

Charged Lepton Flavor Violation (LFV)

at future circular e^+e^- and linear colliders

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UC SANTA CRUZ

Motivation and Outline

Clean probe of BSM physics.

Flavor oscillations already occur in the neutrino/quark sector.

Aim:

Study process $e^+e^- \rightarrow \tau\mu$ in the Standard Model Effective Field Theory (SMEFT) at FCC-ee, CEPC, ILC and CLIC.

Discuss the constraints we obtain on the SMEFT coefficients.

Compare against constraints from low-energy tau decays.

B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek arXiv:1008.4884

suppressed by New Physics

scale

Wilson coefficients

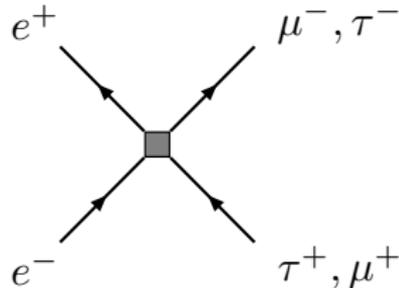
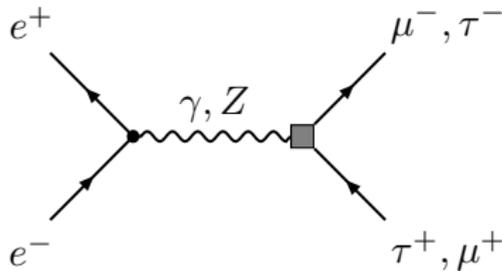
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)}$$

New Physics (NP) \gtrsim TeV scale.

EFT \Rightarrow Model-independent parametrization

59 $O_i^{(6)}$ of which only a few can contribute to $e^+e^- \rightarrow \tau\mu$ at tree-level.

Flavor-violating operators



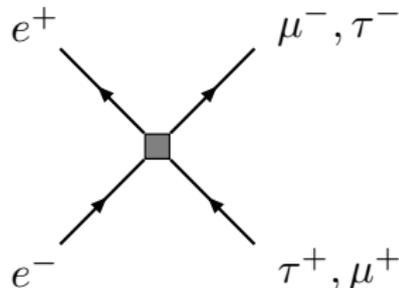
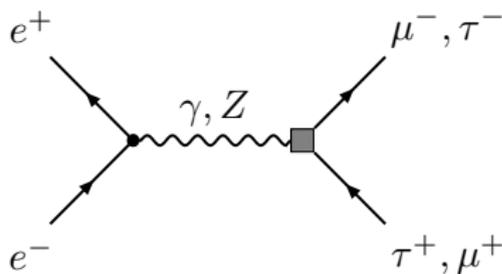
Dipole	Higgs-current	4-fermion
$(C_\gamma^{LR})_{\mu\tau} \frac{1}{\sqrt{2}} \frac{v}{\Lambda^2} (\bar{\mu}\sigma^{\alpha\beta} P_R\tau) F_{\alpha\beta}$	$(C_Z^{LL})_{\mu\tau} \frac{v^2}{2\Lambda^2} (\bar{\mu}\gamma^\alpha P_L\tau) \frac{g}{c_W} Z_\alpha$	$(C_V^{LL})_{\mu\tau} \frac{1}{\Lambda^2} (\bar{e}\gamma_\alpha P_L e) (\bar{\mu}\gamma^\alpha P_L\tau)$
$(C_Z^{LR})_{\mu\tau} \frac{1}{\sqrt{2}} \frac{v}{\Lambda^2} (\bar{\mu}\sigma^{\alpha\beta} P_R\tau) Z_{\alpha\beta}$	$(C_Z^{RR})_{\mu\tau} \frac{v^2}{2\Lambda^2} (\bar{\mu}\gamma^\alpha P_R\tau) \frac{g}{c_W} Z_\alpha$	$(C_V^{LR})_{\mu\tau} \frac{1}{\Lambda^2} (\bar{e}\gamma_\alpha P_L e) (\bar{\mu}\gamma^\alpha P_R\tau)$
...		...

Dipole : $C_\gamma^{LR}, C_\gamma^{RL}, C_Z^{LR}, C_Z^{RL}$

Higgs-current : C_Z^{LL}, C_Z^{RR}

4-fermion : $C_V^{LL}, C_V^{RR}, C_V^{RL}, C_V^{LR}, C_S^{LR}, C_S^{RL}$.

