Performance study of the ATLAS Forward Proton Time-of-Flight Detector System

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The performance of the ATLAS Forward Proton Time-of-Flight (ToF) detector is studied using the ATLAS LHC data collected in the 2017 running period of LHC Run2. A study of efficiency and time resolution of the ToF is performed. Good time resolutions of individual ToF channels, ranging between 20 ps to 50 ps are found, although the efficiency observed is well below 10% in major parts of the analysed data. The events from ATLAS physics runs at moderate pile-up taken at the end of 2017 are selected with signals in the two opposite ToF stations located at both sides of the ATLAS interaction region. The overall time resolution based on resolutions of the individual channels in these data is found to be $20 \pm 4$ ps and $26 \pm 5$ ps for the two ToF detectors. This represents a superb time resolution for a detector operating a few millimetres from the LHC beams. The difference of the primary vertex z-position measured by ATLAS and the value obtained by the ToFs is studied. The distribution of the difference constitutes of a background component from combinatorics since the level of pile-up is not negligible and a significantly narrower signal component from events where protons from interactions taking place in the primary vertex are detected in ToF. The fits are performed to the distributions yielding resolution of about $5 \text{ mm} \pm 1 \text{ mm}$ which is in agreement with the expectation based on single-channel resolutions.

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1. Introduction

Observation of protons at high rapidities carrying large fraction of the initial state proton momentum serves as a signature of reactions $pp \rightarrow pXp$ commonly referred to as diffractive or photon induced processes. The accelerator optics separates the leading protons from the beam to such extent that the deviations can be measured. For this purpose there are four AFP detectors installed in pairs at $\sim 200$ m on both sides of the ATLAS interaction point [1]. The AFP (Roman Pot) stations are equipped with Silicon tracker (SiT, [2]) which measures the positions ($x, y$) and slopes ($x', y'$) of the scattered proton trajectory with respect to the nominal beam and which are correlated with leading proton kinematics in the interaction point. In case of pile-up the detection of leading protons becomes too complicated due to combinatorial background. The information about the primary vertex position of the $pp \rightarrow pXp$ event can be, however, extracted by comparing the arrival times of the leading protons. For this purpose the two outermost AFP stations called FAR-C an FAR-A station for clockwise and anticlockwise directions, respectively, are equipped with ToF detectors.

![Figure 1: The general of AFP layout in ATLAS.](image)

2. Description of the Time-of-Flight detector

The ToF is an optical detector, collecting the Cherenkov photons produced by leading protons traversing $4 \times 4$ matrix of L-shaped Quartz bars (LQ) [3]. Photons enter the micro-channel-plate photomultiplier (MCP-PMT, [4]) producing a voltage pulse processed by the constant fraction discriminator (CFD) and high-performance time-to-digital converter (HPTDC) for time measurement. Each bar (channel) provides measurement of time. Set of four bars labelled as $0-3$ or (A,B,C,D) is called a train. See Figures 2 and 3 for notion of design and function.
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3. Data

The analysed data were recorded in 2017 by the ATLAS detector. The efficiency and single-channel resolution studies are measured in the low-$\mu$ runs 331202 and 336505 and also in run 336506 at a high-$\mu$. Only the data from the AFP calibration stream were used recorded with a SiT based trigger condition. The same high voltage of $-2$ kV was applied on the ToF PMTs in these runs.

For the vertex matching analysis a late 2017 run number 341419 was used taken in moderate pile-up conditions of $\langle \mu \rangle \sim 2$ with ToF PMTs high voltage of $-1950$ V using a SiT based trigger. The AFP data were recorded together with the physics data from the central detector in the run 341419.

4. Measurement of efficiency

Event samples where single track criteria are imposed on the SiT are used for measurement of
the efficiency defined as
\[ \varepsilon_{ik} = \frac{N(\text{channel}_{ik} \cap \text{track}_k)}{N(\text{track}_k)} \] (4.1)

where the first index \( i \) labels the channel corresponding to the bar position in the train \( k \) and the \( \text{track}_k \) refers to events with reconstructed SiT tracks physically pointing to the train \( k \). The train efficiency is obtained using a logical OR over the trains' channels.

5. Measurement of time resolution in single channels

The time measured by a single channel reads,
\[ t_i = t_{\text{proton}} + t_{\text{delay}} + t_{\text{smeared}} - t_{\text{clock}}, \]
where the \( t_{\text{proton}} \) is the true proton arrival time, \( t_{\text{clock}} \) is the reference clock signal, \( t_{\text{delay}} \) is a constant time offset of each channel and \( t_{\text{smeared}} \) is the contribution smeared by all stochastic effects that play a role. It is the \( t_{\text{smeared}} \) whose variance defines the single-channel resolution. The resolutions are measured by using other bars of the same train as a reference. The time differences \( \Delta t_{ij} = t_i - t_j \) are measured on the event-by-event basis in events where the signal is present in a single train only. The widths, \( \sigma_{ij} \), of the \( \Delta t_{ij} \) distributions given as \( \sigma_{ij}^2 = \text{Var}(\Delta t_{ij}) \) are parametrized as \( \sigma_{ij}^2 = \sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j \), where \( \sigma_i \) represent the single-channel resolutions and the \( \rho_{ij} \) is a correlation factor between the two 'smeared' times. The resulting single channel resolutions minimise the \( \chi^2 \) value defined as
\[ \chi^2 = \sum_{i\neq j} \frac{(\sigma_{ij} - \sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j})^2}{(\delta_{\sigma_{ij}}^2)^2}, \] (5.1)

where \( \delta_{\sigma_{ij}} \) is the statistical uncertainty of the \( \sigma_{ij} \) value obtained from fits to \( \Delta t_{ij} \) distributions. In addition, three constant choices of \( \rho_{ij} \) (0, ±0.2) are used as systematics.

