Particle Flow and ILC Detector Design

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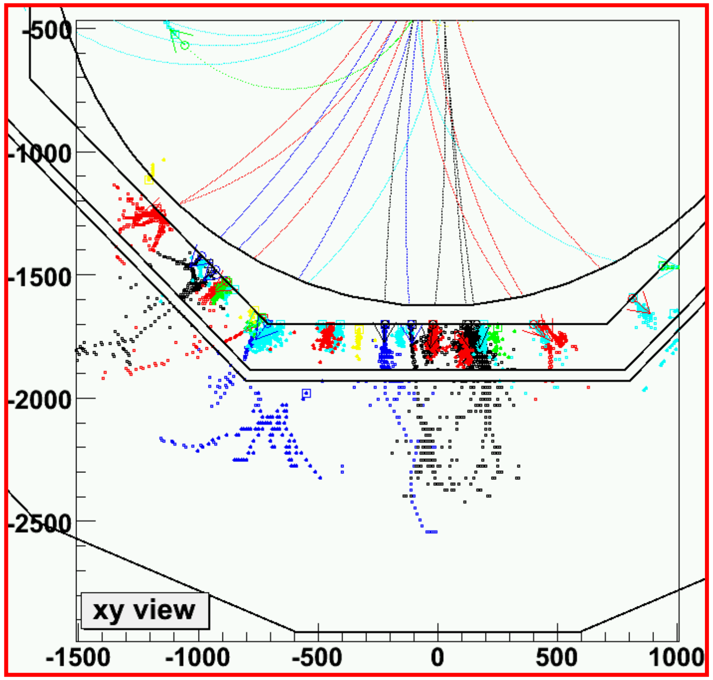


This Talk:

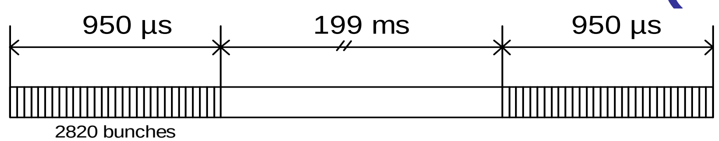
- ★ The ILC : Accelerator and Physics
- ★ ILC Detector Concepts
- ★ The LDC (TESLA) Concept
- ★ Particle Flow and its role in detector design and optimisation
- ★ A new Particle Flow Algorithm
- ★ Conclusions

➊The ILC

★ILC baseline parameters currently being discussed
- main features "known"

- Center-of-Mass Energy : ~ 90 – 1000 GeV
- Baseline Luminosity : ~2×10^{34} $cm^{-2}s^{-1}$ (>1000xLEP)
- Time Structure : 5 (10?) Bunch-trains/s
  - Time between collisions: ~ 300 (150) ns

e.g. TESLA TDR



- "Physics" Event Rate (fairly modest):

$e^+e^-\to qq$ ~100/hr $e^+e^-\to W^+W^-$ ~1000/hr

$e^+e^-\to tt$ ~50/hr $e^+e^-\to HX$ ~10/hr

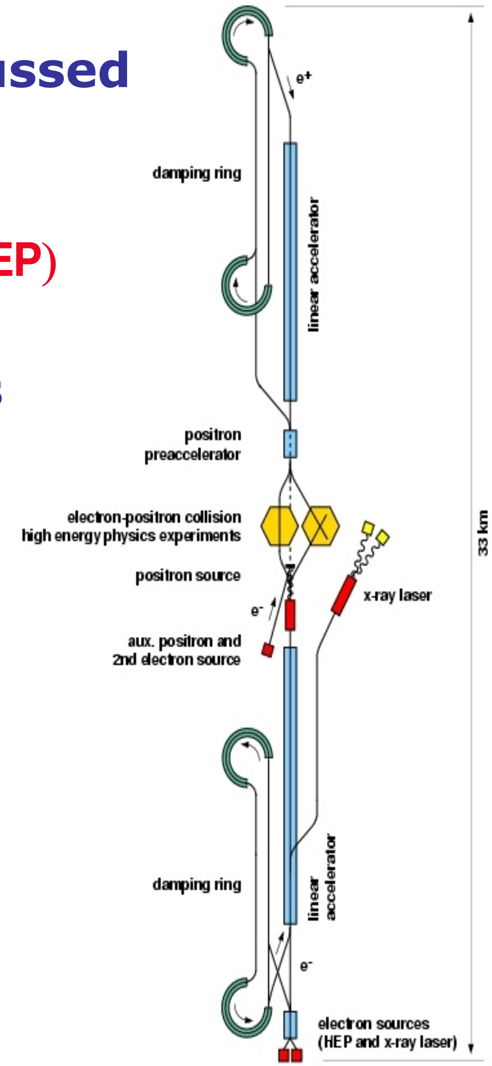
- "Backgrounds" (depends on ILC parameters)

$e^+e^-\to qq$ ~0.1 /Bunch Train

$e^+e^-\to\gamma\gamma\to X$ ~200 /Bunch Train

~500 hits/BX in Vertex det.

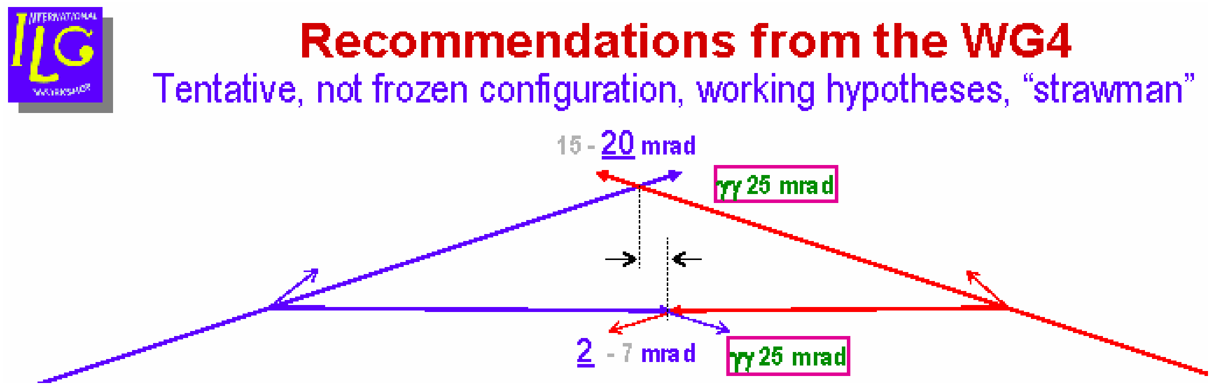
~5 tracks/BX in TPC



★ Event rates/backgrounds modest (small compared to LHC)

Impact on Detector Design

- ★ **Radiation hardness does not dictate detector design**
- ★ **Modest timing requirements (~300 ns)**
- ★ **Must be able to cope with modest gamma-gamma background**
- ★ **Impact of non-zero crossing angle ?**



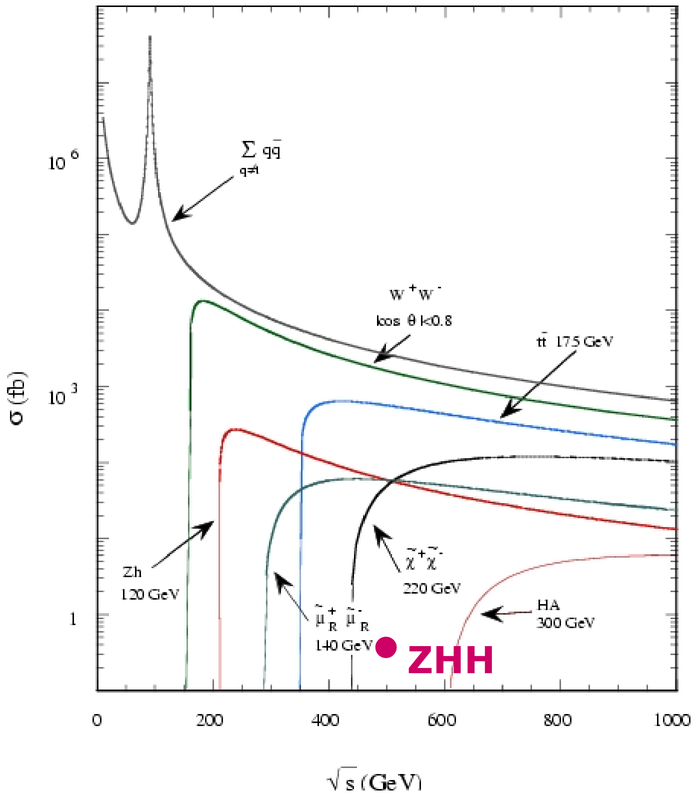
★ **PHYSICS not the machine drives ILC Detector design**

+ crossing-angle may also important

Linear Collider Physics

Precision Studies/Measurements

- ★ **Higgs sector**
- ★ **SUSY particle spectrum**
- ★ **SM particles (e.g. W-boson, top)**
- ★ **and much more...**



Physics characterised by:

★ **High Multiplicity final states often 6/8 jets**

★ **Small cross-sections**

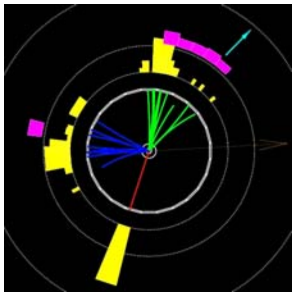
e.g. $\sigma(e^+e^-\rightarrow ZHH) = 0.3$ fb

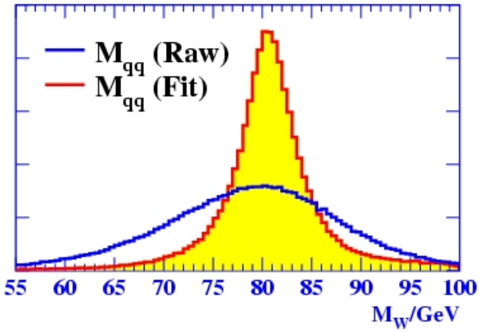
✸ **Require High Luminosity**

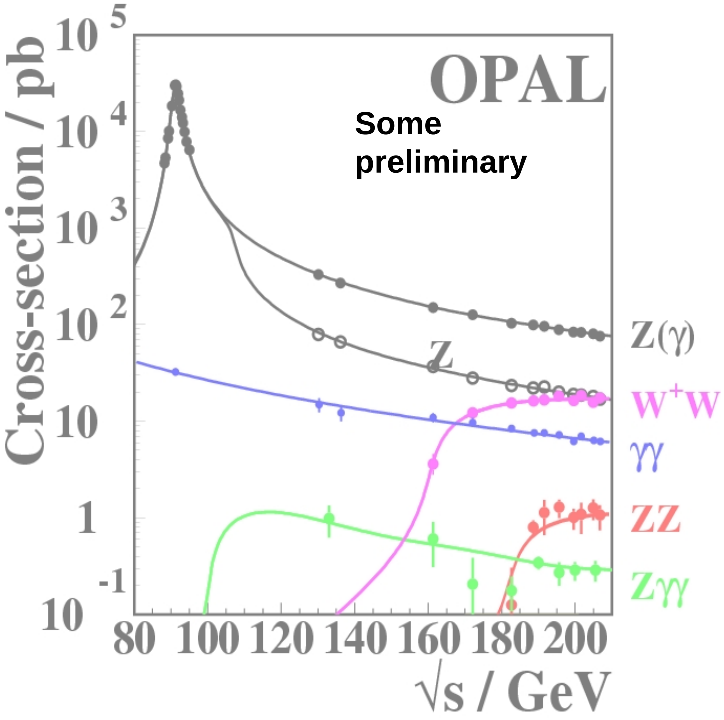
✸ **Detector optimized for precision measurements in difficult multi-jet environment**

Compare with LEP

- ★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate
  - backgrounds not too problematic
- ★ Kinematic fits used for mass reco.
  - good jet energy resolution not vital







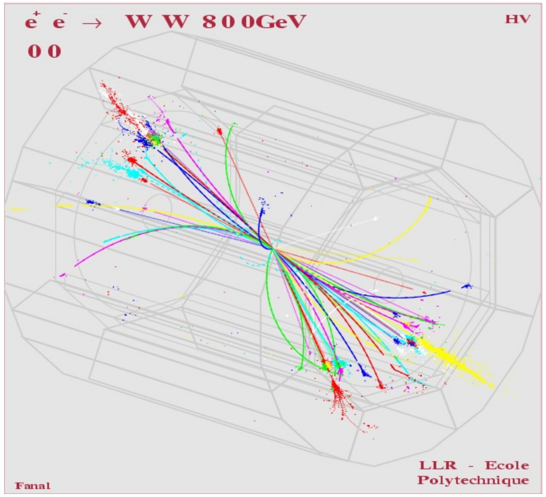
At the ILC:

- ★ Backgrounds dominate 'interesting' physics
- ★ Kinematic fitting much less useful (Beamsstrahlung)

> ✸ Physics performance depends **critically** on the detector performance (not true at LEP)
>
> ✸ Stringent requirements on the ILC detector

ILC Detector Requirements

- ★ **momentum:** $\sigma_{1/p} < 7\times10^{-5}$/GeV (1/10 x LEP)
  (e.g. mass reconstruction from charged leptons)
- ★ **impact parameter:** $\sigma_{d0} < 5\mu m \oplus 5\mu m/p(GeV)$ (1/3 x SLD)
  (c/b-tagging in background rejection/signal selection)
- ★ **jet energy:** $\delta E/E = 0.3/E(GeV)$ (1/2 x LEP)
  (invariant mass reconstruction from jets)
- ★ **hermetic down to :** θ = 5 mrad
  (for missing energy signatures e.g. SUSY)
- ★ **Radiation hardness not a significant problem**
  1st layer of vertex detector : 10^{9} n cm^{-2} yr^{-1}
  c.f. 10^{14} n cm^{-2} yr^{-1} at LHC



Must also be able to cope with high track densities due to high boost and/or final states with 6+ jets, therefore require:

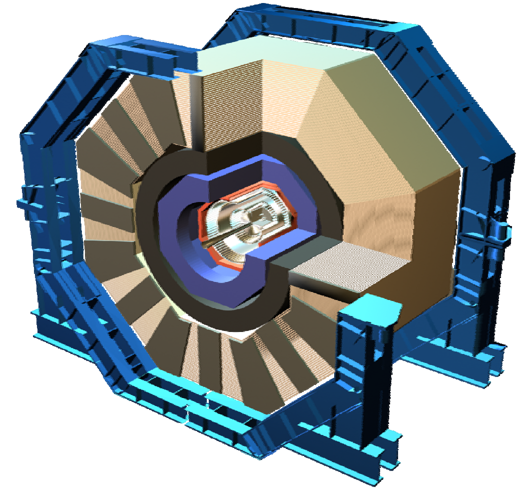
- ★ High granularity
- ★ Good two track resolution

❷The ILC Detector Concepts

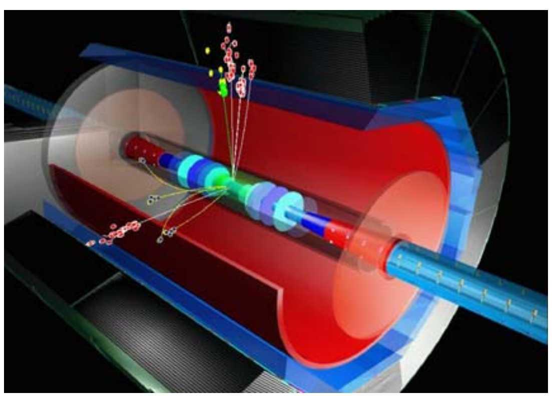
<u>The 3 Concepts:</u>

- ★ILC Detector Design work centred around 3 detector "concepts"
- ★Each will produce a costed conceptual design report (CDR) by end of **2006**
- ★Ultimately lead to TDRs

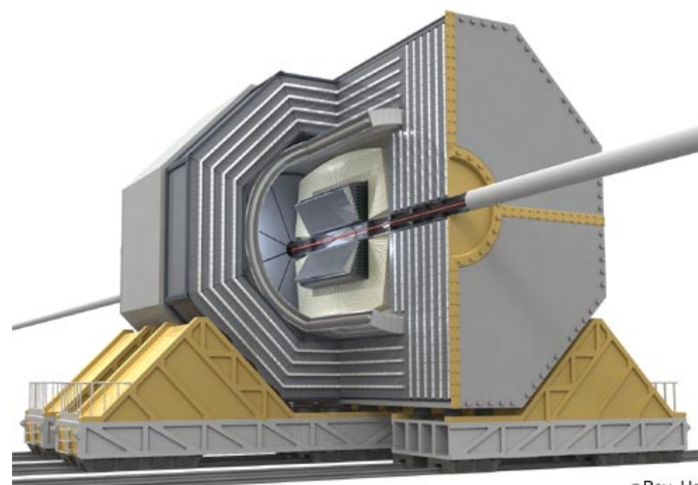
SiD : Silicon Detector



LDC : Large Detector Concept
(spawn of TESLA TDR)

