CMS Tracker Alignment: First results from Run 3

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Abstract. The CMS Inner Tracker performs excellent measurements of the charged particles tracks needed for an accurate vertex reconstruction and efficient jet tagging. The rotational and linear shifts of the individual substructures of the tracker detectors are caused by the change in the operating conditions during data taking, such as variations in temperature and magnetic field. Frequent updates in the detector geometry are necessary to describe accurately the position, orientation, and curvature of the tracker modules. The procedure in which alignment corrections to the tracker geometry are derived is referred to as the tracker alignment. The latter is performed regularly during data taking using reconstructed tracks from both collisions and cosmic rays data. In parallel, a streamlined automated alignment calibration is performed which monitors continuously the movements of the pixel substructures. In this work, we present the performance of the alignment calibration of the CMS Tracker during data-taking and for the reprocessing of the 2022 data taken until the technical shutdown, corresponding to a total integrated luminosity of 11 fb^{-1}. The granularity of the automated alignment of the pixel mechanical structures has been increased in 2022. The resulting performance of tracking and vertexing with the updated set of alignment constants are carefully validated.

1. Introduction

The CMS Tracker [1] is responsible for measuring the trajectory of charged particles, also known as "tracks", and it consists of two sub-detectors - the silicon pixel and strip detectors. The pixel detector, which is closest in proximity to the interaction point, is composed of a barrel region (BPIX) and two forward endcaps (FPIX). In the "Phase-0" configuration [1], which was in operation until the end of the 2016 data-taking period, the BPIX had three layers and each FPIX endcap had two disks, for a total of 1440 modules. The "Phase-1" pixel detector [2], which has been in operation since 2017, has an additional layer in the BPIX and one additional disk in each FPIX endcap, resulting in 1856 modules. The strip detector, which surrounds the pixel detector, consists of 15 148 modules and is composed of four subsystems: the Tracker Inner Barrel and Disks (TIB and TID), the Tracker Outer Barrel (TOB), and the Tracker Endcaps (TEC).

Maximizing the tracking performance is a crucial aspect for several physics analyses, such as electroweak precision and b-physics measurements. The computation of track momentum relies on an accurate determination of the track curvature induced by the magnetic field, which requires a well-calibrated and well-aligned detector. To ensure the CMS Tracker provides excellent tracking performance, it is crucial to know the positions and orientations of the tracker modules with high precision. The tolerance of the mechanical alignment during installation is of the order of 0.1 mm, which exceeds the design precision of the local hit reconstruction of the tracker modules of O(10 µm). To achieve a precision well below the spatial resolution of the silicon sensors, track-based alignment procedures are used.

2. Track-based alignment

The CMS Collaboration uses a track-based alignment method to align the tracker [3], assigning a position to each recorded hit in the detector and forming a set of tracks using a combination of these hits. Each track has its own set of track parameters, including those related to the track's curvature and deflection angles due to multiple scattering, as well as the alignment parameters. The alignment process minimizes the sum of squares of the normalized track-hit residuals from a set of tracks, refitting the tracks with the new geometry defined by the new set of alignment parameters and updating the track momentum measurement. The method for minimizing the residuals can follow a global approach as in the MillePede-II algorithm [4], which performs a simultaneous fit of the entire set of track and alignment parameters whilst taking their correlations into consideration. The HipPy algorithm [5] provides complementary method with a local approach, in which the position and orientation of each sensor are determined independently of the others. The main difference with respect to the MillePede-II algorithm is the iterative procedure needed to solve correlations between the sensor parameters, resulting a more intense CPU usage for track-fitting. For practical purposes, the results presented are hence derived with the MillePede-II algorithm. The set of alignment constants derived in the fit is subsequently validated with data-driven methods that monitor the tracking and vertexing performance.

3. Strategy for Tracker alignment with Run 3 data

The precision of the alignment that can be achieved depends on the amount and type of recorded tracks in the CMS Tracker. At the start of each data-taking period, the high-level mechanical structures are aligned using available cosmic ray data, providing an initial non-refined determination of the alignment constants. An automated alignment continuously monitors the high-level structure movements of the pixel detector and corrects the geometry in an iterative procedure if the alignment corrections exceed certain thresholds. A track-based alignment is also periodically run offline using a set of tracks with complementary topologies to connect different detector components. Such manual alignment updates are needed to align both the pixel and strip detectors at the level of the individual tracker modules. Potential biases in the detector geometry that leave the χ^2 of the track-hit residuals invariant, also known as *weak modes* are also investigated. The aim of the automated alignment in the Prompt Calibration Loop (PCL) is to account for translations and rotational shifts of the subpartitions of the pixel detector during data taking. During Run 3, one of the main developments in the automatization of the calibration workflow has been the increased granularity of the PCL alignment to the level of smaller support structures, i.e. ladders and panels in the barrel and forward pixel regions, respectively.

