Baryon Asymmetry Generation in the E_6CHM

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Outline

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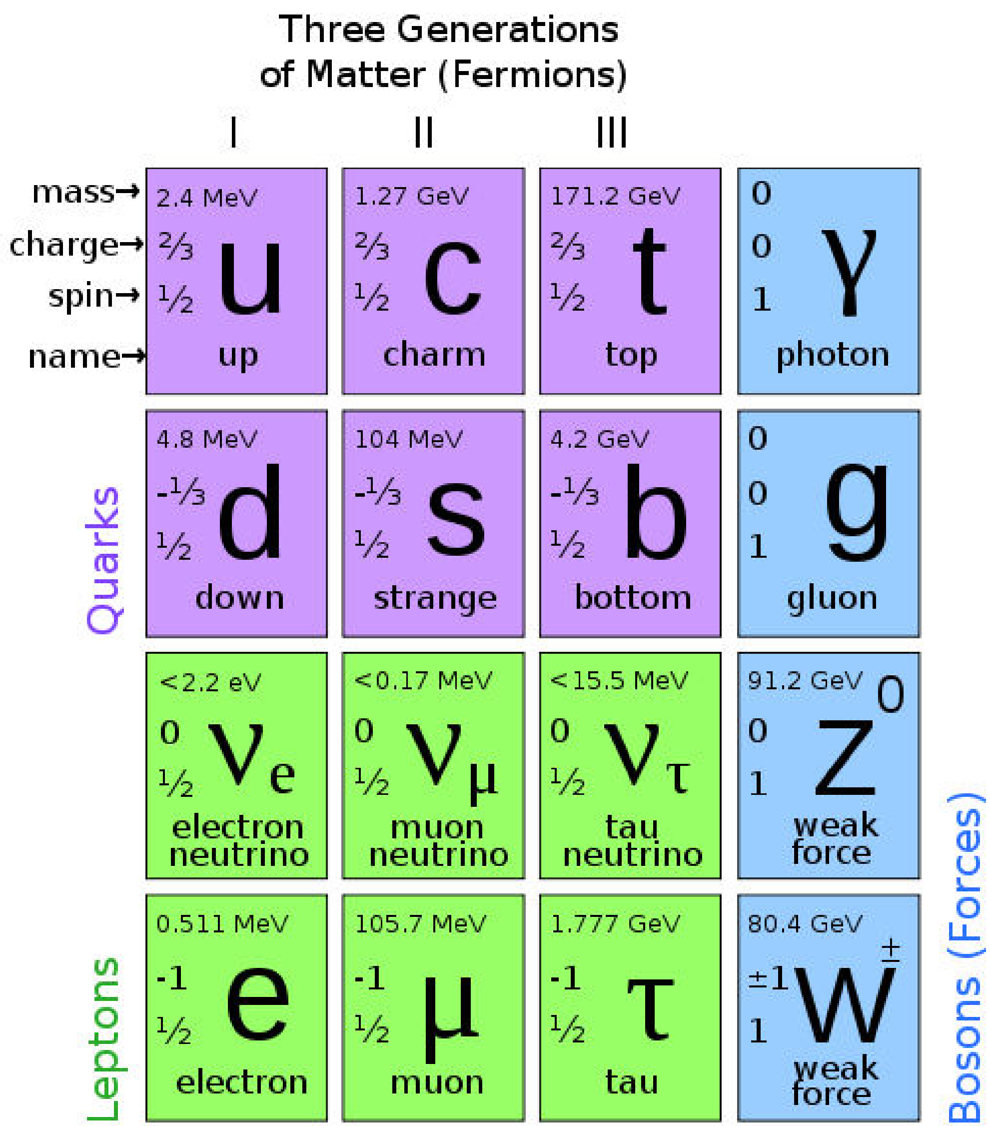
Based on:

R. Nevzorov and A. W. Thomas, Phys. Lett. B **774** (2017) 123 [arXiv:1706.02856 [hep-ph]];

R. Nevzorov and A. W. Thomas, J. Phys. G **44** (2017) 075003 [arXiv:1605.07313 [hep-ph]];

R. Nevzorov and A. W. Thomas, Phys. Rev. D **92** (2015) 075007 [arXiv:1507.02101 [hep-ph]].

Introduction



+

H

125 GeV

+

New Physics

- dark matter;
- neutrino physics;
- baryogenesis...

