Contributions of axionlike particles to lepton dipole moments

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Contributions of a spin-0 axionlike particle (ALP) to lepton dipole moments, $g - 2$ and EDMs are examined. Barr-Zee and light-by-light loop effects from a light pseudoscalar ALP are found to be capable of resolving the longstanding muon $g - 2$ discrepancy at the expense of relatively large ALP-$\gamma\gamma$ couplings. The compatibility of such large couplings with direct experimental constraints and perturbative unitarity bounds is discussed. Future tests of such a scenario are described. For *CP*-violating ALP couplings, the electron EDM is found to probe much smaller, theoretically more easily accommodated ALP interactions. Future planned improvement in electron EDM searches is advocated as a way to not only significantly constrain ALP parameters, but also potentially unveil a new source of *CP* violation which could have far-reaching ramifications.

I. INTRODUCTION

Light spin-0 scalars and pseudoscalars, sometimes generically referred to as axionlike particles (ALPs), often occur in extensions of the Standard Model (SM). Their lightness, relative to the scale of new physics (NP) from which they stem, can be understood in terms of their pseudo-Goldstone boson nature, i.e. connection with an underlying broken symmetry. ALPs are a generalization of the well-known QCD axion, but with the caveat that their mass and couplings to other particles are arbitrary parameters to be determined or bounded by experiment. In that context, we concentrate here on ALP couplings to photons (ALP-$\gamma\gamma$ interactions) [1] and their Yukawa couplings to leptons. We restrict our attention to ALPs in the approximate mass range of 100 MeV–1 GeV where experimental constraints [1,2] are currently rather loose, leaving open the possibility of potentially new observable effects.

In this study, we examine indirect effects of ALPs on lepton electromagnetic dipole moments. For the mass range and couplings considered, the muon anomalous magnetic moment $a_\mu = (g - 2)_\mu / 2$ provides a potentially sensitive probe of NP [3,4]. Currently, comparison of the SM prediction with the experimental value shows an interesting $\sim 3.4\sigma$ discrepancy,

$$\Delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = 273(80) \times 10^{-11}, \qquad (1)$$

based on $a_\mu^{\text{EXP}} = 116592091(63) \times 10^{-11}$ [5] and $a_\mu^{\text{SM}} = 116591818(49) \times 10^{-11}$ [6–17]. For an alternative up-to-date analysis that leads to a larger 4.0σ discrepancy, see Ref. [18]. On the theory side, there is a fairly general consensus that hadronic loop uncertainties alone cannot explain such a large discrepancy. Nevertheless, considerable effort is being expended to reduce the uncertainty in

the SM prediction. Regarding the experimental result [5] in Eq. (1), an anticipated new measurement at Fermilab, E989, is expected to improve the precision by a factor of 4 [19]. In addition, a completely new low-energy approach to measuring the muon $g - 2$ is being developed by the E34 Collaboration at J-PARC [20]. In a few years, we should know much better whether the discrepancy in Eq. (1) is due to NP. For comparison, we note that for the electron, $\Delta a_e = -91(82) \times 10^{-14}$ [21]; i.e. there is relatively good agreement between theory and experiment.

Already, a possible resolution of the muon $g - 2$ discrepancy by one-loop contributions from scalar particles with relatively large Yukawa couplings to muons, of $\mathcal{O}(10^{-3})$, has been considered [22] [see Fig. 1(a)]. In the case of a pseudoscalar, the one-loop contribution had the wrong sign to resolve the discrepancy on its own. Here, we extend that discussion to include ALP-$\gamma\gamma$ couplings as well as Yukawa couplings. In that way, two new ALP contributions to lepton dipole moments are potentially important:
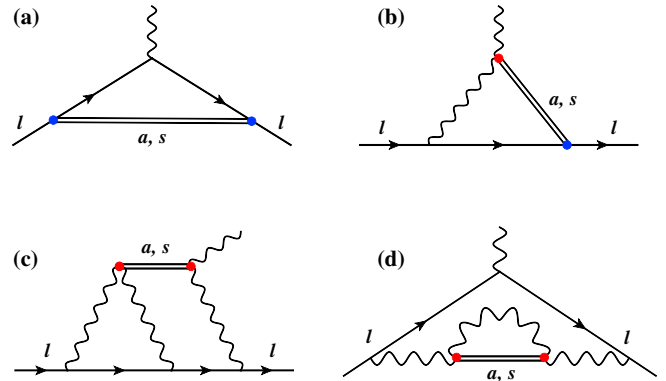

