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The muon (g-2) Standard-Model prediction and GeV-scale new physics

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The discrepancy between the standard model (SM) prediction for the muon anomalous magnetic moment and the experimental result is accompanied by other anomalies. A crucial input for the prediction is the hadronic vacuum polarization inferred from hadronic data. However, the two most accurate determinations from KLOE and BaBar disagree by almost 3σ. Additionally, the combined data-driven result also disagrees with the most precise lattice determinations in the intermediate energy window at the level of $\sim 4.2\sigma$. We show with a simple model that all these discrepancies could be accounted for by a new boson produced resonantly around the KLOE centre-of-mass energy and decaying promptly yielding lepton pairs and missing energy in the final states, while complying with all phenomenological constraints.

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1. Introduction

The recent measurement by FNAL for the anomalous magnetic moment of the muon has brought the confirmation of a strong 4.2σ tension between the so-called data-driven Standard Model (SM) prediction [1]

$$a_\mu^{\rm SM} = 11659181.0(4.3)\cdot 10^{-10}\,, \tag{1}$$

and the current experimental average [2]

$$a_\mu^{\rm exp} = 11659206.1(4.1)\cdot 10^{-10}\,. \tag{2}$$

Among the various contributions to this observable in the SM, the so-called hadronic vacuum polarization (HVP) term, corresponding to the contribution of off-shell hadronic states, stands out by its value $a_\mu^{\rm LO,HVP}|_{\rm data-driven} = 693.1(4.0)\cdot 10^{-10}$, around thirty times larger than the discrepancy. This result arises by the careful study and combination of a host of measurements of the cross-section: $e^+e^- \to \gamma^* \to$ hadrons by several experimental collaborations [3–7], although with an almost $3\,\sigma$ discrepancy between the two most precise estimates from KLOE [5] and BaBar [6]. By contrast, another estimate of $a_\mu^{\rm LO,HVP}$ relies on ab-initio lattice-QCD simulations. The most precise result is currently given by BMW collaboration [8], $a_\mu^{\rm LO,HVP}|_{\rm BMW} = 707.5(5.5)\cdot 10^{-10}$ which leads to a reduction of the difference with the experimental value and is in tension at around 2σ with the data-driven estimate. Remarkably, this later discrepancy was recently significantly increased by lattice estimates focusing on the so-called "intermediary window" range [9] corresponding to scales around the GeV. The lattice average in this window, $a_\mu^{\rm W}$ [8, 10, 11] differs from the data-driven estimate [12] by $4.2\,\sigma$. We will show in these proceedings that new physics at the GeV-scale introduced in order to modify the muon a_μ also affects the HVP data-driven estimate by adding new physics (NP) in the experimental datasets $e^+e^- \to \gamma^* \to$ hadrons, thus solving both 4σ anomalies at once.

2. Indirect new physics effect in the data-driven approach

At leading order the data-driven method relies on the optical theorem to get the hadronic loop contribution to $a_\mu^{\rm SM}$:

$$a_\mu^{\rm LO,HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\sigma_{\rm had}(s)\,, \tag{3}$$

where, $\sigma_{\rm had}$ is the bare $e^+e^- \to \gamma^* \to$ hadrons (γ) cross-section, in which an infinite string of hadronic vacuum polarisation insertions in the photon propagator has been removed and $K(s)$ is the kernel function (see, e.g. [1, 13]). At the foundation of the data-driven approach lies the assumption that all of the collected data arise from SM processes only. As we will see, the presence of GeV-scale new physics with couplings large enough to affect the muon $(g-2)_\mu$ implies that this hypothesis fails.

We will focus in the following on the dominant $\pi^+\pi^-$ contribution. Experimentally, the bare $\pi^+\pi^-$ cross-section is obtain schematically from

$$\frac{d\sigma_{\rm had}}{ds'} \propto \frac{N_{\pi^+\pi^-} - N_{\rm bkd}}{\epsilon(s')\mathcal{L}(s')}\,\sigma^0_{\mu^+\mu^-}\,, \tag{4}$$

