

Charged Lepton Flavour Violation in effective field theories with dimension 6 operators

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Lepton Flavour Violation: a conceptual challenge

The Dim-4 SM provides an accidental flavour symmetry:

- it holds in QCD and EM interactions;
- in the quark sector, it's broken by EW interactions.

The lepton sector strictly conserves the flavour.

At the same time, we have remarkable phenomenological evidences of FV in the neutrino sector, but...

... No evidence of the following phenomenological realisations:

- $l_h^\pm \rightarrow \gamma + l_i^\pm$ where $h, i = e, \mu, \tau,$
- $l_h^\pm \rightarrow l_i^\pm l_j^\pm l_k^\mp$ where $h, i, j, k = e, \mu, \tau,$
- $Z \rightarrow l_h^\pm l_i^\mp$ where $h, i = e, \mu, \tau,$
- $H \rightarrow l_h^\pm l_i^\mp$ where $h, i = e, \mu, \tau,$
- ...

Experimental “observations”

CURRENT TRENDS IN MUONIC LEPTON FLAVOUR VIOLATION

- $\text{BR}(\mu \rightarrow 3e) < 1.0 \times 10^{-12}$ at the 90% C.L.
SINDRUM collaboration, Nucl. Phys. B **299** (1988) 1;
- $\sigma(\mu^- \rightarrow e^-)/\sigma(\text{capt.})|_{\text{Au}} < 7.0 \times 10^{-13}$ at the 90% C.L.
SINDRUM II collaboration, Eur. Phys. J. C **47** (2006) 337;
- $\text{BR}(\mu \rightarrow \gamma + e) < 4.2 \times 10^{-13}$ at the 90% C.L.
MEG collaboration, Eur. Phys. J. C **76** (2016) 434;
- $\text{BR}(\mu \rightarrow 3e) < 5.0 \times 10^{-15}$ at the 90% C.L.
Mu3e collaboration;
- $\sigma(\mu^- \rightarrow e^-)/\sigma(\text{capt.})|_{\text{Al}} < 1.0 \times 10^{-16}$ at the 90% C.L.
Mu2e and COMET collaborations;
- $\text{BR}(\mu \rightarrow \gamma + e) < 4.0 \times 10^{-14}$ at the 90% C.L.
MEG II collaboration.

From a theorist's point of view

We can contribute in two ways:

- 1 performing precision calculations for cLFV backgrounds;
- 2 interpreting properly the current absence of signals.

1) Typical low-energy cLFV background computations:

- **radiative decays**, $l_1 \rightarrow l_2 + \gamma + 2\nu$;
- **rare decays**, $l_1 \rightarrow 3l_2 + 2\nu$, $l_1 \rightarrow 2l_2 + l_3 + 2\nu$.

2) Typical interpretive approaches:

- **bottom-up**, effective field theoretical formulations;
- **top-down**, UV-complete extensions of the SM.

Precision calculations for cLFV backgrounds

Leptonic radiative and rare decays are known at the Next-to-leading order in the Fermi Theory.

- $l_1 \rightarrow l_2 + \gamma + 2\nu$

M. Fael, L. Mercolli and M. Passera, JHEP **07** (2015) 153

G. Luisoni, GMP, A. Signer and Y. Ulrich, Manuscript prepared for submission

- $l_1 \rightarrow 3l_2 + 2\nu$

M. Fael, C. Greub, JHEP **1701**, 084 (2017)

GMP, A. Signer and Y. Ulrich, Phys. Lett. B **765** (2017) 280

Fully differential NLO Monte Carlo for the radiative/rare decays of a polarised lepton is now available.

Predictions can be tailored on future experiments, arbitrary kinematical cuts can be implemented!

Extending the interactions of the SM

Assumptions: SM is merely an effective theory, valid up to some scale Λ . It can be extended to a field theory that satisfies the following requirements:

- its gauge group should contain $SU(3)_C \times SU(2)_L \times U(1)_Y$;
- all the SM degrees of freedom must be incorporated;
- at low energies (i.e. when $\Lambda \rightarrow \infty$), it should reduce to SM.

Assuming that such reduction proceeds via decoupling of New Physics (NP), the Appelquist-Carazzone theorem allows us to write such theory in the form:

