Collider phenomenology of the E_6SSM

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Outline

- Introduction
- Exceptional SUSY model
- Z' and exotica phenomenology
- Higgs phenomenology
- Conclusions

Based on:

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher, Phys. Rev. D 83 (2011) 075013;
S. F. King, R. Luo, D. J. Miller and R. Nevzorov, JHEP 0812 (2008) 042;
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

- SUSY leads to a partial unification of the SM gauge interactions with gravity within SUGRA models.
- But MSSM being incorporated in supergravity suffers from the μ problem. Indeed

$$W_{SUGRA} \simeq W_0(h_m) + \mu(h_m)(\hat{H}_d \hat{H}_u) + h_t(\hat{Q}\hat{H}_u)\hat{U}^c + h_b(\hat{Q}\hat{H}_d)\hat{D}^c + ...,$$

where $\mu(h_m) \sim M_{Pl}$ or $\mu(h_m) = 0$.

- The correct pattern of EW symmetry breaking requires

$$\mu(h_m) \sim 100 - 1000\,\text{GeV}\,.$$

- In the superstring inspired E_6 models gauge symmetry forbids any bilinear terms in W allowing interaction

$$W_{E_6} = \lambda \hat{S}(\hat{H}_d \hat{H}_u) + \ldots .$$

- 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.
- At the EW scale field S acquires VEV breaking $U(1)_N$ and providing natural solution of the μ–problem

$$\mu_{eff} = \lambda < S > \ .$$

Exceptional SUSY model

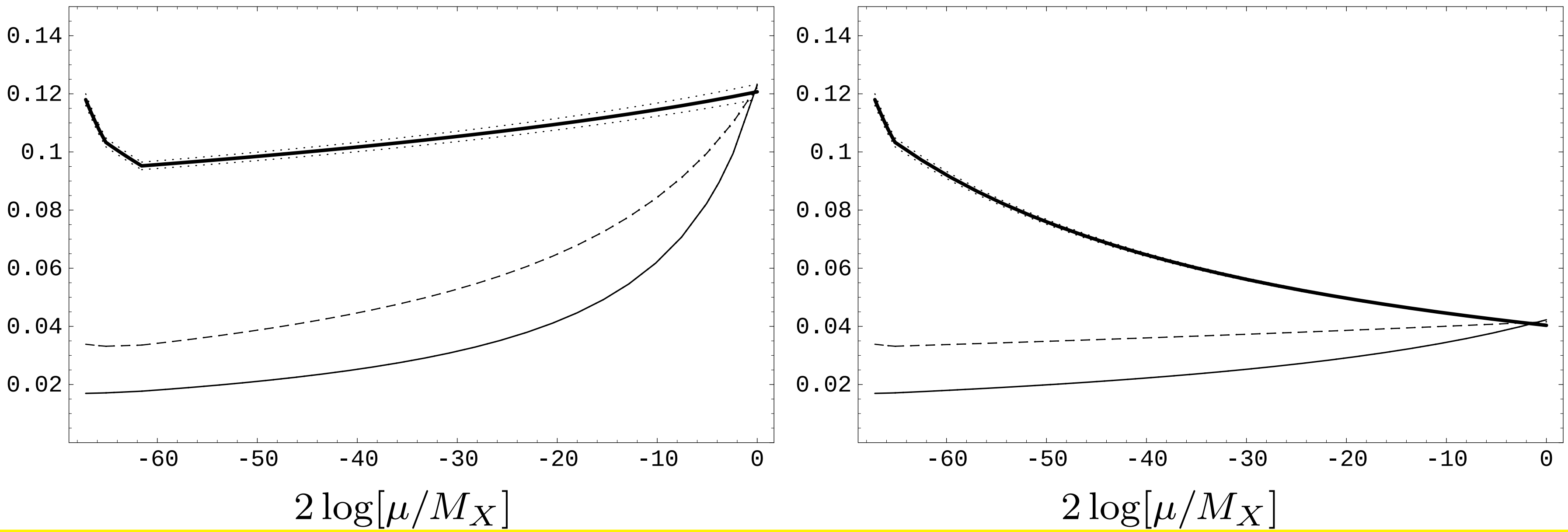
- To ensure anomaly cancellation the particle content of the E$_6$SSM is extended to include three complete 27_i representations of E_6.
- In addition the spectrum of the E$_6$SSM is supplemented by $SU(2)$ doublet and anti-doublet from extra $27'$ and $\overline{27'}$ (L_4 and $\overline{L}_4$) to preserve 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 $\overline{D}_i$ are exotic quarks.
  - 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 prevent rapid proton decay the invariance under some discrete symmetry should be imposed.
- 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:

