*ALPS 2018*

# Charged Lepton Flavour Violation

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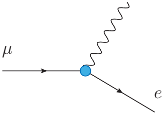
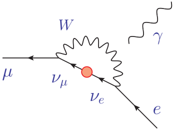
## *why cLFV ?*

if you draw 

you fail in QED course

but 


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

neutral LF is violated
quark flavour is violated } so why should cLFV be conserved?

absence of cLFV: accident in SM, but not in BSM dim 4: SM = most general gauge and Lorentz invariant Lagrangian

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

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

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

cLFV a unique window with a view deep into the UV

## cLFV: golden channels

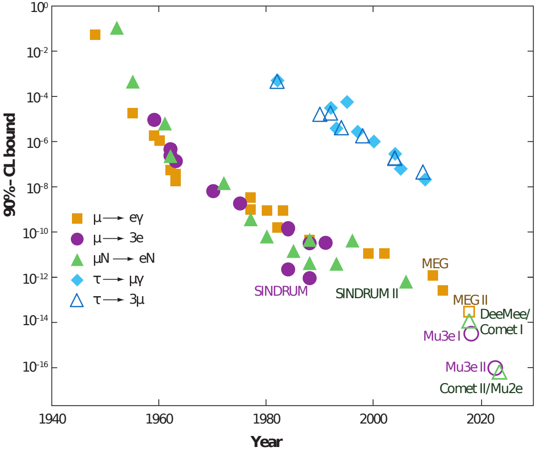
- $\mu \to e\gamma$ @PSI
  - current MEG (2016) $\mathrm{Br}(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$
  - MEG II: (2018–2021) expect: $\mathrm{Br}(\mu \to e\,\gamma) \sim \times 10^{-14}$
- $\mu \to eee$ @PSI
  - current Sindrum (1988) $\mathrm{Br}(\mu \to eee) < 1 \times 10^{-12}$
  - new experiment Mu3e

    Phase 1 (2020++): $\mathrm{Br} \sim \mathrm{few} \times 10^{-15}$,

    Phase 2 (20??++): new beamline $\mathrm{Br} \sim 10^{-16}$
- $\mu N \to eN$ PSI $\to$ JPARC & FNAL
  - current Sindrum II (2006) $\mathrm{Br}(\mu\ \mathrm{Au} \to e\ \mathrm{Au}) < 7 \times 10^{-13}$
  - new experiment DeeMe ? (201?): $\mathrm{Br} \sim 10^{-14}$
  - new experiments Comet (2019/ 2021–22)

    and Mu2e (2022–24): $\mathrm{Br} \sim 10^{-16}$
  - ?? Prism/Prime ?? (20??) : $\mathrm{Br} \sim 10^{-18}$

evolution of limits $\rightarrow$ very rich experimental programme with substantial improvements on all muon-related processes expected in near future



examples (ordered according to increasing energy):

[Mu2e, Comet, Babar, Belle, SHiP?, LHCb, CMS, Atlas ...]

- $M(\mu^- e^+) \leftrightarrow \bar{M}(\mu^+ e^-)$ oscillation
- $\mu^- N \to e^+ N'$ experimentally 'easy' but nuclear 'mess'
- golden channels with $\tau$

  $\mathrm{BR}(\tau \to 3\ell) \lesssim (1-2) \times 10^{-8}, \quad \mathrm{BR}(\tau \to \ell\gamma) \lesssim 4 \times 10^{-8}$
- hadronic decays with $\tau$ such as $\tau \to \ell h$ or $\tau \to \ell h^+ h^-$
- involving $B$ decays (very topical !!)

