A Study of Lepton Flavor Violating $\mu N(eN) \to \tau X$ Reactions in Supersymmetric Models

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We study a lepton flavor violating $\mu N \to \tau X$ reaction in deep inelastic scattering region in supersymmetric models. The contribution from the Higgs boson mediation could be important for this reaction. For that case, the cross section is constrained by the experimental limit of the pseudoscalar coupling from $\tau \to \mu \eta$ decays. We find that at a muon energy ($E_{\mu}$) higher than 50 GeV, the predicted cross section increases significantly due to the contribution from sea $b$-quarks. As a result, with $10^{20}$ muons per year, at most a number of $\mathcal{O}(10^4)$ is expected for $\mu N \to \tau X$ events at $E_{\mu}=300$ GeV, whereas $\mathcal{O}(10^5)$ events are given at $E_{\mu}=50$ GeV. Furthermore, the $\mu N \to \tau X$ phenomenology, in particular that for the signal and backgrounds, is briefly discussed. 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 to studies of rare tau decays and have potential to improve sensitivities to lepton flavor violation significantly.

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I. INTRODUCTION

Lepton flavor violation (LFV) for charged leptons is clear evidence to indicate physics beyond the standard model. A type of models based on supersymmetry (SUSY) naturally induces LFV couplings at loop levels due to the slepton mixing. The predicted branching ratios of LFV processes in SUSY models are only a few orders of magnitude smaller than the present experimental limits, and therefore they could be reached by future experiments. Various LFV processes can be experimentally searched. For the electron-muon sector, rare muon decay processes such as $\mu \to e\gamma$ and $\mu \to eee$ as well as $\mu \to e$ conversion in a muonic atom have been studied and will be further examined by forthcoming experiments.

In SUSY models, there are two types of LFV couplings: namely those mediated by the neutral gauge bosons and those by the neutral Higgs bosons. In particular, the Higgs-mediated LFV couplings attract much interest recently, because their contributions do not decouple even if the soft SUSY breaking scale is as large as $\mathcal{O}(1)$ TeV. It is in contrast to the case of the gauge boson mediation. Since the Higgs-mediated LFV couplings are proportional to the mass of the relevant charged leptons, the tau-associated processes are useful to study them. In recent years, the LFV couplings associated with a tau lepton have been measured at $B$ factories by searches for rare tau decays, such as $\tau \to \mu \gamma$, $\tau \to 3\mu$, $\tau \to \mu \pi \pi$, $\tau \to \mu \eta$, etc. Direct searches for the Higgs LFV coupling via decays of the Higgs bosons ($\Phi^0$, $\Phi^0 \to \tau^\pm \mu^\mp$), have been proposed by several authors, either at CERN Large Hadron Collider (LHC) or at a Linear Collider (LC).

In this letter, we would like to discuss an alternative approach of searching for the LFV couplings associated with a tau lepton by a $\mu N \to \tau X$ reaction at the deep inelastic scattering (DIS) region with high-intensity and high-energy muon beams. Here, $N$ is a target nucleon, and $X$ represents all final state particles. Recently, Sher and Turan have discussed this process in a model independent approach. Instead, we here study this process in the framework of SUSY, and evaluate the cross section under the current experimental constraints from the other LFV limits.

The $\mu \to \tau$ transition processes have been estimated by the effective LFV couplings. The upper limits on the four-Fermi LFV couplings have been studied without assuming specific theoretical models in Ref. When the scalar LFV coupling is independent of the other types of couplings, its experimental constraint only comes from the process in which a tau decays into a muon and a pion pair ($\tau \to \mu \pi \pi$). 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 ($E_{\mu}$) of 50 GeV. For this case, with $10^{20}$ muons per year on a $\mathcal{O}(10^2)$ g/cm$^2$ target mass, about $10^9$ 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. However, in SUSY models, the effective scalar coupling which is mediated by the CP-even Higgs bosons ($h^0$ and $H^0$) is correlated with the pseudo-scalar coupling which is mediated by the CP-odd Higgs boson ($A^0$). Therefore, the constraint on the pseudo-scalar coupling from the $\tau \to \mu \pi$ result must be applied to the scalar coupling. Consequently, the predicted $\mu N \to \tau X$ cross section would become smaller than that in Ref.