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

  where $\alpha, \beta = 1, 2$ and $i = 1, 2, 3$.
  - $\hat{H}_u$, $\hat{H}_d$ and $\hat{S}$ play the role of Higgs superfields.

- The Z_2^H symmetry can only be approximate since it ensures that the lightest exotic quark is stable.
  - If D–quarks were stable they would be confined in heavy hadrons which relative concentrations would be 10^{-10} per nucleon.
  - The experimental limits on the abundances of such stable relics vary from 10^{-15} to 10^{-30} per nucleon [T.K. Hemmick et al., Phys.Rev.D 41 (1990) 2074.]
- There are two different ways to impose an appropriate Z_2 symmetry leading to the baryon and lepton number conservation which imply

– exotic quarks are diquarks, i.e. $B_{D,\overline{D}} = \mp 2/3$;

– exotic quarks are leptoquarks, i.e. $B_{D,\overline{D}} = \pm 1/3, \; L_{D,\overline{D}} = \pm 1$.

- The terms which allow D and $\overline{D}$ to decay are given by

$$W_1 = g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \overline{D}_i d^c_j u^c_k \,.$$

if exotic quarks are diquarks and

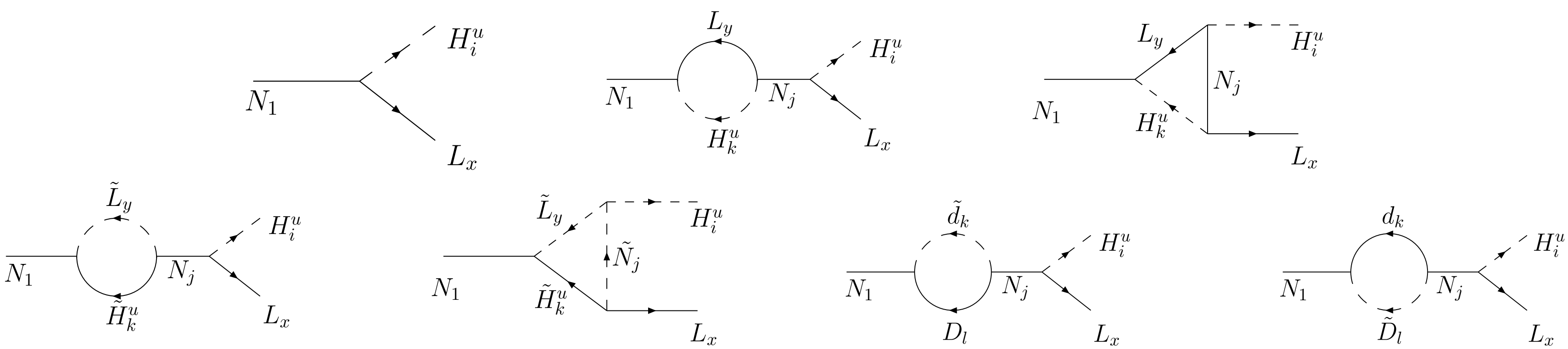
$$W_2 = g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} (Q_i L_j) \overline{D}_k \,,$$

if exotic quarks are leptoquarks.

- Since Z_2^H symmetry violating operators give rise to FCNC processes ($K^0 - \overline{K}^0$ oscillations, $\mu \to e^- e^+ e^-$ and etc.) the corresponding Yukawa couplings are expected to be small ($\lesssim 10^{-4} - 10^{-3}$).
- In the E$_6$SSM lepton asymmetry can be dynamically generated via the decay of N_1^c and then gets converted into baryon asymmetry due to sphaleron interactions.

