Probing new physics with the leptonic g-2

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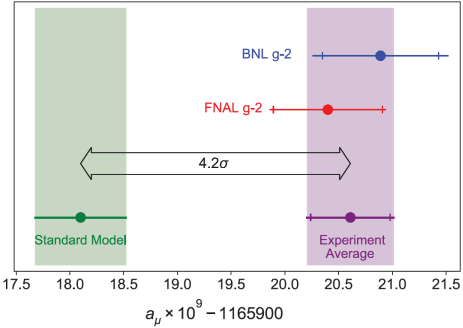
Plan of the talk

1. **Experimental and theoretical status of the muon $a_\mu \equiv \frac{g_\mu - 2}{2}$**
   - Hadronic LO contribution from $e^+e^- \to hadrons$
   - Hadronic LO contribution from Lattice QCD (LQCD)
2. **New Physics explanations of the (possible) muon $g - 2$ anomaly**
   - Electroweak scale NP: the supersymmetric (SUSY) solution
   - Heavy NP: Effective Field Theory (EFT) approach
   - Light NP: the axion-like particle (ALP) solution
3. **Testing the muon $g - 2$ anomaly at a Muon Collider**
4. **Testing the muon $g - 2$ anomaly with the electron $g - 2$**
5. **Outlook**

- **Muon $g-2$: FNAL confirms BNL!**



3.7 σ

3.3 σ

4.2 σ

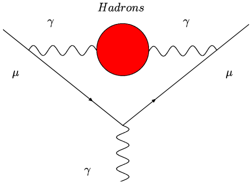
a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [0.54ppm] BNL E821

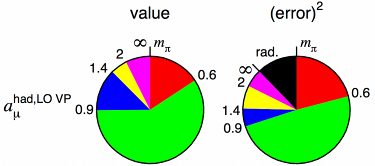
a_μ^{EXP} = (116592040 ± 54) x 10^{-11} [0.46ppm] FNAL E989 Run 1

a_μ^{EXP} = (116592061 ± 41) x 10^{-11} [0.35ppm] WA

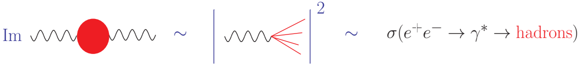
- **FNAL aims at 16×10^{-11}. First 3 runs completed, 4th in progress.**
- **Muon $g-2$ proposal at J-PARC: Phase-1 with similar BNL precision.**

HLO contribution from $e^+e^- \to hadrons$

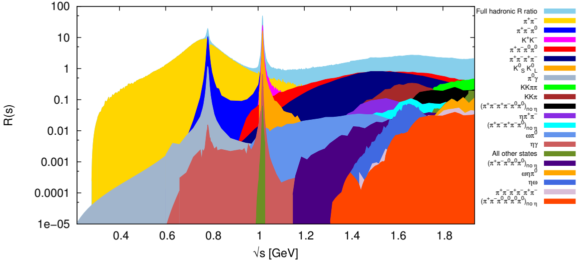




Keshavarzi, Nomura, Teubner 2018



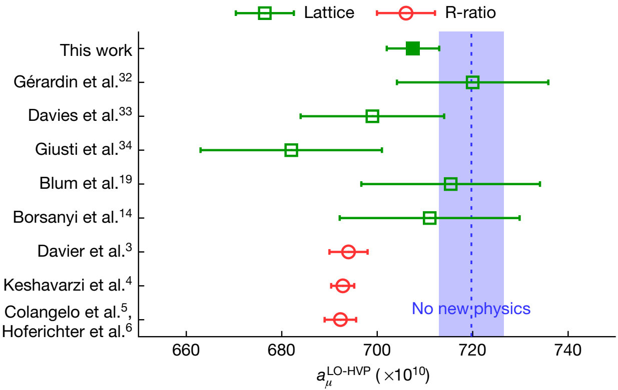
$$a_\mu^{\text{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}\,K(s)\,R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



$$a_{\mu,e^+e^-}^{\text{HLO}} = 6931(40)\times 10^{-11}(0.6\%)$$ [WP20]

HLO contribution from lattice QCD

- Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision: $\boldsymbol{a^{\rm HLO}_{\mu,\rm LQCD} = 7075(23)_{\rm stat}(50)_{\rm syst} \times 10^{-11}}$ [Borsanyi et al., Nature 2021].

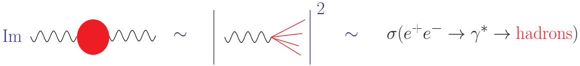


- BMW results weakens the long-standing muon $g-2$ discrepancy but it shows a tension with dispersive evaluations of $\boldsymbol{a^{\rm HLO}_{\mu,e^+e^-} = 6931(40) \times 10^{-11}}$.

