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Search for Charged Lepton Flavor Violation at future lepton colliders with Z′ model

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Charged lepton flavor violation (CLFV) poses a compelling indicator of potential physics beyond the standard model by violating the conservation of lepton flavor. A model is utilized featuring an additional Z′ gauge boson to conduct an extensive comparative analysis of CLFV investigations at future lepton collider facilities, including a 240 GeV electron-positron collider and a muon collider at the TeV scale. Employing fast Monte-Carlo simulations and data analyses, we evaluate the detection prospects for Z′-induced CLFV interactions, specifically targeting the $e\mu$, $e\tau$, and $\mu\tau$ couplings. The results are compared with the existing and anticipated limits determined by low-energy experiments and the high-energy pursuits at the LHC. The sensitivity on the τ related CLFV coupling strength can be significantly improved in comparison to the current best constraints and prospect constraints.

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1. Introduction

The Standard Model (SM) has demonstrated remarkable success over the past decades, particularly following the discovery of the Higgs boson, the final piece of the puzzle. In the SM, lepton flavor is conserved during interactions, which prohibits CLFV at tree-level and one-loop level. However, the discovery of neutrino mass and neutrino oscillations enables loop-level CLFV within the SM, although highly suppressed by a factor of $(\Delta m_{ij}/M_W)^4$ due to the tiny masses of neutrinos [1].

In the coming decades, the LHC and High-Luminosity LHC (HL-LHC), along with future collider designs, will further explore the SM and search for Beyond the Standard Model (BSM) physics. The proposed machines, mainly lepton colliders, aim for precise Higgs boson measurements. Key proposals include linear and circular electron-positron colliders [2–4] and muon colliders [5]. This study investigates Charged Lepton Flavor Violation (CLFV) at these future colliders, building on existing literature [6–8].

Various BSM models enhance CLFV effects to detectable levels, including supersymmetry [9], heavy Z′ bosons [10–12], and scalar neutrinos in R-parity-violating scenarios [16]. The Z′ boson, resulting from a new $U(1)$ gauge symmetry, can interact with W bosons [15].

This study assumes a Z′ with quark couplings similar to the SM Z [17–19] and focuses on its interactions with charged leptons. Only one CLFV coupling $\lambda_{ij} (i \neq j)$ is assumed to be non-zero at any time for the purpose of setting the upper limits, while the diagonal couplings $\lambda_{ll} (l = e, \mu, \tau)$ are always set as 1. The coupling matrix is defined as:

$$\lambda_{ij} = \begin{pmatrix} \lambda_{ee} & \lambda_{e\mu} & \lambda_{e\tau} \\ \lambda_{\mu e} & \lambda_{\mu\mu} & \lambda_{\mu\tau} \\ \lambda_{\tau e} & \lambda_{\tau\mu} & \lambda_{\tau\tau} \end{pmatrix}. \tag{1}$$

We also compare our results with constraints from low-energy muon experiments. The CLFV coupling $\lambda_{e\mu}$ can be derived from the branching ratio R for $\mu - e$ conversion [21]:

$$\begin{aligned} \lambda_{e\mu}^2 =& \frac{2\pi^2 \Gamma_{\text{capture}} Z R}{G_F^2 \alpha^3 m_\mu^5 Z_{eff}^4 |F(q)|^2} \frac{M_{Z'}^4}{M_Z^4} \times \frac{1}{s_W^4 + (s_W^2 - \frac{1}{2})^2} \\ & \times \frac{1}{[(2Z+N)(\frac{1}{2} - \frac{4}{3}s_W^2) + (Z+2N)(-\frac{1}{2} + \frac{2}{3}s_W^2)]^2}. \end{aligned} \tag{2}$$

Γ_{capture} is calculated by the muon captured lifetime τ on target, G_F is the Fermi constant, α is the fine structure constant, m_μ is the rest mass of muon, Z_{eff} and $F(q)$ are nuclear parameters [23], Z is the atomic number, N is the number of neutrons in the nucleus, and s_W is the sine of the weak mixing angle. The branching ratio R is normalized to the total nuclear muon capture rate Γ_{capture} measured experimentally, the limit R is taken from PDG corresponding to the experiment using ${}^{197}_{79}$Au or ${}^{48}_{22}$Ti as the target [22].

