The Underlying-Event Model in PYTHIA (6&8)
**Min-Bias, Zero Bias, etc.**

= Experimental trigger conditions

**“Theory for Min-Bias”?**

Really = Model for ALL INELASTIC

*But … how can we do that?*

… in minimum-bias, we typically do not have a hard scale, wherefore all observables depend significantly on IR physics …

A) Start from perturbative model (dijets) and extend to IR

B) Start from soft model (Pomerons) and extend to UV
A) Start from perturbative model (dijets) and extend to IR

\[ pQCD \]

\[ 2 \rightarrow 2 \]

= Sum of

- \( qq' \rightarrow qq' \)
- \( qq' \rightarrow q'q' \)
- \( gg \rightarrow gg \)
- \( gg \rightarrow gg' \)
- \( gg \rightarrow qq \)

≈ Rutherford  
(t-channel gluon)


\[ \sigma_{pp} \]

\[ \sigma \approx \text{Rutherford} \]

(t-channel gluon)

Becomes larger than total pp cross section?

At \( p_\perp \approx 5 \text{ GeV} \)

Lesson from bremsstrahlung in pQCD: divergences → fixed-order unreliable, but pQCD still ok if resummed (unitarity)

→ Resum dijets? Yes → MPI!

Dijet Cross Section vs \( p_T \) cutoff

Parton Shower Cutoff (for comparison)
A) Start from perturbative model (dijets) and extend to IR

\[ pQCD \]

\[ 2 \rightarrow 2 \]

= Sum of

- \( qq' \rightarrow qq' \)
- \( qq \rightarrow q'q' \)
- \( qg \rightarrow qg \)
- \( gg \rightarrow gg \)
- \( gg \rightarrow q\bar{q} \)

\[ \approx \text{Rutherford (t-channel gluon)} \]

Regularise cross section with \( p_{\perp 0} \) as free parameter

\[
\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_4^2} \rightarrow \frac{\alpha_s^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2}
\]

with energy dependence

\[ p_{\perp 0}(E_{CM}) = p_{\perp 0}^{ref} \times \left( \frac{E_{CM}}{E_{CM}^{ref}} \right)^{\epsilon} \]


Normalize to total cross section:

\[ f(x_{\perp}) = \frac{1}{\sigma_{nd}(s)} \frac{d\sigma}{dx_{\perp}} \quad x_{\perp} = 2p_{\perp}/E_{cm} \]

+ Resum/Unitarize \( \rightarrow \) Probability

\[ f(x_{\perp 1}) \exp \left\{ - \int_{x_{\perp 1}}^1 f(x'_{\perp}) \, dx'_{\perp} \right\} \]

\( \rightarrow \) This is now our basic (UV & IR) \( 2 \rightarrow 2 \) cross section
**Naive Factorization: \( \sigma_{\text{eff}} \)**

**Interactions independent (naive factorization) \( \rightarrow \) Poisson**

**Often used for simplicity**

(i.e., assuming corrections are small / suppressed)

---

*CDF Collaboration, Phys. Rev. Lett. 79 (1997) 584*

**Measurement of Double Parton Scattering in \( \bar{p}p \) Collisions at \( \sqrt{s} = 1.8 \) Tev**

The double parton scattering (DP) process [1], in which two parton-parton hard scatterings take place within one \( \bar{p}p \) collision, can provide information on both the distribution of partons within the proton and on possible parton-parton correlations, topics difficult to address within the framework of perturbative QCD. The cross section for DP comprised of scatterings \( A \) and \( B \) is written

\[
\sigma_{\text{DP}} \equiv \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}},
\]

(1)

with a process-independent parameter \( \sigma_{\text{eff}} \) [2–5]. This expression assumes that the number of parton-parton interactions per collision is distributed according to Poisson statistics [6], and that the two scatterings are distinguishable [7]. Previous DP measurements have come

\( \sigma_{\text{eff}} \approx \) “first moment” of true MPI distributions

But only exists within very crude/naive approximation

---

**No MC model is that crude!**

Extracting \( \sigma_{\text{eff}} \) is fine, but need model-independent physical observables to test MC models
Beyond naive factorization: Correlations & Multi-Parton PDFs

How are the initiators and remnant partons correlated?

