Nonstandard Higgs decays in the E_6 inspired SUSY models

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Outline

- Introduction
- E_6 inspired SUSY models with extra $U(1)_N$ symmetry
- Inert neutralinos
- Exotic Higgs decays
- Conclusions

Based on:

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R. Nevzorov, Phys. Rev. D **87** (2013) 015029 [arXiv:1205.5967 [hep-ph]].

S. F. King, S. Moretti and R. Nevzorov, Phys. Lett. B 650 (2007) 57;

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

- Recent astrophysical and cosmological observations indicate that $22\% - 25\%$ of the energy density of the Universe exists in the form of dark matter.
- The existence of dark matter is the strongest piece of evidence for physics beyond the SM.
- Dark sector may affect the Higgs decay rates to SM particles and give rise to new channels of Higgs decays.
- In particular, there exist several extensions of the SM in which Higgs can decay into invisible final states.
  - SUSY models;
  - models with compact and large extra dimensions;
  - littlest Higgs model with T-parity...
- It is interesting to study Higgs phenomenology and dark sector within well motivated extensions of the SM.

E_6 inspired SUSY models

- At high energies E_6 may be broken to

$$E_6 \to SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N \times Z_2^M\,,$$

$$U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi\,, \qquad Z_2^M = (-1)^{3(B-L)}\,,$$

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

- In the E_6 inspired SUSY models with extra $U(1)_N$ symmetry right–handed neutrinos do not participate in the gauge interactions.
- Thus right–handed neutrinos can be superheavy, shedding light on the origin of the mass hierarchy in the lepton sector.
- In this case lepton asymmetry can be dynamically generated via the decays of N_1^c and then gets converted into baryon asymmetry due to sphaleron interactions.

- 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

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

  - 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.

- To suppress baryon number violating and flavour changing processes one can postulate $\tilde{Z}_2^H$ symmetry under which all superfields except $H_d \equiv H_3^d$, $H_u \equiv H_3^u$, $S \equiv S_3$, L_4 and $\overline{L}_4$ are odd.
- The $\tilde{Z}_2^H$ symmetry reduces the structure of Yukawa interactions to:

$$W_{\mathrm{E_6SSM}} \simeq \lambda S(H_u H_d) + \lambda_{\alpha\beta} S(H^d_\alpha H^u_\beta) + \kappa_{ij} S(D_i \overline{D}_j) + \tilde{f}_{\alpha\beta} S_\alpha (H^d_\beta H_u)$$
$$+ f_{\alpha\beta} S_\alpha (H_d H^u_\beta) + g^D_{ij} (Q_i L_4) \overline{D}_j + h^E_{i\alpha} e^c_i (H^d_\alpha L_4) + \mu_L L_4 \overline{L}_4$$
$$+ \frac{1}{2} M_{ij} \hat{N}^c_i \hat{N}^c_j + h^N_{\alpha j} (\hat{H}^u_\alpha \hat{L}_4) \hat{N}^c_j + h_{ij} (\hat{H}_u \hat{L}_i) \hat{N}^c_j + W_{MSSM}(\mu = 0)\,.$$

where $\alpha, \beta = 1, 2$ and $i = 1, 2, 3$.
- H_u, H_d and S play the role of Higgs superfields.
- The $U(1)_N$ symmetry forbids bilinear term $\mu H_u H_d$ in the superpotential but allows interaction $\lambda S(H_u H_d)$.

- 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 $\tan\beta = v_2/v_1$.
- The VEV of S breaks $U(1)_N$ inducing the masses of Z' boson and exotic particles as well as providing solution of the μ–problem $\mu_{eff} = \lambda s/\sqrt{2}$.
- 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 mass of the lightest Higgs particle in the E_6SSM does not exceed $150 - 155$ GeV.

Inert neutralinos

- The interactions of inert Higgs superfields H^d_α, H^u_α and S_α are described by

$$W_{IH} = \lambda_{\alpha\beta} S(H^d_\alpha H^u_\beta) + f_{\alpha\beta} S_\alpha (H_d H^u_\beta) + \tilde{f}_{\alpha\beta} S_\alpha (H^d_\beta H_u)\,.$$

- The fermionic components of these superfields form inert neutralino and chargino states.
- 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 ($s \gtrsim 8$ TeV);
  - the validity of perturbation theory up to the GUT scale that constrains the allowed range of all Yukawa couplings

- Our analysis indicates that
  - the lightest and second lightest Inert neutralinos (χ_1 and χ_2), which are predominantly Inert singlinos, are always light ($m_{\chi_1,\chi_2} \lesssim 60-65\,\text{GeV}$);
  - χ_1 and χ_2 may have rather small couplings to Z so that they could escape detection at LEP.
- The Lagrangian that describes interactions of the Z-boson with χ_1 and χ_2 can be written as

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

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

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

- Z_2^M and $\tilde{Z}_2^H$ symmetries ensure that χ_1 and the lightest ordinary neutralino $\tilde{\chi}_1$ are absolutely stable.
- 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 the extremely large dark matter density.
- 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.
- However the SM-like Higgs boson decays more than 95% of the time into either χ_1 or χ_2 in this case while the branching ratios into SM particles are suppressed.
- The simplest phenomenologically viable scenarios imply that χ_1 is substantially lighter than 1 eV.

