Light Scalar and Lepton Anomalous Magnetic Moments

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Muon Magnetic Moment

- Magnetic moment of Leptons:
  \[ \vec{\mu}_B = g_\mu \frac{e}{2m_\mu} \vec{S} \]

- Landé’ g- factor:
  \[ g_\mu = 2 \]

- Due to Quantum corrections, \((g - 2)_\mu \neq 0\).

- Anomalous Magnetic Moment:
  \[ a_\mu = \frac{(g - 2)_\mu}{2} \]

\[ a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} \]
Current Status of muon (g-2)

\[ 10^{11} a_\mu = \begin{cases} 
116591810(43) \text{ SM} \\
116592040(54) \text{ Exp} 
\end{cases} \]

\[ \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 251(59) \times 10^{-11} \]

Fermilab Muon g-2 Collaboration, B. Abi et al. (2021)
Possible Explanations in different contexts..
Current Status of electron (g-2)

Recent improved determination of the fine structure constant, leads to a negative discrepancy between the measured AMM of electron and the corresponding SM prediction.

\[ 10^{12} a_e = \begin{cases} 115965218.161(23) & \text{SM} \\ 115965218.073(28) & \text{Exp} \end{cases} \]

\[ \Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -87(36) \times 10^{-14} \]

Challenges

A simultaneous explanation of these two anomalies is challenging

➢ Opposite Sign:

\[
\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9} \\
\Delta a_e = -(8.7 \pm 3.6) \times 10^{-13}
\]
Possible Explanations

- **With Lepto-quarks:**
  - I. Dorsner, S. Fajfer, S. Saad (2020)
  - I. Bigaran, and R. R. Volkas (2020)

- **With additional Fermions and Scalars:**
  - S. Jana, VPK, S. Saad, W. Rodejohann (2020)

- **With light Z’:**
  - A. Bodas, R. Coy, and S. King (2021)
Possible Explanations

- With light $Z'$:
  - A. Bodas, R. Coy, and S. King (2021)

- With additional Fermions and Scalars:
  - S. Jana, VPK, S. Saad, W. Rodejohann (2020)

- With Lepto-quarks:
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Is it possible to resolve these two anomalies in a more minimal setup?

Without any:
- 1. gauge extension
- 2. BSM fermions
- 3. Colored scalars

S. Jana, VPK, S. Saad, W. Rodejohann (2020)
A light neutral scalar that has coupling with the charged leptons can possibly resolve these two anomalies simultaneously.

Muon AMM can be explained via a one-loop contribution, whereas the electron AMM via a two-loop Barr-Zee diagram.

S. Jana, VPK, S. Saad (2020)
However, such a light scalar also leads to a two-loop contribution to muon AMM and a one-loop contribution to electron AMM.
Light Scalar

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Is it possible with singlet scalar extension of SM? No! small Yukawa couplings.
Light Scalar

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What about in Two Higgs Doublet Model?
Light Scalar: 2HDM

Scalar Sector:

\[
\mathcal{V} = M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - [M_{12}^2 H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2} \lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2} \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{1}{2} \lambda_5 (H_1^\dagger H_2)^2 + [\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\}.
\]

\[H_1 = \left( \frac{G^+}{\sqrt{2} v + H_1^0 + A^0} \right), \quad H_2 = \left( \frac{H_2^+}{\sqrt{2} v + H_1^0 + A^0} \right).\]

Alignment Limit: \( \alpha \approx \beta \), SM Higgs decouples from the other CP-even Higgs.

Considering \( m_H^2 \ll m_{H^+}^2 \approx m_A^2 \sim \mathcal{O}(110) \text{ GeV} \).
Yukawa Sector:

\[-\mathcal{L}_Y \supset \left[ Y_{\ell,ij} H^0 + i Y_{\ell,ij} A^0 \right] \bar{\ell}_{Li} \ell_{Rj} + Y_{\ell,ij} \bar{\nu}_{Li} \ell_{Rj} H^+ \sqrt{2} + h.c.,\]

For $Y_\ell$, we assume a diagonal texture $Y_\ell = \text{diag}(y_e, y_\mu, y_\tau)$. 

Light Scalar: 2HDM
Light Scalar: from 2HDM

**Muon AMM**

\[
\Delta a_{1,\ell}^H = -\frac{1}{8\pi^2} Q_{\ell} \left( \gamma_{\ell}^{\phi^0} \right)^2 \int_0^1 dx \frac{x^2(1-x+1)}{x^2 + z_H^2(1-x)},
\]

\[
z_H = \frac{m_H}{m_\ell}
\]

**Electron AMM**

\[
\Delta a_{2,\ell}^H = \frac{\alpha}{8\pi^3} m_\ell Y_{\ell}^H \sum_f \frac{N_f^2 Q_f^2 Y_f^H}{m_f} F_H \left[ \frac{m_f^2}{m_H^2} \right],
\]

\[
F_H [z_H] = z_H \int_0^1 dx \frac{2x(1-x) - 1}{x(1-x) - z_H} \ln \frac{x(1-x)}{z_H}.
\]
Light Scalar: from 2HDM

Setting $m^2_H \ll m^2_{H^+} \approx m^2_A \sim O(110) \text{ GeV}$

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Other Constraints

❖ Fixed Target Experiments: Electron beam dump experiments put a severe constraint on the light scalar that has coupling with electrons.

