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A POWERFUL TOOL FOR MEASURING HIGGS BOSON ASSOCIATED LEPTON FLAVOUR VIOLATION

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Abstract

In models with extended Higgs sectors, Higgs-boson-mediated Lepton Flavour Violation (LFV) can naturally appear. We study the physics potential of an electron-photon collider on searching LFV processes $e^-\gamma \to \ell^-\varphi$ ($\ell = \mu, \tau; \varphi = H, A$) where H and A are extra CP even and odd Higgs bosons, respectively, in the minimal supersymmetric standard model and the effective two Higgs doublet model. The production cross section can be significantly large for the maximal allowed values of the LFV coupling constants under the current experimental data. Present experimental upper bounds on the effective LFV coupling constants would be considerably improved by searching these processes, which would be better than MEG and COMET experiments and also those at LHCb and SuperKEKB. Moreover, one can separately measure chirality of effective LFV coupling constants via these processes by selecting electron polarizations.

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Lepton Flavour Violation (LFV) for charged leptons is, if it exists, a clear signature of new physics beyond the Standard Model (SM). Various new physics scenarios such as supersymmetric extensions of the SM can naturally predict observable phenomena of LFV, whose details would relate to fundamental flavour structures at very high energies. Hence, experimental detection of LFV phenomena cannot only provide an evidence of new physics, but also its detailed information can be used to distinguish new physics models. Phenomenologically there are two kinds of LFV processes; i.e., the gauge boson (γ, Z) mediation and the Higgs boson mediation.

LFV coupling constants in association with Higgs bosons can appear in models with extended Higgs sectors. In supersymmetric extensions of the SM whose Higgs sectors have at least two scalar isospin doublet fields, LFV Yukawa interactions can be radiatively induced from slepton mixing [1, 2]. Flavour mixing between "left-handed" sleptons may be induced by the quantum effect via the neutrino Yukawa coupling constants in the minimal supersymmetric SM with heavy right-handed neutrinos (MSSMRN) when flavour blind structure is assumed at the grand unification scale [1]. In a general framework of supersymmetric SMs, not only mixing between "left-handed" sleptons but also that between "right-handed" sleptons can be considered [2]. Such a difference in patterns of LFV in various models can be studied by measuring effective LFV parameters in the Yukawa interaction as well as those in the effective LFV gauge interactions.

The effective LFV parameters have been tested at the experiments for rare decay processes of muons and tau leptons, and their upper bounds have been obtained [3–5]. They are expected to be improved at PSI MEG [6] and J-PARC COMET [7] experiments via rare decays of muons, and at CERN LHCb [8] and KEK super-B factory [9] via rare decays of tau leptons. In addition, high energy collider experiments at the CERN Large Hadron Collider (LHC) [10], the International Linear Collider (ILC) [11] and the Neutrino Factory [12] can also be useful to search Higgs-boson-mediated μ–τ and e–τ mixing [5, 13–15].

In this letter, we discuss the possibility that a high energy $e\gamma$ collider, which can be realized as an optional experiment at the ILC, can be a powerful tool for measuring Higgs-boson-mediated LFV parameters in two Higgs doublet models (THDMs) including Minimal Supersymmetric SMs (MSSMs). We consider the processes $e^-\gamma \to \ell^-\varphi$ $(\ell = \mu, \tau; \varphi = h, H, A)$, which contain the LFV couplings of $e^-\ell^+\varphi$, where h, H and A are neutral Higgs bosons. Advantages of these processes turn out to be the following. i) The total cross sections for $e^-\gamma \to \tau^- A$ $(e^-\gamma \to \mu^- A)$ can be about 10.6 fb (7.3 fb) for the collision energy of e^-e^- system to be $\sqrt{s_{ee}} = 522$ GeV (471 GeV), where $m_A = 350$ GeV, $\tan\beta = 50$ and allowed maximal values of the LFV parameters under the constraint from the current experimental data are taken, where $\tan\beta$ is the ratio of vacuum expectation values for the two Higgs doublets. ii) These processes are basically background free. Therefore, the current upper bound on the LFV parameters in the effective Yukawa interaction can be improved by several orders of magnitude by assuming moderate properties for $e\gamma$ colliders. iii) Information of the Higgs-boson-mediated LFV couplings can directly be extracted. Produced Higgs bosons can be reconstructed by tagging its decay product $b\bar{b}$. iv) The use of polarized beams for incident electrons makes it possible to discriminate the chirality of the LFV parameters, thereby we may be able to distinguish scenarios for more fundamental physics models.

