Flavor Physics at Future Colliders

Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

New Opportunities for Particle Physics 2024
July 19 - 21, 2024
IHEP, Chinese Academy of Sciences, Beijing

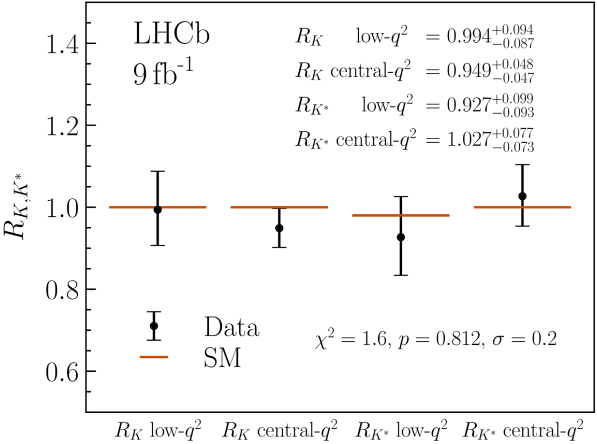
Part 1:

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

based on 2306.15017 with A. Gadam and S. Profumo

Lepton Flavor Universality Tests in $b \to s\ell\ell$

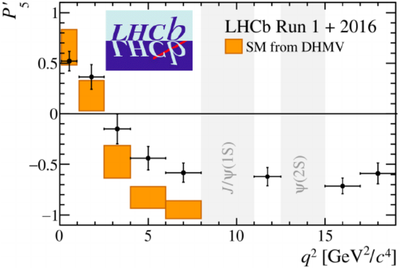
LHCb 2212.09152, 2212.09153



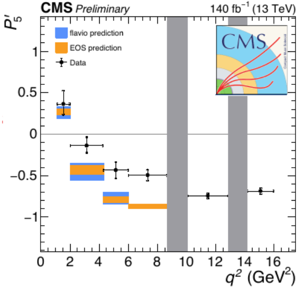
R_K and R_{K^*} are consistent with SM expectations at the $\sim 5\%$ level

New Physics in $b \to s\mu\mu$?

Many other experimental results on $b \to s\mu\mu$ don't agree well with SM predictions.
"Anomalies" both in branching ratios and angular distributions (P_5').

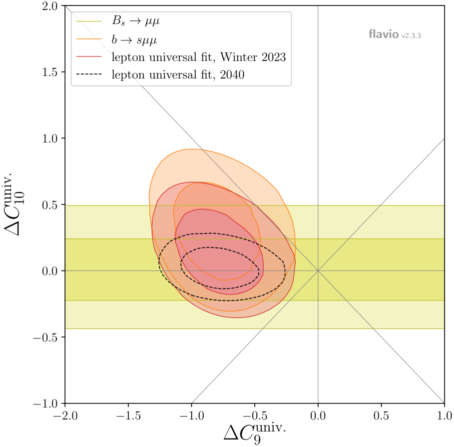


[PRL 125 (2020) 011802]



[CMS-PAS-BPH-21-002]

Fits of $b \to s\ell\ell$ Data to Lepton Universal New Physics



WA, Gadam, Profumo 2306.15017

(also Greljo et al. 2212.10497; Ciuchini et al. 2212.10516; Alguero et al. 2304.07330; Guadagnoli et al. 2308.00034; Bordone et al. 2401.18007; ...)

$$\Delta C_9^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)$$

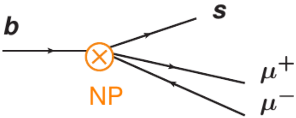
$$\Delta C_{10}^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

- LFU ratios don't give constraints (by construction)
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables (P_5' and semileptonic BRs) prefer non-standard C_9
- our fit finds a $\sim 3\sigma$ preference for new physics in C_9

