

Prerequisites

MCnet Tutorial for summer schools

1 Introduction

The Docker containers used in this tutorial can be obtained by running

```
docker pull cteqschool/tutorial:herwig-7.1.5
docker pull cteqschool/tutorial:pythia-8.2.40
docker pull cteqschool/tutorial:sherpa-2.2.7
```

Should you have problems with disk space, consider running `docker containers prune` and `docker system prune`. The event generators are installed in `/usr/local`. Running the docker containers is simplified by defining an alias. We also add an environment variable needed for Rivet analyses.

```
alias docker-run-herwig='docker run -it -u $(id -u $USER) \
--rm -v "$HOME:$HOME" -w "$PWD" --env="RIVET_ANALYSIS_PATH=." \
cteqschool/tutorial:herwig-7.1.5'
alias docker-run-pythia='docker run -it -u $(id -u $USER) \
--rm -v "$HOME:$HOME" -w "$PWD" --env="RIVET_ANALYSIS_PATH=." \
cteqschool/tutorial:pythia-8.2.40'
alias docker-run-sherpa='docker run -it -u $(id -u $USER) \
--rm -v "$HOME:$HOME" -w "$PWD" --env="RIVET_ANALYSIS_PATH=." \
cteqschool/tutorial:sherpa-2.2.7'
```

The tutorial can be obtained by running

```
git clone https://gitlab.com/shoeche/tutorials.git
```

All paths referenced to in these instructions are relative to the `tutorials/` directory created in this step. We will use a dedicated Rivet analysis, which is made available in the directory `rivet/`. As a first step, please compile this analysis and copy the resulting library to your run directory using the sequence of commands

```
cd rivet/
docker-run-sherpa rivet-buildplugin MC_TTB.cc
cp RivetAnalysis.so ../mc/herwig/PartII/
cp RivetAnalysis.so ../mc/pythia/
cp RivetAnalysis.so ../mc/sherpa/
```

Herwig Tutorial



Part I

Introduction to Herwig 7

In this first part of the tutorials you will get to know Herwig. The actual tutorial is part of the online Herwig documentation. The Herwig homepage is at <http://herwig.hepforge.org/>. On the Herwig homepage you find a section *Tutorials*. In this tutorial you work through the section *Getting Started* which contains the subsections

- The first run
 - We have prepared for you starting input file: LHC-Matchbox.in. You can find in the herwig folder (see PartI sub-folder) on your VM.
 - Due to limited time of the session to get started we switch to LO matrix elements in LHC-Matchbox.in. (If you would like to play with NLO matching please contact me I have prepared a virtual farm for you! The virtual farm has more CPUs so you can make calculations faster and have full installation of Herwig 7.1! **Warning:** the farm is an experimental setup and all the tutorial can be done on your VM.)
- A look at input files.
- More runs, switching things on and off.
- Using different matrix elements and showers. Play with it but please stick to LO matrix element. Check how to switch showers.
- More on matrix elements. Due to VM size limitations we have not installed external matrix element providers. However, you can have a look and if you would like to try them use the virtual farm.

Part II

$t\bar{t}$ and non-perturbative effects

Based on what you have learned in the Section I you should be able now to:

1. Create an input file for LO $t\bar{t}$ production at $\sqrt{s} = 7$ TeV for both angular (default shower in H7) and dipole showers. Go and do it!

Hints:

- There are useful snippet files which you can use. See the example file from the part I or the online Herwig documentation.
 - Read carefully the section on dipole shower you need to use Five Flavours scheme. There is a snippet for it!
 - Set the scale (ScaleChoice) to TopPairMTScale (see for example <https://arxiv.org/pdf/1606.03350.pdf> for a discussion on the possible scale choices for this process).
 - Does the generator complains about something when you try to use the file? Maybe consider setting HardProcessWidth to 0 for both t and \bar{t} in the Hard Process.
 - The analysis which we are going to use is implemented as MC_TTB Rivet plugin is for semi-leptonic $t\bar{t}$ production (by the way please add the analysis to the input file!) . In order to set it please see a snippet in PartII folder.
2. Switch off MPI, and compare the results using rivet-mkhtml (the same script which you used for the Python Parton Shower tutorial).
 3. Switch off Hadronization and generate events.
 4. Switch off Colour reconnection model. Hint you could also set the probability of reconnection to 0. Do you know how to do it? Look at the online manual, you can also check default settings of Herwig in /opt/hep/share/Herwig/defaults. If you want to know more on Effects of color reconnection on tt final states at the LHC see <https://arxiv.org/abs/1407.6653>.
 5. Switch off intrinsic momentum smearing in the dipole parton shower.

Part III

Additional variations

Most likely you won't have time to try it but of course in Herwig you can also do:

- Parton Shower scale variation see <https://arxiv.org/abs/1605.01338> and <https://arxiv.org/abs/1605.08256> as well as the online manual.
- NLO matching to the matrix element using two Showers and two matching schemes. You can see the plots at the Herwig webpage: https://herwig.hepforge.org/plots/herwig7.0/Rivet-LHC-Jets/MC_TTBAR/index.html.

That's it!

Thanks for trying Herwig! Please ask as much as you can here, but if you have any questions later on, please email us at herwig@projects.hepforge.org or have a look at our online documentation, where many how-tos can be found, and we'll add more on request. For detailed documentation refer to our manual, [arxiv:0803.0883](https://arxiv.org/abs/0803.0883), and the MCnet review paper, [arxiv:1101.2599](https://arxiv.org/abs/1101.2599).



LUND UNIVERSITY



 **Fermilab**

PYTHIA 8.2 Worksheet

For tutorials
at Summer Schools
or self-study
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1 Introduction

The PYTHIA 8.2 program is a standard tool for the generation of high-energy collisions (specifically, it focuses on centre-of-mass energies greater than about 10 GeV), comprising a coherent set of physics models for the evolution from a few-body high-energy (“hard”) scattering process to a complex multihadronic final state. The particles are produced in vacuum. Simulation of the interaction of the produced particles with detector material is not included in PYTHIA but can, if needed, be done by interfacing to external detector-simulation codes.

The PYTHIA 8.2 code package contains a library of hard interactions and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and interfaces to external programs.

The objective of this exercise is to teach you the basics of how to use the PYTHIA 8.2 event generator to study various physics aspects. As you become more familiar you will better understand the tools at your disposal, and can develop your own style to use them. Within this first exercise it is not possible to describe the physics models used in the program; for this we refer to the PYTHIA 8.2 introduction [1], to the full PYTHIA 6.4 physics description [2], and to all the further references found in them.

PYTHIA 8 is, by today’s standards, a small package. It is completely self-contained, and is therefore easy to install for standalone usage, e.g. if you want to have it on your own laptop, or if you want to explore physics or debug code without any danger of destructive

interference between different libraries. Section 2 describes the installation procedure, which is what we will need for this introductory session. It does presuppose a working Unix-style environment with C++ compilers and the like; check Appendix D if in doubt.

When you use PYTHIA you are expected to write the main program yourself, for maximal flexibility and power. Several examples of such main programs are included with the code, to illustrate common tasks and help getting started. Section 3 gives you a simple step-by-step recipe how to write a minimal main program, that can then gradually be expanded in different directions, e.g. as in Section 4.

In Section 5 you will see how the parameters of a run can be read in from a file, so that the main program can be kept fixed. Many of the provided main programs therefore allow you to create executables that can be used for different physics studies without recompilation, but potentially at the cost of some flexibility.

The final sections provide suggestions for optional further studies, and can be addressed in any order. Section 6 deals with the important topic of merging of external matrix-element input of different orders, introducing the CKKW-L scheme as a suitable starting point. For the MC4BSM tutorial 2016, we have added Section 7, which applies CKKW-L merging to the Higgs+jets process. Section 8 describes how you can, using stand-alone `Pythia8`, explore various physics aspects of the Standard Model Higgs production and decay. Section 9, finally, collects suggestions for a few diverse studies.

Note for the CTEQ school tutorial : You should view this tutorial sheet also as a user reference. So do not be scared of the length of the document. For a one-day tutorial session, you should be able to complete Section 6. Section 7 then gives you the opportunity to be explore some topics beyond the scope of the CTEQ tutorial.

