The stau exchange contribution to muon $g - 2$ in the decoupling solution

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Abstract

We study the possibility that the lepton-flavor changing process can induce the suitable magnitude of the muon anomalous magnetic moment $(g_\mu - 2)$ in the decoupling solution to the flavor problem in the minimal supersymmetric standard model. Our analyses introduce the flavor mixings of left- and right-handed stau and smuon phenomenologically. It is found that if both the left- and right-handed sleptons have sizable flavor mixings, the correction to $g_\mu - 2$ from the lighter slepton can reach to 10^{-9} while the correction to the branching ratio of $\tau \to \mu\gamma$ satisfies the current experimental bound. On the other hand, when only the left-handed or right-handed sleptons have the large flavor mixing, the suitable magnitude of the correction to $g_\mu - 2$ is not realized owing to the experimental bound of $\tau \to \mu\gamma$.

While the minimal supersymmetric (SUSY) standard model (MSSM) is one of the promising candidates beyond the standard model (SM), introduction of the SUSY breaking terms may lead to the flavor changing neutral current (FCNC) and CP problems. The decoupling solution (sometime called as "effective SUSY") [1] has been proposed to solve these problems. In this solution, the squarks and sleptons in the first and second generations are heavy enough so that their contributions to the FCNC or CP violating processes are sufficiently suppressed. On the other hand, the gauginos, higgsinos and the sfermions in the third generation are appropriately light to satisfy the naturalness condition on the Higgs boson mass. In

other words, the sfermions whose fermionic partners have the large Yukawa couplings belong to the "lighter group" because they are responsible for the quantum corrections to the Higgs boson mass.

The muon anomalous magnetic moment, conventionally parameterized as $a_\mu \equiv (g_\mu - 2)/2$, has been measured precisely by the E821 experiment at the Brookhaven National Laboratory. The current world average of a_μ is about 2.6σ away from the SM prediction [2]:

$$a_\mu(\exp) - a_\mu(SM) = 426(165) \times 10^{-11}, \qquad (1)$$

which may suggest that new physics exists around the TeV scale [3]. After the announcement, the many works to understand the implication of (1) to physics beyond the SM have been done [4]. It will take

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more time to confirm if (1) is really a signal of new physics from theoretical and experimental points of view. However, once it is confirmed, the constraint on models beyond the SM will be stronger.

It has been considered that the decoupling solution is disfavored from this observation, since the smuon and the muon-sneutrino are too heavy to give a sizable contribution to $g_\mu - 2$. However, if the stau and the tau-sneutrino have the couplings to the muon in this model, their mediation may be able to enhance $g_\mu - 2$ suitably. When $\tan\beta$ is small, the Yukawa coupling of tau lepton is also small, and it is model dependent whether the stau is classified to the lighter or heavier group in the decoupling solution. In the case, even if one slepton belongs to the lighter group, the slepton may not necessarily correspond to the scalar component of the tau-lepton superfield and may be some mixture of the stau and the smuon. The neutrino oscillation data [5] may suggest the left-handed stau and smuon have a large mixing [6]. If the energy scale of the SUSY-breaking mediation to the MSSM is higher than the mass scale of the right-handed neutrino, this spectrum should be realized so that the tau-neutrino Yukawa coupling does not destabilize the naturalness of the Higgs boson mass.

In this Letter, we examine the possibility that the lepton-flavor changing process can induce the suitable magnitude of the muon anomalous magnetic moment in the decoupling solution to the flavor problem. We introduce the mixings of the left- and right-handed stau and smuon phenomenologically. We find that if both the left- and right-handed sleptons have the sizable mixings between the second and the third generations, the correction to $g_\mu - 2$ from the lighter slepton can reach to 10^{-9} which corresponds to about 2σ lower bound of a_μ, while the correction to the branching ratio of $\tau \to \mu\gamma$ satisfies the current experimental bound. When only the left-handed sleptons have a large mixing between the second and third generations, the supersymmetric contribution to $g_\mu - 2$ is constrained to be smaller than 10^{-10} from the experimental bound of $\tau \to \mu\gamma$. On the other hand, in the case with a large mixing only in the right-handed slepton between the second and third generations, the magnitude of the model contribution to $g_\mu - 2$ is at most a few 10^{-10}, and the contribution is positive when the higgsino mass (the μ-term) is negative.

