

Loop-level lepton flavor violation and diphoton signals in the minimal left-right symmetric model

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The left-right symmetric model (LRSM) could not only restore parity of the weak interaction, but also provide natural explanations of the tiny active neutrino masses via the seesaw mechanisms. The $SU(2)_R$ -breaking scalar H_3 can induce lepton flavor violating (LFV) effects in the minimal version of LRSM at the 1-loop order, originating from the mixing of heavy right-handed neutrinos (RHNs). If H_3 is light, say below the GeV scale, it will lead to rich signals, e.g., the LFV muon and tauon decays $\ell_\beta \rightarrow \ell_\alpha + X$ (X being either visible or invisible final states) and the anomalous supernova signatures. Combined with the diphoton coupling of H_3 , and recasting the existing constraints onto the light H_3 scenario, the right-handed scale v_R is excluded up to 2×10^9 GeV. In the future, the v_R scale can be probed up to 5×10^9 GeV in high-precision muon experiments, if the Yukawa couplings for RHN masses are of order one and the RHN mixing is maximal, and further up to 6×10^{11} GeV by supernova observations, reaching the nonresonant leptogenesis scale in the LRSM.

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I. INTRODUCTION

The precision of mixing of active neutrinos has been improved significantly in the last decades [1], in particular in light of the very recent JUNO data [2] (the matter effects are about 4% on the oscillation parameters [3]). The tiny neutrino masses can be explained naturally and economically by the seesaw mechanism. The left-right symmetric model (LRSM) [4–6], based on the gauge group of $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, was originally proposed to understand parity violation in the weak interaction [7,8], and offers a well-motivated framework for the type-I [9–13] and type-II [14–18] seesaw mechanisms.

In the conventional minimal version of LRSM, the $SU(2)_R$ gauge symmetry and parity is broken spontaneously by a triplet scalar Δ_R . The neutral CP -even component H_3 of Δ_R plays a central role, not only in the breaking of the $SU(2)_R$ gauge symmetry, but also for generation of the masses of the heavy scalars, right-handed neutrinos (RHNs) and the W_R and Z_R bosons. The relevant rich phenomenologies have been investigated extensively in the literature [19–40]. A unique feature of H_3 lies in the fact

that it does not couple directly to the SM particles, which has far reaching phenomenological implications. Unlike other particles in LRSM, the direct constraints on H_3 are rather weak. In certain regions of parameter space, H_3 could be very light with respect to the $SU(2)_R$ -breaking v_R scale [25,27,28]. For $v_R \gtrsim 10^{15}$ GeV H_3 can even play the role of decaying dark matter if its mass is below the MeV scale [39].

For a light H_3 with mass m_{H_3} below the GeV scale, its couplings to the standard model (SM) particles can arise from mixing with the SM Higgs and the heavy bidoublet scalar H_1 . The resultant rich signals such as $B \rightarrow K + H_3$ have been studied in great details in Refs. [27,28]. H_3 can also couple to the SM particles at the 1-loop order, which is induced by the heavy particles in the LRSM. A typical example is the coupling of H_3 to two photons. In this letter, we focus more on the radiative couplings of H_3 to charged leptons at the 1-loop order, induced by the doubly charged scalars, W_R boson and RHNs N_i [25]. The Feynman diagrams are shown in Fig. 1. Decoupling the left-handed doubly charged scalar, the charged lepton flavor violating (LFV) couplings of H_3 intrinsically originate from the mixing of RHNs N_i via the Yukawa coupling matrix f_R of H_3 with N_i . This provides a well-motivated example to build up connects between charged LFV and oscillations of active neutrinos.

The LFV couplings of light H_3 can lead to very rich interesting signals, which depend on the mass m_{H_3} and the v_R scale, as all the heavy particles masses in the loops in Fig. 1 are at the v_R scale. In some sense, this is very

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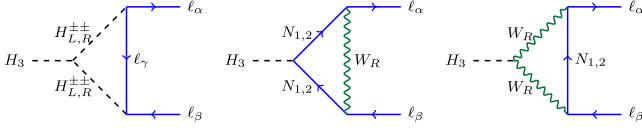


FIG. 1. The 1-loop Feynman diagrams for the LFV couplings of H_3 in the minimal LRSM.

similar to the dependence of the couplings of axionlike particles (ALPs) on the decay constant f_a . It turns out that the most stringent LFV constraints are from the rare muon decays $\mu \rightarrow e + \text{inv}$ [41–43], $\tau \rightarrow \ell + X$ (with $\ell = e, \mu$, and X invisible or visible) [44,45] and the supernova limits [46–48]. With Yukawa couplings of order one and the maximal mixing of RHNs, the $SU(2)_R$ -breaking v_R scale is excluded up to 4×10^8 GeV. The supernova constraints on the diphoton coupling of H_3 are more stringent [49–51], excluding v_R up to 2×10^9 GeV. These limits are orders of magnitude higher than the direct LHC limits from the direct searches of W_R boson [52,53], the constraints from the LFV effects induced by the doubly charged scalars [54–66] and the W_R boson and N_i [54,56,58–61,64,67–74]. It is remarkable that the sensitivities of the v_R scale can be improved up to 5×10^9 GeV in future high-precision muon experiments via the LFV coupling, and further higher up to 6×10^{11} GeV by future supernova observations via the diphoton coupling, reaching the nonresonant leptogenesis scale in the LRSM [75,76]. For small Yukawa couplings or small mixing angle of RHNs, the current LFV limits on the right-handed scale v_R and future prospects will be weakened accordingly.

II. LFV COUPLINGS OF H_3

In the minimal LRSM, the scalar sector consists of a Higgs bidoublet Φ , a left-handed triplet Δ_L and a right-handed triplet Δ_R

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \Delta_{L,R}^+/\sqrt{2} & \Delta_{L,R}^{++} \\ \Delta_{L,R}^0 & -\Delta_{L,R}^+/\sqrt{2} \end{pmatrix}. \quad (1)$$

The left-right gauge symmetry is broken by the vacuum expectation value (VEV) of the real component of Δ_R^0 to the SM gauge group. The corresponding physical scalar field is H_3 , which is responsible for the mass generation of the heavy scalars, RHNs and the W_R and Z_R bosons in the LRSM. Even if the radiative corrections of all these heavy LRSM particles to its mass m_{H_3} are taken into account, H_3 could be much lighter than the v_R scale in some regions of the parameter space [27,28]. The constraint of electroweak precision data on the large mass splitting of H_3 with other components of Δ_R via the oblique parameters are also

rather weak, suppressed by v^2/v_R^2 (with v the electroweak scale) [77].

In the limit of vanishing mixing with the SM Higgs and other neutral scalars in the LRSM, the scalar H_3 does not couple directly to charged leptons. Such couplings can be induced at the 1-loop order by the couplings of H_3 with the left- and right-handed doubly charged scalars $H_{L,R}^{\pm\pm}$, RHNs N_i and the W_R boson, as seen in Fig. 1. In the first diagram, the couplings of $H_L^{\pm\pm}$ to charged leptons are from the term of $f_L \psi_L^\dagger C i \sigma_2 \Delta_L \psi_L + \text{H.c.}$ (with ψ the lepton doublet, σ_2 the second Pauli matrix and C the charge conjugation operator), which is responsible for generation of active neutrino masses via the type-II seesaw. The rest diagrams in Fig. 1 are all relevant to the Yukawa couplings of H_3 with the heavy RHNs

$$\mathcal{L}_Y = -f_R \psi_R^\dagger C i \sigma_2 \Delta_R \psi_R + \text{H.c.}, \quad (2)$$

where f_R is the Yukawa coupling matrix and plays a central role in this paper. In particular, the mass matrix for the heavy RHNs is $M_N = f_R v_R$. In minimal LRSM the matrices $f_{L,R}$ can be different from each other. The left-handed triplet Δ_L can even decouple from the low-energy physics in the D -parity violating case [78]. For simplicity, we neglect the contribution from Δ_L and consider in this letter the LFV effects only from the RHNs via the matrix f_R . For illustration purpose, we adopt the simplest case with only two RHNs $N_{1,2}$, with the Yukawa couplings $f_{1,2}$ and mixing angle θ without any CP violation. Then the LFV effects originate from the mixing of $N_{1,2}$.

