PROCEEDINGS OF SCIENCE

Automated alignment calibration in CMS during Run 3

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The LHC physics program requires a robust and efficient reconstruction of the trajectories of charged particles, as well as precise measurement of primary and secondary vertices and impact parameters. Several changes during data-taking, including the radiation damage introduced by the high particle flux, influence the particle position measurements. In order to exploit the physics potential of the Compact Muon Solenoid (CMS) detector, the calibration challenge consists of providing calibration constants with a fast turnaround, addressing the changes in the running conditions to ensure an efficient online event selection by the high-level trigger system and good quality first reconstruction of physics objects. To achieve this, several automated workflows have been developed. The update of the tracker detector geometry is performed by one such automated workflow, running on the most recent data and regularly updating the so-called alignment parameters within 48 hours. Thus, changes to the position and orientation of the tracker modules are periodically accounted for in the reconstruction. This contribution reviews the design and operational experience of the automated alignment calibration in place for the alignment of the CMS tracker detector, with an emphasis on the recent developments for the Run 3 data-taking period.

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1. Automation of calibrations in CMS

The Compact Muon Solenoid (CMS) is a general-purpose detector operated at the Large Hadron Collider (LHC), comprising different subdetectors – the pixel and strip tracker, the electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL) and the muon chambers – each performing a specific task. A detailed description of the CMS detector can be found in Ref. [1]. To make full use of the physics potential of the CMS experiment, it is paramount to calibrate and align the different subdetectors from time to time.

One of the critical assets for detector operations is having the most accurate calibrations available with a fast turnaround. This enables the delivery of good-quality data that can be used for physics analyses within 48-72 hours of their acquisition. Furthermore, the need to perform additional data reprocessing is reduced by ensuring improved calibration for initial physics object reconstruction. An elaborate framework called the Prompt Calibration Loop (PCL) was thus developed to fulfil this need for fast calibrations [2]. The PCL includes several low-latency alignment and calibration workflows that are run automatically at the Tier-0 processing farm at CERN for each acquired run. The strategy for running these is based on the 48-hour delay between the data acquisition and the reconstruction of the bulk of this data for physics analyses, called prompt reconstruction. Figure 1 shows a schematic illustrating the steps used by the different PCL workflows to compute alignment and calibration constants. Within 1-2 hours of the data collection, a limited selection of these data, called the express stream, is first reconstructed to provide rapid feedback on detector status and physics performance and serves as input to calibration workflows. The express data is further skimmed by customising the event content for each Alignment and Calibration (AlCa) workflow, thus producing AlCaRECO datasets. The calibration algorithms are then executed in parallel, using the AlCaRECO datasets as inputs to produce intermediate calibration products (histograms or calibration constants computed by a single job). The last step, called AlCa Harvesting, involves the aggregation of all the intermediate products for a given run into a set of conditions (database payloads) for future consumption by the reconstruction jobs. Initially stored as SQLite files, the payloads are then transferred to the Oracle-based CMS AlCa database [3]. In addition, histograms are also produced and loaded into an instance of the Data Quality Monitoring (DQM) [4] framework to allow a review of the performance of calibration algorithms.

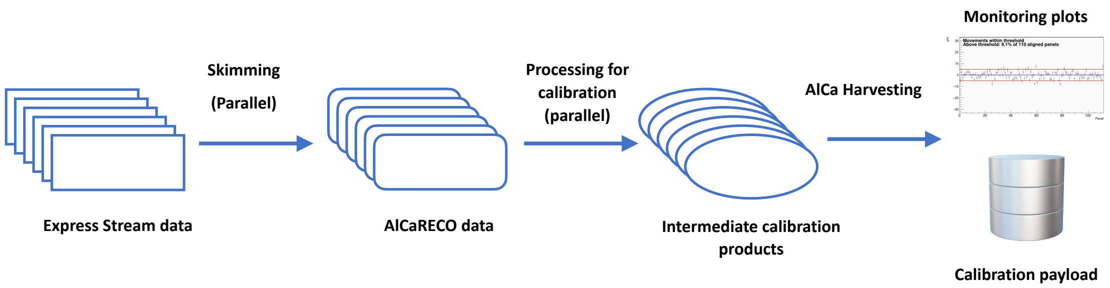

Figure 1: Schematic view of the working of the automated alignment and calibration workflows to compute conditions for one run.

