Alignment of the CMS Tracker during Run 3 data taking

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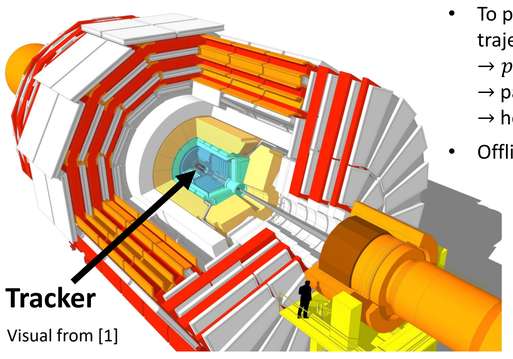
The CMS Tracker



Visual from [1]

Purpose of the Tracker:

- To perform precise measurement of the trajectories (tracks) of charged particles
  → p_T and vertex measurement
  → particle identification
  → heavy flavor tagging …
- Offline reconstruction and Trigger
  → high granularity
  → fast response

Phase-1 Tracker layout [2]:

- Pixel detector (BPIX+FPIX)
  → 1856 modules
- Strip detector (TIB+TID+TOB+TEC)
  → 15148 modules

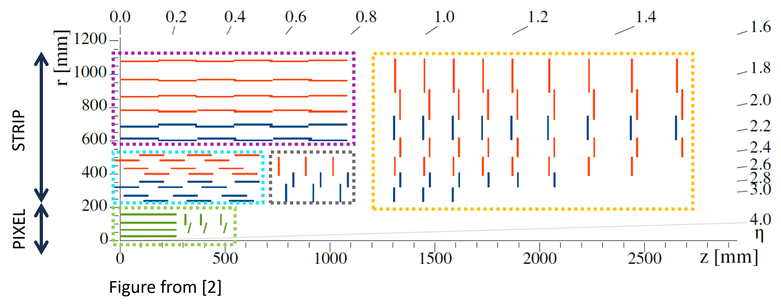
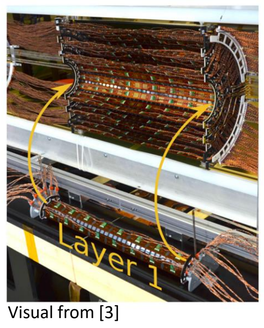


Figure from [2]



Visual from [3]

Detector refurbished during LS-2:

- Pixel detector was extracted from experimental cavern and kept cold
- Repairs were performed
  → exchange of damaged modules
  → upgrade of power supplies …
- Innermost BPIX layer (Layer 1) was fully replaced

Beginning of Run 3 operation [4][5]:

- Hit detection efficiency above 98% (99%) for Pixel (Strip) detector
- Only ≈4% of module components flagged as bad for offline reconstruction

Aligning the largest silicon-based detector

Designed with excellent **hit resolution** $\sigma_{\text{hit}} \approx \mathcal{O}(0.01\ \text{mm})$
But burdened by suboptimal **precision of mechanical alignment** $\sigma_{\text{align}} \approx \mathcal{O}(0.1\ \text{mm})$

Tracker Alignment methods employed

1) **Mille-Pede-II [9]** MPII
   → global fit
   → simultaneous estimation of all local and global parameters

2) **HipPy [10]**
   → iterative approach
   → sensor position/orientation determined independently

Problem leading to limited performance

$$\sigma_{\text{align}} \gg \sigma_{\text{hit}}$$

Figure from [7]

Module alignment push measured hit position closer to real trajectory

Alignment is time-dependent

Source of movement:

- Cooling cycles $\mathcal{O}(0.01\ \text{mm})$
- Magnet cycles $\mathcal{O}(1\ \text{mm})$
- Aging $\mathcal{O}(0.001\ \text{mm})$

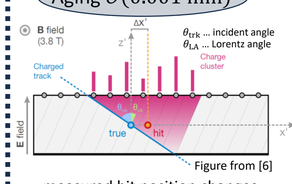


Figure from [6]

measured hit position changes over time by $\Delta x' \propto \tan\theta_{\text{LA}}$ due to high radiation environment

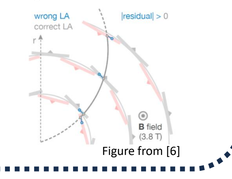


Figure from [6]

Alignment narrowed down to minimization problem

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

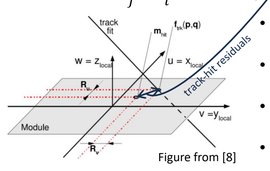


Figure from [8]

- $\boldsymbol{p} \leftrightarrow$ alignment parameters (module position, rotation, …)
- $\boldsymbol{q} \leftrightarrow$ track parameters (curvature, deflection, …)
- $m \pm \sigma^m \leftrightarrow$ measurements (hits, …) and their uncertainty
- $f \leftrightarrow$ prediction

Solved by track-based alignment!