- The properties of a new scalar particle, observed by the ATLAS and CMS, strongly suggest that it is the SM–like Higgs boson.
- In the SM the Higgs scalar potential is given by

$$V(H) = m_H^2 H^\dagger H + \lambda (H^\dagger H)^2 \,.$$

- The discovery of the BEH boson with $m_h \simeq 125\,\text{GeV}$ allows to estimate the values of parameter

$$m_H^2 \approx -(90\,\text{GeV})^2, \qquad \lambda \approx 0.13\,.$$

- Coupling λ can be small if Higgs emerges as a pseudo–Nambu–Goldstone boson (pNGB) from the spontaneous breaking of an approximate global symmetry in the composite Higgs models.

- The idea of a composite Higgs boson was proposed in the 70's [H. Terazawa, K. Akama, Y. Chikashige, Phys. Rev. D 15 (1977) 480; H. Terazawa, Phys. Rev. D 22 (1980) 184.].
- The idea, that confining gauge interaction may bind massive elementary fermions into massless composite Goldstone bosons, was introduced in the 80's [S. Dimopoulos, J. Preskill, Nucl. Phys. B 199 (1982) 206; D. B. Kaplan, H. Georgi, S. Dimopoulos, Phys. Lett. B 136 (1984) 187.].
- Similar idea can be realised in Randall–Sundrum (RS) extra–dimensional scenarios, with the SM fields in the bulk [R. Contino, Y. Nomura, A. Pomarol, Nucl. Phys. B 671 (2003) 148 [hep-ph/0306259]; K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B 719 (2005) 165 [hep-ph/0412089].].
- Via the AdS/CFT correspondence, these scenarios are dual to the $4D$ composite Higgs scenarios.

- The composite Higgs models involve weakly–coupled elementary and strongly interacting sectors.
- The sector of weakly–coupled elementary particles includes the SM gauge bosons and SM fermions.
- The strongly interacting sector results in a set of bound states that involves Higgs doublet as well as composite partners of quarks, leptons and gauge bosons.
- The elementary states couple weakly to the composite operators of the strongly interacting sector.
- At low energies those states identified with SM fermions (bosons) (ψ^i_a) are a mixture of the corresponding elementary fermionic (bosonic) states ($\tilde{\psi}^i_a$) and their fermionic (bosonic) composite partners ($\tilde{\Psi}^i_a$), i.e.

$$|\psi^i_a>= c^i_a|\tilde{\psi}^i_a> + s^i_a|\tilde{\Psi}^i_a> \; .$$

- The couplings of the SM states to the composite Higgs are determined by the fractions of the compositeness of these states. For up– and down–quarks one gets

$$y^u_{ij} = s^i_q Y^u_{ij} s^j_u\,, \qquad y^d_{ij} = s^i_q Y^d_{ij} s^j_d\,, \qquad i,\, j = 1, 2, 3\,.$$

- The observed mass hierarchy in the quark and lepton sectors can be accommodated through partial compositeness if the fractions of compositeness of the first and second generation fermions are quite small.
- In this case the non-diagonal flavor transitions and the modifications of the W and Z couplings associated with the light SM fermions are suppressed.
- At the same time, the top quark is so heavy that the right–handed top quark (t^c) should have sizeable fraction of compositeness.