Flavor-violating operators



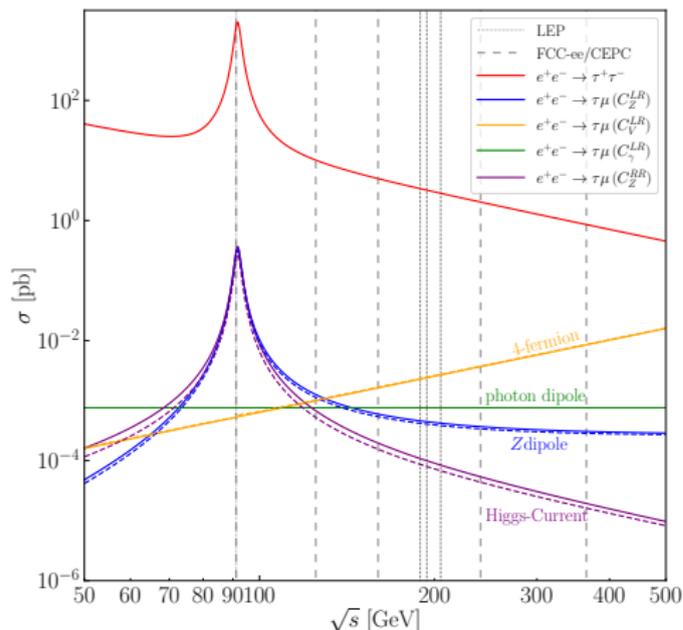
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$(C_Z^{LR})_{\mu\tau} \frac{1}{\sqrt{2}} \frac{v^2}{\Lambda^2} (\bar{\mu}\sigma^{\alpha\beta} P_R\tau) Z_{\alpha\beta}$	$(C_Z^{RR})_{\mu\tau} \frac{v^2}{2\Lambda^2} (\bar{\mu}\gamma^\alpha P_R\tau) \frac{g}{c_W} Z_\alpha$	$(C_V^{LR})_{\mu\tau} \frac{1}{\Lambda^2} (\bar{e}\gamma_\alpha P_L e) (\bar{\mu}\gamma^\alpha P_R\tau)$
...		...

Dipole : $C_\gamma^{LR}, C_\gamma^{RL}, C_Z^{LR}, C_Z^{RL}$

Higgs-current : C_Z^{LL}, C_Z^{RR} linear combinations of SMEFT coefficients.

4-fermion : $C_V^{LL}, C_V^{RR}, C_V^{RL}, C_V^{LR}, C_S^{LR}, C_S^{RL}$.

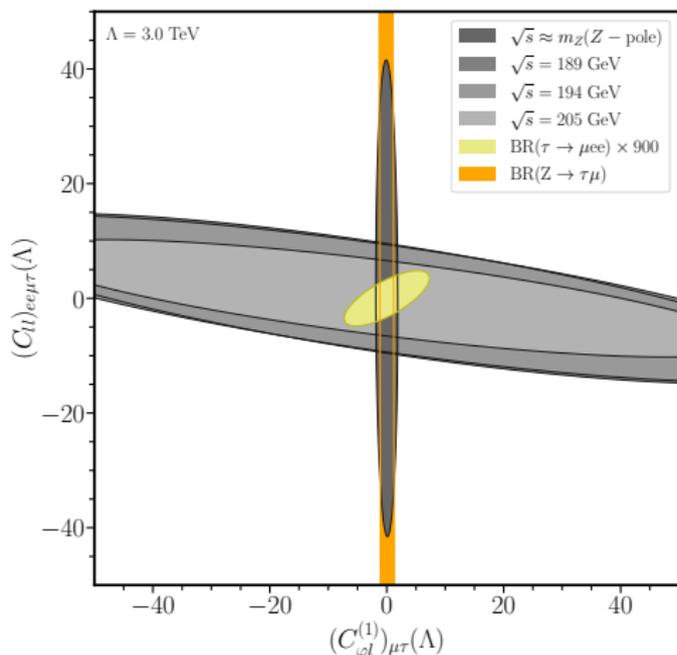
$e^+e^- \rightarrow \tau\mu$ cross-section



- 4-fermion operators scale with s .
- Dipole operators are constant.
- Higgs-current operators scale as $\frac{1}{s}$.
- Z boson propagator \Rightarrow resonance on Z -pole.

RGE effects (dashed) negligible for $\Lambda = 3$ TeV.

Existing constraints



$\text{BR}(\tau \rightarrow \mu e^+ e^-) < 1.8 \times 10^{-8}$
(BaBar, Belle).

$\text{BR}(Z \rightarrow \tau \mu) < 6.5 \times 10^{-6}$ (LHC).

LEP Opal analysis \rightarrow direct constraints on $\sigma(e^+ e^- \rightarrow \tau \mu)$ at high \sqrt{s} and constrains $N_{\tau \mu} < 9.9$ near Z-pole.

