HEFT 2017

cLFV with EFT

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Lepton flavour is violated,

so why should charged lepton flavour be conserved?

- introduction (stating the obvious)
- the golden channels $\mu \to e\gamma, \quad \mu \to 3e, \quad \mu N \to eN$
- EFT above m_W, $\mathcal{L}_{\rm smeft}$
- EFT below m_W, $\mathcal{L}_{\rm eff}$
- beyond the golden channels

playing with SM fields only:

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

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

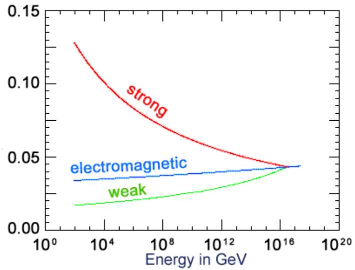
dim 5 violates lepton number, but doesn't affect SM much

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

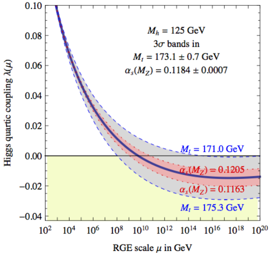
cLFV a unique window with a view deep into the UV scale of cLFV experiments $m_{\rm mu} \le \mu \le m_W$

high-energy behaviour might reveal properties of underlying theory

unified theory?



stable universe ?

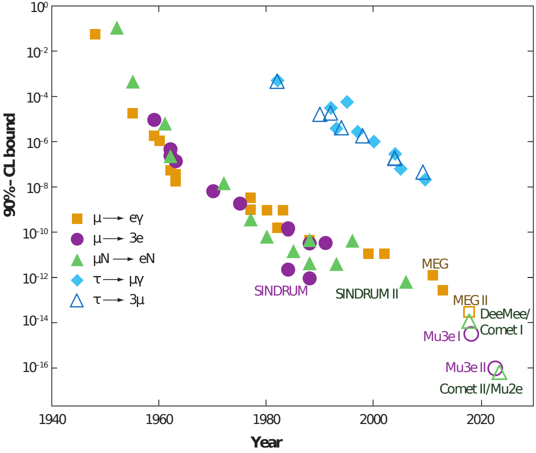


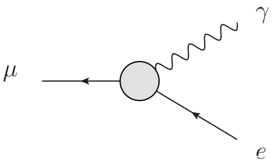
use EFT to evolve from to $m_{\rm mu}$ to m_W (to combine experiments)
and from m_W to $\Lambda_{\rm uv} \gg m_w$ (to get information on BSM)

cLFV with muons

- πE5 beamline at PSI: 10^8 mu/s $\;\rightarrow\; \sim 10^{15}$ mu/y
  - $\tau_{\rm mu} \sim 2.2\ \mu$s $\;\rightarrow\; \sim 5\times 10^{12}$ mu/y for single μ in target
  - operate with many μ in target $\;\rightarrow\;$ accidental bg
- $\mu \rightarrow e\gamma$
  - current MEG (2016) $\mathrm{Br}(\mu\rightarrow e\,\gamma) < 4.2\times 10^{-13}$
  - MEG II: (2018-2021) expect: $\mathrm{Br}(\mu\rightarrow e\,\gamma) \sim \times 10^{-14}$
- $\mu \rightarrow eee$
  - current Sindrum (1988) $\mathrm{Br}(\mu\rightarrow eee) < 1\times 10^{-12}$
  - new experiment Mu3e
    Phase 1 (2020++): $\mathrm{Br} \sim \mathrm{few}\times 10^{-15}$,
    Phase 2 (20??++): new beamline $\mathrm{Br} \sim 10^{-16}$
- $\mu N \rightarrow eN$
  - current Sindrum II (2006) $\mathrm{Br}(\mu\ \mathrm{Au}\rightarrow e\ \mathrm{Au}) < 7\times 10^{-13}$
  - new experiment DeeMe ? (2017++): $\mathrm{Br}\sim 10^{-14}$
  - new experiments Comet and Mu2e (2020++): $\mathrm{Br}\sim 10^{-16}$

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



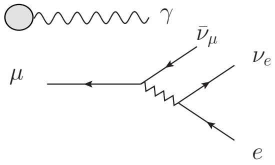


signal: monoenergetic, simultaneous, back-to-back e and γ

in SM (with massive ν):