Using Equation 2, we can obtain the constraints on the CLFV coupling from $\mu - e$ conversion. Additional low energy limits, those from $\mu \to e\gamma$ and $\mu \to eee$, are taken from Ref. [24]. For comparison with the next generation $\mu - e$ conversion experiments, the prospect upper limit with $^{27}_{13}$Al target in Mu2e [26] or COMET [27] experiment is also considered.

Assuming that $\tau \to e\gamma$ is similar to $\mu \to e\gamma$, the same method is used to get the limits for τ channels, with the exception of substituting μ with τ and applying the approximation that $m_\tau \gg m_e$.

2. Sample and Analysis framework

The CLFV searches are performed at a 240 GeV circular electron positron collider (CEPC), and a 6 or 14 TeV muon collider in this paper. Potential signal processes include $ee \to e\mu$, $ee \to e\tau$, $\mu\mu \to e\mu$ and $\mu\mu \to \mu\tau$. Simulations are conducted for both colliders with specified collision energies and integrated luminosities.

Both signal and background events are generated using MadGraph5_aMC@NLO [28] (MG5aMC) version 3.1.1, followed by showering and hadronization with Pythia8 [29]. For CEPC, initial-state radiation effects are included [30]. Detector simulations employ Delphes [31] version 3.5 with default settings for the respective collider detectors.

Event selection criteria require exactly two leptons with $p_T > 10$ GeV and $|\eta| < 2.5$ while maintaining lepton flavor and charge conservation from the Z′ decay. The tracking efficiencies for μ and τ are specified, and various physical quantities are utilized to distinguish signal from background, optimizing invariant mass cuts to maximize sensitivity [32–34].

After selection, binned histograms of final state lepton p_T distributions are analyzed to establish upper limits on CLFV couplings. The analysis employs a per-event weight to account for cross-section differences and defines the test statistic Z for exclusion and discovery limits, following the methodology outlined in Equation 3.

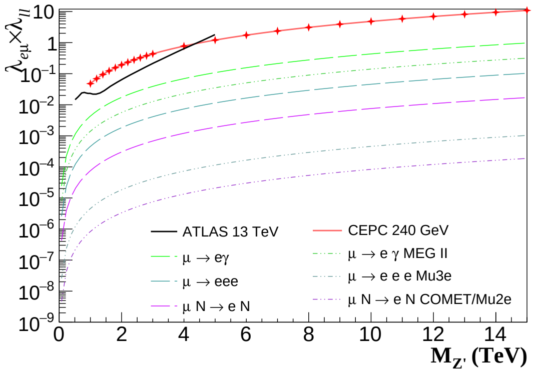
$$
\begin{aligned}
&Z = \sum_{i=1}^{bins} Z_i, \\
&\begin{cases} Z_i := 2\left[n_i - b_i + b_i \ln(b_i/n_i)\right] & 95\%\ \text{C.L. Exclusion} \\ Z_i := 2\left[b_i - n_i + n_i \ln(n_i/b_i)\right] & 5\sigma\ \text{Discovery}, \end{cases}
\end{aligned}
\tag{3}
$$

3. Results

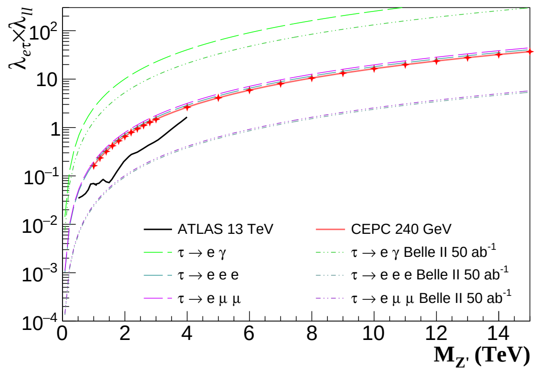
The exclusion limits at 95% confidence level (C.L.) from CEPC, ATLAS, and both current and upcoming low-energy μ and τ experiments are converted into coupling limits $\lambda_{e\mu} \times \lambda_{ll}$ and $\lambda_{e\tau} \times \lambda_{ll}$ using the formula in Ref. [24], the exclusion curves derived from present and future experimental constraints align closely with those observed in low-energy experiments, indicating similar sensitivities across different ranges of Z' masses, shown in Figure. 1a and 1b.

