The HERWIG Event Generator

Bryan Webber

Univ. Cambridge

CDF Lectures, October 2004

Lecture 2: Event Generation

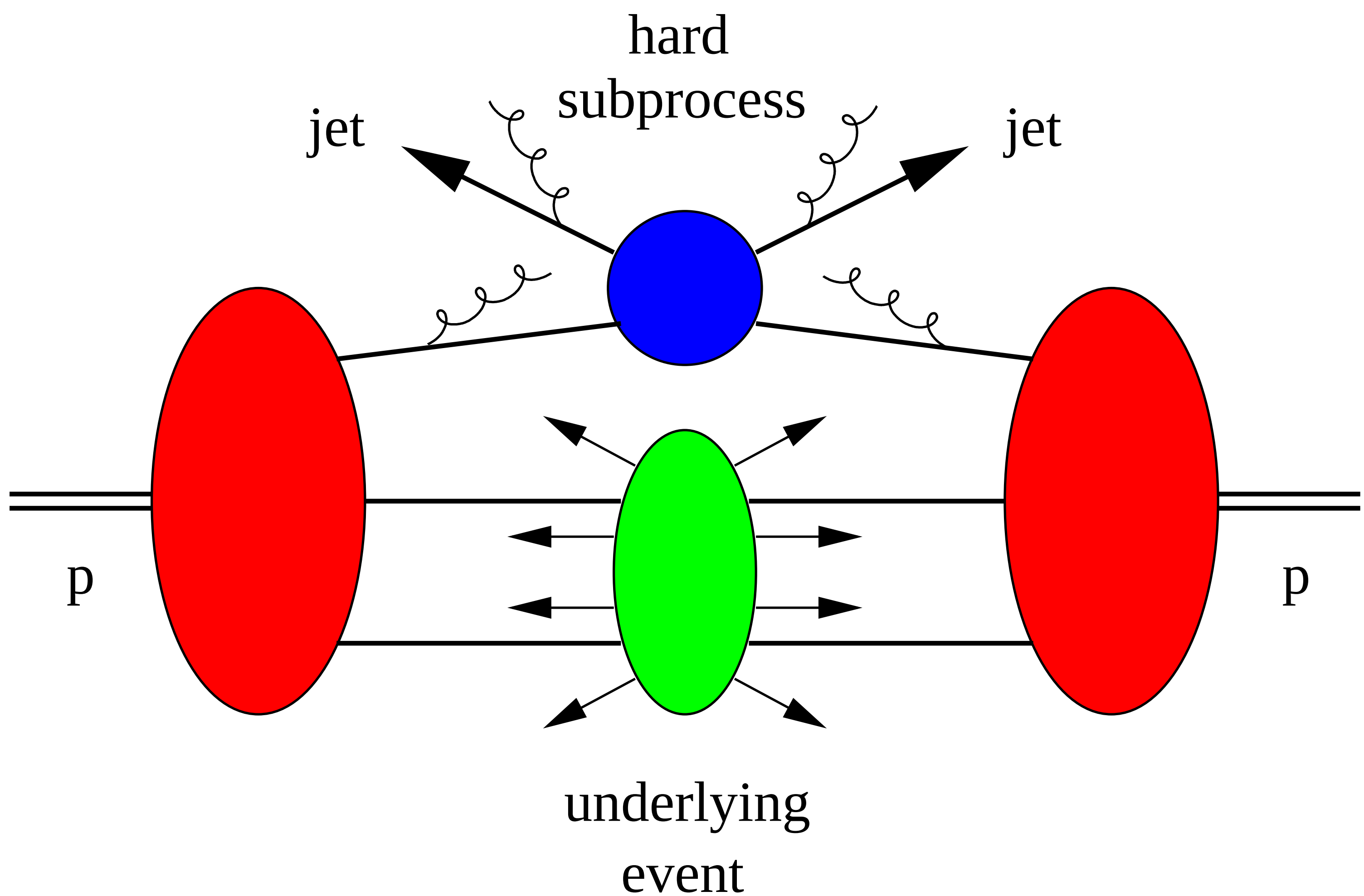
- HERWIG generator
  - Coherent branching
  - Hadronization model
  - LEP comparisons
  - Underlying event
- Sample program
- Future plans/Conclusions

HERWIG 5.1: G Marchesini, BRW, G Abbiendi, IG Knowles, MH Seymour, L Stanco, BW, Comput Phys Commun 67 (1992) 465-508

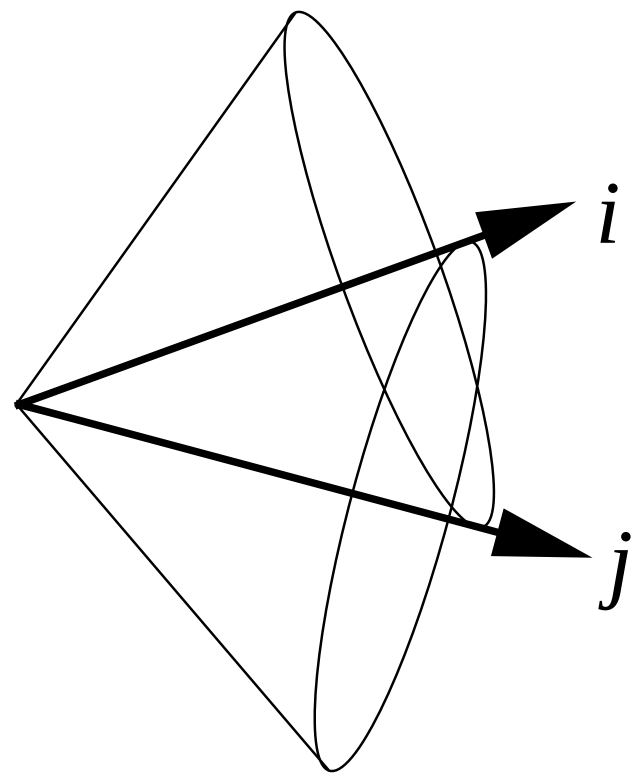
HERWIG 6.1: G Corcella, IG Knowles, G Marchesini, S Moretti, K Odagiri, P Richardson, MH Seymour, BW, JHEP 0101 (2001) 010

HERWIG Event Generator

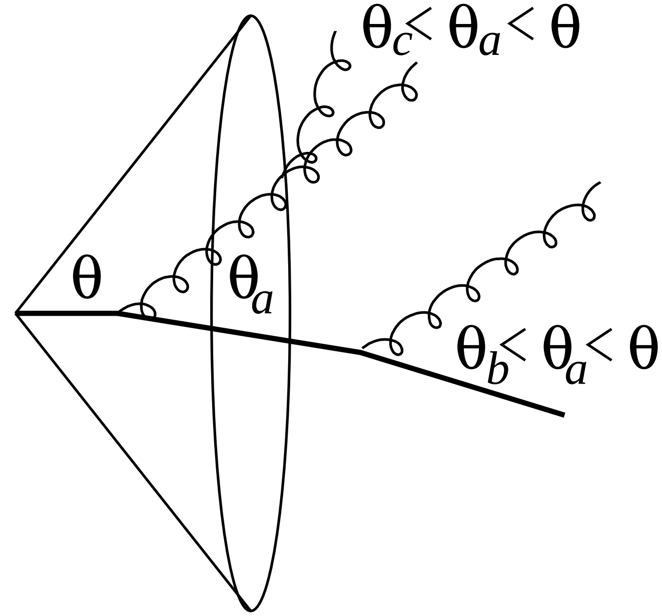
- Basic event structure



- Colour coherence is simulated by angular ordering:
  - Angular region for shower from parton i is cone bounded by direction of j (and vice-versa), where i and j are colour-connected:



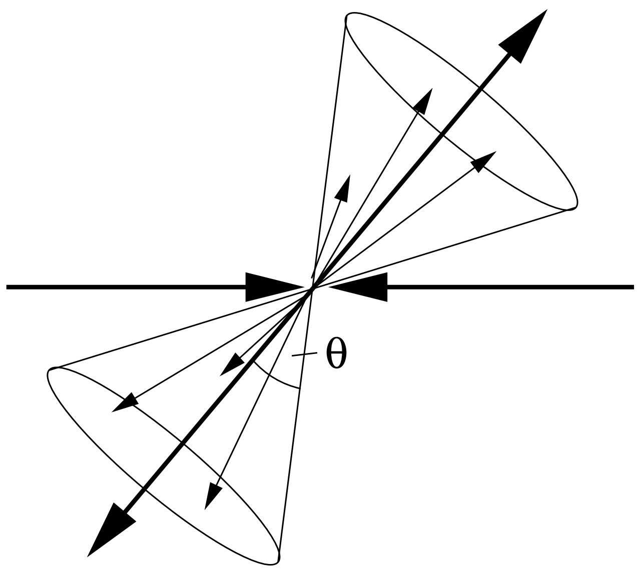
- Angles within shower decrease away from hard subprocess:



