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Probing the decoupled seesaw scalar in rare Higgs boson decay

Yu Gao,^a Mingjie Jin^{b,a} and Kechen Wang^c

^aKey Laboratory of Particle Astrophysics, Institute of High Energy Physics,
Chinese Academy of Sciences, Beijing, 100049, China

^bDepartment of Physics, Beijing Normal University,
Beijing, 100875, China

^cDepartment of Physics, School of Science, Wuhan University of Technology,
430070 Wuhan, Hubei, China

E-mail: gaoyu@ihep.ac.cn, jinmj@ihep.ac.cn, kechen.wang@whut.edu.cn

ABSTRACT: The Higgs boson can mix with a singlet scalar that dynamically generates the Majorana mass of the right-handed neutrino N_R . We show that even a tiny mixing between the Higgs boson and a ‘decoupled’ singlet scalar allows for Higgs-mediated pair production of N_R without significant mixings between the active neutrinos and N_R , and thus testable at colliders via a characteristic signal of two same-sign same-flavor lepton pairs, plus missing energy. We demonstrate that this search channel is mostly background-free in pp -collision and can be a highly sensitive probe of the Higgs-singlet mixing at the current and future pp colliders. Such channel provides a clean signal to discover the singlet scalar and explore the origin of neutrino masses.

KEYWORDS: Beyond Standard Model, Higgs Physics, Neutrino Physics

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1 Introduction

The seesaw mechanism has been extensively studied to generate the tiny active neutrino mass. By adding a right-handed neutrino N_R and introducing a Dirac neutrino mass $m_D \nu_L N_R$, the Standard Model's (SM's) neutrino ν_L and the hypothetical N_R can mix into the active neutrino ν and a heavy neutrino N , where the active neutrino mass $m_\nu \sim m_D^2/M$ can be brought down to sub-eV scale by having a high-scale Majorana mass M of N_R .

The heavy N is an important target of new physics searches as the crucial seesaw ingredient. At colliders it can be weakly produced via its active neutrino component or by its N_R component's coupling to SM particles. One major difficulty for the weak production is that it is limited by N_R 's typically small mixing with the weakly charged ν_L . Nowadays Large Hadron Collider (LHC) searches [1, 2] and electroweak precision measurements [3, 4] probe the effective $\nu_l - N_R$ mixing parameters $|V_{lN}|^2$ [5] to $\sim 10^{-5}$. Alternatively, a N_R uncharged under SM gauge interactions can still have a sizable coupling to massive Beyond the Standard Model (BSM) scalars which mix with the SM Higgs boson. Well-motivated scenarios include the N_R coupling to the neutral scalar components in Left-Right symmetric models [6], gauged $U(1)_{B-L}$ symmetric models [7], and seesaw models with gauge-singlet scalars [8], etc.

While direct massive BSM mediator production is an important aspect of future high energy searches, their contribution to the rare decay of the SM bosons must be carefully examined for a potentially tiny N_R related mixing. Well known instances include the rare Higgs decay channel $h \rightarrow l^\pm l^\pm 4j$ that is enhanced by the Higgs-BSM scalar mixing [8–10], which have been studied as a good test of lepton number violation (LNV) in case

of a Majorana heavy neutrino. N_R characteristic and collider-testable rare Higgs decay channels are very important precision searches, especially as so far collider searches show no robust sign of BSM mediators.

Generally, a singlet scalar that dynamically generates the Majorana mass of the N_R can mix with the Higgs boson, which allows the Higgs boson's decay mode of $h \rightarrow NN$ without requiring sizeable left-right neutrino mixings. Such a singlet extension of the SM is often motivated for the dynamical N_R mass generation, and it potentially helps understanding several important phenomena: the baryon number asymmetry via a strong first order electroweak phase transition [11, 12], the abundance of dark matter [13, 14] and the issue of vacuum stability [15–17], etc. In this study we advocate that such new singlet scalar could be discovered at pp colliders by searching for the fully leptonic rare Higgs decay channel $h \rightarrow NN \rightarrow 4l + \cancel{E}_T$.

