Leptogenesis studied in minimal left-right symmetric model with A_4 modular symmetry

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Presented by - Ankita Kakoti
Department of Physics, Tezpur University
(Under the supervision of Prof. Mrinal Kumar Das)

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Left-Right Symmetric Model

- **Left-Right Symmetric Model (LRSM)**
  - An extension of Standard Model of Particle Physics.
  - The gauge group is $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ [1, 2, 3, 4, 5].
  - Type-I and Type-II seesaw masses appear naturally in LRSM.
  - The scalar sector in the model consists of a Higgs bidoublet, ϕ(2,2,0), and two scalar triplets namely, $\Delta_R(1,3,2)$ and $\Delta_L(3,1,2)$.

Gauge group	l_L	l_R	ϕ	Δ_L	Δ_R
$SU(2)_L$	2	1	2	3	1
$SU(2)_R$	1	2	2	1	3
$U(1)_{B-L}$	-1	-1	0	2	2

Table 1: Charge assignments for the particle content of the model

Left-Right Symmetric Model

- For the fermions to attain mass in our model, a Yukawa Lagrangian is necessary which couples to the bidoublet ϕ.
- The corresponding Yukawa Lagrangian is given by,

$$\mathcal{L_D} = \overline{l_{iL}}(Y^l_{ij}\phi + \widetilde{Y^l_{ij}}\widetilde{\phi})l_{jR} + h.c$$

- The Yukawa Lagrangian for incorporating the scalar triplets which will give rise to Majorana masses to the neutrinos is given as,

$$\mathcal{L_M} = f_{L,ij}{\Psi_{L,i}}^T Ci\sigma_2\Delta_L\Psi_{L,j} + f_{R,ij}{\Psi_{R,i}}^T Ci\sigma_2\Delta_R\Psi_{R,j} + h.c$$

Left-Right Symmetric Model

The light neutrino mass after symmetry breaking is generated within a type-I+II seesaw as,

$$\mathcal{M}_\nu = \mathcal{M}_\nu^{\mathcal{I}} + \mathcal{M}_\nu^{\mathcal{II}}$$

$$\mathcal{M}_\nu = \mathcal{M}_{\mathcal{D}} \mathcal{M}_{\mathcal{RR}}{}^{-1} \mathcal{M}_{\mathcal{D}}^{\mathcal{T}} + \mathcal{M}_{\mathcal{LL}}$$

where,

$$\mathcal{M}_{\mathcal{LL}} = \sqrt{2} \nu_L f_L$$

$$\mathcal{M}_{\mathcal{RR}} = \sqrt{2} \nu_R f_R$$

Modular Symmetry

- An element q of the modular group acts on a complex variable τ which belongs to the upper half of the complex plane given as

$$q\tau = \frac{a\tau + b}{c\tau + d}$$

  where a, b, c, d are integers and $ad - bc = 1$, $\text{Im}\tau > 0$.
- The modular group is isomorphic to the projective special linear group PSL(2,Z) = SL(2,Z)/Z_2 where, SL(2,Z) is the special linear group of integer 2×2 matrices having determinant unity and $Z_2 = (I, -I)$ is the centre, I being the identity element [6].

Modular Symmetry

N	No. of modular forms	$\Gamma(N)$
2	k + 1	S_3
3	2k + 1	A_4
4	4k + 1	S_4
5	10k + 1	A_5
6	12k	
7	28k - 2	

Table 2: No. of modular forms corresponding to modular weight 2k.

LRSM with A_4 Modular Symmetry

- After incorporation of modular symmetry [6], the Yukawa Lagrangian in the lepton sector can be constructed as,

$$\mathcal{L}_{\mathcal{Y}} = \overline{l_L}\phi l_R Y + \overline{l_L}\tilde{\phi} l_R Y + {l_R}^T C \iota\tau_2 \Delta_R l_R Y + {l_L}^T C \iota\tau_2 \Delta_L l_L Y$$

	Y (modular forms)
A_4	3
k_I	2

Table 3: Charge assignment and modular weight for the corresponding modular Yukawa forms for the model

- Each of the particle in the model is now assigned with a particular modular weight, given as,

LRSM with A_4 Modular Symmetry

Particles	l_L	l_R	ϕ	Δ_L	Δ_R
k_I	0	-2	0	-2	2

Table 4: Modular weights for the particle content of the model

- From the Yukawa Lagrangian and using the A_4 multiplication rules, we have determined the Dirac and Majorana mass matrices, given by,
- The Dirac mass matrix is given as,

$$M_D = v\begin{pmatrix} 2Y_1 & -Y_3 & -Y_2 \\ -Y_2 & -Y_1 & 2Y_3 \\ -Y_3 & 2Y_2 & -Y_1 \end{pmatrix}$$