4. Alignment Performance in 2022

During the LHC Long Shutdown 2 (2018-2021) the CMS Barrel Pixel detector was disassembled and its innermost layer was fully replaced. Following the refurbishment of the pixel detector, several iterations of the track-based alignment were performed with 2021 data to correct for the shifts observed in the pixel detector subpartitions [7]. The last iteration was used as an initial geometry from which an early alignment was derived and used during the data-taking in 2022 until the technical stop. The latter was obtained using $\approx$ 300K cosmic ray tracks recorded at 3.8T magnetic field and 6.7M collision tracks recorded during pp collision runs at 900 GeV. A customised track selection with looser transverse momentum thresholds has been used to have a sufficient amount of collision tracks at this intermediate center-of-mass energy.

The pixel detector was hence aligned at the level of single modules, while the strip detector structures have been kept fixed. The alignment geometry for reprocessing has been derived using 120M collision tracks recorded st $\sqrt{s} = 13.6$ TeV and 8.5M cosmic ray tracks at 3.8T magnetic field for the first portion of the 2022 data, corresponding to an integrated luminosity of 9fb^{-1}. Alignment corrections were obtained at the level of single modules for both the pixel and the strip detector. The alignment constants for the last period of data-taking prior to the technical shutdown corresponding to a recorded integrated luminosity of 2fb^{-1} are provided by the automated alignment with the High Granularity Prompt Calibration Loop. In the following section, both the early alignment geometry and the one used for the reprocessing of the data have been validated with a random subsample of tracks produced in proton-proton collisions at $\sqrt{s} = 13.6$ TeV.

4.1. Distributions of median residuals

The distribution of the median of the track-hit residuals per module (DMRs) is a measure of the tracking performance in track-based alignment. In this method, each track is refitted without the hit under consideration to obtain unbiased residuals [6]. The distribution of the median of these residuals should be narrow and centered around zero, reflecting the minimization of the sum of the track-hit residuals performed by track-based alignment. The width of the distribution provides a measure of the local precision of the alignment calibration, while deviations of the mean from zero may indicate possible biases due to changing detector conditions. The mean μ and the width σ are extracted by means of a Gaussian fit from the distribution of the medians of the track-hit residuals computed per module in a given tracker substructure:

$$\mu = \langle \mathrm{med}\{ r_{ij}(p, q_j) \,|_{i \in \mathrm{mod}} \} \rangle \big|_{\mathrm{mod} \in \mathrm{subdet}} = \langle \mathrm{med}\{ (m_{ij} - f_{ij}(p, q_j)) \,|_{i \in \mathrm{mod}} \} \rangle \big|_{\mathrm{mod} \in \mathrm{subdet}} \tag{1}$$

where p represent the alignment parameters, q the track parameters, m the measurements (e.g. hits), and f the corresponding predictions. The width has an intrinsic component due to the limited number of tracks. DMRs are monitored for all sub-detectors, and a clear improvement in the performance of the alignment corrections derived for the reprocessing is reflected in a reduction of the distribution width and in the bias of the peak position. This effect is illustrated in Figure 1 for the barrel and forward pixel detector, showing the DMRs for the local x-coordinate of the modules.

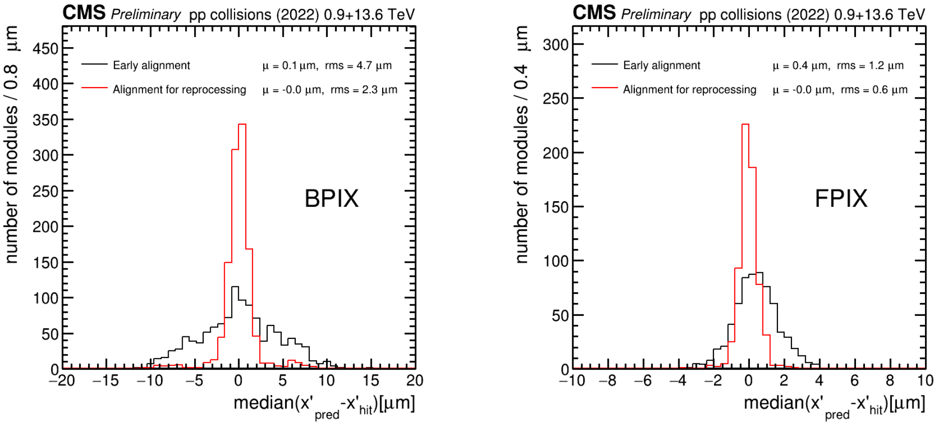

Figure 1. The distribution of median residuals is shown for the local x'-direction for all 1184 modules in the barrel (left) and the 672 modules in the forward (right) pixel detector for two geometries: the early alignment used during data-taking (black curve) and the alignment geometry used for the reprocessing of the 2022 data (red). The validation is performed with a random subsample of pp collision events collected by the CMS detector at full magnetic field (3.8T) at a center of mass energy of 13.6 TeV. Taken from [8].

