Sherpa BSM Tutorial

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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].

This tutorial, however, focuses on the simulation of New Physics. There exists a variety of pre-implemented New Physics models in Sherpa that are readily available for event generation. However, given the multitude of Beyond to Standard Model physics scenarios, a more flexible approach to simulate BSM signatures is needed. For this purpose Sherpa offers an interface to the FeynRules package [4], in particular to UFO format of communicating BSM models [5]. A description of the corresponding Sherpa interface can be found in [6].

To exemplify the usage of the interface and corresponding BSM signal and SM background simulations with Sherpa, a stripped down version of the MC4BSM2014 tutorial will be studied [7].

1.1 The BSM Model

Notation	Spin	Mass	SU(3)	SU(2)	U(1)
Φ_1	0	M_1	1	1	0
Φ_2	0	M_2	1	1	0
U	1/2	M_U	3	1	2/3
E	1/2	M_E	1	1	-1

Table 1: The BSM field content (with quantum numbers) of the reference toy model

The tutorial relies on a toy BSM model whose particle content is shown in Table 1. The model contains two real scalar fields, ϕ^1 and ϕ^2. They are singlets under all SM gauge groups. Their mass terms are[1]:

$$\mathcal{L}_{\text{s.m.}} = -\frac{m_1^2}{2}\phi_1^2 - \frac{m_2^2}{2}\phi_2^2 - m_{12}^2\phi_1\phi_2\,. \tag{1}$$

The corresponding mass eigenstates will be denoted by Φ_1 and Φ_2, and their mass eigenvalues by M_1 and M_2, respectively. For definiteness we will assume that $M_1 < M_2$.

The model also contains two new Dirac fermion fields, U and E. Their SM quantum numbers are those of the SM u_R and e_R, respectively. These fields have mass terms

$$\mathcal{L}_{\text{f.m.}} = M_U\bar{U}U + M_E\bar{E}E\,. \tag{2}$$

[1]All Lagrangian parameters, here and below, are assumed to be real.

and interact with the new scalars via

$$\mathcal{L}_{\rm Yuk} = \lambda_1 \phi_1 \bar{U} P_R u + \lambda_2 \phi_2 \bar{U} P_R u + \lambda_1' \phi_1 \bar{E} P_R e + \lambda_2' \phi_2 \bar{E} P_R e \,, \tag{3}$$

where u and e are the SM up-quark and electron fields. Note that there is a $\mathcal{Z}_2$ symmetry under which all fields we added ($\phi_{1,2}$, U, E) flip sign, while all SM fields do not, so the new particles must be pair-produced, and the lightest new particle (LNP) is stable. This same $\mathcal{Z}_2$ also forbids $U-u$ and $E-e$ mixing via Yukawa couplings with the SM Higgs.

We assume the following ordering of masses:

$$M_U > M_2 > M_L > M_1 \,, \tag{4}$$

so that Φ_1 is the LNP. Not having any SM interactions, it appears as MET in the detector. The ultimate goal of the tutorial is to simulate the process

$$pp \to \bar{U}U \,, \tag{5}$$

at an 8 TeV LHC, and the subsequent U decays:

$$U \quad \to \quad u\Phi_1 \,, \tag{6}$$

$$U \quad \to \quad u\Phi_2 \,, \quad \Phi_2 \to eE \,, \quad E \to e\Phi_1 \,. \tag{7}$$

1.2 Getting started

Start the virtual machine. Sherpa has been pre-installed, and the standard examples are located at

```
/opt/hep/share/SHERPA-MC/Examples
```

and its documentation is found online [8]

You will find the tutorial in the directory `~/tutorial/bsm/sherpa`. Change to this directory

```
cd ~/tutorial/bsm/sherpa
```

The UFO files needed for the tutorial are stored in the directory `MC4BSM_2012_UFO`. The first step is to make the model information contained in these files accessible to Sherpa. This process is fully automated, and you simply have to run a single command:

```
Sherpa-generate-model MC4BSM_2012_UFO
```

The UFO files will be parsed, the Lorentz calculators for the model will be generated, and the particle and coupling information as well as the Lorentz calculators will be compiled into a dynamic library `libSherpaMC4BSM_2012_UFO.so` that is installed in your Sherpa library path (`/opt/hep/lib/SHERPA-MC`). Sherpa will dynamically load this library whenever you specify `MODEL=MC4BSM_2012_UFO` (cf. the instructions below).