FIG. 1. Representative contributions of a scalar s and a pseudoscalar a ALP to the lepton ℓ dipole moments.

(i) Barr-Zee (BZ) [23] one-loop diagrams that involve both ALP-$\gamma\gamma$ and ALP Yukawa interactions with leptons [see Fig. 1(b)], and (ii) two-loop light-by-light (LbL) and vacuum polarization diagrams stemming only from ALP-$\gamma\gamma$ interactions [see Figs. 1(c) and 1(d)]. As we shall show, for relatively large ALP-$\gamma\gamma$ couplings, they can potentially resolve (fully or partially) the muon $g-2$ discrepancy. In fact, even with a fairly large negative pseudoscalar contribution from Fig. 1(a), their positive contribution can dominate.

If ALPs have both CP-even and CP-odd components, their combination can lead to CP-violating fermion electric dipole moments (EDMs) through the diagrams in Fig. 1. One-loop pure Yukawa diagrams [see Fig. 1(a)] have been already considered in Ref. [22]. In this case, the electron EDM d_e, which is currently constrained at the level of $|d_e| \leq 8.7 \times 10^{-29} e$ cm [24], turns out to be a very sensitive probe of our scenario. The expected future experimental sensitivity $|d_e| \lesssim 10^{-30} e$ cm [25] will further strengthen the impact of this observable and nicely complement the SHiP proposal [26] at CERN's SPS fixed-target facility. That experiment is intended (among its many goals) to directly search for ALPs produced via the Primakoff effect in a dense target.

The scenario we are advancing requires relatively large ALP-$\gamma\gamma$ couplings. For that reason, we will address current and potential future direct experimental constraints on such a coupling as well as a possible breakdown of perturbative unitarity in the diagrammatic use of such effective couplings in loop calculations.

II. ALPS CONTRIBUTIONS TO LEPTON $g-2$

The possibility that the discrepancy in Eq. (1) is a NP signal has been widely discussed in the literature for a number of NP scenarios [3,4]. Here, we examine contributions to the lepton $g-2$ induced by ALPs primarily coupled to photons and leptons. In general, ALPs can be scalars or pseudoscalars (or mixed if CP is violated). The effective Lagrangian [assumed valid for scales $< \mathcal{O}(\text{TeV})$] describing the interactions of a pseudoscalar ALP a with photons and SM fermions ψ can be parametrized by

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i y_{a\psi} a \bar{\psi} \gamma_5 \psi, \qquad (2)$$

where $g_{a\gamma\gamma}$ is a dimensionful coupling; $F_{\mu\nu}$ and $\tilde{F}^{\mu\nu}$ are the electromagnetic tensor and its dual, respectively; and $y_{a\psi}$ are real dimensionless Yukawa couplings. The first term of Eq. (2) reproduces the well-known $\pi^0 \to \gamma\gamma$ anomalous coupling for $a \equiv \pi^0$ and $g_{\pi^0\gamma\gamma} \equiv \alpha/(\pi F_\pi)$, where α is the fine-structure constant and $F_\pi = 92$ MeV is the neutral pion decay constant. For the scalar case, replace $\tilde{F}^{\mu\nu}$ with $F^{\mu\nu}$, replace a with s, and delete $i\gamma_5$.

