Probing Lepton Flavor Violation at Future Electron Positron Colliders

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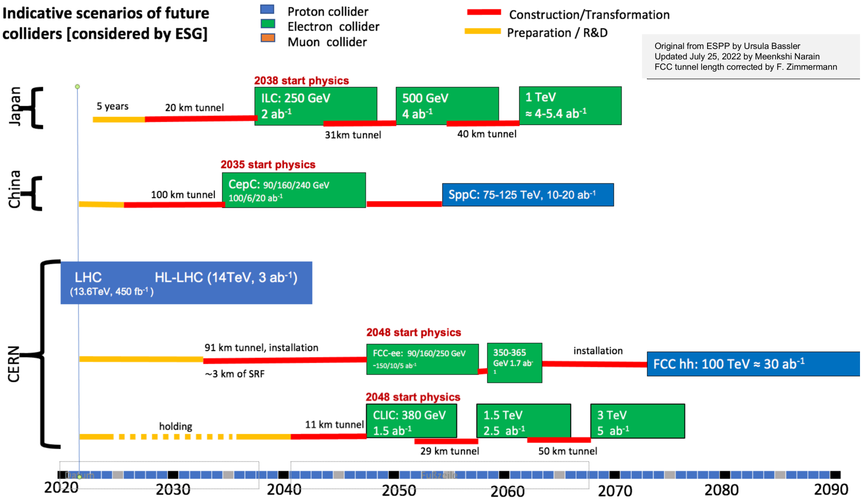
UC SANTA CRUZ

based on arXiv:2305.03869 with Pankaj Munbodh and Talise Oh

Bay Area Particle Theory Seminar
March 15, 2024, San Francisco State University

Future Colliders



Karl Jacobs (ECFA chair) @ 2nd ECFA meeting on e^+e^- Higgs, electroweak, and top factories

Oct 11-13, 2023, Paestum, Italy

Lepton Flavor Violation

- In the SM, charged lepton flavor violation is suppressed by the tiny neutrino mass splittings

$$\text{e.g.} \quad \text{BR}(\mu \to 3e) \sim \text{BR}(\mu \to e\nu_e\nu_\mu) \left| \frac{g^2}{16\pi^2} \frac{\Delta m_\nu^2}{m_W^2} \right|^2 \sim 10^{-50}$$

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3) At high energies in non-resonant production: $e^+e^- \to \tau\mu$, ...

New Physics Sensitivity of LFV at Low Energies

- Generic scaling of a new physics effect with the flavor changing coupling $g_{\rm NP}$ and the new physics scale $\Lambda_{\rm NP}$

$$\frac{\text{BR}(\mu \to 3e)}{\text{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} \sim g_{\rm NP}^2 \left(\frac{v}{\Lambda_{\rm NP}}\right)^4 \lesssim 10^{-12}$$

$$\frac{\text{BR}(\tau \to 3\mu)}{\text{BR}(\tau \to \mu\nu_\mu\bar{\nu}_\tau)} \sim g_{\rm NP}^2 \left(\frac{v}{\Lambda_{\rm NP}}\right)^4 \lesssim 10^{-8}$$

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- For O(1) couplings, this corresponds to new physics scales of

$$\Lambda_{\text{NP}} \gtrsim 100\ \text{TeV} \quad \text{for muons}$$

$$\Lambda_{\text{NP}} \gtrsim 10\ \text{TeV} \quad \text{for taus}$$

New Physics Sensitivity of Heavy Resonance Decays

- Consider LFV decays of the Z boson, the Higgs, the top in the presence of generic new physics

$$\frac{\text{BR}(Z \to \mu e)}{\text{BR}(Z \to \mu\mu)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 ~, \qquad \frac{\text{BR}(H \to \tau\mu)}{\text{BR}(H \to \tau\tau)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4$$

$$\frac{\text{BR}(t \to c\mu e)}{\text{BR}(t \to Wb)} \sim \frac{g_{\text{NP}}^2}{16\pi^2} \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4$$

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- Same dependence on new physics as the low energy probes, but typically much less Z, Higgs, top available in experiments.

- Note: these are extremely generic/naive expectations; situation can be very different in concrete models.

[for a review see WA, Caillol, Dam, Xella, Zhang 2205.10576]

Example: LFV Z Decays

- Results from the LHC: ATLAS (139 fb^{-1})

  Phys.Rev.Lett. 127 (2022) 271801; Nature Phys. 17 (2021) 7, 819-825; ATLAS-CONF-2021-042

$$\mathrm{BR}(Z \to \mu e) < 3.04 \times 10^{-7}$$
$$\mathrm{BR}(Z \to \tau e) < 5.0 \times 10^{-6}$$
$$\mathrm{BR}(Z \to \tau \mu) < 6.5 \times 10^{-6}$$

- Slightly better than LEP bounds for all decay modes.