- New exotic particles predicted by the E_6SSM contribute to the generation of lepton asymmetry.
- In the E_6SSM the substantial lepton CP asymmetries can be induced even for $M_1 \simeq 10^6$ GeV that may allow to avoid gravitino problem [S.King,R.Luo,D.Miller,RN, JHEP 12 (2008) 042].
- New particles predicted by the E_6SSM can be discovered at the LHC in the near future.

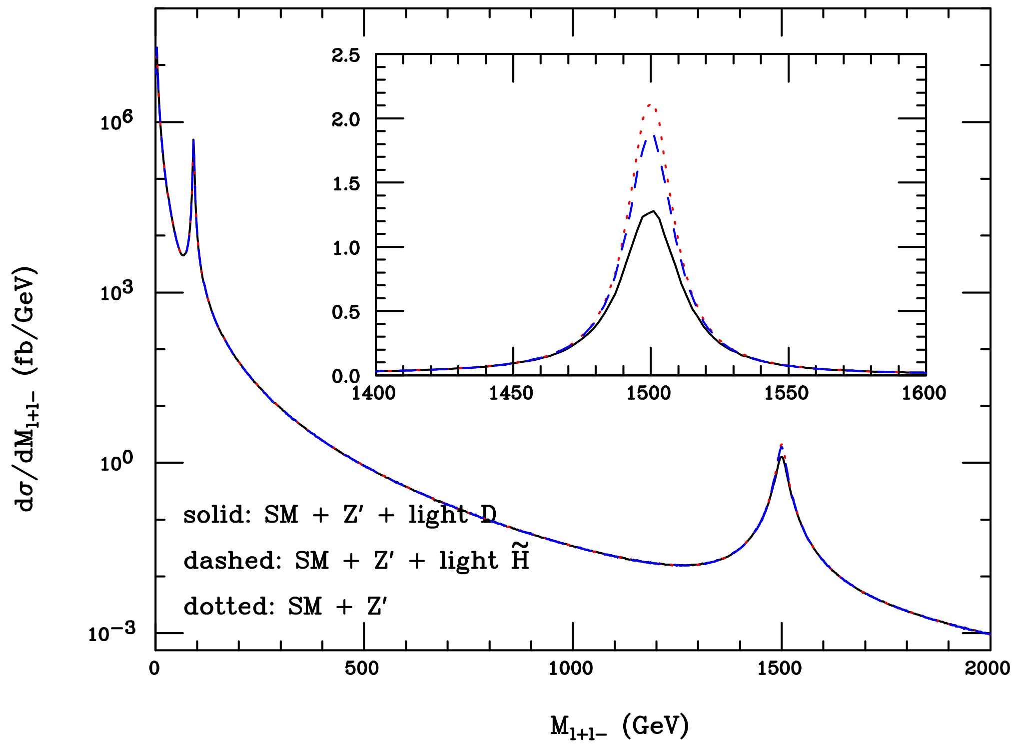
Diagrams that contribute to the generation of lepton asymmetry



Z' and exotica phenomenology

- At the LHC Z' can be discovered if it has a mass below $4 - 4.5$ TeV [J.Kang, P.Langacker, Phys.Rev.D 71 (2005) 035014].
- Its diagnostic via asymmetries should be possible up to $M_{Z'} \simeq 2 - 2.5$ TeV [M.Dittmar, A.Nicollerat, A-S.Djouadi, Phys.Lett.B 583 (2004) 111.].

Cross section for Drell-Yan production at the LHC



- If exotic quarks are light their production cross section at the LHC can be comparable with $\sigma(pp \to t\bar{t} + X)$.
- Assuming that D and $\overline{D}$ couple most strongly with the third family quarks and leptons the exotic quarks decay either via

