Pythia tutorial

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Who am I? Why am I here?

- 4th year PhD student at University of Jyväskylä, Finland.
- My projects aim to improve DIS in Pythia (matching, merging, tuning).
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- He[1] made me do it[2].

[1] well, it was another Pythia author, but Ilkka was *very* encouraging

[2] "It's good practice! You get to meet experts! The subjects at the school are important!"

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  - **Basic knowledge:** how to drive the car, what kind of fuel it needs, how and when to use fog lights etc. (How to run Pythia, what input and settings to use)

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  - **Intermediate level:** How does a combustion engine work? (How does Pythia generate events)

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  - **Intermediate level:** How does a combustion engine work? (How does Pythia generate events)
  - **Expert level:** How to build it from scratch? (Code structure, physics models, mathematical tools and their implementation)
- My goal today is to teach you how to drive the car (run the code).

Setup

- Install Docker Desktop, test with

```
$ docker --version
> Docker version 27.4.0, build bde2b89
```

- For Linux systems, some steps might be required: post-installation steps, re-launch terminal and Docker Desktop.
- Download the image for Pythia8 + Rivet4

```
$ docker pull hepstore/rivet-pythia
```

- Start the container, setting up a shared "host" directory between your local machine and the container

```
$ mkdir PythiaTutorial && cd PythiaTutorial
$ docker run -v $PWD:/host -it --rm hepstore/rivet-pythia
```

Introduction

- What is Pythia?

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- Now in this analogy, Pythia (the MCEG) is Pythia (the oracle), and **you** are the priests.

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- The priests would interpret these as predictions of the future, writing them as poems.
- Now in this analogy, Pythia (the MCEG) is Pythia (the oracle), and **you** are the priests.
- The traffic rules for Pythia, or any MCEG, is to use critical thinking when interpreting the results.

Introduction

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  A general-purpose Monte Carlo event generator

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  A general-purpose Monte Carlo event generator
- What is a general-purpose Monte Carlo event generator?

general-purpose

QCD processes

- Partonic hard scattering ($2 \rightarrow 2$, some $2 \rightarrow 3$)
- Heavy quark production

Electroweak processes

- Prompt photon production
- EW boson production and exchange
- Deep inelastic scattering
- Photon collisions

Onia production

- Charmonium, Bottomonium with different cpin states

Top production

- $t\bar{t}$ pairs and single top

Heavy-ion collisions and cosmic rays

- ^{2}H, ^{16}O, ^{208}Pb, ...

Higgs production

- Standard Model Higgs, also in association with other particles
- Beyond-the-Standard-Model Higgs

Beyond the Standard Model

- Supersymmetry
- Dark matter
- Hidden Valley
- Leptoquarks

Monte Carlo event generator

- Uses random number generation to produce events, owing to the probabilistic nature of Quantum Mechanics.
- Acts as a "transfer function" between theory and experiment: physical theory as input and outgoing on-shell particles as output.
- Also goes the other way: experiments drive the development of MCEGs and constraints of theory

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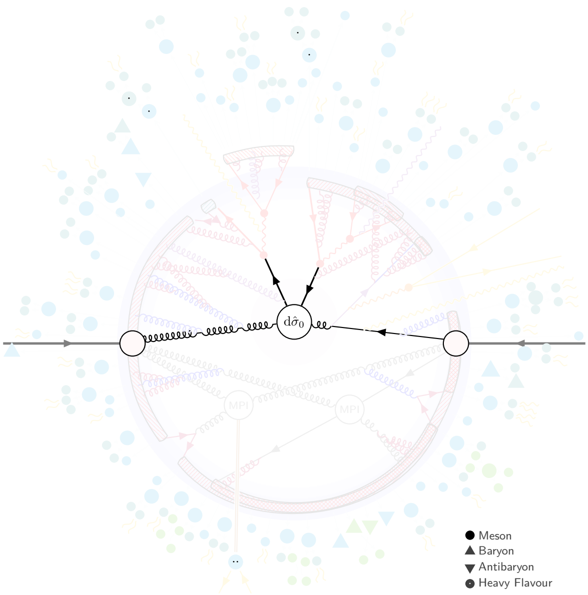
  Some transfer function between theory and experiment
- How does it work?