While PYTHIA can be run standalone, it can also be interfaced with a set of other libraries. One example is HEPMC, which is the standard format used by experimentalists to store generated events. Since the HEPMC library location is installation-dependent it is not possible to give a fool-proof linking procedure, but some hints are provided for the interested in Appendix C. Further main programs included with the PYTHIA code provide examples of linking, e.g., to ALPGEN, MADGRAPH, POWHEG, FASTJET, ROOT, and the Les Houches Accords LHEF, LHAPDF and SLHA.

Appendix A contains a brief summary of the event-record structure, and Appendix B some notes on simple histogramming and jet finding. Appendices C and D have already been mentioned.

2 Installation

Note for the CTEQ school tutorial : You can find the CTEQ containers and instructions at

<http://www.slac.stanford.edu/~shoeche/cteq19/>

you do not need to follow the installation instructions, and may directly continue with section 3; the examples directory containing many example main programs can be found under `/usr/local/share/Pythia8/examples`. The `examples` directory that you should use for the school is `~/tutorials/mc/pythia` for your convenience. This is the directory we will be referring to as `example` directory below. The following instructions here are kept for reference, in case you want to install PYTHIA 8 on your private machine.

Denoting a generic PYTHIA 8 version `pythia82xx` (at the time of writing `xx = 26`), here is how to install PYTHIA 8 on a Linux/Unix/MacOSX system as a standalone package (assuming you have standard Unix-family tools installed, see Appendix D).

1. In a browser, go to
`http://home.thep.lu.se/Pythia`
2. Download the (current) program package
`pythia82xx.tgz`
to a directory of your choice (e.g. by right-clicking on the link).
3. In a terminal window, `cd` to where `pythia82xx.tgz` was downloaded, and type
`tar xvfz pythia82xx.tgz`
This will create a new (sub)directory `pythia82xx` where all the PYTHIA source files are now ready and unpacked.
4. Move to this directory (`cd pythia82xx`) and do a `make`. This will take ~ 3 minutes (computer-dependent). The PYTHIA 8 library is now compiled and ready for physics.
5. For test runs, `cd` to the `examples/` subdirectory. An `ls` reveals a list of programs, `mainNN.cc`, with `NN` from 01 through 28 (and beyond). These example programs each illustrate an aspect of PYTHIA 8. For a list of what they do, see the “Sample Main Programs” page in the online manual (point 6 below).
Initially only use one or two of them to check that the installation works. Once you have worked your way through the introductory exercises in the next sections you can return and study the programs and their output in more detail.

To execute one of the test programs, do

```
make mainNN
./mainNN
```

The output is now just written to the terminal, `stdout`. To save the output to a file instead, do `./mainNN > outNN`, after which you can study the test output at leisure by opening `outNN`. See Appendix A for an explanation of the event record that is listed in several of the runs.

6. If you use a web browser to open the file
`pythia82xx/share/Pythia8/html/doc/Welcome.html`
you will gain access to the online manual, where all available methods and parameters are described. Use the left-column index to navigate among the topics, which are then displayed in the larger right-hand field.

3 A “Hello World” program

We will now generate a single $gg \rightarrow t\bar{t}$ event at the LHC, using PYTHIA standalone.

Open a new file `mymain01.cc` in the `examples` subdirectory with a text editor, e.g. Emacs. Then type the following lines (here with explanatory comments added):

```
// 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 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.
```

The `examples/Makefile` has been set up to compile all `mymainNN.cc`, $NN = 01 - 99$, and link them to the `lib/libpythia8.a` library, just like the `mainNN.cc` ones. Therefore you can compile and run `mymain01` as before:

```
make mymain01
./mymain01 > myout01
```

If you want to pick another name, or if you need to link to more libraries, you have to edit `examples/Makefile` appropriately.

Thereafter you can study `myout01`, especially the example of a complete event record (preceded by initialization information, and by kinematical-variable and hard-process listing for the same event). At this point you need to turn to Appendix A for a brief overview of the information stored in the event record.

An important part of the event record is that many copies of the same particle may exist, but only those with a positive status code are still present in the final state. To exemplify, consider a top quark produced in the hard interaction, initially with positive status code. When later a shower branching $t \rightarrow tg$ occurs, the new t and g are added at the bottom of the then-current event record, but the old t is not removed. It is marked as decayed, however, by negating its status code. At any stage of the shower there is thus only one “current” copy of the top. After the shower, when the final top decays, $t \rightarrow bW^+$, also that copy receives a negative status code. When you understand the basic principles, 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. Also note how the mother/daughter indices tie together the various copies.

4 A first realistic analysis

We will now gradually expand the skeleton `mymain01` program from above, towards what would be needed for a more realistic analysis setup.

- Often, we wish to mix several processes together. To add the process $q\bar{q} \rightarrow t\bar{t}$ to the above example, just include a second `pythia.readString` call

```
pythia.readString("Top:qqbar2ttbar = on");
```

- Now we wish to generate more than one event. To do this, introduce a loop around `pythia.next()`, so the code now reads

```
for (int iEvent = 0; iEvent < 5; ++iEvent) {
    pythia.next();
}
```

Hereafter, we will call this the *event loop*. The program will now generate 5 events; each call to `pythia.next()` resets the event record and fills it with a new event. To list more of the events, you also need to add

```
pythia.readString("Next:numberShowEvent = 5");
```

along with the other `pythia.readString` commands.

- To obtain statistics on the number of events generated of the different kinds, and the estimated cross sections, add a

```
pythia.stat();
```

just before the end of the program.

- During the run you may receive problem messages. These come in three kinds:
 - a *warning* is a minor problem that is automatically fixed by the program, at least approximately;
 - an *error* is a bigger problem, that is normally still automatically fixed by the program, by backing up and trying again;
 - an *abort* is such a major problem that the current event could not be completed; in such a rare case `pythia.next()` is `false` and the event should be skipped.

Thus the user need only be on the lookout for aborts. During event generation, a problem message is printed only the first time it occurs (except for a few special cases). The above-mentioned `pythia.stat()` will then tell you how many times each problem was encountered over the entire run.

- Studying the event listing for a few events at the beginning of each run is useful to make sure you are generating the right kind of events, at the right energies, etc. For real analyses, however, you need automated access to the event record. The PYTHIA event record provides many utilities to make this as simple and efficient as possible. To access all the particles in the event record, insert the following loop after `pythia.next()` (but fully enclosed by the event loop)

```
for (int i = 0; i < pythia.event.size(); ++i) {
```

```

        cout << "i = " << i << ", id = "
            << pythia.event[i].id() << endl;
    }

```

which we will call the *particle loop*. Inside this loop, you can access the properties of each particle `pythia.event[i]`. For instance, the method `id()` returns the PDG identity code of a particle (see Appendix A.1). The `cout` statement, therefore, will give a list of the PDG code of every particle in the event record.

- As mentioned above, the event listing contains all partons and particles, traced through a number of intermediate steps. Eventually, the top will decay ($t \rightarrow Wb$), and by implication it is the last top copy in the event record that defines the definitive top production kinematics, just before the decay. You can obtain the location of this final top e.g. by inserting a line just before the particle loop

```
int iTop = 0;
```

and a line inside the particle loop

```
if (pythia.event[i].id() == 6) iTop = i;
```

The value of `iTop` will be set every time a top is found in the event record. When the particle loop is complete, `iTop` will now point to the final top in the event record (which can be accessed as `pythia.event[iTop]`).

- In addition to the particle properties in the event listing, there are also methods that return many derived quantities for a particle, such as transverse momentum, `pythia.event[iTop].pT()`, and pseudorapidity, `pythia.event[iTop].eta()`. Use these methods to print out the values for the final top found above.
- We now want to generate more events, say 1000, to view the shape of these distributions. Inside PYTHIA is a very simple histogramming class, see Appendix B.1, that can be used for rapid check/debug purposes. To book the histograms, insert before the event loop

```
Hist pT("top transverse momentum", 100, 0., 200.);
```

```
Hist eta("top pseudorapidity", 100, -5., 5.);
```

where the last three arguments are the number of bins, the lower edge and the upper edge of the histogram, respectively. Now we want to fill the histograms in each event, so before the end of the event loop insert

```
pT.fill( pythia.event[iTop].pT() );
```

```
eta.fill( pythia.event[iTop].eta() );
```

Finally, to write out the histograms, after the event loop we need a line like

```
cout << pT << eta;
```

Do you understand why the η distribution looks the way it does? Propose and study a related but alternative measure and compare.

