QCD modelling in Pythia 8

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Outline

- Parton shower modelling (not strictly decoupled from next)
- MPI modelling (not strictly decoupled from latter)
- Beam remnant and hadronisation (not decoupled from latter)
- Plots

This is not a general overview, but rather tailored to this workshop. Some comparisons (and lots of plots) can be found on `http://mcplots.cern.ch`, in the "Jets$\rightarrow$Jets+Veto" section.

Pythia 8 interleaves FSR, ISR and MPI. The probability for a change of state is

$$\begin{aligned}\frac{dP}{dp_\perp} &= \left[\frac{dP^{mpi}}{dp_\perp} + \frac{dP^{fsr}}{dp_\perp} + \frac{dP^{isr}}{dp_\perp}\right] \\ &\times \exp\left\{-\int_{p_\perp}^{p_\perp^{max}} dp'_\perp \left[\frac{dP^{mpi}}{dp'_\perp} + \frac{dP^{fsr}}{dp'_\perp} + \frac{dP^{isr}}{dp'_\perp}\right]\right\}\end{aligned}$$

This means that

- ISR competes with MPI for beam momentum (and $p_\perp$) $\Rightarrow$ "Hard" MPI early in the evolution, possibly before ISR.
- FSR competes with ISR for $p_\perp$ (and beam momentum). $\Rightarrow$ 2nd order competition also between FSR and MPI.

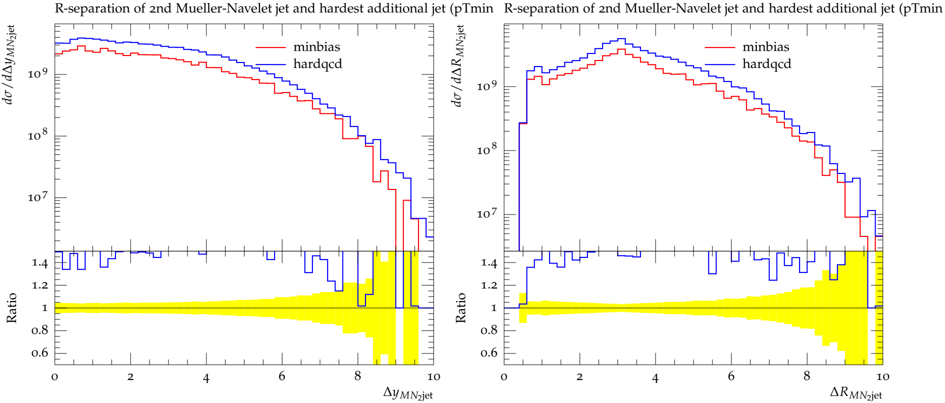
MCEGs typically start by setting up a “hard” $2 \to 2$ scattering and start the evolution from there.

If measurements are very inclusive, then it is important not to bias the structure of the final state not too much by this first choice. More than one alley:

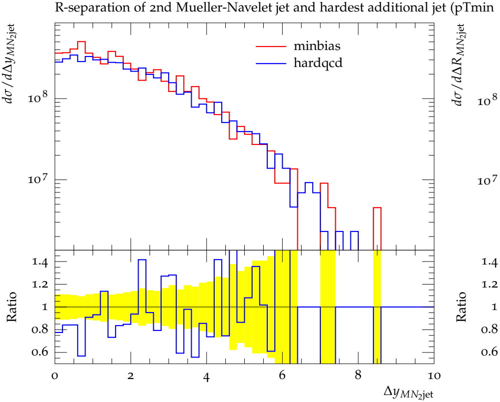
- Hard, perturbative, $2 \to 2$ (QCD) scattering, regularised with $p_{\perp,cut}$.
- Soft, eikonalised $2 \to 2$ (QCD) scattering (see MPI later) + diffractive events.

