The muon g-2 at a high-energy Muon Collider: simplified models analysis

Paride Paradisi [a,b], Olcyr Sumensari [c], **Alessandro Valenti** [b,a]

[a] Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy

[b] Dipartamento di Fisica e Astronomia "G. Galilei", Università di Padova, Italy

[c] IJCLab, Pôle Théorie (Bât. 210), CNRS/IN2P3 et Université Paris-Saclay, 91405 Orsay, France

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Anomalous magnetic moment of the muon: $a_\mu = (g_\mu - 2)/2$.

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59)\times 10^{-11}.$$

The 4.2σ deviation from the SM reference value may be a hint of new physics.
For heavy new physics $M \gg m_h$, the effect may be enclosed in the SMEFT operator $O_{e\gamma}$:

$$\mathcal{L}_{\rm SMEFT} \supset \frac{\bar{C}_{e\gamma}}{M^2}\bar{\ell}\sigma^{\mu\nu} e H F_{\mu\nu} \longrightarrow \Delta a_\mu = \frac{4 m_\mu v_{\rm EW}}{e M^2}\bar{C}_{e\gamma}.$$

The same operator also induces the process $\mu^+\mu^- \to h\gamma$ with a 1-to-1 correlation [4],

$$\sigma_{\mu^+\mu^-\to h\gamma} \approx 0.7\,{\rm ab}\left(\frac{\sqrt{s}}{30\,{\rm TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2.$$

Therefore, a **Muon Collider** is the perfect machine to test new physics behind Δa_μ.
For weakly coupled new physics, $\bar{C}_{e\gamma} \sim e\, g_*^3/16\pi^2$ with $g_* \sim 1$ (chiral enhancement: $g_* \gg y_\mu$).
This forces $M \lesssim 10\,$TeV: *new physics directly accessible at a high-energy Muon Collider!*

EFT breakdown: to extract correct predictions from on-shell new physics, renormalizable **simplified models** are required.

