Nonstandard Higgs Decays and Dark Matter in the E_6SSM

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Based on:

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher, Phys. Rev. D 83 (2011) 075013;
S. F. King, S. Moretti and R. Nevzorov, Phys. Rev. D 73 (2006) 035009;
S. F. King, S. Moretti and R. Nevzorov, Phys. Lett. B 634 (2006) 278.

Introduction

- It is expected that the Higgs particle will be detected at the LHC in the near future.
- Physics beyond the SM may affect the Higgs decay rates to SM particles and give rise to new channels of Higgs decays requiring a drastic change in the strategy for Higgs boson searches.
- In particular, there exist several extensions of the SM in which Higgs can decay into invisible final states.
- Invisible Higgs decay modes may occur in
  - SUSY models;
  - models with compact and large extra dimensions;
  - littlest Higgs model with T-parity;
  - models with an enlarged symmetry breaking sector (Majoron models, SM with extra singlet scalar fields etc.);
  - “hidden valley” models...

- If Higgs is mainly invisible, then the visible branching ratios will be dramatically reduced, making its discovery more difficult.
- At e^+e^- colliders, invisible Higgs can be tagged through the recoiling Z.
- The LEP II collaborations excluded invisible Higgs masses up to 114.4 GeV.
- The possibility of observing an “invisible” Higgs boson at the LHC was analysed.
  - ZH and WH associated production;
  - $t\bar{t}H$ production;
  - central exclusive diffractive production at the LHC;
  - inelastic events with large missing transverse energy and two high E_T jets (Higgs is produced by VV fusion);
  - $t\bar{t}VV$ ($b\bar{b}VV$) production...

Exceptional SUSY model

- Here we consider the exotic decays of the lightest Higgs boson and associated novel collider signatures within the E_6 inspired SUSY model.
- At high energies E_6 may be broken to

$$E_6 \to SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)' \,,$$
$$U(1)' = U(1)_\chi \cos\theta + U(1)_\psi \sin\theta \,,$$

where $E_6 \to SO(10) \times U(1)_\psi, \quad SO(10) \to SU(5) \times U(1)_\chi.$

- $\theta = \arctan\sqrt{15}$ corresponds to $U(1)_N$ symmetry under which right-handed neutrinos have zero charge.
- Only in this exceptional SUSY model (E_6SSM) right–handed neutrino may be superheavy shedding light on the origin of lepton mass hierarchy.

- To ensure anomaly cancellation the particle content of the E_6SSM is extended to include three complete 27_i representations of E_6.
- In addition the spectrum of the E_6SSM is supplemented by $SU(2)$ doublet and anti-doublet from extra $27'$ and $\overline{27'}$ (L_4 and $\overline{L}_4$) to preserve gauge coupling unification.
- Together with survivors the particle content of the E_6SSM becomes

$$3 \times 27_i + L_4 + \overline{L}_4 = 3\left[Q_i,\, u_i^c,\, d_i^c,\, L_i,\, e_i^c\right] + 3(D_i,\, \overline{D}_i) +$$
$$+3(H_i^u) + 3(H_i^d) + 3(S_i) + 3(N_i^c) + L_4 + \overline{L}_4\,.$$

  - D_i and $\overline{D}_i$ are exotic quarks.
  - H_i^d and H_i^u are either Higgs or inert Higgs fields.

- To suppress baryon number violating and flavour changing processes one can postulate Z_2^H symmetry under which all superfields except $H_d \equiv H_{1,3}$, $H_u \equiv H_{2,3}$ and $S \equiv S_3$ are odd.
- The Z_2^H symmetry reduces the structure of Yukawa interactions to:

$$W_{\mathrm{E_6SSM}} \simeq \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \lambda_{\alpha\beta} \hat{S}(\hat{H}^d_\alpha \hat{H}^u_\beta) + \kappa_i \hat{S}(\hat{D}_i \hat{\overline{D}}_i) +$$
$$+ f_{\alpha\beta} \hat{S}_\alpha (\hat{H}_d \hat{H}^u_\beta) + \tilde{f}_{\alpha\beta} \hat{S}_\alpha (\hat{H}^d_\beta \hat{H}_u) + h^E_{4j} (\hat{H}_d \hat{L}_4) \hat{e}^c_j + \mu' (\hat{L}_4 \hat{\overline{L}}_4)$$
$$+ \frac{1}{2} M_{ij} \hat{N}^c_i \hat{N}^c_j + h_{4j} (\hat{H}_u \hat{L}_4) \hat{N}^c_j + h_{ij} (\hat{H}_u \hat{L}_i) \hat{N}^c_j + W_{MSSM}(\mu = 0)\,,$$

  where $\alpha, \beta = 1, 2$ and $i = 1, 2, 3$.
- The Z_2^H symmetry can only be approximate since it ensures that the lightest exotic quark is stable.
- $\hat{H}_u$, $\hat{H}_d$ and $\hat{S}$ play the role of Higgs superfields.

