Probing Flavor Violation at Future Colliders

Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

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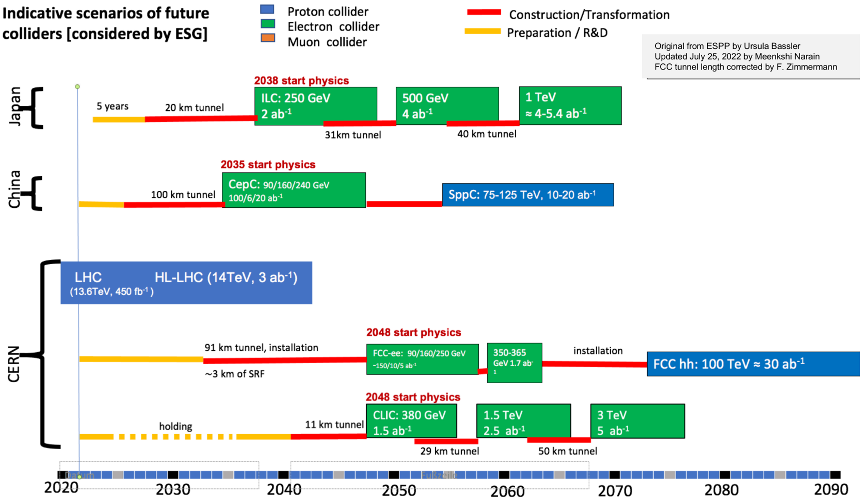
Future Colliders



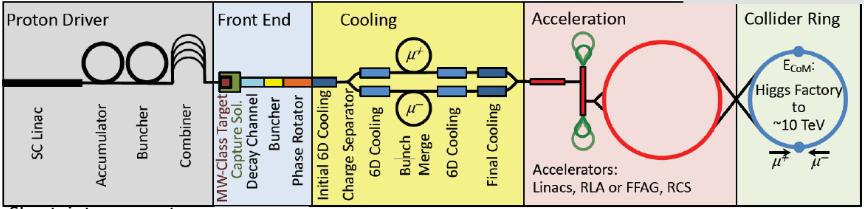
Karl Jacobs @ 2nd ECFA meeting on e^+e^- Higgs, electroweak, and top factories

Oct 11-13, 2023, Paestum, Italy

A Muon Collider?

Muon collider design is driven by finite muon lifetime

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

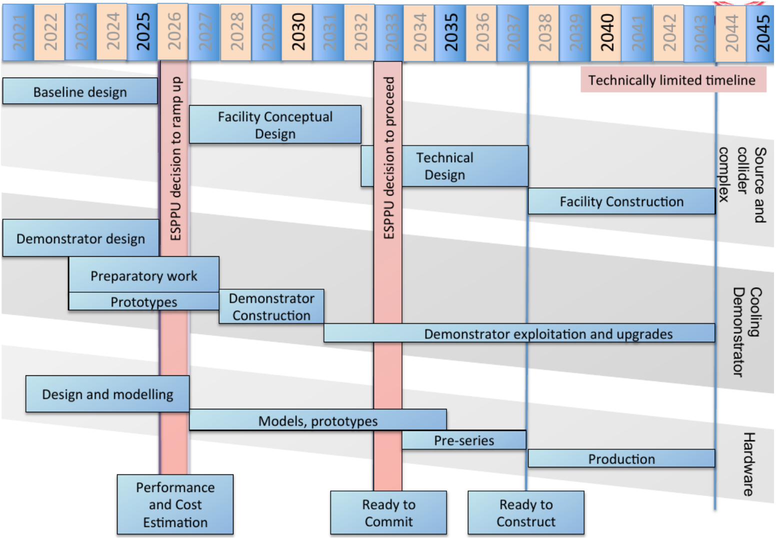
Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

A Muon Collider!



