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Theoretical Motivations for a large Muon EDM

Based on: AC, and M. Hoferichter and P. Schmidt-Wellenburg:
PRD.98.113002, arXiv:1807.11484
Outline

• Introduction: Searching for NP with flavour observables
• Experimental situation: Lepton Flavour Universality Violation
• Anomalous magnetic moments
  – $a_\mu$
  – $a_e$
• Combined explanations
• A large muon EDM
• Conclusions
Physics Beyond the Standard Model

• Dark Matter existence established at cosmological scales
  – New weakly interacting particles
• Neutrinos not exactly massless
  – Right-handed (sterile) neutrinos
• Matter anti-matter asymmetry
  – Additional CP violating interactions

The SM must be extended!
What is the underlying fundamental theory?

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Finding New Physics with Flavour

• At colliders one produces many (up to $10^{14}$) heavy quarks or leptons and measures their decays into light flavours.

Flavour observables are sensitive to higher energy scales than collider searches.
Hints for New Physics

Lepton Flavour Universality Violation (LFUV)

- $a_e > 2\sigma$
- $R(V_{us}) > 3\sigma$
- $a_\mu > 3\sigma$
- $b \rightarrow s\mu\mu > 5\sigma$
- $b \rightarrow d\mu\mu$
- $b \rightarrow u\tau\nu > 1-2\sigma$
- $\tau \rightarrow K_S\pi\nu$

CP violation

- $\varepsilon'/\varepsilon$
- $B_s \rightarrow KK$
- D decays

CP + LFUV $\rightarrow$ muon EDM?
Muon Anomalous Magnetic Moment

- Single measurement from BNL
- Theory prediction sound but challenging because of hadronic effects.

$$\Delta a_\mu = \left(236 \pm 87\right) \times 10^{-11}$$

- Soon new experimental results from Fermilab

3σ deviation (order of SM-EW contribution)
Electron AMM

- AMM usually used to determine $\alpha$
- With *now* best determination of $\alpha$ from Cs atoms

$$a_e^{SM} \bigg|_{\alpha_{Cs}} = 1,159,652,181.61(23) \times 10^{-12}$$

- Compared to the electron AMM measurement

$$\Delta a_e = a_e^{exp} - a_e^{SM} = -0.88(36) \times 10^{-12}$$

- Normalized to the lepton mass

$$-3 \leq \frac{\Delta a_\mu}{m_\mu} \bigg/ \frac{\Delta a_e}{m_e} \leq -130 \text{ or } -0.006 \leq \frac{\Delta a_\mu}{m_\mu^2} \bigg/ \frac{\Delta a_e}{m_e^2} \leq -0.26$$

2.5 $\sigma$ deviation with opposite sign than $a_\mu$
Dipoles in the EFT

• Effective Hamiltonian
  \[ \mathcal{H}_{\text{eff}} = c_R^{\ell_f \ell_i} \bar{\ell}_f \sigma_{\mu\nu} P_R \ell_i F^{\mu\nu} + \text{h.c.} \]

• Anomalous magnetic moment
  \[ a_{\ell_i} = -\frac{4m_{\ell_i}}{e} \Re c_R^{\ell_i \ell_i} \]

• Electric Dipole moment
  \[ d_{\ell_i} = -2 \Im c_R^{\ell_i \ell_i} \]

• Radiative Lepton decays
  \[ \text{Br}[\mu \rightarrow e\gamma] = \frac{m_\mu^3}{4\pi \Gamma_\mu} \left( |c_R^{e\mu}|^2 + |c_R^{\mu e}|^2 \right) \]

Processes intrinsically connected
Explaining the Muon AMM

- Effect of the order of the EW-SM contribution needed

  enhancement necessary

- Light particles
  - Neutral scalars
  - Neutral vector (Z’ Dark Photon)

- Chiral enhancement: Chiriality flip does not come from the muon mass but rather from an NP mass inside the loop

Light particles or chiral enhancement
Light particles and the Muon AMM

- Light particles: $m_W^2 / m^2$
  - Neutral scalars: $\Phi$
  - Neutral vector (Z’ Dark Photon): $V$

$$c_R^{\mu\mu} = \frac{e}{16\pi^2} m_\mu \left( |\Gamma_{\mu L}|^2 + |\Gamma_{\mu R}|^2 \right) \frac{f_{\Phi,V} \left( \frac{M_\Psi^2}{m^2} \right) + Qg \left( \frac{M_\Psi^2}{m^2} \right)}{m^2}$$

$Q =$ charge of the fermion  
$f, g =$ loop functions

- Sime sign in muon and electron AMM
- Strong limits from direct searches for dark photons etc..

