Abstract. We discuss the spectrum of Higgs bosons in the framework of the exceptional supersymmetric standard model. The presence of a $Z'$ and exotic particles predicted by the exceptional SUSY model allows the lightest Higgs particle to be significantly heavier than in the MSSM and NMSSM. When the mass of the lightest Higgs boson is larger than $135 - 140$ GeV the heaviest scalar, pseudoscalar and charged Higgs states lie beyond the TeV range.

One of the strongest theoretical arguments in favour of softly broken supersymmetry (SUSY) is associated with the partial unification of the standard model (SM) gauge interactions with gravity. However, the minimal supersymmetric standard model (MSSM) suffers from the $\mu$ problem. Indeed the superpotential of the MSSM contains one bilinear term $\mu \hat{H}_d \hat{H}_u$, so that $\mu$ is expected to be either zero or of the order of the Planck scale. At the same time, in order to get the correct pattern of electroweak symmetry breaking (EWSB), $\mu$ is required to be in the EW or TeV range. In the framework of the simplest extension of the MSSM — the Next–to–Minimal Supersymmetric Standard Model (NMSSM) — an ‘effective’ $\mu$–term is generated dynamically. (For a review of the MSSM and NMSSM see e.g. [1].)

A similar solution to the $\mu$ problem arises within superstring inspired models based on the $E_6$ gauge group or its rank–6 subgroup $SU(3)_C \times SU(2)_W \times U(1)_{Y} \times U(1)_{\psi} \times U(1)_{\chi}$. Two anomaly-free $U(1)_{\psi}$ and $U(1)_{\chi}$ symmetries of the rank-6 model are defined by [2]: $E_6 \rightarrow SO(10) \times U(1)_{\psi}$, $SO(10) \rightarrow SU(5) \times U(1)_{\chi}$. Near the string scale the rank-6 model can be reduced to an effective rank–5 model with only one extra gauge symmetry $U(1)'$:

$$U(1)' = U(1)_{\chi} \cos \theta + U(1)_{\psi} \sin \theta.$$ (1)

If $\theta \neq 0$ or $\pi$ the extra $U(1)'$ gauge symmetry forbids an elementary $\mu$ term but allows interaction $\lambda S \bar{H}_d H_u$ in the superpotential. After EWSB the scalar component of the SM singlet superfield $S$ acquires a non-zero vacuum expectation value (VEV) breaking $U(1)'$ and an effective $\mu$ term of the required size is automatically generated.
In this article we explore the Higgs sector in the framework of 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. ($\theta = \arctan(\sqrt{15})$. Only in this exceptional supersymmetric standard model ($E_6$SSM) do right-handed neutrinos may be superheavy, shed ing light on the origin of the mass hierarchy in the lepton sector [4]–[5]. The particle content of the $E_6$SSM involves three complete fundamental 27 representations of $E_6$. It ensures anomaly cancellation within each generation. In addition to the complete 27, representations doublet and anti-doublet from extra 27' and 27'' can and must survive to low energies to preserve gauge coupling unification. Thus in addition to a $Z'$ the $E_6$SSM involves extra matter that forms three 5 + 5' representations of $SU(5)$ plus three $SU(5)$ singlets which carry $U(1)_N$ charges.

The $E_6$SSM Higgs sector includes two Higgs doublets $H_u$ and $H_d$ as well as a SM–like singlet field $S$ [4]–[5]. The Higgs effective potential can be written as

$$V = V_F + V_D + V_{soft} + \Delta V,$$

$$V_F = \lambda^2 |S|^2 (|H_d|^2 + |H_u|^2) + \lambda^2 |(H_dH_u)|^2,$$

$$V_D = \frac{g^2}{2} \left( H_d^\dagger \sigma_a H_d + H_u^\dagger \sigma_a H_u \right)^2 + \frac{g'^2}{2} \left( |H_d|^2 - |H_u|^2 \right)^2 + \frac{g''^2}{2} \left( \tilde{Q}_1 |H_d|^2 + \tilde{Q}_2 |H_u|^2 + \tilde{S}|S|^2 \right)^2,$$

$$V_{soft} = m_3^2 |S|^2 + m_1^2 |H_d|^2 + m_2^2 |H_u|^2 + \left[ \lambda A_S (H_u H_d) + h.c. \right],$$

where $g' = \sqrt{3/5} g_1$; $g_2$, $g_1$ and $g_1'$ are $SU(2)_W$, $U(1)_Y$ and $U(1)_N$ gauge couplings; while $\tilde{Q}_1$, $\tilde{Q}_2$ and $\tilde{S}$ are effective $U(1)_N$ charges of $H_d$, $H_u$ and $S$ respectively [4]–[5]. The couplings $g_2$ and $g'$ are known precisely. Assuming gauge coupling unification one can find that $g_1'(Q) \approx g_1(Q)$ for any $Q < M_{GUT}$ [5].