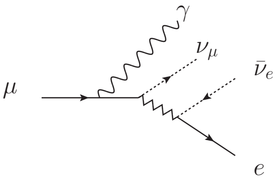
$\mathrm{BR}_{\mathrm{SM}}(\mu \to e\gamma) \sim 10^{-54}$

still, there is background ...



accidental background:

e and γ not quite back-to-back nor quite monoenergetic nor quite simultaneous $\Rightarrow$ upgrade MEG II



SM process radiative decay

in region where ν very little energy

e and γ not quite back-to-back nor quite monoenergetic radiative decay, fully differential [Pruna,AS,Ulrich]

(branching ratio compared with [Fael,Mercolli,Passera])

polarization: $\vec{s} = -0.85\hat{z}$ and toy cuts:

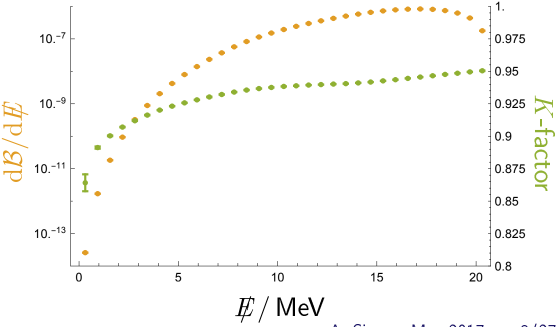
$E_\gamma > 40$ MeV, $|\cos\theta_\gamma| < 0.35$, $|\phi_\gamma| > 2\pi/3$

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

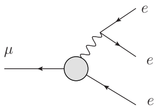
no 2^{nd} photon with $E_\gamma > 2$ MeV

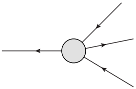
The invisible energy spectrum

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



$\mu \to 3e$

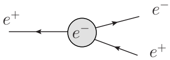


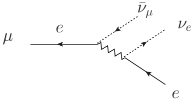


signal: 2 e^+ + 1 e^-, simultaneous, from same vertex, $\sum p_e = m_{\rm mu}$

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

contact part completely new

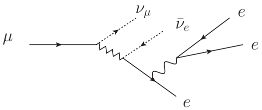




accidental background:

e and γ not quite from same vertex nor quite simultaneous and with missing momentum

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



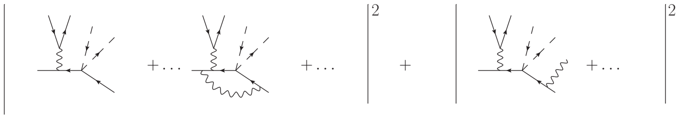
SM process rare decay

in region where ν very little energy

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

fully differential NLO calculation [Pruna,AS,Ulrich]

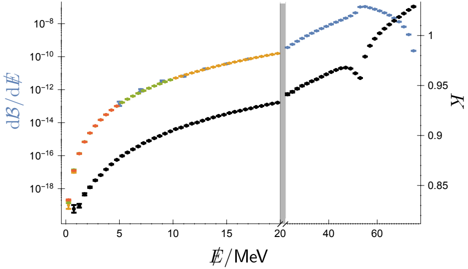
BR (with cuts on invisible energy) compared with [Fael,Greub]



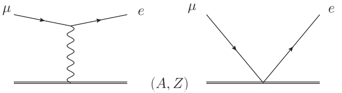
polarization: $\vec{s} = -0.85\hat{z}$ toy cuts: $E_i > 10$ MeV, $|\cos\theta_i| < 0.8$

The invisible energy spectrum

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



$\mu N \to e N$

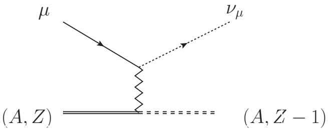


μ conversion: $\mu^- N_Z^A \to e^- N_Z^A$

signal: single 105 MeV e^-

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

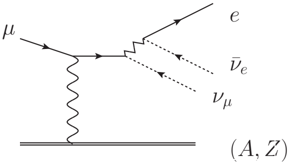
contact part completely new



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

denominator of 'branching' ratio

for larger Z, shorter life time



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

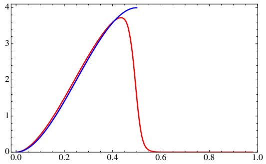
(decay in orbit)

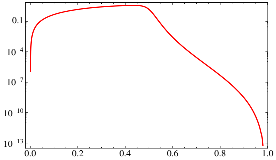
$\sum p_e > m_{\rm mu}/2 \;\to\; m_{\rm mu}$ possible

nuclear recoil

$\mu N \to e N$

DIO
energy spectrum
[Czarnecki et al.]

