thickness crossed by particles corresponds to $\sim 3.4\%$ of a radiation length (or $\sim 1.4\%$ of an interaction length) for the central part of the VD. For the forward part these values are 2.0% and 0.8%, respectively.

Neither the detectors nor the optoelectronic readout require cooling.

A.2 Readout system

The readout system consists of a gateable Vacuum-Image Pipeline (VIP)[7, 8] which delays images from the VD waiting for the Level-1 trigger decision ($\sim 3 \mu\text{s}$), a second VIP waiting for the Level-2 trigger ($\sim 2 \text{ms}$), and an Electron-Bombarded CCD Image Tube (EBCCD IT), (see Fig. A.5).

A prototype of the first VIP has been tested, and a time resolution of 20 ns for 1 μs delay has been measured. The design of the second VIP is under study: its time resolution will be poorer but well adapted to the lower rate of events accepted by the Level-1 trigger. The light signal from the VIPs is intensified and detected by the EBCCD IT: a prototype of this device has been successfully tested[3], giving a spatial precision better than 10 μm . Both VIP and EBCCD IT operate in a uniform magnetic field of $\sim 0.1 \text{T}$ provided by a solenoid which is shielded from the residual field of the spectrometer magnet.

The capillary layers are coupled to the first VIP by image guides of 0.8 m length with an overall light loss of the order of 35%. Remote ends of layers are

covered by mirrors that increase the light output by a factor of ~ 1.8 . The total readout area is 20 cm^2 . This area can be fit to two VIPs (45 mm diameter entrance window) for the Level-1 trigger and then 2 VIPs for the Level-2. Two EBCCD tubes are required, each containing four CCDs. Each CCD has 800×800 pixels, ($20 \times 20 \mu\text{m}^2$ each) and 32 parallel output channels. With this design 5×10^6 pixels are read out by 256 output channels (three orders of magnitude less compared with the SMD!). For a readout frequency of 35 MHz the total readout time is 0.6 ms. The readout time and the number of output channels may be optimized for different trigger rates.

We are also investigating the possibility of using the information of the VD for the Level-1 or Level-2 triggers. This necessitates a fast read out. One end of the capillary bundles can be connected to the readout chain, as described above, while the other end could be read out by fast devices, such as multichannel photomultipliers or Electron-Bombarded Pixel Detectors (EBPD) with parallel readout[9, 10]. The VD would then have two parallel read-out systems, with different granularities, operating at different rates, and could be used simultaneously for high resolution tracking by the slow EBCCD read-out and for a topology trigger using the fast read-out. The existing prototype of EBPD tube has 1,024 output channels with a pixel area of 0.037 mm^2 . If each pixel is connected to a region of the capillary layer corresponding to a pitch of 50 μm , a trigger performance similar to that of the SMD (but with a larger angular acceptance) can be obtained with 40 EBPD tubes (4×10^4 output channels).

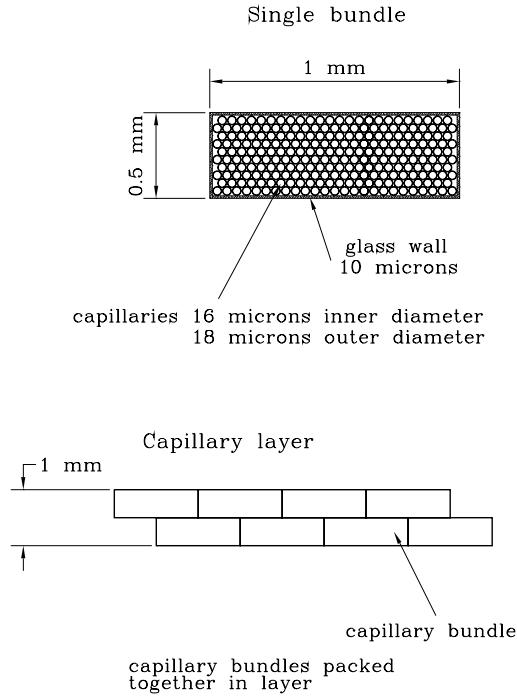


Figure A.3: Capillary array structure of a layer. (n.b. capillaries not drawn to scale)

A.3 Spatial resolution

Geometrical characteristics and spatial precision of the VD are presented in Table A.1.

