

Tracking axionlike particles at the LHC

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Highly boosted axionlike particles decaying into photon pairs are notoriously hard to detect at the LHC. The collimated decay photons cannot be individually reconstructed using only electromagnetic calorimeter information, making the signal less distinguishable from background. In this paper, we propose a search strategy to address this issue, exploiting the fact that a fraction of the decay photons convert into electron-positron pairs inside the tracking detector. The resulting tracks can be resolved with high resolution, making it possible to separate the two collimated photons and resolve a displaced decay vertex. To demonstrate the effectiveness of this approach, we apply it to ALPs in the challenging MeV–GeV range produced via vector boson fusion. We find that such a search could give sensitivity to untested parameter space.

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I. INTRODUCTION

The mass region around 10 MeV–10 GeV is one of the most challenging targets to search for feebly interacting particles (FIPs) [1]. Somewhat surprisingly, relatively strong couplings are most problematic to test. This is due to a combination of several factors. The significant mass of the prospective particle requires reasonably high-energy experiments, suggesting accelerator-based fixed-target or collider experiments. The former, however, suffer from the relatively short lifetimes of the FIPs causing the visible decay products to be absorbed in the shielding, thereby suppressing the signal. Moreover, they usually do not have enough energy to go far beyond the GeV scale. At present, low-energy–high-intensity collider e^+e^- experiments such as Belle II [2,3] seem most promising in this direction.

High-energy colliders such as the LHC, on the other hand, have plenty of energy and sufficient luminosity. Indeed, for an axionlike particle (ALP) with a mass of 200 MeV and a two-photon coupling $g_{a\gamma\gamma} = 1 \text{ TeV}^{-1}$, the production cross section is about a pb such that a few $\times 10^5$ ALPs would have already been produced up to run 2. This is clearly not a small number. The problem is that the typical signal is hard to identify amidst the background. A

prime example of this are ALPs coupled to two photons. In principle, their two-photon decay should enable a search for a peak in the invariant mass spectrum, similar to what was done for the Higgs discovery [4,5]. However, for masses in the 10 MeV to 10 GeV range, ALPs are typically produced with a relatively high boost. As a consequence, the two decay photons are highly collimated, making their individual identification particularly difficult. At the lower end of this mass region, the photons become so collimated that they effectively look like a single photon originating from the point where the ALP was produced. This clearly prevents the determination of an invariant mass but also makes it difficult to identify a (possibly only slightly) displaced vertex. In addition, the region around 100 MeV to GeV is riddled with backgrounds from mesons that have similar or identical decay products. It is therefore imperative to find strategies to mitigate such backgrounds.¹

Work in this direction has already achieved some successes in the past. ATLAS [7] and CMS [8] have implemented dedicated triggers geared toward improving their sensitivity to low-mass diphoton resonances. Along these lines, Ref. [9] has proposed modifying the currently used photon isolation requirements at the trigger level to avoid discarding potential ALP decay events containing collimated photon pairs. More generally, other studies have proposed using modified

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¹One possibility is to select special production channels. For example, if the two-photon coupling is inherited from a generic combination of electroweak couplings, ALPs may be efficiently produced in Z decays, which can then be identified [6].

calorimetric shower-shape variables tailored to collinear multiphoton or photon-jet objects [10–16].

Collimated diphotons can also be discriminated by their increased likelihood of producing a converted photon event, i.e., an increased probability that a photon converts into an electron-positron pair. This was proposed in [17] originally to distinguish diphoton and four-photon final states, thereby detecting the presence of intermediate (pseudo)scalars in the decay of a heavier resonance.

As in [17], in this work we make use of photon conversions but go further by exploiting the exquisite spatial resolution of the ATLAS tracking detector to identify collimated photon pairs originating from the *displaced* decay of a new (pseudo)scalar state. The superior angular resolution of the tracker—orders of magnitude better than the electromagnetic calorimeter—makes it possible to resolve two very collimated photons that are otherwise indistinguishable from a single photon. Requiring the decay vertex to be displaced from the primary interaction vertex additionally suppresses SM hadronic backgrounds.

To showcase its potential, we apply our search strategy to a model of axionlike particles produced through photon and vector boson fusion and decaying to photon pairs. We find that already existing data provide sensitivity to a significant range of so-far untested parameter space. While for concreteness we have focused on a specific example particle and production mechanism, we stress that the same strategy is applicable to ALPs produced through other mechanisms as well as other particles featuring a delayed decay into two or more photons. Moreover, while we focus on ATLAS as a concrete example for the detector, the same technique should also be applicable to CMS or other instruments with the appropriate adjustments.

This paper is structured as follows. We start by specifying the benchmark ALP model and characterize the ALP production and decay processes at the LHC in Sec. II. Our proposed search strategy is described in detail in Sec. III. Section IV is devoted to the discussion of its application to the ALP model under study. Conclusions are drawn in Sec. V.

II. PHYSICS CASE STUDY: AXIONLIKE PARTICLES AT THE LHC

A. Benchmark ALP model

The benchmark model (cf., e.g., Ref. [1]) for many ALP studies is that of an ALP coupled electromagnetically to the SM via the Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}. \quad (2.1)$$

For high-energy probes, such as the ones of interest here, couplings to other electroweak gauge bosons can also play an important role. Thus, it is necessary to specify those in a consistent manner. For concreteness, we consider an ALP coupled to the hypercharge gauge boson field strength $B^{\mu\nu}$

(see, e.g., Refs. [6,18,19]),

$$\begin{aligned} \mathcal{L} &\supset -\frac{1}{4}\frac{1}{c_W^2}g_{a\gamma\gamma}aB_{\mu\nu}\tilde{B}^{\mu\nu} \\ &= -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\frac{s_W^2}{c_W^2}g_{a\gamma\gamma}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} \\ &\quad + \frac{1}{4}\frac{2s_W}{c_W}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{Z}^{\mu\nu}. \end{aligned} \quad (2.2)$$

The second line shows the couplings to the photon and the Z boson after electroweak symmetry breaking (EWSB). In the Lagrangian above, s_W and c_W represent the sine and cosine of the Weinberg angle, and the coupling strengths are normalized to recover the same photon coupling as in Eq. (2.1).

Our mass range of interest is targeted by an extensive program of searches at high-energy experiments looking for axionlike particles with electromagnetic couplings. The impact of these searches in m_a vs $g_{a\gamma\gamma}$ is shown in Fig. 1. At the lowest masses considered here, around (10–100) MeV, ALPs can be copiously produced at electron and proton fixed-target experiments [20]. A combination of experiments [21–25]—among which NA64 [25], NuCal [24], and E137 [23] give the strongest limits—shape the red region labeled as “Beam dumps” in Fig. 1. At intermediate masses, around (0.1 – few) GeV, e^+e^- colliders take over as the prime environment to look for ALPs. The orange region shows the LEP [26,27] limits derived in [6,28], while the green region corresponds to the exclusion by Belle-II [2,3]. To avoid clutter, superseded bounds from PrimEx [29], CLEO [30], BABAR [31], and CDF [32] are not shown in Fig. 1. The most massive ALPs, greater than

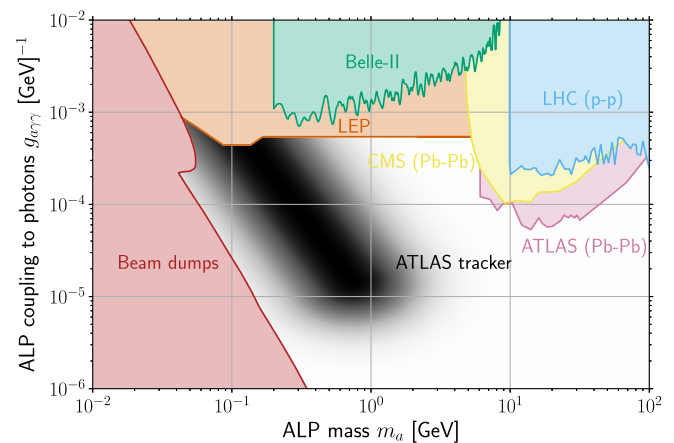


FIG. 1. Existing constraints on electromagnetically coupled ALPs in the relevant mass range around MeV to multi-GeV. We show bounds from beam dump searches [23–25], LEP [6], Belle-II [3], Pb-Pb collisions at CMS [35] and ATLAS [36], and p-p collisions at the LHC [28]. The black shaded region represents the region that we target in our study, based on a simplistic estimation using the ALP decay length and production cross section at the LHC.