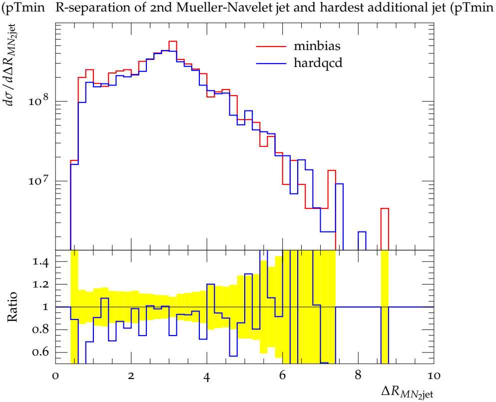
The first choice contains $p_{\perp,cut}$ as parameter, thus defines a “hard” system. The second does not define a hard system, i.e. is “Min-Bias”.

. . . does min-bias vs. hard QCD matter here? Not shapewise.

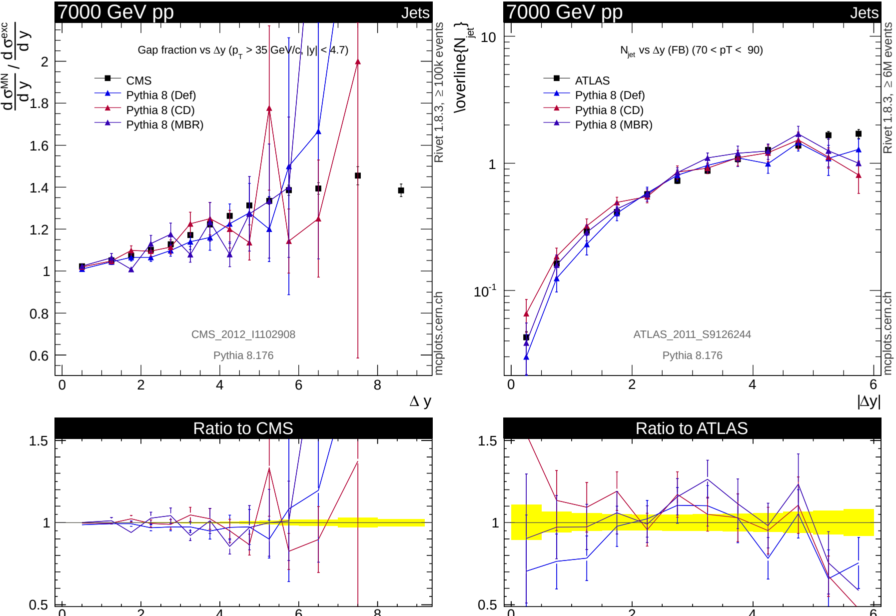


. . . does min-bias vs. hard QCD matter here? No.





...does diffraction matter in data? No.



FSR and ISR are interleaved and $p_\perp$-ordered, where

$$\begin{aligned} p_\perp^{isr} &= (1-z)Q^2 \\ p_\perp^{fsr} &= z(1-z)Q^2 \end{aligned}$$

The splitting probabilities are given by DGLAP splitting kernels (with mass corrections), while the phase space is dipole-like, with

- FSR always has one colour-connected spectator.
- ISR has the whole final state as spectator.

For QCD $2 \rightarrow 2$ scatterings, Pythia 8 will start ISR, FSR and MPI at $\min\{m_{\perp 1}, m_{\perp 2}\}$. Other options are available.

ISR (may) have enforced rapidity ordering by disallowing ISR with

$$p_{\perp,new}^2 > \left(\frac{1 - z_{new}}{z_{new}(1 - z_{old})}\right)^2 \cdot p_{\perp,old}^2$$

to mimic angular vetoes (z_{old} and $p_{\perp,old}$: variables of last *performed* ISR off this dipole).

