# The ATLAS Forward Proton Time-of-Flight Detector System

**Karel Černý*** on behalf of the ATLAS Collaboration
Palacký University in Olomouc, Faculty of Science, Czech Republic
karel.cerny@upol.cz

Poster for presentation at the European Physical Society Conference on High Energy Physics, 26 – 30 July 2021, Hamburg.

## Introduction

Observation of protons at high rapidities carrying large fraction of the initial state proton momentum serves as a signature of reactions $pp \to pXp$ 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 complicated due to combinatorial background. The information about the primary vertex position of the $pp \to pXp$ event can be 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 Time-of-Flight (ToF) detectors.

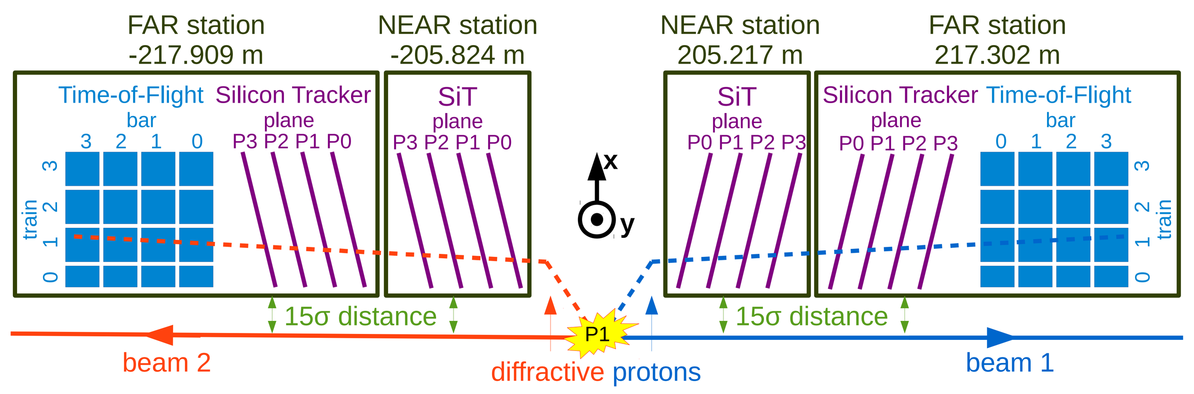


**Figure 1:** The general layout of AFP with the ATLAS interaction point located in the middle.

## Time-of-Flight detector

The ToF function relies on the collection of the Cherenkov photons produced by 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 (A,B,C,D) is called a train.

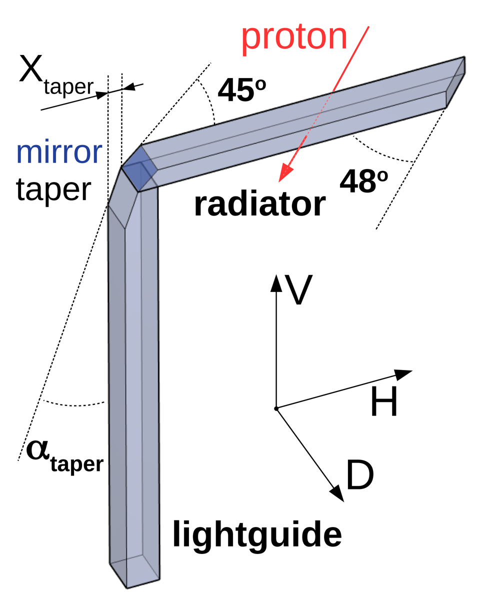


**Figure 2:** The design of the LQ-bar.

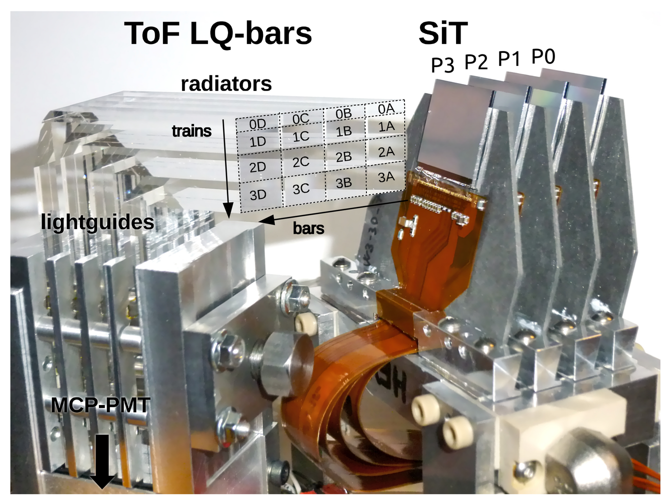


**Figure 3:** The assembled ToF LQ bars and the Silicon tracker.

## Data

The LHC data used for this analysis were recorded in 2017 by the ATLAS detector. For the efficiency and single-channel resolution studies the low$-\mu$ runs 331002 with $\langle\mu\rangle \sim 1$ and 336505 with $\langle\mu\rangle \sim 0.04$ were used as well as run 336506 which is of low statistics but high pile-up of $\langle\mu\rangle \sim 40$ . A late 2017 run 341419 with $\langle\mu\rangle \sim 2$ was used in order to test the ToF primary-vertex reconstruction capabilities.