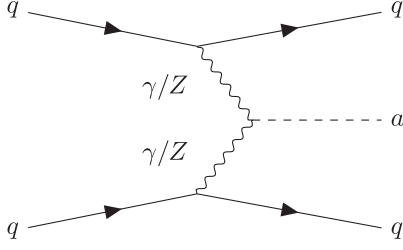


FIG. 2. Vector boson fusion process by which an electromagnetically coupled ALP is produced in proton-proton collisions at the LHC.

or around a few GeV, are best searched for at the LHC [33]. The enhanced $\gamma\gamma$ cross section in ultraperipheral heavy-ion (Pb-Pb) collisions [28,34] enables CMS [35] and ATLAS [36] to place stringent constraints above a few GeV. At the highest masses, searches focus on ALPs produced via photon or vector boson fusion in p-p collisions, which subsequently decay to photon pairs. A combination of multiple searches [4,37–44] and reinterpretations [6,18,28,34,45–47] probes ALPs with masses up to above the TeV scale.

In the present study, we focus on the model of an electromagnetically coupled ALP with the Lagrangian in Eq. (2.2). That said, our proposed methods are applicable in a variety of other situations where two or more highly collimated photons are the primary signal. Examples include more general axionlike particles with additional couplings, which can be produced by different processes such as gluon fusion, decays of Higgs bosons or mesons, etc. Our strategy can thus help to adapt other existing searches for ALPs [19,48–51] to be effective in the 10 MeV – 10 GeV region.

B. ALP production and decay

The leading processes by which electromagnetically coupled ALPs can be produced at the LHC are photon and vector boson fusion. The diagrams corresponding to these processes are shown in Fig. 2. In our benchmark model where the ALP couples to the hypercharge gauge boson, possible channels are $\gamma\gamma \rightarrow a$, $ZZ \rightarrow a$, and $\gamma Z \rightarrow a$. At high energies, the three channels contribute at a similar level.

In order to characterize the kinematic properties of the produced ALPs, we run a simulation using MadGraph5 [52]. The process $pp \rightarrow a(\rightarrow \gamma\gamma)jj$ was simulated at $\sqrt{s} = 13$ TeV with a transverse momentum requirement of 10 GeV for each outgoing photon. No separation requirement was imposed on the photon pairs at this stage. The production cross section,

$$\sigma(pp \xrightarrow{\text{VBF}} a) \simeq 18 \text{ fb} \left(\frac{g_{a\gamma\gamma}}{0.1 \text{ TeV}^{-1}} \right)^2, \quad (2.3)$$

is largely independent of the ALP mass in the range of interest. This value can be used to estimate a lower limit to

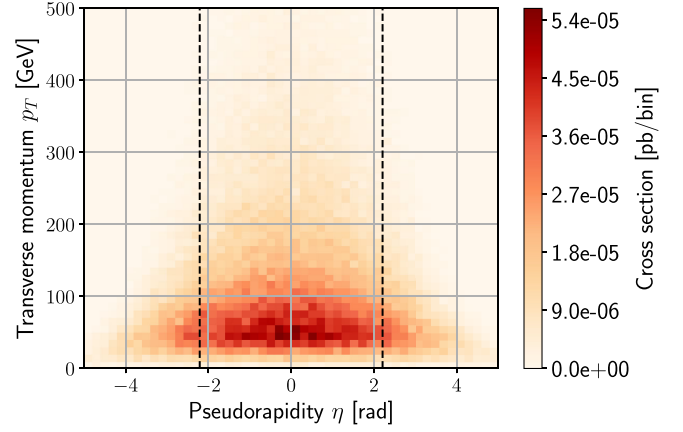


FIG. 3. Pseudorapidity and transverse momentum distribution of ALPs produced through VBF from pp collisions at a center-of-mass energy of 13 TeV. The vertical dashed lines show the angular extent of the ATLAS TRT coverage. For this figure we fix the mass of the ALP to be $m_a = 100$ MeV (the distribution does not appreciably change for values of m_a between 10 MeV and 10 GeV).

the values of the ALP-photon coupling accessible at the LHC. A coupling of $g_{a\gamma\gamma} \sim 0.01 \text{ TeV}^{-1}$ results in 50–60 ALPs being produced through vector boson fusion at run 3 of the LHC. We use this figure as a guideline to estimate the target region of our search strategy in the ALP parameter space shown in Fig. 1, although the actual sensitivity depends on the precise search and detector efficiencies, as discussed below.

As we will see, the most important kinematic variables for our analysis are the ALP transverse momentum (p_T) and pseudorapidity (η). The combined distribution for these quantities is shown in Fig. 3. The production is predominantly central, with around 80% of the events being contained in the $-2.2 \leq \eta \leq 2.2$ region, which corresponds to the TRT coverage. The p_T distribution is mostly concentrated at low momenta $p_T \lesssim 100$ GeV. However, around 25% of the produced ALPs have a transverse momentum larger than 150 GeV (the single-photon trigger at ATLAS was set to 140 GeV during run 2 [7]).

After the ALPs are produced, they decay almost exclusively into two photons (loop-induced decays² to charged fermion-antifermion pairs have small rates, and we neglect them). Decays to other gauge bosons would be possible for ALPs with $m_a \gtrsim 100$ GeV, but in this work we are interested in lighter ALPs with masses below 10 GeV. The decay rate of an ALP to two photons is given by (cf., e.g., Refs. [6,18,19])

$$\Gamma(a \rightarrow \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}. \quad (2.4)$$

²See [53–55] for calculations of the loop-induced coupling and its renormalization group running.

The inverse of this quantity gives the ALP proper lifetime. The decay length in the relativistic limit then follows by multiplication with the relativistic boost factor, p_a/m_a . For the values of ALP mass and photon coupling of interest here, the ALP can have a macroscopic decay length, especially when the boost factor is taken into account. For $p_a = 150$ GeV, which is representative of the typical momentum of ALPs in our analysis, the decay length is

$$\ell_{\text{decay}} \simeq 40 \text{ cm} \left(\frac{p_a}{150 \text{ GeV}} \right) \left(\frac{0.2 \text{ GeV}}{m_a} \right)^4 \left(\frac{0.1 \text{ TeV}^{-1}}{g_{a\gamma\gamma}} \right)^2. \quad (2.5)$$

Decay lengths between a centimeter and a few meters can result in ALP decay vertices that can be identified as displaced in the ATLAS tracker. ALPs with longer decay lengths typically decay outside of the inner detector and thus cannot leave any track in the tracker. A lower limit on the decay length is necessary in order to eliminate background, as we will see. This requirement, together with a sufficient production cross section, delineates a rough region in the ALP parameter space where our proposed search strategy can be applicable, indicated as the black shaded region in Fig. 1.

III. SEARCH STRATEGY: IDENTIFYING HIGHLY COLLIMATED PHOTON PAIRS AND DISPLACED VERTICES WITH THE ATLAS TRACKER

The main challenge for low-mass ALP searches at the LHC is that the two decay photons are highly collimated. For axion momenta $p_a \sim \mathcal{O}(100 \text{ GeV})$, their angular separation

$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} \sim \frac{2m_a}{p_a} \quad (3.1)$$

falls below 10^{-2} for $m_a \lesssim 1 \text{ GeV}$, as confirmed by our simulations (see Fig. 4). The ATLAS ECAL middle layer used in photon reconstruction and identification in run 2 has a cell size of $\Delta R \simeq 0.035$ [56], and the coarser L1 trigger and reconstruction granularity corresponds to $\Delta R \simeq 0.14$; both are larger than the typical photon-pair separation for sub-GeV ALPs. As can be seen in Fig. 4, for $m_a \lesssim 1 \text{ GeV}$ most decay photon pairs deposit their energy in the same ECAL cell and are indistinguishable from a single photon.

Our strategy exploits the fact that a sizable fraction of photons convert into e^+e^- pairs inside the tracking detector, allowing their trajectories to be reconstructed with the far superior position resolution of the tracker. When both photons convert, this makes it possible to not only separate the two-photon event from a single-photon one, but also to locate the ALP decay vertex precisely enough to identify it as displaced, thus suppressing hadronic backgrounds.

