Multiple Interactions in PYTHIA 8

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Overview

1. Multiple Interactions (MI) in PYTHIA 8
2. Rescattering
3. Enhanced Screening
4. PYTHIA 8
5. Conclusions

MI in PYTHIA 8

Introduction

- "A Multiple Interaction Model for the Event Structure in Hadron Collisions," T. Sjostrand and M. van Zijl, Phys. Rev. D **36** (1987) 2019
  - Perturbative QCD and $p_\perp$ ordering
  - Variable impact parameter with a double Gaussian matter distribution
  - Simple PDF rescaling to conserve energy/momentum
  - Colour reconnection
  - No parton showers for subsequent interactions
- "Multiple interactions and the structure of beam remnants," T. Sjostrand and P. Z. Skands, JHEP **0403** (2004) 053
  - Improved PDF rescaling (flavour modification)
  - Radiation from all interactions
- "Transverse-momentum-ordered showers and interleaved multiple interactions," T. Sjostrand and P. Z. Skands, Eur. Phys. J. C **39** (2005) 129
  - Common interleaved $p_\perp$ scale for ISR and MI

- New features in PYTHIA 8
  - Richer mix of underlying-event processes (γ, J/ψ, DY, ...)
  - Possibility for two selected hard interactions in same event
  - Possibility to use one PDF set for hard process and another for rest
- ISR + MI: PDF competition (PYTHIA 6.3)
- FSR is now also interleaved (PYTHIA 8.1)

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

- $p_\perp$ as evolution scale in decreasing resolution/increasing formation time

	time	evolution	probability
FSR	forwards	$p_\perp \searrow 0$	normal & local
ISR	backwards	$p_\perp \searrow 0$	conditional
MI	simultaneous	$p_\perp \searrow 0$	conditional

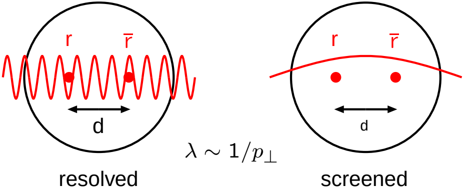
MI in PYTHIA 8

$p_\perp$ Ordering

- Model for non-diffractive events, $\sigma_{nd} \sim (2/3)\sigma_{tot}$
- Ordered in decreasing $p_\perp$ using "Sudakov" trick

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp i}} = \frac{1}{\sigma_{nd}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right)$$

- QCD $2 \to 2$ cross-section is divergent, but not valid at small $p_\perp$ as q, g not asymptotic states



- Regularise cross-section, introducing $p_{\perp 0}$ as a free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_S^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

- At this stage, all parton-parton interactions are independent

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!} \exp(-\langle n \rangle)$$

- Require at least one interaction for a physical event
  - Poissionian is now narrower
- Now add impact parameter, b, with empirically chosen double Gaussian matter distribution

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right)$$

- Time-integrated overlap of hadrons during collision

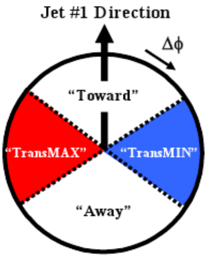
$$\mathcal{O}(b) = \int \mathrm{d}t \int \mathrm{d}^3x \; \rho(x, y, z) \; \rho(x + b, y, z + t)$$

- Average activity at $b \propto \mathcal{O}(b)$
  - Central collisions usually more active
  - $\mathcal{P}_n$ broader than Poissonian

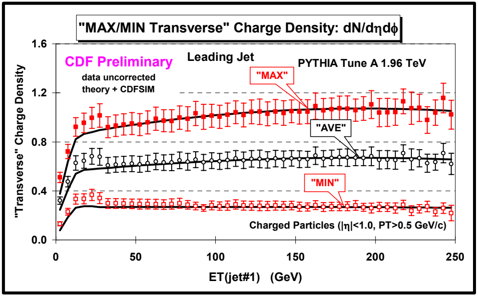
MI in PYTHIA 8

Impact Parameter

- Jet pedestal effect
  - Events with a hard scale have more underlying activity
  - Central collisions have a higher probability of a hard interaction which in turn leads to more underlying activity
  - Effect saturates at $p_{\perp\,hard} \sim 10$ GeV
- Studied in detail by R. Field with CDF data



