LUND UNIVERSITY

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PYTHIA 8.1

Introduction and Tutorial

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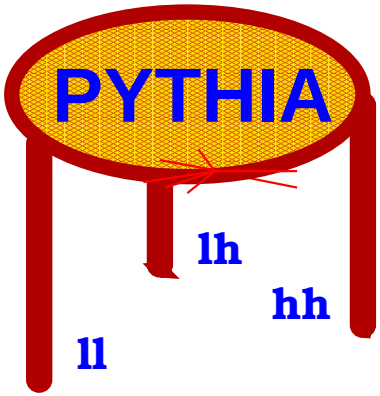
PYTHIA history

the core member of the “Lund Monte Carlo” family

Note: time axis not to scale



1978

JETSET

versions 1–7

string frag.

e^+e^-, FSR

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

Who was Pythia?

The Oracle of Delphi: ca. 1000 B.C. — 390 A.D.

PYTHIA Physics (part I)

Hard processes:

- Built-in library of many leading-order processes.
  Standard Model: almost all $2 \to 1$ and $2 \to 2$, a few $2 \to 3$.
  Beyond the SM: a bit of each (PYTHIA 8 not yet SUSY and TC).
- External input via Les Houches Accord and Les Houches Event Files from MadGraph, CompHep, AlpGen, ...
- Resonance decays, often but not always with angular correlations .

Showers:

- Transverse-momentum-ordered ISR & FSR, but
  PYTHIA 6 still older virtuality-ordered as default.
- Includes $q \to qg$, $g \to gg$, $g \to q\overline{q}$, $f \to f\gamma$, $\gamma \to f\overline{f}$ (f = fermion).
- ISR by backwards evolution.
- Dipole-style approach to recoils.
- Matching to ME's for first (=hardest) emission in many processes, especially gluon emission in resonance decays.

PYTHIA Physics (part II)

Underlying event:

- Multiple interactions, see separate presentation.
- Combined evolution MI + ISR + FSR downwards in $p_\perp$.
- Beam remnants colour-connected to interacting systems.

Hadronization:

- String fragmentation ("the Lund Model").
- Particle decays, usually isotropic.
- Link to external decay packages, say for τ (TAUOLA) or B (EVTGEN).
- Optional Bose-Einstein effects.

Utilities:

- Four-vectors, random numbers, parton densities, . . .
- Event study routines: sphericity, thrust, jet finding.
- Simple built-in histogramming package (line-printer mode).

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:

- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:

- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially SUSY & Technicolor

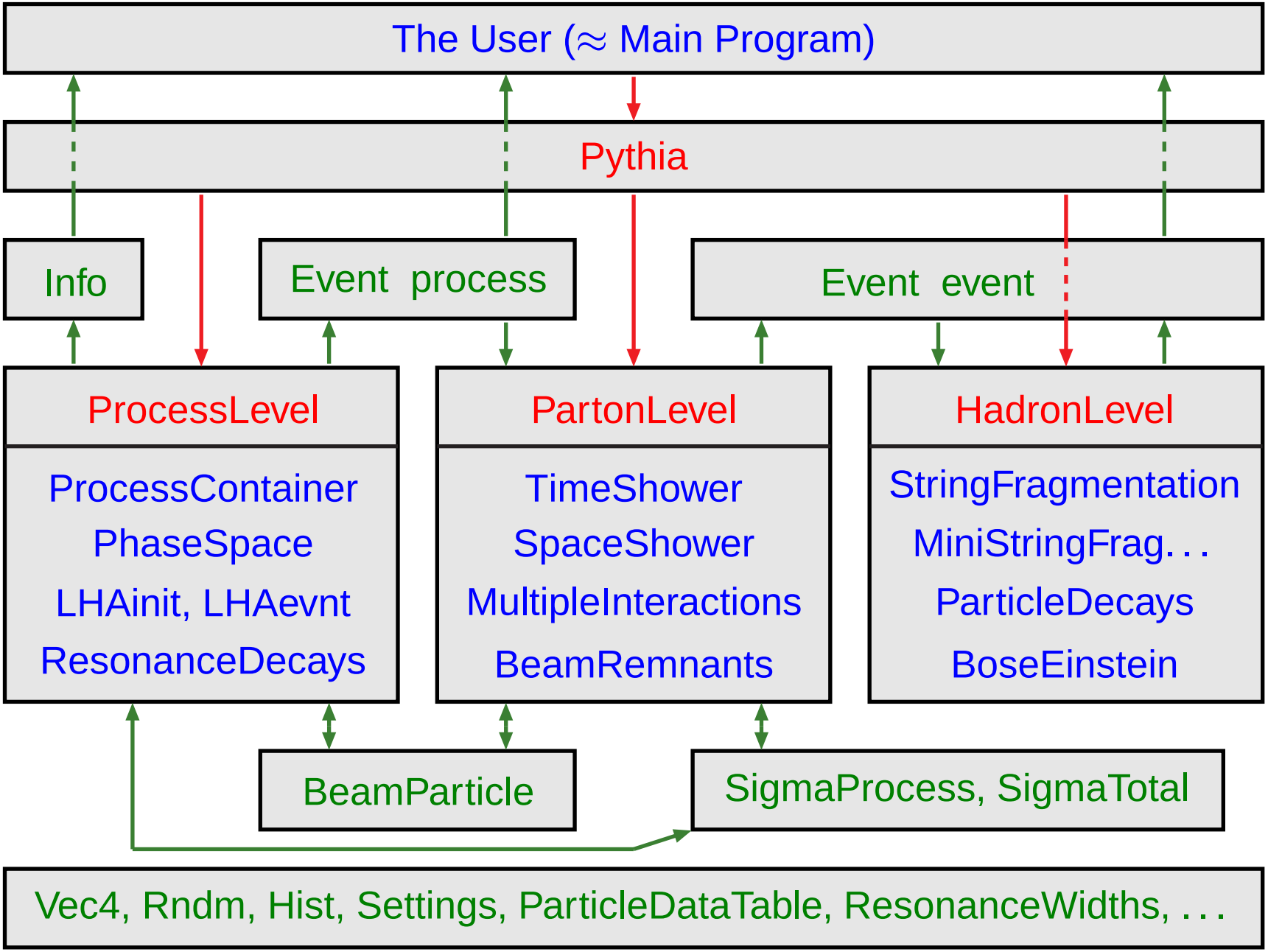
New features, not found in 6.4:

- interleaved $p_\perp$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes (γ, J/ψ, DY, ...)
- possibility for two selected hard interactions in same event
- possibility to use one PDF set for hard process and another for rest
- elastic scattering with Coulomb term (optional)
- updated decay data

Preliminary plans for the future:

- rescattering in multiple interactions
- NLO and L-CKKW matching

PYTHIA 8 structure



Example of a main program

```
// File: main01.cc. The charged multiplicity distribution at the LHC.
#include "Pythia.h"
using namespace Pythia8;
int main() {
  // Generator. Process selection. LHC initialization. Histogram.
  Pythia pythia;
  pythia.readString("HardQCD:all = on");
  pythia.readString("PhaseSpace:pTHatMin = 20.");
  pythia.init( 2212, 2212, 14000.);
  Hist mult("charged multiplicity", 100, -0.5, 799.5);
  // Begin event loop. Generate event. Skip if error. List first one.
  for (int iEvent = 0; iEvent < 100; ++iEvent) {
    if (!pythia.next()) continue;
    if (iEvent < 1) {pythia.info.list(); pythia.event.list();}
    // Find number of all final charged particles and fill histogram.
    int nCharged = 0;
    for (int i = 0; i < pythia.event.size(); ++i)
      if (pythia.event[i].isFinal() && pythia.event[i].isCharged())
        ++nCharged;
    mult.fill( nCharged );
  // End of event loop. Statistics. Histogram. Done.
  }
  pythia.statistics();
  cout << mult;
  return 0;
}
```

Initialization and generation commands

Standard in beginning:

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

Initialization by one of different forms:

- `pythia.init( idA, idB, eA, eB)` along $\pm z$ axis
- `pythia.init( idA, idB, eCM)` in c.m. frame
- `pythia.init( "filename")` for Les Houches Event Files
- `pythia.init()` takes above kinds of input from “cards”
- `pythia.init( LHAinit*, LHAevnt*)` for Les Houches Accord

returns `false` if failed (normally user setup mistake!)