In the SM, the UV cutoff of the effective theory can be roughly interpreted as the cutoff scale of chiral perturbation theory $2\sqrt{2}\pi F_\pi = 820$ MeV, or approximately $m_\rho \sim 770$ MeV. Therefore, a natural parametrization of $g_{a\gamma\gamma}$ is

$$g_{a\gamma\gamma} \equiv \frac{2\sqrt{2}\alpha}{\Lambda} c_{a\gamma\gamma}, \qquad (3)$$

where Λ is the NP UV cutoff, while $c_{a\gamma\gamma}$ is a dimensionless coupling. In the case of the pion, $c_{\pi^0\gamma\gamma} \sim 1$.

The effective $a\gamma\gamma$ and $y_{a\ell}$ vertices induce contributions to the $g-2$ of a lepton ℓ via one-loop BZ diagrams and two-loop LbL diagrams (analogous to the SM hadronic LbL contribution of the neutral pion exchange [12–17]) shown in Fig. 1. In particular, by an explicit calculation, we find the following effects [assuming the pointlike couplings of Eq. (2) and a sharp cutoff Λ]:

$$a_{\ell,a}^{\text{BZ}} \simeq \left(\frac{m_\ell}{4\pi^2}\right) g_{a\gamma\gamma} y_{a\ell} \ln\frac{\Lambda}{m_a}, \qquad (4)$$

$$a_{\ell,a}^{\text{LbL}} \simeq 3\frac{\alpha}{\pi} \left(\frac{m_\ell g_{a\gamma\gamma}}{4\pi}\right)^2 \ln^2\frac{\Lambda}{m_a}, \qquad (5)$$

where m_a is the ALP's mass and we keep only the leading log-enhanced terms, since they should provide the main ALP contribution to the lepton $g-2$ for $\Lambda \sim 1$ TeV and $m_a \lesssim 1$ GeV. In deriving Eqs. (4) and (5) as well as subsequent loop effects, we assume that $g_{a\gamma\gamma}$ remains essentially constant throughout the integration over virtual photon-loop momentum $0 < |k^2| < \Lambda^2$. That requires an effective pointlike coupling $g_{a\gamma\gamma}$ arising from high-mass-scale phenomena of $\mathcal{O}(\Lambda)$.

A muon $g-2$ realization of our generic Barr-Zee analysis for a (pseudo)scalar with a relatively large $\gamma\gamma$ coupling induced by heavy fermion triangle diagrams has been considered some time ago in Refs. [27,28]. We note that for a single fermion triangle diagram with the same magnitude Yukawa couplings for a pseudoscalar and scalar, the effective loop-induced $g_{a\gamma\gamma}$ coupling is a factor of $-3/2$ times the effective $g_{s\gamma\gamma}$ coupling. This factor tends to make $\gamma\gamma$ or gg production of a pseudoscalar more likely than a scalar.

An inspection of Eqs. (4) and (5) leads to the following remarks:

(i) The sign of $a_{\ell,a}^{\text{BZ}}$ depends on the sign of the product $g_{a\gamma\gamma} y_{a\ell}$, while that of $a_{\ell,a}^{\text{LbL}}$ is positive, as needed to accommodate the Δa_μ discrepancy [see Eq. (1)]. In the case of a scalar ALP, the leading LbL contribution changes sign [14], while, for our convention, the BZ does not. If LBL is taken in isolation, that would imply the indirect bound $g_{s\gamma\gamma} < \mathcal{O}(10^{-3} \text{ GeV}^{-1})$.

(ii) $a_{\ell,a}^{\text{LbL}}$ follows the expected scaling $a_{\ell,a}^{\text{LbL}} \propto m_\ell^2$ (this is also true for $a_{\ell,a}^{\text{BZ}}$ if $y_{a\mu}/y_{ae} \sim m_\mu/m_e$). Combining

the NP sensitivity and the present experimental resolutions on the lepton $g-2$, it turns out that a_μ rather than a_e is the better probe of our NP scenario.

(iii) The BZ contribution accommodates the muon $g-2$ discrepancy for $g_{a\gamma\gamma}y_{a\mu} \approx 10^{-7}\text{GeV}^{-1}$. Its effect is typically larger than the LbL unless $y_{a\mu}$ is very small.

