LUND UNIVERSITY

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(NORDITA Workshop on TeV Scale Physics and Dark Matter)
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Introduction to PYTHIA 8

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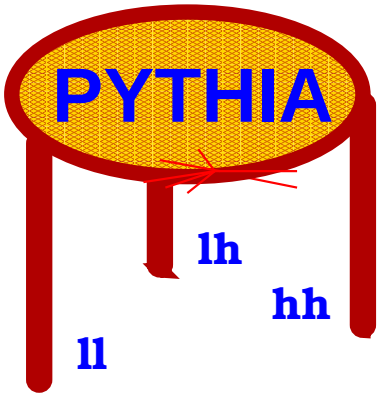
The Oracle of Delphi:
ca. 1000 B.C.
— 390 A.D.

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

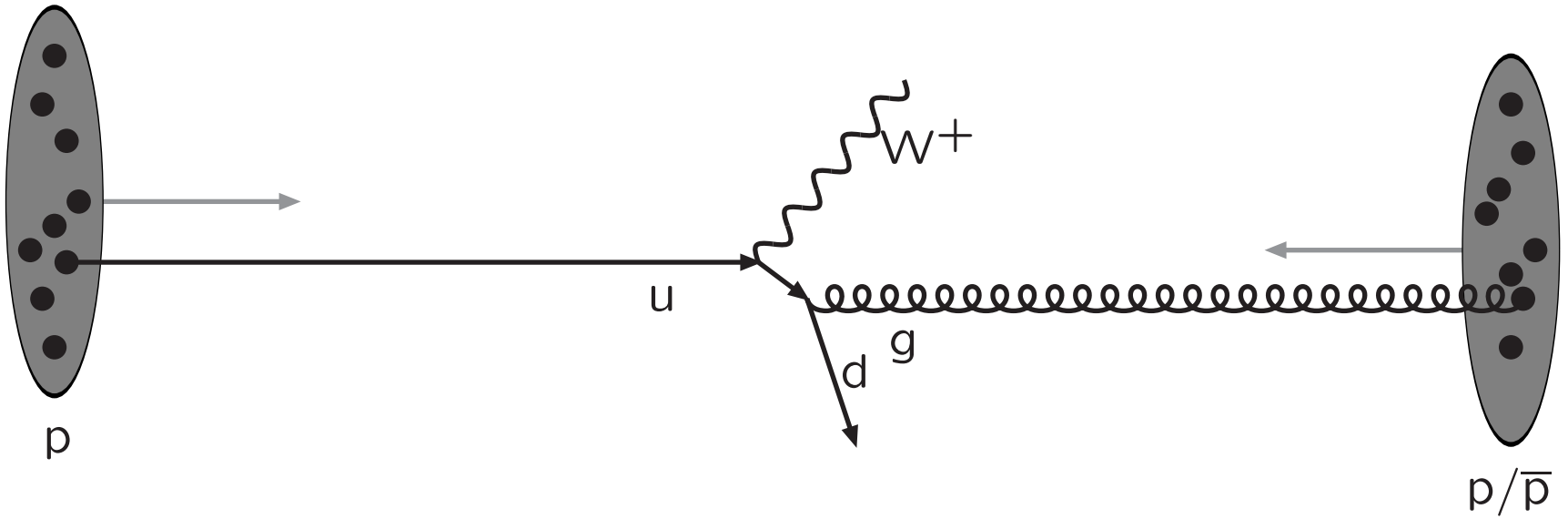
2007

PYTHIA 8.1

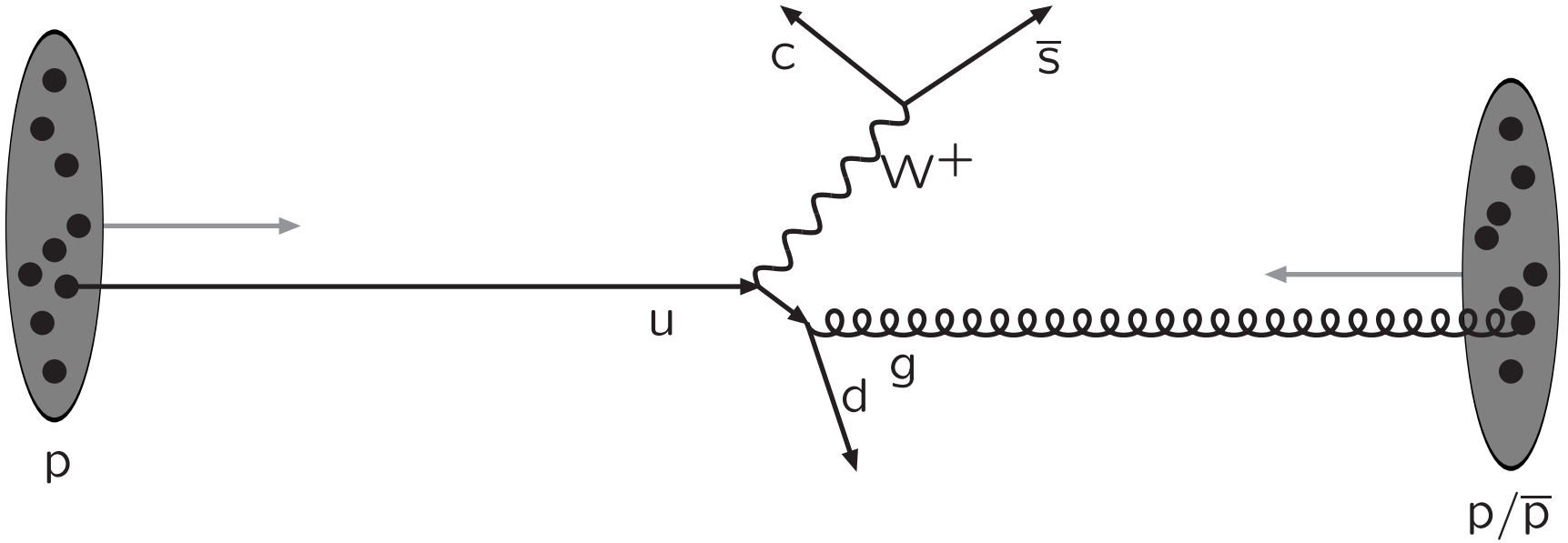
The structure of an event

Warning: schematic only, everything simplified, nothing to scale, . . .