Without loss of generality, the LFV couplings of H_3 with charged leptons can be written as

$$\mathcal{L}_{\text{LFV}} = -H_3 \bar{\ell}_\alpha \left(c_{\alpha\beta}^{(L)} P_L + c_{\alpha\beta}^{(R)} P_R \right) \ell_\beta + \text{H.c.}, \quad (3)$$

where $\alpha, \beta = e, \mu, \tau$, and $c_{\alpha\beta}^{(L)}$ and $c_{\alpha\beta}^{(R)}$ are dimensionless functions of the masses of H_3 , charged leptons and the heavy particles $H_R^{\pm\pm}$, W_R and $N_{1,2}$, given in Eq. (B1) [79]. In some cases it is more convenient to use the combination of $g_{\alpha\beta} \equiv \sqrt{|c_{\alpha\beta}^{(L)}|^2 + |c_{\alpha\beta}^{(R)}|^2}$ for the following calculations. For concreteness, we setup the parameters as follows. (i) The right-handed gauge coupling g_R is set to be the same as the gauge coupling g_L for $SU(2)_L$. (ii) We take the quartic coupling $\rho_2 = 0.25$, such that the right-handed doubly charged mass $m_{H_R^{\pm\pm}} = \sqrt{4\rho_2} v_R = v_R$. (iii) The LFV couplings in Eq. (3) are rather sensitive to the Yukawa couplings $f_{1,2}$. As a benchmark study, we adopt the values of $f_1 = 0.5$ and $f_2 = 1.0$. (iv) The RHN mixing is set to be $\theta = 45^\circ$ to maximize the LFV effect. The analysis of other benchmark scenarios can be found in a followup paper [80].

It should be noted that the RHN mixing does not only leads to the LFV couplings in Eq. (3), but also generates the

LFC couplings $g_\ell H_3 \ell^+ \ell^-$, the corresponding effective coupling g_ℓ is given in Eq. (B10). Another important decay channel for a light H_3 in the LRSM is the diphoton mode, i.e., $H_3 \rightarrow \gamma\gamma$, which is mediated by the singly and doubly charged scalars and the W_R boson [25,27,28]. For our benchmark point values of $f_{1,2}$, the dilepton decay branching ratios (BRs) are comparable to that of the diphoton mode, depending on the mass m_{H_3} (cf. Fig. 5 in Appendix A).

III. LABORATORY LFV CONSTRAINTS

The LFV, LFC and diphoton channels of H_3 are all effectively suppressed by the $SU(2)$ -breaking v_R scale. For $m_{H_3} \lesssim 1$ GeV, H_3 always behaves as a long-lived particle in the laboratory experiments (cf. Fig. 5 in Appendix A), and the leading current laboratory constraints are from the following processes, which are collected in Fig. 2 [29,81–95]. More details can be found in Table I in Appendix D.

(i) *Muon decays.* A light H_3 can be produced in the LFV process $\mu \rightarrow e + H_3$. As H_3 is very long-lived, the signal is $\mu \rightarrow e + \text{inv}$ at muon experiments. The current most stringent constraints in this channel are from the experiments TWIST [41], PIENU [42] and that by Jodiddo *et al.* [43] (see Refs. [83,100,101] for weaker limits). $\text{BR}(\mu \rightarrow e + \text{inv})$ is excluded up to 2.6×10^{-6} , which leads to the limit of $v_R \gtrsim 5 \times 10^8$ GeV. The precision of $\mu \rightarrow e + \text{inv}$ can be largely improved at future muon experiments. With a total number of 2.6×10^{15} muon events, the sensitivity of $\text{BR}(\mu \rightarrow e + \text{inv})$ can be improved up to $\mathcal{O}(10^{-8})$ at Mu3e [96,97] (see Refs. [83,97,102–105] for weaker prospects). The corresponding prospect of v_R scale can be improved by one order of magnitude up to 5×10^9 GeV.

(ii) *Tauon decays.* We can also have the rare LFV tauon decays $\tau \rightarrow \ell + H_3$ (with $\ell = e, \mu$). The most stringent limits at B -factories are from the invisible decays $\tau \rightarrow \ell + \text{inv}$. The scalar H_3 with a GeV-scale mass is not totally invisible, and would induce displaced vertex signatures. To be conservative, we require H_3 to decay outside the detectors by multiplying the factor of $\exp\{-L_{\text{det}}/\gamma_{H_3}\tau_{H_3}\}$, with γ_{H_3} is the Lorentz boost factor of H_3 , and L_{det} the detector size. It turns out that the most constraining one is from the measurements of Belle, with $\text{BR}(\tau \rightarrow e + \text{inv}) < (0.4\text{--}6.4) \times 10^{-4}$ and $\text{BR}(\tau \rightarrow \mu + \text{inv}) < (0.2\text{--}3.5) \times 10^{-4}$. The Belle detector is roughly 8 m in length and 8 m in diameter, which generates $L_{\text{det}} \simeq 8.94$ m [106]. This leads to the limits of $v_R \gtrsim 3 \times 10^5$ and 4×10^5 GeV in the e and μ channels, respectively. The constraints from ARGUS [107], Belle II [108] and Bryman *et al.* [109] are relatively weaker. The sensitivity of $\tau \rightarrow \ell + \text{inv}$ can be greatly improved at future B -factories. With an integrated luminosity of 50 ab^{-1} , $\text{BR}(\tau \rightarrow e + \text{inv})$ can be measured up to $\mathcal{O}(10^{-6})$ at Belle II, over one order of magnitude improvement of v_R up to $\mathcal{O}(10^7)$ GeV [98] (see also Ref. [110] for weak prospect).

Limits have also been obtained on the LFV tauon decays into ALP a via $\tau \rightarrow \ell + a$ (with $\ell = e, \mu$) at proton beam dump experiments such as CHARM [45]. After being produced, ALPs are assumed to decay into dilepton pairs $ee, e\mu$ and $\mu\mu$. The limits on ALP can be reinterpreted and recast onto the light H_3 (see Appendix C for comparison with ALP relevant processes). For simplicity it is assumed in Ref. [45] that $g_{e\tau} = g_{\mu\tau}$ which is a good approximation in the LRSM. It turns out that the v_R scale is excluded up to 5×10^5 GeV for scalar mass up to $\mathcal{O}(100)$ MeV.

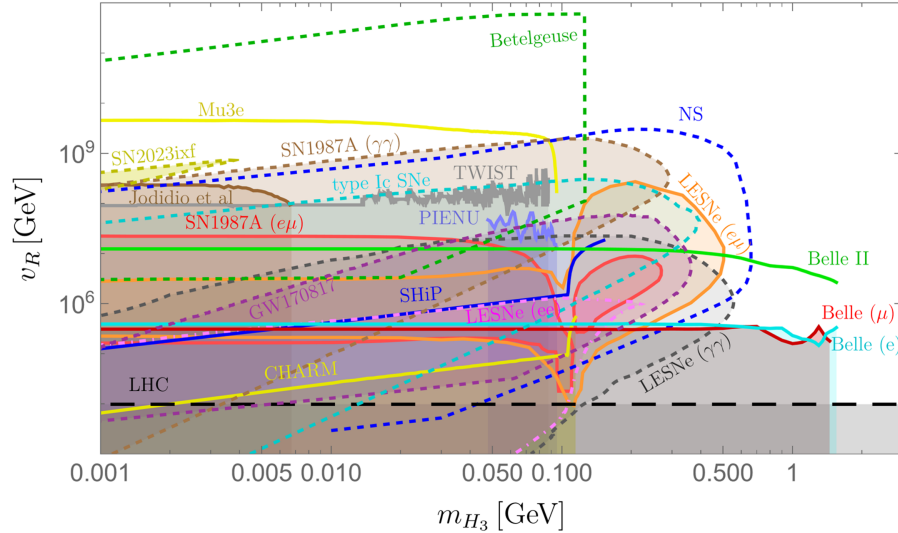


FIG. 2. Constraints on m_{H_3} and v_R from the LFV, LFC and diphoton couplings of H_3 in the minimal LRSM, labeled as solid, dot-dashed and dashed lines, respectively. The shaded regions are for current limits, and the lines are for future prospects. The long dashed back line indicates the current LHC limits from direct searches of heavy W_R boson [52,53]. See text and Tables I and II for details.

The precision of $\tau \rightarrow \ell + a$ can be improved by over one order of magnitude at future beam dump experiments such as SHiP [45], with v_R pushed up to 2×10^7 GeV, as seen in Fig. 2.

The constraints from other LFV processes are rather weak, e.g., those from $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$, as these processes arise at the 2-loop or higher order in the LRSM if H_3 is involved. The limits from the meson decays $\pi^\pm, K^\pm \rightarrow \ell^\pm \nu H_3$, with H_3 emitted from charged leptons, are also rather weak, as the couplings can only be constrained up to $\mathcal{O}(10^{-2})$ [111–113].

