Nonstandard Higgs decays in the E$_6$SSM

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We study the nonstandard decays of the lightest Higgs state within the Exceptional Supersymmetric Standard Model (E$_6$SSM). We argued that the SM–like Higgs boson can decay predominantly into dark matter particles while its branching ratios into SM particles varies from 2% to 4%. This scenario also implies the presence of other relatively light Inert chargino and neutralino states in the particle spectrum with masses below 200 GeV. We argue that in this case the decays of the lightest Higgs boson into $l^+l^- + X$ may play an essential role in the Higgs searches.

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1. E_6SSM

The E_6SSM is based on the $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge group which is a sub-group of E_6 [1]-[2]. The additional low energy $U(1)_N$ is a linear superposition of $U(1)_\chi$ and $U(1)_\psi$, i.e. $U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi$. Two anomaly–free $U(1)_\psi$ and $U(1)_\chi$ symmetries are defined by: $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$. The extra $U(1)_N$ gauge symmetry is defined such that right–handed neutrinos do not participate in the gauge interactions. Since right–handed neutrinos have zero charges they can be superheavy, shedding light on the origin of the mass hierarchy in the lepton sector and providing a mechanism for the generation of the baryon asymmetry in the Universe via leptogenesis [3].

To ensure anomaly cancellation the particle content of the E_6SSM is extended to include three complete fundamental 27 representations of E_6 Each 27_i multiplet contains a SM family of quarks and leptons, right–handed neutrino N_i^c, SM-type singlet fields S_i which carry non-zero $U(1)_N$ charge, a pair of $SU(2)_W$–doublets H_i^d and H_i^u and a pair of colour triplets of exotic quarks $\overline{D}_i$ and D_i which can be either diquarks (Model I) or leptoquarks (Model II) [1]-[2]. S_i, H_i^d and H_i^u form either Higgs or inert Higgs multiplets. In addition to the complete 27_i multiplets the low energy particle spectrum of the E_6SSM is supplemented by $SU(2)_W$ doublet H' and anti-doublet $\overline{H}'$ states from extra $27'$ and $\overline{27'}$ to preserve gauge coupling unification. The analysis performed in [4] shows that the unification of gauge couplings in the E_6SSM can be achieved for any phenomenologically acceptable value of $\alpha_3(M_Z)$ consistent with the measured low energy central value. The presence of a Z' boson and of exotic quarks predicted by the E_6SSM provides spectacular new physics signals at the LHC which were discussed in [1]–[2], [5]–[6]. Recently the particle spectrum and collider signatures associated with it were studied within the constrained version of the E_6SSM [7]–[9].

The superpotential in the E_6 inspired models involves many new Yukawa couplings that induce non–diagonal flavour transitions. To suppress these effects in the E_6SSM an approximate Z_2^H symmetry is imposed. Under this symmetry all superfields except one pair of H_i^d and H_i^u (say $H_d \equiv H_3^d$ and $H_u \equiv H_3^u$) 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

$$W_{E_6SSM} \simeq \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \lambda_{\alpha\beta} \hat{S}(\hat{H}_\alpha^d \hat{H}_\beta^u) + \kappa_{ij} \hat{S}(\hat{D}_i \hat{\overline{D}}_j) + f_{\alpha\beta} \hat{S}_\alpha (\hat{H}_d \hat{H}_\beta^u)$$

$$+ \tilde{f}_{\alpha\beta} \hat{S}_\alpha (\hat{H}_\beta^d \hat{H}_u) + \mu'(\hat{H}'\hat{\overline{H}}') + h_{4j}^E(\hat{H}_d \hat{H}')\hat{e}_j^c + W_{MSSM}(\mu=0) \,, \tag{1.1}$$

where $\alpha, \beta = 1,2$ and $i,j = 1,2,3$. Here we assume that all right–handed neutrinos are heavy. The $SU(2)_W$ doublets $\hat{H}_u$ and $\hat{H}_d$ and SM-type singlet field $\hat{S}$, that are even under the Z_2^H symmetry, play the role of Higgs fields. At the physical vacuum they develop VEVs $\langle H_d \rangle = v_1/\sqrt{2}$, $\langle H_u \rangle = v_2/\sqrt{2}$ and $\langle S \rangle = s/\sqrt{2}$. Instead of v_1 and v_2 it is more convenient to use $\tan\beta = v_2/v_1$ and $v = \sqrt{v_1^2 + v_2^2} = 246\,\text{GeV}$. The VEV of the SM-type singlet field, s, breaks the extra $U(1)_N$ symmetry thereby providing an effective μ term as well as the necessary exotic fermion masses and also inducing that of the Z' boson. In the E_6SSM the Higgs spectrum contains one pseudoscalar, two charged and three CP–even states. In the leading two–loop approximation the mass of the lightest CP–even Higgs boson does not exceed $150-155\,\text{GeV}$ [1].