Generation of next event by:

- `pythia.next()`

with no arguments, but value `false` if failed (rare!)

At the end of the generation loop:

- `pythia.statistics()`

provides some summary information

Settings and Particle Data

Can read in settings and particle data changes by

- `pythia.readString("command")`
- `pythia.readFile("filename")` with one `command` per line in file

Settings come in four kinds

- Flags: on/off switches, `bool`
  (`on = yes = ok = true = 1, off = no = false = 0`)
- Modes: enumerated options, `int`
- Parms: (short for parameters) continuum of values, `double`
- Words: characters (no blanks), `string`

and `command` is of form `task:property = value`, e.g.

`PartonLevel:ISR = off` no initial-state radiation

`SigmaProcess:alphaSorder = 0` freeze α_s

`TimeShower:pTmin = 1.0` cut off final-state radiation at 1 GeV

To access **particle data**, instead `command` should be of form

`id:property = value` or `id:channel:property = value`, e.g.

`3122:mayDecay = no` do not allow Λ^0 to decay

`215:3:products = 211 111 111` to let $a_2^+ \to \pi^+\pi^0\pi^0$

Note: case-insensitive search/matching in databases!

Example of a “cards” file

```
! This file contains commands to be read in for a Pythia8 run.
! Lines not beginning with a letter or digit are comments.

! 1) Settings that could be used in a main program, if desired.
Beams:idA = 2212                    ! first beam, p = 2212, pbar = -2212
Beams:idB = 2212                    ! second beam, p = 2212, pbar = -2212
Beams:eCM = 14000.                  ! CM energy of collision
Main:numberOfEvents = 1000          ! number of events to generate
Main:numberToList = 2               ! number of events to print
Main:timesToShow = 20               ! show how far along run is
Main:showChangedSettings = on       ! print changed flags/modes/parameters
Main:showAllSettings = off          ! print all flags/modes/parameters

! 2) Settings for the hard-process generation.
HiggsSM:gg2H = on                   ! Higgs production by gluon-gluon fusion
25:m0 = 123.5                       ! Higgs mass
25:onMode = off                     ! switch off all Higgs decay channels
25:onIfMatch = 22 22                ! switch back on Higgs -> gamma gamma
SigmaProcess:alphaSvalue = 0.12     ! alpha_s(m_Z) in matrix elements

! 3) Settings for the subsequent event generation process.
SpaceShower:alphaSvalue = 0.13      ! alpha_s(m_Z) in initial-state radiation
MultipleInteractions:pT0Ref = 3.0   ! pT_0 regularization at reference energy
#PartonLevel:MI = off               ! no multiple interactions
#PartonLevel:ISR = off              ! no initial-state radiation
#PartonLevel:FSR = off              ! no final-state radiation
#HadronLevel:Hadronize = off        ! no hadronization
```

Show settings and particle data

Show settings:

