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Lepton flavor violation in the little Higgs model with T parity

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Little Higgs models with T-parity may provide us with a new source of lepton flavor violation, as such, in this paper we consider the anomalous magnetic moment of the muon $(g-2)_\mu$ and the lepton flavor violating decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ in the little Higgs model with T-parity [A. Goyal, hep-ph/0609095.]. Our results show that the present experimental constraints of $\mu \to e\gamma$ are a much more useful tool for constraining the new sources of flavor violation, than from the other processes considered here, which are present in T-parity models.

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I. INTRODUCTION

Electroweak precision data suggests that the physics of electroweak symmetry breaking is weakly coupled, therefore, in order to have a natural theory, the Higgs mass needs to be protected from radiative corrections. As a means to solve this problem a number of extensions to the standard model (SM) have been proposed, where in the effective theory approach the collective symmetry breaking mechanism of little Higgs (LH) models is an interesting possibility [1]. For earlier attempts to solve these issues see Ref. [2]. A detailed review of LH models can be found in Ref. [3] (see also chapter 7 of Ref. [4]). As the electroweak sector of the SM has been tested to a very high accuracy an important test of the validity of LH models is through a comparison with precision data (for reviews treating this subject see Refs. [5,6]). There also exists many studies in the literature concerning the LH model and its implications to electroweak corrections (see, for example, Ref. [7]) and flavor physics both in the hadronic [8] and leptonic sector [9].

Generic to the structure of LH models is the presence of a global symmetry which is broken at a scale f. The smallness of the electroweak scale in these models is ensured by identifying the Higgs with the pseudo-Goldstone bosons of the global symmetry. The new gauge bosons and partners of the SM top quark, with masses of order f, were then introduced to cancel the one-loop quadratic corrections to the Higgs mass from SM particles. One of the most popular implementations of the little Higgs mechanism is known as the ‘‘littlest Higgs model.’’ In this model, in addition to the SM particles, new charged gauge bosons ($W_H^\pm$) and neutral gauge bosons (Z_H, A_H), heavy top quark (T) and a triplet of heavy scalars (Φ) are present. The ‘‘littlest Higgs model’’ has a SU(5) global symmetry which is broken to a SO(5) at the scale f. Note that in the original ‘‘littlest Higgs’’ model there was a problem regarding the breaking of custodial SU(2) symmetry resulting in severe constraints on these models from electroweak precision (EWP) measurements. As such, the scale f was forced into being raised substantially, resulting in the fine-tuning of the Higgs boson mass being reintroduced. Note that the main source of this problem was due to the tree-level contributions of the new heavy particles to the EWP observables.

From the attempts to resolve this problem several new variations of the original ‘‘littlest Higgs’’ model were proposed [10]. These new variations had much larger symmetry structures which respected the custodial SU(2) symmetry, and hence were able to withstand the EWP constraints. Another very interesting approach is the implementation of a Z_2 symmetry called T-parity [11], where T-parity explicitly forbids tree-level contributions from the new heavy gauge bosons to an observable involving only SM particles as external states. It also forbids the interactions that induce triplet vev contributions. In T-parity symmetric LH models (LHT), corrections to precision electroweak observable are generated exclusively at loop level. As a result of the introduction of T-parity the new physics scale f in T-parity models can be significantly lowered to less than a TeV. Because of T-parity the lightest T-odd particle also becomes stable. Note that since this lightest T-odd particle is electrically and color neutral and of $\mathcal{O}(100)$ GeV, it could be a candidate for dark matter [12].

LHT predict heavy T-odd gauge bosons which are the T-partners of the SM gauge boson and also heavy T-odd SU(2) doublet fermions. This structure is unique to LHT, and as the new particle masses can be relatively low the next generation of colliders, such as the Large Hadron Collider (LHC), has the potential to directly produce the T-partners of the SM particles [13]. The peculiar structure

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of these models can also be tested using precision data, from present and future colliders [14], in particular, the flavor structure of the model can be constrained both in the quark sector [15,16] and in the lepton sector [17].

Furthermore, the neutrino oscillation data from experiments demonstrates the existence of small neutrino masses and large neutrino flavor mixing. If the small neutrino mass, as hinted by experiments, is the only source of lepton flavor violation (LFV), then the LFV processes like $\mu \to e\gamma$, $\tau \to \mu\mu\mu$ etc. would be heavily suppressed by the lepton sector Glashow-Iliopoulos-Maiani (GIM) mechanism. However, the presence of new sources of LFV could enhance these processes to the level of present experimental limits, where LHT provide such a possible source. In the following we shall concentrate on the mirror lepton sector, and on the interplay with the heavy T-odd gauge boson sector of the LHT by studying the anomalous magnetic moment of the muon $(g-2)_\mu$ and the lepton flavor violating decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$.

II. LITTLEST HIGGS MODEL WITH T-PARITY

In this section we shall briefly review the Littlest Higgs model with T-parity of Ref. [11] in order to present our notation. We follow here, for the leptons, a notation similar to the one used by Buras *et al.* [15,16] in the analysis of nonminimal flavor violating interactions in the quark sector for LHT, where the model is a nonlinear chiral-type Lagrangian based on the coset SU(5)/SO(5).

The first stage of symmetry breaking is at a scale f in the TeV range, and is due to the vacuum expectation value (vev) of an SU(5) symmetric matrix Σ, that is

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & \mathbb{1} \\ 0 & 1 & 0 \\ \mathbb{1} & 0 & 0 \end{pmatrix}, \tag{1}$$

where $\mathbb{1}$ is the 2×2 identity matrix. This breaking simultaneously breaks the gauge group to a $SU(2) \times U(1)$ subgroup, which is identified with the SM group. The origin of this symmetry breaking is not specified in the model but merely imposed. Therefore LHT are effective theories, valid up to a scale $\Lambda \sim 4\pi f$, as can be established in analogy with similar arguments in chiral Lagrangians. The generators, T^a, of the unbroken SO(5) symmetry, are those which satisfy the relation $T^a\Sigma_0 + \Sigma_0(T^a)^T = 0$. The broken generators, X^a, of SU(5)/SO(5) satisfy the relation $X^a\Sigma_0 - \Sigma_0(X^a)^T = 0$. The SU(5)/SO(5) breaking gives rise to 14 Nambu-Goldstone bosons; four of the 14 Goldstone bosons are absorbed by the broken gauge generators, and the remaining ten Goldstones are parametrized as

$$\Pi = \begin{pmatrix} & h^\dagger/\sqrt{2} & \Phi^\dagger \\ h/\sqrt{2} & & h^*/\sqrt{2} \\ \Phi & h^T/\sqrt{2} & \end{pmatrix}, \tag{2}$$

where h is the SM Higgs doublet and Φ is a complex SU(2) triplet:

$$\Phi = \begin{pmatrix} \Phi^{++} & \Phi^{+}/\sqrt{2} \\ \Phi^{+}/\sqrt{2} & \Phi^0 \end{pmatrix}. \tag{3}$$

The second stage of symmetry breaking takes place as in the SM via the usual Higgs mechanism, at a scale $v = 256$ GeV.

