PHYSICAL REVIEW D **87,** 015030 (2013)

# $\tau \to \mu\gamma$ decay in extensions with a vectorlike generation

Tarek Ibrahim[1,*,†] and Pran Nath[2,‡]

[1]*Department of Physics, Faculty of Science, University of Alexandria, Alexandria 21511, Egypt*
[2]*Department of Physics, Northeastern University, Boston, Massachusetts 02115-5000, USA*
(Received 3 November 2012; published 30 January 2013)

An analysis is given of the decay $\tau \to \mu + \gamma$ in minimal supersymmetric standard model extensions with a vectorlike generation. Here mixing with the mirrors allows the possibility of this decay. The analysis is done at one loop with the exchange of charginos and neutralinos and of sleptons and mirror sleptons in the loops. It is shown that a branching ratio $\mathcal{B}(\tau \to \mu\gamma)$ in the range $4.4 \times 10^{-8} - 10^{-9}$ can be gotten which would be accessible to improved experiment such as at SuperB factories for this decay. The effects of *CP* violation on this decay are also analyzed.

DOI: 10.1103/PhysRevD.87.015030 PACS numbers: 13.40.Em, 12.60.−i, 14.60.Fg

## I. INTRODUCTION

Violation of lepton flavor is an important indicator of new physics beyond the standard model. In the absence of a Cabibbo-Kobayashi-Maskawa-type matrix in the leptonic sector, flavor violations can only arise due to new physics and thus decays such as $l_i \to l_j\gamma$ $(i \neq j)$ are important probes of new physics. We focus here on the decay $\tau \to \mu + \gamma$ on which the *BABAR* Collaboration [1] and Belle Collaboration [2] have put new limits on the branching ratio. Thus the current experimental limit on the branching ratio of this process from the *BABAR* Collaboration [1] based on 470 fb$^{-1}$ of data and from the Belle Collaboration [2] using 535 fb$^{-1}$ of data is

$$\mathcal{B}(\tau \to \mu + \gamma) < 4.4 \times 10^{-8} \quad \text{at 90\% C.L.}(BABAR),$$
$$\mathcal{B}(\tau \to \mu + \gamma) < 4.5 \times 10^{-8} \quad \text{at 90\% C.L.(Belle)}. \qquad (1)$$

At the SuperB factories [3–5] (for a review see Ref. [6]) the limit is expected to reach $\mathcal{B}(\tau \to \mu + \gamma) \sim 1 \times 10^{-9}$ as shown in Fig. 1. Thus it is of interest to see if theoretical estimates for this branching ratio lie close to the current experimental limits to be detectable in improved experiment.

Here we explore this process in the presence of a new vectorlike generation in an extension of the minimal supersymmetric standard model (MSSM). Vectorlike multiplets arise quite naturally in a variety of grand unified models [7] and some of them can escape supermassive mass growth and can remain light down to the electroweak scale. Recently an analysis was given of the electric dipole moment (EDM) of the tau in the framework of an extension of the minimal supersymmetric standard model with a vectorlike multiplet [8]. Specifically mixing of the standard model leptons with the mirror leptons and mixing of the sleptons with mirror sleptons were considered and it was found that such contributions could put the tau EDM in the detectable range. Here we extend this analysis to investigate the contributions from a vectorlike lepton multiplet to the flavor changing process $\tau \to \mu + \gamma$. This decay is forbidden at the tree level due to vector current conservation and can only arise at the loop level. The current work is a logical extension of the previous works where mixings with a vectorlike multiplet and with mirrors were considered [8–12]. Implications of additional vector multiplets in other contexts have been explored by many previous authors (see, e.g., Refs. [13–16]). Several studies already exist on the analysis of $\tau \to \mu\gamma$ decay [17–24]. However, none of them explore the class of models discussed here.

## II. EXTENSION OF MSSM WITH A VECTOR MULTIPLET

We begin with a brief discussion on extension of MSSM where we include vectorlike lepton multiplets since such a

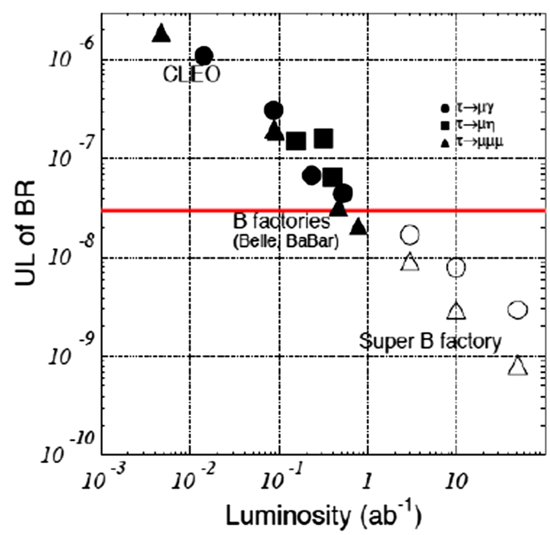


FIG. 1 (color online). A display of the upper limits on the branching ratio $\mathcal{B}(\tau^- \to \mu^-\gamma)$ (and for $\tau^- \to \mu^-\gamma, \mu^-\mu^+\mu^-$) from the previous experiments and for the anticipated experiments as a function of the integrated luminosity. This figure is taken from Ref. [4].

*Present address: Department of Physics, Faculty of Science, Beirut Arab University, Beirut 11-5020, Lebanon.
†tarek-ibrahim@alex-sci.edu.eg
‡nath@neu.edu

 

combination is anomaly free. First under $SU(3)_C \times SU(2)_L \times U(1)_Y$ the leptons of the three generations transform as follows:

$$\psi_{iL} \equiv \begin{pmatrix} \nu_{iL} \\ l_{iL} \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}\right), \qquad l^c_{iL} \sim (1, 1, 1),$$
$$\nu^c_{iL} \sim (1, 1, 0), \qquad i = 1, 2, 3, \tag{2}$$

where the last entry on the right-hand side of each $\sim$ is the value of the hypercharge $Y$ defined so that $Q = T_3 + Y$. These leptons have $V - A$ interactions. We can now add a vectorlike multiplet where we have a fourth family of leptons with $V - A$ interactions whose transformations can be gotten from Eq. (2) by letting $i$ run from 1 to 4. A vectorlike lepton multiplet also has mirrors and so we consider these mirror leptons which have $V + A$ interactions. Their quantum numbers are as follows:

$$\chi^c \equiv \begin{pmatrix} E^c_L \\ N^c_L \end{pmatrix} \sim \left(1, 2, \frac{1}{2}\right), \qquad E_L \sim (1, 1, -1),$$
$$N_L \sim (1, 1, 0). \tag{3}$$

The vectorlike extension also has a quark sector which in addition to the usual sequential generation of quarks

$$q_{iL} \equiv \begin{pmatrix} t_{iL} \\ b_{iL} \end{pmatrix} \sim \left(3, 2, \frac{1}{6}\right), \qquad b^c_{iL} \sim \left(3^*, 1, \frac{1}{3}\right),$$
$$t^c_{iL} \sim \left(3^*, 1, -\frac{2}{3}\right), \qquad i = 1, 2, 3 \tag{4}$$

also has a corresponding mirror generation

$$Q^c \equiv \begin{pmatrix} B^c_L \\ T^c_L \end{pmatrix} \sim \left(3^*, 2, -\frac{1}{6}\right), \qquad B_L \sim \left(3^*, 1, -\frac{1}{3}\right),$$
$$T_L \sim \left(3, 1, \frac{2}{3}\right). \tag{5}$$

The MSSM Higgs doublets as usual have the quantum numbers

$$H_1 \equiv \begin{pmatrix} H^1_1 \\ H^2_1 \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}\right), \qquad H_2 \equiv \begin{pmatrix} H^1_2 \\ H^2_2 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}\right). \tag{6}$$

