HERWIG Event Generator

Bryan Webber

Run II MC Workshop
18 April 2001

- HERWIG Basics
  - Cluster hadronization model
  - Angular-ordered showers
  - Matrix element corrections
  - Parameters and tuning
  - Underlying event

- Recent Additions (Version 6.2)
  - SUSY and Higgs processes
  - Extra dimension physics

- Forthcoming Attractions (Version 6.3)
  - New gauge and Higgs boson processes
  - Negative weights option

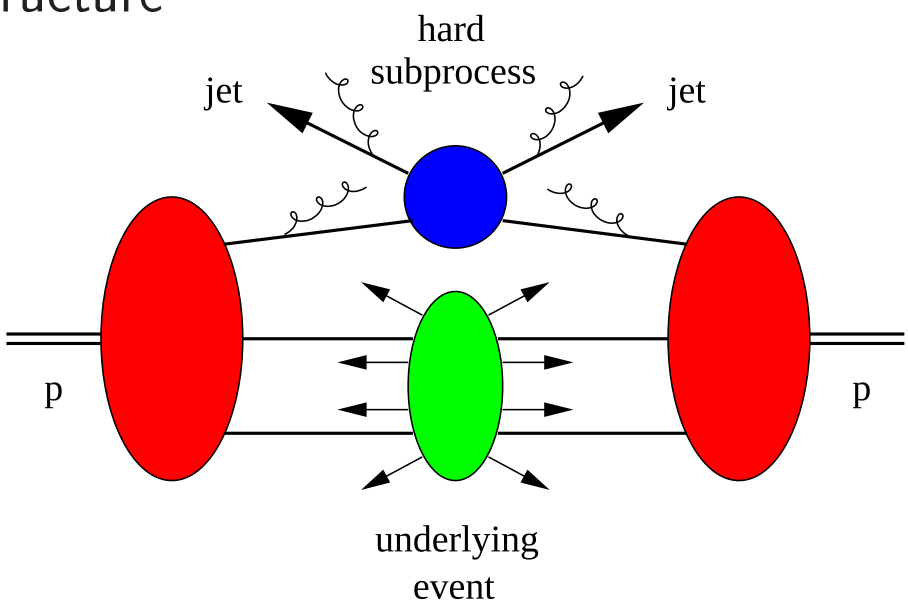
- Future Plans & Conclusions

http://hepwww.rl.ac.uk/theory/seymour/herwig/

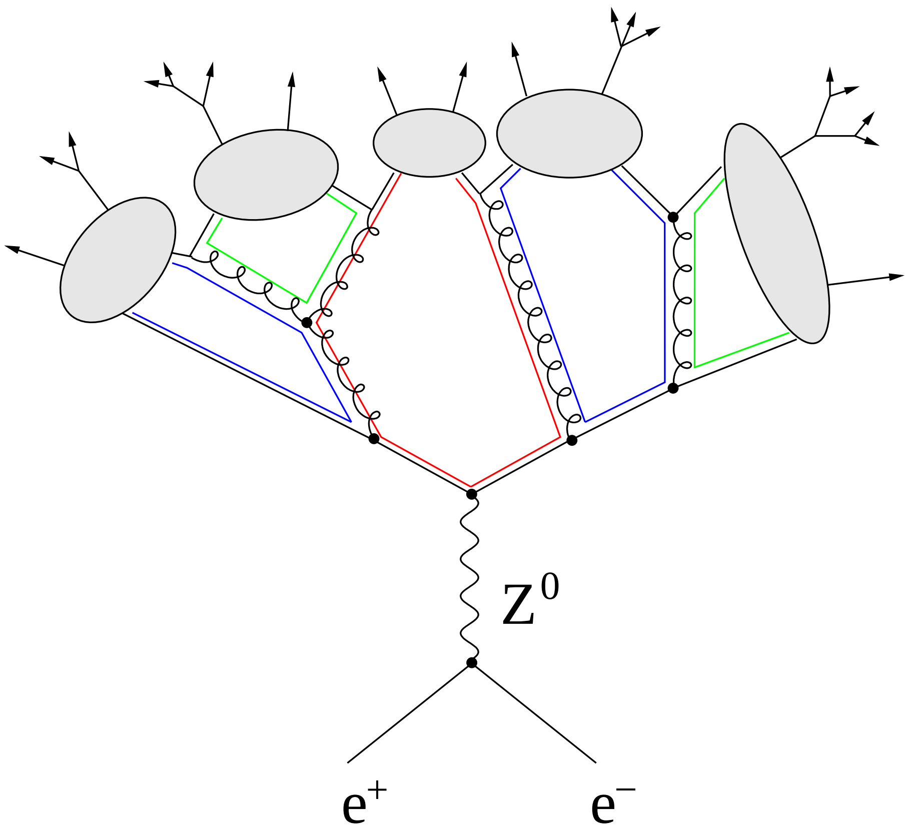
G Corcella, IG Knowles, G Marchesini, S Moretti, K Odagiri, P Richardson, MH Seymour, BRW, JHEP 0101 (2001) 010

HERWIG Basics

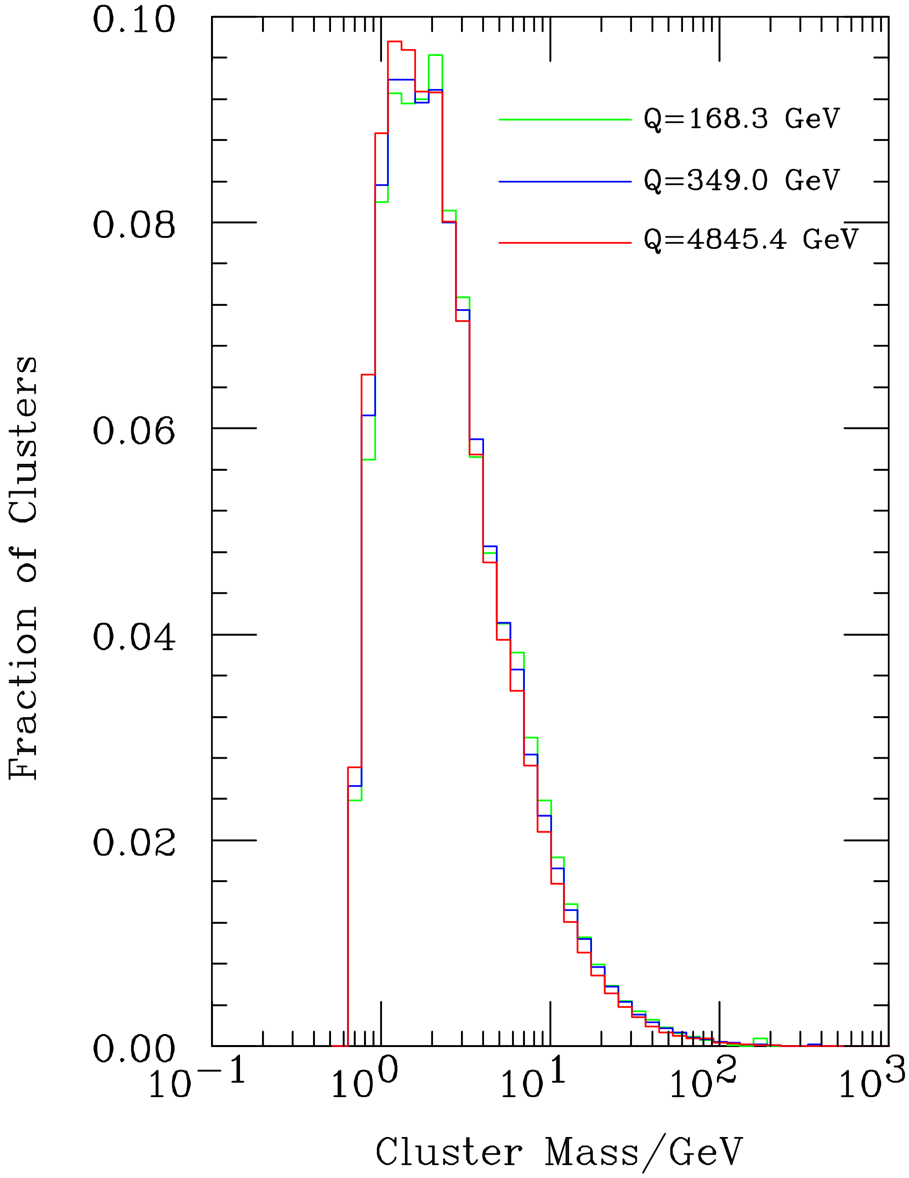
- Event structure



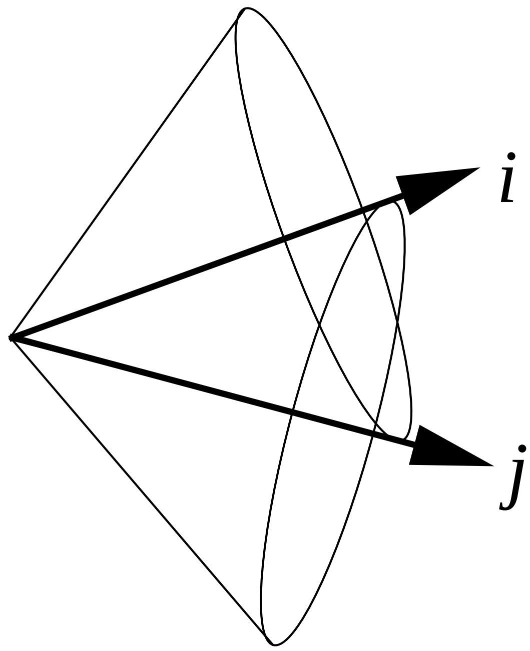
- Parton showers and cluster hadronization model