The effective Yukawa interaction for charged leptons is given in the general framework of the THDM by [4, 5]

$$\mathcal{L}_{\rm lepton} = -\overline{\ell_{Ri}} \left\{ Y_{\ell_i} \delta_{ij} \Phi_1 + \left(Y_{\ell_i} \epsilon^L_{ij} + \epsilon^R_{ij} Y_{\ell_j} \right) \Phi_2 \right\} \cdot L_j + \text{H.c.}, \tag{1}$$

where $\ell_{Ri} (i = 1\text{–}3)$ represent isospin singlet fields of right-handed charged leptons, L_i are isospin doublets of left-handed leptons, Y_{ℓ_i} are the Yukawa coupling constants of ℓ_i, and Φ_1 and Φ_2 are the scalar iso-doublets with hypercharge $Y = 1/2$. Parameters $\epsilon^X_{ij} (X = L, R)$ can induce LFV interactions in the charged lepton sector in the basis of the mass eigenstates. In Model II THDM [16], ϵ^X_{ij} vanishes at the tree level, but it can be generated radiatively by new physics effects [2].

The effective Lagrangian can be rewritten in terms of physical Higgs boson fields. There are eight degrees of freedom in two scalar doublets Φ_1 and Φ_2. Three of them are absorbed by massive gauge bosons via the Higgs mechanism, and remaining five are physical Higgs bosons. Assuming the CP invariant Higgs sector, there are two CP even Higgs bosons h and H $(m_h < m_H)$, one CP odd state A and a pair of charged Higgs bosons $H^\pm$. From Eq. (1), interaction terms can be deduced to [2, 5]

$$\begin{aligned} \mathcal{L}_{e\rm LFV} = & -\frac{m_{\ell_i}}{v \cos^2 \beta} \left(\kappa^L_{i1} \overline{\ell_i} \mathrm{P}_L e + \kappa^R_{1i} \overline{e} \mathrm{P}_L \ell_i \right) \\ & \times \left\{ \cos(\alpha - \beta) h + \sin(\alpha - \beta) H - i\, A \right\} + \text{H.c.}, \end{aligned} \tag{2}$$

where P_L is the projection operator to the left-handed fermions, m_{ℓ_i} are mass eigenvalues of charged leptons, $v = \sqrt{2} \sqrt{\langle \Phi^0_1 \rangle^2 + \langle \Phi^0_2 \rangle^2}$ ($\simeq$ 246 GeV), α is the mixing angle between the CP even Higgs bosons, and $\tan \beta \equiv \langle \Phi^0_2 \rangle / \langle \Phi^0_1 \rangle$. The LFV parameters $\kappa^X_{ij} (X = L, R)$ relate to the original parameters as [1]

$$\kappa^X_{ij} = -\frac{\epsilon^X_{ij}}{\left\{ 1 + \left(\epsilon^L_{33} + \epsilon^R_{33} \right) \tan \beta \right\}^2}, \tag{3}$$

for $\epsilon^X_{ij} \tan \beta \ll 1$.

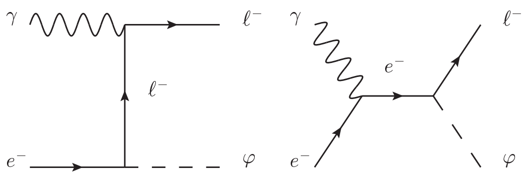

FIG. 1: The Feynman diagrams for $e^-\gamma \to \ell^-\varphi$ ($\ell = \mu, \tau; \varphi = H, A$).

