E_6SSM$^1$

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Abstract. In this talk we discuss an $E_6$ inspired supersymmetric (SUSY) model with an extra $U(1)_N$ gauge symmetry under which right-handed neutrinos have zero charge. In this exceptional supersymmetric standard model ($E_6$SSM) the $\mu$–term is generated dynamically after the electroweak symmetry breaking. We specify the particle content of the model and argue that the presence of a $Z'$ and exotic particles predicted by $E_6$SSM allows the lightest Higgs boson to be significantly heavier than in the MSSM and NMSSM. Other possible manifestations of $E_6$SSM at the LHC are also discussed.

Keywords: Supersymmetry; Extra gauge groups; Electroweak symmetry breaking.

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INTRODUCTION

The cancellation of quadratic divergences in the supersymmetric models does not allow to solve the hierarchy problem of the standard model (SM) entirely. Indeed, the superpotential of the simplest supersymmetric extension of the SM — minimal supersymmetric (SUSY) standard model (MSSM) contains a bilinear term $\mu H_d H_u$. In order to get the correct pattern of electroweak (EW) symmetry breaking the parameter $\mu$ is required to be of the order of electroweak or SUSY breaking scale. At the same time the incorporation of the MSSM into supergravity or Grand Unified theories (GUT) results in $\mu \sim M_X - M_{Pl}$, where $M_X$ and $M_{Pl}$ are GUT or Planck scales respectively. This is the so-called $\mu$–problem.

An elegant solution to the $\mu$ problem naturally arises in the framework of superstring inspired $E_6$ models. At the string scale $E_6$ can be broken directly to the rank-6 subgroup $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\psi \times U(1)_\chi$. Two anomaly-free $U(1)_\psi$ and $U(1)_\chi$ symmetries of the rank-6 model are defined by: $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$. Near the string scale the rank-6 model can be reduced further to an effective rank–5 model with only one extra $U(1)_N$ gauge symmetry. The extra $U(1)_N'$ gauge symmetry forbids an elementary $\mu$ term but allows interaction $\lambda S H_d H_u$ in the superpotential. The scalar component of the SM singlet superfield $S$ acquires a non-zero vacuum expectation value (VEV) breaking $U(1)_N'$ and giving rise to an effective $\mu$ term. Here we review a particular $E_6$ inspired supersymmetric model with an extra $U(1)_N$ gauge symmetry in which right handed neutrinos do not participate in the gauge interactions$^1$.

$^1$ Based on the talks presented by S.King and R.Nevzorov at CICHEP II and ICHEP’06 respectively
At collider energies the gauge group is:

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N \]  

where the Standard Model is augmented by an additional \( U(1)_N \) gauge group which is defined so that right-handed neutrinos are neutral under it and can be superheavy. This gauge group is supposed to descend from an \( E_6 \) GUT gauge group which is broken at the GUT scale. The \( U(1)_N \) gauge group (a particular case of \( U(1)' \)) is broken near the TeV energy scale giving rise to a massive \( Z' \) gauge boson which can be discovered at the LHC.

To ensure anomaly cancellation the low energy particle content of the \( E_6 \) SSM must include complete fundamental 27 representations of \( E_6 \). Thus in addition to the three families of SM quarks and leptons we predict three families of exotic quark states \( D_i, \bar{D}_i \) which carry a \( B-L \) charge \( (\pm \frac{2}{3}) \), and singlet fields \( S_i \) which carry non-zero \( U(1)_N \) charges and therefore survive down to the EW scale. We also predict three families of states \( H_{1i} \) and \( H_{2i} \) which have the quantum numbers of Higgs doublets. We also require a further pair \( H' \) and \( \bar{H}' \) from incomplete extra 27' and \( \bar{27}' \) representations to survive to low energies in order to ensure gauge coupling unification. Thus in addition to a \( Z' \) the \( E_6 \) SSM involves extra matter beyond the MSSM.