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

Dimension-6 operators

2-leptons

$$Q_{eW} = (\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I;$$

$$Q_{eB} = (\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}.$$

$$Q_{\varphi l}^{(1)} = (\varphi^\dagger i D_\mu \varphi) (\bar{l}_p \gamma^\mu l_r)$$

$$Q_{\varphi l}^{(3)} = (\varphi^\dagger i D_\mu^I \varphi) (\bar{l}_p \tau^I \gamma^\mu l_r)$$

$$Q_{\varphi e} = (\varphi^\dagger i D_\mu \varphi) (\bar{e}_p \gamma^\mu e_r)$$

$$Q_{e\varphi} = (\varphi^\dagger \varphi) (\bar{l}_p e_r \varphi)$$

4-leptons

$$Q_{ll} = (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t)$$

$$Q_{ee} = (\bar{e}_p \gamma_\mu e_r) (\bar{e}_s \gamma^\mu e_t)$$

$$Q_{le} = (\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$$

4-fermions

$$Q_{lq}^{(1)} = (\bar{l}_p \gamma_\mu l_r) (\bar{q}_s \gamma^\mu q_t)$$

$$Q_{lq}^{(3)} = (\bar{l}_p \gamma_\mu \tau^I l_r) (\bar{q}_s \gamma^\mu \tau^I q_t)$$

$$Q_{eu} = (\bar{e}_p \gamma_\mu e_r) (\bar{u}_s \gamma^\mu u_t)$$

$$Q_{ed} = (\bar{e}_p \gamma_\mu e_r) (\bar{d}_s \gamma^\mu d_t)$$

$$Q_{lu} = (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$$

$$Q_{ld} = (\bar{l}_p \gamma_\mu l_r) (\bar{d}_s \gamma^\mu d_t)$$

$$Q_{qe} = (\bar{q}_p \gamma_\mu q_r) (\bar{e}_s \gamma^\mu e_t)$$

$$Q_{ledq} = (\bar{l}_p^j e_r) (\bar{d}_s^j q_t^j)$$

$$Q_{lequ}^{(1)} = (\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$$

$$Q_{lequ}^{(3)} = (\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$$

They all provide LF-violation

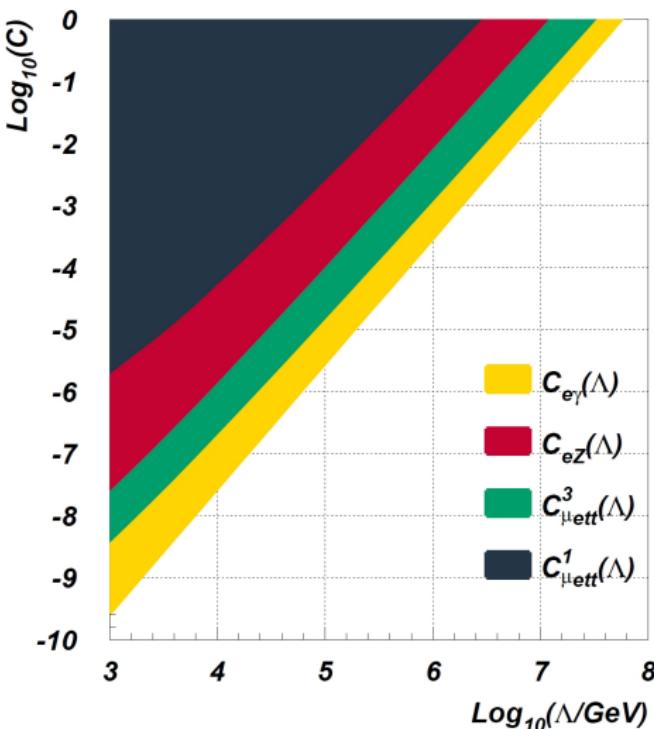
Evolution and bounds from MEG

GMP and A. Signer, JHEP **1410** (2014) 014

A remarkable set of different constraints on coefficients defined at the decoupling scale Λ !

Behaviour is not completely linear: solutions are not analytically simple.

Bounds on $C_{\mu\text{ett}}^{(1,3)}$!



Below the EWSB scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}}$$

$$\begin{aligned}
 &+ \frac{1}{\Lambda^2} \left\{ C_L^D O_L^D + \sum_{f=q,\ell} \left(C_{ff}^{V\,LL} O_{ff}^{V\,LL} + C_{ff}^{V\,LR} O_{ff}^{V\,LR} + C_{ff}^{S\,LL} O_{ff}^{S\,LL} \right) \right. \\
 &\quad \left. + \sum_{h=q,\tau} \left(C_{hh}^{T\,LL} O_{hh}^{T\,LL} + C_{hh}^{S\,LR} O_{hh}^{S\,LR} \right) + C_{gg}^L O_{gg}^L + L \leftrightarrow R \right\} + \text{h.c.},
 \end{aligned}$$