Let us briefly review the muon anomalous magnetic moment and the radiative decay $\tau \to \mu\gamma$ in the SUSY-SM with the lepton flavor violations (LFV). The effective Lagrangian related to $g_\mu - 2$ and $\tau \to \mu\gamma$ is as follows:

$$\mathcal{L}_{\text{eff}} = e\frac{m_{\ell_j}}{2}\bar{\ell}_i\sigma_{\mu\nu}F^{\mu\nu}(L_{ij}P_L + R_{ij}P_R)\ell_j, \qquad (2)$$

where m_{ℓ_i} is a mass of the charged lepton ℓ_i and the indices $i, j = 1, 2, 3$ denote the generation. The coefficients L_{ij} and R_{ij} account for the model dependent contributions to the dipole operators in the quantum level. Then, the muon anomalous magnetic moment is given in terms of L_{ij} and R_{ij} as

$$a_\mu = m_\mu^2(L_{22} + R_{22}), \qquad (3)$$

while the branching ratio of $\tau \to \mu\gamma$ is given by

$$\text{Br}(\tau \to \mu\gamma)$$
$$= \text{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)\frac{48\pi^3\alpha}{G_F^2}(|L_{23}|^2 + |R_{23}|^2), \qquad (4)$$

where G_F is the Fermi constant and $\text{Br}(\tau \to \mu\nu_\tau \times \bar{\nu}_\mu) = 17\%$. In the SUSY-SM with LFV, L_{ij} and R_{ij} are given by contributions from (i) chargino–sneutrino exchange, and (ii) neutralino–charged slepton exchange. The explicit form of L_{ij} and R_{ij} in the framework of the SUSY-SM with LFV can be found, for example, in Ref. [7].

In the effective SUSY-SM, the supersymmetric contributions to both $g_\mu - 2$ and $\tau \to \mu\gamma$ may be dominated by the stau or the tau-sneutrino exchange through the lepton flavor violating interactions.[1] The origin of the flavor violating interactions is the flavor off-diagonal terms in the soft SUSY breaking mass matrix for the sleptons. In the following analysis, we focus on the mixing between the second and third generations of sleptons. In the limit that the left–right mixing terms of the charged sleptons are ignored, the mass eigenstates are given using the mixing angles θ_L and θ_R as follows:

$$\begin{pmatrix} \tilde{\mu}'_L \\ \tilde{\tau}'_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix}\begin{pmatrix} \tilde{\mu}_L \\ \tilde{\tau}_L \end{pmatrix}, \qquad (5)$$

$$\begin{pmatrix} \tilde{\mu}'_R \\ \tilde{\tau}'_R \end{pmatrix} = \begin{pmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{pmatrix}\begin{pmatrix} \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}, \qquad (6)$$

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[1] Note that it is argued in Ref. [8] that two-loop diagrams from an anomalous $H^- - W^+ - \gamma$ coupling may be a sizable contribution to $g_\mu - 2$ for large $\tan\beta$, large μ parameter, and light stop and sbottom.

where $\tilde{\mu}_{L(R)}$ and $\tilde{\tau}_{L(R)}$ are the flavor eigenstates for left (right)-handed sleptons. The mass eigenstates $\tilde{\mu}'_{L(R)}$ are heavier than $\tilde{\tau}'_{L(R)}$. The flavor mixing of the sneutrinos between the second and the third generations are describe by the same unitary matrix with the charged sleptons (r.h.s. in Eq. (5)).

The mass eigenvalues and the mixings are related to the SUSY breaking parameters in the Lagrangian as

$$
m^2_{\tilde{\tau}_{L/R}} = \frac{1}{2}\Big\{ (m^2_{L/R})_{33} + (m^2_{L/R})_{22} \\
- \Big[((m^2_{L/R})_{33} - (m^2_{L/R})_{22})^2 \\
+ 4|(m^2_{L/R})_{12}|^2 \Big]^{1/2} \Big\},
$$
$$
\tan 2\theta_{L/R} = \frac{2(m^2_{L/R})_{12}}{(m^2_{L/R})_{22} - (m^2_{L/R})_{33}}, \qquad (7)
$$

where $(m^2_{L/R})_{ij}$ are for the SUSY breaking parameters of the left-handed (right-handed) sleptons and i, j refer to the generation. Thus, in order to generate lighter stau with the large mixing, $(m^2_{L/R})_{33} \simeq (m^2_{L/R})_{22} \simeq (m^2_{L/R})_{23}$ is required.

