

Introduction to Sherpa

Tutorial for summer schools

1 Prerequisites

For this tutorial, we will be using Docker. To download the image for Sherpa and Rivet, simply type

```
docker pull hepstore/rivet-sherpa:3.1.8
```

You can run the container interactively, e.g. like so

```
docker container run -it -v $PWD:$PWD -w $PWD hepstore/rivet-sherpa:3.1.8 /bin/bash
```

where the `-v $PWD:$PWD -w $PWD` ensures that you have access to your current directory also from within the container. To check that it works, try e.g.

```
rivet --version
```

which should return ‘rivet v3.1.8’.

2 A First Sherpa Run

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 emphasised 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.

2.1 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.

Download the first example run card (it is also available from the indico page, since Sherpa writes out data during its runs, it might be advisable to create separate directories for each run):

```
mkdir TTbar ; cd TTbar
wget \
  https://ipp.dur.ac.uk/~dreichel/Tutorial/TTbar/Run.dat
```

Open the `Run.dat` file 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.

2.2 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 run via Docker or from inside the Docker shell.

```
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
```

(The `firefox` command should be run outside of the Docker shell. Of course you can use any browser on your host machine to open the HTML file.) 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?

2.3 Unstable particles

Open the input file again. Add the setting `HARD_DECAYS On`; (note the underscore, and be aware that Sherpa run cards are case sensitive) 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`.

Run again

```
Sherpa -e1 -o3
```

and observe how the event record changes.

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?

2.4 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. 2.2. Run the new setup. Why does Sherpa compute another cross section?

2.5 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=HepMC3_GenEvent[events_1j]
```

Sherpa will produce a gzipped file called `events_1j.hepmc`, which can be processed with Rivet. Alternatively, you can use Sherpa’s interface to rivet, to analyse event directly without writing out large amounts of data. To do that, add the following line to the (run) section of your run card

```
ANALYSIS Rivet
```

To tell rivet what analysis should be used, you have to add a new section to the run card

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

The option `-a MC_TTBar` 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. You can change the name of the produced yoda file by adding

```
ANALYSIS_OUTPUT=Analysis.yoda
```

in the (run) section or on the command line

```
Sherpa -A Analysis.yoda
```

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

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

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

Now it is your turn: Generate a separate file without ME+PS merging and analyze it with Rivet. Compare the results to your previous analysis using `rivet-mkhtml`. Do you observe any differences? Why?

2.6 Other hard scattering processes

Let us learn how to study a different process. Assume we want to study the production and decay of W bosons, hence want to simulate the production of a lepton and a neutrino. Can you figure out how to change the `(process)` section of your run card? (Hint: Similar to 93 for partons, Sherpa also defines containers 90 for leptons and 91 for neutrinos.)

Note that, by default, the lepton container also includes τ -leptons. You can exclude them by adding

```
MASSIVE[15] 1
```

to the `(run)` section (15 is the PDG code for τ s). You will also need a new section

```
(selector){
  Mass 11 -12 1. E_CMS
  Mass 13 -14 1. E_CMS
  Mass -11 12 1. E_CMS
  Mass -13 14 1. E_CMS
}(selector)
```

Why is this section needed?

Can you turn on merging again?

You can also find a ready made example run card for this process at

<https://ipp.dur.ac.uk/~dreichel/Tutorial/W/Run.dat> and on the tutorial indico page.

2.7 MC@NLO matching

So far we have improved our calculations with merging, i.e. by adding additional hard jets, but ignoring virtual corrections. Including those, we can match to a full NLO calculation. In your W production run card, modify the `(process)` section to read

```
(processes){
  Process 93 93 -> 90 91;
  Order (*,2);
  NLO_QCD_Mode MC@NLO
  Loop_Generator Internal
  ME_Generator Amegic
  RS_ME_Generator Comix
  End process;
}(processes)
```

Note we use `Amegic` as the matrix element generator for the $2 \rightarrow 2$ process, including the virtual correction, and `Comix` as the generator for the real corrections (`RS` \rightarrow real-subtracted). For this simple process we can get the loop corrections from Sherpa's `Internal Loop_Generator`. The first time you run this run card, Sherpa will start writing out some code and then stop, you will have to compile this code using the command

