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ATLAS Forward Proton Time-of-Flight detectors: status, performance and new physics results

Daniel Ernani Martins Neto (on behalf of the ATLAS Forward Detectors)[a,*]

[a] *Institute of Nuclear Physics im. Henryka Niewodniczanskiego, ul. Radzikowskiego 152, Kraków, Poland*

E-mail: daniel.ernani@ifj.edu.pl

ATLAS Forward Proton Time-of-Flight (ToF) detectors of the ATLAS Forward Proton (AFP) system are designed to measure the primary vertex z-position of central exclusive processes by comparing the arrival times measured in the ToF from the two intact protons. The presented results are related to the performance of the AFP ToF detector operation in 2022. The studies used low pile-up data with the average number of interactions per bunch crossing of 0.05 collected in the middle of 2022 using ToF stations at both sides of ATLAS (Far A and Far C). The time resolution of individual channels was measured to be between 20 ps and 40 ps. The AFP ToF efficiency ranged from 5% to 70% in different channels. The distribution of the difference between the primary vertex z-position measured by ATLAS and the vertex reconstructed by the AFP ToFs is studied. The resulting vertex-matching resolution was observed approximately (8 - 10) mm for the different configurations.

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*Speaker

1. Introduction

The ATLAS Forward Proton (AFP) spectrometer [1] is a set of near-beam instruments, housed in 'Roman Pot' devices, used to measure protons scattered at very small angles in diffractive and photon-induced processes. The proton fractional energy loss ξ is defined as $1 - E'_p/E_p$, where E_p and E'_p represent the incoming and scattered proton energies, respectively. A proton scattered at the interaction point (IP) is deflected by the lattice of dipole and quadrupole magnets of the LHC [2, 3] and its momentum can be determined by measuring points on its trajectory downstream [4].

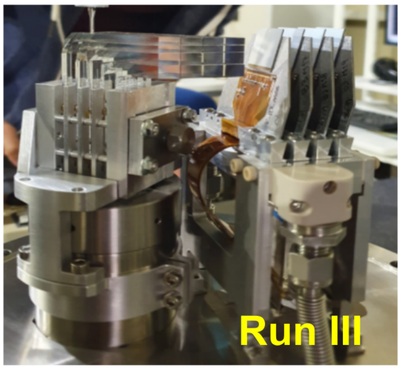

Figure 1: Photography of the instrumentation inside the AFP Far station, comprising the Silicon Tracker (SiT) and Time-of-Flight (ToF) subsystems. The four grey SiT planes can be seen on the right and the transparent ToF bars on the left. The SiT planes are mounted on the Roman Pot flange.

Roman Pots are located on both sides of the IP which are denoted as side A ($+z$) and side C ($-z$). Each arm (sides A or C) has two Roman Pot units, referred to as the Near and Far stations, which are located at $z \simeq \pm 205$ m and ± 217 m, respectively, from the IP. Each station contains a four-layer Silicon Tracking detector (SiT). The Far stations are also equipped with Time-of-Flight (ToF) devices. The ToF is an optical detector collecting the Cherenkov photons produced in Quartz bars, see Figure 1. Each bar consist of two arms: radiator arm (exposed to the scattered protons) and guide arm (directing Cherenkov photons to photomultiplier). In the Run 3 design, each bar was made from a single piece of quartz (glueless connection), forming an L-shape (LQ-bars). The set of four LQ-bars (labeled A, B, C, D) stacked along the beam axis is called a train. There are four trains (containing four bars) placed on top of each other providing an extra spatial segmentation of the ToF detector, resulting in sixteen measurable channels. The 4×4 matrix of the LQ-bar light guides is attached to the micro-channel-plate photomultiplier (MCP-PMT [1]).

In this work the performance of the ATLAS Forward Proton Time-of-Flight (ToF) detector is analysed using the 2022 LHC run III data. The analysed data were collected in a short, dedicated run with the average number of interactions per bunch crossing of $\mu = 0.05$ (Run 428770). The efficiency and time resolution are studied. Finally, the vertex-matching resolution is obtained by measuring the difference between longitudinal vertex position and the ATLAS Inner Detector (ATLAS ID) and the ToF detector.

2. Efficiency and Resolution

Data from ToF are obtained in terms of the proton's arrival time measured in the corresponding channel in a time range of 25 nanoseconds. The efficiency of the ToF channel is measured by determining the fraction of events with this channel fired in a reference sample of events with SiT tracks, $\epsilon = \mathrm{N(bar-ij \cap track-j)/N(track-j)}$, where N(bar-ij ∩ track-j) represents the number of events with signal in the i^{th} ToF bar-channel of the j^{th} train in the sample containing SiT tracks in train number j. N(track-j) represents the total number of events with SiT track in the train number j. This tag and probe method is used to calculate the ToF efficiency for the single track event selection, where the SiT tracking points toward a particular train are counted, however the hits are also counted in the other trains (any). Figure 2 shows the ToF efficiency for events where the SiT track points to train 0 in the Far-A and Far-C stations when the single track selection is applied. The AFP ToF efficiency was observed to be within (5%–70%) in different channels.

