QCD Simulation for LHC and Herwig++

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- Some issues in QCD simulation for LHC
  - Improving shower variables
  - Combining matrix elements and showers
  - Multiscale showering
- Herwig++
  - Overview
  - Hadronization model
  - Results ($e^+e^-$)
  - Outlook

$e^+e^-$ Event Generator

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays
Additional Complications in \textit{pp}

- backward parton evolution
- underlying event (Odagiri talk)
ME involving $q \rightarrow qg$ (or $g \rightarrow gg$) strongly enhanced whenever emitted gluon is almost collinear. Propagator factor

$$\frac{1}{(p_q + p_g)^2} \approx \frac{1}{2E_q E_g (1 - \cos \theta_{qg})}$$

- soft+collinear divergences.
- dominant contribution to the ME.

Collinear factorization

$$|M_{p+1}|^2 d\Phi_{p+1} \approx |M_p|^2 d\Phi_p \frac{dt}{2\pi} \frac{\alpha_s}{\Lambda^2} P(z) dz d\phi$$

$$P(z) = C_F \frac{1 + z^2}{1 - z}$$

→ Parton shower MC.

- Shower resums leading logarithmic contributions.
Quasi–Collinear Limit (Heavy Quarks)

- **Sudakov basis** $p, n$ with $p^2 = m^2$ (‘forward’), $n^2 = 0$ (‘backward’), $p_{\perp}^2 = -p_{\perp}^2$
  \[ p_q = zp + \beta_q n - p_{\perp} \]
  \[ p_g = (1 - z)p + \beta_g n + p_{\perp} \]

- **Quasi-collinear limit** (Catani et al.): for $|p_{\perp}| \sim m \ll p_+$
  \[ P_{qq}(z, p_{\perp}^2, m^2) = C_F \left[ \frac{1 + z^2}{1 - z} - \frac{2z(1 - z)m^2}{p_{\perp}^2 + (1 - z)^2m^2} \right] \]
  \[ \equiv \frac{C_F}{1 - z} \left[ 1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right] \]

- **Generalised angular variable**: for $m \to 0$, $\tilde{q} \sim |p_{\perp}|/z(1 - z) \sim E\theta$
- **Collinear limit**: for $p_{\perp} \to 0$, $\tilde{q} \sim m/z$, $P_{qq} \sim C_F(1 - z)$
New evolution variables

- Adopt \( \tilde{q}^2 \) as new evolution variable:
  \[ \tilde{q}^2 = \frac{p_\perp^2}{z^2(1 - z)^2} + \frac{m^2}{z^2} \quad \text{for} \quad q \rightarrow qg \]
  
- Argument of running \( \alpha_S \) chosen according to
  \[ \alpha_S \left( z^2(1 - z)^2 \tilde{q}^2 = p_\perp^2 + (1 - z)^2 m^2 \right) \]

- Generalized angular ordering in \( \tilde{q}_i \rightarrow \tilde{q}_{i+1} + \tilde{k}_{i+1} \):
  \[ \tilde{q}_{i+1} < z_i \tilde{q}_i \quad \tilde{k}_{i+1} < (1 - z_i) \tilde{q}_i \]

- Reinterpretation of evolution variables: branching probability for \( a \rightarrow bc \) is still
  \[ dP(a \rightarrow bc) = \frac{d\tilde{q}^2}{\tilde{q}^2} \frac{\alpha_S}{2\pi} P_{ba}(z, \tilde{q}) \, dz \, d\phi \]
  
  \[ \rightarrow \text{Sudakov form factors etc. remain the same!} \]

- Allows better treatment of heavy particles, avoiding collinear “dead cones” and overlapping regions in phase space, in particular for soft emissions.
Kinematics

- Sudakov basis $p, n$ with $p^2 = m^2, n^2 = 0$,

\[ q_i = \alpha_i p + \beta_i n + q_{\perp i} \]

