PYTHIA 8 Kickstart

P. Skands (CERN-TH)
PYTHIA 8

● Ambition
  ● Cleaner code
  ● More user-friendly
  ● Easy **interfacing**
  ● Physics Improvements

● Current Status
  ● Ready and tuned for Min-Bias (+ diffraction improved over Pythia 6)
  ● Improved shower model, but bug/problem with underlying event?

**Team Members**
- Stefan Ask (CERN)
- Richard Corke (Lund)
- Stephen Mrenna (FNAL)
- Torbjörn Sjöstrand (Lund)
- Peter Skands (CERN)

**Contributors**
- Bertrand Bellenot
- Lisa Carloni
- Tomas Kasemets
- Mikhail Kirsanov
- Ben Lloyd
- Marc Montull
- Sparsh Navin
- MSTW, CTEQ, H1: PDFs
- DELPHI, LHCb: D/B BRs
- + several bug reports & fixes
Physics (1/3)

- **Hard Physics**
  - SM
    - almost all $2 \rightarrow 1$
    - almost all $2 \rightarrow 2$
    - A few $2 \rightarrow 3$
  - BSM: a bit of everything (see documentation)

- **External Input**
  - Les Houches Accord and LHEF (e.g., from MadGraph, CompHEP, AlpGen, ...)
  - User implementations (semi-internal process)
  - Inheriting from PYTHIA’s $2 \rightarrow 2$ base class, then modify to suit you

**Perturbative Resonance Decays**

- Angular correlations often included (on a process-by-process basis - no generic formalism)
- User implementations (semi-internal resonance)
Physics (2/3)

- **Parton Distributions**
  - Internal *(faster than LHAPDF)*
  - The standard CTEQ and MSTW LO sets, plus a few NLO ones
  - New generation: MSTW LO*, LO**, CTEQ CT09MC
  - Interface to LHAPDF
  - Can use separate PDFs for hard scattering and UE *(to ‘stay tuned’)*

- **Showers**
  - Transverse-momentum ordered ISR & FSR
  - Includes QCD and QED
  - Dipole-style recoils *(partly new)*
  - Improved high-$p_T$ shower behavior *[R. Corke]*

- **Matrix-Element Matching**
  - Automatic first-order matching for most gluon-emission processes in resonance decays, e.g.:
    - $Z \rightarrow qq \rightarrow qqg$
    - $t \rightarrow bW \rightarrow bWg$
    - $H \rightarrow bb \rightarrow bbg$
    - …
  - Automatic first-order matching for internal $2 \rightarrow 1$ color-singlet processes, e.g.:
    - $pp \rightarrow Z/W/Z'/W'+jet$
    - $pp \rightarrow H+jet$
    - More to come …
  - Interface to AlpGen, MadGraph, … via Les Houches Accords
Physics (3/3)

- **Underlying-Event and Min-Bias**
  - Multiple parton–parton interactions
    - Multi-parton PDFs constructed from (flavor and momentum) sum rules
    - Combined (interleaved) evolution MI + ISR + FSR downwards in $p_{\perp}$
    - Option: parton rescattering [R. Corke]
  - Beam remnants
    - String junctions → variable amount of baryon transport
  - Tuned to Tevatron Min-Bias
  - Improved model of diffraction
    - Diffractive jet production [S. Navin]

- **Hadronization**
  - String fragmentation
    - Lund symmetric fragmentation function for (u,d,s) + Bowler modification for heavy quarks (c,b)
      [+ option for Peterson]
  - Hadron and Particle decays
    - Usually isotropic, or:
      - User decays *(DecayHandler)*
      - Link to external packages
        - EVTGEN for B decays
        - TAUOLA for $\tau$ decays
  - Bose-Einstein effects
    - Two-particle model *(off by default)*

- **Output**
  - Interface to HEPMC included
Key differences between PYTHIA 8 and PYTHIA 6

