

Alignment of the ATLAS Inner Detector Upgraded for the LHC Run II

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Abstract. ATLAS is equipped with a tracking system built using different technologies, silicon planar sensors (pixel and micro-strip) and gaseous drift-tubes, all embedded in a 2T axial magnetic field. For the LHC Run II, the tracking system has been upgraded with the installation of a new pixel layer, the Insertable Barrel Layer (IBL). An outline of the track based alignment approach and its implementation within the ATLAS software will be presented. Special attention will be paid to integration in the alignment framework of the IBL, which plays a key role in precise reconstruction of the collider luminous region, interaction vertices and identification of long-lived heavy flavour states. In order to detect as soon as possible deformations and misalignments of the tracking system that may affect the data taking, a fast alignment chain was implemented at the Tier-0 at CERN. Latest upgrades and tests of this fast chain will be discussed, as well as the performance from the Cosmic Ray commissioning run.

1. Introduction

Between Run-I and future Run-II of the LHC a long technical stop, known as the Long Shutdown 1 (LS1), took place. During the LS1 several maintenance works were performed in the ATLAS Inner Detector (ID) [1, 2] and a new detector, the IBL [3], was installed. The Inner Detector alignment software framework has been upgraded to handle with these new features.

The cosmic ray data taking periods of 2014-2015 were the first ones after the LS1. Due to the maintenance works performed on the ID, large initial misalignments were expected for the Pixel detector. Therefore, the alignment has been a major task during these cosmic rays period. These first data have been used to test the performance of the alignment framework with the new subdetectors and to provide a reasonable positioning of the IBL, performing the first module level alignment of the IBL.

2. ATLAS Inner Detector

The ATLAS [1] Inner Detector [2] consists of three subdetectors, the Pixel detector (now including the IBL), the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT), all embedded in a 2T axial magnetic field. The ID has been designed to reconstruct the charged particles trajectories within a pseudorapidity range of $|\eta| < 2.5$ (see Figure 1 for a schematic view of the barrel region). The Pixel detector consists of 1744 silicon pixel modules arranged in three barrel layers and two end caps

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with three disks each. The expected hit resolution is $10\text{ }\mu\text{m}$ in r - ϕ coordinates and $115\text{ }\mu\text{m}$ in z coordinate. During LS1, the IBL was added as an additional layer to the Pixel detector, reducing the distance from the interaction point to the first tracking layer, as IBL is placed at 33.25 mm radius while the inner layer of the rest of the Pixel is placed at 50.5 mm . The IBL is composed of 280 modules, mixing planar and 3D technology. The expected hit resolution is $\sim 8\text{ }\mu\text{m}$ in r - ϕ and $\sim 40\text{ }\mu\text{m}$ in z [3]. In order to simplify the notation throughout the remainder of the note, the term Pixel will be used to refer only to the three outer Pixel layers and the end cap Pixel disks and IBL to the new layer. The SCT consists of 4088 silicon strip modules, arranged in four barrel layers and two end caps with nine wheels each. The intrinsic resolution is $\sim 17\text{ }\mu\text{m}$ and $\sim 580\text{ }\mu\text{m}$ in r - ϕ and z , respectively. The TRT is the outermost detector of the ID subdetectors and is made of 350848 Argon-filled straw tubes with a single hit resolution of $\sim 130\text{ }\mu\text{m}$ along r - ϕ .

