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Performance of CMS Tracker Alignment during LHC Run 2 and Commissioning towards Run 3

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Performance of CMS Tracker Alignment during LHC Run 2 and Commissioning towards Run 3

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Abstract. The CMS experiment's innermost detector, the tracker, is designed to accurately measure the momentum of charged particles and reconstruct the primary vertices. As the operating conditions during data-taking change frequently, movements may occur in the substructures of the tracker, thereby necessitating regular updating of the detector geometry to describe the position, orientation, and curvature of the tracker modules. The process of determining the new geometry parameters is called tracker alignment. Tracker alignment is performed numerous times throughout the data-taking period using reconstructed tracks from collisions and cosmic rays data and further fine-tuned once the data collection is completed. The strategies for and the performance of the tracker alignment during Run 2 (2016-2018) will be presented, emphasising the ultimate accuracy achieved with the legacy reprocessing. The data-driven techniques used to derive the alignment parameters and the methods used to validate the alignment performance will be reviewed. Finally, the preparations of CMS towards tracker alignment during Run 3 (2022-2025)–in particular, the very first alignment performed after the LHC Long Shutdown 2, with cosmic ray muons and collision data at $\sqrt{s}$ = 900 GeV–will be discussed.

1. The CMS Tracker

The innermost, all-silicon component of the CMS detector, the tracker, comprises two sub-detectors - the pixel detector and the strip detector [1]. The pixel detector, consisting of a barrel region (BPIX) and two forward endcaps (FPIX), is the closest in proximity to the beam interaction point. Until the end of the 2016 data-taking period, the BPIX of the so-called "Phase-0" pixel detector consisted of three layers and the FPIX endcaps each consisted of two disks, accounting for a total of 1440 modules. The upgraded "Phase-1" pixel detector, in operation since 2017, features an additional barrel layer and one more disk in each FPIX endcap with an increase in the number of modules to 1856 [2]. The strip detector, surrounding the pixels, contains 15 148 modules and consists of four sub-systems: the Tracker Inner Barrel and Disks (TIB and TID, respectively), the Tracker Outer Barrel (TOB), and the Tracker Endcaps (TEC). The arrangement of the modules in the tracker is such that they form several high-level structures, for example, two half barrels in the BPIX, four half-cylinders in the two FPIX regions, etc.

The purpose of the tracker is the precise determination of the trajectory of charged particles (tracks) from signals (hits), referred to as tracking. Robust tracking and detailed vertex reconstruction are instrumental in exploiting the range of physics accessible at the LHC.

Measuring the track momenta requires an accurate determination of the curvature of the tracks induced by the magnetic field, which in turn demands a well-aligned detector.

2. Alignment of the CMS Tracker

To achieve optimal track parameter resolutions, it is imperative to precisely measure each silicon sensor's position, orientation, and surface deformations. During the installation procedure, the module insertion constraints result in precision in the position of the tracker of $\mathcal{O}(0.1\,\mathrm{mm})$, which is larger than the design hit resolution of $\mathcal{O}(0.01\,\mathrm{mm})$ by one order of magnitude. Therefore, a further correction needs to be derived to push the alignment precision well below 0.01 mm. This correction is commonly referred to as tracker alignment, and the parameters of this correction as alignables.

CMS performs the alignment of the tracker using a track-based alignment method [3]. Every hit registered in the detector is assigned a measured hit position, and a set of tracks is formed from the combination of these hits. Each of these tracks is assigned a unique set of track parameters as well as alignment parameters. The track-based alignment method then follows a least-square approach to derive alignables $\mathbf{p}$ by minimising the following χ^2 function:

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \left(\frac{m_{ij} - f_{ij}\left(\mathbf{p},\mathbf{q}_j\right)}{\sigma_{ij}^{\mathrm{m}}} \right)^2 \tag{1}$$

where

- $\mathbf{q}$ represents the track parameters (e.g. parameters related to the track curvature and the deflection by multiple scattering),
- m represents the measured hit position and f the predicted hit position, and
- σ^{m} represents the uncertainty in measurement.

This minimisation can be carried out either globally using MillePede-II [3, 4], or locally, using HipPy [5, 6]. Subsequently, the tracks are refitted assuming the geometry defined by the updated set of alignables and the track momentum measurement is corrected. This is followed by validation of the new alignment conditions.

