A_4 Modular Symmetry on Linear Seesaw with Leptogenesis

Fermilab Workforce Development & Resources Section

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Abstract

- The ingenuity of this work is to build a model that explains neutrino oscillation data under A_4 Modular symmetry making usage of Linear Seesaw mechanism along with comment on Leptogenesis.
- The Standard Model (SM) is extended by three RH neutrinos (N_{Ri}) and three Sterile neutrinos (S_{Li}) along with one flavon field which eliminates unwanted terms in the Lagrangian and keeping the model consistent.

Introduction

- A_4 **Modular Symmetry:** A_4 modular symmetry minimizes the use of flavon fields and in addition the modular group is the group of linear fractional transformation acting on a complex variable τ.

$$\tau \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}\,, \text{ where } a,b,c,d \in \mathbb{Z}$$
$$\text{and } ad - bc = 1, \ \ \mathrm{Im}[\tau] > 0$$

- The Yukawa couplings: $\mathbf{Y} = (y_1, y_2, y_3)$, transforming as a triplet under A_4 with modular weight $k_I = 2$ can be expressed in terms of Dedekind eta-function $\eta(\tau)$ and its derivative, given as

$$\eta(\tau) = e^{\frac{i\pi\tau}{12}} \prod_{n=1}^{\infty}(1 - e^{2in\tau\pi})$$

where, $\tau \in$ H, $x = e^{2i\pi\tau}$, $|x| < 1$ (H represents upper half plane)

- **Linear Seesaw:** The light neutrino mass matrix under the linear seesaw in the flavor basis of (ν_L, N_R, S_L^c) is expressed as

$$\mathbb{M} = \begin{pmatrix} 0 & M_D & M_{LS} \\ M_D^T & 0 & M_{RS} \\ M_{LS}^T & M_{RS}^T & 0 \end{pmatrix}$$

- The resulting mass formula

$$m_\nu = M_D M_{RS}^{-1} M_{LS}^T + \text{transpose} \tag{1}$$

Model Framework

- The particle content of the model and their Quantum nos are given in Table 1.
- Thus, one can write the interaction Lagrangian for the **Charged Lepton, Dirac, Pseudo-Dirac, Mixing of Heavy fermions** N_R **&** S_L as given in Eqns. 2, 3, 4, 5 respectively

$$\mathcal{L}_{M_\ell} = y_\ell^{ee}\overline{L}_{e_L} H e_R + y_\ell^{\mu\mu}\overline{L}_{\mu_L} H \mu_R + y_\ell^{\tau\tau}\overline{L}_{\tau_L} H \tau_R + \text{h.c.}, \tag{2}$$

$$\mathcal{L}_D = \alpha_D \overline{L}_{e_L}\widetilde{H}(\mathbf{Y}N_R)_1 + \beta_D \overline{L}_{\mu_L}\widetilde{H}(\mathbf{Y}N_R)_{1'} + \gamma_D \overline{L}_{\tau_L}\widetilde{H}(\mathbf{Y}N_R)_{1''} + \text{h.c.}, \tag{3}$$

$$\mathcal{L}_{LS} = \left[\alpha'_D \overline{L}_{e_L}\widetilde{H}(\mathbf{Y}S_L^c)_1 + \beta'_D \overline{L}_{\mu_L}\widetilde{H}(\mathbf{Y}S_L^c)_{1'} + \gamma'_D \overline{L}_{\tau_L}\widetilde{H}(\mathbf{Y}S_L^c)_{1''}\right]\frac{\rho^3}{\Lambda^3} + \text{h.c.}, \tag{4}$$

$$\mathcal{L}_{M_{RS}} = [\alpha_{SN}\mathbf{Y}(\overline{S_L}N_R)_{\text{symm}} + \beta_{SN}\mathbf{Y}(\overline{S_L}N_R)_{\text{Anti-symm}}]\rho + \text{h.c.} \tag{5}$$

Fields	e_R	μ_R	τ_R	L_L	N_R	S_L	H	ρ
$SU(2)_L$	1	1	1	2	1	1	2	1
$U(1)_Y$	-1	-1	-1	$-1/2$	0	0	$1/2$	0
$U(1)_X$	1	1	1	1	1	2	0	1
A_4	1	$1'$	$1''$	$1, 1'', 1'$	3	3	1	1
k_I	1	1	1	1	-1	1	0	0

Table 1: Particle content of the model and their charges under $SU(2)_L \times U(1)_Y \times U(1)_X \times A_4$ where k_I is the number of modular weight.