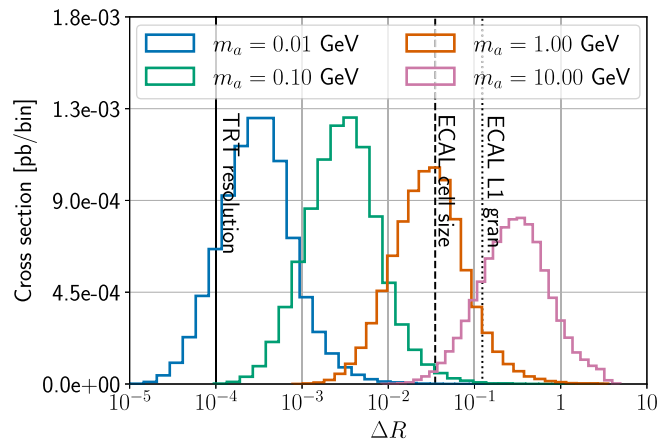


FIG. 4. The ΔR distribution of photon pairs produced in the decays of ALPs generated via VBF at the LHC, for a series of ALP masses and fixed $g_{a\gamma\gamma} = 0.1 \text{ TeV}^{-1}$. The vertical solid line corresponds to the angular resolution of the ATLAS TRT. The vertical dashed line shows the angular resolution of an ECAL tower used for photon selection at the L1 trigger. The vertical dotted line represents the granularity of a single ECAL cell in the middle layer. ALPs with $m_a \lesssim 1 \text{ GeV}$ decay into photons which are usually too collimated to pass isolation requirements at the ATLAS ECAL. Note that in our simulations a cut of $p_T \geq 10 \text{ GeV}$ is placed on the individual photon momenta, but in this figure there is no additional cut on the combined p_T .

A. The tracker and its angular resolution

The ATLAS Inner Detector consists of the Pixel and SemiConductor Tracker (SCT) detectors and the Transition Radiation Tracker (TRT). Its main purpose is to reconstruct the tracks of charged particles that travel through it. It features an incredibly high position measurement accuracy, which in the TRT can reach 0.1 mm [57,58]. The barrel of the TRT extends to $|z| < 720 \text{ mm}$, with an inner and outer radius of 560 and 1080 mm , respectively. The two end caps cover the range $827 < |z| < 2774 \text{ mm}$ and $617 < r < 1106 \text{ mm}$ [58]. Thus, the angular resolution of the TRT is around

$$\Delta R \sim \frac{0.1 \text{ mm}}{1000 \text{ mm}} \sim 10^{-4}. \quad (3.2)$$

This can be compared with the pixel size of the ECAL, which is smallest in the second layer of the LAr, with $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$ [56] (the strips in the first layer have a finer η resolution but worse ϕ one, $\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$). The ATLAS TRT thus offers great prospects for the separation of highly collimated photons. As can be seen in Fig. 4, this angular resolution can help separate photon pairs from ALP decays for ALPs with masses as low as 0.01 GeV .

The use of the tracker in addition to the ECAL offers great prospects for separating highly collimated photons from a new resonance decay. That said, such a signal can be

mimicked by SM processes producing two photons—decays of π^0 , K^0 , and other neutral hadrons copiously produced at the LHC—making background suppression essential, as we discuss in Sec. III E.

B. Photon triggers, identification, and isolation criteria

We propose exploiting the tracking information recorded by the ATLAS inner detector, with an angular resolution as low as around 10^{-4} [see Eq. (3.2)], to distinguish collimated photon pairs. This entails a nontrivial modification of the photon identification and isolation pipeline at ATLAS, which is described in [7,56,59]. The first point to assess is whether trigger requirements allow for the diphoton events under study to be recorded. In most cases, the photon pair is collimated enough to fall within a single trigger tower, and the standard L1 (hardware) trigger on isolated photons will be satisfied by the diphoton event.

The high-level (software) trigger further performs photon identification and isolation tests as detailed in [7,56,59]. Loose identification criteria are based on shower-shape development in the middle ECAL layer, which would reject diphoton events that are not collimated enough to fall within a single calorimeter cell [7]. That said, as we will see, the collimation of the majority of the events of interest for the ALP model is enough for both photons to fall within a single ECAL cell. In fact, most of the events have an angular separation below $\Delta\eta = 0.0031$, which is the size of the strips in the first ECAL layer that are used for tight identification criteria.

Furthermore, a set of isolation requirements are placed on photon candidates [60,61]. These typically put a limit on the amount of extra energy in the angular vicinity of the photon candidate. Given that the signal photons arise from the decay of a singly produced particle, we do not expect isolation requirements to result in any significant signal event rejection. This is unlike the potential backgrounds, which mostly originate from hadronic states that are more likely to originate within a QCD jet.

One may worry that the presence of two collimated photons in our signal can lead to the event not passing the isolation requirements. We do not expect that to be the case given the high collimation of the photon pair. To gauge any potential negative impact, we place a cut on the angular separation between the photons and confirm that the majority of our signal events pass the most restrictive requirement of $\Delta\eta \leq 0.0031$, corresponding to the finest angular resolution of the ECAL. Though this assures that calorimetric isolation variables do not negatively affect our signal, it is worth noting that tracking information is also employed at the photon isolation stage. Thus, a more detailed experiment-level analysis of the impact of tracking isolation variables in our search should be carried out in the future.

Beyond the reconstruction and identification triggers described above and in order to manage the huge

luminosity, ATLAS currently places a 140 GeV cut at the trigger level on the transverse momentum (p_T) of isolated single-photon events [7]. In our case, this trigger requirement has to be satisfied by the combined momenta of the photon pair or, equivalently, by that of the decaying ALP. As can be calculated from the distribution shown in Fig. 3, this shrinks the total signal cross section to about 25% of its original size, but at the same time, it provides a crucial background rejection. As will be shown in Sec. III F, a p_T cut in the 100–150 GeV range, together with a displacement requirement on the ALP decay vertex, is enough to render the search background-free, to the best of our knowledge.

We also note that, during reconstruction (cf. [7,56,59]), after a candidate photon event is identified based on its energy deposition in the ECAL, inner detector tracks and conversion vertices are matched to the ECAL cluster. Currently, only one matching candidate conversion vertex is kept for each ECAL cluster, which precludes the possibility of distinguishing between single and multiple photon events. Allowing more than one conversion vertex to be linked to a single ECAL cluster would make it possible to identify collimated photon pair candidates (cf. [17]). If this could be done at the trigger level, it is conceivable that the aforementioned p_T threshold could be significantly lowered.

C. Separation of converted photons

Once the events are triggered and thus recorded, we have access to their full tracking information, which can be used to discern whether the track matches that left by a single photon or a pair of photons. In practice, photons only leave a track in the TRT after they convert into an electron or positron. We will discuss this conversion probability and its dependence on the photon momentum and direction in Sec. III D. For now, we focus on the inner detector's ability to distinguish two separate tracks on an $a \rightarrow \gamma\gamma$ decay where both photons convert.

In order to assess the ability of the TRT to separate highly collimated converted photons, we calculate the maximum separation between the trajectories of the two photons. This maximum separation is achieved at the edge of the TRT, just before the photons leave the inner detector. To illustrate our results, the left panel of Fig. 5 shows the distribution of separations in the tracker for an exemplary value of the ALP-photon coupling and a few values of the ALP mass. Each dot represents an individual event in a series of 10^5 simulations per value of m_a . The vertical axis shows the maximum separation in the TRT of the two photons originating from a single ALP decay, while the horizontal axis displays the average pseudorapidity of those photons. Note that, for simplicity, we do not account for the bending of trajectories in the magnetic field of the detector. We do not expect that including this known effect in a more realistic simulation significantly changes the results.