## Efficiency

Event samples where single track criteria are imposed on the SiT are used for measurement of the efficiency defined as $\varepsilon_{ijk} = N(\text{channel}_{ij} \cap \text{track}_k)/N(\text{track}_k)$ where the first index $i$ labels the channel corresponding to the bar position in the train $j$ and the 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.

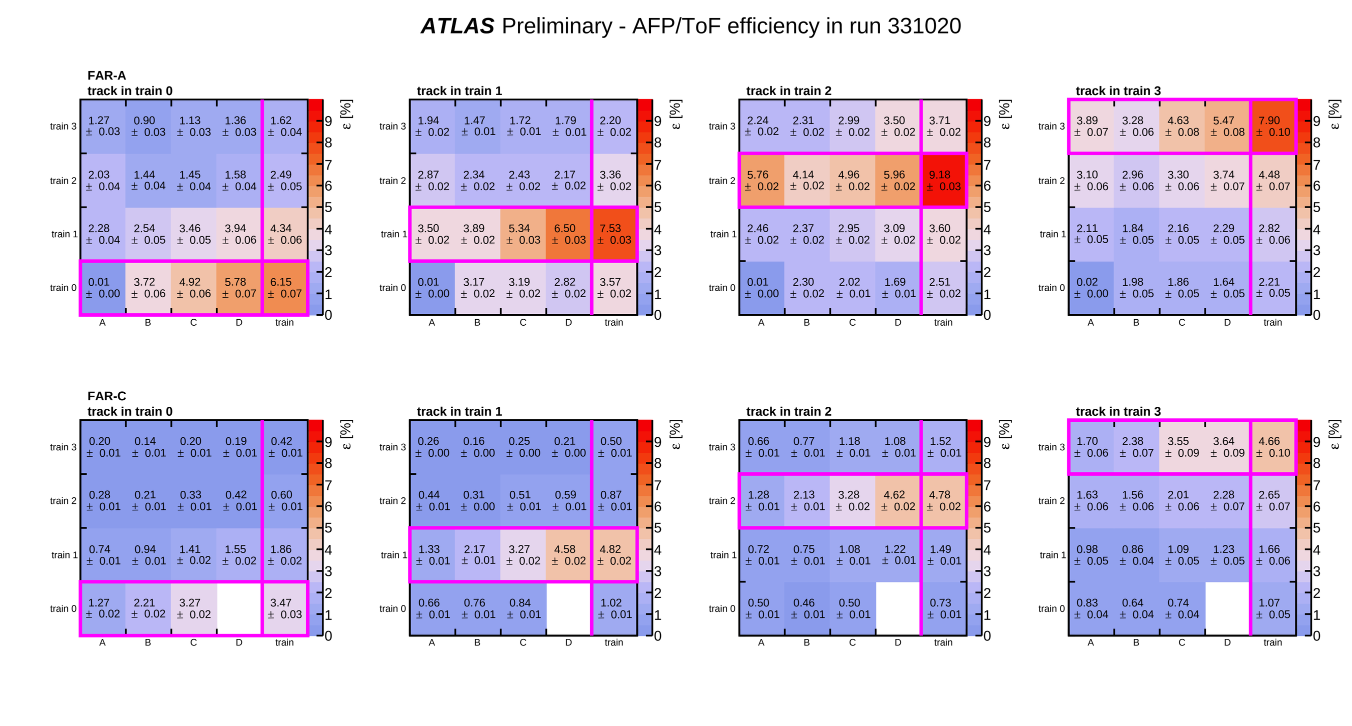


**Figure 4:** The ToF single-channel and train efficiencies in run 331020. For details see [5].

The measured efficiencies reaching 6 to 9% and 3.5 to 5% at most are measured in the FAR-A and FAR-C stations in run 331020 in the trains directly hit by the proton measured in the SiT.

