Study of jet multiplicity for an Axion-Like Particle search in Light-by-Light scattering with the ATLAS central detector and the ATLAS Forward Proton detector – Summer Student Report

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Abstract

This study regarding a search for an Axion-Like-Particle (ALP) focuses on the distributions of the number of jets accompanying the ALP. The ALP study is performed including the data from the ATLAS Forward Proton (AFP) detector. The distributions of the number of jets are compared for the di-photon ALP selection, and the same selection plus a matching of the kinematics of the ATLAS central di-photon kinematics and the AFP proton energy loss on either side of the ATLAS central detector. The distributions in both cases are very similar and thus cannot be used to increase the signal over background ratio significantly.

1 Introduction

Axions and Axion-Like Particles (ALPs) appear in many extensions of the Standard Model and are candidates for the so-called dark matter [1, 2]. The ALP is considered as a hypothetical spin-0 particle and is predicted to solve the strong CP problem (appearance of CP violation in strong interactions) [3]. Usually, ALPs couple to fermions only through dimension-five operators proportional to the fermion mass. Moreover, (pseudo) scalars predominantly couple to gauge 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, including photons, and the Higgs boson. ALPs could be produced in various mechanisms, although in this study, only the process of central exclusive di-photon production (CEP), $pp \to p(\gamma\gamma)p$ is taken into account.

Different aspects of the search for ALPs in CEP production were addressed regarding the event selection [5], the acoplanarity optimization [6], the matching of ATLAS central data and AFP data [7], and the background and sensitivity estimation [8].

Three kinds of processes which depend on the final state of protons are considered (Figure 1): both protons remain intact (referred to as exclusive or elastic), one proton dissociates (referred to as semi-exclusive or single dissociative), or both dissociate (referred to as double dissociative). The radiation of the incoming photons, which are almost on-shell, is described by the equivalent photon approximation [9]; the ALPs decaying into two high-energy photons are measured in the ATLAS central detector. Protons that remain intact after passing through the interaction point can be detected, tagged, and have their kinematics measured by the AFP detectors.

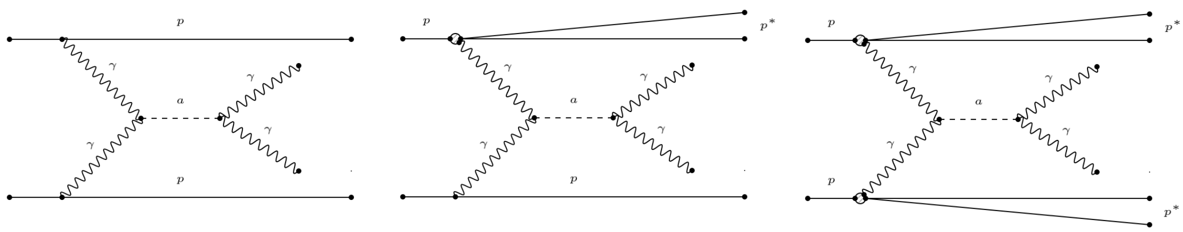

Figure 1: Feynman diagrams of ALP a mediated by light-by-light scattering. This process can take place in three distinct topologies: (left) exclusive $pp \to p(\gamma\gamma \to \gamma\gamma)p$, (center) single dissociative semi-exclusive $pp \to p^*(\gamma\gamma \to \gamma\gamma)p$, and (right) double dissociative $pp \to p^*(\gamma\gamma \to \gamma\gamma)p^*$ [5].

2 Data and simulation

2.1 Data

A total of 32 fb^{-1} luminosity was recorded with the ATLAS central and AFP detectors in 2017. Several variables are measured in the data to select suitable events corresponding to the specific analysis. The data is processed through the STDM2 derivative. Using the STDM2 derivative, events are selected when at least one HLT trigger fires (single photon, di-photon, tri-photon, electron-photon). The AFP information with proton data was added to the STDM2 derivative. In this analysis, a Good Run List (GRL) for which the AFP data is recorded with a tolerable data quality is used. The resulting total integrated luminosity is 14.6 fb^{-1}. Additionally, the blinding of the data has been performed by requiring the di-photon acoplanarity greater than 0.01. This cut would exclude a signal of 1000 GeV ALP and prevent any biased analysis.

2.2 Detector simulation

The ALP signal is generated with SuperChic v3.06 [10] for several ALP masses. This tool provides a common platform for QCD-mediated photon production, and CEP processes. The generator is available to be performed by setting several parameters. The ALP detector simulation was divided into two parts: central detector and AFP detector. The ALP simulation focuses on a mass of 1000 GeV and a coupling constant $g = 0.001$ GeV^{-1}.

