The current status of QCD event generators

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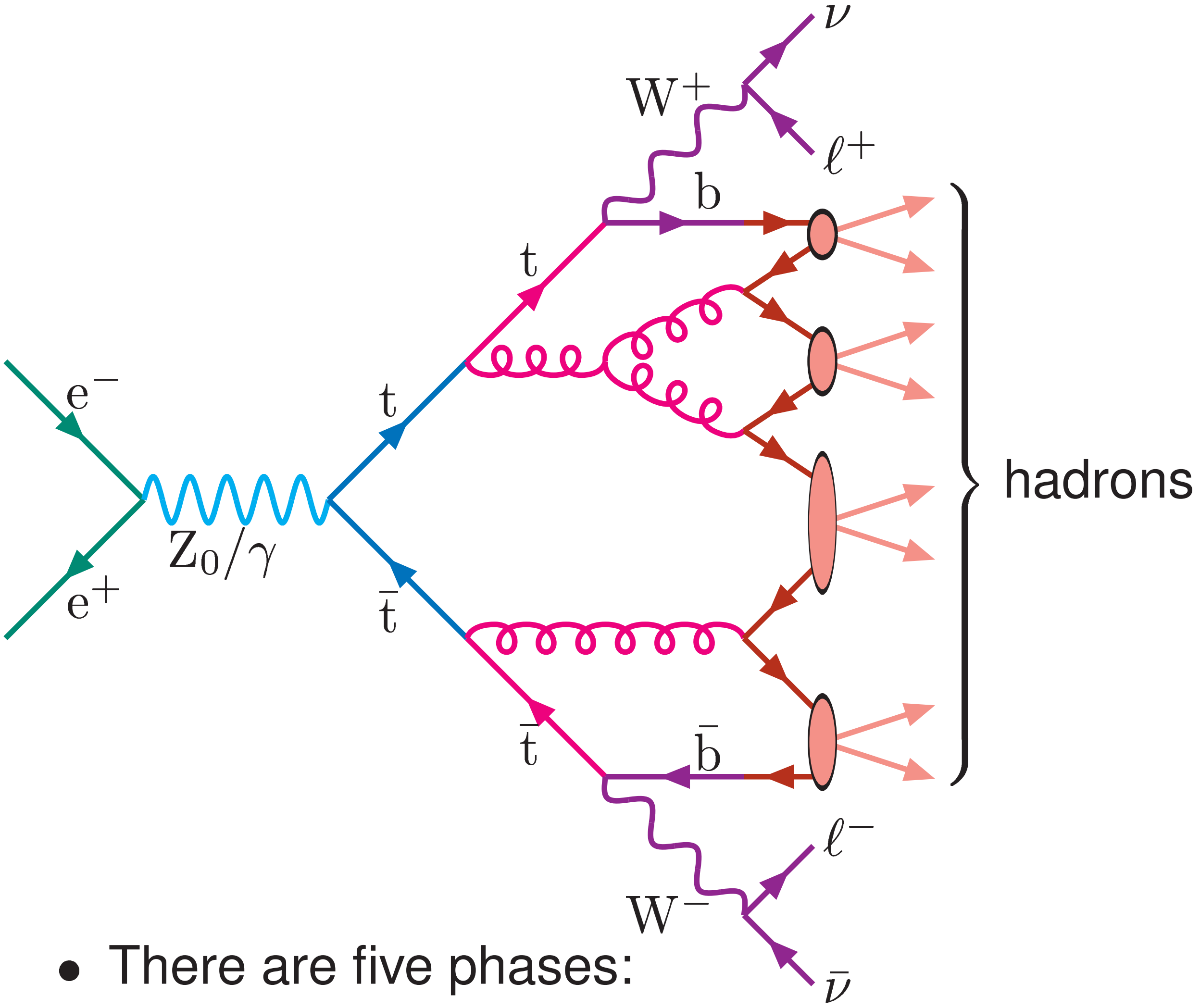
- Introduction to Monte Carlo Event Generators
- Treatment of QCD Radiation
- Hadronization Models
- Agreement with data
- Conclusions

Monte Carlo Event Generators



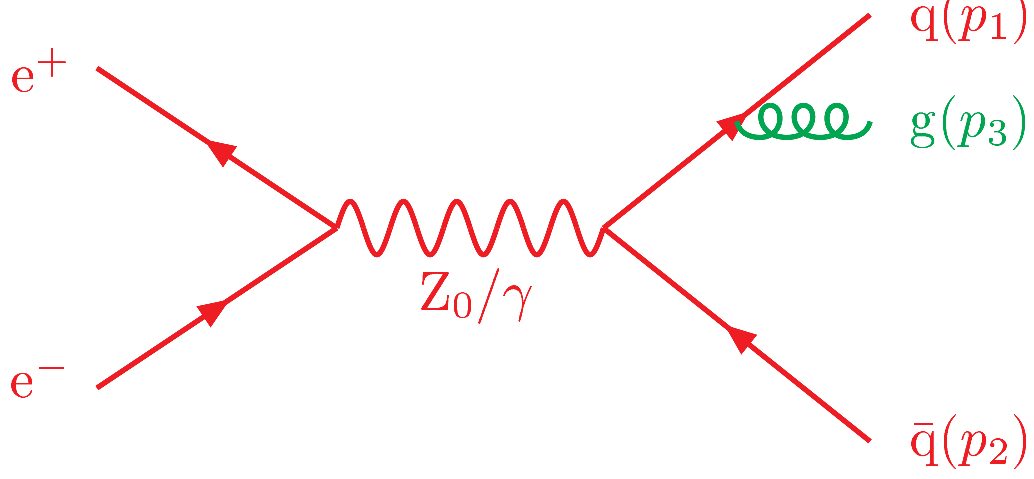
- There are five phases:
  - Hard Process;
  - Parton Shower;
  - Heavy particle decays;
  - Hadronization;
  - Hadron decays.

Monte Carlo Event Generators

- There are a number of QCD event generators available.
- The major general purpose event generators differ in the treatment of perturbative QCD radiation and the modelling of the hadronization process.
- It is hard to decouple the effects of the parton shower and hadronization on experimental results.
- I will briefly recap the different models used and then compare them with experimental data.

QCD Radiation

- It is impossible to calculate and integrate the matrix elements for processes involving large numbers of partons.
- Instead we treat the regions where the emission of QCD radiation is enhanced.
- Consider $\mathrm{e^+e^-} \to \mathrm{q\bar{q}g}$



- The cross section is given by

$$\frac{d\sigma_{q\bar{q}g}}{dx_1 dx_2} = N_c \sigma_0 Q_q^2 C_F \frac{\alpha_s}{2\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

- This diverges as $x_{1,2} \to 1$ where $x_i = 2E_i/\sqrt{s}$.

