Charged Lepton Flavor Violation in Heavy Particle Decays

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based on Whitepaper in preparation with:

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(personal selection of topics, apologies for omissions)

Snowmass Rare and Precision Frontier Meeting

Cincinnati, May 16 - 19, 2022

Heavy State LFV Decays and New Physics

- In the SM, lepton flavor violating decays of the Z, Higgs, and top are suppressed by the tiny neutrino mass splittings

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

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

Constraints from Low Energy

- Consider LFV decays of the Z boson, the Higgs, the top in the presence of generic New Physics

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

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

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- Compare to low energy probes (e.g. muon decays, tau decays)

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

- Same dependence on NP couplings and scale, but much less Z, Higgs, top available in experiments

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

LFV Z Decays

Existing/Expected Bounds from the LHC

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

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

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

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

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

- For the $Z \to \tau e$ and $Z \to \tau\mu$ searches, both leptonic and hadronic tau decays are taken into account.
- Better than LEP 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 $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

- Z couplings are protected by $SU(2)$ gauge symmetry

$\Rightarrow$ generic expectation for a new physics effect

$$\frac{\text{BR}(Z \to \ell\ell')}{\text{BR}(Z \to \ell\ell)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 \sim 4 \times 10^{-7} \times g_{\text{NP}}^2 \left(\frac{10\,\text{TeV}}{\Lambda_{\text{NP}}}\right)^4$$

$\Rightarrow$ sensitivity to New Physics at scales of

$\Lambda_{\text{NP}} \sim$ 10 TeV at the HL-LHC

$\Lambda_{\text{NP}} \sim$ 50 TeV at FCC-ee/CEPC

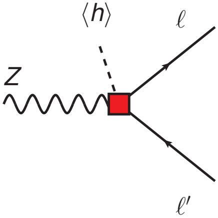
LFV Z Decays in the EFT Framework

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

dipoles

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

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

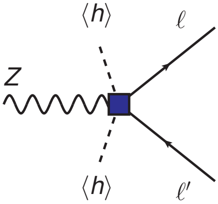


Higgs currents

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

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

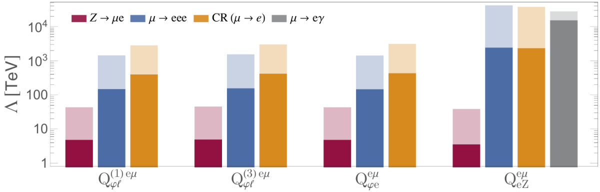
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_R \ell')$$



Complementarity 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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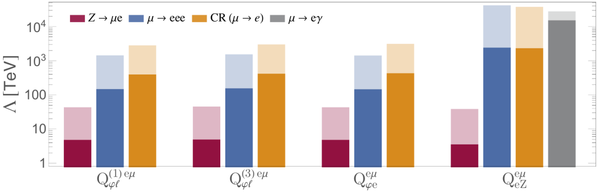
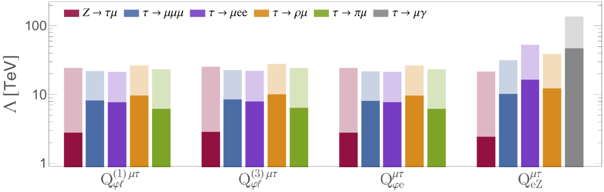


- Complementary sensitivity in the case of taus.



LFV Higgs Decays

Sensitivity at the LHC

- Results from the LHC
  ATLAS 1907.06131 ($\sim 36\,\text{fb}^{-1}$), ATLAS 1909.10235 ($\sim 139\,\text{fb}^{-1}$), CMS 2105.03007 ($\sim 137\,\text{fb}^{-1}$)

$$\text{BR}(H \to \mu e) < 6.1 \times 10^{-5}$$
$$\text{BR}(H \to \tau e) < 0.22\%$$
$$\text{BR}(H \to \tau \mu) < 0.15\%$$

- Expect all sensitivities to improve by $\sim$ 1 order of magnitude at the HL-LHC. (luminosity + improved reconstruction of hadronic taus + improved analysis strategy)

Prospects at Future e^+e^- Colliders

Qin et al. 1711.07243

- Consider electron positron colliders in "Higgs factory mode" $e^+e^- \to HZ$
- Expect: $\sim 10^6$ Higgs bosons at FCC-ee/CEPC and
  $\sim 0.5 \times 10^6$ Higgs bosons at ILC
- Look for hadronic decays of the Z

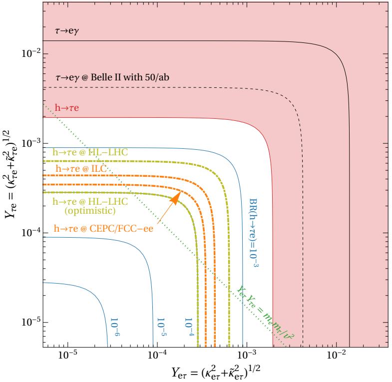
$$\text{BR}(H \to \mu e) \lesssim 1.2 \times 10^{-5} \text{ @FCC-ee/CEPC} , \quad 2.1 \times 10^{-5} \text{ @ILC}$$