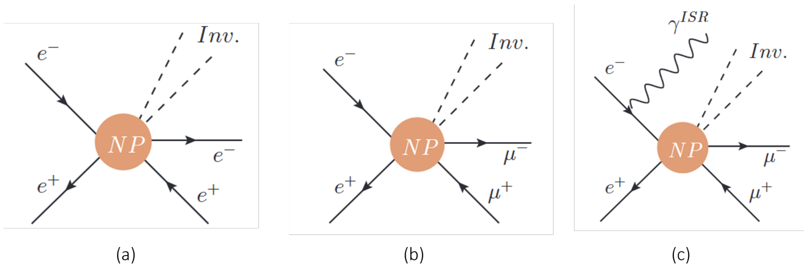

Figure 1: Summary of the three main NP contributions affecting the experimental luminosity estimate via (a) Bhabha scattering, (b) di-muon final states with lost ISR photon, (c) di-muon final state with visible ISR photon.

where $N_{\pi^+\pi^-}$ is the number of di-pion final states events (potentially in association with an Initial State Radiation – ISR – photon), $N_{\rm bkd}$ is the estimated number of background events, $\epsilon(s')$ is the experimental efficiency and $\mathcal{L}(s')$ is the luminosity at Centre-of-Mass (CoM) energy $\sqrt{s'}$. In practice each of these quantities will be affected by the presence of GeV-scale NP. Following [13], we will focus now on the luminosity $\mathcal{L}(s')$, which can be impacted by NP via two main mechanisms whose corresponding diagrams are summarised in Fig. 1.

Luminosity shift from Bhabha scattering. In this approach, relevant for the two first analysis from the KLOE collaboration [5] the total experimental luminosity is studied by measuring Bhabha scattering $e^+e^- \to e^+e^-$ at large angles. The differential luminosity relevant for the ISR events considered by the collaboration is then obtained by comparing the result with Monte-Carlo generators and unfolding the result with a theoretical radiator function. In order to have a significant impact, the NP contribution must be at the nb level [13], which typically requires a resonant enhancement around the ϕ-meson peak (corresponding to the KLOE CoM energy).

Luminosity shift from $\mu\mu\gamma$ events. Most of the recent experimental results [5–7] rely instead on a direct differential measurement of the luminosity from $\mu\mu\gamma$ final states. As the photon from the final state is not always reconstructed and since the cross-section for this final states is much lower than the Bhabha scattering one, this method is much more vulnerable to NP effects, even without relying on resonant production.

As shown in [13], NP final states mimicking the SM processes must be subtracted from the final dataset in order to obtain a proper estimate of the luminosity. The net effect is therefore to increase $\sigma_{\rm had}$ and eventually the data-driven estimate of $a_\mu^{\rm SM}$. Finally, we note that NP may also contribute directly to the prediction of a_μ, as it is the case in the explicit example we will present in the next section.

3. Proof-of-concept model and results

Most GeV-scale models which give a significant loop-induced contribution to a_μ are excluded by various experimental constraints (including in particular resonant and mono-photon searches). However, both these constraints and the measurements used in data-driven approaches typically do not discriminate efficiently between SM events with ISR and NP events with semi-visible final states. We consider now an inelastic dark matter model which leads to such “semi-visible” final

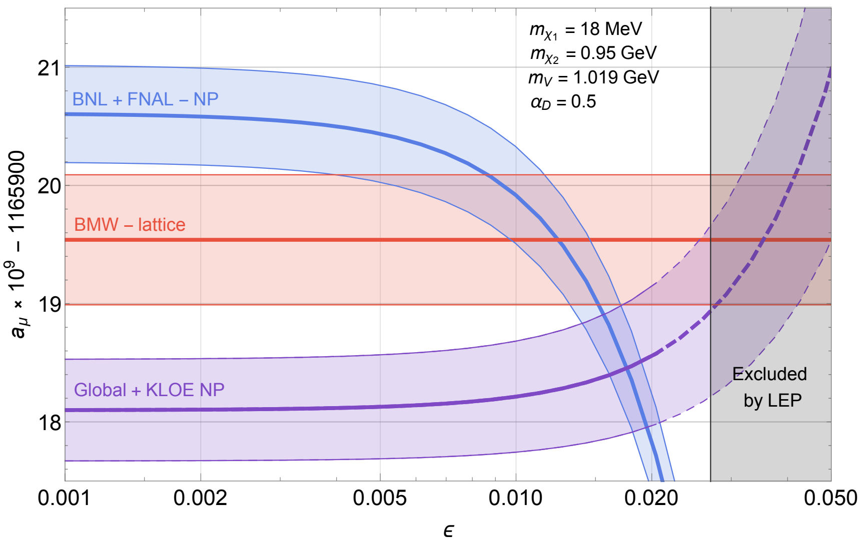

Figure 2: Theoretical prediction (purple) for a_μ as a function of ε for our model (see main text). The dashed purple curve denotes the region where the KLOE08 and KLOE10 results are more than 3σ away. The blue band corresponds to the experimental result after subtracting the direct NP contribution from the dark photon. The red band shows the BMW lattice estimate of $a_\mu^{\text{LO,HVP}}$. The width of the bands represents $1\,\sigma$ uncertainties. The grey region is excluded by LEP.

