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E_6 inspired SUSY benchmarks, dark matter relic density and a 125 GeV Higgs

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ABSTRACT

We explore the relic density of dark matter and the particle spectrum within a constrained version of an E_6 inspired SUSY model with an extra $U(1)_N$ gauge symmetry. In this model a single exact custodial symmetry forbids tree-level flavor-changing transitions and the most dangerous baryon and lepton number violating operators. We present a set of benchmark points showing scenarios that have a SM-like Higgs mass of 125 GeV and sparticle masses above the LHC limits. They lead to striking new physics signatures which may be observed during run II of the LHC and can distinguish this model from the simplest SUSY extensions of the SM. At the same time these benchmark scenarios are consistent with the measured dark matter abundance and necessarily lead to large dark matter direct detection cross sections close to current limits and observable soon at the XENON1T experiment.

1. Introduction

With the discovery of the 125 GeV Higgs boson [1,2] made in run I of the Large Hadron Collider (LHC), the primary goal of run II of the LHC is now to look for signs of physics beyond the standard model (SM). The best motivated class of extensions of the SM are models based on low–energy supersymmetry (SUSY). Supersymmetry is the most general extension of the Poincaré group [3,4]. When the new SUSY partners have masses around the TeV scale the minimal supersymmetric standard model (MSSM) allows to address the hierarchy problem, to achieve the unification of the SM gauge couplings, allowing the MSSM to be embedded into a Grand Unified Theory (GUT), and to predict the correct relic abundance of dark matter (DM) simultaneously.

E_6 inspired SUSY models provide a very attractive framework for GUT scale physics and can arise from $E_8 \times E'_8$ heterotic string theory [5–7]. At low energies these models can lead to an extra $U(1)$ gauge symmetry which is spontaneously broken, giving rise to an effective μ term and a massive Z' gauge boson. E_6 inspired SUSY extensions of the SM gathered a lot of attention in the past (see, for example, [8–18]).

More recently the exceptional supersymmetric standard model (E$_6$SSM) was proposed [19–22] where right-handed neutrinos have zero charge under the extra $U(1)_N$ gauge symmetry. Only in this case can the right-handed neutrinos be superheavy, allowing the see-saw mechanism to explain the mass hierarchy in the lepton sector and providing a mechanism for the generation of the baryon asymmetry in the Universe via leptogenesis [23]. Different modifications of this SUSY model were also considered [24–26].

To obtain realistic phenomenology the E$_6$SSM has an approximate Z_2^H symmetry to forbid large flavor-changing neutral currents (FCNCs), as well as another exact Z_2 symmetry which plays a similar role to R-parity in the MSSM. The existence of light exotic states in this model, which are not present in the MSSM, could explain the observed relic DM density [27]. However such scenarios also imply that the lightest SM-like Higgs boson decays predominantly into DM exotic states, which also have an unacceptably large spin independent elastic cross section [28]. Thus the corresponding scenarios have been ruled out by DM direct detection and LHC experiments. The proposed phenomenologically viable modification of the E$_6$SSM requires the imposition of another discrete symmetry [29] in addition to the set of approximate and exact discrete symmetries mentioned above, to prevent an MSSM-like neutralino from decaying into these exotic states.

Here we investigate for the first time the constrained version of a recently proposed alternative modification of the E$_6$SSM (CSE$_6$SSM) [30]. This model makes use of recent work on E_6 orbifold GUTs [26] where an exact discrete symmetry was found which forbids both couplings that induce large FCNCs and those that lead to rapid proton decay. At the same time the model also

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conserves matter parity, which implies that there is a bino-like or Higgsino-like stable DM candidate. In fact the CSE$_6$SSM has two potential DM candidates, as the discrete symmetry which forbids FCNCs and proton decay leads to the lightest exotic particle also being stable.

