Monte Carlo Method

and Pythia8 tutorial

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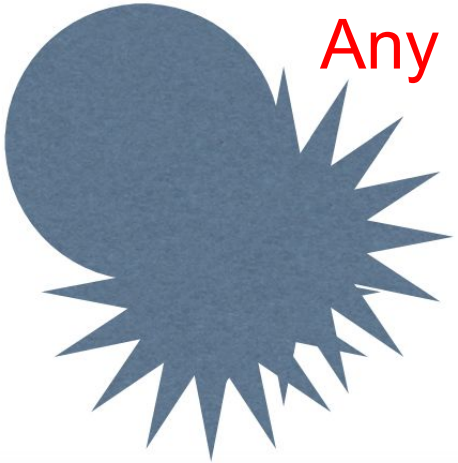
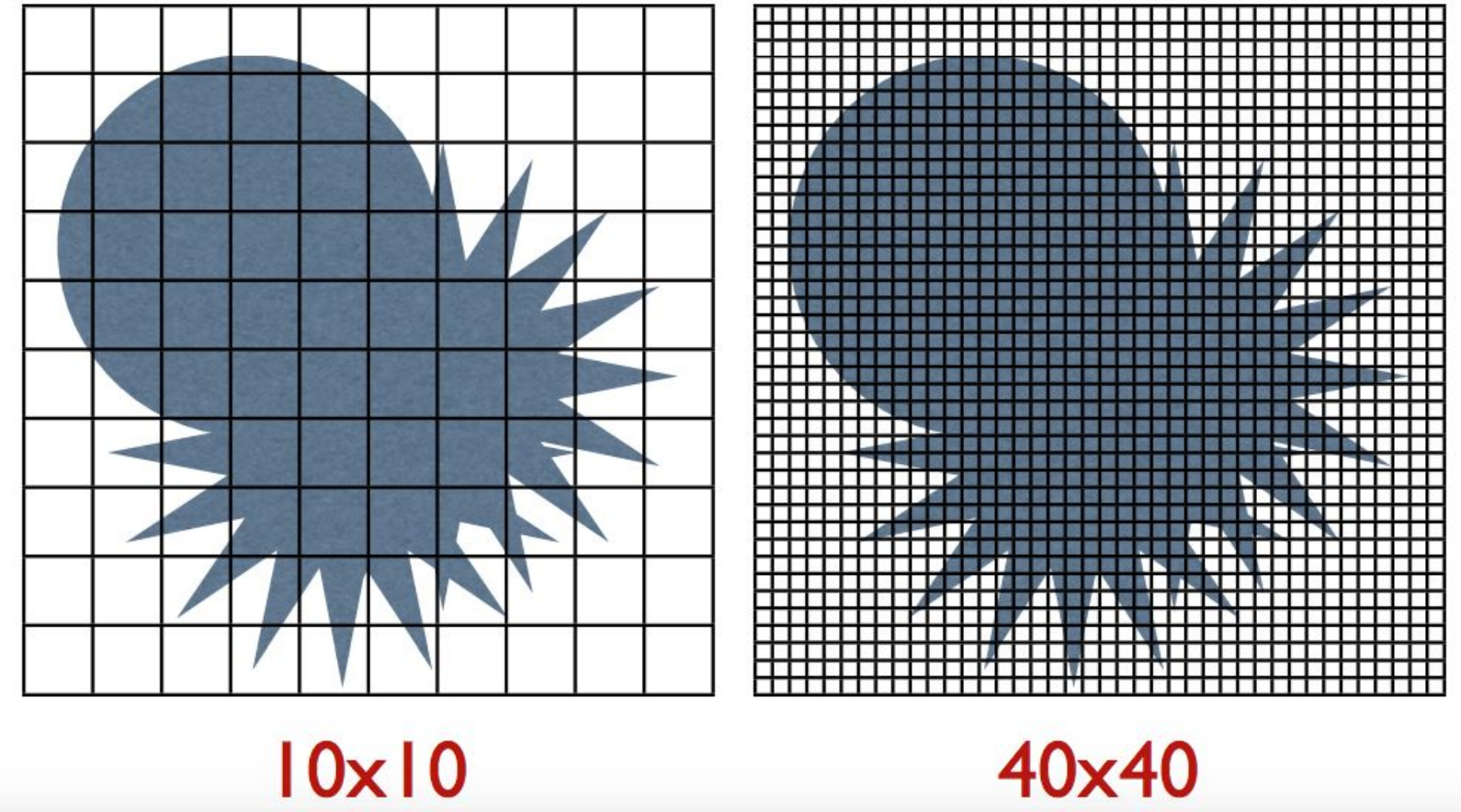
Monte Carlo Method

Monte Carlo techniques are often the only practical way to evaluate difficult integrals or to sample random variables governed by complicated probability density functions.

- General idea is: instead of performing long complex calculations, perform large number of experiments using random number generation and see what happens
- Problem: calculate the area of this shape





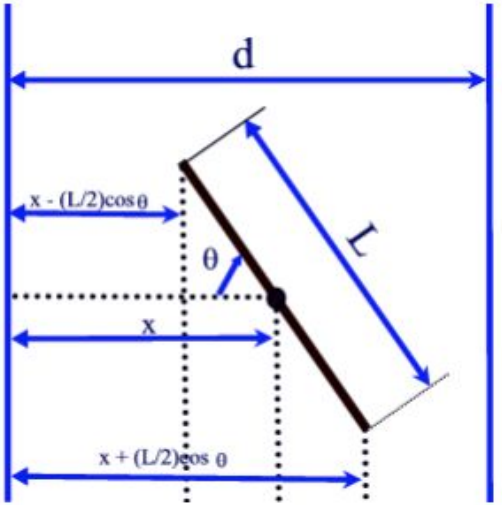
Area = total area x (number of hits) / (number of total)

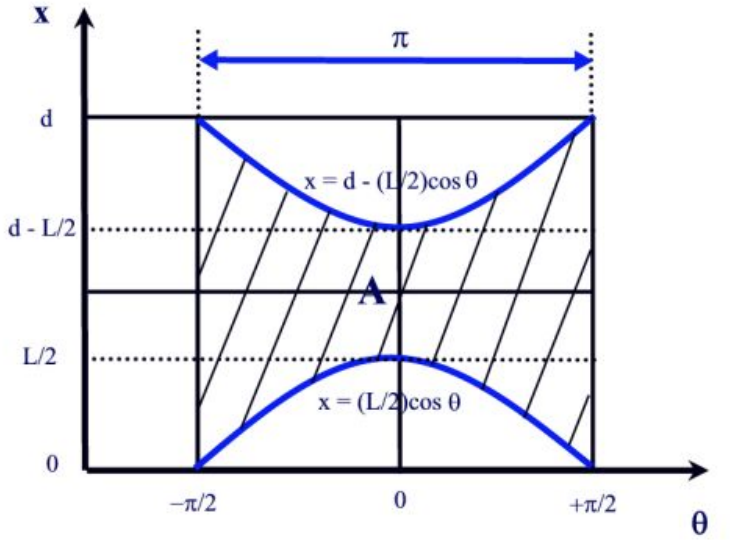
Evaluating π

Buffon's needle problem

An interesting related problem is Buffon's needle problem (1733), that can be used to design a Monte Carlo method for approximating the number π:

- Given a needle of length l dropped on a plane ruled with parallel lines d units apart, what is the probability that the needle will lie across a line upon landing?





Buffon's needle problem

Let x be the distance from the center of the needle to the closest parallel line, and θ the acute angle between the needle and one of the parallel lines. (x and θ are independent variables)

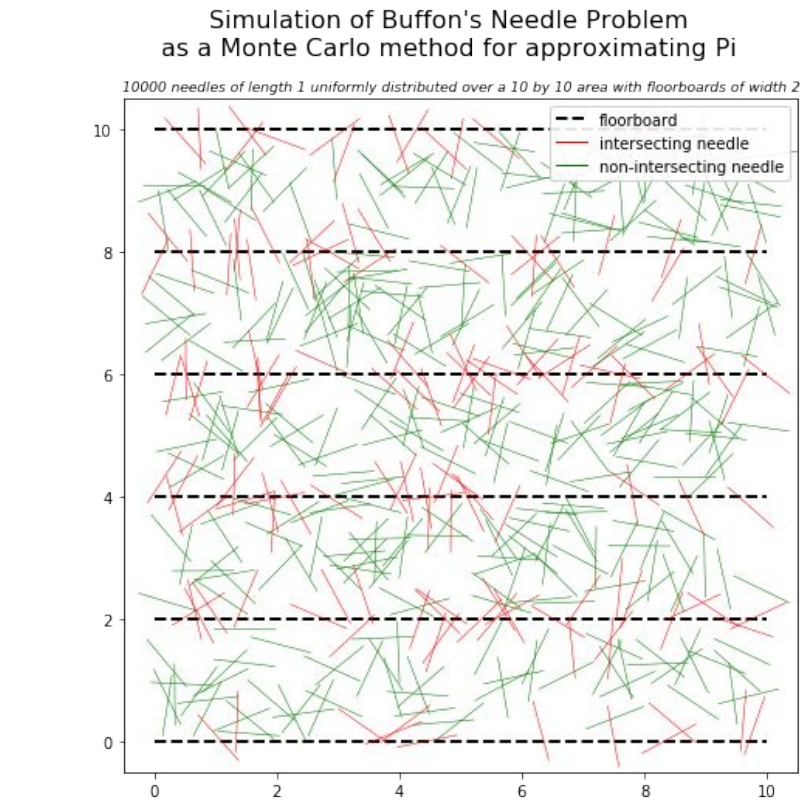
The uniform PDF of x $\begin{cases} \frac{2}{l} & : 0 \leq x \leq \frac{l}{2} \\ 0 & : elsewhere \end{cases}$ and the uniform PDF of θ $\begin{cases} \frac{2}{\pi} & : 0 \leq \theta \leq \frac{\pi}{2} \\ 0 & : elsewhere \end{cases}$

The joint PDF is: $\begin{cases} \frac{4}{l\pi} & : 0 \leq \theta \leq \frac{\pi}{2}\ ,\ 0 \leq \theta \leq \frac{\pi}{2} \\ 0 & : elsewhere \end{cases}$ and if $x \leq \frac{l}{2}\sin\theta$ the needle crosses one line. The probability is: $P = \int_{\theta=0}^{\frac{\pi}{2}} \int_{x=0}^{\frac{l}{2}\sin\theta} \frac{4}{\pi d} dx d\theta = \frac{2l}{\pi d}$

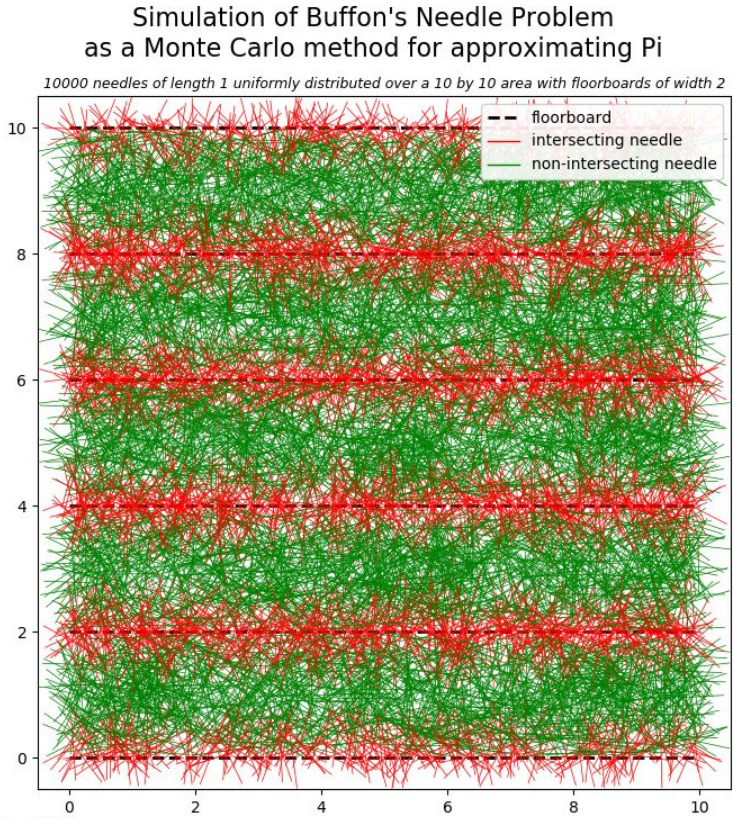
Suppose we drop n needles and find that m of those are crossing lines, so P is approximated by the fraction M/n, then: $\pi = \frac{2ln}{dm}$

Buffon’s needles problem

https://github.com/Analise-Dados-FAE/Aula-MonteCarlo-Pythia8/blob/main/buffon.ipynb



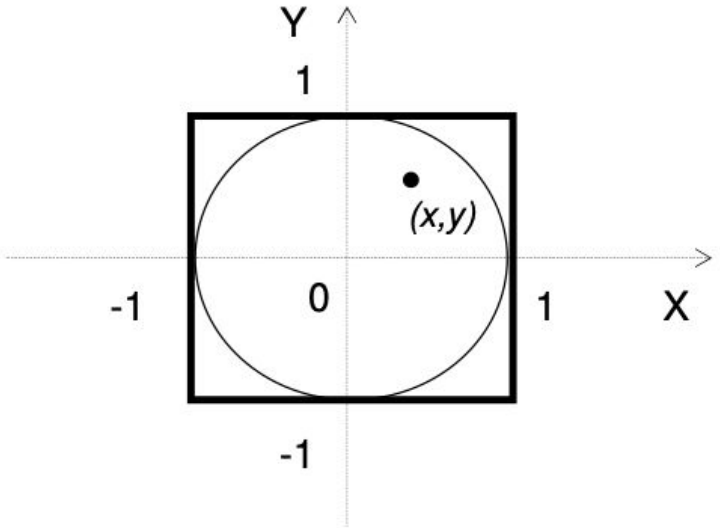
Intersections: 149
Total Needles: 500
Approximation of pi: 3.3557046979865772
Error: 6.815398048251908%



Intersections: 3168
Total Needles: 10000
Approximation of pi: 3.1565656565656566
Error: 0.4766054873076756 7%

Exercise: Evaluating the number π

- Generate points in the square and the points that falls inside the circle will ~π/4



$$P\left((x,y) \in circulo\right) = P\left(x^2 + y^2 \leq 1\right)\frac{\pi}{4}$$

Evaluating integrals

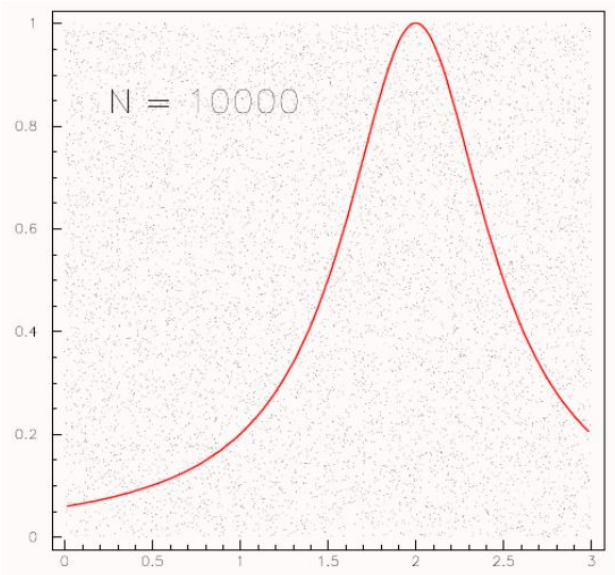
Rejection sampling method

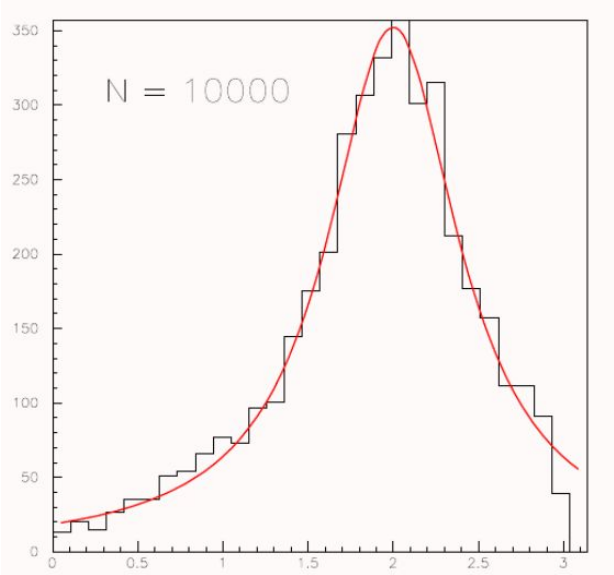
- Rejection sampling is a basic technique used to generate observations from a distribution.
- Using this technique, given one distribution, we can draw samples seemingly from another distribution by some rejection/acceptance to the sample
  - Given a random variable x, it is accepted if is in region defined by the curve f(x), which means: $y \leq f(x)$

Example

We want to generate events based on the Breit-Wigner pdf using the rejection sampling method from 10000 random values distributed uniformly between x=[0, 3] and y=[0,1].

