CMS Tracker Alignment: Legacy results from LHC Run-II and Run-III prospects.

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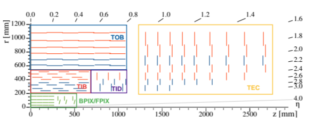
The CMS tracker

- Innermost detector, closest to the interaction point
- Estimates p_T, impact parameter, etc., of charged particles (tracks)

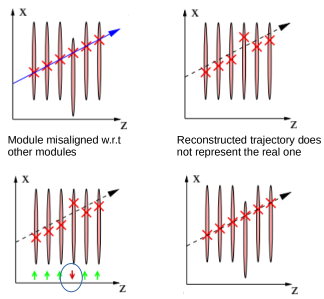
	PIXEL		STRIP			
Subdetectors	BPIX	FPIX	TIB	TOB	TID	TEC
No. of Modules	Phase-0: 1,440 Phase-1: 1,856		15,148			

Phase-0: Run-I & Run-II 2016, Phase-1: Run-II 2017-2018 & Run-III

Tracker layout [1]



Tracker Alignment: Purpose [2]



Module misaligned w.r.t other modules

Reconstructed trajectory does not represent the real one

Shift suggested by alignment

Corrected track reconstruction

Track-based alignment [3]

Goal: To push precision well below the intrinsic hit resolution (~10 µm)

Follows a least-square approach, minimising χ^2 :

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

where **p** : global alignment parameters
$\mathbf{q}_j$: local track parameters
m_{ij}: measured hit position
f_{ij}: predicted hit position
σ_{ij}: hit measurement uncertainty

Two independent (but complementary) approaches used:

MillePede-II
- Global χ^2 minimisation
- Global fit of p and q_j including all correlations

HipPy
- Local χ^2 minimisation
- Iterative procedure wherein position and orientation of each sensor determined independently

Tracker alignment at CMS for Run-II

Alignment during data taking
- Continuous monitoring of high-level structure movements of pixel detector (online)
  - Geometry automatically corrected if alignment corrections exceed certain thresholds
- Track-based alignment periodically run offline
- Improved alignment precision obtained by refining automated alignment with regular updates from offline computations

Alignment for end-of-year re-reconstruction
- Alignment conditions extracted by exploiting full data statistics during one data-taking year

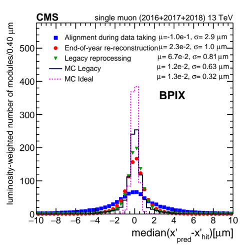
Alignment for legacy reprocessing
- Ultimate accuracy of the alignment calibration used for the final or legacy reprocessing of the data
- Up to ≈ 700k parameters,i.e., 220 geometries over the three campaigns to cover significant changes of the alignment conditions over time

Run-II Legacy Results [4]

Tracking Performance

Analysed using **Distributions of median track-hit residuals (DMRs)**

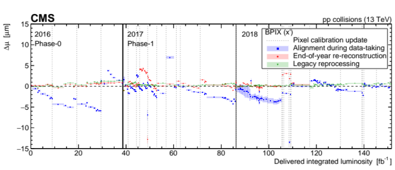
- Each track refitted without the hit under consideration, for unbiased computation
- The median of the residuals per module calculated
- Mean (µ) and width (σ) of the DMR extracted with a Gaussian fit
- For perfect alignment, DMRs expected to be centred at zero
- Below: DMR in the local x (x') coordinate for BPIX averaged over all IOVs



The direction of the Lorentz drift depends on the orientation of the modules. So:
- DMRs also produced for inward- and outward-pointing modules separately
- Difference between the means of the DMRs, Δµ, calculated
  - Non-zero value indicates residual biases due to the accumulated effects from radiation in the silicon sensors

Trends (Vertical dotted lines indicate a change in pixel tracker calibration)

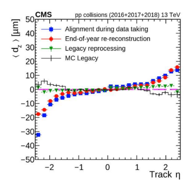
Significant improvement for the legacy reprocessing over the alignment during data taking and end-of-year re-reconstruction
- The finer granularity of time dependence in legacy reprocessing reduces the bias
- The rapidly changing shift from local reconstruction can be absorbed in the position of the ladders and of the modules



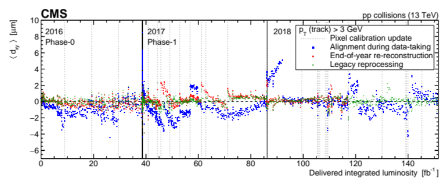
Vertexing Performance

- Distance between tracks and vertex reconstructed without the track under scrutiny
- Impact parameter distributions of the considered track investigated
- Ideally, distributions flat with values equal to zero

- Shown on the right: Mean track-vertex impact parameter in the longitudinal plane d_z as a function of track η.
  - **Performance improved only with the legacy reprocessing.**



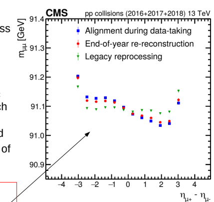
Trends



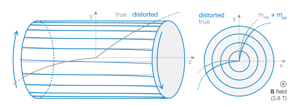
Dimuon invariant mass reconstruction

In an ***ideally aligned*** tracker: the reconstructed $Z \to \mu\mu$ invariant mass minimally dependent on which direction the muons travel in the detector

Below: An example of a systematic distortion (**twist distortion**) to which $Z \to \mu\mu$ decays are very sensitive
- $m_{\mu\mu}$ deviates from the expected value and becomes a function of the track parameters.