In this letter we demonstrate that a DM candidate stabilized by the automatic conservation of matter parity is sufficient to fit the relic DM density within the CSE$_6$SSM while the second candidate is almost massless and therefore contributes negligibly to the DM density in the simplest phenomenologically viable scenarios. In this way we can explain the measured density of DM, while also satisfying LHC constraints such as the 125 GeV Higgs mass measurement and mass limits on sparticles and exotic states. We find that some sparticles and new exotic states can be within reach of run II of the LHC and that DM states have sufficiently large direct detection cross-sections close to current limits and observable soon at the XENON1T experiment. We present benchmark points showing scenarios that could be discovered in the very near future in either of these experiments and urgently need to be investigated. This letter is intended to be followed by a more detailed companion paper which will give analytic expressions used; describe the methodology in detail; provide a thorough exploration of the parameter space, with detailed plots of the interesting regions and make a comparison to the MSSM.

Previously the electroweak symmetry breaking (EWSB) of E_6 models with an extra $U(1)$ has been investigated [31–37] and a mechanism for radiative EWSB demonstrated [38,39]. These models can increase the theoretical upper bound on the lightest Higgs boson mass [37,40,19,20,41–44]. The renormalization of the vacuum expectation values (VEVs) was considered in Refs. [45,46] and the impact of gauge kinetic mixing when two extra $U(1)$ gauge groups are at low energies was investigated [47]. These models may ameliorate the little hierarchy problem but have new contributions to fine tuning from the Z' mass [48,49]. The consequences for neutrino physics have been examined [50,51], as well as leptogenesis [52,23] and electroweak (EW) baryogenesis [53,54]. There have been many studies into the extended set of neutralinos [35,55–64,40]. The muon anomalous magnetic moment [65,66], electric dipole moments [55,56], $\mu \to e\gamma$ [57] and CP-violation in the Higgs sector [67] have been investigated. Anomaly mediated SUSY breaking [68] and family symmetries [69–71] have been studied in these $U(1)$ extensions of the SM.

The signatures associated with the exotic states in these models have been considered [72,73] and Z' mass limits at the LHC and Tevatron were examined [74]. The impact of the 125 GeV Higgs observation and LHC limits on sparticles was examined [75] and was re-examined after calculating higher order corrections to gauge and Yukawa couplings [76]. Non-standard Higgs decays have also been studied [28,77,30]. What a measurement of the first and second generation sfermion masses might tell us about the underlying E_6 GUT model was looked at [78]. Finally the impact of gauge kinetic mixing on Z' and slepton production at the LHC was examined [79].

The structure of this letter is as follows. In Section 2 the model we investigate is described. In Section 3 the procedure used to investigate the model is explained and we describe the results of our investigation. We present benchmark scenarios which fit current data, including the Higgs mass measurement and the relic density of DM. Finally in Section 4 we give our conclusions.

2. The CSE$_6$SSM

Models with an extra $U(1)$ can arise from the breakdown of E_6 GUTs. Such GUT models can emerge from ten dimensional $E_8 \times E_8'$ heterotic string theory after the compactification of extra dimensions, breaking $E_8 \to E_6$ [5–7]. The E_8' then forms a hidden sector which interacts with the visible sector only through gravitational interactions. When local supergravity is broken in the hidden sector these gravitational interactions transmit the SUSY breaking to the visible sector, giving rise to a set of soft breaking masses.

If the E_6 gauge group lives in 5 or 6 dimensions then it may be broken by the boundary conditions. Five and six dimensional orbifold GUTs can then lead to the E_6 inspired model with an exact custodial symmetry [26] and give rise to precisely the low energy model we study in this letter, which we now describe in detail.

The low energy gauge group is that of the SM with an additional $U(1)_N$ symmetry. This $U(1)_N$ is a linear combination of $U(1)_\psi$ and $U(1)_\chi$,

$$U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi\,, \tag{1}$$

which appear in the breakdown of E_6 via $E_6 \to SO(10) \times U(1)_\psi$ and $SO(10) \to SU(5) \times U(1)_\chi$.

The matter content fills three complete generations of E_6 **27**-plets, 27_i, ensuring gauge anomalies automatically cancel. Each 27_i contains one generation of ordinary matter, a SM singlet field S_i, up- and down-type Higgs doublets H_i^u and H_i^d[1] and charged $\pm 1/3$ leptoquarks D_i and $\bar{D}_i$. There are also two additional pairs of states $(L_4, \overline{L}_4)$ and $(S, \overline{S})$ that originate from $\mathbf{27}'$ and $\overline{\mathbf{27}}'$ and automatically cancel anomalies on their own as a consequence. This structure of the low energy matter content allowing this cancellation is not a coincidence, it is a consequence of the E_6 GUT, which is anomaly free, and the specific orbifold GUT construction [26]. The representations and charges of the superfields are given in Table 1, where there and throughout this letter Roman indices run over $i, j, k = 1, 2, 3$ and Greek indices run over $\alpha = 1, 2$.

As a consequence of the E_6 based construction, and the breaking of the $U(1)_\chi$ and $U(1)_\psi$ at some intermediate scale, the model automatically conserves matter parity, $Z_2^M = (-1)^{3(B-L)}$. However there remain dangerous baryon number (B) and lepton number (L) violating interactions. So to avoid rapid proton decay and FCNCs one additional discrete symmetry $\tilde{Z}_2^H$ is imposed. As a consequence the model has not one, but two new stable particles. This can be understood by defining a Z_2^E symmetry by $\tilde{Z}_2^H = Z_2^M \times Z_2^E$. The charges under these discrete symmetries are specified in Table 1. Since $\tilde{Z}_2^H$ and Z_2^M are separately conserved, Z_2^E is also conserved. In the cases studied here this means that both the lightest exotic singlino associated with the $\hat{S}_i$ superfields and the lightest ordinary neutralino are stable.

After imposing $\tilde{Z}_2^H$ symmetry, the low-energy superpotential of the model can be written,

$$\begin{aligned} W = {} & \lambda \hat{S}\hat{H}_d \cdot \hat{H}_u - \sigma\hat{\phi}\hat{S}\hat{\overline{S}} + \frac{\kappa}{3}\hat{\phi}^3 + \frac{\mu}{2}\hat{\phi}^2 + \Lambda_F\hat{\phi} \\ & + \lambda_{\alpha\beta}\hat{S}\hat{H}_\alpha^d \cdot \hat{H}_\beta^u + \kappa_{ij}\hat{S}\hat{D}_i\hat{\overline{D}}_j + \tilde{f}_{i\alpha}\hat{S}_i\hat{H}_u \cdot \hat{H}_\alpha^d \\ & + f_{i\alpha}\hat{S}_i\hat{H}_\alpha^u \cdot \hat{H}_d + g_{ij}^D\hat{Q}_i \cdot \hat{L}_4\hat{\overline{D}}_j \\ & + h_{i\alpha}^E\hat{e}_i^c\hat{H}_\alpha^d \cdot \hat{L}_4 + \mu_L\hat{L}_4 \cdot \hat{\overline{L}}_4 \\ & + \tilde{\sigma}\hat{\phi}\hat{L}_4 \cdot \hat{\overline{L}}_4 + W_{\mathrm{MSSM}}(\mu = 0)\,, \end{aligned} \tag{2}$$

where $W_{\mathrm{MSSM}}(\mu = 0)$ is the MSSM superpotential without the μ term, all superfields appear with a hat and all coefficients of the superfields are couplings of appropriate dimensions, and $\hat{A} \cdot \hat{B} \equiv \epsilon_{\alpha\beta}\hat{A}^\alpha\hat{B}^\beta = \hat{A}^2\hat{B}^1 - \hat{A}^1\hat{B}^2$.

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[1] One pair of these doublets, H_u and H_d, play the role of Higgs fields. The other two generations of H_i^u and H_i^d are denoted "inert Higgs" since their scalar components don't develop VEVs.