Simulation of multiple partonic interactions in Herwig++

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in collaboration with
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pp Event Generator
This talk:

- Philosophy
- Introduction - Evolution of MPI model in Herwig++
- MPI model in Herwig++
- Colour structure
- Comparison with ATLAS results: MB and UE @ 900 GeV and @ 7 TeV
- Outlook
Calculate Everything: solve QCD \( \rightarrow \) requires compromise

- Improve Born-level perturbation theory, by including the ‘most significant’ corrections \( \rightarrow \) complete events \( \rightarrow \) any observable you want

1. **Parton Showers**
2. **Matching**
3. **Hadronisation**
4. **The Underlying Event**

(\( + \) many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

Asking for complete events is a tall order …
"Entities must not be multiplied beyond necessity" (Entia non sunt multiplicanda praeter necessitatem)

[William of Ockham (d’Okham)]

**Occam's razor** (...) is a principle that generally recommends selecting the competing hypothesis that makes the fewest **new assumptions**, when the hypotheses are equal in other respects. For instance, they must both sufficiently explain available data in the first place. (...) That is, the razor is a principle that suggests we should tend towards simpler theories until we can trade some simplicity for increased explanatory power.

[Wikipedia]
UA5 model (deprecated, only for reference)

- Included from Herwig++ 2.0. [Herwig++, hep-ph/0609306]
- Little predictive power.
- Was default in fHerwig. Superseded by JIMMY [JM Butterworth, JR Forshaw, MH Seymour, ZP C72 637 (1996)]
Semihard UE

- Default from Herwig++ 2.1. [Herwig++, 0711.3137]
- Multiple hard interactions, $p_t \geq p_{t}^{\text{min}}$ [Bähr, Gieseke, Seymour, JHEP 0807:076]
- Similar to JIMMY
- Good description of harder Run I UE data (Jet20).
Semihard UE

Good description of Run I Underlying event data ($\chi^2 = 1.3$).

Only $p_T^{\text{jet}} > 20\text{GeV}$.
Semihard+Soft UE

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions, $p_t \leq p_t^{\text{min}}$ [Bähr, Gieseke, Seymour, JHEP 0807:076]
- Theoretical work with simplest possible extension. [Bähr, Butterworth, Seymour, JHEP 0901:065]
- “Hot Spot” model. [Bähr, Butterworth, Gieseke, Seymour, 0905.4671]
Evolution of MPI model in Herwig++

Semihard+Soft UE

\[
\langle N_{\text{ch}}\rangle_{\text{transy}}
\]

- data, uncorrected
- \( p_T^n = 3.5, \mu^2 = 1.50, \chi^2_{\text{ISR}}/N = 3.1 \)
- \( p_T^n = 3.5, \mu^2 = 1.25, \chi^2_{\text{ISR}}/N = 2.9 \)
- \( p_T^n = 4.0, \mu^2 = 1.50, \chi^2_{\text{ISR}}/N = 2.8 \)

Tevatron Run1
Evolution of MPI model in Herwig++

Comparison with MinBias ATLAS data (900 GeV)

- ATLAS charged particles in Min Bias ($N_{ch} \geq 1$, $p_T > 500\,\text{MeV}$, $|\eta| < 2.5$)
- Convenient as the analysis was quickly available in RIVET.

| Choice of PDF set (CTEQ61l vs MSTW LO**) |

Average transverse momentum as function of $N_{ch}$

Charged particle multiplicity as function of $\eta$
Evolution of MPI model in Herwig++

Colour Structure of the Underlying Event

- Colour Reconnection (parameter $p_{reco}$) - Included from Herwig++ 2.5
- Colour Disruption - only Soft UE (parameter $p_{CD}$)
- Retuning to LEP data needed.
- Tests of Colour Reconnection model.
Multiple hard interactions
Starting point: hard inclusive jet cross section.

