PYTHIA 8 Kickstart

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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)
  ● Torbjorn Sjostrand (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-$p_\perp$ shower behavior

- **Matrix-Element Matching**
  - Automatic first-order matching for most gluon-emission processes in resonance decays, e.g.:
    - $Z \rightarrow qq \rightarrow qqg$
    - $t \rightarrow bW \rightarrow bWg$
    - $H \rightarrow bb \rightarrow bg$
    - ...
  - Automatic first-order matching for internal $2 \rightarrow 1$ color-singlet processes, e.g.:
    - $pp \rightarrow ZZ'/WW'+jet$
    - $pp \rightarrow H+jet$
    - 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 $\rightarrow$ 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)

\[
\begin{align*}
\sigma_{\text{tot}} &= \text{EL+INEL} & 7 \text{ TeV} & 4 \text{ ms/event} \\
\text{Min-Bias} &= 7 \text{ TeV} & 6 \text{ ms/event} \\
\text{Drell-Yan (m}\geq 70\text{GeV)} &= 7 \text{ TeV} & 13 \text{ ms/event} \\
\text{Dijets (p}_{\perp}\geq 100\text{GeV)} &= 7 \text{ TeV} & 20 \text{ ms/event}
\end{align*}
\]

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”);`
Included in package:

`/pythia8135/htmdoc/Welcome.html`
(also available on the web)
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

```
Timelike Showers
The PYTHIA algorithm for timelike final-state showers is based on momentum-ordered evolution scheme is introduced. This algorithm is in PYTHIA[Ben87] and by the dipole-emission formulation in Ariadne. It also contains the merging procedure for first-order gluon-emission matrix elements from the QCD model and its minimal supersymmetric extension [Nor01].

The normal user is not expected to call TimeShower directly, but can use the parameters below, in particular TimeShower:alphaS value, would be set to 0.1383

Main variables
Often the maximum scale of the FSR shower evolution is understood by the rescaling of half the resonance mass sets an absolute upper limit. For a hard process, this is a unique. Here the factorization scale has been chosen as the maximum scale of the process, supplemented by mass terms for massive outgoing partons.

Example:

```
Timelike Showers

TimeShower:ptmaxFudge 1.0
(default = 1.0; minimum = 0.25; maximum = 2.0)

While the above rules would imply that \( p_T^{\text{max}} = p_T^{\text{factorization}} \), \( p_T^{\text{MaxFudge}} \) introduced a multiplicative factor \( f \) such that instead \( p_T^{\text{max}} = f \cdot p_T^{\text{factorization}} \). Only applies to the hardest interaction in an event, cf. below. It is strongly suggested that \( f = 1 \), but variations around this default can be useful to test this assumption.

Note: Scales for resonance decays are not affected, but can be set separately by user hooks.

Timelike Showers

TimeShower:ptmaxFudgeMI 1.0
(default = 1.0; minimum = 0.25; maximum = 2.0)

A multiplicative factor \( f \) such that \( p_T^{\text{max}} = f \cdot p_T^{\text{factorization}} \), as above, but here for the non-hardest interactions (when multiple interactions are allowed).

The amount of QCD radiation in the shower is determined by

```
Timelike Showers

TimeShower:alphaSValue 0.1383
(default = 0.1383; minimum = 0.06; maximum = 0.25)

The \( \alpha_s \) value at scale \( M_Z^2 \). The default value corresponds to a crude tuning to LEP data, to be improved.

The actual value is then regulated by the running to the scale \( p_T^2 \), at which the shower evaluates \( \alpha_s \),