,

LRSM with A_4 Modular Symmetry

- The Majorana mass matrix is given as,

$$M_R = v_R \begin{pmatrix} 2Y_1 & -Y_3 & -Y_2 \\ -Y_3 & 2Y_2 & -Y_1 \\ -Y_2 & -Y_1 & 2Y_3 \end{pmatrix}$$

- The type I and type II mass matrices were determined to be,

$$M_I^\nu = \frac{v^2}{v_R} \begin{pmatrix} 2Y_1 & -Y_2 & -Y_3 \\ -Y_2 & -2Y_3 & -Y_1 \\ -Y_3 & -Y_1 & 2Y_2 \end{pmatrix}$$

$$M_{II}^\nu = v_L \begin{pmatrix} 2Y_1 & -Y_3 & -Y_2 \\ -Y_3 & 2Y_2 & -Y_1 \\ -Y_2 & -Y_1 & 2Y_3 \end{pmatrix}$$

Resonant Leptogenesis

- Considering TeV scale model, an adequate amount of leptogenesis is generated by the phenomenon of Resonant Leptogenesis (RL) [7].
- For RL however there is a basic requirement that the a pair of Majorana neutrinos must have a mass difference comparable to their decay widths, that is, $M_i - M_j = \Gamma$, where Γ is the decay width given by, $\Gamma_i = (Y_\nu^\dagger Y_\nu)_{ii} \frac{M_i}{8\pi}$.
- The CP violating asymmetry is given by [8],

$$\epsilon_i = \frac{Im[(Y_\nu^\dagger Y_\nu)_{ij}^2]}{(Y_\nu^\dagger Y_\nu)_{11}(Y_\nu^\dagger Y_\nu)_{22}} . \frac{(M_i - M_j)^2 M_i \Gamma_j}{(M_i^2 - M_j^2) + M_i^2 \Gamma j^2}$$

The variables i, j run over 1 and 2 and $i \neq j$.

Resonant Leptogenesis

- The net baryon asymmetry is then calculated using the following relation [9],

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

k_i being the efficiency factors measuring the washout effects.

Neutrinoless Double Beta Decay

- Neutrinoless Double Beta Decay ($0\nu\beta\beta$) is a lepton number violating process which if proven to exist will directly imply the Majorana nature of neutrinos.

$$N(A, Z) \rightarrow N(A, Z+2) + e^- + e^-$$

- There are in total eight contributions of $0\nu\beta\beta$ within LRSM, however in the present scenario we are concerned only about,
  - Heavy right-handed neutrino contribution
  - λ contribution
  - η contribution

Numerical Analysis

- As type-I and type-II seesaw masses appear naturally in LRSM, so both the terms can have significant contribution towards the determination of light neutrino mass.
- In this work, we have varied the strengths of the type-II seesaw mass using the equation,

$$M_{\nu}^{II(diag)} = XM_{\nu}^{(diag)} \tag{1}$$

where, the parameter X is introduced to describe the relative strength of the type-II seesaw mass term. In our case we have considered $X = 0.3, 0.5, 0.7$ that is, contribution from type-II seesaw term is considered to be $30\%, 50\%, 70\%$ respectively.

Numerical Analysis

- Again in LRSM, M_R can be expressed in terms of the type-II seesaw mass, given by,

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

where, v_R corresponds to the different $SU(2)_R$ breaking scales.

Figures

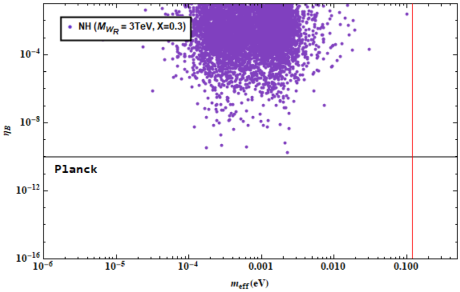

Figure 1: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3\,TeV$ and $X = 0.3$ for normal hierarchy (NH).

Figures

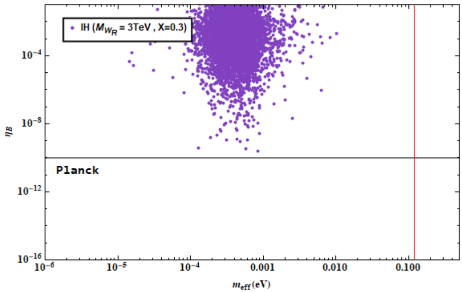

Figure 2: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3TeV$ and $X = 0.3$ for inverted hierarchy (IH).

Figures

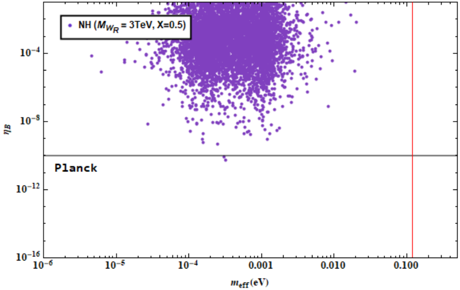

Figure 3: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3\,TeV$ and $X = 0.5$ for NH.