- Longitudinal splitting: $\alpha_i = z_i \alpha_{i-1}$
- Transverse momenta reconstructed from $p_{\perp}$,

\[ q_{\perp i} = p_{\perp i} + z_i q_{\perp i-1}, \quad k_{\perp i} = -p_{\perp i} + (1 - z_i) q_{\perp i-1} \]

- Recursive reconstruction of virtualities and $\beta_i$'s from

\[
q_{i-1}^2 = \frac{q_i^2}{z_i} + \frac{k_i^2}{1 - z_i} + \frac{p_{\perp i}^2}{z_i(1 - z_i)}
\]

\[
\beta_i = \frac{q_{\perp i}^2 + q_i^2 - \alpha_i^2 m^2}{2\alpha_i (p \cdot n)}
\]

- Azimuthal angle $\varphi$ chosen randomly (now), or using azimuthal spin correlations (planned).
Universal cutoff parameter $\delta$

Require threshold in parton shower phase space.

$$\tilde{q} > Q_{\text{thr}} = \beta m_q + \delta \quad (\beta = 0.85)$$

Parametrization of $Q_g$ in terms of $\delta, m_q$

$$Q_g = \frac{\delta - 0.3m_q}{2.3}.$$
$q\bar{q}g$ phase space: old vs new variables

- No overlapping regions in phase space.
- Smooth coverage of soft gluon region.
- No collinear dead cones.
- Larger non-collinear dead region.

Bryan Webber, QCD Simulation for LHC and Herwig++, KEK, 6 April 2004
Points \((x_q, x_{\bar{q}})\) in dead region chosen according to LO \(q\bar{q}g\) matrix element and accepted according to ME weight.

About 3\% of all events are actually hard \(q\bar{q}g\) events.

Red points have weight \(> 1\), practically no error by setting weight to one.

Event oriented according to given \(q\bar{q}\) geometry (Kleiss). Quark direction is kept with weight \(x_q^2/(x_q^2 + x_{\bar{q}}^2)\).
Soft Matrix Element Corrections

- Ratio $\text{ME/PS}$ compares emission with result from true ME if slightly away from soft/collinear region.
- Veto on ‘hardest emission so far’ in $p_\perp$.
- Massive splitting function very important!

Example with heavy quark, $m^2/Q^2 = 0.1$ ($\approx t\bar{t}$ at 500 GeV)

Comparison with massless splitting function

\[ \begin{align*}
\bar{x} = 0.75, \text{massless} & : 75, \\
\bar{x} = 0.9, \text{massless} & : 9, \\
\bar{x} = 0.75, \text{massive} & : 75, \\
\bar{x} = 0.9, \text{massive} & : 9,
\end{align*} \]
Example: $t\bar{t}$ production & decay

1. Hard process (scale $\sim \hat{s}$)
2. Showers from $t, \bar{t}$ ($\hat{s} \rightarrow \Gamma_t$)
3. Decays $t \rightarrow Wb, \bar{t} \rightarrow W\bar{b}$
4. ISR from $t, \bar{t}$ ($m_t \rightarrow \Gamma_t$)
5. FSR from $b, \bar{b}$ ($m_t \rightarrow \Gamma_t$)
6. Global showering ($\Gamma_t \rightarrow \Gamma_b$)

etc.
Heavy Quark Decay

- In $t \rightarrow Wb$, ISR from $t$ fills soft and collinear regions $\rightarrow$ ME correction is finite.

- In Fortran HERWIG, ISR was missing $\rightarrow$ infrared divergence in ME correction.
Combining Matrix Elements and Showers

Above method of hard+soft matrix element corrections is difficult to extend to NLO, or to more complicated processes.

