Tau 2018 Vondelkerk Amsterdam

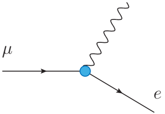
Charged Lepton Flavour Violation

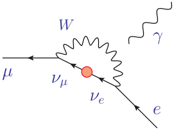
Adrian Signer

Paul Scherrer Institut / Universität Zürich

25 September 2018

why cLFV ?

if you draw  you fail in QED course

but 

- LFV in neutrino sector $\to$ cLFV
- $\mathrm{BR}(\mu \to e\gamma) \sim \alpha \left(\frac{\Delta m^2}{m_W^2}\right)^2 \sim 10^{-54}$
- there is nothing sacred about cLF

absence of cLFV: accident in SM, but not in BSM

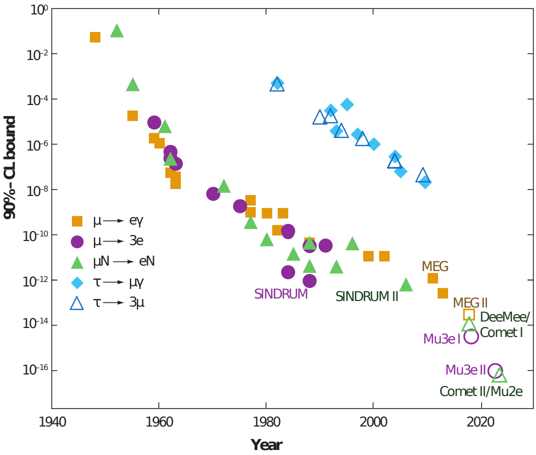
it's not weird to have cLFV in BSM, it's weird not to have cLFV in BSM

- looking for BSM effects that are more difficult to avoid than to have in BSM, unless $\Lambda_{\rm np} \ggg M_{\rm ew}$
- flavour is 'weak point' of SM $\to$ keep probing there (B anomalies are perfect example)
- potential evidence is always indirect

  one experiment will never reveal nature of BSM
- different cLFV experiments ($\ell_i \to \ell_j\gamma, \ell_i \to \ell_j\ell_k\ell_k, \mu N \to eN, \tau \to \ell h \ldots$) should not be seen as competing, but as a part of a 'global' programme
- most experiments done at small scale m_μ, m_τ, m_N

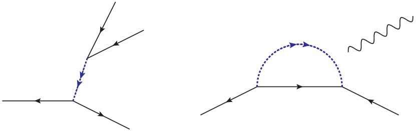
  compare to and combine with high-energy searches ($Z \to \ell_i\ell_j, H \to \ell_i\ell_j \ldots$)
- need theory framework to compare to [Grzadkowski, Iskrzynski, Misiak, Rosiek; Alonso, Jenkins, Manohar, Stoffer, Trott; Feruglio; Ciuchini, Franco, Reina, Silverstini; Pruna, Crivellin, Davidson, . . .]

evolution of limits $\rightarrow$ very rich experimental programme with substantial improvements expected in near future $\rightarrow$ Ana Teixeira's talk



UV complete theory $\leftarrow$ simplified model $\leftarrow$ EFT

Example: doubly charged scalar



- as UV complete model: embed in multiplet, connection m_ν ...

  $++$ valid $\forall\, p^2$, explains everything $--$ requires divine inspiration

- as simplified model: $\mathcal{L}_{\rm int} = \lambda_{fi}\, (\overline{l^c_f} l_i)\, S^{++} \ldots$ few couplings, 1 mass

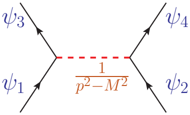
  $+-$ valid for $p^2 > m_S^2$ $-+$ more or less general

- via effective theory: $\mathcal{L}_{\rm int} = c_{fijk}\, (\overline{l_f}\gamma^\mu l_i)\, (\overline{l_j}\gamma_\mu l_k) \ldots$ c's $\leftrightarrow$ λ's

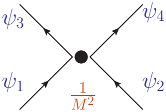
  $--$ valid only for $p^2 \ll m_S^2$ $++$ completely general

EFT vs. models

Processes take place at scale $\mu = m_{\mathrm{mu/tau}}$ or $\mu = \mu_N \sim 1$ GeV



$$\mathcal{O}^i = \frac{1}{\Lambda_{\mathrm{NP}}^2} (\bar\psi_3 \Gamma^a \psi_1)\,(\bar\psi_4 \Gamma^b \psi_2)$$



$$\mathcal{O}^1_{\mathrm{eff}} = (\overline{e_L}\gamma^\rho \mu_L)\,(\overline{e_R}\gamma_\rho e_R)$$
$$\mathcal{O}^2_{\mathrm{eff}} = (\overline{\nu_e}\gamma^\rho \nu_\mu)\,(\overline{e_R}\gamma_\rho e_R)$$

$$\mathcal{O}_{\mathrm{smeft}} = \overline{\begin{pmatrix} \nu_e \\ e_L \end{pmatrix}} \gamma^\rho \begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix} (\overline{e_R}\gamma_\rho e_R)$$

