The search for an Axion-Like-Particle (ALP) is being performed using 30 fb$^{-1}$ data recorded with the ATLAS experiment and the ATLAS Forward Proton (AFP) detector in 2017. The AFP detector is positioned symmetrically at approximately 220 m about the interaction point near the beam pipe and is used to measure the kinematics of surviving protons. The high mass diphoton spectrum is studied to prepare the search for ALP mediated light-by-light scattering. At the current stage of the analysis, the focus falls on a 1 TeV ALP with coupling $g = 0.001 \text{ GeV}^{-1}$, which was simulated. Data containing photon information and AFP containers was also prepared. The blinding strategy was established, along with the next steps to be performed in this search.

I. INTRODUCTION

The existence of light (pseudo) scalar particles, particularly axions, that couple to particles from the Standard Model (SM) would have a large array of consequences across physical scales, from cosmic to subatomic. Mainly, introducing the axion into the SM addresses the strong CP problem [1] and could explain one of the dark matter constituents [2, 3]. Axion-like particles (ALPs) appear in many extensions of the Standard Model, usually as neutral spin-0 particles that couple to fermions through dimension-five operators proportional to the fermion mass and to bosons through dimension-five operators containing derivatives [4]. Thus, in energy regimes exceeding the top quark mass, ALPs are only accessible through their coupling to the gauge bosons and the Higgs boson. In this search, one considers ALP photon coupling exclusively.

Currently, high-energy colliders are the only place where the Schwinger limit of $10^{18} \text{ Vm}^{-1}$ is surpassed. Hence, at the Large Hadron Collider (LHC), the electromagnetic fields between protons are strong enough to facilitate the production of particles [5]. In this context, two protons that narrowly miss each other can create photons that fuse together, subsequently decaying into various final states. Therefore, photon fusion represents a distinct way to search for new physics; the presented search is independent of the strong and weak force couplings that most other LHC searches rely on. High precision measurements of these type of QED processes at the energy frontier are able to set constrains on various phenomena and theories [6].

Light-by-light scattering is a process that can arise under the conditions detailed in the previous paragraph. Standard Model light-by-light scattering is an established quantum mechanical phenomenon that is forbidden in the classical theory of electrodynamics [7]. Thus, the light-by-light scattering reaction is mediated by a virtual box involving electrically charged fermions or $W^{\pm}$ bosons, at order $\alpha_{\text{EM}}^4$. However, in various extensions to the SM, extra contributions are possible which makes the measurement of light-by-light scattering sensitive to new physics, providing an avenue for axion-like particle searches [4, 8].

A search for ALPs in central exclusive diphoton production, $pp \rightarrow p(\gamma\gamma)p$, is presented. Figure 1 shows the Feynman diagrams for this process. The studied interaction comes in three flavors, depending on the final state of the protons: both protons remain intact, one proton can dissociate, or both can dissociate. The photons arise from the electromagnetic fields of the interacting protons and are nearly on-shell, which is described by the equivalent photon approximation [9]; these photons are measured in the central detector. Furthermore, protons that remain intact after passing through the interaction point (IP) are detected, tagged and have their kinematics measured with the ATLAS Forward Proton (AFP) detectors. The presented ALP search is one of the first analyses to use information from this relatively new detector.

This report is structured as follows. A brief description of the detectors is given in Section II. Further, the event selection strategy is explained in Section III, followed by the results in Section IV. Finally, Section V concludes the current progress and describes future work.
FIG. 1. Axion-like particle mediated light-by-light scattering. The process can occur in three distinct topologies: (left) exclusive $pp \to p(\gamma\gamma \to \gamma\gamma)p$ (centre) single dissociative semi-exclusive $pp \to p^*(\gamma\gamma \to \gamma\gamma)p$, and (right) double dissociative $pp \to p^*(\gamma\gamma \to \gamma\gamma)p^*$. The left diagram is the signal. The center and right diagrams are considered as background.

II. THE DETECTORS

The analysis is performed on data from the ATLAS experiment, in conjunction with AFP proton measurements. The addition of AFP proton tags to the conventional ATLAS detector information allows for large background reduction, thus providing an acceptable sensitivity for the light-by-light scattering ALP search. Brief descriptions of the two detectors are presented in the two subsections below.

A. The ATLAS Experiment

The ATLAS detector [10] is a multipurpose particle detector that covers almost the entire solid angle around the interaction point (IP), where protons collide at $\sqrt{s} = 13$ TeV. The detector consists of four layers: the inner detector (ID), used to track charged particles in the pseudorapidity region of $|\eta| < 2.5$, the EM and hadronic calorimeters that measure the energy up to $|\eta| = 4.9$, and the muon spectrometer which covers $|\eta| < 2.7$. Additionally, the forward calorimeters (FCal) [11] cover the range of $3.2 < |\eta| < 4.9$. The zero-degree calorimeters (ZDC) [12], symmetrically located along the beam axis at 140 m from the IP, detect neutral particles.

