Muon g-2 anomaly at a muon collider within the HEFT approach

Fabiola Fortuna

Institute of Physics, UNAM

Work done in collaboration with: Juan Manuel Márquez and Pablo Roig
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UNAM

Contents

Motivation

→ Anomalous magnetic moment of the muon

- It has been an enduring hint for NP.
- The latest measurements by the Muon g-2 collaboration at Fermilab, when combined with earlier results from the Brookhaven E821 experiment, indicate a deviation of 5.1 σ from the SM prediction [1]

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 249(48) \times 10^{-11} \tag{1}$$

- The test of NP in the muon g-2 is (mostly) influenced by hadronic and experimental uncertainties.

[1] *Phys. Rev. Lett., 131(16):161802, 2023.*
Phys. Rev. Lett., 126(14):141801, 2021.
Phys. Rev. D, 73:072003, 2006. *Phys. Rept., 887:1–166, 2020.*

HEFT overview

From measurements of various electroweak observables and high-energy processes, the existence of the three Goldstone bosons and the massive scalar h is well established.

However, it is not yet evident that they are necessarily embedded into the four components of a single $SU(2)_L$ doublet H [2].

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi^2 + i\varphi^1 \\ v + h - i\varphi^3 \end{pmatrix}$$

- SMEFT: The Higgs belongs to an elementary $SU(2)_L$ doublet.
- HEFT
  - The physical Higgs h and the ensemble of the three EW Goldstone bosons $\vec{\pi}$ are treated as independent objects, rather than being collectively described by the Higgs doublet.
  - The physical Higgs h is assigned to a singlet representation of the SM gauge groups.

[2] Isidori et al. The standard model effective field theory at work. *Rev.Mod.Phys. 96 (2024) 1, 015006*

HEFT overview

- Goldstone Bosons (GBs) are described by a dimensionless unitary matrix transforming as a bi-doublet of the global symmetry $SU(2)_L \times SU(2)_R$,

$$U(x) \equiv e^{i\sigma_a \pi^a(x)/v}, \qquad U(x) \to L U(x) R^\dagger \,, \tag{2}$$

being v the EW vacuum expectation value (vev).

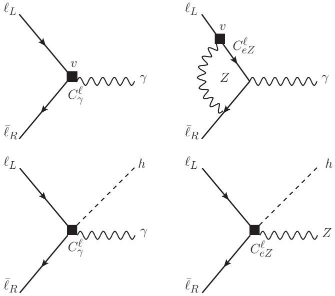
- The dependence on the h field is customarily encoded in generic functions $\mathcal{F}(h)$, that are used as building blocks for the construction of the effective operators

$$\mathcal{F}_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \ldots \tag{3}$$

- The dependence on the structure $(h+v)$, that characterizes the SMEFT Lagrangian is lost in the HEFT and substituted by a generic h/v expansion.

Motivation

- Heavy NP contributions in lepton dipole moments and high-energy cross-sections of lepton pairs into Higgs bosons and γ/Z are connected, both in HEFT and SMEFT.



- A multi-TeV muon collider would enable us to directly probe NP contributions to the muon g-2, not hampered by the hadronic uncertainties that affect the SM prediction.

HEFT Lagrangian

Processes of interest:

$$\mu^+\mu^- \to h + \gamma/Z$$

HEFT Lagrangian for this work [3]

$$\mathcal{L} = C_2^\ell \mathcal{N}_2^\ell + C_4^\ell \mathcal{N}_4^\ell + C_9^\ell \mathcal{N}_9^\ell + C_Z^\ell \mathcal{N}_Z^\ell + C_\gamma^\ell \mathcal{N}_\gamma^\ell, \tag{4}$$

with

$$\begin{aligned}
\mathcal{N}_2^\ell(h) &\equiv -g_z \bar{L}_R \gamma^\mu Z_\mu L_R \mathcal{F}_2 \,, \\
\mathcal{N}_4^\ell(h) &\equiv i g_z \bar{L}_L Z_\mu L_R \partial^\mu \mathcal{F}_4 \,, \\
\mathcal{N}_9^\ell(h) &\equiv i g_z \bar{L}_L \sigma^{\mu\nu} Z_\mu L_R \partial_\nu \mathcal{F}_9 \,, \\
\mathcal{N}_Z^\ell(h) &\equiv \bar{L}_L \sigma^{\mu\nu} L_R Z_{\mu\nu} \mathcal{F}_Z \,, \\
\mathcal{N}_\gamma^\ell(h) &\equiv \bar{L}_L \sigma^{\mu\nu} L_R F_{\mu\nu} \mathcal{F}_\gamma \,.
\end{aligned} \tag{5}$$

where L_L is the SM lepton doublet and a right-handed neutrino does not appear in L_R.