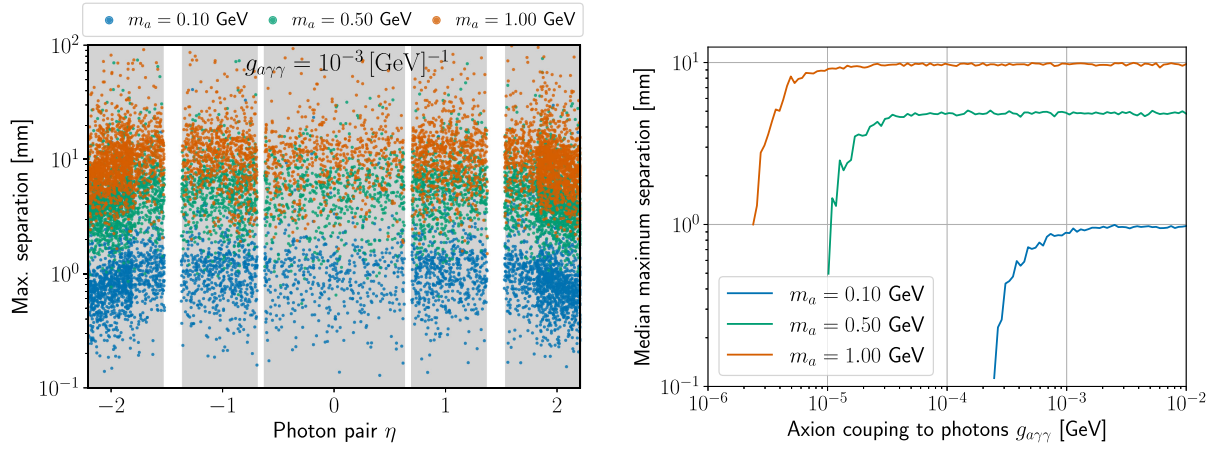


FIG. 5. Maximum separation between the trajectories of each photon in a photon pair originating from an ALP decay, as a function of the pseudorapidity of the photon pair (left) and the ALP coupling to photons (right). On the left panel, the photon coupling is fixed to $g_{a\gamma\gamma} = 1 \text{ TeV}^{-1}$, and each dot corresponds to one of 10^5 simulated events for the values of the ALP mass indicated in the legend. The gray shading indicates the coverage of the TRT; the white gaps correspond to the barrel–end-cap transition at $\eta \sim 0.65$ and a region where photon conversion data are not available at $1.37 < \eta < 1.52$. On the right panel, we take the median over the ALP momenta to more clearly show the trend.

The clear increase of event rate toward the edges of the TRT is mainly due to the fact that the conversion probability of the photons is larger at larger $|\eta|$, as will be discussed in Sec. III D and can be seen in Fig. 6. The typical maximum separation between the photons is largely independent of η across the TRT. It only shows a slight decline at the edge of the end cap, which is caused by a combination of geometric factors and the fact that forwardly produced ALPS typically have a slightly larger momentum than central ones.

The separation depends most strongly on the ALP mass and its momentum, given that the angular separation between the photons is proportional to the ratio m_a/p_a . For fixed values of m_a and p_a , the separation is essentially independent of $g_{a\gamma\gamma}$ while the ALP decay length is small. However, as $g_{a\gamma\gamma}$ decreases enough for the decay length to become larger than a few centimeters, the separation sharply decreases with decreasing $g_{a\gamma\gamma}$, as can be seen in the right panel of Fig. 5. This is due to the fact that in this regime the ALP decay is macroscopically displaced, and

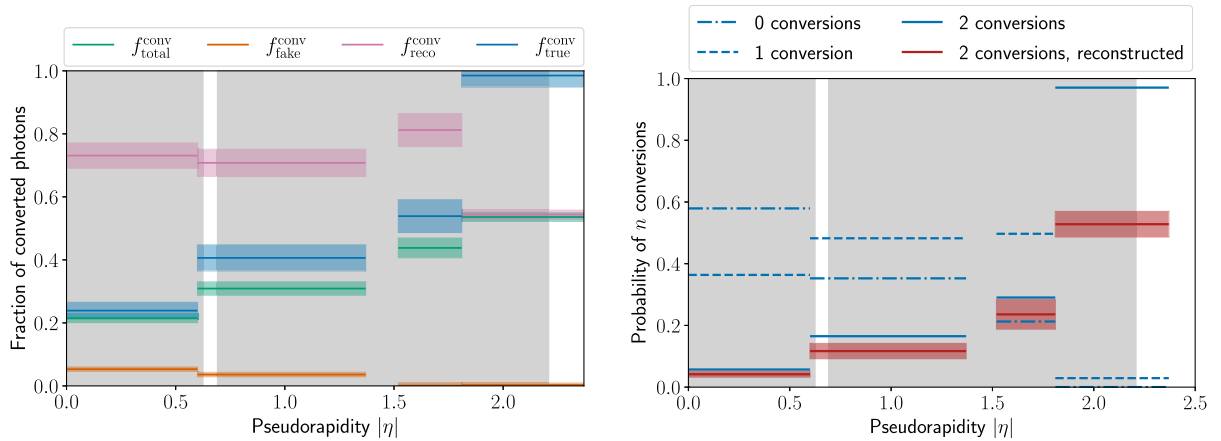


FIG. 6. Left panel: fraction of converted photons in the ATLAS detector in bins of $|\eta|$, as published in [59]. The $f_{\text{conv}}^{\text{total}}$ fraction corresponds to the fraction of all photons that are reconstructed as converted, $f_{\text{fake}}^{\text{conv}}$ is the fraction of true unconverted photons reconstructed as converted, and $f_{\text{reco}}^{\text{conv}}$ is the fraction of true converted photons reconstructed as converted. From those values, it is possible to derive $f_{\text{true}}^{\text{conv}}$, corresponding to the fraction of true converted photons among all photons. Right panel: probability of $n = 0, 1$, or 2 conversions in a highly collimated photon pair in the ATLAS inner detector in bins of $|\eta|$. The blue lines show the true probability of n true conversions, while the red line further takes into account the estimated reconstruction efficiency. In both panels, the width of the shaded bands represents the uncertainty in the probabilities. For our analysis, we incorporate the effect of the finite ALP decay length on the photon conversion probability following Eq. (3.4).

thus the photons travel a shorter distance within the TRT. As a consequence, even if their angular separation stays constant, the physical separation between the photon trajectories at the edge of the tracker is smaller than for a prompt ALP decay. For even longer decay lengths, the ALP decays outside of the inner detector, and therefore the event does not leave any track in the TRT. The impact of the ALP lifetime on our search strategy is further discussed in Sec. III E.

In summary, collimated photon pairs that convert in the tracker can be distinguished from single-photon events if their separation exceeds the tracker resolution. The separation depends primarily on the ALP mass and coupling through the vertex displacement [$\sim p_a/(g_{a\gamma\gamma}^2 m_a^4)$] and the opening angle ($\sim m_a/p_a$), with only modest dependence on pseudorapidity and detector geometry. The standard ATLAS p_T trigger of 140 GeV on isolated photons helps reduce the background from long-lived kaons but significantly reduces the number of signal events; this threshold could potentially be relaxed if a two-photon conversion event or a displaced ALP decay vertex can be identified at the trigger level.

D. Double-photon conversion in the ATLAS inner detector

A photon traveling through the inner detector only leaves a track after it converts to an electron-positron pair. The probability of conversion of a photon before it reaches the ECAL as a function of pseudorapidity in the ATLAS detector is shown in the left panel of Fig. 6 using the data published in [59]. The bands correspond to $1\text{-}\sigma$ uncertainties. This information is given in terms of three quantities: (i) $f_{\text{total}}^{\text{conv}}$, the fraction of all photons that are reconstructed as converted, (ii) $f_{\text{fake}}^{\text{conv}}$, the fraction of true unconverted photons reconstructed as converted, and (iii) $f_{\text{reco}}^{\text{conv}}$, the fraction of true converted photons reconstructed as converted. From these quantities, we can calculate the true fraction of all photons that convert,

$$f_{\text{true}}^{\text{conv}} = \frac{f_{\text{total}}^{\text{conv}} - f_{\text{fake}}^{\text{conv}}}{f_{\text{reco}}^{\text{conv}} - f_{\text{fake}}^{\text{conv}}}. \quad (3.3)$$

This quantity is also shown in the left panel of Fig. 6, and it varies from $f_{\text{true}}^{\text{conv}} \simeq 0.24$ at low η to $f_{\text{true}}^{\text{conv}} \simeq 0.99$ at $\eta \gtrsim 1.831$. Note that no data are provided in the range $1.37 < \eta < 1.52$. The reason why the conversion probability is larger at larger η is simply that the photons traverse more material before reaching the ECAL.