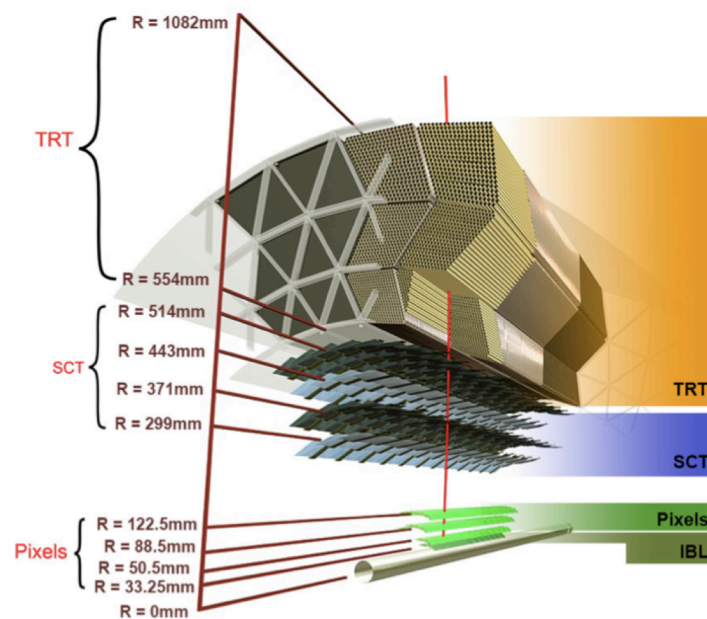


Figure 1. A 3D visualisation of the structure of the barrel of the ID. The beam pipe, the IBL, the three Pixel layers, the four cylindrical layers of the SCT and the 72 straw layers of the TRT are shown.

3. Alignment algorithm

Track based alignment algorithms rely on track-hit residual minimization [4, 5]. Residuals are defined as the distance between the measured hit location and its extrapolated position in the reconstructed track. The residuals χ^2 function and its minimization condition are built as follows:

$$\chi^2 = \sum_{Tracks} [\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})]^T \mathbf{V}^{-1} [\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})] \quad ; \quad \frac{d\chi^2}{d\mathbf{a}} = 0$$

where $\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})$ is the vector of track-to-hit-distance, $\boldsymbol{\tau}$ are the track parameters, $\mathbf{a}$ are the alignment parameters and $\mathbf{V}$ is the covariance matrix of the detector measurements. Figure 2 shows how the position of misaligned module is updated by minimizing the residuals χ^2 function.

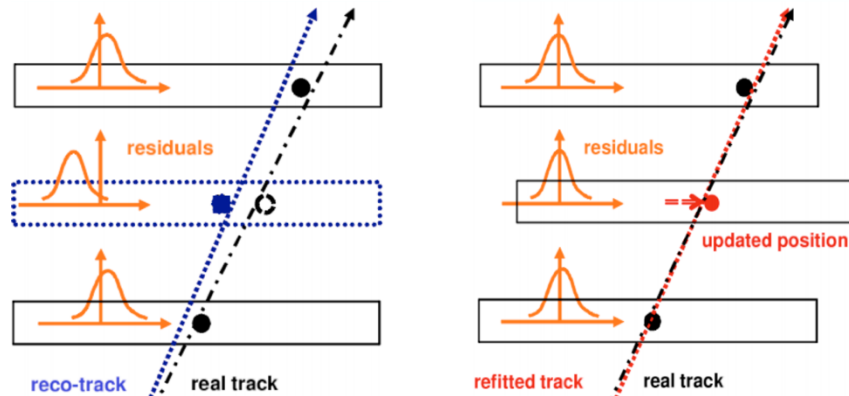


Figure 2. Alignment procedure based on residuals χ^2 function minimization. On the left, the central module position is wrongly determined, biasing its hits and the reconstructed track parameters. On the right, the misalignment is detected by minimizing the residual distributions and the position of the detector is updated.

The ATLAS inner detector is composed of a large number of active detector modules (see section 2 for details). Each module or grouped collection of modules, e.g. a subdetector, can be treated as an alignable structure. When considered as a rigid body, each structure has six degrees of freedom (DOF) that define uniquely its position and orientation in space. The DOFs correspond to three translations (T_x, T_y, T_z) and three rotations (R_x, R_y, R_z). Translations are with respect to the origin of the reference frame and rotations around the Cartesian axes. There are two types of reference frames: A global one, referred to the ATLAS interaction point, which is used for full subdetectors, and the local ones, referred to each module's local coordinates.