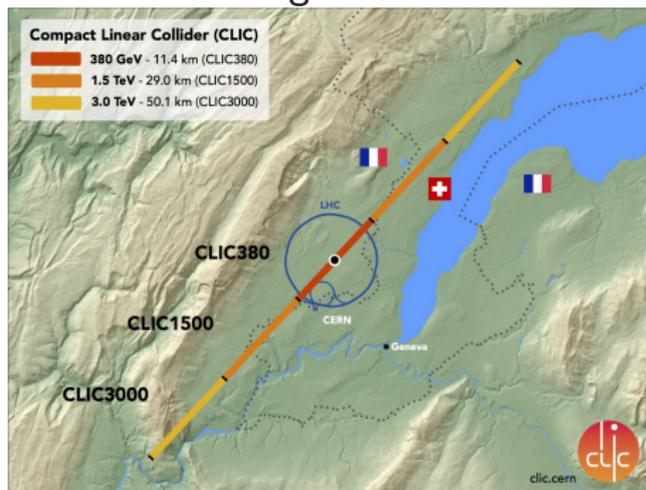
Prospects at future colliders

Future colliders will run at a greater range of energies and will collect larger luminosities. Linear colliders offer polarized beams.

To estimate the sensitivity, we need to assess the background.

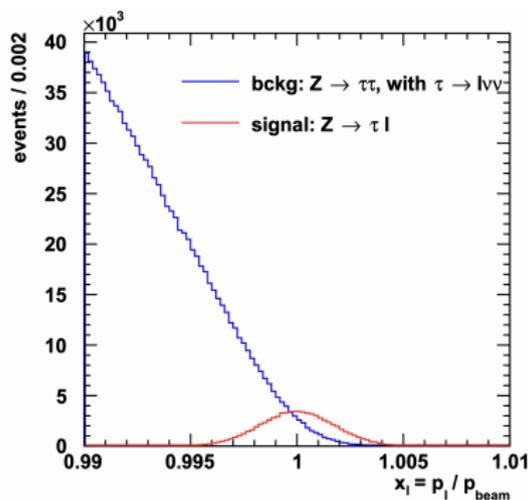


C. Panagiotis CERN

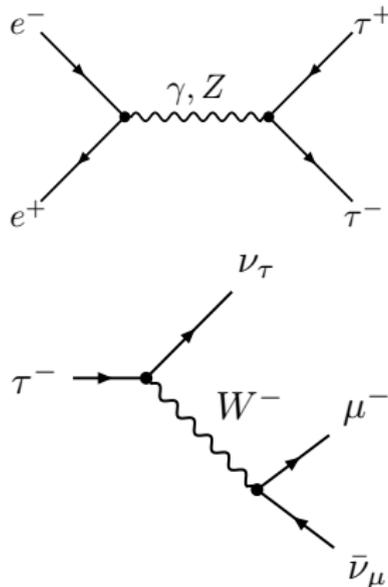


<https://cds.cern.ch/record/2297076>

Dominant background



M. Dam arXiv:1811.09408



Detector performance modeled with Gaussian smearing

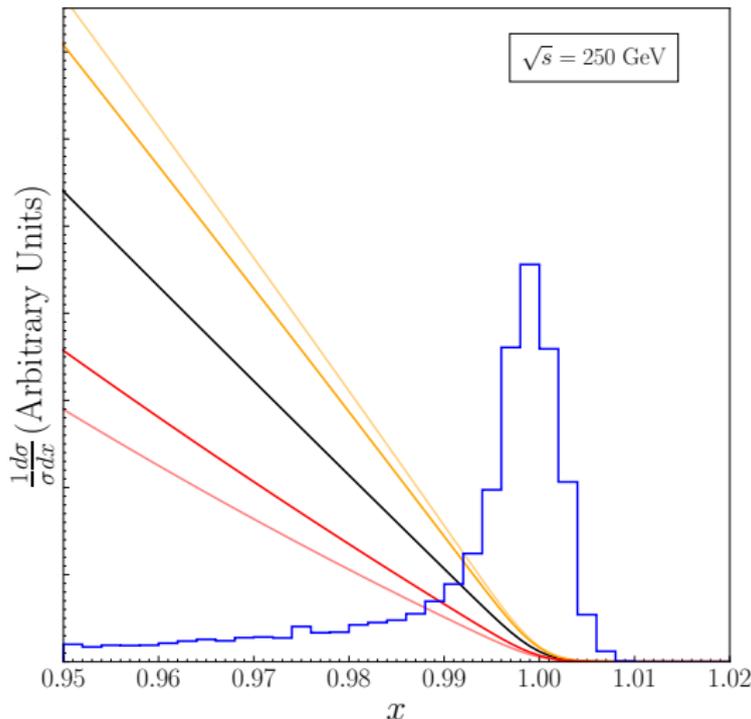
Signal : p_μ is a Gaussian centered around p_b (ISR gives a tail at low x).

Background : Small number of events with $p_\mu > p_b$.

