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Physics Landscape in 10 years

Lepton Flavour Violation in Muon Decays

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Lepton flavour is violated,

so why should charged lepton flavour be conserved?

- introduction (stating the obvious)
- the golden channels $\mu \to e\gamma, \quad \mu \to 3e, \quad \mu N \to eN$
    - experiments: current status / outlook
    - backgrounds !!
    - theory interpretation
- beyond the golden channels
- other things to do with muon decays

playing with SM fields only:

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

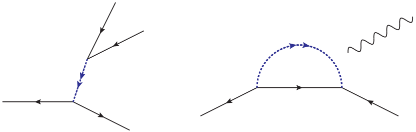
$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu} - \frac{1}{4}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \hat\theta\, G^{\mu\nu}\tilde G_{\mu\nu}$$
$$+ (D_\mu\Phi)^\dagger(D^\mu\Phi) - m_H^2\Phi^\dagger\Phi - \frac{\lambda}{2}(\Phi^\dagger\Phi)^2$$
$$+ i\,\big(\bar\ell \not{D}\,\ell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

dim 5 violates lepton number, but doesn't affect SM much

dim 6, either we have cLFV or a 'problem' (i.e. need an explanation)

cLFV a unique window with a view deep into the UV

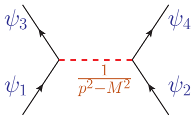
Example: doubly charged Higgs



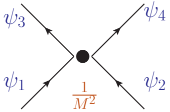
- as UV complete model: embed in multiplet, sort out ρ parameter ...
  $++$ valid $\forall\, p^2$, explains everything $\quad --$ requires divine inspiration
- as simplified model: $\mathcal{L}_{\rm int} = \lambda_{fi}\,(\overline{l^c_f} l_i)\,\phi^{++}\ldots$ few couplings, 1 mass
  $+-$ valid for $p^2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

EFT vs models



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



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

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

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

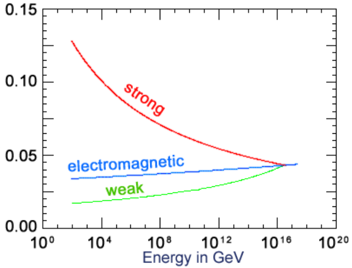
$SU(3)_{\rm QCD} \times SU(2) \times U(1)_Y$

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

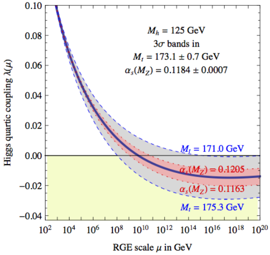
scale of cLFV experiments $m_{\rm mu} \le \mu \le m_W \to c_i(m_{\rm mu})$ "useless"

high-energy behaviour might reveal properties of underlying theory

unified theory?



stable universe ?

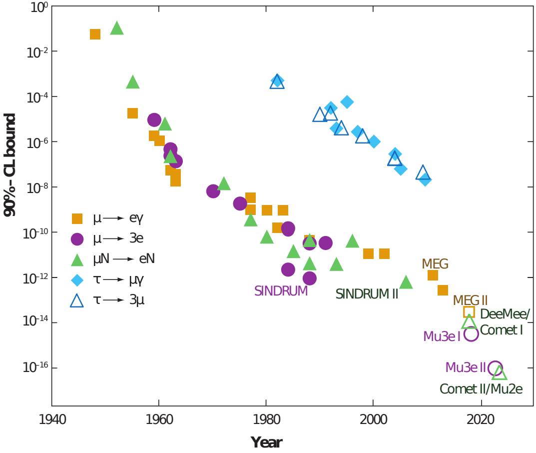


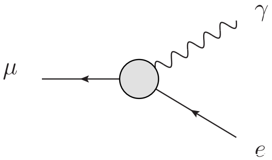
evolve from to $m_{\rm mu}$ to m_W (to combine experiments)

and from m_W to $\Lambda_{\rm uv} \gg m_w$ (to get information on BSM)