- As a final standalone exercise, consider plotting the charged multiplicity of events. You then need to have a counter set to zero for each new event. Inside the particle loop this counter should be incremented whenever the particle `isCharged()` and `isFinal()`. For the histogram, note that it can be treacherous to have bin limits at integers, where roundoff errors decide whichever way they go. In this particular case only even numbers are possible, so 100 bins from -1 to 399 would still be acceptable.

5 Input files

With the `mymain01.cc` structure developed above it is necessary to recompile the main program for each minor change, e.g. if you want to rerun with more statistics. This is not time-consuming for a simple standalone run, but may become so for more realistic applications. Therefore, parameters can be put in special input “card” files that are read by the main program.

We will now create such a file, with the same settings used in the `mymain01.cc` example program. Open a new file, `mymain01.cmd`, and input the following

```
! t tbar production at the LHC
Beams:idA = 2212      ! first incoming beam is a 2212, i.e. a proton.
Beams:idB = 2212      ! second beam is also a proton.
Beams:eCM = 8000.     ! the cm energy of collisions.
Top:gg2ttbar = on     ! switch on the process g g -> t tbar.
Top:qqbar2ttbar = on ! switch on the process q qbar -> t tbar.
```

The `mymain01.cmd` file can contain one command per line, of the type

```
variable = value
```

All variable names are case-insensitive (the mixing of cases has been chosen purely to improve readability) and non-alphanumeric characters (such as `!`, `#` or `$`) will be interpreted as the start of a comment. All valid variables are listed in the online manual (see Section 2, point 6, above). Cut-and-paste of variable names can be used to avoid spelling mistakes.

The final step is to modify our program to use this input file. The name of this input file can be hardcoded in the main program, but for more flexibility, it can also be provided as a command-line argument. To do this, replace the `int main() {` line by

```
int main(int argc, char* argv[]) {
```

and replace all `pythia.readString(...)` commands with the single command

```
pythia.readFile(argv[1]);
```

The executable `mymain01` is then run with a command line like

```
./mymain01 mymain01.cmd > myout01
```

and should give the same output as before.

In addition to all the internal `Pythia` variables there exist a few defined in the database but not actually used. These are intended to be useful in the main program, and thus begin with `Main:.` The most basic of those is `Main:numberOfEvents`, which you can use to specify how many events you want to generate. To make this have any effect, you need to read it in the main program, after the `pythia.readFile(...)` command, by a line like

```
int nEvent = pythia.mode("Main:numberOfEvents");
```

and set up the event loop like

```
for (int iEvent = 0; iEvent < nEvent; ++iEvent) {
```

You are now free to play with further options in the input file, such as:

- `PartonLevel:FSR = off`
switch off final-state radiation.
- `PartonLevel:ISR = off`
switch off initial-state radiation.
- `PartonLevel:MPI = off`
switch off multiparton interactions.
- `Tune:pp = 3` (or other values between 1 and 17)
different combined tunes, in particular to radiation and multiparton interactions parameters. In part this reflects that no generator is perfect, and also not all data is perfect, so different emphasis will result in different optima.
- `Random:setSeed = on`
`Random:seed = 123456789`
all runs by default use the same random-number sequence, for reproducibility, but you can pick any number between 1 and 900,000,000 to obtain a unique sequence.

For instance, check the importance of FSR, ISR and MPI on the charged multiplicity of events by switching off one component at a time.

The possibility to use command-line input files is further illustrated e.g. in `main16.cc` and `main42.cc`.

The online manual also exists in an interactive variant, where you semi-automatically can construct a file with all the command lines you wish to have. This requires that somebody installs the `pythia82xx/share/Pythia8/phpdoc` directory in a webserver. If you lack a local installation you can use the one at

<http://home.thep.lu.se/Pythia/pythia82php/Welcome.php>

This is not a commercial-quality product, however, and requires some user discipline. Full instructions are provided on the “Save Settings” page.

You have now completed the core part of the worksheet — congratulations! The next section is devoted to shower uncertainties. The section after that will then allow you to take off in different directions, depending on your interests, and if you are still hungry for more.

6 Shower uncertainties in top pair production

Event generators try to implement the most precise and complete description of scattering events. The simulation will contain uncertainties because *a*) the calculation of some mechanism might be approximated (e.g. by calculating only to a certain perturbative order), or *b*) if a first-principles calculation of a particular phenomenon is not yet known. Uncertainties due to *b*) are very difficult to quantify without dedicated studies. In the following, we will consider uncertainties of the type *a*) that stem from truncating perturbation theory at some order. Such variations have been considered in [13] and are documented under the menu item “*Automated Shower Variations*” in the PYTHIA online manual.

Parton showers are a crucial component in a realistic event simulation. They are approxi-

mations to perturbative all-order QCD, which model the structure and evolution of jets of partons. In this section, we will investigate some of the uncertainties of a parton shower calculation.

Note for the CTEQ school tutorial : We will use the RIVET analysis tool for this, so that you can easily compare your results to predictions from other generators. RIVET relies on HEPMC event input. Thus, you can follow the instructions in App. C to upgrade your `mymain.cc` program to produce HEPMC events. Alternatively, you can have a look at `main41.cc` and `main42.cc` in your `examples` directory. To avoid unnecessary delays, we recommend that you use the example main program `mymain-hepmc.cc` and the input file `mymain-hepmc.cmd` that are provided on the tutorial virtual machine. This main program produces one HEPMC file for each weight due to from shower variations. To avoid writing many events to disk, it is beneficial to declare the HEPMC output files as FIFO pipes. Your system will then flush the output files after RIVET has read and analysed the events, thus ensuring that no large files have to be stored. We provide the bash script `run.sh` to handle this task. Have a look at `mymain-hepmc.cc` and `run.sh` to make sure you understand what is going on before proceeding!

Parton showers resum large logarithmic enhancements by using (QCD) perturbation theory. They contain a dependence on renormalisation/factorisation scales, and on non-logarithmic pieces that are contained in the splitting functions that are used to define the shower. PYTHIA allows you [13] to vary

- The renormalization scale in final-state and initial-state splittings;
- The finite pieces of the splitting functions used for final-state and initial-state splittings.

We will use both of these to assess which piece of the perturbative calculation produces significant uncertainties for particular observables. Please note that these variations do not span the real envelope of event generator all uncertainties. However, getting a feeling for the perturbative uncertainties is still a useful skill.

6.1 Shower variations: Scales

To enable shower variations, you should first include the setting

```
UncertaintyBands:doVariations = on
```

in your input file `mymain-hepmc.cmd`.

Let us first look varying the renormalization scale in the parton shower, and consider variations in final-state and initial-state splittings separately. For this, use the settings

```
UncertaintyBands:List = {
    scale_fsr_lo fsr:muRfac=0.5,
    scale_fsr_hi fsr:muRfac=2.0,
    scale_isr_lo isr:muRfac=0.5,
    scale_isr_hi isr:muRfac=2.0
}
```

The labels `scale_fsr_lo` etc. are arbitrary, and have no influence on the result. The

first line means that PYTHIA will produce an additional event weight that contains the result of evaluating all final-state splittings with $\alpha_s(\frac{1}{2}\mu_r^{PS})$, and similarly for the following three lines. Thus, PYTHIA will produce four additional event weights that can be used for histogramming. Before moving forward, check if the variation of these weights are reasonable.

