Resonant Leptogenesis and Collider Signals from Discrete Flavor and CP Symmetries

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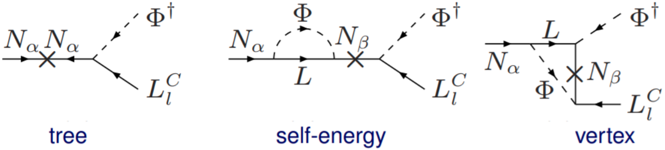
Leptogenesis

[Fukugita, Yanagida (Phys. Lett. B '86)]

- Central idea : Leptonic asymmetry in early Universe is converted to baryonic asymmetry through B-L conserving EW sphaleron interactions.
- Add SM-singlet heavy Majorana neutrinos.

$$\mathcal{L}_l = Y_l \bar{L}_l H l_R + Y_D \bar{L}_l \tilde{H} N + \frac{1}{2} \bar{N}^c M_R N + h.c.$$

- Satisfies all 3 Sakharov conditions.
  - CP violation in the leptonic sector (through complex Y_D and/or U_{PMNS} phases)
  - L violation due to the Majorana nature of the heavy RH neutrinos
  - Departure from thermal equilibrium when $\Gamma_N \leq H$
- It can connect neutrino mass mechanism and matter-antimatter asymmetry.



$$\varepsilon_{l\alpha} = \frac{\Gamma(N_\alpha \to L_l \Phi) - \Gamma(N_\alpha \to L_l^c \Phi^c)}{\sum_k \left[\Gamma(N_\alpha \to L_k \Phi) + \Gamma(N_\alpha \to L_k^c \Phi^c)\right]}$$

Resonant Leptogenesis

- TeV scale leptogenesis, no dependence on initial conditions.
- If $\Delta m_N \sim \Gamma_N \ll m_N$, the self energy contribution (ε-type) to the CP asymmetry becomes dominant and large (even order 1).
- The ε-type CP asymmetry,

$$\varepsilon_{N_i} = \frac{\text{Im}(h^{\nu\dagger}h^{\nu})^2_{ij}}{(h^{\nu\dagger}h^{\nu})_{ii}(h^{\nu\dagger}h^{\nu})_{jj}} \frac{(M^2_{N_i} - M^2_{N_j})M_{N_i}\Gamma_{N_j}}{(M^2_{N_i} - M^2_{N_j})^2 + M^2_{N_i}\Gamma^2_{N_j}}$$

- Order 1 CP aymmetries are possible when, [Pilaftsis '97; Pilaftsis, Underwood '03]

$$M_{N_2} - M_{N_1} \sim \frac{1}{2}\Gamma_{N_{1,2}}$$

$$\frac{\text{Im}(h^{\nu\dagger}h^{\nu})^2_{ij}}{(h^{\nu\dagger}h^{\nu})_{ii}(h^{\nu\dagger}h^{\nu})_{jj}} \sim 1$$

- This helps lower the heavy neutrino scale M_N, which can be as low as EW scale. [Pilaftsis, Underwood '05; Deppisch, Pilaftsis '10; Dev, Millington, Pilaftsis, Teresi '14]

Residual Flavor and CP Symmetries

- High energy neutrino parameters are free parameters in the leptogenesis mechanism.
- We will look at the idea of residual flavor and CP symmetries that determine lepton mixing angles, low- and high energy CP phases with only one free parameter.
- We conjecture the existence of a finite, discrete flavor symmetry G_f at a high-energy scale
- At low energies, G_f is broken to G_l in the charged lepton sector and to G_ν in the neutrino sector.
- G_l determines U_l and G_ν determines U_ν. This leads to the PMNS matrix

$$U_{PMNS} = U_l^\dagger U_\nu$$

- For G_f, we use a group of the form $\Delta(6n^2)$ with n even , $3 \nmid n$ and $4 \nmid n$..
- Residual symmetries : $G_l = Z_3$, $G_\nu = Z_2 \times CP$
- given X (CP transformation) and Z (generator of Z_2 in $\mathbf{3}$)

$$Z^\dagger(\mathbf{3})\, Y_D\, Z(\mathbf{3'}) = Y_D \quad \text{and} \quad X^\star(\mathbf{3})\, Y_D\, X(\mathbf{3'}) = Y_D^\star \ .$$

$$\text{Consistency condition :} X(\mathbf{r})\, Z(\mathbf{r}) = Z(\mathbf{r})^\star\, X(\mathbf{r})$$

- Changing to a different basis by the unitary matrix Ω that fulfills

$$\Omega^\dagger Z \Omega = \text{diag}((-1)^{z_1}, (-1)^{z_2}, (-1)^{z_3})\ z_i = 0, 1$$

it follows then $X = \Omega\Omega^T$ and $\Omega^T Y_D \Omega$ real.

