PYTHIA 8

Richard Corke

Department of Astronomy and Theoretical Physics
Lund University

June 2010

Torbjörn Sjöstrand, Stefan Ask, Stephen Mrenna, Peter Skands,
Lisa Carloni

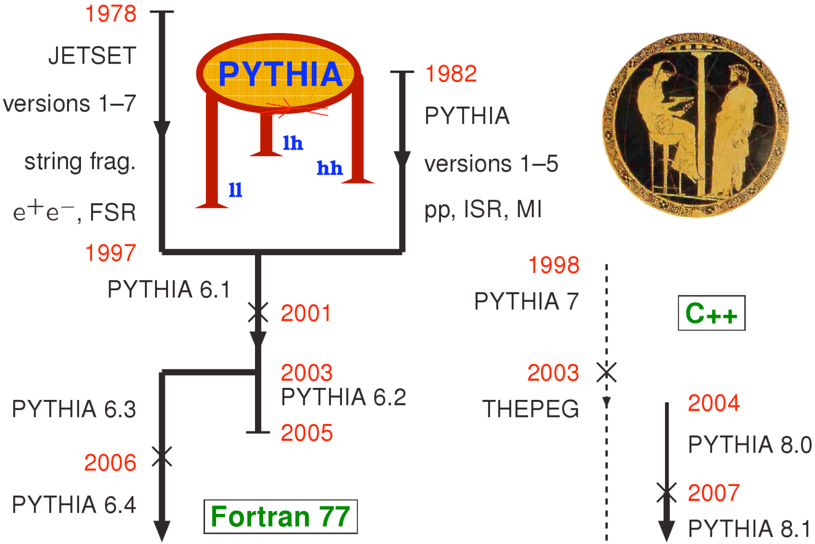
Overview

1. PYTHIA
2. Physics overview
3. BSM Physics
4. Running PYTHIA 8
5. Conclusions

PYTHIA

- General purpose Monte Carlo event generator
- Combine pQCD and models to provide link from theory (quarks, gluons) to experiment (mesons, baryons)
- Full problem "factorised" into different components
  - Hard process
  - Resonance decays
  - Parton showers
  - Underlying event
  - Hadronisation
  - Hadron decays
- Different parts may be handled by other external programs (e.g. Tauola)
- Or (with PYTHIA 8) through plugins (e.g. VINCIA)
- Outputs exclusive hadronic events
  - Analyse (e.g. FastJet)
  - Pass to detector simulator (e.g. GEANT)
  - ...

PYTHIA


1978
JETSET
versions 1–7
string frag.
e+e−, FSR
PYTHIA
lh
hh
ll
1982
PYTHIA
versions 1–5
pp, ISR, MI
1997
PYTHIA 6.1
2001
2003
PYTHIA 6.2
2005
PYTHIA 6.3
2006
PYTHIA 6.4
Fortran 77
1998
PYTHIA 7
C++
2003
THEPEG
2004
PYTHIA 8.0
2007
PYTHIA 8.1

Physics overview

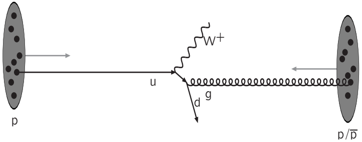
Further reading

- Latest downloads and news:
  - `http://home.thep.lu.se/~torbjorn/Pythia.html`
- "PYTHIA 6.4 Physics and Manual"
  T. Sjöstrand, S. Mrenna and P. Skands,
  JHEP 0605:026,2006, [hep-ph/0603175].
- "A Brief Introduction to PYTHIA 8.1"
  T. Sjöstrand, S. Mrenna and P. Skands,
  Comput. Phys. Comm. 178 (2008) 852 [arXiv:0710.3820].
- And references therein

Physics overview

Beams and hard processes

- Beams
  - Incoming beams: pp, $\mathrm{p\bar{p}}$, $\mathrm{e^+e^-}$, $\mu^+\mu^-$
  - PYTHIA 8: no ep, $\gamma\mathrm{p}$ or $\gamma\gamma$ beam configurations
  - Built in parton distribution function (PDF) sets
    - GRV94L, CTEQ5L
    - MSTW2008 (LO and NLO), MRST LO**
    - CTEQ6L, CTEQ6L1, CTEQ6.6, CT09MC1, CT09MC2, CT09MCS
  - Easy to link to LHAPDF for many more

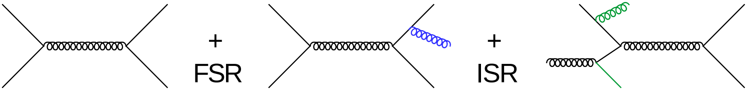


- Hard Processes
  - Built-in library of many leading-order processes
  - SM: almost all $2 \to 1$ and $2 \to 2$, some $2 \to 3$
  - BSM: a bit of everything (more to come)
  - External input through Les Houches Accord (LHA) and Les Houches Event Files (LHEF)

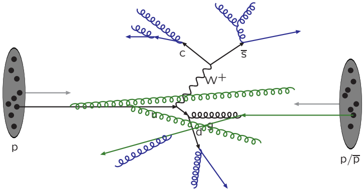
Physics overview

Parton showers

- Regions of phase space where higher-order terms are enhanced
  - Full matrix element calculation not feasible
  - DGLAP evolution equations; leading log approximation of QCD
  - Sudakov form factor; shower evolution as a probabilistic process



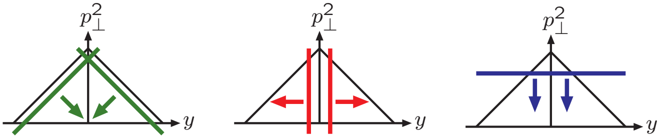
- Initial state radiation performed through backwards evolution
  - Pick a hard $2 \to 2$ process
  - What is the probability that incoming parton b came from a splitting $a \to bc$?
  - PDF factors enter the evolution
- Iterate to build up event



Physics overview

Parton showers

- Still choices to make!
- Ordering
  - Transverse-momentum-ordered showers

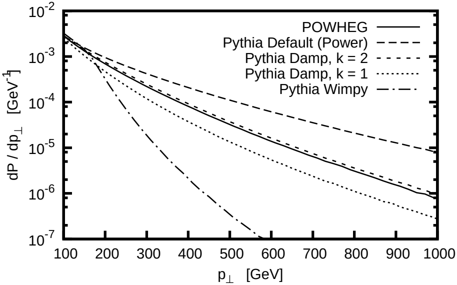


- Recoil strategy
  - Dipole approach to recoil
  - Each radiator parton has a recoiler partner
  - Kinematics constructed directly after each branching
  - All unevolved partons on mass shell