At tree–level the Higgs potential is described by the sum of the first three terms in Eq. (2). The last term $\Delta V$ represents the contribution of loop corrections to the Higgs effective potential. In Eq. (2) $V_F$ and $V_D$ are the $F$ and $D$ terms. The soft SUSY breaking terms are collected in $V_{soft}$. A simple counting shows that the $E_6$SSM Higgs sector contains only one additional singlet field and one extra parameter compared to the MSSM. Therefore it can be regarded as the simplest extension of the Higgs sector of the MSSM.

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1Similar abbreviation – ESSM is used for the Extended Supersymmetric Standard Model which involves two extra vector-like families [16 + 16 of SO(10)] of quarks and leptons with masses of order of one TeV [3]. In contrast our model involves three families of extra 10’s of SO(10) which fill out three families of complete 27’s of $E_6$ near the TeV scale (apart from right-handed neutrinos which are expected to have intermediate scale masses). In our previous publications [4]–[5] we also used the acronym ESSM since we were unaware of the earlier work [5].
At the physical vacuum the $E_6$SSM Higgs fields develop the VEVs $\langle H_u \rangle = \frac{\sqrt{2}}{\tan \beta}, \langle H_d \rangle = \frac{\sqrt{2}}{\tan \beta}$ and $\langle S \rangle = \frac{\sqrt{2}}{\tan \beta}$, thus breaking the $SU(2)_W \times U(1)_Y \times U(1)_N$ symmetry to $U(1)_{EM}$, associated with electromagnetism. Instead of $v_d$ and $v_u$ it is more convenient to use $\tan \beta = \frac{v_u}{v_d}$ and $v = \sqrt{v_u^2 + v_d^2}$, where $v = 246$ GeV. After EWSB 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 form one CP-odd and two charged Higgs states (as in the MSSM) with masses

$$m^2_{A} \simeq \frac{2\lambda^2 s^2 x}{\sin^2 2\beta} + O(M^2_Z), \quad m^2_{H^\pm} \simeq m^2_{A} + O(M^2_Z) \quad (4)$$

respectively and three CP-even states (as in the NMSSM) with masses

$$m^2_{h^1} \simeq m^2_{A} + O(M^2_Z), \quad m^2_{h^2} \simeq g^{'2}_1 Q^2/s^2 + O(M^2_Z), \quad (5)$$

$$m^2_{h^3} \simeq \frac{\lambda^2 v^2}{g^{'2}_1 Q^2} \sin^2 2\beta \pm \sqrt{\frac{\lambda^2 v^2}{g^{'2}_1 Q^2}} \left(1 \pm \frac{g^{'2}_1 s^2}{\lambda^2 v^2} \left(\hat{Q}_1 \cos^2 \beta + \hat{Q}_2 \sin^2 \beta\right) Q_s \right)^2 + \ldots \quad (6)$$

where the auxiliary variable is $x = \frac{4\lambda}{\sqrt{2} m_A} \sin 2\beta$.

At least one CP-even Higgs boson is always heavy preventing the distinction between the $E_6$SSM and MSSM Higgs sectors. Indeed the mass of the singlet dominated Higgs scalar particle $m_{h^3}$ is always close to the mass of $Z'$ boson $M_{Z'} \simeq g_1 Q s \sim g_1 s$ that has to be heavier than $500 – 600$ GeV [6]. The masses of the charged, CP-odd and one CP-even Higgs states are governed by $m_A$. The mass of the SM-like Higgs boson given by Eq.(6) is set by $M_Z$. The last term in Eq.(6) must not be allowed to dominate since it is negative. This constrains $x$ around unity for $\lambda > g_1'$. As a consequence $m_A$ is confined in the vicinity of $\frac{4\lambda}{\sqrt{2} m_A} \tan \beta$ and is much larger than the masses of the $Z'$ and $Z$ bosons. At so large values of $m_A$ the masses of the heaviest CP-even, CP-odd and charged states are almost degenerate around $m_A$.