  $B \to K\ell\ell', \; B \to \pi\ell\ell', \; B_s \to \ell\ell'$
- involving $Z$ and $H$ or anything at $\Lambda \gtrsim m_{\mathrm{ew}}$

  $Z \to \tau\mu, \; H \to \tau\mu$

- looking for BSM effects that are more difficult to avoid than to have in "accessible" BSM
- potential evidence is always indirect

  one experiment will never reveal nature of BSM
- most experiments done at small scale $m_\mu$, $m_\tau$, $m_N$

  compare to and combine with high-energy searches
- use EFT (only a tool, not the goal) with RGE evolution

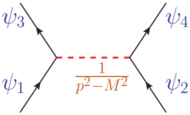
  $\rightarrow$ simplified models $\rightarrow$ UV complete models
- $\mu > m_{\rm ew}$ : $\quad \mathcal{L}_{\rm smeft} \supset \dfrac{C_{e\gamma}}{\Lambda^2} Q_{e\gamma} = \dfrac{C_{e\gamma}}{\Lambda^2} (\bar{L} \sigma_{\mu\nu} e_R)\, H\, F^{\mu\nu}$

  $\mu < m_{\rm ew}$ : $\quad \mathcal{L}_{\rm eff} \supset \dfrac{c_{e\gamma}}{m_{\rm ew}^2} m_\ell (\bar{\ell}_L \sigma_{\mu\nu} \ell_R) F^{\mu\nu}$

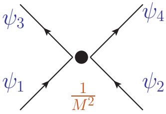
  $\mu \sim \mu_N$ : $\quad \mathcal{L}_{\rm had} \supset \bar{N} \left( i\gamma^5 g_{\pi N N} + \bar{g}_{\pi N N} \right) \vec{\pi} \cdot \vec{\tau}\, N + \ldots$

# EFT vs. models

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




$$\mathcal{O}^i = \frac{1}{\Lambda_{\mathrm{NP}}^2} (\bar{\psi}_3 \Gamma^a \psi_1)\,(\bar{\psi}_4 \Gamma^b \psi_2)$$





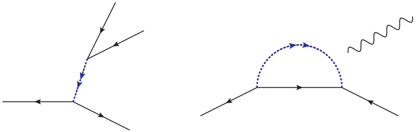
$$\mathcal{O}^1_{\mathrm{eff}} = (\overline{e_L} \gamma^\rho \mu_L)\,(\overline{e_R} \gamma_\rho e_R)$$
$$\mathcal{O}^2_{\mathrm{eff}} = (\overline{\nu_e} \gamma^\rho \nu_\mu)\,(\overline{e_R} \gamma_\rho e_R)$$

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

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

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

Example: doubly charged Higgs



- as UV complete model: embed in multiplet, sort out $\rho$ parameter ...
  $++$ valid $\forall\, p^2$, explains everything $\quad --$ requires divine inspiration
- as simplified model: $\mathcal{L}_{\rm int} = \lambda_{fi}\,(\overline{l^c_f} l_i)\,\phi^{++}\dots$ few couplings, 1 mass
  $+-$ valid for $p^2 > m_\phi^2$ $\quad -+$ more or less general
- via effective theory: $\mathcal{L}_{\rm int} = c_{fijk}\,(\overline{l_f}\gamma^\mu l_i)\,(\overline{l_j}\gamma_\mu l_k)\dots\ \ c$'s $\leftrightarrow \lambda$'s
  $--$ valid only for $p^2 \ll m_\phi^2$ $\quad ++$ completely general

EFT is never the goal, only the tool, (cp. $C_9 = -C_{10}$ for $B$ anomalies)

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

a bit of a mess ...