The alignment is performed at different hierarchical levels, following the structure of the ID. Starting with the largest physical structures at level 1, the detector subsystems are aligned separating into end-caps and barrel regions in order to correct for collective movements. Level 2 treats individual barrel layers and end-cap disks as physical structures (barrel modules and end-cap wheels in case of the TRT). Level 3 corresponds to a silicon module and TRT wire level alignment. The levels are addressed consecutively during the alignment procedure. Table 1 shows the number of DOFs for each detector and level of alignment.

Table 1. Number of DOFs by detector and level of alignment

Levels	IBL	Pixel	SCT	TRT
L1 (structure)	6	6	18	17
L2 (layer/disk)	6	54	132	960
L3 (module)	1680	10464	25528	701696

In preparation for Run II, the alignment levels have been updated in order to accommodate the IBL. At level 1, the IBL is treated as one separate physical structure as it is mechanically attached to the beam pipe and not to the previously installed Pixel detector. Consequently, it is not expected that correlations appear between the IBL movements and the collective movements of the remaining Pixel detector.

4. Alignment procedure

The alignment procedure consists of three steps. The first one is the *accumulation*, which does the reconstruction of the tracks and the calculation of the residuals. At the beginning of the accumulation step a geometry for the detector is loaded, where the position of every ID module is specified. This

step can be divided into multiple processing jobs that are processed in parallel in a batch system. Each of these jobs produces a linear system of equations and a monitoring file containing a set of plots to monitor the alignment performance. The following step is known as the *solving*. In it, all the linear system of equations produced in the accumulation step are merged and solved in common. The solving step cannot be divided into multiple jobs. This produces a set of alignment corrections to the loaded geometry and a new updated geometry. The final step is the *merging* of the individual monitoring files produced during the accumulation into a total monitoring file that allows the testing of the performance of the alignment. Figure 3 shows a diagram summarizing the different steps of the alignment procedure.

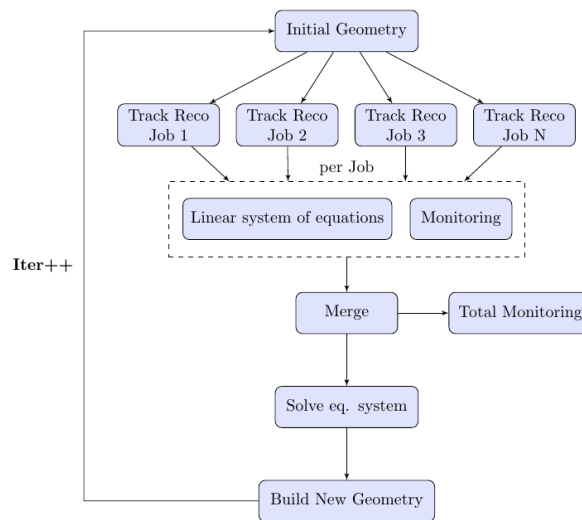


Figure 3. Diagram of the alignment procedure.

To ensure the convergence of the alignment corrections, the alignment procedure is performed iteratively. At the end of each iteration, the updated geometry obtained is used as initial geometry for the next iteration. Also, as explained in section 3, there are different levels of alignment, which are run consecutively, starting at level 1 and ending at level 3.

5. Alignment in the calibration loop

Data collected by the ATLAS experiment are promptly processed at the CERN's Tier-0 [6] to provide fast access to high quality data for physics analysis. The high quality of the data is achieved by a so-called "calibration loop" that relies on the detector calibrations becoming available within 48 hours based on a selected subset of the data, the "Express stream", designed to allow detailed data investigations.

Inner detector alignment was one of the tasks included in the calibration loop during the Run-I. It made use of a specific 50 Hz stream of high transverse momentum (p_T) tracks selected by the High Level Trigger (HLT) called `calibration_IDTracks`. The implementation of the alignment in the calibration loop allows the detection of "on the fly" movements or deformations of the different subdetectors so that these can be corrected as soon as possible. In any case, the detector geometry is not corrected online. It would only be updated after the end of the run if large misalignments were found. The calibration loop alignment procedure has been updated to include the latest changes introduced in the alignment procedure and has been extended to perform a more detailed alignment (up to level 2). It has been successfully tested during the 2015 ATLAS cosmic campaigns.