and the explicit structure of the operators is given by

$$O_L^D = e m_\mu (\bar{e} \sigma^{\mu\nu} P_L \mu) F_{\mu\nu},$$

$$O_{ff}^{V\,LL} = (\bar{e} \gamma^\mu P_L \mu) (\bar{f} \gamma_\mu P_L f),$$

$$O_{ff}^{V\,LR} = (\bar{e} \gamma^\mu P_L \mu) (\bar{f} \gamma_\mu P_R f),$$

$$O_{ff}^{S\,LL} = (\bar{e} P_L \mu) (\bar{f} P_L f),$$

$$O_{hh}^{S\,LR} = (\bar{e} P_L \mu) (\bar{h} P_R h),$$

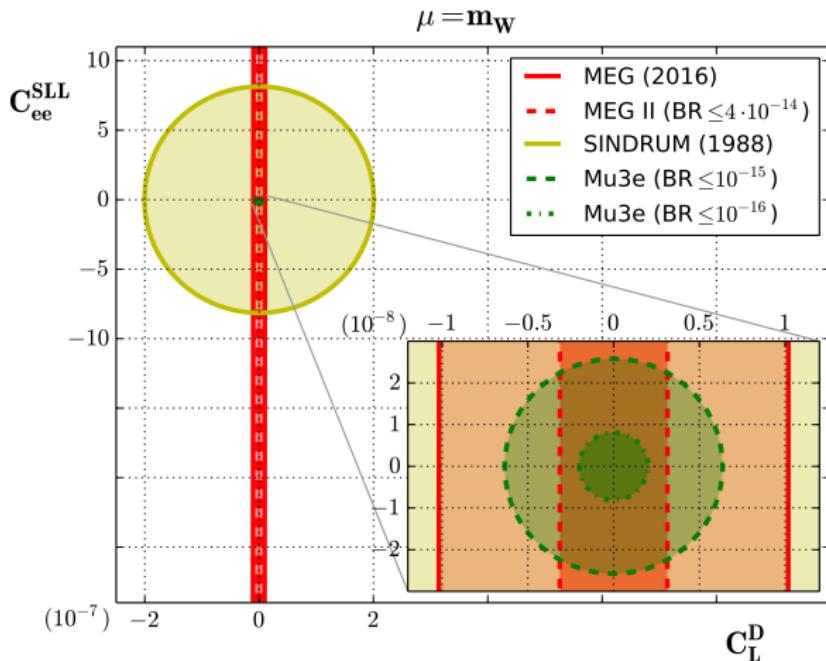
$$O_{hh}^{T\,LL} = (\bar{e} \sigma_{\mu\nu} P_L \mu) (\bar{h} \sigma^{\mu\nu} P_L h),$$

$$O_{gg}^L = \alpha_s m_\mu G_F (\bar{e} P_L \mu) G_{\mu\nu}^a G_a^{\mu\nu}.$$

Interplay between $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

A. Crivellin, S. Davidson, GMP and A. Signer, arXiv:1611.03409 [hep-ph].

Below the EW scale, four-fermion vs dipole:



Dipole evolution below the EWSB scale

At the two-loop level, in the tHV scheme:

$$\begin{aligned}\dot{C}_L^D &= 16 \alpha_e Q_l^2 \boxed{C_L^D} - \frac{Q_l}{(4\pi)} \frac{m_e}{m_\mu} \boxed{C_{ee}^{S\ LL}} - \frac{Q_l}{(4\pi)} \boxed{C_{\mu\mu}^{S\ LL}} \\ &+ \sum_h \frac{8Q_h}{(4\pi)} \frac{m_h}{m_\mu} N_{c,h} \boxed{C_{hh}^{T\ LL}} \Theta(\mu - m_h) \\ &- \frac{\alpha_e Q_l^3}{(4\pi)^2} \left(\frac{116}{9} \boxed{C_{ee}^{V\ RR}} + \frac{116}{9} \boxed{C_{\mu\mu}^{V\ RR}} - \frac{122}{9} \boxed{C_{\mu\mu}^{V\ RL}} - \left(\frac{50}{9} + 8 \frac{m_e}{m_\mu} \right) \boxed{C_{ee}^{V\ RL}} \right) \\ &- \sum_h \frac{\alpha_e}{(4\pi)^2} \left(6Q_h^2 Q_l + \frac{4Q_h Q_l^2}{9} \right) N_{c,h} \boxed{C_{hh}^{V\ RR}} \Theta(\mu - m_h) \\ &- \sum_h \frac{\alpha_e}{(4\pi)^2} \left(-6Q_h^2 Q_l + \frac{4Q_h Q_l^2}{9} \right) N_{c,h} \boxed{C_{hh}^{V\ RL}} \Theta(\mu - m_h) \\ &- \sum_h \frac{\alpha_e}{(4\pi)^2} 4Q_h^2 Q_l N_{c,h} \frac{m_h}{m_\mu} \boxed{C_{hh}^{S\ LR}} \Theta(\mu - m_h) + [\dots].\end{aligned}$$

