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Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS

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Abstract: A search for forward proton scattering in association with light-by-light scattering mediated by an axion-like particle is presented, using the ATLAS Forward Proton spectrometer to detect scattered protons and the central ATLAS detector to detect pairs of outgoing photons. Proton-proton collision data recorded in 2017 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV were analysed, corresponding to an integrated luminosity of 14.6 fb^{-1}. A total of 441 candidate events were selected. A search was made for a narrow resonance in the diphoton mass distribution, corresponding to an axion-like particle (ALP) with mass in the range 150–1600 GeV. No excess is observed above a smooth background. Upper limits on the production cross section of a narrow resonance are set as a function of the mass, and are interpreted as upper limits on the ALP production coupling constant, assuming 100% decay branching ratio into a photon pair. The inferred upper limit on the coupling constant is in the range 0.04–0.09 TeV^{-1} at 95% confidence level.

Keywords: CP Violation, Hadron-Hadron Scattering

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Contents

1 Introduction

The axion [1, 2] is the name given to an as yet unobserved particle whose existence is proposed in order to explain the lack of CP violation in quantum chromodynamics [3–6]. Such a particle must be very light and couple to two photons. Some extensions to the Standard Model (SM) predict the possibility of heavy particles which are axion-like in that they also couple to two photons. Such axion-like particles (ALPs) may be produced in two-photon collisions and subsequently decay into two photons [7–9]; the ALP production process can therefore be identified as a resonant peak at the ALP mass value in the process $\gamma\gamma \to \gamma\gamma$, also known as light-by-light ($\gamma\gamma$) scattering.

Any high-energy source of real or weakly virtual photon pairs in collisions would in principle be capable of producing ALPs. At the LHC, substantial fluxes of virtual photons can be generated by radiation from colliding high-energy protons or ions, and pairs of such photons can interact. In processes of this kind, each incoming charged particle continues to travel close to its original direction. The process $\gamma\gamma \to \gamma\gamma$ can also occur through an intermediate fermion or W boson box diagram. It has been measured at the LHC in nucleus-nucleus collisions using lead-ion beams (Pb-Pb collisions) [10–13], where the $\gamma\gamma \to \gamma\gamma$ cross section is enhanced because of the high nuclear charge. These analyses also searched for an ALP mediated by $\gamma\gamma$ scattering with a mass m_X up to 100 GeV. At higher diphoton masses, the effective $\gamma\gamma$ luminosity in pp collisions surpasses that of Pb-Pb collisions [14], although the scattering cross section is lower than at lower masses.

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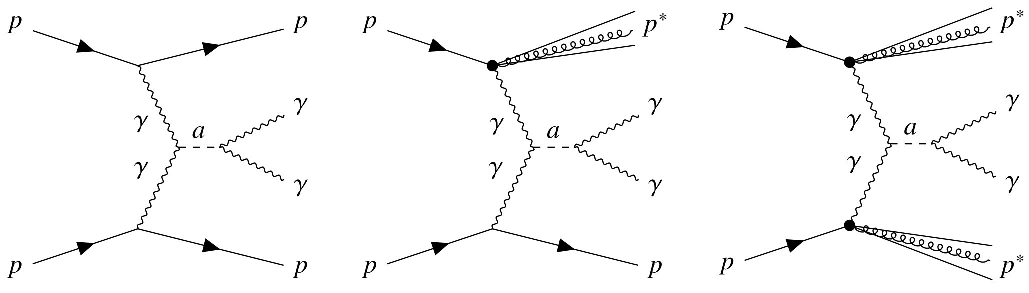


(a) (b) (c)

Figure 1. Feynman diagrams for (a) exclusive, (b) single-dissociative, and (c) double-dissociative light-by-light scattering with outgoing photon pairs mediated by an ALP denoted by a.

A pair of outgoing real photons, which is the signature for ALP production, can be detected in the central detector surrounding the interaction point, while suitable apparatus located in each of the forward directions may be used to detect the outgoing scattered protons (referred to as proton tagging) in pp collisions [8]. The production of lepton pairs by photon-photon interactions, $pp \to p(\gamma\gamma \to \ell^+\ell^-)p^{(*)}$, has been measured by ATLAS and CMS using forward-proton detectors [15, 16].

This analysis presents a search for ALPs produced in light-by-light scattering in proton-proton (pp) collisions using the ATLAS detector. The target mass range is 150–1600 GeV. Three possibilities for the reaction may be considered: the exclusive process $\gamma\gamma \to \gamma\gamma$ measured as $pp \to pp\gamma\gamma$, and single- and double-dissociative processes (SD, DD) in which one or both protons (p^*) dissociate while radiating a virtual photon, as depicted in figure 1. While the undissociated proton may be tagged, the dissociated proton is in practice not measurable.

