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

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1. Introduction

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

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

⇩

Right-handed neutrinos N_R are naturally required by anomaly cancellation

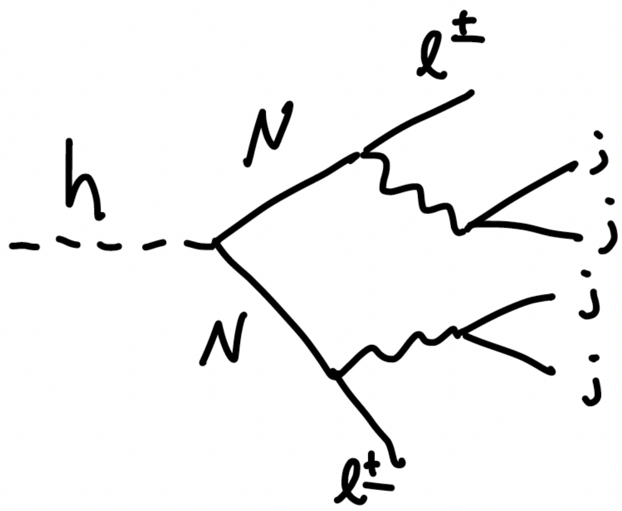
Spontaneously broken U(1)$_X$ ⇨ New scalar field Φ

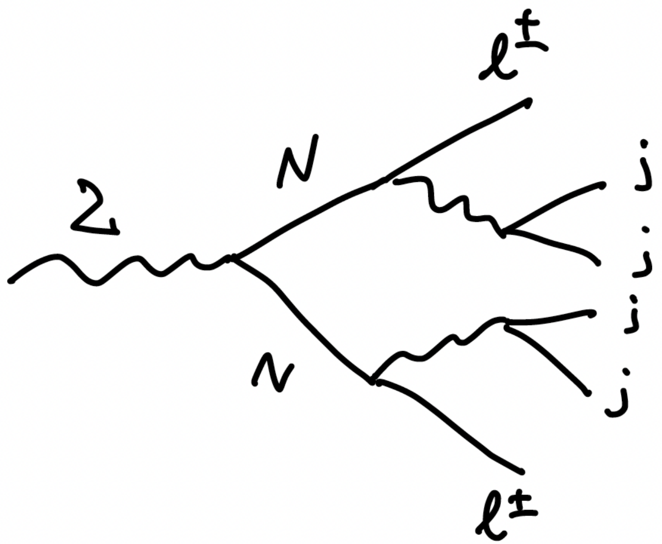
⇨ Lepton number violating (LNV) Yukawa $Y_N \Phi \overline{N_R^C} N_R$

Massive new scalar ϕ and gauge boson Z' that couple with N_R

Connection to neutrino mass generation

LNV signal can be induced via Higgs/Z boson decay





Lepton flavor violation (LFV) can be also induced

*We focus on LNV 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 $(SU(2), U(1)_Y, U(1)_X)$

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

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

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

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

2. Model setup

Interaction Lagrangian and potential

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

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

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \tilde{h} \end{pmatrix} \qquad \Phi = \frac{v_\Phi + \tilde{\phi}}{\sqrt{2}}$$

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

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

LNV Yukawa interaction and mass term

Neutrino mass

Light neutrino mass via type-I seesaw

$$\begin{pmatrix} \overline{\nu'_L} \\ \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu'^c_L \\ N_R \end{pmatrix}$$

$$m_\nu \approx m_D M_N^{-1} m_D^T$$

$$\left(m_D = \frac{Y_\nu}{\sqrt{2}} v, \quad M_N = \frac{Y_N}{\sqrt{2}} v_\Phi \right)$$

Heavy-light neutrino mixing

$$\nu'_l \approx \nu_l + V_{lN_i} N_i$$

$$\left(V_{lN_i} \approx (m_D/M)_{lN_i} \right)$$

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

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

Z-Z' mixing

$$M_{ZZ'} = \begin{pmatrix} M_Z^2 & -\frac{v^2}{2} g_Z g_X x_H \\ -\frac{v^2}{2} g_Z g_X x_H & M_{Z'}^2 \end{pmatrix}$$

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

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

Mixing angle

2. Model setup

Relevant interactions in mass basis

$$\mathcal{L}_{\rm CC} \supset -\sum_{\ell=e,\mu,\tau} \frac{g}{\sqrt{2}} W_\mu \bar{\ell}\gamma^\mu P_L V_{\ell N} N + \text{H.c.},$$

