Charged Lepton-Flavor Violation in Beyond-Standard Models

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I discuss charged lepton-flavor violation in physics beyond the standard model and review topics related to it.

1. Introduction

It is found from discovery of the neutrino oscillation that the lepton-flavor symmetries are not exact in nature, while the charged lepton-flavor violation (cLFV) has not been observed yet. The cLFV is suppressed even if the tiny neutrino masses observed in the experiments are introduced in the standard model (SM). The cLFV processes are proportional to the fourth power of the neutrino masses due to the GIM mechanism, similar to the quark sector. The predicted branching ratio of $\mu \to e\gamma$ is smaller than 10^{-54}. However, the lepton-flavor symmetries are accidental in the SM, and it is a big mystery in particle physics why the cLFV processes are not discovered, when considering beyond-standard models (BSMs) [1].

Searches for cLFV processes have long history. Search for $\mu \to e\gamma$ was performed soon after muons were discovered, and it was found that muons are not an excited state of electrons. On 60's, the two-neutrino hypothesis, in which the lepton flavor conservations were introduced, was proposed to suppress $\mu \to e\gamma$. The tau-lepton flavor conservation has been also tested after tau lepton was discovered on 75'. However, on 98', the neutrino oscillation was discovered at SuperKamiokande experiments.

Now the bounds on the cLFV processes are significantly improved by efforts of experimentalists. The current experimental bounds on the representative cLFV processes of muon are given as follows,

$$\mathrm{Br}(\mu \to e\gamma) \ < \ 1.2 \times 10^{-11} \text{ [2]}, \qquad (1)$$
$$\mathrm{Br}(\mu \to eee) \ < \ 1.0 \times 10^{-12} \text{ [3]}, \qquad (2)$$
$$\mathrm{R}(\mu \to e; \mathrm{Ti}) \ < \ 6.1 \times 10^{-13} \text{ [4]}, \qquad (3)$$
$$\mathrm{R}(\mu \to e; \mathrm{Au}) \ < \ 7.0 \times 10^{-13} \text{ [5]}. \qquad (4)$$

μ-e conversion rates in nuclei, given in Eqs. 3 and 4, are normalized by the muon capture rates. Those for tau-lepton's processes come from the Belle and Babar experiments, and they are[1]

$$\mathrm{Br}(\tau \to \mu\gamma) \ < \ 1.6 \times 10^{-8} \text{ [6]}, \qquad (5)$$
$$\mathrm{Br}(\tau \to e\gamma) \ < \ 9.4 \times 10^{-8} \text{ [6]}, \qquad (6)$$
$$\mathrm{Br}(\tau \to 3l) \ < \ \sim 10^{-8} \text{ [6]}, \qquad (7)$$
$$\mathrm{Br}(\tau \to l + \mathrm{hadron(s)}) \ < \ \sim 10^{-8} \text{ [6]}. \qquad (8)$$

A new experiment for $\mu \to e\gamma$ search, MEG, has been started at PSI this year [10]. It is argued [11] that a successful physics run for 5-6 months reaches to (7-8) $\times 10^{-13}$, which is improvement of more than 10 compared with the current bound derived by the MEGA experiment on 98' [2], and that a goal of the first phase of the experiment is (1-2) $\times 10^{-13}$ after another two years. Further improvement down to $\sim 10^{-14}$ in the second phase may be possible after some upgrades.

The signal in μ-e conversion experiments is monochromatic electron with energy $m_\mu - E_{\rm bound}$ ($E_{\rm bound}$ bounding energy), and then the backgrounds (BGs) are quite suppressed. While the conversion rates are suppressed by $10^{-(2-3)}$ compared with $Br(\mu \to e\gamma)$ in typical BSMs such as supersymmetric models, the high sensitivities to the BSMs are expected. Two experiments for μ-e conversion searches with sensitivities $10^{-(16-17)}$, Mu2e in Fermilab [12] and COMET in J-parc [13], are planed. Furthermore, the PRISM/PRIME experiment, in which very intensive pulsed beam is produced by the FFAG muon storage ring, is also planed. It has ultimate sensitivity as $10^{-(18-19)}$ [13].

