Lepton Flavor Violation in the SM with general Dimension-6 Operators

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Two possible approaches:

1. Construct specific New Physics model; calculate LFV observables; compare with experimental bounds to constrain model parameters.
2. Parametrize New Physics effects in terms of higher dimension operators. Express LFV observables in terms of Wilson coefficients. Need to be done just once - model independent analysis.

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) .$$

- 59 independent operators
- Only few are important in a specific case like LFV.

Full list of dimension 5- an 6-operators given in Buchmiller-Wyler 1986, corrected and reduced in Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP **1010**

Analysis in terms of effective higher dimension operators

- . Physical observables calculation:
  - radiative lepton decays $l \to l'\gamma'$.
  - charged lepton EDMs and $g-2$ anomaly.
  - 3-body LFV charged lepton decays $l \to l'l''l'''$.
  - $Z^0 \to ll'$ decays.

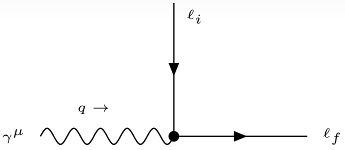
$\ell\ell\ell\ell$		$\ell\ell X\varphi$		$\ell\ell\varphi^2 D$ and $\ell\ell\varphi^3$	
$Q_{\ell\ell}$	$(\bar\ell_i\gamma_\mu\ell_j)(\bar\ell_k\gamma^\mu\ell_l)$	Q_{eW}	$(\bar\ell_o\sigma^{\mu\nu}e_j)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi\ell}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar\ell_i\gamma^\mu\ell_j)$
Q_{ee}	$(\bar e_i\gamma_\mu e_j)(\bar e_k\gamma^\mu e_l)$	Q_{eB}	$(\bar\ell_i\sigma^{\mu\nu}e_j)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi\ell}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar\ell_i\tau^I\gamma^\mu\ell_j)$
$Q_{\ell e}$	$(\bar\ell_i\gamma_\mu\ell_j)(\bar e_k\gamma^\mu e_l)$			$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_i\gamma^\mu e_j)$
				$Q_{e\varphi 3}$	$(\varphi^\dagger\varphi)(\bar\ell_i e_j\varphi)$
$\ell\ell qq$					
$Q^{(1)}_{\ell q}$	$(\bar\ell_i\gamma_\mu\ell_j)(\bar q_k\gamma^\mu q_l)$	$Q_{\ell d}$	$(\bar\ell_i\gamma_\mu\ell_j)(\bar d_k\gamma^\mu d_l)$	$Q_{\ell u}$	$(\bar\ell_i\gamma_\mu l_j)(\bar u_k\gamma^\mu u_l)$
$Q^{(3)}_{\ell q}$	$(\bar\ell_i\gamma_\mu\tau^I\ell_j)(\bar q_k\gamma^\mu\tau^I q_l)$	Q_{ed}	$(\bar e_i\gamma_\mu e_j)(\bar d_k\gamma^\mu d_l)$	Q_{eu}	$(\bar e_i\gamma_\mu e_j)(\bar u_k\gamma^\mu u_l)$
Q_{eq}	$(\bar e_i\gamma^\mu e_j)(\bar q_k\gamma_\mu q_l)$	$Q_{\ell edq}$	$(\bar\ell^a_i e_j)(\bar d_k q^a_l)$	$Q^{(1)}_{\ell equ}$	$(\bar\ell^a_i e_j)\varepsilon_{ab}(\bar q^b_k u_l)$
				$Q^{(3)}_{\ell equ}$	$(\bar\ell^a_i\sigma_{\mu\nu}e_a)\varepsilon_{ab}(\bar q^b_k\sigma^{\mu\nu}u_l)$

After simplifications: **only 9 operators remain in LFV:**

1. **2** $(\ell\ell\varphi X)$ **operators:** $(\bar{\ell}_i \sigma^{\mu\nu} e_j)\tau^I \varphi W^I_{\mu\nu}$, $(\bar{\ell}_i \sigma^{\mu\nu} e_j)\varphi B_{\mu\nu}$
2. **3** $(\ell\ell)(\varphi D \varphi)$ **operators:**
   $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_i \gamma^\mu \ell_j)$, $(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{\ell}_i \tau^I \gamma^\mu \ell_j)$, $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_i \gamma^\mu e_j)$
3. **3 four-lepton contact couplings:**
   $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{\ell}_k \gamma^\mu \ell_l)$, $(\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_l)$, $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{e}_k \gamma^\mu e_l)$
4. **1 two-lepton two-quark coupling:** $(\bar{\ell}^a_i e_j)(\bar{d}_k q^a_l)$

Effective lepton-photon coupling.

