LHC as an Axion Factory: Probing an Axion Explanation for $(g - 2)_\mu$
with Exotic Higgs Decays

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We argue that a large region of so-far unconstrained parameter space for axionlike particles (ALPs),
where their couplings to the standard model are of order $(0.01 – 1) \text{ TeV}^{-1}$, can be explored by searches for
the exotic Higgs decays $h \rightarrowZA$ and $h \rightarrow aa$ in run 2 of the LHC. Almost the complete region in which
ALPs can explain the anomalous magnetic moment of the muon can be probed by searches for these decays
with subsequent decay $a \rightarrow \gamma \gamma$, even if the relevant couplings are loop suppressed and the $a \rightarrow \gamma \gamma$
branching ratio is less than 1.

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Axionlike particles (ALPs) appear in well-motivated extensions of the standard model (SM), e.g., as a way to
address the strong CP problem, as mediators between the SM and a hidden sector, or as pseudo-Nambu-Goldstone
bosons in extensions of the SM with a broken global symmetry. If ALP couplings to muons and photons are
present, the $3.6 \sigma$ deviation of the anomalous magnetic moment of the muon $g_\mu - 2 = (g - 2)_\mu / 2$ from its SM value
can be explained by ALP exchange [1,2]. Collider experiments can be used to search directly and indirectly for
ALPs. Besides ALP production in association with photons, jets, and electroweak gauge bosons [3–6], searches for
the decay $Z \rightarrow \gamma a$ are sensitive to ALPs with up to weak-scale masses [7–9]. Utilizing the exotic Higgs decay
$h \rightarrow aa$ to search for light pseudoscalars was proposed in [10–12]. Several experimental searches for this mode
have been performed, constraining various final states [13–19]. Surprisingly, the related decay $h \rightarrowZA$ has not
been studied experimentally, even though analogous searches for new heavy scalar bosons decaying into heavy Za
have been performed [20]. The reason for this is, perhaps, the suppression of the $h \rightarrowZA$ decay in the decoupling
limit in two-Higgs-doublet models, in general, and supersymmetric models, in particular [21]. In models featuring a
gauge-singlet ALP, there is no dimension-5 operator mediating $h \rightarrowZA$ decay at tree level, and hence, this
mode has not received much theoretical attention either. Here, we point out that fermion-loop graphs arising at
dimension-5 order and tree-level contributions of dimension-7 operators can naturally induce an $h \rightarrowZA$ decay rate
of similar magnitude as the $h \rightarrowZZ$ decay rate in the SM, which is a prime target for run 2 at the LHC. Furthermore,
in certain classes of UV completions, the $h \rightarrowZZ$ branching ratio can be enhanced parametrically to the level of $O(10\%)$ and higher. A search for this decay mode is therefore well motivated and can provide nontrivial information about the underlying UV theory.

In this Letter, we show that searches for $h \rightarrowZA$ and
$h \rightarrow aa$ decays in run 2 at the LHC can probe a large region of
so-far unconstrained parameter space in the planes spanned by the ALP mass and its couplings to photons
or leptons, covering, in particular, the difficult region above 30 MeV and probing ALP-photon couplings as small as
$10^{-10} \text{ GeV}^{-1}$. If the $(g - 2)_\mu$ anomaly is explained by a light pseudoscalar, this particle will be copiously produced
in Higgs decays and should be discovered at the LHC. A detailed discussion of the searches presented here, along
with a comprehensive analysis of electroweak precision bounds, flavor constraints, and the relevance of ALPs to
other low-energy anomalies, will be presented elsewhere [22].

