The Third NCTS School on FeynRules-Madgraph for LHC Physics

Investigating LHC excesses with FeynRules, MadGraph5_aMC@NLO and MadAnalysis5

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(Dated: June 17, 2014)

1. GOALS OF THE TUTORIAL

The aim of this tutorial is to illustrate with a specific example the path linking a theoretical idea (or a new physics model) to predictions for the LHC. We propose three projects finding their origin in recent (2σ and 3σ) excesses observed by ATLAS and CMS [1–3]. Each project can be divided into three steps:

1. New physics model. We start by defining, on the basis of specific theory papers, one benchmark scenario relevant for the physics case of interest, and fix the new physics parameters to appropriate values. The model needs to be implemented into FeynRules [4].
2. Study of a given signature. Parton-level events are generated at the leading-order accuracy with MadGraph5_aMC@NLO [5], on the basis of a decay scheme specific to the considered excess and in the context of the new physics scenario of interest. The generated events are then analyzed with MadAnalysis5 [6], investigating a series of key observables that must be determined.
3. A signal *versus* background study. We first derive the main sources of background for the considered signature. Next, we simulate both signal (with MadGraph5_aMC@NLO, at leading order) and background (with MadGraph5_aMC@NLO, possibly at the next-to-leading order) events and include parton showering and hadronization (as provided by Pythia [7]) and detector simulation (as provided by Delphes [8], using its interface with MadAnalysis5). A cut-based analysis must be implemented in the MadAnalysis5 framework, inspired by the associated experimental publication.

2. PROJECT 1: STUDYING A W^+W^- EXCESS OBSERVED BY THE CMS COLLABORATION

In this first project, we aim to explain a 2σ excess of W^+W^- events reported by the CMS collaboration, using 3.5 fb^{-1} of 8 TeV data [1]. This excess can be explained in a simple supersymmetric context [9], the gap between Standard Model predictions and data being filled by dilepton plus missing energy events originating from the production of a pair of top squarks,

$$pp \to \tilde{t}_1 \tilde{t}_1^* \ . \tag{2.1}$$

Dilepton events arise when each top squark $\tilde{t}_1$ decays into a chargino $\tilde{\chi}_1^\pm$ (assumed to be purely wino) and a bottom quark b, the chargino further decaying into a three-body final state comprised of a lepton ℓ, a neutrino ν and a lightest neutralino $\tilde{\chi}_1^0$ (assumed to be an admixture of a bino and a wino state),

$$\tilde{t}_1 \to \tilde{\chi}_1^+ b \to \ell^+ \nu_\ell \tilde{\chi}_1^0 \ b \ . \tag{2.2}$$

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More precisely, the stop and neutralino mass-eigenstates depend on two mixing angles $\theta_{\tilde t}$ and $\theta_{\tilde\chi}$ and are defined in terms of the stop gauge-eigenstates ($\tilde t_L$ and $\tilde t_R$) and the neutral wino ($\tilde W_3$) and bino ($\tilde B$) fields,

$$\begin{aligned} \tilde t_1 =&\ \cos\theta_{\tilde t}\ \tilde t_L + \sin\theta_{\tilde t}\ \tilde t_R\ , \\ \chi_1^0 =&\ \cos\theta_{\tilde\chi^0}\ \tilde B + \sin\theta_{\tilde\chi^0}\ \tilde W_3 \quad \text{[neglecting the higgsino pieces].} \end{aligned} \tag{2.3}$$

The dynamics of this model is described by the Lagrangian

$$\begin{aligned} \mathcal{L} = \mathcal{L}_{\rm SM} + D_\mu \tilde t_1^\dagger\ D^\mu \tilde t_1 + \frac{i}{2}\bar{\tilde\chi}_1^0 \not\partial \tilde\chi_1^0 + i\bar{\tilde\chi}_1^+ \not\partial \tilde\chi_1^+ - m^2_{\tilde t_1} \tilde t_1^\dagger \tilde t_1 - m_{\tilde\chi_1^\pm} \bar{\tilde\chi}_1^+ \tilde\chi_1^+ - \frac{1}{2} m_{\tilde\chi_1^0} \bar{\tilde\chi}_1^0 \tilde\chi_1^0 \\ - g\cos\theta_{\tilde t}\Big(\bar b^c P_L \tilde\chi_1^+ + \text{h.c.}\Big) - g\sin\theta_{\tilde\chi^0}\Big(W_\mu^- \bar{\tilde\chi}_1^0 \gamma^\mu \tilde\chi_1^+ + \text{h.c.}\Big)\ , \end{aligned} \tag{2.4}$$

where $m_{\tilde t_1}$, $m_{\tilde\chi_1^\pm}$ and $m_{\tilde\chi_1^0}$ denote the masses of the stop, chargino and neutralino, respectively, and g the weak coupling. We neglect all electroweak interactions of the top squark as irrelevant for the process of interest, or we equivalently restrict ourselves to the QCD pieces of the covariant derivative acting on the $\tilde t_1$ field. Along similar lines, we only pick up the relevant interactions involving a chargino and/or a neutralino field.