\[
\sigma^{\text{inc}}(s; p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}}^2} dp_t^2 f_i/h_1(x_1, \mu^2) \otimes \frac{d\hat{\sigma}_{i,j}}{dp_t^2} \otimes f_j/h_2(x_2, \mu^2),
\]

\(\sigma^{\text{inc}} > \sigma_{\text{tot}}\) eventually (for moderately small \(p_t^{\text{min}}\)).
Eikonal model basics

\[ \sigma_{\text{tot}} : \text{DL '92} \]
\[ \sigma_{\text{tot}} : \text{DL '04} \]
\[ \text{QCD2} \rightarrow 2, p_T > 2\text{GeV} \]
Starting point: hard inclusive jet cross section.

\[ \sigma^{\text{inc}}(s; p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}}} dp_t^2 f_{i/h_1}(x_1, \mu^2) \otimes \frac{d\sigma_{i,j}}{dp_t^2} \otimes f_{j/h_2}(x_2, \mu^2), \]

\(\sigma^{\text{inc}} > \sigma^{\text{tot}}\) eventually (for moderately small \(p_t^{\text{min}}\)).

Interpretation: \(\sigma^{\text{inc}}\) counts all partonic scatters that happen during a single \(pp\) collision \(\Rightarrow\) more than a single interaction.

\[ \sigma^{\text{inc}} = \bar{n}\sigma_{\text{inel}}. \]

Also measurement of momentum imbalance in multijet events at CERN ISR, \(\gamma + 3\) jet at TVT.
Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number $m$ of additional scatters,

$$P_m(\vec{b}, s) = \frac{\bar{n}(\vec{b}, s)^m}{m!} e^{-\bar{n}(\vec{b}, s)} .$$

Then we get $\sigma_{\text{inel}}$:

$$\sigma_{\text{inel}} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_m(\vec{b}, s) = \int d^2\vec{b} \left( 1 - e^{-\bar{n}(\vec{b}, s)} \right) .$$
Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number \( m \) of additional scatters,

\[
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\[
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\]

Cf. \( \sigma_{\text{inel}} \) from scattering theory in eikonal approx. with scattering amplitude \( a(\vec{b}, s) = \frac{1}{2i} (e^{-\chi(\vec{b}, s)} - 1) \)

\[
\sigma_{\text{inel}} = \int d^2\vec{b} \left( 1 - e^{-2\chi(\vec{b}, s)} \right) \quad \Rightarrow \quad \chi(\vec{b}, s) = \frac{1}{2} \bar{n}(\vec{b}, s).
\]

\( \chi(\vec{b}, s) \) is called eikonal function.
Calculation of \( \bar{n}(\vec{b}, s) \) from parton model assumptions:

\[
\bar{n}(\vec{b}, s) = L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int dp_t^2 \frac{d\hat{\sigma}_{ij}}{dp_t^2} \\
= \sum_{ij} \frac{1}{1 + \delta_{ij}} \int dx_1 dx_2 \int d^2 \vec{b}' \int dp_t^2 \frac{d\hat{\sigma}_{ij}}{dp_t^2} \\
\times D_{i/A}(x_1, p_t^2, |\vec{b}'|)D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|)
\]
Calculation of $\bar{n}(\vec{b}, s)$ from parton model assumptions:

$$
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= \sum_{ij} \frac{1}{1 + \delta_{ij}} \int d x_1 dx_2 \int d^2 \vec{b}' \int \frac{d^2 \sigma_{ij}}{d^2 p_t} \\
\times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|) \\
= \sum_{ij} \frac{1}{1 + \delta_{ij}} \int d x_1 dx_2 \int d^2 \vec{b}' \int \frac{d^2 \sigma_{ij}}{d^2 p_t} \\
\times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}).$$
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$$

