PROCEEDINGS OF SCIENCE

# ATLAS Inner Detector Alignment for the LHC Run3

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The algorithm used in the alignment of the Inner Detector of the ATLAS experiment at the LHC is based on the track-to-hit residual minimization in a sequence of hierarchical levels (ranging from mechanical assembly structures to individual sensors). It aims to describe the detector geometry and its changes in time as accurately as possible, such that the resolution is not degraded by an imperfect positioning of the signal hit in the track reconstruction. The ID alignment during Run2 has proven to describe the detector geometry with a precision at the level of $\mu$m [1]. The hit-to-track residual minimization procedure is not sensitive to deformations of the detectors that affect the track parameters while leaving the residuals unchanged. Those geometry deformations are called weak modes. The minimization of the remaining track parameter biases and weak mode deformations has been the main target of the alignment campaign in the reprocessing of the Run2 data. New analysis methods for the weak mode measurement have been therefore implemented, providing a robust geometry description, validated by a wide spectrum of quality-assessment techniques. These novelties are foreseen to be the new baseline methods for the Run3 data-taking, in which the higher luminosity would allow an almost real-time assessment of the alignment performance.

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## 1. Introduction

The ATLAS experiment [2] at the LHC [3] is a multipurpose particle detector with a symmetric cylindrical geometry that covers nearly the entire solid angle around the collision point. The Inner Detector (ID) [4] is a high-resolution tracking detector, that reconstructs the trajectories of charged particles passing through. It comprises three sub-detector layers: the Pixel [5], the Semiconductor Tracker (SCT) [6], and the Transition Radiation Tracker (TRT) [7] detectors exploiting different technologies for particle detection. The insertable B-layer (IBL)[8] and the surrounding three layers form the Pixel detector, the closest to the interaction point in the ATLAS experiment. The next is the SCT with 4088 strip modules encircled by the TRT with 350k straw tubes. The ID elements record signals (hits) generated from charged particles. Therefore, these hits are used to reconstruct trajectories (tracks) and estimate the particle track parameters. Therefore the precision achieved in determining the track parameters is affected by how accurately the geometry of the ID is described. The determination of the location and orientation of the detector elements is the goal of the alignment procedure.

As the ID consists of a large number of subsystems, each of them can be separately aligned. In total there are almost 750 000 degrees of freedom. The ID alignment has different hierarchical levels from global mechanical assembly structures to local sensors and address different timescales of detector movements [9]. The procedure consists of a track-based alogrithm minimizing the $\chi^2$ function of the measured track-to-hit residuals. This method is not sensitive to collective movements of the detector that bias the track parameter without changing the $\chi^2$ of the fitted tracks, the so-called *weak modes*. The reduction of the weak modes is a crucial part of the alignment.

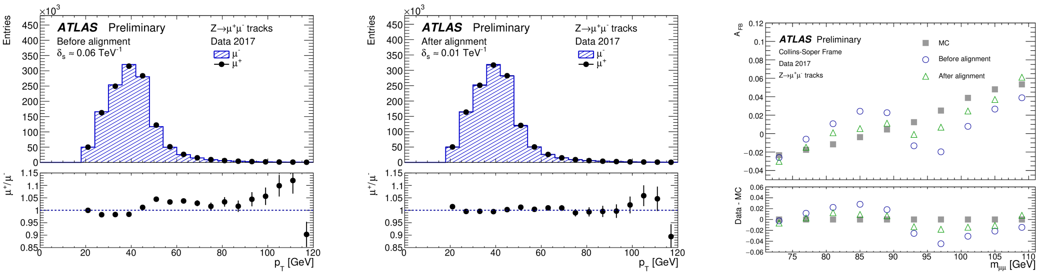
## 2. New algorithm for sagitta bias measurement

The ATLAS tracking software suite for the Run3 introduced a novel Mixture Density Network (MDN) to replace the existing Neural Network (NN) approach for the cluster position estimation int he Pixel detector. It removed an existing bias of the NN algorithm, causing a movement of the residuals. Therefore, the reprocessing of the Run 2 data with the new software required a novel alignment of the detector. One of the challanges of the alignment was the reduction of weak modes causing global sagitta bias on the track momenta, that was solved by ad-hoc methodologies (see Figure 1), as the existing methods (called *Mass* method) for bias measurements is not sensitive to it. In preparation for the Run 3, a novel method has been developed for the measurement of the sagitta bias based on $Z \rightarrow \mu^-\mu^+$ events.