IV. ASTROPHYSICAL LFV CONSTRAINTS

For a sub-GeV (pseudo)scalar, the most stringent astrophysical constraints on the LFV couplings are from the supernova observations.

(i) *SN1987A*. In supernovae, ALP can be produced via the LFV coupling $g_{ae\mu}$ to electron and muon. When ALP is light, the production is dominated by muon decay $\mu \rightarrow e + a$. For a heavy ALP, the $e + \mu \rightarrow a$ process is more important. Within the mass range of roughly (100,110) MeV, the two processes above are kinematically forbidden or suppressed, and the lepton-proton bremsstrahlung process $\ell_\alpha + p \rightarrow \ell_\beta + p + a$ takes over to be the dominant one [46]. Benefiting from the high nucleon density in the supernova core, a sizable parameter space of ALP mass m_a and $g_{ae\mu}$ is excluded by the observed neutrino luminosity of $\mathcal{L}_\nu \simeq 3 \times 10^{52}$ erg/s of SN1987A [46] (see also Ref. [114]). Recast onto the light H_3 , the v_R scale is constrained up to 2×10^7 GeV.

(ii) *low-energy supernovae*. The low-energy supernovae (LESNe) have been identified, and the explosion energy can be as low as 10^{50} erg, which provides extra constraints on light particles [115–123]. Taking into account all the dominant production channels of $\mu \rightarrow e + a$, $e + \mu \rightarrow a$ and $\ell_\alpha + \gamma \rightarrow \ell_\beta + a$, the coupling $g_{ae\mu}$ is constrained up to $\mathcal{O}(10^{-11})$ for ALP mass up to roughly 550 MeV [47,48]. The corresponding constraint on the right-handed scale is $v_R \gtrsim 4 \times 10^8$ GeV, over one order of magnitude stronger than the SN1987A limit above.

There might also be some cosmological constraints on (pseudo)scalars below the GeV scale, e.g., those from the big bang nucleosynthesis and cosmic microwave background. However, these cosmological limits depend largely on the cosmological evolution history such as the reheating temperature [124–135]. Therefore, we will not consider the cosmological constraints in this work.

V. LFC CONSTRAINTS

The laboratory constraints on the LFC couplings are rather weak, e.g., those from the decays $\mu \rightarrow e \nu \bar{\nu} a$ [136], $\tau \rightarrow \nu a$ [45,137], $\pi, K \rightarrow \ell \nu X$ [111–113]. The most stringent constraint on the coupling g_e of H_3 with electrons

are from the supernova observations [83,99,138–141]. The production of ALP in supernovae is dominated by the semi-Compton process $e + \gamma \rightarrow e + a$. When ALP is heavy, the process $e^+ + e^- \rightarrow a$ is also important. The decay of $a \rightarrow e^+ e^-$ in the mantle of LESNe is severely constrained by the limit of deposited energy of 10^{50} erg [142], which excludes the value of g_{ae} down to $\mathcal{O}(10^{-11})$ [99]. Adopting conservatively the SFHo-18.8 supernova model [143] and reinterpreting the limit (see Appendix D for details), the v_R scale is excluded up to 10^6 GeV, as indicated by the dot-dashed magenta line in Fig. 2. There are also some other supernova limits on ALPs, e.g., those from γ -ray signals from SN1987A and the luminosity limits. However, the corresponding constraints on the v_R scale are relatively weaker [80].

The supernova constraints on the coupling of ALP to muons are also obtained [83,141,144]. However, as the muon mass is significantly larger than the typical supernova temperature $T \sim 30$ MeV, the corresponding supernova limits on the couplings of H_3 to muons are expected to differ significantly from that on ALPs [80]. A dedicated analysis is necessary to obtain robust supernova limits on the coupling of H_3 to muons, which is far beyond the main scope of this paper.

VI. PARAMETRIC DEPENDENCE OF THE LFV AND LFC COUPLINGS AND THE v_R CONSTRAINTS

We have taken the specific benchmark values for the Yukawa couplings $f_{1,2}$ and RHN mixing angle θ . For other choices of these parameters, the LFV and LFC couplings and the resulting constraints on the v_R scale could be very different. For illustration purpose, the parametric dependence of the effective couplings $g_{e\mu}$, g_e and g_μ on the Yukawa couplings $f_{1,2}$ and the RHN mixing angle is shown in Fig. 3. The benchmark point of $f_1 = 0.5$ and $f_2 = 1.0$ are labeled by the black dots in both the left and right panels.

(i) *Dependence on f_1* . Let us first take the benchmark values of scalar mass $m_{H_3} = 10$ MeV, the scale $v_R = 10$ TeV and the mixing angle $\theta = 45^\circ$. Fixing the Yukawa coupling ratio $f_1/f_2 = 0.5$, and varying the parameter f_1 , the resulting LFV coupling $g_{e\mu}$ and LFC couplings g_e , g_μ are shown as the solid red, blue, and green lines in the left panel of Fig. 3. It turns out that these effective couplings are universally proportional to the Yukawa couplings via $\propto f_1 f_2$ in such a parameter setup.

(ii) *Dependence on f_1/f_2* . Fixing $f_2 = 1.0$ and other parameters the same as above, let us vary only f_1 (keeping $f_1 \leq f_2$), which is equivalent to changing the ratio f_1/f_2 . The corresponding couplings $g_{e\mu}$, g_e and g_μ are presented as the dashed red, blue, and green lines in the left panel of Fig. 3. As indicated by these lines, in the limit of $f_1 \ll f_2$, the LFV and LFC

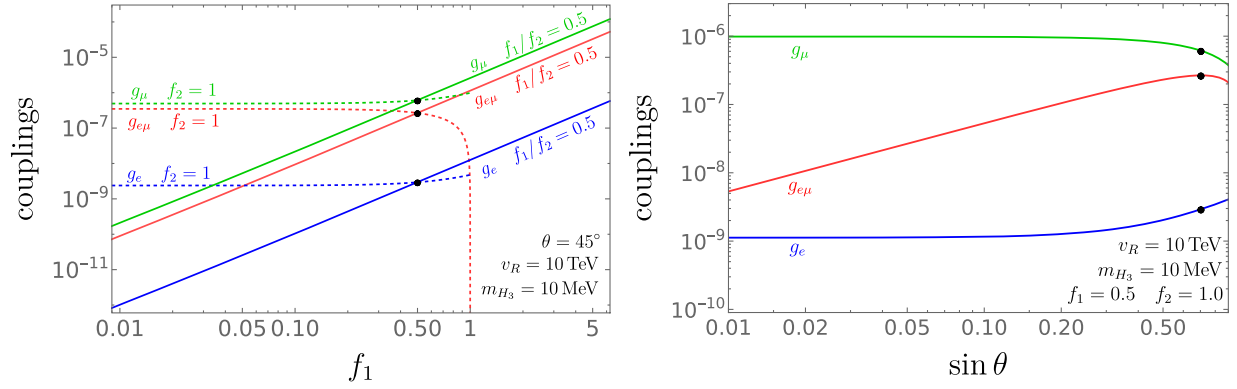


FIG. 3. Parametric dependence of the effective LFV coupling $g_{e\mu}$ (red), and LFC couplings g_e (blue) and g_μ (green) on the Yukawa coupling f_1 with $f_1/f_2 = 0.5$ (solid) or $f_2 = 1$ (dashed) in the left panel, and on the sine of RHN mixing angle $\sin \theta$ in the right panel. The benchmark point of $f_1 = 0.5$, $f_2 = 1.0$ is labeled by the black dots, and other parameters are fixed as shown in the plots.

couplings are both dominated by the larger Yukawa coupling f_2 (or the largest coupling in the case of three coupling involved). In the limit of $f_1 = f_2$, the LFV coupling $g_{e\mu}$ vanishes, as in this case the two RHNs are indistinguishable from each other.

- (iii) *Dependence on $\sin \theta$.* Fixing again $m_{H_3} = 10$ MeV, $v_R = 10$ TeV, and the Yukawa couplings $f_1 = 0.5$, $f_2 = 1.0$, let us vary only the sine of the mixing angle $\sin \theta$. The resultant couplings $g_{e\mu}$, g_e , and g_μ are shown as the solid red, blue and green lines in the right panel of Fig. 3. As expected and explicitly shown in Eqs. (B2) to (B9), the LFV coupling $g_{e\mu}$ depend on the mixing angle of RHNs via $\sin \theta \cos \theta$. The LFC couplings g_e and g_μ are almost constants when the mixing angle θ is small, and get moderately altered when the mixing is significant, as implied by Eqs. (B11) to (B21).