An exclusive signal search has been performed by the CMS-TOTEM collaborations in $9.4\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV, making use of double proton tagging in a diphoton mass range of approximately 900–1800 GeV [17]. A previous inclusive diphoton resonance search with ATLAS targeted the mass range 160–1160 GeV using a higher integrated luminosity, $139\,\mathrm{fb}^{-1}$ [18]. The ATLAS search presented here uses $14.6\,\mathrm{fb}^{-1}$ of 13 TeV pp collision data and requires at least one tagged proton, giving a more specific measurement of the exclusive and SD processes with reduced background, covering a mass range 150–1600 GeV, and with higher experimental acceptance than in the pure double-tagging case.

2 Experimental set-up

The ATLAS experiment [19] at the LHC is a multipurpose particle detector with forward/backward-symmetric cylindrical geometry and near 4π coverage in solid angle.[1]

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The region $z \geq 0$ is referred to as the A-side, and $z < 0$ is referred to as the C-side. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer (not used in the present analysis) surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering.

Forward scattered protons are detected in Roman Pot systems known as the ATLAS Forward Proton (AFP) spectrometer system [20, 21]. These detectors are positioned near the outgoing proton beam and can be moved in the x-direction close to the beam as required. The AFP spectrometer consists of four tracking units located at $z = \pm 205$ m and ± 217 m. They are denoted as Near and Far stations, respectively, with the $+z$ $(-z)$ direction denoted as the A(C)-side. Each station houses a silicon tracker comprising four planes of edgeless silicon pixel sensors [22–25]. The sensors have 336×80 pixels with area 50×250 μm^2. Each sensor is tilted by 14° relative to the x-direction to improve hit efficiency and x-position resolution, resulting in an overall spatial resolution of $\sigma_x = 6$ μm [26]. Data taking with the AFP system commences once the detectors are at a position where the innermost silicon edge is within 2 mm of the beam centre during stable running conditions. The AFP alignment calibration was performed using beam loss monitors [27, 28], beam position monitors [29], and dimuon production events, $\gamma\gamma \to \mu^+\mu^-$ [15].

A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and makes use of a subset of the detector information to accept events at a rate below 100 kHz. It is followed by a software-based trigger that reduces the average accepted event rate to 1 kHz, depending on the data-taking conditions. No trigger with an AFP signal was used because each AFP station reconstructs proton tracks with a probability of around 70% per bunch crossing.

An extensive software suite [30] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

The dataset was collected in 2017 using pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV. The integrated luminosity was 14.6 fb^{-1}, corresponding to the time the AFP system was in operation together with the central detector and after data-quality requirements. The average number of interactions per bunch crossing was 36. The data were recorded using a diphoton trigger that required two clusters of EM calorimeter cells with transverse energies

$E_{\mathrm{T}} = E\sin(\theta)$ above 35 GeV and 25 GeV, respectively [31, 32], after which standard data-quality requirements were applied [33]. For the forward-proton measurement, it was required that every AFP station had at least three operational silicon planes, with correct operation of the AFP data acquisition system [34].

Simulated signal events were produced using the SuperChic 4.02 Monte Carlo (MC) generator [35–37] for the exclusive signals and SuperChic 4.14 [9] for the SD and DD signals. ALP masses in the range $m_X = 150$–1600 GeV were considered, and for each m_X value a sample was generated with the ALP-to-diphoton coupling constant set to[2] $f^{-1} = 0.05\ \mathrm{TeV}^{-1}$, where the natural width of the ALP is $\Gamma = m_X^3/4\pi f^2$. Generator-level selections were applied, requiring photons to have transverse momentum $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$; the diphoton rapidity is required to be $|y_{\gamma\gamma}| < 2.4$. The acceptance A_0 for signal events to pass these fiducial region requirements is in the range 60%–75%, depending on m_X. Typically, the SD production cross section is approximately three times the exclusive cross section, while the DD and exclusive cross sections are similar (the DD contribution drops to a negligible level after applying the selection cuts, especially for the narrow ξ range). The SD and DD events were interfaced with Pythia 8.307 [38] for hadronisation of dissociated-proton systems.

To model the central-detector response, the signal samples were processed with a fast simulation [39] which uses a Geant4-based simulation of the inner tracker and a parameterisation of the calorimeter response [40]. The reconstruction of scattered protons in the data combines information from the AFP tracker and knowledge of the LHC magnet lattice [15, 41], which is used to calculate the proton transport from the IP. The response of the AFP spectrometer in the MC samples was modelled by a fast simulation in which Gaussian smearing, based on the AFP spatial resolution, is applied to the generated proton position in each AFP station. The track is then reconstructed according to the simulated positions and subsequently used in the proton reconstruction. Effects of multiple pp interactions in the same and neighbouring bunch crossings (pile-up), as seen in the central detector, are included in the MC samples by overlaying simulated minimum-bias events generated with Pythia 8.210 [42] using the A3 set of tuned parameters [43]. The distribution of the average number of interactions per bunch crossing in the MC simulation is reweighted to that observed in the data. Before applying the photon identification criteria to simulated events, the shower shape parameters were corrected for small differences in their average values between data and simulation.

