From Lagrangians to Events: Computer Tutorial at the MC4BSM-2012 Workshop

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Abstract: This is a written account of the computer tutorial offered at the Sixth MC4BSM workshop at Cornell University, March 22-24, 2012. The tools covered during the tutorial include: FeynRules, LanHEP, MadGraph, CalcHEP, Pythia 8, Herwig++, and Sherpa. In the tutorial, we specify a simple extension of the Standard Model, at the level of a Lagrangian. The software tools are then used to automatically generate a set of Feynman rules, compute the invariant matrix element for a sample process, and generate both parton-level and fully hadronized/showered Monte Carlo event samples. The tutorial is designed to be self-paced, and detailed instructions for all steps are included in this write-up. Installation instructions for each tool on a variety of popular platforms are also provided.
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1 Introduction

With the advent of the LHC, the field of particle physics has entered an exciting new era. A direct exploration of the TeV energy scale has finally begun. A large number of extensions of the Standard Model (SM), or “Beyond-the-Standard” Models (BSMs) for short, have been proposed over the years, and many of them can be probed by the LHC experiments. To make such tests possible, theoretical predictions of each model must be computed at a level that allows direct comparison to data. Monte Carlo (MC) generators are the basic tool for obtaining such predictions.

Any BSM consistent with basic postulates of quantum mechanics and special relativity is a quantum field theory (QFT) defined by specifying its field content and the interaction Lagrangian $\mathcal{L}$. As long as all interactions can be treated perturbatively, the fully differential cross section for any scattering process of interest can be computed by following the standard procedure of QFT perturbation theory. Namely, starting from $\mathcal{L}$, one derives a set of Feynman rules, draws all possible Feynman diagrams for the process of interest, writes down the invariant matrix element $M$, squares it, and multiplies it by the phase space weight. Since this procedure is completely unambiguous, it should be possible to teach a computer to perform it automatically. A set of automated tools to achieve this task has recently been developed, see Fig. 1. FeynRules [1] and LanHEP [2] perform the derivation of a complete set of Feynman rules from a given Lagrangian. The output of these programs can then be communicated to an automated matrix element calculator such as MadGraph [3] or CalcHEP [4] (or its sister package CompHEP [5, 6]) which generates $|M|^2$ for any process specified by the user. This object in turns serves as an input to the Monte Carlo simulation of the process, first at the parton level with parton-level Monte Carlo event generators like MadGraph or CalcHEP (CompHEP). They create a set of “events”, where each event is a record containing the identity and four-momentum of each of the initial- and final-state particles in the hard scattering process. The events are distributed in momenta, helicities, etc. according to the invariant matrix element $|M|^2$ computed in the previous step. In effect, the MC generator performs a pseudo-experiment: the generated set of events is just a particular statistical realization of the distributions.
| 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.

predicted by the theory for the process of interest. The produced parton-level events are in turn handed to a general purpose event generator such as \textsc{Pythia} [7] or \textsc{Herwig} [8, 9], which creates complete events, including the effects of fragmentation and hadronization of colored particles, initial and final state radiation via parton showers, effects from the underlying event, decays of unstable resonances, etc. The communication between the two classes of generators (parton-level and general purpose) is done following a universally accepted “Les Houches Accord” (LHA) format [10, 11].

The program of the Sixth MC4BSM workshop held at Cornell University in March 2012 centered around hands-on computer tutorials [12] illustrating the tools depicted in Fig. 1. The starting point of the tutorials was a simple toy theory model described in Section 2. Its Feynman rules can then be automatically derived via either \textsc{FeynRules} (Section 3) or \textsc{LanHEP} (Section 4), the end product being the input files necessary to define the model in the parton-level event generators \textsc{MadGraph} and \textsc{CalcHEP}. The next step is to produce parton-level events, which is done in the tutorials covered in Sections 5 and 6, respectively. The parton-level events are then fed into \textsc{Pythia 8} (Section 7) or \textsc{Herwig++} (Section 8). Finally, Section 9 contains a special tutorial on \textsc{Sherpa} [13], which provides an alternative path combining all of the above steps. In principle, each tutorial exercise is self-contained and independent of the others. Typically, each tutorial has two parts: in the first part (the pre-workshop exercise) students download and install the software and perform some simple tests to make sure it runs properly, while the second part deals with the actual physics simulations.

2 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\(^1\):

\[
\mathcal{L}_{\text{s.m.}} = -\frac{m_1^2}{2} \phi_1^2 - \frac{m_2^2}{2} \phi_2^2 - m_{12} \phi_1 \phi_2.
\]  

(2.1)

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 \( M_1 < M_2 \).

\(^1\)All Lagrangian parameters, here and below, are assumed to be real.
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

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

and interact with the new scalars via

$$\mathcal{L}_{\text{Yuk}} = \lambda_1 \phi_1 \bar{U} P_R u + \lambda_2 \phi_2 \bar{U} P_R u + \lambda'_1 \phi_1 \bar{E} P_R e + \lambda'_2 \phi_2 \bar{E} P_R e,$$

where $u$ and $e$ are the SM up-quark and electron fields. Note that there is a $Z_2$ 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 $Z_2$ also forbids $U - u$ and $E - e$ mixing via Yukawa couplings with the SM Higgs.

We assume the following ordering of masses:

$$M_U > M_2 > M_L > M_1,$$

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

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

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

$$U \to u \Phi_1,$$

$$U \to u \Phi_2, \quad \Phi_2 \to e E, \quad E \to e \Phi_1.$$

3 **FeynRules** tutorial

The *FeynRules* tutorial consists of two steps: a pre-workshop exercise described in Section 3.1, and the on-site exercise described in Section 3.2

3.1 **Installation instructions**

The aim of this session is to make the user familiar with the basics of *FeynRules* using the example of the Standard Model included in the distribution. *FeynRules* can be downloaded from [http://feynrules.irmp.ucl.ac.be](http://feynrules.irmp.ucl.ac.be). You need to have Mathematica installed on your machine in order to run *FeynRules*. Simply download the package and untar it.

Next, you can have a look at the SM implementation, contained in the directory `/feynrules-current/models/SM/`. This folder contains various files, but in this introductory session we will only look at two of them:

1. *SM.fr*: the model file (a text file) containing the implementation of the SM in *FeynRules*.
2. *SM.nb*: a Mathematica notebook, showing how to load and run the model to obtain the Feynman rules.

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3.1.1 The \texttt{FeynRules} model file

Open the model file for the SM, \texttt{SM.fr}, in a text editor. In the following we give a very brief account on the general structure of a \texttt{FeynRules} model file. During the tutorial, you will be given the opportunity to write your own \texttt{FeynRules} model file, and we therefore limit ourselves at this stage to describe the generic features.

A generic \texttt{FeynRules} model file contains four parts:

1. A list called $\texttt{M$GaugeGroups}$ containing the definitions of all the gauge groups of the model.
2. A list called $\texttt{M$Parameters}$ containing the definitions of all the parameters of the model.
3. A list called $\texttt{M$ClassesDeclarations}$ containing the definitions of all the fields of the model. Note that the fields are grouped into classes of particles carrying the same quantum numbers.
4. The Lagrangian of the model, written in Mathematica form.

3.1.2 The sample notebook

Next, open the notebook \texttt{SM.nb}. The first few lines of the notebook show how to load \texttt{FeynRules} into Mathematica,

\begin{verbatim}
$FeynRulesPath = SetDirectory["< address of the package >"]
<< FeynRules'
SetDirectory[$FeynRulesPath <> "/Models/SM"];
\end{verbatim}

The first line sets the path to the \texttt{FeynRules} main directory. Note that \texttt{< address of the package >} should be replaced by the path of the \texttt{FeynRules} main directory on your computer. For example, if the \texttt{FeynRules} main directory is in your home folder, then the first line should read

\begin{verbatim}
$FeynRulesPath = SetDirectory["~/feynrules-current"]
\end{verbatim}

The second line loads the \texttt{FeynRules} package. If successful, an output is printed on the screen. The third line changes the path to the subfolder \texttt{Models/SM} that contains the SM implementation.

After \texttt{FeynRules} has been successfully loaded into Mathematica, the SM implementation can be loaded by issuing the command

\begin{verbatim}
LoadModel["SM.fr"]
\end{verbatim}

The next command is optional, and loads some additional files that put the masses of the first two generations of fermions to zero, and restricts the CKM matrix to be diagonal. As this step is optional, we will not describe it any further.
The first section of the notebook, *The SM Lagrangian*, shows the Lagrangian that is implemented in SM.fr. Note that the SM implementation of FeynRules is available in both Feynman and unitary gauge. The boolean variable FeynmanGauge allows to switch between the two gauges. The second section shows how one can use some built-in functions to perform some basic checks on the Lagrangian, e.g., to check if the Lagrangian is hermitian. The last two sections illustrate how to compute the Feynman rules of the model with FeynRules, and how to use the interfaces to the Feynman diagram generators.

### 3.2 On-site tutorial

The aim of this tutorial is to implement a simple extension of the SM into FeynRules. The model itself is described in Section 2. In the following we give detailed instructions of how to implement this model into FeynRules and how to obtain the corresponding model files for CalcHEP, MadGraph 5 and Sherpa.

#### 3.2.1 Preparation of the model file

As the model we are going to implement is a simple extension of the SM, it is not necessary to start from scratch, but we can use the implementation of the SM included in the folder /Models/SM. We therefore start by making a copy of this folder, in order to keep a clean version of the SM. To do so, change directory to the Models subdirectory and make a copy of the SM folder, before going into the new directory

```bash
cd Models
cp -r SM MC4BSM
cd MC4BSM
```

Even though the implementation is based on the model file SM.fr for the Standard Model, the SM sector of the model will be implemented into a separate file that will simply be loaded on top of SM.fr. We therefore start by opening a blank text file called MC4BSM.fr. You can start by personalizing the model file by including a name for you model, the name of the author, etc.,

```plaintext
M$ModelName = "MC4BSM_2012";

M$Information = {Authors -> "C. Duhr",
                Version -> "1.0",
                Date -> "27. 02. 2012",
                Institutions -> "ETH Zurich",
                Emails -> "duhrc@itp.phys.ethz.ch"};
```

Note that his information is purely optional and could be omitted.

#### 3.2.2 Implementation of the new parameters

We start by implementing the new parameters. The model we are considering depends on 9 new parameters, which we assume to be real in the following. FeynRules distinguishes
between two types of parameters, the so-called external parameters given as numerical inputs and the internal parameters, related to other external and/or internal parameters via algebraic expressions. All the parameters of the model, both external and internal, are given in the FEYNRULES model file as a list named $\texttt{M$Parameters}$. Note that if an internal parameter $x$ depends on some other parameter $y$, then $y$ should appear in $\texttt{M$Parameters}$ before the internal parameter $x$.

The new external parameters of the model are

- 5 mass parameters: $m_1$, $m_2$, $m_{12}$, $M_U$, $M_E$.
- 4 coupling constants: $\lambda_1$, $\lambda_2$, $\lambda_1'$, $\lambda_2'$.

Note however that there is a difference between the mass parameters in the scalar and fermionic sectors: while the masses in fermionic sector are physical masses, the mass matrix in the scalar sector is not diagonal. For this reason, we will not discuss in the following the fermion masses $M_U$ and $M_E$, as they will be defined together with the particles rather than as parameters of the model.

Let us now turn to the definition of the mass parameters in the scalar sector. The masses $m_1$, $m_2$ and $m_{12}$ will be denoted in the FEYNRULES model file by $\texttt{MM1}$, $\texttt{MM2}$ and $\texttt{MM12}$. In the following we only show how to implement $\texttt{MM1}$, all other cases being similar. $\texttt{MM1}$ corresponds to the following entry in the list $\texttt{M$Parameters}$,

\[
\texttt{M$Parameters} = \begin{array}{l}
\ldots \\
\texttt{MM1} == \{ \\
\quad \text{ParameterType} \rightarrow \text{External}, \\
\quad \text{Value} \rightarrow 200 \\
\ldots \\
\}\end{array}
\]

The first option tags $\texttt{MM1}$ as an external parameter, while the second option assign a value of 200GeV to $m_1$. We stress that this numerical value can be changed later on in the matrix element generators.

