First alignment of the Run 3 CMS tracker with cosmic rays and collision tracks

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on behalf of the CMS Collaboration

Terascale annual meeting
24.11.2021

Overview

- Track based alignment of the CMS tracker
- First alignment results with 2021 collision data and cosmic rays

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-203
2021/11/16

CMS-TRK-20-001

Strategies and performance of the CMS silicon tracker alignment during LHC Run 2

The CMS Collaboration*

Abstract

The strategies for and the performance of the CMS silicon tracking system alignment during the 2015–2018 data-taking period of the LHC are described. The alignment procedures during and after data taking are explained. Alignment scenarios are also derived for use in the simulation of the detector response. Systematic effects, related to intrinsic symmetries of the alignment task or to external constraints, are discussed and illustrated for different scenarios.

Submitted to Nuclear Instruments and Methods A

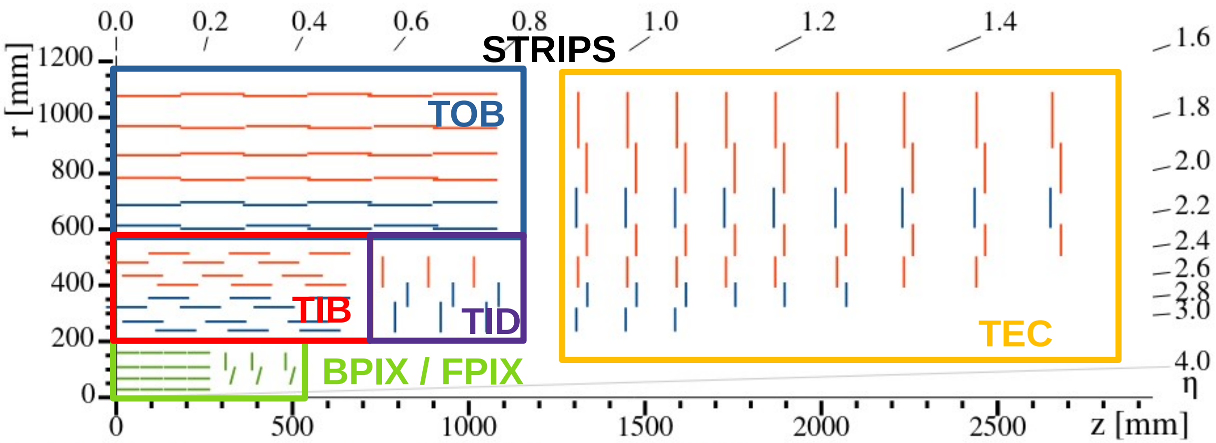
*See Appendix A for the list of collaboration members

CMS-CFT-09-003
CMS-TRK-11-002
CMS-TRK-20-001-003

The CMS tracker system

- Largest fully sillicon-based detector, both in surface area and number of sensors

- Two main subsystems:
  - **The pixel detector** closest to the interaction point
    Phase-1 upgrade in 2017, 1856 silicon modules in 4 cylindrical barrel layers (**BPIX**) and 3 pairs of endcap discs (**FPIX**)
  - **The strip detector** surrounds the pixel tracker
    15148 silicon modules segmented in micro-strip
    Four subsystems: Tracker Inner Barrel (**TIB**), Tracker Inner Disk (**TID**)
    Tracker Outer Barrel (**TOB**), Tracker Endcap (**TEC**)



BPIX layer 1 replaced with new modules for Run 3

CMS-TDR-019
CMS-TDR-011
CMS CR-2021/183

Alignment of the CMS tracker

CMS tracker designed to provide a hit resolution of O(10 μm) but the precision of mechanical alignment is O(100 μm)

- ➔ Position and orientation of each module must be precisely measured

Tracker alignment goal

Determine with a precision of a few μm the position and orientation of ~17k modules of the tracker

- Use tracks to align the tracking detector (**Track based alignment**)
- Wrong assumption of tracker geometry:
  - Bad track reconstruction, worst case ---> no tracks
  - Increase of track-hit residuals

DESY-THESIS-2015-035

Track based alignment

DESY 02-077

Minimize sum of squares of the track-hit residuals:

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

p: global alignment parameters (module position / orientation)
$\mathbf{q}_j$: local track parameters (e.g. parameters related to track curvature and deflection angles due to multiple scattering)
$m_{ij} \pm \sigma_{ij}$: measured hit position
f_{ij}: predicted hit position

Huge linear system

- N modules with six degrees of freedom ---> solve an equation system of 6N parameters
- CMS tracker ~ 17k modules ---> O(100k) parameters to be determined

Alignment algorithms

MillePede-II: Global fit including all correlations of global and local track parameters

HipPy: Position and orientation of each sensor is determined independently in multiple iterations: small matrix inversion on each iteration

- Complementary approaches
- Return the O(100k) alignment parameters
- Today's results obtained with MillePede-II

Solution methods implemented in MillePede-II

Method	Computing time	Solution type	Error calculation
Inversion (Gauss Jordan)	$\sim n^3$	Exact	Yes
Cholesky decomposition	$\sim n^3$	Exact	Skipped (for speed)
MINRES	$\sim n^2 \times n_{it}$	Approximate	No

Used in today's results
Preferred approach but high time consumption
Align at high level structures ---> ~2 hours

