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Probing lepton flavor violation via $e\tau$ production in an effective framework at a future electron-positron circular collider

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Abstract

In the standard model framework, lepton flavor is conserved in the interactions, however, it can be violated in some beyond the standard model scenarios. In this study, we consider $e^{\pm}\tau^{\mp}$ production through a four-Fermi lepton flavor violation interaction at the future electron-positron circular collider (FCC-ee). To constrain the Wilson coefficients at four center-of-mass energies of 157.5, 162.5, 240 and 365 GeV that proposed for the FCC-ee, a standard model effective field theory is considered. The main source of backgrounds are taken into account and the study is performed by including realistic effects of the detector. To improve the result, we combine the individual constraints obtained for each center of mass energy. We show that, the combined limits increase the sensitivity to lepton flavor violation couplings by a factor of around three with respect to the individual results and are comparable to the Belle II prospects.

Contents

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1 Introduction

The Standard Model (SM) of particle physics indicates that the charged leptons flavor does not change at three level interactions, since neutrinos are massless and their oscillations are forbidden in the SM [1]. However, there are a variety of experimental observations which confirm that neutrinos oscillate between different flavors. Neutrino oscillations imply that neutrinos have to be massive [2]. Charged lepton flavor violation (LFV) can occur through neutrino oscillations via loop correction which is highly suppressed due to neutrino tiny mass with respect to the mass of W boson. Although the new physics which can describe the oscillation of neutrinos are still obscure, there are several SM extensions [4–6] which predict a significant enhancement on the constraints on LFV interactions experimentally. Thus, the observation of any charged LFV, can be a hint for the existence of new physics beyond the SM (BSM). Recent LFV searches of Belle II experiments provide a prospect stringent upper bound on the branching fraction of the tau decay to three electrons in order of 10^{-10} [7] and the measurements of BaBar and Belle leads to the most strong limits on this decay which are in order of 10^{-8} both [8, 9]. Moreover, LFV in the charged sector is quite sensitive to new particles which can be probably produced in high energy future colliders [10, 11]. This proceeding is a brief review of studying LFV production of eτ in e^+e^- collision at the future circular collider (FCC-ee). For a detailed description, the reader is encouraged to study Ref [12].

Some other LFV interactions, for example, LFV production through the Higgs and Z boson, as well as LFV decays of Higgs and scalar particles have been considered in several studies [13–20], and LFV in muon sector is studied in the literature [21–23]. In Ref [25] LFV $e^+e^-e^\pm\tau^\mp$ vertex has been considered as a contact interaction including two sources of background, $e\tau\nu_e\nu_\tau$ and $\tau^+\tau^-$ at $\sqrt{s} = 250, 500, 1000, 3000$ GeV. Moreover, similar interaction has been studied in Ref [25] considering the electron and positron beam polarization effects at $\sqrt{s} = 250, 500, 1000$ GeV. Only the $e^\pm\tau^\mp\nu_e\nu_\tau$ process has been considered as background.

In this work, we study the LFV $e^+e^- \to e^\pm\tau^\mp$ process as a four-Fermi contact interaction using a standard model effective field theory (SMEFT) to investigate the potential of the future electron-positron circular collider (FCC-ee) to probe the LFV couplings. Data is generated at four center-of-mass energies of FCC-ee, 157.5, 162.5, 240 and 365 GeV with the integrated luminosities of 5, 5, 5, and 1.5 ab^{-1}, respectively. The main background sources of $\tau^+\tau^-$, $e^\pm\tau^\mp\nu_e\nu_\tau$, $\ell^\pm\ell^\mp\ell'^\pm\ell'^\mp$, $\ell^\pm\ell^\mp jj, \ell\nu jj, (\ell = e, \mu, \tau)$, and $jj, (j = \text{jet})$ are included in the study and a realistic simulation of detector effects is performed via `Delphes` package. In addition, the initial state radiation (ISR) effects are considered in data simulation. At the end, a statistical combination of the four FCC-ee benchmarks is done, which leads to a significant improvement of the individual results.

In the following, section 2 presents the theoretical framework describing the effective theory for the LFV interaction, operators and couplings. In Section 3 the methodology of data simulation and the analysis details are presented. Section 4 is dedicated to the individual and combination results over the LFV couplings. Finally, a conclusion is given in section 5.

