Alignment results of LHC tracking detectors

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Abstract

We present the first results of the alignment of the vertex detectors of the LHC experiments based on the reconstructed tracks from the cosmic data taken during the commissioning runs with the detectors in their final positions. The unprecedented complexity of these detectors poses new challenges in aligning system with several thousands of silicon modules built in different technologies: strip, pixel, and silicon drift chambers. For optimal track-parameter resolution, the position and orientation of the modules need to be determined with a precision of few micrometers. The achieved resolution in all five track parameters is controlled with data-driven validation of the track parameter measurements near the interaction region, and tested against prediction with detailed detector simulation. Outlook for expected tracking performance with the first collisions is given.

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We present the first results of the alignment of the vertex detectors of the LHC experiments based on the reconstructed tracks from the cosmic data taken during the commissioning runs with the detectors in their final positions. The unprecedented complexity of these detectors poses new challenges in aligning systems with several thousands of silicon modules built in different technologies: strip, pixel, and silicon drift chambers. For optimal track-parameter resolution, the position and orientation of the modules need to be determined with a precision of few micrometers. The achieved resolution in all five track parameters is controlled with data-driven validation of the track-parameter measurements near the interaction region, and tested against prediction with detailed detector simulation. Outlook for expected tracking performance with the first collisions is given.
1. Introduction

All the four experiments at the Large Hadron Collider (LHC) feature complex tracking systems based on several thousands mechanically independent sensitive elements (modules), assembled in larger structures (sub-detectors). Modules are built in different detection technologies, and provide either one-dimensional measurements, as in the case of single-sided microstrips, or two-dimensional measurements, as for pixels, double-sided microstrips, double-sided modules composed of single-sided microstrip sensors precisely mounted back-to-back, and silicon drift detectors. All these devices have intrinsic precisions typically of few tens of micrometers.

Alignment is required to reconstruct properly the trajectory of charged particles as the sensitive elements usually are in a position different from design. In the case of the LHC experiments, the goal of the alignment is to keep the relative contribution of the misalignment to the uncertainty on the track parameters below 20%. To this aim, the position of the sensitive elements has to be known with an uncertainty of few micrometers and their orientations with few microradians \(^1\).

Alignment of the tracking systems is achieved by two means: using the informations collected during the construction (surveys) and determining in-situ of the position \(p_m\) of the modules with tracks, as misalignment affect the track-to-hit residuals \(r_i\). The determination of the exact position of the modules is then achieved by minimizing an objective function:

\[
\chi^2(p_m, q_{trks}) = \sum_{\text{residuals}} r_i^T V_i r_i,
\]

built using the residuals \(r_i\) and the covariance matrix \(V_i\) of the measurements. The optimization problem is solved assuming that the objective function can be linearized in terms of the alignment corrections \(\delta p_m = p_m - p_{m0}\), with \(p_{m0}\) being reasonable starting values for the positions of the modules. Finally the system of linear equations to be solved becomes:

\[
\delta p_m = -\left(\frac{d^2 \chi^2}{dp_m^2}\bigg|_{p_{m0}}\right)^{-1}\frac{d \chi^2(p_m)}{dp_m}.
\]

In case of \(N\) modules with six degrees of freedom each to be determined, \(\frac{d^2 \chi^2}{dp_m^2}\bigg|_{p_{m0}}\) is a \(6N \times 6N\) matrix that has to be inverted. The two most common approaches for solving the problem are:

- the global method \([\text{1}]\), where the \(6N \times 6N\) matrix is inverted thus accounting for the correlations between the modules. This is usually feasible adopting an approximation of the actual track model, typically a Kalman filter, used in the reconstruction.

- the local method, where \(N\) matrices \(6 \times 6\), are separately inverted thus neglecting the correlations between different modules. In this method the same track model of the reconstruction is used, but correlations between distant modules are achieved only through several iterations.

