

Lepton number violation from Higgs/Z decays into a pair of right-handed neutrinos

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We explore signatures of lepton number violation (LNV) from decays of the discovered Higgs (h) and Z bosons into a pair of right-handed neutrinos (RHNs). Due to the Majorana nature of RHNs, the final state can be the same-sign dilepton plus jets leading to two units of LNV. As a simple but plausible scenario, we investigate such a signal in models with a new $U(1)_X$ gauge symmetry, which naturally introduces three RHNs for gauge anomaly cancellation and is spontaneously broken down by a vacuum expectation value of an isospin singlet scalar field (ϕ). In this scenario, h and the Z boson can decay into a pair of RHNs via the h - ϕ mixing and the Z - Z' mixing with Z' being a new massive gauge boson, respectively. Estimating the LNV signal and corresponding backgrounds for the $\ell^\pm \ell^\pm 4j$ final states, we find bounds on the h - ϕ mixing and the Z - Z' mixing as a function of a mass of RHNs at Higgs factories, e.g., at the High-Luminosity LHC with $\sqrt{s} = 14$ TeV, future e^-e^+ colliders at $\sqrt{s} = 250$ GeV, muon colliders at $\sqrt{s} = 125$ GeV, as well as at Z factories, e.g., CEPC and Future Circular Collider (FCC-ee) at $\sqrt{s} = 91.2$ GeV. We also discuss limits on the scalar mixing at $e^-\mu^+$ and $\mu^+\mu^+$ collisions (μ TRISTAN) with $\sqrt{s} = 346$ GeV/775 GeV and 2 TeV, respectively.

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I. INTRODUCTION

The long-standing puzzle of the origin of tiny neutrino masses observed by various experiments [1] allows us to step forward beyond the premise of Standard Model (SM) scenarios. Among many interesting aspects, models with a general $U(1)_X$ gauge symmetry [2–4] provide one of the simplest realizations for generating tiny neutrino masses through the seesaw mechanism [5–9], because three right-handed neutrinos (RHNs) are inevitably introduced to cancel gauge anomalies. In this scenario, the Higgs sector is extended to have an additional SM-singlet scalar field (ϕ) charged under $U(1)_X$ whose vacuum expectation value (VEV) gives masses of RHNs as well as a new massive gauge boson Z' .

Despite their significance, it is quite difficult to directly discover RHNs at collider experiments in the minimal type-I seesaw model without the $U(1)_X$ symmetry. This is

mainly due to their very large masses relative to the electroweak scale or their extremely suppressed couplings with the SM sector for lighter RHNs. In contrast, in our $U(1)_X$ scenario, RHNs can be easily produced via the decays of the discovered Higgs boson (h) and the Z boson, where the former (latter) is realized due to a scalar mixing between h and ϕ (a gauge mixing between Z and Z'). In addition, lepton number violation (LNV), another important ingredient in proving the seesaw mechanism, can also be tested via the decay of RHNs into same-sign dileptons plus multijets, which is allowed by the Majorana nature of RHNs [10,11]. Therefore, models with $U(1)_X$ provide not only the simple and natural scenario to realize the seesaw mechanism, but also, its testable framework at collider experiments. The lepton number violating decays of the Higgs boson have been discussed in the left-right symmetric models [12], the minimal type-I seesaw model with a singlet scalar field [13] at muon colliders (MCs), as well as in the effective field theory approach [14].

In this paper, we first discuss the signature of LNV via the decays of h and Z bosons into a pair of RHNs at Higgs factories and Z factories in the $U(1)_X$ model, by which we take constraints on the parameter space of the model, such as a mixing angle of the discovered Higgs boson with a new

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Higgs boson and that of the Z boson with Z' . Production cross section of h at LHC with a center of mass energy $\sqrt{s}$ of $\sqrt{s} = 13$ (14) TeV has been computed to be 48.61 (54.72) pb [15,16] at N³LO QCD and Next-Leading Order (NLO) Electroweak (EW) from the gluon fusion process. At future electron-positron colliders with $\sqrt{s} = 250$ GeV [17–20], the Higgs production in association with the Z boson could reach around 300 [21,22] (230 [23]) fb for polarized (unpolarized) electron-positron beams with polarization $P(e^-, e^+) = (-0.8, 0.3)$. In addition, MCs at $\sqrt{s} = 125$ GeV could produce h in the s -channel process [24–27] with a cross section of 20 pb [27], taking initial state radiation (ISR) and beam energy spread (BES) into consideration. On the other hand, Z factories [28] can be realized at electron-positron colliders with $\sqrt{s} = 91.2$ GeV, by which the cross section is significantly enhanced by the on-shell resonance of the Z boson, and $\mathcal{O}(10^{12})$ number of Z bosons can be produced [29–34]. Recently, $e^-\mu^+$ and $\mu^+\mu^+$ colliders have also been considered as alternative possibilities of the Higgs factory, the so-called μ TRISTAN [35]. The Higgs bosons can be produced via the weak boson fusion process, and their cross sections are given to be about 91 (4) fb from the W (Z) boson fusion at $e^-\mu^+$ collisions with $\sqrt{s} = 346$ GeV and 1 ab^{-1} of the integrated luminosity ($\mathcal{L}_{\text{int}}$), while the cross section can be 54 fb from the Z boson fusion at $\mu^+\mu^+$ collisions with $\sqrt{s} = 2$ TeV and $\mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}$. In addition, $e^-\mu^+$ collisions with $\sqrt{s} = 775$ GeV and $\mathcal{L}_{\text{int}} = 1 \text{ ab}^{-1}$ have also been proposed as μ Tevatron in [35], where the Higgs production cross section is 472 (20) fb from the W (Z) boson fusion.

