SWICH Workshop Murten

a landscape of low-energy precision physics

Adrian Signer

Paul Scherrer Institut / Universität Zürich

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landscape of low energy in 9 seconds: precision $\leftrightarrow$ search for BSM

hit on the weak spots of the SM

- flavour
- dark matter, dark sector
- matter-antimatter asymmetry, $\not{C}\not{P}$
- the unexpected

should take "global" view on low-energy precision physics

- overarching motivation look for BSM

  (bread and butter at the very end)
- looking for effects that are more difficult to avoid than to have in "accessible" BSM
- experiments done at small scale m_μ, m_τ, m_N

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

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

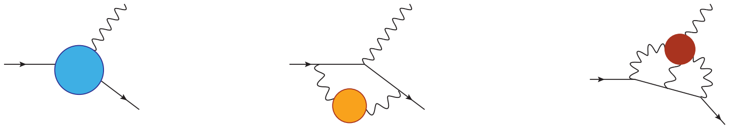
  $\mu < m_{ew}$: $\quad \mathcal{L}_{\rm eff} \supset \dfrac{c_{e\gamma}}{m_{ew}^2} m_\ell (\bar{\ell}_L \sigma_{\mu\nu} \ell_R) F^{\mu\nu}$

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

the (carefully selected) typical example

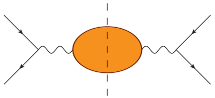
celebrated discrepancy ?? $a_\mu^{\rm exp} - a_\mu^{\rm sm} \simeq 30(8)\times 10^{-10}$ $\sim 3.5\,\sigma$

$\Delta a_\mu^{\rm exp} \sim 6\times 10^{-10} \to$ by 2020 $\lesssim 2\times 10^{-10}$ $\Delta a_\mu^{\rm sm} \sim 5\times 10^{-10}$

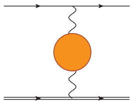


$\Delta a_\mu^{\rm pert} = {}'0'$ $a_\mu^{\rm HVP} \sim (690-10)(3)\times 10^{-10}$ $a_\mu^{\rm LxL} \sim 8(3)\times 10^{-10}$

from experiment, non-pert./lattice $\Rightarrow$ NO show stopper!



$e^+e^- \to$ hadrons $q^2 > 0$



$e^-\mu \to e^-\mu$ $q^2 < 0$

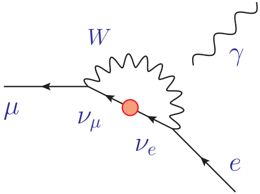
a_μ

- test of coefficient $\mathrm{Re}(C_{e\gamma})/\Lambda^2$ of Dim 6 dipole operator

  $(\bar{L}\sigma_{\mu\nu}e_R)\,H\,F^{\mu\nu} \quad \to \quad e\,m_\ell(\bar{\ell}_L\sigma_{\mu\nu}\ell_R)F^{\mu\nu}$
- testing energy scales $\sim m_{\rm ew} - 100$ TeV
- Q1: is there something ??
- Q2: if yes, what is it ??
- a_μ experiments alone will never answer Q2 conclusively
- a_e known even better, agrees with SM

  (BSM sensitivity $\sim m_\ell^2/\Lambda^2$)
- a_τ experimentally virtually not accessible

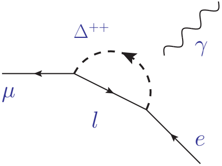
charged LFV: test the same operator flavour off-diagonal ...



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

e.g. seesaw II: add scalar triplet $\vec{\Delta}$

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

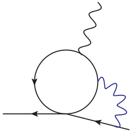


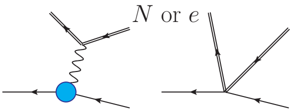
two couplings: Y_Δ and μ_Δ / m_Δ can be very different !

$$\mathcal{L}_{\mathrm{eff}} \supset \frac{Y_\Delta^2}{m_\Delta^2} \underbrace{(\bar{l}_p \gamma^\mu l_q)(\bar{l}_r \gamma^\mu l_s)}_{Q_{ll} \,\to\, \mathrm{cLFV}} \quad \text{and} \quad m_\nu \sim \frac{Y_\Delta\, v^2}{m_\Delta} \frac{\mu_\Delta}{m_\Delta}$$

golden channels $\mu \to e\gamma$ MEG, $\mu \to 3e$ Mu3e, $\mu N \to eN$ Comet/FNAL