2. Lightest Inert neutralinos

The neutral components of the Inert Higgsinos ($\tilde{H}_1^{d0}$, $\tilde{H}_2^{d0}$, $\tilde{H}_1^{u0}$, $\tilde{H}_2^{u0}$) and Inert singlinos ($\tilde{S}_1$, $\tilde{S}_2$) mix and form Inert neutralino states. In the field basis ($\tilde{H}_2^{d0}$, $\tilde{H}_2^{u0}$, $\tilde{S}_2$, $\tilde{H}_1^{d0}$, $\tilde{H}_1^{u0}$, $\tilde{S}_1$) the corresponding mass matrix takes a form

$$M_{IN} = \begin{pmatrix} A_{22} & A_{21} \\ A_{12} & A_{11} \end{pmatrix}, \qquad A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda_{\alpha\beta}s & \tilde{f}_{\beta\alpha}v\sin\beta \\ \lambda_{\beta\alpha}s & 0 & f_{\beta\alpha}v\cos\beta \\ \tilde{f}_{\alpha\beta}v\sin\beta & f_{\alpha\beta}v\cos\beta & 0 \end{pmatrix}, \qquad (2.1)$$

so that $A_{12} = A_{21}^T$. In the following analysis we shall choose the VEV of the SM singlet field to be large enough ($s = 2400\,\text{GeV}$) so that the experimental constraints on Z' boson mass ($M_{Z'} \gtrsim 865\,\text{GeV}$) and $Z - Z'$ mixing are satisfied and all Inert chargino states are heavier than $100\,\text{GeV}$. In addition, we also require the validity of perturbation theory up to the GUT scale. The restrictions specified above set very strong limits on the masses of the lightest Inert neutralinos. In particular, our numerical analysis indicates that the lightest and second lightest Inert neutralinos (χ_1^0 and χ_2^0) are typically lighter than $60 - 65\,\text{GeV}$ [10]–[11]. Therefore the lightest Inert neutralino tends to be the lightest SUSY particle in the spectrum and can play the role of dark matter. The neutralinos χ_1^0 and χ_2^0 are predominantly Inert singlinos. Their couplings to the Z–boson can be rather small so that such Inert neutralinos would remain undetected at LEP.

In order to clarify the results of our numerical analysis, it is useful to consider a simple scenario when $\lambda_{\alpha\beta} = \lambda_\alpha\,\delta_{\alpha\beta}$, $f_{\alpha\beta} = f_\alpha\,\delta_{\alpha\beta}$ and $\tilde{f}_{\alpha\beta} = \tilde{f}_\alpha\,\delta_{\alpha\beta}$. In the limit where off–diagonal Yukawa couplings vanish and $\lambda_\alpha s \gg f_\alpha v, \tilde{f}_\alpha v$ the eigenvalues of the Inert neutralino mass matrix can be easily calculated (see [12]). In particular the masses of two lightest Inert neutralino states (χ_1^0 and χ_2^0) are given by

$$m_{\chi_\alpha^0} \simeq \frac{\tilde{f}_\alpha f_\alpha v^2 \sin 2\beta}{2m_{\chi_\alpha^\pm}}. \qquad (2.2)$$

where $m_{\chi_\alpha^\pm} = \lambda_\alpha s/\sqrt{2}$ are masses of the Inert charginos. From Eq. (2.2) one can see that the masses of χ_1^0 and χ_2^0 are determined by the values of the Yukawa couplings $\tilde{f}_\alpha$ and f_α. They decrease with increasing $\tan\beta$ and chargino masses. In this approximation the part of the Lagrangian, that describes interactions of Z with χ_1^0 and χ_2^0, can be presented in the following form:

$$\mathscr{L}_{Z\chi\chi} = \sum_{\alpha,\beta} \frac{M_Z}{2v} Z_\mu \left(\chi_\alpha^{0T} \gamma_\mu \gamma_5 \chi_\beta^0 \right) R_{Z\alpha\beta}, \qquad (2.3)$$

$$R_{Z\alpha\beta} = R_{Z\alpha\alpha}\,\delta_{\alpha\beta}, \qquad R_{Z\alpha\alpha} = \frac{v^2}{2m_{\chi_\alpha^\pm}^2} \left(f_\alpha^2 \cos^2\beta - \tilde{f}_\alpha^2 \sin^2\beta \right). \qquad (2.4)$$

Eqs. (2.4) demonstrates that the couplings of χ_1^0 and χ_2^0 to the Z-boson can be very strongly suppressed or even tend to zero. This happens when $|f_\alpha|\cos\beta \approx |\tilde{f}_\alpha|\sin\beta$.