The $\mu N \to \tau X$ cross section is known to increase as
$E_\mu$ becomes high. When $E_\mu$ is high enough, for instance more than several GeV, the DIS reaction dominates. Therefore, we calculate the $\mu N \to \tau X$ cross section at the DIS region by using the realistic parton distribution function (PDF), and in particular estimate the contributions from different quarks separately. In SUSY models, the contributions from the down-type quarks are important for the Higgs-mediated LFV interaction for the region of large $\tan\beta$, where $\tan\beta$ is the ratio of the Higgs vacuum expectation values. Since the Yukawa couplings of the Higgs bosons with quarks are proportional to the mass of the associated quarks, the contribution of the $d$-quark is not large, although its PDF contribution is large. For $E_\mu$ of a few GeV, the contribution from the $s$-quark sub-process, $\mu s \to \tau s$, dominates. We find that at energies higher than about 50 GeV, the contribution from the $b$-quarks arising from the gluon splitting becomes important. Therefore, at $E_\mu = 100$ GeV the cross section of $\mu N \to \tau X$ can be one order of magnitude greater than that at $E_\mu = 50$ GeV.

This paper is organized as follows. In the following section, we describe the LFV interaction in the minimum supersymmetric standard model (MSSM), and calculate the maximally allowed $\mu N \to \tau X$ cross sections at the DIS region with experimental constraints. In the subsequent section, the $\mu N \to \tau X$ phenomenology, in particular that for the signal and background, is discussed. In Sec. IV, the $e N \to \tau X$ search at a LC to study the $e \to \tau$ transition is proposed. Conclusions are presented in Sec. V.

II. THE $\mu N \to \tau X$ PROCESS IN MINIMUM SUPERSYMMETRIC STANDARD MODEL

The effective Lagrangian describing the sub-process $\mu q \to \tau q$, where $q$ is a quark, in the MSSM is given by

$$L_{\text{eff}} = \sum_q \sum_X \left\{ (A_X^T)_q (\bar{\tau} \gamma^\mu P_X \mu) (\bar{q} \gamma_\rho q) 
+ (A_X^V)_q \left( \frac{im_{\tau q} q_\rho q_\sigma}{q^2} P_X \mu \right) (\bar{q} \gamma_\rho q) 
+ (C_X^{hH})_q (\bar{\tau} P_X \mu) (\bar{q} \gamma_\rho q) 
+ (C_X^A)_q (\bar{\tau} P_X \mu) (\bar{q} \gamma_\rho q) \right\},$$

where $A_X^{T,V}$ 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 $C_X^{hH}$ and the pseudo-scalar coupling $C_X^A$ are those mediated by $h^0$ and $H^0$, and by $A^0$, respectively. They are induced due to quantum corrections in the MSSM. The details can be found in Ref. [2] for the gauge boson mediation, and in Ref. [7] for the Higgs boson mediation. In the following, the cross section of the $\mu N \to \tau X$ reaction is calculated separately for the cases of the Higgs boson mediation and the gauge boson mediation, since the SUSY parameter regions where each of them is enhanced are different.

First, let us start with the Higgs boson mediation. It is known that this type of effect does not decouple even in the large $m_{\text{SUSY}}$ limit, where $m_{\text{SUSY}}$ is a typical scale of the soft SUSY breaking \[16\] \[15\]. The contribution of the Higgs boson mediation to the differential cross section $\mu^- N \to \tau^- X$ is given by

$$\frac{d^2\sigma}{dz dy} = \sum_q \int f_q(x) \left\{ \left( |C_L^{hH}|^2 + |C_R^{hH}|^2 \right)_q \left( 1 - \frac{P_\mu}{2} \right) 
+ \left( |C_L^{hH}|^2 + |C_R^{hH}|^2 \right)_q \left( 1 + \frac{P_\mu}{2} \right) \right\} \frac{s}{16\pi y^2},$$

where the function $f_q(x)$ is the PDF for $q$-quarks, $P_\mu$ is the incident muon polarization such that $P_\mu = +1$ 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 as

$$x = \frac{Q^2}{2P \cdot q}, \quad y = \frac{2P \cdot q}{s},$$

in the limit of massless tau leptons, where $P$ is the four momentum of the target, $q$ is the momentum transfer, and $Q$ is defined as $Q^2 = -q^2$. As seen in Eq. (2), experimentally, the form factors of $C_L^{hH}$ and $C_R^{hH}$ can be selectively studied by using purely left-handed (right-handed) incident muons. 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 $C_L^{hH}$ and $C_R^{hH}$. Therefore, in the following, we focus only on those $C_L^{hH}$ and $C_R^{hH}$ couplings.