- The minimal composite Higgs model (MCHM) possesses global $SO(5) \times U(1)_X$ symmetry that contains $SU(2)_W \times U(1)_Y$ subgroup.
- Near the scale f the $SO(5)$ symmetry is broken down to $SO(4)$, so that the SM gauge group remains intact.
- This results in a set of the pNGB states which form Higgs doublet.
- The custodial symmetry

$$SU(2)_{cust} \subset SO(4) \cong SU(2)_W \times SU(2)_R$$

  allows one to protect the Peskin–Takeuchi T parameter against new physics contributions.
- The experimental limits on the parameter S imply that the masses of the composite partners of the SM gauge bosons $m_\rho = g_\rho f \gtrsim 2.5$ TeV.

- Even more stringent bounds on f come from the observed suppression of the non–diagonal flavour transitions, i.e $f \gtrsim 10$ TeV.
- In the models with FS $= U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$ symmetry, the bounds that originate from the Kaon and B systems can be satisfied even for $m_\rho \sim 3$ TeV.
- In these models the suppression of the baryon and lepton number violating operators can be achieved if global $U(1)_B$ and $U(1)_L$ symmetries are imposed.
- Thus simplest composite Higgs models are based on

$$SU(3)_C \times SO(5) \times U(1)_X \times U(1)_B \times U(1)_L \times \text{FS} \,.$$

- The couplings of the elementary states to the strongly interacting sector break the $SO(5)$ global symmetry.
- The pNGB Higgs potential arises from loops that leads to the suppression of λ.

E_6CHM

- In the E_6CHM the strongly interacting sector possesses an $SU(6)\times U(1)_L$ global symmetry.
- Near the scale $f \gtrsim 10$ **TeV** the $SU(6)$ global symmetry is broken down to its $SU(5)$ subgroup, that contains the SM gauge group.
- The weakly–coupled elementary sector involves all SM fermions except t^c, i.e.

$$(q_i,\, d^c_i,\, \ell_i,\, e^c_i) + u^c_\alpha + \bar{q} + \bar{d^c} + \bar{\ell} + \bar{e^c}\,,$$

where $i = 1,2,3$ and $\alpha = 1,2$.

- To ensure anomaly cancellation the set of the SM fermions is supplemented by $\bar{q}$, $\bar{d^c}$, $\bar{\ell}$ and $\bar{e^c}$.
- The E_6CHM also implies that below scale f the dynamics of the strongly interacting sector leads to the $10+\overline{5}$ multiplets of $SU(5)$.

- The components of these $SU(5)$ multiplets decompose under $SU(3)_C \times SU(2)_W \times U(1)_Y$ as follows:

$$\begin{aligned}
\mathbf{10} \quad \rightarrow \quad & Q = (U,\, D) = \left(3,\, 2,\, \frac{1}{6}\right)\,, \\
& t^c = \left(3^*,\, 1,\, -\frac{2}{3}\right)\,, \\
& E^c = (1,\, 1,\, 1)\;; \\
\bar{\mathbf{5}} \quad \rightarrow \quad & D^c = \left(\bar{3},\, 1,\, \frac{1}{3}\right)\,, \\
& L = (N,\, E) = \left(1,\, 2,\, -\frac{1}{2}\right)\,.
\end{aligned}$$

- These multiplets get combined with $\bar{q}$, $\bar{d^c}$, $\bar{\ell}$ and $\bar{e^c}$ forming a set of vector–like states.
- The only exceptions are the components of 10–plet associated with the composite t^c, which survive down to the EW scale.

- Since all states in the strongly coupled sector come in complete $SU(6)$ and $SU(5)$ multiplets they contribute equally to the one–loop beta functions b_1, b_2 and b_3 of the $SU(3)_C$, $SU(2)_W$ and $U(1)_Y$ interactions.
- In the one–loop approximation the exact gauge coupling unification takes place for

$$\frac{1}{\alpha_3(M_Z)} = \frac{1}{b_1 - b_2}\left[\frac{b_1 - b_3}{\alpha_2(M_Z)} - \frac{b_2 - b_3}{\alpha_1(M_Z)}\right].$$

- In the E_6CHM the exact gauge coupling unification can be obtained for $\alpha_3(M_Z) \simeq 0.109$.
- This result indicates that within the E_6CHM an approximate gauge coupling unification can be attained.
- Such approximate gauge coupling unification takes place around the scale $M_X \sim 10^{15} - 10^{16}$ GeV.