Tree level LFV contribution exist:



$$i\left(e\gamma^\mu\delta^{fi} + i\sigma^{\mu\nu}\left[C_{\gamma L}^{fi}P_L + C_{\gamma R}^{fi}P_R\right]q_\nu\right)$$

$$C_{fi}^{\gamma R} = C_{fi}^{\gamma L\star} = \frac{v\sqrt{2}}{\Lambda^2}\left(c_W C_{eB}^{fi} - s_W C_{eW}^{fi}\right)$$

$$\sqrt{\left|C_{\varphi\ell}^{(1)12}+C_{\varphi\ell}^{(3)12}\right|^2+\left|C_{\varphi e}^{12}\right|^2+\left|C_Z^{12}\right|^2+\left|C_Z^{21}\right|^2} \leq 0.06\left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2\sqrt{\frac{\mathrm{Br}\left[Z^0\to\mu^\pm e^\mp\right]}{1.7\times10^{-6}}},$$

$$\sqrt{\left|C_{\varphi\ell}^{(1)13}+C_{\varphi\ell}^{(3)13}\right|^2+\left|C_{\varphi e}^{13}\right|^2+\left|C_Z^{13}\right|^2+\left|C_Z^{31}\right|^2} \leq 0.14\left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2\sqrt{\frac{\mathrm{Br}\left[Z^0\to\tau^\pm e^\mp\right]}{9.8\times10^{-6}}}, \tag{1}$$

$$\sqrt{\left|C_{\varphi\ell}^{(1)23}+C_{\varphi\ell}^{(3)23}\right|^2+\left|C_{\varphi e}^{23}\right|^2+\left|C_Z^{23}\right|^2+\left|C_Z^{32}\right|^2} \leq 0.16\left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2\sqrt{\frac{\mathrm{Br}\left[Z^0\to\tau^\pm\mu^\mp\right]}{1.2\times10^{-5}}}.$$

Three-body $l \to l'l''l'''$ decays

3 groups of decays, depending on composition of the final state leptons:

- Three leptons of the same flavor: $\mu^\pm \to e^\pm e^+ e^-$, $\tau^\pm \to e^\pm e^+ e^-$ and $\tau^\pm \to \mu^\pm \mu^+ \mu^-$.
- Three distinguishable leptons: $\tau^\pm \to e^\pm \mu^+ \mu^-$ and $\tau^\pm \to \mu^\pm e^+ e^-$.
- Two lepton of the same flavor and charge and one with different flavor and opposite charge: $\tau^\pm \to e^\mp \mu^\pm \mu^\pm$ and $\tau^\pm \to \mu^\mp e^\pm e^\pm$.

$$C_{\mu eee} \leq 3.29 \times 10^{-5} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}[\mu \to eee]}{1 \times 10^{-12}}}\,,$$
$$C_{\tau eee} \leq 1.28 \times 10^{-2} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}[\tau \to eee]}{2.7 \times 10^{-8}}}\,,$$
$$C_{\tau \mu\mu\mu} \leq 1.13 \times 10^{-2} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}[\tau \to \mu\mu\mu]}{2.1 \times 10^{-8}}}\,,$$

with $C_{\ell_i \ell_f \ell_f \ell_f}$ given by

$$C_{\ell_i \ell_f \ell_f \ell_f} = \Big\{ \Big| 0.46 \left(\mathrm{C}^{(1)fi}_{\phi\ell} + \mathrm{C}^{(3)fi}_{\phi\ell} \right) + \mathrm{C}^{fiff}_{\ell e} \Big|^2 + 2 \Big| \mathrm{C}^{fiff}_{\ell e} - 0.54 \left(\mathrm{C}^{(1)fi}_{\phi\ell} + \mathrm{C}^{(3)fi}_{\phi\ell} \right) \Big|^2$$
$$+ \Big| \mathrm{C}^{fffi}_{\ell e} - 0.54 \mathrm{C}^{fi}_{\phi e} \Big|^2 + 2 \Big| \mathrm{C}^{fiff}_{ee} + 0.46 \mathrm{C}^{fi}_{\phi e} \Big|^2 \Big\}\,.$$

Conclusion

We calculated the expressions for several theoretically important and experimentally well constrained lepton flavor violating processes within the Standard Model extended with the most general set of effective LFV operators of dimensionn-6 invariant under the SM gauge group.