3 Analysis

In this analysis, in order to increase the ALP signal detection sensitivities in the CEP production, the number of jets was investigated besides di-photon information. It is expected that no or only a few jets be detected with di-photon production in the CEP production. The exclusivity of di-photon production can be estimated by counting the number of jets before and after applying proton matching conditions measured by the AFP detector. The analysis has been performed in both signal simulation and the data recorded in 2017. The total numbers of di-photons events after overlap removal are 7,183 events and 974,891 events, respectively.

The ALP signal matching efficiencies are analyzed by performing the matching criteria and the number of jets are studied in different cases.

3.1 Combining data of signal simulation

The structure of the two input files includes different variables in each TTree. Information about jets and protons is separated into two different files. It is preferable to merge two data files into a single data file to process events which have the same **RunNumber** and **EventNumber**. Therefore, the data files are combined into a single file when **RunNumber** and **EventNumber** are the same, and at least one proton is present. Table 1 lists the number of events in each data set from signal simulation.

Table 1: Number of events in each data set from the signal simulation.

Signal simulation			
Data set	Ntuple without jet variables	Ntuple with jet variables	Merged data
Total events	7,377	7,390	7,183

3.2 Overlap removal of jets

In order to remove jets which are also reconstructed as photons, a simple overlap removal was applied. The distribution of the difference of $\Delta\eta = |\eta_{\text{photon}} - \eta_{\text{jet}}|$, $\Delta\phi = |\phi_{\text{photon}} - \phi_{\text{jet}}|$ and $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ between photons and jets are used as detailed in the ATLAS internal note [**Kitagawa:279021**]. No overlap removal is applied at this point, therefore overlapping objects have values distributed around 0. Jet objects which satisfy the condition $0.05 \geq \Delta\eta$ and $0.1 \geq \Delta\phi$ for signal simulation and $0.22 > \Delta R$ for data are removed. The number of jets and distributions for their kinematics are shown in the ATLAS internal note [11]. In most events, two jet objects are removed, which corresponds to the expectation of the di-photon events. The number of jets decreases from 6.21 ± 0.04 to 4.24 ± 0.04 in signal simulation and from 6.554 ± 0.004 to 5.357 ± 0.004 in the data by applying the overlap removal, respectively.

3.3 Matching of AFP and ATLAS central detector

The signal candidates of protons and di-photons mediated by light-by-light scattering are identified by defining the relative proton energy loss ξ according to its final kinematics measured by the ATLAS central detector and the AFP detector. The definitions of ξ_{AFP} (protons) and $\xi_{\gamma\gamma}$ (photons) are:

$$\xi_{\mathrm{AFP}} = 1 - \frac{E}{E_{\mathrm{beam}}}, \tag{1}$$

$$\xi_{\gamma\gamma} = m_{\gamma\gamma} \cdot \frac{e^{\pm\eta}}{2E_{\mathrm{beam}}}. \tag{2}$$

The definition of the parameters are:

- E: energy of the proton measured by AFP detector
- $\mathrm{E_{beam}}$: energy of the proton beam (6.5 TeV)
- $\mathrm{m}_{\gamma\gamma}$: invariant mass of di-photon
- η: pseudorapidity of di-photon, where η = -ln tan$\frac{\theta}{2}$

The positive and negative sign of equation (2) corresponds to the stations on either side of the ATLAS central detector, side A and side C, respectively. As matched candidate events, three kinds of matching criteria were defined. The first matching criterion is defined by requiring that the relative difference between the proton energy loss calculated from the central detector information and the AFP information is less than 10%:

$$\frac{|\Delta\xi|}{\xi_{\gamma\gamma}} = \frac{\xi_{\mathrm{AFP}} - \xi_{\gamma\gamma}}{\xi_{\gamma\gamma}} < 10\% \tag{3}$$

The other two matching criteria are 1σ matching and 2σ matching defined as

$$\Delta\xi < \sigma_{\xi_{\mathrm{AFP}}} + \sigma_{\xi_{\gamma\gamma}}, \tag{4}$$

and,

$$\Delta\xi < 2\left(\sigma_{\xi_{\mathrm{AFP}}} + \sigma_{\xi_{\gamma\gamma}}\right), \tag{5}$$

where $\sigma_{\xi_{\mathrm{AFP}}}$ and $\sigma_{\xi_{\gamma\gamma}}$ are the uncertainty on the measurements of ξ_{AFP} and $\xi_{\gamma\gamma}$. In this analysis, the ξ cleaning cuts for $\xi_{\mathrm{AFP}} > 0.01$ and $\xi_{\gamma\gamma} > 0.01$ are applied.

The ALP signal matching efficiencies are analyzed by performing the matching criteria on the recorded data and on simulated events. The matching efficiencies are summarized in Tables 2 and 3 together with the numbers of events for different matching criteria. It is noted that the efficiency in the signal simulation with the condition of side A or C is much larger compared to the other conditions.

Table 2: Number of matches and their percentages related to the total number of di-photon events with at least one proton present (7,183 events) in signal simulation with ALP mass 1000 GeV. This is consistent with a previous analysis [8].