We study the final states with LNV from the Higgs and Z decays into $\ell^\pm \ell^\pm 4j$ at the Higgs and Z factories and simulate the SM backgrounds (BGs). We then estimate bounds on the scalar mixing and Z - Z' mixing with respect to the mass of RHNs at Higgs and Z factories.

II. FRAMEWORK

Under the $SU(2)_L \otimes U(1)_Y \otimes U(1)_X$ gauge symmetry, the SM quarks, leptons, and Higgs fields are charged as follows:

$$\begin{aligned} q_L^i &\sim \left(2, \frac{1}{6}, \frac{x_H}{6} + \frac{x_\Phi}{3}\right), & u_R^i &\sim \left(1, \frac{2}{3}, \frac{2}{3}x_H + \frac{x_\Phi}{3}\right), \\ d_R^i &\sim \left(1, -\frac{1}{3}, -\frac{x_H}{3} + \frac{x_\Phi}{3}\right), & \ell_L^i &\sim \left(2, -\frac{1}{2}, -\frac{x_H}{2} - x_\Phi\right), \\ e_R^i &\sim (1, -1, -x_H - x_\Phi), & H &\sim \left(2, \frac{1}{2}, \frac{x_H}{2}\right), \end{aligned} \quad (1)$$

where the index i denotes the flavor $i = 1, 2, 3$. As new fields, we introduce three generations of RHNs N_R^i to cancel gauge and mixed gauge-gravity anomalies and an isospin singlet scalar, Φ , being transformed as

$$N_R^i = (1, 0, -x_\Phi), \quad \Phi = (1, 0, 2x_\Phi). \quad (2)$$

Generally, the kinetic-mixing term between $U(1)_Y$ and $U(1)_X$ appears, but we assume that this term is small and neglect it.¹

The scalar potential is given by

$$V = -m_H^2(H^\dagger H) - m_\Phi^2(\Phi^\dagger \Phi) + \lambda_H(H^\dagger H)^2 + \lambda_\Phi(\Phi^\dagger \Phi)^2 + \lambda_{\text{mix}}(H^\dagger H)(\Phi^\dagger \Phi). \quad (3)$$

In the unitary gauge, H and Φ are parametrized as

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \tilde{h} \end{pmatrix} \quad \text{and} \quad \Phi = \frac{v_\Phi + \tilde{\phi}}{\sqrt{2}}, \quad (4)$$

where v and v_Φ are the VEVs with $v \simeq 246$ GeV. We consider $v_\Phi \gg v$ following large electron positron bounds discussed in [36]. After imposing the stationary condition of the scalar potential, we obtain the mass-squared matrix for the scalar fields,

$$M^2 = \begin{bmatrix} 2\lambda_H v^2 & \lambda_{\text{mix}} v v_\Phi \\ \lambda_{\text{mix}} v v_\Phi & 2\lambda_\Phi v_\Phi^2 \end{bmatrix}, \quad (5)$$

in the basis of $(\tilde{h}, \tilde{\phi})$ defined in Eq. (4). These states are related to the mass eigenstates (h, ϕ) via the 2×2 orthogonal rotation matrix O_R as

$$\begin{bmatrix} \tilde{h} \\ \tilde{\phi} \end{bmatrix} = O_R \begin{bmatrix} h \\ \phi \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} h \\ \phi \end{bmatrix}, \quad (6)$$

where α is the mixing angle between these two scalars. The rotation matrix satisfies $O_R^T M^2 O_R = \text{diag}(m_h^2, m_\phi^2)$. Using these relations, we solve for the parameters λ_H , λ_Φ , and λ_{mix} in terms of α and the scalar masses as

$$\begin{aligned} \lambda_H &= \frac{1}{2v^2} (m_h^2 \cos^2 \alpha + m_\phi^2 \sin^2 \alpha), \\ \lambda_\Phi &= \frac{1}{2v_\Phi^2} (m_h^2 \sin^2 \alpha + m_\phi^2 \cos^2 \alpha), \\ \lambda_{\text{mix}} &= \left(\frac{m_h^2 - m_\phi^2}{2v_\Phi v} \right) \sin 2\alpha, \end{aligned} \quad (7)$$

where we identify h with the discovered Higgs boson with $m_h \simeq 125$ GeV, and ϕ with the Beyond the Standard Model (BSM) Higgs boson with its mass being a free parameter.

¹The kinetic mixing can be regenerated by loop effects, so that we here implicitly impose a cancellation between the contributions from loop diagrams and counterterms associated with the kinetic-mixing parameter.

