PROCEEDINGS OF SCIENCE

Alignment procedures for the CMS Silicon Tracker detector during pp collisions

Roberto Castello*
On behalf of the CMS Collaboration
CP3, Université Catholique de Louvain
E-mail: roberto.castello@cern.ch

The CMS all-silicon tracker consists of 16588 modules: aligning them with the desired precision of a few micrometers is only feasible using track based alignment procedures. Ultimate precision is now achieved by the determination of sensor curvatures in addition to the local translation and rotation of modules in space. This challenges the alignment algorithms to determine about 200 000 parameters simultaneously. This is achieved using a standalone algorithm exploiting a global fit approach, interfaced with CMS software. The alignment of the detector is also monitored using its built in Laser Alignment System. The main remaining challenge for the alignment are global distortions that systematically bias the track parameters and thus physics measurements. These distortions are controlled by adding further information into the alignment workflow, e.g. the mass of decaying resonances. The orientation of the tracker with respect to the magnetic field of CMS is determined with a stand-alone chi-square minimization procedure. The resulting geometry is finally carefully monitored by looking at the basic track quantities from both collisions and cosmic muons and physics observables like resonance masses.

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*Speaker.

1. Introduction

Excellent tracking performance is crucial for reaching the scientific goals of the CMS experiment, which places very high demands on the level of precision of the calibration and alignment of the tracking sensors. The primary task of the CMS tracker [1, 2] is to measure the trajectories of charged particles (tracks) with excellent momentum, angle, and position resolution. Design specifications indicate that the tracking must reach a resolution on the transverse momentum (p_T) of 1.5% (10%) for muons of momentum of 100 (1000) GeV/c [3]. Therefore, in order to fully exploit the single hit resolution of 9 μm for pixel and of 23 to 60 μm for strip sensors, the positions of the sensors must be known to a precision of a few micrometers. This can best be achieved by track-based alignment algorithms.

Although the result obtained using cosmic ray tracks only as alignment input [4] has been excellent and was instrumental for the early physics program of CMS, the alignment was still not achieving the final level of accuracy and control of systematic distortions desired, due to limitations in statistics and to the usage of cosmic ray tracks only. With the inclusion of the large statistics of tracks from pp collisions provided by the LHC, the goals of the alignment of the CMS tracker have been to reach the ultimate statistical resolution in all regions of the tracker and to extensively control relevant systematic distortions biasing reconstructed track parameters and thus affecting physics performances.

2. The alignment strategy

Track-hit residual distributions are generally broadened if the assumed positions and orientations of the silicon modules differ from the true ones. Following the least squares approach, alignment algorithms minimise the squares of normalised residuals, summing over many tracks. If the (hit or virtual) measurements m_{ij} with uncertainties σ_{ij} are independent, the minimised function is

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_{j}^{tracks} \sum_{i}^{measurements} \left(\frac{m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)}{\sigma_{ij}} \right)^2 \tag{2.1}$$

where f_{ij} is the track model prediction at the position of the measurement, depending on the alignment ($\mathbf{p}$) and track ($\mathbf{q}_j$) parameters. In a global fit approach as implemented in the MILLEPEDE II program [5] the $\chi^2(\mathbf{p},\mathbf{q})$ is minimised after linearising f_{ij} and the alignment parameters are determined.

A new improved track model [6][7] allowed for a better treatment of multiple scattering effects, achieved by increasing the number of parameters for a charged particle in the magnetic field to $n_{par} = 5 + 2n_{scat}$, e. g. adding two deflection angles for each of the n_{scat} thin scatterers.

The alignment of the CMS tracker in 2011 was performed exploiting this global fit approach with the improved track model, using as input data collected during 1 fb^{-1} of integrated luminosity: about 15 million loosely selected isolated muon tracks, 3 million low momentum tracks, 3.6 million cosmic ray tracks (collected between LHC fills, during collisions and before collision data taking) and 375 thousand muon track pairs from Z boson decays.