- in impact parameter?
- in flavour?
- in $x$ (longitudinal momentum)?
- in $k_T$ (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?
**Interleaved Evolution**

At each step: Competition for \( x \) among ISR and MPI

- in \( p_T \)-ordered model and (optionally) \( Q \)-ordered one: showers off the MPI
- Modifications to subsequent PDFs caused by momentum and (in \( p_T \)-ordered model) flavor conservation from preceding interactions

**Impact-parameter dependence**

Pedestal Effect …

**Color Correlations**

How does the system Hadronize?

- Color connections vs color re-connections … ?
- Re-interactions after hadronization?
The Pedestal Effect

$P_T = 160 \text{ (HP)}$

$P_T = 6000 \text{ (HP)}$

Big jets sit on big pedestals.

Big jets sit on big pedestals.
The Pedestal Effect
and Multiple Parton-Parton Interactions

\[ \text{MINIMUM BIAS} \]

\[ \text{PERIPHERAL} \quad \langle \text{MPI} \rangle = 1 \]

\[ \text{CENTRAL} \quad \langle \text{MPI} \rangle = 3 \]

\[ <\text{MPI}> = 6 / 4 = 1.5 \]

\[ \text{QCD ANALOGUE:} \]

Parton Showers: resum divergent perturbative emission cross sections

MPI: resum divergent perturbative interaction cross sections
The Pedestal Effect
and Multiple Parton-Parton Interactions

Statistically biases the selection towards more central events with more MPI

The assumed shape of the proton affects the rise and \( \langle \text{UE} \rangle / \langle \text{MB} \rangle \)

\[ \langle \text{MPI} \rangle = \frac{4}{2} = 2 \]
Statistically biases the selection towards more central events with more MPI.

The assumed shape of the proton affects the rise and $<\text{UE}>/ <\text{MB}>$. 

Can we tell the difference?
Dissecting the Pedestal

Statistically biases the selection towards more central events with more MPI.

The assumed shape of the proton affects the rise and $\langle \text{UE} \rangle / \langle \text{MB} \rangle$.

$<\text{MPI}> = 4 / 2 = 2$
Analyzing the Pedestal?

Initial rise & \(<\text{UE}>/<\text{MB}>\) → “average” proton shape

Focus on specific x range \((\text{pick jet } p_T \text{ and } y, \text{ for given collider energy})\)

Scan over transverse activity → b dependence for that x ?

And/or look for abundance of minijets in transverse region

S.D. lower than mean, but more than square root of mean.

Suggests tracks not independently produced (c.e.)
Default in PYTHIA (and all other MC*)

Factorization of longitudinal and transverse degrees of freedom

\[ f(x, b) = f(x) \times g(b) \]

OK for inclusive measurements, but:

**Physics:** Shape = delta function at 0 for \( x \to 1 \)

Can also be seen in lattice studies at high \( x \)

**Gribov theory:** high \( s \) ↔ low \( x \) ⇒ Growth of total cross section ↔ size grows \( \propto \ln(1/x) \)

BFKL “intuition”: “random walk” in \( x \) from few high-\( x \) partons at small \( b \) diffuse to larger \( b \) at smaller \( x \) (More formal: Balitsky/JIMWLK and Color Glass Condensates)

A Model for Phenomenological Studies

Basic assumption: Mass distribution = Gaussian. Make width \( x \)-dependent

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

Constrain by requiring \( a_1 \) responsible for growth of cross section
**Initial study + tuning in arXiv:1101.5953**

At least as good MB/UE fits as old model *(based on “Tune 4C”)*

Details will be different!

**E.g.,**

“Homogenous” model: can have (rare) high-x scattering at large $b$:

⇒ *There should be a tail of dijets/DY/… with essentially “no” UE*

E.g., ATLAS “RMS” distributions, and/or take UE/MB density ratios

“X-Dependent” model: high-x scatterings only at small $b$:

⇒ *Enhanced pedestal effect? (increased selection bias)*

(needs to be interpreted with care, due to effects of (re)tuning …)

Model available from next PYTHIA 8 version, ready for playing with …
Other News in PYTHIA 8

Can choose 2\textsuperscript{nd} MPI scattering

- TwoJets (with TwoBJets as subsample)
- PhotonAndJet, TwoPhotons
- Charmonium, Bottomonium (colour octet framework)
- SingleGmZ, SingleW, GmZAndJet, WAndJet
- TopPair, SingleTop

