MPI in PYTHIA

1. Brief overview
2. Color reconnection and the top mass

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Seek unified description of hard jets, UE and MB.

Perturbative origin $\Rightarrow p_\perp$ d.o.f. essential (unlike multi-Pomeron models at the time).

Screening $\Rightarrow \frac{d\rho^2}{p^4} \rightarrow \frac{d\rho^2}{(p^2 + p_{10}^2)^2}$
with $p_{10} \approx 1.5 - 2$ GeV $\Rightarrow$ finite MPI number.

$p_\perp$-ordered generation, Sudakov/shower style.

Hardest MPI standard PDFs, softer modified.

Tuneable impact-parameter picture.

Colour reconnection needed.

Makes use of existing PYTHIA/JETSET components, such as

Lund string fragmentation, and

initial- and final-state parton showers.

1987: the experimental evidence

MPI signals included

- width of charged multiplicity,
- forward–backwards correlations, and
- jet pedestal effect:

CR signal from $\langle p_\perp \rangle(n_{ch})$:

FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, $gg$ scatterings with “maximal” string length; solid line $gg$ scatterings with “minimal” string length.
Today: basic generation of MPI

- **Basic ideas remain**: screening, $p_\perp$-ordered generation, all events contain at least one perturbative interaction.
- Still allow for many different impact-parameter profiles.
- Screening $p_\perp 0$ energy-dependent for post-HERA PDFs.
- Two $\Rightarrow$ three basic generation possibilities:
  0 no separate hard interaction $\Rightarrow$ minbias events,
  1 start from fixed hard interaction $\Rightarrow$ underlying event, or
  2 select two hard interactions, e.g. $W^-W^-$. 
- More sophisticated rescaled PDF’s, taking into account momentum and flavour correlations.
- Possible to kick out several valence quarks ($\Rightarrow$ junctions), and to have more complicated bream remnants.
- Each MPI associated with its ISR and FSR activity.
- MPI machinery also for diffractive events.
Interleaved evolution

- MPI ordered in $p_{\perp}$ from onset.
- Now also $p_{\perp}$-ordered parton showers for ISR and FSR.

⇒ Allows interleaved evolution for MPI, ISR and FSR:

$$\frac{d\mathcal{P}}{dp_{\perp}} = \left( \frac{d\mathcal{P}_{\text{MPI}}}{dp_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_{\perp}} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp_{\perp}} \right) \times \exp \left( -\int_{p_{\perp}}^{p_{\perp}^{\text{max}}} \left( \frac{d\mathcal{P}_{\text{MPI}}}{dp'_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_{\perp}} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp'_{\perp}} \right) dp'_{\perp} \right)$$

Ordered in decreasing $p_{\perp}$ using “Sudakov” trick.

Corresponds to increasing “resolution” of partonic final state: smaller $p_{\perp}$ fill in details of basic picture set at larger $p_{\perp}$.
Often assume that MPI = ...

...but should also include

Same order in \( \alpha_s \), \( \sim \) same propagators, but

- one PDF weight less \( \Rightarrow \) smaller \( \sigma \)
- one jet less \( \Rightarrow \) QCD radiation background \( 2 \rightarrow 3 \) larger than \( 2 \rightarrow 4 \)
  \( \Rightarrow \) will be tough to find direct evidence.

Rescattering grows with number of “previous” scatterings:

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min Bias</td>
<td>QCD Jets</td>
</tr>
<tr>
<td>Normal scattering</td>
<td>2.81</td>
<td>5.09</td>
</tr>
<tr>
<td>Single rescatterings</td>
<td>0.41</td>
<td>1.32</td>
</tr>
<tr>
<td>Double rescatterings</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>
An $x$-dependent proton size

Reasonable to assume that low-$x$ partons are more spread out:

$$\rho(r, x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

$a_1 \approx 0.15$ tuned to rise of $\sigma_{ND}$

$a_0$ tuned to value of $\sigma_{ND}$, given PDF, $p_{\perp 0}$, ...

Consequence: collisions at large $x$ will have to happen at small $b$, and hence further large-to-medium-$x$ MPIs are enhanced.

$a_1 > 0$ not favoured by tunes so far!
Colour reconnection

\( \langle p_\perp \rangle (n_{ch}) \) effect alive and kicking:

\[ \begin{align*}
\text{Colour reconnection (CR):} & \quad \text{reduce total string length} \\
& \quad \Rightarrow \text{reduce hadronic multiplicity}
\end{align*} \]

String width \( \sim \) hadronic width
\[ \Rightarrow \text{Overlap factor } \sim 10! \]

Larger for hard collisions (small impact parameter)
A top mass puzzle

\[ \begin{align*}
\Gamma_t &\approx 1.5 \text{ GeV} \\
\Gamma_W &\approx 2 \text{ GeV} \\
\Gamma_Z &\approx 2.5 \text{ GeV}
\end{align*} \]

\[ \Rightarrow c\tau \approx 0.1 \text{ fm} : \]

p “pancakes” have passed, MPI/ISR/FSR for \( p_\perp \geq 2 \text{ GeV} \), inside hadronization colour fields.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( m_{\text{top}} ) [GeV]</th>
<th>Error due to CR</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>World comb.</td>
<td>173.34±0.76</td>
<td>310 MeV (40%)</td>
<td>arXiv:1403.4427</td>
</tr>
<tr>
<td>CMS</td>
<td>172.22±0.73</td>
<td>150 MeV (20%)</td>
<td>CMS-PAS-TOP-14-001</td>
</tr>
<tr>
<td>D0</td>
<td>174.98±0.76</td>
<td>100 MeV (13%)</td>
<td>arXiv:1405.1756</td>
</tr>
</tbody>
</table>

(S. Argyropoulos)

1. Great job in reducing the errors.
2. CR is one of the dominant systematics.
3. Why is the CR uncertainty going down when there are
   - no advances in theoretical understanding, and
   - no measurements to constrain it?
Top mass shift in Pythia 6

Studies for the Tevatron.

