# FeynRules Tutorial

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## 1 The Model

The model we are going to study is based on the "Hill-model" described in Ref. [1]. This model is a simple extension of the SM, described by the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Hill}, \tag{1}$$

where $\mathcal{L}_{SM}$ is just the usual Standard Model Lagrangian, and $\mathcal{L}_{Hill}$ is the new sector, given by

$$\mathcal{L}_{Hill} = \frac{1}{2}\,\partial_\mu h\,\partial^\mu h - \frac{\lambda_1}{8}\,\Big(f_1\,h - \Phi^\dagger\Phi\Big). \tag{2}$$

$\Phi = \left(\begin{array}{c} 0 \\ (f_0+H)/\sqrt{2}\end{array}\right)$ is just the SM Higgs field (in unitary gauge), and $h$ is a new singlet scalar field (the Hill-field). When the Higgs fields acquires its vev, then the Hill-field acquires a vev as well,

$$\langle\Phi\rangle = \left(\begin{array}{c} 0 \\ f_0/\sqrt{2}\end{array}\right) \Rightarrow \langle h\rangle = \frac{f_0^2}{2f_1}. \tag{3}$$

Furthermore, the two scalar fields mix, and we find the the $2\times 2$ mass matrix

$$\left(\begin{array}{cc} (\lambda_0+\lambda_1)\,f_0^2 & -\lambda_1\,f_0\,f_1 \\ -\lambda_1\,f_0\,f_1 & \lambda_1\,f_1\end{array}\right). \tag{4}$$

In the following we choose, for the sake of the example the following numerical values,

$$\begin{array}{ll} f_0 = 246\,GeV, & \lambda_0 = 0.1, \\ f_1 = 600\,GeV, & \lambda_1 = 0.25. \end{array}$$

After diagonalizing the mass matrix, we find two mass eigenstates $h_1$ and $h_2$, with masses

$$m_1 = 128\,GeV \quad\text{and}\quad m_2 = 420\,GeV, \tag{5}$$

and the relation between the gauge eigenstates and the mass eigenstates is given by

$$\begin{array}{c} H = \cos\alpha\,h_1 - \sin\alpha\,h_2, \\ h = \sin\alpha\,h_1 + \cos\alpha\,h_2. \end{array} \tag{6}$$

## 2 The FeynRules Model file: the particle content

*A full FeynRules model file is available form the Wiki page, together with an example notebook.*

New particles are added in the FeynRules model file to the particle list named `M$ClassesDescription`. The definition of the mass eigenstate $h_1$ could for example look like

```
S[1] == {
  ClassName -> h1,
  SelfConjugate -> True,
  Mass -> {Mh1, 128},
  Width -> {Wh1, 0.005}},
```

and similarly for $h_2$.

FeynRules also offers the possibility to define the gauge eigenstates, together with their relation to the mass eigenstates, via the `Definitions` property. An example is the relation between the SM Higgs-field and the two mass eigenstates $h_1$ and $h_2$,

```
S[3] == {
   ClassName -> H,
   SelfConjugate -> True,
   Unphysical -> True,
   Definitions -> {H -> ca h1- sa h2}},
```

where `ca` and `sa` denote the cos and sin of the misxing angles, defined as parameters in the model file.

## 3 Running FeynRules

### 3.1 Loading FeynRules

FeynRules is loaded into a *Mathematica* notebook via the sequence of instructions

```
$FeynRulesPath = SetDirectory[ < address of the package > ];

<< FeynRules`
```

Once the package is loaded, the model can be loaded into FeynRules via the instructions

```
SetDirectory[ < address of the model file > ];

LoadModel["HillModel.fr"];
```

### 3.2 Getting the Feynman rules

After having loaded the model, the user can enter his Lagrangian (if not yet done so in the model file). The Lagrangian can be written using standard *Mathematica* commands, augmented with some new special commands like Dirac matrices etc. As an example we give here the *Mathematica* expression of the Hill-Lagrangian,

```
LHill = 1/2 del[h, mu]^2 - l1/8 (2 f1 h - HC[Phi].Phi)^2
```

and `Phi` denote the SM Higgs doublet

```
Phi = {0, (f0+H)/Sqrt[2]}
```

It is now straightforward to obtain the Feynman rules. This is done via the command

```
vertices = FeynmanRules[LSM + LHill, FlavorExpand -> True]
```

where the `FlavorExpand` option tells the code that the Feynman rules should be computed with the fields expanded into mass eigenstates. The vertices FeynRules computes are then stored in the variable `vertices` for later use.

FeynRules provides a set of interfaces that output implementations of the BSM model into various matrix element generators. The interfaces write all the files needed by the matrix element generators, without having to touch in file. It is sufficient to copy the output of FeynRules into the corresponding model directory of the matrix element generator (See the MadGraph and CalcHep tutorials for more details). The interfaces are called by the commands

- for MadGraph/MadEvent

  ```
  WriteMGOutput[LSM + LHill]
  ```

- for CalcHep

  ```
  WriteCHOutput[LSM + LHill, MaxExpressionLength -> 100]
  ```

  The option `MaxExpressionLength` is required to set the line length in CalcHep. It should be at least be as long as the longest expression. The interface warns the user in case this number should be increased.

## References

[1] J. J. van der Bij, "The minimal non-minimal standard model," Phys. Lett. B **636**, 56 (2006) [arXiv:hep-ph/0603082].