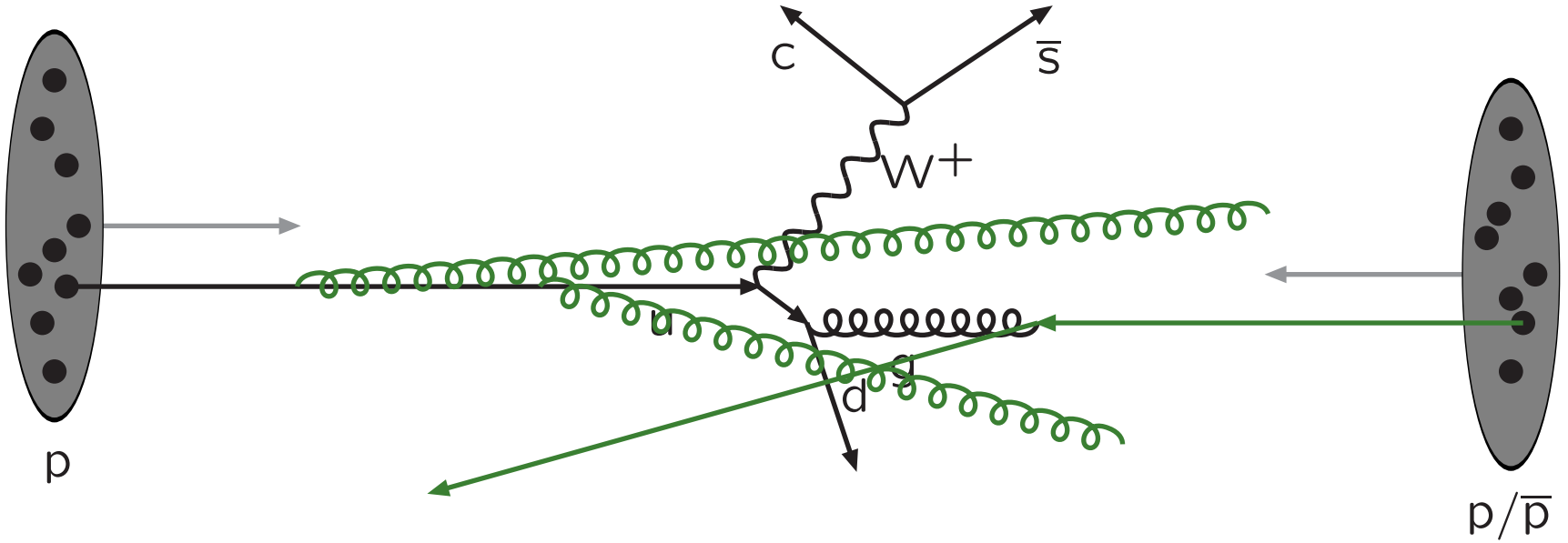
Incoming beams: parton densities



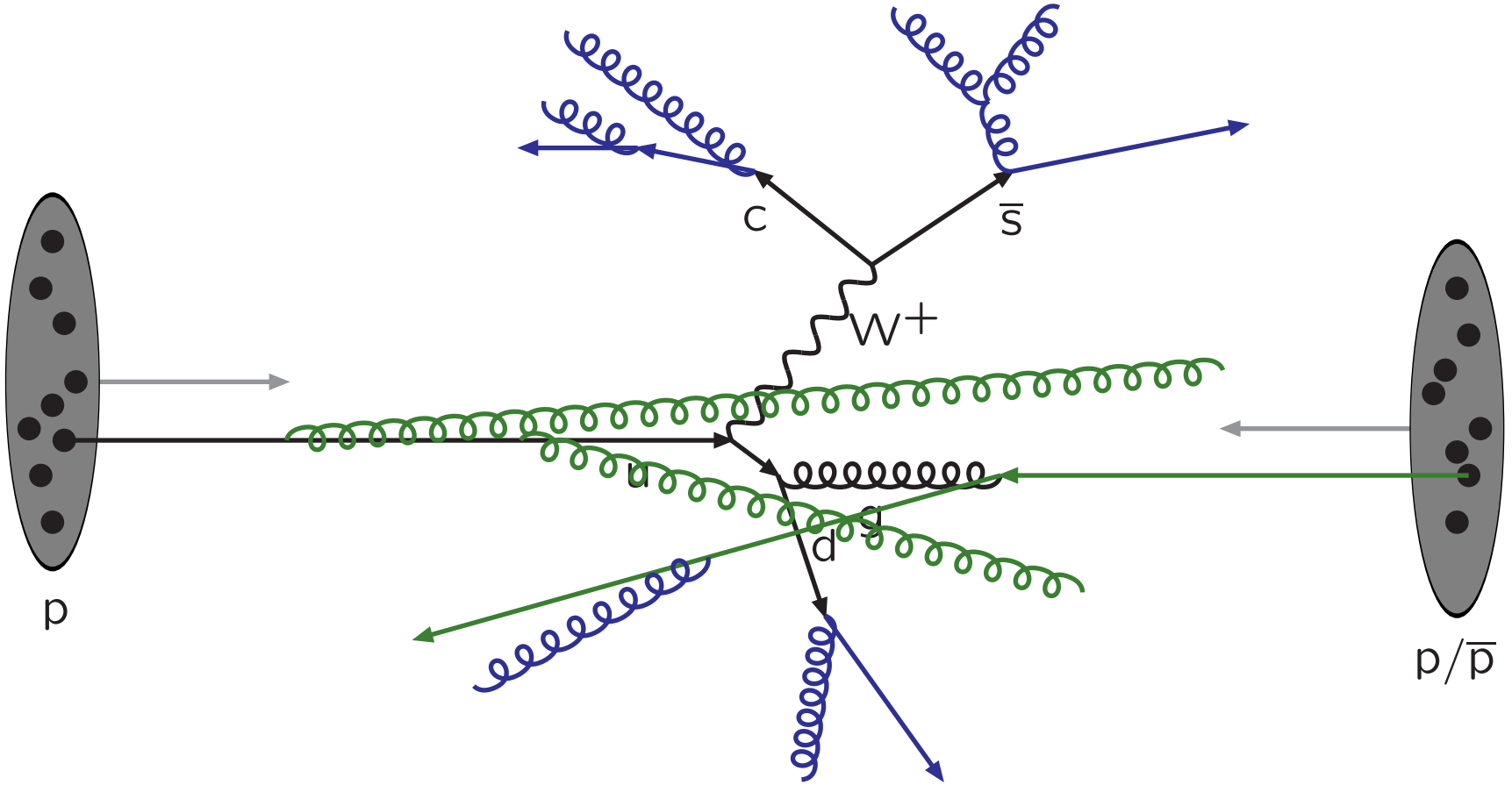
Hard subprocess: described by matrix elements



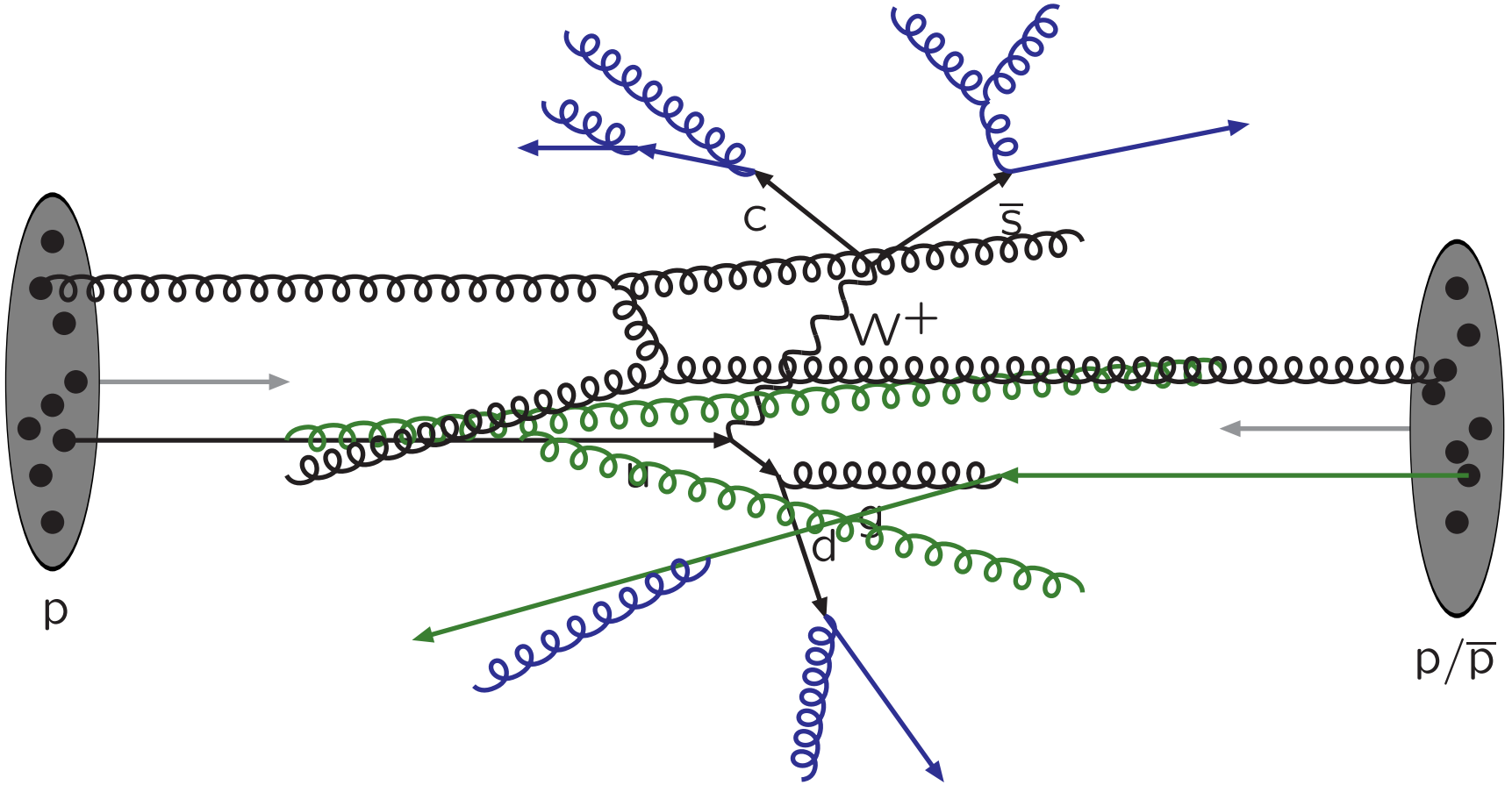
Resonance decays: correlated with hard subprocess



