Lepton Flavor Violating Decays of Neutral Higgses in Extended Mirror Fermion Model

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Abstract

We perform the one-loop induced charged lepton flavor violating decays of the neutral Higgses in an extended mirror fermion model with non-sterile electroweak-scale right-handed neutrinos and a horizontal $A_4$ symmetry in the lepton sector. We demonstrate that for the 125 GeV scalar $h$ there is tension between the recent LHC result $\mathcal{B}(h \to \tau\mu) \sim 1\%$ and the stringent limits on the rare processes $\mu \to e\gamma$ and $\tau \to (\mu \text{ or } e)\gamma$ from low energy experiments.
I. MOTIVATION

As is well known, lepton and baryon number are accidental global symmetries in the fundamental Lagrangian of Standard Model (SM). Processes like $\mu \rightarrow e \gamma$, $p \rightarrow e \gamma$, etc that violating either one (or both) of these two quantum numbers are thus strictly forbidden in the perturbation calculations of SM. Experimental limits for these processes are indeed very stringent. For example, from Particle Data Group [1], we have the following bounds

$$B(\mu^- \rightarrow e^- \gamma) < 5.7 \times 10^{-13} \ (90 \% \ CL),$$

(1)

and

$$\tau(p \rightarrow e^+ \gamma) > 670 \times 10^{30} \ \text{years}.$$  

(2)

Search for lepton flavor violating (LFV) Higgs decay $h \rightarrow \tau \mu$ at hadron colliders was proposed some time ago [2]. Recently both ATLAS [3] and CMS [4] experiments at the Large Hadron Collider (LHC) have reported the following best fit branching ratios

$$B(h \rightarrow \tau \mu) = \begin{cases} 0.84^{+0.39}_{-0.37} \% \ (2.4\sigma) \ [CMS] , \\ 0.77 \pm 0.62 \% \ (1.2\sigma) \ [ATLAS] . \end{cases}$$

(3)

However, at 95% confidence level (CL), the following upper limits can be deduced

$$B(h \rightarrow \tau \mu) = \begin{cases} < 1.85 \% \ (95 \% \ CL) \ [ATLAS] , \\ < 1.51 \% \ (95 \% \ CL) \ [CMS] . \end{cases}$$

(4)

Despite low statistical significance the above best fit results in Eq. (3) are somewhat surprising since for a 125 GeV Higgs the branching ratio for this mode is about $3.6 \times 10^{-6}$ in the SM augmented by the minuscule neutrino mass terms. A positive measurement of this branching ratio in the near future at the percent level would be a clear indication of new physics beyond the SM.
On the other hand, we have stringent limits for LFV radiative decays like $\mu \to e\gamma$ in Eq. (1) as well as

$$B(\tau \to \mu \gamma) < 4.4 \times 10^{-8},$$

(5)

$$B(\tau \to e \gamma) < 3.3 \times 10^{-8},$$

(6)

both at 90% CL from the low energy data of BaBar experiment [5].

Over the years, many authors had studied the flavor changing neutral current Higgs decays $h \to f_i f_j$ in both the SM and its various extensions. For a recent updated calculation on $h \to \tau_i \tau_j$ in the SM we refer the readers to [6] and references therein. For earlier calculations for the leptonic case with large Majorana neutrino masses, see for example [7, 8]. Recently large flux of works on new physics implications for the LHC result Eq. (3) is easily noticed [9–39].

In [40], an up-to-date analysis of a previous calculation [41] of $\mu \to e\gamma$ in a class of mirror fermion models with non-sterile electroweak scale right-handed neutrinos [42] was presented for an extension of the models with a horizontal $A_4$ symmetry in the lepton sector [43]. It was demonstrated in [40] that although there exists parameter space relevant to electroweak physics to accommodate the muon magnetic dipole moment anomaly $\Delta a_\mu = 288(63)(49) \times 10^{-11}$ [1], the current low energy limit Eq. (1) on the branching ratio $B(\mu \to e\gamma)$ from MEG experiment [44] has disfavored those regions of parameter space.

In this work, we present the calculation of LFV decay of the neutral Higgses in an extended mirror fermion model. In Section 2, we briefly review the extended model and show the relevant interactions that may lead to the LFV decays of the neutral Higgses in the model. In Section 3, we present our calculation. Numerical results are given in Section 4. We conclude in Section 5. Detailed formulas for the loop amplitudes are given in the Appendix.
II. THE MODEL AND ITS RELEVANT INTERACTIONS

FIG. 1: One-loop induced Feynman diagram for $\tilde{H}_a(q) \rightarrow l_i(p) + l_j(p')$ in EW-scale $\nu_R$ model. The other two 1-particle reducible diagrams corresponding to the wave function renormalization of the external fermion lines are not shown.

