PUBLISHED VERSION

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Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, 2016; 760:19-25

Originally published at:
http://doi.org/10.1016/j.physletb.2016.06.040

Physics Letters B 760 (2016) 19–25

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form 21 April 2016
Accepted 17 June 2016
Available online 21 June 2016
Editor: G.F. Giudice

Keywords:
Supersymmetry
Dark matter

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_6SSM) 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_6SSM 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_6SSM 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_6SSM (CE_6SSM) [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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http://dx.doi.org/10.1016/j.physletb.2016.06.040

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,

$$\begin{aligned} W = {} & \lambda \hat{S} \hat{H}_d \cdot \hat{H}_u - \sigma \hat{\phi} \hat{S} \hat{\overline{S}} + \frac{\kappa}{3}\hat{\phi}^3 + \frac{\mu}{2}\hat{\phi}^2 + \Lambda_F \hat{\phi} \\ & + \lambda_{\alpha\beta} \hat{S} \hat{H}^d_\alpha \cdot \hat{H}^u_\beta + \kappa_{ij} \hat{S} \hat{D}_i \hat{\overline{D}}_j + \tilde{f}_{i\alpha} \hat{S}_i \hat{H}_u \cdot \hat{H}^d_\alpha \\ & + f_{i\alpha} \hat{S}_i \hat{H}^u_\alpha \cdot \hat{H}_d + g^D_{ij} \hat{Q}_i \cdot \hat{L}_4 \hat{\overline{D}}_j \\ & + h^E_{i\alpha} \hat{e}^c_i \hat{H}^d_\alpha \cdot \hat{L}_4 + \mu_L \hat{L}_4 \cdot \hat{\overline{L}}_4 \\ & + \tilde{\sigma} \hat{\phi} \hat{L}_4 \cdot \hat{\overline{L}}_4 + W_{\text{MSSM}}(\mu = 0), \end{aligned} \tag{2}$$

where $W_{\text{MSSM}}(\mu = 0)$ 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 $\hat{A} \cdot \hat{B} \equiv \epsilon_{\alpha\beta} \hat{A}^\alpha \hat{B}^\beta = \hat{A}^2 \hat{B}^1 - \hat{A}^1 \hat{B}^2$.

[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.

Table 1
Representations of the chiral superfields under the $SU(3)$ and $SU(2)$ gauge groups, and their E_6 normalized $U(1)_Y$ and $U(1)_N$ charges. The transformation properties under the discrete symmetries $\tilde{Z}_2^H$, Z_2^M and Z_2^E are also shown. Note that we omit the pure gauge singlet, $\hat{\phi}$, as it transforms trivially under all of the gauge and discrete symmetries.

	$\hat{Q}_i$	$\hat{u}^c_i$	$\hat{d}^c_i$	$\hat{L}_i$	$\hat{e}^c_i$	$\hat{N}^c_i$	$\hat{S}$	$\hat{\overline{S}}$	$\hat{S}_i$	$\hat{H}_u$	$\hat{H}_d$	$\hat{H}^u_\alpha$	$\hat{H}^d_\alpha$	$\hat{D}_i$	$\hat{\overline{D}}$	$\hat{L}_4$	$\hat{\overline{L}}_4$
$SU(3)$	**3**	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	$\overline{\mathbf{3}}$	**1**	**1**
$SU(2)$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**1**	**2**	$\overline{\mathbf{2}}$
$\sqrt{\frac{5}{3}}Q^Y_i$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{2}$
$\sqrt{40}Q^N_i$	1	1	2	2	1	0	5	−5	5	−2	−3	−2	−3	−2	−3	2	−2
$\tilde{Z}_2^H$	−	−	−	−	−	−	+	+	−	+	+	−	−	−	−	+	+
Z_2^M	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	−	−
Z_2^E	+	+	+	+	+	+	+	+	−	+	+	−	−	−	−	−	−

The above superpotential interactions are supplemented by a set of soft SUSY breaking interactions; namely, soft scalar masses for all chiral superfields, soft breaking scalar trilinear, bilinear and linear terms for each superpotential coupling, and soft breaking gaugino masses. The resulting large number of soft parameters can be substantially reduced by considering constrained SUSY models inspired by gravity mediated SUSY breaking. Here we assume that at the GUT scale, M_X, all scalar masses are unified to a common value m_0, all gaugino masses are unified to $M_{1/2}$, that all soft trilinears are equal to A_0, and all soft bilinears to B_0.