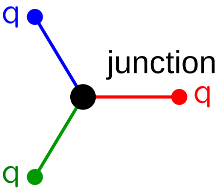
PYTHIA Tune A

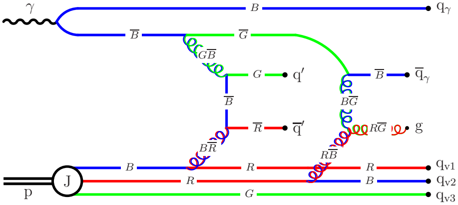


- Original model
  - Rescaled PDFs to ensure momentum conservation

$$x'_i = \frac{x_i}{1 - \sum_{j=1}^{i-1} x_j}$$

  - Dynamic suppression of high-multiplicity tail of $\mathcal{P}_n$
  - Technical limitations with fragmentation meant no ISR for secondary interactions and only a limited set of $\mathrm{q}\bar{\mathrm{q}}$ and gg scatterings allowed
- Junction fragmentation allows arbitrarily complicated beam remnants





MI in PYTHIA 8

PDF Rescaling

- ISR, FSR and MI can lead to changes in the PDF of an incoming hadron
- Squeeze original distribution x range

$$0 < x < 1 \quad \rightarrow \quad 0 < x < \left(1 - \sum x_i\right)$$

- Valence quark initiators
  - Rescale valence PDF
- Sea quarks initiators
  - Sea quark initiator ($\mathrm{q_s}$) leaves behind an anti-sea companion ($\mathrm{q_c}$)
  - $\mathrm{q_c}$ distribution from $\mathrm{g} \rightarrow \mathrm{q_s} + \mathrm{q_c}$ perturbative ansatz
  - Subsequent perturbative evolution of $\mathrm{q_c}$ distribution neglected
- Normalisation
  - Allow normalisation of sea + gluon distributions to fluctuate for total momentum conservation

- Beam Remnants
  - After evolution in $p_\perp$, beam remnant consists of remaining valence content and sea-companion quarks
  - Must carry the remaining fraction of longitudinal momentum
  - Valence content "harder" so carries more momentum
- Primordial $k_\perp$
  - Partons expected to have non-zero $k_\perp$ values due to Fermi motion ($\frac{\hbar}{r_p} \sim 0.3\ \mathrm{GeV}$)
  - Values of $\sim 2\ \mathrm{GeV}$ needed to match data (e.g. $p_\perp$ distributions of Z^0 at CDF)
  - Interpolate based on hardness Q

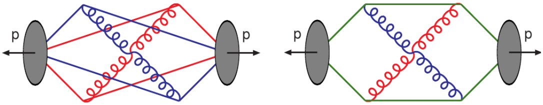
$$\sigma(Q) = \max\left(\sigma_{min}, \sigma_\infty \frac{1}{1 + Q_{\frac{1}{2}}/Q}\right)$$

  - Incoming partons taken from a hadron are given a Gaussian $p_\perp$ kick
  - Recoil shared between all initiator and remnant partons from incoming hadrons
  - $p_\perp$ is then given to all daughter partons by a Lorentz boost

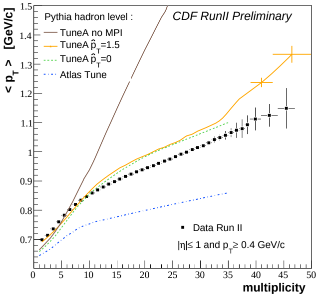
MI in PYTHIA 8

Colour Reconnection

- Rearrangement of final-state colour connections, such that overall string length is reduced



- Large amount of reconnection needed to match data
- Start with $N_C \to \infty$ limit, but real-world has $N_C = 3$
- Changing the colour structure of an event can lead to (dis)agreement with data



