First Alignment of the CMS Tracker and Implications for the First Collision Data

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We present first results from the full alignment of the silicon tracking system of the CMS experiment. The alignment is done using about 3.2 million tracks from cosmic data taken during commissioning runs in 2008 with the detector in its final position named Cosmic Run at Four Tesla (CRAFT), in combination with survey measurements. Results are validated and tested against prediction with detailed detector simulation. The achieved resolution in all five track parameters is controlled. Implications for the CMS physics performance are discussed.

1 Design of the tracking system

The CMS tracker [1] is completely based on silicon pixel and strip modules (Fig. 1). They are mounted concentrically about the beam axis on different mechanical structures called subdetectors. Close to the beam pipe there is the pixel detector containing 1440 pixel modules in two subdetectors, which is surrounded by the strip detector. The 15 148 strip modules are divided among the subdetectors tracker inner barrel (TIB), outer barrel (TOB), inner disks (TID), and end caps (TEC). The modules are assembled into hermetic layers. The solenoid magnet provides an almost homogeneous magnetic field of 3.8 T throughout the tracker volume.

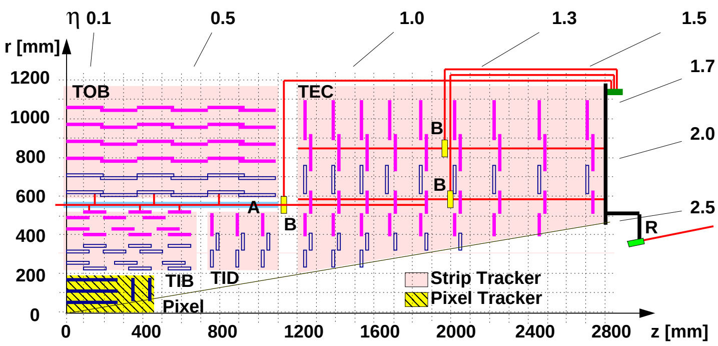

Figure 1: Upper right quarter of the longitudinal section of the CMS tracker. All strip subdetectors are illustrated (TIB, TID, TOB, TEC). Empty boxes show combined strip modules. Full Boxes show pixel modules or single strip modules. Further, the Laser Alignment System is visible (A, B, R).

The tracker is intended to reconstruct trajectories of charged particles ("tracks") based on a set of local coordinate measurements of traversed silicon modules ("hits"). The intrinsic resolution of the modules for hits is in the range 10–30 μm. For 100 GeV/c muons the tracker is expected to achieve a transverse momentum resolution of about 1.5 % and an impact parameter resolution of about 15 μm. The latter is necessary especially for efficient b-tagging. The values are determined from simulation studies based on the design (ideal) geometry [1]. To reach this performance, it is crucial to know the alignment parameters $\mathbf{p}$ (positions x, y, z and orientations α, β, γ of all modules) to very high precision, so that the uncertainty of a measurement along a sensitive coordinate is less than $10\,\mu$m. The following studies are published in detail in [2].

2 Approaches and results of track-based alignment

2.1 Track-based alignment

The mounting precision of $O(100\,\mu\text{m})$ is by far not sufficient for the goals of physics analyses. The desired accuracy is gained with track-based alignment at the module level. It is based on the reconstruction of charged particle tracks:
Hit candidates are constructed from the induced charge distributions on the pixels or strips. For every hit measurement i, position coordinates x_{hit} and corresponding errors are estimated within the local coordinate frames of the modules. Hit candidates are assembled into track candidates by the pattern recognition procedure, and track parameters $\mathbf{q}$ for every track j are estimated by the track fit. This depends strongly on the alignment parameters $\mathbf{p}$.

The alignment procedure uses the constraints implied by the track model to estimate alignment corrections to the geometry. Deviations in geometry are reflected in the hit residual r, which is defined as the difference of the hit and the track prediction on the module's plane, x_{track}, for each independent measurement coordinate,

$$r_{ji} = x_{ji,\text{track}}\,(\mathbf{p}, \mathbf{q}_j) - x_{ji,\text{hit}}\,.$$

The distribution of residuals normalized by their errors is approximately Gaussian with a width of about 1, centered at 0, when there are no uncertainties in alignment parameters. Misalignment increases the spread of the residuals in general. This is reflected in an increase of the total χ^2-function, containing the goodness of all track fits,

$$\chi^2_{\text{tot}}\,(\mathbf{p}, \mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \frac{r_{ji}^2}{\sigma_{ji}^2}\,.$$

The algorithms estimate alignment parameters by minimizing this function using millions of tracks. This needs sophisticated statistical approaches, since the track fits depend on the alignment. Two algorithms are applied. The local method named HIP (Hits and Impact Points) estimates the parameters for each module. Then iterations are needed to take the correlations with the track fit into account. It uses the same track model as the reconstruction. The minimization is stabilized by including the survey information. The global method (Millepede II) fits all track and alignment parameters simultaneously. The advantage is that all correlations are considered, but its current implementation in CMS is restricted to a helical track model.

