Tracker alignment of the CMS detector with Run 3 data

FH-SCiComp workshop

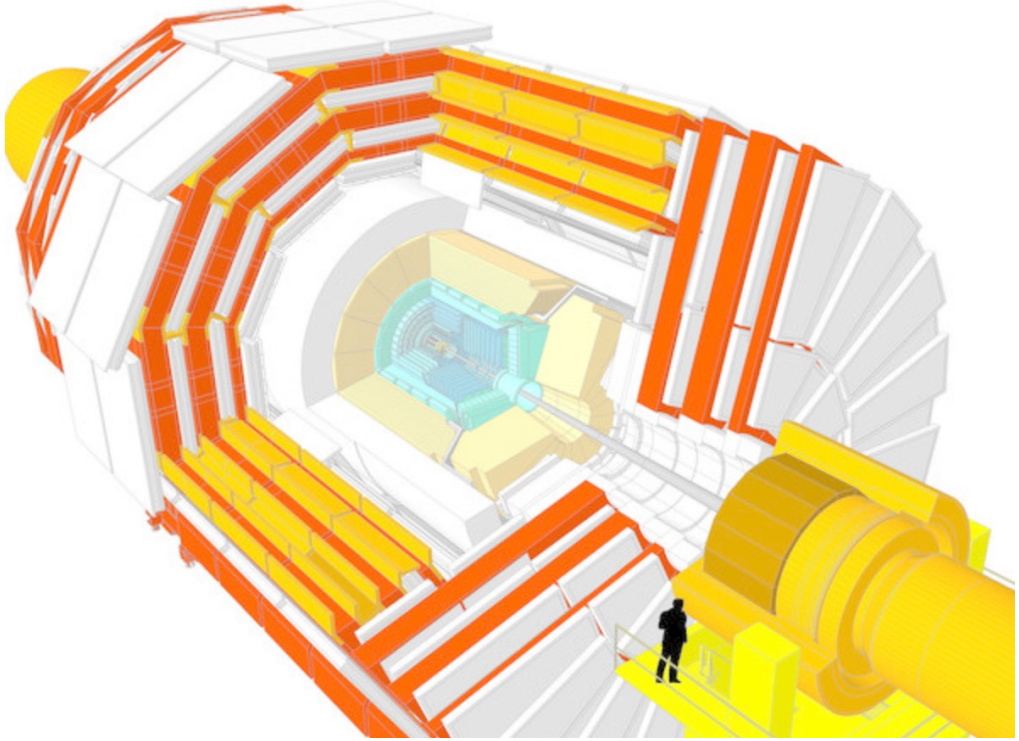
02.07.2024

Henriette Petersen

Alignment of the CMS tracker (Phase-I)

- Challenge of CMS tracker alignment: Largest silicon module tracker in the world!

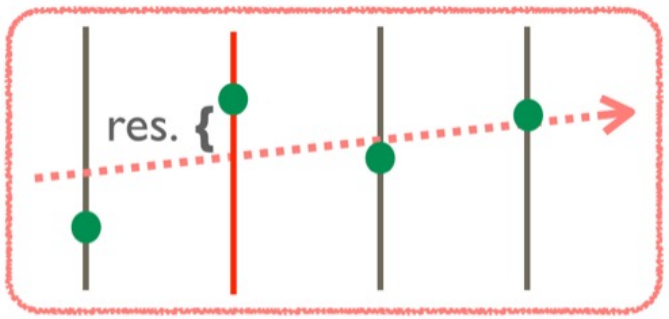
Pixel: 1856 modules
Strip: 15148 modules



- Parameters to align: Position, rotation and curvature
  → $O(10^5)$ parameters!