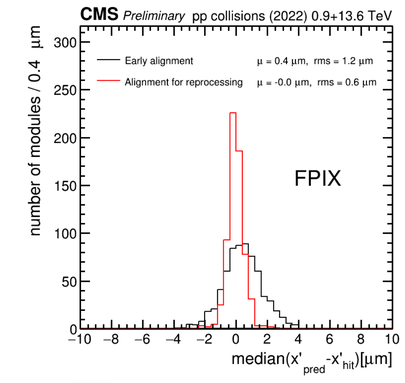
$$\sigma_{\text{align}} \approx \sigma_{\text{hit}}$$

- **Online**
  Automatized alignment
- **Offline**
  More dedicated alignment

Monitoring the alignment performance

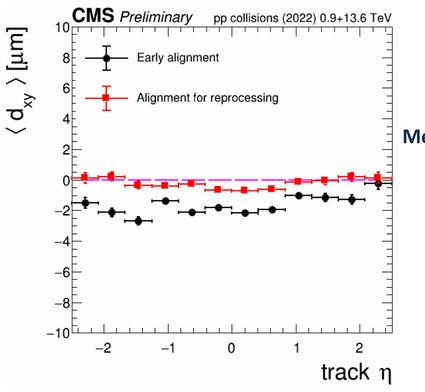
Distributions of Median Residuals (DMR)

- Median of **track-hit residuals** $x'_{\text{pred}} - x'_{\text{hit}}$ is determined for a given number of tracks
- To avoid biasing the measurement, **tracks are first re-fitted** while the hit under consideration is removed
- With **perfectly aligned detector**, distributions are expected to be **centred at zero** value
- **Width** of distribution indicates **local alignment precision**



Primary Vertex (PV) validation

- Performance measured by a quality of primary vertex (i.e. belonging to the highest-p_T track) reconstruction
- Measuring unbiased **track-vertex residuals:**
  → longitudinal d_z and transversal d_{xy}
  → ideally zero
- To avoid biasing measurement, all **PV are first re-fitted** while the track under scrutiny is removed



Early 2022 Alignment results taken from [11] and [12]

Challenges of early 2022 data-taking

Unscheduled magnet ramp-downs and temperature cycles due to the maintenance
→ **regular refitting of alignment constants is needed**

Embedded in CMS data-taking workflow:
→ Compact & reduced datasets are retrieved
→ Aligned conditions are sent back (online)

DMR trends – monitoring alignment progress in time:

Black: automated (online) Low Granularity Prompt Calibration Loop (LG PCL) alignment

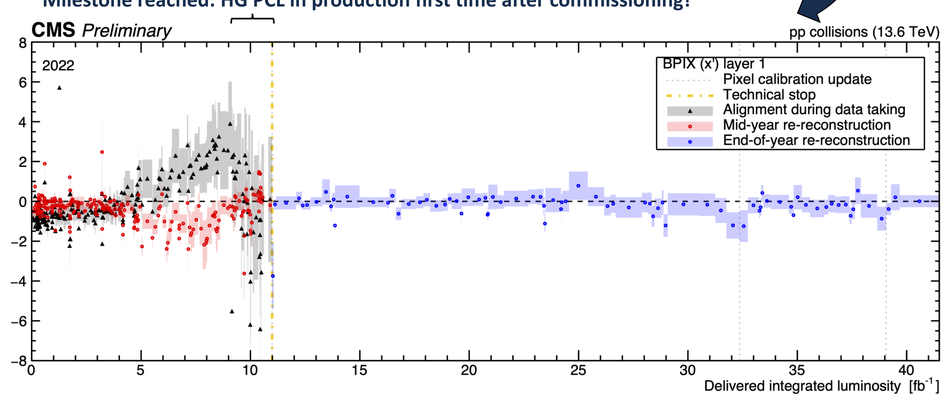
Red: refined offline + High Granularity (HG PCL) alignment (last 2 fb^{-1} before Technical stop)

Blue: improved HG PCL alignment for remaining 30 fb^{-1} of 2022

Both mean and width are increasingly improved

Milestone reached: HG PCL in production first time after commissioning!

