Lepton Flavor Violation within Effective Field Theory Framework

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Outline

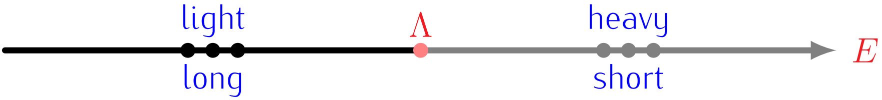
- A brief introduction to Effective Field Theory (EFT):
  - Top-Down approach
  - Bottom-Up approach
- Motivation: Lepton Flavor Violation (LFV) as a guide to physics beyond the Standard Model
- Approach: parametrization of the New Physics effects in terms of effective higher dimension operators
- Our results on charged LFV within EFT framework:

  S.N. "PhD thesis" 2015; Crivellin-S.N.-Rosiek 2014; S.N. *in preparation*

  - $h \to \tau\mu$
  - $\mu \to e\gamma$
  - $\mu \to eee$
  - $(g-2)_\mu$
- Conclusions

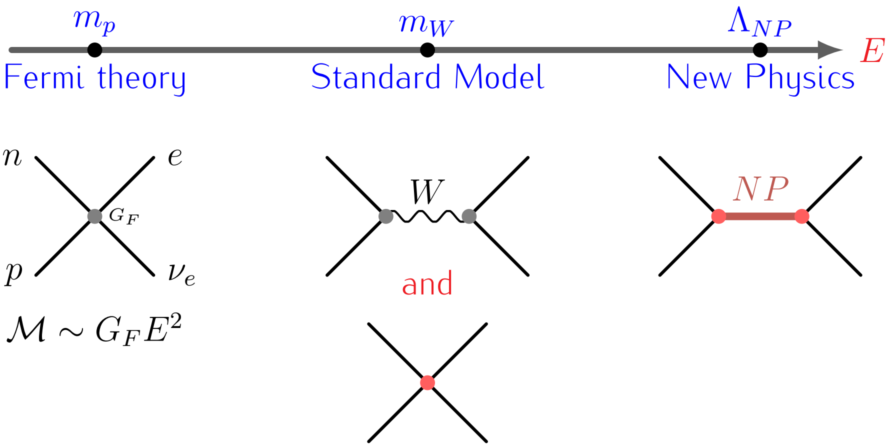
Effective Field Theory

- There are many scales in Nature.



- An estimate over the short-distance physics leads to an effective theory at the long distances.
- We can parametrize the effective theory even if we don't know the short-distance theory.

Effective Field Theory



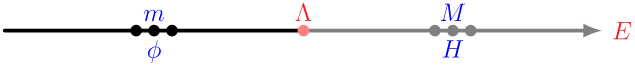
$\mathcal{M} \sim G_F E^2$

$\mathcal{M} \sim G_{NP} E^2$

- We assume $m_p \ll m_W \ll \Lambda_{NP}$.

Effective Field Theory: Top-Down approach

- In the "top down" approach, the full theory is known.



Toy example: ϕ is light scalar field and H is heavy scalar field

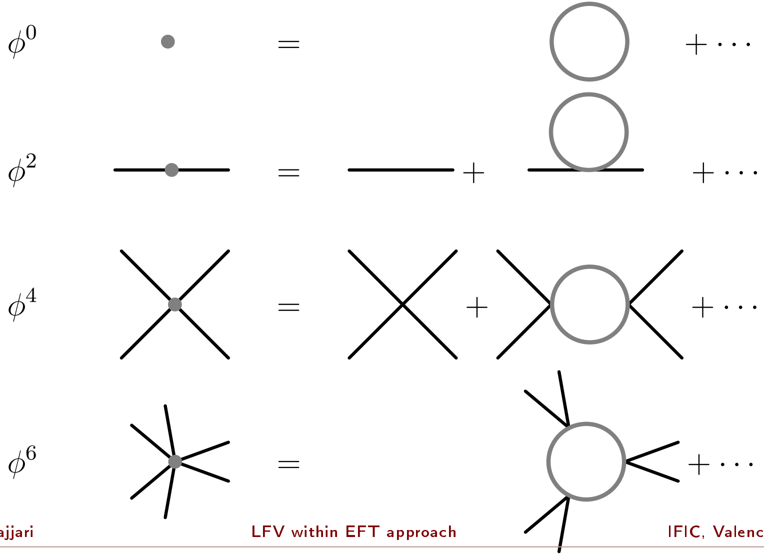
$$\mathcal{L}(\phi, H) = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$
$$+ \frac{1}{2}(\partial_\mu H)^2 - \frac{1}{2}M^2H^2 - \frac{g_2}{4}\phi^2H^2 - \frac{g_4}{4!}H^4$$