In a limit where the relevant SUSY breaking parameters are given by a common mass m_{SUSY}, the SUSY contribution to the muon $g_\mu - 2$ (a_μ^{SUSY}) is approximately given as

$$
a_\mu^{\text{SUSY}} \simeq \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_\mu^2 \tan\beta}{m_{\text{SUSY}}^2} \sin^2\theta_L \\
- \frac{\alpha_Y}{24\pi} \frac{m_\mu^2 \tan\beta}{m_{\text{SUSY}}^2} \sin^2\theta_R \\
+ \frac{\alpha_Y}{96\pi} \frac{m_\mu m_\tau \tan\beta}{m_{\text{SUSY}}^2} \sin 2\theta_L \sin 2\theta_R. \qquad (8)
$$

Here, we keep terms proportional to $\tan\beta$. On the other hand, coefficients L_{23} and R_{23} in Eq. (2) which give $\tau \to \mu\gamma$ (4) are expressed as

$$
L_{23} \simeq -\frac{\alpha_Y}{192\pi} \frac{\tan\beta}{m_{\text{SUSY}}^2} \sin 2\theta_R \\
+ \frac{\alpha_Y}{198\pi} \frac{\tan\beta}{m_{\text{SUSY}}^2} \sin 2\theta_R \cos^2\theta_L, \qquad (9)
$$
$$
R_{23} \simeq \frac{5\alpha_2 + \alpha_Y}{384\pi} \frac{\tan\beta}{m_{\text{SUSY}}^2} \sin 2\theta_L \\
+ \frac{\alpha_Y}{198\pi} \frac{\tan\beta}{m_{\text{SUSY}}^2} \sin 2\theta_L \cos^2\theta_R. \qquad (10)
$$

The SUSY contributions, Eqs. (8), (9) and (10), can be calculated from four diagrams in Fig. 1(a)–(d). Fig. 1(a) gives the first terms in Eqs. (8) and (10),
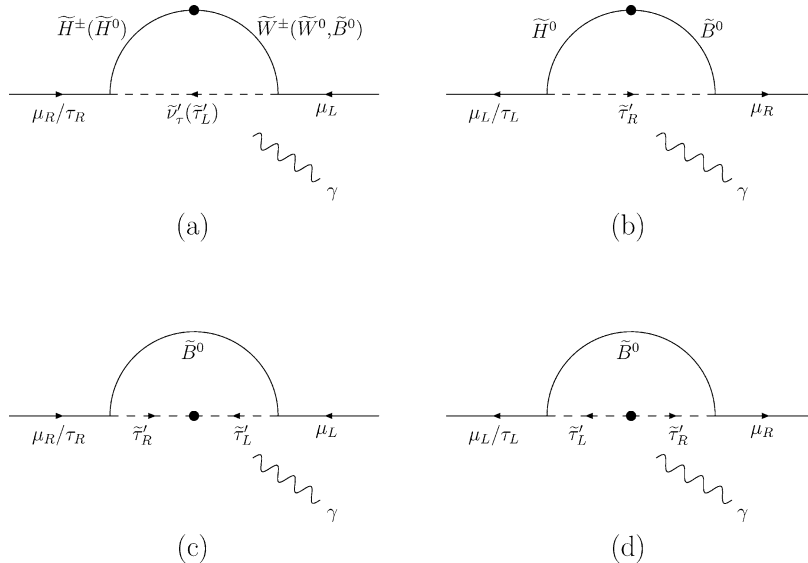

Fig. 1. Feynman diagrams of $g_\mu - 2$ and $\tau \to \mu\gamma$, which are proportional to $\tan\beta$. The symbols $\widetilde{B}^0$, $\widetilde{W}^0$ ($\widetilde{W}^\pm$), and $\widetilde{H}^0$ ($\widetilde{H}^\pm$) are bino, neutral (charged) wino, and neutral (charged) higgsino, respectively. The lightest left-handed (right-handed) charged slepton is denoted by $\tilde{\tau}'_L$ ($\tilde{\tau}'_R$), while $\tilde{\nu}'_\tau$ being the sneutrino.

while Fig. 1(b) gives the second term in Eq. (8) and the first term in Eq. (9). The last terms in Eqs. (8)–(10) correspond to Figs. 1(c) and (d). In the above, we retain the terms which are dominant when $\tan\beta$ is small ($\lesssim 10$ but larger than one). They are useful to understand the following numerical result.