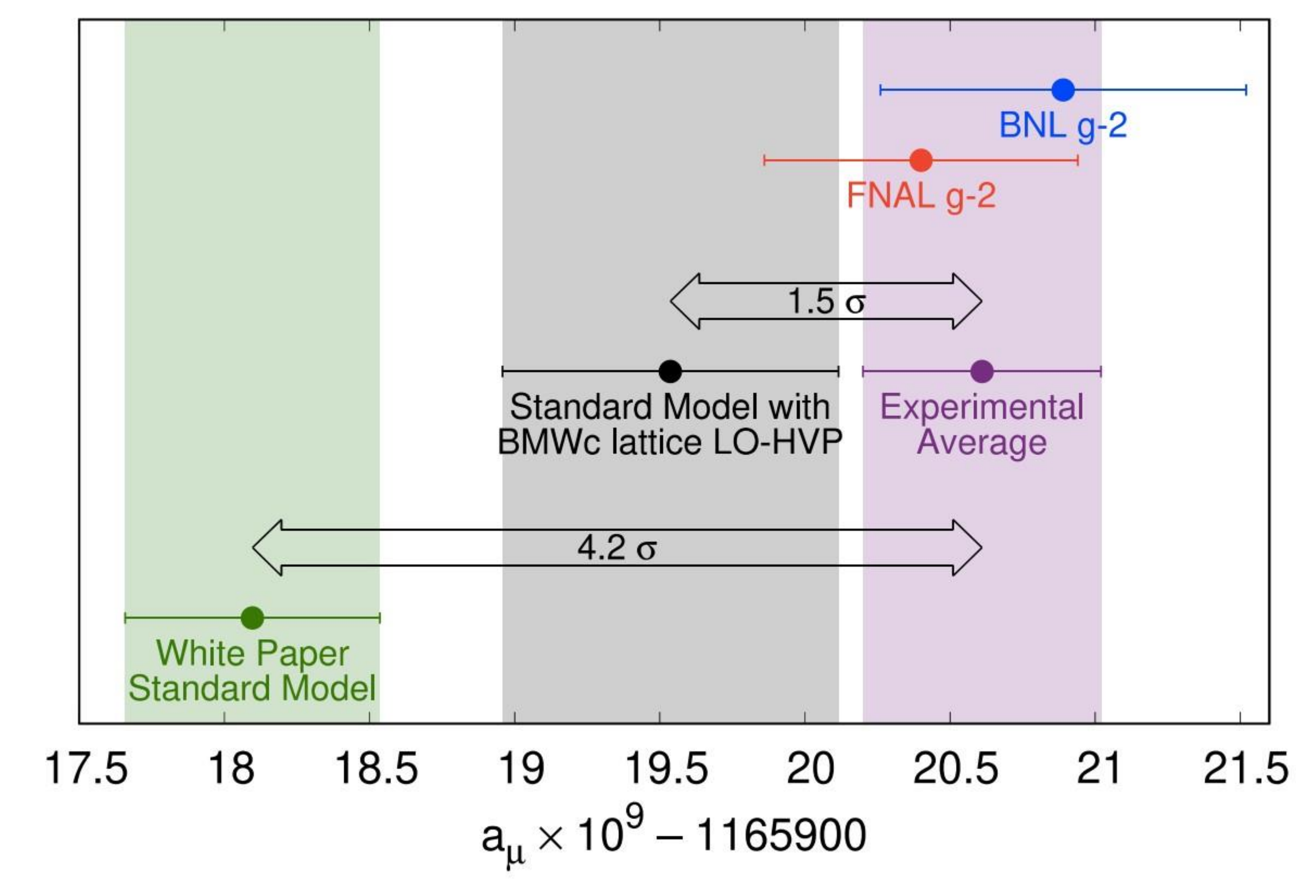


Figure 1: the muon anomalous magnetic moment as measured from the BNL and FNAL collaborations [1] compared to the SM g-2 theory initiative (white paper) [2] and BMWc predictions [3]. Interestingly, the lattice result is at tension with the white paper prediction but not with the experimental data.

To comply with $h\to\mu^+\mu^-, Z\to\mu^+\mu^-$ bounds and provide a Dark Matter candidate, we consider Z_2 models [5]. Two ways to obtain chiral enhancement: models **I** (two scalars $\Phi_{E,L}$ and one VL fermion Ψ) and **II** (two VL fermions $\Psi_{E,L}$ and one scalar Φ), with many possibile $SU(2)_{\rm L}\times U(1)_{\rm Y}$ representations. New Yukawa interactions:

$$\text{I:}\quad \mathcal{L}_{\rm I} = \lambda_L^{\rm I}\,\bar{\ell}\Psi\Phi_L + \lambda_E^{\rm I}\,\bar{e}\Psi\Phi_E + A\,\Phi_L^\dagger\Phi_E\, H + {\rm h.c.}\,,$$

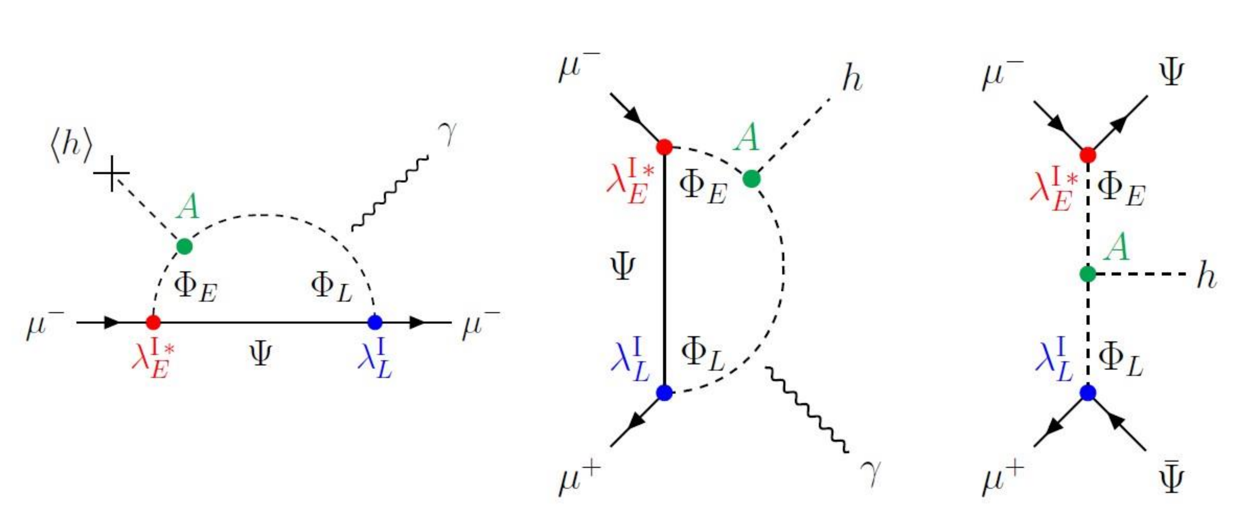
$$\Delta a_\mu^{\rm I} \simeq \frac{m_\mu v_{\rm EW}\,{\rm Re}\left[\lambda_L^{\rm I}\lambda_E^{{\rm I}*}A\right]}{96\pi^2\sqrt{2}M^3}.$$