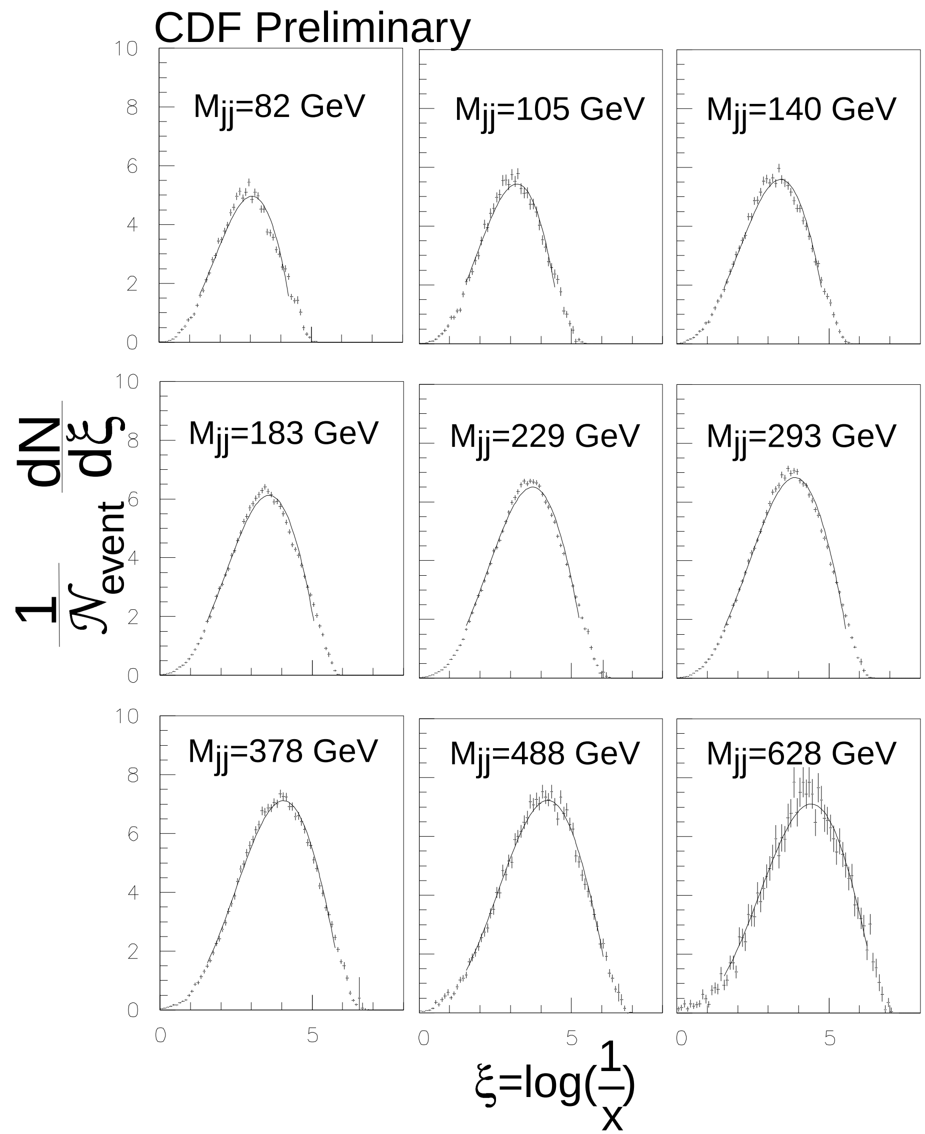
- This suppresses soft gluon/hadron production (MLLA/LPHD).

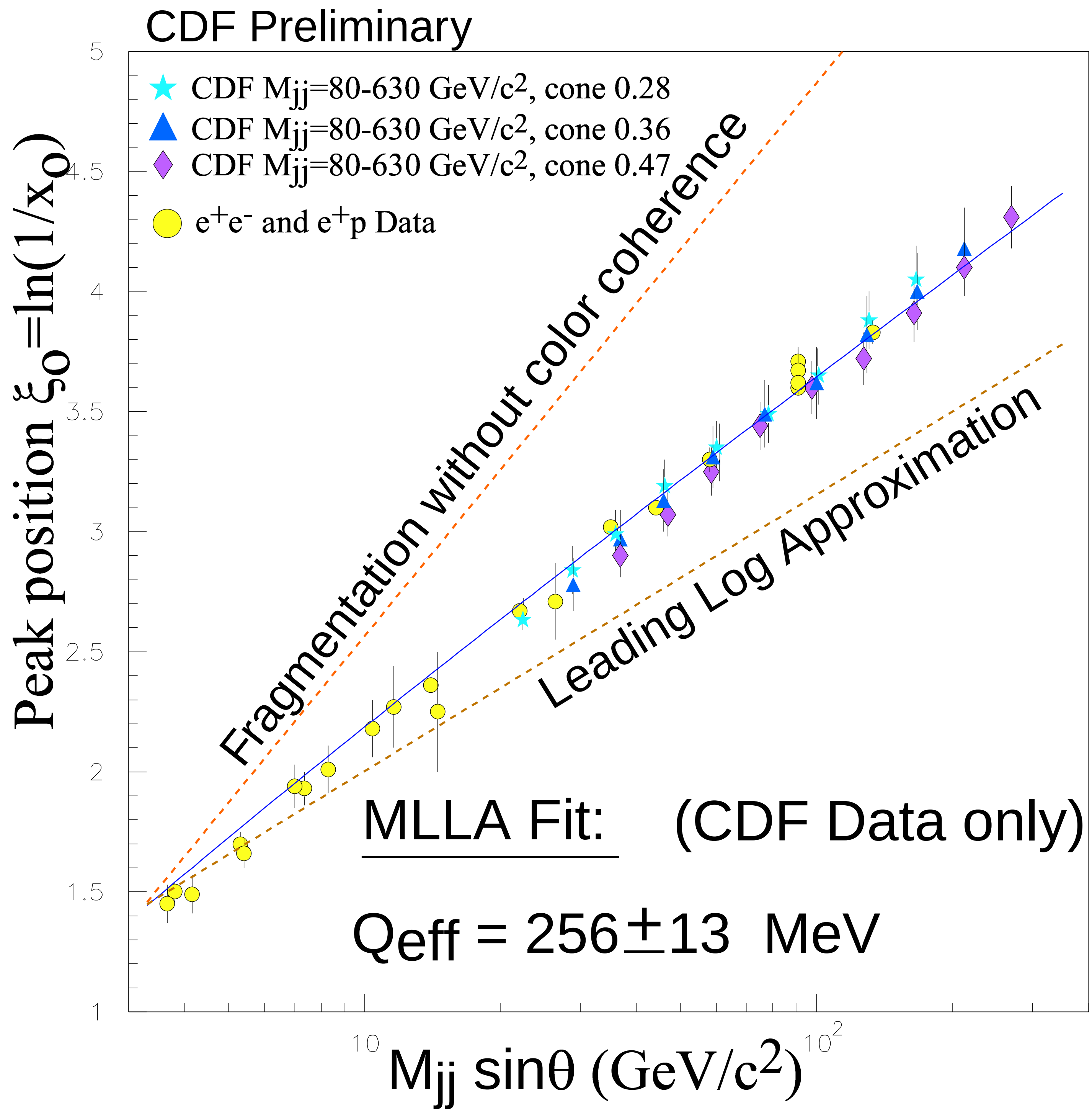
- Beautifully confirmed by Tevatron dijet data