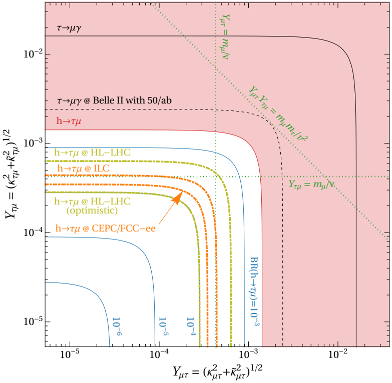
$$\text{BR}(H \to \tau e) \lesssim 1.5 \times 10^{-4} \text{ @FCC-ee/CEPC} , \quad 2.5 \times 10^{-4} \text{ @ILC}$$

$$\text{BR}(H \to \tau \mu) \lesssim 1.5 \times 10^{-4} \text{ @FCC-ee/CEPC} , \quad 2.5 \times 10^{-4} \text{ @ILC}$$

- Study only used leptonically decaying taus. Might be able to improve sensitivity by taking into account also hadronic tau decays.

Bounds on Flavor Violating Higgs Couplings



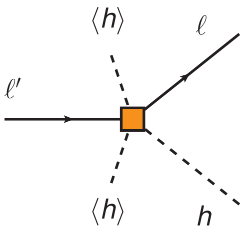


- Weak indirect constraints from $\tau \to \mu\gamma$ and $\tau \to e\gamma$.
- $\mu \to e\gamma$ strongly constrains BR($H \to \mu e$) and BR($H \to \tau\mu$)$\times$BR($H \to \tau e$)

Blankenburg, Ellis, Isidori 1107.1216; Harnik, Kopp, Zupan 1209.1397; Davidson, Verdier 1211.1248

LFV Higgs Decays in the EFT Framework

$$\frac{C_{\ell\ell'}}{\Lambda_{\rm NP}^2}\mathcal{O}_{eh} = \frac{C_{\ell\ell'}}{\Lambda_{\rm NP}^2}(H^\dagger H)(\bar\ell P_R \ell')H$$



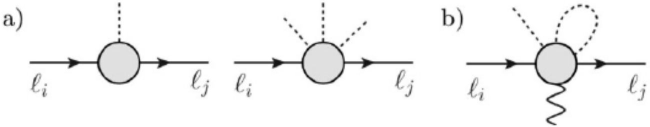
- Gives flavor changing Higgs couplings

$$Y_{\ell\ell'} = \frac{C_{\ell\ell'}}{\sqrt{2}}\frac{v^2}{\Lambda_{\rm NP}^2} \sim 4\times 10^{-4}\left(\frac{10\,\text{TeV}}{\Lambda_{\rm NP}}\right)^2$$

- Expected sensitivities at future machines probe new physics at $\Lambda_{\rm NP} \sim 10$ TeV.

LFV Higgs Decays in NP Models

In new physics models one often encounters strong constraints:
The physics that generates the LFV Higgs coupling, will typically also give direct contributions to radiative decays (Dorsner et al. 1502.07784)



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

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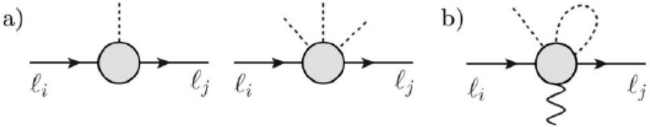


Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

handwavy upper bound in many models

$$\text{BR}(h \to \tau\mu) \sim 26 \times \text{BR}(\tau \to \mu\gamma) \lesssim 10^{-6}$$

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

$\Rightarrow$ Observation of a LFV Higgs decay with expected exp. sensitivities likely implies an additional source of EW symmetry breaking

LFV Top Decays

EFT Setup and Sensitivity to New Physics

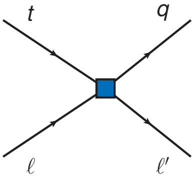
3 body decays that violate lepton and quark flavor $t \to q\ell\ell'$

(Davidson, Mangano, Perries, Sordini 1507.07163)

$$\mathcal{O}_{LL} = (\bar{q}\gamma_\mu P_L t)(\bar{\ell}\gamma^\mu P_L \ell')$$

$$\mathcal{O}_{RR} = (\bar{q}\gamma_\mu P_R t)(\bar{\ell}\gamma^\mu P_R \ell')$$

$+$ many other Dirac structures



The decays are competing with an unsuppressed 2 body decay $t \to Wb$

$$\text{BR}(t \to c\mu e) \sim \frac{g_{\text{NP}}^2}{16\pi^2}\left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 \sim 2 \times 10^{-5} \times g_{\text{NP}}^2 \left(\frac{1\,\text{TeV}}{\Lambda_{\text{NP}}}\right)^4$$

- Strong indirect bounds from B meson decays if left handed quarks are involved.
- For right handed quarks, LHC has the best sensitivity.