- In all searches there are backgrounds $\Rightarrow$ expect sensitivities to improve with $\sqrt{\mathcal{L}}$, i.e. $\sim$ factor of 5 at the HL-LHC.

Expected Sensitivities at Proposed Z Pole Machines

based on FCC-ee study Dam 1811.09408 (see also the FCC-ee whitepaper 2203.06520)

$Z \to \mu e$

- background from $Z \to \tau\tau \to \mu\nu\nu\ e\nu\nu$ is under control. Momentum resolution of 10^{-3} and Z mass constraint implies background rate of $\sim 10^{-11}$.
- main background: $Z \to \mu\mu$ where one muon suffers from "catastrophic" bremsstrahlung and is identified as electron.
- mis-id probability $\sim 10^{-7}$ limits the sensitivity to $\text{BR}(Z \to \mu e) \sim 10^{-8}$.
- With improved e/μ separation (dE/dx) might be able to go down to $\text{BR}(Z \to \mu e) \sim 10^{-10}$.

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$Z \to \tau e$ and $Z \to \tau\mu$

- minimize τ vs μ, e mis-id $\to$ focus on hadronic taus
- background from $Z \to \tau_{\text{had}}\tau \to \tau_{\text{had}}\ell\nu\nu$
- limits sensitivity to $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

LFV Z Decays in the EFT Framework

- Parameterize New Physics in a systematic and controlled way: in terms of dim-6 operators of the SMEFT

dipoles

$$\mathcal{O}_{dW} = (\bar{\ell}\sigma^{\mu\nu}\tau^a P_R \ell')H \;\; W^a_{\mu\nu}$$

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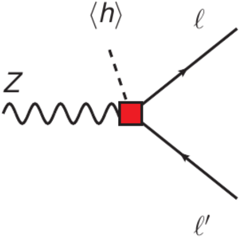

Higgs currents

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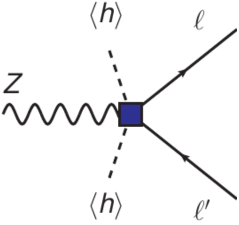
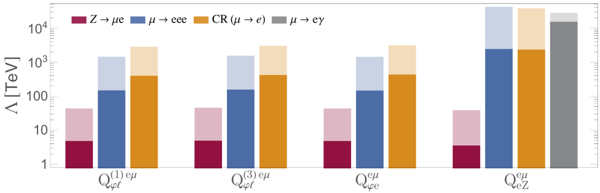


Comparison with Low Energy Probes

- Many flavor violating low energy processes will be affected as well.
- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).

Calibbi, Marcano, Roy 2107.10273



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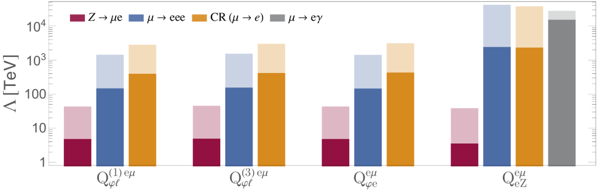
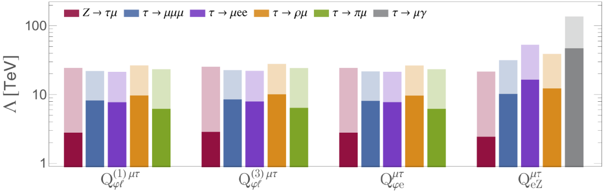


- Complementary sensitivity in the case of taus.



New Physics Sensitivity of Non-Resonant LFV

- The scaling of LFV cross sections with the center of mass energy depends on the type of operator:

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- How sensitive is one to $\tau\mu$ production at future e^+e^- colliders?

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- For some operators one will have enhanced sensitivity at high energies. (Assuming one does not resolve the higher dimensional operators.)

- How sensitive is one to $\tau\mu$ production at future e^+e^- colliders?

- In WA, Munbodh, Oh 2305.03869 we show that high-energy runs of FCC-ee/CEPC have sensitivity that is comparable and complementary to other probes.