Figures

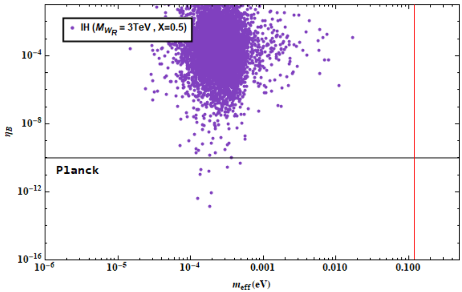

Figure 4: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3TeV$ and $X = 0.5$ for IH.

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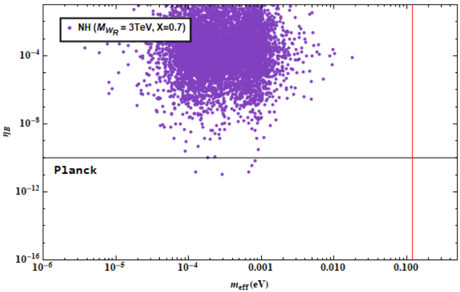

Figure 5: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3\,TeV$ and $X = 0.7$ for NH.

Figures

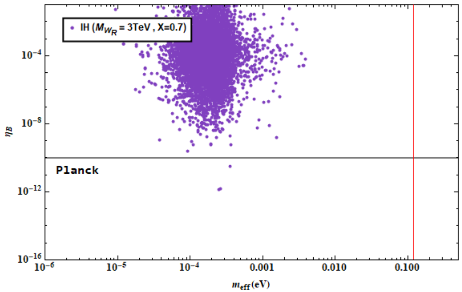

Figure 6: Variation of baryon asymmetry parameter η_B with the effective mass for heavy right-handed neutrino contribution for $M_{W_R} = 3TeV$ and $X = 0.7$ for IH.

Figures

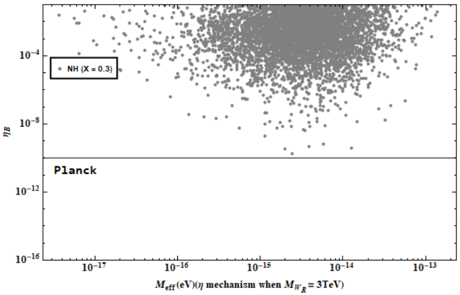

Figure 7: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.3$ for NH.

Figures

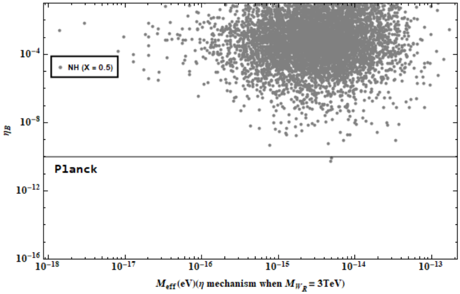

Figure 8: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.5$ for NH.

Figures

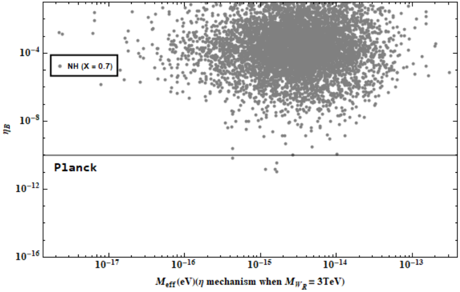

Figure 9: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.7$ for NH.

Figures

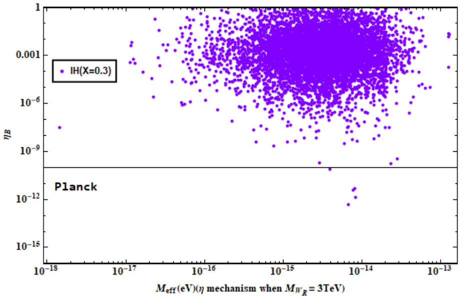

Figure 10: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.3$ for IH.

Figures

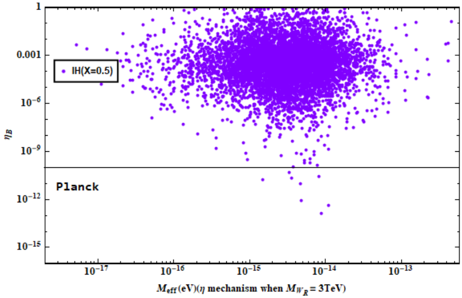

Figure 11: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.5$ for IH.