QCD Radiation

- Physically this happens when

1. The gluon and one of the quarks are collinear

$$(1 - x_1) = \frac{E_2 E_3}{Q^2}(1 - \cos\theta_{2g})$$

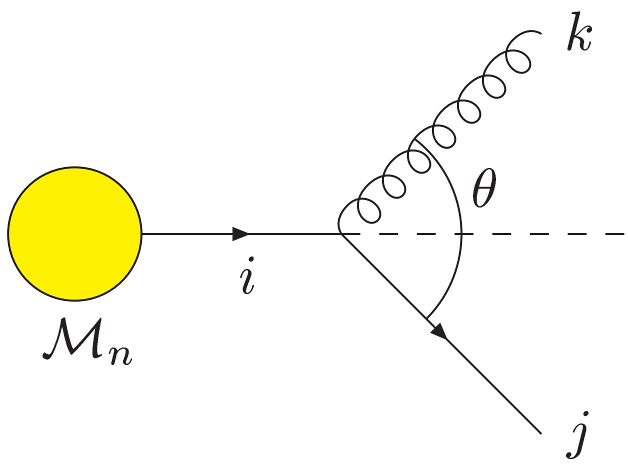
Collinear singularity

2. The energy of the gluon goes to zero

$$x_1 + x_2 + x_3 = 2, x_1, x_2 \to 1 \Rightarrow x_3 \to 0$$

Soft Singularity

Collinear Singularities



- In the collinear limit the cross section for a process factorizes

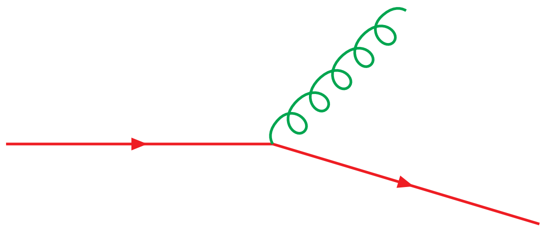
$$d\sigma_{n+1} = d\sigma_n \frac{d\theta^2}{\theta^2}\, dz \frac{\alpha_s}{2\pi} P_{ji}(z),$$

- P_{ji} is the DGLAP splitting function.
- This is singular as $\theta \to 0$.
- What is a parton? (difference between collinear pair and a parton)

Collinear Singularities

- Introduce resolution criterion *e.g.* $k_T > Q_0$.

- Combine virtual corrections & unresolvable emission.



Resolvable Emission
Finite

Unresolvable Emission
Finite

- Unitary: Unresolved + Resolved = 1.

Monte Carlo Procedure

- Probability of Emission between $q^2 + dq^2$ and q^2

$$d\mathcal{P} = \frac{\alpha_s}{2\pi}\frac{dq^2}{q^2}\int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz P(z) \equiv \frac{dq^2}{q^2}\bar{P}(q^2)$$

- Define probability of no emission between Q^2 and q^2 $\Delta(Q^2, q^2)$

$$\frac{d\Delta(Q^2, q^2)}{dq^2} = \Delta(Q^2, q^2)\frac{d\mathcal{P}}{dq^2}$$

$$\Rightarrow \Delta(Q^2, q^2) = \exp\left[-\int_{q^2}^{Q^2}\frac{dk^2}{k^2}\bar{P}(k^2)\right]$$

- $\Delta(Q^2, Q_0^2) \equiv \Delta(Q^2)$ The Sudakov Form Factor probability of emitting no resolvable radiation.

Monte Carlo Procedure

- We can implement this in the following way:
  - Generate a random number $0 < \rho < 1$;
  - If $\rho < \Delta(Q^2)$ no resolvable emission;
  - Otherwise solve

$$\rho = \Delta(Q^2, q^2)$$

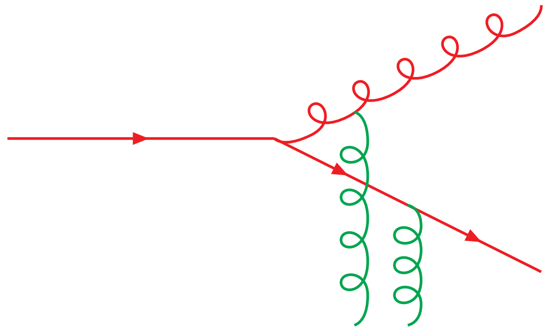
    to give the emission scale q^2.

- A number of formally free choices
  - Evolution scale: $q^2/k_\perp/\theta$
  - z: Energy, light-cone momentum.

Soft Emission

- There are two regions where the emission of QCD radiation is enhanced.

- The soft limit also factorizes but at the amplitude level.



- Soft gluons come from everywhere in the event.

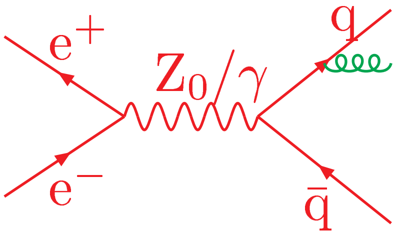
- There is quantum interference between these gluons.

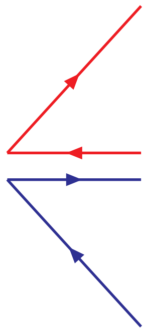
- Does this spoil the parton shower picture?

Angular Ordering

- HERWIG uses the angular-ordered parton shower to resum both the collinear and soft logarithms.

- *e.g.* $e^+e^- \longrightarrow q\bar{q}g$ with radiation of an extra gluon

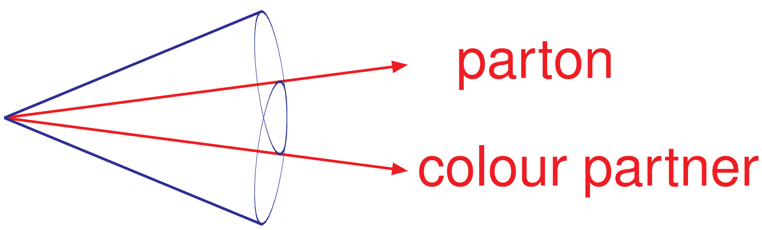




Colour Flow

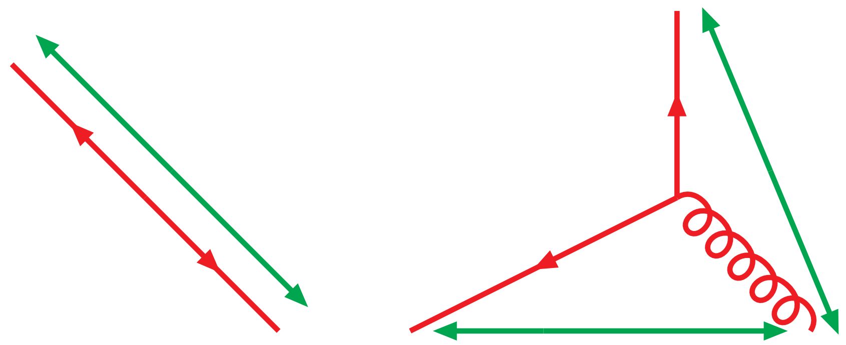
- We then get that
  - q and the g are colour connected.
  - $\bar{q}$ and the g are anticolour connected.

