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Reevaluation of Higgs-mediated μ–e transition in the MSSM

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ABSTRACT

In this Letter, we reevaluated the Higgs-mediated contribution to $\mu \to e\gamma$, $\mu \to 3e$, and μ–e conversion in nuclei in the MSSM, assuming left-handed sleptons have flavor-mixing mass terms. Contrary to previous works, it is found that Barr–Zee diagrams including top quark give dominant contribution to $\mu \to e\gamma$, and those including bottom quark and tau lepton are also non-negligible only when $\tan\beta$ is large. As a result, the Higgs-mediated contribution dominates over the gaugino-mediated contribution at one-loop level in $\mu \to e\gamma$ when $M_{\text{SUSY}}/m_{A^0} \gtrsim 50$, irrespectively of $\tan\beta$ as far as $\tan\beta$ is not large. Here, M_{SUSY} and m_{A^0} are a typical mass scale of the SUSY particles and the CP-odd Higgs boson mass, respectively. Ratio of branching ratios for $\mu \to e\gamma$ and μ–e conversion in nuclei is also evaluated by including both the gaugino- and Higgs-mediated contributions to the processes. It is found that the ratio is sensitive to $\tan\beta$ and M_{SUSY}/m_{A^0} when $M_{\text{SUSY}}/m_{A^0} \sim (10\text{–}50)$ and $\tan\beta \gtrsim 10$.

1. Introduction

Charged lepton-flavor violating (cLFV) processes, such as $\mu \to e\gamma$, are sensitive to physics beyond the standard model (SM) [1]. While the lepton-flavor conservation is not exact in nature due to finite neutrino masses, cLFV processes are quite suppressed in the standard model. Thus, searches for cLFV processes are a unique window to physics beyond the SM, especially, at TeV scale.

Now the MEG experiment is searching for $\mu \to e\gamma$ [2], it would reach to $\sim 10^{-13}$ for the branching ratio on the first stage, which is improvement of two orders of magnitude compared with the current bound. The COMET and Mu2e experiments [3,4], which are searches for μ–e conversion in nuclei, are being planed in J-PARC and Fermilab, respectively. It is argued that they would reach to $\sim 10^{-16}$ for branching ratio of μ–e conversion with target Al. Here, branching ratio of μ–e conversion is ratio of μ–e conversion rate over muon capture rate. Searches for $\mu \to e\gamma$ and μ–e conversion in nuclei are complementary to each other in studies of physics beyond the SM since those processes may be induced by different types of processes.

The minimal supersymmetric (SUSY) standard model (MSSM) is a leading candidate for physics beyond the SM, and cLFV processes are extensively studied in the model. SUSY-breaking slepton mass terms are lepton-flavor violating. It is noticeable that ratios of branching ratios for cLFV processes would give information of mass spectrum in the MSSM, since dominant diagrams in cLFV processes depend on the mass spectrum.

When SUSY particle masses are $\lesssim O(1)$ TeV, the muon LFV processes, such as μ–e transition processes, $\mu \to e\gamma$, $\mu \to 3e$ and μ–e conversion in nuclei, are generated by the gaugino-mediated contribution, which is generated by one-loop diagrams of gauginos and sleptons (and Higgsinos). Branching ratios for the cLFV processes due to the gaugino-mediated contribution are suppressed by $1/M_{\text{SUSY}}^4$, since the effective dipole interaction is dominant in the cLFV processes. Here, M_{SUSY} is a typical mass scale of the SUSY particles. On the other hand, when $M_{\text{SUSY}} \gtrsim O(1)$ TeV, the Higgs-mediated contribution to the processes could be sizable. The non-holomorphic LFV correction is generated to Yukawa coupling of the Higgs bosons at one-loop level, and it is not suppressed by M_{SUSY} [6]. Branching ratio of μ–e conversion in nuclei is more sensitive to the Higgs-mediated contribution [7]. Thus, ratio of branching ratios for $\mu \to e\gamma$ and μ–e conversion in nuclei is a good observable to constrain mass spectrum in the MSSM, since it is sensitive to whether the gaugino-mediated or Higgs-mediated contribution is dominant.

