D-term challenges for supersymmetric gauged abelian flavor symmetries

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Abstract

Attention is called to potentially dangerous lepton-flavor violation (LFV) induced by the $D$-terms of additional $U(1)$ flavor-dependent gauge symmetries in supersymmetric models. In such models, LFV persists despite an arbitrarily high scale for the $U(1)$ breaking and despite arbitrarily small gauge couplings. In light of recent experimental observations of neutrino oscillations, these models are highly motivated experimentally and theoretically. Taking into account also the recent measurement of the muon anomalous magnetic moment, strong bounds are calculated for the magnitude of the $D$-term-induced LFV. Using current data we find that the slepton mass-mixing parameter $(m_{\tilde{e}_L}^2)_{12}/m_{\tilde{e}_L}^2$ is required to be less than $O(10^{-4})$ — a value perhaps already too low compared to expectations. Near future probes will increase sensitivity to $10^{-6}$. 
1 Motivation

Recent atmospheric [1] and solar [2] neutrino experiments provide convincing evidence for physics beyond the standard model (SM). The interesting points are not only that they suggest non-zero neutrino masses, but also that they indicate the existence of large flavor mixings in the lepton sector. The different flavor structure between quark and lepton sectors would be an important hint for the fermion mass hierarchy problem. One interesting approach to accommodate both large mixing in the lepton sector and small mixing in the quark sector is the introduction of a $U(1)$ flavor-dependent symmetry. So far many models with the $U(1)$ flavor symmetry have been proposed to explain the observed fermion masses and mixings [3]. Such a $U(1)$ symmetry may originate from string theory [4].

Another interesting possible indication of new physics beyond the SM is the recent result for the muon anomalous magnetic moment (muon $g-2$) by the E821 experiment at Brookhaven National Laboratory [5]. It is found that the muon $g-2$ measurement is 2.6σ away from the SM prediction [1]:

$$a_\mu(\text{exp}) - a_\mu(\text{SM}) = 43(16) \times 10^{-10}.$$  \hspace{1cm} (1)

Since the size of the deviation is of the same order as the electroweak contribution to muon $g-2$, the result implies new physics around the TeV scale [7].

Weak scale supersymmetric (SUSY) extensions of the SM, which are well motivated by the hierarchy problem, provide a natural explanation of the anomaly of muon $g-2$ [8] when superpartners are light. In the SUSY version of the seesaw mechanism [9], non-zero neutrino masses are also naturally accommodated. For the present experimental status, the SUSY models are the best motivated extensions of the SM.

In general, if there are extra $U(1)$ gauge symmetries present in a supersymmetric model, the breaking of these symmetries will induce $D$-term contributions to the scalar masses [10]. Of the many interesting models with extra $U(1)$ gauge symmetries, we choose to focus on $U(1)$ flavor symmetries due to the recent intriguing neutrino observations. In the proposed models with $U(1)$ flavor symmetry [3], large flavor mixings may exist in the lepton sector. Thus the $D$-term contributions may induce large lepton flavor violation (LFV) through the sleptons. Since relatively light sleptons are expected
to explain the anomaly of muon $g-2$, the sleptons cannot decouple to suppress the large LFV from the $D$-term contributions. Therefore, experimental bounds on LFV processes strongly constrain SUSY models with $U(1)$ flavor symmetry.

2 $l_i \rightarrow l_j \gamma$ and muon $g-2$ correlations

Here we briefly demonstrate constraints on the LFV slepton masses from the $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ processes in light of the recent muon $g-2$ result [11]. Processes $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ are generated by one-loop diagrams mediated by sleptons, neutralinos, and charginos in the presence of LFV in the slepton masses (Fig. 1). When the left-handed sleptons have a LFV mass between the first and second generations ($m_{\tilde{l}_L}^{12}$), $\mu \rightarrow e\gamma$ process is induced. The branching ratio is given by

