Probing Lepton Flavor Violation at Circular Electron Positron Colliders

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based on arXiv:2305.03869 with Pankaj Munbodh and Talise Oh

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Lepton Flavor Violation

(see talk by Lorenzo in the previous session)

- 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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2) At high energies in decays of heavy resonances: $Z \to \mu e$, $h \to \tau\mu$, ...
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_{NP} and the new physics scale Λ_{NP}

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

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

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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

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

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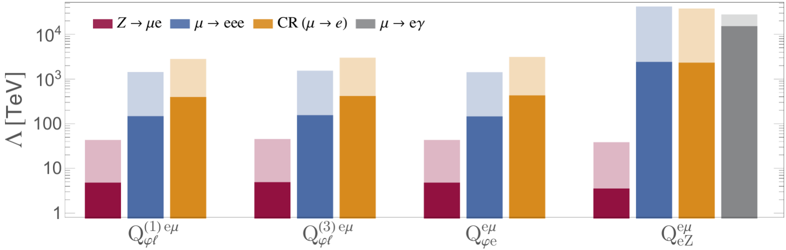
- Same dependence on new physics as the low energy probes, but typically much less Z, Higgs, top available in experiments.

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

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

- Parameterize the new physics in SMEFT and compare Z decays with low energy probes.

Calibbi, Marcano, Roy 2107.10273 (also Li, Schmidt 1809.07924)



- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).

Comparison in SMEFT

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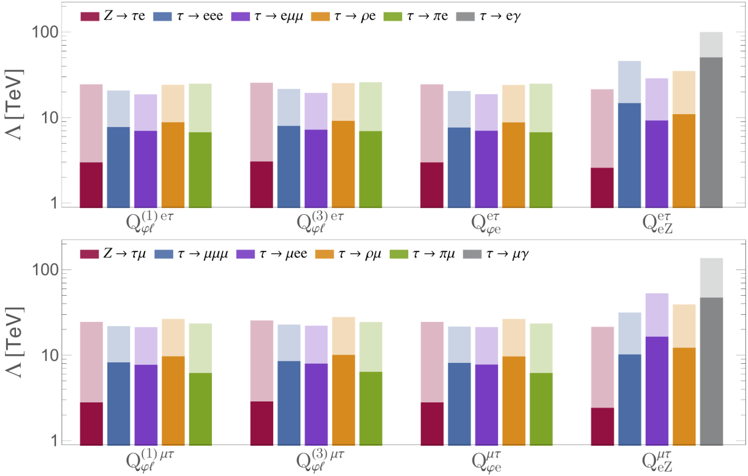

- Comparable sensitivity in the case of taus.

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:

$$\frac{\sigma(e^+e^- \to \tau\mu)}{\sigma(e^+e^- \to \tau^+\tau^-)} \sim$$

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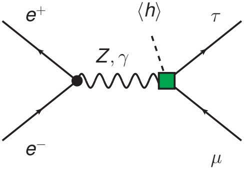
- In WA, Munbodh, Oh 2305.03869 we show that 160 GeV, 240 GeV, 350 GeV runs of CEPC have sensitivity that is comparable and complementary to other probes.

dipoles

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

$$\mathcal{O}_{dB} = (\bar{\tau}\sigma^{\alpha\beta} P_R \mu) H \;\; B_{\alpha\beta}$$



Systematic SMEFT Parameterization of New Physics

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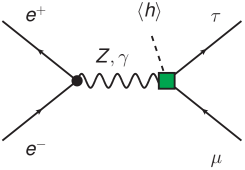
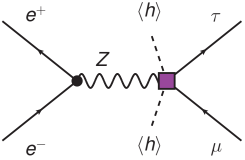


Higgs currents

$$\mathcal{O}^{(3)}_{hl} = (H^\dagger i \overleftrightarrow{D}^a_\alpha H)(\bar{\tau}\gamma^\alpha T^a P_L \mu)$$

$$\mathcal{O}^{(1)}_{hl} = (H^\dagger i \overleftrightarrow{D}_\alpha H)(\bar{\tau}\gamma^\alpha P_L \mu)$$

$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\alpha H)(\bar{\tau}\gamma^\alpha P_R \mu)$$



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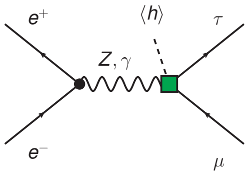

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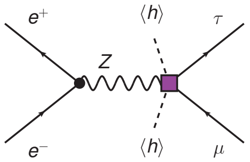


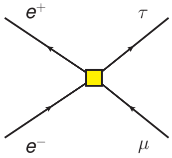
4-fermion contact interactions

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

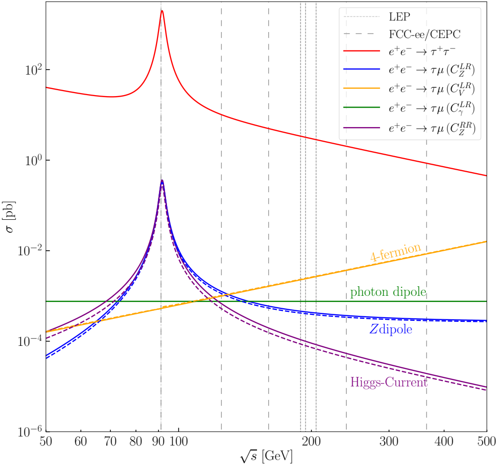
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