- QCD radiation only occurs in a cone up to the direction of the colour partner. (Marchesini & Webber)



Colour Dipole Model

- There is an entirely different approach available to the QCD evolution, Colour Dipole Model.
- Instead of considering the emission from partons considers the emission from dipoles.
- *e.g.* the emission of a gluon from a $\mathrm{q}\bar{\mathrm{q}}$ pair can be considered as emission from the dipole between the q and $\bar{\mathrm{q}}$.
- The emission of a further softer gluon can then be considered as emission from the two independent dipoles between the q and g and between the $\bar{\mathrm{q}}$ and the g.



Parton Shower

- ISAJET uses the original parton shower algorithm which only resum collinear logarithms.

- HERWIG uses the angular ordered parton shower algorithm which resums both soft and collinear singularities.

- PYTHIA use the collinear algorithm with an angular veto to try to reproduce the effect of the angular ordered shower.

- ARIADNE uses the colour dipole model.

- The collinear algorithm implemented in ISAJET does not give good agreement for angular ordering variables in hadron collisions or the string effect in e^+e^- collisions.

- HERWIG tends to give the best agreement for the hadron-hadron observables which are sensitive to soft effects.

Hadronization

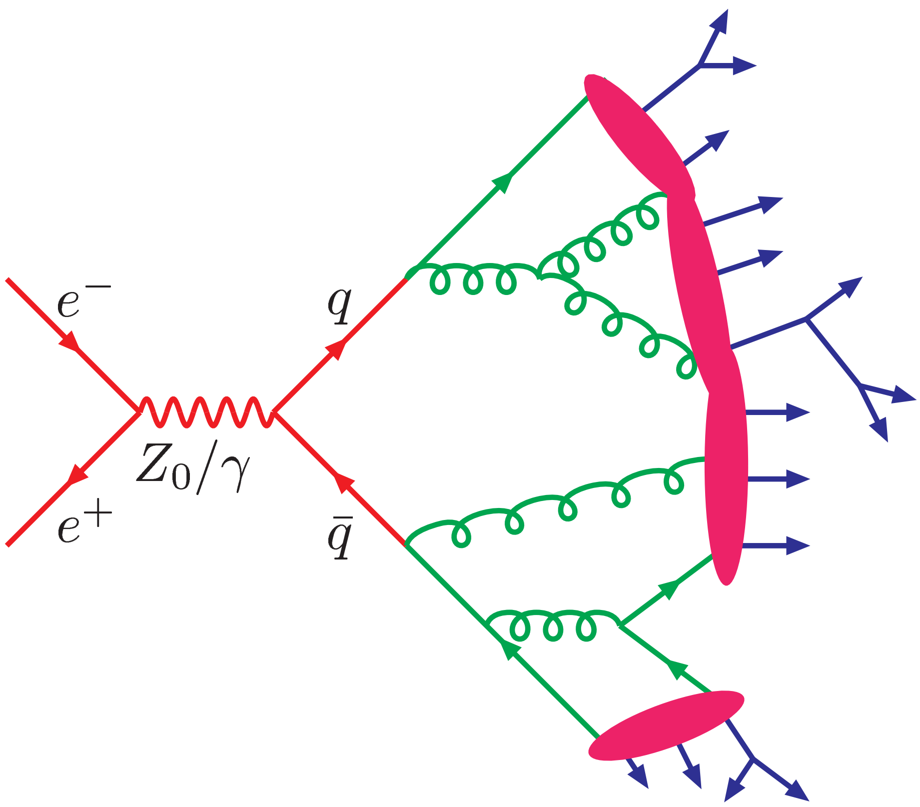
- ISAJET uses the original independent fragmentation model of Feynman and Field.
- PYTHIA uses the Lund string model.
- HERWIG uses the cluster hadronization model.
- ARIADNE uses the Lund string model.
- The independent fragmentation model cannot fit the LEP data.
- The cluster model gives good agreement with the LEP data on event shapes but doesn't fit the identified particle spectrum as well.
- The Lund string model give the best agreement with the LEP data.

Independent Fragmentation Model

- Original hadronization model, Feynman and Field
- Recursively split $\mathrm{q} \to \mathrm{q}' + \mathrm{hadron}$.
- Hook up the soft q and $\bar{\mathrm{q}}$ at the end.
- Strongly frame dependent.
- Doesn't agree with the data.

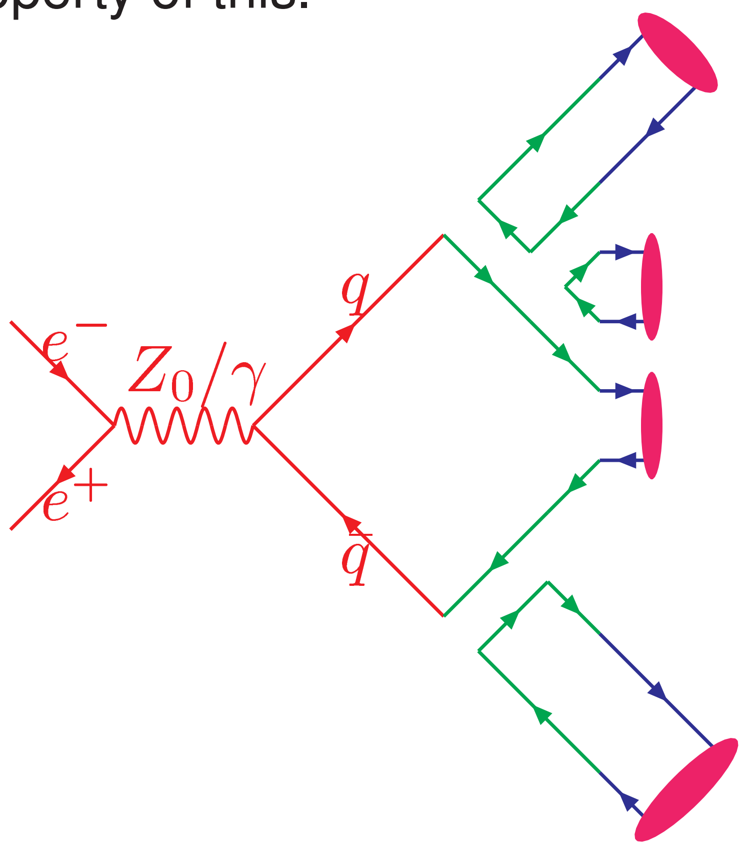
LUND String Model

- Assume quark and antiquark produced in $\mathrm{e}^{+}\mathrm{e}^{-}$ collisions joined by a string.
- As the move apart quark-antiquark pairs created by tunneling.
- String breaks up into hadrons.
- Very successful fit to data, however many parameters.