The effective theory at low energy is described by a chiral-type Lagrangian with the appropriate gauging (a $[SU(2) \times U(1)]^2$ subgroup of the global SU(5) symmetry is gauged). T-parity exchanges the two $SU(2) \times U(1)$ factors. The symmetric tensor describing the low energy theory is

$$\Sigma = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0 = \Sigma_0 + \frac{2i}{f}\Pi\Sigma_0 + \mathcal{O}(1/f^2), \tag{4}$$

where f is the scale of symmetry breaking we have just described; similar to f_π in the case of chiral Lagrangians. The kinetic term for the Σ field can be written as

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\,\mathrm{Tr}\{D_\mu\Sigma(D^\mu\Sigma)^\dagger\}, \tag{5}$$

where

$$D_\mu\Sigma = \partial_\mu\Sigma - i\Sigma_j[g_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) + g'_j B_j(Y_j\Sigma + \Sigma Y_j)]. \tag{6}$$

In the above $j = 1, 2$, the Q_j and Y_j are the gauged generators, B_j and W_j^a are the $U(1)_j$ and $SU(2)_j$ gauge fields, respectively, and g_j and g'_j are the corresponding coupling constants.

A. Gauge bosons sector

In the gauge boson sector the gauge boson eigenstates are identified as

$$W_L^a = \frac{W_1^a + W_2^a}{\sqrt{2}}, \qquad B_L = \frac{B_1 + B_2}{\sqrt{2}}, \tag{7}$$

$$W_H^a = \frac{W_1^a - W_2^a}{\sqrt{2}}, \qquad B_H = \frac{B_1 - B_2}{\sqrt{2}}, \tag{8}$$

where L refers to the light (and T-even) states and H the heavy (and T-odd) states. The mass eigenstates are then given, at $\mathcal{O}(v^2/f^2)$, by the following combinations of gauge boson eigenstates:

$$W_L^\pm = \frac{W_L^1 \mp iW_L^2}{\sqrt{2}}, \qquad Z_L = \cos\theta_W W_L^3 - \sin\theta_W B_L, \qquad A_L = \sin\theta_W W_L^3 + \cos\theta_W B_L, \tag{9}$$

$$W_H^{\pm} = \frac{W_H^1 \mp iW_H^2}{\sqrt{2}}, \qquad Z_H = W_H^3 + x_H \frac{v^2}{f^2} B_H,$$
$$A_H = -x_H \frac{v^2}{f^2} W_H^3 + B_H, \tag{10}$$

where θ_W is the weak mixing angle and $x_H = 5gg'/4(5g^2 - g'^2)$ with g and g' being, respectively, the SU(2) and U(1) gauge couplings. The gauge boson masses are then given at $\mathcal{O}(v^2/f^2)$ by

$$M_{W_H} = fg\left(1 - \frac{v^2}{8f^2}\right), \qquad M_{Z_H} \equiv M_{W_H},$$
$$M_{A_H} = \frac{fg'}{\sqrt{5}}\left(1 - \frac{5v^2}{8f^2}\right). \tag{11}$$

The masses of the T-even gauge bosons are zero after the first stage of symmetry breaking and obtain a mass only through the second breaking, their masses being

$$M_{W_L} = \frac{gv}{2}\left(1 - \frac{v^2}{12f^2}\right), \qquad M_{Z_L} = \frac{gv}{2\cos\theta_W}\left(1 - \frac{v^2}{12f^2}\right),$$
$$M_{A_L} = 0. \tag{12}$$

B. Mirror fermion sector and mixing

For each SM $SU(2)_L$ doublet, a doublet under $SU(2)_1$ and another under $SU(2)_2$ are introduced. The T-parity even linear combination is associated with the SM $SU(2)_L$ doublet, while the T-odd combination is given a mass of order the scale f. This being required for a consistent implementation of T-parity in the fermion sector [11]. The fermion doublets are embedded into the incomplete representations of SU(5) (Ψ_1, Ψ_2) and an additional T-odd SO(5) multiplet Ψ_R is introduced as

$$\Psi_1 = \begin{pmatrix} i\psi_1 \\ 0 \\ 0 \end{pmatrix}, \qquad \Psi_2 = \begin{pmatrix} 0 \\ 0 \\ i\psi_2 \end{pmatrix}, \qquad \Psi_R = \begin{pmatrix} \tilde{\psi}_R \\ \chi_R \\ \psi_R \end{pmatrix}, \tag{13}$$

with

$$\psi_i = -\sigma^2 f_i = -\sigma^2 \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \qquad \psi_R = -i\sigma^2 \begin{pmatrix} u_{HR} \\ d_{HR} \end{pmatrix} \tag{14}$$

and $i = 1, 2$. Under T-parity these fields transform in the following way:

$$\Psi_1 \mapsto -\Sigma_0 \Psi_2, \qquad \Psi_2 \mapsto -\Sigma_0 \Psi_1, \qquad \Psi_R \mapsto -\Psi_R, \tag{15}$$

and the T-parity eigenstates of the fermion doublets are

$$f_L = \frac{f_1 - f_2}{\sqrt{2}}, \qquad f_H = \frac{f_1 + f_2}{\sqrt{2}}. \tag{16}$$

f_L are the left-handed SM fermion doublets (T-even), and f_H are the left-handed mirror fermion doublets (T-odd). Where the right-handed mirror fermion doublet is given by ψ_R. The mirror fermions acquire mass through the Yukawa interaction:

$$\kappa_{ij} f(\bar{\Psi}_2^i \xi \Psi_R^j + \bar{\Psi}_1^i \Sigma_0 \Omega \xi^\dagger \Omega \Psi_R^j) + \text{H.c.} \tag{17}$$

where $\xi = e^{i\Pi/f}$. Before electroweak symmetry breaking (EWSB) the T-odd fermions (heavy fermions) acquire mass $\sim\sqrt{2}\kappa_i f$, while after EWSB small mass splitting is introduced between T-odd up and down type quarks [13]:

$$m_{Hi}^d = \sqrt{2}\kappa_i f \equiv m_{Hi}, \tag{18}$$

$$m_{Hi}^u = \sqrt{2}\kappa_i f\left(1 - \frac{v^2}{8f^2}\right) = m_{Hi}\left(1 - \frac{v^2}{8f^2}\right), \tag{19}$$

where κ_i are the eigenvalues of the mass matrix κ. The additional fermions $\tilde{\psi}_R$ and χ_R can be given large Dirac masses, and we assume that they are decoupled from the theory. From the above equation we can see that, to a good approximation, the masses of up and down type T-odd fermions are the same.

