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Testing neutrino mass generation mechanisms from the lepton flavor violating decay of the Higgs boson

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A B S T R A C T

We investigate how observations of the lepton flavor violating decay of the Higgs boson ($h \to \ell\ell'$) can narrow down models of neutrino mass generation mechanisms, which were systematically studied in Refs. [1,2] by focusing on the combination of new Yukawa coupling matrices with leptons. We find that a wide class of models for neutrino masses can be excluded if evidence for $h \to \ell\ell'$ is really obtained in the current or future collider experiments. In particular, simple models of Majorana neutrino masses cannot be compatible with the observation of $h \to \ell\ell'$. It is also found that some of the simple models to generate masses of Dirac neutrinos radiatively can be compatible with a significant rate of the $h \to \ell\ell'$ process.

1. Introduction

Since the discovery of the neutrino oscillation [3], the origin of small masses for neutrinos has been one of the most important problems of particle physics. It would be rather unnatural if the origin of such tiny neutrino masses is the same as the one for quark and charged lepton masses. Therefore, it would be expected that neutrinos obtain masses via a different mechanism from quarks and charged leptons.

There can be two types of the mass for neutrinos; e.g., Majorana masses and Dirac masses, where the former break the lepton number conservation by two units. There are simple scenarios to produce Majorana neutrino masses at the tree level by the seesaw mechanism. In the type-I [4,5], II [5,6], and III [7] seesaw scenarios, the origin of the lepton number violation (LNV) is the mass of heavy right-handed neutrinos, the scalar coupling with an $SU(2)_L$-triplet Higgs field, and the mass of triplet fermions, respectively. As an alternative scenario, neutrino masses are generated at the loop level. The smallness of neutrino masses can be explained not only by the large mass scale but also by the loop suppression factor and new coupling constants which would be less than unity. The first model along this line has been proposed by A. Zee [8],

in which neutrino masses are generated at the one-loop level by introducing an extended Higgs sector. Subsequently, many variant models have been proposed so far. For example, there are models where neutrino masses are generated at the one-loop or higher-loop levels [9–15], some of which involve the dark matter candidate running in the loop [12–15]. Furthermore, using the physics of extended Higgs sectors we may consider a model where not only neutrino masses and dark matter but also the baryon asymmetry of the universe can be explained simultaneously in the context of the electroweak baryogenesis [14]. On the other hand, LNV has not been discovered, so that nontrivial scenarios to generate masses of Dirac neutrinos should also be considered. Similarly to the cases for Majorana masses, Dirac masses can be generated at the tree level [16,17] as well as the loop level [2,18,19] involving the dark matter candidate [2,19].

It is very important to test these models by using various kinds of current and future experiments. Classification of models into several groups by some common features enables us to effectively test neutrino mass generation mechanisms not in model-by-model but in group-by-group. In Refs. [1,2], models of neutrino masses are classified by focusing on the combinations of new Yukawa coupling matrices for leptons as we briefly review in the next section. Such Yukawa interactions determine the flavor structure of the neutrino mass matrix. If LFV phenomena other than neutrino oscillations are observed, the origin of these phenomena can be the same as that of the new physics for neutrino masses, because neutrino oscillations show that lepton flavor conservation is highly

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Table 1

It shows which scalar fields are introduced in the Mechanisms-M1–M8, which generate Majorana neutrino masses. A check-mark means that the Mechanism includes the scalar field. Columns of ℓ'_L and ℓ'_R show the chirality of ℓ' of $\ell \to \ell'\gamma$ in each Mechanism.

	Scalar with leptonic Yukawa int.				Z_2-odd		$\ell \to \ell'\gamma$		
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η	ℓ'_L	ℓ'_R	
$SU(2)_L$	**1**	**1**	**2**	**3**	**1**	**2**			
$U(1)_Y$	1	2	1/2	1	1	1/2			
Unbroken Z_2	+	+	+	+	−	−			Simple models
M1	✓	✓					✓	✓	[9,10]
M2		✓	✓					✓	[1,11]
M3		✓						✓	[12]
M4				✓			✓		[6,11]
M5	✓				✓		✓	✓	[13]
M6			✓		✓			✓	[14]
M7					✓			✓	This letter[1]
M8						✓	✓		[15]

violated in connection to neutrinos. The LFV decays of charged leptons ($\ell \to \ell'\gamma$ and $\tau \to \overline{\ell}_1\ell_2\ell_3$) and the violation of the universality for $\ell \to \ell'\nu\overline{\nu}$ are considered in Refs. [1,2] for the test of the groups of models.