The kinetic terms for the scalar fields are given by

$$\mathcal{L}_{\text{kin}} = |\mathcal{D}_\mu H|^2 + |\mathcal{D}_\mu \Phi|^2. \quad (8)$$

The mass matrix for the massive neutral gauge bosons is extracted as

$$M_{ZZ'} = \begin{pmatrix} M_Z^2 & -\frac{v^2}{2} g_Z g_X x_H \\ -\frac{v^2}{2} g_Z g_X x_H & M_{Z'}^2 \end{pmatrix}, \quad (9)$$

where

$$M_Z^2 = \frac{g_Z^2}{4} v^2, \quad (10)$$

$$M_{Z'}^2 = \frac{g_X^2}{4} (x_H^2 v^2 + 16x_\Phi^2 v_\Phi^2), \quad (11)$$

with g_X being the $U(1)_X$ gauge coupling and $g_Z = g/\cos\theta_W$ and θ_W being the weak mixing angle. For $M_{Z'} \gg M_Z$, the masses of Z and Z' are approximately given by the (1, 1) and (2, 2) elements of the above matrix, respectively, and their mixing angle ζ is given by

$$\zeta \simeq 2 \frac{M_Z^2}{M_{Z'}^2} \frac{g_X x_H}{g_Z}. \quad (12)$$

For instance, ζ is given to be of order 10^{-4} for $M_{Z'} = 10$ TeV and $g_X x_H \simeq g_Z$. We note that the dependence of x_H and x_Φ can be important when we discuss the Z' production and decay. As mentioned, however, we take the Z' mass to be much larger than the Z mass, such that it does not affect our main focus, i.e., $h \rightarrow NN$ and $Z \rightarrow NN$. In this case, x_H and x_Φ appear only via the expressions for $M_{Z'}$ and the Z - Z' mixing given in Eqs. (11) and (12), respectively. In the following discussion, we take $M_{Z'} = 10$ TeV and $g_X x_\Phi = 1$ as an illustration and take the ζ parameter as input.

The relevant Yukawa interactions to the neutrino mass generation can be written as

$$\mathcal{L} \supset -Y_\nu \bar{\ell}_L \tilde{H} N_R - \frac{1}{2} Y_N \Phi \overline{(N_R)^c} N_R + \text{H.c.}, \quad (13)$$

where Y_N and Y_ν are 3×3 Yukawa matrices, with the former being taken to be a diagonal form without loss of generality, and $\tilde{H} = i\tau^2 H^*$, with τ^2 being the second Pauli matrix. From Eq. (13), the Majorana mass for the RHNs are generated by the spontaneous breaking of $U(1)_X$ symmetry, whereas the Dirac mass for the left-handed neutrinos are generated after the electroweak symmetry breaking as

$$m_N = \frac{Y_N}{\sqrt{2}} v_\Phi, \quad m_D = \frac{Y_\nu}{\sqrt{2}} v, \quad (14)$$

which induces the seesaw mechanism to generate the light

active neutrino masses as $-m_D m_N^{-1} m_D^T$ [7,37,38]. It could successfully explain the origin of tiny neutrino masses and their flavor mixing.

The RHNs do not interact with the SM sector directly, but from the seesaw mechanism, we can write the light neutrino flavor eigenstates (ν_ℓ) in terms of the mass eigenstates of the light ν and heavy N neutrinos as

$$\nu_\ell \simeq \nu + V_{\ell N} N, \quad (15)$$

where $V_{\ell N} (= m_D/m_N)$ is the mixing matrix between the light and heavy mass eigenstates. In the discussion below, we consider one flavor of the RHN for simplicity. The charged current (CC) and the neutral current (NC) interactions in terms of the neutrino mass eigenstates can then be written as

$$\mathcal{L}_{\text{CC}} \supset - \sum_{\ell=e,\mu,\tau} \frac{g}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L V_{\ell N} N + \text{H.c.}, \quad (16)$$

$$\mathcal{L}_{\text{NC}} \supset - \sum_{\ell=e,\mu,\tau} \frac{g_Z}{2} Z_\mu \left[\bar{N} \gamma^\mu P_L (V_{\ell N}^\dagger V_{\ell N}) N + \bar{\nu} \gamma^\mu P_L V_{\ell N} N + \text{H.c.} \right], \quad (17)$$

where $P_L = \frac{1}{2}(1 - \gamma_5)$. From these interactions, the RHNs can decay into leptonic and semileptonic modes [39,40]. From Eq. (17), we see that the $Z \rightarrow NN$ mode is suppressed by $|V_{\ell N}|^4$, making it challenging to study at colliders [41], whereas other interactions, including those from Eq. (16), are proportional to $|V_{\ell N}|^2$.