In the original mirror fermion model [42], while the gauge group is the same as SM, every left-handed (right-handed) SM fermion has a right-handed (left-handed) mirror partner, and the scalar sector consists of one SM Higgs doublet $\Phi$, one singlet $\phi_0$ and two triplets $\xi$ and $\tilde{\chi}$ à la Georgi-Machacek [45, 46]. One peculiar feature of the model is that the right-handed neutrinos are non-sterile. They are paired up with right-handed mirror charged leptons to form electroweak doublets. This arrangement allows for the electroweak seesaw mechanism [42]: a small vacuum expectation value (VEV) of the scalar singlet $\phi_0S$ provides Dirac masses for the light neutrinos, while a VEV with electroweak size of the Georgi-Machacek triplets provide Majorana masses for the right-handed neutrinos.

Recently, the original model [42] is augmented with an additional mirror Higgs
doublet $\Phi_M$ in \[47\] so as to accommodate the 125 GeV Higgs observed at the LHC. In addition to the original singlet scalar $\phi_0S$, a $A_4$ triplet of scalars $\{\phi_{kS}\} (k = 1, 2, 3)$ is introduced in \[43\] to implement a horizontal $A_4$ symmetry in the lepton sector which may lead to interesting lepton mixing effects. The three generations of SM leptons are assigned to be in a triplet of $A_4$ while the SM Higgs doublet and the triplets are singlets of $A_4$.

We will consider both extensions with $A_4$ symmetry \[43\] and mirror Higgs doublet \[47\] in our calculation. The relevant Feynman diagram for LFV Higgs decay in the extended mirror model is one-loop induced and is shown in Fig. (1). The relevant interactions are all of Yukawa couplings. The first one is for the singlet $\phi_0S$ and triplet $\phi_{kS}(k = 1, 2, 3)$ \[40\]

\[
\mathcal{L}_S = - \sum_{k=0}^{3} \sum_{i,m=1}^{3} \left( \bar{l}_{Li} U^{Lk}_{im} l_{Rm}^{M} + \bar{l}_{Ri} U^{Rk}_{im} l_{Lm}^{M} \right) \phi_{kS} + \text{H.c.} \tag{7}
\]

where $l_{Li}$ and $l_{Ri}$ are SM leptons, $l_{Rm}^{M}$ and $l_{Lm}^{M}$ are mirror leptons ($i, m$ are generation indices); $U^{Lk}_{im}$ and $U^{Rk}_{im}$ are the coupling coefficients given by

\[
U^{Lk}_{im} \equiv \left( U_{PMNS}^\dagger \cdot M^k \cdot U_{PMNS}^M \right)_{im}, \tag{8}
\]

\[
U^{Rk}_{im} \equiv \left( U_{PMNS}^\dagger \cdot M'^k \cdot U_{PMNS}^M \right)_{im}, \tag{9}
\]

where the matrix elements for the four matrices $M_k^k (k = 0, 1, 2, 3)$ are listed in Table I and $M'^k_{jn}$ can be obtained from $M^k_{jn}$ with the following substitutions for the Yukawa couplings $g_{0S} \to g'_{0S}$ and $g_{1S} \to g'_{1S} \[40\]; $U_{PMNS}$ is the usual neutrino mixing matrix defined as

\[
U_{PMNS} = U_{\nu}^\dagger U_L^i, \tag{10}
\]
and its mirror and right-handed counter-parts $U^M_{PMNS}$, $U'_{PMNS}$ and $U^{M}_{PMNS}$ are defined analogously as

$$U^M_{PMNS} = U^\dagger \nu U^M_R,$$  \hspace{1cm} (11)

$$U'_{PMNS} = U^{\dagger \nu} U^L_R,$$  \hspace{1cm} (12)

and

$$U'^M_{PMNS} = U^{\dagger \nu} U^L_M,$$  \hspace{1cm} (13)

where $U^L_R$ and $U^M_L$ are the unitary matrices relating the gauge eigenstates (fields with superscripts 0) and the mass eigenstates

$$l^0_{L,R} = U^l_{L,R} l^0_{L,R}, \quad l^{M,0}_{R,L} = U^{M}_{R,L} l^{M}_{R,L},$$  \hspace{1cm} (14)

and

$$U^\nu = U^{\nu}_L = U^{\nu}_R = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix},$$  \hspace{1cm} (15)

where $\omega \equiv \exp(i2\pi/3)$ entered in the multiplication rules of $A_4$. The matrix in Eq. (15) was first discussed by Cabibbo and also by Wolfenstein in the context of CP violation in three generations of neutrino oscillations [48].