The resulting dependence of the v_R constraints on the Yukawa couplings $f_{1,2}$ and the sine of RHN mixing angle $\sin \theta$ is presented in Fig. 4. As the LFC limits are much weaker, for illustration purpose we choose the current LFV limit from TWIST and the future prospect of Mu3e in the channel of $\mu \rightarrow e + \text{inv}$, which are presented in Fig. 4 as

the shaded blue regions and the red lines, respectively. As in Fig. 3, the solid and dashed lines in the left panel are for the cases of fixed ratio $f_1/f_2 = 0.5$ and $f_2 = 1$, respectively, while the right panel is for the dependence on the sine of the RHN mixing angle $\sin \theta$. Other fixed parameters are shown in the plots, and the benchmark point of $f_1 = 0.5$ and $f_2 = 1.0$ are indicated by the black dots in both the two panels. The corresponding partial width is proportional to the LFV coupling via $\Gamma(\mu \rightarrow e + H_3) \propto |g_{e\mu}|^2$, therefore the constraints on v_R in Fig. 4 exhibit the same dependence on the Yukawa couplings $f_{1,2}$ and the sine of RHN mixing angle $\sin \theta$ as that for the LFV coupling $g_{e\mu}$ in Fig. 3. In particular, the constraints on v_R will be enhanced when both $f_{1,2}$ are large (with the ratio f_1/f_2 fixed), and get weaker when both $f_{1,2}$ are small, $f_1 \rightarrow f_2$ or $\sin \theta$ is small. For instance, for the benchmark value of $f_1 = 0.5$, $f_2 = 1.0$ and other parameters the same as in the left panel of Fig. 4, the TWIST limit (Mu3e prospect) on v_R is 9.3×10^7 (4.3×10^9) GeV; the limit will weaken to 2.7×10^6 (1.4×10^8) GeV for the case of $f_1 = 0.1$, $f_2 = 0.2$, and to 1.9×10^6 (9.5×10^7) GeV for the almost degenerate case of $f_1 = 0.99$, $f_2 = 1$. When the mixing angle $\sin \theta = 0.01$

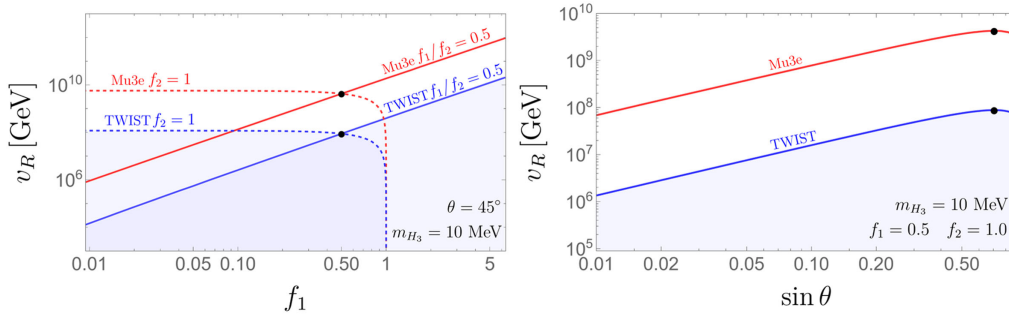


FIG. 4. Parametric dependence of the TWIST limit on v_R (shaded blue) and the future prospect of v_R at the Mu3e experiment (red) on the Yukawa coupling f_1 with $f_1/f_2 = 0.5$ (solid) or $f_2 = 1$ (dashed) in the left panel, and on the sine of RHN mixing angle $\sin \theta$ in the right panel. The benchmark point of $f_1 = 0.5$, $f_2 = 1.0$ is labeled by the black dots, and other parameters are fixed as shown in the plots.

but fixing other parameters as in the right panel of Fig. 4, the TWIST limit (Mu3e prospect) on v_R will decrease to 1.3×10^6 (6.9×10^7) GeV.

VII. DIPHOTON CONSTRAINTS

On the coupling of H_3 with diphoton, the most constraining laboratory limits are from the beam dump experiments, e.g., the current limits from E137 [145], MiniBooNE [146], CHARM [147], NuCal [147] and the prospect of SHiP [147,148] (see Refs. [146–155] for weaker prospects). However, it turns out these constraints are not stringent enough to set limits on v_R above 10 TeV [80].

In comparison, the astrophysical constraints on the coupling of ALP to photons are much more stringent (collected in Fig. 2 and Table II). The production of ALPs inside supernovae via the coupling $g_{a\gamma\gamma}$ is dominated by the Primakoff process $\gamma + \mathcal{N} \rightarrow \mathcal{N} + a$ and photon coalescence $\gamma + \gamma \rightarrow a$. The γ -rays generated from ALP decay from SN1987A, SN2023ixf and type Ic supernovae exclude the coupling $g_{a\gamma\gamma}$ up to $\mathcal{O}(10^{-12})$ GeV $^{-1}$ [49,50,156–159]. The energy deposition of ALPs in LESNe [51,142] and the x-ray and γ -ray observations of the neutron star (NS) merger GW170817 [160,161] provide extra limits, with the coupling $g_{a\gamma\gamma}$ constrained up to $\mathcal{O}(10^{-10})$ GeV $^{-1}$. Depending on its mass, the light scalar H_3 can decay into $\gamma\gamma$ or dileptons e^+e^- , $e^\pm\mu^\mp$, $\mu^+\mu^-$. The leptons from H_3 decay are very likely to annihilate into photons via the process $\ell^+ + \ell^- \rightarrow \gamma + \gamma$. For simplicity, we assume all the decay products of H_3 convert finally into γ -rays. As seen in Fig. 2, the v_R scale is excluded up to 2×10^9 GeV. The sensitivity of $g_{a\gamma\gamma}$ can be largely improved up to 10^{-14} , if supernova explosion happens at the red supergiant Betelgeuse, which is only ~ 200 pc away [156]. The future observation of γ -rays from NS mergers in the next generations telescopes can also explore more open parameter space of $g_{a\gamma\gamma}$ [161]. The corresponding prospects of v_R can reach up to 6×10^{11} GeV, which is expected to be the highest probable range of v_R , as shown in Fig. 2.

VIII. DISCUSSIONS AND CONCLUSION

All the current leading LFV, LFC and diphoton constraints on m_{H_3} and v_R are presented as the shaded regions in Fig. 2, and the predominant future prospects in various laboratory experiments and astrophysical observations are depicted as lines. The LFV, LFC and diphoton constraints are labeled as the solid, dot-dashed and dashed lines, respectively. The γ -rays signals from SN1987A induced by the diphoton coupling provide the current most stringent limit on v_R , up to 2×10^9 GeV, which can be improved up to 6×10^{11} GeV by future observations of Betelgeuse. The baryon asymmetry of the Universe can be naturally

explained by the decay of heavy neutrinos via the leptogenesis mechanism [162]. In the framework of LRSM, it is required that $v_R \gtrsim \mathcal{O}(10^{11})$ GeV if the heavy neutrinos have the hierarchical mass spectrum [75,76]. It is remarkable that the future astrophysical observations could reach the nonresonant leptogenesis scale in the LRSM. In absence of fortune to see a nearby supernova explosion in the near future, the searches of the LFV signal $\mu \rightarrow e + \text{inv}$ in the Mu3e experiment can improve the current SN1987A limit by roughly a factor of 2.5, up to roughly 5×10^9 GeV, if the Yukawa couplings f_i are of order one and the RHN mixing is maximal.

A relatively heavier H_3 can be directly produced at future high-energy lepton colliders via its coupling to photons and leptons, e.g., $e^+ + e^- \rightarrow \gamma + H_3$ [163–168]. Depending on the mass m_{H_3} , the signals may be promptlike or displaced vertices. In analogy to the coupling $H_3\gamma\gamma$, H_3 can also have the coupling to a photon and a Z boson, i.e., in the form of $H_3\gamma Z$, which is induced by the heavy charged scalars and W_R boson [25]. Then we can expect some rare Z decays such as $Z \rightarrow \gamma + H_3 \rightarrow 3\gamma$ at future Tera- Z factories [163,165,169,170]. In addition, H_3 can also have flavor-changing neutral current (FCNC) couplings to quarks, which are induced by the right-handed gauge couplings of W_R boson. However, the FCNC decays $d_j \rightarrow d_i + H_3$ (with $d_{i,j}$ the down-type quarks) are heavily suppressed by the right-handed scale via v_R^{-6} and the corresponding limits are rather weak [80].