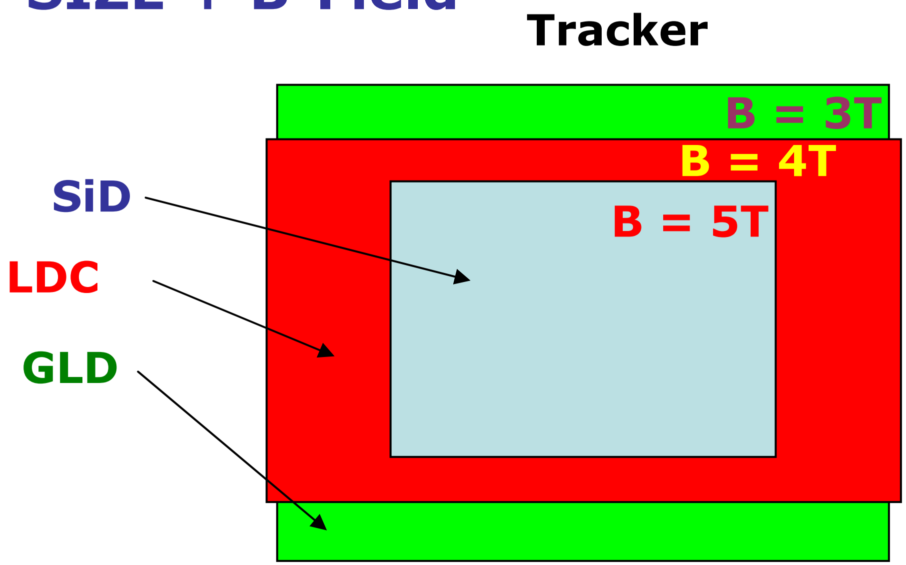


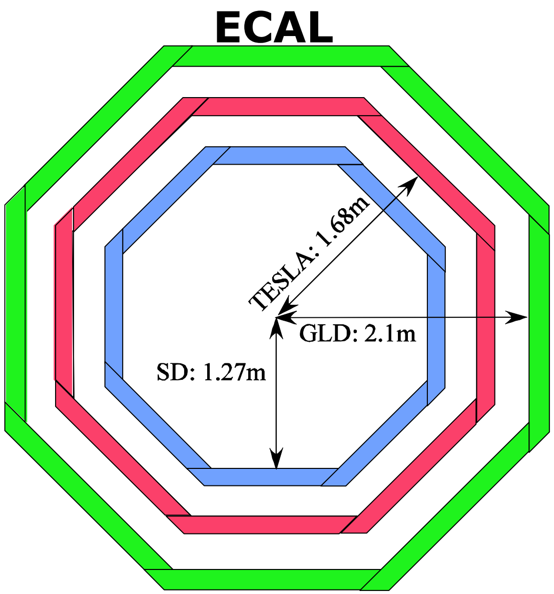
GLD : Global Large Detector



Main Differences:

- **SIZE + B-Field**





- **Central Tracker and ECAL**

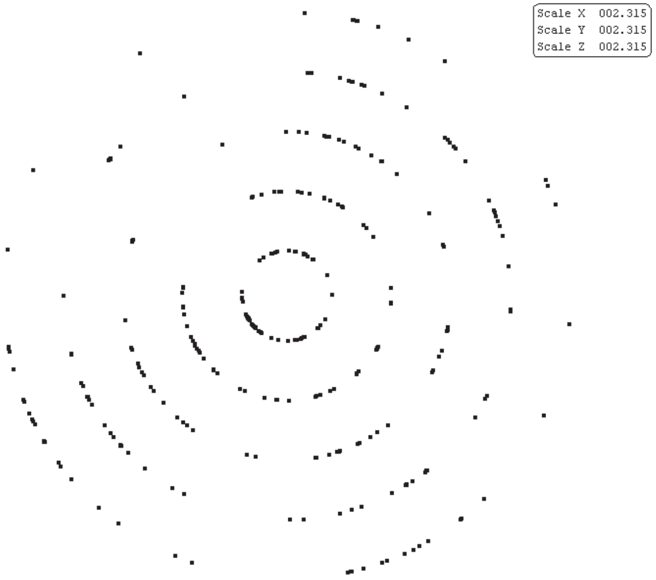
	SiD	LDC	GLD
Tracker	Silicon	TPC	TPC
ECAL	SiW	SiW	Pb/Scint

Design issues

The Big Questions (to first order):

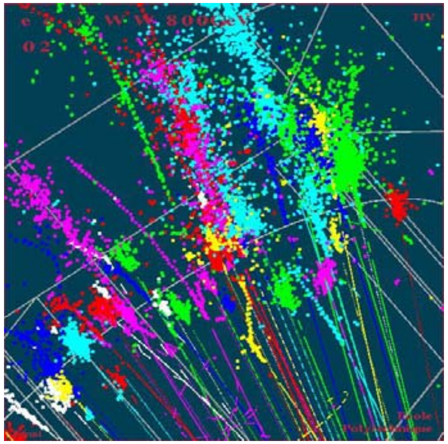
❶ CENTRAL TRACKER

★ **TPC vs Si Detector**



★ **Samples vs. granularity – can Si tracker give acceptable pattern recognition performance in a dense track environment ? (open question)**

❷ ECAL



- ★ Widely (but not unanimously) held view that a **high granularity SiW** ECAL is the right option
- ★ **BUT** it is **very expensive**
- ★ Need to demonstrate that physics gains outweigh cost
- ★ + optimize pad size/layers

❸ HCAL

- ★ High granularity digital vs lower granularity analog option

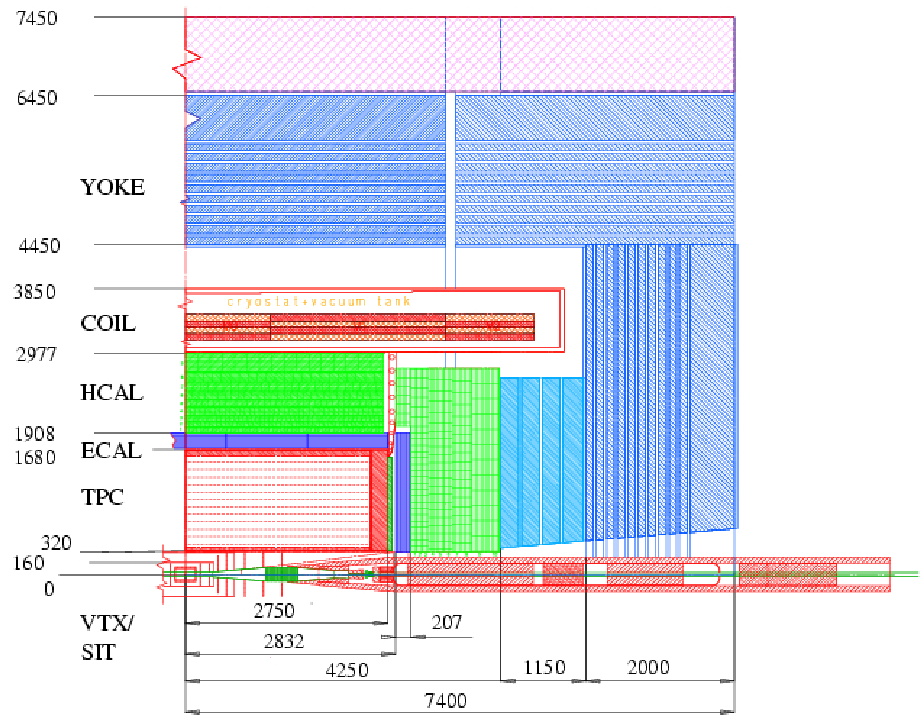
❹ SIZE

- ★ Physics argues for:
  large + **high granularity**
- ★ Cost considerations:
  small + **lower granularity**
- ★ What is the optimal choice (and how to decide) ???

> **Before discussing optimisation will give a brief overview of the TESLA TDR Detector design**

❸The TESLA Detector Concept

- ★Large Gaseous central tracking chamber **(TPC)**
- ★High granularity SiW **ECAL**
- ★High granularity **HCAL**
- ★Precision microvertex detector



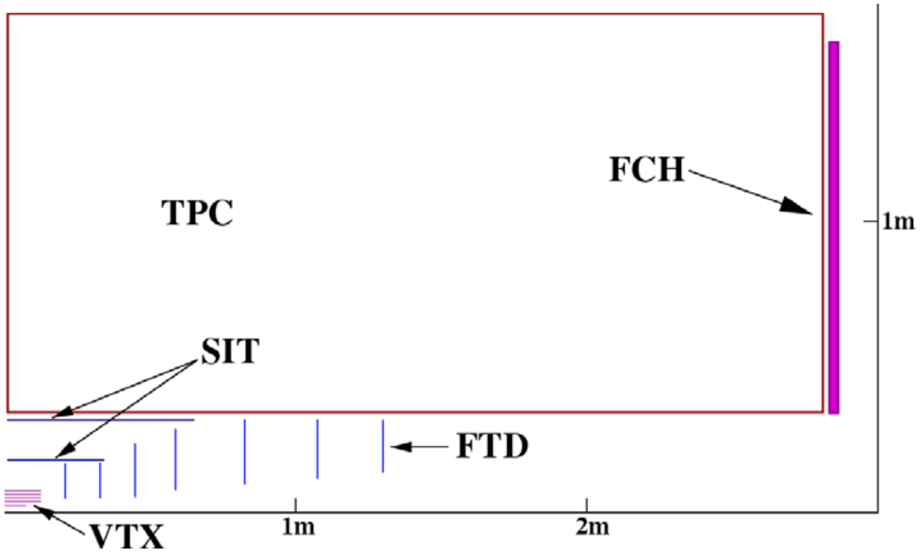
4 T Magnetic Field

- ★ ECAL/HCAL inside coil

- ✷ No hardware trigger, deadtime free continuous readout for the complete bunch train **(1 ms)**
- ✷ Zero suppression, hit recognition and digitisation in front-end electronics

NOTE: the LDC is similar (although slightly smaller) but the precise parameters still being discussed

Overview of Tracking System



Barrel region:
Pixel vertex detector (VTX)
Silicium strip detector (SIT)
Time projection chamber (TPC)

Forward region:
silicon disks (FTD)
Forward tracking chambers (FCH)
(e.g. silicon strips)

Requirements:

★ **Efficient track reconstruction down to small angles**

★ **Independent track finding in TPC and in VTX+SIT (7 points) alignment, calibration**

★ **Excellent momentum resolution $\sigma_{1/p} < 7 \times 10^{-5}$ /GeV**

★ **Excellent flavour-tagging capability**

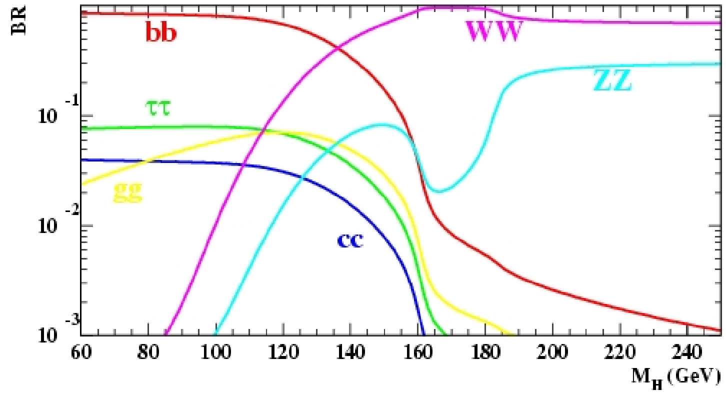
Quark-Flavour Identification

★ **Important for many physics analyses**

e.g. couplings of a low mass Higgs

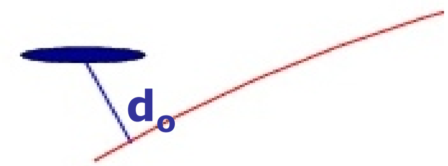
Want to test $g_{Hff} \sim m_f$

O(%) measurements of the branching ratios H→bb,cc,gg



★ **Also important for event ID and background rejection**

Flavour tagging requires a precise measurement of the impact parameter d_o

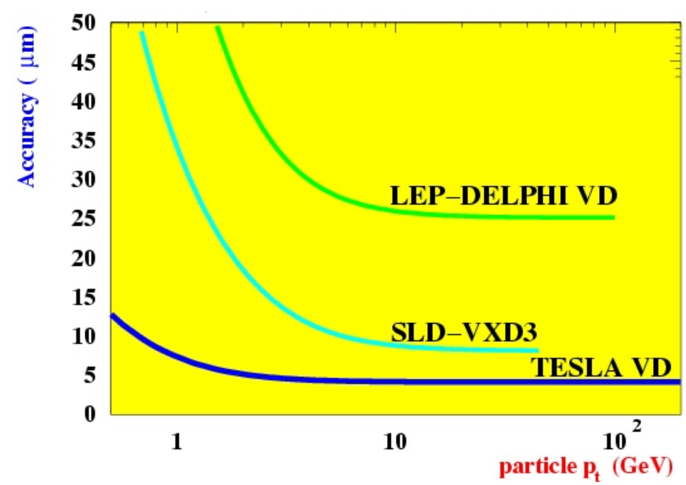


Aim for significant improvement compared to previous detectors

$$\sigma_{d0} \sim a \oplus b/p_T(\mathrm{GeV})$$

Goal: a<5mm, b<5mm

a: point resolution, b : multiple scattering



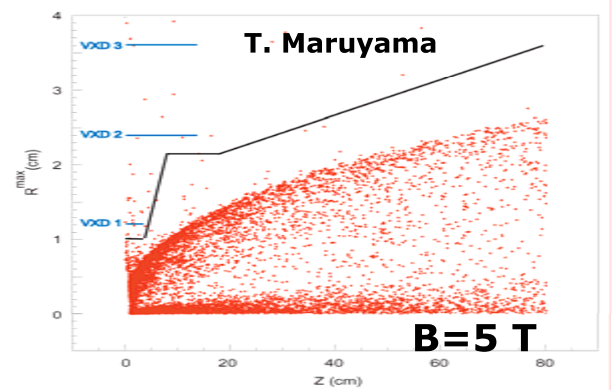
Main design considerations:

- ★Inner radius: as close to beampipe as possible, ~15-25 mm for impact parameter resolution
- ★Layer Thickness: as thin as possible suppression of γ conversions, minimize multiple scattering,...

Constraints:

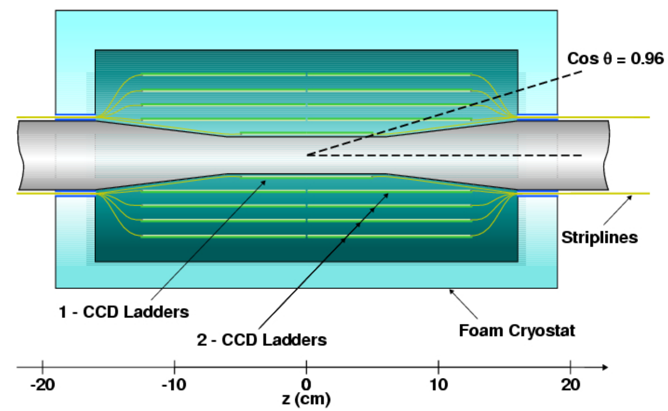
- ★ Inner radius limited by e^+e^- pair bgd. depends on the machine + B field
- ★ Layer thickness depends on Si technology

★ Ultimate design driven by machine + technology !



LDC Baseline design:

- ★Pixels : 20x20μm
- ★Point resolution : 5 μm
- ★Inner radius : 15 mm
- ★Polar angle coverage : $|\cos\theta|<0.96$

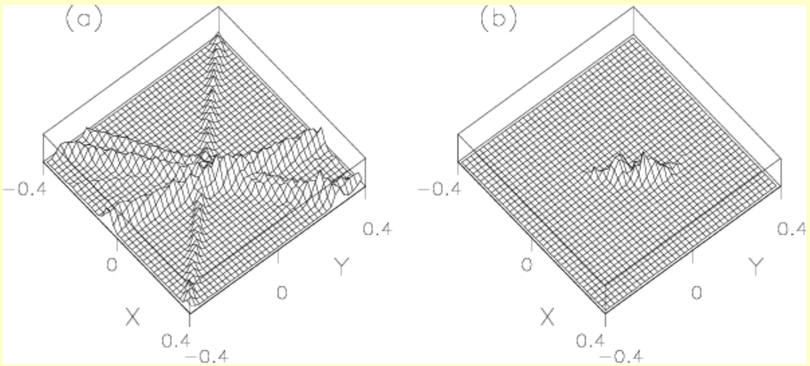


★ BUT ultimate design depends on worldwide detector R&D

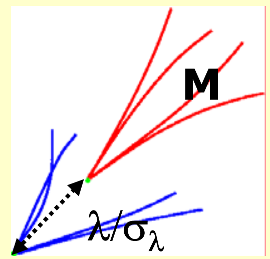
Flavour Tagging

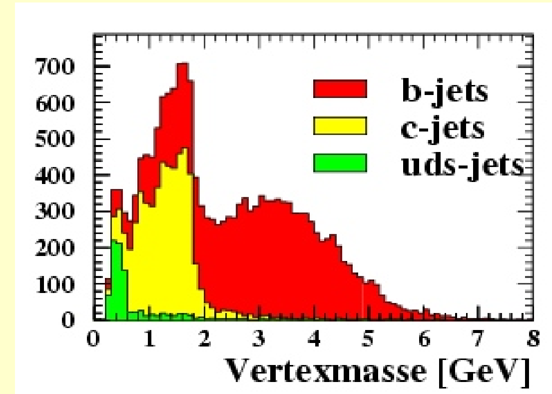
- **Powerful flavour tagging techniques (from SLD and LEP)**

