Search for lepton flavor violation via the intense high-energy muon beam

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A deep inelastic scattering process $\mu N \to \tau X$ is discussed to study lepton flavor violation between muons and tau leptons. In supersymmetric models, the Higgs boson mediated diagrams could be important for this reaction. We find that at a muon energy ($E_\mu$) 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 $O(10^4)$ at $E_\mu = 300$ GeV from $10^{20}$ muons, whereas $O(10^2)$ events are given at $E_\mu = 50$ GeV.

1. Introduction

In a model based on Supersymmetry (SUSY), slepton mixing is a source of Lepton Flavor Violation (LFV). 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 bosson mediation, the contributions from the Higgs-mediation do not decouple even if the soft SUSY breaking scale is as large as $O(1)$ TeV \cite{1}. To study the Higgs-mediated LFV couplings the tau-associated processes are useful because they are proportional to the mass of the relevant charged leptons. The LFV couplings associated with a tau lepton have been measured at $B$ factories by searches for rare tau decays, such as $\tau \to \mu \pi \pi$, $\tau \to \mu \eta$, $\tau \to \mu \pi \pi$, etc. At future collider experiments, they are directly tested via the decays of the Higgs bosons ($\Phi^0$, $\Phi^0 \to \tau^+ \tau^-$) \cite{23}.

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. Here, $N$ is a target nucleon, and $X$ represents all final state particles. Sher and Turan have discussed this process in a model independent approach \cite{4}. Instead, we here consider this process in the framework of SUSY \cite{5}.

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

When the scalar LFV coupling of $\tau \mu q q$ is independent of the other types of couplings, its experimental constraint comes from the $\tau \to \mu \pi \pi$ result. 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 $O(10^2)$ 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 \cite{4}.

In the Minimal Supersymmetric Standard Model (MSSM), the Higgs boson couplings are related each other. In the decoupling region ($m_A \gtrsim 150$ GeV), where $m_H \simeq m_A$ and $\sin(\alpha - \beta) \simeq -1$, the scalar coupling $C^{\chi H}_L$ is nearly equal to the pseudo-scalar coupling $C^A_L$. Therefore, both couplings are determined by the more constrained one, namely the pseudo-scalar coupling $C^A_L$. It is constrained by the $\tau \to \mu \eta$ decay ($Br(\tau \to \mu \eta) < 3.4 \times 10^{-7}$) \cite{7}. In Fig. 1 the total cross sections are shown for the cases of the effective scalar and pseudo-scalar couplings as well as the SUSY model with the maximal value for the couplings under the current data of the rare tau decays. The largest values of $C^{\chi H}_L$ and $C^A_L$ can be realized with $m_{\text{SUSY}} \sim O(1)$ TeV and the Higgsino mass $\mu \sim O(10)$ TeV. It should be noted that in such a situation, the gauge boson mediated couplings...
Figure 1. The upper bounds on the cross section of the $\mu^− N \rightarrow \tau^− X$ DIS process, assuming the effective scalar and pseudo-scalar couplings [4] and the MSSM Higgs coupling constrained from the current data [5]. CTEQ6L is used for the PDF.

Figure 2. Cross section of the $\mu^− N \rightarrow \tau^− X$ 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.

are strongly suppressed.

We evaluate the cross sections of the $\mu N \rightarrow \tau X$ 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 study cases where the gauge-boson mediation is dominant: i.e., $m_{\text{SUSY}} \sim \mathcal{O}(100)$ GeV. Since $\text{Br}(\tau \rightarrow \mu \gamma) < 3.1 \times 10^{-7}$ [3], 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 [9]. Therefore, their contributions can be as large as those for the Higgs boson mediation, if $E_\mu$ is less than 50 GeV [4]. 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.

3. The $\mu N \rightarrow \tau X$ Phenomenology

With the intensity of $10^{20}$ muons per year and the target mass of 100 g/cm$^2$, about $10^4$ (10$^5$) 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. 2. This would provide good potential to improve the sensitivity by four (two) orders of magnitude from the present limit from $\tau \rightarrow \mu \eta$ decay, respectively. Such a muon intensity could be available at a future muon collider and a neutrino factory.

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. In Fig. 2, the $E_\tau$ dependence in the differential cross section is shown for each $\theta$ at $E_\mu = 50$ and 100 GeV.

To identify the tau lepton from the $\mu N \rightarrow \tau X$ reaction, direct measurement of tau lepton tracks (such as by emulsions) might not be possible at such a high beam rate. Instead, the identi-
Figure 3. The differential cross section of the tau from the $\mu^- N \rightarrow \tau^- X$ DIS process as a function of the tau energy ($E_\tau$) and the tau emission angle ($\theta$) with respect to the forward direction for $E_\mu = 50$ GeV (left) and $E_\mu = 100$ GeV (right). It is assumed that the initial muons are purely left-handed.

...fication 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 two-body tau decays. The branching ratios, such as $\tau \rightarrow \nu_\tau \pi$, $\nu_\tau \rho$ and $\nu_\tau \rho_1$, are about 0.3 in total. In particular, in SUSY models with left-handed slepton mixing, the $\tau^-(\tau^+)$ 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. Therefore, 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. Conclusions

This process can be useful to search for the Higgs-boson mediated LFV coupling, especially when $E_\mu$ is higher than 50 GeV. There, the contributions from the sea $b$-quarks become significant, and the cross section is drastically enhanced.

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