4 Object and event selection

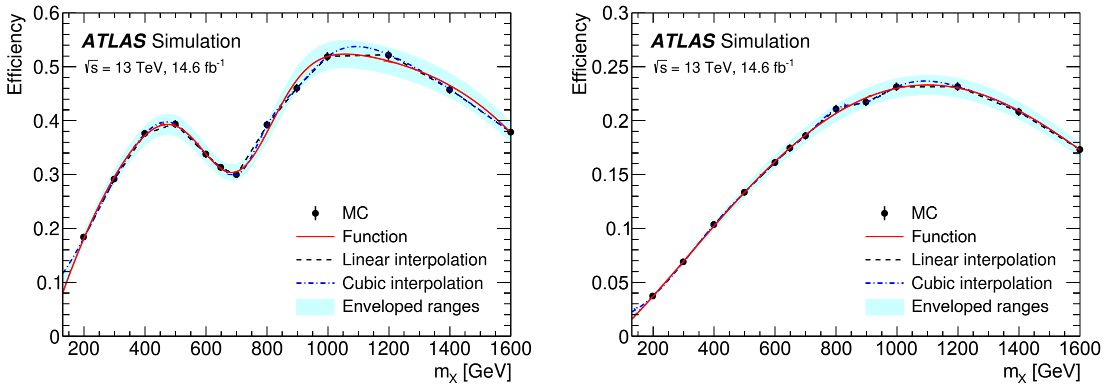
Photon candidates were reconstructed from topological clusters [44] of energy deposits in the ATLAS EM calorimeter and were calibrated as described in ref. [45]. To reduce the background from jets, photon candidates were required to fulfil *tight* identification criteria based on shower shapes in the EM calorimeter and energy leakage into the hadronic calorimeter [45, 46]; these gave a typical identification efficiency above 90% and misidentification efficiency of 20–40%. The photon isolation requirement for further rejection of jets used only the calorimeter information, because track-based isolation

[2] f^{-1} is taken from ref. [8], and the input coupling constant parameter of SuperChic is $g_a = 4f^{-1}$ [9, 36].

would remove photon-induced signal events accompanied by tracks from other interactions in the same bunch crossing if their primary vertices were misidentified as the signal vertex. The calorimeter isolation transverse energy $E_{\mathrm{T}}^{\mathrm{iso}}$ was required to be smaller than $0.022E_{\mathrm{T}} + 2.45$ GeV, where $E_{\mathrm{T}}^{\mathrm{iso}}$ is defined as the sum of transverse energies of the positive-energy topological clusters within a cone of size $\Delta R = 0.4$ around the photon candidate; the main part ("core") of the photon shower was excluded, and a correction was applied for leakage of the photon shower from the core into the rest of the isolation cone. The contributions from the underlying event and pile-up were subtracted using the techniques described in refs. [47, 48]. The event selection required at least two photon candidates with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.37$, matched to the online photon objects that triggered the event, excluding the barrel-to-endcap transition regions of the calorimeter, $1.37 < |\eta| < 1.52$. The azimuthal misalignment between the pair of photons was required to be small, as determined by an acoplanarity $A_{\phi}^{\gamma\gamma} = 1 - |\Delta\phi_{\gamma\gamma}|/\pi < 0.01$.

Protons transported to the AFP by the beamline magnets leave hits in its silicon trackers, which are processed by per-plane clustering and per-station track-finding algorithms [23]. Tracks are reconstructed from clusters found in at least two planes in each station. From the track spatial coordinates, the proton energy and momentum at the IP are inferred, using the known beam optics. The result of the reconstruction is the fractional energy loss of the scattered proton, defined as $\xi = 1 - E_{\mathrm{scattered}}/E_{\mathrm{beam}}$, where $E_{\mathrm{scattered}}$ (E_{beam}) is the scattered (beam) proton energy. The determination of ξ from the AFP stations (ξ_{AFP}) requires tracks in both the Near and Far stations. A ξ_{AFP} calibration was performed in the earlier measurement of dimuon production events recorded during the same data taking [15]. The same calibration was used in the present analysis, and made use of a matching between the central-detector measurement and the AFP measurement, as described below. Events with at least one A-side or C-side tagged proton were accepted, for which the ξ_{AFP} value was required to be within the range $[0.035, 0.08]$.

The ξ value of the forward scattered proton can also be calculated independently of the forward protons, using the kinematics of the central photon pair, and is denoted by $\xi_{\gamma\gamma}$. It is determined from the diphoton mass $m_{\gamma\gamma}$ and rapidity $y_{\gamma\gamma}$ by momentum conservation as $\xi_{\gamma\gamma}^{\pm} = (m_{\gamma\gamma}/\sqrt{s})\, \mathrm{e}^{\pm y_{\gamma\gamma}}$, where + (−) corresponds to the proton on the A(C)-side and negligible transverse momentum transfer to the protons is assumed. If there was more than one proton candidate on the same AFP side (~10% of the cases), the proton with ξ_{AFP} closest to $\xi_{\gamma\gamma}$ was chosen, giving more than 99% efficiency. Proton-tagged diphoton candidates were then selected by requiring kinematic matching on at least one AFP side: $|\Delta\xi| = |\xi_{\mathrm{AFP}} - \xi_{\gamma\gamma}| < \xi_{\mathrm{th}}$, where $\xi_{\mathrm{th}} = 0.004 + 0.1\xi_{\gamma\gamma}$. The second term in ξ_{th} takes account of the uncertainty in the proton propagation through the beam optics between the central detector and the AFP spectrometer, which is proportional to $\xi_{\gamma\gamma}$. For $m_{\gamma\gamma} < 500$ GeV (≥ 500 GeV), the exclusive and SD processes respectively account for about 60% (40%) and 40% (60%) of the selected signal events.