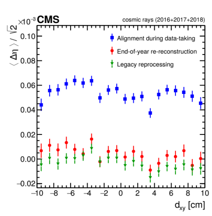
The sigmoid shape, typical of a twist distortion, is reduced in the legacy reprocessing.



Cosmic ray muon track validation

- Two individual track candidates created from each cosmic ray muon track by splitting them at their point of closest approach to the interaction region
- Differences between the track parameters of the two halves can indicate a systematic misalignment

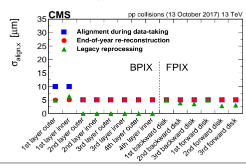
Strategy followed in the legacy alignment procedure has led to better performance
- Indicates improved statistical precision of alignment fit



Alignment Position Errors

Accounts for the uncertainty in the positions of the modules derived from the alignment fit.

Basic idea of APE estimation:
- Hit residual $r = x_{trk} - x_{hit}$ and square of residual error $\sigma_r^2 = \sigma_{trk}^2 + \sigma_{hit}^2$
- Normalized hit residual distributions $r_{norm} = r/\sigma_r$ of each module should equal 1 for perfect alignment
- Broadened if misaligned
- Introduce σ_{align} so that $\sigma'^2_r = \sigma_r^2 + \sigma_{align}^2$
- If σ_{align} correctly estimated, $r'_{norm} = r/\sigma'_r = 1$



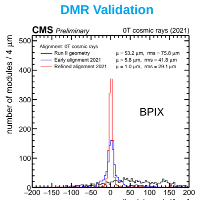
Run-III: Commisioning and Prospects

CRUZET21: Cosmic RUn at ZEro Tesla [5]

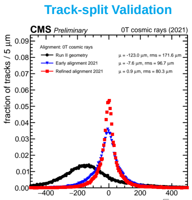
First alignment after detector maintenance and BPIX L1 replacement (Jul-Aug 2021)

Run II geometry: Geometry assumed at the beginning of the 2021 cosmics data taking
Early alignment: 120k tracks, aligned half-barrels in BPIX and half-cylinders in FPIX
Refined alignment: 1.5M tracks, aligned ladders in BPIX and half-cylinders in FPIX

DMR Validation



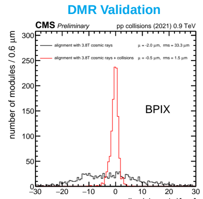
Track-split Validation



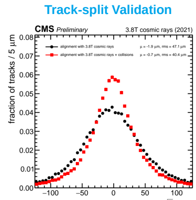
CRAFT21: Cosmic Run At Four Tesla + Collisions at 900 GeV [6]

Alignment with 3.8T cosmic rays: 700k tracks, aligned half-barrels in BPIX and half-cylinders in FPIX
Alignment with 3.8T cosmic rays + collisions: 22M tracks, aligned Pixel at module-level and Strip at half-barrel and half-cylinder levels

DMR Validation



Track-split Validation



Further Steps

- Deploy finer granularity for automated alignment
  - Larger irradiation doses cause stronger variation of Lorentz drift of charged carriers released by charged particles passing through the silicon sensors
  - Alignment procedure sensitive to Lorentz drift changes induced by accumulated radiation after ≈ 1 fb⁻¹ but pixel local reconstruction calibration only performed after ≈ 10 fb⁻¹
  - If the alignment performed at a high enough granularity: inward and outward-pointing modules free to move separately and the bias coming from Lorentz angle miscalibration absorbed

Evident from Δµ vs delivered integrated luminosity plot shown for Run-II tracking performance

- More geometries to be derived to cover significant changes over time.

References
[1]The Phase-2 Upgrade of the CMS Tracker, CMS Collaboration, CERN-LHCC-2017-009, CMS-TDR-014
[2]Momentum bias determination in the tracker alignment and first differential ttbar cross section measurement at CMS, Holger Enderle, CERN-THESIS-2012-248
[3]Alignment of the CMS tracker with LHC and cosmic ray data, CMS Collaboration, 2014 JINST 9 P06009
[4]Strategies and performance of the CMS silicon tracker alignment during LHC Run 2, CMS Collaboration, CMS-TRK-20-001-003
[5]First Tracker Alignment results with 2021 cosmic ray data, CMS Collaboration, CMS-DP-2021-025
[6]CMS Status Report, 148th LHCC Meeting - OPEN Session