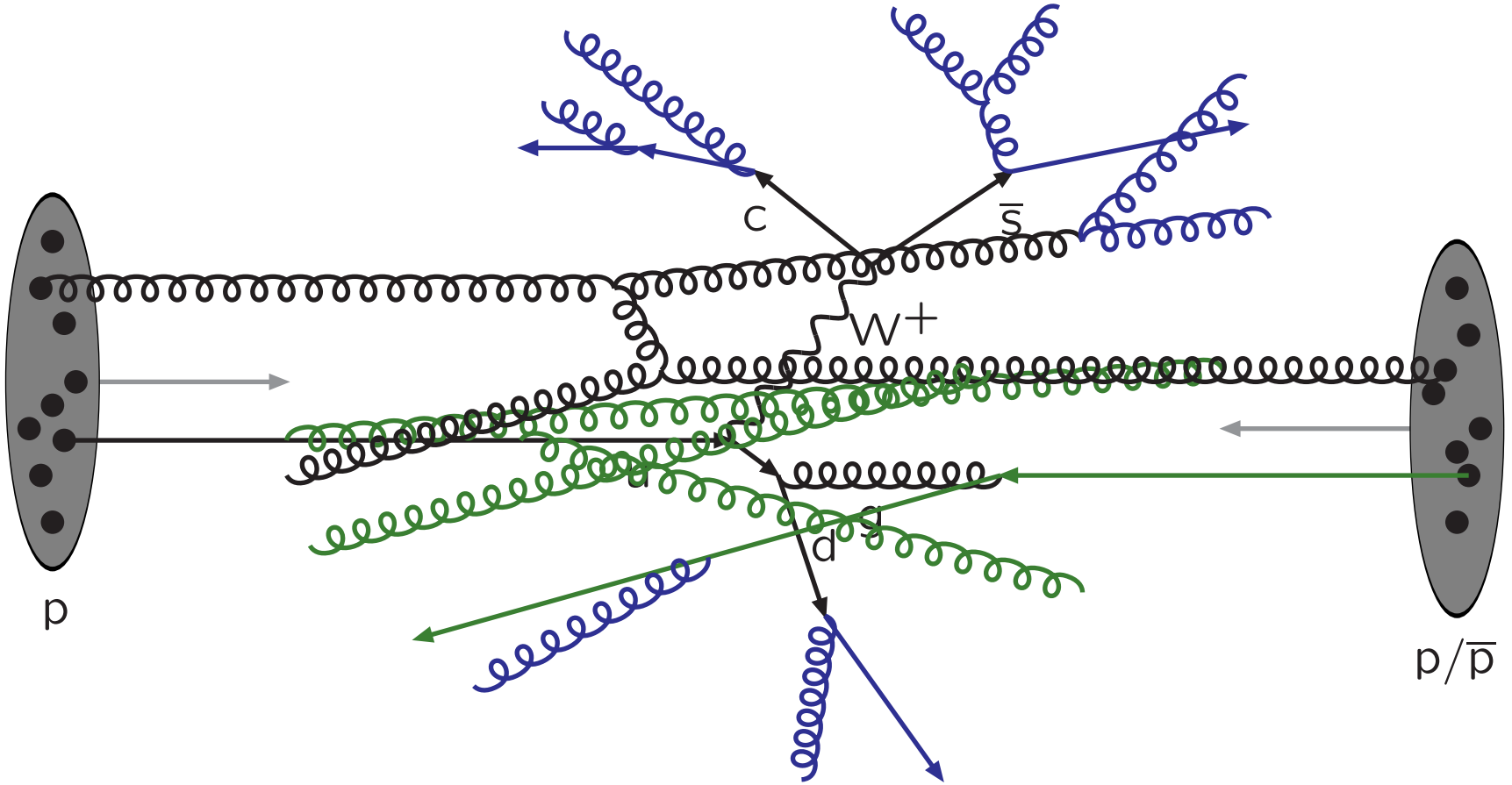
Initial-state radiation: spacelike parton showers



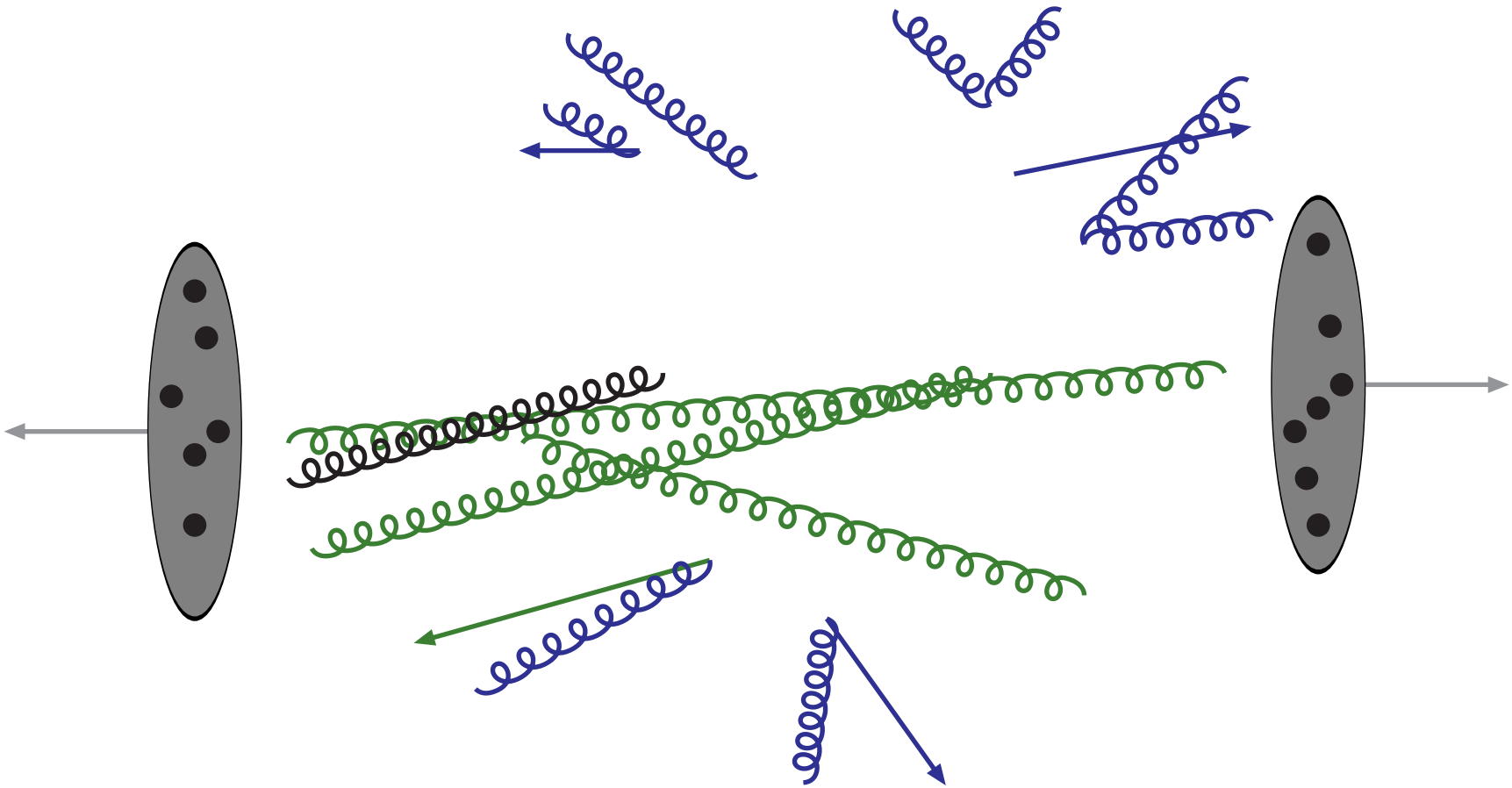
Final-state radiation: timelike parton showers



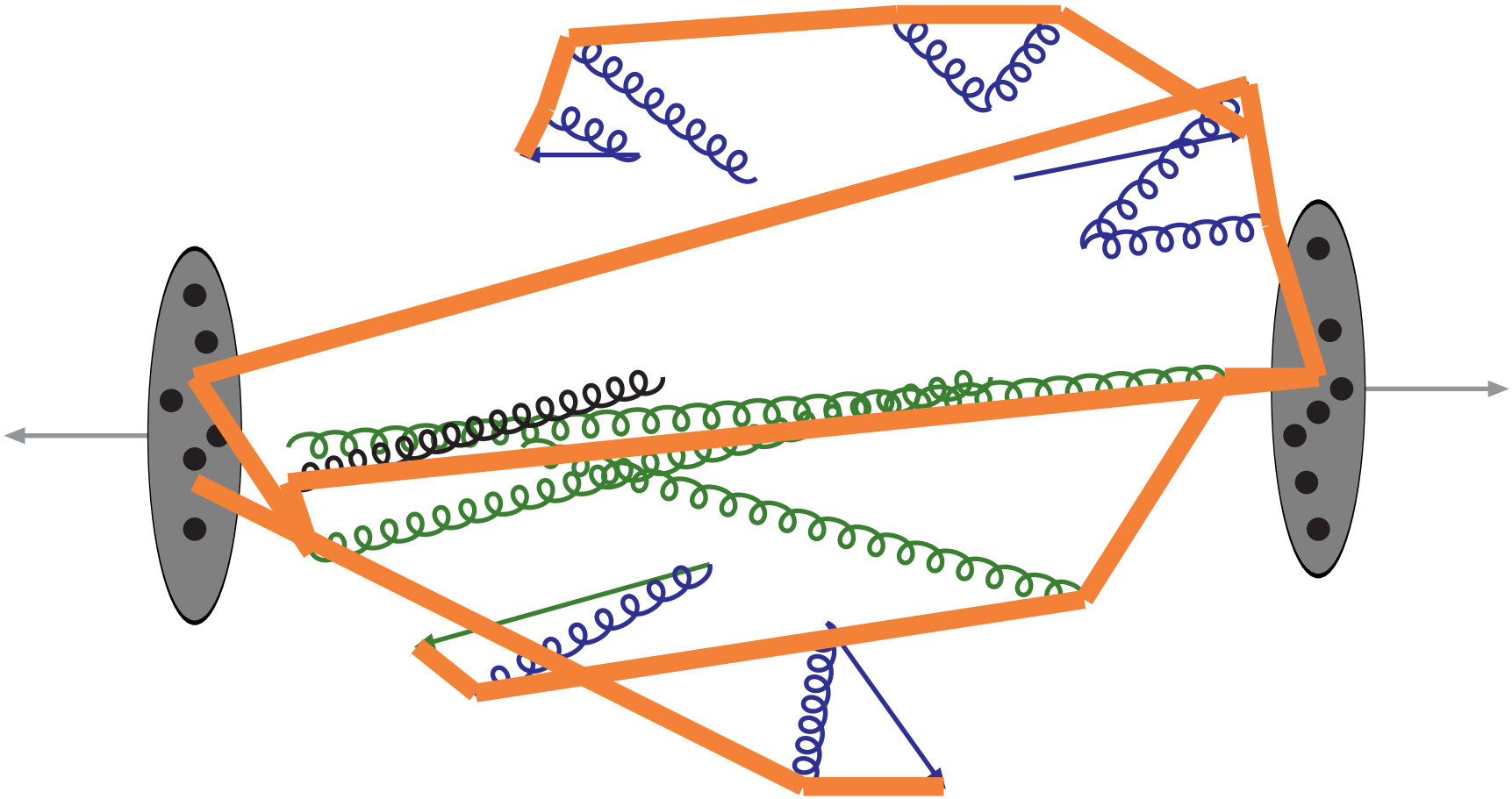
Multiple parton–parton interactions . . .