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

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



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

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

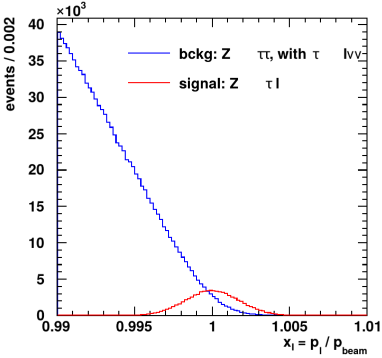
- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

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.



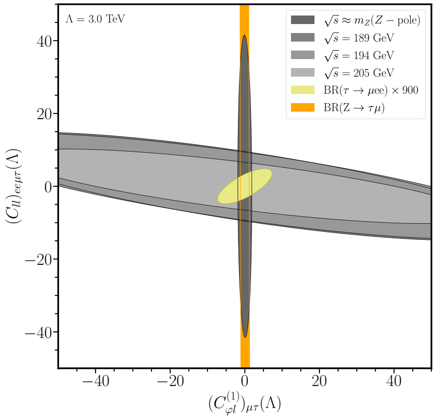
Dam 1811.09408

(study on the Z peak)

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

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 CEPC

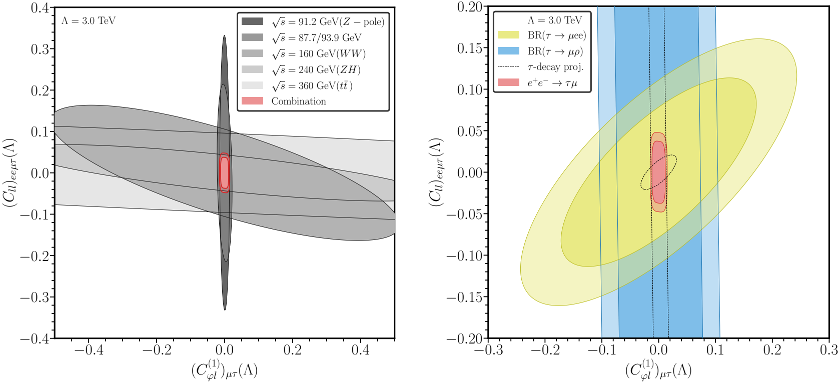
(machine and detector parameters from 1809.00285, 1811.10545, 2203.09451, 2205.08553)

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{x_c}_{\rm bkg}$ [10^{-6}]	$N_{\rm bkg}$	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 ab).

Complementarity of Different Observables

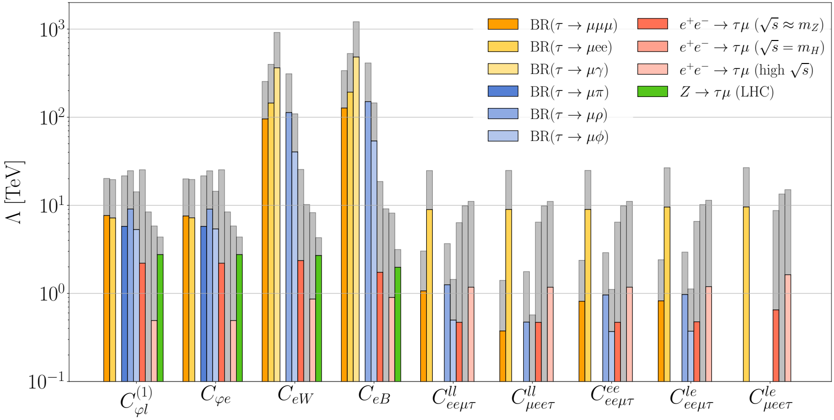
WA, Munbodh, Oh 2305.03869



- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.
- Expected CEPC sensitivity rivals the one from current and future searches for LFV τ decays.

Summary of Generic Sensitivities

WA, Munbodh, Oh 2305.03869



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- 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. $\tau^-\mu^+$)

$$\frac{1}{\sigma_{\rm tot}}\frac{d(\sigma+\bar\sigma)}{d\cos\theta} = \frac{3}{8}(1-F_D)(1+\cos^2\theta) + A_{\rm FB}\cos\theta + \frac{3}{4}F_D\sin^2\theta\ ,$$
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- For a sufficiently large signal, it might be possible to pinpoint the precise operator that is resposible for $e^+e^- \to \tau\mu$

Summary

- Non-resonant $e^+e^- \to \tau\mu$ offers interesting opportunities to probe lepton flavor violation at 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.

Back Up

Another Background at High Energies?

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

- Muon energy 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