ANALYSIS OF AFP TOF DATA FROM EARLY LHC RUN 3*

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The analysis of the early LHC Run 3 data was performed. Efficiencies for the ATLAS Forward Proton (AFP) Time-of-Flight (ToF) detector were studied. Performance studies of the ToF data included the proton–proton vertex reconstruction using matching of ToF and central ATLAS vertex position. After a calibration, a preliminary resolution of the vertex reconstruction was determined with a low-μ ATLAS run.

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1. Introduction

Studies of properties of diffractive and exclusive processes are an important part of the ATLAS physics programme. In addition, they may be used to search for the New Physics. The usual signature of such processes is one or two high-rapidity protons and objects in the "central" part of the ATLAS detector [1]. For example, an exclusive di-photon production, $pp \to p(\gamma\gamma)p$, where both interacting protons are scattered at a small angle and can be measured with forward detectors.

The ATLAS Forward Proton detector (AFP) [2] detects protons undergoing small-angle scattering at the interaction point (IP). The AFP detector consists of four stations, located at ± 210 m from IP, called NEAR and FAR, on both sides of ATLAS. In order to obtain the position of scattered protons, the Silicon Tracker (SiT) is used. In addition, AFP FAR stations are equipped with the ToF detector. It measures time of proton arrival to AFP. Comparison of timing information from both AFP sides allows us to reconstruct the z-position of the interaction vertex. Comparison of such a vertex to the one reconstructed by the ATLAS tracker leads to a reduction

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of the combinatorial background. An example of such a background for the exclusive di-photon production is the $pp \to X(\gamma\gamma)Y$ process with protons in AFP coming from independent, pile-up interactions.

The ToF collects the Cherenkov photons created by protons crossing fused silica bars. Four bars are placed one after another to form a train to improve the timing resolution. On each side 4 such trains are installed. Such "pixelization" helps with cases when multiple protons are outgoing from the interaction vertex.

While ToF is intended to operate in a high-μ environment, the low-μ dataset provides much cleaner events, in which the effects related to the timing reconstruction resolution are better visible. The run, chosen for this analysis, uses LHC fill 8020, which was taken on July 20, 2022 and corresponds to an ATLAS integrated luminosity of 29.65 ± 0.44 nb^{-1}. The average pile-up is 0.05. The chosen run has high-ToF efficiency [3].

2. ToF vertex reconstruction

First, the capability of the ToF detector to measure the z-coordinate of the primary vertex is investigated. The vertex reconstruction using ToF is based on the proton arrival difference. The z-coordinate of the primary vertex (z_{ToF}) can be calculated as the difference of proton arrival time to both FAR stations

$$z_{\mathrm{ToF}} = \frac{c}{2}(t_{\mathrm{C}} - t_{\mathrm{A}})\,. \tag{1}$$

This equation represents a general approach, but cannot be used directly on the data; firstly, the arrival times must be corrected for possible time offsets. For this analysis, the following requirements were imposed on the data:

— Exactly one track reconstructed in the FAR station per event.

— Exactly one active train in the ToF per event.

2.1. Time delays correction

The time measured in one ToF channel i (for example, channel 0A is train 0, bar A) is made up from several components as follows:

$$t_i = t_{\mathrm{proton}} + t_{i,\mathrm{delay}} + t_{i,\mathrm{smear}} - t_{\mathrm{clock}}\,. \tag{2}$$

The t_{proton} is the proton arrival time. The $t_{i,\mathrm{delay}}$ is a time offset in the exact ToF channel. This time delay is constant for the given ToF channel, if there is no intervention into the system. The $t_{i,\mathrm{smear}}$ represents all random effects of the signal processing. The $t_{\rm clock}$ is a reference clock that opens a 25 ns window within which the leading protons from a single bunch-crossing arrive at the ToF.

The $t_{\rm proton}$ and $t_{\rm clock}$ can be abolished by measuring time differences on the event-by-event basis within one ToF train. The delay, $t_{i,{\rm delay}}$, is determined using Δt_{ij} distributions which are defined as follows:

$$\begin{aligned} \langle \Delta t_{ij} \rangle &= \langle t_i - t_j \rangle = \langle t_{i,{\rm smear}} + t_{i,{\rm delay}} - t_{j,{\rm smear}} - t_{j,{\rm delay}} \rangle \\ &= \langle t_{i,{\rm delay}} - t_{j,{\rm delay}} \rangle , \end{aligned} \tag{3}$$

where $\langle t_{i,{\rm smear}} \rangle$ is assumed to be equal to $\langle t_{j,{\rm smear}} \rangle$, thus cancels.