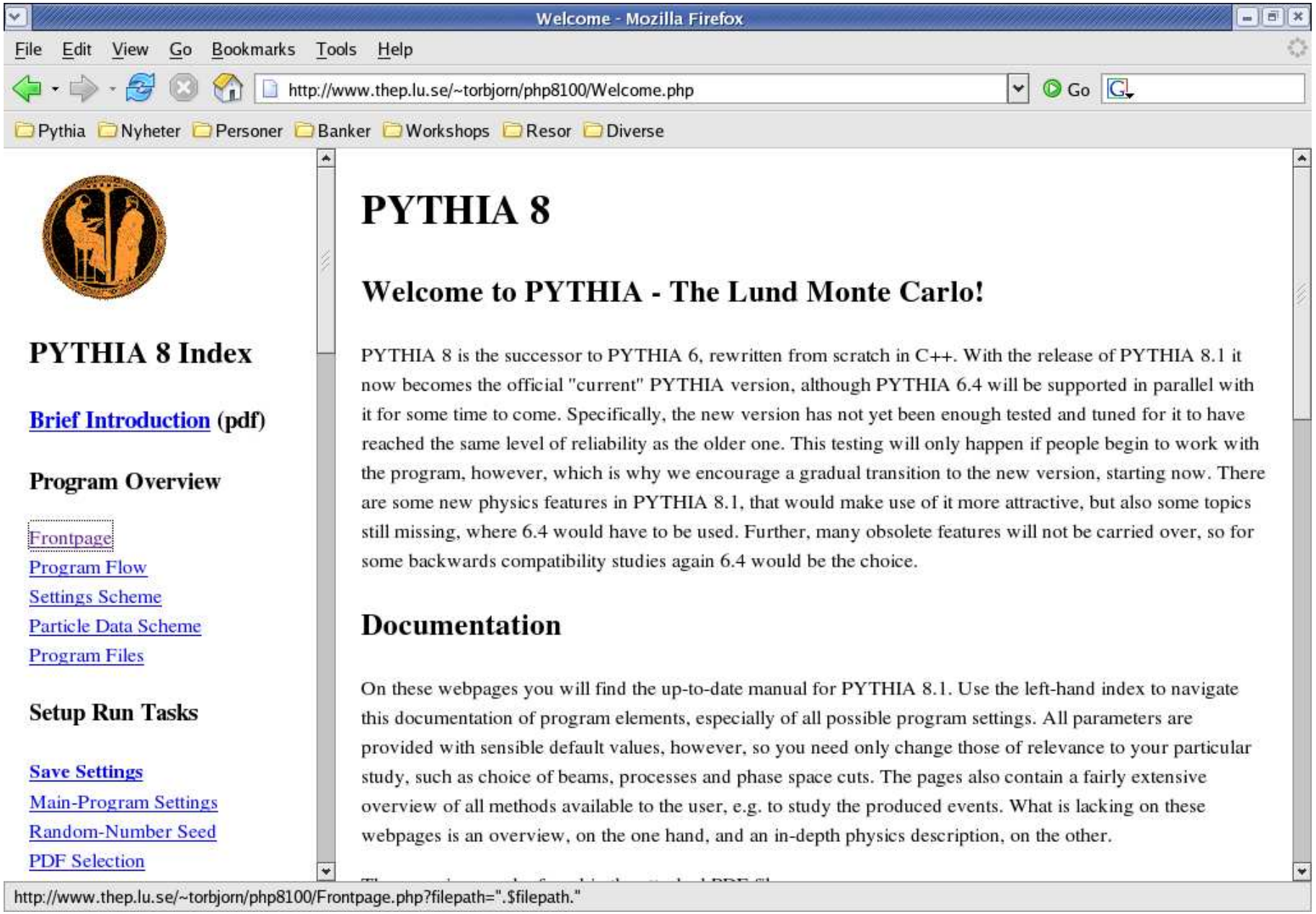
- `pythia.settings.listAll()` : complete list
- `pythia.settings.listChanged()` : only changed ones

```
*-------  PYTHIA Flag + Mode + Parm + Word Settings (changes only)  --------------------------*
|                                                                                              |
| Name                                    |            Now |      Default         Min         Max |
|                                         |                |                                      |
| HardQCD:all                             |             on |          off                         |
| Main:numberToList                       |              1 |            2           0             |
| Main:showChangedParticleData            |             on |          off                         |
| Main:timesToShow                        |             20 |           50           0             |
| MultipleInteractions:pTmin              |        3.00000 |      0.20000     0.10000     10.00000 |
| PhaseSpace:pTHatMin                     |       50.00000 |          0.0         0.0             |
| PromptPhoton:all                        |             on |          off                         |
| SpaceShower:pT0Ref                      |        2.00000 |      2.20000     0.50000     10.00000 |
|                                                                                              |
*-------  End PYTHIA Flag + Mode + Parm + Word Settings  -------------------------------------*
```