Event generation steps

Factorization theorems allow the separation in terms of "hardness"

1. Hard process

Image credit: P. Skands



Event generation steps

Factorization theorems allow the separation in terms of "hardness"

1. Hard process
2. Resonance decays

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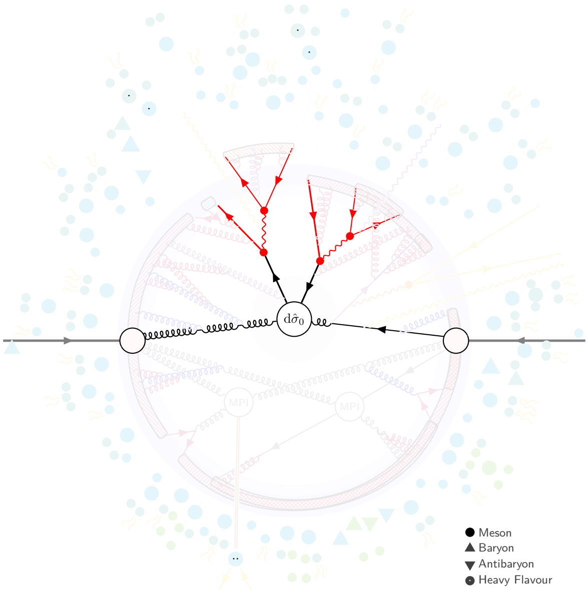
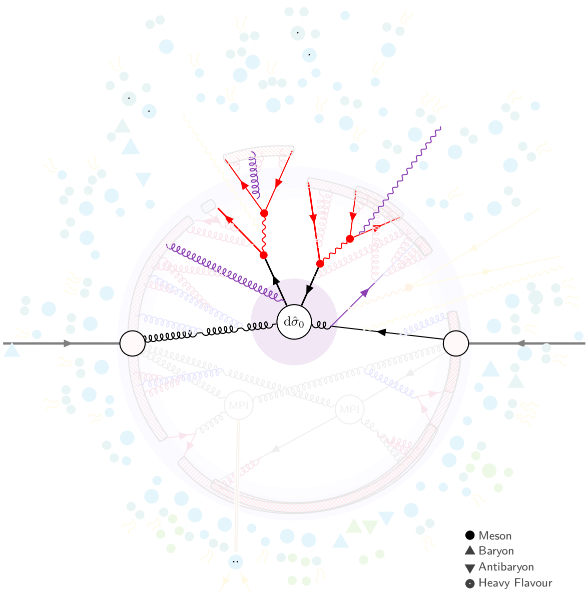


Event generation steps

Image credit: P. Skands

Factorization theorems allow the separation in terms of "hardness"

1. Hard process
2. Resonance decays
3. Matching, merging and matrix-element corrections

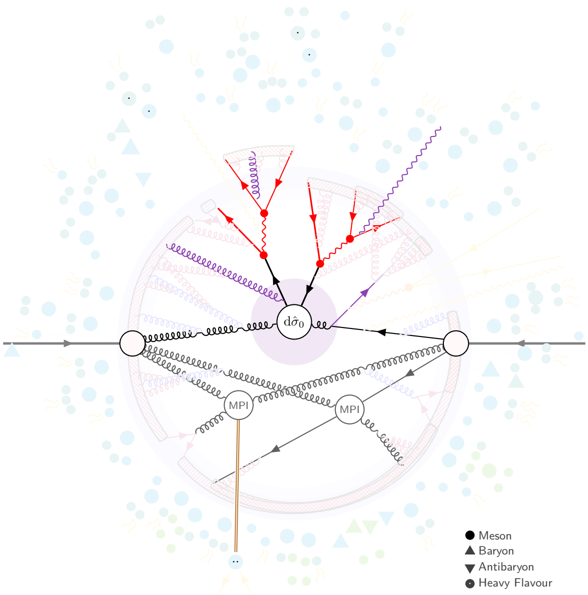


Event generation steps

Factorization theorems allow the separation in terms of "hardness"

1. Hard process
2. Resonance decays
3. Matching, merging and matrix-element corrections
4. Multiparton interactions

Image credit: P. Skands



Event generation steps

Factorization theorems allow the separation in terms of "hardness"

1. Hard process
2. Resonance decays
3. Matching, merging and matrix-element corrections
4. Multiparton interactions
5. Parton showers: ISR, FSR, QED, weak

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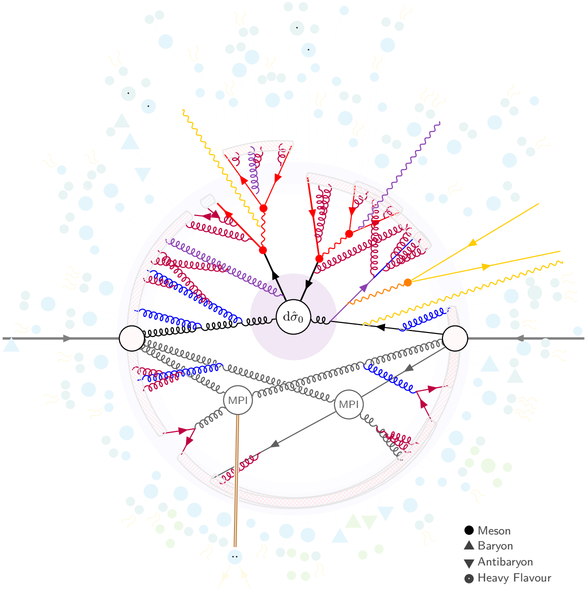