Physics overview

Parton showers

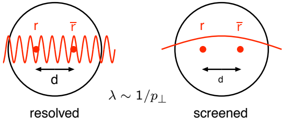
- Matching to ME for first emission in many processes
- Aim to provide better shower behaviour at large $p_\perp$
  - Dampen shower tail in coloured final states
  - Also examine interfacing of POWHEG NLO generators to PYTHIA
  - RC & T. Sjöstrand, arXiv:1003.2384 [hep-ph]



- Implementation of CKKW-L in progress (Stefan Prestel)

Physics overview
Underlying event

- Multiple parton-parton interactions
  - QCD $2 \to 2$, prompt photon production, Drell Yan, Charmonium & Bottomonium
  - Impact parameter dependence
  - Dampened cross section in $p_\perp \to 0$ limit

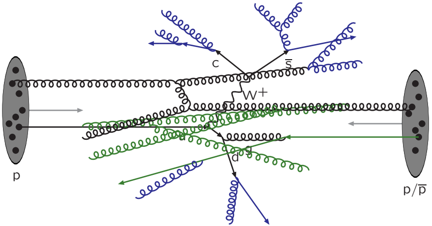


$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_S^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

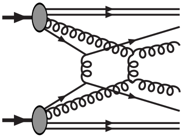
- Interleaved $p_\perp$ evolution with ISR and FSR
  - ISR and MI "compete" for beam
  - Flavour dependent PDF effects
  - Showering from all interactions

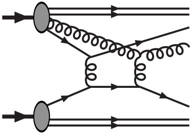
Physics overview
Underlying event

- Picture now a lot more messy



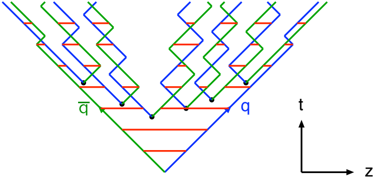
- Rescattering: scattered parton allowed to interact again
  - Same order in α_s, but one PDF weight less
  - Large background $\rightarrow$ will be tough to find direct evidence
  - RC & T. Sjöstrand, JHEP 01 (2010) 035 [arXiv:0911.1909]

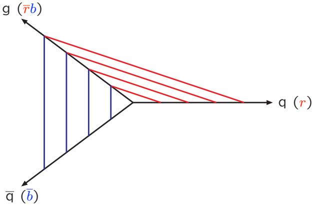




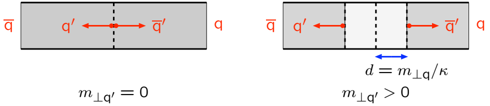
- String fragmentation - “The Lund Model”

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$





- String breaking modelled by tunnelling

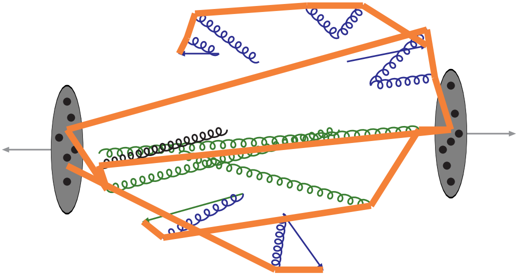


- Particle decays, usually isotropic

Physics overview

Hadronisation

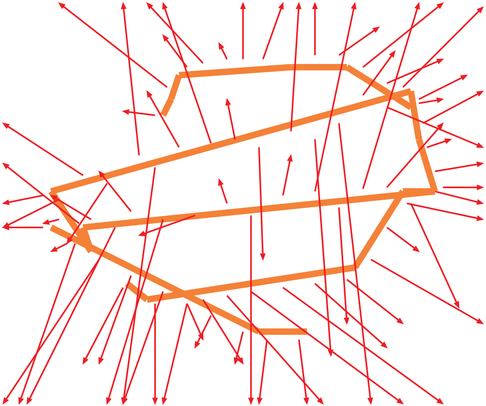
- Everything connected by colour confinement strings
- Strings fragment to produce primary hadrons
- Unstable hadrons decay further



Physics overview

Hadronisation

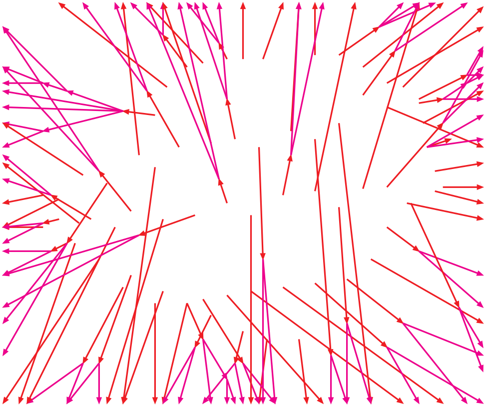
- Everything connected by colour confinement strings
- Strings fragment to produce primary hadrons
- Unstable hadrons decay further



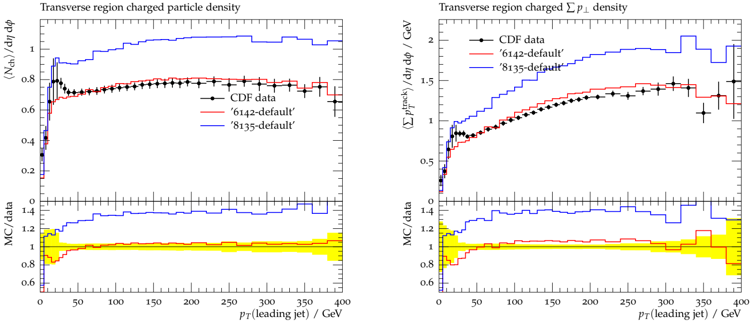
Physics overview

Hadronisation

- Everything connected by colour confinement strings
- Strings fragment to produce primary hadrons
- Unstable hadrons decay further



- Tuning with Rivet + Professor
  A. Buckley et al. [hep-ph/1003.0694, hep-ph/0907.2973]
  - Tuning to e^+e^- data looks okay
  - Hard physics distributions also okay
  - But problems describing the underlying event?