Consequences of the BMW result

- **Can Δa_μ be due to missing contributions in $\sigma(e^+e^- \to had)$?**
  - An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha^{(5)}_{\rm had}(M_Z)$ defined by:
    $\alpha^{-1}(M_Z) = \alpha^{-1}\left[1 - \Delta\alpha(M_Z) - \Delta\alpha^{(5)}_{\rm had}(M_Z) - \Delta\alpha_{\rm top}(M_Z)\right]$

$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma(s)\,, \qquad \Delta\alpha^{(5)}_{\rm had} = \frac{M_Z^2}{4\pi\alpha^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{M_Z^2 - s}$$



- **A change in $\sigma(e^+e^- \to had)$ is strongly disfavoured by:**
  - **EW-fit for $\sqrt{s} \gtrsim 1$ GeV** [Marciano, Passera, Sirlin, '08, Keshavarzi, Marciano, Passera, Sirlin, '20, Crivellin, Hoferichter, Manzari, Montull, '20]. A shift of $\sigma(e^+e^- \to had)$ to accomodate the Δa_μ anomaly would necessarely require new physics to show up in the EW-fit!
  - **Experimental data on $e^+e^- \to \pi^+\pi^-$ for $\sqrt{s} \lesssim 1$ GeV** [Colangelo, Hoferichter, Stoffer, '21]
- **A check of the BMW results by other lattice QCD (LQCD) coll. is worth.**
- **LQCD coll. should provide $\Delta\alpha^{\rm LQCD}_{\rm had}$ to be compared with $\Delta\alpha^{e^+e^-}_{\rm had}$.**

New Physics for the muon $g-2$: at which scale?

- Δa_μ discrepancy at $\sim 4.2\,\sigma$ level:

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.51 \pm 0.59) \times 10^{-9}$$

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

  - NP is at the weak scale ($\Lambda \approx v$) and weakly coupled to SM particles.*
  - NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.
  - NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.

*Favoured by the *hierarchy problem* and by a WIMP DM candidate but disfavoured by the LEP and LHC bounds (supersymmetry being the most prominent example).

$\Lambda \approx v$: SUSY and the muon $(g-2)$

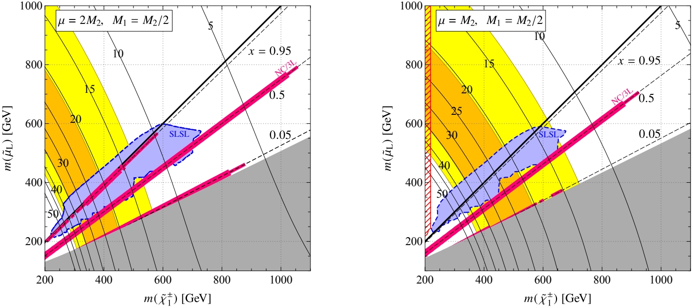
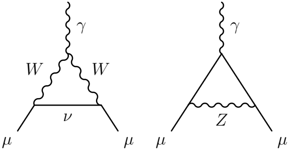
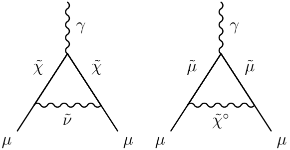


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].



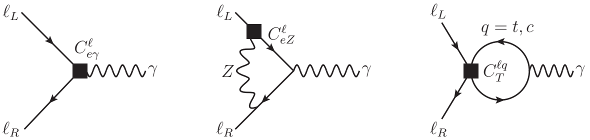


$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

$$a_\mu^{\rm SUSY} \approx \frac{g^2 m_\mu^2 \tan\beta}{32\pi^2 \tilde{m}^2} \underbrace{\approx 2 \times 10^{-9}}_{\tilde{m} = 500\,{\rm GeV}\ \&\ \tan\beta = 40}$$

- **SMEFT Lagrangian relevant for Δa_ℓ**

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



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

$$\frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda}\right)^2 |C^\mu_{e\gamma}| \qquad \frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{50\,\mathrm{TeV}}{\Lambda}\right)^2 |C^\mu_{eZ}|$$

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

- **Strongly coupled NP:** $C^\mu_{e\gamma}, C^{\mu t}_T \sim g^2_{\rm NP}/16\pi^2 \lesssim 1$ 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

