Modeling Hadronic Interactions in PYTHIA

Peter Skands (CERN Theory Dept) (From October: Monash University, Melbourne)
Many interesting dynamical phenomena under active investigation (e.g., higher-order quantum corrections, hadronization, electroweak physics, diffraction, hadron structure, ...)

Strong indications from both theory and experiment, that the mathematical structure of the Standard Model is incomplete

New physics, where art thou? (So far, physics at LHC looks ~ SM)

We are now going into an era of high statistics and high precision
Event Structure at Colliders

Dominated by QCD
More than just a perturbative expansion in $\alpha_s$
Emergent phenomena:

**Jets** (the QCD fractal) $\leftrightarrow$ amplitude structures $\leftrightarrow$
fundamental quantum field theory. Precision jet (structure) studies, jet vetoes.

**Strings** (strong gluon fields) $\leftrightarrow$ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition. Colour correlations.

**Hadrons** $\leftrightarrow$ Spectroscopy (incl excited and exotic states),
lattice QCD, (rare) decays, mixing. Identified particles: rates, spectra (FFs), correlations. Hadron beams $\rightarrow$ PDFs, MPI, diffraction, ...

See eg TASI lectures, e-Print: arXiv:1207.2389
General-Purpose Event Generators

Improve lowest-order perturbation theory, by including the ‘most significant’ corrections → complete events (can evaluate any observable you want)

Calculate Everything ≈ solve QCD → requires compromise!

The Workhorses

+ MORE SPECIALIZED: ALPGEN, MADGRAPH, HELAC, ARIADNE, VINCIA, WHIZARD, (a)MC@NLO, POWHEG, HEJ, PHOJET, EPOS, QGSJET, SIBYLL, DPMJET, LDCMC, DIPSY, HIJING, CASCADE, BLACKHAT, GOSAM, NJETS, ...

Reality is more complicated
A Monte Carlo computer program is presented, that simulates the fragmentation of a fast parton into a jet of mesons. It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

Note:
Field-Feynman was an early fragmentation model now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.
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Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.
PYTHIA anno 2014
(now called PYTHIA 8)

~ 100,000 lines of C++
What a modern MC generator has inside:

- Hard Processes (internal, interfaced, or via Les Houches events)
- BSM (internal or via interfaces)
- PDFs (internal or via interfaces)
- Showers (internal or inherited)
- Multiple parton interactions
- Beam Remnants
- String Fragmentation
- Decays (internal or via interfaces)
- Examples and Tutorial
- Online HTML / PHP Manual
- Utilities and interfaces to external programs

The Pythia program is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state. It contains a library of hard processes and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and interfaces to external programs. [...]

LU TP 07-28 (CPC 178 (2008) 852)
October, 2007

A Brief Introduction to PYTHIA 8.1

T. Sjöstrand, S. Mrenna, P. Skands
**Factorization** → Split the problem into many (nested) pieces

+ **Quantum mechanics** → Probabilities → Random Numbers (MC)

\[ \mathcal{P}_{\text{event}} = \mathcal{P}_{\text{hard}} \otimes \mathcal{P}_{\text{dec}} \otimes \mathcal{P}_{\text{ISR}} \otimes \mathcal{P}_{\text{FSR}} \otimes \mathcal{P}_{\text{MPI}} \otimes \mathcal{P}_{\text{Had}} \otimes \ldots \]

**Hard Process & Decays:**
- Use (N)LO matrix elements
- Sets “hard” resolution scale for process: \( Q_{\text{MAX}} \)

**Initial- & Final-State Radiation (ISR & FSR):**
- Altarelli-Parisi equations → differential evolution, \( dP/dQ^2 \), as function of resolution scale; run from \( Q_{\text{MAX}} \) to \( \sim 1 \) GeV

**MPI (Multi-Parton Interactions)**
- Additional (soft) parton-parton interactions: LO matrix elements
- Additional (soft) “Underlying-Event” activity

**Hadronization**
- Non-perturbative model of color-singlet parton systems → hadrons
Bremsstrahlung
a.k.a. Initial- and Final-state radiation
a.k.a. Parton Showers