In Fig. 2, we illustrate by 1σ bands pseudoscalar (upper) and scalar (lower) ALP solutions to the muon $g-2$ discrepancy as a function of $y_{a\mu}$ and $g_{a\gamma\gamma}$. They correspond to the sum of the pure one-loop Yukawa contribution given in Ref. [22] along with BZ [Eq. (4)] and LbL [Eq. (5)] contributions for $\Lambda = 1$ TeV. For a scalar ALP, the BZ depends on the sign of $y_{s\mu}g_{s\gamma\gamma}$, and LbL changes sign. Note that, although the pure one-loop Yukawa contribution is negative for a pseudoscalar ALP [22], BZ and LbL (for positive $y_{a\mu}g_{a\gamma\gamma}$) dominate the solution, solving the muon $g-2$ discrepancy for $10^{-4} \lesssim g_{a\gamma\gamma}(\text{GeV}^{-1}) \lesssim 10^{-2}$. This corresponds, from Eq. (3) with $\Lambda = 1$ TeV, to a $c_{a\gamma\gamma}$ in the range 5–500. We do not attempt to construct a realistic model with such large ALP coupling to photons, but note that it is likely to require a new type of nonperturbative dynamics and/or a high multiplicity of heavy states contributing to $g_{a\gamma\gamma}$ at the loop level. For a scalar ALP, there are solutions to the muon $g-2$ discrepancy (see
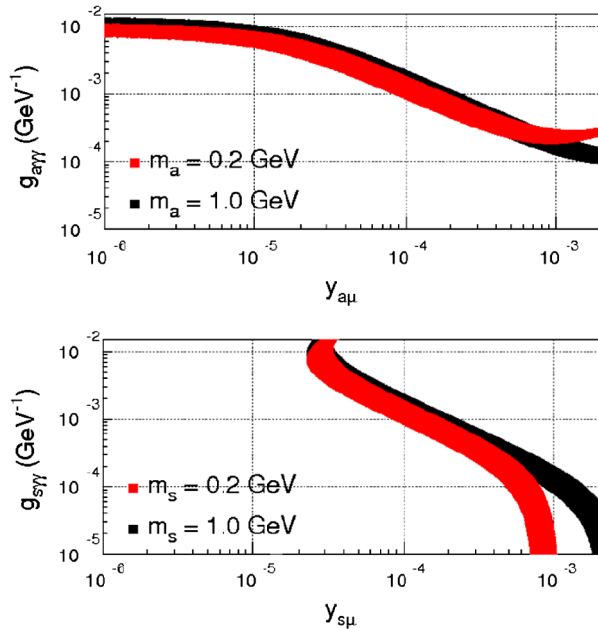

FIG. 2. Pseudoscalar (upper) and scalar (lower) 1σ solution bands to the Δa_μ discrepancy as a function of $y_{a\mu}$ and $g_{a\gamma\gamma}$ for the pseudoscalar, and $y_{s\mu}$ and $g_{s\gamma\gamma}$ for the scalar. They correspond to the sum of pure Yukawa [22], BZ and LbL contributions with BZ taken to be positive and $\Lambda = 1$ TeV. We have truncated the bands at $|y_{a\mu}|, |y_{s\mu}| < 2 \times 10^{-3}$ in order to avoid experimental constraints [29].

lower Fig. 2) dominated by pure one-loop Yukawa contributions for $y_{s\mu} \sim \mathcal{O}(10^{-3})$ and $g_{s\gamma\gamma} < 10^{-4}$ GeV^{-1}. Note that for both plots we assume the rather conservative bound $|y_{a\mu}|, |y_{s\mu}| < 2 \times 10^{-3}$, in keeping with *BABAR* studies of $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ [29].

