

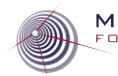
Resonant Leptogenesis and Collider Signals from Discrete Flavor and CP Symmetries

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Work based on GC and Bhupal Dev, arXiv:2106.abcd



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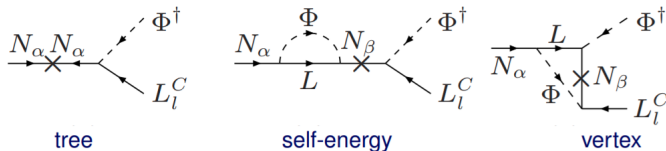


[Fukugita, Yanagida (Phys. Lett. B '86)]

- 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.

$$L_i = Y_l L_i H l_R + Y_D L_i H N + \frac{1}{2} N^c M_R N + h.c.$$

- 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 $N \rightarrow H$
- It can connect neutrino mass mechanism and matter-antimatter asymmetry.



$$\epsilon_{l\alpha} = \frac{\Gamma(N_\alpha \rightarrow L_l \Phi) - \Gamma(N_\alpha \rightarrow L_l^c \Phi^c)}{\sum_k [\Gamma(N_\alpha \rightarrow L_k \Phi) + \Gamma(N_\alpha \rightarrow L_k^c \Phi^c)]}$$

- TeV scale leptogenesis, no dependence on initial conditions.
- If $m_{N_i} \approx m_{N_j}$, the self energy contribution ("s"-type) to the CP asymmetry becomes dominant and large (even order 1).
- The "s"-type CP asymmetry,

$$a_{N_i}^s = \frac{\text{Im}(h^{\nu\gamma} h^\nu)_{ij}^2}{(h^{\nu\gamma} h^\nu)_{ii} (h^{\nu\gamma} h^\nu)_{jj}} \frac{(M_{N_i}^2 - M_{N_j}^2) M_{N_i} M_{N_j}}{(M_{N_i}^2 - M_{N_j}^2)^2 + M_{N_i}^2 M_{N_j}^2}$$

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

$$M_{N_2} \approx M_{N_1} \approx \frac{1}{2} M_{N_{1,2}}$$

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

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

- 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 $(6n^2)$ with n even, $3 - n$ and $4 - n$.
- Residual symmetries : $G_l = Z_3, G_\nu = Z_2$ CP
- given X (CP transformation) and Z (generator of Z_2 in $\mathbf{3}$)

$$Z^Y(\mathbf{3}) Y_D Z(\mathbf{3}^0) = Y_D \quad \text{and} \quad X^*(\mathbf{3}) Y_D X(\mathbf{3}^0) = Y_D^* :$$

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

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

$${}^y Z = \text{diag}((-1)^{z_1}; (-1)^{z_2}; (-1)^{z_3}) \quad z_i = 0; 1$$

it follows then $X = {}^T$ and ${}^T Y_D$ real.

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

$$(s)(\mathbf{3})^Y Y_D (s)(\mathbf{3}^0) = R_{ij}(L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} R_{kl}(R) :$$

- $U_{\text{PMNS}} = (\mathbf{3}) R_{ij}(L) K_\nu ; \quad K_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & i^{k_1} & 0 \\ 0 & 0 & i^{k_2} \end{pmatrix} \quad k_i = 0; 1; 2; 3$

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

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

$$m_\nu : \begin{cases} \frac{1}{M_N} \begin{pmatrix} y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \end{pmatrix} & \mathbf{s \text{ even}} \\ \frac{1}{M_N} \begin{pmatrix} y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \end{pmatrix} & \mathbf{s \text{ odd}} \end{cases}$$

- For $y_1 = 0$ ($y_3 = 0$), we get strong normal (inverted) ordering, with $m_{\text{lightest}} = 0$.

$$\text{NO : } y_1 = 0; y_2 = \frac{\sqrt{M_N \sqrt{m_{\text{sol}}^2}}}{\nu}; y_3 = \frac{\sqrt{M_N \frac{\rho m_{\text{atm}}^2}{j \cos 2\theta_{Rj}}}}{\nu}$$

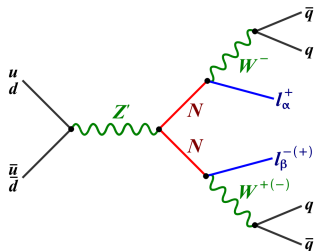
$$\text{IO : } y_3 = 0; y_2 = \frac{\sqrt{M_N \sqrt{m_{\text{atm}}^2}}}{\nu}; y_1 = \frac{\sqrt{M_N \frac{\rho j m_{\text{atm}}^2 m_{\text{sol}}^2}{j \cos 2\theta_{Rj}}}}{\nu}$$