Signal window : kinematic cut $x = \frac{p_\mu}{p_b} > 1$ on the selected events

Initial State Radiation (ISR)

e^+/e^- beams radiate photons before colliding. We provide analytic formula that convolute the effects of ISR, detector smearing and beam energy spread. In practice, we use Monte Carlo simulations.



Events

$$N_{\text{sig}} = \mathcal{L}_{\text{int}} \times \sigma(e^+e^- \rightarrow \tau\mu) \times \mathcal{B}(\tau \rightarrow \text{had})\epsilon_{\text{had}}\epsilon_{\text{sig}}^x\epsilon_{\text{sig}}^{\text{ang}},$$

$$N_{\text{bkg}} = \mathcal{L}_{\text{int}} \times \sigma(e^+e^- \rightarrow \tau^+\tau^-) \times 2 \times \mathcal{B}(\tau \rightarrow \text{had})\epsilon_{\text{had}} \times \mathcal{B}(\tau \rightarrow \mu\nu\nu)\epsilon_{\text{bkg}}^x\epsilon_{\text{bkg}}^{\text{ang}},$$

Tag side identifies clear SM tau decay:

$$\begin{aligned} \mathcal{B}(\tau \rightarrow \text{had})\epsilon_{\text{had}} &= \mathcal{B}(\tau \rightarrow 2\pi\nu)\epsilon_{2\pi} + \mathcal{B}(\tau^\pm \rightarrow \pi^\pm 2\pi^0\nu)\epsilon_{1\text{-prong}} \\ &\quad + \mathcal{B}(\tau^\pm \rightarrow \pi^\pm \pi^+ \pi^- \nu)\epsilon_{3\text{-prong}}, \end{aligned}$$

Sensitivity criterion:

$$N_{\text{sig}} \geq 2\sqrt{N_{\text{bkg}} + N_{\text{sig}}}.$$

Circular colliders

FCC-ee

\sqrt{s} [GeV]	\mathcal{L}_{int} [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\text{bkg}}^{x_c}$ [10^{-6}]	N_{bkg}	σ [ab]
91.2 (Z -pole)	75	0.93	1.35	1.55	9700	45
87.7 (off-peak)	37.5	0.93	1.33	1.46	520	21
93.9 (off-peak)	37.5	0.93	1.37	1.59	930	28
125 (H)	20	0.03	1.60	1.44	12	8
160 (WW)	12	0.93	1.89	2.44	6	10
240 (ZH)	5	1.17	2.60	4.39	2	18
365 ($t\bar{t}$)	1.5	1.32	3.78	8.61	0.5	50

CEPC

\sqrt{s} [GeV]	\mathcal{L}_{int} [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\text{bkg}}^{x_c}$ [10^{-6}]	N_{bkg}	σ [ab]
91.2 (Z -pole)	50	0.92	1.35	1.53	6400	55
87.7 (off-peak)	25	0.92	1.33	1.46	350	27
93.9 (off-peak)	25	0.92	1.37	1.59	620	35
160 (WW)	6	0.99	1.89	2.49	3	17
240 (ZH)	20	1.20	2.60	4.42	7	6.6
360 ($t\bar{t}$)	1	1.41	3.74	8.61	0.3	72

