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**MEASURING HIGGS BOSON ASSOCIATED LEPTON  
FLAVOUR VIOLATION IN ELECTRON-PHOTON  
COLLISIONS AT THE ILC**

Shinya Kanemura

*Department of Physics, University of Toyama, 3190 Gofuku, Toyama 930-8555, Japan*

and

Koji Tsumura

*The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.*

**Abstract**

We study the LFV Higgs production processes  $e^- \gamma \rightarrow \ell^- \varphi$  ( $\ell = \mu, \tau; \varphi = H, A$ ) as a probe of Higgs mediated LFV couplings at an electron-photon collider, where  $H$  and  $A$  are extra CP even and odd Higgs bosons, respectively, in the two Higgs doublet model. Under the constraints from the current data of muon and tau rare decay, the cross section can be significantly large. It would improve the experimental upper bounds on the effective LFV coupling constants. In addition, the chirality nature of the LFV Higgs coupling constants can be measured by selecting electron beam polarizations.

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## 1 Introduction

Lepton Flavour Violation (LFV) is clear evidence of new physics beyond the standard model (SM). It can be naturally induced in various new physics scenarios such as supersymmetric extensions of the SM. The origin of LFV would be related to the structure of the fundamental theory at high energies. Therefore, new physics models can be explored by measuring the LFV processes. In the minimal supersymmetric SM with heavy right-handed neutrinos (MSSMRN), the LFV Yukawa interactions can be radiatively generated via the slepton mixing [2, 3]. The slepton mixing can be induced by the running effect from the neutrino Yukawa interaction even when flavour blind structure is realized at the grand unification scale [2].

The experimental bound on the effective LFV Yukawa couplings have been studied extensively [4, 5, 6]. These constraints will be improved at PSI MEG [7], J-PARC COMET [8] and Fermilab Mu2e [9] experiments via muon rare decays, and at CERN LHCb [10] and KEK super-B factory [11] via tau rare decays. In addition, collider signatures of the LFV phenomena have also been investigated at the CERN Large Hadron Collider (LHC) [12], the International Linear Collider (ILC) [13], and the Neutrino Factory [14]. These collider experiments would be useful to test the Higgs-boson-associated LFV couplings [15, 16, 6, 17].

In this report, we discuss the physics potential of the LFV Higgs boson production process  $e^- \gamma \rightarrow \ell^- \varphi$  ( $\ell = \mu, \tau; \varphi = h, H, A$ ) where  $h$ ,  $H$  and  $A$  are neutral Higgs bosons. It can be an useful tool for measuring Higgs-boson-mediated LFV parameters in two Higgs doublet models (THDMs) including Minimal Supersymmetric SMs (MSSMs). The total cross sections for these processes can be large for allowed values of the LFV couplings under the constraint from the current experimental data. Measuring these processes, the bounds for the Higgs boson associated LFV coupling constants can be improved significantly. Furthermore, the chirality of these couplings can be measured by using the polarized initial electron beam.

## 2 Higgs boson associated LFV coupling constants

The effective Yukawa interaction for charged leptons is given in the general framework of the THDM by [5, 6]

$$\mathcal{L}_{\text{lepton}} = -\overline{\ell_{Ri}} \{Y_{\ell_i} \delta_{ij} \Phi_1 + (Y_{\ell_i} \epsilon_{ij}^L + \epsilon_{ij}^R Y_{\ell_j}) \Phi_2\} \cdot L_j + \text{H.c.}, \quad (1)$$

where  $\ell_{Ri}$  ( $i = 1-3$ ) represent isospin singlet fields of right-handed charged leptons,  $L_i$  are isospin doublets of left-handed leptons,  $Y_{\ell_i}$  are the Yukawa coupling constants of  $\ell_i$ , and  $\Phi_1$  and  $\Phi_2$  are the scalar iso-doublets with hypercharge  $Y = 1/2$ . Parameters  $\epsilon_{ij}^X$  ( $X = L, R$ ) can induce LFV interactions in the charged lepton sector in the basis of the mass eigenstates. In Model II THDM [18],  $\epsilon_{ij}^X$  vanishes at the tree level, but it can be generated radiatively by new physics effects [3]. The effective Lagrangian can be rewritten in terms of physical Higgs boson fields. Assuming the CP invariant Higgs sector, there are two CP even Higgs bosons  $h$  and  $H$  ( $m_h <$