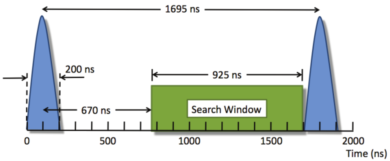


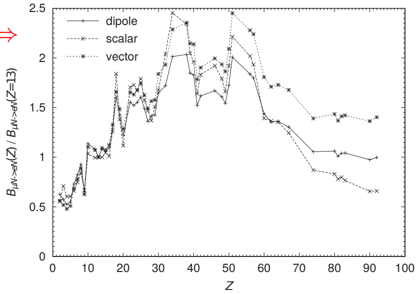


which Z ? [Fässler et al; Cirigliano et al.]

SINDRUM with Au, 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 $\mu N \to e N$)





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

$$\mathcal{L}^{\rm ET}_{\rm BSM} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(5)}}{\Lambda_{\rm NP}}\, \mathcal{O}_i^{(5)} + \sum \frac{c_i^{(6)}}{\Lambda_{\rm NP}^2}\, \mathcal{O}_i^{(6)} + \dots$$

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

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

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

an EFT $\mathcal{L}_{\rm smeft}$ (above the EW scale), respecting also $SU(2)$

'old' and 'new' operators [Grzadkowski et al.], e.g.

$$Q_{eW} = (\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \, \Phi \, W^I_{\mu\nu} = -Q_{e\gamma}\, s_W - Q_{eZ}\, c_W$$
$$Q_{eB} = (\bar{l}_p \sigma^{\mu\nu} e_r) \, \Phi \, B_{\mu\nu} = Q_{e\gamma}\, c_W - Q_{eZ}\, s_W$$

$$Q_{\Phi l(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{l}_p \gamma^\mu l_r) \qquad Q_{\Phi e} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_p \gamma^\mu e_r)$$
$$Q_{le} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t) \qquad Q_{e\Phi} = (\Phi^\dagger \Phi)(\bar{l}_p e_r \Phi)$$
$$Q_{lequ(3)} = (\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t) \qquad Q_{lequ(1)} = (\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$$

$\mu \to e\gamma$ in SMEFT at NLO [Pruna, Signer]

- general vertex for $\mu \to e\,\gamma$:

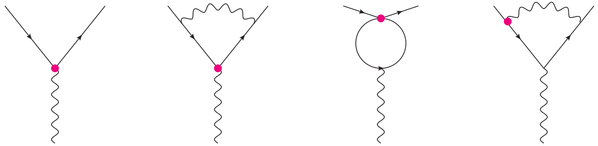
$$V^{\mu}_{pr} \sim \gamma^{\mu} c_{VL} P_L + q^{\mu} c_{SL} P_L + i\,\sigma^{\mu\nu} q_{\mu} c_{TL} P_L + \{L \leftrightarrow R\}$$

- c_{VL}, c_{VR} vanish (gauge invariance) and c_{SL}, c_{SR} do not contribute
- only two dim-6 operators can produce $\mu \to e + \gamma$ at tree-level:
  dipole operators Q_{eW}, Q_{eB} or $Q_{e\gamma}, Q_{eZ}$
- these operators induce $\mathcal{L}_{\rm eff} = \dfrac{ev}{\sqrt{2}} \dfrac{C^{pr}_{e\gamma}}{\Lambda^2_{\rm uv}} \bar{e}_p \sigma^{\mu\nu} e_r F_{\mu\nu} +$ h.c.
- looks like a $\dim 5$ operator, but is a $\dim 6$ operator in disguise
- direct limit on $\dfrac{C^{\mu e}_{e\gamma}}{\Lambda^2_{\rm uv}}$ from MEG
- can we get more information from $\mu \to e\,\gamma$? $\to$ yes

- Structure of $c_{TL/TR}$ at one loop:

$$c_{TL}^{(1)} \sim v \left(C_{e\gamma} \big(1 + e^2 \underbrace{c_{e\gamma}^{(1)}}_{\text{UV and IR sing}} \big) + \sum_{i \neq e\gamma} e^2 \underbrace{c_i^{(1)} C_i}_{\text{UV sing}} \right)$$

- contributions from $c_i(\Lambda_{\rm uv})$ through mixing in rge (and matching at one-loop)

