Neutrino Masses, the Baryon Asymmetry and Dark Matter from a Global U(1) symmetry

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Abstract. We present a U(1) extension of the standard model that accounts after breaking for the small neutrino masses and the observed dark matter abundance. From the presence of the dark matter candidate, an original scenario of leptogenesis emerges, viable in a restricted region of the parameter-space. Relying on a rich scalar sector, this model can deviate from standard model Higgs phenomenology.

The present letter summarizes the model proposed in [1] and its variant discussed in [2]. Three issues of particle physics left unexplained in the Standard Model (SM) are there addressed:

- the smallness of neutrino masses are explained within a seesaw extension of the SM, with both linear and inverse seesaw contributions.
- The Dark Matter (DM) fraction $\Omega_{DM} = 0.2408_{-0.0092}^{+0.0093}$ [3] find its origin in the relic abundance of a scalar field $S$.
- The Baryon Asymmetry of the Universe (BAU) $\Omega_{BAU} = 0.0472 \pm 0.0010$ [3] can be explained by a variant of leptogenesis.

1. The Model
The matter content of the model is given in Table 1 (SM quarks and gauge boson aside). A global U(1)$_X$ symmetry is imposed to the Lagrangian, the SM particles having a $X$ charge equal to their B-L one. The SM Higgs boson $H_1$ is singlet under the new symmetry, and only triggers electroweak-symmetry breaking, via a non-zero vacuum expectation value (vev) $\langle H_1^0 \rangle = v_1/\sqrt{2}$. An additional scalar doublet $H_2$ is introduced: given its non-zero $X$ charge, $H_2$ does not couple to SM fermions, but to neutrinos via an additional Yukawa coupling. The complex singlet $\phi$ has also a non-zero $X$ charge: $H_2$ and $\phi$ jointly break U(1)$_X$ via non-zero vevs $\langle H_2^0 \rangle = v_2/\sqrt{2}$ and $\langle \phi \rangle = v_\phi/\sqrt{2}$. Both particles are required to explain the small neutrino masses. Three
right-handed fermions are introduced: \( N_1 \) and \( N_2 \) singlet [1] or triplet [2] under \( SU(2) \) and with opposite X charge \( \mp 1 \), while \( N_3 \) is a Majorana particle. Finally, a scalar particle \( S \) complete the spectrum, with \( SU(2) \times U(1)_X \) charge equal to that of \( N_1 \); \( S \) is the DM candidate. We first discuss how the small neutrino masses are accounted for.

2. Neutrino Masses

For convenience, a Dirac fermion is build upon \( N_1 \) and \( N_2 \): \( N_D \equiv \operatorname{PR} N_1 + P_L N_2^C \); \( N_D \) has X charge +1. The part of the Lagrangian density involving \( \delta \) inverse-seesaw limit, pseudo-Dirac fermions, with mass \( m_N^2 \).

\[
\mathcal{L} \supset - \left( Y_{\nu 1}^\alpha \overline{N_D} \tilde{H}_1 \gamma^j (T_2^\alpha)^{jk} \ell_j^\beta + Y_{\nu 2}^\gamma \overline{N_D} \tilde{H}_2 \gamma^i (T_2^\gamma)^{ik} \ell_j^\gamma + \frac{\delta N}{\sqrt{2}} \phi \overline{N_D} N_D^C + \text{H.c.} \right)
- m_N \overline{N_D} N_D^C - \frac{1}{2} M_3 \overline{N_D} N_3^C
\]

where we assume \( N_{1,2} \) and \( S \) triplet of \( SU(2) \). in the limit \( \delta N \) \( \propto v \) term acts as a linear seesaw. In our framework its suppression originates from the small ratio \( |\nu_{2i}/m_N^2| \). This latter suppression is naturally obtained via a seesaw limit, where we assume \( \delta N v_\phi \ll m_N \). In the limit \( \delta N v_\phi \ll m_N \), the second term in eq. (2) is an inverse-seesaw contribution [6]. In this regime, \( N_1 \) and \( N_2 \) combine to form two quasi-degenerate Majorana fermion, or so called pseudo-Dirac fermions, with mass \( m_N \pm \delta N v_\phi \). With the particle content of Table 1, two non-zero light neutrino masses are generated, sufficient comply with current observations. In the inverse seesaw limit, \( \delta N v_\phi \ll m_N \), these masses can be approximated by