(a) (b)

Figure 2. Signal selection efficiency as a function of ALP mass m_X for the (a) exclusive and (b) single-dissociative process. The ratio of the number of selected events to the number of generated MC events is given (black points) and is parameterised by an analytic function (red solid line). The linear (black dashed line) and cubic (blue chain line) interpolations of the black points are used to derive the envelopes (cyan filled region) which are regarded as systematic uncertainties.

5 Signal and background modelling

For signal events, the diphoton invariant-mass distribution is expected to peak close to the mass of the ALP, with a spread given by the convolution of its intrinsic decay width and the experimental resolution. For the ALP parameters of interest in this analysis, the ALP intrinsic decay width is narrow enough to be ignored, as inferred from the m_X and f^{-1} values input to the signal MC samples. The experimental resolution of the invariant mass is modelled with a double-sided Crystal Ball (DSCB) function [49, 50]. The six parameters of the DSCB function are determined using the simulated signal MC samples. Each parameter is expressed as a linear function of m_X. The uncertainty due to the fitting procedure for the linear function is used as a systematic uncertainty for each parameter of the DSCB function. The signal fiducial cross section, σ_{fid}, and the signal selection efficiency are also modelled as functions of m_X to derive exclusion upper limits for the cross section. The models are illustrated in figure 2. In the exclusive process, the combination of the AFP geometrical acceptance and the $y_{\gamma\gamma}$ distribution of the expected signal gives rise to a double-peaked mass structure in the exclusive signal efficiency, which is a consequence of the acceptance values integrated over the mass contours overlapping with the shaded region in figure 5.[3]

The dominant source of background after the full event selection arises when a pair of photons (or hadronic jets misidentified as photons) is produced in a pp interaction other than that giving the detected forward proton but within the same bunch crossing. The protons originate from soft-scale events, in most cases single-diffractive processes. These recorded events are collectively referred to as combinatorial backgrounds and are modelled using a fully data-driven method which follows the background estimation procedure. An event

[3]In figure 5, the contours at 400 and 1000-1200 GeV pass maximally through the shaded regions of acceptance, corresponding to peaks in the efficiency distribution, while the contours at 600-800 GeV pass through a smaller acceptance region of acceptance, which generates a dip.

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sample, referred to as a "mixed-data" sample, was constructed by replacing the AFP data from a given event by that from one or more other data events, before the event selection. To maximise the statistical precision, this reassignment was performed using the method described in ref. [15]. It uses each possible combination of diphoton and AFP data from different events within intervals of measured instantaneous luminosity, and suppresses any contribution from signal events and from background events with a single vertex. The normal event selection was then applied to the mixed-data sample, and the events were subsequently inversely weighted by the number of reassignments that were taken for a given diphoton event. This maximal use of proton reassignment gives a mixed-data sample after the kinematic matching that has a distribution in $m_{\gamma\gamma}$ that is as statistically precise as before the matching.

A fit was performed to the mixed-data sample using the background distribution function

$$f\left(x; b, a_0\right) = N\left(1 - x^{1/3}\right)^b x^{a_0}, \tag{5.1}$$

where N, b and a_0 are free parameters to be fitted, and $x = m_{\gamma\gamma}/\sqrt{s}$. This function is a member of a family of functions used in previous diphoton resonance searches [18, 51]. Figure 3 shows the diphoton mass distribution of the mixed-data sample and the fitted result of the background function. Small local deviations are in the range explained by statistical fluctuations and cannot be explained by the effects of other known systematic effects.

The background sample generation was validated by forming a new mixed-data sample in a different kinematic region that is orthogonal to the nominal case. In the data and mixed-data samples, the *tight* photon identification was replaced by a looser requirement [45, 46] and events with *tight* identification were removed. An acoplanarity requirement $A_\phi^{\gamma\gamma} \in [0.01, 0.5]$ was applied to reduce signal contamination in the corresponding data sample. The $m_{\gamma\gamma}$ distributions of this mixed-data sample and the data in the validation region after the event selection were compared, and were found to agree well in shape and normalisation.

Contributions from backgrounds other than the combinatorial background, collectively referred to as single-vertex backgrounds, were investigated using dedicated MC samples. Photon-induced dilepton production $\gamma\gamma \to \ell^+\ell^-$, SM light-by-light scattering $\gamma\gamma \to \gamma\gamma$, and gluon-initiated central exclusive production (CEP) were modelled at generator level with SuperChic 4.13. None of the single-vertex backgrounds has a narrow peak in the diphoton mass distribution, and their sum is small: it is below 1.2% of the estimated combinatorial background contribution in any $m_{\gamma\gamma}$ bin of width 29 GeV. In addition, diffractive processes were investigated as possible single-vertex backgrounds using Pythia 8.306. Such contributions were also judged to be negligible. Thus, the effects of single-vertex background are neglected.

