

**Higgs/Z decays
into
a pair of right-handed neutrinos
inducing
lepton number violating signals**

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**Based on PRD 114, 015001 (2026)
(arXiv : 2512.03302)**

1. Introduction

$U(1)_X$ gauge symmetry extension of the SM

[$U(1)_X$ is generalization of $U(1)_{B-L}$, $U(1)_R$, etc.]



Right-handed neutrinos N_R are naturally required by anomaly cancellation

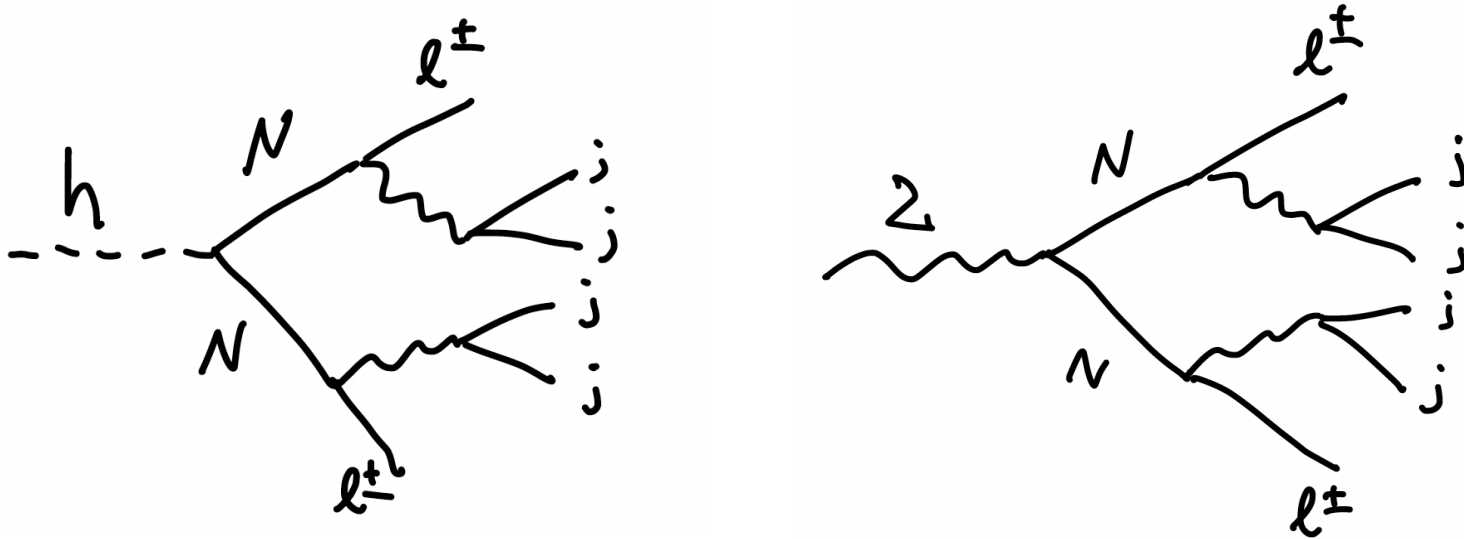
Spontaneously broken $U(1)_X \Rightarrow$ New scalar field Φ

$\Rightarrow$ {
Lepton number violating (LNV) Yukawa $Y_N \Phi \overline{N_R^c} N_R$
Massive new scalar ϕ and gauge boson Z' that couple with N_R

Connection to neutrino mass generation

1. Introduction

LVN signal can be induced via Higgs/Z boson decay



Lepton flavor violation (LFV) can be also induced

*We focus on LVN without LFV in this work

*New scalar and Z' bosons are assumed to be heavy

They are good target in current/future Higgs/Z factories

- LHC
- Future lepton colliders

FCCee, CEPC, ILC, Muon colliders

2. Model setup

The SM is extended adding a local $U(1)_X$ symmetry

Field contents : SM fields

+ one complex singlet scalar Φ

+ Three right-handed neutrinos N_R

Charge assignments ($SU(2)$, $U(1)_Y$, $U(1)_X$)

$$q_L^i: \left(2, \frac{1}{6}, \frac{x_H}{6} + \frac{x_\Phi}{3} \right), \quad u_R^i: \left(1, \frac{2}{3}, \frac{2x_H}{3} + \frac{x_\Phi}{3} \right),$$

