Study of Vertex Reconstructions with Di-Photon Events and First Determination of Time Resolution and Efficiency of the Time-of-Fight (ToF) Detector with LHC Run-3 Data
- Summer Student Report

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Abstract

In summer 2022, first LHC Run-3 $pp$ collision data were recorded with the ATLAS central detector and the ATLAS Forward Proton (AFP) detectors at the Large Hadron Collider. A first analysis of this new data was performed. Efficiencies and resolutions for the Time-of-Flight (ToF) detector were studied with different methods. In addition, we conducted vertex reconstruction studies in this project. They were performed based on data taken in 2017. Different techniques of vertex reconstruction were compared, and the most appropriate one for future di-photon studies was determined. The potential of ToF data for an improved vertex reconstruction and thus reduction of background in an Axion-Like-Particle search using AFP data was demonstrated.
1 Introduction

Many extensions of the Standard Model use Axions and Axion-like particles (ALP), which are considered as candidates for particles that make up missing matter, so-called dark matter. The ALP is hypothetical particle with spin 0, which, according to some predictions, can solve the strong CP problem (appearance of CP violation in strong interactions). Usually, ALPs couple to fermions only through dimension-five operators proportional to fermion mass. Moreover, (pseudo) scalars predominantly couple to gauge bosons through dimension-five operators containing derivatives. Thus, in energy regimes exceeding the top quark mass, ALPs are only accessible through their coupling to the gauge bosons and the Higgs boson. They can be formed in different processes. In this study, the main focus is on the process of central exclusive diphotons production $pp \rightarrow p(\gamma\gamma)p$. These di-photon events are recorded with the ATLAS central detector. Vertex position of di-photons are used as a criteria to separate di-photon events coming from the expected ALP signal from di-photon events produced in other background processes. Therefore, an improved di-photon vertex resolution will contribute to better separate signal and background events. The ToF detector will provide data to improve the vertex reconstruction, in particular for di-photon events, as the photon reconstruction uses calorimeters at a large distance from the interaction point.

The ATLAS Forward Proton (AFP) detector [1] is designed to measure trajectories of leading protons far from an interaction point. The leading protons deviate from a nominal proton beam to such an extent that these deviations can be measured. The two AFP stations are located approximately 210 m on either side of the ATLAS interaction area. The AFP detectors are placed in the so-called Roman pots (RP). They allow sensitive detectors to be placed close to the beam while maintaining vacuum in primary beam tube. The position of the deflected protons is measured by the Silicon pixel Tracker (SiT).

The two AFP FAR stations are equipped with the time-of-flight (ToF) detector. The initial time-of-flight detector performance is determined using early 2022 data. In particular, the detection efficiency and resolution of time measurement in individual channels of the ToF detector are evaluated.

2 AFP-ToF design

The AFP detector consists of four stations, which are located at around 205 m and 217 m - NEAR and FAR stations, on anticlockwise (A) and clockwise (C) sides of the ATLAS interaction region. The FAR stations are only ones equipped with the ToF detectors, and therefore only data from them are subject of the study. In this section only a brief description of design and function of the AFP and ToF are given, for more detail see [1].

For tracking the SiT is used, which consists of four layers of silicon pixel detectors. The active area of detector is approximately $20 \times 20 \text{ mm}^2$, the pixel size is $50 \times 250 \mu\text{m}^2$ and they are forming a pixel grid with size 336 by 80 pixels on each SiT plane. Planes of SiT are tilted by $14^\circ$ providing spatial resolution $10\mu\text{m}$ in $x$ and $30\mu\text{m}$ in $y$, as measured in beam tests [2].

The ToF detectors collect Cherenkov photons created in L-shaped fused silica [3] bars (LQ-bars), which are placed behind the tracker plates. Details of the design are given in [4], only a brief description is provided here. The geometry of the ToF detector was designed to optimise light yield, given the space constraints of the Roman Pot stations. The LQ-bar consists of two arms: a radiator arm exposed to beam protons and a light guide arm. The elbow presents an Al-mirror and a taper cut to achieve better focusing of the Cherenkov photons.