- The breakdown of the global $SU(6)$ symmetry down to $SU(5)$ gives rise to the eleven pNGB states associated with eleven generators $T^{\hat{a}}$ from the coset $SU(6)/SU(5)$.
- It is convenient to use the non–linear representation of the pNGB states in terms of a 6–component unit vector

$$\Omega^T = \Omega_0^T \Sigma^T = e^{i\frac{\phi_0}{\sqrt{15}f}} \left(C\phi_1, C\phi_2, C\phi_3, C\phi_4, C\phi_5, \cos\frac{\tilde{\phi}}{\sqrt{2}f} + \sqrt{\frac{3}{10}} C\phi_0 \right),$$

$$C = \frac{i}{\tilde{\phi}} \sin\frac{\tilde{\phi}}{\sqrt{2}f}, \qquad \tilde{\phi} = \sqrt{\frac{3}{10}\phi_0^2 + |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + |\phi_5|^2},$$

where

$$\Omega_0^T = (0, \quad 0, \quad 0, \quad 0, \quad 0, \quad 1), \qquad \Sigma = e^{i\Pi/f}, \qquad \Pi = \Pi^{\hat{a}} T^{\hat{a}}.$$

- Vector Ω transforms as $\mathbf{5}+\mathbf{1}$ under the transformation of the unbroken $SU(5)$ subgroup where

$$\mathbf{5} = \tilde{\mathbf{H}} \sim (\phi_1, \ \phi_2, \ \phi_3, \ \phi_4, \ \phi_5), \qquad \mathbf{1} = \phi_0.$$

- The first two components of $\tilde{H}$ correspond to the SM–like Higgs doublet.
- Three other components of $\tilde{H}$, $T \sim (\phi_3\ \phi_4\ \phi_5)$, are associated with the $SU(3)_C$ triplet.
- In the leading approximation the Lagrangian, that describes interactions of the pNGB states, is given by

$$\mathcal{L}_{pNGB} = \frac{f^2}{2}\left|\mathcal{D}_\mu\Omega\right|^2 .$$

- The pNGB effective potential can be obtained by integrating out heavy states.
- It was shown that in such models there is a large part of the parameter space where the $SU(2)_W \times U(1)_Y$ gauge symmetry is broken to $U(1)_{em}$, while $SU(3)_C$ remains intact [J. Barnard, T. Gherghetta, T. S. Ray, A. Spray, JHEP **1501** (2015) 067].

- Since in the E_6CHM $f \gtrsim 10$ TeV, a significant tuning, $\sim 0.01\%$, is needed to get the SM–like Higgs with mass 125 GeV.
- It was shown that such tuning can be accomplished.
- In these models the $SU(3)_C$ triplet scalar T tends to be substantially heavier than the SM–like Higgs boson.
- In the simplest $SU(5)$ GUT the Yukawa couplings of the up type quarks originate from

$$\mathcal{L}^u_{SU(5)} \simeq h^u_{ij}\, \mathbf{10}^u_i\, \mathbf{10}^q_j\, \mathbf{5}^h\,.$$

- In the E_6CHM the up–quark Yukawa interactions can be reproduced if the strongly coupled sector results in

$$\mathcal{L}^u_{SU(6)} \sim \mathbf{20} \times \mathbf{15} \times \mathbf{\Omega}\,.$$

- Thus the composite partners of u^c and q should belong to $\mathbf{20}$ and $\mathbf{15}$ or viceversa.
  - $\mathbf{15}$ is an $SU(6)$ antisymmetric second–rank tensor that has the following decomposition in terms of $SU(5)$ representations: $\mathbf{15} = \mathbf{10} \oplus \mathbf{5}$.
  - $\mathbf{20}$ is an $SU(6)$ totally antisymmetric third–rank tensor that has the following decomposition in terms of $SU(5)$ representations: $\mathbf{20} = \mathbf{10} \oplus \overline{\mathbf{10}}$.
- The composite partners of d^c and q can belong to either $\overline{\mathbf{15}}$ and $\mathbf{20}$ or $\overline{\mathbf{6}}$ and $\mathbf{15}$.
- In the simplest scenario the composite partners of e^c and ℓ are components of $\mathbf{15}$ and $\overline{\mathbf{6}}$.

E$_6$CHM and orbifold GUT

- The E$_6$CHM can arise after the breakdown of $E_6 \times G_0$ gauge group down to $SU(3)_C \times SU(2)_W \times U(1)_Y \times G$ subgroup.
- Gauge groups G_0 and G are associated with the strongly coupled sector.
- Fields from the strongly coupled sector can be charged under both E_6 and G_0 (G) gauge symmetries.
- The weakly–coupled sector involves elementary states that participate in the E_6 interactions only.
- The elementary fermions with different baryon or lepton numbers can stem from different 27–plets of E_6.
- All other components of these 27–plets can gain masses of the order of M_X.

- Such a splitting of the 27–plets can occur within the six–dimensional orbifold SUSY GUT based on $E_6 \times G_0$.
- We consider the compactification of two extra dimensions on the orbifold $T^2/(Z_2 \times Z_2^I \times Z_2^{II})$.
- The Z_2, Z_2^I and Z_2^{II} reflection symmetries allow to reduce the physical region to a pillow with the four $4D$ branes located at its corners.
- The components Φ_i and $\overline{\Phi}_i$ of the bulk 27 supermultiplet transform under Z_2, Z_2^I and Z_2^{II} as follows

$$\Phi_i(x,-y,-z) = P_{ii}\Phi_i(x,y,z)\,, \qquad \overline{\Phi}_i(x,-y,-z) = -P_{ii}\overline{\Phi}_i(x,y,z)\,,$$

$$\Phi_i(x,-y',-z) = P^I_{ii}\hat{\Phi}_i(x,y',z)\,, \qquad \overline{\Phi}_i(x,-y',-z) = -P^I_{ii}\overline{\Phi}_i(x,y',z)\,,$$

$$\Phi_i(x,-y,-z') = P^{II}_{ii}\hat{\Phi}_i(x,y,z')\,, \qquad \overline{\Phi}_i(x,-y,-z') = -P^{II}_{ii}\overline{\Phi}_i(x,y,z')\,,$$

where $y' = y - \pi R_5/2$ and $z' = z - \pi R_6/2$.

- The elements of P, P^I and P^{II} can be written in the following form

$$(P)_{ii} = \sigma \exp\{2\pi i \Delta \alpha_i\}\,, \qquad (P^I)_{ii} = \sigma_I \exp\{2\pi i \Delta^I \alpha_i\}\,,$$
$$(P^{II})_{ii} = \sigma_{II} \exp\{2\pi i \Delta^{II} \alpha_i\}\,,$$

where σ, σ_I and σ_{II} are parities of the bulk 27 supermultiplet, i.e. $\sigma, \sigma_I, \sigma_{II} \in \{+,-\}$; α_j are E_6 weights while Δ, Δ^I and Δ^{II} are gauge shifts.

- We choose the following gauge shifts

$$\Delta = \left(0,\,0,\,0,\,\frac{1}{2},\,0,\,0\right), \qquad \Delta^I = \left(\frac{1}{2},\,\frac{1}{2},\,\frac{1}{2},\,\frac{1}{2},\,\frac{1}{2},\,0\right),$$
$$\Delta^{II} = \left(\frac{1}{2},\,\frac{1}{2},\,\frac{1}{2},\,0,\,\frac{1}{2},\,0\right),$$

that correspond to the orbifold parity assignments shown in the Table.

- On the branes O, O_I and O_{II} the E_6 gauge group is broken down to $SU(6) \times SU(2)_N$, $SU(6)' \times SU(2)_W$ and $SO(10)' \times U(1)'$ respectively.
- The unbroken gauge group of the effective $4D$ theory is $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ which is the intersection of the E_6 subgroups at the fixed points.

Orbifold parity assignments in the bulk $27'$ supermultiplet with

$$\sigma = \sigma_I = \sigma_{II} = +1.$$

	q	d^c	u^c	ℓ	e^c	ν^c	h^u	h^d	h	h^c	s
Z_2	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$-$
Z_2^I	$-$	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$+$	$+$	$+$
Z_2^{II}	$-$	$-$	$+$	$+$	$+$	$-$	$-$	$+$	$+$	$-$	$-$

- All fields from the strongly coupled sector are confined on the brane O, where E_6 symmetry is broken down to the $SU(6) \times SU(2)_N$ subgroup.
- The $SU(2)_N$ global symmetry is expected to be broken whereas $SU(6)$ global symmetry remains intact.
- The scalar components of the supremultiplets localised on the branes O_I and O_{II} can be used to break $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ down to the SM gauge group so that $SU(6)$ symmetry remains intact.
- The SM gauge interactions break $SU(6)$ symmetry.
- Nonetheless, if the gauge couplings of G are considerably larger than the SM gauge couplings, then $SU(6)$ can be still an approximate global symmetry of the composite sector at low energies.

Generation of BAU in the E$_6$CHM

- The composite $\mathbf{10} + \overline{\mathbf{5}}$ multiplets of $SU(5)$ can stem from one $\mathbf{15}$–plet and two $\overline{\mathbf{6}}$–plets ($\overline{\mathbf{6}}_\mathbf{1}$ and $\overline{\mathbf{6}}_\mathbf{2}$) of $SU(6)$.
- They have the following decomposition in terms of $SU(3)_C \times SU(2)_W \times U(1)_Y$ representations:

$$\mathbf{15} \quad \to \quad Q = \left(3,\, 2,\, \tfrac{1}{6}\right)\,, \quad t^c = \left(3^*,\, 1,\, -\tfrac{2}{3}\right)\,, \quad E^c = \Big(1,\, 1,\, 1\Big)\,, \quad D = \left(3,\, 1,\, -\tfrac{1}{3}\right)\,, \quad \overline{L} = \left(1,\, 2,\, \tfrac{1}{2}\right)\,;$$

$$\overline{\mathbf{6}}_\alpha \quad \to \quad D^c_\alpha = \left(\bar{3},\, 1,\, \tfrac{1}{3}\right)\,, \quad L_\alpha = \left(1,\, 2,\, -\tfrac{1}{2}\right)\,, \quad N_\alpha = \Big(1,\, 1,\, 0\Big)\,, \quad \alpha = 1, 2\,.$$

- We assume that the Lagrangian of the E$_6$CHM is invariant with respect to an approximate Z_2^B symmetry

$$Z_2^B = (-1)^{3B}\,.$$

- If $\mathbf{15}$ and $\overline{\mathbf{6}}_\mathbf{2}$ are Z_2^B-odd and $\overline{\mathbf{6}}_\mathbf{1}$ is Z_2^B-even then after the $SU(6)$ symmetry breaking

$$\mathcal{L}_{mass} = \mu_L \overline{L} L_2 + \mu_D D_2^c D + \frac{1}{2} M_1 \overline{N_1^c} N_1 + \frac{1}{2} M_2 \overline{N_2^c} N_2 + h.c..$$

- All exotic and composite fermions tend to gain masses which are a few times larger than f.
- Since the masses of all pNGB states are expected to be much lower than f, these resonances are the lightest composite states.
- The pNGB states H and T are Z_2^B-even so that T decays mainly into $T \to \bar{t} + \bar{b}$.
- At the energies $E \lesssim f$ baryon number is conserved to a very good approximation and T manifests itself in the interactions with other states as diquark with $B = -2/3$.

