# 3 Connecting lepton number violation, lepton flavor violation and baryogenesis in left-right symmetric model

In this chapter, we present a model independent phenomenological study of baryogenesis via leptogenesis, neutrinoless double beta decay (NDBD) and charged lepton flavor violation (CLFV) in a generic left-right symmetric model (LRSM) where neutrino mass originates from the type I + type II seesaw mechanism. We studied the new physics contributions to NDBD coming from the left-right gauge boson mixing and the heavy neutrino contribution within the framework of LRSM. We have considered the mass of the RH gauge boson to be specifically 5 TeV, 10 TeV and 18 TeV and studied the effects of the new physics contributions on the effective mass and baryogenesis and compared with the current experimental limit. We tried to correlate the cosmological BAU from resonant leptogenesis with the low energy observables, notably, NDBD and LFV with a view to finding a common parameter space where they coexist.

## 3.1 Introduction

The discovery of neutrino flavor oscillations from different neutrino experiments and hence the evidence of neutrino mass and mixing have an immense impact on our perception of the dynamics of the Universe. As we know that regardless of its enormous success, the Standard Model (SM) of particle physics is considered to be an insufficient theory, owing to the fact that it fails to address some of the vital questions like, the origin of the tiny neutrino mass, lepton number violation (LNV), lepton flavor violation (LFV) and various other cosmological problems like dark matter and baryon asymmetry of the universe (BAU). Out of the different BSM frameworks to realize these observables, we have chosen the left-right symmetric model (LRSM) due to its very appealing nature, in which the seesaw mechanisms arises naturally. Here, the RH neutrinos are a necessary part of the model, which acquires a Majorana mass when the $SU(2)_R$ symmetry is broken at a scale $v_R$. This is quite analogous to the way in which the charged fermions get masses in the SM by Higgs mechanism when $SU(2)_L$ gauge symmetry is broken at a scale $v$. The RH neutrinos which exist in the seesaw mechanism besides explaining the neutrino flavor oscillation and neutrino mass can also throw light on the matter-antimatter asymmetry of the universe, i.e., excess of baryons over anti baryons in the universe.The lightest right-handed (RH) neutrino, $N_1$ when decays can naturally give rise to an excess of baryons over anti baryons in the universe consistent with the cosmological observable constrained by Big bang Nucleosynthesis and determined recently with good precision by WMAP experiment as,

$$\eta_B = \frac{n_B}{n_\gamma} = \left(6.5^{+0.4}_{-0.3}\right) \times 10^{-10}. \tag{3.1}$$

The decay of $N_1$ can satisfy all the three Sakharov conditions [1] as required for successful generation of $\eta_B$ as there is sufficient CP and C violation, there is baryon number violation and can also occur out of thermal equilibrium. TeV scale LRSM provides an alluring class of SS models which can be probed at LHC. Matter-antimatter asymmetry is now generated by a resonant baryogenesis mechanism with at least two Quasi Degenerate RH neutrinos in TeV range with a mass difference comparable to their decay widths [2]. The TeV scale new particles in LRSM also leads to interesting collider signals.

The possible observation of Neutrinoless double beta decay (NDBD) would play a significant role in understanding the origin of BAU as it would imply that lepton number indeed is not conserved ([3, 4, 5]). Furthermore, the Majorana nature [7] of neutrinos would also be established from NDBD. The latest experiments [8] that have improved the lower bound of the half-life of the decay process include KamLAND-Zen [9] and GERDA [85] which uses Xenon-136 and Germanium-76 nuclei respectively. Incorporating the results from the first and second phase of the experiment, KamLAND-Zen imposes the best lower limit on the decay half-life using Xe-136 as $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr at 90% CL and the corresponding upper limit of effective Majorana mass in the range (0.061-0.165) eV.

The observation of CP violation in the lepton sector, in neutrino oscillation experiment and NDBD, would suggest the existence of CP violation at high energy which might be related to the one responsible for leptogenesis. The observation of LNV in NDBD and in addition possibly of CP violation in lepton sector would be a strong indication of leptogenesis as an explanation of baryon asymmetry. It would be enthralling to explore the CP violation in the leptonic sector due to presence of the Majorana CP phases in the light of leptogenesis.

Another important issue of discussion in a collider is the relative values of the mass of the gauge bosons and heavy RH neutrinos. However, there are theoretical arguments based on vacuum stability which suggests that the heavy neutrinos are lighter than the RH gauge bosons that appears in the LRSM for a large parameter space. Again, it has been pointed out in the literature that to account for a successful leptogenesis in TeV scale LRSM, the mass of the RH gauge boson, $M_{W_R}$ has to be larger than the value obtainable at the LHCs. They have found a lower bound of 18 TeV for successful leptogenesis from the decay of heavy RH neutrino with maximum CP asymmetry, $\varepsilon = 1$. [11]. This result is much significant as it can provide a way to falsify leptogenesis if mass of a gauge boson below this limit is found in experiments. From the significant outcome of the work, [11], the authors of [12] have shown that for specific symmetry textures of $M_D$ and $M_{RR}$ in the seesaw formula and by considering larger Yukawa couplings, the bound for leptogenesis can be largely weaker, i.e., $M_{W_R} > 3$ TeV and $M_N \leq M_{W_R}$ which is possible owing to the sizable reduction of dilution effects from $W_R$ mediated decays and scatterings. They have again reanalyzed their work [12] in [13] and came out with a lower bound of $M_{W_R} > 10$ TeV for successful leptogenesis in a generic LRSM with large light-heavy mixing. The consistency has also been pointed out for other low energy constraints like NDBD, LFV etc.

In LRSM, there are several contributions to NDBD that involve left and RH sectors individually as well as others that involve both sectors through left-right mixing accompanied by both light and heavy neutrinos. Left-right mixing is always a ratio of the Dirac and Majorana mass scales ($M_D M_{RR}^{-1}$) which appears in the type I seesaw formula. NDBD involving left-right mixing can be enhanced for specific Dirac matrices. For large left-right mixing, significant contributions to NDBD arises from the mixed diagrams with simultaneous mediation of $W_L$ and $W_R$ accompanied by light LH neutrino and heavy RH neutrinos, known as $\lambda$ and $\eta$ contributions to NDBD, although the later is a bit suppressed by the mixing between left and RH gauge bosons. It has been studied in many of the earlier works in the framework of LRSM (see ref.[14][21][22]). The other new physics contributions are also suppressed for a larger gauge boson mass, $M_{W_R}$ >10 TeV which gives sizable baryogenesis. Furthermore, the LFV processes are seeking great interest in recent times as the experiments to detect them are becoming increasingly precise. The decay processes, ($\mu \rightarrow 3e$) and ($\mu \rightarrow e\gamma$) are simplest to detect with the current experimental limits for these low energy processes as $< 1.0 \times 10^{-12}$ and $< 4.2 \times 10^{-13}$ respectively.

Apart from the new physics contributions to NDBD in LRSM as available in the literature, it is important to study the linkage between baryogenesis and other low scale phenomena like NDBD, LFV etc. In this context, with the previous results aforementioned in mind [11][12][13][14][21][22], we have done a phenomenological study of leptogenesis in TeV scale LRSM by considering different values of RH gauge boson mass within and above the current collider limits. In particular, we have considered the $SU(2)_R$ breaking scale to be 5 TeV, 10 TeV and 18 TeV (the bounds as available in the literature) in order to check the consistency of the results and thereby tried to link baryogenesis with NDBD for these particular values of gauge boson mass. Again regarding the $\lambda$ and $\eta$ contributions to be valid, we need to have a large left-right mixing. But for a generic TeV scale seesaw model, without considering any particular structure for the Dirac and Majorana masses, in order to account for neutrino mass of the order of sub eV, keeping the heavy masses of TeV scale, the Dirac mass is of the order of MeV. This leads to a not so large left-right mixing parameter, $\zeta \approx 10^{-6}$. Since we have seen non-negligible effects of the momentum dependent mechanisms in NDBD for not so large left-right mixing, we studied all the possible contributions to NDBD. To co-relate with baryogenesis, we have considered only the momentum dependent mechanisms of NDBD, i.e., the $\lambda$ and $\eta$ contributions to NDBD due to light-heavy and gauge boson mixing. Since the effective mass governing NDBD is dependent upon the Majorana phases, $\alpha$ and $\beta$, it would be compelling to examine if there exists a link between NDBD and BAU. Besides, the study of LFV processes will also provide insights into the mechanism of NDBD. LRSM at the TeV scale interlinks high energy collider physics to the low energy observables like NDBD and other LFV processes. So we tried to correlate all these high and low energy phenomenon and find out if there exists a common parameter space accessible at colliders where leptogenesis can be simultaneously realized.