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

N decay

$$\mathcal{L}_{\rm int} \supset \frac{x_\Phi g_X}{2} \bar{N}\gamma^\mu\gamma^5 N (Z_\mu \sin\zeta + Z'_\mu \cos\zeta)$$

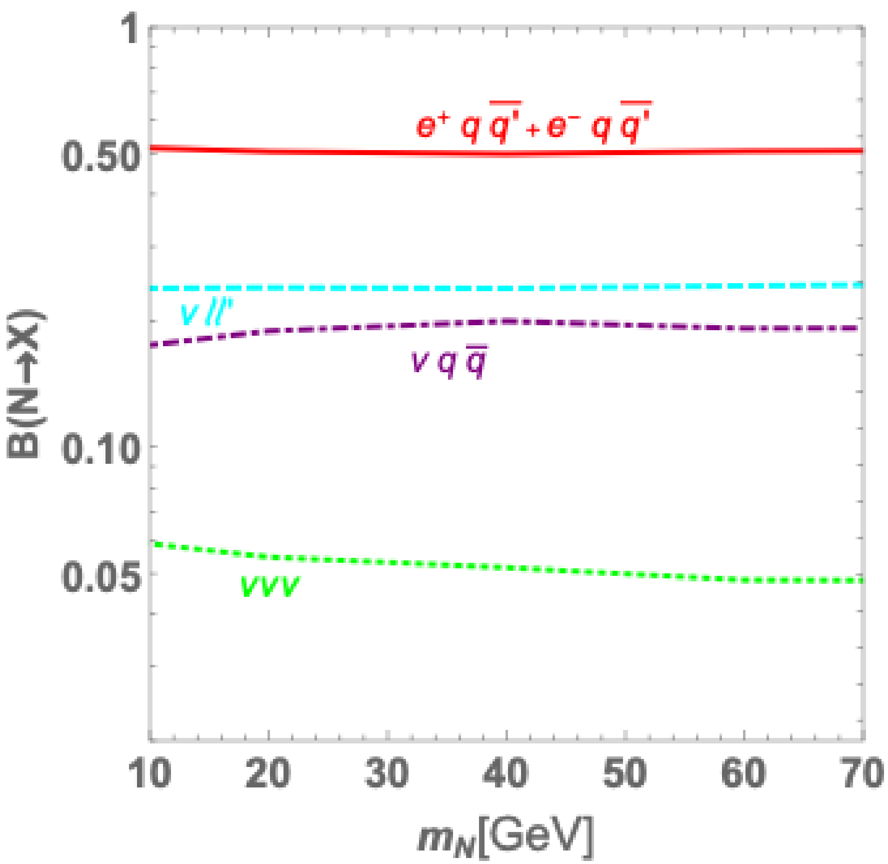
$$L \supset \frac{1}{\sqrt{2}} Y_N (h\ sin\alpha + \phi\ cos\alpha) \overline{N_R^C} N_R$$

Z/h decay into NN

2. Model setup

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

$$\Gamma_{\rm tot} \sim n_f \frac{G_F^2 m_N^5}{192\pi^3} |V_{\ell N}|^2$$
$$\sim 2 \times 10^{-14}\ \mathrm{GeV} \times \frac{n_f}{9} \left(\frac{m_N}{10\ \mathrm{GeV}}\right)^5 \left(\frac{|V_{\ell N}|}{10^{-3}}\right)^2$$



