PROCEEDINGS OF SCIENCE

Tracker alignment of the CMS detector

Patrick L.S. Connor[a,1,*]

[a] *Deutsches Elektronen-Synchrotron,*
Notkestraße 85, 22607 Hamburg, Germany

E-mail: patrick.connor@desy.de

The positions of the nearly twenty-thousand silicon sensors of the CMS central tracking system must be determined with a precision better than their intrinsic resolution in order to provide an optimal reconstruction of charged particle trajectories. The procedure, referred to as the alignment, includes also the adjustment of the orientations and the determination of the deviation from flatness of the sensor surfaces.

Data-driven methods used to carefully align the detector and validate the alignment are presented using CMS Run 2 data, collected from 2016 to 2018. Systematic distortions such as weak modes are discussed, as well as the impact of the variation of the conditions during data taking over time, in particular effects related to radiation damage.

Finally, we illustrate the impact on physics of the recent developments included in the Legacy Reprocessing, which was performed with the aim to greatly improve the physics potential for precision measurements, such as the reconstruction of the invariant mass spectrum of the dilepton systems.

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[1] on behalf of the CMS Collaboration
[*] Speaker

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1. Introduction

The CMS detector [1, 2] features in its very center the largest silicon tracking system to date in the world. It consists of a *strip detector*, containing 15 148 strip modules, and a *pixel detector*, which underwent an upgrade during the winter 2017, going from three layers in the barrel and two discs in the endcaps per side for a total of 1440 modules (Phase-0) to four layers in the barrel and three discs in the endcaps per side for a total of 1852 modules (Phase-1).

While the mechanical alignment of the modules can reach a precision of $O(0.1\,\mathrm{mm})$, the design resolution on the local hit reconstruction of the modules is $O(0.01\,\mathrm{mm})$. Moreover, the modules may move due to variations of the conditions such as the temperature and the magnetic field. A correction to the position, orientation and surface deformations of the sensors, commonly referred to as *alignment*, is calculated in order to exploit optimally the power of resolution of the silicon sensors. At CMS, the preferred approach is based on tracks, and consists in determining the alignment parameters in a simultaneous fit of a large amount of tracks. The CMS Collaboration utilises two different approaches: a global approach with MillePede-II [3] and a local approach with HipPy [4].

Two of the limiting factors to minimise the χ^2 of the fit are the intrinsic symmetries of the alignment procedure, and the external constrains in the tracking algorithm. The former, also known as *weak modes*, arise from the fact that collision tracks come from the interaction point and that the detector has a cylindrical symmetry; they can be reduced by utilising cosmic rays and tracks coming from a resonance such as the Z boson, but require to accumulate a large amount of data. The latter arise not only from variations of the temperature and of the magnetic field, but also from variable, residual effects not covered by the calibration of the hit reconstruction; they can be controlled by performing the alignment separately for the different data taking periods.

The alignment strategy depends on the targeted precision and on the available data; only a small number of degrees of freedom are usually allowed for alignment during data taking, while a large number of degrees of freedom is necessary after a few months of data taking for a finer alignment suitable for physics analysis.

The alignment of the CMS silicon tracker has already been described and documented in Refs. [5, 6]. Recently, the CMS Collaboration has released a large amount of results to describe the performance of the different alignments used in physics analysis [7–9]. In this paper, we report on recent results concerning the alignments derived during data taking.

2. Alignment performed during data taking

At the beginning of a data taking period, only limited data samples are available, therefore only large misalignments are corrected.

Before recording any collision data, a first alignment is performed with cosmic rays. In 2018, for instance, the modules of the pixel detector and the mechanical structures of the strip detector were aligned using cosmic rays recorded both with and without magnetic field. With the first collision tracks available in addition to cosmic rays, thanks to the large collision data sample, a new alignment of the pixel detector with higher precision was derived. In 2018, both HipPy and MillePede-II were used to cross-check one another's results.

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Once we are confident in the alignment, an automated, unsupervised alignment procedure is activated [10]. Only the half barrels and half endcaps in the pixel detector are aligned, and only tracks from collision data are used. The alignment is derived automatically for each run, and deployed if sufficiently large movements are observed for any of the parameters. Figure 1 shows the movements of the global x coordinate (pointing to the centre of the LHC) obtained for each run for the two half-barrels in the barrel pixel (BPIX) detector.