The masses in the scalar sector are not the physical masses, because the mass matrix is not diagonal. In order to obtain the physical masses, we need to diagonalize the mass matrix

\[
\begin{pmatrix}
m_1^2 & m_{12}^2 \\
m_{12}^2 & m_2^2
\end{pmatrix}.
\]

In the following, we denote the eigenvalues by $\texttt{MPe1}$ and $\texttt{MPe2}$. In addition, we need to introduce a mixing angle $\theta$ (th) relating the fields $\phi_i$ to the mass eigenstates $\Phi_i$ by,

\[
\begin{pmatrix}
\phi_1 \\
\phi_2
\end{pmatrix} = \begin{pmatrix}
- \sin \theta & \cos \theta \\
\cos \theta & \sin \theta
\end{pmatrix}
\begin{pmatrix}
\Phi_1 \\
\Phi_2
\end{pmatrix}.
\]
As in this case the mass matrix is only two-dimensional, we can compute the eigenvalues and the mixing angle analytically, and simply implement the analytical formulas into FeynRules. The implementation follows exactly the same lines as for the masses $m_1$, $m_2$, $m_{12}$, with the only differences that

1. the ParameterType is Internal (as these parameters are dependent on the external mass parameters),

2. the Value is given by an analytical expression (in Mathematica syntax).

Next we turn to the implementation of the new coupling constants, which we will call $\lambda_1$, $\lambda_{21}$, $\lambda_{1p}$, $\lambda_{2p}$. They are all external parameters, and thus the implementation follows exactly the same lines as the implementation of the mass parameters, with only one modification: some matrix element generators, like for example MadGraph, keep track of the types of couplings that enter a process. This allows for example to generate a process by only taking into account QCD-type vertices, and to neglect all QED-type vertices. For this reason, it is mandatory to tell the matrix element generator how the new coupling constants should be counted. As in this case we are dealing with new classes of couplings which are a priori independent of QCD or QED interactions, we simply assign a new tag, called interaction order, to the coupling via the option

$$\text{InteractionOrder} \rightarrow \{\text{NP}, 1\}$$

The name of the tag (NP for “new physics” in this case) can be chosen freely. The above option instructs the matrix element generator to count one unit of “NP” for each new coupling.

### 3.2.3 Implementation of the fields

In this section we discuss the implementation of the new fields. The implementation is similar to the implementation of the parameters, i.e., all the fields are entries of a list called M$\$ClassesDescription. In Tab. 2 we show the names of the fields used in the implementation$^2$.

| $U$ | $E$ | $\phi_1$ | $\phi_2$ | $\Phi_1$ | $\Phi_2$ |
|-----|-----|---------|---------|---------|---------|
| $uv$ | $ev$ | $p_{i1}$ | $p_{i2}$ | $p_1$ | $p_2$ |

**Table 2.** Symbols used for the fields in the FeynRules implementation.

We illustrate the implementation of a new field on the example of the particle $U$ ($uv$). The definition of the particle corresponds to an entry in M$\$ClassesDescription of the following form

$^2$Note that the symbol u, e and phi are already in use in the SM implementation. We also avoid using simply uppercase letters, as some matrix element generators are case insensitive.
M$ClassesDescription = {
  ...
  F[10] == {
    ClassName -> uv,
    SelfConjugate -> False,
    Indices -> {Index[Colour]},
    QuantumNumbers -> {Y -> 2/3, Q -> 2/3},
    Mass -> {Muv, 500},
    Width -> {Wuv, 1}
  },
  ...
}

The meaning of this definition is as follows: each particle class has a name of the form $X[i]$, where $X$ is related to the spin of the field (See Tab. 3), and $i$ is an integer that labels the classes. Note that $i$ can be chosen freely, as long as there is no name clash with an already existing class (in this case, there could be a name clash with the SM particles already defined in SM.fr). Each class has a series of options

1. **ClassName**: the symbol by which the particle will be represented in the Lagrangian.

2. **SelfConjugate**: a boolean variable, indicating whether the particle has an antiparticle (False) or not (True). If the field is not self-conjugate, a symbol for the antiparticle is automatically defined by appending “bar” to the name of the particle. In the above example the antiparticle associated to $uv$ will be denoted by $uvbar$. Note that in the case of fermions the symbol for the antiparticle refers to the quantity $\bar{U}$ rather than $U^\dagger$.

3. **Indices**: All indices carried by the field. The available types of indices from the SM implementation are
   - **Generation**: fermion flavor index ranging from 1 to 3,
   - **Colour**: fundamental color index ranging from 1 to 3,
   - **Gluon**: adjoint color index ranging from 1 to 8,
   - **SU2W**: adjoint $SU(2)_L$ index ranging from 1 to 3.

4. **QuantumNumbers**: a list of all $U(1)$ charges carried by the field. In the SM implementation the following $U(1)$ charges are already defined
   - **Y**: weak hypercharge,
   - **Q**: electric charge.

5. **Mass**: the mass of the particle. It is a list of two elements, the first being the symbol used to represent the mass, and the second its value (in GeV). If the value of the mass
is obtained from some analytic expression defined as an internal parameter with the same symbol (as is the case for example in the scalar sector of the model), the value is set to Internal.

6. **Width**: the width of the particle. The definition is similar to Mass. Note that as we do not yet know the widths of the new particles, we simply set it for now to 1GeV, and will determine its exact value later using one of the matrix element generators.

The implementation of the other mass eigenstates (ev, p1, p2) is similar, so we do not discuss it here.

| Spin | 0   | 1/2 | 1   | 2   | ghost |
|------|-----|-----|-----|-----|-------|
| Symbol | S   | F   | V   | T   | U     |

Table 3. Available particle classes in FeynRules.

Let us comment on the implementation of the interaction eigenstates \( \phi_i \). Indeed, while the matrix element generators work exclusively at the level of the mass eigenstates, the interaction eigenstates are in general useful to write the Lagrangian in a compact form. It is therefore useful to define also the fields for the interaction eigenstates \( \phi_i \). The definition of these fields is similar to the mass eigenstates, *e.g.*, 

\[
S[10] \equiv \{
\text{ClassName} \rightarrow \text{pi1},
\text{SelfConjugate} \rightarrow \text{True},
\text{Indices} \rightarrow \{\},
\text{Unphysical} \rightarrow \text{True},
\text{Definitions} \rightarrow \{\text{pi1} \rightarrow -\sin[\text{th}] \text{p1} + \cos[\text{th}] \text{p2}\}
\}
\]

First, note that the Mass and Width options are omitted\(^3\), as these fields are not mass eigenstates. This last fact is made explicit by the option

\[
\text{Unphysical} \rightarrow \text{True},
\]

which instruct FeynRules not to output this field to a matrix element generator. Finally, the relation of the field \( \text{pi1} \) to the mass eigenstates is simply given as a Mathematica replacement rule in the Definitions option.

### 3.2.4 Implementation of the Lagrangian

The definitions in the model file being complete, we now turn to the implementation of the Lagrangian. This can be done either in the model file, or directly in a Mathematica notebook. Here we use the latter approach, and we start by opening a new notebook and load the FeynRules package (see the pre-installation instructions). Next we have to load the model files, both for the SM and for the new sector,

\(^3\)The QuantumNumbers option is also omitted, but for the simple reason that the fields \( \phi_i \) do not carry any \( U(1) \) charges.
\text{LoadModel}["SM.fr", "MC4BSM.fr"]

Note that the new model file should be loaded after SM.fr. Furthermore, we also load two additional files, which restrict the first two fermion generations to be massless and the CKM matrix to be diagonal,

\text{LoadRestriction}["DiagonalCKM.rst", "Massless.rst"]

The new Lagrangian consists of three parts,

\[ \mathcal{L} = \mathcal{L}_{\text{scalar,kin}} + \mathcal{L}_{\text{fermion,kin}} + \mathcal{L}_{\text{Yuk}}. \] (3.3)

The kinetic terms for the new scalars can easily be implemented by using the symbols for the gauge eigenstates and the mass parameters defined in the model file, as well as the symbol for the space-time derivative \( \partial_\mu \) in FEYNRULES, \text{del}[\ldots, \mu]. As an example, we have

\[ \frac{1}{2} \partial_\mu \phi_1 + \partial^\mu \phi_1 - \frac{1}{2} m_1^2 \phi_1^2 \]
\[ \frac{1}{2} \text{del}[p1, \mu] \text{del}[p1, \mu] - \frac{1}{2} MM1^2 p1^2 \]

The kinetic terms for the fermions can be implemented in a similar way. However, as the fermions are charged under the SM gauge group, we have to use the covariant derivative \( \text{D}_\mu \) rather than the space-time derivative \text{del}. Furthermore, we have to use a “.” instead of an ordinary multiplication in order to take the non-commuting nature of the fermions into account. As an example, we have

\[ i \bar{U} \gamma^\mu D_\mu U - M_U \bar{U} U \]
\[ \text{I uvbar.Ga}[\mu].\text{DC}[uv, \mu] - Muv uvbar.uv \]

where \text{Ga}[\mu] is the FEYNRULES symbol for the Dirac matrix \( \gamma^\mu \). Finally, the Yukawa interactions can be implemented in the same way as the kinetic terms for the fermions, e.g.,

\[ \lambda_1 \bar{\phi}_1 \bar{U} P_+ u \]
\[ \text{lam1 pi1 uvbar.ProjP.u} \]

where \( u \) denotes the \( u \) quark field defined in SM.fr and \text{ProjP} denotes the right chiral projector (the left projector is denoted by \text{ProjM}). Note that FEYNRULES contains a function \text{HC[ ]} which allows to obtain the hermitian conjugate of an expression in an automated way.

3.2.5 Computing the Feynman rules and running the interfaces

Our model implementation is now complete, and so we can compute the Feynman rules. The Feynman rules of the new sector can be obtained by issuing the command

\text{FeynmanRules}[ LNew ]

where \( L\text{New} \) is the name of the variable that contains the new Lagrangian.

The Feynman rules can be written to file in a format suitable to various matrix element generators by using the FEYNRULES interfaces. In this tutorial, we will use the interfaces to CALCHEP, MADGRAPH 5 and SHERPA, which can be called via
WriteCHOutput[ LSM + LNew ];
WriteUFO[ LSM + LNew ];
WriteSHOutput[ LSM + LNew ];

where LSM is the SM Lagrangian implemented in SM.fr. Note that the SM implementation is available in both Feynman gauge and unitary gauge. A boolean variable FeynmanGauge allows to switch between both gauges. While CalcHEP and MadGraph 5 support both gauges, Sherpa only supports unitary gauge, and the FeynmanGauge variable should correspondingly be set to False.

4 LANHEP tutorial

LANHEP is a program which allows to create input model files for the programs CompHEP [14] or CalcHEP [15] from a Lagrangian provided by the user. This program is as easy as LaTeX. We define the symmetries, the particles and then write down a Lagrangian, just as we would write them in a paper. Then we compile the write-up and obtain CompHEP- or CalcHEP-specific model files for further collider studies. In short, if you can write down a Lagrangian, and if you have enough knowledge of LaTeX, then your skills are probably enough to use LANHEP as well.

An excellent reference for beginners is the LANHEP manual [16]. Here we will demonstrate how to use LANHEP with the specific example (see Section 2) provided for the MC4BSM 2012 workshop\(^4\). First let us discuss how to install LANHEP.

4.1 Installation

Installation is never an easy job, especially when there are several choices for the operating system. But if you have a working C-compiler in your operating system, there should be no problem.

1 Linux with gcc.

2 OS/X: to use gcc, you need to install Xcode in Apple Appstore. But to use Monte Carlo simulations, you will also need a fortran compiler. Free fortran compilers are available from these sites [18, 19].\(^5\)

3 Windows: we recommend that you use a virtual machine\(^6\) to install Linux under the Windows system or have a dual boot with a Linux partition. Most Monte Carlo simulations are too complicated to run under Cygwin.

The detailed installation instructions are well explained on the LANHEP webpage [17]. Here we will briefly recap the procedures based on the file, “lanhep315.tar” which is the current version at the time of this writing.

\(^4\)MC4BSM 2012 provides a nice homepage [12] for all tutorials.

\(^5\)Starting from Mountain Lion, in Xcode, you need to install “Command Line Tools” which you can find in “Xcode/Preferences/Downloads”. The current version coming from Xcode is gcc 4.2, thus we recommend that you match your versions of gcc, g++ and gcov with the version of gfortran that you download from a third party.

\(^6\)There is a free virtual machine software called VirtualBox [20].
1. Download the LanHEP program from the LanHEP webpage [17].