states. In more details we introduce: a dark Abelian gauge group $U(1)_D$, a dark Higgs S, and two Weyl spinors η, ξ, which can be combined in a singlet Dirac fermion χ:

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{g'\varepsilon}{\cos\theta_w}V_\mu \mathcal{J}^\mu_Y + (D^\mu S)^\dagger(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4 - \frac{\lambda_{SH}}{2}|S|^2|H|^2$$
$$+ \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{2}y_S S(\eta^2 + \xi^{\dagger 2}) + \text{h.c.}\,, \tag{5}$$

Assuming that the dark Higgs mass is large enough that it does not have any direct impact on the phenomenology at the GeV scale, the final relevant spectrum contains the dark photon and two fermions χ_1 and χ_2 with a mass splitting proportional to dark Higgs Yukawa coupling. In particular, the dark photon main decay channel is a multibody final states $V \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-(\mu^+\mu^-)$, where $\text{BR}(V \to \chi_1\chi_2) \sim 100\%$ and $\text{BR}(V \to \ell^+\ell^-) \propto \epsilon^2$. Further details on this model are given in [13–16]. Critically, the dark photon can be produced on-shell (and possibly in a resonant process in KLOE) while producing both e^+e^- and $\mu^+\mu^-$ pairs in the final state.

We have implemented the model in FeynRules [17] files, and used the MadGraph5_aMC@NLO platform [18] in order to generate events with $e^+e^-\chi_1\chi_1$ and $\mu^+\mu^-\chi_1\chi_1$ final states, then used these event datasets to find the experimental sensitivities to these topologies. The resulting shifts in the determination of a_μ as function of the kinetic mixing ε are shown in Fig. 2, where we include the correction to a_μ^{HVP} in the $\sqrt{s} \in [0.6, 0.9]$ GeV range and used a theoretical uncertainty on our result of 35% to account for the missing contributions. The dashed curve denotes the values of ε for which the KLOE08 result is more than 3σ away from the KLOE10 measurement (as our procedure does not affect significantly the later since it has been made at a different CoM energy). The red region shows the $\pm1\sigma$ BMW-lattice computation and the blue region shows the $\pm1\sigma$ band for the

BNL and FNAL experimental results after subtracting the direct contribution to a_μ. Finally, the grey area is excluded by a fit to the electroweak SM couplings.

Note that in the parameter space where the tensions between the theoretical data-driven estimation, the lattice calculations, and the experimental value for a_μ are relaxed, the BaBar/KLOE discrepancy is also reduced below the 2σ-level. Additionally, since the indirect effect arises around the GeV-scale, they naturally affect more the intermediary window part of $a_\mu^{\rm HVP}$ than the short distance contributions and therefore constitutes also a solution to the 4σ tension between lattice and data-driven estimates (see [19]).

4. Conclusions

In this work, we have explored the intriguing possibility that GeV-scale new particles with mass around the ϕ resonance could be produced in e^+e^- collisions then decay into $e^+e^-, \mu^+\mu^-$ with a significant amount of missing energy due to light dark-matter particles being produced in the decay chain. This can affect significantly the estimated experimental luminosity, thus affecting the determination of $\sigma_{\rm had}$ as an indirect effect and resulting in an increase of the data-driven estimate of $a_\mu^{\rm HVP}$ by a few percents. This can solve the tension between the KLOE and BaBar determinations of $\sigma_{\rm had}$ and reconcile the estimate of $a_\mu^{\rm HVP}$ from the data-driven dispersive method with the lattice calculations. When direct and indirect effects are considered together the a_μ discrepancy is solved (with about $1/4$ of the discrepancy accounted by indirect effects, and $3/4$ by direct loop effects). The simple model that we have put forth also provides an adequate light dark-matter candidate with a rich phenomenology which might be worthwhile exploring further.

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