

Lepton Flavor Violation (LFV)

at future circular e^+e^- colliders

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Motivation

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 and CEPC.

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

suppressed by New Physics

scale

Wilson coefficients

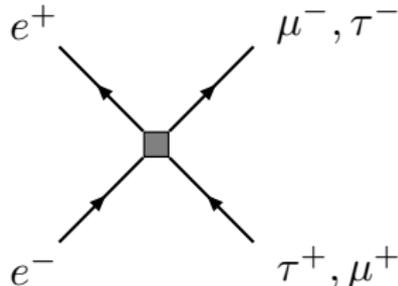
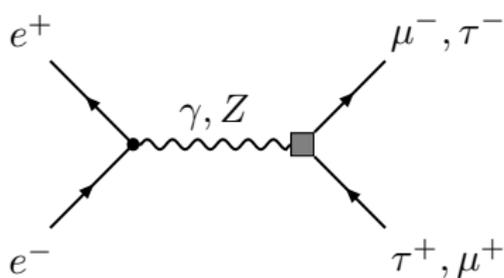
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)}$$

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



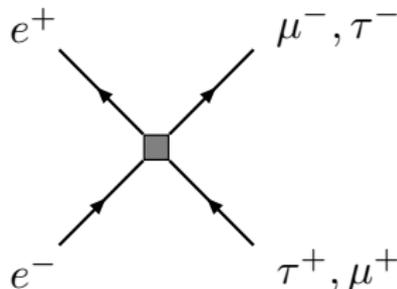
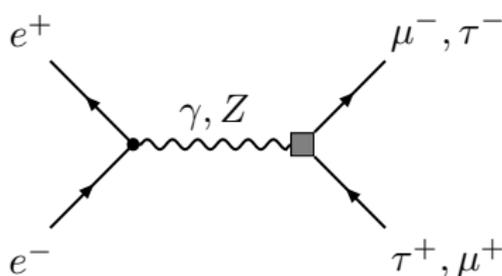
Dipole	Higgs-current	4-fermion
$(C_\gamma^{LR})_{\mu\tau} \frac{1}{\sqrt{2}} \frac{v}{\Lambda^2} (\bar{\mu}\sigma^{\alpha\beta} P_R\tau) F_{\alpha\beta}$	$(C_Z^{LL})_{\mu\tau} \frac{v^2}{2\Lambda^2} (\bar{\mu}\gamma^\alpha P_L\tau) \frac{g}{c_W} Z_\alpha$	$(C_V^{LL})_{\mu\tau} \frac{1}{\Lambda^2} (\bar{e}\gamma_\alpha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

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



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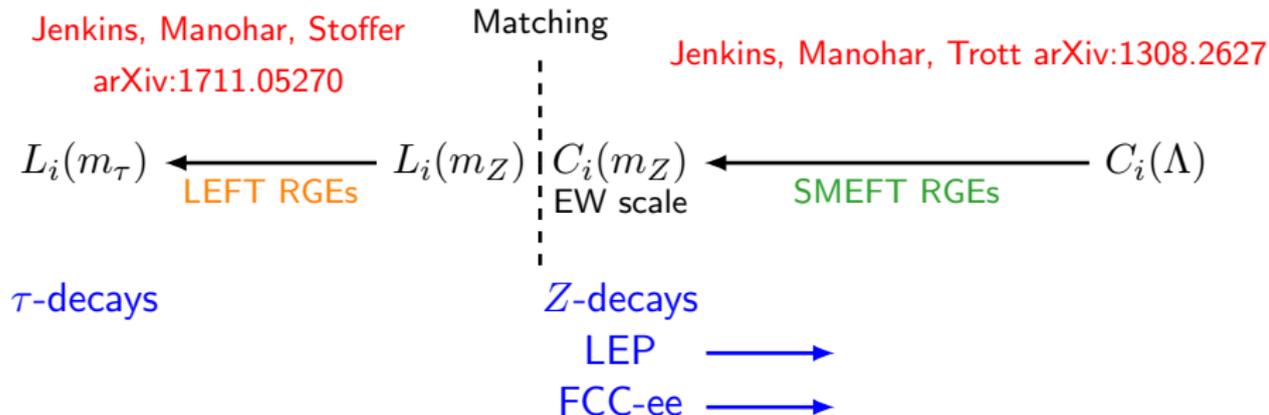
Dipole : $C_\gamma^{LR}, C_\gamma^{RL}, C_Z^{LR}, C_Z^{RL}$