- $\mu \to e\gamma$
  - current MEG (2016) $\mathrm{Br}(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$
  - MEG II: (2018-2021) expect: $\mathrm{Br}(\mu \to e\,\gamma) \sim \times 10^{-14}$
- $\mu \to eee$
  - 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 $\mathrm{Br} \sim 10^{-16}$
- $\mu N \to eN$
  - current Sindrum II (2006) $\mathrm{Br}(\mu\ \mathrm{Au} \to e\ \mathrm{Au}) < 7 \times 10^{-13}$
  - new experiment DeeMe ? (2017++): $\mathrm{Br} \sim 10^{-14}$
  - new experiments Comet (2019/ 2021-22)
    and Mu2e (2022-24): $\mathrm{Br} \sim 10^{-16}$
  - ?? Prism/Prime ?? (20??) : $\mathrm{Br} \sim 10^{-18}$

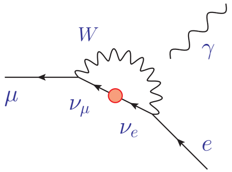
evolution of limits $\rightarrow$ very rich experimental programme with substantial improvements on all muon-related processes expected in near future





signal: monoenergetic, simultaneous, back-to-back e and γ

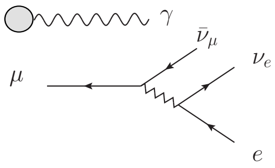
in SM with massive neutrinos



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

still, there is background !!

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

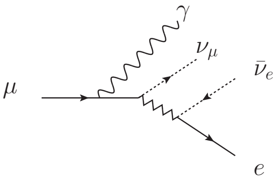


accidental background:

e and γ not quite back-to-back and monoenergetic nor quite simultaneous

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

$\Rightarrow$ upgrade MEG II



irreducible background

SM process radiative decay

in region where ν very little energy

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

radiative decay @NLO fully differential [Pruna,AS,Ulrich]

(BR compared with [Fael,Mercolli,Passera])

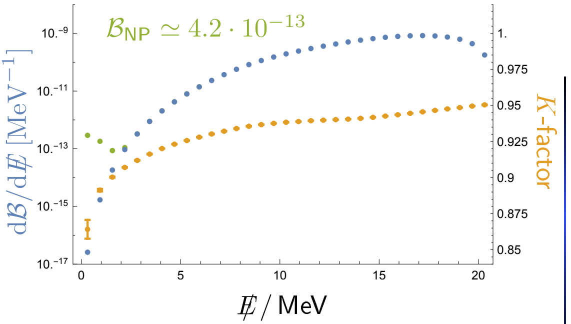
polarization: $\vec{s} = -0.85\hat{z}$ and toy cuts: no $2^{\rm nd}$ photon with $E_\gamma > 2$ MeV

$E_\gamma > 40$ MeV, $|\cos\theta_\gamma| < 0.35$, $|\phi_\gamma| > 2\pi/3$

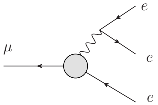
$E_e > 45$ MeV, $|\cos\theta_e| < 0.5$, $|\phi_\gamma| < \pi/3$

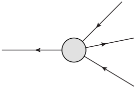
The invisible energy spectrum

$\not{E} = m_{\rm mu} - E_e - E_\gamma$



$\mu \to 3e$



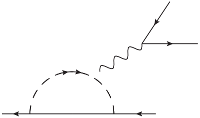


signal: 2 e^+ + 1 e^-, simultaneous, from same vertex, $\sum p_e = m_{\rm mu}$

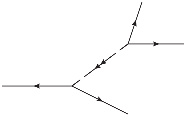
dipole part 'same' as $\mu \to e\gamma$

contact part completely new

e.g. doubly charged Higgs

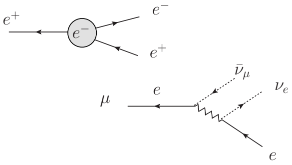


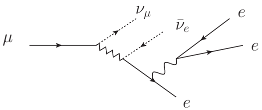
via dipole terms



contact interaction

@ LO @ $\mu = m_{\rm mu}$!!