Although χ_1^0 and χ_2^0 might have extremely small couplings to Z, their couplings to the lightest CP–even Higgs boson h_1 can not be negligibly small if the corresponding states have appreciable masses. When the SUSY breaking scale M_S and the VEV s of the singlet field are considerably larger than the EW scale, the mass matrix of the CP–even Higgs sector has a hierarchical structure

and can be diagonalised using the perturbation theory [13]–[14]. In this case the lightest CP–even Higgs state is the analogue of the SM Higgs field and is responsible for all light fermion masses in the E_6SSM. Therefore it is not so surprising that in the limit when $\lambda_\alpha s \gg f_\alpha v$, $\tilde{f}_\alpha v$ the part of the Lagrangian that describes the interactions of χ_1^0 and χ_2^0 with h_1 takes a form

$$\mathscr{L}_{H\chi\chi} = \sum_{\alpha,\beta} (-1)^{\theta_\alpha + \theta_\beta} X_{\alpha\beta}^{h_1} \left(\psi_\alpha^{0T} (-i\gamma_5)^{\theta_\alpha + \theta_\beta} \psi_\beta^0 \right) h_1 , \qquad X_{\gamma\sigma}^{h_1} \simeq \frac{|m_{\chi_\sigma^0}|}{v} \delta_{\gamma\sigma} , \qquad (2.5)$$

i.e. the couplings of h_1 to χ_1^0 and χ_2^0 is proportional to the mass/VEV. In Eq. (2.5) $\psi_\alpha^0 = (-i\gamma_5)^{\theta_\alpha} \chi_\alpha^0$ is the set of Inert neutralino eigenstates with positive eigenvalues, while θ_α equals 0 (1) if the eigenvalue corresponding to χ_α^0 is positive (negative).

3. Exotic Higgs decays

In our analysis we required that the lightest Inert neutralino account for all or some of the observed dark matter relic density. This sets another stringent constraint on the masses and couplings of χ_1^0. Indeed, because the lightest Inert neutralino states are almost Inert singlinos, their couplings to the gauge bosons, Higgs states, quarks (squarks) and leptons (sleptons) are rather small resulting in a relatively small annihilation cross section of $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to$ SM particles and the possibility of an unacceptably large dark matter density. A reasonable density of dark matter can be obtained only for $|m_{\chi_1^0}| \sim M_Z/2$ when the lightest Inert neutralino states annihilate mainly through an s–channel Z-boson, via its Inert Higgsino doublet components which couple to the Z–boson. If $\tilde{\chi}_1^0$ annihilation proceeds through the Z–boson resonance, i.e. $2|m_{\chi_1^0}| \approx M_Z$, then an appropriate value of dark matter density can be achieved even for a relatively small coupling of $\tilde{\chi}_1^0$ to Z. Since the masses of χ_1^0 and χ_2^0 are much larger than the b–quark mass and the decays of h_1 into these neutralinos are kinematically allowed, the SM–like Higgs boson decays predominantly into the lightest inert neutralino states and has very small branching ratios (2% − 4%) for decays into SM particles.

In order to illustrate the features of the E_6SSM mentioned above we specify a set of benchmark points (see Table 1). Within the E_6SSM relatively large masses for the lightest and the second lightest Inert neutralinos can be obtained only for moderate values of $\tan\beta \lesssim 2$. Even for $\tan\beta \lesssim 2$ the lightest Inert neutralino states can get masses $\sim M_Z/2$ only if at least one light Inert chargino state and two Inert neutralinos states, which are predominantly components of the $SU(2)_W$ doublet, have masses below 200 GeV (see Table 1). The Inert chargino and neutralinos states that are mainly Inert Higgsinos couple rather strongly to W and Z–bosons and therefore can be efficiently produced at the LHC and then decay into the LSP and pairs of leptons and quarks giving rise to remarkable signatures which can be observed in the near future.