- **New features, not found in 6.4**
  - Up-to-date PDFs
  - Up-to-date PDG decay data
  - Improved Underlying Event
    - Interleaved MI + ISR + FSR
    - Richer mix of underlying-event processes ($\gamma$, $J/\psi$, DY, \ldots)
    - Possibility for two selected hard interactions in same event
    - Allow parton rescattering
    - Possibility to use one PDF set for hard process and another for rest
  - Hard scattering in diffractive systems
  - New SM and BSM processes

- **Old features definitely removed**
  - Independent fragmentation
  - Mass-ordered showers

- **Features omitted so far**
  - $ep$, $\gamma p$ and $\gamma\gamma$ beams
  - Some matrix elements, in particular Technicolor, partly SUSY

  SUSY with NMFV and/or CPV (not fully validated)
  Large Extra Dimensions, Unparticles
  Hidden Valley scenario with hidden radiation
Technical Aspects

- Compilation and Linking
- Disk and Memory requirements
- Speed and Optimization
- Documentation
Compilation and Linking

• **Default standalone**
  • You just need a C++ compiler
    • PYTHIA 8 only depends on `stdlib`, no external libraries
    • Can be compiled either as a static (.a) or shared (.so) library (only static switched on by default)
  • No static variables
    • Can have multiple instances
  • Standard build procedure
    • `./configure`
    • `make`
    • Then move to examples/subdirectory and open README file

• **Examples**
  • ~ 40 example programs included in examples/subdirectory
  • Including how to use each of the interfaces, and more

• **Optional Dependencies (examples included)**
  • FastJet
  • LHAPDF
  • HepMC
  • ROOT
Disk and Memory Requirements

- **Disk Space**
  - **Source Code**
    - 1.8M src/
    - 544K include/
    - 12K hepmcinterface/
    - 7.0M xmldoc/
    - 2.1M htmldoc/
    - 2.4M phpdoc/
    - 6.0M examples/
    - =========================
    - 20M pythia8135
  - **Libraries (incl tmp)**
    - 3.6M lib/
    - 4.0M tmp/archive/
    - =========================
    - 28M pythia8135

- **Executables**
  - 2.3M examples/main01.exe
  - **Typical size of standalone executable.**
  - **Bigger if linked to external packages**

- **Memory Usage**
  - ~ 10M standalone
  - **Minimal usage. More if linked to external packages, filling histograms, etc**
Speed and Optimization
(on 3GHz processor)

- **Compiling PYTHIA 8** (from scratch)
  
  real 1m41.053s  
  user 1m23.870s  
  sys 0m6.944s

- **Running PYTHIA 8** (with default flags etc)
  
  $\sigma_{\text{tot}} = \text{EL+INEL}$ 7 TeV 4 ms/event
  
  Min-Bias 7 TeV 6 ms/event
  
  Drell-Yan ($m \geq 70\text{GeV}$) 7 TeV 13 ms/event
  
  Dijets ($p_T \geq 100\text{GeV}$) 7 TeV 20 ms/event

  Multiple Interactions $\geq 50\%$ of total
  
  Hadronization $\sim 10\% - 20\%$ of total

- **Optimization**
  
  - Currently no dedicated optimization for multi-core usage
Steering and Settings

1. Defaults
   - No hardcoded defaults *(in .cc and .h files)*
   - Instead, all default settings read from XML file set
     - Write-protected: **do not change!** (these are the *defaults*)
     - XML → HTML ⇒ User Manual in htmldoc/Welcome.html
       - Minimal risk of inconsistency
       - Also exists as php with added functionality, but must then be installed on a web server

2. Setting and How to Change Parameters
   - Directly in your code: `pythia.readString("parameter = value");`
   - OR: collect any number of such strings in a file *(e.g., cardFile.cmnd)* and use: `pythia.readFile("cardfile.cmnd");`
PYTHIA 8

Welcome to PYTHIA - The Lund Monte Carlo Event Generator

PYTHIA 8 is the successor to PYTHIA 6, rewritten from scratch in C++. With the release of PYTHIA 8.1 it now becomes the official "current" PYTHIA version, although PYTHIA 6.4 will be supported in parallel with it for some time to come.