Instructions for the CTEQ school tutorial : Use the script `run.sh` provided on the VM. In this way, you will be able to produce uncertainty envelopes relatively conveniently. You will also be able to compare your results with the results of other students for other generators. In order to produce the results for this section, update the input file `mymain-hepmc.cmd` with the uncertainty settings listed above and run

```
./run.sh pythiaScales
```

in the tutorial directory. This will produce files that contain the results for each variation (`scale_fsr_lo.yoda`, `scale_fsr_hi.yoda`, `scale_isr_lo.yoda`, `scale_isr_hi.yoda`), and three files that contain the envelope of final-state shower variations (`pythiaScalesFSR.yoda`), of initial-state shower variations (`pythiaScalesISR.yoda`) and a combined envelope (`pythiaScales.yoda`). Plots will be stored in a directory called `pythiaScales`. Check that the weight variation is reasonable by including output in `mymain-hepmc.cc` (and recompiling). If this is not the case, try to understand why, based on what you have learned about the algorithm in the shower coding tutorial. It is also possible to produce the variations separately by running four times using the different settings

- `SpaceShower:renormMultFac = 0.5` (equivalent to `scale_isr_lo`)
- `SpaceShower:renormMultFac = 2.0` (equivalent to `scale_isr_hi`)
- `TimeShower:renormMultFac = 0.5` (equivalent to `scale_fsr_lo`)
- `SpaceShower:renormMultFac = 2.0` (equivalent to `scale_fsr_hi`)

What are the benefits and downsides of performing separate runs? Note that separate runs might turn out to be the preferred option for scale variations of the showers.

Now examine your histograms and try to answer

- For which observable do you find the largest final-state shower variation? Why?
- For which observable do you find the largest initial-state shower variation? Why?
- Do the variation bands have features? Can you explain the features?

6.2 Shower variations: Finite pieces

As a next step, let us check the impact of varying finite pieces of the splitting functions. For this, use

```

UncertaintyBands:List = {
    finitePieces_fsr_lo fsr:cNS=-2.0,
    finitePieces_fsr_hi fsr:cNS=2.0,
    finitePieces_isr_lo isr:cNS=-2.0,
    finitePieces_isr_hi isr:cNS=2.0
}

```

Again, you will receive four additional weights that you can use for histogramming. You can check [13] on how these variations are defined. The variation of finite pieces in the splitting functions should not affect soft and collinear configurations too much.

Instructions for the CTEQ school tutorial : Use the script `run.sh` provided on the VM. In order to produce the results for this section, update the input file `mymain-hepmc.cmd` with the uncertainty settings listed above and run

```
./run.sh pythiaFinites
```

in the tutorial directory. This will produce files that contain the results for each variation (`finitePieces_fsr_lo.yoda`, `finitePieces_fsr_hi.yoda`, `finitePieces_isr_lo.yoda` and `finitePieces_isr_hi.yoda`) and three files that contain the envelope of final-state shower variations (`pythiaFinitesFSR.yoda`), of initial-state shower variations (`pythiaFinitesISR.yoda`) and a combined envelope (`pythiaFinites.yoda`). Plots will be stored in a directory called `pythiaFinites`.

Examine your histograms and try to understand

- For which observable or in which phase space region do you find the largest effect?
- Can you find phase space regions in which this uncertainty dominates over the scale variations?
- What happens if you switch on/off matrix element corrections by invoking the settings `TimeShower:MEcorrections` and `SpaceShower:MEcorrections`?

This concludes the main part of the variations tutorial.

Note for the CTEQ school tutorial : Now it is time for you to compare with the variations produced by the other generators to form a more complete picture of uncertainties. By now, you should have two (or more) `.yoda` files containing envelopes of variations (i.e. `pythiaScales.yoda` and `pythiaFinites.yoda`). If you want to compare the combined envelope with the variation envelope of the other generators, take a look at the `/home/student/tutorials/mc/plotit.sh` script. Note that the `plotit.sh` script assumes that the PYTHIA-produced `.yoda` files are e.g. called `Analysis0.yoda`. You will have to adjust these names to the files you want to plot! You can then produce PYTHIA plots with this script by running

```
/home/student/tutorials/mc/plotit.sh py
```

or produce combined plots for HERWIG, PYTHIA and SHERPA with

```
/home/student/tutorials/mc/plotit.sh hw py sh
```

6.3 Shower variations: Bonus questions

If you still have time and you are willing to generate a large number of events, it might be interesting to check how your uncertainty estimate changes if you assume different correlations between the variations. For now, we have treated the variations as independent. If you e.g. use the settings

```
UncertaintyBands:List = {  
    scale_shower_lo fsr:muRfac=0.5 isr:muRfac=0.5,  
    scale_shower_hi fsr:muRfac=2.0 isr:muRfac=2.0  
}
```

instead, then PYTHIA will provide only two additional weights. The first of these weight is a combination of “down” variations, while the second gives a combination “up” variations. How does the envelope of these weights differ from your previous results? Would you expect significant differences?

7 Further studies

If you have time left, you should take the opportunity to try a few other processes or options. Below are given some examples, but feel free to pick something else that you would be more interested in.

- One popular misconception is that the energy and momentum of a B meson has to be smaller than that of its mother b quark, and similarly for charm. The fallacy is twofold. Firstly, if the b quark is surrounded by nearby colour-connected gluons, the B meson may also pick up some of the momentum of these gluons. Secondly, the concept of smaller momentum is not Lorentz-frame-independent: if the other end of the b colour force field is a parton with a higher momentum (such as a beam remnant) the “drag” of the hadronization process may imply an acceleration in the lab frame (but a deceleration in the beam rest frame).
To study this, simulate b production, e.g. the process `HardQCD:gg2bbbar`. Identify B/B* mesons that come directly from the hadronization, for simplicity those with status code `-83` or `-84`. In the former case the mother b quark is in the `mother1()` position, in the latter in `mother2()` (study a few event listings to see how it works). Plot the ratio of B to b energy to see what it looks like.
- One of the characteristics of multiparton-interactions (MPI) models is that they lead to strong long-range correlations, as observed in data. That is, if many hadrons are produced in one rapidity range of an event, then most likely this is an event where many MPI’s occurred (and the impact parameter between the two colliding protons was small), and then one may expect a larger activity also at other rapidities.
To study this, select two symmetrically located, one unit wide bins in rapidity (or pseudorapidity), with a variable central separation Δy : $[\Delta y/2, \Delta y/2 + 1]$ and $[-\Delta y/2 - 1, -\Delta y/2]$. For each event you may find n_F and n_B , the charged multiplicity in the “forward” and “backward” rapidity bins. Suitable averages over a

sample of events then gives the forward–backward correlation coefficient

$$\rho_{FB}(\Delta y) = \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_B \rangle}{\sqrt{(\langle n_F^2 \rangle - \langle n_F \rangle^2)(\langle n_B^2 \rangle - \langle n_B \rangle^2)}} = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2},$$

where the last equality holds for symmetric distributions such as in pp and $\bar{p}p$.

Compare how $\rho_{FB}(\Delta y)$ changes for increasing $\Delta y = 0, 1, 2, 3, \dots$, with and without MPI switched on (`PartonLevel:MPI = on/off`) for minimum-bias events (`SoftQCD:minBias = on`).

- Z^0 production to lowest order only involves one process, which is accessible with `WeakSingleBoson:ffbar2gmZ = on`. The problem here is that the process is $ff \rightarrow \gamma^*/Z^0$ with full γ^*/Z^0 interference and so a significant enhancement at low masses. The combined particle is always classified with code 23, however. So generate events and study the γ^*/Z^0 mass and p_\perp distributions. Then restrict to a more “ Z^0 -like” mass range with `PhaseSpace:mHatMin = 75.` and `PhaseSpace:mHatMax = 120.`
- Use a jet clustering algorithm, e.g. one of the `SlowJet` options described in Appendix B.2, to study the number of jets found in association with the Z^0 above. You can switch off Z^0 decay with `23:mayDecay = no`, and negate its status code by `pythia.event[iZ].statusNeg()`, so that it will not be included in the jet finding. Here `iZ` is the last copy of the Z^0 , cf. how the last top copy was found above. Again check the importance of FSR/ISR/MPI.

Note that the PYTHIA homepage contains two further tutorials, in addition to older editions of the current one. We would like to mention one area of intense developments for event generators: Matching & merging the parton shower with multi-jet fixed-order matrix elements. Below, we give an introduction to the CKKW-L merging scheme implemented in PYTHIA.