For minimal parameter dependence we start with a *small-mixing* scenario of the BSM scalar sector in a Type I seesaw setup where the L-R mixing is typically small,

$$\mathcal{L} \supset V(\Phi) + V(S) + \frac{\lambda}{2} |\Phi|^2 S^2 + y_N S \bar{N}_R^c N_R + y_D \bar{L} \Phi N_R + \text{c.c.}$$

Φ denotes the scalar field(s) that yield the 125 GeV Higgs boson, and S for a singlet scalar field that couples to the right-hand singlet neutrino N_R . Here we leave out the specific form of the potentials and only assume ‘small-mixing’, which is a very subleading mixing term $\frac{1}{2} \lambda |\Phi|^2 S^2$, so that $V(\Phi)$ and $V(S)$ minimize independently. Φ and S develop their own vacuum expectation values (vev): $\Phi = (v_\Phi + \phi)/\sqrt{2}$ to give rise to electroweak symmetry breaking and generate a Higgs-like boson ϕ , and $S = v_S + s$ to yield a necessary Majorana mass $m_{N_R} = 2y_N v_S$. The small but non-zero mixing term also portals N_R into ϕ decay, yielding our search signal. For simplicity here we neglected the $|H|^2 S$ term which has a dimensional coupling, by assuming its coupling is subdominant to λv_Φ .

The λ term develops a $\phi - s$ mass mixing term $\lambda v_\Phi v_S \cdot \phi s$ after potential minimization, where the scalar mass-square matrix can be parametrized as,

$$\begin{array}{|c|cc|} \hline & \phi & s \\ \hline \phi & m_\phi^2 & \lambda v_\Phi v_S \\ s & \lambda v_\Phi v_S & m_s^2 \\ \hline \end{array} . \quad (1.1)$$

With ‘small mixing’ such that $\lambda v_\Phi v_S \ll m_\phi^2, m_s^2$, this matrix is dominated by the diagonal terms and the mass eigenstate $\{h_{1,2}\}$ is a rotation by a small angle α from the gauge eigenstates $\{\phi, s\}$,

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix}. \quad (1.2)$$

Without loss of generality h_1 identifies with the SM Higgs boson and contains an s -component of the magnitude

$$\alpha = \frac{\lambda v_\Phi v_S}{|m_s^2 - m_\phi^2|}, \quad (1.3)$$

which leads to a decay channel $h_1 \rightarrow NN$ in addition to the SM decays, if kinematically permitted. Similarly h_2 is mostly s and has only a small ϕ -component. Since s does not

couple to the SM fermions, h_1 's s -component leaves the relative branching ratios unchanged from their SM values. Such a mixing can be sizable [18, 19] if S is completely decoupled ($y_N \rightarrow 0$). For small mixings we would take ‘decoupling’ Φ, S conditions:

$$\sin^2 \alpha \ll 1, \quad (1.4)$$

$$\lambda \cdot \max(v_S^2, v_\Phi^2) \ll \min(m_s^2, m_\phi^2). \quad (1.5)$$

The latter simplifies to $\lambda v_S^2 \leq \mathcal{O}(10^{-2}) m_{h_1}^2$ if we consider an h_2 comparable to or heavier than the Higgs boson.

A finite y_N leads to the h_1 decay partial width

$$\Gamma_{h_1 \rightarrow NN} = \frac{1}{2} \sin^2 \alpha \cdot \frac{y_N^2 m_{h_1}}{8\pi} \left(1 - \frac{4m_N^2}{m_{h_1}^2} \right)^{3/2} \quad (1.6)$$

for each N species, where $m_{h_1}=125$ GeV, $m_N = 2y_N v_S$ and the factor $1/2$ is due to N being Majorana. Given the rather small SM Higgs boson's decay width $\Gamma_h \sim 4$ MeV and relatively light heavy neutrino mass $m_N \lesssim m_{h_1}/2$, the branching ratio of h_1 decay to NN is

$$\text{BR}_{h_1 \rightarrow NN} = \frac{\Gamma_{h_1 \rightarrow NN}}{\Gamma_h + \Gamma_{h_1 \rightarrow NN}}. \quad (1.7)$$

This leads to $\text{BR}_{h_1 \rightarrow NN} \approx \Gamma_{h_1 \rightarrow NN}/\Gamma_h$ for $\sin^2 \alpha \ll 1$. In both Majorana and Dirac N_R cases, the subsequent NN decay can lead to a characteristic two same-sign, same-flavor lepton pair, plus missing transverse energy signal $e^\pm e^\pm \mu^\mp \mu^\mp + \cancel{E}_T$.

2 Signal at pp colliders

The Higgs-like h_1 can be copiously produced via gluon fusion during pp collisions with a cross-section $\sigma_{h_1} = \sigma_{pp \rightarrow h_1}$. NN decay then yields a characteristic and *remarkably clean* signal of two same-sign, same-flavor (SSSF) lepton pairs as illustrated in figure 1. The two lepton pairs should have different lepton flavors and opposite charges (i.e. $e^\pm e^\pm \mu^\mp \mu^\mp$ and no opposite-sign, same-flavor lepton pair exists). This channel differs from the LNV $NN \rightarrow l^\pm l^\pm 4j$ case that it does not necessarily violate lepton number conservation (LNC) if N couples to more than one lepton flavor, as the final state ν can be either neutrinos or anti-neutrinos. Therefore, this final state can be present either N is Majorana or Dirac.

