Generation of lepton asymmetry in the minimal Composite Higgs Model

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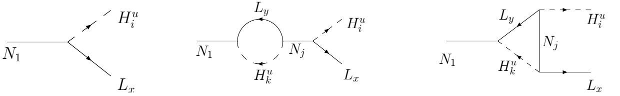
Introduction

- The interactions of heavy right-handed neutrinos N_j with lepton L_x and Higgs H_i^u doublets result in tiny masses of the left-handed neutrinos.
- The generation of lepton asymmetry may occur via the out–of equilibrium decay of the lightest right–handed neutrino N_1.
- This process is controlled by the flavour CP (decay) asymmetries

$$\varepsilon_{1,\,\ell_x} = \frac{\Gamma_{N_1\ell_x} - \Gamma_{N_1\bar{\ell}_x}}{\sum_m \left(\Gamma_{N_1\ell_m} + \Gamma_{N_1\bar{\ell}_m}\right)}\,,$$

  where $\Gamma_{N_1\ell_x}$ and $\Gamma_{N_1\bar{\ell}_x}$ are partial decay widths of $N_1 \to L_x + H^u$ and $N_1 \to \bar{L}_x + \bar{H}^u$.
- At the tree level $\varepsilon_{1,\,\ell_x} = 0$.



- If CP invariance is broken in the lepton sector the non–zero contributions to ε_{1,ℓ_x} arise from the interference between the tree–level amplitudes of the lightest right–handed neutrino decays and one–loop corrections to them.
- The induced lepton asymmetry gets partially converted into a baryon asymmetry due to $(B+L)$–violating sphaleron interactions. [V. A. Kuzmin, V. A. Rubakov, M. E. Shaposhnikov, Phys. Lett. B **155** (1985) 36.].
- In the type I seesaw model and its supersymmetric extension the observed baryon asymmetry can be generated for $|M_{N_1}| \gtrsim 10^9$ ГэВ if $|M_{N_2}| - |M_{N_1}| \gtrsim |M_{N_1}|$ [S. Davidson, A. Ibarra, Phys. Lett. B **535** (2002) 25; K. Hamaguchi, H. Murayama, T. Yanagida, Phys. Rev. D **65** (2002) 043512.].
- In the extensions of the SM and MSSM the decays of the lightest right–handed neutrino can lead to the observed baryon asymmetry even if $|M_{N_1}| \lesssim 10$ ТэВ.

Minimal Composite Higgs Model

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

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

- The measurement of the Higgs mass ($m_h \simeq 125\,\mathrm{GeV}$) allows to estimate m_H^2 and λ, i.e. $m_H^2 \approx -(90\,\mathrm{GeV})^2$ and $\lambda \approx 0.13$.
- Current experimental data does not allow one to distinguish whether the Higgs boson is an elementary particle or a composite state.
- Coupling λ can be small if Higgs doublet emerges as a set of pseudo–Nambu–Goldstone bosons (pNGBs) from the spontaneous breaking of an approximate global symmetry in the CHM.
- The composite Higgs models involve weakly–coupled elementary and strongly interacting sectors.
  - The weakly–coupled sector includes states with quantum numbers of 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.

- At low energies those states identified with SM fermions (bosons) (ψ_a^i) are a mixture of the corresponding elementary fermionic (bosonic) states ($\tilde{\psi}_a^i$) and their fermionic (bosonic) composite partners ($\tilde{\Psi}_a^i$), i.e.

$$|\psi_a^i >= c_a^i|\tilde{\psi}_a^i > + s_a^i|\tilde{\Psi}_a^i > \ .$$

- The couplings of the SM states to the composite Higgs are determined by the fractions of the compositeness of these states. For charged leptons one gets

$$y_{ij}^e = s_L^i Y_{ij}^E s_E^j \,, \qquad\qquad i,j = 1,2,3\,.$$

- 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.
- 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 $m_\rho = g_\rho f \gtrsim 2.5\,\text{TeV}$.
- Even more stringent bounds on f come from the observed suppression of the non–diagonal flavour transitions, i.e $f \gtrsim 10\,\text{TeV}$.
- In the models with $\text{FS} = U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$ symmetry, the bounds that originate from the Kaon and B systems can be satisfied even for $f \sim 1\,\text{TeV}$.
- In these models the suppression of the baryon number violating operators can be achieved if global $U(1)_B$ symmetry is imposed.
- Thus the simplest CHMs with $f \ll 10\,\text{TeV}$ are based on

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

- Here we consider CHMs with $f \sim 10\,\text{TeV}$.