$$d_R^i: \left(1, -\frac{1}{3}, -\frac{x_H}{3} + \frac{x_\Phi}{3} \right), \quad l_R^i: \left(2, -\frac{1}{2}, -\frac{x_H}{2} - \frac{x_\Phi}{3} \right),$$

$$e_R^i: (1, -1, -x_H - x_\Phi), \quad N_R^i: (1, 0, -x_\Phi),$$

$$H: \left(2, \frac{1}{2}, \frac{x_H}{2} \right), \quad \Phi: (1, 0, 2x_\Phi),$$

2. Model setup

Interaction Lagrangian and potential

$$\mathcal{L} \supset -Y_\nu \overline{\ell}_L \tilde{H} N_R - \frac{1}{2} Y_N \Phi \overline{(N_R)^c} N_R + \text{H.c.},$$

$$V = -m_H^2 (H^\dagger H) - m_\Phi^2 (\Phi^\dagger \Phi) \\ + \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_{\text{mix}} (H^\dagger H) (\Phi^\dagger \Phi)$$

$$\left(H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \tilde{h} \end{pmatrix} \quad \Phi = \frac{v_\Phi + \tilde{\phi}}{\sqrt{2}} \right)$$

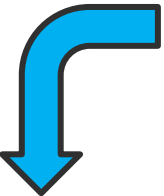
$U(1)_X$ is spontaneously broken by Φ VEV

$$\Rightarrow Y_N \Phi \overline{N_R^c} N_R \rightarrow \frac{1}{\sqrt{2}} Y_N (v_\Phi + \tilde{\phi}) \overline{N_R^c} N_R$$

LNV Yukawa interaction and mass term

Neutrino mass

Light neutrino mass via type-I seesaw


$$\begin{pmatrix} \overline{\nu'_L} \\ \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu'^c_L \\ N_R \end{pmatrix}$$
$$m_\nu \approx m_D M_N^{-1} m_D^T \quad \left[m_D = \frac{Y_\nu}{\sqrt{2}} v, \quad M_N = \frac{Y_N}{\sqrt{2}} v_\Phi \right]$$

Heavy-light neutrino mixing

$$\nu'_l \approx \nu_l + V_{lN_i} N_i \quad \left[V_{lN_i} \approx (m_D/M)_{lN_i} \right]$$

2. Model setup

Scalar mixing

$$M^2 = \begin{bmatrix} 2\lambda_H v^2 & \lambda_{\text{mix}} v v_\Phi \\ \lambda_{\text{mix}} v v_\Phi & 2\lambda_\Phi v_\Phi^2 \end{bmatrix}$$

diagonalizing



$$\begin{bmatrix} \tilde{h} \\ \tilde{\phi} \end{bmatrix} = O_R \begin{bmatrix} h \\ \phi \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} h \\ \phi \end{bmatrix}$$

Z-Z' mixing

$$M_{ZZ'} = \begin{pmatrix} M_Z^2 & -\frac{v^2}{2} g_Z g_X x_H \\ -\frac{v^2}{2} g_Z g_X x_H & M_{Z'}^2 \end{pmatrix} \quad \left(\begin{array}{l} M_Z^2 = \frac{g_Z^2}{4} v^2 \\ M_{Z'}^2 = \frac{g_X^2}{4} (x_H^2 v^2 + 16x_\Phi^2 v_\Phi^2) \end{array} \right)$$



$$\zeta \simeq 2 \frac{M_Z^2}{M_{Z'}^2} \frac{g_X x_H}{g_Z}$$

Mixing angle

2. Model setup

Relevant interactions in mass basis

$$\mathcal{L}_{\text{CC}} \supset - \sum_{\ell=e,\mu,\tau} \frac{g}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L V_{\ell N} N + \text{H.c.},$$
$$\mathcal{L}_{\text{NC}} \supset - \sum_{\ell=e,\mu,\tau} \frac{g_Z}{2} Z_\mu \left[\bar{N} \gamma^\mu P_L (V_{\ell N}^\dagger V_{\ell N}) N + \bar{\nu} \gamma^\mu P_L V_{\ell N} N + \text{H.c.} \right]$$