For simplicity we assume the lightest N couples with only e

$$V_{eN_1} \sim 1 \gg V_{\mu N_1}, V_{\tau N_1}$$

We focus on the lightest N

❖ Higgs decay modes with N_R

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

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

$$\Downarrow$$

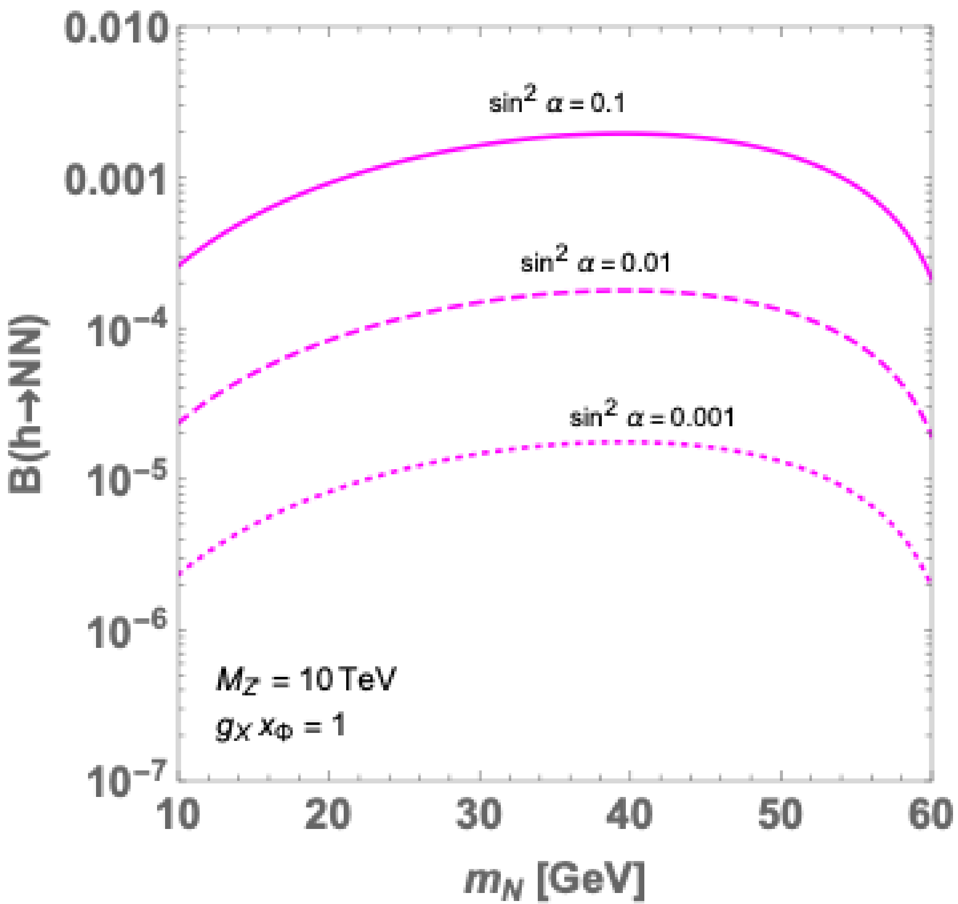
$$\mathcal{B}(h \to NN) = \frac{\Gamma(h \to NN)}{\Gamma_h^{\rm SM}\cos^2\alpha + \Gamma(h \to NN) + 2\Gamma(h \to N\nu)}$$

❖ Z boson decay into a N_R pair

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

$$\Rightarrow \quad \mathcal{B}(Z \to NN) = \frac{\Gamma(Z \to NN)}{\Gamma_Z^{\rm SM} + \Gamma(Z \to NN)}$$

Higgs decay BR for $h \to NN$ mode



3. Signal and analysis

LNV signals from Higgs boson decay

- **Hadron collider**

$$pp \to h \to NN$$
$$\to l^{\pm}l^{\pm}jjjj$$

2-same sign leptons + 4 jets (2SSL4j)

- $\boldsymbol{e^+e^-}$ **colliders**

$$e^+e^- \to Zh \to ZNN$$
$$\to l^{\pm}l^{\pm}jjjjjj$$

2-same sign leptons + 6 jets (2SSL4j)

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

$$\mu^+\mu^- \to h \to NN$$
$$\to l^{\pm}l^{\pm}jjjj$$

2SSL4j

Blas, Gu, Liu, PRD 106 (2022)

Backgrounds and cuts

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

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

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

We simulate signal and BGs using *MadGraph5*

To reduce # of backgrounds we impose kinematical cuts:

$$\left\{\begin{array}{lll} p_T(\ell) > 5 \text{ GeV}, & p_T(j) > 15 \text{ GeV}, & \\ |\eta(\ell)| < 2.4, & |\eta(j)| < 2.4, & \\ \Delta R_{\ell\ell} > 0.2, & \Delta R_{\ell j} > 0.2, & \Delta R_{jj} > 0.2, \\ \multicolumn{3}{l}{110 \text{ GeV} < M_{\ell^+\ell^- 4j} < 140 \text{ GeV}.} \end{array}\right\}$$

For hadron collider

$$\left\{\begin{array}{lll} p_T(\ell) > 5 \text{ GeV}, & p_T(j) > 5 \text{ GeV}, & \\ |\eta(\ell)| < 2.4, & |\eta(j)| < 2.4, & \\ \Delta R_{\ell\ell} > 0.2, & \Delta R_{\ell j} > 0.2, & \Delta R_{jj} > 0.2, \\ \multicolumn{3}{l}{110 \text{ GeV} < M_{\ell^+\ell^- 4j} < 140 \text{ GeV}.} \end{array}\right\}$$

