Charged Lepton Flavor Violation (LFV)

at future circular e^+e^- colliders

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arXiv: 2305.03869

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τ Lepton Physics (TAU2023)

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Motivation and Outline

Clean probe of BSM physics.

Flavor oscillations already occur in the neutrino/quark sector.

Aim:
Study process $e^+e^- \to \tau\mu$ in the Standard Model Effective Field Theory (SMEFT) at FCC-ee and CEPC.

Discuss the constraints we obtain on the SMEFT coefficients.

Compare against constraints from low-energy tau decays.

SMEFT

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

suppressed by New Physics scale

Wilson coefficients

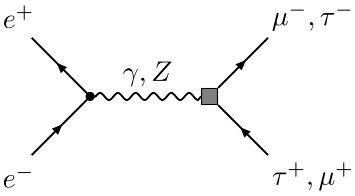
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} O_i^{(6)}$$

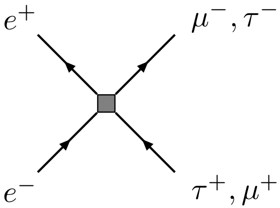
New Physics (NP) $\gtrsim$ TeV scale.

EFT $\Rightarrow$ Model-independent parametrization

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

Flavor-violating operators





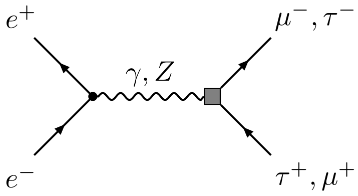
Dipole	Higgs-current	4-fermion
$(C_\gamma^{LR})_{\mu\tau} \frac{1}{\sqrt{2}} \frac{v}{\Lambda^2} (\bar{\mu}\sigma^{\alpha\beta} P_R \tau) F_{\alpha\beta}$	$(C_Z^{LL})_{\mu\tau} \frac{v^2}{2\Lambda^2} (\bar{\mu}\gamma^\alpha P_L \tau) \frac{g}{c_W} Z_\alpha$	$(C_V^{LL})_{\mu\tau} \frac{1}{\Lambda^2} (\bar{e}\gamma_\alpha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

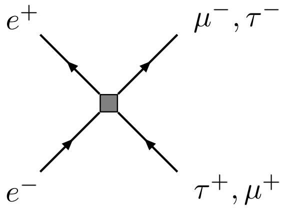
Dipole : $C_\gamma^{LR}, C_\gamma^{RL}, C_Z^{LR}, C_Z^{RL}$

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





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

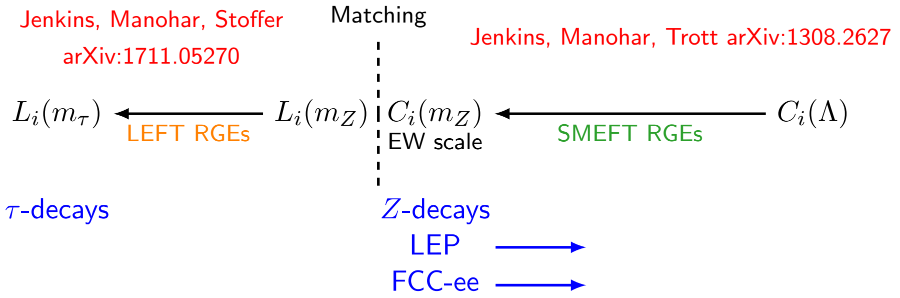
Dipole : C_γ^{LR}, C_γ^{RL}, C_Z^{LR}, C_Z^{RL}

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

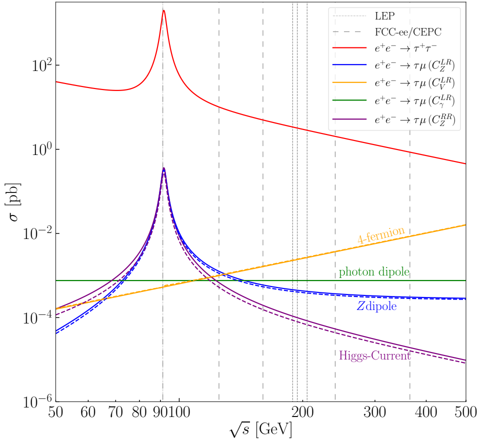
4-fermion : C_V^{LL}, C_V^{RR}, C_V^{RL}, C_V^{LR}, C_S^{LR}, C_S^{RL}.

