Charged Lepton Flavor Violation in Heavy Particle Decays

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Heavy State CLFV 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.

Comparision with Low Energy Probes

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

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

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

Comparision with Low Energy Probes

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

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

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

- 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/naive expectations; situation can be very different in concrete models.

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884

Framing the Discussion Model Independently: SMEFT

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

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Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
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Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
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Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
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$8: (\bar RR)(\bar RR)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
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$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar LL)(\bar RR)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
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$8: (\bar LR)(\bar RL) + \mathrm{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

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$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884

4 fermion interactions

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
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$5: \psi^2 H^3 + \text{h.c.}$	
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$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G_{\mu\nu}^A$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W_{\mu\nu}^I$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
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$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
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Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
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$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
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dipole transitions

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$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q^{(1)}_{lq}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q^{(8)}_{ud}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q^{(1)}_{qd}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l^j_p e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q^{(1)}_{quqd}$	$(\bar q^j_p u_r)\epsilon_{jk}(\bar q^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar q^j_p T^A u_r)\epsilon_{jk}(\bar q^k_s T^A d_t)$
$Q^{(1)}_{lequ}$	$(\bar l^j_p e_r)\epsilon_{jk}(\bar q^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar l^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q^k_s \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884

4 fermion interactions

dipole transitions

“Z-penguins”

Framing the Discussion Model Independently: SMEFT

1 : X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

2 : H^6	
Q_H	$(H^\dagger H)^3$

3 : $H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

5 : $\psi^2 H^3$ + h.c.	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

4 : $X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

6 : $\psi^2 X H$ + h.c.	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H} G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H} W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

7 : $\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

8 : $(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

8 : $(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

8 : $(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
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$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

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"Z-penguins"

"Higgs penguins"

LFV Z Decays

Existing/Expected Bounds from the LHC

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

  PRL 127 (2022) 271801; Nature Phys. 17 (2021) 7, 819-825; PRD 108 (2023) 032015

$$\mathrm{BR}(Z \to \mu e) < 2.62 \times 10^{-7}$$
$$\mathrm{BR}(Z \to \tau e) < 5.0 \times 10^{-6}$$
$$\mathrm{BR}(Z \to \tau \mu) < 6.5 \times 10^{-6}$$

- 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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- With improved e/μ separation (dE/dx) might be able to go down to $\text{BR}(Z \to \mu e) \sim 10^{-10}$.

$Z \to \tau e$ 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 $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

Implications for New Physics

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

$\Rightarrow$ generic expectation for a new physics effect

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

$\Rightarrow$ 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

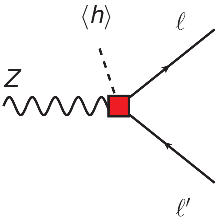
LFV Z Decays in the EFT Framework

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

dipoles

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

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

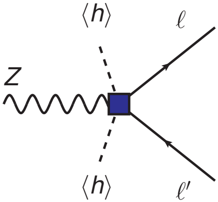


"Z penguins"

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

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

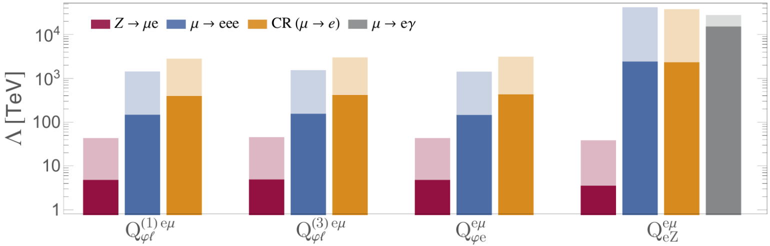
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_R \ell')$$



Complementarity with Low Energy Probes

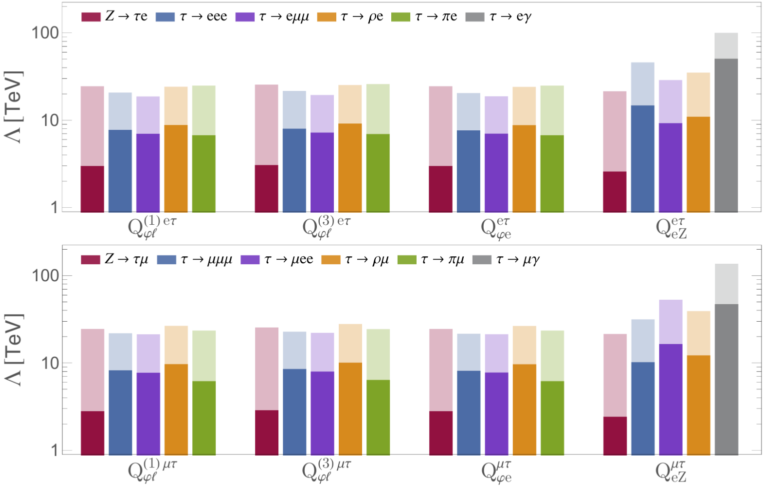
- Many flavor violating low energy processes will be affected as well.
- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).