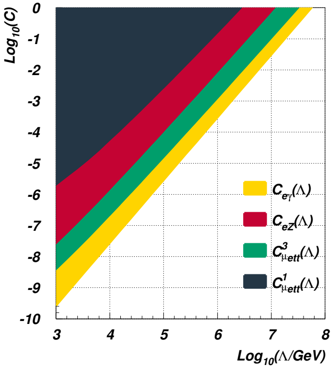


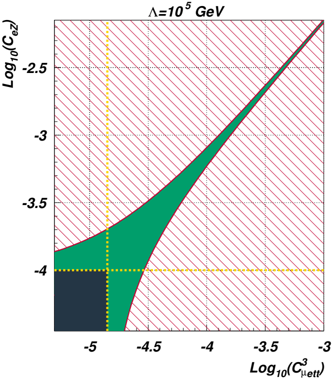
- @ one-loop: $\sim C_{e\gamma}^{\mu e}$, $\sim C_{eZ}^{\mu e}$ and $\sim C_{lequ}^{(3)}$ divergent $\to$ rg-running
- others finite ($C_{le}^{\mu\ell\ell e}$, $C_{\Phi l}^{(1)}$, $C_{\Phi l}^{(3)}$, $C_{e\Phi}^{\mu e}$ and $C_{\Phi e}$) or zero

- closed system of operators (rge at one-loop, matching at tree level)
  $C^{(1)}_{\mu ett} \longrightarrow C^{(3)}_{\mu ett} \longrightarrow C^{\mu e}_{e\gamma}$ and $C^{\mu e}_{eZ}$ compared to [Jenkins et al.]
- rge not (yet) a precision issue, but induces qualitatively new effects
  e.g. forget about $Z \to \mu e$
- obtain limits on $c_i(\Lambda_{\rm uv})$ $\Longrightarrow$ most direct link to underlying theory
- limits not to be understood as strict limits, merely indications:
  e.g. Barr-Zee effect not considered (could be important numerically)
  e.g. naive one-at-a-time limits (not very realistic)

$\mu \to e\gamma$			
Coefficient	at $\Lambda = 10^3$ GeV	at $\Lambda = 10^5$ GeV	at $\Lambda = 10^7$ GeV
$C^{\mu e}_{e\gamma}$	$2.7 \cdot 10^{-10}$	$2.9 \cdot 10^{-6}$	$3.1 \cdot 10^{-2}$
$C^{\mu e}_{eZ}$	$2.5 \cdot 10^{-8}$	$1.0 \cdot 10^{-4}$	$7.1 \cdot 10^{-1}$
$C^{(3)}_{\mu ett}$	$3.6 \cdot 10^{-9}$	$1.4 \cdot 10^{-5}$	$9.8 \cdot 10^{-2}$
$C^{(1)}_{\mu ett}$	$1.9 \cdot 10^{-6}$	$2.5 \cdot 10^{-3}$	n/a

[Pruna,AS: 1408:3565]





- constraints on $c_i(\Lambda_{\rm uv})$
- behaviour is not completely linear

- two couplings non-vanishing at $\Lambda_{\rm uv}$
- large impact, can invalidate previous limits

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

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

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

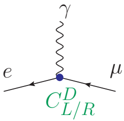
$$+ C_{ff}^{V\,LL}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_L}\gamma_\mu f_L) + C_{ff}^{V\,LR}\,(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_R}\gamma_\mu f_R)\Big]$$

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

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

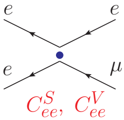
observables

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

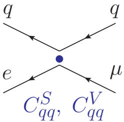


$$\mathrm{Br}\,(\mu \to e\gamma) \simeq \alpha_e m_\mu^5 \left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2 \right)$$

$$\mathrm{Br}(\mu \to 3e) \simeq \alpha_e^2 m_\mu^5 \left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2 \right) \left(8 \log \left[\frac{m_\mu}{m_e} \right] - 11 \right)$$



$$+ m_\mu^5 \left(\left|C_{ee}^{S\,LL}\right|^2 + 16 \left|C_{ee}^{V\,LL}\right|^2 + 8 \left|C_{ee}^{V\,LR}\right|^2 + L \leftrightarrow R \right)$$

