Probing the muon g-2 anomaly at a Muon Collider

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Plan of the talk

1. **Status of the muon $g-2$ as of early 2021**
2. **New Physics explanations of the muon $g-2$ anomaly**
3. **The muon $g-2$ anomaly at a Muon Collider**
4. **Future prospects**

- **Status of the muon $a_\mu \equiv \frac{g_\mu - 2}{2}$ as of early 2021** [T. Aoyama *et al.*, Phys. Rept. '20]

$$a_\mu^{\rm EXP} = 116592089(63) \times 10^{-11} \qquad a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = 279\,(76) \times 10^{-11} \qquad \text{(3.7}\sigma\text{ discrepancy!)}$$

$$\underbrace{(0.1)_{\rm QED}\,,\quad (1)_{\rm EW}\,,\quad (18)_{\rm HLbL}\,,\quad (40)_{\rm HVP}\,,}_{(43)_{\rm TH}}\quad (63)_{\delta a_\mu^{\rm EXP}}\,.$$

  - Hadronic uncertainties (HLbL & HVP) can be hardly go below the current values.
  - The E989 Muon $g-2$ experiment will deliver a measure of $a_\mu^{\rm EXP}$ by this spring.
  - We expect $\delta a_\mu^{\rm EXP} \lesssim 2 \times 10^{-10}$ by the E989 Muon $g-2$ experiment in a few years.

- **Low-energy determinations of Δa_μ assume that systematic and hadronic uncertainties are under control at the outstanding level of $\Delta a_\mu \sim 10^{-9}$!**

A completely independent test of Δa_μ is very desirable!

Connecting $(g-2)_\mu$ with high-energy processes

- **Δa_μ discrepancy at $\sim 3.7\,\sigma$ level:**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.79 \pm 0.76) \times 10^{-9}$$

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

  - A weakly interacting NP at $\Lambda \approx v$ can naturally explain $\Delta a_\mu \approx 2 \times 10^{-9}$.
  - $\Lambda \approx v$ favoured by the *hierarchy problem* and by a WIMP DM candidate.

- **LEP and LHC bounds disfavour $\Lambda \approx v$ and two possibilities emerge:**
  - NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.
  - NP is very heavy ($\Lambda \gg 1$ TeV) and strongly coupled to SM particles.

- **Connecting Δa_μ with high-energy scattering processes ($\Lambda \gg 1$ TeV)**

$$\mathcal{L} = \frac{C_{e\gamma}^{\ell}}{\Lambda^2} \left(\bar{\ell}_L \sigma^{\mu\nu} e_R\right) H F_{\mu\nu} + h.c. \qquad H = v + \frac{h}{\sqrt{2}}$$

$$\boldsymbol{\Delta a_\mu \sim \frac{m_\mu v}{\Lambda^2} C_{e\gamma}^{\mu}} \qquad \Longleftrightarrow \qquad \boldsymbol{\sigma_{\mu\mu\to h\gamma} \sim \frac{s}{\Lambda^4} |C_{e\gamma}^{\mu}|^2}$$

- **SMEFT Lagrangian relevant for Δa_ℓ**

$$\mathcal{L} = \sum_{V=B,W} \frac{C_{eV}^{\ell}}{\Lambda^2} \left(\bar{\ell}_L \sigma^{\mu\nu} e_R\right) H V_{\mu\nu} + \sum_{q=c,t} \frac{C_T^{\ell q}}{\Lambda^2} (\bar{\ell}_L \sigma_{\mu\nu} e_R)(\overline{Q}_L \sigma^{\mu\nu} q_R) + h.c.$$

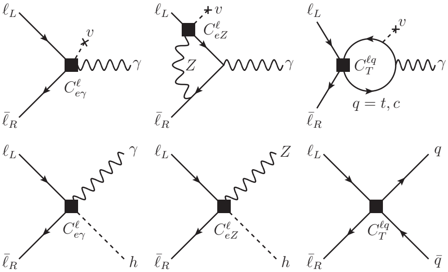


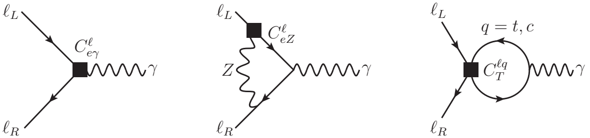
Figure: Connection between the Feynman diagrams for leptonic g-2 (upper row) and high-energy scattering processes (lower row) within the SMEFT.

$$\Delta a_\mu \sim \frac{m_\mu v}{\Lambda^2} C_{eV,T} \quad \Longleftrightarrow \quad \sigma_{\mu\mu\to f} \sim \frac{s}{\Lambda^4} |C_{eV,T}|^2 \qquad (f = e\gamma, eZ, q\bar{q})$$

The muon g-2 in the Standard Model EFT

- **SMEFT Lagrangian relevant for Δa_ℓ**

$$\mathcal{L} = \sum_{V=B,W} \frac{C^\ell_{eV}}{\Lambda^2} (\bar{\ell}_L \sigma^{\mu\nu} e_R) H V_{\mu\nu} + \sum_{q=c,t} \frac{C^{\ell q}_T}{\Lambda^2} (\bar{\ell}_L \sigma_{\mu\nu} e_R)(\overline{Q}_L \sigma^{\mu\nu} q_R) + h.c.$$



$$\Delta a_\ell \simeq \frac{4 m_\ell v}{e\Lambda^2} \left(C^\ell_{e\gamma} - \frac{3\alpha}{2\pi} \frac{c_W^2 - s_W^2}{s_W c_W} C^\ell_{eZ} \log\frac{\Lambda}{m_Z} \right) - \sum_{q=c,t} \frac{4 m_\ell m_q}{\pi^2} \frac{C^{\ell q}_T}{\Lambda^2} \log\frac{\Lambda}{m_q},$$

$$\frac{\Delta a_\mu}{3\times 10^{-9}} \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda} \right)^2 \left(C^\mu_{e\gamma} - 0.2 C^{\mu t}_T - 0.002 C^{\mu c}_T - 0.05 C^\mu_{eZ} \right).$$

- **Strongly coupled NP:** $C^\mu_{e\gamma}, C^{\mu t}_T \sim g^2_{\mathrm{NP}}/16\pi^2 \lesssim 1$ implying $\Lambda \lesssim$ *few* x 100 TeV, beyond the direct production reach of any foreseen collider.

- **Weakly coupled NP:** $C^\mu_{e\gamma}, C^{\mu t}_T \lesssim 1/16\pi^2$ implying $\Lambda \lesssim 20$ TeV maybe within the direct production reach of a very high-energy Muon Collider [Capdevilla et al., '20].

High-energy probes of $(g-2)_\mu$

- **Connecting $\mu^+\mu^- \to h\gamma$ with Δa_μ**

$$\sigma_{\mu\mu\to h\gamma} = \frac{s}{48\pi}\frac{|C^\mu_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\mathrm{ab}\left(\frac{\sqrt{s}}{30\,\mathrm{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2$$

- **SM irreducible background:**
  - $\sigma^{\mathrm{SM}}_{\mu\mu\to h\gamma} \approx (\alpha y_\mu^2/4s) \times \ln(s/m_\mu^2)|_{\sqrt{s}=30\,\mathrm{TeV}} \sim 4\times 10^{-3}\,\mathrm{ab}$: negligible!

- **SM reducible background:**

$$\frac{d\sigma_{\mu\mu\to Z\gamma}}{d\cos\theta} \sim \frac{\pi\alpha^2}{4s}\frac{1+\cos^2\theta}{\sin^2\theta} \qquad \frac{d\sigma_{\mu\mu\to h\gamma}}{d\cos\theta} = \frac{|C^\mu_{e\gamma}|^2}{\Lambda^4}\frac{s}{64\pi}(1-\cos^2\theta)$$

  - The significance of the signal $S = N_S/\sqrt{N_B+N_S}$ maximal for $|\cos\theta| \lesssim 0.6$.

$$\sigma^{\mathrm{cut}}_{\mu\mu\to h\gamma} \approx 0.53\,\mathrm{ab}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2, \qquad \sigma^{\mathrm{cut}}_{\mu\mu\to Z\gamma} \approx 82\,\mathrm{ab} \qquad (\sqrt{s} = 30\,\mathrm{TeV})$$

  - S/B isolation: i) angular distributions and ii) h/Z invariant mass reconstruction.
  - Cut-and-count exp. with $b\bar{b}$ final state, $\mathcal{B}(h/Z \to b\bar{b}) = 0.58/0.15$ and $\epsilon_b = 80\%$.
  - For a Z/h misident. prob. of 10%, $N_{S(B)} = 22(88)$ and $S = 2$ at $\sqrt{s} = 30$ TeV.

High-energy probes of $(g-2)_\mu$

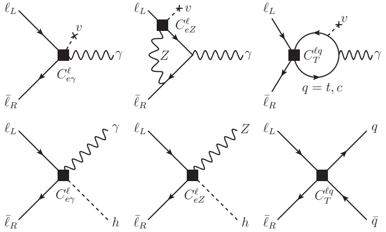
- **Connecting $\mu^+\mu^- \to (h\gamma, Zh, t\bar{t}, c\bar{c})$ with Δa_μ**

$$\sigma^{\rm cut}_{\mu\mu\to h\gamma} \approx 0.5\,\text{ab}\left(\frac{\sqrt{s}}{30\,\text{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to Zh} \approx 38\,\text{ab}\left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to t\bar{t}} \approx 58\,\text{ab}\left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma_{\mu\mu\to c\bar{c}} \approx 100\,\text{fb}\left(\frac{\sqrt{s}}{3\,\text{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$