e.g. topological vertexing



e.g. vertex mass



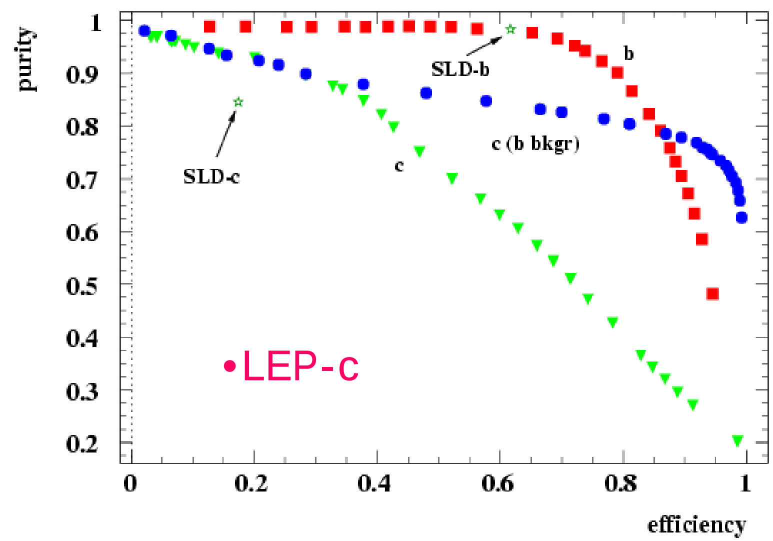


Expected resolution in r,ϕ and r,z

$\sigma \sim 4.2 \oplus 4.0/p_T(\mathrm{GeV})\ \mu m$

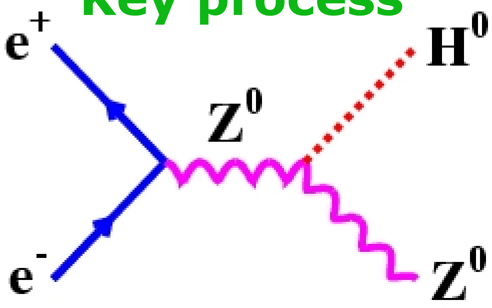
★ **Combine information in ANN**

- **charm-ID**
  significant improvement compared to SLD

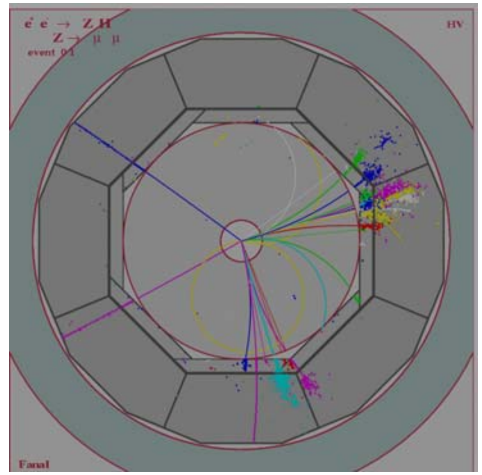


Momentum Resolution

Key process



$e^+e^- \rightarrow Z^* \rightarrow ZH \rightarrow \mu^+\mu^- X$

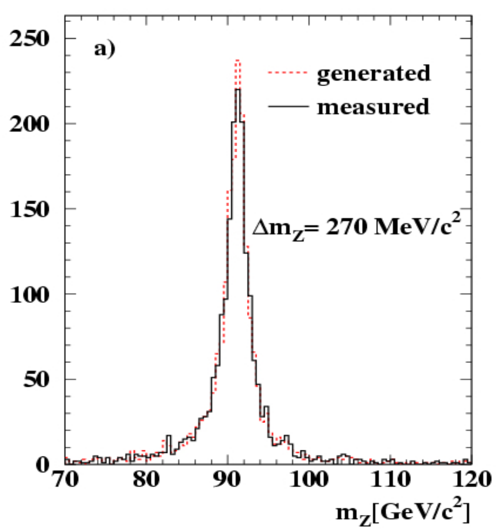


Recoil mass to μ+μ-
⇨ M_H σ_{ZH} , g_{ZHH}

$\mu^+\mu^-$ angular distribution
⇨ **Spin, CP,...**

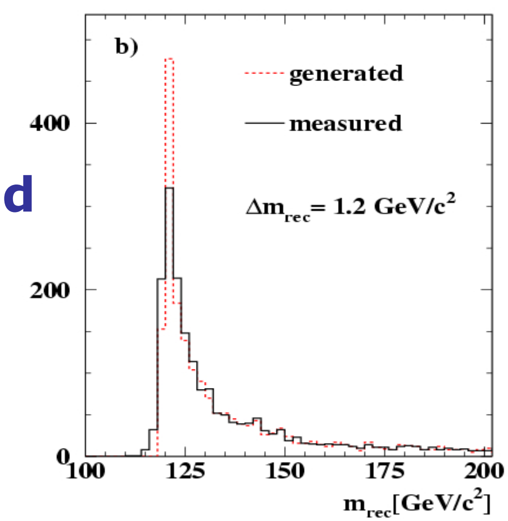
★ **Measurements depend on lepton momentum resolution**

goal: $\Delta M_{\mu\mu} < 0.1 \times \Gamma_Z$ ⇨ $\sigma_{1/p} = 7 \times 10^{-5}$ GeV^{-1}



⇦**rejection of background**

good resolution for ⇨ recoil mass



Motivation for a TPC

Advantages of a TPC:

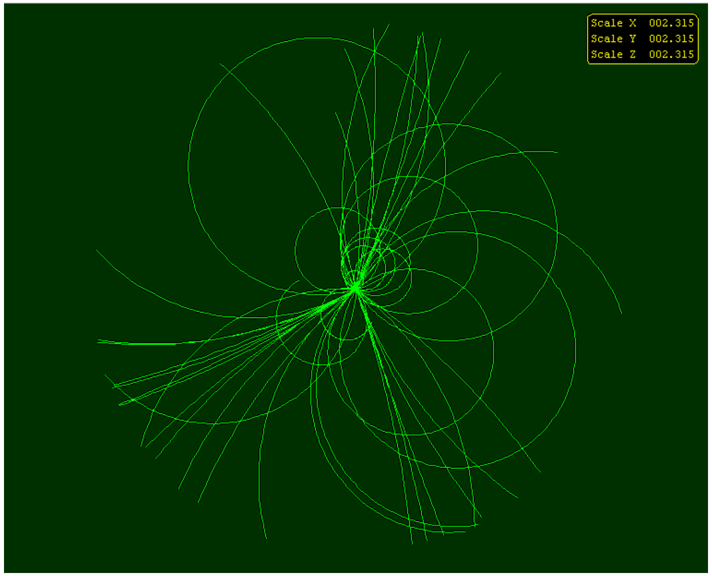
★ **Large number of 3D space points**
  good pattern recognition in dense track environment

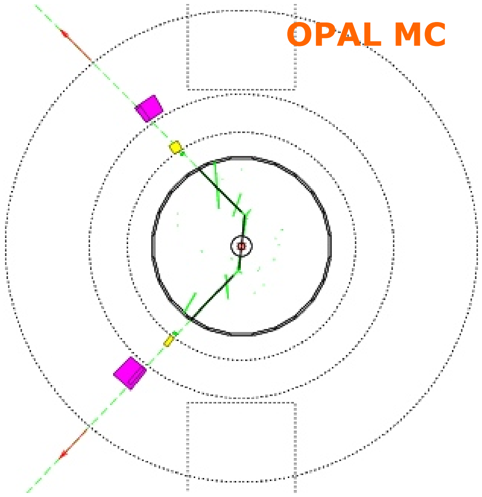
★ **Good 2 hit resolution**

★ **Minimal material**
  little multiple scattering
  little impact on ECAL
  conversions from background γ

★ **dE/dx gives particle identification**

★ **Identification of non-pointing tracks**
  aid energy flow reconstruction of V^0
  signals for new physics
    e.g. Reconstruction of kinks
    GMSB SUSY: $\tilde{\mu} \rightarrow \mu + \tilde{G}$

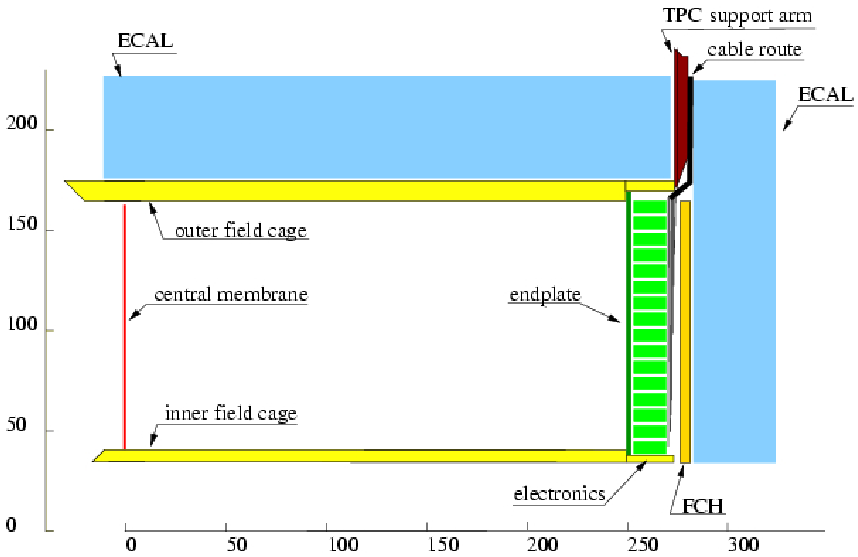




+ Large WORLDWIDE R&D effort suggests that a TPC for an ILC detector is viable

+ Size helps : $\sigma_{1/p} \sim \frac{1}{BR^2}$

TPC Conceptual Design



★ **Readout on 2x200 rings of pads**

★ **Pad size 2x6mm**

★ **Hit resolution: σ < 140 μm**

ultimate aim σ ~100 μm

Drift velocity ~ 5cm μs^{-1}

$ArC0_2$-CH_4 (93-2-5)%

Total Drift time ~ 50μs, integrate over ~160 BX

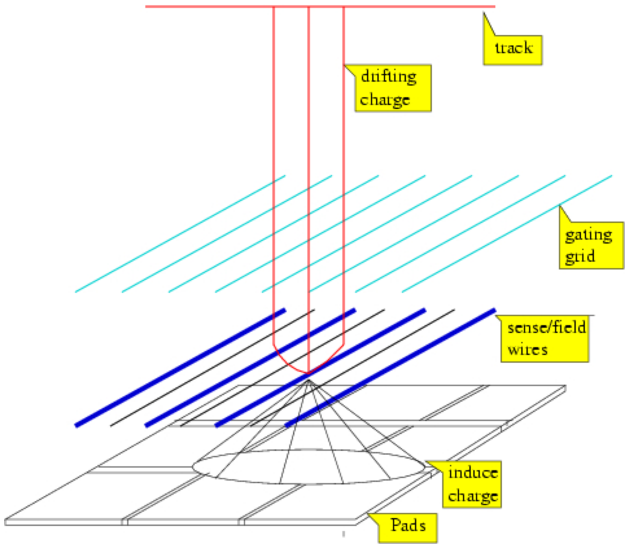
Background ⇨ 80000 hits in TPC

8×10^8 readout cells (1.2 MPads+20MHz)

⇨0.1% occupancy

No problem for pattern recognition/track reconstruction

Gas Amplification



Previous TPCs used multiwire chambers not ideal for ILC.

resolution limited by:

- **ExB effects**

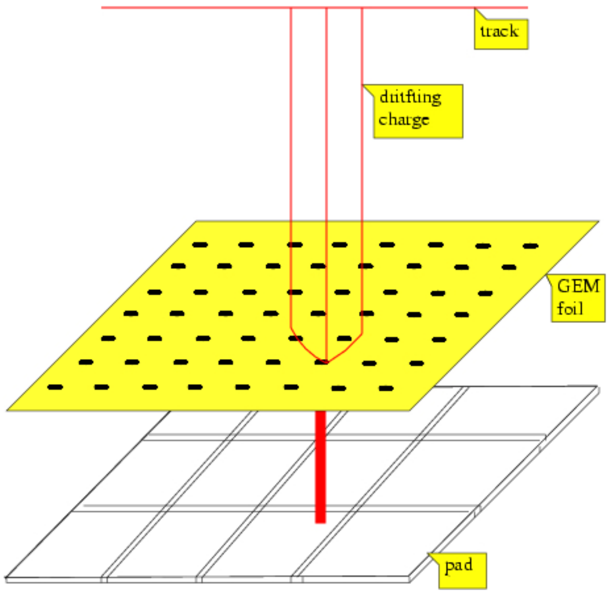
  angle between sense wires and tracks
- **Strong ion feedback – requires gating**
- **Thick endplanes – wire tension**

Gas Electron Multipliers or MicroMEGAS

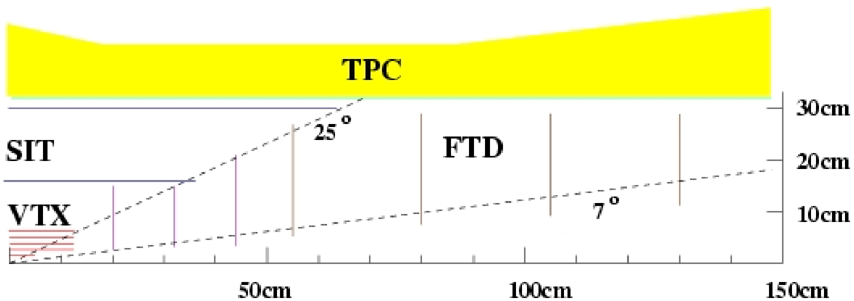
- **2 dimensional readout**
- **Small hole separation ⇨**

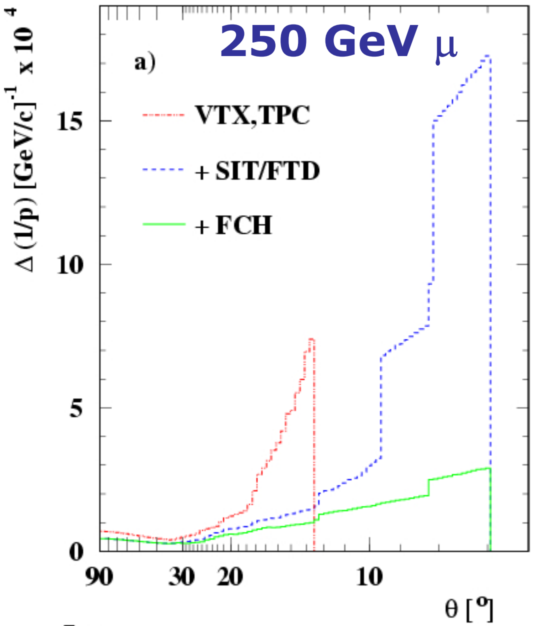
  reduced ExB effects ⇨

  improved point resolution
- **Natural supression of ion feedback**
- **No wire tension ⇨ thin endplates**



Intermediate Tracking Chambers





- At low angles TPC/VTX momentum resolution is degraded

Tracking Improved by:

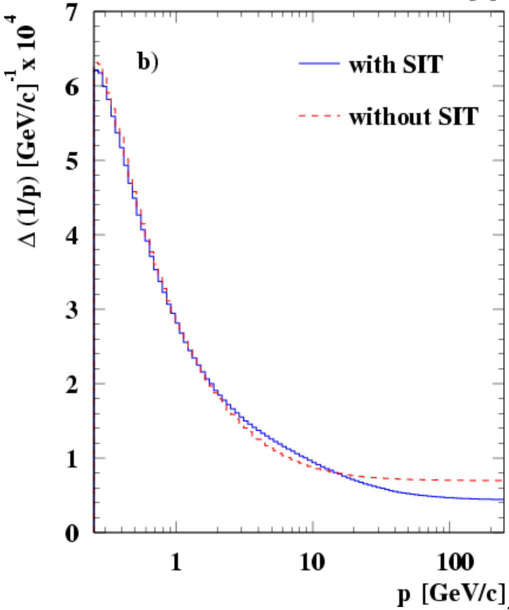
SIT: 2 Layers of SI-Strips $\sigma_{r\phi} = 10\ \mu m$

FTD: 7 Disks

3 layers of Si-pixels $50\text{x}300\mu m^2$

4 layers of Si-strips $\sigma_{r\phi} = 90\mu m$

TPC : $\sigma(1/p) = 2.0 \times 10^{-4}\ GeV^{-1}$
+VTX: $\sigma(1/p) = 0.7 \times 10^{-4}\ GeV^{-1}$
+SIT : $\sigma(1/p) = 0.5 \times 10^{-4}\ GeV^{-1}$



Calorimetry at the ILC

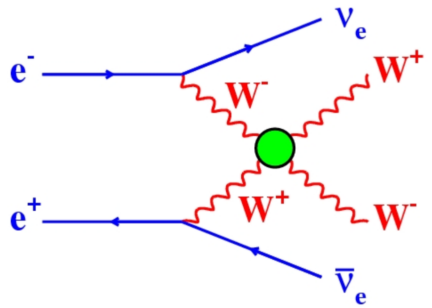
THIS ISN'T EASY !

Jet energy resolution:

Best at LEP (ALEPH):
$\sigma_E/E = 0.6(1+|\cos\theta_{Jet}|)/\sqrt{E(\text{GeV})}$

ILC GOAL:
$\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$

★ **Jet energy resolution directly impacts physics sensitivity**

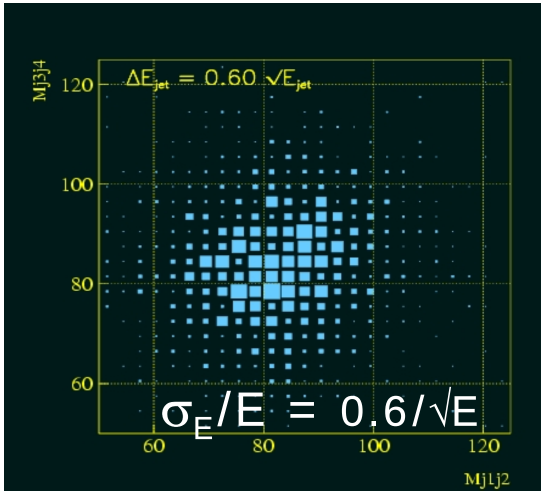


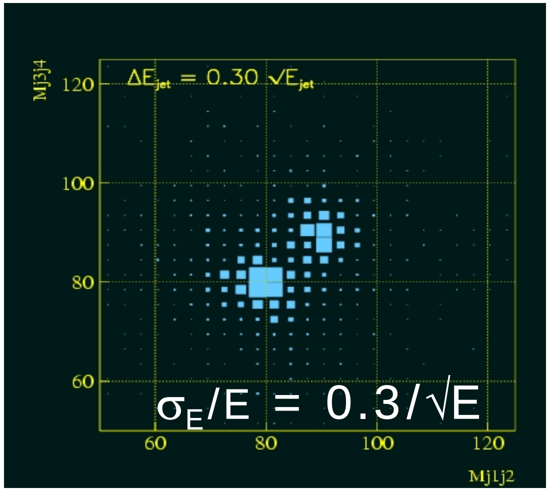
Often-quoted Example:

If the Higgs mechanism is not responsible for EWSB then QGC processes important

$e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$, $e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq$

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states



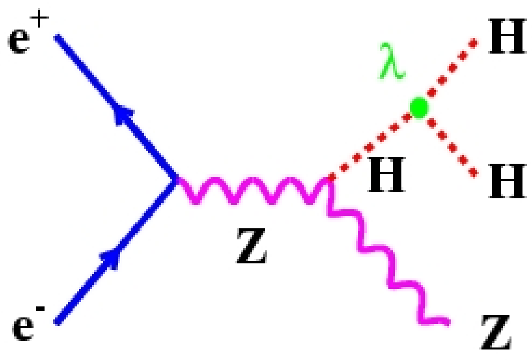


★ **EQUALLY applicable to any final states where want to separate $W\rightarrow qq$ and $Z\rightarrow qq$!**

Another example.....