The second Yukawa interaction is for the couplings of neutral Higgses with the SM fermion pairs and the mirror fermion pairs. It was shown in [47] that the physical neutral Higgs states $(\tilde{H}_1, \tilde{H}_2, \tilde{H}_3)$ were in general mixture of the unphysical neutral Higgs states $(\tilde{H}, \tilde{H}', \tilde{H}'')$ respectively in [47].

\[1\] We note that $(\tilde{H}_1, \tilde{H}_2, \tilde{H}_3)$ was denoted as $(\tilde{H}, \tilde{H}', \tilde{H}'')$ respectively in [47].
TABLE I: Matrix elements for $M^k(k = 0, 1, 2, 3)$ where $\omega \equiv \exp(i2\pi/3)$ and $g_{0S}$ and $g_{1S}$ are Yukawa couplings.

| $M^k_{jn}$ | Value |
|------------|--------|
| $M^0_{12}, M^0_{13}, M^0_{21}, M^0_{23}, M^0_{31}, M^0_{32}$ | 0 |
| $M^0_{11}, M^0_{22}, M^0_{33}$ | $g_{0S}$ |
| $M^1_{11}, M^1_{11}, M^1_{11}$ | $\frac{2}{3} \text{Re}(g_{1S})$ |
| $M^1_{22}, M^1_{22}, M^1_{22}$ | $\frac{2}{3} \text{Re}(\omega^*g_{1S})$ |
| $M^1_{33}, M^1_{33}, M^1_{33}$ | $\frac{2}{3} \text{Re}(\omega g_{1S})$ |
| $M^1_{12}, M^1_{21}$ | $\frac{2}{3} \text{Re}(\omega g_{1S})$ |
| $M^1_{21}, M^1_{21}$ | $\frac{1}{3}(g_{1S} + \omega g_{1S}^*)$ |
| $M^2_{12}, M^2_{21}$ | $\frac{1}{3}(g_{1S}^* + \omega^*g_{1S})$ |
| $M^1_{13}, M^1_{31}$ | $\frac{2}{3} \text{Re}(\omega^*g_{1S})$ |
| $M^1_{33}, M^1_{31}$ | $\frac{1}{3}(g_{1S} + \omega^*g_{1S})$ |
| $M^1_{33}, M^1_{31}$ | $\frac{1}{3}(g_{1S}^* + \omega g_{1S})$ |
| $M^2_{13}, M^2_{31}$ | $\frac{2}{3} \text{Re}(g_{1S})$ |
| $M^2_{23}, M^2_{32}$ | $\frac{2}{3} \text{Re}(g_{1S})$ |
| $M^2_{23}, M^2_{32}$ | $\frac{2}{3} \text{Re}(g_{1S})$ |

Higgs states $(H^0_1, H^0_{1M}, H^{0\prime}_1)$ via an orthogonal transformation $O$ \cite{17}:

$$
\begin{pmatrix}
\tilde{H}_1 \\
\tilde{H}_2 \\
\tilde{H}_3
\end{pmatrix} =
\begin{pmatrix}
a_{1,1} & a_{1,1M} & a_{1,1'} \\
a_{1M,1} & a_{1M,1M} & a_{1M,1'} \\
a_{1',1} & a_{1',1M} & a_{1',1'}
\end{pmatrix}
\cdot
\begin{pmatrix}
H^0_1 \\
H^0_{1M} \\
H^{0\prime}_1
\end{pmatrix}
\equiv O \cdot
\begin{pmatrix}
H^0_1 \\
H^0_{1M} \\
H^{0\prime}_1
\end{pmatrix},
$$

(16)
where $H_1^0$ and $H_{1M}^0$ are the neutral components of the SM Higgs and mirror Higgs doublets respectively, and $H_1^{0'}$ is linear combination of the neutral components in the Georgi-Machacek triplets. The couplings of the physical Higgs $\tilde{H}_a$ with a pair of SM fermions $f$ and a pair of mirror fermions $f^M$ are given by [47]

$$L_{\tilde{H}} = -\frac{g}{2m_W} \sum_{a,f} \tilde{H}_a \left\{ m_f \frac{O_{a1}}{s_2} \bar{f} f + m_{f^M} \frac{O_{a2}}{s_{2M}} \bar{f}^M f^M \right\},$$

(17)

where $g$ is the $SU(2)_L$ weak coupling constant; $m_W$ is the $W$ boson mass; $O_{a1}$ and $O_{a2}$ are the first and second columns of the above orthogonal matrix $O$ in Eq. (16); $s_2$, $s_{2M}$ and $s_M$ are mixing angles defined by

$$s_2 = \frac{v_2}{v},$$

(18)

$$s_{2M} = \frac{v_{2M}}{v},$$

(19)

$$s_M = \frac{2\sqrt{2}v_M}{v},$$

(20)

with $v = \sqrt{v_2^2 + v_{2M}^2 + 8v_M^2} = 246$ GeV, where $v_2$, $v_{2M}$ and $v_M$ are the VEVs of the Higgs doublet, mirror Higgs doublet and Georgi-Machacek triplets respectively. For the original mirror model [42], one can simply set $\tilde{H}_1 \to H_1^0 \equiv h$, $O_{11}/s_2$ and $O_{12}/s_{2M} \to 1$, and drop all other terms with $a \neq 1$ in Eq. (17).