Rescattering

Often assume that MPI =

...but should also include

An explicit model available in PYTHIA 8

- Same order in $\alpha_s$, $\sim$ same propagators, but
- one PDF weight less $\Rightarrow$ smaller $\sigma$

Corke, Sjöstrand, JHEP 01(2010)035
Color Space

The Underlying-Event Model in PYTHIA (6&8)
Colour Connections

Each MPI exchanges color between the beams

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze
Colour Connections

Each MPI exchanges color between the beams

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Questions

Different models make different ansätze
Extremely difficult problem

Here I just remark on currently available models/options and what I think is good/bad about them

1. Most naive

Each MPI ~ independent → start from picture of each system as separate singlets?

E.g., PYTHIA 6 with PARP(85)=0.0 & JIMMY/Herwig++

This is physically inconsistent with the exchanged objects being gluons

Instead, it corresponds to the exchange of singlets, i.e., Pomerons (uncut ones)

→ In this picture, all the MPI are diffractive!

This is just wrong.
2. Valence quarks plus t-channel gluons?

Arrange original beam baryon as (qq)-(q) system

Assume MPI all initiated by gluons → connect them as (qq)-g-g-g-(q)

In which order? Some options:

A) Random (Perugia 2010 & 2011)

B) According to rapidity of hard scattering systems (Perugia 0)

C) By hand, according to rapidity of each outgoing gluon (Tune A, DW, Q20, … + HIJING?)

(pT-ordered PYTHIA also includes quark exchanges, but details not important)

OK, may be more physical …

But both A and B drastically fail to predict, e.g., the observed rise of the \( <p_T> \) (Nch) distribution (and C “cheats” by looking at the final-state gluons)

This must still be wrong (though less obvious)
Color Reconnections?

$N_c \to \infty$

Rapidity
Color Reconnections?

Do the systems really hadronize independently?

Rapidity
Color Reconnections?

How “fat” are color lines?

Rapidity
**In reality:**

The color wavefunction is \( N_C = 3 \) when it collapses

*One parton “far away” from others will only see the sum of their colours \( \rightarrow \) coherence*

On top of this, the systems may merge/fuse/interact with genuine dynamics (e.g., string area law)

And they may continue to do so even after hadronization

*Elastically: hydrodynamics? Collective flow?*

*Inelastically: re-interactions?*

This may not be wrong. But it sure sounds difficult!
Old Model (PYTHIA 6, Tune A and friends)

Outgoing gluons from MPI systems have no independent color flow.

Forced to just form “kinks” on already existing string systems.

Inserted in the places where they increase the “string length” (the “Lambda” measure) the least.

Looks like it does a good job on $<p_T>(N_{ch})$ at least.

Brute force. No dynamical picture.
**pT-Ordered Model** (in PYTHIA 6.4): Colour Annealing

Consider each color-anticolor pair

*If* (reconnect), **sever the color connection**

*Different variants use different reconnect probabilities*

Fundamental string-string reconnect probability PARP(78)

Enhanced by either $n_{\text{MPI}}$ (Seattle type) or local string density (Paquis type)

For all severed connections, construct new color topology:

*Consider the parton which is currently “furthest away” (in $\lambda$) from all others*

*“Sees” the sum of the others $\rightarrow$ connect it to the closest severed parton to it.*

*Strike it off the list and consider the next-furthest parton, etc.*
The Effect of CR

If driven by minimization of Area Law or similar:

Reduces multiplicity

Increases $p_T$

May or may not:

Create rapidity gaps $\rightarrow$ overcount diffraction?