7.1 CKKW-L merging

The main programs we have constructed and studied in the previous sections have one common drawback: all start from the PYTHIA 8 internal library of lowest-order processes, and then add higher-order corrections entirely by the internal parton-shower machinery. This will give reliable results for soft and collinear configurations, but less so for multiple hard, well-separated jets. To model the latter similarly well we need to include external input from higher-order calculations, at least at tree level, but where feasible also at one-loop level. A number of different external programs can provide such input, using the LHA/LHEF standard format [3, 4, 5] to transfer information, usually as LHE files. The hard-process events stored in these files will be accepted or rejected in such a way that doublecounting between different parton multiplicities is removed, resulting in a smooth transition between the multiplicities, and between the external input and the internal handling of parton showers. These two tasks usually go hand in hand.

Many different schemes have been proposed for matrix element + parton shower merging (MEPS), and a comprehensive selection of such schemes is available with the PYTHIA 8 distribution, including

- tree-level merging: MLM jet matching [6] (MADGRAPH- or ALPGEN-style), CKKW-L merging [7], and unitarised ME+PS merging (UMEPS) [8]; and
- next-to-leading order merging: NL^3 merging and unitarised NLO+PS merging (UNLOPS) [9].

The setup of such merging schemes is documented in the online manual, heading “Link to Other Programs”, page “Matching and Merging” with further subpages, and is illustrated in several of the example main programs.

Here we will experiment with the CKKW-L scheme, which was the first merging scheme available in PYTHIA 8, and also is among the simpler to work with. We will take the `main80` example main program as a starting point for our studies¹. In its general structure it closely resembles the main program(s) we already constructed step by step, so we will only need to comment on aspects that are new for the merging game. The process $W^+ + \leq 2$ jets will be taken as an example. It uses the LHE files

```
w+_production_lhc.0.lhe for  $W^+ + 0$  partons
w+_production_lhc.1.lhe for  $W^+ + 1$  parton
w+_production_lhc.2.lhe for  $W^+ + 2$  partons
```

in the `examples` directory to produce a result that simultaneously describes $W^+ + 0, 1, 2$ jet observables with leading-order matrix elements, while also including arbitrarily many shower emissions. Jets are here defined by a clustering procedure on the partons thus generated. (We omit other effects from consideration, such as MPIs or hadronization.)

Say we want to study a one-jet observable, e.g. the transverse momentum of the jet j in events with *exactly* one jet. In this case, we want to take “hard” jets from the $pp \rightarrow Wj$ matrix element (ME), while “soft” jets should be modelled by parton-shower (PS) emissions off the $pp \rightarrow W$ states. In order to smoothly merge these two samples, we have to know in which measure “hard” is defined, and which value of this measure separates the hard and soft regions. In `main80.cmd`, these definitions are

```
Merging:doKTMerging = on
Merging:ktType       = 2
Merging:TMS          = 30.
```

This will enable the merging procedure, with the merging scale defined by the minimal longitudinally invariant k_\perp separation between partons (there are many other possibilities, by `ktType` value or by your own choice of merging procedure), with a merging scale $t_{MS} = 30$ GeV. Such a definition fixes what we mean when we talk about “hard” and “soft” jets:

```
Hard jets:  min{any relative  $k_\perp$  between sets of partons} >  $t_{MS}$ 
Soft jets:  min{any relative  $k_\perp$  between sets of partons} <  $t_{MS}$ 
```

Thus, in order for the merging prescription to work, we need to remove phase space regions with $\min\{any\ k_\perp\} < t_{MS}$ from the $W+1$ -parton matrix element calculation. Otherwise, there would be an overlap between the “soft jet” and “hard jet” samples.

This requirement means that the merging-scale definition should be implemented as a *cut in the matrix element generator*. Alternatively, it is possible to enforce the cut in

¹It might be useful to be aware of the setting `Merging:includeWeightInXsection` to allow easy to assess the value of the “merging weight”.

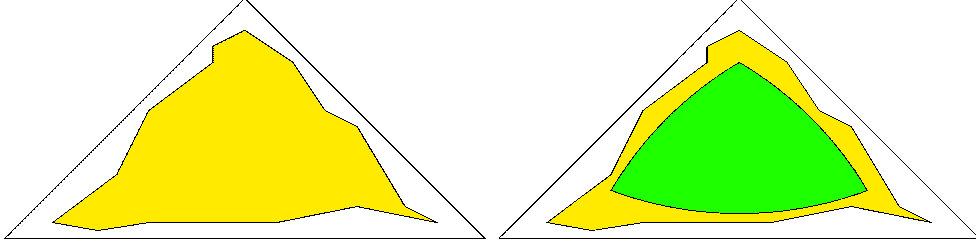


Figure 1: Schematic illustration of how the phase space covered by the external matrix-element generator, yellow region, has to enclose the region passing the PYTHIA 8 cuts, green region.

PYTHIA 8 internally, assuming that the ME is calculated with more inclusive (i.e. loose) cuts. This is illustrated in Figure 1, in which the triangle depicts the whole phase space, with soft or collinear divergences located on the edges. The yellow area symbolises the phase-space region used for the generation of the LHEF events, while the green area represents the phase space after PYTHIA 8 has enforced the merging-scale cut on the input events. In order to correctly apply the merging-scale cut, the green area has to be fully contained inside the yellow one, i.e. the cut in the ME generator has to be more inclusive than the t_{MS} -cut. For optimal efficiency, the yellow and green areas should be identical. This can be the case in MADGRAPH 5 [10], when using the generation cuts `ktdurham` (corresponding to `Merging:doKTMerging = on`) and `ptpythia` (corresponding to `Merging:doPTLundMerging = on`).

After the merging-scale definition, we define the underlying process. To tell PYTHIA 8 that we want to merge additional jets in W-boson production, we specify which is the core process, using MADGRAPH notation, where the final state is defined by the W^+ decay products rather than by the W^+ itself:

```
Merging:Process = pp>e+ve
```

in `main80.cmnd`. Finally, the setting

```
Merging:nJetMax = 2
```

tells the program to include the pre-generated ME events for up to two additional jets.

In `main80.cc`, the input file `main80.cmnd` is read early on by the `pythia.readFile(...)` command. This gives access to the number of events to be read from each LHE file, and the number of LHE files to be processed. The *subrun loop* then handles each LHE file, one at a time. Specifically, the

```
pythia.readFile("main80.cmnd", iMerge);
```

uses the `iMerge` argument when reading the `main80.cmnd` file, so that only those commands following the respective `Main:subrun = iMerge` label are read. (Plus that everything before the first `Main:subrun` is re-read, but that does not matter since it stays the same.) Thus the proper LHE file is picked up for each jet multiplicity. The

```
Beams:frameType = 4
```

also informs PYTHIA that beam parameters should be read from the header section of the LHE file, and not set by the user.

Then we enter the event loop. The already-discussed difference in phase-space coverage can lead to a fair fraction of all input events being rejected. Thus the number of produced

events can be lower than the requested `Main:numberOfEvents` one if the file is not large enough. (When no further events can be read the `pythia.next()` command will return `false`, so that the event loop can be exited at the end of the LHE file.) Those events that survive come with a weight

```
double weight = pythia.info.mergingWeight();
```

which contains Sudakov factors (to remove the double counting between samples of different multiplicity), α_s ratios (to incorporate the α_s running not available in matrix element generators), and ratios of parton distributions (to include variable factorization scales). This weight *must* be used when filling histogram bins, as is e.g. done by

```
pTWnow.fill( pTW, weight);
```

for the p_\perp of the W boson. The sum of weights also goes into the calculation of the total generated cross section.

After the event loop, the contribution to the p_\perp of the W boson from this particular multiplicity is normalised by

```
pTWnow *= 1e9*pythia.info.sigmaGen()/(2.*pythia.info.nAccepted());
```

where the ratio of the two `pythia.info` numbers is the weight per event, the `1e9` is for conversion from mb to pb, and the `2.` compensates for the bin width to give cross section per GeV. This number and more detailed statistics are printed to the terminal. As a final step, the contribution of the current subrun is added to the total histogram

```
pTWsum += pTWnow;
```

and the subrun loop begins over with the next LHE file. The complete histogram, combining all multiplicities, is printed after the sub-run loop has concluded.