With a Majorana N , the NN system has a higher decay branching to this final state as one N can also decay as its own antiparticle. In such case, for each species of N the branching factor of the signal final state from NN is obtained by summing up the LNV and LNC processes,

$$\begin{aligned} \text{BF}_{\text{sig.}} &\equiv \text{BF}_{\text{sig.}}(NN \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp 2\nu) \\ &= \frac{1}{2} \sum_{i \neq j} \left(\frac{|V_{iN}|^2}{\Sigma^2} \text{BF}_j^l \right)^2 \quad (\text{for LNV}) \\ &\quad + \frac{1}{2} \sum_{i \neq j} \left(\frac{|V_{iN}|^2}{\Sigma^2} \text{BF}_j^l \right) \left(\frac{|V_{jN}|^2}{\Sigma^2} \text{BF}_i^l \right) \quad (\text{for LNC}), \end{aligned} \quad (2.1)$$

Figure 1. Representative NN processes that contain two pairs of leptons of the same-sign and the same-flavor. The LNC diagram (left) requires N couples to at least two lepton flavors.

where $\Sigma^2 \equiv |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$, and $i, j = \{e, \mu\}$ for lepton flavors. BF_i^l is the $W^{(*)} \rightarrow l_i \nu$ branching fraction in N decay. Note the $N \rightarrow ll' \nu$ requires charged weak gauge boson mediation, which makes BF_i^l depend on both m_N and whether BSM mediators are present in N decay. The maximal $\text{BF}_{\text{sig.}}$ is reached if N only couples to one lepton flavor, and $\text{BF}_{\text{sig.}} \leq (\text{BF}^l)^2/2$.

Similarly, the h_2 scalar can also be produced via its ϕ -component at a cross-section $\sigma_{h_2} = \sigma_{pp \rightarrow h_2} = \sin^2 \alpha \cdot \sigma_{pp \rightarrow h} \big|_{m_h^{\text{kin.}} = m_{h_2}}$, where the latter is the SM Higgs-like boson production cross-section evaluated for a different kinematical mass m_{h_2} . Since both the $h_1 \rightarrow NN$ branching and the h_2 's production cross-section scale as $\sin^2 \alpha$, assuming a near-unity branching of $h_2 \rightarrow NN$, their contributions are the same order in terms of $h-s$ mixing.

We note that h_2 decay modes depend on the relative size between m_{h_1}, m_{h_2} and m_N . When $m_{h_2} > 2m_{h_1}$, the $h_2 \rightarrow h_1 h_1$ channel opens up, but it is suppressed at small λ . h_2 may also decay to the SM fermion/gauge boson pairs, with an α^2 suppression. Therefore, in case of a kinematically accessible $m_{h_2} > 2m_N$ and a small λ , $h_2 \rightarrow NN$ dominates h_2 decays and acquire a near-unity branching. In case $m_{h_2} \ll m_{h_1}$ and $m_{h_2} < 2m_N$, however, the relative branching ratios become less transparent as h_2 decays via the ϕ - and s - components compete between the α^2 -dependent two-body channels and the $|V_{lN}|^2$, m_N -dependent multi-body channels.

The total signal cross-section is then

$$\sigma_{\text{sig.}} = \sigma_{h_1} \cdot \text{BR}_{h_1 \rightarrow NN} \cdot \text{BF}_{\text{sig.}} \cdot A_{\text{eff}}^{(1)} + \sigma_{h_2} \cdot \text{BR}_{h_2 \rightarrow NN} \cdot \text{BF}_{\text{sig.}} \cdot A_{\text{eff}}^{(2)}, \quad (2.2)$$

where $A_{\text{eff}}^{(1,2)}$ is the detector selection efficiency for h_1, h_2 mediated event samples, which can be separately studied via Monte Carlo simulations. h_2 's event rate may quickly become subdominant with a heavy h_2 mass, and with $m_{h_2} \sim \mathcal{O}(m_{h_1})$ it can still be the main contributor due to its near-unity decay branching into NN . Note this $h_{1,2}$ mediated signal rate bypasses the vertex suppression from $\nu_L - N_R$ mixing, and serves as a probe for low $\nu_L - N_R$ mixing scenarios, e.g. Type-I seesaw models.

