Smallness of neutrino masses and leptogenesis in 331 composite Higgs model

Roman Nevzorov
(Lebedev Physical Inst.)

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Outline

Based on:

R. Nevzorov, Smallness of neutrino masses and leptogenesis in 331 composite Higgs model, Phys. Lett. B **874** (2026) 140210 [arXiv:2509.13245 [hep-ph]].

R. Nevzorov, Leptogenesis in the Composite Higgs Models, Phys. Atom. Nucl. **88** (2025) no.5, 1100-1106.

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 $\lambda \approx 0.13$.
- 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 CHMs.
- The idea of a composite Higgs boson was proposed in the 70's and 80's [H. Terazawa, K. Akama, Y. Chikashige, Phys. Rev. D 15 (1977) 480; S. Dimopoulos, J. Preskill, Nucl. Phys. B 199 (1982) 206.].
- The composite Higgs models involve
  - weakly–coupled sector that includes states with quantum numbers of the SM gauge bosons and SM fermions.
  - strongly interacting sector which results in a set of bound states involving Higgs doublet as well as composite partners of quarks, leptons and gauge bosons.

- 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.
- Most 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, these bounds 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

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

331 composite Higgs model (CHM3)

- The strongly interacting sector of the CHM3 possesses a global $SU(3)_C \times SU(3) \times U(1)_6$ symmetry which contains the SM gauge group as a subgroup and may stem from $SU(6)$ subgroup of E_6.
- Around the scale $f \sim 10\,\mathrm{TeV}$ the $SU(3) \times U(1)_6$ symmetry is broken down to $SU(2)_W \times U(1)_Y$ so that the weak hypercharges Y_i are

$$Y_i = \frac{2\sqrt{3}}{6} T_i^8 + Q_i^6 \,.$$

- This gives rise to a set of the pNGB states which can be parameterised through fundamental representation of $SU(3)$

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

- The first two components of Ω can be identified with the Higgs doublet H while the third component involves the SM singlet scalar ϕ_0.
- To ensure the appropriate breakdown of $SU(3) \times U(1)_6$ symmetry Ω has to carry $U(1)_6$ charge $Q_\Omega^6 = +1/3$.

Generation of fermion masses

- 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 charged leptons one gets

$$y^e_{ij} = s^i_L Y^E_{ij} s^j_E \,, \qquad\qquad i,j = 1,2,3 \,.$$

- 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.

- In the MCHM all composite partners of the SM fermions can be embedded into 5^i_X vector representations of $SO(5)\times U(1)_X$.
- The composite partners U^c_i and D^c_i of the right–handed quarks u^c_i and d^c_i may belong to $\mathbf{5}^i_{-2/3}$ and $\mathbf{5}^i_{+1/3}$.
- There are two types of the partners Q_{1i} and Q_{2i} of the left–handed quarks q_i that belong to $\mathbf{5}^i_{+2/3}$ and $\mathbf{5}^i_{-1/3}$.
- The composite partners of the left–handed and charged right–handed leptons (L_{1i} and E^c_i) can belong to $\mathbf{5}^i_{-1}$ and $\mathbf{5}^i_{+1}$.
- The masses of the left–handed neutrino can be generated if another composite partners of the left–handed leptons L'_{2i}, which are components of $\mathbf{5}^i_0$, are included.
- In the CHM3 the composite partners of elementary quarks stem from $\mathbf{20}$, $\mathbf{15}$ and $\overline{\mathbf{15}}$ of $SU(6)$ so that they have the following decomposition in terms of $SU(3)_C\times SU(3)\times U(1)_6$:

$$U^c_i\in\left(\overline{\mathbf{3}},\mathbf{3},-\frac{1}{3}\right),\ D^c_i\in\left(\overline{\mathbf{3}},\overline{\mathbf{3}},0\right),\ Q_{1i}\in\left(\mathbf{3},\mathbf{3},0\right),\ Q_{2i}\in\left(\mathbf{3},\overline{\mathbf{3}},\frac{1}{3}\right).$$