- **MC@NLO**: subtract approximate NLO contributions generated by showers from exact NLO matrix elements.
  - Regularizes divergences of NLO ME!
  - All NLO results formally reproduced
  - Shower resums soft & collinear divergences to all orders
    \[ \rightarrow \text{Frixione talk.} \]

- **CKKW (+ Krauss, Lönnblad, Mrenna & Richardson)**: generate ME with $k_T$-cutoff $Q_1$, apply corresponding Sudakov form factors, veto $k_T > Q_1$ in showers.
  - $Q_1$ dependence cancels to NLL
  - Can combine different multiplicity ME’s without double counting jet rates (to NLL)
    \[ \rightarrow \text{Mrenna, Schumann talks.} \]
Combining ME & PS: Scales

- Coherent branching $\rightarrow$ evolution in angle, not $k_T$
- $k_T$-cutoff $Q_1$ on ME $\rightarrow$ veto $k_T > Q_1$ in showers
- However, starting scale for showers is not $\tilde{q} = Q_1$
  - Showers must “fill in” radiation at larger angles, with $\tilde{q} > Q_1$ but $k_T < Q_1$
- Construct parton “histories” (gauge invariant) from clustering sequence
  - Each parton evolves from the $\tilde{q}$ scale at which it was “created” (shown in red)
Formally subleading → important for MC@NLO. After showering, hard partons have virtualities $q_i^2 \neq m_i^2$ → boost/rescale jets.

Started with

$$\sqrt{s} = \sum_{i=1}^{n} \sqrt{m_i^2 + p_i^2}$$

We can rescale 3-momenta with common factor $K$, so

$$\sqrt{s} = \sum_{i=1}^{n} \sqrt{q_i^2 + Kp_i^2}$$

to preserve overall energy/momentum.

→ resulting jets are then boosted accordingly.
The new generator Herwig++

A completely new event generator in C++

- Aiming at full multi-purpose generator for LHC and future colliders.
- Preserving main features of HERWIG such as
  - angular ordered parton shower
  - cluster hadronization
- New features and improvements
  - covariant shower formulation
  - improved parton shower evolution for heavy quarks
  - consistent radiation from unstable particles (multiscale evolution)
Use of ThePEG in Herwig++

ThePEG = Toolkit for high energy Physics Event Generation
Leif Lönnblad, http://www.thep.lu.se/ThePEG/

Share administrative overhead, common to event generators with Pythia7

Independent *physics* implementation

Large but very flexible implementation

Common basis for Pythia7/Herwig++

- Lack of independence.
- Less possibility to test codes against each other.
- Physics is still independent.
- Beneficial for the user to have the same framework.
- Running Herwig++ with Lund String Fragmentation from Pythia7 is very simple!
PartialCollisionHandlers

Physics Implementations
Hard interactions

- Basic ME’s included in ThePEG, such as $e^+e^- \rightarrow q\bar{q}$, QCD $2 \rightarrow 2$: we use them.
- Soft and hard matrix element corrections implemented for $e^+e^- \rightarrow q\bar{q}g$.
- AMEGIC++ will provide arbitrary ME’s for multiparton final states via AMEGICInterface.
- CKKW ME+PS foreseen.
- Other authors can easily include their own matrix elements (→ safety of OO code)
Cluster Hadronization Model

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
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Nonperturbative $g \rightarrow q \bar{q}$ splitting ($q = uds$) isotropically. Here, $m_g \approx 750 \text{ MeV} > 2m_q$.

Cluster formation, universal spectrum (see right)

Cluster fission until

$$M^p < M^p_{\max} + (m_1 + m_2)^p$$

where masses are chosen from

$$M_i = \left[\left(M^P - (m_i + m_3)^P\right) r_i + (m_i + m_3)^P\right]^{1/P},$$

with additional phase space constraints. Constituents keep moving in their original directions.

Cluster decay

$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$ 

New! Meson/Baryon ratio is parametrized in terms of diquark weight. In Fortran HERWIG the sum ran over all possible hadrons.
Cluster hadronization is designed, implemented and debugged.

HadronSelector/ ClusterDecayer in different ways.

Tests ongoing.

Lund string model is implemented already in Pythia7 and will work together with Herwig++.