In a similar way to what happens for standard fermions, the mirror sector has weak mixing, parametrized by unitary mixing matrices; two for mirror leptons and two for mirror quarks:

$$V_{H\ell}, \qquad V_{H\nu}, \qquad V_{Hu}, \qquad V_{Hd}, \tag{20}$$

which are related to the well-known quark CKM matrix V_{CKM} and its corresponding analog for leptons V_{PMNS} by the relations:

$$V_{H\nu}^\dagger V_{H\ell} = V_{\text{PMNS}}, \qquad V_{Hu}^\dagger V_{Hd} = V_{\text{CKM}}. \tag{21}$$

Furthermore, this implies that one can not turn off the new mixing effects, except with a universal degenerate mass spectrum for the T-odd doublets. In our analysis we assume all the particles to be Dirac and hence the V_{PMNS}[1] matrix can be parametrized by four parameters (three mixing angles and one phase). The mixing in the lepton sector will be the main focus of our phenomenological analysis, where a detailed discussion of the parametrization of the mirror lepton mixing matrices is given in Sec. IV.

III. ANALYTICAL RESULTS OF $(g-2)_\mu$ AND $\mu \to e\gamma$

In this section we shall summarize our analytic results for the anomalous magnetic moment of the muon $(g-2)_\mu$ and the two lepton flavor violating decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ from the Littlest Higgs model with T-parity.

[1]The V_{PMNS} matrix is the usual Pontecorvo-Maki-Nakagawa-Sakata matrix [18].

A. Anomalous magnetic moment of the muon

For the $(g-2)_\mu$ we have, in addition to SM contribution, the following additional contributions in LHT model:

(i) The $W_H^\pm$ contribution.
(ii) The Z_H contribution.
(iii) The A_H contribution.
(iv) And the Φ (triplet Higgs) contribution.

As such, the additional diagrams which will contribute to $(g-2)_\mu$ (at one-loop level) are given in Fig. 1, and where the contribution to the a_μ due to the new particles can be written as

$$a_\mu^{LH} = a_\mu(W_H) + a_\mu(A_H) + a_\mu(Z_H) + a_\mu(\Phi). \quad (22)$$

Note that the contributions due to triplet Higgs (Φ) can be neglected, as their coupling to SM fermions and T-odd fermions is of order $(v/f)^2$ (see Appendix A of Ref. [15]). As such, Figs. 1(c) and 1(d) will give contributions at the $(v/f)^4$ level (as these diagrams have two vertices involving the triplet Higgs). In order $(v/f)^2$ calculations we can therefore neglect any such contributions. This means we shall only consider contributions due to heavy gauge bosons given by Figs. 1(a) and 1(b).

The various contributions due to gauge bosons in the unitary gauge are

$$a_\mu(W_H) = -\frac{g^2}{32\pi^2}\frac{m_\mu^2}{M_{W_H}^2}\sum_{i=1,3}(V_{H\ell})_{i2}^*(V_{H\ell})_{i2}F_{W_H}(x_i),$$
$$\text{where } x_i = \left(\frac{M_{\nu_{H_i}}}{M_{W_H}}\right)^2, \quad (23)$$

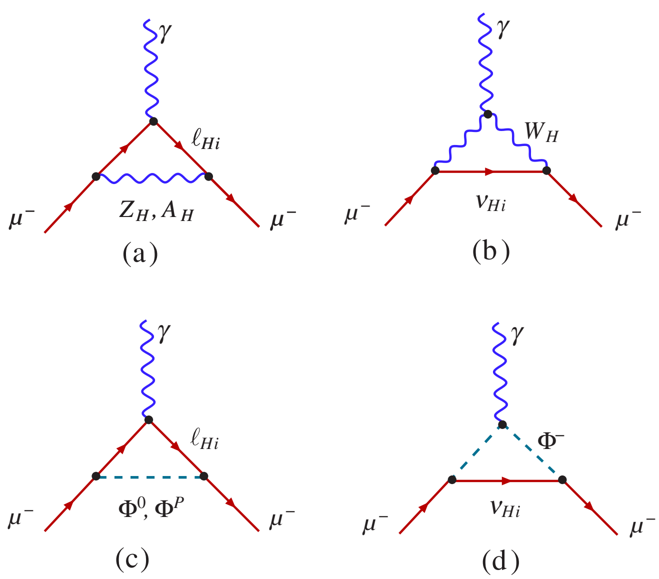

FIG. 1 (color online). Diagrams of the additional contributions to the $(g-2)_\mu$ arising from LHT.

$$a_\mu(Z_H) = \frac{g^2}{32\pi^2}\frac{m_\mu^2}{M_{Z_H}^2}\sum_{i=1,3}(V_{H\ell})_{i2}^*(V_{H\ell})_{i2}F_{Z_H}(y_i),$$
$$\text{where } y_i = \left(\frac{M_{\ell_{H_i}}}{M_{Z_H}}\right)^2, \quad (24)$$

$$a_\mu(A_H) = \frac{g'^2}{800\pi^2}\frac{m_\mu^2}{M_{A_H}^2}\sum_{i=1,3}(V_{H\ell})_{i2}^*(V_{H\ell})_{i2}F_{Z_H}(z_i),$$
$$\text{where } z_i = \left(\frac{M_{\ell_{H_i}}}{M_{A_H}}\right)^2, \quad (25)$$

and where the functions $F_X(x)$ have been defined in Appendix B.

In the next section we shall generate plots of a_μ^{LH} for various values of f and mirror lepton masses.

B. Lepton flavor violating decays

We shall now consider the lepton flavor violating decays of the form $f_1(p_1) \to f_2(p_2)\gamma(q)$, with $q = p_1 - p_2$. In these calculations we shall take the fermions f_1 and f_2 as having masses m_1 and m_2 respectively. As the external fermions are on mass shell, we also have that $p_1^2 = m_1^2$, $p_2^2 = m_2^2$. As such, the amplitude for the decay can be written as $e\epsilon_\mu^*(q)\mathcal{M}^\mu$, where $\epsilon_\mu^*(q)$ is the polarization vector of the emitted photon. The most general $\mathcal{M}^\mu$ for an on-shell photon[2] can be written as [19]

$$\mathcal{M}^\mu = i\bar{u}_2[\sigma^{\mu\nu}q_\nu(\sigma_L P_L + \sigma_R P_R)]u_1, \quad (26)$$

where $P_L = (1-\gamma_5)/2$, $P_R = (1+\gamma_5)/2$ and σ_L, σ_R are the respective coefficients. From the expression given in Eq. (26) we obtain the partial decay width for $f_1 \to f_2\gamma$ as[3]:

$$\Gamma = \frac{(m_1^2 - m_2^2)^3}{16\pi m_1^3}(|\sigma_L|^2 + |\sigma_R|^2). \quad (27)$$

Assuming the fermions f_1 and f_2 interact with a neutral or charged vector boson, B_α, and with another fermion F, the gauge interaction part of the Lagrangian can be written as

$$\mathcal{L} = \sum_{i=1}^{2}[B_\mu\bar{F}\gamma^\mu(L_iP_L + R_iP_R)f_i + B_\mu^*\bar{f}_i\gamma^\mu(L_i^*P_L + R_i^*P_R)F], \quad (28)$$

where L_i and R_i are coefficients of the operators (model dependent). In our case (LHT), from Table I in Appendix A, we can see that we do not have any right-handed currents contributing to the process. As such, $R_i = 0$. Equation (28) then becomes, for our case,

[2]By an on-shell photon we mean $\epsilon_\mu^*(q)q^\mu = 0$.
[3]In our numerical analysis we have not included the suppression factor of ~15% which arises from the electromagnetic corrections [20].