Once these soft mass parameters are evolved down to the EW scale, minimizing the Higgs potential (given in Ref. [30]) leads to the Higgs fields developing VEVs,

$$\langle H_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle H_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \\ \langle S\rangle = \frac{s_1}{\sqrt{2}}, \quad \langle \overline{S}\rangle = \frac{s_2}{\sqrt{2}}, \quad \langle \phi\rangle = \frac{\varphi}{\sqrt{2}}. \tag{3}$$

3. Analysis and results

To determine the sparticle spectrum we created a spectrum generator for the model using FlexibleSUSY-1.1.0 [80,81] coupled with SARAH-4.5.6 [82–85]. Internally FlexibleSUSY also uses some routines from SOFTSUSY [86,87]. We focused on the scenarios where the Z' mass is decoupled from the EWSB conditions, and so choose the SM singlet VEVs to satisfy $s = \sqrt{s_1^2 + s_2^2} = 650$ TeV, giving $m_{Z'} \approx 240$ TeV. At the same time, to reproduce the relic density with a Higgsino or mixed bino–Higgsino DM candidate we looked for scenarios with a small value of $\mu_{\text{eff}} = \lambda s_1/\sqrt{2}$. This implies that the coupling λ should be very small. To find such solutions, we implemented a new solver algorithm in FlexibleSUSY that makes use of semi-analytic solutions to the renormalization group equations (RGEs). This allows us to choose input values of μ_{eff} and $M_{1/2}$ to obtain an acceptable DM candidate. For a given value of A_0 and B_0, the value of m_0 is then fixed by the requirement of correct EWSB. The remaining EWSB conditions are used to fix the ratio $\tan\theta = s_2/s_1$, the VEV φ, and the superpotential linear coupling, Λ_F, as well as its soft breaking counterpart Λ_S. The full details of this procedure will be given in our companion paper [88].

For scenarios with such small values of λ we find that setting the exotic couplings κ_i and λ_α to values much larger than λ induces large mixings amongst exotic scalars, leading to tachyons. Therefore we choose these couplings to be of a similar size to λ. For simplicity we also set the remaining exotic couplings g^D_{ij}, $h^E_{i\alpha}$, $\tilde{f}_{i\alpha}$ and $f_{i\alpha}$ to negligibly small values. The choice of small κ_i and λ_α allows light exotic fermions to be present in the spectrum.

However, the solutions we found also have many heavy states as well, and in particular very heavy stops. To obtain a precise prediction for the lightest Higgs mass we used the effective field theory approach of SUSYHD-1.0.2 [89]. To do this we performed a tree-level matching to the MSSM at the scale $M_S = \sqrt{m^{\overline{\text{DR}}}_{\tilde{t}_1} m^{\overline{\text{DR}}}_{\tilde{t}_2}}$, e.g. by setting the MSSM soft scalar masses to be those obtained in the CSE$_6$SSM after running from the GUT scale. Since the exotic couplings beyond the MSSM are very small, the associated logarithms in the Higgs mass are negligible and so this approach should not degrade the accuracy of our calculations.

The calculated particle spectrum of the model for six benchmark points is given in Table 2. For all of the benchmarks the light Higgs mass is consistent with the measured value [90], within theoretical errors.

The altered RG flow in this model ensures that the sfermions are heavier than the gauginos. Additionally, the requirement of a light μ_{eff} leads to the EWSB conditions imposing a relationship amongst the universal soft masses such that $m_0 > A_0, M_{1/2}$. This means that maximal mixing in the stop sector cannot be used to obtain a 125 GeV Higgs and so in all six benchmarks the sfermions are very heavy and well beyond the reach of the LHC.

Conversely, the light exotic leptoquarks and inert Higgsinos that result from the small exotic couplings can be detectable at the LHC. The leptoquark states, D_i, participate in QCD interactions and may be pair produced at the LHC. When past threshold the differential production cross section is comparable to the pair production of top quarks [73]. These states are R-parity odd and therefore decay with missing energy, through a long cascade decay involving the couplings g^D_{ij} in Eq. (2) to allow the initial decay of the exotic quark into a squark (quark) and exotic lepton (slepton) pair, and also $h^E_{i\alpha}$ for the exotic lepton (or slepton), L_4, to decay. Since there is a hierarchy in the SM Yukawa couplings it seems natural to assume that a similar hierarchy will exist in the leptoquark and $\hat{L}_4$ Yukawa interactions. In this case pair production will therefore give rise to an enhancement of $pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$ and $pp \to b\bar{b} + E_T^{miss} + X$, where X stands for any number of light quark/gluon jets.