This requires that final state gluons are on-shell foreseen in shower.
- FORTRAN HERWIG is reproduced with Hw64Decayer using the same matrix element codes as before (used for hadronic decays right now).
- DecayerAMEGIC gets final states for a decay mode directly from AMEGIC++.
- Works fine in principle, further tests required.
# $Z^0 \rightarrow$ Hadron Multiplicities

<table>
<thead>
<tr>
<th>Particle</th>
<th>Experiment</th>
<th>Measured</th>
<th>Old Model</th>
<th>Herwig++</th>
<th>Fortran</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Charged</td>
<td>M,A,D,L,O</td>
<td>20.924 ± 0.117</td>
<td>20.22*</td>
<td>20.814*</td>
<td>20.532*</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>A,O</td>
<td>21.27 ± 0.6</td>
<td>23.032</td>
<td>22.67</td>
<td>20.74</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>A,D,L,O</td>
<td>9.59 ± 0.33</td>
<td>10.27</td>
<td>10.08</td>
<td>9.88</td>
</tr>
<tr>
<td>$\rho(770)^0$</td>
<td>A,D</td>
<td>1.295 ± 0.125</td>
<td>1.235</td>
<td>1.316</td>
<td>1.07</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>A,O</td>
<td>17.04 ± 0.25</td>
<td>16.30</td>
<td>16.95</td>
<td>16.74</td>
</tr>
<tr>
<td>$\rho(770)^\pm$</td>
<td>O</td>
<td>2.4 ± 0.43</td>
<td>1.99</td>
<td>2.14</td>
<td>2.06</td>
</tr>
<tr>
<td>$\eta$</td>
<td>A,L,O</td>
<td>0.956 ± 0.049</td>
<td>0.886</td>
<td>0.893</td>
<td>0.669*</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>A,L,O</td>
<td>1.083 ± 0.088</td>
<td>0.859</td>
<td>0.916</td>
<td>1.044</td>
</tr>
<tr>
<td>$\eta'(958)$</td>
<td>A,L,O</td>
<td>0.152 ± 0.03</td>
<td>0.13</td>
<td>0.136</td>
<td>0.106</td>
</tr>
<tr>
<td>$K^0$</td>
<td>S,A,D,L,O</td>
<td>2.027 ± 0.025</td>
<td>2.121*</td>
<td>2.062</td>
<td>2.026</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>A,D,O</td>
<td>0.761 ± 0.032</td>
<td>0.667</td>
<td>0.681</td>
<td>0.583*</td>
</tr>
<tr>
<td>$K^*(1430)^0$</td>
<td>D,O</td>
<td>0.106 ± 0.06</td>
<td>0.065</td>
<td>0.079</td>
<td>0.072</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>A,D,O</td>
<td>2.319 ± 0.079</td>
<td>2.335</td>
<td>2.286</td>
<td>2.250</td>
</tr>
<tr>
<td>$K^*(892)^\pm$</td>
<td>A,D,O</td>
<td>0.731 ± 0.058</td>
<td>0.637</td>
<td>0.657</td>
<td>0.578</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>A,D,O</td>
<td>0.097 ± 0.007</td>
<td>0.107</td>
<td>0.114</td>
<td>0.134*</td>
</tr>
<tr>
<td>$p$</td>
<td>A,D,O</td>
<td>0.991 ± 0.054</td>
<td>0.981</td>
<td>0.947</td>
<td>1.027</td>
</tr>
<tr>
<td>$\Delta^{++}$</td>
<td>D,O</td>
<td>0.088 ± 0.034</td>
<td>0.185</td>
<td>0.092</td>
<td>0.209*</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>O</td>
<td>0.083 ± 0.011</td>
<td>0.063</td>
<td>0.071</td>
<td>0.071</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>A,D,L,O</td>
<td>0.373 ± 0.008</td>
<td>0.325*</td>
<td>0.384</td>
<td>0.347*</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>A,D,O</td>
<td>0.074 ± 0.009</td>
<td>0.078</td>
<td>0.091</td>
<td>0.063</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>O</td>
<td>0.099 ± 0.015</td>
<td>0.067</td>
<td>0.077</td>
<td>0.088</td>
</tr>
<tr>
<td>$\Sigma(1385)^\pm$</td>
<td>A,D,O</td>
<td>0.0471 ± 0.0046</td>
<td>0.057</td>
<td>0.0312*</td>
<td>0.061*</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>A,D,O</td>
<td>0.0262 ± 0.001</td>
<td>0.024</td>
<td>0.0286</td>
<td>0.029</td>
</tr>
<tr>
<td>$\Xi(1530)^0$</td>
<td>A,D,O</td>
<td>0.0058 ± 0.001</td>
<td>0.026*</td>
<td>0.0288*</td>
<td>0.009*</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>A,D,O</td>
<td>0.00125 ± 0.00024</td>
<td>0.001</td>
<td>0.00144</td>
<td>0.0009</td>
</tr>
</tbody>
</table>
**Z⁰ → Hadron Multiplicities (ctd’)**