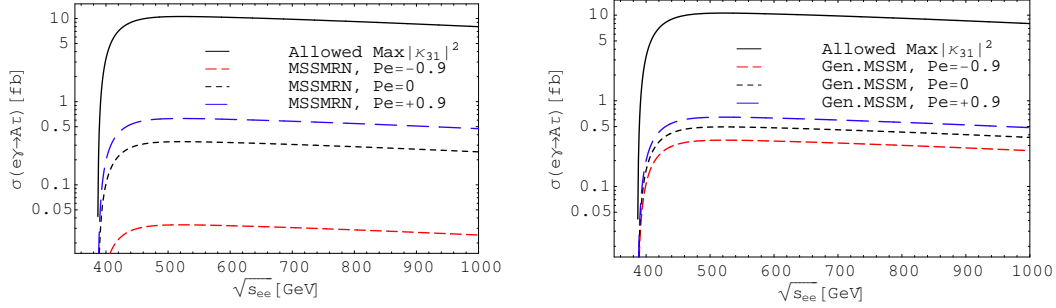


Figure 1: The production cross section of  $e^- \gamma \rightarrow \tau^- A$  as a function of the center-of-mass energy  $\sqrt{s_{ee}}$  of the electron-electron system. Solid curve represents the result in the THDM with the maximal allowed value of  $|\kappa_{31}|^2$  under the current experimental data in both figures.

$m_H$ ), one CP odd state  $A$  and a pair of charged Higgs bosons  $H^\pm$ . From Eq. (1), interaction terms can be deduced to [3, 6]

$$\mathcal{L}_{e\text{LFV}} = -\frac{m_{\ell_i}}{v \cos^2 \beta} (\kappa_{i1}^L \bar{\ell}_i P_L e + \kappa_{1i}^R \bar{e} P_L \ell_i) \{ \cos(\alpha - \beta) h + \sin(\alpha - \beta) H - i A \} + \text{H.c.}, \quad (2)$$

where  $P_L$  is the projection operator to the left-handed fermions,  $m_{\ell_i}$  are mass eigenvalues of charged leptons,  $v = \sqrt{2} \sqrt{\langle \Phi_1^0 \rangle^2 + \langle \Phi_2^0 \rangle^2}$  ( $\simeq 246$  GeV),  $\alpha$  is the mixing angle between the CP even Higgs bosons, and  $\tan \beta \equiv \langle \Phi_2^0 \rangle / \langle \Phi_1^0 \rangle$ .

Once a new physics model is assumed,  $\kappa_{ij}^X$  can be predicted as a function of the model parameters. In supersymmetric SMs, LFV Yukawa coupling constants can be radiatively generated by slepton mixing. Magnitudes of the LFV parameters  $\kappa_{ij}^X$  can be calculated as a function of the parameters of the slepton sector. For the scale of the dimensionful parameters in the slepton sector to be of TeV scales, we typically obtain  $|\kappa_{ij}^X|^2 \sim (1-10) \times 10^{-7}$  [2, 3]. In the MSSMRN only  $\kappa_{ij}^L$  are generated by the quantum effect via the neutrino Yukawa couplings assuming flavour conservation at the scale of right-handed neutrinos.