Once a new physics model is assumed, κ_{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 κ_{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) $\times 10^{-7}$ [1, 2]. In the MSSMRN only κ_{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 κ_{ij}^X are obtained from the data of non-observation for various LFV processes [17]. For e–τ mixing, we obtain the upper bound from the semi-leptonic decay $\tau \to e\eta$ [4];

$$|\kappa_{31}^L|^2 + |\kappa_{13}^R|^2 \lesssim 6.4 \times 10^{-6} \left(\frac{50}{\tan\beta}\right)^6 \left(\frac{m_A}{350\mathrm{GeV}}\right)^4, \tag{4}$$

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–μ mixing is derived from $\mu \to e\gamma$ data [18] as

$$\frac{4}{9}|\kappa_{21}^L|^2 + |\kappa_{12}^R|^2 \lesssim 4.3 \times 10^{-4} \left(\frac{50}{\tan\beta}\right)^6 \left(\frac{m_A}{350\mathrm{GeV}}\right)^4, \tag{5}$$

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 $10^{2\text{–}3}$, while that on $|\kappa_{31}^L|^2 + |\kappa_{13}^R|^2$ is by $10^{1\text{–}2}$ at LHCb and SuperKEKB via rare tau decays [6–9].

We now discuss the lepton flavour violating Higgs boson production processes $e^-\gamma \to \ell^-\varphi$ ($\ell = \mu, \tau; \varphi = h, H, A$) in $e\gamma$ collisions. The Feynman diagrams for the sub processes are depicted in FIG. 1. The differential cross section is calculated by using the effective LFV parameters κ_{ij}^X as

$$\frac{d\widehat{\sigma}_{e^-\gamma\to\ell_i^-\varphi}(\sqrt{s_{e\gamma}})}{d\cos\theta} = \frac{G_F \alpha_{\mathrm{EM}} m_\ell^2 \beta_{\ell\varphi}}{16\sqrt{2}s_{e\gamma}} \frac{|\kappa_{i1}|^2}{\cos^4\beta} \frac{\eta_-(\eta_+^2 + 4z^2) - 16z\, m_\ell^2/s_{e\gamma}}{\eta_-^2}, \tag{6}$$

where we have neglected the mass of electrons, $z = (m_{\ell_i}^2 - m_\varphi^2)/s_{e\gamma}$, $\beta_{\ell\varphi} = \sqrt{\lambda(m_{\ell_i}^2/s_{e\gamma}, m_\varphi^2/s_{e\gamma})}$ with $\lambda(a,b) = 1 + a^2 + b^2 - 2a - 2b - 2ab$. The functions are defined as $\eta_\pm = 1 + z \pm \beta_{\ell\varphi}\cos\theta$