As mentioned already we assume that the vector multiplet escapes acquiring mass at the grand unified theory scale and remains light down to the electroweak scale. As in the analysis of Ref. [8] interesting new physics arises when we consider the mixing of the first three generations of leptons with the mirrors of the vectorlike multiplet. Actually we will limit ourselves to the second and third generations since only these are relevant for the computation of the decay $\tau \rightarrow \mu\gamma$. Thus the superpotential of the model may be written in the form

$$\begin{aligned} W = {} & -\mu\epsilon_{ij}\hat{H}^i_1\hat{H}^j_2 + \epsilon_{ij}[f_1\hat{H}^i_1\hat{\psi}^j_L\hat{\tau}^c_L + f'_1\hat{H}^j_2\hat{\psi}^i_L\hat{\nu}^c_{\tau L} \\ & + f_2\hat{H}^i_1\hat{\chi}^{cj}\hat{N}_L + f'_2 H^j_2\hat{\chi}^{ci}\hat{E}_L + h_1 H^i_1\hat{\psi}^j_{\mu L}\hat{\mu}^c_L \\ & + h'_1 H^j_2\hat{\psi}^i_{\mu L}\hat{\nu}^c_{\mu L}] + f_3\epsilon_{ij}\hat{\chi}^{ci}\hat{\psi}^j_L + f'_3\epsilon_{ij}\hat{\chi}^{ci}\hat{\psi}^j_{\mu L} \\ & + f'_4\hat{\mu}^c_L\hat{E}_L + f'_5\hat{\nu}^c_{\mu L}\hat{N}_L, \end{aligned} \tag{7}$$

where $\hat{\psi}_L$ stands for $\hat{\psi}_{3L}$ and $\hat{\psi}_{\mu L}$ stands for $\hat{\psi}_{2L}$. Here we assume a mixing between the mirror generation and the third lepton generation through the couplings $f_3$, $f_4$ and $f_5$. We also assume mixing between the mirror generation and the second lepton generation through the couplings $f'_3$, $f'_4$ and $f'_5$. "The above six mass terms are responsible for generating lepton flavor changing process $\tau \rightarrow \mu\gamma$."

If we assume a mixing between the mirror generation and the first lepton generation through an additional set of parameters $f''_3$, $f''_4$ and $f''_5$, one can have the corresponding process of $\mu \rightarrow e\gamma$. However, since the mixings with the first generation are independent of the mixings with the second and the third generation, the $\mu \rightarrow e\gamma$ decay is not correlated with the $\tau \rightarrow \mu\gamma$ decay. For this reason we limit our analysis to the $\tau \rightarrow \mu\gamma$ decay. We will focus here on the supersymmetric sector. Then through the terms $f_3$, $f_4$, $f_5$, $f'_3$, $f'_4$, $f'_5$ one can have a mixing between the third generation and the second generation leptons which allows the decay of $\tau \rightarrow \mu\gamma$ through loop corrections that include charginos, neutralinos and scalar lepton exchanges with the photon being emitted by the chargino (see the left diagram of Fig. 2) or by a charged slepton (see the right diagram of Fig. 2). The mass terms for the leptons and mirrors arise from the term

$$\mathcal{L} = -\frac{1}{2}\frac{\partial^2 W}{\partial A_i \partial A_j}\psi_i\psi_j + \text{H.c.}, \tag{8}$$

where $\psi$ and $A$ stand for generic two-component fermion and scalar fields, respectively. After spontaneous breaking of the electroweak symmetry ($\langle H^1_1\rangle = v_1/\sqrt{2}$ and $\langle H^2_2\rangle = v_2/\sqrt{2}$), we have the following set of mass terms written in the 4-component spinor notation:

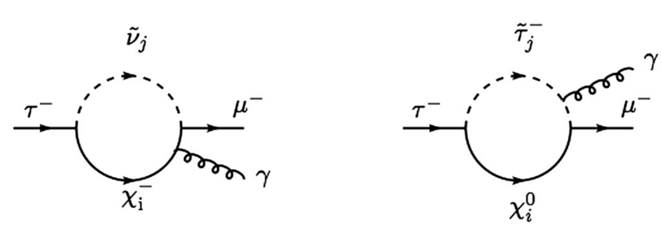


FIG. 2. The diagrams that allow decay of the $\tau$ into $\mu + \gamma$ via supersymmetric loops involving the chargino and the sneutrino (left) and the neutralino and the stau (right) with emission of the photon from the charged particle inside the loop.

$$-\mathcal{L}_m = (\bar{\tau}_R \quad \bar{E}_R \quad \bar{\mu}_R) \times \begin{pmatrix} f_1 v_1/\sqrt{2} & f_4 & 0 \\ f_3 & f_2' v_2/\sqrt{2} & f_3' \\ 0 & f_4' & h_1 v_1/\sqrt{2} \end{pmatrix} \begin{pmatrix} \tau_L \\ E_L \\ \mu_L \end{pmatrix} + (\bar{\nu}_{\tau R} \quad \bar{N}_R \quad \bar{\nu}_{\mu R}) \times \begin{pmatrix} f_1' v_2/\sqrt{2} & f_5 & 0 \\ -f_3 & f_2 v_1/\sqrt{2} & -f_3' \\ 0 & f_5' & h_1' v_2/\sqrt{2} \end{pmatrix} \begin{pmatrix} \nu_{\tau L} \\ N_L \\ \nu_{\mu L} \end{pmatrix} + \text{H.c.} \tag{9}$$

Here the mass matrices are not Hermitian and one needs to use biunitary transformations to diagonalize them. Thus we write the linear transformations

$$\begin{pmatrix} \tau_R \\ E_R \\ \mu_R \end{pmatrix} = D_R^\tau \begin{pmatrix} \tau_{1_R} \\ \tau_{2_R} \\ \tau_{3_R} \end{pmatrix}, \qquad \begin{pmatrix} \tau_L \\ E_L \\ \mu_L \end{pmatrix} = D_L^\tau \begin{pmatrix} \tau_{1_L} \\ \tau_{2_L} \\ \tau_{3_L} \end{pmatrix}, \tag{10}$$

such that

$$D_R^{\tau\dagger} \begin{pmatrix} f_1 v_1/\sqrt{2} & f_4 & 0 \\ f_3 & f_2' v_2/\sqrt{2} & f_3' \\ 0 & f_4' & h_1 v_1/\sqrt{2} \end{pmatrix} D_L^\tau = \text{diag}(m_{\tau_1}, m_{\tau_2}, m_{\tau_3}). \tag{11}$$

The same holds for the neutrino mass matrix

$$D_R^{\nu\dagger} \begin{pmatrix} f_1' v_2/\sqrt{2} & f_5 & 0 \\ -f_3 & f_2 v_1/\sqrt{2} & -f_3' \\ 0 & f_5' & h_1' v_2/\sqrt{2} \end{pmatrix} D_L^\nu = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_2}). \tag{12}$$

In Eq. (11) $\tau_1$, $\tau_2$, $\tau_3$ are the mass eigenstates and we identify the tau lepton with the eigenstate 1, i.e., $\tau = \tau_1$, and we identify $\tau_2$ with a heavy mirror eigenstate with a mass in the hundreds of GeV and $\tau_3$ is identified as the muon. Similarly $\nu_1$, $\nu_2$, $\nu_3$ are the mass eigenstates for the neutrinos, where we identify $\nu_1$ as the light tau neutrino, $\nu_2$ as the heavier mass eigenstate and $\nu_3$ as the muon neutrino. The scalar mass$^2$ matrices of the model are calculated in the Appendix, where we show that they are $6 \times 6$ Hermitian matrices. If we assume a mixing between the mirror generation and the three lepton generations, the lepton mass matrices would be $4 \times 4$ and the scalar lepton mass$^2$ matrices would be $8 \times 8$ Hermitian matrices.

## III. INTERACTIONS OF CHARGINOS AND NEUTRALINOS

The chargino exchange contribution to the decay of the tau into a muon and a photon arises through the left loop diagram of Fig. 2. The relevant part of Lagrangian that generates this contribution is given by

$$-\mathcal{L}_{\tau-\tilde{\nu}-\chi^+} = \sum_{\alpha=1}^{3}\sum_{i=1}^{2}\sum_{j=1}^{6} \bar{\tau}_\alpha [C_{\alpha ij}^L P_L + C_{\alpha ij}^R P_R] \tilde{\chi}_i^c \tilde{\nu}_j + \text{H.c.}, \tag{13}$$

where

$$C_{\alpha ij}^L = g\Big[-\kappa_\tau U_{i2}^* D_{R_{1\alpha}}^{\tau *} \tilde{D}_{1j}^\nu - \kappa_\mu U_{i2}^* D_{R_{3\alpha}}^{\tau *} \tilde{D}_{5j}^\nu + U_{i1}^* D_{R_{2\alpha}}^{\tau *} \tilde{D}_{4j}^\nu - \kappa_N U_{i2}^* D_{R_{2\alpha}}^{\tau *} \tilde{D}_{2j}^\nu\Big],$$
$$C_{\alpha ij}^R = g\Big[-\kappa_{\nu_\tau} V_{i2} D_{L_{1\alpha}}^{\tau *} \tilde{D}_{3j}^\nu - \kappa_{\nu_\mu} V_{i2} D_{L_{3\alpha}}^{\tau *} \tilde{D}_{6j}^\nu + V_{i1} D_{L_{1\alpha}}^{\tau *} \tilde{D}_{1j}^\nu + V_{i1} D_{L_{3\alpha}}^{\tau *} \tilde{D}_{5j}^\nu - \kappa_E V_{i2} D_{L_{2\alpha}}^{\tau *} \tilde{D}_{4j}^\nu\Big], \tag{14}$$

where $\tilde{D}^\nu$ is the diagonalizing matrix of the scalar $6 \times 6$ mass$^2$ matrix for the scalar neutrino as defined in the Appendix. $\kappa_N$, $\kappa_\tau$, etc., that enter in the equation above are defined by

$$(\kappa_N, \kappa_\tau, \kappa_\mu) = \frac{(m_N, m_\tau, m_\mu)}{\sqrt{2} M_W \cos\beta},$$
$$(\kappa_E, \kappa_\nu) = \frac{(m_E, m_\nu)}{\sqrt{2} M_W \sin\beta}. \tag{15}$$

