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.

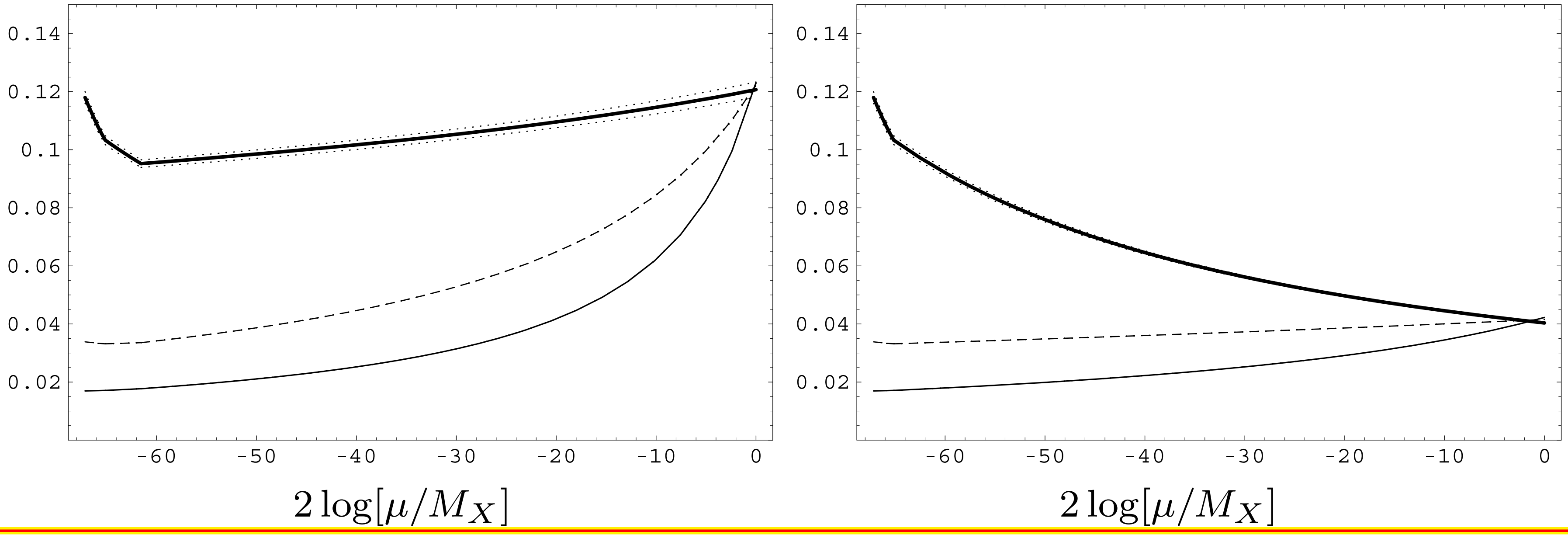
- To ensure anomaly cancellation the particle content of the E$_6$SSM is extended to include three complete 27_i representations of E_6.
- In addition the spectrum of the E$_6$SSM is supplemented by $SU(2)$ doublet and anti-doublet from extra $27'$ and $\overline{27'}$ (L_4 and $\overline{L}_4$) to preserve gauge coupling unification in the one–loop approximation.
- Together with survivors the particle content of the E$_6$SSM becomes

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

  - D_i and $\overline{D}_i$ can be either diquarks or leptoquarks.
  - H^d_i and H^u_i are either Higgs or inert Higgs fields.

- In the E_6SSM two–loop corrections to $\alpha_i(\mu)$ are large and could spoil gauge coupling unification.
- However it was argued that within the E_6SSM gauge coupling unification can be achieved for any value of $\alpha_3(M_Z)$ which is in agreement with current data [S.F.King, S.Moretti, RN, Phys.Lett.B 650 (2007) 57].

Two–loop RG flow of $\alpha_i(\mu)$ in the E_6SSM and MSSM



- 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.

