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

S. M. Etesami [1], R. Jafari[2,3,1,⋆], M. Mohammadi Najafabadi[1] and S. Tizchang [4,1]

[1] School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran.
[2] Department of Physics, University of Tehran, North Karegar Avenue, Tehran 14395-547, Iran.
[3] Department of physics, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran.
[4] Department of Physics, Faculty of Science, Arak University, Arak, 384817758, Iran.
⋆ jafari@ipm.ir

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Abstract

In the Standard Model framework, lepton flavor is conserved in interactions. However, it can be violated in certain scenarios beyond the Standard Model. 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 $157.5, 162.5, 240$, **and** 365 **GeV that have been proposed for the FCC-ee, a Standard Model Effective Field Theory (SMEFT) is used. The main sources of background are accounted for, and the study incorporates realistic detector effects. To enhance the results, we combine the individual constraints obtained at each center-of-mass energy. We show that the combined limits improve the sensitivity to lepton flavor violation couplings by a factor of approximately three compared to the individual results and are competitive with the Belle II prospects.**

Contents

1 Introduction

The Standard Model (SM) of particle physics indicates that the charged lepton's flavor remains conserved in tree-level interactions, as neutrinos are massless and their oscillations are forbidden within the SM [1]. However, various experimental observations confirm that neutrinos oscillate between different flavors. These oscillations imply that neutrinos must have mass [2].

Charged lepton flavor violation (LFV) can occur through neutrino oscillations via loop corrections, but it is highly suppressed due to the tiny neutrino masses compared to the mass of the (W) boson. While the exact nature of new physics explaining neutrino oscillations remains unclear, several extensions of the SM [4–6] predict significant enhancements in LFV interactions that can be probed experimentally. Thus, the observation of any charged LFV would be a strong indication of the existence of new physics beyond the Standard Model (BSM).

Recent LFV searches by the Belle II experiment provide stringent upper bounds on the branching fraction of tau decays to three electrons, on the order of (10^{-10}) [7]. Measurements by BaBar and Belle have set the strongest limits on this decay, with bounds on the order of (10^{-8}) [8, 9]. Furthermore, LFV in the charged sector is highly sensitive to new particles that could potentially be produced in future high-energy colliders [10, 11].

This proceeding provides a brief review of LFV production of $(e\tau)$ in (e^+e^-) collisions at the future circular collider (FCC-ee). For a detailed description, readers are encouraged to refer to Ref. [12].

Several other LFV interactions, such as LFV production through the Higgs and (Z) bosons, as well as LFV decays of Higgs and scalar particles, have been considered in various studies [13–20]. LFV in the muon sector has also been studied in the literature [21–23]. In Ref. [25], the LFV $(e^+e^-e^\pm\tau^\mp)$ vertex was considered as a contact interaction, including two background sources: $(e\tau\nu_e\nu_\tau)$ and $(\tau^+\tau^-)$, at $(\sqrt{s} = 250, 500, 1000, 3000)$ GeV. Furthermore, a similar interaction was studied in Ref. [25], considering the effects of electron and positron beam polarization at $(\sqrt{s} = 250, 500, 1000)$ GeV, with only the $(e^\pm\tau^\mp\nu_e\nu_\tau)$ process 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 explore the potential of the future electron-positron circular collider (FCC-ee) to probe LFV couplings. Data is generated at four center-of-mass energies of FCC-ee: (157.5), (162.5), (240), and (365) GeV, with integrated luminosities of (5), (5), (5), and (1.5) ab$(^{-1})$, respectively. The main background sources $(\tau^+\tau^-)$, $(e^\pm\tau^\mp\nu_e\nu_\tau)$, $(\ell^\pm\ell^\mp\ell'^\pm\ell'^\mp)$, $(\ell^\pm\ell^\mp jj, \ell\nu jj, (\ell = e, \mu, \tau))$, and (jj) (where (j) denotes a jet) are included in the study. A realistic simulation of detector effects is performed using the `Delphes` package, and initial state radiation (ISR) effects are also considered in the data simulation. Finally, a statistical combination of the four FCC-ee benchmarks is performed, leading to a significant improvement over the individual results.

In the following, Section 2 presents the theoretical framework, describing the effective theory for the LFV interaction, operators, and couplings. Section 3 outlines the methodology for data simulation and the analysis details. Section 4 is dedicated to the individual and combined results for the LFV couplings. Finally, the conclusion is presented 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]:

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

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:

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

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

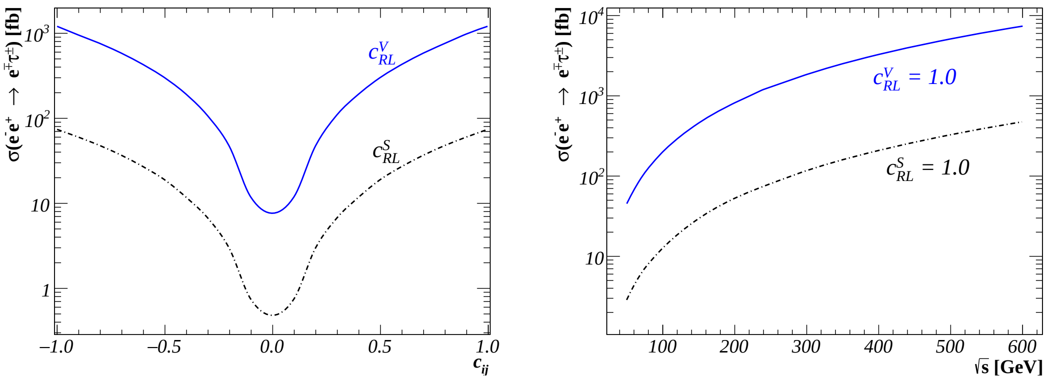

Figure 1: Cross section of $e\tau$ production at e^+e^- collision (**Left**) as a function of center-of-mass energy for $c^S_{RL} = 1.0$ and $c^V_{RL} = 1.0$ signals scenarios, (**Right**) as a function of c^V_{RL} and c^S_{RL} at $\sqrt{s}$ =240 GeV.