The magnitudes of the effective couplings are constrained by the current experimental results of searches for LFV processes of tau decays. In the case that all the effective couplings are independent, the constraints for the vector, axial-vector, scalar, and pseudo-scalar couplings are given in Ref. [14]. In the MSSM, however, the couplings are related each other. In particular, in the decoupling region ($m_A \gtrsim 150$ GeV), the scalar coupling $C_L^{hH}$ is nearly equal to the pseudo-scalar coupling $C_R^A$, since $m_H \approx m_A$ and $\sin(\alpha - \beta) \approx -1$, where $\alpha$ is the mixing angle for the CP-even Higgs bosons. Therefore, both couplings are determined by the one that is more constrained, namely the pseudo-scalar coupling. It is constrained by the $\tau \to \mu \eta$ decay ($\text{Br}(\tau \to \mu \eta) < 3.4 \times 10^{-7}$) \[8\]. Then the constraint is given on the $s$-associated scalar and pseudo-scalar couplings in Eq. (11) by

$$\left( |C_L^{hH}|^2 + |C_R^{hH}|^2 \right)_s \approx 2 |C_R^A|^2,$$

\[11\] \[10\].

It is known that in some models, such as $SU(5)$ grand unified theories, $C_L^{H}$ and $C_R^A$ can be induced due to the right-handed slepton mixing \[14\].
The cross section sharply increases above $E_\mu \sim 50$ GeV in Fig. 1. This enhancement comes from a consequence of the $b$-quark contribution in addition to the $d$ and $s$-quark contributions. The coupling for the $b$-quark is enhanced by a factor of $m_b/m_s$ over the $s$-quark contribution as given by

$$\left(|C_L^b|^2\right)_b = \left(|C_L^d|^2\right)_s.$$

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. In our analysis, we used $m_b = 4.3$ GeV and $m_s = 120$ MeV.

Next we study the case where the gauge-boson mediated interaction is dominant, for instance, that with $m_{\text{SUSY}} \sim \mathcal{O}(100)$ GeV. The differential cross sections for $\mu N \rightarrow \tau X$ with the tensor couplings $A_{L,R}^T$ and the vector couplings $A_{L,R}^V$ are calculated as

$$\frac{d^2\sigma}{dx dy}_{\text{tensor}} = \sum_q x f_q(x) \left\{ \left(|A_{R,L}^T|^2 + |A_{L,R}^T|^2\right) + \mathcal{P}_\mu \left(|A_{R,L}^T|^2 - |A_{L,R}^T|^2\right) \right\},$$

$$\frac{d^2\sigma}{dx dy}_{\text{vector}} = \sum_q x f_q(x) \left\{ \left(|A_{R,L}^V|^2 + |A_{L,R}^V|^2\right) + \mathcal{P}_\mu \left(|A_{R,L}^V|^2 - |A_{L,R}^V|^2\right) \right\},$$

respectively. The effective tensor couplings are strongly constrained by the $\tau \rightarrow \mu \gamma$ process, as

$$\left(|A_{R,L}^T|^2 + |A_{L,R}^T|^2\right)_{d,s,b} \lesssim 6.4 \times 10^{-14} \text{[GeV}^{-4}] \times \text{Br}(\tau \rightarrow \mu \gamma).$$

and

$$\left(|A_{R,L}^V|^2 + |A_{L,R}^V|^2\right)_{u,c} = 4 \times \left(|A_{R,L}^V|^2 + |A_{L,R}^V|^2\right)_{d,s,b}.$$

Since $\text{Br}(\tau \rightarrow \mu \gamma) < 3.1 \times 10^{-7}$, 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. Therefore, their contributions can be as large as those for the Higgs boson mediation, if $E_\mu$ is less than 50 GeV. At higher energies, the cross section for the gauge boson mediation are much smaller than those for the Higgs boson mediation because of no enhancement by the $b$-quark sub-process.

It is concluded that the DIS process $\mu N \rightarrow \tau X$ can be more useful to search the Higgs mediated LFV interaction in the MSSM for higher energy muon beams.

### III. THE $\mu N \rightarrow \tau X$ PHENOMENOLOGY

With the intensity of $10^{20}$ muons per year and the target mass of 100 g/cm², about $10^4$ $(10^5)$ events could be expected for $\sigma(\mu N \rightarrow \tau X) = 10^{-3}$ $(10^{-5})$ fb, which corresponds to $E_\mu = 300$ (50) GeV from Fig. 1. This would provide good potential to improve the sensitivity by four (two) orders of magnitude from the present limit from $\tau \rightarrow \mu \gamma$ decay, respectively. Such a muon intensity could be available at a future muon collider (MC) and a neutrino factory (NF).

