The Muon Magnetic Moment and Physics Beyond the Standard Model

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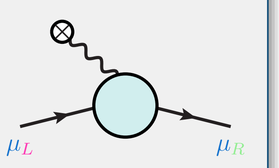
Structure of Δa_μ

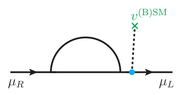
Key Properties



- ❒ Flavor Conserving
- ❒ Chirality flipping
- ❒ Loop Induced
- ❒ CP conserving

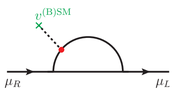
BSM with generic couplings $c_{L,R}$ of the left- and right-handed muons:

① loop preserves muon chirality



$$\sim \frac{|c_{L,R}|^2}{16\pi^2}\frac{m_\mu^2}{M^2}$$

② loop flips muon chirality



$$\sim R_\chi \times \frac{c_L c_R}{16\pi^2}\frac{m_\mu^2}{M^2}$$

$\Longrightarrow$ chiral enhancement R_χ

Relationships to other observables

Other dipole observables

In SM: no CP or flavour violation in lepton sector

$$\Longrightarrow \quad d^{\rm SM}_{e,\mu,\tau} \sim 10^{-40}\, e\cdot{\rm cm}$$
$$\mathrm{BR}(\mu\to e\gamma)_{\rm SM} \sim 10^{-50}$$

BSM scenarios often CPV / LFV
$\hookrightarrow$ prediction of clear signal

Observables related via dipole operator

$$\mathcal{L} \supset L_{\substack{e\gamma\\ij}}\, \overline{e_{Li}}\,\sigma^{\alpha\beta}\, e_{Rj} F_{\alpha\beta} + h.c.$$

CPV phase: $\phi_\mu = \arg L_{\substack{e\gamma\\22}}$

LFV parameter: $\theta_{ij} = L_{\substack{e\gamma\\ij}}/L_{\substack{e\gamma\\22}}$

$$\frac{d_\mu[e\cdot\mathrm{cm}]}{4.1\times10^{-30}} \approx \left(\frac{\Delta a_\mu}{10^{-9}}\right)\left(\frac{\tan\phi_\mu}{2000}\right)$$
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{4.2\times10^{-13}} \approx \left(\frac{\Delta a_\mu}{10^{-9}}\right)\frac{{\theta_{12}}^2+{\theta_{21}}^2}{(5\times10^{-5})^2}$$

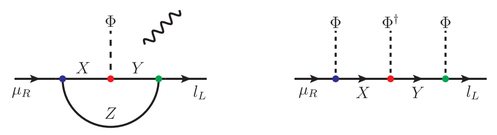
$\Rightarrow$ large CPV still possible, but LFV strongly constrained

Muon–Higgs coupling $\lambda_{\mu\mu}$

flavour-conserving and chirality flipping $\hookrightarrow$ similar chiral enhancement

In SMEFT: $\mathcal{L} \supset C_{\mu\gamma}\left(\overline{l_L}\sigma^{\alpha\beta}\mu_R\Phi\right)F_{\alpha\beta} + C_{\mu\Phi}\left(\overline{l_L}\mu_R\Phi\right)|\Phi|^2$

$$\Delta a_\mu = \frac{4m_\mu v}{e\sqrt{2}}\,\mathrm{Re}\{C_{\mu\gamma}\}$$
$$\lambda_{\mu\mu} = \frac{m_\mu}{v} - C_{\mu\Phi}\frac{v^2}{\sqrt{2}}$$

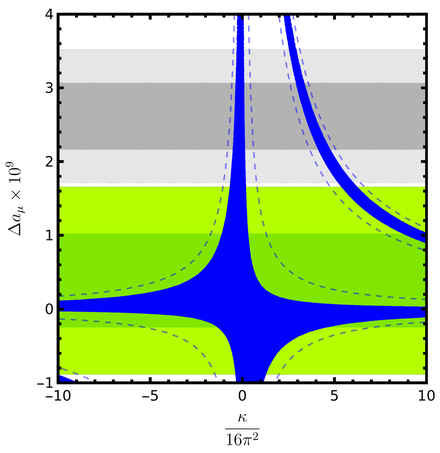


Correlation:

$$C_{\mu\Phi} = \frac{\kappa}{e}C_{\mu\gamma}$$

with model-dependent κ

$$\left|\frac{\lambda_{\mu\mu}}{\lambda^{\rm SM}_{\mu\mu}}\right|^2 = \left|1 - \frac{|\kappa|}{728}\left(\frac{\Delta a_\mu}{10^{-9}}\right)\right|^2 = \underbrace{1.21\pm0.35}_{\text{experiment}}$$