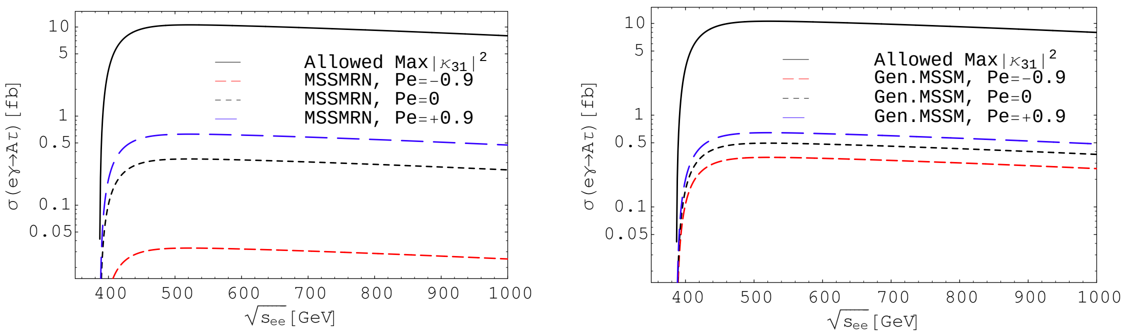

FIG. 2: The production cross section of $e^-\gamma \to \tau^- A$ as a function of the center-of-mass energy $\sqrt{s_{ee}}$ of the electron-electron system. Final state leptons can be detected in the range $\epsilon \le \theta \le \pi - \epsilon$ where $\epsilon = 20$ mrad. Solid curve represents the result in the THDM with the maximal allowed value of $|\kappa_{31}|^2$ under the current experimental data in Eq. (4) in both figures. In the left figure, the result with a set of the typical values of $|\kappa^L_{31}|^2$ and $|\kappa^R_{13}|^2$ in the MSSMRN is shown $[(|\kappa^L_{31}|^2, |\kappa^R_{13}|^2) = (2\times 10^{-7}, 0)]$ for the polarization of the incident electron beam to be $P_e = -0.9$ (dashed), $+0.9$ (long dashed), and $P_e = 0$ (dotted). In the right figure, the result with a set of $(|\kappa^L_{31}|^2, |\kappa^R_{13}|^2) = (2\times 10^{-7}, 1\times 10^{-7})$ is shown in the general framework of the MSSM for $P_e = -0.9$ (dashed), $P_e = +0.9$ (long dashed), and $P_e = 0$ (dotted).

where θ is the scattering angle of the outgoing lepton from the beam direction. The effective LFV parameters $|\kappa_{i1}|^2$ can be written by

$$|\kappa_{i1}|^2 = \left[|\kappa^L_{i1}|^2(1-P_e) + |\kappa^R_{1i}|^2(1+P_e)\right] \times \begin{cases} \cos^2(\alpha-\beta) & \text{for } h \\ \sin^2(\alpha-\beta) & \text{for } H \\ 1 & \text{for } A \end{cases}, \qquad (7)$$

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 [19]. The full cross section can be evaluated from that for the sub process by convoluting with the photon structure function as [19]

$$\sigma\left(\sqrt{s_{ee}}\right) = \int_{x_{min}}^{x_{max}} dx\, F_{\gamma/e}(x)\, \widehat{\sigma}_{e^-\gamma\to\ell^-\varphi}(\sqrt{s_{e\gamma}}), \qquad (8)$$

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 ω_0 to be the frequency of the laser and E_e being the energy of incident electrons, and $x = \omega/E_e$ with ω to be the photon energy in the scattered photon beam. The photon distribution function is given by [19]

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)} \times \left\{1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\right\}, \qquad (9)$$

with

$$D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right) \ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}. \tag{10}$$

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 $e^-\gamma \to \ell^- H$ and $e^-\gamma \to \ell^- A$ can be used to measure the LFV parameters, while the cross section for $e^-\gamma \to \ell^- h$ is suppressed.

In FIG. 2, we show the full cross sections of $e^-\gamma \to \tau^- A$ 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 [20]. The cross section can be around 10 fb with the maximal allowed values for $|\kappa_{31}|^2$ under the constraint from the $\tau \to e\eta$ data in Eq. (4). The results correspond that, assuming the integrated luminosity of the $e\gamma$ collision to be 500 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 $e^-\gamma \to \ell^- A \to \ell^- b\bar{b}$ and $e^-\gamma \to \ell^- H \to \ell^- b\bar{b}$. Therefore, we can naively say that non-observation of the signal improves the upper bound for the e-τ mixing by 2–3 orders of magnitude if the backgrounds are suppressed. In FIG. 2 (left), those with a set of the typical values of $|\kappa_{31}^L|^2$ and $|\kappa_{13}^R|^2$ 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 $(|\kappa_{31}^L|^2, |\kappa_{13}^R|^2) = (2 \times 10^{-7}, 0)$. 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. 2 (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. 3, the full cross sections of $e^-\gamma \to \mu^- A$ 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 $\mu \to e\gamma$ data in Eq. (5) can be 7.3 fb where we here adopted the same escape cut as before discussed [22]. 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 fb^{-1}, assuming tagging efficiencies to be 60% for a b quark and 100% for a muon, and using both $e^-\gamma \to \mu^- A$ and $e^-\gamma \to \mu^- H$. These results imply that $e\gamma$ collider can improve the bound on the e-μ 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, $\mu \to e\gamma$ can be sensitive than the LFV