The searches for cLFV in the tau decay will be continued by the Belle experiment; however, further improvement requires higher luminosity $\mathcal{L}$. Now, two experiments, the Super KEKB [14] and the Super flavor factory [15], are planed. The processes $\tau \to \mu\gamma$ and $\tau \to e\gamma$ already suffer from irreducible BGs from $e^-e^+ \to \tau^+\tau^-\gamma$, Improvements of the sensitivities are scaled as $\sqrt{\mathcal{L}}$ without reduction of the BGs, and the reaches are argued $10^{-(8-9)}$. Other cLFV processes in the tau decay are almost BG-free, and the reaches are argued $10^{-(9-10)}$.

2. CLFV in BSMs

Following are effective operators with cLFV of muon up to $D = 6$,

$$\mathcal{L} = \frac{m_\mu}{\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \frac{1}{\Lambda_F^2}\bar{e}\mu\bar{e}e + \frac{1}{\Lambda_F^2}\bar{e}\mu\bar{q}q. \qquad (9)$$

The first term is for $\mu \to e\gamma$, and the second and third ones are for $\mu \to 3e$ and μ-e conversion in nuclei, respectively. Here, other LFV terms with different

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[1] The bounds on Eqs. 5 and 6 are combined results of Belle [7] and Babar [8, 9].

tensor structures are omitted for simplicity. Roughly speaking, the branching ratios or conversion rates are $\sim (m_W/\Lambda)^4$ or $(m_W/\Lambda_F)^4$. Thus, Λ and Λ_F should be larger than $\sim 10^{(5-6)}$ GeV from the experimental bounds. This implies that the cLFV searches have quite sensitivities to the BSMs.

We have several motivations to consider the BSMs at TeV scale. The naturalness argument for the Higgs boson mass terms is one of them. The dark matter in the universe may be related to physics at TeV scale. In addition, some people consider origin of the neutrino masses at TeV scale.

Why does nature hide clues of the BSMs from FCNC processes including cLFV processes? Some of BSMs, such as the two- or multi-Higgs doublet models and the left-right symmetric models, introduce new Higgs and/or gauge bosons at TeV scale. Some models, such as supersymmetric models, extra dimension models, and the little Higgs model with T parity, introduce partners of leptons and quarks. Those new fields introduce new sources of FCNCs. While FCNCs in the SM are suppressed by small quark/lepton masses or small mixing angle due to the GIM mechanism, the suppression is not necessarily automatic in the BSMs.

First, let us consider the cLFV processes in the supersymmetric standard model (SUSY SM), since it is the leading candidate among the BSMs and also a prototype of the BSMs. Supersymmetry is a symmetry between bosons and fermions, and superpartners for each particles in the SM are introduced to the SUSY SM.

Supersymmetry is not exact in nature. We need to introduce SUSY-breaking mass terms for SUSY particles, which have not yet been discovered. The SUSY-breaking terms are new sources of the flavor violation, since the squark and slepton mass matrices are not necessarily simultaneously diagonalized with those of quarks and leptons.[2] This leads to so-called the SUSY flavor problem. We will discuss this problem from a viewpoint of cLFV in the following.

In the SUSY SM $\mu \to e\gamma$ is generated by one-loop diagrams, and the branching ratio is approximately given as

$$\mathrm{Br}(\mu \to e\gamma) \sim \frac{\alpha}{4\pi} \left(\frac{m_W}{m_{SUSY}} \right)^4 \sin^2 \theta_{\tilde{e}\tilde{\mu}} \left(\frac{\Delta m_{\tilde{l}}^2}{m_{SUSY}^2} \right)^2 , \tag{10}$$

where m_{SUSY} the SUSY breaking scale, $\sin\theta_{\tilde{e}\tilde{\mu}}$ the slepton mixing angle, $\Delta m_{\tilde{l}}^2$ is the slepton mass square difference.