In this Letter we systematically calculate the Higgs-mediated contributions to cLFV reactions in the MSSM, and clarify the dominant process in each cLFV reaction. For this purpose, we first evaluate the Higgs-mediated contribution to $\mu \to e\gamma$ in the MSSM. Barr–Zee diagrams give dominant contribution to $\mu \to e\gamma$ among various diagrams though those are of higher order. We systemati-

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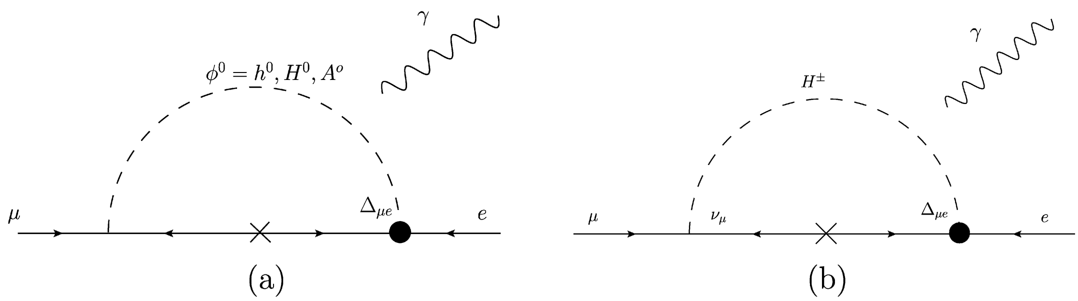

Fig. 1. $\mu \to e\gamma$ induced by Higgs boson exchange at one loop level.

cally evaluate those diagrams, and find that Barr–Zee diagrams including top quark give the largest contribution, and the branching ratio for $\mu \to e\gamma$ induced by the Barr–Zee diagrams is approximately proportional to $\tan^2\beta$. The angle β is defined by $\tan\beta = \langle H_2^0\rangle/\langle H_1^0\rangle$. The Higgs-mediated contribution dominates over the gaugino-mediated one in $\mu \to e\gamma$ when $M_{\rm SUSY}/m_{A^0} \gtrsim 50$, which is almost insensitive to $\tan\beta$. Here, m_{A^0} is the CP-odd Higgs boson mass in the MSSM.

Using this result, we evaluate ratio of branching ratios for $\mu \to e\gamma$ and μ–e conversion in nuclei. When the Higgs-mediated contribution is dominant, the ratio of the branching ratios is scaled by $\tan^4\beta$. It is found that the ratio is quite sensitive to $\tan\beta$ and $M_{\rm SUSY}/m_{A^0}$ when $M_{\rm SUSY}/m_{A^0} \sim (10\text{–}50)$ and $\tan\beta \gtrsim 10$. We also check that the ratio of the branching ratios for $\mu \to e\gamma$ and $\mu \to 3e$ is insensitive to them.

In Refs. [8,9] the Higgs-mediated contribution to the μ–e transition processes in the MSSM is discussed. It is argued that when the Higgs-mediated contribution is dominant, the Barr–Zee diagram including W boson is dominant and branching ratio of $\mu \to e\gamma$ is scaled by $\tan^4\beta$, not $\tan^2\beta$. This is obviously overestimated. We clarify what is wrong in their deviation.

We assume that left-handed sleptons have flavor-mixing mass terms in this Letter, simply because this setup is well-motivated from the SUSY seesaw model [5]. Extension to more general cases will be given elsewhere.

This Letter is organized as follows. In the next section we evaluate the Higgs-mediated contribution for $\mu \to e\gamma$. We show ratio of the Higgs-mediated and gaugino-mediated contributions. In Section 3, we discuss the Higgs-mediated contributions to $\mu \to 3e$ and μ–e conversion in nuclei, and evaluate ratios among the cLFV processes. Section 4 is devoted to conclusions and discussion.

2. Higgs-mediated contribution to $\mu \to e\gamma$ in the MSSM

In the MSSM, LFV in the Higgs coupling originates from the non-holomorphic correction to Yukawa interaction of charged leptons [6]. By including the correction due to one-loop diagrams of gaugino and sleptons, the effective Yukawa coupling is given as follows:

$$-\mathcal{L}_{\rm eff} = \bar{e}'_{Ri} y_{ei} H_1^0 e'_{Li} + \bar{e}'_{Ri} y_{ei}\big(\epsilon_1^{(i)}\delta_{ij} + \epsilon_2^{(ij)}\big) H_2^{0*} e'_{Lj} + \text{h.c.}, \qquad (1)$$