Calibbi, Marcano, Roy 2107.10273 (also Li, Schmidt 1809.07924)



- Complementary sensitivity in the case of taus.

Calibbi, Marcano, Roy 2107.10273 (also Li, Schmidt 1809.07924)



LFV Higgs Decays

Current and Future Sensitivities

- Results from the LHC

  ATLAS JHEP 07 (2023) 166 ($\sim 138\,\mathrm{fb}^{-1}$), ATLAS PLB 801 (2020) 135148 ($\sim 139\,\mathrm{fb}^{-1}$), CMS PRD 104 (2021) 3, 032013 ($\sim 137\,\mathrm{fb}^{-1}$)

$$\mathrm{BR}(H \to \mu e) < 6.1 \times 10^{-5}$$
$$\mathrm{BR}(H \to \tau e) < 0.20\%$$
$$\mathrm{BR}(H \to \tau \mu) < 0.15\%$$

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

- Expect sensitivities at future e^+e^- colliders that are at least as good

  (Qin et al. 1711.07243)

The Higgs and Flavor

$$\mathcal{L}_{\text{Yukawa}} = \lambda_{ij} \, \bar{\Psi}_i \Psi_j \, H$$

In the Standard Model the Yukawa couplings are
the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are
flavor diagonal and CP conserving

$$\frac{1}{v} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$

The Higgs and Flavor

$$\mathcal{L}_{\text{Yukawa}} = \lambda_{ij}\, \bar{\Psi}_i \Psi_j\, H + \frac{\tilde{\lambda}_{ij}}{\Lambda^2}\, \bar{\Psi}_i \Psi_j\, H^3$$

In the Standard Model the Yukawa couplings are the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are flavor diagonal and CP conserving

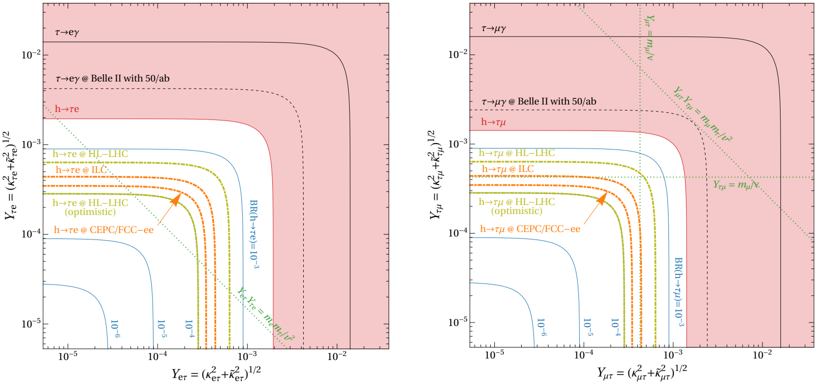
$$\frac{1}{v}\begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \frac{v^2}{\Lambda^2}\begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

1) New Physics can modify the flavor diagonal Higgs couplings
2) New Physics can lead to flavor and CP violating Higgs couplings

Phenomenological parameterization: $\mathcal{L}_{\text{CLFV}} = -Y_{\ell\ell'}\, \bar{\ell} P_R \ell'\, h + \text{h.c.}$

Bounds on Flavor Violating Higgs Couplings

WA, Caillol, Dam, Xella, Zhang 2205.10576

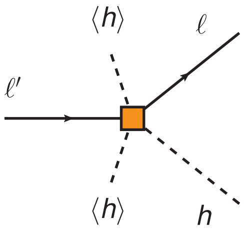


- Weak indirect constraints from $\tau \to \mu\gamma$ and $\tau \to e\gamma$.
- $\mu \to e\gamma$ strongly constrains BR($H \to \mu e$) and BR($H \to \tau\mu$)$\times$BR($H \to \tau e$)

