Discrete Flavor and CP symmetries and Implications for Collider Signatures

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Based on **G.C.** and P. S. Bhupal Dev, [arXiv: 2112.09710]

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- The most common and simplest explanation of neutrino masses is through addition of N

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

Type-I seesaw

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- In flavor basis, type-I seesaw mass matrix

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

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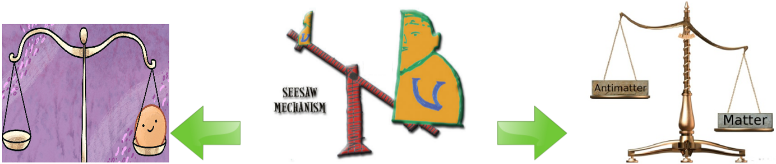
- It can connect neutrino mass mechanism and matter-antimatter asymmetry.



Type-I seesaw with Discrete Symmetries

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$$G_f \text{ and } \text{CP}$$

$$\swarrow \qquad\qquad \searrow$$

charged leptons	neutrinos
$G_e = Z_3$	$G_\nu = Z_2 \times \text{CP}$
U_e	U_ν

- Given X (CP transformation) and Z (generator of Z_2 in $\mathbf{3}$)

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- Changing to a different basis by the unitary matrix Ω that diagonalizes Z.
- Then we have Y_D as

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

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- $U_{\text{PMNS}} = \Omega(\mathbf{3})\,R_{ij}(\theta_L)\,K_\nu,$ $\qquad K_\nu =$ Re-phasing Matrix

Decay Lengths

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

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

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- 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) , \\
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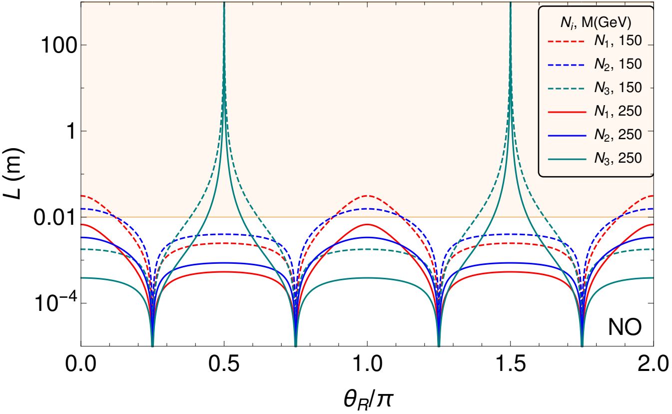
- Near points of ERS , N_3 can have a very long lifetime $\to$ may be detected in long-lived particle searches.

Assuming $Z' \to NN$ and $M_{Z'} = 4$ TeV



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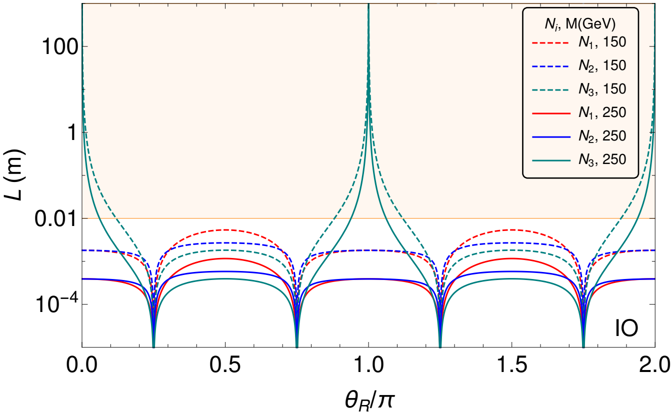
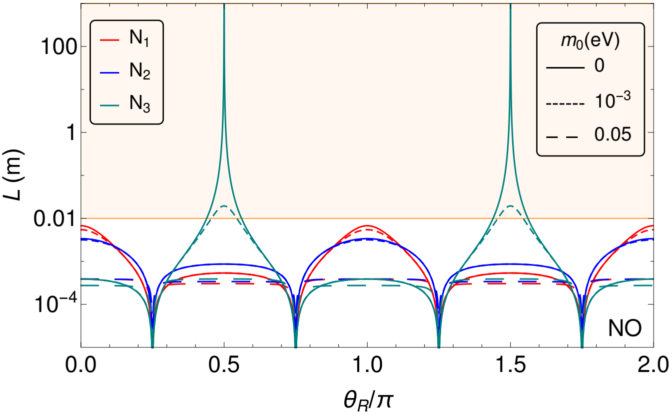


