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Muon Dipole Moment Experiments: Interpretation and Prospects

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We examine the prospects for discovering new physics through muon dipole moments. The current deviation in $g_\mu - 2$ may be due entirely to the muon's *electric* dipole moment. We note that the precession frequency in the proposed BNL muon EDM experiment is also subject to a similar ambiguity, but this can be resolved by up-down asymmetry measurements. We then review the theoretical expectations for the muon's electric dipole moment in supersymmetric models.

I. INTRODUCTION

The Standard Model of particle physics provides an extremely successful description of all known particles and their interactions, but fails to address many deeper questions concerning their physical origin. Among the least understood phenomena is CP violation. At present, the only observed source of CP violation in the Standard Model is the phase of the CKM matrix. Its fundamental origins are unknown. Further, while CP violation is an essential ingredient of almost all attempts to explain the matter-antimatter asymmetry of the universe [1] (alternative explanations are subject to stringent bounds: see, *e.g.*, Ref. [2]), the amount of CP violation present in the CKM matrix is insufficient to explain the observed asymmetry [3]. Searches for CP violation beyond the CKM matrix are necessary to shed light on this puzzle and are also probes of physics beyond the Standard Model.

Electric dipole moments (EDMs) violate both parity (P) and time reversal (T) invariance. If CPT is assumed to be an unbroken symmetry, a permanent EDM is, then, a signature of CP violation [4]. A non-vanishing permanent EDM has not been measured for any of the known elementary particles. In the Standard Model, EDMs are generated only at the multi-loop level and are predicted to be many orders of magnitude below the sensitivity of foreseeable experiments [5]. A non-vanishing EDM therefore would be unambiguous evidence for CP violation beyond the CKM matrix, and searches for permanent EDMs of fundamental particles are powerful probes of extensions of the Standard Model. In fact, current EDM bounds are already some of the most stringent constraints on new physics, and they are highly complementary to many other low energy constraints, since they require CP violation, but not flavor violation.

The field of precision muon physics will be transformed in the next few years [6]. The EDM of the muon is therefore of special interest. A new BNL experiment [7] has been proposed to measure the muon's EDM at the level of

$$d_\mu \sim 10^{-24}\ e\ \mathrm{cm}\ , \tag{1}$$

more than five orders of magnitude below the current bound [8]

$$d_\mu = (3.7 \pm 3.4) \times 10^{-19}\ e\ \mathrm{cm}\ , \tag{2}$$

and even higher precision might be attainable at a future neutrino factory complex [9].

The interest in the muon's EDM is further heightened by the recent measurement of the muon's anomalous magnetic dipole moment (MDM) $a_\mu = (g_\mu - 2)/2$, where g_μ is the muon's gyromagnetic ratio. The current measurement $a_\mu^{\mathrm{exp}} = 11\ 659\ 202\,(14)\,(6) \times 10^{-10}$ [10] from the Muon $(g-2)$ Experiment at Brookhaven differs from the Standard Model prediction a_μ^{SM} [11, 12] by 2.6σ:

$$\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (43 \pm 16) \times 10^{-10}\ . \tag{3}$$

The muon's EDM and MDM arise from similar operators, and this tentative evidence for a non-Standard Model contribution to a_μ also motivates the search for the muon's EDM [13]. In fact, the deviation of Eq. (3) may be partially, or even entirely attributed to a muon EDM! [13] In Section II we discuss the interplay between the new physics contributions to the muon MDM and EDM, and their manifestation in muon dipole moment experiments. Then in Section III we present model-independent predictions for the muon EDM, based on the current $g_\mu - 2$ measurement. Finally in Section IV we review the theoretical expectations for the size of the muon EDM in supersymmetry.

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II. INTERPRETATION OF MUON DIPOLE EXPERIMENTS

Modern measurements of the muon's MDM exploit the equivalence of cyclotron and spin precession frequencies for $g = 2$ fermions circulating in a perpendicular and uniform magnetic field. Measurements of the anomalous spin precession frequency are therefore interpreted as measurements of a_μ.