By the discovery of the Higgs boson [20] with the mass 125 GeV, we obtained new observables to test models of new physics beyond the standard model (SM). In particular, Higgs boson couplings can be sensitive to new physics effects. For example, LFV decay of the Higgs boson can be a clear signature of new physics (see e.g., Refs. [21–24]). The CMS experiment with the 19.7 fb^{-1} integrated luminosity at 8 TeV gives upper bounds on branching ratios at the 95% confidence level as BR($h \to e\mu$) $< 3.5 \times 10^{-4}$ [25], BR($h \to e\tau$) $< 6.9 \times 10^{-3}$ [25], and BR($h \to \mu\tau$) $< 1.51 \times 10^{-2}$ [26], where BR($h \to \ell\ell'$) $\equiv$ BR($h \to \ell\overline{\ell'}$) + BR($h \to \overline{\ell}\ell'$). The best fit value BR($h \to \mu\tau$) $= 0.84^{+0.39}_{-0.37} \times 10^{-2}$ at the CMS [26] corresponds to the 2.4σ excess. The CMS experiment also gives the best fit value BR($h \to \mu\tau$) $= -0.76^{+0.81}_{-0.84} \times 10^{-2}$ with 2.3 fb^{-1} at 13 TeV [27]. The ATLAS experiment [28] with 20.3 fb^{-1} at 8 TeV obtained upper bounds (best fit values) as BR($h \to e\tau$) $< 1.04 \times 10^{-2}$ ($-0.34^{+0.64}_{-0.66} \times 10^{-2}$) and BR($h \to \mu\tau$) $< 1.43 \times 10^{-2}$ ($0.53^{+0.51}_{-0.51} \times 10^{-2}$). See e.g., Refs. [29–33] for the works to explain the excess at the CMS. It is expected that Higgs boson couplings are measured as precisely as possible at current and future collider experiments. For BR($h \to \mu\tau$), expected sensitivities are $\mathcal{O}(10^{-4})$ at the LHC [34] and the ILC [35]. Even if the excess for $h \to \mu\tau$ at the CMS is not confirmed, there can be other signal for $h \to \ell\ell'$ in the future.

In this letter, we discuss impact of future discoveries of $h \to \ell\ell'$ on the mechanisms to generate neutrino masses. Since the Higgs sector is extended in many models for neutrino masses, such models can naturally connect Higgs physics to LFV phenomena. By utilizing systematic analyses in Refs. [1,2] for mechanisms of neutrino masses, the simple models for Majorana neutrino masses cannot be compatible with $h \to \ell\ell'$ signals because of constraints from $\ell \to \ell'\gamma$, for which there are no degrees of freedom for cancellation in these models. However, we find that some simple models for masses of Dirac neutrinos can be consistent with $h \to \ell\ell'$ signals with possible suppression of $\ell \to \ell'\gamma$ by cancellation. Namely, if $h \to \ell\ell'$ is observed, the observation might indicate that neutrinos are not Majorana particles but Dirac particles with lepton number conservation.

Section 2 is devoted to a brief review of Refs. [1,2], where models of neutrino masses are systematically classified into some "Mechanisms" according to combinations of new Yukawa coupling

matrices with leptons. In Section 3, we discuss LFV decays of the Higgs boson for simple models in these Mechanisms. Conclusions are given in Section 4.

2. Classification of models for generating neutrino mass

In Ref. [1], all possible Yukawa interactions between leptons and new scalar fields are taken into account for mechanisms to generate Majorana neutrino masses. By focusing only on the combinations of such Yukawa coupling matrices which are the origin of the flavor structure of the neutrino mass matrix, we can efficiently classify the models without specifying details of the models, such as the concrete shape of the scalar potential, sizes of new coupling constants, and so on.