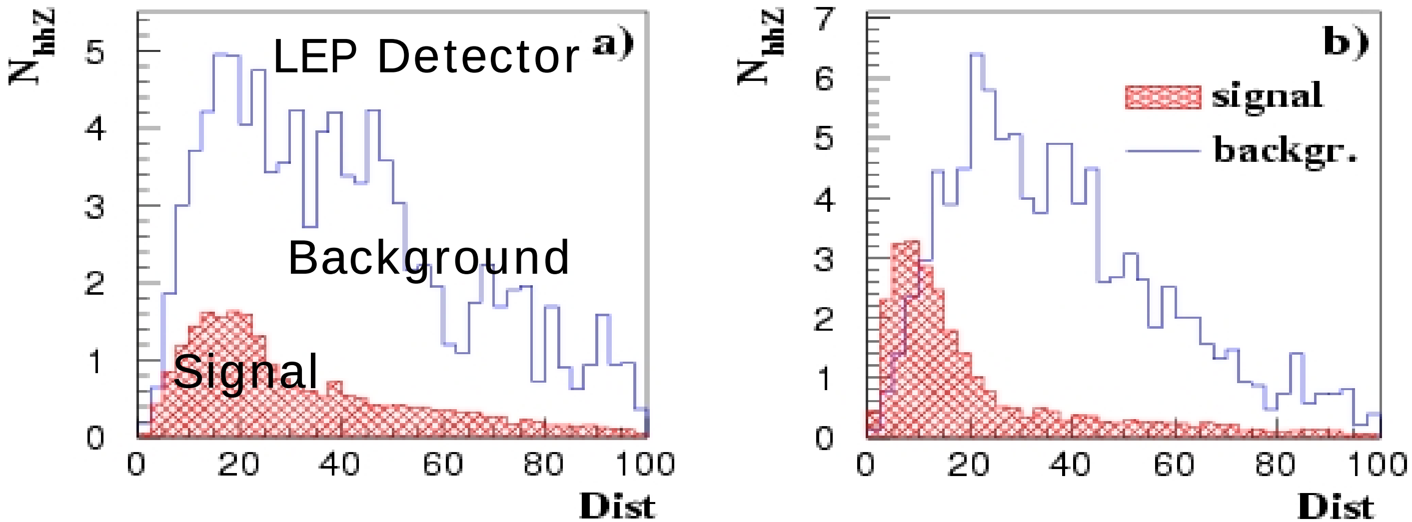
e.g. measurement of trilinear HHH coupling via **$e^+e^- \to ZHH \to qqbbbb$**

- ★Probe of Higgs potential
- ★Small cross-section
- ★Large combinatoric background
- ★6 jet final state



- Use jet-jet invariant masses to extract signal

$$Dist=((M_H- M_{12})^2+ (M_z- M_{34})^2 + (M_H- M_{56})^2)^{1/2}$$



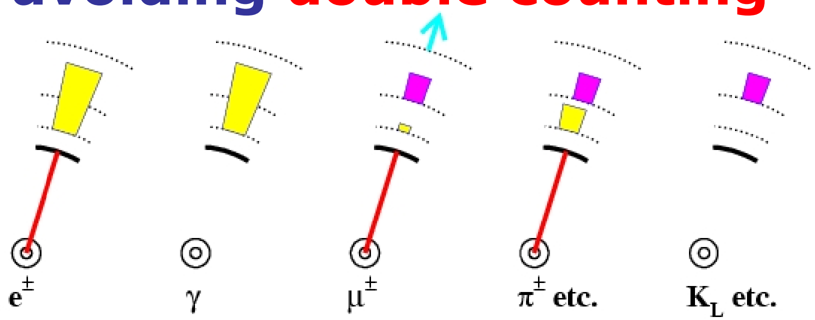
★ **Good jet energy resolution give ~5σ signal**

The Particle Flow Paradigm

- ★ Much ILC physics depends on reconstructing invariant masses from jets in hadronic final states
- ★ Often kinematic fits won't help – Unobserved particles (e.g. ν) + Beamstrahlung, ISR
- ★ Aim for jet energy resolution ~ Γ_Z for "typical" jets - the point of diminishing return
- ★ Jet energy resolution is the key to calorimetry at the ILC
- ★ Generally (but not uniformly) accepted that PARTICLE FLOW is the only way to achieve $\sigma_E/E = 0.3/\sqrt{E(GeV)}$

<u>The Particle Flow Analysis (PFA):</u>

- Reconstruct momenta of individual particles avoiding double counting



Charged particles in tracking chambers
Photons in the ECAL
Neutral hadrons in the HCAL (and possibly ECAL)

- ★ Need to separate energy deposits from different particles
- ★ Not calorimetry in the traditional sense

★ **TESLA TDR resolution : $\sim 0.30\sqrt{E_{jet}}$**

Component	Detector	Frac. of jet energy	Particle Resolution	Jet Energy Resolution
Charged Particles($X^{\pm}$)	Tracker	0.6	$10^{-4}\,E_X$	neg.
Photons(γ)	ECAL	0.3	$0.11\sqrt{E_\gamma}$	$0.06\sqrt{E_{jet}}$
Neutral Hadrons(h^0)	HCAL	0.1	$0.4\sqrt{E_h}$	$0.13\sqrt{E_{jet}}$

★ **Energy resolution gives $0.14\sqrt{E_{jet}}$ (dominated by HCAL)**

★ **In addition, have contributions to jet energy resolution due to "confusion", i.e. assigning energy deposits to wrong reconstructed particles (double-counting etc.)**

$$\sigma_{jet}^2 = \sigma_{x^\pm}^2 + \sigma_\gamma^2 + \sigma_{h^0}^2 + \sigma_{confusion}^2 + \sigma_{threshold}^2$$

★ **Single particle resolutions not the dominant contribution to jet energy resolution !**

granularity more important than energy resolution

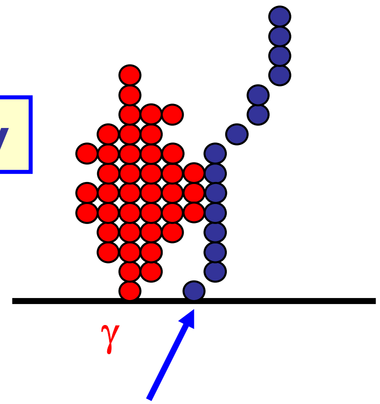
PFA : Basic issues

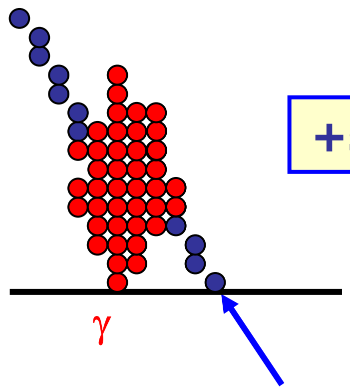
- ★ What are the main issues for PFA ?
- ★ Separate energy deposits + avoid double counting

e.g.

- ★ Need to separate "tracks" (charged hadrons) from photons

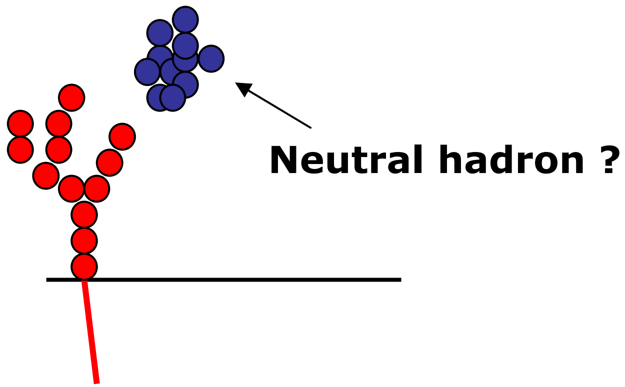
granularity





+software

- ★ Need to separate neutral hadrons from charged hadrons



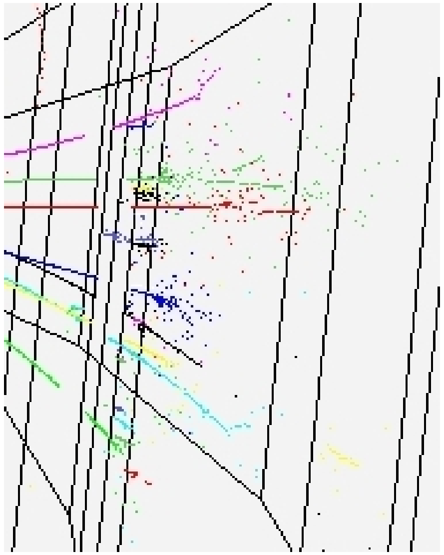
Granularity helps
But less clear…

Calorimeter Requirements

- Excellent energy resolution for jets – i.e. high granularity
- Good energy/angular resolution for photons – how good ?
- Hermeticity
- Reconstruction of non-pointing photons

Particle flow drives calorimeter design:

★ Separation of energy deposits from individual particles
- small X_0 and $R_{Moliere}$: compact showers
- high lateral granularity : $O(R_{Moliere})$



★ Discrimination between EM and hadronic showers
- small X_0/λ_I
- longitudanal segmentation

★ Containment of EM showers in ECAL

★ SiW: sampling calorimeter is a good choice

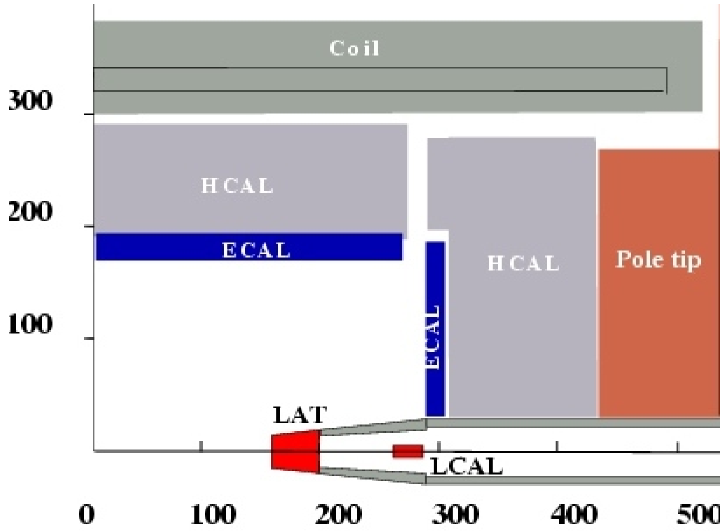
- Tungsten is great : $X_0 / \lambda_I = 1/25$, $R_{Moliere} \sim 9mm$

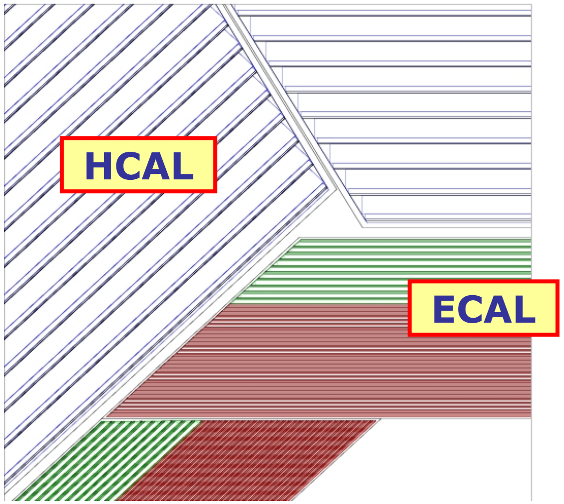
  EM showers are short/Had showers long

  + narrow EM showers
- However not cheap !

TESLA Calorimeter Concept

ECAL and HCAL inside coil





ECAL: silicon-tungsten (SiW) calorimeter:

- **Tungsten : $X_0\ /\lambda_{had} = 1/25$, $R_{Moliere} \sim 9mm$**
  (gaps between Tungsten increase effective $R_{Moliere}$)
- **Lateral segmentation: $1cm^2$ matched to $R_{Moliere}$**
- **Longitudinal segmentation: 40 layers ($24\, X_0$, $0.9\lambda_{had}$)**
- **Resolution: $\sigma_E/E = 0.11/\sqrt{E(GeV)} \oplus 0.01$**

$$\sigma_\theta = 0.063/\sqrt{E(GeV)} \oplus 0.024 \text{ mrad}$$

Hadron Calorimeter

Highly Segmented – for Energy Flow

- **Longitudinal: 40 samples**
- **4 – 5 λ (limited by cost - coil radius)**
- **Would like fine (1 cm^2 ?) lateral segmentation**
- **For 10000 m^2 of 1 cm^2 HCAL = 10^8 channels – cost !**

Two Options:

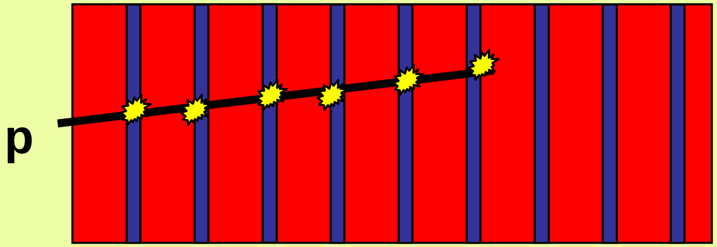
★ **Tile HCAL (Analogue readout)**
  Steel/Scintillator sandwich
  Lower lateral segmentation
    5x5 cm^2 (motivated by cost)

★ **Digital HCAL**
  High lateral segmentation
    1x1 cm^2
  digital readout (granularity)
  RPCs, wire chambers, GEMS…

The Digital HCAL Paradigm

- **Sampling Calorimeter:**

  Only sample small fraction of the total energy deposition



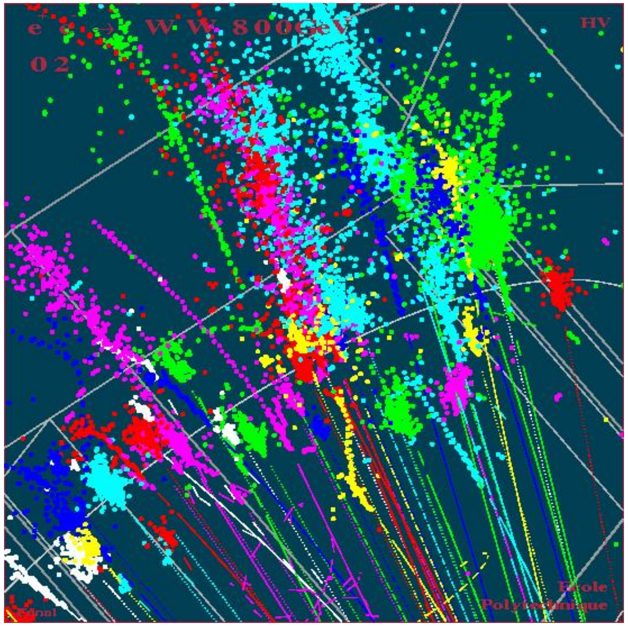
- **Energy depositions in active region follow highly asymmetric Landau distribution**

Calorimeter Reconstruction

★ **High granularity calorimeter – <u>very different</u> from previous detectors**

★ **"Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction**

★ **+PARTICLE FLOW**



★ **ILC calorimeter performance = HARDWARE + SOFTWARE**

★ **Performance will depend on the software algorithm**

➡ **Nightmare from point of view of detector optimisation**

❹ PFA and ILC detector design ?