Linear colliders

ILC

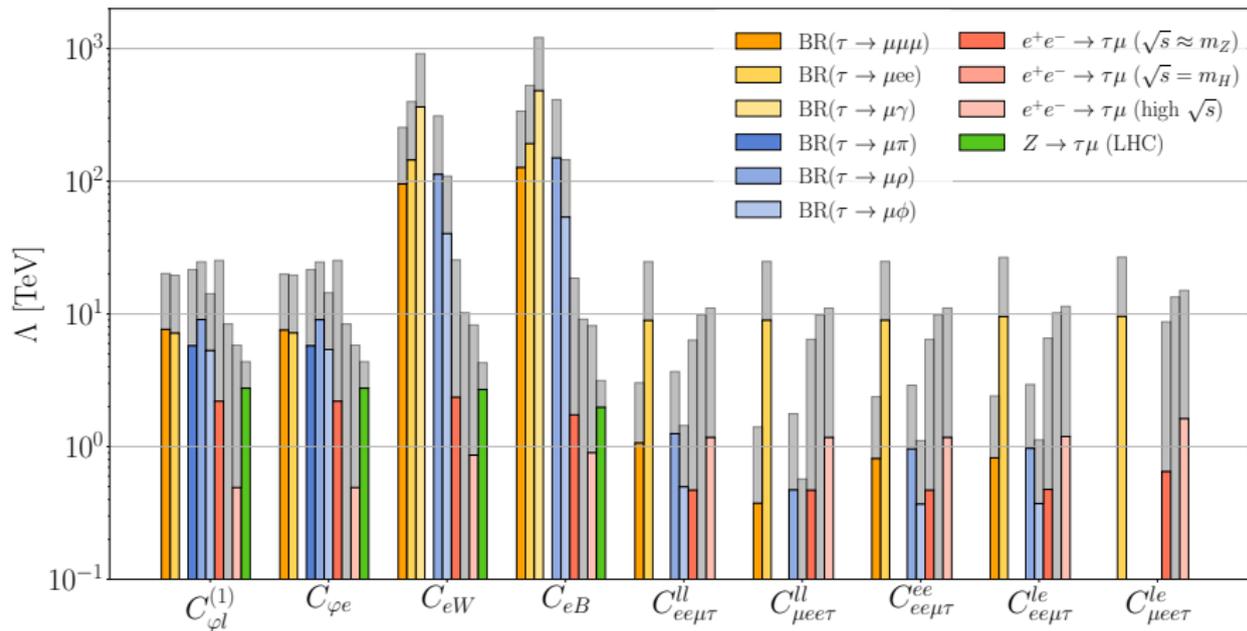
\sqrt{s} [GeV]	\mathcal{L}_{int} [ab^{-1}]	$\{\mathcal{L}_{\text{int}}^{(++)}, \mathcal{L}_{\text{int}}^{(+-)}, \mathcal{L}_{\text{int}}^{(-+)}, \mathcal{L}_{\text{int}}^{(--)}\} / \mathcal{L}_{\text{int}}$	$\{\sigma_{\text{sig}}^{(++)}, \sigma_{\text{sig}}^{(+-)}, \sigma_{\text{sig}}^{(-+)}, \sigma_{\text{sig}}^{(--)}\}$ [ab]
250	2	{5%, 45%, 45%, 5%}	{580, 82, 70, 590}
350	0.2	{5%, 68%, 22%, 5%}	{5400, 420, 1200, 5400}
500	4	{10%, 40%, 40%, 10%}	{140, 45, 37, 140}
1000	8	{10%, 40%, 40%, 10%}	{61, 23, 18, 65}

CLIC

\sqrt{s} [GeV]	\mathcal{L}_{int} [ab^{-1}]	$\{\mathcal{L}_{\text{int}}^{(+)}, \mathcal{L}_{\text{int}}^{(-)}\} / \mathcal{L}_{\text{int}}$	$\{\sigma_{\text{sig}}^{(+)}, \sigma_{\text{sig}}^{(-)}\}$ [ab]
380	1.5	{50%, 50%}	{66, 78}
1500	2.5	{20%, 80%}	{79, 27}
3000	5.0	{20%, 80%}	{39, 15}