TABLE I. Where $x_H = 5gg'/4(5g^2 - g'^2)$.

Particles	Vertices	Particles	Vertices
$\bar{\ell}_i W_L^{-\mu} \nu_j$	$i\frac{g}{\sqrt{2}}(V_{\rm PMNS})_{ij} P_L$	$\bar{\nu}_{H_i} W_H^{+\mu} \ell_j$	$i\frac{g}{\sqrt{2}}(V_{H\ell})_{ij} P_L$
$\bar{\ell}_i Z_L^{\mu} \ell_j$	$\frac{ig}{\cos\theta_w}\gamma^\mu[(-\frac{1}{2} + \sin^2\theta_w)P_L + \sin^2\theta_w P_R]\delta_{ij}$	$\bar{\ell}_{H_i} Z_H^{\mu} \ell_j$	$i(-\frac{g}{2} + \frac{g'}{10} x_H \frac{v^2}{f^2})(V_{H_\ell})_{ij}\gamma^\mu P_L$
$\bar{\ell}_i A_L^{\mu} \ell_j$	$-ig'\gamma^\mu \delta_{ij}$	$\bar{\ell}_{H_i} A_H^{\mu} \ell_j$	$i(\frac{g'}{10} + \frac{g'}{10} x_H \frac{v^2}{f^2})(V_{H_\ell})_{ij}\gamma^\mu P_L$

$$\mathcal{L} = \sum_{i=1}^{2}[B_\mu \bar{F}\gamma^\mu L_i P_L f_i + B_\mu^* \bar{f}_i \gamma^\mu L_i^* P_L F]. \tag{29}$$

In the LH model we will also have contributions from loops containing mirror fermions, W_H, Z_H and A_H, as shown in Fig. 2. Their contributions to σ_L and σ_R [as defined in Eq. (26)] can be defined as[4]:

$$\begin{aligned} \sigma_L &= (\sigma_L)_{W_H} + (\sigma_L)_{Z_H} + (\sigma_L)_{A_H}, \\ \sigma_R &= (\sigma_R)_{W_H} + (\sigma_R)_{Z_H} + (\sigma_R)_{A_H}. \end{aligned} \tag{30}$$

Where the expressions for the σ's above are given in Appendix C. However, as one final note, in our case (with T-parity) Eq. (28) can be expressed as, using the vertices given in Table I:

$$\begin{aligned} \mathcal{L} = {}& \frac{ig}{\sqrt{2}}\sum_{ij}\bar{\nu}_{H_i}\gamma_\mu P_L (V_{H\ell})_{ij}\ell_j W_H^\mu + i\Big(-\frac{g}{\sqrt{2}} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big) \\ & \times \sum_{ij}\bar{\ell}_{H_i}\gamma_\mu P_L (V_{H\ell})_{ij}\ell_j Z_H^\mu + i\Big(\frac{g'}{10} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big) \\ & \times \sum_{ij}\bar{\ell}_{H_i}\gamma_\mu P_L (V_{H\ell})_{ij}\ell_j A_H^\mu + \mathcal{O}\Big(\frac{v^4}{f^4}\Big). \end{aligned} \tag{31}$$

In the next section we shall study how the branching ratios for the decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ change for different values of the parameter f, and for various mirror lepton masses.

IV. NUMERICAL ANALYSIS AND DISCUSSION

Before presenting our numerical analysis we would like to point out that though we can have no direct information, or constraints, on the mixing matrices $V_{H\nu}$ and $V_{H\ell}$ required for our calculation, Eq. (20) relates their product to the matrix $V_{\rm PMNS}$. Furthermore, as data from neutrino masses, neutrino mass differences, and neutrino oscillations do place constraints on this latter matrix, this shall be the only constraint one has to respect in discussing our numerical results.

As such, for our numerical results we shall use the standard parametrization the of $V_{\rm PMNS}$ matrix, which can be written as

$$\begin{aligned} V_{\rm PMNS} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\rm atm} & s_{\rm atm} \\ 0 & -s_{\rm atm} & c_{\rm atm} \end{pmatrix} \begin{pmatrix} c_{\rm rct} & 0 & s_{\rm rct}e^{-i\delta_r} \\ 0 & 1 & 0 \\ -s_{\rm rct}e^{i\delta_r} & 0 & c_{\rm rct} \end{pmatrix} \\ &\quad \times \begin{pmatrix} c_{\rm sol} & s_{\rm sol} & 0 \\ -s_{\rm sol} & c_{\rm sol} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &= U(\theta_{\rm atm})U(\theta_{\rm rct})U(\theta_{\rm sol}), \end{aligned}$$

where the $\theta_{\rm atm}$, $\theta_{\rm rct}$, and $\theta_{\rm sol}$ are the atmospheric, reactor, and solar mixing angles. From neutrino oscillation experiments we have $\triangle m_{12}^2 \sim 8 \times 10^{-5}$ eV^{-2}, $\sin^2 2\theta_{\rm sol} \sim 0.31$, $|\triangle m_{13}^2| \sim 2.6 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{\rm atm} \sim 1.0$, and $\sin\theta_{\rm rct} \leq 0.2$ (for our calculations we have taken $\sin\theta_{\rm rct} = 0.2$). From WMAP constraints we also have that $\sum_{i=1,2,3} m_i < 2$ eV (that is, the sum of the masses of the three SM neutrino species). As such, the structure of the leptonic sector mixing matrix, $V_{\rm PMNS}$, which is analogous to the quark sector Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, can give rise to the lepton flavor violating processes (such as $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to \mu(\pi, K)$, $\tau^- \to \mu^-(e^-)\mu^+\mu^-$, etc.) within the SM. Within the SM these flavor violating processes will be dependent upon the structure of the mixing matrix ($V_{\rm PMNS}$) and the neutrino masses. The smallness of the neutrino mass, as indicated by WMAP data, ensures the suppression of these processes to a level which cannot be probed even in the foreseeable future. The lepton sector GIM mechanism suppresses the branching ratio of $\mu \to e\gamma$ to a value of less than 10^{-40} within the SM. As such, we shall refer to this situation as minimal flavor violation (MFV) [21].