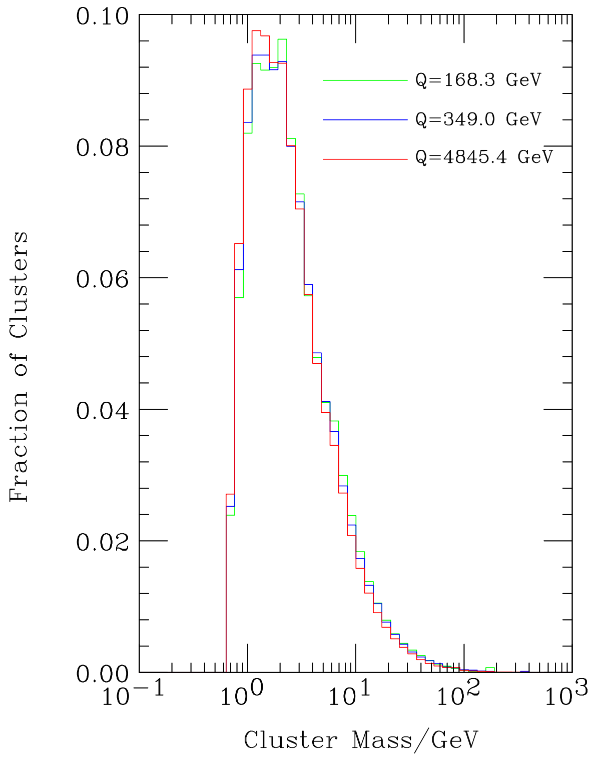
Cluster Hadronization Model

- HERWIG includes angular-ordered parton showers.
- The hadronization model is based on one property of this.



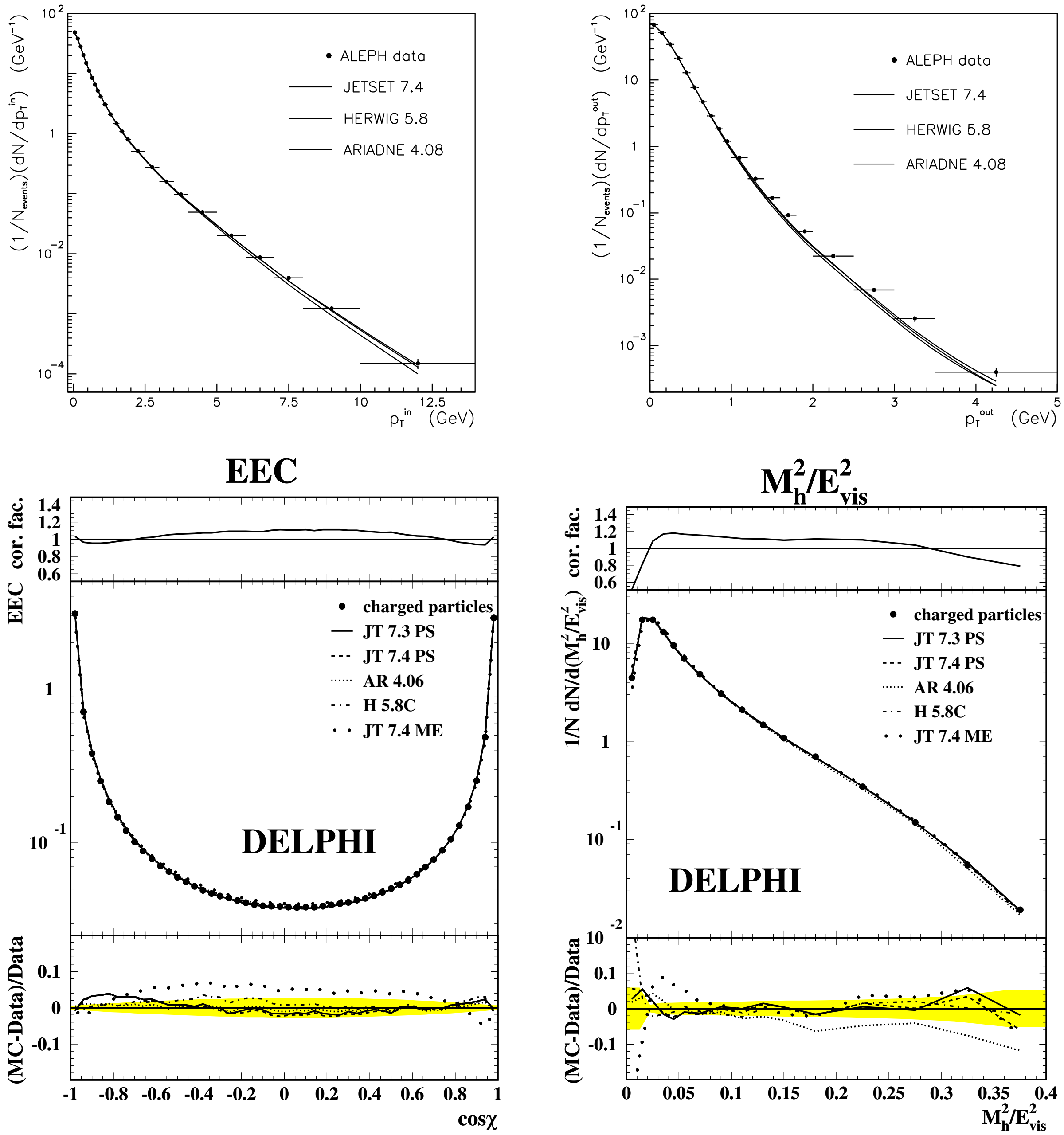
- First split the gluons into $\mathrm{q\bar{q}}$ pairs.
- Each quark is then uniquely paired with an antiquark in a colour singlet.
- Form these into colour singlet clusters.

Cluster Hadronization Model



- The mass spectrum of pairs of colour singlet clusters after gluon splitting.
- Called colour 'pre-confinement'.
- Assume these clusters are superpositions of resonances.
- Decay according to phase space to hadrons.
- The hadrons decays are then performed using phase space and the measured branching ratios.