N decay

$$\mathcal{L}_{\text{int}} \supset \frac{x_\Phi g_X}{2} \bar{N} \gamma^\mu \gamma^5 N (Z_\mu \sin \zeta + Z'_\mu \cos \zeta)$$
$$L \supset \frac{1}{\sqrt{2}} Y_N (h \sin \alpha + \phi \cos \alpha) \overline{N_R^c} N_R$$

Z/h decay into NN

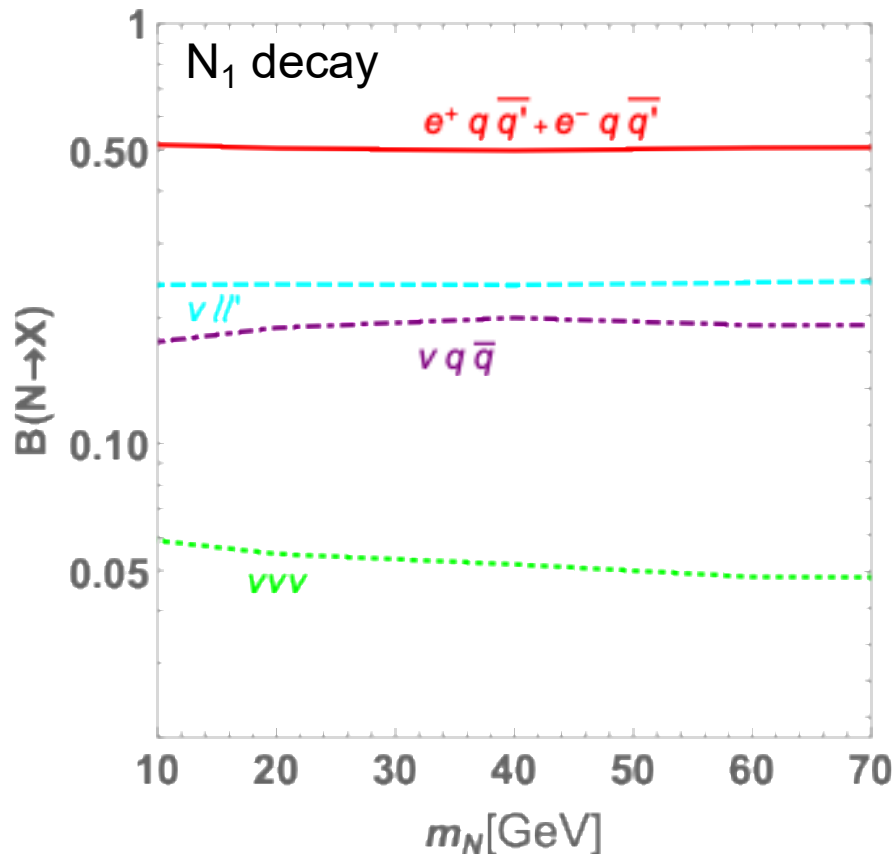
2. Model setup

❖ N_R decay : $N_R \rightarrow W^{\pm*} l^{\mp} \rightarrow l^{\mp} jj$

$$\Gamma_{\text{tot}} \sim n_f \frac{G_F^2 m_N^5}{192\pi^3} |V_{\ell N}|^2$$

✓ We don't consider long-lived N

$$\sim 2 \times 10^{-14} \text{ GeV} \times \frac{n_f}{9} \left(\frac{m_N}{10 \text{ GeV}} \right)^5 \left(\frac{|V_{\ell N}|}{10^{-3}} \right)^2$$



For simplicity we assume the lightest N couples with only e



$$V_{eN_1} \sim 10^{-3} \gg V_{\mu N_1}, V_{\tau N_1}$$

And we focus on the lightest N

2. Model setup

❖ Higgs decay modes with N_R

$$\Gamma(h \rightarrow NN) = \frac{m_N^2 m_h \sin^2 \alpha}{16\pi v_\Phi^2} \left(1 - 4 \frac{m_N^2}{m_h^2}\right)^{3/2}$$

$$\Gamma(h \rightarrow N\bar{\nu}) = \frac{|V_{\ell N}|^2 m_N^2 m_h}{8\pi v^2} \left(1 - \frac{m_N^2}{m_h^2}\right)^2$$



$$\mathcal{B}(h \rightarrow NN) = \frac{\Gamma(h \rightarrow NN)}{\Gamma_h^{\text{SM}} \cos^2 \alpha + \Gamma(h \rightarrow NN) + 2\Gamma(h \rightarrow N\nu)}$$