$$\text{Br}(\mu \rightarrow e\gamma) \simeq \frac{\pi}{75} \alpha \left( \alpha_2 + \frac{5}{4} \alpha_Y \right)^2 \frac{\tan^2 \beta}{G_F^2 m_{\text{SUSY}}^4} \left( \frac{(m_{\tilde{l}_L}^{12})_{12}}{m_{\text{SUSY}}^2} \right)^2, \quad (2)$$

where, for illustrative purposes, we simply assumed that all SUSY mass parameters are the same scale $m_{\text{SUSY}}$. From the current experimental limit \text{Br}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$ (MEGA) [12], we get a constraint on the LFV slepton mass:

$$\frac{(m_{\tilde{l}_L}^{12})_{12}}{m_{\text{SUSY}}^2} < 3 \times 10^{-4} \left( \frac{30}{\tan \beta} \right) \left( \frac{m_{\text{SUSY}}}{400 \text{ GeV}} \right)^2. \quad (3)$$

Note that if SUSY particles get heavier, the limit becomes weaker. Therefore, one solution to suppress the large LFV would be a “decoupling solution” in which the first and second generation sleptons are heavy enough to avoid the LFV problem [13].
However, when considering the muon $g-2$ measurement, the limit in Eq. (3) becomes much stricter. Since the $\mu \to e\gamma$ process originates from the same type of diagrams as muon $g-2$ (but without the slepton mass-mixing) (Fig. [1]), the branching ratio of $\mu \to e\gamma$ and the SUSY contribution to muon $g-2$ are correlated as stressed in Ref. [11]. If we take the soft mass parameters $M_1, M_2, m_{\tilde{l}},$ and $\mu$ to be equal at the weak scale, the SUSY contribution to $a_\mu$ is given by

$$\delta a_{\mu}^{\text{SUSY}} \approx \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_\mu^2}{m_{\text{SUSY}}^2} \tan \beta,$$

and

$$= 24 \times 10^{-10} \left( \frac{\tan \beta}{30} \right) \left( \frac{400 \text{ GeV}}{m_{\text{SUSY}}} \right)^2.$$

Note that a relatively light SUSY scale of the order $\mathcal{O}(100 \text{ GeV})$ can explain the E821 experiment in Eq. (1).

From Eqs. (2) and (5), we can obtain a relation between $\text{Br}(\mu \to e\gamma)$ and $\delta a_{\mu}^{\text{SUSY}}$. Then taking into account the limit on $\text{Br}(\mu \to e\gamma)$ and $\delta a_{\mu}^{\text{SUSY}}$ ($\delta a_{\mu}^{\text{SUSY}} > 10^{-9}$ at 2$\sigma$), we obtain a constraint on the LFV mass in terms of observables [11]:

$$\frac{(m_{\tilde{l}_L}^2)_{12}}{m_{\text{SUSY}}^2} < 7 \times 10^{-4} \left( \frac{10^{-9}}{\delta a_{\mu}^{\text{SUSY}}} \right) \left( \frac{\text{Br}(\mu \to e\gamma)}{1.2 \times 10^{-11}} \right)^{1/2}.$$

Comparing this result with that of Eq. (3), we should note an important difference. That is, we cannot have the decoupling solution if $\delta a_{\mu}^{\text{SUSY}}$ is fixed. Similarly, from $\tau \to \mu\gamma$, we have a bound on the LFV mass $(m_{\tilde{l}_L}^2)_{23}$ from the present experimental limit $\text{Br}(\tau \to \mu\gamma) < 1 \times 10^{-6}$ [14]:

$$\frac{(m_{\tilde{l}_L}^2)_{23}}{m_{\text{SUSY}}^2} < 5 \times 10^{-1} \left( \frac{10^{-9}}{\delta a_{\mu}^{\text{SUSY}}} \right) \left( \frac{\text{Br}(\tau \to \mu\gamma)}{1 \times 10^{-6}} \right)^{1/2}.$$

These findings signify an important correlation between the muon $g-2$ result and the problem of SUSY LFV. Therefore, the search for LFV processes will be significantly sensitive to any origins of LFV slepton masses. So far it has been pointed out that high-energy flavor-violating interactions [13], such