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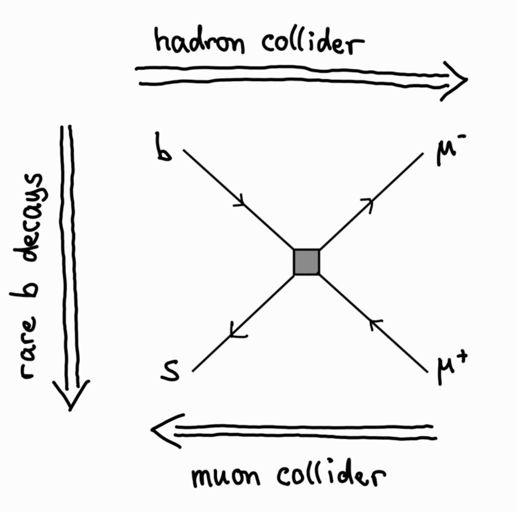
Part 1:

Collider Probes of
$b \to s\mu\mu$

based on 2306.15017 with A. Gadam and S. Profumo

Collider Probes of $b \to s\mu\mu$



$$\Delta C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell) \quad , \quad \Delta C_{10}(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

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$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Total cross section increases with the center of mass energy
(unless the contact interaction is resolved)

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2 \, s \, \left(|\Delta C_9|^2 + |\Delta C_{10}|^2\right)$$

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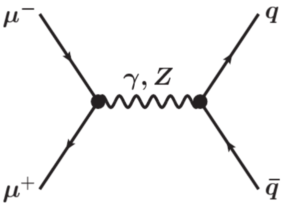
Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3\mathrm{Re}(\Delta C_9 \Delta C_{10}^*)}{2(|\Delta C_9|^2 + |\Delta C_{10}|^2)}$$

Need charge tagging to measure the forward backward asymmetry

Main Background



- Mistagged dijets

$$\sigma_{bg}^{jj} = \sum_{q=b,c,s,d,u} 2\epsilon_q(1-\epsilon_q)\sigma(\mu^+\mu^- \to q\bar{q})$$

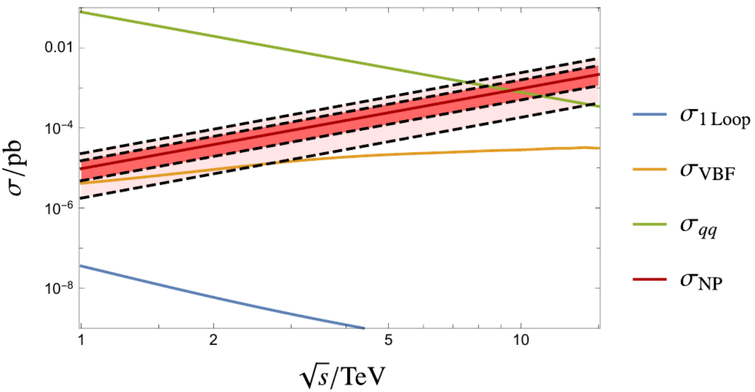
- Assume b tagging comparable to current LHC performance

$$\epsilon_b = 70\% \ , \quad \epsilon_c = 10\% \ , \quad \epsilon_u = \epsilon_d = \epsilon_s = 1\%$$

- Turns out to be the dominant background.

Signal vs. Background

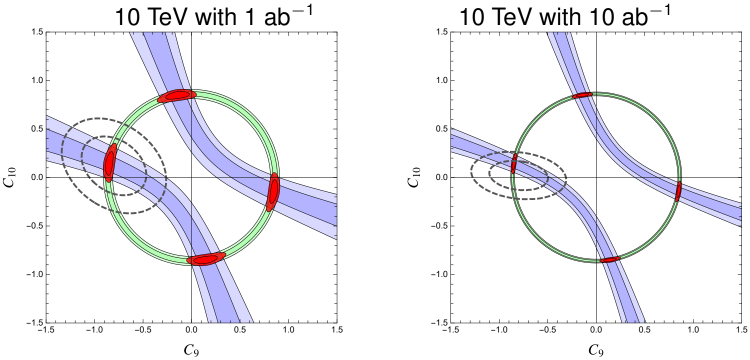
WA, Gadam, Profumo 2203.07495, 2306.15017



- Main background falls with $\sqrt{s}$; new physics signal increases.
- Signal/Background $\sim$ 1 for $\sqrt{s} \sim$ 10 TeV.