Our chosen case : $\Delta(6n^2)$

- $\Omega^T Y_D \Omega$ can be diagonalized by two rotation matrices from the left and right, respectively

$$\Omega(s)(\mathbf{3})^\dagger \, Y_D \, \Omega(s)(\mathbf{3}') = R_{ij}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} R_{kl}(-\theta_R)\,.$$

- $U_{\mathrm{PMNS}} = \Omega(\mathbf{3}) \, R_{ij}(\theta_L) \, K_\nu, \qquad K_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & i^{k_1} & 0 \\ 0 & 0 & i^{k_2} \end{pmatrix} \; k_i = 0, 1, 2, 3$

- The light neutrino mass matrix m_ν follows from the type-I seesaw mechanism

$$m_\nu = m_D \, M_R^{-1} \, m_D^T\,.$$

Our chosen case : $\Delta(6n^2)$

- $$\mathrm{m}_\nu : \begin{cases} \frac{1}{M_N}\begin{pmatrix} y_1^2\,\cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \end{pmatrix} & \textbf{s even} \\ \frac{1}{M_N}\begin{pmatrix} -y_1^2\,\cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \end{pmatrix} & \textbf{s odd} \end{cases}$$
- For $y_1 = 0\,(y_3 = 0)$, we get strong normal (inverted) ordering, with $m_{\text{lightest}} = 0$.

$$\text{NO :} \qquad y_1 = 0, \quad y_2 = \pm\frac{\sqrt{M_N\sqrt{\Delta m^2_{\text{sol}}}}}{v}, \; y_3 = \pm\frac{\sqrt{M_N\frac{\sqrt{\Delta m^2_{\text{atm}}}}{|\cos 2\theta_R|}}}{v}$$

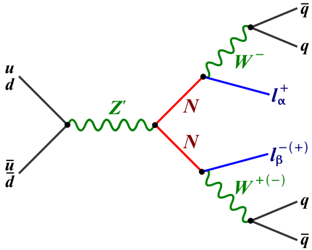
$$\text{IO :} \qquad y_3 = 0, \quad y_2 = \pm\frac{\sqrt{M_N\sqrt{\Delta m^2_{\text{atm}}}}}{v}, \; y_1 = \pm\frac{\sqrt{M_N\frac{\sqrt{|\Delta m^2_{\text{atm}}|-\Delta m^2_{\text{sol}}}}{|\cos 2\theta_R|}}}{v}$$

- Only free parameters : M_N and θ_R

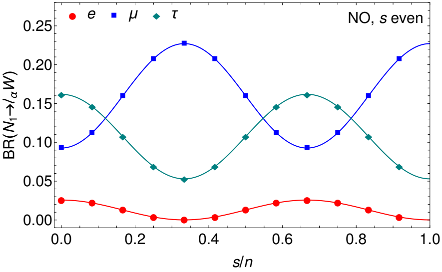
- In our scenario, $y_i \lesssim 10^{-6}$ supresses the Drell Yan production

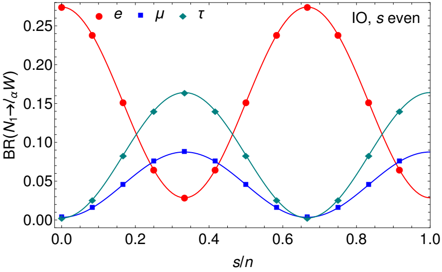
$$pp \to W^{(*)} \to N_i l_\alpha$$

- We need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- This scenario can also be embedded in SM with extended gauge symmetry
- We consider minimal $U(1)_{B-L}$ extension for enhanced production of N_i at colliders.