```
Timelike Showers

TimeShower:alphaSOrder (default = 1; minimum = 0; maximum = 2)
Order at which alpha_s runs,
- 0 : zeroth order, i.e. alpha_s is kept fixed.
- 1 : first order, which is the normal value.
- 2 : second order. Since other parts of the code do not go to second order there is no strong reason to use this option, but there is also nothing wrong with it.
```
Sample Main Programs

Descriptions of available classes, methods and settings are all very good and easy to find. However, you may still want to be able to fine-tune your runs to the task at hand. To get going, however, not a bad place to start. This is what is provided in the examples subdirectory, along with instructions on how to use each.

- main01.cc: a simple study of the charged multiplicity for jet events at the LHC.
- 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

Contents of examples/ directory also documented here (and more on how to use each of the interfaces)
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

1-T

Obl

C

D

Hadron level

(default PYTHIA 8.135)
More Event Shapes

Jet Masses and Jet Broadening

Hadron level
Jet Rates

Jet Resolution

E.g., $y_{23} = k_T^2 / E_{vis}^2$ = scale where event goes from having 2 to 3 jets

Hadron level

At $E_{vis} = 91$ GeV

$y=2 \rightarrow k_T \approx 33$ GeV

$y=4 \rightarrow k_T \approx 12$ GeV

$y=6 \rightarrow k_T \approx 4.5$ GeV

$y=8 \rightarrow k_T \approx 1.6$ GeV

$y=10 \rightarrow k_T \approx 0.6$ GeV

Theory vs LEP

(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

$P_s/P_{u,d}$
$P_{\text{Baryon}}/P_{\text{Meson}}$
$P_{\text{Vector}}/3P_{\text{Scalar}}$
$\Lambda_{\text{QCD}}$
$\alpha_s$ (IR)
$Q_{\text{cutoff}}$
$f(z,Q^2)$
$f_{c,b}(z,Q^2)$
$p_{\perp F}$

$\eta, \eta'$ suppression
Before

**PYTHIA 8.100**

\[ N_{\text{ch}} \quad \text{Mesons} \quad \text{Baryons} \quad \text{Ln}(1/x) \]
PYTHIA 8.135

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

**PYTHIA 8.135 + VINCIA 1.023**

(Different shower, same hadronization model)

N_{ch}  Mesons  Baryons  Ln(1/x)
Initial-State Radiation

Drell-Yan $p_T$ distribution

1800 GeV $p+p\bar{p}$ Drell-Yan

Transverse Momentum of $Z/\gamma^*$ [$66 < M_{Z/\gamma^*}/GeV < 116$]

- 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, PRL84(2000)845

1960 GeV $p+p\bar{p}$ Drell-Yan

Transverse Momentum of $Z/\gamma^*$ [$40 < M_{Z/\gamma^*}/GeV < 200$]

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

Pythia 6.423
Data from D0 Collaboration, PRL100(2008)102002

CDF

DO

Peak

Tail
Tuning for Min-Bias and Underlying-Event

(+ some physics spillover)
Interleaved Evolution

Add exclusivity progressively by evolving everything downwards.

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

“New” Pythia model

\rightarrow Underlying Event

(note: interactions correlated in colour: hadronization not independent)

\sim “Finegraining”

\rightarrow 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
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

Diffractive ambiguities?

Charged Particle Multiplicity ($|\eta|<1.0$, $p_{T}>0.4\text{GeV}$)

- 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, PRD50(2002)072006

Pythia 6.423

Data from CDF QCD Public Page
Hadrons are composite, with time-dependent structure:

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

**Intuitive picture**

Hard Probe

- Short-Distance
- Long-Distance

Compare with normal PDFs

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

Linguistics (example):

\[ F_2(x, Q^2) = \sum_i e_i^2 \frac{x f_i(x, Q^2)}{x f_i(x, Q^2)} \]
Hadrons are composite, with time-dependent structure:

\[ u, d, g \] = \text{number density of partons at momentum fraction } x \text{ and probing scale } Q^2. 

Linguistics (example):

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

\( Q < \Lambda \) 

\( n^0 \) 

\( p^+ \) 

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

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

\( \rightarrow \) Diffractive PDFs
Long-Distance

Par ton Distr ibution Functions

Hadrons are composite, with time-dependent structure:

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

Linguistics (example):

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

\[ \rightarrow \text{structure function parton distributions} \]

Hard Probe

Very Long-Distance

\[ Q < \Lambda \]

Virtual \( \pi^+ \) (“Reggeon”) → Diffractive PDFs

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Diffraction in PYTHIA 8

**Diffractive Cross Section Formulae:**
\[
\frac{d\sigma_{sd(AX)}(s)}{dt \, dM^2} = \frac{g_{3p}}{16\pi} \beta_{AIp}^2 \beta_{BIP} \frac{1}{M^2} \exp(B_{sd(AX)} t) F_{sd},
\]
\[
\frac{d\sigma_{dd}(s)}{dt \, dM_1^2 \, dM_2^2} = \frac{g_{3p}^2}{16\pi} \beta_{AIp} \beta_{BIP} \frac{1}{M_1^2} \frac{1}{M_2^2} \exp(B_{dd} t) F_{dd}.
\]

**Partonic Substructure in Pomeron:**

Follows the approach of Pompyt

\[ p_i \quad \rightarrow \quad p_i \quad \rightarrow \quad x^P \quad \rightarrow \quad x' \quad \rightarrow \quad p_f \]

\[ LRG \]

\[ x \]

- \[ M_X \leq 10 \text{GeV} \]: original longitudinal string description used
- \[ M_X > 10 \text{GeV} \]: new perturbative description used

**Status:** Supported and actively developed

**Legend:**

- Pythia 8.130
- Pythia 6.414
- Phojet 1.12
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)

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

A. Fundamental objects

| 1  | 11 | e^- | 21 | g  | 32 | Z^0  | add – sign for antiparticle, where appropriate |
| 2  | 12 | ne  | 22 | g  | 33 | Z'0  |
| 3  | 13 | mu- | 23 | Z^0 | 34 | W^+  |
| 4  | 14 | nu_m | 24 | W^0 | 35 | W'^+ |
| 5  | 15 | tau- | 25 | h^0 | 36 | A^0  |
| 6  | 16 | tau | 26 | h^0 | 37 | H^+  |

B. Mesons

100 |q_1| + 10 |q_2| + (2s + 1) with |q_1| ≥ |q_2|
particle if heaviest quark u, s, c, b; else antiparticle

| 111 | 311 | K^+ | 221 | eta^0 | 411 | D^+ | 431 | Ds^+ |
| 211 | 321 | K^+ | 310 | K_S^0 | 331 | eta'^0 | 421 | D^0 | 443 | J/psi |

C. Baryons

1000 q_1 + 100 q_2 + 10 q_3 + (2s + 1)
with q_1 ≥ q_2 ≥ q_3, or Lambda-like q_1 ≥ q_3 ≥ q_2

| 2112 | n  | 3122 | Lambda^0 | 2224 | Delta^++ | 3214 | Sigma^*0 |
| 2212 | p  | 3212 | Sigma^0  | 1114 | Delta^-  | 3334 | Omega^- |