A hit density of 8.5/mm was measured at short distances from the photodetector in a beam test[3]. Taking into account the loss of light in the guide and the gain in light obtained if one places a mirror at the remote end of the bundles, we estimate that a hit density of ~ 10 hits/mm can be reached. A spatial precision of $14 \mu\text{m}$ was measured[3], corresponding to $\sim 5 \mu\text{m}$ for each layer. This allows a measurement precision of $69 \mu\text{m}$ in the decay length of 3-prong vertices.

The results presented in Table A.1, have been obtained taking into account multiple scattering in capillary layers and an Al window $100 \mu\text{m}$ thick. The influence of multiple scattering on the vertex precision is relatively small because the accuracy on the vertex position is essentially determined by a few capillary layers close to the vertex.

The precision can be further improved by magnifying the images with tapered bundles. This reduces the contribution of the read-out system to the spatial precision, but requires an increase in the number

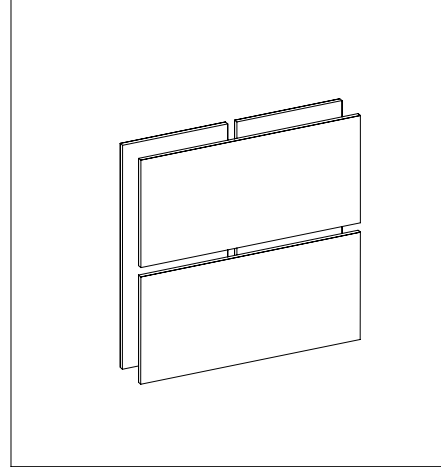


Figure A.4: Front view of x, y capillary layers.

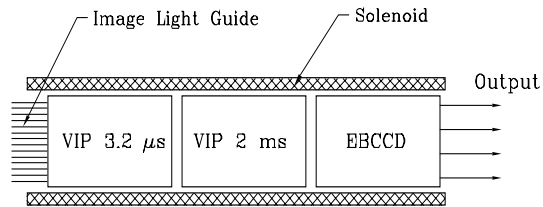


Figure A.5: Readout chain.

of read-out chains. A hit precision $6 \mu\text{m}$ instead of $14 \mu\text{m}$ has been obtained in a test using $16 \mu\text{m}$ capillaries and a magnification factor of ~ 5 (Fig. A.6).

High spatial resolution is crucial for the event recognition, in particular in the region near the beam line. The measurement of a track vector in a capillary layer permits the search for corresponding track segments in adjacent layers. This significantly reduces ambiguities and improves the track reconstruction efficiency. According to our simulations the track reconstruction efficiency will be near 100% even at the highest luminosity envisaged for LHC-B running.

A.4 Radiation resistance

Table A.2 shows the radiation doses at different luminosities and at different distances R (cm) from the beam. We have assumed a dose of $6/R^2$ Mrad/year at the LHC-B nominal luminosity $\mathcal{L} = 1.5 \times$

Item	Value
Capillary diameter	16 μm
Dimensions of layers	12x12 cm^2 , 3x3 cm^2
Number of layers	8x+8y, 3x+3y
Thickness of layer	1 mm
No. hits/mm	10
No. hits/track (aver.)	100
$\sigma_{x,y}/\text{hit}$	14 μm
Two-track resolution	33 μm
$\sigma_{x,y}/\text{layer}$	5 μm
$\sigma_{x,y}$ primary vertex	2.5 μm
σ_z primary vertex	20 μm
$\sigma_{x,y}$ B-vertex 3-prong	6.5 μm
σ_z B-vertex 3-prong	66 μm
σ decay length	69 μm

Table A.1: Spatial precision of the VD

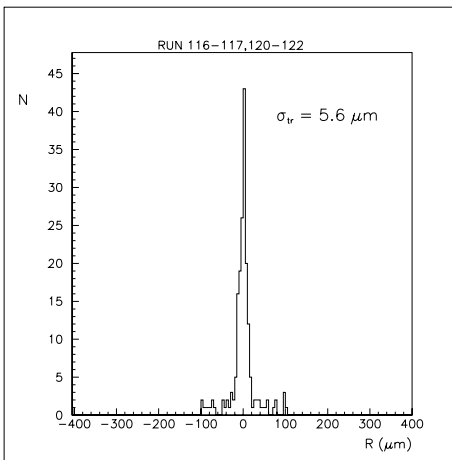


Figure A.6: Track residual distribution measured for a bundle of 16 microns capillaries[3].