Photons emitted along proton trajectory inside the radiator arm propagate to the light-guide
arm and to the end of the bars which is attached to a photo-multiplier. To minimise the number of total reflections, the radiator arms are tilted under the Cherenkov angle of $48^\circ$ with respect to the beam axis, which leads to optimisation of the time needed for light propagation through the bar. To reflect downwards emitted photons back to the bar, the trailing ends of the radiators are cut parallel to the beam axis. Four bars are placed one after another to form a train. There are four trains on each side. The bars and the corresponding channels are denoted as A, B, C, D (or 0 − 3), bar A being the first one to be crossed by protons. Each ToF detector consists of four trains numbered from 0 to 3, 0 being the closest to the beam. The geometry of the bars is such that the optical path in all bars is equalised. Figure 1 shows the design of the assembled LQ bars and SiT mounted on the Roman Pot flange.

![Figure 1: AFP SiT and ToF LQ-bars.](image)

The Cherenkov photon statistics translates to the number of photo-electrons via the quantum efficiency of the PMT photo-cathode. The number of photo-electrons is amplified by the high voltage applied to the micro-channel plates of the PMTs. The voltage pulses from the PMT anodes are amplified and processed by a constant fraction discriminator (CFD [5]) providing a square signal for a high performance time-to-digital converter (HPTDC [6]). The signals are sampled in 1024 bins of about 25 ps time window which corresponds to the LHC bunch spacing. The overall time resolution of the detector is therefore influenced at several stages during the formation of the signal and its read-out in the front-end electronics [7].

3 Vertex reconstruction

Two approaches were used for determining the vertex of interaction, i.e. photon pointing and calorimeter pointing methods. For the photon pointing method, a Primary Vertex (PV) is selected from PV candidates reconstructed using tracks. This method has a good resolution, but for the vertices of photons it can give false information (as photons do not leave tracks). The second method uses the calo pointing tool [8] to obtain the vertex of the two photons.

This study was conducted prior to the collection of the first data from LHC Run-3. Therefore, Run-2 data taken in 2017 with integrated luminosity of 14.3 $fb^{-1}$ were used for this analysis. As for a rejection factor calculation, a simple simulation of the ToF data was used.

3.1 Photon pointing

For this analysis, earlier prepared ntuples for the ALP with AFP search were used for the photon pointing method. They were created on the basis of the simulated AODs [9] corresponding to the ALP masses from 100 to 2000 GeV with the coupling constant $g = 0.2$. These ntuples
contain the truth primary and the reconstructed vertices. The difference between them defines the resolution of the method. The photon pointing method selects one Primary Vertex from the PV candidates reconstructed using tracks. There can be two types of photons, namely converted and unconverted photons. The resolutions are plotted for 2 unconverted and 2 converted photons. Conversion means production of an electron and positron pair. This is caused by the electromagnetic interaction with the material in the detectors. Electrons and positrons have electric charge, so they interact with the tracker and leave their tracks. The conversion occurs at about 30% probability. Unless conversion occurs, there is no track around the PV, and we cannot obtain precise information about the PV position.

Figure 2 shows the resolutions for the different masses of the ALP for the photon pointing method in simulated data. The widths of these distributions are shown in Figure 3 as a function of mass.

Figure 2: Resolutions using the photon pointing method for converted (left) and unconverted (right) photons for different ALP masses in simulated data.

Figure 3: Widths of resolutions using photon pointing method for converted (left) and unconverted (right) photons for different ALP masses in simulated data.

For the unconverted photons a slight slope with increasing ALP mass is observed. In contrast, there is no dependence on the ALP mass for converted photons.

3.2 Calorimeter pointing

3.2.1 Resolutions

In the previous section it was noted that the photon pointing method can give false information, since unconverted photons do not leave any tracks. For this reason another pointing
method was used, the calorimeter pointing method. This method uses "traces" which photons leave in the calorimeter to reconstruct the displaced di-photon vertex.

