IMPROVEMENT OF THE TIMING CALIBRATION IN THE CMS PPS TIMING DETECTORS*

Tomasz Ostafin

on behalf of the CMS Collaboration

AGH University of Krakow, al. Mickiewicza 30, 30-059 Kraków, Poland

Received 31 March 2025, accepted 3 April 2025,
published online 26 June 2025

The Precision Proton Spectrometer is a subdetector of the CMS experiment at the LHC used for detecting forward protons. It comprises tracking and timing detectors located around 220 meters from the CMS detector, along the LHC beam pipe, on both sides. Due to their challenging operating environment, they require frequent calibration. Procedures for performing these calibrations have already been developed in LHC Run 2 (2015–2018), but in Run 3 (2022–2026), the timing detector calibration algorithm has been shown not to perform ideally for most of the data-taking runs due to data anomalies and irregularities. Moreover, calibrating so many runs every year is a tedious task. As a result, an in-house parallel processing automation framework has been developed to perform the calibration and validate its results. In the paper, an improved timing calibration algorithm was shown, as well as anomalies and irregularities that were observed and corrected using it.

DOI:10.5506/APhysPolBSupp.18.5-A26

1. Introduction

The Precision Proton Spectrometer (PPS) is a near-beam subdetector of the CMS detector, which extends the physics program to Central Exclusive Production processes, in which both protons remain intact after the collision at the CMS Interaction Point [1]. The PPS detectors can measure the proton longitudinal momentum, which, correlated with the information from the central CMS detector, allows for the mass and rapidity of the central system to be reconstructed.

There are two types of PPS detectors: timing and tracking. Both are located symmetrically, around 220 m from IP 5. They are mounted in movable devices called Roman Pots (RPs), which allow them to get extremely close to the beam (around 1.5 mm) [2].

* Presented at the 31st Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

2. PPS timing detector

The PPS timing detector focuses on precise time-of-flight (ToF) measurements. When the difference between the ToF of two protons (Δt) is known, the z vertex position can be computed

$$z_{pp} = \frac{c}{2}\Delta t\,. \tag{1}$$

This value is later correlated with one of the vertices reconstructed by the CMS detector and can be used to observe whether the two protons came from the same vertex or not.

The PPS timing detector comprises 2 sectors with 2 stations in each, 4 planes in each station, and 10 to 12 double-diamond readout channels in each plane, as seen in figure 1.

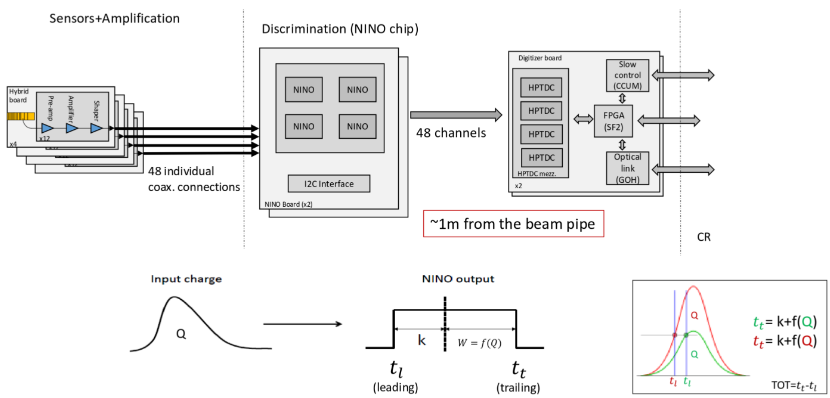

Fig. 1. The three-step digitization process of the PPS timing detector. The output charge is proportional to the input charge ($W = f(Q)$). A proton passing through many consecutive planes can deposit different energy, which causes the time walk effect, which needs to be corrected [3].

3. PPS timing calibration

A two-step timing calibration procedure has already been established in Run 2 [3]. Its results are presented in figure 2. It consists of:

1. Timing correction and alignment: used for correcting the time walk effect based on data fitting.
2. Timing resolution: an iterative algorithm for computing the time resolution of each detector channel. It is based on the corrected signal from the previous step.

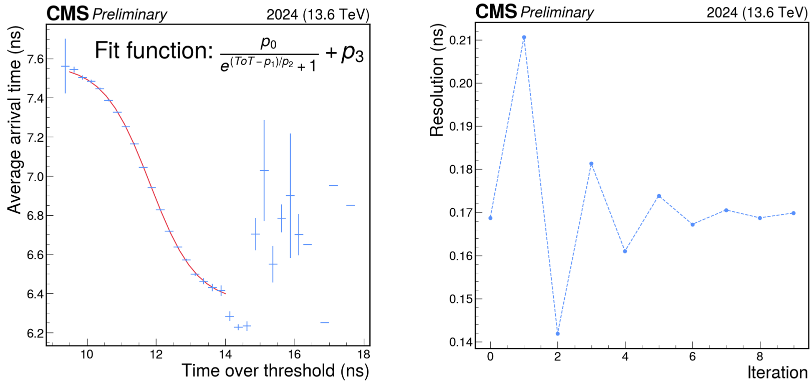

Fig. 2. Results of the timing calibration: timing correction and alignment (left) and timing resolution (right) [4].