Tracker alignment strategy during data taking

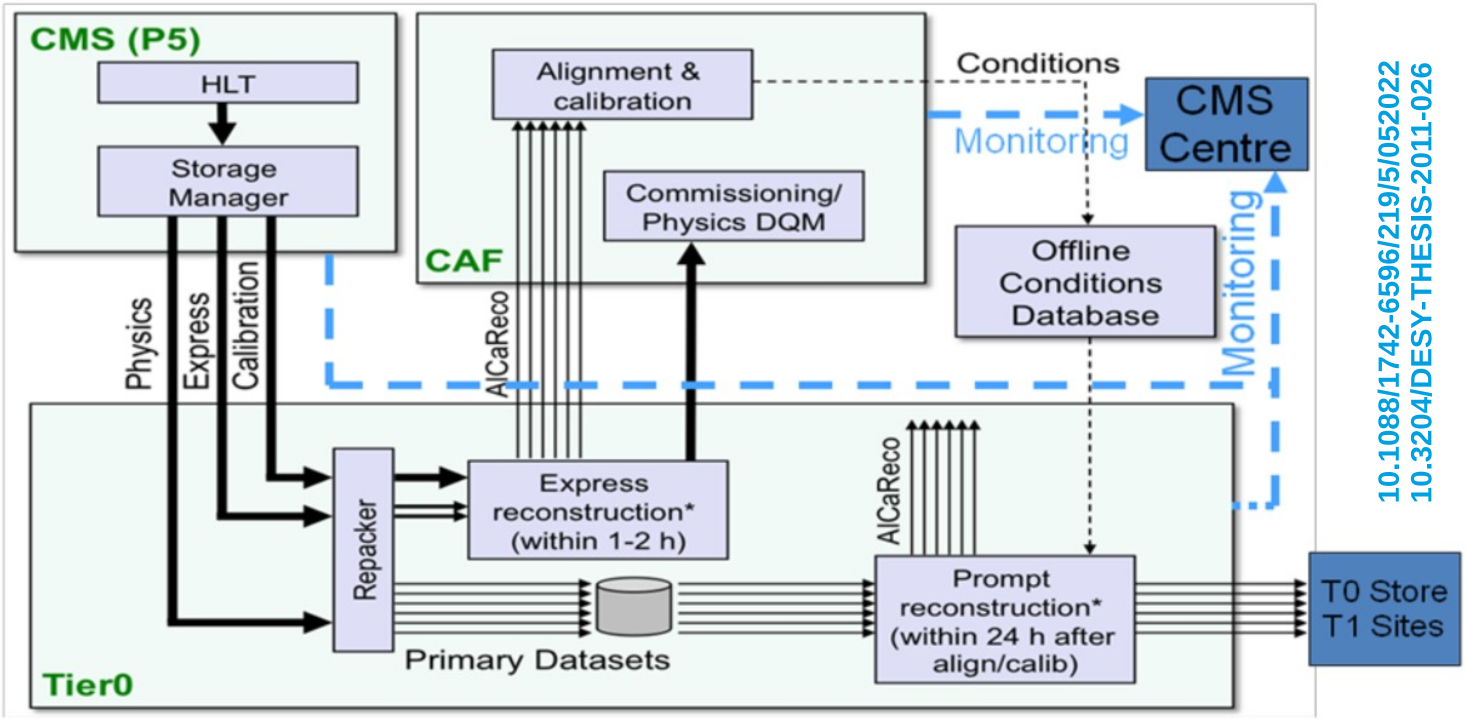
Offline alignment

- Restarting the detector using only limited statistics after the technical shutdown --> align large mechanical structures first
- Increase alignment granularity up to module-level as more statistics is available
- Track-based alignment periodically run offline

Automated alignment

- Continuous monitoring of the pixel detector at the level of large mechanical structures
- Geometry automatically corrected if alignment corrections are within certain thresholds
- Regularly refined with campaigns going on parallel offline

Prompt alignment and calibration workflows



10.1088/1742-6596/219/5/052022
10.3204/DESY-THESIS-2011-026

Embedded in the reconstruction chain of the data recorded by CMS

- Data is sent from CMS (P5) to the Tier-0 centre
- Dedicated calibration and express streams are processed and sent to CAF within a very short latency, where new calibration and alignment constants are computed
- Condition databases are updated and full event reconstruction can start at Tier-0

CMS data-taking during summer 2021

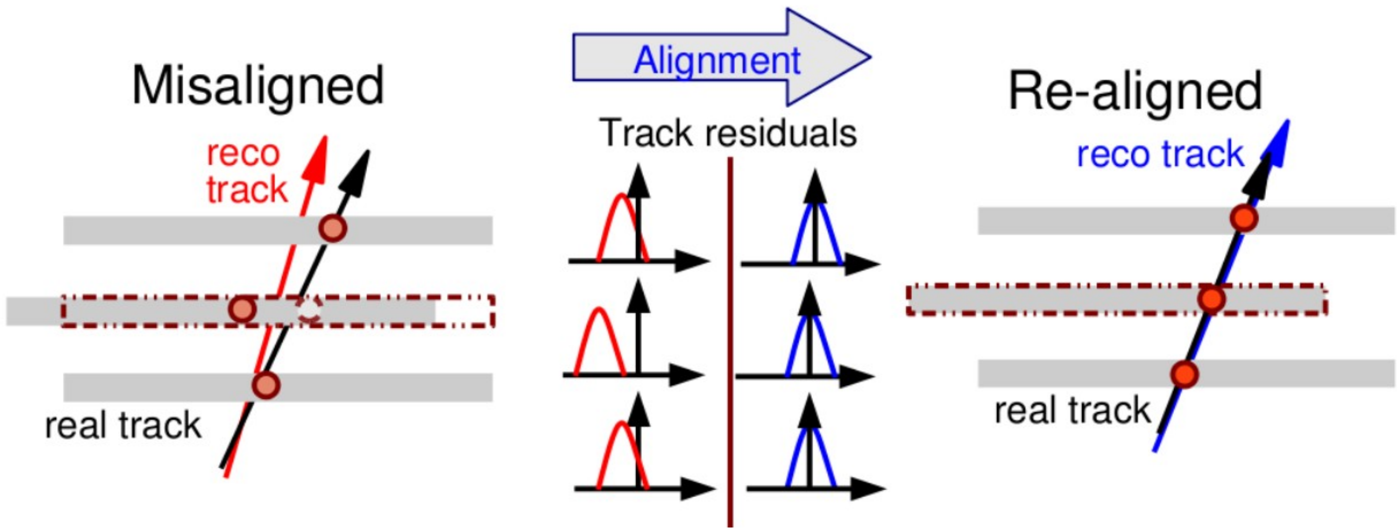
- July-August - data from cosmic rays at 0 T (CRUZET) was collected
- Tracker operated together with all subdetectors
- Alignment obtained with CRUZET:
  - **Early alignment**: starting from the **Run-II geometry.**
    Aligned pixel and strips at large mechanical structures level, 120k tracks used
  - **Refined alignment**: increased granularity in BPIX, 1.5M track