As discussed earlier, in LHT we can have new mechanisms for lepton flavor violation(LFV) arising from the flavor mixing in the mirror fermion sector. The mixing in that mirror fermion sector can, furthermore, give rise to a *TeV scale GIM mechanism*. This has been extensively

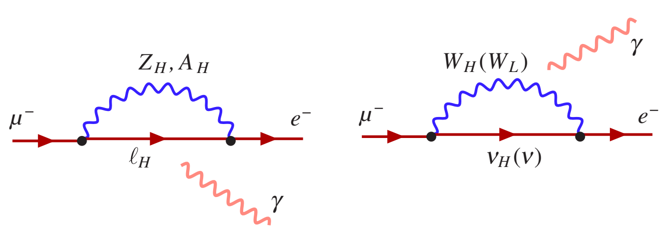

FIG. 2 (color online). The Feynman diagrams for $\mu \to e\gamma$ in LHT.

[4]Note that we have neglected the Higgs exchange diagrams which contribute at higher order in $(v/f)^2$.

discussed in the case of hadronic decays [15]. The possible implications of this TeV scale GIM mechanism in the case of lepton sector has been stressed in the T-parity model [17]. As such, there is a possibility of large enhancement of LFV decays in the T-parity model, despite the presence of a TeV scale GIM mechanism in the lepton sector. We shall quantify this by calculating some definite values of the mixing matrix and other LH parameters.

The new mixing matrix which gives rise to flavor violation in the lepton sector ($V_{H\ell}$) in general has four parameters, namely, three angles and one phase. The presence of this mixing matrix arises from the possibility of a departure from MFV, which was present within the SM. We therefore parametrize this mixing matrix with three mixing angles (θ_{12}, θ_{23}, θ_{13}) and a phase (δ) as

$$V_{H\ell} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} = U(\theta_{23})U(\theta_{13})U(\theta_{12}).$$

Furthermore, the parameters of the little Higgs model with T-parity relevant to our study are

$$f, m_{H_1}, m_{H_2}, m_{H_3}, \theta_{12}, \theta_{23}, \theta_{13}, \delta,$$

where f is the global symmetry breaking scale, $m_{H_i}(i = 1, 2, 3)$ are the masses of the three generations of mirror leptons, θ_{ij} and δ are the mixing angles and phases of the mixing matrix $V_{H\ell}$ as defined above. Additional to this the LHT has an additional parameter x_L, which indicates the mixing of the top sector of the model. This parameter however is not relevant to our current analysis as we have assumed the mixing matrix $V_{H\ell}$ to be real ($\delta = 0$). The other parameters listed above can be constrained by the experimental bounds on a large number of LFV processes, namely $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\tau \to \mu\mu\mu$, $\tau \to eee$, etc. In this work we have tried to highlight the importance of the existence of the new GIM mechanism in the mirror lepton sector by studying the $\mu \to e\gamma$ and $\tau \to \mu\gamma$ channels. Similar to the study of rare hadronic decay modes of Ref. [15], the new mixing angles θ_{12}, θ_{13}, and θ_{23}, and the pattern of mirror lepton masses, can in principle be determined from the lepton flavor violating loop decays (as T-parity forbids the existence of these processes at tree level).

At this point we would like to stress that for the departure from MFV, the following conditions need to be satisfied:

(1) The matrix $V_{H\ell}$ should be different from the Identity matrix.

(2) The three generations of mirror fermions should not be degenerate in mass.

For a few typical cases (that satisfy these conditions) which we shall use below, as the means to present our results, are: Case A Where we assume that $V_{H\ell}$ is related to $V_{\rm PMNS}$. In this case we have four input LHT model parameters, namely, the three masses of the mirror leptons and the symmetry breaking scale f.

Case B Where we assume the hierarchy of the mixing angles to be

$$s_{12} \ll s_{13} \ll s_{23}. \tag{32}$$

Case C Where we assume that the hierarchy of the mixing angles is

$$s_{12} \ll s_{23} \ll s_{13}. \tag{33}$$

We shall now analyze the effects of the above cases on our observables for $(g-2)_\mu$, $\mu \to e\gamma$ and $\tau \to \mu\gamma$, where the present experimental bounds for the observable are [22]

$$\delta a_\mu = 22(10) \times 10^{-10},$$
$$\mathrm{Br}(\mu \to e\gamma) \leq 1.2 \times 10^{-11} \qquad [90\%\mathrm{C.L.}],$$
$$\mathrm{Br}(\tau \to \mu\gamma) \leq 6.8 \times 10^{-8} \qquad [90\%\mathrm{C.L.}].$$

A. Anomalous magnetic moment of muon (δa_μ)

First, we shall present the results for δa_μ in the case where the mirror leptons have degenerate mass and the mixing matrix ($V_{H\ell}$) is the identity matrix. In this case we only have two parameters in the model, namely, the LH scale (f) and mass of the mirror leptons. The results are plotted in Fig. 3. As mentioned above, this is the MFV case of the SM, and hence $\mu \to e\gamma$ and $\tau \to \mu\gamma$ will stay at their SM levels. Note that, as can be observed from the graph, although δa_μ shows substantial variation as a function of the LH scale, its value is still much lower than the present experimental bounds. We have also tried to estimate the value of δa_μ for the other cases listed above, and found that the results are much less than the present

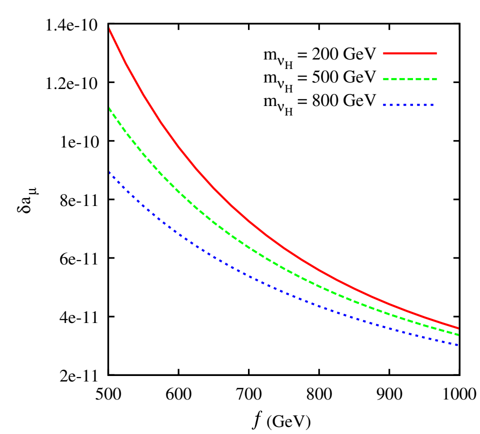

FIG. 3 (color online). δa_μ, where we have assumed $m_{\ell_H} = m_{\nu_H}$, i.e. the same mass for all the mirror fermion doublets.