Collider Limits

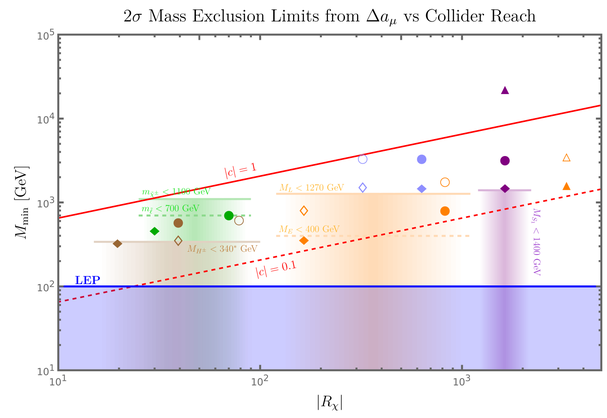
Generic chiral enhancement with $c_{L,R} \sim \mathcal{O}(1)$:

positive Δa_μ

$$M \gtrsim \sqrt{R_\chi} \times 206\ \mathrm{GeV}$$

negative Δa_μ

$$M \gtrsim \sqrt{R_\chi} \times 282\ \mathrm{GeV}$$



Specific BSM Scenarios

Light gauge bosons

$\Rightarrow$ additional (broken) $\mathrm{U}(1)_X$ gauge group with massive vector boson

❒ Z': SM leptons charged, e.g. $L_\mu - L_\tau$

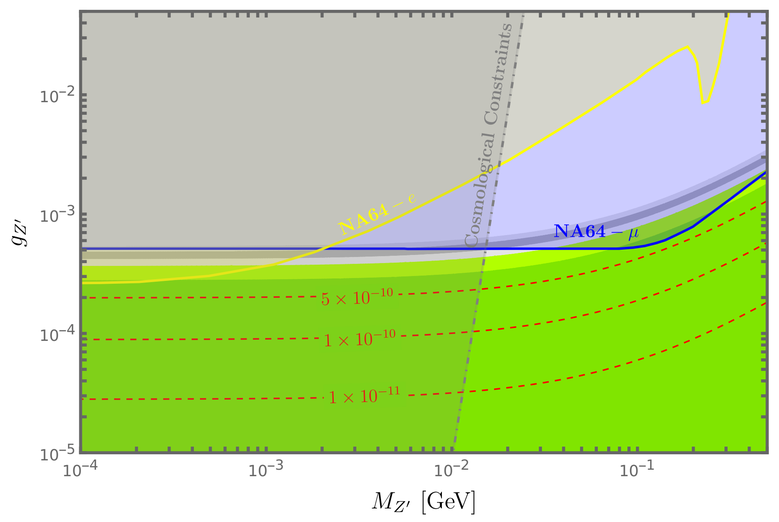
$$\mathcal{L} \supset -g_{Z'}\left(\bar\mu\gamma^\alpha\mu - \bar\tau\gamma^\alpha\tau + \bar\nu_\mu\gamma^\alpha\nu_\mu - \bar\nu_\tau\gamma^\alpha\nu_\tau\gamma\right)Z'_\alpha$$

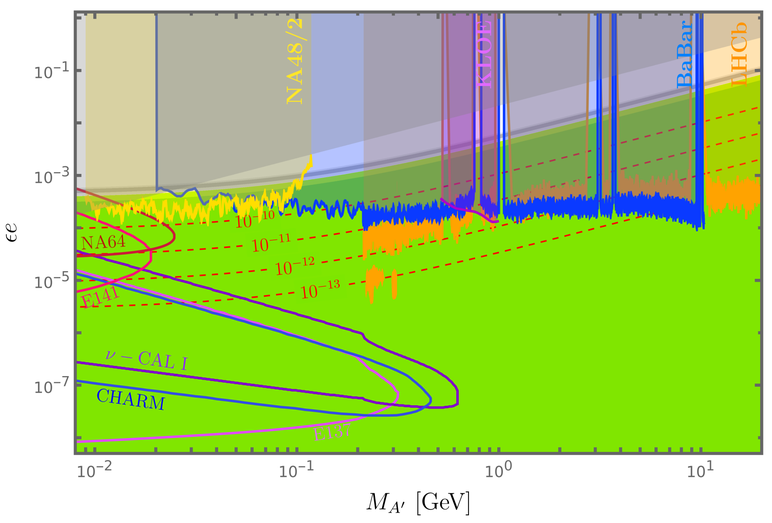
constraints from cosmology ($N_{\rm eff}$) and $Z' \to \nu\bar\nu$ (NA64-e/μ)
$\to$ maximum possible $\Delta a_\mu^{Z'} \lesssim 2\times10^{-9}$ ($M_{Z'} \approx 20$ MeV)

❒ A': SM leptons not charged $\hookrightarrow$ interactions only from kinetic mixing

$$\mathcal{L} \supset -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} \overset{A_\mu\to A_\mu+\epsilon A'_\mu}{\longrightarrow} \mathcal{L} \supset -\epsilon A'_\mu j^\mu_{\rm em}$$

