Studies of Axion-Like Particle Searches with the ATLAS Forward Proton (AFP) Detector for Run-3 and HL-LHC – Summer Student Report

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Abstract

This summer student project investigates the potential sensitivity increase of Axion-Like Particle (ALP) detection at the Large Hadron Collider (LHC) from Run-2 to Run-3 and to the High Luminosity LHC (HL-LHC). A particular focus is on incorporating information provided by the ATLAS Forward Proton (AFP) detector. ALPs, hypothetical particles arising from extensions of the Standard Model of particle physics, are of great interest due to their potential implications for various astrophysical phenomena. The AFP detector enables precise tagging of forward protons produced in proton-proton interactions. By analyzing previous results from ATLAS di-photon events recorded by the central ATLAS detector, both with and without the AFP detector contribution, the impact of incorporating AFP data on the detection of ALPs is assessed. The study focuses on three distinct types of light-by-light scattering processes (exclusive, single-dissociative and double-dissociative), which are essential for understanding the interactions involving ALPs. The ALP search concentrates on the first two processes, as they are expected to have the most significant sensitivity to ALP signals. Advancing the search for ALPs by exploiting the unique capabilities of the AFP detector and analyzing various light-by-light scattering processes will contribute significantly to the field of particle physics and open new avenues for future research in the exciting realm of physics beyond the Standard Model.

1 Introduction

Enhancing the sensitivity is the main focus in the search for axion-like particles (ALPs) using data from LHC Run-3 and HL-LHC, with particular emphasis on the incorporation of the AFP detector. Details of this project are given in the internal ATLAS note [1].

The axion [2, 3] is a proposed particle that would explain the lack of CP violation in quantum chromodynamics [4–7]. Such a particle must be very light and couple to two photons. Axion-like particles, on the other hand, are predicted by extensions of the Standard Model to be particles of higher masses that have similar behaviour to axions in that they also couple to two photons. They were introduced as a potential class of particles that could effectively suppress the CP-violating effects. This concept creates a different perspective in theoretical physics between particle physics and fundamental forces. Such axion-like particles (ALPs) may be produced in two-photon collisions and subsequently decay into two photons [8–10]. The ALP production process is predicted to show up as a resonant peak in future analysis at the ALP mass value in the process $\gamma\gamma \to \gamma\gamma$, also known as light-by-light scattering.

The purpose of the ATLAS Forward Proton (AFP) detector [11] is to track leading protons at a considerable distance from the interaction point. These protons deviate significantly from the expected proton beam trajectory, allowing precise measurements of these deviations. Positioned around 210 m on both sides of the ATLAS interaction region, the two AFP stations play a crucial role in enhancing the sensitivity of ALP search efforts. The ATLAS central detector measures the decay of ALPs into two high-energy photons. The intact protons that pass through the interaction point can be identified, labeled, and their kinematics assessed using the ATLAS Forward Proton (AFP) detector (Figure 1).

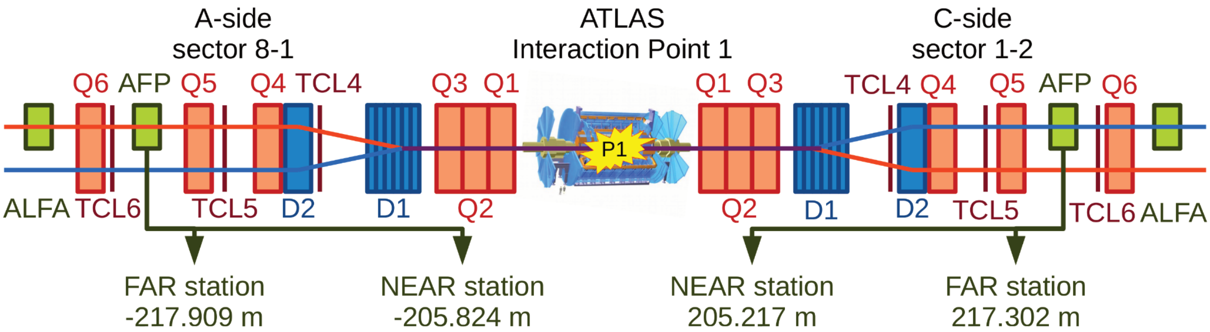

Figure 1: Schematic view of the ATLAS central and AFP detectors. The scattered protons at the interaction point (P1) are deflected outside the beam line by the LHC magnets; the dipoles (D1, D2) bend and quadruple magnets (Q1-Q6) focus the beam.