Let us discuss the typical size of the width for N in our scenario. The total width of N can be estimated by neglecting masses of final state fermions as

$$\Gamma_{\text{tot}} \sim n_f \frac{G_F^2 m_N^5}{192\pi^3} |V_{\ell N}|^2 \sim 2 \times 10^{-14} \text{ GeV} \times \frac{n_f}{9} \left(\frac{m_N}{10 \text{ GeV}} \right)^5 \left(\frac{|V_{\ell N}|}{10^{-3}} \right)^2, \quad (18)$$

where G_F is the Fermi constant, and n_f is the degrees of freedom of final state fermions coming from the decay of off-shell W . In this estimation, we assumed that N dominantly couples with the first generation of the SM lepton. This size of the width, $\mathcal{O}(10^{-14})$ GeV, corresponds to the decay length of N to be of order cm or smaller, so that N decays inside detectors. On the other hand, the typical magnitude of $V_{\ell N}$ can be estimated by using the seesaw relation, i.e.,

$$|V_{\ell N}| \sim \sqrt{\frac{0.1 \text{ eV}}{m_N}} \sim 3 \times 10^{-6} \times \sqrt{\frac{10 \text{ GeV}}{m_N}}. \quad (19)$$

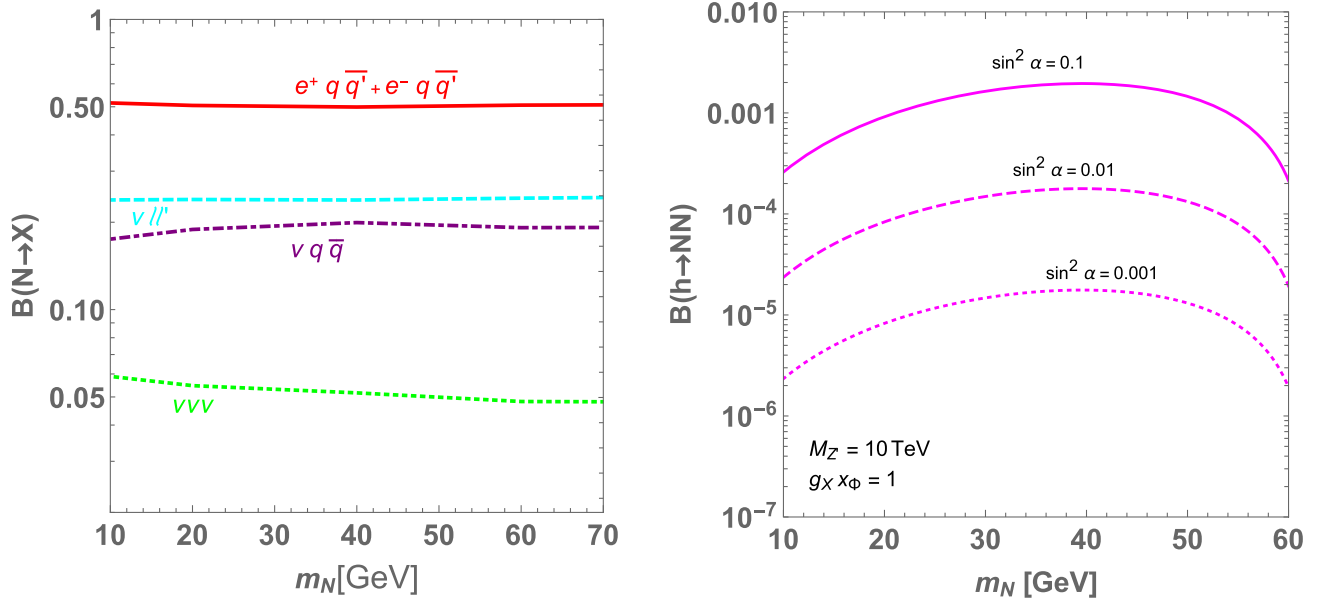


FIG. 1. Left: branching ratios of N as a function of m_N , where $q, q' \neq t$. We assumed that N dominantly couples with the first generation of the SM lepton. Right: branching ratios of $h \rightarrow NN$ as a function of m_N for $\sin^2 \alpha = 0.1$ (solid), 0.01 (dashed), and 0.001 (dotted).

By comparing the above with Eq. (18), we see that N is typically long-lived. In this paper, we consider the case with $|V_{\ell N}| \gtrsim 10^{-3}$ such that the prompt decay of N is realized, which is possible by imposing a cancellation among contributions to masses of active neutrinos from heavy neutrinos [42]. We note that the current upper limit of $|V_{\ell N}|$ has been found to be $|V_{\ell N}|^2 \simeq (m_D/m_N)^2 \lesssim 5 \times 10^{-6}$ from the recent searches [43–46] for $m_N = \mathcal{O}(10)$ GeV considering prompt decays of heavy neutrinos at the LHC.

In the left panel of Fig. 1, the branching ratios of N are shown as a function of m_N . In this plot, we consider the decay of the lightest heavy neutrino N , and N is assumed to be dominantly coupled with the first generation of the SM lepton. We see that the $N \rightarrow \ell^\pm q \bar{q}'$ mode is dominant throughout the mass range under consideration. In the numerical analysis below, we adopt the branching ratios in estimating the number of signal events.

III. HEAVY NEUTRINO PRODUCTION FROM h AND Z DECAYS

In the following discussion, we consider the scenario with $m_\phi, M_{Z'} \gg m_h > m_N/2$. In this case, N can be produced via the decays of h and Z .