Now, we can compute the probability for zero, one, or two conversions in a highly collimated photon pair as a function of pseudorapidity. As can be seen in the right panel of Fig. 6, the fraction of events where two conversions occurs ranges from about 5% at low η to almost 100% at the edge of the TRT. A quantity that is more challenging to estimate is the probability for the doubly converted photon

pairs to be identified as such in the reconstruction procedure. In the standard single-photon case, this probability is around $f_{\text{reco}}^{\text{conv}} \sim 0.5\text{--}0.8$ depending on η (see left panel of Fig. 6). Although it is likely that the reconstruction probability is lower in the double-conversion case, it is difficult to make a quantitative guess without a dedicated experimental study, which is beyond our capabilities. Thus, for our exploratory study we will take the reconstruction probability for double conversions to equal the one for single conversions, that is, $f_{\text{reco}}^{\text{conv}}$. Implementing this leads to the red lines and associated uncertainties shown in the right panel of Fig. 6.

The conversion probabilities shown in Fig. 6 are applicable to prompt photons, but in our model the photons originate from the ALP decay, which may be displaced from the primary interaction vertex (IV). In order to evaluate how the conversion probability scales with the distance traveled within the inner detector, in principle, one needs a detailed characterization of the material that is traversed by the particle, as is done in [59]. However, for simplicity, in our estimates we take the inner detector to be homogeneous.³ In this approximation, the conversion probability is constant along the photon's path through the detector, so the total probability for it to convert if the trajectory starts at a distance x from the primary interaction vertex is $f_{\text{true}}^{\text{conv}}(1 - x/L_{\text{TRT}})$. Here, $L_{\text{TRT}} = L_{\text{TRT}}(\eta)$ is the total extent of the TRT in the direction of travel. Combining this with the probability for the ALP to decay at a given distance from its production point, the conversion probability for photons originating from a long-lived ALP is

$$\begin{aligned} f_{\text{true}}^{\text{conv}}(\ell_{\text{decay}}) &= \int_0^{L_{\text{TRT}}} \frac{dx}{\ell_{\text{decay}}} e^{-\frac{x}{\ell_{\text{decay}}}} f_{\text{true}}^{\text{conv}} \left(1 - \frac{x}{L_{\text{TRT}}}\right) \\ &= f_{\text{true}}^{\text{conv}} \left[1 - \left(1 - e^{-\frac{L_{\text{TRT}}}{\ell_{\text{decay}}}}\right) \frac{\ell_{\text{decay}}}{L_{\text{TRT}}}\right], \end{aligned} \quad (3.4)$$

with ℓ_{decay} the ALP decay length given in Eq. (2.5). As expected, the conversion probability is strongly suppressed for $\ell_{\text{decay}} \gtrsim L_{\text{TRT}}$. In our simulations, we randomly decide whether the photons convert and generate the location for the conversion vertices based on the above probability.

E. Displaced ALP decay vertex

As highlighted by Eq. (2.5), the decay length of a sub-GeV ALP with couplings below the TeV^{-1} range is macroscopic on collider scales. Since neutral pions and other promptly decaying hadronic resonances that produce $\gamma\gamma$ pairs are much shorter-lived, identifying a nonzero

³Since the densest parts of the ATLAS inner detector are near its center, this assumption may result in an overestimation of the conversions. However, improving this approximation requires a full simulator-level characterization of the detector, which is beyond our capabilities.

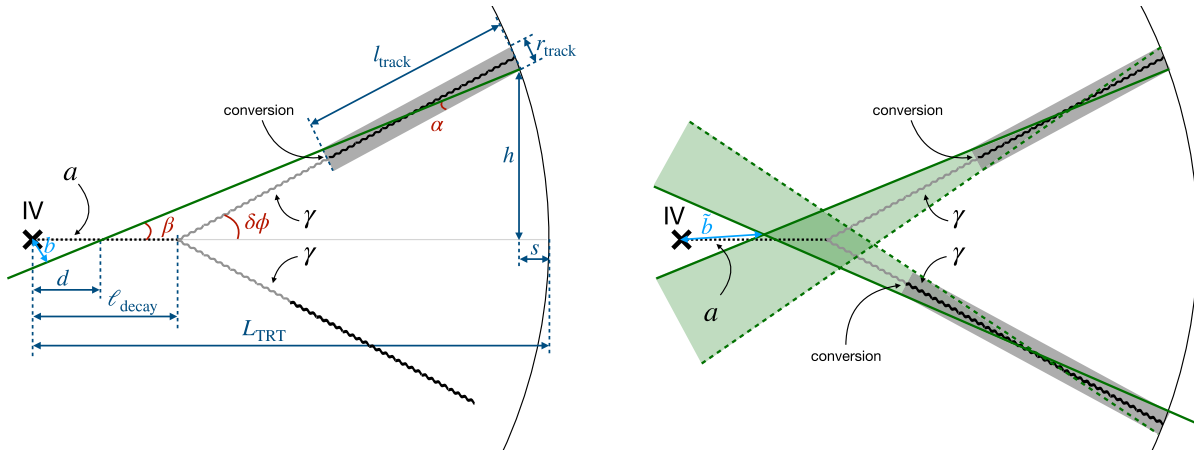


FIG. 7. Geometry of the displaced decay $a \rightarrow \gamma\gamma$ projected onto the transverse plane. In the left panel, the observable transverse impact parameter b of a photon trajectory with respect to the IV depends on the collimation angle $\delta\phi$, the track length l_{track} , and the resolution r_{track} . In the right panel, we show that using both converted photons narrows the possible vertex location to the intersection of the two uncertainty cones (green), giving a larger combined displacement estimator $\tilde{b} \geq b$. Note that these sketches do not represent the typical conditions of the events of interest here, where $\delta\phi$ is much smaller.

transverse displacement of the $a \rightarrow \gamma\gamma$ decay vertex with respect to the primary IV immediately rejects those backgrounds. The only exception is K_L , discussed in Sec. III F.

In practice, measuring the displacement is hampered by the high collimation of the decay products. The geometry of the problem is sketched in Fig. 7, projected onto the transverse plane. The key parameters are the azimuthal angle $\delta\phi$ between the ALP trajectory and a decay photon (typically $\lesssim 0.01$ rad for sub-GeV ALPs, see Fig. 4), the track length l_{track} after photon conversion, and the TRT position resolution r_{track} . As a benchmark we take $r_{\text{track}} \sim 0.1$ mm, comparable to the nominal TRT resolution [57,58]; a larger (smaller) value degrades (improves) the reach, as shown in Sec. IV.

The full derivation of the displacement estimators is given in Appendix. Here, we summarize the key results. The worst-case reconstructed photon trajectory deviates from the true one by an angle α defined via $\tan \alpha = r_{\text{track}}/l_{\text{track}}$, spanning an angle $\beta = \delta\phi - \alpha$ with the ALP direction. The resulting minimal transverse impact parameter with respect to the IV is, in the small-angle limit,

$$b \approx \delta\phi \ell_{\text{decay}} - \alpha L_{\text{TRT}}. \quad (3.5)$$

The condition $b > 0$, required to tag the decay as displaced, demands $\alpha \leq \delta\phi$: The track-reconstruction uncertainty must not wash out the geometric collimation. For $\ell_{\text{decay}} \lesssim 1$ m and $\delta\phi \lesssim 10^{-2}$, typical impact parameters are $b \sim 10$ cm, well within the sub-cm displaced-vertex accuracy demonstrated by ATLAS [62]. When both photons convert and individually satisfy $b > 0$, the two-photon displacement estimator $\tilde{b}$ (see Appendix) is always parametrically larger than b , increasing the tagging acceptance.

In our simulations we require both converted photons to contribute to the displaced vertex tag. Our benchmark requires $\tilde{b} > 10$ cm, relaxed to $\tilde{b} > 1$ cm for the optimistic scenario. This rejects all known backgrounds to the level necessary for our search, except for K_L . Another possible handle for background rejection is to reconstruct the invariant mass of the photon pair, when possible. All the results in this work are obtained without exploiting any invariant mass information; exploring that option is left for future work.

