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Exceptional supersymmetric standard model

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Abstract

We discuss some phenomenological aspects of an E_6 inspired supersymmetric standard model with an extra $U(1)_N$ gauge symmetry under which right-handed neutrinos have zero charge, allowing a conventional see-saw mechanism. The μ problem is solved in a similar way to the NMSSM, but without the accompanying problems of singlet tadpoles or domain walls. The above exceptional supersymmetric standard model (ESSM) involves the low energy matter content of three 27 representations of E_6, which is broken at the GUT scale, and allows gauge coupling unification due to an additional pair of Higgs-like doublets. The ESSM predicts a Z' boson and exotic quarks which, if light enough, will provide spectacular new physics signals at the LHC. We study the LHC phenomenology of the Z' and extra quarks, including their production and decay signatures particular to the ESSM. We also discuss the two-loop upper bound on the mass of the lightest CP-even Higgs boson, and show that it can be significantly heavier than in either the MSSM or the NMSSM.

1. Introduction

The minimal supersymmetric standard model (MSSM) provides a very attractive supersymmetric extension of the standard model (SM) in which the superpotential contains the bilinear term $\mu H_d H_u$, where $H_{d,u}$ are the two Higgs doublets which develop vacuum expectation values (VEVs) at the weak scale and μ is the supersymmetric Higgs mass parameter which can be present before SUSY is broken. However, despite its attractiveness, the MSSM suffers from the μ problem: one would naturally expect μ to be either zero or of the order of the Planck scale, while, in order to get the correct pattern of electroweak symmetry breaking (EWSB), μ is required to be in the TeV range. The next-to-minimal supersymmetric standard model (NMSSM) is an attempt to solve the μ problem of the MSSM by generating the aforementioned term dynamically as the low energy VEV of a singlet field S via the interaction $\lambda S H_d H_u$. In order to avoid a low energy global $U(1)$ symmetry, the superpotential is also supplemented by a trilinear term S^3. However the superpotential of the NMSSM remains invariant under a discrete Z_3 symmetry which, when broken at the weak scale, leads to the formation of domain walls in the early universe, which are inconsistent with modern cosmology. In an attempt to break the Z_3 symmetry, operators suppressed by powers of the Planck scale could be introduced. But these give rise to quadratically divergent tadpole contributions which would destabilize the mass hierarchy. (For a review of the MSSM and NMSSM see, e.g., [1].)

An elegant solution to the μ problem can emerge in the framework of ten-dimensional heterotic superstring theory based on $E_8 \times E_8'$ [2]. Compactification of the extra dimensions results in the breakdown of E_8 down to E_6 or one of its subgroups in the observable sector [3]. At the string scale, E_6 can be broken directly to the rank-6 subgroup $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\psi \times U(1)_\chi$ via the Hosotani mechanism [4]. Two anomaly-free $U(1)_\psi$ and $U(1)_\chi$ symmetries of the rank-6 model are defined by [5]: $E_6 \to SO(10) \times U(1)_\psi, SO(10) \to SU(5) \times U(1)_\chi$. In this Letter we explore a particular E_6 inspired supersymmetric model with one extra $U(1)_N$ gauge symmetry defined by

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

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under which right-handed neutrinos have no charge and thus may gain large Majorana masses in accordance with the see-saw mechanism (for a review see, e.g., [6]). The extra $U(1)_N$ gauge symmetry survives to low energies and serves to forbid an elementary μ term as well as terms like S^n in the superpotential but allows the interaction $\lambda S H_d H_u$. After EWSB the scalar component of the singlet superfield acquires a non-zero VEV, $\langle S\rangle = s/\sqrt{2}$, breaking $U(1)_N$ and an effective $\mu = \lambda s/\sqrt{2}$ term is automatically generated. Clearly there are no domain wall problems in such a model since there is no discrete Z_3 symmetry, and instead of a global symmetry there is a gauged $U(1)_N$. Anomalies are canceled by complete 27 representations of E_6 which survive to low energies, even though E_6 is broken at the GUT scale.

We refer to the model described above as the exceptional supersymmetric standard model (ESSM). The ESSM thus represents a low energy alternative to the MSSM or NMSSM, and provides a solution to the μ problem without domain wall problems. The ESSM contains a rich phenomenology accessible to the LHC in the form of a Z' plus three families of exotic quarks and non-Higgs doublets. In a companion paper we have made a comprehensive study of the theory and phenomenology of the ESSM [7]. The purpose of this accompanying Letter is to summarize the phenomenological highlights of our study, including the two loop upper bound on the lightest CP-even Higgs mass, and the LHC phenomenology of the Z' and exotic quarks (including some new phenomenological results) in a form that will be more easily accessible to our phenomenological and experimental colleagues. For more details we refer the interested reader to the accompanying full length paper [7]. Previously, the implications of SUSY models with an additional $U(1)_N$ gauge symmetry had been studied in the context of leptogenesis [8], EW baryogenesis [9] and neutrino physics [10]. Supersymmetric models with a $U(1)_N$ gauge symmetry under which right-handed neutrinos are neutral have been specifically considered in [11] from the point of view of Z–Z' mixing and the neutralino sector, in [12] where a renormalization group (RG) analysis was performed, and in [13] where a one-loop Higgs mass upper bound was presented.