PFA plays a special role in design of an ILC Detector

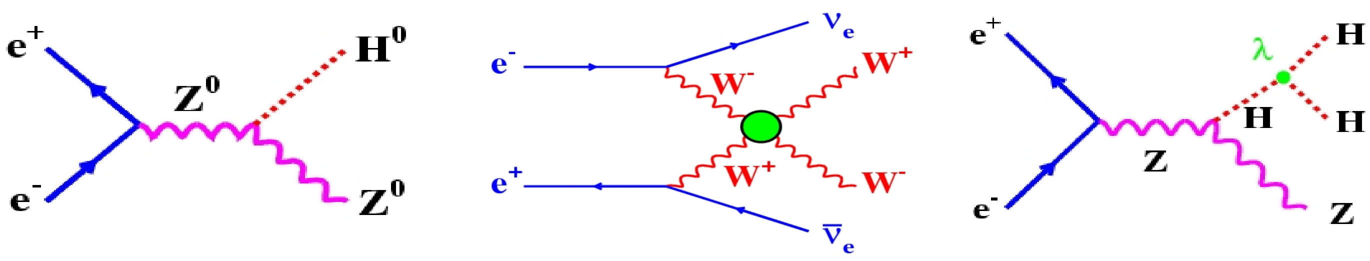
- ★ **VTX : design driven by heavy flavour tagging, machine backgrounds, technology**
- ★ **Tracker : design driven by σ_p, track separation**
- ★ **ECAL/HCAL : single particle σ_E not the main factor**
  - ➡ **<u>jet energy resolution</u> ! Impact on particle flow drives calorimeter design + detector size, B field, …**

PFA is a (the?) major cost driver for the ILC Detectors

<u>BUT:</u> **Don't really know what makes a good detector from point of view of PFA (plenty of personal biases – but little hard evidence)**

<u>How to optimise/compare ILC detector design(s) ?</u>

- ★ **Need to choose the key "benchmark" processes (DONE)**

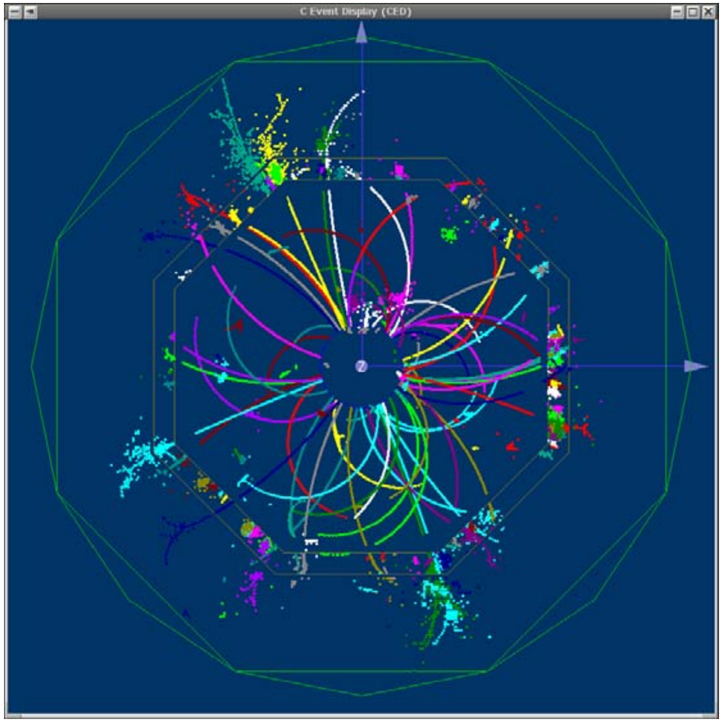


★ **The rest is VERY DIFFICULT !**

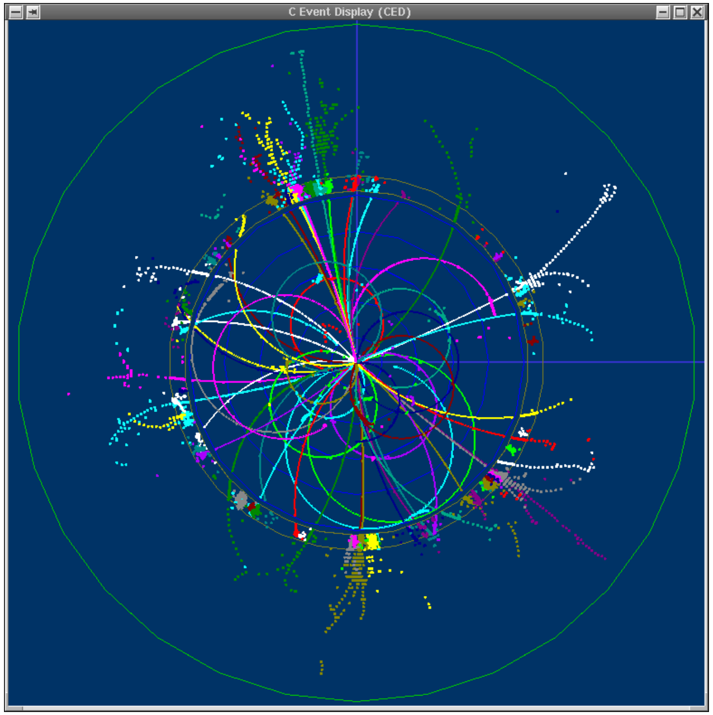
For example:

★ **Would like to compare performance of say LDC and SiD detector concepts**

e.g. tt event in LDC



e.g. tt event in SiD

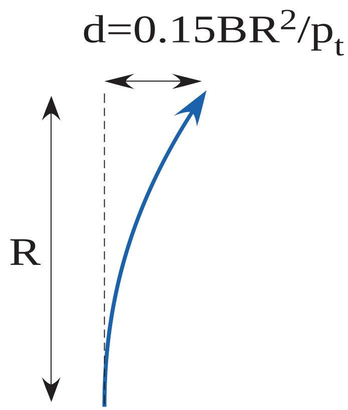


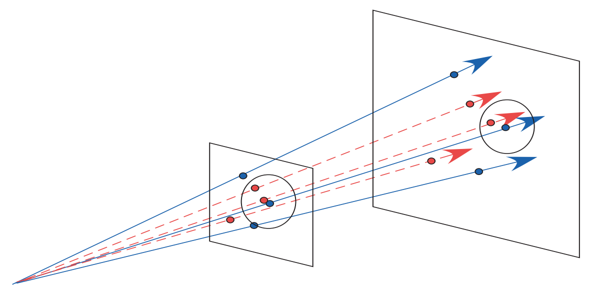
★ **However performance = DETECTOR + SOFTWARE**

★ **Non-trivial to separate the two effects**

PFA : "Figure of Merit"

- **For good jet energy resolution need to separate energy deposits from different particles**
  - **Large detector – spatially separate particles**
  - **High B-field – separate charged/neutrals**
  - **High granularity ECAL/HCAL – resolve particles**





Often quoted "figure-of-merit": $\frac{BR^2}{\sigma}$

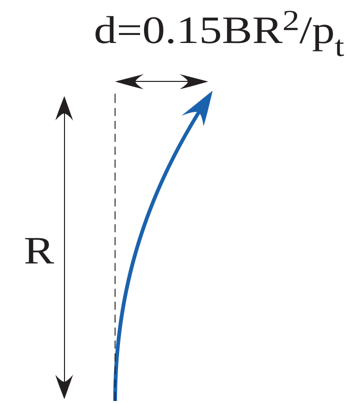
- BR^2 ← **Separation of charge/neutrals**
- σ ← **Calorimeter granularity/$R_{Moliere}$**

- **Physics argues for : large + high granularity + ⇧ B**
- **Cost considerations: small + lower granularity + ⇩ B**

But not that simple…….

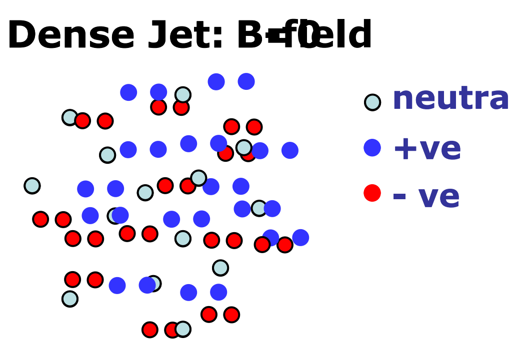
- Often quoted F.O.M. for jet energy resolution:
  BR^2/σ ($R=R_{ECAL}$; σ = 1D resolution)
  i.e. transverse displacement of tracks/"granularity"
- Does this work ?
  - compare **OPAL/ALEPH** (W→qq no kinematic fit)

	BR^2	BR^2/σ	$\sigma_E/\sqrt{E}$	R^2/σ
OPAL	2.6 Tm²	26 Tm	0.9	60 m
ALEPH	5.1 Tm²	170 Tm	0.6	110 m



My guess for FoM: R^2/σ

- **B-field just spreads out energy deposits from charged particles in jet**
  – not separating collinear particles
- **Size more important - spreads out energy deposits from all particles**
- **R more important than B ??**
- **Don't really know what drives PFA performance….**



❺ A New Particle Flow Algorithm

- Developed new "state of art" particle flow algorithm with aim of directly feeding into ILC detector design studies
- Work-in-Progress – but does a pretty good job + much better feel for what really matters….

Philosophy:

- Try to develop "generic" PFA which will take advantage of a high/very high granularity ECAL
- ECAL/HCAL Clustering + PFA performed in a single algorithm
- Aim for fairly generic algorithm
  - applicable to multiple detector concepts
- Use tracking information to help ECAL/HCAL clustering
- Initial clustering is fairly loose
  - ⇨ ProtoClusters
- ProtoClusters are then linked together…
- Finally Clusters linked to tracks at a number of levels

Will describe this in some detail to highlight some of the issues involved…

The Algorithm: PandoraPFA

Overview:

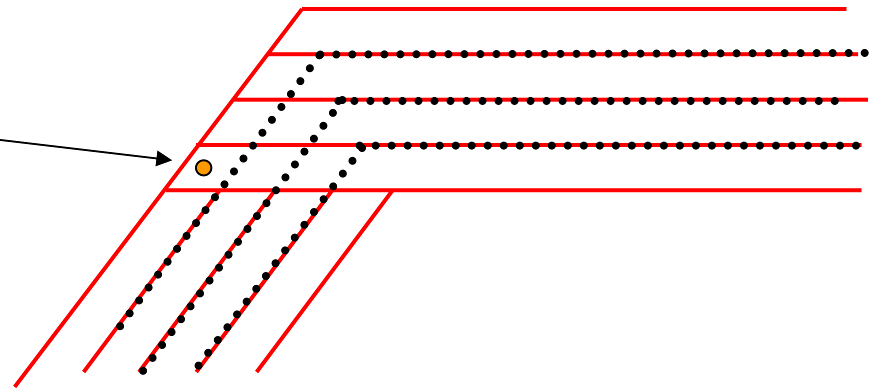
- ★ **Preparation**
  - ★ **Isolation cuts, hit ordering, track quality**
- ★ **Initial clustering to form ProtoClusters**
  - ★ **ProtoClusters are heavyweight object:**
    - ★ **collection of hits**
    - ★ **know how to grow (configured when created)**
    - ★ **information about shape, direction, isPhoton,…**
    - ★ **+much more…**
- ★ **Cluster association/merging**
  - ★ **Tight Topological linking of clusters**
  - ★ **Looser merging of clusters**
  - ★ **Track-driven merging**
- ★ **PFA**
  - ★ **Final track-cluster matching**

- **In the next few slides will outline what's done in each stage - skipping over details**
- **Aim to give impression of the issues involved in this new type of "calorimetry"**

Preparation: I

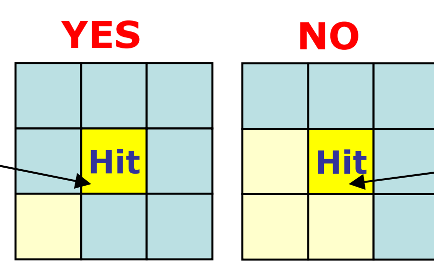
★ **Arrange hits into PSEUDOLAYERS**
- **i.e. order hits in increasing depth within calorimeter**
- **PseudoLayers follow detector geometry**
- **therefore reduce algorithm dependence on detector geometry**

- **Hit in early layer**
- **But high PseudoLayer**



★ **In addition tag hits as possibly track-like by pulse-height/isolation**

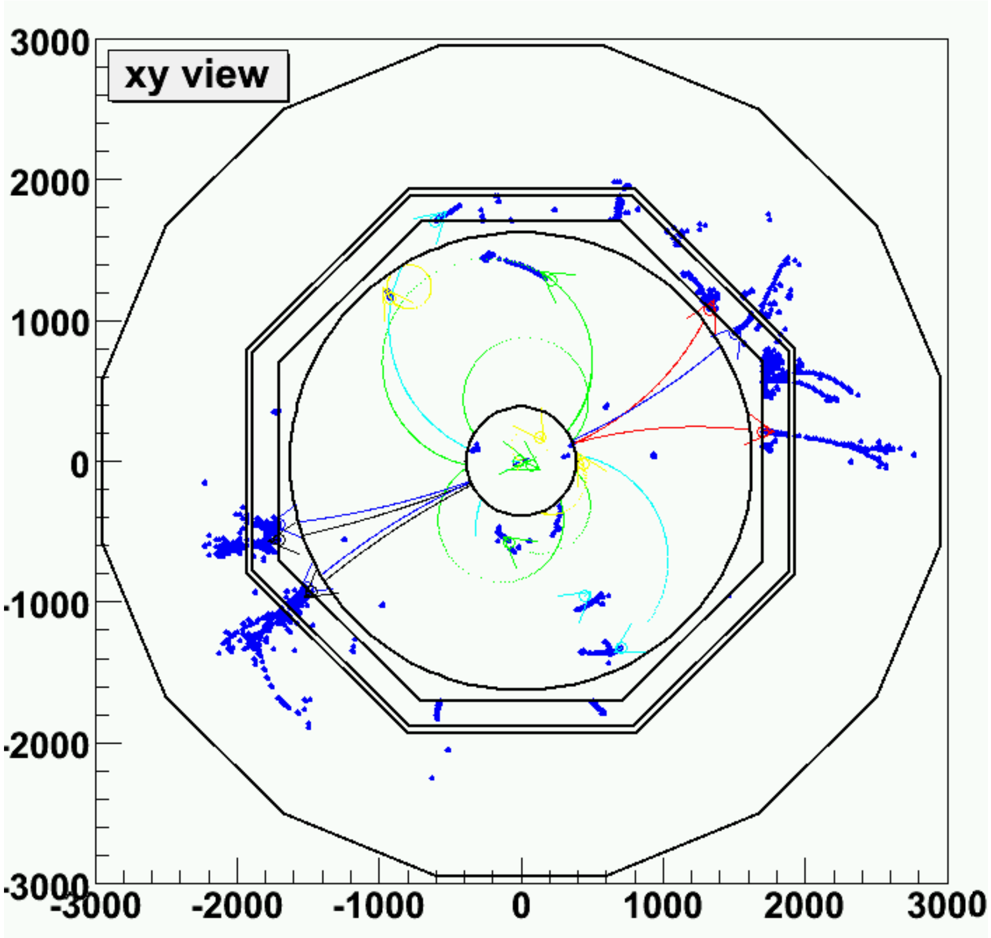
Could be from minimum-ionizing track



Likely to be from EM cluster

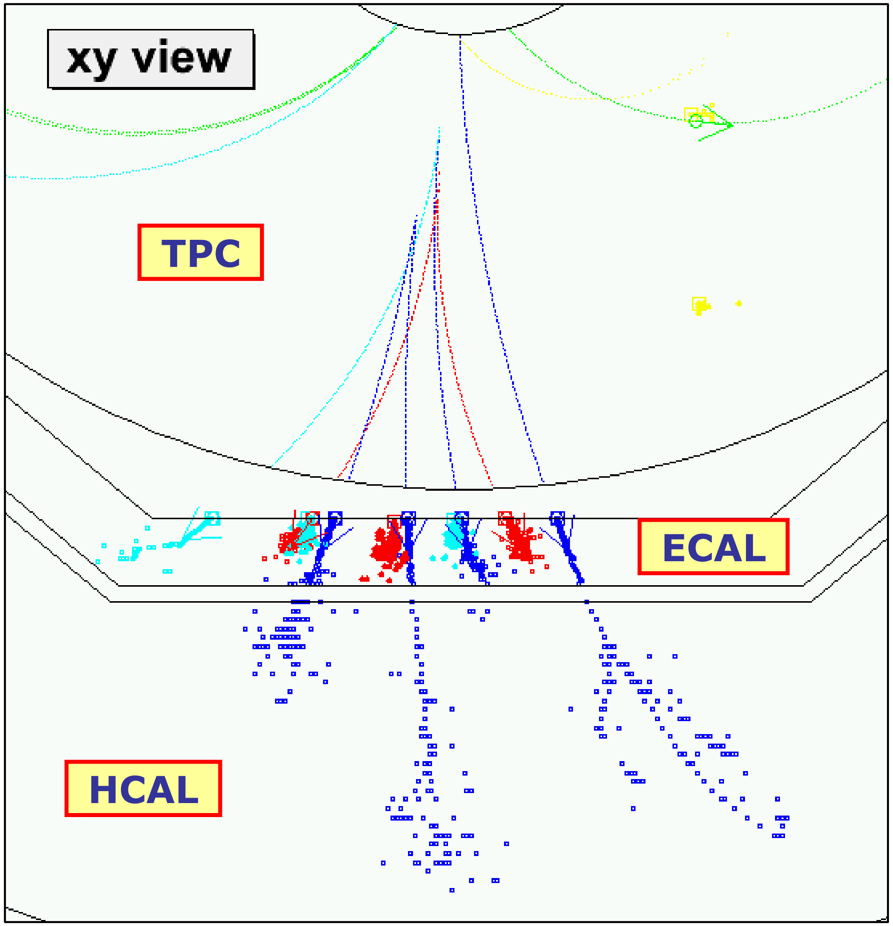
Preparation II: Isolation

- ★ Divide hits into isolated and non-isolated
- ★ Only cluster **non-isolated** hits
- ★ "Cleaner"/Faster clustering
- ★ Significant effect for scintillator HCAL (large cross section for neutrons)



- ✦ Removal of isolated hits degrades HCAL resolution
- ✦ <u>e.g. LDC scintillator HCAL</u>
  $50\ \%/\sqrt{E/\mathrm{GeV}} \rightarrow$
  $60\ \%/\sqrt{E/\mathrm{GeV}}$

Preparation III: Tracking



★ Tracks formed from MC Hits in **TPC/FTD/VTX**

★ Simple Helix Fit $\Rightarrow$ track params

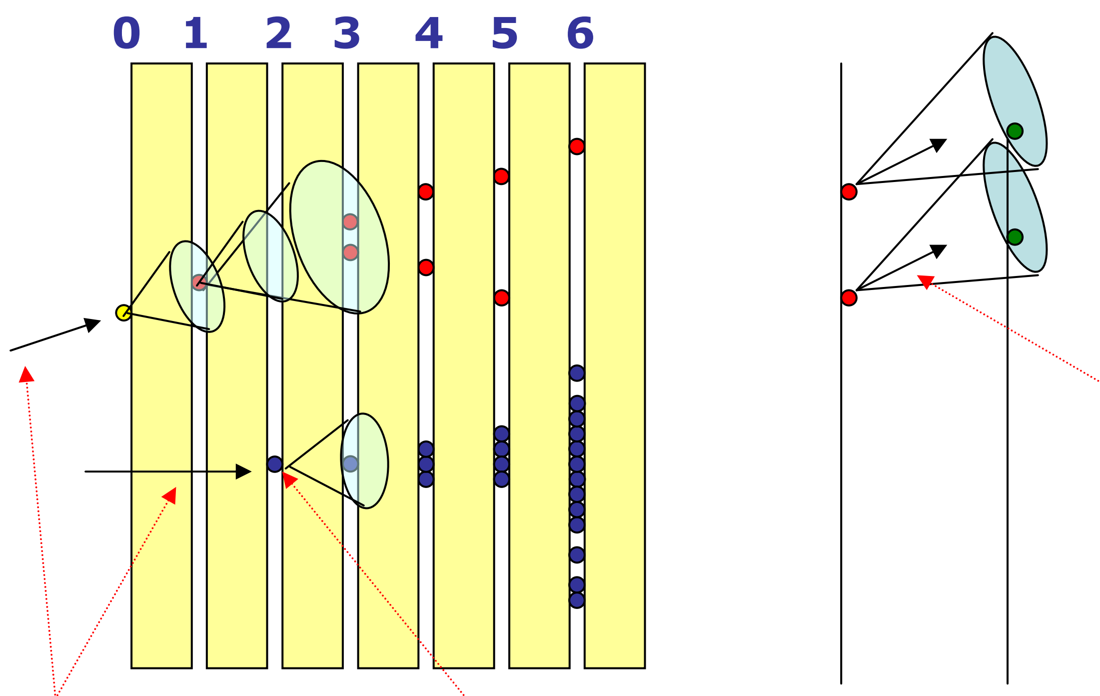
★ Cuts (primary tracks):