Event Shapes at M_Z



- Generally good agreement

Event Shapes at 130-136 GeV

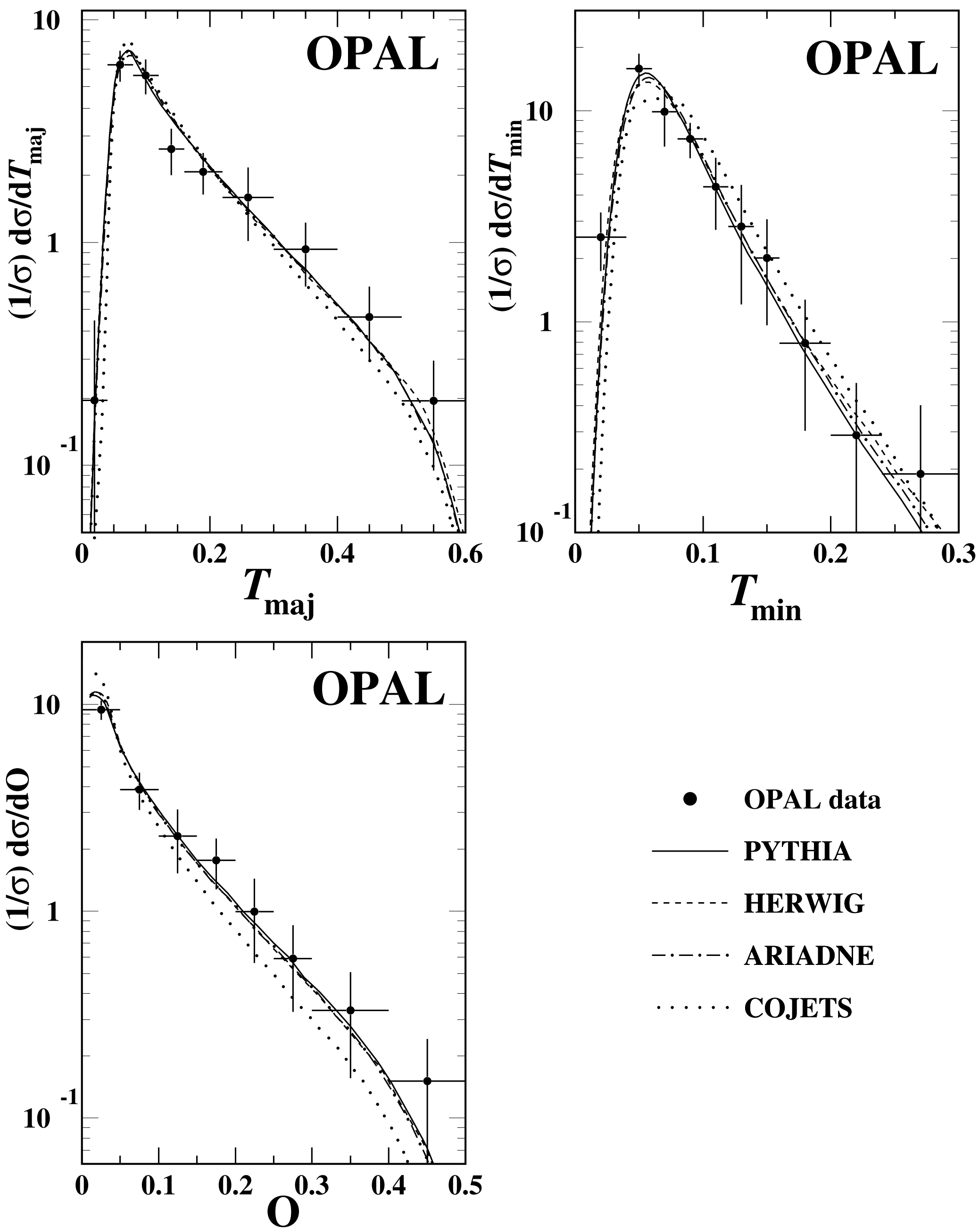
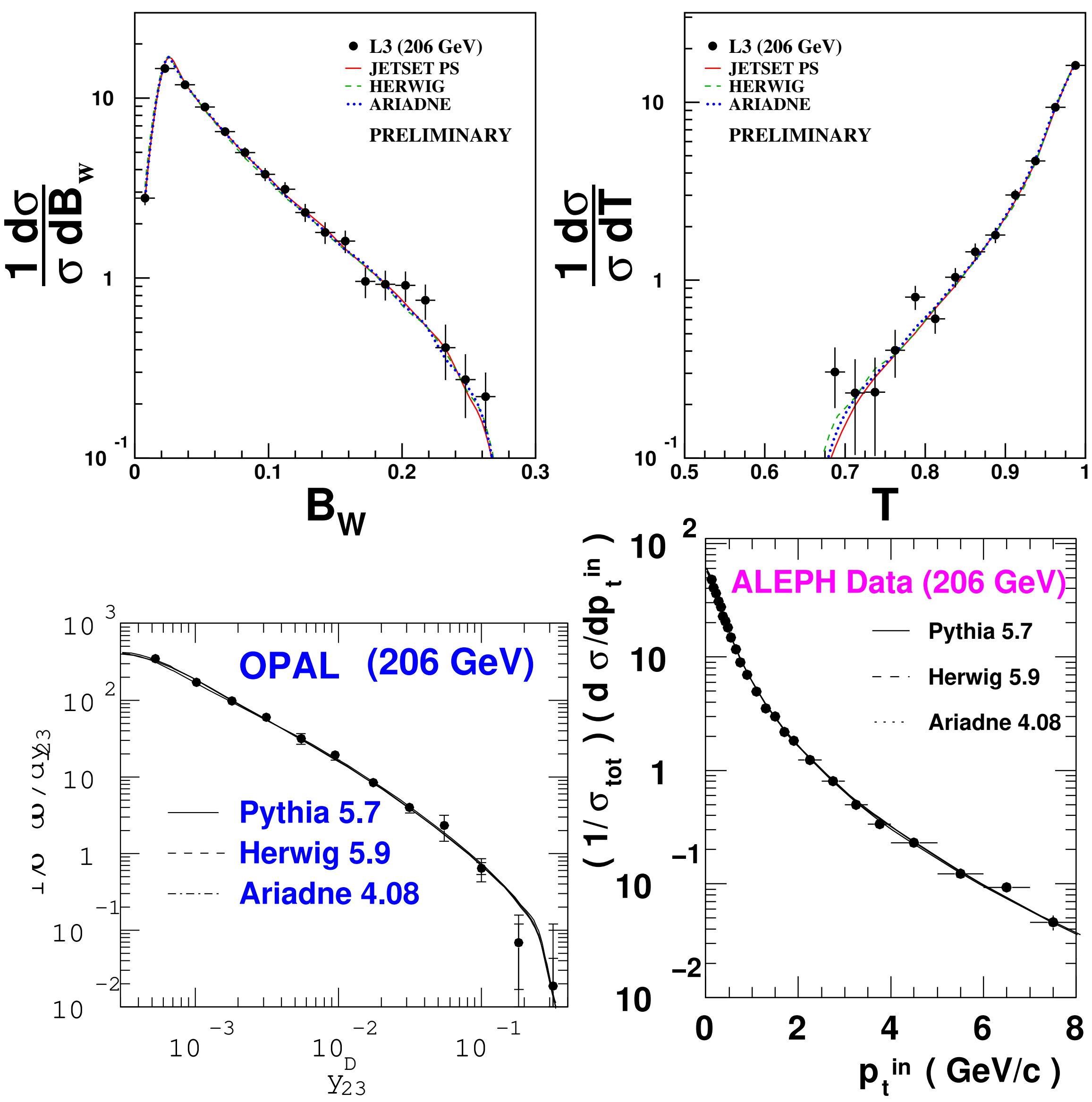