[3] Brivio et al. The complete HEFT Lagrangian after the LHC Run I. *Eur.Phys.J.C 76 (2016) 7, 416.*

Δa_μ

As mentioned before, $\mathcal{N}_Z^\ell$ and $\mathcal{N}_\gamma^\ell$ operators are analogous to the ones also appearing in the SMEFT dimension-six Lagrangian.

Computing the Feynman diagrams that contribute to the g-2, one obtains

$$\Delta a_\ell \simeq \frac{4 m_\ell v}{\sqrt{2} e \Lambda^2} \left(C_{e\gamma}^\ell - \frac{3\alpha}{2\pi} \frac{\cos^2\theta_W - \sin^2\theta_W}{\sin\theta_W \cos\theta_W} C_{eZ}^\ell \log\frac{\Lambda}{m_Z} \right), \quad (6)$$

where θ_W is the weak mixing angle.

HEFT $\mu^+\mu^- \to h\gamma$ cross section

The total cross section for the $\mu^+\mu^- \to h\gamma$ process, assuming that $\sqrt{s} \gg m_h$, where $\sqrt{s}$ is the collider center-of-mass energy, are given by

$$\sigma_{h\gamma}^{\text{HEFT}} = \frac{8\pi a_\gamma^2 |C_\gamma^\mu|^2 s}{3v^2\Lambda^2}, \tag{7}$$

where one recovers the SMEFT expression by taking $a_\gamma = 1$ and rescaling the HEFT Wilson coefficient:

$$C_\gamma^\mu = \frac{v\, C_{e\gamma}^\mu}{8\pi\sqrt{2}\,\Lambda}, \tag{8}$$

with $C_{e\gamma}^\mu$ the coefficient in the SMEFT Lagrangian [4].

[4] Dario Buttazzo and Paride Paradisi. Probing the muon g—2 anomaly with the Higgs boson at a muon collider. *Phys. Rev. D, 104(7):075021, 2021.*

Method (following Buttazzo and Paradisi [5])

- Cut-and-count experiment in the $b\bar{b}$ final state ($h \to b\bar{b}$).
- Significance of the signal defined as

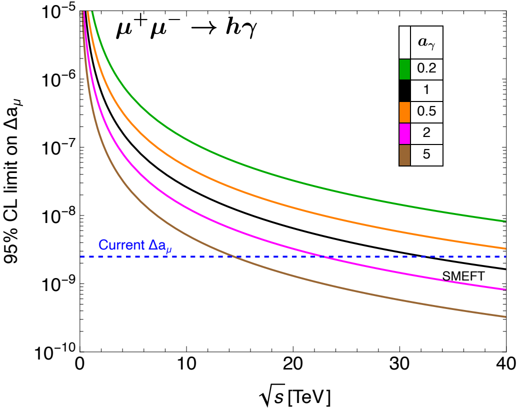
$$N_S/\sqrt{N_S + N_B}. \tag{9}$$

- Assuming a plausible b-tagging efficiency, $\epsilon_b = 80\%$, one gets the 95% C.L. reach (significance of 2σ) on the muon anomalous magnetic moment Δa_μ, as a function of the collider center-of-mass energy, $\sqrt{s}$. $\Delta a_\mu = \Delta a_\mu(\sqrt{s})$.
- $N_S = L \times \sigma_{h\gamma}^{\text{HEFT}} \times \mathrm{BR}(h \to b\bar{b}) \times \epsilon_b$.
- $N_B = L \times \sigma_{Z\gamma}^{\text{SM}} \times \mathrm{BR}(Z \to b\bar{b}) \times \epsilon_b \times P_{Z/h}$.