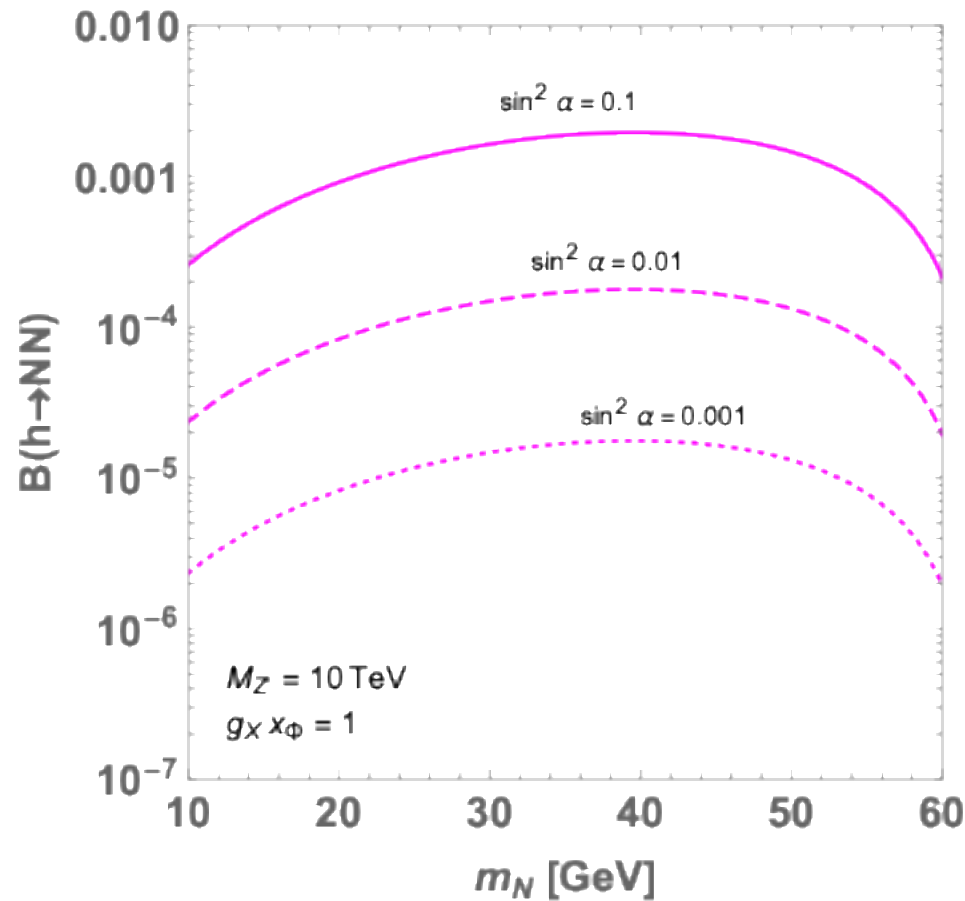
❖ Z boson decay into a N_R pair

$$\Gamma(Z \rightarrow NN) \simeq \frac{(x_\Phi g_X)^2 \zeta^2}{24\pi} M_Z \left(1 - 4 \frac{m_N^2}{M_Z^2}\right)^{3/2}$$


$$\mathcal{B}(Z \rightarrow NN) = \frac{\Gamma(Z \rightarrow NN)}{\Gamma_Z^{\text{SM}} + \Gamma(Z \rightarrow NN)}$$

2. Model setup

Higgs decay BR for $h \rightarrow NN$ mode



3. Signal and analysis

LV signals from Higgs boson decay

➤ **Hadron collider**

$$pp \rightarrow h \rightarrow NN \quad \text{2-same sign leptons} \\ \rightarrow l^{\pm} l^{\pm} jjjj \quad \text{+ 4 jets (2SSL4j)}$$

➤ **$e^{+}e^{-}$ colliders**

$$e^{+}e^{-} \rightarrow Zh \rightarrow ZNN \quad \text{2-same sign leptons} \\ \rightarrow l^{\pm} l^{\pm} jjjjjj \quad \text{+ 6 jets (2SSL4j)}$$

➤ **$\mu^{+}\mu^{-}$ colliders (for Higgs production)**

$$\mu^{+}\mu^{-} \rightarrow h \rightarrow NN \quad \text{2SSL4j} \quad \text{Blas, Gu, Liu, PRD 106 (2022)} \\ \rightarrow l^{\pm} l^{\pm} jjjj$$

