Alignment of the CMS Tracker: Results from LHC Run 3

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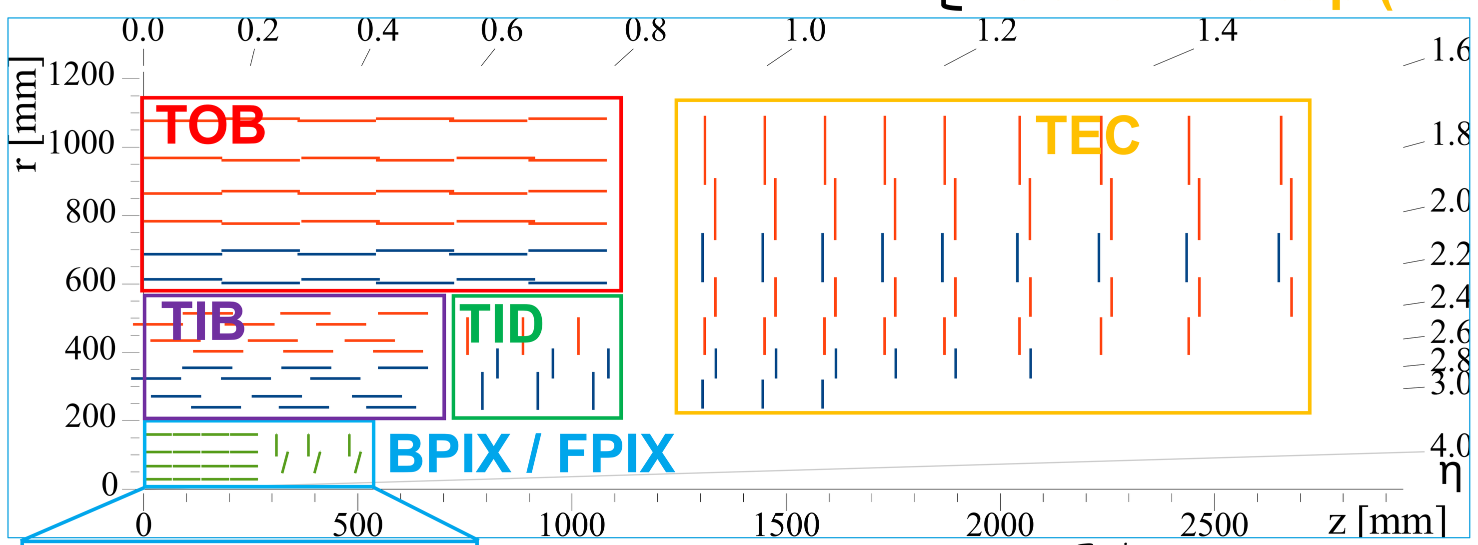
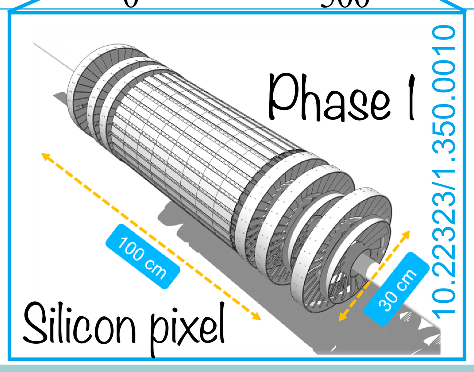
CMS tracker detector

Layout

Inner tracking system of CMS experiment

- **Silicon pixel detector** — 1856 modules after upgrade in 2017 (ref. to Phase 1)
  - Barrel Pixel (BPIX)
  - Forward Pixel (FPIX)
- **Silicon strip detector** — 15 148 modules
  - Tracker Inner Barrel (TIB)
  - Tracker Outer Barrel (TOB)
  - Tracker Inner Disk (TID)
  - Tracker Endcap (TEC)