- To get the effective theory, we "integrate out" the heavy d.o.f.

$$\boxed{e^{iS_{eff}[\phi]} = \int \mathcal{D}H e^{iS_{full}[\phi,H]}}$$

EFT Top-Down approach: Matching

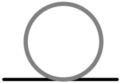
Effective Theory | **Full Theory**



EFT Top-Down approach: Decoupling Theorem

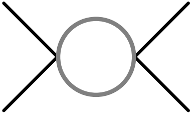
- Effects of heavy fields are encoded into the renormalized couplings of light fields.

$$\Delta m^2 =$$



$$= \frac{g_2}{32\pi^2}\left(\Lambda^2 - M^2 \ln\left(\frac{\Lambda^2}{\mu^2}\right)\right)$$

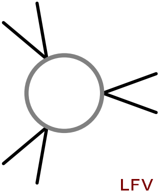
$$\Delta\lambda =$$



$$= -\frac{3g_2^2}{32\pi^2}\ln\left(\frac{\Lambda^2}{\mu^2}\right)$$

where μ is the renormalization scale.

- Heavy fields allow new non-renormalizable interactions



$$\Rightarrow \frac{g_2^3}{M^2}\phi^6$$ dimsion-six operator

Effective bottom-up approach: Toy example

- Effective theory contains all the terms allowed by the symmetries of the theory, e.g. $\phi \to -\phi$

Effective Lagrangian

$$\mathcal{L}_{eff}(\phi) = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_{eff}^2 \phi^2 - \frac{\lambda_{eff}}{4!}\phi^4 - \sum_{i=1}^{\infty}\left(\frac{c_i}{M^{2i}}\phi^{4+2i} + \cdots\right)$$

- Dimensionality of an operator $\delta_i \equiv [\mathcal{O}_i]$ and its relevance:
  - $\delta_i < 4$ relavant, renormalizable
  - $\delta_i = 4$ marginal, renormalizable
  - $\delta_i > 4$ irelavant, non-renormalizable

- Only a finite number of operators are necessary to describe the low-energy physics up to certain precision.

EFT Bottom-Up approach

- EFT bottom-up approach (Wilsonian principle):
  - Relevant degrees of freedom (theory) at the given energy scale (e.g. SM at the electroweak scale).
  - Identify the symmetries of the theory.
  - Write down the lowest dimensional operators (allowed by the symmetries).

Effective Lagrangian

$$\mathcal{L}_{eff}[\phi] = \mathcal{L}_0[\phi] + \sum_{i=1}^{\infty} \frac{\mathcal{C}_i}{\Lambda^{\delta_i - 4}} \mathcal{O}_i[\phi]$$

Lepton Flavor Violation: Motivation

- Neutrino oscillation ($\nu_\tau \to \nu_\mu, \nu_e$) implies (neutral) lepton flavor violation.
- Recently ATLAS and CMS have observed a hint of nonzero signal for $h \to \tau\mu$.
- Potential experimental discovery can lead to:
  - clear evidence of new physics
  - deeper understanding of the origin of lepton flavor pattern
- Task for theoreticians: estimate expected size of LFV effects in various SM extensions!

Charged LFV within the (ν)SM

- "νSM" - minimally extended SM, standard particle content and couplings plus (small) neutrino mass terms.
- cLFV processes ($\mu \to e\gamma$, $\mu \to eee$) exists in νSM but very small.
- Effects are GIM-suppressed by $\frac{m_\nu^2}{M_W^2} \sim 10^{-25}$, e.g. ($U$ is the PMNS matrix):

$$\boxed{\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha_{em}}{32\pi} \sum_{i=1}^{3} U_{ei}^* U_{\mu i} (\frac{m_{\nu_i}^2}{M_W^2}) \cong (2.5 - 3.9) \times 10^{-55}}$$

- For comparison

$$\boxed{\mathcal{B}(\mu \to e\gamma)^{exp} \leq 5.7 \times 10^{-13}}$$

- Any cLFV discovery points to New Physics effect!

Effective New Physics parametrization

Numerous BSM models exist – hard to analyze them all!

Solution

- parameterize 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.
- only the values of Wilson coefficients of new operators need to be calculated within a given model of NP. This part of analysis is always model dependent.