In Eq. (14) $U$ and $V$ are the matrices that diagonalize the chargino mass matrix $M_C$ so that

$$U^* M_C V^{-1} = \text{diag}(m_{\tilde{\chi}_1}^+, m_{\tilde{\chi}_2}^+). \tag{16}$$

The neutralino exchange contribution to the tau decay arises through the right loop diagram of Fig. 2. The relevant part of Lagrangian that generates this contribution is given by

$$-\mathcal{L}_{\tau-\tilde{\tau}-\chi^0} = \sum_{\alpha=1}^{3}\sum_{i=1}^{4}\sum_{j=1}^{6} \bar{\tau}_\alpha [C_{\alpha ij}'^L P_L + C_{\alpha ij}'^R P_R] \tilde{\chi}^0{}_i \tilde{\tau}_j + \text{H.c.}, \tag{17}$$

where as stated earlier $\tau = \tau_1$ and $\mu = \tau_3$. In Eq. (17) $C_L'$ and $C_R'$ are defined by, respectively,

$$C_{\alpha ij}'^L = \sqrt{2}\Big[\alpha_{\tau i} D_{R_{1\alpha}}^{\tau *} \tilde{D}_{1j}^\tau - \delta_{Ei} D_{R_{2\alpha}}^{\tau *} \tilde{D}_{2j}^\tau - \gamma_{\tau i} D_{R_{1\alpha}}^{\tau *} \tilde{D}_{3j}^\tau + \beta_{Ei} D_{R_{2\alpha}}^{\tau *} \tilde{D}_{4j}^\tau + \alpha_{\mu i} D_{R_{3\alpha}}^{\tau *} \tilde{D}_{5j}^\tau - \gamma_{\mu i} D_{R_{3\alpha}}^{\tau *} \tilde{D}_{6j}^\tau\Big],$$
$$C_{\alpha ij}'^R = \sqrt{2}\Big[\beta_{\tau i} D_{L_{1\alpha}}^{\tau *} \tilde{D}_{1j}^\tau - \gamma_{Ei} D_{L_{2\alpha}}^{\tau *} \tilde{D}_{2j}^\tau - \delta_{\tau i} D_{L_{1\alpha}}^{\tau *} \tilde{D}_{3j}^\tau + \alpha_{Ei} D_{L_{2\alpha}}^{\tau *} \tilde{D}_{4j}^\tau + \beta_{\mu i} D_{L_{3\alpha}}^{\tau *} \tilde{D}_{5j}^\tau - \delta_{\mu i} D_{L_{3\alpha}}^{\tau *} \tilde{D}_{6j}^\tau\Big], \tag{18}$$

where $\tilde{D}^\tau$ is the diagonalizing matrix of the $6 \times 6$ slepton mass$^2$ matrix.

$$\alpha_{E_j} = \frac{g m_E X^*_{4j}}{2 m_W \sin\beta},$$
$$\beta_{E_j} = e X'_{1j} + \frac{g}{\cos\theta_W} X'_{2j}\left(\frac{1}{2} - \sin^2\theta_W\right),$$
$$\gamma_{E_j} = e X'^*_{1j} - \frac{g \sin^2\theta_W}{\cos\theta_W} X^{*'}_{2j}, \qquad \delta_{E_j} = -\frac{g m_E X_{4j}}{2 m_W \sin\beta}, \tag{19}$$

and

$$\alpha_{\tau j} = \frac{g m_\tau X_{3j}}{2 m_W \cos\beta}, \qquad \alpha_{\mu j} = \frac{g m_\mu X_{3j}}{2 m_W \cos\beta},$$
$$\beta_{\tau j} = \beta_{\mu j} = -e X'^*_{1j} + \frac{g}{\cos\theta_W} X'^*_{2j}\left(-\frac{1}{2} + \sin^2\theta_W\right),$$
$$\gamma_{\tau j} = \gamma_{\mu j} = -e X'_{1j} + \frac{g \sin^2\theta_W}{\cos\theta_W} X'_{2j}, \tag{20}$$
$$\delta_{\tau j} = -\frac{g m_\tau X^*_{3j}}{2 m_W \cos\beta}, \qquad \delta_{\mu j} = -\frac{g m_\mu X^*_{3j}}{2 m_W \cos\beta},$$

where

$$X'_{1j} = (X_{1j}\cos\theta_W + X_{2j}\sin\theta_W),$$
$$X'_{2j} = (-X_{1j}\sin\theta_W + X_{2j}\cos\theta_W), \tag{21}$$

and where the matrix $X$ diagonalizes the neutralino mass matrix so that

$$X^T M_{\tilde{\chi}^0} X = \mathrm{diag}(m_{\chi^0_1}, m_{\chi^0_2}, m_{\chi^0_3}, m_{\chi^0_4}). \tag{22}$$

## IV. THE ANALYSIS OF $\tau \to \mu + \gamma$ BRANCHING RATIO

The decay $\tau \to \mu + \gamma$ is induced by one-loop electric and magnetic transition dipole moments, which arise from the diagrams of Fig. 2. In the dipole moment loop, the incoming muon is replaced by a tau lepton. For an incoming tau of momentum $p$ and a resulting muon of momentum $p'$, we define the amplitude

$$\langle \mu(p') | J_\alpha | \tau(p) \rangle = \bar{u}_\mu(p') \Gamma_\alpha u_\tau(p), \tag{23}$$

where

$$\Gamma_\alpha(q) = \frac{F_2^{\tau\mu}(q) i \sigma_{\alpha\beta} q^\beta}{m_\tau + m_\mu} + \frac{F_3^{\tau\mu}(q) \sigma_{\alpha\beta}\gamma_5 q^\beta}{m_\tau + m_\mu} + \cdots \tag{24}$$

with $q = p - p'$ and where $m_f$ denotes the mass of the fermion $f$. The branching ratio of $\tau \to \mu + \gamma$ is given by

$$\mathcal{B}(\tau \to \mu + \gamma) = \frac{24\pi^2}{5 G_F^2 m_\tau^2 (m_\tau + m_\mu)^2} \times \{|F_2^{\tau\mu}(0)|^2 + |F_3^{\tau\mu}(0)|^2\}, \tag{25}$$

where the form factors $F_2^{\tau\mu}$ and $F_3^{\tau\mu}$ arise from the chargino and the neutralino contributions, respectively, as follows:

$$F_2^{\tau\mu}(0) = F_{2\chi^+}^{\tau\mu} + F_{2\chi^0}^{\tau\mu}, \quad F_3^{\tau\mu}(0) = F_{3\chi^+}^{\tau\mu} + F_{3\chi^0}^{\tau\mu}. \tag{26}$$