> Organized in barrel and endcaps

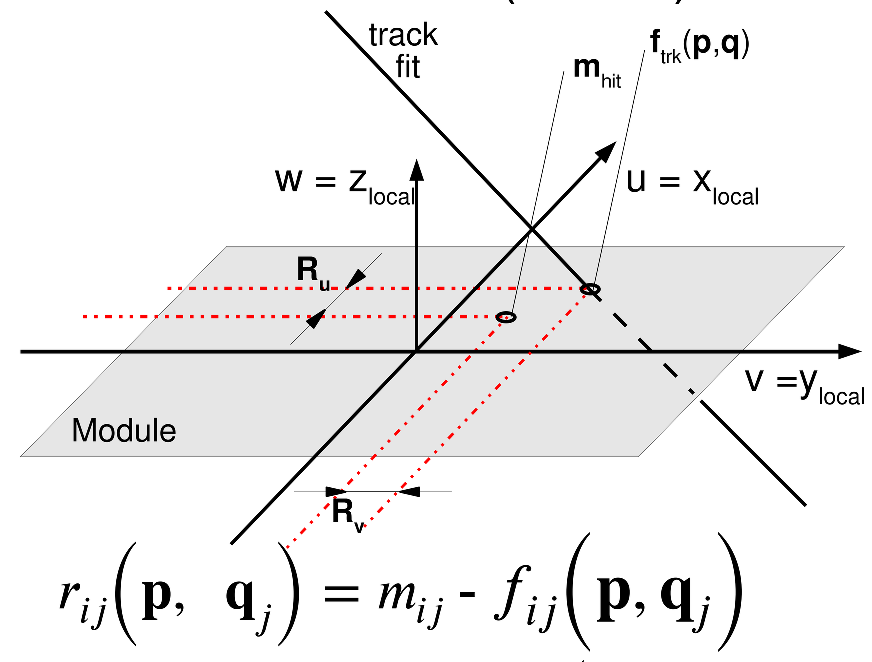
> Hierarchical structure

barrels -> half barrels -> layers -> modules

Track-based alignment

From installation precision to precision for physics analysis

Goal: determine with a precision down to a few µm the position of all silicon modules of the tracker (× 6 dof)



$$r_{ij}(\mathbf{p},\ \mathbf{q}_j) = m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)$$

$$\chi^2(\mathbf{p},\ \mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{measurements}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p},\ \mathbf{q}_j)}{\sigma_{ij}}\right)^2$$

$m_{ij} \pm \sigma_{ij}$: measured hit position

f_{ij}: predicted hit position

p: global alignment parameters

$\mathbf{q}_j$: local track parameters [1,2]

> Minimisation of sum of squares of normalised track-hit residuals

Automated alignment

- continuous online monitoring of high-level structure movements of pixel detector
- geometry automatically corrected if alignment corrections exceed certain thresholds

Offline Alignment

- track-based alignment run offline for refinement of online calibration, silicon strip detector alignment, and recovering from weak modes making use of increased track kinematic variety

Alignment algorithms

Complementary approaches

> Two independent implementations of track-based alignment used in CMS

MillePede

- performs global fit including all correlations of global alignment parameters and local track parameters
- contains two steps
  - **Mille**
    - integrated in alignment software
    - produce dedicated binary files (from track/hit data)
  - **Pede**
    - standalone solver
    - build linear equation system from binary files
    - solve linear equation system

HipPy

- position and orientation of each sensor determined independently
- multiple iterations to solve correlations between sensor parameters
- small matrix inversion on each iteration

Method	Computing time	Solution type	Error calculation
Inversion (Gauss–Jordan)	$\sim n^3$ (n: number of parameters)	Exact	Yes
Cholesky decomposition	$\sim n^3$	Exact	Skipped (for speed)
MinRes	$\sim n^2 \times n_{it}$ (n_{it}: number of internal iterations)	Approximate	No

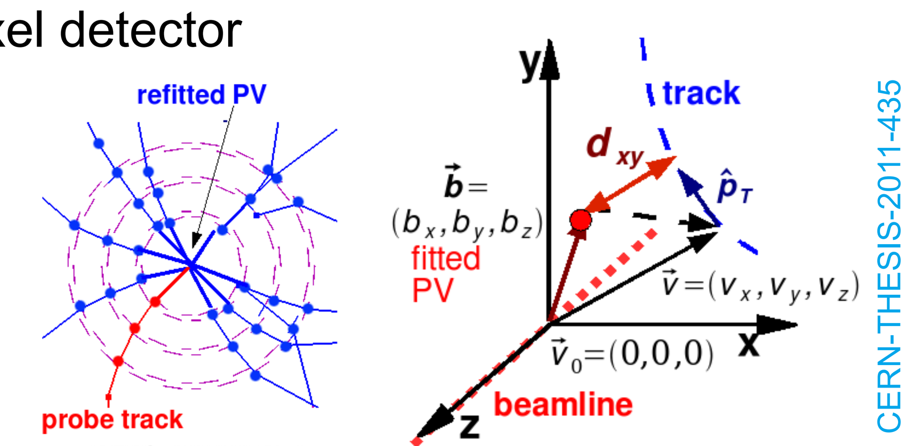
[2]