In the analyses in Ref. [1], the following simplifications are taken:

i) No colored scalars (e.g., leptoquarks) are introduced in order to concentrate on the lepton sector.

ii) Scalar fields do not have flavors in order to avoid complication. Therefore, flavor symmetries and the supersymmetry are not introduced.

iii) Each of quarks and leptons does not interact with two or more $SU(2)_L$-doublet Higgs fields. Then, the flavor changing neutral current (FCNC) interactions for quarks and charged leptons are absent at the tree level. This can be achieved by using the softly-broken Z_2 symmetry, which is often the case for two Higgs doublet models [36–39].

iv) For Majorana neutrino masses, only ψ_R^0 are introduced as fermions, which is a singlet under the SM gauge group with the odd parity for the unbroken Z_2 symmetry. Therefore, $(\psi_R^0)^c$ are not mixed with ν_L, which are Z_2-even. The type-I and type-III seesaw mechanisms, where new fermions are mixed with ν_L, are not included in the analyses because new physics effects of them at the low energy are highly suppressed by large masses of new fermions. Of course, right handed neutrinos ν_R are also introduced for analyses of masses of Dirac neutrinos in Ref. [2].

v) Three tiny neutrino masses are generated by a diagram. Introduced scalar fields are only the ones that are necessary for the diagram.

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[1] Scalar lines for the Mechanism-M7 can be closed by introducing a real $SU(2)_L$-triplet scalar Δ_2 (Z_2-odd) via $\Phi^T \epsilon \Delta_2 \Phi s_2^-$.

It was found that only four combinations (the Mechanisms-M1–M4 in Table 1) of new Yukawa interactions (or equivalently new scalar fields) can generate Majorana neutrino masses. Although another combination exists in principle, which corresponds the case in a simplified version of the Zee model such that there is no FCNC at the tree-level [8,40], the flavor structure of the neutrino mass matrix has already been excluded by neutrino oscillation data [41]. There appear additional four combinations (the Mechanisms-M5–M8 in Table 1) if singlet fermions ψ_R^0 and additional scalar fields for Yukawa interactions between ψ_R^0 and leptons are introduced with the odd parity under an unbroken Z_2 symmetry. Such Z_2-odd particles can provide the dark matter candidate. In Ref. [1], it was also found that these eight Mechanisms can be further classified into only three "Groups" according to the combination of new interactions between two leptons, where ψ_R^0 are integrated out. These Groups can be tested by measurements of the absolute neutrino mass, the neutrinoless double beta decay and by $\tau \to \overline{\ell}_1 \ell_2 \ell_3$. Predictions in these Groups are not applicable to the type-I (and III) seesaw scenario because of the absence of new scalar particles. Notice that representations of new scalar fields associated with the new interaction between two leptons are hidden by the classification into Groups, e.g., the interaction between two ℓ_R can be accompanied with a doubly-charged scalar, two singly-charged scalars or some other scalar fields. In this letter, we rely on the classification into not Groups but Mechanisms in order to discuss the chiral structure for $\ell \to \ell' \gamma$, which requires representations of scalar fields to be fixed.

In Table 1, we show the combinations of new scalar fields that can generate Majorana neutrino masses. Scalar fields s_L^+, s^{++}, and s_2^+ are all singlet under SU(2)$_L$. Fields s_L^+ and s_2^+ have hypercharge $Y = 1$ while s^{++} has $Y = 2$. The second SU(2)$_L$-doublet field Φ_2 has $Y = 1/2$. In order to avoid the FCNC at the tree level, each of right-handed quarks and leptons has the Yukawa interaction with only an SU(2)$_L$-doublet Higgs field by implicitly introducing softly-broken Z_2 symmetries [36–39]. In this letter, we take such that ℓ_R couples with Φ_2 without loss of generality. Another SU(2)$_L$-doublet field $\eta = (\eta^+, \eta^0)^T$ with $Y = 1/2$ as well as s_2^+ and gauge singlet fermions ψ_R^0 are odd under the unbroken Z_2 symmetry. The SU(2)$_L$-triplet field[2] with $Y = 1$ is denoted by Δ. Simple realizations of these Mechanisms correspond to the models in references in the last column, where scalar lines for these Mechanisms are explicitly closed by using appropriate scalar interactions.