[5] Dario Buttazzo and Paride Paradisi. Probing the muon g−2 anomaly with the Higgs boson at a muon collider. *Phys. Rev. D, 104(7):075021, 2021.*

95% C.L. reach from $\mu^+\mu^- \to h\gamma$ on Δa_μ

After the Wilson coefficient rescaling, the only difference between SMEFT and HEFT approaches is due to the "a_γ" parameter that appears in the HEFT $\mathcal{F}$-function expansion. We analyze cases where $\frac{1}{5} < a_i \leq 5$ [6], as a first reasonable approach



[6] *Phys. Rev. D, 106(5):053004, 2022.*

HEFT $\mu^+\mu^- \to hZ$ cross section

Using the HEFT Lagrangian, the cross sections for the process $\mu^+\mu^- \to hZ$ at $\sqrt{s} \gg m_h$ are

$$\sigma_{\text{HEFT}} = \frac{C_2^2 s}{384\pi m_Z^2} + \frac{s}{24\pi\Lambda^2}\left[|C_Z|^2 + \frac{3|C_4|^2 s}{16 m_Z^2} + \frac{|C_9|^2 s}{16 m_Z^2} - \frac{\text{Re}\left(C_9^* C_Z\right)}{2}\right], \quad (10)$$

where, for simplicity, we have redefined the coefficients as follows

$$C_Z \to \frac{2(4\pi)a_Z}{v} C_Z^\mu, \;\; C_9 \to \frac{2ia_9}{v} C_9^\mu g_z,$$
$$C_2 \to \frac{-2a_2}{v} C_2^\mu g_z, \;\; C_4 \to \frac{2ia_4}{v} C_4^\mu g_z. \quad (11)$$

Method

- Cut-and-count experiment in the $b\bar{b}$ final state ($h \to b\bar{b}$).
- Significance of the signal defined as

$$N_S/\sqrt{N_S + N_B}. \tag{12}$$

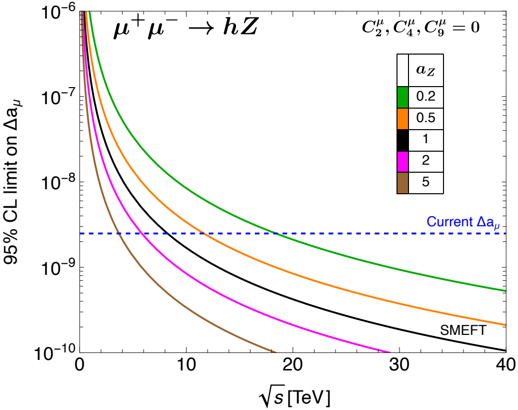
- Assuming a plausible b-tagging efficiency, $\epsilon_b = 80\%$, one gets the 95% C.L. reach (significance of 2σ) on the muon anomalous magnetic moment Δa_μ, as a function of the collider center-of-mass energy, $\sqrt{s}$. $\Delta a_\mu = \Delta a_\mu(\sqrt{s})$
- $N_S = L \times \sigma_{hZ}^{\text{HEFT}}(\Delta a_\mu) \times \mathrm{BR}(h \to b\bar{b}) \times \mathrm{BR}(Z \to \mathrm{had}) \times \epsilon_b$.
- $N_B = L \times \sigma_{hZ}^{\text{SM+HEFT}} \times \mathrm{BR}(h \to b\bar{b}) \times \mathrm{BR}(Z \to \mathrm{had}) \times \epsilon_b$.

Explicit dependence of Δa_μ on all the HEFT Wilson coefficients

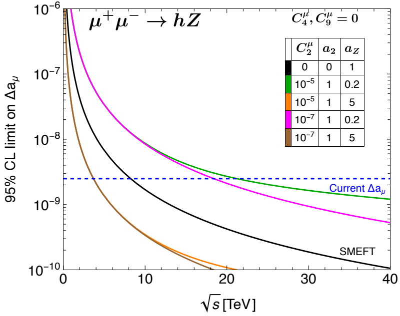
$$\Delta a_\mu \approx \frac{10^{-8}}{a_Z}\Bigg\{16 a_9 \mathrm{Im}(C_9^\mu) + 3.4\Bigg[\frac{1.1}{s^2} + 21 a_9^2 (\mathrm{Im}(C_9^\mu))^2 + \frac{12}{s}\Bigg(\frac{3.4}{s^2} + 3.7\times 10^5 a_2^2 |C_2^\mu|^2 + s\big\{1.1\times 10^2 a_4^2 |C_4^\mu|^2 + 37 a_9^2 |C_9^\mu|^2\big\}\Bigg)^{1/2}\Bigg]^{1/2}\Bigg\} \tag{13}$$

