Lepton flavor violating $\mu N(eN) \to \tau X$ reactions in supersymmetric models

Shinya Kanemura[a] *

[a]Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

We discuss a deep inerastic scattering process $\mu N \to \tau X$ to study lepton flavor violation between muons and tau leptons. In supersymmetric models, the Higgs boson mediated diagrams could be important. At a muon energy (E_μ) higher than 50 GeV, the predicted cross section significantly increases due to the contribution from sea b-quarks. The number of produced tau leptons can be $\mathcal{O}(10^4)$ at E_μ= 300 GeV from 10^{20} muons, whereas $\mathcal{O}(10^2)$ events are given at $E_\mu = 50$ GeV. Another promising possibility to search for the $eN \to \tau X$ reaction at an electron-positron linear collider is also discussed. Searches for these reactions would be competitive with studies of rare tau decays and have potential to improve sensitivities to lepton flavor violation significantly.

1. Introduction

Lepton flavor violation (LFV) is clear evidence to indicate physics beyond the standard model. A type of models based upon supersymmetry (SUSY) naturally induces sizable LFV couplings at loop levels due to slepton mixing [1,2]. The branching ratios of LFV processes predicted in SUSY models would be slightly smaller than the present experimental limits, and therefore they could be reached by future experiments.

In a model based on SUSY, two types of effective LFV couplings are induced at low energies; i.e., those mediated by the neutral gauge bosons and those by the neutral Higgs bosons. In contrast to the gauge boson mediation, the contributions from the Higgs-mediation do not decouple even if the soft SUSY breaking scale is as large as $\mathcal{O}(1)$ TeV. The tau-associated processes are useful to study the Higgs-mediated LFV couplings, because they are proportional to the mass of the relevant charged lepton. The LFV couplings associated with a tau lepton have been measured at B factories by searches for rare tau decays, such as $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, $\tau \to \mu\pi\pi$, $\tau \to \mu\eta$, etc. At future collider experiments, they can be tested directly via the decays of the Higgs bosons (Φ^0), $\Phi^0 \to \tau^\pm\mu^\mp$ [3].

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In this talk, we discuss a $\mu N \to \tau X$ reaction at the deep inelastic scattering (DIS) region with high-intensity and high-energy muon beams as an alternative approach of searching for the LFV couplings associated with a tau lepton[4]. Here, N is a target nucleon, and X represents all final state particles. We also discuss another promising possibility to search for the $e-\tau$ transition via the $eN \to \tau X$ reaction at an electron-positron linear collider (LC).

2. The $\mu N \to \tau X$ cross section

The effective Lagrangian describing the subprocess $\mu q \to \tau q$, where q is a quark, in the minimal supersymmetric standard model (MSSM) is given by

$$\begin{aligned}\mathcal{L}_{\rm eff} = \sum_q \sum_X \big\{ & (\mathcal{A}^V_X)_q \, (\overline{\tau}\gamma^\rho \mathrm{P}_X\mu)\,(\bar{q}\gamma_\rho q) \\ & + (\mathcal{A}^T_X)_q \left(\overline{\tau}\frac{\mathrm{i}m_\tau q_\sigma \sigma^{\rho\sigma}}{q^2}\mathrm{P}_X\mu\right)(\bar{q}\gamma_\rho q) \\ & + (\mathcal{C}^{hH}_X)_q \, (\overline{\tau}\mathrm{P}_X\mu)\,(\overline{q}q) \\ & + (\mathcal{C}^A_X)_q \, (\overline{\tau}\mathrm{P}_X\mu)\left(\overline{q}\gamma^5 q\right)\big\}, \qquad (1)\end{aligned}$$

where $\mathcal{A}^{T,V}_X$ are the effective couplings for the gauge boson mediation with the projection operator P_X for the chirality $X = L$ and R. The scalar coupling $\mathcal{C}^{hH}_X$ and the pseudo-scalar coupling $\mathcal{C}^A_X$

are those mediated by the CP-even neutral Higgs bosons h^0 and H^0, and by the CP-odd state A^0, respectively. They are induced due to loop corrections in the MSSM. The details can be found in Ref. [1] for the gauge boson mediation, and in Ref. [2] for the Higgs boson mediation.