In absence of interplay at the EWSB scale

	$\text{Br}(\mu^+ \rightarrow e^+ \gamma)$ $4.2 \cdot 10^{-13}$ $4.0 \cdot 10^{-14}$		$\text{Br}(\mu^+ \rightarrow e^+ e^- e^+)$ $1.0 \cdot 10^{-12}$ $5.0 \cdot 10^{-15}$		$\text{Br}_{\mu \rightarrow e}^{\text{Au/Al}}$ $7.0 \cdot 10^{-13}$ $1.0 \cdot 10^{-16}$	
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
C_{ee}^{SLL}	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{e\mu}^{SLL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{SLL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{TLL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
C_{bb}^{SLL}	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
C_{bb}^{TLL}	$2.1 \cdot 10^{-9}$	$6.4 \cdot 10^{-10}$	$4.1 \cdot 10^{-8}$	$2.9 \cdot 10^{-9}$	$4.2 \cdot 10^{-8}$	$6.0 \cdot 10^{-10}$
C_{ee}^{VRR}	$3.0 \cdot 10^{-5}$	$9.4 \cdot 10^{-6}$	$2.1 \cdot 10^{-7}$	$1.5 \cdot 10^{-8}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
$C_{\mu\mu}^{VRR}$	$3.0 \cdot 10^{-5}$	$9.4 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$	$1.1 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
$C_{\tau\tau}^{VRR}$	$1.0 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.9 \cdot 10^{-8}$
C_{bb}^{VRR}	$3.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.8 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
C_{bb}^{RA}	$4.2 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$6.5 \cdot 10^{-3}$	$4.6 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$	$2.2 \cdot 10^{-5}$
C_{bb}^{RV}	$2.1 \cdot 10^{-3}$	$6.4 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.7 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$

Limits on the various coefficients $C_i(m_W)$ from current and future experimental constraints, assuming that (at the high scale m_W) only one coefficient at a time is non-vanishing and not including operator-dependent efficiency corrections.

Conclusion

- ✓ In the past few years, theoretical efforts were devoted to:
 - delivering NLO predictions for cLFV background processes
 - interpreting the absence of signals by means of a consistent QFT approach
- ✓ EFT techniques were adopted/developed to interpret the absence of cLFV signals above and below the EWSB scale via
 - an explicit matching of the LFV Wilson coefficients of the SMEFT to the dipole operator (up to the one-loop level)
 - RGE-improved analysis above (leading order, up to the one-loop contribution) and below (leading order, up to the two-loop contribution) the EWSB scale
- ✓ the constraints on the parameter space of the cLFV Wilson coefficients from current and future experiments are now better understood

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LFV
○○○

Background
○

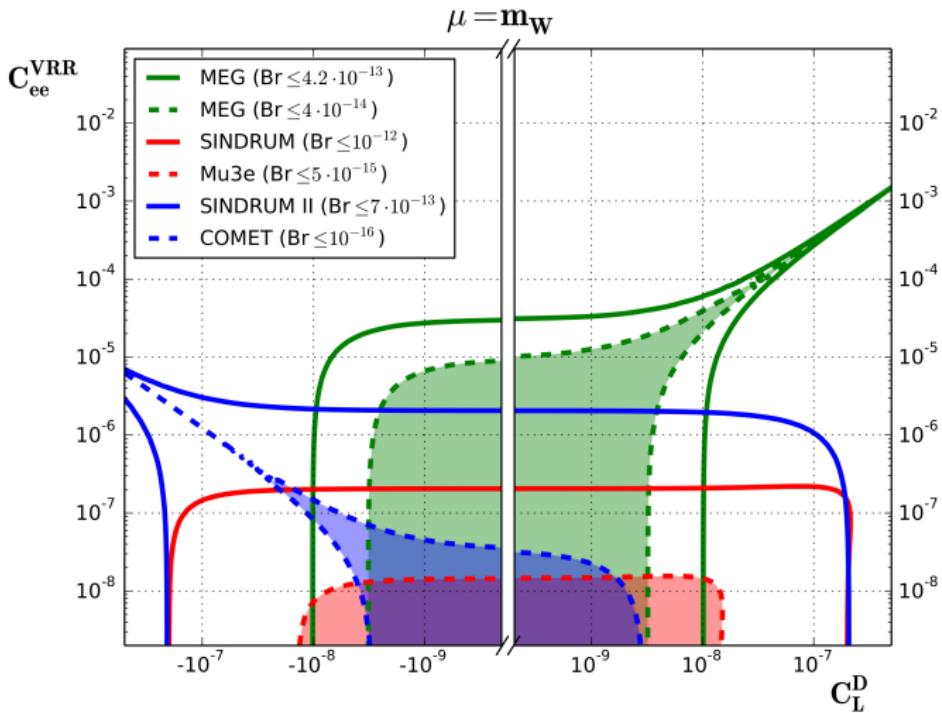
SMEFT
○○○

QEDEFT
○○○○

Conclusion
○

BACKUP SLIDES

Interplay at the EWSB scale



Comparing different experimental performances