2. Make a proper directory for the LanHEP installation. For example

   \texttt{mkdir $HOME/MC4BSM}

3. Move the downloaded file to the directory that you just created:

   a. Let’s suppose that you made an MC4BSM directory under your $HOME directory, and you downloaded a “lhep315.tar” file in the “$HOME/Downloads” directory, then you can move the file into your MC4BSM folder by typing

      \texttt{mv $HOME/Downloads/lhep315.tar $HOME/MC4BSM/}

   b. Unzip “lhep315.tar” file by typing

      \texttt{tar -xvf lhep315.tar}

3. Go to the “lanhep315” directory and read the “README” file.

4. Compile LanHEP by typing

   \texttt{make}

4.2 Warm-Up exercise

Before we begin the real MC4BSM exercise, it would be good to start with a very simple example, “QED”, which is the first example in the LanHEP manual version 3.0 [2]. You can find its model files in the “mdl” directory as “qed.mdl”. The contents of this file are the following

\begin{verbatim}
model qed/1.
parameter ee = 0.3133: 'Electric charge'.
vector A/A:photon.
let F^mu^nu=deriv^mu*A^nu-deriv^nu*A^mu.
spinor e1:E1:(electron, mass me=0.000511).
lterm ee*E1*gamma*A*e1.
\end{verbatim}

Without looking at the manual, we can easily guess that there are two fields, an electron (e1) and a photon (A). In this particular model file, there are missing terms from the Lagrangian (if you compare it to the text in the manual). You can modify this model file by writing down the missing terms. Thus a complete simple “QED” model file will look like

\begin{verbatim}
model qed/1.
parameter ee=0.3133: 'elementary electric charge'.
spinor e1/E1:(electron, mass me=0.000511).
vector A/A:(photon).
let F^mu^nu=deriv^mu*A^nu-deriv^nu*A^mu.
lterm -1/4*(F^mu^nu)**2 - 1/2*(deriv^mu*A^mu)**2.
lterm E1*(i*gamma*deriv+me)*e1.
lterm ee*E1*gamma*A*e1.
\end{verbatim}

At this stage we can ask some simple questions:
1. What is the relation between $e_1$ and $E_1$?

2. How can we use a covariant derivative instead of splitting the Lagrangian into pieces?\(^7\)

3. What is the unit of mass in \textsc{LanHEP}?

In order to create the model files for the actual \textsc{CompHEP} or \textsc{CalcHEP} program, we need to compile this model file. It would be better to make a separate directory for the "compiled" model. Let's make the directory inside your \textsc{LanHEP} directory (if you are in the mdl directory, go one level up). For example,

```
mkdir QED
```

Now compile the “qed.mdl” file by using the “lhep” command as follows\(^8\)

```
./lhep -OutDir QED mdl/qed.mdl -CalcHEP
```

You will get this “warning” message

```
File mdl/qed.mdl processed, 0 sec.
Warning: property 'pdg' is not defined for particle 'e1'
```

"PDG" is a number which is defined for each particle according to the Particle Data Group for various Monte Carlo simulators. For example the PDG number for an electron is 11. Our particle “e1" defined in the “qed.mdl” file was not assigned a PDG number. There are two ways to resolve this warning. If you open the “calchep.rc” file in the mdl directory, you will see the following contents.

```
prtcformat fullname: 'Full Name ',
    name: ' P ', aname: ' aP ', pdg: ' number ',
    spin2, mass, width, color, aux, texname: ' \LaTeX(A) ',
atexname: ' LateX(A+) '.
prtcproperty pdg: (A=22, Z=23, 'W+'=24, G=21,
    d=1, u=2, s=3, c=4, b=5, t=6,
    ne=12, nm=14, nl=16,
    e=11, m=13, l=15,
    ~ne=1000012, ~nm=1000014, ~nl=1000016,
    ~e1=1000011, ~m1=1000013, ~l1=1000015,
    ~e2=2000011, ~m2=2000013, ~l2=2000015,
    ~el=1000011, ~ml=1000013,
    ~eR=2000011, ~mR=2000013,
    ~u1=1000002, ~c1=1000004, ~t1=1000006,
    ~u2=2000002, ~c2=2000004, ~t2=2000006,
    ~ul=1000002, ~cl=1000004,
    ~uR=2000002, ~cR=2000004,
```

\(^7\)See Section 3.4 in the manual 3.0 [2].

\(^8\)If you type "./lhep" without any options, you will see the available choices.
Thus, we can edit this file directly to include a PDG number (11) for our field ‘e1’, or we can use a function “prtcproperty pdg” during our write-up of the Lagrangian.

4.2.1 Output

After compiling the model file “qed.mdl”, we will get four files in the QED directory.

1. lgrng1.mdl : This file contains the Feynman rules.
2. prtcls1.mdl: This file contains the list of particles and their properties, for example, spin, mass and width.
3. vars1.mdl: This file contains parameters that we defined, for example, the gauge coupling “ee” and the mass of the electron “me”.
4. func1.mdl: If we want to introduce a function which depends on the above parameters, then this file contains the definition of this function.

Since these files are specific to COMPHEP and CALCHEP, it would be good to consult their manual [4] and the TASI 2012 lecture note [21] for more detailed information.

4.3 MC4BSM 2012 on-site exercise

In the MC4BSM 2012 workshop tutorial, we work with the simple model described in Section 2. In this section, we will show the additional Lagrangian terms for this model,

\[ L_{s.m} = -\frac{m_1^2}{2} \phi_1^2 - \frac{m_2^2}{2} \phi_2^2 - m_{12}^2 \phi_1 \phi_2, \quad (4.1) \]

\[ L_{f.m} = M_U \bar{U} U + M_E \bar{E} E, \quad (4.2) \]

\[ L_{Yuk} = \lambda_1 \phi_1 \bar{U} P_R u + \lambda_2 \phi_2 \bar{U} P_R u + \lambda_1' \phi_1 \bar{E} P_R e + \lambda_2' \phi_2 \bar{E} P_R e + \text{h.c.}, \quad (4.3) \]

with corresponding kinetic terms. LANHEP already contains a model file for the SM in the “mdl” directory, thus it is convenient to start from this pre-existing model file, in our case, “newsm.mdl” file. To write down a model file using LANHEP, we need to understand

1. How to read a pre-defined model file and how to use this in our model file.
2. How to relate mass eigenstates to interaction eigenstates.
3. How to check whether our model file is written up correctly or not.
4.3.1 Setup

Let’s name our file “mc4bsm.mdl” and save it in the “mdl” directory since this directory contains files that we will be using.

```
read newsm.
keys CKMdim=1.
keys SMmassless=1.
keys gauge_fixing=Feynman.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Remove the 1st and 2nd generation mass
do_if SMmassless==1.
  parameter Mm = 0 , Ms =0, Mc=0 .
end_if.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Make CKM a diagonal Matrix.
do_if CKMdim==1.
  parameter Vub=0, Vcb=0, Vtd=0, Vts=0, Vtb=1, Vud=1, Vus=0, Vcs=1, Vcd=0.
end_if.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

do_if gauge_fixing==Feynman.
  model 'MC4BSM_feynman'/4.
do_else_if gauge_fixing==unitary.
  model 'MC4BSM_unitary'/3.
end_if.
```

On the first line in this code, we see the “read” command. This command allows us to use a model file which is already defined in the “mdl” directory, in our case “newsm.mdl”. There are also lines starting with “keys” and below them a section with “do_if, end_if”. By using this method, we can control different set-ups for our model file. If you look into “newsm.mdl” file, the CKM entries, Gauge choice and masses of SM particles are already defined. But after we read this model file, we can over-write/replace those pre-defined parameters with new values of our choice. We put the CKMdim and SMmassless flags since the FeynRules example from Section 3 uses restrictions on the CKM and Particle masses. In above code, we can also see that “%” is a flag to comment out a line.

4.3.2 Particles and corresponding parameters

We will follow the same conventions as the FeynRules tutorial in Section 3 (see Table 4).

| Fields  | $U$ | $E$ | $\phi_1$ | $\phi_2$ | $\Phi_1$ | $\Phi_2$ |
|---------|-----|-----|----------|----------|----------|----------|
| LANHEP  | $uv$| $ev$| $pi_1$   | $pi_2$   | $p_1$    | $p_2$    |

Table 4. Symbols used for the fields in the LANHEP implementation.
For the scalar fields, \((\Phi_1, \Phi_2)\) are the mass eigenstates (physical states) of \((\phi_1, \phi_2)\) with mixing angle \(\theta\):

\[
\begin{pmatrix}
\phi_1 \\
\phi_2
\end{pmatrix}
= \begin{pmatrix}
-\sin \theta & \cos \theta \\
\cos \theta & -\sin \theta
\end{pmatrix}
\begin{pmatrix}
\Phi_1 \\
\Phi_2
\end{pmatrix},
\]

coming from the eigen states of the following mass matrix, \(M^2\),

\[
M^2 = \begin{pmatrix}
m_1^2 & m_{12}^2 \\
m_{12}^2 & m_2^2
\end{pmatrix}.
\]

(4.4)

Thus there are five mass parameters, including the two eigenvalues \(\text{MPe}_1, \text{MPe}_2\) of the mass matrix, and a corresponding mixing angle \(\theta\), summarized in Table 5.

| Mass parameters | \(m_1\) | \(m_2\) | \(m_{12}\) | \(M_U\) | \(M_E\) | \(\tan(\theta)\) |
|-----------------|--------|--------|---------|-------|-------|-----------|
| \text{LANHEP}  | \text{MM1} | \text{MM2} | \text{MM12} | \text{Muv} | \text{Mev} | \text{tth} |

Table 5. Symbols used for the mass parameters in the \text{LANHEP} implementation.

For coupling constants, we use the notation in Table 6.

| Coupling constants | \(\lambda_1\) | \(\lambda_2\) | \(\lambda'_1\) | \(\lambda'_2\) |
|-------------------|--------|--------|--------|--------|
| \text{LANHEP}    | \text{lam1} | \text{lam2} | \text{lam1p} | \text{lam2p} |

Table 6. Symbols used for coupling parameters in the \text{LANHEP} implementation.

We sum up the above set-up for the particles in the following:

```plaintext
% Define new parameters.
parameter MM1 = 200 : 'Mass parameter for pi1',
    MM2 = 300 : 'Mass parameter for pi2',
    MM12 = 50 : 'Mixing term for pi1 and pi2',
    lam1 = 1 : 'Yukawa interaction for pi1, U and u',
    lam2 = 1 : 'Yukawa interaction for pi2, U and u',
    lam1p = 1 : 'Yukawa interaction for pi1, E and e',
    lam2p = 1 : 'Yukawa interaction for pi2, E and e',
    Muv = 500.0 : 'Mass parameter for uv and v',
    Mev = 250.0 : 'Mass parameter for ev and e'.

parameter
    MPe1 = sqrt(MM2**2+MM1**2-sqrt(4.0*MM12**4+(MM2**2-MM1**2)**2))/Sqrt2,
    MPe2 = sqrt(MM2**2+MM1**2+sqrt(4.0*MM12**4+(MM2**2-MM1**2)**2))/Sqrt2.

parameter
    tth = (MM2**2-MM1**2+sqrt(4.0*MM12**4+(MM2**2-MM1**2)**2))/(2.0*MM12**2).
parameter sth = tth/sqrt(1+tth**2), cth = 1.0/sqrt(1+tth**2).
angle sin=sth, cos=cth, tan=tth, texname='\theta'.

% Define new particles.
spinor ev:('heavy electron',mass Mev, width Wev=auto),
```
uv:('heavy quark', color c3, mass Muv, width Wuv=auto).

scalar p1/p1:('LNP',mass MPe1),
p2/p2:('Heavy scalar',mass MPe2, width Wpe2=auto).

let pi1= -sth*p1+cth*p2, pi2=cth*p1+sth*p2.

prtcproperty pdg:( ev=9000009,uv=9000008,p1=9000006,p2=9000007).

As we notice here, the mathematical commands are similar with Fortran, for example 
\[ x^2 \rightarrow x \ast \ast 2. \] For more information, we refer the user to the manual v.3.0 [2]. There are three major points that need to be explained:

1. Particle width: COMPHEP/CALCHEP can calculate the width of a particle on the fly. Thus in the particle definition, we can set it to “auto” and then COMPHEP/CALCHEP will calculate it.

   width Wev=auto

2. Physical state: We defined the physical states \((\Phi_1, \Phi_2)\) in the particle definitions and can use the “let” command to define interaction eigenstates:

   let pi1= -sth*p1+cth*p2, pi2=cth*p1+sth*p2.

   We will define our Lagrangian in terms of interaction eigenstates and LANHEP will automatically replace terms with the mass eigenstates. A Width of p1 is not defined, because p1 is a stable particle in our model. By default, its width = 0.

3. PDG number: We set the PDG number to be consistent with the model from FEYNRULES. In this onsite exercise, we will not change the “calchep.rc” file, but use the following command instead

   prtcproperty pdg:( ev=9000009,uv=9000008,p1=9000006,p2=9000007).