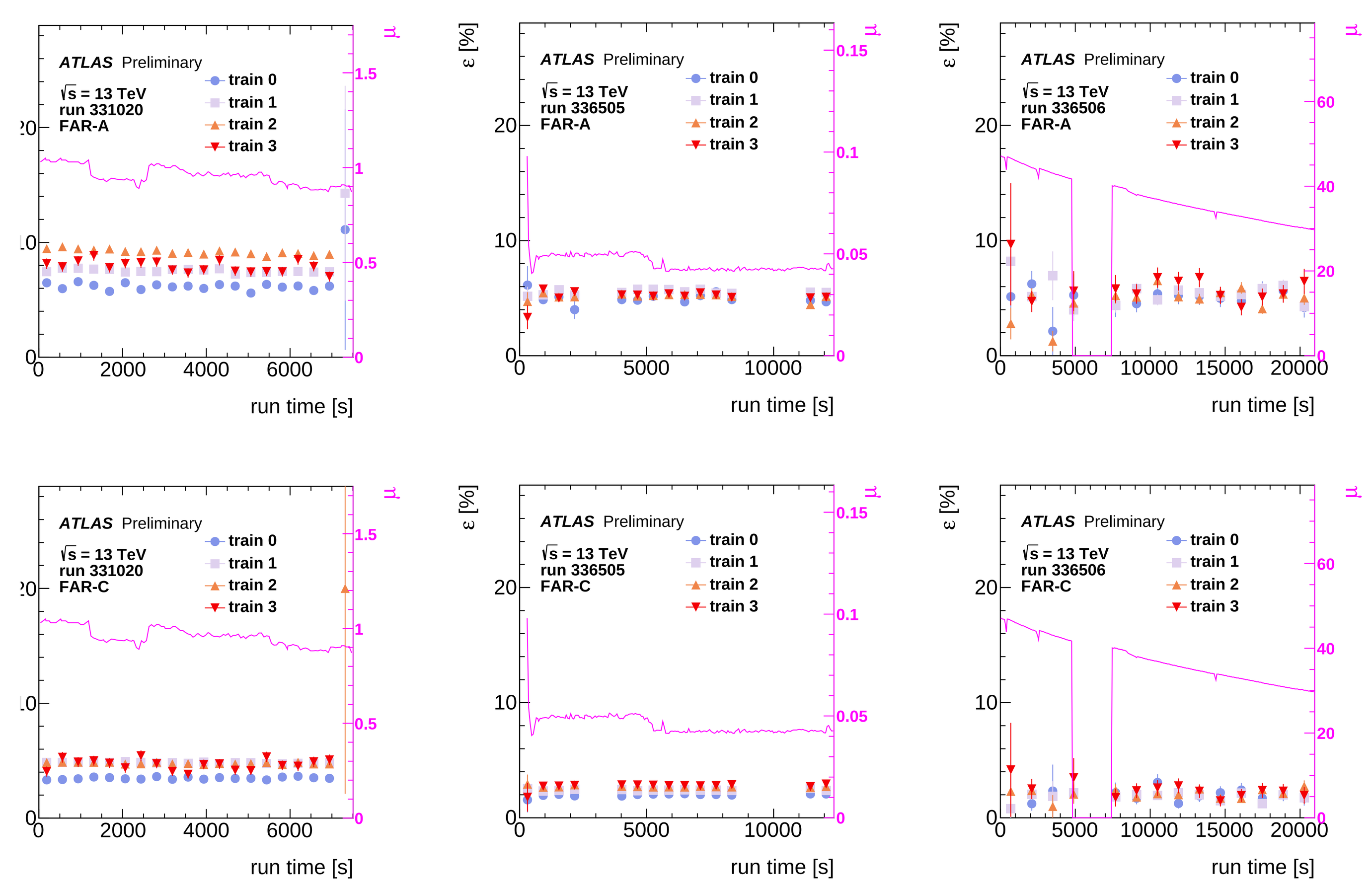

**Figure 5:** The ToF train efficiencies in the low$-\mu$ runs 331020, 336505 and the high$-\mu$ run 336506 as a function of time in run. For details see [5].

The lower overall train efficiencies are measured in the run 336505 separated by a two month data taking period evidencing a continuous degradation of the PMT. The train efficiencies seem to be insensitive to the $\mu$ levels if the values measured in the run 336506 and 336505 are compared.