Mean of DMR value μ [μm]



Tracker alignment during Run 3

Which 2023 alignment conditions do we compare?

1. **3.8T cosmic rays** ≈ 187k cosmic ray tracks
   - Granularity of alignment:
     → **BPIX (FPIX): ladders (half-cylinders)**
     → Strip: half-barrels and half-cylinders
2. **3.8T cosmic rays + 900 GeV pp collisions** ≈ 71k cosmic ray tracks ≈ 4.5M pp collisions
   - Granularity of alignment:
     → **Pixel: level of single modules**
     → Strip: fixed in the fit
3. **3.8T cosmic rays + 13.6 TeV pp collisions** ≈ 295k cosmic ray tracks ≈ 16M pp collisions
   - Granularity of alignment:
     → **Pixel: ladders and panels**
     → Strip: fixed in the fit

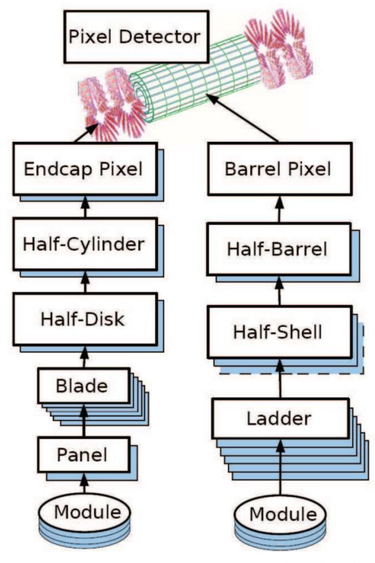
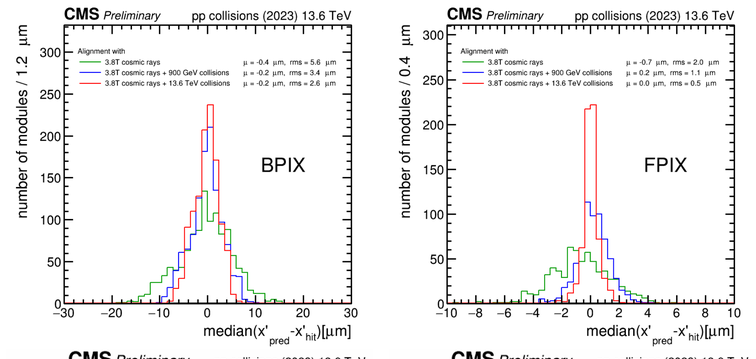


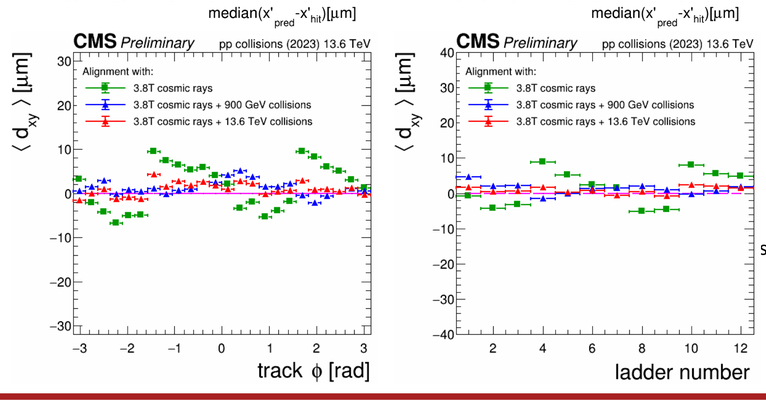
Figure from [8]

2023 Alignment results taken from [13]

Fruit of dedicated offline alignment

Tracker geometry in 2022? ⟶ **Starting point for 2023** alignment!





DMR validation

Major improvement for FPIX and BPIX towards latest alignment conditions

PV validation

Improvement also visible for unbiased distributions of impact parameters

Residual differences from zero show the typical alignment precision

References:

[1] J. Phys.: Conf. Ser. 513 022032
[2] CMS-TDR-019
[3] JINST-17-C09017
[4] CMS DP-2022/067
[5] CMS-DP-2023-030
[6] CMS-TRK-20-001
[7] DESY-THESIS-2015-035
[8] CMS-THESIS-2011-435
[9] DESY-02-077
[10] CERN-CMS-DP-2022-044
[11] CMS-DP-2022-044
[12] CMS-DP-2022-070
[13] TWiki-TkAl-2023

Online:

LP2023 Conference Melbourne, July 2023