The exotic charged and neutral inert Higgsino states may be produced in pairs through off-shell W and Z bosons. They subsequently decay into an on-shell Z or W and a singlino from f- and $\tilde{f}$-coupling induced mixing.[2] Thus the presence of these states at very low energies should enhance $pp \to ZZ + E_T^{miss} + X$, $pp \to WZ + E_T^{miss} + X$ and $pp \to WW + E_T^{miss} + X$. Note that this signature differs from the one which has been considered in previous E_6 constructions, where they decayed into fermion–sfermion pairs via couplings that are forbidden in this model by the $\tilde{Z}_2^H$ symmetry.

[2] They may also decay through the f- and $\tilde{f}$-couplings into a Higgs boson and a singlino state.

Table 2
Parameters for the benchmark points BM1–BM6 and the resulting sparticle masses. For all points we fix $s = 650$ TeV, $\tan\beta(M_Z) \equiv v_2/v_1 = 10$, $\sigma(M_X) = 0.02$, $\kappa(M_X) = 0.01$, $\mu(M_X) = 0$ GeV, $\mu_L(M_X) = 10$ TeV, $\tilde{\sigma}(M_X) = 0$ and $B_0 = 0$ GeV. The couplings $\tilde{f}_{i\alpha}$, $f_{i\alpha}$, $h^E_{i\alpha}$ and g^D_{ij} are all set to negligibly small values, as they do not have a significant impact on the spectrum. For brevity, we show an approximate mass $m_{\tilde{q}_{1,2}}$ for the first and second generation up- and down-type squarks. The exact masses of all four states are within ±100 GeV of this value. Similarly, $m_{\tilde{l}}$ represents an approximate mass for all sleptons, with the exact masses all lying within ±150 GeV of the given value.

	BM 1	**BM 2**	**BM 3**	**BM 4**	**BM 5**	**BM 6**
$\lambda(M_X)$	0.0009152	0.0009886	0.0007052	0.002295	0.00047	0.0005
$\lambda_{1,2}(M_X)$	0.001	0.0013	0.0012	0.003	0.0016	0.0012
$\kappa_{1,2,3}(M_X)$	0.001	0.0013	0.0012	0.00135	0.0016	0.0012
$M_{1/2}$ [GeV]	2227.79	2407.79	1617.79	5800.98	1900.00	2017.79
m_0 [GeV]	9586.46	9494.22	8800.16	$1.084 \cdot 10^4$	7396.89	7410.12
A_0 [GeV]	−7281.96	−6481.96	−7541.96	2129.63	−4600.00	−4441.96
$1 - \tan\theta$	$1.5 \cdot 10^{-6}$	$1.9 \cdot 10^{-6}$	$2.4 \cdot 10^{-6}$	$9.4 \cdot 10^{-7}$	$5.3 \cdot 10^{-6}$	$2.7 \cdot 10^{-6}$
φ [TeV]	−1633	−1493	−1737	−708	−1713	−1621
$\Lambda_F^{1/2}$ [TeV]	127	120	131	108	139	133
$\Lambda_S^{1/3}$ [TeV]	98	91	102	61	101	96
$m_{\tilde{q}_{1,2}}$ [GeV]	9400	9400	8500	12500	7300	7350
$m_{\tilde{l}}$ [GeV]	9500	9400	8700	11000	7330	7350
$m_{\tilde{b}_1}$ [GeV]	7577	7616	6759	10801	5927	5992
$m_{\tilde{b}_2}$ [GeV]	9361	9364	8438	12411	7287	7345
$m_{\tilde{t}_1}$ [GeV]	5476	5550	4802	8582	4326	4396
$m_{\tilde{t}_2}$ [GeV]	7580	7619	6762	10803	5931	5995
$m_{H^\pm} \approx m_{A_2} \approx m_{h_3}$ [GeV]	9381	9312	8576	11056	7245	7266
m_{A_1} [GeV]	5193	6605	2723	9978	931	3650
m_{A_3} [GeV]	42896	39797	44939	25797	43985	41946
m_{h_1} [GeV]	125.22	125.04	124.96	125.04	124.04	124.10
m_{h_2} [GeV]	8208	8289	7985	8048	7072	7195
m_{h_4} [GeV]	38770	36136	40469	24529	39664	37913
$m_{Z'} \approx m_{h_5}$ [GeV]	$2.4 \cdot 10^5$	$2.4 \cdot 10^5$	$2.4 \cdot 10^5$	$2.4 \cdot 10^5$	$2.4 \cdot 10^5$	$2.4 \cdot 10^5$
$m_{\tilde{D}_1}(1,2,3)$ [GeV]	8523	8430	7016	12308	4520	5562
$m_{\tilde{D}_2}(1,2,3)$ [GeV]	10376	10516	9966	12662	9698	9062
$\mu_D(1,2,3)$ [GeV]	1243	1575	1499	1540	1943	1489
$m_{H_1^\pm}(1,2)$ [GeV]	8938	8762	7862	10433	5799	6309
$m_{H_2^\pm}(1,2)$ [GeV]	10056	10091	9490	11986	8696	8328
$m_{H_1}(1,2)$ [GeV]	13406	13332	12935	14251	12123	12189
$m_{H_2}(1,2)$ [GeV]	17161	17113	16944	17584	16560	16494
$\mu_{\tilde{H}^\pm}(1,2) \approx \mu_{\tilde{H}^0_{1,2}}(1,2)$ [GeV]	580	750	700	1663	929	699
$m_{S_{1,2,3}}$ [GeV]	25593	25516	25663	24875	25583	25567
$m_{L^\pm_{4,1}}$ [GeV]	17580	17468	17355	17512	16663	16657
$m_{L^\pm_{4,2}}$ [GeV]	18465	18422	18021	19611	17470	17513
$m_{L^0_{4,1}}$ [GeV]	19994	19886	19870	19671	19345	19336
$m_{L^0_{4,2}}$ [GeV]	20771	20724	20449	21557	20039	20072
$\mu_{\tilde{L}_4^\pm} \approx \mu_{\tilde{L}^0_{4,1}}, \mu_{\tilde{L}^0_{4,2}}$ [GeV]	15358	15314	15439	14955	15436	15447