Histogram of random events generated by rejection sampling method, distributed by the pdf on the left. The x values are the accepted with satisfy the condition $y \leq f(x)$

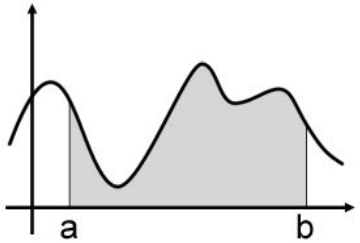




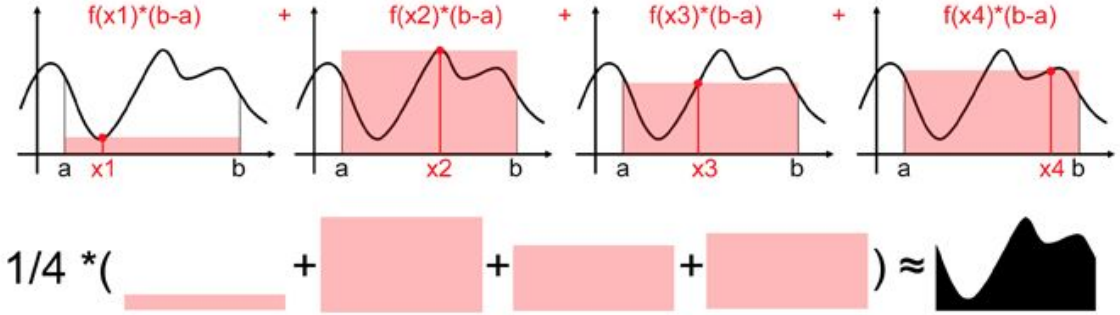
Evaluating Integrals

- The principle of a basic Monte Carlo estimation is this: imagine that we want to integrate a one-dimensional function f(x) from a to b such as:

$$F = \int_a^b f(x)\, dx.$$



- As you may remember, the integral of a function f(x) can be interpreted as calculating the area below the function's curve

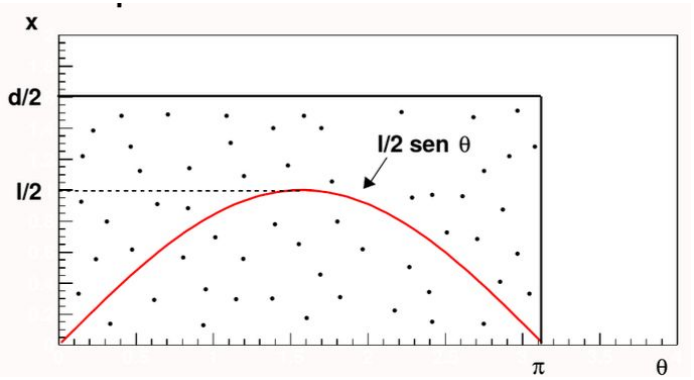


$$\langle F^N \rangle = (b-a)\frac{1}{N}\sum_{i=0}^{N-1} f(X_i).$$

Evaluating Integrals using Rejection Sampling

- First we evaluate the area under the function's curve ($f(x) = \frac{l}{2}\sin\theta$) in the range of *0* and π
- Then we generate random points (*x, y*)
- Using the rejection sampling method, we accept the *m* points below the curve after *N* events
- Like the Buffon problem, the value of the integral will be defined as (A is the area under de curve)

$$I = \int_0^{\pi} \frac{l}{2}\sin\theta = \frac{Am}{N}$$



Evaluating Integrals using Monte Carlo method

- We can also evaluate the integral in the range (a,b) defined as $I = \int_a^b f(x)dx$
- We can estimate directly using uniform distributions of random values in the range (0,1)
  - We should transform the integral as a integral in the range (0,1): $x' = \frac{x-a}{b-a}$

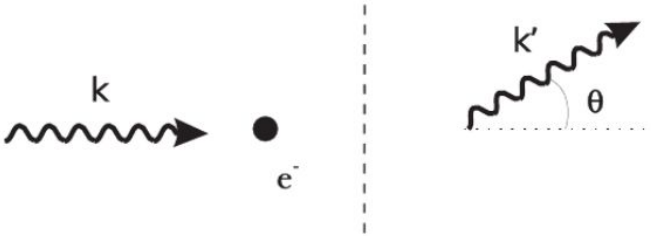
$$I = (b-a)\int_0^1 f[x'(b-a)+a]dx'$$

$$I = \frac{(b-a)}{N}\sum_{i=1}^{N} f[x_i(b-a)+a]$$

Generating events

Generating events

- Compton scattering



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m^2}\left(\frac{k'}{k}\right)^2\left(\frac{k'}{k} + \frac{k}{k'} - \sin^2\theta\right)$$

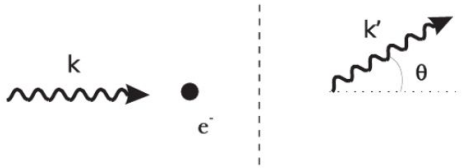
$$k' = \frac{k}{1 + (k/m)(1 - \cos\theta)}$$

- Rutherford scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}.$$

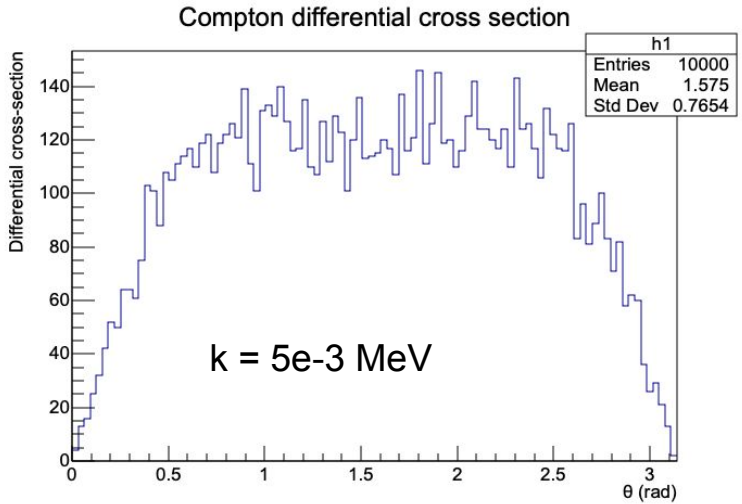
Compton Scattering

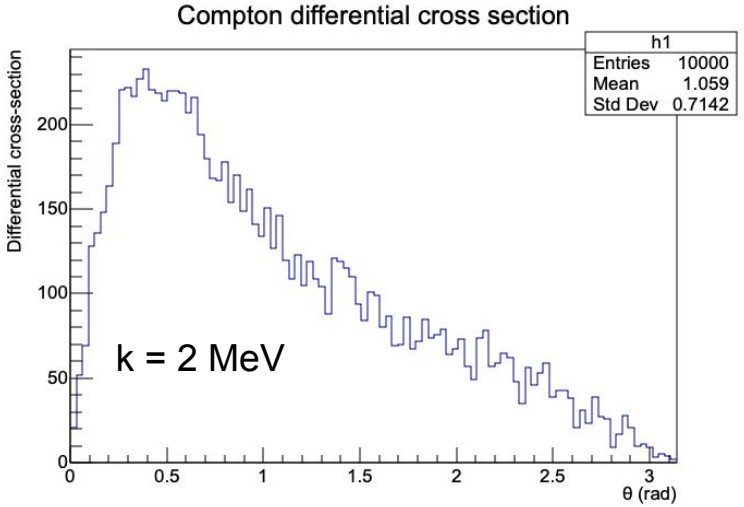
https://github.com/Analise-Dados-FAE/Aula-MonteCarlo-Pythia8/blob/main/compton.ipynb



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m^2}\left(\frac{k'}{k}\right)^2\left(\frac{k'}{k} + \frac{k}{k'} - \sin^2\theta\right)$$

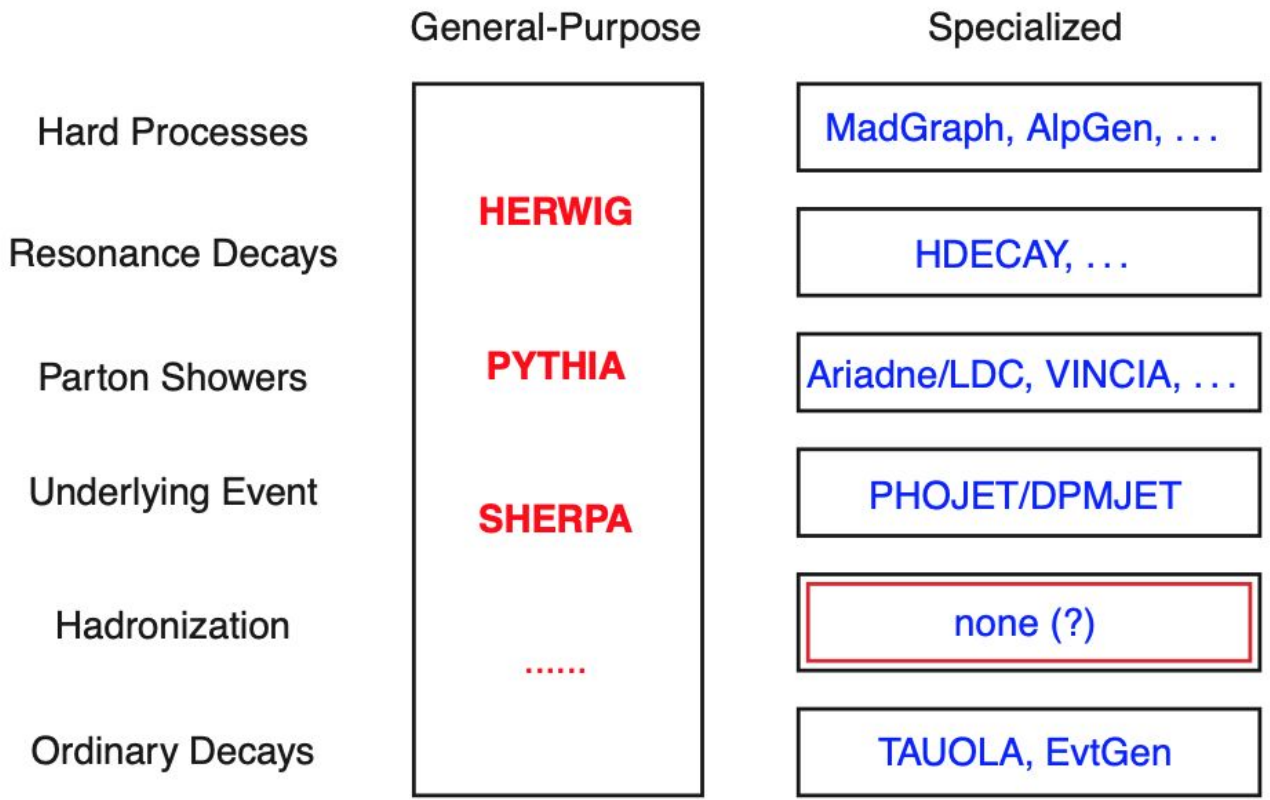
$$k' = \frac{k}{1 + (k/m)(1 - \cos\theta)}$$





Monte Carlo in HEP

Some Generators



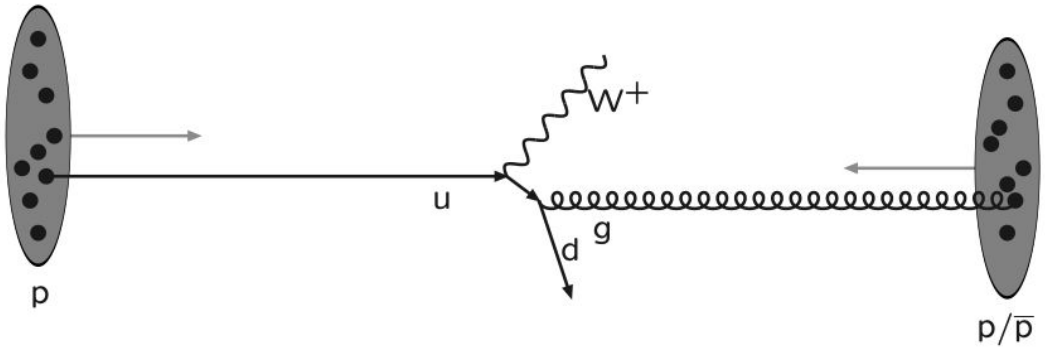
Specialized often best at given task, but need General-Purpose core

The Structure of a Event

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

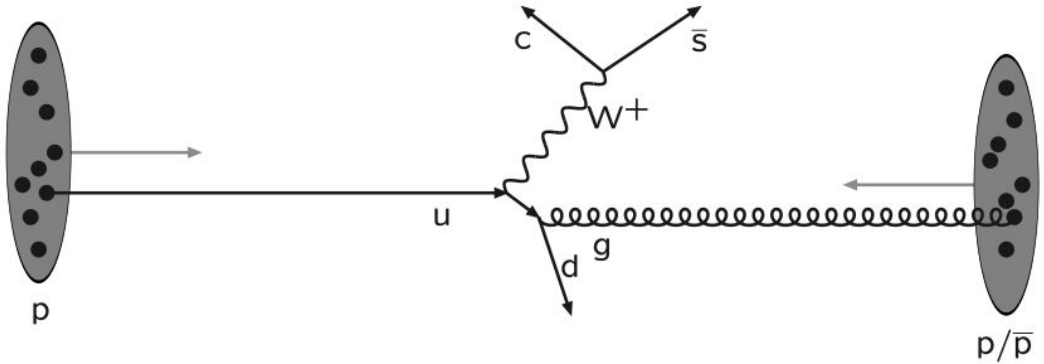
Incoming beams: parton densities

The Structure of a Event



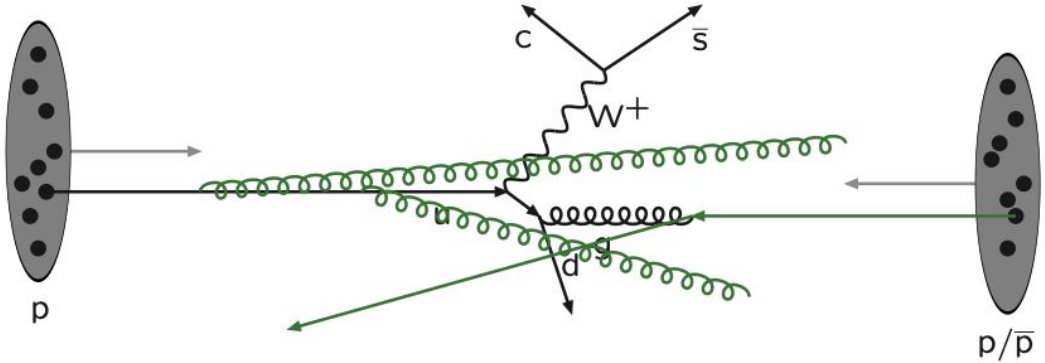
Hard subprocess: described by matrix elements

The Structure of a Event



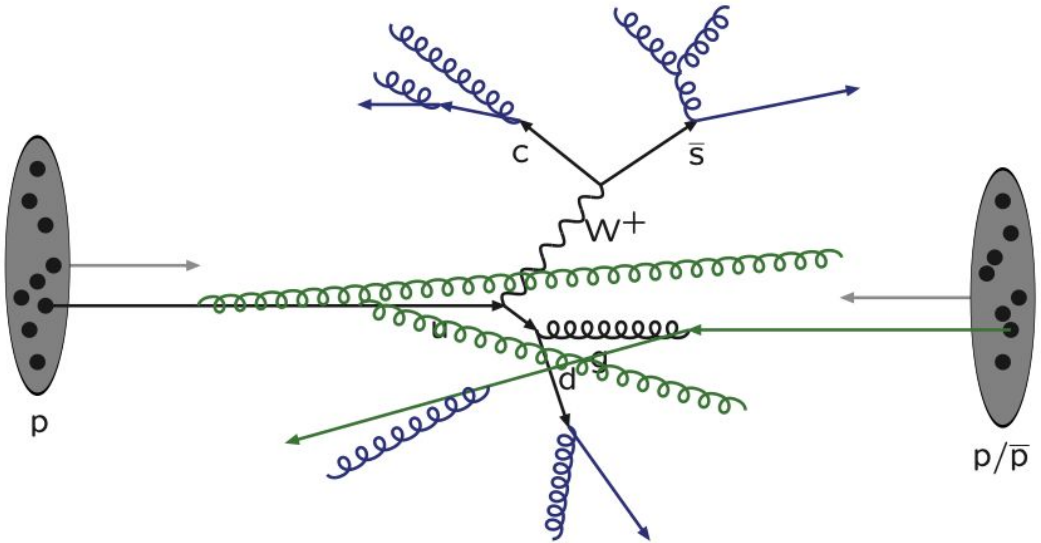
Resonance decays: correlated with hard subprocess