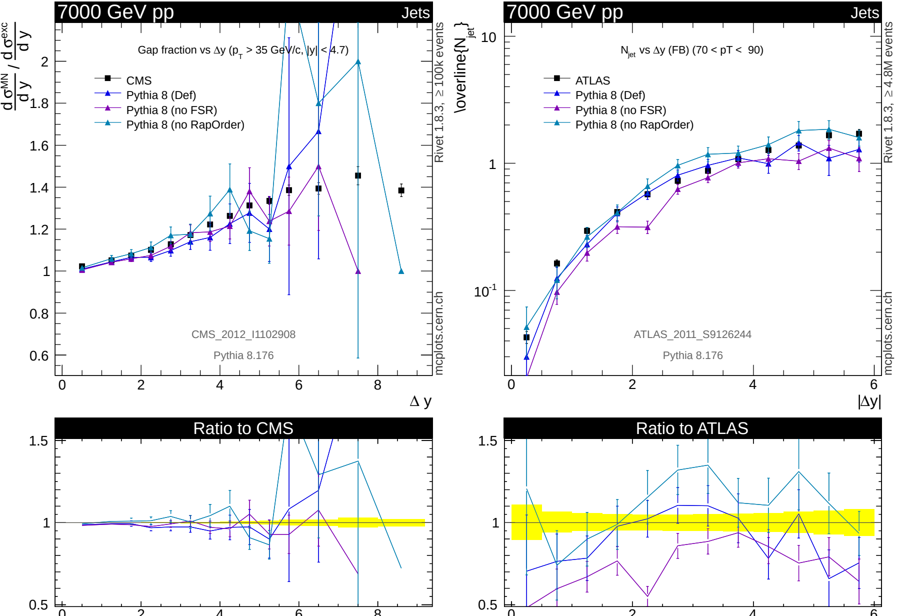
ISR has a hard cut-off at $\mathcal{O}(0.5 \text{ GeV})$.

Before that, it is damped by replacing

$$\frac{\alpha_s(p_\perp^2)}{p_\perp^2} \longrightarrow \frac{\alpha_s(p_{\perp 0}^2 + p_\perp^2)}{p_{\perp 0}^2 + p_\perp^2}$$

in accordance with the competing MPI. $p_{\perp 0}^2$ is of $\mathcal{O}(2 \text{ GeV})$ (very tune-dependent).

. . . does the y-ordering matter in data? No.



MPI are competing with ISR (and FSR). Probability for an MPI:

$$\frac{dP^{mpi}}{dp_\perp} = \frac{1}{\sigma_{nd}}\frac{d\sigma}{dp_\perp}\exp\left\{-\int_{p_\perp}^{p_\perp^{max}} dp'_\perp \frac{1}{\sigma_{nd}}\frac{d\sigma}{dp'_\perp}\right\}$$

These $2 \to 2$ splittings are regularised by

$$\frac{d\hat{\sigma}}{dp_\perp} \approx \frac{\alpha_s(p_\perp^2)}{p_\perp^4} \longrightarrow \frac{\alpha_s(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

where

$$p_{\perp 0}^2 = p_{\perp 0,ref}^2 \left(\frac{E_{cm}}{E_{cm,ref}}\right)^{p_{cm,ref}}$$

MPI initiate their own cascades, which are again in competition with other ISR and FSR.

After an MPI, the x-range for initial state splittings is restricted to

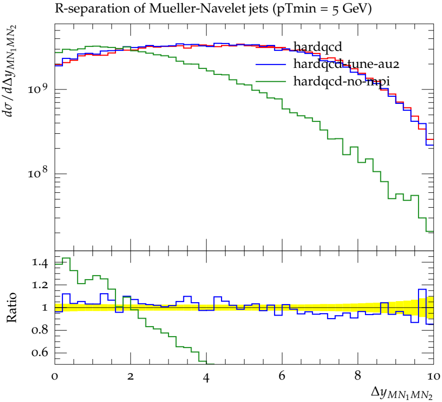
$$0 < x < \sum_{i \in interactions} x_i$$

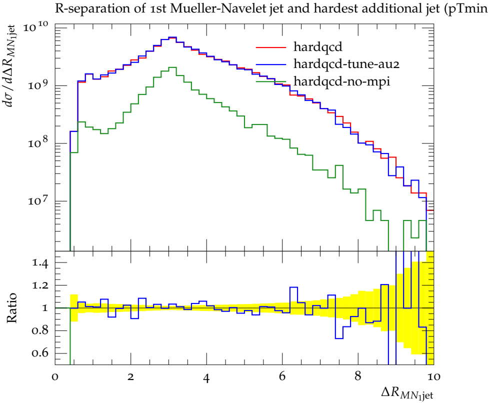
PDFs are rescaled accordingly.

