RESONANT LEPTOGENESIS IN MINIMAL U$(1)_X$ EXTENSIONS OF THE STANDARD MODEL*

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Received 28 March 2025, accepted 29 September 2025, published online 19 December 2025

We investigate a general U$(1)_X$ scenario where we introduce three generations of Standard Model (SM) singlet right-handed neutrinos (RHNs) to generate the light neutrino mass through the seesaw mechanism after the breaking of U$(1)_X$ and electroweak symmetries. In addition to that, a general U$(1)_X$ scenario involves an SM-singlet scalar field and due to the U$(1)_X$ symmetry breaking, the mass of a neutral beyond the SM (BSM) gauge boson Z' is evolved. The RHNs, being charged under the U$(1)_X$ scenario, can explain the origin of the observed baryon asymmetry through the resonant leptogenesis process. Applying observed neutrino oscillation data, we study Z' and BSM scalar-induced processes to reproduce the observed baryon asymmetry. Hence, we estimate bounds on the U$(1)_X$ gauge coupling and the mass of the Z' for different U$(1)_X$ charges and benchmark masses of RHN and SM-singlet scalar. Finally, we compare our results with limits obtained from the existing limits from LEP-II and LHC.

DOI:10.5506/APhysPolBSupp.18.6-A25

1. Introduction

The origin of the baryon asymmetry in the present Universe is one of the big mysteries in cosmology. The WMAP satellite [1] observed that the ratio of the baryon minus anti-baryon density ($n_{B-\bar{B}}$) over the entropy density of the Universe (s) is $Y_B = 8.7 \times 10^{-11}$ at an accuracy of 10% precision level. A strong first-order phase transition could be required to explain the origin of baryon (B) asymmetry induced by the electroweak baryogenesis [2] within the Standard Model (SM) framework, however, the observation of the SM Higgs mass around 125 GeV [3, 4] does not indicate such a phenomenon. As a result, electroweak baryogenesis is possibly ruled out in the SM scenario.

* Presented at the V4-HEP 4 — Theory and Experiment in High Energy Physics Workshop, Warsaw, Poland, 28–31 October, 2024.

The baryon asymmetry of the Universe could be established by the see-saw scenario by an attractive possibility called leptogenesis [5]. The out-of-equilibrium decay of the Majorana-type right-handed neutrinos (RHNs) can generate lepton asymmetry in the Universe which can be converted into baryon asymmetry through the sphaleron transition violating $(B+L)$ quantum number [6, 7]. In this context, we mention that thermal leptogenesis imparts a lower bound on the Majorana neutrinos (M_N) to generate sufficient amount of baryon asymmetry as $M_N > 10^{10}$ GeV [8]. Such heavy Majorana neutrinos cannot be observed at the hadron and lepton colliders.

The $\mathrm{U}(1)_X$ scenarios considered in this paper are at the TeV scale prohibiting thermal leptogenesis from occuring. The CP asymmetry parameter in this case is proportional to the square of the Dirac Yukawa coupling (Y_D) between the RHNs and the SM lepton doublet. Due to the smallness of Y_D, the right amount of baryon asymmetry of the Universe cannot be generated. It has also been found that if two RHNs are almost degenerate in masses, an enhancement [9] of the CP asymmetry parameter can take place making the leptogenesis scenario viable for the TeV scale RHNs. This is called resonant leptogenesis [10]. In this case, the maximum attainable enhancement could be achieved if the mass difference between the two generations of the RHNs is $(\mathcal{O}(\mathit{\Gamma}_{N_i}))$, with the total decay width $(\mathit{\Gamma}_{N_i})$ of either of the generations of the RHNs (N_i). Hence, in principle, by tuning the mass difference between any two generations of the RHNs, the CP asymmetry parameters (ϵ_i) could be attained around $\mathcal{O}(1)$, however, in the presence of $\mathrm{U}(1)_X$ extension, the lepton asymmetry through RHN decay is suppressed due to the interaction with the TeV scale Z' gauge boson. As a result, such a scenario makes the generation of the CP asymmetry of the Universe non-trivial [11].