The plan of this chapter is outlined as follows. In the next section, 3.2, we summarize the implications of TeV scale LRSM in processes like BAU and other low energy observables like NDBD, LFV. In section 3.3, we present our numerical analysis and results and then give our conclusion in section 3.4.

## 3.2 Resonant Leptogenesis, NDBD and LFV in TeV scale LRSM

As has been presented in the previous two chapters, in the generic LRSM [24, 25, 26, 27, 28], the fermions are assigned to the gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which is a very simple extension of the SM gauge group, $SU(3)_c \times SU(2)_L \times U(1)_Y$, that provides a UV complete seesaw model where the type I and II seesaw arises naturally. The $6 \times 6$ neutrino mass matrix in LRSM as shown in reference [14] and as defined in chapter 1, equation (1.75) can be diagonalized by a $6 \times 6$ unitary matrix as defined in (1.79, (1.80) where the relevant terms are defined by the subsequent equations. T and S in equations (1.84, 1.85) describes the left-right mixing and can be written as $\frac{L}{R}$, gauge boson mixing angle $\xi$, as defined in (1.69)is of order $\left(\frac{L}{R}\right)^2$.

As illustrated in several earlier works, for TeV scale seesaw models, a simple approach for generating adequate lepton asymmetry is to use resonant leptogenesis (RL) [32, 33, 34, 35, 36], which craves for at least two heavy RH Majorana neutrinos to be nearly degenerate, which we have already considered in our analysis. With Quasi degenerate RH neutrino masses for at least two RH neutrinos, BAU/leptogenesis can be efficient at lower mass scales, but for this case generally a specific flavor structure is considered which allows for large Yukawa couplings which serve the twin purpose of leptogenesis to be efficient as well as it can be tested in experiments. Nevertheless, as far as Dirac neutrino mass matrix is concerned, we have not considered any particular structure of the matrix but a general form which is obtained from the type I seesaw when the Majorana mass matrix and the light neutrino mass matrix is considered to be known. The neutrino mass matrices is such that it fits the current neutrino oscillation data. The basic focus of our work is to relate the lepton asymmetry with the low observable phenomenons like NDBD, rather than only BAU and NDBD or LFV and to find a common parameter space where all them holds.

In the framework of TeV scale LRSM, the presence of the RH neutrinos (type I SS) and the scalar triplets (type II SS) suggests their decays which give rise to lepton asymmetry. However, we will only consider the decay of the heavy RH neutrinos for generating lepton asymmetry. The decay of the scalar triplet $\Delta_L$ would not much affect on our result as above TeV scale, decay of the RH neutrinos are in thermal equilibrium and hence they would wash out any kind of preexisting lepton asymmetry and so we have ignored it [13]. So the dominant contribution would come from the type I seesaw term.

The two heavy RH Majorana neutrinos decay via the decay modes, $N_i \rightarrow l + \phi^c$ and its CP conjugate process, $N_i \rightarrow l^c + \phi$ which can occur at both tree and one loop levels. Hence, their CP violating asymmetry $\epsilon_i$ which arises from the interference between the tree-level amplitude and its self-energy [37, 38, 39] correction is defined in[40] and in equation (1.95).The decay rates of the heavy neutrino decay processes are governed by the Yukawa couplings and is given by equation (1.96). An essential condition for RL is that the mass difference between the two heavy RH neutrinos must be comparable to the decay width ( i.e., $M_i - M_j \approx \Gamma$). In this case, the CP asymmetry becomes very large (even of order 1). The CP violating asymmetry $\epsilon_i$ is as defined in (1.97). The CP violating asymmetries $\epsilon_1$ and $\epsilon_2$ can give rise to a net lepton number asymmetry provided the expansion rate of the universe is larger than $\Gamma_1$ and $\Gamma_2$. This can further be partially converted into baryon asymmetry of the universe by B+L violating sphaleron [41] processes.

Now that there are several new heavy particles in LRSM, many new physics contributions to NDBD arises in addition to the standard contribution. It has been extensively studied in many of the earlier works (see ref. [21][22]). Amongst the new physics contributions to $0\nu\beta\beta$ decay, notable are the contributions coming from the exchange of the heavy gauge bosons ( ${W_L}^-$ and ${W_R}^-$ ), both the left and RH gauge bosons (mixed diagrams, $\lambda$ and $\eta$) as well the scalar triplet ($\Delta_L$ and $\Delta_R$ ) contributions. The amplitude of these processes mostly depends upon the mixing between light and heavy neutrinos, the leptonic mixing matrix elements, the mass of the heavy neutrino ($M_i$), the mass of the gauge bosons, ${W_L}^-$

and ${W_R}^-$, the mass of the triplet Higgs as well as their coupling to leptons, $f_L$ and $f_R$.

However, in this work, we have considered only three of the aforesaid contributions to NDBD. The ones mediated by ${W_R}^-$ and the momentum dependent mechanisms, i.e., the contributions to NDBD from $\lambda$ and $\eta$ diagrams which involves the light and heavy neutrino mixings and the mixing between ${W_L}^-$ and ${W_R}^-$ bosons (considering a small light-heavy neutrino mixing of $\mathcal{O}(10^{-6})$. The amplitudes of the contributions are given in several earlier works like [22]. The mass scales for the heavy particles have been assumed to be $\approx TeV$, with $M_{W_R} > M_N$. Under these assumptions, the amplitude for the light-heavy mixing contribution which is proportional to $\frac{{M_D}^2}{M_R}$ remains very small (since $m_\nu \approx \frac{{M_D}^2}{M_R} \approx (0.01 - 0.1)eV$, $M_D \approx (10^5 - 10^6)$ eV which implies $\frac{M_D}{M_R} \approx (10^{-7} - 10^{-6})$ eV).

Again, the contribution from ${\Delta_L}^-$, ${W_L}^-$ is suppressed by the type II seesaw contribution to light neutrino mass and hence neglected here. Considering these contributions we have studied NDBD and tried to correlate the effective mass governing the process with the BAU for different gauge boson masses in TeV scale LRSM.

As has been pointed out that successful low scale RL requires an absolute lower bound of 18 TeV on the mass of the RH gauge boson and recent work predicted that it can be produced for the considerably lower value of $M_{W_R}$ accessible at LHCs considering relatively large Yukawa couplings. Again, although it has been illustrated as the light-heavy neutrino mixing to be sufficiently large in TeV scale LRSM in order to get dominant NDBD contributions from the momentum dependent mixed diagrams, $\lambda$ and $\eta$, we have seen that a sizable amount of BAU and effective mass governing NDBD ( from $\lambda$ and $\eta$ diagrams) consistent with the experimental value is observed by considering a general structure of the Dirac mass matrix and not so large light-heavy neutrino mixing parameter. Without considering any special structure of $M_D$ and $M_{RR}$ in generic TeV scale LRSM, to get light neutrino mass of the order of sub eV, $M_D$ has to be fine-tuned to be very small which results in a lower value of the light-heavy neutrino mixing parameter, $\zeta$. But, in our present work, by considering a smaller $\zeta$ value, we have tried to correlate the effective mass from purely RH contribution and the suppressed effective mass coming from $\lambda$ and $\eta$ contributions with leptogenesis at a TEV scale LRSM.