The spin precession frequency also receives contributions from the muon's EDM, however. For a muon traveling with velocity $\boldsymbol{\beta}$ perpendicular to both a magnetic field $\boldsymbol{B}$ and an electric field $\boldsymbol{E}$, the anomalous spin precession vector is

$$\begin{aligned} \boldsymbol{\omega}_a &= -a_\mu \frac{e}{m_\mu} \boldsymbol{B} - d_\mu \frac{2c}{\hbar} \boldsymbol{\beta} \times \boldsymbol{B} - d_\mu \frac{2}{\hbar} \boldsymbol{E} \\ &\quad - \frac{e}{m_\mu c} \left(\frac{1}{\gamma^2 - 1} - a_\mu \right) \boldsymbol{\beta} \times \boldsymbol{E} \ . \end{aligned} \qquad (4)$$

In recent experiments, the last term of Eq. (4) is removed by running at the 'magic' $\gamma \approx 29.3$, and the third term is negligible. For highly relativistic muons with $|\boldsymbol{\beta}| \approx 1$, then, the anomalous precession frequency is found from

$$\frac{|\boldsymbol{\omega}_a|}{|\boldsymbol{B}|} \approx \left[\left(\frac{e}{m_\mu} \right)^2 \left(a_\mu^{\rm SM} + a_\mu^{\rm NP} \right)^2 + \left(\frac{2c}{\hbar} \right)^2 d_\mu^{\rm NP\,2} \right]^{1/2} , \qquad (5)$$

where NP denotes new physics contributions, and we have assumed $d_\mu^{\rm NP} \gg d_\mu^{\rm SM}$.

The observed deviation from the Standard Model prediction for $|\boldsymbol{\omega}_a|$ has been assumed to arise entirely from a MDM and has been attributed to a new physics contribution of size Δa_μ. However, from Eq. (5), we see that, more generally, it may arise from some combination of magnetic and electric dipole moments from new physics. More quantitatively, the effect can also be due to a combination of new physics MDM and EDM contributions satisfying

$$\begin{aligned} \left| d_\mu^{\rm NP} \right| &\approx \frac{\hbar e}{2 m_\mu c} \sqrt{2\, a_\mu^{\rm SM} \left(\Delta a_\mu - a_\mu^{\rm NP} \right)} \\ &\approx 3.0 \times 10^{-19}\ e\ {\rm cm} \sqrt{1 - \frac{a_\mu^{\rm NP}}{43 \times 10^{-10}}} \ , \end{aligned} \qquad (6)$$

where we have taken into account that $a_\mu^{\rm NP} \ll a_\mu^{\rm SM}$ and normalized $a_\mu^{\rm NP}$ to the current central value given in Eq. (3). In Fig. 1 we show the regions in the $(a_\mu^{\rm NP}, d_\mu^{\rm NP})$ plane that are consistent with the observed deviation in $|\boldsymbol{\omega}_a|$. The current 1σ and 2σ upper bounds on $d_\mu^{\rm NP}$ [8] are also shown. We see that a large fraction of the region allowed by both the current $g_\mu - 2$ measurement Eq. (3) and the d_μ bound Eq. (2) is already within the sensitivity of phase I of the newly proposed experiment (with sensitivity $\sim 10^{-22}\ e$ cm).

In fact, the observed anomaly may, in principle, be due entirely to the muon's EDM! This is evident from

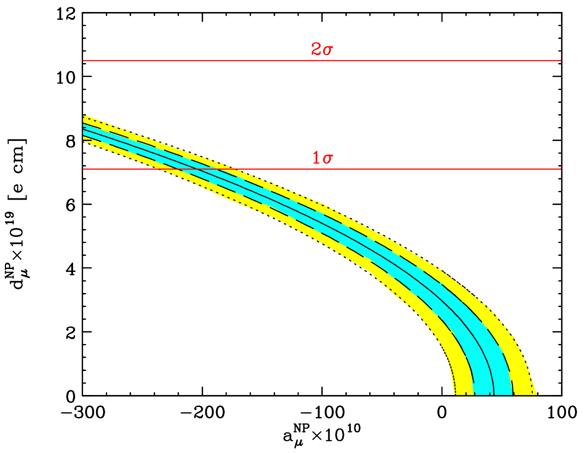

FIG. 1: Regions in the $(a_\mu^{\rm NP}, d_\mu^{\rm NP})$ plane that are consistent with the observed $|\boldsymbol{\omega}_a|$ at the 1σ and 2σ levels. The current 1σ and 2σ bounds on $d_\mu^{\rm NP}$ [8] are also shown.