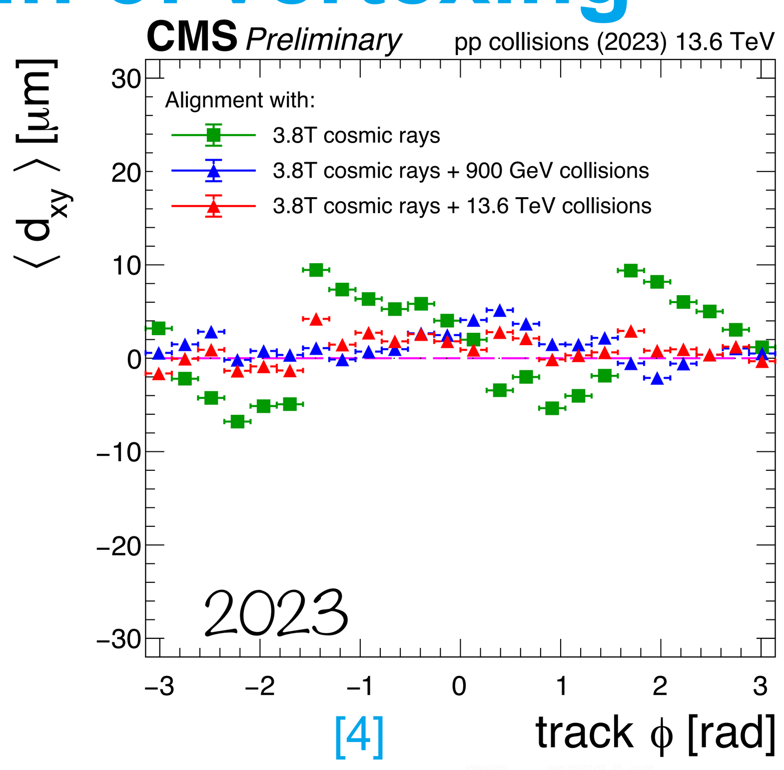
Performance in Run 3: vertexing

Track-vertex impact parameter

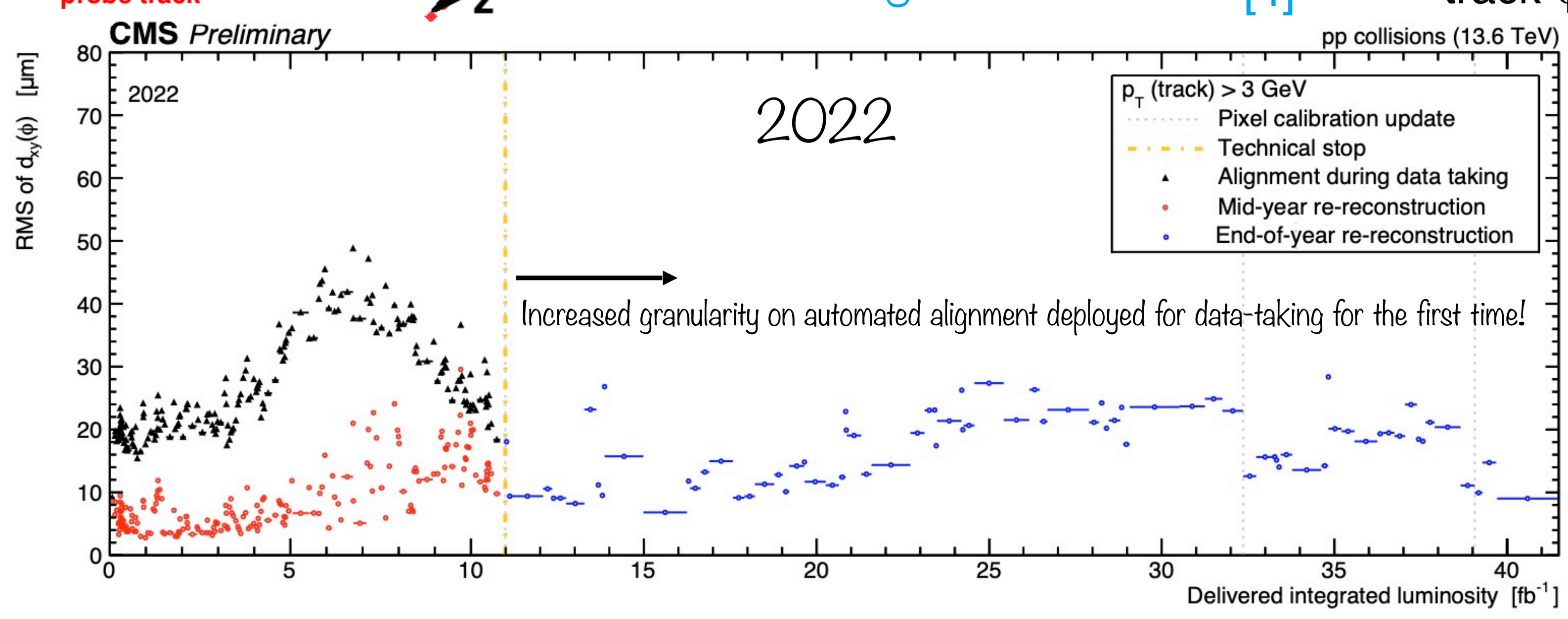
> distance between track and vertex reconstructed without track under scrutiny