The heavy Majorana neutrinos that take part in explaining BAU, as well as NDBD, also plays a significant role in giving rise to experimentally testable rates of LFV processes like, $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ etc. The different neutrino Yukawa couplings for each lepton flavor have a considerable impact on leptogenesis with nearly degenerate heavy neutrino mass. Owing to the presence of some new heavy particles in the LRSM, the LFV processes are mediated by these heavy neutrinos and doubly charged triplet Higgs bosons.

The relevant BR for the processes ($\mu \to 3e$) [42] and ($\mu \to e\gamma$) are as defined in chapter 2, equations (2.16) and (2.17). Several new sources of LFV are present in new physics BSM in LRSM due to the additional RH current interactions, which could lead to considerable LFV rates for TeV scale $v_R$. LFV in the LRSM has been studied in many previous works. There are various LFV processes providing constraints on the masses of the RH neutrinos and doubly charged scalars. It turns out that the process $\mu \to 3e$ induced by doubly charged bosons $\Delta_L^{++}$ and $\Delta_R^{++}$ and $\mu \to e\gamma$ provides the most relevant constraint. The upper limits of the branching ratio of the process $\mu \to 3e$ is $< 1.0 \times 10^{-12}$ [44] at 90% CL was obtained by the SINDRUM experiment. Furthermore, the Mu3e collaboration has also submitted a letter of intent to PSI to perform a new improved search for the decay $\mu \to 3e$ with a sensitivity of $10^{-16}$ at 95% CL [45] which corresponds to an improvement by four orders of magnitude compared to the former SINDRUM experiment. While for the LFV process, $\mu \to e\gamma$, the BR is established to be $< 4.2 \times 10^{-13}$ [46] at 90% CL by the MEG collaboration. Considering these contributions from heavy RH neutrinos and Higgs scalars, the expected branching ratios and conversion rates of the above processes have been calculated in the LRSM in the work (first reference in [47]).

## 3.3 Numerical analysis and results

With reference to several earlier works [11][12][13][22][48] for TeV scale LRSM, we carried out an extensive study for RL, NDBD and LFV, with a view to finding a common parameter space for these observables. It is reasonable to check if the mass matrices that can explain the BAU of the universe can also provide sufficient parameter space for other low energy observables like NDBD, LFV etc. For NDBD, we have considered the mixed LH-RH contribution along with the purely RH neutrino contribution, considering a generalized structure for the Dirac mass matrix. The Dirac and Majorana mass matrices in our case are determined using the type I seesaw formula (as shown in the appendix A.2) and type II seesaw (equation (3.6)) respectively which satisfies the recent neutrino oscillation data. Whereas, in the previous works, the authors have considered specific Dirac and Majorana textures resulting in light neutrinos via type I seesaw with large light-heavy neutrino mixing. They have chosen large Yukawa couplings as allowed by specific textures for calculation of the lepton asymmetry. As stated in [13], we have been found that it is possible to observe BAU with a lower $W_R$ mass, in our case it is 5 TeV. Further, we have also correlated the LFV of the process, $\mu \to 3e$, $\mu \to e\gamma$ and with lightest neutrino mass and atmospheric mixing angle. In this section we present a detailed analysis of our work by dividing it into several subsections, firstly BAU, then NDBD and then LFV.

### 3.3.1 Baryogenesis via Leptogenesis

The formula for light $\nu$ masses in LRSM can be written as,

$$M_\nu = {M_\nu}^I + {M_\nu}^{II}, \tag{3.2}$$

where the type I seesaw mass term is,

$$ {M_\nu}^I = M_D {M_{RR}}^{-1} {M_D}^T. \tag{3.3}$$

We have considered a tribimaximal mixing (TBM) pattern, such that,

$$ {M_\nu}^I = U_{(TBM)} U_{Maj} {M_\nu}^{I(diag)} {U_{Maj}}^T {U_{(TBM)}}^T, \tag{3.4}$$

where $\mathrm{M}_\nu{}^{\mathrm{I(diag)}} = \mathrm{XM}_\nu{}^{\mathrm{(diag)}}$ [49], the parameter X is introduced to describe the relative strength of the type I and II seesaw terms. It can take any numerical value provided the two seesaw terms gives rise to correct light neutrino mass matrix. In our case, we have considered X=0.5 [49], i.e., equal contributions from both the seesaw terms. Thus, equation (3.2) can be written as,

$$U_{PMNS} {M_\nu}^{(diag)} {U_{PMNS}}^T = {M_\nu}^{II} + U_{(TBM)} U_{Maj} X {M_\nu}^{(diag)} {U_{Maj}}^T {U_{(TBM)}}^T, \tag{3.5}$$

where, $\mathrm{U_{PMNS}}$ is the diagonalizing matrix of the light neutrino mass matrix, $M_\nu$ as defined in equation (1.28). For our analysis, we have adopted the neutrino oscillation data from

[50]. From type II seesaw mass term,$\mathrm{M_{RR}}$ can be written in the form (from reference [49]) as,

$$M_{RR} = \frac{1}{\gamma}\left(\frac{v_R}{M_{W_L}}\right)^2 {M_\nu}^{II}, \tag{3.6}$$

$$U_R {M_{RR}}^{(diag)} {U_R}^T = \frac{1}{\gamma}\left(\frac{v_R}{M_{W_L}}\right)^2 {M_\nu}^{II}, \tag{3.7}$$

$${M_\nu}^{II} = U_{PMNS} {M_\nu}^{(diag)} {U_{PMNS}}^T - U_{(TBM)} U_{Maj} X {M_\nu}^{(diag)} {U_{Maj}}^T {U_{(TBM)}}^T. \tag{3.8}$$

Where, ${M_{RR}}^{(diag)} = diag(M_1, M_2, M_3)$. We have fine-tuned the dimensionless parameter, $\gamma \sim 10^{-10}$. The variation of the RH gauge boson mass with heavy RH neutrino mass as shown in fig. 3.1, corresponds to the condition $M_{W_R} > M_N$. As previously mentioned we have considered three different values of the $SU(2)_R$ breaking scale, $v_R$ for our further analysis, specifically 5 TeV, 10 TeV and 18 TeV respectively, which will be useful to study the common parameter space of the phenomena we have considered, i.e., BAU, NDBD, LFV. The left-handed (LH) gauge boson is $M_{W_L} = 80$ GeV and determined the RHS of equation terms of lightest neutrino mass by varying the Majorana phases from 0 to $2\pi$. By considering a very tiny mass splitting of the Majorana masses $M_1$ and $M_2$ as per requirement of resonant leptogenesis, we equated both sides of equation (3.6) and obtained $M_1$, $M_2$ and $M_3$, where, $M_1 \approx M_2$.

