Herwig++

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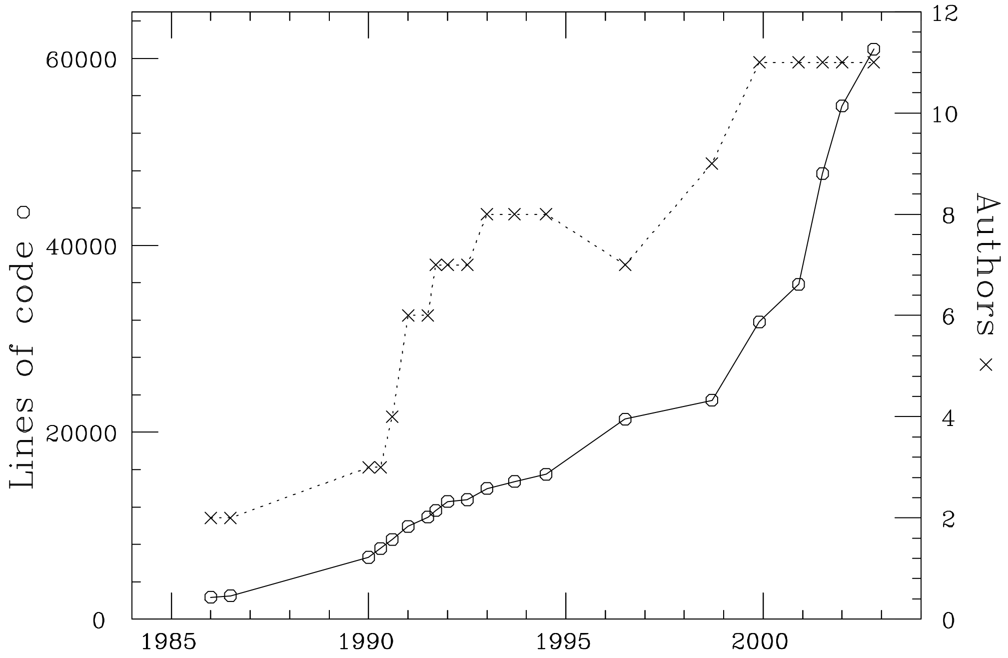
Herwig++:- S. Gieseke, A. Ribon, M. Seymour, P. Stephens, B.R. Webber

- Introduction
- What's done
- What's next
- Conclusions

Introduction

- Fortran HERWIG was a very successful program.

- Expanded and improved for about 20 years.



- However many physics changes were impossible due to the structure and maintenance was becoming harder.

- The decision was taken to produce a new program using the same philosophy and physics ideas but with many improvements.