When $\tan\beta \lesssim 2$ the mass of the lightest CP–even Higgs boson is very sensitive to the choice of the coupling $\lambda(M_t)$. In particular, to satisfy LEP constraints $\lambda(M_t)$ must be larger than $g_1' \simeq 0.47$. Large values of $\lambda(M_t)$ lead to a qualitative pattern of the Higgs spectrum which is rather similar to the one which arises in the PQ symmetric NMSSM [15]–[16]. In the considered limit the heaviest CP–even, CP–odd and charged states are almost degenerate around m_A and lie beyond the TeV range while the mass of the second lightest CP–even Higgs state is set by $M_{Z'}$ [1].

If the masses of χ_1^0 and χ_2^0 are very close then the decays of h_1 into $\chi_\alpha \chi_\beta$ will not be observed at the LHC giving rise to a large invisible branching ratio of the SM–like Higgs boson. When the

	A	B	C	D
$\lambda_{22}(M_t)$	0.094	0.001	0.001	0.468
$\lambda_{21}(M_t)$	0	0.094	0.079	0.05
$\lambda_{12}(M_t)$	0	0.095	0.08	0.05
$\lambda_{11}(M_t)$	0.059	0.001	0.001	0.08
$f_{22}(M_t)$	0.53	0.001	0.04	0.05
$f_{21}(M_t)$	0.053	0.69	0.68	0.9
$f_{12}(M_t)$	0.053	0.69	0.68	0.002
$f_{11}(M_t)$	0.53	0.001	0.04	0.002
$\tilde{f}_{22}(M_t)$	0.53	0.001	0.04	0.002
$\tilde{f}_{21}(M_t)$	0.053	0.49	0.49	0.002
$\tilde{f}_{12}(M_t)$	0.053	0.49	0.49	0.05
$\tilde{f}_{11}(M_t)$	0.53	0.001	0.04	0.65
$|m_{\chi_1^0}|/\text{GeV}$	35.42	45.60	45.1	46.24
$|m_{\chi_2^0}|/\text{GeV}$	51.77	45.95	55.3	46.60
$|m_{\chi_3^0}|/\text{GeV}$	105.3	158.7	133.3	171.1
$|m_{\chi_4^0}|/\text{GeV}$	152.7	162.1	136.9	171.4
$|m_{\chi_5^0}|/\text{GeV}$	162.0	204.7	178.4	805.4
$|m_{\chi_6^0}|/\text{GeV}$	201.7	207.8	192.2	805.4
$|m_{\chi_1^\pm}|/\text{GeV}$	100.1	158.5	133	125.0
$|m_{\chi_2^\pm}|/\text{GeV}$	159.5	162.3	136.8	805.0
$\Omega_\chi h^2$	0.107	0.0886	0.0324	0.00005
$R_{Z\chi_1^0\chi_1^0}$	-0.115	-0.0205	-0.0217	-0.0224
$R_{Z\chi_2^0\chi_2^0}$	-0.288	-0.0208	-0.0524	-0.0226
$R_{Z\chi_1^0\chi_2^0}$	0.046	0.0015	-0.0020	-0.213
$Br(h \to \chi_2\chi_2)$	20.3%	48.0%	12.3%	47.9%
$Br(h \to \chi_2\chi_1)$	0.25%	0	0	0
$Br(h \to \chi_1\chi_1)$	76.3%	49.5%	83.4%	49.3%
$Br(h \to b\bar{b})$	2.82%	2.28%	3.93%	2.56%
$Br(h \to \tau\bar{\tau})$	0.30%	0.24%	0.42%	0.27%
Γ^{tot}/MeV	81.7	101	58.6	89.8

Table 1: Benchmark scenarios. The branching ratios, masses of the Inert neutralinos and charginos and couplings of the Inert neutralinos are calculated for $s = 2400\,\text{GeV}$, $\tan\beta = 1.5$, $\lambda = g_1' = 0.468$, $A_\lambda = 600\,\text{GeV}$, $m_Q = m_U = M_S = 700\,\text{GeV}$, $X_t = \sqrt{6}M_S$ that correspond to the two–loop lightest Higgs boson mass $m_{h_1} \simeq 116\,\text{GeV}$. The one–loop masses of the heavy Higgs states are $m_A \simeq m_{H^\pm} \simeq m_{h_3} = 1145\,\text{GeV}$ and $m_{h_2} \simeq M_{Z'} \simeq 890\,\text{GeV}$.

mass difference between the second lightest and the lightest Inert neutralinos is larger than $10\,\text{GeV}$ the invisible branching ratio remains dominant but some of the decay products of χ_2 might be observed at the LHC. In particular, there is a chance that soft $\mu^+\mu^-$ pairs could be detected. Since the branching ratios of h_1 into SM particles are extremely suppressed, the decays of the SM–like Higgs boson into $l^+l^- + X$ could be important for Higgs searches [10].

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