Sensitivity Projections

WA, Gadam, Profumo 2203.07495 and 2306.15017

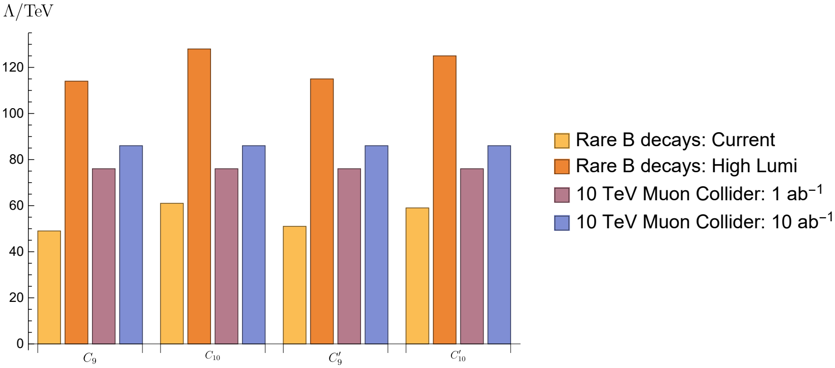


- Branching ratio (green) and A_{FB} (blue) are complementary.
- In dashed: our global rare B decay fit.
- If there is new physics in $b \to s\ell\ell$ at a level of O(10%) of the SM amplitude, a 10 TeV muon collider would clearly see it, and one does not need to worry about hadronic uncertainties.

(see also Huang et al. 2103.01617; Asadi et al. 2104.05720; Azatov et al. 2205.13552)

In the Absence of New Physics

WA, Gadam, Profumo 2203.07495 and 2306.15017



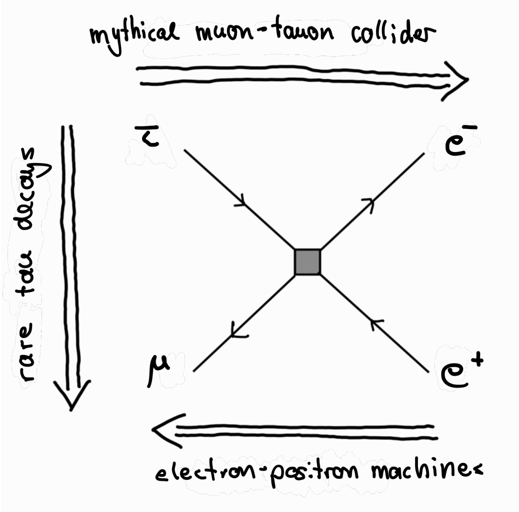
- In the absence of new physics, rare B decays and a 10 TeV muon collider have comparable sensitivity to muon specific new physics.
- Rare B decays have the advantage that a small new physics amplitude can interfere with the SM.
- At a muon collider one has to look for $|\text{new physics}|^2$.

Part 2:

Collider Probes of Lepton Flavor Violation

based on 2305.03869 with P. Munbodh and T. Oh
and work in progress with P. Munbodh

Collider Probes of Lepton Flavor Violation



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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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

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

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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]

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

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- 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.

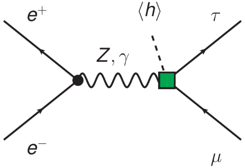
(see also Murakami, Tait 1410.1485; Jahedi, Sarkar 2408.00190)

Systematic SMEFT Parameterization of New Physics

dipoles

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

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



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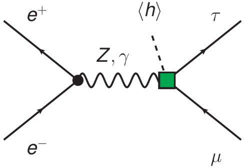
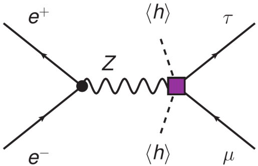


Higgs currents

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

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

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



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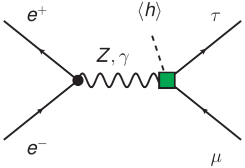
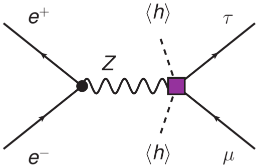