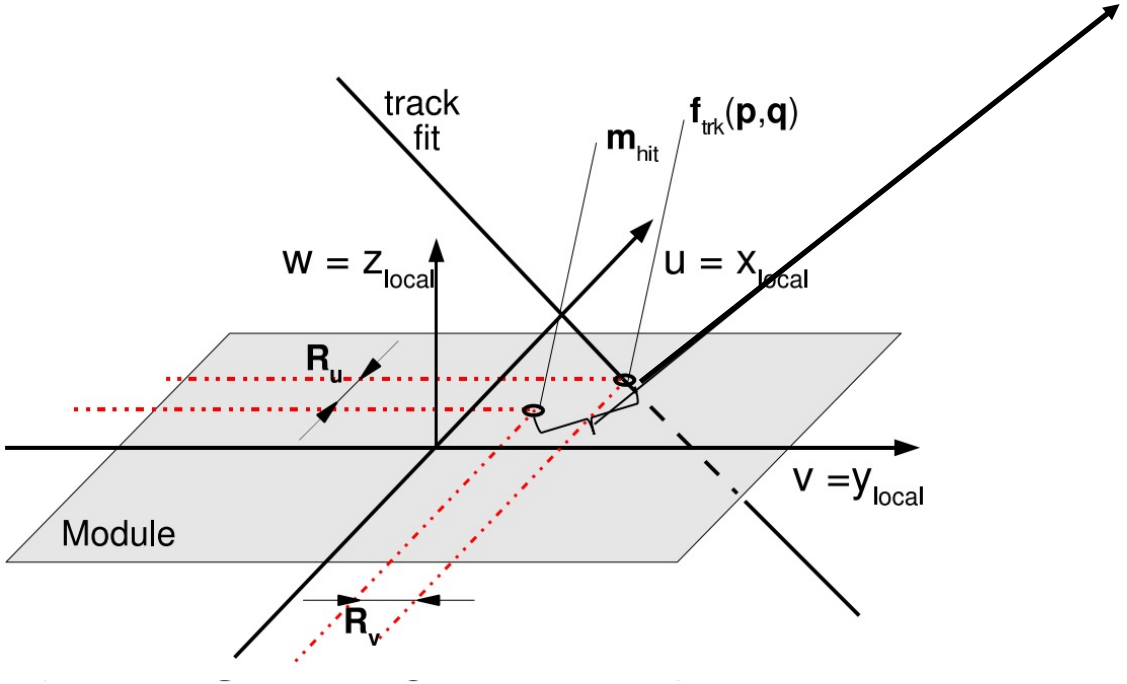
- Goal is to find corrections to modules such that
  → $\sigma_{\text{align}} \lesssim \sigma_{\text{hit}}$.

Track-based alignment



Track-based alignment using MillePede-II

Simultaneous fit of all track and alignment parameters (correlations taken into account)



CERN-THESIS-2011-435

Least-square minimization of sum of squares of normalised **track-hit residuals**

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

$$r_{ij}(p, q_j) = m_{ij} - f_{ij}(p, q_j)$$

Ingredients:
alignment parameters, track parameters
measurements, predictions
uncertainties

