Snowmass2021 - Letter of Interest

Opportunities and New Physics Implications for $(g-2)_{e,\mu}$

Thematic Areas:

■ (RF3) Fundamental Physics in Small Experiments
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (EF08) BSM: Model specific explorations
■ (TF8) BSM model building

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Abstract: The anomalous magnetic moments (AMMs) of the electron and the muon are the most precisely measured quantities in elementary particle physics, and they are providing important tests of the Standard Model. The current discrepancies between experimental measured values and theory predictions are in between two and half to four standard deviations, which strongly point towards physics beyond the Standard Model. In this proposal, we demonstrate how a light neutral scalar originating from a second Higgs doublet and residing in the $\mathcal{O}(10)$-MeV to $\mathcal{O}(1)$-GeV mass range can address both these anomalies. This theory has the great potential to be discovered by the improved measurements of the current low energy experiments as well as can be tested at the LHC by looking at the novel process $pp \to H^\pm H^\pm jj \to l^\pm l^\pm jj + \not{E}_T$ via same-sign pair production of charged Higgs bosons. Furthermore, we briefly point out several other mechanisms that can simultaneously explain these aforementioned discrepancies.

For a charged elementary particle with half-integer intrinsic spin, the Landé g-factor at the tree-level has the value $g = 2$. Any departure from this is called the anomalous magnetic moment (AMM) defined by $a = (g-2)/2$. Our current best understanding of physics at the fundamental scale is precisely described by the Standard Model (SM) and, within this theory, contribution to a_{SM} arises from loops containing Quantum Electrodynamics (QED) corrections, hadronic (QCD) processes, and electro-weak (EW) pieces. For the electron and the muon, the QED contributions to the AMMs, which are the most dominant corrections, have been computed up to 5-loop order. Since the electron and the muon AMMs $a_{e,\mu}$ can be measured with great precision in the experiments, and simultaneously can be computed with outstanding accuracy within the SM, these two quantities are the most crucial observables in particle physics. A slight deviation of these measured quantities from the SM values will be a direct indication of physics beyond the SM (BSM). Hence, any BSM particle that couples to a lepton ($\ell = e$ and/or μ), either directly or indirectly, and contributes to its AMM a_ℓ can be probed in the experiments.

In the muon sector, there has been a longstanding tension between the theoretical prediction[1–4] and the value measured at the Brookhaven National Laboratory[5], corresponding to a deviation:

$$\Delta a_\mu = (2.74 \pm 0.73) \times 10^{-9}. \tag{1}$$

The ongoing experiment at Fermilab[6;7] and one planned at J-PARC[8] are aiming to reduce this uncertainty. On the other hand, just recently an improved measurement[9] of the fine-structure constant α using Caesium atom points toward a deviation in the electron AMM from theoretical prediction[10] as well:

$$\Delta a_e = -(8.7 \pm 3.6) \times 10^{-13}. \tag{2}$$

Eq. (2) corresponds to a negative $\sim 2.4\sigma$ discrepancy for the electron, whereas Eq. (1) for the muon signifies a positive $\sim 3.7\sigma$ deviation from the SM predictions. These tantalizing disparities could play a significant role in finding clues of new physics BSM. Note however that having opposite signs of these two anomalies, along with the fact that the mass ratio of the muon to the electron is $\sim \mathcal{O}(100)$, makes it more difficult to explain them simultaneously within a common BSM origin.

Here we demonstrate how this can be achieved in an elegant fashion[11] within the framework of the well-motivated two-Higgs-doublet-model (2HDM)[12;13]. We choose to work in the Higgs basis[14] where only one of the Higgs doublets gets a VEV. Furthermore, we work in the aligment limit[13] so that the field that acquires the VEV is identified with the SM Higgs h, and has negligible mixing with the other CP-even state H. Additionally, this theory also has a CP-odd A, and a charged $H^\pm$ scalars. We are interested in a special case of $m_H^2 \ll m_{H^+}^2 = m_A^2$, which can be consistently[11] realized. Whereas LEP provides a lower bound on the mass of the charged scalar $m_{H^\pm} \geq 110$ GeV, its neutral partner $\phi^0 \equiv H$ can remain significant light. Such light states however mediate dangerous flavor violating processes, which we suppress by assuming its negligible Yukawa couplings to quarks, and diagonal couplings to charged leptons: $Y_\ell = diag(y_e, y_\mu, y_\tau)$, where, couplings y_ℓ are uncorrelated to the masses of the leptons and we take them to be real. Then the desired new physics contributions[11] to the lepton AMMs are presented in Fig. 1.