4.3.3 Setting up the Lagrangian

We start this subsection with the code for the Lagrangian, which we will then explain step by step.

% Kinematics terms for new fermion particles
% New fermion field is a counter part of SM right-handed particle

let PR = (1+g5)/2.

lterm anti(psi)*gamma*PR*(i*deriv - Y*g1*B1)*psi
where
  psi=ev, Y= -1;
  psi=uv, Y= 2/3.

lterm GG*anti(uv)*lambda*gamma*G*uv.
% Kinematic terms for scalars
lterm deriv*pi1*deriv*pi1/2 + deriv*pi2*deriv*pi2/2.

% New mass term
lterm -MM1**2/2 * pi1*pi1 - MM2**2/2 * pi2*pi2 - MM12**2*pi1*pi2.
lterm -Muv*anti(uv)*uv - Mel*anti(ev)*ev.

% New Yukawa type interaction.
lterm lam1*pi1*anti(uv)*PR*u + lam2*pi2*anti(uv)*PR*u + lam1p*pi1*anti(ev)*PR*e + lam2p*pi2*anti(ev)*PR*e + AddHermConj.

% Checking a Lagrangian
CheckHerm.

Fermions.

1. We defined a right-handed projector PR with g5 (g5 is defined in newsm.mdl as g5=γ5.)

2. We used “where” grammar to reduce unnecessary repeats and to give a clear structure.
   - psi is a generic notation for fermions here. B1 is U(1)Y gauge field defined in “newsm.mdl” file.
   - anti(ψ) denotes ψ, similarly to the FEYNRULES conventions.
   - Y is the hypercharge of the new particles, and g1 is defined to be the U(1)Y coupling in “newsm.mdl”.
   - For uv(colored particle) there is an interaction with G (Gluon) through the strong coupling GG defined in “newsm.mdl”.

For example,

\[
\text{Lagrangian} \quad \bar{\psi} \gamma^{\mu} (\partial_{\mu} - Y \psi g_{1} B_{1\mu}) \psi
\]

\[
\text{LANHEP} \quad \text{anti}(\psi) * \text{gamma} * \text{PR} * (i * \text{deriv} - Y * g_{1} * B_{1}) * \psi
\]

Notice that we can omit the Lorentz indexes when they are summed up. Alternatively, as in the “qed.mdl” file, we can write them down explicitly:

\[
\text{anti}(\psi) * \text{gamma}^{\mu} * \text{PR} * (i * \text{deriv}^{\mu} - Y * g_{1} * B_{1}^{\mu}) * \psi
\]

Scalar particles. Usually, it is easy to write down the Lagrangian in terms of interaction eigenstates, instead of mass eigenstates (or physical states). Thus when we define Lagrangians, we use interaction eigenstates. During compiling of LANHEP, the interaction states will be replaced with physical states and we will not see unphysical states in the COMPHEP/CALCHEP model files.

To summarize, the procedure is the following:

1. Define physical states.
2. Relate unphysical states to the corresponding physical states using the “let” command.

3. Describe Lagrangian in terms of unphysical states.

The same technique is applied in “newsm.mdl” for gauge fields, thus we recommend the user to read the “newsm.mdl” file at this stage.

4.3.4 Finalizing the Lagrangian script

We add

+ AddHermConj

to the Yukawa interaction to get a hermitian conjugate term. To check our script for the Lagrangian, we add the

CheckHerm.

command to make sure that our Lagrangian is hermitian. For additional commands for cross-checks, see section 6 of the LANHEP manual 2.0 [2].

We can get a model file for COMPHEP/CALCHEP by compiling in the LANHEP directory

```bash
mkdir tutorial
./lhep -OutDir tutorial mdl/mc4bsm.mdl -CalcHEP
```

so that we do not mix up our newly created model files with existing “mdl” files.

5 MadGraph tutorial

5.1 Preamble

MadGraph5 [22] can be run on a local computer or via the web at one of the following website:

- http://madgraph.hep.uiuc.edu
- http://madgraph.phys.ucl.ac.be

The registration is straightforward, and you can instantly creates optimized code for the computation of the cross-section of any processes. That code can be run directly on the web or downloaded and run locally. However, for security reason, generating events on the web is allowed only after that you have sent an email to one of the authors of MadGraph5. Since most of the functions are available on the internet, most users will not need to install MadGraph5.

The MadGraph5 collaboration plans to continue to improve this code both by adding new functionalities and by making the code easier to use. In particular the way to compute decay widths presented in this paper will soon be improved. New tutorials and updates on this tutorial can be found at [23].
5.2 Installation of MadGraph5

5.2.1 Installation on Windows

MadGraph5 and the associated programs are designed and tested on Linux and MacOs operating systems. The windows compatibility via cygwin is currently not supported. For Windows user, we advise they install Linux in dual boot. Virtual machines are another possibility. Note that some virtualbox packages do not include the library readline. This library is not mandatory but enables the auto-completion (See the paragraph associated to python installation to learn how to solve this).

5.2.2 Installation on Linux / MacOS

MadGraph 5  The last version of MadGraph5 can be found at the following page: https://launchpad.net/madgraph5. This website is also the place, where you can ask question, make suggestions or report a bug. The installation is straightforward since you have only to untar it

```
tar -xzpf MadGraph5_v1.X.Y.tgz
```

No compilation are required for MadGraph5, you can just launch it.

```
./MadGraph5_v1.X.Y/bin/mg5
```

If you don’t have a valid python version, MadGraph 5 will crash directly with an explicit message. In this case, you will need to install Python2.7.

If you have admin rights on your system, you can run the following command:

```
sudo ln -s MadGraph5_v1.X.Y/bin/mg5 /usr/local/bin
```

such that MadGraph5 can be launched from any directory.

Python  The only requirement for MadGraph5 is to have a current version of Python (version 2.6 or 2.7). In most cases, it can be installed via your favorite repository manager. However, some of the linux repository distributes python 2.5. In that case, you will need to download python at the following link: http://www.python.org/download/ and follows the associate instructions.

Note that for some linux versions (especially in virtual machine), the library readline is not present on the system. This will disable the auto-completion. If you care about that point, you will should first install that library (via your repository) and then to recompile python from the source code.
Optional package  Various optional packages can be linked to MadGraph5 in order to customize the output, create plots, ... The installation of those packages is easy since you can install them by launching mg5 and typing

```
mg5> install NAME
```

Where NAME is one of the following package name:

- MadAnalysis: A package to draw automatically various histogram linked to the event generation.
- ExRootAnalysis [24]: A package to convert the various output in a ROOT format.
- pythia-pgs: A package containing PYTHIA6 [25] and PGS [26]. PYTHIA6 is able to shower and to hadronize your events and is able to perform the matching [25, 27] for multi-jet production. PGS is a fast detector simulation package.
- Delphes [28]: A package allowing to have a fast detector simulation, in replacement of PGS.

Note that some of those programs might have some extra-dependencies (especially in Root).

Additional instructions for MacOS  Compared to Linux the installation on MacOS might be more complex since MacOS doesn’t provide various set of default programs present on Linux. Two important programs which are not present by default are gmake and gfortran-4.x. We advise you to first check if those program are install via the commands.

```
$> make --version
$> gfortran --version
```

In order to install gmake it is easiest to install xcode (free but requiring an apple developer account)

- MacOs 10.5: https://connect.apple.com/cgi-bin/WebObjects/MemberSite.woa/wa/getSoftware?bundleID=20414
- MacOs 10.6: http://connect.apple.com/cgi-bin/WebObjects/MemberSite.woa/wa/getSoftware?bundleID=20792
- MacOs 10.7: http://itunes.apple.com/us/app/xcode/id448457090?mt=12

Concerning gfortran you can download it from the following link:

- MacOs 10.5: http://prdownloads.sourceforge.net/hpc/gcc-lion.tar.gz?download
- MacOs 10.6: http://prdownloads.sourceforge.net/hpc/gcc-snwleo-intel-bin.tar.gz?download
- MacOs 10.7: http://sourceforge.net/projects/hpc/files/hpc/gcc/gcc-leopard-intel-bin.tar.gz/download
5.2.3 Testing the installation and learning the syntax

MadGraph5 includes a build-in tutorial.

$> ./bin/mg5
mg5> tutorial

Then just follow the instructions on the screen and you will learn the basic command/usage of MadGraph5. This takes around 15-20 minutes.

5.3 MC4BSM exercise

In this section, we will study a full example on how to generate events for BSM theories. We will assume that you have your own UFO model \([29]\) according to the FeynRules \([1]\) tutorial. If you don’t, you can download the associated model at the following address:

http://feynrules.irmp.ucl.ac.be/attachment/wiki/WikiStart/MC4BSM_2012_UFO.tgz

We will split this example into three sections. First we will show how you can test the validity of the model, second, we will present how to create a valid set of parameters associated with the model, and finally we will present how you can generate BSM events, both with and without the associated decays.

5.3.1 Importing and checking the model

The simplest way to have access to a model in MG5 is to put it in the directory: MG5_DIR/models after that you can simply import it by typing

    mg5> import model MC4BSM_2012_UFO

or

    mg5> import model MC4BSM_2012_UFO --modelname

The option \(--modelname\) tells MG5 to use the name of the particles defines in the UFO model, and not the usual MG5 conventions for the particles of the SM/MSSM. For this particular model, this changes only the name associated to \(\tau\) lepton (ta- and tt- respectively).

If you have developed your own model following the FeynRules tutorial from Section 3, this will be the first time that you are going to use this model. It is therefore crucial to start by checking the model. MadGraph5 performs some sanity checks the first time that you load the model, but those test are quite weak. We therefore suggest to test, three properties for on a series of processes.

- The gauge invariance, by testing the Ward identities.
- The Lorentz invariance.
- The ALOHA \([30]\) consistency, by evaluating the same square matrix element by different set of Helicity amplitudes.
For instance, we present how to check those properties for all the $2 \to 2$ BSM particles productions:

```plaintext
mg5> import model MC4BSM_2012_UFO
mg5> define new = uv uv~ ev ev~ p1 p2
mg5> check p p > new new
```

which results in the following output:

**Gauge results:**

| Process      | matrix | BRS     | ratio            | Result       |
|--------------|--------|---------|------------------|--------------|
| $g \ g > uv$ | uv     | 7.4113020914e-01 | 1.0055761722e-31 | 1.356814434e-31 | Passed |
| $u \ u > p1$ | uv     | 3.8373877873e-02 | 6.1629758220e-33 | 1.6060341471e-31 | Passed |
| $u \ u > p2$ | uv     | 2.5726129500e-02 | 4.4176419953e-33 | 1.7171809678e-31 | Passed |
| $u^\sim \ u > p1$ | p1    | 2.0117011717e-08 | 8.3456964257e-34 | 4.1485766093e-33 | Passed |
| $u^\sim \ u > p2$ | p2    | 1.9705216573e-01 | 1.8809915790e-32 | 9.5456529090e-32 | Passed |

Summary: 5/5 passed, 0/5 failed

**Lorentz invariance results:**

| Process      | Min element | Max element | Relative diff. | Result       |
|--------------|-------------|-------------|----------------|--------------|
| $g \ g > uv$ | uv          | 4.8743514998e-01 | 1.0055761722e-31 | 1.1388417769e-16 | Passed |
| $u \ u > p1$ | uv          | 1.3897148577e-01 | 1.3897148577e-01 | 1.1983282238e-15 | Passed |
| $u \ u > p2$ | uv          | 5.7988729593e-02 | 5.7988729593e-02 | 5.9829676840e-16 | Passed |
| $u^\sim \ u > p1$ | p1    | 8.8655875905e-03 | 8.8655875905e-03 | 1.7610238605e-15 | Passed |
| $u^\sim \ u > p2$ | p2    | 1.0373598029e-01 | 1.0373598029e-01 | 8.0267932700e-16 | Passed |
| $u \ u^\sim > uv$ | p1    | 2.1536620557e+00 | 2.1536620557e+00 | 1.1858171084e-15 | Passed |
| $u \ u^\sim > uv$ | p2    | 8.4033626775e-01 | 8.4033626775e-01 | 2.1138643036e-15 | Passed |
| $u \ u^\sim > p1$ | p1    | 7.6001259005e-03 | 7.6001259005e-03 | 2.9672410014e-15 | Passed |
| $u \ u^\sim > p2$ | p2    | 9.5102790993e-05 | 9.5102790993e-05 | 2.7645774018e-14 | Passed |
| $u \ u^\sim > p2$ | p2    | 4.6427735529e-04 | 4.6427735529e-04 | 8.6404128750e-15 | Passed |
| $u \ u^\sim > p2$ | p2    | 2.3919237366e-03 | 2.3919237366e-03 | 2.7165737676e-15 | Passed |
| $c \ c^\sim > uv$ | uv     | 8.5752329113e-01 | 8.5752329113e-01 | 2.3304340127e-15 | Passed |
| $c \ c^\sim > uv$ | uv     | 8.9275046680e-01 | 8.9275046680e-01 | 3.2335576000e-15 | Passed |
| $d^\sim \ d > ev$ | ev     | 4.8145327614e-04 | 4.8145327614e-04 | 5.6298410782e-16 | Passed |
| $s \ s^\sim > uv$ | uv     | 8.8941849408e-01 | 8.8941849408e-01 | 3.6199458330e-15 | Passed |
| $u^\sim \ u^\sim > uv$ | p1    | 2.3800428911e+00 | 2.3800428911e+00 | 3.185874237e-15 | Passed |