We have studied the signal events of the $\mu N \rightarrow \tau X$ reaction. In the Higgs boson mediated interaction, the tau leptons in the $\mu N \rightarrow \tau X$ reaction are emitted at a relatively large angle with respect to the beam direction.
It is in contrast to the gauge mediated interaction where the tau leptons are forward-peaked. The differential cross section is given as a function of the tau energy ($E_{\tau}$) and the tau emitted angle ($\theta$) from the beam direction by

$$
\frac{d^2\sigma}{dE_{\tau}d\theta} = \frac{2E_{\mu}E_{\tau}\sin\theta}{s(E_{\mu} - E_{\tau})}.
$$

(10)

In Fig. 2 the $E_{\tau}$ dependence in the differential cross section is shown for each $\theta$ at $E_{\mu}=50$ GeV and $E_{\mu}=100$ GeV. For $E_{\mu}=50$ GeV, there are two peaks for each emission angle $\theta$ of the tau leptons. The peak at lower $E_{\tau}$ for each curve corresponds to the contribution from the s-quark sub-process, and the other does to the b-quark contribution. The tau leptons from the b-quark sub-process are emitted with larger emission angles with relatively low energies, while those from the s-quark contribution carry higher energies with smaller emission angles. For $E_{\mu}=100$ GeV, the contribution from the b-quark sub-process is dominant. The tau leptons are emitted with large angles around $\theta = 0.16$.

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 as discussed in Ref. [21]. Another candidate could be to detect a hadron from the two-body tau decays. The branching ratios, such as $\tau \to \nu_\tau\pi$, $\nu_\tau\rho$ and $\nu_\tau a_1$, are about 0.3 in total. In SUSY models with left-handed slepton mixing, the $\tau^-$ produced through the Higgs-mediated interaction is only right-handed (left-handed) for an incident left-handed $\mu^-$ beam (right-handed $\mu^+$ beam). The hadrons from the right-handed $\tau^-$ decay (left-handed $\tau^+$ decay) tend to be emitted in the direction of the parent tau lepton, and therefore be rather energetic [21]. At the same time, the neutrino from the tau decay would carry a part of the energy of the tau lepton, resulting in missing energy. Therefore, the signature of the events could be a hard hadron from decay of the tau lepton produced 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.

Discrimination of pions from muons could be the most critical issue, since a muon from the DIS process $\mu N \to \mu X$ would mimic the signal if it is misidentified as a pion. Therefore, they should be rejected with high efficiency. The rate of the DIS process $\mu N \to \mu X$ is very high, of the order of $O(1)$ $\mu$b in total. Since the muon from $\mu N \to \mu X$ is very forward peaked, elimination of forward-going particles would give rejection in addition to the particle identification with a cost of the signal acceptance. The rejection of muons and the acceptance of hadrons from the tau leptons in $\mu N \to \tau X$ might be optimized in consideration of the aimed signal sensitivity. In either case, realistic Monte Carlo studies should be necessary.

It should be noted that in the models where the scalar and pseudo-scalar couplings are independent, such as in the two Higgs doublet model, the experimental con-

\[ \text{FIG. 2: The differential cross section of the tau from the } \mu^- N \to \tau^- X \text{ DIS process as a function of the tau energy (} E_{\tau} \text{) and the tau emission angle (} \theta \text{) with respect to the forward direction for } E_{\mu} = 50 \text{ GeV (left) and } E_{\mu} = 100 \text{ GeV (right). It is assumed that the initial muons are purely left-handed.} \]
strains become rather weak, in contrast to the MSSM models which we have so far discussed. The cross sections allowed could become larger by about $\mathcal{O}(10^3)$, yielding $\sigma(eN \rightarrow \tau X) \sim \mathcal{O}(10)$ fb at the muon energy of $\mathcal{O}(100)$ GeV. At present, the muon beam line at CERN can provide a muon beam with energy up to 190 GeV and $10^{14}$ muons per year. By using this, for instance, we could expect about $\mathcal{O}(10^2)$ events from $e\mu$ or $e\tau$ decays at the $\tau X$ transition to search for the possible $e\rightarrow\tau$ transition at future LCs, which is similar to the bound on the $\tau \rightarrow \tau X$ transition from the $\tau \rightarrow \mu\eta$ result. For the scalar coupling, the results of the $e\mu \rightarrow \tau X$ transition to search for the possible $e\rightarrow\tau$ transition at future LCs, and the $e\rightarrow\tau$ searches at HERA.