Standard Model Effective Field Theory

Effective parametrization of the SM extensions:

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \underbrace{\frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)}}_{\text{dimension 5 term}} + \underbrace{\frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)}}_{\text{dimension 6 terms}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- Unique dimension-5 operator (the Weinberg operator) - give rise to neutrino masses but irrelevant for cLFV.
- 59 independent dimension-6 operators

Grzadkowski-Iskrzyński-Misiak-Rosiek 2010

Charged Lepton Flavor Violation

$$\mu \to e\gamma$$

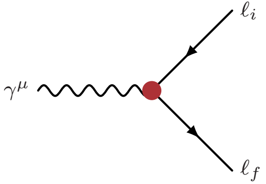
$$\mu \to eee$$

$$(g-2)$$

Charged LFV with Dimension-6 operators

$$\boxed{\mathcal{O}_{eX} = (\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^a \varphi X^a_{\mu\nu}}$$

φ - Higgs doublet, X - $U(1)$ and $SU(2)$ field strength tensors



$$\left[\gamma^\mu \delta_{fi} + \sigma^{\mu\nu}\left(C^{fi}_{\gamma L} P_L + C^{fi}_{\gamma R} P_R\right) q_\nu\right]$$

$$C^{fi}_{\gamma R} = C^{fi*}_{\gamma L} = \frac{v\sqrt{2}}{\Lambda^2}(C_W C^{fi}_{eB} - S_W C^{fi}_{eW})$$

- Experimental upper bound

$$\boxed{\mathcal{B}(\mu \to e\gamma) \leq 5.7 \times 10^{-13}}$$

dimension-6 operators which contribute to the LFV observables.

$\ell\ell\ell\ell$		$\ell\ell X\varphi$		$\ell\ell\varphi^2 D$ 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}	$(\bar e_i\gamma^\mu e_j)(\bar q_k\gamma_\mu q_l)$	$Q_{\ell edq}$	$(\bar\ell^a_i e_j)(\bar d_k q^a_l)$	$Q^{(1)}_{\ell equ}$	$(\bar\ell^a_i e_j)\varepsilon_{ab}(\bar q^b_k u_l)$
				$Q^{(3)}_{\ell equ}$	$(\bar\ell^a_i\sigma_{\mu\nu}e_a)\varepsilon_{ab}(\bar q^b_k\sigma^{\mu\nu}u_l)$

Charged Lepton Flavor Violation

Problem: many input parameters, simplifications required:

- Only 19 baryon-number conserving dim-6 operators contribute to cLFV.
- some operators do not contribute to cLFV processes - shown *a posteriori*, by direct calculation
- some terms suppressed by m_l/M_Z or m_l/M_H and negligible.

Only 9 operator classes remain in cLFV analysis

- Number of free parameters still large
- Wilson coefficients carry flavor indices
- Hence many experimental result are necessary for constraints.

Dimension-6 operators in cLFV analysis

1. 2 $(\ell\ell\varphi X)$ operators: $(\bar{\ell}_i\sigma^{\mu\nu}e_j)\tau^I\varphi W^I_{\mu\nu}$, $(\bar{\ell}_i\sigma^{\mu\nu}e_j)\varphi B_{\mu\nu}$

   $\boxed{\text{tree level: } \ell \to \ell'\gamma,\ \ell \to \ell'\ell''\ell''',\ Z^0 \to \ell\ell'}$

2. 3 $(\ell\ell)(\varphi D\varphi)$ operators:
   $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{\ell}_i\gamma^\mu\ell_j)$, $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{\ell}_i\tau^I\gamma^\mu\ell_j)$, $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_i\gamma^\mu e_j)$

   $\boxed{\text{tree level: } \ell \to \ell'\ell''\ell''',\ \text{1-loop level: } \ell \to \ell'\gamma}$

3. 3 four-lepton contact operators:
   $(\bar{\ell}_i\gamma_\mu\ell_j)(\bar{\ell}_k\gamma^\mu\ell_l)$, $(\bar{e}_i\gamma_\mu e_j)(\bar{e}_k\gamma^\mu e_l)$, $(\bar{\ell}_i\gamma_\mu\ell_j)(\bar{e}_k\gamma^\mu e_l)$

   $\boxed{\text{tree level: } \ell \to \ell'\ell''\ell''',\ \text{1-loop level: } \ell \to \ell'\gamma}$