Exotic Higgs decays

- In this case χ_1 forms hot dark matter in the Universe but gives only a very minor contribution to the dark matter density.
- The lightest ordinary neutralino may account for all or some of the observed cold dark matter density.
- Since χ_1 is extremely light it does not affect Higgs phenomenology.
- The presence of χ_2 with the GeV scale mass gives rise to the substantial branching ratio of the nonstandard Higgs decays $h_1 \to \chi_2\chi_2$.
- The lifetime of χ_2, which decays into $\chi_1 + f\bar{f}$ via virtual Z, tends to be rather long

$$\tau_{\chi_2} \sim \frac{1}{|R_{Z12}|^2 m_{\chi_2}^5}.$$

- Thus χ_2 decays outside the detectors resulting in the invisible branching ratio of the SM-like Higgs.
- We require that χ_2 decays before BBN, i.e. $\tau_{\chi_2} < 1\,\text{sec}$.
- This requirement basically rules out too light χ_2.
- It is quite problematic to satisfy this restriction if $m_{\chi_2} \lesssim 100\,\text{MeV}$.
- The branching fraction of the nonstandard Higgs decays depends rather strongly on m_{χ_2}.
- If χ_2 is heavier than 2.5 GeV the branching ratio of the exotic Higgs decays can be as large as 20-30%.
- When χ_2 is lighter than 0.5 GeV this branching ratio can be as small as $10^{-3} - 10^{-4}$.

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

Parameters : $\tan\beta = 1.5, \quad s = 12000, \quad \lambda = 0.6$

$m_{Q,U} = M_S = 4000, \quad X_t = \sqrt{6} M_S, \quad m_{h_1} \simeq 125,$

$-\lambda_{22} = \lambda_{11} = 0.012, \; \lambda_{12} = \lambda_{21} = 0, \; f_{12} = 0.00001, \; f_{21} = -0.1,$

$f_{11} = -f_{22} = \tilde{f}_{11} = \tilde{f}_{22} = 0.1, \quad \tilde{f}_{12} = 0.000011, \; \tilde{f}_{21} = 0.1\,.$

Spectrum: $m_{\chi^\pm_2} \simeq 101.8, \quad m_{\chi_6} \simeq 105.2, \quad m_{\chi_5} \simeq 104.9, \quad m_{\chi_4} \simeq 104.1,$

$m_{\chi^\pm_1} \simeq 101.8, \quad m_{\chi_3} \simeq 101.8, \quad m_{\chi_2} \simeq 2.67, \quad m_{\chi_1} \simeq 6.5 \cdot 10^{-11},$

Couplings : $|R_{Z\chi_1\chi_1}| \simeq -0.0212, \quad |R_{Z\chi_1\chi_2}| \simeq 0.0271, \quad R_{Z\chi_2\chi_2} \simeq 0.0103,$

Higgs Decay rates: $Br(h_1 \to \chi_2\chi_2) \simeq 21.9\%,$

$Br(h_1 \to b\bar{b}) \simeq 46.4\%, \qquad \Gamma^{tot} \simeq 0.0051.$

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

Parameters : $\tan\beta = 1.5, \quad s = 12000, \quad \lambda = 0.6$

$m_{Q,U} = M_S = 4000, \quad X_t = \sqrt{6} M_S, \quad m_{h_1} \simeq 125,$

$-\lambda_{22} = \lambda_{11} = 0.06,\ \lambda_{12} = \lambda_{21} = 0,\ f_{12} = 0.00001,\ f_{21} = -0.1,$

$f_{11} = -f_{22} = \tilde{f}_{11} = \tilde{f}_{22} = 0.1, \quad \tilde{f}_{12} = 0.000011,\ \tilde{f}_{21} = 0.1\,.$

Spectrum: $m_{\chi^\pm_2} \simeq 509.1, \quad m_{\chi_6} \simeq 509.8, \quad m_{\chi_5} \simeq 509.7, \quad m_{\chi_4} \simeq 509.6,$

$m_{\chi^\pm_1} \simeq 509.1, \quad m_{\chi_3} \simeq 509.1, \quad m_{\chi_2} \simeq 0.55, \quad m_{\chi_1} \simeq 1.4 \cdot 10^{-11},$