2 Theoretical framework

There are various SM extensions, such as compositeness and supersymmetry, that can predict LFV interactions in the charged sector. LFV can also be produced through heavy neutrino, Higgs and top quark loops, leptoquark and heavy Z' particles in BSM scenarios. In this project, we study the LFV $e\tau$ production in e^+e^- collisions using four-Fermi contact interaction in a SMEFT framework which is an efficient tool and includes higher dimension operators to the effective Lagrangian with respect to the SM Lagrangian terms. There are two scalar and four vector type operators which violate the lepton number conservation. The LFV effective Lagrangian including these six operators is [26]:

$$\mathcal{L}_{\rm LFV} = \sum_{\alpha,\beta} \sum_{ij} \frac{c^{ij}_{\alpha\beta}}{\Lambda^2} \mathcal{O}^{ij}_{\alpha\beta}\,, \tag{1}$$

where Λ is the energy scale of new physics, $\alpha\beta$ indicate the Lorentz structures, and $c^{ij}_{\alpha\beta}$ shows the LFV Wilson coupling between flavor leptons of i and j. The relevant four fermion operators, which are invariant under the gauge symmetry of the SM, are given by:

$$\begin{aligned}
\mathcal{O}^{V,ij}_{RR} &= \left(\bar{\ell}_{iR}\gamma^{\mu}\ell_{jR}\right)\left(\bar{\ell}_{jR}\gamma_{\mu}\ell_{jR}\right), \quad \mathcal{O}^{V,ij}_{LL} = \left(\bar{\ell}_{iL}\gamma^{\mu}\ell_{jL}\right)\left(\bar{\ell}_{V,jL}\gamma_{\mu}\ell_{jL}\right),\\
\mathcal{O}^{V,ij}_{LR} &= \left(\bar{\ell}_{iL}\gamma^{\mu}\ell_{jL}\right),\left(\bar{\ell}_{jR}\gamma_{\mu}\ell_{jR}\right), \quad \mathcal{O}^{V,ij}_{RL} = \left(\bar{\ell}_{iR}\gamma^{\mu}\ell_{jR}\right)\left(\bar{\ell}_{iL}\gamma_{\mu}\ell_{iL}\right),\\
\mathcal{O}^{S,ij}_{RL} &= \left(\bar{\ell}_{jL}\ell_{iR}\right)\left(\bar{\ell}_{jL}\ell_{jR}\right), \qquad \mathcal{O}^{S,ij}_{LR} = \left(\bar{\ell}_{iR}\ell_{jL}\right)\left(\bar{\ell}_{jR}\ell_{jL}\right),
\end{aligned} \tag{2}$$

where S and V indicate the scalar and vector type operators, respectively. LFV interactions between muon and electron are bounded strongly in several studies [27–29] and the constraints on the electron-tau and muon-tau LFV couplings are not tight as well as bounds on the muon-electron LFV coupling. In this research, we consider $e^+e^- \to e^{\pm}\tau^{\mp}$ LFV process.

The following section describes the methodology that contains the simulation of data and analysis strategy and details for the LFV production of $e\tau$ to study the sensitivity of FCC-ee to the LFV couplings.

3 Methodology

3.1 Data simulation

We simulate the FCC-ee events to produce $e\tau$ in a four fermion interaction at four benchmark center-of-mass energies of 157.5, 162.5, 240 and 365 GeV. To import the effective Lagrangian and LFV four-Fermi dimension-six operators which are presented in sec. 2, a Universal FeynRule Output (UFO) model [30] is built using FeynRule program [31] and implemented to the `MadGraph5_aMC@NLO 2.6.6` [32–34] package to generate events for the signal samples. There are six signal samples according to the six LFV Wilson coefficients in the Eq. (1). The final state in the signal process includes an electron (positron) and a τ^+ (τ^-) which is considered to decay into hadrons only. The cross section of two different signal scenarios for the scalar and vector type operators as a function of LFV couplings, and as a function of center-of-mass energy, are presented in Fig. 1 on the left and right side, respectively. As it is seen, the value of signal cross section increases with the collision energy as it is proportional to the square of center-of-mass energy. The other point is that the cross section of signal process for vector type couplings is larger than the scalar types, and it comes from the theoretical function of cross section in Ref [35]. The main sources of the background events included in the analysis, are as follows