First, taking the $\mathcal{N}_Z^\ell$ operator only

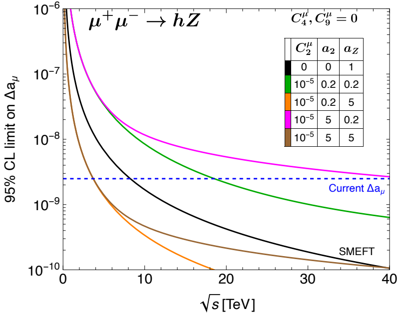
After the Wilson coefficient rescaling ($C_Z = \frac{C^\mu_{\text{eZ}}}{\sqrt{2}\Lambda}$), the only difference between SMEFT and HEFT is now due to the "a_Z" parameter that appears in the HEFT $\mathcal{F}$-function expansion.



Effects of the new $\mathcal{N}_2^\mu$ together with $\mathcal{N}_Z^\mu$



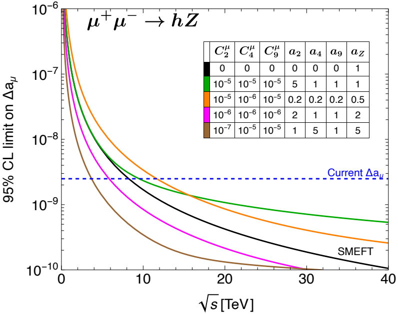
(a) C_2^μ WC effect for a fixed a_2 value



(b) a_2 effect for a fixed C_2^μ WC

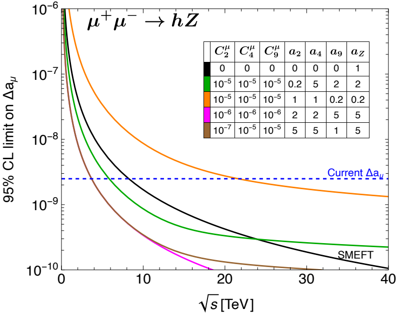
Effects of $\mathcal{N}_2^\mu, \mathcal{N}_4^\mu$ and $\mathcal{N}_9^\mu$ together with $\mathcal{N}_Z^\mu$

Using reasonable values for the C_i^μ Wilson coefficient and a_i parameters.



C_2^μ	C_4^μ	C_9^μ	a_2	a_4	a_9	a_Z
0	0	0	0	0	0	1
10^{-5}	10^{-5}	10^{-5}	5	1	1	1
10^{-5}	10^{-6}	10^{-5}	0.2	0.2	0.2	0.5
10^{-6}	10^{-6}	10^{-6}	2	1	1	2
10^{-7}	10^{-5}	10^{-5}	1	5	1	5

(a)



C_2^μ	C_4^μ	C_9^μ	a_2	a_4	a_9	a_Z
0	0	0	0	0	0	1
10^{-5}	10^{-5}	10^{-5}	0.2	5	2	2
10^{-5}	10^{-5}	10^{-5}	1	1	0.2	0.2
10^{-6}	10^{-6}	10^{-6}	2	2	5	5
10^{-7}	10^{-5}	10^{-5}	5	5	1	5

(b)

Conclusions

- The HEFT approach provides a more general framework than SMEFT to search for NP in the Higgs sector, and could lead to different phenomenological scenarios.
- We explore, within the HEFT formalism, the possibility to test the discrepancy between the theoretical and experimental values of the muon g-2, by measuring the $\mu^+\mu^- \to h + \gamma/Z$ cross sections in a muon collider.
- We could test, in a model-independent way, a precise low-energy prediction of the SM (the muon g-2) using the tools of the high-energy physics frontier (muon collider).
- We find that, in some reasonable cases, the HEFT approach could lead to a higher sensitivity to test the NP contributions in the muon g-2, requiring thus a less energetic muon collider for such a purpose.

Thank you!
Questions are welcome.