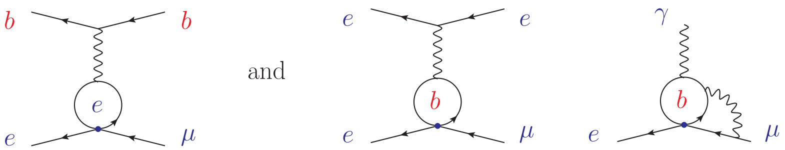


$$\Gamma^N_{\mu\to e} = m_\mu^5 \left| e\, C_L^D\, D_N + f(C_{hh}^{S\,LL} + C_{hh}^{S\,LR}, C_{hh}^{V\,LL} + C_{hh}^{V\,LR}) \right|^2 + L \leftrightarrow R$$

effective lagrangian

- express $\mathrm{BR}(\mu \to e\gamma)$ and $\mathrm{BR}(\mu \to 3e)$ through $C_i(m_{\mathrm{mu}})$ and $\mathrm{BR}(\mu N \to eN)$ through $C_i(\mu_N)$ (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



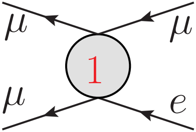
$$(\overline{e_L}\gamma^\mu \mu_L)(\overline{b_L}\gamma_\mu b_L) \to (\overline{e_L}\gamma^\mu \mu_L)(\overline{e_L}\gamma_\mu e_L) \text{ or } (\overline{e_L}\sigma^{\mu\nu}\mu_L)F_{\mu\nu}$$

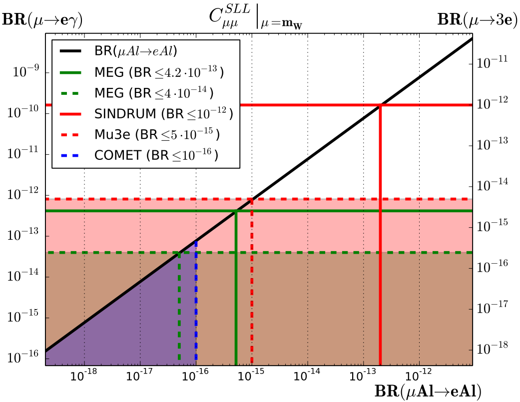
naive one-at-a-time limits on (some) coefficients $C_i(m_W)$

	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}^{\mathrm{Au/Al}}_{\mu\to e}$	
	$4.2 \cdot 10^{-13}$	$4.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-15}$	$7.0 \cdot 10^{-13}$	$1.0 \cdot 10^{-16}$
C_L^D	$1.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$	$2.0 \cdot 10^{-7}$	$2.9 \cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-7}$	$5.8 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3 \cdot 10^{-7}$	$7.2 \cdot 10^{-8}$	$4.6 \cdot 10^{-6}$	$3.3 \cdot 10^{-7}$	$7.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$2.4 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$2.4 \cdot 10^{-5}$	$3.5 \cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9 \cdot 10^{-9}$	$9.0 \cdot 10^{-10}$	$5.7 \cdot 10^{-8}$	$4.1 \cdot 10^{-9}$	$5.9 \cdot 10^{-8}$	$8.5 \cdot 10^{-10}$
$C_{bb}^{S\,LL}$	$2.8 \cdot 10^{-6}$	$8.6 \cdot 10^{-7}$	$5.4 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$9.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
$C_{bb}^{T\,LL}$	$2.1 \cdot 10^{-9}$	$6.4 \cdot 10^{-10}$	$4.1 \cdot 10^{-8}$	$2.9 \cdot 10^{-9}$	$4.2 \cdot 10^{-8}$	$6.0 \cdot 10^{-10}$
$C_{ee}^{V\,RR}$	$3.0 \cdot 10^{-5}$	$9.4 \cdot 10^{-6}$	$2.1 \cdot 10^{-7}$	$1.5 \cdot 10^{-8}$	$2.1 \cdot 10^{-6}$	$3.5 \cdot 10^{-8}$
$C_{bb}^{V\,RR}$	$3.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.8 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
C_{bb}^{LP}	$4.7 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$9.3 \cdot 10^{-5}$	$6.6 \cdot 10^{-6}$	$9.6 \cdot 10^{-5}$	$1.4 \cdot 10^{-6}$
C_{bb}^{LS}	$6.7 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$1.3 \cdot 10^{-4}$	$9.2 \cdot 10^{-6}$	$9.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-8}$
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}	$2.1 \cdot 10^{-3}$	$6.4 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.7 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$