We consider a light, gauge-singlet CP-odd boson $a$, whose mass is protected by a (approximate) shift symmetry.
Its interactions with SM fermions and gauge fields start at dimension-5 order and are described by the effective
Lagrangian [23]

$$L_{\text{eff}} = g_a^2 C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^A G^{\mu\nu,A} + g^2 C_{WW} \frac{a}{\Lambda} W^A_{\mu\nu} \bar{W}^{\mu\nu,A} +$$

$$+ g^2 C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \bar{B}^{\mu\nu} + \sum_f \frac{C_{\gamma\gamma}}{2} \frac{\partial^\mu a}{\Lambda} \bar{f} \gamma^\mu f.$$ (1)

Here, $\Lambda$ is the characteristic scale of global symmetry breaking, which we assume to be above the weak scale. It is
common practice in the ALP literature to absorb potential loop factors, which could arise in weakly coupled UV
completions, into the Wilson coefficients $C_{\gamma\gamma}$. After electroweak symmetry breaking, the effective ALP coupling
to two photons is described by a term analogous to the hypercharge coupling, but with gauge coupling $e^2$ and
coefficient $C_{\gamma\gamma} = C_{WW} + C_{BB}$. Note that at this order, there are no ALP couplings to the Higgs doublet $\phi$. They appear
first at dimensions 6 and 7 and read
\[ L_{\text{eff}}^{D\geq 6} = \frac{C_{\phi h}}{\Lambda^4} (\partial^\mu a)(\partial^\mu a)\phi^i \phi + \frac{C_{\phi h}^{(7)}}{\Lambda^6} (\partial^\mu a)\phi^i iD_\mu \phi + \text{H.c.})\phi^i \phi + \cdots. \]  

The first term is the leading Higgs-portal interaction allowed by the shift symmetry, while the second term is the leading polynomial operator mediating the decay \( h \to Za \) at tree level [24]. If the electroweak symmetry is realized nonlinearly, insertions of \( \phi^i \phi \) are accompanied by factors \( 1/f^2 \) rather than \( 1/\Lambda^2 \), where \( f \) is the analog of the pion decay constant [25]. As a result, the contribution of \( C_{Zh}^{(7)} \) can be enhanced by a factor \( \sim \Lambda^2 / f^2 \) if \( f < \Lambda \) [6]. Importantly, in models featuring heavy particles which receive their mass from electroweak symmetry breaking, an additional nonpolynomial dimension-5 operator can be generated [24]. It gives a contribution to the \( h \to aa \) amplitude that is parametrically enhanced compared with the \( h \to z a \) amplitude. The decay \( h \to Za \) is unique in the sense that a tree-level dimension-5 coupling can only arise from a nonpolynomial operator. A search for this decay mode can thus provide complementary information to \( h \to aa \) searches and offer important clues about the underlying UV theory.

In this Letter, we consider decays of the ALP into photons and charged leptons, with decay rates given by

\[ \Gamma(a \to \gamma \gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} C_{Z\gamma}^2, \]

\[ \Gamma(a \to \ell^+ \ell^-) = \frac{m_a^2 m_\ell^2}{8\pi\Lambda^2} C_{Z\ell}^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}}. \]  

The same couplings enter the diagrams shown in Fig. 1, which show the ALP-induced contributions to the anomalous magnetic moment \( a_\mu \) of the muon, whose experimental value [26] differs by more than \( 3\sigma \) from the SM prediction:

\[ a_\mu^\text{exp} - a_\mu^\text{SM} = (27.4 \pm 7.6) \times 10^{-10} \]  

It has been emphasized recently that this discrepancy can be explained by postulating the existence of an ALP with sizable couplings to both photons and muons [2]. While the first graph in Fig. 1 gives a contribution of the wrong sign [28,29], the second diagram can overcome this contribution if the Wilson coefficient \( C_{Z\gamma} \) is sufficiently large [1,2]. At one-loop order, we find the new-physics contribution

\[ \delta a_\mu = \frac{m_a^2}{\Lambda^2} \left[ \frac{c_{\mu\gamma}^2}{16\pi^2} h_1(x) - \frac{2\alpha}{\pi} c_{\mu\tau} C_{Z\tau} \left( \ln \frac{\Lambda^2}{m_\mu^2} - h_2(x) \right) \right], \]  