. . . with its initial- and final-state radiation

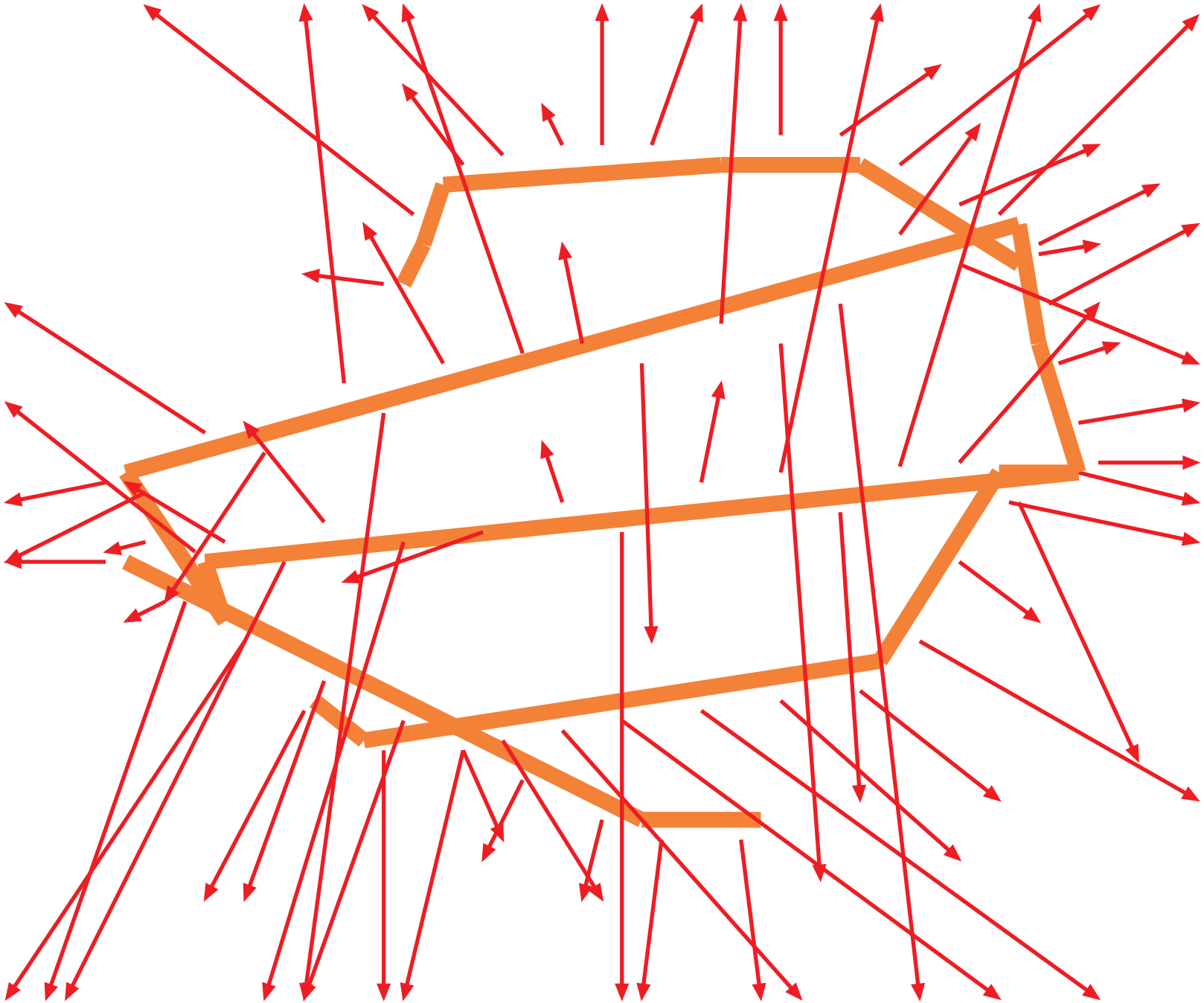


Beam remnants and other outgoing partons

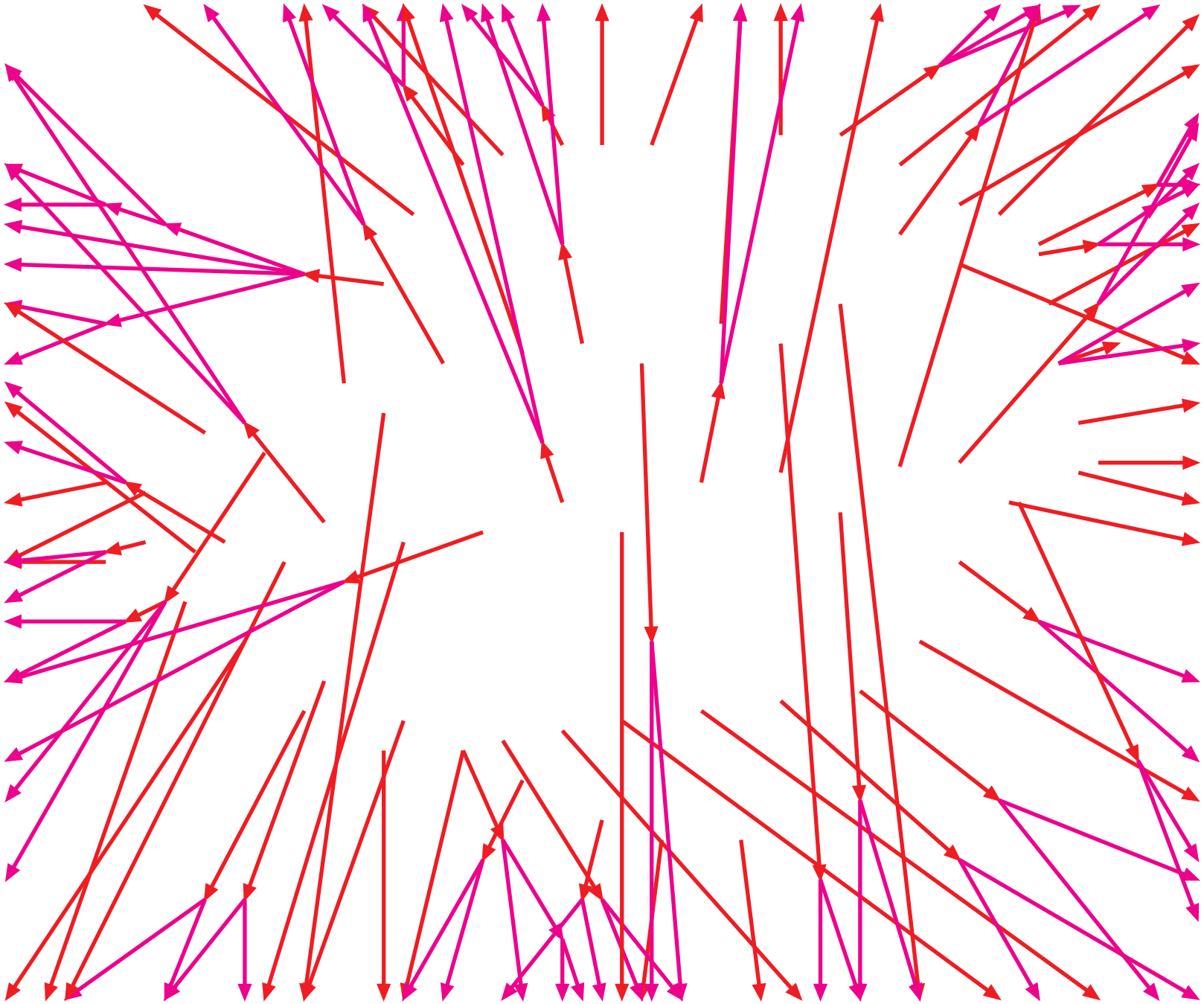


Everything is connected by colour confinement strings

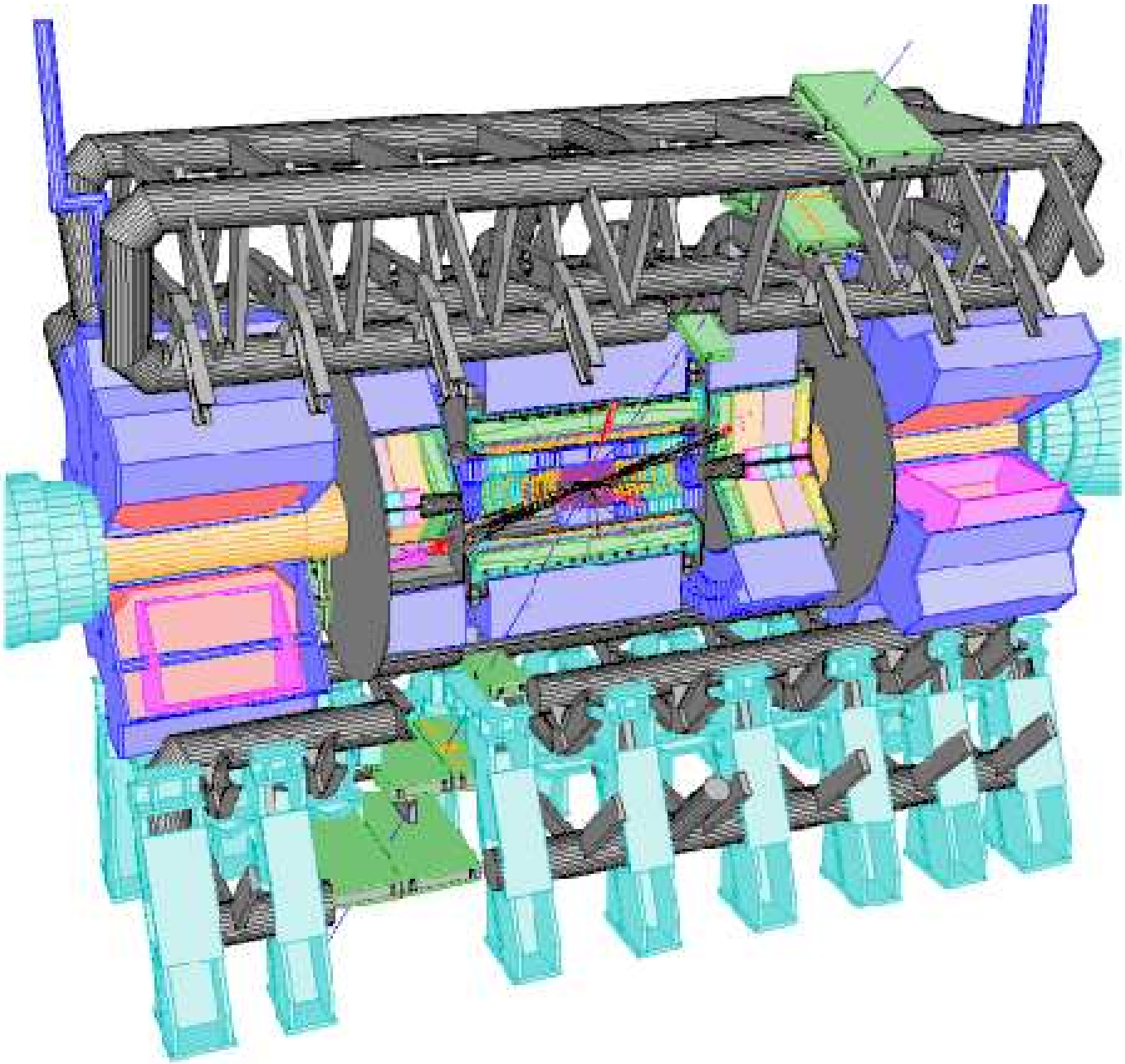
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons



Many hadrons are unstable and decay further



These are the particles that hit the detector

On To C++

Currently HERWIG and PYTHIA are successfully being used,
also in new LHC environments, using C++ wrappers

Q: Why rewrite?

A1: Need to clean up!

A2: Fortran 77 is limiting

Q: Why C++?

A1: All the reasons for ROOT, Geant4, . . .

(“a better language”, industrial standard, . . .)

A2: Young experimentalists will expect C++

(educational and professional continuity)

A3: Only game in town! Fortran 90

So far mixed experience:

- Conversion effort: everything takes longer and costs more

(as for LHC machine, detectors and software)

- The physics hurdle is as steep as the C++ learning curve

C++ Players

PYTHIA 7 project $\Longrightarrow$ **ThePEG**
Toolkit for High Energy Physics Event Generation
(L. Lönnblad; D. Grellscheid, P. Richardson)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions
(L. Lönnblad; N. Lavesson)

HERWIG++: complete reimplementation
November 2007: first full-fledged version (2.1; now 2.2.0)
(P. Richardson; M. Bähr, S. Gieseke, M. Gigg, D. Grellscheid,
K. Hamilton, O. Latunde-Dada, S. Plätzer, M.H. Seymour,
A. Sherstnev, B.R. Webber, arXiv:0803:0883)