While the branching ratio of $\mu \to e\gamma$ is suppressed by one-loop factor, we need much more suppression in order to make it below the experimental bound. Three directions are proposed. First is the universal scalar mass hypothesis, in which the squarks and sleptons with common quantum numbers are degenerate in mass ($\Delta m_{\tilde{l}}^2 \ll m_{SUSY}^2$). Many models are constructed following this direction; the gravity mediation [17], the gauge mediation [18], the gaugino mediation [19], and the anomaly mediation [20]. Second is the alignment hypothesis ($\sin\theta_{\tilde{e}\tilde{\mu}} \ll 1$). It is assumed that squark and slepton mass matrices can be diagonalized in the same basis as those of quarks and leptons due to some flavor symmetries or some mechanism [21]. Third is the decoupling hypothesis ($m_{SUSY} \gg m_W$). Squarks and sleptons in the first and second generations are so heavy ($O(10^{4-5})$ GeV) that the flavor violation in the first and second generations are suppressed [22].

In these three hypothesis, the cLFV processes are suppressed. However, the improvements of the experimental sensitivities may probe the origin of the SUSY breaking terms and also physics beyond the SUSY SM.

In the universal scalar mass hypothesis, if some physics has LFV interactions below the SUSY-breaking mediation scale, the LFV slepton mass terms are induced radiatively by the renormalization-group effect [23]. In this case the LFV mass terms are not suppressed by powers of the energy scale for the LFV interactions. The seesaw mechanism and the GUTs are nowadays ones of attractive models from the phenomenological and theoretical points of view. In these models, LFV Yukawa interactions are introduced. Thus, if the SUSY breaking mediation scale is higher than the GUT [24] or the right-handed neutrino mass scale [25], sizable LFV processes might be predicted. In Fig. 1, Br($\mu \to e\gamma$) in the SUSY seesaw model is shown. The observed large neutrino mixing angles enhances the cLFV processes of muon and tau lepton [26, 27]. Various studies are performed under the universal scalar mass hypothesis. See references in Ref. [1].

In the decoupling hypothesis, squarks and sleptons in the third generation may have large flavor violation. In addition, even when SUSY particle masses larger than O(1-10) TeV, the Higgs boson exchange may give sizable contributions to the cLFV processes [28]. The SUSY SM has two doublet Higgs bosons (H_1 and H_2), and their effective couplings for leptons are

$$-\mathcal{L}_Y = \bar{e}_{Ri} Y_{li} L_i H_1 + \bar{e}_{Ri} \Delta_{ij} L_j H_2^\dagger + h.c., \tag{11}$$

where Y_{li} is the tree-level Yukawa coupling and Δ_{ij} is non-holomorphic correction generated at one-loop level. Δ_{ij} is not suppressed by the SUSY breaking scale, in addition to enhancement of $\tan\beta$. Then, when the SUSY particles are heavy enough, the Higgs boson exchange dominates in the cLFV processes. Fig. 2 shows the branching ratios for cLFV processes

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[2] The R parity is assumed here. When it is violating, new LFV sources are introduced in the SUSY SM. See Ref. [16] for the detail discussion.

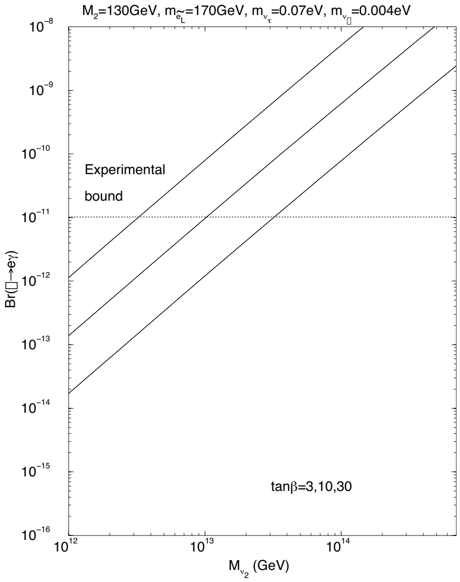

Figure 1: Br($\mu \to e\gamma$) in the SUSY seesaw model. This figure comes from Ref. [26].