\footnote{In muon $g-2$, SUSY contribution from charginos and left-handed sleptons loop tend to be dominant. Therefore, if only right-handed sleptons have LFV masses, the correlation between $\text{Br}(\mu \to e\gamma)$ and $\delta a_{\mu}^{\text{SUSY}}$ becomes weaker (Ref. [11]).}
as GUT interactions [10] and large neutrino Yukawa interactions [17], can induce significant LFV in the slepton masses [18]. In the next section, we will show that $D$-term contributions of a $U(1)$ vector multiplet may generate large LFV in the slepton masses, and therefore searches for LFV severely constrain SUSY models with extra $U(1)$ gauge symmetries.

3 $D$-terms and sfermion mass-mixing

Although $D$-terms are a generic feature of extra $U(1)$ gauge symmetries in SUSY models, the Froggatt-Nielsen mechanism [19] is chosen to illustrate their effects on sfermion masses and mass-mixings while also addressing the fermion mass hierarchy problem for the quarks and leptons. In this letter, we consider only one $U(1)$ flavor symmetry denoted $U(1)_F$. However in the more general case of multiple $U(1)$ vector multiplets, there will simply be an additive effect of the $D$-terms. In this framework, Yukawa couplings originate from the following operator:

$$W_{\text{Yukawa}} = f_{ij} \left( \frac{\phi}{M_*} \right)^{Q_i+Q_j} \bar{\psi}_i \psi_j H \text{ (or } \bar{H} \text{).}$$ (8)

Here $M_*$ is a fundamental scale of the theory. Field $\psi_i$ represents ordinary quarks and leptons, whose $U(1)_F$ charge is $Q_i$ ($Q_i \geq 0$ by construction). Here we assumed that the $U(1)_F$ charges of the Higgs fields ($H$ and $\bar{H}$) and a field $\phi$ are 0 and $-1$, respectively. After the $U(1)_F$ symmetry is broken, the $\phi$ field gets a vacuum expectation value (vev) with $\langle \phi \rangle < M_*$, generating the hierarchical Yukawa couplings.

In SUSY models, if the $U(1)_F$ is a local symmetry, the breaking induces $D$-term contributions to the scalar masses. If the $U(1)_F$ symmetry is broken by fields $\phi_\pm$ of charge $\pm 1$, the $D$-term ($D_F$) obtains a vev

$$\langle D_F \rangle = g_F \left( \langle \phi_+ \rangle^2 - \langle \phi_- \rangle^2 \right) \simeq \frac{-1}{g_F} (m^2_+ - m^2_-).$$ (9)

Here $m_\pm$ are SUSY breaking masses for the $\phi_\pm$ fields, and $g_F$ is the $U(1)_F$ gauge coupling. The non-zero vev for the $D$-term gives contributions to the squark and slepton masses [10]:

$$\mathcal{L}_{\text{mass}} = - \sum_i Q_i \Delta m^2 \bar{\tilde{\psi}}_i \tilde{\psi}^*_i,$$ (10)

3Explicit models for the $U(1)_F$ breaking can be found in Ref. [10].
where $\Delta m^2 = m_+^2 - m_-^2$. Different Yukawa interactions between $\phi_{\pm}$ induce non-zero $\Delta m^2$ through the renormalization group (RG) running from the fundamental scale $M_*$ to the $U(1)_F$ breaking scale $M_F$ ($M_F \sim \langle \phi_{\pm} \rangle$) even if $m_+^2 = m_-^2$ is assumed at $M_*$. Large Yukawa couplings are expected to radiatively break the $U(1)_F$; therefore, $\Delta m^2$ is expected to be of order (weak scale)$^2$.