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\times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|)
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$$
= \sum_{ij} \frac{1}{1 + \delta_{ij}} \int dx_1 dx_2 \int d^2\vec{b}' \int dp_t^2 \frac{d\hat{\sigma}_{ij}}{dp_t^2}
$$

$$
\times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|)
$$

$$
= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}).
$$

$$
\Rightarrow \chi(\vec{b}, s) = \frac{1}{2} \bar{n}(\vec{b}, s) = \frac{1}{2} A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}).
$$
From assumptions:

- at fixed impact parameter $b$, individual scatterings are independent,
- the distribution of partons in hadrons factorizes with respect to the $b$ and $x$ dependence.

we get the average number of partonic collisions at a given $b$ value is

$$\bar{n}(b, s) = A(b)\sigma^{inc}(s; p_t^{\text{min}}) = 2\chi(b, s)$$

where $A(b)$ is the partonic overlap function of the colliding hadrons

$$A(b) = \int d^2\tilde{b}'G_A(|\tilde{b}'|)G_B(|\tilde{b} - \tilde{b}'|)$$

$G(\tilde{b})$ from electromagnetic FF:

$$G_p(\tilde{b}) = G_p(\tilde{b}) = \int \frac{d^2k}{(2\pi)^2} \frac{e^{ik\cdot b}}{(1 + k^2/\mu^2)^2}$$

But $\mu^2$ not fixed to the electromagnetic 0.71 GeV$^2$.

Free for colour charges.

$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\text{min}}$. 
Overlap function

\[ A(\vec{b}) = \int d^2\vec{b}' G_A(|\vec{b}'|)G_B(|\vec{b} - \vec{b}'|) \]

\( G(\vec{b}) \) from electromagnetic FF:

\[ G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2k}{(2\pi)^2} \frac{e^{i\vec{k} \cdot \vec{b}}}{(1 + k^2/\mu^2)^2} \]

But \( \mu^2 \) not fixed to the electromagnetic 0.71 GeV\(^2\).
Free for colour charges.

\[ \Rightarrow \text{Two main parameters: } \mu^2, p_t^{\text{min}}. \]
Unitarized cross sections

\[ \sigma_{\text{tot}} \text{ from DL} \]
\[ \sigma^{\text{inc}}, p_T > 2 \text{ GeV} \]
\[ \sigma^{\text{inel}}, p_T > 2 \text{ GeV} \]
\[ \sigma^{\text{inc}}, p_T > 3.1 \text{ GeV} \]
\[ \sigma^{\text{inel}}, p_T > 3.1 \text{ GeV} \]
Good description of Run I Underlying event data ($\chi^2 = 1.3$).

Only $p_T^{\text{jet}} > 20\text{GeV}$. 
So far only hard MPI.
Now extend to soft interactions with

\[ \chi_{\text{tot}} = \chi_{\text{QCD}} + \chi_{\text{soft}}. \]

Similar structures of eikonal functions:

\[ \chi_{\text{soft}} = \frac{1}{2} A_{\text{soft}}(\vec{b}) \sigma_{\text{inc}}^{\text{soft}}. \]
So far only hard MPI. Now extend to soft interactions with

\[ \chi_{\text{tot}} = \chi_{\text{QCD}} + \chi_{\text{soft}}. \]

Similar structures of eikonal functions:

\[ \chi_{\text{soft}} = \frac{1}{2} A_{\text{soft}}(\vec{b}) \sigma_{\text{inc}} \]

Simplest possible choice:

\[ A_{\text{soft}}(\vec{b}; \mu) = A_{\text{hard}}(\vec{b}; \mu) = A(\vec{b}; \mu). \]

Then

\[ \chi_{\text{tot}} = \frac{A(\vec{b}; \mu)}{2} \left( \sigma_{\text{inc}}^{\text{hard}} + \sigma_{\text{inc}}^{\text{soft}} \right). \]

One new parameter \[ \sigma_{\text{inc}}^{\text{soft}}. \]
Extending into the soft region