III. THE CALCULATION

The matrix element for the process $\tilde{H}_a(q) \to l_i(p) + l_j(p')$ (Fig. 1) can be written as

$$i\mathcal{M} = i \frac{1}{16\pi^2} \overline{u}_i(p) \left( C_{aL}^{aij} P_L + C_{aR}^{aij} P_R \right) v_j(p'),$$

(21)

where $P_{L,R} = (1 \mp \gamma_5)/2$ are the chiral projection operators. In terms of scalar and pseudoscalar couplings the above amplitude can be rewritten as

$$i\mathcal{M} = i \frac{1}{16\pi^2} \overline{u}_i(p) \left( A^{aij} + iB^{aij} \gamma_5 \right) v_j(p'),$$

(22)
where
\[ A^{aij} = \frac{1}{2} \left( C^{aij}_L + C^{aij}_R \right), \quad B^{aij} = \frac{1}{2i} \left( C^{aij}_R - C^{aij}_L \right). \] (23)

The partial decay width is given by
\[ \Gamma^{aij} = \frac{1}{211\pi^5} m_{H_a} \lambda^\frac{1}{2} \left( 1, \frac{m_i^2}{m_{H_a}^2}, \frac{m_j^2}{m_{H_a}^2} \right) \times \left[ |A^{aij}|^2 \left( 1 - \frac{(m_i + m_j)^2}{m_{H_a}^2} \right) + |B^{aij}|^2 \left( 1 - \frac{(m_i - m_j)^2}{m_{H_a}^2} \right) \right], \] (24)

where \( \lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + yz + zx) \). The one-loop induced coefficients \( A^{aij} \) and \( B^{aij} \) are related to \( C^{aij}_L \) and \( C^{aij}_R \) according to Eq. (23). The formulas for the latter are given in the Appendix.

We now comment on the divergent cancellation in the calculation. For the original mirror model [42] in which there is only one Higgs doublet with Yukawa couplings to the SM fermions and to the mirror fermions that are differ only by the corresponding fermion masses, the divergence in the one-loop diagram in Fig. (1) will cancel with those in the two 1-particle reducible diagrams associated with wave function renormalization. On the other hand, for the extended model [47] these divergences do not cancel each other. Recall that in the extended model, besides the SM Higgs doublet an additional mirror Higgs doublet was introduced. Both Higgs doublets can then couple to the SM fermions and may lead to LFV decay of the Higgses at tree level. In [42], a global \( U(1) \times U(1) \) symmetry was employed such that the SM Higgs doublet only couples to the SM fermions, while the mirror Higgs doublet only couples to the mirror fermions. Hence there will be no tree level LFV vertices for the SM Higgs decays into SM fermions. However this global symmetry is broken by a term in the scalar potential. This term also provide the Higgs mixings in Eq. (16) that eventually responsible to LFV decays of the Higgses in the extended model. Due to renormalizability, the presence of this symmetry breaking term in the scalar potential forces one to reintroduce the Yukawa terms that are forbidden by the symmetry.
Hence tree level LFV decays of the Higgses are generally present in the extended model. According to the general analysis in [39] such tree level LFV couplings are constrained to be quite small by low energy data. For our purpose, we will assume these tree level LFV couplings are vanishing small and the main reason for their existence is to provide counter terms to absorb the divergences in the calculation in the extended model. The results of $C_{\alpha \beta}^{abij}$ should then be regarded as renormalized quantities.

The amplitude for $l_i \rightarrow l_j \gamma$ in the extended model can be found in [40].

IV. NUMERICAL ANALYSIS

We will focus on the case of lightest neutral Higgs $\tilde{H}_1 \rightarrow \tau \mu$ with $\tilde{H}_1$ identified as the 125 GeV Higgs, and adopt the following strategy which has been used in [40] for the numerical analysis of $\mu \rightarrow e\gamma$:

- Two scenarios were specified according to the following forms of the three unknown mixing matrices:

Scenario 1 (S1): $U'_{PMNS} = U^M_{PMNS} = U'^M_{PMNS} = U_\nu = $ Eq. [15]

Scenario 2 (S2): $U'_{PMNS} = U^M_{PMNS} = U'^M_{PMNS} = U_{PMNS}$, where

$$U^{NH}_{PMNS} = \begin{pmatrix} 0.8221 & 0.5484 & -0.0518 + 0.1439i \\ -0.3879 + 0.07915i & 0.6432 + 0.0528i & 0.6533 \\ 0.3992 + 0.08984i & -0.5283 + 0.05993i & 0.7415 \end{pmatrix}$$
and

\[
U_{\text{PMNS}}^{\text{IH}} = \begin{pmatrix}
0.8218 & 0.5483 & -0.08708 + 0.1281i \\
-0.3608 + 0.0719i & 0.6467 + 0.04796i & 0.6664 \\
0.4278 + 0.07869i & -0.5254 + 0.0525i & 0.7293
\end{pmatrix}
\]

for the neutrino masses with normal and inverted hierarchies respectively. The Majorana phases have been ignored in the analyses. For each scenario, we consider these two possible solutions for the \( U_{\text{PMNS}} \). Due to the small differences between these two solutions, we expect our results are not too sensitive to the neutrino mass hierarchies.