By construction real, i.e. no EDMs
Chiral enhancement

- Enhancement by the mass of the fermion in the loop

\[ c_R^{fi} = \frac{e}{16\pi^2} \Gamma^{\mu L^*} \Gamma^{\mu R} M_\Psi \left( f \left( \frac{M_\Psi^2}{M^2} \right) + Qg \left( \frac{M_\Psi^2}{M^2} \right) \right) \]

\[ Q, M_\Psi = \text{charge, mass of the fermion} \quad f, g = \text{loop functions} \]

- MSSM: \((\tan(\beta))\)
- Leptoquarks: \(m_t/m_\mu\)
- Model with vector like fermions: \(m_\Psi/m_\mu\)

A priori arbitrary phase
Leptquarks in $a_\mu$

- Chirally enhanced effects via top-loops

\[ \lambda^L, R \] Left-, right-handed muons-top coupling

$Z \rightarrow \mu\mu$ at future colliders

E. Leskow, A.C., G. D'Ambrosio, D. Müller

arXiv:1612.06858
Chirally enhancement of $m_\mu/m_e$
Common explanation of $a_\mu$ and $a_e$

- Opposite sign: no single light mediator
- Minimal Flavour Violation:
  \[ \frac{\Delta a_\mu}{\Delta a_e} \neq \frac{m_\mu^2}{m_e^2} \]
  generic flavour structure
- Single new particle:
  \[ \text{Br}[\mu \to e\gamma] = \frac{\alpha m_\mu^2}{16m_e \Gamma_\mu} |\Delta a_\mu | \Delta a_e | \sim 8 \times 10^{-5} \]
  8 orders of magnitude too large
  several new particles

Muon and electron sector must be decoupled
Models for a common explanation

• MSSM
  • Constrained MFV does not work
  • With generic A-terms has problem with vacuum stability
  • With large tan(β) and flavour violation

• 2HDMs & LQs: Problems with $\mu \rightarrow e\gamma$

• Extra dimensions
  • Can only explain the muon or the electron AMM because of $\mu \rightarrow e\gamma$

Most popular models do not work
Model with new vector-like leptons

\[ \mathcal{L}_M = -M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.}, \]

\[ \mathcal{L}_H = -\kappa_L \bar{L}_L H E_R - \kappa_E \bar{L}_R H E_L \]

\[ -\lambda_L \bar{L}_L \ell_R H - \lambda_E \bar{E}_R \tilde{H} \ell_L + \text{h.c.} \]

Chirally enhanced by \( v \kappa_{L,R}/m_\mu \)
Model with new vector-like leptons

Works for $a_e$ but tension with $a_\mu$
Modifications to the model

• Add neutral scalar
  • Effect in $a_\mu$ possible without affecting $h\rightarrow\mu\mu$
• Impose abelian flavour symmetry (e.g. $L_\mu-L_\tau$) in order to avoid $\mu\rightarrow e\gamma$
• More minimal model with one generation of vector-like fermions possible if $a_e$ is explained by the SM Higgs and $a_\mu$ via a new scalar
• New scalar could be $L_\mu-L_\tau$ flavon

Many realizations possible
Limits on the Muon EDM

- MFV:
- Contribution only starts at the 3-loop level

\[
|d_\mu| \leq \left[ \left( \frac{15}{4} \zeta(3) - \frac{31}{12} \right) \frac{m_e}{m_\mu} \left( \frac{\alpha}{\pi} \right)^3 \right]^{-1} |d_e|
\]

\[
|d_\mu| \leq 0.9 \times 10^{-19} e \text{ cm} \quad 90\% \text{ C.L.}
\]

- Direct limit

\[
|d_\mu| < 1.5 \times 10^{-19} e \text{ cm}
\]

Improvement of direct limit important
Future experimental sensitivity

Dedicated experiment needed?!
Implications

- $a_\mu > 0$
- $a_e > 0$
- small $a_e > 0$

- $a_\mu > 0$
- $a_e < 0$

- $a_\mu > 0$
- $a_e > 0$

- MFV
- Generic chiral enhancement
- Light particles

- small $d_\mu$
- $d_\mu$ unconstrained
- zero $d_\mu$

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R(D\((\ast)\)) implications for \(n_d\)

AC, F. Saturnino
arxiv:1905:08257

Similar correlations for muon EDM?
Conclusions