The Structure of a Event



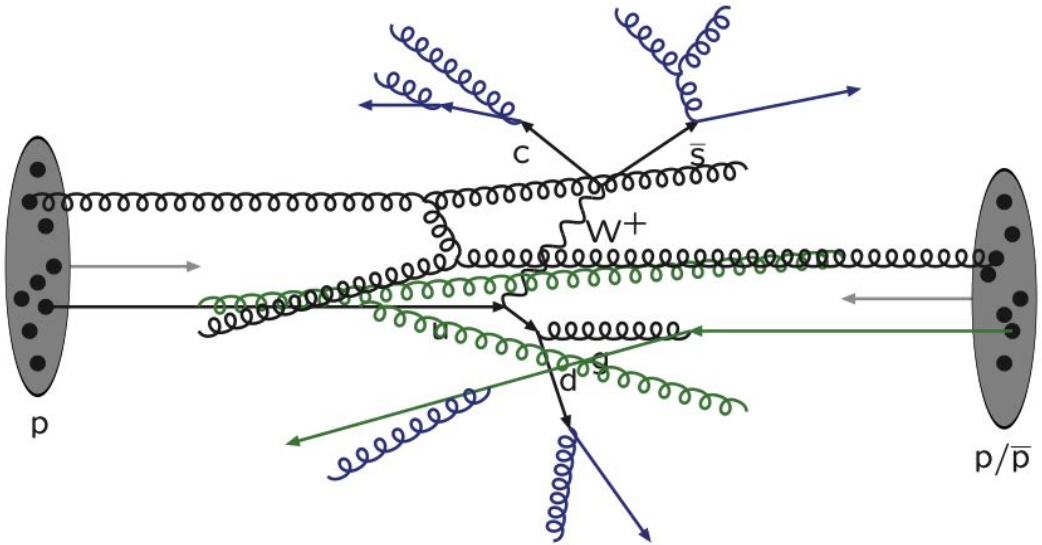
Initial-state radiation: spacelike parton showers

The Structure of a Event



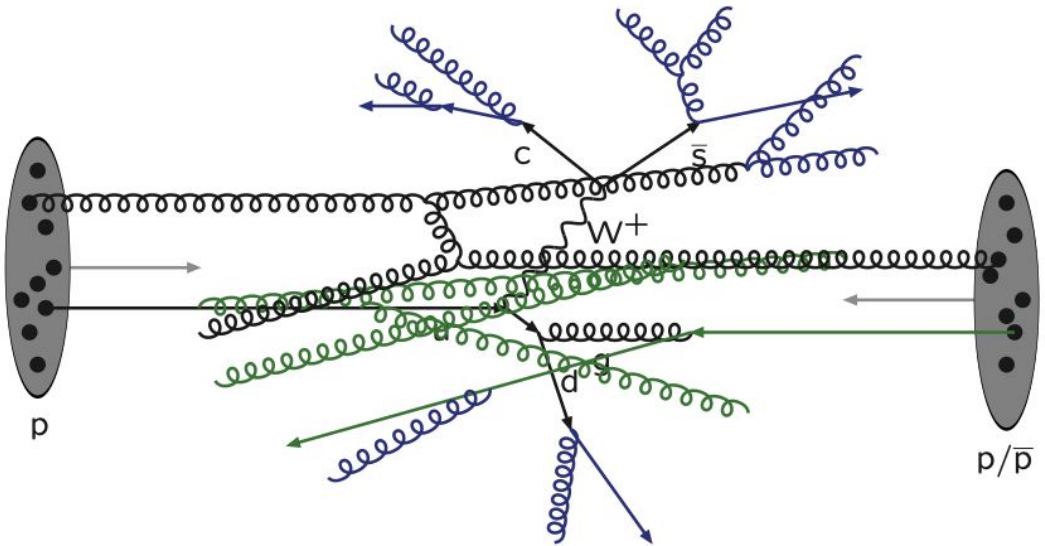
Final-state radiation: timelike parton showers

The Structure of a Event



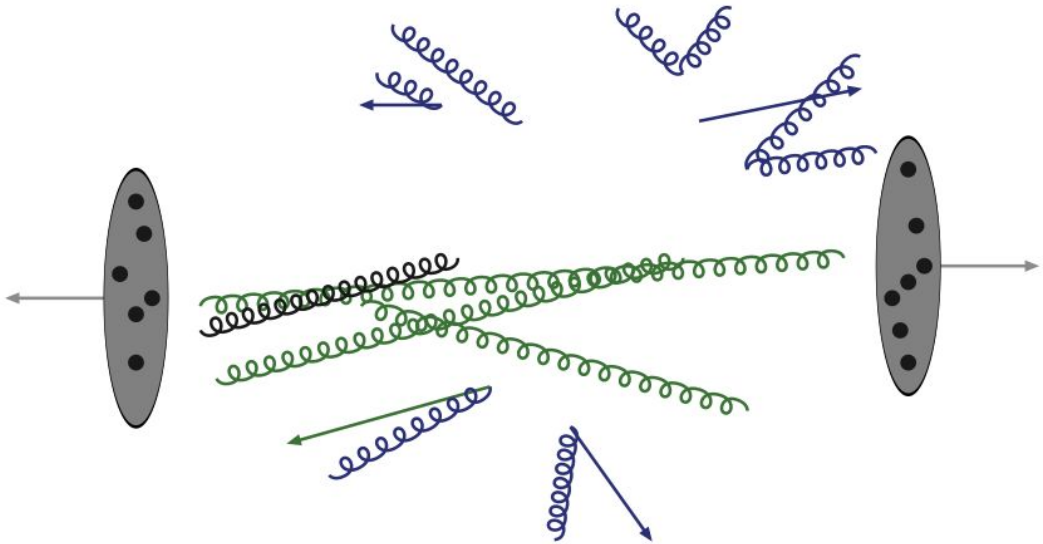
Multiple parton–parton interactions . . .

The Structure of a Event



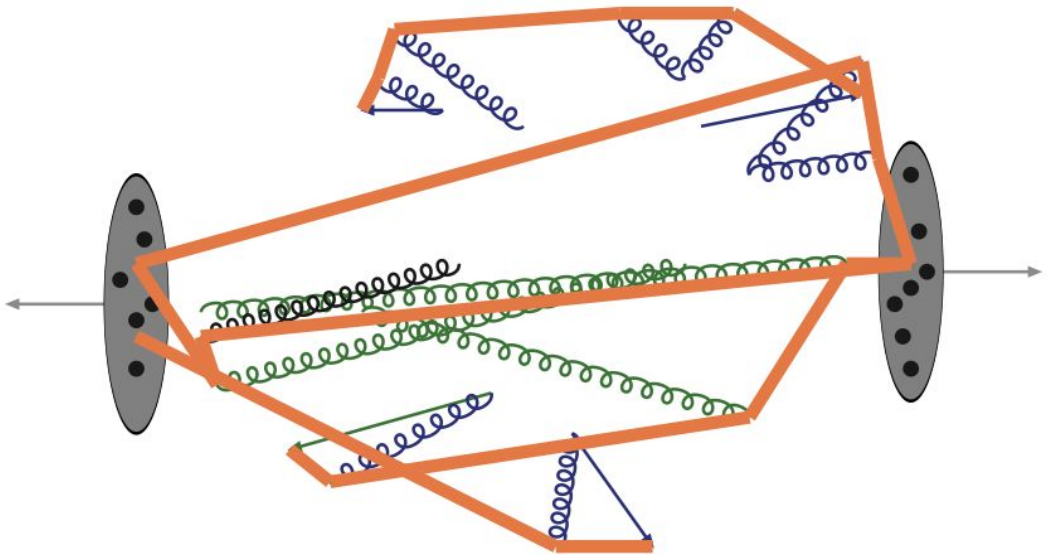
. . . with its initial- and final-state radiation

The Structure of a Event



Beam remnants and other outgoing partons

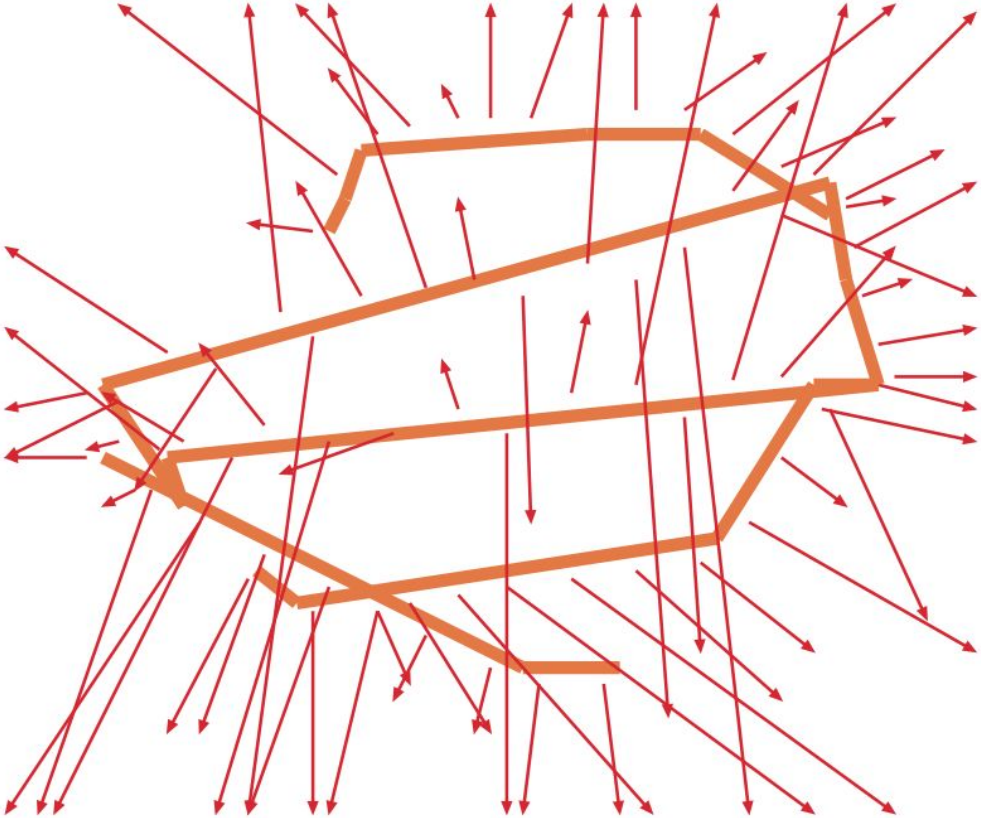
The Structure of a Event



Everything is connected by colour confinement strings

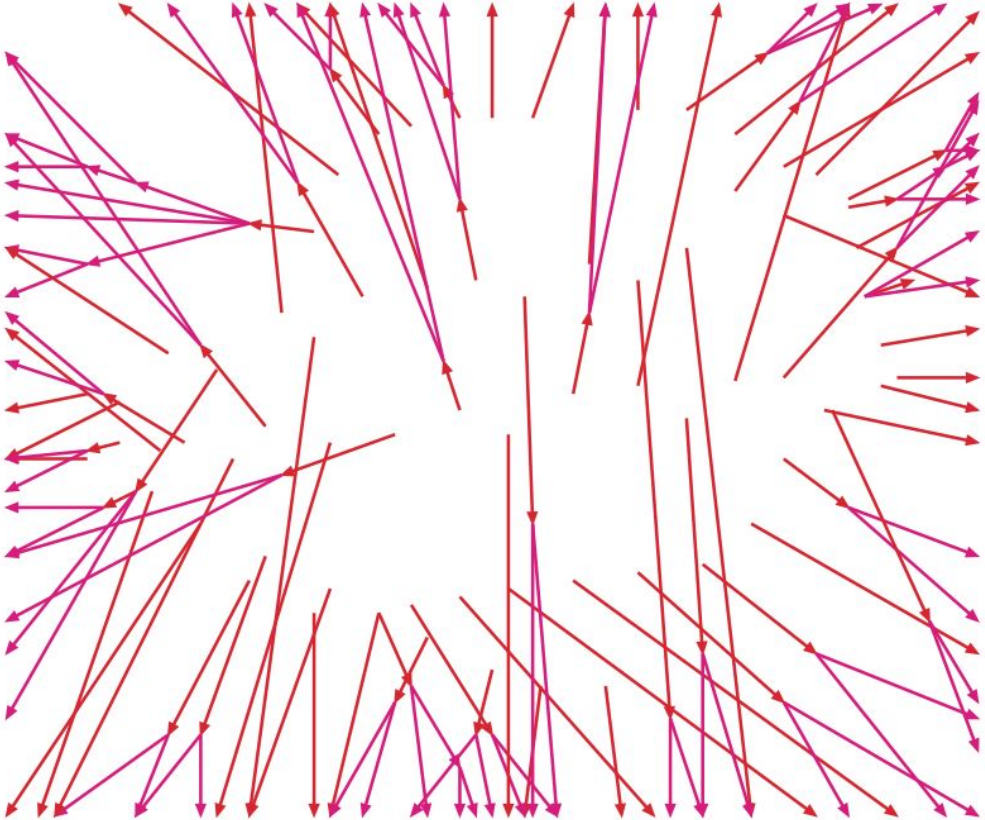
Recall! Not to scale: strings are of hadronic widths

The Structure of a Event



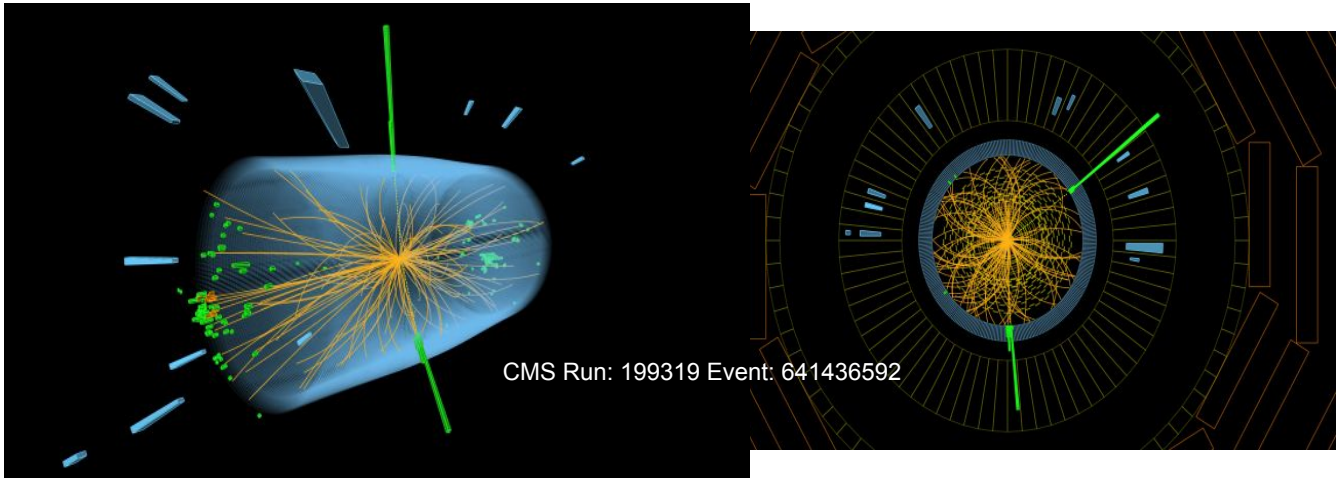
The strings fragment to produce primary hadrons

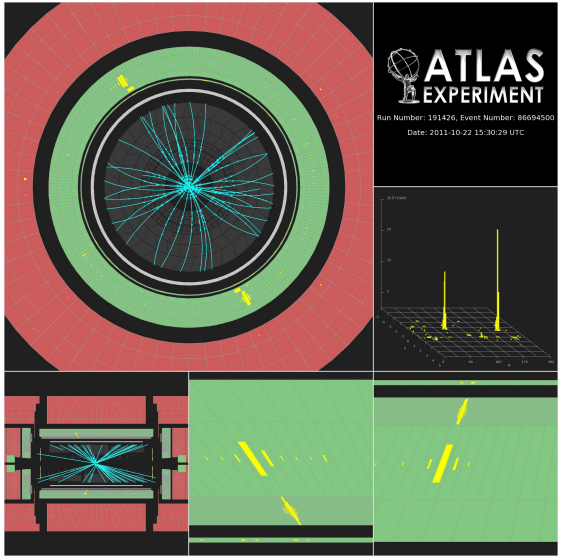
The Structure of a Event

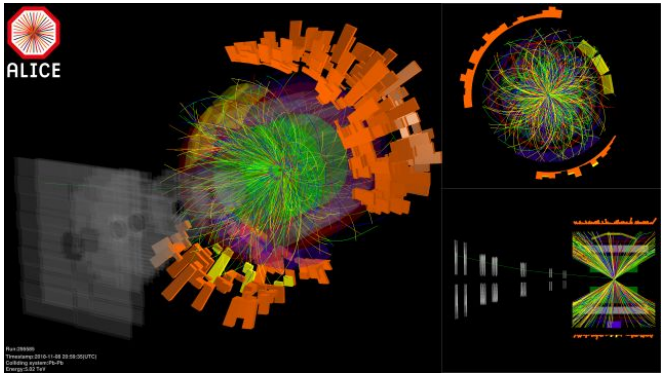


Many hadrons are unstable and decay further

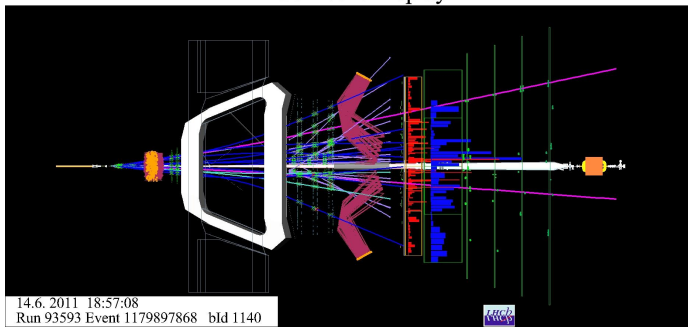
The Structure of a Events







LHCb Event Display

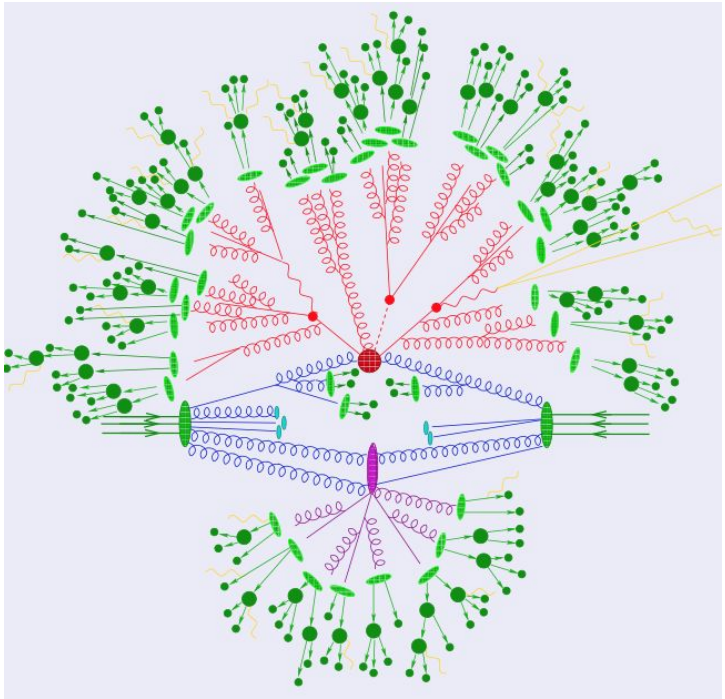


Simulation of a Collision Event

JHEP 0402 (2004) 056

Basic strategy: divide event into stages, separated by different scales

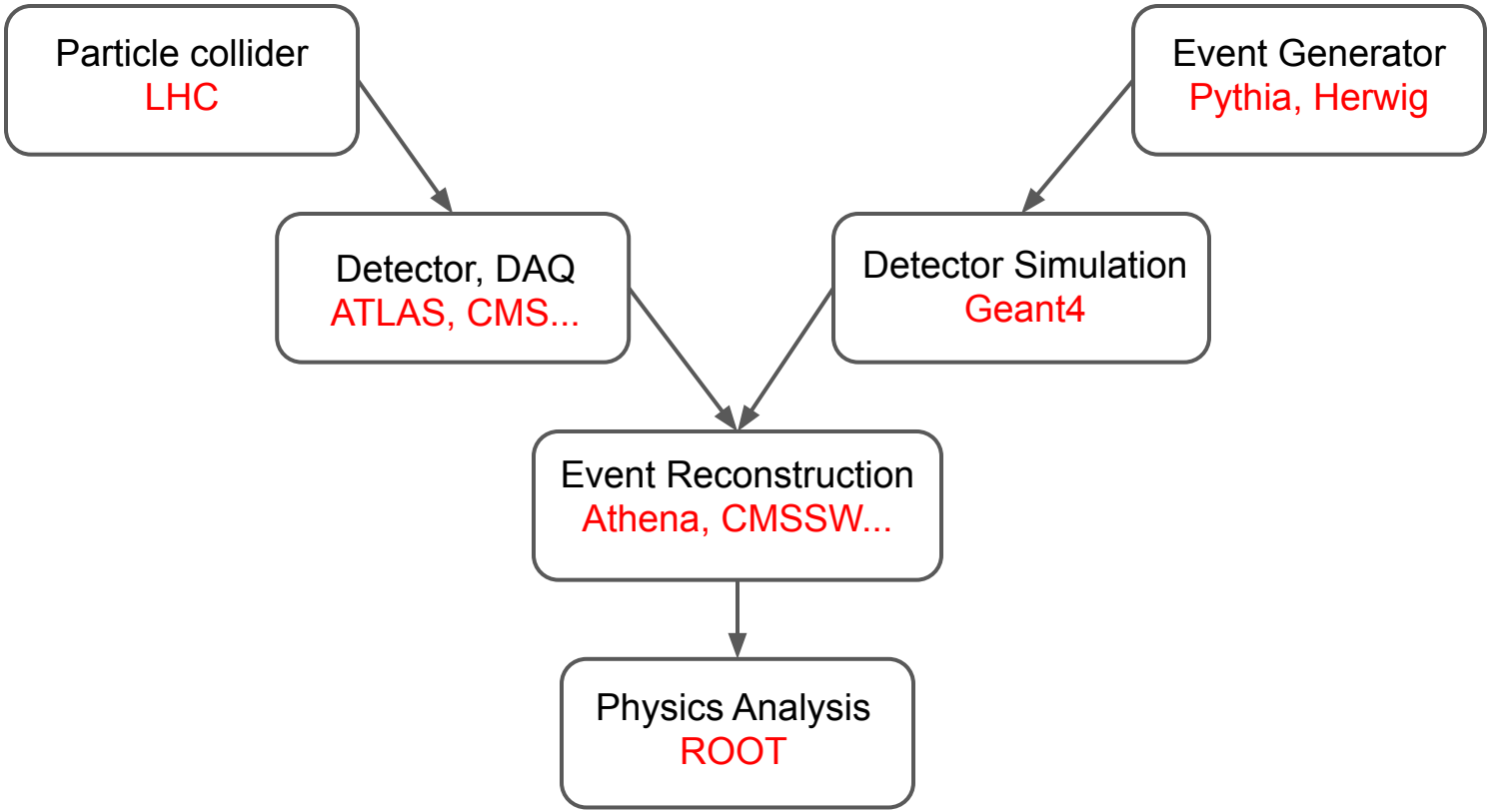
- Signal/background: exact matrix elements
- QCD-bremsstrahlung: parton showers (also initial state)
- Multiple interaction: beyond factorization, modelling
- Hadronization: non-perturbative, modelling



Calculation: →**partonic** subprocess

Measurement: →**hadrons**

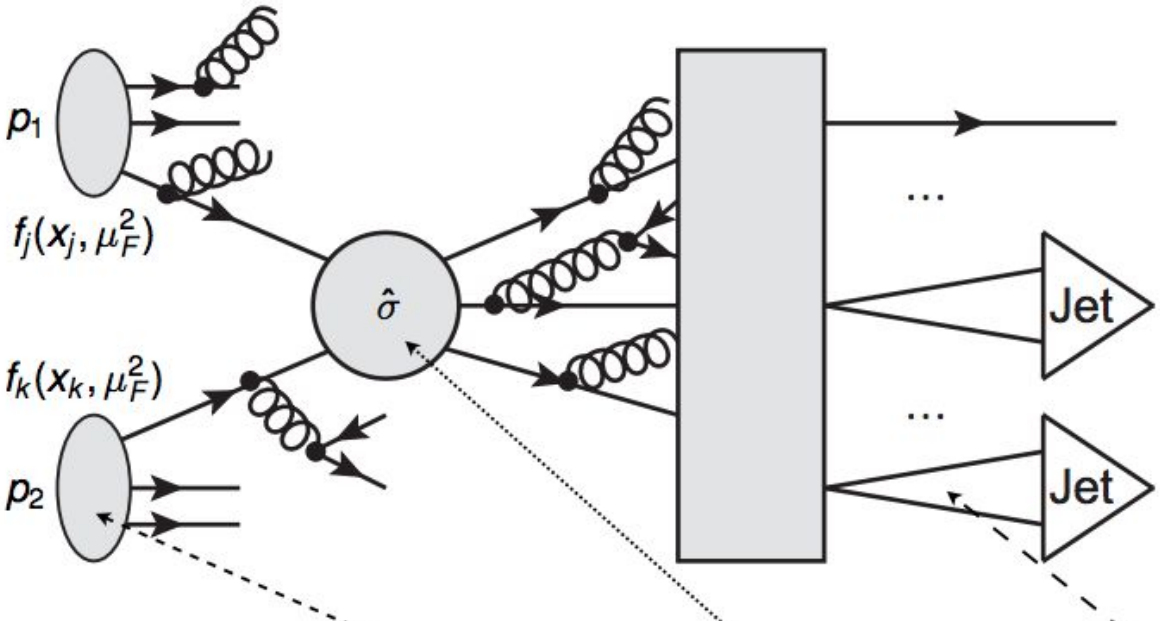
Monte Carlo in Particle Physics



Monte Carlo Event Generators

- Goal: **realistic simulation** of all relevant physics processes in a particle collision
- Problem: **complexity** of hadron-hadron collisions
  - Initial state: hadrons = compound objects, constituents (quarks and gluons) confined in hadron (running of α_s)
  - Final state:many hadrons and leptons
- Solution: **QCD factorisation**
  - **Separate treatment** of processes at low and high Q^2.
  - High Q^2 (“hard scattering process”): **perturbation theory** in leading order or higher orders
  - Low Q^2 (“soft physics”): phenomenological **models**

QCD Factorisation Theorem



$$\sigma_{\mathrm{QCD}} = \sum_{jk} \int \mathrm{d}x_j \, \mathrm{d}x_k \, f_j(x_j, \mu_F^2) \, f_k(x_k, \mu_F^2) \cdot \hat{\sigma}(x_j x_k s, \mu_F^2, \alpha_S(\mu_R^2)) \otimes \text{Hadronization}$$

Cross section = PDFs ⊗ hard process ⊗ hadronization

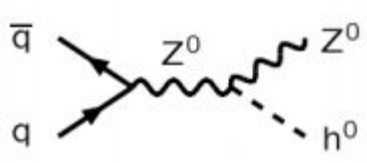
Overview of MC Generators

- Central step in any MC generator: **MC integration** of cross section of hard scattering process in fixed order perturbation theory using PDFs
- Parton-level MC generators
  - Simulation stops at level of partons (quarks and gluons)
  - No hadronisation, only events weighted with differential cross-section → no full event simulation (still useful for theoretical studies)
- Particle-level MC generators
  - Full event simulation: parton level + parton shower + hadronisation (number of MC events corresponds to theoretical expectation)
  - Provided as single comprehensive package or as combination of ME provider and parton shower MC (SMC) programme

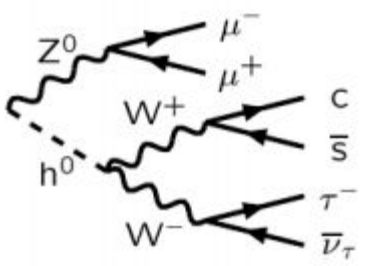
Overview: Monte Carlo Generation

Matrix Elements (ME):

1. Hard subprocess: $|M^2|$, Breit-Wigners, parton densities.

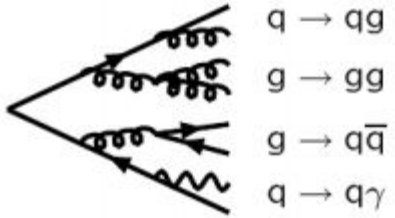


2. Resonance decays: includes correlations

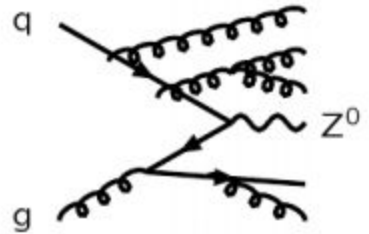


Parton Showers (PS):

3. Final-state parton showers

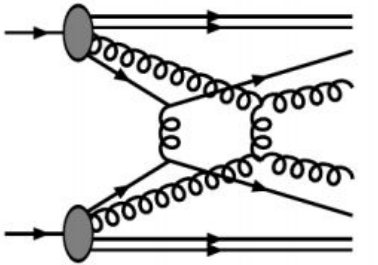


4. Initial-state parton showers

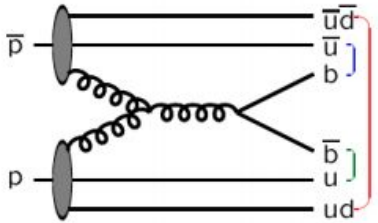


Overview: Monte Carlo Generation

5. Multiple parton-parton interactions

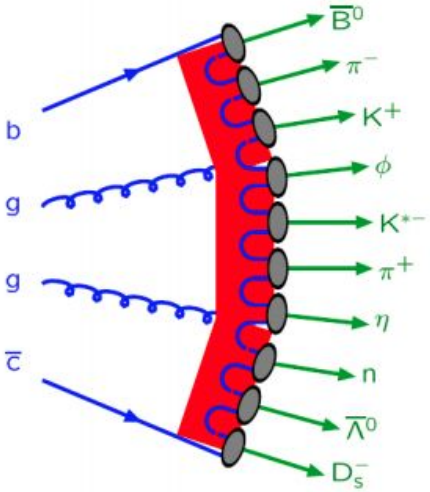


6. Beam remnants with colour connections

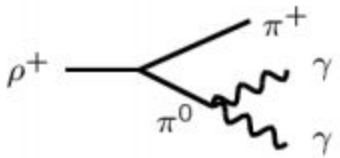


5+6 = Underlying Event

7. Hadronization



8. Ordinary decays: hadronic, τ ,charm,...



Pythia8 tutorial

Pythia8

http://home.thep.lu.se/~torbjorn/pdfdoc/pythia8200.pdf

- 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)
- Outputs exclusive hadronic events
  - Analyse
  - Pass to detector simulator (e.g. GEANT)
  - ...

