Charged Lepton Flavour Change and Non-Standard Neutrino Interactions (or Lepton Number Violation)

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Content

- Consider non standard neutrino interactions (NSIs) generated at heavy scales
- flavour structure of NSIs generates lepton flavour violation (LFV)
  - at tree-level
  - but also at loop-level $\leftarrow$ this talk
- Use Standard Model Effective Theory (SMEFT) to study this model independently
- Lepton number violating $d = 5$ operators also generate LFV

Non-Standard Interactions of Neutrinos

- Production and detection ← charged current interactions
- Propagation in matter ← neutral current interactions
- Non-Standard Neutrino Interactions (NSIs)
  - Modify Propagation of Neutrinos in matter
- This talk: consider NSIs for $q^2 \ll M_W^2$

$$\mathcal{L} \supset -2\sqrt{G_F}\varepsilon^{\rho\sigma}_{f,(L)}(\overline{\nu}_\rho \gamma_\alpha \nu_\sigma)(\bar{f}\gamma^\alpha (P_L) f)$$

- Neutrino experiments percent level sensitivity
- Wider class of NSIs studied

Generating NSIs

- Generate NSI either via
  a) (not so) heavy mediators above M_W
  b) via new light degrees of freedom
- a) can be studied model independently using effective field theories
- This talk: use SMEFT operators up to $d(O) = 8$:

$$\mathcal{L} = \lambda/2(H^\dagger H)^2 - M^2(H^\dagger H) + \cdots + \sum_{O\rho\sigma} \frac{C_O^{\rho\sigma}}{\Lambda^{d(O)-4}} O^{\rho\sigma}$$

- b) have to be studied for each new light degree of freedom. Perturbative calculations could be done for wide classes of models, see e.g. [1903.05116] for the calculation of the Z-Penguin in renormalisable theories.

SMEFT up to $d(O) = 6$

- Fields: $q \in \left\{ \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right\}$ and $f \in \{u_R, d_R, e_R\}$.

$$O^{\rho\sigma}_{M2,f} = (\bar{\ell}_\rho \gamma_\alpha \ell_\sigma)(\bar{f}\gamma^\alpha f)$$
$$O^{\rho\sigma}_{M2,q} = (\bar{\ell}_\rho \gamma_\alpha \ell_\sigma)(\bar{q}\gamma^\alpha q), \quad O^{\rho\sigma}_{LQM2,q} = (\bar{\ell}_\rho \gamma_\alpha q)(\bar{q}\gamma^\alpha \ell_\sigma)$$

- NSI, LFV & charged currents for $q^2 \ll M_W^2$:

$$O^{\rho\sigma}_{M2,f} \rightarrow (\bar{e}_\rho \gamma_\alpha e_{L,\sigma} + \bar{\nu}_\rho \gamma_\alpha \nu_\sigma)(\bar{f}\gamma^\alpha f_R)$$
$$O^{\rho\sigma}_{M2,q} \rightarrow (\bar{e}_\rho \gamma_\alpha e_{L,\sigma} + \bar{\nu}_\rho \gamma_\alpha \nu_\sigma)(\bar{u}\gamma^\alpha u_L + \bar{d}\gamma^\alpha d_L)$$
$$O^{\rho\sigma}_{LQM2,q} \rightarrow (\bar{e}_\rho \gamma_\alpha e_{L,\sigma})(\bar{d}\gamma^\alpha d_L) + (\bar{\nu}_\rho \gamma_\alpha \nu_\sigma)(\bar{u}\gamma^\alpha u_L) + (\bar{\nu}_\rho \gamma_\alpha e_{L,\sigma})(\bar{d}\gamma^\alpha u_L) + (\bar{\nu}_\rho \gamma_\alpha e_\sigma)(\bar{u}\gamma^\alpha d_L)$$