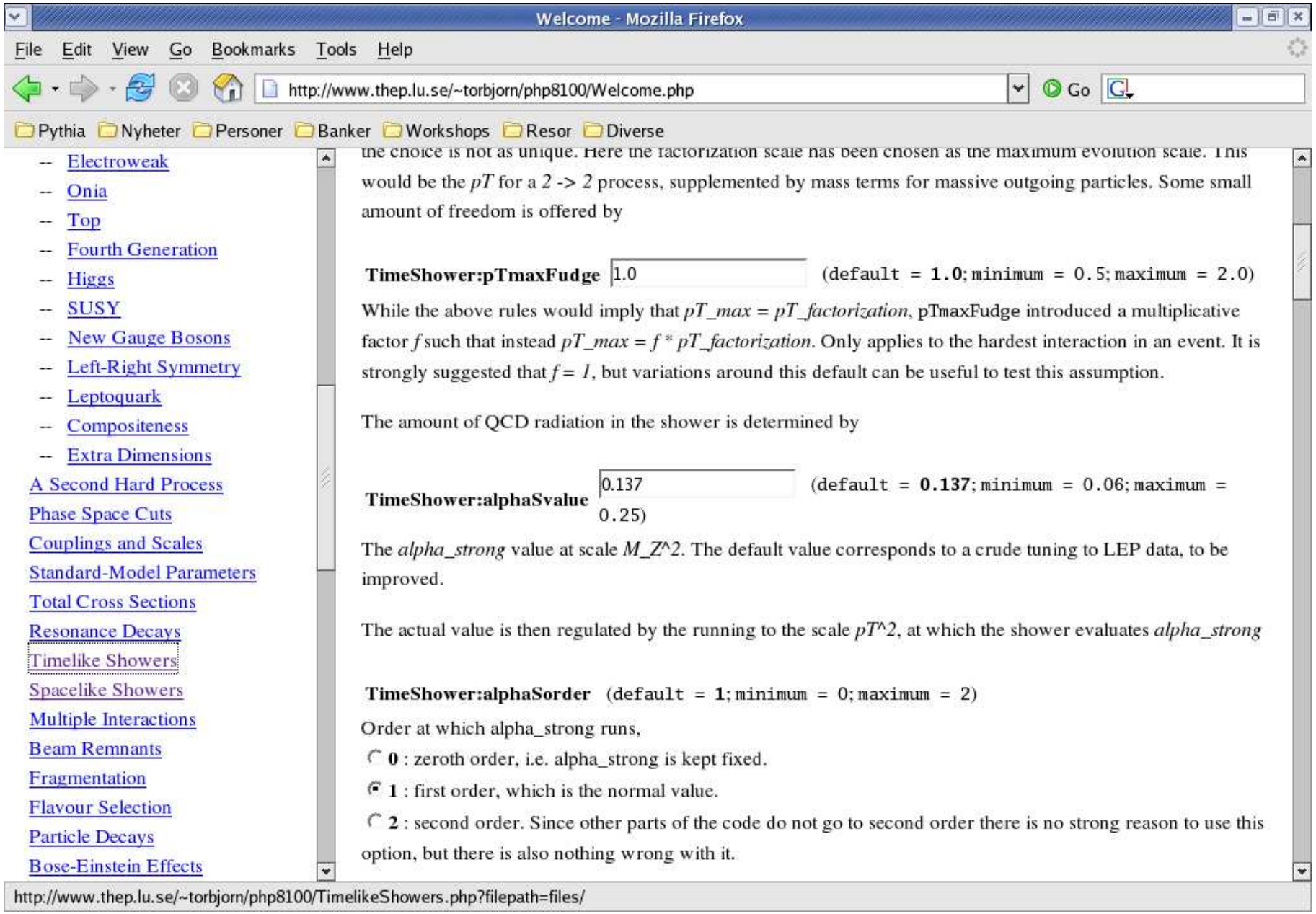
Show particle data:

- `pythia.particleData.listAll()` : complete list
- `pythia.particleData.listChanged()` : only changed ones
- `pythia.particleData.list(id)` : only one (or `vector<int>`)

Online manual $\Longrightarrow$ Graphical User Interface



Example: timelike parton showers



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The Particle class in the event record

Each `Particle` object stores the properties:

- `id()` : particle identity, by PDG codes.
- `status()` : status code. Provides info on where and why a given particle was produced. Negative code = no longer existing particle.
- `mother1(), mother2()` : first and last mother indices.
- `daughter1(), daughter2()` : first and last daughter indices.
- `col(), acol()` : colour and anticolour tags, Les Houches Accord.
- `px(), py(), pz(), e()` : four-momentum components (in GeV).
- `m()` : mass.
- `scale()` : scale at which a parton was produced; model-specific.
- `xProd(), yProd(), zProd(), tProd()` : production vertex (in mm).
- `tau()` : proper lifetime.