\[
m_\nu^\pm \simeq \frac{v_1 v_2}{m_N} |y_1| |y_2| (1 \pm |\cos (\theta_{12})|)
\]

with \( \theta_{12} \) the angle between \( y_1 \) and \( y_2 \): if aligned, only one light neutrino is massive, in contradiction with observations. Their fit implies

\[
|y_1| |y_2| \simeq \left( \frac{3.4}{5.6} \right) \times 10^{-8} \left( \frac{m_N}{1 \text{TeV}} \right) \left( \frac{v_2}{10 \text{MeV}} \right)^{-1} \left| \cos (\theta_{12}) \right| \simeq \left( \frac{0.93}{0.87} \right)
\]

in the normal / inverse hierarchy cases. For our later purpose, only the strength of the Yukawa couplings matter as we did not consider flavour effects, and so we enforce the first relation quoted above.

3. Baryon Asymmetry Generation

We assume that the breaking of the global \( U(1)_X \) symmetry occurs together with the breaking of the electroweak symmetry. Therefore, as long as sphalerons are active, \( U(1)_X \) is conserved, and no lepton asymmetry can be generated via \( N_1 \) or \( N_2 \) decays. To remedy this, we introduce a third
right handed neutrino, but of a very different nature than $N_{1,2}$: $N_3$ is assumed to be a Majorana fermion. It does not couple directly to leptons, but to $N_D$ via a Yukawa coupling involving the scalar $S$, our DM candidate. A two-steps leptogenesis is then possible: during $N_3$ decays, asymmetries in $N_D$ (and $S$) are produced, i.e. $N_1$ and $N_2$ are produced in different amounts. This step is similar to the standard thermal leptogenesis, with competitive depletion effects and other spectator processes that influence their production. While being asymmetrically produced, $N_1$, $N_2$ interacts with SM leptons, via X-conserving scatterings or decays. The net $N_1 - N_2$ number is then reprocessed into a net lepton number. During this stage as well, spectator processes influence the efficiency of this asymmetry transfer.

We stated that this leptogenesis scenario was only possible thanks to the addition of $S$: this is obvious when looking at the diagram responsible for $CP$-violation in $N_3$ decays, shown in figure 1. The $CP$ asymmetry generated in these decays linearly depends on the parameter $\delta_N$, which appears in the neutrino mass matrix eq.(2). In the inverse seesaw limit, $\delta_N$ only provides a subdominant contribution to light neutrino masses, so the $CP$-asymmetry and neutrino masses are decorrelated. The constraints on the couplings a successful leptogenesis imposes depend on whether $N_{1,2}$ are singlet or triplet of SU(2). Indeed, in the latter case additional gauge boson scatterings are present, reducing the efficiency of the first stage of asymmetry production: smaller couplings are required.

In [1] and [2], we mainly focus on the possibility of low-energy realization of this leptogenesis mechanism. In the singlet case, fermion masses $m_N \sim$ few 100 GeV are allowed without demanding large suppression of the couplings. The case of light fermion triplets requires stronger tuning, as illustrated in Figure 2. The baryon asymmetry resulting from leptogenesis is shown, in function of a degeneracy parameter $1 - (\mu_S + m_N)/M_3$ and of $m_N$ (left plot), or in function of the parameters $\mu''$ and $\delta_N$ (right plot) which both control the amount of $CP$ violation in $N_3$ decays and the strength of depletion effects. In the low mass regime, couplings of $\sim 10^{-6}$ are typically required, together with a certain tuning among $N_3$, $N_{1,2}$ and $S$ masses. Larger masses relax these constraints. Although a systematic study was not conducted, an approximate lower bound of $m_N \sim 1.5$ TeV on the triplet fermion mass was found: if neutrino masses are explained via eq.(1), the observation of $N_{1,2}$ at LHC would rule-out this leptogenesis mechanism as an explanation of the observed BAU.