> evaluate performance of alignment in pixel detector





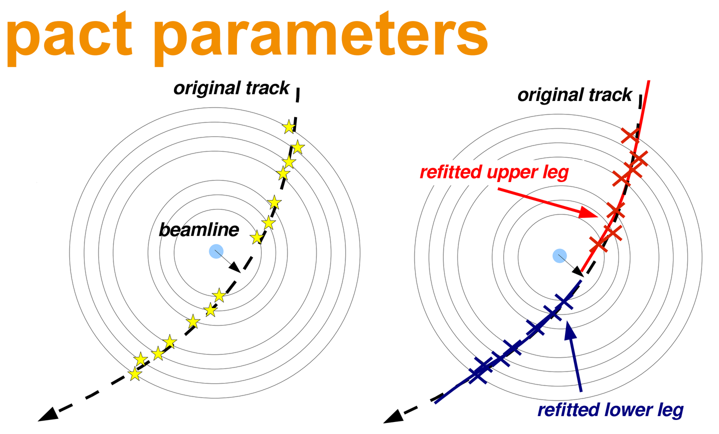
[4]

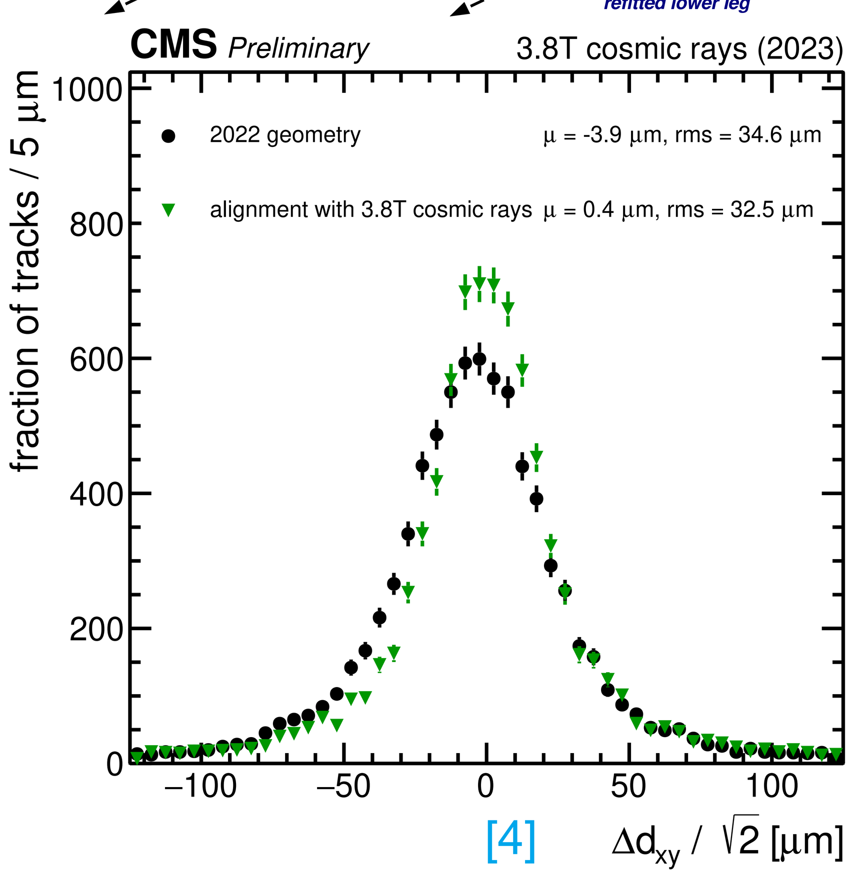


[3]