Summary: 16/16 passed, 0/16 failed

Not checked processes: $c \ c^\sim > ev \ ev^\sim$, $s \ s^\sim > ev \ ev^\sim$

**Process permutation results:**

| Process      | Min element | Max element | Relative diff. | Result       |
|--------------|-------------|-------------|----------------|--------------|
| $g \ g > uv$ | uv          | 4.9184278197e-01 | 4.9184278197e-01 | 2.2572721717e-16 | Passed |
| $u \ u > p1$ | uv          | 4.1859552985e-02 | 4.1859552985e-02 | 3.3153215496e-16 | Passed |
| $u \ u > p2$ | uv          | 2.0129184319e-01 | 2.0129184319e-01 | 1.1030978772e-15 | Passed |
| $u^\sim \ u^\sim > p1$ | p1    | 9.5566536137e-02 | 9.5566536137e-02 | 5.8086390357e-16 | Passed |
| $u^\sim \ u^\sim > p2$ | p2    | 3.6165811126e-03 | 3.6165811126e-03 | 3.8372671248e-15 | Passed |
More informations about these checks (like the values of the random phase-space points) can be obtained via the commands:

```
mg5> display checks
```

The display commands is very useful in order to obtained information on the particles, couplings, interactions, ... For example:

```
mg5>display particles
Current model contains 21 particles:
ve/ve¯ vm/vm¯ vt/vt¯ e-/e+ m-/m+ tt-/tt+ u/u¯ c/c¯ t/t¯ d/d¯ s/s¯
b/b¯ w+/w¯ uv/uv¯ ev/ev¯ a z g h p1 p2
mg5>display particles p1
Particle p1 has the following properties:
{
    'name': 'p1',
    'antiname': 'p1',
    'spin': 1,
    'color': 1,
    'charge': 0.00,
    'mass': 'MPe1',
    'width': 'Wpe1',
    'pdg_code': 9000006,
    'texname': 'p1',
    'antitexname': 'p1',
    'line': 'dashed',
    'propagating': True,
    'is_part': True,
    'self_antipart': True
}
```

\[^9\]Note that the spin is written in the $2S + 1$ convention.
5.3.2 Computation of the width and of the branching ratio

The first requirement in order to have valid event generation is to have a valid set of input parameters. This includes having the correct widths and branching ratios (needed by PYTHIA). Currently, MadGraph5 is not able to compute these automatically and requires that you prescribe all decay channels. Note that this limitation will be resolved in a near future.

So with the current version of MadGraph, you need to do the following in order to compute the width:

```
mg5> import model MC4BSM_2012_UFO
mg5> generate uv > u p1
mg5> add process uv > u p2
mg5> add process p2 > ev e+
mg5> add process p2 > ev~ e-
mg5> add process ev > e- p1
mg5> output
mg5> launch
```

The last command will ask you if you want to change the mass spectrum and/or the cuts. In principle all cuts should be set to zero for width computation. Then your browser will automatically open an html page with the results. One of the results will be the new param_card.dat. Note that this script modified only the width of the particles present in the initial states of the generated processes. This means that the width of $p_1$ is not modified and therefore is still has its default value (1.0) which is not correct. You have to modify this card manually before using it for an event generation.

5.3.3 Generating events

In this section, we start the computation of the cross-sections and the generation of events for the proposed process of interest:

$$pp \rightarrow U\bar{U}$$

First we will generate this exact process, Pythia being in charge of the decays. Note that in this way, you lose the full spin-correlations.

```python
import model MODELNAME
generate p p > uv uv~
output
launch
```

If you have installed the Pythia-PGS/Delphes package, you will be asked if you want to run the package. Next a question will ask if you want to edit one of the cards. At this stage, you can enter the path of the card that you have created in the previous step and/or edit those manually.

---

10 You can de-activated this behavior by modifying the configuration files present at the following path: ./input/mg5_configuration.txt
In this case, the number of decay channels is quite limited, it’s therefore possible to prescribe all the steps of the decay chain. The syntax for the decay chains is the following: the production first, then the decays of the final states separate by a comma. To avoid ambiguity parenthesis should be present in the case of sub-decay.

```python
import model MC4BSM_2012_UFO
generate p p > uv uv~ , uv > u p1, uv~ > u~ p1
define l = e+ e-
define lv = ev ev~
add process p p > uv uv~, uv > u p1, 
    (uv~ > u~ p2, (p2 > l lv, lv > l p2))
add process p p > uv uv~, uv~ > u~ p1,
    (uv > u p2, (p2 > l lv, lv > l p2))
add process p p > uv uv~, (uv > u p2, (p2 > l lv, lv > l p2)), 
    (uv~ > u~ p2, (p2 > l lv, lv > l p2))
output
launch
```

The validity of this calculation must be considered, since specifying the decay sequence means the contribution of non-resonance Feynman diagram have been neglected. This is however valid since the interferences with those diagrams are negligible if the intermediate particles are on-shell. In order to ensure such a condition, we have associate to each of the decaying particles an additional cuts called $BW_{cut}$:

\[
|m_{virt} - m_0| < BW_{cut} \times \Gamma
\]

This cut can be specified in the run_card.dat.

If you have installed the MadAnalysis package, you should have automatically distributions created at parton level, after PYTHIA and at the reconstructed level –if runned–. Those one can be used to check the sanity of the productions but also to search the potential observables of this production.

## 6 CalcHEP tutorial

### 6.1 Installation of CalcHEP

Download CalcHEP from:

```
http://theory.sinp.msu.ru/~pukhov/CALCHEP/calchep_3.4.0.tgz
```

Move it to the directory where you would like to do the tutorial. For example:

```
mv ~/Downloads/calchep_3.4.0.tgz \
~/physics/projects/MC4BSM-2012/Sandbox/calchep_3.4.0.tgz
```

Change to that directory. For example:

\[\text{If your OS already unzipped the file, change the endings appropriately.}\]
cd ~/physics/projects/MC4BSM-2012/Sandbox

Unpack the CalCHEP code:\footnote{If your OS already unzipped, then you would do tar xvf calchep_3.4.0.tar Or, if your OS already fully unpacked the file, you can skip this step.}

tar xvzf calchep_3.4.0.tgz

Change to the codes directory:

cd calchep_3.4.0

Compile the code:\footnote{Note that you need the X11 development libraries installed on your system to use the graphical user interface (gui). For Mac, these used to come on the X11 disk. Now, I assume you get it through the app store. For Linux, your distribution likely has it in a repository. Google X11 development libraries and your distribution to see how to install it. However, note that it is not strictly necessary to have the gui working for this tutorial.}

make

Create a working directory for your calculations:\footnote{mkUsrDir is planned to change to mkWorkDir.}

./mkUsrDir ../ch_3.4.0

Change directory to the working directory:

cd ../ch_3.4.0

If you have the X11 development libraries installed, you can start the symbolic session gui (otherwise skip this step):

./calchep &

Feel free to try some processes out and play. This will not be part of the tutorial.

6.2 Install the MC4BSM 2012 model

Download the CalCHEP model files from:

http://feynrules.irmp.ucl.ac.be/raw-attachment/wiki/WikiStart/MC4BSM_2012-CH.tgz

Move this file to a convenient location. For example:\footnote{Again, change the ending as appropriate.}

mv ~/Downloads/MC4BSM_2012-CH.tgz \
~/physics/projects/MC4BSM-2012/Sandbox/MC4BSM_2012-CH.tgz

Change to this directory:
Unpack model files (if not already done):

```
tar xzvf MC4BSM_2012-CH.tgz
```

Install the model\textsuperscript{16}. We need to change the model number to one that is not already used. Since we just freshly installed CALCHEP, we know there are only three models included by default (the Standard Model with general CKM matrix, the Standard Model with diagonal CKM matrix and the Standard Model with effective Higgs vertices). The model number is given by the integer in the model file names. We will change it to 4.

Change to the model file directory:

```
cd MC4BSM_2012-CH
```

Change the file names in such a way that the 1 becomes a 4.

```
mv prtcls1.mdl prtcls4.mdl
mv vars1.mdl vars4.mdl
mv func1.mdl func4.mdl
mv lgrng1.mdl lgrng4.mdl
mv extlib1.mdl extlib4.mdl
```

Now, copy the model files to the models subdirectory of the CALCHEP work directory:

```
cp *4.mdl ../ch_3.4.0/models/.
```

Change directory back to the CALCHEP working directory:

```
cd ../ch_3.4.0
```

If you have the X11 development libraries installed, you can start the symbolic session gui (otherwise skip this step):

```
./calchep &
```

You should see the tutorial model as the third model in the list. You can check your model for syntactical correctness, change it, calculate cross sections and generate distributions. Feel free to play. This will not be part of the tutorial.

\textbf{6.3 Generate events}

We, next, write a batch file to generate events.

Open your favorite text editor (emacs, vi, gedit,...). For example:

```
emacs &
```

At the top of the file, we will choose the model. Add the lines:

\textsuperscript{16}\textit{The model can be installed more easily using the gui, but I will describe the process that will work for everyone.}
Model: MC4BSM_2012
Gauge: Feynman

The model name can be found at the top of the file models/prtcls3.mdl.

We next specify the process we are interested in:

- Process: \(p, p \rightarrow \nu \bar{v}, \nu \bar{v}\)
- Decay: \(\nu \bar{v} \rightarrow u, p_1\)
- Decay: \(\nu \bar{v} \rightarrow u^-, p_1\)
- Decay: \(\nu \bar{v} \rightarrow u, p_2\)
- Decay: \(\nu \bar{v} \rightarrow u^-, p_2\)
- Decay: \(p_2 \rightarrow e^-, e^-v\)
- Decay: \(p_2 \rightarrow e^+, e^-\)
- Decay: \(e^-v \rightarrow e^-, p_1\)
- Decay: \(e^-v \rightarrow e^+, p_1\)

Alias: \(p = u, u^-, d, d^-, G\)

We next specify the parton distribution function. We will use the built in CTEQ 6L set:

- pdf1: cteq6l (proton)
- pdf2: cteq6l (proton)

Specify the momenta:

- \(p_1: 4000\)
- \(p_2: 4000\)

Specify the number of events to generate and the filename to use:

- Number of events (per run step): 10000
- Filename: MC4BSM

Specify your parallelization info:

- Parallelization method: local
- Max number of cpus: 2
- sleep time: 1

I entered 2 for the max number of cpus because I have a dual core machine. You should change this as appropriate.

Specify how many times Vegas should run:

- \(n_{\text{Sess}}_1: 5\)
- \(n_{\text{Calls}}_1: 10000\)
- \(n_{\text{Sess}}_2: 5\)
- \(n_{\text{Calls}}_2: 100000\)
The first five runs improve the grid. Then the statistics are cleared, the grid is frozen and 5 more runs are done to calculate the cross section, widths and prepare the event generator.

After you have all of these pieces entered, save the file. Call it “batch_file” in your work directory.

Now, run the batch program by:

./calchep_batch batch_file

The batch program will begin by stating where you can find information about the progress of your job. For example,

Processing batch:
Progress information can be found in the html directory.
Simply open the following link in your browser:
file:///Users/neil/physics/projects/MC4BSM-2012/Sandbox/ch_3.4.0/html/index.html
You can also view textual progress reports in /Users/neil/physics/projects/MC4BSM-2012/Sandbox/ch_3.4.0/html/index.txt
and the other .txt files in the html directory.
Events will be stored in the Events directory.

Note, the line that begins file:. You can copy and paste this line into your web browser’s url bar. This shows the progress of your calculation. There is also a link on the left called Help which contains detailed instructions about how to write batch files. There are many options that we did not discuss in this tutorial.