accidental background:

e and γ 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

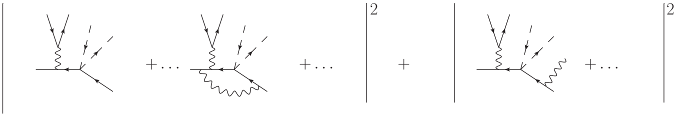
in region where ν very little energy

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

irreducible background

$\mu \to 3e + 2\nu$ fully differential @NLO [Pruna,AS,Ulrich]

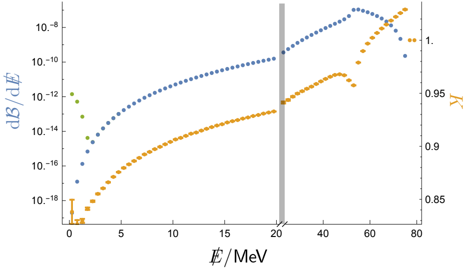
BR (with cuts on invisible energy) compared with [Fael,Greub]

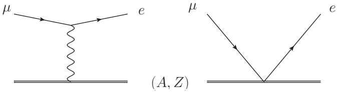


polarization: $\vec{s} = -0.85\hat{z}$ toy cuts: $E_i > 10$ MeV, $|\cos\theta_i| < 0.8$

The invisible energy spectrum

$$\not{E} = m_{\text{mu}} - \sum E_i$$





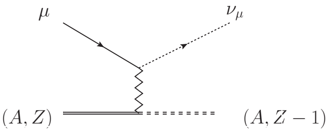
μ conversion: $\mu^- N_Z^A \to e^- N_Z^A$

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



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

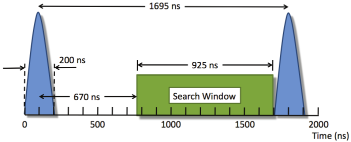
denominator of 'branching' ratio

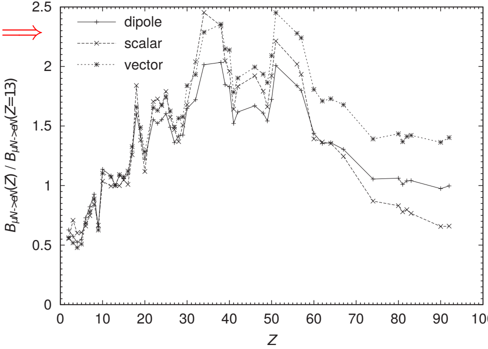
for larger Z, shorter life time

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

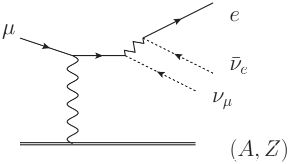
SINDRUM with Au (Ti, Pb), COMET/Mu2e plan Al (initially)
large Z $\to$ increase sensitivity $\to$ small life time (?? pulsed beams ??)

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





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

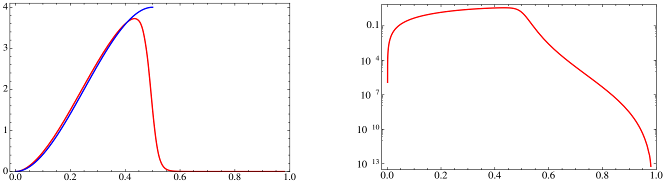


DIO: $\mu^- N_Z^A \to e^- \, \bar{\nu}_e \, \nu_\mu N_Z^A$

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

nuclear recoil

DIO energy spectrum [Czarnecki et al.]



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

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

$$SU(3)_{\rm QCD} \times U(1)_{\rm QED} \qquad SU(3)_{\rm QCD} \times SU(2) \times U(1)_Y$$

$$\Lambda_{\rm NP} \leq m_W \qquad \Lambda_{\rm NP} \gg m_W$$

$\mathcal{L}_{\rm eff}$ below m_W

effective Lagrangian $\mathcal{L}_{\rm eff}$ (below EW scale) for $\mu \to e$ processes

allow for $\mu \to e$ but otherwise flavour diagonal (i.e. no small^2)

what is often used: [Kuno,Okada:hep-ph/9909265]
ok if coefficients are interpreted at $\mu = m_{\rm mu}$ no link with e.g. $Z \to e\mu$