$\theta_R \approx 0, \pi$ (ERS points)

For $M_{Z'} = 4$ TeV, $M_N = 250$ GeV



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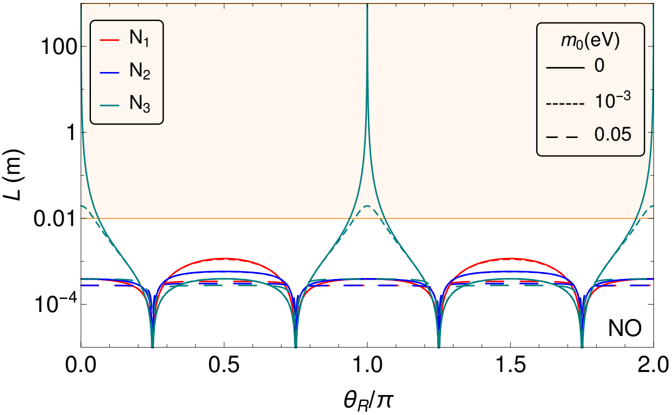

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- In our scenario, $y_i \lesssim 10^{-6}$ supresses the Drell Yan production

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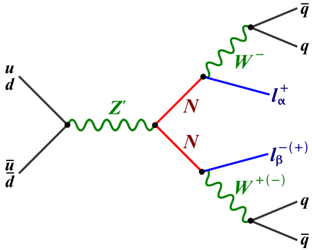
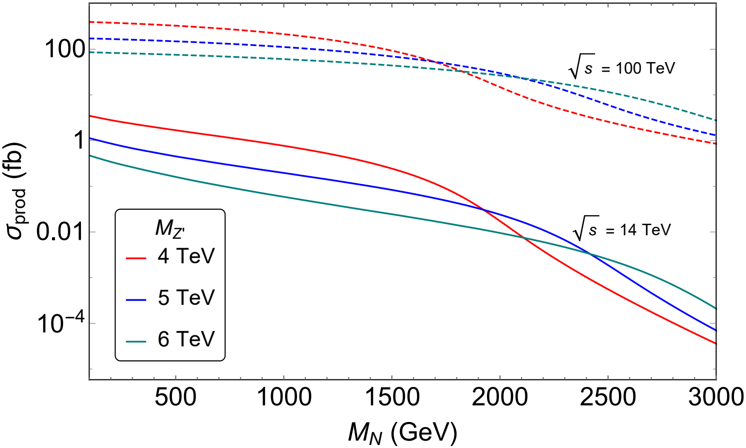
- This scenario can also be embedded in SM with extended gauge symmetry
- We consider minimal $U(1)_{B-L}$ extension for enhanced production of N_i at colliders.





For $\sqrt{s} = 14$ TeV and $M_{Z'} = 4$ TeV, events $\lesssim O(1)$
For $\sqrt{s} = 14$ TeV and $M_{Z'} = 6$ TeV, events $\sim O(10)$
For $\sqrt{s} = 100$ TeV and $M_{Z'} = 4$ TeV, events ~ 800

Conclusion

- Type-I seesaw can generate neutrino masses and baryon asymmetry.
- Generically free, parameters in Type-I can be constrained through flavor and CP symmetries.
- The decay lengths of heavy neutrinos determined by Y_D, might exhibit ERS points.
- At ERS, N_3 becomes long-lived which can be probed at LLP searches.
- While remaining two N_i can be searched for via either prompt or displaced vertex signals at the LHC.
- Effiecient production requires embedding in a UV complete model like $U(1)_{B-L}$.

Thank you!

Supplementary Material

- Given X (CP transformation) and Z (generator of Z_2 in $\mathbf{3}$)

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- 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

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

where $s = 0$ to $n-1$.

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

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- This determines all the mixing angles, Dirac phase and the Majorana phases.

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

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

- 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).

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- $$\mathrm{m}_\nu : \begin{cases} \frac{1}{M_N} \begin{pmatrix} y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \end{pmatrix} & \textbf{s even} \\ \frac{1}{M_N} \begin{pmatrix} -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\ 0 & y_2^2 & 0 \\ -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \end{pmatrix} & \textbf{s odd} \end{cases}$$

Collider Signal - Branching Ratio

Let's look at $s = 2$, $n = 26$