We considered the lepton number violating and CP violating decays of two heavy RH Majorana neutrinos, $N_1$ and $N_2$ via the decay modes, $N_i \to l + \phi^c$ and its CP conjugate process, $N_i \to l^c + \phi$, $i = 1, 2$. Firstly, we determined the leptonic CP asymmetry, $\epsilon_1$ and $\epsilon_2$ using equation (1.97) where $Y_\nu = \frac{M_D}{v}$, $v$ being the VEV of Higgs bidoublet and is 174 GeV. The decay rates in equation (1.97) can be obtained using equation (1.96). The Dirac mass, $M_D$ as mentioned before is not of any specific texture, but we have obtained it from the type I seesaw equation in which we have considered the light neutrino mass $M_{LL}$ and the heavy RH Majorana neutrino mass to be known, which satisfies the current neutrino oscillation data. The CP violating asymmetries $\epsilon_1$ and $\epsilon_2$ can give rise to a net lepton number asymmetry, provided the expansion rate of the universe is larger than $\Gamma_1$ and $\Gamma_2$. The net baryon asymmetry is then calculated using [40][51, 52],

$$\eta_B \approx -0.96 \times 10^{-2} \sum_i (k_i \epsilon_i), \tag{3.9}$$

$k_1$ and $k_2$ being the efficiency factors measuring the washout effects linked with the out of equillibrium decay of $N_1$ and $N_2$. We can define the parameters, $K_i \equiv \frac{\Gamma_i}{H}$ at temperature, $T = M_i$, $H \equiv \frac{1.66\sqrt{g_*}T^2}{M_{Planck}}$ is the Hubble's constant with $g_* \simeq 107$ and $M_{Planck} \equiv 1.2 \times 10^{19} GeV$ is the Planck mass. The decay width can be estimated using equation (1.96). For simplicity, the efficiency factors, $k_i$ can be calculated using the formula (3.10),

$$k_1 \equiv k_2 \equiv \frac{1}{2}\left(\sum_i K_i\right)^{-1.2} \tag{3.10}$$

which holds validity for two nearly degenerate heavy Majorana masses and $5 \leq K_i \leq 100$. We have used the formula (3.9) in calculating the baryon asymmetry. The result is shown as a function of lightest neutrino mass by varying the Majorana phases from 0 to 2 $\pi$ in fig. 3.2 for different values of RH gauge boson mass. It is evident from the figure that the cosmological observed BAU from RL can be obtained for varying gauge boson mass $M_{W_R}$, distinctively, 5, 10 and 18 TeV in our case, which is in accordance to several prior works. In the case of mass hierarchy, IH seems to give better results in our analysis. The required amount of BAU is perceived for lightest neutrino mass of around (0.05-0.1) eV. For $M_{W_R} =$ 18 TeV, greater parameter space satisfies the observed BAU than for 5 TeV.

### 3.3.2 NDBD from heavy RH neutrino, gauge boson mixing and light-heavy neutrino mixing

In LRSM, owing to the presence of several new heavy particles, many new contributions arises to NDBD amplitudes. In the previous chapter, we have considered the new physics contributions coming from the ones mediated by ${W_R}^-$ and $\Delta_R$ respectively. In this work, besides the heavy RH neutrino contribution coming from the exchange of $W_R$ bosons, we also considered the momentum dependent mechanisms i.e., the $\lambda$ and $\eta$ contributions to NDBD due to gauge boson mixing since we have seen non negligible contributions from these momentum dependent mechanisms in our case. The effective neutrino mass corresponding to the heavy RH neutrino contribution from the exchange of $W_R$ gauge bosons is given by,

$$\mathrm{M_{eff}^{N}} = \mathrm{p}^2 \frac{\mathrm{M_{W_L}}^4}{\mathrm{M_{W_R}}^4} \frac{\mathrm{U_{Rei}}^{*}2}{\mathrm{M_i}}. \tag{3.11}$$

Here, $< \mathrm{p}^2 >= \mathrm{m_e m_p} \frac{\mathrm{M_N}}{\mathrm{M_\nu}}$ is the typical momentum exchange of the process, where $\mathrm{m_p}$ and $\mathrm{m_e}$ are the mass of the proton and electron respectively and $\mathrm{M_N}$ is the NME corresponding to the RH neutrino exchange. The allowed value of p (the virtuality of the exchanged neutrino) is in the range $\sim$ (100-200) MeV. In our analysis, we have taken p$\simeq$180 MeV [22]. As in the case of BAU, herein, we have considered different values of $M_{W_R}$, namely, 5, 10 and 18 TeV respectively. $U_{Rei}$ are the first row elements of the diagonalizing matrix of the heavy RH Majorana mass matrix $\mathrm{M_{RR}}$ and $\mathrm{M_i}$ is its mass eigenvalues, $\mathrm{M_i}$.

- In case of $\lambda$ contribution, the particle physics parameter that measures the lepton number violation is given by,

$$|\eta_\lambda| = \left(\frac{M_{W_L}}{M_{W_R}}\right)\left|\sum_i U_{e_i} T^*_{e_i}\right|. \tag{3.12}$$

- While the $\eta$ contribution to NDBD due to $W_L - W_R$ mixing is described by the parameter, $\tan\xi$, as in equation (1.69), with particle physics parameter,

$$|\eta_\eta| = \tan\xi \left|\sum_i U_{ei} T^*_{ei}\right|. \tag{3.13}$$

In the above equations $U_{e_i}$ represents the elements of the matrix as defined by equation (1.82) and T is represented by equation (1.85), the term $|\sum_i U_{ei} T^*_{ei}|$ can be simplified to the form $\left[M_D M_{RR}^{-1}\right]_{ee}$ (as in [42]). $V_\nu$ in the expression for T is the diagonalizing matrix of $M_\nu$. The effective Majorana neutrino mass due to $\lambda$ and $\eta$ contribution is thus given by,

$$M^\lambda_{eff} = \frac{\eta_\lambda}{m_e}, M^\eta_{eff} = \frac{\eta_\eta}{m_e}. \tag{3.14}$$

The half lives corresponding to these effective mass values is given by,

$$\left[T_{\frac{1}{2}}{}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z)\left|M_N^{0\nu}\right|^2 \frac{\left|M^N_{eff}\right|_N^2}{m_e{}^2}, \tag{3.15}$$

$$\left[T_{\frac{1}{2}}{}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z)\left|M_\lambda^{0\nu}\right|^2 \frac{\left|M^\lambda_{eff}\right|_N^2}{m_e{}^2}, \tag{3.16}$$

$$\left[T_{\frac{1}{2}}{}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z)\left|M_\eta^{0\nu}\right|^2 \frac{\left|M^\eta_{eff}\right|_N^2}{m_e{}^2}, \tag{3.17}$$

where, $G^{0\nu}$ and $|M^{0\nu}|$ represents the phase space factor and the nuclear matrix elements of the processes which holds different values as in [23].

Fig. 3.3 to 3.7 shows the effective mass and half-life governing NDBD from RH neutrino, $\lambda$ and $\eta$ contribution against the lightest neutrino mass. For new physics contribution coming from purely RH current, the effective mass governing NDBD is consistent with the experimental results as propounded by KamLAND-Zen for all the cases ($M_{W_R}$= 5, 10, 18 TeV) although better results are obtained for 18 TeV. It is not much dependent on the mass hierarchy. Whereas, for NDBD contributions from $\lambda$ and $\eta$ mechanisms, the effective mass is found to be within the experimental limit but of lower magnitude than the RH neutrino contributions. We have seen that $\eta$ contribution $(10^{-6} - 10^{-8})$ eV is around two orders of magnitude less than the $\lambda$ contribution $(10^{-4} - 10^{-6})$ eV in all the cases (Fig. 3.4) irrespective of the mass hierarchies. Similar results are obtained for the half-lives of the process, as seen in figures 3.6, 3.7.

Fig. 3.8 to 3.10 shows the correlation of NDBD and BAU for the different contributions. It is seen that BAU and NDBD (for RH $\nu$ contribution) can simultaneously satisfy the experimental results for $M_{W_R}$ = 10 and 18 TeV in our case, although for 10 TeV case only IH is consistent with the experimental bounds. As far as the mixed contributions are concerned, a common parameter space for NDBD and BAU is observed only for RH gauge boson mass to be 5 TeV and for IH only.