The chargino contribution $F_{2\chi^+}^{\tau\mu}$ is given by

$$F_{2\chi^+}^{\tau\mu} = \sum_{i=1}^{2}\sum_{j=1}^{6}\left[\frac{m_\tau(m_\tau + m_\mu)}{64\pi^2 m^2_{\tilde{\chi}_i^+}}\{C^L_{3ij}C^{L*}_{1ij} + C^R_{3ij}C^{R*}_{1ij}\} \times F_1\left(\frac{M^2_{\tilde{\nu}_j}}{m^2_{\tilde{\chi}_i^+}}\right) + \frac{(m_\tau + m_\mu)}{64\pi^2 m_{\tilde{\chi}_i^+}}\{C^L_{3ij}C^{R*}_{1ij} + C^R_{3ij}C^{L*}_{1ij}\} \times F_2\left(\frac{M^2_{\tilde{\nu}_j}}{m^2_{\tilde{\chi}_i^+}}\right)\right], \tag{27}$$

where

$$F_1(x) = \frac{1}{3(x-1)^4}\{-2x^3 - 3x^2 + 6x - 1 + 6x^2 \ln x\} \tag{28}$$

and

$$F_2(x) = \frac{1}{(x-1)^3}\{3x^2 - 4x + 1 - 2x^2 \ln x\}. \tag{29}$$

The neutralino contribution $F_{2\chi^0}^{\tau\mu}$ is given by

$$F_{2\chi^0}^{\tau\mu} = \sum_{i=1}^{4}\sum_{j=1}^{6}\left[\frac{-m_\tau(m_\tau + m_\mu)}{192\pi^2 m^2_{\tilde{\chi}_i^0}}\{C'^L_{3ij}C'^{L*}_{1ij} + C'^R_{3ij}C'^{R*}_{1ij}\} \times F_3\left(\frac{M^2_{\tilde{\tau}_j}}{m^2_{\tilde{\chi}_i^0}}\right) - \frac{(m_\tau + m_\mu)}{64\pi^2 m_{\tilde{\chi}_i^0}}\{C'^L_{3ij}C'^{R*}_{1ij} + C'^R_{3ij}C'^{L*}_{1ij}\} \times F_4\left(\frac{M^2_{\tilde{\tau}_j}}{m^2_{\tilde{\chi}_i^0}}\right)\right], \tag{30}$$

where

$$F_3(x) = \frac{1}{(x-1)^4}\{-x^3 + 6x^2 - 3x - 2 - 6x \ln x\} \tag{31}$$

and

$$F_4(x) = \frac{1}{(x-1)^3}\{-x^2 + 1 + 2x \ln x\}. \tag{32}$$

The chargino contribution $F_{3\chi^+}^{\tau\mu}$ is given by

$$F_{3\chi^+}^{\tau\mu} = \sum_{i=1}^{2}\sum_{j=1}^{6}\frac{(m_\tau + m_\mu) m_{\tilde{\chi}_i^+}}{32\pi^2 M^2_{\tilde{\nu}_j}}\{C^L_{3ij}C^{R*}_{1ij} - C^R_{3ij}C^{L*}_{1ij}\} \times F_5\left(\frac{m^2_{\tilde{\chi}_i^+}}{M^2_{\tilde{\nu}_j}}\right), \tag{33}$$

where

$$F_5(x) = \frac{1}{2(x-1)^2}\left\{-x + 3 + \frac{2\ln x}{1-x}\right\}. \tag{34}$$

The neutralino contribution $F^{\tau\mu}_{3\chi^0}$ is given by

$$F^{\tau\mu}_{3\chi^0} = \sum_{i=1}^{4}\sum_{j=1}^{6} \frac{(m_\tau + m_\mu) m_{\tilde{\chi}_i^0}}{32\pi^2 M^2_{\tilde{\tau}_j}} \{C'^{L}_{3ij} C'^{R*}_{1ij} - C'^{R}_{3ij} C'^{L*}_{1ij}\} \times F_6\left(\frac{m^2_{\tilde{\chi}_i^0}}{M^2_{\tilde{\tau}_j}}\right), \tag{35}$$

where

$$F_6(x) = \frac{1}{2(x-1)^2}\left\{x + 1 + \frac{2x \ln x}{1-x}\right\}. \tag{36}$$

If we consider a mixing of the mirror generation with the three lepton generations, the phenomenologically parallel quantity $\mathcal{B}(\mu \to e + \gamma)$ would be possible. The corresponding expression can be obtained from Eq. (25) by replacing every $\mu$ by $e$ and every $\tau$ by $\mu$. However, the denominator does not have the number 5 in it in this case. The reason for this is that in the case of $\tau$ decay we have three extra possible channels into $\mu + \nu_\tau + \bar{\nu}_\mu$, $s + \nu_\tau + \bar{u}$ and $d + \nu_\tau + \bar{u}$ besides the process $e + \nu_\tau + \bar{\nu}_e$ that is similar to the one that occurs in the case of $\mu$ decay $e + \nu_\mu + \bar{\nu}_e$. We note that since the mixings of the mirror with the first generation are independent of the mixings of the mirror with the second and the third generations, the branching ratio of $\mu \to e\gamma$ is not directly correlated to the branching ratio $\tau \to \mu\gamma$. For this reason we focus on the decay $\tau \to \mu\gamma$ without trying to correlate it with the decay $\mu \to e\gamma$.

## V. ESTIMATE OF SIZE OF $\mathcal{B}(\tau \to \mu\gamma)$

In this section we give a numerical analysis of $\mathcal{B}(\tau \to \mu\gamma)$ for the model where we include a leptonic vector multiplet. As discussed in the previous sections the flavor changing processes arise from the mixings between the standard model leptons and the mirrors in the vector multiplet. The mixing matrices between leptons and mirrors are diagonalized using biunitary transformations with matrices $D^\tau_R$ and $D^\tau_L$. The input parameters for this sector of the parameter space are $m_\tau$, $m_E$, $m_\mu$, $f_3$, $f_4$, $f'_3$, $f'_4$, where $f_3$, $f_4$, $f'_3$ and $f'_4$ are complex masses with $CP$ violating phases $\chi_3$, $\chi_4$, $\chi'_3$, $\chi'_4$. For the slepton mass$^2$ matrices we need the extra input parameters of the supersymmetry breaking sector, $\tilde{M}\tau_L$, $\tilde{M}_E$, $\tilde{M}_\tau$, $\tilde{M}_\chi$, $\tilde{M}_{\mu_L}$, $\tilde{M}_\mu$, $A_\tau$, $A_E$, $A_\mu$, $A_N$, $\mu$, $\tan\beta$. For the sneutrino mass$^2$ matrices we have more input parameters, $\tilde{M}_N$, $\tilde{M}_{\nu_\tau}$, $\tilde{M}_{\nu_\mu}$, $A_{\nu_\mu}$, $A_N$, $A_{\nu_e}$, $m_N$, $f_5$, $f'_5$. The chargino and neutralino sectors need the extra two parameters $\tilde{m}_1$, $\tilde{m}_2$. In the analysis we will include phases since dipole moments are sensitive to phases (for a review see Ref. [25]). Here for simplicity we assume that the only parameters that are complex in the above matrix elements are $A_E$, $A_N$, $A_\tau$, $A_\mu$, $A_\nu$, $f_5$ and $f'_5$ which have the phases $\alpha_E$, $\alpha_N$, $\alpha_\tau$, $\alpha_\mu$, $\alpha_\nu$, $\chi_5$ and $\chi'_5$. To simplify the analysis we set $\alpha_\nu = \alpha_\mu = \alpha_\tau = 0$. Thus the $CP$ violating phases that would play a role in this analysis are

$$\chi_3, \chi_4, \chi_5, \chi'_3, \chi'_4, \chi'_5, \alpha_E, \alpha_N. \tag{37}$$

With the above in mind, the electric dipole moments of the electron, the neutron and the Hg atom vanish and we do not need to worry about them satisfying their upper limit constraints. To reduce the number of input parameters we assume equality of the scalar masses and of the trilinear couplings so that $\tilde{M}_a = m_0$, $a = \tau_L, E, \tau, \chi, \nu, \mu, \mu_L, N$ and $|A_i| = |A_0|$, $i = E, N, \tau, \nu, \mu$.

Figure 3 gives an analysis of $\mathcal{B}(\tau \to \mu\gamma)$ as a function of $m_0$ for values of $\tan\beta = 5, 10, 15, 20$ with other inputs as given in the caption of Fig. 3. The branching ratio depends on the chargino and neutralino exchange contributions to $F^{\tau\mu}_2(0)$ and $F^{\tau\mu}_3(0)$ defined in Eq. (26) which depend on $m_0$ through the slepton masses that enter the loops. Figure 3 exhibits a sharp dependence on $\tan\beta$ which enters $F^{\tau\mu}_2(0)$ and $F^{\tau\mu}_3(0)$ also via the slepton masses as well as through the chargino and neutralino mass matrices. Further, the couplings $C^{L,R}$ and $C'^{L,R}$ are also affected by variations in $m_0$ and $\tan\beta$. The analysis of Fig. 3 shows that there is a significant part of the parameter space where $\mathcal{B}(\tau \to \mu\gamma)$ lies in the range $O(10^{-8})$ consistent with the upper limit of Eq. (1). Figure 4 gives an analysis of $\mathcal{B}(\tau \to \mu\gamma)$ as a function of $|f_3|$, where $f_3$ is an off diagonal term in the mass matrix of Eq. (9), for $\tan\beta$ values as in Fig. 3 and the other inputs are as given in the caption of Fig. 4. As in Fig. 3 one finds a sharp dependence on $\tan\beta$. This dependence of $|f_3|$ arises since it enters in the matrix elements diagonalizing matrices $D^\tau_{L,R}$ and this way it affects both chargino and neutralino exchange contributions. The entire parameter space exhibited in this figure is consistent with the upper limits of Eq. (1).