$$\begin{aligned}
&e^-e^+ \to e^{\pm}\tau^{\mp}\nu\bar{\nu}, && e^-e^+ \to \ell^{\pm}\nu jj, && e^-e^+ \to \tau^+\tau^-,\\
&e^-e^+ \to \ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp}, && e^-e^+ \to jj, && e^-e^+ \to \ell^{\pm}\ell^{\mp}jj,
\end{aligned}$$

where $\ell, \ell' = e, \mu, \tau$ and j is jet. For generating signal and background samples, the initial state radiation (ISR) effects are also included using MGISR plugin program [36, 37] in `MadGraph5_aMC@NLO 2.6.6`. For showering and hadronization, hard events are passed through `PYTHIA 8` [38,39], and a realistic simulation of ILD detector effects [40] is performed

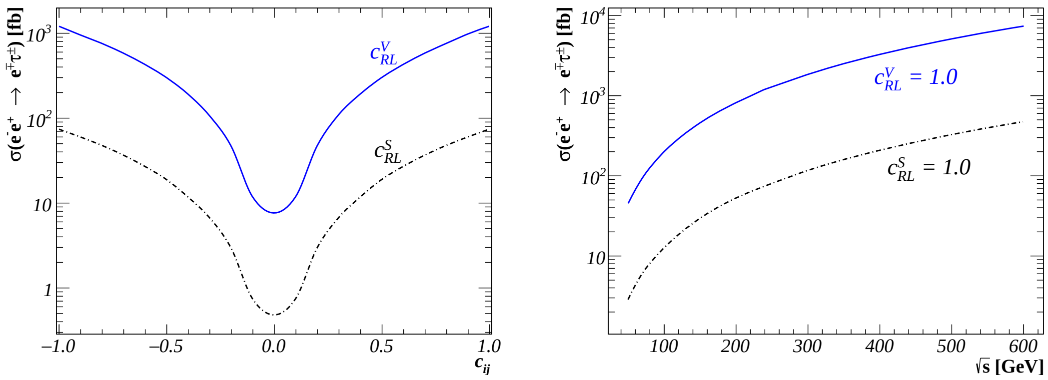

Figure 1: Cross section of $e\tau$ production at e^+e^- collision (**Left**) as a function of center-of-mass energy for $c^S_{RL} = 1.0$ and $c^V_{RL} = 1.0$ signals scenarios, (**Right**) as a function of c^V_{RL} and c^S_{RL} at $\sqrt{s}$ =240 GeV.

using `Delphes 3.4.2` [41]. Based on the ILD `Delphes` card, the efficiency of electron identification is 95% considering $p_T > 10$ GeV and $|\eta| \leq 2.5$, and the efficiency of tau-tagging is 40%. The signal and background cross sections are presented in Table 1. To calculate the signal cross sections, the new physics energy scale is supposed to be $\Lambda = 1$ TeV, and the dimension-six four-Fermi Wilson coefficients are considered as $c^{V,S}_{ij} = 0.1$, where $i = j = L,R$.

$\sqrt{s}$ [GeV]	c^V_{LR}	c^S_{LR}	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\bar{\ell}\ell'\bar{\ell}'$	$\ell\bar{\ell}jj$	$\ell\nu jj$	jj
157.5	4.72	0.29	22.33	11076.5	39.86	80.95	272.9	32032
162.5	5.02	0.31	102.12	10275.8	42.23	83.06	1198.05	29133
240	10.98	0.69	415.63	4196.8	86.24	217.8	4552.7	10481
365	25.26	1.57	327.59	1803.6	85.05	195.13	3247.02	4306

Table 1: The cross sections of signal, $e^-e^+ \to e^\pm\tau^\mp$, and background processes considering ISR effects for the four FCC-ee energy benchmarks [12]. For the signal cross sections, it is assumed that $\Lambda = 1$ TeV and $c^V_{LR} = 0.1$, $c^S_{LR} = 0.1$.

In the following, the analysis strategy to reduce the background events and to increase the sensitivity of signal is described.

3.2 Analysis details

For selection of signal events, it is requested for each event to have exactly one isolated electron (or positron) and one hadronically decaying τ-tagged object. These two candidates in the final state must be opposite sign and it is required to have pseudorapidity range of $|\eta^\ell| < 2.5$ both, and $p^e_T > 10$, $p^\tau_T > 20$ GeV, and $\Delta R_{e,\tau} > 0.5$. In order to have a well isolated electron, it is considered RelIso < 0.15 which is defined as the fraction of the sum of transverse momentum of charged particle tracks inside a cone size of 0.5 around the electron track over the electron p_T. The background events including leptons with same flavors are rejected using these preselection requirements.