A web site was developed, which is used in parallel to the standard calibration loop processing to monitor the results of the alignment. Figure 4 shows the T_x corrections for the Run-I data taken in 2012.

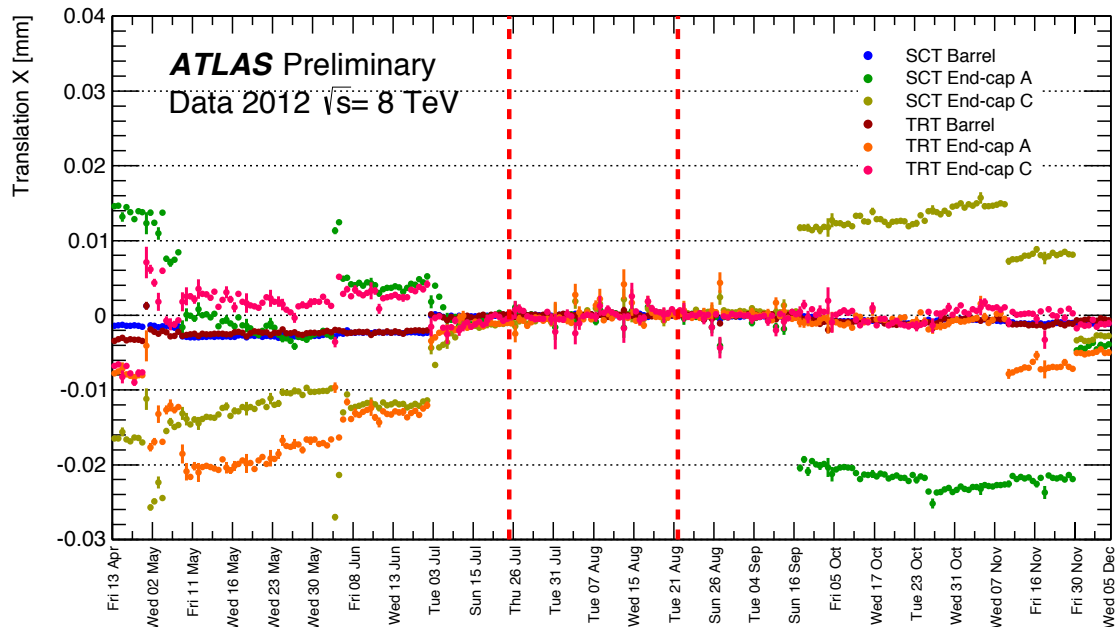


Figure 4. The corrections to the global X position (T_x) of all ID sub-detectors with respect to the Pixel detector during 2012. The vertical dashed lines separate the data-taking periods in which the baseline constants were determined. Errors shown correspond to statistical uncertainties on a determined alignment parameter and crucially depend on the statistics of data recorded in a given run.

6. Cosmic ray data campaign

Data recorded by ATLAS during the 2014 and 2015 cosmic-ray campaigns were used to perform a first alignment of the detector after the LS1 and to test the performance of the new IBL detector. Results shown here were obtained using 1.1 M events recorded during February 2015. These data include $\sim 3 \times 10^5$ ID tracks, which are used for alignment. The data were taken in a configuration with the toroid field off and solenoid field on. After the track selection requirements, ~ 50000 tracks were used in alignment. More details about the track selection and the obtained results can be found elsewhere [7].

During LS1, the Pixel detector was removed from ATLAS for the performance of maintenance and put back in place with a precision from the survey of $\sim 100 \mu\text{m}$. The IBL was installed during LS1 for the first time, so there was no previous experience from Run-I. The SCT and TRT barrels were not moved during LS1, so it was expected that they would be in the same position as at the end of Run-I. Because of that, the alignment was focused in the Pixel and the IBL. They were both aligned up to module level alignment (level 3). The SCT barrel was aligned up to level 2 and the TRT was fixed as a reference point.