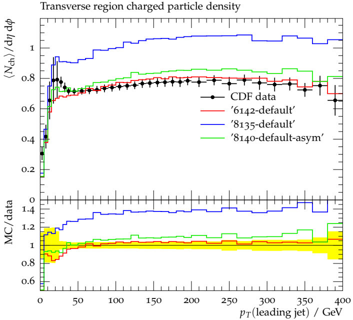


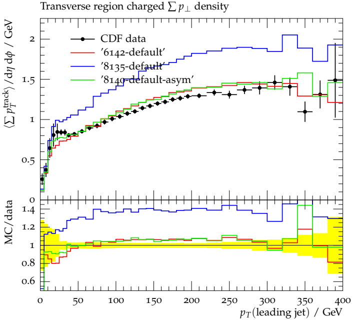
- Possible causes
  - Final-state dipoles with initial-state recoil
  - Azimuthal asymmetry of radiation

Physics overview

Current status

- Initial results promising, but still much to be checked





- Go further?
  - Compare first parton shower emission to $2 \to 3$ matrix elements
  - How does $2 \to 2 \otimes \mathrm{PS}$ fill the phase space?
  - Work ongoing!

BSM Physics

Overview

- Much early focus on SM physics
- Emphasis on providing solid links to external programs
  - Les Houches Accord (LHA) and Les Houches Events Files (LHEF) can be used to read in parton-level events for showering and hadronisation
  - Easy to use PYTHIA to simulate a wide range of BSM processes in this way
  - Important to understand what choices need to be made and what PYTHIA can and can't do
- But also complemented by a library of common BSM processes

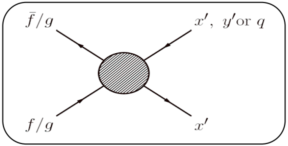
Available BSM Processes

Fourth Generation

Production of fourth generation quarks and leptons

Provide a template for models with new particles with similar characteristics

Include most quark scenarios (x = t,b):



and one lepton scenario: $f\bar{f} \rightarrow \tau'\nu'$

Parameters:

- Masses
- 4th generation CKM matrix elements

One/Two Higgs Doublets

($H_{i=1\text{-}3}$ = physical states of the h, H and A fields)

Contains:

- The standard set of SM processes
- Single H_i and $H^{+/-}$ production
- H_i and $H^{+/-}$ pair production
- Higher order processes for high-p_T samples

Parameters:

- Higgs mass(es)

(SM)

- Higgs width parameters (**cubicWidth** and **runningLoopMass**)

(BSM)

- Individual couplings to the SM particles
- SUSY couplings will be given by SLHA
- tan(β)
- Scalar / pseudo-scalar mixing, including CP violating interference

Available BSM Processes

New Gauge Bosons

From a new SU(2) or U(1) gauge group

Z':

Z' production with Z and/or γ^* interference

No dedicated high-pT processes, but proper matching of ISR to the Z'+1 jet ME

Parameters:
- g_v / g_a couplings for any fermion
- WW coupling + decay-angle parameter

W':

Same as for Z' but with less g_v / g_a flexibility

R^0 ("Horizontal" gauge boson):

Only mass parameter

Left-Right Symmetry

New SU(2)_R gauge group and extended Higgs sector

Contains:
- Production of W_R and Z_R
- Production of $H^{++/--}$
- Allow for right handed neutrino decays and cascade decays depending on mass hierarchy

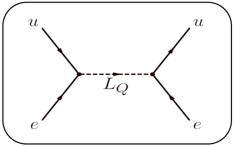
Other Higgs processes controlled by 2HD category

Parameters:
- Masses
- g_L, g_R and Higgs couplings
- v_L Vacuum Expectation Value

Available BSM Processes

Leptoquark

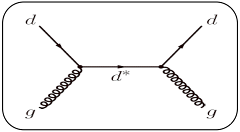
Production of a scalar leptoquark
(Conserved, but variable flavors)



Parameters:
- Mass
- Coupling

Compositeness

Production of excited leptons and quarks
(and anomalous couplings)



Parameters:
- Masses
- Coupling
- Compositeness scale

Supersymmetry

In Progress!

- Only groups of processes can be turned ON/OFF.
- All masses and couplings are given to Pythia 8 by SLHA1 or SLHA2 files.
- Currently gluino, squark, neutralino and chargino pair production (LO) is available, e.g.

  SUSY:gg2gluinogluino

  SUSY:qqbar2gluinogluino

  SUSY:qg2squarkgluino

  etc.

Processes related to an extended Higgs sector is kept in the Higgs section

- Allows for non-minimal flavour and/or CP violation.

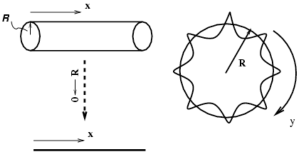
G. Bozzi et al., NPB 787 (2007) 1.

Remaining

- Direct slepton production processes, using the same general SUSY 2->2 structure as developed for the above processes.
- Decays, initially based only on phase space and externally computed total widths from BSM-LHEF or SLHA DECAY tables. Later including the matrix elements.
- Only R-parity conserving processes to start with.

Large Extra Dimension (LED) Scenario

Reminder: Compactified Extra Dimension



- Momentum modes in ED give KK tower.
- Large ED give dense KK states, i.e. effectively continuous mass distribution.
- ED phase space could compensate small gravitational coupling (aka ADD scenario).

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, PLB 429 (1998) 263

LED model parameters in Pythia8

n = integer nr of large extra dimensions.
M_D = scale of gravity in D = 4 + n dimensions.
Λ_T = cut-off scale for virtual G exchange.

G.F. Giudice, R. Rattazzi, J.D. Wells, NPB 544 (1999) 3

other popular conventions

$$M^{n+2} = 2M_D^{n+2}$$

E.A. Mirabelli, M. Perelstein, M.E. Peskin, PRL 82 (1999) 2236

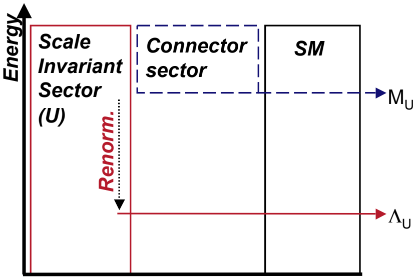
$$M_S^{n+2} = 8\pi^{1-\frac{n}{2}}\Gamma\left(\frac{n}{2}\right)M_D^{n+2}$$

T. Han, J.D. Lykken, R.-J. Zhang, PRD 59 (1999) 105006

$$\Lambda_H^4 = \frac{2}{\pi}\Lambda_T^4$$

J.L. Hewett, T.G. Rizzo, JHEP 0712 (2007) 009

Analogous Unparticle Scenario



Unpartices (U) belong to a scale invariant sector, only interacting with the SM via a connector sector at a high energy scale.

H. Georgi, PRL 98 (2007) 221601

Gives rise to

- Continuous U mass spectrum.
- Non-integer d_U-body phase space.

