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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- 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

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

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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]

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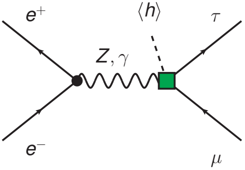
- In WA, Munbodh, Oh 2305.03869 we show that 160 GeV, 240 GeV, 350 GeV runs of circular e^+e^- colliders have sensitivity that is comparable and complementary to other probes.

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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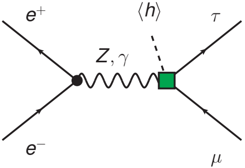
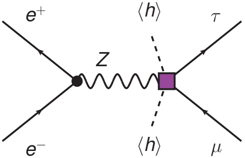


Higgs currents

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

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

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



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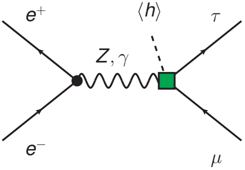

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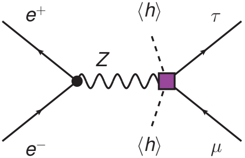


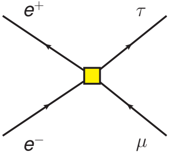
4-fermion contact interactions

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

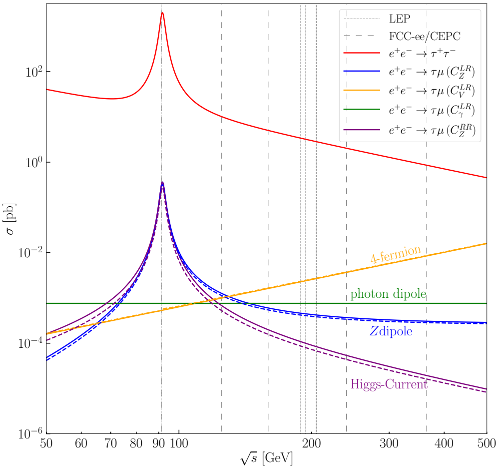
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

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

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



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

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

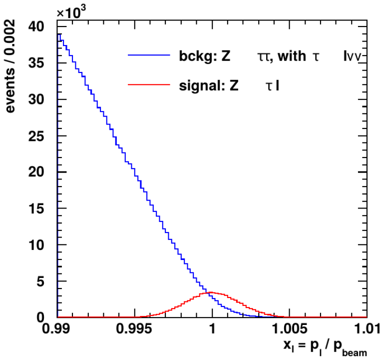
- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

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.



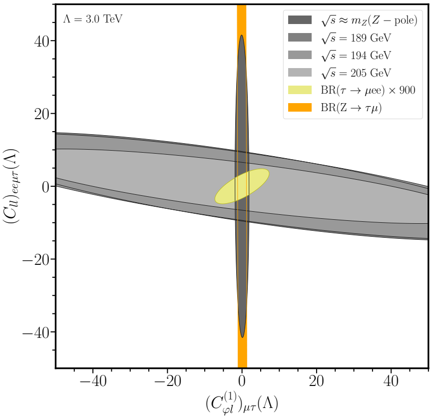
Dam 1811.09408

(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 Circular e^+e^- Colliders

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

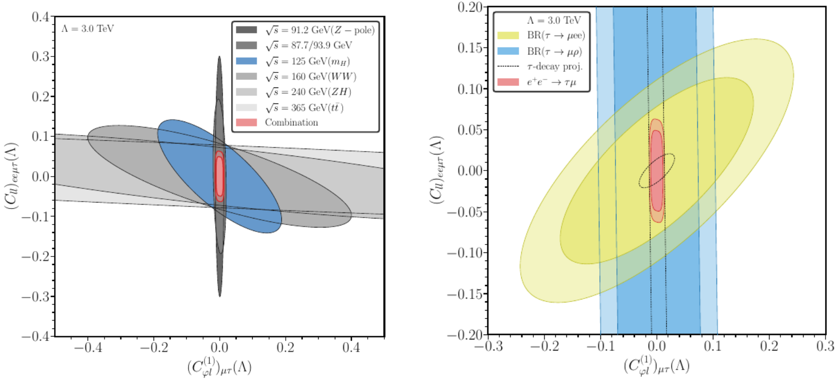
(table for CEPC looks very similar)

$\sqrt{s}$ [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)	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).

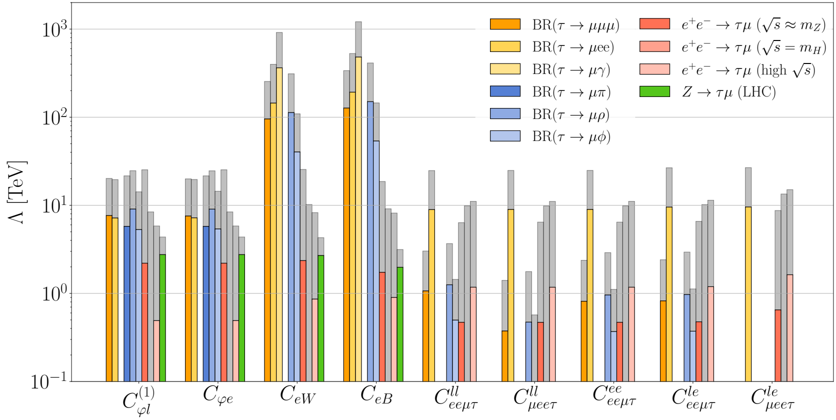
Complementarity of Different Observables

WA, Munbodh, Oh 2305.03869



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

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

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

- For a sufficiently large signal, it might be possible to 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 circular e^+e^- machines.
- 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 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.