$$\text{II:}\quad \mathcal{L}_{\rm II} = \lambda_L^{\rm II}\,\bar{\ell}\Psi_L\Phi + \lambda_E^{\rm II}\,\bar{e}\Psi_E\Phi + \kappa\,\bar{\Psi}_L\Psi_E\, H + {\rm h.c.}\,,$$

$$\Delta a_\mu^{\rm II} \simeq \frac{m_\mu v_{\rm EW}\,{\rm Re}\left[\lambda_L^{\rm II}\lambda_E^{{\rm II}*}\kappa\right]}{96\pi^2\sqrt{2}M^2}.$$

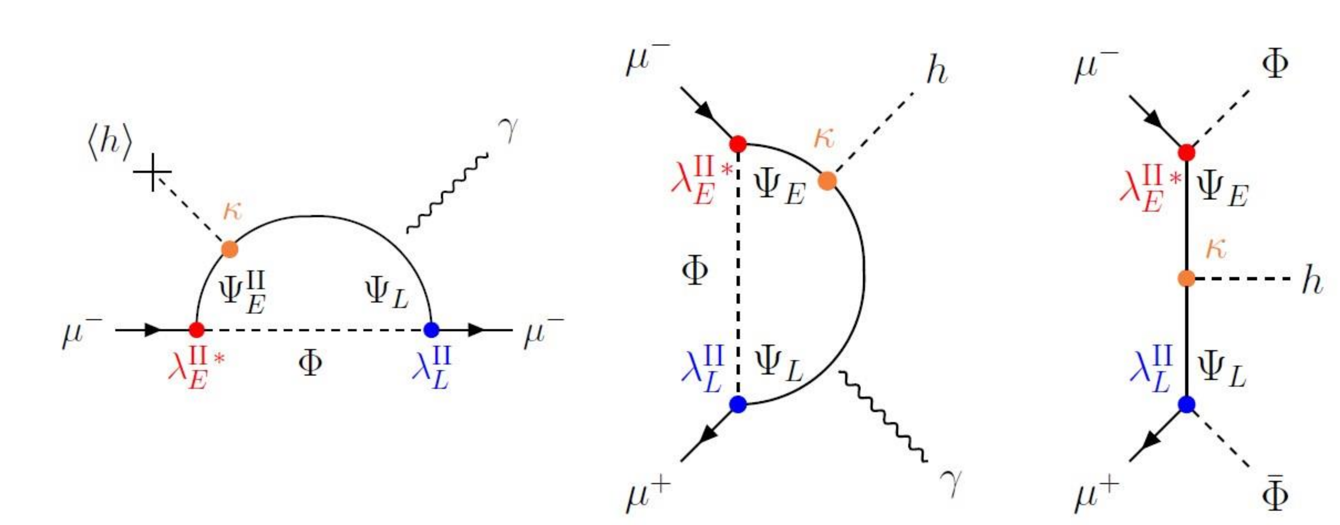
These interactions provide a **striking signature**: three *1-to-1 correlated* observables, with the same parametric dependence on the new couplings entirely fixed by the muon g-2 anomaly:

a) *low-energy indirect:* Δa_μ, **b)** *high-energy indirect*: $\mu^+\mu^-\to h\gamma$, **c)** *high-energy direct:* $\mu^+\mu^-\to\bar{\Psi}\Psi h$ (I) or $\mu^+\mu^-\to\bar{\Phi}\Phi h$ (II).