2 Understanding Sherpa's input structure

Change to the directory `Intro` and open the input file `Run.dat`. The file consists of various sections, which are marked as `(run)`, `(processes)`, and `(ufo)`.

The `(ufo)` section can be compared to the `param_card.dat` file which steers a MadGraph run. It is model specific, and you will find there the definitions of the new particles, together with standard model particle and coupling definitions.

The `(run)` section is used to

- Define the collider type (pp) and the cms energy (8 TeV).

```
BEAM_1 2212; BEAM_ENERGY_1 4000;
BEAM_2 2212; BEAM_ENERGY_2 4000;
```

- Declare the model.

```
MODEL MC4BSM_2012_UFO;
```

- Set a scale at which the strong coupling is to be evaluated. In this case we are using $\hat{s}$, computed as the absolute value squared of the sum of the two incoming parton momenta.

```
SCALES VAR{Abs2(p[0]+p[1])};
```

- Request the number of events to be generated.

```
EVENTS 0;
```

The `(processes)` section defines the reaction of interest. Here we simulate the process $u\bar{u} \to U\bar{U}$. We also instruct Sherpa to write out Latex files depicting the Feynman graphs.

```
Process 2 -2 -> 9000008 -9000008;
Print_Graphs graphs;
End process;
```

Run the simple example using

```
Sherpa
```

The program will compute a cross section for the process $u\bar{u} \to U\bar{U}$. As we have set the number of events to zero, the run will then stop.
Have a look at the Feynman graphs that contribute to the process

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

3 Simulating parton-level events

Change back to the original directory and then change to `ToyModel_PartonLevel`.

Have a look at the `Run.dat` input file. In the `(run)` section we disable the hadronization module by using `FRAGMENTATION Off`, the parton shower by using `SHOWER_GENERATOR None`, the multiple scattering simulation by using `MI_HANDLER None`, and the YFS soft photon generator by using `ME_QED Off`.

We also enable the inclusive decay simulation and compute partial widths. This is steered by

- The global switch for hard deays.

```
HARD_DECAYS On;
```

- A flag to overwrite width settings from the `(ufo)` section with the widths computed by the decay module.

```
HDH_SET_WIDTHS 1;
```

- Switches to set the non-SM particles unstable.

```
STABLE[9000007] 0; WIDTH[9000007] 0;
STABLE[9000008] 0; WIDTH[9000008] 0;
STABLE[9000009] 0; WIDTH[9000009] 0;
```

We disable higher-order QED corrections in decays via `HDH_QED_CORRECTIONS 0`. In the `(processes)` section, we instruct Sherpa to generate all processes that contribute to $pp \to U\bar{U}$ production. As the U is set unstable, its decay and all subsequent decays will automatically be simulated.

Run this setup using

```
Sherpa
```

Sherpa will first compute the partial widths and branching ratios needed for the decay simulation. They are summarized in decay table outputs like this:

```
Decay table for : ev.
                 Total width: 0.293445 GeV
               Flavour width: 0.293445 GeV
----------------------------------------
9000009,9000006,11ev --> p1 e-        0.293445   GeV, BR= 100   %
----------------------------------------
```

The cross section will then be computed and Sherpa will generate 10000 events. Near the end of the output you should see the following message

```
+-----------------------------------------------------------+
|                                                           |
|  Total XS is 0.452731 pb +- ( 0.00428502 pb = 0.94 % )  |
|                                                           |
+-----------------------------------------------------------+
```

The precise value of the cross section, as well as the branching ratios, depends on the masses you have chosen for the U, E and $\phi_{1/2}$. It is important that you use this cross section, when computing event rates, rather than any of the cross sections quoted during the integration step. A detailed explanation why can be found in section three of the Sherpa online manual,
http://sherpa.hepforge.org/doc/SHERPA-MC-2.2.1.html#Cross-section.

4 Simulating and analyzing hadron-level events

We are now in place to generate full events and analyze them with Sherpa. For simplicity, we will not include a detector simulation in this exercise. However, Sherpa can be combined e.g. with PGS to simulate detector effects. For details on this procedure, please refer to the online manual, section 4
http://sherpa.hepforge.org/doc/SHERPA-MC-2.2.1.html#PGS-interface.
Sherpa also has a built-in Rivet-interface and it can output events in HepMC format. For more details, please refer to the online manual. Rivet has been installed on your virtual machine, and you may use it to analyze the events generated by Sherpa.