Figures

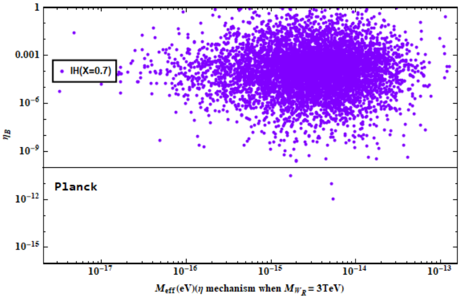

Figure 12: Variation of baryon asymmetry parameter η_B with the effective mass for η contribution for $M_{W_R} = 3TeV$ and $X = 0.7$ for IH.

Figures

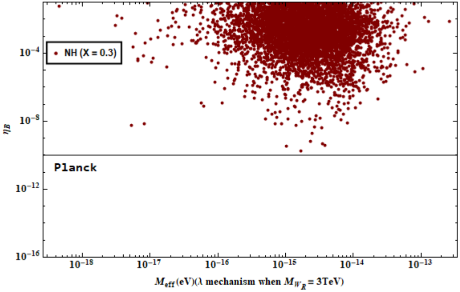

Figure 13: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3TeV$ and $X = 0.3$ for NH.

Figures

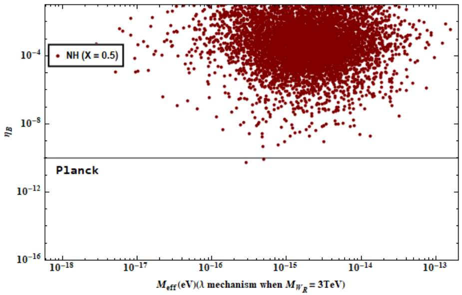

Figure 14: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3TeV$ and $X = 0.5$ for NH.

Figures

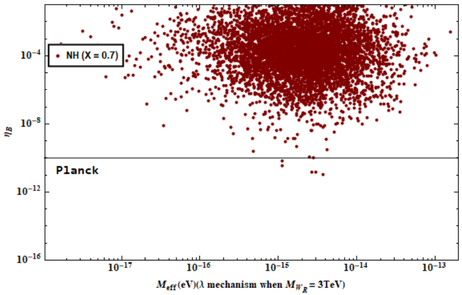

Figure 15: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3TeV$ and $X = 0.7$ for NH.

Figures

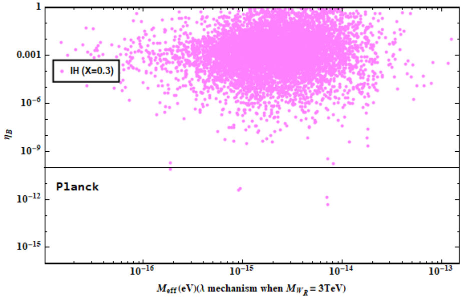

Figure 16: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3TeV$ and $X = 0.3$ for IH.

Figures

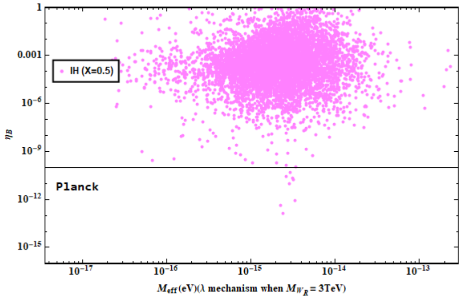

Figure 17: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3TeV$ and $X = 0.5$ for IH.

Figures

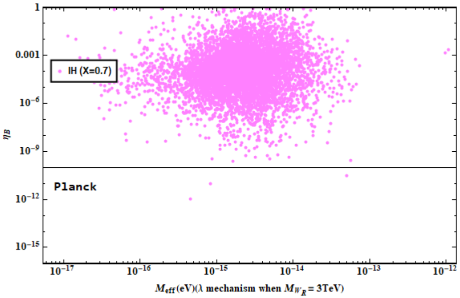

Figure 18: Variation of baryon asymmetry parameter η_B with the effective mass for λ contribution for $M_{W_R} = 3\,TeV$ and $X = 0.7$ for IH.

Discussion

- The modular symmetry when implemented on the model does not demand the use of extra particles, and as such the model remains minimal.
- The Yukawa couplings are expressed in terms of modular forms and the mass matrices hence determined from the Lagrangian come up to be dependent on (Y_1, Y_2, Y_3). Hence, the values of these modular forms will highly influence the values for the neutrino masses obtained from the model.

Discussion

- It is to be noted that the present model has been designed in the non-SUSY framework and as such, the Left-Right Symmetric Model does not restrict the use of an infinite number of modular forms, but as we are using $\Gamma(3)$ modular group having weight 2, we will have three number of modular forms represented as (Y_1, Y_2, Y_3). As such, the mass matrices corresponding to the present model have been expressed in terms of these three modular forms.

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Thank You