$$\overline{D} \to t + \tilde{b}\,, \qquad \overline{D} \to b + \tilde{t}$$

if exotic quarks $\overline{D}_i$ are diquarks or via

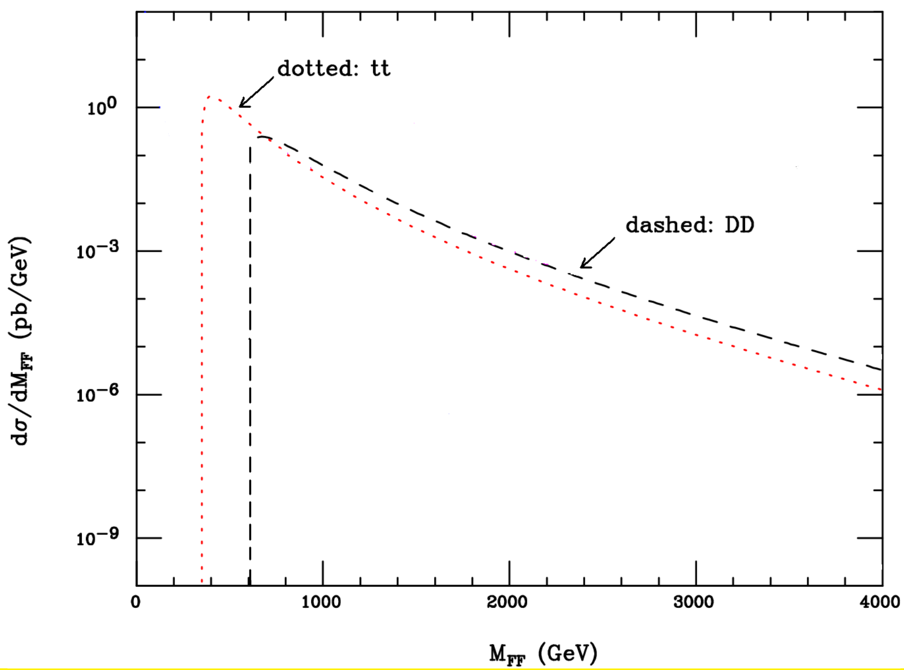
$$D \to t + \tilde{\tau}\,, \qquad D \to \tau + \tilde{t}\,,$$
$$D \to b + \tilde{\nu}_\tau\,, \qquad D \to \nu_\tau + \tilde{b}\,,$$

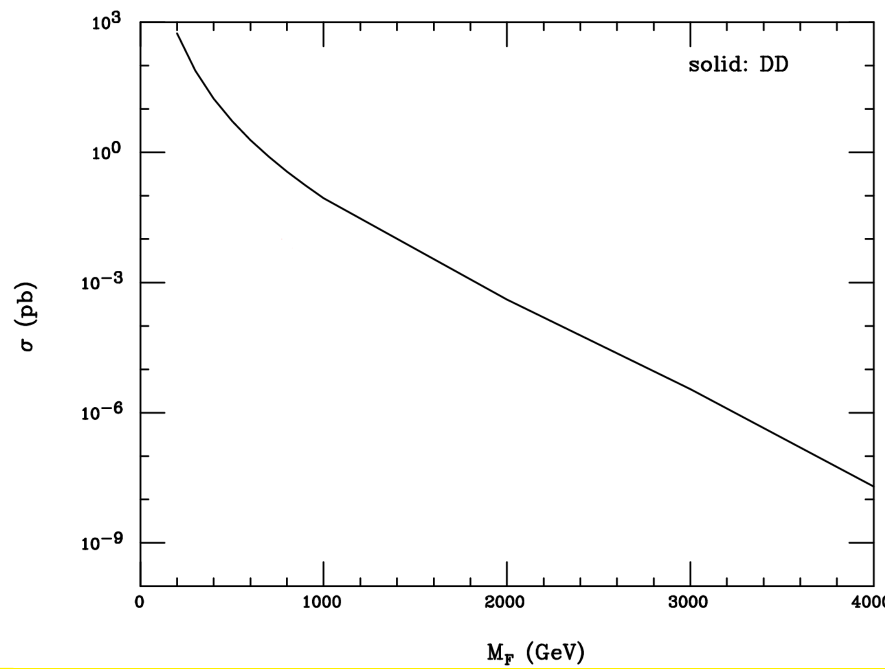
if exotic quarks D_i are leptoquarks.