In general, a higher theory may present the fermions in the gauge interaction basis to be different from the mass basis, as seen in Eq. (8). After rotating to the mass eigenstates ($\psi'_i = V_{ij}^{\dagger} \psi_j$) for the fermions, the sfermion mass terms in Eq. (10) get flavor mixings:

$$L_{\text{mass}} = - \sum_{ijk} V_{ki}^* Q_k \Delta m^2 V_{kj} \tilde{\psi}_i^* \tilde{\psi}_j.$$  

(11)

If the mixing $V_{ij}$ is large, the $D$-term contributions may generate large flavor violating sfermion masses provided $Q_k$ are not all the same value. Therefore Eq. (11) embodies two strong statements that may affect large classes of model building: The scalar masses induced by the $D$-term does not explicitly depend on the gauge coupling $g_F$ nor the $U(1)_F$ breaking scale $M_F$. This feature is not limited the Froggatt-Nielsen mechanism. That is, this effect persists for any SUSY model of $U(1)$ flavor-dependent gauge bosons with arbitrarily high mass and arbitrarily small gauge couplings.\(^4\)

In the models\(^3\) motivated by recent neutrino results, large mixings exist in the lepton sector. For example, in Ref.\(^{[21]}\), lopsided $U(1)_F$ charges to the left-handed lepton doublets $l_i$ ($i = 1 - 3$), namely $Q_{t_2} = Q_{t_3} = 0$ and $Q_{t_1} = +1$, naturally explain the large mixing for atmospheric neutrinos (and solar neutrinos if the solar neutrino solution is the large mixing angle solution (LMA))\(^{[1]}\). In this model, a large mixing can be induced in the left-handed slepton masses due to the $D$-term contribution in Eq. (11):

$$(m_{l_i}^2)_{12} = V_{11}^* \Delta m^2_V \frac{m_{\text{SUSY}}^2}{m_{\text{SUSY}}^2} V_{12}$$  

(12)

If the solar neutrino solution is the LMA solution (which is the most favored solar neutrino solution by SuperKamiokande and SNO experiments at

\(^4\) If there is an additional $U(1)$ flavor-independent gauge symmetry, there is a mechanism to suppress the $U(1)_F$ $D$-term contributions along the lines of Ref.\(^{[20]}\), which introduces an additional $U(1)$ flavor symmetry group. In our context, to effectively banish all possible problematic $D$-terms, the additional symmetry should be flavor-independent with much larger gauge coupling than the original flavor symmetry.
Figure 2: The slepton mass-mixing magnitude vs. the $\mu \rightarrow e\gamma$ branching ratio (left axis) and the muon conversion ratio $R = \sigma(\mu N \rightarrow eN)/\sigma(\mu N \rightarrow \nu N')$ for titanium (right axis). The parameters $M_2 = 125$ GeV, $\tan \beta = 30$, $\mu > 0$, and $A_0 = 0$ are applied to the mSUGRA scenario. The extra $U(1)$ is broken at $10^{15}$ GeV. The value of the left-handed slepton mass parameter is varied for the diagonal lines. The horizontal lines are the current (MEGA and SINDRUM II) and near future (MEG and MECO) experimental limits from $\mu \rightarrow e\gamma$ and $\mu \rightarrow e$ conversion experiments. The future experiments MEG and MECO will both approximately equally place the strongest experimental limits on the slepton mass-mixing.

In Fig. 2, the $\mu \rightarrow e\gamma$ branching ratio and $\mu \rightarrow e$ conversion rate are shown.
as a function of the slepton-mixing \( (m^2_{\tilde{l}_L})_{12}/(m^2_{\tilde{l}_L})_{11} \) assumed to originate from a \( U(1)_F \) D-term. Here the universal soft SUSY breaking parameters are defined at the GUT scale. The RG equations for the couplings and masses are numerically solved, and at the weak scale we calculate the event rates for \( \mu \to e\gamma \) and \( \mu \to e \) conversion in Ti. We take \( \tan\beta = 30, \mu > 0, M_2 = 125 \) GeV at the weak scale, and \( A_0 = 0 \) at the GUT scale, and vary the slepton mass \( m_{\tilde{l}_L} \) at the weak scale. We assume that \( U(1)_F \) breaking scale \( M_F \) is \( 10^{15} \) GeV. In general, the \( U(1)_F \) gauge interaction can induce the flavor violating effect through the RG running from GUT scale to \( M_F \). However, here we neglect the RG effect of the \( U(1)_F \) gauge coupling, and hence our calculated event rates will be conservative. Here we also assume that only the left-handed sleptons have the LFV masses. If there are flavor mixings in the right-handed slepton sector, the branching ratio will be increased. Thus our calculated rates will be very conservative.