- Only free parameters : M_N and θ_R

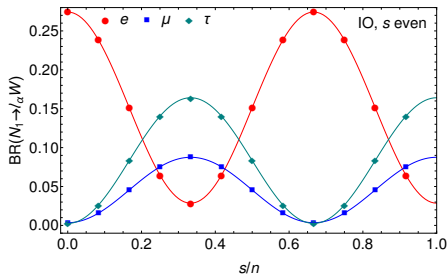
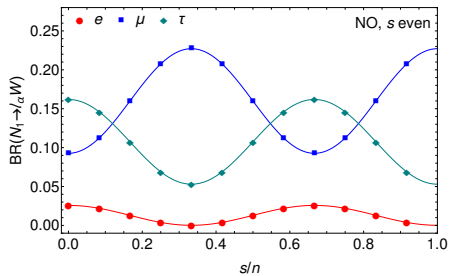
- In our scenario, $y_i \sim 10^{-6}$ suppresses the Drell Yan production

$$pp \rightarrow W^{(\pm)} \rightarrow N_i l_\alpha$$

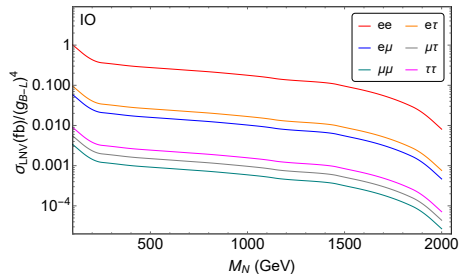
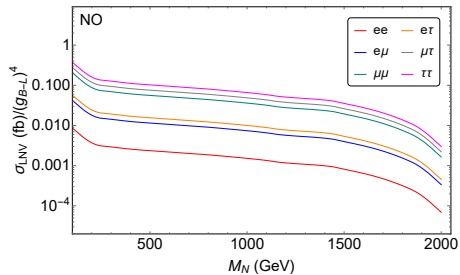
- We need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- This scenario can also be embedded in SM with extended gauge symmetry
- We consider minimal $U(1)_{B-L}$ extension for enhanced production of N_i at colliders.



Collider Signal - Branching Ratio



For $M_{Z^0} = 4 \text{ TeV}$ and $s = 2, n = 26$



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

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

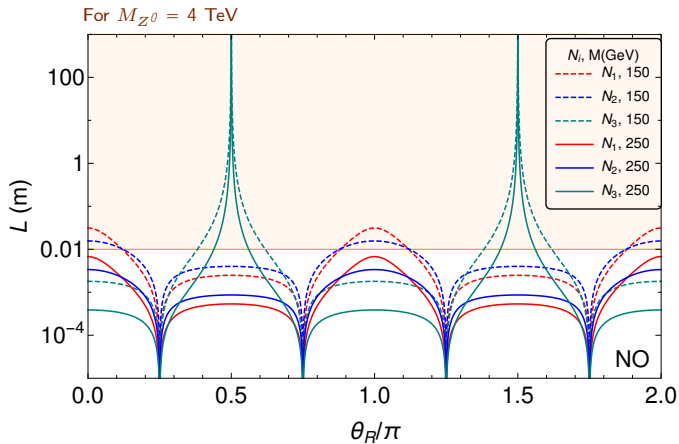
- The expressions for decay widths of the 3 heavy RH neutrinos :

$$1 \quad \frac{M}{24} (2y_1^2 \cos^2 \theta_R + y_2^2 + 2y_3^2 \sin^2 \theta_R) ;$$

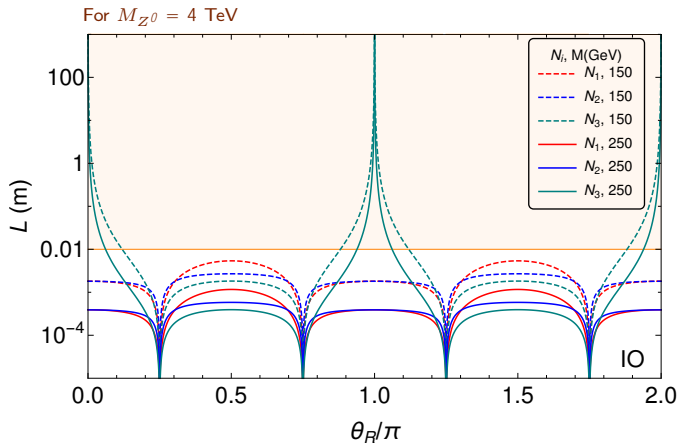
$$2 \quad \frac{M}{24} (y_1^2 \cos^2 \theta_R + 2y_2^2 + y_3^2 \sin^2 \theta_R) ;$$

$$3 \quad \frac{M}{8} (y_1^2 \sin^2 \theta_R + y_3^2 \cos^2 \theta_R) ;$$

- If $\theta_R = 2; 3 = 2$ (for strong NO) or $\theta_R = 0$; (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 ! N_3 may be detected in long-lived particle searches such as in MATHUSLA detector.