A bias on sagitta $\delta_s$ converts into a bias in the track momentum as $p = p_0(1 + qp_{0T}\delta_s^{-1})$, where $p$ and $p_0$ are reconstructed and true momenta of a particle, $p_{0T}$ transverse momentum and $q$ charge. From this equation one can derive the following expression for the reconstructed mass of di-muon system in $Z \rightarrow \mu^+\mu^-$ events: [9]:

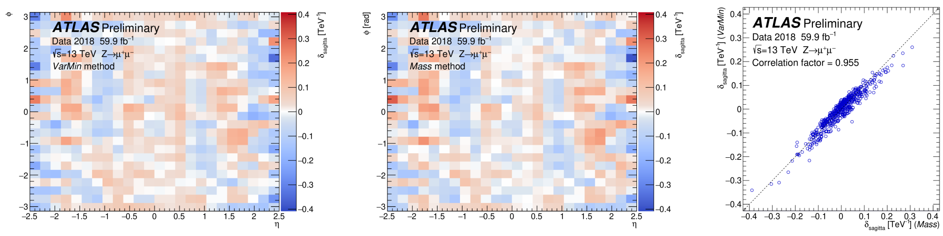
$$\frac{m_{\mu\mu}^2 - m_Z^2}{m_{\mu\mu}^2} = (p_T^-\delta^- - p_T^+\delta^+). \tag{1}$$

In case of a global bias, that is an homogeneous bias over the detector, $\delta_s^- = \delta_s^+$. In $Z \rightarrow \mu^+\mu^-$ events, the momenta of the two opposite-sign muons are the same on average at first order



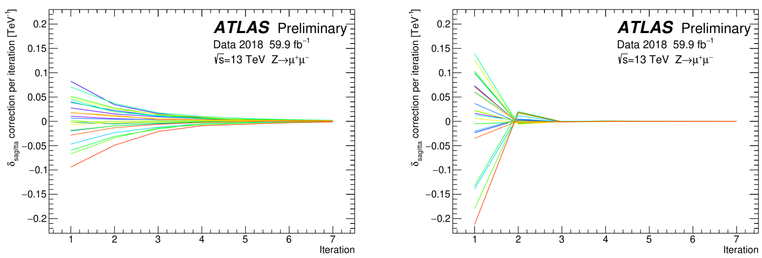

**(a)** **(b)** **(c)**

**Figure 1:** Muon $p_{\mathrm{T}}$ distributions for the $Z \to \mu^+\mu^-$ events before (a) and after (b) alignment applied. (c) Reconstructed forward-backward asymmetry in Run2: the "wiggle" produced by the presence of a global sagitta bias is reduced by the alignment procedure. Plots are from: [1].




**(a)** **(b)** **(c)**

**Figure 2:** Maps of the sagitta bias as measured by the VarMin (a) and Mass (b) methods. (c) Correlation between the two maps. Plots are from: [1].




**(a)** **(b)**

**Figure 3:** Convergence of $\delta_s$ corrections per iteration for the Mass (a) and VarMin methods (b). Plots are from: [1].

$(\langle p_{\mathrm{T}}^+\rangle = \langle p_{\mathrm{T}}^-\rangle)$. Therefore, a global bias does not move the reconstructed mass of the di-muon system from the reference in average, and methods that are based on this difference for the sagitta bias measurement (such as the Mass method) are not sensitive to it. Conversely, the width of the reconstructed di-muon mass is enlarged by the presence of a global sagitta bias. The new VarMin method measures the values of sagitta biases over the detector $\vec{\delta}$ by minimizing the reconstructed

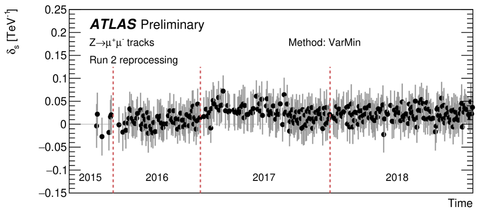



**Figure 4:** The measured sagitta bias over data-taking. Plot is from: [1].

di-muon mass:

$$0 = \frac{\partial}{\partial \delta} Var[m^2_{\mu\mu\bullet}] \quad \text{where} \quad m^2_{\mu\mu\bullet i} = m^2_{\mu\mu i} - m^2_Z - \vec{e}_i \cdot \vec{\delta}, \tag{2}$$

$\vec{\delta}$ contains sagitta corrections and $\vec{e}$ includes muon momentums and dimuon system reconstructed masses [1]. In Figure 2 measured sagitta bias for the two methods are highly compatible, that also indicates the global scale bias being almost negligible in the analysed dataset. The VarMin additionally improved the Mass method in terms of computation time: while the Mass method needs at least 6-7 iterations to converge, the VarMin method converges with 2 iterations, as shown in Figure 3.

## 3. Summary and outlook

The ATLAS Inner Detector alignment main development for the LHC Run 3 is implementation of the VarMin method. The VarMin method made the sagitta bias determination sensitive to global bias and significantly reduced the execution time. The value of the sagitta bias for Run 2 over years shown on Figure 4 is below 0.1 TeV$^{-1}$, with the mean value stands around 0.02 TeV$^{-1}$ indicating a bias lower than 0.4% on tracks of 40 GeV.

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