- **SMEFT Lagrangian relevant for Δa_ℓ**

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

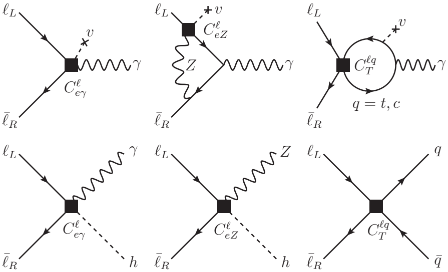


Figure: Connection between the Feynman diagrams for leptonic g-2 (upper row) and high-energy scattering processes (lower row) within the SMEFT: $\boldsymbol{H = v + h/\sqrt{2}}$

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

- **At high energy $\sigma_{\mu\mu\to f}$ can compete with Δa_μ to test the very same NP!**

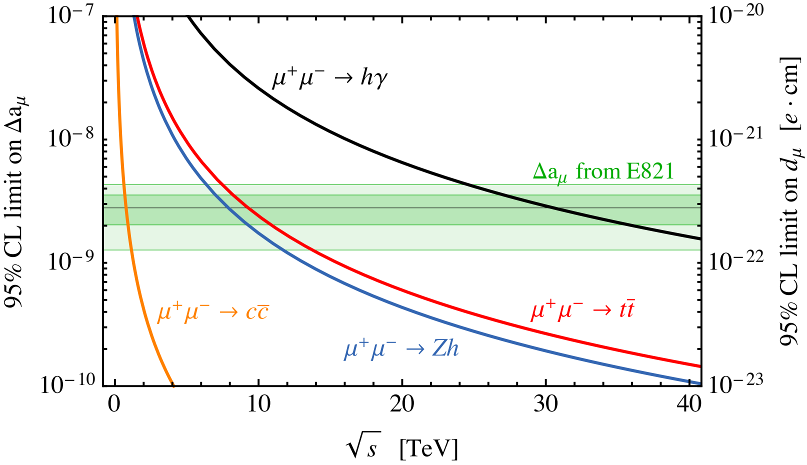


Figure: 95% C.L. reach on Δa_μ, as well as on the muon EDM d_μ, as a function of $\sqrt{s}$ from various processes for the reference integrated luminosity $\mathcal{L} = \left(\sqrt{s}/10\,\mathrm{TeV}\right)^2 \times 10\,\mathrm{ab}^{-1}$.

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

Axion-like Particle effective Lagrangian

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2} \frac{\partial^\nu a}{\Lambda} \bar{\mu}\gamma_\nu\gamma_5\mu$$

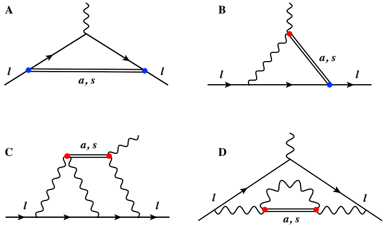


Figure: Contributions of a scalar 's' and a pseudoscalar 'a' ALP to the $(g-2)_\ell$.

[Marciano, Masiero, P.P., Passera '16]

[Bauer, Neubert, Renner, Schnubel, Thamm, '19]

[Cornella, P.P., Sumensari '19]

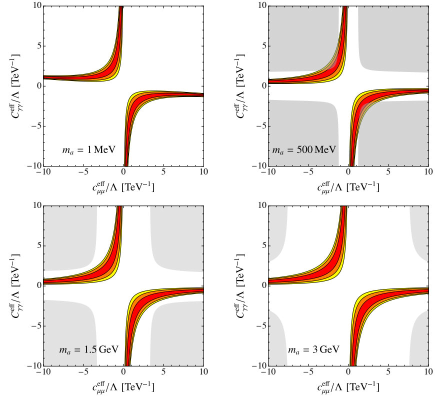


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left[\frac{12\alpha^3}{\pi} C_{\gamma\gamma}^2 \ln^2\frac{\Lambda^2}{m_\mu^2} - \frac{(c_{\mu\mu})^2}{16\pi^2} h_1\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi} c_{\mu\mu} C_{\gamma\gamma} \ln\frac{\Lambda^2}{m_\mu^2}\right]$$

On leptonic dipoles: $\ell \to \ell'\gamma$

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^\star_{\ell\ell'}\ell_R\right)F^{\mu\nu} \qquad \ell,\ell' = e,\mu,\tau\,,$$

  - **Branching ratios of $\ell \to \ell'\gamma$**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

  - **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

  - **"Naive scaling":** a broad class of NP theories contributes to Δa_ℓ and d_ℓ as

$$\frac{\Delta a_\ell}{\Delta a_{\ell'}} = \frac{m_\ell^2}{m_{\ell'}^2}, \qquad \frac{d_\ell}{d_{\ell'}} = \frac{m_\ell}{m_{\ell'}}\,.$$

Model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

- **EDMs vs.** $(g-2)_\mu$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}}\right) \; e\,\mathrm{cm}\,,$$

