論文の内容の要旨

Improved Evaluations of Lepton-Flavor Violating Processes and Neutron Electric Dipole Moment by non-Standard Higgs Interactions

(非標準的ヒッグスの相互作用による レプトンフレーバー非保存過程及び 中性子電気双極子モーメントの改善された評価)

氏名　梁　正樹

The Standard Model (SM) of particle physics [1, 2, 3] is a highly successful theory of nature, that explains various experimental results comprehensively. On July 4th 2012, the ATLAS and the CMS experiments at the Large Hadron Collider (LHC) independently announced the formal discovery of a new boson with mass around 126 GeV [4,5]. The properties of the new boson has been consistent with the SM Higgs boson so far, and this apparent detection of the Higgs boson completes the set of the SM particles. Hereafter, various decay modes of the new boson, and especially, Yukawa couplings with SM particles will be analyzed more precisely at the LHC, and future project, the International Linear Collider (ILC) [6].

Nevertheless, because the SM involves several theoretical and experimental shortcomings, more fundamental physics should be exist beyond the SM. For this reason, various extensions of the SM have been considered so far. If one consider the hierarchy problem seriously, the new physics may exist around the TeV scale, such as supersymmetry (SUSY). New physics models frequently possess the extended Higgs sector, and additional non-standard Higgs fields, such as CP-even heavy Higgs H, CP-odd Higgs A, and charged Higgs $H^{\pm}$. These Higgs fields can have non-standard Yukawa interactions, which violate flavor or CP symmetry, and then, they generate observable flavor or CP violating processes.

In this case we could investigate the Higgs sector by flavor and CP violating observables, and in principle, also explore the underlying models, that might be the origin of the non-standard Yukawa interactions. Hence, various researches about rare processes such as flavor violating Higgs decay, c.f. $H \to \tau\mu$, lepton flavor violation (LFV), electric dipole moment (EDM), have been widely studied such as in the SUSY, multi-Higgs models, and others. However, in some of these studies, specific contributions to the flavor or CP observable are incorrect or has not been considered.

In this thesis, we improve the evaluations of charged lepton-flavor violating (cLFV) processes and neutron electric dipole moment (nEDM) by non-standard Higgs interactions. Although these studies are motivated by SUSY, they do not always require SUSY. If the additional Higgs fields are discovered by the LHC or the future ILC, direct searches for their Yukawa couplings might be insufficient in accuracy. At the moment, flavor or CP violating observable would provides more precise constraints for the Higgs sector, and the new physics beyond the Standard Model. In the following, we describe each topic more precisely.

[In Chapter 6] In the SUSY models, each of two Higgs doublet $H_1(H_2)$ couples only to down(up)-type quarks, and flavor changing neutral currents (FCNC) by Higgs exchange are prohibited at the

Lagrangian level. However, SUSY breaking effects generate additional couplings with the form $Y_u' U^c Q H_1^*$ and $Y_d' D^c Q H_2^*$ at the one-loop level [7] Generally these couplings lead to FCNC or CP violating processes. Note that this effect is sizable for heavy fermion, such as t, b quarks and τ lepton.

The flavor changing effect was widely studied recently, for quarks such as $B^0 \to \mu^+\mu^-$ [8], $K \to \pi\nu\bar{\nu}$ [9], $\tau \to l_j l_k l_k$ [10], and for leptons (lepton flavor violation, LFV), $\tau \to l_j \eta$ [11], $B^0 \to l_j \tau$ [12] $\mu \to e$ conversion in Nuclei [13, 14]. These FCNCs are induced by a tree level Higgs-exchange, nonetheless, this Higgs exchange effects can have a sizable impact also in loop-induced processes, such as $\tau \to \mu\gamma, \tau \to e\gamma$ and $\mu \to e\gamma$ [15, 16]. It was argued that when the Higgs-mediated contribution is dominant, the two-loop Barr–Zee diagram [17] including W boson has largest effect for $\mu \to e\gamma$ decay. However, it is found to be overestimated.

Then, in this chapter, we systematically calculate μ - e transition effects, $\mu \to e\gamma$, $\mu \to 3e$, and μ-e conversion in nuclei ($\mu\text{N} \to e\text{N}$), caused by Higgs exchange in the minimal supersymmetric standard model (MSSM) [18]. As a result, contrary to the previous works, it is found that Barr–Zee diagrams including top quark give the largest contribution to $\mu \to e\gamma$, and those including bottom quark and tau lepton are also non-negligible only when $\tan\beta$ is large [18].

[In Chapter 7]

Using the result of Chapter 6, we evaluate ratio of branching ratios for $\mu \to e\gamma$ and μ-e conversion in nuclei. The important fact is that $\mu\text{N} \to e\text{N}$ is more sensitive to the Higgs-mediated contribution [13, 14]. Therefore, ratio of branching ratios for $\mu \to e\gamma$ and μ-e conversion in nuclei ($\text{BR}(\mu\text{N} \to e\text{N})/\text{BR}(\mu \to e\gamma)$) is sensitive to whether SUSY or Higgs exchange contribution is dominant.

We study non-decoupling μ - e transition effects by Higgs exchange in the MSSM, when some SUSY mass parameters are much greater than TeV scale [19]. We assume the CP-odd Higgs mass m_{A^0} is much lighter than SUSY particles, $m_{A^0} \ll M_{\text{SUSY}}$. Although it is difficult to realize in SUSY models, we set this condition phenomenologically. In order to treat m_{A^0} as a free parameter, we consider the non-universal Higgs mass model (NUHM) which is a generalization of the famous mSUGRA assumption, and assume the only left- or right-handed sleptons had flavor-mixing mass terms.