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3. Results

3.1 Track-to-hit residuals

An estimation of the achieved statistical precision in the minimization procedure described above is provided by track-based validation. The input to the validation are isolated muon tracks with a transverse momentum of $p_T > 40$ GeV and at least ten hits in the tracker. The tracks are refitted taking the new determined module positions into account. Hit residuals are determined with respect to the track prediction, which is obtained without using the hit in question to avoid any correlation between hit and track. From the residual distribution of the unbiased hit residuals in each module, the median is taken and histogrammed for all modules in a detector subsystem. The median is relatively robust against stochastic effects from multiple scattering, and thus the distribution of medians of residuals (DMR) is taken as a measurement of achieved accuracy. Only modules comprising at least 30 entries in their residual distribution are considered.
Compared to the alignment with cosmic rays alone [4], the most striking improvements are observed in the end caps of the pixel tracker, where the addition of tracks from collision events leads to a huge boost of statistics, especially for innermost parts of the tracker. An example of corresponding DMR along u coordinate is shown in the left plot of Figure 1; their RMS is well below 3 μm in both directions, compared to about 13 μm in the cosmics-only alignment. These numbers are only slightly larger than the ones obtained in simulation without any misalignment, which are between 1–3 μm, and far below the expected hit resolution.

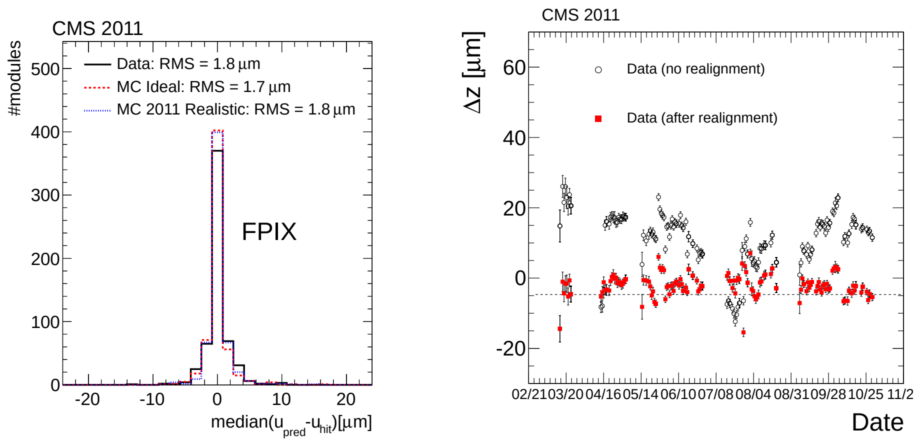

Figure 1: Left: Distributions of the medians of the residuals, for the Pixel Endcap modules in u coordinate. The distributions after alignment with 2011 data, in comparison with simulations without any misalignment and simulation tuned to reproduce the misalignment after the 2011 alignment procedure are shown. Right: Day-by-day value of the relative longitudinal shift between the two half-shells of Pixel Barrel as measured with the primary vertex residuals.

3.2 Time dependent corrections of the Pixel high hierarchy structures

In addition also unbiased track-vertex residuals are used to monitor the position of the two

pixel half barrels relative to each other, in particular along the z direction. Each primary vertex is refitted after removal of one of its tracks. This is repeated for each track of the vertex. The track-vertex residuals Δz along the beam line are averaged as a function of the polar angle ϕ of the track. A difference of the mean values for tracks stemming from the one half barrel or the other indicates a relative misplacement. Jumps of up to 30 μm are seen before alignment.
After the alignment with time dependent parameters for the positions and orientations of large pixel structures, the remaining half barrel separations are well below 10 μm (see right plot of Figure 1), a value that has no effect on the alignment sensitive b-tagging algorithms.
In the process of monitoring the large structures, also the Laser Alignment System (LAS) [8] provides a source of alignment information independent from tracks. It is based on 40 near-infrared (1075 nm) laser beams passing through a subset of the silicon sensors that are used for the tracking. With this limited number of laser beams one can align large scale structures such as Tracker Outer Barrel (TOB), Tracker Inner Barrel (TIB), and both Tracker EndCap (TEC). The mechanical accuracy of LAS components limits the absolute precision of this alignment method to 50 μm in comparison to the alignment with tracks which are reaching better than 10 μm resolution. Within this margin of accuracy, the LAS measurement indicates a very good stability of the strip detector geometry over the whole run period.

3.3 Sensor and module shape parametrization

In the CMS software the module translations u, v, w as well as the rotations α, β, γ around these axes are defined in the local reference system of the module [4] and determined by the alignment procedure. This assumes flat sensor surfaces. In reality, however, the surfaces of the sensors are not flat. To take this effect into account, for each sensor the sum of second order modified Legendre polynomials has been introduced [9] in order to parametrise the sensor surface. The curvatures of the sensor surfaces are referred to as *bows*. Furthermore, all TOB modules and the TEC modules at radii $r > 60$ cm consist of two individual daisy-chained sensors. With respect to alignments of the CMS tracker performed in earlier years, the treatment of these double sensor modules has been improved by allowing the separate determination of the alignment parameters for both sensors. This improvement is referred to as the determination of *kinks*.
The parametrization with polynomials describes the sensors very well. This can be seen in Figure 2 (left), where the offsets dw are calculated from the residuals in u and the track angle ψ from the sensor normal in the uw plane. For an alignment with the flat sensor assumption, a parabolic shape is seen that vanishes taking into account the additional parameters. Also, high momentum tracks from the interaction region cross the strip modules under small angles relative to the module normal. Therefore sensor curvatures have only a small effect. This is different for cosmic ray tracks that cross the tracker with a large closest distance to the beam line, d_0. The larger d_0, the larger the average track angle from the module normal, leading to degraded fit results for the flat module assumption, as shown in Figure 2 (right). If curvature parameters on sensor level are determined, the average fit probability is almost flat as a function of d_0 up to 50 cm, thus improving substantially the consistency between tracks from the interaction point and cosmic rays.

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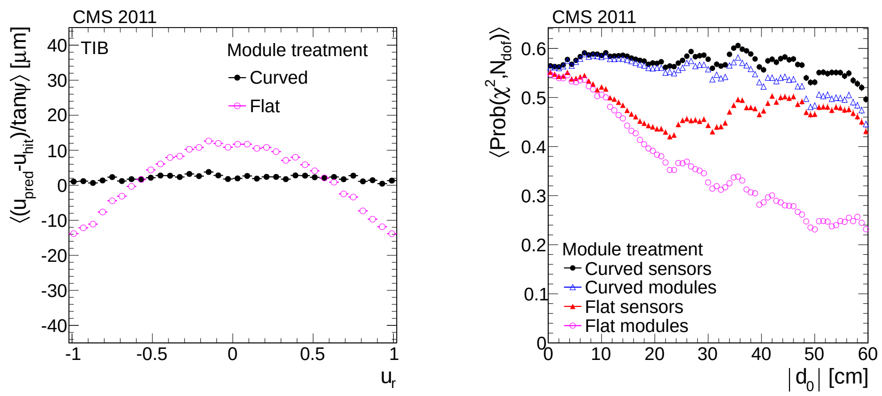

Figure 2: Left: Distributions of the weighted means of the $\Delta w = \Delta u/\tan\psi$ track-hit residuals in TIB as a function of the relative position of tracks from pp-collisions on the modules along the local u-axis before (magenta) and after (black) parametrization of the module shapes. Each residual is weighted by $\tan^2\psi$ of the track. Right: Mean probability of cosmic ray track fits as a function of their distance of closest approach to the nominal beam line for the different approaches to parametrize the module shapes.

4. Monitoring and control of global deformations

Generally, by minimising the function defined in equation 2.1 not all possible distortions of the tracker can be resolved. The residuals can be insensitive to certain global deformations referred to as *weak* modes. Weak modes correspond to global transformations that preserve the validity of the track model for the track sample under consideration, i.e. the transformed hits are to a high degree still consistent with a valid trajectory. Such systematic distortions have very little impact on the goodness-of-fit of the track. However, these distortions might significantly bias the track parameters and other quantities such as invariant masses.

Systematic momentum biases for tracks have therefore been investigated using events with a Z boson decaying into oppositely charged muons. For example, without using the virtual Z-mass information in the alignment, a large dependence of the position of the mass peak as a function of the pseudorapidity η of the decaying positively charged muon is observed (Figure 3, left).

This dependence can be attributed to a *twist* of the whole tracker defined as $\Delta\phi_i = c \times z_i$ where $\Delta\phi_i$ is the change of the azimuthal angle of a module i. In contrast, using Z mass information in the alignment fit, the remaining spread of Z-mass peak values is almost as small as in the detector simulation with perfect alignment.

In order to study the sensitivity of the alignment to weak modes, the possible deformations of the geometry are parametrized in the cylindrical coordinates r, z, and ϕ [11] and applied to 2011 geometry. Afterwards, to test the capabilities of the alignment to correct for the introduced misalignment, the module-by-module position differences with respect to the summer 2011 geometry are determined, subtracting global movements and rotations of the whole tracker, as shown in Figure 3 (central). In addition, track χ^2 distributions for collision tracks are also shown for the summer 2011 geometry, for the misaligned and the re-aligned geometry. It can be noticed that the twist de-

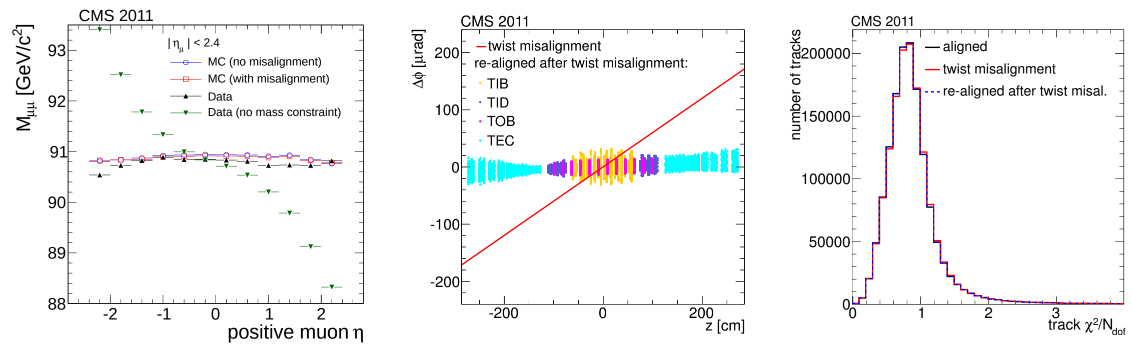

Figure 3: Left: Distribution from 2011 data alignment is shown with black markers, the one from a simulation with no misalignment is shown in blue. The same distribution using the 2011 data but with a geometry not exploiting the mass constraint is presented with green markers. Central: module-by-module position difference between the re-aligned geometry after the introduction of Twist deformation and Summer 2011 geometry (after subtraction of global movements and rotations). Right: Track χ^2 using loosely selected isolated muons from a statistically independent sample from the one used in the alignment procedure ($p_T > 5\,\mathrm{GeV}$).

formation is indeed a weak modes for collision tracks, because after the introduced misalignment the χ^2 distribution for collision tracks remains basically unchanged (Figure 3, right). However, the introduced twist deformation is fully corrected by the alignment procedure using the Z boson decay information.

5. Conclusions

The alignment procedure for the CMS tracker and its results for the first high-luminosity data taking period are presented. The alignment is based on global minimisation of track-to-hit residuals using the MILLEPEDE II program. The performance of the alignment fulfills and exceeds the requirements for the CMS tracker. The resulting alignment constants provided are a key asset for achieving the accuracy of track reconstruction, which is the basis of many track-related physics results and discoveries achieved by the CMS experiment during the first two years of data taking.

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