\(^1\)In the LHC experiments, track parameters are usually expressed in right-handed coordinate systems, global coordinates, with the origin at the nominal collision point and with the \(z\)-axis directed along the beamline. The azimuthal angle (\(\phi\)) is measured from the positive \(x\)-axis in the \(x-y\) plane, whereas the radius (\(r\)) denotes the distance from the \(z\)-axis. Local coordinate systems, defined for each module, are used instead for the reconstruction of the position of the hits. The precisely measured coordinate is usually defined as \(x_{local}\).
Alignment procedures were extensively tested by the four experiments using the data collected in the commissioning runs of 2008 [3], mainly cosmic ray tracks, and were validated on the data themselves at two different levels:

- at low level, checking the effective improvement of the post-alignment unbiased residuals, that is residuals where the hit under inspection was excluded from the track fit;
- at high level, both comparing segments of split cosmic ray tracks (see below) and with the analysis of the residuals in overlapping regions of the detector.

The comparison of track segments exploits the cosmic ray tracks being long tracks crossing the entire volume of the detector. These tracks are split into two halves, usually at the point of closest approach to the nominal beamline. Each leg is refitted separately, and finally the five track parameters of each leg, computed at the common perigee, are compared. To better reproduce the topology of the tracks expected in collisions, tracks are usually required to cross the volume of the pixel detector. The analysis of the overlaps instead benefits of the small errors due to track extrapolation and to the presence of a small amount of material between the two measurements, thus being sensitive only to the misalignment between adjacent modules.

2. Alignment of ALICE, ATLAS and CMS

We start from the description of the analyses performed in ALICE, ATLAS and CMS which have similar configurations of their tracking detectors, and for which the data taken during the commissioning were cosmic ray tracks.

Data were collected both with the solenoids off and on. Because of their geometrical acceptance, pixels were the sub-detectors where the alignment was mostly affected by the limited statistics as they were traversed only by few percents of the total number of tracks. The total number of tracks in the pixels collected in 2008 was between 100 000 and 200 000 per experiment.

2.1 ALICE

The Inner Tracking System (ITS) of ALICE is composed of three different sub-detectors: two inner layers of pixels (240 modules), two intermediate layers of silicon drift detectors (260 modules), and two outer layers of silicon double-sided microstrip sensors (1698 modules). Alignment of ITS was performed in three steps on the data collected with no magnetic field and using a global method [3]. First, an internal alignment of the pixels was done followed by the alignment of the pixels with respect to strips, assuming for the positions of the strip modules those measured in the survey. Finally the silicon drift detectors, which require in addition the calibration of the drift velocity and of the $t_0$, were aligned with respect pixels and strips. After the internal alignment of the pixels, the standard deviation of a Gaussian fit to the core of the distribution of track-to-hit residuals was $\sigma(r\phi)=26 \, \mu m$, to be compared to $\sigma(r\phi)=17 \, \mu m$ expected for a perfectly aligned detector.

In ALICE, the comparison of track segments was done with tracks made of four hits, all collected either in the pixels or in the strips. Track parameters were compared at the midplane $y=0$. Two different kinds of splitting were investigated: top versus bottom layers or inner versus
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Entries: 17214
Constant: 13.5 ± 1195.7
Mean: 0.5 ± -0.7
Sigma: 0.5 ± 48.8

Figure 1: Definition of the mismatch $\Delta d_{xy}$ of the transverse impact parameters between the top and bottom segments of the cosmic ray track evaluated at the midplane $y=0$ (left) and its distribution measured by the pixels of the ALICE ITS (right).

outer layers. In both cases the resolution on the mismatch of the track parameters could be related through the geometry to the resolution on the local coordinate $x_{\text{local}}$ (Figure 1):

$$\sigma^2(\Delta d_{xy}) = 2 \frac{r_{\text{out}}^2 + r_{\text{in}}^2}{(r_{\text{out}} - r_{\text{in}})^2} \sigma^2(x_{\text{local}}),$$

in case of top-bottom layers splitting and

$$\sigma^2(\Delta \phi) = \frac{1}{2} \left( \frac{1}{r_{\text{out}}} + \frac{1}{r_{\text{in}}} \right) \sigma^2(x_{\text{local}}),$$

in case of inner-outer layers splitting. The standard deviation of a Gaussian fit to the core of the distribution of the mismatch of the transverse impact parameters $\Delta d_{xy}$ gave a resolution $\sigma(x_{\text{local}})=14 \ \mu m$, to be compared to $\sigma(x_{\text{local}})=11 \ \mu m$ expected for a perfectly aligned detector.