Getting Started

- Download and untar the Pythia 8 source

```
Wget http://home.thep.lu.se/~torbjorn/pythia8/pythia8303.tgz
tar -xzvf pythia8303.tgz
cd pythia8303.tgz
```

- Configure and compile the source (just requires C++ compiler)

```
./configure --with-root=root-installation-directory
make
```

- Build and run an example

```
cd examples
make main01
./main01
```

```
// Example main program
#include "Pythia8/Pythia.h"
void main() {
   // Initialise
   Pythia8::Pythia pythia;
   pythia.readString("HiggsSM:all = on");
   pythia.init();
   pythia.next();
}
```

Install Pythia8 via Conda

https://github.com/conda-forge/pythia8-feedstock

- Installing pythia8 from the `conda-forge` channel can be achieved by adding `conda-forge` to your channels with:

```
conda config --add channels conda-forge
```

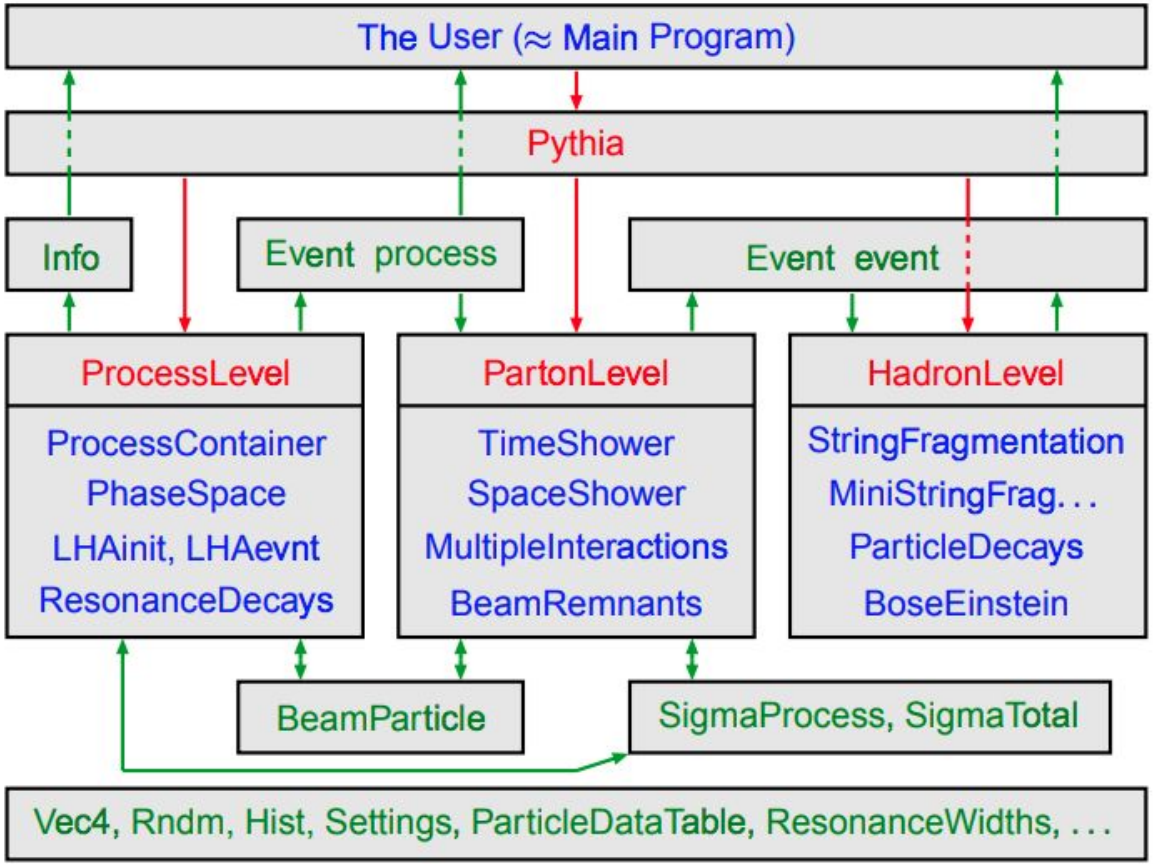
- Once the conda-forge channel has been enabled, pythia8 can be installed with:

```
conda install pythia8
```

- It is possible to list all of the versions of pythia8 available on your platform with:

```
conda search pythia8 --channel conda-forge
```

Pythia8 structure



Physics Overview - Beams and hard processes

- Beams
  - Incoming beams: **hadron-hadron** or **lepton-lepton** collisions
    - Hadron: (anti)proton, (anti)neutron, pion as pomeron
  - Built-in PDFs sets:
    - GRV 94L, 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→1 and 2→2, some 2→3
  - BSM: a bit of everything
  - External input through Les Houches Accord (LHA) and Les Houches Event Files (LHEF)

The Event Record

- The event record is set up to store every step in the evolution from an initial low-multiplicity partonic process to a final high-multiplicity hadronic state, in the order that new particles are generated.
- The record is a vector of particles, that expands to fit the needs of the current event.
- Thus `event[i]` is the i'th particle of the current event, and you may study its properties by using various `event[i].method()` possibilities.
- The event.list() listing provides the mais properties of each particles, by column:
  - `no`, the index number of the particle (`i` above);
  - `id`, the PDG particle identity code (method `id()`);
  - `name`, a plaintext rendering of the particle name (method `name()`), within brackets for initial or intermediate particles and without for final-state ones;
  - `status`, the reason why a new particle was added to the event record (method `status()`);
  - `mothers` and `daughters`, documentation on the event history (methods `mother1()`, `mother2()`, `daughter1()` and `daughter2()`);
  - `colours`, the colour flow of the process (methods `col()` and `acol()`);
  - `p_x`, `p_y`, `p_z` and `e`, the components of the momentum four-vector (p_x,p_y,p_z,E), in units of GeV with c = 1 (methods `px()`, `py()`, `pz()` and `e()`);
  - `m`, the mass, in units as above (method `m()`).

Identity codes

- A complete specification of the PDG codes is found in the Review of Particle Physics. An online listing is available from

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-monte-carlo-numbering.pdf

- A short summary of the most common `id` codes would be:

1	d	11	e^-	21	g	211	π^+	111	π^0	213	ρ^+	2112	n
2	u	12	ν_e	22	γ	311	K^0	221	η	313	K^{*0}	2212	p
3	s	13	μ^-	23	Z^0	321	K^+	331	η'	323	K^{*+}	3122	Λ^0
4	c	14	ν_μ	24	W^+	411	D^+	130	K_L^0	113	ρ^0	3112	Σ^-
5	b	15	τ^-	25	H^0	421	D^0	310	K_S^0	223	ω	3212	Σ^0
6	t	16	ν_τ			431	D_s^+			333	ϕ	3222	Σ^+

- Antiparticles to the above, where existing as separate entities, are given with a negative sign

Status codes

- When a new particle is added to the event record, it is assigned a positive status code that describes why it has been added, as follows:

code range	explanation
11 – 19	beam particles
21 – 29	particles of the hardest subprocess
31 – 39	particles of subsequent subprocesses in multiparton interactions
41 – 49	particles produced by initial-state-showers
51 – 59	particles produced by final-state-showers
61 – 69	particles produced by beam-remnant treatment
71 – 79	partons in preparation of hadronization process
81 – 89	primary hadrons produced by hadronization process
91 – 99	particles produced in decay process, or by Bose-Einstein effects

- The `isFinal()` method return `true/false` for positive/negative status code

History and colour flow information

- History Information:

The two mother and two daughter indices of each particle provide information on the history relationship between the different entries in the event record.

- Colour flow information:

Is based on the Les Houches Accord convention. In it, the number of colours is assumed infinite, so that each new colour line can be assigned a new separate colour. These colours are given consecutive labels: 101, 102, 103,... A gluon has both a colour and an anticolour label, an (anti)quark only (anti)colour

Some Facilities

- Histograms: the class Hist implemented on Pythia can be used to make histograms like ROOT
  - As a first step you need to declare a histogram, with name, title, number of bins and x range (from, to), like `Hist pTH("Higgs transverse momentum", 100, 0., 200.);`
  - Once declared, its contents can be added by repeated calls to fill, `pTH.fill( 22.7, 1.);` where the first argument is the x value and the second the weight. Since the weight defaults to 1 the last argument could have been omitted in this case.
  - Histogram values can also be output to a file `pTH.table("filename");` which produces a two-column table, where the first column gives the center of each bin and the second one the corresponding bin content.

Some Facilities

- Jet finding: the SlowJet class offer jet finding by the k⊥, Cambridge/Aachen and anti-k⊥ algorithms
  - You set up `SlowJet` initially with `SlowJet slowJet( pow, radius, pTjetMin, etaMax);`
    - where `pow = -1` for anti-k⊥ (recommended), `pow = 0` for Cambridge/Aachen, `pow = 1` for k⊥, while `radius` is the R parameter, `pTjetMin` the minimum p⊥ of jets, and `etaMax` the maximum pseudorapidity of the detector coverage.
  - Inside the event loop, you can analyze an event by a call `slowJet.analyze( pythia.event );`
  - The jets found can be listed by `slowJet.list();`, but this is only feasible for a few events. Instead you can use the following methods:
    - `slowJet.sizeJet()` gives the number of jets found,
    - `slowJet.pT(i)` gives the p⊥ for the i'th jet, and
    - `slowJet.y(i)` gives the rapidity for the i'th jet.
  - The jets are ordered in falling p⊥.

Program Structure

- Proper header file must be included:

```
#include “Pythia8/Pythia.h”
using namespace Pythia8;
```

- Create a generator object: `Pythia pythia;`
- Pythia’s settings and particle data

```
pythia.readString(string);  // for changing a single variable
pythia.readFile(fileName);  // for changing a set of variables, one per line in the input file
```

- Initialize all aspects of the subsequent generation: `pythia.init();`
- Generate the next event: `pythia.next();`
- Run statistics: `pythia.stat();`

Example of a main program: examples/main01.cc

```
11  #include "Pythia8/Pythia.h"
12  using namespace Pythia8;
13  int main() {
14    // Generator. Process selection. LHC initialization. Histogram.
15    Pythia pythia;
16    pythia.readString("Beams:eCM = 8000.");
17    pythia.readString("HardQCD:all = on");
18    pythia.readString("PhaseSpace:pTHatMin = 20.");
19    pythia.init();
20    Hist mult("charged multiplicity", 100, -0.5, 799.5);
21    // Begin event loop. Generate event. Skip if error. List first one.
22    for (int iEvent = 0; iEvent < 100; ++iEvent) {
23      if (!pythia.next()) continue;
24      // Find number of all final charged particles and fill histogram.
25      int nCharged = 0;
26      for (int i = 0; i < pythia.event.size(); ++i)
27        if (pythia.event[i].isFinal() && pythia.event[i].isCharged())
28          ++nCharged;
29      mult.fill( nCharged );
30    // End of event loop. Statistics. Histogram. Done.
31    }
32    pythia.stat();
33    cout << mult;
34    return 0;
35  }
```

11: Reading header files = “tools you need”
13: Starting calculation
15: Make “object” of class called Pythia
16-18: Reading parameters to set up. You can also read it from file: pythia.readFile(fileName);
19: Initialization

22-31 Event generation

Pythia member function
readString
next(): generate next event
event[i]: array of particles of an events
size(): size of the events
isFinal(): final state or not
isCharged()
stat(): print out statistics

Compile and Execute: examples/main01.C

```
cd examples
make main01
./main01 >& test_main01
less test_main01
```

```
*-------  PYTHIA Process Initialization  ------------------------*
|                                                                |
| We collide p+ with p+ at a CM energy of 8.000e+03 GeV          |
|                                                                |
|----------------------------------------------------------------|
|                                                  |             |
| Subprocess                                  Code |   Estimated |
|                                                  |    max (mb) |
|                                                  |             |
|----------------------------------------------------------------|
|                                                  |             |
| g g -> g g                                   111 |   1.403e+00 |
| g g -> q qbar (uds)                          112 |   1.817e-02 |
| q g -> q g                                   113 |   1.010e+00 |
| q q(bar)' -> q q(bar)'                       114 |   1.100e-01 |
| q qbar -> g g                                115 |   8.378e-04 |
| q qbar -> q' qbar' (uds)                     116 |   3.698e-04 |
| g g -> c cbar                                121 |   5.988e-03 |
| q qbar -> c cbar                             122 |   1.225e-04 |
| g g -> b bbar                                123 |   5.400e-03 |
| q qbar -> b bbar                             124 |   1.160e-04 |
|                                                  |             |
*-------  End PYTHIA Process Initialization ----------------------*

*-------  PYTHIA Multiparton Interactions Initialization  ---------*
|                                                                |
|                  sigmaNonDiffractive =    51.78 mb             |
|                                                                |
|    pT0 =  2.35 gives sigmaInteraction =   257.10 mb: accepted  |
|                                                                |
*-------  End PYTHIA Multiparton Interactions Initialization  -----*

*-------  PYTHIA Flag + Mode + Parm + Word + FVec + MVec + PVec + WVec Settings (changes only)  -------------------*
|                                                                                                                  |
| Name                                    |                   Now |      Default         Min         Max |
|                                         |                       |                                              |
| Beams:eCM                               |              8000.000 |    14000.000    10.00000                     |
| HardQCD:all                             |                   on |          off                                 |
| PhaseSpace:pTHatMin                     |              20.00000 |          0.0         0.0                     |
|                                                                                                                  |
*-------  End PYTHIA Flag + Mode + Parm + Word + FVec + MVec + PVec + WVec Settings  ----------------------------*
```

Process code:
`pythia.info.code()`

Number of Multi Partonic Interaction:
`pythia.info.nMPI()`

Event Information: examples/main01.C

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

    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   8000.000   8000.000
     1       2212  (p+)              -12      0     0     3     0     0     0      0.000      0.000   4000.000   4000.000      0.938
     2       2212  (p+)              -12      0     0     4     0     0     0      0.000      0.000  -4000.000   4000.000      0.938
     3         21  (g)               -21      1     0     5     6   101   102      0.000      0.000    148.263    148.263      0.000
     4         21  (g)               -21      2     0     5     6   103   101      0.000      0.000     -2.904      2.904      0.000
     5         21  g                  23      3     4     0     0   103   104     18.969      6.722     54.243     57.856      0.000
     6         21  g                  23      3     4     0     0   104   102    -18.969     -6.722     91.115     93.311      0.000
                                 Charge sum:  0.000          Momentum sum:      0.000      0.000    145.358    151.167     41.503

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

Final Cross Section: examples/main01.C

------- PYTHIA Event and Cross Section Statistics ---

Subprocess	Code	Number of events			sigma +- delta	
		Tried	Selected	Accepted	(estimated)	(mb)
g g -> g g	111	414	65	65	1.977e-01	1.482e-02
g g -> q qbar (uds)	112	8	2	2	2.626e-03	8.808e-04
q g -> q g	113	277	26	26	1.216e-01	1.158e-02
q q(bar)' -> q q(bar)'	114	33	6	6	2.056e-02	4.284e-03
q qbar -> g g	115	0	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	3.914e-03	3.914e-03
q qbar -> c cbar	122	0	0	0	0.000e+00	0.000e+00
g g -> b bbar	123	0	0	0	0.000e+00	0.000e+00
q qbar -> b bbar	124	0	0	0	0.000e+00	0.000e+00
sum		733	100	100	3.464e-01	1.970e-02

------- End PYTHIA Event and Cross Section Statistics ---

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 ±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*, LHAevent*) 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

- At the end of the generation loop: pythia.statistics() provides 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 4 types:
  - 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 = values`, 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 a form `id:property = value` or `id:channel:property = value` , e.g.:
  - `3122:mayDecay = no` do not allow Λ^0 decay
  - `215:3:products = 211 111 111` to let $a_2^+ \to \pi^+\pi^0\pi^0$

Setup: example of W’ and so on

- Beam energy: `pythia.readString("Beams:eCM = 8000.");`
- Process: `pythia.readString("NewGaugeBoson:ffbar2Wprime = on");`
- Particle mass, decay mode:
  - `pythia.readString("4:m0 = 2000.");`
  - `pythia.readString("34:onMode = off");` switch off decay
  - `pythia.readString("34:onIfAny = 24");` then is final state contain pdg code 24 (namely, W)
- Energy of hard interaction, minimum pT (important to reduce the number of events to be generated)
  - `pythia.readString("PhaseSpace:mHatMin = 1300.");`
  - `pythia.readString("haseSpace:pTHatMin = 500.");`

Advanced Setup

- Choice of PDF:
  - `pythia.readString("PDF:pSet = 7");` CTEQ 6L NLO
  - Using LHAPDF (PDF package):

```
using LHAPDF
pythia.readString("PDF:pSet = LHAPDF6:CT10");
pythia.readString("Random:setSeed = on");
```

  - External input (specify numbers when you rin the code)
- If you do not specify anything, code produce same events. If you what to make huge number of events, you have to restart your code with different random number seed:

```
    string iseed = argv[1]
    string dummy = "Random:seed = "+iseed;  // This makes longer
"string"
    pythia.readString(dummy);
```

- Final state radiation: `pythia.readString("Tune::pp = 11");` // using Tunes

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.
Main:idBeamA = 2212                ! first beam, p = 2212, pbar = -2212
Main:idBeamB = 2212                ! second beam, p = 2212, pbar = -2212
Main: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
```

More on Settings

- Settings are stored in 4 separated maps (flags/modes/parms/words)
- For each setting, need to store:
  - name: of form `task:property`, e.g. `TimeShower:pTmin`
  - default value
  - current value
  - allowed range: minimum/maximum on/off (not for flags)
- Useful commands:
  - `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:eCM                            |     14000.000 |     1960.000    10.00000              |
| 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  -------------------------------------*
```