4. 1 two-lepton two-quark operator: $(\bar{\ell}^a_i e_j)(\bar{d}_k q^a_l)$

   $\boxed{\text{1-loop level: } \ell \to \ell'\gamma}$

Physical observables for cLFV

- Following physical observables depend on the effective flavor violating lepton-photon vertex:
  - Radiative lepton decays $\ell \to \ell' \gamma$,
  - charged lepton EDMs and $g-2$ anomaly

- Effective flavor violating lepton-photon vertex

$$V_{\ell\ell\gamma}^{IJ\ \mu} = \frac{i}{\Lambda^2}[\gamma^\mu(F_{VL}^{IJ}P_L + F_{VR}^{IJ}P_R) + (F_{SL}^{IJ}P_L + F_{SR}^{IJ}P_R)q^\mu$$
$$+ i(F_{TL}^{IJ}\sigma^{\mu\nu}P_L + F_{TR}^{IJ}\sigma^{\mu\nu}P_R)q_\nu]$$

- Only tensor form-factors F_{TL}^{IJ} and F_{TR}^{IJ} contribute to the physical observables.

Observables depending on lepton-photon vertex

- $\ell_i \to \ell_j \gamma$ decay rate

$$\boxed{\mathcal{B}\left(\ell^J \to \ell^I \gamma\right) = \frac{m_{\ell_J}^3}{16\pi\Lambda^4\,\Gamma_{\ell_J}}\left(\left|F_{TR}^{IJ}\right|^2 + \left|F_{TL}^{IJ}\right|^2\right)}$$

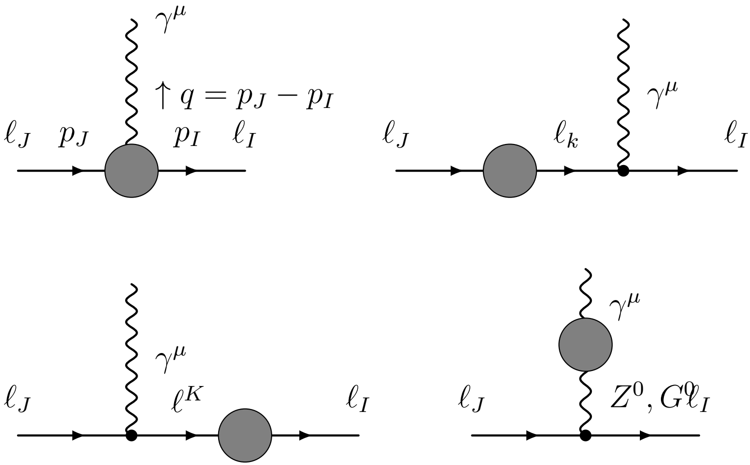
- lepton Electric Dipole Moments (EDM)

$$\boxed{d_{\ell_i} = \frac{-1}{\Lambda^2}\,\mathrm{Im}\left[F_{TR}^{ii}\right]}$$

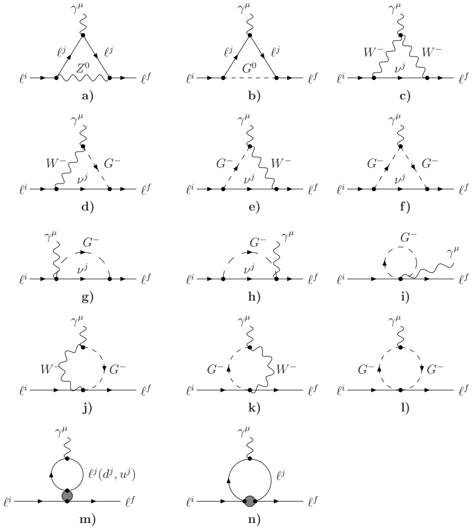
- lepton Anomalous Magnetic Moments (AMM)

$$\boxed{a_{\ell_i} = \frac{2m_{\ell_i}}{e\Lambda^2}\,\mathrm{Re}\left[F_{TR}^{ii}\right]}$$

Topologies of diagrams contributing to $\ell^J \to \ell^I \gamma$



1-loop diagrams for $\ell_i \to \ell_j \gamma$



$\ldots +$ reducible self-energy diagrams

Calculational technique

- Calculations done with the use of Mathematica codes.
- We performed exact calculations in the fixed Feynman gauge – Passarino-Veltman reduction of loop tensor integrals. SN, PhD Thesis 2015
- Important test:
  - gauge invariance requires vector form-factors F_{VL}, F_{VR} to vanish for on-shell particles.
- Our final results pass all tests and are simple and compact.
- Results depend on <u>6 classes</u> of Wilson coefficients