Similar to LED $$d_U = \frac{n}{2} + 1$$

Particle with access to one ED appears with a 1.5 particle phase space.

K. Cheung, W.Y. Keung, T.C. Yuan, PRD 76 (2007) 055003

Unparticle model parameters in Pythia8

Spin = 0, 1 or 2.
d_U = scale dimension parameter.
Λ_U = unparticle renormalization scale.
λ = coupling between U and SM (related to M_U).

MANCHESTER 1824

Common LED / Unparticle Processes

ATLAS

Common implementation, based on unparticle formulae, where the G process is obtained (when possible) from spin-2 unparticle matrix elements.

These common implementations simplifies for comparisons between the similar processes.

U to G Emission

$$d_U = \frac{n}{2} + 1$$
$$A(d_U) \leftrightarrow S(n)$$
$$\Lambda_U = M_D$$
$$\lambda_1 = \lambda_2 = 1$$

(phase space factors)

U to G Exchange

$$d_U = 2$$
$$\Lambda_U = \Lambda_T$$
$$\lambda^2 \cdot \chi = 4\pi$$

(factor from U propagator)

Doc: arXiv:0912.4233v1 [hep-ph]

MAN/HEP/2009/20
MCnet/09/20
DESY 09-214
Dec 2009

arXiv:0912.4233v1 [hep-ph] 21 Dec 2009

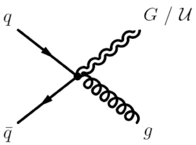
Real Emission and Virtual Exchange of Gravitons and Unparticles in Pythia8

S. Ask[1*], I. V. Akin[2], L. Benucci[3], A. De Roeck[3,4], M. Goebel[5,6], J. Haller[6]
1) *University of Manchester, UK.*
2) *Middle East Technical University, Ankara, Turkey.*
3) *Universiteit Antwerpen, Belgium.*
4) *CERN, Geneva, Switzerland.*
5) *DESY, Hamburg, Germany.*
6) *Universität Hamburg, Germany.*
* E-mail: Stefan.Ask@manchester.ac.uk

Abstract

Models with large extra dimensions as well as unparticle models could give rise to new phenomena at collider experiments due to real emission or virtual exchange of gravitons or unparticles. In this paper we present the common implementation of these processes in the Monte Carlo generator PYTHIA8, using relations between the parameters of the two models. The program offers several options related to the treatment of the UV region of the effective theories, including the possibility of using a form factor for the running gravitational coupling. Characteristic results obtained with PYTHIA8 have been used to validate the implementations as well as to illustrate the key features and effects of the model parameters. The results presented in this paper are focused on mono-jet, di-photon and di-lepton final states at the LHC.

Already Available	***Processes***



Mono-jet: **`gg2Gg, qg2Gq, qqbar2Gg`**

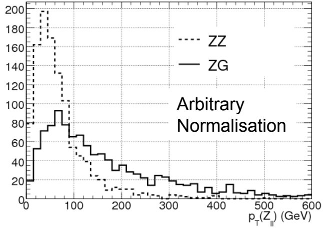
Mono-photon: **`ffbar2Ggamma`**

Mono-Z: **`ffbar2GZ`**

G and U options separated into **`ExtraDimensionsLED`** and **`ExtraDimensionsUnpart`** sections and name differ with **`G`** replaced by **`U`**.

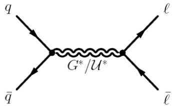
SA, EPJC 60 (2009) 509.

- Mono-photon process corresponds to the photon limit of the mono-Z process.
- No interference between photon/Z.
- The Z decays isotropically.
- No spin-2 U Matrix elements for mono-jet processes, i.e. G only spin-2 mono-jet scenario.



Virtual G / U* Exchange (LED/U)*

Already Available



Processes Di-lepton: **`gg2llbar, qqbar2llbar`**

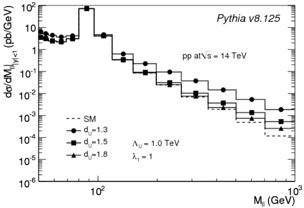
Di-photon: **`gg2gammagamma, qqbar2gammagamma`**

Include helicity dependent couplings between a spin-1 U and fermions (same options as for eta parameter on slide 6).

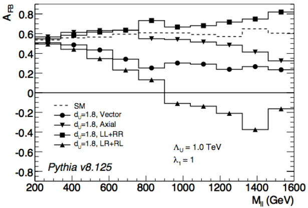
Could lead to interesting interference patterns and effects on the angular distribution.

H. Georgi, PLB 650 (2007) 275

Di-lepton production at the LHC



Forward-Backward Asymmetry



Resonances from Extra Dimensions

Smaller extra dimension models often give rise to resonances due the KK modes (smaller size, larger KK mode separation).

Complementary set of related resonances

- Graviton resonance,
  - gg and ffbar initiated / spin-2 / colour singlet.
  - Common coupling to all SM particles (RS1 with SM on the TeV brane).
  - Flavour dependent couplongs (RS1 with SM in bulk).

Already Available

in Progress!

- Z' resonance,
  - ffbar initiated / spin-1 / colour singlet.
  - Possible to specify any combination of couplings and SM interf.

Already Available

- Z_{KK} + gamma_{KK} resonances, ***(See Mark Suttons Talk!)***
  - ffbar initiated / spin-1 / colour singlet.
  - Include Z_{KK}/gamma_{KK} interference and multiple KK modes.

Next Version

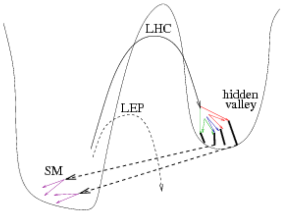
- Gluon resonance,
  - qqbar initiated / spin-1 / colour octet.

Next Version

BSM Physics

Hidden Valleys

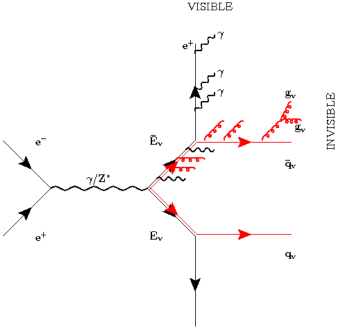
- "Echoes of a hidden valley at hadron colliders"
  M. Strassler, K. Zurek, Phys.Lett.B651:374-379,2007 [hep-ph/0604261]
  - Hidden gauge sector which does not couple to SM particles
  - Low mass scale
  - Barrier separates this sector from the SM
  - Coupling through e.g. heavy communicators
  - Decays via tunneling



- Whole class of models
  - What are the gauge groups of the hidden sector?
  - What are the communicators?