2. Alignment of the CMS tracker

The CMS tracker comprises two sub-detectors - the silicon pixel and silicon strip detectors. The pixel detector, consisting of a barrel region (BPIX) and two forward endcaps (FPIX), with a total of 1 856 modules [5], is the closest to the beam interaction point. The strip detector surrounding the pixels contains 15 148 modules. The CMS tracker is designed for precise tracking, i.e. determining the trajectories of charged particles (tracks) from signals (hits) and accurate vertex reconstruction. These, in turn, demand a well-aligned detector where each sensor's position, orientation, and surface deformation are precisely known. The tracker has a design hit resolution of $O(10\,\mu\text{m})$. Therefore, corrections need to be derived to push the alignment precision well below this resolution. The track-based alignment method used to do this follows a least squares approach to derive alignables $\mathbf{p}$ by minimising the following χ^2 function:

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

where $\mathbf{q}$ represents the track parameters and the track-hit residual $(m_{ij} - f_{ij})$ is obtained by subtracting the hit prediction (f_{ij}) from the measured hit position (m_{ij}) [6]. σ_{ij} corresponds to the uncertainty in m_{ij}. This minimisation can be done either globally using the MillePede-II [7] or locally using the HipPy algorithm [8].

3. Automated tracker alignment

During data-taking, the different components of both the pixel and strip tracker may shift because of changes in the magnetic field or the temperature. Being closest to the interaction point, the pixel detector is subjected to much higher levels of radiation than the strip detector, the effects of which also have to be taken into account when deriving alignment parameters. As changes occur frequently in the pixels, an automated alignment procedure is needed to correct them. Thus, the automated alignment workflow, now called the low-granularity PCL (LG-PCL), was first implemented as part of the PCL during Run 2 of LHC. It works as explained in Section 1 and accounts for the movement of the high-level structures in the pixel detector, i.e. two half-barrels and two half-cylinders. It derives corrections using the MillePede-II alignment algorithm based on 36 degrees of freedom - the positions (x, y, z) as well as the rotations $(\theta_x, \theta_y, \theta_z)$ for each of the structures.

The LG-PCL, active throughout Run 2, showed stable performance during this period and helped correct large movements caused by magnet cycles, which is explained in more detail in Ref. [8]. However, it has a few shortcomings. A quantity sensitive to the radiation dose which plays a role in alignment is the Lorentz drift, which depends on the electric field and the mobility of the charge carriers in the silicon sensors, among other factors. Because of the high radiation dose, the mobility of the charge carriers changes quickly in the pixel detector. If not accounted for properly, this will cause systematic biases. This is corrected using a dedicated local calibration method, and the residual effects need to be corrected in the alignment procedure. The effectiveness of this can be monitored by producing the distribution of medians of track-hit residuals (DMR) separately for the inward- and outward-facing modules (which have different directions of electric fields and thus different directions of the Lorentz drift) and calculating the differences between the means of the DMRs, $\Delta\mu$. Ideally, the value of $\Delta\mu$ must be zero, and a different value hints at residual biases due to the accumulated effects from radiation in the sensors. Figure 2 shows the $\Delta\mu$ distributions for the BPIX for the years 2016-2018 as a function of the delivered integrated luminosity. Though successful on several fronts, the LG-PCL (blue curve) cannot fully mitigate the radiation effects, as the granularity of the alignment parameters used is too coarse to account for these changes. The bias could only be treated during the legacy reprocessing of Run 2 data by using additional parameters.