- Because $\tilde{f} \to f + \chi^0$ the exotic quark will produce either t and b–quarks or t–quark and τ–lepton in the final state with rather high probability.

- Since $\sigma(pp \to D\overline{D} + X)$ may be comparable with $\sigma(pp \to t\bar{t} + X)$ the presence of light exotic quark results in enhancement of the cross sections of
  - $pp \to Q\overline{Q}Q'\overline{Q}' + E_T^{miss} + X$ if D and $\overline{D}$ are diquarks;
  - $pp \to Q\overline{Q}l\bar{l} + E_T^{miss} + X$ if D and $\overline{D}$ are leptoquarks.

Cross sections for pair production of exotic quarks at the LHC



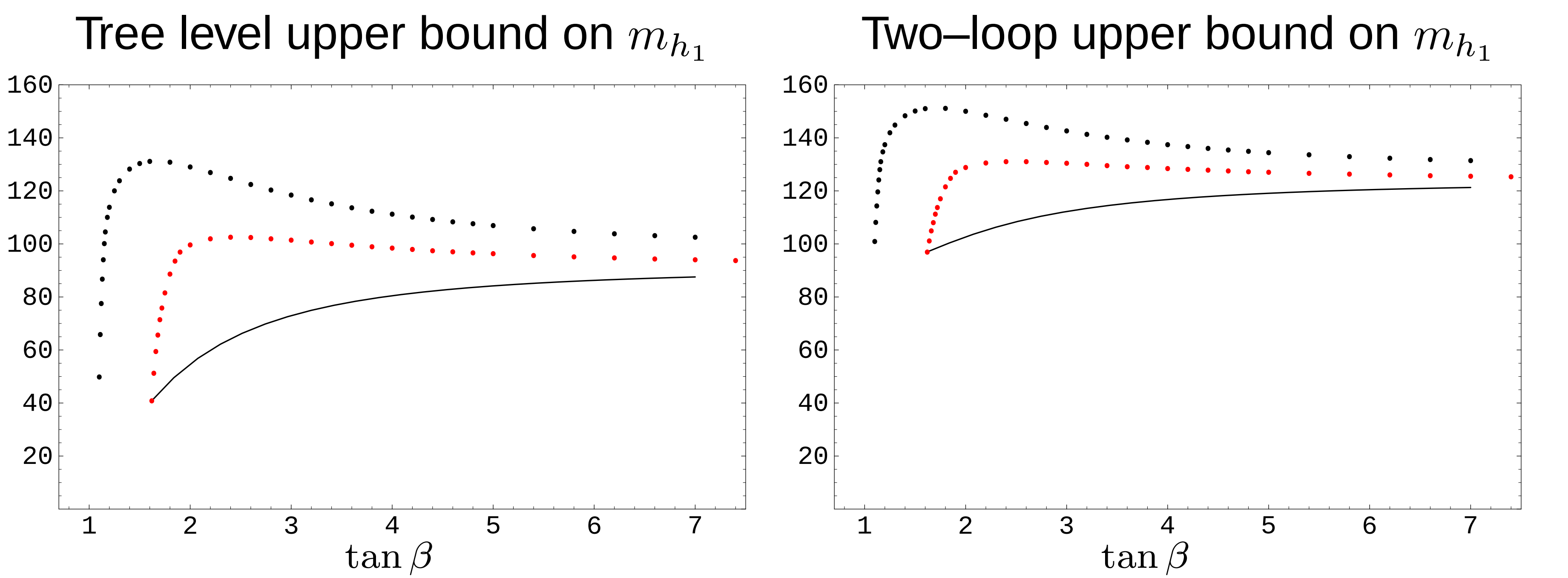


Higgs phenomenology

- The E_6SSM Higgs sector involves H_d, H_u and S.
- 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 mass of the lightest Higgs particle in the E_6SSM is limited from above