To improve the sensitivity of signal with respect to the backgrounds, a cuts are applied on two distributions of Fig. 2, the invariant mass of final state e and τ ($M_{e\tau}$), and the energy of electron (E_e) which show a significant discrimination between signal and background events among the kinematic distributions. We find the optimized cut values on these two plots to suppress the background events as much as possible. To determine the optimized cut values, the upper bound of the signal cross section is calculated for different cuts on E_e and $M_{e\tau}$ and the value of cut which minimizes the upper bound on the cross section of signal, is chosen as the optimized cut value. For instance, the graph of upper limit on the signal cross section versus the values of cuts applying on (E_e), is displayed in Fig. 3. By applying the optimum cut values, a large number of background events are removed and the best sensitivity is achieved. Final efficiencies of two signal scenarios and background processes are presented in Table 2.

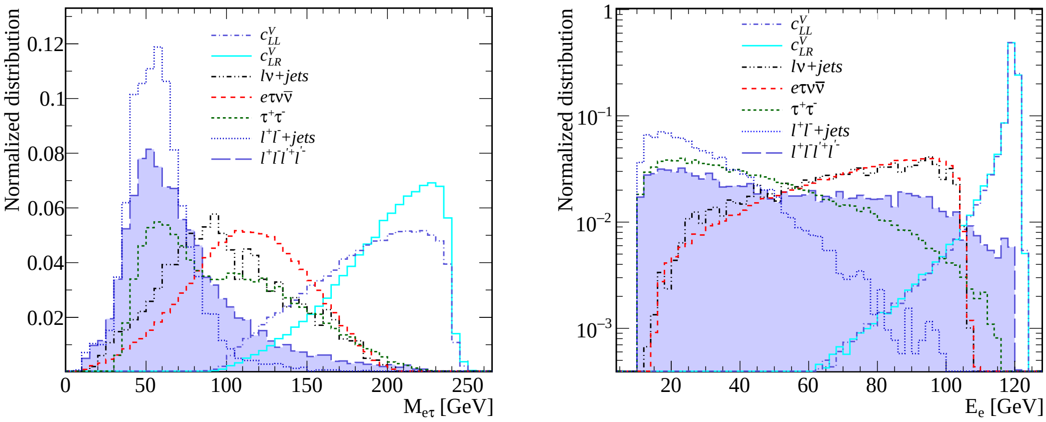

Figure 2: The two final state leptons invariant mass (left), and the energy of electron candidate (right) distributions are presented for $c^V_{LR} = 0.1$ and $c^V_{LR} = 0.1$ signal scenarios, at $\sqrt{s} = 240$ GeV [12].

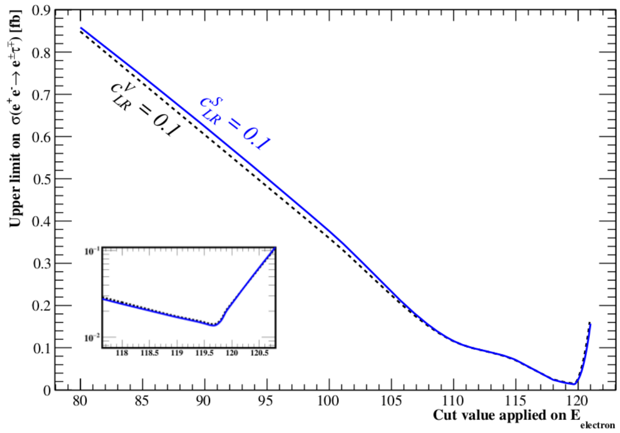

Figure 3: The upper limit over the signal cross section versus the value of cut applying on the energy of final state electron, at $\sqrt{s} = 240$ GeV. The blue solid line shows $c^S_{LR} = 0.1$, and the black dashed shows $c^V_{LR} = 0.1$ signal scenario.

