Neutrinos at the High Energy Frontier

Charged Lepton Flavour Violation

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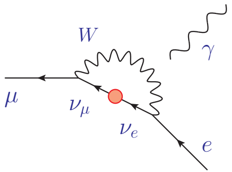
why cLFV at a neutrino workshop?



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

- could cLFV be much larger?
- in general: certainly yes
- cLFV through neutrinos / seesaw ?
  - $\mathcal{L} = \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}^{(5)}}_{\Delta m \neq 0} + \underbrace{\mathcal{L}^{(6)}}_{\text{additional cLFV}} + \ldots$
- additional cLFV naturally present, neutrinos $\leftrightarrow$ cLFV

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outline

- introduction
  - the obvious
  - EFT vs models; above m_W vs below m_W
- neutrinos $\leftrightarrow$ cLFV
  - above m_W: seesaw $\to$ cLFV
  - below m_W: NSI below m_W $\to$ cLFV
- cLFV
  - 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
- conclusion

playing with SM fields only:

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

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

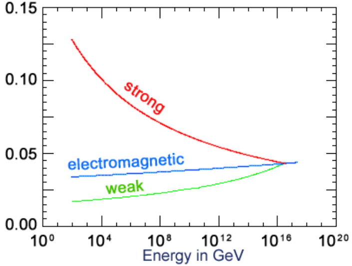
dim 5 violates lepton number, but might not affect SM much

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

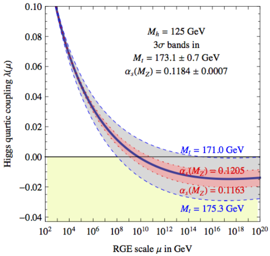
cLFV a unique window with a view deep into the UV scale of cLFV experiments $m_{\text{mu}} \leq \mu \leq m_W$

high-energy behaviour might reveal properties of underlying theory

unified theory?



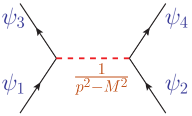
stable universe ?



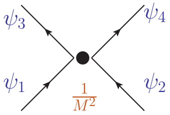
need to evolve from to m_{mu} to m_W (to combine experiments)

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

EFT vs models



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



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

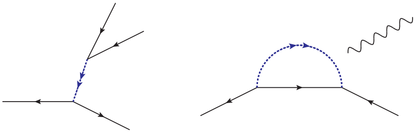
$$\mathcal{O}_{\rm eff}^1 = (\overline{e_L}\gamma^\rho\mu_L)\,(\overline{e_R}\gamma_\rho e_R)$$
$$\mathcal{O}_{\rm eff}^2 = (\overline{\nu_e}\gamma^\rho\nu_\mu)\,(\overline{e_R}\gamma_\rho e_R)$$

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

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

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

Example: doubly charged Higgs



- as UV complete model: embed in multiplet, sort out ρ parameter ...
  ++ valid $\forall\, p^2$, explains everything −− 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 $p^2 > m_\phi^2$ −+ 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 $p^2 \ll m_\phi^2$ ++ completely general

the EFT is never the goal, only the tool

(cp. $C_9 = -C_{10}$ scenario for B anomalies) add fermion singlet(s) N_p: $\mathcal{L} \supset Y_e\, \bar{l}\, \Phi\, e + Y_N\, \bar{l}\, \tilde{\Phi} N - \frac{1}{2} \bar{N}\, m_N\, N^c$

assuming $m_N \gg m_W$ integrate out $N \equiv \nu_R$

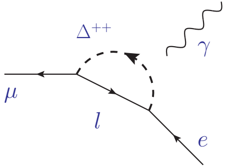
apart from usual $\mathcal{L}^{(5)} \sim \frac{c_{pr}^{(5)}}{m_N} (\bar{l}_p^c \tilde{\Phi}^*)(\tilde{\Phi}^\dagger l_r)$ we get also

$$\mathcal{L}^{(6)} \supset \frac{c_{pr}^{(6)}}{m_N^2} \Big\{ \underbrace{(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{l}_p \gamma^\mu l_r);}_{Q_{\Phi l(1)} \to \text{cLFV}} \quad \underbrace{(\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{l}_p \tau^I \gamma^\mu l_r);}_{Q_{\Phi l(3)} \to \text{cLFV}} \quad \underbrace{\text{dipole}}_{Q_{e\gamma}} \Big\}$$