The decay rate of $h \rightarrow NN$ is given as

$$\Gamma(h \rightarrow NN) = \frac{m_N^2 m_h \sin^2 \alpha}{16\pi v_\phi^2} \left(1 - 4 \frac{m_N^2}{m_h^2}\right)^{3/2}, \quad (20)$$

which will be interesting to study at the Higgs factory

considering $\sin^2 \alpha \simeq 0.1$ for $m_\phi \gg m_h$ [47,48]. Other decay rates of h into SM particles are given by the corresponding SM value times $\cos^2 \alpha$ [49,50]. The Higgs boson can also decay into $N\nu$ via the Yukawa coupling Y_ν , and the decay rate is given by

$$\Gamma(h \rightarrow N\bar{\nu}) = \frac{|V_{\ell N}|^2 m_N^2 m_h}{8\pi v^2} \left(1 - \frac{m_N^2}{m_h^2}\right)^2. \quad (21)$$

Hence, the branching ratio of $h \rightarrow NN$ is calculated as

$$\mathcal{B}(h \rightarrow NN) = \frac{\Gamma(h \rightarrow NN)}{\Gamma_h^{\text{SM}} \cos^2 \alpha + \Gamma(h \rightarrow NN) + 2\Gamma(h \rightarrow N\nu)}, \quad (22)$$

where $\Gamma_h^{\text{SM}} = 4.1$ MeV is the total width of the SM Higgs boson [51], and the factor 2 comes in the denominator combining $h \rightarrow N\nu$ and $h \rightarrow N\bar{\nu}$ modes [52–54]. We show the branching ratio of $h \rightarrow NN$ as a function of m_N for different $\sin^2 \alpha$ in the right panel of Fig. 1. We find that $\mathcal{B}(h \rightarrow NN)$ can be maximum for $m_N \simeq 40$ GeV due to its dependence on m_N , as shown in Eq. (20). We then obtain the lepton number violating signal from the Higgs decay chain of $h \rightarrow NN \rightarrow \ell^\pm \ell^\pm 4j$.

Next, let us discuss the decay of $Z \rightarrow NN$. As mentioned, the $\bar{N}NZ_\mu$ coupling from the NC is highly suppressed by $|V_{\ell N}|^2$, so that its contribution to the decay is negligibly small. However, there is another source giving the $\bar{N}NZ_\mu$ coupling via the Z - Z' mixing. Namely,

$$\mathcal{L}_{\text{int}} \supset \frac{x_\Phi g_X}{2} \bar{N} \gamma^\mu \gamma^5 N (Z_\mu \sin \zeta + Z'_\mu \cos \zeta). \quad (23)$$

Hence, the decay rate of $Z \rightarrow NN$ is given by

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

Therefore, the branching ratio of $\mathcal{B} \rightarrow NN$ is calculated as

$$\mathcal{B}(Z \rightarrow NN) = \frac{\Gamma(Z \rightarrow NN)}{\Gamma_Z^{\text{SM}} + \Gamma(Z \rightarrow NN)}, \quad (25)$$

with $\Gamma_Z^{\text{SM}} \simeq 2.5$ GeV being the total width of the Z boson in the SM [55–57]. The magnitude of the Z - Z' mixing is constrained to be $|\zeta| < \mathcal{O}(10^{-3})$ from the electroweak precise measurements [58]. Putting $x_\Phi g_X = 1$ and $\zeta = 10^{-3}$, the branching ratio of $Z \rightarrow NN$ is estimated to be about 5×10^{-7} . This could be tested at Z factories with $\mathcal{O}(10^{12})$ of the production of the Z boson. Similar to the Higgs decay, we can prove the LNV via the decay chain of $Z \rightarrow NN \rightarrow \ell^\pm \ell^\pm 4j$.

IV. RESULTS AND DISCUSSION

We estimate the signal significance for the LNV signal $h/Z \rightarrow NN \rightarrow \ell^\pm \ell^\pm 4j$ by performing detector level simulations. We first consider the h decay. For the Higgs production, we consider $gg \rightarrow h$, $e^+e^- \rightarrow hZ$, and $\mu^+\mu^- \rightarrow h$ at the LHC, future electron-positron colliders, and MCs, respectively. For the hZ process, we consider hadronic decays of the Z boson. At MCs, we take into account the effects of the ISR and the BES [27]. The production cross sections are given in Table I.

In order to simulate signals and BG processes, we use MadGraph5 [59] for event generation and PYTHIA 8.3 [60] for hadronization. We used IDEA card from DELPHES [61] for lepton colliders and CMS card for LHC. The significance of the LNV signal is defined by

$$S_{\text{LNV}} = \frac{\epsilon_{\text{eff}} N_S}{\sqrt{\epsilon_{\text{eff}} N_S + 2\epsilon_{\text{miss}} N_B}}, \quad (26)$$

where $N_S(N_B)$ is the number of signal (BG) events, ϵ_{eff} denotes the efficiency for the signal events, and ϵ_{miss}

TABLE I. Simulation for the LNV signature at each Higgs factory. For e^+e^- colliders, σ_h^{SM} indicates hZ production with unpolarized beam.