2. $\mathrm{U}(1)_X$ extensions of Standard Model

The $\mathrm{U}(1)_X$ extensions of the SM involve an SM-singlet scalar $\mathit{\Phi}$ and three generations of the SM-singlet RHNs. Apart from participating in the neutrino mass generation mechanism, the RHNs also help to cancel gauge and mixed gauge–gravity anomalies. We write the Yukawa interactions respecting the $\mathcal{G}_{\mathrm{SM}}\otimes \mathrm{U}(1)_X$ gauge symmetry as

$$\begin{aligned}\mathcal{L}^{\mathrm{Yukawa}} &= -Y_u^{\alpha\beta}\,\overline{q_{\mathrm{L}}^{\alpha}}\,H u_{\mathrm{R}}^{\beta} - Y_d^{\alpha\beta}\,\overline{q_{\mathrm{L}}^{\alpha}}\,\tilde{H} d_{\mathrm{R}}^{\beta} - Y_e^{\alpha\beta}\,\overline{\ell_{\mathrm{L}}^{\alpha}}\,\tilde{H} e_{\mathrm{R}}^{\beta} - Y_D^{\alpha\beta}\,\overline{\ell_{\mathrm{L}}^{\alpha}}\,H N_{\mathrm{R}}^{\beta} \\ &\quad - Y_N^{\alpha}\mathit{\Phi}\,\overline{\left(N_{\mathrm{R}}^{\alpha}\right)^c}\,N_{\mathrm{R}}^{\alpha} + \mathrm{H.c.}\,, \qquad (1)\end{aligned}$$

where α, β are the generation indices indicating three generations of the fermions involved in the theory. Here, H is the SM Higgs doublet, and $\tilde{H} = i\tau^2 H^*$ with τ^2 being the second Pauli matrix. After the $\mathrm{U}(1)_X$ symmetry breaking, the last term becomes a Majorana mass term.

3. Leptogenesis

To obtain the baryon asymmetry in our Universe, we solve the Boltzmann equations. The Boltzmann equations that govern the yields of the RHNs, the singlet scalar, and the B–L number density are written as

$$\begin{aligned}
\frac{\mathrm{d}Y_{N_i}}{\mathrm{d}z} &= -\frac{z}{sH}\left[\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}}-1\right)\gamma_{D_i}+\left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_i}}\right]^2-1\right)\gamma_{Z'}\right.\\
&\quad\left.+\left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2-\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2\right)\left(\gamma_{Z',\Phi}+\gamma_{N,\Phi}\right)\right], \qquad (2)\\
\frac{\mathrm{d}Y_{\Phi}}{\mathrm{d}z} &= -\frac{z}{sH}\left[\sum_{i=1}^{2}\left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2-\left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2\right)\left(\gamma_{Z',\Phi}+\gamma_{N,\Phi}\right)\right.\\
&\quad\left.+\left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2-1\right)\gamma_{Z',h}\right], \qquad (3)\\
\frac{\mathrm{d}Y_{B-L}}{\mathrm{d}z} &= -\frac{z}{sH}\left[\sum_{i=1}^{2}\left(\frac{1}{2}\frac{Y_{B-L}}{Y^{eq}_{\ell}}+\epsilon_i\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}}-1\right)\right)\gamma_{D_i}\right.\\
&\quad\left.+\frac{Y_{B-L}}{Y^{eq}_{\ell}}\left(\sum_{i=1}^{2}\frac{Y_{N_i}}{Y^{eq}_{N_i}}\gamma_{h,s}\right)\right], \qquad (4)
\end{aligned}$$

where

$$\begin{aligned}
\epsilon_i &= -\sum_{j\neq i}\frac{m_{N_i}}{m_{N_j}}\frac{\Gamma_j}{m_{N_j}}\left(\frac{V_j}{2}+S_j\right)\frac{\mathrm{Im}\left[\left(y_D y_D^{\dagger}\right)^2_{ij}\right]}{\left(y_D y_D^{\dagger}\right)_{ii}\left(y_D y_D^{\dagger}\right)_{jj}}, \qquad (5)\\
V_j &= 2\frac{m^2_{N_j}}{m^2_{N_i}}\left[\left(1+\frac{m^2_{N_j}}{m^2_{N_i}}\right)\log\left(1+\frac{m^2_{N_i}}{m^2_{N_j}}\right)-1\right], \qquad (6)\\
S_j &= \frac{m^2_{N_j}\Delta M^2_{ij}}{\left(\Delta M^2_{ij}\right)^2+m^2_{N_i}\Gamma^2_j}, \qquad \Delta M^2_{ij}\equiv m^2_{N_j}-m^2_{N_i}, \qquad (7)
\end{aligned}$$

and γs are given by

$$\gamma_a=\frac{m_N}{64\pi^4 z}\int \mathrm{d}s\,\hat{\sigma}_a(s)\sqrt{s}K_1\left(\frac{z\sqrt{s}}{m_N}\right). \qquad (8)$$

