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ATLAS Forward Proton Time-of-Flight Detectors: Status, Performance and New Physics Results

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The Time-of-Flight (ToF) detectors of the ATLAS Forward Proton (AFP) system are designed to measure the primary vertex z-position of the $pp \rightarrow pXp$ processes by comparing the arrival times measured in the ToF detector of the two intact protons in the final state. We present the results obtained from a performance study of the AFP ToF detector operation in 2017. A time resolution of individual channels ranging between 20 ps and 40 ps is extracted, even though the AFP ToF efficiency is below 10%. The overall time resolution of each ToF detector is found to be 20 (26) ± 4 (5) ps for side A(C). This demonstrates the time resolution for a detector operating at a few millimetres from the LHC beams. Events from ATLAS physics runs at moderate pile-up taken at the end of 2017 are selected with signals in ToF stations at both sides of ATLAS. The difference of the primary vertex z - position measured by ATLAS and the value obtained by the AFP ToFs is studied. The distribution of the time difference constitutes of a background component from combinatorics due to non-negligible pile-up, and significantly narrower signal component from events where protons from the same interaction are detected in ToF detector. The fits performed to the distribution of the reconstructed time difference yield the vertex position resolution (of about 6 ± 1 mm at best) that is in agreement with the expectation based on single-ToF detector channel resolutions.

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1. Introduction

The ATLAS Forward Proton (AFP) detector [1] at the LHC [2] is optimised for measuring protons from Pomeron-induced and photon-induced processes ($pp \to pXp$). These protons emerge from pp collisions intact and are accompanied by a large rapidity gap on each side of the interaction point between the proton and central system X which is usually explained by an absence of color connections between them. This enables to reconstruct kinematics of the incoming particle (photon or Pomeron) which is not possible by using only information from the central detector. Together with measuring the arrival times of the intact protons, it is then possible to extract (semi)exclusive processes by suppressing all important backgrounds including combinatorics. This has a potential to enlarge ATLAS [3] physics program which is based on measuring inclusive processes. The AFP detector naturally provides intact proton information in both, SM processes (see Ref. [4] about the exclusive dilepton measurement) and beyond SM processes (see Ref. [5] about the axion-like particle searches in exclusive diphoton measurement). Potential to measure other (semi)exclusive final states is large, see Ref [6–12]. The role of ToF detector granularity, pile-up dependence and resolution is studied in Ref. [13], see also Ref. [14].

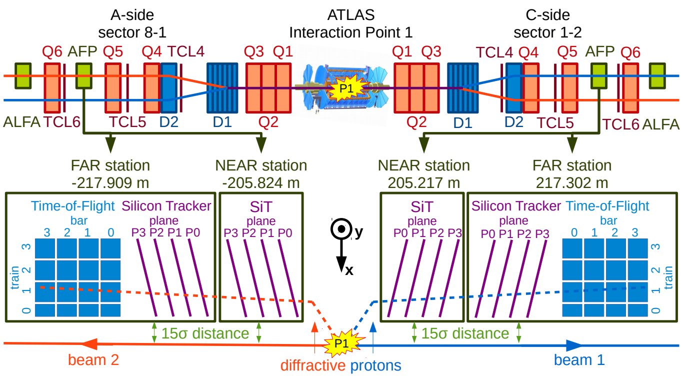

Figure 1: Schematic layout of the ATLAS Forward Proton detector with respect to the ATLAS experiment and LHC beam elements.

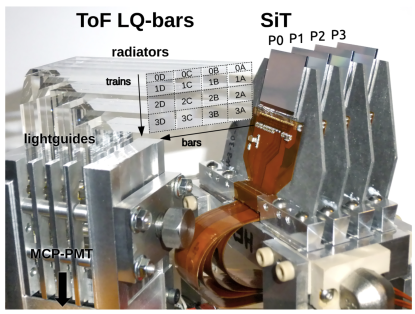

Figure 2: AFP Far Station, displaying the assembled ToF LQ-bars and SiT detectors.