MCHM with an approximate Z_2 symmetry

- The breakdown of $SO(5)\times U(1)_X$ symmetry down to $SO(4)\times U(1)_X$ results in four pNGB states which can be parameterised by

$$\Omega^T = \Omega_0^T \Sigma^T = \left(Ch_1, Ch_2, Ch_3, Ch_4, \cos\frac{\tilde{h}}{f} \right),$$

$$C = \frac{1}{\tilde{h}} \sin\frac{\tilde{h}}{f}, \qquad \tilde{h} = \sqrt{h_1^2 + h_2^2 + h_3^2 + h_4^2},$$

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

- The pNGB states h_i form Higgs doublet H.
- Vector $SO(5)$ representation has the following decomposition in terms of $SU(2)_W \times SU(2)_R$:

$$\mathbf{5} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1}).$$

- All composite partners of the SM fermions can be embedded into 5^i_X.
- The composite partners E^c_i of the charged right–handed leptons e^c_i may belong to

$$\mathbf{5}^i_{+1} = \left(\mathbf{X}^i_1 \left(\mathbf{2}, +\frac{3}{2}\right), \mathbf{X}^i_2 \left(\mathbf{2}, +\frac{1}{2}\right) \right) \oplus \mathbf{E}^c_i(\mathbf{1}, +1).$$

- The composite partners L_{1i} of the left–handed leptons ℓ_i can belong to

$$\mathbf{5}^{i}_{-1} = \left(\mathbf{L}_{1i}\left(\mathbf{2},\,-\frac{1}{2}\right),\,\mathbf{X}^{i}_{3}\left(\mathbf{2},\,-\frac{3}{2}\right)\right)\oplus\mathbf{X}^{i}_{4}(\mathbf{1},\,-1)\,.$$

- Vector Ω is identified with 5_0.
- The masses of charged leptons are induced via interaction

$$Y_{ij}f(\Omega^T\mathbf{5}^{i}_{-1})(\Omega^T\mathbf{5}^{j}_{+1})\longrightarrow Y_{ij}(L_{1i}H)E^c_j\,.$$

- To generate the neutrino masses one needs to introduce L_{2i}

$$\mathbf{5}^{i}_{0} = \left(\mathbf{X}^{i}_{5}\left(\mathbf{2},\,+\frac{1}{2}\right),\,\mathbf{L}_{2i}\left(\mathbf{2},\,-\frac{1}{2}\right)\right)\oplus\mathbf{N}^{i}_{0}(\mathbf{1},\,0)\,.$$

- Then the corresponding interaction is given by

$$\varkappa_{ij}f(\Omega^T\mathbf{5}^{i}_{0})(\Omega^T\mathbf{5}^{j}_{0})\longrightarrow\frac{\varkappa_{ij}}{f}(L_{2i}H^c)(L_{2j}H^c)\,.$$

- L_{1i} and L_{2i} are superpositions of mass eigenstates

$$\begin{aligned}L_{1i} &= s_{1i}\ell_i + c_{11i}\tilde{L}_{1i} + c_{12i}\tilde{L}_{2i}\,,\\ L_{2i} &= s_{2i}\ell_i + c_{21i}\tilde{L}_{1i} + c_{22i}\tilde{L}_{2i}\,.\end{aligned}$$

- The smallness of neutrino masses implies that $s_{2i}\ll s_{1i}$.

- The smallness of the electron and neutrino masses might be caused by an approximate Z_2 symmetry under which

$$\mathbf{5}^i_0 \to -\mathbf{5}^i_0\,, \qquad \mathbf{5}^1_{-1} \to -\mathbf{5}^1_{-1}\,.$$

- This Z_2 symmetry results in $s_{2i}, s_{11} \ll s_{12}, s_{13}$ and $Y_{1j} \ll 1$.
- In this case $s_{2i} \lesssim s_{11}$, while the masses of the components of $\mathbf{5}^1_{-1}$ can be considerably smaller than f.
- The corresponding phenomenologically acceptable scenario implies that $f \gtrsim 10$ ТэВ.
- It is expected that below compositeness scale $SU(2)_W \times SU(2)_R \times U(1)_X$ symmetry gets broken down to $SU(2)_W \times U(1)_Y$, that gives rise to the mixing between L_{11} и L_{2i}.
- Such breakdown also leads to three pseudo–Nambu–Goldstone bosons that compose one scalar with charge ± 1 and one neutral scalar with masses substantially smaller than f.