SHERPA: new program, written from scratch
operational since $\sim$2006 (now 1.1.0 (first independent of Fortran PYTHIA))
(F. Krauss; T. Gleisberg, S. Hoeche, R. Matyszkiewicz,
S. Schumann, F. Siegert, J. Winter)

PYTHIA 8: complete reimplementation
October 2007: first full-fledged version (8.100; now 8.108)
(T. Sjöstrand, S. Mrenna, P. Skands,
Comput. Phys. Comm. **178** (2008) 852 [arXiv:0710.3820])

MCnet

• EU Marie Curie training network •

• Approved for four years starting 1 Jan 2007 •

• Involves THEPEG/ARIADNE, HERWIG, SHERPA and PYTHIA •

(CERN, Durham, Lund, Karlsruhe, UC London; leader: Mike Seymour)

• 4 postdocs & 2 graduate students: generator development and tuning •

• short-term studentships: 33 @ 4 months each •

(applications processed every three months; next deadline 30 June)

theory or experiment

• Annual Monte Carlo school: •

Durham, UK, 18 – 20 April 2007

CTEQ – MCnet, Debrecen, Hungary, 8 – 16 August 2008

Lund 2009, 30 June - 2 July ??

• Support for other such schools: •

Physics at the Terascale Monte Carlo School, DESY, 21 – 24 April 2008

• non-EU participation up to 30% •

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 events and minimum-bias events:

- Multiple parton–parton interactions,
  with dampening of cross-section in $p_\perp \longrightarrow 0$ limit,
  impact-parameter dependence, and tailormade PDF's.
- Combined evolution MI + ISR + FSR downwards in $p_\perp$.
- Beam remnants colour-connected to interacting systems,
  and detailed modelling of flavour and momentum structure.

