Massive neutrinos in a Grounds-up Approach with Quark-Lepton Similarity

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Abstract. 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 to $N_3$ which is the heaviest right-handed Majorana neutrino. The inherently large $\tan \beta$ of this model can naturally account for the large top 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 $\theta_{13} \simeq 0.017$ at 99% CL, and a very restrictive prediction for the atmospheric mixing angle: $42.90^0 < \theta_{\text{atm}} < 45.20^0$ 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 through a CP-asymmetry in the decays of the $N_1$ (lightest right-handed Majorana) which is $\tan^2 \beta$ enhanced compared to the CP-asymmetry obtained in models for leptogenesis with one Higgs doublet or in the MSSM. This enhancement allows us to relax the lower bound on $M_{N_1}$ and consequently also the lower bound on the reheating temperature of the early universe.

Keywords: neutrino mixing & masses, two Higgs doublets, 3rd generation fermions, leptogenesis

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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:

$$m_\nu \sim \frac{m_t^2}{M_{GUT}}. \tag{1}$$

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

$$m_\nu \sim \frac{m_D^2}{M_{VR}}. \tag{2}$$
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. 2, the triple-relation in Eq. 1 stands as a very strong hint for Dirac neutrino masses of $m_D \sim O(\mu)$ and for the existence of super-heavy right-handed Majorana neutrinos with a typical mass of $M_{\nu_R} \sim O(M_{\text{GUT}})$.

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 $\nu$-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).

### 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 $\nu_t/\nu_f \equiv \tan \beta >> O(1)$, which, therefore, becomes the "working assumption" of the 3g2HDM.

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

$$L_Y = -Y_d \bar{Q}_L \phi_d R - Y^u_1 \bar{Q}_L \phi_f u_R - Y^u_2 \bar{Q}_L \phi_f u_R - Y^c L_L \phi_f \ell_R - Y^\nu_1 \bar{L}_L \phi_f N - Y^\nu_2 \bar{L}_L \phi_f N + h.c. ,$$

(3)

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

$$Y^u_{1,2} \equiv \begin{pmatrix} a^u_{1,2} & b^u_{1,2} & 0 \\ a^u_{1,2} & b^u_{1,2} & 0 \\ 0 & 0 & \delta b^u_{1,2} \end{pmatrix}, \quad Y^\nu_{1,2} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c^u_{1,2} \\ 0 & c^u_{1,2} \end{pmatrix},$$

(4)

such that, in both the quark and leptonic sectors, $\phi_t$ couples only to the third generation right-handed up-fermions. Note also that $m_D, \ m_u = v_f (Y^u_{1} + \tan \beta Y^u_{2}) / \sqrt{2}$, where $m_D, \ m_u$ are the Dirac mass matrices of the neutrinos and up-quarks, respectively.
NEUTRINO OSCILLATIONS IN THE 3G2HDM

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

$$m_\nu = m_\nu^0 \begin{pmatrix} \varepsilon & \varepsilon & \delta \bar{\varepsilon} \\ \varepsilon + \omega & \delta \bar{\varepsilon} + \omega \\ \delta^2 \bar{\varepsilon} + \omega \end{pmatrix} ,$$

where

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

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., $m_1 << m_2 << m_3$,[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]

$$m_3 \sim \frac{m_2^2}{M_{N3}} ,$$

where $M_{N3} \sim M_{GUT}$ 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:

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

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

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

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

$$M_{N1} \sim 100M , M_{N2} \sim 0.01M , M_{N3} >> 10^{-6}M ,$$

with $M \sim 10^{13}$ GeV.
LEPTOGENESIS IN THE 3G2HDM

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

$$n_L/s = \varepsilon_{N_i} Y_{N_i} (T \gg M_{N_i}) \eta,$$  \hspace{1cm} (11)

where $Y_{N_i} (T \gg M_{N_i}) = 135 \xi (3)/(4 \pi^4 g_*)$ 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 sphaleron processes: In our case (i.e., two scalar doublets) we obtain:

$$n_B/s \sim -1.4 \times 10^{-3} \varepsilon_{N_i} \eta.$$ \hspace{1cm} (12)

As seen from Eq. 10, 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., $\varepsilon_{N_i} \rightarrow \varepsilon_{N_1}$ and we get:

$$\varepsilon_{N_1} \sim -\frac{3}{16\pi} \frac{t_\beta^2 \sqrt{\Delta m^2_{solar}}}{m^2_t} \epsilon M_{N_1} \sin 2(\theta_b - \theta_a) \sim -\varepsilon_{N_1}^{\text{max}} \times \frac{2\epsilon}{\omega} t_\beta^2 \sin 2(\theta_b - \theta_a),$$ \hspace{1cm} (13)

where the CP-phases arise from the possible complex entries in $Y^\nu$: $a = |a|e^{i\theta_a}$ and $b = |b|e^{i\theta_b}$, and $\varepsilon_{N_1}^{\text{max}}$ is the maximum of the CP-asymmetry in models where only one Higgs doublet couples to the neutrino fields (see e.g., [3]). Thus, the CP-asymmetry in the 3g2HDM is a factor of $\sim \frac{2\epsilon}{\omega} t_\beta^2 \sim 20$ larger than the CP-asymmetry in the SM or the in MSSM, since in our model $\epsilon \sim 0.5$ and $\omega \sim 5$ are fixed by oscillation data and $t_\beta \sim O(10)$ in order to account for the large top-quark mass.

For the Baryon asymmetry we then obtain (by calculating the washout factor $\eta$ and using Eq. [12]):

$$\frac{n_B}{s} \sim 10^{-17} \tan^2 \beta \frac{\sqrt{\Delta m^2_{solar}}}{2m^2_t} \epsilon M_{N_1} \left( \frac{M_{N_1}}{\text{GeV}} \right)^{1.2} \sin 2(\theta_b - \theta_a).$$ \hspace{1cm} (14)

Eq. 14 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 $\Delta m^2_{solar} \sim 8.2 \cdot 10^{-5}$ eV$^2$ (these values are consistent with the observed oscillation data), along with $t_\beta \sim 10$ and $m_t \sim 170$ GeV, Eq. [14] 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 $M_{N_1} \sim 10^9$ if CP is maximally violated in the sense that $\sin 2(\theta_b - \theta_a) \sim 1$.

REFERENCES

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