Mean $p_\perp$ as a function of multiplicity, CDF, Run II
Measurement of Inelastic $P\bar{P}$ Inclusive Cross Sections at $\sqrt{s}$=1.96 TeV, The CDF Collaboration, Preliminary

- Original model
  - Tune A: PARP(85) = 0.90, PARP(86) = 0.95
  - PARP(85): Probability of additional interactions giving two gluons with 'nearest neighbour' colour connections
  - PARP(86): As PARP(85), but also with possibility of closed gluon loops
  - Remaining fraction of quark-antiquark pairs
- System with a hard scale, $p_\perp$, is merged to with one with a harder scale with probability

$$\mathcal{P} = \frac{{p_\perp}_{Rec}^2}{({p_\perp}_{Rec}^2 + p_\perp^2)} \qquad {p_\perp}_{Rec} = RR * {p_\perp}_0^{MI}$$

- Low $p_\perp$ systems have larger spatial extent, so easier to reconnect

- Consider a $4 \to 4$ and a $3 \to 3$ process

- Interaction cross-section

$$\frac{\mathrm{d}\sigma_{\mathrm{int}}}{\mathrm{d}p_\perp^2} = \sum \int \mathrm{d}x_1 \int \mathrm{d}x_2 \int f_1(x_1, Q^2)\, f_2(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

- Paver and Treleani (1984)

$$\frac{\mathrm{d}\sigma_{\mathrm{int}}}{\mathrm{d}p_\perp^2} \sim N_1 N_2\, \hat{\sigma}$$

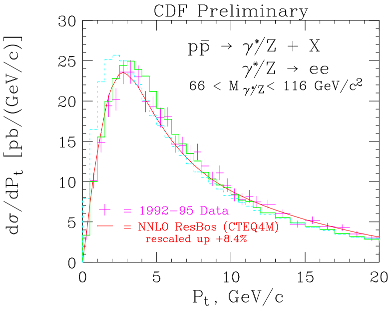
$$\sigma_{4\to4} \sim (N_1 N_2\, \hat{\sigma})(N_1' N_2'\, \hat{\sigma}) \qquad \sigma_{3\to3} \sim (N_1 N_2\, \hat{\sigma})(N_1'\, \hat{\sigma})$$

$$\frac{\sigma_{3\to3}}{\sigma_{4\to4}} \sim \frac{1}{N_2'} \to \mathrm{small}$$

Rescattering

Why? Some examples

- Because it is there
- Will play a role in the collective effects of MI
- Multi-jet topologies
  - Introduces a new source of 3-jet production
  - Visible in low $p_\perp$ jets where not dominated by radiation?
- Rescattering will generate more $p_\perp$ in perturbative region
  - May be able to reduce amount of primordial $k_\perp$ needed
  - May be able to reduce amount of colour reconnection needed



Low $p_\perp$ Z^0 distribution from CDF Run 1. PYTHIA predictions - blue dashed primordial $k_\perp = 0.44$ GeV, green $k_\perp = 2.15$ GeV

Higgs production: A comparison of parton showers and resummation, C. Balazs, J. Huston and I. Puljak, Phys. Rev. D **63** (2001) 014021

- Typical case of small angle scatterings between partons from 2 incoming hadrons, such that they are still associated with their original hadrons

$$f(x, Q^2)\,\mathrm{d}x \rightarrow f(x, Q^2)_{rescaled}\,\mathrm{d}x + \sum_n \delta(x - x_n) = f_u(x, Q^2) + f_\delta(x, Q^2)$$