Higgs sector

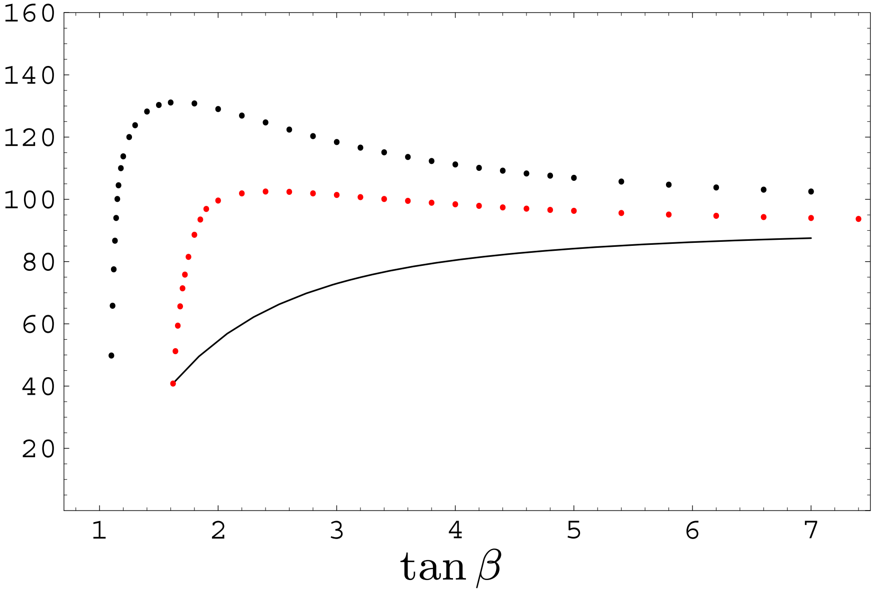
- The E$_6$SSM Higgs sector involves H_d, H_u and S.
- At the physical vacuum $\langle H_d\rangle = \dfrac{v_1}{\sqrt{2}}$, $\langle H_u\rangle = \dfrac{v_2}{\sqrt{2}}$, $\langle S\rangle = \dfrac{s}{\sqrt{2}}$,

  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$_6$SSM so that the Higgs spectrum contains
  - one pseudoscalar m_A^2,
  - two charged states $m^2_{H^\pm} = m_A^2 + O(M_Z^2)$,
  - three scalars $m^2_{h_3} = m_A^2 + O(M_Z^2)$, $m^2_{h_2} = M^2_{Z'} + O(M_Z^2)$.
- The mass of the lightest Higgs particle in the E$_6$SSM is limited from above

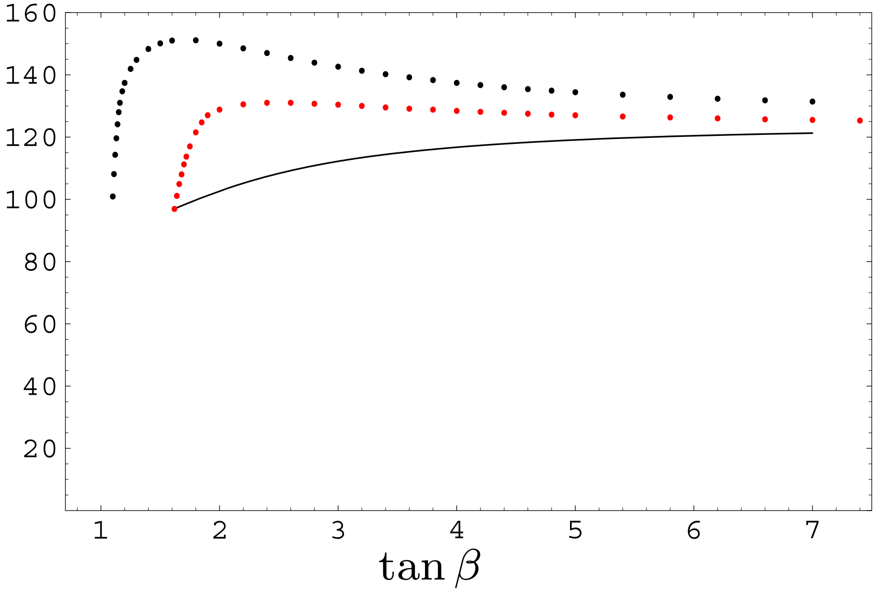
$$m^2_{h_1} \lesssim M_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta + \\ + g_1'^2 v^2 (\tilde{Q}_1 \cos^2\beta + \tilde{Q}_2 \sin^2\beta)^2 + \Delta\,.$$

- Larger values of $\alpha_i(t)$ increase the allowed range of the Yukawa couplings at the EW scale.
- As a result the upper limit on m_{h_1} in the E_6SSM is considerably larger than in the MSSM and NMSSM.
- Even at the tree level m_{h_1} can be heavier $120\,$GeV.