- tree level & $d(O) = 6$): NSI and LFV correlated

Generate flavour changing NSI from SMEFT

When considering SMEFT only up to dimension $d = 6$

- LFV and NSI correlated at tree-level
- singlet case: basically no observable effects for NSI
- letpon doublet case: tree-LFV cancel in

$$O^{\rho\sigma}_{LQM2,\ell} - O^{\rho\sigma}_{M2,\ell}$$

For New Physics not much heavier than M_W

- we can also have cancellations between d=6 and d=8 operators

SMEFT up to $d(O) = 8$ & singlet case

$$O^{\rho\sigma}_{NSI,f} = (\bar{\ell}_\rho \epsilon H^*)\gamma_\alpha(H\epsilon\ell_\sigma)(\bar{f}\gamma^\alpha f), \quad O^{\rho\sigma}_{H2,f} = (\bar{\ell}_\rho H\gamma_\alpha H^\dagger \ell_\sigma)(\bar{f}\gamma^\alpha f)$$

- NSI & LFV for $H \to (0, v)^T$:

$$O^{\rho\sigma}_{M2,f} \to (\bar{e}_\rho\gamma_\alpha e_{L,\sigma} + \bar{\nu}_\rho\gamma_\alpha\nu_\sigma)(\bar{f}\gamma^\alpha f_R)$$
$$O^{\rho\sigma}_{H2,f} \to v^2(\bar{e}_\rho\gamma_\alpha e_{L,\sigma})(\bar{f}\gamma^\alpha f_R)$$
$$O^{\rho\sigma}_{NSI,f} \to -v^2(\bar{\nu}_\rho\gamma_\alpha\nu_\sigma)(\bar{f}\gamma^\alpha f_R)$$

- LFV $\to 0$ if $rC_{H2} + C_{M2} = 0$, where $r \equiv \frac{M^2}{\lambda\Lambda^2} \to \frac{v^2}{\Lambda^2}$

Singlet case up to d=8

For each f ∈ {u_R ,d_R, e_R}) and flavour ρ and σ we have

- 3 operators
- 1 constraint from tree-level LFV

$$C_{V,LR}^{\rho\sigma ff} = \frac{v^2}{\Lambda^2}\left(r\ C_{H2}^{\rho\sigma} + C_{M2}^{\rho\sigma}\right)$$

  where $O_{V,XY}^{\mu eff} = (\bar{\mu}\gamma^{\mu}P_X e)(\bar{f}\gamma_{\mu}P_Y f)$

- 2 remaining directions to generate NSI

$$\varepsilon_f^{\rho\sigma} = \frac{v^2}{\Lambda^2}\left(r\ C_{NSI}^{\rho\sigma} - C_{M2}^{\rho\sigma}\right)$$

What about perturbative corrections?

- SMEFT generated above weak with no tree-level LFV
- Does leading log give LFV?

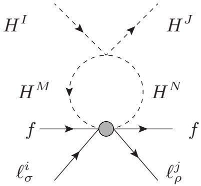
$$\mu d \frac{d}{d\mu}\vec{C} = \Gamma^T \vec{C}$$

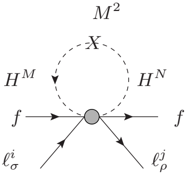
gives (neglecting running of g_2, y_t & λ):

$$\vec{C}(\mu_f) = \vec{C}(\mu_i)\left(1 + \Gamma \log \frac{\mu_f}{\mu_i} + \frac{1}{2}\Gamma\Gamma \log^2 \frac{\mu_f}{\mu_i} + ...\right)$$

- Leading log corrections are scheme independent

Higgs loop contributions





In the basis $(C_{NSI}, C_{H2}, C_{M2})$ we obtain

$$\Gamma = \frac{\lambda}{(4\pi)^2}\begin{pmatrix} -4 & 2 & -2r \\ 2 & -4 & 2r \\ 0 & 0 & 0 \end{pmatrix}$$

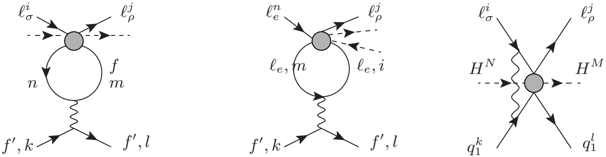
$\Gamma^T(C_{NSI}, 0, 0)(\Lambda) \to$ log for: C_{H2} & C_{H2}, no $C_{VLR}(M_W)$ log

[Biggio,Blennow,Fernandez,Martinez]X

$\Gamma^T(0, -C_{M2}, C_{M2}r)(\Lambda) \to$ log for: C_{H2}, C_{H2} and $C_{VLR}(M_W)$

- what about other corrections and $\log^2$?