Fig. 1. Distributions of T_{maj}, T_{min}, and Oblateness. Statistical and systematic errors are shown added in quadrature

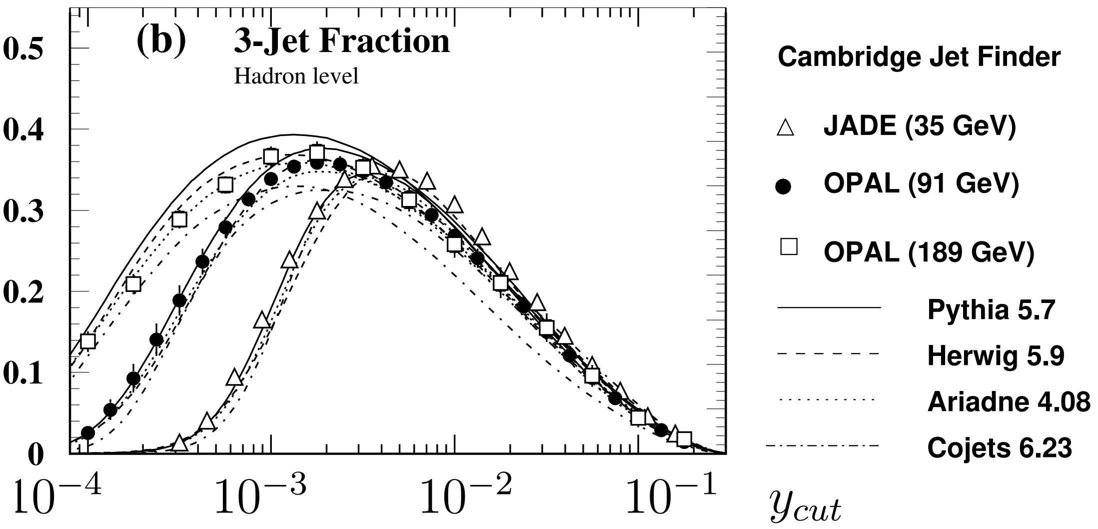
- Remember only tuned at M_Z

Event Shapes at 206 GeV



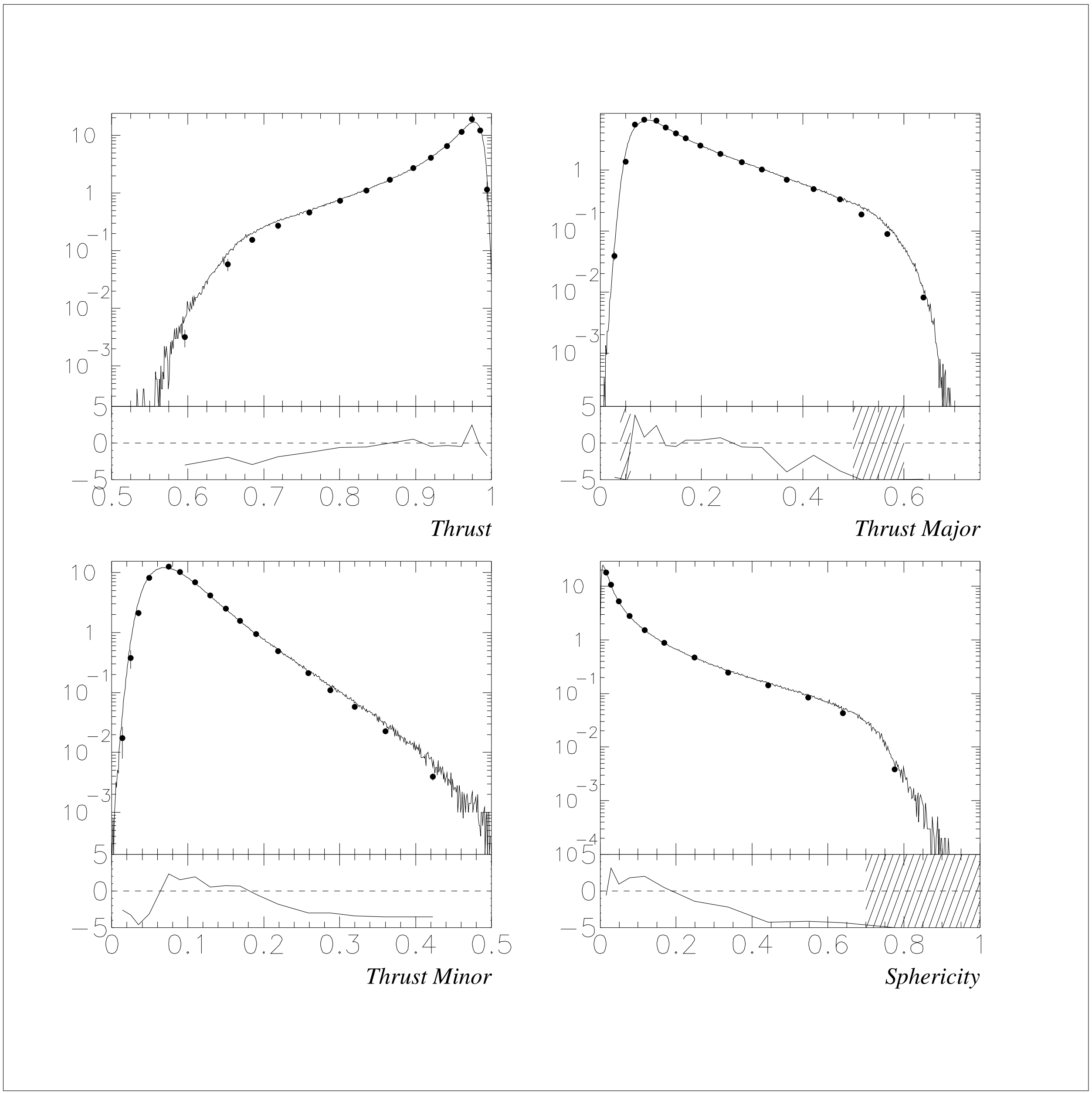
- Remember only tuned at M_Z