Figures 5 and 6 show the improvement achieved by the alignment on local x' (left) and local y' (right) residual distributions for the IBL and Pixel, respectively. Alignment corrections may be referred either to the global or local reference frames but the residuals are always computed in the local reference frame. A misalignment of 40 (28) μm in the local x' (y') direction of the IBL is corrected, with the

FWHM/2.35 being reduced from 197 (153) μm to 32 (97) μm , respectively. Similarly, a bias of 30 (-1) μm in the Pixel barrel local x' and local y' direction has been corrected. The width of the distribution has been reduced from 68 (167) μm to 28 (156) μm in x' and y' , respectively [6].

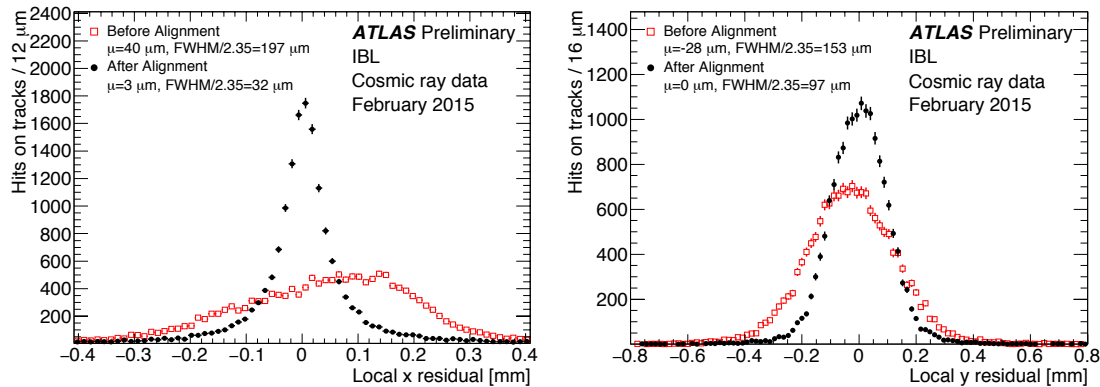


Figure 5. The IBL local x' (left) and local y' (right) residual distribution for the cosmic-ray data sample reconstructed before (red) and after (black) alignment. The distributions are integrated over all hits associated to tracks (hits-on-tracks) in IBL modules. The parameter μ represents the mean of the distributions.

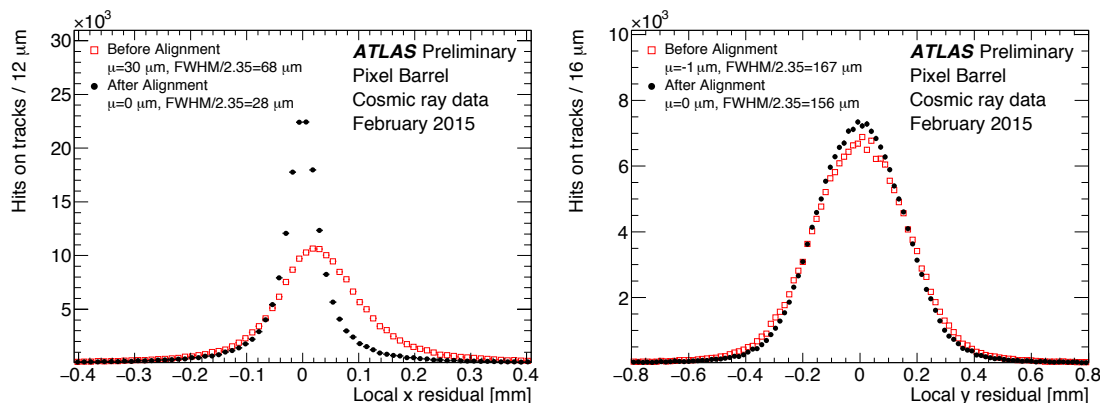


Figure 6. The Pixel local x' (left) and local y' (right) residual distribution for the cosmic-ray data sample reconstructed before (red) and after (black) alignment. The distributions are integrated over all hits associated to tracks (hits-on-tracks) in the barrel modules of Pixel layers one, two and three. The parameter μ represents the mean of the distributions.