Eqs. (2) and (6), or from Fig. 1. Alternatively, in the absence of fine-tuned cancellations between $a_\mu^{\rm NP}$ and $d_\mu^{\rm NP}$, *the results of the Muon* $(g-2)$ *Experiment also provide the most stringent bound on* d_μ *to date*, with 1σ and 2σ upper limits

$$\begin{aligned} \Delta a_\mu &< 59\ (75) \times 10^{-10} \Longrightarrow \\ \left| d_\mu^{\rm NP} \right| &< 3.5\ (3.9) \times 10^{-19}\ e\ {\rm cm} \ . \end{aligned} \qquad (7)$$

Of course, the effects of d_μ and a_μ are physically distinguishable: while a_μ causes precession around the magnetic field's axis, d_μ leads to oscillation of the muon's spin above and below the plane of motion. This oscillation is detectable in the distribution of positrons from muon decay, and further analysis of the recent a_μ data should tighten the current bounds on d_μ significantly. Such analysis is currently in progress [14] and should be able to further restrict the allowed region depicted in Fig. 1.

The proposed dedicated muon EDM experiment will use a different setup from the one described above, by applying a constant radial electric field. As can be seen from Eq. (4), the anomalous precession frequency will then have both a radial component,

$$- d_\mu \frac{2c}{\hbar} \boldsymbol{\beta} \times \boldsymbol{B} - d_\mu \frac{2}{\hbar} \boldsymbol{E} \ , \qquad (8)$$

and a vertical component,

$$- a_\mu \frac{e}{m_\mu} \boldsymbol{B} - \frac{e}{m_\mu c} \left(\frac{1}{\gamma^2 - 1} - a_\mu \right) \boldsymbol{\beta} \times \boldsymbol{E} \ . \qquad (9)$$

Then for any given γ, and *assuming the SM value for* a_μ, the electric field can be tuned to cancel the precession from Eq. (9) due to a_μ. The remaining radial component of $\boldsymbol{\omega}_a$ will lead to an oscillating up-down asymmetry in the counting rate. Measurements of both the asymmetry and the spin precession frequency can be used to deduce a limit on $d_\mu^{\rm NP}$.

As in the $g_\mu - 2$ experiment, however, the measurement of the spin precession frequency in the muon EDM experiment receives, in principle, contributions from both the muon EDM and MDM. In the presence of a sizable new physics contribution to a_μ, the cancellation in Eq. (9) is not perfect, leaving a residual radial component

$$- a_\mu^{\rm NP} \frac{e}{m_\mu} \left(\boldsymbol{B} - \frac{1}{c}\, \boldsymbol{\beta} \times \boldsymbol{E} \right) . \tag{10}$$

From Eqs. (8) and (10) we then obtain for the magnitude of the anomalous precession frequency

$$|\boldsymbol{\omega}_a|^2 = |\boldsymbol{B}|^2 \left[\left(a_\mu^{\rm NP} \frac{e}{m_\mu} \right)^2 \left(1 - \frac{a_\mu^{\rm SM}}{a_\mu^{\rm SM} - \frac{1}{\gamma^2-1}} \right)^2 + \left(d_\mu^{\rm NP} \frac{2}{\hbar} \right)^2 \left(c|\boldsymbol{\beta}| + \frac{a_\mu^{\rm SM}}{\frac{|\boldsymbol{\beta}|}{c} \left(a_\mu^{\rm SM} - \frac{1}{\gamma^2-1} \right)} \right)^2 \right] , \tag{11}$$

where we have used the tuning condition for Eq. (9) to eliminate the electric field. In the setup of the proposed experiment, $\gamma \approx 5$, and we can approximate $|\boldsymbol{\beta}| \approx 1 \gg 1/(\gamma^2 - 1) \gg a_\mu^{\rm SM}$ to get

$$|\boldsymbol{\omega}_a|^2 \approx |\boldsymbol{B}|^2 \left[\left(\frac{e}{m_\mu} a_\mu^{\rm NP} \right)^2 + \left(\frac{2c}{\hbar} d_\mu^{\rm NP} \right)^2 \right] . \tag{12}$$

We see that the measurement of $\boldsymbol{\omega}_a$ again constrains only a combination (albeit a different one — cf. Eq. (5)) of $a_\mu^{\rm NP}$ and $d_\mu^{\rm NP}$. This time, the constraint contours are ellipses centered on the origin in Fig. 1. Only by combining both measurements can the muon EDM and MDM be determined unambiguously. Of course, the up-down asymmetry is CP-violating, and so provides unambiguous information about $d_\mu^{\rm NP}$ without contamination from $a_\mu^{\rm NP}$. The measurement of the up-down asymmetry is therefore extremely valuable.