3. Signal and analysis

Backgrounds and cuts

$$pp \rightarrow \ell^+ \ell^- 4j,$$

BGs: $e^+ e^- \rightarrow \ell^+ \ell^- jjZZ / \ell^+ \ell^- jjWZ$, **With charge misidentification**

$$\mu^+ \mu^- \rightarrow \ell^+ \ell^- 4j,$$

We simulate signal and BGs using *MadGraph5*

To reduce # of backgrounds we impose kinematical cuts:

$$\left\{ \begin{array}{l} p_T(\ell) > 5 \text{ GeV}, \quad p_T(j) > 15 \text{ GeV}, \\ |\eta(\ell)| < 2.4, \quad |\eta(j)| < 2.4, \\ \Delta R_{\ell\ell} > 0.2, \quad \Delta R_{\ell j} > 0.2, \quad \Delta R_{jj} > 0.2, \\ 110 \text{ GeV} < M_{\ell^+ \ell^- 4j} < 140 \text{ GeV}. \end{array} \right\} \quad \text{For hadron collider}$$

$$\left\{ \begin{array}{l} p_T(\ell) > 5 \text{ GeV}, \quad p_T(j) > 5 \text{ GeV}, \\ |\eta(\ell)| < 2.4, \quad |\eta(j)| < 2.4, \\ \Delta R_{\ell\ell} > 0.2, \quad \Delta R_{\ell j} > 0.2, \quad \Delta R_{jj} > 0.2, \\ 110 \text{ GeV} < M_{\ell^+ \ell^- 4j} < 140 \text{ GeV}. \end{array} \right\} \quad \text{For lepton collider}$$

3. Signal and analysis

Signal cross sections and events

❖ Signal from Higgs decay (with cuts, BR=1)

m_N [GeV]	10	20	30	40	50	60
$\sigma(\text{LHC 13 TeV})$ [pb]	2.68	2.41	2.68	3.48	4.82	6.69
$\sigma(\text{LHC 14 TeV})$ [pb]	3.02	2.72	3.02	3.92	5.43	7.53
$\sigma(e^+e^- 250 \text{ GeV})$ [fb]	38.5	54.7	73.1	93.7	116	0.141
$\sigma(e^+e^- 240 \text{ GeV})$ [fb]	33.5	47.6	63.6	81.5	101	123
$\sigma(\mu^+\mu^- 125 \text{ GeV})$ [pb]	4.15	4.98	6.23	7.90	9.99	12.5

❖ Background cross section after cuts

	σ_B (without IM cut)	σ_B (with IM cut)
LHC 13 TeV	33.2 [pb]	316 [fb]
LHC 14 TeV	37.7 [pb]	387 [fb]
$e^+e^- 250(240) \text{ GeV}$	$\mathcal{O}(10^{-5})$ [fb]	$\ll \mathcal{O}(10^{-5})$ [fb]
$\mu^+\mu^- 125 \text{ GeV}$	10.1 [fb]	10.1 [fb]