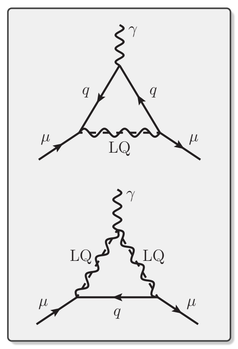
many constraints due to uniform coupling to all SM fermions
$\to$ maximum possible $\Delta a_\mu^{A'} \lesssim 5\times10^{-10}$ ($M_{A'} \approx 20$ MeV)





Leptoquarks

$\to$ interaction with SM leptons and quarks (typical in GUT).
Chiral enhancement is possible if LQ couples to μ_L and μ_R



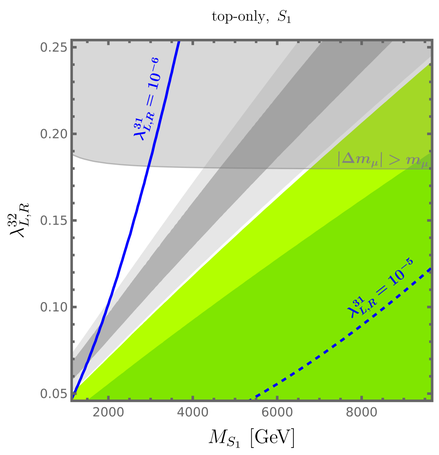
e.g. scalar LQ $S_1 \in (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$:

$$\mathcal{L} \supset -\lambda_L^{ij}\overline{q_{Li}^C}\epsilon l_{Lj}S_1 - \lambda_R^{ij}\overline{u_{Ri}^C}e_{Rj}S_1$$

$\hookrightarrow$ chirality flip on heavy quark line:

$$\Longrightarrow\ \Delta a_\mu \propto N_c\frac{\lambda_L^{32}\lambda_R^{32}}{16\pi^2}\frac{m_\mu m_t}{M_{S_1}^2}$$

Constraints:
- $M_{S_1} \gtrsim 2$ TeV (LHC)
- flavour-violation
- fine-tuning in $\Delta m_\mu^{1\ell}$



Δa_μ contours and exclusion from BR($\mu \to e\gamma$) (blue)

Vector-like leptons

Dirac fermions $F = F_L + F_R$ with same representation of $F_{L,R}$ under SM gauge group
$\hookrightarrow$ mass term allowed *before* EWSB: $\mathcal{L} \supset M_F\overline{F_R}F_L + h.c.$

Vector-like Leptons: couple to the SM leptons and Higgs doublet at tree-level, e.g. $E \in \mathbf{1}_{-1}$, $L \in \mathbf{2}_{-\frac{1}{2}}$.

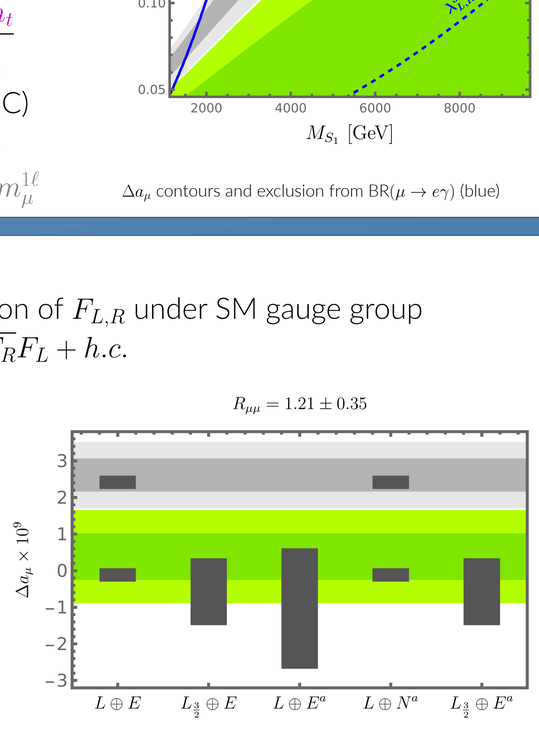
$$\mathcal{L} \supset -\lambda_L\overline{L_L}\mu_R\Phi - \lambda_E\overline{l_L}E_R\Phi - \bar\lambda\overline{L_R}E_L\Phi$$

$\to$ large chiral enhancement from VLL couplings

$$\Delta a_\mu, \lambda_{\mu\mu} \propto \lambda_L\lambda_E\bar\lambda$$

correlated as above with $\kappa \sim \mathcal{O}(16\pi^2)$

Constraints:
- $M_F \gtrsim 1000$ GeV (LHC)
- bounds on λ_i from Z-pole PO and vacuum stability



Ranges of Δa_μ allowed in the different VLL models.
(green: WP25, gray: WP20)