Save to .hepmc files: examples/main41.cc

```
17  #include "Pythia8/Pythia.h"
18  #include "Pythia8Plugins/HepMC3.h"
19
20  using namespace Pythia8;
21
22  int main() {
23    // Interface for conversion from Pythia8::Event to HepMC event.
24    HepMC3::Pythia8ToHepMC3 topHepMC;
25    // Specify file where HepMC events will be stored.
26    HepMC3::WriterAscii ascii_io("hepmcout41.dat");
27    // Generator. Process selection. LHC initialization. Histogram.
28    Pythia pythia;
29    pythia.readString("Beams:eCM = 8000.");
30    pythia.readString("HardQCD:all = on");
31    pythia.readString("PhaseSpace:pTHatMin = 20.");
32    pythia.init();
33    Hist mult("charged multiplicity", 100, -0.5, 799.5);
34    // Begin event loop. Generate event. Skip if error.
35    for (int iEvent = 0; iEvent < 100; ++iEvent) {
36      if (!pythia.next()) continue;
37      // Find number of all final charged particles and fill histogram.
38      int nCharged = 0;
39      for (int i = 0; i < pythia.event.size(); ++i)
40        if (pythia.event[i].isFinal() && pythia.event[i].isCharged())
41          ++nCharged;
42      mult.fill( nCharged );
43      // Construct new empty HepMC event and fill it.
44      // Default units are ( HepMC3::Units::GEV, HepMC3::Units::MM)
45      // but can be changed in the GenEvent constructor.
46      HepMC3::GenEvent hepmcevt;
47      topHepMC.fill_next_event( pythia, &hepmcevt );
48      // Write the HepMC event to file.
49      ascii_io.write_event(hepmcevt);
50    // End of event loop. Statistics. Histogram.
51    }
52    pythia.stat();
53    cout << mult;
54    // Done.
55    return 0;
56  }
```

17: and 18 Need new function written in HepMC2.h
24: Tool to convert pythia events to HepMC
26: Name of the output file
46: Memory of HepMC event
47: Copy and convert Pythia events to HepMC
49: Write to hepmcout41.dat file

Using ROOT for plotting different quantities

ex1.C

```
#include "Pythia8/Pythia.h"
#include "TH1.h"
#include "TTree.h"
#include "TFile.h"
using namespace Pythia8;

int main() {
// Generator. Process selection. LHC initialization. Histogram.
 Pythia pythia;
 pythia.readString("Beams:idA = 2212");
 pythia.readString("Beams:idB = 2212");
 pythia.readString("Beams:eCM = 14000.");
 pythia.readString("HardQCD:all = on");
 pythia.readString("PhaseSpace:pTHatMin = 20.");
 pythia.init();
 TFile *file = TFile::Open("ex1.root","recreate");
 Event *event = &pythia.event;
 TTree *T = new TTree("T","ev1 Tree");
 T->Branch("event",&event);
 TH1F *mult = new TH1F("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;
   // 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 );
   T->Fill();
 // End of event loop. Statistics. Histogram. Done.
 }
 pythia.stat();
 cout << mult;
 T->Print();
 T->Write();
 delete file;
 return 0;
}
```

goex1

```
rootcint -f pythiaDict.cxx -c -I$PYTHIA8/include pythiaROOT.h
pythiaLinkdef.h
g++ -o ex1 ex1.C pythiaDict.cxx -I$PYTHIA8/include `root-config --cflags
--glibs` \
-lEG -lEGPythia8 -L$PYTHIA8/lib -lpythia8
```

pythiaLinkdef.h

```
#ifdef __CINT__

#pragma link off all globals;
#pragma link off all classes;
#pragma link off all functions;

#pragma link C++ namespace Pythia8;
#pragma link C++ class Pythia8::ParticleData+;
#pragma link C++ class Pythia8::Event+;
#pragma link C++ class Pythia8::Particle+;
#pragma link C++ class Pythia8::Junction+;
#pragma link C++ class Pythia8::Vec4+;
#pragma link C++ class Pythia8::DecayChannel+;
#pragma link C++ class Pythia8::Pythia+;
#pragma link C++ class Pythia8::CoupSM+;
#pragma link C++ class Pythia8::InBeam+;
#pragma link C++ class Pythia8::InPair+;
#pragma link C++ class Pythia8::Info+;
#pragma link C++ class Pythia8::Rndm+;
#pragma link C++ class Pythia8::Settings+;
#pragma link C++ class Pythia8::ResonanceWidths+;
#pragma link C++ class Pythia8::ParticleDataEntry+;
#pragma link C++ class Pythia8::SigmaProcess+;
#pragma link C++ class std::map<int,ParticleDataEntry>+;
#endif
```

pythiaROOT.h

```
#include <Pythia8/Pythia.h>
using namespace Pythia8;
```

How to run:

```
> ./goex1
> ./ex1
```

https://github.com/Analise-Dados-FAE/Aula-MonteCarlo-Pythia8/tree/main/ex1

Pythia8 and C++

- `Pythia8` and `HepMC` are “class”
- Pythia8 can generate events and it also contain another class
- You can use objects in the different class by writing
  - `Pythia8::name`
  - `hepMC::name`
- HepMC objects are defined in HepMC2.h
- If you use `namespace Pythia8;` allows you to omit `Pythia8::`
- Object defined with * is an address; without *, it is the contents at the address.
- Member can be accessed by `object->member_name` for the object defined by the address, and if it is not the address, access by `object.member_name`
- If you create by method `new`, then `delete` to avoid memory leak

Exercises - part 1

1. Write a code that estimate the area of a unit disk using the hit-or-miss Monte Carlo method. We know the radius of the unit disk is 1 thus the unit circle is inscribed within a square of length 2. Tip: generate samples within this square and count the number of points falling within the disk. To test whether the point is inside (hit) or outside (miss) the disk, we simply need to measure the distance of the sample from the origin (the center of the unit disk) and check whether this distance is smaller (or equal) than the disk radius (which is equal to 1 for a unit disk).

2. Evaluate the integral using both methods. $\int_0^3 (1 - x^2)^2 dx$

3. Write a code to calculate the differential cross section of the Rutherford scattering

4. Using the simplifies skeleton, modify the script to generate some events in LHC environment (at √s=14 TeV and √s=7 TeV).
   a. The process to be considered are `HardQCD:qqbar2bbbar`, `HardQCD:gg2bbbar`, `HardQCD:gg2qqbarg`, `HardQCD:qqbar2qqbargDiff`and `HardQCD: qqbar2qqbargSame`. You should also turno on all quark flavours by `HardQCD:nQuark New = 5`
   b. How can we select only events containing b quarks? How can we select only B-mesons?
   c. Save particle information into a tree

Exercises - part 2

5. Use e+e- annihilation as an environment for the clean study of final-state QCD radiation. Specifically study how the average number of final-state partons increases with ECM. Also, how well/badly the number of partons is described by Poisson distributions. Hint: some useful settings are:

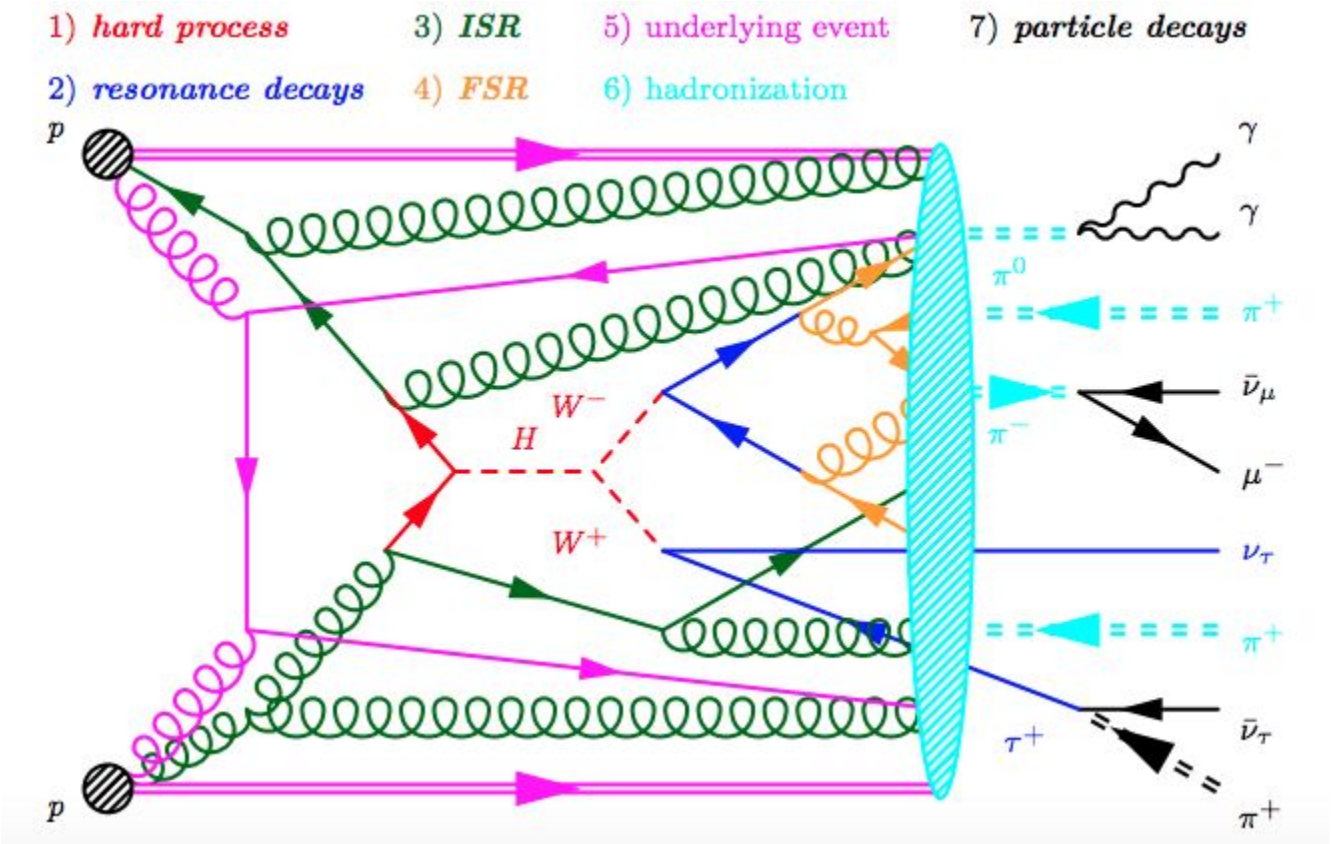
```
WeakSingleBoson:ffbar2gmZ = on
PDF:lepton = off
HadronLevel:all = off
23:onMode = off
23:onIfAny = 1 2 3 4 5
```

6. Study the properties of “minimum-bias” events, e.g. the distributions dn/dη, dn/dp⊥ and ⟨p⊥⟩ of charged final-state particles at the LHC. Study how these distributions changed if MPIs are switched off. Hint: Some useful commands are

```
SoftQCD:minBias = on
PartonLevel:MI = off
```

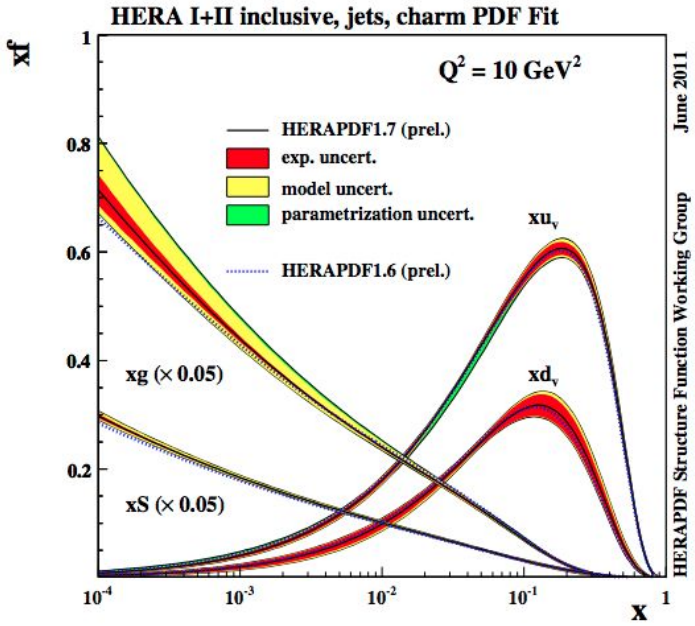
Backup Slides

Event Anatomy



The Parton Density Function (PDF)

- Proton is not a point-like particle, it's full of partons
- Need to calculate:
  - Probability of propagator interacting with quarks/gluon
  - Needed as a function of Q^2 and x
- Various groups provide PDFs
- Parametrised differently
- LHC uses:
  - CTEQ
  - MSTW
  - NNPDF
- Get a different result using different PDFs

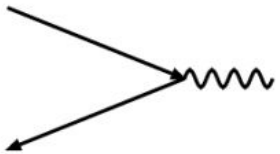


⇒Theoretical modelling uncertainty

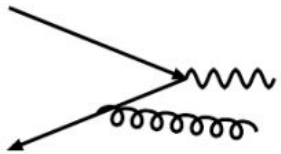
Matrix Element Calculation

Normally calculated at LO or NLO

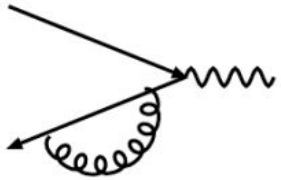
I. Lowest order, $\mathcal{O}(\alpha_{em})$: $q\bar{q} \rightarrow Z^0$



II. First-order real, $\mathcal{O}(\alpha_{em}\alpha_s)$: $q\bar{q} \rightarrow Z^0 g$ etc.



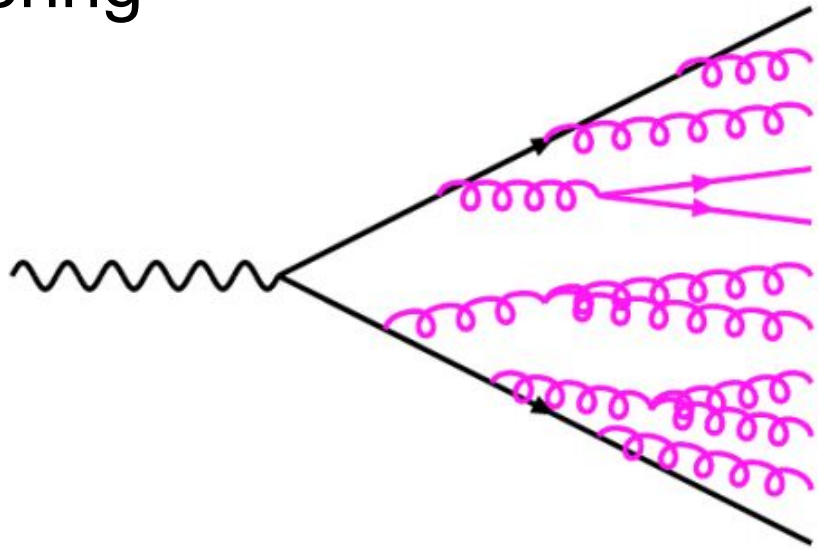
III. First-order virtual, $\mathcal{O}(\alpha_{em}\alpha_s)$: $q\bar{q} \rightarrow Z^0$ with loops



- Higher order corrections are important
  - Normalisation and shape of kinematic distributions
  - Multiplicity of objects like jets
- Higher order correction are hard to calculate and CPU intensive
- Several programs that will do the calculation
  - Different calculation techniques
  - Different assumptions
  - Different results

⇒Theoretical modelling uncertainty

Parton Showering



- Need to go from 2→2 scattering to 100’s of particles
  - A particle can decay into more particles
  - A particle can emit another particle
  - All controlled by random numbers
- Parton shower evolution is a probabilistic process
  - Occurs with unit total probability

Parton Showering

2 common approaches to parton showering

- Need to avoid divergences and infinites in calculations
  - See your QCD course fow why these occur
  - Solution require the final state partons to be ordered
- There are 2 common approaches to do this
- `Pythia`: $Q^2 = m^2$
  - The parton with the highest pT is calculated first
- `Herwig`: $Q^2 \approx E^2(1-\cos\theta)$
  - The parton with the largest angle is calculated first

⇒This represents a theoretical modelling uncertainty

- Both provide a good description of data but which is correct?
  - Neither is correct, but nature is unknown, we only have models
- All physics measurements need to take this into account
  - Expect to see a parton shower systematic for every result
  - Use both methods for calculation of physics result
  - Difference between results is a theoretical modelling systematic

Hadronisation

Going from partons to hadrons

- Partons are not observed directly in nature, only hadrons
- Hadronisation occurs at low energy scales
  - Perturbation theory is not valid
  - Cannot calculate this process from first principals
- Require models to simulate what happens
- 2 common approaches are used
  - `Pythia`: Lund string model
  - `Herwig`: Cluster model

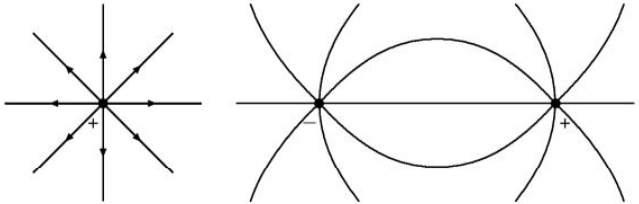
⇒ This is another theoretical modelling uncertainty