- The generalisation of the $SU(5)$ structure of the quark Yukawa interactions to the case of $SU(6)$ symmetry is given by

$$\mathcal{L}^{q}_{SU(6)} \sim Y^{u}_{ij}\,\mathbf{20}(U^c_i)\times\mathbf{15}(Q_{1j})\times\mathbf{6}_H + Y^{d}_{ij}\,\mathbf{20}(Q_{2i})\times\overline{\mathbf{15}}(D^c_j)\times\overline{\mathbf{6}}_H + h.c..$$

- The composite partners of the right-handed charged leptons e^c_i originate from **15** of $SU(6)$ whereas two types of the partners of the left–handed leptons ℓ_i come from $\overline{\mathbf{15}}$ and $\overline{\mathbf{6}}$, so that

$$E^c_i \in \overline{\mathbf{3}}'^{i}_{+2/3} = \left(\mathbf{1},\,\overline{\mathbf{3}},\,\frac{2}{3}\right), \qquad L_{1i} \in \mathbf{3}'^{i}_{-2/3} = \left(\mathbf{1},\,\mathbf{3},\,-\frac{2}{3}\right),$$

$$L_{2i} \in \overline{\mathbf{3}}'^{i}_{-1/3} = \left(\mathbf{1},\,\overline{\mathbf{3}},\,-\frac{1}{3}\right).$$

- Multiplets $\overline{\mathbf{3}}'^{i}_{-1/3}$ and $\mathbf{3}'^{i}_{+1/3}$ get combined forming vectorlike states.
- To ensure that the left–handed neutrino states gain tiny masses approximate $U(1)_L$ and discrete Z_2 symmetries are imposed.
- All multiplets except $\mathbf{3}'^{i}_{+1/3}$ are even under approximate Z_2 while $\mathbf{3}'^{i}_{+1/3}$ are Z_2 odd.
- Multiplets $\overline{\mathbf{3}}'^{i}_{+2/3}$ and $\mathbf{3}'^{i}_{-2/3}$ carry $U(1)_L$ charges (-1) and $(+1)$ respectively whereas all other multiplets of the composite states have zero $U(1)_L$ charges.

- Interactions in the strongly interacting sector

$$\mathcal{L}_e = \tilde{Y}^e_{ij} f(\overline{\mathbf{3}}^i_{+2/3}\Omega)(\Omega^\dagger \mathbf{3}^j_{-2/3}) + \tilde{\varkappa}_{ij} f(\overline{\mathbf{3}}^i_{-1/3}\Omega)(\overline{\mathbf{3}}^j_{-1/3}\Omega)$$

give rise to operators

$$\mathcal{L}_l =\simeq Y^e_{ij} E^c_i (L_{1j} H^c) + \frac{\varkappa_{ij}}{f} (L_{2i} H)(L_{2j} H)\,.$$

- The mixing between the elementary lepton doublets and their composite partners results in the SM lepton doublets ℓ_i as well as vectorlike fermion doublets $\tilde{L}_{1i}$ and $\tilde{L}_{2i}$ so that

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

- The parameters $c_{11i} \approx c_{22i} \approx 1$ while s_{1i}, s_{2i}, s_{12i} and s_{21i} are small.
- The masses of the charged leptons are determined by $Y^e_{ij} \sim 1$, s_{1i} and the fractions of the compositeness of the right–handed leptons s_{ei}.
- All measured charged lepton masses can be reproduced when $|s_{1i}|$ and $|s_{ei}|$ vary between 0.001 and 0.1 .

Smallness of neutrino masses in CHM3

- In the leading order the neutrino mass matrix is given by

$$\mathcal{M}^{\nu}_{ij} = -\frac{\varkappa_{ij}}{2f} s_{2i} s_{2j} v^2 \,, \qquad v \simeq 246\,\text{GeV}\,.$$

- Since $\varkappa_{ij} \sim 1$, the appropriate neutrino mass scale ($\sim 0.1\,\text{eV}$) requires that $s_{2i} \lesssim 10^{-5}$, i.e. $s_{2i} \ll s_{1i}$.
- The smallness of s_{2i} can be caused by both $U(1)_L$ and approximate Z_2 symmetries.
- If the mixing between $\tilde{L}_{2i}$ and elementary states vanishes then $s_{12i} = s_{21i} = s_{2i} = 0$ and the Lagrangian of the CHM3 possesses an exact global $U(1)_L$ symmetry because in the strongly interacting sector the lepton number violating operators cannot be induced.
- When Z_2 symmetry is exact, $\tilde{L}_{2i}$ remain massless and the values of s_{12i}, s_{21i} and s_{2i} go to zero.
- The approximate Z_2 symmetry implies that s_{2i} are small and $\tilde{L}_{2i}$ are much lighter than f.