Jet Event at 2.36 TeV Collision Energy
2009-12-14, 04:30 CET, Run 142308, Event 482137

cf. equivalent-photon approximation
Weiszäcker, Williams ~ 1934
Bremsstrahlung
a.k.a. Initial- and Final-state radiation
a.k.a. Parton Showers

Accelerated Charges

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Associated field (fluctuations) continues
Bremsstrahlung
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Accelerated Charges

Associated field (fluctuations) continues
Bremsstrahlung
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The harder they get kicked, the harder the fluctuations that continue to become strahlung
Most bremsstrahlung is driven by divergent propagators → simple structure

Amplitudes factorize in singular limits (→ universal “conformal” or “fractal” structure)

**Jets \approx Fractals**

**Most bremsstrahlung** is driven by divergent propagators → simple structure

**Amplitudes factorize in singular limits** (→ universal "conformal" or "fractal" structure)

Partons ab → "collinear":

\[ |\mathcal{M}_{F+1}(\ldots, a, b, \ldots)|^2 \xrightarrow{\alpha} g_s^2 C \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots, a + b, \ldots)|^2 \]

P(z) = DGLAP splitting kernels, with z = energy fraction = \(E_a/(E_a+E_b)\)

Jets ≈ Fractals

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Gluon $j$ → “soft”:

Coherence → Parton $j$ really emitted by $(i,k)$ “colour antenna”

\[ |\mathcal{M}_{F+1}(\ldots, i, j, k, \ldots)|^2 \overset{jg}{\longrightarrow} 0 \quad g_s^2 C \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots, i, k, \ldots)|^2 \]

+ scaling violation: $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

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Gluon $j$ → “soft”:

$$|\mathcal{M}_{F+1}(\ldots, i, j, k, \ldots)|^2 \xrightarrow{\text{soft}} g_s^2 C \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots, i, k, \ldots)|^2$$

+ scaling violation: $g_s^2 \to 4\pi\alpha_s(Q^2)$


Can apply this many times → nested factorizations
Factorization of Production and Decay:

= “Narrow-width approximation”
Valid up to corrections $\Gamma/m \rightarrow$ breaks down for large $\Gamma$
More subtle when colour/charge flows *through* the diagram

Factorization of Long and Short Distances

Scale of fluctuations inside a hadron

$\sim \Lambda_{QCD} \sim 200$ MeV

Scale of hard process $\gg \Lambda_{QCD}$

$\rightarrow$ proton looks “frozen”

Instantaneous snapshot of long-wavelength structure, independent of nature of hard process
For any basic process $d\sigma_X = \checkmark$ (calculated process by process)
For any basic process $d\sigma_X = \sqrt{\text{calculated process by process}}$

$$d\sigma_{X+1} \sim N C 2g^2 \frac{d{s}_{i1}}{s_{i1}} \frac{d{s}_{1j}}{s_{1j}} d\sigma_X$$
For any basic process $d\sigma_X = \checkmark$ (calculated process by process)

$$d\sigma_{X+1} \sim NC^2g_s^2 \frac{d_{i1}}{s_{i1}} \frac{d_{1j}}{s_{1j}} d\sigma_X \checkmark$$
For any basic process $d\sigma_X = \checkmark$ (calculated process by process)

$$d\sigma_{X+1} \sim NC2g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X$$

$$d\sigma_{X+2} \sim NC2g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1}$$
For any basic process $d\sigma_X = \sqrt{ }$ (calculated process by process)

$$d\sigma_{X+1} \sim N_C 2g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X \sqrt{ }$$

$$d\sigma_{X+2} \sim N_C 2g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1} \sqrt{ }$$
Practical Examples

For any basic process $d\sigma_X = \checkmark$ (calculated process by process)

\[ d\sigma_{X+1} \sim NC2g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X \checkmark \]

\[ d\sigma_{X+2} \sim NC2g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1} \checkmark \]

\[ d\sigma_{X+3} \sim NC2g_s^2 \frac{ds_{i3}}{s_{i3}} \frac{ds_{3j}}{s_{3j}} d\sigma_{X+2} \ldots \]
Practical Examples