$SU(3)_{\mathrm{QCD}} \times U(1)_{\mathrm{QED}}$

$SU(3)_{\mathrm{QCD}} \times SU(2) \times U(1)_Y$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_{\rm np}} c^{(5)} \mathcal{O}^{(5)}_{\rm smeft} + \frac{1}{\Lambda^2_{\rm np}} \sum_i c^{(6)}_i \mathcal{O}^{(6)}_{i\,\rm smeft}$$

dim 4: SM = most general gauge and Lorentz invariant Lagrangian

$$\begin{aligned}\mathcal{L}_{\rm SM} = &-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \hat\theta\, G^{\mu\nu} \tilde{G}_{\mu\nu} \\ &+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - m_H^2 \Phi^\dagger \Phi - \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 \\ &+ i \left(\bar\ell \not{D}\, \ell + \bar e \not{D}\, e + \ldots\right) - \left(Y_e\, \bar\ell\, e\, \Phi + \ldots + \text{h.c.}\right) \\ &+ \text{nothing with } \nu_R \quad \to \quad \text{no cLFV}\end{aligned}$$

dim $5/\Lambda_{\rm np}$ violates lepton number, but doesn't affect SM much

dim $6/\Lambda^2_{\rm np}$, either we have cLFV or a 'problem' $\left\{ \begin{array}{l} \Lambda_{\rm np} \ggg \Lambda_{\rm ew} \\ \text{need an explanation} \end{array} \right.$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm QCD} + \sum_i \frac{c_i^{(5)}}{\Lambda_{\rm ew}} Q_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_{\rm ew}^2} Q_i^{(6)} + \dots$$

dipole	
$Q_{e\gamma}$	$e\, m_{[pr]} (\bar{l}_p \sigma^{\mu\nu} P_L l_r) F_{\mu\nu} + \text{h.c.}$

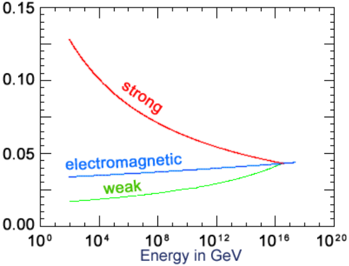
scalar/tensorial		vectorial	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \text{h.c.}$	Q_{VLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_L l_t)$
		Q_{VRL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \text{h.c.}$	Q_{VlqLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \text{h.c.}$	Q_{VlqLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p \sigma^{\mu\nu} P_L l_r)(\bar{q}_s \sigma_{\mu\nu} P_L q_t) + \text{h.c.}$	Q_{VlqRL}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_R q_t)$

if EFT, then properly i.e. include running and mixing

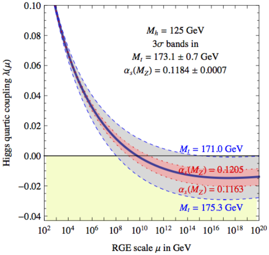
scale of cLFV experiments $m_{\rm mu} \le \mu \le m_W \to c_i(m_{\rm mu})$ "useless"

high-energy behaviour might reveal properties of underlying theory

unified theory?



stable universe ?

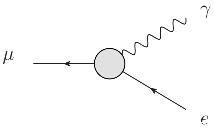


evolve from to $m_{\rm mu}$ to m_W (to combine experiments)

and from m_W to $\Lambda_{\rm uv} \gg m_w$ (to get information on BSM) allow for $\mu\to e$ but otherwise flavour diagonal (i.e. no small^2)