where \( x = m_a^2 / m_\mu^2 \). The functions \( h_i(x) \) are positive and satisfy \( h_1(0) = h_2(0) = 1 \) and \( h_1(x) \approx 0, h_2(x) \approx (\ln x + \frac{1}{2}) \) for \( x \gg 1 \). Their analytical expressions will be given in [22]. Our result for the logarithmically enhanced contribution proportional to \( C_{Z\gamma} \) agrees with [2]. We omit the numerically subdominant contribution from \( Z \) exchange, which is suppressed by \( (1 - 4\sin^2 \theta_W)^2 \) and comes with a smaller logarithm \( \ln (\Lambda^2 / m_\mu^2) \). A positive shift of \( a_\mu \) can be obtained if \( c_{\mu\mu} \) and \( C_{Z\gamma} \) have opposite signs. Figure 2 shows the parameter space in the \( c_{\mu\mu} - C_{Z\gamma} \) plane in which the muon anomaly can be explained in terms of an ALP with mass of 1 GeV (we use \( \Lambda = 1 \) TeV in the argument of the logarithm). The contours are insensitive to \( m_\mu \) for lighter ALP masses and broaden slightly for \( m_\mu > 1 \) GeV. A resolution of the anomaly is possible without much tuning as long as one of the two coefficients is of order \( \Lambda / \text{TeV} \), while the other can be of similar order or larger. Since \( c_{\mu\mu} \) always enters observables in combination with \( m_\mu \), it is less constrained by perturbativity than \( C_{Z\gamma} \). We thus consider the region with \( |C_{Z\gamma}| / \Lambda \lesssim 2 \) TeV\(^{-1} \) and \( |c_{\mu\mu}| \geq |C_{Z\gamma}| \) as the most plausible parameter space.

We now turn our attention to the exotic Higgs decays \( h \to Za \) and \( h \to aa \), arguing that over wide regions of parameter space—including the region motivated by \( (g - 2)_\mu \)—the high-luminosity LHC can serve as an ALP factory. At the tree level, the effective interactions in (2) and (3) yield the decay rates

\[ \Gamma(h \to Za) \approx \frac{m_a^2 m_h^2}{16\pi^2} \]

\[ \Gamma(h \to aa) \approx \frac{m_a^2 m_h^2}{16\pi^2} ]\]
The boost factor is \( (1 - x - y)^2 - 4xy \), and we have defined \( C_{Zh} \equiv C_{Zh}^{(5)} \cdot (\lambda^2/2\Lambda^2)C_{Zh}^{(7)} \). Integrating out the top quark yields the one-loop contributions \( \Delta C_{Zh} \approx -0.016c_t^2 \), and \( \Delta C_{ah} \approx 0.17c_t^2 \). For natural values of the Wilson coefficients, the rates in (6) can give rise to large branching ratios. For instance, one finds \( Br(h \to Z\alpha) = 0.1 \) for \( C_{Zh}/\Lambda \approx 0.34\text{TeV}^{-1} \) and \( Br(h \to aa) = 0.1 \) for \( C_{ah}/\Lambda \approx 0.62\text{TeV}^{-2} \). Even in the absence of large tree-level contributions, the loop-induced top-quark contribution yields \( Br(h \to aa) = 0.01 \) for \( C_{ah}/\Lambda \approx 0.04\text{TeV}^{-1} \), while a combination of the top-quark contribution and the dimension-7 contribution from \( C_{Zh}^{(7)} \) can give \( Br(h \to Z\alpha) = \mathcal{O}(10^{-3}) \) without tuning. With such rates, large samples of ALPs will be produced in run 2 of the LHC. The model-independent bound \( Br(h \to \text{BSM}) < 0.34 \) derived from the global analysis of Higgs couplings [30] implies \( |C_{Zh}|/\Lambda \lesssim 0.72 \text{TeV}^{-1} \) and \( |C_{ah}|/\Lambda^2 < 1.34 \text{TeV}^{-2} \) at 95% C.L.