$\hat{\sigma}_a$s are reduced cross sections listed in [12]. We discuss the CP asymmetry parameter, Eq. (5). We consider resonant leptogenesis and two Majorana masses are degenerated: $\Delta M_{12}^2 = m_{N_1}\Gamma_2$. We assume that the third generation of the RHN is a Dark Matter candidate and the rank of the neutrino mass matrix is two. In that case, the Dirac neutrino mass matrix can be written using the Casas–Ibarra parametrization [13]

$$m_D = U_{\rm MNS}^* \left(\begin{array}{ccc} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{array} \right) O \left(\begin{array}{ccc} \sqrt{m_{N_1}} & 0 & 0 \\ 0 & \sqrt{m_{N_2}} & 0 \\ 0 & 0 & \sqrt{m_{N_3}} \end{array} \right), \tag{9}$$

where

$$m_1 = 0\,, \quad m_2 = m_{2\rm NH}\,, \quad m_3 = m_{3\rm NH}\,, \quad O = \left(\begin{array}{ccc} 0 & 0 & 1 \\ \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \end{array} \right), \tag{10}$$

for the normal hierarchy (NH) case. α is a complex phase. In this case, the CP asymmetry parameter is given by observed values and a complex phase $\alpha = \alpha_r + i\alpha_i$

$$\begin{aligned} |\epsilon_1| &= \left| \frac{1}{2} \frac{\mathrm{Im}\left[\left(m_D m_D^\dagger\right)_{ij}^2\right]}{\left(m_D m_D^\dagger\right)_{ii}\left(m_D m_D^\dagger\right)_{jj}} \right| \\ &= \left| \frac{\left(m_{2\rm NH}^2 - m_{3\rm NH}^2\right)\sin(2\alpha_r)\sinh(2\alpha_i)}{(m_{2\rm NH}-m_{3\rm NH})^2\cos(2\alpha_r)^2 - (m_{2\rm NH}+m_{3\rm NH})^2\cosh(2\alpha_i)^2} \right| \\ &\leq \frac{m_{3\rm NH}-m_{2\rm NH}}{2(m_{3\rm NH}+m_{2\rm NH})} = 0.353\,, \end{aligned} \tag{11}$$

where $m_{2\rm NH} = 0.00861$ eV, $m_{3\rm NH} = 0.0502$ eV [14]. The equality of Eq. (11) holds when $\alpha = \pm\frac{\pi}{4} + \frac{i}{2}\log(1+\sqrt{2}\,)$. We use the maximum CP asymmetry parameter in this paper. The maximum value of the CP asymmetry parameter in the inverted hierarchy (IH) case is much smaller than in the NH case, therefore, we do not consider the IH case in this paper.

We discuss the contribution of the scalar boson. We assume that the scalar mixing is very small and neglect its effects. The scalar boson couples to the Z' boson and RHNs. For the Z' exchange process, the scalar boson is in thermal equilibrium and the decoupling temperature is similar to that of the RHNs. Therefore, the deviation of the scalar density from thermal equilibrium changes the baryon asymmetry in our Universe. Figure 1 shows the ratio of the B–L asymmetry with and without the scalar contribution. When the scalar mass is lighter than the Majorana mass, the scalar contribution becomes very large.