4 Results

The constraints on $c^{S,V}_{ij}$ LFV parameters, i, j is L and R, are estimated at $\sqrt{s} = 157.5$, 162.5, 240 and 365 GeV with $\mathcal{L}_{int} = 5, 5, 5$ and 1.5 ab^{-1}, respectively, according to the FCC-ee benchmarks. The bounds on the scalar-type coefficients are about 4 times weaker than the vector-type couplings. For increasing the sensitivity of the FCC-ee to the LFV couplings, the results

$\sqrt{s}$ [GeV]	Signal		Backgrounds				
	c^V_{LR}	c^S_{LR}	$e\tau\nu\bar{\nu}$	$\tau\bar{\tau}$	$\ell\ell\ell'\ell'$	$\ell\ell jj$	$\ell\nu jj$
157.5	0.10	0.08	2.8×10^{-8}	1.5×10^{-7}	6.02×10^{-6}	1.7×10^{-7}	0.0
162.5	0.11	0.09	6×10^{-8}	2.0×10^{-7}	3.61×10^{-6}	2.1×10^{-7}	0.0
240	0.11	0.10	2.1×10^{-8}	1.5×10^{-7}	1.2×10^{-5}	2.4×10^{-7}	0.0
365	0.10	0.10	2.6×10^{-8}	3.2×10^{-7}	2.6×10^{-5}	1.4×10^{-7}	0.0

Table 2: The efficiencies of signal scenarios of $c^V_{LR}=0.1$, $c^S_{LR}=0.1$, and the background processes after all cuts at $\sqrt{s}=157.5$, 162.5, 240 and 365 GeV [12].

for these four center-of-mass energies are statistically combined. In Table 3, individual and combined limits are presented and compared to the results of the Belle II experiment future prospects with 50 ab^{-1} integrated luminosity. The results for the FCC-ee from this study are comparable with the Belle II prospects. The expected upper limits on the c^V_{LR} and c^V_{RL} from our FCC-ee benchmarks are a little better than the Belle II predicted bounds. Another comparison with a phenomenological study at 1 TeV center-of-mass energy, including the polarization effects on the initial $e^{\pm}$ beams is considered.

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [ab^{-1}]	$c^S_{RL}[\times10^{-15}]$	$c^S_{LR}[\times10^{-15}]$	$c^V_{LL}[\times10^{-15}]$	$c^V_{RR}[\times10^{-15}]$	$c^V_{RL}[\times10^{-15}]$	$c^V_{LR}[\times10^{-15}]$
365	1.5	15.8	15.8	3.9	3.9	3.9	3.9
240	5.0	14.8	14.7	3.7	3.5	3.7	3.5
162.5	5.0	21.4	23.1	5.7	5.4	5.6	5.3
157.5	5.0	21.2	22.6	5.8	5.5	5.7	5.4
Combined		5.1	5.3	1.3	1.2	1.3	1.3
Belle II prospects		4.3	4.3	1.1	1.1	1.6	1.6
Polarized beams, 1 TeV		13	5.9	4.3	1.1	1.6	1.8

Table 3: Upper limits on the LFV scalar and vector type couplings at $\sqrt{s}=157.5$, 162.5, 240 and 365 GeV at 95% CL in the unit of GeV^{-2} and $\Lambda=1$ TeV [12]. The combined limits, Belle II expected results [7] and the limits for $\sqrt{s}=1$ TeV considering the polarization effects [25] are also presented.

5 Conclusion

In the SM, neutrinos are massless and have no mixing with each other. However, several experiments have confirmed the existence of neutrino oscillations, which can come from the LFV interactions in the charged sector. In this study, we focus on the LFV $e^-e^+\to e^{\pm}\tau^{\mp}$ process in an effective four-Fermi framework to check the potential of FCC-ee and estimate its sensitivity to the LFV couplings. Hard events for the LFV signal and main SM backgrounds are generated using `MadGraph5_aMC@NLO` package including the ISR effects at $\sqrt{s}=157.5$, 162.5, 240 and 365 GeV. Then events are passed through `Pythia` for showering, hadronization and decay of unstable particles. A realistic detector effect is simulated via `Delphes` considering ILD-like detector card. The τ-tagging method is used to select the τs which decay hadronically. To improve the sensitivity of signal area with respect to the background events, in addition to the pre-selection cuts, the optimized cuts are applied on the electron energy, and on the invariant mass of the leptons in the final state. The limits on the scalar and vector-type LFV couplings are estimated at the four FCC-ee benchmarks at 95% CL. Furthermore, a statistical combination of the individual limits for the four center-of-mass energies is performed, and it is shown that the combined results are contesting to the Belle II future prospects with 50 ab^{-1} data.

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