of muon, induced by the Higgs boson exchange in the SUSY SM. This figure comes from Ref. [29]. $\mu \to e\gamma$ is induced by the Barr-Zee type loop diagrams, while $\mu \to 3e$ and $\mu \to e$ conversion in nuclei are Higgs-boson exchange processes effectively at tree-level. The Higgs boson exchange contributions to the cLFV processes of tau lepton are also discussed in Ref. [30].

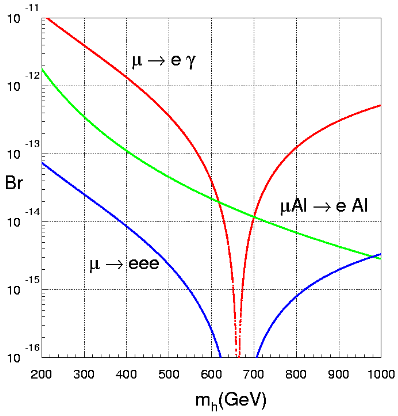

Figure 2: Branching ratios for cLFV processes of muon induced by the Higgs boson exchange in the SUSY SM. This figure comes from Ref. [29].

If the alignment between lepton and slepton masses is not complete in the third hypothesis, the cLFV processes are predicted. Let us show an example with $U(1) \times U(1)$ flavor symmetries, which is given in Ref. [31]. The charge assignments of the right- and left-handed leptons are

$$\bar{E}_1(1,0),\ \bar{E}_2(1,-2),\ \bar{E}_3(0,-3),$$

$$L_1(4,0),\ L_2(2,2),\ L_3(0,4),$$

and the flavor symmetries are broken by VEVs of flavon fields, $\phi_1(-1,0)$ and $\phi_2(0,-1)$. In this case, the charged lepton mass matrix is

$$(m_l) \sim \lambda \begin{pmatrix} \lambda^4 & 0 & 0 \\ \lambda^4 & \lambda^2 & 0 \\ \lambda^4 & \lambda^2 & 1 \end{pmatrix}, \tag{12}$$

and the hierarchical structure of lepton masses is explained with $\lambda \sim 0.1 - 0.2$. In this setup, the slepton mass matrices are aligned, and the left-handed and right-handed slepton mixings are suppressed as $\theta_{\tilde{\mu}_L\tilde{e}_L} \sim \lambda^4$ and $\theta_{\tilde{\mu}_R\tilde{e}_R} \sim \lambda^2$. However, these mixings are marginal to the bounds from $\mu \to e\gamma$.

The SUSY flavor problem is one of the guidelines to construct realistic SUSY SMs. As shown above, in the proposed ideas and models to suppress the FCNC processes, the cLFV processes are not necessarily suppressed, and the on-going and planed experiments cover the predictions.

The cLFV processes also have good sensitivities to non-SUSY models at TeV scale as expected. The BSMs at TeV scale are severely constrained from the cLFV processes, unless some mechanism works to suppress them. In the following, some concrete examples are reviewed.

First is the little Higgs model [32] with T parity [33]. In the little Higgs model, the Higgs boson is a pseudo Nambu-Goldstone boson for symmetry breaking, and quadratic divergence in the radiative correction to the Higgs boson mass term is cancelled by heavy particles at one-loop level. The T parity is introduced for the heavy particles not to contribute to the electroweak observables at tree level. This extension has a bonus. The lightest T-odd particle is stable and a candidate of the dark matter in the universe.

