Flavor mixed sleptons and its consequences at one-loop level

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Abstract. In this work we explore a lepton flavor violation effect induced at one-loop level in an extended version of the minimal supersymmetric standard model with a flavor structure which mix second and third families in the trilinear terms of the soft supersymmetric Lagrangian. In particular, we find a finite expression for $BR(\tau \rightarrow \mu \gamma)$ and $BR(h \rightarrow \mu \tau)$ decay, produced by flavor mixed sleptons running in the loop. We would also calculate the $\mu \rightarrow \mu \gamma$ 1-loop extra contribution that can lead to a solution of the muon $g-2$ problem in some regions of parameter space.

1. Introduction

In the Standard Model (SM) lepton flavor violation processes are forbidden by lepton number conservation, which is not associated with a gauge symmetry. The spontaneous breaking of the electroweak symmetry produces eigenstates of the remaining gauge group that are not in general eigenstates of the mass matrix, but after diagonalization of the mass matrix, the electroweak coupling matrix is also diagonal in the mass basis, therefore there is no possibility for lepton flavor violation. Nevertheless, this symmetry is lost once the neutrino oscillations are considered, forcing the model structure to go beyond the SM.

This lost symmetry on leptons evidenced in the neutrino mixing opens also the possibility of lepton flavor violation in the charged sector. The original structure of the SM with massless, and thus degenerate neutrinos, implied separately $\tau, \mu, e$ number conservation. In particular, the processes $\tau^\pm \rightarrow l^\pm \gamma, (l = \mu^\pm, e^\pm)$ through gauge bosons loops are predicted to give\(^1 \) very low rates [1]. Experimental data taken from CMS at 8 TeV with 19.7 fb\(^{-1}\) had shown an excess for $BR(h^0 \rightarrow \tau \mu)$ of 2.4σ with best fit branching fraction of 0.84\(^{+0.39}_{-0.37}\%\) [2]. Nevertheless data from ATLAS has shown only a 1σ significance for the same process [3]. Moreover, also recent measurements at 13 TeV, although only with 2.3 fb\(^{-1}\) of data, have shown no evidence of excess. It was even reported in [4] a best fit branching fraction of −0.56%. The sign change may imply a statistical error in the data. Even for these latest reports, if they are confirmed, they will indicate a very low range for this lepton flavor violation processes to occur at these energies, which will set stringent bounds to any model beyond the SM. One of the works toward this direction is

\(^1\) A maximal mixing and a value of $\Delta_{23}^\text{sol} \approx 3 \times 10^{-3}(eV/fc^2)^2$ gives $B(\tau \rightarrow \mu \gamma) \approx O(10^{-54})$
done in [5], where it has been explored in a Two Higgs Doublet Model type III (THDM-III) with flavor violation in the Yukawa couplings [6]. In the model we propose in this work, i.e. a scalar flavor extended MSSM in the soft sector, these bounds should show exclusion regions in the parameter space.

The most recent data by the LHC at 13 TeV have not shown evidence for supersymmetry for different channels and observables as events with one lepton as final state [4], jets and leptons or three leptons [7], and missing energy [8]. The experimental search is mainly for the Lightest Supersymmetric Particle (LSP) as missing energy, and the data is analyzed in simplified supersymmetric models at this specific energy. The results of these analyses have reduced the parameter space for the Minimal Supersymmetric Standard Model (MSSM). Nevertheless, it is important to fully explore the possible parameter space for different non-minimal supersymmetric low energy models since supersymmetry still solves many phenomenological issues [9, 10] and is also a requisite for many GUT models. A review on flavor violation processes in the MSSM considering neutrino mixing can be found in [11]. In this work we implement a flavor structure which implies flavour violation and non-universality of sfermions, this was previously introduced in [12] and was used also in a similar work in [13].

2. Flavor mixed sleptons

As the evidence on flavor violation in charged lepton is not yet conclusive but gives low values for these branching ratios, one possibility is to have a mixed flavor structure in an unseen sector as the sfermions, and then this mixing will induce flavor violation through radiative corrections.

