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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 $\theta_{13}$: $-0.96^0 \lesssim \theta_{13} \lesssim 1.36^0$ at 99% CL, and a very restrictive prediction for the atmospheric mixing angle: $42.9^0 \lesssim \theta_{atm} \lesssim 45.2^0$ 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.

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## 1. 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., $m_\nu$ 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 $m_\nu$ and $m_t$ may be encoded within the following triple-relation between $m_\nu$, $m_t$ (or the Electroweak scale) and the GUT mass-scale $M_{GUT} \sim 10^{16}$ GeV:

$$m_\nu \sim \frac{m_t^2}{M_{GUT}} . \tag{1.1}$$

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

$$m_\nu \sim \frac{m_D^2}{M_{\nu_R}} , \tag{1.2}$$

where $m_D$ is a Dirac neutrino mass term and $M_{\nu_R}$ is the mass of heavy right-handed Majorana neutrinos. Thus, based on the seesaw formula in Eq. 1.2, the triple-relation in Eq. 1.1 stands as a very strong hint for Dirac neutrino masses of $m_D \sim \mathscr{O}(m_t)$ and for the existence of super-heavy right-handed Majorana neutrinos with a typical mass of $M_{\nu_R} \sim \mathscr{O}(M_{GUT})$.

In this work [1] we seriously take the triple-relation in Eq. 1.1 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 $\nu$-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 rigger 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).

## 2. 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 $\phi_t$ [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 $\phi_f$ (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 $v_t/v_f \equiv \tan\beta >> O(1)$, which, therefore, becomes the "working assumption" of our 3g2HDM.

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

$$\mathscr{L}_Y = -Y^d \overline{Q}_L \phi_f d_R - Y_1^u \overline{Q}_L \tilde{\phi}_f u_R - Y_2^u \overline{Q}_L \tilde{\phi}_t u_R - Y^e \overline{L}_L \phi_f \ell_R - Y_1^\nu \overline{L}_L \tilde{\phi}_f N - Y_2^\nu \overline{L}_L \tilde{\phi}_t N + h.c. \; , \quad (2.1)$$

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]

$$Y_1^{u,\nu} \equiv \begin{pmatrix} a^{u,\nu} & b^{u,\nu} & 0 \\ a^{u,\nu} & b^{u,\nu} & 0 \\ 0 & \delta b^{u,\nu} & 0 \end{pmatrix} \; , \; Y_2^{u,\nu} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c^{u,\nu} \\ 0 & 0 & c^{u,\nu} \end{pmatrix} \; , \quad (2.2)$$

such that, in both the quark and leptonic sectors, $\phi_t$ 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.

## 3. Neutrino oscillations in the 3g2HDM

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

$$m_\nu = m_\nu^0 \begin{pmatrix} \varepsilon & \varepsilon & \delta\bar{\varepsilon} \\ \cdot & \varepsilon + \omega & \delta\bar{\varepsilon} + \omega \\ \cdot & \cdot & \delta^2 \bar{\varepsilon} + \omega \end{pmatrix} \; , \quad (3.1)$$

where

$$m_\nu^0 \equiv \frac{(v_1)^2}{2M} \; , \; \varepsilon \equiv \frac{a^2}{\varepsilon_{M1}} + \frac{b^2}{\varepsilon_{M2}} \; , \; \bar{\varepsilon} \equiv \varepsilon - \frac{a^2}{\varepsilon_{M1}} \; , \; \omega \equiv \frac{c^2 t_\beta^2}{\varepsilon_{M3}} \; . \quad (3.2)$$

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. 3.1, we find that in the normal mass-hierarchy scheme, i.e., $m_1 << m_2 << m_3$, [1]:

- The mass of the heaviest light-neutrino follows the triple relation in Eq. 1.1:

$$m_3 \sim \frac{m_t^2}{M_{N_3}} \; , \quad (3.3)$$

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

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

$$\begin{aligned} 28.0^0 \lesssim & \quad \theta_{sol} \quad \lesssim 36.0^0 \quad 99\% \text{ CL} \; , \\ 1.0 \cdot 10^{-3} \; (\text{eV})^2 \lesssim & \quad \Delta m^2_{atm} \quad \lesssim 3.7 \cdot 10^{-3} \; (\text{eV})^2 \quad 99\% \text{ CL} \; , \\ 7.3 \cdot 10^{-5} \; (\text{eV})^2 \lesssim & \quad \Delta m^2_{sol} \quad \lesssim 9.1 \cdot 10^{-5} \; (\text{eV})^2 \quad 99\% \text{ CL} \; , \end{aligned} \quad (3.4)$$

with a very restrictive prediction for $\theta_{13}$ and the atmospheric mixing angle:

$$-0.96^0 \lesssim \theta_{13} \lesssim 1.36^0 \quad 99\%\ \mathrm{CL}\ ,$$
$$42.9^0 \lesssim \theta_{atm} \lesssim 45.2^0 \quad 99\%\ \mathrm{CL}\ . \tag{3.5}$$

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

$$M_{N_3} \sim 100M\ ,\ M_{N_2} \sim 0.01M\ ,\ M_{N_1} >> 10^{-6}M\ , \tag{3.6}$$

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

## 4. Leptogenesis in the 3g2HDM

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

$$n_L/s = \varepsilon_{N_i} Y_{N_i}(T >> M_{N_i})\eta\ , \tag{4.1}$$

where $Y_{N_i}(T >> M_{N_i}) = 135\zeta(3)/(4\pi^4 g_*)$ and $g_*$ being the effective number of spin-degrees of freedom in thermal equilibrium. Also, $\eta$ 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 spheleron processes. In our case (i.e., two scalar doublets) we obtain:

$$n_B/s \sim -1.4\times 10^{-3}\varepsilon_{N_i}\eta\ . \tag{4.2}$$

As seen from Eq. 3.6, our 3g2HDM can lead to a hierarchical mass spectrum for the heavy Majorana neutrinos, $M_{N_1} << M_{N_2} << M_{N_3}$. In this case, only the CP-asymmetry produced by the decay of $N_1$ survives, i.e., $\varepsilon_{N_i} \to \varepsilon_{N_1}$. Calculating the CP-asymmetry $\varepsilon_{N_1}$ and the corresponding washout factor $\eta$ we obtain [1]:

$$\frac{n_B}{s} \sim 10^{-17}\tan^2\beta\frac{\sqrt{\Delta m^2_{sol}}}{2m_t^2}\varepsilon M_{N_1}\left(\frac{M_{N_1}}{\mathrm{GeV}}\right)^{1.2}\sin 2(\theta_b-\theta_a)\ . \tag{4.3}$$

where the CP-phases arise from the possible complex entries in $Y_1^\nu$: $a = |a|e^{i\theta_a}$ and $b = |b|e^{i\theta_b}$. Eq. 4.3 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 $\varepsilon \sim 0.5$ and $\Delta m^2_{sol} \sim 8.2\cdot 10^{-5}$ eV$^2$ (these values are consistent with the observed oscillation data), along with $\tan\beta \sim 10$ and $m_t \sim 170$ GeV, Eq. 4.3 reproduces the observed baryon asymmetry for e.g., $M_{N_1} \sim 10^{10}$ GeV and $\sin 2(\theta_b-\theta_a) \sim 0.1$, or for $M_{N_1} \sim 3.6\cdot 10^9$ GeV if CP is maximally violated in the sense that $\sin 2(\theta_b-\theta_a) \sim 1$.

## References

[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].