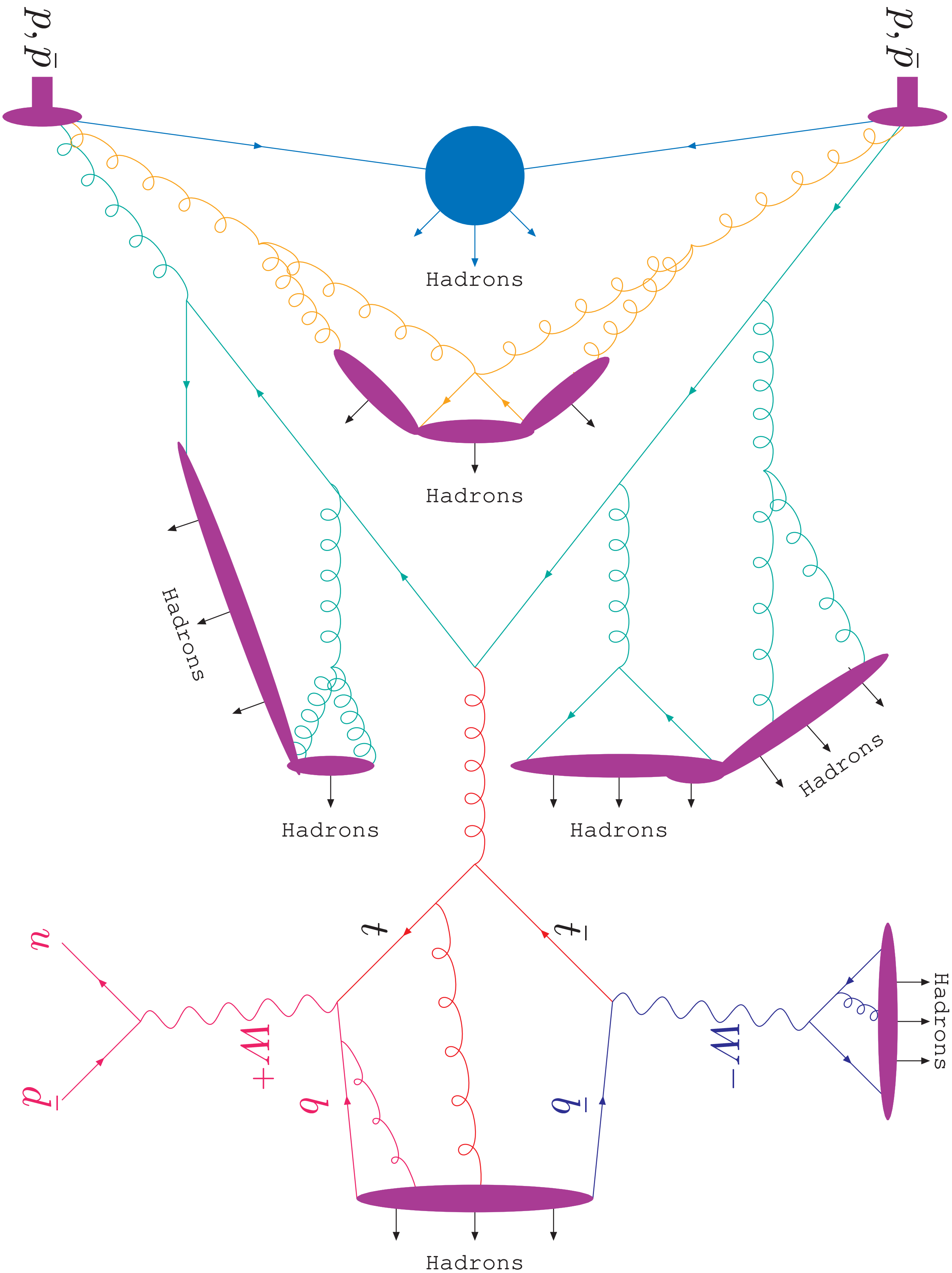
- Given the experimental change to C++ that was the natural language.

ThePEG

- At an early stage of the project we made the decision to use the same structure as Pythia7.
- This has a number of advantages
  - Didn't have to spend years designing our own structure.
  - Allows HERWIG and PYTHIA physics models to be used together.
- These common infrastructure pieces of Pythia7 have evolved into the Toolkit for high energy Physics Event Generation.
- This structure should also allow other people, who are not authors of HERWIG or PYTHIA, to contribute physics modules.
- If one of the C++ experts was giving the talk they'd show lots of class diagrams, however I'll skip that and get on to the physics.

Physics of Herwig++

- Before discussing the physics in detail its useful to start by recalling the general features of the event generation process.
- All event generators split the simulation up into a number of parts:
  - Hard Process;
  - Parton Shower;
  - Secondary Decays;
  - Multiple Scattering/Soft Underlying Event;
  - Hadronization;
  - Hadron Decays.
- The general approach is the same in different programs but the models and approximations used are different.
- For Herwig++ we will be using many of the same ideas as in the FORTRAN program but either improving the existing models or starting again with better models.



$p, \bar{p}$
$p, \bar{p}$
Hadrons
Hadrons
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t
$\bar{t}$
u
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W^+
W^-
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$\bar{b}$

Physics of Herwig++

- I will start by discussing the major pieces of physics which are currently implemented in Herwig++.
  - Parton Shower
  - Hadronization
- These illustrate the two types of improvement that we hope to make.
- For the parton shower the evolution variable has been changed to improve the simulation while retaining the coherence properties which were successful in the FORTRAN program.
- For the hadronization model less significant changes were made to correct some properties of the cluster model.

Parton Shower

Work by Stefan Gieseke, Phil Stephens and Bryan Webber

- The FORTRAN Herwig parton shower was based on angular ordering via evolution in