CDF Collaboration

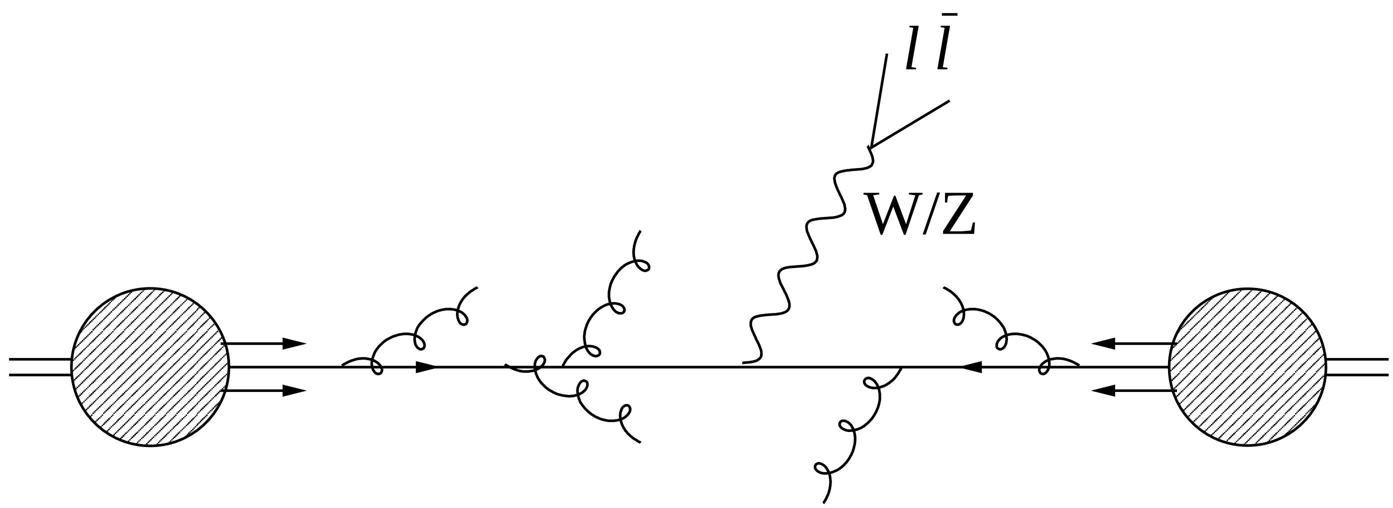


$x = p_{had}/E_{jet}$

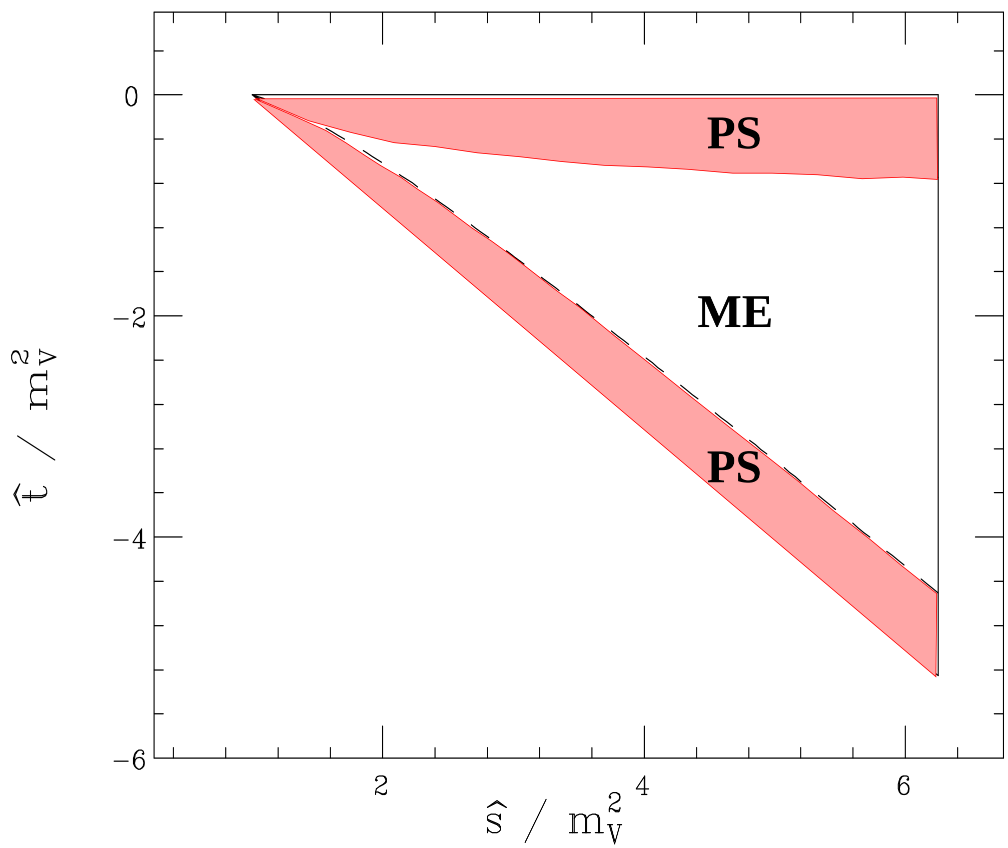



CDF Preliminary
CDF Mjj=80-630 GeV/c2, cone 0.28
CDF Mjj=80-630 GeV/c2, cone 0.36
CDF Mjj=80-630 GeV/c2, cone 0.47
e+e- and e+p Data
Fragmentation without color coherence
Leading Log Approximation
MLLA Fit: (CDF Data only)
Qeff = 256±13 MeV
Peak position ξo=ln(1/xo)
Mjj sinθ (GeV/c2)
5
4.5
4
3.5
3
2.5
2
1.5
1
10
10^2

- Parton showers inside cones do not populate whole phase space. We also have to include (less singular) matrix element corrections
- For example, in W/Z hadroproduction

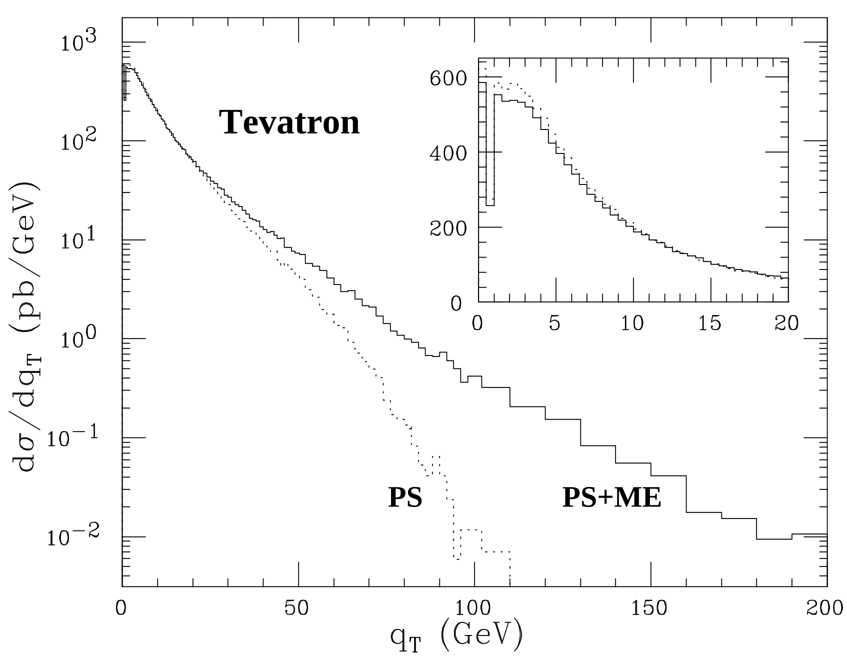


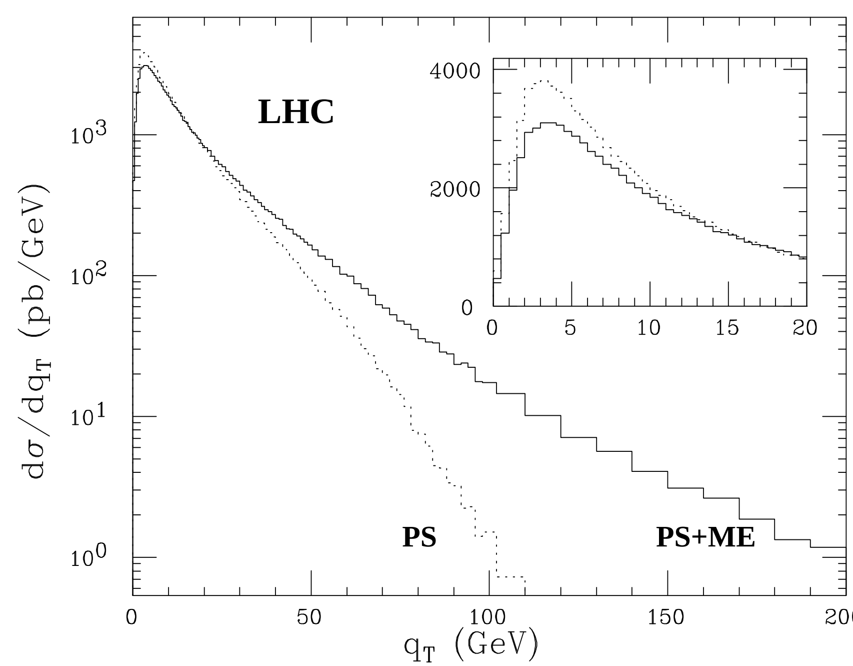
- Phase space for W + jet



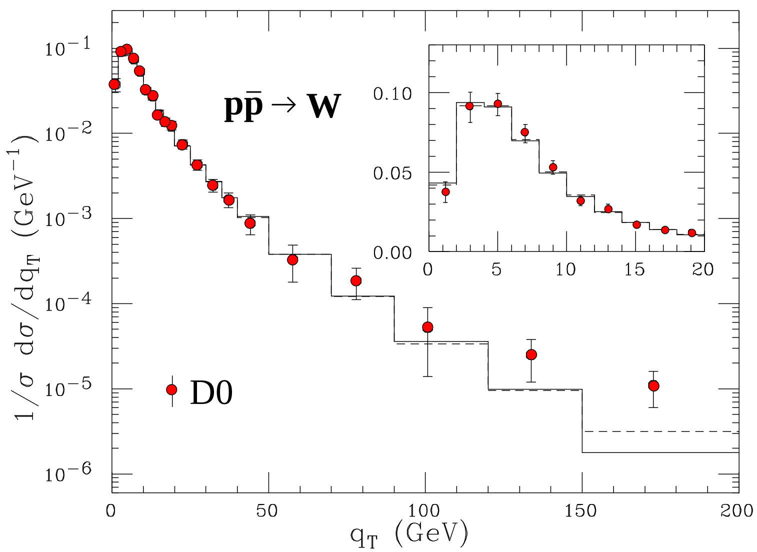
- ME corrections essential for W/Z production at large transverse momentum (important background to new physics):

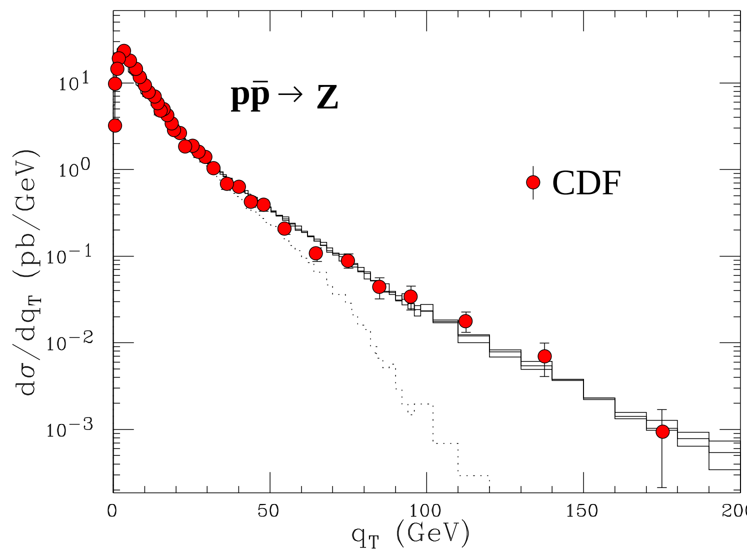
G Corcella & MH Seymour, Nucl Phys B565(2000)227