First, let us start with the Higgs boson mediation. It is known that this type of effect does not decouple even in the large $m_{\rm SUSY}$ limit, where $m_{\rm SUSY}$ is a typical scale of the soft SUSY breaking. The contribution of the Higgs boson mediation to $\mu^- N \to \tau^- X$ is given by

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y} = \sum_q x f_q(x) \left\{ \left(\left|\mathcal{C}_L^{hH}\right|^2 + \left|\mathcal{C}_L^{A}\right|^2 \right)_q \left(\frac{1-\mathcal{P}_\mu}{2} \right) + \left(\left|\mathcal{C}_R^{hH}\right|^2 + \left|\mathcal{C}_R^{A}\right|^2 \right)_q \left(\frac{1+\mathcal{P}_\mu}{2} \right) \right\} \frac{s}{16\pi} y^2, \qquad (2)$$

where the function $f_q(x)$ is the parton distribution function (PDF) for q-quarks, $\mathcal{P}_\mu$ is the incident muon polarization such that $\mathcal{P}_\mu = +1$ and -1 correspond to the right- and left-handed polarization, respectively, and s is the center-of-mass (CM) energy. The parameters x and y are defined in the limit of massless tau leptons as

$$x \equiv \frac{Q^2}{2P\cdot q}, \qquad y \equiv \frac{2P\cdot q}{s}, \qquad (3)$$

where P is the four momentum of the target, q is the momentum transfer, and Q is defined as $Q^2 \equiv -q^2$. As seen in Eq. (2), experimentally, the form factors of $\mathcal{C}_L^{hH}$ and $\mathcal{C}_L^{A}$ ($\mathcal{C}_R^{hH}$ and $\mathcal{C}_R^{A}$) can be selectively studied by using purely left-handed (right-handed) incident muons.

When the scalar LFV coupling $(\mathcal{C}_X^{hH})_q$ of $\tau\mu qq$ is independent of the other types of couplings, its experimental constraint comes from the $\tau \to \mu\pi\pi$ result [5]. The total cross section of the process $\mu N \to \tau X$ mediated by the scalar LFV coupling could then be as large as 0.5 fb at muon energy (E_μ) of 50 GeV. For this case, with 10^{20} muons per year on a $\mathcal{O}(10^2)$ g/cm^2 target mass, about 10^6 of the $\mu N \to \tau X$ events can be produced, or no observation of the $\mu N \to \tau X$ signal would improve the limits by six orders of magnitude [6].

In the MSSM, the Higgs boson couplings are related each other [2]. In the decoupling region ($m_A \gtrsim 150$ GeV), where $m_H \simeq m_A$ and $\sin(\alpha-\beta) \simeq -1$, the scalar coupling $\mathcal{C}_L^{hH}$ is nearly equal to the pseudo-scalar coupling $\mathcal{C}_L^{A}$. Therefore, both couplings are determined by the more constrained one, namely the pseudo-scalar coupling [7]. It is constrained by the $\tau \to \mu\eta$ decay ($\mathrm{Br}(\tau \to \mu\eta) < 3.4\times 10^{-7}$) [8]. The branching ratio can be expressed in terms of the s-associated pseudo-scalar couplings $(\mathcal{C}_X^{A})_s$ ($X = L$ and R) by

$$\mathrm{Br}(\tau \to \mu\eta) = \frac{9\tau_\tau m_\tau m_\eta^4}{256\pi} \left(\frac{F_\eta^8}{m_s} \right)^2 \left(1 - \frac{m_\eta^2}{m_\tau^2} \right)^2 \times \left(\left|\mathcal{C}_R^{A}\right|^2 + \left|\mathcal{C}_L^{A}\right|^2 \right)_s, \qquad (4)$$

where τ_τ is the lifetime of tau leptons, and F_η^8 is the parameter of the η meson decay constant [5, 7]. Then the constraint is given both on the s-associated scalar and pseudo-scalar couplings.

In SUSY models such as the MSSM with heavy right-handed neutrinos, LFV is radiatively induced due to the left-handed slepton mixing, which only affects $\mathcal{C}_L^{hH}$ and $\mathcal{C}_L^{A}$. Therefore, in the following, we focus only on those $\mathcal{C}_L^{hH}$ and $\mathcal{C}_L^{A}$ couplings. The largest values of $\mathcal{C}_L^{hH}$ and $\mathcal{C}_L^{A}$ can be realized with $m_{\rm SUSY} \sim \mathcal{O}(1)$ TeV and the Higgsino mass parameter $\mu \sim \mathcal{O}(10)$ TeV. In such