Performance of new tracker geometry compared to previous (validations):
- Check the improvement of the post-alignment track-hits residuals
- Check impact of alignment in physics observables

Alignment Performance: DMR validation

Each track is refitted using the alignment parameters under study

- The hit prediction for each module is obtained from all hits except the one under consideration
- A histogram is filled with the median of the distribution of track-hit residuals of each module



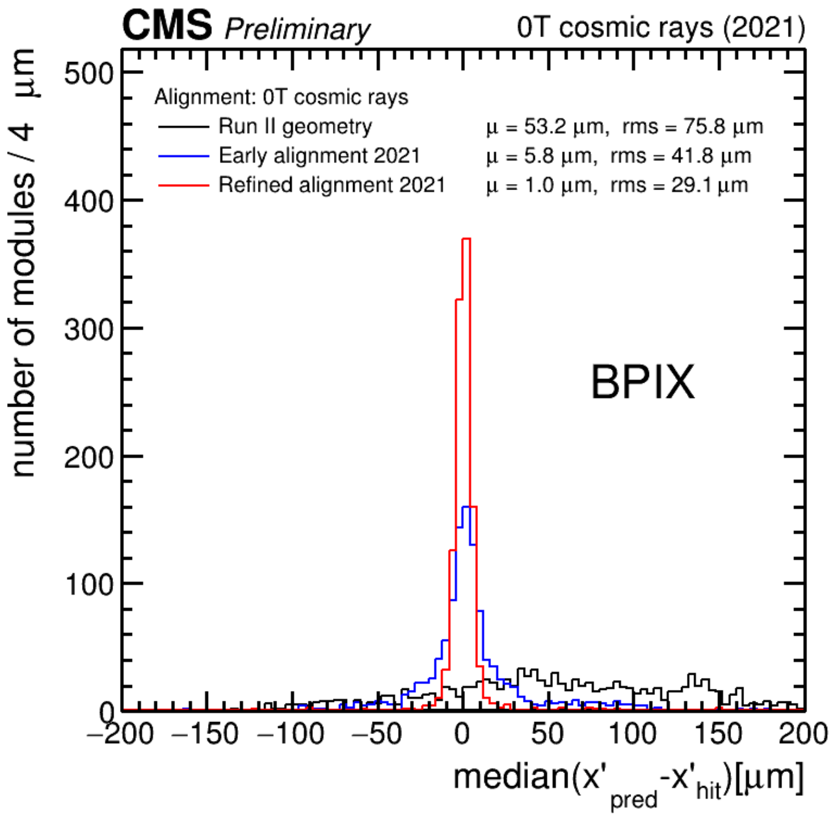
CMS-THESIS-2011-435

Mean deviation from 0 indicates possible biases

Width measure of the local precision of the alignment

Alignment Performance: DMR validation

Distribution of median of residuals along the local x direction for BPIX.
Alignment with 2021 CRUZET data (0T cosmic rays)



CMS-DP-2021-025

Significant improvement in both mean and RMS of the distribution with the Early and Refined alignment wrt. the Run-II geometry