In Section 2 we briefly review the ESSM. In Section 3 we analyse the upper bound on the lightest CP-even Higgs boson mass including leading two-loop corrections. Then in Section 4 we discuss the phenomenology of some of the extra particles predicted by the ESSM and analyze their production cross sections and signatures at the LHC. Our results are summarized in Section 5.

2. The ESSM

One of the most important issues in models with additional Abelian gauge symmetries is the cancellation of anomalies. In E_6 theories the anomalies are canceled automatically. Therefore any model based on E_6 subgroups which contains complete representations should be anomaly-free. Thus in order to ensure anomaly cancellation the particle content of the ESSM should include complete fundamental 27 representations of E_6. These multiplets decompose under the $SU(5)\times U(1)_N$ subgroup of E_6 [12] as follows:

$$27_i \to (10,1)_i + \left(5^*,2\right)_i + \left(5^*,-3\right)_i + (5,-2)_i + (1,5)_i + (1,0)_i. \tag{2}$$

The first and second quantities in the brackets are the $SU(5)$ representation and extra $U(1)_N$ charge while i is a family index that runs from 1 to 3. An ordinary SM family which contains the doublets of left-handed quarks Q_i and leptons L_i, right-handed up- and down-quarks (u^c_i and d^c_i) as well as right-handed charged leptons, is assigned to $(10,1)_i + (5^*,2)_i$. Right-handed neutrinos N^c_i should be associated with the last term in Eq. (2) $(1,0)_i$. The next-to-last term in Eq. (2) $(1,5)_i$ represents SM-type singlet fields S_i which carry non-zero $U(1)_N$ charges and therefore survive down to the EW scale. The pair of $SU(2)$-doublets (H_{1i} and H_{2i}) that are contained in $(5^*,-3)_i$ and $(5,-2)_i$ have the quantum numbers of Higgs doublets. Other components of these $SU(5)$ multiplets form color triplet of exotic quarks D_i and $\bar{D}_i$ with electric charges $-1/3$ and $+1/3$, respectively. The matter content and correctly normalized Abelian charge assignment are in Table 1.

Table 1
The $U(1)_Y$ and $U(1)_N$ charges of matter fields in the ESSM, where Q^N_i and Q^Y_i are here defined with the correct E_6 normalization factor required for the RG analysis

	Q	u^c	d^c	L	e^c	N^c	S	H_2	H_1	D	$\bar{D}$	H'	$\bar{H}'$
$\sqrt{\frac{5}{3}}Q^Y_i$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{2}$
$\sqrt{40}Q^N_i$	1	1	2	2	1	0	5	-2	-3	-2	-3	2	-2

The most general renormalizable superpotential which is allowed by the E_6 symmetry can be written in the following form:

$$\begin{aligned} W_{E_6} &= W_0 + W_1 + W_2,\\ W_0 &= \lambda_{ijk} S_i (H_{1j} H_{2k}) + \kappa_{ijk} S_i (D_j \bar{D}_k) + h^N_{ijk} N^c_i (H_{2j} L_k)\\ &\quad + h^U_{ijk} u^c_i (H_{2j} Q_k) + h^D_{ijk} d^c_i (H_{1j} Q_k) + h^E_{ijk} e^c_i (H_{1j} L_k),\\ W_1 &= g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \bar{D}_i d^c_j u^c_k,\\ W_2 &= g^N_{ijk} N^c_i D_j d^c_k + g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} (Q_i L_j) \bar{D}_k. \end{aligned} \tag{3}$$

Although $B-L$ is conserved automatically, some Yukawa interactions in Eq. (3) violate baryon number conservation resulting in rapid proton decay. The baryon and lepton number violating operators can be suppressed by imposing an appropriate Z_2 symmetry which is usually called R-parity. But the straightforward generalization of the definition of R-parity, assuming $B_D = 1/3$ and $B_{\bar{D}} = -1/3$, implies that W_1 and W_2 are forbidden by this symmetry and the lightest exotic quark is stable. Models with stable charged exotic particles are ruled out by different experiments [14].

To prevent rapid proton decay in E_6 supersymmetric models a generalized definition of R-parity should be used. There are two ways to do that. If H_{1i}, H_{2i}, S_i, D_i, $\bar{D}_i$ and the quark superfields (Q_i, u^c_i, d^c_i) are even under a discrete Z^L_2 symmetry while the lepton superfields (L_i, e^c_i, N^c_i) are odd all terms in W_2 are forbidden (model I). Then the remaining superpotential is invariant with respect to a $U(1)_B$ global symmetry if the exotic quarks $\bar{D}_i$ and D_i are diquark and antidiquark, i.e., $B_D = -2/3$