However, the analysis of Run 3 data has shown new problems [4]:

— Non-converging time-of-arrival (ToA) *versus* time-over-threshold (ToT) fits for many readout channels.

— Bad quality of the fits (wrong shape, high χ^2/n.d.f., *etc.*).

— Leading edge *double peak*.

4. Fit improvement

In Run 2, the behavior of the PPS timing detector was more predictable, hence, the fit results were pretty consistent. However, in Run 3, the fit often fails to describe accurately the most populated ToT regions. As a result, many fits do not converge, which in turn leads to meaningless timing resolution results. Even when the fits do converge, they often end up with questionable quality as their χ^2/n.d.f. is very high.

To overcome these issues, new improvements were introduced to the timing alignment and correction algorithm:

1. Changing the fit parameters limits: previously, only two of them were bounded, and the old limits were not adequate for Run 3 data.
2. Increasing the maximum function call limit of the minimizer.
3. Introducing iterative thresholds: the fit bounds based on ToT threshold fractions, which give the best χ^2/n.d.f. and are selected iteratively.

The third point is the most important. In Run 2, the fit had constant bounds: $[10.2, \mu_{\mathrm{ToT}}+2.5]$. In Run 3, to overcome the issue of non-predictable data, the bounds were based on an arbitrary constant ToT fraction of its distribution maximum.

While this approach alleviated some issues, it still was not perfect because the correct fraction value had to be picked, which not only varied from run to run but also from channel to channel. This is why an iterative procedure based on the best χ^2/n.d.f. was introduced, as seen in figure 3.

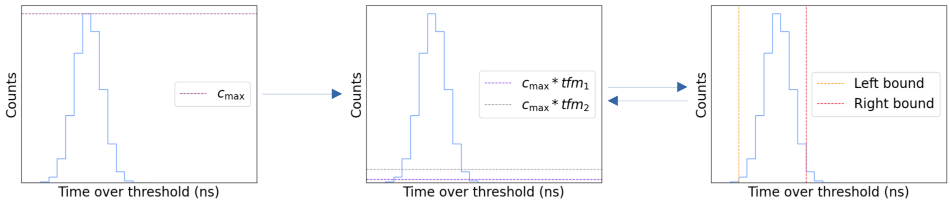

Fig. 3. The iterative thresholds approach [4].

Firstly, the bin with the maximum count c_{max} is found. Then, two threshold fractions tfm_1 and tfm_2 are iteratively picked for the left and right bounds, respectively. The thresholds are computed by multiplying c_{max} with both fractions, and the bins with the minimum count which are still above the thresholds are found to determine the fit bounds. If this fraction pair gives the best χ^2/n.d.f. so far, these bounds are saved.

These three improvements combined allowed for processing all of 2024 data-taking runs without a single fit failing, except when unrelated temporary hardware malfunctions compromised the data quality. Additionally, the quality of the fits visibly improved, as presented in figure 4.

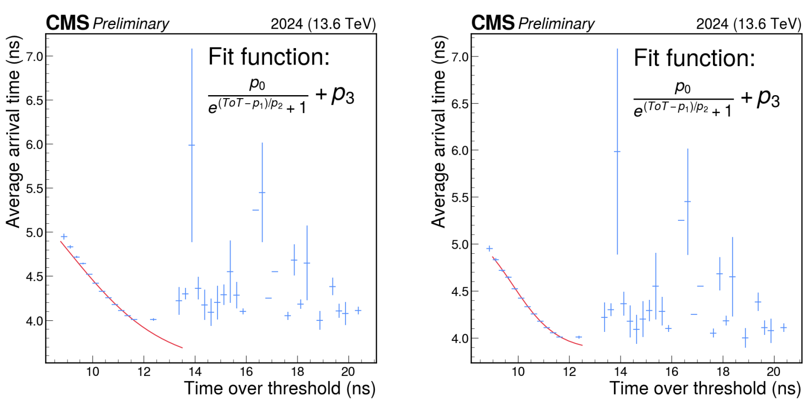

Fig. 4. Results of the fit improvement: before (left) with χ^2/n.d.f. = 1649.34/15 and after (right) with χ^2/n.d.f. = 67.34/11 [4].

5. Double peak

The PPS timing detector is tuned to have the signal leading edges concentrated around a certain value (around 5 ns). This ensures that the trailing edge of the signal (around 13 ns) is registered in the 25 ns acquisition window. Sometimes, during a data-taking run, a shift happens to either higher or lower values, as seen in figure 5. The probable reason for this is a phase shift of the precision clock used for the timing measurement, possibly due to a single event upset in the clock distribution circuitry. This shift is permanent and constant until a power cycle is applied.