Tree level upper bound on m_{h_1}

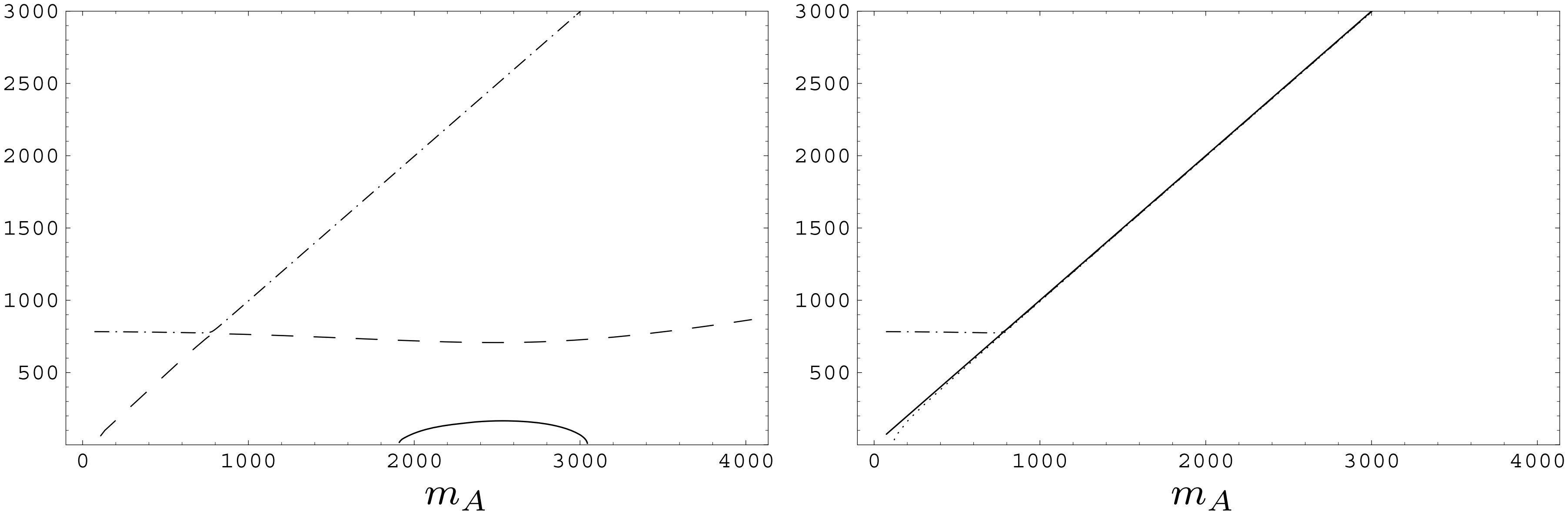


Two–loop upper bound on m_{h_1}



- In the two–loop approximation the upper bound on m_{h_1} does not exceed $150 - 155$ GeV.
- When $m_{h_1} > 130 - 135$ GeV the requirement of vacuum stability maintains mass hierarchy in the Higgs spectrum so that charged, CP–odd and heaviest CP–even states lie beyond the TeV range.

One–loop Higgs boson spectrum



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 ($m_{\chi_1,\chi_2} \lesssim 60 - 65\,\mathrm{GeV}$);
  - 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

$$m_{\chi^\pm_\alpha} = \frac{\lambda_\alpha}{\sqrt{2}}\,s\,.$$

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

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

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

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

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

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

Parameters : $\tan\beta = 1.564,\ s = 2400,\ k_i = g'_1 = 0.468,\ \lambda = 0.6\ A_\lambda = 1600,$

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

, $\lambda_{22} = \lambda_{11} = 0.0001,\ \lambda_{12} = \lambda_{21} = 0.06,\ f_{12} = 0.466,\ f_{21} = 0.476,$

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

Spectrum: $m_{\chi^{\pm}_2} \simeq 102.0, \quad m_{\chi_6} \simeq 140.4, \quad m_{\chi_5} \simeq 139.8, \quad m_{\chi_4} \simeq 103.5,$

$m_{\chi^{\pm}_1} \simeq 101.7, \quad m_{\chi_3} \simeq 103.1, \quad m_{\chi_2} \simeq 36.9, \quad m_{\chi_1} \simeq 36.7,$

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 rates: $Br(h_1 \to \chi_2\chi_2) \simeq 49.2\%, \quad Br(h_1 \to \chi_1\chi_1) \simeq 49.1\%,$

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

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

- 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.