For any basic process $d\sigma_X = \checkmark$ (calculated process by process)

\[
d\sigma_{X+1} \sim N_C g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X \checkmark
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\]

\[
d\sigma_{X+3} \sim N_C g_s^2 \frac{ds_{i3}}{s_{i3}} \frac{ds_{3j}}{s_{3j}} d\sigma_{X+2} \ldots
\]

**Singularities:** mandated by gauge theory

**Non-singular terms:** process-dependent

\[
\frac{|\mathcal{M}(Z^0 \rightarrow q_i g_j \bar{q}_k)|^2}{|\mathcal{M}(Z^0 \rightarrow q_i \bar{q}_K)|^2} = g_s^2 2C_F
\]

\[
\frac{2s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left( \frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} \right)
\]

**SOFT**

\[
\frac{|\mathcal{M}(H^0 \rightarrow q_i g_j \bar{q}_k)|^2}{|\mathcal{M}(H^0 \rightarrow q_i \bar{q}_K)|^2} = g_s^2 2C_F
\]

\[
\frac{2s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left( \frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} + 2 \right)
\]

**COLLINEAR**

**COLLINEAR+F**
Start from an arbitrary lowest-order process (green = QFT amplitude squared)

Parton showers generate the bremsstrahlung terms of the rest of the perturbative series (approximate infinite-order resummation)

Universality (scaling)
Jet-within-a-jet-within-a-jet-...

Unitarity

Cancellation of real & virtual singularities

Exponentiation fluctuations within fluctuations
Start from an arbitrary lowest-order process (green = QFT amplitude squared)

**Parton showers** generate the bremsstrahlung terms of the rest of the perturbative series (approximate infinite-order resummation)

But ≠ full QCD! Only LL Approximation
Process-Dependence
(Matrix-Element Corrections)
This talk is not about matrix-element matching.
That said, PYTHIA 8 contains a large number of implementations of matching schemes, based on “UserHooks” and Les Houches event files [ask S. Prestel]
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**Tree Level**
- CKKW-L
- MLM (jet matching, a la AlpGen or MadGraph)
- UMEPS (~unitarized CKKW-L)

**Loop Level**
- POWHEG
- NL3 (~ CKKW-L @ NLO)
- UNLOPS (~ multileg POWHEG)
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**TREE LEVEL**
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Les Houches Accord
- SUSY Les Houches Accord
- HepMC Interface
- Semi-Internal Processes
- Semi-Internal Resonances
- MadGraph 5 Processes
- Alpgen Event Interface
- Matching and Merging
  - POWHEG Merging
  - CKKW-L Merging
  - Jet Matching
  - UMEPS Merging
  - NLO Merging
- User Hooks
- Hadron-Level Standalone
- External Decays

**UserHooks gives further possibilities to control event generation / implement new schemes**
Can also implement own processes, decays, or shower model(s) (e.g., VINCIA plug-in)
Slicing: the “MLM” & “CKKW-L” prescriptions

Figure 24: Slicing, with up to two additional emissions beyond the basic process. The showers off $F$ and $F+1$ are set to zero above a specific “matching scale”. (The number of coefficients shown was reduced a bit in these plots to make them fit in one row.)

Region by definition includes no hard jets), yielding the pure shower answer in that region, Matched (below matching scale) = shower $z$ | { Approximate + correction $z$ | { (Exact Approximate)

This type of strategy is illustrated in figure 24. As emphasized above, since this strategy is discontinuous across phase space, a main point here is to ensure that the behavior across the matching scale be as smooth as possible. CKKW showed [114] that it is possible to remove any dependence on the matching scale through NLL precision by careful choices of all ingredients in the matching; technical details of the implementation (affecting the $O(\alpha_s)$ terms in eq. (67)) are important, and the dependence on the unphysical matching scale may be larger than NLL unless the implementation matches the theoretical algorithm precisely [115, 116, 120]. Furthermore, since the Sudakov factors are generally computed using showers (MLM, L-CKKW) or a shower-like formalism (CKKW), while the real corrections are computed using matrix elements, care must be taken not to reintroduce differences that could break the detailed real-virtual balance that ensures unitarity among the singular parts, see e.g., [119].