All the astrophysical constraints on the couplings of H_3 to charged leptons and photons are from the corresponding ALP limits in the literature, and the conversion of the LFV, LFC and diphoton couplings are performed separately. In light of the well-defined ultraviolet structure of the minimal LRSM, a combined analysis of all these channels in the framework of LRSM is phenomenologically in demand for more robust astrophysical constraints on the LRSM. Furthermore, it is very likely that such dedicated analysis could explore even higher values of the right-handed scale v_R .

In summary, we have performed a detailed study on the 1-loop couplings of light $SU(2)_R$ -breaking scalar H_3 in the minimal LRSM, and focused mainly on the radiative LFV, LFC, and diphoton couplings of H_3 . In the limit of decoupling left-handed triplet Δ_L , the LFV couplings originate from the mixing of heavy RHNs. These LFV, LFC, and diphoton couplings are severely constrained by the high-precision laboratory experiments and astrophysical observations. The current most stringent limit is from the γ -ray observations of SN1987A, which exclude the right-handed scale v_R up to 2×10^9 GeV. Improved precision and unprecedented amount of data in future high-precision muon experiments and supernova observations can push the right-handed scale up to 5×10^9 GeV (assuming the RHNs are at the order of the v_R scale and the RHN mixing is maximal) and 6×10^{11} GeV, respectively.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [171].

APPENDIX A: PARTIAL WIDTHS FOR THE LFV, LFC, AND DIPHOTON DECAYS

The expressions of the LFV couplings $c_{\alpha\beta}^{(L,R)}$ in Eq. (3) can be found in Eq. (B1). With these couplings, it is trivial to get the partial width for the LFV decay of H_3

$$\begin{aligned}\Gamma(H_3 \rightarrow \ell_\alpha^\pm \ell_\beta^\mp) &\equiv \Gamma(H_3 \rightarrow \ell_\alpha^+ \ell_\beta^-) + \Gamma(H_3 \rightarrow \ell_\alpha^- \ell_\beta^+) \\ &= \frac{m_{H_3}}{8\pi} \left[\left(|c_{\alpha\beta}^{(L)}|^2 + |c_{\alpha\beta}^{(R)}|^2 \right) (1 - \eta_\alpha - \eta_\beta) - 4\text{Re} \left(c_{\alpha\beta}^{(L)} c_{\alpha\beta}^{(R)*} \right) \sqrt{\eta_\alpha \eta_\beta} \right] \\ &\quad \times \left[\left(1 - (\sqrt{\eta_\alpha} + \sqrt{\eta_\beta})^2 \right) (1 - (\sqrt{\eta_\alpha} - \sqrt{\eta_\beta})^2) \right]^{1/2},\end{aligned}\quad (\text{A1})$$

with $\eta_\alpha \equiv m_{\ell_\alpha}^2/m_{H_3}^2$. For the case of $m_{H_3} < m_{\ell_\beta} - m_{\ell_\alpha}$, the decay $\ell_\beta \rightarrow \ell_\alpha H_3$ is kinematically allowed, and the corresponding partial width is

$$\begin{aligned}\Gamma(\ell_\beta \rightarrow \ell_\alpha H_3) &= \frac{m_{\ell_\beta}}{32\pi} \left[\left(|c_{\alpha\beta}^{(L)}|^2 + |c_{\alpha\beta}^{(R)}|^2 \right) (1 - \lambda_\alpha - \lambda_{H_3}) + 4\text{Re} \left(c_{\alpha\beta}^{(L)} c_{\alpha\beta}^{(R)*} \right) \sqrt{\lambda_\alpha} \right] \\ &\quad \times \left[\left(1 - (\sqrt{\lambda_\alpha} + \sqrt{\lambda_{H_3}})^2 \right) \left(1 - (\sqrt{\lambda_\alpha} - \sqrt{\lambda_{H_3}})^2 \right) \right]^{1/2},\end{aligned}\quad (\text{A2})$$

where $\lambda_X \equiv m_X^2/m_{\ell_\beta}^2$. For the LFC couplings, the partial width reads

$$\Gamma(H_3 \rightarrow \ell^+ \ell^-) = \frac{g_\ell^2 m_{H_3}}{8\pi} (1 - 4\eta_\ell)^{3/2}, \quad (\text{A3})$$

where the expression for the coupling g_ℓ is given in Eq. (B10).

The coupling of H_3 with diphoton are induced at the 1-loop order by the singly charged scalar $H_1^\pm$ from the bidoublet Φ , the singly charged scalar $H_L^\pm$ and doubly charged scalar $H_L^{\pm\pm}$ from the left-handed triplet Δ_L , and the doubly charged scalar $H_R^{\pm\pm}$ from the right-handed triplet Δ_R . In the limit of vanishing mixing of H_3 with the SM Higgs and other heavy scalars in the LRSM, the partial width for the diphoton decay channel is [25,27,28]

$$\Gamma(H_3 \rightarrow \gamma\gamma) = \frac{m_{H_3}^3}{32\pi v_R^2} \frac{\alpha^2}{(4\pi)^2} |F|^2. \quad (\text{A4})$$

The loop function is

$$\begin{aligned}F &= A_0(\eta_{H_1^\pm}) + A_0(\eta_{H_L^\pm}) + 4A_0(\eta_{H_L^{\pm\pm}}) + 4A_0(\eta_{H_R^{\pm\pm}}) \\ &\quad + A_1(\eta_{W_R}),\end{aligned}\quad (\text{A5})$$

where the factor of 4 is from the square of charges for the doubly charged scalars, and the loop functions

$$A_0(x) = -x[1 - xf(x)], \quad (\text{A6})$$

$$A_1(x) = -[2 + 3x(1 + (2-x)f(x))], \quad (\text{A7})$$

with

$$f(x) \equiv \begin{cases} \arcsin^2 \sqrt{x^{-1}}, & \tau \geq 1, \\ -\frac{1}{4} \left[\log \left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} \right) - i\pi \right]^2, & \tau < 1. \end{cases} \quad (\text{A8})$$

In the limit of $m_{H_3} \rightarrow 0$, the loop functions

$$A_0(\infty) = \frac{1}{3}, \quad A_1(\infty) = -7, \quad (\text{A9})$$

which lead to

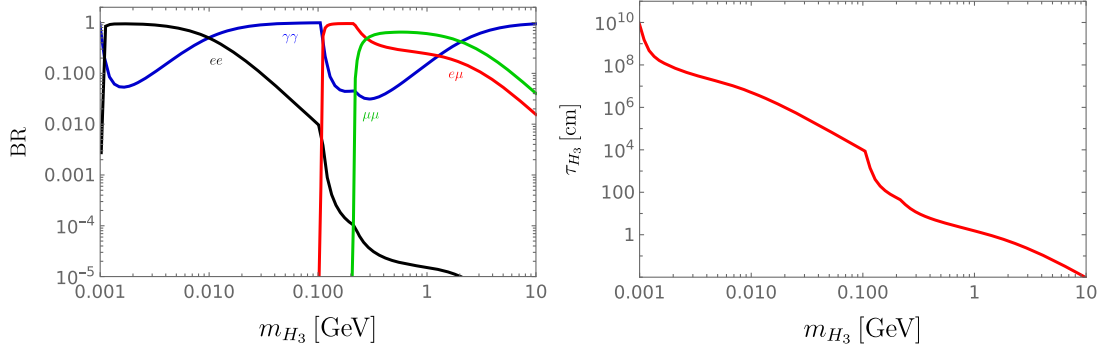


FIG. 5. Left panel: the BRs of H_3 decaying into e^+e^- , $e^\pm\mu^\mp$, $\mu^+\mu^-$ and $\gamma\gamma$ as functions of its mass m_{H_3} . Right panel: the proper lifetime of H_3 as function of its mass m_{H_3} . We have set $v_R = 10$ TeV. Other parameter setups can be found in the main text.

$$F \cong (1 + 1 + 4 + 4) \times \frac{1}{3} + (-7) = -\frac{11}{3}. \quad (\text{A10})$$

For illustration purpose, the decay BRs of $H_3 \rightarrow e^+e^-$, $e^\pm\mu^\mp$, $\mu^+\mu^-$, $\gamma\gamma$ as functions of m_{H_3} are shown in the left panel of Fig. 5. The proper lifetime of H_3 is presented in the right panel of Fig. 5, with the benchmark value of $v_R = 10$ TeV.