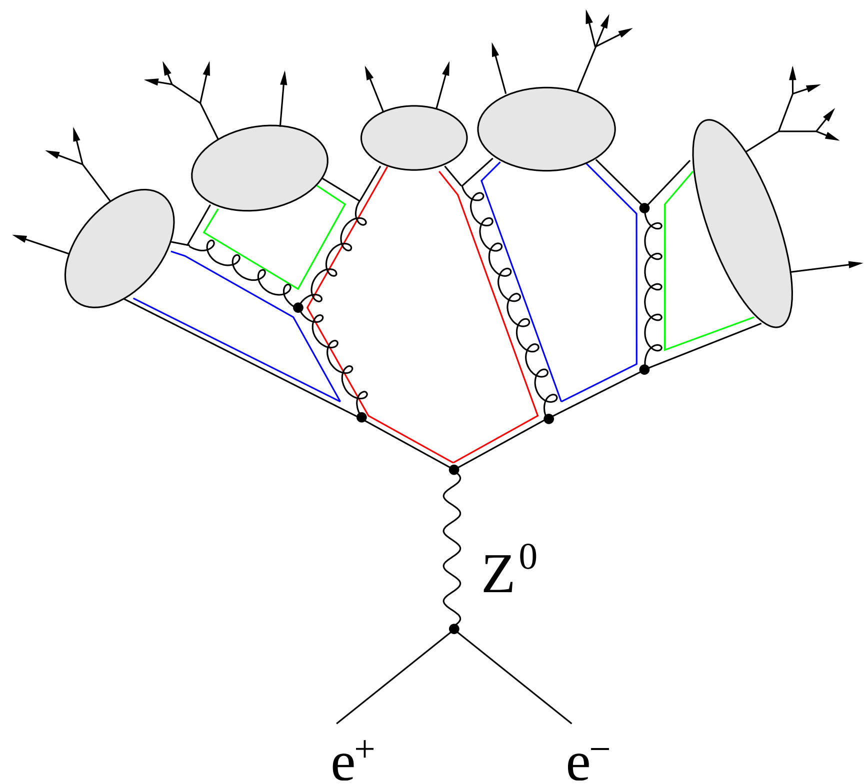


- Comparisons with Tevatron data:

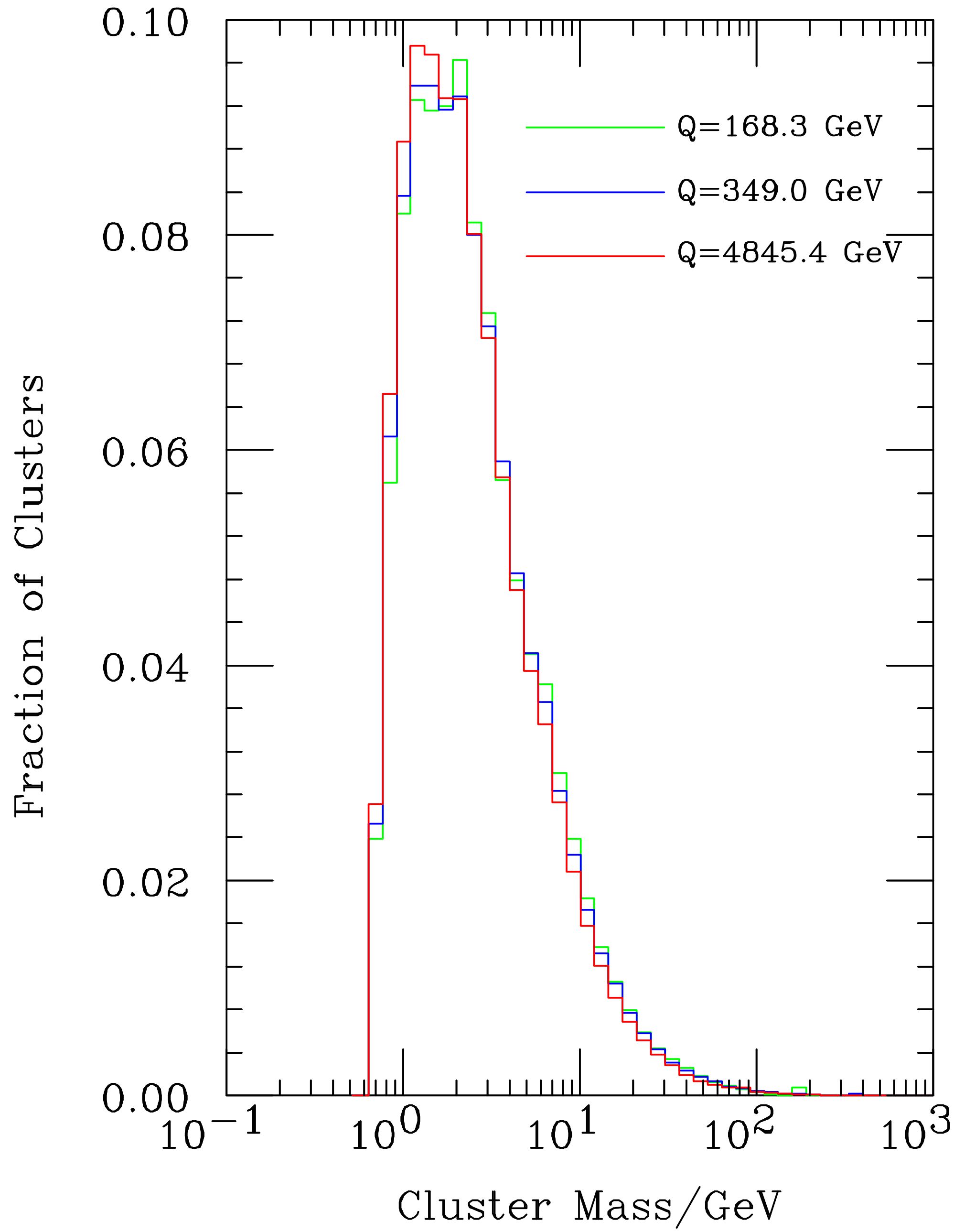




Cluster hadronization model



- Cluster mass spectrum is universal



- HERWIG's adjustable parameters:

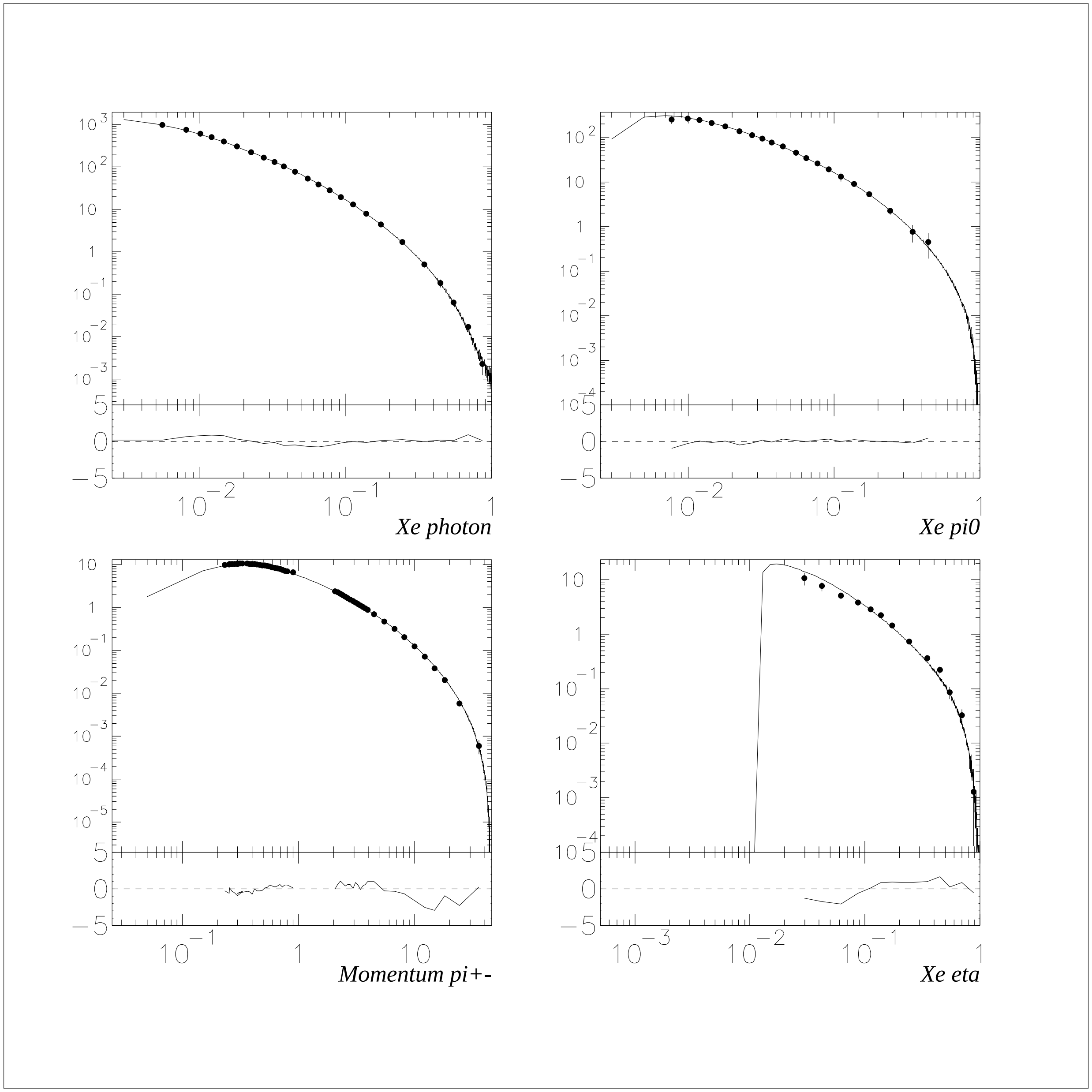
Parameter	Affects	Default	OPAL
QCDLAM	$\Lambda \sim \Lambda^{(5)}_{\overline{\mathrm{MS}}}$	0.180	D
RMASS(13)	cutoff "m_g"	0.750	D
CLMAX	cluster mass limit	3.35	D
CLPOW	cluster splitting	2.0	D
PSPLT(1)	cluster spectrum (udsc)	1.0	D
PSPLT(2)	cluster spectrum (b)	1.0	0.33
CLSMR(1)	cluster decay (udsc)	0.0	0.40
CLSMR(2)	cluster decay (b)	0.0	D
PWT(3)	s quark weight	1.0	–
PWT(7)	diquark weight	1.0	–
SNGWT	baryon weight (1)	1.0	–
DECWT	baryon weight (10)	1.0	0.7