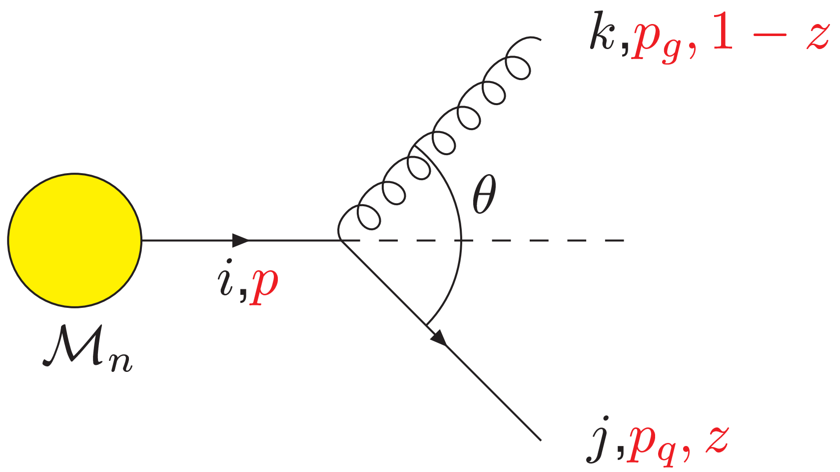
$$\xi = E^2(1-\cos\theta)$$

- together with the dead cone for heavy particles, i.e. no radiation with angle $\theta < m/E$.

- This algorithm was not Lorentz invariant and the implementation of the dead cone was too drastic.

- The idea for the C++ shower was to use recent ideas from dipole subtraction techniques and quasi-collinear splitting to produce a shower with better Lorentz properties and mass effects while retaining the coherence effects of angular ordering.

Parton Shower



- The parton shower is based on collinear factorisation with angular ordering for soft effects.

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

- Similarly can define the quasi-collinear limit

$$\begin{aligned} p_q &= zp + \beta_q n - q_\perp \\ p_g &= (1-z)p + \beta_g n + q_\perp, \end{aligned} \qquad (1)$$

where $p^2 = M^2$, $n^2 = 0$ and $q_\perp$ is the transverse momentum.

Parton Shower

- Gives a splitting function

$$P = \frac{C_F}{1-z}\left[1+z^2-2\frac{m^2}{z\tilde{q}^2}\right]$$

where

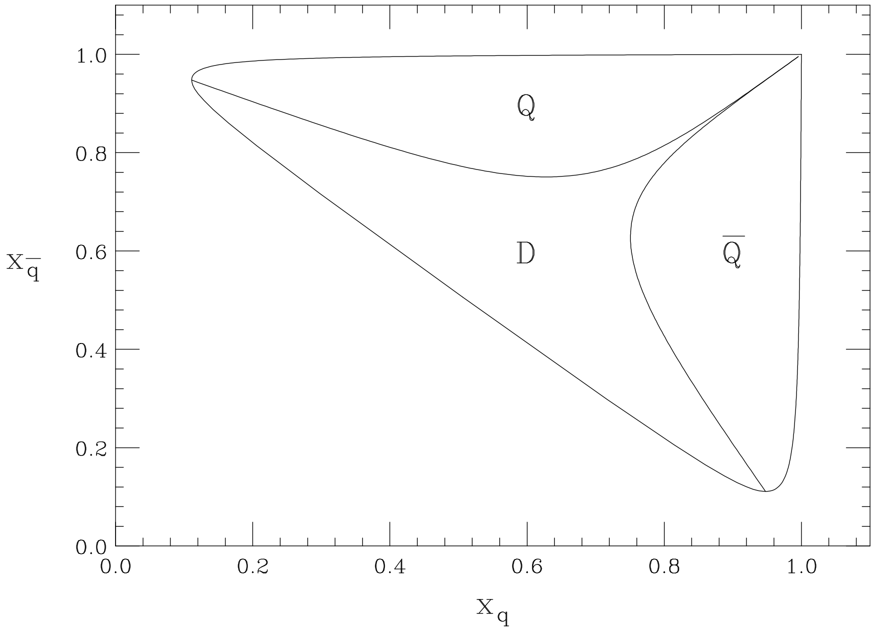
$$\tilde{q}^2 = \frac{\mathbf{q}^2}{z^2(1-z)^2}+\frac{m^2}{z^2}$$

