The Constrained $E_6$SSM

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We present a self–consistent $E_6$ inspired supersymmetric model with an extra $U(1)_N$ gauge symmetry under which right–handed neutrinos have zero charge. We explore the particle spectrum within the constrained version of this exceptional supersymmetric standard model ($E_6$SSM) and discuss its possible collider signatures.

1. INTRODUCTION

The unification of gauge couplings in the supersymmetric (SUSY) models allows one to embed the gauge group of the standard model (SM) into Grand Unified Theories (GUTs) based on simple gauge groups such as $SU(5)$, $SO(10)$ or $E_6$. On the other hand gauge coupling unification permits one to incorporate SUSY models into superstring theories that make possible partial unification of gauge interactions with gravity. At high energies the $E_6$ symmetry in the superstring inspired models can be broken to $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ where $U(1)' = U(1)_{\chi} \cos \theta + U(1)_{\psi} \sin \theta$. Two anomaly–free $U(1)_\chi$ and $U(1)_\psi$ symmetries originate from the breakdown of $E_6$ and $SO(10)$ respectively, i.e. $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$. Here we concentrate on a particular $E_6$ inspired supersymmetric model with an extra $U(1)_N$ gauge symmetry that corresponds $\theta = \arctan \sqrt{15}$. Only in this exceptional supersymmetric standard model ($E_6$SSM) the right–handed neutrinos do not participate in gauge interactions. Therefore they may be superheavy shedding light on the origin of lepton mass hierarchy. The extra $U(1)_N$ gauge symmetry survives to low energies and forbids a bilinear term $\mu H_d H_u$ in the superpotential of the considered model but allows the interaction $\lambda S H_d H_u$. At the low energy scale the scalar component of the SM singlet superfield $S$ acquires a non–zero vacuum expectation value (VEV), $\langle S \rangle = s/\sqrt{2}$, breaking $U(1)_N$ and an effective $\mu = \lambda s/\sqrt{2}$ term is automatically generated. Thus the $\mu$ problem in the $E_6$SSM is solved in a similar way to the next-to-minimal supersymmetric standard model (NMSSM), but without the accompanying problems of singlet tadpoles or domain walls.

2. THE $E_6$SSM

The $E_6$SSM is based on the $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge group which is a subgroup of $E_6$. To ensure anomaly cancellation the particle content of the $E_6$SSM is extended to include three complete 27 representations of $E_6$. Each $27_i$ multiplet contains a SM family of quarks and leptons, right–handed neutrino $N^c_i$, SM singlet field $s_i$ which carries a non–zero $U(1)_N$ charge, a pair of $SU(2)_W$–doublets $H_{1i}$ and $H_{2i}$ with the quantum numbers of Higgs doublets and a pair of colour triplets of exotic quarks $\overline{T}_i$ and $D_i$ which can be either diquarks (Model I) or leptoquarks (Model II). $H_{1i}$ and $H_{2i}$ form either Higgs or inert Higgs multiplets. We also require a further pair $H'$ and $\overline{H'}$ from incomplete extra 27 representations to survive to low energies to ensure gauge coupling unification. Our analysis reveals that the unification of the gauge couplings in the $E_6$SSM can be achieved for any phenomenologically acceptable value of $\alpha_3(M_Z)$, consistent with the central measured low energy value, unlike in the MSSM which requires significantly higher values of $\alpha_3(M_Z)$, well above central measured value $\frac{1}{2}$.

Since right–handed neutrinos have zero charges in the considered model they can acquire very heavy Majorana masses. The heavy Majorana right–handed neutrinos may decay into final states with lepton number $L = \pm 1$, thereby creating a lepton asymmetry in the early Universe. Because the Yukawa couplings of exotic particles are not
constrained by the neutrino oscillation data the substantial values of the CP asymmetries in the considered model can be induced even for a relatively small mass of the lightest right-handed neutrino ($M_1 \sim 10^9\text{GeV}$) so that the successful thermal leptogenesis may be achieved without encountering gravitino problem.