3. PROJECT 2: STUDYING A TRILEPTON EXCESS OBSERVED BY THE ATLAS COLLABORATION

Recently, the ATLAS collaboration has investigated all recorded 8 TeV data and searched for hints of charginos and neutralinos [2]. The experimental publication reports a 2σ excess of trilepton events that feature, in addition, a large amount of missing energy and no b-jet. This excess can be explained by a simplified model inspired by the Minimal Supersymmetric Standard Model (MSSM), where the Standard Model is supplemented by a chargino assumed to be purely wino, and two neutralinos that are mostly gaugino-like [9]. The latter can indeed be approximately considered as admixtures of the neutral bino and wino states ($\tilde B$ and $\tilde W_3$) and exhibit a negligible non-vanishing higgsino fraction,

$$\chi_1^0 \approx \cos\theta_{\tilde\chi^0}\ \tilde B + \sin\theta_{\tilde\chi^0}\ \tilde W_3 \qquad \text{and} \qquad \chi_2^0 \approx -\sin\theta_{\tilde\chi^0}\ \tilde B + \cos\theta_{\tilde\chi^0}\ \tilde W_3\ . \tag{3.1}$$

In this case, the associated production of a chargino with the heaviest of the two neutralinos,

$$pp \to \tilde\chi_1^\pm \tilde\chi_2^0\ , \tag{3.2}$$

can be manifest through events containing three leptons and missing energy, in cases where both gauginos decay as

$$\tilde\chi_1^\pm \to W^\pm \tilde\chi_1^0 \to \ell^\pm \nu \tilde\chi_1^0 \qquad \text{and} \qquad \tilde\chi_2^0 \to Z\tilde\chi_1^0 \to \ell^+\ell^- \tilde\chi_1^0\ . \tag{3.3}$$

Considering only the MSSM interactions relevant for the process of interest, the dynamics of the simplified model is described by

$$\begin{aligned} \mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\bar{\tilde\chi}_1^0 \not\partial \tilde\chi_1^0 + \frac{i}{2}\bar{\tilde\chi}_2^0 \not\partial \tilde\chi_2^0 + i\bar{\tilde\chi}_1^+ \not\partial \tilde\chi_1^+ - m_{\tilde\chi_1^\pm} \bar{\tilde\chi}_1^+ \tilde\chi_1^+ - \frac{1}{2} m_{\tilde\chi_1^0} \bar{\tilde\chi}_1^0 \tilde\chi_1^0 - \frac{1}{2} m_{\tilde\chi_2^0} \bar{\tilde\chi}_2^0 \tilde\chi_2^0 \\ - g\Big(\sin\theta_{\tilde\chi^0} W_\mu^- \bar{\tilde\chi}_1^0 \gamma^\mu \tilde\chi_1^+ + \cos\theta_{\tilde\chi^0} W_\mu^- \bar{\tilde\chi}_2^0 \gamma^\mu \tilde\chi_1^+ + \text{h.c.}\Big) - \alpha \frac{g}{2\cos\theta_w} Z_\mu \bar{\tilde\chi}_1^0 \gamma^\mu \gamma_5 \tilde\chi_2^0\ , \end{aligned} \tag{3.4}$$

where α is a small number related to the Higgsino fraction of both neutralinos, θ_w and g are the weak mixing angle and coupling constant and $m_{\tilde\chi_1^\pm}$, $m_{\tilde\chi_1^0}$ and $m_{\tilde\chi_2^0}$ are the masses of the supersymmetric particles of the model.

4. PROJECT 3: STUDYING A MULTILEPTON EXCESS IN CMS EVENTS

In this last project, we study a CMS analysis using all 8 TeV data and probing a multileptonic final state signature [3]. The experimental publication reports a 3σ excess in a signal region defined by requiring three electrons or muons that are not compatible with a Z-boson, one hadronically decaying tau, no b-jet and a low hadronic activity. It has been shown that this excess can be explained in a simplified MSSM context when supersymmetry is broken via general gauge mediation [10]. In this setup, the Standard Model is supplemented by three right-handed sleptons, a heavy bino and a gravitino. The excess is then accommodated by the production of a pair of right-handed sleptons,

$$pp \to \tilde\ell_R^+ \tilde\ell_R^- \tag{4.1}$$

each of them further decaying (via an off-shell bino) into a charged lepton, a pair of taus and a gravitino,

$$\tilde{\ell}^-_R \to \ell^- \tau^\pm \tilde{\tau}^\mp_R \to \ell^- \tau^+ \tau^- \tilde{G} \ . \tag{4.2}$$

The signal region is populated after a combination of leptonic and hadronic decays of the final state taus.

Making use of the goldstino-gravitino equivalence, the spin-3/2 gravitino field is replaced by the spin-1/2 goldstino field χ, the resulting Lagrangian being

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\bar{\tilde{B}}\not{\partial}\tilde{B} - \frac{1}{2}m_{\tilde{B}}\bar{\tilde{B}}\tilde{B} - \frac{1}{2}m_{32}\bar{\chi}\chi + \sum_f \Big\{ & D_\mu \tilde{\ell}^+_{Rf} D^\mu \tilde{\ell}^-_{Rf} - m^2_{\tilde{\ell}_{Rf}} \tilde{\ell}^+_{Rf}\tilde{\ell}^-_{Rf} \\ & - \sqrt{2}g' \Big[\tilde{\ell}^+_{Rf}\bar{\tilde{B}}P_R \ell^-_f + \text{h.c.}\Big] + \frac{\sqrt{3}\big(m^2_{\tilde{\ell}_{Rf}} - m^2_{\ell_f}\big)}{3m_{3/2}m_P}\Big[i\ \tilde{\ell}^+_{Rf}\bar{\chi}P_R\ell^- + \text{h.c.}\Big]\Big\} \ ,\end{aligned} \tag{4.3}$$

where f is a generation index, g' the hypercharge coupling constant and m_P the Planck mass. The masses of the gravitino, of the bino and those of the (s)leptons are denoted by m_{32}, $m_{\tilde{B}}$ and m_{ℓ_f} ($m_{\tilde{\ell}_{Rf}}$), respectively.

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