For convenience in phenomenology study we consider the simplified case where only the mass of one heavy neutrino N_1 lies below $\frac{1}{2}m_{h_1}$ and N_1 mixes with only one active neutrino

flavor ν_μ . In this case only the LNV diagram in figure 1 contributes, and $\text{BF}_{\text{sig.}}$ reaches its maximum $\text{BF}_{\text{sig.}} = 0.16\%$. Complication rises when both m_N and $|V_{LN}|^2$ are small the N lifetime can be quite long, which leads to displaced decay at colliders. Our study relies on reconstructing decay kinematics so we require N decays inside the detector. Note that this decay-length issue can be circumvented in BSM models: $|V_{LN}|^2$ can be enhanced by inverse-seesaw [20] after introducing mixture into an extra singlet fermion; also if N_R is charged under BSM interactions, e.g. in extra-U(1) and Left-Right symmetric models, N gains extra partial width that helps make its decay visible but it also suppresses BF^l at the same time.

The major kinematic difference from a similar large invariant-mass search for doubly-charged Higgs [21, 22] is that our four leptons are much softer in energy, only adding up to a fraction of the Higgs boson mass in the optimal mass range $m_N < \frac{1}{2}m_{h_1}$. In addition, the same-sign lepton pair must rise from different parent particles in the NN decay, leading to different kinematic topologies. Moreover, our final state contain two neutrinos which act as missing energy.

3 Background and multivariate analysis

The $e^\pm e^\pm \mu^\mp \mu^\mp + \cancel{E}_T$ signal has very few SM background events at the pp colliders due to the presence of two pairs of SSSF leptons. The irreducible background includes contribution from $pp \rightarrow 4\tau, WWZ (Z \rightarrow 2\tau)$ channels in which the flavor combinatorics among the four e/μ leptons after τ, W decays can produce the same final state. Because 4τ channel is mainly $ZZ \rightarrow 4\tau$ after all selection cuts, it is related to the di-boson production, and is the leading background at lower invariant masses. The $pp \rightarrow 4W$ channel is much subdominant due to its higher number of weak interaction vertices. Another potential background may arise from events with jets, usually from decays of hadrons into leptons, misidentified as leptons. However, a reliable fake-lepton background is usually obtained by the “data-driven” approach, which relies on experimental data. A very relevant experiment study [22] which has a similar signal final state shows that the background from doubly faked leptons can be subdominant to di-boson production. Besides, our signal requires two muons while faked leptons are mostly electrons. Thus, it might indicate that the fake-lepton contribution is controllable in our case. We include 4τ and WWZ channels as the main background in our pp collision event simulations, and leave the fake-lepton process for further study when data become available.

We quote the measured Higgs boson’s single production cross-section via gluon fusion process $\sigma_{pp \rightarrow h} = 54.7$ pb at 14-TeV [24] and 740 pb at 100-TeV [25]. As h_2 is also mostly produced by gluon fusion, we adopt the $N^3\text{LO}$ scalar mass dependence [26] to scale the h_2 production rate in σ_{h_2} . For data simulations we use MadGraph5_aMC@NLO version 2.6.1 [27] for parton level event generation, Pythia6 [28] for the parton shower and hadronization, and Delphes 3.4.1 [29] for detector simulation.

At the HL-LHC (FCC-hh/SppC), we generate about 150 (165) million 4τ , 10 (15) million WWZ , and 0.1 million signal events for kinematic analyses. Simulated events are analyzed to reject the SM background and maximize the signal significance. First the

following pre-selection is applied: (a) exactly four leptons with $p_T(l_{1,2}) > 10 \text{ GeV}$ and $p_T(l_{3,4}) > 5 \text{ GeV}$; (b) one same-sign $e^\pm e^\pm$ pair and one $\mu^\mp \mu^\mp$ pair; (c) no tagged τ leptons or b -jets.

After pre-selection, in order to construct useful kinematical observables, the stransverse mass M_{T2} [30–32] is exploited to identify the electron and muon from the same heavy neutrino decay. Since the final state has four leptons (e.g. $\mu_1^+ \mu_2^+ e_1^- e_2^-$) and the two leptons from the same N decay must have opposite sign and different flavor (i.e. $\mu^+ e^-$), we calculate the M_{T2} values corresponding to two different combinations of the two-lepton system for μ_1 (i.e. $\mu_1^+ e_1^-$ and $\mu_1^+ e_2^-$). The combination with smaller M_{T2} value (e.g. $\mu_1^+ e_2^-$) is considered from the same N decay, while the remaining lepton pair (i.e. $\mu_2^+ e_1^-$) is considered to be from the other N . We then input a comprehensive collection of 53 kinematic observables to the TMVA package [33] to perform the MVA.