In the MSSM the conventional mechanism to introduce LFV is through the Yukawa couplings of the right handed neutrinos, $N_i$, that generate off-diagonal entries in the mass matrices for sleptons through renormalization effects [14, 15], particularly in the $LL$ block of the sleptons mass matrix. Then the predicted rates for the $\tau \rightarrow \mu \gamma$ and $\mu \rightarrow e \gamma$ decays are not suppressed. In Ref. [16] the authors analyzed the left-right mixing terms in the slepton mass matrix, and their contributions to the LFV processes, finding that these can be large even when the off diagonal Yukawa couplings elements are small. For their loop calculation they used an approximation method known as Mass Insertion Approximation. In another paper [17], they incorporated the full mixing of the slepton masses and mixing in the neutralino and chargino sector and then performed a numerical diagonalization of the slepton mass matrices, using again MIA. An interesting result of their analysis is that the contribution from the left-right mixing is only important in the region where the mixing term is $m_{\tau \mu} \tan \beta \sim O(\tilde{m}_3^2)$ and they consider the trilinear soft terms $A_{E,i,j}$ contribution to be zero.

In our work we do not assume alignment of $A$-terms with the Yukawa matrix, we consider a specific flavor structure of $A$-terms, which only mix second and third families. This mixing may come from a discrete flavor symmetry, as for instance $Q_6$ [18]. We find the mass eigenstates, which are no longer flavor defined, then FV is introduced directly on the couplings and there is no need of a Mass Insertion term. We assume that the Bino is the lightest neutralino and is decoupled from the others, so that their contributions are strongly suppressed. In the case of sfermions, as they are scalar particles ($SU(2)$ singlets), the $L,R$ are just labels which identify their fermionic SM partners, but they do not have left and right $SU(2)$ properties. In the MSSM there is a $2 \times 2$ mixing, here the mixing would be for four states and may arise from a flavor structure in the mass matrix

$$\tilde{\mu}_{L,R},\tilde{\tau}_{L,R} \rightarrow \tilde{l}_{1,2,3,4}. \tag{1}$$

These type of structures have been studied before from different sources of FV in the scalar sector [19] as well as their link to the muon $g - 2$. In a previous work [20] we performed the one-loop calculation and integrated with no approximations to obtain thus the expressions reported
We calculate slepton mixing from one-loop contributions to the soft supersymmetric Lagrangian, the FV couplings appear once we obtain explicitly the physical states for the sfermions

\[
\mathcal{L}^I_{\text{soft}} = - \sum_{ij} \tilde{M}^2_{ij} \tilde{f}_i \tilde{f}_j - (A^I_{ij} \tilde{f}_i H_1 \tilde{f}^c_j + h.c.),
\]

where \( \tilde{f} \) are the scalar fields in the supermultiplet. Once the EW symmetry breaking is considered, the trilinear term of the soft SUSY Lagrangian (second term in eq. (2)) for the slepton sector takes the following form

\[
\mathcal{L}_{H_f}^{f_i f_j} = \frac{A^{ij}}{\sqrt{2}} \left[ (\phi^0_1 - i\chi^0_1) \tilde{\nu}_{R i} \tilde{\nu}_{R j} L - \sqrt{2} \phi^0_1 \bar{t}_{R i} \bar{t}_{R j} L + v_1 \tilde{\nu}_{R i} \tilde{\nu}_{R j} L + h.c. \right].
\]

We can see, from the flavor non-minimal structure of the trilinear terms of the soft breaking Lagrangian, that we would have FV couplings in charged sleptons, but also with sleptons and sneutrinos via the charged Higgs boson, and the last term implies an extra contribution also to the mass of the sleptons. The contribution to the elements of the sfermion mass matrix come from the interaction of the Higgs scalars with the sfermions, which appear in different terms of the superpotential and soft-SUSY breaking terms as is fully explained in [22, 23]. We work on a model which considers flavor violation between two families in the trilinear scalar couplings. This would give rise to a 4 \times 4 matrix, diagonalizable through a unitary matrix \( Z_i \), such that \( M^I_{\text{flavor}} Z_i = M^I_{\text{diag}} \). For the complete and explicit development of the mixing flavor slepton model we refer to [20]. From those results we calculate the amplitude matrices for the different processes we analyze here. The physical non-degenerate slepton masses are given by

\[
m^2_{\tilde{t}_{1,2,3,4}} = \frac{1}{2} \left[ 2m_S^2 \pm X_m - X_t \pm R \right],
\]

where \( R = \sqrt{4A^2_y + (X_t - X_m)^2} \) with \( A_y = \frac{1}{\sqrt{2}} y A_0 v \cos \beta \), \( X_m = \frac{1}{\sqrt{2}} w A_0 v \cos \beta - \mu_{\text{susy}} m_{\mu} \tan \beta \) and \( X_t = \frac{1}{\sqrt{2}} A_0 v \cos \beta - \mu_{\text{MSSM}} \tan \beta \).