When the program finishes, you will have the following file:

Events/MC4BSM-single.lhe.gz

which contains your events in LHE format.

Enjoy!

7 PYTHIA 8 tutorial

7.1 Introduction

This exercise corresponds to the PYTHIA 8 part of the more general MC tutorial given at the MC4BSM workshop at Cornell University 2012 [12]. It is for this reason focused on the particular task within this tutorial, however, should still serve as a good starting point to get familiar with the basics of how to use the PYTHIA 8 event generator. Much of these instructions were based on earlier PYTHIA 8 tutorials, which can be found on the homepage [31] and often include additional material than what is covered here.

Within this first exercise it is not possible to describe the physics models used in the program; for this we refer to the online manual [32], PYTHIA 8.1 brief introduction [7], to the full PYTHIA 6.4 physics description [25], and to all the further references found in them.

Finally, a good way to continue after the tutorial is often to chose a particular physics study your interest and then start to explore the different simulation and analysis aspects, using the different example programs together with the online manual, along the lines of the tutorial.
7.2 Installation and pre-workshop exercise

PYTHIA 8 is, by today’s standards, a small package. It is completely self-contained, and is therefore easy to install for standalone usage, e.g. if you want to have it on your own laptop, or if you want to explore physics or debug code without any danger of destructive interference between different libraries.

Denoting a generic PYTHIA 8 version `pythia81xx` (at the time of writing `xx = 62`), here is how to install PYTHIA 8 on a Linux/Unix/MacOSX system as a standalone package.

1. In a browser, go to
   
   `http://www.thep.lu.se/~torbjorn/Pythia.html`

2. Download the (current) program package
   `pythia81xx.tgz`
   to a directory of your choice (e.g. by right-clicking on the link).

3. In a terminal window, `cd` to where `pythia81xx.tgz` was downloaded, and type
   `tar xvfz pythia81xx.tgz`
   This will create a new (sub)directory `pythia81xx` where all the PYTHIA source files are now ready and unpacked.

4. Move to this directory (`cd pythia81xx`) and do a `make`. This will take ~3 minutes (computer-dependent). The PYTHIA 8 libraries are now compiled and ready for physics.

5. For test runs, `cd` to the `examples/` subdirectory. An `ls` reveals a list of programs, `mainNN`, with `NN` from 01 through 28 (and beyond). These example programs each illustrate an aspect of PYTHIA 8. For a list of what they do, see the “Sample Main Programs” page in the online manual (point 6 below).
   In order to test that the program installed successfully, most examples are suitable, however, for this tutorial (using version 8.162) a good choice would be `main11.cc`, which reads in a test LHEF called `ttbar.lhe`
   To execute this test program, do
   ```
   make main11
   ./main11.exe
   ```
   The output is now just written to the terminal, `stdout`, and if everything worked one should see (specific for main11.cc) a text based histogram, showing the a charge particle multiplicity, at the end of the program output. To save the output to a file instead, do `./main11.exe > main11.out`, after which you can study the test output at leisure by opening `main11.out`. See Appendix A for a brief explanation of the event record.

6. If you use a web browser to open the file
   `pythia81xx/htmldoc/Welcome.html`
   you will gain access to the online manual, where all available methods and parameters are described. Use the left-column index to navigate among the topics, which are then displayed in the larger right-hand field.
7.3 On-site exercise

The task at hand for the Pythia 8 part of the tutorial is to read in the events, provided in LHEF format from the earlier steps, and continue the event simulation following the hard scatter generation. Given that the LHEF includes both the information for initialization and of the actual events, this is very straightforward. Copy first the LHEF events_with_decay.lhe.gz into the examples directory and unpack it using:

```
gunzip events_with_decay.lhe.gz
```

The LHEF should now be readable just like any ASCII file.

The BSM model as well as the hard process is described in detail in the earlier steps of this tutorial, but as a short reminder the events consists of, \( pp \rightarrow U \bar{U} \), production at the LHC with \( E_{cm} = 8 \text{ TeV} \). The \( U \) fermions have a mass of 500 GeV and the two following decay scenarios are possible:

\[
U \rightarrow u \Phi_1; \\
U \rightarrow u \Phi_2 \rightarrow u e E \rightarrow u e e \Phi_1.
\]

The second step is to create our own main program. Open a new file mymain.cc in the examples subdirectory with a text editor, e.g. Emacs. Then type the following lines (here with explanatory comments added):

```cpp
// Headers and Namespaces.
#include "Pythia.h" // Include Pythia headers.
using namespace Pythia8; // Let Pythia8:: be implicit.

int main() { // Begin main program.

    // Set up generation.
    Pythia pythia; // Declare Pythia object
    pythia.readString("Beams:frameType = 4"); // Beam info in LHEF.
    pythia.readString("Beams:LHEF = events_with_decay.lhe");
    pythia.init(); // Initialize; incoming pp beams is default.

    // Generate event(s).
    for (int iEvent = 0; iEvent < 1; ++iEvent) {
        if (!pythia.next()) {
            if (pythia.info.atEndOfFile()) break; // Exit at end of LHEF.
            continue; // Skip event in case of problem.
        }
    }

    pythia.stat(); // Print run statistics.
    return 0;
}
```
This will use one event from the LHEF and pass it through the remaining Pythia 8 simulation. Go through the lines in the program and try to understand them by consulting the online manual [32].

Next you need to edit the Makefile (the one in the examples subdirectory) so it knows what to do with mymain.cc. The lines

```bash
# Create an executable for one of the normal test programs
main00 main01 main02 main03 ... main09 main10 main10 \ 
and the three next enumerate the main programs that do not need any external libraries.
Edit the last of these lines to include also mymain:
main31 ... main40 mymain: \ 
```

Now it should work as before with the other examples:
```
make mymain
./mymain.exe > mymain.out
```

whereafter you can study mymain.out, especially the example of a complete event record (preceded by initialization information and by kinematical-variable listing for the same event). For this reason Appendix A contains a brief overview of the information stored in the event record.

At this point you have in principle achieved your goal, the first event in the LHEF have been fully simulated by Pythia 8, using the default values of all settings. On the other hand, and despite only having one event, we only have access to the information of the individual particles in the event record, so interesting for technical validation but not much of real physics interest yet.

7.4 A simple jet analysis

We will now gradually expand the skeleton mymain program from above, in order to make a simple analysis, including jet reconstruction. The common standard, used in the experimental communities, is to produce fully simulated MC events in the HepMC format, either for analysis or further detector simulation. However, in order to keep the software infrastructure at a minimum we will in this part only use the analysis functionality already available within Pythia 8. For further information regarding how to produce HepMC, the reader is referred to the online manual [32] together with other tutorials on the home page [31]. The final version of mymain.cc, with all steps included, is kept in Appendix B. Hence one can look there in case the instructions are unclear, however, that should of course be considered as the last resort, if getting completely stuck.

The BSM events generated in this tutorial will always include jets, from the $U$ decay, and missing $\Phi_1$ particles. They will some times also contain electrons, depending on the $U$ decay channel. For this reason we start with reconstructing jets from the final state particles in the event. For this we use the Pythia 8 SlowJet program (found in the manual under Event Analysis), which is a simpler version of the commonly used FastJet jet finder. The SlowJet program supports both the kT, anti-kT, and Cambridge/Aachen algorithms, where we will use the anti-kT which is a common choice within the LHC experiments. For further information about the jet reconstruction algorithms we recommend the online manual together with its references to the FastJet program.
Insert the following line before the event loop, in order to create a \texttt{SlowJet} object,
\begin{verbatim}
  \texttt{SlowJet::SlowJet sJets(-1, 0.4, 50., 5., 1, 2);

\end{verbatim}
The first argument specifies the anti-kT algorithm, the second is the related R measure
which roughly corresponds to the radius of the jet cone in ($y, \phi$). The next two corresponds
to, minimum $p_T$ and maximum $|\eta|$, acceptance cuts usually implied by the experiment of
interest. The last two arguments specifies respectively to use all final state particles and
to use their actual mass in the reconstruction. The selection of which particles to include
is normally done more carefully, however, in a trade–off between illustrating the physics
without spending too much time on technical details and infrastructure, we chose a rather
unsophisticated approach here. Just after this line, you should also create the following two
histograms,
\begin{verbatim}
  Hist nJ( "Nr Jets", 10, -0.5, 9.5);
  Hist j1pT( "Leading Jet pT", 100, 0., 1000.);
\end{verbatim}
which corresponds to our final analysis results.

The next step is to reconstruct jets from the final state particles in each event according
to the jet algorithm we just defined. After that we also want to fill our histograms, once
per event, and at the end of the program print them to our output. To do this, include
the following lines inside the event loop, but at the end so that \texttt{pythia.next()} has been
executed,
\begin{verbatim}
// Jet analysis.
  if (sJets.analyze(pythia.event)) {
    nJ.fill(sJets.sizeJet());
    j1pT.fill(sJets.pT(0));
  }
\end{verbatim}
The \texttt{pythia} member \texttt{.event} corresponds to the event record and you can try to find out the
meaning of these lines by using the online manual. To write the histograms to the output
include the following line at the very end, just before the \texttt{return} statement,
\begin{verbatim}
  std::cout << nJ << j1pT;
\end{verbatim}

Now increase the number of events in the event loop, \textit{e.g.} to 1000, compile and run the
program. At the end of the output one should now see the number of jets and leading jet
$p_T$ distributions, in traditional text based histograms.

During the run you may receive problem messages. These come in three kinds:

\begin{itemize}
  \item a \textit{warning} is a minor problem that is automatically fixed by the program, at least
       approximately;
  \item an \textit{error} is a bigger problem, that is normally still automatically fixed by the program,
       by backing up and trying again;
  \item an \textit{abort} is such a major problem that the current event could not be completed; in
       such a rare case \texttt{pythia.next()} is \texttt{false} and the event should be skipped.
\end{itemize}

Thus the user need only be on the lookout for aborts. During event generation, a problem
message is printed only the first time it occurs. The above-mentioned \texttt{pythia.stat()} will
then tell you how many times each problem was encountered over the entire run.
What we did so far is clearly not what we want to do, since first we include the $\Phi_1$ which should be invisible and second the electrons produced in the decay chains, potentially also with high $p_T$, are included.

For the purpose of this tutorial we use a rather ugly trick in order to eliminate particles with respect to the jet reconstruction. We simply loop through the event record and when we find a $\Phi_1$ (id == 9000006) we set its status to a negative value, since the jet reconstruction only considers final state particles, i.e. with positive status. In order to do this, insert the following lines, just before the jet analysis part,

```c++
for (int iPart = 0; iPart < pythia.event.size(); ++iPart) {
    if (pythia.event[iPart].idAbs() == 9000006) {
        int stat = pythia.event[iPart].status();
        if (stat > 0) pythia.event[iPart].status(-stat);
    }
}
```

These lines hence illustrate both how to loop over the particles in the event record and how to access their properties, in this case the id and status codes. Now compile and run the program again. The mean number of jets should now have been reduced by approximately two (from 4.8 to 3.1), due to the two $\Phi_1$ in the events. The leading $p_T$ jet should now dominantly originate from the quarks in the $U$ decay and the mean $p_T$ therefore is around half of the $U$ mass, 500 GeV.

We now leave it as an exercise to also eliminate any final state electrons in the event and see how the distributions are affected. Another easy thing to investigate would be to see how the number of reconstructed jets varies with the minimum $p_T$ requirement specified for the jet finder.

### 7.5 The event record

The event record is set up to store every step in the evolution from an initial low-multiplicity partonic process to a final high-multiplicity hadronic state, in the order that new particles are generated. The record is a vector of particles, that expands to fit the needs of the current event (plus some additional pieces of information not discussed here). Thus `event[i]` is the $i$'th particle of the current event, and you may study its properties by using various `event[i].method()` possibilities.

The `event.list()` listing provides the main properties of each particles, by column:

- **no**, the index number of the particle ($i$ above);
- **id**, the PDG particle identity code (method `id()`);
- **name**, a plaintext rendering of the particle name (method `name()`), within brackets for initial or intermediate particles and without for final-state ones;
- **status**, the reason why a new particle was added to the event record (method `status()`);
- **mothers** and **daughters**, documentation on the event history (methods `mother1()`, `mother2()`, `daughter1()` and `daughter2()`);
• **colours**, the colour flow of the process (methods col() and acol());

• \(p_x, p_y, p_z\) and \(e\), the components of the momentum four-vector \((p_x, p_y, p_z, E)\), in units of GeV with \(c = 1\) (methods px(), py(), pz() and e());

• \(m\), the mass, in units as above (method m()).