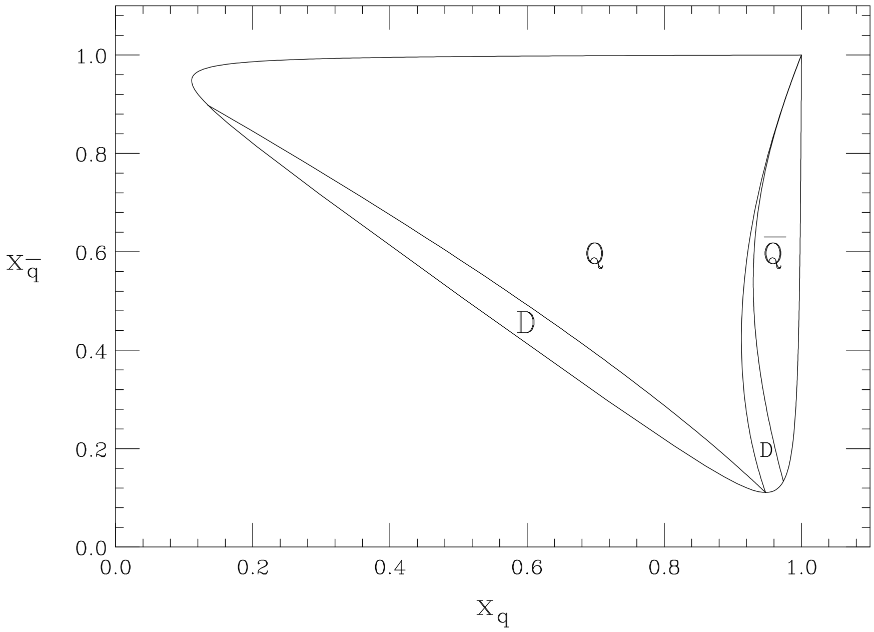
is the evolution variable and angular ordering gives

$$\tilde{q}_{i+1} < z_i\tilde{q}_i \qquad\qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i.$$

Parton Shower

- Gives better phase-space coverage, for example $e^+e^- \to q\bar{q}g$ at LEP for bottom quarks.