For this method the "Calo Pointing tool" was used. Starting from the DAOD_HIGG1D1 ntuples created from the simulated data for the ALP masses in the range 100-2000 GeV with a coupling constant $g = 0.2$.

Figure 4 shows the resolutions for the different masses of the ALP using the calo pointing method in the simulated data with a cut on the transverse momentum $p_T > 40$ GeV. The widths of these distributions are shown in Figure 5 as a function of ALP mass. There is no dependence on the ALP mass. The resolutions were obtained as differences between the truth vertices and the reconstructed vertices using the calo pointing method.

![Figure 4](image1.png)

Figure 4: Resolutions using calo pointing method for converted (left) and unconverted (right) photons for different masses of ALP in simulated data.

![Figure 5](image2.png)

Figure 5: Widths of resolutions using calo pointing method for converted (left) and unconverted (right) photons for different ALP masses in simulated data.

Using the calo pointing tool on the data, collected in 2017, ntuples for 20 different data sets were created. Figure 6 shows the distributions for the resolutions in data for different runs as a function of the run number. There is no dependence on the run number. Resolutions were obtained as a difference between vertices of two photons in the data 2017.

![Figure 6](image3.png)
Table 1 summarises the comparison of the photon pointing and the calo pointing methods as widths of the distributions for the simulated samples. For the case of converted photons, the photon pointing method has a thin peak and wider peak around zero. In the table the value of the think peak is listed.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Converted</th>
<th>Unconverted</th>
<th>Converted</th>
<th>Unconverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>8.25</td>
<td>23.62</td>
<td>41.81</td>
<td>38.82</td>
</tr>
<tr>
<td>400</td>
<td>8.10</td>
<td>23.24</td>
<td>42.21</td>
<td>39.19</td>
</tr>
<tr>
<td>800</td>
<td>8.10</td>
<td>24.22</td>
<td>42.62</td>
<td>38.37</td>
</tr>
<tr>
<td>1600</td>
<td>7.93</td>
<td>25.89</td>
<td>43.73</td>
<td>38.15</td>
</tr>
</tbody>
</table>

Table 1: Width (mm) of resolutions using photon and calo pointing methods for different ALP masses.

Figure 7 compares the resolutions in simulated and recorded data. For the simulated sample the ALP mass is 400 GeV. Distributions of simulated and recorded data are plotted normalized to the same number of events.

Figure 7: Compared resolutions for converted (left) and unconverted (right) photons for simulated and recorded data using the calo pointing method.

The width for the case of the converted (unconverted) photons of the simulated and the recorded data distributions are 42.21 mm (39.19 mm) and 71.51 mm (57.51 mm), respectively. The reason for the large value in the recorded data could be that the di-photons in the data do not result from the simulated ALP process.
3.2.2 Background rejection

In order to study how the information from the Time-of-Flight (ToF) detector can help to reduce background, a simple event simulation of the vertex position was created. This simulation is based on design information about the time resolutions of the ToF detector, namely 20 ps ($\approx 6$ mm) and 26 ps ($\approx 7.8$ mm) for A-side and C-side, respectively. The combined resolution is obtained as square root of the sum of the squared resolutions for each side, and equals to about 9.8 mm.

The reduction of the background was calculated as a rejection factor for the assumed $\pm 1\sigma$, $\pm 2\sigma$, $\pm 3\sigma$ ToF time resolutions. The following method to obtain the rejection factor was used: for each simulated signal event, the number of background events is determined within the ToF uncertainty.

$$\text{The rejection factor} = \frac{\text{all data}}{\text{selected data}}$$

In addition, the sensitivity was defined:

$$\text{sensitivity} = \frac{\text{signal}}{\sqrt{\text{background}}},$$

where $\text{signal} = \frac{1}{\text{rejection factor(signal)}}$, and $\text{background} = \frac{1}{\text{rejection factor(background)}}$.

The results for the rejection factors were obtained for cases with converted and unconverted photons, as given in Table 2. As simulated sample a 400 GeV ALP was used. The data was collected in 2017. Based on these results it is clear that using the ToF detector can help much to reduce the background in the ALP search.