We discuss now the effect of $CP$ phases on $\mathcal{B}(\tau \to \mu\gamma)$. As mentioned above the phases of Eq. (37) have no effect on the EDMs of the electron, on the EDM of the neutron or on EDM of the Hg atom and these phases only affect

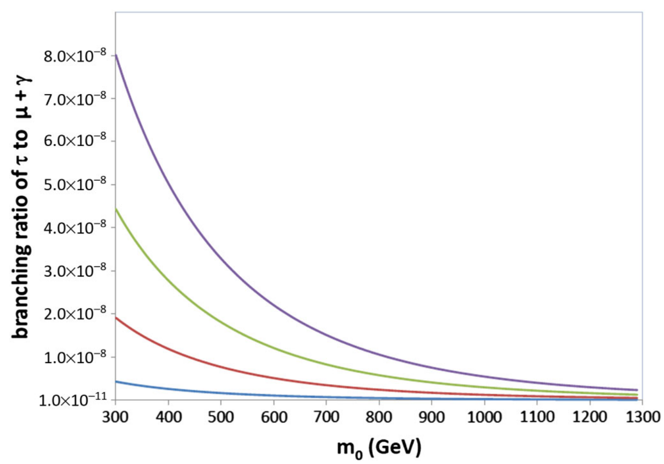


FIG. 3 (color online). An exhibition of the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $m_0$ when $m_N = 120$, $m_E = 150$, $|f_3| = |f'_3| = 90$, $|f_4| = |f'_4| = 100$, $|f_5| = |f'_5| = 80$, $|A_0| = 150$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\chi_3 = \chi'_3 = 0.6$, $\chi_4 = \chi'_4 = 0.4$, $\chi_5 = \chi'_5 = 0.6$, $\alpha_E = 0.5$, $\alpha_N = 0.8$, and $\tan\beta = 5, 10, 15, 20$ (in ascending order at $m_0 = 300$). Here and in Figs. 4–7 masses are in GeV and angles are in rad.

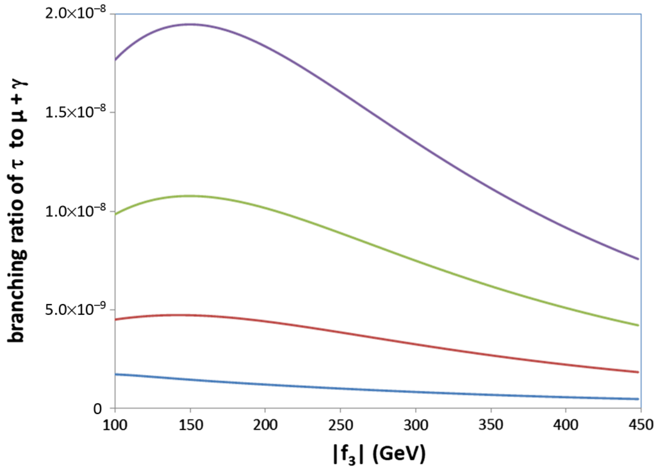


FIG. 4 (color online). An exhibition of the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $|f_3|$ when $m_0 = 900$, $m_N = 150$, $m_E = 180$, $|f_3'| = 100$, $|f_4| = |f_4'| = 100$, $|f_5| = |f_5'| = 70$, $|A_0| = 100$, $\tilde{m}_1 = 50$, $\tilde{m}_2 = 100$, $\mu = 150$, $\chi_3 = \chi_3' = 0.6$, $\chi_4 = \chi_4' = 0.4$, $\chi_5 = \chi_5' = 0.6$, $\alpha_E = 0.5$, $\alpha_N = 0.8$, and $\tan\beta = 5$, 10, 15, 20 (in ascending order at $|f_3| = 100$).

phenomena related to the second and the third generation leptons. Figure 5 gives a display of $\mathcal{B}(\tau \to \mu\gamma)$ as a function of $\chi_3$ for values of $m_0 = 900$, 800, 700, 600, 500 GeV (in ascending order) when $\tan\beta = 10$ and the other inputs are as shown in the caption of Fig. 5. Here one finds that $\mathcal{B}(\tau \to \mu\gamma)$ has a significant dependence on $\chi_3$. Thus, for instance, for the case $m_0 = 500$ GeV (top curve) one finds that $\mathcal{B}(\tau \to \mu\gamma)$ can vary in the range $(1 \times 10^{-8}$–$4 \times 10^{-8})$ as $\chi_3$ varies in the range $(0, \pi)$. Again $\mathcal{B}(\tau \to \mu\gamma)$ displayed in this analysis is consistent with the upper limit of Eq. (1) over the entire range of parameters exhibited.

Another analysis on the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $CP$ phases is exhibited in Fig. 6 where a plot of $\mathcal{B}(\tau \to \mu\gamma)$ as a function of $\chi_4$ is given for the case when $|f_3| = (300, 250, 200, 150)$ GeV (in ascending order), $\tan\beta = 15$ and other inputs are as given in the caption of Fig. 6. Again a very significant variation in $\mathcal{B}(\tau \to \mu\gamma)$ is seen as $\chi_4$ varies in the range $(0, \pi)$. Specifically one finds that for the case $|f_3| = 150$, $\mathcal{B}(\tau \to \mu\gamma)$ varies in the range $(8 \times 10^{-9}$–$3 \times 10^{-8})$. Further, over the entire parameter space analyzed in Fig. 6 $\mathcal{B}(\tau \to \mu\gamma)$ is consistent with the upper limit of Eq. (1). Finally, in Fig. 7 we exhibit the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $\tan\beta$ when $\chi_3 = 1.2$, 0.8, 0.5, 0.1 (in ascending order) with other parameters as defined in the caption of Fig. 7. A sharp dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $\tan\beta$ can be seen. Specifically one finds that for the case $\chi_3 = 0.1$ (the top curve) $\mathcal{B}(\tau \to \mu\gamma)$ varies in the range $(1 \times 10^{-10}$–$3 \times 10^{-8})$ which is more than an order of magnitude variation as $\tan\beta$ varies in the range (5–30).

In summary in the analyses presented in Figs. 3–7, one finds that $\mathcal{B}(\tau \to \mu\gamma)$ can be quite large often lying just below the current experimental limits which implies that this part of the parameter space will be accessible to future experiments, specifically SuperB factories which can probe $\mathcal{B}(\tau \to \mu\gamma)$ as low as $10^{-9}$. We note that the flavor changing interactions of Eq. (7) also contribute to the muon anomalous magnetic moment $g_\mu - 2$ which is very precisely determined experimentally. This can come about by the exchange of a tau and a photon in the loop but since each vertex is one-loop order, the contribution is three-loop order which would be tiny compared to other standard model electroweak contributions. One should also consider the constraints arising from the $S$ and $T$ parameters. However, the $S$ and $T$ constraints are not very stringent

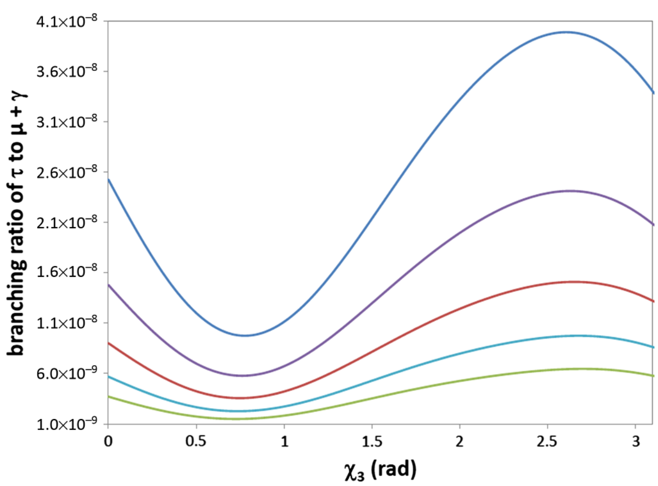


FIG. 5 (color online). An exhibition of the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $\chi_3$ when $\tan\beta = 10$, $m_N = 170$, $m_E = 200$, $|f_3| = |f_3'| = 250$, $|f_4| = |f_4'| = 400$, $|f_5| = |f_5'| = 90$, $|A_0| = 130$, $\tilde{m}_1 = 90$, $\tilde{m}_2 = 80$, $\mu = 120$, $\chi_3' = 0.8$, $\chi_4 = \chi_4' = 0.9$, $\chi_5 = \chi_5' = 1.6$, $\alpha_E = 1.0$, $\alpha_N = 0.9$, and $m_0 = 900$, 800, 700, 600, 500 (in ascending order at $\chi_3 = 0.0$).