- . . . and many more, testing energy scales $10^3 - 10^7$ GeV





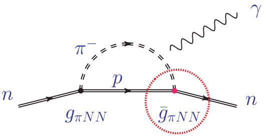
- $\mu \to e\gamma$ is very sensitive to contact interactions !!
- crucial to do all of them, Q2 !! competition vs. complementarity
- more observables: $\bar{M} - M$ oscillations, $\mu^- N \to e^+ N'$
- τ decays: test the 'same' operators, different generation,
  more decays possible $\tau \to l\,\gamma, \quad \tau \to l_a l_b l_c, \quad \tau \to l\,h$
- 'by-products': e.g. dark photons @ Mu3e

electric dipole moments of leptons (and quarks)

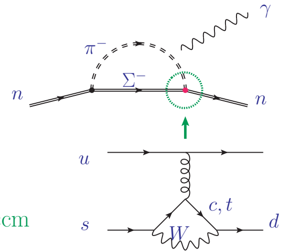
- test $\mathrm{Im}(C_{e\gamma})$ of Dim 6 flavour diagonal dipole operator $Q_{e\gamma}$
  or chromo-electric dipole $Q_{qG} = (\bar{Q}\sigma_{\mu\nu}T^a q_R)\, H\, G^{\mu\nu}_a$
- $d_e \sim 10^{-38}\ e$ cm $\neq 0$ in SM
  (appear at 3/4-loop for q/ℓ through V_{CKM})
- current expt. limit $d_e \leq 8.7 \times 10^{-29}\ e$ cm
- relation: $\dfrac{d_\ell}{e} = \dfrac{\Delta a_\ell}{2m_\ell}\,\dfrac{\mathrm{Re}(C_{\ell\ell})}{\mathrm{Im}(C_{\ell\ell})}$
- naive expectation: $\dfrac{\Delta a_a}{\Delta a_b} \sim \dfrac{m_a^2}{m_b^2}$ and $\dfrac{\Delta d_a}{\Delta d_b} \sim \dfrac{m_a}{m_b}$

- Lagrangian $\mathcal{L}_{\rm had} = \bar{N}\left(i\gamma^5 g_{\pi NN} + \bar{g}_{\pi NN}\right)\vec{\pi}\cdot\vec{\tau}\, N + \ldots$
- $\not{CP}$ coupling: $\bar{g}_{\pi NN}$ (and other $\not{CP}$ couplings of $\mathcal{L}_{\rm had}$) potentially get contributions from all $\not{CP}$ sources
- loop is IR and UV divergent $\quad d_n = \dfrac{g_{\pi NN}\,\bar{g}_{\pi NN}}{4\pi^2\, m_N}\ln\dfrac{m_N}{m_\pi}$
- need d_n, d_p (and more) to disentangle source

in SM



$\bar{g}_{\pi NN} \simeq \bar{\theta}$ from $\bar{\theta} G\tilde{G}$



$d_n \sim \bar{\theta}\, 10^{-15}\, ecm \qquad d_n \sim 10^{-32}\, ecm$

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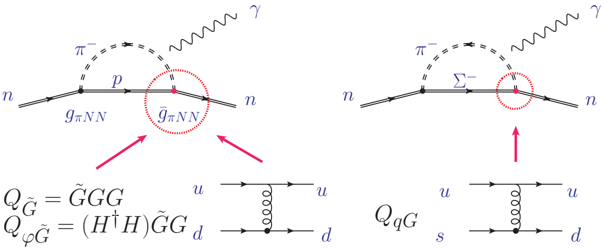
in BSM



making "boring" measurements

- bottle measurement of $\tau_n = 879(1)$ s (n dissapearance)
- beam measurement of $\tau_n = 888(2)$ s (p appearance)
- $\sim 4\ \sigma$ discrepancy $\rightarrow$ why bother
  - relative abundance of H, He ...
  - measure V_{ud}, unitarity check $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- instead got an unexpected puzzle, back to Q1 and Q2
- other decays than β decay ?? (stability of matter!)
  - $n \rightarrow \chi\gamma$, dark fermion χ: experimentally ruled out
  - $n \rightarrow \chi A'$, dark boson A': consistency with neutron stars

more “boring” measurements

- what could be more boring than radius of proton? well, well ...
- one measurement alone is always dangerous !
- two measurements that agree are still dangerous ...
- e and μ spectroscopy plus e-p and μ-p scattering, all of them HyperMu, MUSE
- after all there are also many measurements for e.g. $m_{\rm top}$ and $b \to s\ell\ell$
- and μ seem to be trouble makers
- similar story for μ-e scattering MUonE (??)

take your pick they are all the same price

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nobody wants this: