Novel gluino cascade decays in $E_6$ inspired models

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We point out that the extra neutralinos and charginos, generically appearing in a large class of $E_6$ inspired models, lead to distinctive signatures from gluino cascade decays involving longer decay chains, more visible transverse energy, softer jets and leptons and less missing transverse energy than in the Minimal supersymmetric Standard Model (MSSM). On the one hand, this makes the gluino harder to discover for certain types of conventional analysis. On the other hand, the $E_6$ inspired models have enhanced 3- and 4-lepton signatures, as compared to the MSSM. making the gluino more visible in these channels. After extensive scans over the parameter space, we focus on representative benchmark points for the two models, and perform a detailed Monte Carlo analysis of the 3-lepton channel, showing that $E_6$ inspired models are clearly distinguishable from the MSSM in gluino cascade decays.

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INTRODUCTION

The general idea of softly broken supersymmetry (SUSY) provides a very attractive framework for physics models beyond the standard model (SM), in which the hierarchy problem is solved [1]. In addition SUSY may provide a dark matter (DM) candidate, a route towards a Grand Unified Theory (GUT), and indirect support for string theory. However, it is not strictly necessary that the theory be perturbative right up to the GUT scale.

The simplest SUSY extension to the SM, the minimal supersymmetric standard model (MSSM), has been subjected to particularly close scrutiny at the CERN Large Hadron Collider (LHC). For example, searches at ATLAS [2] and CMS [3], under certain assumptions, constrain the MSSM gluino mass to be greater than about 500–700 GeV, while the squarks of the first and second family are typically constrained to be heavier than about 1 TeV. ATLAS and CMS indications of a Higgs boson with a mass in the region $\sim 124–126$ GeV [4,5] also suggest that some of the third family squark masses should also exceed 1 TeV, although this is not necessary in more general SUSY models such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [6-9].

The idea of SUSY is more general than either the MSSM or the NMSSM. Here we shall focus on theoretically plausible models which are motivated by an $E_6$ gauge group, typically arising in many string constructions, and which involve three complete 27 representations families of $E_6$ at the TeV scale, each family consisting of a complete 16-component SM family $Q, \tilde{u}, \tilde{d}, L, \tilde{e}, \nu, c$, colour triplet and antitriplet $D, \tilde{T}$, two Higgs doublets $H_u, H_d$ and one SM singlet $S$. For definiteness we shall consider a particular model called the $E_6$SSM [10], where the right-handed neutrinos $\nu_3$ are decoupled at a high scale, although analogous results apply more generally to the other $E_6$ models [11] with a low energy gauged $U(1)^\prime$ [12]. It is well known [13] that in such $E_6$ models the neutralino and chargino sectors of the MSSM are augmented by eight additional neutralino states: two associated with the fermionic partners to the $Z$ and third singlet $S_3$ (denoted USSM neutralinos), two further singlinos $S_{1,2}$ and four neutral Higgsinos. It is the singlet $S_3$ which acquire a vacuum expectation value (VEV) $\langle S_3 \rangle = s/\sqrt{2}$ and provides an effective $\mu$-term, $\sqrt{2} S_{3/2}$. There are also two additional chargino states. Moreover, it has been pointed out that two of the extra singlet-dominated neutralino states must be light, with one of them most likely being the lightest supersymmetric particle (LSP), providing a new possible source of dark matter [13] as well as interesting Higgs phenomenology.

In this paper we show that the augmented neutralino and chargino sectors of the $E_6$ models lead to distinctive signatures from gluino decays. This is significant since colour octet gluinos are expected to be pair produced at the LHC with rather large cross-sections, then, due to $R$-parity conservation, decay into pairs of the LSP together with leptons and jets. We point out that in $E_6$ models, due to the augmented neutralino and chargino sectors, the gluino cascade decays will generically involve more links in the decay chains and less missing transverse energy than in the MSSM. To illustrate this, we perform scans over parameter space and focus on particular benchmark points in the MSSM and $E_6$SSM which we subject to a detailed Monte Carlo (MC) analysis.

PARAMETER SPACES

WMAP [15] puts a bound on the LSP’s relic density and the recent XENON100 experiment [16] puts a bound on the direct detection cross-section for the LSP
TABLE I. The scanning region, where \( \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle} \) is the ratio of the third family Higgs vevs, \( M_A \) is the mass of the pseudoscalar Higgs boson and \( A \) is the soft trilinear coupling. A common squark and sleptron mass scale was fixed to \( M_S = 2 \) TeV. For the E\(_6\)SSM a large number of Yukawa couplings were scanned over which is omitted from this table.

for a given relic density. These constraints exclude large portions of the parameter space for SUSY models. We have used CalcHEP \cite{17} and MicrOMEGAs \cite{18} when scanning the parameter spaces of the MSSM and E\(_6\)SSM to pick out benchmarks which satisfy these constraints on the LSP as well as constraints from collider experiments. The scanning regions are presented in Tab. I and points, including benchmarks, are plotted in the plane of the LSP relic density and the direct detection cross-section in Fig. 1.

The gluino decay chain length, \( l \), relevant here is defined as the number of steps in the gluino decay chain after the first squark and illustrated in Fig. 2. To be able to compare the models on a common basis the gaugino masses were fixed so that a gluino mass of 700 GeV, a wino mass around 300 GeV and a bino mass around 150 GeV were provided. By contrast the squarks are all assumed to be much heavier, which is a characteristic feature of the constrained E\(_6\)SSM \cite{19}, with universal high energy soft scalar and gaugino masses, although here we only consider the low energy version of the model.

BENCHMARKS

The benchmarks considered for MC event analysis are summarized in Tab. I and encircled in Fig. 1. These benchmarks do not provide the whole observed amount of dark matter and so an additional source of dark matter is assumed. For the chosen MSSM benchmark the LSP is bino-like and annihilates via the pseudoscalar Higgs resonance, reducing its relic abundance below the observed value. For the E\(_6\)SSM benchmark the overwhelmingly inert-neutralino-like LSP contains significant inert Higgsino components and annihilates via the Higgs resonance, near 125 GeV.

FIG. 1. The scanned regions of the parameter space projected onto the plane spanned by the spin independent cross-section, \( \sigma_{SI} \), and the relic density, \( \Omega h^2 \). The area right of the vertical solid line is excluded by WMAP \cite{15} and the area above the diagonal line is excluded by XENON100 \cite{16} where the direct detection cross-section exclusion of the LSP gets weighted by its relic density. The colouring represents the effective gluino decay chain length \( l_{\text{eff}} = \sum_l P(l) \) for each point, where \( P(l) \) is the probability for a chain length of \( l \), as defined in Fig. 2. The chosen benchmarks of MSSM and E\(_6\)SSM are encircled.

FIG. 2. The definition of the gluino decay chain length, \( l \).

EVENT ANALYSIS

Since the E\(_6\)SSM introduces new neutralinos, naturally lighter than the MSSM LSP, the gluino decay chains will be longer than the MSSM’s in general. This is confirmed and illustrated by the parameter scans in Fig. 1 and benchmarks in Tab. I. An effect of longer decay chains is that there will be less missing momentum in collider experiments. This affects the main SUSY searches based on jets and missing energy, e.g. \cite{2} and \cite{20}, which provide the best statistics and strongest exclusions. In these searches the E\(_6\)SSM is disfavoured compared to the MSSM and the acquired exclusions do not hold for this model. The main reason for the suppression of the E\(_6\)SSM comes from hard cuts on missing energy and its ratio with the effective mass. Our analysis show that the distributions for these variables are significantly different for these models. The distributions of the missing transverse momentum, \( p_T \), and the effective mass, \( M_{\text{eff}} = \sum_{\text{visible}} p_T \), before cuts are plotted in Fig. 3 for our benchmarks to illustrate this difference. We have generated MC events using CalcHEP \cite{17} with CTEQ6L PDFs and we assume 30 fb\(^{-1}\) of LHC data at \( \sqrt{s} = 8 \) TeV. In this setup the cross-section for gluino pair-production at LHC for our benchmarks is 93 fb im-
where the leading lepton has instead the \( E^+ \) favourble channel of discovery and a channel in which certain guino decay chain lengths, \( l \), and relic density and spin independent direct detection cross-section of the LSP. To the right: masses of neutralinos (absolute values), charginos and the lightest Higgs. In the notation for neutralino and chargino states the subscript \( M \) denotes a MSSM-like state, \( U \) a USSM-like state and \( E \) an \( E_6 \)SSM-like state. This distinction is reasonable since these sectors are very weakly coupled. The following number orders the states by mass. The squark and slepton mass scale is set to 2 TeV. Additional Yukawa couplings for the \( E_6 \)SSM benchmark is given in Tab. 11.

\[
\begin{align*}
\lambda_{22} &= -5 \times 10^{-4} \, f_{a22} \
\lambda_{21} &= 4.2 \times 10^{-2} \, f_{a21} \
\lambda_{12} &= 4.5 \times 10^{-2} \, f_{a12} \
\lambda_{11} &= 1 \times 10^{-3} \, f_{a11}
\end{align*}
\]

\[
\sigma_{SI} = 0.04 \times 10^{-8} \, 15.3 \times 10^{-8} \, \text{[GeV]}^3
\]

TABLE II. Properties of the benchmarks. To the left: input parameters, including the soft gaugino masses \( M_1, M_2, M_3 \), and the physical gluino mass \( m_{\tilde{g}} \). Table entries \( P(l) \) are branchings, \( P(l) \) of certain guino decay chain lengths, \( l \), and of the leading lepton with \( \mu \leq 20 \text{GeV} \). We have also applied a Gaussian smearing of lepton and jet energies to take into account the detector energy resolution typical for the ATLAS and CMS detectors. The dominant background is coming from \( ZWj \) and \( t\bar{t}V \), other important contributions come from \( ZW \) and \( t\bar{t} \). Our background predictions agree well with backgrounds used in multi-lepton searches by CMS [21] and ATLAS [22]. By choosing a signal region defined by the cut \( M_{\text{eff}} > 900 \text{GeV} \), \( S = 36 \) signal events and \( B = 5 \) background events are expected. Using the definition of statistical significance, \( S_{12} = 2(\sqrt{S + B} - \sqrt{B}) \), valid for small statistics [23, 24], a 8.3\( \sigma \) excess is predicted. Even for 15\( \text{fb}^{-1} \) integrated luminosity the signal is discoverable with a 5.9\( \sigma \) excess.

![FIG. 3. Feynman diagrams for the leading gluino decay chains for each benchmark. The branching ratios for produced particles are denoted in brackets.](image-url)

![FIG. 4. Missing transverse momentum and the effective mass before cuts.](image-url)

![FIG. 5. Lepton multiplicity and jet multiplicity, requiring \( p_T > 10 \text{GeV}, |\eta| < 2.5 \) and \( \Delta R(\text{lepton, jet}) > 0.5 \) for leptons and \( p_T > 20 \text{GeV} \) and \( |\eta| < 1.5 \) for jets.](image-url)
CONCLUSIONS

We have demonstrated that the extra neutralinos and charginos, generically appearing in $E_6$ inspired models, lead to gluino decays involving longer decay chains, more visible transverse energy, softer jets and leptons and less missing transverse energy than in the MSSM. This makes the $E_6$ inspired gluino harder to discover for certain types of conventional analysis based on large missing energy with a conventional multi-jet or 1-lepton analyses, and it is possible that the gluino signal in the E$_6$SSM could be missed in these channels. On the other hand, the $E_6$ signatures have an enriched lepton multiplicity, providing distinctive 3- and 4-lepton decay modes, which are disfavoured in the MSSM, making the $E_6$ inspired gluino more visible in these channels. For example, the 3-lepton signature from gluino cascade decays, may easily be visible for the E$_6$SSM, while the analogous signal for the MSSM would be buried under the background.

In conclusion, the gluino is not only a key prediction of SUSY, but also distinguishes different SUSY models since its visibility depends strongly on the model and on the search channel. These specific features of the E$_6$SSM and analogous models should be taken into account and included in current experimental searches. This could provide different limits for the E$_6$SSM gluino, as compared to the MSSM, or perhaps even to an earlier SUSY discovery.

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