### 3.3.3 Lepton Flavor Violation

In our analysis, we further studied the LFV processes, $\mu \to 3e$ and $\mu \to e\gamma$ and correlated the branching ratios(BR) with the lightest neutrino mass and the atmospheric mixing angle respectively as in chapter 2. For calculating the BR, we used the expressions given in equations (2.16, 2.17). The lepton Higgs coupling $h_{ij}$ in (2.16) can be computed explicitly for a given RH neutrino mass matrix as shown in equation (3.6) by diagonalizing the RH neutrino mass matrix and obtaining the mixing matrix element, $V_i$ and the eigenvalues $M_i$. For evaluating $M_{RR}$, we need to know ${M_\nu}^{II}$, as evident from equation (3.7). We computed ${M_\nu}^{II}$ from equation (3.6). For determining the BR for $\mu \to 3e$, we imposed the best fit values of the parameters, ${\Delta m_{sol}}^2$, ${\Delta m_{atm}}^2$, $\delta$, $\theta_{13}$, $\theta_{23}$, $\theta_{12}$ in $M_\nu$. The numerical values of ${M_\nu}^{I}$ can be computed considering TBM mixing pattern in our case. Thus, we get ${M_\nu}^{II}$ as a function of the parameters $\alpha, \beta$ and $m_{lightest}$. Then varying both the Majorana phases, $\alpha, \beta$ from 0 to $2\pi$, we obtained $\mathrm{M}_{\nu}{}^{\mathrm{II}}$ as a function of $m_{lightest}$. Similarly, for $\mu \to e\gamma$ we substituted the values of the lightest mass (m1/m3) for (NH/IH) as (0.07eV/0.065eV) and best fit values for the parameters $\Delta m_{sol}{}^2$, $\Delta m_{atm}{}^2$, $\delta$, $\theta_{13}$, while varying both the Majorana phases, $\alpha, \beta$ from 0 to $2\pi$ and thus obtained $\mathrm{M}_{\nu}{}^{\mathrm{II}}$ and hence $\mathrm{M_{RR}}$ as a function of the atmospheric mixing angle $\theta_{23}$. Thus BR can be obtained as a function of $\sin^2\theta_{23}$ from equation (3.7). We have varied the value of $\sin^2\theta_{23}$ in its $3\sigma$ range as in [54] and the lightest neutrino mass from $10^{-3}$ to $10^{-1}$ and obtained the values of BR. Like the previous cases (BAU and NDBD), we have considered three values of the RH gauge boson mass, 5 TeV, 10 TeV and 18 TeV respectively and different results have been obtained for these different values.

The variation is shown in figure (3.11) and (3.12) for both NH and IH. It is obvious from the figures that for both the LFV process, a good amount of parameter space is consistent with the experimental results for the different RH gauge boson mass we have considered i.e., 5, 10 and 18 TeV. We have shown a summarized form of our results in tabular form in table 3.1.

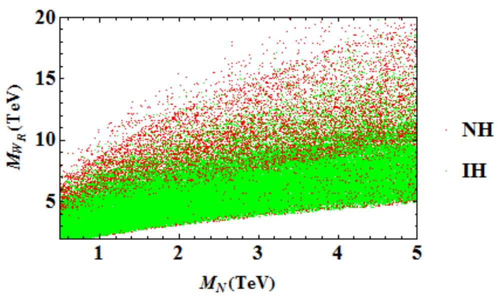


Figure 3.1: $M_{W_R}$ against heavy Majorana neutrino mass $M_1$ in TeV For NH and IH.

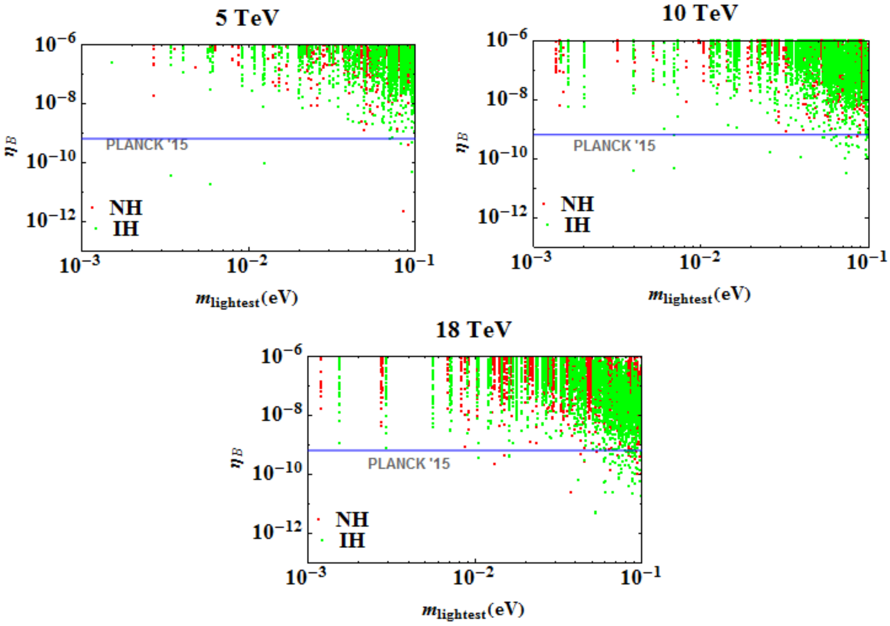


Figure 3.2: BAU as a function of lightest neutrino mass, $m_1/m_3$ (in eV)for NH/IH. The blue solid line represents the observed BAU in PLANCK '15[55] for different values of RH gauge boson mass, 5, 10 and 18 TeV respectively.

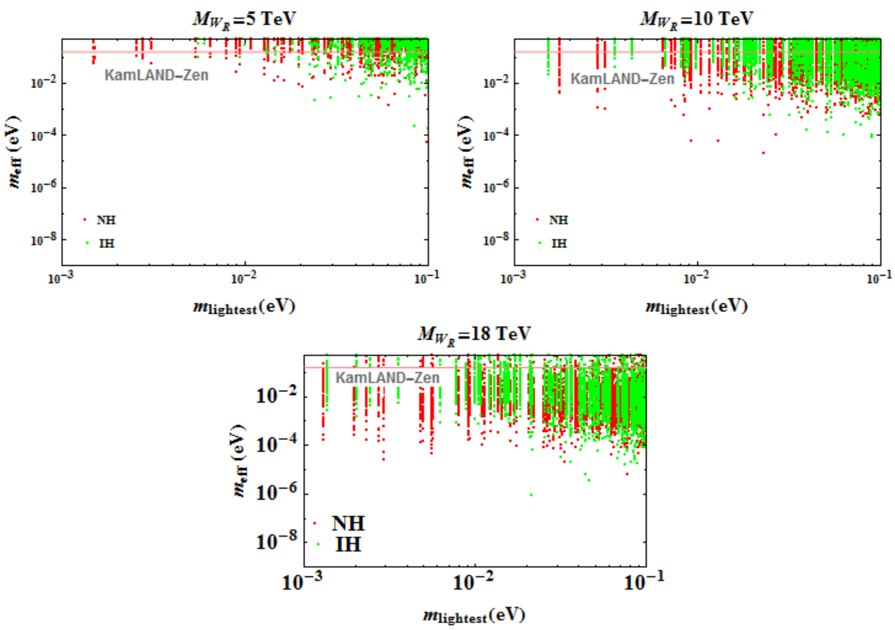


Figure 3.3: Effective Majorana mass for $0\nu\beta\beta$ as a function of lightest neutrino mass, for new physics contribution coming from RH $\nu$ for both NH and IH. The pink solid line represents the KamLAND-Zen upper bound on the effective neutrino mass.