Higgs currents

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

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

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



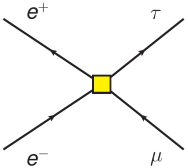
4-fermion contact interactions

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

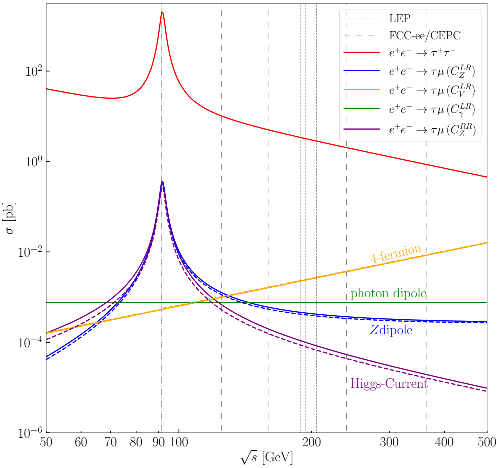
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

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

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



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

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

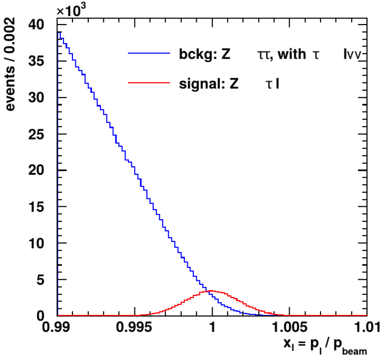
- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

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 $x = p_\mu/p_{\rm beam} = 1$
- 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.



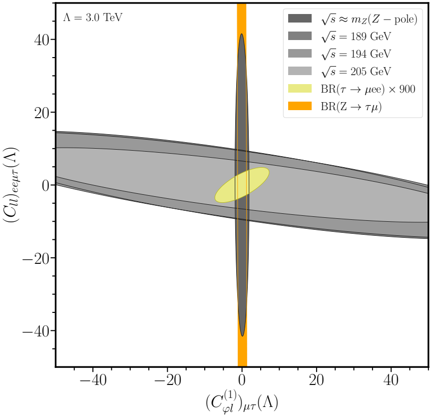
Dam 1811.09408

(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 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}]	$\epsilon^{x_c}_\text{bkg}$ [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

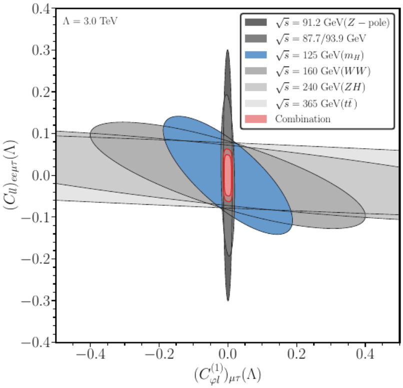
machine and detector parameters from 1809.00285, 1811.10545, 2203.09451, 2205.08553

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\rm bkg}^{x_c}$ [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 (FCC-ee)

WA, Munbodh, Oh 2305.03869



- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.

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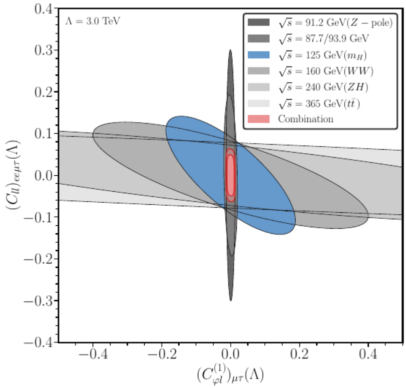
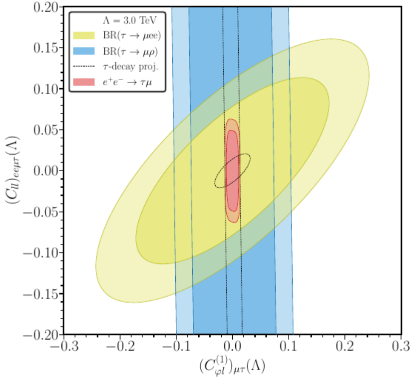
WA, Munbodh, Oh 2305.03869