By extrapolating previous results from ATLAS di-photon analyses recorded by the central ATLAS detector, both with and without the AFP detector inclusion, this study explores three types of light-by-light scattering processes (Figure 2):

– Exclusive or Elastic (EL): Both protons remain intact.

– Semi-Exclusive or Single Dissociative (SD): One proton dissociates.

– Double Dissociative (DD): Both protons dissociate.

The primary focus of the ALP with AFP search lies in the first two processes, as they hold the greatest potential for detecting ALP signals.

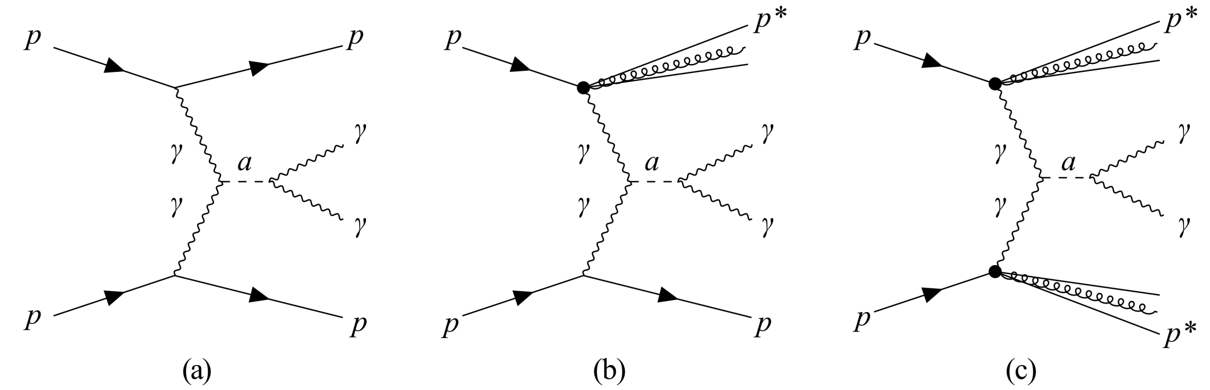

Figure 2: Feynman diagrams for (a) exclusive, (b) single-dissociative, and (c) double-dissociative light-by-light scattering with outgoing photon pairs mediated by an ALP.

In order to analyze ALPs effectively, various key parameters are considered. The luminosity (expressed in inverse femtobarns [fb^{-1}]) determines the total number of interactions expected from the recorded data. The coupling constant f^{-1} quantifies the strength of interactions between particles, providing crucial insights into ALP behavior. The inverse of the natural width Γ corresponds to the lifetime at which ALPs decay into other particles, influencing their detectability.

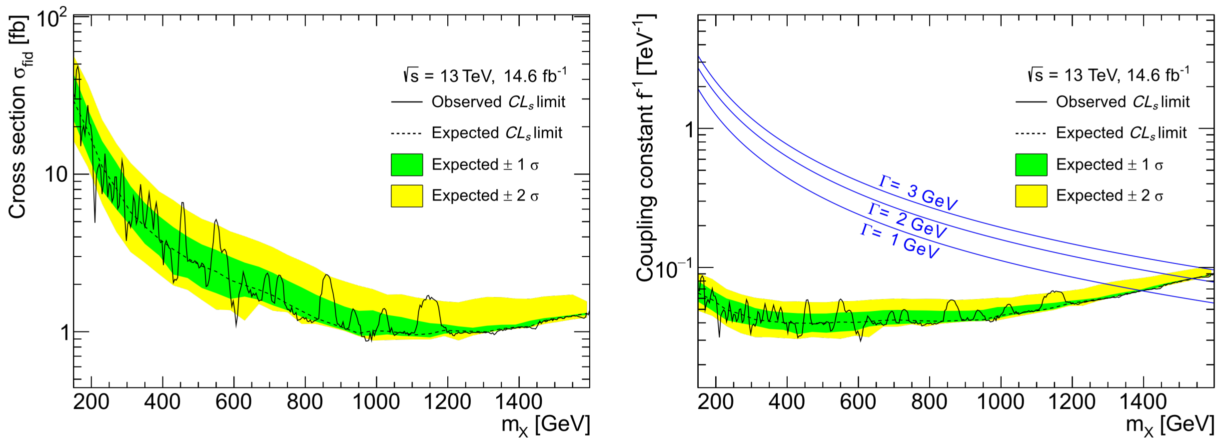

Figure 3: Expected and observed 95% CL upper limits on (a) the signal fiducial cross-section σ_{fid} and (b) the ALP coupling constant, assuming 100% branching ratio for ALP decay into two photons, as functions of the hypothetical ALP mass m_X. The 1σ and 2σ confidence intervals are shown by the colored bands. Contours of the ALP natural width Γ are illustrated by the smooth blue solid lines.