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

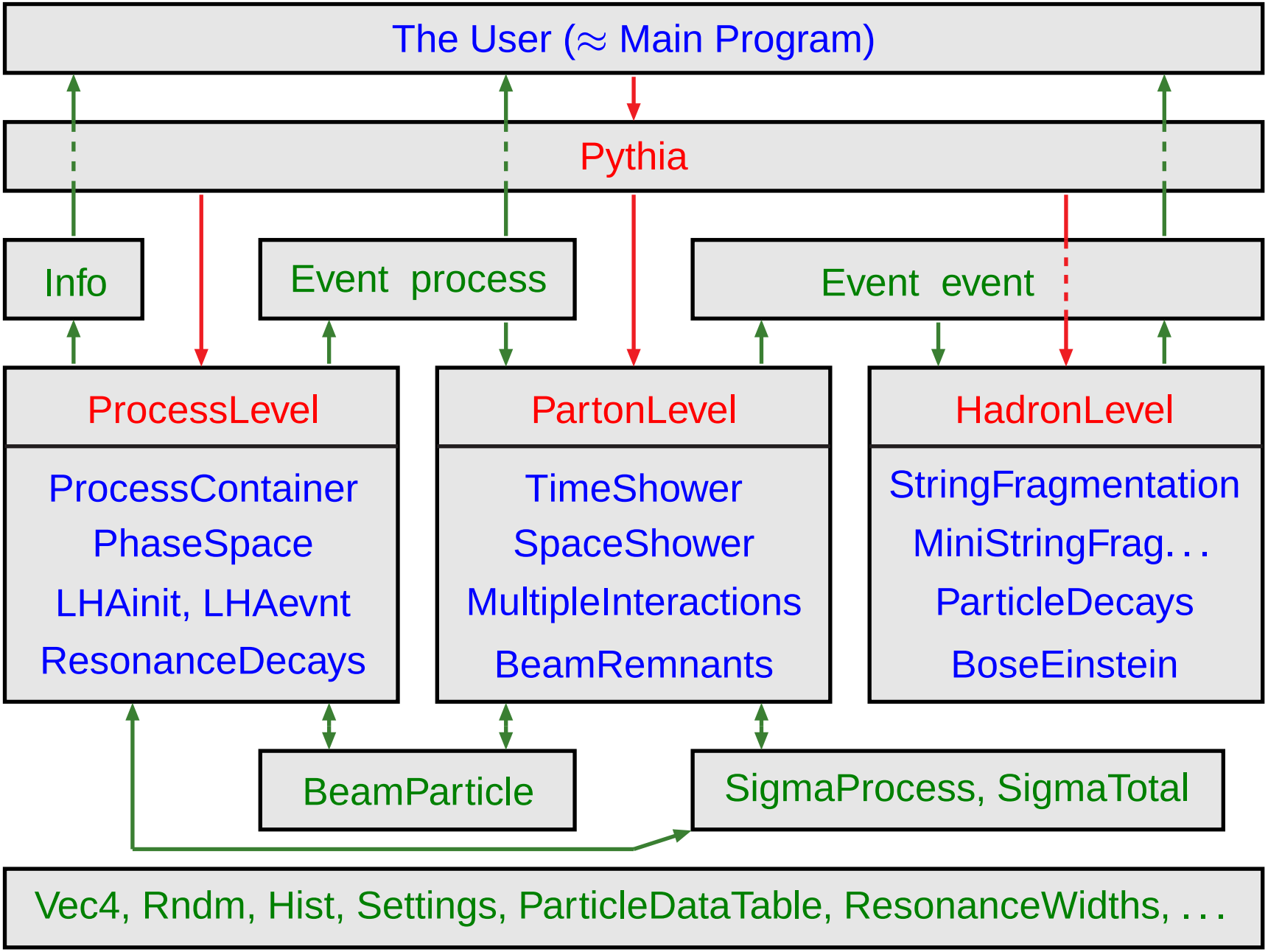
New features, not found in 6.4:

- 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

Plans for the future:

- rescattering in multiple interactions (with Florian Bechtel & Richard Corke)
- more ME/PS matching (with Richard Corke)

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 $a_2^+ \to \pi^+\pi^0\pi^0$

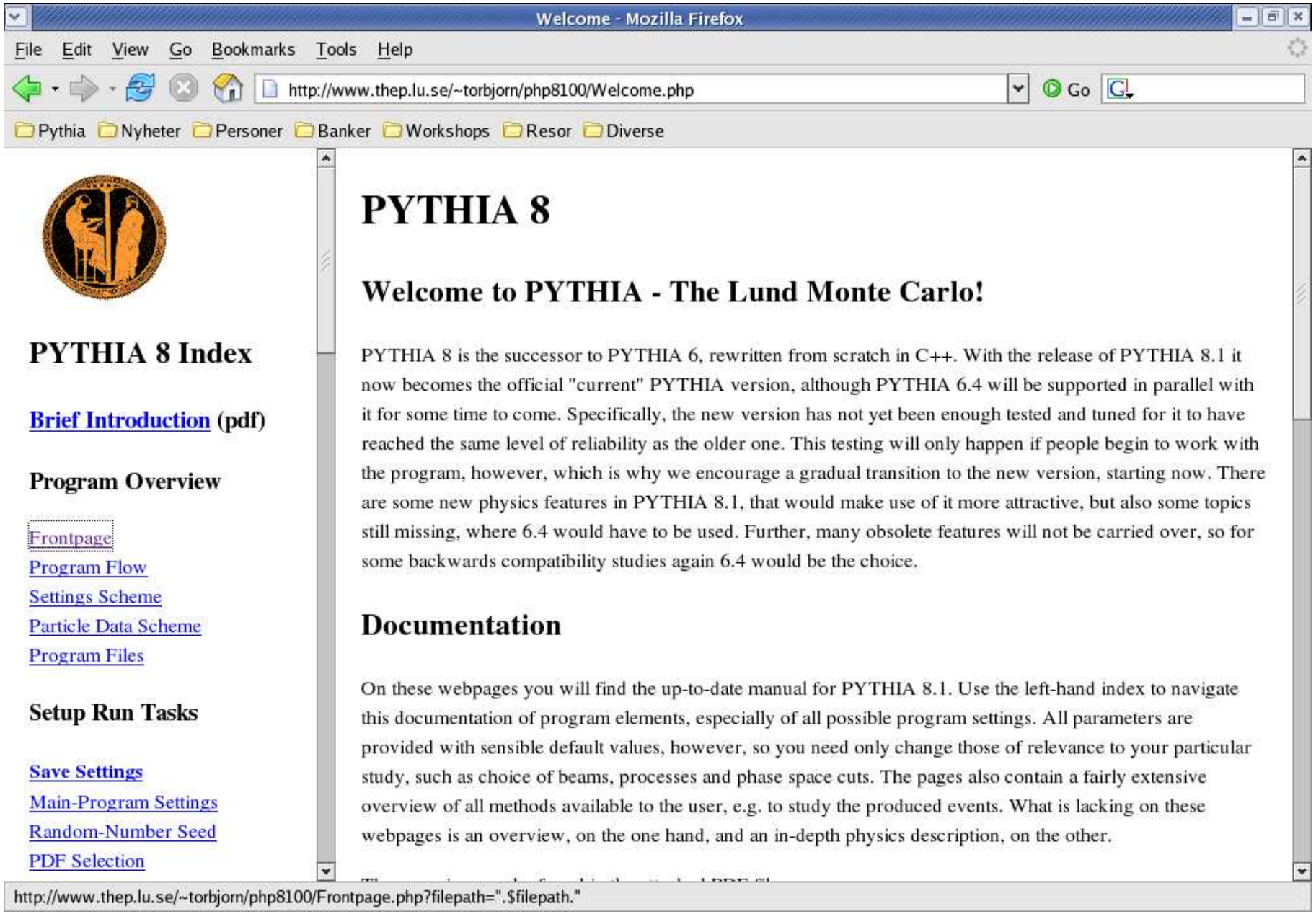
Note: case-insensitive search/matching in databases!

Example of a “cards” file

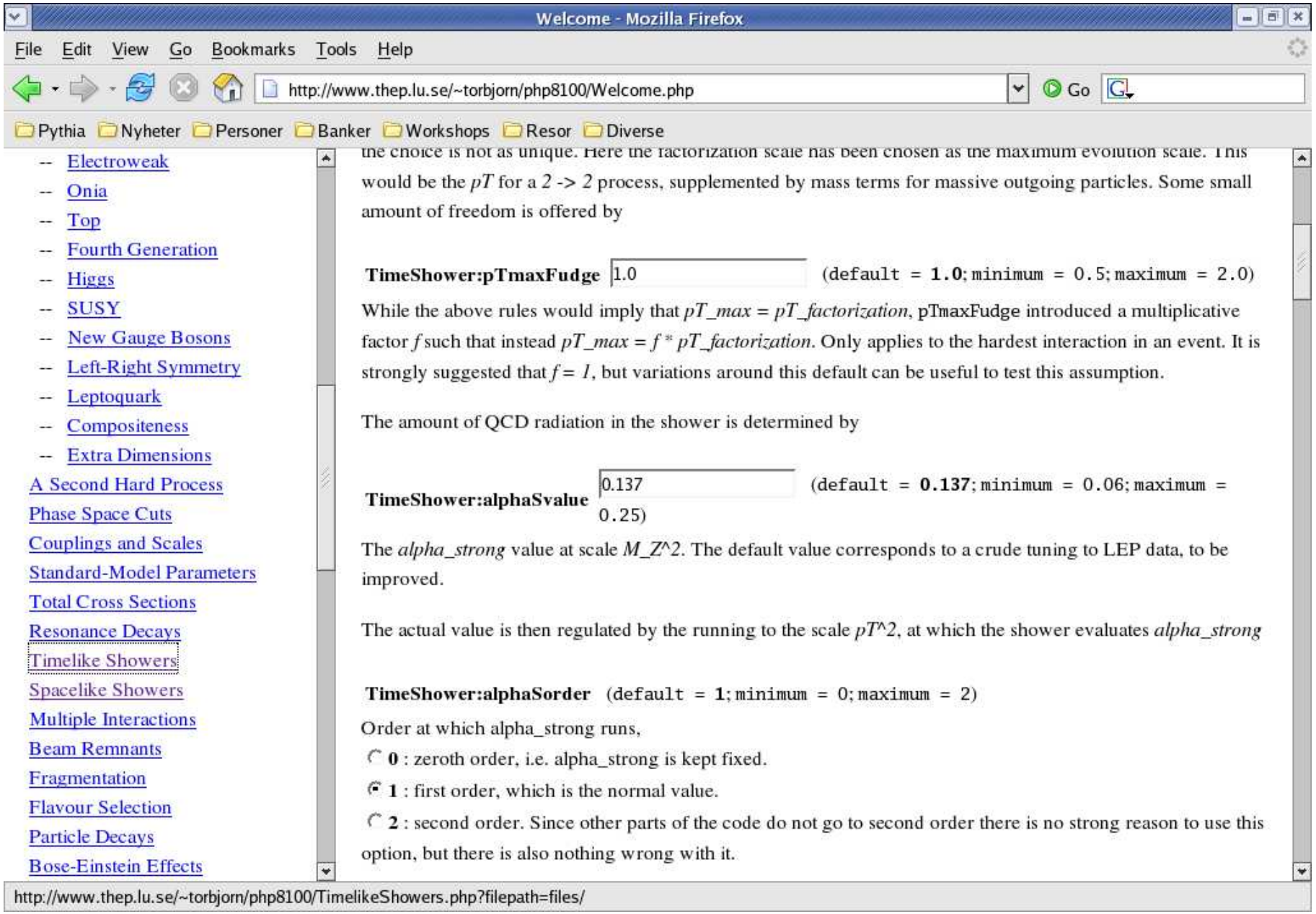
```
! This file contains commands to be read in for a Pythia8 run.
! Lines not beginning with a letter or digit are comments.

! 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
```