Weak boson loops



- Vertex corrections and penguin insertions

$$\Gamma = \frac{1}{(4\pi)^2}\begin{pmatrix} d & 0 & 0 \\ 0 & d & 0 \\ 0 & 0 & d' \end{pmatrix} + \frac{\lambda}{(4\pi)^2}\begin{pmatrix} 0 & 2 & -2r \\ 2 & 0 & 2r \\ 0 & 0 & 0 \end{pmatrix}$$

$$d = -(9g^2/2 + 4\lambda + g'^2[1.5 - 6Y_f - 4N_{c,f}Y_f^2/3])$$
$$d' = g'^2(6Y_f + 4/3N_cY_f^2$$

Log^2 contributions

The $\log^2$ term is given by $\Gamma^T\Gamma^T)^2\vec{C}/2$

$$\Gamma\Gamma = \begin{pmatrix} d^2+4\lambda^2 & 4\lambda d & 4\lambda\eta - 2\eta(d+d') \\ 4\lambda d & d^2+4\lambda^2 & -4\lambda\eta + 2\eta(d+d') \\ 0 & 0 & d'^2 \end{pmatrix}$$

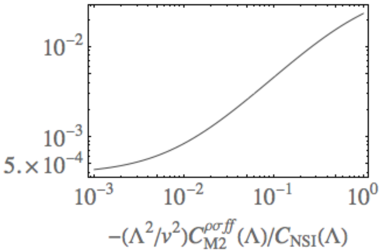
- Now $\Gamma^T\Gamma^T \cdot (C_{NSI}, 0, 0)$ gives $C_{H2} \neq -rC_{M2}$
- Will constrain $C_{NSI}(\Lambda)$ at leading log: $\frac{1}{(4\pi)^4}\log^2\left(\frac{\Lambda}{M_W}\right)$

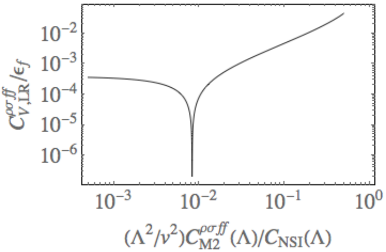
Explicit results

$$\Delta C^{\rho\sigma}_{H2,f}(m_W) = C^{\rho\sigma}_{H2,f}(\Lambda) \times \frac{d}{(16\pi^2)} \log\frac{\Lambda}{m_W}$$
$$+ C^{\rho\sigma}_{NSI,f}(\Lambda) \times \left(\frac{2\lambda}{(16\pi^2)} \log\frac{\Lambda}{m_W} + \frac{4\lambda d}{2(16\pi^2)^2} \log^2\frac{\Lambda}{m_W} + \ldots \right)$$
$$\Delta C^{\rho\sigma}_{M2,f}(m_W) = C^{\rho\sigma}_{M2}(\Lambda) \times \frac{d' - 2\lambda}{(16\pi^2)} \log\frac{\Lambda}{m_W}$$
$$+ C^{\rho\sigma}_{NSI,f}(\Lambda) \times \left(-\frac{2\eta}{(16\pi^2)} \log\frac{\Lambda}{m_W} + \frac{4\lambda\eta - 2\eta(d+d')}{2(16\pi^2)^2} \log^2\frac{\Lambda}{m_W} + \ldots \right)$$

$$\Delta C^{\rho\sigma ff}_{V,LR} = \frac{C^{\rho\sigma}_{NSI,f}(\Lambda) v^4}{\Lambda^4} \frac{2\lambda(d-d') + 4\lambda^2}{2(16\pi^2)^2} \log^2\frac{\Lambda}{m_W} \rightarrow \sim 10^{-4}\varepsilon_f$$
$$+ \frac{C_{M2}(\Lambda) v^2}{(16\pi^2)\Lambda^2} \left[-(d-d') - 2\lambda \right] \log\frac{\Lambda}{m_W} \rightarrow \sim 2\times 10^{-2}\varepsilon_f$$

