Effect of supersymmetric phases on lepton dipole moments and rare lepton decays

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ABSTRACT: We study the effect of SUSY phases on rare decays of leptons and on their magnetic and electric dipole moments. We focus on two scenarios: (i) selectron - stau mixing and (ii) general three generation mixing. In both cases we consider the most general mass matrices for sleptons within the MSSM including left–right mixing, flavour mixing and complex phases. We emonstrate that contrary to common belief the phase of μ can be large even for slepton masses as small as 200 GeV provided the lepton flavour violating parameters are complex.

1. Introduction

The results of the recent neutrino experiments [1] are a clear indication for non-vanishing neutrino masses and violation of individual lepton numbers. For this reason one expects also flavour violating effects also for charged leptons. However, lepton flavour violation (LFV) of charged leptons is severely constrained by experiments: $BR(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$, $BR(\tau \to e\gamma) < 2.7 \cdot 10^{-6}$, $BR(\tau \to \mu\gamma) < 1.1 \cdot 10^{-6}$ [2]. In analogy to quarks, lepton flavour violation may also be related to CP violation. The limits on leptonic CP violation, such as the bound of 10^{-27} ecm on the electric dipole moment of the electron, are also quite strong. Within the standard model (SM) framework this is somewhat less significant because the leptonic dipole moments, being a three–loop effect, are generically small [3].

Supersymmetric (SUSY) extensions of the SM contain additional sources for LFV and CP violation in the slepton sector and the corresponding effects can be generically large. Moreover, there are additional sources for CP violation in the chargino and neutralino sector. Consequently, rare processes and CP violation impose significant bounds on the flavour violating terms in the slepton mass matrices. Various phenomenological implications of LFV with real mass matrices for sleptons were extensively studied in the literature

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[4]. The main result is that large lepton flavour violating signals are predicted in production and decays of supersymmetric particles despite the stringent experimental bounds on flavour violating lepton decays. On the other hand, studies with complex parameters have been mainly performed for specific SUSY models, e. g. the mSUGRA model [5, 6, 7], or only some parameters were taken to be complex [8, 9].

Here we study lepton flavour violation and CP violation in the lepton sector in the general situation, where all parameters can be complex, in particular the LFV entries of the slepton mass matrices. This important generalization is quite natural and is motivated by the close analogy between quarks and leptons and their supersymmetric partners. The phase of the CKM matrix is large and the the smallness of certain CP-violating observables (in the K-system) is due to the structure of the theory.

The present experiments impose rather stringent bounds on SUSY phases because CP-violating effects such as electric dipole moments can be quite large in SUSY. Therefore it is often suggested that the phases are small altogether [10]. Since this view is in a sense contradictory to the large phase of the standard model, it is desirable to carry out a general study of flavour and CP violation with complex parameters in order to see whether the restrictions can be softened. Furthermore, large leptonic CP violation together with leptogenesis [11] may also be the key to the baryon asymmetry of the universe. One goal of our work therefore is to determine whether large phases are indeed possible and not in contradiction with experiment.

General models with soft SUSY breaking terms contain a large number of complex parameters. Consequently, each observable can have contributions from several parameters and no clear statements on their allowed ranges may be possible. As a second goal of our study, we want to show that, nevertheless, important results can be obtained because the present limits on rare processes in the lepton sector are so strong. Furthermore, several experiments with substantially increased sensitivity are planned for the near future and will lead to even more decisive information. Future measurements of d_e [12] and d_μ [13] may substantially improve the sensitivity to 10^{-29} and 10^{-24}, respectively. New experiments for the search of the rare decay $\mu \to e\gamma$ at the level of 10^{-14} [14] are also underway.

As there are many parameters involved, we will fix the modulus of the flavour conserving parameters and vary the flavour violating parameters as well as all possible phases. We have checked that the qualitative features of this study do not change if one varies the flavour conserving parameters. The processes we will study are the rare leptonic decays $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ and the electric (EDM) and magnetic dipole moments (MDM) of e, μ and τ. We will use the present experimental bounds, $d_e < 1.5 \cdot 10^{-27}$ ecm [15], $d_\mu < 1.5 \cdot 10^{-18}$ ecm [16], $d_\tau < 1.5 \cdot 10^{-16}$ ecm [2]. For the magnetic moments we assume that the supersymmetric contribution is limited by the experimental errors of $\pm 10^{-12}$ and ± 0.058 for a_e and a_τ respectively. For the muon, there are new measurements of a_μ [17], but there are still several uncertainties in the theoretical value of a_μ^{SM} [18]. We will take the conservative range $a_\mu^{exp} - a_\mu^{SM} = 43 \cdot 10^{-10}$, which corresponds to the largest deviation in the calculations.

The organization of the paper is as follows: In the next section we define the parameters and fix the notation. In section 3 we study a scenario with complex parameters but without flavour violation. In section 4 the general situation with lepton flavour violation and complex parameters is studied. The conclusions are drawn in section 5.

2. The basic parameters

The model under study is the general Minimal Supersymmetric Standard Model (MSSM). The parameters relevant for this study are the lepton Yukawa coupling Y^E and higgsino mixing parameter μ of the superpotential as well as the following part of the soft SUSY breaking Lagrangian:

$$\mathcal{L} = M^2_{L,ij}\tilde{l}_{L,i}\tilde{l}^*_{L,j} + M^2_{E,ij}\tilde{l}_{R,i}\tilde{l}^*_{R,j} + (A_{ij}H_1\tilde{l}_{L,i}\tilde{l}^*_{R,j} + M_1\tilde{b}\tilde{b} + M_2\tilde{w}^a\tilde{w}^a + h.c.) \tag{2.1}$$

M_1 and M_2 are the $U(1)$ and $SU(2)$ gaugino mass parameters, respectively. M^2_L and M^2_E are the soft SUSY breaking mass matrices for left and right sleptons, respectively, and the A_{ij} are the trilinear soft SUSY breaking couplings of the sleptons and Higgs boson. M_1, M_2, $M^2_{L,ij} = (M^2_{L,ji})^*$, $M^2_{E,ij} = (M^2_{E,ij})^*$ and A_{ij} are complex; note that $A_{ij} \neq A^*_{ji}$ for $i \neq j$. The most general charged slepton mass matrix including left-right mixing as well as flavor mixing is usually written in the form

$$M^2_{\tilde{l}} = \begin{pmatrix} M^2_{LL} & M^{2\dagger}_{LR} \\ M^2_{LR} & M^2_{RR} \end{pmatrix}, \tag{2.2}$$

where the entries are 3×3 matrices. In terms of the parameters introduced in (2.1), they are given by

$$M^2_{LL,ij} = M^2_{L,ij} + \frac{v_d^2 Y^{E*}_{ki} Y^E_{kj}}{2} + \frac{\left(g'^2 - g^2\right)(v_d^2 - v_u^2)\delta_{ij}}{8}, \tag{2.3}$$

$$M^2_{LR,ij} = \frac{v_d A^*_{ij} - \mu v_u Y^E_{ij}}{\sqrt{2}}, \tag{2.4}$$

$$M^2_{RR,ij} = M^2_{E,ij} + \frac{v_d^2 Y^E_{ik} Y^{E*}_{jk}}{2} - \frac{g'^2(v_d^2 - v_u^2)\delta_{ij}}{4}. \tag{2.5}$$

The indices $i, j, k = 1, 2, 3$ characterize the flavors e, μ, τ. v_u and v_d are the vacuum expectation values of the neutral Higgs fields (with $\tan\beta = v_u/v_d$). In what follows we will work in a basis where M_2 is real and where the lepton Yukawa coupling is real and flavour diagonal. Both assumptions can be done without loss of generality, because (i) only phase differences matter and (ii) there are no right-handed neutrinos in the low energy spectrum. Similarly, one finds for the sneutrinos

$$M^2_{\tilde{\nu},ij} = M^2_{L,ij} + \frac{\left(g^2 + g'^2\right)(v_d^2 - v_u^2)\delta_{ij}}{8}. \tag{2.6}$$

After diagonalizing the mass matrices in Eqs. (2.2) and (2.6) one obtains a Lagrangian which contains complex lepton flavour violating couplings. The corresponding formulas are given in ref. [19]. These couplings give, at the 1-loop level, contributions to the anomalous

Figure 1: Generic diagrams contributing to Δa_l, d_l, $l_j \to l_i\,\gamma$.