Renormalization Group Equations (RGE) Running

Below the Electroweak (EW) scale, t, $W^{\pm}$,Z, h are integrated out to give the Low-Energy Effective Theory (LEFT).



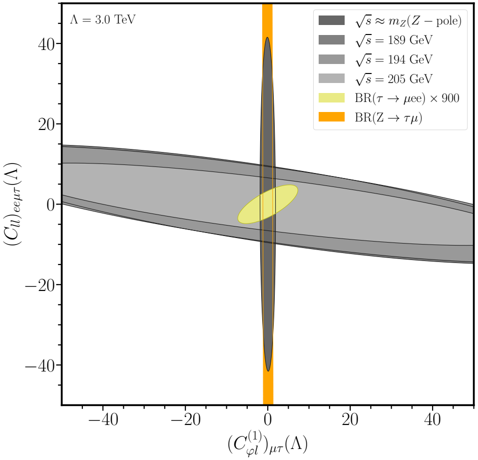
$e^+e^- \to \tau\mu$ cross-section



- 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



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

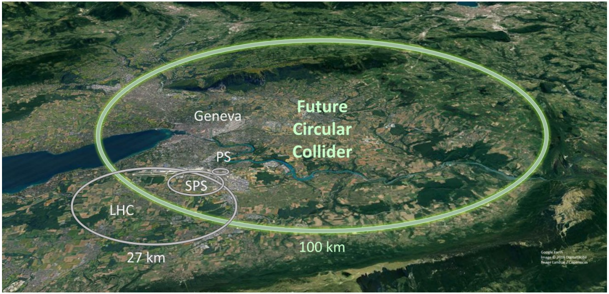
$\text{BR}(Z \to \tau\mu) < 6.5 \times 10^{-6}$ (LHC).

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

Prospects at future colliders

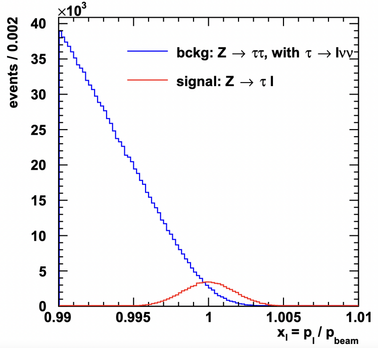
FCC-ee/CEPC will run at a greater range of energies and will collect larger luminosities.

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

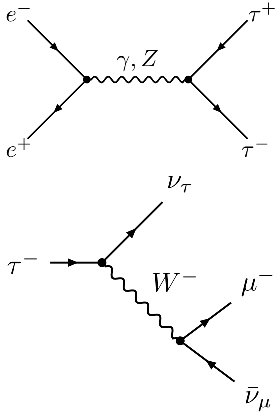


C. Panagiotis CERN

Dominant background



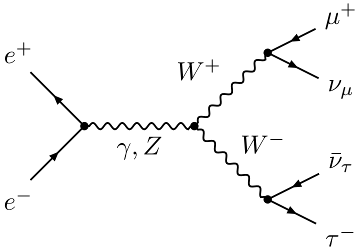
M. Dam arXiv:1811.09408

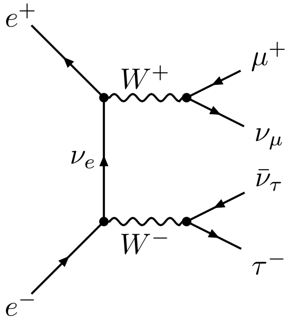


Detector performance modeled with Gaussian smearing

Signal : p_μ is a Gaussian centered around p_b.
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

Additional Background?