B. The ATLAS Forward Proton Detector

A schematic of the detector is presented in Fig. 2. In principle, the AFP detects protons undergoing small angle scattering at the IP, mainly due to losing energy through, e.g., coherent photon emission. The scattered protons are deflected outside the beam profile by the LHC magnets, thus reaching the Roman Pot (RP) systems [13] inserted near the beam. Once in the RP region, the protons are measured by the AFP and Absolute Luminosity for ATLAS (ALFA) detectors.

Each side of the RP is referred to as a separate arm. The arm to the left of ATLAS when looking down from the center of the LHC tunnel is side A (+z), while the arm to the right is side C (−z). There are two tracking units per arm, referred to as the NEAR and FAR stations. These subdivisions of the AFP detector are located at $z_{\text{NEAR}} \approx \pm 205$ m and $z_{\text{FAR}} \approx 217$ m respectively from the IP. Each station has four planes made from 3D silicon pixel sensors (3D-Si) that form the silicon tracker. These sensors have $336 \times 80$ pixels with $50 \times 250 \mu m^2$ area each and spatial resolution of $\sigma_x = 6 \mu m$, $\sigma_y = 30 \mu m$; they are tilted 14 degrees with respect to the x-axis to improve the resolution in x direction. The 3D-Si planes measure the trajectories of the scattered protons.

III. EVENT SELECTION

The event selection has two parts: the initial selection uses only central detector information, while the latter part of the selection includes AFP information. All the selection cuts to be applied in this analysis, as of writing this, are summarized in Table I. In the central detector, events containing only two photons pass preselection. Protons that lose momentum through central exclusive photon production are steered outside the beam envelope and can enter the AFP acceptance. Thus, the proton fractional momentum loss $\xi = \Delta p/p$ can be determined indirectly from the kinematics of the central photon pair and directly from the direct measurement of the AFP. In conventional exclusive production searches, one usually relies on vetoes on the detector activity (for example, absence of calorimeter activity). In addition to this basic approach, here the protons surviving coherent photon emission are tagged and their kinematics are correlated with the centrally detected photons. This sets a kinematical constraint on the final state that facilitates an efficient offline selection for the $\gamma\gamma \to \gamma\gamma$ process, with large background rejection factors.
A. Data and Simulated Samples

Only data recorded in 2017 is used in this analysis. This is the first year the AFP was installed on both sides during high-luminosity runs and was able to record data suitable for forward-central correlation. Conversely, 2018 AFP data was synchronised with the incorrect bunch crossing so there is no forward-central correlation; for this reason, the 2018 runs cannot be used for this search. Thus, STDM2 2017 data was found suitable for this analysis, as exclusive diphoton events with low acoplanarity in the main detector are of interest. Originally, the STDM2 did not contain AFP information, however this was requested and added to the derivation. The ALP simulation was performed using SuperChic v3.03 and was validated within the Exotics group, where a full simulation of the signal is to be performed.

B. Central Detector

The preselection criteria requires exactly two signal photons. The 10 GeV cut on the transverse momentum is a standard "cleaning" cut, since low $p_T$ events are not considered in this analysis. To select central exclusive diphoton events, further requirements are imposed, as follows. An invariant mass higher than 6 GeV allows for good separation between prompt photons and fake signatures due to calorimeter noise, cosmic ray muons or non-prompt photons coming from the decay of neutral hadrons. Additionally, to suppress $\gamma\gamma \rightarrow e^+e^-$ background and to enforce exclusivity of the diphoton pair, events containing "standard" charged particle tracks with $p_T > 0.1$ GeV, $|\eta| < 2.5$ and at least six hits in the pixel and microstrip detectors, including at least one pixel hit, are rejected. Most diphotons produced through photon fusion are expected to be back-to-back, so they have very low acoplanarity $A = 1 - |\Delta\phi_{\gamma\gamma}/\pi| < 0.01$.

Through conservation of 4-momentum for a given beam center of mass $\sqrt{s}$, the fractional proton energy loss $\xi$ can be completely determined from the photon system

$$\xi_{\gamma\gamma}^\pm = \frac{m_{\gamma\gamma}}{\sqrt{s}} e^{\pm y_{\gamma\gamma}}, \quad \begin{cases} 
\xi_{\gamma\gamma}^+ &= \xi_{\gamma\gamma}^A \\
\xi_{\gamma\gamma}^- &= \xi_{\gamma\gamma}^C
\end{cases} \quad (1)$$

where $y_{\gamma\gamma}$ is the rapidity of the diphoton system, + corresponds to stations 0, 1 (side A) and − corresponds to stations 2, 3 (side C).