Results for F_{TL}, F_{TR} form-factors

Tree level

$$F_{TL}^{IJ} = v\sqrt{2}\Big[c_W C_{eB}^{JI\star} - s_W C_{eW}^{JI\star}\Big]$$
$$F_{TR}^{IJ} = v\sqrt{2}\Big[c_W C_{eB}^{IJ} - s_W C_{eW}^{IJ}\Big]$$

1-loop

$$F_{TL}^{IJ} = \frac{4e}{(4\pi)^2}\left[\frac{C_{\phi l}^{(1)IJ} m_I (1+s_W^2) - (C_{\phi l}^{(3)IJ} m_I + C_{\phi e}^{IJ} m_J)(\frac{3}{2} - s_W^2)}{3} + \sum_{K=1}^{3} C_{\ell e}^{IKKJ} m_K\right]$$
$$F_{TR}^{IJ} = \frac{4e}{(4\pi)^2}\left[\frac{C_{\phi l}^{(1)IJ} m_J (1+s_W^2) - (C_{\phi l}^{(3)IJ} m_J + C_{\phi e}^{IJ} m_I)(\frac{3}{2} - s_W^2)}{3} + \sum_{K=1}^{3} C_{\ell e}^{KJIK} m_K\right]$$

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$$F_{TR}^{IJ} = \frac{4e}{(4\pi)^2}\left[\frac{C_{\phi l}^{(1)IJ} m_J(1+s_W^2) - (C_{\phi l}^{(3)IJ} m_J + C_{\phi e}^{IJ} m_I)(\frac{3}{2} - s_W^2)}{3} + \sum_{K=1}^{3} C_{\ell e}^{KJIK} m_K\right]$$

Experimental upper limits on the branching ratios of the radiative lepton decays.

Process	Experimental bounds
$\mathcal{B}\left[\tau \to \mu\gamma\right]$	$\leq\ 4.4 \times 10^{-8}$
$\mathcal{B}\left[\tau \to e\gamma\right]$	$\leq\ 3.3 \times 10^{-8}$
$\mathcal{B}\left[\mu \to e\gamma\right]$	$\leq\ 5.7 \times 10^{-13}$

Our results

$$\sqrt{\left|C_\gamma^{12}\right|^2 + \left|C_\gamma^{21}\right|^2} \;\leq\; 2.45 \times 10^{-10} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}\left[\mu \to e\gamma\right]}{5.7 \times 10^{-13}}}$$

$$\sqrt{\left|C_\gamma^{13}\right|^2 + \left|C_\gamma^{31}\right|^2} \;\leq\; 2.35 \times 10^{-6} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}\left[\tau \to e\gamma\right]}{3.3 \times 10^{-8}}}$$

$$\sqrt{\left|C_\gamma^{23}\right|^2 + \left|C_\gamma^{32}\right|^2} \;\leq\; 2.71 \times 10^{-6} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)^2 \sqrt{\frac{\mathrm{Br}\left[\tau \to \mu\gamma\right]}{4.4 \times 10^{-8}}}$$

Our results

$$a_e = 1.17\times 10^{-6}\ \mathrm{Re}\left[2\times 10^{-5}\ C_{\ell e}^{3113} + C_\gamma^{11}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

$$a_\mu = 2.43\times 10^{-4}\ \mathrm{Re}\left[2\times 10^{-5}\ C_{\ell e}^{3223} + C_\gamma^{22}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

$$\begin{aligned} a_\tau = 4.1\times 10^{-3}\ \mathrm{Re}\Big[10^{-5}\times\ \Big(&1.6\ C_{\varphi\ell}^{(1)33} + 2.0\ C_{\ell e}^{3333} \\ &- 1.7\ \left(C_{\varphi\ell}^{(3)33} + C_{\varphi e}^{33}\right)\Big) + C_\gamma^{33}\Big]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \end{aligned}$$

Experimental upper bounds on electric dipole moments of the charged leptons

EDMs	$\lvert d_e \rvert$	$\lvert d_\mu \rvert$	d_τ
Bounds (e cm)	8.7×10^{-29}	1.9×10^{-19}	$\in [-2.5,\, 0.8] \times 10^{-17}$

$$d_e = -2.08 \times 10^{-18}\ \mathrm{Im}\left[2 \times 10^{-5}\ C_{\ell e}^{3113} + C_{\gamma}^{11}\right] \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 e\,\mathrm{cm}\,,$$

$$d_\mu = -2.08 \times 10^{-18}\ \mathrm{Im}\left[2 \times 10^{-5}\ C_{\ell e}^{3223} + C_{\gamma}^{22}\right] \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 e\,\mathrm{cm}\,,$$

$$d_\tau = -2.08 \times 10^{-18}\ \mathrm{Im}\left[C_{\gamma}^{33}\right] \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 e\,\mathrm{cm}\,.$$