• All Yukawa couplings \( g_{0S}, g_{1S}, g'_{0S} \) and \( g'_{1S} \) are assumed to be real. For simplicity, we will assume \( g_{0S} = g'_{0S}, g_{1S} = g'_{1S} \) and study the following 6 cases:

  (a) \( g_{0S} \neq 0, g_{1S} = 0 \). The \( A_4 \) triplet terms are switched off.
  (b) \( g_{1S} = 10^{-2} \times g_{0S} \). The \( A_4 \) triplet couplings are merely one percent of the singlet ones.
  (c) \( g_{1S} = 10^{-1} \times g_{0S} \). The \( A_4 \) triplet couplings are 10 percent of the singlet ones.
  (d) \( g_{1S} = 0.5 \times g_{0S} \). The \( A_4 \) triplet couplings are one half of the singlet ones.
  (e) \( g_{1S} = g_{0S} \). Both \( A_4 \) singlet and triplet terms have the same weight.
  (f) \( g_{0S} = 0, g_{1S} \neq 0 \). The \( A_4 \) singlet terms are switched off.

• For the masses of the singlet scalars \( \phi_{kS} \), we take

\[
m_{\phi_{0S}} : m_{\phi_{1S}} : m_{\phi_{2S}} : m_{\phi_{3S}} = M_S : 2M_S : 3M_S : 4M_S
\]

with a fixed common mass \( M_S = 10 \) MeV. As long as \( m_{\phi_{kS}} \ll m_{l^m} \), our results will not be affected much by this assumption.
For the masses of the mirror lepton $l^M_m$, we take
\[ m_{l^M_m} = M_{\text{mirror}} + \delta_m \]
with $\delta_1 = 0$, $\delta_2 = 10$ GeV, $\delta_3 = 20$ GeV and vary the common mass $M_{\text{mirror}}$.

As shown in [47], the 125 GeV scalar resonance $h$ discovered at the LHC identified as the lightest state $\tilde{H}_1$ can be belonged to the Dr. Jekyll scenario in which the SM Higgs doublet $H^0_1$ has a major component or the Mr. Hyde scenario in which it is an impostor with $H^0_1$ only a sub-dominant component. Of all the explicit examples found for both of these scenarios, we will study the two following cases [47]:

- Dr. Jekyll case (Eq. (50) of [47]):
\[
O = \begin{pmatrix}
0.998 & -0.0518 & -0.0329 \\
0.0514 & 0.999 & -0.0140 \\
0.0336 & 0.0123 & 0.999
\end{pmatrix}, \tag{25}
\]
with $\text{Det}(O) = +1$, $m_{\tilde{H}_1} = 125.7$ GeV, $m_{\tilde{H}_2} = 420$ GeV, $m_{\tilde{H}_3} = 601$ GeV, $s_2 = 0.92$, $s_{2M} = 0.16$ and $s_M = 0.36$. In this case,
\[
h \equiv \tilde{H}_1 \sim H^0_1, \quad \tilde{H}_2 \sim H^0_{1M}, \quad \tilde{H}_3 \sim H^0_1. \tag{26}
\]
Hence the 125 GeV Higgs identified as $\tilde{H}_1$ is composed mainly of the neutral component of the SM doublet in this scenario.

- Mr. Hyde case (Eq. (55) of [47]):
\[
O = \begin{pmatrix}
0.187 & 0.115 & 0.976 \\
0.922 & 0.321 & -0.215 \\
0.338 & -0.940 & 0.046
\end{pmatrix}, \tag{27}
\]
with $\text{Det}(O) = -1$, $m_{\tilde{H}_1} = 125.6$ GeV, $m_{\tilde{H}_2} = 454$ GeV, $m_{\tilde{H}_3} = 959$ GeV, $s_2 = 0.401$, $s_{2M} = 0.900$ and $s_M = 0.151$. In this case,

$$h \equiv \tilde{H}_1 \sim H_1^0, \quad \tilde{H}_2 \sim H_1^0, \quad \tilde{H}_3 \sim H_{1M}^0.$$  \hspace{1cm} (28)

Hence the 125 GeV Higgs identified as $\tilde{H}_1$ is an impostor in this scenario; it is mainly composed of the two neutral components in the Georgi-Machacek triplets.