- Similar type of uncertainty as for parton showering
  - We don’t know exactly how nature works
  - We have 2 reasonable models
  - Calculate physics result using each method
  - Difference is a theoretical modelling systematic

Hadronisation

The Lund string model

- In WED, field lines go all the way to infinity
- Photons do not interact with each other

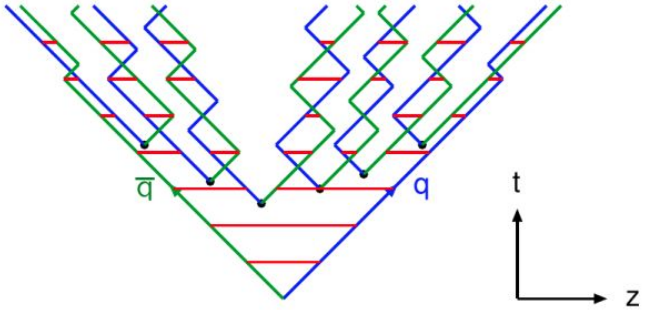


- In QCD, for large charge separation, field lines seem to be compressed into tube-like regions ⇒ string(s)
- Self-interaction among soft gluons in the vacuum

Hadronisation

The Lund string model

- The strings connecting the 2 partons breaks as they move apart
- Fragmentation starts in the middle and spreads out

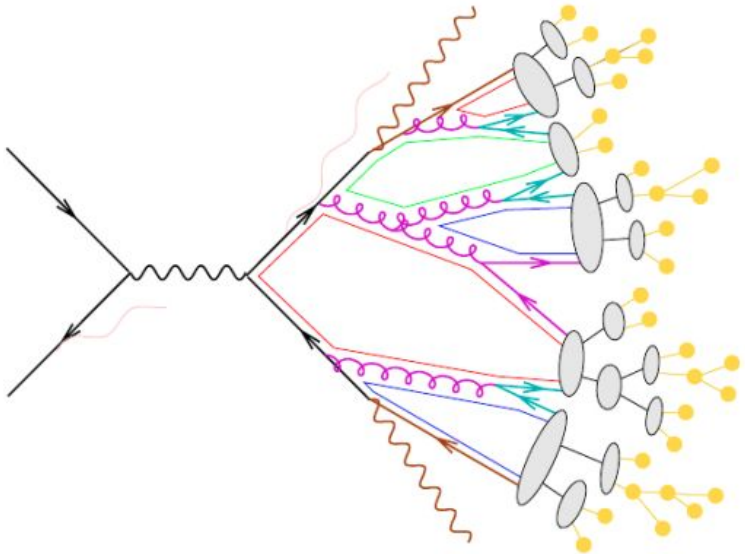


- The breakup vertices become causally disconnected
- This is governed by many internal parameters
- Implemented by the `Pythia` MC program

Hadronisation

The Cluster model

- Pre-confinement colour flow is local
- Forced g qqbar branchings
- Colour singlet clusters are formed
- Clusters decay isotropically to hadrons
- Relatively few internal parameters
- Implemented by the `Herwig` MC program



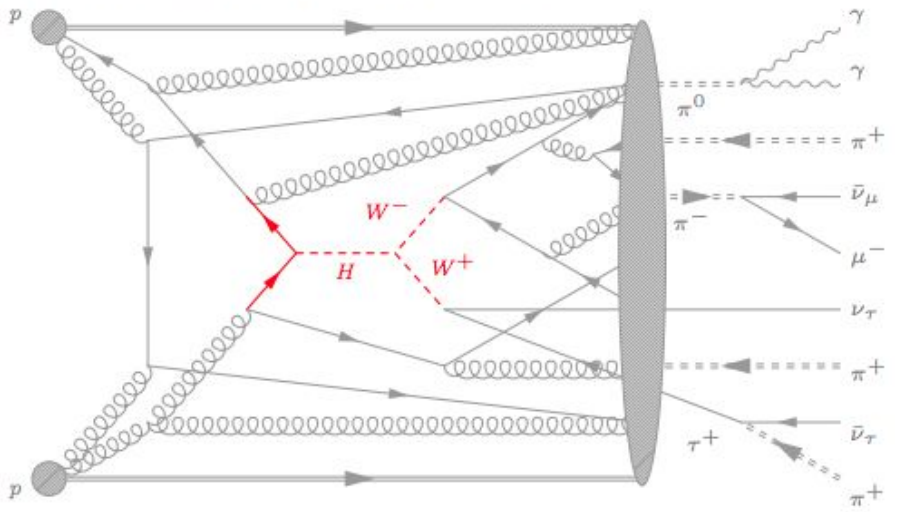
Internal Hard Processes

Internal Hard Processes

Process Selection
- -- QCD
- -- Electroweak
- -- Onia
- -- Top
- -- Fourth Generation
- -- Higgs
- -- SUSY
- -- New Gauge Bosons
- -- Left-Right Symmetry
- -- Leptoquark
- -- Compositeness
- -- Hidden Valleys
- -- Extra Dimensions

A Second Hard Process
Phase Space Cuts
Couplings and Scales
Standard-Model Parameters
Total Cross Sections
Resonance Decays
Timelike Showers
Spacelike Showers
Automated Shower Variations
Weak Showers
Multiparton Interactions
Beam Remnants
Colour Reconnection
Diffraction
Fragmentation
Flavour Selection
Particle Decays
R-hadrons

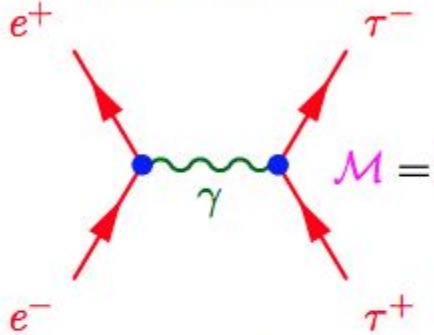
1) *hard process* 3) *ISR* 5) underlying event 7) *particle decays*
2) *resonance decays* 4) *FSR* 6) hadronization



Introduction

$$\mathcal{L}_{\text{QED}} = i\psi^\dagger \gamma_\mu \partial^\mu \psi - m\psi^\dagger \psi - iQg_e A_\mu \psi^\dagger \gamma^\mu \psi - (\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu)$$

- build matrix element from diagrams



$$\mathcal{M} = \bar{v}_{e^+} iQg_e \gamma^\mu u_{e^-} \frac{-ig_{\mu\nu}}{q^2} \bar{u}_{\tau^-} iQg_e \gamma^\nu v_{\tau^+}$$

- integrate over phase-space for partonic cross-section

$$\hat{\sigma} = \int \left(\frac{1}{8\pi}\right)^2 \frac{\left\langle |\mathcal{M}|^2 \right\rangle}{(E_{e^-} + E_{e^+})} \frac{\left|\vec{p}_{\mu^-}\right|}{\left|\vec{p}_{e^-}\right|} \mathrm{d}\Omega$$

- convolute with PDFs for full cross-section

$$\sigma_{a_1 a_2 \to B} = \int\int x_{a_1}\left(x_{p_1}, Q^2, p_1\right) x_{a_2}\left(x_{p_2}, Q^2, p_2\right) \sigma_{p_1 p_2 \to B} \, \mathrm{d}x_{p_1} \, \mathrm{d}x_{p_2}$$

SUSY

- MSSM and nMSSM implementations of SUSY production
  - all MSSM cross-sections validated
  - $q\bar{q} \to \tilde{\chi}^0\tilde{\chi}^0$, $q\bar{q} \to \tilde{\chi}^{\pm}\tilde{\chi}^0$, $q\bar{q} \to \tilde{\chi}^+\tilde{\chi}^-$
  - $q\bar{g} \to \tilde{\chi}^0\tilde{q}$, $q\bar{g} \to \tilde{\chi}^{\pm}\tilde{q}$
  - $gg \to \tilde{g}\tilde{g}$, $q\bar{q} \to \tilde{g}\tilde{g}$
  - $qg \to \tilde{q}\tilde{g}$
  - $gg \to \tilde{q}\bar{\tilde{q}}$, $q\bar{q} \to \tilde{q}\bar{\tilde{q}}$, $qq \to \tilde{q}\tilde{q}$
  - $qq \to \bar{\tilde{q}}$
- $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ processes include EW contributions
  - `qq2squarksquark:onlyQCD` and `qq2squarkantisquark:onlyQCD`
- possible to turn on all SUSY production and select requested final state(s)
  - `SUSY:idA`, `SUSY:idB`, `SUSY:idVecA`, `Susy:idVecB`

SUSY

- super-CKM basis used to describe the mass eigenstates
  - $R^u : (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R) \to (\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)$
  - $R^d : (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R) \to (\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)$
  - $\mathcal{N} : (i\tilde{B}, -i\tilde{W}_3, H_1, H_2) \to (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$
  - $\mathcal{U} : (iW^+, H^+) \to (\tilde{\chi}_1^+, \tilde{\chi}_2^+)$
  - $\mathcal{V} : (iW^-, H^-) \to (\tilde{\chi}_1^-, \tilde{\chi}_2^-)$
- couplings and masses must be provided with an SLHA spectrum
  - from LHEF ⟨`slha`⟩ blocks: `SLHA:readFrom = 1`
  - directly from SLHA file: `SLHA:file = spectrum.slha`
  - either SLHA 1 or 2 allowed, but SLHA 2 preferred
  - fine-grained options on which parameters taken from SLHA

Higgs

- SM Higgs production
  - $f\bar{f} \to H$, $gg \to H$, $\gamma\gamma \to H$
  - $f\bar{f} \to HZ$, $f\bar{f} \to HW^{\pm}$
  - $f\bar{f} \to Hf\bar{f}$, $q\bar{q} \to Ht\bar{t}/b\bar{b}$, $gg \to Ht\bar{t}/b\bar{b}$
  - $qg \to Hq$, $gg \to Hg$, $q\bar{q} \to Hg$
  - partial widths can be scaled to NLO: `HiggsSM:NLOWidths`
- BSM Higgs production
  - generic two Higgs doublet model, H_u and H_d
  - five Higgs bosons defined: h^0/H_1^0(`H1`), H^0/H_2^0(`H2`), A^0/H_3^0(`A3`), $H^{\pm}$
  - $f\bar{f} \to H^{\pm}$, $bg \to H^{\pm}t$
  - $f\bar{f} \to A^0h^0$, $f\bar{f} \to A^0H^0$, $f\bar{f} \to H^{\pm}h^0$, $f\bar{f} \to H^{\pm}H^0$, $f\bar{f} \to H^+H^-$
- standard MSSM $\mathcal{CP}$-even/$\mathcal{CP}$-odd and mass ordering not required
  - couplings can be read from SLHA spectrum
  - can also be set via individual coupling parameters: `HiggsH1:coup2d`, `H1:coup2u`, ...

More BSM

- new gauge boson production
  - $f\bar{f} \to Z'$, $f\bar{f} \to W'^{\pm}$
  - fully flexible $\gamma/Z/Z'$ interference: `Zprime:gmZmode`
  - non-universal couplings allowed: `Zprime:vd`, `Zprime:ad`, ...
- left-right symmetries
  - includes a $SU(2)_R$ group at a larger scale from the SM $SU(2)_L$
  - based on the model of Nucl. Phys. B **487**, 27 (1997)
  - includes Z_R, $W_R^{\pm}$, and $H_L^{++/--}$ production
- leptoquarks
  - simple scalar leptoquark model with arbitrary quark/lepton flavor
  - $q\ell \to LQ$, $qg \to LQ\,\ell$, $gg \to LQ\,\overline{LQ}$, $q\bar{q} \to LQ\,\overline{LQ}$
  - default ue^- LQ-numbers can be changed: `42:0:products = Q L`
  - required to decay *before* fragmentation, cannot be stable
  - cross-section and width modified by k-factor: `LeptoQuark:kCoup`

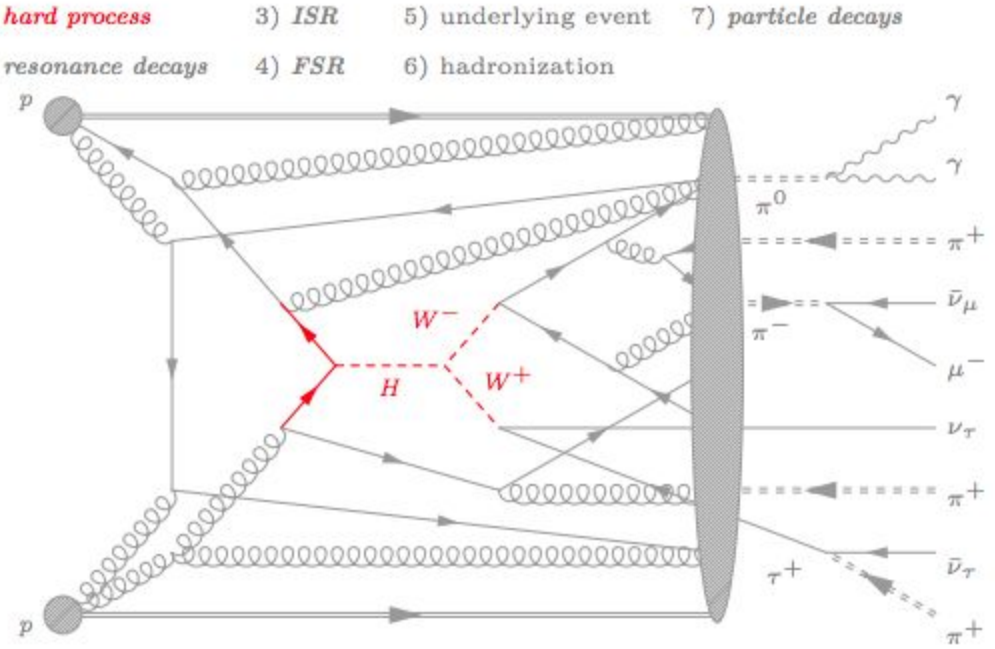
Even More BSM

- compositeness
  - composite fermions can result in excited sharp resonances
  - $2 \to 1$ processes via gauge boson interactions: $dg \to d^*, \ldots$
  - $2 \to 2$ processes via contact interactions: $qq \to d^* q, \ldots$
  - decays include matrix element corrections
  - only gauge boson interaction decays implemented: $d^* \to \gamma d$
- hidden valleys
  - based on the work of JHEP **1104**, 091 (2011)
  - hidden unbroken $SU(N)$ symmetry: `HiddenValley:Ngauge`
  - hidden sector mirrors SM fermions: d_v, e_v^-, $\ldots$
  - $gg \to q_v \bar{q}_v$, $q\bar{q} \to g \to q_v \bar{q}_v$, $f\bar{f} \to \gamma^*/Z \to f_v \bar{f}_v$
  - f_v can radiate g, γ, and γ_v/g_v
- extra dimensions
  - Randall-Sundrum resonances based on Phys. Lett. B **503**, 341 (2001) (G^*) and JHEP **1201**, 018 (2012) (Kaluza-Klein g_{KK})
  - γ_{KK} and Z_{KK} excited electroweak resonances and unparticle production

External Hard Processes

External Hard Processes

Les Houches Accord
SUSY Les Houches Accord
HepMC Interface
ProMC Files
Semi-Internal Processes
Semi-Internal Resonances
MadGraph5 Processes
Alpgen Event Interface
Matching and Merging
-- **POWHEG Merging**
-- aMC@NLO Matching
-- CKKW-L Merging
-- Jet Matching
-- UMEPS Merging
-- NLO Merging
User Hooks
Hadron-Level Standalone
External Decays
Beam Shape
Parton Distributions
Jet Finders
Random Numbers
Implement New Showers
RIVET usage
ROOT usage
A Python Interface



Les Houches Accord

- read in Les Houches Event Format files with versions 1, 2, or 3
  - set beam input to LHEF: `Beams:frameType = 4`
  - provide the LHEF name: `Beams:LHEF = events.lhe`
  - optionally provide separate header: `Beams:LHEFheader = header.lhe`
  - full examples provided in `main25.cc`, `main31.cc`, `main32.cc`, `main37.cc`, `main38.cc`, and `main43.cc`
- create an `LHAup` derived class to pass LHA information to PYTHIA
  - set beam input to `LHAup`: `Beams:frameType = 5`
  - pass `LHAup` pointer to PYTHIA instance

```
pythia.setLHAupPtr(LHAupPtr);
```

  - `LHAupFortran` reads `HEPRUP` and `HEPEUP` FORTRAN common blocks

Semi-Internal Processes

- create a `SigmaProcess` derived class to pass to PYTHIA
  - `Sigma1Process`, `Sigma2Process`, and `Sigma3Process` for $2 \to 1$, 2, and 3

```
pythia.setSigmaPtr(SigmaProcessPtr);
```