In the little Higgs model with T parity, SU(2)$_L$ doublet mirror leptons with T parity odd are introduced. The mirror leptons have coupling with leptons and the heavy gauge bosons, which is lepton-flavor violating. The cLFV processes are generated at one-loop level, similar to the SUSY SM. In Fig. 3, Br($\mu \to e\gamma$) and Br($\mu \to 3e$) are shown in this model. It is shown in Ref. [34] that the accidental cancellation reduces Br($\mu \to e\gamma$) and two processes have comparable branching ratios. Then, this model still is viable even the mirror leptons are around 1 TeV.

Next is the SM on the Randall-Sundrum (RS) background. The RS geometry is known as a solution of the hierarchy problem [35]. In addition, when the SM fermions and gauge bosons propagate in the full five-dimensional space, the fermion mass hierarchy is also explained even from the “anarchic” structure [36]. In this model the Kaluza-Klein (KK) particles have the LFV interaction. In Fig. 4 Br($\mu \to e\gamma$) and R($\mu \to e;\mathrm{Ti}$) are shown for the KK scale 10 TeV. The current experimental bounds give constraints on

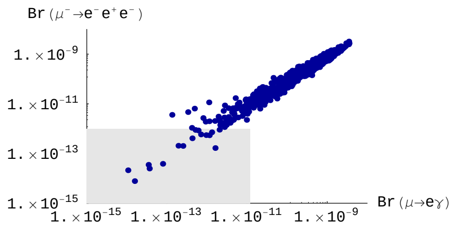

Figure 3: Br($\mu \to e\gamma$) and Br($\mu \to 3e$) in the little Higgs model with T parity. Here, the mirror leptons masses are taken from 300 GeV and 1.5 TeV. This figure comes from Ref. [34].

this model. While $\mu \to e\gamma$ is a one-loop process, the $\mu \to e$ conversion is generated at tree level.

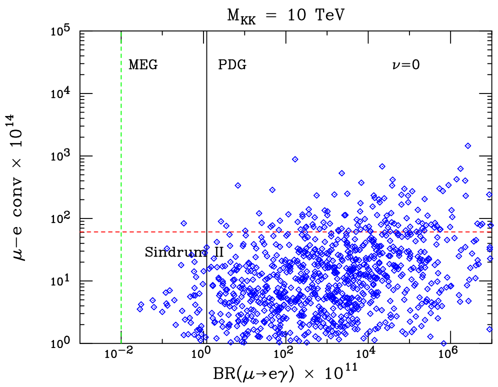

Figure 4: Br($\mu \to e\gamma$) and R($\mu \to e$; Ti) in the SM on the Randall-Sundrum background. Here, the Kaluza-Klein scale is 10 TeV. This figure comes from Ref. [37].

Finally, we discuss the relation of the cLFV processes and the neutrino masses. The seesaw mechanism is the most promising in the candidates of the neutrino masses. In many models the mechanism is realized at much higher energy scale than the TeV scale. In such models we cannot expect some direct relations between the cLFV processes and the origin of the neutrino masses. Exceptions are the SUSY seesaw models [38, 39]; however, the relations are indirect. On the other hand, there are attempts to construct models of the neutrino mass origin at TeV scale.

One of the models is the triplet Higgs model (type-II seesaw model) [40]. In this model, the triplet Higgs boson with mass at TeV scale has sizable lepton-flavor violating coupling, and the coupling is directly linked to the neutrino mass matrix. In Fig. 5 the branching ratios for the cLFV processes of muon in this model are shown. The pattern depends on the neutrino mass structure [41].