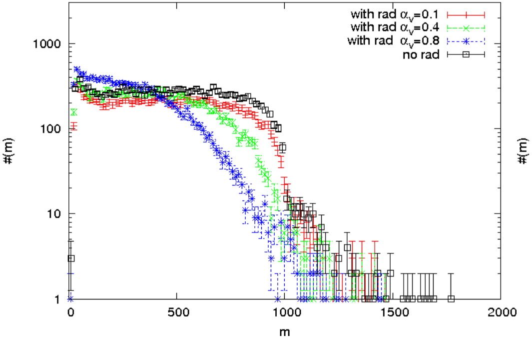
BSM Physics
Hidden Valleys

- "Visible Effects of Invisible Hidden Valley Radiation"
  L. Carloni and T. Sjöstrand, arXiv:1006.2911 [hep-ph]
  - Tools for Hidden Valley shower in PYTHIA 8
  - HV contains Abelian U(1) or non-Abelian unbroken SU(N) gauge group
  - Particles (F_v) content mirrors SM flavour structure
  - F_v are charged under both SM and HV gauge groups
  - Decays to SM particle and invisible, massive HV particle (q_v): $F_v \to f q_v$



BSM Physics
Hidden Valleys

- MT2 distribution
  - Lesters-Summers [hep-ph/9906349], Matchev [hep-ph/0910.3679]
  - $m_T^2 = M_e^2 + M_{q_v}^2 + 2(E_T^e \not{E}_T^{q_v} - \mathbf{p}_T^e \cdot \not{\mathbf{p}}_T^{q_v})$
  - Endpoint gives M_{E_v}
- Effects at LHC @ 14 TeV
- $L = 100 fb^{-1}$, $M_{D_v} = 1\,\mathrm{TeV}$, $M_{q_v} = 10\,\mathrm{GeV}$
- Tools coming in PYTHIA 8.140



Running PYTHIA 8
Overview

- Latest code available from:
  - `http://home.thep.lu.se/~torbjorn/Pythia.html`
- To get up and running:
  - `tar zxvf pythia81xx.tgz`
  - `cd pythia81xx`
  - `./configure; make`
- Some important files:

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

Running PYTHIA 8

Overview

- PYTHIA 8 is compiled to a library
- One include file and namespace:
  - `#include "Pythia.h"`
  - `using namespace Pythia8;`
- Generator object is created by instantiating the Pythia class
  - `Pythia pythia;`
- Different ways to initialise
  - `pythia.init( idA, idB, eCM );`
  - `pythia.init( "LHEF filename" );`
- Generate next event
  - `pythia.next();`
- Event record is a C++ vector of ‘Particle’ class
  - `pythia.event[3].id();`
  - `pythia.event[10].isCharged();`
  - `pythia.event[10].p();`
- Summary information
  - `pythia.statistics();`

- Internal settings database
  - pythia.readString("command");
  - pythia.readFile("filename");
  - Where filename contains one command per line
- A command has the form (not case sensitive):
  - Settings: 'task:property = value'

Command		Description
PartonLevel:FSR	= off	Master switch for FSR
SpaceShower:pTmin	= 1.25	Lower cutoff for ISR
SigmaProcess:alphaSorder	= 2	2nd order α_s running (for hard process)
SoftQCD:minBias	= on	Switch on minimum bias processes
HiggsSM:gg2H	= on	Switch on Standard Model Higgs production

  - Particle data 'id:property = value' or 'id:channel:property = value'

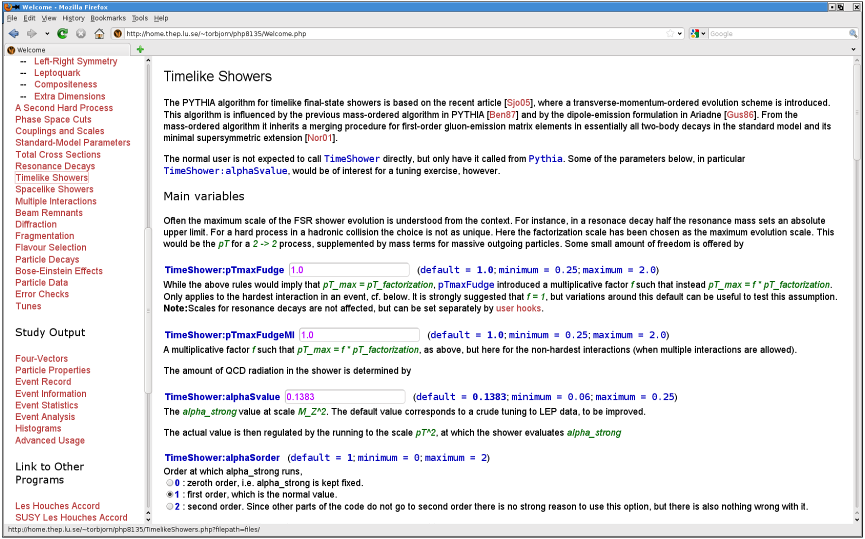
Command		Description
25:m0	= 150.0	Set Higgs mass to 150.0 GeV
25:onMode	= off	Turn off all Higgs decays
25:onIfAll	= 23 23	Turn on Higgs to ZZ decays
111:mayDecay	= 0	Turn off π^0 decays
215:3:products	= 211 111 111	Let $a_2^+ \to \pi^+\pi^0\pi^0$

- Full details of all commands in the HTML documentation

Running PYTHIA 8

PHP/HTML documentation

- Change settings in PHP pages and write out command file



Welcome - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://home.thep.lu.se/~torbjorn/php8135/Welcome.php

Welcome

-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Extra Dimensions
A Second Hard Process
Phase Space Cuts
Couplings and Scales
Standard-Model Parameters
Total Cross Sections
Resonance Decays
Timelike Showers
Spacelike Showers
Multiple Interactions
Beam Remnants
Diffraction
Fragmentation
Flavour Selection
Particle Decays
Bose-Einstein Effects
Particle Data
Error Checks
Tunes

Study Output

Four-Vectors
Particle Properties
Event Record
Event Information
Event Statistics
Event Analysis
Histograms
Advanced Usage

Link to Other Programs

Les Houches Accord
SUSY Les Houches Accord

Timelike Showers

The PYTHIA algorithm for timelike final-state showers is based on the recent article [Sjo05], where a transverse-momentum-ordered evolution scheme is introduced. This algorithm is influenced by the previous mass-ordered algorithm in PYTHIA [Ben87] and by the dipole-emission formulation in Ariadne [Gus86]. From the mass-ordered algorithm it inherits a merging procedure for first-order gluon-emission matrix elements in essentially all two-body decays in the standard model and its minimal supersymmetric extension [Nor01].