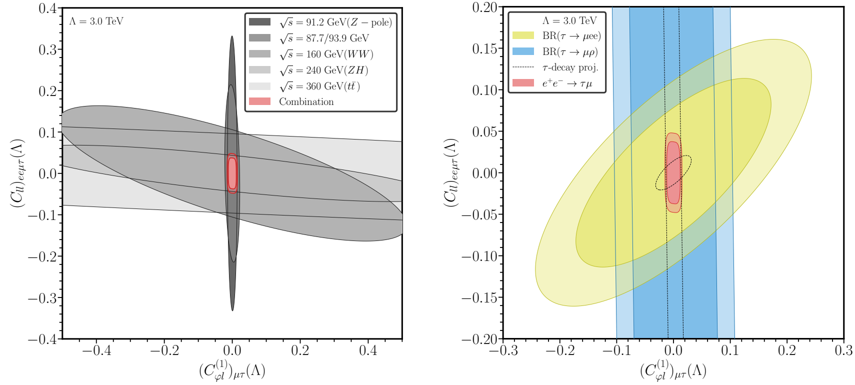


- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.
- Expected FCC-ee sensitivity rivals the one from current (BaBar/Belle) and future (Belle II) searches for LFV τ decays.

(Note: FCC-ee/CEPC can probably test rare τ decays even better than Belle II.)

Complementarity of Different Observables (CEPC)

WA, Munbodh, Oh 2305.03869



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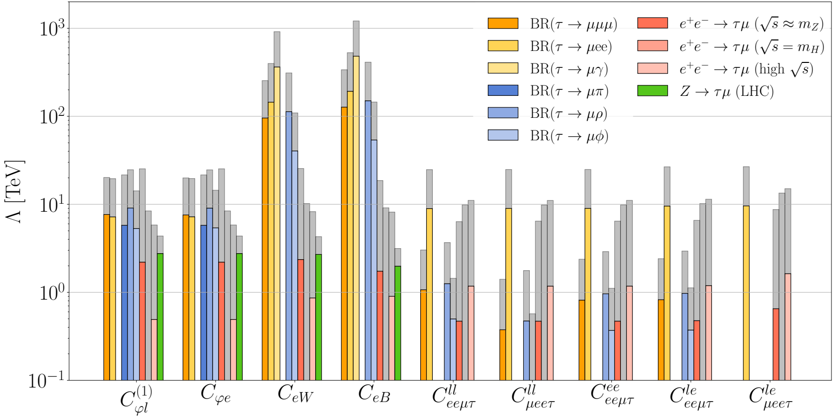
Summary of Generic Sensitivities

WA, Munbodh, Oh 2305.03869



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
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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 significantly narrow down the chirality structure of the operator that is responsible for $e^+e^- \to \tau\mu$

Summary

- Future colliders are flavor factories and offer novel opportunities to probe flavor violation.

- $\mu^+\mu^- \to bs$ at a 10 TeV muon collider could probe flavorful new physics at scales of $\sim$ 80 TeV.
- Could test the "B anomalies" without having to worry about non-perturbative hadronic physics.

- $e^+e^- \to \tau\mu$ 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.

Back Up

Forward Backward Asymmetry and Charge Tagging

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\mathrm{FB}}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\mathrm{FB}}\cos\theta\right)$$

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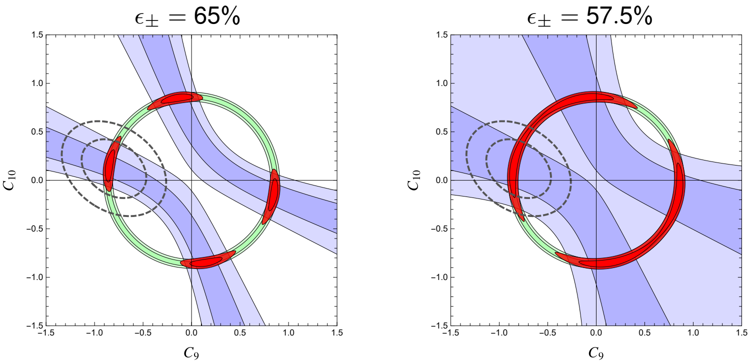
Need charge tagging to measure the forward backward asymmetry

Imperfect charge tagging dilutes the forward backward asymmetry

$$A_{\rm FB}^{\rm obs} = (2\epsilon_\pm - 1)\left(\frac{N_{\rm sig}}{N_{\rm tot}}A_{\rm FB} + \frac{N_{\rm bg}}{N_{\rm tot}}A_{\rm FB}^{\rm bg}\right)$$

As a benchmark, we assume charge tagging efficiency as at LEP
$\epsilon_\pm \simeq 70\%$ (how realistic is this?)