$\ell \to \ell'\ell''\ell'''$ decays

- Tree-level calculation — using of 1-loop lepton-photon vertex.
- 3-body decay $\mathcal{B}(\ell \to \ell'\ell''\ell''')$ calculation rather complicated:
  - many operators contribute to amplitude, tedious matrix element calculations
  - non-trivial phase space integration - photon propagator singular in the limit $m_{lepton} \to 0$, final state masses cannot be neglected

Experimental upper limits on the branching ratios of the three body charged lepton decays

Process	Experimental bound
$\mathcal{B}\left[\tau^- \to \mu^-\mu^+\mu^-\right]$	2.1×10^{-8}
$\mathcal{B}\left[\tau^- \to e^-e^+e^-\right]$	2.7×10^{-8}
$\mathcal{B}\left[\tau^- \to e^-\mu^+\mu^-\right]$	2.7×10^{-8}
$\mathcal{B}\left[\tau^- \to \mu^-e^+\mu^-\right]$	1.7×10^{-8}
$\mathcal{B}\left[\mu^- \to e^-e^+e^-\right]$	1.0×10^{-12}

Expression for the 3-body decay branching ratio

(A) Three lepton with the same flavor in the final state: $\mu^\pm \to e^\pm e^+ e^-$, $\tau^\pm \to e^\pm e^+ e^-$ and $\tau^\pm \to \mu^\pm \mu^+ \mu^-$.

(B) Three different (distinguishable) leptons in the final state: $\tau^\pm \to e^\pm \mu^+ \mu^-$ and $\tau^\pm \to \mu^\pm e^+ e^-$.

(C) Two lepton of the same flavor (opposite charge) in the final state: $\tau^\pm \to e^\mp \mu^\pm \mu^\pm$ and $\tau^\pm \to \mu^\mp e^\pm e^\pm$.

Results

$$\mathcal{B}(\ell_i \to \ell_j \ell_k \bar{\ell}_l) = \frac{N_c M^5}{6144\pi^3 \Lambda^4 \Gamma_{\ell_i}} \Big(4\Big(|C_{VLL}|^2 + |C_{VRR}|^2 + |C_{VLR}|^2 + |C_{VRL}|^2\Big) + |C_{SLL}|^2 + |C_{SRR}|^2 + |C_{SLR}|^2 + |C_{SRL}|^2 + 48\left(|C_{TL}|^2 + |C_{TR}|^2\right) + X_\gamma\Big)\,,$$

$$X_\gamma^{(A)} = -\frac{16ev}{M}\mathrm{Re}\left[\left(2C_{VLL} + +C_{VLR} - \frac{1}{2}C_{SLR}\right)C^\star_{\gamma R} + \left(2C_{VRR} + C_{VRL} - \frac{1}{2}C_{SRL}\right)C^\star_{\gamma L}\right] + \frac{64e^2v^2}{M^2}(\log\frac{M^2}{m^2} - \frac{11}{4})(|C_{\gamma L}|^2 + |C_{\gamma R}|^2),$$

Results

$$
\begin{aligned}
C_{VLL} &= 2\left((2s_W^2-1)\left(C_{\phi\ell}^{(1)ji}+C_{\phi\ell}^{(3)ji}\right)+C_{\ell\ell}^{jijj}\right),\\
C_{VRR} &= 2\left(2s_W^2 C_{\phi e}^{ji}+C_{ee}^{jijj}\right),\\
C_{VLR} &= -\frac{1}{2}C_{SRL}=\left(2s_W^2\left(C_{\phi\ell}^{(1)ji}+C_{\phi\ell}^{(3)ji}\right)+C_{le}^{jijj}\right),\\
C_{VRL} &= -\frac{1}{2}C_{SLR}=\left((2s_W^2-1)C_{\phi e}^{ji}+C_{\ell e}^{jjji}\right),\\
C_{SLL} &= C_{SRR}=C_{TL}=C_{TR}=0,\\
C_{\gamma L} &= 2\sqrt{2}s_W\left(c_W C_{eB}^{if\star}-s_W C_{eW}^{if\star}\right),\\
C_{\gamma R} &= 2\sqrt{2}s_W\left(c_W C_{eB}^{fi}-s_W C_{eW}^{fi}\right).
\end{aligned}
$$