Change back to the original directory and then go to `ToyModel_HadronLevel`. Have a look at the `Run.dat` input file.

In the `(run)` section we have now removed the switches that disabled parton showers and fragmentation. Instead there is a new switch, instructing Sherpa to perform a simple analysis.

Open the `Analysis.dat` input file. It contains instructions for the built-in analysis module.

- `Finder 93 20 -4.5 4.5 0.4 1`
  Construct k_T-jets (kf-code 93) with $D = 0.4$, $p_T > 20$ GeV and $|\eta| < 4.5$.
- `Finder 11 15 -2.5 2.5`
  Reconstruct electrons (kf-code 11) with $p_T > 15$ GeV and $|\eta| < 2.5$.
- `DRMin 11 -11 0.2`
  Require electrons to be separated from each other by $\Delta R > 0.2$.
- `DRMin 11 93 0.4`
  Require electrons to be separated from jets by $\Delta R > 0.4$.

Finally, we analyze the di-jet invariant mass distribution in the range $0 \leq m_{jj} \leq 2000$ on a linear scale with 100 bins:

```
Mass 93 93 0 2000 100 Lin LeptonsJets
```

Run this setup using

```
Sherpa
```

As we have linked the `Process/` and `Results/` directory from the previous run, Sherpa will immediately start generating events.

Once it has finished, plot the results of the analysis using

```
./plot_results.sh
```

and have a look at the invariant mass distributions in `plots.ps`. The different histograms show the changes when going from a pure parton-level simulation to hadron level.

5 Z+j backgrounds at LO and at NLO

We will now proceed to simulate some important Standard-Model backgrounds. Sherpa will run substantially longer than in the previous steps. You may consider doing the following part of the tutorial in parallel with another tutorial or after the workshop.

Change back to the original directory and then go to `Backgrounds_ZJets`. Have a look at the `Run.dat` input file.

In the `(processes)` section you find the following:

```
Process 93 93 -> 11 -11 93{1}
Order (*,2); CKKW sqr(30/E_CMS);
End process;
```

These lines instruct Sherpa to generate the process $pp \to e^+e^-$ with up to one additional light parton. The tag `CKKW` indicates that the various sub-processes are to be merged using the truncated parton shower scheme. `sqr(30/E_CMS)` sets the value of Q_{cut} to 30 GeV.

Run this setup using

```
Sherpa
```

Once Sherpa has finished, plot the results of the analysis using

```
./plot_results.sh
```

and have a look at the invariant mass distributions in `plots.ps`.

If you like, check out the difference between a tree-level prediction of the background and the respective MENLOPS result. Run the MENLOPS setup using

```
Sherpa -f Run.NLO.dat
```

Sherpa will stop with the message

```
 New libraries created. Please compile.
```

In contrast to the previous runs, the matrix-element generator AMEGIC++ was invoked to simulate the MC@NLO **S**-events. AMEGIC++ generates process-specific source code, which must be compiled before the simulation can start. Do so by typing

```
./makelibs
```

After the compilation has finished, run Sherpa again

```
Sherpa -f Run.NLO.dat
```

Once Sherpa has finished computing the NLO cross section and simulating events, plot the results of the analysis again, using

```
./plot_results.sh
```

and have a look at the invariant mass distributions in `plots.ps`. Note that the NLO prediction is smoother because we have generated enhanced weighted events, cf. the `Run.NLO.dat` file.

6 Top backgrounds

Change back to the original directory and then go to `Backgrounds_TTBar`. Have a look at the `Run.dat` input file.

Run the setup using

```
Sherpa
```

Once Sherpa has finished, plot the results of the analysis using

```
./plot_results.sh
```

and have a look at the invariant mass distributions in `plots.ps`.

Now you can devise a strategy to reduce the Standard-Model backgrounds ☺

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.

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[4] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr and B. Fuks, "FeynRules 2.0 - A complete toolbox for tree-level phenomenology" Comput. Phys. Commun. **185** (2014) 2250.

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[6] S. Höche, S. Kuttimalai, S. Schumann and F. Siegert, "Beyond Standard Model calculations with Sherpa" Eur. Phys. J. C **75** (2015) no.3, 135.

[7] S. Ask *et al.*, "From Lagrangians to Events: Computer Tutorial at the MC4BSM-2012 Workshop", arXiv:1209.0297 [hep-ph].

[8] https://sherpa.hepforge.org/doc/SHERPA-MC-2.2.1.html.