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

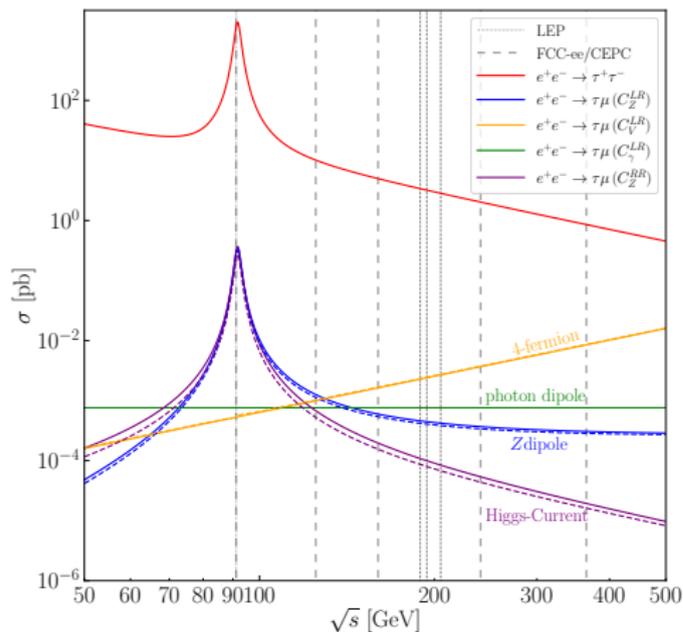
4-fermion : $C_V^{LL}, C_V^{RR}, C_V^{RL}, C_V^{LR}, C_S^{LR}, C_S^{RL}$.

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).



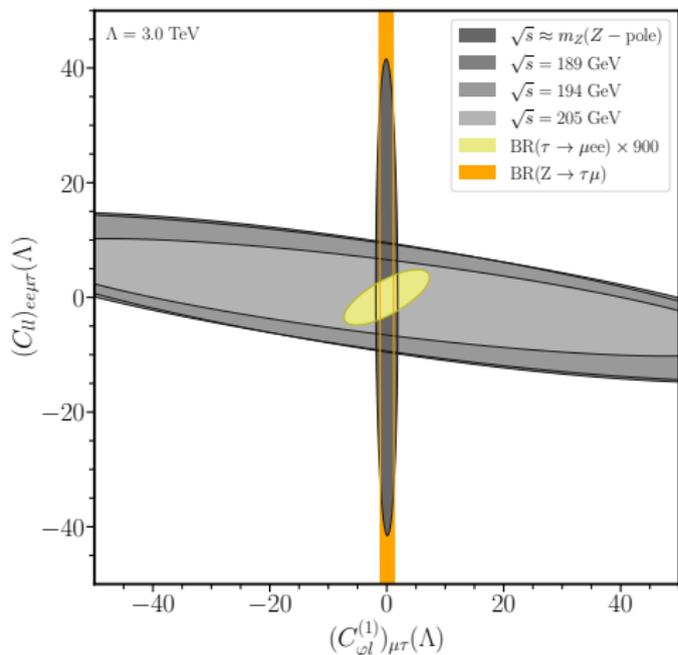
$e^+e^- \rightarrow \tau\mu$ cross-section



- 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} .

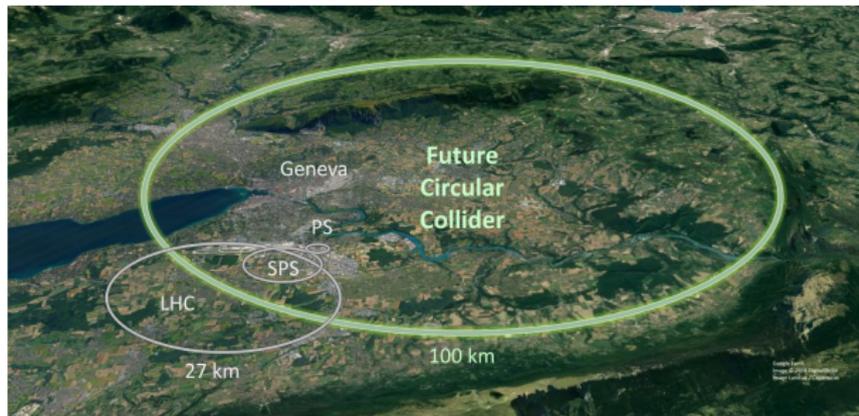
(Opal) Near Z -pole, $N_{\tau\mu} < 9.9$ quoted. Convert to bound on σ

