

## Introduction

- **Lepton flavor violation (LFV)** is absent in the Standard Model (SM).
- But, neutrino oscillation indicates flavor violation in the neutral sector.
- Experimental searches for **charged lepton flavor violation (cLFV)**:
  - $\mu \rightarrow e\gamma$  (MEG, MEG II),  $\mu \rightarrow 3e$  (Mu3e),  $\mu \rightarrow e$  (COMET).
  - $\tau \rightarrow e\gamma$ ,  $\tau \rightarrow 3e$ ,  $\tau \rightarrow \ell\pi/\ell\rho/\ell\phi$  (Belle, BaBar, Belle II).
  - $Z \rightarrow e\mu/e\tau/\mu\tau$  (LEP, LEP II, LHC),  $h \rightarrow e\mu/e\tau/\mu\tau$  (LHC).
- However, there hasn't been any significant evidence of cLFV till date.

**We investigate cLFV induced by flavor non-diagonal SMEFT operators via  $\ell^+\ell^- \rightarrow \ell^\pm\tau^\mp$  production at future high-energy  $e^+e^-$  and  $\mu^+\mu^-$  colliders.**

### Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i C_i \mathcal{O}_i + \sum_j \sum_{p,r} [C_j]_{pr} [\mathcal{O}_j]_{pr} + \sum_k \sum_{p,r,s,t} [C_k]_{prst} [\mathcal{O}_k]_{prst}$$

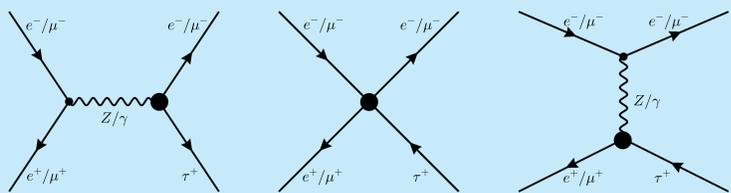
- $\mathcal{O}$ : Operators constructed out of SM fields.  $C$ : **Wilson's coefficients (WCs)**.
- Flavor indices ( $p, r, s, t$ ). Non-diagonal indices quantify flavor violating effects.

## Framework

- List of SMEFT operators relevant for cLFV studies at  $e^+e^-/\mu^+\mu^-$  colliders:

Operators: Dipole ( $\Psi^2 H X$ )	Operator: Four-Fermion ( $\Psi^4$ , LLLL)
$[\mathcal{O}_{eW}]_{pr}$ ( $\bar{l}_p \tau^a \sigma^{\alpha\beta} e_r$ ) $H W_{\alpha\beta}^a$	$[\mathcal{O}_{ll}]_{prst}$ ( $\bar{l}_p \gamma^\alpha l_r$ ) ( $\bar{l}_s \gamma_\alpha l_t$ )
$[\mathcal{O}_{eB}]_{pr}$ ( $\bar{l}_p \sigma^{\alpha\beta} e_r$ ) $H B_{\alpha\beta}$	Operator: Four-Fermion ( $\Psi^4$ , LLRR)
Operators: Current ( $\Psi^2 H^2 D$ )	$[\mathcal{O}_{le}]_{prst}$ ( $\bar{l}_p \gamma^\alpha l_r$ ) ( $\bar{e}_s \gamma_\alpha e_t$ )
$[\mathcal{O}_{Hl}]_{pr}$ ( $\bar{l}_p \gamma^\alpha l_r$ ) ( $H^\dagger i \overleftrightarrow{D}_\alpha H$ )	Operator: Four-Fermion ( $\Psi^4$ , RRRR)
$[\mathcal{O}_{He}]_{pr}$ ( $\bar{e}_p \gamma^\alpha e_r$ ) ( $H^\dagger i \overleftrightarrow{D}_\alpha H$ )	$[\mathcal{O}_{ee}]_{prst}$ ( $\bar{e}_p \gamma^\alpha e_r$ ) ( $\bar{e}_s \gamma_\alpha e_t$ )

- We study LFV processes:  $e^+e^- \rightarrow e^\pm\tau^\mp/\mu^+\mu^- \rightarrow \mu^\pm\tau^\mp$ , where one of the initial state remains intact in the final state. If dipole/current operators are considered, in addition to  $s$ -channel, a  $t$ -channel diagram (shown in Feynmann diagram below), which is not suppressed at higher energies, distinctive from LFV processes like  $e^+e^- \rightarrow \mu^\pm\tau^\mp/\mu^+\mu^- \rightarrow e^\pm\tau^\mp$ .