Variation with energy



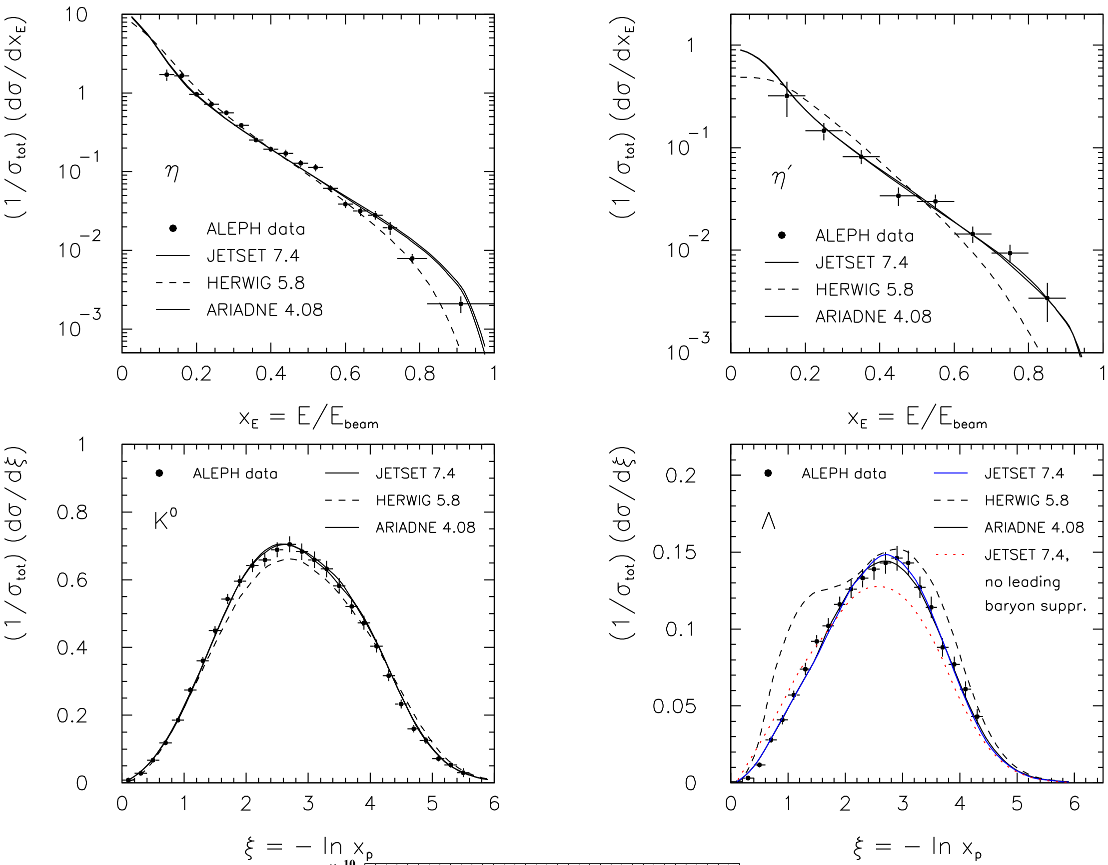
- COJETS which uses the incoherent shower and independent fragmentation gives poor evolution.
- HERWIG scaling better than PYTHIA.

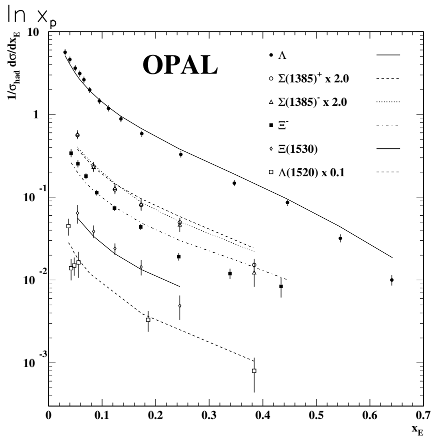
Event Shapes with HERWIG



- Comparison of HERWIG6.1(tuned) and OPAL data.