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</thead>
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<tr>
<td>f₂⁺(1270)</td>
<td>D,L,O</td>
<td>0.168 ± 0.021</td>
<td>0.113</td>
<td>0.150</td>
<td>0.173</td>
</tr>
<tr>
<td>f₂⁺(1525)</td>
<td>D</td>
<td>0.02 ± 0.008</td>
<td>0.003</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>D⁻</td>
<td>A,D,O</td>
<td>0.184 ± 0.018</td>
<td>0.322*</td>
<td>0.319*</td>
<td>0.283*</td>
</tr>
<tr>
<td>D⁺</td>
<td>A,D,O</td>
<td>0.182 ± 0.009</td>
<td>0.168</td>
<td>0.180</td>
<td>0.151*</td>
</tr>
<tr>
<td>D₀</td>
<td>A,D,O</td>
<td>0.473 ± 0.026</td>
<td>0.625*</td>
<td>0.570*</td>
<td>0.501</td>
</tr>
<tr>
<td>Dˢ⁺</td>
<td>A,O</td>
<td>0.129 ± 0.013</td>
<td>0.218*</td>
<td>0.195*</td>
<td>0.127</td>
</tr>
<tr>
<td>Dˢ⁻</td>
<td>O</td>
<td>0.096 ± 0.046</td>
<td>0.082</td>
<td>0.066</td>
<td>0.043</td>
</tr>
<tr>
<td>J/Ψ</td>
<td>A,D,L,O</td>
<td>0.00544 ± 0.00029</td>
<td>0.006</td>
<td>0.00361*</td>
<td>0.002*</td>
</tr>
<tr>
<td>Λᶜ⁺</td>
<td>D,O</td>
<td>0.077 ± 0.016</td>
<td>0.006*</td>
<td>0.023*</td>
<td>0.001*</td>
</tr>
<tr>
<td>Ψ⁽³⁾(3685)</td>
<td>D,L,O</td>
<td>0.00229 ± 0.00041</td>
<td>0.001*</td>
<td>0.00178</td>
<td>0.0008*</td>
</tr>
</tbody>
</table>

# of *’s = observables with more than 3σ deviation:

**Old Model : Herwig++ : Fortran = 9 : 7 : 13**

**N.B.** No systematic parameter tuning yet.
Charged Particle Multiplicity

Good indicator for quality of hadronization.
Still very sensitive to shower cutoff:

![Graph showing charged particle multiplicity](image)

- $\delta = 1.7$ GeV
- $\delta = 2.3$ GeV
- $\delta = 3.2$ GeV

OPAL 99
Jet Rates (Durham/$k_T$ Algorithm)

\[ R_n = \sigma(n\text{-jets})/\sigma(\text{jets}) \quad (n = 2, 5) \]

\[ R_6 = \sigma(>5\text{-jets})/\sigma(\text{jets}) \]
Cutoff dependence largely cancels between shower and hadronization.
Jet Multiplicity (PETRA, LEP, LEPII)

\( \sqrt{s} = \{35, 91.2, 189\} \text{ GeV} \)

**Partons**

\[ \langle n_{\text{jet}} \rangle \]

**Hadrons**

\[ \langle n_{\text{jet}} \rangle \]