## Time resolution

The time measured in a single ToF channel $i$ can be written as $t_i = t_{i,\text{proton}} + t_{i,\text{delay}} + t_{i,\text{smear}} - t_{\text{clock}}$, where the $t_{i,\text{proton}}$ is the true proton arrival time, $t_{\text{clock}}$ is the reference clock signal, $t_{i,\text{delay}}$ is a constant time offset specific to each channel due to e.g. cable lengths and $t_{i,\text{smear}}$ is the contribution smeared by all stochastic effects that play a role, such as photo-electron statistics or noise in the electronics. The $t_{i,\text{smear}}$ variance defines the single-channel resolution. The resolutions are measured for each channel 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 'smear' times. The single channel resolutions are obtained by minimisation of

$$\Sigma_{ij} \frac{\left(\sigma_{ij} - \sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j}\right)^2}{(\delta_{\text{fit}}\sigma_{ij})^2} \qquad (1)$$

against $\sigma_i$ and $\sigma_j$ with three constant choices of $\rho_{ij}$ $(0, \pm 0.2)$ taken as systematics.

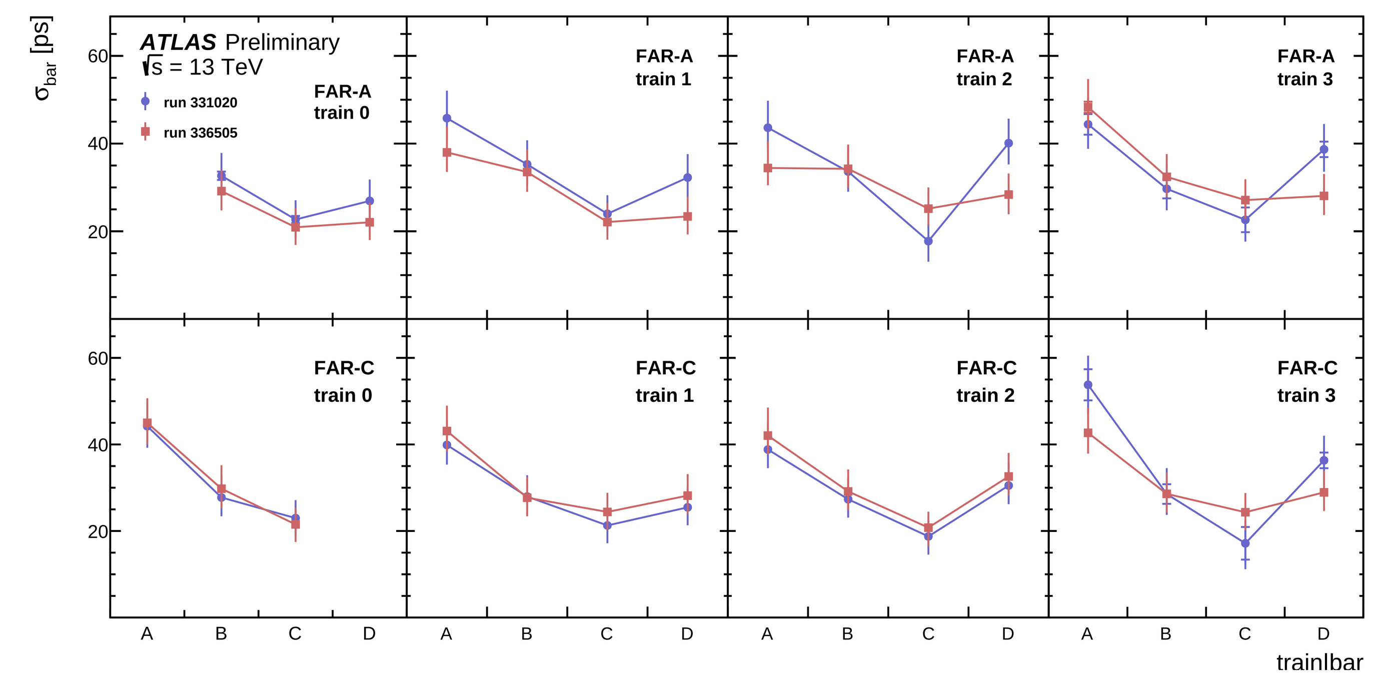

**Figure 6:** The single-channel resolutions in runs 331020 and 336505. For details see [5].

## Vertex matching

The $pp \to pXp$ interaction vertex is reconstructed from proton arrival times measured by ToF, $z_{\text{ToF}}$. The resolution of the $z_{\text{ToF}}$ is the evaluated by measuring distribution of $\Delta z = z_{\text{ATLAS}} - z_{\text{ToF}}$, where $z_{\text{ATLAS}}$ is the primary vertex $z-$position measured by ATLAS. Due to the pile-up the $\Delta z$ distribution also contains background contribution from random coincidences of protons measured in ToF not originating in a single $pp \to pXp$ interaction. The background shape can be estimated by a data-driven technique of event mixing (ME) using ToF times and $z_{\text{ATLAS}}$ from unrelated events. The times measured in each station were corrected for the channel time delays and time offset existing between the stations as well as for variations of the ATLAS beamspot position.