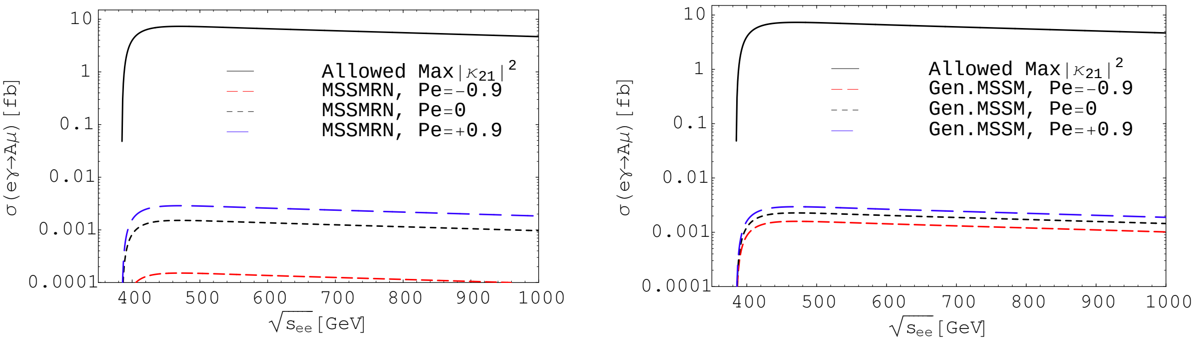

FIG. 3: The production cross section of $e^-\gamma \to \mu^- A$ as a function of the center-of-mass energy $\sqrt{s_{ee}}$ of the electron-electron system. Scattering angle of leptons are restricted as $\epsilon \leq \theta \leq \pi - \epsilon$ where $\epsilon = 20$ mrad. Solid curve represents the result in the THDM with the maximal allowed value of $|\kappa_{21}|^2$ under the current experimental data in Eq. (5) in both figures. In the left figure, the result with a set of the typical values of $|\kappa^L_{21}|^2$ and $|\kappa^R_{12}|^2$ in the MSSMRN is shown $[(|\kappa^L_{21}|^2, |\kappa^R_{12}|^2) = (2 \times 10^{-7}, 0)]$ for the polarization of the incident electron beam to be $P_e = -0.9$ (dashed), $+0.9$ (long dashed), and $P_e = 0$ (dotted). In the right figure, the result with $(|\kappa^L_{21}|^2, |\kappa^R_{12}|^2) = (2 \times 10^{-7}, 1 \times 10^{-7})$ is shown in the general framework of the MSSM for $P_e = -0.9$ (dashed), $P_e = +0.9$ (long dashed), and $P_e = 0$ (dotted).

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. 3 (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 $(|\kappa^L_{21}|^2, |\kappa^R_{12}|^2) = (2 \times 10^{-7}, 0)$. 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. 3 (right), the results with $(|\kappa^L_{21}|^2, |\kappa^R_{12}|^2) = (2 \times 10^{-7}, 1 \times 10^{-7})$ are shown in general supersymmetric models in a similar manner.

It is understood that these processes are clear against backgrounds. For the processes of $e^-\gamma \to \tau^-\varphi \to \tau^- b\bar{b}$. The tau lepton decays into various hadronic and leptonic modes. The main background comes from $e^-\gamma \to W^- Z\nu$, 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 $e^-\gamma \to \mu^-\varphi \to \mu^- b\bar{b}$ also comes from $e^-\gamma \to W^- Z\nu \to \mu^- b\bar{b}\nu\bar{\nu}$ 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. A detailed simulation study will clarify this observation.

We have discussed the processes $e^-\gamma \to \ell^-\varphi$ $(\ell = \mu, \tau; \varphi = H, A)$. Many new physics models can violate lepton flavour in the scalar sector. Cross sections for the lepton flavour violating

Higgs boson production production at the $e\gamma$ collider can be substantial for the maximal allowed values under the current experimental data. Measurements of these processes can significantly improve the present upper bounds of the LFV Yukawa coupling constants. Expected precision of the e-μ-φ ($\varphi = A, H$) measurements at the e-gamma collider can be better than those at MEG and COMET experiments. For e–τ mixing, its experimental reach is much greater than those at LHCb and SuperKEKB. In addition, chirality of the Higgs boson mediated LFV coupling can be measured separately. Therefore, the $e\gamma$ collider can be an useful tool to measure the Higgs associated LFV. Detailed phenomenological study will be elsewhere [21].

Acknowledgments

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[22] 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 τ-φ (μ-φ) process.