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Factorization theorems allow the separation in terms of "hardness"

1. Hard process
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6. Hadronization, beam Remnants

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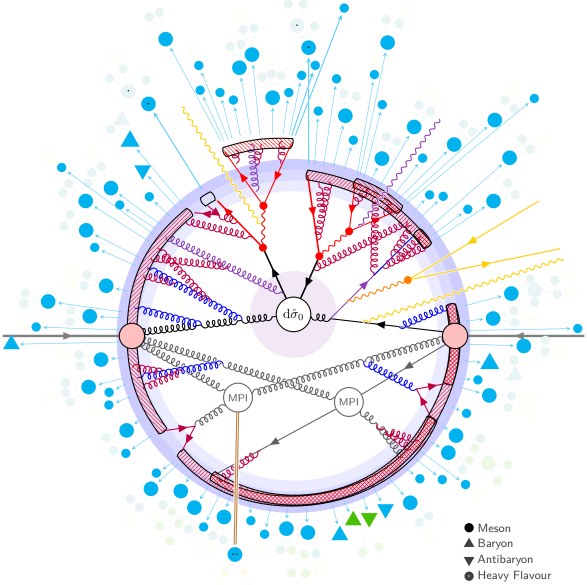

Event generation steps

Factorization theorems allow the separation in terms of "hardness"

1. Hard process
2. Resonance decays
3. Matching, merging and matrix-element corrections
4. Multiparton interactions
5. Parton showers: ISR, FSR, QED, weak
6. Hadronization, beam Remnants
7. Decays,rescattering

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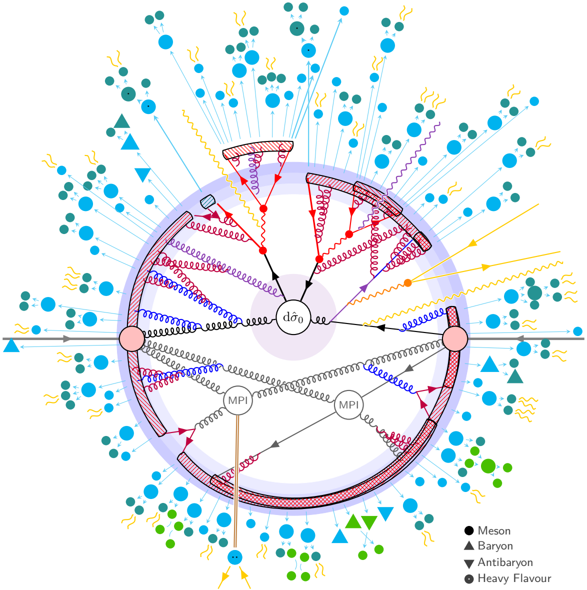

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  A general-purpose Monte Carlo event generator
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- What is Pythia?

  A general-purpose Monte Carlo event generator
- What is a general-purpose Monte Carlo event generator?

  Some transfer function between theory and experiment
- How does it work?
- Have you used Pythia or any other MCEG?

Hands-on

Setup

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```

Open Pythia - Latest Online Manual and Pythia 8.3 worksheet, section 3 on page 4.

First run

- Go to the host directory, copy the build configuration files and make a new file called `mymain01.cc`
- You can see and open the files in your local directory

```
$ cd /host
$ cp /usr/local/share/Pythia8/examples/Makefile* .
$ touch mymain01.cc
```

- Fill the example file with the contents on page 4.
- Compile and run the example:

```
$ make mymain01 && ./mymain01
```

You should get a bunch of output from Pythia: a welcome card, initialization and process information, a bunch of particles in the event listing, and the message

```
0 no errors or warnings to report
```

Let's wait until everyone has gotten this far, then we move on to some examples.

mymain01.cc at the start

```
// Headers and Namespaces.
#include "Pythia8/Pythia.h" // Include Pythia headers.
using namespace Pythia8; // Let Pythia8:: be implicit.

int main() { // Begin main program.

    // Set up generation.
    Pythia pythia; // Declare a Pythia object
    pythia.readString("Top:gg2ttbar = on"); // Switch on process.
    pythia.readString("Beams:eCM = 8000."); // 8 TeV CM energy.
    pythia.init(); // Initialize; incoming pp beams is default.

    // Generate event(s).
    pythia.next(); // Generate an(other) event. Fill event record.

    return 0;
} // End main program with error-free return.
```

Exercise 1: Event record

- Let's go through the basics together, starting with the event record.
- Read through section 3 in the worksheet, and try to answer the problem: "see if you can find several copies of the top quarks, and check the status codes to figure out why each new copy has been added."