magnetic moments of the leptons a_l, the electric dipole moments d_l and to rare lepton decays such as $l_j \to l_i\,\gamma$. All these observables are induced by the same type of amplitude

$$T = ie\epsilon^{\mu *}\frac{q^\nu}{2m_{l_j}}\bar{l}_i\sigma_{\mu\nu}(a^L_{ij}P_L + a^R_{ij}P_R)l_j \tag{2.7}$$

arising from the diagrams shown in Fig. 1. Here we take $i \le j$. The formulas for the coefficients a^L_{ij} and a^R_{ij} can be found in ref. [19]. The observables Δa_i, d_i and $l_j \to l_i\gamma$ can be expressed as:

$$\Delta a_i = \frac{1}{2}\mathrm{Re}\left(a^L_{ii} + a^R_{ii}\right) \tag{2.8}$$

$$\frac{1}{e}d_i = \frac{1}{2}\mathrm{Im}\left(-a^L_{ii} + a^R_{ii}\right) \tag{2.9}$$

$$\Gamma(l_j \to l_i\gamma) = \frac{\alpha m_{l,j}}{16}\left(|a^L_{ij}|^2 + |a^R_{ij}|^2\right) \tag{2.10}$$

where in the last equation we have neglected terms of order $\mathrm{O}(m_{l_i}/m_{l_j})$.

3. The flavour conserving case

We begin our investigation with a point which is close to the SPS#1a point [20]: $M^2_{L,11} = M^2_{L,22} = 202.3^2$ GeV^2, $M^2_{L,33} = 201.5^2$ GeV^2, $M^2_{E,11} = M^2_{E,22} = 138.7^2$ GeV^2, $M^2_{E,33} = 136.3^2$ GeV^2, $A_{11} = -7.567 \cdot 10^{-3}$ GeV, $A_{22} = -1.565$ GeV, $A_{33} = -26.326$ GeV, $M_1 = 107.9$ GeV, $M_2 = 208.4$ GeV, $\mu = 365$ GeV, $\tan\beta = 10$. Note that the A parameters are already multiplied by the lepton Yukawa couplings. We obtain the following SUSY contributions to the observables: $d_e = d_\mu = d_\tau = 0$, $\Delta a_e = 6.8 \cdot 10^{-14}$, $\Delta a_\mu = 2.9 \cdot 10^{-9}$, $\Delta a_\tau = 8.4 \cdot 10^{-7}$.

In the flavour conserving case the electron EDM constrained the phase φ_μ of the parameter μ severely [10, 21, 22, 23]. In some regions of the parameter space φ_μ can be about $\pi/10$ for slepton masses as light as O(200) GeV provided there are cancellations between the chargino and neutralino contributions [22]. This is due to an interplay of the phases $\varphi_{A_{11}}$ and φ_{U_1}, where φ_{U_1} is the phase of the M_1 parameter. In Fig. 2a we show the range of the φ_μ–φ_{U_1} plane allowed by the electron EDM; $\varphi_{A_{11}}$ is varied in the full range. The two bands collapse to lines for fixed $\varphi_{A_{11}}$. Similar results have also been found in [23]. In Fig. 2b the SUSY contribution Δa_μ to the anomalous magnetic moment of the muon is shown. The two bands correspond to the cases $\varphi_\mu \simeq 0$ and $\varphi_\mu \simeq \pi$. We see that while the EDM leaves a twofold ambiguity for the phase φ_μ, the CP-conserving anomalous magnetic