- $\mathcal{L}^{(5)}$ violates L (lepton number), $\mathcal{L}^{(6)}$ does not violate L.
- not unnatural to expect $c^{(5)} \ll c^{(6)}$ in general
- e.g. $Q_{\Phi l(1)}$ leads to cLFV $Z \to l_p\, l_r$ (and $Z \to \nu_p\, \nu_r$)

add scalar triplet $\vec{\Delta} \supset (\Delta^{++}, \Delta^{+}, \Delta^{0})$

$\mathcal{L} \supset Y_\Delta\, \bar{l}^c\, \vec{\tau} \cdot \vec{\Delta}\, l + \mu_\Delta\, \tilde{\Phi}^\dagger\, \vec{\tau} \cdot \vec{\Delta}\, \Phi + \vec{\Delta}^\dagger m_\Delta^2 \vec{\Delta}$



assuming $m_\Delta \gg m_W$ integrate out $\vec{\Delta}$

$\mathcal{L}^{(4)} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)}$ with $c^{(5)} \sim \dfrac{Y_\Delta \mu_\Delta}{m_\Delta^2}$

two couplings: Y_Δ and μ_Δ / m_Δ can be very different !

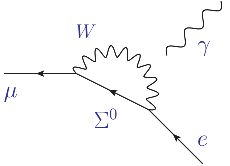
$$\mathcal{L}^{(6)} \supset \Big\{ \frac{c^{ll}_{pqrs}}{m_\Delta^2} \underbrace{(\bar{l}_p \gamma^\mu l_q)(\bar{l}_r \gamma^\mu l_s)}_{Q_{ll} \,\to\, \text{cLFV}}; \quad \frac{c^{\phi\, D}}{m_\Delta^2} \underbrace{(\Phi^\dagger D^\rho \Phi)^\dagger (\Phi^\dagger D_\rho \Phi)}_{Q_{\phi D}}; \quad \underbrace{\text{dipole}}_{Q_{e\gamma}} \Big\}$$

with $c^{ll}_{pqrs} \sim Y_\Delta^2$ and $c^{\phi\, D} \sim \dfrac{\mu_\Delta^2}{m_\Delta^2}$ and $m_\nu \sim \dfrac{Y_\Delta\, v^2}{m_\Delta} \dfrac{\mu_\Delta}{m_\Delta}$

add fermion triplet $\vec{\Sigma} \supset (\Sigma^{\pm}, \Sigma^0)$

$$\mathcal{L} \supset Y_\Sigma \, \bar{\Sigma} \, \tilde{\Phi}^\dagger \vec{\tau} \, l - \frac{1}{2} \bar{\Sigma} \, m_\Sigma \, \Sigma^c$$

assuming $m_\Sigma \gg m_W$ integrate out Σ



apart from $\mathcal{L}^{(5)}$

we get $\mathcal{L}^{(6)} \supset \Big\{ \underbrace{(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{l}_p \gamma^\mu l_r)}_{Q_{\Phi l(1)} \to \text{cLFV}}; \quad \underbrace{(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{l}_p \tau^I \gamma^\mu l_r)}_{Q_{\Phi l(3)} \to \text{cLFV}}; \quad \underbrace{\text{dipole}}_{Q_{e\gamma}} \Big\}$

compare to seesaw I:

EFT does not care any longer where operators come from

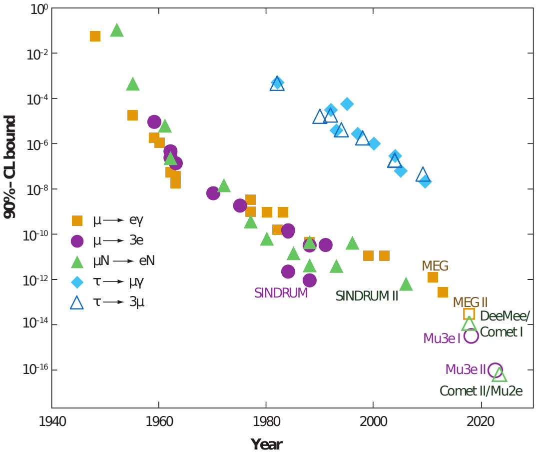
possible 'conspiracies' are lost

(e.g. $Q_{\Phi l(1)} - Q_{\Phi l(3)}/2$ of seesaw I does not produce $Z \to l_p \, l_r$)

