
Gauge coupling unification and leptogenesis in the E_6 SSM with approximate Z_2^H symmetry

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Outline

- Introduction
- Exceptional SUSY model
- Gauge coupling unification
- Lepton CP asymmetries
- Conclusions

Based on:

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

- Although SUSY ensures the cancellation of quadratic divergences the MSSM being incorporated in SUGRA or GUTs suffers from the μ problem.
- Indeed, in SUGRA models we have

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

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

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

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- At high energies E_6 may be broken to

$$E_6 \rightarrow SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)',$$

$$U(1)' = U(1)_\chi \cos \theta + U(1)_\psi \sin \theta,$$

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

- $\theta = \arctan \sqrt{15}$ corresponds to $U(1)_N$ symmetry under which right-handed neutrinos have zero charge.
- Only in this **exceptional SUSY model** (E_6 SSM) 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

$$\mu_{eff} = \lambda \langle S \rangle .$$

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

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

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

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- To suppress flavour changing processes as well as baryon number violating operators one can postulate an approximate Z_2^H symmetry under which all superfields except $H_d \equiv H_3^d$, $H_u \equiv H_3^u$ and $S \equiv S_3$ are odd.
 - The Z_2^H symmetry reduces the structure of Yukawa interactions to:

$$\begin{aligned}
W_{E_6SSM} \simeq & \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \lambda_\alpha \hat{S}(\hat{H}_\alpha^d \hat{H}_\alpha^u) + \kappa_i \hat{S}(\hat{D}_i \hat{\bar{D}}_i) + f_{\alpha\beta}(\hat{H}_d \hat{H}_\alpha^u) \hat{S}_\beta \\
& + \tilde{f}_{\alpha\beta}(\hat{H}_\alpha^d \hat{H}_u) \hat{S}_\beta + h_{4j}^E(\hat{H}_d \hat{L}_4) \hat{e}_j^c + \mu'(\hat{L}_4 \hat{\bar{L}}_4) + \frac{1}{2} M_{ij} \hat{N}_i^c \hat{N}_j^c \\
& + h_{4j}(\hat{H}_u \hat{L}_4) \hat{N}_j^c + h_{ij}(\hat{H}_u \hat{L}_i) \hat{N}_j^c + W_{MSSM}(\mu = 0),
\end{aligned}$$

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.
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- 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 diquark and anti diquark, i.e. $B_{D, \bar{D}} = \mp 2/3$;
 - exotic quarks are leptoquarks, i.e. $B_{D, \bar{D}} = \pm 1/3, L_{D, \bar{D}} = \pm 1$.
 - To provide the correct breakdown of EW symmetry and to suppress FCNC processes we assume that
 - new Yukawa interactions have some hierarchical structure
 $\kappa_i \sim \lambda \gtrsim \lambda_{1,2} \gg f_{\alpha\beta}, \tilde{f}_{\alpha\beta}, h_{4j}^E$;
 - Z_2^H symmetry violating Yukawa couplings are small. In particular the Yukawa couplings of inert Higgs fields to the quarks and leptons of the first two generations are less than 10^{-4} and 10^{-3} respectively.
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Gauge coupling unification

- At high energies the two-loop RG flow of gauge couplings can be parametrised as