The above remarks raise the question of whether perturbative unitarity is respected for such a large $g_{a\gamma\gamma}$ coupling. We therefore compute the partial wave unitarity bounds of $\gamma\gamma \to \gamma\gamma$ amplitudes mediated by a pseudoscalar a, obtaining

$$\sqrt{s} < 4\sqrt{2\pi}g_{a\gamma\gamma}^{-1}. \qquad (6)$$

For $g_{a\gamma\gamma} = 10^{-2}$ GeV^{-1}, Eq. (6) gives $\sqrt{s} \lesssim 1$ TeV; while for $g_{a\gamma\gamma} = 10^{-4}$ GeV^{-1}, it implies $\sqrt{s} \lesssim 100$ TeV. The calculation of the partial wave unitary constraint from the process $a\gamma \to a\gamma$ leads to the same result. Therefore, our effective theory remains unitary up to energies at or above the TeV scale; at even higher scales NP unitarization is expected. If other scattering channels exist with larger couplings, e.g. $gg \to gg$, perturbative unitarity may break down well before the TeV scale.

The effective coupling $a\gamma\gamma$ in our Lagrangian also induces a photon vacuum polarization which provides another contribution to the lepton $g-2$ [see Fig. 1(d)]. In this case, there is an analogous SM effect, arising from the π^0 exchange, which is included in the hadronic contribution to a_μ^{SM} through the dispersive calculation [8–10,30]. If we keep only the dominant log-enhanced term, we find

$$a_{\ell,a}^{\text{VP}} \simeq \frac{\alpha}{\pi}\left(\frac{m_\ell g_{a\gamma\gamma}}{12\pi}\right)^2 \ln\frac{\Lambda}{m_a}. \qquad (7)$$

For a scalar ALP, just replace a with s in Eq. (7). However, employing $g_{a\gamma\gamma} \lesssim 10^{-2}$ GeV^{-1} [2] in Eq. (7), we obtain $a_{\mu,a}^{\text{VP}} \lesssim 2 \times 10^{-11}$, which is much smaller than the LbL effect in Eq. (5) and can therefore be neglected.

III. ALPS CONTRIBUTIONS TO LEPTON EDMS

So far, we have restricted our discussion to the effects induced by pure pseudoscalar or scalar bosons to the lepton $g-2$, since the Lagrangian in Eq. (2) is CP conserving. However, more generally, if the scalar and pseudoscalar states mix due to the presence of CP-violating sources, lepton EDMs d_ℓ are also generated. Calling this mixed state Φ, we can generalize the Lagrangian of Eq. (2) as follows:

$$\mathcal{L} = \frac{\tilde{g}_{\Phi\gamma\gamma}}{4}\Phi F\tilde{F} + \frac{g_{\Phi\gamma\gamma}}{4}\Phi F^2 + (y_{\Phi\psi}\Phi\bar{\psi}P_L\psi + \text{H.c.}), \qquad (8)$$

where $y_{\Phi\psi}$ is a complex Yukawa coupling and $P_L = (1-\gamma_5)/2$. Starting from the above Lagrangian, we can compute the leading BZ contributions to a_ℓ and d_ℓ:

$$a_\ell^{\text{BZ}} \simeq m_\ell \left[\frac{g_{\Phi\gamma\gamma}\text{Re}(y_{\Phi\ell}) + \tilde{g}_{\Phi\gamma\gamma}\text{Im}(y_{\Phi\ell})}{4\pi^2} \right] \ln\frac{\Lambda}{m_\Phi}, \quad (9)$$

$$\frac{d_{\ell,\Phi}^{\text{BZ}}}{e} \simeq \frac{g_{\Phi\gamma\gamma}\text{Im}(y_{\Phi\ell}) + \tilde{g}_{\Phi\gamma\gamma}\text{Re}(y_{\Phi\ell})}{8\pi^2} \ln\frac{\Lambda}{m_\Phi}, \quad (10)$$

as well as the corresponding LbL contributions:

$$a_{\ell,\Phi}^{\text{LbL}} \simeq 3\frac{\alpha}{\pi}\frac{m_\ell^2}{16\pi^2}(\tilde{g}_{\Phi\gamma\gamma}^2 - g_{\Phi\gamma\gamma}^2)\ln^2\frac{\Lambda}{m_\Phi}, \quad (11)$$

$$\frac{d_{\ell,\Phi}^{\text{LbL}}}{e} \simeq 3\frac{\alpha}{\pi}\frac{m_\ell}{16\pi^2}(g_{\Phi\gamma\gamma}\tilde{g}_{\Phi\gamma\gamma})\ln^2\frac{\Lambda}{m_\Phi}. \quad (12)$$