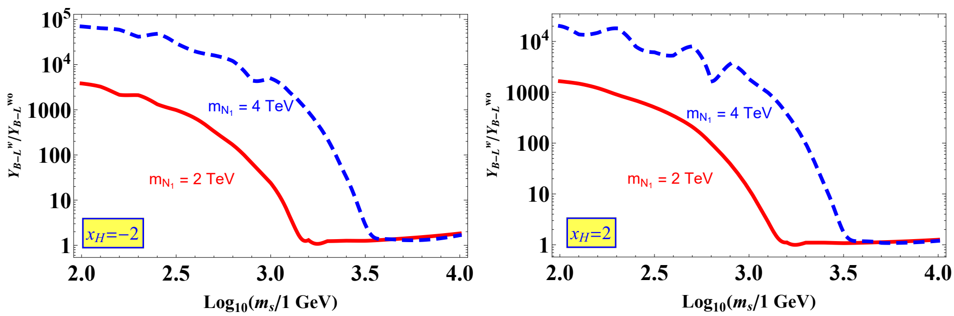

Fig. 1. The ratios of the B–L asymmetry with scalar contributions ($Y^{\rm w}_{B-L}$) and without the contribution ($Y^{\rm wo}_{B-L}$) as functions of the scalar mass. The red solid line represents $m_{N_1} = 2$ TeV and the blue dashed line represents $m_{N_1} = 4$ TeV. The U(1)$_X$ gauge coupling and Z' boson mass for different x_H fixing $g_X = 0.1$ and $M_{Z'} = 6$ TeV.

4. Collider

We estimate bounds on g_X for different $M_{Z'}$ from the LEP-II searches [15–17] for different x_H considering $M_{Z'} \gg \sqrt{s}$ utilizing the contact interaction for the $e^-e^+ \to f\bar{f}$ process as

$$\mathcal{L}_{\rm eff} = \frac{g_X^2}{(1+\delta_{ef})\left(\Lambda^{f\pm}_{AB}\right)^2} \sum_{A,B={\rm L,R}} \eta_{AB}(\bar{e}\gamma^\mu P_A e)\left(\bar{f}\gamma_\mu P_B f\right) , \tag{12}$$

where $\delta_{ef} = 1$ (0) for $f = e$ ($f \neq e$). Here, $\eta_{AB} = \pm 1$ or 0, and $\Lambda^{f\pm}_{AB}$ is assumed to be the scale of contact interaction where constructive (destructive) interference with the SM processes $e^+e^- \to f\bar{f}$ [18, 19] are represented by a plus (minus) sign. The Z' exchange matrix element under the U(1)$_X$ scenario can be written as

$$\frac{g_X^2}{{M_{Z'}}^2 - s}\left[\bar{e}\gamma^\mu(\tilde{x}_\ell P_{\rm L} + \tilde{x}_e P_{\rm R})e\right]\left[\bar{f}\gamma_\mu(\tilde{x}_{f_{\rm L}} P_{\rm L} + \tilde{x}_{f_{\rm R}} P_{\rm R})f\right] , \tag{13}$$

where $\tilde{x}_{f_{\rm L}}$ and $\tilde{x}_{f_{\rm R}}$ are the U(1)$_X$ charges of left-handed and right-handed fermions ($f_{\rm L}$, $f_{\rm R}$), respectively, from Table 1. We estimate bounds on

$M_{Z'}/g_X$ for different values of $\Lambda^{f\pm}_{AB}$ at 95% for different x_H from [17] assuming universality in the contact interactions where AB = LL, RR, LR, RL, VV, and AA. The estimated lines are shown in Fig. 2 for LEPII (red, solid), ILC250 (red, dotted), ILC500 (red, dashed), and ILC1000 (red, dot-dashed), respectively.

Table 1. Particle content of the $\mathrm{U}(1)_X$ extensions of the SM, where $i(=1,2,3)$ represents the family index. The quantity x_H is a real parameter.

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$
q^i_{L}	**3**	**2**	$\frac{1}{6}$	$\frac{1}{6}x_H+\frac{1}{3}$
u^i_{R}	**3**	**1**	$\frac{2}{3}$	$\frac{2}{3}x_H+\frac{1}{3}$
d^i_{R}	**3**	**1**	$-\frac{1}{3}$	$-\frac{1}{3}x_H+\frac{1}{3}$
ℓ^i_{L}	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H-1$
e^i_{R}	**1**	**1**	-1	$-x_H-1$
N_{R}	**1**	**1**	0	-1
H	**1**	**2**	$-\frac{1}{2}$	$-\frac{1}{2}x_H$
Φ	**1**	**1**	0	2