In Fig. (2), we plot the contours of the branching ratios $\mathcal{B}(h \rightarrow \tau \mu) = 0.84\%$ (red), $\mathcal{B}(\mu \rightarrow e\gamma) = 5.7 \times 10^{-13}$ (black), $\mathcal{B}(\tau \rightarrow \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $\mathcal{B}(\tau \rightarrow e\gamma) = 3.3 \times 10^{-8}$ (green) on the $(\log_{10}(M_{\text{mirror}}), \log_{10}(g_{0Sor1S}))$ plane for both Scenarios 1 and 2, normal and inverted mass hierarchies and the 6 different cases of the Yukawa couplings (Figs. (2a)-(2f)) in the Dr. Jekyll scenario as specified by Eqs. (25)-(26). For the four lines with the same color (hence same process), solid and dashed lines are for Scenario 1 and 2 with normal mass hierarchy (NH) respectively, while dotted and dot-dashed lines are for Scenario 1 and 2 with inverted mass hierarchy (IH) respectively.

Figs. (3a)-(3f) are the same as Figs. (2a)-(2f) respectively but for Mr. Hyde scenario as specified by Eqs. (27)-(28).

By studying in details of all the plots in these two figures, we can deduce the following results:

- The bumps at $M_{\text{mirror}} \sim 200$ GeV at all the plots in these two figures are due to large cancellation in the amplitudes between the two one-particle reducible (wave function renormalization) diagrams and the irreducible one-loop diagram shown in Fig. (1). As a result, the Yukawa couplings have to be considerable larger in the contour lines of fixed branching ratios of the processes.
FIG. 2: Contour plots of $B(h \to \tau \mu) = 0.84\%$ (red), $B(\mu \to e\gamma) = 5.7 \times 10^{-13}$ (black), $B(\tau \to \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $B(\tau \to e\gamma) = 3.3 \times 10^{-8}$ (green) on the $(\log_{10}(M_{\text{mirror}}/\text{GeV}), \log_{10}(g_0 \text{ or } g_1 S))$ plane for the Dr. Jekyll scenario. Solid: NH, S1; Dotted: IH, S1; Dashed: NH, S2; Dot-dashed: IH, S2. See text in Sec. IV for details.
FIG. 3: Contour plots of $\mathcal{B}(h \to \tau \mu) = 0.84\%$ (red), $\mathcal{B}(\mu \to e\gamma) = 5.7 \times 10^{-13}$ (black), $\mathcal{B}(\tau \to \mu\gamma) = 4.4 \times 10^{-8}$ (blue) and $\mathcal{B}(\tau \to e\gamma) = 3.3 \times 10^{-8}$ (green) on the 
$(\log_{10}(M_{\text{mirror}}/\text{GeV}), \log_{10}(g_0 S_{\text{or} 1S}))$ plane for the Mr. Hyde scenario. Solid: NH, S1; 
Dotted: IH, S1; Dashed: NH, S2; Dot-dashed: IH, S2. See text in Sec. IV for details.
• For the two processes $\tau \rightarrow \mu \gamma$ (blue lines) and $\tau \rightarrow e \gamma$ (green lines) in all these plots, the solid and dotted lines are coincide to each other while the dashed and dot-dashed lines are very close together. Thus there are essentially no differences between the normal and inverted mass hierarchies in both Scenarios 1 and 2 in these two processes. However, for the process $\mu \rightarrow e \gamma$ (black lines), only the solid and dotted lines are coincide to each other. Thus there are some differences between normal and inverted mass hierarchies in Scenario 2 but not in Scenario 1 for this process, in particular for cases (a)-(d) in which $g_{1S} \leq 0.5 g_{0S}$.

• For $h \rightarrow \tau \mu$ (red lines), the solid (dashed) and dotted (dot-dashed) lines are either very close (in Fig. (2) for Dr. Jekyll scenario) or mostly coincide (in Fig. (3) for Mr. Hyde scenario).

• Note that the regions to the right side of the black, blue and green lines in all the plots in these two figures are excluded by the low energy limits of $B(\mu \rightarrow e \gamma)$, $B(\tau \rightarrow \mu \gamma)$ and $B(\tau \rightarrow e \gamma)$ respectively. The CMS result of $B(h \rightarrow \tau \mu) = 0.84\%$ (red lines), if not due to statistical fluctuations, is compatible with these low energy limits only if there are intersection points of the red lines with the corresponding black, blue and green lines.

Take Fig. (2a) as an example. For case of Dr. Jekyll and in Scenario 1, the solid (or dotted) red line intersects with the solid (or dotted) blue and green lines at $M_{\text{mirror}} \sim 4.47$ TeV where $g_{0S} \sim 0.0676$. In Scenario 2, the dashed (or dot-dashed) red line intersects the dashed (or dot-dashed) blue or green lines at $M_{\text{mirror}} \sim 3.55$ TeV with a considerable larger $g_{0S} \sim 5.01$. For the black lines from the most stringent limit of $\mu \rightarrow e \gamma$, their intersections with the red lines are well beyond 10 TeV for the mirror lepton masses. Similar statements can be obtained from the other plots in these two figures. From
TABLE II: The lower (upper) limit of mirror fermion masses (couplings).