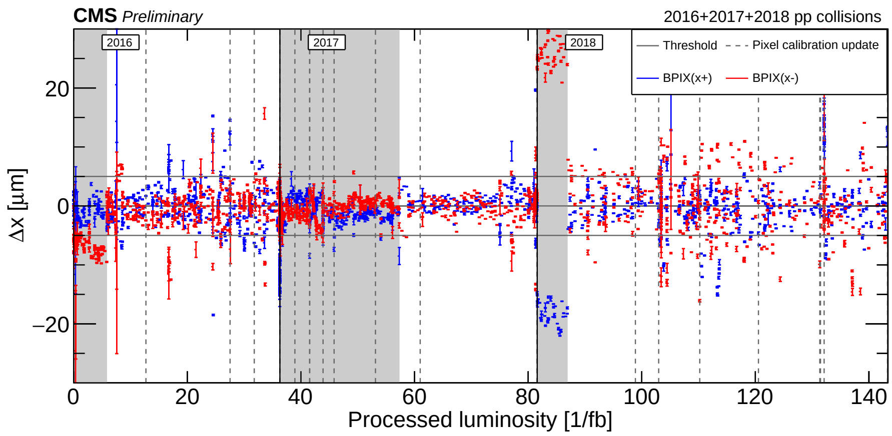

Figure 1: Movements in the barrel pixel detector along the global x coordinate obtained in the automated alignment during data taking as a function of the processed luminosity. Each point represents a run; the plain, horizontal lines correspond to the thresholds beyond which the alignment is deployed; the dashed, vertical lines correspond to changes of calibration of the local reconstruction; the shaded areas correspond to periods where the deployment of the automated alignment was deactivated.

3. High-performance alignment

Whilst during data taking only part of the parameters are determined in the alignment procedure, the best precision can only be achieved if all parameters are determined simultaneously. This is only possible once a sufficient amount of cosmic rays and tracks from resonances have been recorded.

In order to control weak modes without including tensions from periods of data taking too distant in time, a *hierarchy* is introduced among the parameters: the absolute positions and orientations of so-called *high-level structures* (typically corresponding to mechanical structures) are determined for short data taking periods, corresponding to a few inverse femtobarns at most, whereas the relative positions and orientations of the sensors with respect to the high-level structures are determined for a whole year. The CMS Collaboration can proceed to such an alignment only after several months of data taking.

The tracking performance is estimated from the track-hit residuals; for each residual, the track is refitted without the hit under scrutiny. Instead of investigating the distributions for each individual module, the tracking performance is estimated from the *Distribution of the Median of the Residuals* (DMR), here shown for the local x coordinate in BPIX (*i.e.* along the global azimuthal coordinate, in the direction of the short dimension of the pixels). Similarly, the vertexing performance is estimated from the measurement of the impact parameter of a track belonging to a vertex, both being refitted

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independently. Figure 2 shows the improvement of the tracking and vertexing performance for three representative alignments for the year 2017 (out of a hundred) and for the Monte Carlo (MC) scenario. For each year, only one MC scenario was derived and tuned to have a performance slightly better than the average data performance.

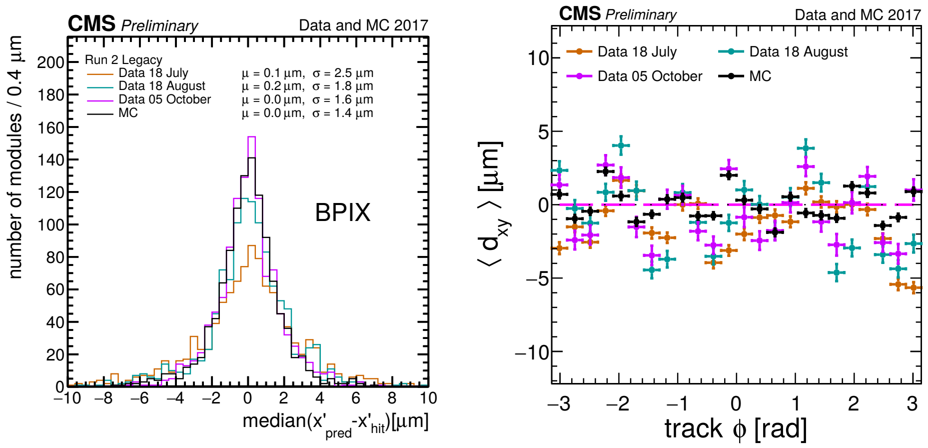

Figure 2: Tracking (left) and vertexing (right) performance for three particular alignments in data during 2017 and for the MC scenario.

Different strategies of alignment were attempted during Run 2 and evolved with the increase of instantaneous luminosity and with the installation of the Phase-1 pixel detector. At the end of 2016, a global alignment including around thirty-five periods was derived with MillePede-II, on top of which HipPy was run to refine the local precision. At the end of 2017, instead of using the approach based on a hierarchy, fourteen alignments were derived independently with either HipPy or MillePede-II. During 2018, the global approach was again attempted, but faster changes in the alignment appeared necessary to avoid tensions among different periods of data taking; a hybrid hierarchy was introduced, with around ten (hundred) periods of alignment in the strip (pixel) detector, allowing a progressive absorption of residual effects from the irradiation of the modules.