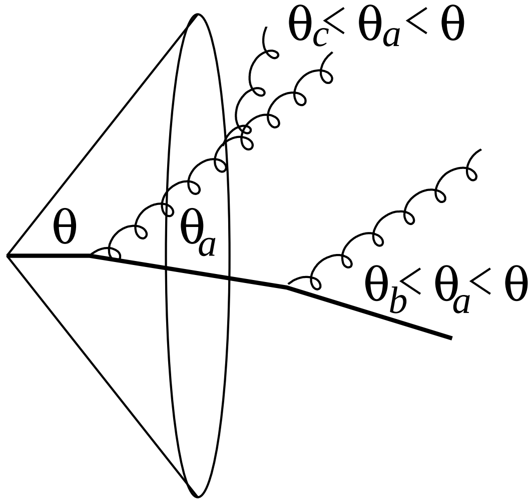
Cluster mass spectrum is universal



- 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:



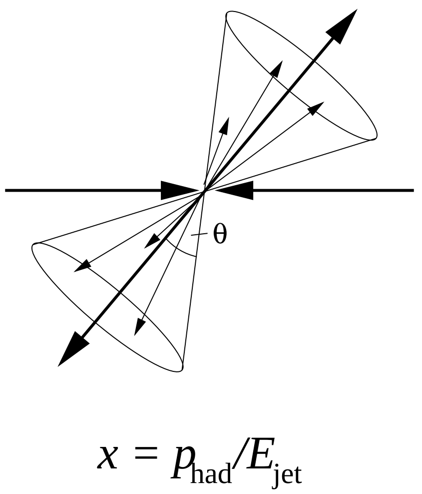
  - Angles within shower decrease away from hard subprocess:

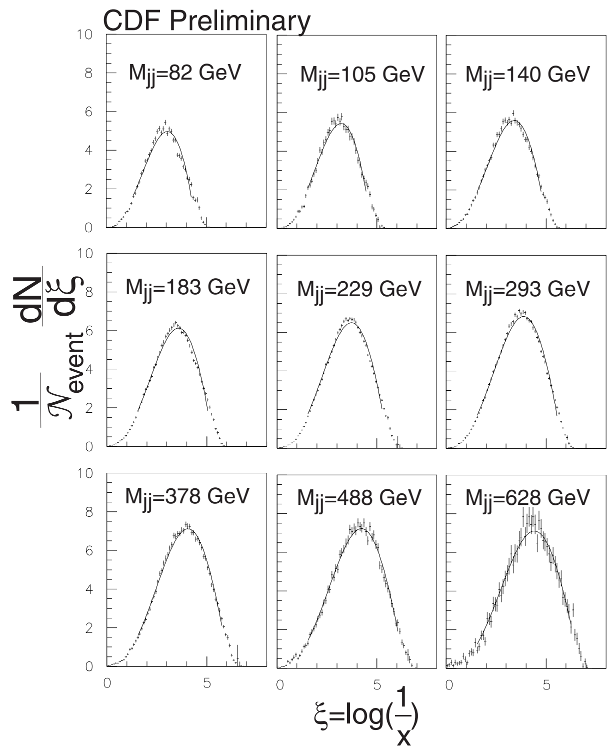


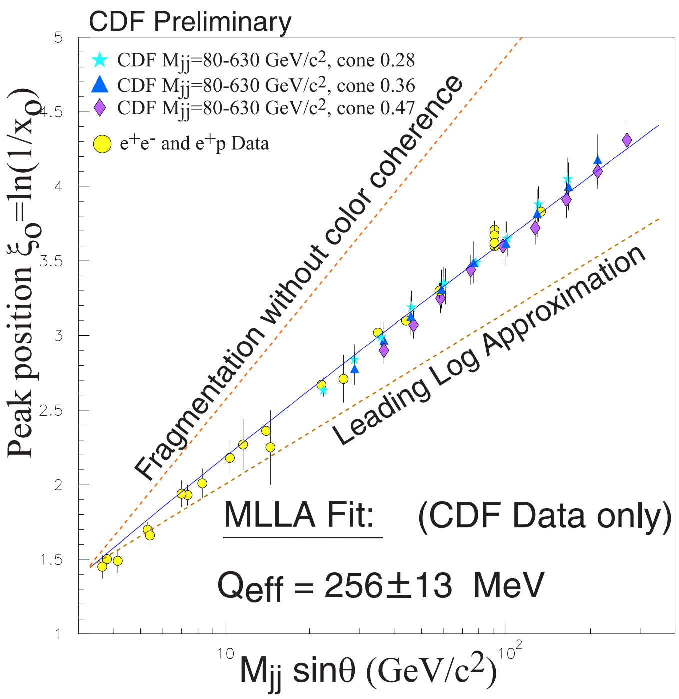
  - This suppresses soft gluon/hadron production (MLLA/LPHD).

- Beautifully confirmed by Tevatron dijet data

CDF Collaboration

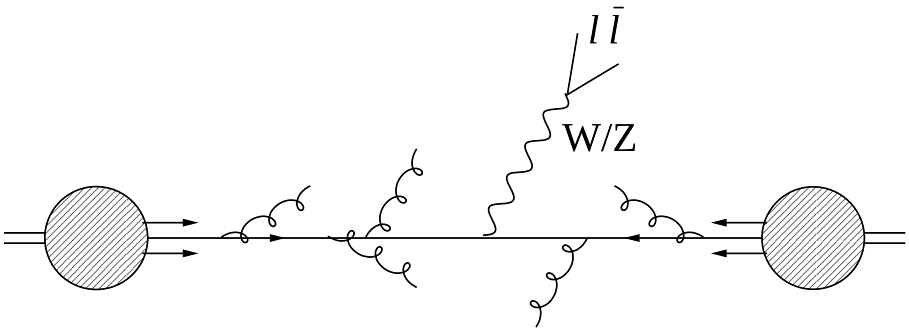




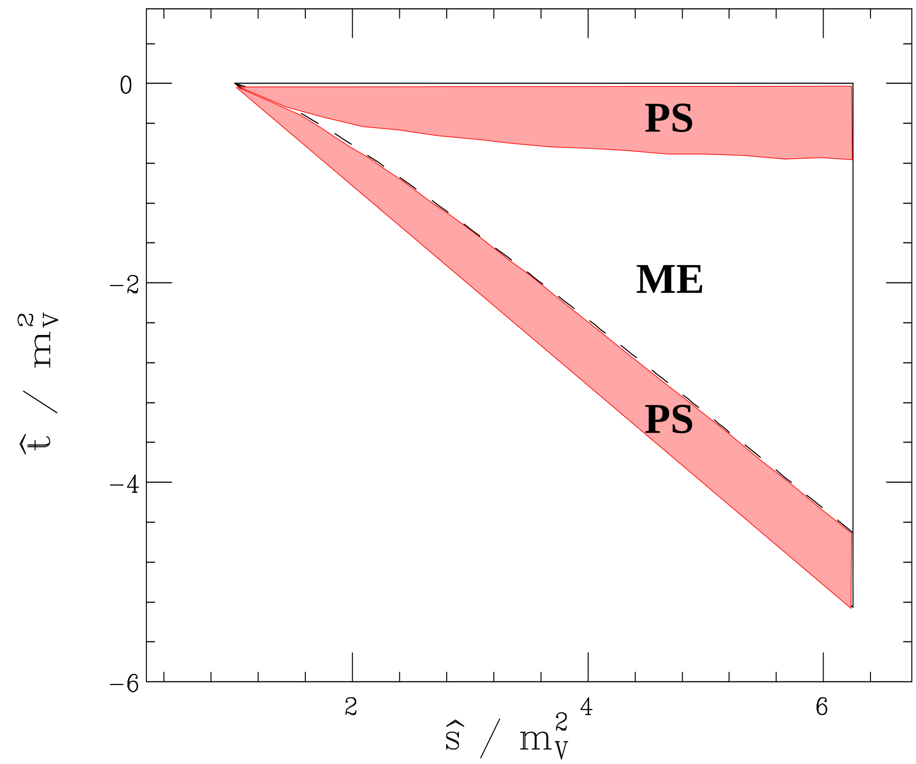


- Parton showers inside cones do not populate whole phase space. We also have to include matrix element corrections (talk by Gennaro Corcella)