Similarly, the classification of models to generate masses of Dirac neutrinos is achieved in Ref. [2], where ν_R are introduced with the lepton number conservation. In order to forbid the Yukawa interaction of neutrinos with the SM Higgs doublet field, the softly-broken Z_2 symmetry (denoted as Z_2') is also introduced such that ν_R has the odd parity while fields exist in the SM have the even parity. It was shown that Dirac neutrino masses can be generated by seven combinations of new Yukawa coupling matrices (the Mechanisms-D1–D7 in Table 2). If we introduce Z_2-odd fields (e.g., ψ_R^0) similarly to the cases for Majorana neutrino masses, additional eleven combinations (the Mechanisms-D8–D18 in Table 2) can generate Dirac neutrino masses. These eighteen Mechanisms to generate Dirac neutrino masses can be further classified into seven Groups according to the combination of new interactions between two leptons, where ψ_R^0 are integrated out. Some of these Groups can be tested by measurements of the absolute neutrino mass and $\tau \to \ell' \nu \overline{\nu}$ [2].
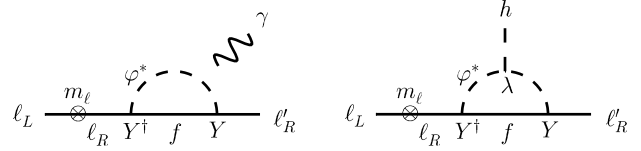

Fig. 1. Diagrams for $\ell \to \ell' \gamma$ (left) and $h \to \ell \ell'$ (right).

The combinations of new scalar fields for masses of Dirac neutrinos are listed in Table 2. Scalar fields s^0, s_R^+, and s_2^0 are all singlet[3] under SU(2)$_L$. Hypercharges of s^0 and s_2^0 are zero, and s_R^+ has $Y = 1$. Since s_R^+ and s_2^0 are Z_2'-odd fields, they can couple to a ν_R. This property is the difference of s_R^+ from s_L^+. The Z_2'-odd field Φ_ν is an SU(2)$_L$-doublet field with $Y = 1/2$, which has Yukawa interaction only with ν_R. For the cases of Dirac neutrino masses, conserving lepton numbers are assigned to these new scalar fields as shown in Table 2. Singlet fermions ψ_R^0 do not have the lepton number, and then they can have Majorana mass terms without the LNV. Due to these assignments of conserving lepton numbers, an unbroken Z_2 symmetry appears automatically.

3. Lepton flavor violating Higgs boson decay

In this section, we discuss $h \to \ell \ell'$ in order to clarify the impact of future discovery of the decay on the Mechanisms in Tables 1 and 2. First of all, let us take only a new Yukawa interaction $Y_{a\ell} \overline{f_a} \ell_X \varphi$ between a charged lepton ℓ and a charged[4] scalar φ, where $X = L, R$ denote chirality of ℓ. The particle f is a certain fermion. For example, the Zee–Babu model [9,10] of the Mechanism-M1 has the interaction with $f = (\ell_R)^c$, $\ell_X = \ell_R$, and $\varphi = s^{++}$; for the Ma model [15] of the Mechanism-M8, $f = \psi_R^0$, $\ell_X = \ell_L$, and $\varphi = \eta^+$. This interaction causes $\ell \to \ell'_X \gamma$ with the diagram in Fig. 1 (left), whose branching ratio is given by

$$\text{BR}(\ell \to \ell'_X \gamma)$$

$$\simeq \begin{cases} \dfrac{\alpha \pi^4}{3(16\pi^2)^2 G_F^2} \dfrac{(2 - 3Q_\varphi)^2 \left| S^2(Y^\dagger Y)_{\ell\ell'} \right|^2}{m_\varphi^4} \text{BR}(\ell \to e\nu_\ell \overline{\nu_e}) \\ \quad (m_f \ll m_\varphi) \\[2ex] \dfrac{\alpha \pi^4}{3(16\pi^2)^2 G_F^2} \dfrac{(1 - 3Q_\varphi)^2 \left| S^2(Y^\dagger Y)_{\ell\ell'} \right|^2}{m_f^4} \text{BR}(\ell \to e\nu_\ell \overline{\nu_e}) \\ \quad (m_f \gg m_\varphi), \end{cases}$$

$$(1)$$

where G_F is the Fermi constant, α is the fine structure constant, and Q_φ is the electric charge of φ. The electric charge of f is $Q_\varphi - 1$. Masses of φ and f_a are denoted as m_φ and m_f (assumed to be common for f_a), respectively. The factor S is taken to be 2 for the case where the Yukawa matrix Y is symmetric or antisymmetric, and 1 for the other cases.