Results I

W. Altmannshofer, P.M. and T. Oh [arXiv: 2305.03869](https://arxiv.org/abs/2305.03869) FCC-ee/CEPC

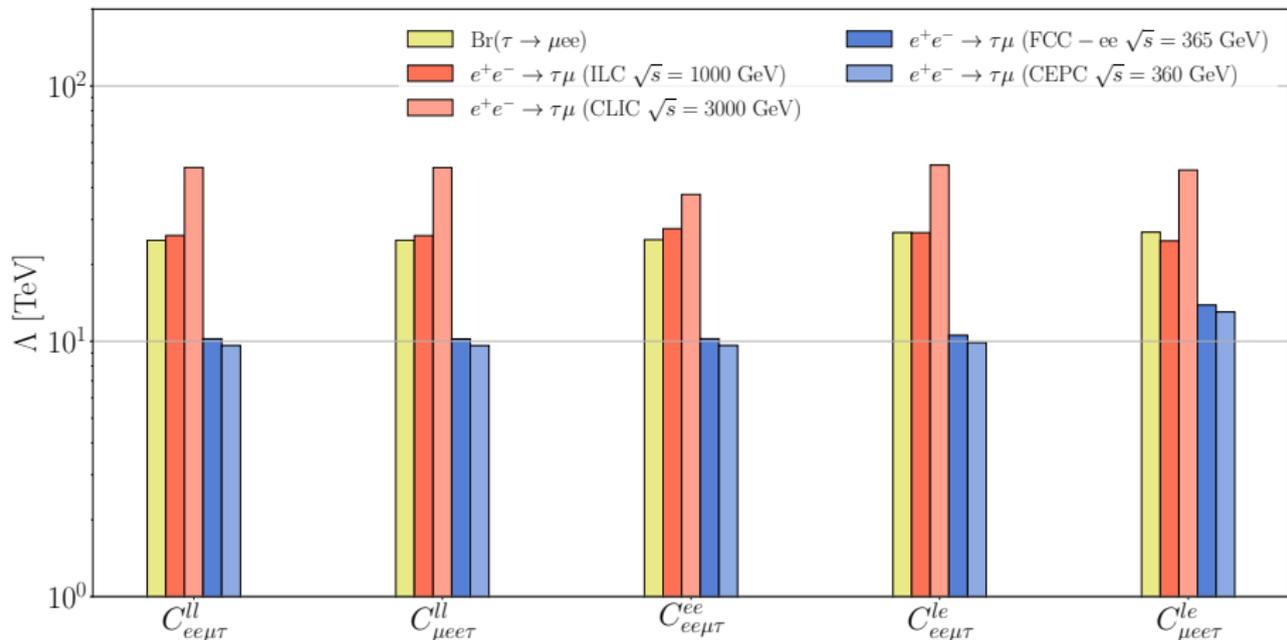


Setting $C_i = 1$ one at a time allows us to probe $\Lambda \sim O(20 \text{ TeV})$ in

$C_{\phi l}^{(1)}, C_{\phi e}$.

Results II

W. Altmannshofer, P.M. [arXiv: 2505.11653](https://arxiv.org/abs/2505.11653) ILC/CLIC

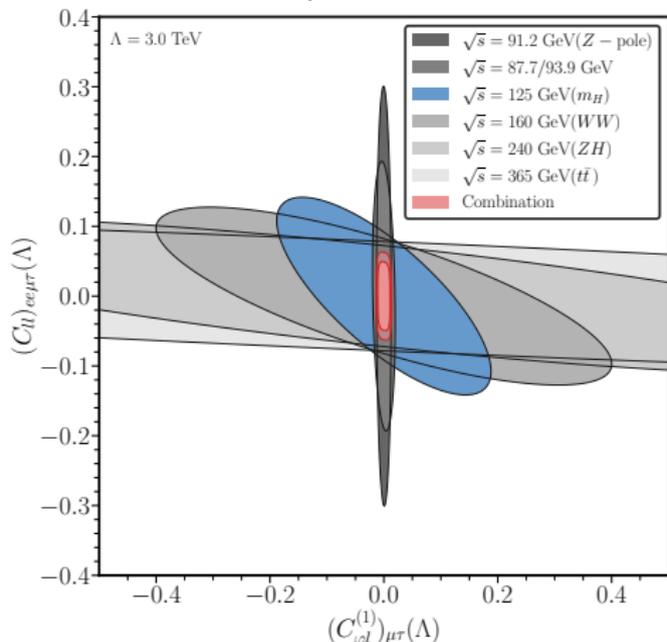
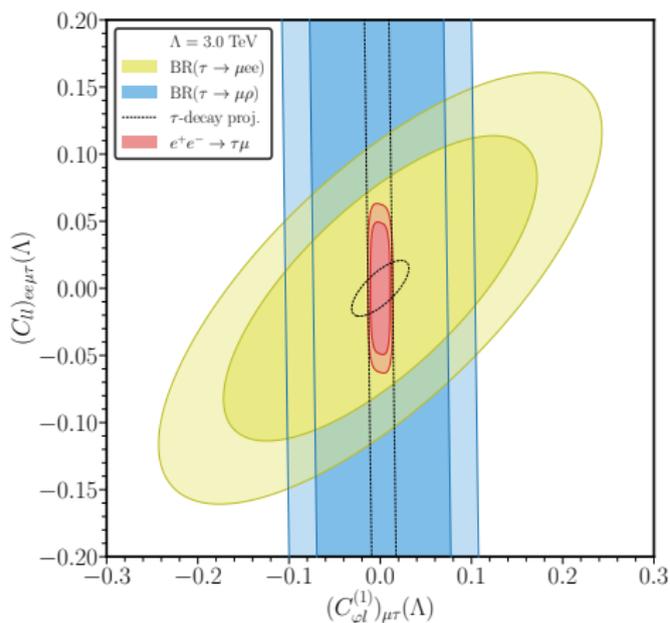


Setting $C_i = 1$ one at a time allows us to probe $\Lambda \sim O(50 \text{ TeV})$ at CLIC.

Results III

W. Altmannshofer, P.M. and T. Oh [arXiv: 2305.03869](https://arxiv.org/abs/2305.03869)

FCC-ee $\Lambda = 3$ TeV (CEPC plots look similar)