ProcessGroup	ProcessName
SoftQCD	minBias,elastic, singleDiffractive, doubleDiffractive
HardQCD	gg2gg, gg2qqbar, qg2qg, qq2qq, qqbar2gg, qqbar2qqbarNew, gg2ccbar, qqbar2ccbar, gg2bbbar, qqbar2bbbar
PromptPhoton	qg2qgamma, qqbar2ggamma, gg2ggamma, ffbar2gammagamma, gg2gammagamma
WeakBosonExchange	ff2ff(t:gmZ), ff2ff(t:W)
WeakSingleBoson	ffbar2gmZ, ffbar2W, ffbar2ffbar(s:gm)
WeakDoubleBoson	ffbar2gmZgmZ, ffbar2ZW, ffbar2WW
WeakBosonAndParton	qqbar2gmZg, qg2gmZq, ffbar2gmZgm, fgm2gmZf qqbar2Wg, qg2Wq, ffbar2Wgm, fgm2Wf
Charmonium	gg2QQbar[3S1(1)]g, qg2QQbar[3PJ(8)]q, ...
Bottomonium	gg2QQbar[3S1(1)]g, gg2QQbar[3P2(1)]g, ...
Top	gg2ttbar, qqbar2ttbar, qq2tq(t:W), ffbar2ttbar(s:gmZ), ffbar2tqbar(s:W)
FourthBottom	gg2bPrimebPrimebar, qq2bPrimeq(t:W) , ...
FourthTop	qqbar2tPrimetPrimebar, fbar2tPrimeqbar(s:W), ...
FourthPair	ffbar2tPrimebPrimebar(s:W), fbar2tauPrimenuPrimebar(s:W)
HiggsSM	ffbar2H, gg2H, ffbar2HZ, ff2Hff(t:WW), ...
HiggsBSM	h, H and A as above, charged Higgs, pairs
SUSY	qqbar2chi0chi0 (SUSY barely begun)
NewGaugeBoson	ffbar2gmZZprime, ffbar2Wprime, ffbar2R0
LeftRightSymmmetry	ffbar2ZR, ffbar2WR, ffbar2HLHL, ...
LeptoQuark	ql2LQ, qg2LQl, gg2LQLQbar, qqbar2LQLQbar
ExcitedFermion	dg2dStar, qq2uStarq, qqbar2muStarmu, ...
ExtraDimensionsG*	gg2G*, qqbar2G*, ...

Online manual $\Longrightarrow$ Graphical User Interface



Example: timelike parton showers



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– Onia
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The Event and Particle classes

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

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

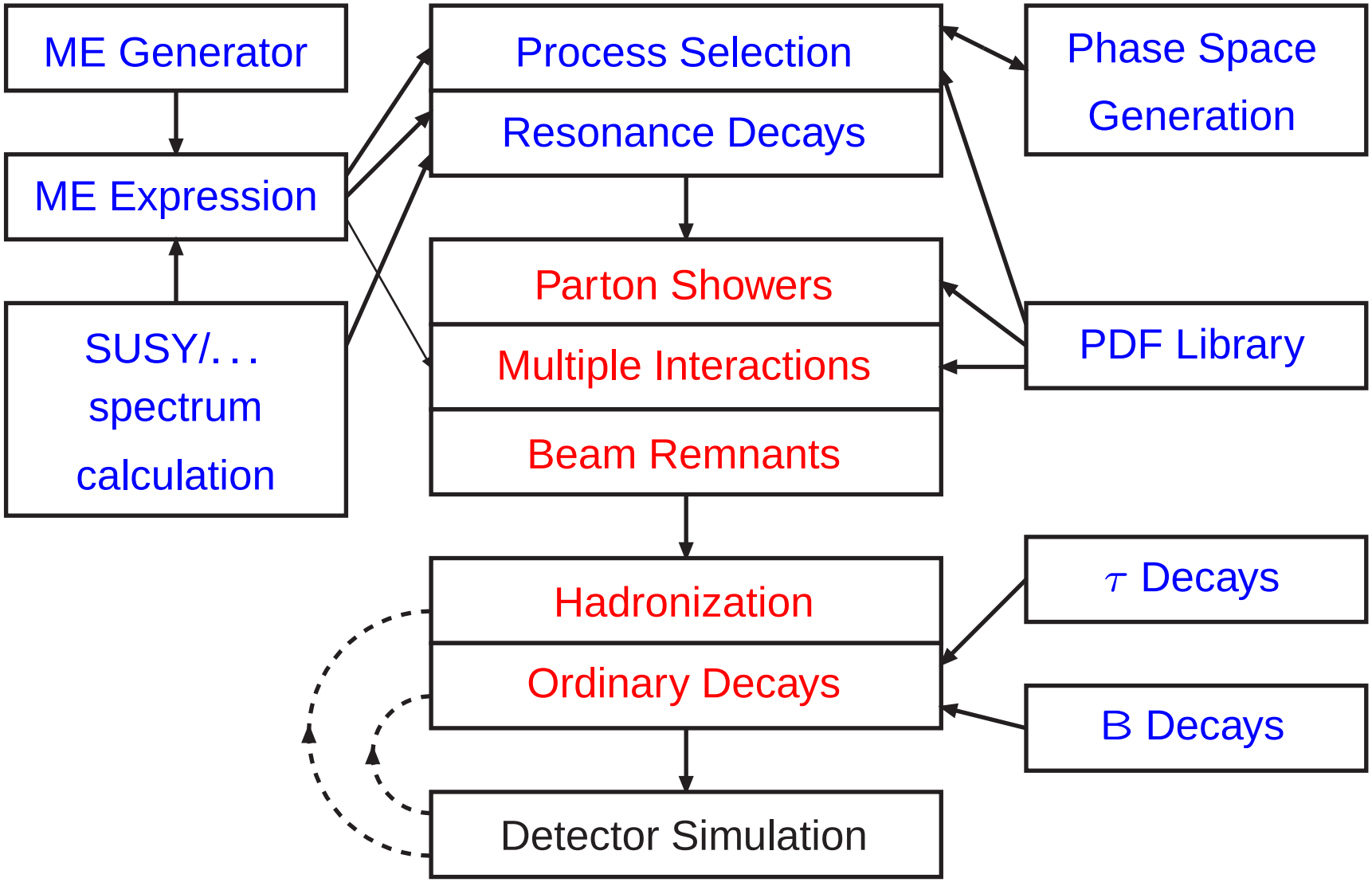
An `Event` ≈ a `vector<Particle>`

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(), m()` : four-momentum and mass (GeV).
- `xProd(), yProd(), zProd(), tProd()` : production vertex (mm).
- `tau()` : proper lifetime.
- some more, e.g. name & charge (via pointer to particle database)

+ Further event information, on hard subprocess PDF's and much more.

The Bigger Picture



need standardized interfaces (LHA/LHEF, LHAPDF, SUSY LHA, HepMC, . . .)

Links to other program

PYTHIA is standalone, but several ways to link to it.

Possibilities similar to PYTHIA 6.4:

- Input from Les Houches Accord & Les Houches Event Files
- Output to HepMC event format (more robust than PYTHIA 6!?)
- SUSY Les Houches Accord (input file with masses, couplings, . . .)
- Link to external decays, e.g. for τ and B.
- Link to LHAPDF version 5.3.0 or later, or to your own PDF.

