Signature of the Minimal Supersymmetric Standard Model with Right-Handed Neutrinos in Long Baseline Experiments

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1 Introduction

The processes of the lepton flavor violation in the charged lepton sector (cLFV) are the clear signature beyond the standard model (SM), and they have been searched for by many experiments. In the minimal supersymmetric standard model with right-handed neutrinos (MSSMRN), the effective cLFV interactions are originated from the off-diagonal elements of the left-handed slepton mass matrix, $(m^2_{\tilde{L}})_{ij}$ $(i \neq j)$, which are induced by the radiative corrections with neutrino Yukawa interaction [1, 2, 3]. The size of the cLFV processes in many classes of such a model can reach the sensitivity of the forthcoming experiments. Therefore, the cLFV search is one of the promising experiments to find evidence of the new physics. However, we here propose an alternative process — the lepton flavor violation with neutrinos (nLFV). The feasibility study on the nLFV interaction search without the specific models has already been made by Refs.[4, 5, 6, 7, 8, 9, 10]. It is pointed out that the nLFV signal in a long baseline oscillation experiment is enhanced by the interference between the amplitude with the nLFV interactions and that of the standard oscillation [8, 9, 10].

We here investigate the nLFV interaction in the MSSMRN. Since the origin of the nLFV processes is the same as that of the cLFV processes and, in addition, there is an enhancement mechanism due to the interference, the detectable nLFV coupling can be expected. We show the numerical result on the size of the nLFV coupling and the correlation with the cLFV process.

In the next section, the enhancement mechanism is explained and the way to parameterize the nLFV effect in an oscillation experiment is shown. We here deal with the nLFV process, $\mu^- \to e^- \bar{\nu}_e \nu_\tau$ in $\nu_\mu \to \nu_\tau$ channel at a neutrino factory. In Sec.3, we evaluate numerically the size of the effective coupling for the nLFV interaction in the MSSMRN. Finally, the conclusions are given in Sec.4.

2 Enhancement mechanism in nLFV interaction search

In the neutrino oscillation experiments, we only observe the charged particles which interact with the neutrino, namely, the neutrino appears only in the intermediate state. Therefore, the

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existence of the nLFV interactions suggests that there are some amplitudes whose initial and final states are the same as the standard oscillation (SO) amplitude. Let us show one example. In $\nu_\mu \to \nu_\tau$ oscillation measurement at a neutrino factory, we can only know the decay of the muon at the muon storage ring and the appearance of the tau lepton at the detector. These observations are interpreted by the standard oscillation scenario as the muon decays into a muon neutrino and it oscillates to the tau neutrino and it produces a tau lepton through the charged current interaction, so the amplitude for this process can be written by the product of the sub-amplitudes as follows:

$$A_{\rm SO}(\mu^- + I \to \tau^- + F) = A(\mu^- \to \nu_\mu \bar{\nu}_e e^-)A(\nu_\mu \to \nu_\tau)A(\nu_\tau d \to \tau^- u). \tag{1}$$

However, the same result can be reproduced by the other process which includes the nLFV interaction, the muon decays into a tau neutrino:

$$A_{\rm nLFV}(\mu^- + I \to \tau^- + F) = A(\mu^- \to \nu_\tau \bar{\nu}_e e^-)A(\nu_\tau \to \nu_\tau)A(\nu_\tau d \to \tau^- u). \tag{2}$$

The oscillation probability for $\nu_\mu \to \nu_\tau$ is modified to

$$P_{\mu^- \to \tau^-} = |A_{\rm SO}|^2 + 2{\rm Re}[A^*_{\rm SO} A_{\rm nLFV}] + \cdots . \tag{3}$$

The second term comes from the interference effect, which is proportional to the nLFV coupling itself not its square. We define $\epsilon^s_{\mu\tau}$ as the ratio between the coupling of the standard interaction and the nLFV interaction[1]:

$$\epsilon^s_{\mu\tau} \equiv A(\mu^- \to \nu_\tau \bar{\nu}_e e^-)/A(\mu^- \to \nu_\mu \bar{\nu}_e e^-). \tag{4}$$

We can deal with this effect by treating the initial neutrino state (the source state) as the flavor mixture state [4]:

$$|\nu^s_\mu\rangle = |\nu_\mu\rangle + \epsilon^s_{\mu\tau}|\nu_\tau\rangle. \tag{5}$$

The other types of nLFV interaction can enter the neutrino propagation process as the exotic matter effect potential [5, 6, 7, 8, 9, 10] and also the neutrino detection process [4]. They are investigated in Ref[11], we here concentrate our attention on the nLFV interaction at the source state.

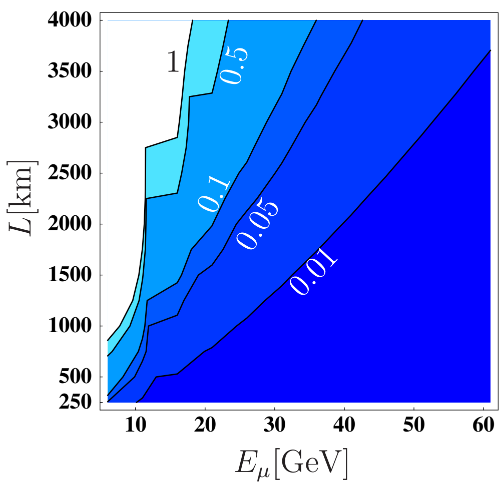

Figure 1: The necessary exposure (= muon number × detector size) to detect the nLFV interaction $\epsilon^s_{\mu\tau} = 3.0 \times 10^{-3} {\rm e}^{{\rm i}(\pi/2)}$ at 90% CL in $\nu_\mu \to \nu_\tau$ channel [9]. The holizontal axis denotes energy of the parent muon and the vertical axis is the baseline length. The numbers in this figure are normalized by 10^{21} muons × 100 ktons detector.