Performance in Run 3

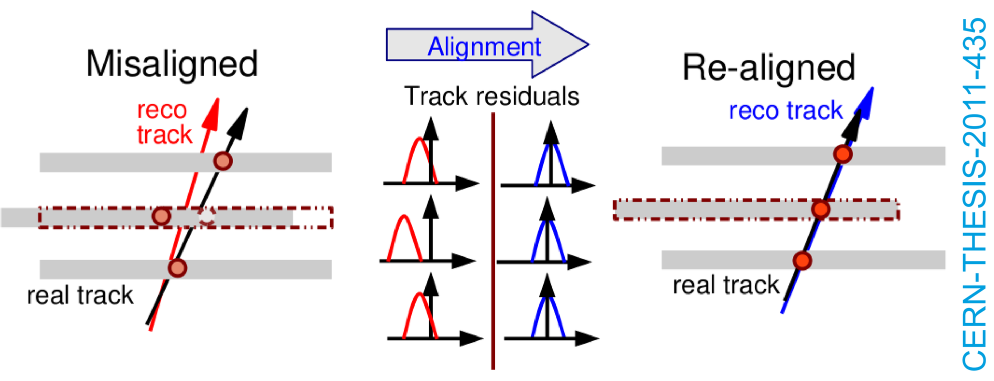
Difference of transverse impact parameters

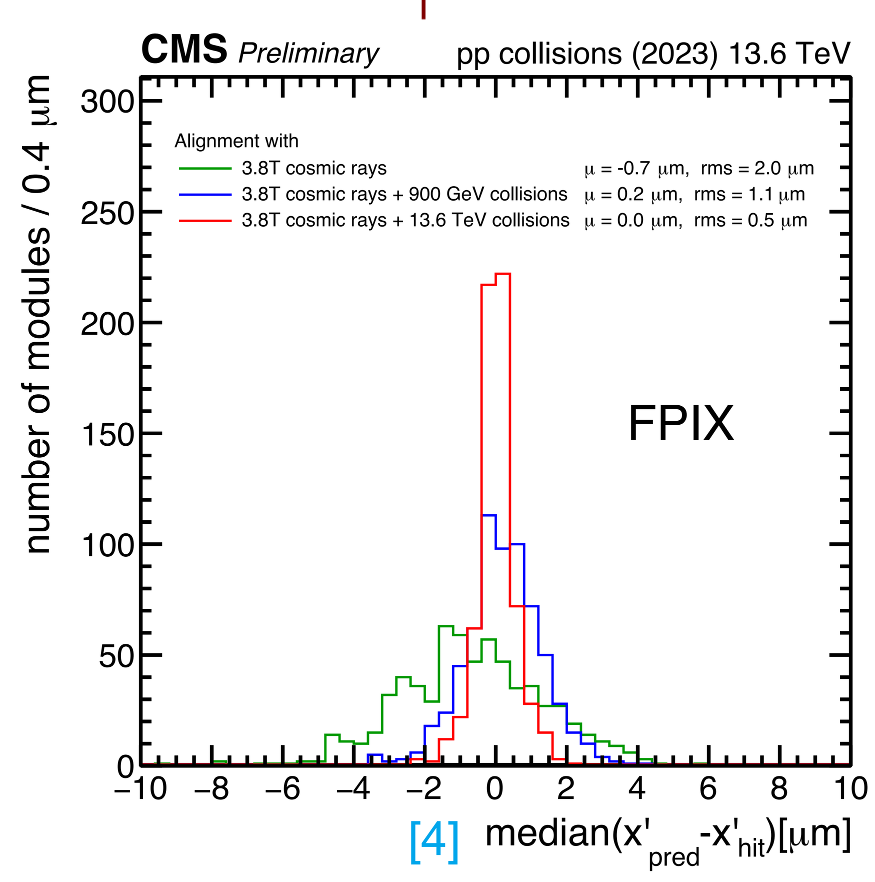




[4]

Distribution of median of track-hit residuals





[4]

Summary

> Alignment effort on derivation of tracker alignment constants during first two years of LHC Run 3

- **2022**
- **early 2023**

> Focus on improving quality of alignment calibration already during initial data reconstruction by optimising automated workflows

Set of validations showing performance of physics observables after alignment

- Tracking performance (Distribution of median residuals)
- Vertexing performance (Track-vertex impact parameter)
- Monitoring of systematic distortions (Muon Track split validation)

show we are on the right path towards this goal

> Excellent Run 3 start in terms of alignment precision as base for ongoing efforts on derivation of refined set of constants for "legacy" reprocessing of 2022 and 2023 datasets

References:

[1] CMS Collaboration "Strategies and performance of the CMS silicon tracker alignment during LHC Run 2", doi:10.1016/j.nima.2022.166795

[2] CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data", doi:10.1088/1748-0221/9/06/P06009

[3] The CMS Collaboration, "Tracker alignment performance in 2022 (addendum)", CERN-CMS-DP-2022-070

[4] The CMS Collaboration, "Tracker alignment performance in early 2023", CERN-CMS-DP-2023-039

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