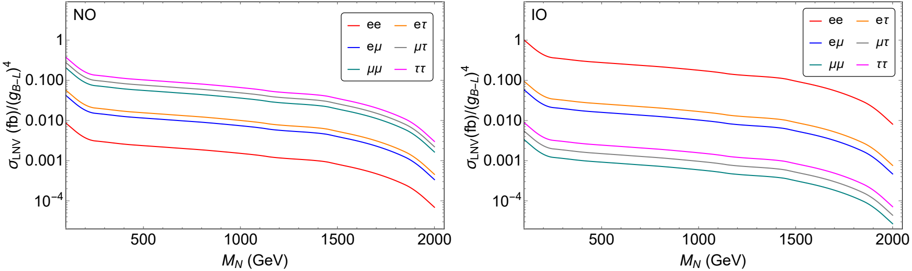


Collider Signal - Branching Ratio





For $M_{Z'} = 4$ TeV and $s = 2$, $n = 26$



Decay Lengths

- The decay widths Γ_i of the RH neutrinos N_i are given at the tree level by

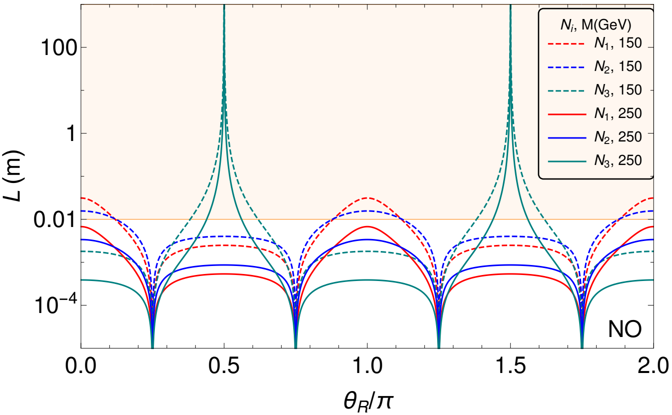
$$\Gamma_i \approx \frac{(\hat{Y}_D^\dagger \, \hat{Y}_D)_{ii}}{8\,\pi} M_i = \frac{(\hat{m}_D^\dagger \, \hat{m}_D)_{ii}}{8\,\pi\, v^2} M_i$$

- The expressions for decay widths of the 3 heavy RH neutrinos :

$$\begin{aligned}
\Gamma_1 &\approx \frac{M}{24\,\pi} \left(2\, y_1^2 \, \cos^2\theta_R + y_2^2 + 2\, y_3^2 \, \sin^2\theta_R\right) \,, \\
\Gamma_2 &\approx \frac{M}{24\,\pi} \left(y_1^2 \, \cos^2\theta_R + 2\, y_2^2 + y_3^2 \, \sin^2\theta_R\right) \,, \\
\Gamma_3 &\approx \frac{M}{8\,\pi} \left(y_1^2 \, \sin^2\theta_R + y_3^2 \, \cos^2\theta_R\right) \,.
\end{aligned}$$

- If $\theta_R \approx \pi/2,\, 3\pi/2$ (for strong NO) or $\theta_R \approx 0,\, \pi$ (for strong IO), Γ_3 tends to zero. (termed Enhanced Residual Symmetry points)
- Near points of ERS , N_3 can have a very long lifetime $\rightarrow$ N_3 may be detected in long-lived particle searches such as in MATHUSLA detector.

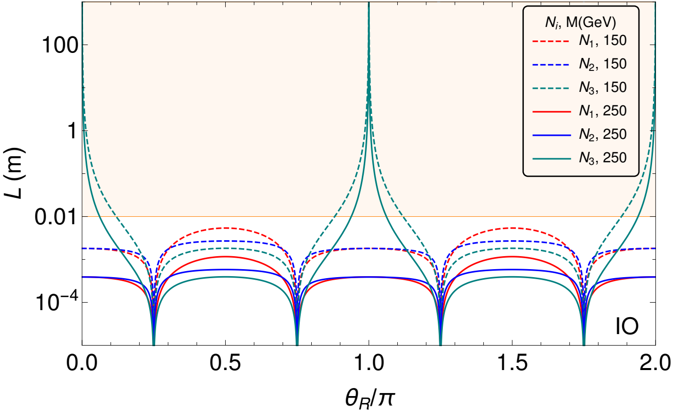
For $M_{Z'} = 4$ TeV



$\theta_R \approx \pi/2, 3\pi/2$ (ERS points)