Signal simulation				
Matching condition	side A	side C	side A or C	side A and C
10%	3,643	3,620	5,600	1,663
	50.7%	50.4%	78.0%	23.2%
1σ	3,652	3,635	5,618	1,669
	50.8%	50.6%	78.2%	23.2%
2σ	3,661	3,653	5,633	1,681
	51.0%	50.9%	78.4%	23.4%

Table 3: Number of matches related to the total number of di-photon events with at least one proton present (974,891 events) in the data.

Data in 2017 (14.6 fb^{-1})				
Matching condition	side A	side C	side A or C	side A and C
10%	14,760	15,908	30,644	24
1σ	19,786	21,378	41,118	46
2σ	39,090	41,762	80,636	216

4 Results

The numbers of jets per event for different matching criteria for simulated events and data events are shown in Tables 4 and 5. The ALP signal matching efficiency for each matching criteria are given in Tables 2 and 3. In general, the jet multiplicity decreases in the exclusive production of ALP by photon induced interaction, because only the di-photons are produced. The distributions of the number of jets with the mean value and its statistical uncertainty are given in the ATLAS internal note [11]. Furthermore, an additional cut on ξ_{AFP} is applied in the data and is compared to the other results. According to the results summarized in Tables 4 and 5, the mean of the number of jets after applying matching criteria is almost unchanged compared to the situation of no matching criteria. It is therefore likely that the jets are a result of the underlying event, and therefore largely independent of the di-photon production, even if the di-photon is produced exclusively.

Table 4: Mean number of jets with different matching criteria, 10% matching, 1σ matching and 2σ matching and without matching in signal simulation of an ALP with mass 1000 GeV.

Signal simulation				
Matching condition	side A	side C	side A or C	side A and C
10%	4.23 ± 0.06	4.22 ± 0.05	4.24 ± 0.05	4.19 ± 0.08
1σ	4.23 ± 0.06	4.23 ± 0.05	4.24 ± 0.05	4.19 ± 0.08
2σ	4.23 ± 0.06	4.22 ± 0.05	4.24 ± 0.05	4.19 ± 0.08
No matching	4.24 ± 0.04			

Table 5: Mean number of jets with different matching criteria, 10% matching, 1σ matching and 2σ matching and without matching in recorded data.

Data in 2017 (14.6 fb^{-1})					
Matching condition	side A	side C	side A or C	side A and C	additional cut condition
10%	5.60 ± 0.03	5.61 ± 0.03	5.60 ± 0.02	7.92 ± 0.82	-
	5.96 ± 0.05	5.98 ± 0.04	5.96 ± 0.03	7.92 ± 0.82	$2\% \leq \xi_{\mathrm{AFP}} \leq 12\%$
	5.88 ± 0.07	5.98 ± 0.07	5.93 ± 0.05	8.33 ± 1.90	$3.5\% \leq \xi_{\mathrm{AFP}} \leq 8\%$
1σ	5.60 ± 0.03	5.62 ± 0.03	5.61 ± 0.02	7.52 ± 0.57	-
	5.97 ± 0.04	5.96 ± 0.04	5.96 ± 0.03	7.52 ± 0.57	$2\% \leq \xi_{\mathrm{AFP}} \leq 12\%$
	5.91 ± 0.06	5.95 ± 0.06	5.92 ± 0.04	8.31 ± 1.11	$3.5\% \leq \xi_{\mathrm{AFP}} \leq 8\%$
2σ	5.57 ± 0.02	5.57 ± 0.02	5.56 ± 0.01	7.00 ± 0.28	-
	5.92 ± 0.03	5.92 ± 0.03	5.92 ± 0.02	7.00 ± 0.28	$2\% \leq \xi_{\mathrm{AFP}} \leq 12\%$
	5.92 ± 0.04	5.86 ± 0.04	5.89 ± 0.03	6.88 ± 0.41	$3.5\% \leq \xi_{\mathrm{AFP}} \leq 8\%$
No matching	5.411 ± 0.004				

5 Conclusions

An analysis of jet multiplicity for an ALP search in light-by-light scattering in 13 TeV proton-proton collisions with the ATLAS detector and AFP detector has been performed using the data recorded in 2017 and the simulated data of an ALP mass with 1000 GeV. In order to increase the detection sensitivities, the number of jets was investigated together with the proton matching of the ATLAS central detector and the AFP detector. First, overlap removal was applied on jets to remove double-counted objects, which are also reconstructed as photons in both signal simulation and recorded data. The matching efficiency of the data combined with jet information was calculated for three types of matching criteria, 10% matching, 1σ matching, and 2σ matching. The results obtained from the number of matches in signal simulation was found to be consistent with that of the previous analysis. The number of jets was determined for the three matching criteria and compared to that of no matching condition. The resulting distributions of the numbers of jets are quite similar in signal simulation and recorded data, and thus would not contribute much to increasing the sensitivity for detecting an ALP signal.

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