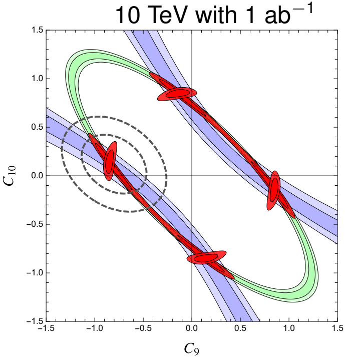
Impact of Charge Tagging

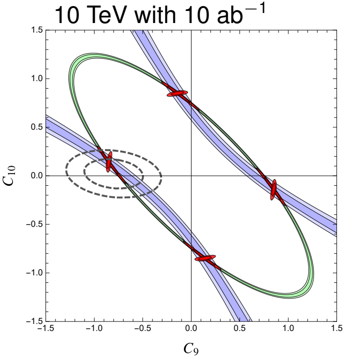


- The forward backward asymmetry gives useful information for charge tagging as low as $\sim 60\%$.
- For $\epsilon_\pm \lesssim 57.5\%$ two of the four red regions start to merge.

Impact of Beam Polarization

WA, Gadam, Profumo 2203.07495 and 2306.15017





- So far had assumed that muon beams are upolarized.
- Can expect a typical residual polarization of $\sim 20\%$ from pion decay. Higher polarization could be obtained at the cost of luminosity.
- Plots show the case of 50% polarization.

Example: LFV Z Decays

- Results from the LHC: ATLAS ($139\,\mathrm{fb}^{-1}$)

  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 $Z \to \tau\mu$

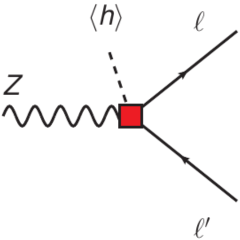
- minimize τ vs μ, e mis-id $\to$ focus on hadronic taus
- background from $Z \to \tau_{\text{had}}\tau \to \tau_{\text{had}}\ell\nu\nu$
- limits sensitivity to $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

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

dipoles

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

$$\mathcal{O}_{dB} = (\bar{\ell}\sigma^{\mu\nu} P_R \ell')H \;\; B_{\mu\nu}$$

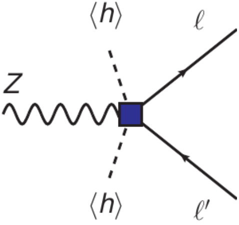


Higgs currents

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

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

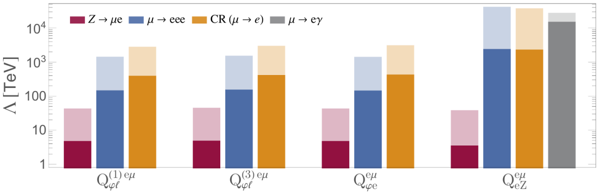
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_R \ell')$$



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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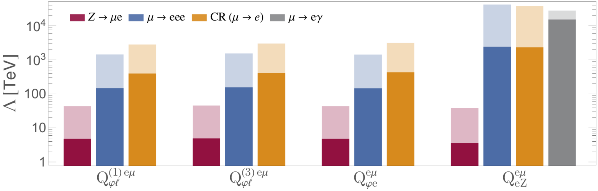
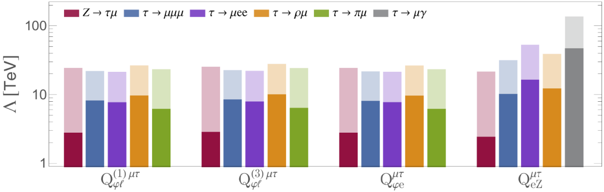


- Complementary sensitivity in the case of taus.



Another $\tau\mu$ 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.