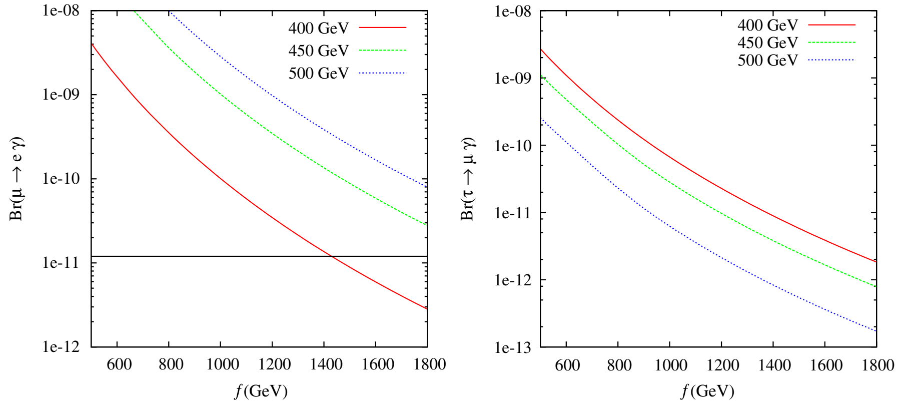

FIG. 4 (color online). Case A - I ($V_{H\ell} = V_{\rm PMNS}$): $\mu \to e\gamma$ ($\tau \to \mu\gamma$) as a function of f in the left (right) panel for different values of the second generation mirror lepton masses. The masses of the first and third generation mirror leptons are 400 GeV and 500 GeV, respectively.

experimental bounds. Our numerical analysis thus shows that the anomalous magnetic moment of the muon cannot provide any useful constraint on the LHT model parameters.

B. Lepton flavor violation

1. Case A

In this case we shall consider $V_{H\ell}$ as being related to $V_{\rm PMNS}$, where in this case we have the minimum number of additional parameters. The additional input parameters for this case are f and the masses of three generation of mirror fermions. For $V_{\rm PMNS}$ we take the standard parametrization, with parameters given by the neutrino experiments. Furthermore, we shall discuss the four cases, in analogy to the discussion given in Ref. [23], namely:

(I) $V_{H\ell} = V_{\rm PMNS}$.
(II) $V_{H\ell} = U(\theta_{\rm atm})U(\theta_{\rm rct})$.
(III) $V_{H\ell} = U(\theta_{\rm atm})$.
(IV) $V_{H\ell} = I$.

Case A - I: We have presented our results of case I in Fig. 4. As can be seen from the figure, in this case the branching ratios are very sensitive to the mass splittings of the mirror leptons. Furthermore, in this case the experimental measurement of $\mu \to e\gamma$ practically rule out any substantial mass splitting between all three generations of the mirror leptons. For this case we have also shown a scatter plot of the correlation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$ in Fig. 5. In this plot we have varied the masses of the mirror leptons in the range 500–600 GeV. As can be seen from this figure, the $\mu \to e\gamma$ decay practically rules out most of the region where there is splitting between the mirror lepton masses. However, there are still some regions where we can have a fairly high (although still within the experimental limits) rate for the $\tau \to \mu\gamma$ decay. Note that any improvement in the $\tau \to \mu\gamma$ decay rate in the future would further constrain these parameters.

Case A - II & III: In these cases there is no significant change in the rate of the $\mu \to e\gamma$ decay for the range of mirror lepton masses considered here. The reason for this is

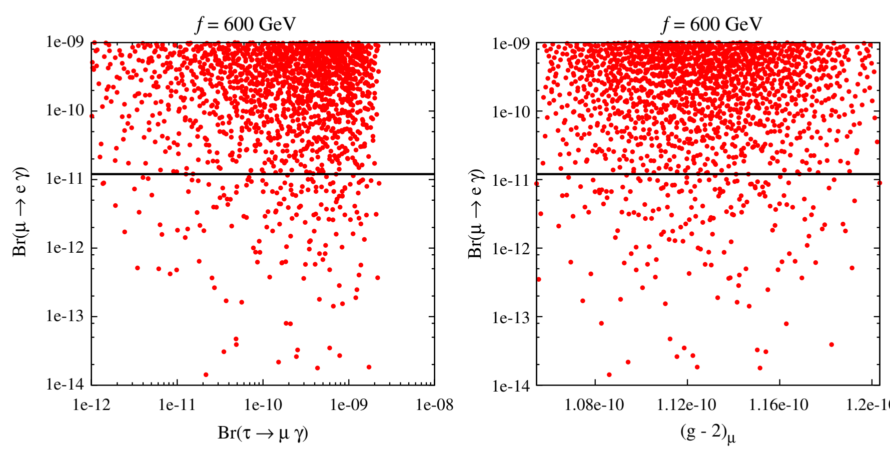

FIG. 5 (color online). Case A Co-relation between the $\tau \to \mu\gamma$ and $\mu \to e\gamma$ decays (left panel) and the $\mu \to e\gamma$ and $(g-2)_\mu$ (right panel). Masses of the heavy (mirror) leptons are varied randomly in the range $500 < m_{\ell_H} < 700$ GeV and $f = 600$ GeV.

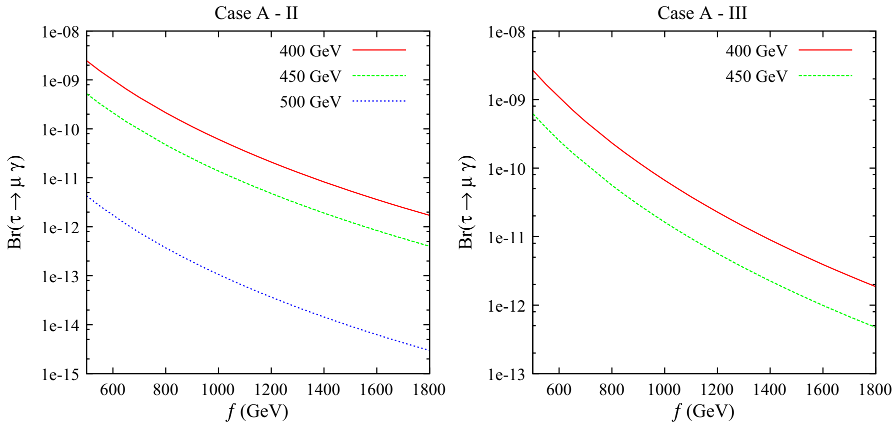

FIG. 6 (color online). Case A - II (left panel), III (right panel): $\tau \to \mu\gamma$ decay as a function of f for different values of the second generation mirror lepton mass. The masses of the first and third generation of the mirror leptons are 400 GeV and 500 GeV, respectively.

due to these cases corresponding to the situation where $V_{H\ell} = V_{\mathrm{PMNS}}$ and $s_{12} = 0$ for case II, and $s_{12} = s_{13} = 0$ for case III. In this case we do not have any appreciable mixing in the first two generations of the mirror leptons, and hence no great change in the predictions of the $\mu \to e\gamma$ decay. However, the rate of the $\tau \to \mu\gamma$ decay can be substantially changed. We have plotted the rate of the $\tau \to \mu\gamma$ decay as a function of the LH scale for case II and III in Fig. 6. As can be seen from these plots in Fig. 6, the predictions are still below the present experimental bounds. However, if data for the $\tau \to \mu\gamma$ decay were improved in the future, from high luminosity SuperB factories, this would help to constrain the possibilities greatly.

Case A - IV: This is the MFV limit of the LHT. In this case, as there is no mixing in mirror lepton sector, there will be no contribution to LFV processes.

