Lepton flavor violation in Higgs boson decays

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Abstract

We discuss lepton flavor violation (LFV) associated with tau leptons in the framework of the two-Higgs-doublet model. Current data for rare tau decays provide substantial upper limits on the LFV Yukawa couplings in the large $\tan \beta$ region where $\tan \beta$ is the ratio of vacuum expectation values of the two Higgs doublets. We show that measuring the LFV Higgs boson decays $h \to \tau^\pm \mu^\mp$ at future colliders can be useful to further constrain the LFV couplings especially in the relatively small $\tan \beta$ region.

1 Lepton flavor violation in the two-Higgs-doublet model

Lepton flavor violation (LFV) is one of the most obvious signatures of physics beyond the Standard Model (SM). It can naturally appear in extend Higgs sectors [1, 2]. Some theories (supersymmetric models, the little Higgs model, the Zee model, etc.) predict such extended Higgs sectors. Therefore the LFV is an important probe to find the signal of new physics.

The Higgs sector of the two-Higgs-doublet Model (THDM) is expressed as

$$-\mathcal{L}_{\text{Higgs}} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \left( m_3^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 \right\} + \text{H.c.},$$

where $\Phi_1$ and $\Phi_2$ are the scalar iso-doublets with hypercharge 1/2. We consider the model in which the discrete $Z_2$ symmetry is explicitly broken in the leptonic Yukawa interaction, and treat the CP conserving Higgs potential with the soft-breaking parameter $m_3^2$. There are eight degrees of freedom in the two Higgs doublet fields. Three of them are absorbed by the weak gauge bosons via the Higgs mechanism, and remaining five are physical states. After the diagonalization of the mass matrices, they correspond to two CP-even ($h$ and $H$), a CP-odd ($A$), and a pair of charged ($H^\pm$) Higgs bosons. We define such that $h$ is lighter than $H$. The eight real parameters $m_{1-3}^2$ and $\lambda_{1-5}$ can be described by the same number of physical parameters; i.e., the vacuum expectation value $v$ ($\simeq 246$ GeV), the Higgs boson masses $m_h, m_H, m_A$ and $m_{H^\pm}$, the mixing angle $\alpha$ between the CP-even Higgs bosons, the ratio $\tan \beta$ ($\equiv |\Phi_2^0|/|\Phi_1^0|$) of the vacuum expectation values for two Higgs doublets, and the soft-breaking scale $M$ ($\equiv \sqrt{m_3^2 / \sin \beta \cos \beta}$) for the discrete symmetry. Parameters of the model are constrained from experimental results (the $\rho$ parameter [4], $b \to s\gamma$ [5]) and also from requirements of theoretical consistencies such as vacuum stability and perturbative unitarity [6, 7].

The tau lepton associated LFV couplings are parameterized in the mass eigenbasis of each field as [1, 2, 3]

$$-\mathcal{L}_{\tau \text{LFV}} = \frac{m_\tau}{v \cos^2 \beta} \left( \kappa_{3i}^L \mathcal{P}_L \ell_i + \kappa_{3i}^R \mathcal{P}_R \ell_i \right) \cos (\alpha - \beta) h + \text{H.c.},$$

where $\mathcal{P}_L$ ($\mathcal{P}_R$) is the projection operator to the left(right)-handed field, and $\ell_1$ and $\ell_2$ represent $e$ and $\mu$ respectively. When a new physics model is specified at the high energy scale, $\kappa_{ij}^{L,R}$ can be predicted as a function of the model parameters.

2 Rare tau decay results and LFV Higgs boson decay

We concentrate on the LFV coupling $|\kappa_{32}|$, where $|\kappa_{32}|^2 \equiv |\kappa_{32}^L|^2 + |\kappa_{32}^R|^2$. We take into account the data for rare tau decay processes such as $\tau \to \mu P^0$, $\tau \to \mu M^+ M^-$, $\tau \to \mu \ell^+ \ell^-$, and $\tau \to \mu \gamma$, etc.
We have found that the parameter space calculated to be similar way to Eq. (3), the maximal allowed value \(|\kappa_{32}|^2\) can be obtained for the model parameters by measuring each of them. When all the masses of Higgs bosons are large, these decay processes decouple by a factor of \(1/m^4_{h}\). These branching ratios are complicated functions of the mixing angles, each of them can be simply expressed to be proportional to \(\tan \beta\) for tan \(\beta \gg 1\) in the SM like region (\(\sin(\alpha - \beta) \sim -1\)). This \(\tan^6 \beta\) dependence is a common feature of the tau-associated LFV processes with the Higgs-mediated 4-Fermi interactions.