- At the physical vacuum $\langle H_d \rangle = \frac{v_1}{\sqrt{2}}$, $\langle H_u \rangle = \frac{v_2}{\sqrt{2}}$, $\langle S \rangle = \frac{s}{\sqrt{2}}$, where $v^2 = v_1^2 + v_2^2 = (246\,GeV)^2$ and $\tan\beta = v_2/v_1$.
- At the tree level CP is preserved in the Higgs sector of the E_6SSM so that the Higgs spectrum contains
  - one pseudoscalar m_A^2 ,
  - two charged states $m_{H^\pm}^2 = m_A^2 + O(M_Z^2)$,
  - three scalars $m_{h_3}^2 = m_A^2 + O(M_Z^2)$, $m_{h_2}^2 = M_{Z'}^2 + O(M_Z^2)$.
- The upper limit on the lightest Higgs mass m_{h_1} in the E_6SSM is considerably larger than in the MSSM and NMSSM.
- In the two–loop approximation the upper bound on m_{h_1} does not exceed $150 - 155$ GeV.

Inert charginos and neutralinos

- Since Z_2^H symmetry violating couplings are expected to be small ($\lesssim 10^{-4} - 10^{-3}$) the neutralino and Inert neutralino states as well as chargino and Inert chargino states do not mix.
- 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 mass matrix of the Inert neutralino sector takes a form

$$M_{IN} = \begin{pmatrix} A_{22} & A_{21} \\ A_{12} & A_{11} \end{pmatrix},$$

$$A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda_{\alpha\beta} s & \tilde{f}_{\beta\alpha} v \sin\beta \\ \lambda_{\beta\alpha} s & 0 & f_{\beta\alpha} v \cos\beta \\ \tilde{f}_{\alpha\beta} v \sin\beta & f_{\alpha\beta} v \cos\beta & 0 \end{pmatrix},$$

- In the basis of Inert chargino interaction states $(\tilde{H}_2^{u+}, \tilde{H}_1^{u+}, \tilde{H}_2^{d-}, \tilde{H}_1^{d-})$ the corresponding mass matrix is given by

$$M_{IC} = \begin{pmatrix} 0 & C^T \\ C & 0 \end{pmatrix}, \qquad C_{\alpha\beta} = \frac{1}{\sqrt{2}} \lambda_{\alpha\beta}\, s\,.$$

- We require
  - all Inert charginos to be heavier than 100 GeV to satisfy LEP constraints;
  - s to be large enough to avoid lower experimental bound on the Z' mass ($s \gtrsim 2400$ GeV);
  - the validity of perturbation theory up to the GUT scale that constrains the allowed range of all Yukawa couplings.

- Our numerical analysis indicates that
  - the lightest and second lightest Inert neutralinos (χ_1 and χ_2), which are predominantly Inert singlinos, are always light ($m_{\chi_1,\chi_2} \lesssim 60 - 65$ GeV);
  - χ_1 and χ_2 may have rather small couplings to Z so that they could escape detection at LEP;
  - the couplings of χ_1 and χ_2 to the SM-like Higgs boson are always large if they have appreciable masses.
- In order to clarify the obtained results let us consider

$$\lambda_{\alpha\beta} = \lambda_\alpha\, \delta_{\alpha\beta}, \qquad f_{\alpha\beta} = f_\alpha\, \delta_{\alpha\beta}, \qquad \tilde{f}_{\alpha\beta} = \tilde{f}_\alpha\, \delta_{\alpha\beta}\,.$$

- In this case the masses of the Inert charginos are

$$m_{\chi_\alpha^\pm} = \frac{\lambda_\alpha}{\sqrt{2}}\, s\,.$$

- In the limit when $\lambda_\alpha\, s \gg \tilde{f}_\alpha\, v,\ f_\alpha\, v$ the masses of two lightest Inert neutralinos are

$$m_{\chi_\alpha} \approx \frac{\tilde{f}_\alpha f_\alpha v^2 \sin 2\beta}{2 m_{\chi^\pm_\alpha}}\,, \qquad \tilde{f}_\alpha \sim f_\alpha < 0.6 - 0.65\,.$$