	LHC	e^+e^- colliders	$\mu^+\mu^-$ colliders
$\sqrt{s}$	13 (14) TeV	250 (240) GeV	125 GeV
$\mathcal{L}_{\text{int}}$ [ab $^{-1}$]	0.138 (3)	2 (21.6)	0.02
σ_h^{SM} [pb]	48.61 (54.72)	0.23 (0.20)	20
BG process	$\ell^+ \ell^- 4j$	$\ell^+ \ell^- jjZZ(ZW)$	$\ell^+ \ell^- 4j$

denotes the charge misidentification rate explained below (the factor 2 appears since we count misidentification of both ℓ^+ and ℓ^-). The number of signal events is estimated by

$$N_S = \sigma_h^{\text{SM}} \cos^2 \alpha \times \mathcal{L} \times \mathcal{B}(h \rightarrow NN) \times [\mathcal{B}^2(N \rightarrow \ell^+ jj) + \mathcal{B}^2(N \rightarrow \ell^- jj)], \quad (27)$$

where $\ell = e, \mu$ and σ_h^{SM} is the h production cross section in the SM (see Table I), and $\mathcal{L}$ is the integrated luminosity. Regarding the BG, we consider the following processes at each collider:

$$\begin{aligned} pp &\rightarrow \ell^+ \ell^- 4j, \\ e^+ e^- &\rightarrow \ell^+ \ell^- jjZZ / \ell^+ \ell^- jjWZ, \\ \mu^+ \mu^- &\rightarrow \ell^+ \ell^- 4j, \end{aligned} \quad (28)$$

where one of the leptons is charge-misidentified with the rate of ϵ_{miss} at detectors. Here, all the processes providing these final states are included in generating the BGs. We impose cuts on the transverse momentum (p_T), the pseudorapidity (η), the separation between leptons ($\Delta R_{\ell\ell}$), lepton jet ($\Delta R_{\ell j}$), and jets (ΔR_{jj}) as well as the invariant mass (IM) for the $\ell^+ \ell^- 4j$ system ($M_{\ell^+ \ell^- 4j}$) at the LHC:

$$\begin{aligned} p_T(\ell) &> 5 \text{ GeV}, & p_T(j) &> 15 \text{ GeV}, \\ |\eta(\ell)| &< 2.4, & |\eta(j)| &< 2.4, \\ \Delta R_{\ell\ell} &> 0.2, & \Delta R_{\ell j} &> 0.2, & \Delta R_{jj} &> 0.2, \\ 110 \text{ GeV} &< M_{\ell^+ \ell^- 4j} &< 140 \text{ GeV}. \end{aligned} \quad (29)$$

On the other hand, we impose the following cuts for lepton colliders (including e^+e^- , $\mu^+\mu^-$, μ^+e^- , $\mu^+\mu^+$):

$$\begin{aligned} p_T(\ell) &> 5 \text{ GeV}, & p_T(j) &> 5 \text{ GeV}, \\ |\eta(\ell)| &< 2.4, & |\eta(j)| &< 2.4, \\ \Delta R_{\ell\ell} &> 0.2, & \Delta R_{\ell j} &> 0.2, & \Delta R_{jj} &> 0.2, \\ 110 \text{ GeV} &< M_{\ell^+ \ell^- 4j} &< 140 \text{ GeV}. \end{aligned} \quad (30)$$

In Table I, we summarize the center of mass energy, integrated luminosity, Higgs production cross section, and BG process for each collider experiment. In Table II, the signal cross section $\sigma_h^{\text{SM}} \times \mathcal{B}$, after imposing the kinematical cuts, is summarized, where $\mathcal{B}$ indicates the products of branching ratio for h and N decays, and we here set $\mathcal{B} = 1$ for illustration. The signal efficiency ϵ_{eff} is estimated by the ratio of the original Higgs production cross sections in Table I and the cross sections after cuts in Table II. In Table III, we show the BG cross section before and after the IM cut, where all the other kinematical cuts are already imposed on both the cross sections. In this analysis, we

TABLE II. Signal cross sections after cuts for Higgs production case where we set $\mathcal{B}(h \rightarrow NN)\mathcal{B}(N \rightarrow \ell jj)^2 = 1$ for illustration.

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

TABLE III. Cross sections of BG process for Higgs production signals before and after IM cuts including detector efficiency.

	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]

have used a mistagging efficiency of light jets as 1% [62], whereas the efficiencies for electrons and muons are 80% and 95% [63,64], respectively, for low p_T leptons at the LHC. In the case of e^+e^- colliders, we adopt the same efficiency for light jets misidentification, considering electron (muon) identification efficiency as 100 (95)% [20,65–67].