$$
\begin{aligned}
\mathcal{L}_{\rm eff} &= \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm QCD} \\
&+ \frac{4G_F}{\sqrt{2}}\Big[A_R\, m_\mu\, \overline{\mu_R}\sigma^{\mu\nu} e_L\, F_{\mu\nu} + L \leftrightarrow R \\
&+ g_1 (\overline{\mu_R} e_L)(\overline{e_R} e_L) + g_2 (\overline{\mu_L} e_R)(\overline{e_L} e_R) \\
&+ g_3 (\overline{\mu_R}\gamma^\mu e_R)(\overline{e_R}\gamma_\mu e_R) + g_4 (\overline{\mu_L}\gamma^\mu e_L)(\overline{e_L}\gamma_\mu e_L) \\
&+ g_5 (\overline{\mu_R}\gamma^\mu e_R)(\overline{e_L}\gamma_\mu e_L) + g_6 (\overline{\mu_L}\gamma^\mu e_L)(\overline{e_R}\gamma_\mu e_R) + \text{h.c.}\Big]
\end{aligned}
$$

effective Lagrangian $\mathcal{L}_{\rm eff}$ (below EW scale) for $\mu \to e$ processes

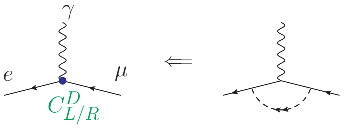
allow for $\mu \to e$ but otherwise flavour diagonal (i.e. no small^2)

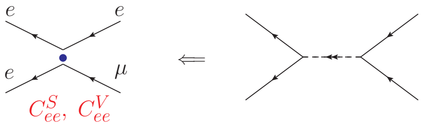
what should be used: [Crivellin,Davidson,Pruna,AS:1702.03020]
needed if coefficients are to be evolved (e.g. up to $\mu = m_W$)

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

express observables $\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$ through $\mathcal{L}_{\rm eff}$ e.g.

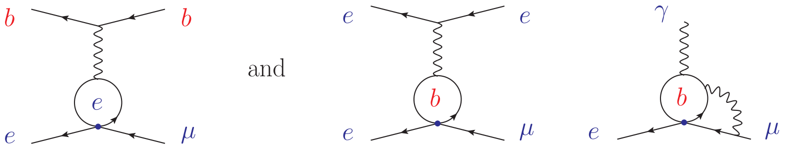
$$\mathrm{Br}(\mu \to 3e) \simeq \alpha_e^2 m_\mu^5 \left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2\right)\left(8\log\left[\frac{m_\mu}{m_e}\right] - 11\right)$$
$$+ m_\mu^5 \left(\left|C_{ee}^{S\,LL}\right|^2 + 16\left|C_{ee}^{V\,LL}\right|^2 + 8\left|C_{ee}^{V\,LR}\right|^2 + L \leftrightarrow R\right)$$





for $\mathrm{BR}(\mu \to e\gamma)$ and $\mathrm{BR}(\mu \to 3e)$: $C_i(m_{\rm mu})$
for $\mathrm{BR}(\mu N \to eN)$: $C_i(\mu_N)$ (we choose $\mu_N = 1$ GeV)

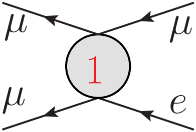
- match at tree level, run at one loop
- include 'leading' two-loop effects
  mixing of vectors into dipole as for $b \to s\gamma$
- Wilson coefficients run and mix, we want $C_i(m_W)$
- operators mix under RGE: one loop two loop