Continuation of the differential cross section into the soft region $p_t < p_t^{\text{min}}$
(here: $p_t$ integral kept fixed)

$$\frac{d\sigma_{\text{soft}}}{dp_t} \sim p_t e^{-\beta (p_t^2 - p_t^{\text{min}})^2}$$

Graph showing the behavior of $1/\sigma(5 \text{ GeV}) \frac{d\sigma}{dp_t}$ as a function of $p_t$ for different values of $p_t^{\text{min}}$. The graph includes two curves: a solid line for $p_t^{\text{min}} = 3 \text{ GeV}, \beta = -0.5 \text{ GeV}^{-2}$ and a dotted line for $p_t^{\text{min}} = 5 \text{ GeV}, \beta = 0.06 \text{ GeV}^{-2}$. The graph also shows the behavior of $1/(5 \text{ GeV}) \frac{d\sigma}{dp_t}$.
Exploit knowledge of $\sigma_{\text{tot}}$ in eikonal model:

$$\sigma_{\text{tot}} = 2 \int d^2 \vec{b} \left( 1 - e^{-\chi_{\text{tot}}(\vec{b}, s)} \right)$$

$$= 2 \int d^2 \vec{b} \left( 1 - e^{-\frac{A(\vec{b}; \mu)}{2}} (\sigma_{\text{inc hard}} + \sigma_{\text{inc soft}}) \right)$$

$\sigma_{\text{tot}}$ well measured. Fixes $\sigma_{\text{inc soft}}$.

Energy extrapolation from Donnachie–Landshoff

- DL ’92
  
- DL ’92 normalized at TVT
  
- DL ’04

[D&L, PLB296, 227 (1992)]

[D&L, PLB595, 393 (2004)]
Find constraints on \((p_t^{\text{min}}, \mu)\).

- Require \(\sigma_{\text{inc soft}} > 0\) mb, while describing \(\sigma_{\text{tot}}\).
- Require elastic \(t\)-slope,
  \[
  b_{\text{el}}(s) = \left[ \frac{d}{dt} \left( \ln \frac{d\sigma_{\text{el}}}{dt} \right) \right]_{t=0},
  \]
  to be correctly described
  \[
  b_{\text{el}}(s) = \int d^2 \vec{b} \frac{b^2}{\sigma_{\text{tot}}} \left[ 1 - e^{-\chi_{\text{tot}}} \right].
  \]
- Final state tune of \textbf{semi-hard} MPI (MRST2001)
What to expect at 14 TeV?

- $\sigma_{\text{soft}}^{\text{inc}} > 0$ mb. $\sigma_{\text{tot}}$ from Regge fit
- Require $\bar{n}_{\text{hard}} < 10$
- Require elastic $t$-slope to be correctly described.

Get range of possible measurements from DL ‘92 and predictions for $b_\text{el}$

[Khoze, Martin, Ryskin, 0710.2494]
[Gotsman, Levin, Maor, 0708.1506]
- $\sigma_{\text{soft}}^{\text{inc}}$ rises artificially fast (expect $\sim s^{0.08}$).
- Forced to have energy dependent parameters (would like to have the choice, i.e. let measurements decide).
- Measurement of $b_{\text{el}}$ fixes $\mu^2$ at Tevatron:
  
  $$\mu^2 = 0.56 \pm 0.01 \text{ GeV}^2$$

  $$\sigma_{\text{eff}} = (\int d^2 b A^2(b))^{-1}$$ as measured by CDF in $\gamma + 3j$:
  
  $$\mu^2 = 3.0 \pm 0.5 \text{ GeV}^2.$$
\( \sigma_{\text{soft}}^{\text{inc}} \) rises artificially fast (expect \( \sim s^{0.08} \)).