The normal user is not expected to call TimeShower directly, but only have it called from Pythia. Some of the parameters below, in particular TimeShower:alphaSvalue, would be of interest for a tuning exercise, however.

Main variables

Often the maximum scale of the FSR shower evolution is understood from the context. For instance, in a resonance decay half the resonance mass sets an absolute upper limit. For a hard process in a hadronic collision the choice is not as unique. Here the factorization scale has been chosen as the maximum evolution scale. This would be the *pT* for a *2 -> 2* process, supplemented by mass terms for massive outgoing particles. Some small amount of freedom is offered by

TimeShower:pTmaxFudge 1.0 (default = **1.0**; minimum = 0.25; maximum = 2.0)
While the above rules would imply that *pT_max = pT_factorization*, pTmaxFudge introduced a multiplicative factor *f* such that instead *pT_max = f * pT_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.

TimeShower:pTmaxFudgeMI 1.0 (default = **1.0**; minimum = 0.25; maximum = 2.0)
A multiplicative factor *f* such that *pT_max = f * pT_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

TimeShower:alphaSvalue 0.1383 (default = **0.1383**; minimum = 0.06; maximum = 0.25)
The *alpha_strong* 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 *pT^2*, at which the shower evaluates *alpha_strong*

TimeShower:alphaSorder (default = **1**; minimum = 0; maximum = 2)
Order at which alpha_strong runs,
- **0** : zeroth order, i.e. alpha_strong 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.

http://home.thep.lu.se/~torbjorn/php8135/TimelikeShowers.php?filepath=files/

Running PYTHIA 8

First example: main01.cc

```
#include "Pythia.h"
using namespace Pythia8;

int main() {
  Pythia pythia;                                                  // Generator
  pythia.readString("HardQCD:all = on");                          // Process selection
  pythia.readString("PhaseSpace:pTHatMin = 20.");                 // Cuts
  pythia.init( 2212, 2212, 14000.);                               // LHC initialisation
  pythia.settings.listChanged();                                  // Print settings
  Hist mult("charged multiplicity", 100, -0.5, 799.5);            // Book histogram

  for (int iEvent = 0; iEvent < 100; ++iEvent) {                  // Start of event loop
    if (!pythia.next()) continue;                                 // Generate event
    if (iEvent < 1)
      { pythia.info.list(); pythia.event.list(); }                // Print first event

    int nCharged = 0;                                             // Count nChg
    for (int i = 0; i < pythia.event.size(); ++i)
      if (pythia.event[i].isFinal() &&
          pythia.event[i].isCharged()) ++nCharged;
    mult.fill( nCharged );                                        // Fill histogram
  }                                                               // End of event loop

  pythia.statistics();                                            // Print statistics
  cout << mult;                                                   // Print histogram
  return 0;                                                       // Done
}
```

Running PYTHIA 8

Understanding the output: pythia.init()

- Not much to see yet; estimated cross sections and MI initialisation

```
*-------  PYTHIA Process Initialization  --------------------------*
|                                                                  |
| We collide p+ with p+ at a CM energy of 1.400e+04 GeV            |
|                                                                  |
|------------------------------------------------------------------|
|                                                      |           |
| Subprocess                                      Code |  Estimated |
|                                                      |   max (mb) |
|                                                      |           |
|------------------------------------------------------------------|
|                                                      |           |
| g g -> g g                                       111 |  4.206e+00 |
| g g -> q qbar (uds)                              112 |  4.407e-02 |
| q g -> q g                                       113 |  2.294e+00 |
| q q(bar)' -> q q(bar)'                           114 |  2.149e-01 |
| q qbar -> g g                                    115 |  1.454e-03 |
| q qbar -> q' qbar' (uds)                         116 |  6.426e-04 |
| g g -> c cbar                                    121 |  1.453e-02 |
| q qbar -> c cbar                                 122 |  2.129e-04 |
| g g -> b bbar                                    123 |  1.323e-02 |
| q qbar -> b bbar                                 124 |  2.018e-04 |
|                                                                  |
*-------  End PYTHIA Process Initialization ----------------------*

*-------  PYTHIA Multiple Interactions Initialization  ------------*
|                                                                  |
|                  sigmaNonDiffractive =    54.72 mb               |
|                                                                  |
|    pT0 =  3.68 gives sigmaInteraction =  192.71 mb: accepted     |
|                                                                  |
*-------  End PYTHIA Multiple Interactions Initialization  --------*
```

Running PYTHIA 8

Understanding the output: pythia.settings.listChanged() & pythia.info.list()

- `pythia.settings.listChanged()`: check setup

```
*-------  PYTHIA Flag + Mode + Parm + Word Settings (changes only)  ------------------------------------------*
|                                                                                                              |
| Name                                            |                      Now |      Default         Min          Max |
|                                                 |                          |                                         |
| HardQCD:all                                     |                       on |          off                            |
| PhaseSpace:pTHatMin                             |                 20.00000 |          0.0          0.0                |
|                                                                                                              |
*-------  End PYTHIA Flag + Mode + Parm + Word Settings  ------------------------------------------------------*
```

- `pythia.info.list()`: event information (all properties available in code; see HTML documentation → Event Information)

```
 --------  PYTHIA Info Listing  ----------------------------------------

 Beam A: id =   2212, pz =  7.000e+03, e =  7.000e+03, m =  9.383e-01.
 Beam B: id =   2212, pz = -7.000e+03, e =  7.000e+03, m =  9.383e-01.

 In 1: id =   21, x =  2.147e-03, pdf =  2.023e+01 at Q2 =  6.659e+02.
 In 2: id =   21, x =  6.857e-03, pdf =  9.931e+00 at same Q2.

 Subprocess g g -> g g with code 111 is 2 -> 2.
 It has sHat =  2.886e+03,    tHat = -1.042e+03,    uHat = -1.844e+03,
       pTHat =  2.581e+01,   m3Hat =  0.000e+00,   m4Hat =  0.000e+00,
    thetaHat =  1.289e+00,  phiHat =  2.024e+00.
     alphaEM =  7.707e-03,  alphaS =  1.571e-01    at Q2 =  6.659e+02.

 Impact parameter b = 3.972e-01 gives enhancement factor =  2.548e+00.
 Max pT scale for MI =  2.581e+01, ISR =  2.581e+01, FSR =  2.581e+01.
 Number of MI =     5, ISR =    20, FSRproc =   148, FSRreson =     0.

 --------  End PYTHIA Info Listing  ------------------------------------
```