Although the sfermions are rather heavy, in all benchmark points other than BM4 the MSSM-like neutralinos and charginos are also light in addition to the exotic states. The neutralino and chargino masses are shown in Table 3. While these are weakly interacting states, they are very light, so it is reasonable to expect some discovery potential, in particular from the production of a neutralino–chargino pair, which leads to an enhancement of $pp \to lll + E_T^{miss} + X$. The branching ratios for the processes $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l\bar{l}$ and $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l\nu_l$, obtained using a CalcHEP [91] model generated using SARAH-4.5.6, are shown in Table 3. For the scenarios considered here, the process $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l\bar{l}$ proceeds almost entirely through diagrams involving a virtual Z, with diagrams involving a virtual Higgs being a negligible contribution due to the small mass splitting between $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ and the small Higgs couplings to leptons and quarks.[3] Therefore the discovery prospects are expected to be rather similar to those in the WZ-mediated scenario of Ref. [92].

Currently, stronger constraints can be placed on the gaugino sector by the measurement of the relic density of DM and limits on the spin independent (SI) cross section from direct detection experiments. The composition of the lightest neutralino, relic density along with a breakdown of the various contributions to the annihilation cross section and the SI and spin dependent cross sections are also given in Table 3. To calculate DM observables in the model, the generated CalcHEP model files were used to implement the model in micrOMEGAs-4.1.8 [93–99]. The inert singlinos are almost massless and so have a negligible contribution to the total relic density. The total relic density shown is that due to the lightest neutralino.

To obtain the observed relic density [100] one may use a pure Higgsino DM candidate with a mass of about 1 TeV. However this then requires a very heavy bino to ensure the lightest neutralino is pure Higgsino and that in turn means the gluino must be above the reach of LHC run II in this constrained model. BM4 is an ex-

[3] Note that the decay of $\tilde{\chi}_2^0$ into $\tilde{\chi}_1^0 + t\bar{t}$ is not kinematically allowed.

