Probing Scalar and Pseudoscalar Solutions of the g-2 Anomaly

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I investigate a class of models with scalar and pseudoscalar solutions to the \( g - 2 \) anomaly in the mass range between 1 MeV and 40 GeV. In particular, I investigate the constraints from BaBar, beam dump experiments and from Z decay measured quantities. I find that most of the favored region in this mass range is excluded except for a small window between \( \sim 30 \) MeV and 200 MeV. This open window is expected to be covered by the proposed NA64 experiment. The results can be readily applied to other proposed solutions of the anomaly, such as solutions with \( Z' \) or with the dark photon.

I. INTRODUCTION

One of the most exciting pieces of evidence for the existence of physics Beyond the Standard Model (BSM) is the discrepancy between the predicted and measured values of the muon anomalous magnetic moment \( a_\mu \equiv (g_\mu - 2)/2 \). The current measured value [1] shows a 3.5\( \sigma \) discrepancy compared with the SM prediction [5–7]:

\[
\Delta a_\mu = a_{\mu,\text{Exp}} - a_{\mu,\text{SM}} = 273 \pm 80 \times 10^{-11}
\]

A similar less significant discrepancy of about 1.1\( \sigma \) was also observed for the electron [8]:

\[
\Delta a_e = a_{e,\text{Exp}} - a_{e,\text{SM}} = -91 \pm 82 \times 10^{-14}
\]

Although both discrepancies fall short of the 5\( \sigma \) limit required to confirm their existence, they nonetheless pose tantalizing evidence for physics BSM. In addition, current experiments at Fermilab [9, 10] and at the J-PARC E34 collaboration [11, 12] are expected to yield improved experimental results in the near future.

New physics explanations of this anomaly include Supersymmetry (see [13] for a review), a light \( Z' \) boson [14–21] (also see [22] for a review), a scalar contribution within the framework of the 2 Higgs Doublet Model (2HDM) [23–27], additional fermions [28], leptoquarks [29, 30] and dark photon [31].

Recently, there have been proposed solutions to this anomaly through a scalar [5] or a pseudoscalar Axion-Like Particle (ALP) [6] in a general framework. In this short paper, I will investigate the viability of these solutions, explore the relevant experimental limits, and propose experimental probes for their discovery in the mass range between 1 MeV and 40 GeV.

In the case of a pseudoscalar, the effective interaction with photons and fermions can be parametrized by:

\[
\mathcal{L} = \frac{1}{4} g_{\sigma \gamma \gamma} \sigma F_{\mu \nu} F^{\mu \nu} + i Y_{\sigma \psi} \psi \bar{\psi} \gamma_5 \psi
\]

where \( g_{\sigma \gamma \gamma} \) is a dimensionful coupling, \( Y_{\sigma \psi} \) is a dimensionless Yukawa coupling and \( F^{\mu \nu}, \tilde{F}^{\mu \nu} \) are the magnetic field strength tensor and its dual respectively. For a scalar, \( \tilde{F}^{\mu \nu} \) is replaced by \( F^{\mu \nu} \) and there is no \( i \gamma_5 \) in the second term. In this paper, I will focus on models where the Yukawa couplings are proportional to the lepton mass:

\[
Y_{\sigma \ell l} = \frac{m_l}{v} \equiv m_l g_{\sigma \ell l}
\]

where \( m_l \) is the mass of the lepton and \( v \equiv g_{\sigma \ell l}^{-1} \) is some model-dependent energy scale, such as the axion decay constant or the radion constant.

It was shown in [5] that the discrepancy in \( g_\mu - 2 \) can be explained by a scalar with \( Y_{\sigma \mu} \sim O(10^{-3}) \), while in [6], it was shown that an ALP pseudoscalar can explain both of the electron and muon anomalies by considering the NLO contributions.

The LO and NLO contributions to the \( \Delta a_{\mu, e} \) are shown in Fig. 1. The LO contribution was calculated in [5]

\[
\Delta a_l = \frac{Y_{\sigma \ell l}^2}{8\pi^2} r^{-2} \int_0^1 dz \left( 1 + z \right)^2 \frac{1}{2} \frac{1}{r^{-2} \left( 1 - z \right)^2 + z}
\]

where \( r \equiv \frac{m_\sigma}{m_l} \). On the other hand, the NLO contribution includes the Barr-Zee (BZ) contribution (top right diagram in 1), the two-loop Light-By-Light (LBL) contribution (bottom left diagram in 1), and the Vacuum Polarization (VP) contribution (bottom right diagram in 1). These contributions are given by [6]:

