Performance Studies of Axion-Like Particle Searches with the ATLAS Forward Proton (AFP) Detector

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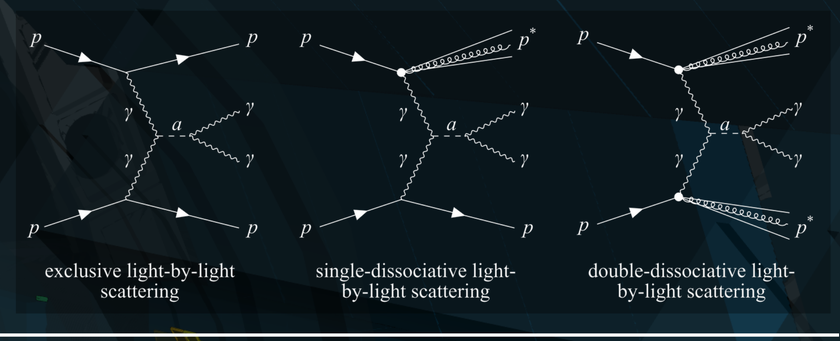
This summer student project focuses on the sensitivity increase of axion-like particles with LHC Run-3 and HL-LHC data including the AFP detector. The AFP detector is used to tag a forward proton from a proton-proton interaction. This study utilizes previous results of ATLAS di-photon analyses recorded by the ATLAS central detector, with and without using the AFP detector in addition. There are three types of light-by-light scattering processes illustrated (exclusive, single-dissociative and double-dissociative). The ALP with AFP search focuses on the first two processes.



exclusive light-by-light scattering | single-dissociative light-by-light scattering | double-dissociative light-by-light scattering

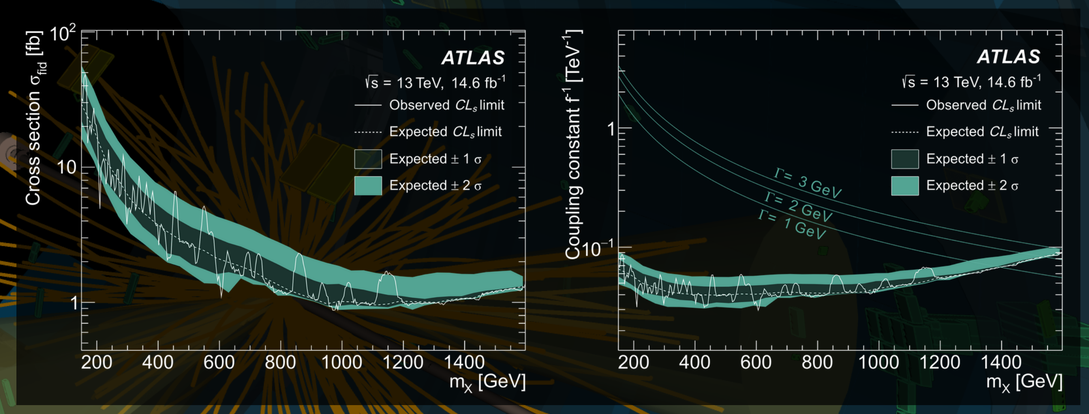
Introduction

• Luminosity [fb^{-1}] – the number of particles passing through a given area per unit of time and is a key factor in determining the total number of interactions and the production rate of rare processes during experiments. Luminosity is typically expressed in units of inverse area, such as inverse femtobarns (fb^{-1} ≈ 10^{28} m^{-2}).

• Coupling constant (f^{-1}) – quantifies the strength of the interaction between particles. A larger value of f^{-1} indicates a stronger interaction, while a smaller value indicates a weaker interaction.

• The natural width (Γ) is a measure of how quickly the ALP decays into other particles. If an ALP has a wider natural width, it would decay faster into other particles. However, it was found that for the masses, the natural width is relatively small:
Γ ≈ 1 GeV for mX = 1400 GeV and Γ ≈ 3 GeV for mX = 1600 [1]

• ALP mass [GeV] – By investigating ALPs at different mass ranges, one can study their potential interactions with other particles, predict their behavior, and determine the coupling limits (f^{-1}) for each mass scenario.



Expected and observed 95% confidence level (CL) upper limits on:
a) the signal cross-section (σ)
b) the ALP coupling constant with the assumption of 100% branching ratio for ALP decay into two photons, as functions of the hypothetical ALP mass (mX).
The colored bands represent the 1σ and 2σ confidence intervals. Additionally, the smooth blue solid lines depict the contours of the ALP natural width (Γ) [1].

Objectives

- Performance studies of the ATLAS Forward Proton Detector (AFP)
- Search for new particles beyond the standard model

Methodology

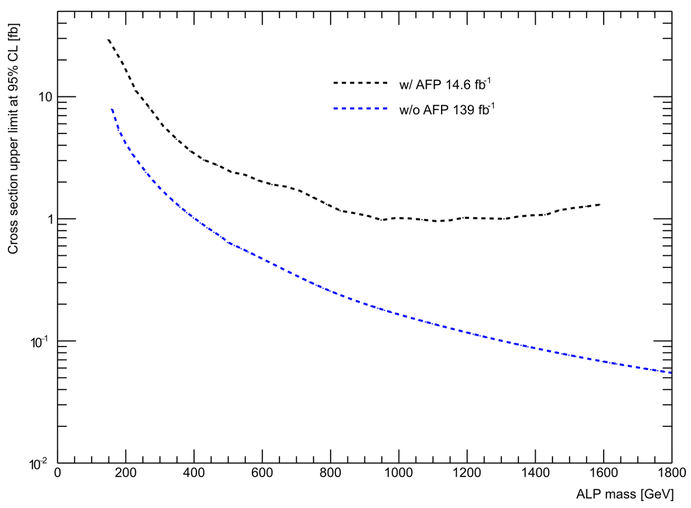
1. Cross section data collection:
   - w/ AFP at 14.6 fb^{-1} luminosity
   - w/o AFP at 140 fb^{-1} luminosity
3. Scaling for 180, 300, 3000 fb^{-1} with and without the AFP detector