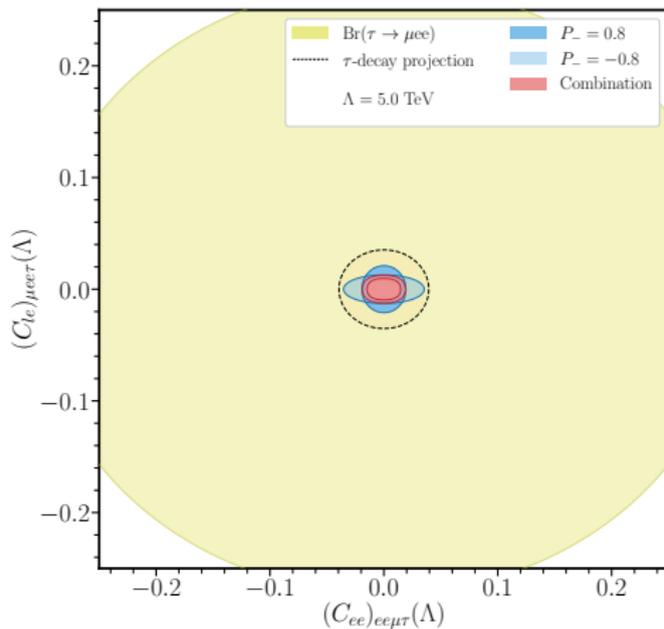
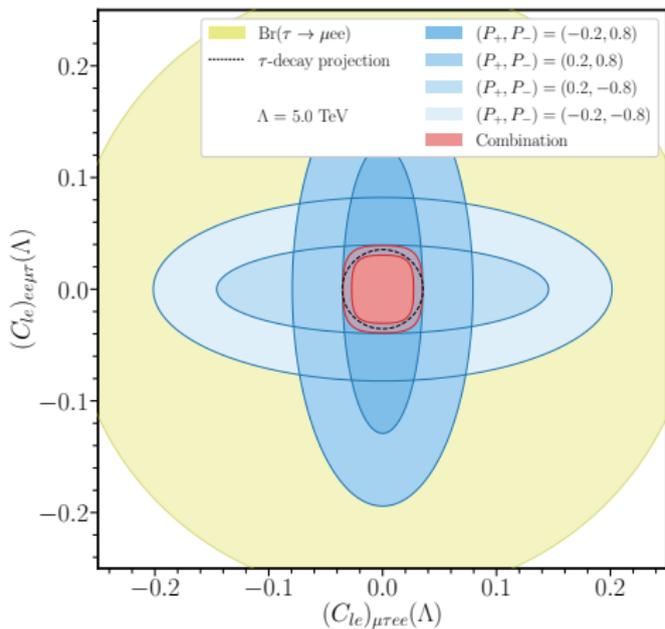


→ **Complementarity** between FCC-ee and the low-energy tau decays $\text{BR}(\tau \rightarrow \mu ee)$ and $\text{BR}(\tau \rightarrow \mu\rho)$.

Results IV

W. Altmannshofer and P.M. arXiv: 2505.11653

CLIC $\Lambda = 5$ TeV



→ **Complementarity** between different polarizations. CLIC surpasses Belle-II projections.

Summary

Future electron-positron colliders can provide complementary information in constraining New Physics energy scales/operators that would contribute to $e^+e^- \rightarrow \tau\mu$ in the SMEFT framework, rivaling and in some cases surpassing the projected sensitivities from τ -decays.

- Linear colliders such as ILC and CLIC which run at greater $\sqrt{s} \sim \text{TeV}$ range offer enhanced sensitivity to 4-fermion operators and allow to probe the chirality structure through polarized e^+e^- beams.
- Circular colliders such as FCC-ee and CEPC have enhanced sensitivity to Higgs current operators on the Z -pole.
- Complementarity with tau decays is visible in planes of 2 different operators. Thus colliders probe different parts of the multi-dimensional space of SMEFT coefficients.

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Thank you!

Backup slide : Wilson coefficients

Convenient basis : Define Wilson coefficients as linear combinations of SMEFT coefficients.

$$\begin{aligned}(C_\gamma^{LR})_{\mu\tau} &= c_W(C_{eB})_{\mu\tau} - s_W(C_{eW})_{\mu\tau} , & (C_Z^{LR})_{\mu\tau} &= -c_W(C_{eW})_{\mu\tau} - s_W(C_{eB})_{\mu\tau} , \\(C_\gamma^{RL})_{\mu\tau} &= c_W(C_{eB})_{\tau\mu}^* - s_W(C_{eW})_{\tau\mu}^* , & (C_Z^{RL})_{\mu\tau} &= -c_W(C_{eW})_{\tau\mu}^* - s_W(C_{eB})_{\tau\mu}^* , \\(C_Z^{LL})_{\mu\tau} &= (C_{\varphi\ell}^{(1)})_{\mu\tau} + (C_{\varphi\ell}^{(3)})_{\mu\tau} , & (C_Z^{RR})_{\mu\tau} &= (C_{\varphi e})_{\mu\tau} , \\(C_V^{LR})_{\mu\tau} &= (C_{le})_{ee\mu\tau} , & (C_V^{RL})_{\mu\tau} &= (C_{le})_{\mu\tau ee} , \\(C_S^{LR})_{\mu\tau} &= -2(C_{le})_{\mu ee\tau} , & (C_S^{RL})_{\mu\tau} &= -2(C_{le})_{e\tau\mu e} ,\end{aligned}$$

$$\begin{aligned}(C_V^{LL})_{\mu\tau} &= (C_{ll})_{ee\mu\tau} + (C_{ll})_{\mu\tau ee} + (C_{ll})_{e\tau\mu e} + (C_{ll})_{\mu ee\tau} , \\(C_V^{RR})_{\mu\tau} &= (C_{ee})_{ee\mu\tau} + (C_{ee})_{\mu\tau ee} + (C_{ee})_{e\tau\mu e} + (C_{ee})_{\mu ee\tau} .\end{aligned}$$