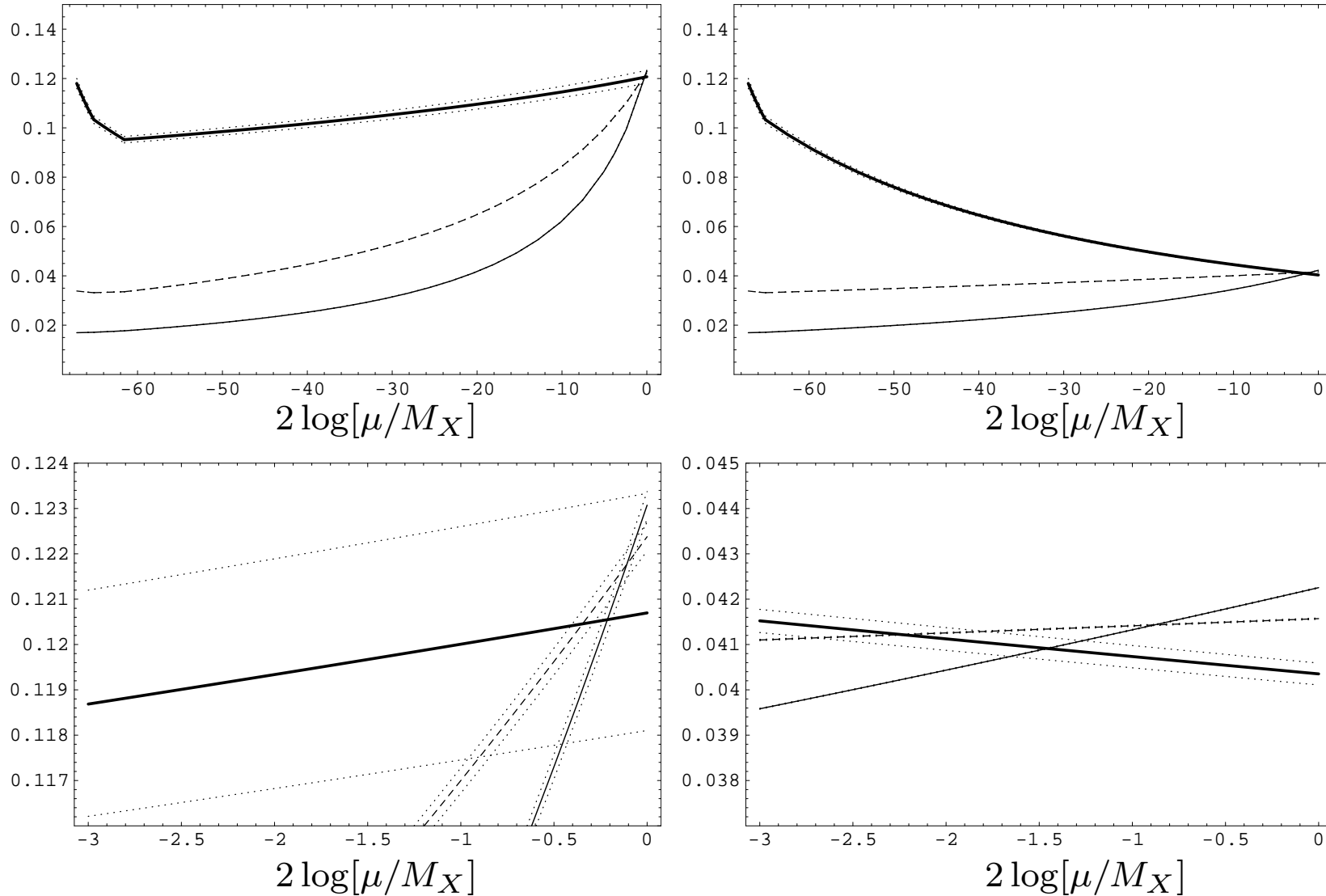
$$\frac{1}{\alpha_i(t)} = \frac{1}{\alpha_i(M_Z)} - \frac{b_i}{2\pi} t - \frac{C_i}{12\pi} - \Theta_i(t) + \frac{b_i - b_i^{SM}}{2\pi} \ln \frac{T_i}{M_Z},$$

where $t = \ln(\mu/M_Z)$; $C_1 = 0$, $C_2 = 2$, $C_3 = 3$; b_i and b_i^{SM} are one-loop beta functions; $\Theta_i(t)$ are two-loop corrections and

$$T_i = \prod_{k=1}^N \binom{m_k}{m_k} \frac{\Delta b_i^k}{b_i - b_i^{SM}}$$

- In the MSSM: $b_1 = 33/5$, $b_2 = 1$, $b_3 = -3$.
- In the E_6 SSM: $b_1 = 48/5$, $b_2 = 4$, $b_3 = 0$.
- We fix $\tan \beta = 10$, $M_{Z'} = 1.5 \text{ TeV}$, $\kappa_i(M_{Z'}) = \lambda_i(M_{Z'}) = g_1'(M_{Z'})$, $\alpha(M_Z) = 1/127.9$, $\sin^2 \theta_W = 0.231$ and $\alpha_s(M_Z) = 0.116 - 0.120$.

