Leptogenesis in a Left-Right Symmetric Model with double seesaw

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Introduction

Leptogenesis is a widely studied phenomenon to explain the observed matter-antimatter asymmetry of the universe. However, it depends on high energy parameters, which could be inaccessible to probe in current or future experiments. Motivated by these constraints, we investigate the relationship between the low-energy CP-violating Dirac phase (δ) and the high-energy CP asymmetry parameter (ϵ, relevant for leptogenesis) in a Left-Right Symmetric Model (LRSM) with scalar bidoublet and doublets. We establish a novel approach to directly connect low and high-energy CP violations without employing any parametrization for M_D. This connection is an exciting motivation for current long baseline experiments like NOvA, T2K, DUNE and future experiments like JUNO to indirectly probe leptogenesis through δ.

Model Framework

$$\mathcal{G}_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

Fermion Sector

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix};\; q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix};$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix};\; \ell_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} + \underbrace{S_L}_{\text{Singlet \& per gen}}$$

Scalar Sector

$$\underbrace{\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}}_{\text{Higgs bidoublet}};\; \underbrace{H_L = \begin{pmatrix} h_L^+ \\ h_L^0 \end{pmatrix}}_{\text{Higgs doublet}};\; \underbrace{H_R = \begin{pmatrix} h_R^+ \\ h_R^0 \end{pmatrix}}_{\text{Higgs doublet}}$$

LR Symmetry

Charge Conjugation: C

Double Seesaw (Neutrino Mass Generation)

Interaction Lagrangian

$$\mathcal{L}_{LRDSM} = \mathcal{L}_{M_D} + \mathcal{L}_{M_{RS}} + \mathcal{L}_{M_S}$$

$$= -\sum_{\alpha,\beta} \overline{\nu_{\alpha L}}[M_D]_{\alpha\beta} N_{\beta R} - \sum_{\alpha,\beta} \overline{S_{\alpha L}}[M_{RS}]_{\alpha\beta} N_{\beta R}$$

$-\frac{1}{2}\sum_{\alpha,\beta} \overline{S^c_{\alpha R}}[M_S]_{\alpha\beta} S_{\beta L}$+ h.c.

After SSB, the complete 9×9 neutral fermion mass matrix in the flavor basis of (ν_L, N_R^c, S_L)

$$\mathcal{M}_{LRDSM} = \begin{bmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_{RS} \\ 0 & M_{RS}^T & M_S \end{bmatrix}$$

Block diagonalization with the assumption $|M_D| \ll |M_{RS}| < |M_s|$, gives [1,2]

Double Seesaw (DSS) Result

$$m_\nu \cong -M_D\left(-M_{RS}M_S^{-1}M_{RS}^T\right)^{-1} M_D^T$$
$$m_N \equiv M_R \cong -M_{RS}M_S^{-1}M_{RS}^T,$$
$$m_S \cong M_S\,.$$

Deriving $\mathrm{M_D}$

Basis Choice

- In our basis, the charged lepton mass matrix is diagonal.
- Light neutrino Majorana mass matrix is diagonalized with $U_\nu \equiv U_{PMNS}$, $\hat{m}_\nu = U_\nu^\dagger m_\nu U_\nu^*$.
- Right handed neutrino mass matrix is diagonalized by U_N as $\hat{m}_N = U_N^\dagger m_N U_N^*$.

Screening

We consider the screening condition [3]:

$$M_D = \frac{M_{RS}^T}{k} \rightarrow M_S = k^2 m_\nu$$

$$\implies \underbrace{U_S = U_\nu \implies \hat{m}_S = U_\nu^\dagger M_S U_\nu^*}_{\text{screening result}}$$

We have $m_N = -M_{RS}M_S^{-1}M_{RS}^T$.
Using screening result for M_S and by utilising the DSS result, we can write $\hat{m}_N$ as:

$$\hat{m}_N = U_N^\dagger m_N U_N^* = -\underbrace{U_N^\dagger M_{RS} U_\nu^*}\,\hat{m}_S^{-1}\,\underbrace{U_\nu^\dagger M_{RS}^T U_N^*}$$

For above equation to be consistent, RHS should be diagonal. As $\hat{m}_S^{-1}$ is diagonal, it implies that

$$U_N^\dagger M_{RS} U_\nu^* = \hat{m}_{RS}$$

We have considered $\mathbf{C}$ **symmetry as the LR discrete symmetry** in our model framework, therefore M_D and M_{RS} are symmetric matrices. This implies that $U_N = U_\nu$

We have relations: $m_N = -M_{RS}M_S^{-1}M_{RS}^T$ and $M_S = k^2 m_\nu$. Thus, we get

$$\implies M_{RS} = m_\nu\sqrt{-k^2 m_\nu^{-1} m_N}$$

Using all the results deduced for unitary mixing matrices and extracting the square root of matrices, we get M_D as:

$$\mathbf{M_D = \frac{1}{k}M_{RS} = i.U_\nu \hat{m}_\nu (\hat{m}_\nu^{-1}\hat{m}_R)^{1/2} U_\nu^T}$$