New possibilities, based on derived classes and pointers to them:

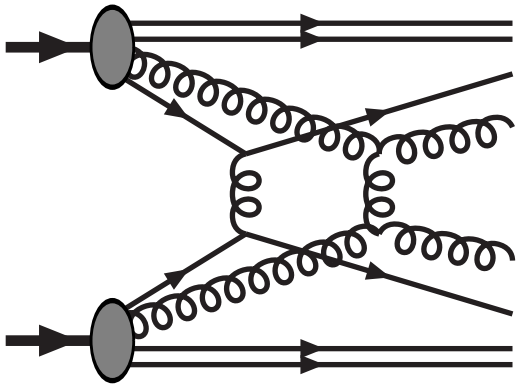
- Semi-internal process: write derived matrix-element class,

```
SigmaProcess* mySigma = new MySigma();
pythia.setSigmaPtr( mySigma);
```

  and let PYTHIA do phase space integration, process mixing, . . .
- Semi-internal resonance in same style: calculate partial widths
- Link to external random-number generator.
- Link to external shower, e.g. VINCIA for FSR.
- User hooks: veto events early on or reweight cross section.

Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019:
first models for event properties
based on perturbative multiple interactions,
still in frequent use
(Tune A, Tune DWT, ATLAS tune, . . .)



- Is only a model for nondiffractive events, i.e. for $\sigma_{\mathrm{nd}} \simeq (2/3)\sigma_{\mathrm{tot}}$
- Smooth turn-off at $p_{\perp 0}$ scale

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_{\mathrm{s}}^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_{\mathrm{s}}^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

- Require ≥ 1 interaction in an event
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$ by "Sudakov" trick (what happens "first"?)

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp i}} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right]$$

- After each interaction rescaled new PDF's for momentum conservation
- Leads to n_{int} narrower than Poissonian, except that . . .

- Hadrons are extended,
  e.g. double Gaussian (“hot spots”):

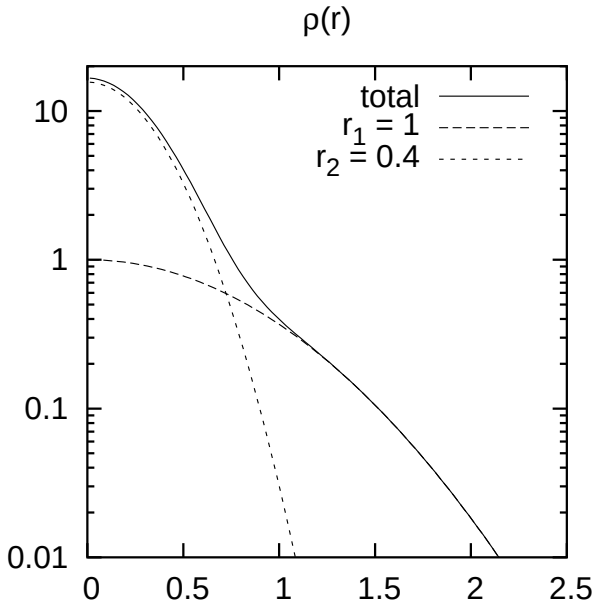
$$\rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

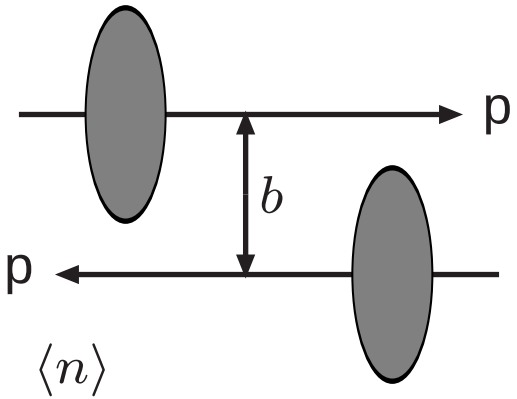
  where $r_2 \neq r_1$ represents “hot spots”
- Events are distributed in impact parameter b
- Overlap of hadrons during collision

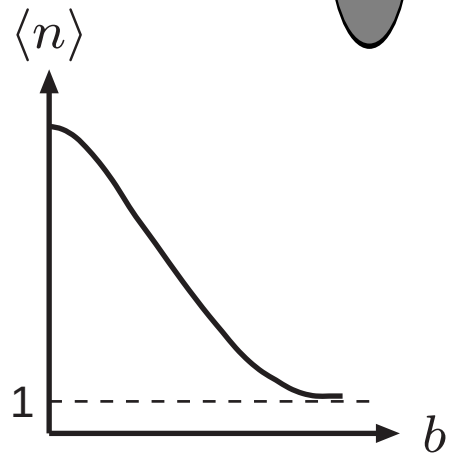
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\; \rho^{\text{boosted}}_{1,\text{matter}}(\mathbf{x},t)\rho^{\text{boosted}}_{2,\text{matter}}(\mathbf{x},t)$$

- Average activity at b proportional to $\mathcal{O}(b)$
  $\Rightarrow$ central collisions normally more active
  $\Rightarrow$ $\mathcal{P}_n$ broader than Poissonian

- Time-consuming $(b, p_\perp)$ generation
- Problems if many valence quarks kicked out
  $\Rightarrow$ Simplify after first interaction:
  only gg or $\mathrm{q\bar{q}}$ outgoing, no showers, . . .







Multiple Interactions: A New Evolution Equation

	time	evolution	probability
FSR	forwards	$p_\perp \searrow 0$	normal & local
ISR	backwards	$p_\perp \searrow 0$	conditional
MI	simultaneous	$p_\perp \searrow 0$	conditional

ISR + MI: PDF competition $\Rightarrow$ interleaving (PYTHIA 6.3)

FSR: previously at end, now also interleaved (PYTHIA 8.1):

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp}\right) \times \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)$$

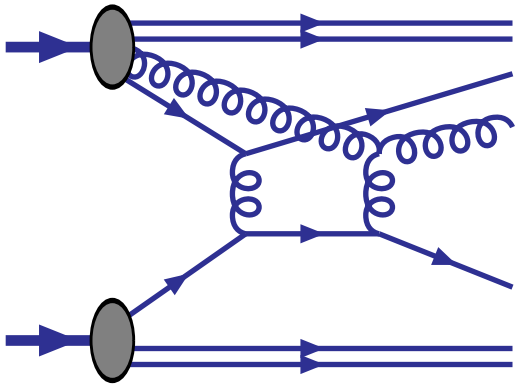
“resolution evolution”

Monte Carlo: winner takes all

+ many other assumptions/models

Next step: rescattering

added in same spirit



PYTHIA 8 status

task	status
administative structure	operational; extensions planned
hard processes, internal	much of PYTHIA 6; SUSY & TC & more to do
resonance decays	much of PYTHIA 6; SUSY & TC & more to do
hard processes, external	interfaces to LHA F77, LHEF, PYTHIA 6
SUSY(+more) parameters	SLHA2; more needed
initial-state showers	operational
final-state showers	operational
matching ME's to showers	some exists; much more needed
multiple interactions	operational; extensions planned
beam remnants & colour flow	operational; alternatives to come
parton densities	only 2 internal, but interface to LHAPDF
string fragmentation	operational; improvements planned
decays & particle data	operational; may need updates
Bose-Einstein	operational; off by default (tuning)
analysis	some simple tools; may be enough
graphical user interface	operational; could be extended
tuning	major task for MCnet postdocs!
testing	major task for experimentalists!
ep, γp, $\gamma\gamma$	not in the foreseeable future

News since PYTHIA 8.100

- Acolliner beams and beam momentum spread.
- Beam vertex spread.
- Reduced use of `static`:
  possibility to have several almost separate `Pythia` instances,
  e.g. signal + background events in pileup.
- Combine event records with new = and += methods.
- Updated `SusyLesHouches` interface handles SLHA version 2.
- Neutralino pair production now operational.
- Updated routine for HepMC conversion; support for version 1 dropped;
  bug fix for onium $\to$ ggg or γgg.
- Improved capability for standalone hadronization.
- Improved handling of Higgs width.
- Safety checks on $\alpha_{\rm S}$ at small scales.
- Changed for compilation with gcc 4.3.0 and with `-Wshadow` option.
- Some further minor improvements and bug fixes.

Trying It Out

- Download `pythia8108.tgz` from
  `http://www.thep.lu.se/~torbjorn/Pythia.html`
- `tar xvfz pythia8108.tgz` to unzip and expand
- `cd pythia8108` 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` contains step-by-step instructions
  and exercises how to write and run a main program

Summary

Legacy PYTHIA 6.418 (9 June):

- reduced but nonzero activity (recently: UED)
- 78,000 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 8.108 (4 May):

- 53,000 lines of code (including comments/blanks),
- 27 page A Brief Introduction to PYTHIA 8.1,
  T. Sjöstrand, S. Mrenna and P. Skands,
  Comput. Phys. Comm. **178** (2008) 852 [arXiv:0710.3820].
- + online manual, sample main programs, worksheets, etc.

+ Thanks to the GENSER group, and especially Mikhail Kirsanov,
  for help with Makefiles, configure scripts and HepMC interface.

– Adoption of PYTHIA 8 by experimental collaborations has been slow.