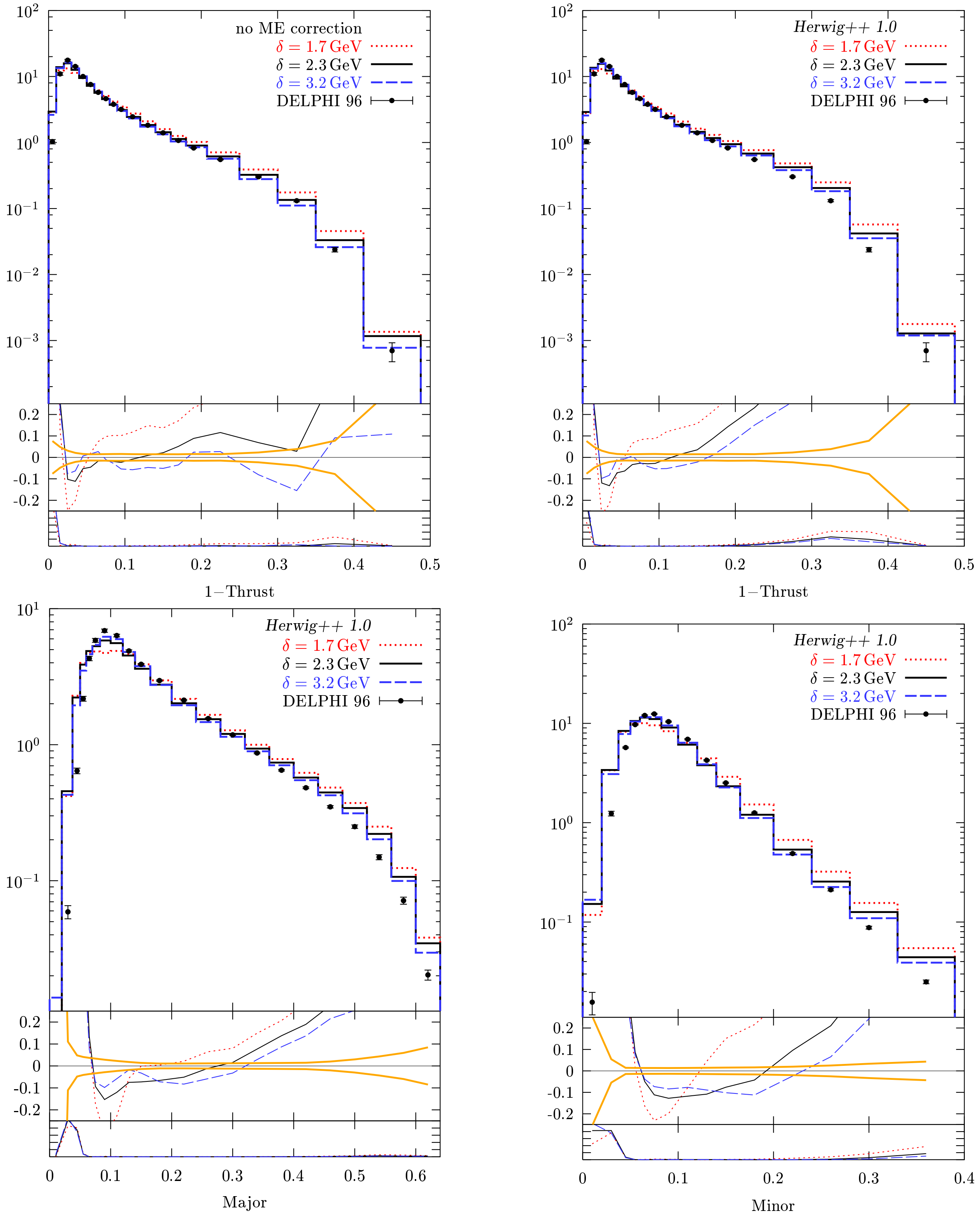




Parton Shower

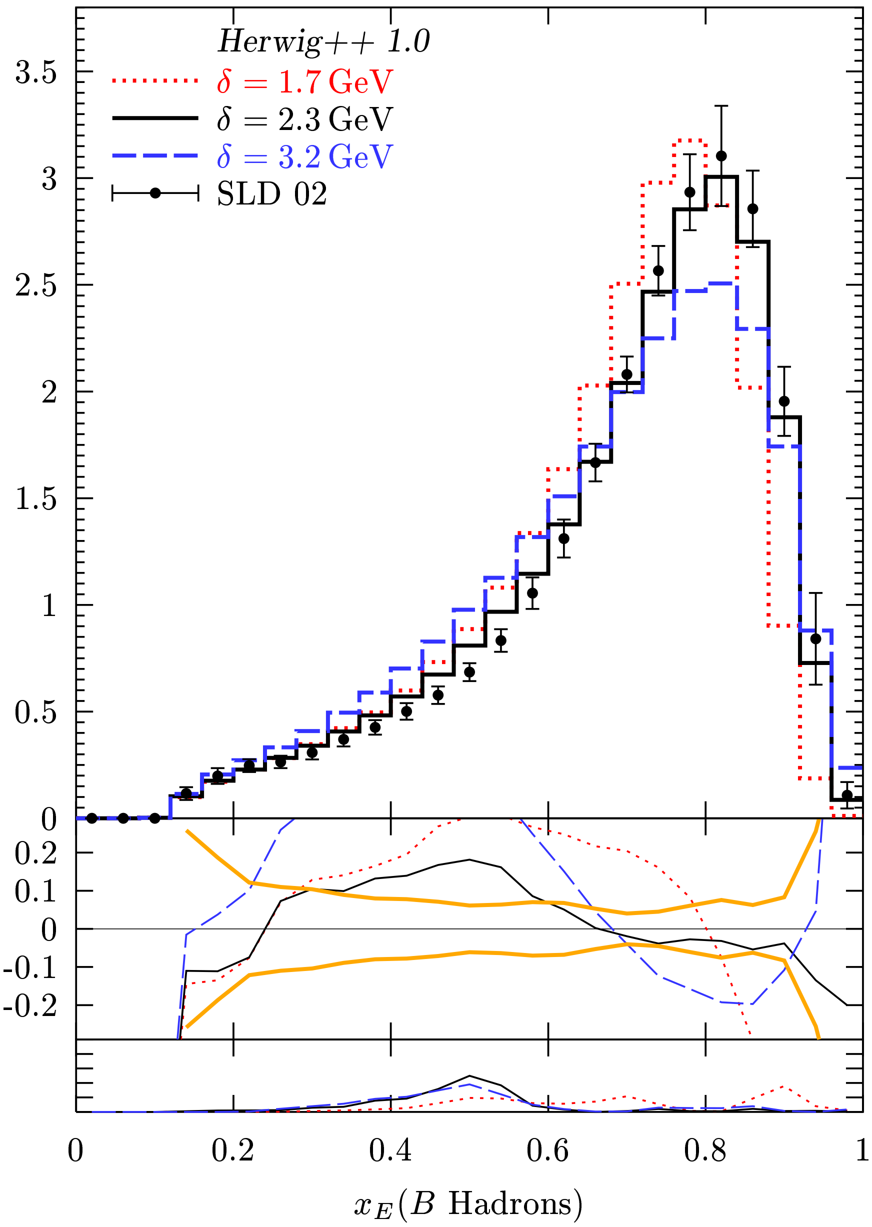
- By varying the initial conditions the amount of phase space covered can be increased.
- In FORTRAN the parameter which was used as the infrared cut-off in the Sudakovs for the shower was the same as the fictitious gluon mass needed by the cluster hadronization model.
- This meant that the gluons at the end of the shower had mass M_g and even if it had been technically possible the HERWIG shower could not have been used with the LUND string model.
- In C++ the two parameters are decoupled so that the gluons produced in the shower can have zero mass.