$R = 2; 3 = 2$ (ERS points)



$R = 0; \quad (\text{ERS points})$

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

$$M_1 = M_N (1 + 2 \epsilon) \text{ and } M_2 = M_3 = M_N (1 - \epsilon) :$$

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

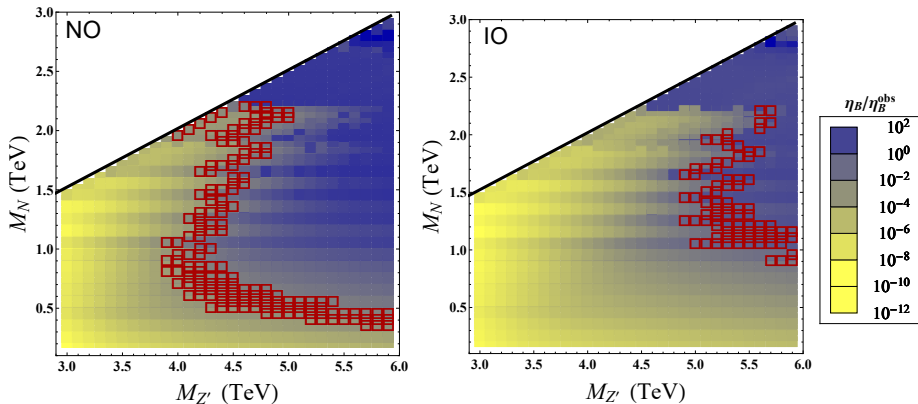
$$a_{i\alpha} = \sum_j \text{Im}(\hat{Y}_{D,\alpha i} Y_{D,\alpha i}) \text{Re}(\hat{Y}_D^y Y_D)_{ij} F_{ij}$$

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

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

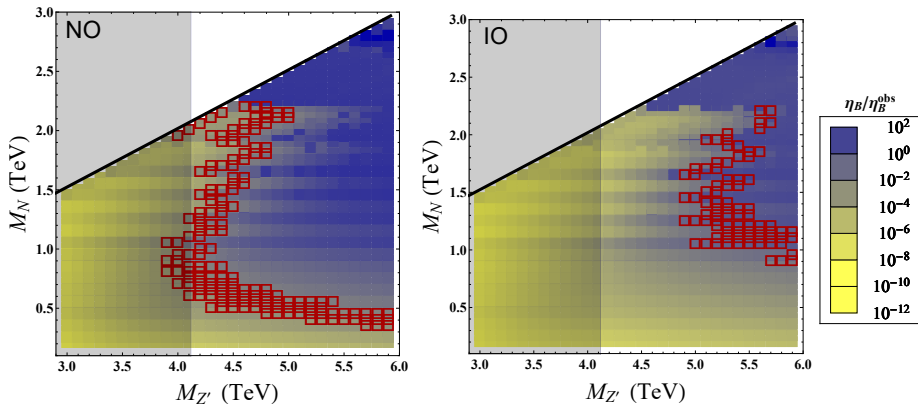
$$a_{1\alpha} = \frac{y_1 y_2}{9} (2y_2^2 + y_1^2 (1 + \cos 2\theta_R)) \sin 3\theta_s \sin 2\theta_R \sin \theta_{L,\alpha} F_{12} \text{ (IO)}$$

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



$g_{B L} = 0:1$, $s = 2$, $n = 26$
 and $R = \frac{\pi}{2}$ (0) for strong NO
 (IO)

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

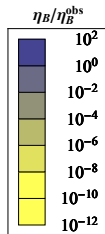
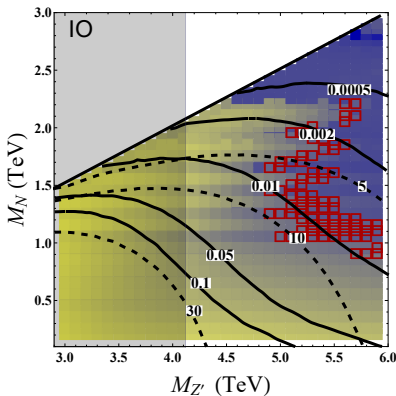
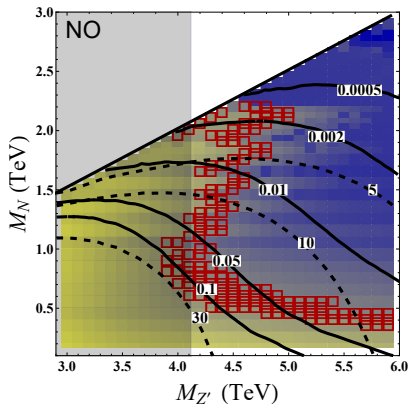