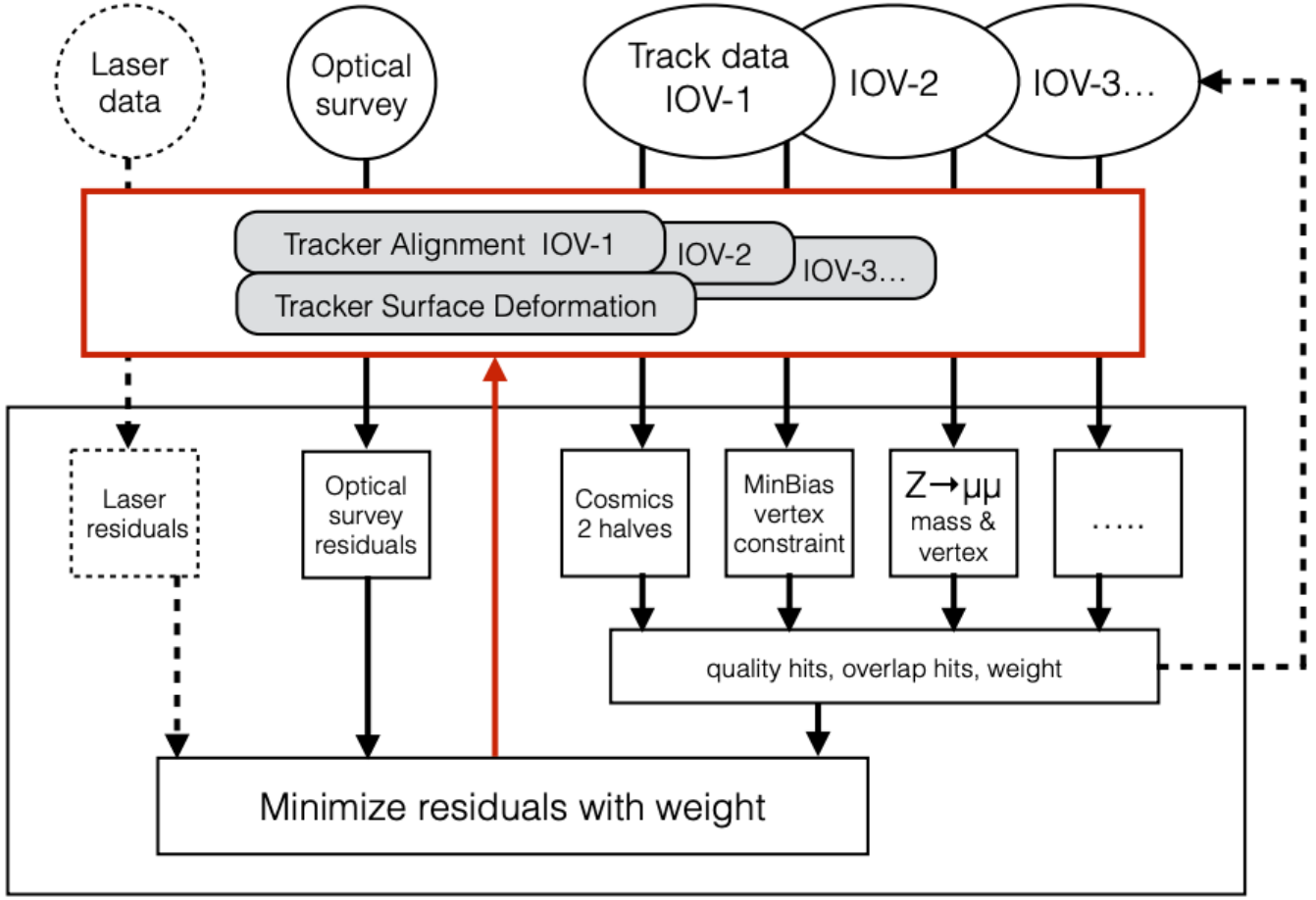
V. Blobel and C. Kleinwort, *A New Method for the High-Precision Alignment of Track Detectors,* DESY 02-077 (June 2002). [arXiv:hep-ex/0208021v1].

Track-based alignment using HipPy

- The HIPPY algorithm is based on the hits-and-impact-points algorithm
- Position and orientation of each sensor are determined independently of the other sensors
- Provides valuable cross check of MP!