(a) Indirect low-energy probe. (b) Indirect high-energy probe. (c) Direct high-energy probe.

Figure 2: Feynman diagrams for the three 1-to-1 correlated observables in Models I.



(a) Indirect low-energy probe. (b) Indirect high-energy probe. (c) Direct high-energy probe.

Figure 3: Feynman diagrams for the three 1-to-1 correlated observables in Models II.

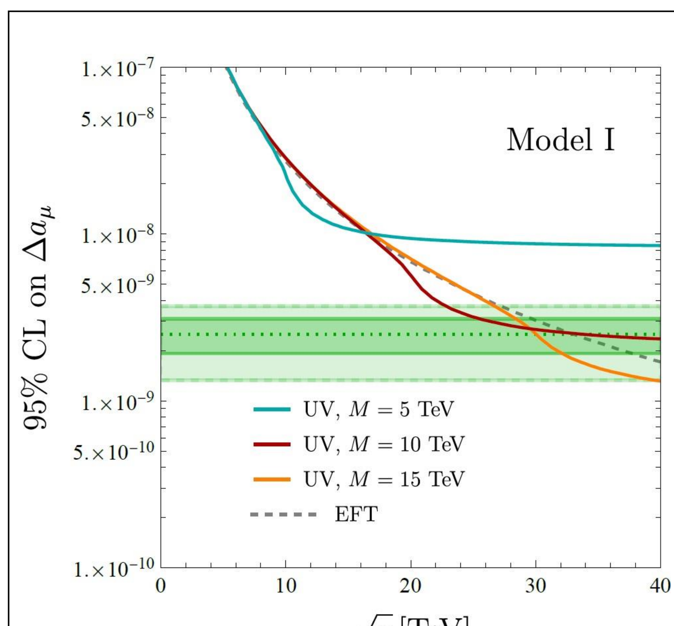


Figure 4

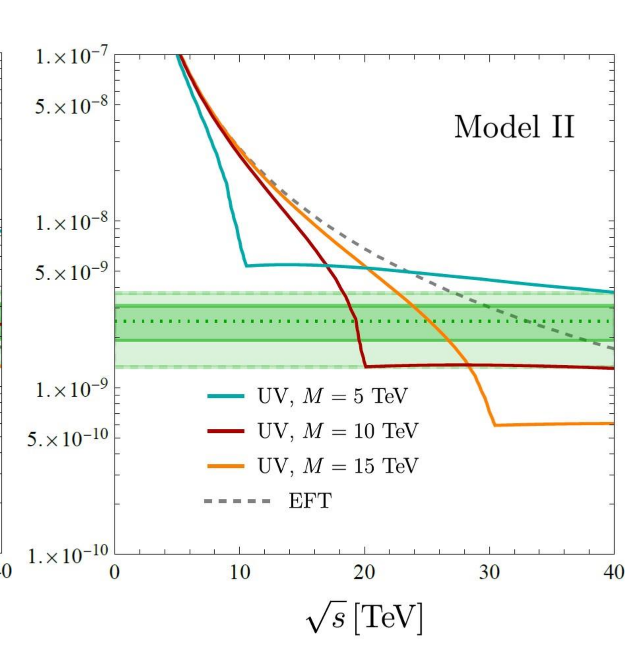


Figure 5

Reach of the process $\mu^+\mu^-\to h\gamma$ on Δa_μ at 95% confidence level in the EFT and in the simplified models I and II with degenerate BSM fields masses. The main source of background is the SM process $\mu^+\mu^-\to hZ$, where the Z boson is misrinstructed as an Higgs, while the SM irreducible $\mu^+\mu^-\to h\gamma$ is proportional to y_μ and thus negligible.
The EFT works remarkably well up to $\sqrt{s}\simeq M$, while for energies close to the resonant-production threshold $\sqrt{s}\simeq 2M$ the simplified models provide the correct estimate, with an even higher sensitivity to Δa_μ. As $\sqrt{s}\gg 2M$ the reach becomes constant in the simplified models, as a biproduct of the $1/s$ scaling of the cross-section at high-energies with the scaling of the expected luminosity of a Muon Collider $\mathcal{L}\propto s$. This feature cannot be captured by the EFT, whose cross section keeps increasing till breaking of unitarity.