- For example, in W/Z hadroproduction

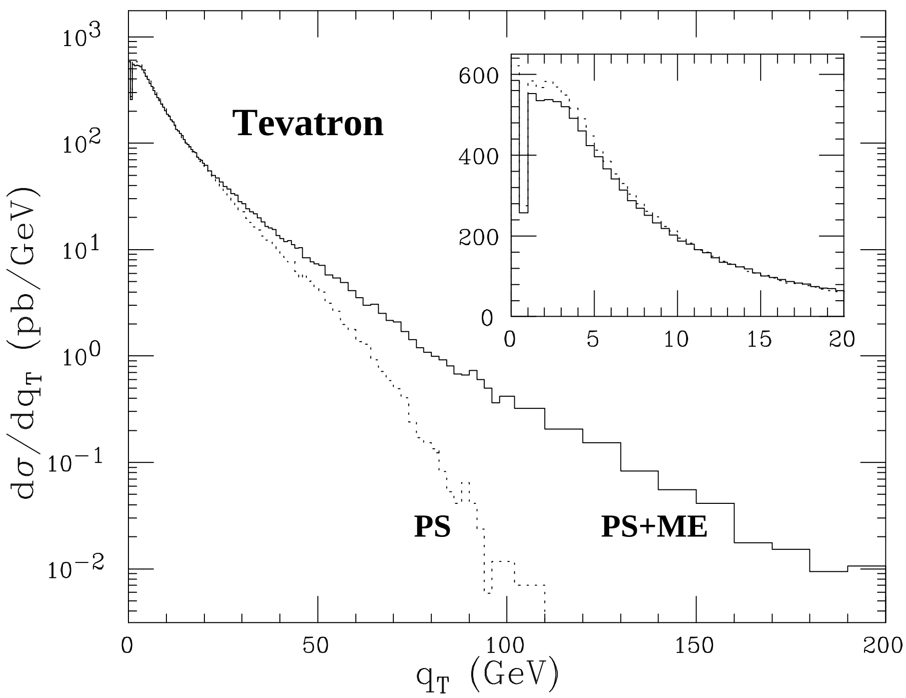


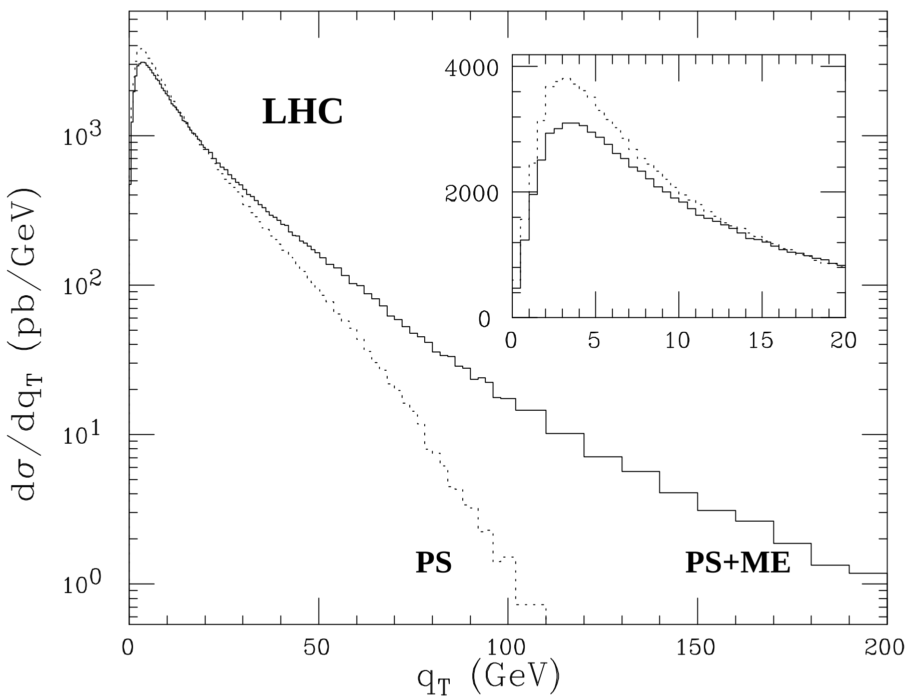
- Phase space for W + jet



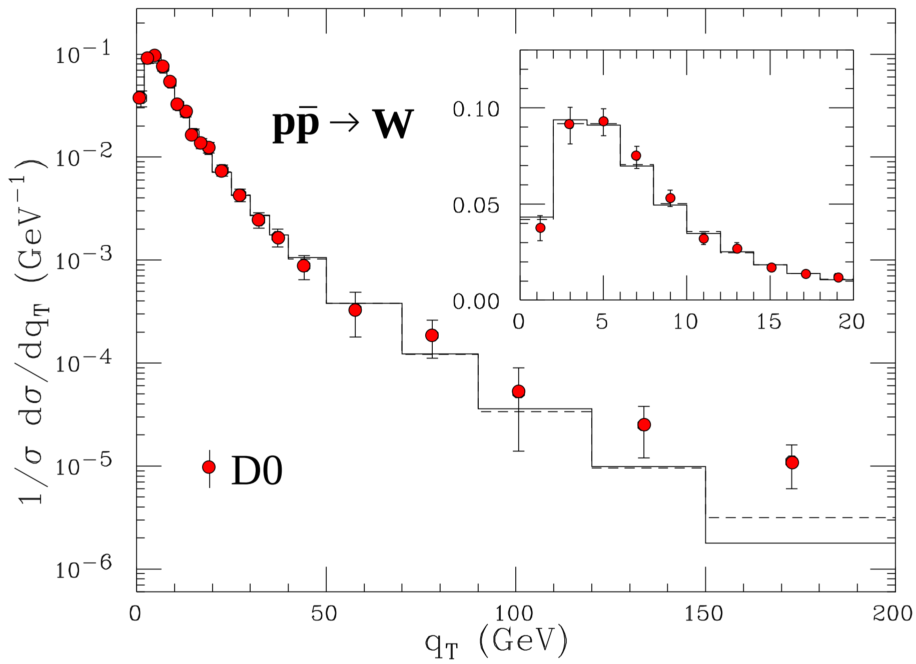
- ME corrections essential for W/Z production at large transverse momentum (important background to new physics):

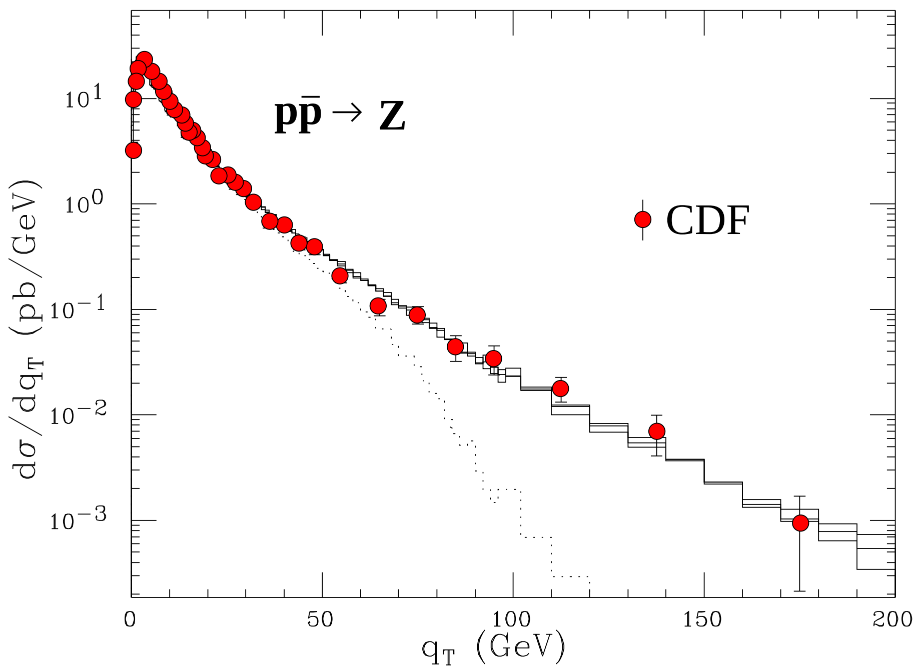
G Corcella & MH Seymour, Nucl Phys B565(2000)227





- Comparisons with Tevatron data:





- HERWIG's adjustable parameters:

Parameter	Affects	Default	OPAL
QCDLAM	$\Lambda \sim \Lambda^{(5)}_{\overline{\text{MS}}}$	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