Simplifying and rewriting in matrix form, we have

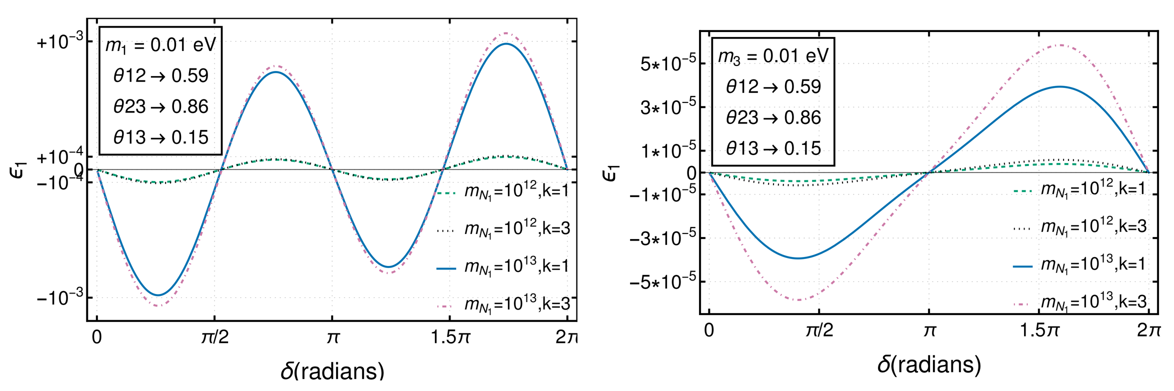
$$M_D = i.U_\nu \begin{bmatrix} \sqrt{m_1.m_{N_1}} & 0 & 0 \\ 0 & \sqrt{m_2.m_{N_2}} & 0 \\ 0 & 0 & \sqrt{m_3.m_{N_3}} \end{bmatrix} U_\nu^T$$

High-Low CP-Violation Connection

$$\underbrace{\epsilon}_{\text{CP-Asymmetry}} \approx -\frac{3.m_{N_1}}{16\pi v^2 (M_D^\dagger M_D)_{11}}\left[\frac{Im[(M_D^\dagger M_D)_{21}^2]}{m_{N_2}} + \frac{Im[(M_D^\dagger M_D)_{31}^2]}{m_{N_3}}\right]$$

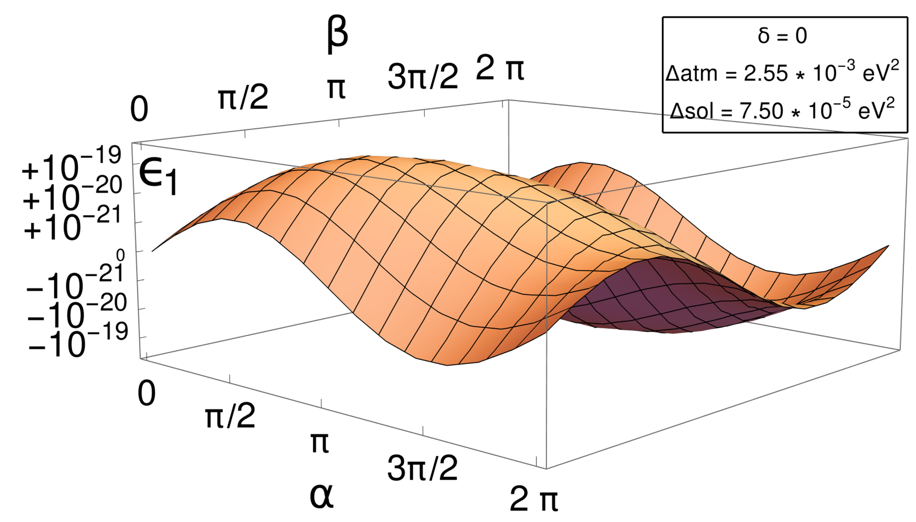
This CP-asymmetry parameter (ϵ) is the high-energy CP-violating parameter.
As $U_\nu \equiv U_\nu(\delta) \implies M_D(\delta) \implies \epsilon(\delta)$. Therefore, the high-energy CP-violation is connected with the low-energy CP-violating phase (Dirac phase δ).