Green bands: old virtuality-ordered showers.

Blue bands: new $p_{\perp}$-ordered showers.

In total $\pm 1.0$ GeV, whereof $\pm 0.7$ GeV perturbative, and $\pm 0.5$ GeV nonperturbative.

(M. Sandhoff and P. Z. Skands, FERMILAB-CONF-05-518-T;)
Only one CR model:

- Starting from lowest-$p_\perp$ MPI and moving upwards define its

\[ P_{\text{rec}}(p_T) = \frac{(R_{\text{rec}} p_T_0)^2}{(R_{\text{rec}} p_T_0)^2 + p_T^2}, \]

with any higher-$p_\perp$ MPI. $R_{\text{rec}}$ one free parameter of model.

- Find colour dipoles of highest-$p_\perp$ MPI.

- Consecutively attach each gluon of each lower-$p_\perp$ MPI to be reconnected where it increases the string length $\lambda$ the least.

- Repeat for lower-$p_\perp$ MPIs that form separate systems.

End result: fewer but bigger systems, with reduced total $\lambda$.

Three CR options for top:

- no CR at all
- late resonance decays: t/W decays after CR
- early resonance decays: t/W decays before CR
Further Pythia 8.2 CR models


Basic idea: produce range of models to study how big $\Delta m_{\text{top}}$ could be without contradicting data.

Top CR as afterburner:
- toy / **stealth** models
  - forced random
  - forced nearest
  - forced farthest
  - forced smallest $\Delta \lambda$
  - smallest $\Delta \lambda$

Top CR on equal footing:
- more sophisticated / fragile
  - swap
  - move
  - swap + flip
  - move + flip

so as to reduce $\lambda$

The $\lambda$ measure of an event is approximated by

$$\lambda \approx \lambda_{\text{approx}} = \sum_{\text{dipoles}} \ln \left(1 + \frac{m_{ij}^2}{m_0^2}\right)$$

with $m_0 \approx m_{\text{hadronic}} \approx 1$ GeV.
Some ways to perform a reconnection

**swap:**

**move:**

**flip:**
Effects on top mass before tuning

Reconstructed top mass, $m_W \in [75, 85]$ GeV, $p_T(\text{jets}) > 40$ GeV

$$1/N dN/dm_{\text{top}} \ [\text{GeV}^{-1}]$$

- CR off
- default
- forced random

Asymmetric spread:
$\Delta m_{\text{top}} < 0$ easy,
$\Delta m_{\text{top}} > 0$ difficult.

Parton showers already prefer minimal $\lambda$.

Main effect from jet broadening, some from jet–jet angles.

$\Delta m_{\text{top}}$ relative to no CR:

<table>
<thead>
<tr>
<th>model</th>
<th>$\Delta m_{\text{top}}$ [GeV]</th>
<th>$\Delta m_{\text{top}}$ rescaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>default (late)</td>
<td>$-0.415$</td>
<td>$+0.209$</td>
</tr>
<tr>
<td>default early</td>
<td>$+0.381$</td>
<td>$+0.285$</td>
</tr>
<tr>
<td>forced random</td>
<td>$-6.970$</td>
<td>$-6.508$</td>
</tr>
</tbody>
</table>
No publicly available measurements of UE in top events.
• Afterburner models tuned to ATLAS jet shapes in $t\bar{t}$ events ⇒ high CR strengths disfavoured.
• Early-decay models tuned to ATLAS minimum bias data ⇒ maximal CR strengths required to (almost) match $\langle p_\perp \rangle (n_{ch})$.

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<th>model</th>
<th>$\Delta m_{\text{top}}$ rescaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>default (late)</td>
<td>+0.239</td>
</tr>
<tr>
<td>forced random swap</td>
<td>−0.524</td>
</tr>
<tr>
<td></td>
<td>+0.273</td>
</tr>
</tbody>
</table>

$\Delta m_{\text{top}}$ relative to no CR

$\text{max}_{\text{top}} - \text{min}_{\text{top}} \approx 0.80 \text{ GeV}$

Excluding most extreme (unrealistic) models down to

$\text{max}_{\text{top}} - \text{min}_{\text{top}} \approx 0.50 \text{ GeV}$

(in line with Sandhoff, Skands & Wicke)

Studies of top events could help constrain models:
• jet profiles and jet pull (skewness)
• underlying event
Summary and Outlook

- MPI key PYTHIA component since almost 30 years.
- Original concepts still hold: screening with $p_{\perp 0} \approx 2$ GeV, $p_{\perp}$-order, $n_{\text{pert}} \geq 1$, reconnection, strings, etc.
- Many aspects gradually becoming more sophisticated, notably interleaved evolution MPI + ISR + FSR.
- Everything mixed up $\Rightarrow$ experimental tests indecisive, e.g. rescattering and $x$-dependent proton size.
- Colour reconnection one of big known unknowns.
- Experimental $\Delta m_{\text{top}}$ CR error out of control?
- Need dedicated experimental studies of CR in top events.
- New CR model/framework by J.R. Christiansen and P. Skands coming up (next).