3. Tracker Alignment Strategy for Run 2

Every year during Run 2 (2016-2018), before the start of LHC collisions, at least the high-level structures of the tracker were aligned using the cosmic ray data available from the commissioning of the detector. This initial alignment allowed a preliminary coarse determination of the alignables, which can reveal substantial shifts (due to temperature and magnetic field changes, or the reinstallation of detector components during the detector shutdown, etc.) with regard to the initially assumed geometry. These alignment parameters were then used online during the data taking. The movements of the high-level structures of the pixel detector are continuously monitored by an automated alignment, which corrects the geometry if the alignment corrections exceed specific thresholds. Alongside, track-based alignments were also run offline regularly at different granularities of the tracker– from module-level to high-level structures. The automated alignment was then refined with regular updates from these offline computations. At the end of the data-taking period, the complete statistics of the dataset collected during the year were exploited to extract the alignment conditions and perform the "end-of-year (EOY) reconstruction". After the completion of Run 2, the ultimate accuracy of the alignment calibration was derived using the data collected over the three years and used for the final or legacy reprocessing of the data. Over these three years, about 700 000 parameters and 220 geometries, for various intervals of validity (IOVs), were calculated, covering the considerable variations in alignment circumstances over time.

4. Run 2 Results

The performance of different sets of alignment parameters derived during the data-taking, EOY reconstruction and legacy reprocessing [7] are illustrated in this section. The validation procedures used to compare the quality of these sets of alignables are also explained.

4.1. Tracking Performance

A good measure of the tracking performance is the distribution of median track-hit residuals (DMRs) per module. Each track is refitted, removing the hit under consideration to avoid any bias in the measurement. Ideally, the distribution should be narrow and centred at zero. The width of the DMR is influenced by random misalignment of the modules, while deviations of the mean from zero may be indicative of a systematic shift of the structure under scrutiny. The DMRs are calculated for all tracker substructures, as shown in Fig. 1. It is observed that after the dedicated alignment for the legacy reprocessing, the mean value μ of the DMRs is shifted closer to zero.

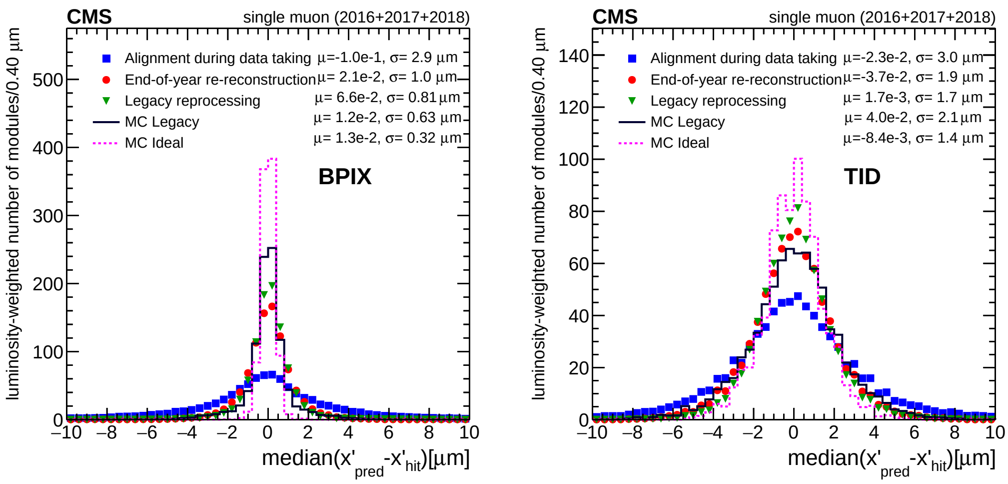

Figure 1. Distributions of median track-hit residuals per module in the local x (x') coordinate, for the BPIX (left) and TID (right). The distributions are averaged over all IOVs, where each IOV is weighted with the corresponding delivered integrated luminosity. The quoted means μ and standard deviations σ are the parameters of a Gaussian fit to the distributions.

4.2. Vertexing Performance

Studying the vertexing performance is essential to understand the effect of the alignment calibration on the reconstruction of physics objects. The unbiased track-vertex residuals, i.e. the distance between the tracks and the vertex reconstructed excluding the track under scrutiny, is examined to search for potential biases in the primary vertex reconstruction. As explained in the previous section, a deviation of the mean of the distribution from zero indicates a systematic misalignment. Fig. 2 shows the trends in the average unbiased track-vertex residuals in the transverse plane as a function of the delivered integrated luminosity, indicating an improved performance with legacy reprocessing.

