MPI in PYTHIA

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

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1987: the (almost) original PYTHIA model

- 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 $\Rightarrow \mathrm{d}p_\perp^2/p_\perp^4 \to \mathrm{d}p_\perp^2/(p_\perp^2 + p_{\perp 0}^2)^2$ with $p_{\perp 0} \approx 1.5 - 2$ 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.

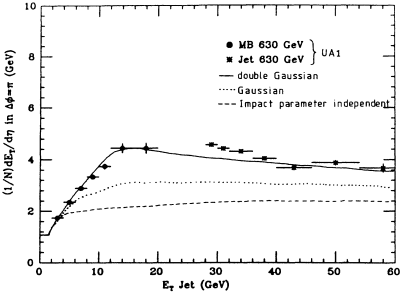
Makes use of existing PYTHIA/JETSET components, such as

- Lund string fragmentation, and
- initial- and final-state parton showers.

TS & M. van Zijl, Phys.Rev. D36 (1987) 2019

MPI signals included

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



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

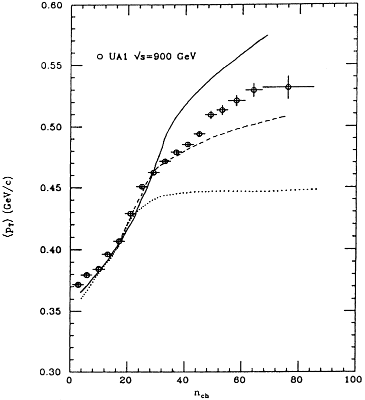


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings 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. $\mathrm{W}^-\mathrm{W}^-$.
- 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.

$\Rightarrow$ Allows interleaved evolution for MPI, ISR and FSR:

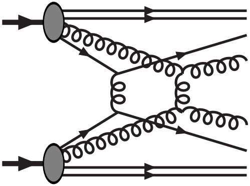
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right)$$
$$\times \exp \left(- \int_{p_\perp}^{p_{\perp\mathrm{max}}}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

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

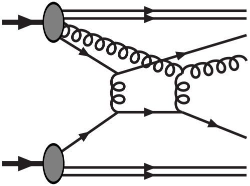
Corresponds to increasing “resolution” of partonic final state:
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

Rescattering

Often assume that MPI =



. . . but should also include



Same order in α_s, $\sim$ same propagators, but

- one PDF weight less $\Rightarrow$ smaller σ
- one jet less $\Rightarrow$ QCD radiation background $2 \to 3$ larger than $2 \to 4$

$\Rightarrow$ will be tough to find direct evidence.

Rescattering grows with number of “previous” scatterings:

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

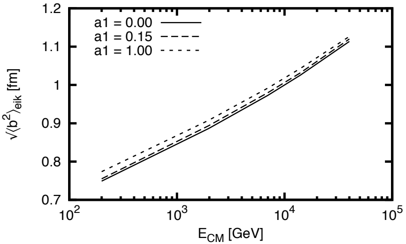
An x-dependent proton size

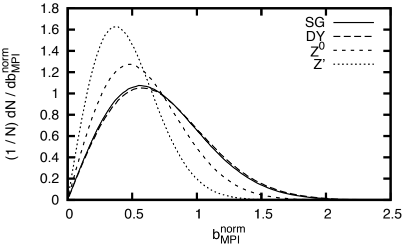
Reasonable to assume that low-x partons are more spread out:

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

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

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



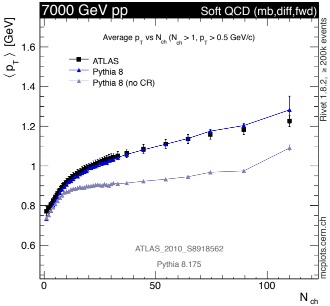


Consequence: collisions at large x will have to happen at small b, and hence further large-to-medium-x MPIs are enhanced.

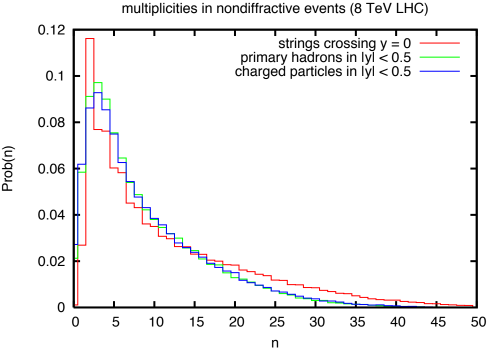
$a_1 > 0$ not favoured by tunes so far!

Colour reconnection

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



Colour reconnection (CR): reduce total string length
$\Rightarrow$ reduce hadronic multiplicity



String width $\sim$ hadronic width

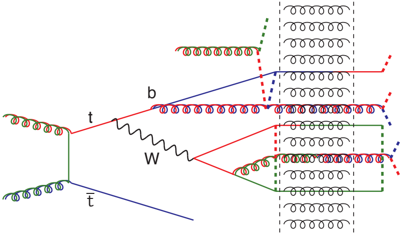
$\Rightarrow$ **Overlap factor $\sim$ 10!**

Larger for hard collisions
(small impact parameter)

A top mass puzzle

$$\left.\begin{array}{l}\Gamma_{\mathrm{t}} \approx 1.5 \text{ GeV} \\ \Gamma_{\mathrm{W}} \approx 2 \text{ GeV} \\ \Gamma_{\mathrm{Z}} \approx 2.5 \text{ GeV}\end{array}\right\} \Rightarrow c\tau \approx 0.1 \text{ fm}:$$

p "pancakes" have passed,
MPI/ISR/FSR for $p_{\perp} \geq 2$ GeV,
inside hadronization colour fields.



Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34±0.76	310 MeV (**40%**)	arXiv:1403.4427
CMS	172.22±0.73	150 MeV (**20%**)	CMS-PAS-TOP-14-001
D0	174.98±0.76	100 MeV (**13%**)	arXiv:1405.1756

(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.

Fit $\to$ scaled: Jet Energy Scaling.

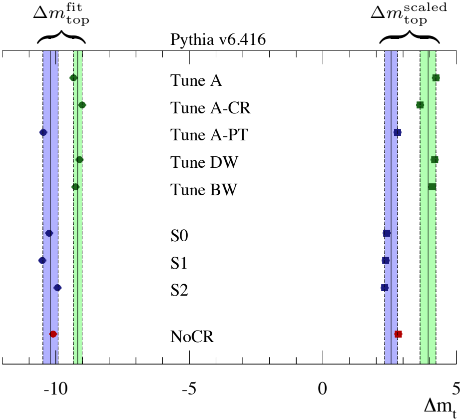
Green bands: old virtuality-ordered showers.

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

In total ± 1.0 GeV,

whereof ± 0.7 GeV perturbative,

and ± 0.5 GeV nonperturbative.



(M.Sandhoff and P.Z Skands, FERMILAB-CONF-05-518-T;)
D. Wicke and P.Z. Skands, EPJ C52 (2007) 133, Nuovo Cim. B123 (2008) S1

PYTHIA 8.1 CR model

Only one CR model:

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

$$\mathcal{P}_{\mathrm{rec}}(p_T) = \frac{(R_{\mathrm{rec}}\ p_{T0})^2}{(R_{\mathrm{rec}}\ p_{T0})^2 + p_T^2},$$

  with any higher-$p_\perp$ MPI. R_{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 λ the least.
- Repeat for lower-$p_\perp$ MPIs that form separate systems.

End result: fewer but bigger systems, with reduced total λ.

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

S. Argyropoulos & TS: arXiv:1407.6653 [hep-ph] $\Rightarrow$ JHEP

Basic idea: produce range of models to study how big Δm_{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

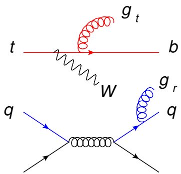
so as to reduce λ

The λ measure of an event is approximated by

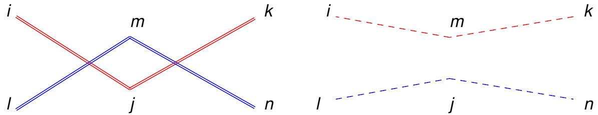
$$\lambda \approx \lambda_{\mathrm{approx}} = \sum_{\mathrm{dipoles}} \ln\left(1 + \frac{m_{ij}^2}{m_0^2}\right)$$

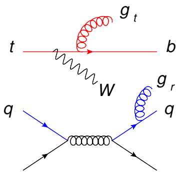
with $m_0 \approx m_{\mathrm{hadronic}} \approx 1$ GeV.

Some ways to perform a reconnection

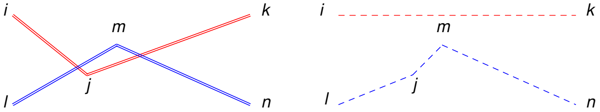


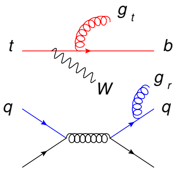
swap:



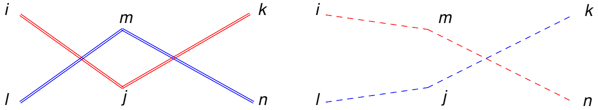


move:

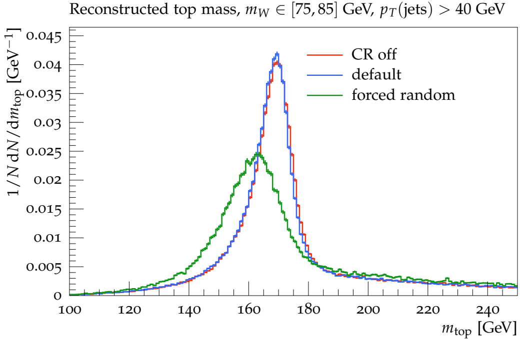




flip:



Effects on top mass before tuning



Δm_{top} relative to no CR:

model	Δm_{top} [GeV]	Δm_{top} rescaled
default (late)	-0.415	$+0.209$
default early	$+0.381$	$+0.285$
forced random	-6.970	-6.508

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

Parton showers already prefer minimal λ.

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

Effects on top mass after tuning

No publicly available measurements of UE in top events.

- Afterburner models tuned to ATLAS jet shapes in $\mathrm{t\bar{t}}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_\perp \rangle (n_{\mathrm{ch}})$.

model	Δm_{top} rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

Δm_{top} relative to no CR

$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.80}$ **GeV**

Excluding most extreme (unrealistic) models down to

$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.50}$ **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, $n_{\mathrm{pert}} \geq 1$, reconnection, strings, ...
- 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 Δm_{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).