Running PYTHIA 8

Understanding the output: pythia.event.list()

-------- PYTHIA Event Listing (complete event) --

no	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
0	90	(system)	-11	0	0	0	0	0	0	0.000	0.000	0.000	14000.000	14000.000
1	2212	(p+)	-12	0	0	296	0	0	0	0.000	0.000	7000.000	7000.000	0.938
2	2212	(p+)	-12	0	0	297	0	0	0	0.000	0.000	-7000.000	7000.000	0.938
3	-1	(dbar)	-21	6	0	5	5	0	101	0.000	0.000	204.251	204.251	0.000
4	1	(d)	-21	7	7	5	5	101	0	0.000	0.000	-10.210	10.210	0.000
5	23	(Z0)	-22	3	4	8	8	0	0	0.000	0.000	194.041	214.461	91.332
6	-1	(dbar)	-41	47	47	9	3	0	103	0.000	0.000	307.261	307.261	0.000
7	1	(d)	-42	12	12	4	4	101	0	-0.000	-0.000	-10.210	10.210	0.000
8	23	(Z0)	-44	5	5	49	49	0	0	8.809	11.101	212.343	231.586	91.332
9	21	(g)	-43	6	0	10	11	101	103	-8.809	-11.101	84.708	85.885	0.000
10	21	(g)	-51	9	0	40	40	104	103	-4.019	-12.530	18.187	22.448	0.000
11	21	(g)	-51	9	0	17	18	101	104	-4.790	1.429	64.882	65.075	0.000
12	1	(d)	-53	19	19	7	7	101	0	-0.000	-0.000	-11.848	11.848	0.000
13	21	(g)	-31	27	0	15	16	106	107	0.000	0.000	0.449	0.449	0.000
14	2	(u)	-31	28	28	15	16	105	0	0.000	0.000	-1439.239	1439.239	0.000
15	21	(g)	-33	13	14	29	29	105	107	-3.210	5.131	-20.260	21.145	0.000
16	2	(u)	-33	13	14	30	30	106	0	3.210	-5.131	-1418.530	1418.543	0.330

...

- Cheated a bit; this is a Z^0 event (but with a lot to see)
  - Hard process
  - Initial state radiation (note: the Z^0 now has $p_\perp$)
  - Final state radiation
  - Multiple interaction
- Doesn't end there!

Running PYTHIA 8

Understanding the output: pythia.event.list()

```
--------  PYTHIA Event Listing  (complete event)  ---------------------------------------------------------
no     id   name        status    mothers   daughters     colours    p_x        p_y        p_z         e          m
...
296    -1   (dbar)        -61      1     0   223   223     0   103  -0.453     -0.938    707.715    707.716      0.000
297     1   (d)           -61      2     0    60    60   157     0   0.850     -0.456    -16.777     16.804      0.000
298    23   (Z0)          -62     61    61   399   400     0     0   8.292     10.315    210.714    230.038     91.332
299    21   (g)           -62    274   274   474     0   150   145   0.060     -0.041      0.221      0.233      0.000
300    21   (g)           -62    177   177   473     0   108   140   0.433     -0.078      3.610      3.637      0.000
...
399     1   (d)           -23    298     0   401   402   102     0  -6.292    -30.751     27.566     41.776      0.330
400    -1   (dbar)        -23    298     0   403   403     0   102  14.583     41.066    183.148    188.262      0.330
401     1   (d)           -51    399     0   404   405   202     0  -8.192    -31.438     31.555     45.291      0.330
402    21   (g)           -51    399     0   406   406   102   202   6.210     12.823     50.136     52.121      0.000
403    -1   (dbar)        -52    400   400   427   427     0   102  10.274     28.930    129.023    132.626      0.330
...
```

- Resonance decays
  - Short lived resonances → decay already considered at the hard process stage (and then “stitched” onto the event)
  - In several cases, decay angular distributions are encoded as part of the specific process
- Subsequent resonance shower from decay products

Running PYTHIA 8

Understanding the output: pythia.event.list()

```
--------  PYTHIA Event Listing  (complete event)  ---------------------------------------------------------
no      id   name     status   mothers     daughters     colours      p_x        p_y        p_z         e          m
...
938     22   gamma       91   803    0     0     0     0     0    -0.009      0.094     -0.171      0.195      0.000
939    211   pi+         91   812    0     0     0     0     0     0.118      0.116     -0.507      0.552      0.140
940   -211   pi-         91   812    0     0     0     0     0     0.108     -0.140     -0.390      0.450      0.140
941    221   (eta)      -91   812    0   973   975     0     0     0.066      0.059     -0.993      1.137      0.548
942   -211   pi-         91   813    0     0     0     0     0    -0.036      0.848     -1.590      1.808      0.140
943    111   (pi0)      -91   813    0   976   977     0     0     0.394      0.098     -0.938      1.031      0.135
...
971     11   e-          91   928    0     0     0     0     0    -0.186     -0.002     -1.766      1.776      0.001
972    -11   e+          91   928    0     0     0     0     0    -0.086      0.000     -0.798      0.803      0.001
973    211   pi+         91   941    0     0     0     0     0    -0.161      0.075     -0.677      0.714      0.140
974   -211   pi-         91   941    0     0     0     0     0     0.196     -0.014     -0.232      0.335      0.140
975     22   gamma       91   941    0     0     0     0     0     0.031     -0.002     -0.083      0.089      0.000
976     22   gamma       91   943    0     0     0     0     0     0.124     -0.007     -0.412      0.431      0.000
977     22   gamma       91   943    0     0     0     0     0     0.270      0.106     -0.525      0.600      0.000
                       Charge sum:  2.000          Momentum sum:      0.000      0.000      0.000  14000.000  14000.000

--------  End PYTHIA Event Listing  -----------------------------------------------------------------------
```

- Events get large, but easy to process in code
- All particles with positive status codes are final
- All particle properties displayed in the listing (and others as well) are accessible through appropriate methods
  - e.g. `pythia.event[977].px();`
  - HTML documentation → Particle Properties
  - Also contains a list of status codes and their meanings