```
./makelibs
```

and run **Sherpa** again to start the actual calculation. To save you some setup time, you can download a tarball containing all the integration results:

```
wget https://ipp.dur.ac.uk/~dreichel/Tutorial/WNLO.tar.gz
tar -xzf WNLO.tar.gz
cd WNLO
Sherpa
```

Run Sherpa again and compare your results to the merged result.

3 Advanced options

If you want to explore more advanced options to use with Sherpa, here are some suggestions for things you can try.

3.1 Uncertainty estimates

Using Sherpa, you can study the renormalization and factorization scale dependence of the simulation as well as the uncertainty related to the PDF fit. Thanks to reweighting techniques, this can be done on-the-fly, without running Sherpa multiple times. 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 NNPDF30_nnlo_as_0118;
PDF_VARIATIONS NNPDF30_nnlo_as_0118[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 `NNPDF30_nnlo_as_0118`, which is interfaced through LHAPDF. Finally, the default PDF is set to `NNPDF30_nnlo_as_0118`. Depending on the rivet version used, you might have to add

```
HEPMC_USE_NAMED_WEIGHTS 1;
SKIPWEIGHTS 0;
```

in the (analysis) section, after the `BEGIN_RIVET` line.

3.2 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?

3.3 Changing model parameters

You can change model parameters like coupling strengths, particle widths and particle masses in the run card. Have a look in the manual for a full overview of the available options. To change, for example, the mass of the W boson, you would include the following line (which in fact sets the mass to its default value)

```
MASS[24] = 80.385;
```

3.3.1 Side note: Tags

A useful feature of Sherpa run cards are "tags": A line like

```
FOO:=5
```

will define a tag "FOO" to represent "5". Any occurrence of "FOO" in the run card will then be replaced by "5" (be aware of unwanted consequences however, something like `ALPHA:=foo; ALPHAS(MZ) 0.1188;` will obviously cause problems). Tags, as well as any other parameter, can also be set on the command line. Adding the following to your run card

```
MW:=385
MASS[24] = 80.MW;
ANALYSIS_OUTPUT = Analysis_mWMW
RESULT_DIRECTORY = Results_mWMW
```

will for example allow you to run Sherpa with different W masses like

```
Sherpa MW:=385
```

which will recalculate the cross section and generate events with the modified W mass and write the results for different masses into different files.

3.4 Variation of the merging cut

ME+PS merging is based on phase-space slicing, and the slicing cut is called the merging scale. Is 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/
```

3.5 QED Corrections

Higher order QED corrections are effected both on hard interaction and, upon their formation, on each hadron's subsequent decay. The Photons module is called in both cases for this task. It employs a YFS-type resummation of all infrared singular terms to all orders and is equipped with complete first order corrections for the most relevant cases (all other ones receive approximate real emission corrections built up by Catani-Seymour splitting kernels). Add the following flags to the (run) section

```
YFS_MODE = [0,1,2]
YFS_USE_ME = [0,1]
```

`YFS.MODE`, unsurprisingly, specifies the mode in which Photons will treat the resummation. `YFS.MODE = 0` turns off Photons completely. `YFS.MODE = 1` is a "soft only" treatment, meaning soft emissions will be treated correctly to all orders but no hard emission corrections will be included. To include hard emission corrections up to first order in α_{QED} set the mode to `YFS.MODE=2`. The switch `YFS.USE_ME = [0,1]` specifies how the hard emissions are treated. If `YFS.USE_ME = 0`, then Photons will use collinearly approximated real emission matrix elements. Virtual emission matrix elements of order α_{QED} are ignored. If, however, `YFS.USE_ME = 1`, then exact real and/or virtual emission matrix elements are used wherever possible. This treatment is completely exclusive in the photon multiplicity and the event will include additional photons. You can verify this by checking your HepMC output file. Since we now have soft emissions, how do we ensure we have an infrared and collinear safe observable?

References

- [1] T. Gleisberg et al. “Event generation with SHERPA 1.1.” JHEP **02** (2009) 007.
- [2] A. Buckley et al. “General-purpose event generators for LHC physics.” Phys. Rept. **504** (2011) 145.
- [3] <https://sherpa.hepforge.org/doc/SHERPA-MC-2.0.0.html>.