Sensitivity to $\epsilon_{fR}^{\mu e}$





In left (right) panel $C_{M2}^{\rho\sigma}$ and $C_{NSI}^{\rho\sigma}$ contribute (destructively) to $\varepsilon^{\rho\sigma}$ -Generically one-loop (1-l) corrections apply.

f	$C_{V,LR}^{\mu\ \mathrm{eff}}$	$\varepsilon_{fR}^{\mu\ e}$(1l)	$\varepsilon_{fR}^{\mu\ e}$(2l)
e	$< 9.3 \cdot 10^{-7}$	$< 5 \cdot 10^{-5}$	$9 \cdot 10^{-3}$
u	$< 5.4 \cdot 10^{-8}$	$< 3 \cdot 10^{-6}$	$5 \cdot 10^{-4}$
d	$< 6.3 \cdot 10^{-8}$	$< 3 \cdot 10^{-6}$	$6 \cdot 10^{-4}$

Operators

5 independent operators involving 2 lepton, 2 quark and 2 Higgs:

$$
\begin{aligned}
O^{\rho\sigma}_{NSI,q} &= (\bar{\ell}_\rho \epsilon H^*)\gamma_\mu (H\epsilon \ell_\sigma)(\bar{q}\gamma^\mu q) \\
O^{\rho\sigma}_{H2,q} &= (\bar{\ell}_\rho H)\gamma_\mu (H^\dagger \ell_\sigma)(\bar{q}\gamma^\mu q) \\
O^{\rho\sigma}_{CCLFV,q} &= (\bar{\ell}_\rho \gamma_\mu q)(\bar{q}H)\gamma_\mu (H^\dagger \ell_\sigma) \\
[\mathcal{O}^\dagger_{CCLFV,q}]^{\rho\sigma} &= (\bar{\ell}_\rho H)\gamma_\mu (H^\dagger q)(\bar{q}\gamma_\mu \ell_\sigma) \\
O^{\rho\sigma}_{CCNSI+,q} &= (\bar{\ell}_\rho \gamma_\mu q)(\bar{q}\epsilon H^*)\gamma_\mu (H\epsilon \ell_\sigma) \\
&\quad + (\bar{\ell}_\rho \epsilon H^*)\gamma_\mu (H\epsilon q)(\bar{q}\gamma_\mu \ell_\sigma)
\end{aligned}
$$

(alternative basis [Berezhiani Rossi])

Anomalous dimensions – doublet case I

for the basis (C_{NSI}, C_{H2}, $(C_{CCLFV} + C^{\dagger}_{CCLFV})/2$, $(C_{CCNSI} + C^{\dagger}_{CCNSI})/2$, $(C_{CCLFV} - C^{\dagger}_{CCLFV})/2$):

$$[\Gamma] = -\frac{3g^2}{\kappa}\begin{bmatrix} \frac{5}{2} & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & \frac{5}{2} & -1 & 0 & 0 & 0 & 0 \\ 2 & -2 & \frac{3}{2} & -1 & 0 & 0 & 0 \\ -2 & 2 & -1 & \frac{3}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{5}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -2 \\ 0 & 0 & 0 & 0 & 0 & -2 & 1 \end{bmatrix}$$

$$+\frac{g^2 N_c}{3\kappa}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -2 & 2 & 0 & 0 & 0 & 0 \\ -2 & 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} + \frac{1}{\kappa}\begin{bmatrix} -4\lambda & 2\lambda & 0 & 0 & 0 & 0 & -2\eta \\ 2\lambda & -4\lambda & 0 & 0 & 0 & 0 & 2\eta \\ 0 & 0 & -4\lambda & 2\lambda & 0 & 4\eta & 0 \\ 0 & 0 & 2\lambda & -4\lambda & 0 & -4\eta & 0 \\ 0 & 0 & 0 & 0 & -2\lambda & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