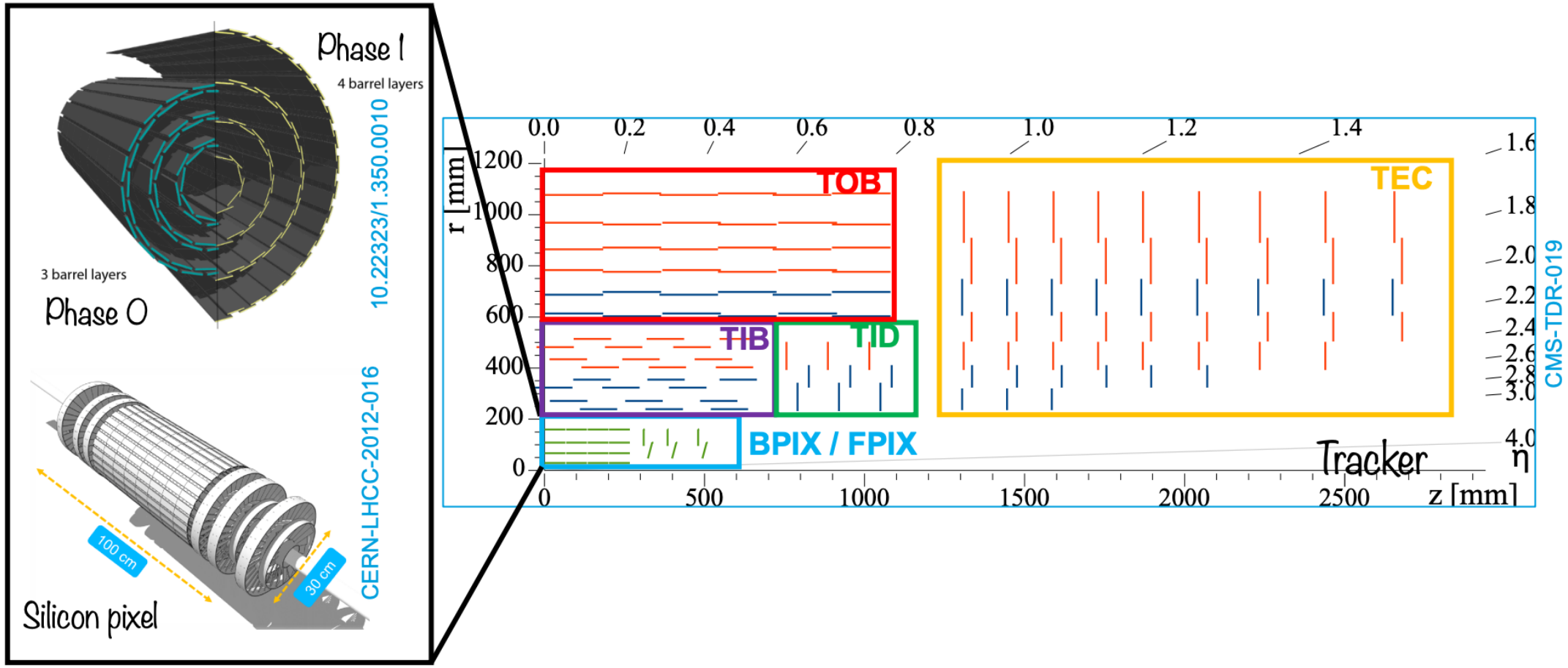
Pro:
Native integration with CMSSW – allows for easy implementation of constraints!

Con:
Requires a high number of iterations!



CMS-TRK-20-001

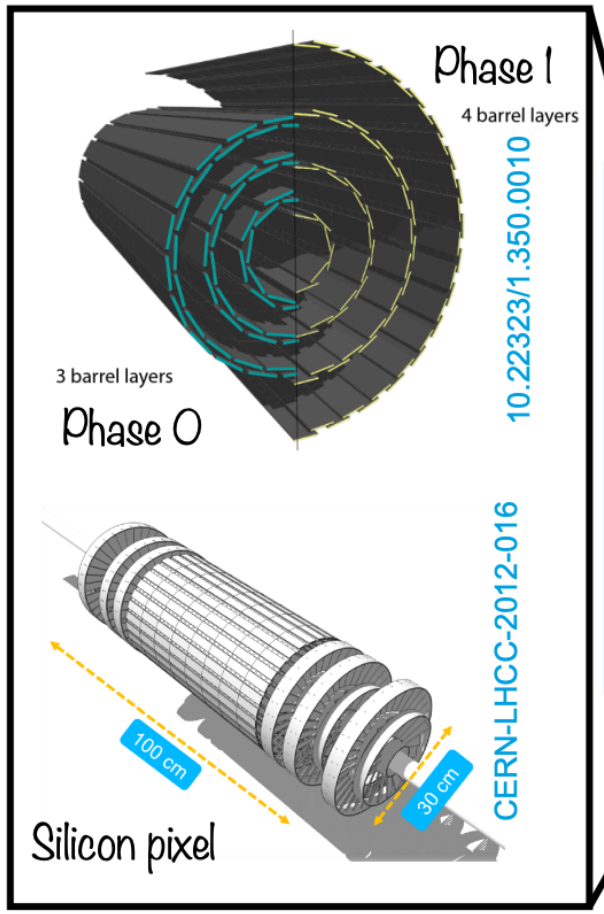
How does time dependence arise in the alignment?