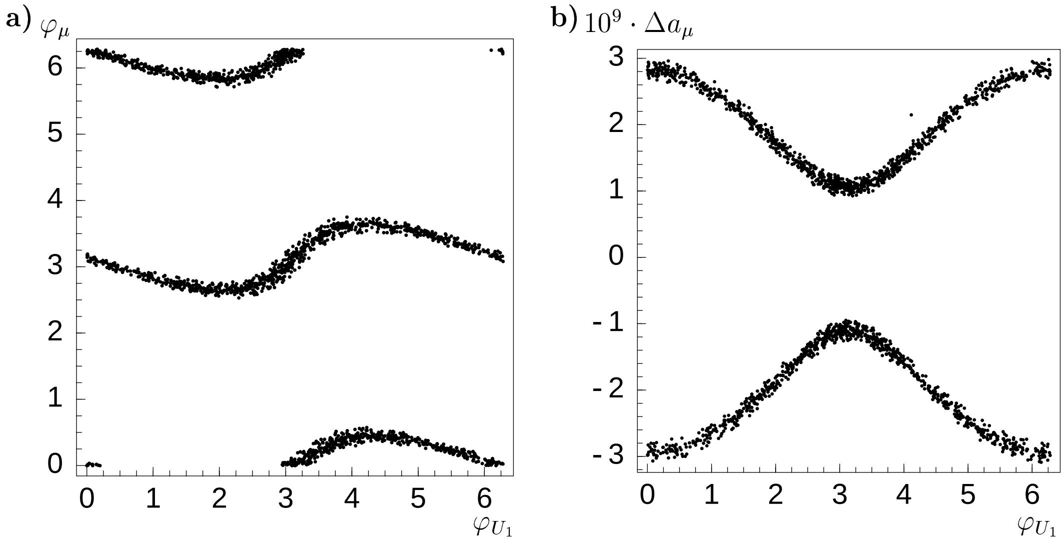

Figure 2: a) Allowed regions in the φ_μ–φ_{U_1} plane by the electron EDM; b) SUSY contribution Δa_μ to the anomalous magnetic moment of the muon.

moment discriminates between the two values - indeed the lower band is already excluded and φ_μ must be near π as has been also observed in ref. [24]. This clearly shows that phases are also important for CP-conserving observables and that a combined analysis of all effects is necessary.

Despite the new freedom, μ is still basically real. Unless the A parameters are substantially larger, this conclusion remains. However, bigger values of $|A_{11}|$ are in contradiction with stability arguments for the potential. As we will see, the complex phases of flavour violating parameters change this picture.

4. Including flavour violation

In this section we consider two scenarios. First we study the case of $\tilde{e}$-$\tilde{\tau}$ mixing and in a second step the general three generation case. Details for $\tilde{e}$-$\tilde{\mu}$ mixing as well as for $\tilde{\mu}$-$\tilde{\tau}$ mixing can be found in ref. [19].

4.1 $\tilde{e}$-$\tilde{\tau}$ mixing

Starting from our reference point, we add the following flavour violating terms: $M^2_{L,13} =$ 1500 GeV^2, $M^2_{E,13} = 2000$ GeV^2, $A_{31} = A_{13} = 20$ GeV yielding BR$(\tau \to e\,\gamma) = 1.05 \cdot 10^{-6}$. The effect of the phases is shown in Fig. 3. Each individual contribution from the various phases $\varphi_{M^2_{E,13}}$, $\varphi_{M^2_{L,13}}$, $\varphi_{A_{13}}$ and $\varphi_{A_{31}}$ is similar in size to that of φ_μ. If only one of these phases would generate the electron EDM, it would have to be very near zero or π because the effect is of order 10^{-23} ecm as seen in the figure. But if there are several contributions, the phases can be arbitrarily large, since various contributions can cancel each other. Such a cancellation is not obvious, because the bounds on Δa_e and BR$(\tau \to e\,\gamma)$ must be satisfied and the parameters are already constrained.