---

Charged Particle Multiplicities in pp Dependence on color correlations

- $\xi_R = 1.0$
- $\xi_R = 0.33$ (Perugia 0)
- $\xi_R = 0.0$
- $\xi_R = 0.0$ (Perugia 0)
- no MPI

![Graph showing charged particle multiplicities in pp with different color correlation strengths and impact parameter profiles.](chart)
Diffraction

The Underlying-Event Model in PYTHIA (6&8)
**Diffraction**

**Diffraction Cross Section Formulae:**

\[
\begin{align*}
\frac{d\sigma_{sd(AX)}(s)}{dt\,dM_1^2} &= \frac{g_3^{MP}}{16\pi} \beta_{AIP}^2 \beta_{BIP} \frac{1}{M_1^2} \exp(B_{sd(AX)}t) F_{sd}, \\
\frac{d\sigma_{dd}(s)}{dt\,dM_1^2\,dM_2^2} &= \frac{g_3^{MP}}{16\pi} \beta_{AIP}^2 \beta_{BIP} \frac{1}{M_1^2} \frac{1}{M_2^2} \exp(B_{dd}t) F_{dd}.
\end{align*}
\]

**Partonic Substructure in Pomeron:**

Follows the Ingelman-Schlein approach of Pompyt

\[\begin{array}{c}
\text{F} \\
p_f \\
\text{x} \\
p_x \quad \text{LRG} \\
\text{X} \\
p_t
\end{array}\]

- \( M_X \leq 10\text{GeV} \): original longitudinal string description used
- \( M_X > 10\text{GeV} \): new perturbative description used (incl full MPI+showers for \( \text{Pp} \) system)

Choice between 5 Pomeron PDFs. Free parameter \( \sigma_{\text{Pp}} \) needed to fix \( \langle n_{\text{interactions}} \rangle = \sigma_{\text{jet}}/\sigma_{\text{Pp}} \).

Framework needs testing and tuning, e.g. of \( \sigma_{\text{Pp}} \).

Navin, arXiv:1005.3894
**Framework needs testing and tuning**

E.g., interplay between non-diffractive and diffractive components

+ LEP tuning used directly for diffractive modeling

*Hadronization preceded by shower at LEP, but not in diffraction → dedicated diffraction tuning of fragmentation pars?*

Study this hump

+ Room for new models, e.g., KMR (SHERPA)

Others?
Energy Scaling

The Underlying-Event Model in PYTHIA (6&8)
Energy Scaling

Multiple Parton Interactions (MPI)

Regularise cross section with $p_{\perp 0}$ as free parameter

IR Regularization

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

with energy dependence

Energy Scaling

$$p_{\perp 0}(E_{\text{CM}}) = p_{\perp 0}^{\text{ref}} \times \left( \frac{E_{\text{CM}}}{E_{\text{ref}}^{\text{CM}}} \right)^{\epsilon}$$


From Tevatron to LHC

Tevatron tunes appear to be “low” on LHC data

Problem for “global” tunes.

Poor man’s short-term solution: dedicated LHC tunes

E.g., Rick Field

See the figure for Energy Scaling and From Tevatron to LHC.
Evolution of PARP(83) with energy dependence

Evolution of PARP(82) with energy dependence

Evolution of PARP(78) with energy dependence
Crucial Task for run at 2.8 TeV
Make systematic studies to resolve possible Tevatron/LHC tension

Measure regions that interpolate between Tevatron and LHC
E.g., start from same phase-space region as CDF
$|\eta| < 1.0 \quad p_T > 0.4$ GeV
Compromise between Tevatron and LHC?

“Perugia 2010” : Larger UE at Tevatron → better at LHC

PYTHIA 6
Recommended: Perugia 2010
(or dedicated LHC tunes AMBT1, Z1)

For more on tuning PYTHIA 6, see PS, arXiv:1005.3457

PYTHIA 6 @ 1.8 TeV

PYTHIA 6 @ 7 TeV

(next iteration: fusion between Perugia 2010 and AMBT1, Z1?)
Underlying Event

**PYTHIA 6**

Recommended:

Perugia 2010 (→ 2011)
(or dedicated LHC tunes AMBT1, Z1)

For more on tuning PYTHIA 6, see PS, arXiv:1005.3457

**PYTHIA 8**

Recommended:

Tune 4C

(probably default from next version)

(Also has damped diffraction following ATLAS-CONF-2010-048)

For more on tuning PYTHIA 8, see Corke, Sjostrand, arXiv:1011.1759

(Plots from mcplots.cern.ch)
Summary

**PYTHIA6 is winding down**
- Supported but not developed
- Still main option for current run (sigh)
- *But not after long shutdown 2013!*