Neglecting one-loop pure Yukawa diagrams already considered in Ref. [22], the experimental bound [24] on d_e is satisfied for

$$|g_{\Phi\gamma\gamma}\text{Im}(y_{\Phi e})|, \quad |\tilde{g}_{\Phi\gamma\gamma}\text{Re}(y_{\Phi e})| \lesssim 5 \times 10^{-14} \text{ GeV}^{-1}, \quad (13)$$

$$\sqrt{|g_{\Phi\gamma\gamma}\tilde{g}_{\Phi\gamma\gamma}|} \lesssim 6 \times 10^{-5} \text{ GeV}^{-1}, \quad (14)$$

where we assume masses for Φ in the range $0.1 \lesssim m_\Phi(\text{GeV}) \lesssim 1$ and $\Lambda = 1$ TeV. For *CP*-violating phases of $\mathcal{O}(1)$—that is, $g_{\Phi\gamma\gamma} \sim \tilde{g}_{\Phi\gamma\gamma}$—LbL effects to d_e are already probing the TeV scale provided $c_{a\gamma\gamma} \sim \mathcal{O}(1)$; see Eq. (3). A sensitivity up to a scale of $\Lambda \sim 10$ TeV could be reached in the future thanks to the expected experimental sensitivity $|d_e| \lesssim 10^{-30}e$ cm [25]. Such high-scale ALP interactions could also be studied by the SHiP proposal [26]. The BZ contribution to d_e is much larger than the LbL one unless $y_{\Phi e}$ is very small, as shown by Eqs. (13), (14).

IV. EXPERIMENTAL TESTS AT e^+e^- COLLIDERS

As recently shown in Refs. [2,31], e^+e^- colliders can set bounds on ALP-$\gamma\gamma$ couplings over a broad range of ALP masses. In particular, the pseudoscalar ALP production mechanism proceeds through the process $e^+e^- \to \gamma^* \to \gamma a$, which is characterized by the following differential cross section:

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{\gamma a} = \frac{\alpha}{64}g_{a\gamma\gamma}^2\left(1 - \frac{m_a^2}{s}\right)^3(1 + \cos^2\theta), \quad (15)$$

where θ is the angle between the ALP and the beam axis in the center of mass. For $m_a \lesssim 1$ GeV, the process $e^+e^- \to \gamma a$ at very high energies (e.g. LEPII) followed by $a \to \gamma\gamma$ could simulate the process $e^+e^- \to 2\gamma$, since the two photons from $a \to \gamma\gamma$ are very collimated. With this assumption, the authors of Ref. [31] suggest a bound $g_{a\gamma\gamma} \lesssim 10^{-3}$ GeV^{-1} based on $e^+e^- \to 2\gamma$ OPAL data [32], but no detailed discussion is given. Although we agree that LEPII data can likely provide a better constraint than the

$g_{a\gamma\gamma} \lesssim 10^{-2}$ GeV^{-1} bound of Ref. [2], a detailed study of detector acceptances and efficiencies is required before drawing firm conclusions [33]. Here, we note that the more restrictive $\mathcal{O}(10^{-3}$ GeV$^{-1})$ bound on $g_{a\gamma\gamma}$ would significantly reduce the LbL contribution, while the BZ one could still provide a solution to the muon $g-2$ discrepancy for $y_{a\mu} \gtrsim 10^{-4}$; see upper Fig. 2.