If both W's are on-shell, then

$$x = \frac{p_\mu}{p_{\text{beam}}} < \frac{1}{2}\left(1 + \sqrt{1 - 4\frac{m_W^2}{s}}\right) < 1\ .$$

Numerical Monte Carlo simulations on MadGraph5 aMC@NLO confirm
$\Rightarrow$ negligible for $x > 1$.

Sensitivity

FCC-ee

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{xc}_{\text{bkg}}$ [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

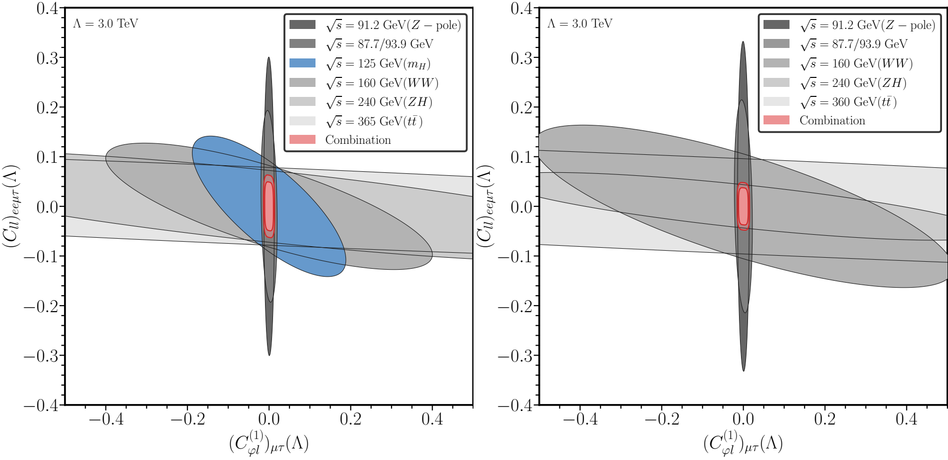
CEPC

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{xc}_{\text{bkg}}$ [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

Results I

W. Altmannshofer, P.M. and T. Oh   arXiv: 2305.03869

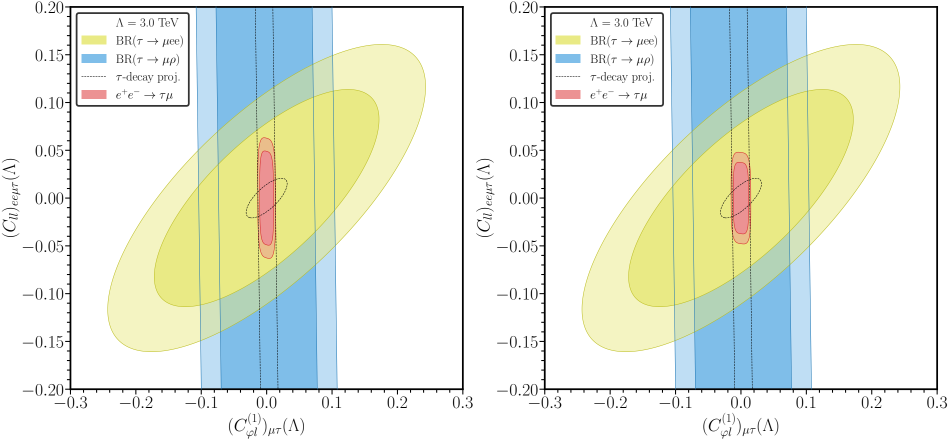
Left : FCC-ee , Right : CEPC, $\Lambda = 3$TeV