It is worth to note that each diagram in Fig. 1 is proportional to $M_1\mu$ or $M_2\mu$, where M_1 and M_2 are the U(1)$_Y$ and SU(2)$_L$ gaugino masses, respectively, and μ denotes the higgsino mass. This proportionality is not explicitly shown in Eqs. (8)–(10) because the equations are derived in the limit where all SUSY particles have the common mass m_{SUSY} so that $M_1 = M_2 = \mu = m_{\mathrm{SUSY}}$ are cancelled by some powers of m_{SUSY} in the denominator which come from the propagators. When only the right-handed sleptons
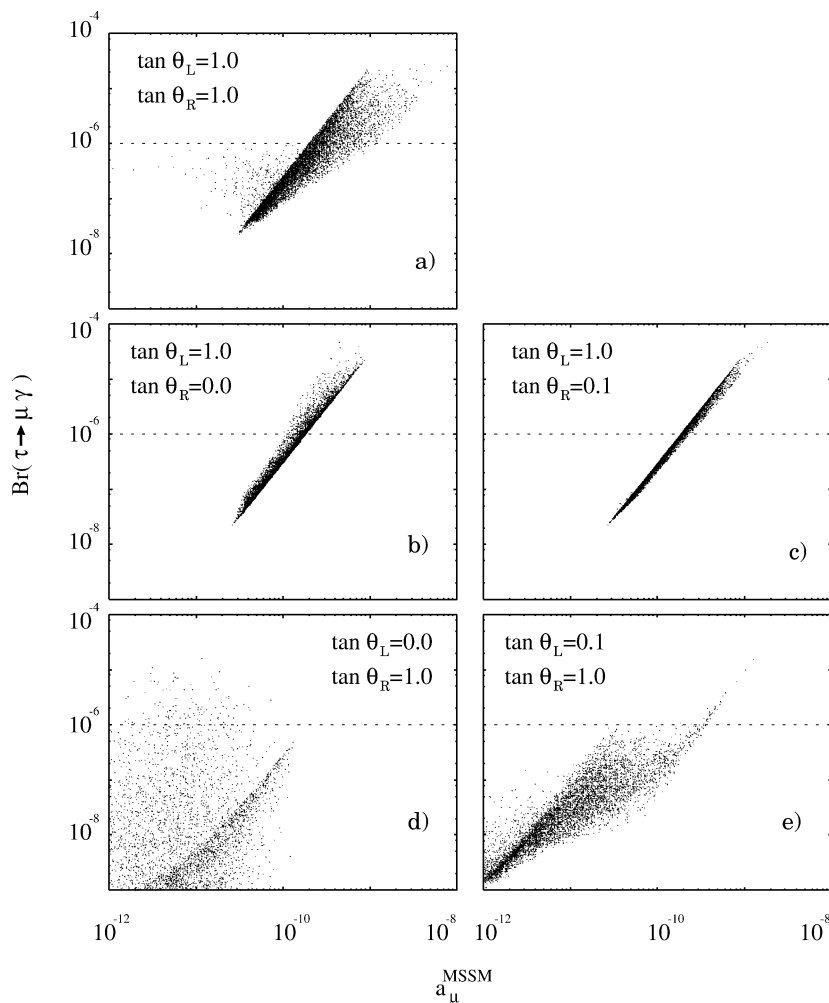

Fig. 2. Prediction of the effective SUSY-SM on the muon $g - 2$ and the branching ratio $\tau \to \mu\gamma$ for $\tan\beta = 3$. The dependence of the mixing angles θ_L and θ_R are examined for $(\tan\theta_L, \tan\theta_R) = (1.0, 1.0)$ (a), $(1.0, 0.0)$ (b), $(1.0, 0.1)$ (c), $(0.0, 1.0)$ (d) and $(0.1, 1.0)$ (e). The soft SUSY breaking masses for the SU(2)$_L$ doublet and singlet sleptons in the third generation are taken as 100–1000 GeV while those in the second generation are fixed by 10 TeV. The higgsino mass and the SU(2)$_L$ gaugino mass are examined between 100 and 500 GeV, and the A-terms for the charged sleptons are fixed by zero. The relative sign between the higgsino and the gaugino masses is taken to be positive for (a)–(c) and (e), while it is negative for (d). The bounds on the stau and chargino from the direct search experiment, $m_{\tilde\tau} > 85$ GeV and $m_{\tilde\chi_1^-} > 103.5$ GeV, are taken into account [9]. The horizontal dotted-line in each figure denotes the 90% CL upper bound of Br($\tau \to \mu\gamma$) [10].