- large QED corrections $O(36\%)$

Prospects at future colliders

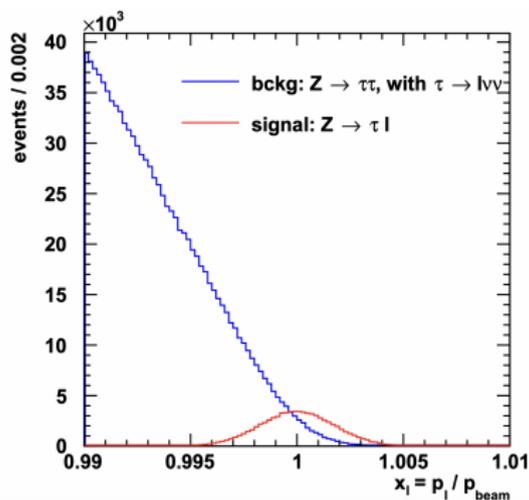
FCC-ee/CEPC will run at a greater range of energies and will collect larger luminosities.

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

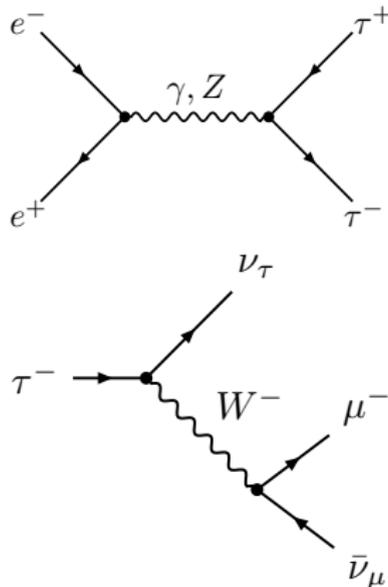


C. Panagiotis CERN

Dominant background



M. Dam arXiv:1811.09408



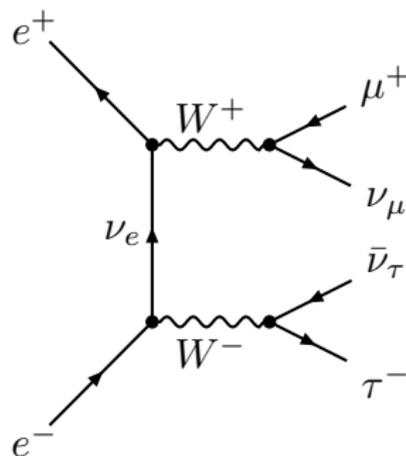
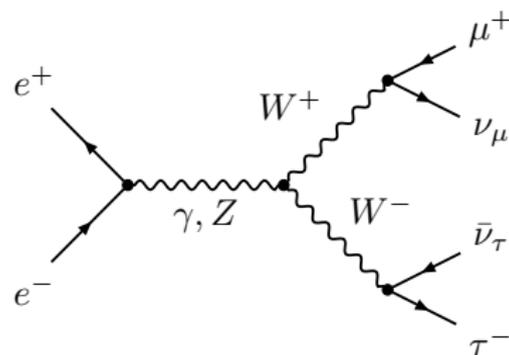
Detector performance modeled with Gaussian smearing

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}_{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

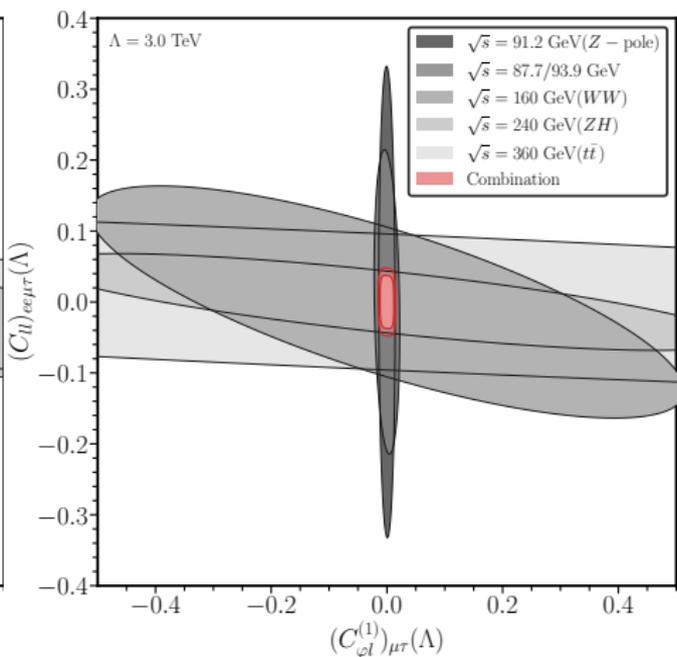
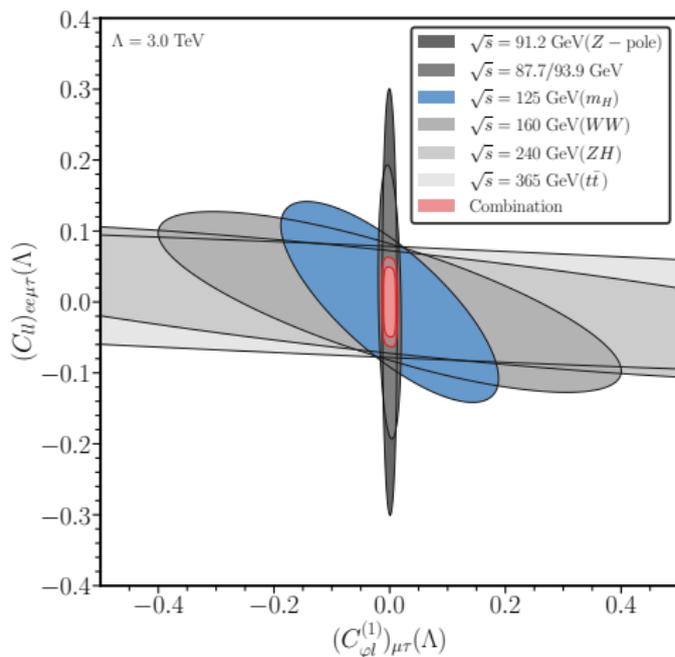
CEPC

\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

Results I

W. Altmannshofer, P.M. and T. Oh (on arXiv tonight)

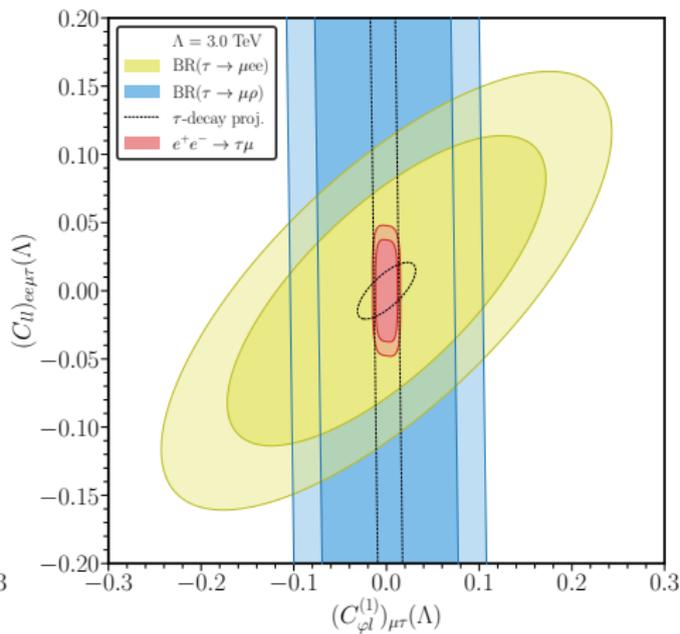
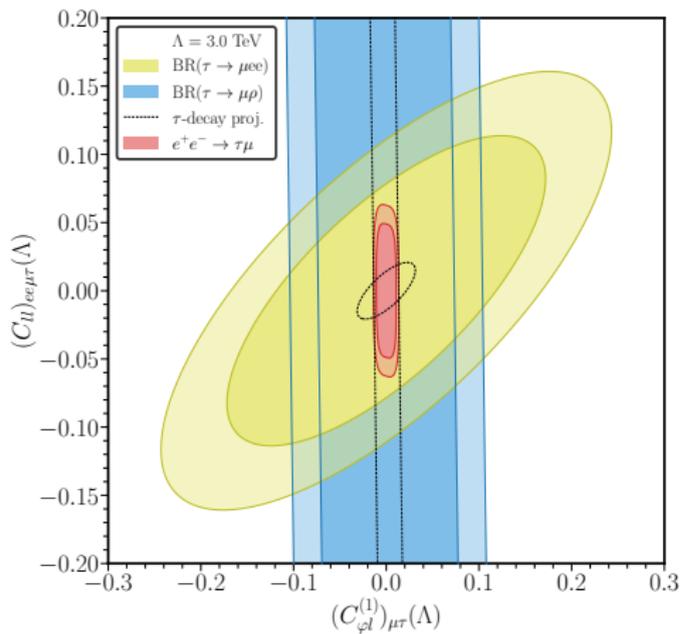
Left : FCC-ee , Right : CEPC, $\Lambda = 3\text{TeV}$