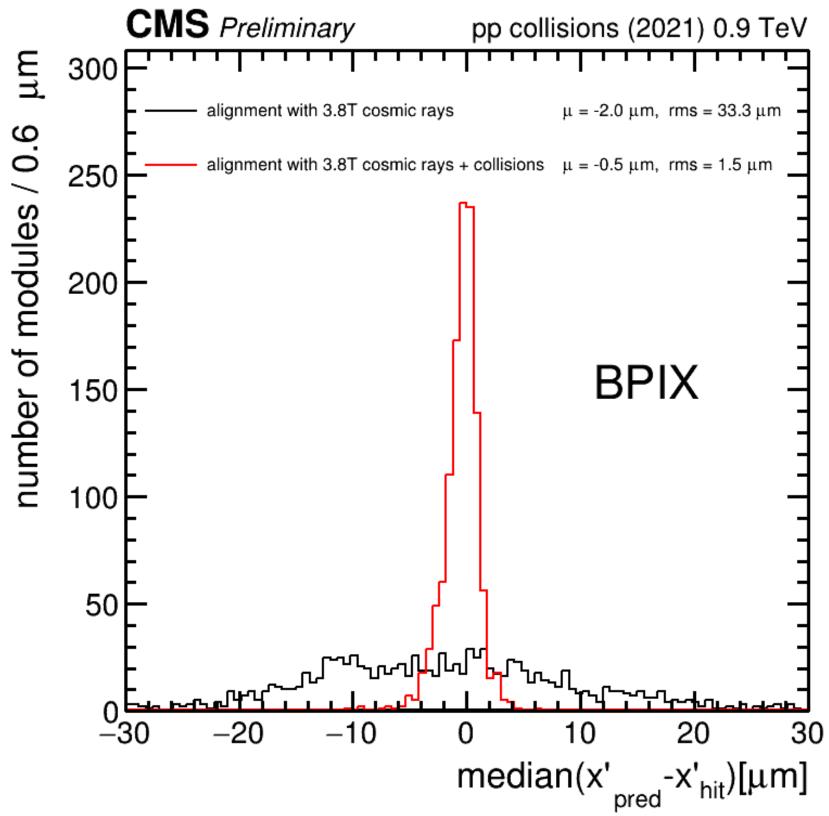
CMS data-taking during autumn 2021

- October - cosmic rays at 3.8 T (CRAFT) data was taken, followed by a collision data taking exercise (October/November)
- Tracker operated together with all subdetectors
- **Alignment with CRAFT:**
  Pixels and strips were aligned at the level of large mechanical structures, 700k tracks used.
- **Alignment with CRAFT + collisions + cosmic rays during collisions:**
  First alignment with collision data after the long shutdown
  Starting from the geometry obtained with **CRAFT**
  Pixels aligned at module level and strips at large mechanical structures
  22M tracks used

Performance of new tracker geometry compared to previous

Alignment Performance: DMR validation

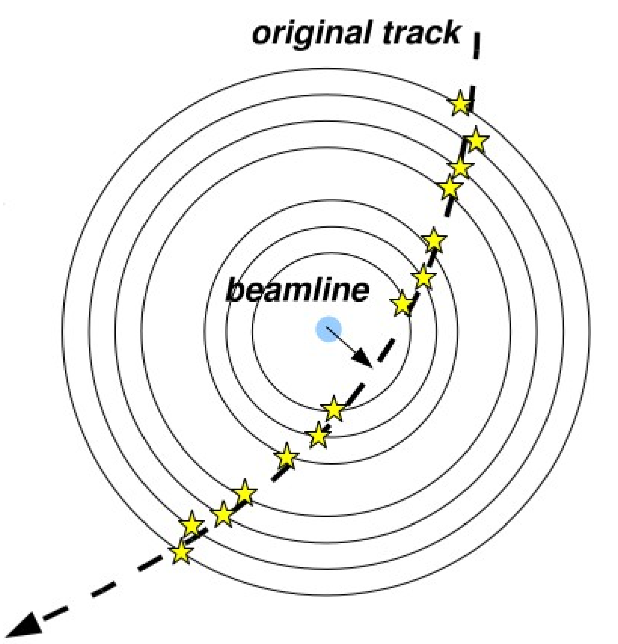
Distribution of median of residuals along the local x direction for the barrel pixel (BPIX)

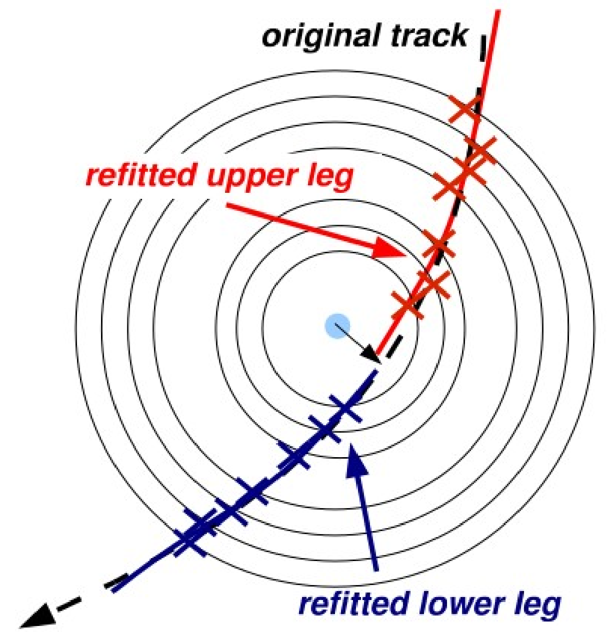


Improvement in both mean and RMS of the distribution in alignment with cosmic rays and collision data at 3.8T wrt. previous alignment.