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>$\sigma$ (mm)</th>
<th>Signal gaus(%)</th>
<th>Photons type</th>
<th>Rejection factor(data)</th>
<th>Rejection factor (signal)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pm 1\sigma$</td>
<td>9.83</td>
<td>68</td>
<td>Converted</td>
<td>1026.40</td>
<td>18.31</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unconverted</td>
<td>2391.50</td>
<td>19.47</td>
<td>2.51</td>
</tr>
<tr>
<td>$\pm 2\sigma$</td>
<td>19.66</td>
<td>95</td>
<td>Converted</td>
<td>437.93</td>
<td>9.03</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unconverted</td>
<td>1035.86</td>
<td>9.69</td>
<td>3.32</td>
</tr>
<tr>
<td>$\pm 3\sigma$</td>
<td>29.50</td>
<td>99.7</td>
<td>Converted</td>
<td>262.54</td>
<td>5.93</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unconverted</td>
<td>578.23</td>
<td>6.30</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Table 2: Rejection factors and sensitivity for converted and unconverted photons for 3 regions ($\pm 1\sigma$, $\pm 2\sigma$, $\pm 3\sigma$).

4 First analysis of the ToF detector with LHC Run-3 Data

For the resolution and the efficiency analyses ATLAS run number 429142, taken on July 25 2022, was chosen due to advise of the data quality team. This run has clear stairs-like structure in the correlation SiT versus ToF data, which is needed to identify a ”good run”. This data was collected with CFD [5] thresholds set to 250 mV and corresponds to ATLAS integrated luminosity of 43.92 fb$^{-1}$ from the general integrated luminosity of 44.17 fb$^{-1}$.

Pre-processing of data includes the correction of the channel map and creating ntuples from AODs [9] on the grid.

Before obtaining the resolutions and efficiencies, some general requirements on the data sample were applied:
• One track in the SiT per event.
• One cluster per plane in the SiT per event.

Also two more optional requirements were used:
• One active train in the ToF per event.
• Cut on measured ToF arriving time period.

4.1 Time Resolution

The HPTDC measures the time in terms of one of the 1024 raw time bin numbers within a 25 ns time window. The time stored in AOD is in nanoseconds although it is an uncalibrated HPTDC output (raw time). A HPTDC calibration following the 2017 data analysis will be performed later. The raw time in terms of one of the 1024 HPTDC bin numbers (0..1023) is translated to nanoseconds by

\[
\text{time[ns]} = \text{rawbin} \times \left(\frac{25}{1024}\right).
\]

The 25 ns corresponds to the 40 MHz LHC frequency.

In raw time distributions small peaks are seen near the main peaks. There is also "noise" and it was cleaned for obtaining better resolutions. This is one of the additional requirements. Figure 8 shows the raw time distribution before and after this additional requirement for only one channel (0A - train 0, bar A). Such distributions were created for each ToF channel. The left peak corresponds to the C-side and right one to the A-side.

Figure 8: Raw time distribution before (left) and after (right) additional cuts on time were applied.

Figure 9 shows the raw time distributions separately for each side. The effect of the HPTDC non-calibration are seen clearly.

The previous analysis with 2017 data concluded that the HPTDC calibration does not effect much the time resolution. Thus, in this analysis, the calibration was not applied yet to obtain time resolutions.

The resolutions can be obtained as single-channel resolutions for each channel of the ToF. The following requirements were imposed on the data:

• One track in the SiT per event.
• One cluster per plane in the SiT per event.
• Cut on measured ToF arriving time period.
Figure 9: Raw time distribution separately for each side: A-side(left) and C-side(right).

- One active train in the ToF per event.

Figure [10] shows an example of typical $\Delta t$ distribution.

Figure 10: $\Delta t$ distributions for one of ToF channels in A-side.