I. global observables:

I.1) the missing transverse energy $\cancel{E}_T$;

I.2) $M_{T2}(\mu_1 + e, \mu_2 + e)$.

II. observables for the system of lepton(s):

II.1) p_T and the pseudorapidity η of lepton $p_T(\mu_1)$, $p_T(\mu_2)$, $p_T(e_1)$, $p_T(e_2)$, $\eta(\mu_1)$, $\eta(\mu_2)$, $\eta(e_1)$, $\eta(e_2)$;

II.2) p_T , η and the invariant mass M of leptons $p_T(\mu_1 + \mu_2)$, $\eta(\mu_1 + \mu_2)$, $M(\mu_1 + \mu_2)$, $p_T(e_1 + e_2)$, $\eta(e_1 + e_2)$, $M(e_1 + e_2)$, $p_T(\mu_1 + e)$, $\eta(\mu_1 + e)$, $M(\mu_1 + e)$, $p_T(\mu_2 + e)$, $\eta(\mu_2 + e)$, $M(\mu_2 + e)$, $p_T(\mu_1 + \mu_2 + e_1 + e_2)$, $\eta(\mu_1 + \mu_2 + e_1 + e_2)$, $M(\mu_1 + \mu_2 + e_1 + e_2)$;

II.3) the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$ of the system of leptons $\Delta\eta(\mu_1, \mu_2)$, $\Delta\phi(\mu_1, \mu_2)$, $\Delta\eta(e_1, e_2)$, $\Delta\phi(e_1, e_2)$, $\Delta\eta(\mu_1, e)$, $\Delta\phi(\mu_1, e)$, $\Delta\eta(\mu_2, e)$, $\Delta\phi(\mu_2, e)$, $\Delta\eta(\mu_1 + e, \mu_2 + e)$, $\Delta\phi(\mu_1 + e, \mu_2 + e)$.

III. observables between the missing energy and lepton(s):

III.1) $\Delta\phi$ between the missing transverse momentum and lepton(s) $\Delta\phi(\cancel{E}_T, \mu_1)$, $\Delta\phi(\cancel{E}_T, \mu_2)$, $\Delta\phi(\cancel{E}_T, e_1)$, $\Delta\phi(\cancel{E}_T, e_2)$, $\Delta\phi(\cancel{E}_T, \mu_1 + \mu_2)$, $\Delta\phi(\cancel{E}_T, e_1 + e_2)$, $\Delta\phi(\cancel{E}_T, \mu_1 + e)$, $\Delta\phi(\cancel{E}_T, \mu_2 + e)$, $\Delta\phi(\cancel{E}_T, \mu_1 + \mu_2 + e_1 + e_2)$;

III.2) the transverse mass M_T of the system formed by the missing momentum plus lepton(s) $M_T(\cancel{E}_T, \mu_1)$, $M_T(\cancel{E}_T, \mu_2)$, $M_T(\cancel{E}_T, e_1)$, $M_T(\cancel{E}_T, e_2)$, $M_T(\cancel{E}_T, \mu_1 + \mu_2)$, $M_T(\cancel{E}_T, e_1 + e_2)$, $M_T(\cancel{E}_T, \mu_1 + e)$, $M_T(\cancel{E}_T, \mu_2 + e)$, $M_T(\cancel{E}_T, \mu_1 + \mu_2 + e_1 + e_2)$.

Here μ_1 , μ_2 , e_1 , e_2 denote muons or electrons with the first or second leading transverse momentum, while for $(\mu_1 + e)$ or (μ_1, e) the muon and electron are two leptons from the same N decay. The variables can be ranked according to their importance in the TMVA analysis. For the benchmark case with signal from $h_1 \rightarrow NN$ and $m_N = 20 \text{ GeV}$, at the HL-LHC, the most useful observables are found to be $M_{T2}(\mu_1 + e, \mu_2 + e)$, $\Delta\phi(\mu_2, e)$, $M(\mu_1 + e)$, $\Delta\phi(\mu_1, e)$, $M(\mu_2 + e)$, $\Delta\eta(\mu_2, e)$, $\Delta\eta(\mu_1, e)$, $M_T(\cancel{E}_T, \mu_1 + \mu_2 + e_1 + e_2)$, $\Delta\phi(\cancel{E}_T, \mu_1 + \mu_2)$,

Figure 2. Distributions of BDT responses for the signal event sample (black, filled), and those for the SM background samples including 4τ (red) and WWZ (blue). This figure illustrates an h_1 decay signal by gluon fusion at the HL-LHC, with $m_N=20$ GeV.