III. IMPLICATIONS OF THE $g_\mu - 2$ RESULT FOR THE MUON'S EDM

The muon's EDM and anomalous MDM are defined through (here and below we set $\hbar = c = 1$)

$$\mathcal{L}_{\rm EDM} = -\frac{i}{2} d_\mu\, \bar\mu \sigma^{mn} \gamma_5 \mu\, F_{mn} \tag{13}$$

$$\mathcal{L}_{\rm MDM} = a_\mu \frac{e}{4m_\mu}\, \bar\mu \sigma^{mn} \mu\, F_{mn} , \tag{14}$$

where $\sigma^{mn} = \frac{i}{2} [\gamma^m, \gamma^n]$ and F is the electromagnetic field strength.

These operators are closely related. Assuming that they have the same origin, it is useful to write the new physics contributions to their coefficients as

$$d_\mu^{\rm NP} = \frac{e}{2m_\mu}\, \mathcal{I}m A , \tag{15}$$

$$a_\mu^{\rm NP} = \mathcal{R}e A , \tag{16}$$

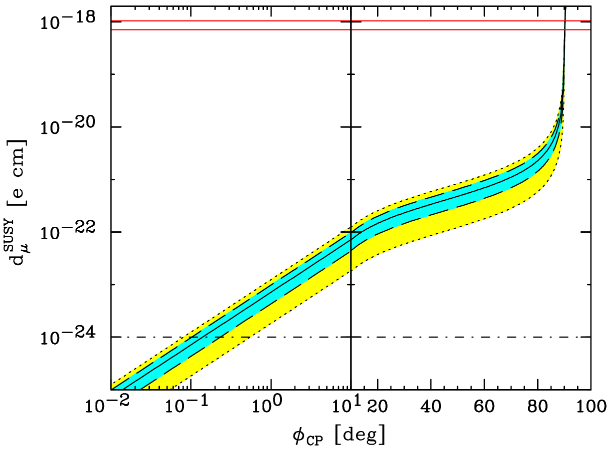

FIG. 2: Regions of the $(\phi_{\rm CP}, d_\mu^{\rm NP})$ plane allowed by the measured central value of $|\boldsymbol{\omega}_a|$ (solid) and its 1σ and 2σ preferred values (shaded). The horizontal dot-dashed line marks the proposed experimental sensitivity to $d_\mu^{\rm NP}$. The red horizontal solid lines denote the current 1σ and 2σ bounds on $d_\mu^{\rm NP}$ [8].

with $A \equiv |A| e^{i\phi_{\rm CP}}$. This defines an experimentally measurable quantity $\phi_{\rm CP}$ which quantifies the amount of CP violation in the new physics, independently of its energy scale. Upon eliminating $|A|$, we find

$$d_\mu^{\rm NP} = 4.0 \times 10^{-22}\ e\ {\rm cm}\ \frac{a_\mu^{\rm NP}}{43 \times 10^{-10}}\ \tan\phi_{\rm CP} . \tag{17}$$

The measured discrepancy in $|\boldsymbol{\omega}_a|$ then constrains $\phi_{\rm CP}$ and $d_\mu^{\rm NP}$. Eliminating $a_\mu^{\rm NP}$ from Eq. (5) and Eq. (17), we find

$$|d_\mu^{\rm NP}| = \frac{e}{2m_\mu} a_\mu^{\rm SM} \sin\phi_{\rm CP} \left[-\cos\phi_{\rm CP} + \left(\cos^2\phi_{\rm CP} + \frac{(2a_\mu^{\rm SM} + \Delta a_\mu)\Delta a_\mu}{(a_\mu^{\rm SM})^2} \right)^{1/2} \right] , \tag{18}$$

The preferred regions of the $(\phi_{\rm CP}, d_\mu^{\rm NP})$ plane are shown in Fig. 2. For 'natural' values of $\phi_{\rm CP} \sim 1$, $d_\mu^{\rm NP}$ is of order 10^{-22} e cm. With the proposed $d_\mu^{\rm NP}$ sensitivity of Eq. (1), all of the 2σ allowed region with $\phi_{\rm CP} > 10^{-2}$ rad yields an observable signal.