  - example in `main22.cc`
- `double SigmaProcess::sigmaHat()` calculates the cross-section
  - $2 \to 1$: return $\hat{\sigma}(\hat{s})$
  - $2 \to 2$: return $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$
  - $2 \to 3$: return $|\mathcal{M}|^2$ with normalization $\hat{\sigma} = \int |\mathcal{M}|^2/(2\hat{s})\,\mathrm{d}\Phi$
- `string SigmaProcess::inFlux()` defines the incoming partons
  - `gg`, `qg`, `fgm`, `ggm`, `gmgm`
  - `qq`, `qqbar`, `qqbarSame`, `ff`, `ffbarSame`, `ffbarChg`

PowhegBox

- POWHEGBOX matrix elements, see http://powhegbox.mib.infn.it, can be passed via LHAup pointer
  - POWHEGBOX binaries require special compilation flags

```
sed -i "s/F77= gfortran/F77= gfortran -rdynamic -fPIE -fPIC -pie/g→
    " Makefile
```

  - configure PYTHIA with --with-powheg-bin=/powheg/bin
- PowhegProcsIn handles loading the LHAup pointer
  - full example given in main33.cc

```
Pythia pythia;
PowhegProcs procs(&pythia, "hvq");
// Read POWHEGBOX configuration from file.
procs.read
// Or read from strings passed.
procs.readString("ih1 1");
pythia.readString("Beams:frameType = 5");
procs.init();
pythia.init();
```

- shower matching parameters should be set: POWHEG:*

MadGraph

- two options for using MadGraph with Pythia
  - output LHEF and pass to Pythia
  - create `SigmaProcess` class and pass to Pythia
- first option automated through `LHAupMadgraph` class
  - can run with either `MG5` or `aMC@NLO` output
  - configure Pythia with `--with-gzip`
  - creates a GRID-pack structure for fast additional runs
  - full example given in `main34.cc`

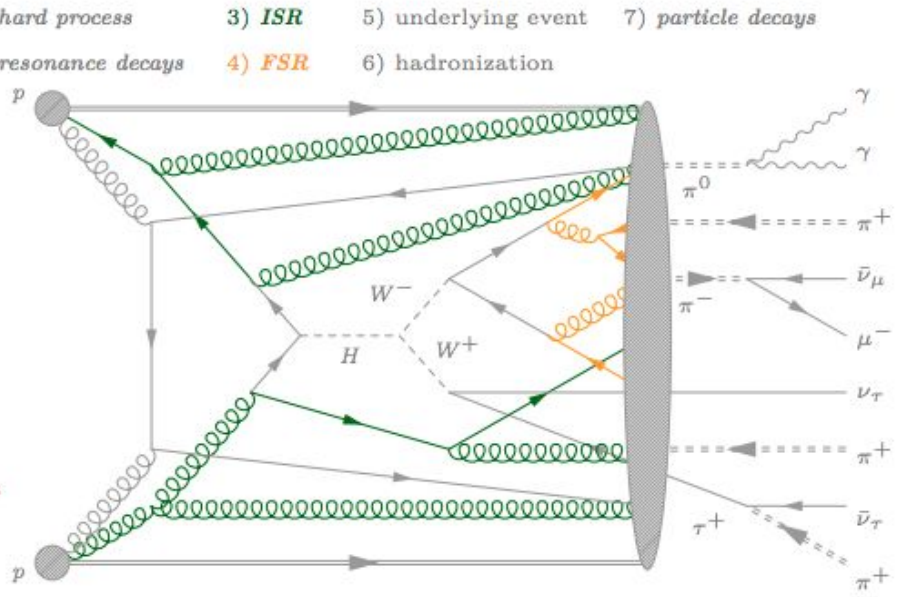
```
LHAupMadgraph madgraph(&pythia, true, "madgraphrun", "mg5_aMC");
madgraph.readString("generate p p > mu+ mu-");
madgraph.readString(" set ebeam1 6500");
madgraph.readString(" set ebeam2 6500");
madgraph.readString(" set mmll 80");
pythia.readString("Random:setSeed = on");
pythia.readString("Random:seed = 1");
pythia.setLHAupPtr(&madgraph);
pythia.init();
```

- remember to set up matching/merging correctly

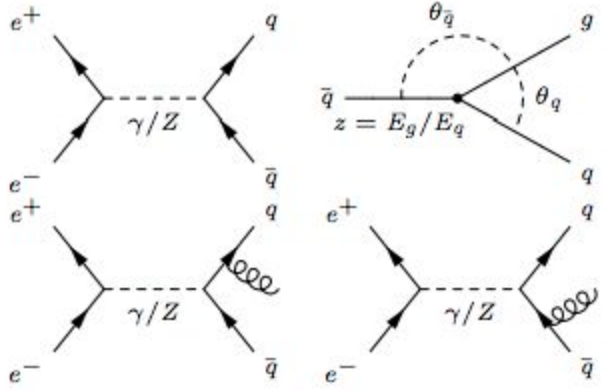
Showers

Showers

Process Selection
-- QCD
-- Electroweak
-- Onia
-- Top
-- Fourth Generation
-- Higgs
-- SUSY
-- New Gauge Bosons
-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Hidden Valleys
-- Extra Dimensions
A Second Hard Process
Phase Space Cuts
Couplings and Scales
Standard-Model Parameters
Total Cross Sections
Resonance Decays
Timelike Showers
Spacelike Showers
Automated Shower Variations
Weak Showers
Multiparton Interactions
Beam Remnants
Colour Reconnection
Diffraction
Fragmentation
Flavour Selection
Particle Decays
R-hadrons



Introduction



- diverges for three scenarios
  - $z \to 0$ (soft)
  - $\theta \to 0$ (collinear to q)
  - $\theta \to \pi$ (collinear to $\bar{q}$)

- factorize collinear divergences as independent emissions

$$\mathrm{d}\sigma_{e^+e^-\to q\bar{q}g} \approx \sigma_{e^+e^-\to q\bar{q}} \sum_i \left(\left(\frac{\mathrm{d}\theta^2_{p_i}}{\theta^2_{p_i}} \right) \left(\frac{\alpha_s}{2\pi} \right) \left(\frac{N_c^2 - 1}{2N_c} \right) \left(\frac{1 + (1-z)^2}{z} \right) \mathrm{d}z \right)$$

- generalize for all processes with splitting functions $\mathcal{P}_{b_j b_i}$

$$\mathrm{d}\sigma_{A\to Bb_j} \approx \sigma_{A\to B} \sum_i \left(\left(\frac{\mathrm{d}\theta^2_{b_i}}{\theta^2_{b_i}} \right) \mathcal{P}_{b_j b_i}(z, \alpha_s)\, \mathrm{d}z \right)$$

- parton b_i emits parton b_j

Internal Showers

- timelike shower (final state radiation) is fully interleaved p_{T}-ordered

$$\Delta_{ij}(q_1^2, q_2^2) = \exp\left(- \int_{q_2^2}^{q_1^2} \frac{1}{q^2} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} \mathcal{P}_{ji}(z, \alpha_s)\, \mathrm{d}z\, \mathrm{d}q^2 \right)$$

- spacelike showers (initial state radiation) is fully interleaved p_{T}-ordered

$$\Delta_{ij}(q_1^2, q_2^2, x) = \exp\left(- \int_{q_2^2}^{q_1^2} \frac{1}{q^2} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} \mathcal{P}_{ij}(z, \alpha_s) \left(\frac{x}{zx}\right) \left(\frac{f(x/z, q^2, j)}{f(x, q^2, i)}\right) \mathrm{d}z\, \mathrm{d}q^2 \right)$$

  - high Q^2 and small x to small q^2 and large x
- define cut-off Q_0: `TimeShower:pTmaxMatch`, `SpaceShower:pTmaxMatch`
  - 1 - *wimpy*: factorization scale
  - 2 - *power*: half the dipole mass

Automatic Shower Variations

[arXiv:1605.08352]

- available only for QCD showers
- variations on renormalization scale (multiplicative) and non-singular terms (additive)
- variations turned on with: `UncertaintyBands:doVariations`
- specified by: `UncertaintyBands:List = {name fsr:muRfac=0.5 isr:muRfac=0.5, ...}`
- keywords for variable terms
  - `fsr:muRfac`, `isr:muRfac`: renormalization scale factor
  - `fsr:cNS`, `isr:cNS`: additive non-singular term
  - `fsr:G2GG:muRfac`, `fsr:Q2QG:muRfac`, `fsr:G2QQ:muRfac`, `fsr:X2XG:muRfac`: finer grain control
- accessed via `Pythia::info.weight(i)`

Weak Showers

- weak showers are available, with a few caveats
  - Bloch-Nordsieck violations from $W^{\pm}$ flavor changing are not accounted for
  - γ^*/Z interference is not handled: low masses use γ^* and high masses are Z
- activated via: `TimeShower:weakShower` and `SpaceShower:weakShower`
- specify the allowed splittings: `TimeShower:weakShowerMode` and `TimeShower:weakShowerMode`
  - `0` $W^{\pm}$ and Z
  - `1` only $W^{\pm}$
  - `1` only Z

External Showers

- DIRE (dipole resummation)
  - Eur. Phys. J. C **75**, no. 9, 461 (2015)
  - careful treatment of collinear enhancements
  - very modular and extensible
  - implemented both as PYTHIA plugin and within SHERPA
  - available from `https://direforpythia.hepforge.org/`
- VINCIA (Virtual Numerical Collider with Interleaved Antennae)
  - arXiv:1605.06142
  - dipole-antenna shower plugin to PYTHIA
  - provide $2 \to 3$ shower kernels
  - captures both collinear dynamics and soft singularities
  - available from `http://vincia.hepforge.org`

Matching and Merging

- MLM (`main89.cc`)
  - calculate Sudakov factor on all lines
  - shower, reject emission using factor
- CKKW-L
  - perform shower and cluster jets
  - match jets to partons, reject if $N_p \neq N_{\text{jets}}$
- POWHEG (`main31.cc`)
  - pick largest p_T emission from NLO normalized $\mathcal{M}$
  - evolve shower downwards to p_T scale
- UMEPS
  - unitarized matrix element and parton shower merging
  - tree-level n-leg merging without inclusive cross-section modification
- UNLOPS
  - unitarized next-to-leading-order parton shower
  - n-leg merging at NLO but more generalized
- FXFX
  - R. Frederix and S. Frixione
  - merging and matching of aMC@NLO

Decays

Decays

Process Selection
-- QCD
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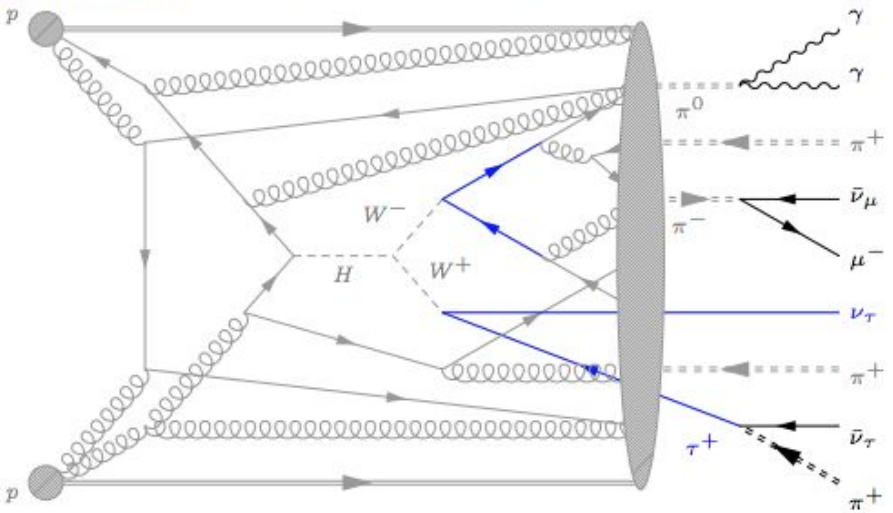
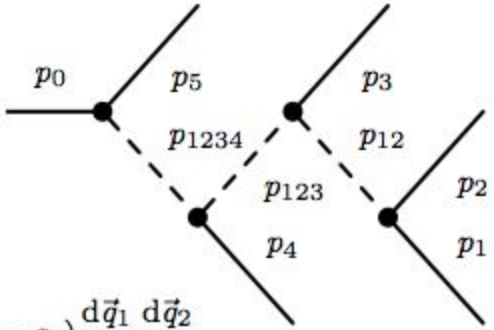
Flavour Selection
Particle Decays
R-hadrons

1) *hard process* 3) *ISR* 5) underlying event 7) ***particle decays***
2) *resonance decays* 4) *FSR* 6) hadronization



Introduction

- *m*-generator
  - mass generator
  - two-body decays through intermediate masses



$$\mathrm{d}\Phi_2(q_0, q_1, q_2) = \left(\frac{1}{(2\pi)^2 2^2}\right) \delta(q_0 - q_1 - q_2) \frac{\mathrm{d}\vec{q}_1}{E_1} \frac{\mathrm{d}\vec{q}_2}{E_2}$$

$$\mathrm{d}\Phi_3(q_0, q_1, q_2, q_3) = \left(\frac{2}{\pi}\right) \mathrm{d}\Phi_2(q_0, q_{12}, q_3) m_{12}\, \mathrm{d}m_{12}\, \mathrm{d}\Phi_2(q_{12}, q_1, q_2)$$

- re-weight by $\mathcal{M}$ for the phase-space point
- difference between *resonance* and *particle* purely technical
  - *resonances*: states with a typical lifetime shorter than the hadronization scale
  - *particles*: states with a lifetime comparable to or longer than the hadronization scale

Resonance Decays

- any state with $m_0 > 20$ GeV is resonance by default
  - light SUSY particles also treated as resonances
- resonance branching fractions modify the relevant cross-section
- SUSY resonance decays implemented with weighting
  - $\tilde{q} \to \tilde{\chi}$, $\tilde{q}W/Z$, qq, lq
  - $\tilde{g} \to \tilde{q}q$
  - $\tilde{\chi} \to \tilde{\chi}W/Z$, $\tilde{q}q$, $\tilde{\ell}\ell$
  - $\tilde{\chi}^0 \to qqq$
  - $\tilde{\ell} \to l\tilde{\chi}$, $\tilde{\ell}W/Z$
- long-lived $\tilde{g}$, $\tilde{b}$, and $\tilde{t}$ can be allowed to hadronize:
  `RHadrons:allow`
- unknown resonances decayed with flat phase-space decays
  - partial width can be forced, or allowed to run with various schemes

Particle Decays

- most particle decays are flat phase-space with some exceptions
  - $\omega, \phi \to \pi^+\pi^-\pi^0$
  - $V \to PS\,PS$ with V from $PS \to PS\,V$ or $PS \to \gamma V$
  - Dalitz decay $X \to Y\ell^+\ell^-$
  - double Dalitz decay $X \to \ell^+\ell^-\ell^+\ell^-$
  - weak decays
  - $B \to \gamma X$
- τ decays are not flat phase-space and can handle spin effects
  - spin effects calculated internally
  - correlations handled for W, Z, W', Z', H, h^0, H^0, A^0, and $H^\pm$
  - lepton-flavor violating gauge boson decays allowed
  - $\mathcal{CP}$-mixing of the extended Higgs can be specified
  - external spin information can override internal calculation

External Decays

- create a `ResonanceWidths` derived class to pass to PYTHIA
  - does not re-weight the decay
  - `void ResonanceWidth::calcWidth` calculates total width
  - full example given in `main22.cc`
- create a `DecayHandler` derived class to pass to PYTHIA
  - $1 \to n$ decays specified via `bool DecayHandler::decay`
  - chains specified via `bool DecayHandler::decayChain`
  - full example given in `main17.cc`
- external decays via EVTGEN, `http://evtgen.warwick.ac.uk`
  - plugin class `EvtGenDecays` applies decays to PYTHIA event record
  - allows forced decays and provides event weight
  - full example given in `main48.cc`

Outlook

- PYTHIA designed to be simple and easy-to-use, yet flexible
- large selection of internal hard processes for fast use
  - external hard process from LHEF input, `LHAup` pointers, or `SigmaProcess`
  - dedicated plugins for POWHEGBOX and MADGRAPH
- robust shower algorithms
  - Hidden Valley showers and weak shower available
  - alternative DIRE and VINCIA shower plugins
  - exhaustive collection of matching and merging schemes
- spin correlated tau decays and resonance SUSY decays
- not mentioned today
  - multi-parton interaction framework
  - Lund string fragmentation model for hadronization
- new PYTHON interface!
- questions on anything? please ask!