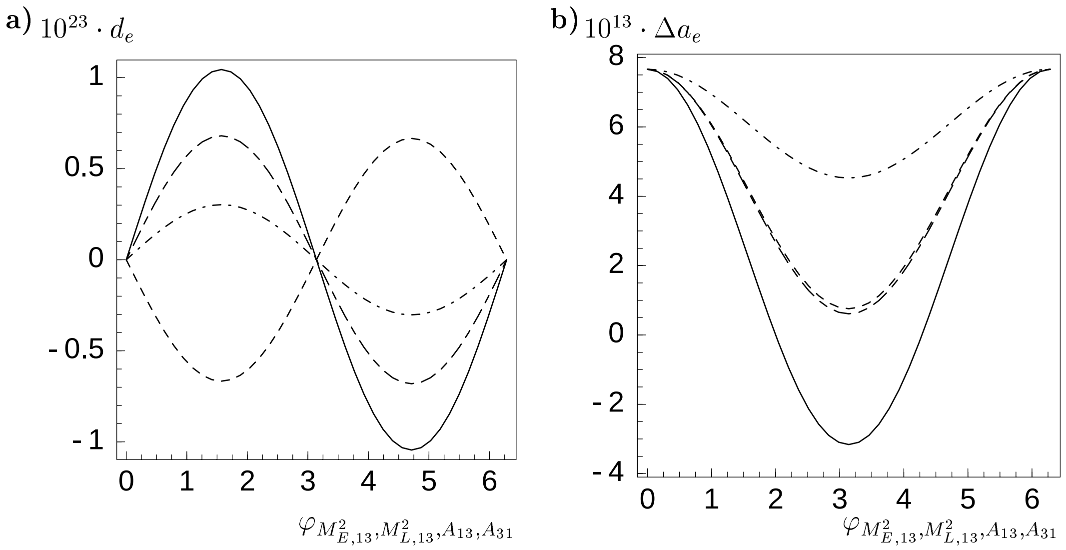

Figure 3: a) d_e and b) SUSY contributions to a_e as a function of $\varphi_{M^2_{E,13}}$ (full line), $\varphi_{M^2_{L,13}}$ (dashed line), $\varphi_{A^l_{13}}$ (dashed dotted line) and $\varphi_{A_{31}}$ (long-short dashed line) for $\varphi_\mu = 0$.

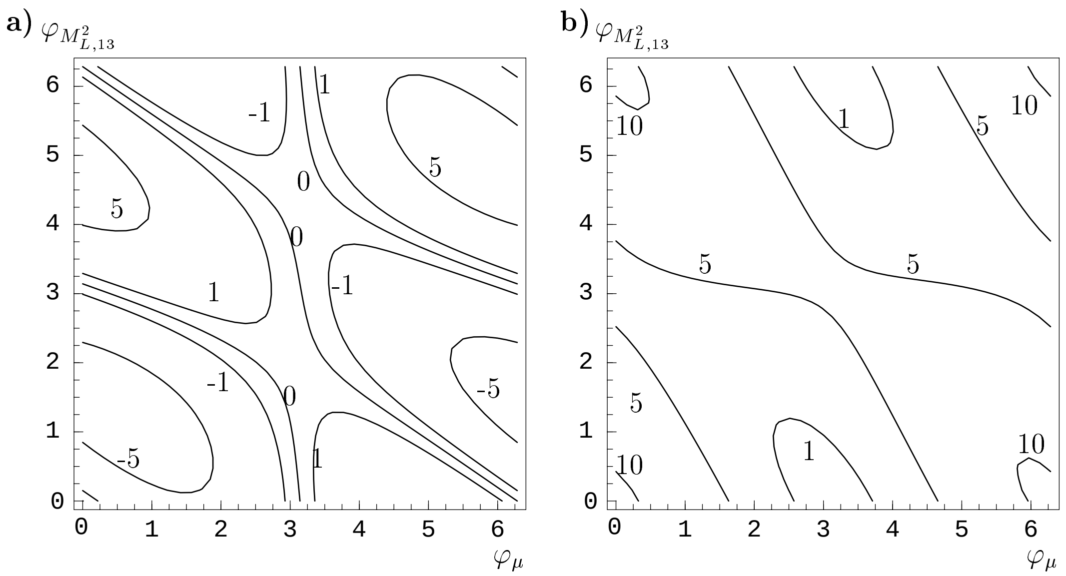

Figure 4: a) $10^{24} d_e$ and b) 10^7 BR($\tau \to e\,\gamma$) in the $\varphi_\mu - \varphi_{M^2_{L,13}}$ plane.

In Fig. 4 the contour plot for d_e as a function of φ_μ and $\varphi_{M^2_{L,13}}$ is shown. Very small d_e consistent with the experimental upper bound can be obtained for all (!) values of φ_μ provided that also the phase $\varphi_{M^2_{L,13}}$ of the flavour violating parameter $M^2_{L,13}$ is large. There are roughly two allowed regions. In one region, the two phases are equal and opposite and there is a cancellation between the lepton flavour conserving and the lepton flavour violating contributions. In this case, the phase of μ can be large indeed. In the other region, φ_μ is around π and there is only a weak dependence on $\varphi_{M^2_{L,13}}$. In this situation, the contribution from $M^2_{L,13}$ is not important for the dipole moment. Note that here only the phases shown in the plot are varied, while the others are set equal to 0. Similar results are obtained in the $\varphi_\mu - \varphi_{M^2_{E,13}}$ plane and in the $\varphi_\mu - \varphi_{A_{31}}$ plane [19].

As can be seen from Fig. 4b, the decay rate for $\tau \to e\gamma$ varies within an order of magnitude over the plot. However, if further experiments would establish a considerably lower limit or measure the branching ratio with 50% or better, the phases could be severely constrained. This underlines clearly the strength of a combined analysis, once the basic supersymmetric parameters are known.