($\eta = \lambda r$ and $\kappa = (4\pi)^2$)

Anomalous dimensions – doublet case II

If three fermions have the same flavour:

- 3 operators become linearly dependent
- In the basis (C_{NSI}, C_{H2}, C_{CCNSI+},C_{M2}):

$$[\Gamma] = -\frac{3g^2}{\kappa}\begin{bmatrix} \frac{5}{2} & 0 & -1 & 0 \\ 2 & \frac{1}{2} & -1 & 0 \\ 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} + \frac{g^2 N_c}{3\kappa}\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -5 & 1 & 4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} + \frac{1}{\kappa}\begin{bmatrix} -4\lambda & 2\lambda & 0 & -2\eta \\ 2\lambda & -4\lambda & 0 & 2\eta \\ -4\lambda & +4\lambda & -2\lambda & -4\eta \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

As in the singlet case, we have log contribution

$$\varepsilon^{e\sigma}_{e_L} = \frac{v^2}{\Lambda^2}\left(-C^{e}_{M2,q} + r(C^{e}_{NSI,q} + C^{e}_{CCNSI+,q})\right)$$

$$\Delta C^{e\sigma ee}_{V,LL} = \frac{v^2}{\Lambda^2}\frac{\log(\Lambda/m_W)}{16\pi^2}\left([\frac{15}{2}g^2 + 2\lambda]C^{e\sigma}_{M2,\ell} + \frac{g^2}{3}C^{e\sigma}_{CCNSI+,\ell}\right)$$

$\frac{1}{(4\pi)^4} log^2$ contribution can be derived in similar manner

Summary NSI $\leftrightarrow$ LFV

We typically have one-loop sensitivities to charged lepton flavour violation form NSI with flavour structure. If tree level is tuned to zero.

If one-loop is also tuned to zero, we obtain $\frac{1}{(4\pi)^2}$ contributions.

Also for $\rho\sigma qq$ and $\tau\mu$ ee

Lepton Number Violation and LFV

In SMEFT neutrino masses are generated via dimension-5 lepton number violating operators

- neutrino oscillations imply non-trivial flavour structure
- this will generate charged lepton flavour violation via RGEs

$\Delta L = 2$ operators in 2HDM

Dimension-5 Operator Generate Neutrino Masses

$$\begin{aligned}\delta\mathcal{L} \;=\; & +\frac{C_5^{\alpha\beta}}{2\Lambda}(\overline{\ell_\alpha}\varepsilon H_1^*)(\ell_\beta^c\varepsilon H_1^*) + \frac{C_5^{\alpha\beta *}}{2\Lambda}(\overline{\ell_\beta^c}\varepsilon H_1)(\ell_\alpha\varepsilon H_1) \\ & +\frac{C_{21}^{\alpha\beta}}{2\Lambda}\Big((\overline{\ell_\alpha}\varepsilon H_2^*)(\ell_\beta^c\varepsilon H_1^*) + (\overline{\ell_\beta}\varepsilon H_1^*)(\ell_\alpha^c\varepsilon H_2^*)\Big) + \text{h.c.} \\ & +\frac{C_{22}^{\alpha\beta}}{2\Lambda}(\overline{\ell_\alpha}\varepsilon H_2^*)(\ell_\beta^c\varepsilon H_2^*) + \frac{C_{22}^{\alpha\beta *}}{2\Lambda}(\overline{\ell_\beta^c}\varepsilon H_2)(\ell_\alpha\varepsilon H_2) \\ & -\frac{C_A^{\alpha\beta}}{2\Lambda}(\overline{\ell_\alpha}\varepsilon\ell_\beta^c)(H_1^\dagger\varepsilon H_2^*) - \frac{C_A^{\alpha\beta *}}{2\Lambda}(\overline{\ell_\beta^c}\varepsilon\ell_\alpha)(H_2\varepsilon H_1)\end{aligned}$$