LHCC open session

Alignment Performance: Track split validation



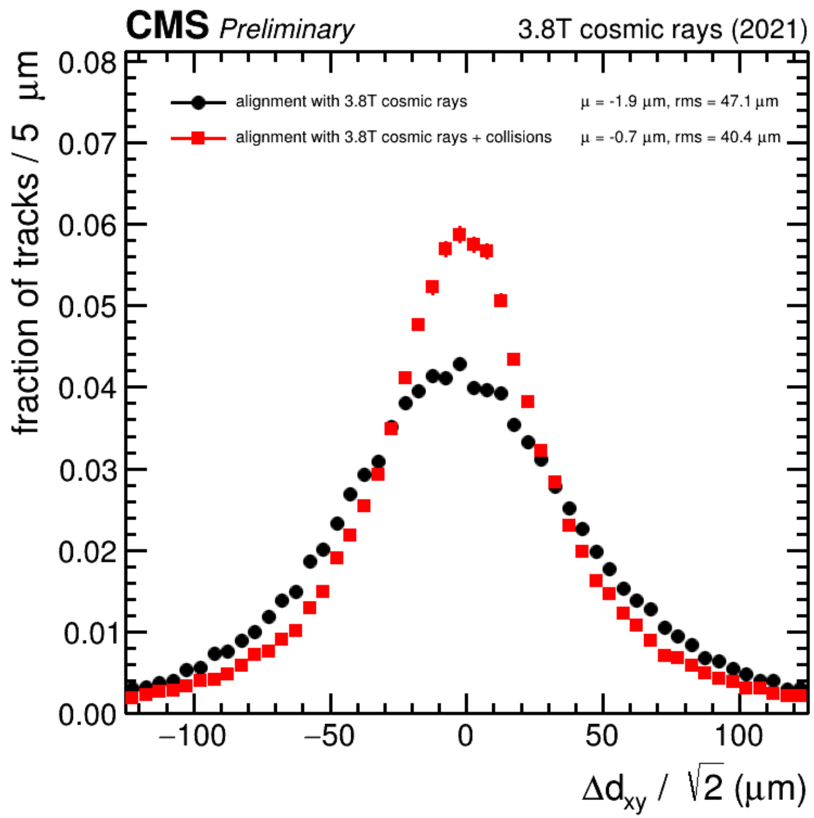


Create two individual track candidates from each cosmic track by splitting the cosmic tracks at their point of closest approach to the interaction point

- Compare the track parameters of the two track candidates (e.g. difference of transverse and longitudinal impact parameters)
- Method sensitive to off-centering of the barrel layers and endcap rings

Alignment Performance: Track split validation

Normalised difference between two halves of a cosmic track in the track transverse impact parameter

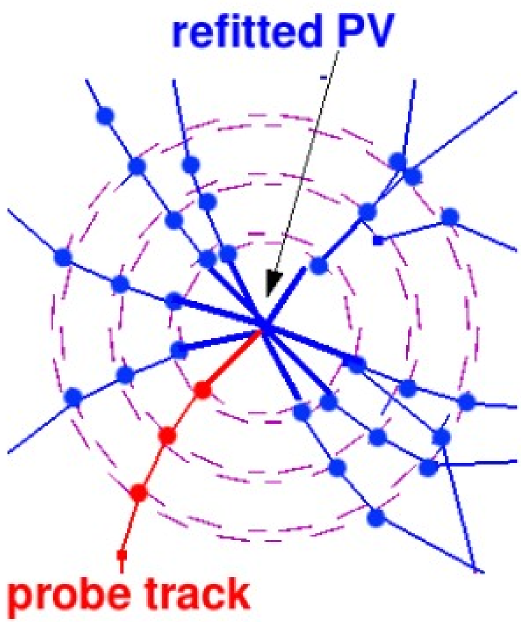


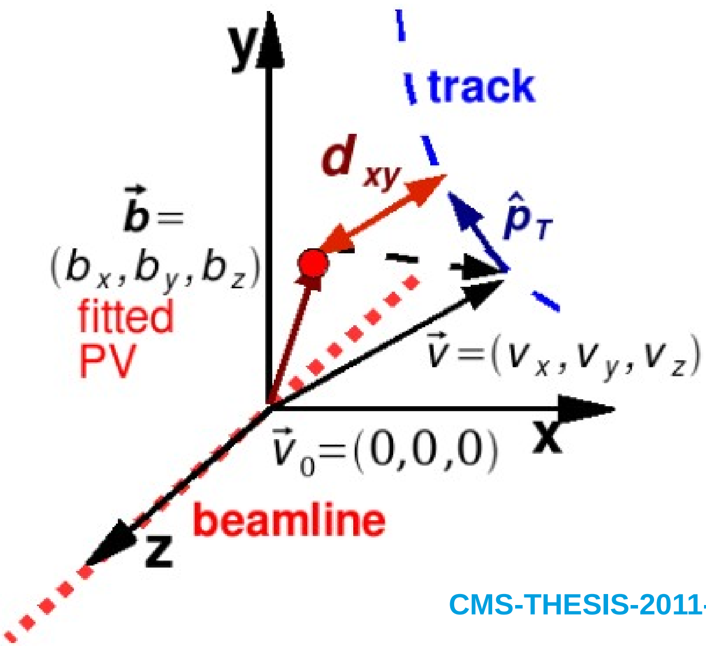
LHCC open session

The mean and RMS values show that the bias is reduced for the alignment with cosmic rays and collision data at 3.8T wrt. previous alignment

Alignment Performance: PV validation

- Select a sample of collision tracks and extract hits of a **probe track**
- Fit the primary vertex with the remaining ones and evaluate the impact parameter of the probe track wrt. the vertex
- Iterate over all good tracks