- $|d_0| < 5$ mm
- $|z_0| < 5$ mm
- >4 non-Si hits

+ V_0 and Kink finding:

ECAL/HCAL Clustering

- Start at inner layers and work outward
- Associate Hits with existing **Clusters**
- If multiple clusters **"want"** hit then **Arbitrate**
- Step back **N** layers until associated
- Then try to associate with hits in current layer (M pixel cut)
- If no association made form new Cluster
- + tracks used to seed clusters



Simple cone algorithm based on current direction + additional N pixels

Cones based on either:
initial PC direction or
current PC direction

Initial cluster direction

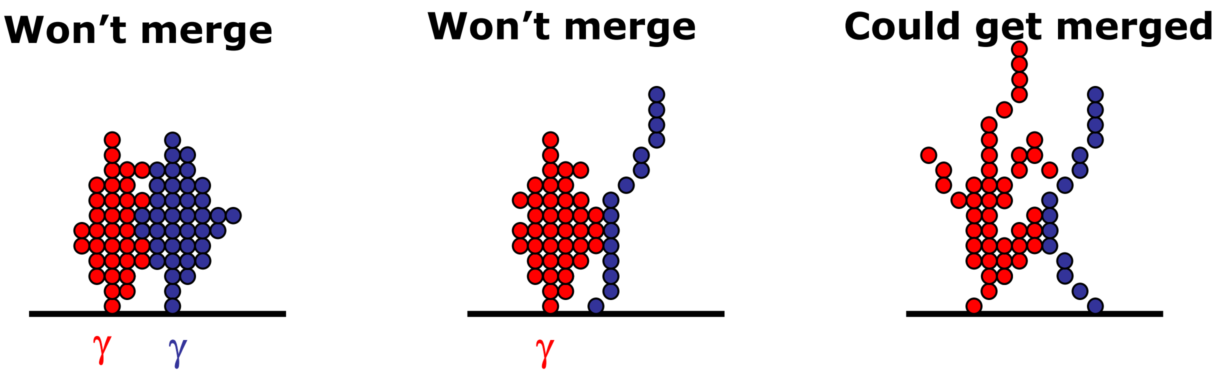
Unmatched hits seeds new cluster

Cluster Association

- ✦ By design, clustering errs on side of caution
  i.e. clusters tend to be split
- ✦ **Philosophy:** easier to put things together than split them up
- ✦ Clusters are then associated together in two stages:
  - 1) Tight cluster association - clear topologies
  - 2) Loose cluster association – catches what's been missed but rather crude

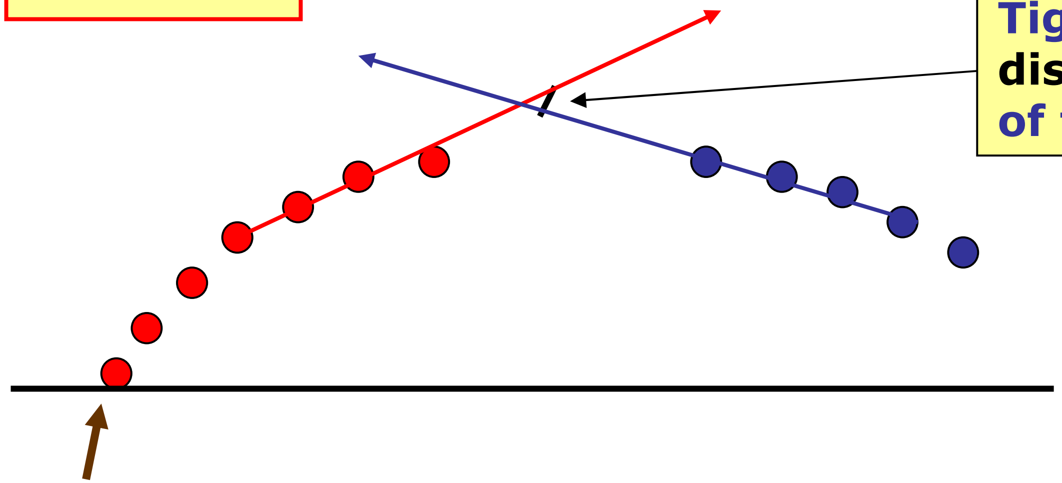
Photon ID

- ★ Photon ID plays important role
- ★ Simple "cut-based" photon ID applied to all clusters
- ★ Clusters tagged as photons are immune from association procedure – just left alone



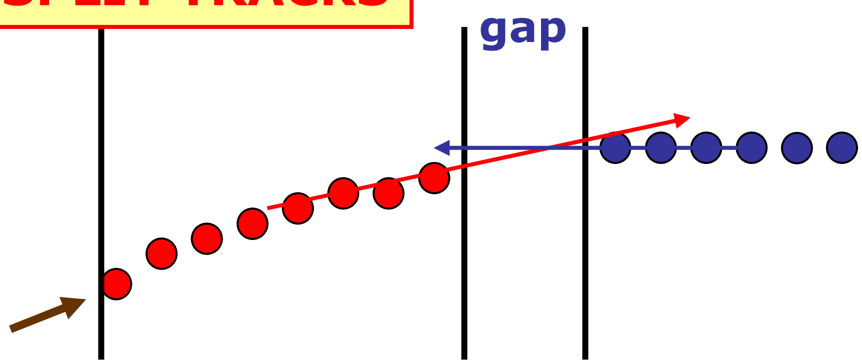
Cluster Association I : track merging

LOOPERS



Tight cut on extrapolation of distance of closest approach of fits to ends of tracks

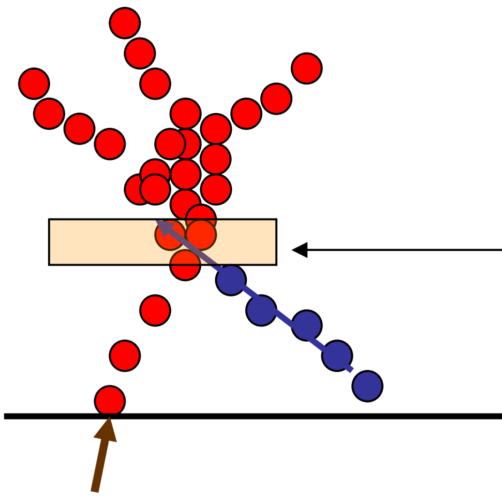
SPLIT TRACKS



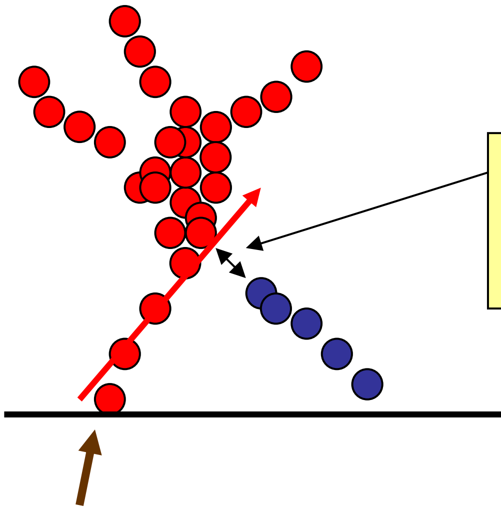
Tight cut on extrapolation of distance of closest approach of fits to end of inner tracks and start of outer track

Cluster Association II : Backscatters

- ★ **Forward propagation clustering algorithm has a major drawback: back scattered particles form separate clusters**



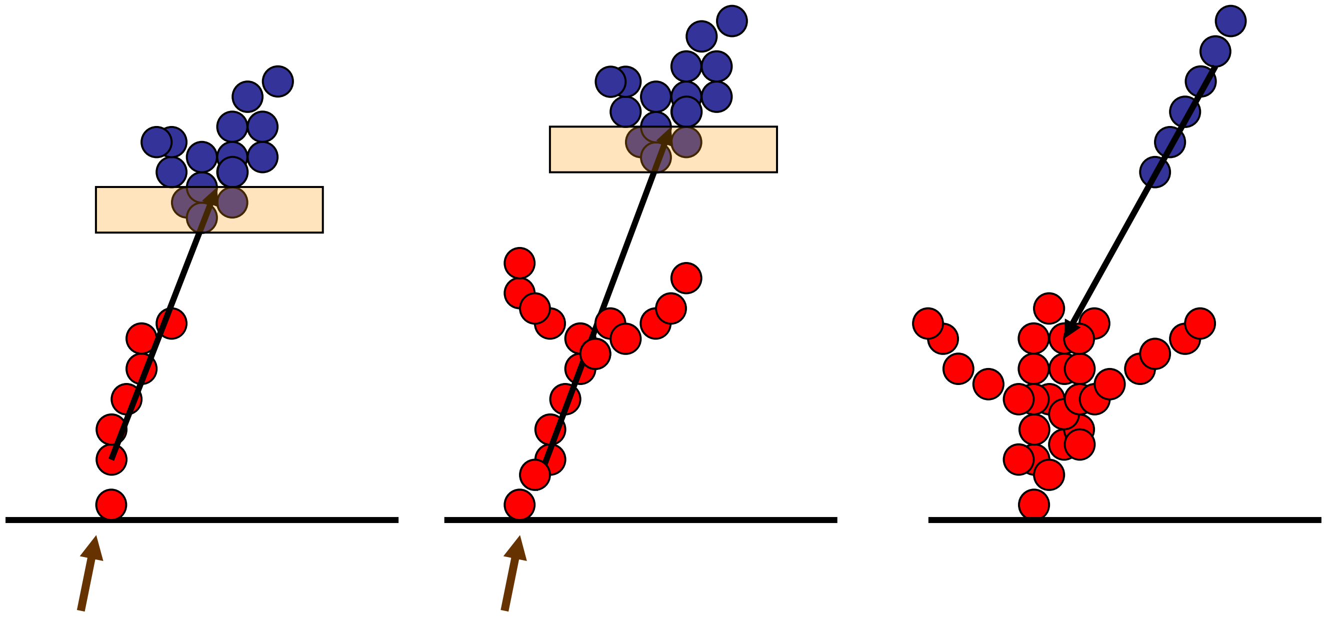
Project track-like clusters forward and check distance to shower centroids in subsequent N layers



Also look for track-like segments at start of cluster and try to match to end of another cluster

Cluster association III : MIP segments

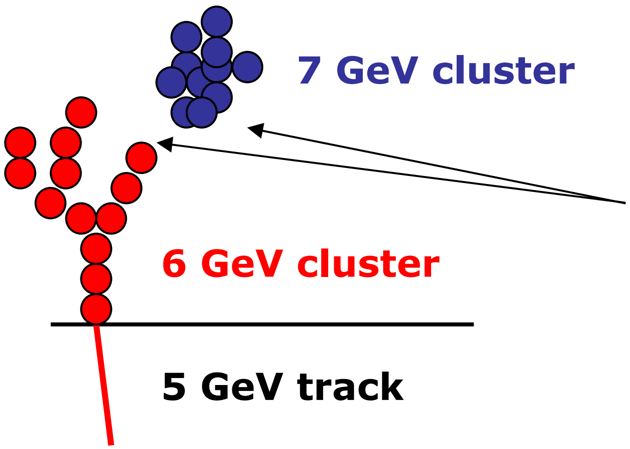
★ **Look at clusters which are consistent with having tracks segments and project backwards/forward**



★ **Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi^2]**

Cluster Association Part II

- Have made very clear cluster associations
- Now try "cruder" association strategies
- BUT first associate tracks to clusters (temporary association)
- Use track/cluster energies to "veto" associations, e.g.



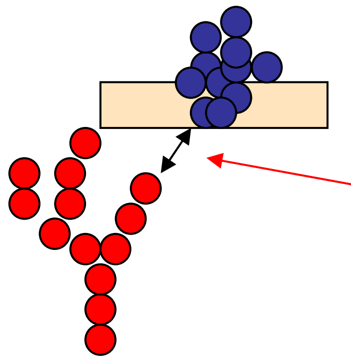
This cluster association would be forbidden if $|E_1 + E_2 - p| > 3\,\sigma_E$

Provides some protection against "silly" mistakes

★ Cluster reconstruction and PFA not independent

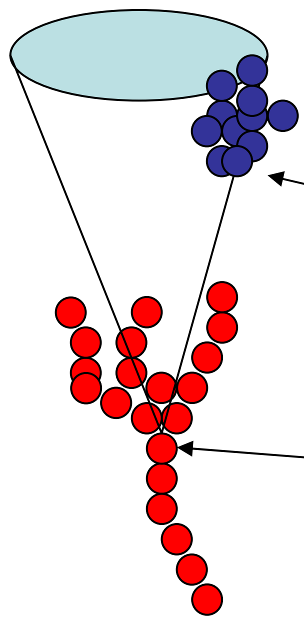
Sledgehammer Cluster Association

Proximity



Distance between hits -limited to first layers

Shower Cone



Associated if fraction of hits in cone > some value

Shower start identified

+Track-Driven Shower Cone

Apply looser cuts if have low E cluster associated to high E track

Current Performance

Example Reconstruction

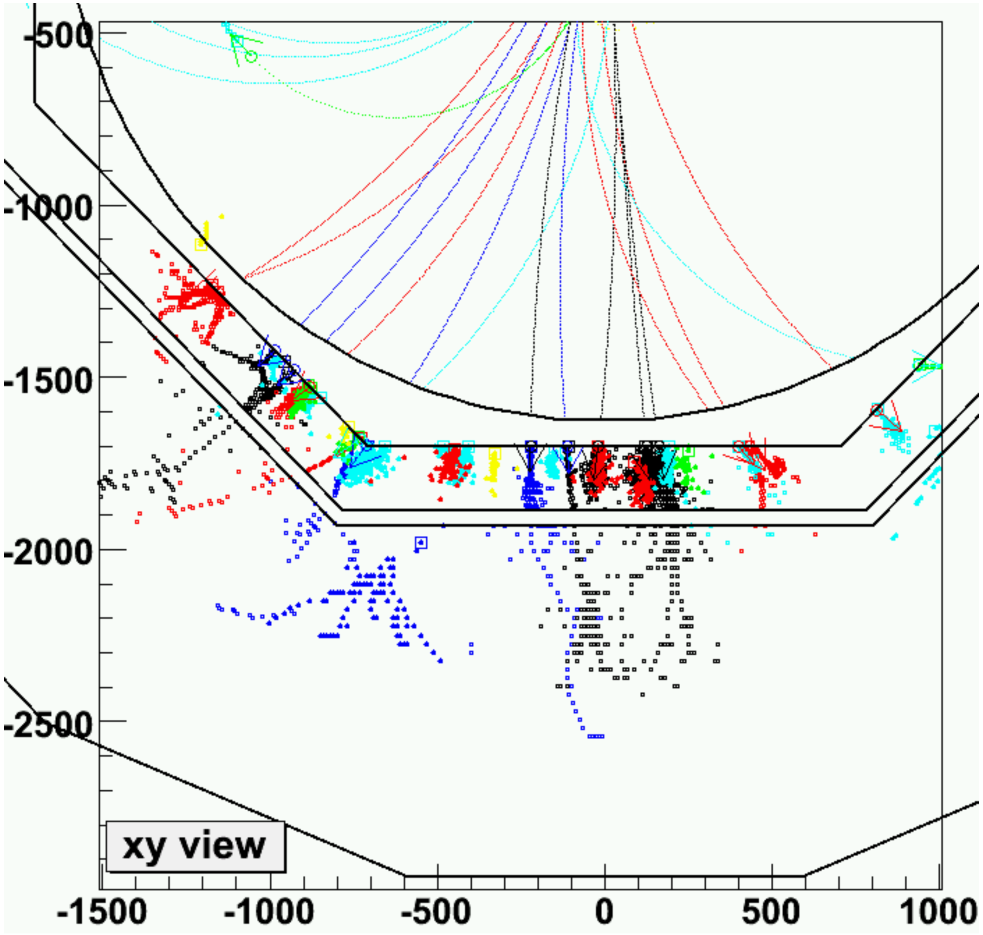
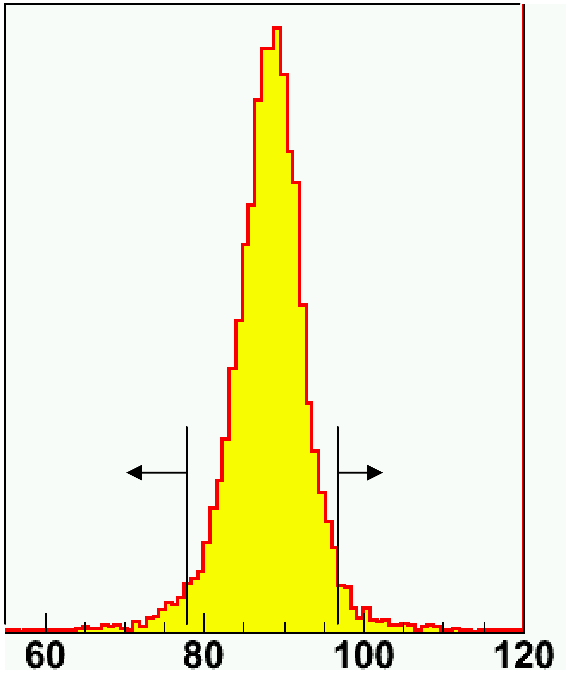
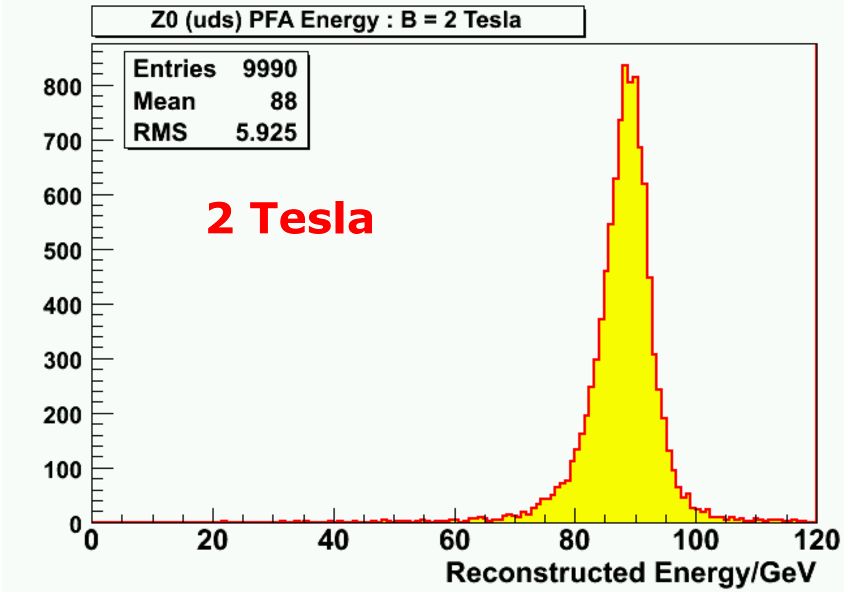