The new Yukawa interaction used above also gives the lepton flavor violating decay of the Higgs boson h at the one-loop level as shown in Fig. 1 (right). The decay branching ratio $\text{BR}(h \to \ell \ell')$ ($\equiv \text{BR}(h \to \ell \overline{\ell'}) + \text{BR}(h \to \overline{\ell} \ell')$), where $\ell \neq \ell'$ and $m_\ell > m_{\ell'}$, can be calculated as

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[2] The FCNC for ν_L via Δ^0 is acceptable.

[3] The FCNC for ν_R via s^0 is acceptable.

[4] We assume that there is no FCNC for quarks and charged leptons at the tree level.

Table 2
It shows which scalar fields are introduced in the Mechanisms-D1–D18, which generate Dirac neutrino masses. A check-mark means that the Mechanism includes the scalar field. Columns of ℓ'_L and ℓ'_R show the chirality of ℓ' of $\ell \to \ell'\gamma$ in each Mechanism. Two check-marks in a cell for ℓ'_R mean that two scalar fields contribute to $\ell \to \ell'_R\gamma$.

	Scalar with leptonic Yukawa int.							Z_2-odd			$\ell \to \ell'\gamma$		
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R	
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**2**	**3**	**1**	**1**	**2**			
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2			
Lepton number	−2	−2	−2	−2	0	0	−2	−1	−1	−1			
Z'_2	+	+	−	+	−	+	+	−	+	+			Simple models
D1		✓	✓								✓	✓	[18]
D2		✓					✓				✓	✓	[2]
D3		✓	✓	✓								✓✓	[2]
D4		✓	✓									✓✓	[2]
D5	✓	✓		✓								✓	[2]
D6	✓	✓										✓	[2]
D7					✓						✓		[16]
D8	✓							✓	✓		✓	✓	[2]
D9							✓	✓	✓		✓	✓	[2]
D10		✓								✓	✓	✓	[2]
D11		✓			✓				✓			✓✓	[2]
D12		✓							✓			✓✓	[2]
D13		✓			✓			✓				✓	[2]
D14		✓						✓				✓	[2]
D15						✓		✓	✓			✓	[2]
D16								✓	✓			✓	[2]
D17			✓						✓	✓	✓	✓✓	[2]
D18									✓	✓	✓		[19]

$\mathrm{BR}(h \to \ell\ell')$

$$
\simeq
\begin{cases}
\dfrac{v^2 m_h}{128\pi(16\pi^2)^2\Gamma_{\mathrm{tot}}} \dfrac{\lambda^2 m_\ell^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_\varphi^4} \\
\quad (m_f \ll m_\varphi) \\[2mm]
\dfrac{v^2 m_h}{128\pi(16\pi^2)^2\Gamma_{\mathrm{tot}}} \dfrac{\lambda^2 m_\ell^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_f^4} \left(3 - \ln \dfrac{m_\psi^2}{m_\varphi^2}\right)^2 \\
\quad (m_f \gg m_\varphi),
\end{cases}
$$
(2)

where λ is the coupling constant of the interaction $\lambda v h |\varphi|^2$ with the vacuum expectation value v $(= 246$ GeV). The Higgs boson mass is denoted by m_h $(= 125$ GeV), and Γ_{tot} stands for the total width of the Higgs boson [42]. With the ratio of eqs. (1) and (2), it is clear that magnitudes of $\mathrm{BR}(h \to \ell\ell')$ and $\mathrm{BR}(\ell \to \ell'\gamma)$ are similar to each other except for the cases with $Q_\varphi = 2/3$ (see e.g., Ref. [43] for leptoquarks) and 1/3. Under the constraint from the current bounds $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [44] and $\mathrm{BR}(\tau \to \ell'\gamma) \lesssim 10^{-8}$ [45], $\mathrm{BR}(h \to \ell\ell')$ is too small to be observed if it is radiatively produced. If $\mathrm{BR}(h \to \ell\ell')$ is observed, such a simple model is excluded. Then, we might take FCNC at the tree level in order to explain the signal [22,29] or take some extension to suppress $\ell \to \ell'\gamma$ by cancellation (see, e.g. Ref. [31] for the cancellation).