The increase of the sensitivity of future upgrades for the detectors has been studied.

Through the use of the ATLAS central detector and the AFP detector, this study is aimed at comparing how different approaches can shed light on the existence of ALPs and their interactions with other particles. A future discovery of an ALP would expand our understanding of the fundamental constituents of the universe. The methods used obtaining Figure 3 [12] to convert the cross-section σ_{fid} into the coupling constant f^{-1} were used in this study.

2 Methodology

2.1 Data Collection

The first step of the project is to collect information on analysis done with and without the AFP detector. It was obtained from the analyses conducted at a center-of-mass energy of $\sqrt{s} = 13$ TeV and a luminosity of 14.6 fb^{-1} with the AFP [12] and 139 fb^{-1} without the AFP detector [13].

2.2 Determining Coupling Limits

To assess the coupling limits for the ALP, the measured cross-section values obtained previously were used. The coupling limit (f^{-1}) was derived from the relation [14]:

$$f^{-1} = \frac{g}{4}, \tag{1}$$

$$g = g_{\text{sim}} \sqrt{\frac{\sigma_{\text{lim}}}{\sigma_{\text{sim}}}}, \tag{2}$$

where σ_{lim} is the cross-section for the expected signal limit at 95% CL, and σ_{sim} denotes the simulated cross-section (EL signals) [15].

2.3 Scaling for Different Luminosities

In order to account for varying luminosities, scaling for four different luminosity scenarios was performed: 180 fb^{-1} with AFP, 300 fb^{-1} without AFP, and 3000 fb^{-1} both with and without using the AFP detector. The scaling process involved calculating the coupling limits (f^{-1}) for each luminosity using the following equation:

$$f^{-1} = \frac{1}{4} g_{\text{sim}} \sqrt{\frac{\sigma_{\text{lim}}}{\sigma_{\text{sim}}}} \sqrt{\frac{\mathrm{L}_{\text{existing}}}{\mathrm{L}_{\text{new}}}} \tag{3}$$

where $\mathrm{L}_{\text{existing}}$ is the luminosity in a current analysis, and L_{new} is the luminosity in a future analysis.

2.4 Statistical Analysis

To evaluate the reliability and confidence of the results, a statistical analysis was performed. The uncertainties associated with the measured cross-section were assessed, considering experimental errors and systematic uncertainties.

2.5 Comparison and Interpretation

A comparison of the coupling limits f^{-1} was performed, obtained with and without the AFP detector for the different luminosities. The scaling behavior for the ALP coupling limit was analysed and the results given in Figure 6 were interpreted. It is important for the comparison and interpretation of the obtained curves to keep in mind how much the AFP affects the results when it comes to eliminating background.

3 Expected Cross-Section Limits With and Without the ATLAS Forward Proton Detector

The search for ALPs uses simulated data based on proton-proton collisions. Simulations of their production resulting from these collisions were investigated for the cross-section limits. The scenarios with and without the integration of the contribution to the AFP detector were investigated. This analysis can help to determine when to shift the focus from the data of the AFP detector to solely concentrating on the data from the ATLAS central detector. The investigation involves analyzing different numbers of backgrounds and signals across a wide range of masses. At low masses, the AFP detector effectively eliminates more background, whereas at high masses, it removes valuable signals.