The qualitative pattern of the Higgs spectrum obtained for $\lambda > g_1'$ in the leading one-loop approximation is shown in Fig. 1. The numerical analysis reveals that the heaviest CP-even, CP-odd and charged Higgs states lie beyond the TeV range in the considered case. The second lightest CP-even Higgs boson is predominantly a singlet field so that it will be quite difficult to observe this particle at future colliders. With decreasing $\lambda$ the allowed range of $m_A$ enlarges so that charged, CP-odd and second lightest CP-even Higgs states may have masses in the $200 – 300$ GeV range when $\lambda < g_1'$. But for $m_A < 500$ GeV and $\lambda < g_1'$ we get a MSSM-type Higgs spectrum with the lightest SM-like Higgs boson below $130 – 135$ GeV and with the heaviest scalar above $600$ GeV being...
Figure 1: The one-loop masses of the CP-even Higgs bosons versus $m_A$ for $\lambda(M_t) = 0.794$, $\tan\beta = 2$, $M_{Z'} = M_S = 700$ GeV and $X_t = \sqrt{6}M_S$. Solid, dashed and dashed-dotted lines correspond to the masses of the lightest, second lightest and heaviest Higgs scalars.

singlet dominated and irrelevant. The non-observation of Higgs particle at LEP rules out most parts of the $E_6$SSM parameter space in this case.

From Fig. 1 and Eq. (6) it becomes clear that at some value of $m_A$ (or $x$) the lightest CP-even Higgs boson mass $m_{h_1}$ attains its maximum value. At tree-level the upper bound on $m_{h_1}$ is given by the sum of the first three terms in Eq. (6). The inclusion of loop corrections increase the bound on the lightest CP-even Higgs boson mass in SUSY models substantially. In Fig. 2 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 $\sim 150 - 155$ GeV at $\tan\beta = 1.5 - 2$. In the considered part of the parameter space the theoretical restriction on the mass of the lightest CP-even Higgs boson in the NMSSM exceeds the corresponding limit in the MSSM because of the extra contribution to $m_{h_1}^2$ induced by the additional $F$-term in the Higgs scalar potential of the NMSSM. The size of this contribution, which is described by the first term in Eq. (6) is determined by the Yukawa coupling $\lambda$. The upper limit on the coupling $\lambda$ caused by the validity of perturbation theory in the NMSSM is more stringent than in the $E_6$SSM due to the presence of exotic $5 + \bar{5}$-plets of matter in the particle spectrum of the $E_6$SSM. This is the reason why the upper limit of $m_{h_1}$ in the NMSSM is considerably less than
Figure 2: The dependence of the two-loop upper bound on the lightest Higgs boson mass on \( \tan \beta \) for \( m_t (m_t) = 165 \text{ GeV} \), \( m^2_{Q} = m^2_{U} = M^2_S \), \( X_t = \sqrt{6} M_S \) and \( M_S = 700 \text{ GeV} \). The solid, lower and upper dotted lines represent the limit on \( m_{h_1} \) in the MSSM, NMSSM and E\(_6\)SSM.

in the E\(_6\)SSM at moderate values of \( \tan \beta \).

At large \( \tan \beta > 10 \) the contribution of the \( F \)-term of the SM–type singlet field to \( m^2_{h_1} \) vanishes. Therefore with increasing \( \tan \beta \) the upper bound on the lightest Higgs mass in the NMSSM approaches the corresponding limit in the MSSM. In the E\(_6\)SSM the theoretical restriction on \( m_{h_1} \) also diminishes when \( \tan \beta \) rises but it is still \( 4 - 5 \text{ GeV} \) larger than the one in the MSSM because of the \( U(1)_N \) \( D \)-term contribution to \( m^2_{h_1} \) (the third term in Eq. (6)).

The discovery at future colliders of superpartners of observed quarks and leptons as well as a relatively heavy SM–like Higgs boson with mass \( 140 - 155 \text{ GeV} \), that corresponds to \( \lambda > g^1_t \) in the E\(_6\)SSM, will permit to distinguish the E\(_6\)SSM from the simplest supersymmetric (like MSSM and NMSSM) and other extensions of the SM. Another possible manifestations of the exceptional SUSY model at the LHC are related with the enhanced production of \( l^+l^- \), \( t\bar{t} \) and/or \( b\bar{b} \) pairs coming from either a \( Z' \) boson or exotic particle decays.

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