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Connecting simplified models: Constraining supersymmetry on triangles

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ABSTRACT

We investigate an approach for the presentation of experimental constraints on supersymmetric scenarios. It is a triangle-based visualization that extends the status quo wherein the LHC results are reported in terms of simplified models under the assumption of 100% branching ratios. We show that the (re)interpretation of the LHC data on triangles allows the extraction of accurate exclusion limits for a multitude of more realistic models with arbitrary branching ratios. We demonstrate the utility of this triangle visualization approach using the example of gluino production and decay in several common supersymmetric scenarios.

1. Introduction

The extent to which supersymmetric scenarios are excluded by data from the LHC experiments is obscured by the breadth of realizations with which such scenarios might manifest themselves. In order to make this problem more tractable while avoiding the prejudices of specific UV completions (e.g. CMSSM), the ATLAS and CMS experiments have adopted the strategy of distilling theoretical scenarios into "Simplified Models" [1–3] that reduce the parameters of the theory to those that directly affect the experimental observability of the supersymmetric signal. While this has been a significant improvement in the way the LHC experimental constraints on supersymmetry are presented, this approach also has a number of shortcomings. In this Letter, we present an extension of the simplified model approach that addresses one such limitation, namely the commonly made, though often unrealistic assumption that any new particles produced will have 100% Branching Ratio (BR) into the experimental final states over which the search is conducted.

In this work we will focus on the gluino as an example of a SUSY particle where the existence of a number of possible decay modes complicates the interpretation of the experimental results produced by the LHC collaborations. Even in scenarios in which the gluino decays only to the lightest neutralino plus a quark–antiquark pair, there are distinct possibilities for the decay that are optimized with different search strategies. In principle, the possibility of two different decay modes for a pair-produced supersymmetric particle could significantly weaken the exclusion limits obtained by assuming 100% BR into the final states considered in the experimental search. The triangle approach we adopt here for presentation of the experimental limits allows one to visualize this effect.

2. Points on the triangle

By definition, the sum of a particle's branching ratios add up to one. A particle with 100% BR into a single set of final states represents a Simplified Model Scenario (SMS) which is a single point on the parameter space of all possible models of the particle. Models with branching ratios of a particle into two independent final states all lie on a straight line given the constraint on the total branching ratio. Similarly, all models of the particle with three independent decay modes are confined to a triangle since there are only two free parameters. Note that models with greater than 3 decay final states cannot be visualized in the same manner on a 2-dimensional plot. Nevertheless, all models with up to three decay final states can be presented by adopting the triangle visualization method. Let us denote the three decay branching fractions of a supersymmetric particle as $\mathcal{B}_A$, $\mathcal{B}_B$, and $\mathcal{B}_C$. The space spanned by scanning over values of $(\mathcal{B}_A, \mathcal{B}_B, \mathcal{B}_C)$ is a triangular plane. Each point on the 2-dimensional space can be written in terms of the branching ratios as:

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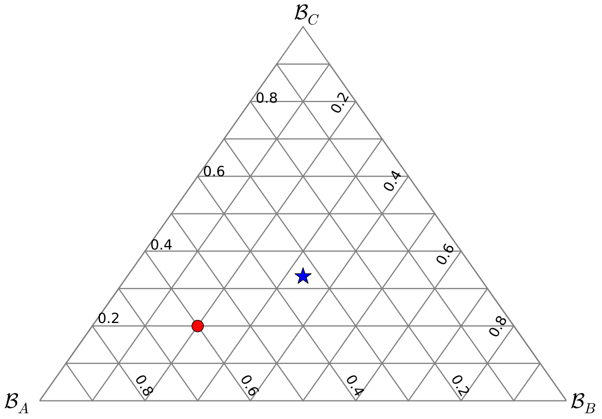

Fig. 1. Every point in this skeleton grid has a unique value for branching ratios $\mathcal{B}_A$, $\mathcal{B}_B$, and $\mathcal{B}_C$. Each particular branching ratio decreases from 1 at a vertex to 0 at the side opposite to that vertex. The grid lines are drawn to show the variation of the branching ratios in each direction inside the triangle. The point marked by a ★ denotes the centroid of the triangle and is composed of equal branching ratios, $(\mathcal{B}_A, \mathcal{B}_B, \mathcal{B}_C) = (33\%, 33\%, 33\%)$. The point marked by ● is composed of branching ratios, $(\mathcal{B}_A, \mathcal{B}_B, \mathcal{B}_C) = (60\%, 20\%, 20\%)$.

$$(x, y) = \left(\frac{1}{2}\frac{2\mathcal{B}_B + \mathcal{B}_C}{\mathcal{B}_A + \mathcal{B}_B + \mathcal{B}_C}, \frac{\sqrt{3}}{2}\frac{\mathcal{B}_C}{\mathcal{B}_A + \mathcal{B}_B + \mathcal{B}_C}\right) \qquad (1)$$

With the constraint that $\mathcal{B}_A + \mathcal{B}_B + \mathcal{B}_C = 1$, the three vertices of the equilateral triangle (with the vertices located at $(0, 0)$, $(1, 0)$ and at $(\frac{1}{2}, \frac{\sqrt{3}}{2})$) correspond to simplified models with $\mathcal{B}_A = 1$, $\mathcal{B}_B = 1$, and $\mathcal{B}_C = 1$ respectively. The skeleton grid representing each point on the 2-dimensional plane is shown in Fig. 1. The grid lines serve as a guide to read off the composition of branching ratios at each point within the triangle. For example, the point marked by a ★ denotes the centroid of the triangle and is composed of equal branching ratios, $(\mathcal{B}_A, \mathcal{B}_B, \mathcal{B}_C) = (33\%, 33\%, 33\%)$. Similarly, the point marked by ● is composed of branching ratios, $(\mathcal{B}_A, \mathcal{B}_B, \mathcal{B}_C) = (60\%, 20\%, 20\%)$.

In this representation, the vertices are the Simplified Model Scenarios (SMS) for which experimental constraints have been published in the literature. The edges connecting any two vertices of the triangle are models with various combinations of the two branching ratios located at the respective vertices. The rest of the triangle, however, contains more realistic scenarios with multiple decay modes of the parent particle that have not been explicitly confronted with LHC data (though in principle they could be). In fact, the advantages of such triangular visualization have already been demonstrated in two non-supersymmetric BSM analyses, namely the search for vector-like top partners, "T quarks" [4, 5]. Since a T quark can decay into three final states: bW, tZ or tH, by presenting the experimental constraints on triangles, CMS and ATLAS were able to conduct the search without making any assumptions on the branching fractions and place the most stringent bounds on the entire parameter space. In this work, we apply the triangle visualization approach to searches for supersymmetry where it will be useful, given the fact that most supersymmetric particles decay into multiple final states as stated in the Introduction.

3. Example: gluino decays

In Ref. [6], the CMS collaboration searched for evidence of supersymmetry in events with large missing energy, jets, b-jets and no leptons. In addition, events were required to have $\Delta\hat{\phi}_{\text{min}} > 4.0$, where $\Delta\hat{\phi}_{\text{min}} = \min(\Delta\phi_i/\sigma_{\Delta\phi_i})$ and $\Delta\phi$ is the angle between a jet and the negative of the $\not{E}_T$ vector, and $\sigma_{\Delta\phi_i}$ is the estimated resolution of $\Delta\phi$. By requiring $\Delta\hat{\phi}_{\text{min}} > 4.0$, most of the QCD background was eliminated. The observed number of events in several signal regions was consistent with the expected SM backgrounds and 95% upper limits on the presence of new physics were extracted. The upper limits were interpreted as bounds on gluino production in two different SMS: (i) 100% branching ratio of $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$ (T1bbbb) and (ii) 100% branching ratio of $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ (T1tttt). By requiring b-jets and vetoing events with leptons, the search was most sensitive to the T1bbbb SMS. At 95% C.L., gluinos lighter than 1170 GeV were excluded in the T1bbbb SMS and gluinos lighter than 1050 GeV in the T1tttt SMS. In this section, we will show that the results from the "$\Delta\hat{\phi}$" analysis in Ref. [6] can be reinterpreted to obtain stringent constraints on a wide range of more realistic models with the triangle visualization approach.

We pick three branching ratios and consider benchmarks points along the grid in Fig. 1. For each point, the procedure is similar. We generate 10,000 gluino pair-production events for 8 TeV LHC using `PYTHIA 8.175` [7]. `PYTHIA` decays the gluino pair according to the branching ratios at the point on the triangle and hadronizes the decay products. Next, a detector simulation is employed to estimate the Acceptance × Efficiency $(A \times \varepsilon)$ for these signal events to pass the selection criteria of Ref. [6]. While the most accurate estimation of $A \times \varepsilon$ can only be achieved by a full `GEANT` [8] simulation of the detector (which can only be performed by the experimental collaborations), a decent parametric simulation of the detector is sufficient for our purposes and for this we use `Delphes 3.0.9` [9]. We use the default "CMS" detector card provided by `Delphes` adapted to account for the electron and muon isolation criteria applied in the CMS analysis and modified to match the track and jet reconstruction parameters quoted in Ref. [6]. In addition, we modify the b-tagging efficiency in the `Delphes` CMS detector card using the efficiency information for the combined-secondary-vertex algorithm reported in Ref. [10].

Finally, our dedicated C++ code reads in the `ROOT` file output from `Delphes` and implements the event selection from Ref. [6]. The events that pass the selection criteria in each signal region are scaled by the appropriate NLO cross-section [11] and normalized to an integrated luminosity of 19.6 fb^{-1} to be consistent with the published analysis. The expected number of signal events, $N_{\text{sig}} = \sigma_{\text{NLO}} \times \int \mathcal{L}dt \times (A \times \varepsilon)$, obtained in this manner are compared to the observed number of events quoted by the experimental collaboration in their published analysis [6]. A specific model is considered excluded if $N_{\text{sig}} > N_{\text{UL}}$ where N_{UL} is the 95% Bayesian upper limit (assuming a flat prior) on events produced by the BSM process, computed given the estimated SM backgrounds and the observed number of events, reported in Ref. [6]. Using this procedure, we fill the skeleton grid shown in Fig. 1 with color maps of the gluino exclusion limit at 95% C.L. from the best signal region of the $\Delta\hat{\phi}$ analysis and the results are presented in Figs. 2, 3(a) and 3(b). There is a kinematic lower bound on the gluino mass for each model. In addition, the experimental efficiencies degrade rapidly for small mass differences between the gluino and LSP due to the relatively low momenta of the decays products. Consequently, the bounds do not extend all the way to zero-mass of the gluino and we consider the range of gluino mass specified by the analysis, which in this case is 400 GeV and above.

The first result we present is for the simplest scenario where only one neutralino is lighter than the gluino. In this case, the gluino predominantly decays into $q\bar{q}\tilde{\chi}_1^0$, $b\bar{b}\tilde{\chi}_1^0$, $t\bar{t}\tilde{\chi}_1^0$. The triangle with the branching fractions for these decay modes set to 100% at the vertices, with the neutralino mass set to 100 GeV and all other supersymmetric particles decoupled is shown in Fig. 2. Note, we can check our $\Delta\hat{\phi}$ reinterpretation analysis against the CMS analysis at the vertices that correspond to the T1bbbb and T1tttt sim-