For a complete description of these and other particle properties (such as production and decay vertices, rapidity, \(p_{\perp}\), etc), open the program’s online documentation in a browser (see Section 7.2, point 6, above), scroll down to the “Study Output” section, and follow the “Particle Properties” link in the left-hand-side menu. For brief summaries on the less trivial of the ones above, read on.

#### 7.5.1 Identity codes

A complete specification of the PDG codes is found in the Review of Particle Physics [33]. An online listing is available from

http://pdg.lbl.gov/2008/mcdata/mc_particle_id_contents.html

A short summary of the most common id codes would be

| code range | explanation |
|------------|-------------|
| 11 – 19    | beam particles |
| 21 – 29    | particles of the hardest subprocess |
| 31 – 39    | particles of subsequent subprocesses in multiparton interactions |
| 41 – 49    | particles produced by initial-state-showers |
| 51 – 59    | particles produced by final-state-showers |
| 61 – 69    | particles produced by beam-remnant treatment |
| 71 – 79    | partons in preparation of hadronization process |
| 81 – 89    | primary hadrons produced by hadronization process |
| 91 – 99    | particles produced in decay process, or by Bose-Einstein effects |

Whenever a particle is allowed to branch or decay further its status code is negated (but it...
is never removed from the event record), such that only particles in the final state remain with positive codes. The isFinal() method returns true/false for positive/negative status codes.

7.5.3 History information
The two mother and two daughter indices of each particle provide information on the history relationship between the different entries in the event record. The detailed rules depend on the particular physics step being described, as defined by the status code. As an example, in a \( a \rightarrow b \rightarrow c \) process, the locations of \( a \) and \( b \) would set the mothers of \( c \) and \( d \), with the reverse relationship for daughters. When the two mother or daughter indices are not consecutive they define a range between the first and last entry, such as a string system consisting of several partons fragment into several hadrons.

There are also several special cases. One such is when “the same” particle appears as a second copy, e.g. because its momentum has been shifted by it taking a recoil in the dipole picture of parton showers. Then the original has both daughter indices pointing to the same particle, which in its turn has both mother pointers referring back to the original. Another special case is the description of ISR by backwards evolution, where the mother is constructed at a later stage than the daughter, and therefore appears below in the event listing.

If you get confused by the different special-case storage options, the two pythia.event.motherList(i) and pythia.event.daughterList(i) methods are able to return a vector of all mother or daughter indices of particle \( i \).

7.5.4 Color flow information
The colour flow information is based on the Les Houches Accord convention [34]. In it, the number of colours is assumed infinite, so that each new colour line can be assigned a new separate colour. These colours are given consecutive labels: 101, 102, 103, .... A gluon has both a colour and an anticolour label, an (anti)quark only (anti)colour.

While colours are traced consistently through hard processes and parton showers, the subsequent beam-remnant-handling step often involves a drastic change of colour labels. Firstly, previously unrelated colours and anticolours taken from the beams may at this stage be associated with each other, and be relabeled accordingly. Secondly, it appears that the close space–time overlap of many colour fields leads to reconnections, i.e. a swapping of colour labels, that tends to reduce the total length of field lines.

7.6 The jet analysis program
This is the final mymain.cc at the end of the tutorial,

```c++
#include "Pythia.h" // Include Pythia headers.
using namespace Pythia8; // Let Pythia8: be implicit.

int main() { // Begin main program.
```
// Set up generation.
Pythia pythia; // Declare Pythia object
pythia.readString("Beams:frameType = 4"); // Beam info in LHEF.
pythia.readString("Beams:LHEF = events_with_decay.lhe");
pythia.init(); // Initialize; incoming pp beams is default.

SlowJet::SlowJet sJets(-1, 0.4, 50., 5., 1, 2);
Hist nJ( "Nr Jets", 10, -0.5, 9.5);
Hist j1pT( "Leading Jet pT", 100, 0., 1000.);

// Generate event(s).
for (int iEvent = 0; iEvent < 1000; ++iEvent) {
    if (!pythia.next()) {
        if (pythia.info.atEndOfFile()) break; // Exit at end of LHEF.
        continue; // Skip event in case of problem.
    }

    // Loop through event record.
    for (int iPart = 0; iPart < pythia.event.size(); ++iPart) {
        if (pythia.event[iPart].idAbs() == 9000006) {
            int stat = pythia.event[iPart].status();
            if (stat > 0) pythia.event[iPart].status(-stat);
        }
        if (pythia.event[iPart].idAbs() == 11) {
            int stat = pythia.event[iPart].status();
            if (stat > 0) pythia.event[iPart].status(-stat);
        }
    }

    // Jet analysis.
    if (sJets.analyze(pythia.event)) {
        nJ.fill(sJets.sizeJet());
        j1pT.fill(sJets.pT(0));
    }
}

pythia.stat(); // Print run statistics.

std::cout << nJ << j1pT;
return 0;
8 HERWIG++ tutorial

8.1 Introduction

HERWIG++ [35, 36], is a general-purpose Monte Carlo event generator for the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron collisions.

Some of the main features, in random order, are:

1. Many matrix elements natively and capability of reading in Les Houches-accord event files.
2. A description of the underlying event via multiple parton interactions.
3. Initial- and final-state QCD parton showering.
4. Next-to-leading order: Several POWHEG [37, 38] processes and compatibility with MC@NLO [39].
5. Cluster hadronization.
6. Individually modelled hadron and tau decays.
7. QED radiation.
8. Analysis via RIVET [40], native analysis handlers, or output to HepMC events.

This tutorial aims to guide you through the steps of going from the HERWIG++ source distribution through to some basic analysis for a specific model, which is described in Section 2. The model events are generated in MADGRAPH [22], and will be ‘fed’ into the event generator via the Les Houches interface\(^\text{17}\).

Note that Wiki page for this tutorial also exists at: http://herwig.hepforge.org/trac/wiki/MC4BSM.

8.2 Installation and setup

8.2.1 Required libraries

Throughout this tutorial, it will be assumed that you have created a working directory in your home directory, which we will be referring to as \$MCBSM from now on. If you wish, you may define \$MCBSM (in bash shell):

```
export MCBSM=/target/directory
```

In c-shell you need to use:

```
setenv MCBSM "/target/directory"
```

All the source tarballs will be assumed to be placed in \$MCBSM/source.

If the libraries do not already exist on your system, you will need to compile and install the following:

\(^{17}\)In the future, HERWIG++ will include automated creation of the model internally via a FEYNRULES UFO interface [29].
• GNU Scientific Library (GSL),
  http://mirror.switch.ch/ftp/mirror/gnu/gsl/gsl-1.15.tar.gz.
  Recommended installation in $MCBSM/gsl.

• LHAPDF, the Les Houches Accord PDF Interface,
  http://www.hepforge.org/archive/lhapdf/lhapdf-5.8.7.tar.gz.
  Recommended installation in $MCBSM/lhapdf.

• The PDF used in this tutorial, cteq6ll,
  http://www.hepforge.org/archive/lhapdf/pdfsets/current/cteq6ll.LHpdf.
  To be placed in $MCBSM/lhapdf/share/lhapdf/PDFsets (the directory may need to
  be created).

Important: Make sure that any program binaries and libraries you install appear in your
$PATH and $LD_LIBRARY_PATH$ ($DYLD_LIBRARY_PATH$ in MacOS X) respectively, otherwise
the binaries or libraries will not be found by the system.

Note that when compiling, if you have a multi-core machine, you may use make -jX,
where X is the number of cores, to speed up the process.

GSL Compilation and installation in the conventional way:

tar xvzf gsl-1.15.tar.gz; cd gsl-1.15
./configure --prefix=$MCBSM/gsl
make

If everything is successful (i.e. there are no errors):

make install

LHAPDF Equivalent to GSL with the necessary change of target directory through:

--prefix=$MCBSM/lhapdf

Once installed, make sure cteq6ll.LHpdf is placed in $MCBSM/lhapdf/share/lhapdf/PDFsets.

8.2.2 Installing Herwig++ and ThePEG

HERWIG++ is based on ThePEG, (Toolkit for High Energy Physics Event Generation),
which is essentially a library that contains the necessary building blocks for constructing
an event generator.

First we need to compile and install ThePEG. Get the latest version at:
http://www.hepforge.org/archive/thepeg/ThePEG-1.7.3.tar.bz2.

To compile and install:

tar xvfj ThePEG-1.7.3.tar.bz2; cd ThePEG-1.7.3
./configure --prefix=$MCBSM/thepeg --with-gsl=$MCBSM/gsl
--with-LHAPDF=$MCBSM/lhapdf
make; make install
For instructions on how to do this on the MacOS X operating system, consult: http://herwig.hepforge.org/trac/wiki/HwOsX

Once ThePEG is installed, you are ready to install Herwig++, linking to all the necessary libraries. Get the latest stable release (currently version 2.5.2) at: http://www.hepforge.org/archive/herwig/Herwig++-2.5.2.tar.bz2.

To compile and install:

tar xvfj Herwig++-2.5.2.tar.bz2; cd Herwig++-2.5.2
./configure --prefix=$MCBSM/hpp --with-thepeg=$MCBSM/thepeg
--with-gsl=$MCBSM/gsl
make; make install

8.2.3 Herwig++ preliminaries

To run Herwig++ one needs to set up a working directory. In this tutorial, this will be taken to be $MCBSM/hppwork. Create this directory and copy the following:18

cp $MCBSM/source/Herwig++-2.5.2/src/*.in $MCBSM/hppwork
cp $MCBSM/source/Herwig++-2.5.2/src/*.model $MCBSM/hppwork
cp $MCBSM/source/Herwig++-2.5.2/src/defaults/*.in $MCBSM/hppwork

This copies all the necessary input files, including the ones containing the default settings, as well as different .model files (such as the MSSM, ADD, and so on) for future use. Once this is done, change into the $MCBSM/hppwork directory and execute:

Herwig++ init

If the program has compiled correctly, the binaries and libraries are in your $PATH and $LD_LIBRARY_PATH respectively, and all the necessary .in files have been copied properly, there should be no errors.

Most of the copied .in files contain inputs for the default settings (e.g. PDF.in includes defaults for PDF handling, Cuts.in includes the default cuts and so on). It is not recommended in general to change the settings for running in those files directly. Instead, one should use a customized input file for the individual runs. The simplest example to look at is the file LHC.in. In there, you need to choose the desired energy at which you wish to run the event generator. The default in this input file is LHC at 7 TeV:

############################
## sqrt(s) = 7000 GeV ##
############################
set LHCGenerator:EventHandler:LuminosityFunction:Energy 7000.0
set /Herwig/UnderlyingEvent/KtCut:MinKT 3.06
set /Herwig/UnderlyingEvent/UECuts:MHatMin 6.12

18The subdirectory source will not be required if you have not put the source files in there!
You may wish to examine the construction of the \texttt{LHCGenerator} in the file \texttt{HerwigDefaults.in}, which is of type \texttt{EventHandler}.\textsuperscript{19} It is recommended \textit{not} to make any changes in \texttt{HerwigDefaults.in}, instead, these should be made in \texttt{LHC.in}, as also mentioned previously. A useful thing to be able to do is change the type of the hard process to be generated. The default in \texttt{LHC.in} is Drell-Yan \(Z/\text{photon}:
\begin{verbatim}
# Drell-Yan Z/gamma
insert SimpleQCD:MatrixElements[0] MEqq2gZ2ff
\end{verbatim}
Let’s comment this out (by adding a \# in front) and instead uncomment:
\begin{verbatim}
# top-antitop production
insert SimpleQCD:MatrixElements[0] MEHeavyQuark
\end{verbatim}
and execute:
\begin{verbatim}
Herwig++ read LHC.in
\end{verbatim}
If there are no errors, the command should return no text output. It should create a file \texttt{LHC.run}, which will contain internal instructions to the event generator, which are not human-readable. To make a short run, say, of 100 events of top-antitop events, including initial/final-state radiation, hadronization, and the underlying event, simply type:
\begin{verbatim}
Herwig++ run LHC.run -N100
\end{verbatim}
The run will initialize and commence generating events. \textbf{This point is a good place to stop the pre-workshop part of the tutorial.}
Running the file with the above command will not produce any significant output apart from the file \texttt{LHC.out}, which will contain the cross section of the chosen process (you may even choose more than one process). A log file may obtained by adding \texttt{-d1} to the above:
\begin{verbatim}
Herwig++ run LHC.run -N100 -d1
\end{verbatim}
This will print the first 10 events of the run (determined by \texttt{setLHCGenerator:PrintEvent 10} in the \texttt{LHC.in} file) in \texttt{LHC.log}. Have a look at it and see if you can recognize the different steps of the event generation, and follow through the decay products of the top and antitop. For a full explanation have a look at the Wiki page:
\url{http://herwig.hepforge.org/trac/wiki/EventRecordFormat}.
You may also wish to enable the built-in analysis for top-antitop:
\begin{verbatim}
# analysis of top-antitop events
insert LHCGenerator:AnalysisHandlers 0 /Herwig/Analysis/TTbar
\end{verbatim}
Note that every time a change is made in the .\texttt{in} file, one needs to invoke the ‘read’ command.
After running the event generator again, the analysis will produce a file \texttt{LHC-TTbar.top}.
This is made to be read by \texttt{TOPDRAWER}, a rather archaic, but useful, plotting package.
\textsuperscript{19}The \texttt{EventHandler} class is a general class of \texttt{ThePEG}, responsible for the generation of events.
Unfortunately it is difficult to compile it from source, and pre-compiled binaries may or may not work on your system. You may try the binaries subdirectory of:

http://www.rcnp.osaka-u.ac.jp/~okamura/ftp/pub/index.php?dir=topdrawer/

If the executable works, you may try to create a postscript file by running:

td -d ps LHC-TTbar,

and using GhostView (gv) to view it.