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

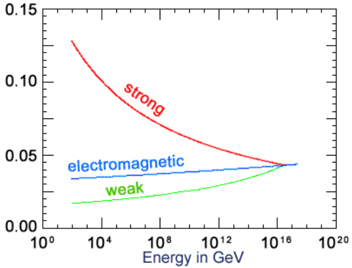
| scalar/tensorial | | vectorial | |
|---|---|---|---|
| $Q_S$ | $(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \text{h.c.}$ | $Q_{VLL}$ | $(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_L l_t)$ |
| | | $Q_{VRL}$ | $(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_R l_t)$ |
| | | $Q_{VRR}$ | $(\bar{l}_p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

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

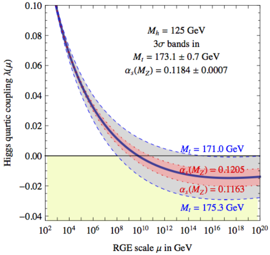
scale of cLFV experiments $m_{\rm mu} \le \mu \le m_W \to c_i(m_{\rm mu})$ "useless"

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 $\text{small}^2$)

[Crivellin,Davidson,Pruna,AS:1702.03020]

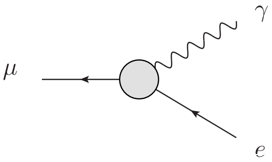
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm QCD}$$

$$+ \frac{1}{\Lambda^2}\Bigg[C_L^D\, e\, m_\mu (\overline{e_L}\sigma^{\mu\nu}\mu_L)F_{\mu\nu} + \sum_{f=q,\ell}\Big[C_{ff}^{S\,LL}\,(\overline{e_R}\mu_L)(\overline{f_R}f_L)$$

$$+ C_{ff}^{V\,LL}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_L}\gamma_\mu f_L) + C_{ff}^{V\,LR}\,(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_R}\gamma_\mu f_R)\Big]$$

$$+ \sum_{h=q,\tau}\Big[C_{hh}^{T\,LL}(\overline{e_R}\sigma_{\mu\nu}\mu_L)(\overline{h_R}\sigma^{\mu\nu}h_L) + C_{hh}^{S\,LR}\,(\overline{e_R}\mu_L)(\overline{h_L}h_R)\Big]$$

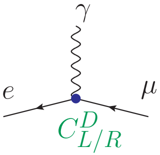
$$+\alpha_s\, m_\mu G_F(\overline{e_R}\mu_L)G^a_{\mu\nu}G_a^{\mu\nu} + L \leftrightarrow R + \text{h.c.}\Bigg]$$



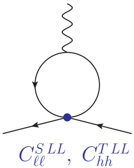

signal: monoenergetic, simultaneous, back-to-back $e$ and $\gamma$

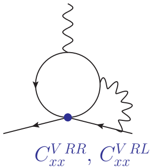
$\mathrm{BR_{SM}} \sim 10^{-54}$

still, there is background !!




$$\mathrm{Br}\,(\mu \to e\gamma) \simeq \alpha_e m_\mu^5 \left( \left| C_L^D \right|^2 + \left| C_R^D \right|^2 \right)$$

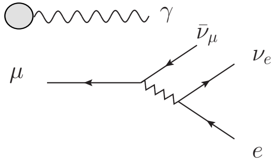



$$C_L^D(m_{\mathrm{mu}}) \leftarrow C^{S\,LL}_{\ell\ell}(m_W), C^{V\,RL}_{xx}(m_W) \ldots$$

very sensitive to contact interactions

PSI: continuous beam of muons, $10^8\, s^{-1}$

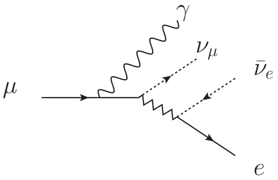



accidental background:

$e$ and $\gamma$ not quite back-to-back and mono-energetic nor quite simultaneous

$\Rightarrow$ timing, vertex and momentum resolution very important

$\Rightarrow$ upgrade MEG II



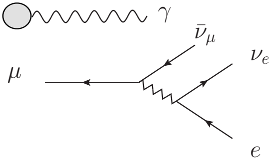

irreducible background

SM process radiative decay

in region where $\nu$ very little energy

missing momentum $p_e + p_\gamma \neq m_{\text{mu}}$

PSI: continuous beam of muons, $10^8\,s^{-1}$

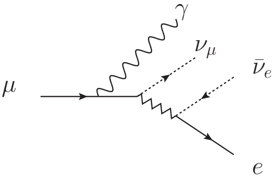



accidental background:

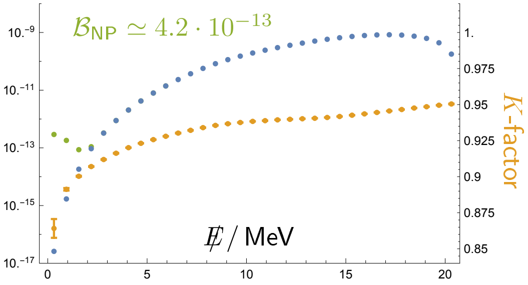
$e$ and $\gamma$ not quite back-to-back and mo-noenergetic nor quite simultaneous

$\Rightarrow$ timing, vertex and momentum resolu-tion very important

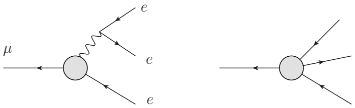
$\Rightarrow$ upgrade MEG II




[Pruna,AS,Ulrich]



# $\mu \to 3e$

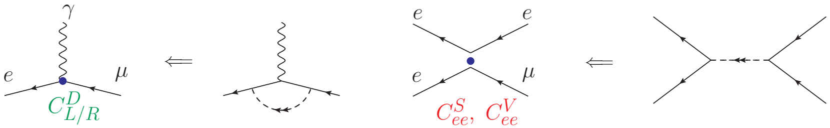



signal: 2 $e^+$ + 1 $e^-$, simultaneous, from same vertex, $\sum p_e = m_{\rm mu}$

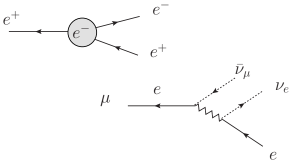
dipole part 'same' as $\mu \to e\gamma$

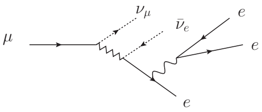
contact part @ $\mu = m_{\rm mu}$ new

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



# $\mu \to 3e$ background




accidental background:

$e$ and $\gamma$ not quite from same vertex nor quite simultaneous and with missing momentum

$\Rightarrow$ timing, vertex and momentum resolution very important

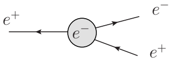
irreducible background

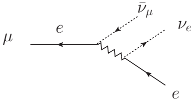
SM process rare decay

in region where $\nu$ very little energy

missing momentum $\sum p_e \neq m_{\text{mu}}$

# $\mu \to 3e$ *background*

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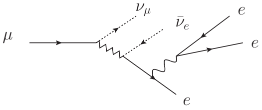
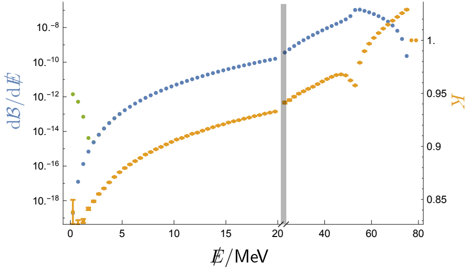
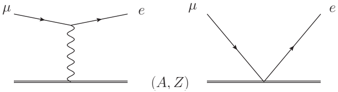



[Pruna,AS,Ulrich]