We may write the transformation which diagonalizes the mass matrix and rotates the nonphysical flavor states \( (\tilde{\mu}_L, \tilde{\tau}_L, \tilde{\mu}_R, \tilde{\tau}_R) \) to the physical mixed flavor \( \tilde{t}_{1,2,3,4} \), eigenstates eq. (1) by the rotation matrix \( Z_i \), which is a 4 \times 4 rotation matrix, explicitly having the form

\[
Z_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi & -\Phi \\ \Phi \sigma^3 & \Phi \sigma^3 \end{pmatrix},
\]

where \( \sigma_3 \) is the Pauli matrix and

\[
\Phi = \begin{pmatrix} -\sin \frac{\varphi}{2} & -\cos \frac{\varphi}{2} \\ \cos \frac{\varphi}{2} & -\sin \frac{\varphi}{2} \end{pmatrix}, \quad \tan \varphi = \frac{2A_y}{X_m - X_t},
\]

3. One-loop flavor violation processes within muons and taus

We calculate slepton mixing flavor one-loop contributions to the \( BR(\tau \rightarrow \mu \gamma) \), muon \( g - 2 \) and the radiative induced Higgs flavor violation decay \( h^0 \rightarrow \mu \tau \). We have showed in [20] that the total amplitude for \( BR(\tau \rightarrow \mu \gamma) \) and the muon \( g - 2 \) diagrams are gauge invariant and free of UV divergences. We show here that the decay \( h^0 \rightarrow \mu \tau \) is UV finite, eqs. (11) and (10). Notice that the total amplitude includes all possible combinations of sleptons in the internal lines, for which we have \( \mathcal{M}_{T} = \sum_{j,k} \mathcal{M}_{jk} \).
Figure 1. Numerical results for $BR(\tau \to \mu \gamma)$ dependence on the ratio of Bino mass $M_1$ and the SUSY mass breaking scale $\tilde{m}_S$. The gray points (in top) are excluded by direct experimental bounds. Points which do not solve the $g-2$ muon problem are shown in red (mostly around $0 \lesssim M_1/\tilde{m}_S \lesssim 1.5$); the ones that solve it partially are in blue (mostly for $1.3 \lesssim M_1/\tilde{m}_S \lesssim 1.5$), and points which solve it completely in black (mostly for $1.5 \lesssim M_1/\tilde{m}_S \lesssim 2.4$).

We calculate the supersymmetric sfermion-Bino one-loop contribution to the leptonic flavor violation process $\tau \to \mu + \gamma$ and also for the muon $g-2$. The experimental bound to the branching ratio for this decay at 90\% C.L. [24] is $BR(\tau^{\pm} \to \mu^{\pm}\gamma) < 4.4 \times 10^{-8}$. The branching ratio of the $\tau \to \mu + \gamma$ decay is given by the expression [20]

$$BR(\tau \to \mu \gamma) = \frac{(1-x^2)^3 m_\tau^3}{4\pi \Gamma_\tau} |E|^2 + |F|^2.$$  

(6)

Numerical results of the above are shown in Fig. 1, where the gray points are excluded from direct experimental bounds. The red points are FV allowed points which do not solve the muon $g-2$ problem; in blue are FV points that also partially solve $g-2$, whereas the black points show the parameter space where these contributions solve it completely.

3.1. Higgs flavor violation coupling with sleptons

The Lagrangian which gives the interaction of scalar neutral light Higgs $h^0$-slepton-slepton is given as

$$L_{h^0\tilde{l}\tilde{l}} = Q_I \left[ \tilde{l}_L^* \tilde{l}_L + \tilde{l}_R^* \tilde{l}_R \right] h^0 + G \left[ \left(-\frac{1}{2} + s_w^2\right) \tilde{l}_L^* \tilde{l}_L - s_w^2 \tilde{l}_R^* \tilde{l}_R \right] h^0 + \chi_I \left[ \tilde{l}_L^* \tilde{l}_R + \tilde{l}_R^* \tilde{l}_L \right] h^0,$$

(7)

where

$$Q_{\mu,\tau} = \frac{g m_{\mu,\tau}^2 \sin \alpha}{M_w \cos \beta}, \quad G = g_d M_2 \sin(\alpha + \beta), \quad \chi_{\mu,\tau} = \frac{g m_{\mu,\tau}^2 \sin \alpha}{2 M_w \cos \beta} (A_{\mu,\tau} - \mu \cot \alpha).$$