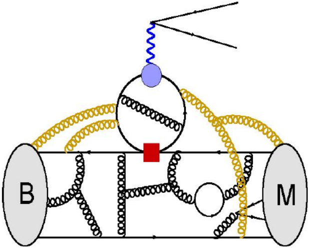
$$\Delta C_9^{\text{univ.}} \simeq -0.80 \pm 0.22$$

$$\Delta C_{10}^{\text{univ.}} \simeq +0.12 \pm 0.20$$

New Physics or Underestimated Hadronic Effects?



or



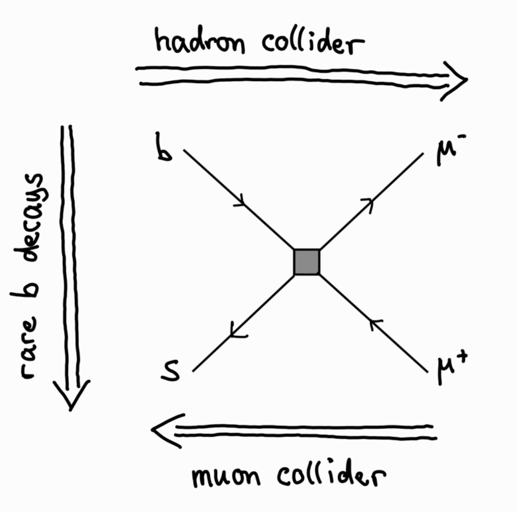
It is very difficult to distinguish lepton flavor universal new physics in C_9 from a long distance hadronic effect ("charm loops")

$$\Delta C_9^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)$$

Lot's of activity to better understand the "charm loops":
lattice QCD, QCD factorization, dispersion relations, unitarity bounds, data driven methods, generic parameterizations, models, ...

Ciuchini et al. 2212.10516; Gubernari, Reboud, van Dyk, Virto 2206.03797, 2305.06301;
LHCb 2312.09102, 2405.17347; Isidori, Polonski, Tinari 2405.17551 ... many others

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



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

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

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

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

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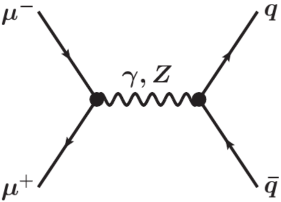
Forward backward asymmetry is sensitive to the chirality strcuture

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

Need charge tagging to measure the forward backward asymmetry

Main Background



- Mistagged dijets

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

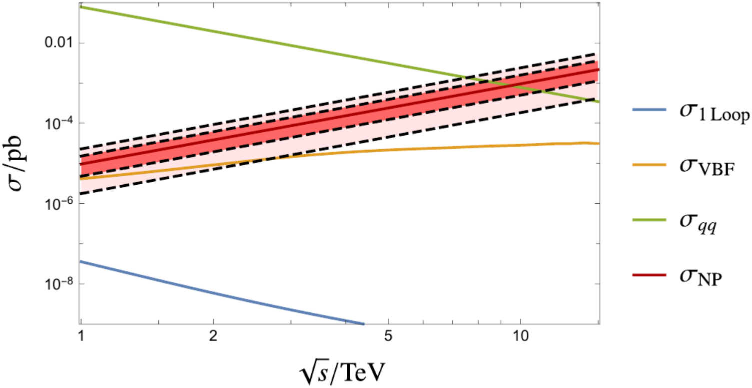
- Assume b tagging comparable to current LHC performance

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

- 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 ~ 1 for $\sqrt{s} \sim 10$ TeV.