4.2. Vertexing performance

The quality of the alignment is evaluated not only by its impact on tracking performance but also on its effect on the reconstruction of physics objects such as the primary vertex (PV). The pixel detector plays a crucial role in this regard since it has the best intrinsic hit position resolution and is located closest to the interaction point. To measure the vertex reconstruction performance, the unbiased track-vertex residuals, which provide a measurement of the distance between the tracks and the vertex reconstructed excluding the track under scrutiny, are used. This measurement is based on data and is used to study potential biases in the primary vertex reconstruction. In an ideal alignment scenario, the mean values of these residuals should be centered at zero. Random misalignments of the modules increase the width of the distributions but do not bias their mean. Systematic misalignments, on the other hand, introduce a bias that depends on the nature and size of the misalignment. Figure 2 shows the average unbiased track-vertex residuals as a function of the track angular parameters, the azimuthal angle ϕ and pseudorapidity η. The flattening of the ϕ and η-dependent structures in the alignment geometry derived for reprocessing highlights the reduction in the pixel misalignment.

After the end of the 2022 data-taking period, the entire statistics of the data collected during the year will be used to provide a more accurate alignment calibration for the legacy reprocessing of the Run 3 data.

5. Summary

In these proceedings, we reviewed the performance of the tracker alignment corresponding to the initial set of alignment conditions used during data-taking and for the reprocessing of the 2022 data, which have been collected until the technical shutdown, amounting to a total luminosity of 11 fb^{-1}. The methods adopted to obtain the set of alignment conditions as well as the set of validations employed to assess the tracking and vertexing performance were discussed. The alignment calibration will be further refined in the legacy reprocessing of the Run 3 data.

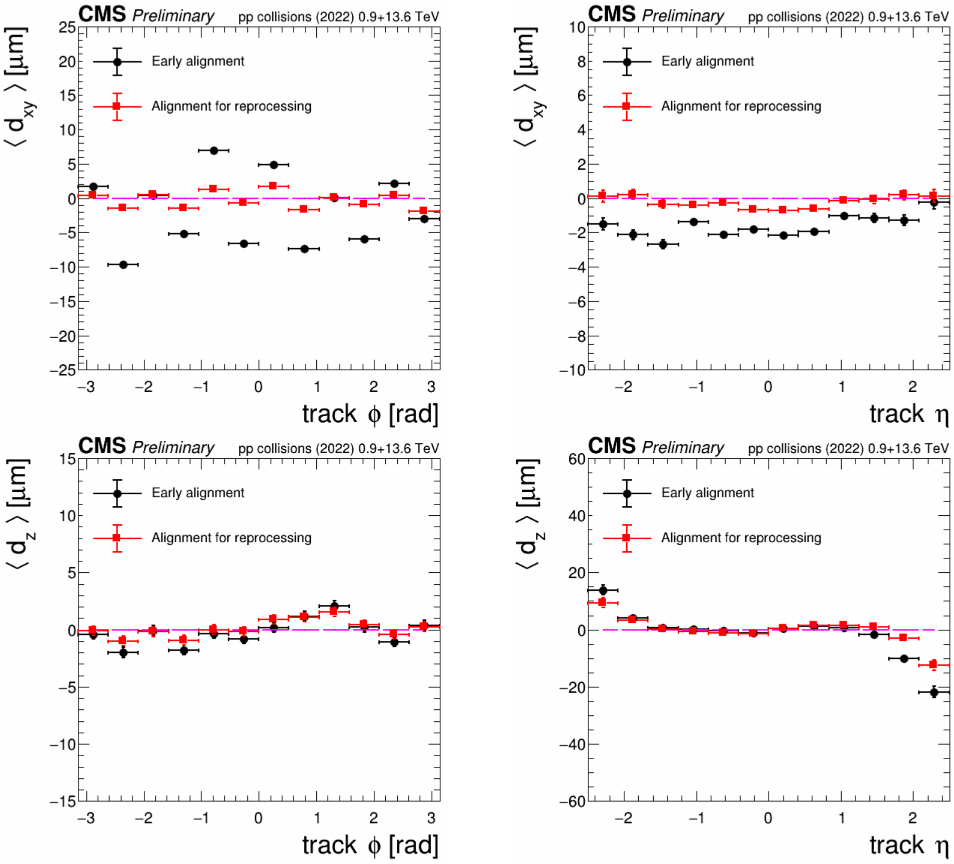

Figure 2. Mean-value distributions of unbiased transverse (top) and longitudinal (bottom) track-vertex residuals in bins of the track azimuthal angle ϕ (left) and pseudorapidity η (right) for the early alignment geometry (black) and the one for the reprocessing (red). In this validation, *pp* collision events selected with minimum bias triggers are used, which have been collected by the CMS detector at the full magnetic field (3.8T) at $\sqrt{s}$ =13.6 TeV. Deviations from the zero line are an indication for misalignment. Taken from [8].

References

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