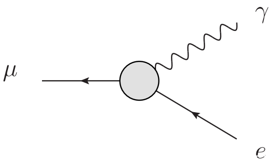
model X

- just write down any dim 6 operator that can lead to cLFV
- worry about interpretation, once something is found (recall B anomalies)
- above m_W: $\to \mathcal{L}_{\text{smeft}}$
  related to seesaw, 'low scale' means $c^{(6)}/m_X^2$ not too small
- below m_W: $\to \mathcal{L}_{\text{eff}}$ related to NSI
  $\mathcal{L} \sim G_F \sum (\bar{\nu}_i \gamma^\rho \nu_j)(\bar{f}\gamma_\rho f) \to\sim G_F \sum (\bar{l}_i \gamma^\rho l_j)(\bar{f}\gamma_\rho f)$
- for $\mathcal{L}_{\text{eff}}$ (below m_W) might need to work with simplified models

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



- πE5 beamline at PSI: 10^8 mu/s $\to$ $\sim 10^{15}$ mu/y
  - $\tau_{\rm mu} \sim 2.2\ \mu$s $\to$ $\sim 5\times 10^{12}$ mu/y for single μ in target
  - operate with many μ in target $\to$ accidental bg
- $\mu \to e\gamma$
  - 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 and Mu2e (2020++): $\mathrm{Br}\sim 10^{-16}$

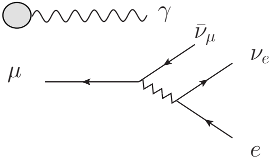


signal: monoenergetic, simultaneous, back-to-back e and γ

in SM (with massive ν):

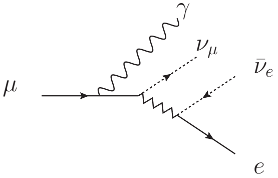
$\mathrm{BR}_{\mathrm{SM}}(\mu \to e\gamma) \sim 10^{-54}$

still, there is background ...



accidental background:

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

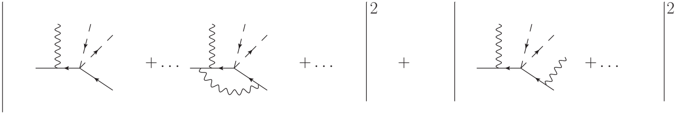


SM process radiative decay

in region where ν very little energy

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

radiative decay, fully differential



polarization: $\vec{s} = -0.85\hat{z}$ and toy cuts: $E_\gamma > 40$ MeV, $E_e > 45$ MeV

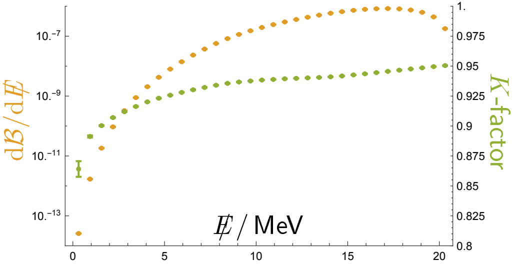
$|\cos\theta_\gamma| < 0.35,\ |\phi_\gamma| > 2\pi/3, |\cos\theta_e| < 0.5,\ |\phi_\gamma| < \pi/3$

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

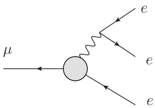
e.g. the invisible energy spectrum

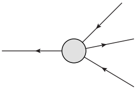
$\not{E} = m_{\rm mu} - E_e - E_\gamma$

[Pruna,AS,Ulrich; 1705.03782]



$\mu \to 3e$

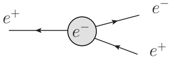


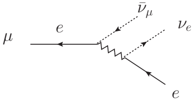


signal: 2 e^+ + 1 e^-, simultaneous, from same vertex, $\sum p_e = m_{\mathrm{mu}}$

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

contact part completely new

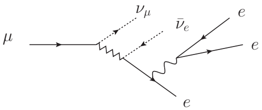




accidental background:

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

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

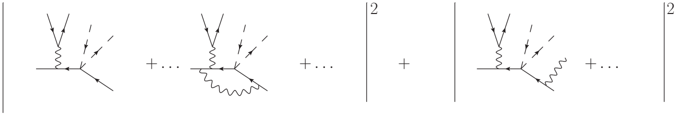


SM process rare decay

in region where ν very little energy

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

fully differential NLO calculation

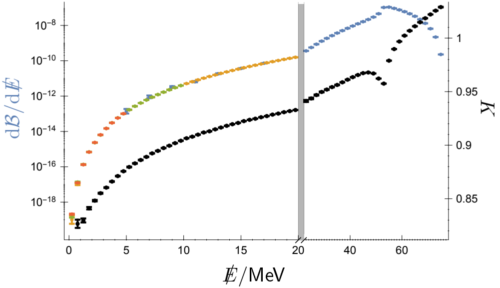


polarization: $\vec{s} = -0.85\hat{z}$ toy cuts: $E_i > 10$ MeV, $|\cos\theta_i| < 0.8$

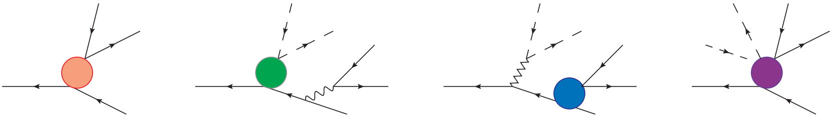
e.g. the invisible energy spectrum

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

[Pruna,AS,Ulrich; 1611.03617]



beyond cLFV, other weird stuff



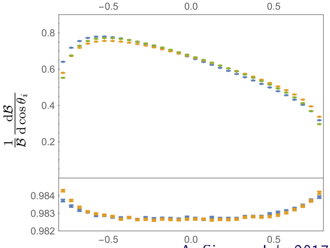
- better suited for small-coupling small-mass scenario
- simplified-model scenario better suited?
  e.g. doubly charged Higgs or dark photon or neutrinos

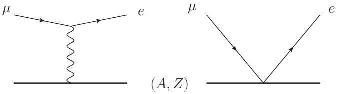
[Pruna,AS,Ulrich; 1611.03617]

e.g. $\cos\theta$ of hard e^+, soft e^+, e^-

no stringent cuts: $\Delta_{\text{theory}} < 0.1\%$

diagnostics @ Mu3e very useful



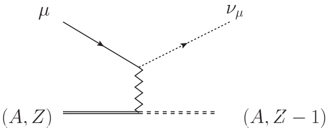


μ conversion: $\mu^- \, N_Z^A \to e^- \, N_Z^A$

signal: single 105 MeV e^-

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

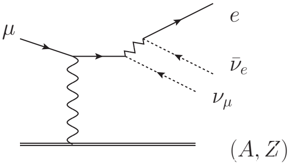
contact part completely new



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

denominator of 'branching' ratio

for larger Z, shorter life time



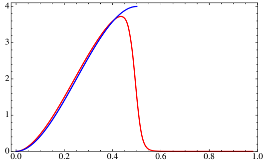
DIO: $\mu^- N_Z^A \to e^- \, \bar{\nu}_e \, \nu_\mu N_Z^A$

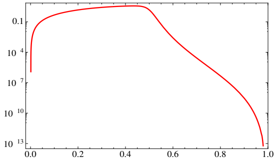
(decay in orbit)

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

nuclear recoil

DIO
energy spectrum
[Czarnecki et al.]

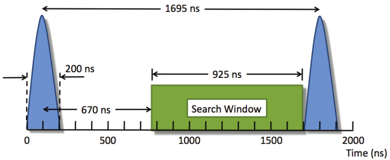


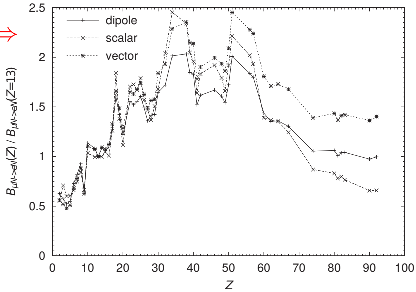


which Z ? [Fässler et al; Cirigliano et al.]