Event Shapes



B quark Fragmentation

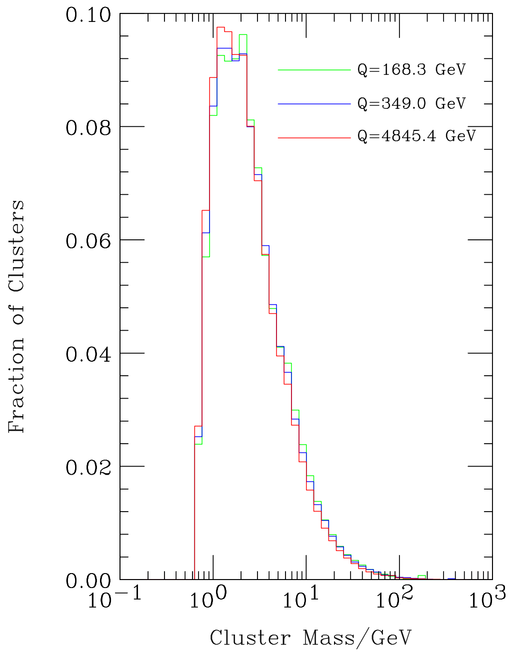
- Also an improvement in the heavy quark fragmentation function.



Hadronization

Work by Alberto Ribon and Phil Stephens

- The gluons decay isotropically to two quarks.
- Leaves a set of colour singlet clusters with a universal mass spectrum.



- In the FORTRAN there were problems with the addition of new resonances effecting the multiplicities of lower mass states.
- Together with other improvements this gives better hadron multiplicities.

Hadron Multiplicities

Particle	Experiment	Measured	Old Model	Herwig++	Fortran
All Charged	M,A,D,L,O	20.924 ± 0.117	20.22^*	20.814	20.532^*
γ	A,O	21.27 ± 0.6	23.03	22.67	20.74
π^0	A,D,L,O	9.59 ± 0.33	10.27	10.08	9.88
$\rho(770)^0$	A,D	1.295 ± 0.125	1.235	1.316	1.07
$\pi^\pm$	A,O	17.04 ± 0.25	16.30	16.95	16.74
$\rho(770)^\pm$	O	2.4 ± 0.43	1.99	2.14	2.06
η	A,L,O	0.956 ± 0.049	0.886	0.893	0.669^*
$\omega(782)$	A,L,O	1.083 ± 0.088	0.859	0.916	1.044
$\eta'(958)$	A,L,O	0.152 ± 0.03	0.13	0.136	0.106
K^0	S,A,D,L,O	2.027 ± 0.025	2.121^*	2.062	2.026
$K^*(892)^0$	A,D,O	0.761 ± 0.032	0.667	0.681	0.583^*
$K^*(1430)^0$	D,O	0.106 ± 0.06	0.065	0.079	0.072
$K^\pm$	A,D,O	2.319 ± 0.079	2.335	2.286	2.250
$K^*(892)^\pm$	A,D,O	0.731 ± 0.058	0.637	0.657	0.578
$\phi(1020)$	A,D,O	0.097 ± 0.007	0.107	0.114	0.134^*
p	A,D,O	0.991 ± 0.054	0.981	0.947	1.027
Δ^{++}	D,O	0.088 ± 0.034	0.185	0.092	0.209^*
Σ^-	O	0.083 ± 0.011	0.063	0.071	0.071
Λ	A,D,L,O	0.373 ± 0.008	0.325^*	0.384	0.347^*
Σ^0	A,D,O	0.074 ± 0.009	0.078	0.091	0.063
Σ^+	O	0.099 ± 0.015	0.067	0.077	0.088
$\Sigma(1385)^\pm$	A,D,O	0.0471 ± 0.0046	0.057	0.0312^*	0.061^*
Ξ^-	A,D,O	0.0262 ± 0.001	0.024	0.0286	0.029
$\Xi(1530)^0$	A,D,O	0.0058 ± 0.001	0.026^*	0.0288^*	0.009^*
Ω^-	A,D,O	0.00125 ± 0.00024	0.001	0.00144	0.0009
$f_2(1270)$	D,L,O	0.168 ± 0.021	0.113	0.150	0.173
$f_2'(1525)$	D	0.02 ± 0.008	0.003	0.012	0.012
$D^\pm$	A,D,O	0.184 ± 0.018	0.322^*	0.319^*	0.283^*
$D^*(2010)^\pm$	A,D,O	0.182 ± 0.009	0.168	0.180	0.151^*
D^0	A,D,O	0.473 ± 0.026	0.625^*	0.570^*	0.501
$D_s^\pm$	A,O	0.129 ± 0.013	0.218^*	0.195^*	0.127
$D_s^{*\pm}$	O	0.096 ± 0.046	0.082	0.066	0.043
J/Ψ	A,D,L,O	0.00544 ± 0.00029	0.006	0.00361^*	0.002^*
Λ_c^+	D,O	0.077 ± 0.016	0.006^*	0.023^*	0.001^*
$\Psi'(3685)$	D,L,O	0.00229 ± 0.00041	0.001^*	0.00178	0.0008^*

Ongoing work

- The existing version has the same level of sophistication for the simulation of $\mathrm{e}^+\mathrm{e}^-$ events as FORTRAN HERWIG.

- Work is now ongoing to add the additional features needed to simulate hadron collisions and replace some parts of the code which were copied from the FORTRAN.

- This work is in a number of areas.
  - Initial-State radiation.
  - Underlying event modelling.
  - radiation in particle decays
  - Correlation effects and hadron decays.

Initial-State radiation and Underlying Event

- In order to simulate hadron-hadron events we need the initial as well as the final-state shower.
- Work is currently ongoing to implement the initial-state shower using the new evolution variables as for the final-state shower.
- We also need to model the underlying event.
- As a first step we will implement the UA5 underlying event model.
- This will be followed by a multiple interaction model including the ideas of JIMMY and developments by M. Seymour and I Borozan.

Radiation in Particle Decays

- In the FORTRAN program we treated the radiation from the production and decay of heavy particles separately.

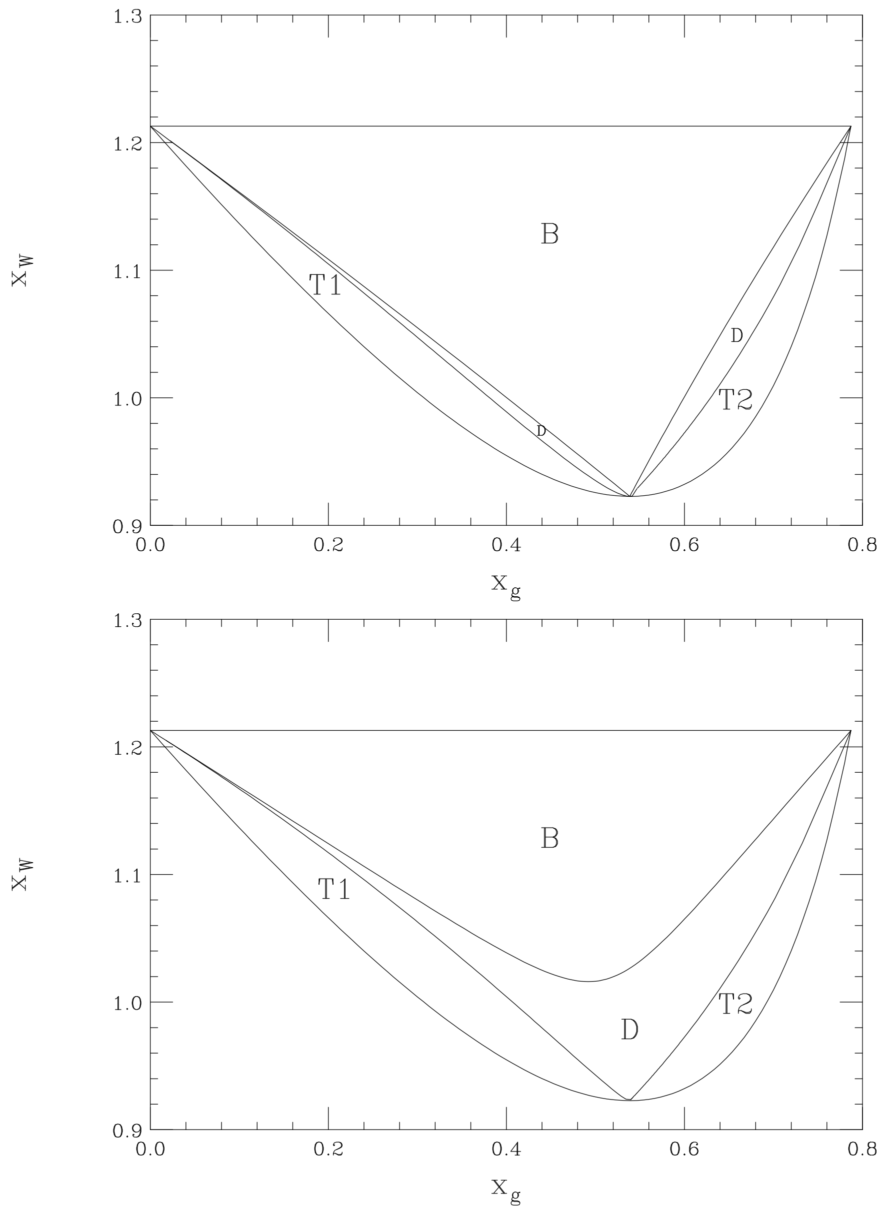
- The radiation from the decay was simulated in the rest frame of the decaying particle and did not cover the full soft phase space.

- In the C++ we intend to use a multi-scale shower, for example for top there would be three stages
  - Radiation in the production up to the top quark width, using the production colour flow.
  - Radiation in the decay up to the top quark width, using the decay colour flow.
  - Radiation from decay products using the dipole between the two bottom quarks between the top width and the cut-off.

- Effects probably not important for the top quark but may be for SUSY particles.

Radiation in Particle Decays

- Using the new variables in addition to radiation from the bottom produced in the top quark decay there will also be radiation from the top quark in the decay process.
- This ensures that the full soft phase space is covered.



Correlations and Decays

- In the FORTRAN simulation we had
  - Correlations due to spin effects in the parton shower.
  - Correlations between the production and decay of heavy particles.
- The two effects could not be combined due to the structure of the code.
- In C++ we hope to combine these correlations to have full correlations in the perturbative phase of the event.

Hadronic Decays

- In FORTRAN and currently in the C++ we only include a few hadronic matrix elements and use phase space for the rest of the decays.

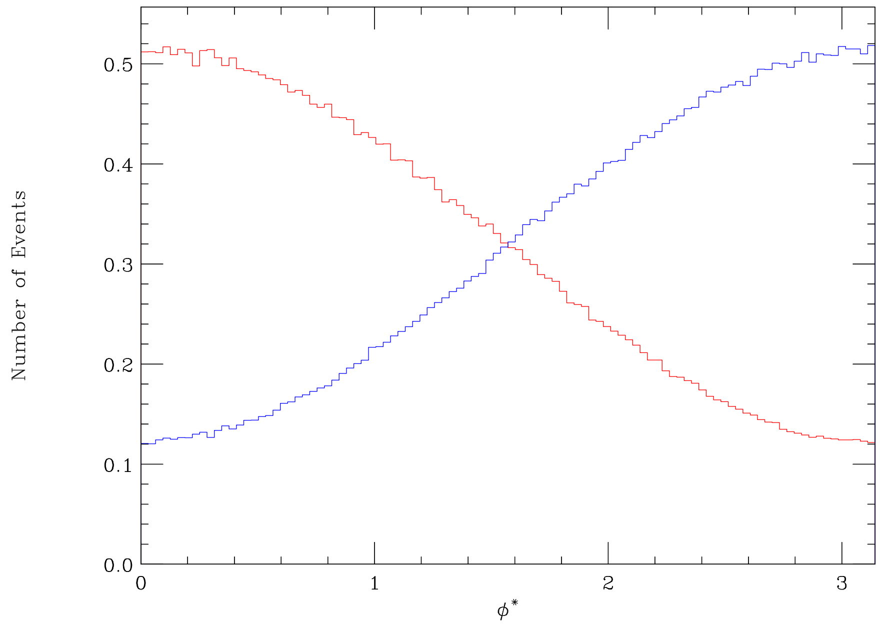
- The same algorithm we use for correlations in the perturbative phase of the event can be used for hadronic decays, and currently is in for example the BaBar Monte Caro EvtGen.

- We plan to include some important decay matrix elements inside Herwig++, for example tau decays, and interface to EvtGen for the rest as an initial step.

- We can then add more decay modes as time allows.

Correlations

- We have made some progress in this area, for example the correlation between the decay planes for $H \to \tau^+\tau^-$ followed by $\tau \to \pi\nu$



- the red line is for a scalar Higgs and the blue for a pseudoscalar.

Conclusions

- Herwig++ is already a sophisticated event generator for $\mathrm{e}^+\mathrm{e}^-$ collisions.

- Work is underway to add the features needed for hadron-hadron collisions.

- Hopefully a generator capable of generating hadron-hadron events will be available by the end of the year.

- Then need to think about other things, for example
  - CKKW.
  - MC@NLO.
  - Large angle soft emission.
  - BSM physics

- The list is endless but unfortunately the manpower is very limited.