It is advisable not to choose the matching scale too low. This is again essentially due to the approximate scale invariance of QCD imploring us to write the matching scale as a ratio, rather than as an absolute number. If one uses a very low matching scale, the higher-multiplicity matrix elements will already be quite singular, leading to very large LO cross sections before matching. After matching, these large cross sections are tamed by the Sudakov factors produced by the matching scheme, and hence the final cross sections may still look reasonable. But the higher-multiplicity matrix elements in general contain subleading singularity structures, beyond those accounted for by the shower, and hence the delicate line of detailed balance that ensures unitarity has most assuredly been overstepped. We therefore recommend not to take the matching scale lower than about an order of magnitude below the characteristic scale of the hard process.

One should also be aware that all strategies of this type are quite computing intensive. This is basically due to the fact that a separate phase-space generator is required for each of the $n$-parton correction terms, with each such sample a priori consisting of weighted events. (Mangano, 2002) (CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

(Alwall et al., EPJC53(2008)473)
Examples

**Slicing:** the “MLM” & “CKKW-L” prescriptions

F @ LO × LL-Soft (excl)  
\[ \sigma_0^{(2)} \ldots \]  
F+1 @ LO × LL-Soft (excl)  
\[ \sigma_0^{(1)} \sigma_1^{(1)} \sigma_2^{(0)} \ldots \]  
F+2 @ LO × LL (incl)  
\[ \sigma_0^{(2)} \sigma_1^{(1)} \sigma_2^{(0)} \ldots \]  
F @ LO_2 × LL (MLM & (L)-CKKW)  
\[ \sigma_0^{(2)} \ldots \]

(CKKW & Lönnblad, 2001)  
(Mangano, 2002)  
(+many more recent; see Alwall et al., EPJC53(2008)473)

**Corrected Showers:**  
the “GKS” prescription

Reinterpret higher-order matrix elements as radiation functions  
Unitarity + Speed  
+ systematic uncertainties

**NEW**

LO: Giele, Kosower, Skands, PRD84(2011)054003  

**Virtues:**  
No “matching scale”  
No negative-weight events  
Can be very fast

**VINCIA**
Examples

Slicing: the “MLM” & “CKKW-L” prescriptions

(CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

Corrected Showers: the “GKS” prescription

Reinterpret higher-order matrix elements as radiation functions

Unitarity + Speed

+ systematic uncertainties

**NEW**

Start from pure shower
Correct each coefficient

**Virtues:**
No “matching scale”
No negative-weight events
Can be very fast

**LO:** Giele, Kosower, Skands, PRD84(2011)054003

**NLO:** Hartgring, Laenen, Skands, arXiv:1303.4974
**Examples**

**Slicing:** the “MLM” & “CKKW-L” prescriptions

- **F @ LO×LL-Soft (excl)**
- **F+1 @ LO×LL-Soft (excl)**
- **F+2 @ LO×LL (incl)**
- **F @ LO₂×LL (MLM & (L)-CKKW)**

(CKKW & Lönnblad, 2001)  
(Mangano, 2002)  
(+many more recent; see Alwall et al., EPJC53(2008)473)

**Corrected Showers:** the “GKS” prescription

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**Examples**

<table>
<thead>
<tr>
<th>F @ LO×LL-Soft (excl)</th>
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(CKKW & Lönnblad, 2001)

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**VIRTUES:**
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**ALPGEN HERWIG MADGRAPH SHERPA...**

**VINCI A**
Slicing: the “MLM” & “CKKW-L” prescriptions

F @ LO×LL-Soft (excl) + F+1 @ LO×LL-Soft (excl) + F+2 @ LO×LL (incl) = F @ LO²×LL (MLM & (L)-CKKW)

(CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

Corrected Showers: the “GKS” prescription

Reinterpret higher-order matrix elements as radiation functions

Unitarity + Speed

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Examples
The text is a detailed explanation of various processes in high-energy physics, focusing on the implementation of matching scales and the computation of cross sections.