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\]

\[
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\]

\rightarrow \text{ Relax the constraint of identical overlap}

\[
A_{\text{soft}}(b) = A(b, \mu_{\text{soft}})
\]

If \( \mu > \mu_{\text{soft}} \): \textbf{Hot Spots} functions:
Fix the two parameters $\mu_{\text{soft}}$ and $\sigma_{\text{soft}}^{\text{inc}}$ in

$$\chi_{\text{tot}}(\vec{b}, s) = \frac{1}{2} \left( A(\vec{b}; \mu) \sigma_{\text{hard}}^{\text{inc}}(s; p_{\text{min}}^t) + A(\vec{b}; \mu_{\text{soft}}) \sigma_{\text{soft}}^{\text{inc}} \right)$$

from two constraints. Require simultaneous description of $\sigma_{\text{tot}}$ and $b_{\text{el}}$ (measured/well predicted),

$$\sigma_{\text{tot}}(s) \equiv 2 \int d^2\vec{b} \left( 1 - e^{-\chi_{\text{tot}}(\vec{b}, s)} \right) ,$$

$$b_{\text{el}}(s) \equiv \int d^2\vec{b} \frac{b^2}{\sigma_{\text{tot}}} \left( 1 - e^{-\chi_{\text{tot}}(\vec{b}, s)} \right) .$$
Constraint: describe $\sigma_{\text{tot}}$ and $b_{\text{el}}$. TVT (left), LHC 14 TeV (right)
So far: only indirect constraints from $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$.

Now use model in Herwig++ with $\bar{n}(\vec{b}, s)$ as input for MPI.

Remaining free parameters $(p_{t}^{\text{min}}, \mu^2)$.

Look at $\chi^2$/dof for Tevatron Run I data in the $(p_{t}^{\text{min}}, \mu^2)$ plane.
$\chi^2$ for Rick’s Run1 Jet analysis for all regions
Detailed look at observables: Transverse Region

- data, uncorrected
- $p_t^{\text{min}} = 3.5, \mu^2 = 1.50, \chi^2_{\text{tot}}/N = 3.1$
- $p_t^{\text{min}} = 3.5, \mu^2 = 1.25, \chi^2_{\text{tot}}/N = 2.9$
- $p_t^{\text{min}} = 4.0, \mu^2 = 1.50, \chi^2_{\text{tot}}/N = 2.8$
What we have so far:

- Unitarized jet cross sections
- Fulfil constraints from $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$.
- Simple model with similar overlap functions.
- No additional (explicit) energy dependence.
- Left with freedom in parameter space.

Look at LHC results (900 GeV).

- ATLAS charged particles in Min Bias.
- Convenient as the analysis was quickly available in RIVET;-)

Three points from 'valley' ($p_{\text{min}}/\text{GeV}$, $\mu^2/\text{GeV}^2$) = (3.0, 1.0); (4.0, 1.5); (5.0, 2.0).
What we have so far:

- Unitarized jet cross sections
- Fulfil constraints from $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$.
- Simple model with similar overlap functions.
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  \((p_t^{\text{min}} / \text{GeV}, \mu^2 / \text{GeV}^2) = (3.0, 1.0); (4.0, 1.5); (5.0, 2.0)\)
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- ATLAS charged particles in Min Bias ($N_{ch} \geq 1$, $p_T > 500\text{MeV}$, $|\eta| < 2.5$)
- Convenient as the analysis was quickly available in RIVET.

Average transverse momentum as function of $N_{ch}$

<table>
<thead>
<tr>
<th>$N_{ch}$</th>
<th>MC</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>30</td>
<td>0.9</td>
<td>1.4</td>
</tr>
<tr>
<td>40</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>50</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>60</td>
<td>1.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Charged particle multiplicity as function of $\eta$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>MC</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>-1</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>1</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- oops, not so nice...
- despite very good agreement with Rick Field’s CDF UE analysis.
- choice of PDF set (CTEQ61l vs MSTW LO** (our default))
- Failure of a physically motivated model usually points to more, interesting physics ... colour structure?
Colour structure of the soft interactions, $p_t \leq p_t^{\text{min}}$