Axion-like Particles

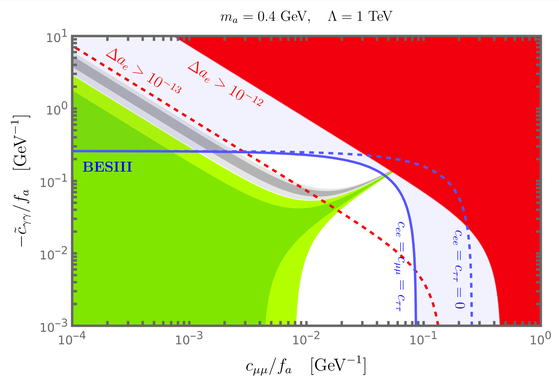
Pseudoscalar a with shift-symmetric interactions

$$\mathcal{L} \supset \frac{c_{\mu\mu}}{2}\frac{\partial_\mu a}{f_a}\bar\mu\gamma^\mu\gamma^5\mu + c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde F^{\mu\nu}$$

Competing one- and two-loop contributions

$$\Delta a_\mu^{1\ell} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \qquad \Delta a_\mu^{2\ell} \propto -\frac{c_{\mu\mu}c_{\gamma\gamma}\alpha}{16\pi^3}$$

strong constraints from $J/\Psi \to \gamma^* \to a\gamma$ (BES III)



Two-Higgs-doublet Model

SM + second ($Y = \frac{1}{2}$) $\mathrm{SU}(2)_L$ doublet scalar Φ_2.
$\Rightarrow$ 5 physical scalars h ($M_h = 125$ GeV), H, A and $H^\pm$

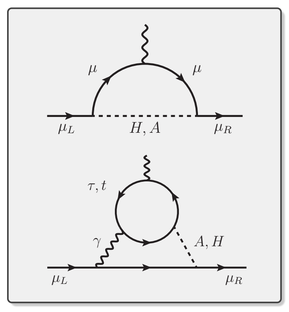
SM leptons can couple to both doublets

$$\mathcal{L} \supset \sum_{a=1,2}\overline{l_L}Y_a^l e_R\Phi_a + h.c.$$

Flavour-aligned 2HDM: $Y_2^f = \zeta_f Y_1^f$

Contribution to Δa_μ

From one-loop *and* two-loop Barr-Zee diagrams



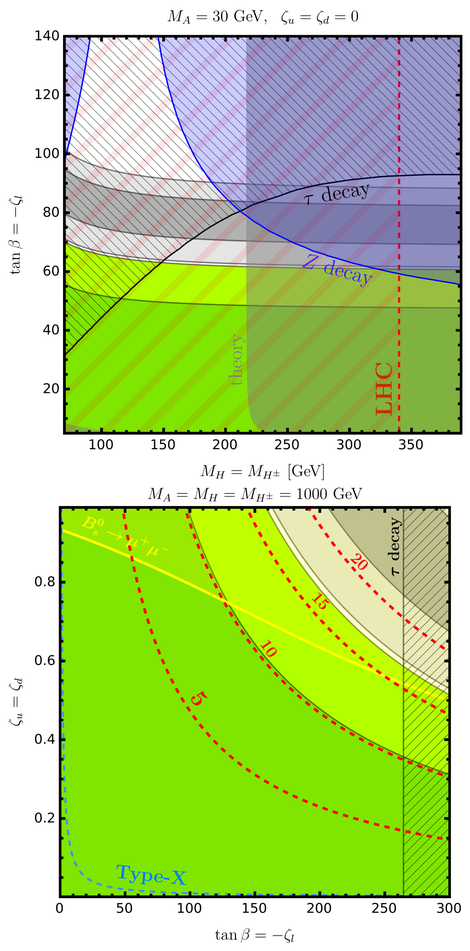
$$\Delta a_\mu^{1\ell} \sim \mp\frac{\zeta_l^2}{8\pi^2}\frac{m_\mu^4}{v^2M_S^2},$$

$$\Delta a_\mu^{2\ell} \sim -\frac{\zeta_l\zeta_u m_\mu^2 m_i^2}{8\pi^2\, v^2 M_S^2}\frac{\alpha}{\pi}N_c Q_t^2$$

Constraints:

light $M_A \lesssim 100$ GeV $\to$ strong exclusion limits from LHC

heavy $M_i \sim 1$ TeV $\to$ bounds on ζ_f from flavour and EW precision observables



Supersymmetry

❒ Scenarios with light SUSY and dark matter still possible:
e.g. Bino LSP $\to$ DM coannihilation needs small mass splitting
$\to$ LHC is insensitive

$\hookrightarrow$ complementary constraint from Δa_μ

❒ on the other hand... many scenarios (e.g. CMSSM, GMSB, ...) with small Δa_μ are viable again.