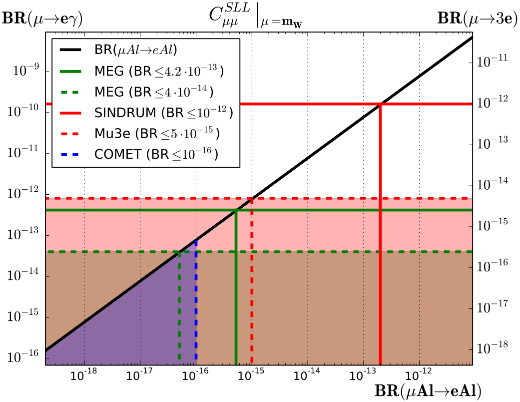


$$(\overline{e_L}\gamma^\mu \mu_L)(\overline{b_L}\gamma_\mu b_L) \to (\overline{e_L}\gamma^\mu \mu_L)(\overline{e_L}\gamma_\mu e_L) \text{ or } (\overline{e_L}\sigma^{\mu\nu}\mu_L)F_{\mu\nu}$$

naive one-at-a-time limits $C_i(m_W)$

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





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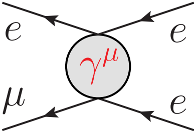
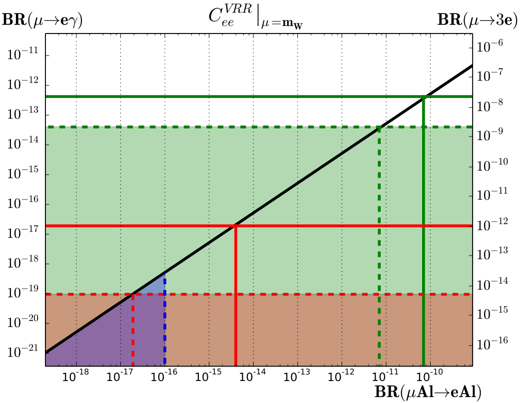
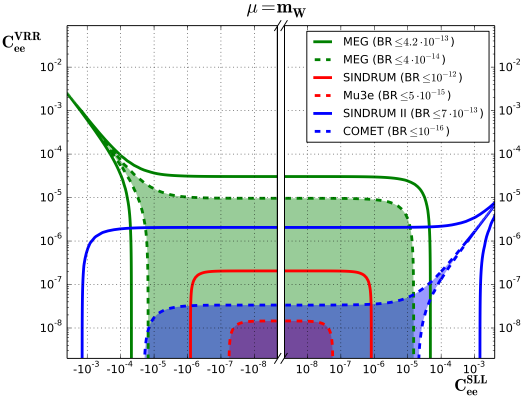


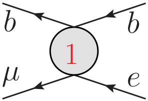


naive two-at-a-time limits

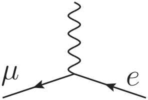


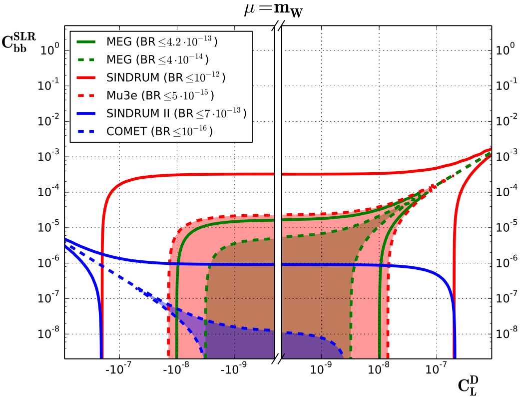
. . . and complementarity

naive two-at-a-time limits

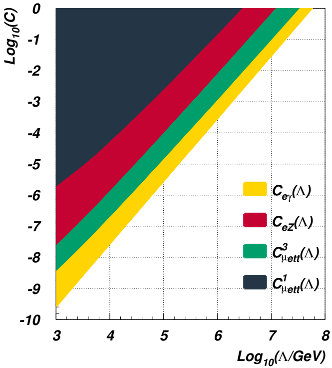


vs.