To evaluate the background-modelling uncertainty, the procedure in ref. [52] was followed. The $m_{\gamma\gamma}$ distribution of the selected mixed-data sample was smoothed using the functional decomposition (FD) method [53] as shown in figure 4(a). Assuming the smoothed shape to be identical to the true background distribution, signal-plus-background fits were performed for each ALP mass at 2 GeV intervals in the search range. The resulting signal yields, so-called spurious signals, are regarded as representing the degree to which the background function fails to fit the true background distribution. The spurious signals

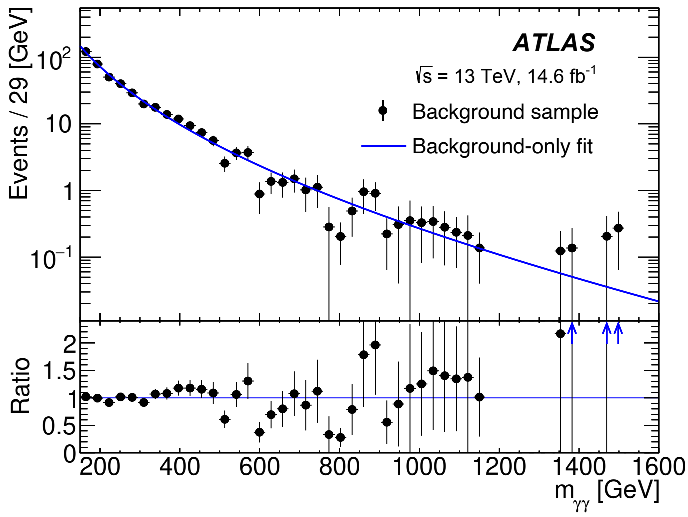
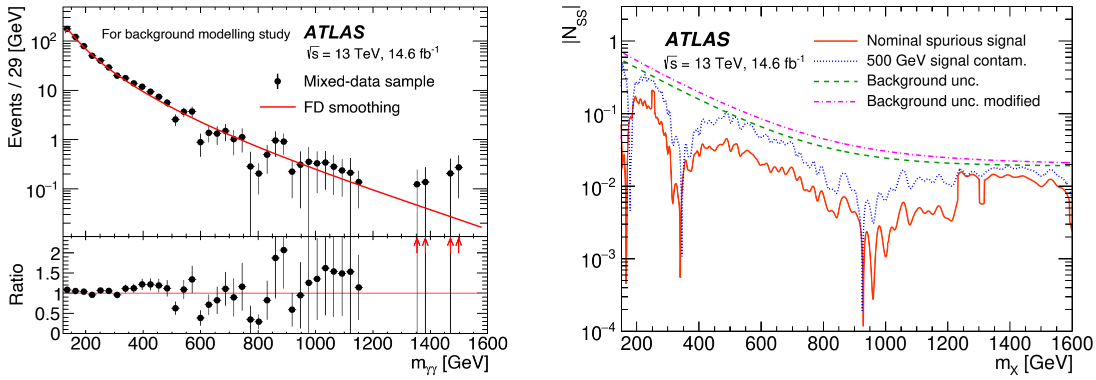


Figure 3. Comparison of the $m_{\gamma\gamma}$ distributions after the full nominal event selection, showing the mixed-data sample (black points) and the background function fitted to it (blue line) in the diphoton mass range $[150, 1600]$ GeV. The ratio of the mixed-data to the fitted function is shown in the lower panel.

were also evaluated for cases where ALP signals are included in the data and thus can contaminate the mixed-data sample. The ALP signals were generated as described in section 3, with the protons in the signal MC samples replaced by protons randomly taken from the data. The largest effect of the contamination is for $m_X = 500$ GeV. An envelope of the absolute values of the spurious signals is used as the absolute systematic uncertainty of signal yield originating from the background modelling as a function of ALP mass. Since the assumption about the FD shape may not be exactly correct, an FD smoothing bias was evaluated to allow for the uncertainty using a procedure similar to that in ref. [54]. Pseudo-datasets were generated from a number of known background shapes, taken as true background distributions. The FD smoothing result from each pseudo-dataset was compared with each shape, in terms of the spurious signals. The relative difference in the results was combined with the original uncertainty. Figure 4(b) shows the spurious signal for the nominal case and the largest-effect signal-contamination case. The bare envelope and the modified one considering the FD bias are also shown.