If the ALP is light or weakly coupled to SM fields, its decay length can become macroscopic, and hence only a small fraction of ALPs decay inside the detector. Since to a good approximation Higgs bosons at the LHC are produced along the beam direction, the average decay length of the ALP perpendicular to the beam is \( \bar{L}_{\perp}(\theta) = \sin \theta \bar{L}_{\perp}(\theta)/\Gamma_a \), where \( \theta \) is the angle of the ALP with respect to the beam axis in the Higgs-boson rest frame, \( \beta_\gamma \) and \( \gamma_\alpha \) are the usual relativistic factors in that frame, and \( \Gamma_a \) is the total decay width of the ALP. The ALP is observed in the decay mode \( \alpha \to XX \), we can express its total width in terms of the branching fraction and partial width for this decay, i.e.,

\[
L_{\perp}(\theta) = \sin \theta \sqrt{\gamma_\alpha - 1} \frac{Br(\alpha \to XX)}{\Gamma(\alpha \to XX)}.
\]

The boost factor is \( \gamma_\alpha = (m_h^2 - m_X^2 + m_a^2)/(2m_a m_h) \) for \( h \to Z\alpha \) and \( \gamma_\alpha = m_h/(2m_a) \) for \( h \to aa \). As a consequence, only a fraction of events given by

\[
\bar{f}_{\text{dec}} = 1 - \langle e^{-L_{\text{dec}}/L_{\perp}(\theta)} \rangle,
\]

where the brackets mean an average over the solid angle, decays before the ALP has traveled a distance \( L_{\text{det}} \) set by the relevant detector components. We define the effective branching ratios

\[
Br(h \to Z\alpha \to \ell^+\ell^- XX)_{\text{eff}} = Br(h \to Z\alpha)Br(\alpha \to XX)f_{\text{dec}} \times Br(Z \to \ell^+\ell^-),
\]

\[
Br(h \to aa \to 4X)_{\text{eff}} = Br(h \to aa)Br(\alpha \to XX)^2 f_{\text{dec}}^2,
\]

where \( Br(Z \to \ell^+\ell^-) = 0.0673 \) for \( \ell = e, \mu \). If the ALPs are observed in their decay into photons, we require \( L_{\text{det}} = 1.5 \) m, such that the decay occurs before the electromagnetic calorimeter. For a given value of the Wilson coefficients \( C_{Zh} \) or \( C_{ah} \), we can now present the reach of high-luminosity LHC searches for \( h \to Z\alpha \to \ell^+\ell^- \gamma \gamma \) and \( h \to aa \to 4\gamma \) decays in the \( m_\alpha < |C_{TT}| \) plane. We require at least 100 signal events in a data set of 300 fb\(^{-1}\) at \( \sqrt{s} = 13 \text{ TeV} \) (run 2), considering

\[
C_{Zh}, C_{ah} \rightarrow \text{SUMICO} \quad \gamma \gamma \quad \text{SN1987a} \quad \text{Cosmology}
\]