**THE SUPERPOTENTIAL AND PARAMETER COUNTING**

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 \( Z^H_2 \) 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 \( Z^H_2 \) symmetry reduces the structure of the Yukawa interactions to:

\[ W_{E_6,SSM} \simeq \lambda_i S (H_{1i} H_{2i}) + \kappa_i S (D_i \bar{D}_i) + f_{\alpha \beta} S_\alpha (H_d H_2^\beta) + \bar{f}_{\alpha \beta} S_\alpha (H_1^\beta H_u) + W_{MSSM} (\mu = 0), \]  

where \( \alpha, \beta = 1, 2 \) and \( i = 1, 2, 3 \). In Eq. (2) we ignore \( H' \) and \( \bar{H}' \) for simplicity. Here we define \( \lambda \equiv \lambda_3 \). The \( SU(2) \) doublets \( H_u \) and \( H_d \) play the role of Higgs fields generating the masses of quarks and leptons after electroweak symmetry breaking (EWSB). Therefore it is natural to assume that only \( S, H_u \) and \( H_d \) acquire non-zero VEVs. If \( \lambda \) or \( \kappa_i \) are large at the grand unification (GUT) scale \( M_X \) they affect the evolution of the soft scalar mass \( m_3^2 \) of the singlet field \( S \) rather strongly resulting in negative values of \( m_3^2 \) at low energies that trigger the breakdown of the \( U(1)_N \) symmetry. To guarantee that only \( H_u, H_d \) and \( S \) acquire a VEV we impose a certain hierarchy between the couplings \( H_{1i} \) and \( H_{2i} \) to the SM-type singlet superfields \( S_i \): \( \lambda \gg \lambda_{12}, f_{\alpha \beta} \) and \( \bar{f}_{\alpha \beta} \).

The masses of the fermion components of \( H' \) and \( \bar{H}' \) are induced by the term \( \mu' H' \bar{H}' \) in the superpotential. The corresponding mass term is not involved in the process of EWSB. Therefore parameter \( \mu' \) remains arbitrary. Gauge coupling unification requires
μ′ to be within 100 TeV. The masses of scalar components of $H'$ and $H''$ are determined by the soft masses $m_{H_1}^2$ and $m_{H_{21}}^2$ as well as by $\mu'$ and the corresponding bilinear scalar coupling $B'$ in the scalar potential. Because $\mu'$ and $B'$ can be complex the spectrum of survival components of $27'$ and $\overline{27}'$ is determined by six parameters.

The superpotential (2) contains 14 new Yukawa couplings as compared to the MSSM with $\mu = 0$. They are accompanied by 14 trilinear scalar couplings in the SUSY scalar potential. In addition the scalar potential of $E_6$SSM includes 13 soft SUSY masses: six masses of exotic squarks $m_{\tilde{D}_i}$ and $m_{\tilde{D}'_i}$, four masses of non–Higgs fields $m_{\tilde{H}_{1,\alpha}}$ and $m_{\tilde{H}_{2,\alpha}}$ ($\alpha = 1, 2$) and three masses of SM singlet scalar fields $m_S^2$. Because Yukawa and trilinear scalar couplings can be complex the $Z_2^H$–symmetric $E_6$SSM involves 75 new parameters in comparison to the MSSM with $\mu = 0$ which determine masses and couplings of extra fields. Thirty of them are phases. Some of these phases can be eliminated by the appropriate redefinition of new superfields.

Although $Z_2^H$ eliminates any problem related with baryon number violation and non-diagonal flavour transitions it also forbids all Yukawa interactions that would allow the exotic quarks to decay. Since models with stable charged exotic particles are ruled out by different experiments [2] the $Z_2^H$ symmetry must be broken. But the breakdown of $Z_2^H$ should not give rise to the operators leading to rapid proton decay. There are two ways to overcome this problem. The resulting Lagrangian has to be invariant either with respect to $Z_2^L$ symmetry, under which all superfields except lepton ones are even, or with respect to $Z_2^B$ discrete symmetry, which implies that exotic quark and lepton superfields are odd whereas the others remain even. The terms in the superpotential which permit exotic quarks to decay and are allowed by the $E_6$ symmetry can be written in the following alternative forms, depending on which discrete symmetry is imposed. If $Z_2^L$ is imposed then the following couplings are allowed:

$$W_1 = g^{Q}_{ijk} D_i (Q_j Q_k) + g^{d}_{ijk} \overline{D}_i d_j u_k^c , \quad (3)$$

which implies that exotic quarks are diquarks. If $Z_2^B$ is imposed then the following couplings are allowed:

$$W_2 = g^E_{ijk} e_i^c D_j u_k^c + g^D_{ijk} (Q_i L_j) \overline{D}_k . \quad (4)$$

which implies that exotic quarks are leptoquarks. We assume that the violation of the $Z_2^H$ symmetry in the $E_6$SSM is mainly caused by the Yukawa couplings of the exotic particles to the quarks and leptons of the third generations. This assumption results in three (six) extra Yukawa couplings if exotic quarks are diquarks (leptoquarks). Thus together with the trilinear scalar couplings this would increase the total number of independent parameters by 12 (24) degrees of freedom.