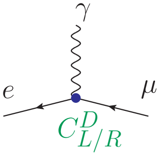
[Crivellin,Davidson,Pruna,AS:1702.03020]

$$
\begin{aligned}
\mathcal{L}_{\rm eff} &= \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm QCD} \\
&+ \frac{1}{\Lambda^2}\Bigg[C_L^D\, e\, m_\mu(\overline{e_L}\sigma^{\mu\nu}\mu_L)F_{\mu\nu} + \sum_{f=q,\ell}\Big[C_{ff}^{S\,LL}\,(\overline{e_R}\mu_L)(\overline{f_R}f_L) \\
&\quad + C_{ff}^{V\,LL}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_L}\gamma_\mu f_L) + C_{ff}^{V\,LR}\,(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_R}\gamma_\mu f_R)\Big] \\
&\quad + \sum_{h=q,\tau}\Big[C_{hh}^{T\,LL}(\overline{e_R}\sigma_{\mu\nu}\mu_L)(\overline{h_R}\sigma^{\mu\nu}h_L) + C_{hh}^{S\,LR}\,(\overline{e_R}\mu_L)(\overline{h_L}h_R)\Big] \\
&\quad + \alpha_s\, m_\mu G_F(\overline{e_R}\mu_L)G^a_{\mu\nu}G_a^{\mu\nu} + L\leftrightarrow R + \text{h.c.}\Bigg]
\end{aligned}
$$

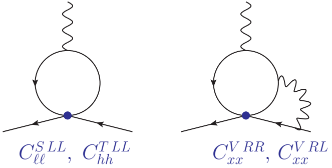


@ tree level: test of $C^D_{L/R}(m_\mu) \equiv (C_{e\gamma})^{21}$

dipole term only ??



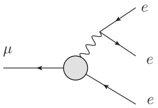
$$\mathrm{Br}\,(\mu \to e\gamma) \simeq \alpha_e m_\mu^5 \left(\left|C^D_L\right|^2 + \left|C^D_R\right|^2 \right)$$

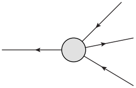


$C^D_L(m_{\mathrm{mu}}) \leftarrow C^{S\,LL}_{\ell\ell}(m_W), C^{V\,RL}_{xx}(m_W)\ldots$

very sensitive to contact interactions

$\mu \to 3e$

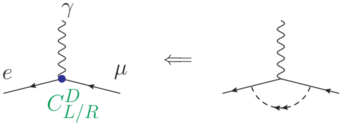


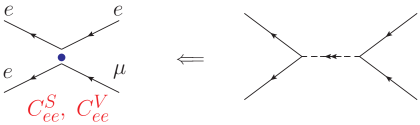


dipole part 'same' as $\mu \to e\gamma$

contact part @ $\mu = m_{\rm mu}$ new

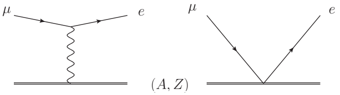
$$\mathrm{Br}(\mu \to 3e) \simeq \alpha_e^2 m_\mu^5 \left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2\right) \left(8 \log\left[\frac{m_\mu}{m_e}\right] - 11\right)$$
$$+ m_\mu^5 \left(\left|C_{ee}^{S\,LL}\right|^2 + 16\left|C_{ee}^{V\,LL}\right|^2 + 8\left|C_{ee}^{V\,LR}\right|^2 + L \leftrightarrow R \right)$$





PAUL SCHERRER INSTITUT PSI Universität Zürich

$\mu N \to eN$

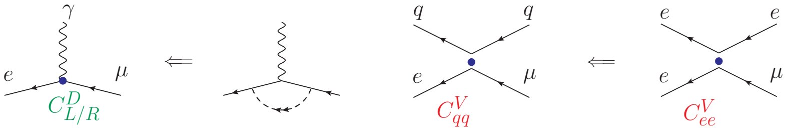


μ conversion: $\mu^- N_Z^A \to e^- N_Z^A$

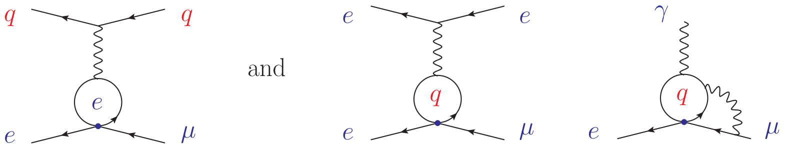
dipole part 'same' as $\mu \to e\gamma$

contact part completely new

$$\mathrm{Br}(\mu N \to eN) \simeq m_\mu^5 \left| e D_N C_L^D + \ldots\ C_{qq}^S \ldots\ C_{qq}^V \right|^2 + L \leftrightarrow R$$



- match at tree level, run at one loop
- include 'leading' two-loop effects
  mixing of vectors into dipole as for $b \to s\gamma$
- Wilson coefficients run and mix, we want $C_i(m_W)$
- operators mix under RGE: one loop two loop

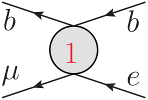


$$(\overline{e_L}\gamma^\mu \mu_L)(\overline{q_L}\gamma_\mu q_L) \to (\overline{e_L}\gamma^\mu \mu_L)(\overline{e_L}\gamma_\mu e_L) \text{ or } (\overline{e_L}\sigma^{\mu\nu} \mu_L)F_{\mu\nu}$$