$\Delta\phi(\cancel{E}_T, e_1 + e_2)$, $\Delta\phi(\mu_1, \mu_2)$, $M(\mu_1 + \mu_2 + e_1 + e_2)$. We note that since the kinematics vary with m_N , the rank may also change for different heavy neutrino masses.

Figure 5 in the appendix A illustrates the distributions of a few input observables for a $m_N=20$ GeV signal sample (black, filled), and those for the SM background including 4τ (red) and WWZ (blue) processes after the pre-selection cuts. Many observables show clear distinctions between the signal and background. It is worth noting that the signal's transverse mass M_{T2} distribution develops a sharp end-point around m_N , which means that it can be used to determine the mass of the heavy neutrino as well if this new physics scenario is discovered.

The resulting Boosted Decision Trees (BDT) distributions from the MVA demonstrate excellent separation between signal and background, as shown in figure 2, which can reduce the background to a negligible level. Since the kinematics vary with m_N , here we show a representative result of h_1 decay with $m_N = 20$ GeV. Table 1 lists the corresponding background event rate estimated after pre-selection and the MVA, where the BDT cut is optimized for the signal significance, given by

$$\sigma_{\text{stat}} = \sqrt{2 \left[(N_s + N_b) \ln \left(1 + \frac{N_s}{N_b} \right) - N_s \right]}, \quad (3.1)$$

where N_s (N_b) is the number of signal (total background) events after all selection cuts with 3 ab^{-1} integrated luminosity at the HL-LHC or 20 ab^{-1} integrated luminosity at the FCC-hh/SppC. Note that table 1 does not include h_2 contribution; h_2 increases the signal but the BDT cut needs to be re-optimized according to its fraction in the signal.

		NN	4τ	WWZ
HL-LHC	initial	16.4	2.9×10^5	1.1×10^3
	pre-selection	1.8	7.0	1.4
	BDT > 0.267	1.5	6.6×10^{-2}	9.6×10^{-4}
FCC-hh/SppC	initial	1481	1.2×10^7	1.1×10^5
	pre-selection	343	1183	346
	BDT > 0.170	298	7.5	1.5×10^{-1}

Table 1. Event rates for the signal from $h_1 \rightarrow NN \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp 2\nu$ with $m_N = 20$ GeV and $\text{BF}_{h_1 \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp 2\nu} = 10^{-7}$ and for background processes of 4τ and WWZ . The numbers at the HL-LHC (FCC-hh/SppC) correspond to center-of-mass energy $\sqrt{s} = 14(100)$ TeV and 3 (20) ab^{-1} integrated luminosity.

4 Collider sensitivities

Since the final state kinematics vary with the heavy neutrino mass, We simulate the signal sample and perform the MVA for each M_N case from 10 to 60 GeV, at increment of 10 GeV. The corresponding BDT distributions at the HL-LHC with $\sqrt{s} = 14$ TeV are shown in figure 6, and distributions at the FCC-hh/SppC with $\sqrt{s} = 100$ TeV are shown in figure 7, see appendix B.

As m_N increases, the kinematics of the 4τ background becomes similar to that of the signal process NN , which renders its BDT distribution largely overlapping with that of the signal. At each m_N , the BDT criterion is optimized for maximal signal significance from its BDT distribution. The selection efficiencies for both NN signal and background processes at the HL-LHC and FCC-hh/SppC for different heavy neutrino masses are presented in table 2.

Figure 3 shows the 95% confidence level (C.L.) limits on the combined branching fraction of Higgs boson into our final state when h_2 is heavy and only h_1 is relevant to the NN signal. Here, the 95% C.L. limits correspond to $2\text{-}\sigma$ signal significance given by the eq. (3.1). The number of events after all selections, $N_s(N_b)$, is the product of the production cross-section, luminosity and total selection efficiency for the signal (total background). Note the signal production cross-section is proportional to the Higgs decay branching fraction, cf. eq. (2.2). The m_N dependence of the limit is the result of two competing reasons: the four-lepton pre-selection efficiencies increase at larger m_N , while the BDT cuts reject background more efficiently at lower m_N . When $m_N = 20$ GeV, the combined branching fraction can be probed to as tiny as 4.4×10^{-7} , 6.7×10^{-8} , 1.9×10^{-9} at the 13, 14, 100 TeV pp collision runs, respectively. Since the kinematics are quite similar between 13-TeV and 14-TeV, the 13-TeV limits are derived by adopting the same detector selection efficiencies as those for 14-TeV. $\sigma_{pp \rightarrow h} = 48.6$ pb at 13-TeV [23] is used for signal production cross-section. For background processes, their production cross-sections at 13 TeV are calculated by MadGraph5.