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

- **Main messages:**
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ **requires a nearly flavor and CP conserving NP**
  - **Large effects in the muon EDM** $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ **are still allowed!**

[Giudice, P.P., & Passera, '12]

Testing new physics with the electron $g-2$

- **Longstanding muon $g-2$ anomaly**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.51 \pm 0.59) \times 10^{-9}$$

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

- **Testing the muon $g-2$ anomaly through the electron $g-2$**

$$\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} \quad \Longleftrightarrow \quad \Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}$$

- a_e has never played a role in testing NP effects. From $a_e^{\rm SM}(\alpha) = a_e^{\rm EXP}$, we extract α which was is the most precise value of α up to 2018!
- The situation has now changed thanks to th. and exp. progresses.
- α can be extracted from atomic physics and a_e used to perform NP tests!

[Giudice, P.P, & Passera, '12]

The Standard Model prediction of the electron $g-2$

- **Status of Δa_e as of 2012**

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM} = -9.2\,(8.1) \times 10^{-13},$$

$$\delta a_e \times 10^{13}: \quad (0.6)_{\rm QED4}, \ (0.4)_{\rm QED5}, \ (0.2)_{\rm HAD}, \ (7.6)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\rm EXP}}.$$

  - The errors from QED4 and QED5 will be reduced soon to 0.1×10^{-13} [Kinoshita]
  - We expect a reduction of $\delta a_e^{\rm EXP}$ to a part in 10^{-13} (or better). [Gabrielse]
  - Work is also in progress for a significant reduction of $\delta\alpha$. [Nez]

- **Status of Δa_e as of 2018: 2.4σ discrepancy** [Parker et al., Science, '18]

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM}(\alpha_{\rm Berkeley}) = -8.8\,(3.6) \times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\rm QED5}, \ (0.1)_{\rm HAD}, \ (2.3)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\rm EXP}}.$$

- **Status of Δa_e as of 2020: 1.6σ discrepancy** [Morel et al., Nature, '20]

$$\Delta a_e = a_e^{\rm EXP} - a_e^{\rm SM}(\alpha_{\rm LKB2020}) = 4.8\,(3.0) \times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\rm QED5}, \ (0.1)_{\rm HAD}, \ (0.9)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\rm EXP}}.$$

- **$\Delta a_e \lesssim 10^{-13}$ is not too far! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.** [Giudice, P.P, & Passera, '12]

Outlook

- The muon $g-2$ represents the most longstanding hint of New Physics now, thanks to the E989 experiment at FNAL, growing to 4.2σ.
- LQCD results by the BMWc weaken the muon $g-2$ discrepancy to 1.6σ but they are in tension with the EW-fit and $e^+e^- \to$ *hadrons* experimental data:
  - The MUonE experiment can provide an independent measure of $\Delta\alpha_{\rm had}$.
- Both heavy New Physics ($\Lambda \gg 1\,\mathrm{TeV}$) and ligh New Physics ($\Lambda \lesssim$ *few* $\times\,\mathrm{GeV}$) scenarios have the potential to account for the muon $g-2$ anomaly.
- A Muon Collider running at $\sqrt{s} \gg 1$ TeV would provide a unique opportunity to probe heavy 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 $\Delta a_\mu \sim 10^{-9}$.
- Testing New Physics effects in the electron $g-2$ at the 10^{-13} is not too far! This will bring a_e to play a pivotal role in probing New Physics in the leptonic sector.
- The NP accounting for the muon $g-2$ anomaly can lead to potentially relevant enhancements in leptonic EDMs and LFV physics.

Message: an exciting Physics program is in progress at the Intensity Frontier!

Backup slides

- **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:**
  - $\sigma^{\rm SM}_{\mu\mu\to h\gamma} \approx (\alpha y_\mu^2/4s)\times \ln(s/m_\mu^2)|_{\sqrt{s}=30\,\mathrm{TeV}} \sim 4\times 10^{-3}\,\mathrm{ab}$: 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 $|\cos\theta| \lesssim 0.6$.

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

  - 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.

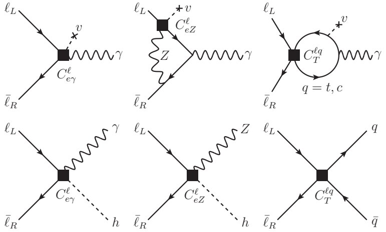
- **Connecting $\mu^+\mu^- \to (h\gamma, Zh, t\bar{t}, c\bar{c})$ with Δa_μ**

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

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

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

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



- **Δa_μ predictions in the SMEFT**

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

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

- **SM irreducible background**

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

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