For details see http://home.cern.ch/webber/hwtune.html

- LEP and Tevatron data are reproduced well overall, with some discrepancies near kinematic boundaries. Baryon and heavy flavour yields are less well described.
- Strongest constraints are from LEP1 data (Z^0 decay):

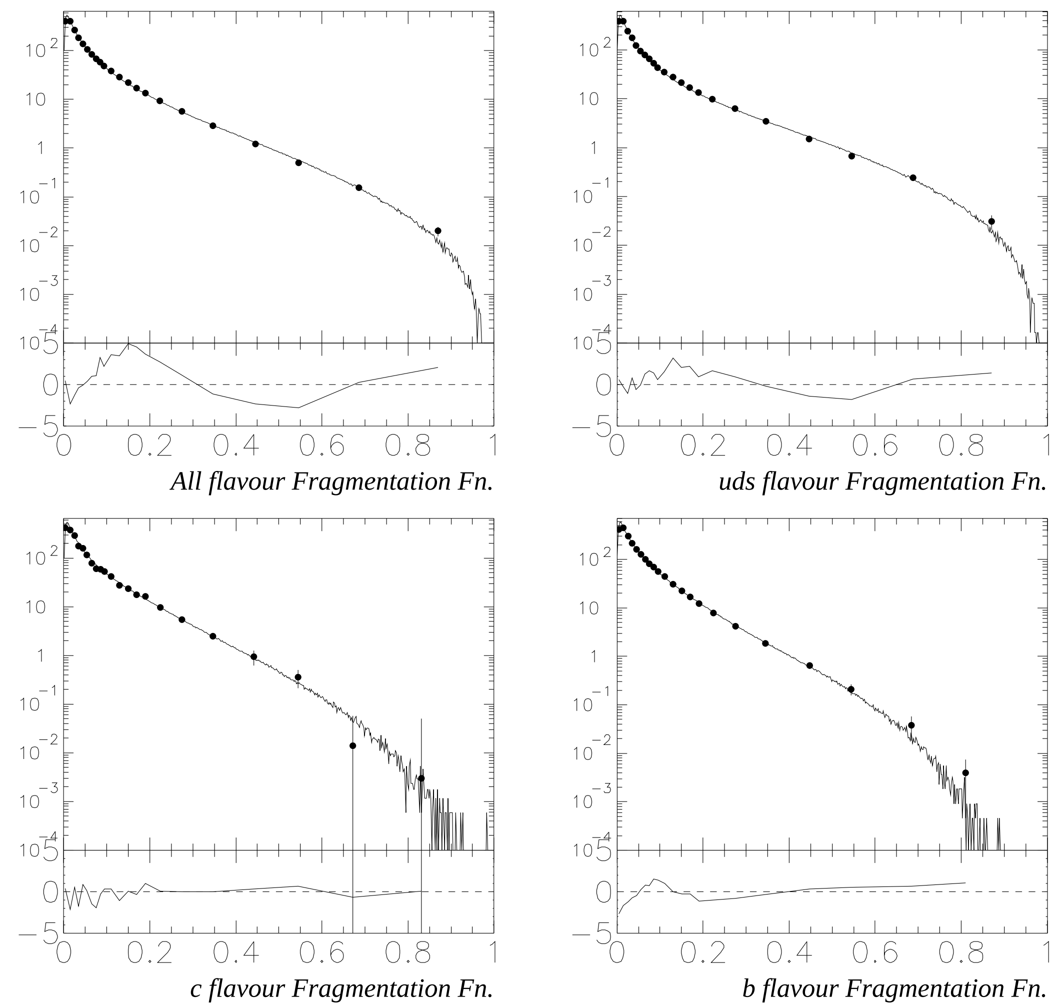
- Identified particle spectra

OPAL Collaboration



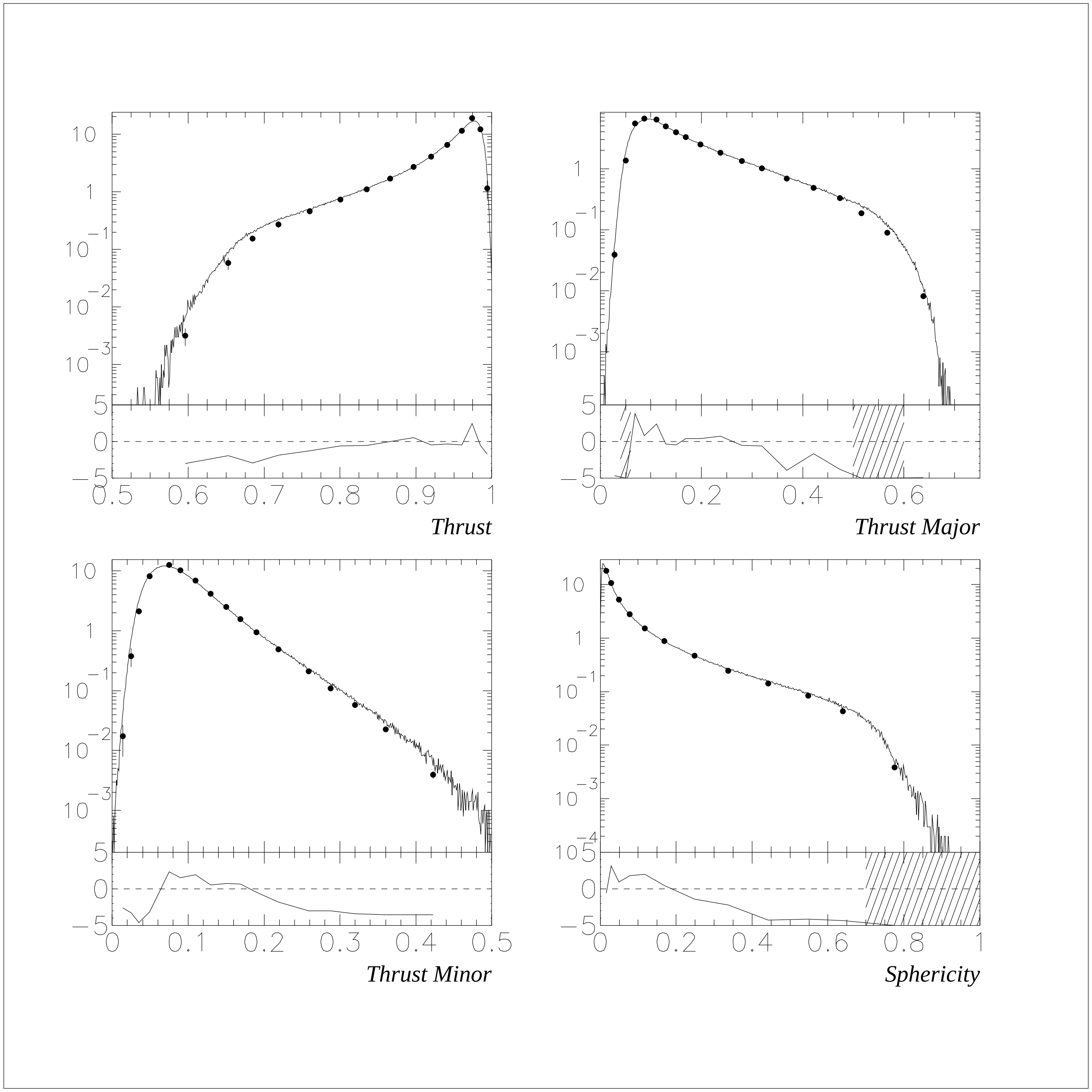
- Quark fragmentation functions

OPAL Collaboration



- Event shapes

OPAL Collaboration

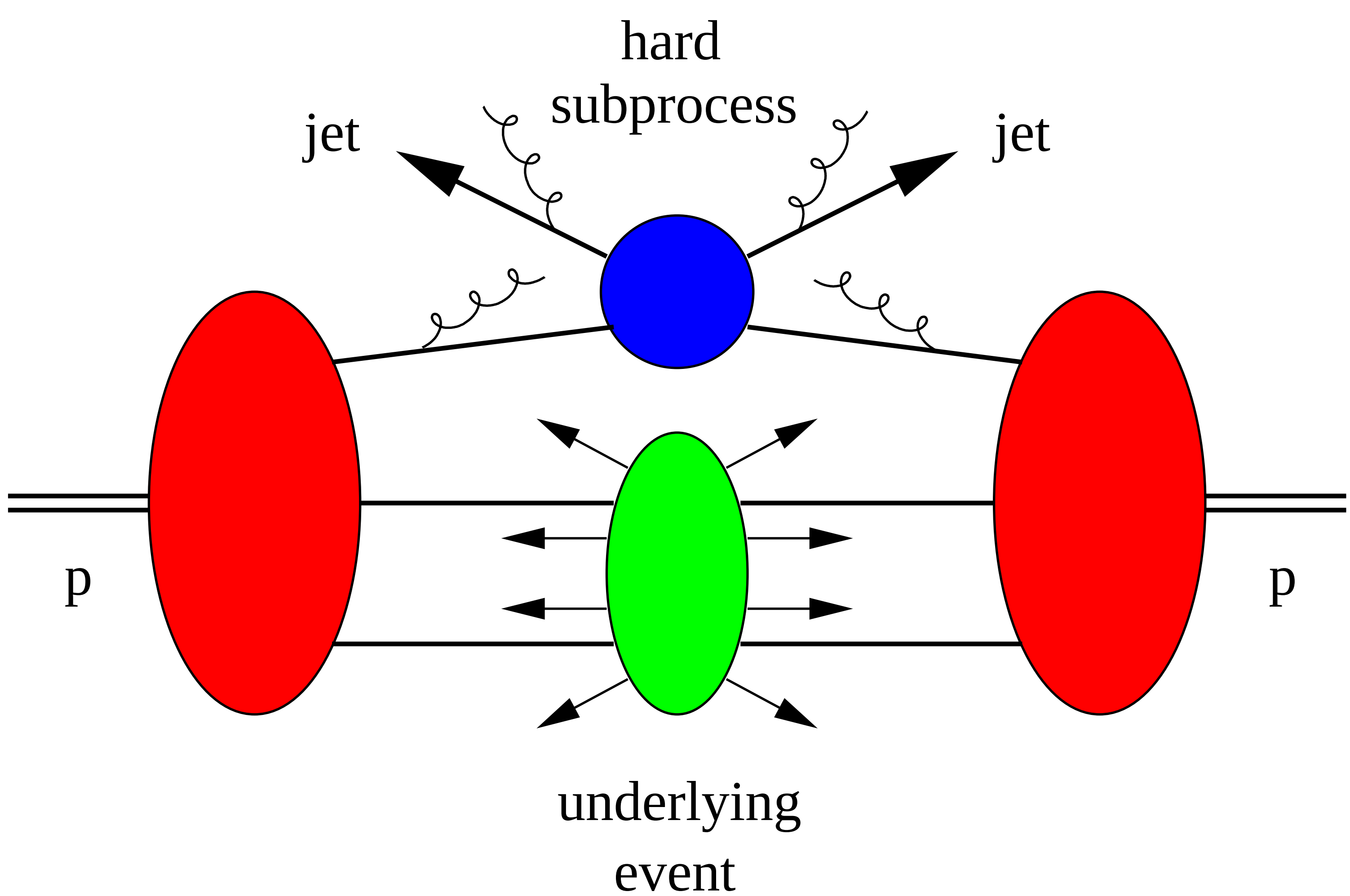


Identified particle yields

Particle	J^P	Experiment	Reference	Rate/event Measured	Rate/ev HW6.1 default	Rate/ev HW6.1 tuned
All charged		M,A,D,L,O	[13, 17, 33, 35, 36] [57, 62, 69, 89]	20.924 ± 0.117	20.453*	21.137
γ	1^-	A,O	[32, 94]	21.27 ± 0.60	20.056	20.657
π^0	0^-	A,D,L,O	[30, 51, 57, 63, 94]	9.59 ± 0.33	9.549	9.772
$\pi^\pm$	0^-	A,O	[34, 77]	17.04 ± 0.25	16.308	17.410
η	0^-	A,L,O	[32, 27, 63, 94]	0.956 ± 0.049	0.625*	0.808*
$\rho(770)^0$	1^-	A,D	[27, 43]	1.295 ± 0.125	1.000	1.201
$\rho(770)^\pm$	1^-	O	[94]	2.40 ± 0.43	1.930	2.305
$\omega(782)$	1^-	A,L,O	[27, 65, 94]	1.083 ± 0.088	0.972	1.182
$\eta'(958)$	0^-	A,L,O	[32, 65, 94]	0.152 ± 0.030	0.100	0.113
$f_0(980)$	0^+	D,L,O	[43, 61, 93]	0.142 ± 0.011	0.010*	0.006*
$a_0(980)^\pm$	0^+	O	[94]	0.27 ± 0.11	0.021	0.030
$\phi(1020)$	1^-	A,D,O	[27, 55, 93]	0.097 ± 0.007	0.128*	0.135*
$f_2(1270)$	2^+	D,L,O	[43, 61, 93]	0.168 ± 0.021	0.169	0.173
$f_2'(1525)$	2^+	D	[54]	0.020 ± 0.008	0.012	0.024
$K^\pm$	0^-	A,D,O	[34, 41, 77]	2.319 ± 0.079	2.102	2.383
K^0	0^-	S,A,D,L,O	[21, 37, 43, 60, 88, 14]	2.027 ± 0.025	1.971	2.262*
$K^*(892)^\pm$	1^-	A,D,O	[32, 37, 43, 76]	0.731 ± 0.058	0.545*	0.735