In the following, we focus on direct experimental searches for ALPs with dominant $\gamma\gamma$ couplings and masses up to a few GeV at low-energy e^+e^- colliders. The relevant processes are

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-a, \quad (16)$$

$$e^+e^- \to \gamma^* \to \gamma a, \quad (17)$$

where the production cross section $\sigma(e^+e^- \to e^+e^-a) \equiv \sigma_{eea}$ is dominated by the t channel with quasireal photons, especially for $\sqrt{s} \gtrsim 1$ GeV. In the equivalent photon approximation, the total cross section σ_{eea} reads [34]

$$\sigma_{eea} \simeq \frac{\alpha^2}{4\pi}g_{a\gamma\gamma}^2\left(\ln\frac{E_b}{m_e}\right)^2 f\left(\frac{m_a}{2E_b}\right), \quad (18)$$

where $E_b \equiv \sqrt{s}/2$ is the beam energy and $f(z)$ is

$$f(z) = (z^2 - 1)(z^2 + 3) - (z^2 + 2)^2 \ln z. \quad (19)$$

If we take, for example, $\sqrt{s} = 1$ GeV and $m_a = m_{\pi^0}$, we find

$$\sigma_{eea}(\sqrt{s} = 1 \text{ GeV}) \approx 31 \text{ pb}\left(\frac{g_{a\gamma\gamma}}{10^{-2} \text{ GeV}^{-1}}\right)^2, \quad (20)$$

$$\sigma_{\gamma a}(\sqrt{s} = 1 \text{ GeV}) \approx 9 \text{ pb}\left(\frac{g_{a\gamma\gamma}}{10^{-2} \text{ GeV}^{-1}}\right)^2, \quad (21)$$

where $\sigma_{\gamma a}$ is the total cross section obtained by integrating $\left(\frac{d\sigma}{d\cos\theta}\right)_{\gamma a}$ over $\cos\theta$. Let us focus on the process in Eq. (16), as it is the most sensitive to NP effects for $\sqrt{s} \gtrsim 1$ GeV. Figure 3 shows the predictions for σ_{eea}, in the plane $(m_a, 2E_b)$, imposing $g_{a\gamma\gamma} = 10^{-2}$ GeV^{-1}. We consider beam energies in the range $1 \leq \sqrt{s}(\text{GeV}) \leq 10$ in order to monitor the signal cross section that could be expected at the KLOE2 [35], CMD3 [36], SND [37], BES III [38] and Belle II [39] experiments. For comparison, the SM production cross sections for $a \equiv \pi^0$, η computed using Eq. (18) at $\sqrt{s} = 1, 2, 10$ GeV are $\sigma_{ee\pi} \simeq 0.3, 0.5, 1.2$ nb and $\sigma_{ee\eta} \simeq 0.04, 0.2, 0.8$ nb, respectively. As illustrated by Fig. 3, σ_{eea} grows with energy, whereas $\sigma_{\gamma a}$ is essentially constant even well above threshold. Although we are not aware of any dedicated search for the nonstandard process $e^+e^- \to e^+e^-a$, we believe it would be worthwhile studying it at running and upcoming e^+e^- colliders.
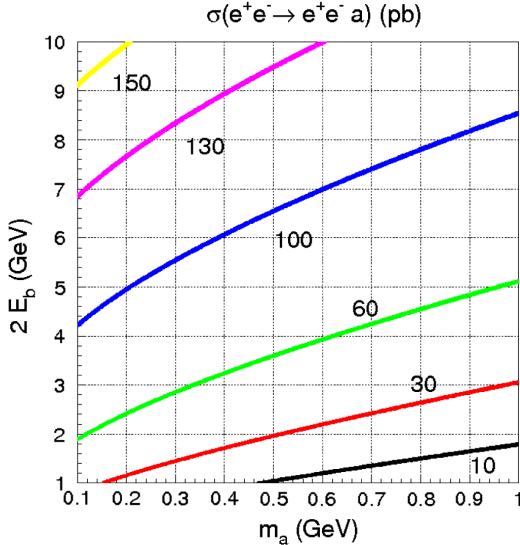
FIG. 3.   Contour plot for $\sigma(e^+e^- \rightarrow e^+e^- a)$ in the $(m_a, 2E_b)$ plane imposing $g_{a\gamma\gamma} = 10^{-2}$ GeV^{-1}. For smaller $g_{a\gamma\gamma}$, the cross section is quadratically reduced.

