Sherpa Tutorial at the MC4BSM-2013 Workshop

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Contents

Note that Sections 1-3 should ideally be completed before the tutorial starts, to avoid spending half an hour with installation during the tutorial. Especially if you want to try running this on a Mac you should have experience with compiling software on the Mac as we do not have enough Mac expertise to provide support for it during the tutorial. It might be a better option to install everything on a Linux workstation into which you then ssh for the tutorial.

1 Requirements

You will need a PC running Linux or a Mac to follow this exercise. Many of the Macs the SHERPA team came across required some special tweaks to guarantee smooth installation. Linux should therefore be the preferred operating system for this exercise.

You should have the GNU autotools installed. They will also come in handy for other applications. Try to locate `libtoolize`, `automake` and `autoconf` on your system. If they are missing, and there is no package manager that provides easy installation, you can download the sources from

- http://ftp.gnu.org/gnu/autoconf/autoconf-2.65.tar.gz
- http://ftp.gnu.org/gnu/automake/automake-1.11.1.tar.gz
- http://ftp.gnu.org/gnu/libtool/libtool-2.2.6b.tar.gz

Follow the installation instructions provided in the tarballs.

Although not mandatory for this exercise, it will be useful to have metapost installed. It will be used to plot the Feynman graphs generated by SHERPA.

To visualize the analysis results, you will need gnuplot or a similar plotting tool. The instructions given here assume that you have gnuplot installed.

2 Installation

There are two methods to install SHERPA on your system

2.1 ... via package download

The SHERPA sources for this exercise are obtained from:

- http://sherpa.hepforge.org/trac/wiki/SherpaDownloads/Sherpa-2.0.beta2

After the package download go to the download directory and follow these steps

```
tar -xzf SHERPA-MC-2.0.beta2.tar.gz
cd SHERPA-MC-2.0.beta2/
./configure --enable-analysis
make -j2 install
```

If successful, you should now find a SHERPA executable in the `bin/` subdirectory. On a Mac with 64 bit system, use `FC='gfortran -m64' ./configure --enable-analysis` instead of the above configure command.

2.2 ... via svn checkout

If you have a subversion client installed on your system, you can check out SHERPA as follows. This will be an easier option if you try to keep your version up-to-date with bugfixes. Note that you *must* have the GNU autotools installed to proceed with this method. Follow these steps

```
svn co http://sherpa.hepforge.org/svn/branches/rel-2-0-beta2
cd rel-2-0-beta2/
autoreconf -i
./configure --enable-analysis
make -j2 install
```

If successful, you should now find a SHERPA executable in the `bin/` subdirectory. On a Mac with 64 bit system, use `FC='gfortran -m64' ./configure --enable-analysis` instead of the above configure command.

2.3 Dealing with problems

If there are problems during the installation process, please send an email to info@sherpa-mc.de or list the issue on our bug tracker. Some advice can also be found in Section 2 - "Getting started" - of the online manual, which is available at http://sherpa.hepforge.org/doc/SHERPA-MC-2.0.beta2.html

3 Testing your SHERPA installation

To guarantee a successful installation of SHERPA, we will try to simulate the production of $W^{\pm}$-boson plus jets final states at the LHC. To make this test quick and simple, we disable features like multi-jet merging, NLO accuracy, and multiple parton interactions on the command line. Follow these steps:

```
cd Examples/V_plus_Jets/LHC_WJets
../../../bin/Sherpa NJET:=0 LJET:=0 MI_HANDLER=None EVENTS=10000
```

The example should take less than 5 minutes to run.
You should see the following output:

```
Welcome to Sherpa, <username>. Initialization of framework underway.
-------------------------------------------------------------------------------
-----------    Event generation run with SHERPA started .......   -----------
-------------------------------------------------------------------------------
```

... lots more following ...

```
+-----------------------------------------------------+
|                                                     |
|  Total XS is 18801.2 pb +- ( 214.6 pb = 1.14 % )    |
|                                                     |
+-----------------------------------------------------+
```

... some more following ...

```
Time: 1m 35s on Wed Apr 17 11:37:26 2013
 (User: 1m 34s, System: 0s, Children User: 0s, Children System: 0s)
```

If this output shows up in your terminal, you have successfully installed SHERPA.

Congratulations!

4 Getting started

The setup is available from

- http://cern.ch/fsiegert/mc4bsm/

Download the tarball `mc4bsm_sherpa.tar.gz` and unpack the setup files using

```
tar -xzf mc4bsm_sherpa.tar.gz
```

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, ϕ_1 or ϕ_2, the particle widths have to be recomputed. Section 8 explains how to do this. You can work through Sec. 8 first, but it is recommended to follow Secs. 5-8 in order, as this will help to understand the input structure of Sherpa.

For the remainder of this exercise we will assume that Sherpa was installed into a directory called `<sherpa_prefix>/`. You should be able to locate the executeable in the subdirectory `<sherpa_prefix>/bin/`, cf. the pre-workshop instructions.

5 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, ϕ_1 and ϕ_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_prefix>/bin/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_prefix>/bin/Sherpa
```

The program will now dynamically link the libraries which have just been created and compute a cross section for the process $u\bar{u} \to U\bar{U}$.
Have a look at the Feynman graphs that contribute to this process

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

6 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_prefix>/bin/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_prefix>/bin/Sherpa
```

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 0.444465 pb +- ( 0.00429378 pb = 0.96 % )  |
|                                                         |
+---------------------------------------------------------+
```

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.

7 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 $\Delta R > 0.4$.

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_prefix>/bin/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.

8 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_prefix>/bin/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.

9 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{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_{cut} to 30 GeV.

Run this setup using

```
<sherpa_prefix>/bin/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_prefix>/bin/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.

10 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_prefix>/bin/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)
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.

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, ϕ^1 and ϕ^2. They are singlets under all SM gauge groups. Their mass terms are[1]:

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

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

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

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 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

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

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.