- At the LHC T can be pair produced resulting in the enhancement of the cross section of $pp \to T\bar{T} \to t\bar{t}b\bar{b}$.
- If N_1 is the lightest exotic fermion in the spectrum the baryon asymmetry can be generated via the out–of equilibrium decays $N_1 \to T + \bar{d}_i$ and $N_1 \to T^* + d_i$.
- The corresponding interactions of N_1 and N_2 are described by the Lagrangian

$$\mathcal{L}_N = \sum_{i=1}^{3} \left(g^*_{i1} T d^c_i N_1 + g^*_{i2} T d^c_i N_2 + h.c. \right) .$$

- Since N_1 is Z_2^B–even g^*_{i1} tend to be very small.
- The process of the baryon asymmetry generation is controlled by the flavour CP asymmetries

$$\varepsilon_{1,k} = \frac{\Gamma_{N_1 d_k} - \Gamma_{N_1 \bar{d}_k}}{\sum_m \left(\Gamma_{N_1 d_m} + \Gamma_{N_1 \bar{d}_m} \right)} .$$

- When T couples primarily to the b–quarks the induced baryon asymmetry can be estimated as

$$Y_{\Delta B} \sim 10^{-3}\Big(\varepsilon_{1,3}\eta_3\Big)\,, \qquad Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}\bigg|_0 = (8.75 \pm 0.23)\times 10^{-11}\,.$$

- In the strong washout scenario the efficiency factor η_3 is given by

$$\eta_3 \simeq H(T=M_1)/\Gamma_3\,, \qquad \Gamma_3 = \Gamma_{N_1 d_3} + \Gamma_{N_1 \bar{d}_3} = \frac{3|g_{31}|^2}{16\pi}\,M_1\,,$$

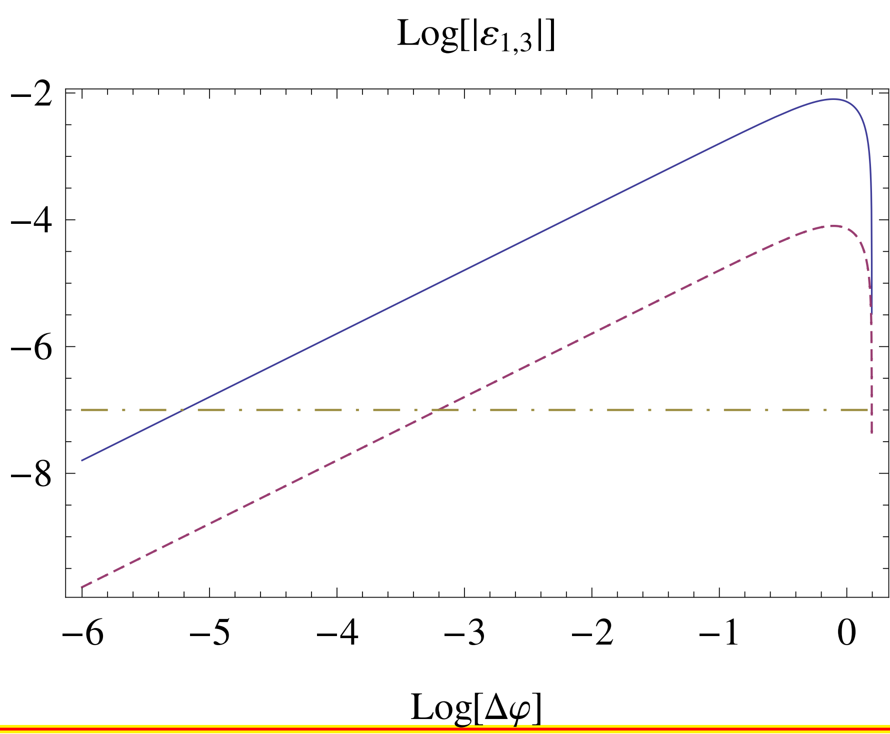
$$H = 1.66 g_*^{1/2} T^2/M_{Pl}\,, \qquad g_* = n_b + \frac{7}{8}\,n_f \simeq 113.75\,.$$