Forward Backward Asymmetry and Charge Tagging

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Need charge tagging to measure the forward backward asymmetry

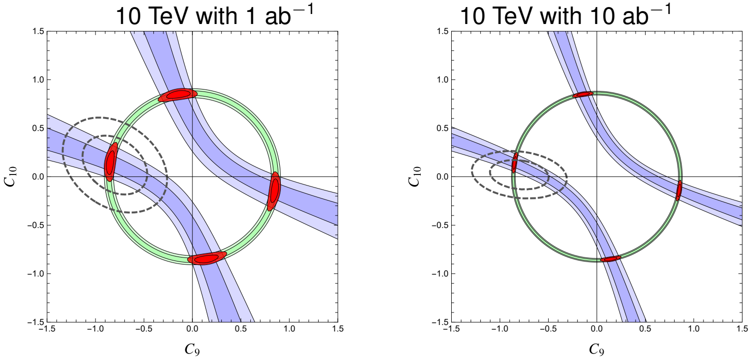
Imperfect charge tagging dilutes the forward backward asymmetry

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

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

Sensitivity Projections

WA, Gadam, Profumo 2203.07495 and 2306.15017

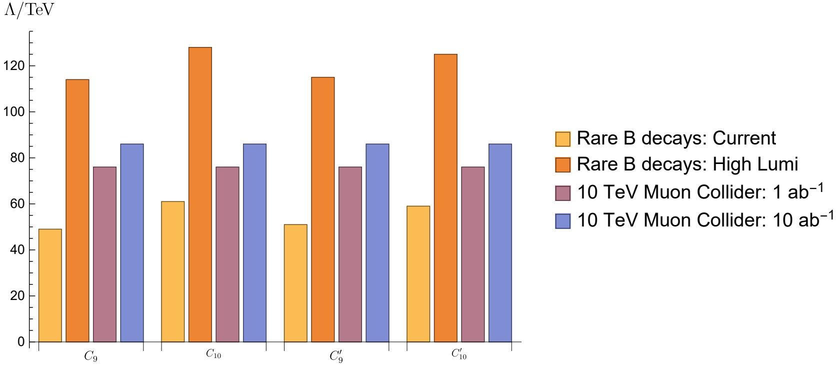


- Branching ratio (green) and A_{FB} (blue) are complementary.
- In dashed: our global rare B decay fit.
- If there is new physics in $b \to s\ell\ell$, a 10 TeV muon collider would clearly see it, and one does not need to worry about hadronic uncertainties.

(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



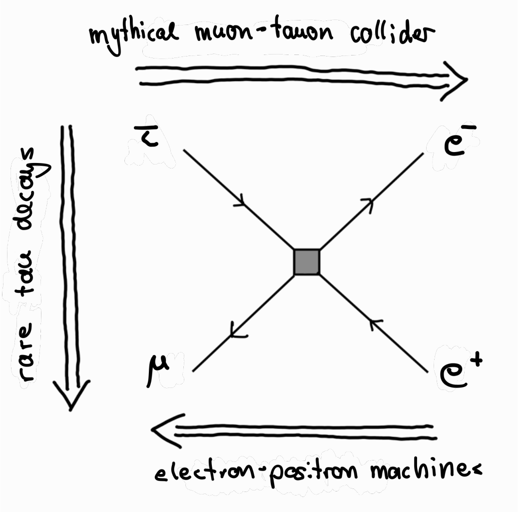
- In the absence of new physics, rare B decays and a 10 TeV muon collider have comparable sensitivity to muon specific new physics.
- Rare B decays have the advantage that a small new physics amplitude can interfere with the SM.
- At a muon collider one has to look for $|\text{new physics}|^2$.

Part 2:

Collider Probes of Lepton Flavor Violation

based on 2305.03869 with P. Munbodh and T. Oh

Collider Probes of Lepton Flavor Violation



Lepton Flavor Violation

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

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

- Any observation in the foreseeable future would be an unambiguous sign of new physics.

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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

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

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

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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]

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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- 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.