The superpotential of the E$_6$SSM involves a lot of new Yukawa couplings in comparison to the SM. In general these new interactions violate baryon number conservation and induce non-diagonal flavour transitions. To suppress baryon number violating and flavour changing processes one can postulate a $Z_2^H$ symmetry under which all superfields except one pair of $H_{1i}$ and $H_{2i}$ (say $H_d \equiv H_{13}$ and $H_u \equiv H_{23}$) and one SM-type singlet field ($S \equiv S_3$) are odd. The $Z_2^H$ symmetry reduces the structure of the Yukawa interactions to:

$$W_{E_6\text{SSM}} \rightarrow \lambda_i S(H_{1i}H_{2i}) + \kappa_i S(D_i\overline{D_i}) + f_{\alpha\beta} S(H_dH_{2\beta}) + \tilde{f}_{\alpha\beta} S(H_{1\beta}H_u)$$

$$+ h_{4j}^E (H_dH') e_j^c + \mu'(H]^eH) \quad + W_{\text{MSSM}}(\mu = 0),$$

(1)

where $\alpha, \beta = 1, 2$ and $i = 1, 2, 3$. Here we assume that all right–handed neutrinos are relatively heavy so that they can be integrated out. The $SU(2)_W$ doublets $H_u$ and $H_d$, that are even under $Z_2^H$ symmetry, play the role of Higgs fields generating the masses of quarks and leptons after the EW symmetry breaking (EWSB). The singlet field $S$ must also acquire large VEV to induce sufficiently large masses for the exotic charged fermions and $Z'$ boson to avoid conflict with direct particle searches at present and former accelerators. This implies that the Yukawa couplings $\lambda_i$ and $\kappa_i$ should be large enough so that the evolution of the soft scalar mass $m_S^2$ of the singlet field $S$ results in negative values of $m_S^2$ at low energies, triggering the breakdown of $U(1)_Y$ symmetry. To guarantee that only $H_u, H_d$ and $S$ acquire VEVs in the E$_6$SSM a certain hierarchy between the Yukawa couplings is imposed, i.e. $\kappa_i \sim \lambda_i \gg f_{\alpha\beta}, \tilde{f}_{\alpha\beta}, h_{4j}^E$.

After the breakdown of the gauge symmetry $H_u, H_d$ and $S$ form three CP-even, one CP-odd and two charged states in the Higgs spectrum. The mass of the one CP–even Higgs particle is always very close to the $Z'$ boson mass $M_{Z'}$. The masses of another CP–even, CP–odd and charged Higgs states are almost degenerate. As in the MSSM and NMSSM one of the CP–even Higgs bosons is always light irrespective of the SUSY breaking scale. However in contrast with the simplest SUSY models the lightest Higgs boson in the E$_6$SSM can be heavier than $110 – 120\text{GeV}$ even at the tree level. In the two–loop approximation the lightest Higgs boson mass does not exceed $150 – 155\text{GeV}$.

Thus the SM–like Higgs boson in the E$_6$SSM can be considerably heavier than in the MSSM and NMSSM.

3. PARTICLE SPECTRUM IN THE CONstrained E$_6$SSM

The E$_6$SSM contains many new parameters. Even if we neglect $f_{\alpha\beta}, \tilde{f}_{\alpha\beta}$ and $h_{4j}^E$ the simplified superpotential of the E$_6$SSM involves seven extra couplings ($\mu', \kappa_i$ and $\lambda_i$) as compared with the MSSM with $\mu = 0$. The soft breakdown of supersymmetry gives rise to many new parameters. The number of fundamental parameters can be reduced drastically within the constrained version of the E$_6$SSM (cESSM). Constrained SUSY models imply that all soft scalar masses are set to be equal to $m_0^2$ at the scale $M_X$, all gaugino masses $M_i(M_X)$ are equal to $M_{1/2}$ and trilinear scalar couplings $A_i(M_X) = A$. Thus cESSM is characterised by the set of Yukawa couplings, which are allowed to be of the order of unity, and universal soft SUSY breaking terms, i.e.