where the subscript u/δ is the unscattered/scattered component

$$\int_0^1 x\, f_{rescaled}(x, Q^2) dx + \sum_n x_n = 1$$

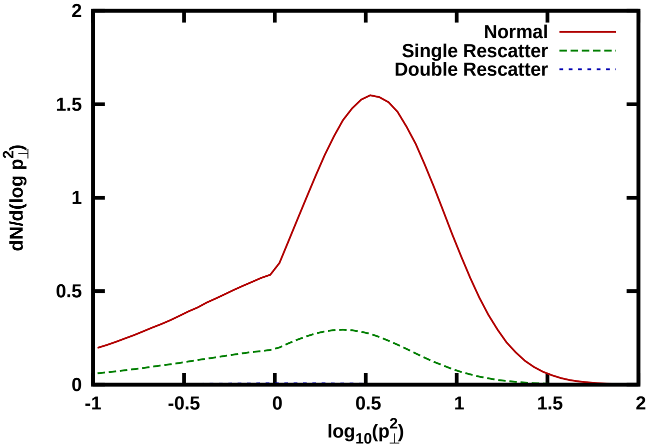
- In general it is not possible to uniquely identify a scattered parton with one hadron. Use approximate prescription, e.g. rapidity based
- Possibility of u-δ, δ-u and δ-δ interactions in addition to original u-u.

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} \rightarrow \frac{\mathrm{d}\mathcal{P}_{\mathrm{uu}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{u}\delta}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}_{\delta\mathrm{u}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}_{\delta\delta}}{\mathrm{d}p_\perp}$$

Rescattering

Rescattering in PYTHIA 8

	Min Bias	$\hat{p}_{\perp min} = 20$ GeV	LHC Min Bias
Scatterings	2.81	5.11	5.21
Single rescatterings	0.37	1.20	0.93
Double rescatterings	0.01	0.03	0.02



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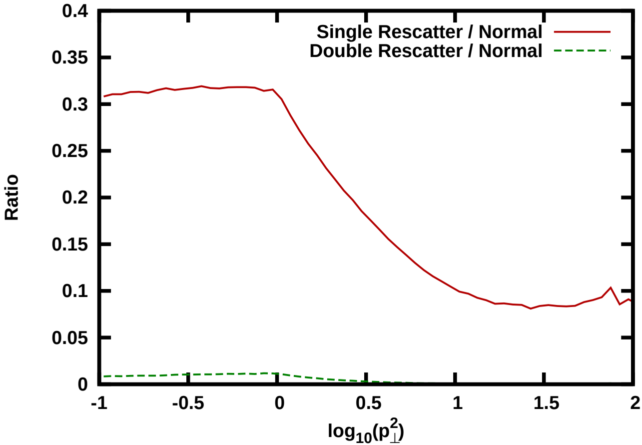
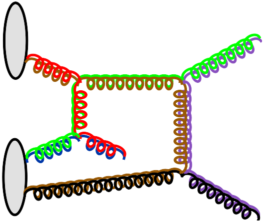


Rescattering
Status

- Preliminary framework in place to get hadronic final states
- Non-trivial kinematics with rescattering, FSR and primordial $k_\perp$
  - A radiating parton will shuffle momentum with a recoiler parton
    - FSR: usually nearest colour neighbour
  - Primordial $k_\perp$ given by boosting scattering sub-systems
  - Rescattering: colour dipoles can span between scattering sub-systems
  - Momentum shuffled between systems is given a different primordial $k_\perp$ boost