Specifically, the new version has not yet been enough tested and tuned for it to have reached the same level of reliability as the older one. This testing will only happen if people begin to work with the program, however, which is why we encourage a gradual transition to the new version, starting now. There are some new physics features in PYTHIA 8.1, that would make use of it more attractive, but also some topics still missing, where 6.4 would have to be used.

Further, many obsolete features will not be carried over, so for some backwards compatibility studies again 6.4 would be the choice.

Documentation

On these webpages you will find the up-to-date manual for PYTHIA 8.1. Use the left-hand index to navigate this documentation of program elements, especially of all possible program settings. All parameters are provided with sensible default values, however, so you need only change those of relevance to your particular study, such as choice of beams, processes and phase space cuts. The pages also contain a fairly extensive survey of all methods available to the user, e.g. to study the produced events. What is lacking on these webpages is an overview, on the one hand, and an in-depth physics description, on the other.

The overview can be found in the attached PDF file:

A Brief Introduction to PYTHIA 8.1
You are strongly recommended to read this summary when you start out to learn how to use PYTHIA 8.1. Note that some details have changed since the 8.100 version described there.

For the physics description we refer to the complete

PYTHIA 6.4 Physics and Manual
T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026, which in detail describes the physics (largely) implemented also in PYTHIA 8, and also provides a more extensive bibliography than found here.

When you use PYTHIA 8.1, you should therefore cite both, e.g. like:

Furthermore, a separate

PYTHIA 8 Worksheet,
also an attached PDF file, offers a practical introduction to using the generator. It has been developed for and used at a few summer schools, with minor variations, but is also suited for self-study.
Documentation

Also available as php (must be installed on web server)

Can then set and change parameters “online” in the manual - then click the special “save” button to store the modifications as a new card file, ready to use in PYTHIA.
Sample Main Programs

Descriptions of available classes, methods and settings are all very good and allow you to be able to fine-tune your runs to the task at hand. To get going, however, not all of the study. This is what is provided in the examples subdirectory, along with instructions.

- **main01.cc**: a simple study of the charged multiplicity for jet events at the LHC, with jet analysis using the CellJet cone-jet finder.
- **main02.cc**: a simple study of the $p_T$ spectrum of Z bosons at the Tevatron.
- **main03.cc**: a simple single-particle analysis of jet events, where input
- **main04.cc**: a simple study of several different kinds of events, with the choice to be made in the main04.cmd "cards file".
- **main05.cc**: generation of QCD jet events at the LHC, with jet analysis using the CellJet cone-jet finder.
- **main06.cc**: tests of cross sections for elastic and diffractive topologies, using main06.cmd to pick process.
- **main07.cc**: tests of cross sections for minimum-bias events, using main07.cmd to pick options.
- **main08.cc**: generation of the QCD jet cross section by splitting the run into subruns, each in its own $p_T$ bin, and adding the results properly reweighted. Two options, with limits set either in the main program or by subrun specification in the main08.cmd file.
- **main09.cc**: generation of LEP1 hadronic events, i.e. $e^+e^- \rightarrow \gamma^*Z^0 \rightarrow q\bar{q}$, with charged multiplicity, spherical, thrust and jet analysis.
- **main10.cc**: illustration of how user-hooks can be used to directly with the event-generation process.
- **main11.cc**: generation of two predetermined hard interactions in each event.
- **main12.cc**: a study of top events, fed in from the Les Houches Event File `ttbar.lhe`, here generated by PYTHIA 6.4. This file currently only contains 100 events so as to the distributed PYTHIA package too big, and so serves mainly as a demonstration of the principles involved.
- **main13.cc**: a more sophisticated variant of main12.cc, where two Les Houches Event Files (`ttbar.lhe` and `ttbar2.lhe`) successively are used as input. Also illustrating some other aspects, like the capability to mix in internally generated events.
- **main14.cc**: a systematic comparison of several cross section values with their corresponding values in PYTHIA 6.4, the latter available as a table in the code.
- **main15.cc**: loop over several tries, either to redo B decays only or to redo the complete hadronization chain of an event. Since much of the generation process is only made once this is a way to increase efficiency.
- **main16.cc**: put all user analysis code into a class of its own, separate from the main program; provide the "cards file" name as a command-line argument.
- **main17.cc**: collect the Pythia calls in a wrapper class, thereby simplifying the main program; provide the "cards file" name as a command-line argument.
Tuning
3 Kinds of Tuning