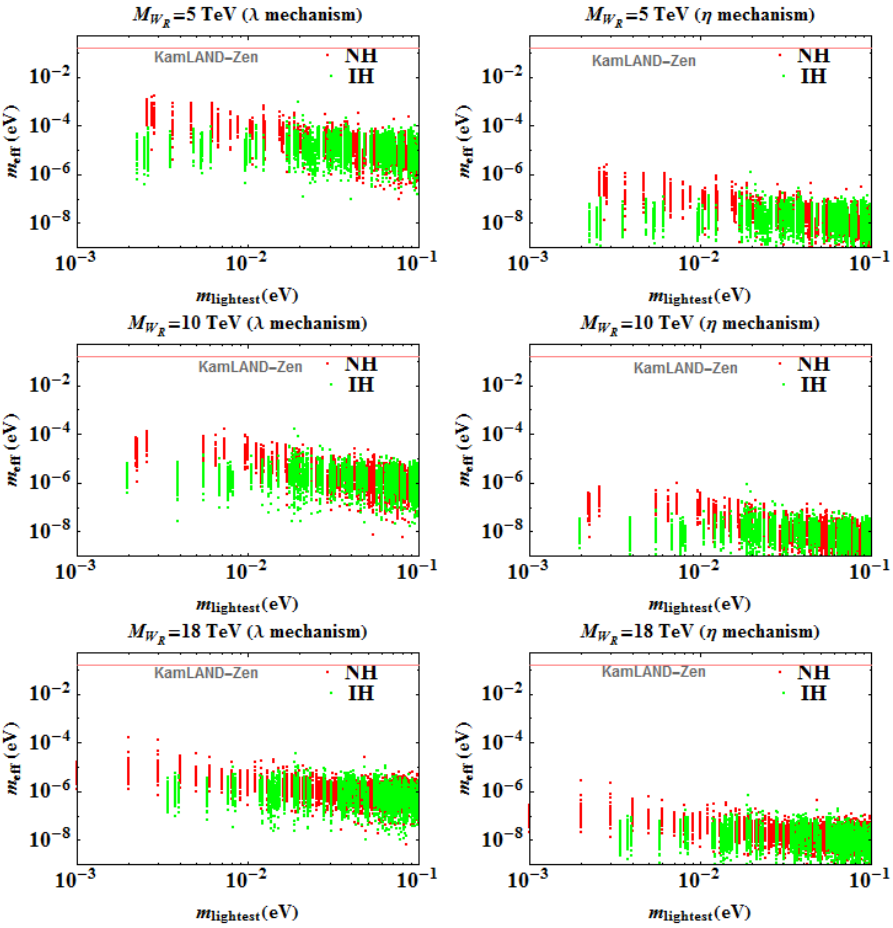


Figure 3.4: Effective Majorana mass for $0\nu\beta\beta$ as a function of lightest neutrino mass, for new physics contribution coming from $\lambda$ (left figures)and $\eta$ mechanisms( right figures) for NH and IH for different RH gauge boson masses. The pink solid line represents the KamLAND-Zen upper bound on the effective neutrino mass.

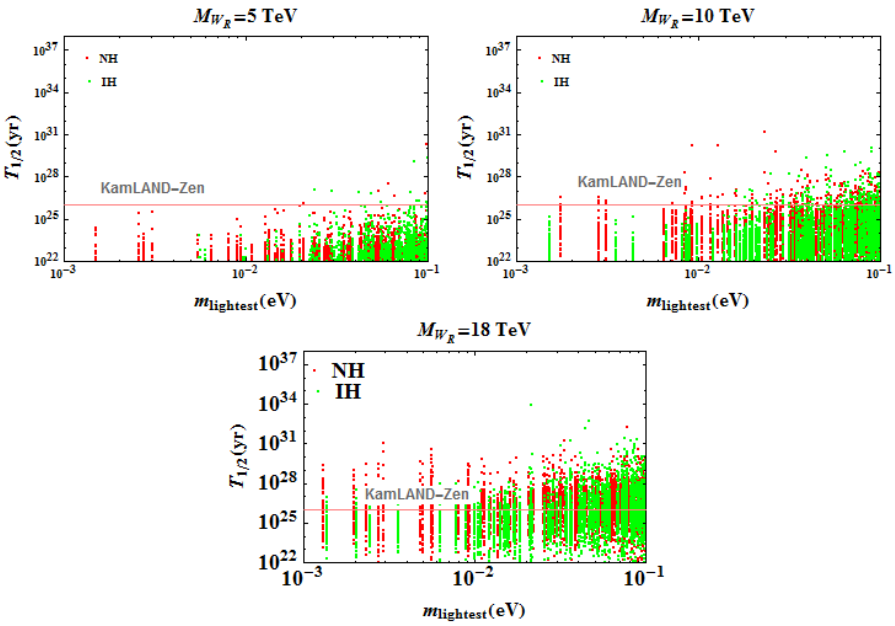


Figure 3.5: Half-life for $0\nu\beta\beta$ as a function of lightest neutrino mass for NH and IH for heavy RH neutrino contribution. The horizontal line represents the KamLAND-Zen lower bound on the half-life of NDBD.

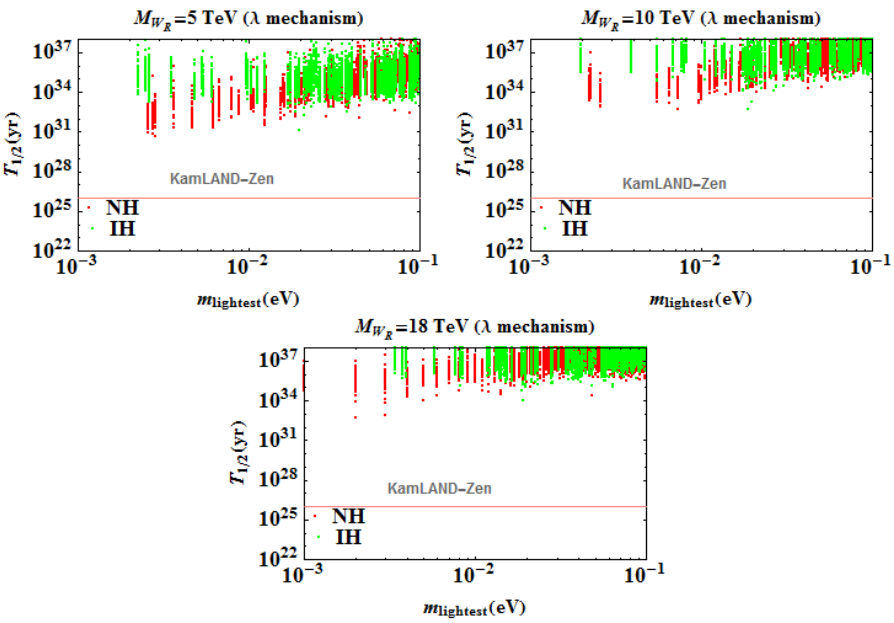


Figure 3.6: Half-life for $0\nu\beta\beta$ as a function of lightest neutrino mass for NH and IH for $\lambda$ mechanism. The horizontal line represents the KamLAND-Zen lower bound on the half-life of NDBD.

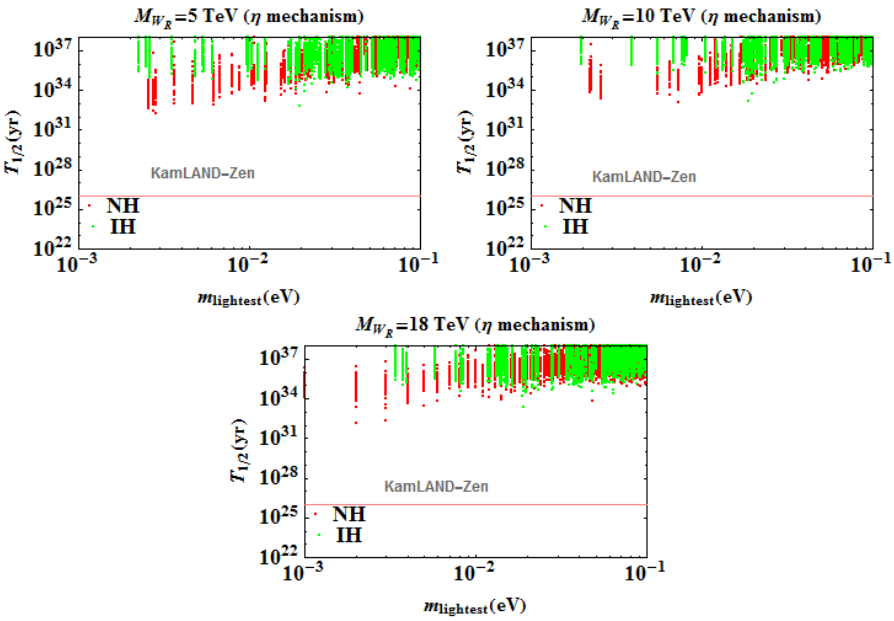


Figure 3.7: Half-life for $0\nu\beta\beta$ as a function of lightest neutrino mass for NH and IH for $\eta$ mechanism. The horizontal line represents the KamLAND-Zen lower bound on the half-life of NDBD.