This value was confirmed by the analysis of overlaps, based on the track-to-hit residuals computed for a second hit in a layer (“extra-cluster”) which was not used neither in the reconstruction of the track nor in the alignment. The standard deviation of a Gaussian fit gave a resolution in the measurement coordinate $\sigma(x_{\text{local}})=14 \ \mu m$ in the pixels and $\sigma(x_{\text{local}})=19 \ \mu m$ in the strips, indicating a remaining misalignment less than 5 \ \mu m. Remarkably, the result for the strips was obtained using only the position of the modules as measured in the survey.

2.2 ATLAS

The ATLAS Inner Detector (ID) is composed by a Pixel detector, with three layers in the barrel and three disks in each of the two endcaps, and a strip detector (SCT), made of four layers of double-sided modules in the barrel, and nine disks in each of the two endcaps. In total there are 1788 pixel and 4088 strip modules. The system is surrounded by layers of straw tubes forming the Transition Radiation Tracker (TRT) which will not be discussed further.
The alignment of the ID was performed in three steps, from larger structures down to the module level in the barrel. Survey data were used as starting point. Alignments with the local and with the global method were both performed, with the best results being obtained by the latter [4]. Performance of the low level validation were evaluated from the distributions of the track-to-hit residuals fitted by a sum of two Gaussians (Figure 2). The standard deviations of the innermost Gaussian were $\sigma_x = 24 \, \mu m$ for the Pixel and $\sigma_x = 30 \, \mu m$ for the SCT, indicating a remaining module-to-module random misalignment of about $20 \, \mu m$.

Also in ATLAS the comparison of track segments was performed at midplane $y=0$. Only tracks with transverse momentum $p_T > 2$ GeV/$c$ and with at least three pixel hits in the Pixels, with one at least in the barrel pixels, were used. Since tails were low, the mismatch of the longitudinal $d_{xy}$ and transverse $d_z$ components of the impact parameter could be fitted by a single Gaussian with standard deviations $\sigma(\Delta d_{xy}) = 49 \, \mu m$ and $\sigma(\Delta d_z) = 166 \, \mu m$, respectively.

2.3 CMS

The CMS inner tracking system (Tracker) consists of a silicon pixel detector surrounded by a complex of silicon strip detectors. Pixels system is composed of three layers in the barrel (BPIX) and two endcaps (FPIX) with two disks each. The strip system in turn is made of four sub-detectors: the Tracker Inner and Outer Barrel (TIB and TOB), with four and six layers respectively, the Tracker Inner Disks (TID) and the Tracker Endcaps (TEC) made of three and nine disks respectively. In total there are 1440 pixel and 15148 strip modules.

Both a local and a global method were used for the alignment of the Tracker, but the best performance were obtained with a combined method where the local method was run on the geometry obtained using the global method [5]. Because of the large number of degrees of freedom to be determined, about 100 000, the success of the optimization procedure was evaluated looking at the median of the distribution of the post-alignment track-to-hit residuals module-by-module. Distributions of the median of the residuals in BPIX and TOB are shown in Figure 3. Here the figure of merit is the RMS of the distributions, as stochastic effects, like multiple Coulomb scattering or
the intrinsic resolution on the hit, which dominates the width of the distribution of post-alignment residuals, cancel out.

In CMS the comparison of the track segments was done splitting the tracks at the point of closest approach to the nominal beamline, and then selecting only tracks with transverse momentum $p_T > 4 \text{ GeV}/c$ and with at least three pixel hits in each of the legs. The RMS of differences between upper and lower track segment parameters measured at the common perigee and scaled by $1/\sqrt{2}$, were found to be $0.000864 \text{ c/GeV}$ ($0.000836 \text{ c/GeV}$) for the curvature $1/p_T$, $29 \mu\text{m}$ ($29 \mu\text{m}$) for the transverse impact parameter $d_{xy}$, and $44 \mu\text{m}$ ($41 \mu\text{m}$) for the longitudinal impact parameter $d_z$, where the values in parentheses are those expected from a simulation with ideal detector geometry.