At the same time, while this model-independent analysis indicates that natural values of $\phi_{\rm CP}$ prefer $d_\mu^{\rm NP}$ well within reach of the proposed muon EDM experiment, very large values of $d_\mu^{\rm NP}$ also require highly fine-tuned $\phi_{\rm CP}$. For example, we see from Fig. 2 that values of $d_\mu^{\rm NP} \gtrsim 10^{-20}$ e cm are possible only if $|\pi/2 - \phi_{\rm CP}| \sim 10^{-3}$. This is a consequence of the fact that EDMs are CP-odd and $d_\mu^{\rm SM} \approx 0$, and so $d_\mu^{\rm NP}$ appears only quadratically in $|\boldsymbol{\omega}_a|$. Without a strong motivation for $\phi_{\rm CP} \approx \pi/2$, it is therefore natural to expect the EDM contribution to $|\boldsymbol{\omega}_a|$ to be negligible.

IV. THEORETICAL EXPECTATIONS FOR d_μ IN SUPERSYMMETRY

Our discussion up to now has been completely model-independent. In specific models, however, it may be difficult to achieve values of d_μ large enough to saturate the bound of Eq. (7). For example, in supersymmetry, assuming flavor conservation and taking extreme values of superparticle masses ($\sim$ 100 GeV) and $\tan\beta$ ($\tan\beta \sim 50$) to maximize the effect, the largest possible value of a_μ is $a_\mu^{\max} \sim 10^{-7}$ [15]. Very roughly, one therefore expects a maximal muon EDM of order $(e\hbar/2m_\mu c)a_\mu^{\max} \sim 10^{-20}$ e cm in supersymmetry.

With additional model assumptions, however, it is possible to further narrow down the expected range of $d_\mu^{\rm NP}$ in supersymmetry. The EDM operator of Eq. (13) couples left- and right-handed muons, and so requires a mass insertion to flip the chirality. The natural choice for this mass is the lepton mass. On dimensional grounds, one therefore expects

$$d_\mu^{\rm NP} \propto \frac{m_\mu}{\tilde{m}^2} \ , \qquad (19)$$

where $\tilde{m}$ is the mass scale of the new physics. If the new physics is flavor blind, $d_f \propto m_f$ for all fermions f, which we refer to as 'naive scaling.' In particular,

$$d_\mu \approx \frac{m_\mu}{m_e} d_e \ . \qquad (20)$$

The current bound on the electron EDM is $d_e = 1.8\,(1.2)\,(1.0) \times 10^{-27}$ e cm [16]. Combining the statistical and systematic errors in quadrature, this bound and Eq. (20) imply

$$d_\mu \lesssim 9.1 \times 10^{-25}\ e\ \text{cm} \ , \qquad (21)$$

at the 90% CL, which is barely below the sensitivity of Eq. (1). Naive scaling must be violated if a non-vanishing d_μ is to be observable at the proposed experiment. On the other hand, the proximity of the limit of Eq. (21) to the projected experimental sensitivity of Eq. (1) implies that even relatively small departures from naive scaling may yield an observable signal.

Is naive scaling violation well-motivated, and can the violation be large enough to produce an observable EDM for the muon? To investigate these questions quantitatively, we consider supersymmetry [17]. (For violations of naive scaling in other models, see, for example, Ref. [18].) Many additional mass parameters are introduced in supersymmetric extensions of the Standard Model. These are in general complex and are new sources of CP violation, leading to a separate, major challenge for SUSY model building along with flavor violation. For a recent discussion of the supersymmetric CP problem in various supersymmetry breaking schemes, see Ref. [19].