In the left panel of Fig. 2, we show the results for the LNV signal at the Higgs factories. Points on each solid curve satisfy $S_{\text{LNV}} = 2$ on the m_N - $\sin^2\alpha$ plane, where we adopt $\epsilon_{\text{mis}} = 0.01$ for all colliders. We thus find that current LHC data can test $\sin^2\alpha \simeq 0.06$ for $m_N \simeq 40$ GeV. Furthermore, the sensitivity for $\sin^2\alpha$ can reach around 10^{-2} by HL-LHC, ILC, and MC and 10^{-3} by Circular Electron Positron Collider (CEPC) (upgraded) for $m_N \simeq 40$ GeV. Due to the nature of $\mathcal{B}(h \rightarrow NN)$ and its dependence on m_N , we find that strongest limit on the scalar mixing could be obtained for $m_N \simeq 40$ GeV. For comparison, we also show current and future perspective for testing $\sin^2\alpha$ from the Higgs coupling measurements at LHC Run-II [68], HL-LHC [16,47], CLIC [47], and from direct searches for ϕ , assuming $m_\phi = 1$ TeV at the HL-LHC [16,47,69] and CLIC [47,70].

In addition, we study limits on $\sin^2\alpha$ taking $m_N = 40$ GeV at $e^-\mu^+$ and $\mu^+\mu^+$ colliders with $(\sqrt{s}, \mathcal{L}_{\text{int}}) = (346 \text{ GeV}, 1 \text{ ab}^{-1})$ and $(2 \text{ TeV}, 100 \text{ fb}^{-1})$, respectively, under BG-free scenarios ($\mu\text{TRISTAN}$).² The Higgs boson

can mainly be produced via the W boson fusion process, and its cross section is given to be about 91 fb at the $e^-\mu^+$ collider. Using Eq. (26), we obtain the upper limit of $\sin^2\alpha = 0.053$, which will be comparable with the expectation given at the HL-LHC. In a similar fashion, we obtain the upper limit of $\sin^2\alpha = 0.092$ from the $\mu^+\mu^+$ collider, where the Higgs boson is produced via the Z boson fusion, and its cross section is given to be about 54 fb. For the $e^-\mu^+$ collision with $(\sqrt{s}, \mathcal{L}_{\text{int}}) = (775 \text{ GeV}, 1 \text{ ab}^{-1})$, i.e., $\mu\text{Tevatron}$, the Higgs production cross section is 472 fb from the W boson fusion. Using Eq. (26), we obtain the upper limit of $\sin^2\alpha = 0.0097$, which could be compared to the bounds obtained from the ILC from Fig. 2.

Finally, we discuss the signal significance of the $\ell^\pm\ell^\pm 4j$ signal from the Z boson decay into a pair of N at Z factories. In particular, we focus on Tera- Z experiments, where 10^{12} Z bosons are expected to be produced at the Z -pole energy, corresponding to $\sim 100 \text{ ab}^{-1}$ of the integrated luminosity. A possible BG process in the SM is $e^+e^- \rightarrow \ell^+\ell^- 4j$, where it mimics the signal if the detector misidentifies the charge of one lepton. Similar to the case for the Higgs decay, we generate the signal and BG events by using MadGraph5 [59] followed by PYTHIA 8.3 [60] for hadronization and DELPHES [61] for detector simulation. We then apply the following kinematical cuts:

$$\begin{aligned}
p_T(\ell) &> 5 \text{ GeV}, & p_T(j) &> 5 \text{ GeV}, \\
|\eta(\ell)| &< 2.4, & |\eta(j)| &< 2.4, \\
\Delta R_{\ell\ell} &> 0.2, & \Delta R_{\ell j} &> 0.2, & \Delta R_{jj} &> 0.2. \quad (31)
\end{aligned}$$

After the kinematical cuts given in Eq. (31), we obtain the BG cross section as

$$\sigma(e^+e^- \rightarrow \ell^+\ell^- 4j) \simeq 6.8 \text{ fb}. \quad (32)$$

For the signal events, the efficiency ϵ_{eff} under the p_T cut is also estimated, and we find $\epsilon_{\text{eff}} \simeq 0.091$ to $\epsilon_{\text{eff}} \simeq 0.35$ for $m_N = 10$ GeV to 40 GeV. Then, we calculate the signal significance by using Eq. (26). The number of events is

²In this case, the possible BGs are $\mu^+\mu^+ + \ell^+\ell^- 4j$ and $\ell^+\ell^- 4j +$ missing energy for the signals coming from the Higgs productions via the Z boson and W boson fusion, respectively. These final states include many particles, and the cross section would be sufficiently small, as in the BG for the e^+e^- collider case. In addition, we expect that the BGs can be reduced by adopting cuts like forward-backward muon tagging for $\mu^+\mu^+ +$

$\ell^+\ell^- 4j$ and missing energy cuts for $\ell^+\ell^- 4j +$ missing energy BGs. Then, we simply assume the background free condition at $\mu\text{TRISTAN}$.