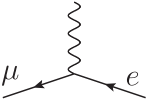
complementarity

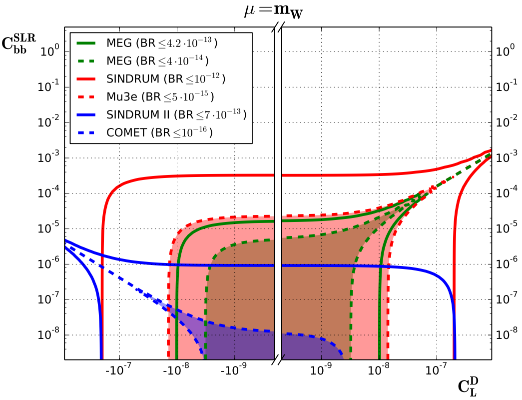
'naive' two-at-a-time limits

see Ann-Kathrin Perrevoort's poster



vs.





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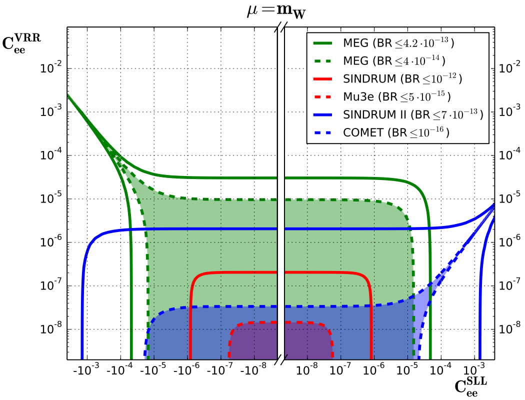
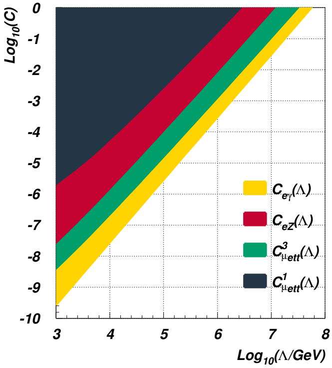


Constraints from $\mu \to e\gamma$



[Pruna,AS: 1408:3565]

- contact interactions $C^1_{\mu ett} \to C^3_{\mu ett} \to$ dipole interaction $C_{e\gamma}$
- probing very high energy range !
- even indirect limits can be very constraining

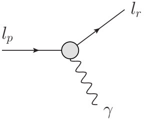
an example: $SU(2)$ singlet doubly charged scalar (DCS) S^{++}

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) + \left(\lambda_{ab}\, \overline{(\ell_R)}^c_a\, (\ell_R)_b\, S^{++} + \text{h.c.}\right) + \lambda_2 \left(H^\dagger H\right)\left(S^{--} S^{++}\right) + \lambda_4 \left(S^{--} S^{++}\right)^2 + [\ldots]$$

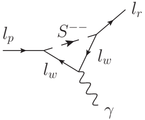
focus on 6 couplings λ_{ab} and mass m_S

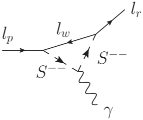
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm QCD} + \frac{1}{m_S^2} \sum_i C_i Q_i,$$

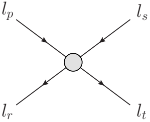
doubly charged scalar



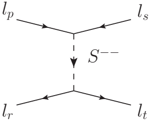
$$C_{e\gamma}^{pr}(m_W) \sim \sum_{w=1}^{3} (\lambda_{rw}\lambda_{pw}^*)$$





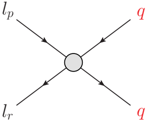


$$C_{VRR}^{prst}(m_W) = \frac{\lambda_{rt}\lambda_{ps}^*}{2}$$



$$\rightarrow \{Q_{e\gamma}, Q_{VRR}, Q_{VRL}, Q_{VlqRR}, Q_{VlqRL}\}(m_\ell) \subset \mathcal{L}_{\text{eff}}$$

we will get muon conversion!