You can compile and run `main80.cc` by issuing the commands

```
make main80
./main80
```

When you run the program, note that some warning messages are issued routinely as part of the merging machinery, in the steps where a clustering history is found and where it is decided whether an event fails the merging scale cuts. Warnings from the SLHA interface also are irrelevant. So no reason to worry about any of that.

After the first run with the main program as is, you can try different variations.

- Convince yourself that the variation of the “merging weight” is moderate.
- Check in which p_\perp regions which jet multiplicity contributes most.
- Study how the individual contributions and the sum changes when you run with a maximum of 1 or 0 jets, instead of the default 2.
- Compare the p_\perp spectrum of the W with what you get from running the internal PYTHIA production process, by straightforward modifications of your `mymain01` program.
- Check the variation of merged predictions with t_{MS} . You can do this by using an “inclusive” event sample, and having PYTHIA enforce a stronger t_{MS} cut. In which phase-space region is the t_{MS} variation most visible? A major limitation is the size of the event files that come with the standard PYTHIA distribution, for space reasons. If you have a decent Internet connection you can download larger files, with 100 000 events for each multiplicity up to $W + 4$ partons. Do this from the

PYTHIA home page, in the “Tutorials” section of it, files `wp_tree_0.lhe.gz` through `wp_tree_4.lhe.gz`.

A 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 (plus some additional pieces of information not discussed here). 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 main 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()`).

For a complete description of these and other particle properties (such as production and decay vertices, rapidity, p_\perp , etc), open the program’s online documentation in a browser (see Section 2, point 6, above), scroll down to the “Study Output” section, and follow the “Particle Properties” link in the left-hand-side menu. For brief summaries on the less trivial of the ones above, read on.

A.1 Identity codes

A complete specification of the PDG codes is found in the Review of Particle Physics [11]. 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.

Note that simple meson and baryon codes are constructed from the constituent (anti)quark codes, with a final spin-state-counting digit $2s + 1$ (K_L^0 and K_S^0 being exceptions), and with a set of further rules to make the codes unambiguous.

A.2 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 (see the online manual for the meaning of each specific code):

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

Whenever a particle is allowed to branch or decay further its status code is negated (but it is *never* removed from the event record), such that only particles in the final state remain with positive codes. The `isFinal()` method returns `true/false` for positive/negative status codes.

A.3 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. The detailed rules depend on the particular physics step being described, as defined by the status code. As an example, in a $2 \rightarrow 2$ process $ab \rightarrow cd$, the locations of a and b would set the mothers of c and d , with the reverse relationship for daughters. When the two mother or daughter indices are not consecutive they define a range between the first and last entry, such as a string system consisting of several partons fragment into several hadrons.

There are also several special cases. One such is when “the same” particle appears as a second copy, e.g. because its momentum has been shifted by it taking a recoil in the

dipole picture of parton showers. Then the original has both daughter indices pointing to the same particle, which in its turn has both mother pointers referring back to the original. Another special case is the description of ISR by backwards evolution, where the mother is constructed at a later stage than the daughter, and therefore appears below it in the event listing.

If you get confused by the different special-case storage options, the two `motherList()` and `daughterList()` methods return a **vector** of all mother or daughter indices of a particle.

A.4 Colour flow information

The colour flow information is based on the Les Houches Accord convention [3]. 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.

While colours are traced consistently through hard processes and parton showers, the subsequent beam-remnant-handling step often involves a drastic change of colour labels. Firstly, previously unrelated colours and anticolours taken from the beams may at this stage be associated with each other, and be relabelled accordingly. Secondly, it appears that the close space-time overlap of many colour fields leads to reconnections, i.e. a swapping of colour labels, that tends to reduce the total length of field lines.

B Some facilities

The PYTHIA package contains some facilities that are not part of the core generation mission, but are useful for standalone running, notably at summer schools. Here we give some brief info on histograms and jet finding.

B.1 Histograms

For real-life applications you may want to use sophisticated histogramming programs like ROOT, which however take much time to install and learn. Within the time at our disposal, we therefore stick with the very primitive `Hist` class. Here is a simple overview of what is involved.

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.

A set of overloaded operators have been defined, so that histograms can be added, subtracted, divided or multiplied by each other. Then the contents are modified accordingly bin by bin. Thus the relative deviation between two histograms **data** and **theory** can be found as

```
diff = (data - theory) / (data + theory);
```

assuming that **diff**, **data** and **theory** have been booked with the same number of bins and x range.

Also overloaded operations with double real numbers are available. Again these four operations are defined bin by bin, i.e. the corresponding amount is added to, subtracted from, multiplied by or divided by each bin. The double number can come before or after the histograms, with obvious results. Thus the inverse of a histogram result is given by `1./result`. The two kind of operations can be combined, e.g.

```
allpT = ZpT + 2. * WpT
```

A histogram can be printed by making use of the overloaded `<<` operator, e.g.

```
cout << ZpT;
```

The printout format is inspired by the old HBOOK one. To understand how to read it, consider the simplified example

```
3.50*10^ 2  9
3.00*10^ 2  X   7
2.50*10^ 2  X  1X
2.00*10^ 2  X6 XX
1.50*10^ 2  XX5XX
1.00*10^ 2  XXXXX
0.50*10^ 2  XXXXX
```

Contents

```
*10^ 2  31122
*10^ 1  47208
*10^ 0  79373
```

Low edge --

```
*10^ 1  10001
*10^ 0  05050
```

The key feature is that the **Contents** and **Low edge** have to be read vertically. For instance, the first bin has the contents $3 * 10^2 + 4 * 10^1 + 7 * 10^0 = 347$. Correspondingly, the other bins have contents 179, 123, 207 and 283. The first bin stretches from $-(1 * 10^1 + 0 * 10^0) = -10$ to the beginning of the second bin, at $-(0 * 10^1 + 5 * 10^0) = -5$.

The visual representation above the contents give a simple impression of the shape. An **X** means that the contents are filled up to this level, a digit in the topmost row the fraction to which the last level is filled. So the 9 of the first column indicates this bin is filled 9/10 of the way from $3.00 * 10^2 = 300$ to $3.50 * 10^2 = 350$, i.e. somewhere close to 345, or more precisely in the range 342.5 to 347.5.

The printout also provides some other information, such as the number of entries, i.e.

how many times the histogram has been filled, the total weight inside the histogram, the total weight in underflow and overflow, and the mean value and root-mean-square width (disregarding underflow and overflow). The mean and width assumes that all the contents is in the middle of the respective bin. This is especially relevant when you plot a integer quantity, such as a multiplicity. Then it makes sense to book with limits that are half-integers, e.g.

```
Hist multMPI( "number of multiparton interactions", 20, -0.5, 19.5);
```

so that the bins are centered at 0, 1, 2, ..., respectively. This also avoids ambiguities which bin gets to be filled if entries are exactly at the border between two bins. Also note that the `fill(xValue)` method automatically performs a cast to double precision where necessary, i.e. `xValue` can be an integer.

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. This may be used for plotting e.g. with Gnuplot.

B.2 Jet finding

The `SlowJet` class offer jet finding by the k_{\perp} , Cambridge/Aachen and anti- k_{\perp} algorithms. By default it is now a front end to the FJcore subset, extracted from the FastJet package [12] and distributed as part of the PYTHIA package, and is therefore no longer slow. It is good enough for basic jet studies, but does not allow for jet pruning or other more sophisticated applications. (An interface to the full FastJet package is available for such uses.)

You set up `SlowJet` initially with

```
SlowJet slowJet( pow, radius, pTjetMin, etaMax);
```

where `pow = -1` for anti- k_{\perp} (recommended), `pow = 0` for Cambridge/Aachen, `pow = 1` for k_{\perp} , while `radius` is the R parameter, `pTjetMin` the minimum p_{\perp} 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_{\perp} for the i 'th jet, and

```
slowJet.y(i)
```

gives the rapidity for the i 'th jet.

The jets are ordered in falling p_{\perp} .

C Interface to HepMC

The standard HEPMC event-record format is frequently used in the MCnet school training sessions, notably since it is required for comparisons with experimental data analyses

implemented in the Rivet package. Then a ready-made installation is used. However, for the ambitious, here is sketched how to set up the PYTHIA interface, assuming you already have installed HEPMC. A similar procedure is required for interfacing to other external libraries, so the points below may be of more general usefulness.