have the flavor mixing, the contribution to $g_\mu - 2$ tends to be positive for $M_1\mu < 0$, that is favored from the current measurement of muon $g - 2$ (1). In the following numerical study, μ is taken to be negative when only the right-handed sleptons have the flavor mixing, while it is positive for the other cases.

Let us examine the muon $g - 2$ and the branching ratio of $\tau \to \mu\gamma$ in the effective SUSY-SM quantitatively, taking account of the flavor mixing of sleptons between the second and third generations. We show the prediction of the effective SUSY-SM on the muon $g - 2$ and Br($\tau \to \mu\gamma$) for $\tan\beta = 3$ in Fig. 2. The dependence of the mixing angles θ_L and θ_R are examined for $(\tan\theta_L, \tan\theta_R) = (1.0, 1.0)$ (a), $(1.0, 0.0)$ (b), $(1.0, 0.1)$ (c), $(0.0, 1.0)$ (d) and $(0.1, 1.0)$ (e). The soft SUSY breaking masses for the $SU(2)_L$ doublet and singlet sleptons in the third generation are taken as 100–1000 GeV while those in the second generation are fixed by 10 TeV. The higgsino mass μ and the $SU(2)_L$ gaugino mass M_2 are taken as 100 GeV $\leqslant |\mu|, M_2 \leqslant 500$ GeV with the GUT relation $M_2/M_1 = 3\alpha_2/5\alpha_Y$. The A-terms for the charged sleptons are fixed at zero. The relative sign between the higgsino and the gaugino masses is taken to be positive for (a)–(c) and (e), while it is negative for (d), as mentioned above. In the analysis, the bounds on the stau and the chargino masses from the direct search experiment, $m_{\tilde\tau} > 85$ GeV and $m_{\tilde\chi_1^-} > 103.5$ GeV, are taken into account [9]. The horizontal dotted-line in each figure shows the experimental bound on Br($\tau \to \mu\gamma$) at 90% CL [10],

$$\text{Br}(\tau \to \mu\gamma) < 1.0 \times 10^{-6}. \tag{11}$$

Let us first see Fig. 2(a). Here, we examine the case in which the flavor mixing angles for both the left- and the right-handed sleptons are assumed to be maximal, i.e., $\theta_L = \theta_R = \pi/4$. It seems that there may be a certain proportionality between a_μ^{SUSY} and $\tau \to \mu\gamma$. This is because both a_μ^{SUSY} and $\tau \to \mu\gamma$ are given by the coefficients L_{ij} and R_{ij} as Eqs. (3) and (4). Fig. 2(a) shows that a_μ^{SUSY} is predicted to be much larger than that in the other four figures. When the flavor mixings for both the left- and right-handed sleptons are sizable and their magnitudes are close to each other, the last term in Eq. (8) may become sizable because the term is proportional to m_τ due to the left–right mixing of the tau-sleptons. Since

this effect disappears when one of the mixing angles is much smaller than the others, this is why a_μ^{SUSY} could be large comparing with other four sets of the mixing angles, Figs. 2(b)–(e). Taking account of the bounds on Br($\tau \to \mu\gamma$) (11), we find that $a_\mu^{\text{SUSY}} \sim 10^{-9}$, which corresponds to about 2σ lower bound, is expected in the certain region of the parameter space.

We show a_μ^{SUSY} and $\tau \to \mu\gamma$ when the flavor mixing of the left-handed sleptons is dominantly large $(\tan\theta_L = 1.0, \tan\theta_R \sim 0)$ in Fig. 2(b) and (c). In the small θ_R limit, the first term in Eq. (8) and R_{23} in Eq. (10) dominate a_μ^{SUSY} and $\tau \to \mu\gamma$, respectively, while the other two terms in Eq. (8) and L_{23} are highly suppressed by small θ_R. We find in Fig. 2(b) and (c) that a_μ^{SUSY} and $\tau \to \mu\gamma$ are strongly correlated each other and it may be difficult to obtain the suitable magnitude of the muon $g - 2$ in this set of the mixing angles by taking account of the experimental bound of $\tau \to \mu\gamma$.