Methods above can also be used, with argument, for setting properties.
Many further methods for extraction only, e.g. for rapidity.
Also pointer to `ParticleDataTable` entry; gives e.g. `name()` and `charge()`.

The Event class

Two `Event` objects inside a `Pythia` object:

- `process` : hard subprocess, roughly like Les Houches.
- `event` : complete event history.

An `Event` $\approx$ a `vector<Particle>`

e.g. `pythia.event[i].id()` = identity of i'th particle

index 0 = event-as-a-whole; not really part of history

- $\Rightarrow$ throw line 0 for HepMC conversion
- $\Rightarrow$ mother/daughter = 0 $\Leftrightarrow$ empty

Specific methods include:

- `size()` : 0 $\leq$`i`$<$ `event.size()`.
- `list()` : provide event listing.
- `motherList(i), daughterList(i), sisterList()` : a `vector<int>` of mothers, daughters, sisters.
- `iTopCopy(i), iBotCopy(i)` : top or bottom "carbon copy".

But *no* methods to edit the event.

Sample event listings

First with `pythia.process.list()`, truncated to fit:

```
--------  PYTHIA Event Listing  (hard process)  -----------------------------------

   no        id   name            status     mothers   daughters     colours      p_x
    0        90   (system)           -11     0     0     1     2     0     0     0.000
    1      2212   (p+)               -12     0     0     3     0     0     0     0.000
    2      2212   (p+)               -12     0     0     4     0     0     0     0.000
    3        -2   (ubar)             -21     1     0     5     6     0   101     0.000
    4         2   (u)                -21     2     0     5     6   102     0     0.000
    5        -6   (tbar)             -22     3     4     7     8     0   101   -73.897
    6         6   (t)                -22     3     4     9    10   102     0    73.897
    7       -24   (W-)               -22     5     0    11    12     0     0     2.825
    8        -5   bbar                23     5     0     0     0     0   101   -76.721
    9        24   (W+)               -22     6     0    13    14     0     0    72.384
   10         5   b                   23     6     0     0     0   102     0     1.513
   11         3   s                   23     7     0     0     0   103     0   -26.914
   12        -4   cbar                23     7     0     0     0     0   103    29.739
   13       -11   e+                  23     9     0     0     0     0     0     6.458
   14        12   nu_e                23     9     0     0     0     0     0    65.926
                                 Charge sum:  0.000           Momentum sum:     0.000

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

next with `pythia.event.list()`, omissions to fit:

-------- 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	1	2	0	0	0.000	0.000	0.000	14000.000	14000.000
1	2212	(p+)	-12	0	0	279	0	0	0	0.000	0.000	7000.000	7000.000	0.938
2	2212	(p+)	-12	0	0	280	0	0	0	0.000	0.000	-7000.000	7000.000	0.938
3	-2	(ubar)	-21	7	7	5	6	0	101	0.000	0.000	54.594	54.594	0.000
4	2	(u)	-21	8	0	5	6	102	0	0.000	0.000	-1042.471	1042.471	0.000
5	-6	(tbar)	-22	3	4	9	9	0	101	-73.897	-53.244	-174.768	261.166	171.372
6	6	(t)	-22	3	4	10	10	102	0	73.897	53.244	-813.108	835.899	171.131
7	-2	(ubar)	-42	12	0	3	3	0	101	0.000	0.000	54.594	54.594	0.000
8	2	(u)	-41	13	13	11	4	104	0	-0.000	-0.000	-1191.549	1191.549	0.000
9	-6	(tbar)	-44	5	5	14	14	0	101	-71.565	-51.768	-210.234	285.251	171.372