Systematic SMEFT Parameterization of New Physics

dipoles

$$\mathcal{O}_{dW} = (\bar{\tau}\sigma^{\alpha\beta} T^a P_R \mu) H \;\; W^a_{\alpha\beta}$$

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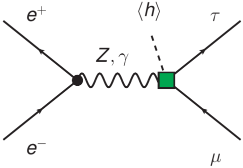

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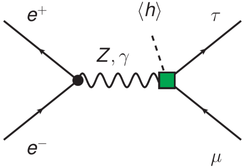

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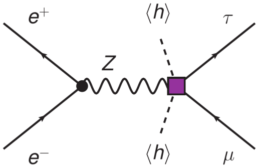

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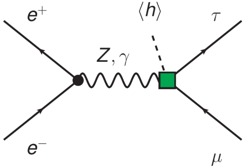

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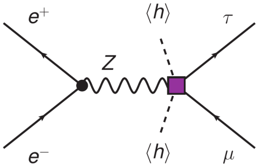


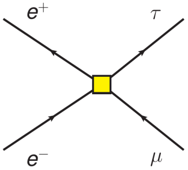
4-fermion contact interactions

$$\mathcal{O}_{\ell\ell} = (\bar{e}\gamma^\alpha P_L e)(\bar{\tau}\gamma_\alpha P_L \mu)$$

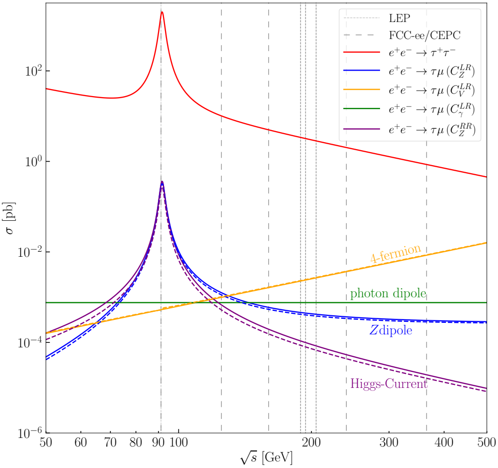
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

$$\mathcal{O}_{\ell e} = (\bar{e}\gamma^\alpha P_L e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

$$\mathcal{O}_{e\ell} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_L \mu)$$



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

(in the plot $\Lambda_{NP} = 3$ TeV, $C_i = 1$)

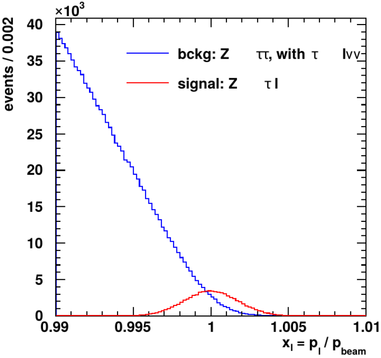
- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

Signal and Most Important Background

signal: $e^+e^- \to \tau\mu$

bkg: $e^+e^- \to \tau^+\tau^- \to \tau\mu\nu\nu$

- Signal is a sharp peak at $x = p_\mu/p_\text{beam} = 1$
- Background is a smooth distribution with $x \lesssim 1$
- Width of the signal peak and spread of background to $x > 1$ is determined by the beam energy spread and the muon momentum resolution.



Dam 1811.09408

(study on the Z peak)

- Impact of initial state radiation? (work in progress with Munbodh)

Another Background at High Energies?

$$e^+e^- \to W^+W^- \to \tau\mu\nu\nu$$

- Muon momentum does not extend all the way to $x = 1$
- Decay kinematics is such that

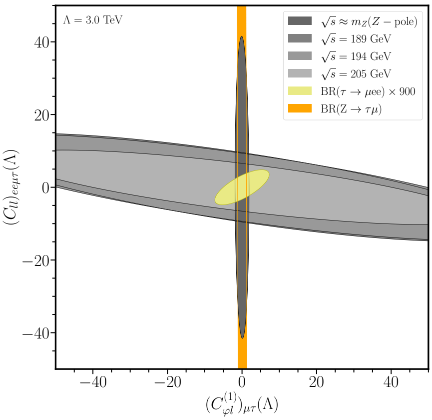
$$x < \frac{1}{2}\left(1 + \sqrt{1 - \frac{4m_W^2}{s}}\right) < 1$$

- e.g. for $\sqrt{s} = 240$ GeV one has $x \lesssim 0.87$

$\Rightarrow$ this background is not an issue.