Results II

W. Altmannshofer, P.M. and T. Oh   arXiv: 2305.03869

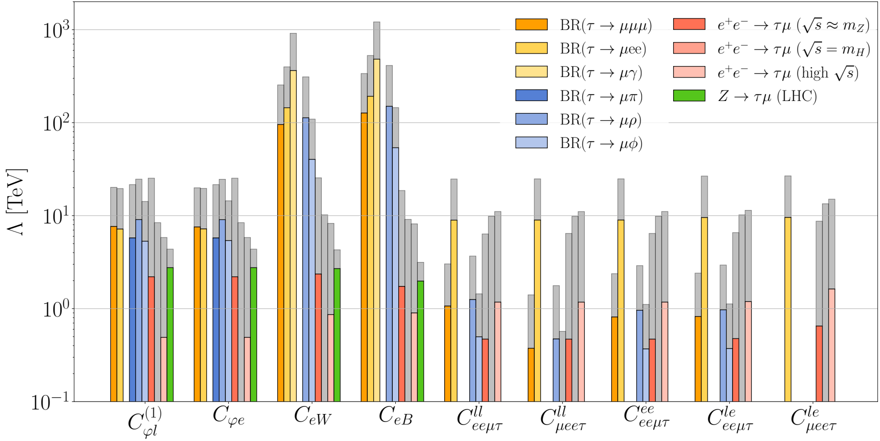
Left : FCC-ee , Right : CEPC, $\Lambda = 3$ TeV



$\rightarrow$ Complementarity between FCC-ee and the low-energy tau decays BR($\tau \to \mu ee$) and BR($\tau \to \mu\rho$).

Results III

W. Altmannshofer, P.M. and T. Oh   arXiv: 2305.03869



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

Summary

Circular electron-positron colliders can provide complementary information in constraining New Physics energy scales/operators that would contribute to $e^+e^- \to \tau\mu$ in the SMEFT framework.

Interesting avenues we are currently exploring

- Linear colliders such as ILC which run at greater $\sqrt{s} \sim$ TeV range. These also allow to probe the chirality structure through polarized e^+e^- beams.
- Analyse LFV in the τe and μe sector.

Summary

Circular electron-positron colliders can provide complementary information in constraining New Physics energy scales/operators that would contribute to $e^+e^- \to \tau\mu$ in the SMEFT framework.

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- Linear colliders such as ILC which run at greater $\sqrt{s} \sim$ TeV range. These also allow to probe the chirality structure through polarized e^+e^- beams.
- Analyse LFV in the τe and μe sector.

Thank you!

Backup slide : Wilson coefficients

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

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

$$(C_V^{LL})_{\mu\tau} = (C_{\ell\ell})_{ee\mu\tau} + (C_{\ell\ell})_{\mu\tau ee} + (C_{\ell\ell})_{e\tau\mu e} + (C_{\ell\ell})_{\mu ee\tau} \ ,$$
$$(C_V^{RR})_{\mu\tau} = (C_{ee})_{ee\mu\tau} + (C_{ee})_{\mu\tau ee} + (C_{ee})_{e\tau\mu e} + (C_{ee})_{\mu ee\tau} \ .$$

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

Backup Slide II

$$N_{\mathsf{sig}} = \sigma(e^+e^- \to \tau\mu) \sum_{j=2,3,4} \mathsf{BR}(\tau \to j\pi\nu)\mathcal{L}_{\mathsf{int}}\epsilon_{\mathsf{sig}}A$$

$$N_{\mathsf{bkg}} = 2\sigma(e^+e^- \to \tau\tau) \sum_{j=2,3,4} \mathsf{BR}(\tau \to j\pi\nu)\mathsf{BR}(\tau \to \mu\bar{\nu}\nu)\mathcal{L}_{\mathsf{int}}\epsilon_{\mathsf{bkg}}A$$

Apply Gaussian smearing

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

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

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

Backup Slide III

LEP : $N_{\tau\mu} < 9.9$ (Z-pole), $\sigma_{e^+e^-\to\tau\mu} < 115$ fb $\quad \sqrt{s} = 189$ GeV

$\sigma_{e^+e^-\to\tau\mu} < 116$ fb $\quad \sqrt{s} = 194$ GeV

$\sigma_{e^+e^-\to\tau\mu} < 64$ fb $\quad \sqrt{s} = 205$ GeV

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

τ-decays :

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

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\end{aligned}
$$