APPENDIX B: FUNCTIONS FOR THE 1-LOOP LFV AND LFC COUPLINGS

1. LFV couplings

In this subsection, we collect all the loop functions for the LFV couplings in Eq. (3), with the same notation

convention of the A, B, C loop functions as in Ref. [79]. The effective couplings in Eq. (3) can be decomposed into the following contributions:

$$c_{\alpha\beta}^{(X)} = \sum_{i=1}^6 c_{\alpha\beta}^{(X),i}, \quad (\text{B1})$$

with $X = L, R$. In the first diagram in Fig. 1 with a right-handed doubly charged scalar $H_R^{\pm\pm}$, the charged lepton flavor $\gamma = \alpha$ or $\gamma = \beta$ (assuming $\alpha \neq \beta$) in the case of mixing of two RHNs. For the cases of $\gamma = \alpha$ and $\gamma = \beta$, the effective couplings are labeled with the superscripts 1 and 2, respectively

$$\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_{\alpha\beta}^{(L),1} = -8m_{H_R^{\pm\pm}}^2(m_{N_1} - m_{N_2})((m_{N_1} - m_{N_2}) \cos 2\theta + m_{N_1} + m_{N_2})C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\alpha^2), \quad (\text{B2})$$

$$\begin{aligned} \left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_{\alpha\beta}^{(R),1} &= 16m_{H_R^{\pm\pm}}^2(m_{N_1} - m_{N_2})\sin^2\theta(m_{N_1} \cot^2\theta + m_{N_2}) \left[C_0(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\alpha^2) \right. \\ &\quad \left. + C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\alpha^2) + C_2(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\alpha^2) \right], \end{aligned} \quad (\text{B3})$$

$$\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_{\alpha\beta}^{(L),2} = -16m_{H_R^{\pm\pm}}^2(m_{N_1} - m_{N_2})\sin^2\theta(m_{N_1} + m_{N_2} \cot^2\theta)C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\beta^2), \quad (\text{B4})$$

$$\begin{aligned} \left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_{\alpha\beta}^{(R),2} &= 16m_{H_R^{\pm\pm}}^2(m_{N_1} - m_{N_2})\sin^2\theta(m_{N_1} + m_{N_2} \cot^2\theta) \left[C_0(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\beta^2) \right. \\ &\quad \left. + C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\beta^2) + C_2(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{H_R^{\pm\pm}}^2, m_{H_R^{\pm\pm}}^2, m_\beta^2) \right], \end{aligned} \quad (\text{B5})$$

where $m_{\alpha,\beta}$ are the masses of the charged leptons with flavors α and β , respectively.

For the second diagram in Fig. 1, the couplings for the case with the RHN N_1 running in the loop are

$$\begin{aligned} & \left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_{\alpha\beta}^{(L),3} \\ & \simeq -6m_{N_1}^2 B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 4m_{N_1}^2 B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2m_{N_1}^2 (m_{N_1}^2 - 2m_{W_R}^2) C_0(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad + 4m_{N_1}^2 C_{00}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + 4m_{N_1}^2 (m_{N_1}^2 + 2m_{W_R}^2) C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad + 4m_{H_3}^2 m_{N_1}^2 C_{11}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) - 2m_{N_1}^2 (-m_{H_3}^2 - m_\alpha^2 + m_\beta^2) C_{12}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad - 4m_\alpha^2 m_{N_1}^2 C_2(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2), \end{aligned} \quad (B6)$$

$$\begin{aligned} & \left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_{\alpha\beta}^{(R),3} \\ & \simeq -2m_{N_1}^2 B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2m_{N_1}^2 (3m_{N_1}^2 + 2m_{W_R}^2) C_0(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad - 4m_{N_1}^2 C_{00}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) - 2m_{N_1}^2 (m_{H_3}^2 + m_\alpha^2 - m_\beta^2) C_{22}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad - 4m_{H_3}^2 m_{N_1}^2 C_{11}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) - 2m_{N_1}^2 (3m_{H_3}^2 + m_\alpha^2 - m_\beta^2) C_{12}(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad - 4m_{N_1}^2 (m_{N_1}^2 + 2m_{W_R}^2) \left[C_1(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + C_2(m_{H_3}^2, m_\beta^2, m_\alpha^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \right]. \end{aligned} \quad (B7)$$

Here we have neglected the terms of $m_{H_3, \alpha, \beta} \ll m_{W_R, N_1, N_2}$ for example $m_\alpha^2 + m_{W_R}^2 \simeq m_{W_R}^2$. The corresponding couplings $c_{\alpha\beta}^{(L),4}$ and $c_{\alpha\beta}^{(R),4}$ for the diagram with the RHN N_2 can be easily obtained by substituting m_{N_1} with m_{N_2} , and replacing $\sin \theta$ with $-\sin \theta$ in the prefactor.

For the last diagram in Fig. 1, if the RHN N_1 is in the propagator, the couplings are

$$\begin{aligned} & \left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_{\alpha\beta}^{(L),5} \\ & \simeq 2(m_{N_1}^2 - m_{W_R}^2) B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + 2B_{00}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + 2(m_{N_1}^2 - m_{W_R}^2) B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad + (m_{H_3}^2 - m_\alpha^2 + m_\beta^2) B_{11}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + m_{W_R}^2 (3m_\alpha^2 + m_\beta^2 - m_{H_3}^2) C_{12}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad - 2m_{W_R}^4 C_0(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 2m_{W_R}^2 C_{00}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad - 4m_\alpha^2 C_{001}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 4(m_{H_3}^2 - m_\beta^2) C_{002}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad + m_{W_R}^2 (m_{H_3}^2 + 3m_\alpha^2 - m_\beta^2) C_1(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad + m_\alpha^2 (m_{H_3}^2 + m_\alpha^2 - m_\beta^2) \left[C_{11}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 2C_{112}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right] \\ & \quad - ((m_{H_3}^2 - m_\beta^2)^2 + m_\alpha^2 (2m_{H_3}^2 - 3m_\alpha^2 + 2m_\beta^2)) C_{122}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad - 6m_{W_R}^4 C_2(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + ((m_{H_3}^2 - m_\alpha^2)^2 - m_\beta^4) C_{222}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad + m_{W_R}^2 (m_\alpha^2 + 3m_\beta^2 - m_{H_3}^2) C_{22}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2), \end{aligned} \quad (B8)$$

$$\begin{aligned} & \left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_{\alpha\beta}^{(R),5} \simeq 2A_0(m_{W_R}^2) + 2(m_{N_1}^2 - m_{W_R}^2) B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2B_{00}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \\ & \quad + (m_{H_3}^2 - m_\alpha^2 + 3m_\beta^2) B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2m_{W_R}^4 C_0(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad + 2m_{W_R}^2 C_{00}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 4(m_{H_3}^2 + 2m_\alpha^2 - m_\beta^2) \\ & \quad \times C_{001}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 4(m_\alpha^2 - m_{H_3}^2) C_{002}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\ & \quad - 6m_{W_R}^4 C_1(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + m_{W_R}^2 (3m_\alpha^2 + m_\beta^2 - m_{H_3}^2) \\ & \quad \times C_{11}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 2m_\alpha^2 (m_{H_3}^2 + m_\alpha^2 - m_\beta^2) \end{aligned}$$

$$\begin{aligned}
& \times C_{111}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) - ((m_{H_3}^2 - m_\beta^2)^2 + m_\alpha^2(2m_{H_3}^2 - 3m_\alpha^2 + 2m_\beta^2)) \\
& \times C_{112}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + m_{W_R}^2(m_\alpha^2 + 3m_\beta^2 - m_{H_3}^2) \\
& \times C_{12}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + ((m_{H_3}^2 - m_\alpha^2)^2 - m_\beta^4)C_{122}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
& + m_{W_R}^2(m_{H_3}^2 - m_\alpha^2 + 3m_\beta^2)C_2(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
& + (m_{H_3}^2 - m_\alpha^2)(m_{H_3}^2 - m_\alpha^2 + m_\beta^2)C_{22}(m_\alpha^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2).
\end{aligned} \tag{B9}$$

The corresponding couplings $c_{\alpha\beta}^{(L),6}$ and $c_{\alpha\beta}^{(R),6}$ for the diagram with the RHN N_2 can be obtained by substituting m_{N_1} with m_{N_2} , and replacing $\sin \theta$ with $-\sin \theta$ in the prefactor.