In Fig. 2, we also show the SUSY contribution to the muon \( g-2 \) observable \( \delta a_{\mu}^{\text{SUSY}} \). As can be seen from the figure, the present \( \mu \to e\gamma \) null results from MEGA strongly constrain the LFV mass \( (m^2_{\tilde{l}_L})_{12} \) in the region where the present muon \( g-2 \) result is favored: \( (m^2_{\tilde{l}_L})_{12}/(m^2_{\tilde{l}_L})_{11} \leq 10^{-4} \). This detailed analysis confirms the naive estimate of the constraint on the LFV masses in the previous section. Therefore, many models with the gauged \( U(1) \) flavor symmetry are significantly constrained.

In SUSY models with slepton mixings, the photon penguin diagram tends to dominate \( \mu \to eee \) and \( \mu \to e \) conversion in nuclei. Thus the following relations amongst the event rates are approximately held:

\[
\frac{R(\mu \to e \text{ in Ti (Al)})}{\text{Br}(\mu \to e\gamma)} \simeq 5 \times 10^{-3};
\]

\[
\frac{\text{Br}(\mu \to eee)}{\text{Br}(\mu \to e\gamma)} \simeq 6 \times 10^{-3}.
\]

As shown in Table 1, the proposed experiments MEG at PSI \[24\] for \( \mu \to e\gamma \) and MECO at BNL \[25\] for \( \mu \to e \) conversion will increase sensitivities of the event rates to \( 10^{-14} \) and \( 10^{-16} \) respectively, and hence they will probe nearly two orders of magnitude past the current \( (m^2_{\tilde{l}_L})_{12}/(m^2_{\tilde{l}_L})_{11} \) limit of Eq. (6).

\[\text{We have checked that our event rates do not strongly depend on the } U(1)_F \text{ breaking scale } M_F. \text{ However, if the scale } M_F \text{ is close to TeV scale, the extra } U(1)_F \text{ gauge boson also contributes to the LFV processes } \text{(23)}, \text{ and the event rates will be increased.}\]
| Process            | Current limit | Proposed sensitivity | Further possibility |
|--------------------|---------------|----------------------|---------------------|
| $\mu \to e\gamma$ | $1.2 \times 10^{-11}$ (MEGA) | $2 \times 10^{-14}$ (MEG) | $\sim 10^{-15}$     |
| $\mu N \to eN$    | $6.1 \times 10^{-13}$ (SINDRUM II) | $5 \times 10^{-17}$ (MECO) | $\sim 10^{-18}$     |
| $\mu \to eee$    | $1.0 \times 10^{-12}$ (SINDRUM) | —                     | $\sim 10^{-16}$     |

Table 1: Current limits and proposed sensitivities for event rates of muon flavor violating processes.

(Fig. 3). Further distant experiments that utilize intense sources of low energy muons (PRISM and NuFACT) \[26\] will probe to nearly three orders of magnitude over the current limit. Such a bound of $(m^2_{\tilde{l}\tilde{l}})_{12}/(m^2_{\tilde{l}\tilde{l}})_{11}$ less than nearly $10^{-7}$ has potential to greatly change our theoretical perspective. These probes of LFV therefore warrant great attention.

The $\tau \to \mu\gamma$ process is also important since it can independently put a constraint on the other LFV mass. Although the present constraint is not very strong, the effort to improve the sensitivity of $\tau \to \mu\gamma$ will be very important.

In light of the recent muon $g-2$ result, we have shown that LFV searches are quite sensitive to the $D$-term contributions induced by a $U(1)$ flavor symmetry. Already the present experiments strongly constrain SUSY models with $U(1)$ flavor symmetry. The future LFV experiments as well as neutrino and muon $g-2$ experiments will either find signals of flavor violation or force us to reevaluate what general approaches to the theory of flavor are viable.

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