6 Statistical procedure

The statistical analysis uses unbinned maximum-likelihood fits made to the $m_{\gamma\gamma}$ distribution using the DSCB signal function and the background function defined in Equation (5.1). All the parameters of the background function are free parameters, with initial values obtained using the fit shown in figure 3. In these fits, the statistical uncertainty dominates over the systematic uncertainty. The systematic uncertainties on the signal function parameters listed in table 1 are accounted for in the fits by using nuisance parameters constrained by Gaussian penalty terms in the likelihood function. They include the experimental uncertainties in the luminosity determination, pile-up profile, trigger efficiency, and photon



(a) (b)

Figure 4. (a) The diphoton mass distribution of the mixed-data sample (black points) and its FD smoothing result (red line). (b) Absolute value of the number of spurious signal events $|N_{\mathrm{SS}}|$ as a function of hypothetical ALP mass m_X. The nominal (red solid line) and signal-contamination (blue dotted line) cases are illustrated. The envelope (green dashed line) is derived from the local maxima and modified considering the FD bias (magenta chain line).

identification and reconstruction. Additional systematic uncertainties in the signal shape come from the uncertainties in the photon energy resolution and scale, but their effect on the signal yield is small. An uncertainty in the beam optics between the central detector and AFP spectrometer affects the proton transport simulation used in proton reconstruction. The AFP global alignment is the distance between the AFP edge and the beamline. Its preliminary measurement is corrected using the photon-initiated dimuon production events, $\gamma\gamma \to \mu^+\mu^-$ [15]. This correction is also regarded as the uncertainty in the distance determination and is the largest component of the signal yield uncertainty. The proton reconstruction efficiency and its uncertainty are determined by evaluating the efficiency for each station using the tag-and-probe method between the Near and Far stations. Showering from the signal protons in the AFP may affect the proton reconstruction efficiency. The showering can occur in the steel window of the Roman Pot enclosing the AFP [55] or in the AFP itself. This effect is evaluated by varying the required number of clusters for AFP track reconstruction from two to three.

For the signal cross section, a theoretical uncertainty associated with the soft survival factor is included, which considers the possible presence of additional colour flow between the two scattered protons that makes both protons dissociate. The relative uncertainty in the modelling of the soft survival factor is at the level of 1% in the exclusive channel [56], with very small sensitivity to model variations in the QCD hadron-hadron interactions. For the SD channel, the interaction is less peripheral; a reasonable variation in the modelling of soft QCD interactions gives an uncertainty of order 10%. Other theoretical uncertainties are neglected [57].

Statistical tests were performed in the search range $m_X = 150$–1600 GeV, using the conventional test statistics q_0 for significance and $\tilde{q}_\mu$ for exclusion upper limits [58]. The tests were performed in steps of 4 GeV in m_X. This is smaller than the expected full resonance

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Source	Uncertainty
Signal yield uncertainty	
Pile-up reweighting	$^{+2.7}_{-2.6}\%$
Luminosity	$\pm 2.4\%$
Photon identification efficiency	$^{+1.6}_{-1.5}\%$
Photon isolation efficiency	$\pm 1.9\%$
Beam optics between ATLAS central and AFP detectors	$^{+0.8}_{-3.4}\%$
AFP global alignment	$^{+10.0}_{-8.6}\%$
Proton reconstruction efficiency	$^{+3.0}_{-2.2}\%$
Showering in the AFP	$^{+0.0}_{-6.6}\%$
Background modelling (mass-dependent)	$\pm$(0.02–0.7) events
Signal modelling	
Photon energy resolution	$^{+14.1}_{-4.8}\%$
Photon energy scale	$\pm$(0.5–1.0)%
Signal cross-section uncertainty	
Soft survival factor (exclusive process)	$\pm 2\%$
Soft survival factor (single-dissociative process)	$\pm 10\%$
Soft survival factor (double-dissociative process)	$\pm 50\%$

Table 1. Summary of the systematic uncertainties. The photon energy scale and resolution uncertainties are applied to the parameters of the DSCB function.

width, which is mostly associated with the signal mass resolution and varies from 4.3 GeV for $m_X = 150$ GeV to 27 GeV for $m_X = 1600$ GeV. Local p-values and their significance for the background-only hypothesis were calculated using pseudo-experiments for the q_0 distribution. Global significance values were computed using the same pseudo-experiment samples to account for the look-elsewhere effect [59, 60]. The maximum q_0 with respect to m_X, denoted $q_0^{\max}$, was calculated for each pseudo-experiment, and the $q_0^{\max}$ distribution was used to obtain the global p-value.

Pseudo-experiments were used to derive the expected and observed 95% confidence level (CL) exclusion upper limits on the fiducial cross section times branching ratio into two photons, computed using a modified frequentist approach, $\mathrm{CL_s}$ [61, 62].