Existing Constraints from LEP

WA, Munbodh, Oh 2305.03869



- LEP has searched for $e^+e^- \to \tau\mu$ at the Z pole (e.g. OPAL Z.Phys.C 67 (1995) 555-564) and at $\sqrt{s} \sim 200$ GeV (OPAL PLB 519, (2001) 23-32).
- Z pole search mainly sensitive to the Higgs current operators.
- High $\sqrt{s}$ search mainly sensitive to 4-fermion operators.
- LEP searches have sensitivity comparable to $Z \to \tau\mu$ at the LHC, but cannot compete with tau decays.

Projections for FCC-ee

machine and detector parameters from FCC-ee CDR vol. 2, 1909.12245, 2107.02686, 2203.06520

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\text{bkg}}^{x_c}$ [10^{-6}]	N_{bkg}	σ [ab]
91.2 (Z-pole)	75	0.93	1.35	1.55	9700 ± 100	45
87.7 (off-peak)	37.5	0.93	1.33	1.46	520 ± 20	21
93.9 (off-peak)	37.5	0.93	1.37	1.59	930 ± 30	28
125 (H)	20	0.03	1.60	1.44	12 ± 3	8
160 (WW)	12	0.93	1.89	2.44	6 ± 2	10
240 (ZH)	5	1.17	2.60	4.39	2 ± 1	18
365 ($t\bar{t}$)	1.5	1.32	3.78	8.61	0.5 ± 0.7	50

- Estimate background efficiency by imposing a cut $x > 1$.
  (could be further optimized)
- Expect sizable background on the Z-peak, very few background events at higher energies.
- Can achieve sensitivity to $e^+e^- \to \tau\mu$ cross sections of $\mathcal{O}$(10 ab).

Projections for CEPC

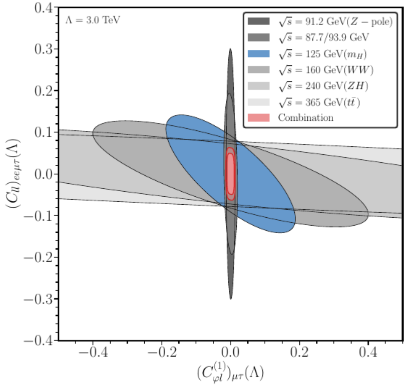
machine and detector parameters from 1809.00285, 1811.10545, 2203.09451, 2205.08553

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\text{bkg}}^{x_c}$ [10^{-6}]	N_{bkg}	σ [ab]
91.2 (Z-pole)	50	0.92	1.35	1.53	6400 ± 80	55
87.7 (off-peak)	25	0.92	1.33	1.46	350 ± 20	27
93.9 (off-peak)	25	0.92	1.37	1.59	620 ± 25	35
160 (WW)	6	0.99	1.89	2.49	3 ± 2	17
240 (ZH)	20	1.20	2.60	4.42	7 ± 3	6.6
360 ($t\bar{t}$)	1	1.41	3.74	8.61	0.3 ± 0.5	72

- Estimate background efficiency by imposing a cut $x > 1$. (could be further optimized)
- Expect sizable background on the Z-peak, very few background events at higher energies.
- Can achieve sensitivity to $e^+e^- \to \tau\mu$ cross sections of $\mathcal{O}(10\text{ ab})$.

Complementarity of Different Observables (FCC-ee)

WA, Munbodh, Oh 2305.03869



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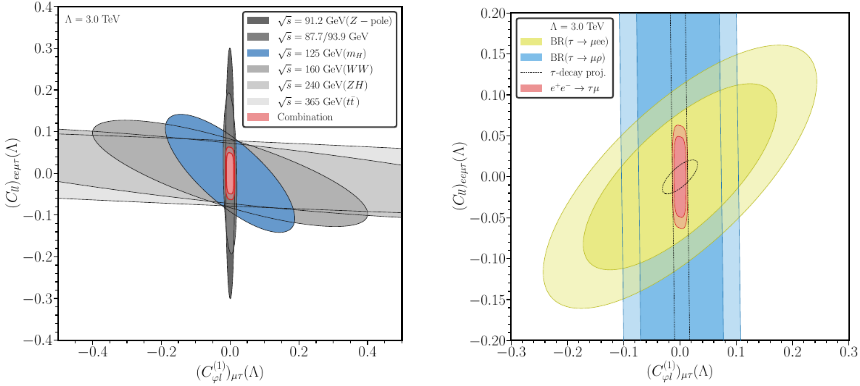

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- Expected FCC-ee sensitivity rivals the one from current and future searches for LFV τ decays.