Dependence on Dirac Phase

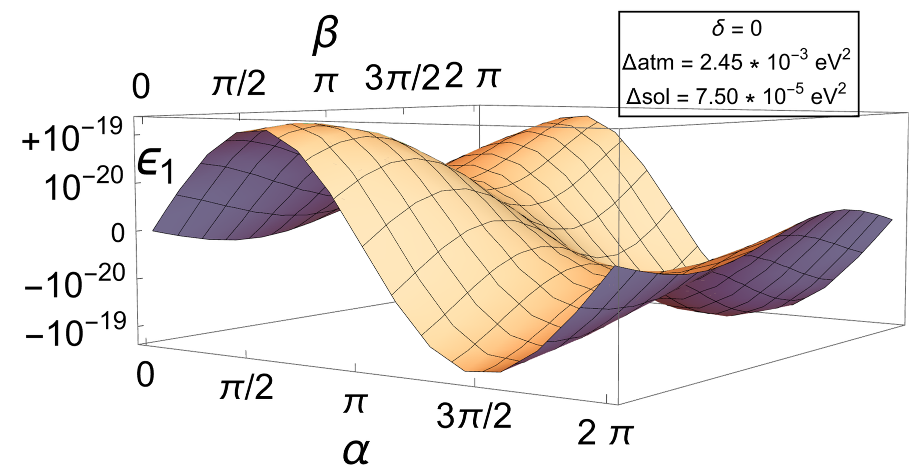


Strong dependence on Dirac phase (δ) for Normal Ordering (NO) [Left Panel] and Inverted Ordering (IO) [Right Panel]. We have:
$M_{N_2} = 1 \times 10^k \times M_{N_1}$ and $M_{N_3} = 5 \times 10^k \times M_{N_1}$.

Dependence on Majorana Phases



NO with $\delta = 0$.



IO with $\delta = 0$.

Negligible dependence on Majorana Phases, so we set α and β equal to 0 ahead.

Numerical Results

We put in relevant input parameters for the **NO** case and choose RHN masses in *GeV* **(for thermal unflavored leptogenesis)** as:

$$\mathbf{m_{N_1} = 10^{13}; m_{N_2} = 3 \times 10^{14}; m_{N_3} = 5 \times 10^{14};}$$

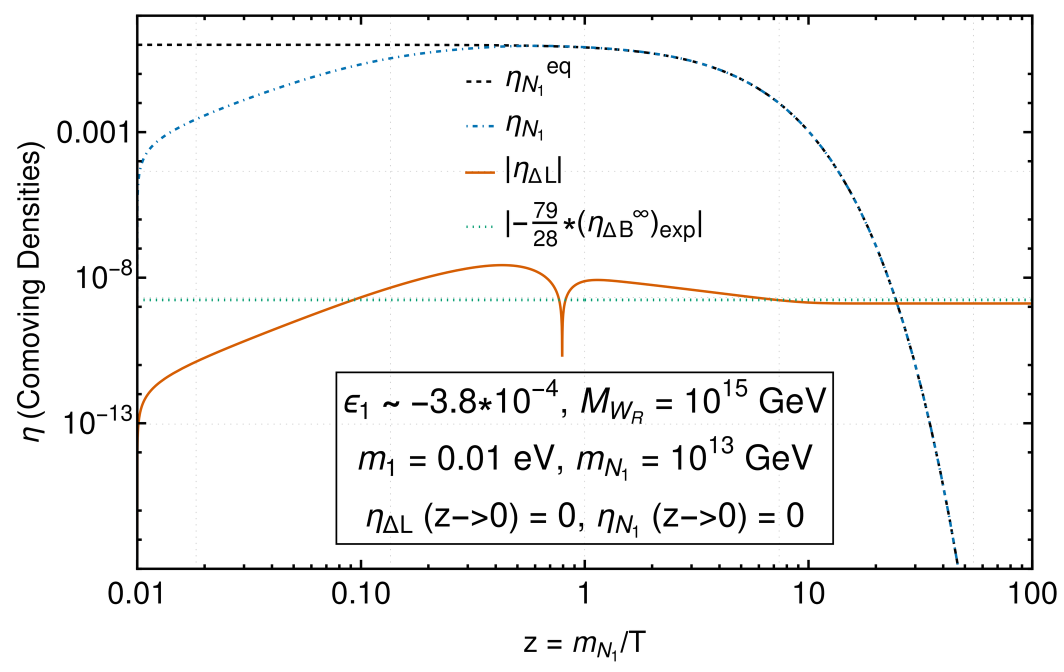
With this, CP-Asymmetry comes out to be

$$\boldsymbol{\epsilon_1 \approx -3.8 \times 10^{-4}}$$

Boltzmann Evolution | Sphelaron Process

$$\mathbf{Y_{\Delta B} \approx 6 \times 10^{-10}}$$

Asymmetry evolution for the NO case



The obtained (ϵ_1) gives a $Y_{\Delta B}$ fairly comparable to the observational results for the **NO** case.

For the **IO** case, we obtain the $Y_{\Delta B}$ value with a negative sign ($Y_{\Delta B} \approx -6 \times 10^{-10}$). Hence, it is ruled out for the considered parameter space.

Conclusion

1. A direct connection between low and high-energy CP violations by deriving M_D in the context of double-seesaw within LRSM with a small number of unknown parameters.
2. Highlights δ as the prime source for generating the required baryon asymmetry. Negligible dependence of ϵ_1 on Majorana Phases.
3. For some other choice of input parameters, a dependence on Majorana Phases may be obtained but might deviate us from the thermal unflavored regime. [A motivation for future scope]

References

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