If incident muons are polarized, T-odd correlations between the muon spin and the tau momentum and spin polarization vectors can be examined in the $\mu N \rightarrow \tau X$ reaction. The T-odd correlation would give opportunity to study CP violation in SUSY. They will be studied in our coming publications.

IV. PROBING $e \rightarrow \tau$ TRANSITION VIA $eN \rightarrow \tau X$ REACTION

We would like to comment on another LFV search for $e \rightarrow \tau$ transition through $eN \rightarrow \tau X$ with a high energy electron (or positron) beam. In the MSSM, similar to the $\bar{\tau}_R \mu L^0$ coupling, the $\bar{\tau}_R \mu L^0$ coupling is proportional to the tau lepton mass, where $l^0$ could be either $h^0, H^0$ or $A^0$, and $l_R$ and $l_L$ are the corresponding right-handed and left-handed leptons, respectively. The coupling of $\bar{\tau}_R e_L^0 \Phi^0$ could be as large as that of $\bar{\tau}_R e_L^0 \Phi^0$, when the slepton mixing between $\bar{\tau}_L$ and $\bar{\tau}_L$ is similar to that between $\bar{\tau}_L$ and $\bar{\tau}_L$. Therefore, our discussions on the $\mu N \rightarrow \tau X$ DIS reaction can be directly applied to the case of $eN \rightarrow \tau X$ reaction. Experimental constraints on the effective form factors for $e \rightarrow \tau$ transition are given by $\tau \rightarrow \eta e$ and $\tau \rightarrow \eta e + \pi$ decays at the $B$ factories and the $e \rightarrow \tau$ searches at HERA. The strongest bound on the pseudo-scalar coupling for $e \rightarrow \tau$ transition comes from the $\tau \rightarrow \eta e$ result, which is similar to the bound on the $\mu \rightarrow \tau$ transition from the $\tau \rightarrow \mu\eta$ result. For the scalar coupling, the results of the $e\mu \rightarrow \tau X$ search at HERA give stronger bounds than the $\tau \rightarrow \eta e + \pi$ result. In the MSSM, therefore, the maximally-allowed cross section for $eN \rightarrow \tau X$ is in the same order of magnitude as that for $\mu \rightarrow \tau X$ for the same incident beam energy. At a future electron-positron LC with the CM energy of 500 GeV and the luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$, $10^{22}$ 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/cm², we could expect about $10^{-5}$ to $10^{-3}$ fb for $eN \rightarrow \tau X$ events for $\sigma(eN \rightarrow \tau X) \sim 10^{-3}$ fb. Therefore, significant improvement, by several orders of magnitude, on the $e \rightarrow \tau$ coupling can be expected over the present limits. Experimental issues in the $eN \rightarrow \tau X$ search, such as background rejections, would be very different from the $\mu N \rightarrow \tau X$ case. Further studies will appear in our future publications.

Combining both the $e \rightarrow \tau$ searches at a LC and the $\mu \rightarrow \tau$ searches at a MC and a NF, we could study the slepton mixing and SUSY breaking in more details.

V. CONCLUSIONS

We have calculated the cross sections for $\mu N \rightarrow \tau X$ at the DIS region in the MSSM separately for the Higgs boson mediation and the gauge boson mediation. We have found that this process can be useful to search for the Higgs-boson mediated LFV coupling. In the MSSM, the Higgs boson mediation is constrained from the $\tau \rightarrow \mu\eta$ result, so that the cross section is at most $10^{-5}$ fb at the incident muon energy $E_\mu$ of 50 GeV. If $E_\mu$ is higher than 50 GeV, contributions from the sea $b$-quarks become more significant, and thereby the cross section is drastically enhanced. For $E_\mu = 300$ GeV, for instance, the cross section can be as large as $10^{-3}$ fb. Experimental issues on the tau identification and background rejection have been briefly examined. We also studied the $eN \rightarrow \tau X$ transition to search for the possible $e \rightarrow \tau$ transition at a future LC, and expect significant improvements. 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 $\mu N \rightarrow \tau X$ and $eN \rightarrow \tau X$ reactions would be competitive to studies of rare tau decays at planned future super $B$ factories.

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