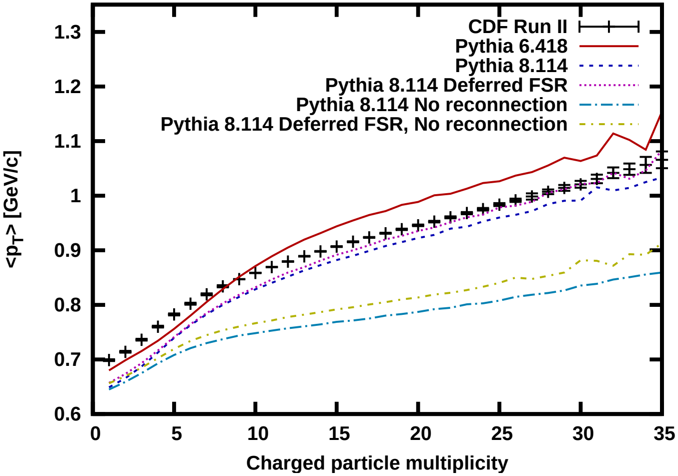


- Temporary solution of deferring FSR until after primordial $k_\perp$ is added

Rescattering

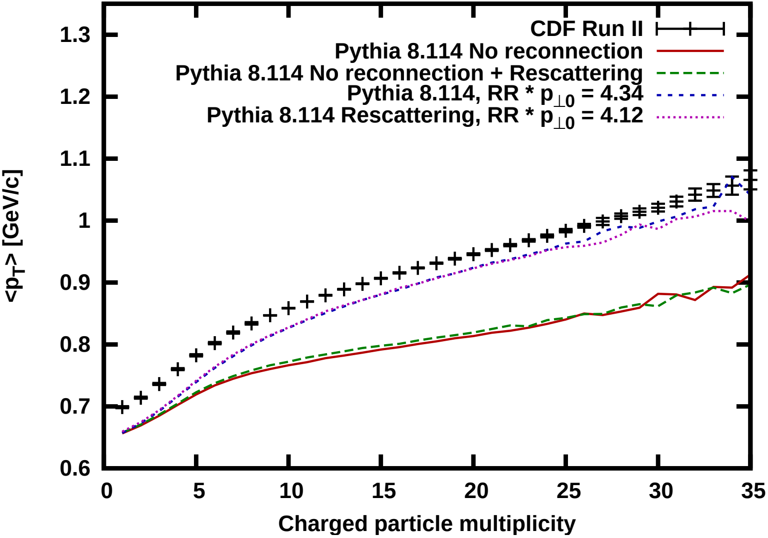
Status - Deferred FSR

- $|\eta| \leq 1$ and $p_\perp \geq 0.4\ GeV/c$
- MI $p_{\perp 0}$ parameter tuned to maintain $\langle N_{ch} \rangle$ in central region



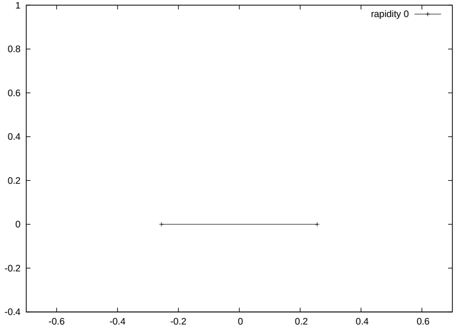
Rescattering

Results - Mean $p_\perp$ vs. Charged Multiplicity



Enhanced Screening
Introduction

- Idea of Gösta Gustafson from work on modelling initial states with an extended Mueller dipole formalism
  - "Elastic and quasi-elastic *pp* and $\gamma^\star p$ scattering in the Dipole Model," C. Flensburg, G. Gustafson and L. Lonnblad, arXiv:0807.0325 [hep-ph].



- Even at a fixed impact parameter, initial state will contain more/less fluctuations on an event-by-event basis
  - More activity $\rightarrow$ more screening

Enhanced Screening

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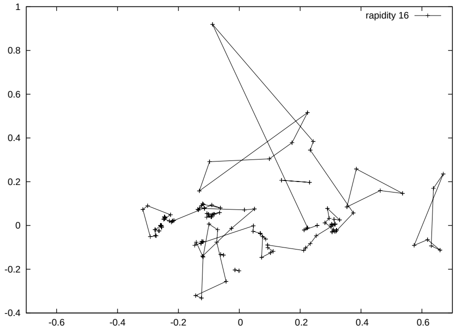