FIG. 3. Constraints on the ALP mass and coupling to photons derived from various experiments (colored areas without boundaries, adapted from [5]) along with the parameter regions (shaded in light green) that can be probed in LHC run 2 (300 fb\(^{-1}\) integrated luminosity) using the Higgs decays \( h \to Z\alpha \to \ell^+\ell^- \gamma \gamma \) (top) and \( h \to aa \to 4\gamma \) (bottom). We require at least 100 signal events in each channel. The contours in the upper panel correspond to \( |C_{Zh}|/\Lambda = 0.72 \text{TeV}^{-1} \) (solid), 0.1 TeV\(^{-1}\) (dashed), and 0.015 TeV\(^{-1}\) (dotted). Those in the lower panel refer to \( |C_{ah}|/\Lambda^2 = 1 \text{TeV}^{-2} \) (solid), 0.1 TeV\(^{-2}\) (dashed), and 0.01 TeV\(^{-2}\) (dotted). The red band shows the preferred parameter space where the \( (g - 2)_\mu \) anomaly can be explained at 95% C.L.
gluon-fusion-induced Higgs production with cross section $\sigma(pp \to h + X) = 48.52 \text{ pb}$ [31] and the effective Higgs branching ratios defined above. Figure 3 shows this parameter space in light green. In the upper panel we present the reach of run-2 searches for $h \to Za = e^+e^\gamma\gamma$ decays assuming $|C_{Zh}|/\Lambda = 0.72 \text{ TeV}^{-1}$ (solid contour), $0.1 \text{ TeV}^{-1}$ (dashed contour), and $0.015 \text{ TeV}^{-1}$ (dotted contour). The lower panel shows the reach of searches for $h \to aa \to 4\gamma$ decays assuming $|C_{ah}|/\Lambda^2 = 1 \text{ TeV}^{-2}$ (solid), $0.1 \text{ TeV}^{-2}$ (dashed), and $0.01 \text{ TeV}^{-2}$ (dotted). Reaching sensitivity to couplings smaller than $|C_{Zh}|/\Lambda < 0.01 \text{ TeV}^{-1}$ and $|C_{ah}|/\Lambda^2 < 0.005 \text{ TeV}^{-2}$ would require larger luminosity. These contours are essentially independent of the $a \to \gamma\gamma$ branching ratio unless this quantity falls below certain threshold values. For $h \to Za$, one needs $\text{Br}(a \to \gamma\gamma) > 3 \times 10^{-4}$ (solid), $0.011$ (dashed), and $0.46$ (dotted). For $h \to aa$, one needs instead $\text{Br}(a \to \gamma\gamma) > 0.006$ (solid), $0.049$ (dashed), and $0.49$ (dotted). It is thus possible to probe the ALP-photon coupling even if the ALP predominantly decays into other final states. The insensitivity of the contours to $\text{Br}(a \to \gamma\gamma)$ can be understood by considering the behavior of the quantity $f_{\text{dec}}$ in (8). The contours limiting the green regions from the left arise from the region of large ALP decay length, $L_a > L_{\text{det}}$, in which case $f_{\text{dec}} \approx (\pi/2)L_{\text{det}}/L_a \propto \Gamma(a \to X\gamma)/\text{Br}(a \to XX)$. In this region the effective branching ratios in (9) become independent of $\text{Br}(a \to \gamma\gamma)$ and only depend on the partial rate $\Gamma(a \to X\gamma) \propto m_a^2 C_{\gamma \gamma}^2$. On the other hand, the number of signal events inside the probed contour regions is bounded by the yield computed with $f_{\text{dec}} = 1$ (prompt ALP decays), and this number becomes too small if $\text{Br}(a \to XX)$ falls below a critical value.

The red band in the panels shows the parameter region in which the $(g - 2)_\mu$ anomaly can be explained. We consider only the theoretically preferred region $|c_{\mu\mu}| \gtrsim |C_{\gamma\gamma}|$ and impose the constraint $|c_{\mu\mu}|/\Lambda \lesssim 10 \text{ TeV}^{-1}$. In principle, larger values of $|C_{\gamma\gamma}|$ can also explain the anomaly. Almost the entire parameter space where the red band is not excluded by existing experiments—the region between $30 \text{ MeV}$ and $60 \text{ GeV}$—can be covered by searches for exotic Higgs decays. Even if the relevant couplings $C_{Zh}$ and $C_{ah}$ are loop suppressed, large event yields in this region can be expected in run 2.