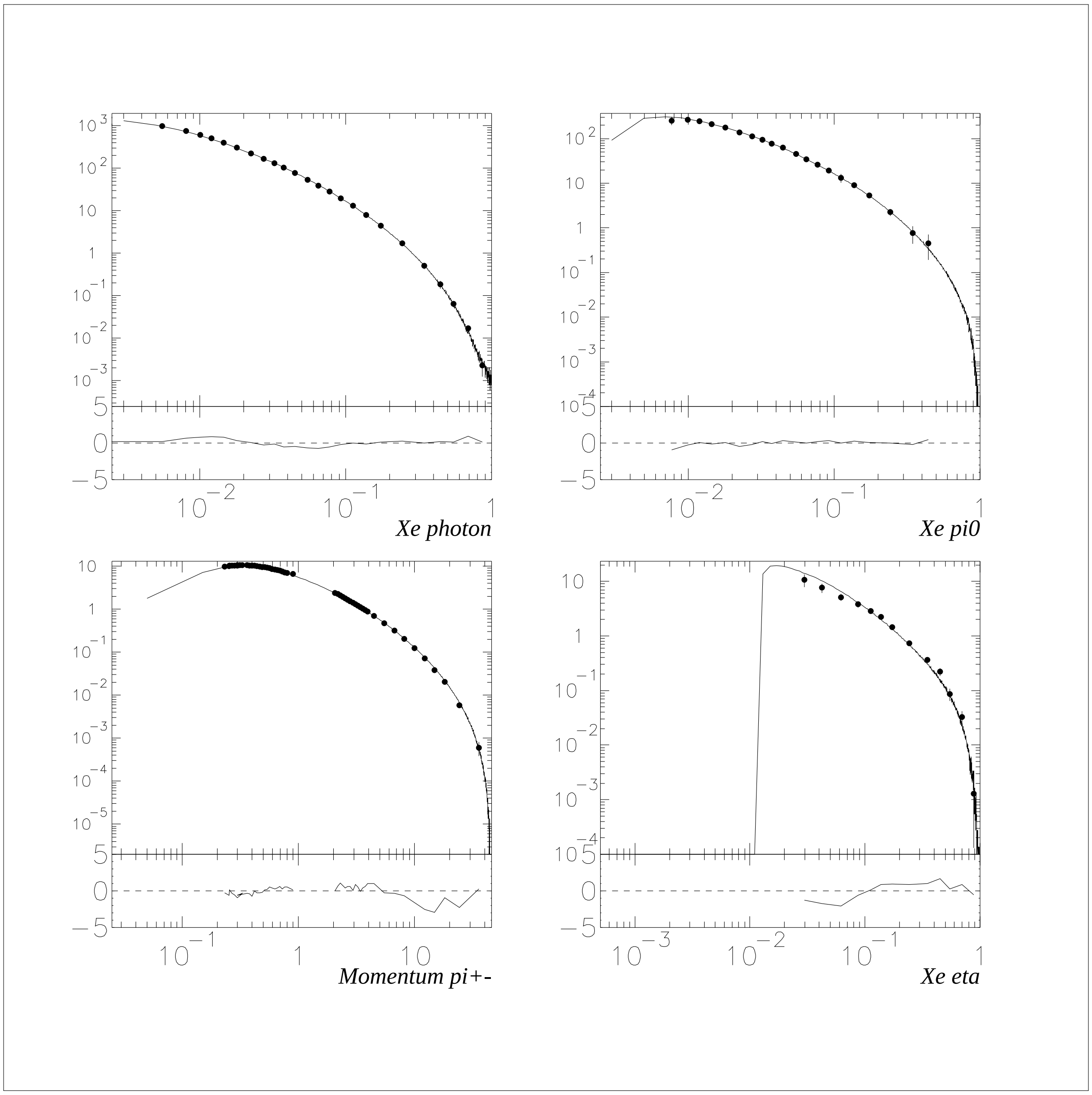
For details see http://home.cern.ch/webber/hwtune.html

- 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):