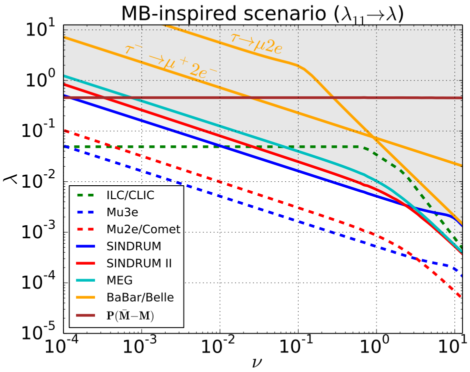


C_{qq}^V

'global' analysis $\to$ there is no best experiment, all are important

low-energy (μ and τ, $\bar{M} - M$)

high-energy (LC. mainly via t-channel exchange $e^+e^- \to \ell_i \bar{\ell}_j$)



For illustrative purpose:

$$\lambda_{ab} = \lambda \begin{pmatrix} +1 & \nu & \nu^2 \\ \nu & 1 & \nu \\ \nu^2 & \nu & 1 \end{pmatrix}$$

6 $\to$ 2 parameters

[Crivellin, Ghezzi, Panizzi, Pruna, AS]

'global' analysis $\rightarrow$ there is no best experiment, all are important

low-energy (μ and τ, $\bar{M} - M$)

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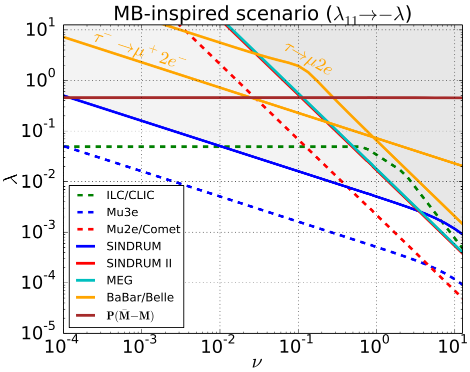

For illustrative purpose:

$$\lambda_{ab} = \lambda \begin{pmatrix} -1 & \nu & \nu^2 \\ \nu & 1 & \nu \\ \nu^2 & \nu & 1 \end{pmatrix}$$

$6 \rightarrow 2$ parameters

[Crivellin, Ghezzi, Panizzi, Pruna, AS]

'global' analysis $\to$ there is no best experiment, all are important

low-energy (μ and τ, $\bar{M}-M$)
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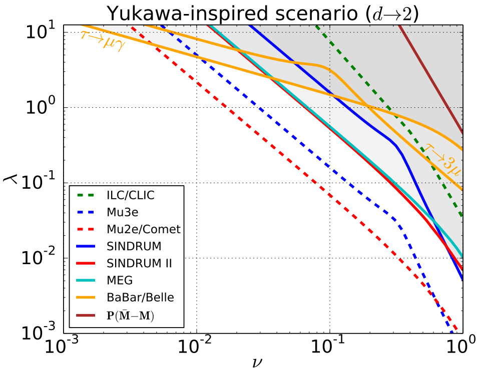

For illustrative purpose:

$$\lambda_{ab} = \lambda \begin{pmatrix} \nu^4 & \nu^3 & \nu^2 \\ \nu^3 & \nu^2 & \nu \\ \nu^2 & \nu & 1 \end{pmatrix}$$

6 $\to$ 2 parameters

[Crivellin, Ghezzi, Panizzi, Pruna, AS]

doubly charged scalar

'global' analysis $\to$ there is no best experiment, all are important

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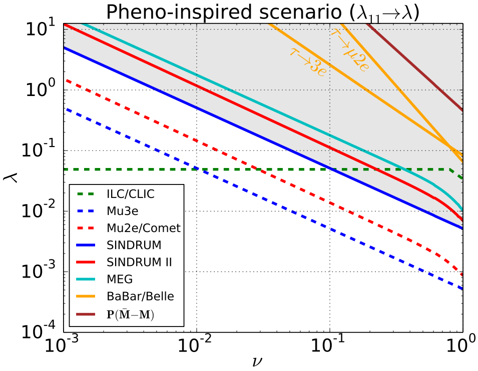

For illustrative purpose:

$$\lambda_{ab} = \lambda \begin{pmatrix} 1 & \nu^2 & \nu^3 \\ \nu^2 & \nu^4 & \nu^5 \\ \nu^3 & \nu^5 & \nu^6 \end{pmatrix}$$

$6 \to 2$ parameters

[Crivellin, Ghezzi, Panizzi, Pruna, AS]

- cLFV is a window with a view deeply beyond EW scale
- huge experimental progress expected within $5 - 10$ years
- if cLFV is natural in BSM, why have we not seen it then?
  Is $\Lambda_{\rm np}$ just too large? or BSM still cLF conserving??
- EFT approach is ideal first step for investigating cLFV
  EFT $\to$ simplified models $\to$ the UV complete model
  need many experiments
- beware of common misconceptions
  - EFT is a QFT !
  - RGE is not a precision issue, but qualitatively new effects
  - $\mu \to e\gamma$ is very sensitive to contact interactions !!
  - one/two-at-a-time limits only for presentation