Running PYTHIA 8

Understanding the output: pythia.statistics()

```
*-------  PYTHIA Event and Cross Section Statistics  -------------------------------------------------------------*
|                                                                                                                 |
| Subprocess                                    Code |            Number of events       |      sigma +- delta    |
|                                                    |       Tried   Selected   Accepted |     (estimated) (mb)   |
|                                                    |                                   |                        |
|-----------------------------------------------------------------------------------------------------------------|
|                                                    |                                   |                        |
| g g -> g g                                     111 |      521518      60320      60320 |   4.857e-01  1.058e-03 |
| g g -> q qbar (uds)                            112 |        5484       1255       1255 |   9.788e-03  1.476e-04 |
| q g -> q g                                     113 |      284792      34105      34105 |   2.752e-01  8.361e-04 |
| q q(bar)' -> q q(bar)'                         114 |       26781       3451       3451 |   2.741e-02  2.555e-04 |
| q qbar -> g g                                  115 |         194         51         51 |   3.611e-04  2.473e-05 |
| q qbar -> q' qbar' (uds)                       116 |          79         28         28 |   2.318e-04  1.987e-05 |
| g g -> c cbar                                  121 |        1857        402        402 |   3.292e-03  8.640e-05 |
| q qbar -> c cbar                               122 |          29          6          6 |   6.940e-05  1.243e-05 |
| g g -> b bbar                                  123 |        1654        372        372 |   3.100e-03  8.429e-05 |
| q qbar -> b bbar                               124 |          34         10         10 |   6.189e-05  9.902e-06 |
|                                                    |                                   |                        |
| sum                                                |      842422     100000     100000 |   8.052e-01  1.386e-03 |
|                                                                                                                 |
*-------  End PYTHIA Event and Cross Section Statistics ----------------------------------------------------------*
```

- Overview of number of events generated and estimated cross sections
  - Tried events reflect the original number of phase-space points probed, as part of the upper estimate
  - Selected events correspond to those that survive the internal Monte-Carlo selection procedure
  - Accepted events are those that also survive the additional user cuts

Running PYTHIA 8

Understanding the output: pythia.statistics()

```
*-------  PYTHIA Error and Warning Messages Statistics  ----------------------------------------------------------*
|                                                                                                                  |
|  times   message                                                                                                 |
|                                                                                                                  |
|      1   Error in BeamRemnants::setKinematics: kinematics construction failed                                    |
|    367   Error in Pythia::next: hadronLevel failed; try again                                                    |
|     15   Error in SpaceShower::pT2nearQCDthreshold: stuck in loop                                                |
|    255   Error in StringFragmentation::fragment: stuck in joining                                                |
|    112   Error in StringFragmentation::fragmentToJunction: caught in junction flavour loop                       |
|      1   Warning in MultipleInteractions::init: maximum increased                                                |
|     38   Warning in MultipleInteractions::pTnext: weight above unity                                             |
|      3   Warning in ParticleDataEntry::initBWmass: switching off width                                           |
|     12   Warning in Pythia::check: energy-momentum not quite conserved                                           |
|     21   Warning in SpaceShower::pT2nextQCD: weight above unity                                                  |
|     99   Warning in StringFragmentation::fragmentToJunction: bad convergence junction rest frame                 |
|                                                                                                                  |
*-------  End PYTHIA Error and Warning Messages Statistics  ------------------------------------------------------*
```

- Warnings and errors
  - Messages are printed only the first time it occurs; after that, counted only
  - Warning: minor problem that is automatically fixed by PYTHIA
  - Error: bigger problem, but still automatically fixed by backing up and trying again
- When to worry?
  - `pythia.next()` returns true (event okay) or false (abort)
  - An abort means an event could not be completed
  - Can skip such events, but may be a sign that something isn't right!

- The final result!

```
2010-06-26 22:38          charged multiplicity

       4.35*10^ 3                       1  1
       4.20*10^ 3                       X87X 2
       4.05*10^ 3                     79XXXX9X
       3.90*10^ 3                   69XXXXXXXX7
       3.75*10^ 3                   XXXXXXXXXXX8
       3.60*10^ 3                  XXXXXXXXXXXXX
       3.45*10^ 3                 7XXXXXXXXXXXXX81
       3.30*10^ 3                 XXXXXXXXXXXXXXXX
       3.15*10^ 3               34XXXXXXXXXXXXXXXX
       3.00*10^ 3               XXXXXXXXXXXXXXXXXX1
       2.85*10^ 3              1XXXXXXXXXXXXXXXXXXX3
       2.70*10^ 3              XXXXXXXXXXXXXXXXXXXXX
       2.55*10^ 3             2XXXXXXXXXXXXXXXXXXXXX
       2.40*10^ 3             XXXXXXXXXXXXXXXXXXXXXX5
       2.25*10^ 3             XXXXXXXXXXXXXXXXXXXXXXX4
       2.10*10^ 3            8XXXXXXXXXXXXXXXXXXXXXXXX3
       1.95*10^ 3            XXXXXXXXXXXXXXXXXXXXXXXXXX
       1.80*10^ 3            XXXXXXXXXXXXXXXXXXXXXXXXXX3
       1.65*10^ 3            XXXXXXXXXXXXXXXXXXXXXXXXXXX
       1.50*10^ 3           9XXXXXXXXXXXXXXXXXXXXXXXXXXX2
       1.35*10^ 3           XXXXXXXXXXXXXXXXXXXXXXXXXXXXX3
       1.20*10^ 3           XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
       1.05*10^ 3          4XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX6
       0.90*10^ 3          XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX9
       0.75*10^ 3          XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4
       0.60*10^ 3         5XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX62
       0.45*10^ 3         XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX5
       0.30*10^ 3        5XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX931
       0.15*10^ 3      14XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX765332111 1

         Contents
           *10^ 3  0000000001222333333444444443333222211110000000000000000000000000000000000000000000000000
           *10^ 2  0000002594047004688002112008743873196329865432211000000000000000000000000000000000000000
           *10^ 1  0000152268721360039041752275122732699849863879061974321010000000000000000000000000000000
           *10^ 0  0001282123780837351829340990520094007274176141150554999922826233000000000100000000000000

         Low edge  -
           *10^ 2  0000000000000111111111111222222222222233333333333344444444444445555555555556666666666666
           *10^ 1  0012344567889012234566789001234456788901223456678900123445678890122345667890012344567889
           *10^ 0  1864208642086420864208642086420864208642086420864208642086420864208642086420864208642086

 Entries  =      100000    Mean =  1.9158e+02    Underflow =  0.0000e+00    Low edge  = -5.0000e-01
 All chan =  1.0000e+05    Rms  =  6.9434e+01    Overflow  =  0.0000e+00    High edge =  7.9950e+02
```

Conclusions

- PYTHIA 8 is a general purpose Monte Carlo event generator
- Simple to use..
- .. but a lot going on behind the scenes!
- Full tuning still to come
- Worksheet is a great place to get start
- Feedback always welcome!