$K^*(892)^0$	1^-	A,D,O	[27, 38, 55, 78]	0.761 ± 0.032	0.548*	0.735
$K_2^*(1430)^0$	2^+	D,O	[55, 78]	0.106 ± 0.060	0.072	0.113
$D^\pm$	0^-	A,D,O	[20, 46, 90]	0.184 ± 0.018	0.276*	0.273*
D^0	0^-	A,D,O	[20, 46, 90]	0.473 ± 0.026	0.491	0.499
$D_s^\pm$	0^-	A,O	[29, 90]	0.129 ± 0.013	0.127	0.129
$D^*(2010)^\pm$	1^-	A,D,O	[20, 46, 95]	0.182 ± 0.009	0.153*	0.159
$D_s^{*\pm}$	0^-	O	[96]	0.096 ± 0.046	0.045	0.046
J/Ψ	1^-	A,D,L,O	[26, 42, 66, 72, 84]	$(5.44 \pm 0.29)10^{-3}$	0.00186*	0.00183*
$\Psi(3685)$	1^-	D,L,O	[42, 66, 84]	$(2.29 \pm 0.41)10^{-3}$	0.0009*	0.0009*
p	$\frac{1}{2}^+$	A,D,O	[34, 41, 77]	0.991 ± 0.054	1.521*	0.836
Δ^{++}	$\frac{3}{2}^+$	D,O	[50, 86]	0.088 ± 0.034	0.295*	0.144
Λ	$\frac{1}{2}^+$	A,D,L,O	[21, 37, 40, 60, 91]	0.373 ± 0.008	0.642*	0.399*
Σ^+	$\frac{1}{2}^+$	O	[92]	0.099 ± 0.015	0.133	0.082
Σ^0	$\frac{1}{2}^+$	A,D,O	[32, 49, 92]	0.074 ± 0.009	0.100	0.068
Σ^-	$\frac{1}{2}^+$	O	[92]	0.083 ± 0.011	0.109	0.072
Ξ^-	$\frac{1}{2}^+$	A,D,O	[32, 37, 48, 91]	0.0262 ± 0.0010	0.0776*	0.0549*
$\Sigma(1385)^\pm$	$\frac{3}{2}^+$	A,D,O	[32, 48, 91]	0.0471 ± 0.0046	0.2135*	0.1100*
$\Xi(1530)^0$	$\frac{3}{2}^+$	A,D,O	[32, 48, 91]	0.0058 ± 0.0010	0.0364*	0.0218*
Ω^-	$\frac{3}{2}^+$	A,D,O	[32, 49, 91]	0.00125 ± 0.00024	0.00967*	0.00586*
Λ_c^+	$\frac{1}{2}^+$	D,O	[52, 90]	0.077 ± 0.016	0.014*	0.008*

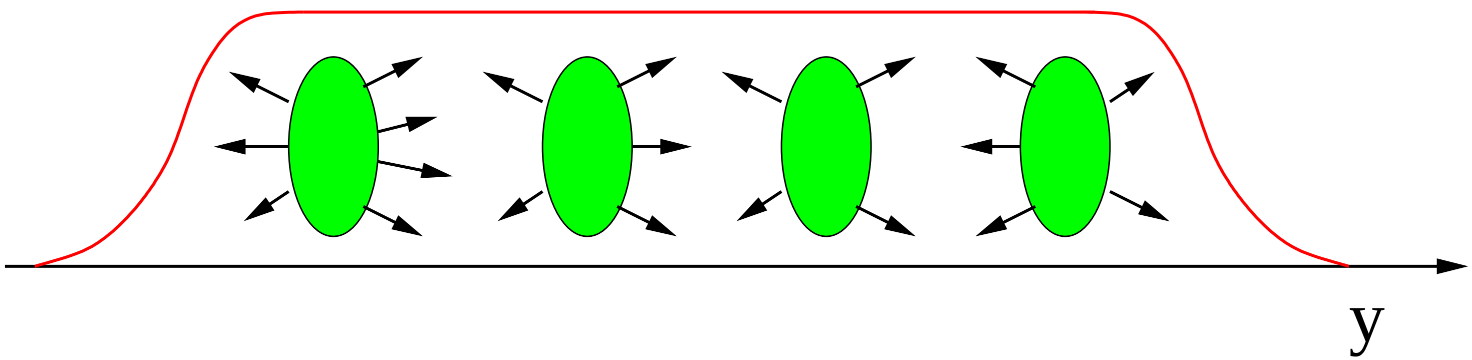
Table 1: Particle Production rates at 91.21 GeV compared with default and OPAL-tuned versions of HERWIG61. The experiments are Aleph(A), Delphi(D), L3(L), Opal(O), MK2(M), and SLD(S). Particle and anti-particle rates are summed and sequential particle decay is activated. * indicates that the rate differs from measurement by more than three standard deviations.