4.2 The three generation case

We now study the most general mixing in the slepton sector. We take our reference point and add all possible phases and generation mixing terms. The moduli of the off-diagonal terms vary between zero and the following upper bounds: $|M^2_{E,12}|, |M^2_{L,12}| \leq 10$ GeV^2, $|M^2_{E,13}|, |M^2_{E,23}|, |M^2_{L,13}|, |M^2_{L,23}| \leq 1000$ GeV^2, $|A_{12}|, |A_{21}| \leq 0.05$ GeV, $|A_{13}|$, $|A_{31}|$, $|A_{23}|$, $|A_{32}| \leq 20$ GeV. All phases are varied in the range between 0 and 2 π.

In Fig. 5 we depict a scatter plot of the allowed values of φ_μ and φ_{U_1} obeying all constraints from the EDMs and the rare lepton decays. Comparing Fig. 5 with Fig. 2 one sees that maximal values for both φ_μ and φ_{U_1} are possible. This is due to cancellations between the lepton flavour conserving and the lepton flavour violating contributions. Note that such cancellations are possible even for slepton masses as small as 200 GeV. In Fig. 5b we show the SUSY contribution Δa_μ to the anomalous magnetic moment of the muon as a function of φ_{U_1}, varying all parameters and phases in the range given above and fulfilling the constraints from the EDMs and the rare lepton decays.

Lepton flavour violation leads to the violation of the naive scaling relations like $d_e/d_\mu \simeq m_e/m_\mu$ [8]. Similarly one also expects deviations from the relation $\Delta a_e/\Delta a_\mu \propto (m_e/m_\mu)^2$. In Fig. 6 we show the results for Δa_e versus Δa_μ and d_e versus d_μ. One sees that the naive relation $\Delta a_e/\Delta a_\mu \propto (m_e/m_\mu)^2$ is largely maintained after imposing the experimental constraints arising from EDMs and rare decays even if one allows for the most general flavour structure. However, there are parameter points where the simple $\Delta a_\mu - \Delta a_e$ scaling is violated, as has also been noted in refs. [8, 6].

The situation changes completely for the electric dipole moments where the correlation between d_e and d_μ is completely destroyed once all possible flavour violating parameters are taken into account. The reason for the difference between EDMs and the MDMs is that in the case of the d_e cancellations of at least of two orders of magnitude are required to satisfy the experimental bounds implying that d_e is no longer proportional to m_e. We have checked that in the case, where a larger modulus of d_e is allowed, the proportionality to m_e is restored except for the region around 0. Moreover, we have checked that the ratio d_μ/d_τ is still proportional to m_μ/m_τ.

Fig. 7 shows the allowed regions for the complex parameters $M^2_{E,13}$ and A_{13} for $\varphi_\mu = \pi/2$. All other phases have been varied in the range $(0, 2\pi)$. Similar results are obtained for the parameters $M^2_{L,13}$ and A_{31} [19]. Again, the allowed regions are large. Note, that the $|M^2_{E,13}|$, $|M^2_{L,13}|$ can go up to 5% of $|M^2_{E,33}|$ and $|M^2_{L,33}|$, respectively. $|A_{13}|$ and $|A_{31}|$ can have the same order of magnitudes as $|A_{33}|$. In case of $\varphi_\mu = 0$ roughly the same areas

