

Massive Neutrinos in a Grounds-Up Approach

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Massive neutrinos in a grounds-up approach

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We examine neutrino oscillations in a two Higgs doublet model (2HDM) in which the second doublet couples only to the third generation right-handed up-fermions, i.e., to t_R and N_3 which is the heaviest right-handed Majorana neutrino. The inherently large $\tan\beta$ of this model can naturally account for the large top-quark mass and, based on a quark-lepton similarity ansatz, when embedded into a seesaw mechanism it can also account for the observed neutrino masses and mixing angles giving a very small θ_{13} : $-0.96^\circ \lesssim \theta_{13} \lesssim 1.36^\circ$ at 99% CL, and a very restrictive prediction for the atmospheric mixing angle: $42.9^\circ \lesssim \theta_{atm} \lesssim 45.2^\circ$ at 99% CL. The large value of $\tan\beta$ also sets the mass scale of the heaviest right-handed Majorana neutrino N_3 and triggers successful leptogenesis.

I. INTRODUCTION

In the past decade we have witnessed two remarkable findings: (i) the discovery of the top-quark which turned out to be enormously heavy compared to all the other fermions: $m_t \sim 175$ GeV, i.e., “weighing” almost as much as a Gold atom!, and (ii) the discovery of neutrino oscillations implying that neutrinos are massive with a typical mass in the sub-eV range, i.e., m_ν is more than 12 orders of magnitudes smaller than m_t . This two monumental discoveries of the 90’s present us with the pressing challenge of reconciling the apparent enormous hierarchy in the masses of fundamental fermions.

A possible resolution to this huge hierarchy between m_ν and m_t may be encoded within the following triple-relation between m_ν , m_t (or the Electroweak scale) and the GUT mass-scale $M_{GUT} \sim 10^{16}$ GeV:

$$m_\nu \sim \frac{m_t^2}{M_{GUT}}. \quad (1)$$

Indeed, the beautiful seesaw mechanism dictates that (see also next sections):

$$m_\nu \sim \frac{m_D^2}{M_{\nu_R}}, \quad (2)$$

where m_D is a Dirac neutrino mass term and M_{ν_R} is the mass of heavy right-handed Majorana neutrinos. Thus, based on the seesaw formula in Eq. 2, the triple-relation in Eq. 1 stands as a very strong hint for Dirac neutrino masses of $m_D \sim \mathcal{O}(m_t)$ and for the existence of super-heavy right-handed Majorana neutrinos with a typical mass of $M_{\nu_R} \sim \mathcal{O}(M_{GUT})$.

In this work [1] we seriously take the triple-relation in Eq. 1 at “face-value”, suggesting that the impressive findings in the neutrino sector are closely related to the heaviness of the top-quark. In particular, we construct a model that, based on a grounds-up approach, explicitly yields the triple-relation between the large m_t , the observed ν -oscillation data (i.e., masses and mixing angles) and the super-heavy mass scale of the right-handed Majorana neutrinos. In addition, our model can trigger successful leptogenesis which can account for the observed Baryon asymmetry in the universe.

Our model is a two Higgs doublet model (2HDM) which treats the 3rd generation neutrino in a completely analogous manner to the top-quark. We have, therefore, named our model “the 2HDM for the 3rd generation” (3g2HDM).

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II. THE TWO HIGGS DOUBLET MODEL FOR THE 3RD GENERATION (3G2HDM)

The 3g2HDM extends the idea of the so called “2HDM for the top-quark” (t2HDM) [2] to the leptonic sector. In particular, as in the t2HDM, we assume that ϕ_t [the Higgs doublet with a much larger vacuum expectation value (VEV)] couples *only* to the top-quark and to the 3rd generation right-handed Majorana neutrino, while the other Higgs doublet ϕ_f (with a much smaller VEV) couples to all the other fermions. The large mass hierarchy between the top-quark and all other fermions is then viewed as a consequence of $v_t/v_f \equiv \tan \beta \gg O(1)$, which, therefore, becomes the “working assumption” of our 3g2HDM.