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 $\mu N \to eN$)





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

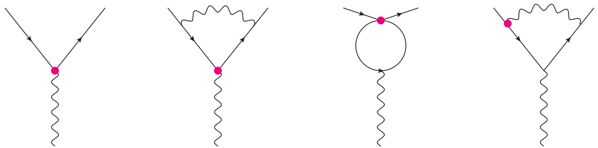
'old' and 'new' operators , e.g.

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

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

$\mu \to e\gamma$ in SMEFT at NLO

- only two dim-6 operators can produce $\mu \to e + \gamma$ at tree-level:
  dipole operators Q_{eW}, Q_{eB} or $Q_{e\gamma}, Q_{eZ}$
- direct limit on $C_{e\gamma}^{\mu e}/\Lambda_{\rm uv}^2$ from MEG
- can we get more information from $\mu \to e\,\gamma$? $\to$ yes
- contributions 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

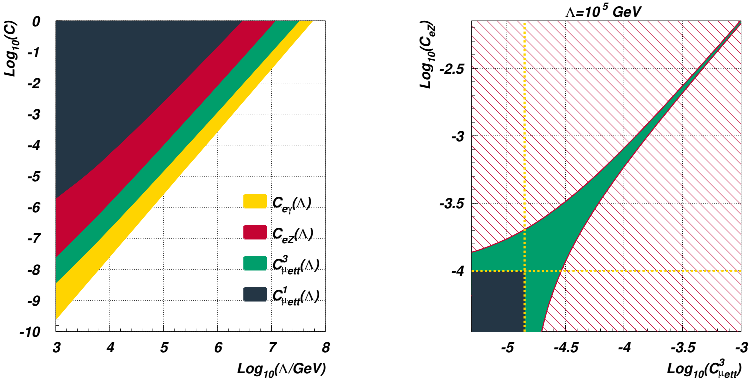
- closed system of operators (rge at one-loop, matching at tree level)

$$C^{(1)}_{\mu ett} \longrightarrow C^{(3)}_{\mu ett} \longrightarrow C^{\mu e}_{e\gamma} \text{ and } C^{\mu e}_{eZ}$$

- rge not (yet) a precision issue, but induces qualitatively new effects
- obtain limits on $c_i(\Lambda_{\rm uv}) \implies$ 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)

$\mu \to e\gamma$ [Pruna,AS: 1408:3565]			
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 $\mu = m_W$)

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

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

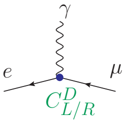
$$+ C_{ff}^{V\,LL}(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_L}\gamma_\mu f_L) + C_{ff}^{V\,LR}\,(\overline{e_L}\gamma^\mu\mu_L)(\overline{f_R}\gamma_\mu f_R)\Big]$$

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

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

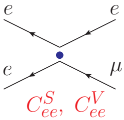
observables

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

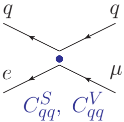


$$\text{Br}\,(\mu \to e\gamma) \simeq \alpha_e m_\mu^5 \left(\left|C_L^D\right|^2 + \left|C_R^D\right|^2 \right)$$

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



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

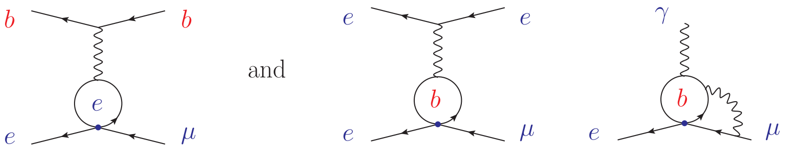


$$\Gamma^N_{\mu\to e} = m_\mu^5 \left| e\, C_L^D\, D_N + f(C_{hh}^{S\;LL} + C_{hh}^{S\;LR}, C_{hh}^{V\;LL} + C_{hh}^{V\;LR}) \right|^2 + L \leftrightarrow R$$

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)
- include 'leading' two-loop effects

  mixing of vectors into dipole as for $b \to s\gamma$
- at low scale only few operators contribute, at high scale 'all' do
- 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}	$2.1 \cdot 10^{-3}$	$6.4 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$4.7 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$

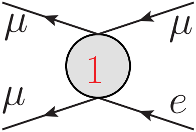
what to read from these tables, and what not