C. Central-Forward Matching

The final state kinematics of the ALP mediated light-by-light scattering measured in the central detector are correlated with the initial state kinematics inferred by the forward protons. The proton candidates are ordered by increasing energy. The proton with the with the highest energy loss is selected as

$$\xi_{\text{AFP}} = 1 - \frac{E_{\text{AFP}}}{E_{\text{beam}}} \quad (2)$$

where $E_{\text{beam}}$ is the energy of the proton beam (6.5 TeV).

A matched candidate is defined as the event in which $\xi_{\text{AFP}}$ is within 10% of the expected fractional energy loss from the diphoton $\xi_{\gamma\gamma}$, as shown in Table I:

$$\text{Matched candidate} = \frac{|\xi_{\text{AFP}} - \xi_{\gamma\gamma}|}{\xi_{\gamma\gamma}} < 10\% \quad (3)$$

where one divides by $\xi_{\gamma\gamma}$ since this measurement is more accurate than the AFP one. As a proof of principle, the matching is demonstrated with a dimuon analysis [14].
<table>
<thead>
<tr>
<th>Observable</th>
<th>Preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of photons</td>
<td>Exactly 2 signal</td>
</tr>
<tr>
<td>(p_T)</td>
<td>&gt; 10 GeV</td>
</tr>
<tr>
<td></td>
<td>Central exclusivity selection</td>
</tr>
<tr>
<td>(N_{\text{tracks}}^{p_T&gt;0.1 \text{ GeV}})</td>
<td>Exactly 0</td>
</tr>
<tr>
<td>(</td>
<td>\eta_{\text{track}}</td>
</tr>
<tr>
<td>Acoplanarity (1 -</td>
<td>\Delta\phi_{\gamma\gamma}</td>
</tr>
<tr>
<td>(\xi_{\gamma\gamma})</td>
<td>&gt; 0.01</td>
</tr>
<tr>
<td></td>
<td>Forward–central detector matching</td>
</tr>
<tr>
<td>(\xi_{\text{AFP}})</td>
<td>(\in [0.015, 0.15])</td>
</tr>
<tr>
<td>allowSingleStationReco</td>
<td>true (unless explicitly stated otherwise)</td>
</tr>
<tr>
<td>Number of protons</td>
<td>No requirement (unless explicitly stated otherwise)</td>
</tr>
<tr>
<td>((\xi_{\text{AFP}} - \xi_{\gamma\gamma})/\xi_{\gamma\gamma})</td>
<td>&lt; 10% (unless explicitly stated otherwise)</td>
</tr>
</tbody>
</table>

**TABLE I.** Summary of all event selection cuts that are to be applied in this analysis.

### IV. RESULTS

The analysis is still in its preparation stages. Thus, production of the STDM2 data with the AFP container and the axion-like particle simulation are still on going at the time of writing this report. The code to be used in making the analysis ntuples, as well as code that applies the cuts detailed above and creates the final histograms, are ready to be applied to the data. These have already been tested on the STDM7 data (contains AFP information), HIGG1D data and STDM2 data.

After investigating the diphoton invariant mass spectrum as well as the acoplanarity of the diphoton system, the blinding strategy was discussed. It was determined that inverting the acoplanarity cut, shown in Table 1, and limiting the maximum acoplanarity at 0.02 or 0.1, is sufficient to obtain a satisfactory blinded data set in which the presented analysis can be executed.

### V. CONCLUSION AND FUTURE WORK

The initial stages of the search for ALPs in light-by-light scattering with AFP proton tagging were done. The blinding strategy was established and the analysis code was prepared. Several technical issues pertaining to STDM2 data containers and the AFP data tool were overcome and documented. An ATLAS internal note describing all the technical details was made available.

After completing the initial studies, the search for axion-like particles using light-by-light scattering and the AFP proton tag stands as a promising analysis. The 1 TeV ALP, with coupling constant \(g = 0.001 \text{ GeV}^{-1}\), is within the predicted sensitivity limits. A set of initial results will be obtained once the simulation of the ALP signal is finished, along with the inclusion of the AFP container in the STDM2 data. Recently, it was agreed that the right way to approach this analysis is to try to fit the diphoton invariant mass spectrum, thus performing a bump hunt around 1 TeV. Once the details of the fit are elucidated and the uncertainties are quantified, the unblinded spectrum will be fitted and a definite result will be obtained. Afterwards, one can extend the same analysis to other ALP masses or couplings, until the parameter space specified in Ref. [4] is covered. Finally, in the far future, there are plans to perform a similar measurement for SM light-by-light scattering, this time with 13 TeV \(pp\) and AFP proton-tagging.