where y_{ei} stands for the i-th charged-lepton Yukawa coupling constant at tree level and e'_{Ri} and e'_{Li} represent right-handed and left-handed leptons, respectively, in a basis where the tree-level lepton Yukawa matrix is diagonal. The non-holomorphic interaction $\epsilon_2^{(ij)}$ $(i \neq j)$ is generated by flavor-violating slepton mass terms. As mentioned in Section 1, we assumed that left-handed sleptons have flavor-violating mass terms. We parametrize $\epsilon_2^{(ij)}$ with mass insertions (MIs) parameters, $\delta_{ij}^{LL} = (\Delta m^2_{\tilde{l}_L})_{ij}/\tilde{m}^2_{\tilde{l}_L}$, where $(\Delta m^2_{\tilde{l}_L})_{ij}$ is off-diagonal element of left-handed slepton mass matrix and $\tilde{m}_{\tilde{l}_L}$ is an average left-handed slepton mass. When the SUSY-breaking mass parameters in the MSSM are taken to be a common value ($M_{\rm SUSY}$), the non-holomorphic corrections $\epsilon_1^{(i)}$ and $\epsilon_2^{(ij)}$ are reduced to

$$\epsilon_1^{(i)} = \frac{g_Y^2}{64\pi^2} - \frac{3g_2^2}{64\pi^2},$$
$$\epsilon_2^{(ij)} = \left(-\frac{g_Y^2}{64\pi^2} + \frac{g_2^2}{64\pi^2}\right)\delta_{ij}^{LL}. \qquad (2)$$

Note that $\epsilon_1^{(i)}$ and $\epsilon_2{}^{(ij)}$ do not vanish even in a limit of large masses of SUSY particles. This is quite different from LFV effective dipole operators induced by the gaugino-slepton loops, whose coefficients are suppressed by masses of internal SUSY particles.

In a mass-eigenstate basis for both leptons and Higgs bosons, $\mathcal{L}_{\rm eff}$ for μ–e transition is described as [6]

$$-\mathcal{L}_{\rm eff}^{\mu-e} = \frac{m_\mu \Delta_{\mu e}^L}{v\cos^2\beta}(\bar{\mu}P_L e) \times \big[\cos(\alpha-\beta)h^0 + \sin(\alpha-\beta)H^0 - iA^0\big] + \text{h.c.}, \qquad (3)$$

where h^0 and H^0 are the CP-even Higgs fields ($m_{h^0} < m_{H^0}$), and A^0 is the CP-odd Higgs field. The LFV parameter $\Delta_{\mu e}^L$ is given by $\Delta_{\mu e}^L = \epsilon_2^{(\mu e)}/(1+\epsilon_1^{(\mu)}\tan\beta)^2$. When we treat $\epsilon_1^{(\mu)}$ and $\epsilon_2^{(\mu e)}$ as a perturbation, we may neglect $\epsilon_1^{(\mu)}$ of the denominator at the first order. In this Letter, we set $\Delta_{\mu e}^L = \epsilon_2^{(\mu e)}$.

In the MSSM, LFV interaction of h^0 in Eq. (3) vanishes when the masses of H^0 and A^0 go to infinity, since $\cos(\alpha-\beta)$ behaves as

$$\cos(\alpha-\beta) \sim \frac{-2m_{Z^0}^2}{m_{A^0}^2\tan\beta}. \qquad (4)$$

This comes from a fact that SM does not have LFV and the light Higgs boson h^0 becomes SM-like in above limit. Therefore the contributions from H^0 and A^0 should be included in cLFV processes.

Now we consider the Higgs-mediated contribution to $\mu \to e\gamma$ in the MSSM. Effective amplitude for $\mu \to e\gamma$ is parametrized as

$$T = e\epsilon^{*\mu}(q)\bar{u}_e(p-q)\big[m_\mu i\sigma_{\mu\nu}q^\nu\big(A^L P_L + A^R P_R\big)\big]u_\mu(p), \qquad (5)$$

and branching ratio of $\mu \to e\gamma$ is derived as $\text{BR}(\mu \to e\gamma) = (48\pi^3\alpha_{\rm em}/G_F^2)(|A^L|^2 + |A^R|^2)$. Here, $\alpha_{\rm em}(\equiv e^2/4\pi)$ is the fine structure constant and G_F is the Fermi constant. While this amplitude could be induced at one-loop level (Fig. 1), it is suppressed by three chiral flips, i.e., one chirality flip in the lepton propagator and two lepton Yukawa couplings. Indeed two-loop diagrams may be significant contribution. As shown in Fig. 2, two-loop diagrams, called as Barr–Zee diagrams, involve only one chiral flip (from lepton Yukawa coupling), and hence their contribution is much larger than that at one-loop level.

Following Refs. [8,9], we consider Barr–Zee diagrams which involve effective γ–γ–ϕ^0 vertices ($\phi^0 = h^0$, H^0, and A^0). The effective vertices are induced by heavy fermion or weak gauge/Higgs