Exercise 1: Event record

- Let's go through the basics together, starting with the event record.
- Read through section 3 in the worksheet, and try to answer the problem: "see if you can find several copies of the top quarks, and check the status codes to figure out why each new copy has been added."
- If you follow the worksheet, you should have written output in the file `mymain01.log`. Now check this file for the event record.

```
no id name status mothers daughters colours p_x p_y p_z e m
...
 5 6 (t) -22 3 4 9 9 101 0 90.224 -14.092 183.317 269.072 174.515
 9 6 (t) -44 5 5 14 14 103 0 24.487 -44.352 12.944 182.090 174.421
 14 6 (t) -44 9 9 20 20 103 0 29.202 -49.636 14.203 184.230 174.421
 20 6 (t) -44 14 14 30 30 103 0 27.237 -55.269 13.092 185.447 174.421
...
```

Exercise 1: Event record

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- Read through section 3 in the worksheet, and try to answer the problem: "see if you can find several copies of the top quarks, and check the status codes to figure out why each new copy has been added."
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...
```

- The status codes are explained in the worksheet appendix A.
- The top quarks come from the hard process and go through initial-state radiation, beam remnant treatment and finally decay into W^+ and b.

Exercise 2: Event loop and particle loop

- Follow the instructions on section 4, halfway through page 6:
  - Include the process $q\bar{q} \to t\bar{t}$.
  - Introduce the event loop and particle loop.
  - Print out the transverse momentum and pseudorapidity of the final top-quark found in the event record.
  - Remember to build with `make mymain01` after changing the code.
- Some information in the worksheet might not work as expected in my Docker container, so please don't hesitate to ask!
- Work together! Share ideas and solutions, compare your results.

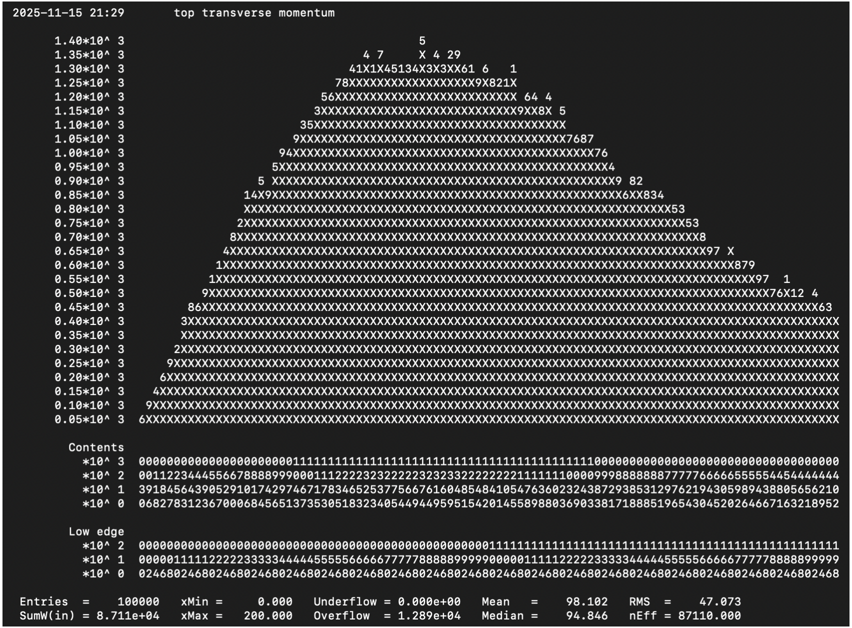
mymain01.cc after Exercise 2

```
// Headers and Namespaces.
#include "Pythia8/Pythia.h" // Include Pythia headers.
using namespace Pythia8; // Let Pythia8:: be implicit.

int main() { // Begin main program.

        // Set up generation.
        Pythia pythia; // Declare a Pythia object
        pythia.readString("Top:gg2ttbar = on"); // Switch on process.
        pythia.readString("Top:qqbar2ttbar = on"); // Another process.
        pythia.readString("Beams:eCM = 8000."); // 8 TeV CM energy.
        pythia.readString("Next:numberShowEvent = 5"); // How many events to show.
        pythia.init(); // Initialize; incoming pp beams is default.