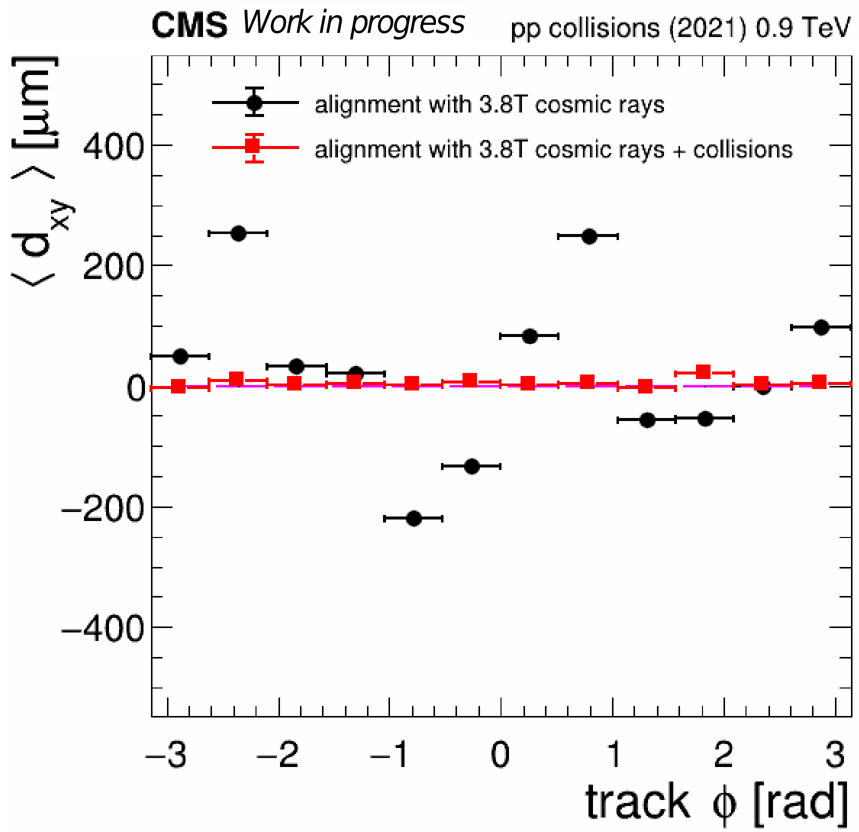




CMS-THESIS-2011-435

Alignment Performance: PV validation

Mean track vertex residuals in the transverse direction as a function of ϕ



The distribution is below to 50 μm for the alignment with cosmic rays and collision data at 3.8T, while for previous alignment are up to 250 μm

Summary

- The track-based alignment and the alignment strategy for 2021 data taking were explained
- The CMS alignment and calibration workflows and turn-arounds were described, as well as the use of the CMS CERN Analysis Facility (CAF) for this purpose
- First Run-III tracker alignment results with were presented
  - Set of validations to evaluate the achieved performance of the proposed alignment were described
  - The results comparing the obtained alignment achieved with collision data and cosmic rays were shown

Thank you

Contact

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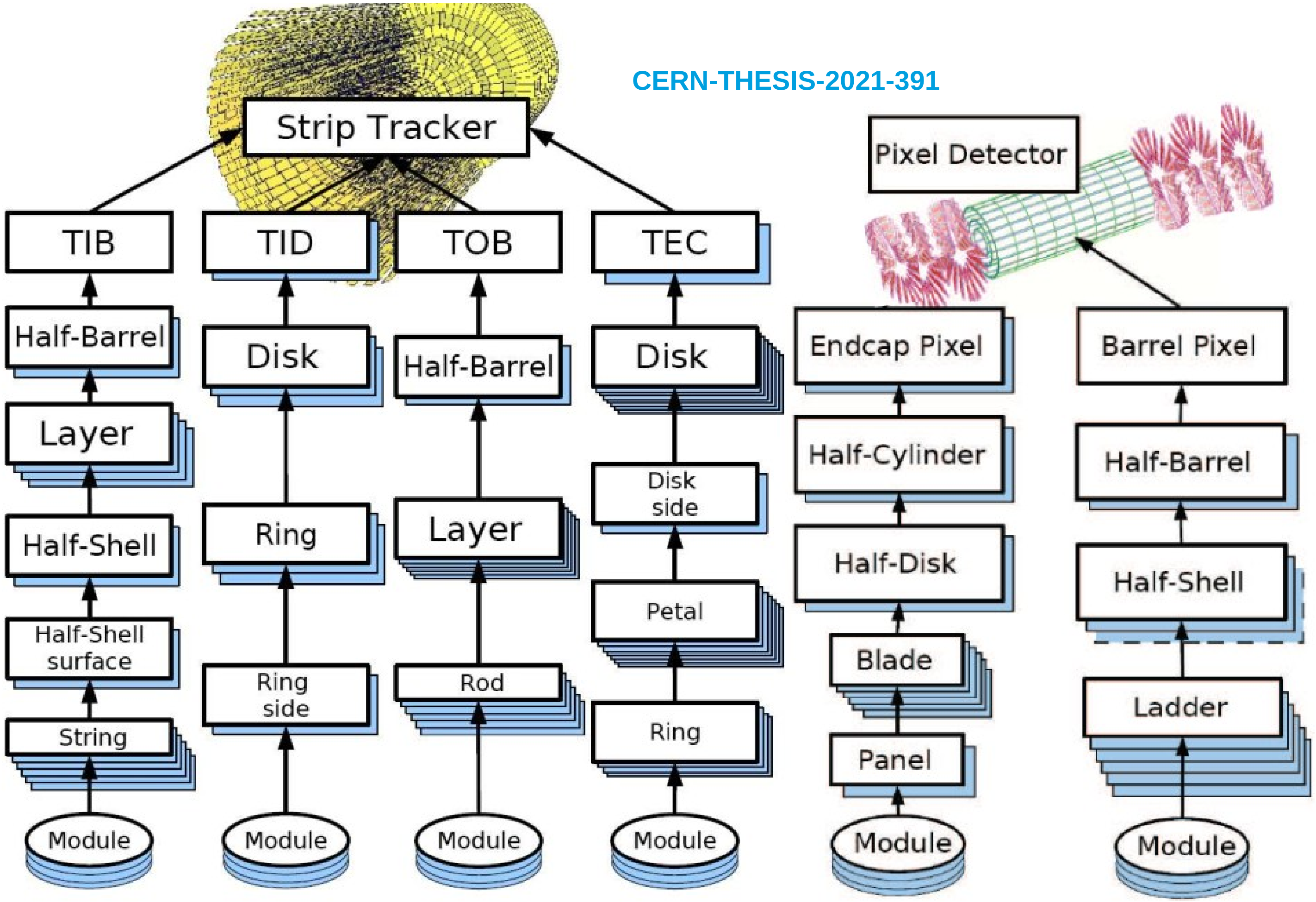
Backup