10	6	(t)	-44	6	6	15	15	102	0	82.715	58.828	-926.573	947.695	171.131
11	21	(g)	-43	8	0	16	16	104	102	-11.150	-7.060	-0.149	13.198	0.000
25	21	(g)	-51	23	0	37	37	106	105	19.037	28.329	38.331	51.325	0.000
26	21	(g)	-51	23	0	39	39	101	106	6.832	-19.532	2.861	20.889	0.000
27	-6	(tbar)	-52	20	20	34	34	0	101	-88.187	-52.597	-231.302	305.635	171.372
44	21	(g)	-31	48	0	46	47	114	113	0.000	0.000	0.707	0.707	0.000
45	1	(d)	-31	49	49	46	47	113	0	0.000	0.000	-255.118	255.118	0.000
46	21	(g)	-33	44	45	50	50	114	115	2.524	5.061	-11.187	12.535	0.000
47	1	(d)	-33	44	45	51	51	115	0	-2.524	-5.061	-243.224	243.290	0.330
378	2	(u)	-63	1	0	492	492	113	0	-0.319	-0.512	1340.638	1340.638	0.330
379	2101	(ud_0)	-63	1	0	492	492	0	113	-0.427	-1.024	3266.905	3266.906	0.579
380	2	(u)	-63	1	0	493	493	108	0	-0.720	-1.118	56.936	56.952	0.330
381	-3	(sbar)	-63	1	0	519	519	0	117	-0.382	-0.112	1364.384	1364.384	0.500
486	-11	e+	23	441	0	0	0	0	0	7.949	-14.875	-217.791	218.443	0.001
487	12	nu_e	23	441	0	0	0	0	0	70.533	75.395	-668.054	675.985	0.000
502	1	(d)	-71	342	342	505	508	115	0	-3.404	-4.046	-233.825	233.885	0.330
503	21	(g)	-71	367	367	505	508	181	115	-0.384	-0.368	-9.293	9.309	0.000
504	-2	(ubar)	-71	370	370	505	508	0	181	-3.167	-0.517	-68.782	68.858	0.330
505	311	(K0)	-83	502	504	789	789	0	0	-2.046	-0.406	-58.420	58.460	0.498
506	331	(eta')	-83	502	504	941	942	0	0	-1.070	-2.000	-93.597	93.629	0.958
507	-323	(K*-)	-83	502	504	790	791	0	0	-2.736	-2.575	-132.287	132.344	0.943
508	111	(pi0)	-84	502	504	943	944	0	0	-1.102	0.050	-27.596	27.618	0.135
789	130	K_L0	91	505	505	0	0	0	0	-2.046	-0.406	-58.420	58.460	0.498
790	-311	(Kbar0)	-91	507	0	932	932	0	0	-0.900	-1.003	-55.248	55.267	0.498
791	-211	pi-	91	507	0	0	0	0	0	-1.836	-1.571	-77.039	77.077	0.140
792	-211	pi-	91	516	0	0	0	0	0	0.117	-0.161	-1.617	1.635	0.140
793	111	(pi0)	-91	516	0	1069	1070	0	0	-0.431	-0.098	-0.498	0.680	0.135
794	2212	p+	91	537	0	0	0	0	0	-1.175	0.093	-0.721	1.670	0.938
795	211	pi+	91	537	0	0	0	0	0	-0.414	0.352	-0.340	0.657	0.140
1316	22	gamma	91	1313	0	0	0	0	0	-1.574	0.014	-0.839	1.783	0.000
1317	22	gamma	91	1313	0	0	0	0	0	-0.887	0.068	-0.569	1.056	0.000
			Charge sum:	2.000				Momentum sum:		-0.000	0.000	-0.000	14000.000	14000.000

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

Other event information

You can use `pythia.info.method()` to extract one-of-a-kind information, such as:

- `idA(), idB(), eCM()` : incoming beams and cm energy.
- `name(), code()` : the name and code of the subprocess.
- `id1(), id2(), x1(), x2()` : the identities and x fractions of the two partons coming in to the hard subprocess.
- `pdf1(), pdf2(), Q2Fac()` : parton densities $x\,f(x, Q^2)$ evaluated for the two incoming partons, and the associated Q^2 scale.
- `alphaS(), alphaEM(), Q2Ren()` : α_s, α_{em} and their Q^2 scale.
- `mHat(), sHat(), tHat(), uHat()` : the invariant mass of the hard subprocess and the Mandelstam variables.
- `pTHat(), thetaHat(), phiHat()` : transverse momentum and polar and azimuthal scattering angles of the hard subprocess.
- `bMI(), nMI()` : impact parameter (rescaled) and number of multiple interactions.
- `list()` : list some information on output.
- `sigmaGen(), sigmaErr()` : the process-summed estimated cross section and its estimated statistical error, in mb.

Statistics

Output from `pythia.statistics()` (some blanks removed for space):