Decay Lengths

For $M_{Z'} = 4$ TeV



$\theta_R \approx 0, \pi$ (ERS points)

Leptogenesis results

- At leading order, we have three degenerate RH neutrinos.
- Higher-order corrections can break the residual symmetries :

$$M_1 = M_N\,(1 + 2\,\kappa) \text{ and } M_2 = M_3 = M_N\,(1 - \kappa)\,.$$

- CP asymmetries in the decays of N_i are given by :

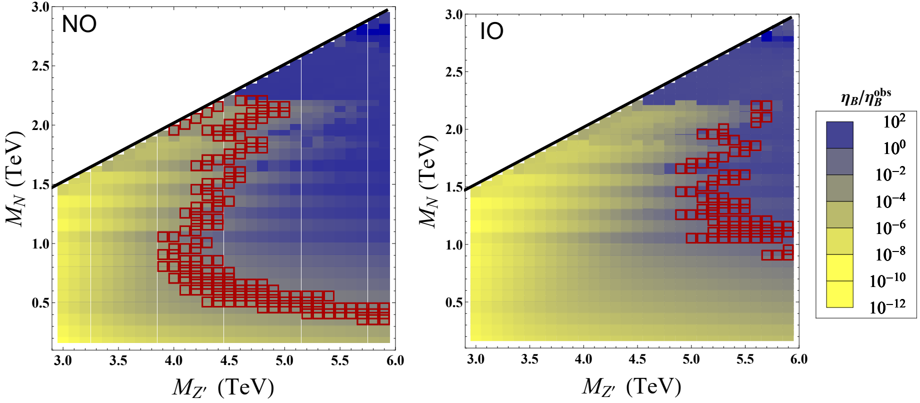
$$\epsilon_{i\alpha} \sim \sum_j \mathrm{Im}(\hat{Y}^*_{D,\alpha i} Y_{D,\alpha i})\ \mathrm{Re}(\hat{Y}^\dagger_D Y_D)_{ij}\ F_{ij}$$

- F_{ij} are related to the regulator in ReL and are proportional to the mass splitting of N_i.
- We find

$$\varepsilon_{1\alpha} \sim \frac{y_2 y_3}{9}(-2y_2^2 + y_3^2(1 - \cos 2\theta_R)) \sin 3\phi_s \sin 2\theta_R \sin \theta_{L,\alpha} F_{12} \text{ (NO)}$$

$$\varepsilon_{1\alpha} \sim \frac{y_1 y_2}{9}(-2y_2^2 + y_1^2(1 + \cos 2\theta_R)) \sin 3\phi_s \sin 2\theta_R \sin \theta_{L,\alpha} F_{12} \text{ (IO)}$$

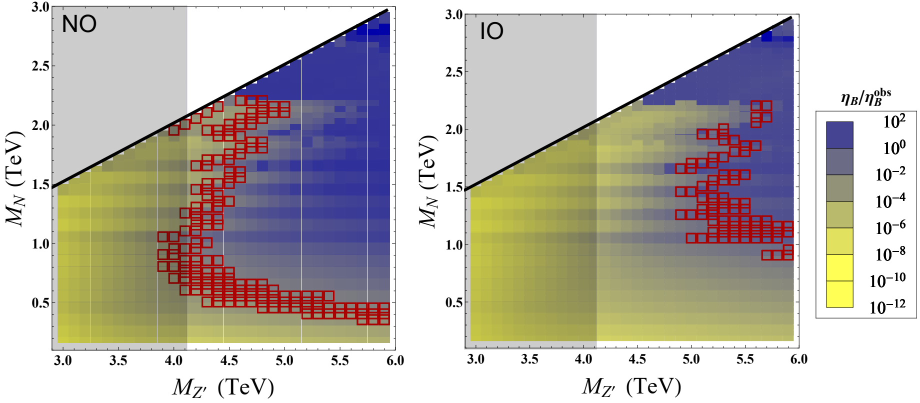
with $\theta_{L,\alpha} = \theta_L + \rho_\alpha 4\pi/3$ and $\rho_e = 0, \rho_\mu = 1, \rho_\tau = -1$