**Slicing:**
- The "MLM" & "CKKW-L" prescriptions

**Corrected Showers:**
- The "GKS" prescription
  - Reinterpret higher-order matrix elements as radiation functions
  - Unitarity + Speed
  - + systematic uncertainties

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**Examples**

**F @ LO x LL-Soft (excl)**

**F+1 @ LO x LL-Soft (excl)**

**F+2 @ LO x LL (incl)**

**F @ LO_2 x LL (MLM & (L)-CKKW)**

**NEW**

**LO:** Giele, Kosower, Skands, PRD84(2011)054003

**NLO:** Hartgring, Laenen, Skands, arXiv:1303.4974
**Comparison**: A Tale of Two Paradigms

**Standard Paradigm**: consider a single physical system; a single physical process

- Explicit solutions (to given perturbative order)
  - Standard-Model: typically NLO or NNLO
  - Beyond-SM: typically LO or NLO

- Limited generality

**Shower Paradigm**: consider all possible physical processes (within perturbative QFT)

- Approximate solutions
  - Process-dependence = subleading correction (→ matching)

- Maximum generality
  - Emphasis is on universalities; physics
  - Common property of all processes is, for instance, limits in which they factorize!
Hadronization
Hadronization

→ how do coloured partons (quarks and gluons) turn into colourless hadrons ...

P. Skands
Fast: It starts at a high factorization scale
\[ Q = Q_F = Q_{\text{hard}} \]

It showers (perturbative bremsstrahlung)

It ends up at a low effective factorization scale
\[ Q \sim m_\rho \sim 1 \text{ GeV} \]

... the fragmentation of a fast parton into a jet ...
How about I just call it a hadron?
How about I just call it a hadron?

→ “Local Parton-Hadron Duality”
Early models: “Independent Fragmentation”

Local Parton Hadron Duality (LPHD) can give useful results for inclusive quantities in collinear fragmentation.

Motivates a simple model:

But ...

The point of confinement is that partons are coloured.

Hadronization = the process of colour neutralization

→ Unphysical to think about independent fragmentation of a single parton into hadrons
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)
→ More physics needed
A physical hadronization model

Should involve at least 2 partons, with opposite color charges (e.g., R and anti-R)

Strong “confining” field emerges between the two charges when their separation > ~ 1fm
Linear Confinement $\rightarrow$ Strings

Lattice QCD

Linear potential (without string breaks)

$V(r)$

quenched QCD

full QCD

Coulomb part

Illustrations by T. Sjöstrand
**Linear Confinement → Strings**

**Lattice QCD**
Linear potential (without string breaks)

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \iff V(r) \approx \kappa r \]

~ Force required to lift a 16-ton truck

Illustrations by T. Sjöstrand
Linear Confinement → Strings

**Lattice QCD**
Linear potential (without string breaks)

\[ V(r) \propto \text{const.} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]

\( F(r) \approx \text{const.} = \kappa \approx 1 \text{ GeV/fm} \)

~ Force required to lift a 16-ton truck

\[ \sim \text{Gaussian } p_T \text{ spectrum (string tension = tuning parameter)} \]

\[ \sim \text{Heavier quarks suppressed. Prob}(q=d,u,s,c) \approx 1 : 1 : 0.2 : 10^{-11} \]

**Lund Model**
+ string breaks via Quantum Tunneling

\[ \mathcal{P} \propto \exp \left( \frac{-m_q^2 - p_{\perp}^2}{\kappa / \pi} \right) \]

(simplified colour representation)

Illustrations by T. Sjöstrand
Iterative String Breaks

**Iterate** String → Hadron + String’

**Causality** + Left-Right Symmetry:

\[
f(z) \propto \frac{1}{z} (1 - z)^a \exp \left( -\frac{b(m_h^2 + p_{\perp h}^2)}{z} \right)
\]