❖ Dark Photon Searches: **KLOE** collaboration and **BaBar** collaboration searches for the dark photons $A_d$ through the process: $e^+e^- \rightarrow \gamma A_d$, with $A_d \rightarrow e^+e^-$

❖ LEP experiments: $e^-e^+ \rightarrow far{f}$ process constrained by the LEP experiments, which can be used to constrain the masses of the neutral scalar and its corresponding coupling with charged fermions.
Other Constraints

- **Dark Photon Searches**: For a scalar mass \( m_H > 200 \text{ MeV} \), the dark-boson searches at the BaBar can be used to impose limits on \( H \mu^+ \mu^- \) coupling via \( e^+ e^- \rightarrow \mu^+ \mu^- H \) process.

- **Rare Z-decay**: Exotic Z decay of the type \( Z \rightarrow 4\mu \) has been searched by both the ATLAS and the CMS collaborations.
LHC Prospects

The most promising signal of the model is $pp \rightarrow \tau^- \tau^+ jj + E_T$ at the LHC.

If the mass splitting between the CP-even and CP-odd neutral scalars is turned off, then the amplitude for this process will be exactly zero. Correspondingly, our scenario will fail to explain the lepton AMMs.

At the HL-LHC with an integrated luminosity of $3 \text{ ab}^{-1}$, the charged scalars of mass up to 282 GeV can be probed.

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Muon Anomalous Magnetic Moment and Electron Anomalous Magnetic Moment

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Conclusions

We have proposed a novel scenario that can explain the anomalies related to the lepton anomalous magnetic moments.

We have shown that a light scalar of mass $\mathcal{O}(10)\ MeV \sim \mathcal{O}(1)\ GeV$ can contribute simultaneously to both electron and muon AMM with correct sign and magnitude needed to explain these anomalies.

We analyze possible ways to probe new-physics signals at colliders and find that this scenario can be tested at the LHC by looking at the novel process $pp \to \tau^-\tau^+ jj + E_T$ via same-sign pair production of charged Higgs bosons.

Thank You!
Δa_c^{\text{Rb}} ≡ a_c^{\text{exp (Rb)}} - a_c^{\text{SM}} = (4.8 \pm 3.0) \times 10^{-13}.

Electroweak Precision Constraints

- T parameter in the alignment of 2HDM

\[
T = \frac{1}{16\pi s_w^2 M_W^2} \left\{ \mathcal{F}(m_{H^+}^2, m_A^2) + \mathcal{F}(m_{H^+}^2, m_h^2) - \mathcal{F}(m_{H^+}^2, m_A^2) \right\},
\]

\[
\mathcal{F}(m_1^2, m_2^2) = \frac{1}{2} (m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \left( \frac{m_1^2}{m_2^2} \right).
\]

- Our scenario, \( m_H^2 \ll m_{H^+}^2 \approx m_A^2 \sim \mathcal{O}(110) \text{ GeV} \) is well consistent with the EW precision constraints.
Fixed Target Experiments

- Electron beam-dump experiments can probe light scalars that have coupling with the electrons.

- Light Scalars are produced via $e + N \rightarrow e + N + H$ process.

- For a scalar of mass $m_H < 2m_\mu$, after traveling macroscopic distances, it would decay back to electron pairs.

- Lack of such events constrain the mass of scalar and its corresponding coupling with the electron.

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Dark-photon Searches

- There are several experiments that search for the presence of dark-photons and their null observations can be translated to provide stringent constraints on the allowed parameter space of light scalars.

- **KLOE** collaboration and **BaBar** collaboration searches for the dark photons $A_d$ through the process: $e^+ e^- \rightarrow \gamma A_d$, with $A_d \rightarrow e^+ e^-$. 

- Lack of such events constrain the mass of scalar and its corresponding coupling with the electron.
Dark-photon Searches

- For a scalar mass $m_H > 200\text{ MeV}$, the dark-boson searches at the BaBar can be used to impose limits on $H \mu^+\mu^-$ coupling via $e^+e^- \rightarrow \mu^+\mu^- H$ process.

- Lack of such events constrain the mass of scalar and its corresponding coupling with the electron.
Rare Z-decay constraints

- Rare Z-decay constraints: Exotic Z decay of the type $Z \rightarrow 4\mu$ has been searched by both the ATLAS and the CMS collaborations.

- The LHC results can be interpreted as constraints on the process $Z \rightarrow \mu^+\mu^- H$, with $H \rightarrow \mu^+\mu^-$. 
LEP constraints

- $e^- e^+ \rightarrow ff$ process constrained by the LEP experiments, which can be used to constrain the masses of the neutral scalar and its corresponding coupling with charged fermions.