Now we interpret these limits in the content of our ‘small mixing’ scenario. By eq. (1.3) the mixing angle is most sensitive to the mass-square difference between ϕ and s , which

Figure 3. 95% C.L. limits on the combined branching fraction $\text{BF}_{h_1 \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp 2\nu} = \text{BF}_{h_1 \rightarrow NN} \cdot \text{BF}_{\text{sig.}}$ at the 13-TeV LHC, 14-TeV HL-LHC and 100-TeV FCC-hh/SppC with 280 fb^{-1} , 3 ab^{-1} , 20 ab^{-1} luminosities, respectively. For these limits, h_2 is assumed to be heavy and only h_1 decay contributes to the NN signal.

can be approximated the mass-square difference between h_1 and h_2 , off by a correction $\Delta m_{s,\phi}^2 = \Delta m_{h_2,h_1}^2 \cdot [1 + \mathcal{O}(\sin^2 \alpha)]$. Generally, m_s can be lighter than v_S and it is possible to have h_2 at the same (or lower) mass scale as the SM Higgs, so that $|\Delta m_{s,\phi}^2| \sim m_h^2$ even if v_S is more massive, at the TeV scale or above. So we adopt a 150 GeV h_2 as a showcase scenario, with the consideration that an m_{h_2} below the $2m_W$ threshold can avoid a dramatic increment in $\text{BF}_{h_2 \rightarrow WW,ZZ}$ which suppresses the NN branching and complicate our physics picture. In this scenario, both h_2 and h_1 decays contribute significantly. Figure 4 illustrates the 95% C.L. contour limits on λ, v_S from various pp collision runs. The width of each filled band is due to varying m_N from 10 to 60 GeV, which affects the cut efficiencies. R is the fraction of h_1 contribution in the total NN signal events. h_1 contributes mostly to the signal at low v_S , while h_2 can also contribute due to its relatively light mass, and becomes dominant towards $v_S \sim \text{TeV}$. The limits indicate that the 13-TeV LHC with 280 fb^{-1} data can access the weak-scale v_S part of the decoupling region, while the future HL-LHC and FCC-hh/SppC can be sensitive to even lower $\Phi - S$ mixing region, where the singlet components in h_1 can be as low as 10^{-4} to 10^{-6} .

For heavier h_2 , at the TeV scale, h_2 's contribution to the signal diminishes and the mixing $\sin^2 \alpha$ is suppressed by the TeV m_s . However, since $y_N = m_N/(2v_S)$, an $m_N < \frac{1}{2}m_{h_1}$ also significantly suppresses the hNN coupling, leading to m_s^{-4} suppression in the signal rate. Therefore, a large m_s would require a sizable λ to yield a detectable signal rate, which could violate the decoupling condition as v_S is generally expected to be comparable to or higher than m_s . In such cases, the $h - s$ mixing needs to be parametrized under specific models where Φ, S sectors are no longer independent. Note in $\text{SU}(2)_L$ doublet(s)+singlet scalar models, the joint scalar potential minimization removes λ dependence from the diagonal scalar mass-square terms at the tree-level, indicating eq. (1.5) to be a strong requirement if $\lambda \ll 1$, which suppresses the singlet's loop contribution to the Higgs mass.

Figure 4. Projected 95% C.L. sensitivity on v_S and λ for a benchmark $m_{h_2}=150$ GeV scenario. The yellow, green and blue bands denote limits at the current 13-TeV LHC, 14-TeV HL-LHC and 100-TeV FCC-hh/SppC with 280 fb^{-1} , 3 ab^{-1} , 20 ab^{-1} luminosity, respectively. The black solid ‘ $\Phi - S$ decoupling’ line represents decoupled Φ, S sectors, satisfying $\lambda v_S^2 \leq 10^{-2} m_{h_1}^2$.

5 Conclusion

We show that the fully leptonic Higgs decay channel $e^\pm e^\pm \mu^\mp \mu^\mp + \cancel{E}_T$ is almost SM background-free and is accessible in both the lepton number violating and conserving heavy neutrino N decays. This rare channel can be a high-precision probe for the mixing between the Higgs boson and a singlet scalar boson which dynamically gives the N mass in the $|V_{lN}|$ -suppressed simple seesaw scheme. We consider a generic ‘decoupled’ scenario where the Higgs and singlet scalar bosons only share a small mixing, and demonstrate that the signal channel is capable of testing such decoupled scenario if the singlet and the Higgs bosons are in the comparable mass range. Comprehensive signal and SM background analyses with machine-learning MVA yield stringent limits on the signal Higgs boson decay branching fraction at the current and future pp colliders. For a benchmark case with the singlet-dominated h_2 at 150 GeV, the 13-TeV LHC, future HL-LHC and FCC-hh/SppC are sensitive to the Higgs-singlet mixing to 10^{-3} , 10^{-4} and 10^{-6} with 280 fb^{-1} , 3 ab^{-1} , and 20 ab^{-1} pp collision luminosities, respectively. In addition, this test does not require a sizable left-right neutrino mixing and it is complimentary to the existing $|V_{lN}|^2$ -based searches.