1. Fragmentation Tuning
   - Non-perturbative: hadronization modeling & parameters
   - Perturbative: jet radiation, jet broadening, jet structure

2. Initial-State Tuning
   - Non-perturbative: PDFs, primordial $k_T$
   - Perturbative: initial-state radiation, initial-final interference

3. Underlying-Event & Min-Bias Tuning
   - Non-perturbative: Multi-parton PDFs, Color (re)connections, collective effects, impact parameter dependence, …
   - Perturbative: Multi-parton interactions, rescattering
LEP Event Shapes

Event Shapes

Theory vs LEP

Hadron level

(default PYTHIA 8.135)
More Event Shapes

Jet Masses and Jet Broadening

Hadron level

Theory vs LEP

Theory/LEP
# Jet Rates

## Jet Resolution

E.g., \( y_{23} = \frac{k_T^2}{E_{\text{vis}}^2} \) = scale where event goes from having 2 to 3 jets

### Hadron level

<table>
<thead>
<tr>
<th>( y )</th>
<th>( k_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>33 GeV</td>
</tr>
<tr>
<td>4</td>
<td>12 GeV</td>
</tr>
<tr>
<td>6</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>8</td>
<td>1.6 GeV</td>
</tr>
<tr>
<td>10</td>
<td>0.6 GeV</td>
</tr>
</tbody>
</table>

At \( E_{\text{vis}} = 91 \text{ GeV} \):
- \( y=2 \rightarrow k_T \approx 33 \text{ GeV} \)
- \( y=4 \rightarrow k_T \approx 12 \text{ GeV} \)
- \( y=6 \rightarrow k_T \approx 4.5 \text{ GeV} \)
- \( y=8 \rightarrow k_T \approx 1.6 \text{ GeV} \)
- \( y=10 \rightarrow k_T \approx 0.6 \text{ GeV} \)

(default PYTHIA 8.135)
Tuning in the Infrared

1. Fragmentation Tuning

Constrain incalculable model parameters

Good model $\rightarrow$ good fit. Bad model $\rightarrow$ bad fit $\rightarrow$ improve model

\[
\begin{align*}
P_s/P_{u,d} & \\
P_{\text{Baryon}}/P_{\text{Meson}} & \\
P_{\text{Vector}}/3P_{\text{Scalar}} & \\
\Lambda_{\text{QCD}} & \\
\text{IR } \alpha_s & \\
Q_{\text{cutoff}} & \\
f(z,Q^2) & \\
f_{c,b}(z,Q^2) & \\
p_{\perp F} & \\
\eta, \eta' \text{ suppression} & \\
\end{align*}
\]
Before

**Pythia 8.100**

- $N_{\text{ch}}$
- Mesons
- Baryons
- $\ln(1/x)$
After

**PYTHIA 8.135**

\[ N_{\text{ch}} \quad \text{Mesons} \quad \text{Baryons} \quad \ln(1/x) \]
(with VINCIA antenna shower)

**PYTHIA 8.135 + VINCIA 1.023**

(Different shower, same hadronization model)

\[ \text{N}_{\text{ch}} \quad \text{Mesons} \quad \text{Baryons} \quad \text{Ln}(1/x) \]
Initial-State Radiation

Drell-Yan $p_T$ distribution

1800 GeV $p+p\bar{p}$

- **Peak**
- **Tail**

1960 GeV $p+p\bar{p}$

- **Peak**
- **Tail**
Tuning for Min-Bias and Underlying-Event

(+ some physics spillover)
Interleaved Evolution

Add exclusivity progressively by evolving everything downwards.