        // Generate events.
        for (int iEvent = 0; iEvent < 5; ++iEvent) {
        pythia.next();
        int iTop = 0; // Integer to find last top quark in process.

                for (int i = 0; i < pythia.event.size(); ++i) {
                        cout << "i = " << i << ", id = " << pythia.event[i].id() << endl;
                        if (pythia.event[i].id() == 6) iTop = i;
                }
        cout << "Top pT  = " << pythia.event[iTop].pT() << endl;
        cout << "Top eta = " << pythia.event[iTop].eta() << endl;
        }

        pythia.stat();

        return 0;
} // End main program with error-free return.
```

Exercise 3: Histograms

- Continue the instructions on section 4.
- Declare and fill histograms for top quark p_{T} and η.
- Write out the histograms.
- Try to produce the histogram for charged multiplicity as well.

Exercise 3: pT histogram, 100K events



Exercise 3: η histogram, 100K events

```
2025-11-15 21:29       top pseudorapidity

      2.00*10^ 3                                       3  3               1    1
      1.92*10^ 3                                      3X18X8              X5685X123
      1.84*10^ 3                                   3  XXXXXX8327 18     88XXXXXXXXX75
      1.76*10^ 3                                  8X59XXXXXXXXXX7XX 4 18XXXXXXXXXXXXXX
      1.68*10^ 3                                 8XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX2
      1.60*10^ 3                                7XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.52*10^ 3                               3XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX6 2
      1.44*10^ 3                              3XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX9X
      1.36*10^ 3                             1XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX9
      1.28*10^ 3                             XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX3
      1.20*10^ 3                            9XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.12*10^ 3                           XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX8
      1.04*10^ 3                          1XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4
      0.96*10^ 3                         5XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      0.88*10^ 3                        1XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX7
      0.80*10^ 3                       2XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      0.72*10^ 3                       XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      0.64*10^ 3                      5XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX6
      0.56*10^ 3                     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX5
      0.48*10^ 3                   3XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX62
      0.40*10^ 3                  3XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX5
      0.32*10^ 3                18XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX65
      0.24*10^ 3              23XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX62
      0.16*10^ 3           539XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX7621
      0.08*10^ 3  32344879XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX97745423

        Contents
          *10^ 3  0000000000000000000000000111111111111111111111111111111111111111111111111110000000000000000000000000
          *10^ 2  0000000001111123344557899112345677778989998778778676678898898988887764443219887654432221110000000000
          *10^ 1  2123365771057840427693017298867648156450402871362817942227908245619618355209752014258707329875534312
          *10^ 0  3763414486713157656386891305273372833515324748495028012089051756478034270462892867079669975429812570

        Low edge  --------------------------------------------------
          *10^ 0  5444444444433333333332222222222111111111100000000000000000001111111111222222222233333333334444444444
          *10^-1  0987654321098765432109876543210987654321098765432101234567890123456789012345678901234567890123456789
          *10^-2  0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
```

Exercise 4: Input files

- Follow section 5 to run your code using a command file.
- The benefit is that you no longer need to build between different runs, since all changes should be done to command file.
- Try to produce charged multiplicity histograms with 3 setups:
  1. ISR, FSR and MPI turned on.
  2. ISR and FSR turned on, MPI turned off.
  3. ISR, FSR and MPI turned off
- Save results in output log files with

```
$ ./mymain01 mymain01.cmnd > mymain01_ISR-on_FSR-on_MPI-on.log
$ ./mymain01 mymain01.cmnd > mymain01_ISR-on_FSR-on_MPI-off.log
$ ./mymain01 mymain01.cmnd > mymain01_ISR-off_FSR-off_MPI-off.log
```

Exercise 4: N_{ch}, 100K events

```
2025-11-15 23:59       charged multiplicity

      2.32*10^ 3                                                       1
      2.24*10^ 3                                                   8   X5 4
      2.16*10^ 3                                                 2XX794XX X6692
      2.08*10^ 3                                                4XXXXXXXX9XXXXX41
      2.00*10^ 3                                              XXXXXXXXXXXXXXXXXXX4
      1.92*10^ 3                                           726XXXXXXXXXXXXXXXXXXXX
      1.84*10^ 3                                          4XXXXXXXXXXXXXXXXXXXXXXX98
      1.76*10^ 3                                        52XXXXXXXXXXXXXXXXXXXXXXXXXX46
      1.68*10^ 3                                       1XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.60*10^ 3                                    1 9XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX5
      1.52*10^ 3                                    X9XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX833
      1.44*10^ 3                                   8XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.36*10^ 3                                  6XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX83
      1.28*10^ 3                                 9XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.20*10^ 3                                6XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      1.12*10^ 3                               5XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX3
      1.04*10^ 3                               XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX83
      0.96*10^ 3                             3XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4
      0.88*10^ 3                             XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX1
      0.80*10^ 3                            8XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX7
      0.72*10^ 3                            XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX4
      0.64*10^ 3                           XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX9
      0.56*10^ 3                          7XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX61
      0.48*10^ 3                         6XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      0.40*10^ 3                        7XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX73
      0.32*10^ 3                       7XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX434
      0.24*10^ 3                      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX94
      0.16*10^ 3                   34XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX853511
      0.08*10^ 3              1336XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