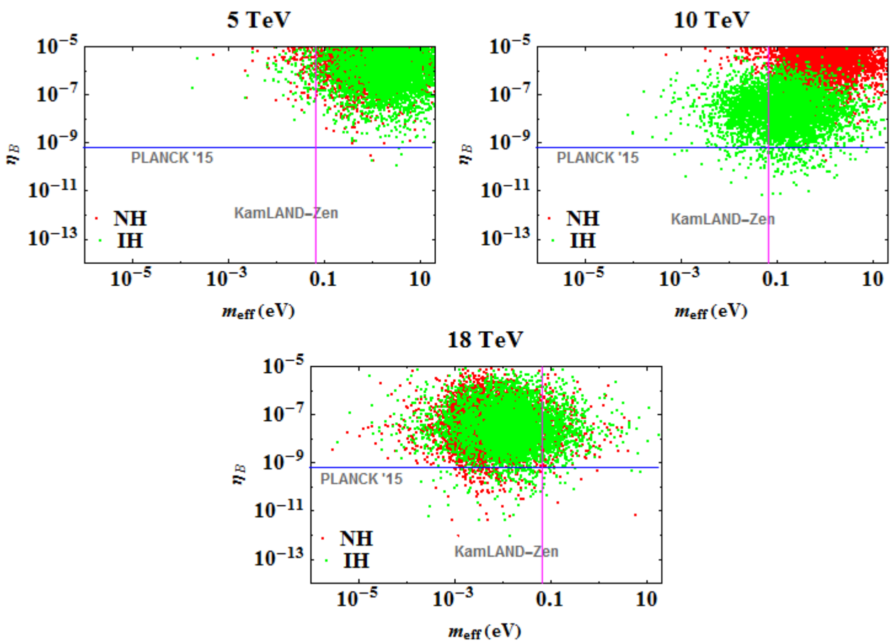


Figure 3.8: BAU against effective Majorana neutrino mass for RH $\nu$ contribution.The solid blue and pink line represents the observed BAU and the KAMLAND upper bound on effective Majorana neutrino mass respectively.

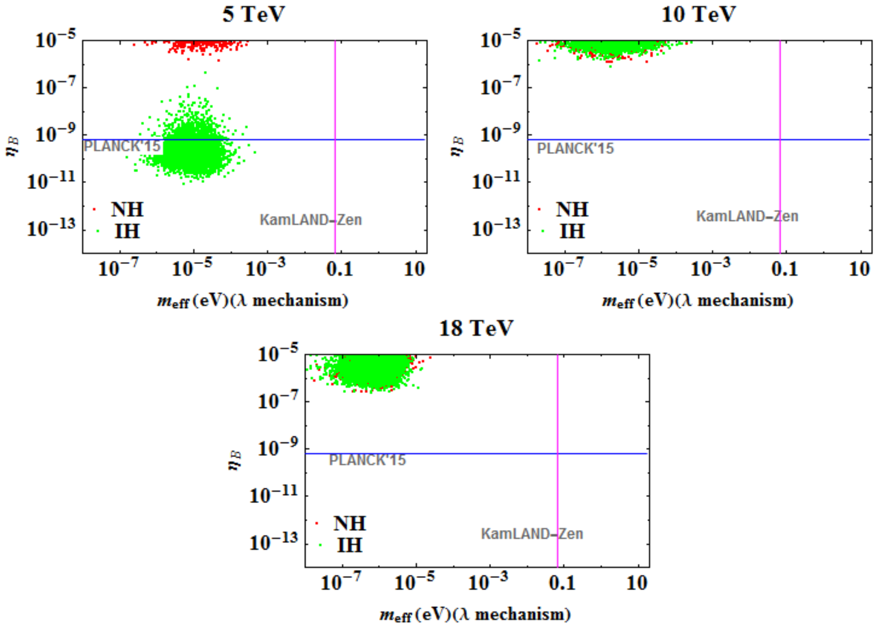


Figure 3.9: BAU against effective Majorana neutrino mass (for $\lambda$ mechanism) . The solid blue and pink line represents the observed BAU and the KAMLAND upper bound on effective Majorana neutrino mass respectively.

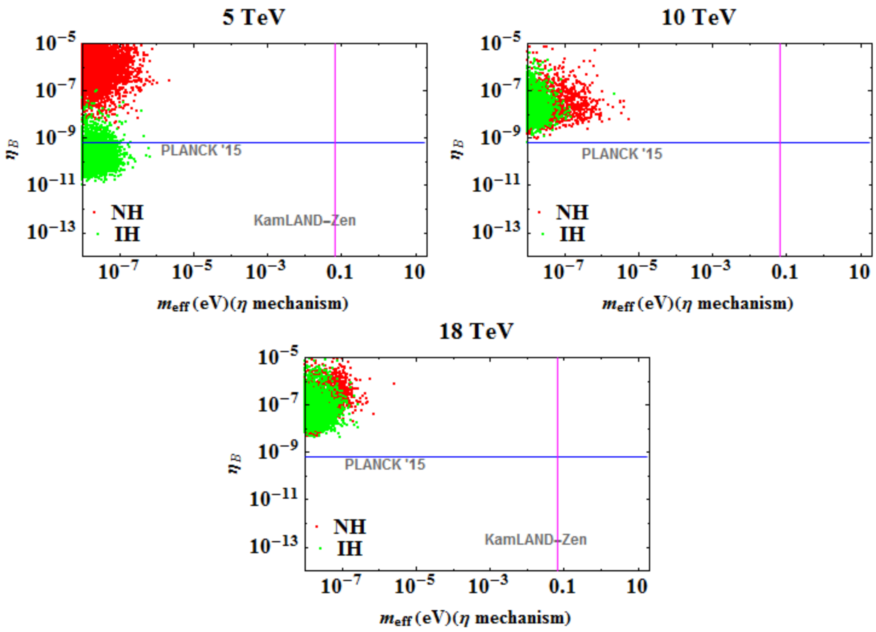


Figure 3.10: BAU against effective Majorana neutrino mass (for $\eta$ mechanism).The solid blue and pink line represents the observed BAU and the KAMLAND upper bound on effective Majorana neutrino mass respectively.

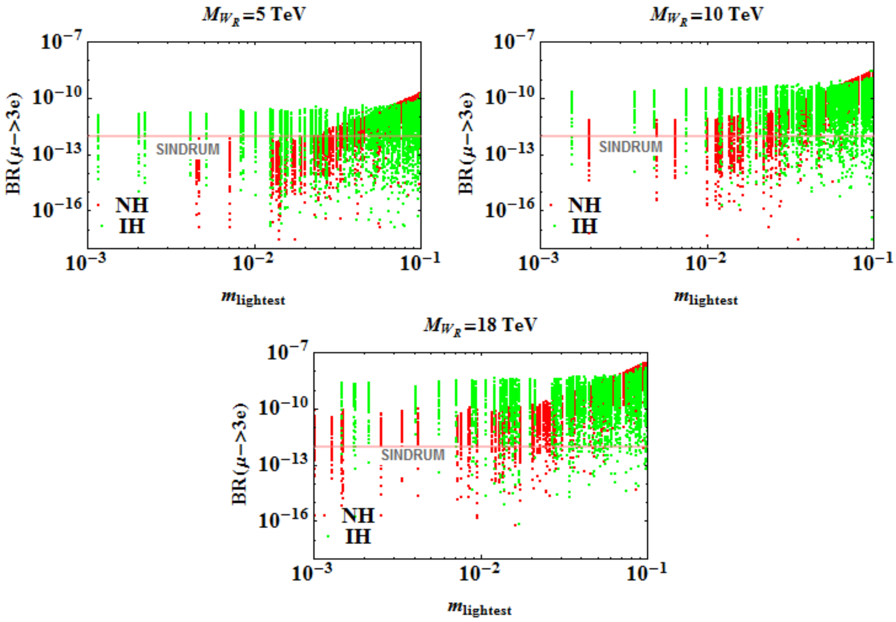


Figure 3.11: BR for $\mu \to 3e$ shown as a function of the lightest neutrino mass. The horizontal line represents the limit of BR as given by SINDRUM experiment.