- Simplified WCs to reduce parameters, while retaining operator structures:

$$h_{\ell\tau} = [C_{Hl}]_{\ell\tau} = [C_{He}]_{\ell\tau} \quad d_{\ell\tau} = [C_{eW}]_{\ell\tau} = [C_{eB}]_{\ell\tau}$$

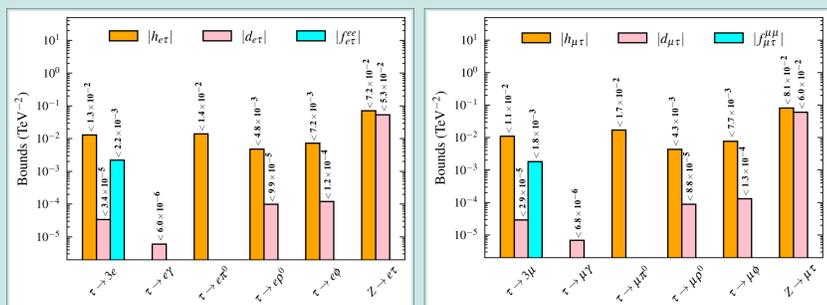
$$f_{\ell\tau}^{\ell\ell} = [C_{ll}]_{\ell\tau\ell\tau} = [C_{le}]_{\ell\tau\ell\tau} = [C_{ee}]_{\ell\tau\ell\tau} = [C_{ll}]_{\ell\tau\ell\ell} = [C_{le}]_{\ell\tau\ell\ell} = [C_{ee}]_{\ell\tau\ell\ell}$$

## Constraints

- Stringent constraints on cLFV branching ratios of  $\tau/Z$  from experiments:

$$\begin{aligned} \mathcal{B}(\tau \rightarrow 3e) &< 2.7 \times 10^{-8} & \mathcal{B}(\tau \rightarrow 3\mu) &< 1.9 \times 10^{-8} \\ \mathcal{B}(\tau \rightarrow e\gamma) &< 3.3 \times 10^{-8} & \mathcal{B}(\tau \rightarrow \mu\gamma) &< 4.2 \times 10^{-8} \\ \mathcal{B}(\tau \rightarrow e\pi^0) &< 8.0 \times 10^{-8} & \mathcal{B}(\tau \rightarrow \mu\pi^0) &< 1.1 \times 10^{-7} \\ \mathcal{B}(\tau \rightarrow e\rho^0) &< 2.2 \times 10^{-8} & \mathcal{B}(\tau \rightarrow \mu\rho^0) &< 1.7 \times 10^{-8} \\ \mathcal{B}(\tau \rightarrow e\phi) &< 2.0 \times 10^{-8} & \mathcal{B}(\tau \rightarrow \mu\phi) &< 2.3 \times 10^{-8} \\ \mathcal{B}(Z \rightarrow e\tau) &< 5.0 \times 10^{-6} & \mathcal{B}(Z \rightarrow \mu\tau) &< 6.5 \times 10^{-6} \end{aligned}$$

- Constraints on cLFV WCs translated from different  $\tau/Z$  decay branchings:



- Constraints on dipole WCs are too stringent to be probed even at higher energies. Hence, we only study four-fermion and current interactions.

## Analysis

- We organize our analysis into two complementary lepton collider setups:

Processes	$e^+e^- \rightarrow e^\pm\tau^\mp$	$\mu^+\mu^- \rightarrow \mu^\pm\tau^\mp$
Collider Setup, ( $\sqrt{s}$ )	CLIC ( $\sqrt{s} = 3$ TeV)	$\mu$ C3 ( $\sqrt{s} = 3$ TeV)
Luminosity, ( $\mathcal{L}_{\text{int}}$ )	$1 \text{ ab}^{-1}$	$1, 10 \text{ ab}^{-1}$
Polarization, ( $P_{\ell^+}, P_{\ell^-}$ )	Unpolarized, (0, $\pm 80\%$ )	Unpolarized

- Polarized ( $\pm$ ) setup:  $0.5 \text{ ab}^{-1}$  with (0,  $+80\%$ ), and  $0.5 \text{ ab}^{-1}$  with (0,  $-80\%$ ).
- We study the effect of both luminosity and polarization on sensitivities.
- Signal:  $\ell(\mu/e)\tau_h$ , where,  $\tau_h$ : hadronic  $\tau$  jet. SM backgrounds:  $W^+W^-$ ,  $\tau^+\tau^-$ .

$$\text{Cuts: } M_{\ell\tau} > 2 \text{ TeV}, \quad E_{\text{miss}} < 1 \text{ TeV.}$$

- Cut efficiency ( $\epsilon$ ): Signal  $\approx 75\%$ ; Background:  $W^+W^- \approx 25\%$ ,  $\tau^+\tau^- \approx 12\%$ .