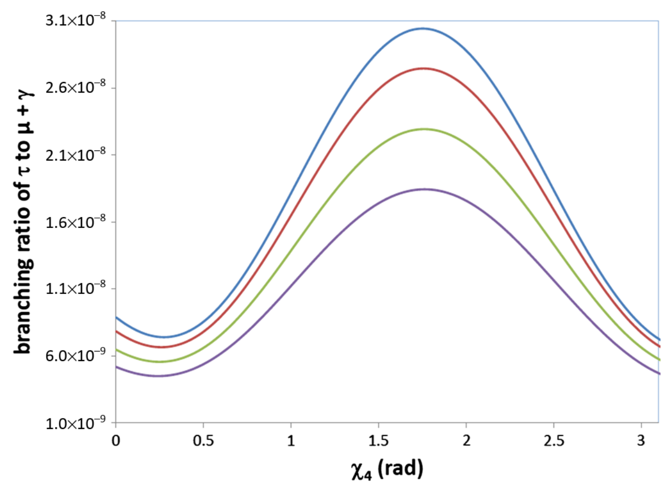


FIG. 6 (color online). An exhibition of the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $\chi_4$ when $m_0 = 800$, $\tan\beta = 15$, $m_N = 160$, $m_E = 220$, $|f_3'| = 150$, $|f_4| = |f_4'| = 200$, $|f_5| = |f_5'| = 100$, $|A_0| = 160$, $\tilde{m}_1 = 100$, $\tilde{m}_2 = 90$, $\mu = 150$, $\chi_3 = \chi_3' = 0.6$, $\chi_4' = 0.8$, $\chi_5 = \chi_5' = 1.0$, $\alpha_E = 0.4$, $\alpha_N = 0.8$, and $|f_3| = 300$, 250, 200, 150 (in ascending order at $\chi_4 = 0.0$).

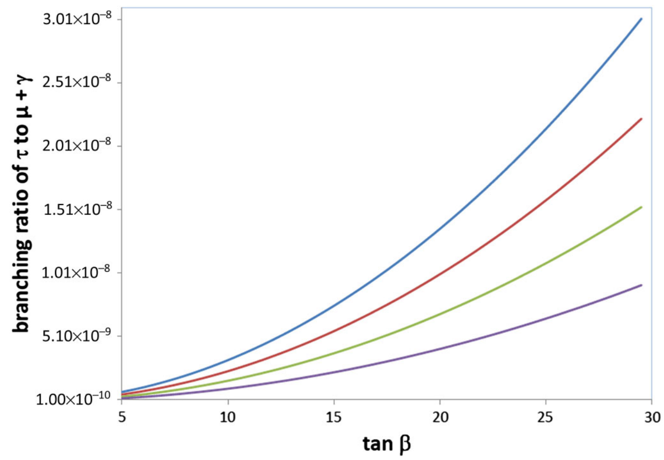


FIG. 7 (color online). An exhibition of the dependence of $\mathcal{B}(\tau \to \mu\gamma)$ on $\tan\beta$ when $m_0 = 700$, $m_N = 200$, $m_E = 300$, $|f_3| = |f_3'| = 180$, $|f_4| = |f_4'| = 100$, $|f_5| = |f_5'| = 150$, $|A_0| = 360$, $\tilde{m}_1 = 120$, $\tilde{m}_2 = 80$, $\mu = 140$, $\chi_3 = \chi_3' = 0.7$, $\chi_4 = \chi_4' = 0.9$, $\chi_5 = \chi_5' = 0.6$, $\alpha_E = 0.9$, $\alpha_N = 0.4$, and $\chi_3 = 1.2, 0.8, 0.5, 0.1$ (in ascending order at $\tan\beta = 30$).

for a vectorlike multiplet; see, e.g., Ref. [26]. The choice of parameters in our analysis is consistent with this work.

## VI. CONCLUSION

Lepton flavor changing processes provide an important window to new physics beyond the standard model. In this work we have analyzed the decay $\tau \to \mu + \gamma$ in extensions of the MSSM with vectorlike leptonic multiplets which are anomaly free. Specifically we consider mixings between the standard model generations of leptons with the mirror leptons in the vector multiplet. "It is because of these mixings which are parametrized by $f_3$, $f_4$, $f_5$ and $f_3'$, $f_4'$, $f_5'$ as defined in Eq. (7) that lepton flavor violations appear." We focus on the supersymmetric sector and compute contributions to this process arising from diagrams with exchange of charginos and sneutrinos in the loop and with the exchange of neutralinos and staus in the loop. These loops do not preserve lepton flavor. A full analytic analysis of these loops was given which constitutes the main result of this work. A numerical analysis was also carried out and it is found that there exists a significant part of the parameter space where one can have the branching ratio for this process in the range $4.4 \times 10^{-8} - 10^{-9}$, where $4.4 \times 10^{-8}$ at 90% C.L. is the upper limit from *BABAR* [see Eq. (1)] and the lower limit is the sensitivity that the SuperB factories will achieve. Thus it is very likely that improved experiment with a better sensitivity may be able to probe this class of models.

Finally we wish to remark on the implications of the recent LHC data specifically as it relates to the Higgs boson discovery for the present analysis. Here we note that the precise determination of the Higgs mass achieved in recent LHC data has no direct implication on the analysis. However, the new vectorlike multiplet could have an effect on the loop corrections to the Higgs decay branching ratios such as $h \to \tau\bar{\tau}$, $W^+W^-$, etc. Computation of such corrections is outside the scope of this work. The current work also has implications for collider phenomenology. Some of the collider phenomenology for this class of models specifically as relates to the mirrors was discussed in Ref. [11] (see also Ref. [27]). The signatures for a vectorlike lepton multiplet would arise from a Drell-Yan process such as in $pp \to Z^* + X$ with $Z^* \to E^c + \bar{E}^c$ with $E^c + \bar{E}^c$ decaying into $\tau\bar{\tau}$. Thus one should see an excess of $\tau\bar{\tau}$ events. However, the detection efficiency of taus is poorer than the detection efficiency for the muons and for this reason the detection of the vectorlike leptons and vectorlike sleptons will be more difficult than the detection of, for example, smuons produced by the Drell-Yan process. A more detailed discussion of this issue requires a separate analysis and is outside the scope of this work.

## ACKNOWLEDGMENTS

One of us (T. I.) would like to thank the Faculty of Science at BAU for hospitality. This research is supported in part by NSF Grants No. PHY-0757959 and No. PHY-0704067.

## APPENDIX

In this Appendix, we consider the mixings of the charged sleptons and the charged mirror sleptons. The mass$^2$ matrix of the slepton-mirror slepton comes from three sources, the $F$ term, the $D$ term of the potential and soft supersymmetry breaking terms. Using the superpotential of Eq. (7) the mass terms arising from it after the breaking of the electroweak symmetry are given by $\mathcal{L}_F$ and $\mathcal{L}_D$:

$$\begin{aligned}
-\mathcal{L}_F ={}& (m_E^2 + |f_3|^2 + |f_3'|^2)\tilde{E}_R\tilde{E}_R^* + (m_N^2 + |f_3|^2 + |f_3'|^2)\tilde{N}_R\tilde{N}_R^* + (m_E^2 + |f_4|^2 + |f_4'|^2)\tilde{E}_L\tilde{E}_L^* \\
&+ (m_N^2 + |f_5|^2 + |f_5'|^2)\tilde{N}_L\tilde{N}_L^* + (m_\tau^2 + |f_4|^2)\tilde{\tau}_R\tilde{\tau}_R^* + (m_{\nu_\tau}^2 + |f_5|^2)\tilde{\nu}_{\tau R}\tilde{\nu}_{\tau R}^* + (m_\tau^2 + |f_3|^2)\tilde{\tau}_L\tilde{\tau}_L^* \\
&+ (m_\mu^2 + |f_4'|^2)\tilde{\mu}_R\tilde{\mu}_R^* + (m_\mu^2 + |f_3'|^2)\tilde{\mu}_L\tilde{\mu}_L^* + (m_{\nu_\tau}^2 + |f_3|^2)\tilde{\nu}_{\tau L}\tilde{\nu}_{\tau L}^* + (m_{\nu_\mu}^2 + |f_3'|^2)\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}^* \\
&+ (m_{\nu_\mu}^2 + |f_5'|^2)\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}^* + \{-m_\tau\mu^*\tan\beta\tilde{\tau}_L\tilde{\tau}_R^* - m_N\mu^*\tan\beta\tilde{N}_L\tilde{N}_R^* - m_{\nu_\tau}\mu^*\cot\beta\tilde{\nu}_{\tau L}\tilde{\nu}_{\tau R}^* - m_\mu\mu^*\tan\beta\tilde{\mu}_L\tilde{\mu}_R^* \\
&- m_{\nu_\mu}\mu^*\cot\beta\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu R}^* - m_E\mu^*\cot\beta\tilde{E}_L\tilde{E}_R^* + (m_E f_3^* + m_\tau f_4)\tilde{E}_L\tilde{\tau}_L^* + (m_E f_4 + m_\tau f_3^*)\tilde{E}_R\tilde{\tau}_R^* + (m_E f_3'^* + m_\mu f_4')\tilde{E}_L\tilde{\mu}_L^* \\
&+ (m_E f_4' + m_\mu f_3'^*)\tilde{E}_R\tilde{\mu}_R^* + (m_{\nu_\tau} f_5 - m_N f_3^*)\tilde{N}_L\tilde{\nu}_{\tau L}^* + (m_N f_5 - m_{\nu_\tau} f_3^*)\tilde{N}_R\tilde{\nu}_{\tau R}^* + (m_{\nu_\mu} f_5' - m_N f_3^*)\tilde{N}_L\tilde{\nu}_{\mu L}^* \\
&+ (m_N f_5' - m_{\nu_\mu} f_3'^*)\tilde{N}_R\tilde{\nu}_{\mu R}^* + f_3' f_3^*\tilde{\mu}_L\tilde{\tau}_L^* + f_4 f_4'^*\tilde{\mu}_R\tilde{\tau}_R^* + f_3' f_3^*\tilde{\nu}_{\mu L}\tilde{\nu}_{\tau_L^*} + f_5 f_5'^*\tilde{\nu}_{\mu R}\tilde{\nu}_{\tau R}^* + \text{H.c.}\}. \qquad \text{(A1)}
\end{aligned}$$

Similarly the mass terms arising from the $D$ term are given by

$$-\mathcal{L}_D = \frac{1}{2} m_Z^2 \cos^2\theta_W \cos 2\beta\{\tilde{\nu}_{\tau L}\tilde{\nu}^*_{\tau L} - \tilde{\tau}_L\tilde{\tau}^*_L + \tilde{\nu}_{\mu L}\tilde{\nu}^*_{\mu L} - \tilde{\mu}_L\tilde{\mu}^*_L + \tilde{E}_R\tilde{E}^*_R - \tilde{N}_R\tilde{N}^*_R\} + \frac{1}{2} m_Z^2 \sin^2\theta_W \cos 2\beta\{\tilde{\nu}_{\tau L}\tilde{\nu}^*_{\tau L} + \tilde{\tau}_L\tilde{\tau}^*_L + \tilde{\nu}_{\mu L}\tilde{\nu}^*_{\mu L} + \tilde{\mu}_L\tilde{\mu}^*_L - \tilde{E}_R\tilde{E}^*_R - \tilde{N}_R\tilde{N}^*_R + 2\tilde{E}_L\tilde{E}^*_L - 2\tilde{\tau}_R\tilde{\tau}^*_R - 2\tilde{\mu}_R\tilde{\mu}^*_R\}. \tag{A2}$$

In addition we have the following set of soft breaking terms:

$$V_{\rm soft} = \tilde{M}^2_{\tau L}\tilde{\psi}^{i*}_{\tau L}\tilde{\psi}^i_{\tau L} + \tilde{M}^2_\chi \tilde{\chi}^{ci*}\tilde{\chi}^{ci} + \tilde{M}^2_{\mu L}\tilde{\psi}^{i*}_{\mu L}\tilde{\psi}^i_{\mu L} + \tilde{M}^2_{\nu_\tau}\tilde{\nu}^{c*}_{\tau L}\tilde{\nu}^c_{\tau L} + \tilde{M}^2_{\nu_\mu}\tilde{\nu}^{c*}_{\mu L}\tilde{\nu}^c_{\mu L} + \tilde{M}^2_\tau\tilde{\tau}^{c*}_L\tilde{\tau}^c_L + \tilde{M}^2_\mu\tilde{\mu}^{c*}_L\tilde{\mu}^c_L + \tilde{M}^2_E\tilde{E}^*_L\tilde{E}_L + \tilde{M}^2_N\tilde{N}^*_L\tilde{N}_L + \epsilon_{ij}\{f_1A_\tau H_1^i\tilde{\psi}^j_{\tau L}\tilde{\tau}^c_L - f_1'A_{\nu_\tau}H_2^i\tilde{\psi}^j_{\tau L}\tilde{\nu}^c_{\tau L} + h_1A_\mu H_1^i\tilde{\psi}^j_{\mu L}\tilde{\mu}^c_L - h_1'A_{\nu_\mu}H_2^i\tilde{\psi}^j_{\mu L}\tilde{\nu}^c_{\mu L} + f_2A_NH_1^i\tilde{\chi}^{cj}\tilde{N}_L - f_2'A_EH_2^i\tilde{\chi}^{cj}\tilde{E}_L + \text{H.c.}\}. \tag{A3}$$

From $\mathcal{L}_{F,D}$ and by giving the neutral Higgs their vacuum expectation values in $V_{\rm soft}$ we can produce the the mass$^2$ matrix $M^2_{\tilde{\tau}}$ in the basis $(\tilde{\tau}_L, \tilde{E}_L, \tilde{\tau}_R, \tilde{E}_R, \tilde{\mu}_L, \tilde{\mu}_R)$. We label the matrix elements of these as $(M^2_{\tilde{\tau}})_{ij} = M^2_{ij}$, where

$$\begin{aligned}
M^2_{11} &= \tilde{M}^2_{\tau L} + m_\tau^2 + |f_3|^2 - m_Z^2\cos 2\beta\left(\frac{1}{2} - \sin^2\theta_W\right),\\
M^2_{22} &= \tilde{M}^2_E + m_E^2 + |f_4|^2 + |f_4'|^2 + m_Z^2\cos 2\beta\sin^2\theta_W,\\
M^2_{33} &= \tilde{M}^2_\tau + m_\tau^2 + |f_4|^2 - m_Z^2\cos 2\beta\sin^2\theta_W,\\
M^2_{44} &= \tilde{M}^2_\chi + m_E^2 + |f_3|^2 + |f_3'|^2 + m_Z^2\cos 2\beta\left(\frac{1}{2} - \sin^2\theta_W\right),\\
M^2_{55} &= \tilde{M}^2_{\mu L} + m_\mu^2 + |f_3'|^2 - m_Z^2\cos 2\beta\left(\frac{1}{2} - \sin^2\theta_W\right),\\
M^2_{66} &= \tilde{M}^2_\mu + m_\mu^2 + |f_4'|^2 - m_Z^2\cos 2\beta\sin^2\theta_W,\\
M^2_{12} &= M^{2*}_{21} = m_E f_3^* + m_\tau f_4,\\
M^2_{13} &= M^{2*}_{31} = m_\tau(A^*_\tau - \mu\tan\beta), \qquad M^2_{14} = M^{2*}_{41} = 0,\\
M^2_{15} &= M^{2*}_{51} = f_3' f_3^*, \qquad M^{2*}_{16} = M^{2*}_{61} = 0,\\
M^2_{23} &= M^{2*}_{32} = 0, \qquad M^2_{24} = M^{2*}_{42} = m_E(A^*_E - \mu\cot\beta),\\
M^2_{25} &= M^{2*}_{52} = m_E f_3' + m_\mu f_4'^*, \qquad M^2_{26} = M^{2*}_{62} = 0,\\
M^2_{34} &= M^{2*}_{43} = m_E f_4 + m_\tau f_3^*, \qquad M^2_{35} = M^{2*}_{53} = 0,\\
M^2_{36} &= M^{2*}_{63} = f_4 f_4'^*, \qquad M^2_{45} = M^{2*}_{54} = 0,\\
M^2_{46} &= M^{2*}_{64} = m_E f_4'^* + m_\mu f_3',\\
M^2_{56} &= M^{2*}_{65} = m_\mu(A^*_\mu - \mu\tan\beta).
\end{aligned} \tag{A4}$$