Mass Matrix and Mixing Angles Expression

$$M_\ell = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \ M_D = \frac{v}{\sqrt{2}}\begin{pmatrix} y_1\alpha_d & y_3 & y_2 \\ y_2 & y_1\beta_d & y_3 \\ y_3 & y_2 & y_1\gamma_d \end{pmatrix}, \ M_{LS} = \frac{v v_\rho{}^3}{\sqrt{2}\Lambda^3}\begin{pmatrix} y_1\alpha_d & y_3 & y_2 \\ y_2 & y_1\beta_d & y_3 \\ y_3 & y_2 & y_1\gamma_d \end{pmatrix}$$

$$M_{RS} = \frac{v_\rho}{\sqrt{2}}\left[\alpha_{NS}\begin{pmatrix} 2y_1 & -y_3 & -y_2 \\ -y_3 & 2y_2 & -y_1 \\ -y_2 & -y_1 & 2y_3 \end{pmatrix} + \beta_{NS}\begin{pmatrix} 0 & y_3 & -y_2 \\ -y_3 & 0 & y_1 \\ y_2 & -y_1 & 0 \end{pmatrix}\right]$$

$$\sin^2\theta_{13} = |U_{13}|^2, \quad \sin^2\theta_{23} = \frac{|U_{23}|^2}{1 - |U_{13}|^2}, \quad \sin^2\theta_{12} = \frac{|U_{12}|^2}{1 - |U_{13}|^2}. \ [U \text{ diagonalizes matrix (1)}]$$

Results

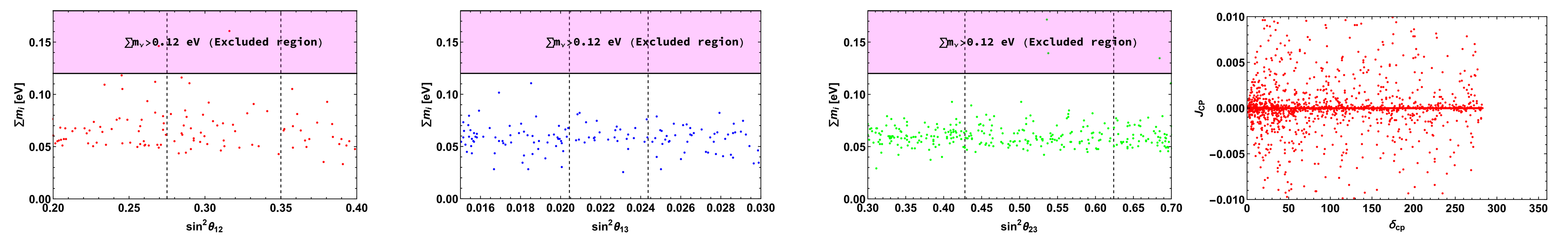

Figure 1: These plots express mixing angles $\sin^2\theta_{12}$ (extreme left), $\sin^2\theta_{13}$ & $\sin^2\theta_{23}$ (middle) versus Σm_i[eV], J_{CP} vs Dirac CP phase (δ_{CP}) (extreme right).

Leptogenesis

- To incorporate leptogenesis, a higher dimensional mass term is introduced for the Majorana fermion (N_R) as in eqn.(6), prompting a small mass splitting between the heavy fermions, which lead the way to observe lepton asymmetry, where α_R is the coupling.

$$L_M = -\alpha_R Y \overline{N_R^c} N_R \frac{\rho^2}{\Lambda} + \text{ H.c.}, \tag{6}$$

- This mass splitting generates lepton asymmetry through resonant leptogenesis for benchmark values $|y_1| = 1$, $|y_2| = 0.5$, $m_\nu = 0.07$ eV & $\Delta M = 5.3 \times 10^{-4}$ GeV we obtain $\epsilon_{CP} = 9.5 \times 10^{-6}$.

Conclusion

- We have studied the linear seesaw mechanism under modular A_4 symmetry along with the $U(1)_X$ global symmetry, where these symmetries forbid unnecessary terms and restrict structures of relevant Yukawa interactions.
- We were able to successfully explain the observed neutrino oscillation data (mixing angles and the mass-squared differences) as well as the cosmological bound on neutrino masses i.e., $\Sigma m_i \leqslant 0.12$ eV.
- Due to a small mass splitting generated by the presence of higher dimension mass term helps to observe a nonzero CP asymmetry and lepton asymmetry whose order is $\approx 10^{-10}$, which successfully elucidate the current baryon asymmetry.
- For more details please refer paper M. K. Behera, S. Mishra, S. Singirala and R. Mohanta *Implications of A_4 modular symmetry on Neutrino mass, Mixing and Leptogenesis with Linear Seesaw*, arXiv:2007.00545 [hep-ph].