**PYTHIA8 is the natural successor**
- Already several improvements over PYTHIA6 on soft physics
  - (including modern range of PDFs (CTEQ6, LO*, etc) in standalone version)
  - Though still a few things not yet carried over (such as \(e^p\), some SUSY, etc)
- If you want new features (e.g., \(x\)-dependent proton size, rescattering, \(\psi'\), MadGraph-5 and VINCIA interfaces, …) then be prepared to use PYTHIA8

Provide Feedback, both what works and what does not
- Do your own tunes to data and tell outcome

**There is no way back!**

---

**Recommended for PYTHIA 6:**
- Global: “Perugia 2010” (MSTP(5)=327)
- Perugia 2011 (MSTP(5)=350)
- LHC MB: “AMBT1” (MSTP(5)=340)
- LHC UE “Z1” (MSTP(5)=341)

---

**Recommended for PYTHIA 8:**
- “Tune 4C” (Tune:pp = 5)
Tuning of PYTHIA 8

Tuning to e+e- closely related to $p_{\perp}$-ordered PYTHIA 6.4. A few iterations already. First tuning by Professor (Hoeth) $\rightarrow$ FSR ok?

- C Parameter
- Out-of-plane $p_T$

(Plots from mcplots.cern.ch)
Interesting discrepancies in strange sector

+ problems with Λ/K and s spectra also at LEP?

Grows worse (?) for multi-strange baryons

Flood of LHC data now coming in!

Interesting to do systematic LHC vs LEP studies
# PYTHIA 8 Tune Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tune 2C</th>
<th>Tune 2M</th>
<th>Tune 4C</th>
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<td>N/A</td>
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</tr>
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</table>

## Strangeness Tunable Parameters

### Flavor Sector
(These do not affect pT spectra, apart from via feed-down)

<table>
<thead>
<tr>
<th>Main Quantity</th>
<th>PYTHIA 6</th>
<th>PYTHIA 8</th>
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<tr>
<td>s/u</td>
<td>K/π</td>
<td>PARJ(2)</td>
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<tr>
<td>Vector/Scalar (strange)</td>
<td>K*/K</td>
<td>PARJ(12)</td>
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</tbody>
</table>

Note: both programs have options for c and b, for special baryon production (leading and “popcorn”) and for higher excited mesons. PYTHIA 8 more flexible than PYTHIA 6. Big uncertainties, see documentation.

For pT spectra, main parameters are shower folded with: **longitudinal and transverse fragmentation function** (Lund a and b parameters and \(p_T\) broadening (PARJ(41,42,21)), with possibility for larger a for Baryons in PYTHIA 8, see “Fragmentation” in online docs).
UE Contribution to Jet Shapes

anti-$k_t$ jets $R = 0.6$

$|y| < 2.8$

Data $\int L \, dt = 0.7 \text{nb}^{-1} - 3 \text{pb}^{-1}$

- PYTHIA-Perugia2010
- PYTHIA-Perugia2010 without UE
- PYTHIA-DW

ATLAS
LESS than Perugia-SOFT
(at least for protons, in central region)

But MORE than Perugia-0
(at least for Lambdas, in forward region)
From a brief look at the ’94 HIJING paper (so apologies for misunderstandings and things not up to date), the HIJING pp model appears to be:

• **Basic MPI formalism ~ Herwig++ (JIMMY+IVAN) model, with**
  • Dijet cross section integrated above $p_0$ (with no unitarization?)
    • Poisson distribution of number of interactions
    • $p_0$ plays same main role as PYTHIA’s $p_T_0$, but is much more closely related to the Herwig++
cutoff parameter (which in turn is very highly correlated with the assumed proton shape, so
hard to interpret independently of that)
    • The interactions appear to undergo ISR and FSR showers (using PYTHIA or something
else??), with possibility to add medium modifications to evolution
  • “Soft” interactions below $p_0$
    • These are somehow also showered (below $p_0$), using ARIADNE it seems?
    • Soft + Hard constructed to add up to total inelastic (non-diffractive??)

• **The multiple scatterings only involve gluons (?)**
  • The outgoing gluons are color-ordered in rapidity (unlike Herwig++)
    • (Equivalent to **highly** correlated production mechanism ~ PYTHIA and/or CR models)

• **Some unclear points:**
  • Transverse mass distribution: Fourier transform of a dipole?
    • Related to EM form factor of Herwig++? To PYTHIA forms? Evolves with E? Does it get
Smaller/Bigger?