"New" Pythia model

\[
\frac{dP}{dp_\perp} = \left( \frac{dP_{\text{MI}}}{dp_\perp} + \sum \frac{dP_{\text{ISR}}}{dp_\perp} + \sum \frac{dP_{\text{JI}}}{dp_\perp} \right) \times \exp\left( -\int_{p_\perp}^{p_{\perp i-1}} \left( \frac{dP_{\text{MI}}}{dp_\perp'} + \sum \frac{dP_{\text{ISR}}}{dp_\perp'} + \sum \frac{dP_{\text{JI}}}{dp_\perp'} \right) dp_\perp' \right)
\]

→ Underlying Event
(note: interactions correlated in colour: hadronization not independent)

~ "Finegraining"

→ correlations between all perturbative activity at successively smaller scales

Main parameter: \( p_{\perp \text{min}} \) (perturbative cutoff)

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?

Spiky: large event-to-event fluctuations

Smooth: smaller fluctuations
Colour and the UE

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

The colour flow determines the hadronizing string topology

• Each MPI, even when soft, is a color spark
• Final distributions crucially depend on color space

Note: this just color connections, then there may be color reconnections too
Minimum-Bias

630 GeV Multiplicity Distribution 1960 GeV
Minimum-Bias

Average Track $p_T$ vs Multiplicity

1960 GeV $p+p\bar{p}$ Inelastic, Non-Diffractive

Average Charged Particle $p_T$ ($|\eta|<1.0$, $p_\perp>0.4\text{GeV}$)

- CDF data
- 8.100 default
- 8.105 default
- 8.120 default
- 8.125 default
- 8.130 default
- Perugia 0

Pythia 6.423

Data from CDF Collaboration, Phys. Rev. D79(2009)112005
Hadrons are composite, with time-dependent structure: $u_d(g_u p_f(x, Q^2)) = \text{number density of partons at momentum fraction } x$ and probing scale $Q^2$.

Linguistics (example): $F_2(x, Q^2) = \sum_i e_i^2 x_i f_i(x, Q^2)$

Compare with normal PDFs

Intuitive picture

Hard Probe

Short-Distance

Long-Distance

$p^+$
Long-Distance

Parton Distribution Functions

Hadrons are composite, with time-dependent structure:

\[ u_d(x, Q^2) = \text{number density of partons} \text{ at momentum fraction } x \text{ and probing scale } Q^2. \]

Linguistics (example):

\[ F_2(x, Q^2) = \sum_i e_i^2 x f_i(x, Q^2) \]

Hard Probe

\[ n_0 \rightarrow \text{Diffractive PDFs} \]

Virtual $\pi^+$ ("Reggeon")

Virtual "glueball" ("Pomeron") = (gg) color singlet

\[ p^+ \parr p^+ \]

(\(+\) Diffraction)

“Intuitive picture”

Compare with normal PDFs

Very Long-Distance

\[ Q < \Lambda \]

\[ n_0 \]
(+ Diffraction)

“Intuitive picture”

Compare with normal PDFs

Hard Probe

Short-Distance

Long-Distance

Very Long-Distance

$Q < \Lambda$

$\rightarrow$ Diffractive PDFs

$\rightarrow$ Diffractive PDFs

$p^+$

$p^+$

Virtual $\pi^+$ (“Reggeon”)
**Diffraction in PYTHIA 8**

- **Diffractive Cross Section Formulae:**
  \[
  \frac{d\sigma_{sd}(AX)}{dt \, dM^2} = \frac{g_{3IP}^2}{16\pi} \beta_{AIP}^2 \beta_{BIP}^2 \frac{1}{M^2} \exp(B_{sd}(AX)t) F_{sd},
  \]
  \[
  \frac{d\sigma_{dd}(s)}{dt \, dM^2 \, dM_1^2 \, dM_2^2} = \frac{g_{3IP}^2}{16\pi} \beta_{AIP} \beta_{BIP} \frac{1}{M^2_1 M^2_2} \exp(B_{dd}t) F_{dd}.
  \]

- **Partonic Substructure in Pomeron:**
  Follows the approach of Pompyt

- **Status:** Supported and actively developed

  - \( M_{X} \leq 10 \text{GeV} \): original longitudinal string description used
  - \( M_{X} > 10 \text{GeV} \): new perturbative description used
But Rivet+Professor (H. Hoeth) shows it fails miserably for UE (Rick Field’s transverse flow as function of jet $p_\perp$):

Where did we go wrong?