Table 3
Masses of the charginos and neutralinos, the bino, wino and higgsino components of the lightest neutralino ($|(Z_N)_{11}|^2$, $|(Z_N)_{12}|^2$ and $|(Z_N)_{13}|^2+|(Z_N)_{14}|^2$, respectively), the branching ratios for the decays $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 l\bar{\nu}_l$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l\bar{l}$ (with $l=e,\mu$) and the predicted relic density and WIMP-nucleon scattering cross sections for the benchmark points BM1–6. Also shown are the approximate percentage contributions to the annihilation cross section from the indicated channels for each benchmark. Note that the contributions to the total relic density are computed using the freeze-out approximation.

	BM 1	**BM 2**	**BM 3**	**BM 4**	**BM 5**	**BM 6**
$m_{\tilde{g}}$ [GeV]	2099	2256	1541	5230	1716	1839
$m_{\tilde{\chi}_1^\pm}$ [GeV]	422	454	320	1034	216	231
$m_{\tilde{\chi}_2^\pm} \approx m_{\tilde{\chi}_4^0}$ [GeV]	780	845	570	2129	645	682
$m_{\tilde{\chi}_1^0}$ [GeV]	375	409	264	1024	204	219
$m_{\tilde{\chi}_2^0}$ [GeV]	433	464	338	1038	226	241
$m_{\tilde{\chi}_3^0}$ [GeV]	445	479	338	1159	336	358
$m_{\tilde{\chi}_5^0}$ [GeV]	25394	23602	26745	14546	26437	25249
$m_{\tilde{\chi}_6^0}$ [GeV]	29853	27651	31546	16364	31173	29737
$m_{\tilde{\chi}_7^0}$ [GeV]	231028	232102	230097	238639	230406	231254
$m_{\tilde{\chi}_8^0}$ [GeV]	258656	257259	259681	249541	259532	258784
$\|(Z_N)_{11}\|^2$	0.6318	0.6075	0.7210	0.0691	0.0679	0.0624
$\|(Z_N)_{12}\|^2$	0.0081	0.0075	0.0106	0.0028	0.0180	0.0165
$\|(Z_N)_{13}\|^2+\|(Z_N)_{14}\|^2$	0.3601	0.3850	0.2685	0.9281	0.9141	0.9211
$\mathrm{BR}(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 l\bar{\nu}_l)$	0.2220	0.2220	0.2220	0.2280	0.2260	0.2260
$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l\bar{l})$	0.0689	0.0689	0.0684	0.0733	0.0670	0.0674
Ωh^2	0.1188	0.1185	0.1187	0.1184	0.01055	0.009626
σ_{SI}^p [$\times 10^{-45}$ cm^2]	5.88	6.14	4.84	2.35	4.67	4.32
σ_{SD}^p [$\times 10^{-41}$ cm^2]	6.4	5.58	10.0	0.3529	15.8	12.8
σ_{SI}^n [$\times 10^{-45}$ cm^2]	5.97	6.24	4.91	2.39	4.75	4.39
σ_{SD}^n [$\times 10^{-41}$ cm^2]	4.9	4.27	7.66	0.2699	12.1	9.78
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$ (%)	44.9	39.0	60.0	0.6	0.5	3.3
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ (%)	20.6	19.4	21.6	5.0	27.9	22.0
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ$ (%)	13.2	12.8	11.4	3.9	18.4	14.1
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Zh_1$ (%)	2.9	2.7	2.9	0.7	0.0	1.7
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_1h_1$ (%)	0.5	0.4	0.9	0.02	0.1	0.1
$\tilde{\chi}_1^0\tilde{\chi}_1^- \to W^-Z$ (%)	0.8	1.1	0.2	1.4	0.2	1.4
$\tilde{\chi}_1^0\tilde{\chi}_1^- \to W^-h_1$ (%)	1.3	1.6	0.3	1.5	2.7	2.6
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$ (%)	0.1	0.1	$2\cdot 10^{-3}$	1.9	0.5	0.7
$\tilde{\chi}_1^0\tilde{\chi}_1^- \to \gamma W^-$ (%)	0.6	0.8	0.1	1.4	1.5	1.5
$\tilde{\chi}_1^0\tilde{\chi}_1^- \to d_i\bar{u}_i$ (%)	8.8	12.0	1.6	25.7	29.4	30.0
$\tilde{\chi}_1^0\tilde{\chi}_1^- \to l_i^-\bar{\nu}_{l_i}$ (%)	2.7	3.8	0.5	8.8	10.7	10.8
$\tilde{\chi}_2^0\tilde{\chi}_1^- \to d_i\bar{u}_i$ (%)	0.2	0.4	$3\cdot 10^{-3}$	12.0	0.7	1.2
$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to d_i\bar{d}_i$ (%)	0.9	1.4	0.07	6.4	1.5	2.0
$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to u_i\bar{u}_i$ (%)	0.8	1.3	0.06	4.7	0.9	1.3
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to d_i\bar{d}_i$ (%)	0.1	0.2	$4\cdot 10^{-3}$	3.0	0.9	1.2
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to u_i\bar{u}_i$ (%)	0.2	0.3	$6\cdot 10^{-3}$	4.9	1.1	1.6
$\tilde{\chi}_2^0\tilde{\chi}_1^- \to l_i^-\bar{\nu}_{l_i}$ (%)	0.1	0.1	$9\cdot 10^{-4}$	4.1	0.2	0.4