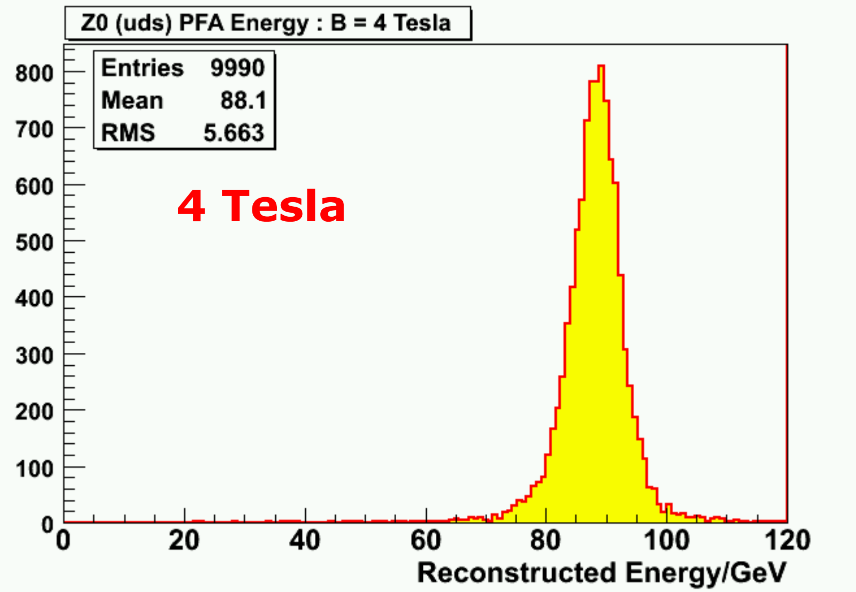
Figure of Merit:

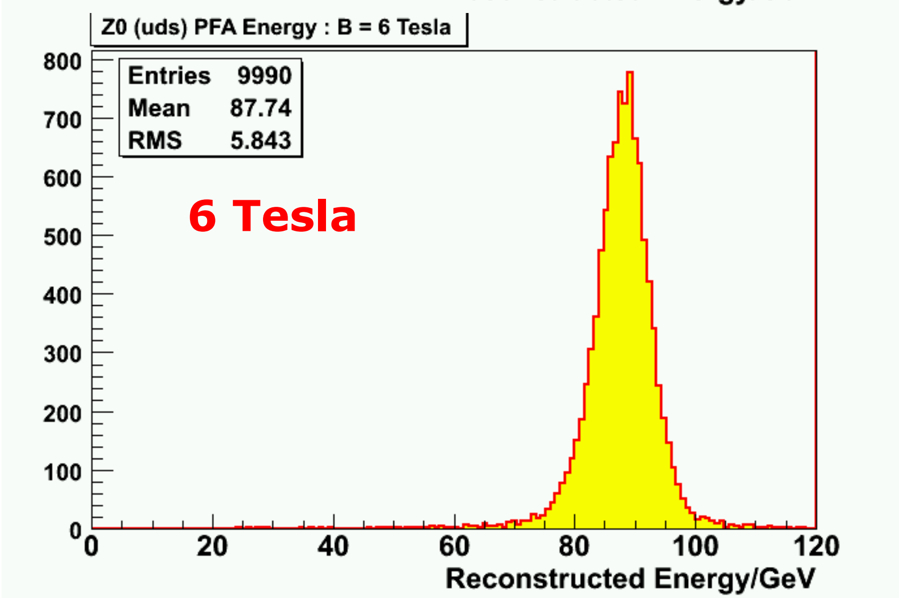


- ★ **Find smallest region containing 90 % of events**
- ★ **Determine rms in this region**

PandoraPFA Results (Z →uds)







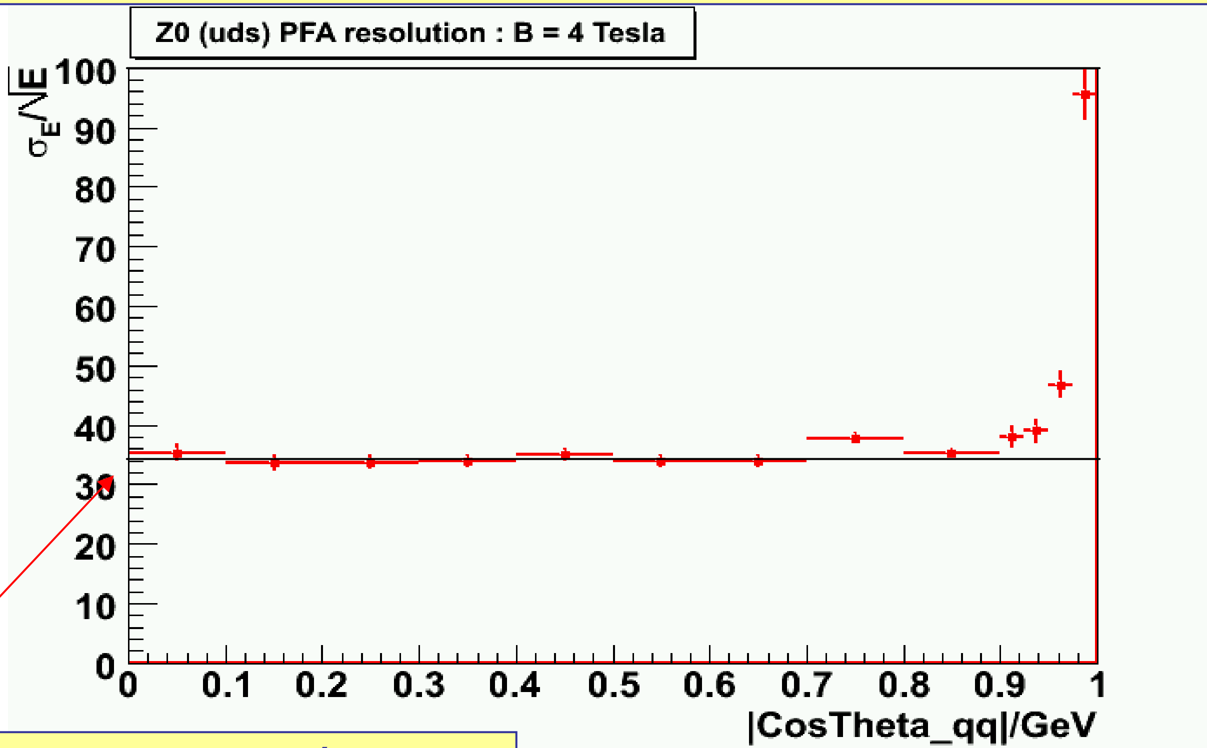
- RMS of Central 90 % of Events

B-Field	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$
2 Tesla	35.3±0.3%
4 Tesla	35.8±0.3 %
6 Tesla	37.0±0.3 %

- only weakly depends on B

Angular dependence

✦ Plot resolution vs "generated" polar angle of qq system



✦ In barrel : 34 %/ √E(GeV)

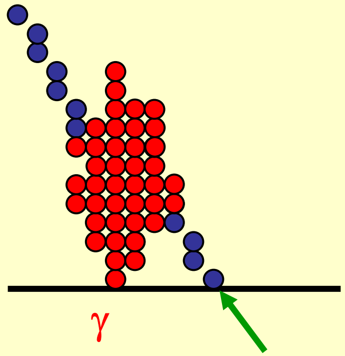
★ Quite good (state-of-the-art): but these are only Z events…

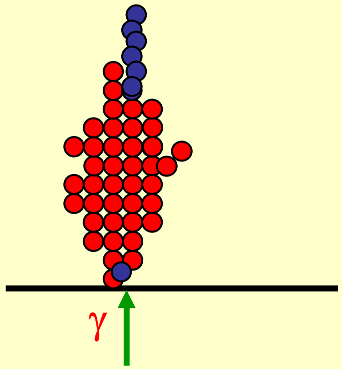
★ With some work this should improve: 30-33 % in barrel

LDC can probably reach ILC goal

❻ What next…?

- ★ Algorithm looks promising - good performance for 91.2 GeV Z events
- ★ Can be improved:
  - ✦ algorithm parameters not optimised
  - ✦ still a few "features" (i.e. does something silly)
  - ✦ more clever ways of estimating hadronic energy
  - ✦ better photon ID…
  - ✦ + some new ideas (for high density events)





e.g.
Use track to separate overlapping MIPs and EM showers

- ★ Will soon be in position to start full-simulation detector optimisation studies
- ★ Already have "interesting" result that PFA performance doesn't appear to depend strongly on B-field

❼ Conclusions

- ★ Great deal of effort (worldwide) in the design of the ILC detectors
- ★ Centred around 3 "detector concept" groups: GLD, LDC, SiD
- ★ Two main strands:
  - Detector R&D: e.g. LCFI, CALICE, TPC-studies,....
  - Simulation and optimisation studies
- ★ Widely believed that calorimetry and, in particular, jet energy resolution drives detector design
- ★ Also widely believed that PFA is the key to achieving the ILC goal:

$$\sigma_E/E = 0.3/\sqrt{E(\mathrm{GeV})}$$

- ★ Calorimetry at the ILC = HARDWARE + SOFTWARE (new paradigm)
- ★ Will be difficult to disentangle detector/algorithm....
- ★ Recently have started to develop a new PFA algorithm: PandoraPFA
- ★ Already getting to close to ILC goal (for $Z \rightarrow uds$ events)
- ★ More importantly, getting close to being able to address real issues:
  - ⊙ What is optimal detector size/B-field
  - ⊙ What ECAL/HCAL granularity is needed
  - ⊙ How does material budget impact performance
  - ⊙ ....
- ★ <u>A lot of work</u> needed for concepts to evolve into optimised detector designs and ultimately ILC detector collaborations

Fortunately..... This work is both INTERESTING and FUN !

RESERVE SLIDES

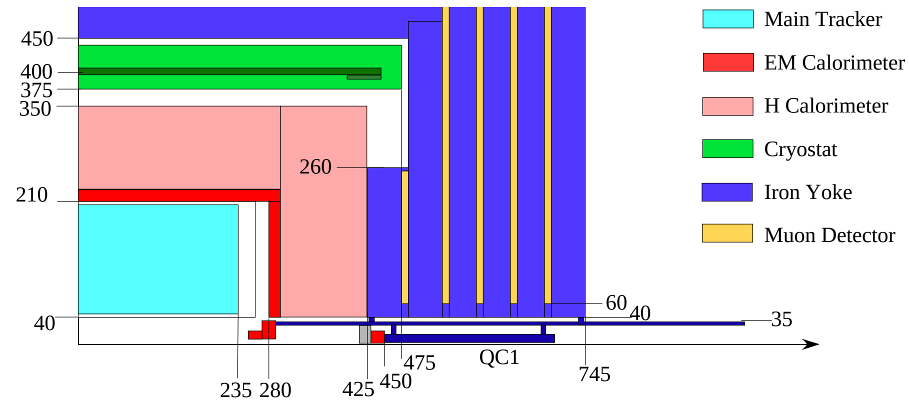
Some serious Design issues

<u>Main questions (in some order of priority):</u>

1) B-field : why 3 T ? Does B help jet energy resolution
2) ECAL inner radius/TPC outer radius
3) TPC length/Aspect ratio
4) Tracking efficiency – forward region
5) How much HCAL – how many interactions lengths 4, 5, 6…
6) Longitudinal segmentation – pattern recognition vs sampling frequency for calorimetric performance
7) Transverse segmentation ECAL/HCAL
   ECAL : does high/very high granularity help ?
8) Compactness/gap size
9) Impact of dead material
10) How important are conversions, V^0s and kinks
11) HCAL absorber : Steel vs. W, Pb, U…
12) Circular vs. Octagonal TPC (are the gaps important)
13) HCAL outside coil – probably makes no sense but worth demonstrating this (or otherwise)
14) TPC endplate thickness and distance to ECAL
15) Material in VTX – how does this impact PFA

GLD Calorimeter Concept

★ **ECAL and HCAL inside coil**

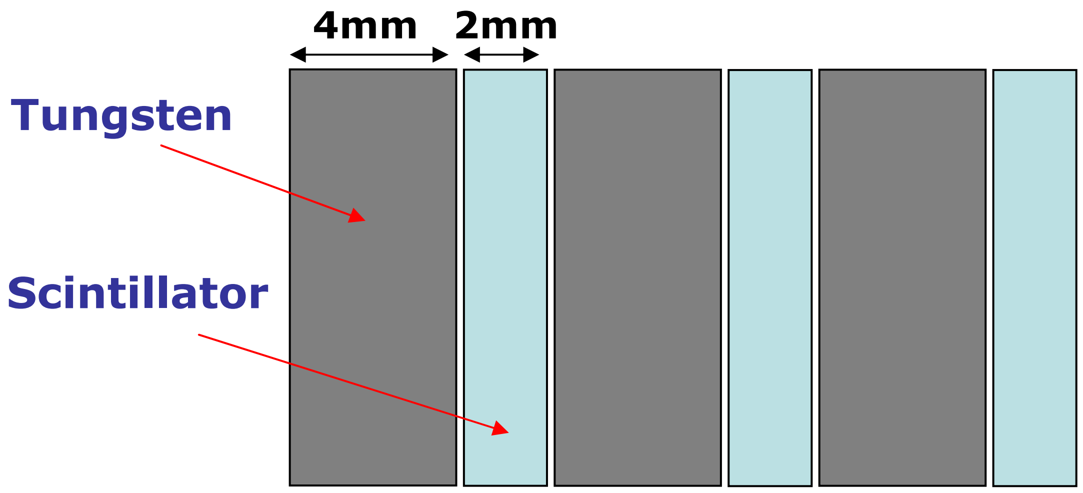


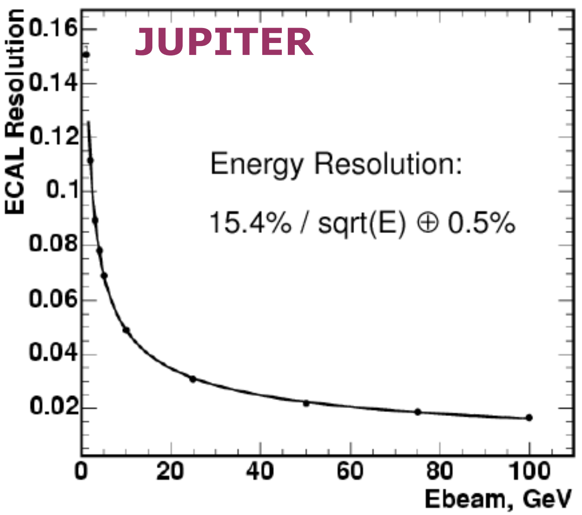
ECAL:

Longitudinal segmentation: 39 layers (~25 X_0; ~1 λ_I)

Achieves Good Energy Resolution:

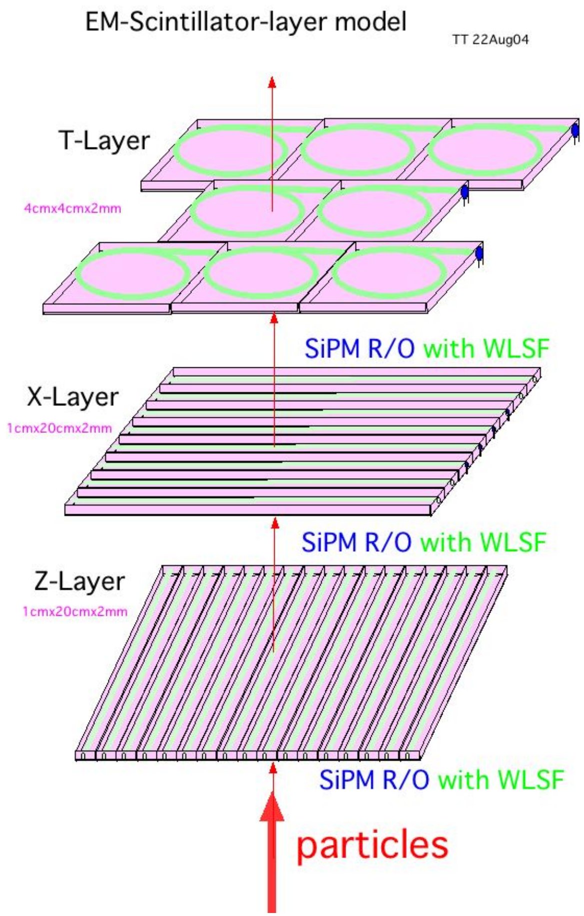
$$\sigma_E/E = 0.15/\sqrt{E(\mathrm{GeV})} \oplus 0.01$$





ECAL Structure

- $R_{Moliere}$ ~ 9mm for solid tungsten
  + scintillator layers increase effective $R_{Moliere}$ ~ 15 mm
- Aim for segmentation ~ $R_{Moliere}$
  ideally (?) ~ 1cm x 1cm - but cost !