- Since the masses of χ_1 and χ_2 are determined by v their couplings to the SM-like Higgs boson are

$$g_{h\chi_\alpha\chi_\alpha} \approx m_{\chi_\alpha}/v\,.$$

- The Lagrangian that describes interactions of the Z-boson with χ_1 and χ_2 can be written as

$$L_{Z\chi\chi} = \frac{\bar{g}}{4} Z_\mu \Big(\chi_\alpha \gamma_\mu \gamma_5 \chi_\beta \Big) R_{Z\alpha\beta}\,,$$

$$R_{Z\alpha\beta} = R_{Z\alpha\alpha}\, \delta_{\alpha\beta}\,, \qquad R_{Z\alpha\alpha} = \frac{v^2}{2 m^2_{\chi^\pm_\alpha}} \Big(f_\alpha^2 \cos^2\beta - \tilde{f}_\alpha^2 \sin^2\beta \Big)\,.$$

  - Couplings $\tilde{f}_\alpha$ and f_α can be chosen so that $R_{Z\alpha\alpha}$ are small.

Exotic Higgs decays

- Since χ_1 has mass which is less than 60 GeV it tends to be the LSP, that can form dark matter in the Universe.
- When $m_{\chi_1} \ll M_Z/2$ the lightest Inert neutralino has rather small couplings and $\sigma(\chi_1\chi_1 \to anything)$ is too small leading to $\Omega_{CDM}h^2 \gg 0.110$.
- The reasonable dark matter density can be obtained for $m_{\chi_1} \sim M_Z/2$ when the s-channel annihilation through the Z-boson is the dominant annihilation channel.
- This scenario implies that the lightest Higgs boson decays predominantly into $\chi_1\chi_1$ and $\chi_2\chi_2$.
- Since $\chi_2 \to \chi_1 + f\bar{f}$ the decays of $h \to l^+l^- + X$ might be observed at the LHC if $m_{\chi_2} - m_{\chi_1}$ is large enough.
- This scenario is realized only when $\chi_1^\pm$, χ_3 and χ_4 have masses below 200 GeV and $\tan\beta < 2$.

- Benchmark point A (All mass parameters are given in GeV):

Parameters : $\tan\beta = 1.5, \quad s = 2400, \quad \lambda = k_i = g_1' = 0.468, \quad A_\lambda = 600,$

$m_{Q,U} = M_S = 700, \quad X_t = \sqrt{6}M_S, \quad m_{h_1} \simeq 115.9,$

$\lambda_{22} = \lambda_{11} = 0.001, \ \lambda_{12} = 0.080, \ \lambda_{21} = 0.079, \ f_{12} = f_{21} = 0.68$

$f_{11} = f_{22} = \tilde{f}_{11} = \tilde{f}_{22} = 0.04, \quad \tilde{f}_{12} = \tilde{f}_{21} = 0.49.$

Spectrum: $m_{\chi_2^\pm} \simeq 136.8, \quad m_{\chi_6} \simeq 192.2, \quad m_{\chi_5} \simeq 178.4, \quad m_{\chi_4} \simeq 136.9,$

$m_{\chi_1^\pm} \simeq 133.0, \quad m_{\chi_3} \simeq 133.3, \quad m_{\chi_2} \simeq 55.34, \quad m_{\chi_1} \simeq 45.08,$

Couplings : $R_{Z\chi_1\chi_1} \simeq -0.0217, \quad R_{Z\chi_1\chi_2} \simeq -0.0020, \quad R_{Z\chi_2\chi_2} \simeq -0.0524,$

$\Omega_\chi h^2 \simeq 0.0324, \qquad \sigma_{SI} \simeq 6.0 - 24.4 \cdot 10^{-44}$ cm^2,

Higgs Decay rates: $Br(h_1 \to \chi_2\chi_2) \simeq 12.3\%, \quad Br(h_1 \to \chi_1\chi_1) \simeq 83.4\%,$

$Br(h_1 \to b\bar{b}) \simeq 3.95\%, \qquad Br(h_1 \to \tau\bar{\tau}) \simeq 0.41\%,$

$\Gamma^{tot} \simeq 0.0588.$

- Benchmark point B (All mass parameters are given in GeV):

Parameters : $\tan\beta = 1.564,\ s = 2400,\ k_i = g_1' = 0.468,\ \lambda = 0.6\ A_\lambda = 1600,$