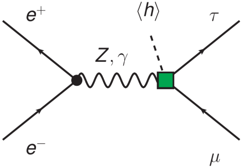
(see also Murakami, Tait 1410.1485 for a study of $e^+e^- \to \tau e$ at linear colliders)

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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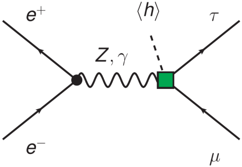
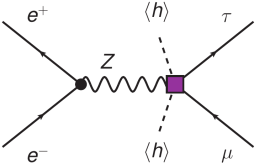


Higgs currents

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

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

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



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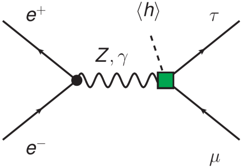

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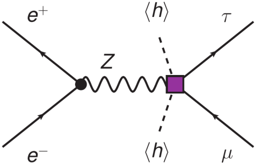
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\alpha H)(\bar{\tau}\gamma^\alpha P_R \mu)$$



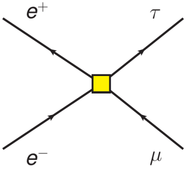
4-fermion contact interactions

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

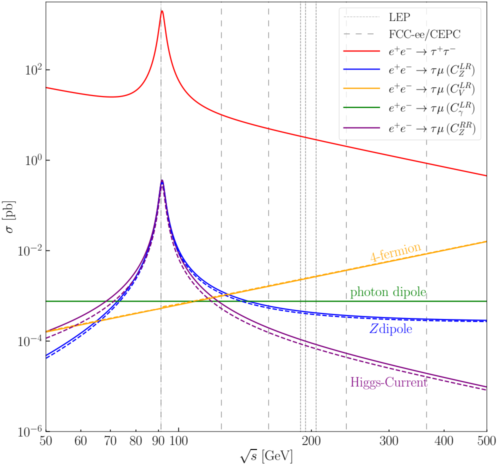
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

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

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



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

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

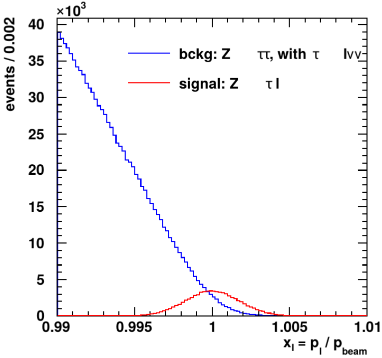
- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

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

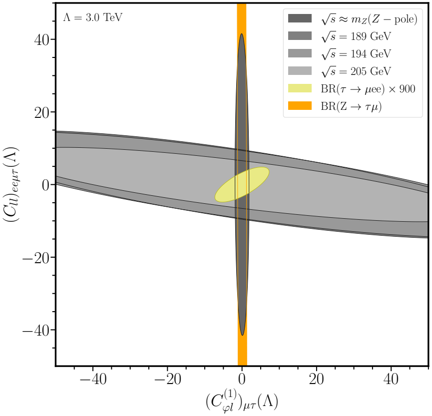


Dam 1811.09408
(study on the Z peak)

- 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 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]	$\mathcal{L}_{\text{int}}$ [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

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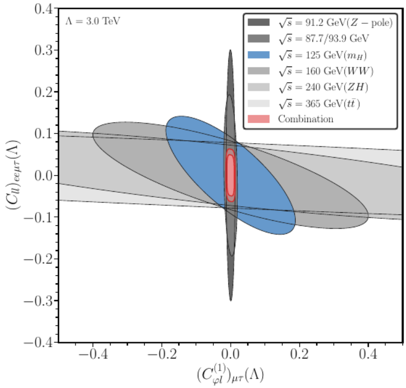
Complementarity of Different Observables (FCC-ee)

WA, Munbodh, Oh 2305.03869



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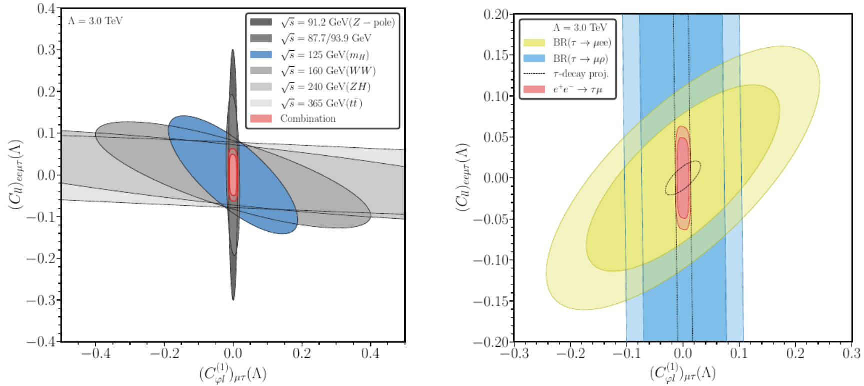

- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.
- Expected FCC-ee sensitivity rivals the one from current (BaBar/Belle) and future (Belle II) searches for LFV τ decays.

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

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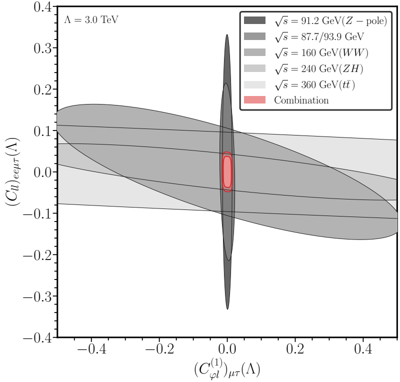

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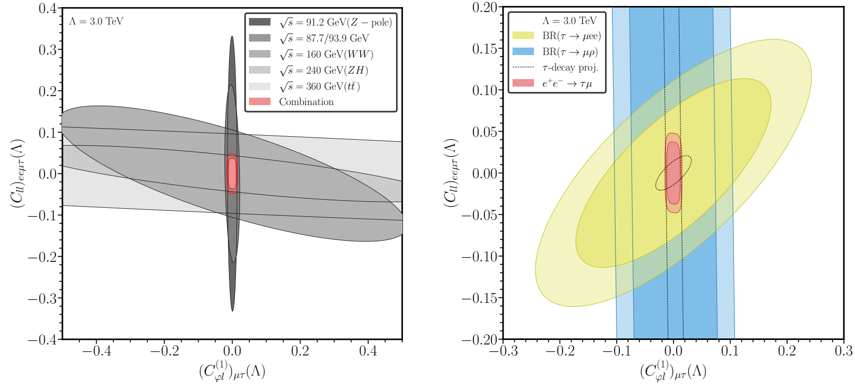

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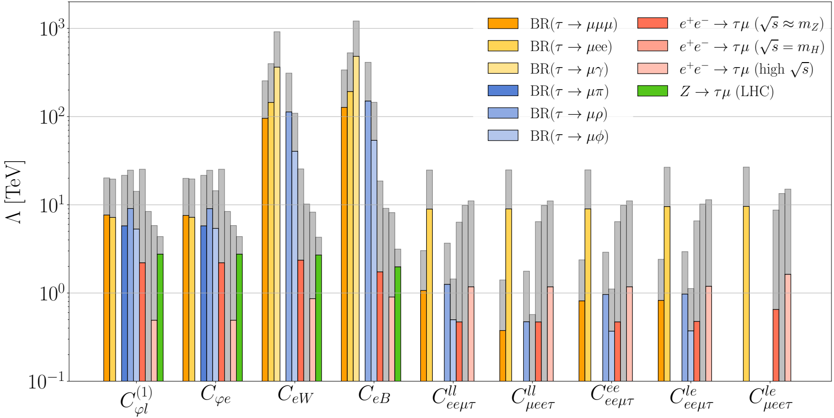
Summary of Generic Sensitivities

WA, Munbodh, Oh 2305.03869



If a Signal is Seen ...

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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

- $\mu^+\mu^- \to$ *bs* at a 10 TeV muon collider is a interesting probe of new physics.
  - Could test the “B anomalies” without having to worry about hadronic effects.
  - In the absence of new physics, could probe $(\mu\mu)$(*bs*) contact interactions at scales of $\sim$ 80 TeV.