6. Analysis of matching primary and Time-of-Flight vertex

The \( pp \rightarrow pXp \) interaction vertex position, \( z_{\text{ToF}} \), is reconstructed from proton arrival times measured by ToF (corrected for channel delays and beamspot position). The resolution of the \( z_{\text{ToF}} \) is evaluated by measuring distribution of \( z_{\text{ATLAS}} - z_{\text{ToF}} \), where \( z_{\text{ATLAS}} \) is the primary vertex \( z \)–position measured by the central ATLAS detector. In case of pile-up the distribution of \( z_{\text{ATLAS}} - z_{\text{ToF}} \) also contains the background contribution from random coincidences of protons measured in ToF not originating in a single interaction. By utilising the measured times from non-related events (event mixing) the shape of the background component is well approximated.

7. Results

The measured single-channel and train efficiencies are presented in Figure 4 for run 331020 based on a statistics of about 2M(3M) tracks reconstructed in the FAR-A(C) station. Horizontal magenta boxes indicate the train with a reconstructed SiT track. The train efficiencies measured by requiring at least one bar hit in the given train are indicated by vertical magenta lines. A general feature of the applied selection is that with a non-negligible probability signals can be generated also in bars of trains neighbouring the SiT-track train, that is the one the proton track is pointing to.
The efficiencies measured in the SiT-track containing trains vary between 6 − 9% and 3.5 − 5% in stations FAR-A and FAR-C, respectively, in the run 331020.

In Figure 5 the efficiencies in trains with track are shown as a function of time in the runs 331020, 336505 and 336506. An efficiency drop due to a continuous MCP-PMT degradation is observed between the run 331020 and the two runs 336505 and 336506 as the latter two ones were recorded after another two months of data taking after 331020. The track statistics amounts to 1M(7M) in the run 336505 and to 60k(40k) in the run 336506 for the FAR-A(C) side. Within the large uncertainties the efficiencies in the runs 336505 and 336506 are not dependent on the absolute scale of $\mu$, superimposed as a magenta histogram. No variation of the train efficiencies correlated with the $\mu$ time dependence is observed either.

The single-channel time resolutions are presented in Figure 6 for the runs 331020 and 336505. The statistics of the event samples of single-train topologies used for the measurement equals to 70k(110k) in the run 331020 and 20k(100k) in the run 336505 for the FAR-A(C) side. The worst resolutions between 40 − 50 ps are observed in the first channels of the trains which have lowest photon yield. The following bars profit from photon enrichment yielding resolutions of 30 − 20 ps, respectively. The total uncertainty equals to 6 ps at most, covering both the statistical and systematic ones.

The vertex matching analysis is performed by fits to the $z_{\text{ATLAS}} - z_{\text{ToF}}$ distributions using a double-Gaussian p.d.f. accounting for the signal and background components. The values of the background mean and width and the signal width are fixed from a previous fit to mixed event data. The signal width obtained in three cut scenarios with respect to the number of reconstructed event vertices in the central detector, $N_{\text{vtx}}$, are within uncertainties in agreement with the value calculated from the single-channel resolutions, see Figure 7.

8. Conclusions

While the measured single-channel time resolutions are promising, ranging between 20 ps and 50 ps, the ToF performance is burdened mainly by low efficiency of 1 − 7% in the single channels and 5 − 10% in the trains caused by a continuous degradation of the MCP-PMT. Improvements of all parts of the timing detectors are under development including the use of long-life MCP-PMTs and a new (glue-less) production technique of the LQ-bars.

Observation of a significantly narrower peak in the $z_{\text{ATLAS}} - z_{\text{ToF}}$ distribution provides a hint of presence of the signal $pp \rightarrow pXp$ events. The width of the signal peak reaches value of about 6 ± 1 mm which is broadly consistent with the expected resolution 5 ± 1 mm.

References

Figure 4: The ToF single-channel and train efficiencies in run 331020.

Figure 5: The ToF train efficiencies in the low—μ runs 331020, 336505 and the high—μ run 336506 as a function of time in run.
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Figure 6: The single-channel resolutions in runs 331020 and 336505.

Figure 7: The distributions of $z_{\text{ATLAS}} - z_{\text{ToF}}$ measured in events with ToF signals on both sides of the interaction region in run 341419, where $z_{\text{ATLAS}}$ is the primary vertex $z$-position reconstructed by ATLAS. The distributions shown in figures a)-c) correspond to ATLAS data containing a reconstructed primary vertex together with coincidence of signals in both ToF detectors in three cut scenarios with respect to number of vertices reconstructed by ATLAS, no $N_{\text{vtx}}$ cut, $N_{\text{vtx}} \leq 5$ and $N_{\text{vtx}} \leq 3$, respectively. A double Gaussian function representing the signal and background components is fitted to unbinned data samples using the extended likelihood fit as implemented in RooFit in all $N_{\text{vtx}}$ cut scenarios. The mean of the signal component as well as the mean and width of the background component are always estimated from a Gaussian fit to the mixed event data in each $N_{\text{vtx}}$ cut scenario separately, denoted as $\mu_{\text{sig}}$, $\sigma_{\text{sig}}$, $\mu_{\text{bgd}}$ and $\sigma_{\text{bgd}}$. The mixed event data $z_{\text{ATLAS}} - z_{\text{ToF}}$ distributions are obtained by random mixing of times measured by ToF in either station and the $z_{\text{ATLAS}}$ values which do not originate in the same collision event. The expected resolution of the ToF detector, quoted as $\sigma_{\text{ToF}}$, is obtained from the known single-channel resolutions convoluted with the actual channel-hit-patterns observed in the data in the no $N_{\text{vtx}}$ cut scenario.