Figs. 2(d) and (e) show a_μ^{SUSY} and $\tau \to \mu\gamma$ between the second and third generations are maximal for the right-handed sleptons $(\tan\theta_R = 1.0)$, but very small or zero for the left-handed sleptons $(\tan\theta_L = 0.1$ or 0). We find that this set of the mixing angles makes both a_μ^{SUSY} and $\tau \to \mu\gamma$ to be smaller than the other set of the mixing angles. As seen in (8), a_μ^{SUSY} is proportional to the $U(1)_Y$ gauge coupling because the first and third terms in (8) are suppressed due to small $\sin\theta_L$. On the other hand, only the coefficient L_{23} (9) is responsible for $\tau \to \mu\gamma$, since R_{23} (10) are negligible in the small θ_L limit. Furthermore, L_{23} itself also becomes small because both terms in Eq. (9) may be cancelled out for small θ_L. Then, we find that almost all parameter region satisfies the bound from $\tau \to \mu\gamma$, but suitable magnitude of a_μ^{SUSY} cannot be expected in the region.

We have so far studied a_μ^{SUSY} and $\tau \to \mu\gamma$ in the effective SUSY-SM quantitatively. Our results are restricted in the case of $\tan\beta = 3$. One may have an interest for the large $\tan\beta$ case. Let us recall the expressions of a_μ^{SUSY} and $\tau \to \mu\gamma$ in the common SUSY mass limit, Eqs. (8)–(10). The $\tan\beta$ dependence of a_μ^{SUSY} is linear while that of Br($\tau \to \mu\gamma$) is quadratic because $|L_{23}|^2 + |R_{23}|^2$ appears in the branching ratio. Thus, the sizable enhancement of a_μ^{SUSY} may be possible for large $\tan\beta$, but Br($\tau \to \mu\gamma$) is also much

enhanced by $\tan^2 \beta$ so that it is disfavored from the current experimental bound.

The numerical study in the above tells us that, in order to explain simultaneously the experimental data of the muon $g - 2$ and the radiative decay $\tau \to \mu\gamma$ in the framework of the effective SUSY-SM, not only the flavor mixing between the second and third generations of the left-handed sleptons, but also that of the right-handed sleptons must be large. In addition, the mixing between the left- and right-handed tau-sleptons plays an important role to induce the suitable magnitude of the muon $g - 2$. It is worth to look for the model of effective SUSY where the flavor mixing of both the left- and right-handed sleptons are predicted to be large, but it is beyond our scope in this Letter.

In summary, we have examined the possibility that the lepton-flavor changing process can induce the suitable magnitude of the muon anomalous magnetic moment in the effective SUSY-SM. In our analysis, the slepton flavor mixings between the second and third generations are introduced phenomenologically. We find that if both the left- and right-handed sleptons have sizable flavor mixings, the supersymmetric contributions to $g_\mu - 2$ from the lighter slepton can reach to 10^{-9} which corresponds to about 2σ lower bound of a_μ, while the correction to the branching ratio of $\tau \to \mu\gamma$ satisfies the current experimental bound. The constraints from $g_\mu - 2$ and $\tau \to \mu\gamma$ cannot be satisfied simultaneously when there is the lack of the flavor mixing in either the left- or the right-handed sleptons. When only the left-handed slepton have the large flavor mixing between the second and the third generations, the supersymmetric contribution to $g_\mu - 2$ is constrained to be smaller than 10^{-10} owing to the experimental bound of $\tau \to \mu\gamma$. We also find that the suitable magnitude of a_μ^{SUSY} cannot be expected when only the right-handed sleptons have the large flavor mixing although almost all parameter region satisfies the bound from $\tau \to \mu\gamma$.