The experimental upper limit on \(|\kappa_{32}|^2\) can be obtained by using the experimental results and analytic expressions for the decay branching ratios. For instance, let us consider the bound from the \(\tau \rightarrow \mu \eta\) results. We define the maximal allowed value for \(|\kappa_{32}|^2\)

\[
\left(\frac{|\kappa_{32}|^2}{|\kappa_{32}|^2_{\tau \rightarrow \mu \eta}}\right)_{\tau \rightarrow \mu \eta} \equiv \frac{256\pi \text{Br}(\tau \rightarrow \mu \eta)_{\exp} m_A^4}{9 G_F^2 m_\mu^2 m_\eta^4 F_\eta^2 \Gamma_{\eta}} \left(1 - \frac{m_\mu^2}{m_\tau^2}\right)^2 \sin^2 \beta, \tag{3}
\]

where \(|\kappa_{32}|^2 \leq \left(\frac{|\kappa_{32}|^2}{|\kappa_{32}|^2_{\tau \rightarrow \mu \eta}}\right)_{\tau \rightarrow \mu \eta}\), \(G_F\) is the Fermi constant, \(F_\eta\) is the decay constant for \(\eta\), and \(\text{Br}(\tau \rightarrow \mu \eta)_{\exp}\) is the experimental upper limit on the branching ratio of \(\tau \rightarrow \mu \eta\). It can be easily seen that the bound \(\left(\frac{|\kappa_{32}|^2}{|\kappa_{32}|^2_{\tau \rightarrow \mu \eta}}\right)_{\tau \rightarrow \mu \eta}\) is rapidly relaxed in the region with a smaller \(\tan \beta\) and a larger \(m_A\). In a similar way to Eq. (3), the maximal allowed value \(|\kappa_{32}|^2_{\tau \rightarrow \mu \eta}\) can be calculated for each mode. The combined upper limit \(|\kappa_{32}|^2\) is then given by

\[
|\kappa_{32}|^2 \equiv \min \left\{\left(\frac{|\kappa_{32}|^2}{|\kappa_{32}|^2_{\tau \rightarrow \mu \eta}}\right)_{\tau \rightarrow \mu \eta}, \left(\frac{|\kappa_{32}|^2}{|\kappa_{32}|^2_{\tau \rightarrow \mu \gamma}}\right)_{\tau \rightarrow \mu \gamma}, \cdots\right\}. \tag{4}
\]

We have found that \(\tau \rightarrow \mu \eta\) and \(\tau \rightarrow \mu \gamma\) give the strongest upper limits on \(|\kappa_{32}|^2\) in a wide range of the parameter space.

We here consider LFV Higgs boson decay; i.e., \(h \rightarrow \tau^\pm \mu^\mp\). Branching ratios for \(h\) decay is calculated to be

\[
\text{Br}(h \rightarrow \tau^\pm \mu^\mp) = \frac{m_\tau^2 \cos^2 (\alpha - \beta)}{16 \pi v^2 \cos^4 \beta} \frac{|\kappa_{32}|^2 m_h}{\Gamma(h \rightarrow \text{all})}, \tag{5}
\]

where \(\Gamma(h \rightarrow \text{all})\) is the total width for \(h\). The LFV Higgs boson decay can give restriction for LFV couplings

\[
|\kappa_{32}|^2 = \text{Br}(h \rightarrow \tau \mu)_{\exp} \times \frac{3 m_\tau^2 \cos^2 \beta \sin^2 \alpha}{m_\eta^2 \cos^2 (\alpha - \beta)}, \tag{6}
\]

with the same way as rare tau decays.

In Fig. 1 we show the bound on \(|\kappa_{32}|^2\) from rare tau decays and also from the Higgs boson decay \(h \rightarrow \tau \mu\) as the function of \(\tan \beta\). We take the upper limit \(\text{Br}(h \rightarrow \tau \mu)_{\exp} = 0.8 \times 10^{-3}\), which is

Figure 1: The upper bounds on \(|\kappa_{32}|^2\) from rare tau decays and also from LFV Higgs boson decay.
expected to be tested at the future linear collider [1]. The parameters are taken to be $m_h = 120$ GeV, $m_A = m_H = m_{H^\pm} = 350$ GeV and $\sin(\alpha - \beta) = -0.9999$. We have found that in the smaller tan $\beta$ region LFV coupling $|\kappa_{32}|$ can be further constrained from LFV Higgs boson decay in comparison with that from rare tau decays [3].

3 Conclusions

Lepton flavor violating decays of Higgs bosons have been studied in the framework of the LFV THDM. The LFV coupling $|\kappa_{32}|^2$ are bounded from above by using the current data for rare tau LFV decays.

It has been found that among the rare tau decay data those for $\tau \rightarrow \mu \eta$ and $\tau \rightarrow \mu \gamma$ give the most stringent upper limits on $|\kappa_{32}|^2$ in a wide range of the parameter space. In the large tan $\beta$ region, the upper limit on $|\kappa_{32}|^2$ due to the rare tau decay data turns out to be substantial. The upper limit would be improved in future by about one order of magnitude at the experiment at (super) B factories. For smaller values of tan $\beta$, the upper limit is rapidly relaxed, and no more substantial constraint is obtained from the rare tau decay results.

We have shown that a search for the LFV decays $h \rightarrow \tau^\pm \mu^\mp$ can be useful to further constrain the LFV Yukawa couplings at future collider experiments. LFV decay of the lightest Higgs boson can be one of the important probes to find the evidence for the extended Higgs sector when the SM-like situation would be preferred by the data at forthcoming collider experiments. The branching ratio for $h \rightarrow \tau^\pm \mu^\mp$ can be larger than $O(10^{-3})$ except for the high tan $\beta$ region. At future collider experiments, such a size of the branching fractions can be tested. Therefore, we conclude that the search of LFV in the Higgs boson decay at future colliders can further constrain the LFV Yukawa couplings especially in the relatively small tan $\beta$ region, where rare tau decay data cannot reach.

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