\[
a_{l,\sigma}^{\text{BZ}} \simeq \left( \frac{m_l}{4\pi} \right) g_{\sigma \gamma \gamma} Y_{\sigma \ell l} \ln \frac{\Lambda}{m_\sigma}
\]

\[
a_{l,\sigma}^{\text{LBL}} \sim \frac{3\alpha}{\pi} \left( \frac{m_l g_{\sigma \gamma \gamma}}{4\pi} \right)^2 \ln \frac{\Lambda}{m_\sigma}
\]

\[
a_{l,\sigma}^{\text{VP}} \sim \frac{\alpha}{12\pi} \left( \frac{m_l g_{\sigma \gamma \gamma}}{12\pi} \right)^2 \ln \frac{\Lambda}{m_\sigma}
\]

where \( \sigma \) is either a scalar or a pseudoscalar, \( g_{\sigma \gamma \gamma} \) is the dimensionful coupling of \( \sigma \) to photons, and \( \Lambda \) is some UV

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cutoff scale. Notice here that all contributions are positive except for BZ, which depends on the sign of $g_{\sigma \gamma \gamma}Y_{\sigma ll}$. Given that the central measured value of $\Delta a_{\mu}$ is positive and that for $\Delta a_e$ it is negative, one might be tempted to assume that $g_{\sigma \gamma \gamma}Y_{\sigma ll} < 0$ in order to produce the central measured anomaly for the electron, however, such an assumption leads only to nonperturbative solutions for the couplings. Therefore, I shall assume that all couplings are positive. In addition, I will set the cutoff scale $\Lambda = 1$ TeV throughout this paper.

![LO (top left diagram) and NLO scalar/pseudoscalar contributions to the lepton anomalous magnetic moment.](image)

Fig. 1. LO (top left diagram) and NLO scalar/pseudoscalar contributions to the lepton anomalous magnetic moment.

Notice that since the Lagrangian in (3) is CP-conserving, there will be no contribution to the lepton's Electric Dipole Moment (EDM). I will ignore the more general case where CP-violating terms are present.

II. FAVORED REGION

In this section, I will investigate the parameter space and try to establish the favored region. We have three parameters, namely $m_\sigma$, $g_{\sigma ll}$ and $g_{\sigma \gamma \gamma}$. First, I estimate the favored range of $g_{\sigma \gamma \gamma}$ by minimizing the $\chi^2$ of the electron and muon measurements:

$$\chi^2 = \frac{(\Delta \mu_{\text{Exp}} - \Delta \mu_{\sigma})^2}{\sigma_{\mu}^2} + \frac{(\Delta e_{\text{Exp}} - \Delta e_{\sigma})^2}{\sigma_{e}^2}$$

(9)

Fig. 2 shows $\chi^2$ for several values of $g_{\sigma \gamma \gamma}$. As the plot shows, $g_{\sigma \gamma \gamma} \lesssim 10^{-6}$ GeV$^{-1}$ yields the lowest values of $\chi^2$. Notice that $\chi^2$ becomes almost constant for smaller couplings. This is reasonable as when the coupling to photons becomes very small, the NLO contributions become negligible and the LO contribution is dominant. This high level analysis seems to favor smaller couplings to photons, suggesting that the coupling to leptons is the dominant coupling. I will focus on this scenario and I will choose $g_{\sigma \gamma \gamma} = 10^{-6}$ and $10^{-11}$ GeV$^{-1}$ as two benchmark points. Notice that to a good level of accuracy, the second benchmark point would be representative of the entire region of $g_{\sigma \gamma \gamma} \lesssim 10^{-8}$ GeV$^{-1}$, with very similar ranges for the predicted mass and coupling.

Next, I will use eq. (6) in order to find the allowed region in the $m_\sigma - Y_{\sigma ll}$ parameter space corresponding to a 2$\sigma$ deviation from the central value. Fig. 3 shows the allowed region corresponding to the two benchmark points. The plots show the 2$\sigma$ bands for the Yukawa couplings to electrons and muons assuming that eq. (4) holds. In addition, the plots also show the region where the contribution to $\Delta a_e$ is within 2$\sigma$ of the measured value assuming that the Yukawa couplings to leptons are independent of one another. Notice that the brown region corresponds to $\Delta a_e^2 \in (0, \Delta a_e^2 + 2\sigma_e]$ since we are assuming positive couplings. Therefore, there is no point in the parameter space that can yield the central value of the measured $\Delta a_e = -91 \times 10^{-14}$.