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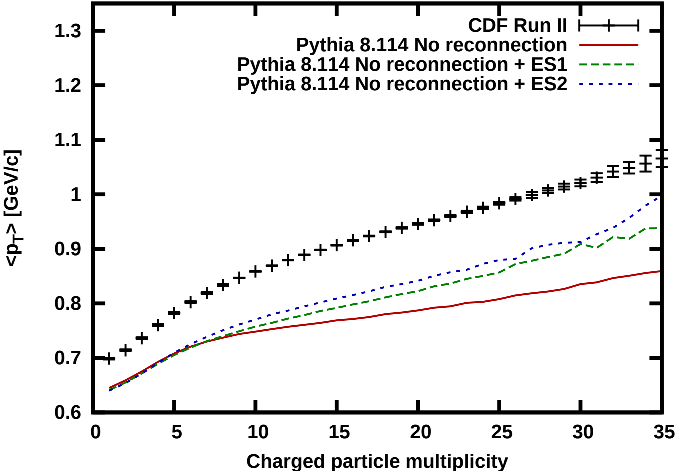
Enhanced Screening

Enhanced Screening in PYTHIA

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \rightarrow \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(n\,p_{\perp 0}^2 + p_\perp^2)^2}$$

ES1: n = no. of MI
ES2: n = no. of MI + ISR



Enhanced Screening

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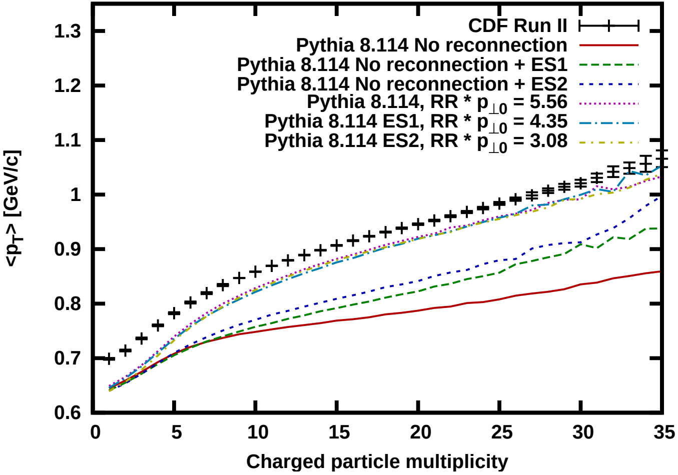

PYTHIA 8

- Focus on LHC and Tevatron applications
- Some features of PYTHIA 6.4 are no longer present
  - Independent fragmentation
  - Mass-ordered showers
- Hard processes
  - SM: Almost all $2 \rightarrow 1$ and $2 \rightarrow 2$, some $2 \rightarrow 3$
  - External input via Les Houches Accord and Les Houches Event Files (MadGraph, CompHEP, AlpGen etc..)
- Parton showers
  - Transverse momentum ordered ISR/FSR with interleaved MI
  - Dipole-style approach to recoils
  - Matching to matrix elements for first (hardest) emission in many processes
- Lund string model hadronisation
  - Link to external decay packages (Tauola, EvtGen etc..)
  - Optional Bose-Einstein effects

PYTHIA 8

- PYTHIA 8.1 has been released
  - http://www.thep.lu.se/∼torbjorn/Pythia.html
- Download latest release tarball
  - ./configure; make
  - Some important files:

README	More detailed installation instructions (HepMC, LHAPDF, PYTHIA 6, etc..)
htmldoc/pythia8100.pdf	A Brief Introduction to PYTHIA 8.1
htmldoc/Welcome.html	Full manual
phpdoc/	Interactive manual when installed on a PHP webserver
examples/	Over 30 example programs (make mainNN; ./mainNN.exe)

- Online interactive manual
- Worksheet with step-by-step instructions and exercises on writing and running a main program

Conclusions

- PYTHIA 8 MI
  - Well developed framework in place
  - Full tuning to data still needed
- Rescattering
  - Preliminary framework in place to handle rescattering with hadronic final states
  - Fully interleaved ISR/FSR with primordial $k_\perp$ still to come
  - Small increase in mean $p_\perp$ vs multiplicity
  - Other observables still to study e.g. 3-jet production rate
- Enhanced Screening
  - Rise in mean $p_\perp$ vs multiplicity
  - Change in low $p_\perp$ gluon spectrum?
- Work in progress