F. Backgrounds

1. Irreducible background from K_L

The long-lived state in the neutral kaon pair— K_L —has a lifetime $\tau_{K_L} \simeq 5 \times 10^{-8}$ s and a branching ratio to photons of $\text{Br}(K_L \rightarrow \gamma\gamma) \simeq 5 \times 10^{-4}$ [63]. This means that K_L can produce the same signal that we target in our search strategy. It is therefore crucial to estimate the rate at which this background process occurs at the LHC.

The first step is to characterize the angular and momentum distributions of the long-lived neutral kaons produced in pp collisions at 14 TeV center-of-mass energy. For this purpose, we make use of the FORESEE package [64], which provides such distributions for a number of hadronic states, including K_L .⁴ The left panel of Fig. 8 shows the two-dimensional $\theta - p$ distribution of K_L . Bins outside of the

⁴Since K_L decays to two photons, it features an effective coupling to two photons $g_{K_L\gamma\gamma}$. Kaons produced through vector boson fusion via this coupling have a similar distribution to that of the ALPs. However, the effective coupling is very small, $g_{K_L\gamma\gamma} \lesssim 10^{-8} \text{ GeV}^{-1}$, and this source of background can be safely neglected.

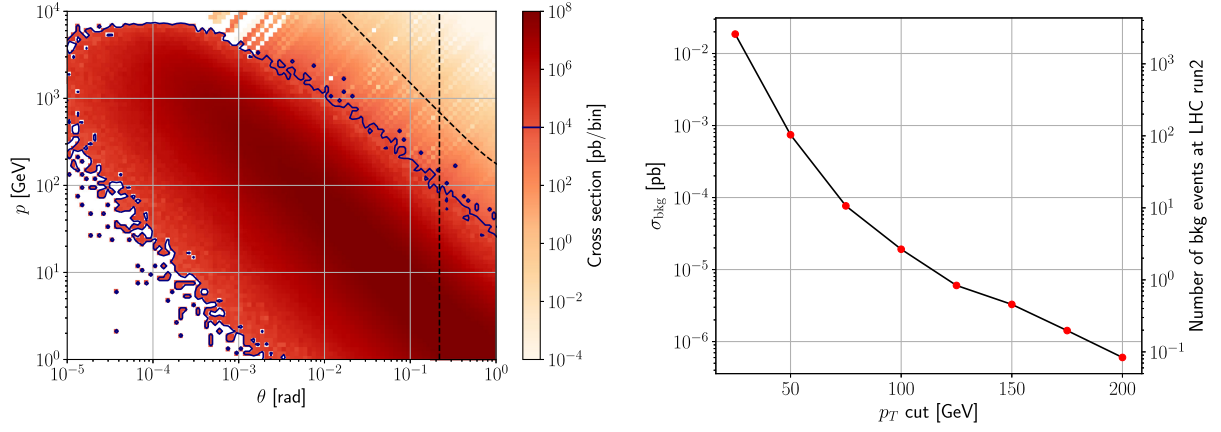


FIG. 8. Characterization of the irreducible background coming from $K_L \rightarrow \gamma\gamma$ events. On the left panel and delimited by a blue line, we show the θ vs p distribution of K_L produced at the LHC as calculated in [64], which has a resolution of 10^4 pb/bin. We also show our extrapolation of this distribution to the signal region for our search, above and to the right of the black dashed lines. The right panel displays the cross section of $K_L \rightarrow \gamma\gamma$ events in the signal region as a function of the cut in the transverse momentum of the final-state photons. Note that this constitutes an upper limit to the number of background events that pass all of our signal selection criteria. For easy reference, we also display the corresponding number of background events at run 2 of the LHC.

dark blue line have cross sections below the 10^4 pb threshold used for the simulation. The distribution is fairly straightforward, especially for high momentum kaons. The dashed vertical line shows the angular extension of the TRT, which extends down to $\eta \simeq 2.2$ or $\theta \simeq 0.22$ rad. The dashed diagonal line corresponds to a cut $p_T > 150$ GeV. As can be seen from the figure, the signal region for our search corresponds to the upper right corner of the $\theta - p$ plane, where no data for the K_L production cross section are available due to the lack of resolution of the simulations [64]. To overcome this, we extrapolate the results of [64] to our signal region using a simple two-dimensional power-law fit. The result corresponds to the colored area outside the blue line in the left panel of Fig. 8.

Once the production cross section for K_L in the $\theta - p$ signal region is obtained, we need to estimate the amount of $K_L \rightarrow \gamma\gamma$ decays that are expected to leave tracks in the ATLAS TRT. First, there is a suppression of the rate by the small branching fraction $\text{Br}(K_L \rightarrow \gamma\gamma) \simeq 5 \times 10^{-4}$. Second, only a few K_L decay within the TRT due to their large decay length,

$$\ell_{K_L} \simeq 4.6 \text{ km} \frac{p}{150 \text{ GeV}}. \quad (3.6)$$

Given that the TRT extends to a maximum distance of around 1 m from the IV, only a fraction of around 2×10^{-4} of the kaons decay within the tracker. A further suppression

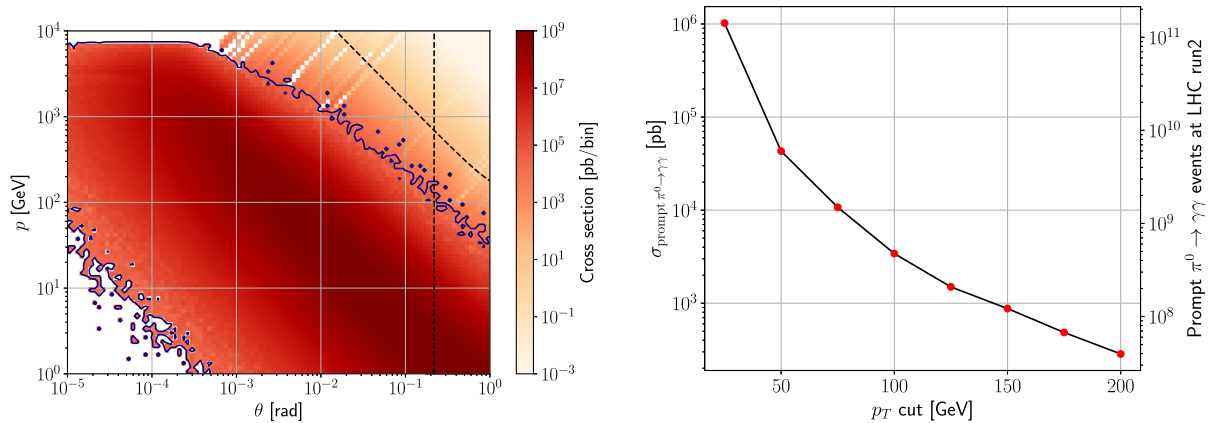


FIG. 9. Characterization of the prompt π^0 production. On the left panel and delimited by a blue line, we show the θ vs p distribution of π^0 produced at the LHC as calculated in [64], which has a resolution of 10^4 pb/bin. We also show our extrapolation of this distribution to the momentum and pseudorapidity region of interest for our search, above and to the right of the black dashed lines. The right panel displays the cross section of $\pi^0 \rightarrow \gamma\gamma$ events in the p and η region as a function of the cut in the transverse momentum of the final-state photons. For easy reference, we also display the corresponding number of background events at run 2 of the LHC. Note that due to the short π^0 lifetime, the π^0 background can be rejected by requiring a minimum displacement of the signal event decay vertices.

factor is due to the photon conversion probability as given by Eq. (3.4). After these considerations are taken into account, we can estimate an upper limit for the cross section of K_L background events in the signal region. This is shown in the right panel of Fig. 8 as a function of the lower p_T requirement to define the signal region. For easy reference, we show the number of background events corresponding to each value of the cross section for the 139 fb^{-1} integrated luminosity of the second observation run of the LHC (the third observation run is expected to double the current integrated luminosity, while the HL-LHC is planned to further boost it by a factor of 10). The background cross section depends strongly on the p_T cut applied, and the expected number of background events at run 2 of the LHC is below 1 for a p_T above around 120 GeV.