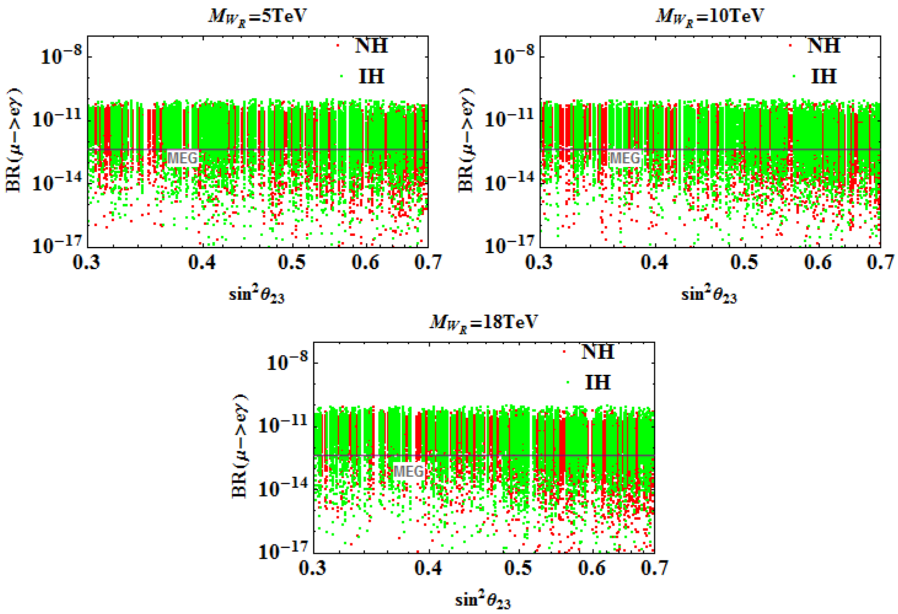


Figure 3.12: BR for $\mu \to e\gamma$ shown as a function of the atmospheric mixing angle. The horizontal line shows the limit of BR as given by MEG experiment.

| OBSERVABLES | 5 TeV NH (IH) | 10 TeV NH (IH) | 18 TeV NH (IH) |
|---|---|---|---|
| NDBD($N_R$) | ✓(✓) | ✓(✓) | ✓(✓) |
| NDBD($\lambda$) | ✓(✓) | ✓(✓) | ✓(✓) |
| NDBD($\eta$) | ✓(✓) | ✓(✓) | ✓(✓) |
| BAU | ✓(✓) | ✓(✓) | ✓(✓) |
| BAU and NDBD($N_R$) | ×(×) | ×(✓) | ✓(✓) |
| BAU and NDBD($\lambda$) | ×(✓) | ×(×) | ×(×) |
| BAU and NDBD($\eta$) | ×(✓) | ×(×) | ×(×) |
| BR($\mu \to 3e$) | ✓(✓) | ✓(✓) | ✓(✓) |
| BR($\mu \to e\gamma$) | ✓(✓) | ✓(✓) | ✓(✓) |

Table 3.1: summarized form of the results for NDBD, BAU, LFV for both NH and IH. The ✓ and × symbol are used to denote if the observables are (not are) in the current experimental limit

## 3.4 Discussion and conclusion

While calculating the NDBD contribution and BAU we concentrated on an important issue that whether both the phenomena can be correlated in TeV scale or not. As addressed by the author in [11] TeV-scale LRSM, there are complications due to the presence of RH gauge interactions that contribute to the dilution and washout of the primordial lepton asymmetry generated via resonant leptogenesis. Combined with the dilution effects from inverse decays and entropy, this implies that even for maximal CP asymmetry the observed baryon-to-photon ratio can be obtained only if $M_{W_R} \geq 18$ TeV. They have focused on the possibilities of falsification of leptogenesis owing to the possible experimental observation of RH gauge boson mass of around $(3-5)$ TeV. But in the recent papers, [12] [13] authors have taken up this issue and claim that one can generate the baryon asymmetry within the experimental limit even if RH gauge boson mass is as low as 5 TeV. In their work, instead of assuming maximal CP asymmetry, they calculated the primordial CP asymmetry as demanded by their specific neutrino fix. Furthermore, they have also shown the consistency of their model with other low energy constraints like NDBD, LFV etc. thereby specifying the fact that just the possible observation of $W_R$ at LHC alone cannot falsify leptogenesis as a mechanism to generate a matter-antimatter asymmetry of the universe. Since the main purpose of our work is to see if there is a common parameter space where we can establish a linkage between baryogenesis and the low scale phenomenon like NDBD and LFV, we have done a phenomenological study of these phenomenon at a TeV scale LRSM considering some specific values of RH Gauge boson mass, 5 TeV, 10 TeV and 18 TeV (as found separately in the earlier works) and check the consistency of the previous results. Based on our study, we could arrive at the following conclusions,

- For a low scale model independent seesaw model, one can account for successful leptogenesis and also the constraints that come after regarding mass of the RH gauge bosons is that larger parameter space for BAU with the observed cosmological value is obtained for $M_{W_R}$ = 18 TeV than for 5 TeV.

- New Physics contributions to NDBD in TeV scale LRSM for different $M_{W_R}$ shows that dominant contribution comes from the exchange of RH gauge boson rather than the mixed, LH-RH gauge boson mixing contributions. The $\lambda$ contributions to NDBD is a bit suppressed owing to the less Yukawa coupling and not so large left-right mixing in our analysis while $\eta$ contribution is further suppressed by two orders of magnitude that the $\lambda$ contribution.

- It is possible to obtain a common parameter space for both NDBD and BAU. This corresponds to the NDBD contribution coming from the heavy RH neutrino for both NH and IH. However, in this case, better results are obtained for 18 TeV RH gauge boson mass. Whereas, as far as the momentum dependent $\lambda$ and $\eta$ mechanisms are concerned, both NDBD and BAU can be simultaneously explained for $M_{W_R}$ =5 TeV or $\leqslant$ 10 TeV and only for IH.

- Sizable implications for other low energy observable, charged LFV of the processes, $\mu \rightarrow 3e$ and $\mu \rightarrow e\gamma$ are obtained for a minimal TeV scale LRSM which simultaneously accounts for BAU and NDBD.

  For LFV, the BR prediction for $\mu \rightarrow e\gamma$ is not much dependent on the atmospheric mixing angle, $\theta_{23}$.

Having done an extensive study of several of the earlier works, we have found that our results are in accordance with the previous works where low scale phenomena are discussed. That successful leptogenesis can be found within the vicinity of the experimental limit for RH gauge boson mass as low as 5 TeV and is not much dependent on the mass hierarchy, NH or IH. However, both low scale BAU and effective mass governing NDBD can be simultaneously obtained only for some parameter space that depends on the mass hierarchy and the $W_R$ mass as mentioned in the above points. Notwithstanding a more detailed study is preferred to give a strong concluding remark.

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