Two-loop RG flow of $\alpha_i(\mu)$ in the E_6 SSM and MSSM



- One can find the value of $\alpha_3(M_Z)$ for which exact gauge coupling unification takes place:

$$\frac{1}{\alpha_3(M_Z)} = \frac{1}{b_1 - b_2} \left[\frac{b_1 - b_3}{\alpha_2(M_Z)} - \frac{b_2 - b_3}{\alpha_1(M_Z)} \right] - \frac{1}{28\pi} + \Theta_s + \frac{19}{28\pi} \ln \frac{T_S}{M_Z},$$

$$\Theta_s = \left(\frac{b_2 - b_3}{b_1 - b_2} \Theta_1 - \frac{b_1 - b_3}{b_1 - b_2} \Theta_2 + \Theta_3 \right), \quad \Theta_i = \Theta_i(M_X),$$

- Due to the remarkable cancellation the absolute value of Θ_s is much smaller in the E_6 SSM than in the MSSM.

Two-loop corrections in the MSSM and E_6 SSM.

	Θ_1	Θ_2	Θ_3	Θ_s
MSSM	0.556	0.953	0.473	-0.764
E_6 SSM I	1.558	2.322	2.618	-0.250
E_6 SSM II	1.602	2.389	2.627	-0.326

- The threshold effects lower the prediction for $\alpha_3(M_Z)$. In the MSSM

$$T_S = M_S \simeq \mu \left(\frac{m_A}{\mu} \right)^{3/19} \left(\frac{M_2}{\mu} \right)^{4/19} \left(\frac{M_2}{M_3} \right)^{28/19} \left(\frac{m_{\tilde{l}}}{m_{\tilde{q}}} \right)^{3/19} \simeq \mu/6$$

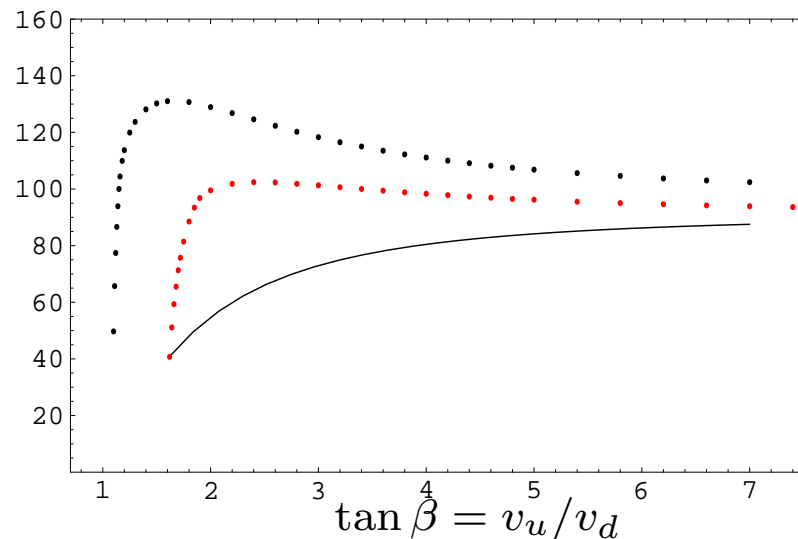
while in the E_6 SSM

$$T_S = M_S \cdot \frac{m_{H_\alpha}^{12/19} \mu_{\tilde{H}_\alpha}^{24/19} \mu'^{18/19}}{m_{\tilde{D}_i}^{18/19} \mu_{D_i}^{36/19}} = \mu' \cdot \left(\frac{M_{weak}}{M_{colour}} \right)^{4.5}.$$

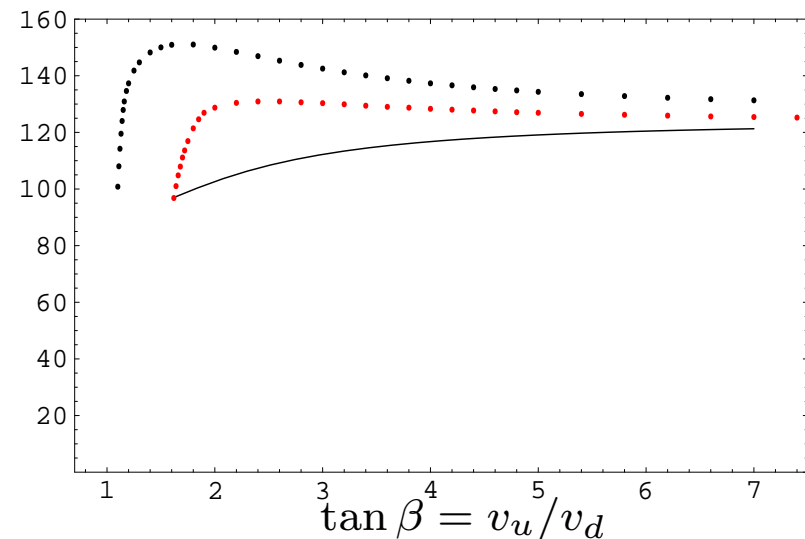
- The parameter μ' can be always chosen so that T_S lies in a few hundred GeV range.
- This allows to achieve the exact unification of gauge couplings for any value of $\alpha_3(M_Z)$ which is in agreement with current data [S.F.King, S.Moretti, RN, Phys.Lett.B 650 (2007) 57].

- Larger values of $\alpha_i(t)$ extend the allowed range of the Yukawa couplings at the EW scale.
- As a result the upper limit on the lightest Higgs boson mass in the E_6 SSM is considerably larger than in the MSSM and NMSSM.
- The mass of the SM like Higgs boson in the E_6 SSM does not exceed **150 – 155 GeV**.

Tree level upper bound on m_{h_1}



Two-loop upper bound on m_{h_1}



Lepton CP asymmetries

- 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**.
- In the exact Z_2^H symmetry limit the part of the E_6 SSM superpotential describing the interactions of N_i^c with other fields can be written as

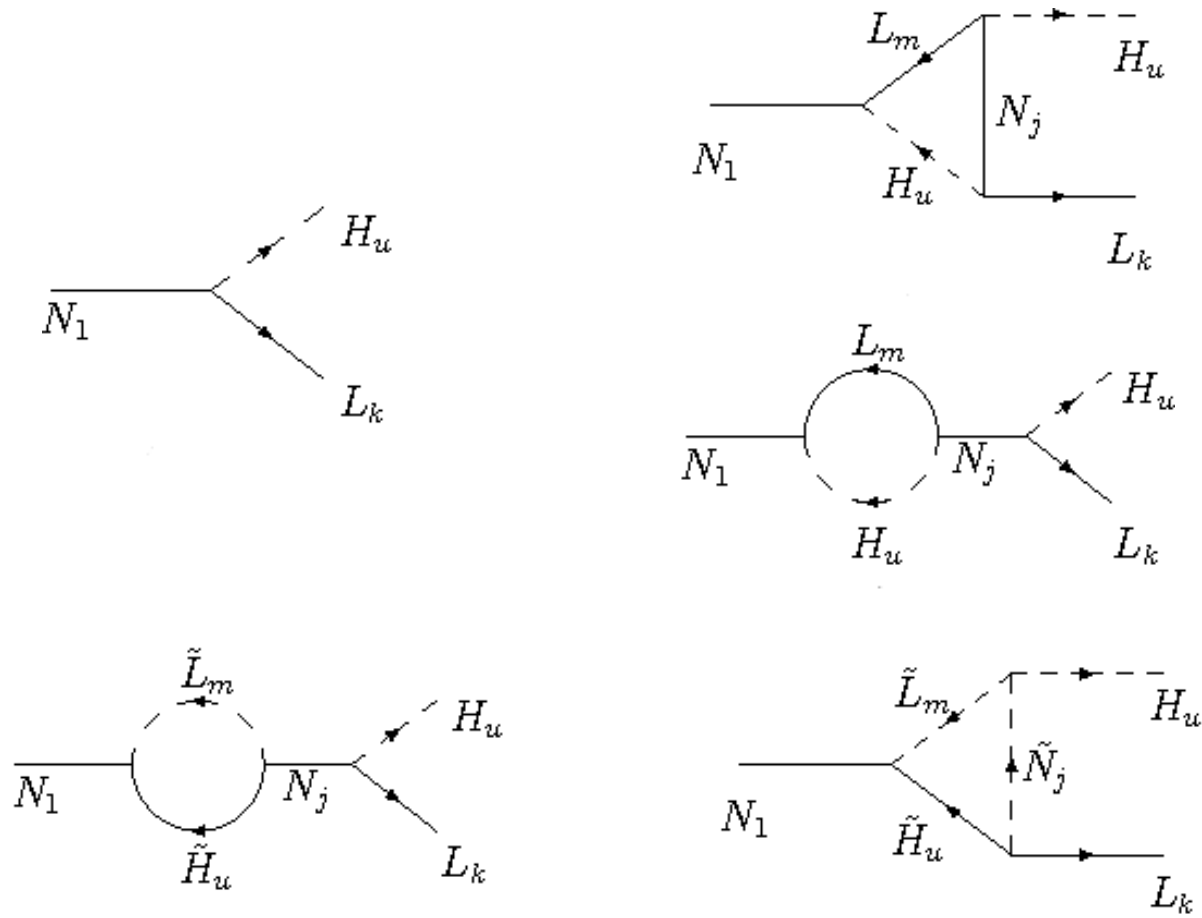
$$W_N = h_{4j}(\hat{H}_u \hat{L}_4) \hat{N}_j^c + h_{ij}(\hat{H}_u \hat{L}_i) \hat{N}_j^c = h_{mj}(\hat{H}_u \hat{L}_m) \hat{N}_j^c .$$