The muon collider, with its cleaner environment and higher center-of-mass energy, could outperform CEPC in CLFV searches. The exclusion limits for the processes $\mu\mu \to e\mu$ and $\mu\mu \to \mu\tau$ processes at 6 and 14 TeV muon collider are converted to coupling limits $\lambda_{e\mu} \times \lambda_{ll}$ and $\lambda_{\mu\tau} \times \lambda_{ll}$ shown in Figure. 1c and 1d.

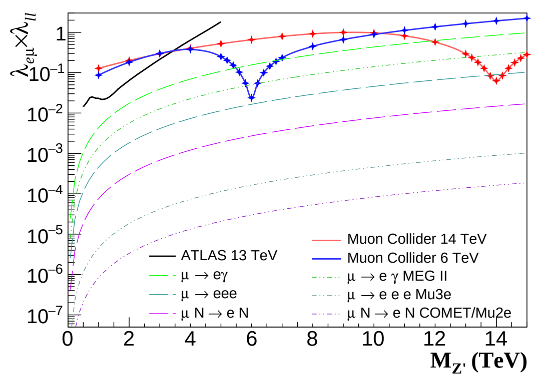
For the $\mu\tau$ channel, this study provides the most stringent limits, especially when the Z′ mass exceeds 10 TeV, where the 14 TeV muon collider surpasses other existing constraints. Notably, the



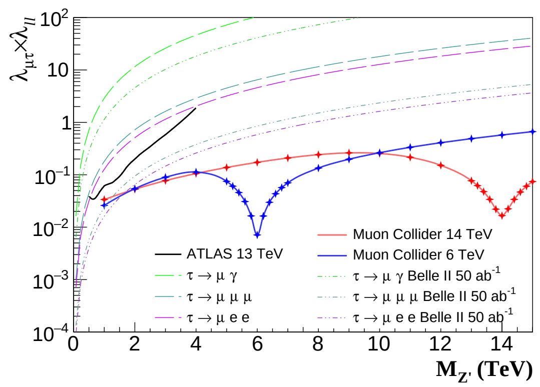
(a)



(b)



(c)



(d)

Figure 1: 95% C.L. exclusion lines of CLFV on the couplings $\lambda_{e\mu}$ (a) and $\lambda_{e\tau}$ (b) products the diagonal coupling λ_{ll} at CEPC (red line), on the couplings $\lambda_{e\mu}$ (c) and $\lambda_{\mu\tau}$ (d) products the diagonal coupling λ_{ll} at a 6 TeV (red line) and 14 TeV (blue line) muon collider and ATLAS experiment (black line). The curves are plotted as functions of $M_{Z'}$ from the cross-section times branching ratio limits. The exclusion lines with the current low-energy (dashed lines) and future experiments (dash-dotted lines) are also plotted. [32]

6 TeV muon collider offers the best constraints on $\mu\tau$ coupling, achieving a limit near 10^{-3} when the Z′ is 6 TeV, outperforming all current and most projected CLFV experimental limits.

4. Summary

This study conducts a comparative analysis of CLFV searches using a typical extra Z′ boson model at several future colliders, including a 240 GeV electron-positron collider and 6 and 14 TeV scale muon colliders. Upper limits at the 95% confidence level are set across different Z′ mass ranges. Our findings indicate that future colliders can greatly enhance the sensitivity to τ-related CLFV couplings, surpassing current best limits. For the $\mu\tau$ channel at higher Z′ masses, the muon collider constraints outperform even the prospect limits, highlighting the advantages of future lepton colliders in CLFV searches.

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