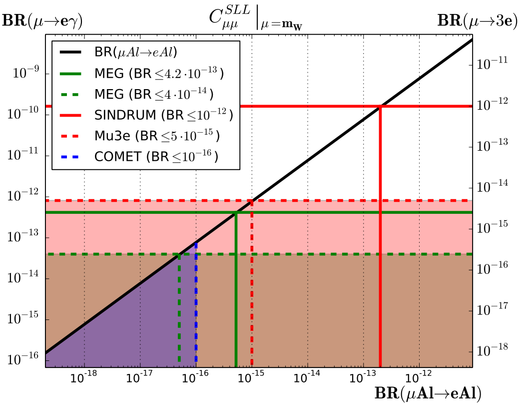
- absolute value of Wilson coefficients is irrelevant (depends on conventional prefactors)
- limits are naive (no acceptance included)
  one-at-a-time (only for presentation !!)

BUT

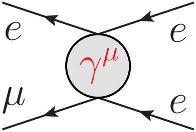
- statements like
  "$\mu \to e\gamma$ is not sensitive to contact interactions"
  "$\mu N \to eN$ is not sensitive to axial vector interactions"
  are plain wrong, completley wrong, horrendously wrong
- if you have a new model and want to check it:
  - check all operators
  - match at high scale, use combined rge
  - check if there are numerically important (formally) higher-order contributions missing

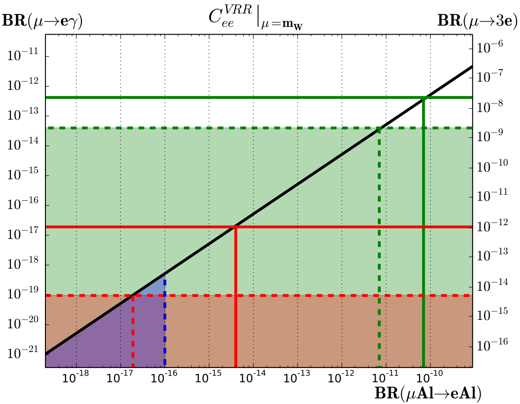
naive one-at-a-time limits compare golden channels



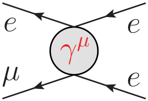


naive one-at-a-time limits compare golden channels

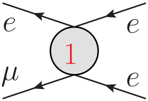


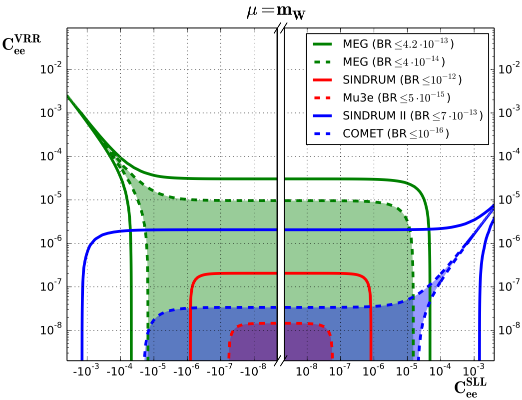


naive two-at-a-time limits

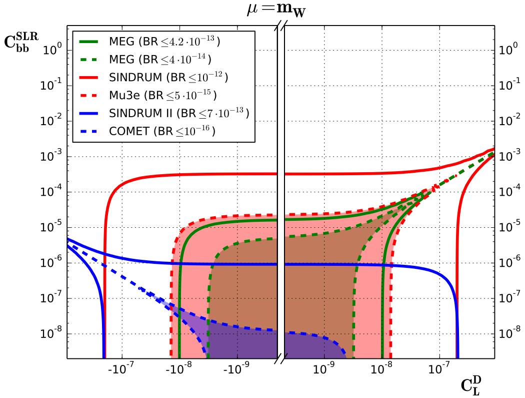


vs.





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
- suppressing cLFV in BSM models requires tweaking
- not seeing cLFV could mean that new physics simply is at a very high scale

* * *

- EFT approach is ideal for investigating cLFV
  of course, we still want the explicit BSM in the end
- quantum corrections are essential, an EFT is a QFT
  here not a precision issue but qualitatively new effects
- huge experimental progress expected within $5 - 10$ years

* * *

- what can cLFV tell us about light 'heavy' neutrinos ??
- can we agree on neutrino mixing $\leftrightarrow$ limits on cLFV ??