Lund Symmetric String Fragmentation Function

... the fragmentation of a fast parton into a jet ...

\[ Q_{uv} \]

\[ \text{shower} \]

\[ Q_{IR} \]

\[ u(\vec{p}_{\perp 0}, p_+) \]

\[ \pi^+(\vec{p}_{\perp 0} - \vec{p}_{\perp 1}, z_1 p_+) \]

\[ d\bar{d} \]

\[ K^0(\vec{p}_{\perp 1} - \vec{p}_{\perp 2}, z_2(1 - z_1)p_+) \]

\[ s\bar{s} \]

The Lund
Tuning means different things to different people
Tuning means different things to different people

10% agreement is great for (N)LO + LL

MB/UE/Soft: larger uncertainties since driven by non-factorizable and non-perturbative physics

Complicated dynamics: “If a model is simple, it is wrong” (T. Sjöstrand)
Recent PYTHIA Models/Tunes

**Note**: I focus on default / author tunes here
(Important complementary efforts undertaken by LHC experiments)
Recent PYTHIA Models/Tunes

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### PYTHIA 8.1

**Current Default = 4C (from 2010)**

*Tunes 2C & 4C: e-Print: arXiv:1011.1759*

- LEP tuning undocumented (from 2009)
- LHC tuning only used very early data based on CTEQ6L1

**Aims for the Monash 2013 Tune**


- Revise (and document) constraints from $e^+e^-$ measurements
  - In particular in light of possible interplays with LHC measurements

- Test drive the new NNPDF 2.3 LO PDF set (with $\alpha_s(m_Z) = 0.13$) for pp & ppbar
  - Update min-bias and UE tuning + energy scaling → 2013
  - Follow “Perugia” tunes for PYTHIA 6: use same $\alpha_s$ for ISR and FSR
  - Use the PDF value of $\alpha_s$ for both hard processes and MPI

Set M13 Tune:
in PYTHIA 8

- Tune:ee = 7
- Tune:pp = 14
Recent PYTHIA Models/Tunes

**Note:** I focus on default / author tunes here
(Important complementary efforts undertaken by LHC experiments)

### PYTHIA 8.1

Current Default = 4C (from 2010)

LHC tuning only used very early data based on CTEQ6L1

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- Test drive the new NNPDF 2.3 LO PDF set (with $\alpha_s(m_Z) = 0.13$) for pp & ppbar
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### PYTHIA 6.4 (warning: no longer actively developed)

Default: still rather old $Q^2$-ordered tune $\sim$ Tevatron Tune A

Most recent: Perugia 2012 set of $p_T$-ordered tunes (370 - 382) + Innsbruck (IBK) Tunes (G. Rudolph)
Monash 2013 Tune Highlights


10% more strangeness

Average $\bar{K}^+$ Multiplicity vs ECM

- HEPDATA
- PY8 (Monash) $\chi^2/N_{\text{bins}} = 2.0 \pm 0.0$
- PY8 (Default) $\chi^2/N_{\text{bins}} = 1.8 \pm 0.0$
- PY8 (Fischer)

Data from HEPDATA
Pythia 8.183

Short Strings

Long Strings

E_{cm}$ (not to scale)

$<\chi_2>$

1.5

1.0

0.5

0.0

0.6

1.0

1.4

Pythia 8.183

14 22 35 44 91 131 135 149 161 163 189 250 350 500 1.0k 3.0k

Better agreement with ee identified-strange measurements across all energies, and with Kaons at LHC

Softer D and B spectra near $z = 1$

$x(D^\pm) (x > 0.1)$

- ALEPH
- PY8 (Monash) $\chi^2/N_{\text{bins}} = 1.4 \pm 0.1$
- PY8 (Default) $\chi^2/N_{\text{bins}} = 2.8 \pm 0.2$
- PY8 (Fischer) $\chi^2/N_{\text{bins}} = 3.2 \pm 0.2$