The MPI modelling in Pythia 8 also includes

- Rescattering, e.g. $3 \rightarrow 3$ processes.
- MPI can be QCD, QED (including *t*-channel Ws and Zs), or Onia-prodction.
- Diffraction

. . . does MPI tuning matter in data? MPI do, tuning does not.





Beam remnants

MPI are intimately connected with the remnant treatment. This includes

- Primordial $k_\perp$
  Chosen with two Gaussians in p_x and p_z, with width
  $k_\perp = \frac{k_{\perp soft}\mu_{1/2} + k_{\perp hard}\mu_r}{\mu_{1/2} + \mu_r} \frac{m}{m_{1/2} + m}$
  with μ_r: scale of the hard process, m: mass of the system,
  $\mu_{1/2}$: half-point between soft and hard physics,
  $m_{1/2}$: half-point between high and low mass systems.
  $k_{\perp hard}$ is of $\mathcal{O}(2\text{ GeV})$, $k_{\perp soft}$ is of $\mathcal{O}(0.5\text{ GeV})$.
- Colour reconnection.

Colour reconnection

After MPI, many coloured partonic (sub)systems exist. These are entwined with each other my colour reconnection: The gluons of low-$p_\perp$ systems are merged into higher-$p_\perp$ ones. The probability for merging two systems is

$$P = \frac{p_{\perp R}^2}{p_{\perp R}^2 + p_\perp^2} \, , \qquad p_{\perp R} = R \cdot p_{\perp 0}$$

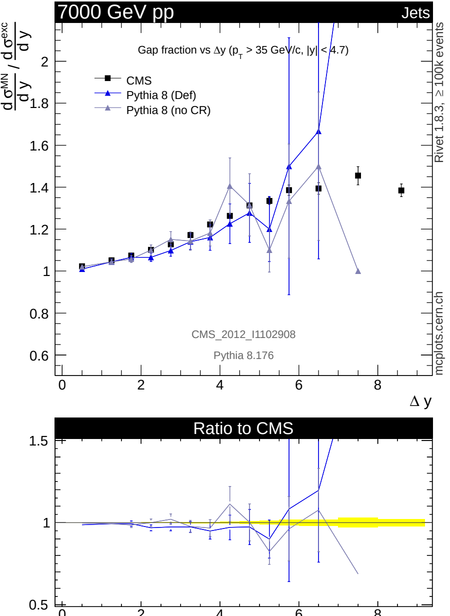
with R of $\mathcal{O}(2)$ (huge spread among tunes).

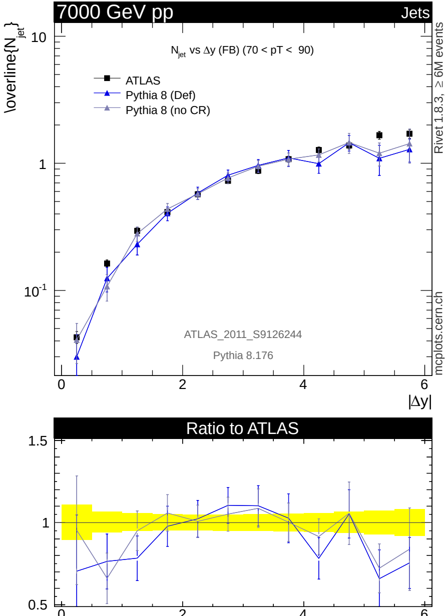
If two systems are merged, the gluons of the softer system are inserted into the colour dipoles ij of the harder system for which $\frac{(p_g p_i)(p_g p_j)}{(p_i p_j)}$ is minimal. The same is done for $\mathrm{q\bar{q}}$ pairs from gluon splitting, if the q, $\mathrm{\bar{q}}$ are not connected to the beam.

(Radiation off) resonance decay products are not reconnected.

A large amount of CR is necessary to describe data.

. . . does colour reconnection matter in data? No.





Summary

- Pythia 8 includes many different aspects of QCD.
- There are some small differences between hard- and soft QCD descriptions.
- The enforced rapidity ordering in ISR does not seem to have a large impact.
- MPI should be important for low $p_{\perp}$ jets. Different tunes do not seem inconsistent.
- Colour reconnection does not seem to play a major role.

Thanks for your time.