ALP decay widths could perhaps be measured at JLab via the Primakoff effect. Indeed, with the advent of JLab's 12 GeV upgrade, which aims at gathering high-precision measurements of the two-photon decay widths of η and η' [40], this possibility could become realistic. For instance, for $m_a = m_{\eta'}$ and $g_{a\gamma\gamma} = 10^{-2}$ GeV^{-1}, we find that $0.1 \lesssim \Gamma(a \rightarrow \gamma\gamma)/\Gamma(\eta' \rightarrow \gamma\gamma) \lesssim 0.2$. It has to be seen whether such effect is within JLab's resolution. Instead, for $0.1 \lesssim m_a(\text{GeV}) \lesssim 0.2$, we find that Primakoff-type experiments already set the constraint $g_{a\gamma\gamma} \lesssim 0.005$ GeV^{-1}. For $m_a \lesssim 0.2$ GeV, an even higher sensitivity to $g_{a\gamma\gamma}$ could be potentially reached at the PADME experiment in Frascati [41].

V. CONCLUSIONS

In this work, we have examined the contributions of ALPs to lepton dipole moments, both $g - 2$ and EDMs. We concentrated on the ALP mass range ~ 0.1–1 GeV, a region where the relatively loose constraints on ALP couplings to photons and leptons leave open the possibility of significant effects. Light-by-light pseudoscalar ALP loop effects were shown to resolve the muon $g - 2$ discrepancy for ALP-$\gamma\gamma$ couplings near the published bound [2] of $\mathcal{O}(10^{-2}$ GeV$^{-1})$, but their effect drops quadratically with decreasing values, becoming negligible near $\mathcal{O}(10^{-3}$ GeV$^{-1})$. This result is to be contrasted with Barr-Zee effective loop calculations, where the

product of $g_{a\gamma\gamma} y_{a\mu} \sim 10^{-7}$ GeV^{-1} provides a fairly robust solution to the muon $g - 2$ discrepancy for a range of $g_{a\gamma\gamma}$ values extending down to 10^{-4} GeV^{-1} (see Fig. 2). Such large $g_{a\gamma\gamma}$ couplings are currently allowed by direct published [2] experimental constraints and perturbative unitarity. However, they can be better tested by new experiments at e^+e^- facilities such as KLOE2 [35], CMD3 [36], SND [37], BES III [38], and Belle II [39] through dedicated searches for $e^+e^- \rightarrow e^+e^- a$ (see Fig. 3). In addition, a thorough analysis [31] of high-energy $e^+e^- \rightarrow \gamma\gamma$ in LEPII data, including experimental acceptances and efficiencies, is likely to provide improved sensitivity to $g_{a\gamma\gamma}$ via $e^+e^- \rightarrow a\gamma \rightarrow 3\gamma$. For a scalar ALP, the leading LbL contribution was found to have the wrong sign relative to the muon $g - 2$ discrepancy. However, the BZ contribution could have either sign depending on the relative sign of $g_{s\gamma\gamma}$ and $y_{s\mu}$. If only the LbL piece is considered (e.g. $y_{s\mu}$ effects are assumed to be negligible), one can obtain the rather stringent indirect bound $g_{s\gamma\gamma} < \mathcal{O}(10^{-3}$ GeV$^{-1})$. For CP-violating ALP couplings, the electron EDM was found to probe much smaller, theoretically better accommodated ALP interactions over a range of parameters that overlap with the SHiP proposal [26]. Future improvements in electron and nucleon EDM searches is strongly warranted both as a way to explore ALP parameters and to potentially unveil a new source of CP violation. Indeed, any new source of CP violation beyond SM expectations could impact our understanding of the matter-antimatter asymmetry of our Universe.

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