For $g_{B L} = 0:1$; M_{Z^0} & 4:12 TeV

For $g_{B L} = 1$; M_{Z^0} & 7 TeV

Leptogenesis results

all cross sections in ab



For $g_{B L} = 1$; $M_{Z^0} \approx 7$ TeV
 Enhancement from $g_{B L}^A \approx 10^4$

- 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

$$T_{1/2}^{0\nu\beta\beta} = \frac{1}{G^{0\nu} M^{0\nu} f^2} \frac{m_{ee}}{m_e}$$

$$m_{ee} = |U_{\text{PMNS},11}^2 m_1 + U_{\text{PMNS},12}^2 m_2 + U_{\text{PMNS},13}^2 m_3|$$

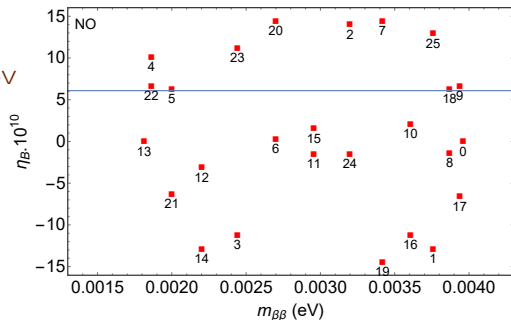
$$m_{ee} = \left| \cos^2 \theta_{12} \cos^2 \theta_{13} m_1 + \sin^2 \theta_{12} \cos^2 \theta_{13} e^{i\alpha} m_2 + \sin^2 \theta_{13} e^{i\beta} m_3 \right| :$$

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

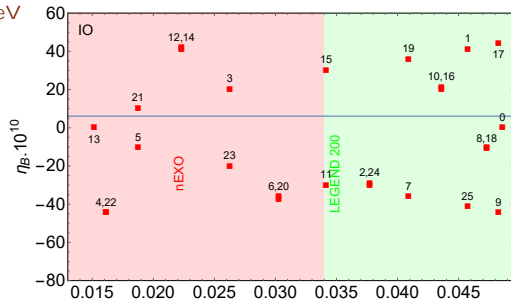
$$m_{\beta\beta} : \frac{1}{3} \begin{cases} \left| \sqrt{m_{\text{sol}}^2} + 2(\Delta m_{21}^2)^{s+k+1} \sin^2 \theta_L e^{6i\phi_s} \sqrt{m_{\text{atm}}^2} \right| & \text{(NO)} \\ \left| 1 + 2(\Delta m_{21}^2)^{s+k+1} \cos^2 \theta_L e^{6i\phi_s} \right| \sqrt{m_{\text{atm}}^2} & \text{(IO)} \end{cases}$$

$0\nu\beta\beta$ results

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



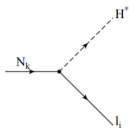
$15 \text{ meV} \lesssim m_{\beta\beta} \lesssim 48 \text{ meV}$



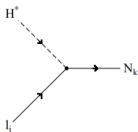
- Leptogenesis is an attractive mechanism to explain the BAU.
- Resonant Leptogenesis leads to order 1 CP asymmetry and reduces the energy scale of BAU production to TeV scale.
- The high-energy CP violating physics is disconnected from low-energy neutrino data, can be connected through role of residual 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

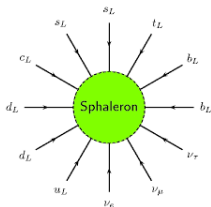
- Generation of L asymmetry in heavy Majorana neutrino N_k decay :



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



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



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

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

$$a^3 = e; c^n = e; d^n = e; cd = dc; aca^{-1} = c^{-1}d^{-1}; ada^{-1} = c$$

$$b^2 = e; (ab)^2 = e; bcb^{-1} = d^{-1}; bdb^{-1} = c^{-1};$$

- For case in consideration : $Z = c^{n/2}$ and $X = abc^s d^{2s}$ with $s = 0; 1; \dots; n-1$
- 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:

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

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