        Contents
          *10^ 3  0000000000000000000000000000111111111111111222222222222222222222111111111111110000000000000000000000
          *10^ 2  0000000000000000111223456799012345556767888000012111122011110009887755443310099876655443322221111100
          *10^ 1  0000000000001224701639753480587732309119995800295235140682249315220250664096281076262907476739420288
          *10^ 0  0000000000321247640273214070701212082074354411889535493999499321978465162177403968937019421102126287

        Low edge  -
          *10^ 2  0000000000000000000000000011111111111111111111111112222222222222222222222222333333333333333333333333
          *10^ 1  0001112233344555667778899900111223334455566777889990011122333445556677788999001112233344555667778899
          *10^ 0  1371593715937159371593715937159371593715937159371593715937159371593715937159371593715937159371593715
```

Exercise 4: N_{ch} histogram, MPI off, 100K events

```
2025-11-16 00:21       charged multiplicity

      6.50*10^ 3                             1
      6.25*10^ 3                            5X6
      6.00*10^ 3                            XXX5
      5.75*10^ 3                           6XXXX8
      5.50*10^ 3                          2XXXXXX8
      5.25*10^ 3                          XXXXXXXX
      5.00*10^ 3                          XXXXXXXX1
      4.75*10^ 3                         XXXXXXXXXX
      4.50*10^ 3                         XXXXXXXXXX2
      4.25*10^ 3                        8XXXXXXXXXXX
      4.00*10^ 3                        XXXXXXXXXXXX3
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      2.50*10^ 3                     8XXXXXXXXXXXXXXXXX2
      2.25*10^ 3                     XXXXXXXXXXXXXXXXXXX
      2.00*10^ 3                    7XXXXXXXXXXXXXXXXXXX
      1.75*10^ 3                    XXXXXXXXXXXXXXXXXXXXX
      1.50*10^ 3                   8XXXXXXXXXXXXXXXXXXXXXX
      1.25*10^ 3                  2XXXXXXXXXXXXXXXXXXXXXXX9
      1.00*10^ 3                  XXXXXXXXXXXXXXXXXXXXXXXXX6
      0.75*10^ 3                 9XXXXXXXXXXXXXXXXXXXXXXXXXX93
      0.50*10^ 3               2XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX63
      0.25*10^ 3           1257XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX8653322111

        Contents
          *10^ 3  0000000000000000111223445566655544332211100000000000000000000000000000000000000000000000000000000000
          *10^ 2  0000000000011347049494172612186473826274297533111000000000000000000000000000000000000000000000000000
          *10^ 1  0000000002528091441558949428578470377959101792941885431110000000000000000000000000000000000000000000
          *10^ 0  0000000146972283477088621737539026114635607332794421066717433220201100000000000000000000000000000000

        Low edge  -
          *10^ 2  0000000000000000000000000011111111111111111111111112222222222222222222222222333333333333333333333333
          *10^ 1  0001112233344555667778899900111223334455566777889990011122333445556677788999001112233344555667778899
          *10^ 0  1371593715937159371593715937159371593715937159371593715937159371593715937159371593715937159371593715

 Entries  =     100000   xMin =    -1.000   Underflow = 0.000e+00   Mean   =    113.77   RMS  =     26.35
 SumW(in) = 1.000e+05   xMax =   399.000   Overflow  = 0.000e+00   Median =    112.62   nEff = 1.000e+05
```

Exercise 4: N_{ch} histogram, parton showers off, MPI off, 100K events