**PHENOMENOLOGICAL IMPLICATIONS**

The $E_6$SSM Higgs sector includes two Higgs doublets $H_u$ and $H_d$ as well as a SM–like singlet field $S$. After the breakdown of the gauge symmetry two CP-odd and two charged Goldstone modes in the Higgs sector are absorbed by the $Z$, $Z'$ and $W^\pm$ gauge bosons so
that only six physical degrees of freedom are left. They represent three CP-even (as in the NMSSM), one CP-odd and two charged Higgs states (as in the MSSM).

As in any other SUSY model the mass of the lightest CP–even Higgs boson $m_h$ in the $E_6$SSM is limited from above. In Fig. 1 we plot the two-loop upper bounds on the mass of the lightest Higgs particle in the MSSM, NMSSM and $E_6$SSM as a function of $\tan \beta$. At moderate values of $\tan \beta$ ($\tan \beta = 1.6 - 3.5$) the upper limit on the lightest Higgs boson mass in the $E_6$SSM is considerably higher than in the MSSM and NMSSM. It reaches the maximum value 150 – 155 GeV at $\tan \beta = 1.5 - 2$ [1]. The main reason for the increased Higgs mass in the $E_6$SSM is due to the increased upper limit on the coupling $\lambda$ (caused by the extra exotic states) which controls the important F-term contribution to $m_h$. At large $\tan \beta > 10$ the theoretical restriction on $m_h$ in the $E_6$SSM is 4 – 5 GeV larger than the one in the MSSM and NMSSM because of the $U(1)_N$ D-term contribution to $m_h^2$. The discovery at future colliders of a relatively heavy SM-like Higgs boson with mass $140 – 155$ GeV will permit to distinguish the $E_6$SSM from the MSSM and NMSSM.

Other possible manifestations of our exceptional SUSY model at the LHC are related with the presence of a $Z'$ and of exotic multiplets of matter. For instance, a relatively light $Z'$ will lead to enhanced production of $l^+l^-$ pairs ($l = e, \mu$). Fig. 2 shows the differential distribution in invariant mass of the lepton pair $l^+l^-$ (for one species of lepton $l = e, \mu$) in Drell–Yan production at the LHC with and without light exotic quarks with representative masses of exotic quarks $\mu_{D_i} = 250$ GeV for all three generations and with $M_{Z'} = 1.2$ TeV. This distribution is promptly measurable at the CERN collider with a high resolution and would enable one to not only confirm the existence of a $Z'$ state but also to establish the possible presence of additional exotic matter, by simply fitting to the data the width of the $Z'$ resonance. The analysis performed in [3] revealed that a $Z'$ boson in $E_6$ inspired models can be discovered at the LHC if its mass is less than

![FIGURE 1](image-url)  

**FIGURE 1.** Two-loop upper bound on the lightest Higgs mass versus $\tan \beta$. The solid, lower and upper dotted lines correspond to the theoretical restrictions on the lightest Higgs mass in the MSSM, NMSSM and $E_6$SSM respectively.
FIGURE 2. Differential cross section in the final state invariant mass, denoted by $M_{ll^-}$, at the LHC for DY production ($l = e$ or $\mu$ only) in presence of a $Z'$ with and without the (separate) contribution of exotic $D$-quarks with $\mu_{Di} = 250\text{GeV}$ for $M_{Z'} = 1.2\text{TeV}$.

$4 - 4.5\text{TeV}$. At the same time the determination of its couplings should be possible up to $M_{Z'} \sim 2 - 2.5\text{TeV}$ [4].

The exotic quarks can be also relatively light in the $E_6$SSM since their masses are set by the Yukawa couplings $\kappa_i$ and $\lambda_i$ that may be small. Then the production cross section of exotic quark pairs at the LHC can be comparable with the cross section of $t\bar{t}$ production (see Fig. 3). Since we have assumed that $Z_H^2$ is mainly broken by operators involving quarks and leptons of the third generation the lightest exotic quarks decay into either two heavy quarks $QQ$ or a heavy quark and a lepton $Q\tau$ ($\nu_\tau$), where $Q$ is either a $b$- or $t$-quark. This results in the growth of the cross section of either $pp \to QQ'\bar{Q}'\tilde{Q}' + X$ or $pp \to QQl^+l^- + X$. 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.

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Cross section at the LHC for pair production of exotic $D$-quarks as a function of the invariant mass of $D\bar{D}$ pair. Similar cross sections of $t\bar{t}$ and $b\bar{b}$ production are also included for comparison.

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