Constraints from $\mu \to e\gamma$



[Pruna,AS: 1408:3565]

- contact interactions $C^1_{\mu ett} \to C^3_{\mu ett} \to$ dipole interaction $C_{e\gamma}$
- energy range probed up to $\sim 10^7$ TeV
- even indirect limits can be very constraining

beware of common misconceptions

- $\mu \to e\gamma$ is very sensitive to contact interactions !!
- $\mu N \to eN$ is very sensitive to pseudo scalar and axial vector interactions !!
- RGE is not a precision issue, but yields qualitatively new results (mixing)
- one-at-a-time / two-at-a-time limits only for presentational purposes

many ways to go beyond the golden channels

examples (ordered according to increasing energy):
[Mu2e, Comet, Babar, Belle, 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 τ [Babar, Belle]

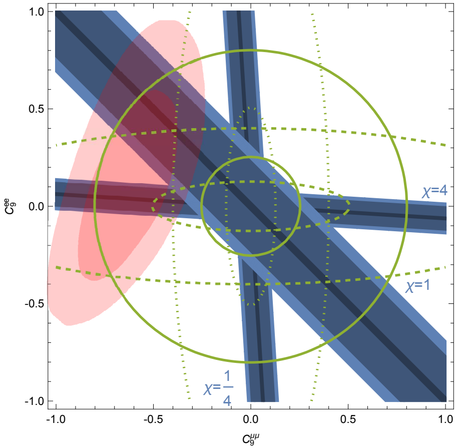
  $\mathrm{BR}(\tau \to 3\ell) \lesssim (1-2) \times 10^{-8}, \quad \mathrm{BR}(\tau \to \ell\gamma) \lesssim 4 \times 10^{-8}$
- hadronic decays with τ such as $\tau \to \ell K^{(*)}$ or $\tau \to \ell \pi^+\pi^-$
- involving B decays (very topical !!)

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

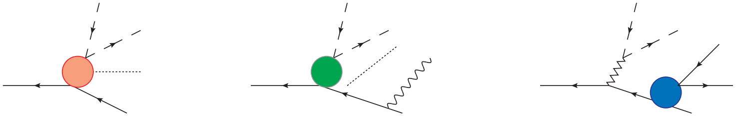
  $Z \to \tau\mu, \; H \to \tau\mu$

connection cLFV with B anomalies

- if B anomalies are due to BSM → scale of NP not very high
- signals in cLFV are also possible
- e.g. leptoquarks $\sim$ TeV
  $C_9 = -C_{10}$
  [Crivellin et al.]
- $b \to s\mu^+\mu^-$
  $\mu \to e\gamma$
  $B \to K\mu^\pm e^\mp$



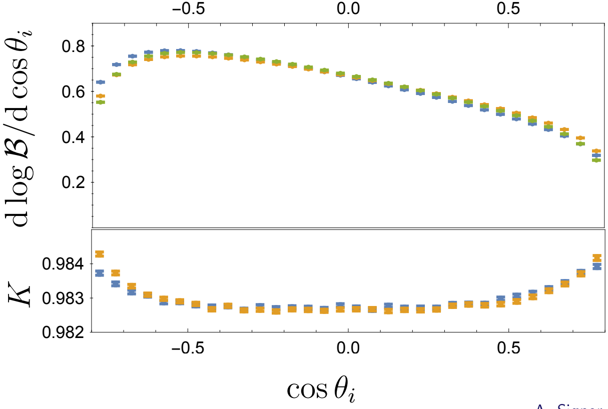
looking for deviations from SM with $\mu \to e(+2e/ + \gamma) + X$



- looking for the weird and wonderful, typically MeV scale
- dark photons, "heavy" neutrinos, 17 MeV $5^{\rm th}$ force ...
- recall: $3.5\,\sigma$ discrepancy of $\mathrm{BR}(\tau \to e\nu\bar{\nu}\gamma)$ from
  Babar vs NLO (??) QED
  probably 'just' QED [Pruna,AS,Ulrich]

BSM potential in $\mu \to e\nu\bar{\nu} + e^+e^-$

- in general: very precise predictions, theory error $\ll 0.1\%$ as long as not squeezed into corner of phase space
- e.g. angular distributions for the hard e^+, soft e^+ and e^-
- $K \approx 0.98 \Rightarrow$ shape very precise



- cLFV is a window with a view deeply beyond EW scale
- why do we not see it then?
  Is Λ_{NP} just too large? or BSM still cLF conserving??
- EFT approach is ideal for investigating cLFV
  of course, we still want the explicit BSM in the end
- quantum corrections are essential
  not a precision issue but qualitatively new effects
- huge experimental progress expected within $5 - 10$ years