For determination of the delay correction constants, an approach described in Ref. [4] was used with the z-position of the luminous ATLAS beamspot, $z_{\rm BS}$, which is measured by the central ATLAS detector. The $z_{\rm ToF}$ value, determined using equation (1), in its mean value should reflect the z-position of the luminous ATLAS beamspot. Therefore, the following relation was used:

$$\left\langle z_{\rm ToF}^{(ij)} \right\rangle = z_{\rm BS} - \left(D_{\rm A}^i - D_{\rm C}^j \right) , \tag{4}$$

where $D_{\rm A}^i$ and $D_{\rm C}^j$ are mentioned above delay correction constants for the given ToF channels i and j in A and C sides, respectively. The mean value is obtained over the time period of one ATLAS luminosity block (LB), corresponding to ~ 1 minute of data-taking. These constants are unique for each pair of the ToF channels, and only their difference matters to correct position of the $z_{\rm ToF}$. The following equation was used, assuming that the mean value is obtained over the one LB, and the fact that $z_{\rm BS}$ does not change within one LB:

$$\left\langle \sum_{\rm LB} z_{\rm ToF}^{(ij)} - z_{\rm BS} \right\rangle = D_{\rm C}^j - D_{\rm A}^i . \tag{5}$$

With the event-by-event approach, only double-tag events are used, meaning a signal is required on both sides of the AFP system. However, this reduces the data statistics. Therefore, the event mixing technique was used to create pseudo-double-tag events from single-tag ones. The time buffers are filled with time values measured during the one LB, and pseudo-double-tag events are produced.

The ToF has 16 channels on each side, meaning $16 \times 16 = 256$ combinations. For each, the distribution corresponding to equation (5) was created and a Gaussian fit was applied to determine the mean value. It defines the differences between the constants. These 256 differences can be parameterized in terms of the D_A^i and D_C^j to find 32 correction factors. Finally, all correction constants were determined for each channel, and the z_{ToF} position was corrected.

The dependence of the z_{BS} on LB is not uniform and may differ from run to run. As the distribution of z_{ToF} matches the distribution of z_{BS}, the procedure of obtaining time delay corrections is checked by comparing the dependence of the z_{BS} and z_{ToF} per LB.

2.2. Vertex matching

The ToF detector reconstructs the vertex in the case of a signal detected in both FAR stations. Some of them are due to protons from unrelated, pile-up events.

If z_{ToF} is measured from protons coming from the same ATLAS vertex, a narrow peak is observed in the $z_{ATLAS}-z_{ToF}$ distribution, as shown in figure 1. z_{ATLAS} here is the z-coordinate of the reconstructed by the central ATLAS detector primary vertex, with resolution at the level of $\approx$ 30 μm. The z_{ToF} is corrected on time delays, discussed in Section 2.1.

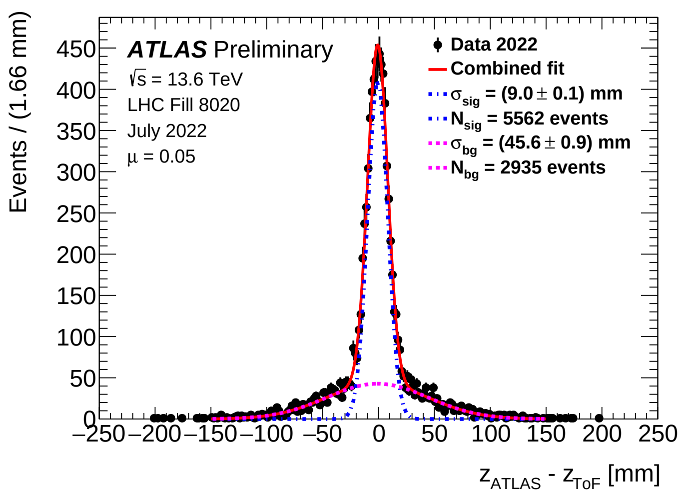

Fig. 1. The distribution of the $z_{ATLAS}-z_{ToF}$ for the low-μ LHC fill 8020.

In other words, the vertex position in ATLAS (z_{ATLAS}) and z-position from ToF (z_{ToF}) are correlated for the signal processes. The projection to the $z_{ATLAS}-z_{ToF}$ is a convenient way for searching for such correspondence.

Combinatorial background coming from pile-up protons can be reduced using $z_{ATLAS}-z_{ToF}$ observable. As usual, selecting a window around the signal peak, whose width is driven by the resolution, would result in some statistics being lost, but the signal being enriched, because the sub-selected sample contains a larger fraction of genuine signal events than the whole sample.

3. Summary

A performance study of the ToF detector was conducted using the first LHC Run 3 data. A time delay calibration procedure of the ToF detector was performed. A primary proton–proton vertex reconstruction using the ToF detector and a vertex matching analysis with the central ATLAS detector were studied.

This work is a part of a bigger performance study, which includes efficiency and resolution determination of the channels of the ToF detector. The latest results are given on the ATLAS public web-page [3].

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