Leptogenesis in the MCHM

- Let us now assume that the particle spectrum involves an additional elementary Majorana fermion n_1 with mass around $M_{n_1} \sim 10\,\text{TeV}$ while its composite partner N_1 has a mass $M_{N_1} \gtrsim f \gtrsim 10\,\text{TeV}$.
- The Lagrangian, that describes the decays of n_1 and N_1, is given by

$$\mathcal{L}_N = \sum_{i=1}^{3} \left(g_{i1} \ell_i H^c n_1 + g_{i2} \ell_i H^c N_1 + h.c. \right) + \left(h_{11} L_{11} H^c n_1 + h_{12} L_{11} H^c N_1 + h.c. \right).$$

- If N_1 is Z_2 odd field then the coupling h_{12} is not suppressed, i.e. $|h_{12}| \sim 1$.
- On the other hand $|g_{i1}| \ll |h_{11}|$, $|g_{i2}| \ll |h_{12}|$ and $|h_{11}| \ll |h_{12}|$, so that g_{i1} and $|g_{i2}|$ can be neglected.
- Lepton asymmetry can be induced in this case due to the decays $n_1 \to L_{11} + H^c$ и $n_1 \to \overline{L}_{11} + H$.

- The process of the lepton asymmetry generation is controlled by the CP asymmetry

$$\varepsilon_{11} \simeq \frac{\Gamma_{n_1 L_{11}} - \Gamma_{n_1 \bar{L}_{11}}}{\left(\Gamma_{n_1 L_{11}} + \Gamma_{n_1 \bar{L}_{11}}\right)}\,.$$

- The induced baryon asymmetry can be estimated as

$$Y_{\Delta B} \sim 10^{-3}\left(\varepsilon_{11}\cdot\eta\right), \qquad Y_{\Delta B} = \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23)\times 10^{-11}\,,$$

  where s is an entropy density.

- Parameter η, which is an efficiency factor, is given by

$$\eta \simeq H(T = M_1)/\Gamma_{11}\,, \qquad \Gamma_{11} = \Gamma_{n_1 L_{11}} + \Gamma_{n_1 \bar{L}_{11}} = \frac{|h_{11}|^2}{8\pi} M_1\,,$$

$$H = 1.66 g_*^{1/2} T^2/M_{Pl}\,, \qquad g_* = n_b + \frac{7}{8} n_f \simeq 127.25\,.$$

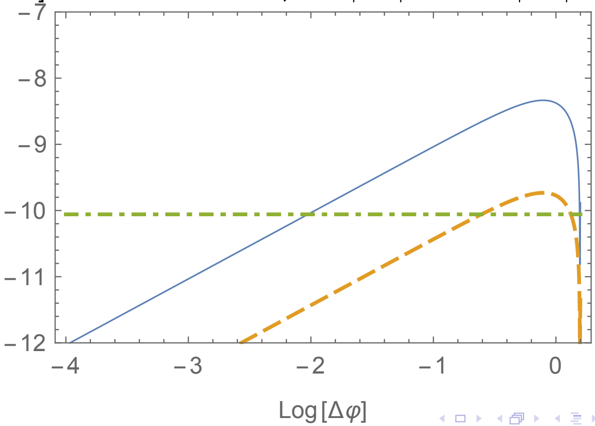
- Assuming that $M_{N_1} = 12\,\text{ТэВ}$, $M_{n_1} = 10\,\text{ТэВ}$ and $|h_{11}| \simeq 10^{-5}$, one finds $\eta \simeq 0.0039$.

- When $h_{11} = |h_{11}|e^{i\varphi_{11}}$ and $h_{12} = |h_{12}|e^{i\varphi_{12}}$, one gets

$$\varepsilon_{11} \simeq \frac{1}{(8\pi)}|h_{12}|^2 g\left(\frac{M^2_{N_1}}{M^2_{n_1}}\right)\sin 2\Delta\varphi\,, \qquad \Delta\varphi = \varphi_{12} - \varphi_{11}\,,$$

$$g(x) = \sqrt{x}\left[\frac{1}{1-x} + 1 - (1+x)\ln\frac{1+x}{x}\right].$$

$\log[Y_{\Delta B}]$ as a function of $\Delta\varphi$ for $|h_{12}| = 0.1$ и $|h_{12}| = 0.02$



Conclusions

- In the minimal composite Higgs model the observed mass hierarchy in the lepton sector can be caused by the approximate discrete Z_2 symmetry.
- This Z_2 symmetry may also lead to relatively light $SO(5)$ multiplet that involves the composite partner of electron.
- In particular, three vectorlike fermions with charges ± 1 and vectorlike fermion with charge ± 2 may have masses within the $1 - 2\,\mathrm{TeV}$ range.
- If the particle spectrum of the MCHM contains an additional elementary Majorana fermion n_1 then the out–of equilibrium decays of n_1 can induce the appropriate baryon asymmetry.