We calculate limits on the $g_X - M_{Z'}$ plane in the $\mathrm{U}(1)_X$ scenario for different x_H from the dilepton and dijet searches in ATLAS and CMS [20, 21] experiments of the LHC. The corresponding cross sections for these scenarios are estimated as σ_{model} involving the Z' contribution for different x_H from $\mathrm{U}(1)_X$ model considering a trial value of the general $\mathrm{U}(1)_X$ gauge coupling g_{model} at 13 TeV varying $M_{Z'}$. Comparing these estimated cross sections (σ_{model}) with the observed cross sections from the LHC (σ_{obs}) to estimate limits on the gauge coupling for different $M_{Z'}$ and x_H following

$$g_X = \sqrt{g^2_{\mathrm{model}}\left(\frac{\sigma_{\mathrm{obs}}}{\sigma_{\mathrm{model}}}\right)} \tag{14}$$

to estimate 95% constraints on the $g_X - M_{Z'}$ plane. The bounds on the g_X–$M_{Z'}$ plane are shown in Fig. 2. The dilepton bounds provide strong constraints for different x_H compared to the dijet bounds.

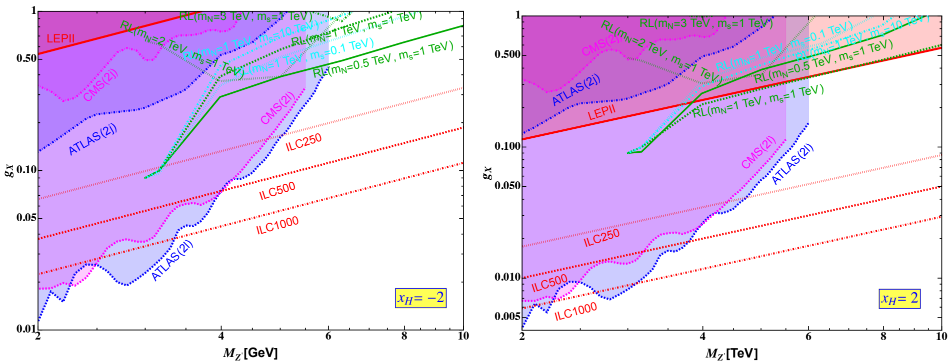

Fig. 2. Limits from dilepton (dotted), dijet (dot-dashed) searches of CMS (magenta), ATLAS (blue), LEP-II (red, solid), and prospective ILC experiments for $\sqrt{s} = 250$ GeV (red, dotted), 500 GeV (red, dashed), and 1 TeV (red, dot-dashed). We show the limits from resonant leptogenesis (RL) scenario (green and cyan) for different benchmarks of RHNs (m_N) and scalar (m_s) masses varying x_H. We represent RL limes for fixed scalar mass $m_s = 1$ TeV with varying RHN mass $m_N = 0.5$ TeV (solid green), $m_N = 1$ TeV (green dashed), $m_N = 2$ TeV (green dotted), and $m_N = 3$ TeV (green dot-dashed), respectively. RL limits for fixed RHN mass at $m_N = 1$ TeV with different scalar mass $m_s = 10$ TeV (cyan dot-dashed) and $m_s = 0.1$ TeV (cyan dotted), respectively.

5. Conclusion

We consider $\mathrm{U}(1)_X$ scenarios where we have three generations of SM-singlet RHNs which are charged under $\mathrm{U}(1)_X$ scenarios. After cancelling gauge and mixed gauge–gravity anomalies, we find that left- and right-handed charged leptons interact differently with Z'. These scenarios affect the generation of CP asymmetry mediated by Z' and scalars, while induced by SM and BSM fermions and scalars applying resonant leptogenesis. Reproducing the CP asymmetry by applying different benchmark scenarios of the RHN and SM-singlet BSM scalar masses, we estimate the bounds on the $g_X - M_{Z'}$ plane for different $\mathrm{U}(1)_X$ charges. We estimate limits on $\mathrm{U}(1)_X$ coupling for different $M_{Z'}$ using $M_{Z'} > \sqrt{s}$ for LEP-II and prospective ILC using electron–positron scattering. Comparing with the estimated dilepton and dijet cross sections at the proton–proton collider with the LHC searches, we estimate limits on the $g_X - M_{Z'}$ plane for different $\mathrm{U}(1)_X$ charges. We find that limits obtained from resonant leptogenesis provide stronger bounds compared to those obtained from LHC for $M_{Z'} > 5.8$ TeV. Limits obtained from LEP-II for $x_H = 2$ provide stronger bounds compared to the resonant leptogenesis scenario.

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