Results II

W. Altmannshofer, P.M. and T. Oh (on arXiv tonight)

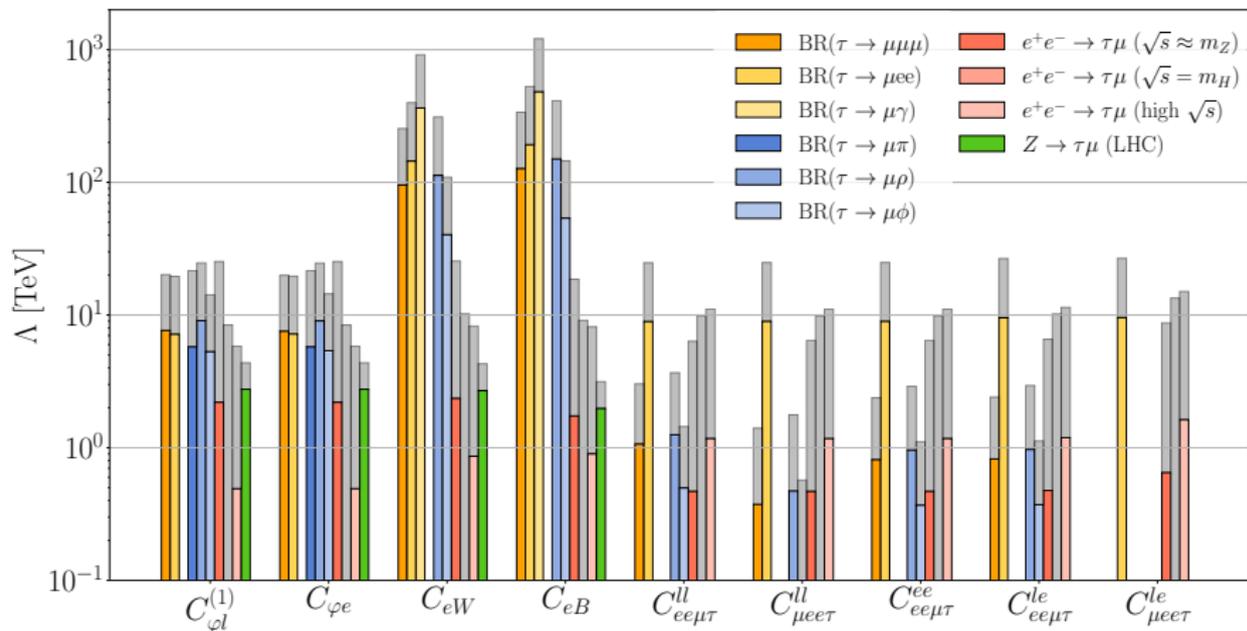
Left : FCC-ee , Right : CEPC, $\Lambda = 3$ TeV



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

Results III

W. Altmannshofer, P.M. and T. Oh (on arXiv tonight)



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

Summary

Circular 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.

Interesting avenues to explore

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

Backup slide : Wilson coefficients

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

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

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

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

Backup Slide II

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

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

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](#).