$10^{32}\text{cm}^{-2}\text{s}^{-1}$, independent of the z -coordinate.

The radiation resistance of a long capillary detector (1-2 m) has been measured to be more than 60 Mrad without changing the liquid scintillator. Our VD is much shorter (3-12 cm in length) and only a part of it would be exposed to the maximum radiation. The degradation of the attenuation length will therefore be less. For our LS based on 1-methyl-naphthalene (1MN) and the new dye R39 we measured a reduction in scintillation efficiency of 20% at a dose of 110 Mrad and 30% at a dose of 190 Mrad[6] (see Fig. A.7). We estimate that the VD can efficiently operate at doses of several hundreds of Mrad without changing the LS. In view of this radiation resistance a capillary VD could safely operate at the nominal luminosity at distances down to 2 mm from the beam. At high

\mathcal{L} ($\text{cm}^{-2}\text{s}^{-1}$)	dose/year (Mrad)	R (cm)
10^{31}	40	0.1
10^{31}	10	0.2
10^{32}	400	0.1
10^{32}	100	0.2
10^{32}	44	0.3
10^{33}	1000	0.2
10^{33}	440	0.3
10^{33}	40	1.0

Table A.2: Radiation doses

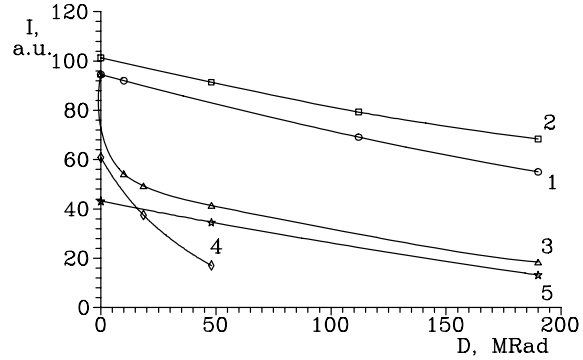


Figure A.7: Light output of different LSs versus irradiation dose. Results for LSs based on 1MN and dyes R6, R39, R45, and Bicon LS are presented. 1 - 1MN + R6; 2 - 1MN + R39; 3 - 1MN + R45; 4 - BC-599-13G; 5 - BC-599-13B.

luminosity $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$, the capillary VD can operate at $R = 3\text{ mm}$, but the LS will need replacing every year (a relatively simple and cheap procedure). Since the cost of capillaries filled with LS is much less than the cost of the readout chain. One could envisage increasing the luminosity about 30 times the nominal LHC-B luminosity and replacing the capillaries every year.

A.5 Costs

An estimation of the cost of the components is presented in Table A.3.

A.6 Inner tracking system based on capillary layers

A capillary detector with a fast readout system based on EBPD tubes satisfies all the conditions required

Component	Number	Cost(kSF)
Liquid scintillator		20
Capillary layers	22	60
Image guides	22	80
VIP	4	200
Solenoid for VIP	2	80
EBCCD IT (4 CCDs)	2	160
Electronics for EBCCD		60
DAQ for EBCCD		80
Support and mechanics		60
Total		800

Table A.3: Cost estimation of the VD

for the inner tracking system. We discuss here a configuration using capillaries over the whole $40 \times 40 \text{ cm}^2$ area of all stations 1-12 of the inner tracking detectors, as summarized in Table A.4.

In each station there are three layers, each 1 mm thick, with capillaries arranged respectively along x , y directions and along a direction rotated by an angle of 5° with respect to the vertical, in order to resolve multi-particle ambiguities. The distance between layers in one station is about 1 mm.