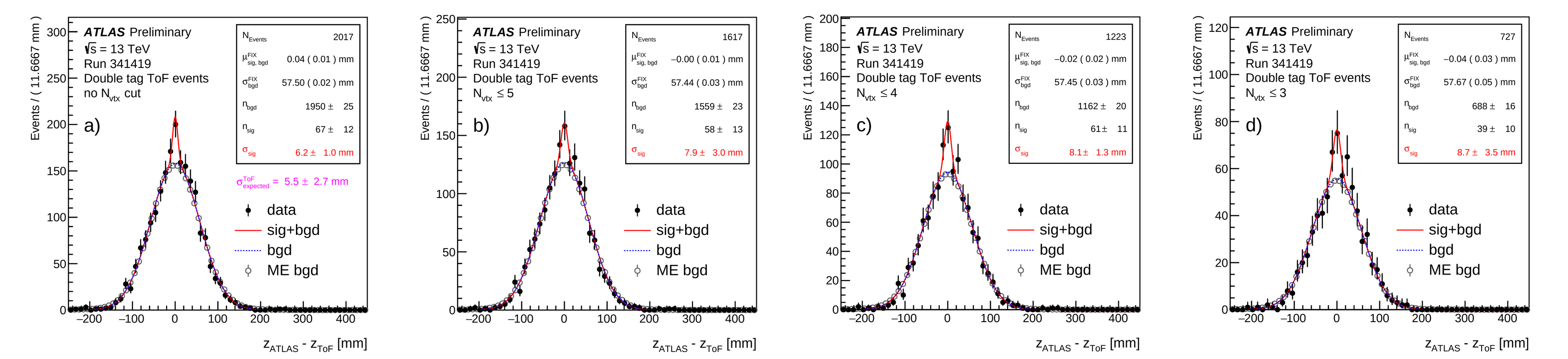

**Figure 7:** The distributions of $z_{\text{ATLAS}} - z_{\text{ToF}}$ measured in events with ToF signals on both sides of the interaction region in run 341419, where $z_{\text{ATLAS}}$ is the primary vertex $z$-position reconstructed by ATLAS. The distributions shown in figures a)-c) correspond to three cut scenarios with respect to number of vertices reconstructed by ATLAS, no $N_{\text{vtx}}$ cut, $N_{\text{vtx}} \leq 5, \leq 4$ and $\leq 3$, respectively. The Gaussian-shaped signal and background components is fitted to unbinned data samples using the extended likelihood fit 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 estimated from fits to the mixed event data, denoted as $\mu_{\text{sig}}^{\text{FIX}}$, $\mu_{\text{bgd}}^{\text{FIX}}$ and $\sigma_{\text{bgd}}^{\text{FIX}}$. The expected resolution of the ToF detector, quoted as $\sigma_{\text{expected}}^{\text{ToF}}$ 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. For details see [5].

## Results

The ToF single-channel efficiencies were measured of $1-9$ %. The measured train efficiencies range between 5 and 10 % and are insensitive to the $\mu-$levels. The ToF single-channel resolutions are measured of 20 ps at best worsening to about 50 ps usually for the train channels corresponding to first LQ-bars.

The vertex matching analysis provides a hint of presence of the signal $pp \to pXp$ events by observation a significantly narrower peak in the $z_{\text{ATLAS}} - z_{\text{ToF}}$ distribution. The width of the signal peak extracted from the fit to the data suggests the resolution of the ToF method of about $6 \pm 1$ mm to $9 \pm 4$ mm which is within uncertainties compatible with the expected resolution of $6 \pm 3$ mm obtained from extrapolation of the single channel resolutions.

## References

[1] Adamczyk, L. et al., Tech. Rep. ATL-COM-LUM-2011-006, CERN, Geneva (2011), AFP technical proposal.
[2] Lange, J. et al., 3D silicon pixel detectors for the High-Luminosity LHC, JINST, 2016,vol 11, no. 11, pp. 11024.
[3] Nozka, L. et al. , Opt. Express, 2014, vol. 22, no. 23, 3815 pp. 28984 – 28996.
[4] PHOTONIS USA Pensylvania Inc., miniPLANACON XPM85112 datasheet.
[5] The ATLAS Collaboration, ATL-FWD-PUB-2021-002, CERN, Geneva (2021), Performance of the ATLAS Forward Proton Time-of-Flight Detector in 2017.

* The work was supported by the Operational Programme Research, Development and Education - European Regional Development Fund, project no. CZ.02.1.01/0.0/0.0/16_019/0000754, of the Ministry of Education, Youth and Sports of the Czech Republic.