```
*-------  PYTHIA Event and Cross Section Statistics  -------------------------------------*
|                                                                                          |
| Subprocess                    Code |            Number of events       |      sigma +- delta    |
|                                    |       Tried   Selected   Accepted |     (estimated) (mb)   |
|                                    |                                   |                        |
|------------------------------------------------------------------------------------------|
|                                    |                                   |                        |
| g g -> g g                     111 |         502         65         65 |   5.114e-01  3.247e-02 |
| g g -> q qbar (uds)            112 |           2          0          0 |   0.000e+00  0.000e+00 |
| q g -> q g                     113 |         247         34         34 |   3.038e-01  2.772e-02 |
| q q(bar)' -> q q(bar)'         114 |          24          0          0 |   0.000e+00  0.000e+00 |
| q qbar -> g g                  115 |           1          0          0 |   0.000e+00  0.000e+00 |
| q qbar -> q' qbar' (uds)       116 |           0          0          0 |   0.000e+00  0.000e+00 |
| g g -> c cbar                  121 |           1          1          1 |   3.483e-03  3.483e-03 |
| g g -> b bbar                  123 |           2          0          0 |   0.000e+00  0.000e+00 |
|                                    |                                   |                        |
| sum                                |         779        100        100 |   8.187e-01  4.284e-02 |
|                                                                                          |
*-------  End PYTHIA Event and Cross Section Statistics -----------------------------------*

*-------  PYTHIA Error and Warning Messages Statistics  ----------------------------------*
|                                                                                          |
|  times   message                                                                         |
|                                                                                          |
|      3   Error in Pythia::next: hadronLevel failed; try again                            |
|      3   Error in StringFragmentation::fragmentToJunction: caught in junction flavour loop  |
|      3   Warning in ParticleDataEntry::initBWmass: switching off width                   |
|                                                                                          |
*-------  End PYTHIA Error and Warning Messages Statistics  ------------------------------*
```

Trying It Out

- Download `pythia8107.tgz` from
  `http://www.thep.lu.se/~torbjorn/Pythia.html`
- `tar xvfz pythia8107.tgz` to unzip and expand
- `cd pythia8107` to move to new directory
- `./configure ...` needed for external libraries + debug/shared
  (see `README`, libraries: HepMC, LHAPDF, PYTHIA 6)
- `make` will compile in $\sim$ 3 minutes
  (for archive library, same amount extra for shared)
- The `htmldoc/pythia8100.pdf` file contains A Brief Introduction
- Open `htmldoc/Welcome.html` in a web browser for the full manual
- Install the `phpdoc/` directory on a webserver and open
  `phpdoc/Welcome.html` in a web browser for an interactive manual
- The `examples` subdirectory contains $>$ 30 sample main programs:
  standalone, link to libraries, semi-internal processes, ...
  (`make mainNN` and then `./mainNN.exe > outfile`)
- A `Worksheet` (on the web pages) contains step-by-step
  instructions and exercises how to write and run a main program

Summary

Legacy PYTHIA 6.416:

- 75,000 lines of code (including comments/blanks).
- 580 page PYTHIA 6.4 Physics and Manual,
  T. Sjöstrand, S. Mrenna and P. Skands,
  JHEP**05** (2006) 026 [hep-ph/0603175].
- + update notes, sample main programs, etc.

Current PYTHIA 8.107:

- 53,000 lines of code (including comments/blanks),
- 27 page A Brief Introduction to PYTHIA 8.1,
  T. Sjöstrand, S. Mrenna and P. Skands,
  arXiv:0710.3820, to appear in Computer Physics Communications.
- + online manual, sample main programs, etc.

Future:

- PYTHIA/JETSET the most used event generator in the last 25 years.
- Adoption of PYTHIA 8 has been slow.
- Will PYTHIA survive transition Fortran $\longrightarrow$ C++ as a key player?
- The answer rests with you!