![The 2$\sigma$ bands corresponding to the allowed region for electrons and muons for the benchmark points $g_{\sigma \gamma \gamma} = 10^{-11}$ GeV$^{-1}$ (top) and $10^{-6}$ GeV$^{-1}$ (bottom).](image)

Fig. 2. $\chi^2$ Vs. the coupling to photons. The plot shows that smaller couplings are favored.
We can carry the $\chi^2$ analysis further to find the favored region in the $m_\sigma - g_{\sigma ll}$ parameters space for the benchmark points. Fig. 3 shows the radion mass and coupling to leptons that minimizes $\chi^2$, together with the 68% and 95% confidence level contours. Notice that this region is a subset of the favored region in Fig. 4. For $g_{\sigma \gamma \gamma} = 10^{-11}$ GeV$^{-1}$, we find a predicted (pseudo-)scalar mass of $\sim 540$ MeV, with $g_{\sigma ll} \simeq 1.45 \times 10^{-2}$ GeV$^{-1}$. For this point, one finds a predicted anomaly $\Delta a_\mu(e) = 273 \times 10^{-11} (8 \times 10^{-18})$. On the other hand, for the second benchmark point ($g_{\sigma \gamma \gamma} = 10^{-6}$ GeV$^{-1}$), the predicted mass and coupling are 64 MeV and $5 \times 10^{-3}$ GeV$^{-1}$ respectively, with $\Delta a_\mu(e) = 272 \times 10^{-11} (5 \times 10^{-17})$. Notice that the favored region can cover a wide range of masses from $\sim O$(KeV) - $O$(GeV), while the coupling is more constrained ($\lesssim 0.03$ GeV$^{-1}$ for the first point and $\lesssim 0.01$ GeV$^{-1}$ for the second). This is consistent with the results found in [5]. I will focus on the mass range from 1 MeV to 40 GeV.

![Graph showing favored point in the $m_\sigma - g_{\sigma ll}$ parameter space with 68% and 95% confidence level contours for $g_{\sigma \gamma \gamma} = 10^{-11}$ GeV$^{-1}$ (top) and $10^{-6}$ GeV$^{-1}$ (bottom).]

III. EXPERIMENTAL PROBES AND LIMITS

For the mass range of interest, the most relevant constraints come from BaBar, beam dump experiments and from the measured quantities of the $Z$ decay. The constraints are summarized in Fig. 6. Below I discuss each one in some detail.

A. BaBar

Recent results from BaBar [32] searching for the reaction $e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^- Z$; excludes much of the parameter space between the dimuon threshold and a few GeV, with $g_{\sigma ll} \gtrsim 0.03$ GeV$^{-1}$. The excluded part of the parameter space is shown in the light gray region in Fig. 6. I should point out however, that due to the noisy signal in BaBar’s reported results, the lower bound of the excluded region is somewhat uncertain. In Fig. 6 I took the most conservative limit, however, a less conservative estimate that excluded the noisy portion of the results would relax the constraint by a factor of a few.

B. Z Decay

The excellent measurements of the $Z$ decay width and branching fractions present us with a very suitable tool for probing the parameter space. In particular, we can explore the limits on the decay $Z \rightarrow ll\sigma$, in addition to the limits associated with the (pseudo)-scalar loop correction to the $Z$ decay to a pair of leptons.

1. $Z \rightarrow ll\sigma$

Given the precise measured value of the $Z$ decay width of $2.4852 \pm 0.0023$ GeV [33], we can set limits on the parameter space by calculating the LO decay width of $Z \rightarrow ll\sigma$. With eq. 4 in mind, and assuming that the coupling of $\sigma$ to $Z$ is subleading, it’s easy to see that the decay to $\tau^+\tau^-\sigma$ gives the dominant contribution. The limits are shown in the blue and green regions in Fig. 6 for the case of $\sigma$ being a scalar and a pseudoscalar respectively. As the plot shows, the parameter space is more constrained for the case of a scalar, especially at lower masses, while at masses $\gtrsim 1$ GeV, the limits become almost identical. Notice that the constraints do not exclude any part of the $g-2$ favored region, although they exclude larger deviations from the central value.

2. Loop Correction to $Z \rightarrow ll$

The (pseudo-)scalar loop corrections can significantly affect the leptonic decay width of the $Z$ boson. The NLO corrections to $Z \rightarrow ll$ are shown in Fig. 5 where the coupling of $\sigma$ to $Z$ is assumed to be suppressed. Notice here that the leg corrections cancel the UV divergence of the vertex correction, and that for a massive $\sigma$ the result is free of IR divergences.