(8)

Then, in the slepton physical states, the explicit couplings to the light Higgs boson are given in [25].

$$\Gamma(h^0 \to \mu \tau) = \sum_{jk} B |\alpha_{jk}|^2 \left( C|S_{jk}|^2 + D|P_{jk}|^2 \right)$$

(9)

$S_{jk}$ is the scalar part and $P_{jk}$ is the pseudoscalar part of the matrix amplitude $M_{jk}$, their explicit forms are given below in Table 1. The parameter $\alpha_{jk}$ is build from all the constants coming from
functions that appear:

\[ \eta \]

Explicit form of the scalar and pseudoscalar parts of the matrix amplitude of the loop,

Table 1.

the product of the three couplings \( g_{h} f_{j} f_{k} g_{B} f_{j} \mu g_{B} f_{k} \tau \); and \( B, C \) and \( D \) are constants given by the external particle masses.

The functions in Table 1 \( f^{jk} \) involve all masses and are given by

\[ f^{jk} = \left( m^{2}_{h_{0}} - (m_{\mu} - m_{\tau})^{2} \right) \left( -m^{2}_{B}(m_{\mu} + m_{\tau}) + m_{\tau} \left( m^{2}_{f_{j}} - m^{2}_{h_{0}} + m_{\tau}(m_{\mu} + m_{\tau}) \right) + m^{2}_{f_{k}} m_{\mu} \right) . \]

We can see that the loops are UV finite from the following relations on the Passarino-Veltmann functions that appear:

\[ F^{jk}_{C} = \frac{i}{16\pi^{2}} C_{0}(m^{2}_{h_{0}}, m^{2}_{\mu}, m^{2}_{\tau}, m^{2}_{f_{j}}, m^{2}_{f_{k}}, m^{2}_{B}) \]

\[ F^{jk}_{B} = \frac{i}{16\pi^{2}} \left\{ m^{2}_{h_{0}} m_{\mu} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) - B_{0}(m^{2}_{\mu}, m^{2}_{B}, m^{2}_{f_{j}}) \right] \right. \]

\[ + \left. m^{2}_{h_{0}} m_{\tau} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) - B_{0}(m^{2}_{\tau}, m^{2}_{B}, m^{2}_{f_{j}}) \right] \right. \]

\[ + \left. m^{3}_{\mu} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) - B_{0}(m^{2}_{\mu}, m^{2}_{B}, m^{2}_{f_{j}}) \right] - m^{3}_{\tau} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) - B_{0}(m^{2}_{\tau}, m^{2}_{B}, m^{2}_{f_{j}}) \right] \right. \]

\[ + \left. m^{2}_{\mu} m_{\tau} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) + B_{0}(m^{2}_{\mu}, m^{2}_{B}, m^{2}_{f_{j}}) - 2B_{0}(m^{2}_{\tau}, m^{2}_{B}, m^{2}_{f_{j}}) \right] \right. \]

\[ + \left. m_{\mu} m^{2}_{\tau} \left[ B_{0}(m^{2}_{h_{0}}, m^{2}_{f_{j}}, m^{2}_{f_{k}}) + B_{0}(m^{2}_{\mu}, m^{2}_{B}, m^{2}_{f_{j}}) - 2B_{0}(m^{2}_{\tau}, m^{2}_{B}, m^{2}_{f_{j}}) \right] \right. \]

\[ (11) \]
4. Conclusions

In this work we consider a flavor structure on trilinear soft terms assuming a two family mixing in the sleptons, we explore the consequences of this structure in a particular process involving lepton flavor violation for the Higgs boson. We obtain non-degenerate slepton masses for four of the sleptons which are decoupled from the first family and mixed in flavor. We also found that in the physical basis two specific couplings of the Higgs boson with sleptons are zero, i.e. \[ g_{h\tilde{l}^1\tilde{l}^3} = g_{h\tilde{l}^2\tilde{l}^4} = 0 \]. For our ansatz consideration, the contribution to processes involving first family mixing are absent. We obtain the expressions for the one-loop radiative corrections of the specific process \( \tau \to \mu \gamma \) and \( h^0 \to \tau \mu \). The expressions we obtain are found to be UV-finite and can be used to constrain the parameter space of the supersymmetric model applied to this process, as it is very restricted by the experimental data. This kind of structure also gives extra contributions to the muon anomalous magnetic moment \( g - 2 \). A complete exploration of the parameter for all these processes will be a goal for a future work.

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