Current experimental bounds on the effective LFV parameters  $\kappa_{ij}^X$  are obtained from the data of non-observation for various LFV processes [19]. For  $e$ - $\tau$  mixing, we obtain the upper bound from the semi-leptonic decay  $\tau \rightarrow e \eta$  [5];  $|\kappa_{31}^L|^2 + |\kappa_{13}^R|^2 \lesssim 6.4 \times 10^{-6} (\frac{50}{\tan \beta})^6 (\frac{m_A}{350 \text{ GeV}})^4$ , for  $\tan \beta \gtrsim 20$  and  $m_A \simeq m_H \gtrsim 160$  GeV (with  $\sin(\beta - \alpha) \simeq 1$ ). The most stringent bound on  $e$ - $\mu$  mixing is derived from  $\mu \rightarrow e \gamma$  data [20] as  $(4/9) |\kappa_{21}^L|^2 + |\kappa_{12}^R|^2 \lesssim 4.3 \times 10^{-4} (\frac{50}{\tan \beta})^6 (\frac{m_A}{350 \text{ GeV}})^4$ , for  $\tan \beta \gtrsim 20$  and  $m_A \simeq m_H \gtrsim 160$  GeV (with  $\sin(\beta - \alpha) \simeq 1$ ). The upper bound on  $(4/9) |\kappa_{21}^L|^2 + |\kappa_{12}^R|^2$  is expected to be improved at future experiments such as MEG and COMET for rare muon decays by a factor of  $10^{2-3}$ , while that on  $|\kappa_{31}^L|^2 + |\kappa_{13}^R|^2$  is by  $10^{1-2}$  at LHCb and SuperKEKB via rare tau decays [7, 8, 10, 11].

### 3 LFV Higgs production processes

We now discuss the lepton flavour violating Higgs boson production processes  $e^- \gamma \rightarrow \ell^- \varphi$  ( $\ell = \mu, \tau; \varphi = h, H, A$ ) in  $e\gamma$  collisions. The differential cross section is calculated by using the effective LFV parameters  $\kappa_{ij}^X$  as

$$\frac{d\hat{\sigma}_{e^- \gamma \rightarrow \ell_i^- \varphi}(\sqrt{s_{e\gamma}})}{d \cos \theta} = \frac{G_F \alpha_{\text{EM}} m_{\ell_i}^2 \beta_{\ell\varphi}}{16\sqrt{2} s_{e\gamma}} \frac{|\kappa_{i1}|^2}{\cos^4 \beta} \frac{\eta_-(\eta_+^2 + 4z^2) - 16z m_{\ell_i}^2 / s_{e\gamma}}{\eta_-^2}, \quad (3)$$

where  $z = (m_{\ell_i}^2 - m_{\varphi}^2) / s_{e\gamma}$  and  $\beta_{\ell\varphi} = \sqrt{\lambda(m_{\ell_i}^2 / s_{e\gamma}, m_{\varphi}^2 / s_{e\gamma})}$  with  $\lambda(a, b) = 1 + a^2 + b^2 - 2a - 2b - 2ab$ . The functions are defined as  $\eta_{\pm} = 1 + z \pm \beta_{\ell\varphi} \cos \theta$  where  $\theta$  is the scattering angle of the outgoing lepton from the beam direction. The effective LFV parameters can be written by

$$|\kappa_{i1}|^2 = [|\kappa_{i1}^L|^2(1 - P_e) + |\kappa_{i1}^R|^2(1 + P_e)] \times \begin{cases} \cos^2(\alpha - \beta) & \text{for } h \\ \sin^2(\alpha - \beta) & \text{for } H, \\ 1 & \text{for } A \end{cases} \quad (4)$$

where  $P_e$  is the polarization of the incident electron beam:  $P_e = -1$  (+1) represents that electrons in the beam are 100% left- (right-) handed.

At the ILC, a high energy photon beam can be obtained by Compton backward-scattering of laser and an electron beam [21]. The full cross section can be evaluated from that for the sub process by convoluting with the photon structure function as [21]

$$\sigma(\sqrt{s_{ee}}) = \int_{x_{min}}^{x_{max}} dx F_{\gamma/e}(x) \hat{\sigma}_{e^- \gamma \rightarrow \ell^- \varphi}(\sqrt{s_{e\gamma}}), \quad (5)$$

where  $x_{max} = \xi / (1 + \xi)$ ,  $x_{min} = (m_{\ell}^2 + m_{\varphi}^2) / s_{ee}$ ,  $\xi = 4E_e \omega_0 / m_e^2$  with  $\omega_0$  to be the frequency of the laser and  $E_e$  being the energy of incident electrons, and  $x = \omega / E_e$  with  $\omega$  to be the photon energy in the scattered photon beam. The photon distribution function is given in Ref. [21]. We note that when  $\sin(\beta - \alpha) \simeq 1$  and  $m_H \simeq m_A$  (In the MSSM, this automatically realizes for  $m_A \gtrsim 160$  GeV) signal from both  $e^- \gamma \rightarrow \ell^- H$  and  $e^- \gamma \rightarrow \ell^- A$  can be used to measure the LFV parameters, while the cross section for  $e^- \gamma \rightarrow \ell^- h$  is suppressed.