The Snag!
Summary & Outlook

**PYTHIA 6**

Supported *(bug fixes etc)* - But not actively developed *(no new physics)*

**PYTHIA 8**

Actively developed and supported *(though check with your MC responsibles before mailing questions directly - there are just a few of us)*

Core program ready and tuned

- Extensive documentation and example programs
- Problem with UE description under investigation

Flexible structure with many user I/O possibilities

- Steerable by cards
- Built-in interfaces *(e.g., LHEF, HepMC, FastJet, LHAPDF, VINCIA)* + User hooks to veto events or modify cross sections *(e.g., for matching with AlpGen, MadGraph, etc)*
- User derived classes *(e.g., user processes, user resonance decays, user particle decays, even user parton showers)* inheriting from the base Pythia classes
PYTHIA 8 Kickstart
Preparation for Pythia 8

• The code is entirely standalone. All you need is a C compiler

• Download the tarball from the Pythia 8 web site (you can also just type Pythia in google, but be careful to get PYTHIA 8, not 6)

  http://home.thep.lu.se/~torbjorn/pythia8/pythia8135.tgz

  • Unpack it, move to the pythia8135/ directory
  • ./configure
    (open the README file if you want to know about possible fancy options you can use)
  • make
Examples to try

Move to the examples/ subdirectory

.../pythia8135/examples/

Compile the first example program, main01

make main01
./main01.exe

Familiarize yourselves with the event record it prints

(open the HTML manual in a browser, scroll down to “Study Output” and look at “particle properties”, “event record”, and any other topics you find interesting)

.../pythia8135/htmldoc/Welcome.html

Back in the examples/ directory, open the README file to look for more interesting example programs
# PDG Codes

## A. Fundamental objects

<table>
<thead>
<tr>
<th>1</th>
<th>d</th>
<th>11</th>
<th>e⁻</th>
<th>21</th>
<th>g</th>
<th>add – sign for antiparticle, where appropriate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>u</td>
<td>12</td>
<td>νₑ</td>
<td>22</td>
<td>γ</td>
<td>Z⁰</td>
</tr>
<tr>
<td>3</td>
<td>s</td>
<td>13</td>
<td>μ⁻</td>
<td>23</td>
<td>Z⁰</td>
<td>Z''⁰</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>14</td>
<td>νµ</td>
<td>24</td>
<td>W⁺</td>
<td>W'⁺</td>
</tr>
<tr>
<td>5</td>
<td>b</td>
<td>15</td>
<td>τ⁻</td>
<td>25</td>
<td>h⁰</td>
<td>H⁰</td>
</tr>
<tr>
<td>6</td>
<td>t</td>
<td>16</td>
<td>ντ</td>
<td>36</td>
<td>A⁰</td>
<td>39</td>
</tr>
</tbody>
</table>

## B. Mesons

100 | q₁ | + 10 | q₂ | + (2s + 1) with | q₁ | ≥ | q₂ |
particle if heaviest quark u, s, c, b; else antiparticle

| 111 | π⁰ | 311 | K⁰ | 130 | K⁺ | 221 | η⁰ | 411 | D⁺ | 431 | Dˢ⁺ |
| 211 | π⁺ | 321 | K⁺ | 310 | K⁰ | 331 | η⁰' | 421 | D⁰ | 443 | J/ψ |

## C. Baryons

1000 q₁ + 100 q₂ + 10 q₃ + (2s + 1) with q₁ ≥ q₂ ≥ q₃, or Λ-like q₁ ≥ q₃ ≥ q₂

| 2112 | n | 3122 | Λ⁰ | 2224 | Δ⁺⁺ | 3214 | Σ⁺⁰ |
| 2212 | p | 3212 | Σ⁰ | 1114 | Δ⁻ | 3334 | Ω⁻ |