$g_{B-L} = 0.1$, $s = 2$, $n = 26$ and $\theta_R = \frac{\pi}{2}$ (0) for strong NO (IO)

$$\frac{\varepsilon_{NO}}{\varepsilon_{IO}} = \left(\frac{\Delta m^2_{\text{atm}}}{\Delta m^2_{\text{sol}}}\right)^{3/4}$$

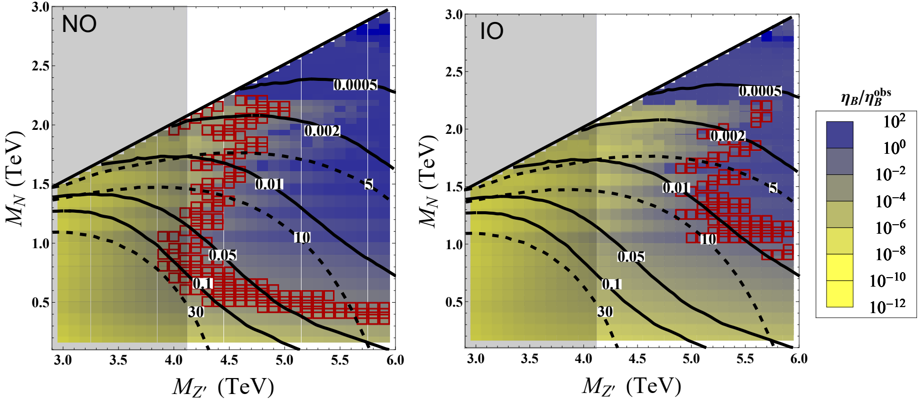
Leptogenesis results



For $g_{B-L} = 0.1, \quad M_{Z'} \gtrsim 4.12$ TeV
For $g_{B-L} = 1, \quad M_{Z'} \gtrsim 7$ TeV

Leptogenesis results

all cross sections in ab



For $g_{B-L} = 1, \quad M_{Z'} \gtrsim 7$ TeV
Enhancement from $g_{B-L}^4 \to 10^4$

- Neutrinoless double beta ($0\nu\beta\beta$) decay is one of the most important theorised LNV process to discern the Majorana nature of the neutrinos.
- The predictions for this yet unobserved process depends explicitly on the Majorana phases α and β.
- A nuclear isotope decaying through $0\nu\beta\beta$ decay would exhibit a half-life $T_{1/2}^{0\nu\beta\beta}$ of

$$\Gamma^{0\nu\beta\beta} = \frac{1}{T_{1/2}^{0\nu\beta\beta}} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{m_{ee}}{m_e}$$

$$m_{ee} = \left|U^2_{\mathrm{PMNS},11}\, m_1 + U^2_{\mathrm{PMNS},12}\, m_2 + U^2_{\mathrm{PMNS},13}\, m_3\right|$$

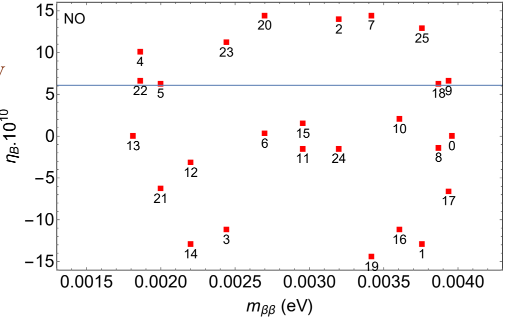
$$m_{ee} = \left|\cos^2\theta_{12}\, \cos^2\theta_{13}\, m_1 + \sin^2\theta_{12}\, \cos^2\theta_{13}\, e^{i\alpha}\, m_2 + \sin^2\theta_{13}\, e^{i\beta}\, m_3\right| .$$

- In our example case, the light neutrino contribution to $0\nu\beta\beta$ is restricted to :