Experimental Sensitivity

- Look for $t\bar{t}$ production followed by a rare top decay $t \to q\mu e$ and also for non-standard single top production $gq \to t\mu e$.

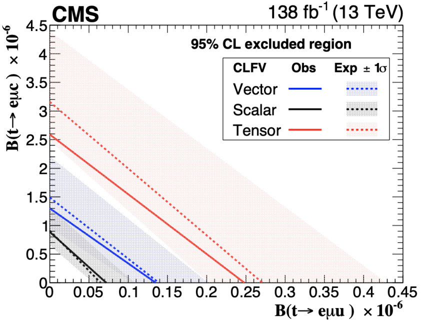
- Main background from $t\bar{t}$, which gives two b-jets
- Signal has only a single b-jet
- Translation into top branching ratio depends on the Dirac structure of the operator

$$\text{BR}(t \to u\mu e) \lesssim 10^{-7}$$

$$\text{BR}(t \to c\mu e) \lesssim 10^{-6}$$

- Expect factor of ~ 5 improvement at HL-LHC
- For further improvement need FCC-hh

CMS 2201.07859 (138 fb^{-1})



LFV New Physics Resonances

LFV New Physics Resonances at the LHC

- Many BSM scenarios contain neutral resonances that can have lepton flavor violating couplings
  e.g. Z' bosons, or additional neutral Higgs bosons H.

- Extend the Z and Higgs searches to higher (and lower!) masses

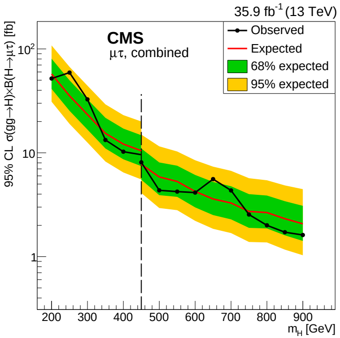
$$pp \to Z' \to e\mu, e\tau, \mu\tau \ , \qquad pp \to H \to e\mu, e\tau, \mu\tau$$

- In contrast to standard high-mass di-lepton resonance searches, no irreducible background from Drell-Yan

- Main background from $t\bar{t}$ and di-bosons, or multi-jets, W+jets with jets misidentified as leptons

Example : search for high mass Higgs bosons decaying to $\tau\mu$

CMS 1911.10267



Example Results from the LHC

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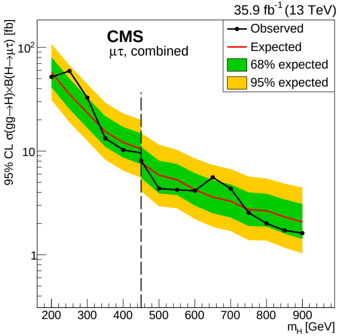
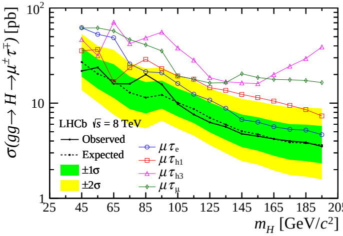
CMS 1911.10267



LHCb has interesting sensitivities at low masses.

Example: search for light Higgs bosons decaying to $\tau\mu$

LHCb 1808.07135



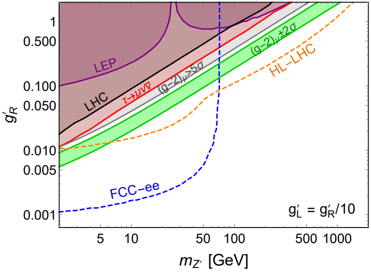
- If the new resonance couples to electrons:

$$e^+e^- \to Z' \to e\mu, e\tau, \mu\tau \ , \qquad e^+e^- \to H \to e\mu, e\tau, \mu\tau$$

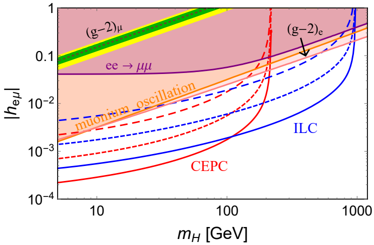
- If the new resonance has only lepton flavor violating couplings one can get spectacular same sign lepton pair signatures

$$\text{e.g.} \quad e^+e^- \to Z'\tau^+\mu^- \to \tau^+\tau^+\mu^-\mu^-$$

update of WA, Chen, Dev, Soni 1607.06832



Dev, Mohapatra, Zhang 1711.08430



Summary

- Lepton flavor violating decays of Z, Higgs, top are clear signatures of NP.
- With the expected experimental sensitivities one can probe NP scales of 10 TeV or even higher.
- Often strong indirect constraints from low energy lepton flavor violating processes ($\mu \to e\gamma$ etc.), but in many cases there is complementary sensitivity to the NP.
- BSM resonances can also give prominent lepton flavor violating signatures. Worthwhile to extend the searches to a as broad mass range as possible.