For lepton collider

Signal cross sections and events

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

m_N [GeV]	10	20	30	40	50	60
σ(LHC 13 TeV) [pb]	2.68	2.41	2.68	3.48	4.82	6.69
σ(LHC 14 TeV) [pb]	3.02	2.72	3.02	3.92	5.43	7.53
$\sigma(e^+e^- 250\ \mathrm{GeV})$ [fb]	38.5	54.7	73.1	93.7	116	0.141
$\sigma(e^+e^- 240\ \mathrm{GeV})$ [fb]	33.5	47.6	63.6	81.5	101	123
$\sigma(\mu^+\mu^- 125\ \mathrm{GeV})$ [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) GeV	$\mathcal{O}(10^{-5})$ [fb]	$\ll \mathcal{O}(10^{-5})$ [fb]
$\mu^+\mu^-$125 GeV	10.1 [fb]	10.1 [fb]

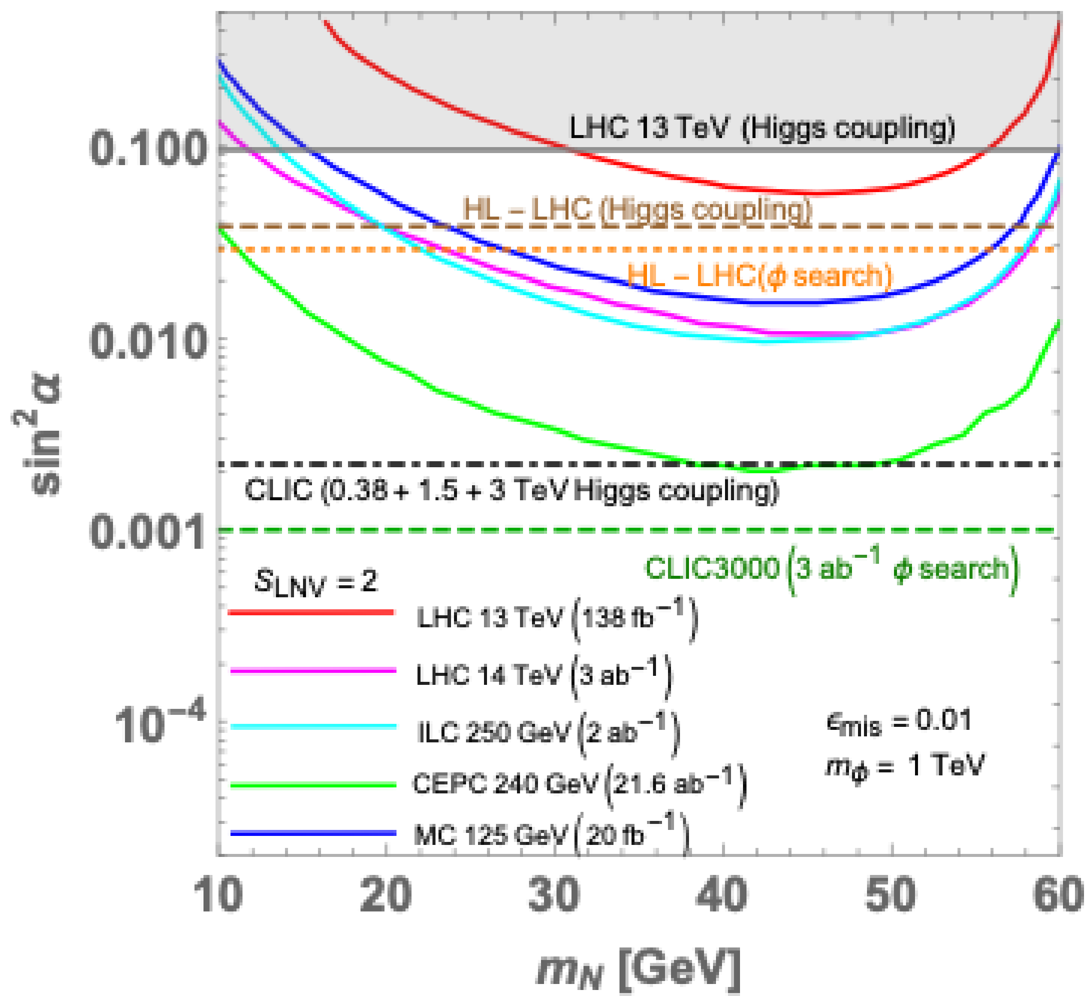
❖ Significance

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

ϵ_{eff}: signal efficiency

Charge misidentification rate

Sensitivity to scalar mixing via LNV Higgs decay signal



LNV signals from Z boson decay