Bryan Webber, QCD Simulation for LHC and Herwig++, KEK, 6 April 2004
Event Shape Variables, Definition

**Thrust**

\[ F(n) = \frac{\sum_\alpha |p_\alpha \cdot n|}{\sum_\alpha |p_\alpha|} \]

Find \( n \), such that thrust

\[ T = \max_n F(n) = F(n_T), \]

thrust major

\[ M = \max_{n \perp n_T} F(n) = F(n_M), \]

thrust minor

\[ n_m = n_T \times n_M \]

\[ m = F(n_m) \]

**Sphericity**

\[ Q_{ij} = \frac{\sum_\alpha (p_\alpha)_i (p_\alpha)_j}{\sum_\alpha p^2_\alpha} \]

Diagonalize, eigenvalues

\[ \lambda_1 > \lambda_2 > \lambda_3 \]

\[ \lambda_1 + \lambda_2 + \lambda_3 = 1 \]

Then

\[ S = \frac{3}{2}(\lambda_2 + \lambda_3) \]

\[ P = \lambda_2 - \lambda_3 \]

\[ A = \frac{3}{2}\lambda_3 \]

Eigenvector \( n_S \) sphericity axis etc.

**C, D parameter**

\[ L_{ij} = \frac{\sum_\alpha (p_\alpha)_i (p_\alpha)_j}{\sum_\alpha |p_\alpha|} \]

Diagonalize, eigenvalues

\[ \lambda_1 + \lambda_2 + \lambda_3 = 1 \]

and define

\[ C = 3(\lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_3 \lambda_1) \]

\[ D = 27\lambda_1 \lambda_2 \lambda_3 \]
Thrust — ME Corrections off/on

no ME correction
\[ \delta = 1.7 \text{GeV} \]  
\[ \delta = 2.3 \text{GeV} \]  
\[ \delta = 3.2 \text{GeV} \]  
DELPHI 96

\[ \text{Herwig++ 1.0} \]  
\[ \delta = 1.7 \text{GeV} \]  
\[ \delta = 2.3 \text{GeV} \]  
\[ \delta = 3.2 \text{GeV} \]  
DELPHI 96

Bryan Webber, QCD Simulation for LHC and Herwig++, KEK, 6 April 2004
All Thrust–related distributions slightly wide, i.e. too many 2-jet like on one side and too many spherical events on the other side.
More emphasis on large momenta in quadratic tensor.
Four–Jet Angles — Definitions

- Bengtsson–Zerwas angle
  \[ \chi_{BZ} = \angle (p_1 \times p_2, p_3 \times p_4) \]

- Körner–Schierholz–Willrodt angle
  \[ \Phi_{KSW} = \frac{1}{2} [\angle (p_1 \times p_3, p_2 \times p_4) + \angle (p_1 \times p_4, p_2 \times p_3)] \]

- (Modified) Nachtmann–Reiter angle
  \[ \theta^*_{NR} = \angle (p_1 - p_2, p_3 - p_4) \]

- Angle between softest jets
  \[ \alpha_{34} = \angle (p_3, p_4) \]

N.B. No four-parton ME in Herwig++ (yet).
Four–Jet Angles II

Herwig++ 1.0

\(\delta = 1.7 \text{ GeV}\)

\(\delta = 2.3 \text{ GeV}\)

\(\delta = 3.2 \text{ GeV}\)

DELPHI

\(|\cos \theta_{NR}^*|\)

\(\cos \alpha_{34}\)
Single particle distributions: $p_{\perp,\text{in}}^T$
$p_{\perp,\text{out}}^T$ and $y^T$
Scaled momentum (all, $uds$, $b$)

$\delta = 1.7$ GeV
$\delta = 2.3$ GeV
$\delta = 3.2$ GeV
SLD 03

Herwig++ 1.0

$\delta = 1.7$ GeV
$\delta = 2.3$ GeV
$\delta = 3.2$ GeV
SLD 03

Bryan Webber, QCD Simulation for LHC and Herwig++, KEK, 6 April 2004
Proton momentum (all, $uds$, $b$)

Bryan Webber, QCD Simulation for LHC and Herwig++, KEK, 6 April 2004
\( K^\pm, (\Lambda, \bar{\Lambda}) \) momentum

\[ x_p(K^\pm) \text{ [all]} \]

\[ p(\Lambda, \bar{\Lambda})/\text{GeV} \]
Only parton shower parameters varied!
Recommended parameters

No systematic parameter tuning yet.