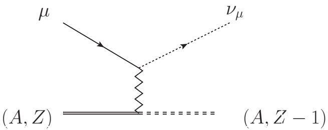

$\mu$ conversion: $\mu^- N_Z^A \to e^- N_Z^A$

signal: single 105 MeV $e^-$

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

contact part completely new

nucleus not affected (only recoil) $\to$ dirty nuclear physics under control




$\mu$ capture: $\mu^- N_Z^A \to \nu_\mu N_{Z-1}^A$

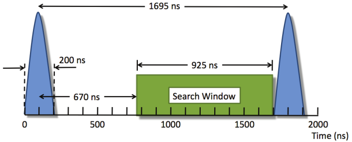
denominator of 'branching' ratio

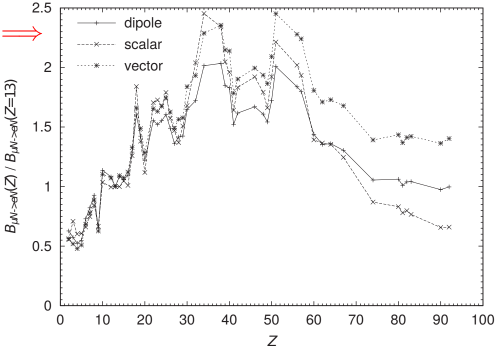
for larger $Z$, shorter life time

which $Z$ ? [Fässler et al; Cirigliano et al.]

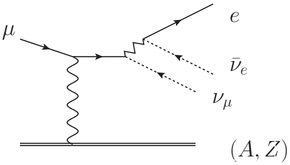
SINDRUM with Au (Ti, Pb), COMET/Mu2e plan Al (initially)
large $Z$ $\to$ increase sensitivity $\to$ small life time ( ?? pulsed beams ??)

at $\mu = \mu_N$ no axial couplings $\Longrightarrow$
(coherent $\mu N \to eN$)



decay in orbit: irreducible background for $\mu N \to e N$

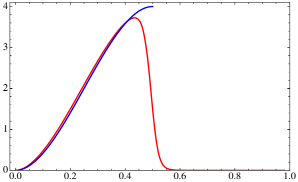


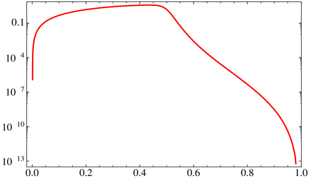

DIO: $\mu^- N_Z^A \to e^- \, \bar\nu_e \, \nu_\mu N_Z^A$

$\sum p_e > m_{\rm mu}/2 \;\; \to \;\; m_{\rm mu}$ possible

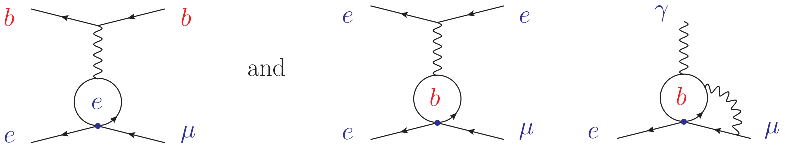
nuclear recoil

DIO energy spectrum [Czarnecki et al.]



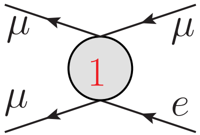
- match at tree level, run at one loop
- include 'leading' two-loop effects
  mixing of vectors into dipole as for $b \to s\gamma$
- Wilson coefficients run and mix, we want $C_i(m_W)$
- operators mix under RGE: one loop two loop

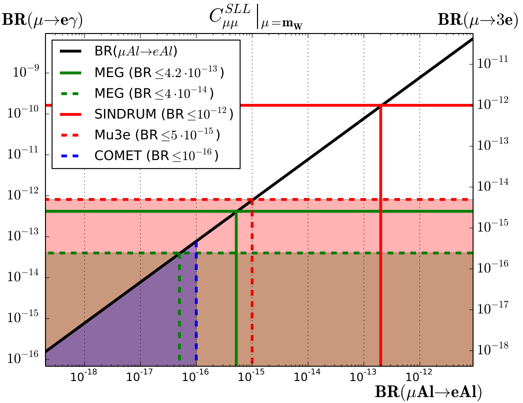



$$(\overline{e_L}\gamma^\mu \mu_L)(\overline{b_L}\gamma_\mu b_L) \to (\overline{e_L}\gamma^\mu \mu_L)(\overline{e_L}\gamma_\mu e_L) \text{ or } (\overline{e_L}\sigma^{\mu\nu}\mu_L)F_{\mu\nu}$$