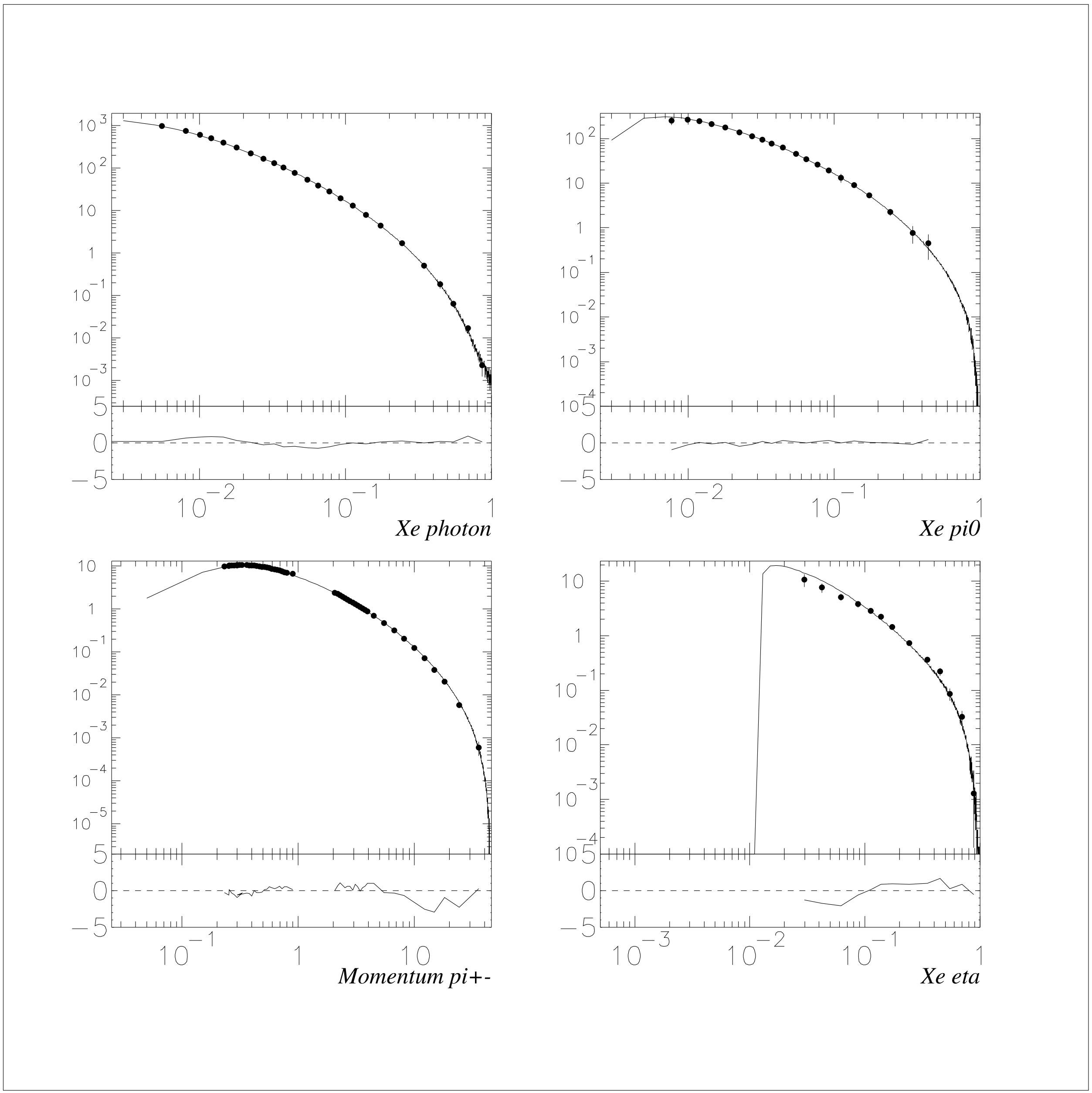
Identified particle spectra





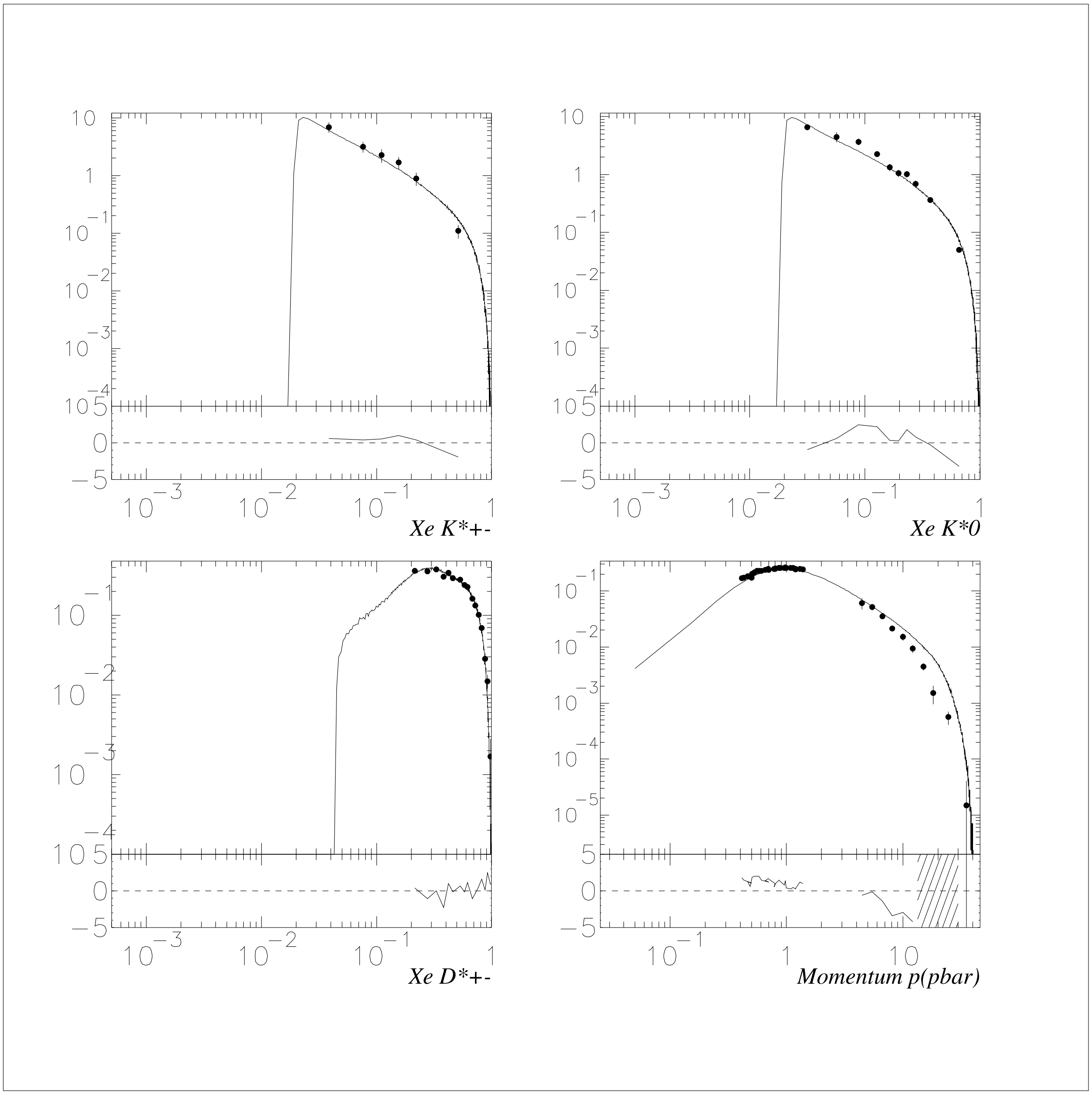
- PYTHIA and ARIADNE generally better.
- All have problems with baryons, especially HERWIG.

Production of Mesons in HERWIG



- Comparison of HERWIG6.1(tuned) and OPAL data.

Production of Baryons in HERWIG



- Comparison of HERWIG6.1(tuned) and OPAL data.

Production of Hadrons in HERWIG

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.

Agreement with data

- The various generators are tuned by the LEP collaborations to data.
- Generally this is to data on event shapes and particle spectra.
- The basic message is
  - HERWIG, PYTHIA and ARIADNE all give good fits to event shapes.
  - PYTHIA and ARIADNE give the best fit to particle spectra.
  - ARIADNE gives the best overall fit.
- Conclusions from this
  - The perturbative QCD is well modelled by all the generators which include coherence.
  - HERWIG and ARIADNE are the most sophisticated for QCD.
  - The LUND string model is the best hadronization model.
  - Baryon production is a problem.
  - Heavy quark production is also problematic.

The Future

- The experimental collaborations are moving to C++.
- Therefore the event generators are too.
- PYTHIA will be a straight rewrite.
- HERWIG will include physics improvements.
- Still a long way to go.

Conclusions

- QCD event generators contain a sophisticated treatment of perturbative QCD.
- They give a good description of experimental data.
- The LUND string model gives a good description of hadronization, the other models perform less well.
- These programs should give a good description of the energy evolution of observables.
- BUT before using them you should check that they give good agreement for the observables you are interested in at LEP.