❖ Significance

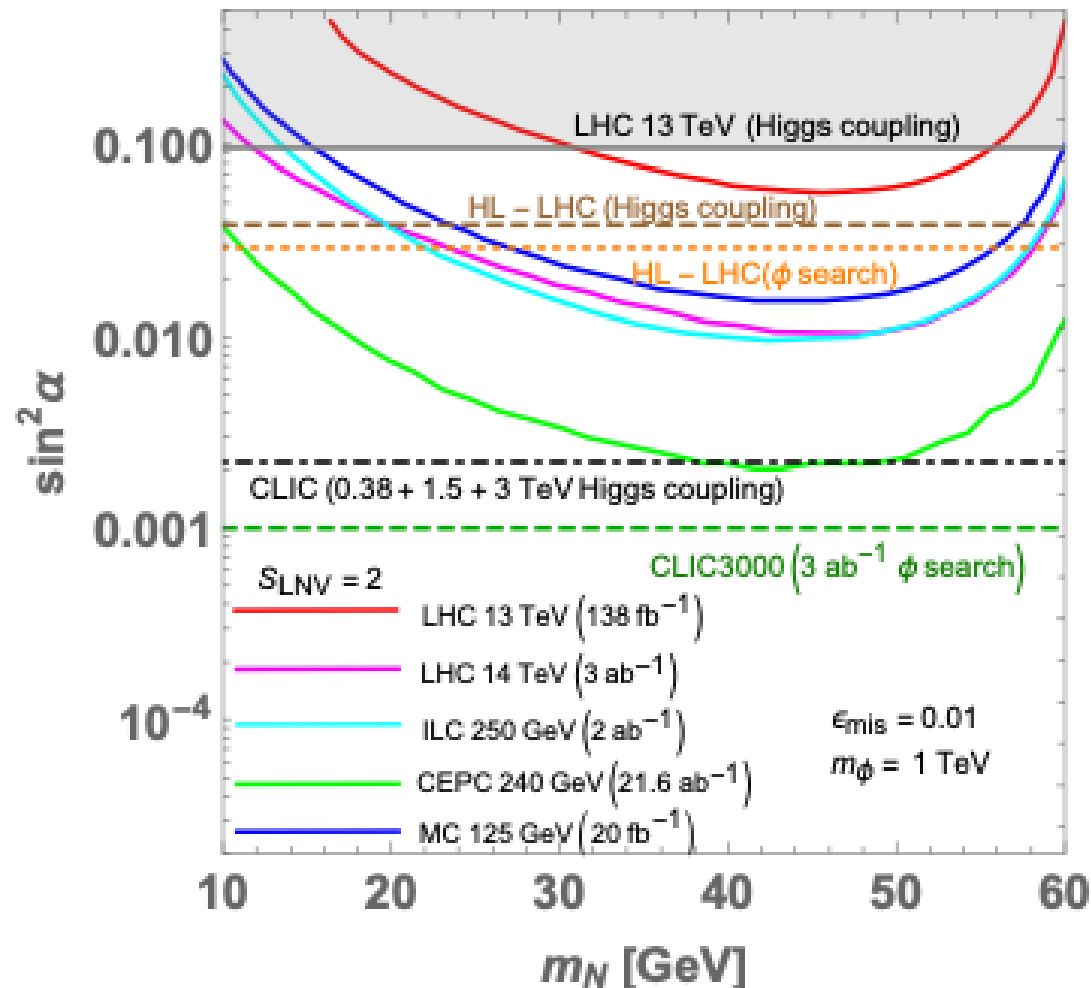
$$S_{LNV} = \frac{\epsilon_{eff} N_S}{\sqrt{\epsilon_{eff} N_S + 2 \epsilon_{miss} \epsilon_{eff}^B N_B}}$$

ϵ_{eff} : signal efficiency

Charge misidentification rate

3. Signal and analysis

Sensitivity to scalar mixing via LNV Higgs decay signal



LNV signals from Z boson decay

$$\begin{aligned} e^+ e^- &\rightarrow Z \rightarrow NN \\ &\rightarrow l^\pm l^\pm jjjj \end{aligned} \quad \mathbf{2SSL4j}$$

Backgrounds: $e^+ e^- \rightarrow l^+ l^- jjjj$ With charge misidentification

Kinematical cuts

$$\begin{aligned} p_T(\ell) &> 5 \text{ GeV}, & p_T(j) &> 5 \text{ GeV}, \\ |\eta(\ell)| &< 2.4, & |\eta(j)| &< 2.4, \\ \Delta R_{\ell\ell} &> 0.2, & \Delta R_{\ell j} &> 0.2, & \Delta R_{jj} &> 0.2. \end{aligned}$$

$$\Rightarrow \sigma(e^+ e^- \rightarrow \ell^+ \ell^- 4j) \simeq 6.8 \text{ fb}$$