2. Case B

In this case we have assumed the pattern $s_{12} \ll s_{13} \ll s_{23}$. In Fig. 7 we have shown the results for the fixed values of the angles, as given by

$$s_{23} \sim 0.2, \qquad s_{13} \sim 0.02, \qquad s_{12} \sim 0.002.$$

This pattern ensures a very small mixing in the first two generations of the mirror leptons, which ensures we keep the $\mu \to e\gamma$ decay rate rather low. However, in this case we can still have sufficient mixing in the second and third generations to have a higher rate (although still within the present experimental bounds) for the $\tau \to \mu\gamma$ decay.

3. Case C

In this case we are assuming a hierarchy $s_{12} \ll s_{23} \ll s_{13}$, where in Fig. 8 we have plotted for specific values of the angles, given by

$$s_{23} \sim 0.02, \qquad s_{13} \sim 0.2, \qquad s_{12} \sim 0.002.$$

In this case the mixing matrix $V_{H\ell}$ is essentially diagonal. As such, there is very little mixing between the mirror leptons, which results in a lower value for the decay rates of $\mu \to e\gamma$ and $\tau \to \mu\gamma$.

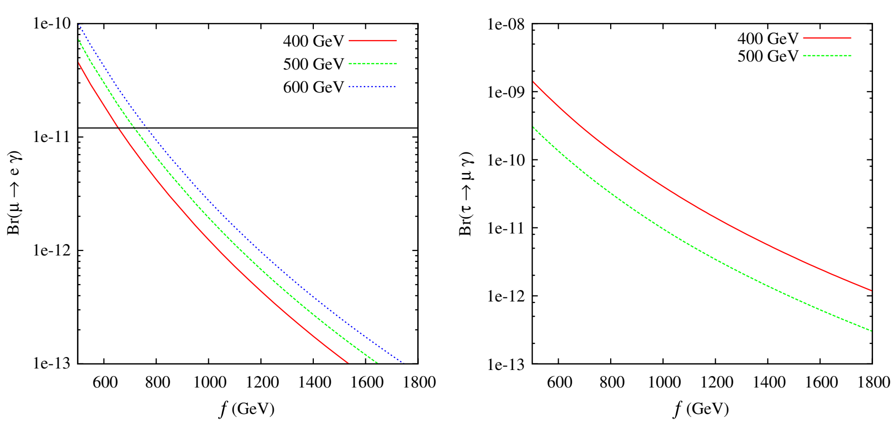

FIG. 7 (color online). Case B: The $\mu \to e\gamma$ ($\tau \to \mu\gamma$) decay as a function of f, in the left (right) panel, for different values of the second generation mirror lepton mass. The masses of the first and third generation of mirror leptons are 400 GeV and 600 GeV, respectively.

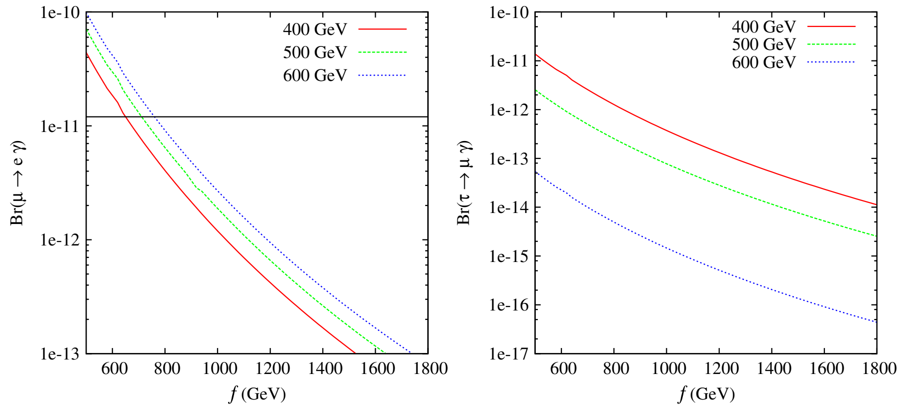

FIG. 8 (color online). Case C: The $\mu \to e\gamma$ ($\tau \to \mu\gamma$) decay as a function of f, in the left (right) panel, for different values of the second generation mirror lepton mass. The masses of the first and third generation of mirror leptons are 400 GeV and 600 GeV, respectively.

C. Final remarks

To summarize, the experimental results for the anomalous magnetic moment of the muon (δa_μ) do not constrain the LHT. However, as T-parity models provide new sources of lepton flavor violation one can extract useful constraints on model parameters from various lepton flavor violating processes. In this paper we have analyzed the effects of these new flavor violations in T-parity models on the decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$. From the present experimental results of the $\mu \to e\gamma$ decay, rather strong constraints on the texture of the new flavor violating mixing matrix and the mass splitting of mirror leptons, can be derived. The proposed MEG experiment, which is expected to further improve the measurement of branching fraction $\mu \to e\gamma$ up to 10^{-14} [24], could provide even more useful constraints to the structure of the mirror lepton sector of the LHT. Furthermore, there are practically no constraints from the $\tau \to \mu\gamma$ decay on the model parameters from present experimental results. Future SuperB factories, which may observe the $\tau \to \mu\gamma$ and $\tau \to e\gamma$ decays at rates of 10^{-10}, may provide very useful constraints on the model parameters.

Note that in a recent work a much more detailed study of various lepton flavor violating processes within the context of T-parity models has been done [25]. They agree qualitatively with our results.

ACKNOWLEDGMENTS

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APPENDIX A: FEYNMAN RULES

In this appendix we list all the relevant Feynman rules for our analysis, which have been summarized in Table I [15].

APPENDIX B: FUNCTIONS FOR $(g-2)_\mu$

The functions used in the determination of the LH contribution to $(g-2)_\mu$ are [26]

$$F_{W_H}(x_i) = \int_0^1 dy \frac{-2y^2(1+y) - x_i(2y - 3y^2 + y^3) - x_\mu y^2(y-1)}{y + x_\mu(y^2 - y) + x_i(1-y)}, \tag{B1}$$

$$F_{Z_H}(y_i) = \int_0^1 dx \frac{(x-x^2)(x-2) - \frac{1}{2}(y_i(x^3+x^2) + x_\mu(x^3 - x^2))}{(1-x) + x_\mu(x^2 - x) + y_i x}, \tag{B2}$$

with $x_\mu = (\frac{m_\mu}{M_{W_H}})^2$.