Sensitivity to parameter:
- $\text{colourDisrupt} = P(\text{disrupt colour lines})$ as opposed to hard QCD.
- $\text{colourDisrupt} = 1$, completely disconnected.
Colour reconnection (CR) in Herwig++

Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement*
  \[ \Rightarrow \text{colour-anticolour pairs form highly excited hadronic states, the clusters} \]

\[ \text{physical motivation: exchange of soft gluons during non-perturbative hadronization phase} \]

\[ \text{implementation 1 for details look at Christians Röhr's Diploma thesis} \]
Colour reconnection (CR) in Herwig++

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Colour reconnection (CR) in Herwig++

Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, e.g. \((il) + (jk)\)
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Extending the hadronization model in Herwig(++):

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- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

**Implementation\(^1\)**

- Allow CR if the cluster mass decreases,
  \[ M_{il} + M_{kj} < M_{ij} + M_{kl}, \]
  where \(M^2_{ab} = (p_a + p_b)^2\) is the (squared) cluster mass
- Accept alternative clustering with probability \(p_{\text{reco}}\) (model parameter) ⇒ this allows to switch on CR smoothly

\(^1\)For details look at Christians Röhr’s Diploma thesis
Hadronization sensitive to CR model.
Proper study requires re-tune to LEP data.
Many thanks to the Professor team for help and hints how to use their program!

Mean charged multiplicity

Out-of-plane $p_{\perp}$ in GeV w.r.t. sphericity axes

Agreement on same level as w/o CR model.
Hadronization sensitive to CR model.

Proper study requires re-tune to LEP data.

Many thanks to the Professor team for help and hints how to use their program!

Result scatter for ReconnectionProbability

Preferred by LEP data is: $0.2 \leq p_{\text{reco}} \leq 0.6$
We used two LEP analyses (sensitive to color reconnection) to test the new model:

- OPAL Collaboration arXiv:hep-ex/0306021v1:
  “Tests of models of color reconnection and a search for glueballs using gluon jets with a rapidity gap”

  particles flow in $WW \rightarrow 4j$ at LEP

Result:

- Herwig++ with and w/o colour rec. seems to describe these data at the same level.

News:

- Work on new colour reconnection algorithms is ongoing.
small effects here

marginal improvement (if at all)

Proper comparison: lack of diffraction in Herwig++!
We used a diffractive suppressed sample with cut: \( N_{ch} \geq 6 \)
Charged particle multiplicity as function of $\eta$ (0.9 TeV, $N_{\text{ch}} \geq 6$)

$\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ch}}}{d\eta}$

-2 -1 0 1 2

0.6 0.8 1 1.2 1.4 1.6 1.8 2

MC/data

Charged particle density (0.9 TeV, $N_{\text{ch}} \geq 6$)

$\frac{1}{N_{\text{ev}}} \frac{dN_{e\gamma}}{dN_{\text{ch}}}$

10 20 30 40 50 60

0.6 0.8 1 1.2 1.4 1.6 1.8 2

MC/data
Charged particle multiplicity as function of $p_\perp$ (0.9 TeV, $N_{\text{ch}} \geq 6$)

Average transv. momentum as function of $N_{\text{ch}}$ (0.9 TeV, $N_{\text{ch}} \geq 6$)
2nd MB ATLAS publication [arXiv 1012.5104], more phase spaces. 
\( N_{ch} \geq 1, \ p_T > 2500 \text{ MeV}, \ |\eta| < 2.5 \)

Charged particle \( \eta \) at 900 GeV, track \( p_\perp > 2500 \text{ MeV} \), for \( N_{ch} \geq 1 \)

\[ \frac{1}{N_{ev}} \frac{dN_{ch}}{d\eta} \]

\[ \langle p_\perp \rangle \text{ [GeV]} \]

This was not tuned! We used tune to ATLAS MB data for \( N_{ch} \geq 6, \ p_T > 500 \text{ MeV} \) presented in MB&UE WG in September 2010
2nd MB ATLAS publication [arXiv 1012.5104], more phase spaces. 