4. An Extended Higgs Sector
The model contains 2 scalar doublet $H_{1,2}$ and a complex singlet $\phi$ with quantum numbers given in Table 1, responsible of the symmetry breaking $SU(2) \times U(1)_Y \times [U(1)_X] \rightarrow U(1)_{em} \times [Z_2]$. The scalar potential reads

$$V_{SB} = -\mu_1^2 (H_1^\dagger H_1) + \lambda_1 (H_1^\dagger H_1)^2 - \mu_2^2 (H_2^\dagger H_2) + \lambda_2 (H_2^\dagger H_2)^2 - \mu_3^2 \phi^* \phi + \lambda_3 (\phi^* \phi)^2$$
shown in the right plot of Figure 3, where the ratio $\Gamma(h\rightarrow\gamma\gamma)/\Gamma(h\rightarrow\gamma\gamma)_{SM}$ is plotted against $m_h$, where the $\text{BR}(h\rightarrow\gamma\gamma)$ manifests itself in a possible enhancement of the diphoton decay channel, cf e.g. [8], as shown in the right plot of Figure 3, where the ratio $\Gamma(h\rightarrow\gamma\gamma)/\Gamma(h\rightarrow\gamma\gamma)_{SM}$ is plotted against

$\mu/\sqrt{2} \left( (H_1^\dagger H_2)\phi + (H_2^\dagger H_1)\phi^* \right)$.  

The last term of eq.(5) deserves some attention. Minimization of $V_{SB}$ enforces at tree-level three relations

$$\frac{\partial V_{SB}}{\partial v_1} = 0 \leftrightarrow -\mu_2^2 v_i + \frac{v_2}{2} \left( v_2^2 \tilde{\kappa}_{ij} + v_2^2 \tilde{\kappa}_{ik} \right) + 2 v_1^3 \lambda_i = \frac{v_j v_k \mu'}{2}, \quad i,j,k = 1,2,\phi,  \quad (6)$$

with $\tilde{\kappa}_{12} = \kappa_{12} + \kappa'_{12}$ and $\tilde{\kappa}_{ij} = \kappa_{ij}$ otherwise. As noted in [4] or [5], this term acts as a pivot for a seesaw among the Higgs vevs, yielding $v_2 \ll v_{1,\phi}$ (eq. [2]) granted $\mu' \ll v_{1,\phi}$ (eq. [2]). In [4], the scalar $\phi$ being absent, the $\mu'$ term was introduced as a soft breaking term of the global $U(1)_X$. Here the breaking is spontaneous, therefore a Goldstone boson, the Majoron, remains massless after $U(1)_X$ breaking. Its couplings to SM fermions impose the vev hierarchy $v_2 \ll v_{1,\phi}$. Therefore, SM gauge boson masses receive a negligible contribution from $H_2$ doublet and $v_1 \simeq 174 \text{ GeV}$. The physical spectrum is rich, with a charged scalar $H^\pm$, 3 neutral $CP$-even scalars $h^0$, $H^0$ and $h_A$, plus 2 neutral $CP$-odd scalars $A^0$ and $J$ the massless Goldstone boson.

With the vev hierarchy $v_2 \ll v_{1,\phi}$, only $\text{Re}(H_1^0)$ and $\text{Re}(\phi)$ can significantly mix: $H_1$ being the SM Higgs doublet, departure from SM Higgs observations can be expected. Besides from this mixing, we have additional charged particles that can modify Higgs observations.