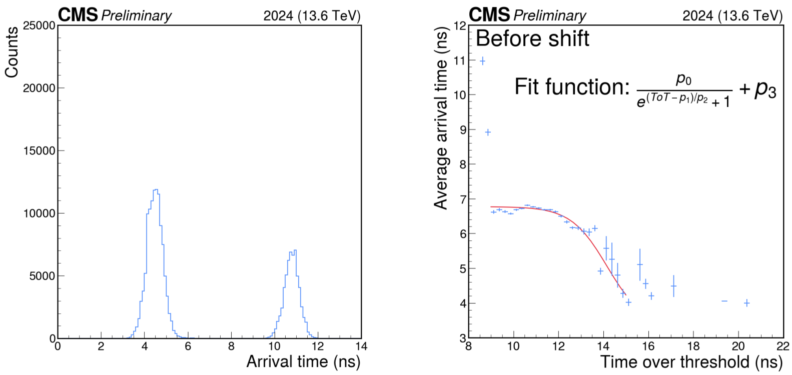

Fig. 5. Double peak plots: the ToA distribution (left) and ToA *versus* ToT profile (right) with $\chi^2/\text{n.d.f.} = 645.2/21$ [4].

This created the need for a new algorithm based on shifting the leading edge of the signal as presented in figure 6. Firstly, the lumisection at which the double peak occurs is detected by going through a 2D histogram of ToA *versus* lumisection of a plane with a sliding window. Once this value is found, the y-axis is projected, and two Gaussians are fitted representing the two peaks. The shift can be computed by subtracting their means. This solution is also backward compatible as these two values can be stored in an already existing database field not used for its original purpose in Run 3.

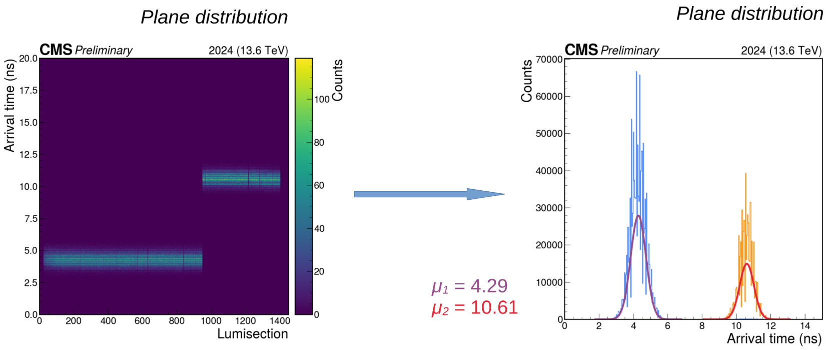

Fig. 6. The double peak correction algorithm [4].

The final results can be seen in figure 7.

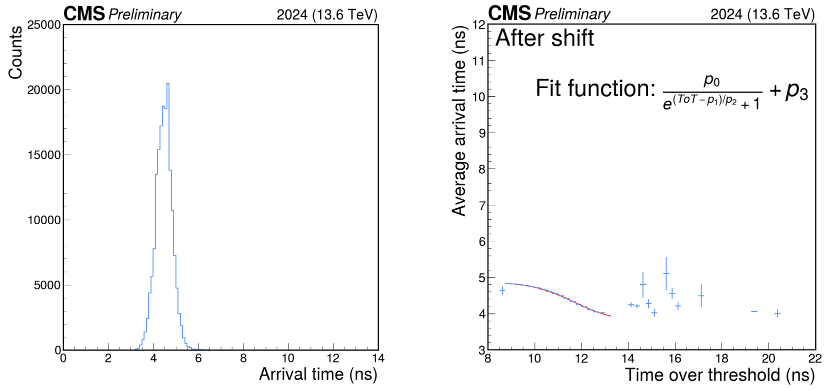

Fig. 7. Double peak plots after the correction: the ToA distribution (left) and ToA *versus* ToT profile (right) with χ^2/n.d.f. = 40.34/14 [4].

6. PPS automation framework

The PPS automation framework allows for running automation workflows. It is based on an automation library created by ECAL and utilizes industry-grade technologies such as Jenkins and Grafana [5]. Additional features were added, such as run filters or the ability to validate the results of the calibration workflows. The improved automation framework helped detect and mitigate the PPS timing detector problems in Run 3.

This research was partially funded by the Ministry of Science and Higher Education, Poland, grant 2022/WK/14.

REFERENCES

[1] CMS-TOTEM Collaboration (M. Albrow *et al.*), https://cds.cern.ch/record/1753795

[2] E. Bossini, talk presented at the 13th FAST 2023 workshop, Elba Island, Italy, 28 May–1 June, 2023, https://indico.cern.ch/event/1214183/contributions/5417505/

[3] CMS Collaboration, https://cds.cern.ch/record/2696212

[4] CMS Collaboration, https://cds.cern.ch/record/2921893

[5] A. Bellora, T. Ostafin, poster presented at the Conference on Computing in High Energy and Nuclear Physics (CHEP 2024), Kraków, Poland, 19–25 October, 2024, https://indico.cern.ch/event/1338689/contributions/6018635/