GLOBAL ALIGNMENT OF ATLAS FORWARD PROTON DETECTORS*

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The AFP global alignment method using photon-fusion-induced lepton pair production is discussed. The alignment corrections are derived from a comparison of the expected proton positions to the measured ones. Results obtained with di-muon events are verified with di-electron events.

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1. Introduction

The ATLAS Forward Proton (AFP) detectors [1] are a subsystem of the ATLAS experiment [2] at the Large Hadron Collider (LHC). They are designed to detect forward protons produced in Standard Model (SM) diffractive [3] and photon-induced processes [4] and play a role in beyond Standard Model (BSM) searches [5].

The AFP detectors measure the trajectories of the scattered protons in proximity of the beam. The trajectory information is used to reconstruct proton kinematics [6]. This would not be possible without accurate information about the position of the AFP detector [7]. In order to reach the best possible accuracy, data-driven alignment procedures are used. This paper is devoted to global alignment, *i.e.* the determination of the distance between the AFP tracking detector and the LHC beam.

2. AFP detector

The AFP detectors are installed on both sides of the ATLAS interaction point. AFP comprises four stations — two on each side (following an ATLAS convention, the two sides are called arm A and arm C). The *near*

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stations are placed approximately 205 m from the interaction point, the *far* stations around 217 m. Each station is equipped with a silicon tracking detector consisting of four silicon planes. Additionally, the far stations contain quartz-based Cherenkov time-of-flight detectors.

Detectors are meant to operate at a distance of around 2–4 mm away from the beam. However, they cannot be near the beam when it is unstable. Therefore, the detectors are placed in Roman Pots (RPs) — movable devices inserted into the LHC beam pipe and retracted away on demand.

The AFP RPs are inserted horizontally. Each Pot is independently controlled by a fine-resolution stepper motor. The Roman Pot mechanism is equipped with springs that provide mechanical retraction of the Pot in the case of a power failure or other emergencies. The RPs operate without interfering with the LHC main vacuum and hold a secondary vacuum maintained by dedicated pumps.

The AFP detectors record protons deflected from the beam. This deflection happens mainly in the field of LHC dipole magnets, depends on the proton energy, and is typically expressed as the fractional energy loss variable

$$\xi_{\mathrm{AFP}} = 1 - \frac{E_{\mathrm{S}}}{E_{\mathrm{B}}}\,, \tag{1}$$

where E_{S} is the scattered proton energy and E_{B} is the beam energy. The larger the ξ value, the farther away the proton is from the beam.

3. Global alignment procedure

The first step of the AFP global alignment is the Beam-Based Alignment (BBA). It is performed after each long technical stop of the LHC operation or when the settings of the magnetic lattice, known as the accelerator optics, are changed. At first, the beam is precisely trimmed by collimators. Then, each Roman Pot is slowly inserted into the beam pipe towards the beam. A Beam Loss Monitor (BLM), installed behind the AFP station, registers changes in the surrounding radiation. The moment the RP touches the beam, the rate measured by BLM suddenly increases.

The settings of the trimming collimators define the width of the beam. The centre of the beam is calculated using the width and the RP bottom edge position. The data-taking position can be easily calculated, for example, by comparing the positions of the stepper motor.

The BBA method still leaves room for improvement in alignment. One of the reasons is that it delivers the position of the RP floor, while for the measurement, one needs to know the position of the tracking detector, which is inside the RP. This is where the physics-driven *di-lepton* method [8] is employed.

The di-lepton method uses the photon-induced lepton-pair production process: $pp \to p\gamma\gamma p \to pl\bar{l}p$.

To select exclusive di-lepton signal, events showing additional tracks in the immediate surroundings of the di-lepton production vertex are excluded from the analysis. Additionally, the transverse momentum of the lepton pair (p_{T}) is required to be small, as back-to-back production is ideally associated with $p_{\mathrm{T}} = 0$.

ATLAS detector records the di-lepton event and reconstructs its invariant mass (m_{ll}) and rapidity (y_{ll}). Having the beam centre-of-mass energy ($\sqrt{s}$), one may calculate the fractional energy loss

$$\xi_{ll} = \frac{m_{ll}}{\sqrt{s}}\,\mathrm{e}^{\pm y_{ll}}\,. \tag{2}$$

The transport simulation, taking into account all the required LHC optics parameters, allows for calculating the expected proton position in the AFP: $x_{ll}(\xi_{ll})$. The sign of the rapidity depends on whether the proton is detected on the A-side or C-side of the ATLAS detector. The AFP records the spatial position of a corresponding proton x_{AFP}. The difference

$$\Delta x = x_{\mathrm{AFP}} - x_{ll}(\xi_{ll}) \tag{3}$$

quantifies the alignment correction to be applied.

The distribution of the Δx variable is presented in figure 1 (left). The horizontal axis shows the difference between the actual and expected proton positions, Δx. The vertical axis shows the number of events per bin associated with a given Δx. The signal peak is clearly visible close to $\Delta x = 0$. In addition, one can observe a long tail of the distribution, which indicates the presence of a background. The background main source is a coincidence of independent pp collisions taking place in the same events: one leading to the production of the lepton pair (for example, the Drell–Yan process), the other, to the production of the forward proton (for example, soft diffractive interaction).

The presence of the background can bias the position of the signal peak, which needs to be taken into account. The shape of the background distribution is estimated using a data-driven method called *event mixing*. This method calculates Δx using the x_{AFP} and x_{ll} from two different events. Such a way ensures a decorrelation between these two variables. The background distribution is normalized to the data in the tail and subtracted from the data. As an example, the resulting background-subtracted distribution for the A near station is presented in figure 1 (right) together with a Gaussian fit, which is used to determine the peak position.