In addition, during the Long Shutdown 2 (2019-2020), the alignments of the years 2016 and 2017 were fully re-derived in the context of a global reprocessing of Run 2 data. While the changes for 2016 simply consisted in re-running the same configuration with a refined version of the calibration of the hit reconstruction, the alignment of the data recorded in 2017 was completely re-derived according to a similar strategy as the one applied in 2018.

Figure 3 shows the sensitivity to the residual effects due to the ageing of the modules due to the radiation for three different series of alignments: the *alignment during data taking*, a mix of alignments derived by operators and of alignments derived automatically; the *end-of-year re-reconstruction*, used for most published physics analysis to date; and the *Legacy reprocessing*, corresponding to the most performant alignment, which will become the default alignment for most upcoming Run 2 physics measurements, as well as for the Open Data. The variable $\Delta\mu$ corresponds to the difference of the means of the DMRs determined for the inward- and outward-pointing modules separately; it is sensitive to residual effects from the irradiation, as the Lorentz drift inside of the sensors is expected to take place in opposite directions and causes systematic biases in opposite directions. In particular, it can be seen that the slopes observed especially for

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the alignment during data taking, as well as for the end-of-year re-reconstruction in 2017, were significantly reduced in the Legacy Reprocessing.

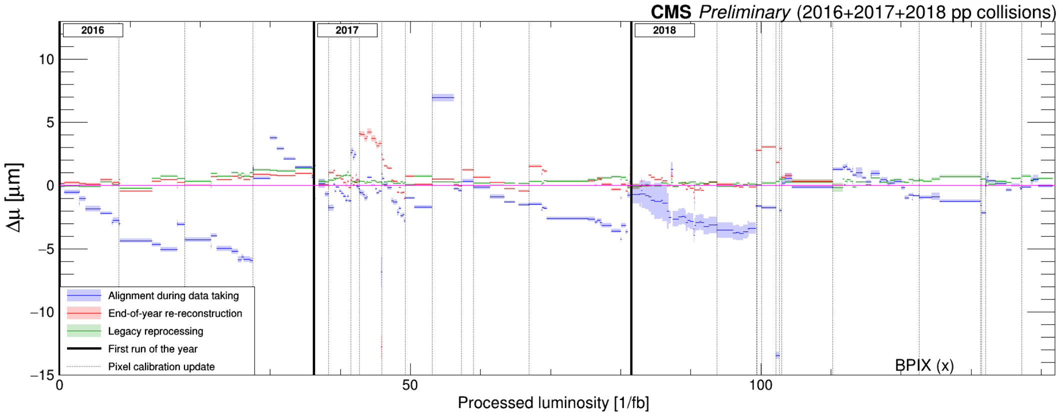

Figure 3: Stability of different versions of the alignment as a function of the processed luminosity. Each colour corresponds to a different campaign of alignments; the vertical, dashed lines represent the changes of local calibration in the Legacy Reprocessing (they do not necessarily coincide with the changes that took place during data taking or with the end-of-the-year re-reconstruction). The $\Delta\mu$ is extracted from the DMRs in BPIX determined in each alignment for the inward- and outward-pointing modules separately.

The improvement of the alignment can have a significant impact on physics. The performance of these three same alignments can be compared by reconstructing the mass of the di-muon system close to the peak of the Z boson. A constant value close to 91.2 GeV being expected, deviations from a constant behaviour highlight systematic biases present in the alignment: either a weak mode or non-corrected effects from the irradiation. Such a comparison is provided in Figure 4 and shows a very significant improvement of the performance with the Legacy reprocessing. Note that raw kinematics are used, *i.e.* as obtained from the reconstruction algorithm with different alignments without any additional calibration.

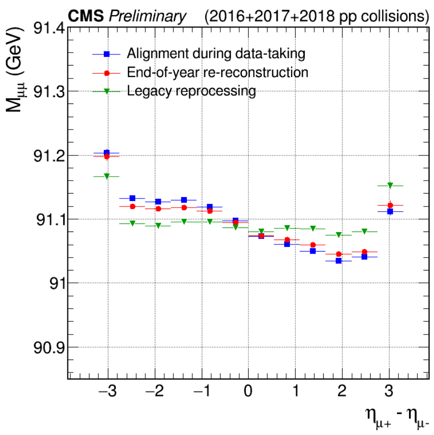

Figure 4: Di-muon mass as a function of the difference of pseudorapidity of the outgoing muons for different alignments.

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4. Summary

General concepts of alignment of the CMS experiment were introduced, including track-based alignment, time variations, intrinsic symmetries, and interplay with local reconstruction. Strategies during and after data taking were addressed. Finally, improvements of the alignment with the Legacy reprocessing were shown, such as Z boson mass distributions, track-hit residuals, and the impact parameter.

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