## naive one-at-a-time limits $C_i(m_W)$ [Crivellin, Davidson, Pruna, AS]

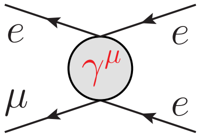
absolute value of Wilson coefficients is irrelevant (depends on conventional prefactors)

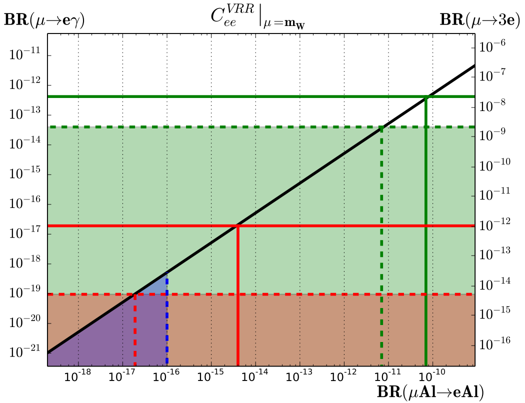


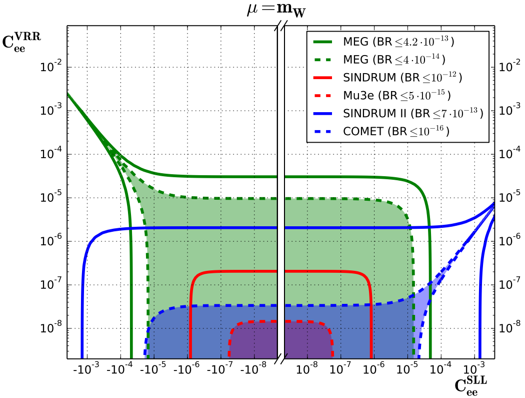
naive one-at-a-time limits $C_i(m_W)$ [Crivellin, Davidson, Pruna, AS]

absolute value of Wilson coefficients is irrelevant (depends on conventional prefactors)



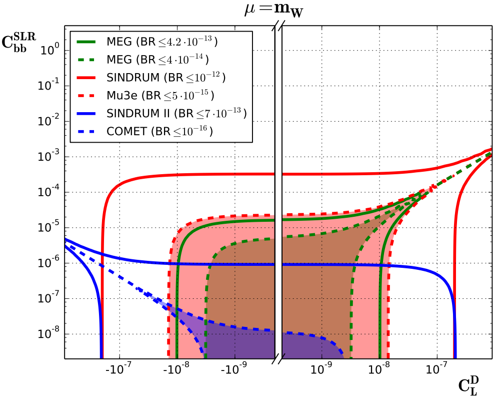



naive two-at-a-time limits

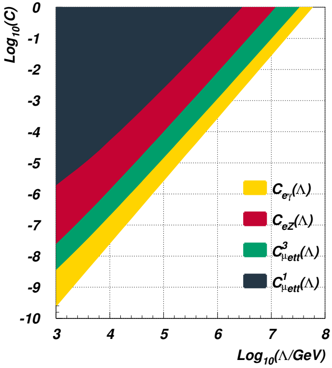



# ... and complementarity

naive two-at-a-time limits

## 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

- cLFV is a window with a view deeply beyond EW scale
- huge experimental progress expected within $5 - 10$ years
- why have we not seen it then?
  Is $\Lambda_{\rm NP}$ just too large? or BSM still cLF conserving??
- EFT approach is ideal for investigating cLFV
  but we still want the explicit BSM in the end
- beware of common misconceptions
  - $\mu \to e\gamma$ is very sensitive to contact interactions !!
  - $\mu N \to e N$ is very sensitive to pseudo scalar and axial vector interactions !!
  - RGE is not a precision issue, but qualitatively new effects
  - one/two-at-a-time limits only for presentation