2. Determining Coupling Limits:
   - using scaling formulas

   σ - cross section
   f^{-1} - coupling limit

$$g = \sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}} \qquad f^{-1} = \frac{g}{4}$$

Analysis, Results & Interpretation



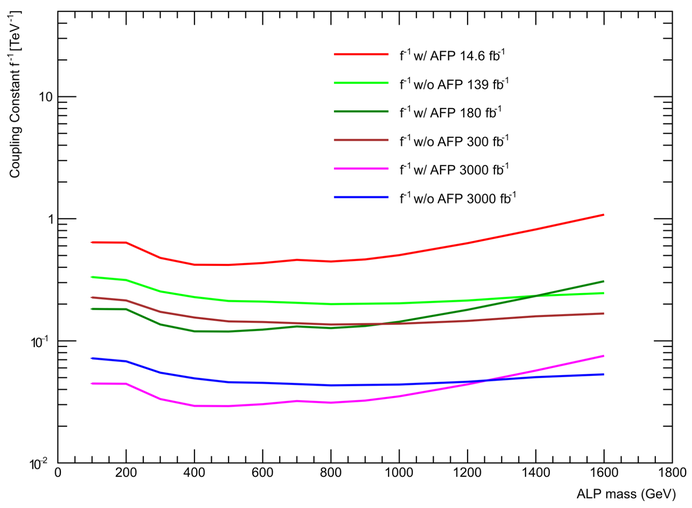
- Simulated data was collected for the cross section analysis from the proton-proton collision in the search of ALPs.
- The dashed black line represents the cross section line derived from figure 8a from the most recent ATLAS publication [1] when the signals from the AFP are taken into consideration and the luminosity is 14.6 fb^{-1}.
- The dashed blue line shows the data taken only from the ATLAS central detector [3] and it corresponds to a luminosity of 139 fb^{-1}.
- Using the formulas given below, these values were used to acquire the coupling constant:

$$g = \sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}}$$

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

σ_{lim} - the cross section for assumed signal events [3] for collected data with and without the AFP detector.

σ_{sim} - the simulated data (EL signals) for the theoretical cross section [1]



After implementing the calculations, the red and green plot lines were obtained. The additional curves were generated using a scaling method described below.

Interpretation of the plot:

— Derived and transformed from data recorded in 2017 at a centre-of-mass energy of √s = 13 TeV corresponding to an integrated luminosity of 14.6 fb^{-1} [1].

— Data is taken from the search for resonances decaying into photon pairs in 139 fb^{-1} of pp collisions at √s = 13 TeV [1].

— The curve is the expected coupling constant for Run-3 using the AFP, which was calculated from the cross-section data with the formula given below.

$$f^{-1} = \frac{1}{4}\sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}} \cdot \sqrt{\frac{14.6}{180}}$$

— The plotted line is the expected f^{-1} from the combination of Run-2 and Run-3 data, illustrating that at higher masses a combination of the AFP and the ATLAS central detector signals is need in order to obtain good sensitivity at low and high masses.

$$f^{-1} = \frac{1}{4}\sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}} \cdot \sqrt{\frac{139}{300}}$$

— The curves are the expected coupling constants for the next runs of the high luminosity LHC which should be operational from the beginning of 2029 [4], with and without the AFP.

$$f^{-1} = \frac{1}{4}\sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}} \cdot \sqrt{\frac{14.6}{3000}} \qquad f^{-1} = \frac{1}{4}\sqrt{\frac{\sigma_{lim}}{\sigma_{sim}}} \cdot \sqrt{\frac{139}{3000}}$$

Conclusion

This summer student project at CERN has been a significant step towards the search for ALPs at low and high masses, by analyzing data from forward proton scattering and light-by-light scattering with the AFP detector and central ATLAS detector. In the upcoming weeks, the main focus will be combining the plots for both low (w/ AFP) and high mass (w/o AFP) ALPs, which will contribute to achieving better sensitivity and deeper insights into these elusive particles, which are one way of exploring the fundamental mysteries of the universe.

Related Literature

[1] The ATLAS Collaboration - "Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS", CERN-EP-2023-049, 21 April 2023 arXiv:2304.10953v1 [hep-ex].

[2] Tomáš Chobola - "Study of light-by-light scattering with the ATLAS Forward Proton (AFP) Detector at CERN", 1 June 2020, CERN-THESIS-2020-058

[3] The ATLAS Collaboration - "Search for resonances decaying into photon pairs in 139 fb−1 of $p\,p$ collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", Phys. Lett. B 822 (2021) 136651, arXiv: 2102.13405 [hep-ex].

[4] CERN: "High-Luminosity LHC", URL: https://home.web.cern.ch/science/accelerators/high-luminosity-lhc

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