Existing searches for $h \to aa \to 4\gamma$ decay already imply interesting bounds on the ALP parameter space. ATLAS has performed dedicated searches for this signature at $m_a = 100 \text{ MeV}$, $200 \text{ MeV}$, and $400 \text{ MeV}$ [32], as well as in the high-mass region $m_a = 10$—$62.5 \text{ GeV}$ [16]. Lighter ALPs produced in Higgs decays would be highly boosted, and the final-state photon pairs would therefore be strongly collimated. For $m_a < 100 \text{ MeV}$ these pairs cannot be resolved in the calorimeter and would be reconstructed as single photons [10,12,33,34]. Hence, the existing measurements of the $h \to \gamma\gamma$ rate [30] can also be used to derive constraints on the ALP couplings. At present, nontrivial exclusion regions can be derived for values $|C_{ah}|/\Lambda^2 \gtrsim 0.1 \text{ TeV}^{-2}$ [22]. Currently, there exist no dedicated searches for the $h \to Za = e^+e^\gamma\gamma\gamma$ decay channel. However, for $m_a < 50 \text{ MeV}$ the current upper bounds on the $h \to Z\gamma$ rate [35,36] imply a weak constraint. Since the $h \to Za$ signal does not interfere with the decay $h \to Z\gamma$, its

![FIG. 4. Constraints on the ALP mass and coupling to electrons derived from various experiments (colored areas without boundaries, adapted from [37,38]) along with the parameter regions (shaded in light green) that can be probed in LHC run 2 (300 fb$^{-1}$ integrated luminosity) using the Higgs decays $h \to Za = e^+e^\gamma\gamma\gamma$ (top) and $h \to aa = e^+e^-e^+e^-$ (bottom). We require at least 100 signal events in each channel. The contours in the upper panel correspond to $|C_{Zh}|/\Lambda = 0.72 \text{ TeV}^{-1}$ (solid), $0.1 \text{ TeV}^{-2}$ (dashed), and $0.01 \text{ TeV}^{-2}$ (dotted). Those in the lower panel refer to $|C_{ah}|/\Lambda^2 = 1 \text{ TeV}^{-2}$ (solid), $0.1 \text{ TeV}^{-2}$ (dashed), and $0.01 \text{ TeV}^{-2}$ (dotted).]
contribution would lead to an enhancement of the $h \to Z\gamma$ rate. This would provide a very interesting signal once the decay $h \to Z\gamma$ becomes within reach of the LHC.

The couplings of ALPs to other SM particles can be probed in an analogous way. In Fig. 4 we consider the decay $a \to e^+e^-$. We use $L_{\text{det}} = 2$ cm, such that reconstructed events correspond to decays before the inner tracker, and we require 100 signal events in a data set of 300 fb$^{-1}$. The two panels show the reach of run-2 searches for $h \to Z\gamma \to \ell^+\ell^-e^+e^-$ (top) and $h \to aa \to e^+e^-\gamma\gamma$ (bottom), using the same values for the Wilson coefficients $C_{Zh}$ and $C_{ah}$ as in Fig. 3. Once again, the contours are essentially independent of the $a \to e^+e^-$ branching ratio unless this quantity falls below certain threshold values, which are the same as before. For $h \to Za$, one needs $\text{Br}(a \to e^+e^-) > 2 \times 10^{-4}$ (solid), 0.011 (dashed), and 0.46 (dotted). For $h \to aa$, one needs instead $\text{Br}(a \to e^+e^-) > 0.006$ (solid), 0.049 (dashed), and 0.49 (dotted).

In summary, we have shown that LHC searches for the exotic Higgs decays $h \to Z\gamma$ and $h \to aa$ in run 2 with an integrated luminosity of 300 fb$^{-1}$ can probe the ALP couplings to photons and electrons over a large region in parameter space, which almost perfectly complements the regions covered by existing searches. Importantly, the parameter space, which almost perfectly complements the regions covered by existing searches. Importantly, the parameter space in which an ALP can provide an explanation of the $(g − 2)_\mu$ anomaly is almost completely covered by these searches. The reach can be extended with more luminosity (the event yields increase by a factor $\sim 10.7$ for 3000 fb$^{-1}$ luminosity at $\sqrt{s} = 14$ TeV), and similar searches can be performed at a future lepton collider. Our yield estimates can be improved using dedicated analyses, including reconstruction efficiencies and exploiting displaced-vertex signatures. Analogous limits can also be obtained for ALP decays into pairs of muons, taus, jets, and heavy quarks, as well as for invisible decays or metastable ALPs [22].

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