These operators mix into the Z-Penguin and
other dimension 6-Operators.
Calculation in SMEFT completes ADMs up to dimension 6

Anomalous Dimensions

$Q_{HL(1)} = i\,(\bar{e}_L\,\gamma^\mu\,\mu_L)(\Phi^\dagger D_\mu \Phi)$, $Q_{HL(3)} = i\,(\bar{e}_L\,\gamma^\mu\,\tau^a\,\mu_L)(\Phi^\dagger\,\tau^a\,D_\mu \Phi)$

$$
\begin{aligned}
(\vec{C}[\tilde{\gamma}]\vec{C}^\dagger)^{\beta\alpha}_{H\ell(1)} &= -C_5^{\beta\rho}\frac{3\delta_{\rho\sigma}}{2}C_5^{*\sigma\alpha} \\
&\quad -C_{21}^{\beta\rho}\frac{3\delta_{\rho\sigma}}{2}C_{21}^{*\sigma\alpha} + C_A^{\beta\rho}\frac{\delta_{\rho\sigma}}{2}C_A^{*\sigma\alpha} \\
(\vec{C}[\tilde{\gamma}]\vec{C}^\dagger)^{\beta\alpha}_{H\ell(3)} &= C_5^{\beta\rho}\delta_{\rho\sigma}C_5^{*\sigma\alpha} \\
&\quad +C_{21}^{\beta\rho}\delta_{\rho\sigma}C_{21}^{*\sigma\alpha} + C_A^{\beta\rho}\frac{\delta_{\rho\sigma}}{2}C_{21}^{*\sigma\alpha} - C_{21}^{\beta\rho}\frac{\delta_{\rho\sigma}}{2}C_A^{*\sigma\alpha}
\end{aligned}
$$

RGE govern mixing into the Z-Penguin:

$$(16\pi^2)\mu\frac{d}{d\mu}\tilde{C} = \tilde{C}\hat{\gamma} + \vec{C}[\tilde{\gamma}]\vec{C}^\dagger$$

And then e.g. constrained by $Br(\mu \to 3e) < 10^{-10}$

$$|C_{\ell\ell}^{e\mu ee} + C_{\ell\ell}^{eee\mu} + g_L^e[C_{H\ell(1)}^{e\mu} + C_{H\ell(3)}^{e\mu}] - \delta C_{penguin}^{e\mu}| < 7.1 \times 10^{-7}$$

Sensitivities

$$|C_{\ell\ell}^{e\mu ee} + C_{\ell\ell}^{eee\mu} + g_L^e[C_{H\ell(1)}^{e\mu} + C_{H\ell(3)}^{e\mu}] - \delta C_{penguin}^{e\mu}| < 7.1 \times 10^{-7}$$

From the left-handed contribution to Br($\mu \to 3e$) < 10^{-10}

This results in a sensitivity to the dimension 5-operator Wilson coefficients:

$$\left| C_{21}^{ee} C_{21}^{e\mu *} + 0.5 C_{22}^{ee} C_{22}^{e\mu *} + 0.1 \sum_{\sigma} \left(C_A^{e\sigma} - C_{21}^{e\sigma} \right) \left(C_A^{\sigma\mu *} + C_{21}^{\sigma\mu *} \right) \right| < \frac{1}{5.2 \ln\left(\Lambda/m_{22}\right)} \left(\frac{\Lambda}{10\text{TeV}} \right)^2$$

Conclusion

If heavy new physics generates NSI

- Charged LFV is sensitivity to the off-diagonal NSI parameter space
- There could be cancellations between tree-level and one-loop
- or between one-loop and two-loop

Obviously lepton number violation gives non observable contribution to LFV for a standard model field content

- This can change if one considers an extended Higgs sector