$$e^+e^- \to Z \to NN$$
$$\to l^\pm l^\pm jjjj$$

2SSL4j

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

Kinematical cuts

$$p_T(\ell) > 5\ \mathrm{GeV}, \qquad p_T(j) > 5\ \mathrm{GeV},$$
$$|\eta(\ell)| < 2.4, \qquad |\eta(j)| < 2.4,$$
$$\Delta R_{\ell\ell} > 0.2, \qquad \Delta R_{\ell j} > 0.2, \qquad \Delta R_{jj} > 0.2.$$

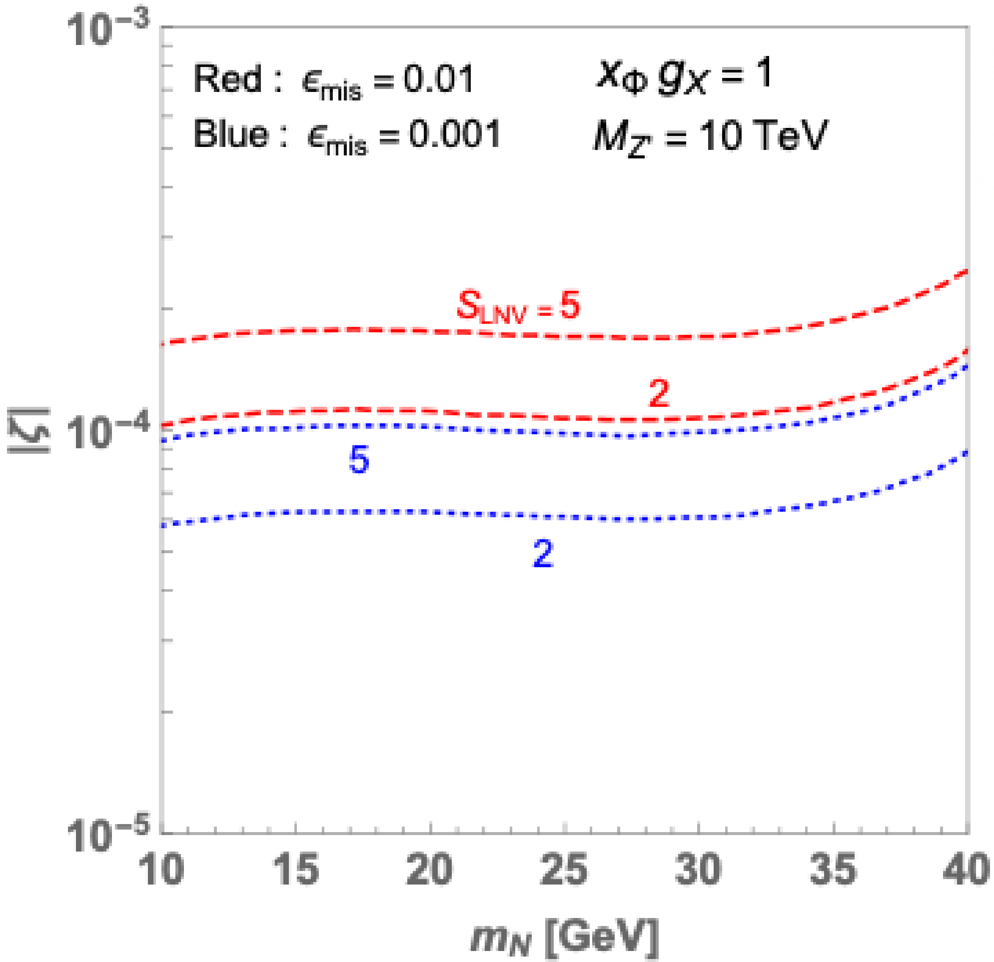
$$\Rightarrow \sigma(e^+e^- \to \ell^+\ell^-4j) \simeq 6.8\ \mathrm{fb}$$

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

Signal efficiency under cuts

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

Sensitivity for LNV Z decay signal



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

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

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

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