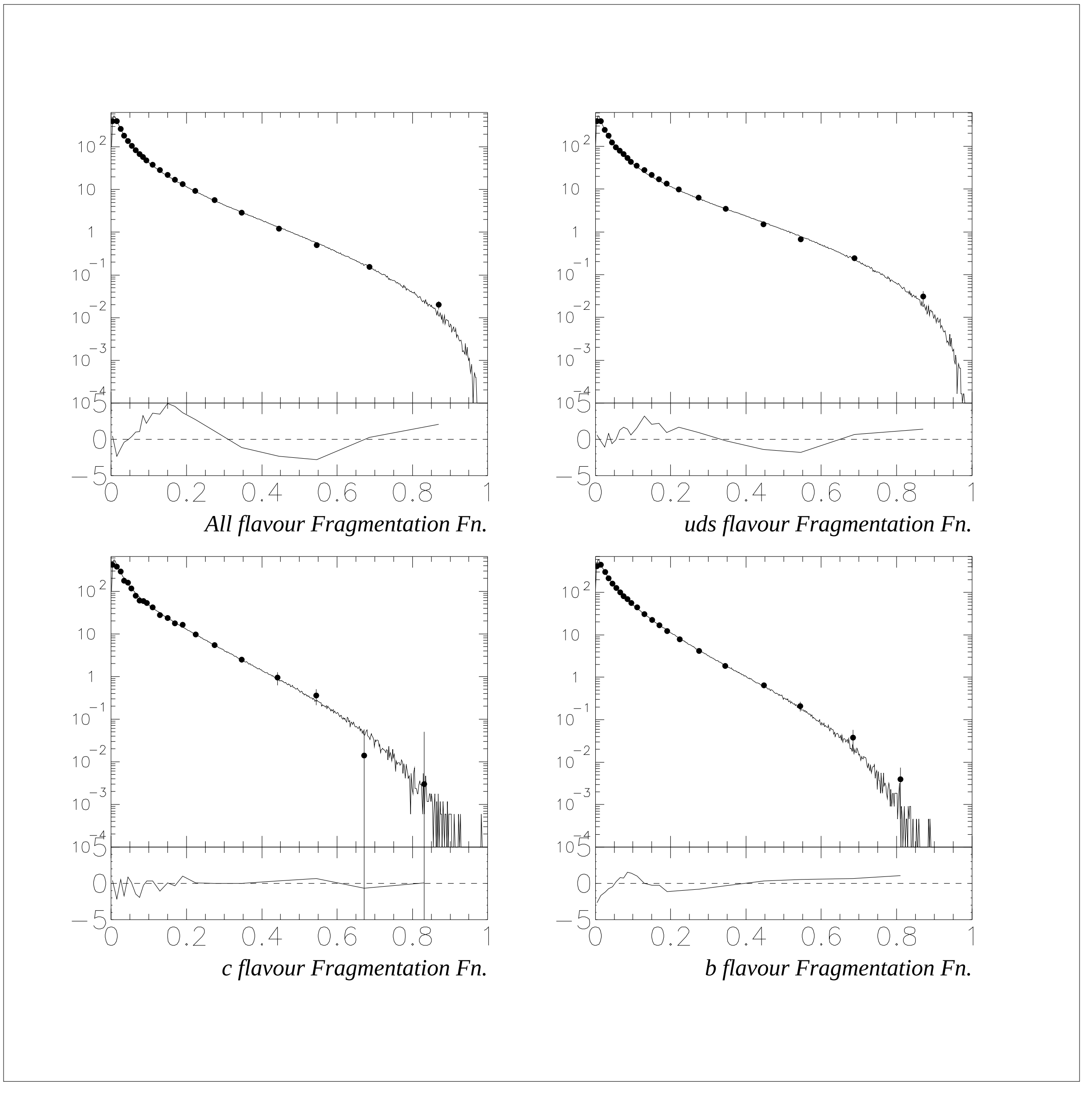
Identified particle spectra

OPAL Collaboration



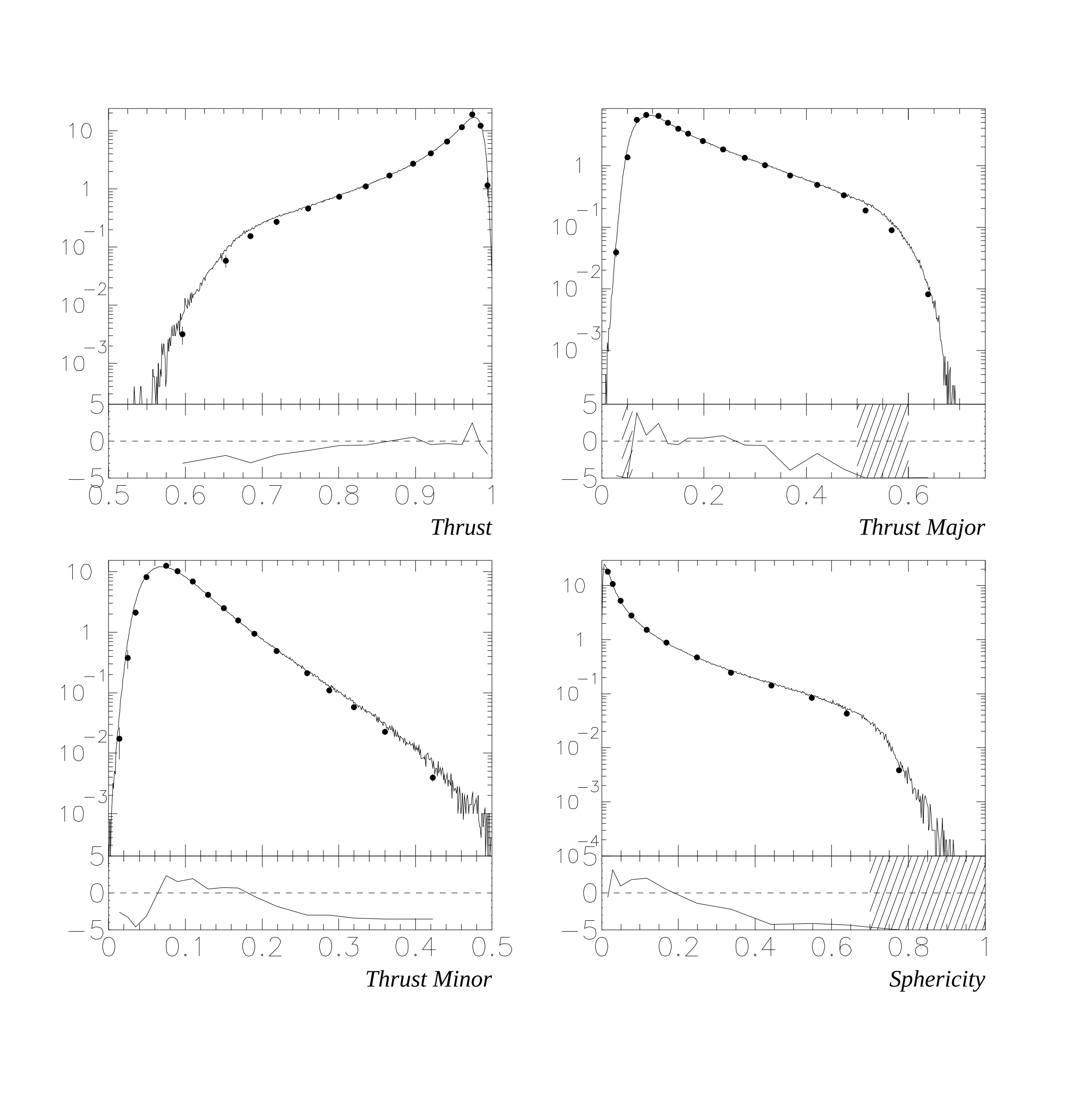
Quark fragmentation functions

OPAL Collaboration



Event shapes

OPAL Collaboration



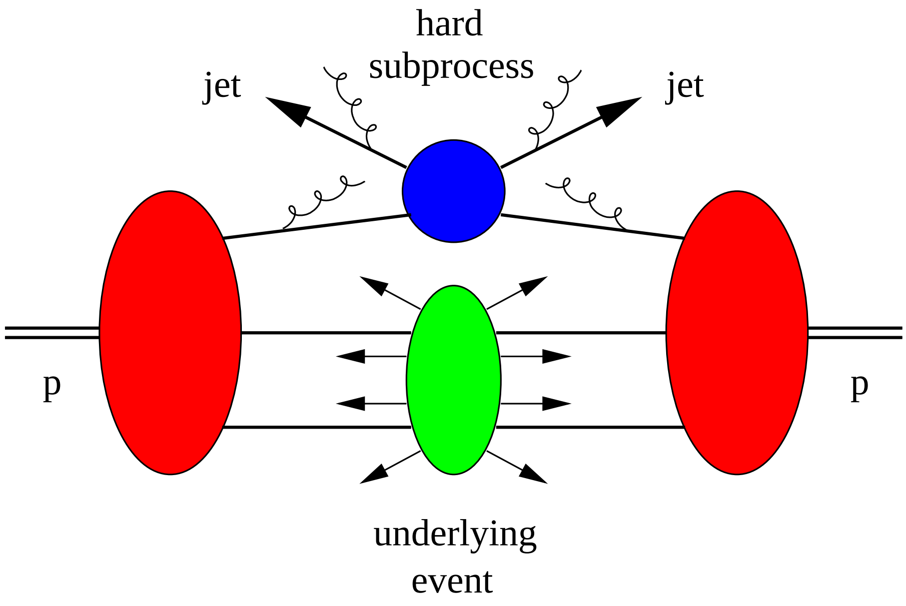
Identified particle yields in Z^0 decay

OPAL Collaboration

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*

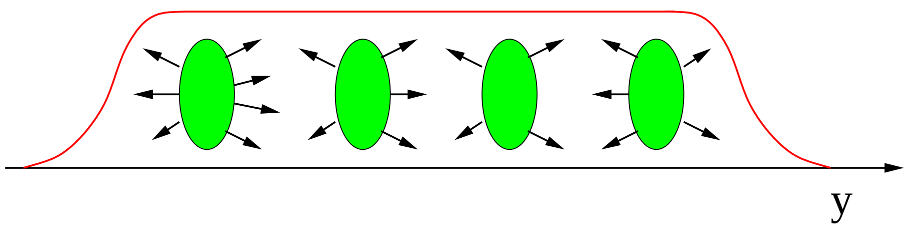
Table 1: Particle Production rates at 91.21 GeV compared with default and OPAL-tuned versions of HERWIG61. The experiments are Aleph(A), Delphi(D), L3(L), Opal(O), MK2(M), and SLD(S). Particle and anti-particle rates are summed and sequential particle decay is activated. * indicates that the rate differs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



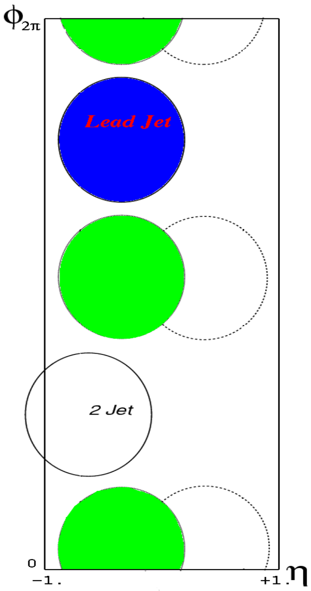
  - ❖ Negative binomial distribution sampled for n_{ch}
  - ❖ Clusters generated until preselected n_{ch} is reached

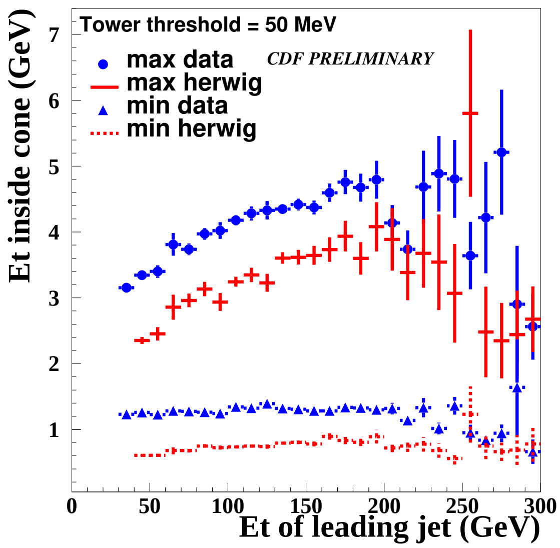
- Better understanding of underlying event is vital. Studying two regions away from jets can help

  G Marchesini & BRW, Phys Rev D38 (1988) 3419

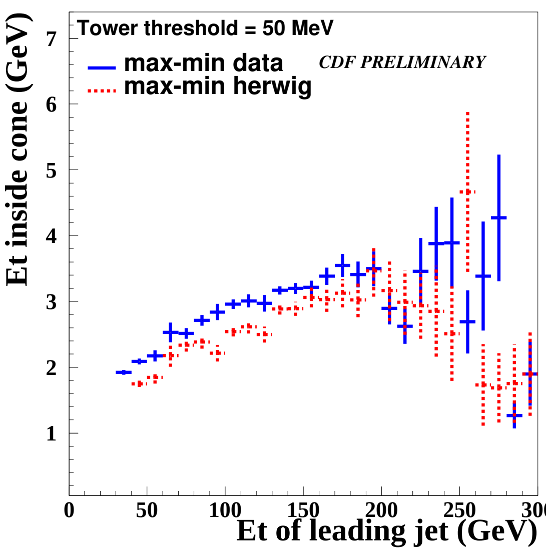
  - max has underlying event plus hard process activity
  - min has underlying event, less hard process activity

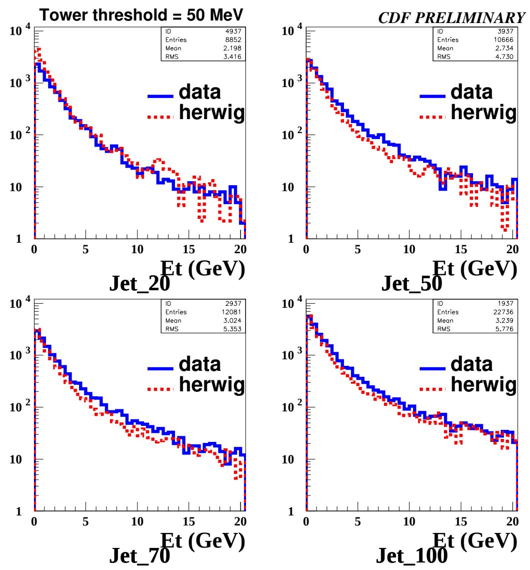
  J Huston & V Tano, in hep-ph/0005114





- min–max subtracts most of underlying event:





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

Recent Additions (Version 6.2)

- SUSY 2→ 2 processes (talk by Peter Richardson)
  - Interface to ISAJET for input SUSY spectra & decays
  - R-parity violation allowed
  - No parton showering on spartons

- SM Higgs processes

IPROC	Process
1600+ID	$gg/q\bar{q} \to H^0_{\mathrm{SM}}$
1900+ID	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0_{\mathrm{SM}}$
2500+ID	$gg/q\bar{q} \to t\bar{t}H^0_{\mathrm{SM}}$
2600+ID	$q\bar{q}' \to W^\pm H^0_{\mathrm{SM}}$
2700+ID	$q\bar{q} \to Z^0 H^0_{\mathrm{SM}}$

  - ID controls Higgs decay

ID	Decay
1–6	$H^0_{\mathrm{SM}} \to q\bar{q}$
7–9	$H^0_{\mathrm{SM}} \to \ell\bar{\ell}$
10,11	$H^0_{\mathrm{SM}} \to W^+W^-, Z^0Z^0$
12	$H^0_{\mathrm{SM}} \to \gamma\gamma$
99	$H^0_{\mathrm{SM}} \to$ anything

- MSSM Higgs processes

IPROC	Process
3310,3315	$q\bar{q}' \to W^\pm h^0,\, H^\pm h^0$
3320,3325	$q\bar{q}' \to W^\pm H^0,\, H^\pm H^0$
3335	$q\bar{q}' \to H^\pm A^0$
3350	$q\bar{q} \to W^\pm H^\mp$
3355	$q\bar{q} \to H^\pm H^\mp$
3360,3365	$q\bar{q} \to Z^0 h^0,\, A^0 h^0$
3370,3375	$q\bar{q} \to Z^0 H^0,\, A^0 H^0$
3410	$bg \to b\ h^0$ + ch. conj.
3420	$bg \to b\ H^0$ + ch. conj.
3430	$bg \to b\ A^0$ + ch. conj.
3450	$bg \to t\ H^-$ + ch. conj.
3610	$q\bar{q}/gg \to h^0$
3620	$q\bar{q}/gg \to H^0$
3630	$q\bar{q}/gg \to A^0$

- Extra dimension physics: graviton resonance production

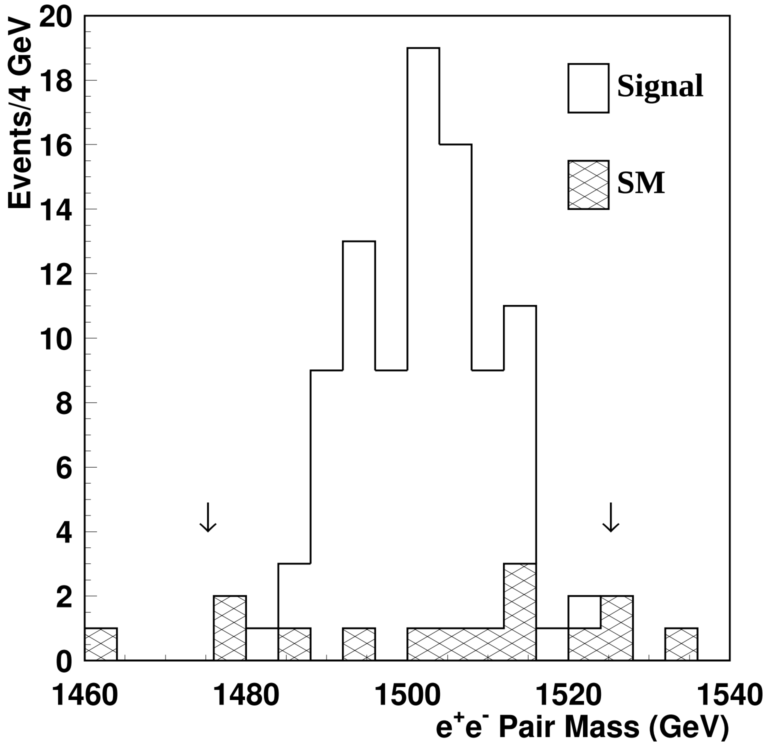
IPROC	Process
4210	$gg/q\bar{q} \to G \to gg/q\bar{q}$ (all partons)
4210+IQ	$gg/q\bar{q} \to G \to q\bar{q}$ (IQ for q flavour)
4220	$gg/q\bar{q} \to G \to gg$
4250	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (all leptons)
4250+IL	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (IL for ℓ flavour)
4260	$gg/q\bar{q} \to G \to \gamma\gamma$
4270	$gg/q\bar{q} \to G \to W^+W^-/Z^0Z^0/H^0_{\mathrm{SM}}H^0_{\mathrm{SM}}$
4271	$gg/q\bar{q} \to G \to W^+W^-$
4272	$gg/q\bar{q} \to G \to Z^0Z^0$
4273	$gg/q\bar{q} \to G \to H^0_{\mathrm{SM}}H^0_{\mathrm{SM}}$

Searching for Graviton Resonances at LHC

BC Allanach, K Odagiri, MA Parker & BRW, JHEP 0009(2000)019

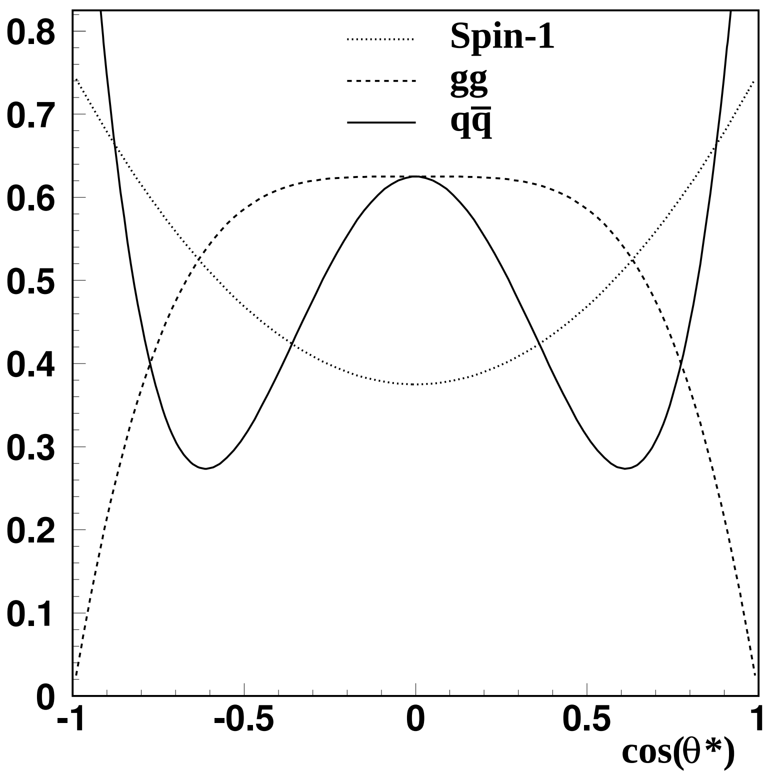
- In non-factorisable geometry (Randall-Sundrum) models there may be narrow graviton excitations G with TeV-scale masses.

- $G \to e^+e^-$ is a good mode to study:

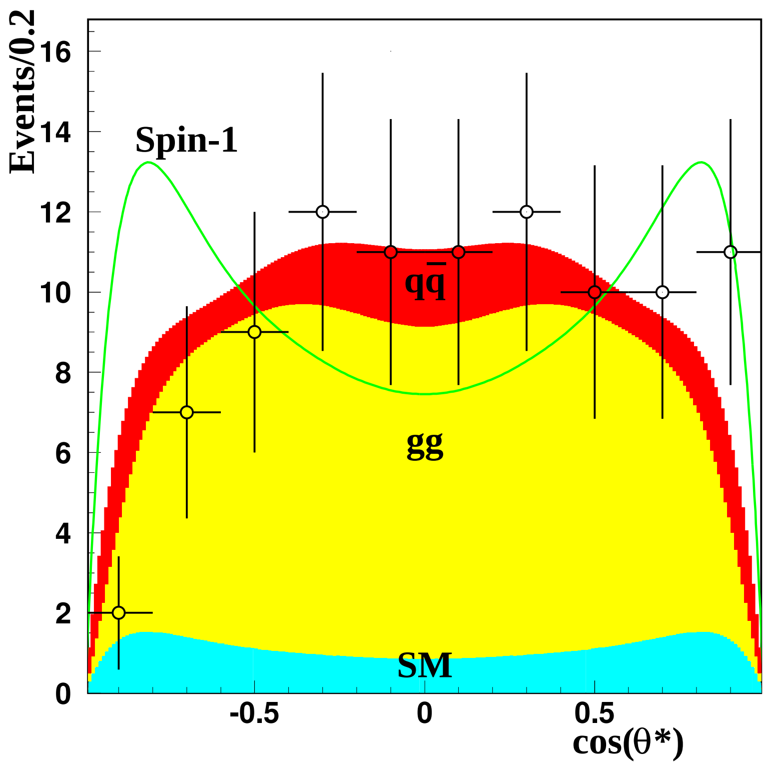


- Observed width $\gg \Gamma_G \sim 200$ MeV, due to detector effects.