So far, we have not imposed any requirement on the collimation, i.e., the ΔR , of the two photons arising from the K_L decay, which would result in a further suppression factor. However, this is not easy to estimate without a full simulation with the sufficient statistics to populate the signal region delineated in the left panel of Fig. 8. As this task is beyond the scope of the present work, we will take the results shown in the right panel of Fig. 8 as an upper limit to the $K_L \rightarrow \gamma\gamma$ background cross section. Furthermore, the photon isolation criteria would also reject a significant fraction of K_L produced within QCD jets.

We thus conclude that it is reasonable to expect our search to be background-free at the LHC run 2 (and possibly LHC run 3) as long as the p_T cut placed on the photon pair is at least around 120 GeV. In particular, a search using events recorded with the current 140 GeV cut for isolated photons would satisfy the background-free requirement.

2. Reducible background from π^0

The even more copious neutral pions have a much shorter decay length,

$$\ell_{\pi^0} \simeq 3 \times 10^{-5} \text{ m} \left(\frac{p}{150 \text{ GeV}} \right), \quad (3.7)$$

so requiring a vertex displacement of at least 1 cm is, in principle, sufficient to eliminate them. In practice, this relies on the misreconstruction rate of the pion decay vertex being negligible, which requires a dedicated experimental study. Using the spectra from [64] and extrapolating to higher momenta (Fig. 9), we estimate that for $p_T \geq 150 \text{ GeV}$ a rejection factor of $R_{\pi^0}^{\text{reject}} \sim 10^8$ is needed for a background-free search at run 2 luminosity. For a displacement cut of 10 cm, this naively seems achievable; for 1 cm it may be more challenging since this corresponds to decays inside the beampipe. Pions produced within QCD jets are additionally suppressed by the photon isolation requirements.

Other reducible backgrounds, like decays where particles are misidentified as photons or lost in reconstruction, are beyond the scope of this phenomenological study.

IV. RESULTS

We simulate 10^6 ALP productions and decays for each point in a $(m_a, g_{a\gamma\gamma})$ grid and compute the fraction of events yielding photon pairs separable at the tracker. Figure 10 shows the sensitivity reach as each analysis parameter is varied in turn, with the rest held at their benchmark values.

- (i) *Number of signal events.* Assuming the search to be background-free, we require three signal events. This gives the sensitivity reach shown in the upper left panel of Fig. 10 for run 2 (orange), run 3 (green), and HL-LHC (blue) luminosities; requiring more events reduces the reach if additional backgrounds are found.
- (ii) *Diphoton transverse momentum.* The benchmark $p_T > 150 \text{ GeV}$, slightly above the 140 GeV ATLAS run 2 isolated-photon trigger [7], fully rejects the $K_L \rightarrow \gamma\gamma$ background at run 2 luminosity (Fig. 8, right). Lowering the cut modestly extends the reach (upper right panel), but below around 100 GeV K_L contamination will set in and a dedicated K_L simulation would be needed to determine the optimal threshold.
- (iii) *Track resolution.* We use $r_{\text{track}} = 0.2 \text{ mm}$ (twice the nominal TRT resolution) as our conservative benchmark. The middle left panel of Fig. 10 shows that a poorer resolution significantly shrinks the reach, while achieving the nominal 0.1 mm yields modest gains.
- (iv) *Vertex displacement requirement.* Our benchmark requires $\tilde{b} > 10 \text{ cm}$; the middle right panel shows that relaxing this to $\tilde{b} > 1 \text{ cm}$ extends the reach to heavier, more strongly coupled ALPs with shorter decay lengths.
- (v) *Separation resolution.* We require the two photon tracks to be separated by at least 0.5 mm at the TRT edge (5 times the nominal resolution). The lower left panel shows the expected trend: Achieving 0.1 mm separation pushes the reach to lighter ALPs, while coarser separation degrades the low-mass sensitivity.
- (vi) *Maximum angular separation.* To ensure the signal passes ECAL shower-shape criteria, we require $\Delta R_{\gamma\gamma} \leq 0.035$ (one ECAL cell). As shown in the lower right panel, loosening this to the L1 trigger granularity ($\Delta R \leq 0.14$) or tightening it to the strip resolution ($\Delta\eta \leq 0.0031$) leaves the reach essentially unchanged, confirming that the vast majority of signal events are well within any of these thresholds.
- (vii) *Benchmark sensitivity scenarios.* Combining the results of the paragraphs above, we construct two

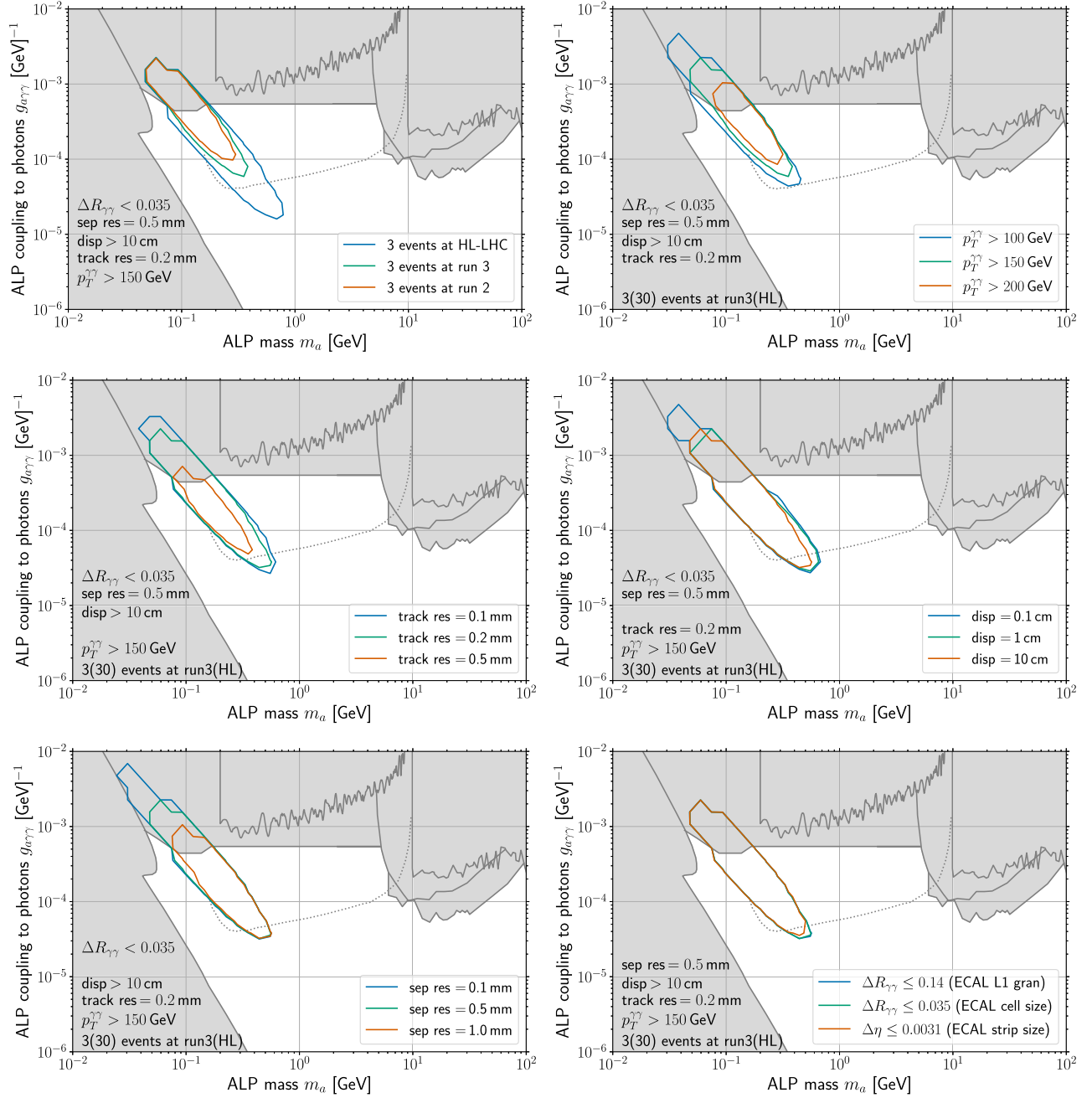


FIG. 10. Effect of varying different specifications on the reach of our proposed search strategy in the ALP mass vs photon coupling plane. From left to right and top to bottom, we examine the effects of changing the required number of events, the cut on the p_T of the photon pair, the resolution of the ATLAS TRT, the minimum discernible vertex displacement, and the maximum angular separation of the individual photons within the pair.

benchmark scenarios for the sensitivity of our proposed search strategy to test the ALP parameter space. These correspond to a more conservative and a more optimistic set of choices for all the parameters discussed above, and their projected sensitivities are shown in Fig. 11. For our conservative estimate, we use the integrated luminosity of run 2 of the LHC, that is, data that are already recorded and could be reanalyzed at present. In contrast, our more

optimistic forecast makes use of the full expected data to be collected by the high-luminosity phase of the LHC.