Ignoring the lepton mass in the loops, and only keeping $m_\sigma$ as an IR regulator, the NLO correction is approximately given by:
for probing the mass range $\sim 1 - 200$ MeV. However, there is a triangular region between $m \sim 30 - 200$ MeV with $g_{\sigma\ell\ell} \sim 6 \times 10^{-4} - 10^{-2}$ GeV$^{-1}$ that is still open. This window is projected to be explored by the proposed NA64 project at CERN [37, 38]. The NA64 is a fixed-target experiment that can run in the muon mode with a beam energy of 160 GeV, and is designed for searching for missing energy $\gtrsim 50$ GeV. This experiment can help close the remaining gap in the mass range between 1 MeV and 40 GeV. This projected region of the parameter space is shown by the dashed line in Fig. 6.

Another proposed experiment is Fermilab’s displaced decay search with muon beam energy of 3 GeV [39]. However, the projected sensitivity of this experiment covers only a part of the projected sensitivity of the NA64 experiment, therefore I will not plot it here.

D. Other Constraints from SN1987, Horizontal Branch Stars and Cosmology

Supernova 1987 (SN1987), Horizontal Branch (HB) stars and cosmological constraints can impose stringent constraints on ALPs for masses $\lesssim 1$ GeV (see [40, 41] for instance). However, such constraints are only relevant if the ALP’s dominant coupling is to photons. Since the coupling to photons in the type of models we are considering in this paper is favored to be much less than that to leptons, such limits do not apply in such case, and we can ignore them here. Nonetheless, constraints from SN1987, HB stars and cosmology can help explore masses lighter than 1 MeV and should be investigated. For instance, the energy loss due to ALP bremsstrahlung in $ee \to ee\sigma$ should not exceed that observed in the neutrino burst of SN1987. In addition, this energy loss could also affect the lifetime of HB stars. Such cosmological observations would help put limits on ALPs’ masses and couplings.

In other words, the limits in [40, 41] need to be revised for the case the dominant coupling of ALPs is to leptons rather than photons. However, this is beyond the scope of this paper.

E. Discussion

We have shown that the constraints from BaBar, beam dump experiments and from the $Z$ decay exclude much of the parameter space. From Fig. 6, we can see that most of the mass range from 1 MeV to 40 GeV is excluded except for a triangular region between $\sim 30$ MeV and 200 MeV. In particular, the first benchmark point corresponding to $g_{\sigma\gamma\gamma} = 10^{-11}$ GeV$^{-1}$ is excluded by BaBar and by the NLO $Z$ decay corrections. However, part of the region surrounding the $\chi^2$ minimum point could still be open if a less conservative limit is adopted.
from the BaBar results. On the other hand, the second benchmark point corresponding to \( g_{\sigma \gamma \gamma} = 10^{-6} \text{ GeV}^{-1} \) is still within the open window. It is projected that the NA64 experiment will be able to explore this open window and therefore improve the limits on this class of models.

We should note however, that masses heavier than 40 GeV or less than 1 MeV are less constrained by either the \( Z \) decay or by beam dump experiments under consideration, which suggests focusing on exploring these regions of the parameter space. It is expected that masses lower than 1 MeV would be heavily constrained by beam dump experiment and cosmological observation. On the other hand, masses \( \gtrsim 40 \) GeV are expected to be less constrained.

Also notice that due to our assumption in [4], the dominant coupling will be to the tau lepton, and therefore the limits from the \( Z \) decay will be more stringent. If we assume a different type of coupling to leptons, say by assuming a suppressed coupling to the tau compared to the muon, the \( Z \) decay constraints will be less stringent, and more of the parameter space will open. We will briefly discuss one model that can achieved this in next section.

**IV. A RADION SOLUTION FOR THE \( g_{\mu} - 2 \) ANOMALY?**

In the Randall-Sundrum (RS) model [42], the radion is the scalar field that parametrizes the fluctuations of the extra dimension around it’s potential minimum. The radion could pose an interesting possibility for solving the \( g_{\mu} - 2 \) anomaly due to its unique couplings to matter. More specifically, the radion coupling to matter is highly model-dependent and varies according to the localization of the matter fields one either of the branes or along the bulk. The coupling to brane-localized matter is given by [43]:

\[
\sigma(x) \frac{\Lambda_{UV,IR}}{T_{\mu\nu}}
\]

where \( \sigma(x) \) is the 4D radion field, \( \Lambda_{UV,IR} \) is the radion constant on the UV and IR branes respectively and \( T_{\mu\nu} \) is the stress energy tensor. Since the UV scale is typically many orders of magnitude larger than the IR scale, it is possible to suppress the coupling to the tau lepton compared to the muon by assuming that the former is localized on the UV brane, while assuming that the latter is localized on the IR brane. This way, one can alleviate the constraints stemming from the \( Z \) decay. For instance, the limits from the loop correction to the \( Z \) decay will be rescaled by \( m_\tau^2/m_\mu^2 \), while the constraints from \( Z \to ll \) will much less stringent and almost irrelevant. This would open the mass range \( \gtrsim 5 \) GeV as can be seen from Fig. [6]