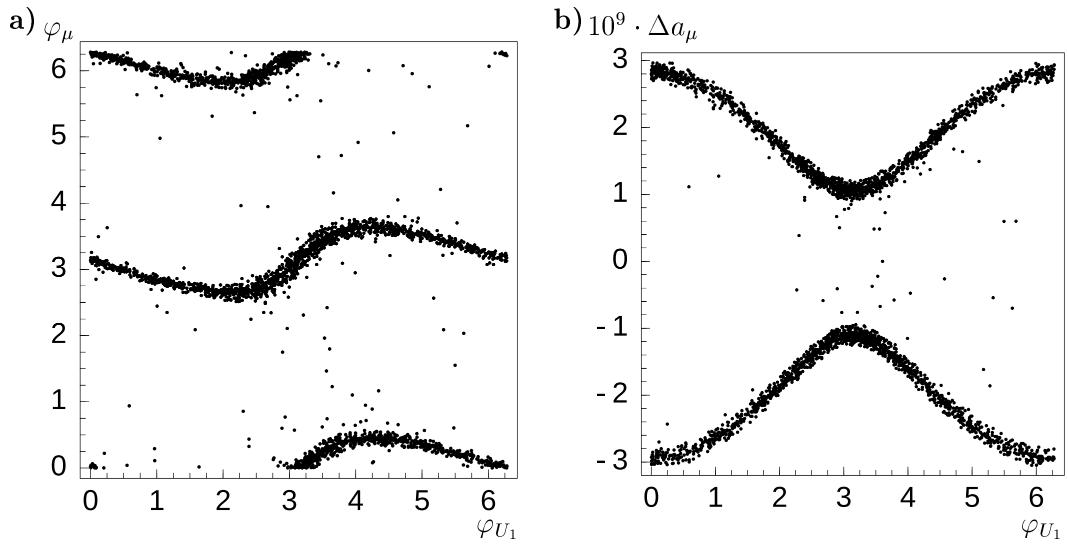

Figure 5: a) Allowed regions in the φ_μ–φ_{U_1}; b) SUSY contribution Δa_μ to the anomalous magnetic moment of the muon. Here we have taken the most general form for the slepton mixings.

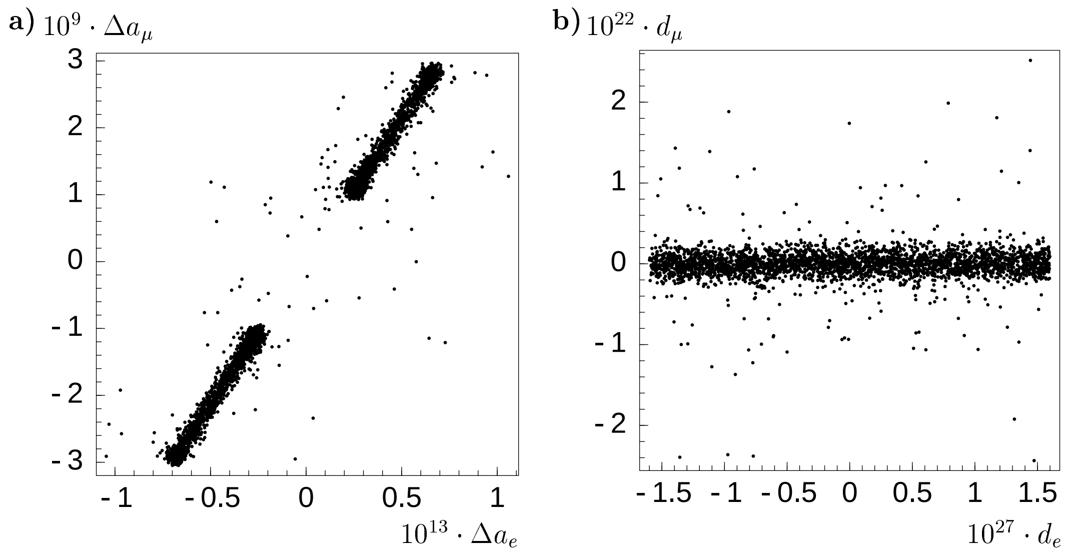

Figure 6: Correlation between a) Δa_e and Δa_μ and b) d_e and d_μ.

would be allowed. The major differences compared to $\varphi_\mu = \pi/2$ are: (i) The moduli of the A parameters are smaller by about 25%. (ii) There are less points with large moduli.

5. Conclusions

In this paper we analysed the implications on supersymmetric phases coming from the experimental restrictions on anomalous magnetic and electric dipole moments of the charged leptons and on the rare decays $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$. Here we have considered the most general mass matrices for sleptons within the MSSM, including left–right mixing,