Underlying Event



- HERWIG uses UA5 multi-cluster (min bias) model

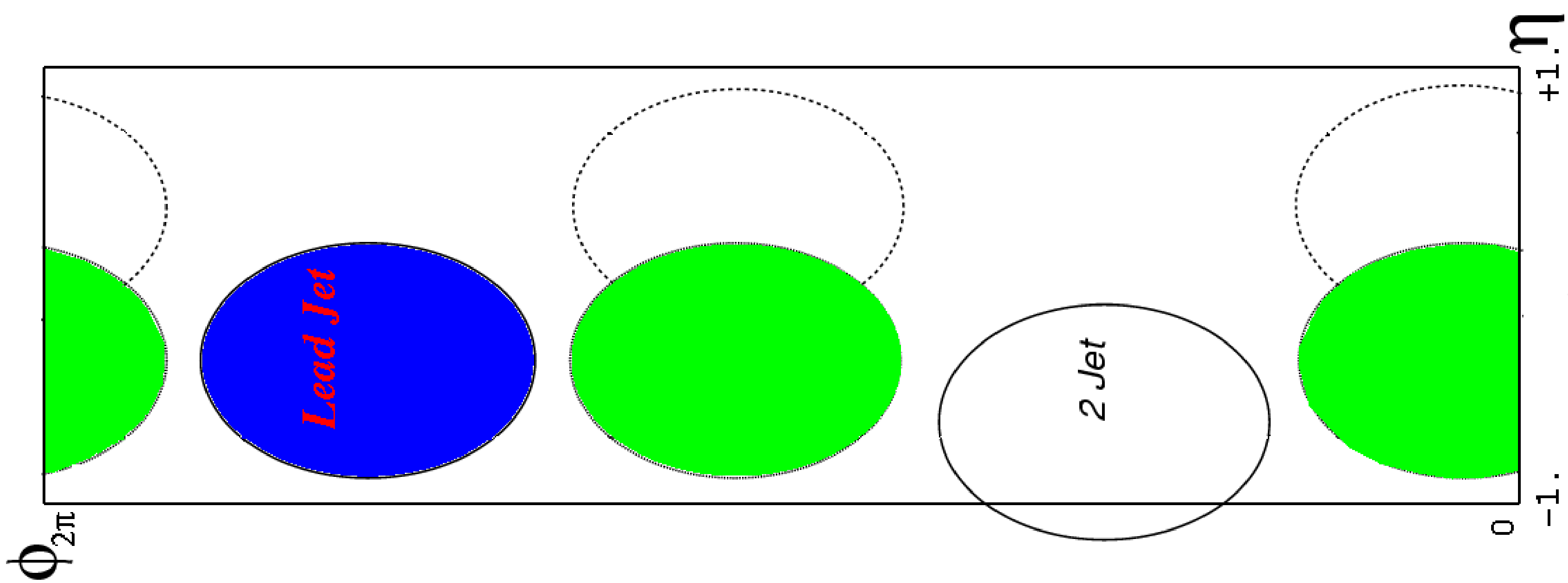
GJ Alner et al., Nucl Phys B291 (1987) 445

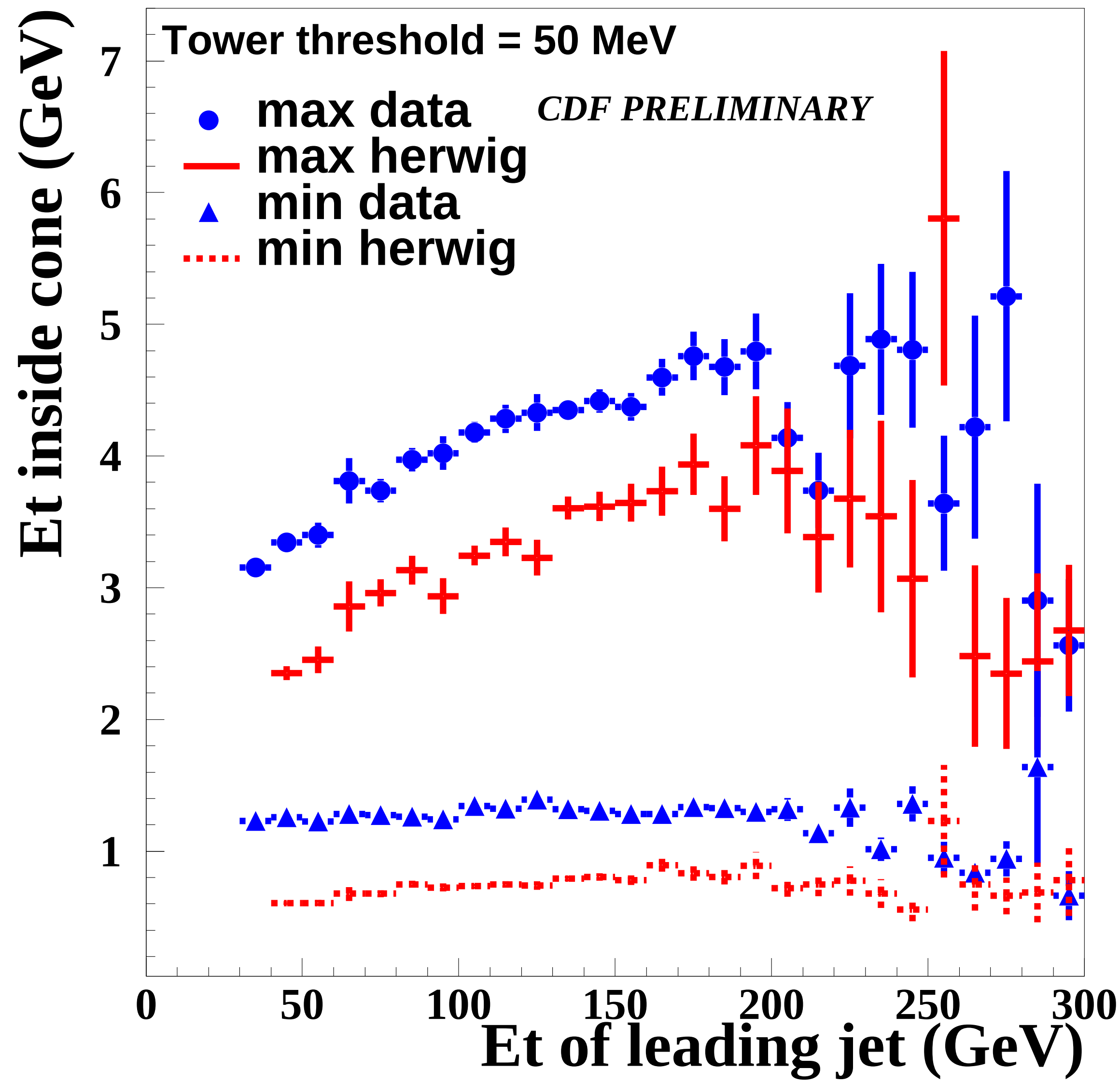


- Negative binomial distribution sampled for n_{ch}
- Clusters generated until preselected n_{ch} is reached