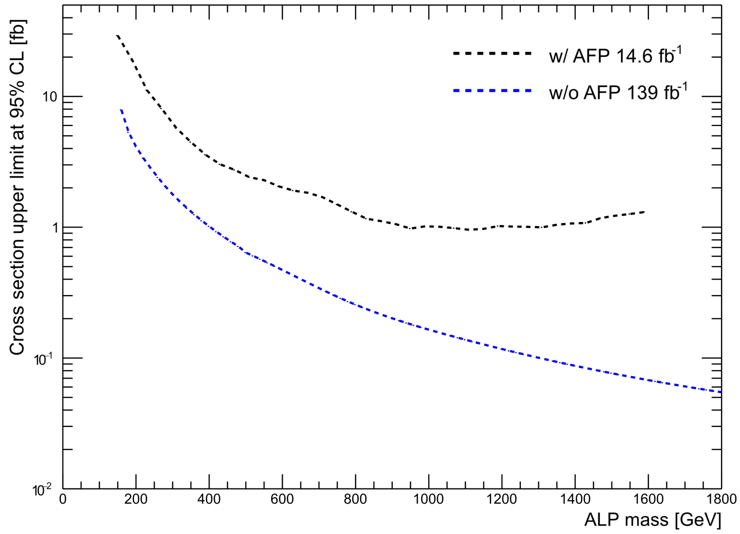

Figure 4: Cross-section expected upper limit at 95% confidence level (CL) determined with the AFP detector at a luminosity of 14.6 fb^{-1} [12] and a cross-section expected limit using only the ATLAS central detector with a luminosity of 139 fb^{-1} [15].

Two primary analysis results are used that are presented in Figure 4:

- The dashed black line represents the expected cross-section limit derived from the latest ATLAS publication [12], including the AFP and a luminosity of 14.6 fb^{-1}.
- The dashed blue line corresponds to data solely from the ATLAS central detector, with a luminosity of 139 fb^{-1} [13], using an interpretation beyond the publication.

4 Coupling Constant Determination

The coupling constant is a fundamental parameter in theoretical models that determine the expected ALP rate. Different theories and models predict different values for the coupling constant, and experimental results can be used to constrain or validate these theoretical frameworks. The coupling constant determines the strength of the interaction between particles. In the context of ALP searches, coupling constant f^{-1} determines how ALPs interact.

A smaller value for the coupling constant limit indicates a better chance of detecting an ALP. New experiments need to consider the sensitivity of their apparatus to the expected interaction strength. Therefore, an analysis of this kind would need to be considered for any future detector design, to support theoretical predictions for ALPs.

For this study, the coupling constant is calculated using the following equations:

$$g = g_{\text{sim}} \cdot \sqrt{\frac{\sigma_{\text{lim}}}{\sigma_{\text{sim}}}} \tag{4}$$

$$f^{-1} = \frac{g}{4} \tag{5}$$

In these equations, the terms are defined as follows:

- σ_{lim}, the cross-section limit for signal events, considering both data with and without the AFP detector.
- σ_{sim}, the simulated (theoretical) cross-section (EL signals).
- f^{-1}, the coupling constant in the theory model.

The simple equations (4) and (5) allow to convert the cross-section limit to a coupling limit. This assumes that the cross-section is proportional to the coupling squared, and it only takes EL into account.

5 Effects of Different Light Scattering Processes

A discovery of ALPs would develop a comprehensive understanding of light-by-light scattering processes. Such processes can be exclusive, single dissociative, and double-dissociative processes (EL, SD, DD) and have a significant influence in distinguishing genuine ALP signals from background noise. The accuracy of the predictions requires a thorough consideration of process efficiencies [12].

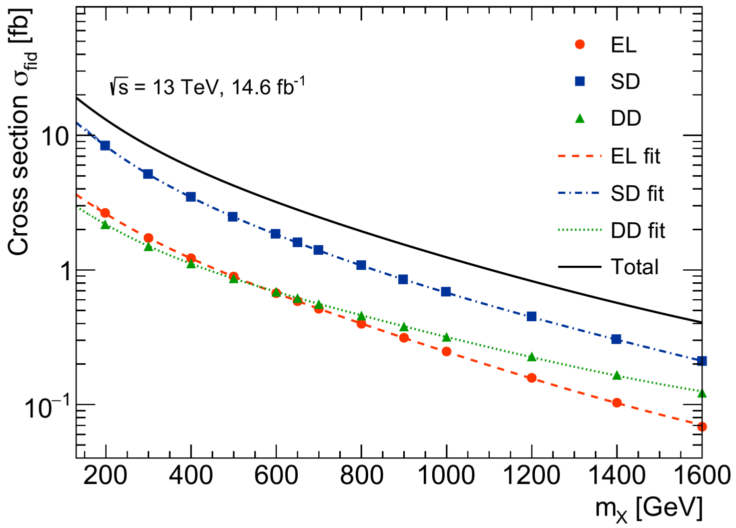

Figure 5: Fiducial cross-sections and parametrisation for the coupling constant $f^{-1} = 0.05$ TeV^{-1}.

Figure 5 shows the signal fiducial cross-sections and their parametrisation for coupling constant $f^{-1} = 0.05$ TeV^{-1}. The cross-section is parameterised by an analytical function for each type of process. The number of expected signal events is obtained by multiplying the signal efficiency times the acceptance and by the integrated luminosity.

6 Data Analysis and Interpretation

The calculation of the expected coupling limit at higher luminosities involves modeling and fitting the cross-section limit, the signal strength yield, μ and the coupling limit with and without using the AFP detector. Based on the provided data from [12], a scaling method is applied to obtain Figure 6.

The data analysis was executed using a combination of Python and the ROOT framework.

6.1 Data Processing

The code framework enables a systematic approach to data handling, analysis, and visualization. After defining the cross-section as a parameterized function, it is converted into the coupling limit subsequently.

Using this code, which takes into account the different efficiencies for the light-by-light scattering processes, the coupling limits were determined. These coupling limits are scaled for higher assumed luminosities. The expected coupling limit, based on the incorporation of the AFP detector, is given as a function of the ALP mass [16]. The expressions given below, were used to obtain the coupling constant limit for data only taken from the ATLAS central detector [13]:

$$\sigma_{95} = \mu_{95} \cdot \sigma_{\text{std}} \tag{6}$$

$$f_{95}^{-1} = \sqrt{\mu_{95}} \cdot f_{\text{std}}^{-1} \tag{7}$$

7 Results and Discussion

The results of the data analysis are as follows.

7.1 Coupling Constant

After implementing the functions of the EL, SD and DD production cross-section, the coupling limits are plotted.

Interpretation of the expected coupling constant limits shown in Figure 6:

- The dashed black line is derived and transformed from data recorded in 2017 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with an integrated luminosity of 14.6 fb^{-1} [12].
- The dashed blue line represents data taken from the search for resonances decaying into photon pairs in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV [13].
- The green and red line is the expected coupling constant from the combination of Run-2 and Run-3 data, illustrating that across the range of masses a combination of the AFP

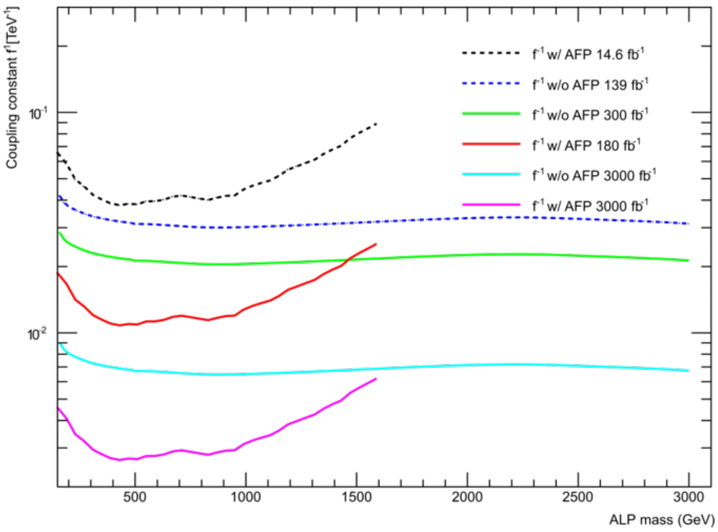

Figure 6: Coupling constant scaled at different sensitivities, taking into account data simulated with and without the AFP detector.

and the ATLAS central detector signals is needed in order to obtain good sensitivity at low and at high masses. The green line was created using Equation (3):

$$L_{\text{existing}} = 139\,\text{fb}^{-1}$$

$$L_{\text{new}} = 300\,\text{fb}^{-1}$$

$$g_{\text{sim}} = 200\,\text{GeV}^{-1}$$

$$f^{-1} = \frac{1}{4} \cdot 200 \cdot \sqrt{\frac{\sigma_{\text{lim}}}{\sigma_{\text{sim}}}} \sqrt{\frac{L_{\text{existing}}}{L_{\text{new}}}}$$

The red curve is the expected coupling constant for Run-3 data using the AFP detector, which was calculated using the same equation as before.

$$L_{\text{existing}} = 14.6\,\text{fb}^{-1}$$

$$L_{\text{new}} = 180\,\text{fb}^{-1}$$

$$g_{\text{sim}} = 200\,\text{GeV}^{-1}$$

$$f^{-1} = \frac{1}{4} \cdot 200 \cdot \sqrt{\frac{\sigma_{\text{lim}}}{\sigma_{\text{sim}}}} \sqrt{\frac{L_{\text{existing}}}{L_{\text{new}}}}$$