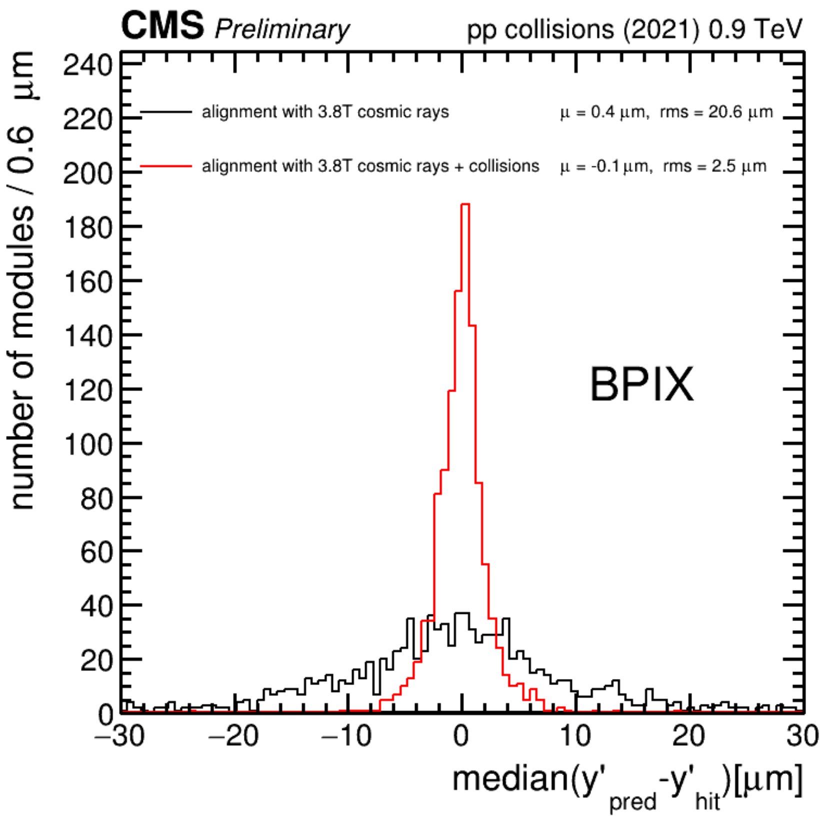
Structure of the CMS tracker system

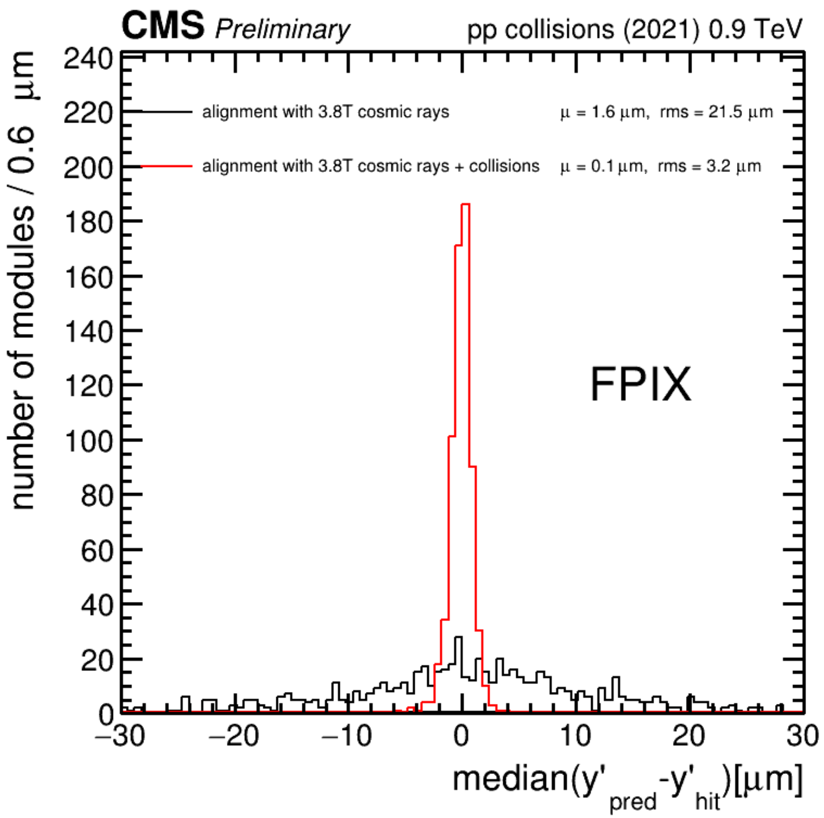


Hierarchical structure from higher level structures down to module level

Alignment Performance: DMR validation

Distribution of median of residuals along the y direction for the pixel detector





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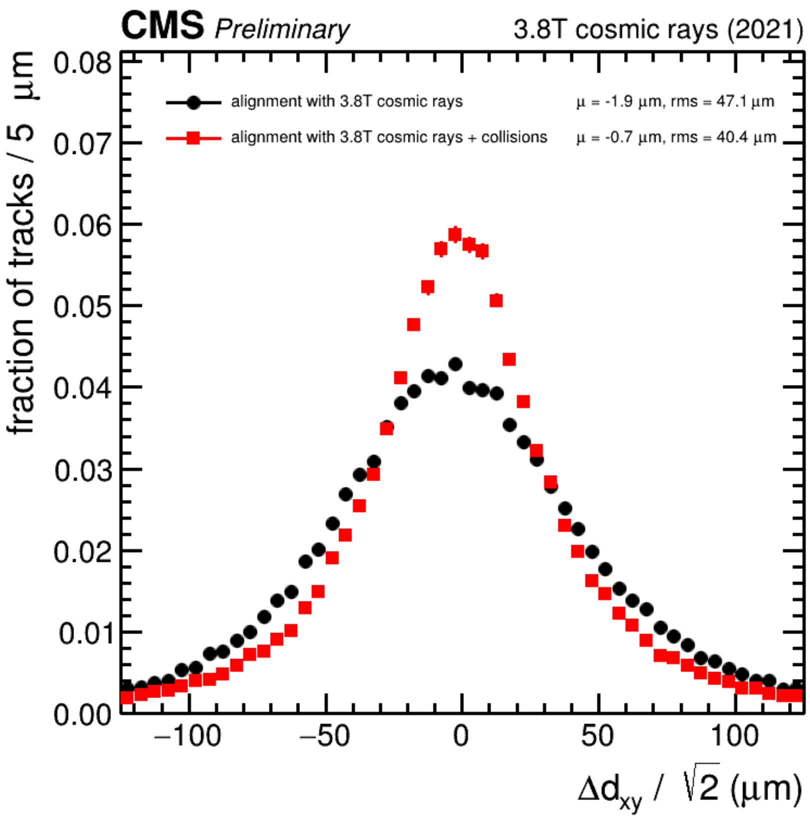
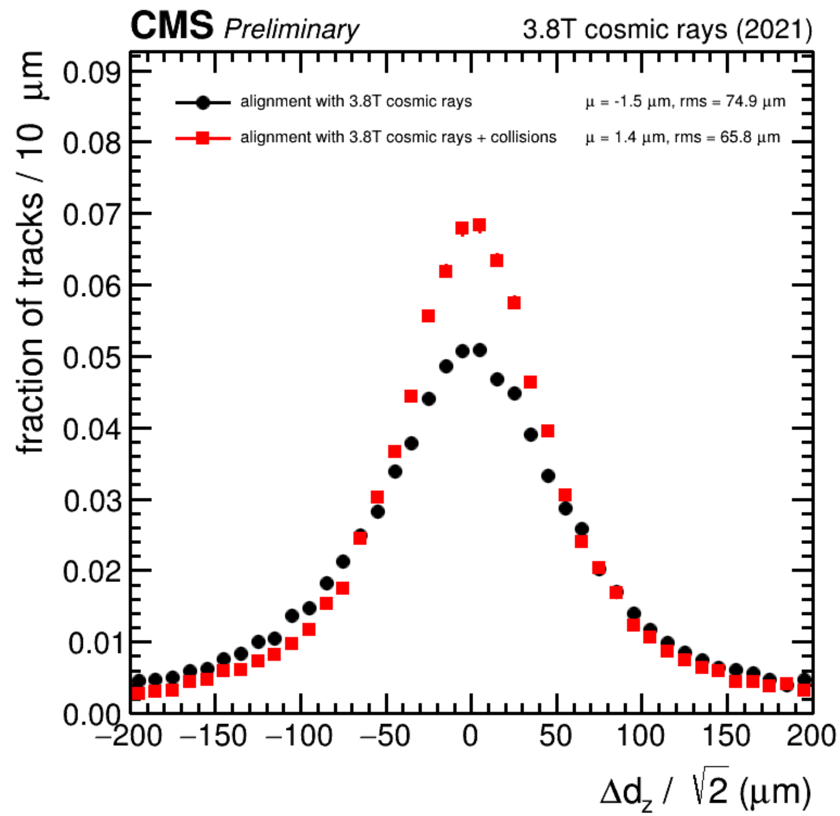
Alignment Performance: Tracksplit validation

Normalised difference between two halves of a cosmic track in the track transverse and longitudinal impact parameters





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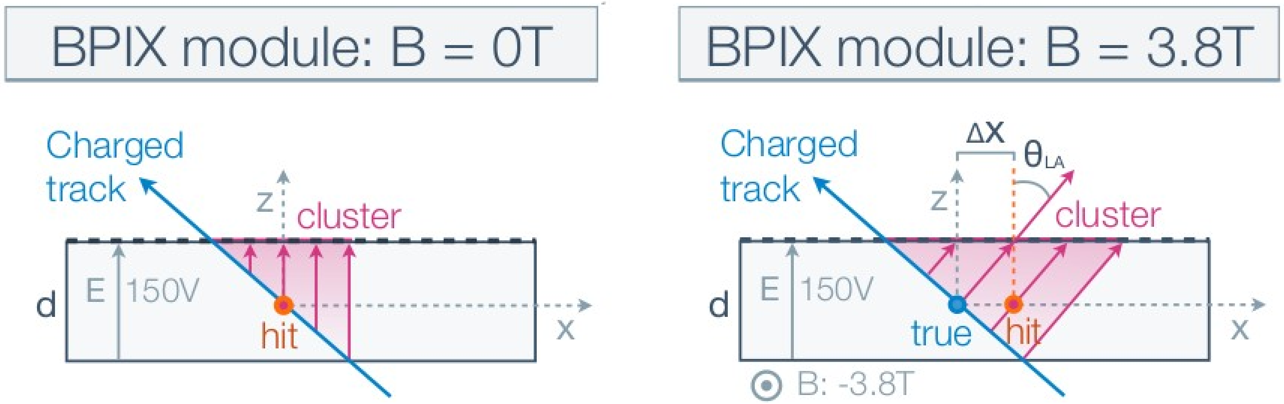
Run 3 prospects

- Aiming at obtaining a finer granularity in the alignment at earlier stages wrt. Run 2
- Tools update in progress: Finer granularity in automated alignment, improvement of the triggers for cosmics collection during collisions, imporvement on the pixel barycentre tool, etc.
- Integrated luminosity of Run 2 is expected to be doubled, so stronger deviations are expected due to the effects of the magnetic field on the charge carriers (Lorentz drift).
  - To compensate for this effect it is necessary to achieve a high granularity alignment, and update blades and ladders in each IOV.



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