ample of such a scenario. In this scenario the SI cross section is reasonably far from the current best exclusion limit of LUX [101], though XENON1T will be in a position to either discover this or rule it out.

The SI cross section increases in scenarios where the lightest neutralino is a mixture of bino and Higgsino. In such cases the SI cross section is very close to the LUX limit[4] and will be discoverable in the “early data” of XENON1T. BMs 1–3 are examples of this. In this case the correct relic density is achieved with a much lighter DM candidate and subsequently the gluino is within reach of the LHC and gluino pair production will lead to a considerable enhancement of $pp \to q\bar{q}q\bar{q} + E_T^{miss} + X$. BM1 has exotic leptoquarks with masses below current limits on the gluino and should be easily discoverable at the LHC run II, while for BM2 the exotic quarks are now heavier but should still be within the reach of the LHC run II. In both BM1 and BM2 the gluino mass is fairly large though the LHC should still be able to discover them, at least with the high luminosity upgrade [103]. In BM3 both the gluino and the leptoquarks are very light and discovery of these should be possible with 300 fb^{-1} of integrated luminosity (IL).

[4] In fact while this document was in preparation a reinterpretation of the LUX limits appeared on the arXiv pre-print server [102], which makes the tension more severe. However despite this tension it is still possible that points like these could be discovered by XENON1T and therefore they remain very interesting.

Finally, BM5 and BM6 represent scenarios with a Higgsino DM candidate that is too light to account for all of the observed DM relic density. This substantially decreases the direct detection event rate, allowing the LUX cross section limits to be evaded and reducing the sensitivity of XENON1T to these points. At the same time, both the gluino and exotic quark masses are light enough to be accessible at run II. In contrast to BMs 1–3, these points could therefore be discovered at run II of the LHC, without being in tension with the current LUX limits or being observed in the early XENON1T data. However, this comes at the cost of requiring an additional source of DM in this scenario in order to explain the observed relic density. BM5 also shows that the leptoquarks can be heavier than in the other benchmarks so that it may be challenging to find with 300 fb^{-1} of IL, but it still should be possible to discover these at the LHC. In contrast in BM6 the leptoquark is comparatively light but the gluino may require longer running to be discovered.

4. Conclusions

In this letter we have presented benchmark scenarios in a new well motivated E_6 inspired model, all of which predict states which can be discovered at both XENON1T and run II of the LHC. With initial run II results already available and new results from XENON1T expected very soon these scenarios are of urgent interest.

In BMs 1–3 we show that the model can explain DM, fitting the observed relic density, while having exotic leptoquarks, gluinos, and possibly even neutralinos and charginos discoverable at the LHC run II. Further the bino–Higgsino DM candidate for these points should be discovered immediately in "early data" from the XENON1T experiment.

BM4 on the other hand shows a Higgsino dominated DM candidate, where mixing with the bino is suppressed as the bino is rather heavy. In this case gaugino mass universality and the RG flow make the gluino far too heavy for the LHC reach. However the model can still be discovered through exotic leptoquarks. This emphasizes the need for dedicated studies on these exotic states. The DM is still within discovery range of XENON1T but should take a little longer to discover than the other benchmarks.

Finally we also presented BM5 and BM6 where we showed that one can also have scenarios with light phenomenology within reach of the LHC, where the relic density is not fully explained. In such a case the sensitivity of XENON1T will be limited by the substantially reduced relic density for the lightest neutralino. However even in this case the state ought to be discoverable by the end of the XENON1T experiment.

Acknowledgements

This work was supported by the University of Adelaide and the Australian Research Council through the ARC Centre of Excellence for Particle Physics at the Terascale.

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