Fig. A.8 shows one capillary layer which consists of 4 sections. The two outer sections, with a capillary length of 40 cm, and the two inner sections, with shorter capillaries starting near the vacuum pipe, are read out from opposite sides. There is almost no dead space near the beam pipe as is the case for other types of inner detectors. The dead space between the four sections of the capillary layer is negligible.

The capillary diameter is $20 \mu\text{m}$. The amount of material in one station (3 layers) is $1 \% X_0$. The capillary layers are coupled to the EBPD's by image guides of differing lengths (from 0.3 m for the first station up to 4 m for the last station) in order to place readout tubes and electronics outside the outer tracking system. Glass image guides 1 mm thick ($0.79\% X_0$), connected to layers of the same station, are not superimposed on each other. The ends of the capillaries not attached to the read-out are equipped with mirrors to increase the light output.

For those stations operating near or inside the Dipole Magnet, magnetic focusing EBPDs will be used. Outside the magnet we plan to use electrostatic focusing devices shielded from the residual magnetic field.

Approximately four photoelectrons per layer are expected to be detected on average. Each pixel of the EBPD is connected to a $0.11 \times 1 \text{ mm}^2$ region of the capillary layer corresponding to a pitch of $110 \mu\text{m}$ and a spatial precision of $30 \mu\text{m}$ per station.

Using the existing prototype of the EBPD tube,

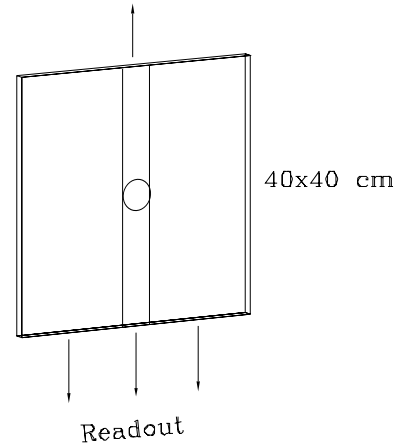


Figure A.8: Capillary array structure of a layer.

which has 1,024 parallel output channels, the total number of tubes would be 12 per station and 144 for the whole inner detector. The total number of channels is 147,456. With the progress in EBPD development, we expect to increase the number of output channels per tube with a consequent reduction of the cost per channel.

The decay time of light emission from our LS is about 6 ns with no slow component [4] (unlike plastic scintillators). Due to the relatively small size and capacity of each pixel and the use of fast, low noise preamplifiers, we estimate an occupancy of the order of 2 % per interaction.

The radiation resistance of the capillary detector permits its use at a very short distance from the beam. For a minimum distance of 12.5 mm (1st station), the capillary inner tracking detector can operate for many years without changing the LS.

A comparison with the various options for the inner tracking detector, as described in in Chapt. 5, is given in Table A.4. In the capillary option, excellent radiation resistance, higher spatial resolution, and avoidance of dead space around the vacuum pipe, are combined with a smaller amount of material and lower occupancy.

We estimate a total cost of the capillary inner tracking detector of the order of 3,000 kSF.

The solution described above, using the capillary technique for the whole inner tracking detector, seems to be an attractive one, but we are also consider-

Item	MCSC	MSGC	Capillary Detector
Stations	part of 1,2 all of 3-12	part of 1,2 all of 3-12	all of 1-12
Pitch	500-1000 μm	200 μm	110 μm
Precision per station	$\leq 40 \mu\text{m}$	$\leq 40 \mu\text{m}$	30 μm
Material per station	1.5% X_0	1.27% X_0	1% X_0
Occupancy	$\sim 5\%$	$\leq 5\%$	$\sim 2\%$
Number of output channels	81,900	131,600	147,456

Table A.4: Inner Tracking detectors

ing the possibility of using capillary detectors in the most critical region near the beam pipe to supplement other types of detector which could be sited further from the beam line. Capillary planes, with a reduced size, $10 \times 10 \text{ cm}^2$, and the same structure, can be used. In this case four EBPD tubes per station, and 48 tubes for the whole capillary detector are required. With such a configuration the total cost of the capillary detector is reduced by a factor of three.

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