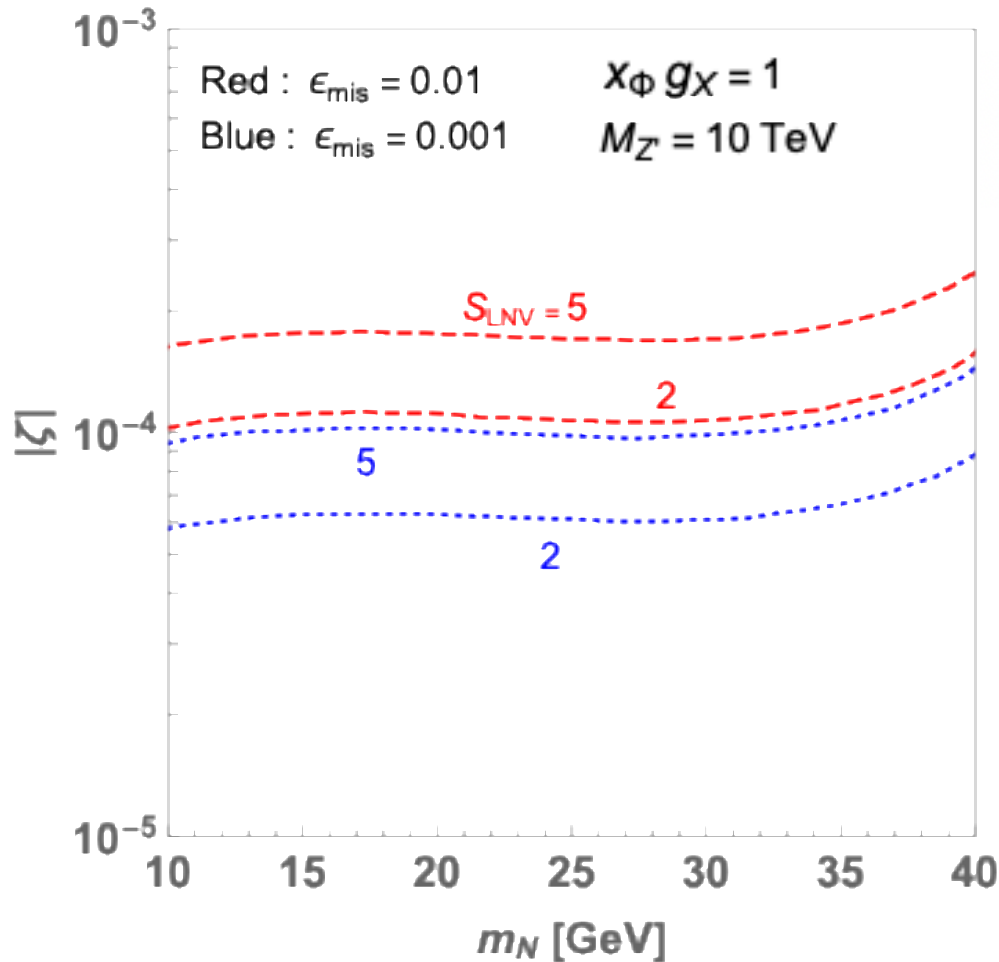
$$\begin{aligned} N_S &= 4.1 \times 10^{12} \times \mathcal{B}(Z \rightarrow NN) \\ &\times [\mathcal{B}(N \rightarrow \ell^+ jj)^2 + \mathcal{B}(N \rightarrow \ell^- jj)^2] \end{aligned}$$

Signal efficiency under cuts

$$\epsilon_{eff} \sim 0.091 - 0.035$$

3. Signal and analysis

Sensitivity for LNV Z decay signal



$$\Gamma(Z \rightarrow NN) \simeq \frac{(x_\Phi g_X)^2 \zeta^2}{24\pi} M_Z \left(1 - 4 \frac{m_N^2}{M_Z^2}\right)^{3/2}$$

$$\zeta \simeq 2 \frac{M_Z^2}{M_{Z'}^2} \frac{g_X x_H}{g_Z}$$

$$S_{\text{LNV}} = \frac{\epsilon_{\text{eff}} N_S}{\sqrt{\epsilon_{\text{eff}} N_S + 2\epsilon_{\text{miss}} \epsilon_{\text{eff}}^B N_B}}$$

Summary and Discussions

❖ $U(1)_X$ extension of the SM

- ✓ Three right-handed neutrinos from anomaly cancellation
- ✓ Spontaneous symmetry breaking via new scalar VEV
- ✓ Z' and scalar boson couples to right-handed neutrinos
- ✓ Z - Z' and scalar mixings induce Higgs/ Z decay into NN mode

❖ LNV signal in Higgs/ Z boson decays

- ✓ A NN pair from Higgs/ Z decay
- ✓ N decay induce LNV signals
- ✓ Current LHC constraint
- ✓ Estimating sensitivity at future collider experiments

❖ Future directions

- ✓ Analysis for LNV + LFV signals
- ✓ Long-lived right-handed neutrino case