Although the typical mass of the radion is comparable to the Electroweak (EW) scale \( (\sim 100 \) GeV), much lighter masses can be achieved through the Continuo-Pomarol-Rattazzi (CPR) mechanism [44] as was demonstrated in [45, 46].

Another interesting aspect of a radion solution is that the radion could couple to nucleons and pions through quarks and gluons [45], which presents additional experimental probes. Focusing on the coupling to pions, we can write the effective Lagrangian as:

\[
\mathcal{L}_{\sigma \pi \pi} = g_{\sigma \pi \pi} m_\pi^2 \sigma \pi \pi
\]

where \( g_{\sigma \pi \pi} \) is the effective radion coupling to pions with dimension \((mass)^{-1}\). If the radion is heavy enough, it could decay to \( \pi^+ \pi^- \):

\[
\Gamma(\sigma \to \pi^+ \pi^-) = \frac{g_{\sigma \pi \pi}^2 m_\pi}{16\pi m_\sigma} \left( 1 - \frac{4m_\pi^2}{m_\sigma^2} \right) \frac{m_\pi}{4m_\sigma} \]

The decay width in [17] can be small for typical values of \( g_{\sigma \pi \pi} \) but can still be measurable. For instance,
the decay width for a 1 GeV radion at a coupling of 0.2 GeV$^{-1} \simeq 0.015$ MeV.

For lighter masses, searches for the rare pion decay $\pi^- \rightarrow \mu^- \nu\sigma$ can provide an interesting search option. If we assume that $g_{\sigma\pi\pi}$ dominates over $g_{\rho\ell\ell}$, then the branching fraction of this hypothetical decay would be given by:

$$\text{Br}(\pi \rightarrow \mu \nu \sigma) \simeq 3.5 \times 10^{-2} \left( \frac{g_{\sigma\pi\pi}}{\text{GeV}^{-1}} \right)^2 \% \quad (18)$$

For instance, $g_{\sigma\pi\pi} \sim 10^{-3}$ GeV$^{-1}$ would yield a branching fraction comparable to the observed rare decay $\pi^+ \rightarrow e^+ \nu_e e^+ e^-$. 

V. CONCLUSIONS

The $g-2$ anomaly remains one of the best routes for searching for physics BSM. In this paper I investigated a class of models with a scalar/ pseudoscalar that has a coupling to leptons proportional to the lepton’s mass.

We saw in this paper that smaller couplings to photons are favored, and we established the corresponding favored region in the $m_\sigma - g_{\rho\ell\ell}$ parameter space that correspond to two representative benchmark points. We investigated the experimental constraints from BaBar, beam dump experiments and $Z$ decay and saw that in the mass range between 1 MeV and 40 GeV most of the favored region is excluded. However, there remains an open window between $\sim 30$ MeV and 200 MeV where the proposed NA64 experiment is expected to cover.

In particular, constraints from $Z$ decay, especially from the loop correction, can be significant. These constraints can be alleviated for models with coupling types different from the one in [4]. For instance, I showed that this can easily be accommodated in the RS model by localizing the tau lepton on the UV brane and the muon on the IR brane. The measurements related to the $Z$ decay can also be used to constrain other types of solutions to the $g-2$ anomaly, such as solutions that adopt the $Z'$ or the dark photon to explain it. I expect that the limits on these solution will not be too different from the scalar/pseudoscalar case, they nonetheless are worthwhile investigating. Furthermore, constraints from cosmology, especially for masses below 1 GeV, should be revised for the case where the ALP coupling to photon is subdominant.

It is also interesting to explore the regions of the parameter space with masses $> 40$ GeV or $< 1$ MeV. For the former, collider searches might be the best approach to explore them given that the favored region covers somewhat larger couplings. On the other hand, for the region with masses lighter than 1 MeV, beam dump experiment and cosmological observation might be good ways to explore it.

ACKNOWLEDGMENTS

I would like to thank my adviser John Terning for his valuable supervision. I would also like to thank John Conway and Max Chertok for answering my questions.

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