\[ N_{ch} \geq 1, \ p_T > 2500 \text{ MeV}, \ |\eta| < 2.5 \]

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\[ N_{ch} \geq 6, \ p_T > 500 \text{ MeV} \] presented in MB&UE WG in September 2010
Underlying Event 7000 GeV (ATLAS-CONF-2010-029)

\( N_{ch}/\text{StdDev transverse vs } p_{t}^{lead}/\text{GeV} \)

Slide from MPI@LHC 2010 in Glasgow

\( p^{\text{min}}_t = 3.2 \text{ GeV}, \quad \mu^2 = 0.81 \text{ GeV}^2, \quad p_{\text{reco}} = 0.61, \quad p_{\text{disrupt}} = 0.34 \)
Those observables (in transverse region) were used for the tuning.
Underlying Event 7000 GeV

This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow

\[ \frac{d^2 p_{\perp}}{d \eta d \Delta \phi} \] vs \( \Delta \phi \) wrt leading track, \( p_{\text{lead}} > 5 \text{ GeV}, \sqrt{s} = 7 \text{ TeV} \)

\[ \frac{d^2 N_{\text{ch}}}{d \eta d \Delta \phi} \] vs \( \Delta \phi \) wrt leading track, \( p_{\text{lead}} > 5 \text{ GeV}, \sqrt{s} = 7 \text{ TeV} \)
This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow
This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow.
Particle Density vs. $P_T^{lead}$

Particle density increases by a factor of ~2 but the conclusion is the same.
This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow.

In Glasgow Arthur Moraes asked us how it would look like for $p_T = 100$ MeV.

Tunes (input files, plots) are available at Herwig++ wiki page.
Particle Density, Scalar $\Sigma P_T$ vs. $\eta^{\text{lead}}$

Lower particle activities in MC tunes
Particle density & scalar $\Sigma P_T$ independent of $\eta^{\text{lead}}$
This was not tuned! We used tune to ATLAS UE presented during MPI@LHC 2010 on 1 December 2010 in Glasgow.

In Glasgow Arthur Moraes asked us how it would look like for $p_T = 100$ MeV.

Tunes (input files, plots) are available at Herwig++ wiki page.
Herwig++ 2.5

- POWHEG NLO parton shower matching scheme with:
  - Vector Boson Pair Production
  - $e^+ e^- \rightarrow q\bar{q}$
  - Higgs Decay
- MC@NLO program now can be used with Herwig++
- Colour Reconnection
- Diffractive and Photon Initiated Processes
- BSM Physics
  (ADD Model, Leptoquarks, NMSSM, Transplanckian Scattering)
- New Matrix Elements

For details please look at the release note.
First look at LHC data.

Need colour reconnection model.

First tunes to 900 GeV and 7000 GeV Min Bias ($N_{ch} \geq 6$) give good results.

Non-diffractive physics under good control

So is this the end of the story?
First look at LHC data.

Need colour reconnection model.

First tunes to 900 GeV and 7000 GeV Min Bias \((N_{ch} \geq 6)\) give good results.

Non-diffractive physics under good control

So is this the end of the story? No! This is just the beginning...

When we are happy with the description of existing data we should ask more and more detailed questions (fb asymmetries, event shapes).

Experiments provide more and more data (better statistics: \(N_{ch} \geq 20\), new observables: strange particle and proton production, LHC@2.8TeV ... )
Open question:

- Energy dependent parameters?
- More involved overlap function ($x$-dependent)?
- Understanding of colour reconnection?  
  (OPAL “rapidity gap analysis’ - done, new CR algorithms - soon)
- Universal tune of UE parameters?
- New model of diffraction R&D
- Treatment of remnant pdfs too naive?
- Minimum bias/underlying event/diffraction under constant improvement!