# Sherpa BSM Tutorial at the MadGraph school 2013

*(Based on MC4BSM-2012 tutorial, arXiv:1209.0297)*

## Contents



## 1 Getting started

Sherpa has been installed on your virtual machine in the subdirectory `Sherpa`. To begin, set some relevant environment variables by sourcing the configuration file

```
. /home/sluser/Sherpa/env.sh
```

Note that we use a given set of FeynRules output files, which are stored in the subdirectory `FeynRules_Output`. They correspond to the toy model described in Sec. A. You can overwrite these files with your own. However, if you alter the masses of $U$, $E$, $\phi_1$ or $\phi_2$, the particle widths have to be recomputed. Section 5 explains how to do this. You can work through Sec. 5 first, but it is recommended to follow Secs. 2-5 in order, as this will help to understand the input structure of Sherpa.

## 2 Understanding the input structure

Change to the directory `Intro` and open the input file `Run.dat`. The file consists of various sections, which are marked as `(model)`, `(beam)`, `(process)`, etc.

The `(model)` section contains an instruction to use the SHERPA-internal FEYNRULES interface and to flag the particles $E$, $\phi_1$ and $\phi_2$ as unstable.

The `(beam)` section is used to set up the collider type ($pp$) and its cms energy (8 TeV).

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.

The `(me)` section is used to set a scale at which the strong coupling is to be evaluated.

Run the simple example using

```
Sherpa
```

SHERPA will stop with the message

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

followed by some citation info. Now you need to compile the process-specific source code generated by SHERPA using

```
./makelibs
```

After the compilation has finished, run SHERPA again

```
Sherpa
```

The program will now dynamically link the libraries which have just been created and compute a cross section for the process $u\bar{u} \to U\bar{U}$.

If you have LaTeX installed on your VM (it is not installed by default), you can have a look at the Feynman graphs that contribute to this process:

```
./plot_graphs graphs/Amegic
```

## 3 Simulating parton-level events

Change back to the original directory and then go 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` and the YFS soft photon generator by using `ME_QED Off`.

In the `(processes)` section, we instruct SHERPA to generate the following reactions:

- $pp \to U[\to \phi_1 u]\ \ \bar{U}[\to \phi_1 \bar{u}]$
- $pp \to U[\to \phi_2[\to \phi_1\ e^+e^-]\ u]\ \ \bar{U}[\to \phi_1 \bar{u}]$

- $pp \to U[\to \phi_1 u]\;\; \bar{U}[\to \phi_2[\to \phi_1\; e^+e^-]\; \bar{u}]$
- $pp \to U[\to \phi_2[\to \phi_1\; e^+e^-]\; u]\;\; \bar{U}[\to \phi_2[\to \phi_1\; e^+e^-]\; \bar{u}]$

Run this setup using

```
Sherpa
```

Again, Sherpa will stop with the message

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

followed by some citation info. You need to compile the process-specific source code generated by Sherpa using `./makelibs`. After the compilation has finished, run Sherpa again

```
Sherpa BEAM_REMNANTS=0
```

The cross sections will be computed (ca. 3 minutes for each of the 4 processes) and Sherpa will generate 10000 events. Near the end of the output you should see the following message

```
+----------------------------------------------------------+
|                                                          |
|  Total XS is 0.454729 pb +- ( 0.00445874 pb = 0.98 % )   |
|                                                          |
+----------------------------------------------------------+
```

where the precise value of the cross section depends on the mass parameters you have chosen for the $U$, $E$ and $\phi_{1/2}$ fields. This is the total generated cross section, which is to be used when computing event rates (rather than any of the cross sections quoted during the integration step). A detailed explanation why this can be different especially in the context of ME+PS merging can be found in section three of the Sherpa online manual,
http://sherpa.hepforge.org/doc/SHERPA-MC-2.0.beta2.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,
http://sherpa.hepforge.org/doc/SHERPA-MC-2.0.beta2.html#Event-output-formats.
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.

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 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 $\Delta R > 0.4$.

You need to add one more line to the `Trigger` section, which should read

```
Qual NotLepton&!KF(9000006)
```

This will instruct the analysis module to treat the $\phi_1$ particle like missing energy.

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`. Page one shows the changes when going from a pure parton-level simulation to hadron level, while page two has separate analyses of the various sub-processes.

## 5 Computing the partial widths

Change to the directory `Widths` and open the input file `Run.dat`.
The `(processes)` section contains setups for the following decays

- $U \to u\,\phi_1$
- $U \to u\,\phi_2$
- $E \to e^-\phi_1$

- $\phi_2 \to e^- e^+ \phi_1$

Comix is activated in the `(me)` section using `COMIX_ALLOW_BSM 1`.

Let SHERPA compute the widths using

```
Sherpa
```

Update the widths in the file `Particle.dat`. This file is linked from `../FeynRules_Output` and will be used in all toy model setups.

## 6 Z+j backgrounds at LO and at NLO

We will now proceed to simulate some important Standard-Model backgrounds. 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{2}
Order_EW 2; CKKW sqr(30/E_CMS);
End process;
```

These lines instruct SHERPA to generate the process $pp \to e^+e^-$ with up to two additional light partons. 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 $Q_{\rm cut}$ 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
```

Once SHERPA has finished, 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.

## 7 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.

| Notation | Spin | Mass | SU(3) | SU(2) | U(1) |
| --- | --- | --- | --- | --- | --- |
| $\Phi_1$ | 0 | $M_1$ | 1 | 1 | 0 |
| $\Phi_2$ | 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.

## A The reference BSM model used in the tutorials

The tutorial exercises are illustrated with a toy reference BSM model whose particle content is shown in Table 1. The model contains two real scalar fields, $\phi^1$ and $\phi^2$. They are singlets under all SM gauge groups. Their mass terms are[1]:

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

The corresponding mass eigenstates will be denoted by $\Phi_1$ and $\Phi_2$, 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

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

and interact with the new scalars via

$$\mathcal{L}_{\text{Yuk}} = \lambda_1\phi_1\bar{U}P_Ru + \lambda_2\phi_2\bar{U}P_Ru + \lambda_1'\phi_1\bar{E}P_Re + \lambda_2'\phi_2\bar{E}P_Re\,, \tag{A.3}$$

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:

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

so that $\Phi_1$ 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

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

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

$$U \to u\Phi_1\,, \tag{A.6}$$

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

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