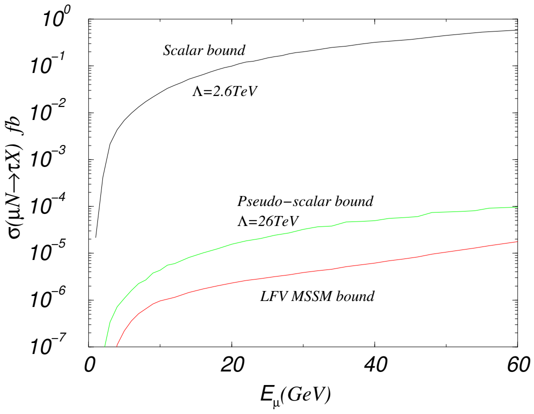

Figure 1. The upper bounds on the cross section of the $\mu^- N \to \tau^- X$ DIS process, assuming the effective scalar and pseudo-scalar couplings [6] and the MSSM Higgs coupling constrained from the data [4]. CTEQ6L is used for the PDF.

a situation, the gauge boson mediated couplings are strongly suppressed. In Fig. 1, the total cross sections are shown for the cases of the independent scalar and pseudo-scalar couplings as well as the SUSY model with the maximal value for these couplings under the current data of the rare tau decays. The largest values of $\mathcal{C}_L^{hH}$ and $\mathcal{C}_L^{A}$ can be realized with $m_{\rm SUSY} \sim \mathcal{O}(1)$ TeV and the Higgsino mass $\mu \sim \mathcal{O}(10)$ TeV. It should be noted that in such a situation, the gauge boson mediated couplings are strongly suppressed.

We evaluate the cross sections of the $\mu N \to \tau X$ reaction in the DIS region for the Higgs-mediated interaction with the maximally allowed values of the effective couplings for each quark contribution: see Fig.2. The cross section sharply increases above $E_\mu \sim 50$ GeV. This enhancement comes from a consequence of the b-quark contribution in addition to the d and s-quark contributions. The cross section is enhanced by one order of magnitude when the muon energy changes from 50 GeV to 100 GeV. Typically, for $E_\mu = 100$ GeV and $E_\mu = 300$ GeV, the cross section is 10^{-4} fb and 10^{-3} fb, respectively.

Next, we comment on the cases where the gauge boson mediation is dominant; i.e., $m_{\rm SUSY} \sim \mathcal{O}(100)$ GeV. The contribution from the tensor interaction is found to be smaller than that from the Higgs boson mediation by about five orders of magnitude. On the other hand, the vector and axial-vector interactions are suppressed at the same level as the pseudo-scalar interaction [5]. Therefore, their contributions can be as large as those for the Higgs boson mediation, if E_μ is less than 50 GeV [6]. At higher energies, the cross section for the gauge boson mediation becomes much smaller than that for the Higgs boson mediation because of no enhancement by the b-quark sub-process. Therefore, the DIS process $\mu N \to \tau X$ can be more useful to search for the Higgs mediated LFV interaction in the MSSM for higher energy muon beams.

3. The $\mu N \to \tau X$ phenomenology

With the intensity of 10^{20} muons per year and the target mass of 100 g/cm^2, about 10^4 (10^2) events could be expected for $\sigma(\mu N \to \tau X) =$

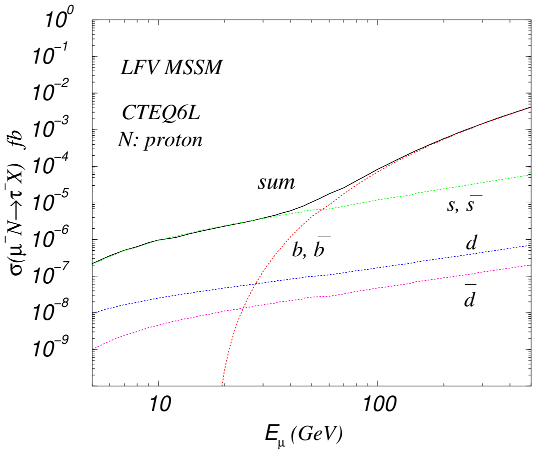

Figure 2. Cross section of the $\mu^- N \to \tau^- X$ DIS process as a function of the muon energy for the Higgs mediated interaction. It is assumed that the initial muons are purely left-handed. CTEQ6L is used for the PDF.

10^{-3} (10^{-5}) fb, which corresponds to $E_\mu = 300$ (50) GeV from Fig. 2. This would provide good potential to improve the sensitivity by four (two) orders of magnitude from the present limit from $\tau \to \mu\eta$ decay, respectively. Such a muon intensity could be available at a future muon collider (MC) and a neutrino factory (NF).