Finally a validation of the alignment was made looking at the double difference between the predicted and the measured positions of the two hits in the overlap. Non zero means of the Gaussian fits to these distributions are an indication of a relative shift between adjacent modules not corrected by the alignment procedure. The RMS of the distributions of the shifts for $x_{\text{local}}$ scaled by $1/\sqrt{2}$ are in the range 5-7 $\mu\text{m}$, slightly larger than the values found for the distribution of the median of

Figure 3: Distribution of the unbiased track-to-hit residuals in CMS, shown for BPIX (top left) and TOB (top right), and compared with the distribution of the median of the residuals ($\mu_{1/2}$) in the same sub-detectors, BPIX (bottom left) and TOB (bottom right). The $u'$ coordinate corresponds to $x_{\text{local}}$ but with a direction defined to be always positive in $\phi$. In the distributions of the medians only modules with more than 30 hits are shown. Despite the difference in the spread of the distributions of the residuals of BPIX and TOB even after the alignment, the RMS of the post-alignment distributions of $\mu_{1/2}$ are similar thus indicating similar performance of the alignment reached in the two sub-detectors.
the residuals, possibly indicating yet unquantified systematics effects, like the aplanar distortion of modules.

3. Alignment of LHCb VELO

The LHCb VErtex LOcator (VELO) consists of 2 halves with 21 modules each. Because the modules are small and placed vertically, cosmic ray tracks are scarcely useful for alignment. Alignment of VELO in 2008 was instead performed using about 2 000 tracks produced on a beam-dump (TED) located about 350 m down-stream from LHCb. As particles from TED cross LHCb in the opposite direction with respect those expected in collisions, a standalone reconstruction of tracks using only the hits recorded in VELO was used.

The alignment of VELO was performed at the module level, using two different implementations of the global method [6], with one of the two properly including in the track model the Kalman filter used in the reconstruction of the tracks [7]. For each module two translations, \( x \) and \( y \), in the plane of the module and one rotation \( \phi_z \) around the beamline were determined. As tracks were reconstructed using only hits recorded in the VELO, use of data from survey was needed to remove a global shearing \( \Delta x = c_1 z \).

Good agreement was found both between the constants determined by the two methods, better than 5 \( \mu \)m, and between the constants obtained by the track-based methods and those from survey, better than 10 \( \mu \)m. The reproducibility of the alignment constants extracted in two different sets of data is shown in Figure 4.

4. Readiness for collisions of ATLAS and CMS

The physics performance expected at the LHC startup, after the alignment of the ATLAS and CMS tracking detectors done with the cosmic rays data, is best represented by the resolution on
the track parameters derived by the comparison of the track segments and shown in Figure 5. In particular the resolutions both on the momentum and on the impact parameter show the expected behavior as a function of $p_T$, showing the onset of the contribution of multiple Coulomb scattering at low $p_T$ values. Both for ATLAS and CMS the performance approach those expected on a sample of cosmic ray events reconstructed with a perfectly aligned detector.

Anyway ATLAS and CMS have investigated possible “weak modes”, that is systematics distortions which leave the track-to-hit residuals unchanged but introduce systematic biases in the track reconstruction. Weak modes typically arise when a sample of tracks of only one topology is used in the alignment.

Following the approach of Ref. [8], CMS applied nine systematic distortions, in $\Delta r$, $\Delta \phi$ and $\Delta z$ as a function of $r$, $\phi$ and $z$, to the aligned geometry obtained with cosmic ray data. The systematically misaligned geometries were then used as starting point for repeating the alignment. Finally the nine geometries obtained after the new alignments were compared to the original aligned geometry to see if the distortions could be recovered by the alignment procedure. It was found that usually the $\Delta \phi$ deformations, like the layer rotation $\Delta \phi = c_0 + c_1 r$, are reflected in a degradation of the track $\chi^2$ and then can be recovered using cosmic ray tracks. The $\Delta z$ distortions instead, like the $z$-expansion $\Delta z = c_1 z$, change only marginally the track $\chi^2$ thus not being recovered.

The effect of a layer rotation not yet corrected at the LHC startup was investigated in AT-
LAS [9]. Since a layer rotation gives opposite biases to the reconstructed $p_T$ of positively and negatively charged particles, a remaining distortion degrades the resolution on the mass of $Z \rightarrow \mu^+\mu^-$ to 2.67 GeV at the startup (32% deterioration), being reduced to 2.42 GeV after one million collected high $p_T$ muon tracks (20% deterioration). This value is close to the 2.29 GeV resolution expected from the remaining random module-to-module misalignment after 100 days of collisions data taking (14% deterioration), indicating that systematic errors will become soon the dominant source of uncertainty.

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