Neutrino Masses and Leptogenesis in a $L_e - L_\mu - L_\tau$ model

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Abstract. We present a simple extension of the Standard Model with three right-handed neutrinos in a SUSY framework, with an additional $\mathrm{U(1)_F}$ abelian flavor symmetry with a non standard leptonic charge for lepton doublets and arbitrary right-handed charges. We show how it is possible to provide the correct predictions for the mixing angles of the PMNS matrix and for the $r = \Delta m^2_{\mathrm{sun}}/\Delta m^2_{\mathrm{atm}}$ parameter with a moderate fine tuning. The baryon asymmetry of the Universe is generated via thermal leptogenesis through CP-violating decays of the heavy right-handed neutrinos. We present a detailed numerical solution of the relevant Boltzmann equation accounting for the impact of the distribution of the asymmetry in the lepton flavors.

1. Introduction

In order to reproduce the experimental form of the U_{PMNS} reported in [1], we propose a SUSY model based on a broken $\mathrm{U(1)_F}$ flavor symmetry with charge $L_e - L_\mu - L_\tau$ for lepton doublets and arbitrary charges for the right-handed SU(2) singlet fields, in a similar spirit as e.g. [2]. We propose both a dimension 5 and a concrete seesaw realization. In the latter case, we solve the semi-classical Boltzmann Equations to test the possibility of viable leptogenesis.

2. Low energy model building

First of all we work in the limit of exact SUSY, so that the form of the Lagrangian we will consider is simplified. Moreover we choose to treat neutrinos as Majorana particles. Furthermore, since in the case of exact $\mathrm{U(1)_F}$ the neutrino phenomenology is not reproduced [3], we decided to introduce two complex scalar fields Φ and Θ, called *flavons*, which are associated with the breaking of the Froggatt-Nielsen symmetry. The idea is that above some high energy scale M_F, there is an unbroken flavor symmetry $\mathrm{U(1)_F}$ and both the SM fermions and the two flavons are charged under this Abelian symmetry. At suitable energy scale the symmetry is broken by the vev of the flavons. Below this energy scale, we can integrate them out and write the following non-renormalizable effective lagrangian:

$$\mathcal{L}_{\mathrm{eff}} = \frac{x_{ij}}{\Lambda} l_i l_j \left(\frac{\langle\Theta\rangle}{M_F}\right)^{\alpha_{ij}} \left(\frac{\langle\Phi\rangle}{M_F}\right)^{\beta_{ij}} H_u H_u + a_{ij} l_i l^c_j \left(\frac{\langle\Theta\rangle}{M_F}\right)^{\rho_{ij}} \left(\frac{\langle\Phi\rangle}{M_F}\right)^{\sigma_{ij}} H_d. \quad (1)$$

Here Λ is a large mass scale, l_i represents the three families of SU(2) lepton doublets, l^c_j represents the three right-handed charged leptons, $H_{u,d}$ are the uncharged Higgs fields while x_{ij} and a_{ij} are

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generic $O(1)$ coefficients; also α_{ij}, β_{ij}, ρ_{ij} and σ_{ij} are integer numbers chosen such that $\mathcal{L}_{\rm eff}$ is $\mathrm{U(1)_F}$ invariant. After the spontaneous symmetry breaking the entries of the mass matrices are expressed in terms of the ratio of the flavon vacuum expectation value and the heavy mass scale (M_F), *i.e.* $\lambda \equiv \langle\Theta\rangle / M_F = \langle\Phi\rangle / M_F$. This is the symmetry breaking parameter, which is a free parameter in our model, that we fix to $\lambda = 0.22$. With this choice, and with the following set of charge assignments:

	l_e	l_μ	l_τ	l_e^c	l_μ^c	l_τ^c	Θ	Φ
$\mathrm{U(1)_F}$	$+1$	-1	-1	-13	7	3	$+2$	-2

the neutrino m_ν and the charged lepton m_l mass matrices are as follows:

$$m_\nu = m_0 \begin{pmatrix} x_1\lambda & 1 & x \\ 1 & x_2\lambda & x_3\lambda \\ x & x_3\lambda & x_4\lambda \end{pmatrix}, \qquad m_l = m_\tau \begin{pmatrix} \lambda^5 & \lambda^3 & \lambda \\ \lambda^6 & \lambda^2 \mathrm{e}^{i\phi_{22}} & \mathrm{e}^{i\phi_{23}} \\ \lambda^6 & \lambda^2 \mathrm{e}^{i\phi_{32}} & 1 \end{pmatrix}. \tag{2}$$

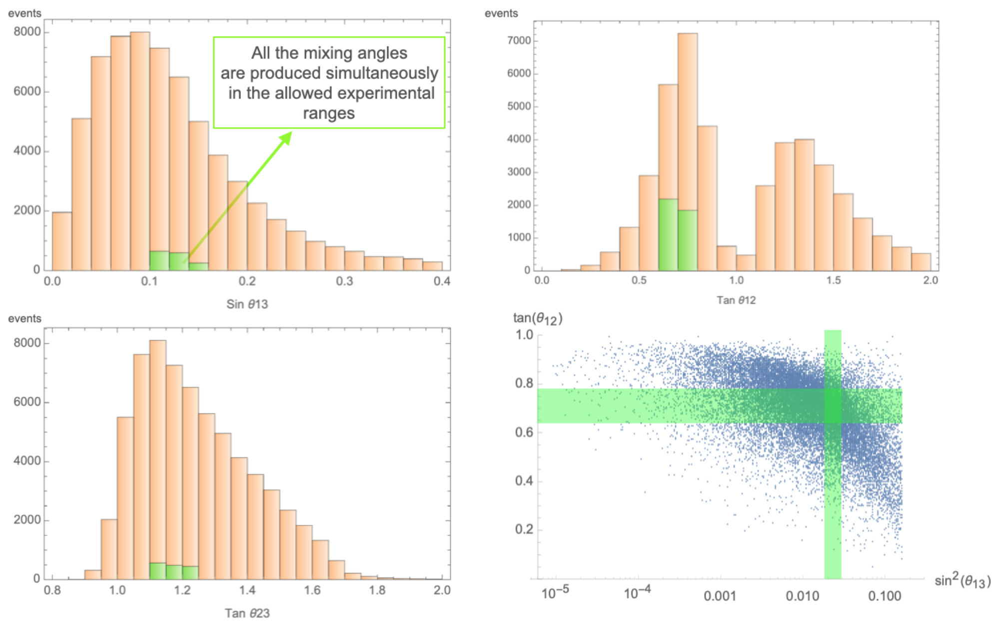

Figure 1: *The distributions for the three mixing angles are reported. The 2D scatter plot shows the correlation between θ_{12} and θ_{13}. The green points represent the realizations in which all the three angles are produced simultaneously in the right experimental ranges at 3σ [1].*

In m_ν the $O(1)$ coefficients are normalized on x_{12} and $m_0 = (x_{12}v^2)/\Lambda$. Also in m_l only few phases are explicitly shown, since the others would contribute to the phenomenology with terms suppressed by higher orders in λ. The charged lepton mass hierarchy is predicted in the allowed experimental range, *i.e.* $m_e : m_\mu : m_\tau = \lambda^5 : \lambda^2 : 1$, as well as the parameter r (after a moderate fine tuning in the neutrino mass matrix) and the three mixing angles. Indeed, after diagonalizing the lepton mass matrices, we can build the mixing matrices U_L and U_ν and, identifying the product $U_L^\dagger U_\nu$ with the PMNS matrix through the procedure in [4], we find the distributions reported in fig.(1). In green we have highlighted those realizations such that all three mixing angles are reproduced simultaneously in the allowed experimental ranges. But what about the $\delta_{\rm cp}$ phase?