2. ATLAS Forward Proton Detector

The ATLAS Forward Proton detector is a Roman Pot technology which positions the AFP to be very close to the LHC beam during stable beams. This allows for scattered protons to reach the geometric acceptance of AFP during ATLAS data recording. The layout of the AFP detector with respect to the ATLAS detector and LHC can be seen in Figure 1. On each side of the ATLAS detector, there are two stations. The NEAR station, closer to the ATLAS interaction point (IP), consists of a Silicon Tracker (SiT) [15]. The second station, called FAR, hosts the same SiT tracker and also a Time-of-Flight (ToF) detector [16]. The SiT detector is constructed from Silicon Pixel sensor planes, which measures position of the protons. The Time-of-Flight of the AFP detector measures timing using Cherenkov light produced by protons traversing L-shaped Quartz (LQ) bars. The signal produced is then amplified, processed and delivered to the ATLAS [16]. The 16 LQ bars are set up in a 4×4 arrangement as seen in Figure 2. The protons traverse through multiple bars, creating a signal in each bar. The four bars located next to each other form a train. The signal created in each bar contributes to the calculation of the timing value. The timing information from AFP can be used to calculate the vertex of the process in the ATLAS experiment. This can be compared to the vertex measured by the ATLAS Inner Detector, helping to reduce the combinatorial background.

3. Time-of-Flight Efficiency

The efficiency of a given ToF detector LQ-bar is calculated with respect to reconstructed tracks in the SiT detector which point to the geometric acceptance of the ToF bars. Counting the number of events with a signal in the given ToF Bar_{ij} and track pointing to corresponding train k, the efficiency is calculated as $\varepsilon_{ijk} = \mathrm{N}(\mathrm{Bar}_{ij} \cap \mathrm{Track}_k)/\mathrm{N}(\mathrm{Track}_k)$. With data collected in low pile-up conditions in 2017, the efficiencies of each ToF LQ train and bar was calculated as shown in Figure 3.

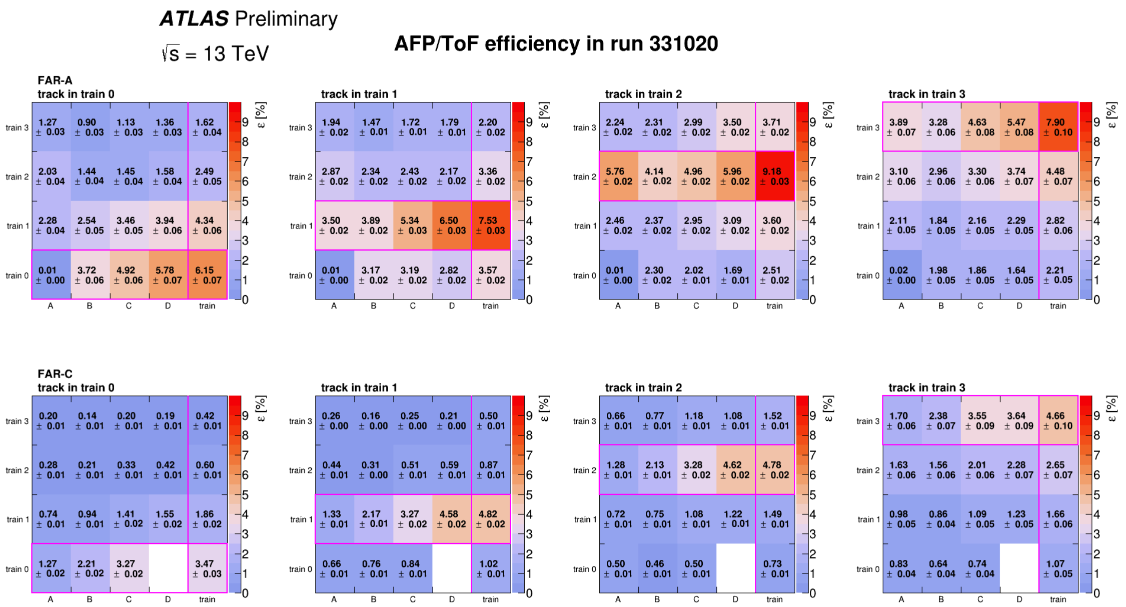

Figure 3: The ToF detector single-channel and train efficiencies (in percent) in the ATLAS run 331020 [16]

Over the AFP ToF detector data recording period, the efficiencies decreased with time, caused primarily by the degradation of the photomultipliers due to their exposure. Comparing the efficiencies in different pile-up conditions, it is observed that the efficiency of the LQ-bars is independent of the pile-up. [16].