To begin with, you need to go back to the installation procedure of section 2 and insert/redo some steps.

1. Move back to the main `pythia82xx` directory (`cd ..` if you are in `examples`).
2. Configure the program:

```
./configure --with-hepmc2=path
```

where the directory-tree `path` would depend on your local installation. If the library is in a standard location you can omit the `=path` part.
3. Use `make` as before, to make the configure information available in the `examples/Makefile.inc` file, and move back to the `examples` subdirectory.
4. You can now also use the `main41.cc` and `main42.cc` examples to produce HEPMC event files. The latter may be most useful; it presents a slight generalisation of the command-line-driven main program you constructed in Section 5. After you have built the executable you can run it with

```
./main42 infile hepmcfile > main42.out
```

where `infile` is an input “card” file (like `mymain01.cmnd`) and `hepmcfile` is your chosen name for the output file with HEPMC events.

Note that the above procedure is based on the assumption that you will be running your main programs from the `examples` subdirectory. For experts there is a `make install` step to install the library and associated components in locations of your choice, and a `bin/pythia8-config` script to help you link to the library from anywhere.

D Preparations before starting the tutorial

Normally, you will run this tutorial on your own (laptop or desktop) computer. It is therefore important to make sure that you will be able to extract, compile, and run the code.

PYTHIA is not a particularly demanding package by modern standards, but some basic facilities such as Emacs (or an equivalent editor), gcc (g++), make, and tar must be available on your system. Below, we give some very basic instructions for standard installations on Linux, Mac OS X, and Windows platforms, respectively.

In the context of summer schools, students are strongly recommended to make sure that the above-mentioned facilities have been properly installed before traveling to the school, especially if the school is in a location which is likely to offer limited bandwidth.

D.1 Linux (Ubuntu)

The default tutorial instructions are intended for Linux (or other Unix-based) platforms, so this should be the easiest type of system to work with. The presence of the required development tools should be automatic on most Linux distributions.

Nonetheless, it seems that at least default installations of Ubuntu 12 do not include the full set of tools. These can be obtained by installing the “build-essential” package, by opening a terminal window and typing

```
sudo apt-get install build-essential
```

D.2 Max OS X

Mac OS X does not include code development tools by default, but they can relatively easily be obtained by installing Apple’s Xcode package, which is free of charge from the App Store; just type “xcode” in the search field to find it. Note that downloading and installing Xcode and the Command Line Tools that come with it can take quite some time, and if you don’t already have an Apple ID it will take even longer, so this should be done well before starting the tutorial.

With Xcode installed, you will also be able to use MacPorts (www.macports.org), a convenient package management system for Macs, which makes it very easy to install and maintain compiler suites, L^AT_EX, ROOT, and many other packages. Emacs is not part of the Xcode Command Line Tools, so is another useful example.

D.3 Windows

Unfortunately Microsoft Windows is not currently supported. If you don’t have access to a regular Linux environment, e.g. via dual boot on your Windows laptop, we are aware of three possible approaches to take. We have no direct experience with either of them, however, so cannot help you in case of trouble.

- Install Linux in a Virtual Machine (VM) on your Windows system, and then work within this virtual environment as on any regular Linux platform. You could e.g. download the VirtualBox

<https://www.virtualbox.org/>

and install either Ubuntu or CernVM (Scientific Linux)

<http://cernvm.cern.ch/>

on it. If you install an Ubuntu VM, please see the instructions above for Ubuntu systems.

- Install the Cygwin package, intended to allow Linux apps to run under Windows, see

<https://www.cygwin.com/>

Be sure to install the Dev tools, which appears in the list of options to include, but won’t be installed by default. Then put the `pythia82xx` folder

in the `Cygwin/home` directory, and compile and work with it as usual. (The `include/Pythia8Plugins/execinfo.h` file provides dummy versions of methods needed for proper compilation.)

- The `nuget.org` website
<http://www.nuget.org/packages/Pythia8/>
contains pre-built PYTHIA packages ready to be used under Windows Visual Studio.

Note that linking with other libraries may involve further problems, in particular for the dynamic loading of LHAPDF. The exercises here only rely on PYTHIA standalone, however.

References

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Introduction to Sherpa

Tutorial for summer schools

1 Introduction

Sherpa is a complete Monte-Carlo event generator for particle production at lepton-lepton, lepton-hadron, and hadron-hadron colliders [1]. The simulation of higher-order perturbative QCD effects, including NLO corrections to hard processes and resummation as encoded in the parton shower, is emphasized in Sherpa. QED radiation, underlying events, hadronization and hadron decays can also be simulated. Alternatively, Sherpa can be used for pure parton-level NLO QCD calculations with massless or massive partons.

Many reactions at the LHC suffer from large higher-order QCD corrections. The correct simulation of Bremsstrahlung in these processes is essential. It can be tackled either in the parton-shower approach, or using fixed-order calculations. Sherpa combines both these methods using a technique known as Matrix Element + Parton Shower merging (ME+PS). Details are described in Ref. [2] and have been discussed in the lectures. This tutorial will show you how to use the method in Sherpa.

The Docker container used in this tutorial can be obtained by running

```
docker pull cteqschool/tutorial:sherpa-2.2.7
```

Should you have problems with disk space, consider running `docker containers prune` and `docker system prune`. Sherpa is installed in `/usr/local`, and its documentation is found online [3]. Example setups are located in `/usr/local/Sherpa`. To run the docker container, use the following command

```
docker run -it -u $(id -u $USER) --rm -v $HOME:$HOME -w $PWD cteqschool/tutorial:sherpa-2.2.7
```

You may simplify this by defining an alias. We also add an environment variable needed for Rivet analyses

```
alias docker-run-sherpa='docker run -it -u $(id -u $USER) \
--rm -v $HOME:$HOME -w $PWD --env="RIVET_ANALYSIS_PATH=." cteqschool/tutorial:sherpa-2.2.7'
```

The tutorial can be obtained by running

```
git clone https://gitlab.com/shoeche/tutorials.git
```

All paths referenced to in these instructions are relative to the `tutorials/` directory created in this step. We will use a dedicated Rivet analysis, which is made available in the directory `rivet/`. As a first step, please compile this analysis and link the resulting library to your run directory using the sequence of commands

```
cd rivet/
docker-run-sherpa rivet-buildplugin MC_TTB.cc
cp RivetAnalysis.so ../mc/sherpa/
```

1.1 The Input File

Sherpa is steered using input files, which consist of several sections. A comprehensive list of all input parameters for Sherpa is given in the Sherpa manual [3]. For the purpose of this tutorial, we will focus on the most relevant ones.

Change to the directory `tutorials/mc/sherpa` and open the file `Run.dat` in an editor. Have a look at the section which is delimited by the tags `(run){` and `}(run)` (We will call this section the `(run)` section in

the following). You will find the specification of the collider, i.e. its beam type and center-of-mass energy, as well as a couple of other parameters, which will be explained later.

The (**processes**) section specifies, which reactions are going to be simulated. Particles are identified by their PDG codes, i.e. 1 stands for a down-quark, -1 stands for an anti-down, 2 for an up-quark, etc. The special code 93 represents a “container”, which comprises all light quarks, b-quarks, and the gluon. It is also called the “jet” container.

1.2 Running Sherpa

Have you found out which physics process is going to be generated? You can verify your guess by running the command line (Note that all commands in this section must be prefixed by **docker-run-sherpa** or run inside a shell started by **docker-run-sherpa bash**. Running inside a shell is recommended. See the introduction for details.)

```
Sherpa -e1 -o3
```

When run for the first time, Sherpa will produce diagram information for the calculation of hard scattering processes. It will also compute that hard scattering cross sections, which are stored, together with the diagram information, for subsequent runs.

The option **-e1** used above instructs Sherpa to produce one event, and the option **-o3** will print the result of event generation on the screen. You will see Sherpa’s internal event record. Search for **Signal Process** inside the output and check incoming and outgoing particles. What happens to the unstable particles after they have been produced in the hard scattering? Is this result physically meaningful?