Both benchmark scenarios showcase significant sensitivity to new parameter space, untested by other experiments and observations. Interestingly and importantly, our search strategy is most sensitive in the region of relatively large couplings and masses, corresponding to relatively short decay lengths that are hard to access in fixed-target

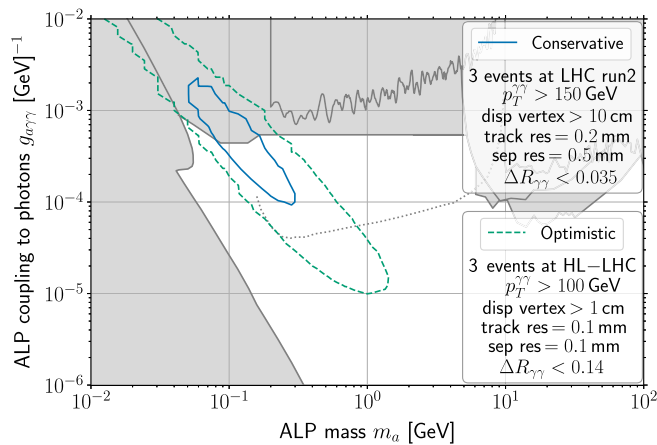


FIG. 11. Potential reach of our proposed search strategy in the ALP mass vs photon coupling parameter space. The solid line corresponds to a conservative estimate making use of existing data, while the dashed line is a more futuristic goal with more data, lower p_T cuts, and the highest resolution to distinguish displaced vertices. Existing constraints are shaded in gray (see Fig. 1), and the gray dotted line is a projected limit using the full Belle-II luminosity [2].

experiments. Our proposal therefore provides powerful complementarity and offers the possibility to probe new parameter space using already collected data.

V. DISCUSSION AND CONCLUSIONS

Axionlike particles in the mass range 10 MeV – 10 GeV with moderately large photon couplings $g_{a\gamma\gamma} \sim (10^{-6} - 10^{-3}) \text{ GeV}^{-1}$ fall right between the traditional sensitivities of collider and fixed-target searches. In this paper, we have proposed a search strategy that may allow the LHC to gain sensitivity in this region by exploiting the high position resolution of the inner tracker to separate highly collimated photon pairs from the displaced decay of boosted (pseudo)scalar resonances. Already existing data may allow us to probe new, untested parameter space, and future HL-LHC data will further extend the reach.

The key idea is to require that the decay photons convert into e^+e^- pairs inside the tracker, whose angular resolution ($\sim 10^{-4}$) is 2 orders of magnitude better than the ECAL. We have shown that this enables separation of ALP decay products for masses as low as 10 MeV. Crucially, requiring the decay vertex to be displaced from the interaction vertex suppresses the dominant background from promptly decaying hadronic resonances such as π^0 . Our estimates suggest that irreducible backgrounds from long-lived K_L mesons are small in the target signal region for $p_T \gtrsim 120$ GeV at run 2, though further dedicated studies are needed for a definitive statement. The projected sensitivity, shown in Fig. 11, demonstrates significant complementarity with existing searches and the ability to probe new parameter space.

It must be emphasized that our analysis is a theoretical feasibility study. Putting this strategy into practice requires closer investigation of potential experimental pitfalls. In particular, it is important to verify that events featuring two pairs of conversion tracks per calorimeter cluster are not discarded or misidentified and to assess whether the tracks from the four nearby charged particles can be correctly matched across detector components. Moreover, precisely quantifying the double-conversion reconstruction efficiency also calls for a full detector simulation. A careful, experiment-level determination of reducible backgrounds from misreconstruction and particle misidentification is also needed.

Beyond the displaced-vertex technique studied here, several avenues for improvement remain open. The magnetic field causes the conversion electrons and positrons to curve, potentially enabling a momentum measurement of the individual photons and an invariant mass reconstruction of the decaying resonance—a useful additional handle for background suppression. Single-conversion events (requiring only one of the two photons to convert) may also be worth exploring: They are less suppressed by the conversion efficiency but face larger backgrounds, and the trade-off warrants investigation. Finally, while we have focused on the TRT, including inner silicon detector components with higher position resolution could yield further gains.

The search strategy proposed here is applicable beyond ALPs to any particle decaying into photons with a small but macroscopic decay length. We strongly encourage detector experts at ATLAS and CMS to investigate the feasibility of this approach with full simulations.

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APPENDIX: DISPLACED VERTEX ESTIMATORS

Here, we derive the displacement estimators b and $\tilde{b}$ used in Sec. III E. The geometry is sketched in Fig. 7, projected onto the transverse plane.

1. Single-photon estimator b

The worst-case reconstructed photon trajectory deviates from the true one by an angle

$$\tan \alpha = \frac{r_{\text{track}}}{l_{\text{track}}} \quad (\text{A1})$$

The minimal transverse impact parameter of this worst-case trajectory with respect to the IV is

$$b = d \sin \beta. \quad (\text{A5})$$

In the small-angle limit ($s \approx 0$) this reduces to Eq. (3.5) in the main text.

2. Two-photon estimator $\tilde{b}$

When both photons convert and individually satisfy $b > 0$ (i.e., $\delta\phi_i > \alpha_i L_{\text{TRT}}/\ell_{\text{decay},i}$), the possible vertex location is the intersection of the two uncertainty cones. With $d_1 \leq d_2$ the individual single-photon distances from Eq. (A2), the point in the intersection region closest to the IV gives

$$\begin{aligned} \tilde{b} &= \sqrt{\sin^2 \beta_1 x^2 + (d_1 + x)^2}, \\ x &= \frac{\sin \beta_2}{\sin \beta_1 + \sin \beta_2} (d_2 - d_1). \end{aligned} \quad (\text{A6})$$

and makes an angle $\beta = \delta\phi - \alpha$ with the ALP trajectory. Defining the auxiliary lengths h and s as in Fig. 7, the distance between the IV and the intersection of the worst-case trajectory with the ALP direction is

$$d = L_{\text{TRT}} - s - \frac{h}{\tan \beta}, \quad (\text{A2})$$

where

$$h = \tan \delta\phi \left(L_{\text{TRT}} - \ell_{\text{decay}} - \frac{r_{\text{track}}}{2 \sin \delta\phi} - s \right), \quad (\text{A3})$$

and s is the smaller root of

$$[1 + \tan^2 \delta\phi] s^2 - 2 \left[L_{\text{TRT}} + 4 \left(L_{\text{TRT}} - \ell_{\text{decay}} - \frac{r_{\text{track}}}{2 \sin \delta\phi} \right) \tan^2 \delta\phi \right] s + 4 \tan^2 \delta\phi = 0. \quad (\text{A4})$$

The quantity $\tilde{b}$ incorporates the reconstruction uncertainties for both photons. For highly collimated photons satisfying the condition above, $\tilde{b}$ is always numerically larger than b , increasing the tagging acceptance. In the small-angle limit, Eq. (A6) simplifies to

$$\begin{aligned} \tilde{b} &\approx \frac{1}{\beta_1 + \beta_2} (\delta\phi_1 \ell_{\text{decay},1} + \delta\phi_2 \ell_{\text{decay},2}) \\ &\quad - L_{\text{TRT}} \left(\frac{\delta\phi_1 + \delta\phi_2}{\beta_1 + \beta_2} - 1 \right), \end{aligned} \quad (\text{A7})$$

where $\beta_i = \delta\phi_i - \alpha_i$. Although $\delta\phi_1 \simeq \delta\phi_2 \simeq \delta\phi_{\gamma\gamma}/2$, the angles α_1 and α_2 can differ significantly depending on where each photon converts.

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