$\sigma(e^+e^- \rightarrow \tau\mu)$ depends on center-of-mass energy \sqrt{s} and 12 independent Wilson coefficients.

Backup Slide II

Apply Gaussian smearing

$$\epsilon_{\text{bkg}} \approx \int_1^{\infty} dx \int_{x-5\sigma(x)}^{x+5\sigma(x)} dy f_{\text{bkg}}(y) \frac{1}{\sqrt{2\pi}\sigma(x)} e^{-\frac{(x-y)^2}{2\sigma(x)^2}}$$

Outgoing muon momentum distribution $f_{\text{bkg}}(y)$ is known.

$\sigma(x)$ represents total momentum resolution combining **collision energy spread** and **detector momentum resolution**.

Backup Slide III

$$\begin{aligned} \text{LEP : } N_{\tau\mu} < 9.9 \text{ (Z-pole), } \sigma_{e^+e^- \rightarrow \tau\mu} < 115 \text{ fb} & \quad \sqrt{s} = 189 \text{ GeV} \\ & \quad \sigma_{e^+e^- \rightarrow \tau\mu} < 116 \text{ fb} \quad \sqrt{s} = 194 \text{ GeV} \\ & \quad \sigma_{e^+e^- \rightarrow \tau\mu} < 64 \text{ fb} \quad \sqrt{s} = 205 \text{ GeV} \end{aligned}$$

$$\text{LHC : BR}(Z \rightarrow \tau\mu) < 6.5 \times 10^{-6} \quad \text{BR}(Z \rightarrow \tau\mu) \lesssim 10^{-6}$$

τ -decays :

$$\begin{aligned} \text{BR}(\tau^- \rightarrow \mu^- e^+ e^-) &< 1.8 \times 10^{-8} & \text{BR}(\tau^- \rightarrow \mu^- e^+ e^-) &< 3 \times 10^{-10} \\ \text{BR}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) &< 2.1 \times 10^{-8} & \text{BR}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) &< 4 \times 10^{-10} \\ \text{BR}(\tau^- \rightarrow \mu^- \gamma) &< 4.2 \times 10^{-8} & \text{BR}(\tau^- \rightarrow \mu^- \gamma) &< 10^{-9} \\ \text{BR}(\tau^- \rightarrow \mu^- \pi^0) &< 1.1 \times 10^{-7} & \text{BR}(\tau^- \rightarrow \mu^- \pi^0) &< 5 \times 10^{-10} \\ \text{BR}(\tau^- \rightarrow \mu^- \rho^0) &< 1.2 \times 10^{-8} & \text{BR}(\tau^- \rightarrow \mu^- \rho^0) &< 2 \times 10^{-10} \\ \text{BR}(\tau^- \rightarrow \mu^- \phi) &< 8.4 \times 10^{-8} & \text{BR}(\tau^- \rightarrow \mu^- \phi) &< 1.5 \times 10^{-9}. \end{aligned}$$

Backup Slide III

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Backup Slide IV : Polarizations

$$P_- = \frac{N_{e_R^-} - N_{e_L^-}}{N_{e_R^-} + N_{e_L^-}}, \quad P_+ = \frac{N_{e_R^+} - N_{e_L^+}}{N_{e_R^+} + N_{e_L^+}},$$

$$\begin{aligned} \frac{d\sigma(e^+e^- \rightarrow \mu^-\tau^+)}{d\cos\theta} &= \frac{1}{4} \left[(1+P_+)(1+P_-) \frac{d\sigma(e_R^+e_R^- \rightarrow \mu^-\tau^+)}{d\cos\theta} \right. \\ &\quad + (1-P_+)(1-P_-) \frac{d\sigma(e_L^+e_L^- \rightarrow \mu^-\tau^+)}{d\cos\theta} \\ &\quad \left. + (1+P_+)(1-P_-) \frac{d\sigma(e_R^+e_L^- \rightarrow \mu^-\tau^+)}{d\cos\theta} + (1-P_+)(1+P_-) \frac{d\sigma(e_L^+e_R^- \rightarrow \mu^-\tau^+)}{d\cos\theta} \right], \end{aligned}$$