2. LFC couplings

For the LFC couplings, the effective coupling g_ℓ can be decomposed as

$$g_\ell = \sum_{i=1}^6 \left(c_\ell^{(L),i} + c_\ell^{(R),i} \right). \tag{B10}$$

Let us first consider the coupling of H_3 with ℓ_β . For the first diagram in Fig. 1, the charged leptons running in the loop can be of either flavor α or β . The corresponding couplings are, respectively

$$\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_\beta^{(L),1} = 8 \sin 2\theta m_{H_R}^2 (m_{N_1} - m_{N_2})^2 C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\alpha^2), \tag{B11}$$

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_\beta^{(R),1} = & -8 \sin 2\theta m_{H_R}^2 (m_{N_1} - m_{N_2})^2 \left[C_0(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\alpha^2) \right. \\
& \left. + C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\alpha^2) + C_2(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\alpha^2) \right],
\end{aligned} \tag{B12}$$

$$\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_\beta^{(L),2} = 16 \tan \theta m_{H_R}^2 (m_{N_1} \sin \theta + m_{N_2} \cos \theta \cot \theta)^2 C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\beta^2), \tag{B13}$$

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_\beta^{(R),2} = & -16 \sin^2 \theta \tan \theta m_{H_R}^2 (m_{N_1} + m_{N_2} \cot^2 \theta)^2 \left[C_0(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\beta^2) \right. \\
& \left. + C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\beta^2) + C_2(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{H_R}^2, m_{H_R}^2, m_\beta^2) \right].
\end{aligned} \tag{B14}$$

For the second diagram in Fig. 1 with the RHN N_1 , the couplings are

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3} \right)^{-1} c_\beta^{(L),3} \simeq & m_{N_1}^2 \tan \theta \left\{ 6B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + 4B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \right. \\
& + 2(m_{N_1}^2 - 2m_{W_R}^2)C_0(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) - 4C_{00}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\
& - 4(m_{N_1}^2 + 2m_{W_R}^2)C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) - 4m_{H_3}^2 C_{11}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\
& \left. - 2m_{H_3}^2 C_{12}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + 4m_\beta^2 C_2(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \right\},
\end{aligned} \tag{B15}$$

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\beta^{(R),3} &\simeq m_{N_1}^2 \tan \theta \left\{ 2B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + 2(3m_{N_1}^2 + 2m_{W_R}^2)C_0(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \right. \\
&+ 4C_{00}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + 4(m_{N_1}^2 + 2m_{W_R}^2)C_1(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\
&+ 4m_{H_3}^2 C_{11}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + 6m_{H_3}^2 C_{12}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \\
&\left. + 4(m_{N_1}^2 + 2m_{W_R}^2)C_2(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) + 2m_{H_3}^2 C_{22}(m_{H_3}^2, m_\beta^2, m_\beta^2, m_{N_1}^2, m_{N_1}^2, m_{W_R}^2) \right\}. \quad (B16)
\end{aligned}$$

The corresponding couplings $c_\beta^{(L),4}$ and $c_\beta^{(R),4}$ for the diagram with the RHN N_2 can be obtained by substituting m_{N_1} with m_{N_2} , and replacing $\tan \theta$ with $\cot \theta$ in the prefactor on the right-hand side (rhs).

For the last diagram in Fig. 1 with the RHN N_1 , the couplings are

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\beta^{(L),5} &\simeq \tan \theta \left\{ (-2m_{N_1}^2 + 2m_{W_R}^2)B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2B_{00}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \right. \\
&+ 2(m_{W_R}^2 - m_{N_1}^2)B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - m_{H_3}^2 B_{11}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \\
&+ 2m_{W_R}^4 C_0(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) - 2m_{W_R}^2 C_{00}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&+ 4m_\beta^2 C_{001}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + (4m_\beta^2 - 4m_{H_3}^2)C_{002}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- m_{W_R}^2 (m_{H_3}^2 + 2m_\beta^2)C_1(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- m_{H_3}^2 (m_{H_3}^2 - 2m_\beta^2)C_{222}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- m_{H_3}^2 m_\beta^2 \left[C_{11}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 2C_{112}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right] \\
&+ m_{W_R}^2 (m_{H_3}^2 - 4m_\beta^2) \left[C_{12}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + C_{22}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right] \\
&\left. + m_{H_3}^4 C_{122}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 6m_{W_R}^4 C_2(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right\}, \quad (B17)
\end{aligned}$$

$$\begin{aligned}
\left(\frac{m_\beta \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\beta^{(R),5} &\simeq \tan \theta \left\{ -2A_0(m_{W_R}^2) + (2m_{W_R}^2 - 2m_{N_1}^2)B_0(m_\beta^2, m_{N_1}^2, m_{W_R}^2) + 2B_{00}(m_\beta^2, m_{N_1}^2, m_{W_R}^2) \right. \\
&- (m_{H_3}^2 + 2m_\beta^2)B_1(m_\beta^2, m_{N_1}^2, m_{W_R}^2) - 2m_{W_R}^2 C_{00}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- m_{W_R}^2 (m_{H_3}^2 + 2m_\beta^2)C_2(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- 4(m_{H_3}^2 + m_\beta^2)C_{001}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- 4(m_\beta^2 - m_{H_3}^2)C_{002}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&+ 2m_{W_R}^4 [C_0(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + 3C_1(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2)] \\
&- 2m_{H_3}^2 m_\beta^2 C_{111}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + m_{H_3}^4 C_{112}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&- m_{W_R}^2 (4m_\beta^2 - m_{H_3}^2) \left[C_{11}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) + C_{12}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right] \\
&- m_{H_3}^2 (m_{H_3}^2 - 2m_\beta^2)C_{122}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \\
&\left. - m_{H_3}^2 (m_{H_3}^2 - m_\beta^2)C_{22}(m_\beta^2, m_{H_3}^2, m_\beta^2, m_{N_1}^2, m_{W_R}^2, m_{W_R}^2) \right\}. \quad (B18)
\end{aligned}$$

The corresponding couplings $c_\beta^{(L),6}$ and $c_\beta^{(R),6}$ for the diagram with the RHN N_2 can be obtained by substituting m_{N_1} with m_{N_2} , and replacing $\tan \theta$ with $\cot \theta$ in the prefactor on the rhs.

For the coupling of H_3 with the charged lepton ℓ_α , the coefficients for the first diagram in Fig. 1 are a little bit different from the case of ℓ_β

$$\left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\alpha^{(L),1} = 4 \sec \theta \csc \theta m_{H_R^\pm}^2 ((m_{N_1} - m_{N_2}) \cos 2\theta + m_{N_1} + m_{N_2})^2 C_1(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\alpha^2), \quad (\text{B19})$$

$$\left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\alpha^{(R),1} = -4 \sec \theta \csc \theta m_{H_R^\pm}^2 ((m_{N_1} - m_{N_2}) \cos 2\theta + m_{N_1} + m_{N_2})^2 \left[C_0(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\alpha^2) \right. \\ \left. + C_1(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\alpha^2) + C_2(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\alpha^2) \right], \quad (\text{B20})$$

$$\left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\alpha^{(L),2} = 8 \sin 2\theta m_{H_R^\pm}^2 (m_{N_1} - m_{N_2})^2 C_1(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\beta^2), \quad (\text{B21})$$

$$\left(\frac{m_\alpha \sin \theta \cos \theta}{32\sqrt{2}\pi^2 v_R^3}\right)^{-1} c_\alpha^{(R),2} = -8 \sin 2\theta m_{H_R^\pm}^2 (m_{N_1} - m_{N_2})^2 \left[C_0(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\beta^2) \right. \\ \left. + C_1(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\beta^2) + C_2(m_{H_3}^2, m_\alpha^2, m_\alpha^2, m_{H_R^\pm}^2, m_{H_R^\pm}^2, m_\beta^2) \right]. \quad (\text{B22})$$

For the second and third diagram with the RHN N_1 running in the loop, the corresponding couplings $c_\alpha^{(L,R),3}$ and $c_\alpha^{(L,R),5}$ can be obtained from $c_\beta^{(L,R),3}$ and $c_\beta^{(L,R),5}$ by substituting m_β with m_α , and replacing $\tan \theta$ with $\cot \theta$ in the prefactor on the rhs, respectively. If it is the RHN N_2 in the loop, to obtain the couplings $c_\alpha^{(L,R),4}$ and $c_\alpha^{(L,R),6}$, we need to substitute m_{N_1} with m_{N_2} , and replace m_β with m_α in $c_\beta^{(L,R),4}$ and $c_\beta^{(L,R),6}$, respectively.