Couplings : $|R_{Z\chi_1\chi_1}| \simeq -0.00090, \quad |R_{Z\chi_1\chi_2}| \simeq 0.00116, \quad R_{Z\chi_2\chi_2} \simeq 0.00045,$

Higgs Decay rates: $Br(h_1 \to \chi_2\chi_2) \simeq 1.23\%,$

$Br(h_1 \to b\bar{b}) \simeq 58.7\%, \qquad \Gamma^{tot} \simeq 0.004.$

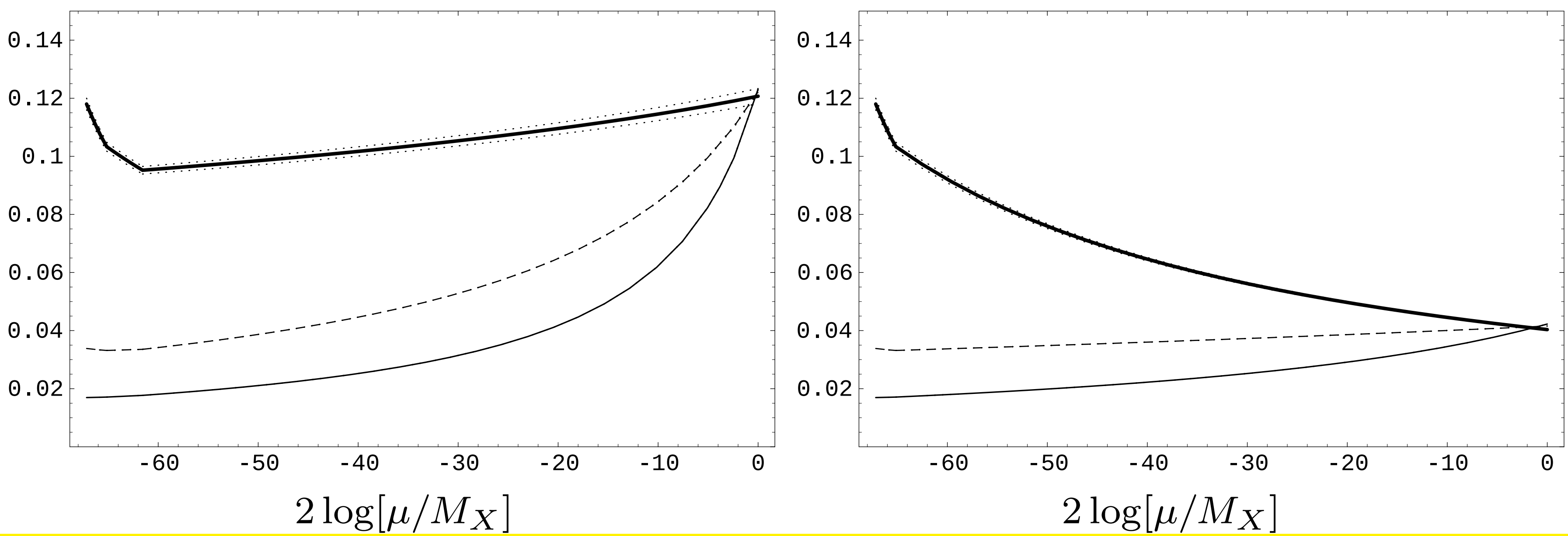
Conclusions

- The E_6 inspired SUSY models with extra $U(1)_N$ symmetry lead to the presence of two light inert neutralinos χ_1 and χ_2 with masses below 60-65 GeV.
- In this model χ_1 and the lightest ordinary neutralino are absolutely stable and can contribute to the dark matter density.
- The simplest phenomenologically viable scenarios imply that χ_1 is considerably lighter than $1\,$eV forming hot dark matter in the Universe.
- If χ_2 has GeV scale mass it tends to be longlived particle with $\tau_{\chi_2} < 1\,$sec.
- Such next–to–lightest inert neutralino can give rise to the substantial invisible branching ratio of the SM–like Higgs boson that can be as large as 20%.

Backup slides

- In the E$_6$SSM two–loop corrections to $\alpha_i(\mu)$ are large and could spoil gauge coupling unification.
- However it was argued that within the E$_6$SSM 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$_6$SSM and MSSM



- In the field basis $(\tilde{H}^{d0}_2,\ \tilde{H}^{u0}_2,\ \tilde{S}_2,\ \tilde{H}^{d0}_1,\ \tilde{H}^{u0}_1,\ \tilde{S}_1)$ 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 $(\tilde{H}^{u+}_2,\ \tilde{H}^{u+}_1,\ \tilde{H}^{d-}_2,\ \tilde{H}^{d-}_1)$ the mass matrix of the inert chargino states is given by

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

- 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 $\lambda_\alpha \, s \gg \tilde{f}_\alpha \, v, \; f_\alpha \, v$ one obtains

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

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

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