Each of the Mechanisms listed in Tables 1 and 2 has new Yukawa interactions with charged leptons, which can produce both $\ell \to \ell'\gamma$ and $h \to \ell\ell'$. According to the discussion in the previous paragraph, Mechanisms for which there is only a check-mark in columns of $\ell \to \ell'\gamma$ will be excluded if $h \to \ell\ell'$ is really observed. Although the Mechanisms-M1, M5, D1, D2, D8, D9 and D10 have two kinds of new Yukawa interactions with charged leptons, their effects to $\ell \to \ell'\gamma$ cannot be cancelled with each other because of different chiralities of charged leptons in these interactions. For

example, s^+ in the Zee–Babu model [9,10] of the Mechanism-M1 gives $\ell \to \ell'_L\gamma$ via $(Y_A^s)_{\ell\ell'}\left[\overline{L_\ell} \epsilon L_{\ell'}^* s_L^-\right]$ while s^{++} in the model does $\ell \to \ell'_R\gamma$ via $(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c} \ell'_R s^{++}\right]$. Even in the type-I and III seesaw scenarios, $\mathrm{BR}(h \to \ell\ell')/\mathrm{BR}(\ell \to \ell'\gamma)$ is not enhanced. This means that all Mechanisms for Majorana neutrino masses in Table 1 as well as the type-I and III seesaw scenarios are not suitable as low-energy effective theories if $h \to \ell\ell'$ is observed. Exclusion of some specific models for neutrino masses are shown in Ref. [33]. Our statement covers the wider class of models to generate neutrino masses by virtue of systematic classification of the models.

On the other hand, it is found that some Mechanisms for Dirac neutrino masses in Table 2 can be compatible with the observation of $h \to \ell\ell'$. In both of the Mechanisms-D3 and D4, s_R^+ and s^{++} interact with ℓ_R via Yukawa interactions $(Y^s)_{\ell i}\left[\overline{(\ell_R)^c} \nu_{iR} s_R^+\right]$ and $(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c} \ell'_R s^{++}\right]$, respectively. Fig. 2 for the Mechanism-D3 and Fig. 3 for the Mechanism-D4 show how ν_L is connected to ν_R in order to generate the Dirac neutrino mass, where $y_\ell = \sqrt{2} m_\ell/v$, and g_2 is the $SU(2)_L$ gauge coupling constant. Contributions of these scalars to $\ell \to \ell'_R\gamma$ can be destructive such as

$$
\mathrm{BR}(\ell \to \ell'\gamma) \propto \left|(-1)\frac{(Y^{s\dagger}Y^s)_{\ell\ell'}}{m_{s_R^+}^2} + (-16)\frac{(Y_S^{s\dagger}Y_S^s)_{\ell\ell'}}{m_{s^{++}}^2}\right|^2
$$

$$
\ll \left|\frac{(Y^{s\dagger}Y^s)_{\ell\ell'}}{m_{s_R^+}^2}\right|^2,
$$
(3)

where $m_{s_R^+}$ and $m_{s^{++}}$ are masses of s_R^+ and s^{++}, respectively. For example, since $\mathrm{BR}(h \to \mu\tau) \sim 10^{-3}$ naively corresponds to $\mathrm{BR}(\tau \to \mu\gamma) \sim 10^{-2}$ for $m_f \ll m_\varphi$ with $\lambda^2/(2 - 3Q_\varphi)^2 \sim 1$, the 10^{-3} tuning of two amplitudes is required for the cancellation
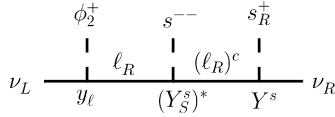
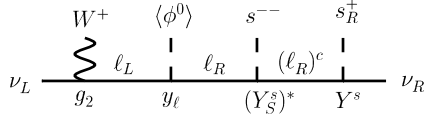**Fig. 2.** The diagram of the Mechanism-D3. (Taken from Ref. [2].)

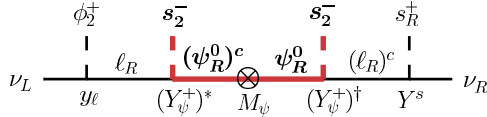**Fig. 3.** The diagram of the Mechanism-D4. (Taken from Ref. [2].)

