Introduction to Heavy State LFV Decays

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Charged Lepton Flavor Violation - Heavy State Decays
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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 a clear sign of new physics.

The Challenge: Constraints from Low Energy

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

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

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

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

LFV Z Decays

Existing Bounds from LEP

- Results from a few $\times 10^6$ Z bosons at LEP
  L3 PLB 316, 427 (1993), OPAL Z. Phys. C67, 555 (1995), DELPHI Z. Phys. C73, 243 (1997)

$$\text{BR}(Z \to \mu e) < 1.7 \times 10^{-6}$$
$$\text{BR}(Z \to \tau e) < 9.8 \times 10^{-6}$$
$$\text{BR}(Z \to \tau \mu) < 1.2 \times 10^{-5}$$

- $Z \to \mu e$ was background free at LEP, but not $Z \to \tau e$ and $Z \to \tau\mu$.
- Main backgrounds from $Z \to \tau\tau$, $Z \to \mu\mu$, $Z \to ee$
  with mis-identified leptons.

Existing/Expected Bounds from LHC

- Results from the LHC

  ATLAS 1804.09568 ($\sim$ 36 fb, run 2), ATLAS 1408.5774 ($\sim$ 20 fb, run 1)

$$\mathrm{BR}(Z \to \mu e) < 7.5 \times 10^{-7}$$
$$\mathrm{BR}(Z \to \tau e) < 5.8 \times 10^{-5}$$
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- In all cases one has to deal with backgrounds.

- Expect sensitivities to improve by $\sim$ 1 order of magnitude at the HL-LHC.

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- Expectations for future colliders (CEPC, FCC-ee)?

Implications for New Physics

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

$\Rightarrow$ generic expectation for a new physics effect

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

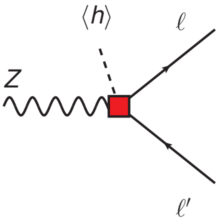
$\Rightarrow$ indirect sensitivity to New Physics up to scales of $\sim$ 10 TeV

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

dipoles

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

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

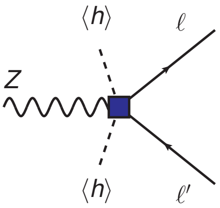


Higgs currents

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

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

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



Complementarity with Low Energy Probes

- Many flavor violating low energy processes will be affected as well.

$$\ell \to \ell' \gamma \quad , \quad \ell \to 3\ell' \quad , \quad \tau \to \ell \pi \quad , \quad ...$$

- Examples of current bounds

$$\text{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13} \quad \text{(MEG 1605.05081)}$$

$$\text{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \quad \text{(BaBar 0908.2381)}$$

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- Will improve by at least 1 order of magnitude at relevant time scales.
- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).
  (e.g. Delepine, Vissani hep-ph/0106287; Davidson, Lacroix, Verdier 1207.4894)
- Complementary sensitivity in the case of taus.

LFV Higgs Decays

Sensitivity at the LHC

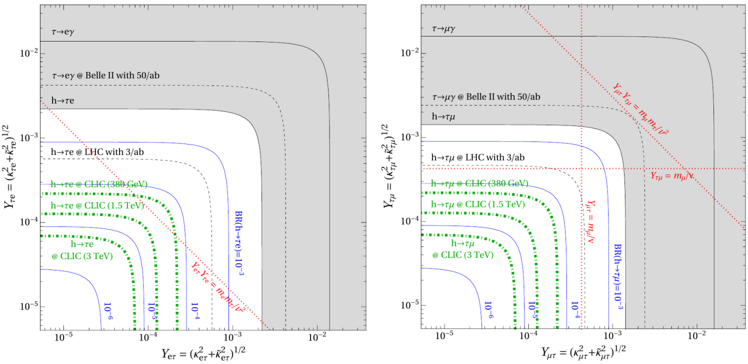
- Results from the LHC

  ATLAS 1907.06131 ($\sim$ 36 fb), ATLAS 1909.10235 ($\sim$ 139 fb), CMS 1712.07173 ($\sim$ 36 fb)

$$\mathrm{BR}(H \to \mu e) < 6.1 \times 10^{-5}$$
$$\mathrm{BR}(H \to \tau e) < 0.28\%$$
$$\mathrm{BR}(H \to \tau \mu) < 0.25\%$$

- Expect all sensitivities to improve by $\sim$ 1 order of magnitude at the HL-LHC.

Bounds on Flavor Violating Higgs Couplings

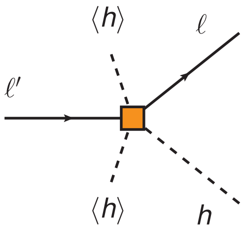


- Weak indirect constraints from $\tau \to \mu\gamma$ and $\tau \to e\gamma$.
- But $\mu \to e\gamma$ strongly constrains BR($H \to \mu e$) and BR($H \to \tau\mu$)×BR($H \to \tau e$)

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

LFV Higgs Decays in the EFT Framework

$$\mathcal{O}_{eh} = (H^\dagger H)(\bar{\ell} P_R \ell')H$$

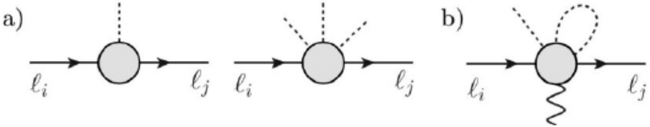


- LFV decays like $\mu \to 3e$ or $\tau \to 3\mu$ are strongly suppressed by small Yukawa couplings.
- Most important constraints from loop induced radiative decays $\tau \to \mu\gamma$, $\tau \to e\gamma$, and $\mu \to e\gamma$

(Careful when calculating loops with modified Higgs couplings. Results might be gauge dependent, see e.g. WA, Gori, Hamer, Patel arXiv:2009.tonight)

LFV Higgs Decays in NP Models

Situation can be rather different in concrete models:
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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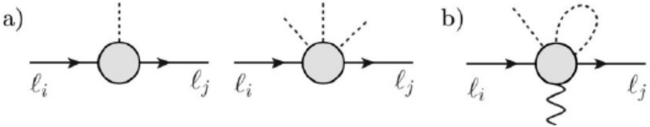


Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

generic 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

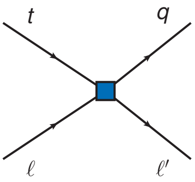
3 body decays that violate lepton and quark flavor $t \to q\ell\ell'$

(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 $t \to Wb$

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

- Possibly in reach of the LHC for New Physics at the TeV scale.
- Often indirect bounds from meson decays.

- Lepton flavor violating decays of Z, Higgs, top are clear signatures of NP.
- With the expected experimental sensitivities one can probe NP scales in the 1 - 10 TeV range.
- 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.

Back Up

LFV Z Decays at Future Colliders

- Preliminary study in the context of FCC-ee (Mogens Dam 1811.09408)

$Z \to \mu e$

- background from $Z \to \tau\tau \to \mu\nu\nu\ e\nu\nu$ under control. Momentum res. of 10^{-3} implies background rate of 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 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 $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$