APPENDIX C: COMPARISON WITH COUPLINGS OF ALPS

For convenience, the LFV couplings of ALP can be written as

$$\mathcal{L} = -ig_{\alpha\beta} a \bar{\ell}_\alpha \gamma_5 \ell_\beta + \text{H.c.} \quad (\text{C1})$$

In the limit of hierarchical structure of charged lepton masses $m_{\ell_\alpha} \ll m_{\ell_\beta}$, the squared amplitudes for the LFV processes $\ell_\beta \rightarrow \ell_\alpha + a$ and $a \rightarrow \ell_\alpha + \ell_\beta$ are both proportional to the factor of $(m_{\ell_\beta}^2 - m_\alpha^2)$, which has the same form as that in Eqs. (A1) and (A2) for the CP -even H_3 in the limit of $m_{\ell_\alpha} \rightarrow 0$. Similarly, for the lepton-proton bremsstrahlung $\ell_\alpha + p \rightarrow \ell_\beta + p + H_3/a$ and semi-Compton $\ell_\alpha + \gamma \rightarrow \ell_\beta + H_3/a$ processes which are relevant to the supernova constraints, the cross sections are the same for scalars and pseudoscalars in the limit of $m_{\ell_\alpha} \rightarrow 0$. See Ref. [80] for more details.

The LFC couplings of an ALP can be written as

$$\mathcal{L} = -ig_{a\ell} a \bar{\ell} \gamma_5 \ell. \quad (\text{C2})$$

If the charged lepton ℓ involved is relativistic, the squared amplitudes for scalars and pseudoscalars are both proportional to the squared (pseudo)scalar mass. Therefore, the ALP constraints can be directly converted to the limits on H_3 for such cases.

The coupling of ALPs to photons can be written in the form of

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (\text{C3})$$

with $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}/2$ the dual of the electromagnetic field. For both the processes of $H_3/a \leftrightarrow \gamma\gamma$ and $\gamma + f \rightarrow f + H_3/a$ (with the fermion f either relativistic or non-relativistic), the squared amplitudes are the same for scalars and pseudoscalars in the limit of massless photon [80]. The Primakoff-like process $\gamma + f \rightarrow f + H_3/a$ is a good approximation for the production of H_3/a in the proton and electron beam-dump experiments. In compact stars such as supernovae and neutron stars, the Primakoff and photon coalescence processes are the dominant production channels of H_3 and a , and $H_3/a \rightarrow \gamma\gamma$ are relevant to their decays.

APPENDIX D: MORE DETAILS ON THE CONSTRAINTS

All the predominant current constraints on the LFV couplings $g_{\alpha\beta}$ and the LFC coupling g_e of H_3 from the laboratory experiments and astrophysical observations and the leading future prospects are collected in Table I. The leading constraints on the coupling of H_3 with photons and future prospects are presented in Table II. In both the two

TABLE I. Leading current limits and future prospects of the LFV couplings $g_{\alpha\beta}$ and the LFC coupling g_e of H_3 from the laboratory experiments and astrophysical observations. The corresponding limits or prospects of v_R are collected in the last column. See Fig. 2 and text for more details.

	Coupling	Experiment	Process	Mass [MeV]	Limit	v_R [GeV]
Laboratory	$g_{e\mu}$	TWIST [41]	$\mu \rightarrow e + \text{inv}$	$\lesssim 80$	$\text{BR} \sim 10^{-5}$	5×10^8
		PIENU [42]	$\mu \rightarrow e + \text{inv}$	(47.8, 95.1)	$\text{BR} \sim 10^{-5}$	7×10^7
		Jodidio <i>et al.</i> [43]	$\mu \rightarrow e + \text{inv}$	$\lesssim 10$	$\text{BR} \sim 10^{-6}$	2×10^8
		Mu3e [96,97]	$\mu \rightarrow e + \text{inv}$	$\lesssim 100$	$\text{BR} \sim 10^{-8}$	5×10^9
	$g_{e\tau}$	Belle [44]	$\tau \rightarrow e + \text{inv}$	< 1600	$\text{BR} \sim 10^{-4}$	3×10^5
		Belle II [98]	$\tau \rightarrow e + \text{inv}$	< 1600	$\text{BR} \sim 10^{-6}$	1×10^7
	$g_{\mu\tau}$	Belle [44]	$\tau \rightarrow \mu + \text{inv}$	< 1600	$\text{BR} \sim 10^{-4}$	4×10^5
	$g_{\ell\tau}$	CHARM [45]	$\tau \rightarrow \ell + a$	$\lesssim 1000$	$f_a \sim 10^8 \text{ GeV}$	5×10^5
		SHiP [45]	$\tau \rightarrow \ell + a$	$\lesssim 1000$	$f_a \sim 10^9 \text{ GeV}$	2×10^7
Astro.	$g_{e\mu}$	SN1987A [46]	$\mu \rightarrow e + a, e + \mu \rightarrow a$ $\ell_a + p \rightarrow \ell_\beta + p + a$	$\lesssim 280$	$g_{aeu} \sim 10^{-9}$	2×10^7
		LESNe [47,48]	$\mu \rightarrow e + a, e + \mu \rightarrow a$ $e + \gamma \rightarrow \mu + a$	$\lesssim 500$	$g_{aeu} \sim 10^{-11}$	4×10^8
	g_e	LESNe [99]	$e + \gamma \rightarrow e + a, e^+ + e^- \rightarrow a$	$\lesssim 200$	$g_{ae} \sim 10^{-11}$	1×10^6

tables, the corresponding constraints on the v_R scale are listed in the last columns. Here are more details for some of the constraints.

The constraints of beam dump experiments on ALP in Ref. [45] can be reinterpreted and applied to the light H_3 in the minimal LRSM. The light H_3 and a are to some extent different, in particular their decay modes. The ALP a is assumed to decay mostly into dileptons ee , $e\mu$ and $\mu\mu$ in Ref. [45], whereas H_3 decays predominantly into diphoton for some of the mass ranges (cf. the left panel of Fig. 5). However, all these decay products are visible particles, and can be easily identified at the detectors. For concreteness, we adopt the anarchical LFV case with universal ALP couplings to the charged leptons in Fig. 6 of Ref. [45], and recast the current limits from CHARM and the prospect of SHiP in the following way.

- (i) The lower boundaries of these constraints are determined by the production of a via the process of $\tau \rightarrow \ell + a$. The corresponding lower boundaries on the f_a parameter for ALP can be directly converted to the LFV coupling $g_{\alpha\beta}$ via the relation of $g_{\tau\ell} = m_\tau/f_a$.

- (ii) The upper boundaries of these constraints are mainly dictated by the decay of ALP. Therefore, setting H_3 and a have the same decay length, i.e. $\tau_{H_3} = \tau_a$ (with τ_a the proper lifetime of a), we can convert these upper boundaries onto the constraints on m_{H_3} and v_R .

We take the energy deposition limit on g_{ae} in the left panel of Fig. 8 of Ref. [99] to set limits on the light H_3 . To this end, we adopt the following procedure for the reinterpretation.

- (i) The lower boundary is mainly determined by the production of a in the supernova core via the $e + \gamma \rightarrow e + a$ and $e^+ + e^- \rightarrow a$ processes. The corresponding limits on g_{ae} can be directly converted to the constraints on v_R in the LRSM.
- (ii) The upper boundary for the energy deposition in the mantle of LESNe is determined mainly by ALP decay within the progenitor. In other words, to effectively deposit energy in the mantle, the lifetime of ALP is required to be within certain range. To set limits on H_3 , we require the lifetime of H_3 to equal that of axion, i.e., $\tau_{H_3} = \tau_a$, with the latter one dominated by the decay $a \rightarrow e^+ e^-$.

TABLE II. The same as Table I, but for the astrophysical constraints on the coupling of H_3 with photons. See Fig. 2 and text for more details.

Experiment	Process	Mass [MeV]	Limits on $g_{\alpha\gamma}$ [GeV $^{-1}$]	v_R [GeV]
SN1987A [49]	$\gamma + \mathcal{N} \rightarrow \mathcal{N} + a, \gamma + \gamma \rightarrow a$	$\lesssim 300$	$\sim 10^{-12}$	2×10^9
SN2023ixf [50]		$\lesssim 4$	$\sim 10^{-11.5}$	7×10^8
Type Ic supernovae [159]		$\lesssim 400$	$\sim 10^{-11}$	3×10^8
LESNe [51]		$\lesssim 550$	$\sim 10^{-10}$	2×10^7
GW170817 [160]		$\lesssim 400$	$\sim 10^{-10}$	5×10^7
Betelgeuse [156]		$\lesssim 100$	$\sim 10^{-14}$	6×10^{11}
NS γ -rays [161]		$\lesssim 660$	$\sim 10^{-12}$	3×10^9

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