It turns out that, if we fix the model parameters to reproduce the observed lepton phenomenology, the obtained $\delta_{\rm cp}$ distribution does not present points falling within the expected ranges, as shown in fig.(2), meaning that the model is predominantly CP-conserving.

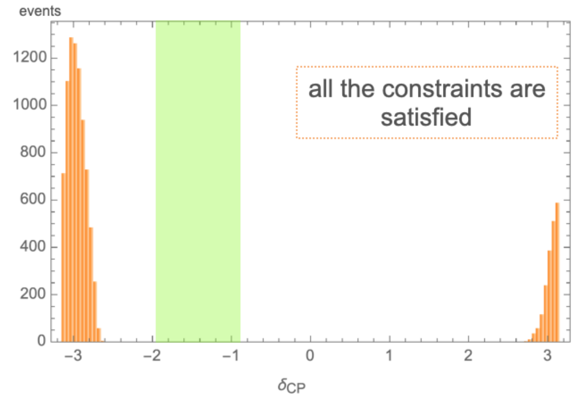

Figure 2: *δ_{cp} distribution, assuming all the three mixing angles simultaneously predicted in the allowed experimental range at 1σ [1]. The green band represents the allowed experimental range at 1σ [1].*

3. Type-I seesaw realization

We provided a simple type-I seesaw realization of the model introducing three right-handed neutrinos, total singlets under the Standard Model and charged under the additional $\mathrm{U}(1)_\mathrm{F}$ symmetry, with charges $N_\mathrm{R} \sim (-1,+1,0)$. We also introduced other two *flavons* Δ and Υ with charges $\pm 1/2$ respectively. These complex scalar fields contribute to the lepton mass matrices, but with operators suppressed by higher orders in λ, so that these additional fields do no change the previous discussion; on the other hand, they are essential to obtain the Dirac (m_D) and Majorana (M_R) mass matrices that assume the following structure:

$$m_\mathrm{D} = v \begin{pmatrix} \lambda e^{i\alpha} & a e^{i\beta} & b e^{i\gamma} \\ c e^{i\delta} & \lambda e^{i\rho} & \lambda e^{i\sigma} \\ \lambda^2 e^{i\zeta} & \lambda^2 e^{i\eta} & \lambda^2 e^{i\psi} \end{pmatrix}, \qquad M_\mathrm{R} = \mathcal{M} \begin{pmatrix} \lambda & W & \lambda^2 \\ W & \lambda & \lambda^2 \\ \lambda^2 & \lambda^2 & Z \end{pmatrix}, \tag{3}$$

with $\mathcal{M}$ being the heavy mass scale of the sterile neutrinos. Through the type-I seesaw master formula $m_\nu = -m_\mathrm{D}^T M_\mathrm{R}^{-1} m_\mathrm{D}$, we can reproduce the light neutrino mass matrix studied at low energies, at the price of a moderate fine tuning among the model parameters. Also, the seesaw mechanism gives the possibility to study the interesting scenario of the thermal leptogenesis [6]. Indeed, the seesaw mechanism requires that lepton number is violated, which produces a baryon number violation via the *sphalerons* processes; in addition it provides in general new CP-violating phases in the neutrino Yukawa interactions and, in a large part of the parameter space, predicts that new heavy singlet neutrinos decay out of equilibrium. Thus, all the three Sakharov conditions are naturally fulfilled in this scenario. One of the most popular scenario, which this work focuses on, is the "thermal leptogenesis", with hierarchical sterile neutrinos, produced by scattering in the thermal bath. In fact, assuming the heavy mass scale $\mathcal{M} \sim 10^{12}$ GeV, our model predicts the lighter right-handed neutrino with mass $M_3 \simeq 10^{12}$ GeV, and two heavier neutrinos with degenerate masses $M_1 = M_2 \simeq 10^{15}$ GeV, close to the GUT scale. Therefore we can assume that only the lighter neutrino is relevant for the leptogenesis. In our case the *two fully flavored regime* applies, meaning that the lepton state describing the lepton produced in the decay of the sterile neutrino can be seen as an incoherent mixture of $|\tau\rangle$ and $|e+\mu\rangle$ components. So the problem of finding the total baryon asymmetry reduces to a case of two flavors, the lepton l_τ, and the non-τ component $l_{\tau_\perp}$. The relevant Boltzmann Equations for the third neutrino number density (Υ_3) and for the $B-L$ asymmetry (Υ^{B-L}) (both normalized to entropy s), may be written as:

$$\begin{aligned} \frac{d\Upsilon_3}{dz} &= -\left(D(z) - S(z)\right)(\Upsilon_3 - \Upsilon_3^{eq}) \\ \frac{d\Upsilon^{B-L}_{\alpha\alpha}}{dz} &= \epsilon^{(3)}_{\alpha\alpha} D(z)(\Upsilon_3 - \Upsilon_3^{eq}) - p^{(0)}_{3\alpha}(W(z) + \Delta W)\Upsilon^{B-L}_{\alpha\alpha} \quad \text{with } \alpha = \tau, \tau_\perp \end{aligned} \tag{4}$$

where $z = M_3/T$. We take into account the decays and inverse decays with the D and W terms, the $\Delta L = 1$ scattering processes are described by the S term, while ΔW refers to the $\Delta L = 2$

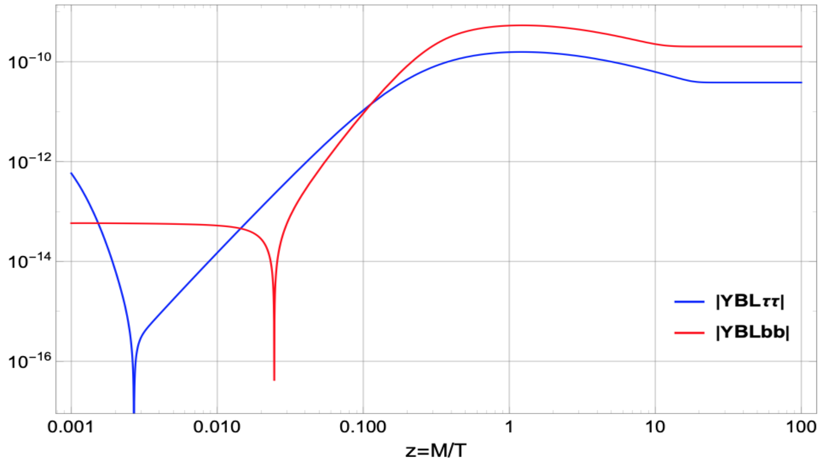

Figure 3: *The evolution of the $B-L$ asymmetry of the Universe is reported.*

scatterings processes. Here $\epsilon_{\alpha\alpha}$ stands for the CP-violation parameter in the $\alpha = \tau, \tau_\perp$ component, and the coefficients $p_{3\alpha}$ are the projection probabilities between the mass and flavor states. A detailed analysis of eq.(4) can be found in [5]. The final evolution of the $B-L$ asymmetry in the Universe is depicted in fig.(3). The final baryon-to-photon number ratio is related to the final $B-L$ asymmetry by the parameter $a_{\rm sph} = 28/79$, which is the sphaleron factor in the Standard Model [6]. The benchmark assignations of the model parameters adopted for the figure corresponds to a value $\eta_B = 6.01 \times 10^{-10}$, very close to the latest fit $6.11 \leq \eta_B \times 10^{10} \leq 6.16$ at 1σ in [7]. We are then confident that regions of the parameter space consistent with the correct baryon asymmetry exist in our model.

4. Conclusions

Our model, with hierarchical sterile neutrinos, seems to be able to reproduce the expected amount of baryonic asymmetry in the Universe, as well as the three mixing angles values and the neutrino mass hierarchy. However the CP-violation is strongly suppressed so that this model is essentially CP-conserving.

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