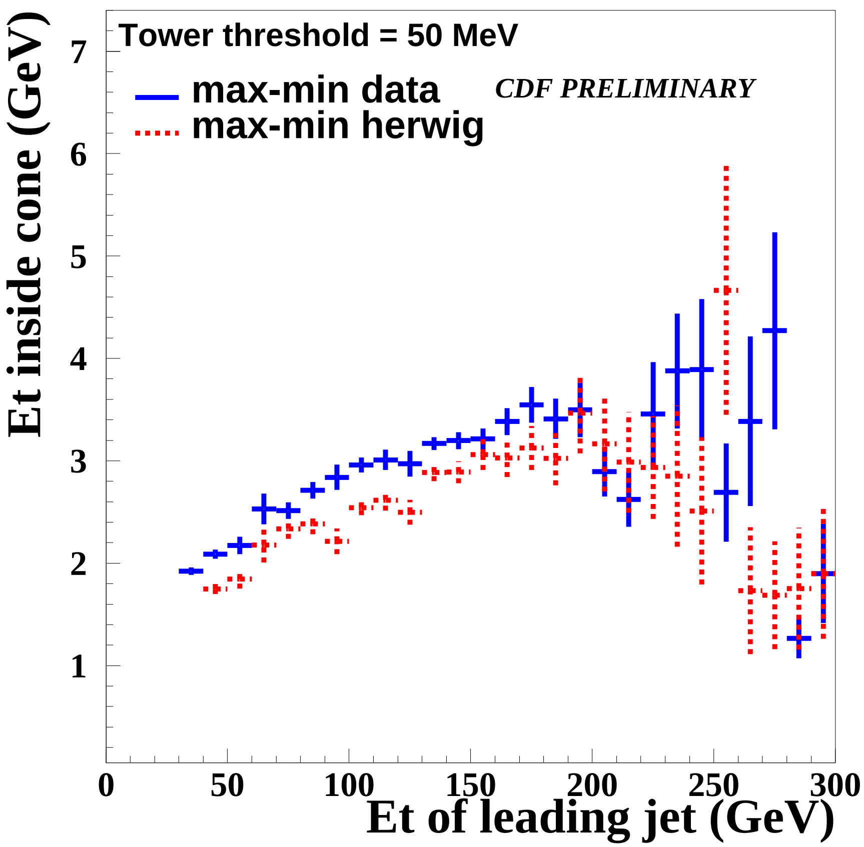
- Better understanding of underlying event is vital. Studying two regions away from jets can help.
  - max has underlying event plus hard process activity
  - min has underlying event, less hard process activity

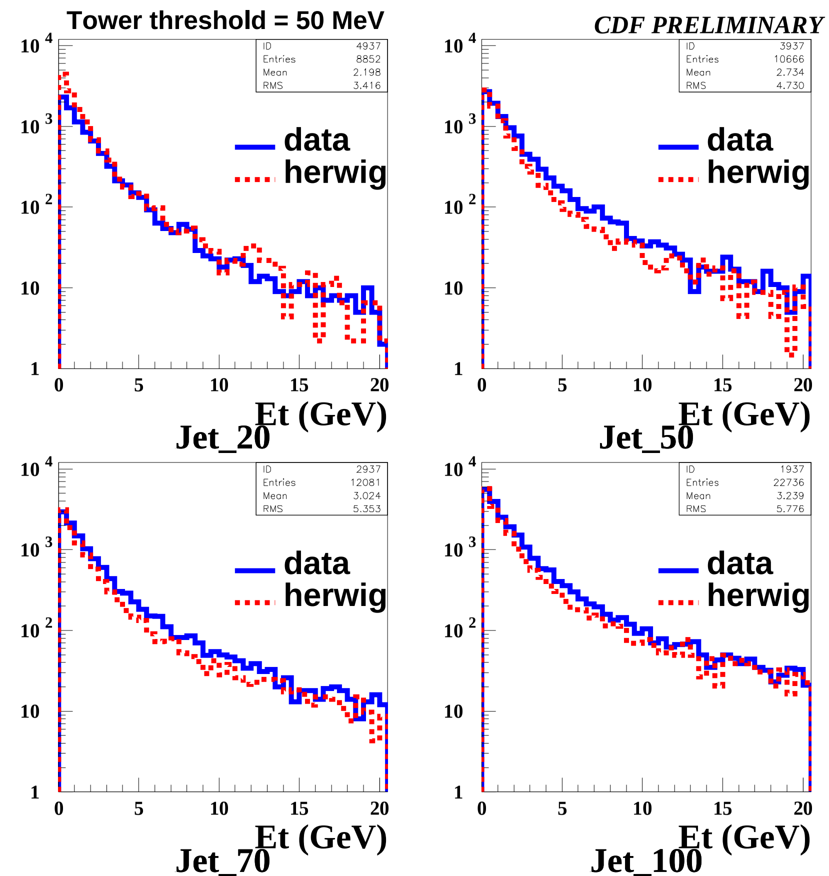
J Huston & V Tano, in hep-ph/0005114





- min–max subtracts most of underlying event:





- HERWIG has right qualitative features but too little and/or too soft underlying event?

Sample Program

```
      PROGRAM HWIGPR
C---COMMON BLOCKS ARE INCLUDED AS FILE HERWIG65.INC
      INCLUDE 'HERWIG65.INC'
      INTEGER N
      EXTERNAL HWUDAT
C---MAX NUMBER OF EVENTS THIS RUN
      MAXEV=10000
C---BEAM PARTICLES
      PART1='PBAR'
      PART2='P'
C---BEAM MOMENTA
      PBEAM1=980.
      PBEAM2=980.
C---PROCESS
      IPROC=1500
C---INITIALISE OTHER COMMON BLOCKS
      CALL HWIGIN
C---USER CAN RESET PARAMETERS AT
C   THIS POINT, OTHERWISE DEFAULT
C   VALUES IN HWIGIN WILL BE USED.
```

```
      NRN(1)=434389
      NRN(2)=417895
      PRVTX=.FALSE.
      PTMIN=50.
      LRSUD=77
      LRDEC=88
      LWSUD=0
      LWDEC=0
C--SUPPRESS UNDERLYING EVENT
      PRSOF=ZERO
c      PRSOF=ONE
      MAXPR=1
C---COMPUTE PARAMETER-DEPENDENT CONSTANTS
      CALL HWUINC
C---CALL HWUSTA TO MAKE ANY PARTICLE STABLE
      CALL HWUSTA('PI0     ')
C---USER'S INITIAL CALCULATIONS
      CALL HWABEG
C---INITIALISE ELEMENTARY PROCESS
      CALL HWEINI
C---LOOP OVER EVENTS
```

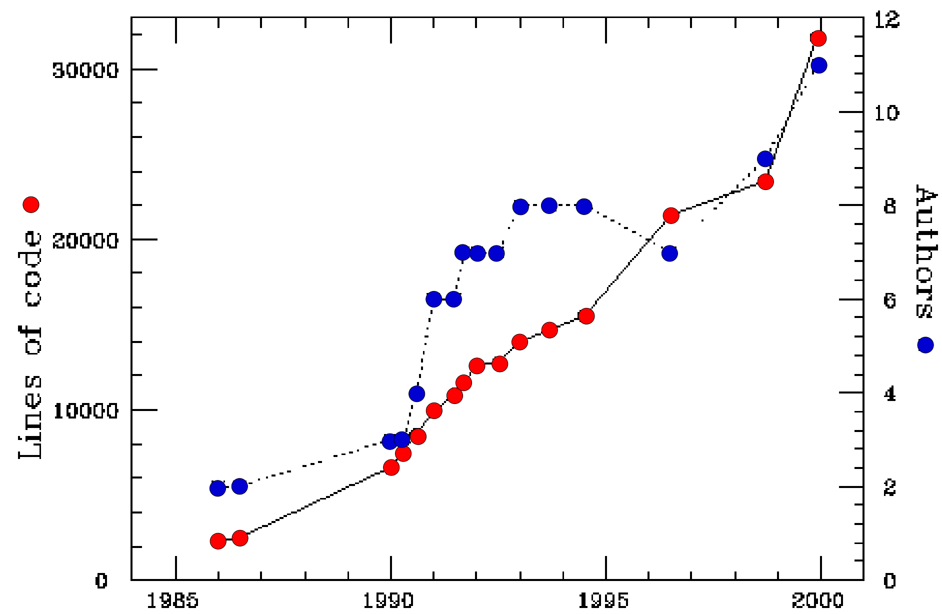
```
      DO 100 N=1,MAXEV
C---INITIALISE EVENT
      CALL HWUINE
C---GENERATE HARD SUBPROCESS
      CALL HWEPRO
C---GENERATE PARTON CASCADES
      CALL HWBGEN
C---DO HEAVY OBJECT DECAYS
      CALL HWDHOB
C---DO CLUSTER FORMATION
      CALL HWCFOR
C---DO CLUSTER DECAYS
      CALL HWCDEC
C---DO UNSTABLE PARTICLE DECAYS
      CALL HWDHAD
C---DO HEAVY FLAVOUR HADRON DECAYS
      CALL HWDHVY
C---ADD SOFT UNDERLYING EVENT IF NEEDED
      CALL HWMEVT
C---FINISH EVENT
      CALL HWUFNE
```

```
C---USER'S EVENT ANALYSIS
      CALL HWANAL
  100 CONTINUE
C---TERMINATE ELEMENTARY PROCESS
      CALL HWEFIN
C---USER'S TERMINAL CALCULATIONS
      CALL HWAEND
      STOP
      END
```

- See http://www.hep.phy.cam.ac.uk/theory/webber/hwsample/ for analysis and output.

Future Plans

- Program has expanded $\times 10$ over 15 years



- Software maintenance and development becoming impossible (and students don't learn Fortran . . .)
- New Object Oriented Program HERWIG++ under construction
  - Standard class structure and interfaces (CLHEP, ThePEG, . . .)
  - New physics (multijets, SUSY showering, . . .)

S. Gieseke, P. Stephens and BW, JHEP **0312** (2003) 045

S. Gieseke, A. Ribon, M. H. Seymour, P. Stephens and BW, JHEP **0402** (2003) 005

Conclusions

- HERWIG contains the right perturbative physics to describe wide range of data from LEP and Tevatron (also HERA):
  - Angular ordered parton showers
  - Matrix element corrections
- Non-perturbative physics needs improvements:
  - Heavy flavour hadronization
  - Baryon production
  - Underlying event
- Multijet simulation
  - New ideas under development
  - Also needed for W+jets, WW+jets, . . .
- Underlying event: more needed
- New physics studies: plenty of scope
- Future: HERWIG++