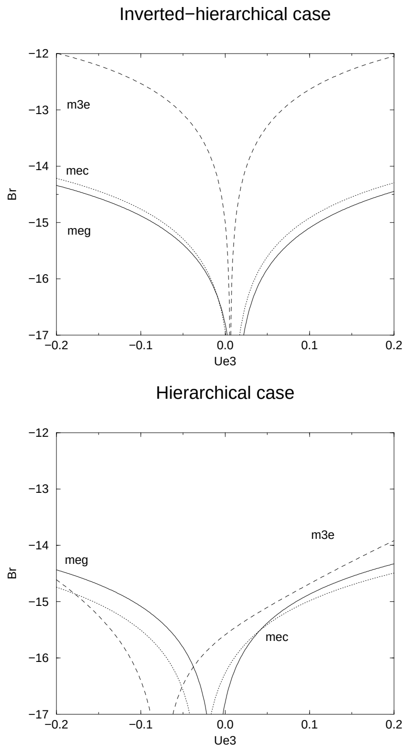

Figure 5: Branching ratios for cLFV processes of muon in the triplet Higgs model. Here, neutrino mass spectrum is inverted-hierarchical (hierarchical) in the upper (lower) figure. These figures come from Ref. [41]

3. Correlations

When the cLFV processes are discovered, it would be important to take correlations among various processes in order to unveil the origin of the lepton-flavor violation and the realistic BSM.

The first correlation is among the cLFV processes with common flavor transition. The correlation discriminates BSMs at TeV scale since the pattern of correlation depends on models. In Table I, the ratios of the cLFV rates of muon are shown in three models; the SUSY SM in which the dipole moment contribution to the cLFV processes is dominant, the SUSY SM in which the SUSY particles are so heavy that the Higgs boson exchange dominates, and the little Higgs model with T parity. While the cLFV processes are radiatively generated in those models, the pattern of the ratio of the cLFV rates are quite different. Correlations among the cLFV processes of τ and among the μ-e conversions in various nuclei [42] are also useful to discriminate models.

The second correlation is among the cLFV processes with different flavor transitions. In some models the cLFV processes are related to the neutrino masses. In the triplet Higgs model, the interaction of the triplet Higgs boson with leptons is directly linked to the neutrino mass matrix (m_ν), as mentioned above. The

Table I Ratios of the cLFV rates of muon in three models. This table comes from [34].

	$\frac{\mathrm{Br}(\mu\to 3e)}{\mathrm{Br}(\mu\to e\gamma)}$	$\frac{\mathrm{R}(\mu\to e;\mathrm{Ti})}{\mathrm{Br}(\mu\to e\gamma)}$
SUSY SM (dipole)	$\sim 6\times 10^{-3}$	$\sim 5\times 10^{-3}$
SUSY SM (Higgs)	$\sim 6\times 10^{-3}$	0.08-0.15
Little Higgs with T parity	0.4-2.5	10^{-2}-10^{2}

model is one of realizations of the minimal flavor violation hypothesis in the lepton sector [43]. As the result, the ratios of the cLFV rates of tau lepton and muon are given as

$$\frac{\mathrm{Br}(\tau\to\mu\gamma)}{\mathrm{Br}(\mu\to e\gamma)} \simeq 0.17\times\left(\frac{(m_\nu m_\nu^\dagger)_{\tau\mu}}{(m_\nu m_\nu^\dagger)_{\tau e}}\right)^2 \sim 300$$

$$\frac{\mathrm{Br}(\tau\to e\gamma)}{\mathrm{Br}(\mu\to e\gamma)} \simeq 0.17\times\left(\frac{(m_\nu m_\nu^\dagger)_{\tau e}}{(m_\nu m_\nu^\dagger)_{\tau e}}\right)^2 \sim 0.2. \quad (13)$$

In the SUSY seesaw models, the cLFV processes are indirectly related to the origin of the neutrino masses even if the energy scale is high. Under the universal scalar mass hypothesis, the cLFV processes give information of the type-I SUSY seesaw model, which is independent of the neutrino mass from a viewpoint of the reconstruction of the model [39]. In the type-II SUSY seesaw model, the relation in Eq. 13 is predicted again [39].

The third correlation is between the hadronic and leptonic FCNC processes. In GUTs, quarks and leptons are unified so that the cLFV processes are correlated with hadronic FCNC processes [44]. Let us consider the SUSY SU(5) GUT with right-handed neutrinos. In this model, lepton doublets and right-handed down-type quarks are embedded in common SU(5) multiplets. Then, neutrino Yukawa coupling affects both the right-handed sdown and left-handed slepton mass matrices [45].