| Mode       | Quantity | Scenario 1 | Scenario 2 |
|------------|----------|------------|------------|
|            |          | Dr. Jekyll | Mr. Hyde   | Dr. Jekyll | Mr. Hyde   |
| $\tau \rightarrow (\mu, e)\gamma$ | Mass (TeV) | 4.47       | 7.08       | 3.55       | 7.08       |
|            | $g_{0S}(g_{1S})$ | 0.07       | 0.09       | 5.01       | 6.76       |
| $\mu \rightarrow e\gamma$ | Mass (TeV) | $\sim 100$ | $> 10^{2.5}$ | $\sim 95$ | $> 10^{2.5}$ |
|            | $g_{0S}(g_{1S})$ | $10^{-2.6}$ | $10^{-2.1}$ | 0.16       | 0.40       |

these intersections in these figures, one can deduce the lower (upper) limits of the mirror fermion masses (couplings) which we summarize in Table II. Such a large mirror lepton mass $M_{\text{mirror}}$ or coupling $g_{0S}$ indicates a break down of the perturbative calculation and/or violation of unitarity. However taking what we have literally there is tension between the large branching ratio $B(h \rightarrow \tau\mu)$ from LHC and the low energy limits of $B(\tau \rightarrow (\mu, e)\gamma)$ and $B(\mu \rightarrow e\gamma)$, in particular the latter one.

- In the event that the CMS result in Eq. (3) is just a statistical fluctuation, the limits in Eq. (4) will be improved further in LHC Run 2. The contour lines of these future limits would be located to the left side of the current red lines in the two Figs. (2) and (3). Their intersections with the black, blue and green lines would then be at lower mirror lepton masses and smaller Yukawa couplings, since the low energy limits of the LFV decays $l_i \rightarrow l_j \gamma$ are unlikely to be changed significantly anytime soon. Certainly this would alleviate the tension mentioned above.
V. CONCLUSION

To summarize, CMS has reported excess in the charged lepton flavor violating Higgs decay $h \rightarrow \tau \mu$ at 2.4$\sigma$ level. More data is needed to collect at Run 2 so as to confirm whether these are indeed true signals or simply statistical fluctuations.

If the branching ratio of $h \rightarrow \tau \mu$ is indeed at the percent level, new physics associated with lepton flavor violation may be at a scale not too far from the electroweak scale. Crucial question is whether this large branching ratio of $h \rightarrow \tau \mu$ is compatible with the current low energy limits of $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow e \gamma$ from Belle experiments and the most stringent limit of $\mu \rightarrow \gamma$ from MEG experiment.

We analyze these lepton flavor violating processes in the context of an extended mirror fermion model with non-sterile electroweak scale right-handed neutrinos as well as a horizontal $A_4$ symmetry imposed on the lepton sector. We found that the masses of the mirror lepton fermions entering the loops of these processes can be of the order of a few hundred GeV to a few TeV depending on the sizes of the Yukawa couplings among the leptons, mirror leptons and the scalar singlets in the model as well as whether or not the 125 GeV scalar boson is a Higgs impostor and which scenario one assumes for the three unknown PMNS-type mixing matrices. We demonstrate that in general there is tension between the LHC result and the low energy limits since these results are compatible only if the mirror lepton masses are quite heavy and/or the Yukawa couplings involving the scalar singlets are large.

Before we depart, we comment on the possible collider signals for the mirror fermions [49]. Mirror leptons if not too heavy can be produced at the LHC via electroweak processes [42], e.g. $q\bar{q} \rightarrow Z \rightarrow l_R^M l_R^M$, $\nu_R \bar{\nu}_R$ and $q\bar{q}' \rightarrow W^{\pm} \rightarrow l_R^M \bar{\nu}_R, \nu_R l_R^M$. The mirror lepton decays as $l_R^M \rightarrow l_L + \phi_S$ or $l_R^M \rightarrow \nu_R + W^{-\ast}$ for $m_{l_R}^M > m_{\nu_R}$ plus the conjugate processes, while the right-handed neutrino can decay as $\nu_R \rightarrow l_L + \phi_S$ or $\nu_R \rightarrow l_R^M + W^{\ast}$ for $m_{\nu_R} > m_{l_R}^M$ followed by $l_R^M \rightarrow l_L + \phi_S$. If kinematics allowed,
the scalar singlet $\phi_S$ can decay into lepton pair as well through mixings; otherwise they would appear as missing energies like neutrinos. Thus the signals at the LHC or future 100 TeV SPPC would be multiple lepton pairs plus missing energies. In the case where the right-handed neutrinos are Majorana fermions, we would have same sign dilepton plus missing energies. Assuming $l_R^M \rightarrow l_L + \phi_S$ is the dominant mode and the Yukawa couplings are small enough, the decay length of the mirror lepton could be as large as a few millimeter $^{49}$. Thus the mirror lepton may lead to a displaced vertex and decay outside the beam pipe. These leptonic final states may have been discarded by the current algorithms adopted by the LHC experiments. It is therefore quite important for the experimentalists to devise new algorithms to search for these mirror fermions that may decay outside the beam pipe.

