MC generators and future challenges
SHERPA Tutorial: $t\bar{t}W$ production

1 Introduction

This worksheet deals with $t\bar{t}W$ production and aims at exemplifying the following features of Sherpa+NLO:

- Flexibility of Sherpa+NLO beyond the typical V+jets examples
- Production of massive coloured particles at NLO
- NLO+PS matching for massive particles
- Factorised handling of the decays of massive particles
- Spin correlations and simple offshell-kinematics effects in the decay treatment

Due to time constraints, we are going to run all of this without non-perturbative effects like hadronisation, hadron decays and multiple parton interactions. Of course, it would be simple to enable these with the appropriate switches using otherwise identical setups.
SHERPA and the loop generators are installed in the central workshop directory an afs. To set the paths, log in to lxplus and execute

```
source /afs/cern.ch/project/theory/LPCC_MC_Workshop/tutorial2/env.sh
```

All of the following instructions should be run in one working directory which you copy from the tutorial examples:

```
cp -r /afs/cern.ch/project/theory/LPCC_MC_Workshop/tutorial2/setups/ttW ttw-sherpa
cd ttw-sherpa
```

Before starting out with a really simple setup, we suggest that in the background (e.g. on a separate lxplus shell) you already start the preparation run of a more complicated setup to make sure it's available by the time we want to use it later. For that, please refer to the instructions in Section 4.1.

2 Getting started: The $t\bar{t}W$ setup

The example run card Run.dat contains three sections: The run section with the parameter setup, the processes section with the definition of the hard scattering process, and the analysis section.

2.1 Run section

In the run section, there are some steering parameters, more of which are also documented in the Sherpa manual:

```
EVENTS=10000 # number of events to generate
ANALYSIS=Rivet; # enable direct Rivet analysis
FRAGMENTATION=Off # disable hadronisation
MI_HANDLER=None # disable multiple parton interactions

BEAM_1  2212; BEAM_ENERGY_1 4000; # collider setup
BEAM_2  2212; BEAM_ENERGY_2 4000; # collider setup
```

Next, some tags are being defined, which can then be used everywhere in the run card to simplify switching between different setups later:

```
LJET:=3; # maximal final-state multiplicity at NLO accuracy
SCF:=1.0; QF:=1.0; # scale variation factors
LGEN:=OpenLoops; # loop matrix element generator
```

Next, we add the chosen loop ME generator to the list, and set the factorisation, renormalisation and resummation scales. For the scales, we use the automatic scales determined by the Sherpa "METS" scale setter as a central value and allow them to be varied by the factors defined above. Note that all scale definitions have to be given as the squared value, also in the factors.

```
ME_SIGNAL_GENERATOR=Comix Amegic LGEN;
SCALES=METS{SCF*MU_F2}{SCF*MU_R2}{QF*MU_Q2};
```

The last relevant part of the run section here deals with the setup of the decays of particles produced in the hard scattering process, i.e. the top quarks and W-boson here.

```
HARD_DECAYS=On
STABLE[6]=0
STABLE[24]=0
WIDTH[6]=0
WIDTH[24]=0
HDH_NO_DECAY={24,2,-1}|{24,4,-3}|{24,16,-15}
HARD_SPIN_CORRELATIONS=1
HARD_MASS_SMEARING=0
```

At first, the unstable particles have to be declared as such using the `STABLE[kfcode]` parameter. Also, their widths have to be set to zero for the hard scattering process to be able to generate them in a gauge invariant way. The `HDH_NO_DECAY` option allows to disable the given list of decay channels (using PDG IDs in the notation), in this example only the leptonic decay modes of the W are left enabled. With `HARD_SPIN_CORRELATIONS` it becomes possible to enable or disable the preservation of spin correlations across the top and W decays. (Disclaimer: The spin correlation algorithm has not yet been fully validated in this setup, so we do not guarantee the results to be identical to the final Sherpa 2.0 release.) Lastly, the `HARD_MASS_SMEARING` parameter can be used to switch on an a-posteriori Breit-Wigner smearing to get simple offshell-kinematics effects in the decay treatment.

2.2 The processes section

In the processes section, the hard scattering process gets defined:

```
Process 93 93 -> 6 -6 24;
NLO_QCD_Mode MC@NLO {LJET};
ME_Generator Amegic {LJET};
Loop_Generator LGEN;
Order_EW 1;
End process;
```

The first line specifies initial and final state particles using PDG codes. The next three lines switch on the MC@NLO simulation for this process. Finally, the `Order_EW` switch restricts the process simulation to diagrams with only one electro-weak coupling.

2.3 The analysis section

We have set up a simple Rivet analysis for a few typical distributions in this process. It is enabled by the `ANALYSIS=Rivet` switch and the corresponding analysis section:

```
(analysis){
  BEGIN_RIVET {
  -a MC_TTW
  } END_RIVET
}(analysis)
```

3 Running at LO+PS

Let's start out with a very simple example and generate events for the above described $t\bar{t}W$ at leading-order accuracy including a parton shower and decays of the top quarks and W-boson. The run card has already been set up such that it's simple to switch between MC@NLO (`LJET:=3`) and LO+PS (`LJET:=0`). Go ahead and start the first run with

```
Sherpa LJET:=0
```

It should first integrate the process (which should only take a few minutes in this simple case and is stored for future runs) and will then go on to generate 10000 events and analyse them with the Rivet analysis.
The histograms are written into a file Analysis-0-1.0-1.0.aida. The plots are created and compiled into a neat html-page by running the command

```
rivet-mkhtml Analysis-0-1.0-1.0.aida
```

Several aida-files can be plotted in the same histogram. This creates a directory called 'plots' containing an index.html, which can be viewed with any web browser, e.g.

```
firefox plots/index.html
```

You can look at 10 events as on-screen output if you specify `EVENTS=10 OUTPUT=3`.
Now you could go ahead and change some of the switches above to see what their influence on the plots are, at least to the extent possible with the limited statistics you can generate in the given time. Some switches (on the command line) you could try are:

- `HARD_SPIN_CORRELATIONS=0` to disable spin correlations in the decays
- `HARD_MASS_SMEARING=1` for a Breit-Wigner shape in the decay kinematics

4 NLO+PS for $t\bar{t}W$

4.1 Preparations

The following steps are necessary to compile process libraries and perform the phase space integrations for a $t\bar{t}W$ NLO+PS run in your `ttw-sherpa` working directory.

```
$ Sherpa
  [ ... will write out process specific library code ... ]
  New libraries created. Please compile.
$ ./makelibs
  [ ... will compile the libraries ... ]
$ Sherpa
  [ ... will start the phase space integrations ... ]
  [ ... this part will take a bit longer ... ]
```

4.2 Further studies

Hopefully, the run you started in Section 4.1 should already/soon be finished. You can check the results you got from the run of 10000 events by comparing them to the results you got from the leading-order setup above:

```
rivet-mkhtml Analysis-0-1.0-1.0.aida:Title=LO+PS Analysis-3-1.0-1.0.aida:Title=NLO+PS
```

Obviously, for a good comparison you would need to generate more events (and possibly unweighted events, including hadronisation, multiple parton interactions, ...), which would take too long for this tutorial, but works in the same spirit as the rest of this tutorial