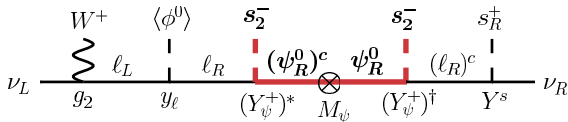**Fig. 4.** The diagram of the Mechanism-D11. (Taken from Ref. [2].)

Fig. 5. The diagram of the Mechanism-D12. (Taken from Ref. [2] correcting a typo as $Y_S^0 \to Y^s$.)

Fig. 6. The diagram of the Mechanism-D17. (Taken from Ref. [2].)

to satisfy $\mathrm{BR}(\tau \to \mu\gamma) \lesssim 10^{-8}$. Even in such cases, contributions of two scalar fields to $h \to \ell\ell'$ can be constructive by utilizing coupling constants for interactions $\lambda_{hs^+} v h |s_R^+|^2$ and $\lambda_{hs^{++}} v h |s^{++}|^2$ such as

$$\mathrm{BR}(h \to \ell\ell') \propto \left| \lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m_{s_R^+}^2} + 4\lambda_{hs^{++}} \frac{(Y_S^{s\dagger} Y_S^s)_{\ell\ell'}}{m_{s^{++}}^2} \right|^2$$

$$\sim \left| \lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m_{s_R^+}^2} \right|^2, \tag{4}$$

where λ_{hs^+} and $\lambda_{hs^{++}}$ should have the opposite sign. Notice that these interactions of scalars are not used to close scalar lines of the diagrams (Figs. 2 and 3) for the neutrino mass generation, and then they are free from constraints from neutrino oscillation experiments. Some explicit examples to close the scalar lines are shown in Ref. [2]. This is also the case for the Mechanisms-D11, D12, and D17,[5] in which s_R^+ and s_2^+ interact with ℓ_R via $(Y^s)_{\ell i}\left[\overline{(\ell_R)^c} \nu_{iR} s_R^+\right]$ and $(Y_\psi^+)_{\ell i}\left[\overline{(\ell_R)^c} \psi_{iR}^0 s_2^+\right]$, respectively. Dirac neutrino masses are generated by connecting ν_L to ν_R as shown in Figs. 4, 5, and 6, where the Majorana mass term $(1/2)M_\psi\left[\overline{(\psi_R^0)^c} \psi_R^0\right]$ and the Yukawa interaction $(Y_\psi^\eta)_{\ell i}\left[\overline{L_{\ell}} \epsilon \eta^* \psi_{iR}^0\right]$ are utilized. Therefore, these Mechanisms of the Dirac neutrino mass would be preferred when $h \to \ell\ell'$ is observed.

As discussed in Ref. [2], the Mechanisms-D3, D4, D11, and D12 can be classified further into a Group that gives the Dirac neutrino

mass matrix $m_D \propto y_\ell X_{SR}^* Y^s$, where the symmetric matrix X_{SR} corresponds to the (effective) interaction between ℓ_R and $(\ell_R)^c$. The case with $X_{SR} = Y_S^s$ gives the Mechanisms-D3 and D4, and the case with $X_{SR} = (Y_\psi^+)^* M_\psi (Y_\psi^+)^\dagger$ does the Mechanisms-D11 and D12. Multiplying y_ℓ^{-1} from the left-hand side, it is expected that some of the new Yukawa interactions prefer to couple to the electron because of the hierarchical structure of y_ℓ^{-1}. Therefore, fine-tuning to suppress $\mu \to e\gamma$ might be required. Notice that the effective interaction $h\overline{\mu}e$ should also be suppressed in order to avoid its contribution to $\mu \to e\gamma$ at the loop level involving h in the loop [23,24]. On the other hand, the Mechanism-D17 is not suffered from such an enhanced interaction with the electron because the Mechanism gives $m_D \propto Y_\psi^\eta (Y_\psi^+)^\dagger Y^s$, in which y_ℓ is not involved.

In addition to $h \to \ell\ell'$, a discovery of the second scalar will make it possible to narrow down the Mechanisms. If the CP-odd Higgs boson A^0 is discovered, the Mechanisms-D3 and D11 in which Φ_2 is involved are selected as candidates for viable Mechanisms. Notice that the neutral component of η in the Mechanism-D17 is a complex scalar (not divided into CP-even and odd ones) because it has the lepton number. Existence of $SU(2)_L$-doublet η, which has no vacuum expectation value, is characteristic in the Mechanism-D17. The Mechanisms-D3 and D11 can also be supported by discovery of a singly-charged scalar (s_R^-) that dominantly decays into $\tau\overline{\nu}$, similarly to the case of the type-X THDM with a large $\tan\beta$ [39,46]. Discovery of a doubly charged scalar that decays into a pair of same-signed charged leptons[6] indicates the Mechanisms-D3 and D4.