Data from Data from Europhys.Lett. 98 (2012) 31002
Pythia 8.183

More forward activity

7000 GeV

$<d_n_{ch}/d\eta> (n_{ch} \geq 1, p_T > 0.04, 5.3<|\eta|<6.5)$

- TOTEM
  - PY8 (Monash 13) $\chi^2/N_{\text{bins}} = 0.2 \pm 0.0$
  - PY8 (4C) $\chi^2/N_{\text{bins}} = 2.6 \pm 0.0$
  - PY8 (2C) $\chi^2/N_{\text{bins}} = 6.1 \pm 0.0$

Data from Europhys.Lett. 98 (2012) 31002
Pythia 8.183

Ultra-hard tail of c and b fragmentation agrees better with LEP and SLD, including event shapes in b-tagged events

Better agreement with TOTEM $N_{ch}$ and with forward E and ET flows. Better pileup?
Monash 2013 Tune Highlights

10% more strangeness

Short Strings

Long Strings

Better agreement with ee identified-strange measurements across all energies, and with Kaons at LHC

Softer D and B spectra near $z = 1$

Ultra-hard tail of c and b fragmentation agrees better with LEP and SLD, including event shapes in b-tagged events

More activity

Better agreement with TOTEM $N_{ch}$ and with forward E and ET flows. Better pileup?

Set M13 Tune:
in PYTHIA 8
Tune: ee = 7
Tune: pp = 14
Puzzles (a selection of)

New:
Monash
Warwick
Alliance
Puzzles (a selection of)

Identified-particle $p_T$ spectra at LHC

New: Monash Warwick Alliance
Puzzles (a selection of)

- Identified-particle $p_T$ spectra at LHC
- Multi-strange and baryon rates at LHC

New: Monash Warwick Alliance
Puzzles (a selection of)

- Identified-particle $p_T$ spectra at LHC
- Multi-strange and baryon rates at LHC
- The physics and consequences of Colour Reconnections (vs Flow?) $\leftrightarrow$ Top Quark Mass

New: Monash Warwick Alliance
Puzzles (a selection of)

Identified-particle $p_T$ spectra at LHC

Multi-strange and baryon rates at LHC

The physics and consequences of Colour Reconnections (vs Flow?) ↔ Top Quark Mass

The role and modeling of diffraction from low to high masses (including UE in diffractive jet events?) ↔ Hard Diffraction, Factorization, CR

New: Monash Warwick Alliance
Puzzles (a selection of)

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Space-time picture of MPI, multi-parton PDFs

New: Monash Warwick Alliance
Puzzles (a selection of)

Identified-particle $p_T$ spectra at LHC

Multi-strange and baryon rates at LHC

The physics and consequences of Colour Reconnections (vs Flow?) $\leftrightarrow$ Top Quark Mass

The role and modeling of diffraction from low to high masses (including UE in diffractive jet events?) $\leftrightarrow$ Hard Diffraction, Factorization, CR

Space-time picture of MPI, multi-parton PDFs

Gluon/Quark discrimination and $G \rightarrow QQ$ splittings in gluon jets

New: Monash Warwick Alliance
Summary

QCD phenomenology is witnessing a rapid evolution:

Driven by demand of **high precision** for LHC environment

**Exploring physics**: infinite-order structure of quantum field theory. Universalities vs process-dependence.

Emergent QCD phenomena: **Jets, Strings, Hadrons**

Non-perturbative QCD is still hard

Lund string model remains best bet, but ~ 30 years old
Lots of input from LHC to spur model building. **Aims for run 2?**

“Solving the LHC” is both interesting and rewarding

New ideas evolving on both perturbative and non-perturbative sides → many opportunities for theory-experiment interplay

**Key to high precision** → max information about the Terascale
What’s the evolution kernel?

DGLAP splitting functions

Can be derived from *collinear limit* of MEs \((p_b + p_c)^2 \to 0\)
+ evolution equation from invariance with respect to \(Q_F \to \text{RGE}\)