In FIG. 1, we show the full cross sections of  $e^- \gamma \rightarrow \tau^- A$  as a function of the center-of-mass energy of the  $e^- e^-$  system for  $\tan \beta = 50$  and  $m_A = 350$  GeV. Scattered leptons mainly go into the forward direction, however most of events can be detected by imposing the escape cut  $\epsilon \leq \theta \leq \pi - \epsilon$  where  $\epsilon = 20$  mrad [22]. The cross section can be around 10 fb with the maximal allowed values for  $|\kappa_{31}|^2$  under the constraint from the  $\tau \rightarrow e\eta$  data. The results correspond that, assuming the integrated luminosity of the  $e\gamma$  collision to be  $500 \text{ fb}^{-1}$  and the tagging efficiencies of a  $b$  quark and a tau lepton to be 60% and 30%, respectively, about  $10^3$  of  $\tau^- b\bar{b}$  events can be observed as the signal, where we multiply factor of two by adding both  $e^- \gamma \rightarrow \ell^- A \rightarrow \ell^- b\bar{b}$  and  $e^- \gamma \rightarrow \ell^- H \rightarrow \ell^- b\bar{b}$ . Therefore, we can naively say that non-observation of the signal improves the upper bound for the  $e\text{-}\tau$  mixing by 2–3 orders of magnitude if the backgrounds are suppressed. In FIG. 1 (left), those with a set of the typical values of  $|\kappa_{31}^L|^2$  and  $|\kappa_{13}^R|^2$  in the

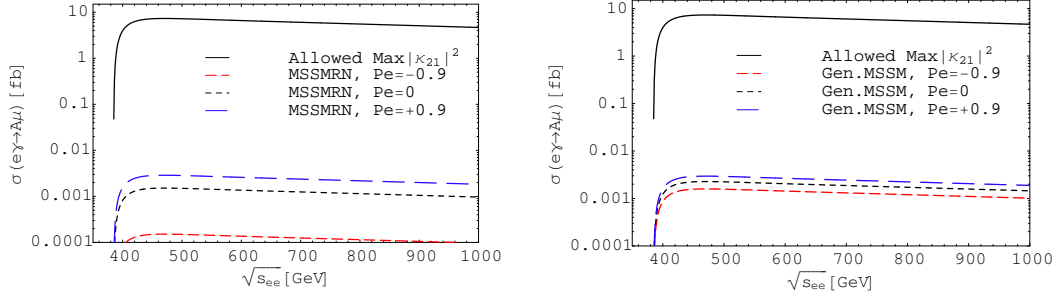


Figure 2: The production cross section of  $e^- \gamma \rightarrow \mu^- A$  as a function of the center-of-mass energy  $\sqrt{s_{ee}}$  of the electron-electron system. Solid curve represents the result in the THDM with the maximal allowed value of  $|\kappa_{21}|^2$  under the current experimental data in both figures.

MSSMRN are shown for  $P_e = -0.9$  (dashed),  $P_e = +0.9$  (long dashed), and  $P_e = 0$  (dotted), where we take  $(|\kappa_{31}^L|^2, |\kappa_{13}^R|^2) = (2 \times 10^{-7}, 0)$ . The cross sections are sensitive to the polarization of the electron beam. They can be as large as 0.5 fb for  $P_e = -0.9$ , while it is around 0.03 fb for  $P_e = +0.9$ . In FIG. 1 (right), the results with  $(|\kappa_{31}^L|^2, |\kappa_{13}^R|^2) = (2 \times 10^{-7}, 1 \times 10^{-7})$  in general supersymmetric models are shown for each polarization of the incident electrons. The cross sections are a few times 1 fb and not sensitive for polarizations. Therefore, by using the polarized beam of the electrons we can separately measure  $|\kappa_{31}^L|^2$  and  $|\kappa_{13}^R|^2$  and distinguish fundamental models with LFV.