7 Results

A total of 441 events are observed in the range $m_{\gamma\gamma} \in [150, 1600]$ GeV. Figure 5 shows $\xi^{+}_{\gamma\gamma}$ vs $\xi^{-}_{\gamma\gamma}$ for these events with $m_{\gamma\gamma}$ and $y_{\gamma\gamma}$ contours. In this sample, 219 (222) events

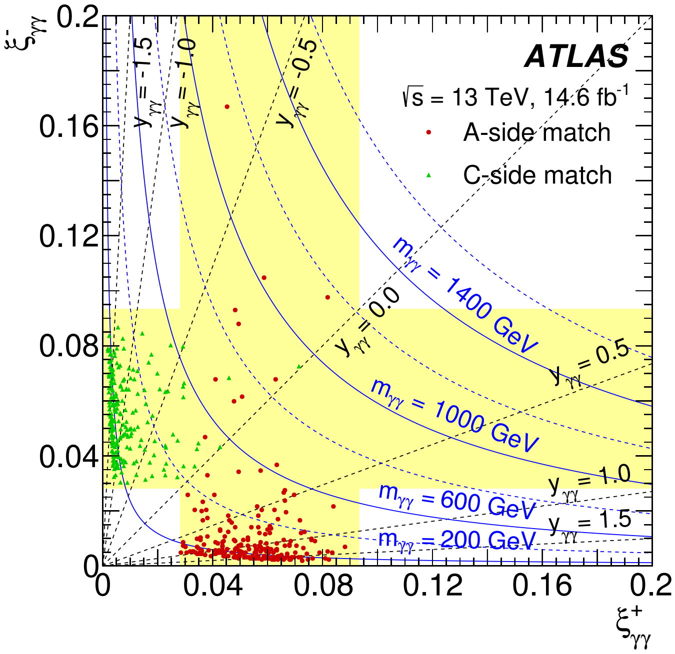

Figure 5. $(\xi^+_{\gamma\gamma}, \xi^-_{\gamma\gamma})$ distribution of the selected data candidates after the full event selection in $m_{\gamma\gamma} \in [150, 1600]$ GeV with $m_{\gamma\gamma}$ contours (blue) and $y_{\gamma\gamma}$ contours (black). The dashed blue lines are additional mass contours that bisect the spacing between adjacent solid mass contours. The range of $\xi_{\gamma\gamma}$ in which forward-proton matching is possible, $[0.035 - \xi_{\text{th}}, 0.08 + \xi_{\text{th}}]$, is indicated by the yellow rectangle for each side. Events passing the matching requirement on the A(C)-side are represented by the red dots (green triangles). No event passed the matching requirement for both the A-side and C-side.

passed the matching selection for the A(C)-side; no event passed the matching for both the A-side and C-side, in accordance with expectations. The diphoton invariant-mass distribution for the selected events is shown in figure 6, along with the background-only fit. The highest-mass diphoton candidate observed in the data has a mass of 1.16 TeV. The probability of compatibility with the background-only hypothesis, quantified as the local p-value, is shown in figure 7 as a function of the hypothesised ALP resonance mass. The most significant excess, observed at $m_X = 454$ GeV, has a local significance of 2.51σ. The global p-value for the null hypothesis is larger than 0.5, from which it is concluded that no significant excess over the background-only hypothesis is observed.

The observed and expected upper limits on the fiducial cross section and coupling constant for ALP production at 95% confidence level, assuming a 100% decay branching ratio into two photons, are shown in figure 8 and are in good agreement, consistent with the absence of a signal. The upper limits on the coupling constant are derived using the relationship between the expected fiducial cross section and coupling constant in ref. [8]. The observed limit on the coupling constant is in the range 0.04–0.09 TeV^{-1}. The ALP natural width is $\Gamma \approx 1$ GeV for $m_X = 1400$ GeV and $\Gamma \approx 3$ GeV for $m_X = 1600$ GeV at the observed limit. Such widths are sufficiently small to be ignored, relative to the detector resolution. The exclusion of a coupling constant f^{-1} much larger than illustrated by the Γ

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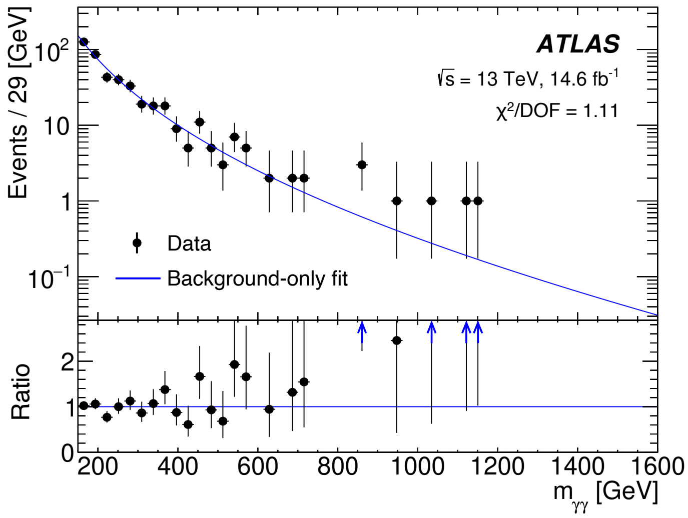

Figure 6. Background-only fit to the observed numbers of events (black points) as a function of the diphoton invariant mass $m_{\gamma\gamma}$. The ratio of the data points to the fitted background (blue line) is shown in the bottom panel. The quantity χ^2/DOF is the chi-squared per degree of freedom in the fit to data.