Here the terms $M^2_{11}$, $M^2_{13}$, $M^2_{31}$, $M^2_{33}$ arise from soft breaking in the sector $\tilde{\tau}_L$, $\tilde{\tau}_R$, the terms $M^2_{55}$, $M^2_{56}$, $M^2_{65}$, $M^2_{66}$ arise from soft breaking in the sector $\tilde{\mu}_L$, $\tilde{\mu}_R$, and the terms $M^2_{22}$, $M^2_{24}$, $M^2_{42}$, $M^2_{44}$ arise from soft breaking in the sector $\tilde{E}_L$, $\tilde{E}_R$. The other terms arise from mixing between the staus, smuons and the mirrors. We assume that all the masses are of the electroweak size so all the terms enter in the mass$^2$ matrix. We diagonalize this Hermitian mass$^2$ matrix by the unitary transformation $\tilde{D}^{\tau\dagger}M^2_{\tilde{\tau}}\tilde{D}^\tau = \text{diag}(M^2_{\tilde{\tau}_1}, M^2_{\tilde{\tau}_2}, M^2_{\tilde{\tau}_3}, M^2_{\tilde{\tau}_4}, M^2_{\tilde{\tau}_5}, M^2_{\tilde{\tau}_6})$. There is a similar mass$^2$ matrix in the sneutrino sector. In the basis $(\tilde{\nu}_{\tau L}, \tilde{N}_L, \tilde{\nu}_{\tau R}, \tilde{N}_R, \tilde{\nu}_{\mu L}, \tilde{\nu}_{\mu R})$ we can write the sneutrino mass$^2$ matrix in the form $(M^2_{\tilde{\nu}})_{ij} = m^2_{ij}$, where

$$\begin{aligned}
m^2_{11} &= \tilde{M}^2_{\tau L} + m^2_{\nu_\tau} + |f_3|^2 + \frac{1}{2}m_Z^2\cos 2\beta,\\
m^2_{22} &= \tilde{M}^2_N + m_N^2 + |f_5|^2 + |f_5'|^2,\\
m^2_{33} &= \tilde{M}^2_{\nu_\tau} + m^2_{\nu_\tau} + |f_5|^2,\\
m^2_{44} &= \tilde{M}^2_\chi + m_N^2 + |f_3|^2 + |f_3'|^2 - \frac{1}{2}m_Z^2\cos 2\beta,\\
m^2_{55} &= \tilde{M}^2_{\mu L} + m^2_{\nu_\mu} + |f_3'|^2 + \frac{1}{2}m_Z^2\cos 2\beta,\\
m^2_{66} &= \tilde{M}^2_{\nu_\mu} + m^2_{\nu_\mu} + |f_5'|^2,\\
m^2_{12} &= m^{2*}_{21} = m_{\nu_\tau}f_5 - m_N f_3^*,\\
m^2_{13} &= m^{2*}_{31} = m_{\nu_\tau}(A^*_{\nu_\tau} - \mu\cot\beta), \qquad m^2_{14} = m^{2*}_{41} = 0,\\
m^2_{15} &= m^{2*}_{51} = f_3' f_3^*, \qquad m^2_{16} = m^{2*}_{61} = 0,\\
m^2_{23} &= m^{2*}_{32} = 0, \qquad m^2_{24} = m^{2*}_{42} = m_N(A^*_N - \mu\tan\beta),\\
m^2_{25} &= m^{2*}_{52} = -m_N f_3' + m_{\nu_\mu}f_5'^*, \qquad m^2_{26} = m^{2*}_{62} = 0,\\
m^2_{34} &= m^{2*}_{43} = m_N f_5 - m_{\nu_\tau}f_3^*, \qquad m^2_{35} = m^{2*}_{53} = 0,\\
m^2_{36} &= m^{2*}_{63} = f_5 f_5'^*, \qquad m^2_{45} = m^{2*}_{54} = 0,\\
m^2_{46} &= m^{2*}_{64} = -m_{\nu_\mu}f_3' + m_N f_5'^*,\\
m^2_{56} &= m^{2*}_{65} = m_{\nu_\mu}(A^*_{\nu_\mu} - \mu\cot\beta).
\end{aligned} \tag{A5}$$

As in the charged slepton sector here also the terms $m^2_{11}$, $m^2_{13}$, $m^2_{31}$, $m^2_{33}$ arise from soft breaking in the sector $\tilde{\nu}_{\tau L}$, $\tilde{\nu}_{\tau R}$, the terms $m^2_{55}$, $m^2_{56}$, $m^2_{65}$, $m^2_{66}$ arise from soft breaking in the sector $\tilde{\nu}_{\mu L}$, $\tilde{\nu}_{\mu_R}$, and the terms $m^2_{22}$, $m^2_{24}$, $m^2_{42}$, $m^2_{44}$ arise from soft breaking in the sector $\tilde{N}_L$, $\tilde{N}_R$. The other terms arise from mixing between the physical sector and the mirror sector. Again as in the charged lepton sector we assume that all the masses are of the electroweak size so all the terms enter in the mass$^2$ matrix. This mass$^2$ matrix can be diagonalized by the unitary transformation $\tilde{D}^{\nu\dagger}M^2_{\tilde{\nu}}\tilde{D}^\nu = \text{diag}(M^2_{\tilde{\nu}_1}, M^2_{\tilde{\nu}_2}, M^2_{\tilde{\nu}_3}, M^2_{\tilde{\nu}_4}, M^2_{\tilde{\nu}_5}, M^2_{\tilde{\nu}_6})$. The states $\tilde{\tau}_i$, $\tilde{\nu}_i$; $i = 1$–$6$ are the slepton and sneutrino mass eigenstates.

[1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **104**, 021802 (2010).

[2] K. Hayasaka *et al.* (Belle Collaboration), Phys. Lett. B **666**, 16 (2008).

[3] B. O'Leary *et al.* (SuperB Collaboration), arXiv:1008.1541.

[4] T. Aushev *et al.*, arXiv:1002.5012.

[5] M. E. Biagini *et al.* (SuperB Collaboration), arXiv:1009.6178.

[6] J. L. Hewett *et al.*, arXiv:1205.2671.

[7] H. Georgi, Nucl. Phys. **B156**, 126 (1979); F. Wilczek and A. Zee, Phys. Rev. D **25**, 553 (1982); J. Maalampi, J. T. Peltoniemi, and M. Roos, Phys. Lett. B **220**, 441 (1989); J. Maalampi and M. Roos, Phys. Rep. **186**, 53 (1990); K. S. Babu, I. Gogoladze, P. Nath, and R. M. Syed, Phys. Rev. D **72**, 095011 (2005); **74**, 075004 (2006); **85**, 075002 (2012); P. Nath and R. M. Syed, Phys. Rev. D **81**, 037701 (2010).

[8] T. Ibrahim and P. Nath, Phys. Rev. D **81**, 033007 (2010).

[9] T. Ibrahim and P. Nath, Phys. Rev. D **84**, 015003 (2011).

[10] T. Ibrahim and P. Nath, Phys. Rev. D **82**, 055001 (2010).

[11] T. Ibrahim and P. Nath, Phys. Rev. D **78**, 075013 (2008).

[12] T. Ibrahim and P. Nath, Nucl. Phys. B, Proc. Suppl. **200–202**, 161 (2010).

[13] K. S. Babu, I. Gogoladze, M. U. Rehman, and Q. Shafi, Phys. Rev. D **78**, 055017 (2008).

[14] C. Liu, Phys. Rev. D **80**, 035004 (2009).

[15] S. P. Martin, Phys. Rev. D **81**, 035004 (2010); **82**, 055019 (2010); **83**, 035019 (2011).

[16] P. W. Graham, A. Ismail, S. Rajendran, and P. Saraswat, Phys. Rev. D **81**, 055016 (2010).

[17] R. L. Arnowitt and P. Nath, Phys. Rev. Lett. **66**, 2708 (1991).

[18] R. Barbieri, L. J. Hall, and A. Strumia, Nucl. Phys. **B445**, 219 (1995).

[19] E. O. Iltan, Phys. Rev. D **64**, 013013 (2001).

[20] S. Lavignac, I. Masina, and C. A. Savoy, Phys. Lett. B **520**, 269 (2001).

[21] K.-m. Cheung and O. C. W. Kong, Phys. Rev. D **64**, 095007 (2001).

[22] A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, and T. Hambye, Phys. Rev. D **78**, 033007 (2008).

[23] S. Davidson and G. J. Grenier, Phys. Rev. D **81**, 095016 (2010).

[24] A. Moyotl and G. Tavares-Velasco, Phys. Rev. D **86**, 013014 (2012).

[25] T. Ibrahim and P. Nath, Rev. Mod. Phys. **80**, 577 (2008); arXiv:hep-ph/0210251; A. Pilaftsis, arXiv:hep-ph/9908373.

[26] G. Cynolter and E. Lendvai, Eur. Phys. J. C **58**, 463 (2008).

[27] W. Skiba and D. Tucker-Smith, Phys. Rev. D **75**, 115010 (2007).