Summary

- $\mu^+\mu^- \to$ *bs* at a 10 TeV muon collider is a interesting probe of new physics.
  - Could test the “B anomalies” without having to worry about hadronic effects.
  - In the absence of new physics, could probe $(\mu\mu)$(*bs*) contact interactions at scales of $\sim$ 80 TeV.
- 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.

Back Up

Another $\tau\mu$ Background at High Energies?

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

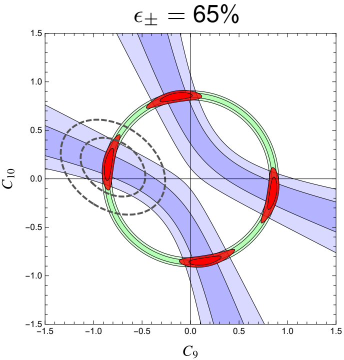
- Muon momentum does not extend all the way to $x = 1$
- Decay kinematics is such that

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

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

$\Rightarrow$ this background is not an issue.

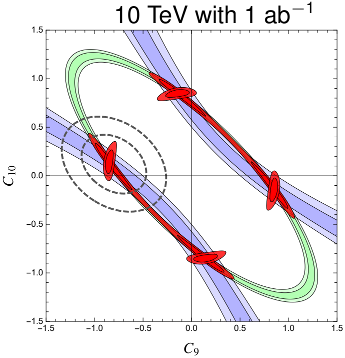
Impact of Charge Tagging

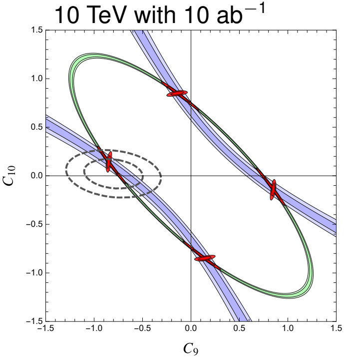


- The forward backward asymmetry gives useful information for charge tagging as low as $\sim 60\%$.
- For $\epsilon_\pm \lesssim 57.5\%$ two of the four red regions start to merge.

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 fb^{-1})

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

$$\text{BR}(Z \to \mu e) < 3.04 \times 10^{-7}$$

$$\text{BR}(Z \to \tau e) < 5.0 \times 10^{-6}$$

$$\text{BR}(Z \to \tau \mu) < 6.5 \times 10^{-6}$$

- Slightly better than LEP bounds for all decay modes.
- In all searches there are backgrounds ⇒ 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 → focus on hadronic taus
- background from $Z \to \tau_{\text{had}}\tau \to \tau_{\text{had}}\ell\nu\nu$
- limits sensitivity to $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

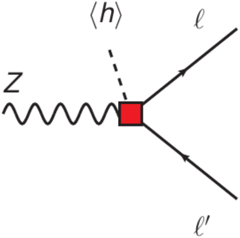
LFV Z Decays in the EFT Framework

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

dipoles

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

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

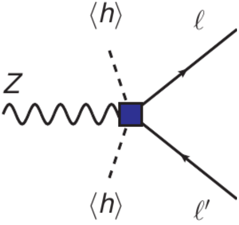


Higgs currents

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

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

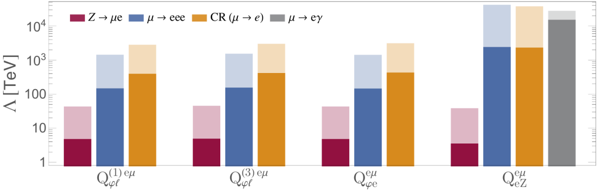
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_R \ell')$$



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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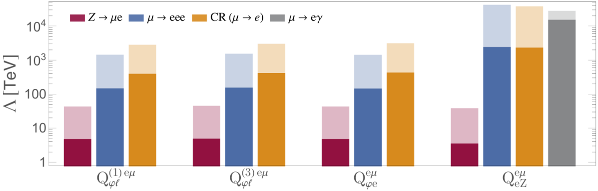

- Complementary sensitivity in the case of taus.