In the limit $x_\mu \to 0$, that is, where we neglect the μ mass when compared to M_{W_L}, the above integrations can be analytically expressed as

$$F_{W_H}(x_i) = -\frac{10 - 43x_i + 78x_i^2 - 49x_i^3 + 4x_i^4 + 18x_i^3\log(x_i)}{6(x_i - 1)^4}, \tag{B3}$$

$$F_{Z_H}(y_i) = \frac{-8 + 38y_i - 39y_i^2 + 14y_i^3 - 5y_i^4 + 18y_i^2\log(y_i)}{12(y_i - 1)^4}. \tag{B4}$$

APPENDIX C: FUNCTIONS FOR $\mu \to e\gamma$ AND $\tau \to \mu\gamma$

In determining the branching ratio for the decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$, we have made use of the following expressions [19]. Firstly note that upon comparing Eq. (29) with Eq. (30), for the $\mu \to e\gamma$ decay, the coefficients L_i will have the values:

$$\begin{aligned}
W_H\text{contribution: } (L_\mu^{W_H})_i^* &= \frac{ig}{\sqrt{2}}(V_{H\ell})_{2i},\\
(L_e^{W_H})_i^* &= -\frac{ig}{\sqrt{2}}(V_{H\ell})_{i1}^*\\
Z_H\text{contribution: } (L_\mu^{Z_H})_i &= i\Big(-\frac{g}{\sqrt{2}} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big)(V_{H\ell})_{2i},\\
(L_e^{Z_H})_i^* &= -i\Big(-\frac{g}{\sqrt{2}} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big)(V_{H\ell})_{i1}^*\\
A_H\text{contribution: } (L_\mu^{A_H})_i &= i\Big(\frac{g'}{10} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big)(V_{H\ell})_{2i},\\
(L_e^{A_H})_i^* &= -i\Big(\frac{g'}{10} + \frac{g'}{10}x_H\frac{v^2}{f^2}\Big)(V_{H\ell})_{i1}^*,
\end{aligned} \tag{C1}$$

where the index i sums over the three generations of mirror fermions, where analogous expressions for the decay $\tau \to \mu\gamma$ are given by selecting the appropriate elements in $V_{H\ell}$. Defining now the product:

$$\lambda_i^X = (L_\mu^X)_i(L_e^X)_i^*, \qquad X = W_H, Z_H, A_H, \tag{C2}$$

the LH contributions to σ, as defined in Eq. (30), can be written as

$$\begin{aligned}
W_H\text{loop: } (\sigma_L)_{W_H} &= Q_{W_H}\lambda_i^{W_H}\bar{y}_2(m_{\nu_H}^i, m_{W_H}),\\
(\sigma_R)_{W_H} &= Q_{W_H}\lambda_i^{W_H}\bar{y}_1(m_{\nu_H}^i, m_{W_H}),\\
Z_H\text{loop: } (\sigma_L)_{Z_H} &= Q_{\ell_H}\lambda_i^{Z_H}y_2(m_{\ell_H}^i, m_{Z_H}),\\
(\sigma_R)_{Z_H} &= Q_{\ell_H}\lambda_i^{Z_H}y_1(m_{\ell_H}^i, m_{Z_H}),\\
A_H\text{loop: } (\sigma_L)_{A_H} &= Q_{\ell_H}\lambda_i^{A_H}y_2(m_{\ell_H}^i, m_{A_H}),\\
(\sigma_R)_{A_H} &= Q_{\ell_H}\lambda_i^{A_H}y_1(m_{\ell_H}^i, m_{A_H}),
\end{aligned} \tag{C3}$$

where Q_{W_H} is the charge of W_H and Q_{ℓ_H} is the charge of the heavy mirror lepton. The loops and y functions are given as

$$\begin{aligned}
y_1(m_F, m_B) &= m_1\Big[2a + 4c_1 + 2c_2 + 2d_1 + 2f + \frac{m_F^2}{m_B^2}(-c_2 + d_1 + f) + \frac{m_2^2}{m_B^2}(c_2 + d_2 + f)\Big],\\
y_2(m_F, m_B) &= m_2\Big[2a + 2c_1 + 4c_2 + 2d_1 + 2f + \frac{m_F^2}{m_B^2}(-c_1 + d_2 + f) + \frac{m_1^2}{m_B^2}(c_1 + d_1 + f)\Big],\\
\bar{y}_1(m_F, m_B) &= m_1\Big[2\bar{c}_2 + 2\bar{d}_1 + 2\bar{f} + \frac{m_F^2}{m_B^2}(\bar{a} - 2\bar{c}_1 - \bar{c}_2 + \bar{d}_1 + \bar{f}) + \frac{m_2^2}{m_B^2}(-\bar{c}_2 + \bar{d}_2 + \bar{f})\Big],\\
\bar{y}_2(m_F, m_B) &= m_2\Big[2\bar{c}_1 + 2\bar{d}_2 + 2\bar{f} + \frac{m_F^2}{m_B^2}(\bar{a} - \bar{c}_1 - 2\bar{c}_2 + \bar{d}_2 + \bar{f}) + \frac{m_1^2}{m_B^2}(-\bar{c}_1 + \bar{d}_1 + \bar{f})\Big].
\end{aligned} \tag{C4}$$

Where in the above equations we have used

$$\begin{aligned}
a &= \frac{i}{16\pi^2}C_0(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2), & c_1 &= \frac{i}{16\pi^2}C_1(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2),\\
c_2 &= \frac{i}{16\pi^2}C_2(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2), & d_1 &= \frac{i}{16\pi^2}C_{11}(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2),\\
d_2 &= \frac{i}{16\pi^2}C_{22}(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2), & f &= \frac{i}{16\pi^2}C_{12}(m_1^2, q^2, m_2^2, m_B^2, m_F^2, m_F^2),
\end{aligned} \tag{C5}$$

and where C_0, C_1, C_2, C_{11}, C_{22}, and C_{12} are the PV functions. If we now use the approximation that $m_1^2 = m_2^2 = 0$ and $q^2 = 0$ the above PV functions can be written in terms of $t = m_F^2/m_B^2$ as [19]

$$a = \frac{i}{16\pi^2 m_B^2}\left[\frac{-1}{t-1} + \frac{\ln t}{(t-1)^2}\right], \qquad c_1 = c_2 = c = \frac{i}{16\pi^2 m_B^2}\left[\frac{t-3}{4(t-1)^2} + \frac{\ln t}{2(t-1)^3}\right],$$
$$d_1 = d_2 = 2f = d = \frac{i}{16\pi^2 m_B^2}\left[\frac{-2t^2+7t-11}{18(t-1)^3} + \frac{\ln t}{3(t-1)^4}\right], \qquad \bar{a} = \frac{i}{16\pi^2 m_B^2}\left[\frac{1}{t-1} - \frac{t\ln t}{(t-1)^2}\right],$$
$$\bar{c}_1 = \bar{c}_2 = \bar{c} = \frac{i}{16\pi^2 m_B^2}\left[\frac{3t-1}{4(t-1)^2} - \frac{t^2\ln t}{2(t-1)^3}\right], \qquad \bar{d}_1 = \bar{d}_2 = 2\bar{f} = \bar{d} = \frac{i}{16\pi^2 m_B^2}\left[\frac{11t^2-7t+2}{18(t-1)^3} - \frac{t^3\ln t}{3(t-1)^4}\right]. \tag{C6}$$

Using Eq. (30) and (C3) in Eq. (27), we obtain the branching ratio.

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