- **Low** cutoff preferred by event shapes, jet rates, differential jet rates.
- **High** cutoff preferred by single particle distributions along thrust or sphericity axis.
- Either **high** or **low** cutoff for \( y_n \).
- **High** cutoff preferred by identified particle spectra, particularly for heavy flavour events.
- **Intermediate** cutoff preferred by \( B \) fragmentation function.

We recommend the intermediate value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_s(M_Z) )</td>
<td>0.118</td>
<td>0.114</td>
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<tr>
<td>( \delta/\text{GeV} )</td>
<td>2.3</td>
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<tr>
<td>( m_g/\text{GeV} )</td>
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<tr>
<td>( Q_{\text{min}}/\text{GeV} ) in ( \alpha_s(Q_{\text{min}}) )</td>
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<tr>
<td>( \text{ClMax}/\text{GeV} )</td>
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<tr>
<td>CIPow</td>
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<td>PSplit1</td>
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<td>—</td>
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<tr>
<td>PSplit2</td>
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<td>CLDir1</td>
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<td>Pwt_(d)</td>
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<tr>
<td>Pwt_(u)</td>
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<tr>
<td>Pwt_(s)</td>
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<td>Pwt_(c)</td>
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<td>Pwt_(b)</td>
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<tr>
<td>Pwt_(di)</td>
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<tr>
<td>Singlet Weight</td>
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<tr>
<td>Decuplet Weight</td>
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<td>1.0</td>
</tr>
</tbody>
</table>
Status of Herwig++

S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens, B.R. Webber
(Cambridge, Manchester, CERN)
http://www.hep.phy.cam.ac.uk/theory/Herwig++

Hard Matrix Elements

- Only simple $2 \to 2$ ME so far.
- Hard and soft ME corrections for $e^+e^- \to q\bar{q}g$.
- We have a working interface to AMEGIC++. For $e^+e^-$ this will do the job for up to 6 jets.
- CKKW ME+PS matching algorithm will be implemented.
- More processes straightforward.
- Users can easily and safely include their own matrix elements.

Parton Shower

- New parton shower developed.
- Multiscale shower designed for treatment of unstable particles (no physics implementation yet).
- New evolution variables for better treatment of heavy quarks and smooth coverage of phase space.
- Extension to spacelike shower for $pp$ and $ep$ ongoing.
Status of Herwig++ (ctnd’)

Hadronization

• Cluster hadronization is designed and implemented completely.
• Improved cluster decays implemented and tested.
• Works very well, further thorough tests ongoing.
• Lund string fragmentation model implemented in Pythia7 will work together with Herwig++.

Decays

• Fortran HERWIG decays are reproduced with class Hw64Decayer using the same ME’s as before.
• DecayerAMEGIC gets final states for decays (eg. $t$ decay, SUSY in future) directly from AMEGIC++
• Works very well, further thorough tests required.
• More to come (EvtGen, . . . )?
What’s next?

Near Future. . .

- Initial state shower:
  - Complete implementation and tests.
- Refine $e^+e^-$:
  - Full CKKW ME+PS matching.
  - Precision tune to LEP data should be possible.
- With IS and FS showers running:
  - Can start to test Drell–Yan and jets in pp collisions.
  - Cross-check with Tevatron data and finally make predictions for the LHC.
- Underlying event.
- Hadronic decays: NEW! $\tau$–decays, spin correlations (P Richardson).
- New ideas: NLO, multiscale, SUSY . . .

Schedule?

- Ready for LHC!