The scale of new physics may be hidden in the lepton flavor violating processes like $h \rightarrow \tau(\mu, e)$, $\tau \rightarrow (\mu, e)\gamma$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu-e$ conversion etc. Ongoing and future experiments at high energy and high intensity frontiers could shed light in the mirror fermion model that may responsible to these lepton flavor violating processes.

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APPENDIX

The dimensionless coefficients $C_{L}^{aij}$ and $C_{R}^{aij}$ defined in Eq. (22) are given by

$$C_{L}^{aij} = \frac{g_{O_{a1}}}{2s_{2}m_{W}(m_{i}^{2} - m_{j}^{2})} \sum_{k,m} \int_{0}^{1} dx \left\{ (1 - x) \left( m_{i}m_{j}^{2}U_{im}^{Lk} (U_{mj}^{Lk})^{*} + m_{j}m_{i}^{2}U_{im}^{Rk} (U_{mj}^{Rk})^{*} \right) \\
+ m_{i}m_{j}M_{m}U_{im}^{Lk} (U_{mj}^{Rk})^{*} \right\} \log \left( \frac{\Delta_{1}}{\Delta_{2}} \right) + M_{m}U_{im}^{Rk} (U_{mj}^{Rk})^{*} \left( m_{i}^{2} \log \Delta_{1} - m_{j}^{2} \log \Delta_{2} \right) \\
+ \frac{g_{O_{a2}}}{2s_{2}m_{W}} \sum_{k,m} M_{m}U_{im}^{Rk} (U_{mj}^{Lk})^{*} \left( \frac{1}{2} - 2 \int_{0}^{1} dx \int_{0}^{1-x} dy \log \Delta_{3} \right) \\
+ (1 - 2x) \frac{m_{i}M_{m}}{m_{i}^{2}H_{a}} U_{im}^{Rk} (U_{mj}^{Lk})^{*} + (1 - x - y) \frac{m_{j}m_{i}}{m_{j}^{2}H_{a}} U_{im}^{Rk} (U_{mj}^{Rk})^{*} \\
- [xy + (1 - x - y)(yr_{i} + xr_{j}) - r_{m}] U_{im}^{Rk} (U_{mj}^{Lk})^{*} \right\},$$

(29)

$C_{R}^{aij}$ can be obtained from $C_{L}^{aij}$ simply by substituting $U^{L} \leftrightarrow U^{R}$, namely

$$C_{R}^{aij} = \frac{g_{O_{a1}}}{2s_{2}m_{W}(m_{i}^{2} - m_{j}^{2})} \sum_{k,m} \int_{0}^{1} dx \left\{ (1 - x) \left( m_{i}m_{j}^{2}U_{im}^{Rk} (U_{mj}^{Rk})^{*} + m_{j}m_{i}^{2}U_{im}^{Lk} (U_{mj}^{Lk})^{*} \right) \\
+ m_{i}m_{j}M_{m}U_{im}^{Rk} (U_{mj}^{Lk})^{*} \right\} \log \left( \frac{\Delta_{1}}{\Delta_{2}} \right) + M_{m}U_{im}^{Lk} (U_{mj}^{Lk})^{*} \left( m_{i}^{2} \log \Delta_{1} - m_{j}^{2} \log \Delta_{2} \right) \\
+ \frac{g_{O_{a2}}}{2s_{2}m_{W}} \sum_{k,m} M_{m}U_{im}^{Lk} (U_{mj}^{Rk})^{*} \left( \frac{1}{2} - 2 \int_{0}^{1} dx \int_{0}^{1-x} dy \log \Delta_{3} \right) \\
+ (1 - 2x) \frac{m_{i}M_{m}}{m_{i}^{2}H_{a}} U_{im}^{Lk} (U_{mj}^{Rk})^{*} + (1 - x - y) \frac{m_{j}m_{i}}{m_{j}^{2}H_{a}} U_{im}^{Lk} (U_{mj}^{Lk})^{*} \\
- [xy + (1 - x - y)(yr_{i} + xr_{j}) - r_{m}] U_{im}^{Lk} (U_{mj}^{Rk})^{*} \right\}.$$
The $\Delta_1$, $\Delta_2$ and $\Delta_3$ are given by

$$\Delta_1 = x r_m + (1 - x) r_k - x (1 - x) r_j - i 0^+,$$

$$\Delta_2 = x r_m + (1 - x) r_k - x (1 - x) r_i - i 0^+,$$

$$\Delta_3 = (x + y) r_m + (1 - x - y) (r_k - y r_i - x r_j) - x y - i 0^+.$$

Here $r_m = M_m^2/m_{H_a}^2$, $r_{i,j} = m_{i,j}^2/m_{H_a}^2$ and $r_k = m_k^2/m_{H_a}^2$ with $M_m$, $m_{i,j}$ and $m_k$ denoting the masses of the mirror leptons, leptons and scalar singlets respectively.

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