analysis, are as follows

$$e^-e^+ \to e^\pm\tau^\mp\nu\bar{\nu}, \qquad e^-e^+ \to \ell^\pm\nu jj, \qquad e^-e^+ \to \tau^+\tau^-,$$
$$e^-e^+ \to \ell^\pm\ell^\mp\ell'^\pm\ell'^\mp, \qquad e^-e^+ \to jj, \qquad e^-e^+ \to \ell^\pm\ell^\mp jj,$$

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 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.

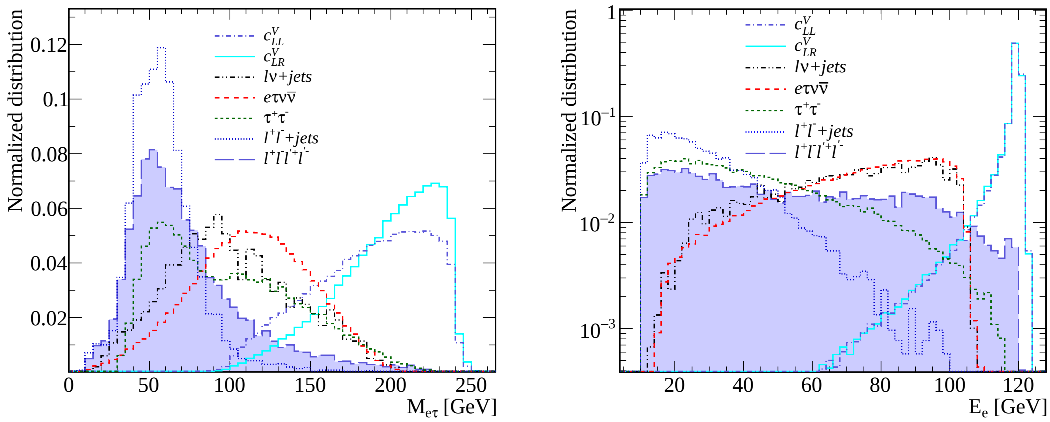

Figure 2: The two final state leptons invariant mass (left), and the energy of electron candidate (right) distributions are presented for $c^V_{LR} = 0.1$ and $c^V_{LR} = 0.1$ signal scenarios, at $\sqrt{s} = 240$ GeV [12].

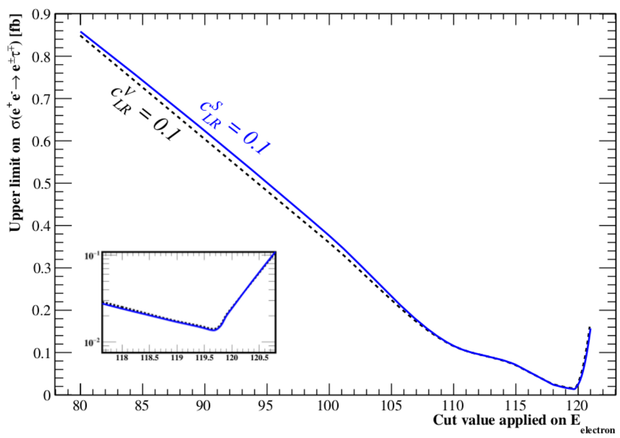

Figure 3: The upper limit over the signal cross section versus the value of cut applying on the energy of final state electron, at $\sqrt{s} = 240$ GeV. The blue solid line shows $c^S_{LR} = 0.1$, and the black dashed shows $c^V_{LR} = 0.1$ signal scenario.

$\sqrt{s}$ [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].

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 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 Standard Model (SM), neutrinos are massless and do not mix with each other. However, several experiments have confirmed the existence of neutrino oscillations, which can result from LFV interactions in the charged sector. In this study, we focus on the LFV ($e^-e^+\to e^{\pm}\tau^{\mp}$) process within an effective four-Fermi framework to explore the potential of the FCC-ee and estimate its sensitivity to LFV couplings. Hard events for the LFV signal and the main SM backgrounds are generated using the `MadGraph5_aMC@NLO` package, including ISR effects at ($\sqrt{s}=157.5, 162.5, 240$, and 365 GeV. The events are then passed through `Pythia` for showering, hadronization, and decay of unstable particles. A realistic detector effect is simulated using the Delphes package, considering an ILD-like detector card. The (τ)-tagging method is applied to select (τ)-leptons that decay hadronically.

To improve the sensitivity of the signal region with respect to the background events, optimized cuts are applied in addition to pre-selection cuts, targeting the electron energy and the invariant mass of the leptons in the final state. Limits on the scalar and vector-type LFV couplings are estimated at the four FCC-ee benchmarks at 95% confidence level (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 competitive with the Belle II future prospects with 50 ab^{-1} of data.

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