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A Distributions of representative input observables

In figure 5, we show the distributions of some observables for the signal (black, filled), and those for the SM background including 4τ (red) and WWZ (blue) processes after the pre-selection cuts. These plots illustrate a h_1 decay signal by gluon fusion at the HL-LHC, with $m_N=20$ GeV.

Figure 5. Distributions of some input observables for the signal event sample (black, filled), and those for the SM background samples including 4τ (red) and WWZ (blue). This plot illustrates a h_1 decay signal by gluon fusion at the HL-LHC, with $m_N=20$ GeV.

B Distributions of BDT responses

In figure 6, we show the distributions of BDT responses of the signal and the SM background processes at the HL-LHC with $\sqrt{s} = 14$ TeV for different m_N assumptions. In these plots, the signals are from h_1 decay only. The distributions at the FCC-hh/SppC with $\sqrt{s} = 100$ TeV are presented in figure 7.

Figure 6. Distributions of BDT responses for the signal event sample (black, filled), and those for the SM background samples including 4τ (red) and WWZ (blue). This figure illustrates an h_1 decay signal by gluon fusion at the HL-LHC, with different m_N assumptions.

Figure 7. The BDT distributions of the same processes as in figure 6, but at the FCC-hh/SppC.

C Selection efficiency table

In table 2, we show selection efficiencies for both signal NN and background processes at the HL-LHC and FCC-hh/SppC for different heavy neutrino masses. The total selection efficiency after both pre-selection and BDT criteria is the product of two efficiencies in the same column. The numbers of events for background after all selections can be calculated by multiplying the initial numbers in the table 1 by the total cut efficiency, while the number of events for signal can be calculated from eq. (2.2) by substituting the total cut efficiency for NN as $A_{\text{eff}}^{(1)}$.

m_N	$\sqrt{s}$	selection	NN	4τ	WWZ
10 GeV	14 TeV	pre-selection	1.10×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.428	9.52×10^{-1}	2.86×10^{-3}	1.50×10^{-4}
	100 TeV	pre-selection	2.26×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT>0.311	8.97×10^{-1}	9.46×10^{-4}	1.57×10^{-5}
20 GeV	14 TeV	pre-selection	1.08×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.267	8.60×10^{-1}	9.43×10^{-3}	6.87×10^{-4}
	100 TeV	pre-selection	2.32×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT>0.170	8.69×10^{-1}	6.30×10^{-3}	4.25×10^{-4}
30 GeV	14 TeV	pre-selection	1.12×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.177	6.82×10^{-1}	1.54×10^{-2}	1.96×10^{-3}
	100 TeV	pre-selection	2.56×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT> 0.150	5.56×10^{-1}	5.25×10^{-3}	1.22×10^{-3}
40 GeV	14 TeV	pre-selection	1.35×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.122	6.58×10^{-1}	3.82×10^{-2}	9.69×10^{-3}
	100 TeV	pre-selection	3.07×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT>0.131	4.35×10^{-1}	5.56×10^{-3}	3.59×10^{-3}
50 GeV	14 TeV	pre-selection	1.56×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.128	5.34×10^{-1}	2.46×10^{-2}	1.13×10^{-2}
	100 TeV	pre-selection	3.62×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT>0.117	4.71×10^{-1}	9.42×10^{-3}	7.20×10^{-3}
60 GeV	14 TeV	pre-selection	1.77×10^{-1}	2.41×10^{-5}	1.33×10^{-3}
		BDT>0.138	5.88×10^{-1}	1.79×10^{-2}	1.16×10^{-2}
	100 TeV	pre-selection	4.03×10^{-1}	1.01×10^{-4}	3.25×10^{-3}
		BDT>0.131	4.95×10^{-1}	5.20×10^{-3}	5.06×10^{-3}

Table 2. Selection efficiencies for the signal NN and background processes of 4τ and WWZ at the HL-LHC (with center-of-mass energy $\sqrt{s} = 14$ TeV) and FCC-hh/SppC (with $\sqrt{s} = 100$ TeV) for $m_N = 10, 20, 30, 40, 50, 60$ GeV, respectively. Here h_2 is assumed to be heavy and only h_1 decay contributes to the signal NN .

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