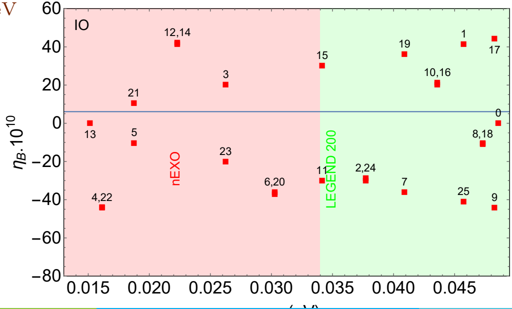
$$\mathrm{m}_{\beta\beta} : \frac{1}{3} \begin{cases} \left|\sqrt{\Delta m^2_{\text{sol}}} + 2(-1)^{s+k+1} \sin^2\theta_L e^{6i\phi_s} \sqrt{\Delta m^2_{\text{atm}}}\right| & \textbf{(NO)} \\ \left|1 + 2(-1)^{s+k+1} \cos^2\theta_L e^{6i\phi_s}\right| \sqrt{\left|\Delta m^2_{\text{atm}}\right|} & \textbf{(IO)} \end{cases}$$

$0\nu\beta\beta$ results

For $n = 26$,
$1.8\,\mathrm{meV} \lesssim m_{\beta\beta} \lesssim 4\,\mathrm{meV}$



$15\,\mathrm{meV} \lesssim m_{\beta\beta} \lesssim 48\,\mathrm{meV}$

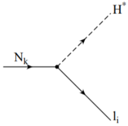


Conclusion

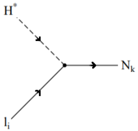
- Leptogenesis is an attractive mechanism to explain the BAU.
- Resonant Leptogenesis leads to order 1 CP asymmetry and reduces the energy scale of BAU production to TeV scale.
- The high-energy CP violating physics is disconnected from low-energy neutrino data, can be connected through role of residual flavor and CP symmetries.
- We have presented a type-I seesaw scenario with a flavour and CP symmetry as well as three RH neutrinos with almost degenerate masses in the few hundred GeV to TeV range.
- Requiring η_B to be generated via resonant leptogenesis constrains the prospects for detecting RH neutrinos at colliders
- Tight predictions for future neutrinoless double beta decay experiments can fully probe our scenario and thus provide complementary information

Supplementary Material

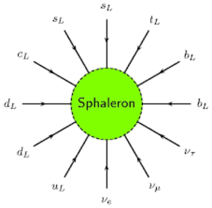
- Generation of L asymmetry in heavy Majorana neutrino N decay :



- Partial washout of the asymmetry due to inverse decay and scatterings with $\Delta L \neq 0$:



- Conversion of the leftover L asymmetry to B asymmetry at $T > T_{sph}$:



Our chosen case : $\Delta(6n^2)$

- For G_f, we use a group of the form $\Delta(6n^2)$ with n even , $3 \nmid n$ and $4 \nmid n$..
- Residual symmetries : $G_l = Z_3$, $G_\nu = Z_2 \times CP$
- $\Delta(6n^2) = (Z_n \times Z_n) \rtimes S_3$

$$a^3 = e\,,\;\; c^n = e\,,\;\; d^n = e\,,\;\; c\,d = d\,c\,,\;\; a\,c\,a^{-1} = c^{-1}d^{-1}\,,\;\; a\,d\,a^{-1} = c$$

$$b^2 = e\,,\;\; (a\,b)^2 = e\,,\;\; b\,c\,b^{-1} = d^{-1}\,,\;\; b\,d\,b^{-1} = c^{-1}\,.$$

- For case in consideration : $Z = c^{n/2}$ and $X = a\,b\,c^s\,d^{2s}$ with $s = 0, 1, ..., n-1$
- As M_R leaves G_f and CP invariant, its form is simply

$$M_R = M_N \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad (1)$$

- Dirac CP phase is trivial $\delta = 0$.
- For $m_{\text{lightest}} = 0$, only one Majorana phase α, which depends on the chosen CP transformation:

$$\sin\alpha = (-1)^{k+r+s}\sin 6\phi_s \text{ and } \cos\alpha = (-1)^{k+r+s+1}\cos 6\phi_s \text{with } \phi_s = \frac{\pi s}{n}$$

where $k = 0(k = 1)$ for $\cos 2\theta_R > 0(\cos 2\theta_R < 0)$ and $r = 0(r = 1)$ for NO(IO).