- The magenta and cyan curves are the expected coupling constants for the runs of the high luminosity LHC which should be operational from the beginning of 2029 [17], with and without the AFP detector. They were calculated in the same way:

– With data from the AFP detector

$$f^{-1} = \frac{1}{4} \cdot 200 \cdot \sqrt{\frac{\sigma_{\mathrm{lim}}}{\sigma_{\mathrm{sim}}}} \sqrt{\frac{14.6}{3000}}$$

– Without using data from the AFP detector

$$f^{-1} = \frac{1}{4} \cdot 200 \cdot \sqrt{\frac{\sigma_{\mathrm{lim}}}{\sigma_{\mathrm{sim}}}} \sqrt{\frac{139}{3000}}$$

The sensitivity increase for high masses without the AFP detector is due to the increasing selection efficiency for those higher masses. The coupling constant for different luminosities is given in Table 1.

Luminosity [fb^{-1}]		**Coupling Constant Limit** f^{-1} [**TeV**$^{-1}$]
14.6	w/ AFP	0.05
139	w/o AFP	0.03
180	w/ AFP	0.013
300	w/o AFP	0.02
3000	w/ AFP	0.003
3000	w/o AFP	0.006

Table 1: Expected ALP coupling constant limits at a mass of 1000 GeV.

7.2 Incorporating Expected Limits in a Summary Plot

The results were integrated into a previous summary plots [18, 19], which aggregates data from various experiments, demonstrating a significance of 2σ. This combination provides a visual representation of potential enhancements in ALP searches, as shown in Figure 7.

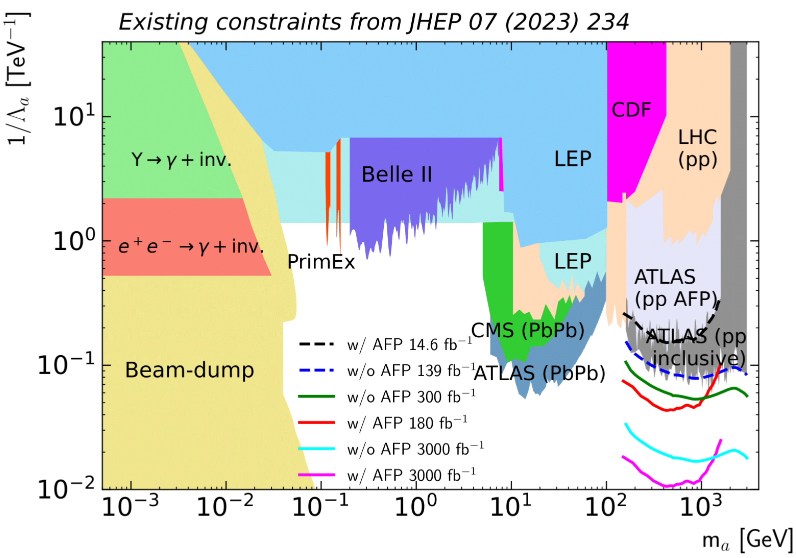

Figure 7: Summary of ALP observed and expected limits at 95% CL. The extrapolation curves for higher luminosities with and without using AFP data are given. $g = 1/\Lambda_a = 4/f$.

8 Conclusion

This project studied the results from ALP searches using data from the ATLAS Forward Proton (AFP) detector and a di-photon analysis with the ATLAS central detector. The investigation focused on understanding the effects of different light-by-light scattering processes, predicting expected coupling constant limits, and analyzing the potential enhancements that the AFP detector can contribute to the sensitivity of ALP searches.

The study has demonstrated the significance of incorporating AFP data into ALP searches, showing how the AFP detector can provide a more comprehensive view of particle interactions and contribute to the identification of ALP signals.

For different luminosities, the expected coupling constant sensitivity for ALPs was calculated and visualized. The presented results show the potential impact of AFP data on the sensitivity of ALP searches, opening new avenues for future research and experiments in the quest to uncover particles beyond the Standard Model.

This project contributes to the collaborative efforts of the ATLAS scientific community, leveraging cutting-edge technology, data analysis techniques, and the capabilities of advanced detectors to improve the understanding of fundamental constituents of the universe. The insights gained from this study contribute to the broader field of particle physics and pave the way for further exploration into the complexities of particle phenomena.

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