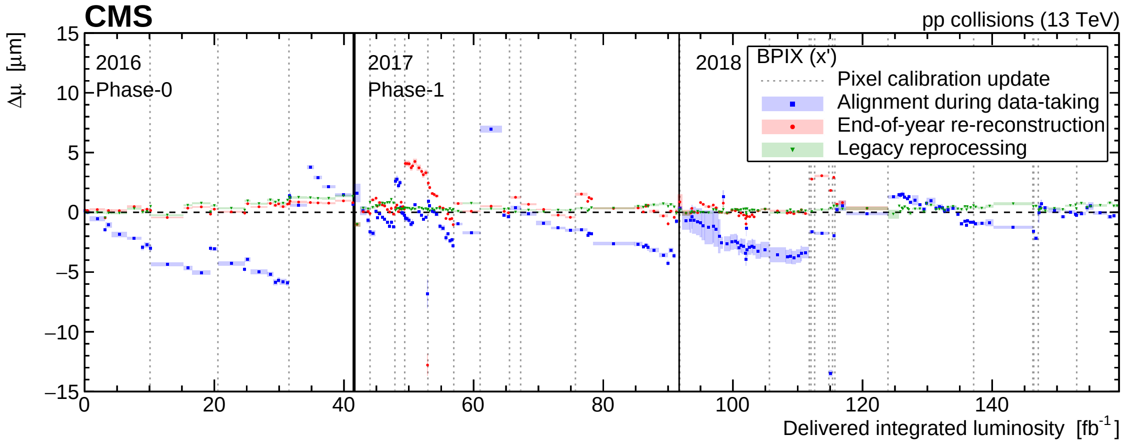

Figure 2: The difference, $\Delta\mu$, between the mean values of the DMRs obtained separately for the modules with the electric field pointing radially inwards or outwards for the local x (x') coordinate in the BPIX detector for the years 2016-2018, as a function of the delivered integrated luminosity [8].

The above is one of the main motivations behind developing the new automated alignment workflow, referred to as the high-granularity PCL (HG-PCL), for Run 3. The HG-PCL also uses the MillPede-II algorithm and is implemented in the central PCL workflow. It aligns the individual ladders and panels of the pixel detector, thus operating at a finer granularity than the LG-PCL and aligning over 5 000 parameters. After extensive testing and validation, the HG-PCL was deployed for data-taking in September 2022 and is successfully providing alignment conditions since then. The HG-PCL reduces the systematic bias induced by radiation damage as the rapidly changing shift from the local reconstruction can be absorbed in the position of the ladders and panels. This can be clearly observed in Figure 3, which shows $\Delta\mu$ for the innermost barrel layer, exposed to the harshest radiation environment, as a function of the delivered integrated luminosity for the year 2022. The blue curve shows the performance of the alignment conditions produced by the HG-PCL, which were also used for the end-of-year reconstruction due to their excellent performance, which allowed to save a lot of time and resources.

4. Summary

A description of the design and operation of the automated alignment calibration of the CMS tracker to cope with the rapid changes in data-taking conditions was given. Developments made in the workflows aiming to improve the alignment conditions used already at the level of prompt reconstruction during Run 3 were discussed. The promising results achieved thus far were presented.

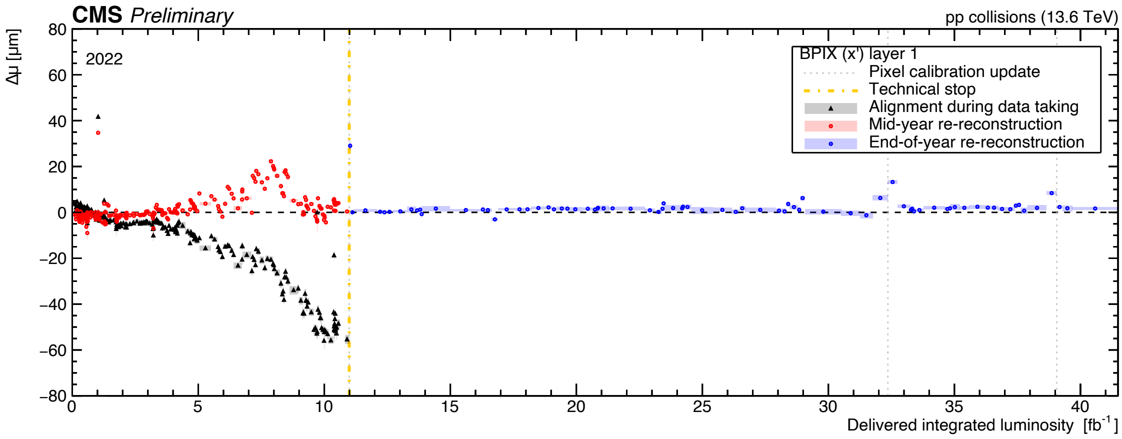

Figure 3: The difference, $\Delta\mu$, between the mean values of the DMRs obtained separately for the modules with the electric field pointing radially inwards or outwards for the local x (x') coordinate in BPIX layer 1 for the year 2022, as a function of the delivered integrated luminosity [9]. The blue curve shows the performance of the alignment constants derived by the HG-PCL.

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