4.3. Validation of Systematic Distortions

Validation is performed to check the influence of misalignments by projecting alignment performance onto a variable of interest. This variable has a known fixed value under perfect

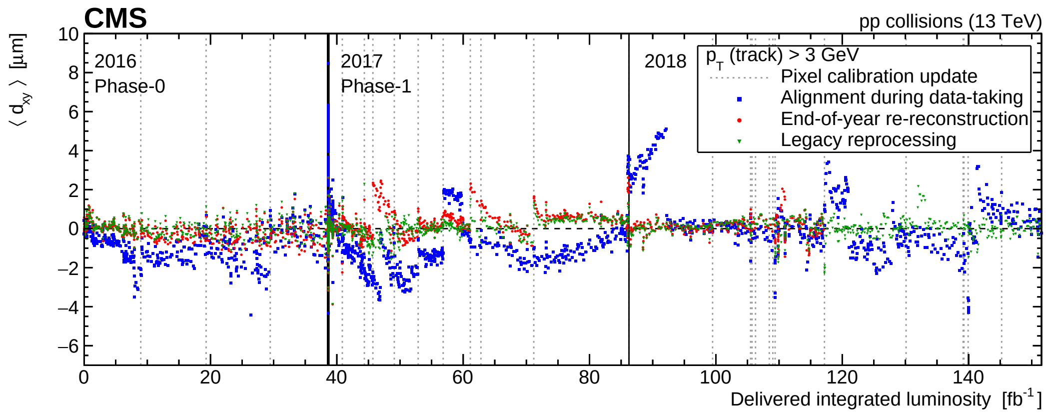

Figure 2. Average impact parameter trends in the transverse plane d_{xy} as a function of the delivered integrated luminosity.

conditions. In an ideally aligned tracker, the reconstructed $Z \to \mu\mu$ invariant mass, $m_{\mu\mu}$, should depend minimally on the direction in which the muons travel in the detector. Therefore, if the mean reconstructed mass differs from the expected m_Z value of 91.2 GeV, it indicates the presence of misalignment in the tracker. The uniformity in $m_{\mu\mu}$ that was achieved only after the legacy reprocessing can be seen in Fig. 3 (left). Cosmic ray muon tracks are another key ingredient used to control systematic distortions. The upper and lower portions of cosmic ray muon tracks that cross the tracker can be independently reconstructed, and the track parameters at the point of closest approach to the nominal beamline can be compared. Systematic differences between the track halves can indicate a misalignment, thus making this method a very powerful tool for validating track parameter resolutions. The mean of the difference in η between the two half-tracks refitted from the hits of a cosmic ray muon traversing the detector as a function of the impact parameter in the transverse plane is shown in Fig. 3 (right). Evidently, the strategy followed in the legacy alignment procedure has led to better performance.

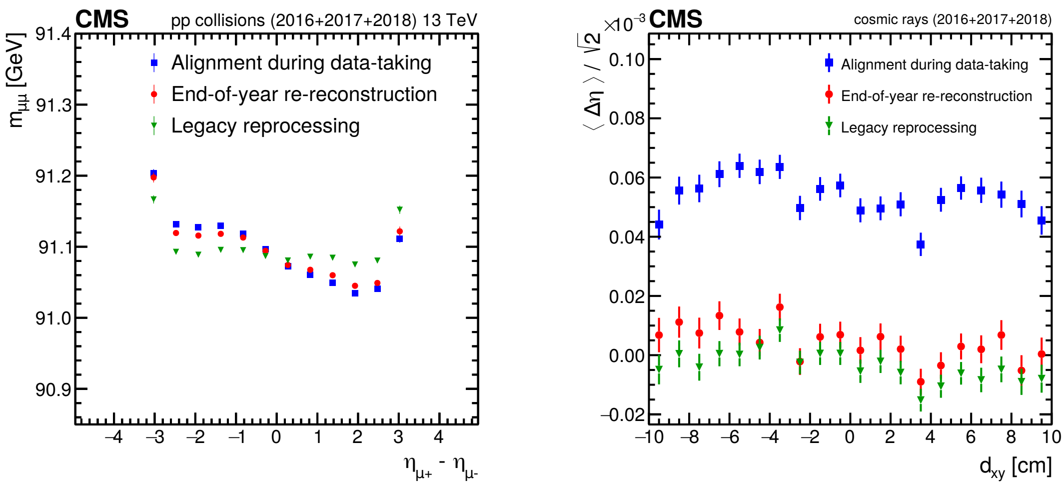

Figure 3. Reconstructed Z boson mass as a function of the difference in η between the positively and negatively charged muons, calculated from the full sample of dimuon events in Run 2 (left). The mean η difference between the two halves of cosmic muon tracks as a function of d_{xy}, scaled down by $\sqrt{2}$ to account for the two independent measurements (right).