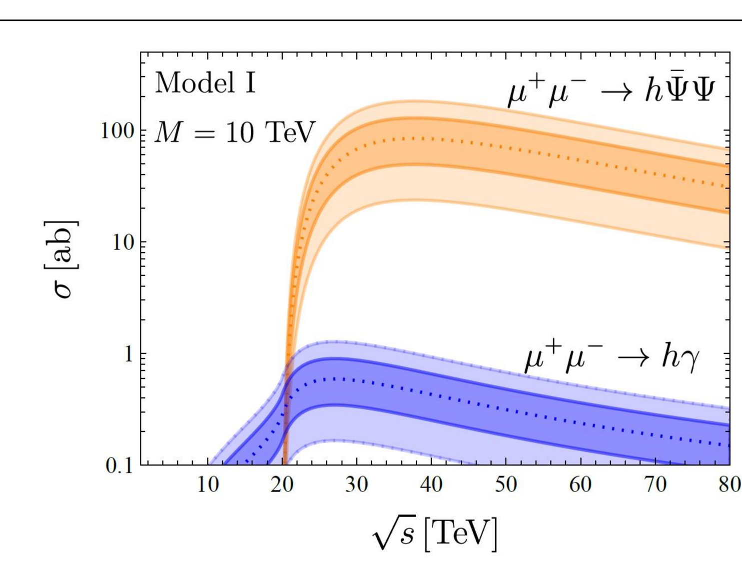


Figure 6

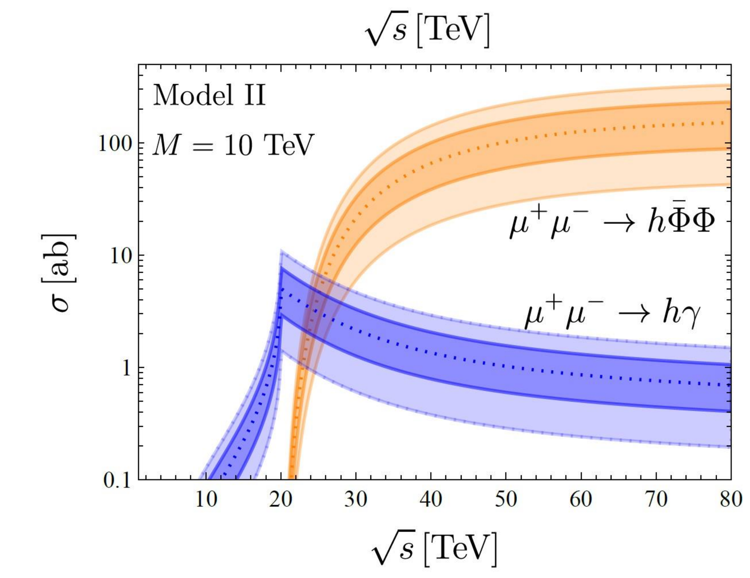


Figure 7

Relative cross-sections of the indirect (**b**) and direct (**c**) high-energy probes in models I (fig. 6) and II (fig. 7). The band is obtained varying Δa_μ in the 1σ and 2σ range. For a Muon Collider running at center-of-mass energies $\sqrt{s}\gtrsim 30\,$TeV we expect hundreds of events for the $2\to 3$ direct process, easily discriminable from the $2\to 2$ background due to the coincidence of a Higgs boson with two BSM particles.

In conclusion,
the muon g-2 anomaly is one of the most promising hint for new physics. This anomaly can be accomodated by weakly coupled new particles in the TeV range, which can be directly accessed at a high-energy Muon Collider. While the EFT approach cannot account for on-shell new physics, renormalizable simplified models provide a concrete way to determine the physical observables. Within this context we have identified three 1-to-1 correlated probes, both direct and indirect, whose parametric dependence is entirely fixed by the muon g-2 anomaly. The correlated study of these direct and indirect new physics signals at a high-energy Muon Collider would be a powerful handle to disentangle among the underlying model accommodating the Δa_μ anomaly.

References:

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