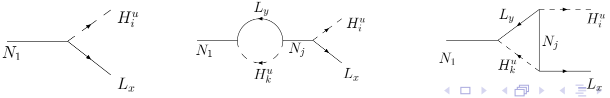
Leptogenesis

- 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 $N_1 \to \bar{L}_x + \bar{H}^u$.
- If CP invariance is broken in the lepton sector the non–zero $\varepsilon_{1,\,\ell_x}$ arise from the interference between the tree–level amplitudes of the N_1 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.].



Leptogenesis in the CHM3

- In the CHM3 the SM singlet components N_i of $\overline{\mathbf{3}}'^{\,i}_{-1/3}$ gain masses around $f \gtrsim 10\,\mathrm{TeV}$.
- The approximate Z_2 ensures that the $SU(2)_W$ doublet components $\tilde{L}_{2i}$ of these multiplets are substantially lighter than f.
- The masses of $\tilde{L}_{2i}$ may vary between $1-2\,\mathrm{TeV}$ so that it might be possible to discover such fermion states in the near future at the LHC.
- The couplings of these composite resonances to the SM leptons are suppressed because they are determined by the small parameters s_{2i}.
- Now suppose that the weakly–coupled sector includes an additional elementary Majorana fermion $n = N_0$ which mixes with N_i and has a mass $M_n \sim 10\,\mathrm{TeV}$.
- We further assume that N_i are somewhat heavier than the elementary fermion $n = N_0$.
- Therefore the decays of $n = N_0$ into leptons and Higgs doublet may induce lepton asymmetry.

- The part of the CHM3 Lagrangian, which describes the decays of N_x $(x = 0, 1, 2, 3)$, is given by

$$\mathcal{L}_N = g_{ix}\ell_i H N_x + h_{jx}\tilde{L}_{2j} H N_x + h.c..$$

- Because ℓ_i and N_0 are mainly elementary fields g_{ix} are very small and can be ignored.
- The couplings h_{ij} are not suppressed so that $|h_{ij}| \gtrsim 0.1$.
- At the same time $|h_{j0}| \ll |h_{ij}|$.
- To simplify our analysis, we neglect the masses of $\tilde{L}_{2i}$ and set $h_{20} = h_{30} = 0$.
- Then the process of the lepton asymmetry generation is controlled by only one CP (decay) asymmetry

$$\varepsilon_0 \simeq \frac{\Gamma_{L_{21}} - \Gamma_{\overline{L}_{21}}}{\left(\Gamma_{L_{21}} + \Gamma_{\overline{L}_{21}}\right)}.$$

- Here $\Gamma_{L_{21}}$ and $\Gamma_{\overline{L}_{21}}$ are partial decay widths of $n \to \tilde{L}_{21} + H$ and $n \to \overline{\tilde{L}}_{21} + H^*$.

- For $h_{1x} = |h_{1x}|e^{i\varphi_x}$ and real values of M_n and M_j the calculation of one–loop diagrams gives

$$\varepsilon_0 \simeq \frac{1}{8\pi}\left[\sum_{j=1,2,3}|h_{1j}|^2 g\left(\frac{M_j^2}{M_n^2}\right)\sin 2\Delta\varphi_j\right], \qquad \Delta\varphi_j = \varphi_j - \varphi_0\,,$$

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

- The induced baryon asymmetry can be estimated as

$$Y_{\Delta B} \sim 10^{-3}\left(\varepsilon_0\cdot\eta_0\right), \quad Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}\bigg|_0 = (8.75\pm 0.23)\times 10^{-11}\,,$$