Figure 7 shows the mean of the local x' (left) and local y' (right) residual distributions as a function of the module location along the stave (η -index). This distribution is integrated over all 14 IBL staves. The distribution of the local x' residuals mean indicates an in-plane deformation of the IBL staves in the negative local x' direction with respect to the nominal geometry. The distribution in local y' indicates a systematic displacement of the modules along the global z -axis of the IBL staves. All IBL staves were loaded with the modules from the stave-center outwards. Then, such a stave elongation with respect to the nominal geometry may be due to a wider intermediary gap between neighbouring modules with respect to the nominal geometry. A module level alignment (level 3) corrects for both observed stave deformations.

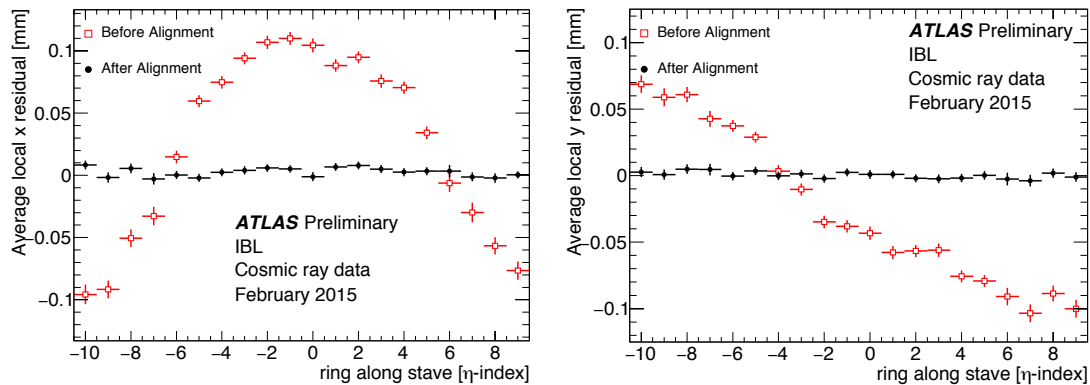


Figure 7. The IBL mean of the local x (left) and local y (right) residual distributions as a function of the η position of the module.

The half-track method has been used to test the goodness of the alignment. Cosmic tracks, which traverse the whole detector, are divided into upper and lower parts, and each part is reconstructed independently. The technique is illustrated in Figure 8.

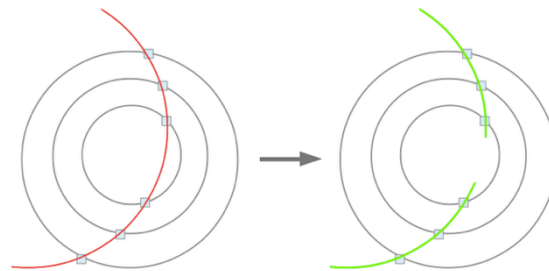


Figure 8. Diagram illustrating the half-track parameter study. In red is shown a full track reconstructed in the inner detector, while in green are shown the two half-tracks reconstructed in the top and bottom parts.

The expected resolution of the perigee track parameters (τ) can be calculated with this method. Since both tracks come from the same particle, their difference for each perigee parameter τ has a variance $\sigma^2(\Delta\tau)$, which is two times the variance of the parameters of each track. The resolution of the track parameter is therefore given by the root mean square of the $\Delta\tau$ distribution divided by $\sqrt{2}$. Biases of $-19 \mu\text{m}$ in Δd_0 and of -9.4 TeV^{-1} in $\Delta(q/p_T)$ have been corrected, with the traverse impact parameter resolution being reduced from 69 to 39 μm and 3.5 to 1.4 TeV^{-1} , respectively. Similarly, the longitudinal impact parameter resolution was reduced from 160 to 134 μm . As muon tracks from cosmic-ray events traverse the detector from top to bottom, the resolutions can only be derived for the barrel detectors. The perigee parameters, τ_{up} and τ_{down} , of each split-track pair are compared to each other and their difference $\Delta(\text{up-down})$ is compared before and after alignment. Examples of the track curvature (q/p_T) and the transverse impact parameter (d_0) distributions are shown in Figure 9.