Assuming $h^0$ is the new particle observed at LHC, we verify in [2] how our model can accommodate LHC data, and if deviations from SM are indeed observed. We construct the Higgs signal strengths, and fit LHC data. The scalar $H^0$ have similar signature that $h^0$, so we impose LHC exclusion constraints over the full $H^0$ spectrum, assuming $m_{h^0} \simeq 126 \text{ GeV} < m_{H^0} \leq 600 \text{ GeV}$. The main results are presented in Figure 3. In the limit of a negligible $H_1^\dagger\phi$ mixing, $h^0 \sim \text{Re}(H_1^0)$ so tree-level $h^0$ decays tend to their SM width. In the opposite case, $h^0$ invisible decays become sizeable, and possibly larger than SM Higgs width (however quite small, $\Gamma_{h^0}^{\text{inv}} \simeq 4.2 \text{ MeV}$ [7] for $m_h \sim 126 \text{ GeV}$), as illustrated in the left plot of Figure 3, where $h^0$ width is compared with the SM Higgs width as a function of the invisible branching ratio of $h^0$ decaying to Majoron $\text{BR}(h^0 \rightarrow J^0 J^0)$. The presence of a charged scalar manifests itself in a possible enhancement of the diphoton decay channel, cf e.g. [8], as shown in the right plot of Figure 3, where the ratio $\Gamma(h^0 \rightarrow \gamma\gamma)/\Gamma(h \rightarrow \gamma\gamma)_{SM}$ is plotted against

Figure 2. Left: Baryon asymmetry $Y_B$ as function of the degree of degeneracy between $M_3$ and $\mu_S + m_N$ and $m_N$ mass (see the main text). Right: variation of $Y_B$ in terms of the parameters $\mu'$ and $\delta_N$, for fixed $M_3$, $\mu_S$ and $m_N$. 

\[ + \kappa_{12} (H_1^\dagger H_1) (H_2^\dagger H_2) + \kappa_{12} (H_1^\dagger H_2) (H_2^\dagger H_1) + \kappa_{13} (H_1^\dagger H_1) \phi^* \phi + \kappa_{23} (H_1^\dagger H_2) \phi^* \phi \]

\[ - \frac{\mu'}{\sqrt{2}} \left( (H_1^\dagger H_2) \phi + (H_2^\dagger H_1) \phi^* \right). \]
**Figure 3.** Left: Total $h^0$ decay width normalized to the SM case as a function of the invisible branching ratio. Right: Ratio $\Gamma(h^0 \rightarrow \gamma\gamma)$ to the SM rate in function of the charged Higgs mass $m_{H^\pm}$. In both cases, the points are the results of our scan, the shaded dark red region corresponds to the 95% C.L. range of the global fit, while the green area stands for observables within (below) their respective 95% C.L. bounds (upper bound).

$m_{H^\pm}$. This ratio also depends on the trilinear coupling $h^0-H^+/H^-$ which is scanned over in this plot, but obviously the heavier $H^\pm$, the more suppressed its contribution to the loop.

### 5. Scalar Dark Matter

Our model also contains a Dark Matter candidate, the scalar $S$. We stated before that the presence of $S$ is mandatory for our leptogenesis mechanism, and that $S$ should have the same quantum numbers (but the spin) than $N_{1,2}$: $S$ is then a stable particle, being odd under the remnant $Z_2$.

The question is thus if its relic abundance can match current observations. The singlet case has been widely studied in the literature, cf. e.g.\cite{9}; the DM relic abundance is fixed by the freeze-out of DM annihilations that proceed through quartic couplings to the SM Higgs. In our model, having several Higgs, many annihilation channels are possible, and in particular $S$ annihilations to pairs of Majoron typically dominate at low $S$ mass. Annihilations through portal couplings are also present in the triplet case, which however contains irreducible and very efficient channels with $S$ annihilating to or via gauge boson \cite{10,11}. Our model contains a complex triplet $S$, viable DM candidate for mass $m_S \geq 1290$ GeV.

### 6. Summary

The smallness of neutrino masses explained via see-saw mechanism, appealingly points towards leptogenesis scenario for the observed BAU. In \cite{1}-\cite{2}, neutrino masses are explained via linear see-saw contribution, whose suppression originates from a see-saw among Higgs vevs, plus an inverse see-saw contribution, however sub-dominant by construction. A global symmetry is imposed to the Lagrangian above electroweak symmetry breaking to justify the various contribution, but this in turn calls for a variant of the standard leptogenesis mechanism. Such a variant is made possible by the introduction of a scalar particle, our Dark Matter candidate. Our model succeeds to account for neutrino masses, BAU and DM densities, although some tuning are required in the low-mass leptogenesis realizations.
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