In the minimal supersymmetric model, naive scaling requires

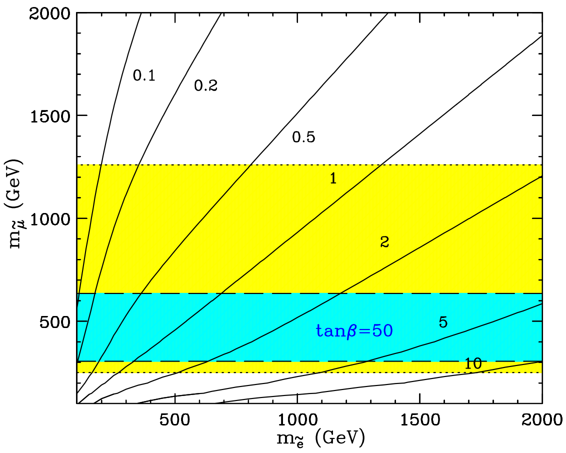

FIG. 3: Contours of $d_\mu \times 10^{24}$ in e cm for varying $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{e}}$ and $m_{\tilde{\mu}_R} = m_{\tilde{\mu}_L} = m_{\tilde{\mu}}$ for vanishing A terms, fixed $|\mu| = 500$ GeV and $M_2 = 300$ GeV, and $M_1 = (g_1^2/g_2^2)M_2$ determined from gaugino mass unification. The CP-violating phase is assumed to saturate the bound $d_e < 4.4 \times 10^{-27}$ e cm. The shaded regions are preferred by a_μ at 1σ and 2σ for $\tan\beta = 50$.

- Degeneracy: Generation-independent slepton masses.
- Proportionality: The A terms must scale with the corresponding fermion mass.
- Flavor conservation: Vanishing off-diagonal elements for the sfermion masses and the A-terms.

We now briefly discuss violations of each of these properties in turn.

Scalar degeneracy is the most obvious way to reduce flavor changing effects to allowable levels. Therefore many schemes for mediating supersymmetry breaking try to achieve degeneracy. However, in many of these, with the exception of simple gauge mediation models, there may be non-negligible contributions to scalar masses that are generation-dependent. For example, scalar non-degeneracy is typical in alignment models [20] or models with anomalous U(1) contributions to the sfermion masses where the sfermion hierarchy is often inverted relative to the fermion mass hierarchy [21].

We now consider a simple model-independent parameterization to explore the impact of non-degenerate selectron and smuon masses. We set $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{e}}$ and $m_{\tilde{\mu}_R} = m_{\tilde{\mu}_L} = m_{\tilde{\mu}}$ and assume vanishing A parameters. For fixed values of M_1, M_2, $|\mu|$, and large $\tan\beta$, then, to a good approximation both d_e and d_μ are proportional to $\sin\phi_{\rm CP}\tan\beta$, and we assume that $\sin\phi_{\rm CP}\tan\beta$ saturates the d_e bound.

Contours of d_μ are given in Fig. 3. Observable values of d_μ are possible even for small violations of non-degeneracy; for example, for $m_{\tilde{\mu}}/m_{\tilde{e}} \lesssim 0.9$, muon EDMs greater than 10^{-24} e cm are possible. The current value of a_μ also favors light smuons and large

EDMs. The smuon mass regions preferred by the current a_μ anomaly are given in Fig. 3 for $\tan\beta = 50$. Within the 1σ preferred region, d_μ may be as large as $4\ (10) \times 10^{-24}\ e$ cm for $m_{\tilde{e}} < 1\ (2)$ TeV. Our assumed value of $\tan\beta$ is conservative; for smaller $\tan\beta$, the preferred smuon masses are lower and the possible d_μ values larger.

Naive scaling is also broken if the A-terms are not proportional to the corresponding Yukawa couplings. Just as in the case of non-degeneracy, deviations from proportionality are found in many models. Although for large $\tan\beta$, the A term contribution to the EDM is suppressed relative to the typically dominant chargino contribution, there are many possibilities that may yield large effects. In Ref. [22], for example, it was noted that A_e may be such that the chargino and neutralino contributions to d_e cancel, while, since $A_e \neq A_\mu$, there is no cancellation in d_μ, and observable values are possible.

Finally, most models of high-scale supersymmetry breaking [19] typically contain flavor violation as well. In particular, smuon-stau mixing leads to a potentially significant enhancement in d_μ, because it breaks naive scaling by introducing contributions enhanced by $\frac{m_\tau}{m_\mu}$. In order to evaluate the significance of this enhancement, we must first determine how large the flavor violation may be. Taking into account the current $\tau \to \mu\gamma$ constraint, we found that values of $d_\mu^{\rm NP}$ as large as $10^{-22} e$ cm are possible [13].

In conclusion, the proposal to measure the muon EDM at the level of $10^{-24}\ e$ cm potentially improves existing sensitivities by five orders of magnitude. While the existing deviation in $g_\mu - 2$ may be interpreted as evidence for new physics in either the muon's MDM or EDM, the proposed experiment will definitively resolve this ambiguity, and may also uncover new physics in a wide variety of superysmmetric extensions of the Standard Model.

Acknowledgments

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