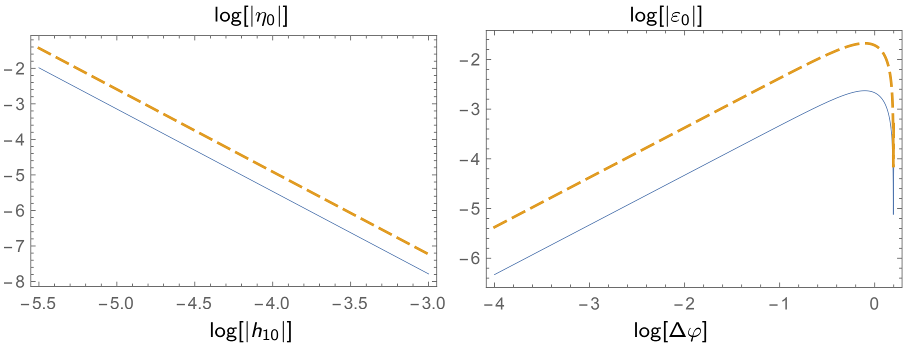
where s is an entropy density.

- In the strong washout scenario η_0, which is an efficiency factor, is given by

$$\eta_0 \simeq \left(\frac{H(T=M_n)}{2\Gamma}\right)^{1.16}, \qquad \Gamma = \Gamma_{L_{21}} + \Gamma_{\overline{L}_{21}} = \frac{|h_{10}|^2}{8\pi}M_n\,,$$

$$H = 1.66 g_*^{1/2} T^2/M_{Pl}\,, \qquad g_* = n_b + \frac{7}{8}n_f \simeq 128.75\,.$$

- This scenario implies that $|h_{10}| \gtrsim 10^{-6}$.



Logarithm (base 10) of the absolute values of the efficiency factor η_0 (**Left**) and decay asymmetry ε_0 (**Right**) for $h_{20} = h_{30} = 0$. The absolute value of η_0 is given as a function of logarithm (base 10) of $|h_{10}|$ for $M_n = 10\,\text{TeV}$ (solid line) and $M_n = 15\,\text{TeV}$ (dashed line). The absolute value of ε_0 is presented as a function of logarithm (base 10) of $\Delta\varphi_1 = \Delta\varphi_2 = \Delta\varphi_3 = \Delta\varphi$ for $M_n = 10\,\text{TeV}$, $M_1 = 12\,\text{TeV}$, $M_2 = 14\,\text{TeV}$, $M_3 = 16\,\text{TeV}$, $|h_{11}| = |h_{12}| = |h_{13}| = |h|$, $|h| = 0.1$ (solid line) and $|h| = 0.3$ (dashed line).

- For such values of $|h_{10}|$ the efficiency factor η_0 diminishes with increasing $|h_{10}|$.
- The appropriate baryon asymmetry can be generated only if $\eta_0 \gtrsim 10^{-7}$.
- For $M_n \simeq 10\,\mathrm{TeV}$ this condition can be fulfilled when $|h_{10}| \ll 0.001$.
- The decay asymmetry ε_0 is set by $|h_{1j}|$ and CP violating phases $\Delta\varphi_j$.
- It also depends on the ratio of masses of Majorana fermions M_j/M_n.
- The absolute value of ε_0 grows monotonically with increasing of $|h_{11}| = |h_{12}| = |h_{13}| = h$.
- When $h \gtrsim 0.1$ the observed baryon asymmetry can be obtained even for small CP violating phases, i.e. $\Delta\varphi_j \sim 0.01$.

Conclusions

- The generation of fermion masses within the 331 composite Higgs model (CHM3), in which the strongly interacting sector possesses approximate $SU(3)_C \times SU(3) \times U(1)_6$ symmetry, have been discussed.
- This global symmetry may originate from $SU(6)$ subgroup of E_6.
- It was argued that the observed mass hierarchy in the lepton sector can be caused by the approximate $U(1)_L$ and discrete Z_2 symmetries.
- If near the scale $f \sim 10\,\mathrm{TeV}$ the approximate $SU(3) \times U(1)_6$ symmetry is broken down to the $SU(2)_W \times U(1)_Y$ subgroup then such Z_2 symmetry may lead to neutral and charged vectorlike fermions with masses $1 - 2\,\mathrm{TeV}$.
- These resonances can be discovered at the LHC in the near future.
- If the particle spectrum of the CHM3 contains an additional elementary Majorana fermion n with mass around $10\,\mathrm{TeV}$ then the out–of equilibrium decays of n can induce the appropriate baryon asymmetry.