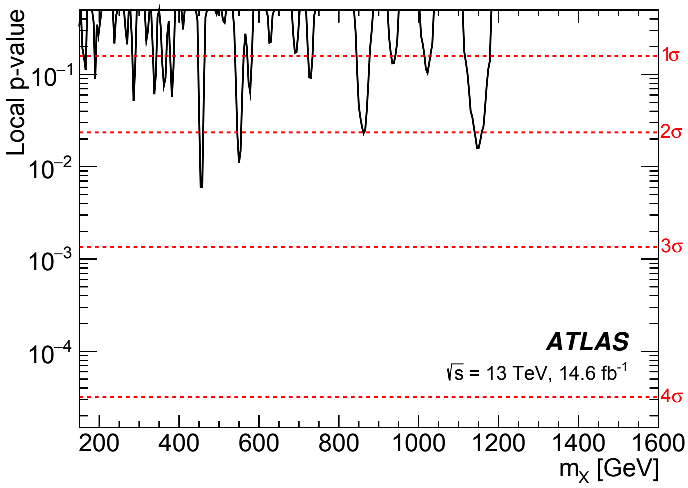

Figure 7. Local p-values for ALP observation on the basis of a null hypothesis as a function of m_X. Significances corresponding to 1σ, 2σ, 3σ, and 4σ in units of standard deviation are indicated by the red dashed lines.

contours is not justified in this analysis because it violates the narrow-width approximation used in the signal modelling.

A previous inclusive diphoton resonance search [18] also has sensitivity to the ALP signal. To estimate the sensitivity of that search to the signal considered in this paper, the efficiency of the ALP signal to pass the event selections defined in that paper, relative to the corresponding fiducial requirements, was evaluated and was found to be similar to the other production mechanisms considered. The inclusive analysis is sensitive to smaller ALP production cross-sections, partly because of the higher integrated luminosity and

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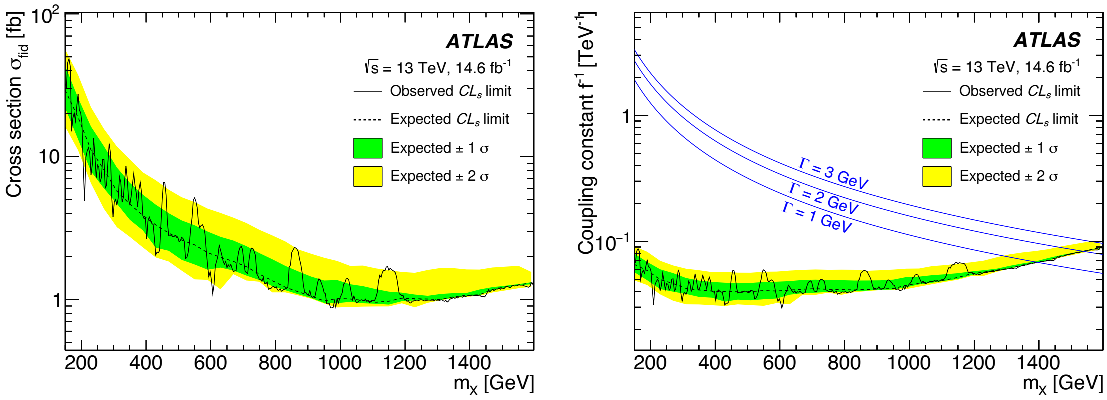

(a) (b)

Figure 8. Expected and observed 95% CL upper limits on (a) the signal fiducial cross section σ_{fid} and (b) the ALP coupling constant, assuming 100% branching ratio for ALP decay into two photons, as functions of the hypothetical ALP mass m_X. The 1σ and 2σ confidence intervals are shown by the coloured bands. Contours of the ALP natural width Γ are illustrated by the smooth blue solid lines.

partly because of the effect of the restricted ξ range used in this paper. However, by requiring a forward-proton tag, the present approach is able to add valuable information and can distinguish cleanly a photon-induced production mechanism from other production mechanisms, should the presence of a signal be observed. The present analysis demonstrates the applicability of forward proton tagging to add precision to ALP searches that may be carried out using present and future data samples. In particular, the sufficiency of a single AFP tag has been shown, along with a method for optimising the background calculation. Both these features validate and improve the statistical significance of the forward-tagging approach.

8 Conclusion

A search for an axion-like particle (ALP) has been carried out with the ATLAS experiment using 14.6 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions at the LHC. Events with centrally produced photon pairs tagged by forward scattered protons have been studied in a search for light-by-light scattering, $pp \to p(\gamma\gamma \to \gamma\gamma)p^{(*)}$, mediated by an ALP resonance. The search was performed in the diphoton mass range $m_{\gamma\gamma} = [150, 1600]$ GeV. No signal is observed, and the data are consistent with a smooth combinatorial background that can be assumed to come from Standard Model processes. The inferred upper limit on the ALP coupling constant, assuming a 100% decay branching ratio into two photons, is in the range 0.04–0.09 TeV^{-1} at 95% confidence level. These results are comparable to those of the CMS-TOTEM collaboration, obtained using a similar approach, and extend their measured mass range to lower values.

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