The Yukawa interaction Lagrangian of our 3g2HDM takes the form:

$$\mathcal{L}_Y = -Y^d \bar{Q}_L \phi_f d_R - Y_1^u \bar{Q}_L \tilde{\phi}_f u_R - Y_2^u \bar{Q}_L \tilde{\phi}_t u_R - Y^e \bar{L}_L \phi_f \ell_R - Y_1^\nu \bar{L}_L \tilde{\phi}_f N - Y_2^\nu \bar{L}_L \tilde{\phi}_t N + h.c. , \quad (3)$$

where N are right-handed Majorana neutrinos with a mass $M_N^{ij} N_i N_j / 2$, Q and L are the usual quark and lepton doublets and the following Yukawa textures are assumed [1]

$$Y_1^{u,\nu} \equiv \begin{pmatrix} a^{u,\nu} & b^{u,\nu} & 0 \\ a^{u,\nu} & b^{u,\nu} & 0 \\ 0 & \delta b^{u,\nu} & 0 \end{pmatrix} , \quad Y_2^{u,\nu} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c^{u,\nu} \\ 0 & 0 & c^{u,\nu} \end{pmatrix} , \quad (4)$$

such that, in both the quark and leptonic sectors, ϕ_t couples only to the third generation right-handed up-fermions. Note also that m_D , $m_u = v_f (Y_1^{\nu,u} + \tan \beta Y_2^{\nu,u}) / \sqrt{2}$, where m_D , m_u are the Dirac mass matrices of the neutrinos and up-quarks, respectively.

III. NEUTRINO OSCILLATIONS IN THE 3G2HDM

In the basis where M_N is diagonal, $M_N = M \cdot \text{diag}(\epsilon_{M1}, \epsilon_{M2}, \epsilon_{M3})$, we obtain from the seesaw mechanism formula $m_\nu = -m_D M_N^{-1} m_D^T$:

$$m_\nu = m_\nu^0 \begin{pmatrix} \epsilon & \epsilon & \delta \bar{\epsilon} \\ \cdot & \epsilon + \omega & \delta \bar{\epsilon} + \omega \\ \cdot & \cdot & \delta^2 \bar{\epsilon} + \omega \end{pmatrix} , \quad (5)$$

where

$$m_\nu^0 \equiv \frac{(v_1)^2}{2M} , \quad \epsilon \equiv \frac{a^2}{\epsilon_{M1}} + \frac{b^2}{\epsilon_{M2}} , \quad \bar{\epsilon} \equiv \epsilon - \frac{a^2}{\epsilon_{M1}} , \quad \omega \equiv \frac{c^2 t_\beta^2}{\epsilon_{M3}} . \quad (6)$$

In the following we will adopt a quark-lepton similarity Ansatz (perhaps motivated by GUT scenarios): $a^u \sim a^\nu \equiv a$, $b^u \sim b^\nu \equiv b$ and $c^u \sim c^\nu \equiv c$, with $a \sim O(10^{-3})$, $b \sim O(10^{-1})$, $c \sim O(1)$ which, in our model, follows from the up-quark sector since $a^u v_f \sim O(m_u)$, $b^u v_f \sim O(m_c)$ and $m_t \sim O(c^u v_f \tan \beta)$. Then, diagonalizing the light-neutrinos mass matrix in Eq. 5, we find that in the normal mass-hierarchy scheme, i.e., $m_1 \ll m_2 \ll m_3$, [1]:

- The mass of the heaviest light-neutrino follows the triple relation in Eq. 1:

$$m_3 \sim \frac{m_t^2}{M_{N_3}} , \quad (7)$$

where $M_{N_3} \sim M_{GUT}$ is the mass of the 3rd and heaviest right-handed Majorana neutrino.

- Performing a minimum χ^2 analysis with respect to each of the oscillation parameters θ_{13} , $\theta_{atm} \equiv \theta_{23}$, $\theta_{sol} \equiv \theta_{12}$ and Δm_{atm}^2 , Δm_{sol}^2 , our 3g2HDM yields the following 99% CL allowed ranges for the mixing parameters:

$$\begin{aligned} 28.0^\circ &\lesssim \theta_{sol} \lesssim 36.0^\circ & 99\% \text{ CL} , \\ 1.0 \cdot 10^{-3} (\text{eV})^2 &\lesssim \Delta m_{atm}^2 \lesssim 3.7 \cdot 10^{-3} (\text{eV})^2 & 99\% \text{ CL} , \\ 7.3 \cdot 10^{-5} (\text{eV})^2 &\lesssim \Delta m_{sol}^2 \lesssim 9.1 \cdot 10^{-5} (\text{eV})^2 & 99\% \text{ CL} , \end{aligned} \quad (8)$$

with a very restrictive prediction for θ_{13} and the atmospheric mixing angle:

$$\begin{aligned} -0.96^\circ &\lesssim \theta_{13} \lesssim 1.36^\circ & 99\% \text{ CL} , \\ 42.9^\circ &\lesssim \theta_{atm} \lesssim 45.2^\circ & 99\% \text{ CL} . \end{aligned} \quad (9)$$

- The mass-spectrum of the heavy Majorana neutrinos (subject to the constraints coming from oscillation data) becomes:

$$M_{N_3} \sim 100M, \quad M_{N_2} \sim 0.01M, \quad M_{N_1} \gg 10^{-6}M, \quad (10)$$

with $M \sim 10^{13}$ GeV.

IV. LEPTOGENESIS IN THE 3G2HDM

A CP-asymmetry, ϵ_{N_i} , in the decay $N_i \rightarrow \ell\phi_j$ can generate the lepton asymmetry [3]:

$$n_L/s = \epsilon_{N_i} Y_{N_i}(T \gg M_{N_i}) \eta, \quad (11)$$

where $Y_{N_i}(T \gg M_{N_i}) = 135\zeta(3)/(4\pi^4 g_*)$ and g_* being the effective number of spin-degrees of freedom in thermal equilibrium. Also, η is the “washout” parameter (efficiency factor) that measures the amount of deviation from the out-of-equilibrium condition at the time of the N_i decay. This lepton asymmetry can then be converted into a baryon asymmetry through nonperturbative sphaleron processes. In our case (i.e., two scalar doublets) we obtain:

$$n_B/s \sim -1.4 \times 10^{-3} \epsilon_{N_i} \eta. \quad (12)$$

As seen from Eq. 10, our 3g2HDM can lead to a hierarchical mass spectrum for the heavy Majorana neutrinos, $M_{N_1} \ll M_{N_2} \ll M_{N_3}$. In this case, only the CP-asymmetry produced by the decay of N_1 survives, i.e., $\epsilon_{N_i} \rightarrow \epsilon_{N_1}$. Calculating the CP-asymmetry ϵ_{N_1} and the corresponding washout factor η we obtain [1]:

$$\frac{n_B}{s} \sim 10^{-17} \tan^2 \beta \frac{\sqrt{\Delta m_{sol}^2}}{2m_t^2} \epsilon M_{N_1} \left(\frac{M_{N_1}}{\text{GeV}} \right)^{1.2} \sin 2(\theta_b - \theta_a). \quad (13)$$

where the CP-phases arise from the possible complex entries in Y_1^ν : $a = |a|e^{i\theta_a}$ and $b = |b|e^{i\theta_b}$. Eq. 13 has to be compared with the observed baryon to photon number ratio $n_B/n_\gamma \sim 6 \times 10^{-10}$, implying $n_B/s \sim 8.5 \times 10^{-11}$. For example, taking $\epsilon \sim 0.5$ and $\Delta m_{sol}^2 \sim 8.2 \cdot 10^{-5} \text{ eV}^2$ (these values are consistent with the observed oscillation data), along with $\tan \beta \sim 10$ and $m_t \sim 170 \text{ GeV}$, Eq. 13 reproduces the observed baryon asymmetry for e.g., $M_{N_1} \sim 10^{10} \text{ GeV}$ and $\sin 2(\theta_b - \theta_a) \sim 0.1$, or for $M_{N_1} \sim 3.6 \cdot 10^9 \text{ GeV}$ if CP is maximally violated in the sense that $\sin 2(\theta_b - \theta_a) \sim 1$.

[1] For more details see, D. Atwood, S. Bar-Shalom and A. Soni, hep-ph/0502234.

[2] A.K. Das and C. Kao, Phys. Lett. **B372**, (1996) 106.

[3] See e.g., P. Di Bari, hep-ph/0406115; T. Hambye, hep-ph/0412053.