## Sensitivity

### Optimal Observable Technique (OOT)

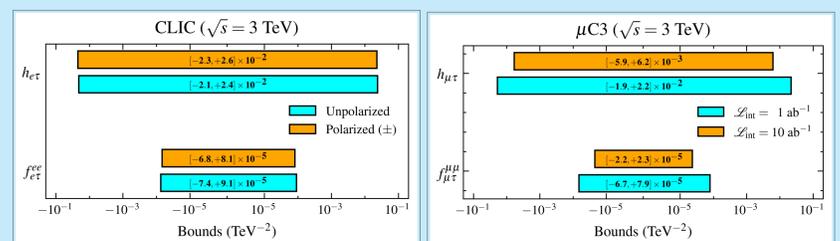
- Say, observable:  $\mathcal{O}$ , function of WCs:  $\{f, h\}$  and phase space variable,  $\cos\theta$ .

$$\mathcal{O}(f, h, \cos\theta) = \frac{d\sigma(f, h, \cos\theta)}{d\cos\theta} = \sum_i g_i(f, h) \mathcal{O}_i(\cos\theta)$$

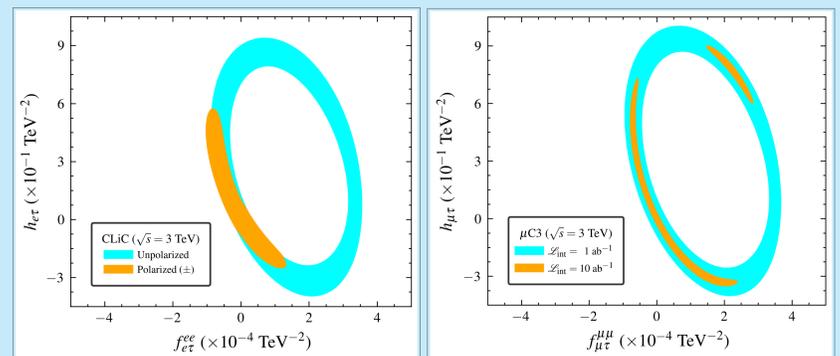
$$\chi_{\text{OOT}}^2 = \mathcal{L}_{\text{int}} \sum_{ij} \delta g_i \delta g_j \int \frac{\mathcal{O}_i(\cos\theta) \mathcal{O}_j(\cos\theta)}{\mathcal{O}(0, 0, \cos\theta)} d(\cos\theta)$$

$$g_i(f, h) = \{g_0, g_1, g_2\}, \quad \mathcal{O}_i(\cos\theta) = \{1, \cos\theta, \cos^2\theta\}$$

- 95% C.L. sensitivity intervals are shown below for different collider setups:



- For  $f$ , sensitivities improve by more than an order of magnitude over  $\tau$  decay. For  $h$ , the sensitivities are comparable to bounds from  $\tau$  decay.



- Polarization  $\rightarrow$  breaks degeneracy. Luminosity  $\rightarrow$  improves sensitivity.

## Conclusion

**Future lepton colliders can improve four-fermion operator sensitivities by over an order of magnitude beyond current bounds from  $\tau$  decay, while the sensitivities of the current operators remain near existing limits, highlighting the strong cLFV reach of future lepton colliders.**

- [1] S. Navas et al. [Particle Data Group [Review]], Phys. Rev. D **110**, no.3, 030001 (2024) doi:10.1103/PhysRevD.110.030001.
- [2] S. Jahedi and A. Sarkar, Phys. Rev. D **110**, no.9, 9 (2024) doi:10.1103/PhysRevD.110.095021 [arXiv:2408.00190 [hep-ph]].
- [3] W. Altmannshofer, P. Munbodh and T. Oh, JHEP **08**, 026 (2023) doi:10.1007/JHEP08(2023)026 [arXiv:2305.03869 [hep-ph]].