TASI2013 FeynRules/MadGraph tutorial

The aim of the tutorial is to illustrate with a fully worked out example the path from a theoretical idea (new physics model), to predictions for the LHC and eventually comparison with data:

I New Physics model : Benchmark scenarios and key parameter setting.

II Most promising signanature identification, simulation, and study

III Signal vs Background study and cut-based analysis

IV Comparison with pseudo-experimental data (detector level).

The simulation tools that will be used in the tutorial are: FeynRules (model implementation), MadGraph 5 (matrix element generation at LO and at NLO), Pythia/Herwig (parton-shower/hadronization), Delphes (detector simulation). The pheno study is done in the MadAnalysis 5 framework. MadWeight is used for an advanced analysis technique.

Let us consider the SM Lagrangian start by adding two real scalar fields, ϕ_1 and ϕ_2. They are singlets under all SM gauge groups. Their mass terms are[1]:

$$\mathcal{L}_{kin,scalar} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{m_1^2}{2}\phi_1^2 - \frac{m_2^2}{2}\phi_2^2 - m_{12}^2\phi_1\phi_2\,. \quad (1)$$

We will call mass eigenstates Φ_1 and Φ_2, and their masses M_1 and M_2, respectively, and we will assume $M_1 < M_2$.

We add two 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

$$\mathcal{L}_{dirac,mass} = M_U\overline{U}U + M_E\overline{E}E \quad (2)$$

They interact with scalars via

$$\mathcal{L}_{FFS} = \lambda_{1,i}\,\phi_1\,\overline{U}P_R u_i + \lambda_{2,i}\,\phi_2\,\overline{U}P_R u_i + \lambda'_{1,i}\,\phi_1\,\overline{E}P_R l_i + \lambda'_2\,\phi_2\,\overline{E}P_R l_i + \text{h.c.}\,, \quad (3)$$

where u_i and l_i are the SM up-type quark and charged lepton fields. Note that there is a $\mathbb{Z}_2$ 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 $\mathbb{Z}_2$ also forbids $U - u_i$ and $E - l_i$ mixing via Yukawas with the SM Higgs.

To begin with let us assume that

$$M_U > M_2 > M_E > M_1\,, \quad (4)$$

provides a reasonable mass hierarchy and therefore Φ_1 is the LNP. For U consider three scenarios, $m_U = 200, 400, 800$ GeV, while we always take $M_2 = 100$ GeV and $M_E = 50$ GeV and $M_1 = 1$ GeV. Consider large mixings between u, t and U and e, μ and E:

Exercise 1: Implement the model into FeynRules and export it in the UFO format.

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

Given that U is the only strongly interacting NP particle, this will be the one most copiously produced at the LHC, via the same subprocesses as top-anti-top are produced:

$$p\,p \to \overline{U}\,U\,. \tag{5}$$

Exercise 2: Generate the process at LO with MadGraph 5, and determine the cross section at the LHC 8 TeV for the three benchmark values of the U mass.

Next consider the possible decay chains given the hierarchy of Eq. (**??**):

$$\begin{aligned} &U \to \{u,c,t\}\,\Phi_1\,, \\ &U \to \{u,c,t\}\,\Phi_2\,, \quad \Phi_2 \to \ell\,E\,, \quad E \to \ell'\,\Phi_1 \Rightarrow U \to \{u,c,t\}\,\ell^+\ell'^-\,\Phi_1\,. \end{aligned} \tag{6}$$

ℓ being a label that includes all flavor, $\ell = e,\mu,\tau$. Obviously having the U decaying to a light quark or a top gives very different final state signatures.

Exercise 3: Compare the values of the widths of U, E, ϕ_2 present in the param_card.dat of the model with those that can be directly obtained by running MadGraph 5. Determine the branching ratios of the decay modes above.

Exercise 4: Classify all possible final states in terms of the number of tops, jets ($j = u, c$) and charged leptons. Then consider the two possible decay modes for the W in the top decays, i.e. hadronically or leptonically.

For the sake of simplicity, focus on the following signatures:

I. $pp \to (U \to j\Phi_1)(\bar{U} \to j\Phi_1)$, i.e., $pp \to 2$ jets + missing E_T.

II. $pp \to (U \to t\Phi_1)(\bar{U} \to \bar{t}\Phi_1)$, i.e., $pp \to t\bar{t}$ + missing E_T.

III. $pp \to (U \to j\Phi_1)(\bar{U} \to j\,\ell^+\ell^-\,\Phi_1)$+h.c , i.e., $pp \to \ell^+\ell^-$+ 2 jets + missing E_T ($\ell = e,\mu$).

IV. $pp \to (U \to j\,\ell^+\ell^-\,\Phi_1)(\bar{U} \to j\,\ell^+\ell^-\,\Phi_1)$ + h.c , i.e., $pp \to \ell^+\ell^-\ell^+\ell^-+$ 2 jets + missing E_T ($\ell = e,\mu$).

Exercise 5: Pick one of the processes/signatures above, allowing yourself to select a specific flavor assignment for the final state leptons. Calculate the corresponding rates first by hand and the comparing with MadGraph at

LO. (You can proceed in various ways). Possibly, identify the cross section corresponding to a simplified detector acceptance.

Exercise 6: Identify the dominant reducible and irreducible SM backgrounds to the signatures above. Generate them with MadAnalysis 5, calculate the corresponding rates and order them in importance. Justify the following choices for the dominant backgrounds:

I. $pp \to (Z \to \nu\bar{\nu})$+2 jets.

II. $pp \to t\bar{t}$

III. $pp \to t\bar{t} \to \ell^+\ell^-$+ 2 b-jets + missing E_T

IV. $pp \to t\bar{t}Z$, $pp \to t\bar{t}W^+W^-$,$pp \to t\bar{t}t\bar{t}$

Exercise 7: Depending on the chosen final state signature create the codes and do event generation for the most relevant backgrounds:

I. $pp \to (Z \to \nu\bar{\nu})$+2 jets with the ME/PS merging of $Z + 0, 1, 2$ partons.

II. $pp \to t\bar{t}$ with aMC@NLO and the decays with the DecayPackage.

III. $pp \to t\bar{t} \to \ell^+\ell^-$+ 2 b-jets + missing E_T with MC@NLO and the decays with the DecayPackage.

IV. $pp \to t\bar{t}Z$, $pp \to t\bar{t}W^+W^-$, $pp \to t\bar{t}t\bar{t}$ at LO (including the decays at the MadGraph 5 level).

Exercise 8: Study the distributions of the signal and the background in the acceptance region and identify simple cuts to enhance $S/\sqrt{B}$ keeping S/B as large as possible. Do this via MadAnalysis 5.

Exercise 9: Pass your events to detector simulation using Delphes and compare your predictions with two sets (A and B) of pseudo LHC data. Set limits or establish evidence of new physics in the data.