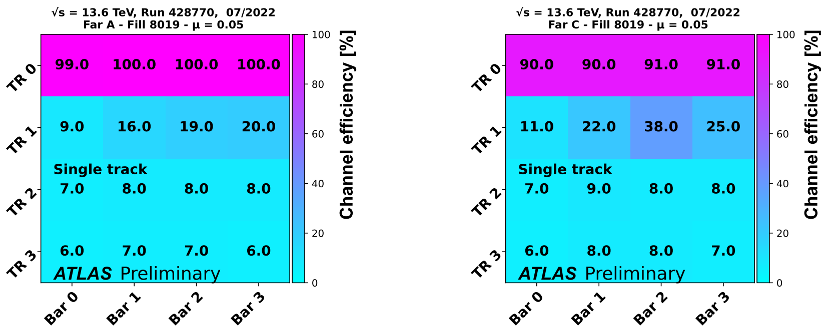

Figure 2: The AFP ToF channel efficiency in LHC fill 8019 with $\mu = 0.05$. The plots present the probability of observing a ToF hit in a given channel when a single track plus a single train is observed in the AFP SiT. The four rows in each plot correspond to the position of the SiT track pointing to the ToF 0 train, respectively, using the single track configuration. The left and right plots correspond to the ToF detectors on Side A and C, respectively.

The method employed to extract the timing resolution in the channels relies on calculating the time difference between the bars in a given train, δt_{ij}. With four bars in a train, one can construct six such combinations. The event selection with single track plus single train counts only the number of hits where the single track matches with the particular train (clean). The clean selection ensures that the Δt_{ij} shapes are well described by Gaussian fits. The resolution extracted from the Gaussian fit applied to the time difference between neighbouring bars was measured to be between 20 ps and 40 ps for different combinations, considering the single track plus the single train selection.

3. ToF-vertex matching

Assuming that two protons reconstructed by the AFP are produced in the same pp interaction, the measurement of the each proton's time-of-arrival in the AFP, t_A and t_C, allows the reconstruction of the interaction vertex $z_{\mathrm{vtx}}^{\mathrm{ToF}} = \frac{c}{2}(t_{\mathrm{C-FAR}} - t_{\mathrm{A-FAR}})$. For the $z_{\mathrm{vtx}}^{\mathrm{ToF}}$ determination one considers the signal of each fired bar to calculate the time average in each of the trains. Noting the reconstructed primary vertex measured in the central detector, $z_{\mathrm{vtx}}^{\mathrm{ATLAS}}$, one can then compute the quantity $\Delta z_{\mathrm{vtx}} = z_{\mathrm{vtx}}^{\mathrm{ATLAS}} - z_{\mathrm{vtx}}^{\mathrm{ToF}}$. The width of the Δz_{vtx} distribution reflects the combined resolution of the $\mathrm{z_{ToF}}$ and $\mathrm{z_{ATLAS}}$ measurements. The event selection applied in the presented study required a single primary vertex reconstructed in the ATLAS ID and four clean hits (four bars) in exactly[1] one ToF train on

[1]Tracks were required to be pointing to the ToF train.

each side (Far-A and Far-C). Considering different trains on each side results in 16 train-A–train-C combinations. The obtained resolution was found to be within the (8-10) mm range, depending on the combinations. Figure 3 shows the vertex matching for two examplary configurations.

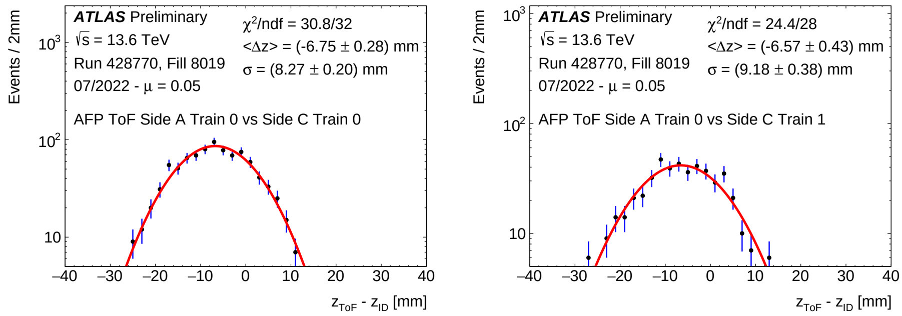

Figure 3: Distributions of the difference between the longitudinal vertex position measured with the AFP ToF and ATLAS ID detectors with the average interactions per bunch crossing of $\mu = 0.05$ for two train combinations: *Train 0 vs. Train 0*, *Train 0 vs. Train 1*. The red line represents the Gaussian fit. The shift of the distribution originates from the fact that the centre of the beam spot is not exactly at $z = 0$ and from the constant time delays of the ToF detector.

4. Summary

In this work, the ToF detector efficiency considering the single track selection for the low-μ data was found to be within the range of 5% to 70%. The time resolution of individual channels was measured to be between 20 ps and 40 ps for different combinations. Finally, the vertex matching reconstructed for the Train 0 vs. Train 0 and Train 0 vs. Train 1 was found to be in the range of (8–10) mm.

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