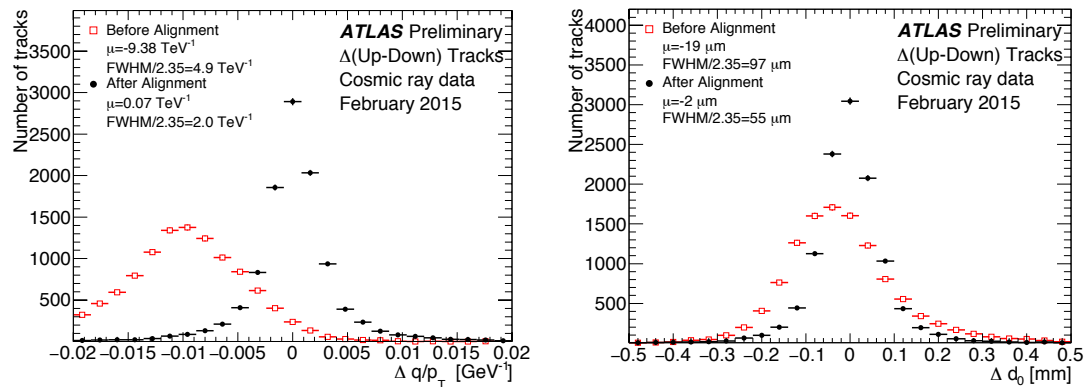


Figure 9. Distribution of the difference of the reconstructed track charge over transverse momentum $\Delta q/p_T$ (left) and of the difference of the reconstructed transverse impact parameter Δd_0 (right) using tracks reconstructed in the top part of the inner detector with respect to track reconstructed in the bottom part.

7. Conclusions

The ID alignment framework has been successfully upgraded to cope with LHC Run-II requirements. The IBL has been added and can be aligned independently from the rest of the Pixel. Alignment in the calibration loop has been adapted to the new requirements from the ID and Tier-0 and successfully recommissioned. A first alignment of the ID after the LS1 has been performed using data recorded during the cosmic ray campaign, in which IBL and Pixel detectors have been aligned up to module level. The IBL global position has been determined at the micron level with an averaged module resolution of 32 μm (local x') and the residual distribution width was reduced by a factor of 5. The resolution of track parameters was measured by comparing two segments of a cosmic-ray track. After detector alignment, the impact parameter resolutions for tracks were found to be 39 μm and 134 μm in the transverse and longitudinal directions, respectively. A large bias in the reconstructed track charge over transverse momentum (q/p_T) has been corrected to 0.07 TeV^{-1} .

8. References

- [1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003.
- [2] ATLAS Collaboration, *ATLAS inner detector: Technical Design Report, 1*, Technical Design Report ATLAS CERN-LHCC-1997-016, Geneva: CERN, 1997.
- [3] M Capeans et al., *ATLAS Insertable B-Layer Technical Design Report*, CERN-LHCC-2010-013. ATLAS-TDR-19 (2010).
- [4] ATLAS Collaboration, *Alignment of the ATLAS Inner Detector and its Performance in 2012*, ATLAS-CONF-2014-047 (2014).
- [5] ATLAS Collaboration, *Common Framework Implementation for the Track-Based Alignment of the ATLAS Detector*, ATL-SOFT-PUB-2014-003 (2014).
- [6] Elsing M., Goossens L., Nairz A. and Negri G.. *The ATLAS Tier-0: Overview and operational experience*, J. Phys.: Conf. Ser. 219 072011.
- [7] ATLAS Collaboration, *ATLAS Inner Detector Alignment Performance with February 2015 Cosmic Ray Data*, ATL-PHYS-PUB-2015-009 (2015).