In Fig. 6 we show the correlation between CP phase of the B_s mixing amplitude, ϕ_{B_s}, and $\mathrm{Br}(\tau\to\mu\gamma)$ in the SUSY SU(5) GUT with right-handed neutrinos. The CP violation in the B_s mixing is suppressed in the SM, and then it is also sensitive to the BSMs. The phase ϕ_{B_s} is defined to be zero in the SM. It is recently announced by the **Ut***fit* collaboration [46] that ϕ_{B_s} deviates more than 3σ from the SM prediction. In the figure, we show the region for ϕ_{B_s}. The deviation of ϕ_{B_s} is constrained from null result of $\tau\to\mu\gamma$ search in this model, and the 95% probability region derived by the **Ut***fit* collaboration is marginal in this model. When the deviation of ϕ_{B_s} is established, search for $\tau\to\mu\gamma$ would be an important test of the SUSY SU(5) GUTs.

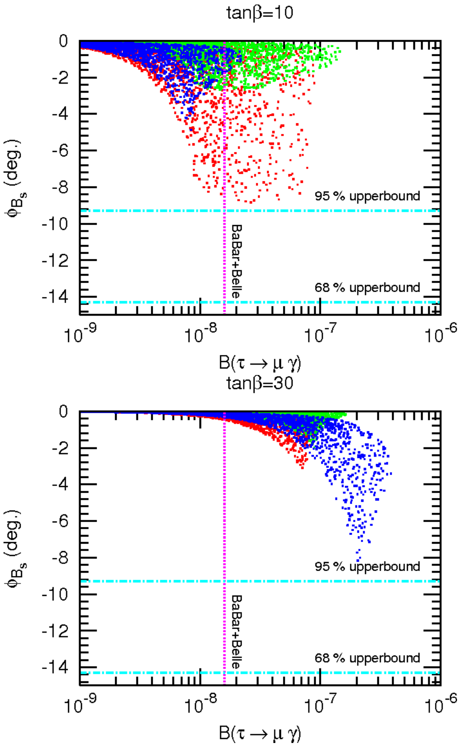

Figure 6: Correlation between CP phase of the B_s mixing amplitude, ϕ_{B_s}, and $\mathrm{Br}(\tau\to\mu\gamma)$ in the SUSY SU(5) GUT with right-handed neutrinos. Here, $\tan\beta = 10$ and 30, and we show the region for ϕ_{B_s}, derived by the **Ut***fit* collaboration. These figures come from Ref. [47]

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When the flavor-violating mass terms for the right-handed squarks are non-vanishing, the hadronic EDMs are generated at one-loop [48] and two-loop levels [49]. The non-zero $(m^2_{\tilde{d}_R})_{23}$ generates the strange-quark chromoelectric dipole moment, which contributes to the hadronic EDMs [50]. Thus, the correlation between the hadronic EDMs and the cLFV processes would be the tests of the SUSY GUTs. But, this program still has difficulties in precisions of the hadronic EDM evaluation [51], and the further improvements would be required for it.

4. Summary

In this talk, I discussed charged lepton-flavor violation in physics beyond the standard model and reviewed topics related to it. The cLFV processes are accidentally suppressed by the GIM mechanism in the SM even after tiny neutrino masses are introduced. On the other hand, the suppression is not necessarily automatic in physics beyond the SM. Studies of cLFVs probe BSMs, hidden flavor symmetries, and underlying flavor structures.

Current bounds on cLFVs give constraints on physics even around $\mathrm{O}(10^{(5-6)})$ GeV. In practical BSMs, cLFVs are suppressed by loop-factors or small flavor-mixing, or accidental cancellation. Thus, coming MEG experiment, and planed experiments, Mu2e, COMET and PRISM/PRIME, will cover interesting regions in various BSMs. Since the cLFVs are pieces of puzzles in the BSMs, it is important to stress that taking various correlations are useful to solve the puzzles.

Acknowledgments

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