5. LHC Run 3

5.1. *Commissioning of the CMS Detector*

The LHC underwent its second long shutdown (LS2) from 2018 to 2021. During this period, the BPIX of the CMS tracker was disassembled and its innermost layer was entirely replaced. Commissioning and calibrations are done, using cosmic ray muons, to ensure the CMS detector's proper working after such changes. Prior to the start of the LHC collisions in 2022, events were recorded during the *Cosmic RUns at ZEro Tesla* (CRUZET) before turning on the magnetic field from July to August 2021. Cosmic ray muon tracks were also recorded in the 3.8 T magnetic field provided by the CMS solenoid during the *Cosmic Runs At Four Tesla* (CRAFT), along with collisions at 900 GeV. These muon tracks are crucial for the alignment procedure as they can be employed to derive the first alignment corrections after the shutdown period. Also, they can be used to constrain several systematic distortions as described in section 4.3. The DMRs obtained after the alignment following CRUZET and CRAFT is shown in Fig. 4.

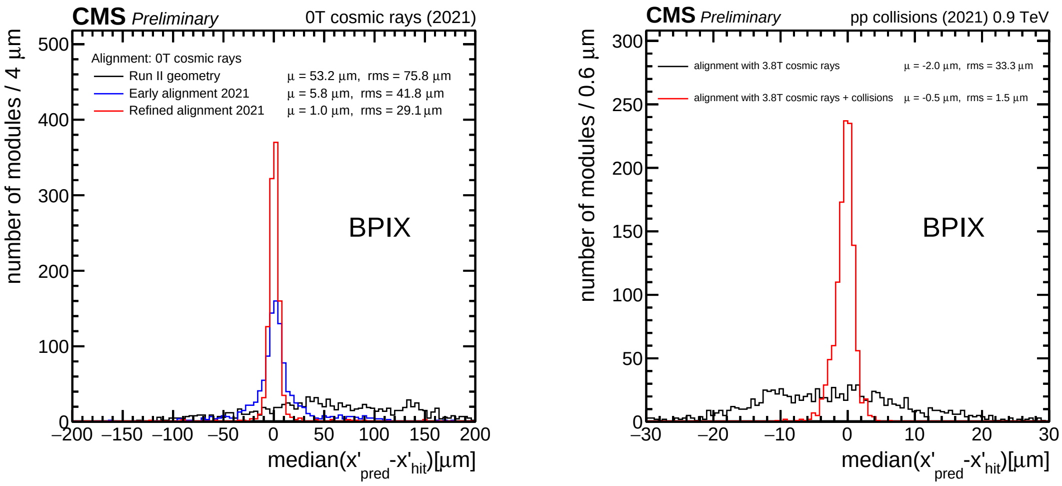

Figure 4. Distribution of median residuals in barrel pixel (BPIX) modules, along the local-x (x') direction obtained using CRUZET [8] (left) and CRAFT [9] (right) data.

5.2. *Alignment Prospects*

One of the significant goals during Run 3 would be to deploy finer granularity for the automated alignment. This run's larger irradiation doses will cause more substantial variation in the Lorentz drift of charge carriers in the tracker. Even though the alignment procedure is sensitive to Lorentz drift changes induced by accumulated radiation after $\approx$1 fb^{-1}, the pixel local reconstruction calibration that corrects for this effect is performed only after $\approx$10 fb^{-1}. If the alignment is done at fine enough granularity, inward and outward-pointing modules can move independently, absorbing the bias coming from Lorentz angle miscalibration. The alignments run offline will also be performed at a finer granularity to cope with the radiation effects.

6. Summary

The strategies and data-driven methods used to derive the alignment parameters for the CMS tracker during the LHC Run 2 were described. The performance of the tracker alignment after the legacy reprocessing was compared to the performances during data-taking and after EOY reconstruction. Systematic distortions arising in the detector geometry were studied using specific distributions. Finally, the commissioning and current status, as well as prospects of the alignment procedure for LHC Run 3, were discussed.

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