$$\lambda_i(M_X), \quad \kappa_i(M_X), \quad h_t(M_X), \quad h_b(M_X), \quad h_\tau(M_X), \quad m_0, \quad M_{1/2}, \quad A,$$

(2)

where $h_t(M_X), h_b(M_X)$ and $h_\tau(M_X)$ are the $t$–quark, $b$–quark and $\tau$–lepton Yukawa couplings. To simplify our analysis we assume that all parameters are real and $M_{1/2}$ is positive. In order to guarantee the correct EWSB $m_0^2$ has to be positive. The set of the cESSM parameters should be in principle supplemented by $\mu'$ and the associated bilinear scalar coupling $B'$. However since $\mu'$ is not constrained by the EWSB and the term $\mu' H]^eH$ in the superpotential is not suppressed by the $E_6$ the parameter $\mu'$ is expected to be $\sim 10\text{TeV}$ so that $H'$ and $\overline{H}$ decouple from the rest of the particle spectrum. As a consequence parameters $B'$ and $\mu'$ are irrelevant for our analysis.

In order to calculate the particle spectrum within the cESSM we evolve all mass parameters from the Grand Unification scale to the SUSY breaking scale for each set of gauge and Yukawa couplings at the scale $M_X$. In our
Table I: Particle spectrum in the constrained E6SSM for $\tan \beta = 10$ (All mass parameters are given in GeV).

| Scenario I | Scenario II |
|------------|-------------|
| $\lambda_3(M_X)$ | -2.0 | -0.395 |
| $\lambda_{1,2}(M_X)$ | 2.6 | 0.1 |
| $\kappa_3(M_X)$ | 2.5 | 0.43 |
| $\kappa_{1,2}(M_X)$ | 2.5 | 0.08 |
| $s$ | 4000 | 2700 |
| $M_{1/2}$ | 389 | 358 |
| $m_0$ | 725 | 623 |
| $A$ | -1528 | 757 |
| $m_{D_1}(3)$ | 1948 | 1445 |
| $m_{D_2}(3)$ | 2200 | 2059 |
| $\mu_D(3)$ | 2060 | 1747 |
| $m_{D_1}(1,2)$ | 1948 | 370 |
| $m_{D_2}(1,2)$ | 2200 | 916 |
| $\mu_D(1,2)$ | 2060 | 391 |
| $|m_{s_1}|$ | 1548 | 1051 |
| $m_{h_3} \approx M_{Z'}$ | 1518 | 1021 |
| $|m_{s_2}|$ | 1490 | 994 |
| $m_{S}(1,2)$ | 1290 | 961 |
| $m_{H_2}(1,2)$ | 1172 | 561 |
| $m_{H_1}(1,2)$ | 903 | 345 |
| $\mu_H(1,2)$ | 1302 | 229 |
| $m_u(1,2)$ | 1007 | 845 |
| $m_d(1,2)$ | 1113 | 903 |
| $m_Q(1,2)$ | 1023 | 862 |
| $m_L(1,2,3)$ | 1015 | 796 |
| $m_e(1,2,3)$ | 873 | 708 |
| $m_{b_2}$ | 1108 | 894 |
| $m_{b_1}$ | 907 | 712 |
| $m_{\tau_2}$ | 921 | 772 |
| $m_{\tau_1}$ | 777 | 474 |

| $|m_{s_1}| \approx |m_{s_2}| \approx |m_{s_3}|$ | 739 | 685 |
| $m_{h_2} \approx m_A \approx m_{H^\pm}$ | 615 | 720 |
| $m_{h_1}$ | 116 | 114 |
| $M_3$ | 350 | 327 |
| $|m_{\chi_1^+}| \approx |m_{\chi_2^0}|$ | 106 | 101 |
| $|m_{\chi_3^0}|$ | 59 | 57 |

In the analysis we use two–loop renormalisation group (RG) equations for the gauge and Yukawa couplings together with two–loop RG equations for $M_a(\mu)$ and $A_i(\mu)$ as well as one–loop RG equations for $m_i^2(\mu)$. At the next stage of our analysis we fix $s$ and $\tan \beta = v_2/v_1$, where $v_2$ and $v_1$ are the VEVs of the Higgs fields $H_u$ and $H_d$, and choose $A$, $m_0$ and $M_{1/2}$ so that the EW symmetry breaking constraints are satisfied, i.e.