DGLAP
(E.g., PYTHIA)

\[
d\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a \to bc}(z) \, dt \, dz .
\]

\[
P_{q \to qg}(z) = C_F \frac{1 + z^2}{1 - z} ,
\]

\[
P_{g \to gg}(z) = N_C \frac{(1 - z(1 - z))^2}{z(1 - z)} ,
\]

\[
P_{g \to q\bar{q}}(z) = T_R \left( z^2 + (1 - z)^2 \right) ,
\]

\[
P_{q \to q\gamma}(z) = \frac{e_q^2}{1 - z} \frac{1 + z^2}{1 - z} ,
\]

\[
P_{\ell \to \ell\gamma}(z) = \frac{e_{\ell}^2}{1 - z} \frac{1 + z^2}{1 - z} ,
\]

\[
dt = \frac{dQ^2}{Q^2} = d\ln Q^2
\]

... with \(Q^2\) some measure of “hardness”
- = event/jet resolution
- measuring parton virtualities / formation time / ...

*Note*: there exist now also alternatives to AP kernels (with same collinear limits!): dipoles, antennae, ...
Coherence

QED: Chudakov effect (mid-fifties)

\[
\text{cosmic ray } \gamma \quad \text{atom} \quad e^+ \quad e^-
\]

emulsion plate reduced ionization normal ionization

Illustration by T. Sjöstrand

QCD: colour coherence for \textbf{soft} gluon emission

\[
\left| \begin{array}{cc}
\text{soft} & \text{gluon} \\
\text{emission} & \text{emission}
\end{array} \right| + \left| \begin{array}{cc}
\text{emission} & \text{emission} \\
\text{emission} & \text{emission}
\end{array} \right|^2 = \left| \begin{array}{cc}
\text{emission} & \text{emission} \\
\text{emission} & \text{emission}
\end{array} \right|^2
\]

→ an example of an interference effect that can be treated probabilistically

More interference effects can be included by matching to full matrix elements
Coherence

QED: Chudakov effect (mid-fifties)

\[ e^+ e^- \]

\[ \text{cosmic ray } \gamma \quad \text{atom} \]

Illustration by T. Sjöstrand

emulsion plate

reduced ionization

normal ionization

Approximations to Coherence:

Angular Ordering (HERWIG)
Angular Vetos (PYTHIA)
Coherent Dipoles/Antennae (ARIADNE, Catani-Seymour, VINCIA)

QCD: colour coherence for soft gluon emission

\[ \begin{bmatrix} \end{bmatrix}^2 \]

\[ \begin{bmatrix} \end{bmatrix}^2 = \begin{bmatrix} \end{bmatrix}^2 \]

→ an example of an interference effect that can be treated probabilistically

More interference effects can be included by matching to full matrix elements
Example: quark-quark scattering in hadron collisions

Consider one specific phase-space point (e.g., scattering at 45°)

2 possible colour flows: a and b

Example taken from: Ritzmann, Kosower, PS, PLB718 (2013) 1345

Another good recent example is the SM contribution to the Tevatron top-quark forward-backward asymmetry from coherent showers, see: PS, Webber, Winter, JHEP 1207 (2012) 151
Example: quark-quark scattering in hadron collisions
Consider one specific phase-space point (e.g., scattering at 45°)
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Coherence at Work

Example taken from: Ritzmann, Kosower, PS, PLB718 (2013) 1345

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Example: quark-quark scattering in hadron collisions
Consider one specific phase-space point (eg scattering at 45°)
2 possible colour flows: a and b

Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.
Initial-State vs Final-State Evolution

FSR:

\[ p^2 > 0 \]

Virtualities are Timelike: \( p^2 > 0 \)

Start at \( Q^2 = Q_F^2 \)

"Forwards evolution"

ISR:

\[ p^2 = t < 0 \]

Virtualities are Spacelike: \( p^2 < 0 \)

Start at \( Q^2 = Q_F^2 \)

Constrained backwards evolution towards boundary condition = proton

Separation meaningful for collinear radiation, but not for soft …