- **Δa_μ predictions in the SMEFT**

$$\frac{|\Delta a_\mu|}{3\times10^{-9}} \approx \left(\frac{250\,\text{TeV}}{\Lambda}\right)^2 |C^\mu_{e\gamma}| \qquad \frac{|\Delta a_\mu|}{3\times10^{-9}} \approx \left(\frac{50\,\text{TeV}}{\Lambda}\right)^2 |C^\mu_{eZ}|$$

$$\frac{|\Delta a_\mu|}{3\times10^{-9}} \approx \left(\frac{100\,\text{TeV}}{\Lambda}\right)^2 |C^{\mu t}_{T}| \qquad \frac{|\Delta a_\mu|}{3\times10^{-9}} \approx \left(\frac{10\,\text{TeV}}{\Lambda}\right)^2 |C^{\mu c}_{T}|$$

- **SM irreducible background**

$$\sigma^{\rm SM,cut}_{\mu\mu\to Z\gamma} \approx 82\,\text{ab}\left(\frac{30\,\text{TeV}}{\sqrt{s}}\right)^2 \qquad \sigma^{\rm SM}_{\mu\mu\to Zh} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2$$

$$\sigma^{\rm SM}_{\mu\mu\to t\bar{t}} \approx 1.7\,\text{fb}\left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2 \qquad \sigma^{\rm SM}_{\mu\mu\to c\bar{c}} \approx 19\,\text{fb}\left(\frac{3\,\text{TeV}}{\sqrt{s}}\right)^2$$

The muon g-2 at a Muon Collider

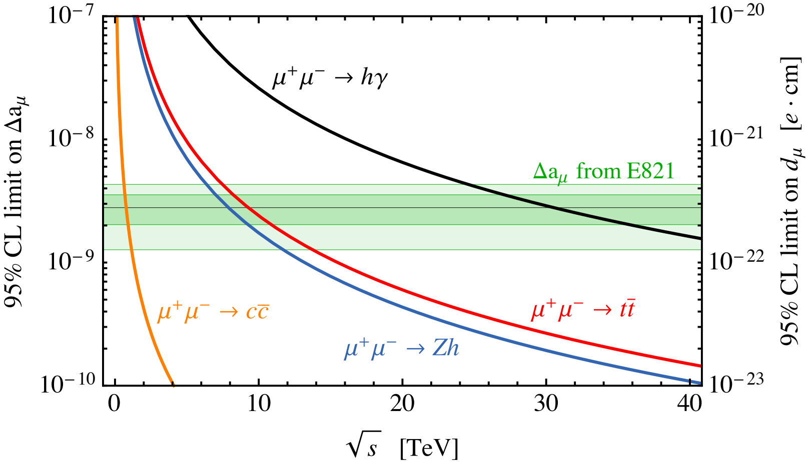


Figure: 95% C.L. reach on the muon anomalous magnetic moment Δa_μ, as well as on the muon EDM d_μ, as a function of the center-of-mass energy $\sqrt{s}$ from various processes.

$$d_\mu = \frac{\Delta a_\mu \tan\phi_\mu}{2m_\mu}\, e \simeq 3\times 10^{-22} \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) \tan\phi_\mu \; e\,\mathrm{cm}$$

Future prospects

- **A MC offers a new way to probe NP which is complementary both to:**
  - Direct searches for new particles at high-energy particle colliders.
  - Indirect searches at low energy through high-precision experiments.

- **A MC running at $\sqrt{s} \gg 1\,\mathrm{TeV}$ provides a unique opportunity to probe new physics effects in the muon g-2 in a model-independent way:**
  - Direct determination of NP, not hampered by the hadronic uncertainties of $a_\mu^{\rm SM}$.
  - A high-energy measurement with $\mathcal{O}(1)$ precision is sufficient to probe $\Delta a_\mu \sim 10^{-9}$.

- **Extraction of the tau $g-2$ through:** [Buttazzo & Paradisi, in progress]
  - Rare Higgs decays $h \to \ell^+\ell^-\gamma$ and $h \to \ell^+\ell^- Z$
  - Drell-Yan process $\mu^+\mu^- \to \tau^+\tau^-$
  - VBF process $\mu^+\mu^- \to \mu^+\mu^-\tau^+\tau^-(\bar{\nu}\nu\,\tau^+\tau^-)$
  - Expected sensitivity: $10^{-5} \lesssim |\Delta a_\tau| \lesssim 10^{-4}$

- **B-physics anomalies and leptonic $g-2$ at a MC**
  - Leptoquarks –favoured by B-physics anomalies– generate semileptonic operators which contribute also to leptonic $g-2$ and can be tested at a MC.

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