Initial GLD ECAL concept:

★ Achieve effective ~1cm x 1cm segmentation using strip/tile arrangement

★ Strips : 1cm x 20cm x 2mm

★ Tiles : 4cm x 4cm x 2mm

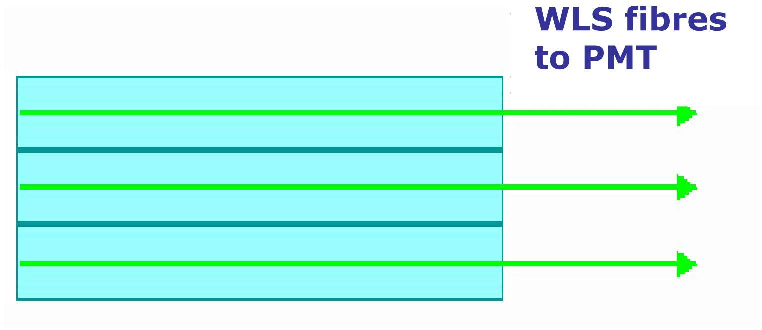
★ Ultimate design needs to be optimised for particle flow performance

+ question of pattern recognition in dense environment

Scintillator Readout

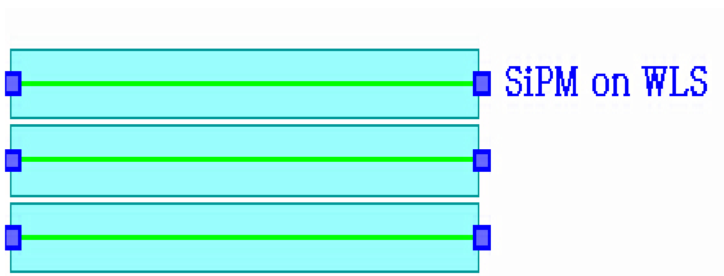
Traditional Approach:

- ★ Readout with Wavelength shifting fibres + Photomultiplier Tubes (PMT)
- ★ Not suitable for ILC Calorimeter
  - ★ PMTs in high B-field
  - ★ Need long fibre lengths to get signals out - attentuation, +....



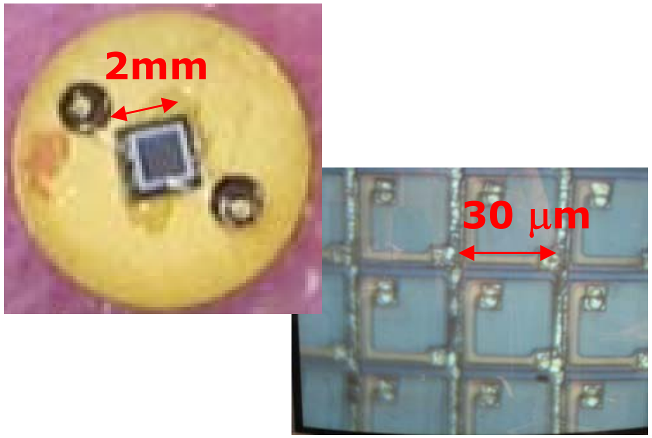
GLD ECAL/HCAL Readout:

- ★ Read out with WLS fibres + Silicon Multipixel Photon Counter directly on fibre at strip end



SiPM:

- ✦ Number of cells up to ~ 1000
- ✦ Effective area ~1mm x 1mm (very compact)
- ✦ High gain (~10^6); Detect + amplification
- ✦ Cheap (a few $/device in future ?)
- ✦ High Quantum efficiency ~ 70+%

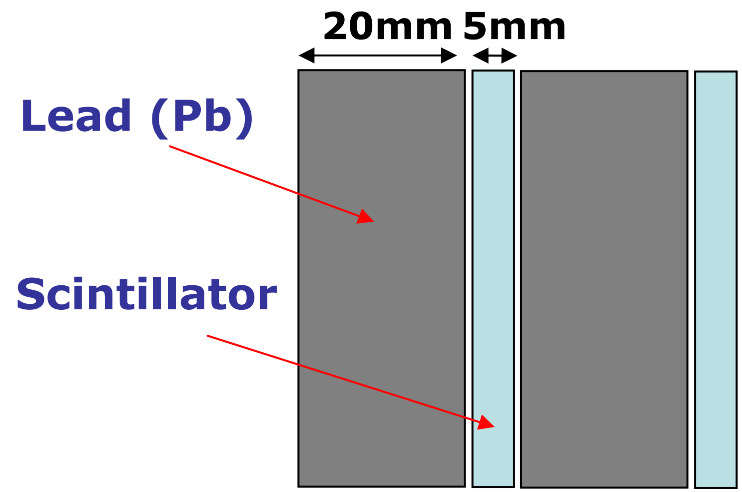


SiPM cost will have significant impact on overall cost-perforance optimisation

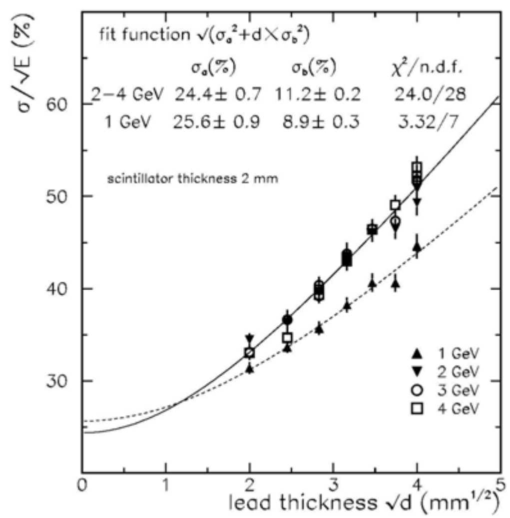
Hadron Calorimeter

Current Baseline Design:

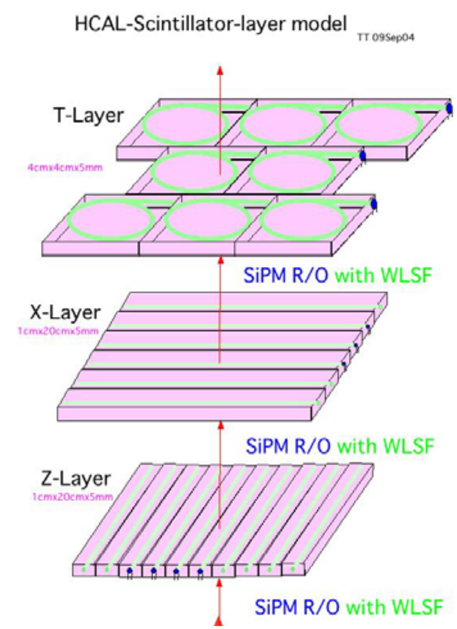
- ★ Pb-Scintillator sampling calorimeter
- ★ Approximate hardware compensation
- ★ 51 layers (~6 λ_I)
- ★ Structure and readout same as ECAL
- ★ Needs to be optimised for PFA



Performance:



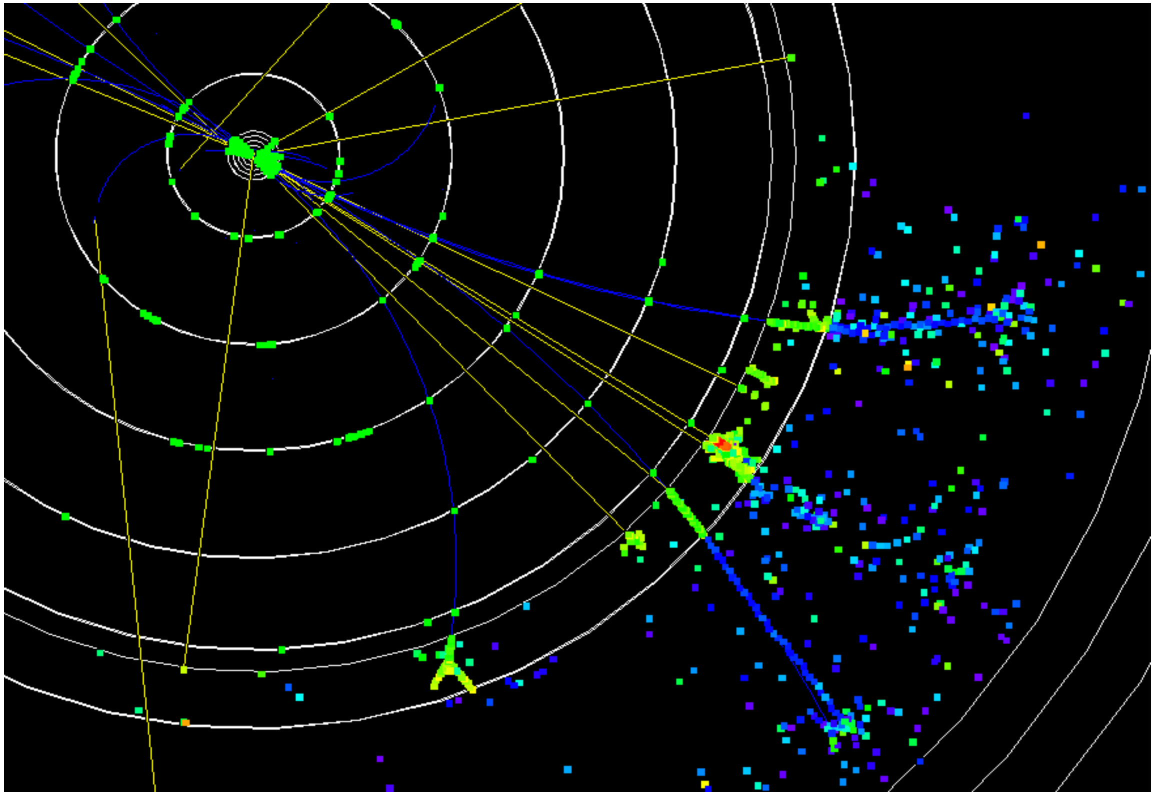
Test beam data



$\sigma_E/E \sim 0.55/\sqrt{E(\mathrm{GeV})}$

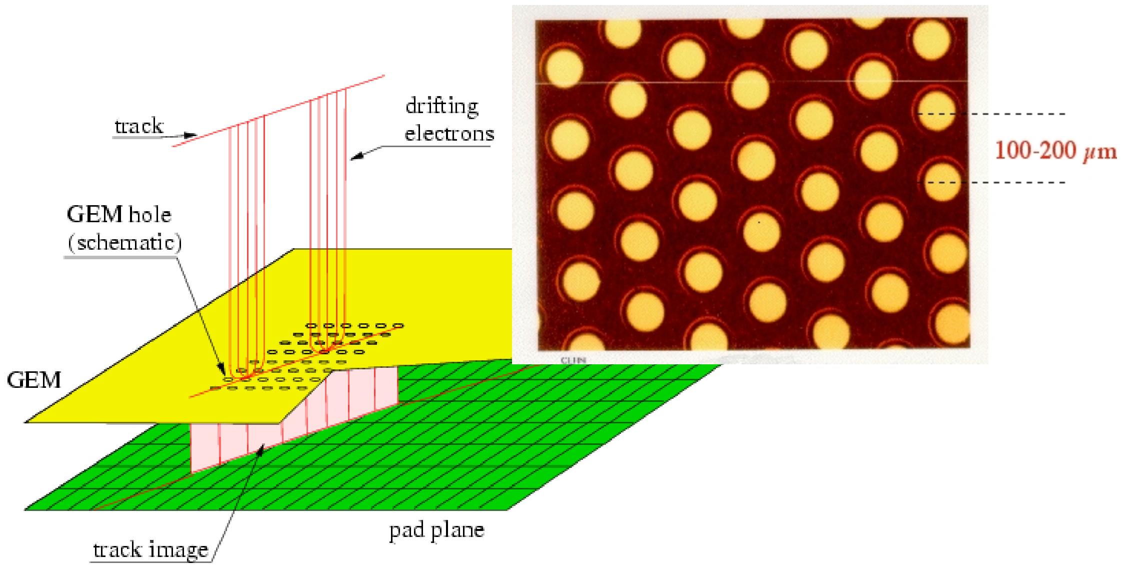
- ★ For low (<10 GeV ?) particles can probably obtain better performance by summing energy deposits "semi-digitally"

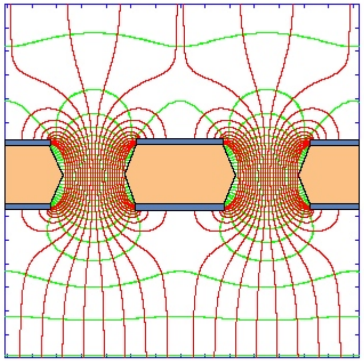
SiD



- A 100 Mpixel jet picture
  - Si and Tungsten

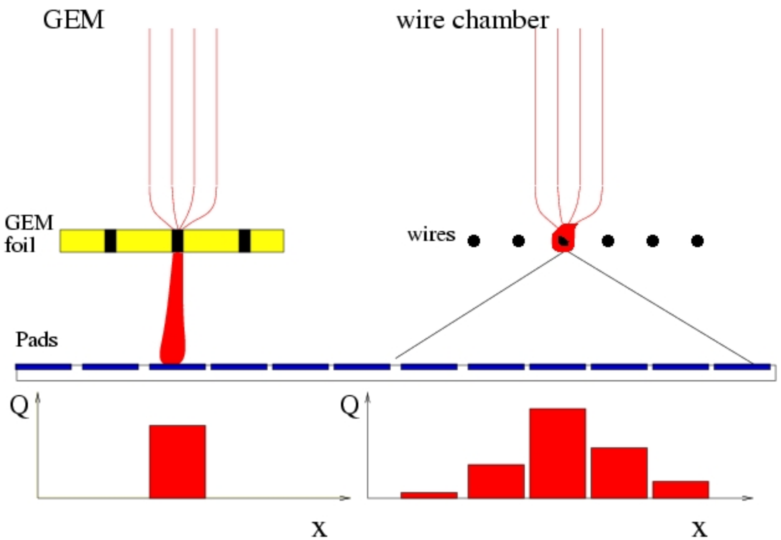
e.g. GEMs





- ★ **High electric field strength in GEM holes ~ 40-80kV/cm**
- ★ **Amplification occurs between GEM foils (50 μm)**
- ★ **Ion feedback is suppressed : achieved 0.1-1 %**
- ★ **Limited amplification (<100) - use stack of 2/3 GEMs**

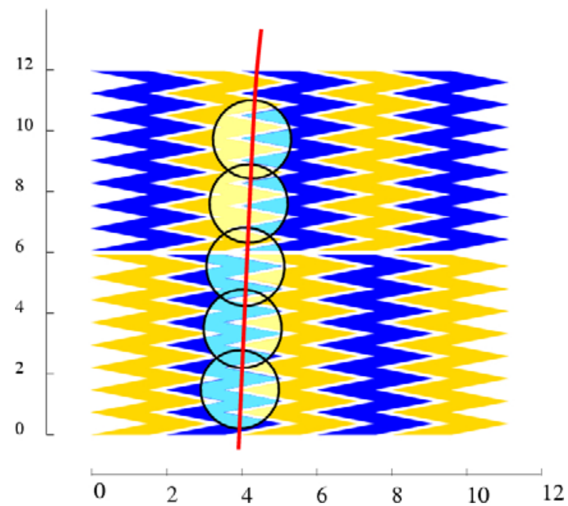
GEM Point Resolution

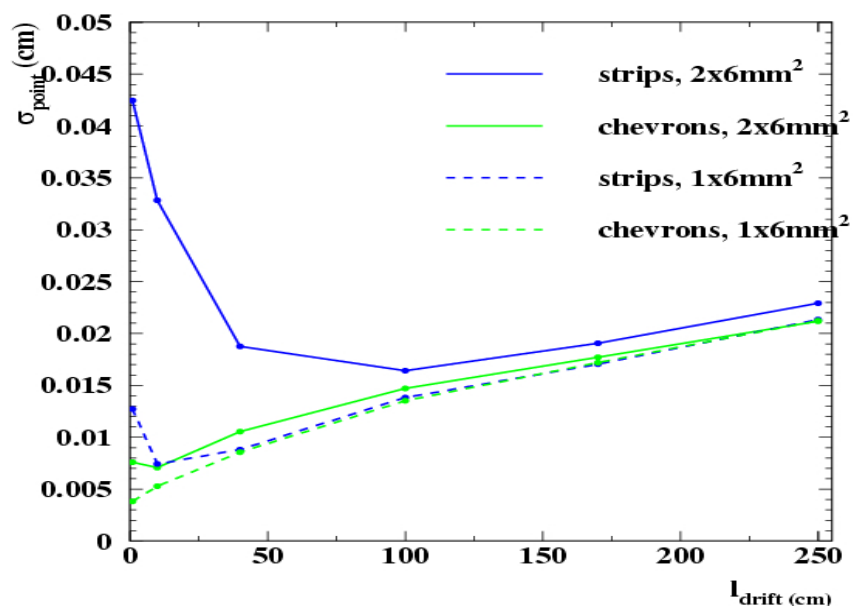


Wire Chamber readout :
- Readout induced charge on pads
- Charge induced on several pads
- Improved point resolution

GEM readout :
- Induced charge too small
- Readout charge on pads
- Limits resolution to pad size

Improve point resolution using chevron/diamond pads





★ **All the necessary tools exist !**

- **that doesn't mean that its time to stop work…**
- **things aren't perfect yet**

We are now in the position to start to learn how to optimise the detector for PFA

<u>But first…</u>

learning from ongoing studies of Perfect Particle Flow (P. Krstonosic)

e.g. $e^+e^- \rightarrow Z \rightarrow qq$ at 91.2 GeV

To be reviewed

Effect	σ[GeV] separate	σ[GeV] not joined	σ[GeV] total ($\% / \sqrt{E}$)	σ % to total
$E_\nu > 0$	0.84	0.84	0.84 (8.80%)	12.28
$Cone < 5^o$	0.73	1.11	1.11(11.65%)	9.28
$P_t < 0.36$	1.36	1.76	1.76(18.40%)	32.20
σ_{HCAL}	1.40	1.40	2.25(23.53%)	34.12
σ_{ECAL}	0.57	1.51	2.32(24.27%)	5.66
M_{neutral}	0.53	1.60	2.38(24.90%)	4.89
M_{charged}	0.30	1.63	2.40(25.10%)	1.57

(assumed sub-detector resolutions: ECAL 11%/√E, HCAL 50%/√E +4%)