```
2025-11-16 00:15       charged multiplicity

      1.30*10^ 4                  3
      1.25*10^ 4                 2X
      1.20*10^ 4                 XX9
      1.15*10^ 4                 XXX
      1.10*10^ 4                 XXX
      1.05*10^ 4                XXXX9
      1.00*10^ 4                XXXXX
      0.95*10^ 4                XXXXX
      0.90*10^ 4                XXXXX
      0.85*10^ 4               9XXXXX
      0.80*10^ 4               XXXXXX5
      0.75*10^ 4               XXXXXXX
      0.70*10^ 4               XXXXXXX
      0.65*10^ 4              5XXXXXXX
      0.60*10^ 4              XXXXXXXX
      0.55*10^ 4              XXXXXXXX7
      0.50*10^ 4              XXXXXXXXX
      0.45*10^ 4             1XXXXXXXXX
      0.40*10^ 4             XXXXXXXXXX
      0.35*10^ 4             XXXXXXXXXX1
      0.30*10^ 4             XXXXXXXXXXX
      0.25*10^ 4            9XXXXXXXXXXX
      0.20*10^ 4            XXXXXXXXXXXX2
      0.15*10^ 4           8XXXXXXXXXXXXX
      0.10*10^ 4          3XXXXXXXXXXXXXX3
      0.05*10^ 4        25XXXXXXXXXXXXXXXX51

        Contents
          *10^ 4  0000000000000011111000000000000000000000000000000000000000000000000000000000000000000000000000000000
          *10^ 3  0000000001246802210753100000000000000000000000000000000000000000000000000000000000000000000000000000
          *10^ 2  0000000263402451694730562000000000000000000000000000000000000000000000000000000000000000000000000000
          *10^ 1  0000018438676610454736857721000000000000000000000000000000000000000000000000000000000000000000000000

        Low edge  -
          *10^ 2  0000000000000000000000000011111111111111111111111112222222222222222222222222333333333333333333333333
          *10^ 1  0001112233344555667778899900111223334455566777889990011122333445556677788999001112233344555667778899
          *10^ 0  1371593715937159371593715937159371593715937159371593715937159371593715937159371593715937159371593715
```

Exercise 5a: Rivet

- Now we know the basics, but a more realistic analysis could use some real-life data.
- Let's take a small detour from the worksheet and try to run some comparisons to experimental data using Rivet.
- Copy and inspect the program main144.cc, and the associated run card main144.cmnd

```
$ cp /usr/local/share/Pythia8/examples/main144.c* .
```

Exercise 5a: Rivet

- Modify the main144.cmnd to run at $\sqrt{s} = 8$ TeV, including hard process and a phase-space cut

```
Beams:eCM = 8000. ! CM energy of collision
SoftQCD:all = off ! All soft QCD processes
HardQCD:all = on ! All hard QCD processes
PhaseSpace:ptHatMin = 50.
```

- Activate Rivet plugin within Pythia, provide an inclusive-jet analysis from ATLAS.

```
Main:runRivet = on
Main:rivetAnalyses = {ATLAS_2017_I1604271}
```

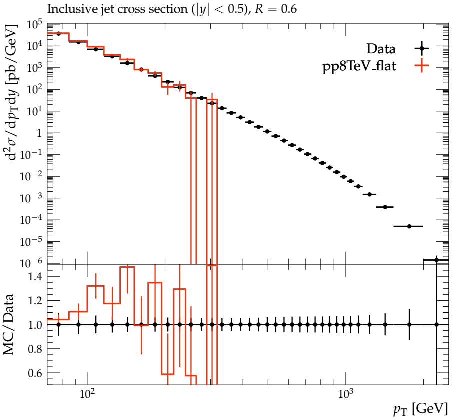
- Run and save Rivet output to file, plot using Rivet

```
$ ./main144 -c main144.cmnd -n 10000 -o pp8TeV_flat # wait until comple
$ rivet-mkhtml pp8TeV_flat.yoda
```

- Inspect by opening the file `rivet-plots/index.html` in a web browser, outside the container

Exercise 5a: Rivet

- The differential cross section scales like
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\hat{p}_T^2} \propto \frac{1}{\hat{p}_T^n},$$
- where $n = 4 - 6$.
- Huge span in magnitude of cross section, need to bias phase-space sampling with $\hat{p}_T$.



Exercise 5a: Rivet

- Next challenge is to use phase-space biasing in the sampling of the hard process. This way, more events will be generated at high-pT, and reweighted to retain the correct cross section.

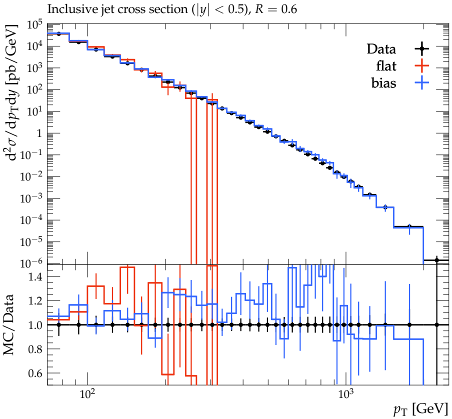
```
PhaseSpace:bias2Selection = on
PhaseSpace:bias2SelectionPow = 4.
PhaseSpace:bias2SelectionRef = 50.
```

- Produce a comparison to the previous run which had flat phase-space sampling in terms of p_{T}.