$$\frac{\partial V}{\partial s} = \frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = 0,$$

where $V$ is a Higgs effective potential. Although the correct EWSB is not guaranteed in the considered model,
remarkably there is always a solution for sufficiently large values of \( \kappa_i \), which drive \( m_{\tilde{S}}^2 \) negative. Finally at the last stage of our analysis we vary Yukawa couplings, \( \tan \beta \) and \( s \) to establish the allowed range of the parameters and qualitative pattern of the particle spectrum in the E\(_6\)SSM.

The results of our study of the particle spectrum in the E\(_6\)SSM are summarised in the Table 1. We find that a set of the lightest SUSY particles in the cE\(_6\)SSM always includes the gluino \( \tilde{g} \), the two lightest neutralino (\( \chi_1^0 \) and \( \chi_2^0 \)) and the lightest chargino \( \chi_1^\pm \). All other SUSY particles can be substantially heavier. Nevertheless there exists a part of the E\(_6\)SSM parameter space where exotic quarks, exotic squarks, inert Higgs bosons and inert Higgsinos can be also relatively light (see Scenario II).

4. COLLIDER SIGNATURES

If neutralino, chargino and gluino are the only lightest SUSY particles then one can expect to observe \( \tilde{g}\tilde{g}, \chi_1^\pm \chi_1^\mp, \chi_2^0 \chi_1^\pm \chi_1^\mp \) and \( \chi_2^0 \chi_2^0 \) pair production at the LHC. Since each gluino will decay further into quark, antiquark and lightest neutralino (or chargino) the gluino pair production will result in an appreciable enhancement of the cross section of \( pp \rightarrow \tilde{g}\tilde{g} + E_T^{miss} + X \). If all squarks are much heavier than the gluino, i.e. particle spectrum has a very hierarchical structure, then gluinos can be relatively long lived particles because \( \Gamma_{\tilde{g}} \propto M_{\tilde{g}}^5/m_{\tilde{g}}^2 \) in the considered case. In particular their lifetime can be comparable with the lifetime of \( W^\pm \) and \( Z \) bosons. At the same time the pair production of the second lightest neutralino also gives rise to a remarkable signature. When \( \chi_1^0, \chi_2^0 \) and \( \chi_1^\pm \) are the lightest SUSY particles the second lightest neutralino will decay predominantly into lepton, antilepton and \( \chi_1^0 \). Thus \( \chi_2^0 \chi_2^0 \) pair production would generate an excess in the cross section of \( pp \rightarrow \tilde{g}\tilde{g} + E_T^{miss} + X \) that should be possible to observe at the LHC.

Other possible manifestations of the E\(_6\)SSM at the LHC are related with the presence of a \( Z' \) and of exotic multiplets of matter. For instance, \( Z' \) boson can be discovered at the LHC if its mass is less than \( 4 - 4.5 \) TeV. When the Yukawa couplings of the exotic particles have a hierarchical structure some of the exotic fermions can be relatively light so that their production cross section at the LHC can be comparable with the cross section of \( t\bar{t} \) production. Assuming that \( D_i \) and \( \bar{D}_i \) couple most strongly with the third family quarks and leptons the lightest exotic quarks decay into either two heavy quarks \( QQ \) or a heavy quark and \( \tau\bar{\tau} \) or \( \mu\bar{\mu} \), where \( Q \) is either a b- or t-quark. This can lead to the substantial enhancement of the cross section of either \( pp \rightarrow \tilde{g}\tilde{g} + E_T^{miss} + X \) or \( pp \rightarrow \tilde{g}\tilde{g} + E_T^{miss} + X \). The discovery of the \( Z' \) and exotic quarks predicted by the E\(_6\)SSM would represent a possible indirect signature of an underlying \( E_6 \) gauge structure at high energies and provide a window into string theory.

Acknowledgments

RN acknowledges support from the SHEFC grant HR03020 SUPA 36878.

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