We here give a comment on some exceptions to the discussion above when $h \to \ell\ell'$ is detected. First, some Mechanisms in Tables 1 and 2 include the second Higgs doublet field Φ_2, which can give the FCNC at the tree-level similarly to the type-III THDM [48] though we assumed the absence of that. Then, $h \to \ell\ell'$ can happen at the tree-level while $\ell \to \ell'\gamma$ can be suppressed as a loop-level process. If we accept the FCNC at the tree-level within experimental constraints, the Zee model can be consistent with the neutrino oscillation data [41]. The discovery of $A^0 \to \ell\ell'$ would indicate such cases. Since radiative mechanisms for $h \to \ell\ell'$ discussed in this letter rely on the interaction $\lambda|\Phi_1|^2|\varphi|^2$, where Φ_1 denotes the SM-like Higgs doublet, there is no $A^0 \to \ell\ell'$ with these mechanisms. Second, there can be a new Yukawa interaction of charged leptons with a charged scalar whose electric charge is 2/3 or 1/3. Their contributions to $\ell \to \ell'\gamma$ are suppressed, e.g., by a factor of m_ψ^4/m_φ^4. Such a Yukawa interaction was not taken into account in our analyses because we used only Yukawa interactions between two leptons or between a lepton and a singlet fermion ψ_R^0. Discovery of new particle associated with leptons and quarks would indicate such cases. Third, models for the neutrino mass can be extended by introducing copies of scalar fields. Then, we can utilize cancellation of their contributions to $\ell \to \ell'\gamma$. If two kinds of doubly charged scalars are discovered, such extensions would be indicated.

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[5] In the Mechanism-D17, a diagram with the chirality flip via the mass of ψ_R^0 seems to contribute to $h \to \ell\ell'$ by using the $h\eta^+ s_2^-$ interaction. However, the contribution is understood as a dimension-4 operator, and such a contribution disappears by the diagonalization of charged lepton mass matrix at the loop level (see e.g., Ref. [24]).
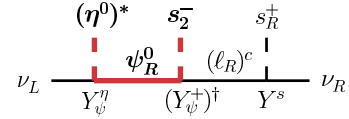
[6] Simple examples to close scalar lines for the Mechanisms-D12 and D17 are shown in Ref. [2] by additionally introducing the $SU(2)_L$-doublet scalar field with $Y = 3/2$. However, its doubly-charged component does not decay into a pair of same-sign charged leptons in the example. See also Ref. [47], where the doublet scalar field with $Y = 3/2$ is utilized to generate neutrino masses.

4. Conclusions

We have studied the LFV decay of the Higgs boson in a wide set of models for neutrino masses where new Yukawa interactions with leptons are introduced. It has been shown that the simple models for masses of Majorana neutrinos are excluded if $h \to \ell\ell'$ is discovered, because constraints from $\ell \to \ell'\gamma$ cannot be evaded in such models. However, we have also found that there are five Mechanisms (D3, D4, D11, D12 and D17 in Table 2) for masses of Dirac neutrinos which can give a significant amount of $h \to \ell\ell'$ with the suppressed $\ell \to \ell'\gamma$ process. This is because these models involve two kinds of scalar particles (s_R^+ and s^{++}, or s_R^+ and s_2^+) which couple to ℓ_R, and then their contributions to $\ell \to \ell'\gamma$ can be cancelled with each other. In these Mechanisms, Dirac neutrino masses are generated as the following two forms, $m_D \propto y_\ell X_{SR}^* Y^s$ and $Y_\psi^\eta (Y_\psi^+)^\dagger Y^s$. Therefore, future discovery of the nonzero BR($h \to \ell\ell'$) shall be a strong probe of models for neutrino masses. Further probe is possible if the second scalar (whatever it is neutral or charged) is discovered in the current and future collider experiments in addition to $h \to \ell\ell'$.

Acknowledgements

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