4.2 Efficiency

Information about the reconstructed SiT tracks are stored in the AfpTrackContainer. This container was used as a basis for the measurement of the ToF response. The fraction is determined where a given ToF channel provided time information with respect to the reference sample of events with reconstructed SiT tracks. For obtaining efficiencies two methods were used: dividing histograms and calculating the ratio of sums of events. For both methods the following requirements were imposed on the data:

- One track in the SiT per event.
- One cluster per plane in the SiT per event.
- One active train in the ToF per event (ON/OFF)

The last requirement was imposed for the most clean signal. However, this requirement decreases the statistics as not all tracks are in one train only. Thus, both cases (ON/OFF) were investigated. For both methods the whole procedure is performed separately for side A and side C.

For the first method, dividing histograms, the regions for the x-value of the SiT, corresponding to the ToF train were defined for each side (A and C). These regions are shown in Table 3. The reference histogram is defined for events passing the selection criteria without the optional requirement (OFF). The other 16 histograms include that additional requirement (ON) for each of the 16 ToF channels.
The next step was dividing each of 16 channel histograms by the reference histogram. It is done bin by bin of the histograms. So, the number of events in each individual bin of one of the 16 histograms of the ToF is divided by the number of events in the corresponding bin of the reference histogram. This ratio defines the efficiency in each bin. In order to define efficiency in each channel the mean value of the bins in the region, corresponding to the exact train, was calculated. For the last train (3) the active region was cut in order to avoid noise.

<table>
<thead>
<tr>
<th>Train No</th>
<th>A-side (mm)</th>
<th>C-side (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&gt; −4.9 and &lt; −2.0</td>
<td>&gt; −5.3 and &lt; −2.0</td>
</tr>
<tr>
<td>1</td>
<td>&gt; −8.0 and &lt; −5.0</td>
<td>&gt; −8.4 and &lt; −5.4</td>
</tr>
<tr>
<td>2</td>
<td>&gt; −13.0 and &lt; −8.1</td>
<td>&gt; −13.4 and &lt; −8.5</td>
</tr>
<tr>
<td>3</td>
<td>&gt; −15.0 and &lt; −13.1</td>
<td>&gt; −15.0 and &lt; −13.5</td>
</tr>
</tbody>
</table>

Table 3: Regions for the x-value of the SiT, corresponding to the ToF trains.

The procedure described above is for the case with the requirement (ON).

The same analysis is repeated without the requirement (OFF).

For the second method, direct numbers, the number of events in the two samples were counted. For the sample one an event has to pass the main requirements (OFF) and in addition it has to be inside a specific region (Table 4). For the sample two, the event has to pass the requirement ON. The efficiency is defined as the ratio of the number of events in the sample two divided by the number of events in the sample one. There are 16 numbers for the sample two (for each channel), and 4 numbers for the sample one (for each train).

The efficiencies for both methods are very similar. The efficiencies for case OFF is higher than for case ON, as far as it includes non ideal events and some background. Details on the time resolutions and efficiencies are given in a specific note [10].

5 Conclusions

The first performance study of recorded Run-3 ToF detector data is performed. It provides a preliminary understanding on efficiencies and resolutions of the ToF detector. Different approaches of obtaining efficiencies were tested and results are comparable with each other. The study was performed on the data set taken on July 25 2022.

As a continuation of this study, the following items are of interest: Studying efficiencies on data with different CFD thresholds. Applying further selections on removing unwanted events for the efficiency and resolution determination. Studying resolutions with the advanced calibrations. Including the recorded ToF data for improved vertex reconstruction.

In addition, the vertex reconstruction study of di-photon events has been part of a larger effort to use the AFP information together with central ATLAS detector information to search for an Axion-Like-Particle (ALP) with a di-photon resonance signature, produced in ultraperipheral $pp$ interactions, also known as Light-by-Light (LbyL) scattering. The vertex information is used to reduce the expected background reactions, and in this study the performance increase is estimated when including ToF detector data. The improved vertex reconstruction of di-photon events helps to suppress background. Two approaches of vertex reconstruction were compared and the calorimeter pointing method is found to be more suitable. Improvement of the vertex reconstruction, including ToF data, is shown to reduce largely the background for a simulated signal of ALP di-photons events.
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References