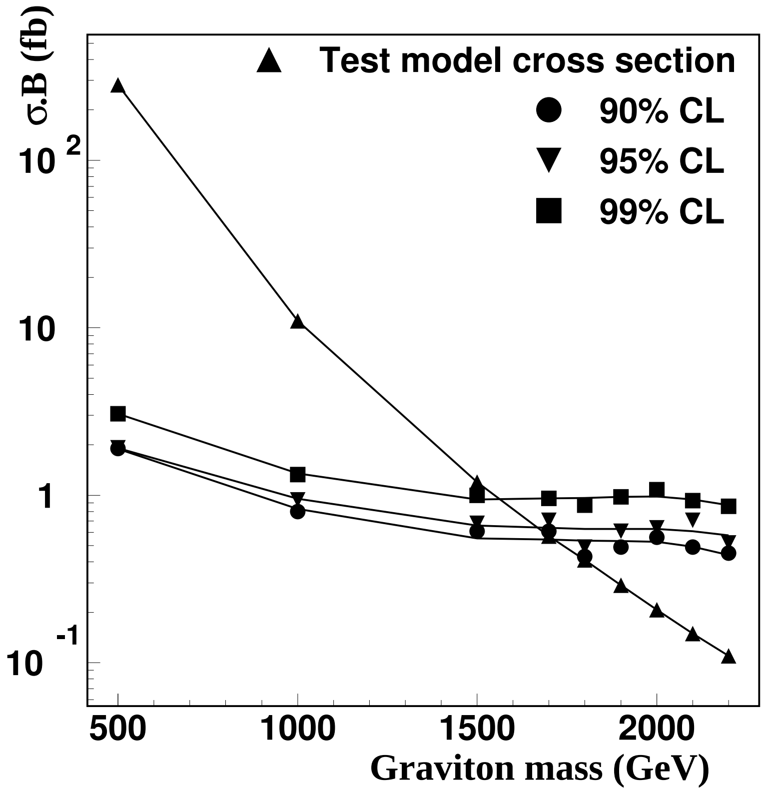
- $q\bar{q} \rightarrow G$ and $gg \rightarrow G$ give characteristic angular distributions:



- After full simulation (including ATLAS detector):



- Can be identified as spin-2 up to > 1500 GeV:



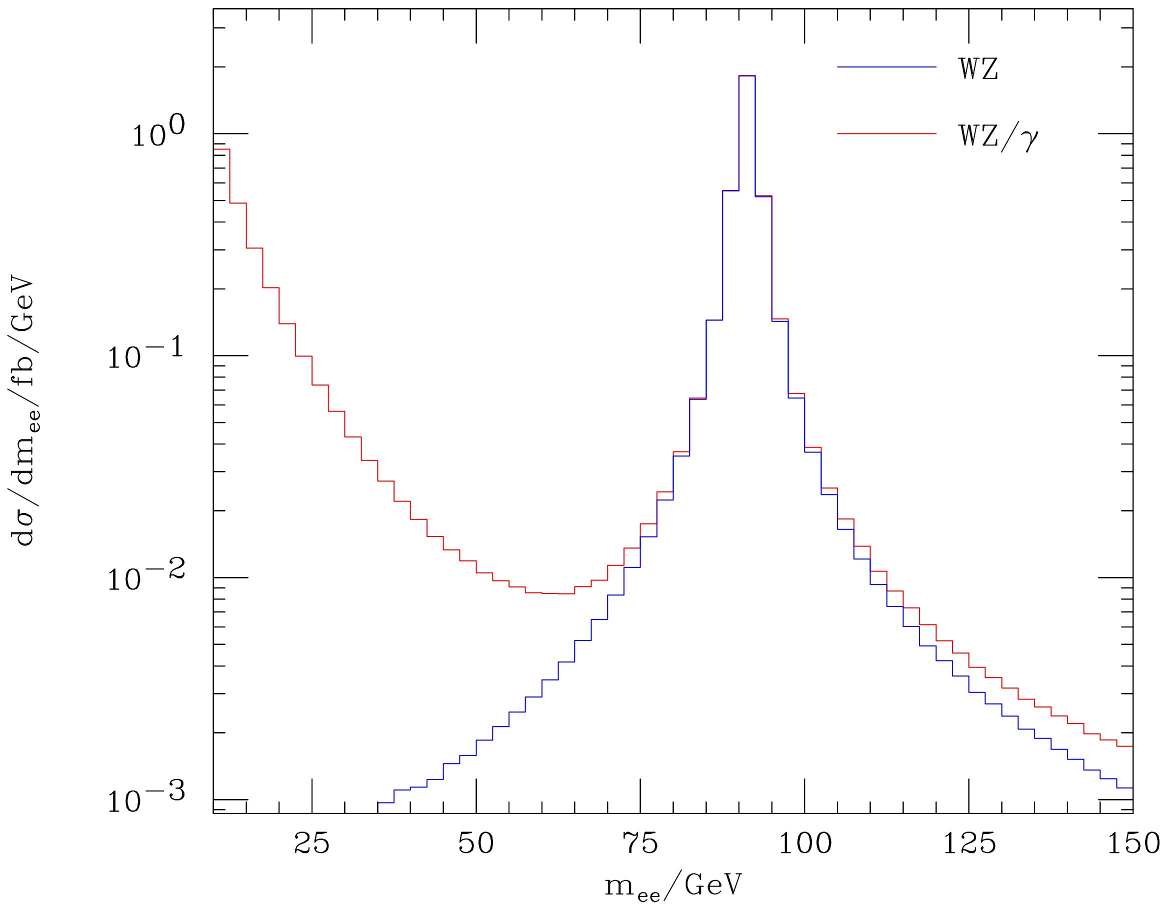
- Other modes can be checked for universality: $\mu^+\mu^-$, $\gamma\gamma$, W^+W^-, . . .

- Tevatron limit?

Forthcoming Attractions (Version 6.3)