2.2 Input data

In 2008, the tracker was operated in its final position for one month to measure cosmic muons with the solenoid at the nominal magnetic field strength of 3.8 T. About 3.2 million tracks were considered to be useful for alignment. The selection contains tracks with at least eight hits and

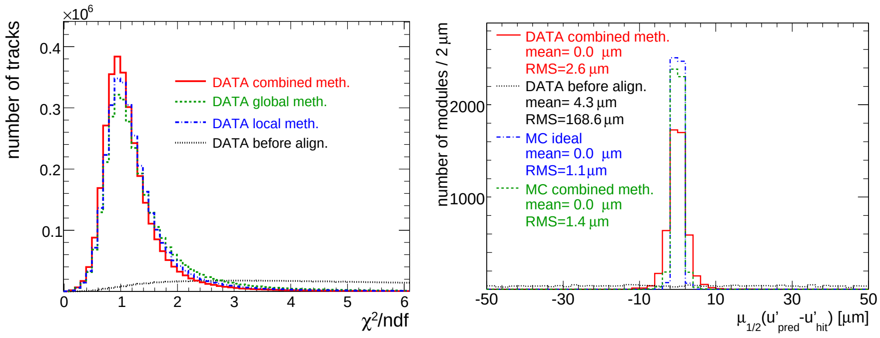

Figure 2: Distribution of normalized χ^2 of tracks (left) and distribution of module-wise medians of the hit residual distributions of TOB modules (right).

momentum $p > 4\,\mathrm{GeV/c}$. Furthermore, a defined measurement of the polar angle θ is required. Finally, only hits passing quality and outlier rejection criteria were used in the track fits.

For comparisons, a similar number of tracks was simulated using the standard Monte Carlo program. They show good agreement in the statistical distribution of the track parameters.

Survey measurements provide another source of alignment information. For all sub-detectors the mounting precision of sub-structures was estimated during integration. For TIB and TID the position of every module was also measured. The information can be used in the track-based alignment to set constraints by adding a term to the total χ^2-function.

2.3 Validation of alignment results

The first step of track-based validation is to analyze the distribution of values of track χ^2 normalized by its number of degrees of freedom (Fig. 2 (left)), and the hit residual distributions grouped per subdetector. While each algorithm applied individually leads to a respectable improvement of the goodness of fit, the best result is obtained by first running the global method and then applying the local method on the geometry based on the global method.

A sensible measure for the remaining misalignment is the distribution of module-wise medians of the residual distributions (DMR), as shown in Fig. 2 (right) for the TOB. Its broadening gives a lower limit for misalignment. Due to the largely vertical nature of the cosmic track data, the achieved alignment accuracy depends on the detector region. However, the observed performance is close to the expectation obtained by applying alignment algorithms to a simulated data sample of comparable statistics. The simulation gives also the smallest width achievable with present statistics for the case where the alignment parameters are fully known.

A particular challenge are weak modes. These are systematic distortions, which influence the χ^2-distribution only slightly, but can cause a significant bias in physics results (see Ref. [2]).

2.3.1 Overlap Residuals

Overlapping modules of the same layer can have hits from the same track. The difference in measured residuals for common tracks allows an understanding of relative misalignment within one layer. The mean of the distribution per pair can be indicative of shifts. Significant improvement is visible for all barrel detectors, as Fig. 3 (left) illustrates in case of the TIB.

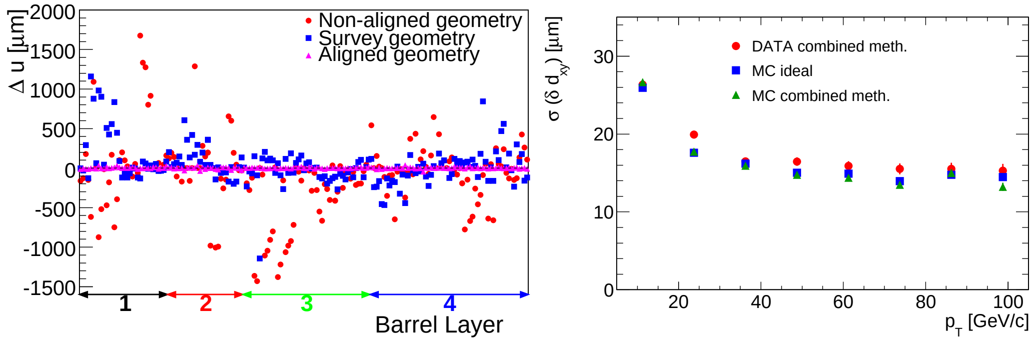

Figure 3: Mean values of overlap residuals for module pairs of TIB layers (left). RMS of the distribution of the difference between transverse impact parameters d_{xy} from track splitting with respect to transverse momentum p_t (right).

3 Tracking performance and impact on physics analyses

Misalignment causes a degradation of the tracking performance and influences the performance of many physics analyses. For example, b-tagging methods resolving lifetime signatures are sensitive to the spatial resolution and hence alignment accuracy. The impact parameter resolution is studied by splitting long tracks passing close to the interaction region at the point of closest approach related to the beam line. Both halves are reconstructed independently and their parameters are compared at the splitting point. The resolution of most parameters is almost as good as in the simulation. For the transverse impact parameter, d_{xy}, less than $20\,\mu$m is achieved for $p_t > 20\,\text{GeV/c}$ (Fig. 3 (right)). However, at this point effects from weak modes cannot be excluded. These can shift the track parameter values systematically and bias subsequent steps.

4 Conclusions

The first track-based alignment with the full tracker has been performed successfully. The local and global methods deliver similar results and show dramatic improvement in the alignment quality. However, a combined approach gives the best results. The cosmic track splitting shows that the resolution of track parameters is excellent, the RMS of the transverse impact parameter is less than $20\,\mu$m for transverse momenta above $20\,\text{GeV/c}$. Updates on predicted misalignment uncertainties and scenarios, as well as studies on weak modes have been performed. An extensive discussion can be found in [2]. The alignment procedure is well advanced and ready for collision data taking.

References

[1] R. Adolphi et al. The CMS experiment at the CERN LHC. *JINST*, 0803:S08004, 2008.

[2] CMS Collaboration. Alignment of the CMS Silicon Tracker during Commissioning with Cosmic Rays. 2009.