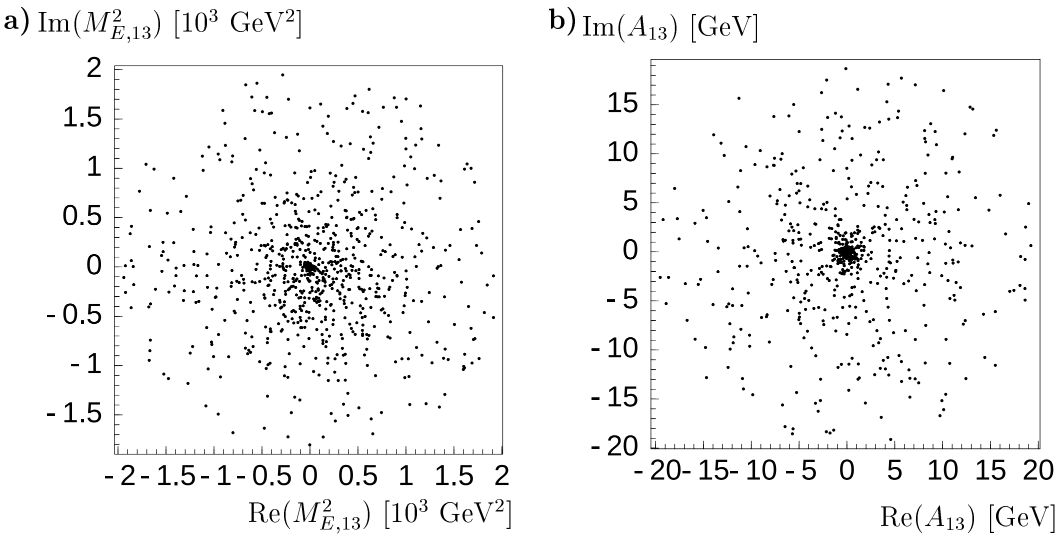

Figure 7: Real and imaginary parts of $M^2_{E,13}$ and A_{13} allowed by the experimental constraints. We have taken $\varphi_\mu = \pi/2$ and the remaining phases have been varied as described in the the text.

flavour mixing and complex phases. For the numerical analysis we have chosen a point close to the ones discussed in the Snowmass report [20].

We have first considered two special situations, because there are many free parameters in a general scenario: (i) We have studied the case where flavour violation in the slepton sector is negligible (no off-diagonal matrix elements). We recover the known results for the phases: In general, all possible phases, especially the phase φ_μ of the μ parameter must be small (or π) in order to be consistent with the electric dipole moments. Only in the case that the phases of M_1 and A_{11} are correlated to the phase of μ, the phases of M_1 and A_{11} can be maximal due to cancellations of different contributions to d_e. (ii) In the case there there is only mixing between selectrons and staus, each individual contribution to d_e due to the phases φ_μ, φ_{U_1}, $\varphi_{M^2_{E,13}}$, $\varphi_{M^2_{L,13}}$, $\varphi_{A_{13}}$, and $\varphi_{A_{31}}$ is of similar magnitude. If only one of these phases is non-vanishing, it must be rather small if the slepton masses are O(100) GeV. However, if two or more phases are present, all of them including φ_μ could be large because the various contributions to d_e may cancel each other.

In the general case with arbitrary three–generation mixing, cancellations between various flavour conserving and flavour violating contributions to d_e are easily possible. In the numerical analysis we have obtained two main results:

(a) Significant restrictions on the allowed ranges are obtained despite the large number of unknown parameters. A good example is given in Fig. 5. From Fig. 5 we see that the allowed range for the new contributions to g–2 are limited by the two wiggly bands. Therefore, if the theoretical analysis of g–2 in the standard model would yield that Δa is in the range $(1-2)\cdot 10^{-9}$ and future collider experiments would measure a similar mass spectrum as considered here, the phase $\phi_{U(1)}$ would have to be near $\pi/2$ or $3\pi/2$.

Fig. 6 shows that the presence of lepton flavour violating phases leads to large deviations of the scaling relations such as $d_e/d_\mu \simeq m_e/m_\mu$, but to much smaller modifications for the scalings of $\Delta a_e/\Delta a_l$. In the case of the electron, the mass is so small that other contribution are also important and may swamp out the mass dependence almost completely. Therefore, it is possible that the EDMs of μ and τ are larger than expected from "naive" scaling.

(b) The lepton flavour violating parameters as well as μ, M_1 and A_{ii} (i=1,2,3) can have large phases, despite the stringent limits on CP violation. In particular, the phase of the parameter μ can be maximal even for O(100) GeV slepton masses, in contrast to naive expectations. Therefore, the phases of the supersymmetric parameters can be as large as those in the standard model and need not be artificially small. While we have used one of the Snowmass points for our presentation of detailed numerical results, we have checked that the qualitative features of our results do not depend on this specific choice.

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