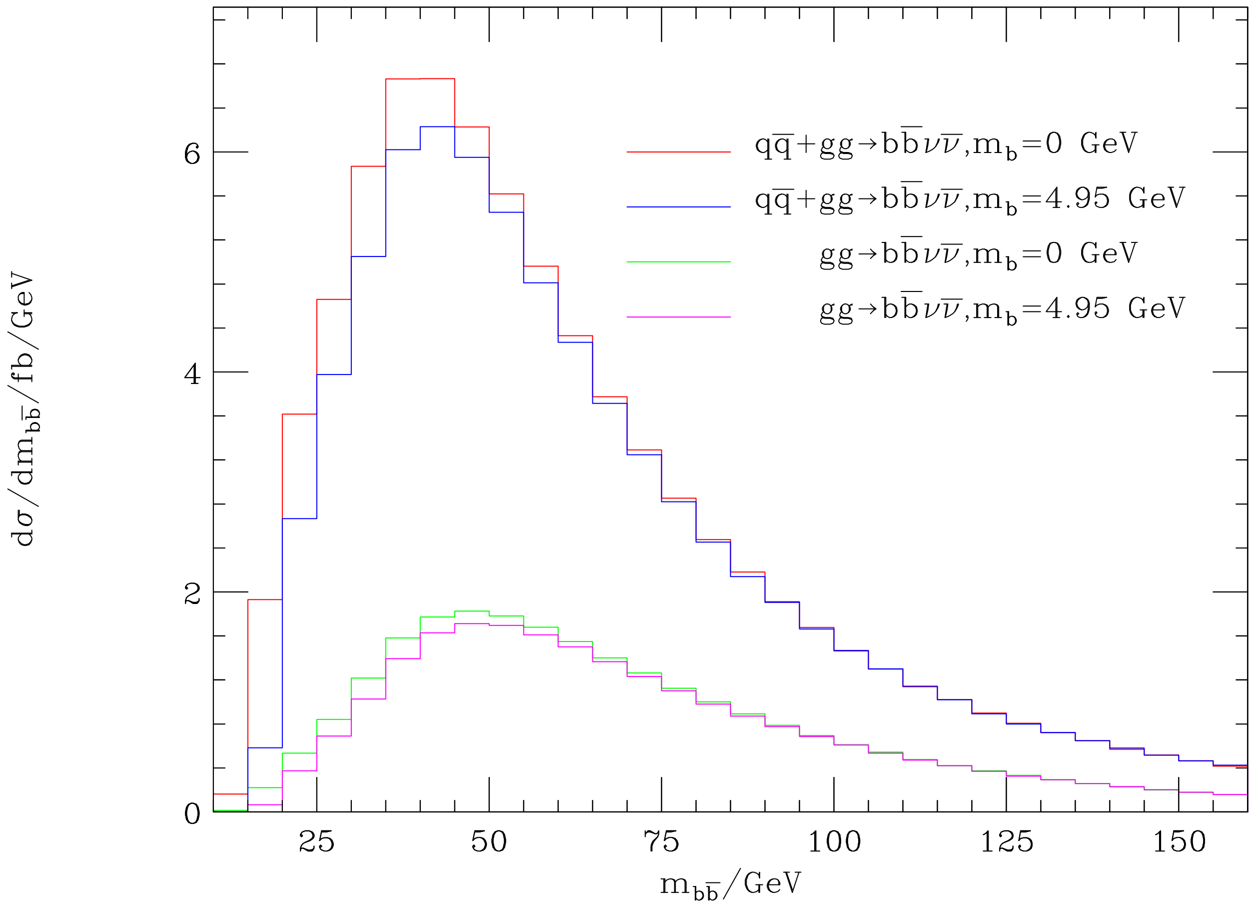
- SM gauge diboson production

IPROC	Process
2800	$q\bar{q} \to WW$
2810	$q\bar{q} \to ZZ$ (including γ^*)
2815	$q\bar{q} \to ZZ$ (Z only)
2820	$q\bar{q} \to WZ$ (including γ^*)
2825	$q\bar{q} \to WZ$ (Z only)



SM gauge boson + $Q\bar{Q}$ production

IPROC	Process
2900+IQ	$gg/q\bar{q} \to Q\bar{Q}Z$ (IQ for Q flavour, massless)
2910+IQ	$gg/q\bar{q} \to Q\bar{Q}Z$ (", massive)



- Fuller coverage of MSSM Higgs production

IPROC	Process
3100+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^{*}H^{\pm}$
3200+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^{*}h, H, A$
3500	$bq \to bq'H^{\pm}$ + ch. conj.
3710	$q\bar{q} \to q'\bar{q}'h$
3720	$q\bar{q} \to q'\bar{q}'H$
3810+IQ	$gg + q\bar{q} \to Q\bar{Q}h$ (IQ for Q flavour)
3820+IQ	$gg + q\bar{q} \to Q\bar{Q}H$ (")
3830+IQ	$gg + q\bar{q} \to Q\bar{Q}A$ (")
3839	$gg + q\bar{q} \to b\bar{t}H^{+}$ + ch. conjg.
3840+IQ	$gg \to Q\bar{Q}h$ (IQ as above)
3850+IQ	$gg \to Q\bar{Q}H$ (")
3860+IQ	$gg \to Q\bar{Q}A$ (")
3869	$gg \to b\bar{t}H^{+}$ + ch. conjg.
3870+IQ	$q\bar{q} \to Q\bar{Q}h$ (IQ as above)
3880+IQ	$q\bar{q} \to Q\bar{Q}H$ (")
3890+IQ	$q\bar{q} \to Q\bar{Q}A$ (")
3899	$q\bar{q} \to b\bar{t}H^{+}$ + ch. conjg.

- NME $= 200$ gives matrix element for free-particle decay $t \to bH^{+}$. But better to use IPROC $= 3839$, which includes Higgsstrahlung and interference.

Negative Weights Option

- Monte Carlo generates weights

$$\sigma = \frac{1}{N_w} \sum_{i=1}^{N_w} w_i \equiv \overline{w}$$

- Error depends on width of weight distribution

$$\frac{\delta\sigma}{\sigma} = \frac{1}{\sqrt{N_w}} \frac{\delta w_{\mathrm{rms}}}{\overline{w}}$$

- If $w_i > 0$, unweighted events can be generated by 'hit and miss': $w'_i = 0$ or 1 with $P(w'_i = 1) = w_i / w_{\mathrm{max}}$. Then

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{w_{\mathrm{max}} - \overline{w}}{N_w \overline{w}}} = \sqrt{\frac{w_{\mathrm{max}} - \overline{w}}{N_e w_{\mathrm{max}}}} \sim \frac{1}{\sqrt{N_e}}$$

  where $N_e = N_w \overline{w} / w_{\mathrm{max}}$ is number of events generated. Time needed (especially for detector simulation) depends mainly on number of events. Hence inefficiency of 'hit and miss' is not a disaster.

- Negative weights can be generated by subtraction procedure for matrix element corrections. These are not a problem of principle but prevent naive 'hit and miss'.

- To generalize 'hit and miss', consider generating unweighted events ($w'_i = 1$) and antievents ($w'_i = -1$) with

$$
\begin{aligned}
\mathrm{sign}(w'_i) &= \mathrm{sign}(w_i) \\
P(w'_i = \pm 1) &= |w_i|/|w|_{\mathrm{max}}
\end{aligned}
$$

- Then

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\overline{|w|}|w|_{\mathrm{max}} - \overline{w}^2}{N_w \overline{w}^2}} \sim \frac{1}{\sqrt{N_e}} \frac{\overline{|w|}}{\overline{w}}$$

where $N_e = N_w \overline{|w|}/|w|_{\mathrm{max}}$ is now the total number of events+antievents generated.

- Again, time $\propto N_e$, so this is tolerable as long as $\overline{|w|} \sim \overline{w}$.

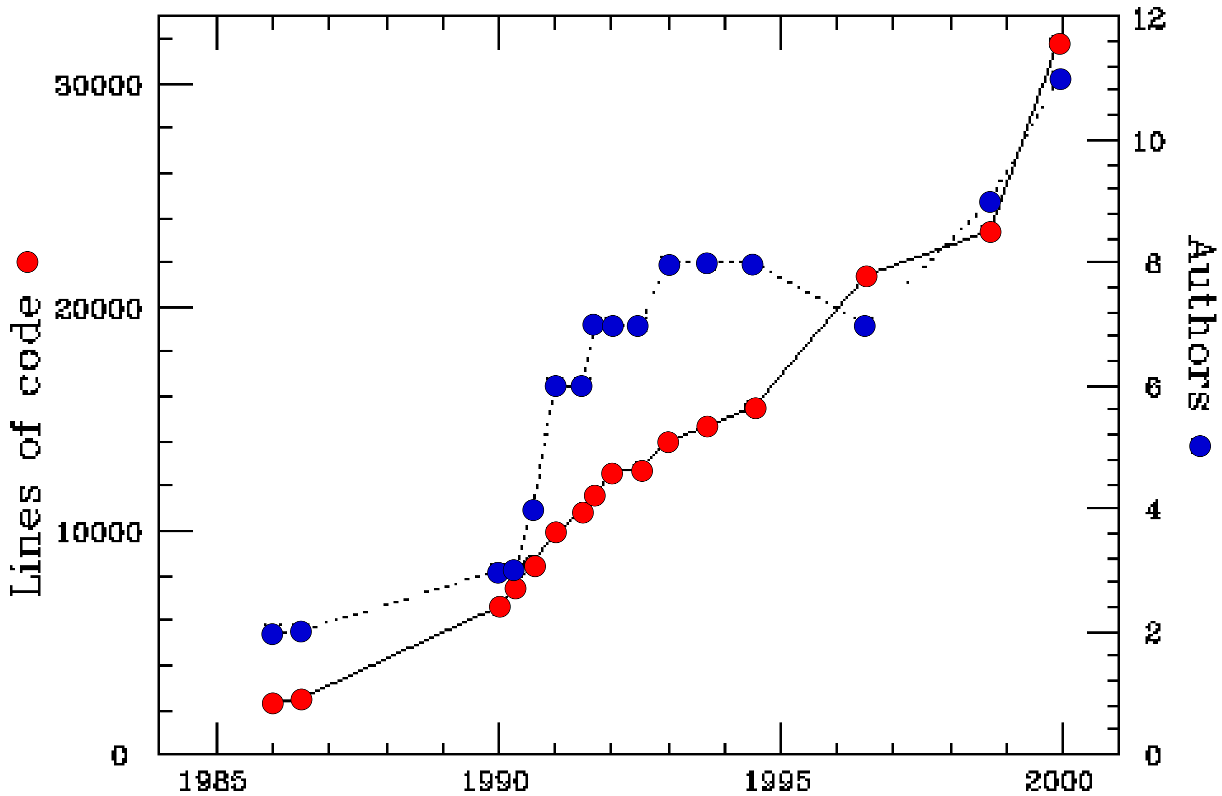
- Cross section after cuts is

$$\sigma_c = \frac{\overline{|w|}}{N_e}(N_+ - N_-)$$

where N_+ events and N_- antievents pass cuts.

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 (talk by Alberto Ribon)
  - Standard class structure and interfaces (CLHEP, PYTHIA7, . . .)
  - New physics (multijets, SUSY showering, . . .)

A Ribon, MH Seymour, AN Other & BRW, 2003?

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
- New physics: plenty of scope
  - SUSY, including RPV
  - SM and MSSM Higgs
  - Extra dimensions
- Negative weights option for NLO
- Future: HERWIG++