naive one-at-a-time limits

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





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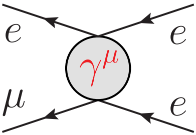
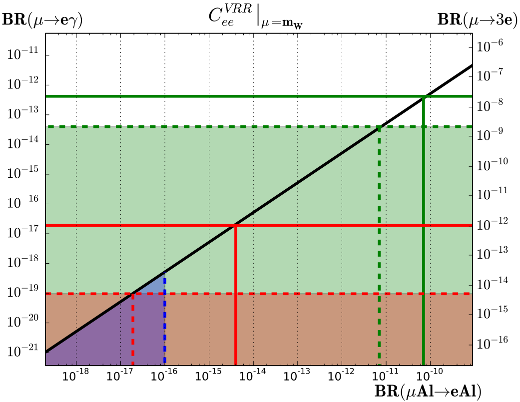
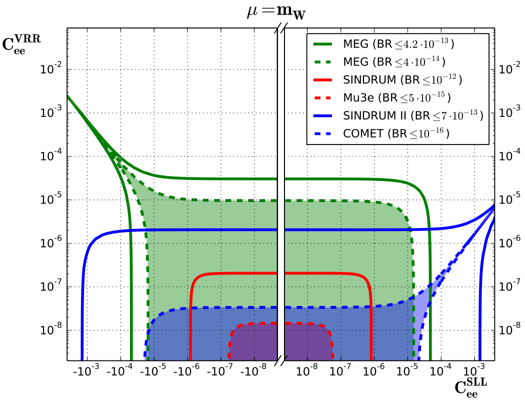
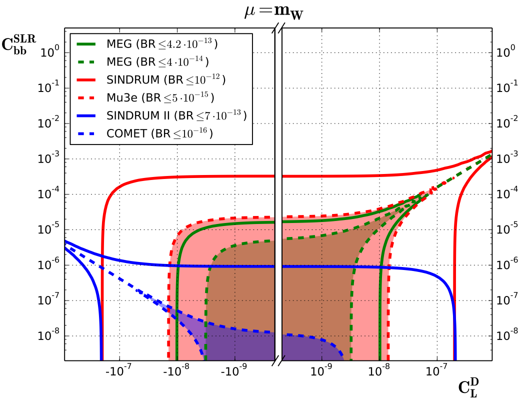




naive two-at-a-time limits



naive two-at-a-time limits



many ways to go beyond the golden channels

examples (ordered according to increasing energy):
[Babar, Belle, LHCb, CMS, Atlas, many theorists . . .]

- 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 $\Lambda \gtrsim m_{\mathrm{EW}}$

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

RGE and matching of $\mathcal{L}_{\rm eff}$ with $\mathcal{L}_{\rm smeft}$
combine processes from $\mu = m_{\rm mu}$ to $\mu = m_{\rm EW}$
obtain limits on Wilson coefficients at $\mu = \Lambda$, here $\lambda = m_Z$

Coeff. $\lambda = m_Z$	$\tau^+ \to \mu^+\gamma$ BR$\leq 4.4 \cdot 10^{-8}$	$Z \to \mu^\pm\tau^\mp$ BR$\leq 1.2 \cdot 10^{-5}$	$\tau^+ \to \mu^+\mu^-\mu^+$ BR$\leq 2.1 \cdot 10^{-8}$
$C_{e\gamma}^{32/23}$	$2.7 \cdot 10^{-12}$		$3.8 \cdot 10^{-11}$
$C_{eZ}^{32/23}$	$1.5 \cdot 10^{-9}$	$1.5 \cdot 10^{-7}$	$8.7 \cdot 10^{-7}$
$C_{\varphi l/\varphi e}^{23}$	$1.7 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	$1.3 \cdot 10^{-8}$
Coeff. $\lambda = m_Z$		$H \to \mu^\pm\tau^\mp$ BR$\leq 1.8 \cdot 10^{-2}$	
$C_{e\varphi}^{32/23}$	$1.9 \cdot 10^{-6}$	$9.0 \cdot 10^{-8}$	$1.6 \cdot 10^{-5}$
$C_{le}^{3112/2113}$	$4.8 \cdot 10^{-4}$		
$C_{le}^{3222/2223}$	$2.3 \cdot 10^{-6}$		$1.1 \cdot 10^{-8}$
$C_{le}^{3332/2333}$	$1.4 \cdot 10^{-7}$		
C_{ll}^{3222}			$4.0 \cdot 10^{-9}$

- cLFV is a window with a view deeply beyond EW scale
- why do we not see it then?
  Is $\Lambda_{\rm NP}$ 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