Note added

After completion of this Letter, we found that the estimate of the hadronic light-by-light scattering was revisited [11]. The new estimate [11] tells us that the sign of pseudo-scalar pole contribution is opposite from the previous estimates [12] and it was confirmed

in Refs. [13,14] recently. Using the new value of the light-by-light scattering contribution in [13], we find that Eq. (1) becomes $a_\mu(\exp) - a_\mu(\mathrm{SM}) = 252(164) \times 10^{-11}$, and the discrepancy between the experimental value and the SM prediction is 1.5σ. Our study in this Letter is valid even under this reduction of the deviation.

Acknowledgements

References

[1] M. Dine, A. Kagan, S. Samuel, Phys. Lett. B 243 (1990) 250;
S. Dimopoulos, G.F. Giudice, Phys. Lett. B 357 (1995) 573;
A. Pomarol, D. Tommasini, Nucl. Phys. B 466 (1996) 3;
A.G. Cohen, D.B. Kaplan, A.E. Nelson, Phys. Lett. B 388 (1996) 588;
J. Hisano, K. Kurosawa, Y. Nomura, Phys. Lett. B 445 (1999) 316;
J. Hisano, K. Kurosawa, Y. Nomura, Nucl. Phys. B 584 (2000) 3.

[2] H.N. Brown et al., Muon g-2 Collaboration, Phys. Rev. Lett. 86 (2001) 2227.

[3] A. Czarnecki, W.J. Marciano, Phys. Rev. D 64 (2001) 013014.

[4] L.L. Everett, G.L. Kane, S. Rigolin, L.T. Wang, Phys. Rev. Lett. 86 (2001) 3484;
J.L. Feng, K.T. Matchev, Phys. Rev. Lett. 86 (2001) 3480;
E.A. Baltz, P. Gondolo, Phys. Rev. Lett. 86 (2001) 5004;
U. Chattopadhyay, P. Nath, Phys. Rev. Lett. 86 (2001) 5854;
R. Arnowitt, B. Dutta, B. Hu, Y. Santoso, Phys. Lett. B 505 (2001) 177;
S. Komine, T. Moroi, M. Yamaguchi, Phys. Lett. B 506 (2001) 93;
J.R. Ellis, D.V. Nanopoulos, K.A. Olive, Phys. Lett. B 508 (2001) 65;
J. Hisano, K. Tobe, Phys. Lett. B 510 (2001) 197;
G.C. Cho, K. Hagiwara, Phys. Lett. B 514 (2001) 123;
K. Choi, K. Hwang, S.K. Kang, K.Y. Lee, W.Y. Song, Phys. Rev. D 64 (2001) 055001;
S.P. Martin, J.D. Wells, Phys. Rev. D 64 (2001) 035003;
K. Cheung, C.H. Chou, O.C. Kong, Phys. Rev. D 64 (2001) 111301;
D.F. Carvalho, J.R. Ellis, M.E. Gomez, S. Lola, Phys. Lett. B 515 (2001) 323;

H. Baer, C. Balazs, J. Ferrandis, X. Tata, Phys. Rev. D 64 (2001) 035004;
S.W. Baek, T. Goto, Y. Okada, K.I. Okumura, Phys. Rev. D 64 (2001) 095001.

[5] Y. Fukuda et al., Super-Kamiokande Collaboration, Phys. Rev. Lett. 81 (1998) 1562;
Y. Fukuda et al., Super-Kamiokande Collaboration, Phys. Rev. Lett. 85 (2000) 3999.

[6] Q. Shafi, Z. Tavartkiladze, Phys. Lett. B 482 (2000) 145.

[7] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, Phys. Rev. D 53 (1996) 2442.

[8] C.H. Chen, C.Q. Geng, Phys. Lett. B 511 (2001) 77.

[9] LEP2 SUSY working group, ALEPH, DELPHI, L3, OPAL experiments, http://lepsusy.web.cern.ch/lepsusy/.

[10] K. Abe et al., BELLE Collaboration, BELLE-CONF-0118.

[11] M. Knecht, A. Nyffeler, hep-ph/0111058;
M. Knecht, A. Nyffeler, M. Perrottet, E. De Rafael, hep-ph/0111059.

[12] J. Bijnens, E. Pallante, J. Prades, Nucl. Phys. B 474 (1996) 379;
M. Hayakawa, T. Kinoshita, Phys. Rev. D 57 (1998) 465.

[13] M. Hayakawa, T. Kinoshita, hep-ph/0112102.

[14] I. Blokland, A. Czarnecki, K. Melnikov, hep-ph/0112117.