```
$ ./main144 -c main144.cmnd -n 10000 -o pp8TeV_bias
$ rivet-mkhtml pp8TeV_flat.yoda:"Title=flat" \
pp8TeV_bias.yoda:"Title=bias"
```

Exercise 5a: Rivet

- Whole phase-space filled, events reweighted to preserve physical cross-section.



Exercise 5b: Rivet Z-boson p_T

- The previous exercise was a good example where there's nothing wrong with the events that are generated, but we just didn't fill enough of the phase space.
- This next exercise aims to showcase how how one might generate events that don't describe the physics you're aiming to simulate, emphasizing the importance of ISR for Z-boson transverse momentum.
- Change the beam energy, turn Z-production on and other processes off

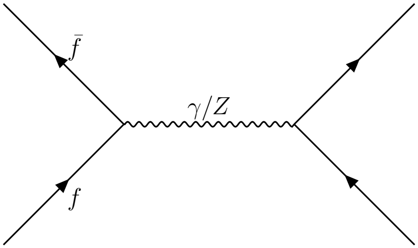
```
Beams:eCM = 7000. ! CM energy of collision
SoftQCD:all = off ! All soft QCD processes
HardQCD:all = off ! All soft QCD processes
WeakSingleBoson:ffbar2gmZ = on  ! Gamma/Z production on
```

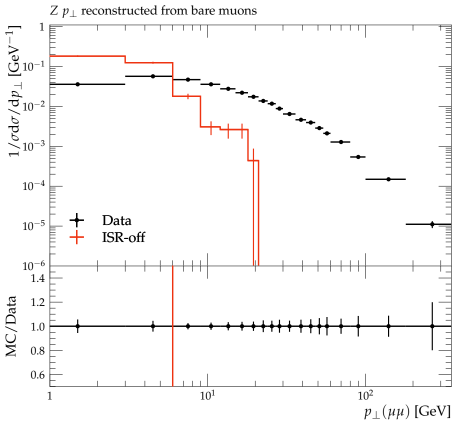
- Turn off ISR, and remove the phase-space biasing

```
PartonLevel:ISR=off
! PhaseSpace:bias2Selection = on
! PhaseSpace:bias2SelectionPow = 4.
! PhaseSpace:bias2SelectionRef = 50.
```

Exercise 5b: Rivet Z-boson p_T

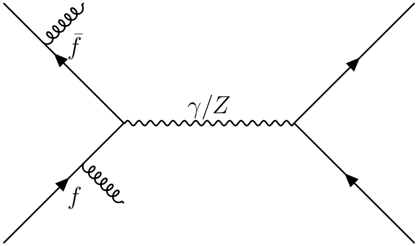
- Add the Z-boson analysis `ATLAS_2011_S9131140`
- The effect is similar: p_T distribution cuts off at some point, but this time the overall shape of the cross section is also wrong.

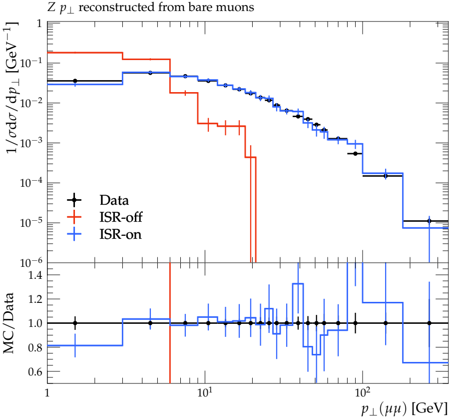




Exercise 5b: Rivet Z-boson p_T

- Without ISR, the Z-boson doesn't acquire much p_T in LO picture. ISR provides p_T kicks through emissions.





Exercises 6-?:

- Congratulations! You now have your drivers license for Pythia, and should be able to tackle the rest of the problems in the worksheet, in any order you wish.
  - Section 6: Jets
  - Section 7: Higgs production
  - Section 8: CKKW-L merging
  - Section 9: Further studies
- Some topics we have covered already which you could try in practice are
  - Factorization and renormalization scale variations (envelope) with SigmaProcess:factorMultFac/renormMultFac
  - Different PDF sets with PDF:pSet
  - Matching and merging: main164.cc and associated .cmnd files

Resources

- pythia.org Online Manual - Very important, especially for basics.
- A comprehensive guide to the physics and usage of PYTHIA 8.3 - More advanced and detailed guide.
- Pythia 8.3 Worksheet - Beginner-friendly tutorial.

thanks