- The process of the lepton asymmetry generation is controlled by the flavour CP (decay) asymmetries $\varepsilon_{1, \ell_k}^i$

$$\varepsilon_{1, f}^k = \frac{\Gamma_{1f}^k - \Gamma_{1\bar{f}}^k}{\sum_{m, f'} \left(\Gamma_{1f'}^m + \Gamma_{1\bar{f}'}^m \right)}, \quad \varepsilon_{\tilde{1}, f}^k = \frac{\Gamma_{\tilde{1}f}^k - \Gamma_{\tilde{1}\bar{f}}^k}{\sum_{m, f'} \left(\Gamma_{\tilde{1}f'}^m + \Gamma_{\tilde{1}\bar{f}'}^m \right)},$$

where Γ_{1f}^k and $\Gamma_{\tilde{1}f}^k$ are partial decay widths of N_1 and \tilde{N}_1 .

Diagrams that give dominant contribution to the CP asymmetries $\varepsilon_{1, \ell_k}^i$ in the E_6 SSM with unbroken Z_2^H symmetry.



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- Supersymmetry ensures that

$$\varepsilon_{1, \ell_k}^k = \varepsilon_{1, \tilde{\ell}_k}^k = \varepsilon_{\tilde{1}, \ell_k}^k = \varepsilon_{\tilde{1}, \tilde{\ell}_k}^k .$$