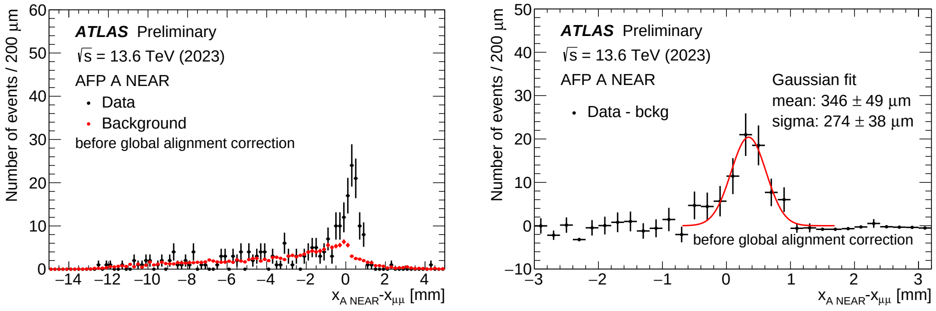

Fig. 1. The distribution of $\Delta x = x_{\mathrm{AFP}} - x_{ll}$ for the data and combinatorial background (left) and the background-subtracted data distribution with a Gaussian fit (right) [9].

4. Results

The alignment procedure is carried out separately for every AFP station using the exclusive $\gamma\gamma \to \mu^+\mu^-$ process. The peak position is determined and used to adjust the alignment parameters during event reconstruction. The procedure is repeated several times until the resulting peak position is as close to zero as possible.

After the above procedure is performed, an additional step of alignment, the so-called *fine-tuning* [8] is applied. It is based on the fact that the reconstructed proton transverse momentum is very sensitive to the relative global alignment between the near and far stations. The procedure is executed per side and involves both near and far stations. The horizontal component of the proton momentum, p_x, is reconstructed, and its distribution is calculated. Then, the near-station position is fixed, and the far station position is adjusted until the centre of the distribution is observed at $p_x = 0$. As an example, the Δx distributions before and after the alignment procedure and the fine-tuning for C far station are presented in figure 2.

The alignment procedure outlined above is initially applied using muon pairs. In the subsequent analysis step, it is validated by applying the same procedure using exclusive $\gamma\gamma \to e^+e^-$ events.

The data were divided into the all-year-period datasets to maintain consistency within the beam parameters and then processed. Results of applying the above-sketched procedure for the $\mu\mu$ and ee case are shown in figure 3 left and right, respectively. Both results are compatible, however, the $\mu\mu$-based alignment is more precise.

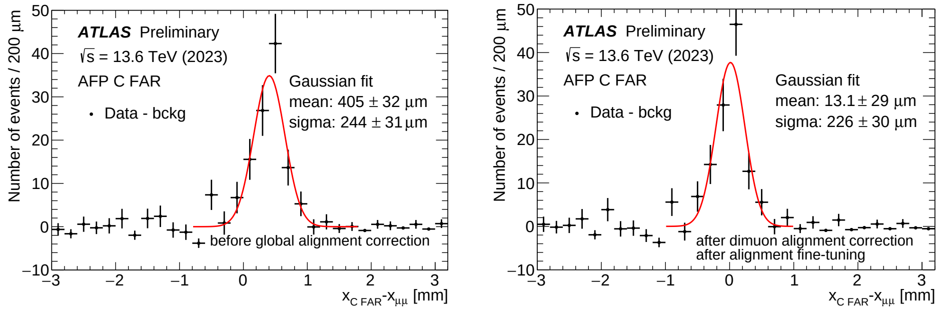

Fig. 2. The background subtracted $\Delta x = x_{\text{AFP}} - x_{ll}$ distribution with a Gaussian fit. Before (left) and after (right) the alignment correction is applied. The C far station data are presented [9].

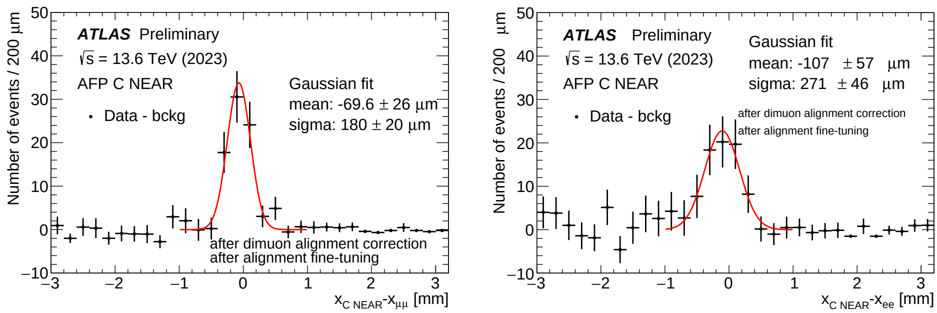

Fig. 3. The background subtracted $\Delta x = x_{\text{AFP}} - x_{ll}$ distribution obtained for the exclusive $\mu\mu$ (left) and ee event (right) samples. The C near station data are presented [9].

5. Summary

In summary, the alignment study was conducted using the 2023 ATLAS data and followed a structured approach:

— Alignment based on the $\gamma\gamma \to \mu\mu$ process;

— Fine-tuning using p_x;

— Determination of alignment correction values;

— Validation using the $\gamma\gamma \to ee$ process;

— Comparison of results.

The study confirmed that the alignment derived from the exclusive $\gamma\gamma \to \mu\mu$ process is consistent with the validation based on $\gamma\gamma \to ee$.

The correction application is essential as the Beam-Based Alignment by itself is not enough to get satisfactory AFP alignment. Precise knowledge of the AFP detector positions is crucial for physics analyses as it leads to a proper proton-energy reconstruction as well as proper identification of an event. The same alignment procedure will be repeated for the 2022 and 2024 data.

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