To run through the rest of the tutorial, you will need to obtain the following tarball:

http://www.itp.uzh.ch/~andreasp/mc4bsm.tar.gz

Extracting this in $MCBSM should create a subdirectory mc4bsm. The details of the contents of $MCBSM will be discussed in Section 8.3.1.

8.3 The on-site tutorial

This tutorial will study the toy model described in Section 2. We assume the existence of MadGraph parton-level (but with the heavy new particles already decayed) event files (see Section 5).

8.3.1 Running Herwig++ with the toy model

Extracting mc4bsm.tar.gz in $MCBSM should create a subdirectory mc4bsm. This in turn contains the following subdirectories:

- analysis: contains the sources of a basic Herwig++ analysis.
- hppinput: contains the input files necessary to run the basic tutorial events.
- madgraph_events: contains the MadGraph events which include decays of the new heavy particles down to ‘stable’ particles.
- results: contains ‘solution’ plots to the tutorials.

We first need to compile the customized analysis handler. To do that, copy the MC4BSMArea.tar.gz to the Herwig++-2.5.2/Contrib subdirectory, and extract:

    tar xvzf MC4BSMArea.tar.gz

This should overwrite the default Herwig++-2.5.2/Contrib/Makefile.am and put the analysis source code in the MC4BSMArea. In the Herwig++-2.5.2/Contrib directory, type:

    sh make_makefiles.sh

This forces the recreation of all the Makefiles from input, and hence also creates a Makefile for our analysis. Change to the Herwig++-2.5.2/Contrib/MC4BSMArea directory and type make. This should compile the library MC4BSMArea.so. Copy this into the Herwig++ installation directory library:

    cp MC4BSMArea.so $MCBSM/hpp/lib/Herwig++
In your HERWIG++ working directory (\$MCBSM/hppwork), copy the contents of hppinput and madgraph_events. These should be the input file MC4BSM.in and the model file MC4BSM.model from the prior directory and events_with_decays.lhe from the latter. Have a look and try to understand at what’s in each of the MC4BSM.* files: The MC4BSM.in file is equivalent to the LHC.in input file, with the appropriate settings to read in a Les Houches-accord event file. The underlying event settings have been chosen for an anticipated 8 TeV run. There’s also a change of PDF to the one used by the input events (cteq6ll), using the LHAPDF library. Even though the input event file provides all the necessary information for the hard process, HERWIG++ needs to know about the existence of the new particles: that is why the second file, MC4BSM.model, is necessary, and is read at the top of MC4BSM.in. It’s easy to construct one manually: it for example, the following defines particle uv with PDG id 9000008, mass 500 GeV and width 1 GeV.

create ThePEG::ParticleData uv
setup uv 9000008 uv 500.0 1.0 10.0 1.973269631e-13 2 3 2 0

The rest of the numbers in order are: maximum number of widths away from central value of mass allowed, the lifetime (calculated from the width), the electromagnetic charge (units of 1/3), the SU(3)c charge (3 implies triplet, 1 implies singlet and so on), the spin 2s + 1 and a boolean for whether the particle is stable or not.

Read in and run the input file in the usual way:

Herwig++ read MC4BSM.in
Herwig++ run MC4BSM.run -N9000

The analysis should create a subdirectory mcplots containing some plots, in TopDrawer format. You may view them using TopDrawer, or copy the data in your favourite plotting program. The plot files are the pseudorapidities and transverse momenta of the first 6 highest-p_T jets in the event (where in this case we are also including the invisibles), the number of jets (Njets) and the total invariant mass in the event (including the invisibles), calculated by:

\[ M^2 = E^2 - \vec{P}^2 , \]

(8.1)

here \( E \) and \( \vec{P} \) are the sums of the all the individual particle energies and 3-momenta respectively, within a certain range of pseudorapidity. The pseudorapidity cut for the jets, as well as other options for the analysis can be found at the relevant section in the input file:

# Choose jet clustering algorithm
set /Herwig/Analysis/MC4BSMAnalysis:JetAlgorithm 2
# Jet ET cut to apply in jet clustering
set /Herwig/Analysis/MC4BSMAnalysis:ETClus 20*GeV
# Cone size used in clustering in merging.
set /Herwig/Analysis/MC4BSMAnalysis:RClus 0.4

\[20\] In a future release, it will be possible to construct it using the FeynRules interface.
# Max |\eta| for jets in clustering in merging.
set /Herwig/Analysis/MC4BSMAnalysis:EtaClusMax 5

The options ETClus, RClus and EtaClusMax correspond to the minimum \( p_T \) of the jets, the clustering parameter for the algorithm and the maximum pseudorapidity for the jets.

Try and see what happens when you switch off the hadronization and underlying event, by uncommenting the relevant pieces:

```
#set LesHouchesHandler:HadronizationHandler  NULL
#set /Herwig/Shower/ShowerHandler:MPIHandler  NULL
```

You may wish to edit the analysis code and see if you can add an extra plot. This can be done by editing `MC4BSMAnalysis.cc` and `MC4BSMAnalysis.h` in the `Contrib/MC4BSMAnalysis` subdirectory. You will need to add a pointer for the new histogram in the `.h` file and then add the analysis code in the `.cc` file to declare the limits of the histogram, fill it in, and write it out. Take the existing histograms as an example. A good one to try is the \( p_T \) of all leptons, for which there already exists commented-out code at the right places in the code for guidance: search for “EXAMPLE NEW HISTOGRAM:” in the code. There should be three points in the `.cc` file and one in the `.h` file.

### 8.3.2 Further reading

For specifics of the **Herwig++** event generator, the manual and release notes for version 2.5 are useful [35, 36]. For further, up-to-date information, you may consult the Wiki pages, at:

http://herwig.hepforge.org/trac/.

For details on the specific inner workings of **Herwig++** and **ThePEG**, consult the Doxygen output at:

http://herwig.hepforge.org/doxygen/index.html
http://thepeg.hepforge.org/doxygen/index.html

Although it may look a bit difficult to navigate through, it is a good starting point to find out how things are interconnected inside the event generator.

### 9 Sherpa tutorial

#### 9.1 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`, `autotake` 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.

9.2 Installation

There are two methods to install SHERPA on your system

9.2.1 ... via package download

The SHERPA sources for this exercise are obtained from either of these sites

• http://sherpa.hepforge.org/trac/wiki/SherpaDownloads/Sherpa-1.4.0
• http://www.slac.stanford.edu/~shoeche/mc4bsm/Sherpa-1.4.0

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

```
tar -xzf SHERPA-MC-1.4.0.tar.gz
cd SHERPA-MC-1.4.0/
./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.

9.2.2 ... 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-1-4-0
cd rel-1-4-0/
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.
9.2.3  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-1.4.0.html

9.3  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 Tevatron using ME+PS merging with up to two jets only (for simplicity). Follow these steps

```
cd Examples/Tevatron_WJets/  
../../bin/Sherpa
```

The example should take about 15 minutes to run.
You should see the following output

```
Welcome to Sherpa, <username>. Initialization of framework underway.  
Run_Parameter::Init(): Setting memory limit to <limit> GB.  
--------------------------------------------------------------------------  
----------- Event generation run with SHERPA started ........ -----------  
--------------------------------------------------------------------------  
... lots more following ...
```

```
+------------------------------------------------------------------+
  |                                                                        |
  | Total XS is 2338.05 pb +- ( 22.9361 pb = 0.98 % ) |
  |                                                                        |
+------------------------------------------------------------------+
```

```
... some more following ...
```

```
Time: 17m 51s on Thu Mar 8 12:31:59 2012  
(User: 17m 49s, System: 2s, Children User: 0s, Children System: 0s)
```

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

Congratulations!

9.3.1  Dealing with problems

If SHERPA refuses to run, please send an email to info@sherpa-mc.de or list the issue on our bug tracker.
9.4 Getting started

The setup is available from

- http://www.slac.stanford.edu/~shoeche/mc4bsm/2012/

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`. 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 9.8 explains how to do this. You can work through Sec. 9.8 first, but it is recommended to follow Secs. 9.5-9.8 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 executable in the subdirectory `<sherpa_prefix>/bin/`, cf. the pre-workshop instructions.

9.5 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 $E$, $\phi_1$ 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_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 Process/P2_2/
```
9.6 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:

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

Run this setup using

\texttt{<sherpa_prefix>/bin/Sherpa}

Again, SHERPA will stop with the message

\texttt{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

\texttt{<sherpa_prefix>/bin/Sherpa}

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

\begin{verbatim}
+---------------------------------------------------------+
| |
| Total XS is 0.444465 pb +- ( 0.00429378 pb = 0.96 % ) |
| |
+---------------------------------------------------------+
\end{verbatim}

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. 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-1.4.0.html#Cross-section.
9.7 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, section 8.5 http://sherpa.hepforge.org/doc/SHERPA-MC-1.4.0.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.

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.
9.8 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

- \( U \rightarrow u \phi_1 \)
- \( U \rightarrow u \phi_2 \)
- \( E \rightarrow e^- \phi_1 \)
- \( \phi_2 \rightarrow e^- e^+ \phi_1 \)

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

Let SHERPA compute the widths using

\(<\text{sherpa_prefix}>/bin/Sherpa\)

Update the widths in the file Particle.dat. This file is linked from \( ./\text{FeynRules}\_\text{Output} \) and will be used in all toy model setups.

9.9 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 \( \rightarrow 11 \, \, -11 \, \, 93\{2\} \)
Order_EW 2; CKKW sqr(30/E_CMS); End process;

These lines instruct SHERPA to generate the process \( pp \rightarrow e^+ e^- \) 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. \( \text{sqr}(30/E_{\text{CMS}}) \) sets the value of \( Q_{\text{cut}} \) to 30 GeV.

Run this setup using

\(<\text{sherpa_prefix}>/bin/Sherpa\)

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

\( ./\text{plot\_results.sh} \)

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

\(<\text{sherpa_prefix}>/bin/Sherpa \, -f \, \text{Run.NLO.dat} \)
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.

### 9.10 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.

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### A The history of the MC4BSM series of workshops

The aim of the MC4BSM series of mini-workshops was to bring together theorists and experimentalists who are interested in developing and using Monte Carlo tools for BSM Physics in preparation for the analysis of data from the LHC. Since simulation of low energy supersymmetry (and the MSSM in particular) was already available from several excellent tools, the focus of the MC4BSM workshops (as the name suggests) was on simulation tools for alternative TeV-scale physics models. The main goals of the workshops were:

- To survey what is available and provide user feedback on experiences with Monte Carlo tools for BSM.
- To identify promising models (or processes) for which the relevant tools are still missing and start filling up those gaps.
- To propose ways to streamline the process of going from from theory models to collider events (see Fig. 1). If this process were made more user-friendly, then a larger community of people would become involved in serious collider studies beyond the MSSM.

The previous MC4BSM workshops were held at Fermilab (2006), Princeton (2007), CERN (2008), UC Davis (2009) and Copenhagen (2010). Many new tools (e.g. BRIDGE [41], MARMOSET [42], CATFISH [43], PYTHIA-UED [44], etc.) and model implementations (e.g. the left-right twin Higgs model [45, 46], the Littlest Higgs model with T-parity [47], Minimal UED [48], etc.) have been reported at these workshops. The latest, 6th installment in the MC4BSM series took place on the beautiful Cornell University campus in Ithaca, NY in March 2012. The weather was unseasonably warm and contributed to the lively atmosphere at the workshop.
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