With our choice of $m_{H^+} = m_A \gg m_H$, the only relevant contributions to lepton AMMs are arising from only ϕ^0. Our detailed study shows that both the discrepancies in the muon and the electron AMMs can be successfully addressed[11] if ϕ^0 resides in the $\mathcal{O}(10)$-MeV to $\mathcal{O}(1)$-GeV mass range. Then the correct size and the sign of Δa_μ (Δa_e) of Eq. (1) (Eq. (2)) are provided dominantly by the one-loop (two-loop) diagram shown in Fig. 1. A light scalar of this kind is subject to a large number of experimental constraints: the y_e coupling is independently constrained from electron beam-dump experiments[15–17], the dark-photon searches through $e^+e^- \to \gamma H$ process at KLOE[18], BaBar[19] and LEP[20] experiment; whereas the y_μ coupling is constrained from the $e^+e^- \to \mu^+\mu^- H$ searches at BaBar[21] and LHC[22] experiments. The $e^+e^- \to \mu^+\mu^- H$ searches at BaBar[21] and $e^+e^- \to \mu^+\mu^-$ searches at LEP[20] depend on both the Yukawa couplings y_e and

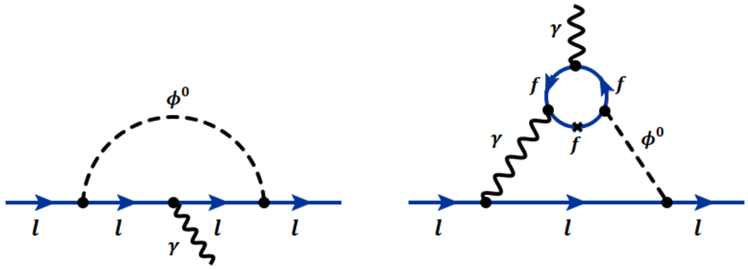

Figure 1: One-loop (left) and two-loop (right) contributions to lepton AMMs arising from beyond-SM neutral scalars.

y_μ. As detailed in our work[11] such a light scalar, even though subject to a number of various experimental constraints, can simultaneously incorporate the deviations observed in the muon and the electron AMMs. Future improvement sensitives of some of these experiments in near future can either rule out this scenario or discover new physics. Furthermore, this scenario can be tested at the LHC by looking at the novel process $pp \to H^\pm H^\pm jj \to l^\pm l^\pm jj + \not{E}_T$ via same-sign pair production of charged Higgs bosons.

The mechanism described above with a single light neutral scalar to address Δa_μ and Δa_e anomalies via one- and two-loop corrections, respectively, is both elegant and minimal in its construction. In the literature, several alternative mechanisms[11;23–50] with extended sectors are proposed to take into account these deviations. Before concluding, here we very briefly outline only a few orthogonal possibilities compared to the scenario described above. Instead of light states, heavy new physics can also simultaneously incorporate Δa_e and Δa_μ anomalies. One such scenario is to have a TeV scalar leptoquark[39;47]; this possibility is particularly exciting since the same leptoquark can be employed to address the recently observed B-meson anomalies*. Heavy vector-like leptons around the TeV scale can also serve the desired purpose[25;49]. Utilizing such vector-like fermions to address electron and muon AMMs can have interesting connections to other observed phenomena beyond the SM, such as dark matter and neutrino mass generation[49].

In short, the improved precision of the current and future experiments in measuring the electron and the muon anomalous magnetic moments are awaiting to discover potential new physics in the near future. For Snowmass 2021, we are interested in extending our study to explore new mechanism for $(g-2)_{e,\mu}$ and confront with other direct measurements.

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*Such a connection is still missing in the literature. However, interlink between flavor anomalies and the muon AMM has been established[51].

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