In FIG. 2, the full cross sections of  $e^- \gamma \rightarrow \mu^- A$  are shown for  $\tan \beta = 50$  and  $m_A = 350$  GeV. Those with the maximally allowed values for  $|\kappa_{21}|^2 = |\kappa_{21}^L|^2 + |\kappa_{12}^R|^2$  from the  $\mu \rightarrow e \gamma$  data can be 7.3 fb where we here adopted the same escape cut as before discussed<sup>a</sup>. This means that about a few times  $10^3$  of the signal  $\mu^- b \bar{b}$  can be produced for the integrated luminosity of the  $e \gamma$  collision to be  $500 \text{ fb}^{-1}$ , assuming tagging efficiencies to be 60% for a  $b$  quark and 100% for a muon, and using both  $e^- \gamma \rightarrow \mu^- A$  and  $e^- \gamma \rightarrow \mu^- H$ . These results imply that  $e \gamma$  collider can improve the bound on the  $e-\mu$  by a factor of  $10^{2-3}$ . Obtained sensitivity can be as large as those at undergoing MEG and projected COMET experiments. Because of the different dependencies on the parameters in the model,  $\mu \rightarrow e \gamma$  can be sensitive than the LFV Higgs boson production for very high  $\tan \beta (\gtrsim 50)$  with fixed Higgs boson mass. We also note that rare decay processes can measure the effect of other LFV origin when Higgs bosons are heavy. Therefore, both the direct and the indirect measurements of LFV processes are complementary to each other. In FIG. 2 (left), those in the MSSMRN are shown for  $P_e = -0.9$  (dashed),  $P_e = +0.9$  (long dashed), and  $P_e = 0$  (dotted), where we take  $(|\kappa_{21}^L|^2, |\kappa_{12}^R|^2) = (2 \times 10^{-7}, 0)$ . They can be as large as a few times  $10^{-3}$  fb for  $P_e = -0.9$  and  $P_e = 0$ , while it is around  $10^{-4}$  fb for  $P_e = +0.9$ . In FIG. 2 (right), the results with  $(|\kappa_{21}^L|^2, |\kappa_{12}^R|^2) = (2 \times 10^{-7}, 1 \times 10^{-7})$  are

<sup>a</sup>If 10 mrad for the cut is taken instead of 20 mrad, the numbers of events are slightly enhanced; 10.6 fb to 11.0 fb (7.3 fb to 8 fb) for the  $\tau-\varphi$  ( $\mu-\varphi$ ) process.

shown in general supersymmetric models in a similar manner.

It is understood that these processes are clear against backgrounds. For the processes of  $e^- \gamma \rightarrow \tau^- \varphi \rightarrow \tau^- b \bar{b}$ . The tau lepton decays into various hadronic and leptonic modes. The main background comes from  $e^- \gamma \rightarrow W^- Z \nu$ , whose cross section is of the order of  $10^2$  fb. The backgrounds can strongly be suppressed by the invariant mass cut for  $b \bar{b}$ . The backgrounds for the process  $e^- \gamma \rightarrow \mu^- \varphi \rightarrow \mu^- b \bar{b}$  also comes from  $e^- \gamma \rightarrow W^- Z \nu \rightarrow \mu^- b \bar{b} \nu \bar{\nu}$  which is small enough. Signal to background ratios are better than  $\mathcal{O}(1)$  before kinematic cuts. They are easily improved by the invariant mass cut, so that our signals can be almost background free.

## 4 Conclusion

We have studied the Higgs boson associated LFV at an electron photon collider. Lots of new physics model can predict the LFV Yukawa interactions. The cross section for  $e^- \gamma \rightarrow \ell^- \varphi$  ( $\ell = \mu, \tau; \varphi = H, A$ ) can be significant for the allowed values of the effective LFV couplings under the current experimental data. By measuring these processes at the ILC, the current upper bounds on the effective LFV Yukawa coupling constants are expected to be improved in a considerable extent. Such an improvement can be better than those at MEG and COMET experiments for the  $e$ - $\mu$ - $\varphi$  vertices, and those at LHCb and SuperKEKB for the  $e$ - $\tau$ - $\varphi$  vertices. Moreover, the chirality of the LFV Higgs coupling can be separately measured via these processes by using the polarized electron beam. The electron photon collider can be an useful tool of measuring Higgs boson associated LFV couplings.

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