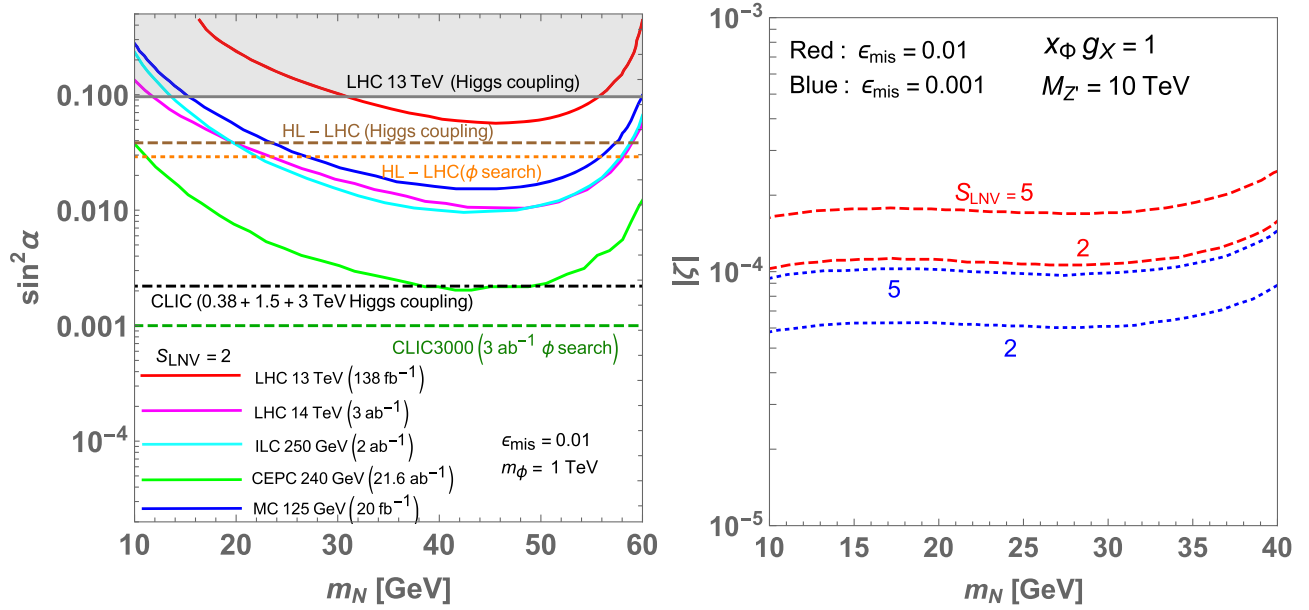


FIG. 2. Left: the LNV signature can be explored from the Higgs decay with the significance $S_{\text{LNV}} = 2$ on each curve in the m_N - $\sin^2 \alpha$ plane. The horizontal lines show the upper limit on $\sin^2 \alpha$ from the Higgs coupling measurements and direct searches for ϕ . Right: the LNV signature can be explored from the Z decay with the significance $S_{\text{LNV}} = 2$ and 5, assuming $\epsilon_{\text{mis}} = 0.01$ (red) and 0.001 (blue) on each curve in the m_N - $|\zeta|$ plane. In both the panels, we assumed that N dominantly couples with the first generation of the SM lepton.

estimated by

$$N_S = 4.1 \times 10^{12} \times \mathcal{B}(Z \rightarrow NN) \times [\mathcal{B}(N \rightarrow \ell^+ jj)^2 + \mathcal{B}(N \rightarrow \ell^- jj)^2], \quad (33)$$

where 4.1×10^{12} is the number of Z bosons at the CEPC Z factory [34]. In the right panel of Fig. 2, we show the significance S_{LNV} for the LNV signal at Z factories, where red-dashed and blue-dotted curves correspond to charge misidentification rate 1% and 0.1% cases, respectively. Thus, the signal can be tested with 90% confidence level, corresponding to $S_{\text{LNV}} = 2$, for $|\zeta| \gtrsim 10^{-4}$ (6×10^{-5}) for $\epsilon_{\text{mis}} = 0.01$ (0.001).

V. CONCLUSIONS

In this work, we have investigated LNV signals from the decays of the 125 GeV Higgs boson h and Z boson into a pair of RHNs (N). The decay of $h \rightarrow NN$ is induced via the mixing with a singlet scalar, which induces Majorana masses for the RHNs after the $U(1)_X$ symmetry breaking. On the other hand, the Z boson decays into NN via the Z - Z' mixing. We have performed simulation studies at the parton level for the LNV signals and BGs at the Higgs/Z factories. It has been found that LNV signals via the Higgs decay can be explored for the scalar mixing $\sin^2 \alpha \gtrsim 10^{-2}$ (10^{-3}) at the

HL-LHC, MCs, and ILC (CEPC) for $m_N \simeq 40$ GeV. We also have shown that a similar sensitivity can be obtained at $e^- \mu^+$ and $\mu^+ \mu^+$ collisions (μ TRISTAN) as those given at the HL-LHC. For the LNV signal from Z decay, we can have sensitivity to test it when Z - Z' mixing is $|\zeta| \gtrsim 10^{-4}$. Therefore, we have shown that future Higgs and Z factories are excellent opportunities to find LNV signals from the decays of Higgs/Z, providing significant avenues to explore the Majorana nature of neutrinos.

Note added. For a future work, we will be considering long-lived heavy neutrino pairs produced from Higgs- and Z-mediated interactions [71].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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