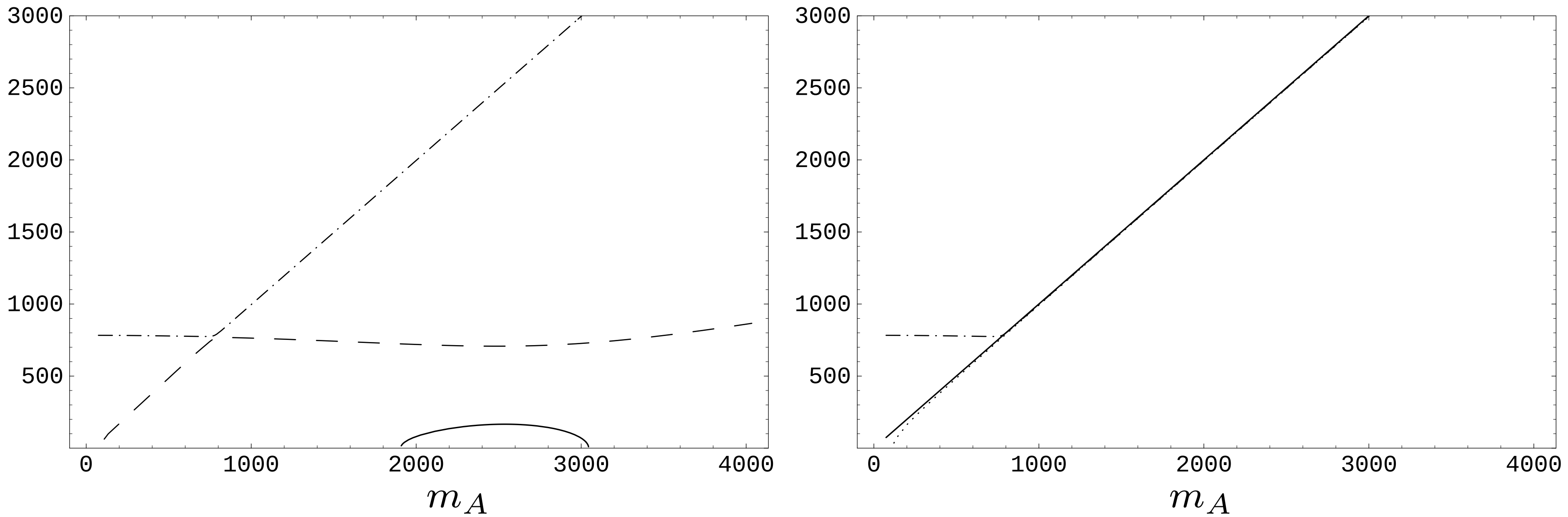
$$m_{h_1}^2 \lesssim M_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta + \\ + g_1'^2 v^2 (\tilde{Q}_1 \cos^2\beta + \tilde{Q}_2 \sin^2\beta)^2 + \Delta\,.$$

- 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$_6$SSM is considerably larger than in the MSSM and NMSSM.
- Even at the tree level m_{h_1} can be heavier 120 GeV.



- 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



- In the E_6SSM two lightest Inert neutralinos have masses which are less than $60 - 65$ GeV so that they tend to be lightest and next-to-lightest SUSY particles (LSP and NLSP).
- The lightest Inert neutralino can account for the observed dark matter relic density if it has mass close to half the Z mass.
- This scenario implies that two lightest Inert neutralinos have large couplings to the SM-like Higgs boson.
- As a result the SM-like Higgs boson decays more than 95% of the time into either LSPs or NLSPs.
- In the considered case the decays of the lightest Higgs boson into $l^+l^- + X$ might play an essential role in the Higgs searches.

Conclusions

- We have presented a self–consistent E_6 inspired SUSY model with extra $U(1)_N$ factor.
  - The E_6SSM predicts Z' boson and exotic quarks which can lead to the spectacular new physics signals at the LHC.
  - New particles and interactions that appear in the E_6SSM can play a key role in generation of baryon asymmetry of the Universe.
- The SM-like Higgs boson mass in the E_6SSM does not exceed $150 - 155$ GeV.
- If the lightest Inert neutralino with mass $\sim M_Z/2$ plays the role of dark matter the SM-like Higgs boson decays more than 95% of the time into either LSPs or NLSPs.
- The discovery of the exotic particles and extra Z' boson predicted by the E_6SSM may provide a window into superstring theory.