Have a look at the Feynman diagrams, which contribute to the simulation of the hard process:

```
plot_graphs.sh graphs/  
firefox graphs/index.html
```

Are these the diagrams you expect to find? If not, which ones are missing? Can you find the setting in the runcard which restricts the set of diagrams?

1.3 Unstable particles

Open the input file again. Add the setting **HARD_DECAYS On;** to the (**run**) section, which instructs Sherpa to automatically decay unstable particles. Verify that the particles you wish to decay are flagged unstable by checking the screen output of Sherpa during runtime. Search for the ‘**List of Particle Data**’. Note that you can set particles stable individually using the switch **STABLE[<PDG ID>]=1**.

For experts: What happens when you change or remove the setting **WIDTH[6] 0;** (Hint: Search for ‘**Performing tests**’ in the screen output of Sherpa). Can you guess what the problem might be?

1.4 ME+PS merging

The current runcard lets Sherpa generate events at lowest order in the strong coupling. To improve the description of real radiative corrections, we can include higher-multiplicity tree-level contributions in the simulation. This is done by changing the process specification

```
Process 93 93 -> 6 -6;
```

to

```
Process 93 93 -> 6 -6 93{1};
```

The last entry instructs Sherpa to produce up to one additional “jet” using hard matrix elements and combine the respective process with the leading-order process. This is known as Matrix Element + Parton Shower merging (ME+PS), or the CKKW method. The essence of the method is a separation of hard from soft radiative corrections, achieved using phase-space slicing by means of a variable called the jet criterion. The slicing parameter is called the merging cut.

Let us assume we want to classify jets of more than 20 GeV transverse momentum as hard. In Sherpa, the corresponding merging cut would be specified as

```
CKKW sqr(20/E_CMS);
```

Therefore, the complete (`processes`) section for the merged event sample reads:

```
(processes){
  Process 93 93 -> 6 -6 93{1};
  CKKW sqr(20/E_CMS);
  Order (*,0);
  End process;
}(processes);
```

If you like, you can have a look at the Feynman graphs again, which contribute to the ME+PS merged event sample. In this case, you should not remove the line `Print_Graphs graphs;` from the (`processes`) section, and rerun the plot command from Sec. 1.2.

Run the new setup. Why does Sherpa compute another cross section?

1.5 Analyses

By default, Sherpa does not store events. Run Sherpa with the following command to write out weighted event files in HepMC format, which can subsequently be analyzed

```
Sherpa EVENT_OUTPUT=HepMC_Short[events_1j] -wW
```

Sherpa will produce a gzipped file called `events_1j.hepmc`, which can be processed with Rivet using the command

```
mkfifo events
gunzip -c events_1j.hepmc > events & \
rivet -a MC_TTB -H analysis_1j.yoda events
```

The option `-a MC_TTB` instructs Rivet to run a Monte-Carlo analysis of semileptonic $t\bar{t}$ events, which will provide us with a few observables that can be used for diagnostic purposes. Using a fifo pipe to extract the compressed event file avoids having to expand this file on disk, which can take substantial time and would unnecessarily take up storage space. This method will prove very useful in the tutorial on boosted final states.

You can view the results of this analysis by running the command

```
rivet-mkhtml --mc-errs analysis_1j.yoda
```

and opening `rivet-plots/index.html` in a browser.

Now it is your turn: Generate a separate event file without ME+PS merging and analyze it with Rivet. Compare the results to your previous analysis using `rivet-mkhtml` (Hint: You can specify multiple yoda input files to `rivet-mkhtml`.) Do you observe any differences? Why?

1.6 Playing with the setup

Here are a few suggestions to try if you have time left during the tutorial.

1.6.1 Changing the functional form of scales

You may have noticed the following line in the runcard

```
CORE_SCALE VAR{sqr(175)};
```

It invokes Sherpa's interpreter to compute the renormalization and factorization scale for the $pp \rightarrow t\bar{t}$ production process as the mass of the top quark (Note that all scales have dimension GeV^2 , hence the scale is squared using the `sqr` function).

You can change this to a different value. For example, you could use the invariant mass of the top quark pair:

```
CORE_SCALE VAR{Abs2(p[2]+p[3])};
```

Note that when you change the scale, the cross section will change and needs to be recomputed! You can instruct Sherpa not to pick up the old result and compute a new one by launching it with the command-line option `-r Result_NewScale/`. New cross section information will then be stored in the directory `Results_NewScale/`, while the old is still present in the directory `Results/`.

How do the observables change with the new scale and why? What is the effect of ME+PS merging when using this scale?

1.6.2 Hadronization and underlying event

So far, multiple parton interactions, which provide a model for the underlying event, have not been simulated. Also, hadronization has not been included in order to speed up event generation. You can enable both by removing or commenting the line

```
MI_HANDLER None; FRAGMENTATION Off;
```

How do the predictions for the observables change and why?

1.6.3 Variation of the merging cut

ME+PS merging is based on phase-space slicing, and the slicing cut is called the merging scale. It is an unphysical parameter, and no observable should depend sizeably on its precise value. Verify this by varying the merging cut by a factor of two up and down.

Note that the initial cross sections that Sherpa computes will be different for different values of the merging cut (Why?). You should therefore instruct Sherpa to use different result directories for each run in the test. The result directory is specified on the command line with option `-r`, for example

```
Sherpa -r MyResultDirectory/
```

1.6.4 Other hard scattering processes

Try to generate other hard scattering processes, like the production of a Drell-Yan muon pair (Hint: The PDG id for the muon is 13.) You will have to insert an additional section into the runcard, which reads

```
(selector){
  Mass 13 -13 66 116;
}(selector);
```

Why is this section needed?

2 Uncertainty estimates

You may ask yourself what the meaningful variations are to assess the uncertainty of your generator prediction. We will try to answer this question in the next part of the tutorial. As it can be quite costly to perform a complete uncertainty study, you will work with your peers and split the workload.

Using Sherpa, you will study the renormalization and factorization scale dependence of the reaction $pp \rightarrow t\bar{t}$ as well as the uncertainty related to the PDF fit. This is done on-the-fly, using reweighting techniques that are similar to the ones you implemented in the tutorial on parton showers. The reweighting is enabled in Sherpa by adding the following flags to the **(run)** section of your input file:

```
SCALE_VARIATIONS 0.25,0.25 0.25,1 1,0.25 1,4 4,1 4,4;
PDF_LIBRARY LHAPDFSherpa; PDF_SET CT14nlo;
PDF_VARIATIONS CT14nlo[all];
```

The line starting with **SCALE_VARIATIONS** instructs Sherpa to perform a six-point variation of the renormalization and factorization scales, with the pairs of numbers representing the scale factors for μ_R^2 and μ_F^2 . The line starting with **PDF_VARIATIONS** instructs Sherpa to perform a variation using all PDFs in the error set **CT14nlo**, which is interfaced through LHAPDF. Finally, the default PDF is set to **CT14nlo**.

We will not let Sherpa write event files in this part of the tutorial, but use the internal interface to Rivet, as it allows us to run the analysis simultaneously for all scale and PDF variations. This is set up by adding the following lines to your runcard:

```
(analysis){
  BEGIN_RIVET {
    -a MC_TTB;
  } END_RIVET;
}(analysis);
```

We need to instruct Sherpa to enable the internal Rivet interface using

```
Sherpa -wW -aRivet -AAanalysis/A
```

If you have enabled the usage of multiple CPUs or multiple CPU cores on your VM you may want to run Sherpa in MPI mode to accelerate the event generation:

```
mpirun -n 2 Sherpa -wW -aRivet -AAanalysis/A
```

To improve the statistical significance of our simulation, we can simulate only the relevant decays of the W^\pm -bosons. To simplify things, we will ignore decays into τ and choose hadronic modes for the W^- and leptonic modes for the W^+ :

```
HDH_STATUS[-24,-12,11] 0;
HDH_STATUS[-24,-14,13] 0;
HDH_STATUS[-24,-16,15] 0;
HDH_STATUS[24,16,-15] 0;
HDH_STATUS[24,2,-1] 0;
HDH_STATUS[24,4,-3] 0;
```

You can use the plot script provided in the top level directory to merge and display the results of the simulation

```
cd ..
./plotit.sh sh
```

References

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