As a result, the ratio $\text{BR}(\mu \to e\gamma)/\text{BR}(\mu\text{Al} \to e\text{Al})$ drastically depends on the mass spectrum structure and chirality of flavor violation. When only right-handed sleptons have flavor-violation, there is some Higgs-dominant region although SUSY particle masses are around TeV scale. We found it is necessary to consider the Higgs effect in the region where the gaugino effect receives destructive interference.

Fig. 1 (a) shows contour plot of $\text{BR}(\mu\text{Al} \to e\text{Al})$ / $\text{BR}(\mu \to e\gamma)$ including both the Higgs and SUSY particle exchange contributions. If the Higgs-mediated contribution is dominant in the cLFV processes, the ratio between $\mu \to e\gamma$ and $\mu\text{N} \to e\text{N}$ is sensitive to $\tan\beta$, but not to M_{SUSY}/m_{A^0}. On the other hand, if gaugino-mediated LFV is dominant, this ratio is about $O(\alpha_{\text{em}})$ since dipole operator contributions dominate the cLFV processes. When $M_{\text{SUSY}}/m_{A^0} \sim (10 - 110)$ and $\tan\beta \gtrsim 10$, both Higgs- and gaugino-mediated diagrams contribute to those processes in different way and we could give constraints M_{SUSY}/m_{A^0} and $\tan\beta$ from $\text{BR}(\mu\text{Al} \to e\text{Al})/\text{BR}(\mu \to e\gamma)$.

[In Chapter 10] The CP violating processes by tree-level Higgs exchange in the SUSY are also studied, such as $\bar{B^0} - B^0$ [23, 24], CP assymetry in $B_d \to \phi K_S$ decay [25, 26], electric dipole moment (EDM) of Thallium [27]. The Barr–Zee diagrams [17] also contributes to neutron (via quark) and electron EDMs [28, 29]. In the Barr-Zee diagrams the heavy-quark loops are connected to light-quark external lines by the neutral scalar boson exchange so that the chromo electric dipole moments (CEDMs) for light quarks are generated at two-loop level at $O(\alpha_s)$. However, it is not clear which renormalization scale should be chosen for α_s. In addition, the contributions from the Barr-Zee diagrams at two-loop level to the quark EDMs vanish at $O(\alpha_s)$. However, it is still unclear that the higher-order corrections to the quark EDMs are negligible in the neutron EDM evaluation.

In order to answer these questions, we derive the renormalization-group equations (RGEs) for the Wilson coefficients for the CP-violating effective operators up to the dimension six at one-loop level, including operator mixing. The RGEs for the EDMs and CEDMs for quarks and the Weinberg operator have been derived in Ref. [30, 31, 32]. The next-leading order corrections to them are also partially included [33]. We include the four-quark operators in the calculation at the leading order. Using the

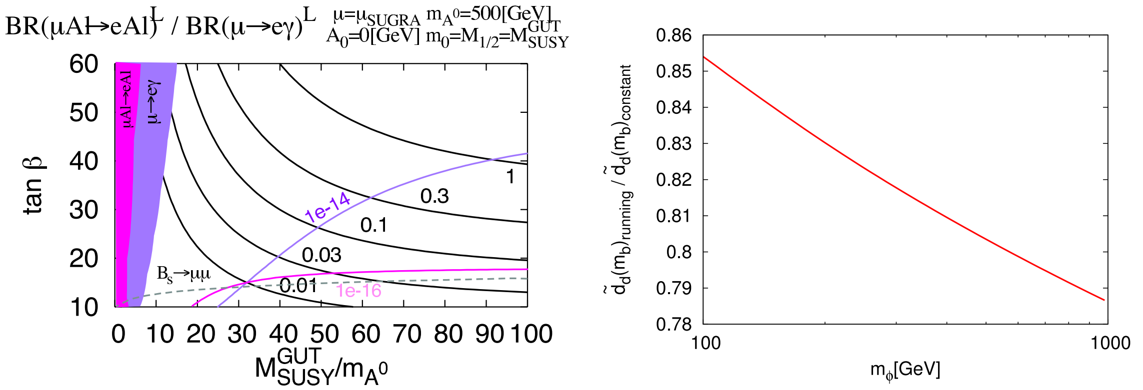

Figure 1: (a) Contour plot of BR(μAl $\to e$Al) / BR($\mu \to e\gamma$), $\tan\beta$ vs $M_{\rm SUSY}^{\rm GUT}/m_{A^0}$ including both the Higgs- and gaugino-mediated contributions. We take the mass insertion parameter $\delta^{LL} = 0.02$, and other parameters are taken as written in figures. The pink (purple) shaded regions are excluded by MEG [20] (the bound for Al nuclei reproduced from the result of SINDRUM II [21]), and the pink (purple) lines are expected bounds of future experiments in each channels. The dashed-line indicates excluded region by the recent $B_s \to \mu^+\mu^-$ observation BR($B_s \to \mu^+\mu^-$) $= (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ [22] (upper regions of each plots are excluded). (b) Ratio of the CEDM for down quark, $\tilde{d}_d$, at $\mu = m_b$ between including and not including running of the strong coupling constant, as a function of m_ϕ.

derived RGEs, we evaluate the EDMs and CEDMs for light quarks and the Weinberg operator induced by the neutral scalar boson exchange including the QCD correction. We also discuss the four-quark operators induced by the color-octet scalar boson.

In Fig. 1 (b) the ratios of the CEDM for down quark at $\mu = m_b$ between including the running effect of α_s and not including it (using the constant coupling $\alpha_s = \alpha_s(m_Z)$), are shown as functions of m_ϕ. It is found that the running coupling $\alpha_s(\mu)$ changes the CEDM by about 20%. This results come from inclusions of the four-quark operators to the RGEs for the Wilson coefficients.

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