4. Time Reconstruction Resolution

The time measured in a given channel of a train i is $t_i = t_{\mathrm{proton}} + t_{i,\mathrm{delay}} + t_{i,\mathrm{smear}} - t_{\mathrm{clock}}$, where t_{proton} is the true arrival time of the proton, $t_{i,\mathrm{delay}}$ is the constant channel time offset and $t_{i,\mathrm{smear}}$ is smearing caused by stochastic effects. The t_{clock} is a reference clock for the signal to be processed and has therefore the same value in all channels in an event. Therefore, the time difference between two given channels of a single train is $\Delta t_{ij} = t_{i,\text{delay}} - t_{j,\text{delay}} + t_{i,\text{smear}} - t_{j,\text{smear}}$. The channel resolution is then defined as $\sigma_{\text{i}}^2 = Var(t_{i,\text{smear}})$, calculated from the time distributions between different channels of the train, as shown in Figure 4. The time resolution is calculated for each station, and is found to be for FAR Station A (FAR Station C) 20(26) ± 4(5) ps.

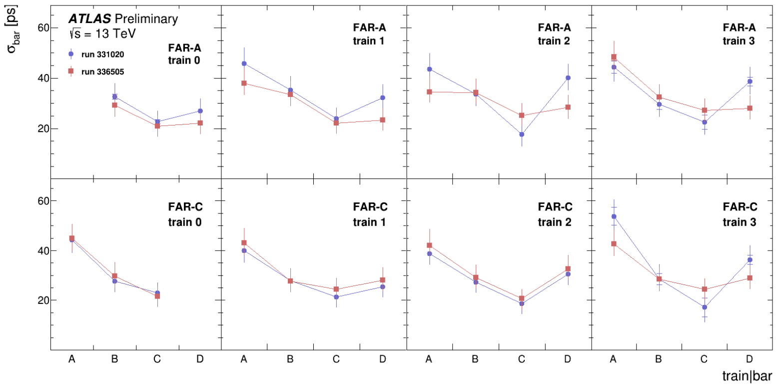

Figure 4: Timing resolution of ToF channels for A and C stations.

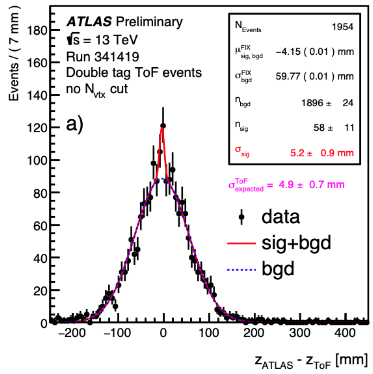

Figure 5: Vertex resolution of AFP ToF detector [16].

5. Vertex Matching

The primary vertex position of the pp interaction in the ATLAS experiment is calculated by AFP if a proton is recorded in both FAR stations in the event. Using the timing values of both sides, the primary vertex position of the (semi)exclusive event can be calculated as $z_{\text{ToF}} = \frac{c}{2}(t_{\text{FAR-C}} - t_{\text{FAR-A}})$. As this measurement is independent of the vertex measured by the ATLAS Inner Detector, the latter can be used to estimate the resolution of the z-coordinate of the primary vertex by ToF measurements, looking at $\Delta z = z_{\text{ATLAS}} - z_{\text{ToF}}$. The Δz distribution for one ATLAS run is shown in Figure 5. The combinatorial background, composed of events with a primary vertex, coming from a hard-scale event, reconstructed in the central ATLAS detector in coincidence with a random, pile-up proton in the AFP ToF detector, is shown by the dashed blue line. A sum of signal and combinatorial background is shown by the red line, clearly indicating the signal by the narrow peak above the broad blue bump. It suggests an observation of the (semi)exclusive signal even without applying additional selection criteria on observables from the central detector information. The resolution of the z-position of the primary vertex observed by fitting the red narrow peak is 5.2 ± 0.9 mm.

6. Conclusion

Performance of the AFP Time-of-Flight detector in the ATLAS experiment has been studied using data collected in 2017 at the LHC. The efficiencies of individual ToF detector channels have been measured based on a requirement of single train reconstructed in the ToF detector per side. They were found to be below 10% and degrading with time. The timing resolution in combination of all channels, is of 20(26) ± 4(5) ps in FAR Station A (C). The timing of the protons recorded in each detector allows for the vertex position to be calculated and compared to the ATLAS inner detector. The resolution of the vertex position is found to be 5.2 ± 0.9 mm.

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