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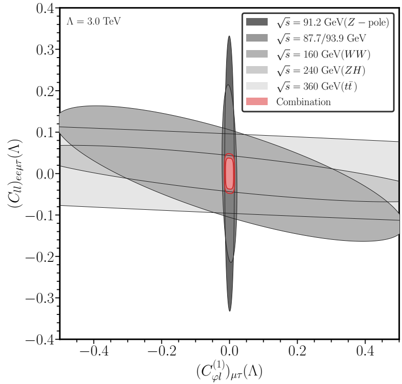

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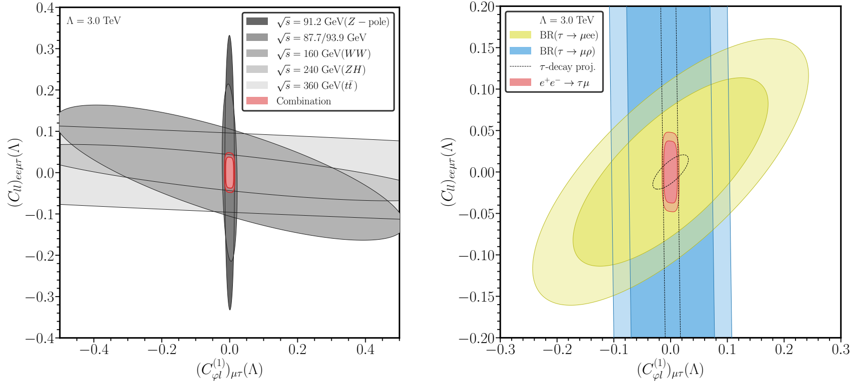

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Summary of Generic Sensitivities

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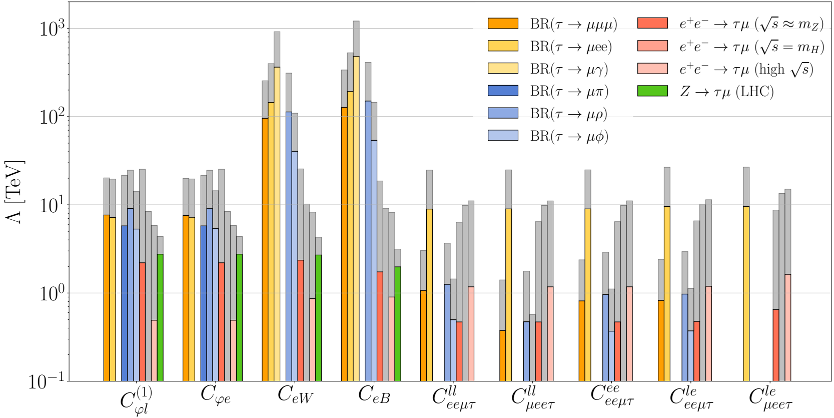

If a Signal is Seen ...

- If a signal is seen at one $\sqrt{s}$:
  $\Rightarrow$ look at different $\sqrt{s}$ to identify the operator class
  (dipole, Higgs current, 4-fermion)

If a Signal is Seen ...

- If a signal is seen at one $\sqrt{s}$:
  $\Rightarrow$ look at different $\sqrt{s}$ to identify the operator class
  (dipole, Higgs current, 4-fermion)

- The signal can be further characterized by angular distributions
  ($\theta =$ angle between the beam axis and the outgoing muon)
  and CP asymmetries ($\tau^+\mu^-$ vs. $\tau^-\mu^+$)

$$\frac{1}{\sigma_{\rm tot}}\frac{d(\sigma+\bar{\sigma})}{d\cos\theta} = \frac{3}{8}(1-F_D)(1+\cos^2\theta) + A_{\rm FB}\cos\theta + \frac{3}{4}F_D\sin^2\theta \ ,$$
$$\frac{1}{\sigma_{\rm tot}}\frac{d(\sigma-\bar{\sigma})}{d\cos\theta} = \frac{3}{8}(A^{\rm CP}-F_D^{\rm CP})(1+\cos^2\theta) + A_{\rm FB}^{\rm CP}\cos\theta + \frac{3}{4}F_D^{\rm CP}\sin^2\theta \ ,$$

- For a sufficiently large signal, it might be possible to significantly narrow down the chirality structure of the operator that is responsible for $e^+e^- \to \tau\mu$

Summary

- Non-resonant $e^+e^- \to \tau\mu$ offers interesting opportunities to probe lepton flavor violation at FCC-ee/CEPC.
- Different LFV operators show characteristic dependence on the center of mass energy.
- Estimated sensitivity rivals the one from rare tau decays.
- Most relevant machine/detector parameters: beam energy spread and muon momentum resolution.
- Linear colliders are also interesting: higher center of mass energy and polarized beams.