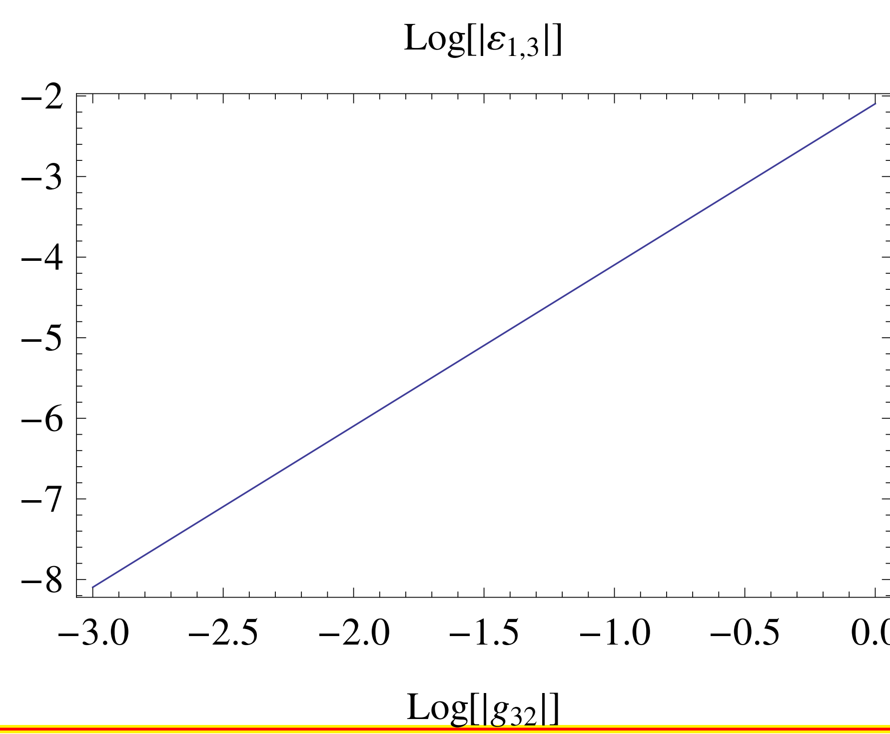
- If $|g_{31}| \simeq 10^{-6}$ and $M_1 \simeq 10$ TeV the efficiency factor η_3 becomes relatively close to unity.

- When $g_{31} = |g_{31}|e^{i\varphi_{31}}$ and $g_{32} = |g_{32}|e^{i\varphi_{32}}$ in the limit $M_2 \gg M_1$ one finds

$$\varepsilon_{1,3} \simeq -\frac{1}{(4\pi)}\frac{|g_{32}|^2 M_1}{M_2}\sin 2\Delta\varphi\,, \qquad \Delta\varphi = \varphi_{32} - \varphi_{31}\,.$$

- The phenomenologically acceptable value of the baryon density can be obtained if $|g_{32}| \gtrsim 0.01$.
- When $|g_{32}| \gtrsim 0.1$ the appropriate baryon density can be induced even if all CP–violating phases are rather small, i.e. $\Delta\varphi \lesssim 0.01$.





Conclusions

- The breakdown of gauge symmetry in the orbifold GUTs may lead to the composite Higgs model (E_6CHM) in which the strongly interacting sector possesses an $SU(6) \times U(1)_L$ global symmetry.
- Near scale $f \gtrsim 10$ TeV the $SU(6)$ global symmetry is broken down to its $SU(5)$ subgroup, that contains the SM gauge group, resulting in a set of pNGBs states.
- This set, in particular, involves the SM–like Higgs doublet and $SU(3)_C$ triplet of scalar fields, T.
- At the LHC the pair production of $T\bar{T}$ can lead to the enhancement of the cross section of $pp \to t\bar{t}b\bar{b}$.
- In the E_6CHM the baryon asymmetry can be induced via the out–of equilibrium decays of the lightest composite fermion even if all CP–violating phases are quite small.