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

LFV Higgs Decays in the EFT Framework

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



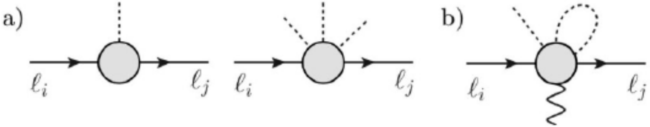
- Gives flavor changing Higgs couplings

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

- 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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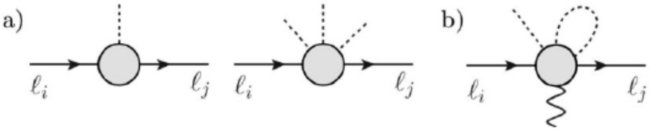


Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

handwavy upper bound in many models

(assuming that the Wilson coefficient of the dipole is $\frac{1}{16\pi^2} \times$ the Wilson coeffcient of the Higgs penguin)

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

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

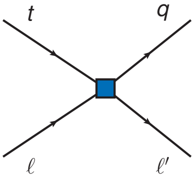
3 body decays that violate lepton and quark flavor $t \to q\ell\ell'$

(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 $gq \to t\mu e$.

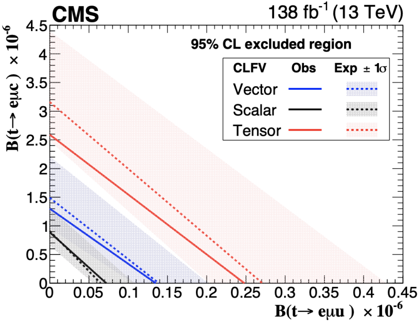
- Main background from $t\bar{t}$, which gives two b-jets
- Signal has only a single b-jet
- Translation into top branching ratio depends on the Dirac structure of the operator

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

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

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

CMS JHEP 06 (2022) 082 (138 fb^{-1})



LFV New Physics Resonances

LFV New Physics Resonances

- Many BSM scenarios contain neutral resonances that can have lepton flavor violating couplings

  e.g. Z' bosons, or additional neutral Higgs bosons H.

- Obvious approach: extend the Z and Higgs searches to higher (and lower!) masses

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

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

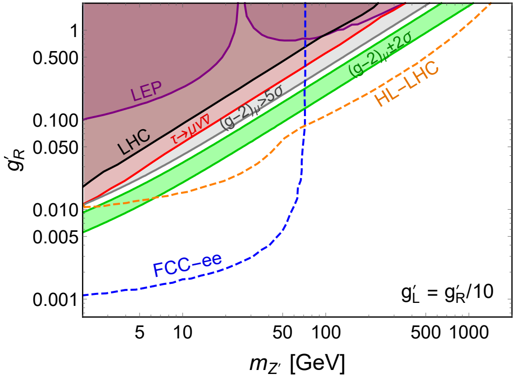
- In contrast to standard high-mass di-lepton resonance searches, no irreducible background from Drell-Yan

Exotic Scenarios

- Can imagine exotic scenarios: e.g. a Z' that couples dominantly in a flavor violating way to $\tau\mu$ (can give a viable explanation of $(g-2)_\mu$)
- Currently weakly constrained, but could give spectacular same sign lepton pair signatures at lepton colliders

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

WA, Caillol, Dam, Xella, Zhang 2205.10576 (update of WA, Chen, Dev, Soni 1607.06832)

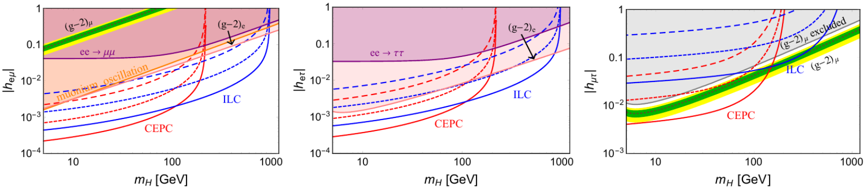


More Exotic Scenarios

- Similar results are found for additional Higgs boson that have only flavor violating couplings

$$\text{e.g.} \quad e^+e^- \to H\mu^+e^- \to \mu^+\mu^+e^-e^-$$

Dev, Mohapatra, Zhang 1711.08430



- Model building challenge: construct a model in which these exotic Z' or Higgs bosons with only flavor violating couplings arise.

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.