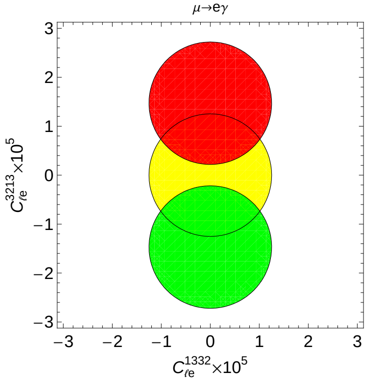
Results

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

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

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

Example: Allowed regions from Br$[\mu \to e\gamma]$ in the $C_{\ell e}^{1332}$–$C_{\ell e}^{3213}$ plane for $\Lambda = 1$ TeV and different values of C_{eW}^{12}.



Yellow: $C_{eW}^{12} = 0$, red: $C_{eW}^{12} = 6 \times 10^{-8}$, green: $C_{eW}^{12} = -6 \times 10^{-8}$.
Several other similar correlations are discussed in the S.N. PhD thesis.

Implications of our results

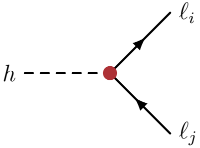
- Form of bounds easy to update with new experimental results
- Bounds are quite strong
- New Physics scale high or specific LFV suppression mechanisms needed in feasible NP models
- Obtained expression can give order of magnitude bounds on Wilson coefficients (assuming no cancellations) or check potential correlations between them.

Higgs LFV decays

$$h \to \tau\mu$$

LFV Higgs decays with Dimension-6 operators

$$\boxed{\mathcal{O}_{e\varphi} = (\varphi^\dagger\varphi)(\bar{\ell}_i e_j \varphi)}$$



$$i\left[\frac{-m_\ell}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\left(C_{\ell\varphi}^{ij*}P_L + C_{\ell\varphi}^{ji}P_R\right)\right]$$

$$\Gamma(h \to \ell_j\ell_j) = \frac{m_h\sqrt{2}}{8\pi}(|C_{ij}|^2 + |C_{ji}|^2)$$

- CMS results 2014: $\mathcal{B}(H \to \tau\mu)$=$(0.84^{+0.39}_{-0.37})$%, (2.4 σ excess)
- ATLAS result 2015: $\mathcal{B}(H \to \tau\mu)$=$(0.77 \pm 0.62)$%

Dim-6 operators contributing to LFV

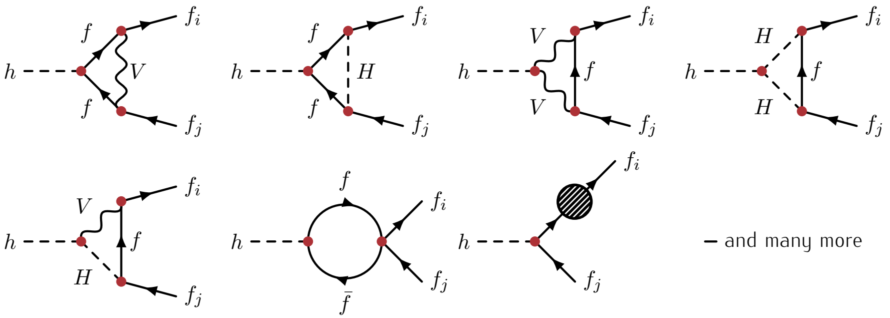
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi W^a_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{\ell}_p\sigma^{\mu\nu}e_r)\tau^a\varphi W^a_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{\ell}_p\gamma^\mu\ell_r)$
$\mathcal{O}_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\widetilde{W}^a_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{\ell}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{\ell}_p\tau^a\gamma^\mu\ell_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^a\varphi W^a_{\mu\nu}$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\varphi B_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\tau^a\varphi W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^a\varphi W^a_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^a\gamma^\mu q_r)$
$\mathcal{O}_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^a\varphi\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
				$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
				$\mathcal{O}_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_\rho\gamma^\mu d_r)$

Dim-6 operators contributing to LFV

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$	
$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_\rho \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_\rho \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_\rho \gamma_\mu \tau^a \ell_r)(\bar{q}_s \gamma^\mu \tau^a q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_\rho \gamma^\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}_\rho \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_\rho \gamma^\mu e_r)(\bar{d}_s \gamma^\mu d_t)$