In the Higgs boson mediated interaction, the tau leptons are emitted at a relatively large angle with respect to the beam direction. This is in contrast to the gauge mediated interaction where the tau leptons are forward-peaked.

To identify the tau lepton from the $\mu N \to \tau X$ reaction, direct measurement of tau lepton tracks (such as by emulsions) might not be possible at such a high beam rate. Instead, the identification might be possible by tagging the tau decay products and observing their decay kinematics. Among various decay modes, one might consider leptonic decays of the tau leptons. Another candidate could be to detect a hadron from the tau decays. The signature of the events could be a hard hadron at a relatively large angle from the beam direction (namely a hadron with large transverse momentum p_T) and some missing energy. Those hadrons from the tau decay should be discriminated from the hadrons from the target nucleons which have mostly soft energies.

4. Probing $e-\tau$ transition via $eN \to \tau X$

We can also discuss another LFV search for $e-\tau$ transition through $eN \to \tau X$ with a high energy electron (or positron) beam. In the MSSM with left-handed slepton mixing, similar to the $\bar{\tau}_R \mu_L \Phi^0$ coupling, the $\bar{\tau}_R e_L \Phi^0$ coupling is proportional to the tau lepton mass, where Φ^0 could be either h^0, H^0 or A^0, and l_R and l_L (l=e, μ, τ) are the corresponding right-handed and left-handed leptons, respectively. The coupling of $\bar{\tau}_R e_L \Phi^0$ could be as large as that of $\bar{\tau}_R \mu_L \Phi^0$, when the slepton mixing between $\tilde{\tau}_L$ and $\tilde{e}_L$ is similar to that between $\tilde{\tau}_L$ and $\tilde{\mu}_L$. Therefore, our discussions on the $\mu N \to \tau X$ DIS reaction can be directly applied to the case of $eN \to \tau X$ reaction. Experimental constraints on the effective form factors for $e-\tau$ transition are given by $\tau \to e\eta$ and $\tau \to e\pi\pi$ decays at the B factories and the $e-\tau$ searches at HERA. The strongest bound on the pseudo-scalar coupling for the $e-\tau$ transition comes from the $\tau \to e\eta$ result, which is similar to the bound on the $\mu-\tau$ transition from the $\tau \to \mu\eta$ result. For the scalar coupling, the results of the $ep \to \tau X$ search at HERA give stronger bounds than the $\tau \to e\pi\pi$ result. In the MSSM, therefore, the maximally-allowed cross section for $eN \to \tau X$ is in the same order of magnitude as that for $\mu N \to \tau X$ for the same beam energy.

At a future electron-positron LC with the CM energy of 500 GeV and the luminosity of 10^{34} cm^{-2} s^{-1}, 10^{22} electrons (or positrons) with the energy 250 GeV would be available per year. Assuming that they could be bombarded on a fixed target with the mass 10 g/cm^2, we could expect about 10^{4-5} of $eN \to \tau X$ events for $\sigma(eN \to \tau X) \sim 10^{-3}$ fb. Therefore, significant improvement, by several orders of magnitude, on the $e-\tau$ coupling can be expected over the present limits. Experimental issues in the $eN \to \tau X$ search, such as background rejections, would be very different from the $\mu N \to \tau X$ case. Further studies will appear in our future publications.

5. Conclusions

We have discussed the cross sections for $\mu N \to \tau X$ at the DIS region. It is found that the DIS process $\mu N \to \tau X$ can be useful to search for the Higgs boson mediated LFV coupling in supersymmetric standard models with slepton flavor mixing, especially when E_μ is higher than 50 GeV. For $E_\mu = 300$ GeV, for instance, the cross section can be as large as 10^{-3} fb. This corresponds that a number of $\mathcal{O}(10^4)$ tau leptons from 10^{20} of the incident muons. This is about two orders of magnitude greater than that for $E_\mu = 50$ GeV.

We also have discussed the possibility of studing the $eN \to \tau X$ cross section to search for the $e-\tau$ transition. A high energy intense electrons (positrons) should be available at future LCs. At a LC, significant improvement of the limit on the $e-\tau$ transition can be expected as compared to the current data from tau's rare decay experiments.

Once high-intensity and high-energy muon and electron beams are available, there would be better opportunity to improve the limit on the LFV couplings for the Higgs boson mediation by a few orders of magnitude. Searches for the $\mu N \to \tau X$ and $eN \to \tau X$ reactions would be competitive to studies of rare tau decays at planned future super B factories.

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