[1]Here, we only consider the $(V-A)(V-A)$ type nLFV interaction.

Figure 1 shows the sensitivity to the nLFV interaction $\epsilon^s_{\mu\tau}$ at a neutrino factory. In this plot, we take 10% uncertainty for the mixing angles and the mass square differences and the matter density parameter, and we treat the CP violating phase in the Maki-Nakagawa-Sakata (MNS) matrix as a freely fitting parameter. The nLFV signal is robust against the adjustment of the standard oscillation parameters because of its characteristic energy dependence [9]. This plot indicates that the nLFV interaction with $\epsilon^s_{\mu\tau} = \mathcal{O}(10^{-4})$ can be observed at a neutrino factory in this oscillation channel.

3 Size of the nLFV coupling in MSSMRN

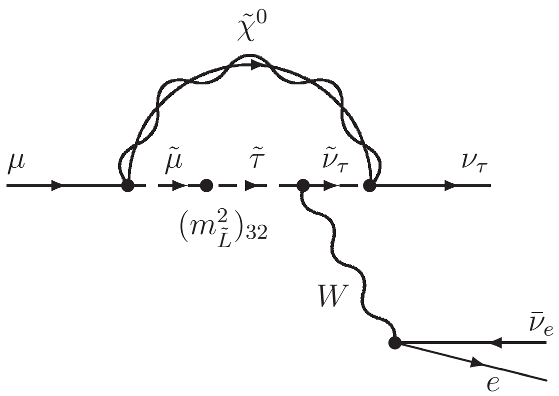

Figure 2: One example of the diagrams which induce the effective interaction $\mu^- \to \nu_\tau \bar{\nu}_e e^-$.

In this section, we turn to the theoretical prediction on the size of $\epsilon^s_{\mu\tau}$ in the MSSMRN. In this model, the nLFV coupling $\epsilon^s_{\mu\tau}$ is induced by the radiative correction. One example is shown in Fig.2. We can roughly estimate the order of $\epsilon^s_{\mu\tau}$ as

$$\epsilon^s_{\mu\tau} \sim \frac{g^2}{(4\pi)^2}\frac{(m^2_{\tilde{L}})_{32}}{m^2_{\rm SUSY}}, \tag{6}$$

where $m_{\rm SUSY}$ is the typical scale for soft SUSY breaking. It is well known that the branching fraction of the cLFV process $\tau \to \mu\gamma$ can be approximated as [2]

$$\mathrm{Br}(\tau \to \mu\gamma) \propto \frac{\alpha^3}{G_F^2}\frac{|(m^2_{\tilde{L}})_{32}|^2}{m^8_{\rm SUSY}}. \tag{7}$$

These equations lead to the correlation between the cLFV process and the nLFV process:

$$\epsilon^s_{\mu\tau} \propto \sqrt{\mathrm{Br}(\tau \to \mu\gamma)} \times m^2_{\rm SUSY}. \tag{8}$$

The numerical result is shown in Fig.3. In this calculation, we scan so called the universal soft mass parameters and the texture of the neutrino Yukawa matrix. The detail is shown in Ref.[11]. This result can be easily understood by Eq.(8).

4 Conclusions

We investigate the size of the nLFV interaction $\mu^- \to \nu_\tau \bar{\nu}_e e^-$ in the framework of the MSSMRN. In this model, the cLFV process such as $\tau \to \mu\gamma$ can be large enough to be detected by

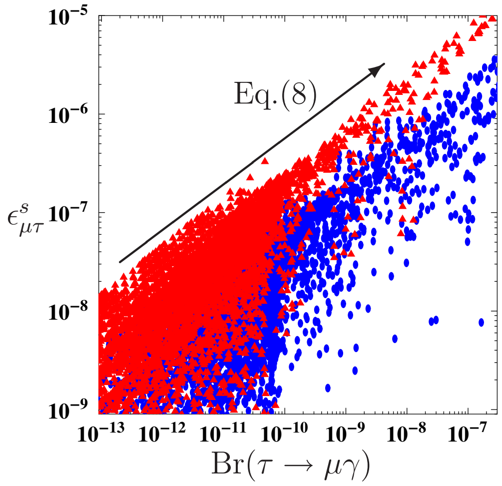

Figure 3: Correlation between $\epsilon^s_{\mu\tau}$ and $\mathrm{Br}(\tau \to \mu\gamma)$. In this calculation, we scan the universal mass parameter with some different texture of the neutrino Yukawa matrix. We fix $a = 0$ and $\mu > 0$. Triangles are for $\tan\beta = 3$ and dots are for $\tan\beta = 10$.

the forthcoming experiments. Since the origin of the cLFV interactions and that of nLFV interactions are the same, and in addition, there is an enhancement mechanism for the nLFV signal due to the interference effect, the sizable nLFV effect can be expected. The sensitivity to $\epsilon^s_{\mu\tau}$ was evaluated as $\mathcal{O}(10^{-4})$ in Ref.[9]. We here evaluate the size of the nLFV coupling $\epsilon^s_{\mu\tau}$ in the MSSMRN and show the correlation with the cLFV process $\tau \to \mu\gamma$. We may have a chance not only to measure the oscillation parameters in the SM but also to detect the new physics effect at a neutrino factory.

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