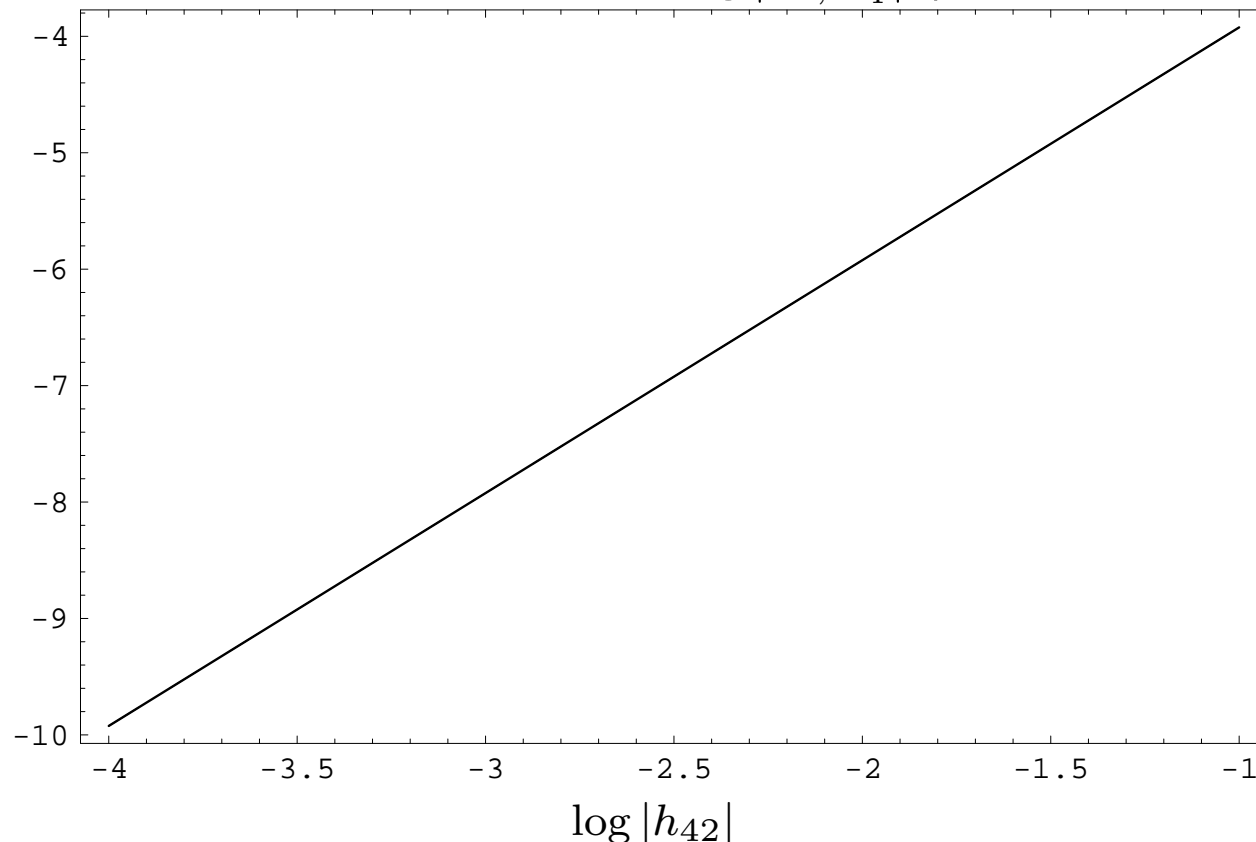
- L_4 contributes to the ordinary CP asymmetries and give rise to extra decay asymmetry ε_{1, L_4} .
- When the right-handed neutrino mass scale is relatively low ($M_1 \ll 10^{13}$ GeV), ε_{1, L_4} tends to dominate.
 - If $M_3 \gg M_2 \gg M_1$ we find

$$|\varepsilon_{1, L_4}| \lesssim \frac{3M_1}{8\pi M_2} |h_{42}|^2 .$$

- At low energies the induced lepton asymmetry is transferred to the ordinary lepton asymmetries via the decays of heavy L_4 and \tilde{L}_4 into leptons (sleptons) and Higgs fields H_d (Higgsinos \tilde{H}_d).

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- In the considered case an appreciable value of $|\varepsilon_{1, L_4}| = 10^{-6} - 10^{-4}$ can be induced even for very low $M_1 = 10^6$ GeV if $|h_{42}|$ vary from 0.01 to 0.1.

Maximal absolute values of $\log |\varepsilon_{1, L_4}|$ ($M_2 = 10 \cdot M_1$)



Conclusions

- We have presented a self-consistent E_6 inspired SUSY model with extra $U(1)_N$ factor which can originate from an E_6 GUT gauge group.
- In the E_6 SSM approximate Z_2^H symmetry can be used to suppress non-diagonal flavour transitions and baryon number violating operators.
- In addition to the three complete 27_i representations of E_6 the particle content of the E_6 SSM includes L_4 and \bar{L}_4 from extra $27'$ and $\overline{27}'$.
 - L_4 and \bar{L}_4 allows to achieve the unification of gauge couplings for any phenomenologically acceptable value of $\alpha_3(M_Z)$.
 - L_4 and \bar{L}_4 can also induce substantial CP asymmetries even for relatively low $M_1 \simeq 10^6$ GeV that may allow to avoid **gravitino problem**.