$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{R}L)$ or $(\bar{L}R)(\bar{L}R)$	
$\mathcal{O}_{\ell e}$	$(\bar{\ell}_\rho \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{\ell edq}$	$(\bar{\ell}_\rho{}^j e_r)(\bar{d}_s \gamma^\mu q_t^j)$
$\mathcal{O}_{\ell u}$	$(\bar{\ell}_\rho \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$		
$\mathcal{O}_{\ell d}$	$(\bar{\ell}_\rho \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar{\ell}_\rho^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$\mathcal{O}_{qe}$	$(\bar{q}_\rho \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$		

Higgs flavor violating decays



– and many more

Figure: Feynman diagrams contributing to flavor violating Higgs decays to two fermions at the one-loop level.

Bounds on Wilson Coefficients

$C_{\ell\varphi}^{ij}$	Bound	Observable
$\sqrt{\lvert C_{\ell\varphi}^{21}\rvert^2 + \lvert C_{\ell\varphi}^{12}\rvert^2}$	$5.09 \times 10^{-6}(\frac{\Lambda}{v})^2$	$\mu \to e\gamma$
$\sqrt{\lvert C_{\ell\varphi}^{21}\rvert^2 + \lvert C_{\ell\varphi}^{12}\rvert^2}$	$4.38 \times 10^{-5}(\frac{\Lambda}{v})^2$	$\mu \to eee$
$Re(C_{\ell\varphi}^{21} C_{\ell\varphi}^{12})$	$[-2.68...3.67] \times 10^{-2}(\frac{\Lambda}{v})^2$	electron g-2
$Im(C_{\ell\varphi}^{21} C_{\ell\varphi}^{12})$	$13.85 \times 10^{-8}(\frac{\Lambda}{v})^2$	electron EDM
$\sqrt{\lvert C_{\ell\varphi}^{21}\rvert^2 + \lvert C_{\ell\varphi}^{12}\rvert^2}$	$1.69 \times 10^{-5}(\frac{\Lambda}{v})^2$	μ-e conversion

Bounds on Wilson Coefficients

$C_{\ell\varphi}^{ij}$	Bound	Observable
$\sqrt{\lvert C_{\ell\varphi}^{31}\rvert^2 + \lvert C_{\ell\varphi}^{13}\rvert^2}$	$1.97 \times 10^{-2}(\frac{\Lambda}{v})^2$	$\mu \to e\gamma$
$\sqrt{\lvert C_{\ell\varphi}^{31}\rvert^2 + \lvert C_{\ell\varphi}^{13}\rvert^2}$	$1.69 \times 10^{-1}(\frac{\Lambda}{v})^2$	$\mu \to eee$
$Re(C_{\ell\varphi}^{13} C_{\ell\varphi}^{31})$	$[-2.96...4.10] \times 10^{-13}(\frac{\Lambda}{v})^2$	electron g-2
$Im(C_{\ell\varphi}^{13} C_{\ell\varphi}^{31})$	$1.55 \times 10^{-8}(\frac{\Lambda}{v})^2$	electron EDM

Bounds on Wilson Coefficients

$C_{\ell\varphi}^{ij}$	Bound	Observable
$\sqrt{\lvert C_{\ell\varphi}^{32}\rvert^2 + \lvert C_{\ell\varphi}^{23}\rvert^2}$	$2.26 \times 10^{-2}(\frac{\Lambda}{v})^2$	$\tau \to e\gamma$
$\sqrt{\lvert C_{\ell\varphi}^{32}\rvert^2 + \lvert C_{\ell\varphi}^{13}\rvert^2}$	$3.53 \times 10^{-1}(\frac{\Lambda}{v})^2$	$\tau \to eee$
$Re(C_{\ell\varphi}^{23} C_{\ell\varphi}^{32})$	$(3.81 \pm 1.06) \times 10^{-3}(\frac{\Lambda}{v})^2$	electron g–2
$Im(C_{\ell\varphi}^{23} C_{\ell\varphi}^{32})$	$(-1.13...1.41)(\frac{\Lambda}{v})^2$	electron EDM

Conclusions

- expressions for several theoretically important and experimentally well constrained lepton flavor observables were calculated
- compact results obtained in terms of Wilson coefficients of all effective operators which could contribute to given process
- "numerical" expressions allow to easily update bounds on Wilson coefficients with improving experimental accuracy
- potential correlation between processes discussed
- hope to help in deeper understanding of the origin of flavor violation!