$m_{Q,U} = M_S = 700, \quad X_t = \sqrt{6}M_S, \quad m_{h_1} \simeq 134.8,$

, $\lambda_{22} = \lambda_{11} = 0.0001,\ \lambda_{12} = \lambda_{21} = 0.06,\ f_{12} = 0.466,\ f_{21} = 0.47$

$f_{11} = f_{22} = \tilde{f}_{11} = \tilde{f}_{22} = 0.001, \quad \tilde{f}_{12} = 0.408, \quad \tilde{f}_{21} = 0.4.$

Spectrum: $m_{\chi_2^\pm} \simeq 102.0, \quad m_{\chi_6} \simeq 140.4, \quad m_{\chi_5} \simeq 139.8, \quad m_{\chi_4} \simeq 103.5,$

$m_{\chi_1^\pm} \simeq 101.7, \quad m_{\chi_3} \simeq 103.1, \quad m_{\chi_2} \simeq 36.9, \quad m_{\chi_1} \simeq 36.7,$

Couplings : $R_{Z\chi_1\chi_1} \simeq -0.132, \quad R_{Z\chi_1\chi_2} \simeq 0.0043, \quad R_{Z\chi_2\chi_2} \simeq -0.133,$

$\Omega_\chi h^2 \simeq 0.107, \qquad \sigma_{SI} \simeq 2.0 - 8.2 \cdot 10^{-44}$ cm^2,

Higgs Decay $Br(h_1 \to \chi_2\chi_2) \simeq 49.2\%, \quad Br(h_1 \to \chi_1\chi_1) \simeq 49.1\%,$

rates: $Br(h_1 \to b\bar{b}) \simeq 1.59\%, \qquad Br(h_1 \to \tau\bar{\tau}) \simeq 0.166\%,$

$\Gamma^{tot} \simeq 0.169.$

- Benchmark point C (All mass parameters are given in GeV):

Parameters : $\tan\beta = 1.5, \quad s = 2400, \quad \lambda = k_i = g_1' = 0.468, \quad A_\lambda = 600,$

$m_{Q,U} = M_S = 700, \quad X_t = \sqrt{6}M_S, \quad m_{h_1} \simeq 116,$

$\lambda_{22} = 0.468, \quad \lambda_{11} = 0.08, \quad \lambda_{12} = \lambda_{21} = 0.05, \quad \tilde{f}_{11} = 0.65,$

$f_{11} = f_{12} = \tilde{f}_{21} = \tilde{f}_{22} = 0.002, \quad f_{22} = \tilde{f}_{12} = 0.05, \quad f_{21} = 0.9,$

Spectrum: $m_{\chi_2^\pm} \simeq 805.0, \quad m_{\chi_6} \simeq 805.4, \quad m_{\chi_5} \simeq 805.4, \quad m_{\chi_4} \simeq 171.4,$

$m_{\chi_1^\pm} \simeq 125.0, \quad m_{\chi_3} \simeq 171.1, \quad m_{\chi_2} \simeq 46.60, \quad m_{\chi_1} \simeq 46.2,$

Couplings : $R_{Z\chi_1\chi_1} \simeq -0.0224, \quad R_{Z\chi_1\chi_2} \simeq -0.213, \quad R_{Z\chi_2\chi_2} \simeq -0.0226,$

$\Omega_\chi h^2 \simeq 0.00005, \qquad \sigma_{SI} \simeq 6.1 - 25.0 \cdot 10^{-44}$ cm^2,

Higgs Decay rates: $Br(h_1 \to \chi_2\chi_2) \simeq 47.9\%, \quad Br(h_1 \to \chi_1\chi_1) \simeq 49.3\%,$

$Br(h_1 \to b\bar{b}) \simeq 2.58\%, \quad Br(h_1 \to \tau\bar{\tau}) \simeq 0.27\%,$

$\Gamma^{tot} \simeq 0.0901.$

Conclusions

- The E_6SSM leads to the presence of two light Inert neutralinos with masses below 60-65 GeV that tend to be the lightest SUSY particles in the spectrum.
- The lightest Inert neutralino with mass $\sim M_Z/2$ can play the role of dark matter.
- In this case the lightest Higgs boson decays into $\chi_1\chi_1$ and $\chi_2\chi_2$ mainly while the total branching ratio of its decays into SM particles is suppressed.
- This scenario implies the presence of relatively light Inert chargino and neutralino states with masses below 200 GeV that can be discovered at the LHC.
- The considered scenario also predicts the large spin–independent part of χ_1^0–nucleon cross section which is on the edge of observability of XENON100.