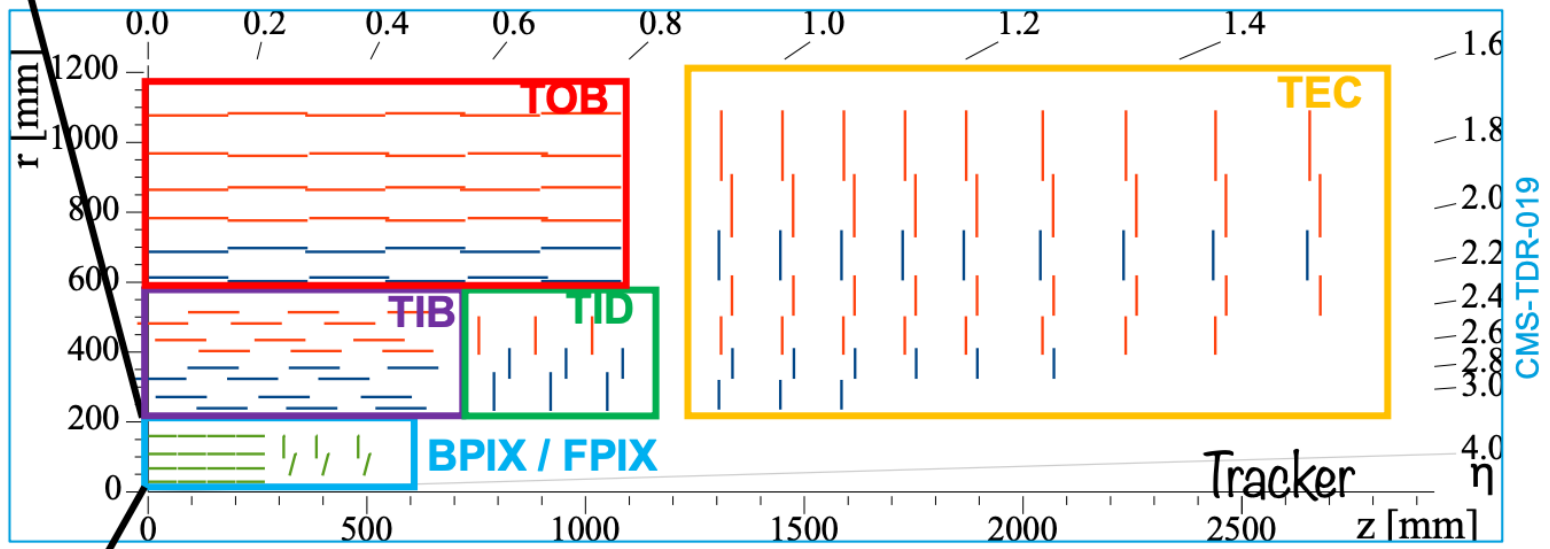


How does time dependence arise in the alignment?

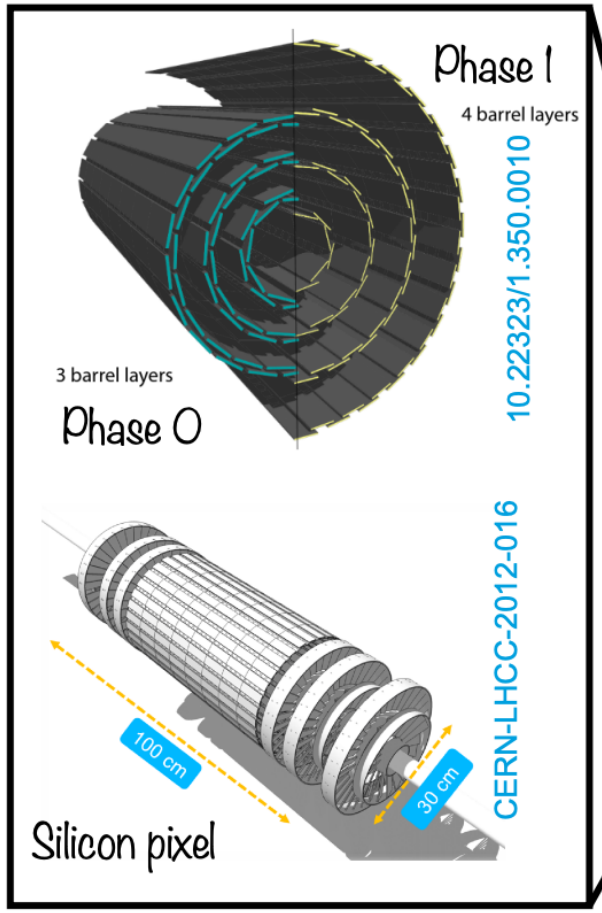
Magnet cycles:

- Detector can be switched on and off for maintenance reasons
- Impacts large mechanical structures: barrel pixel/ forward pixel, tracker outer barrel, tracker inner barrel, tracker inner disks, tracker endcaps (order of a few mm).



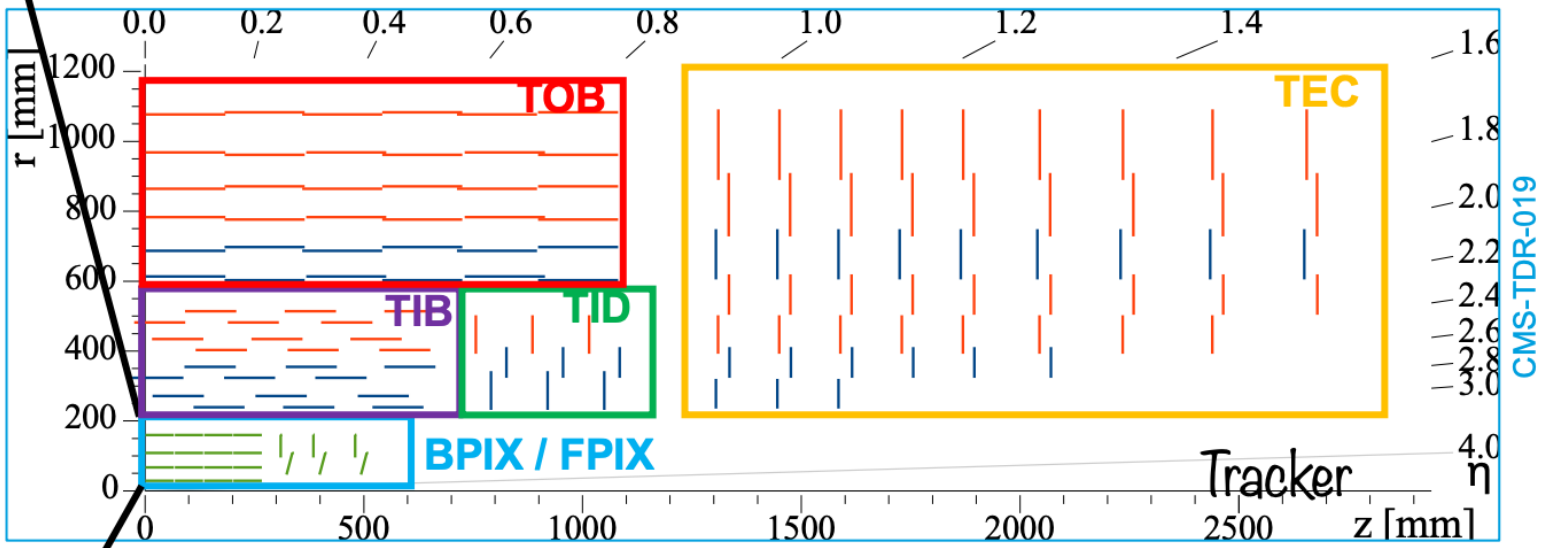


How does time dependence arise in the alignment?



Magnet cycles:

- Detector can be switched on and off for maintenance reasons
- Impacts large mechanical structures: barrel pixel/ forward pixel, tracker outer barrel, tracker inner barrel, tracker inner disks, tracker endcaps (order of a few mm).



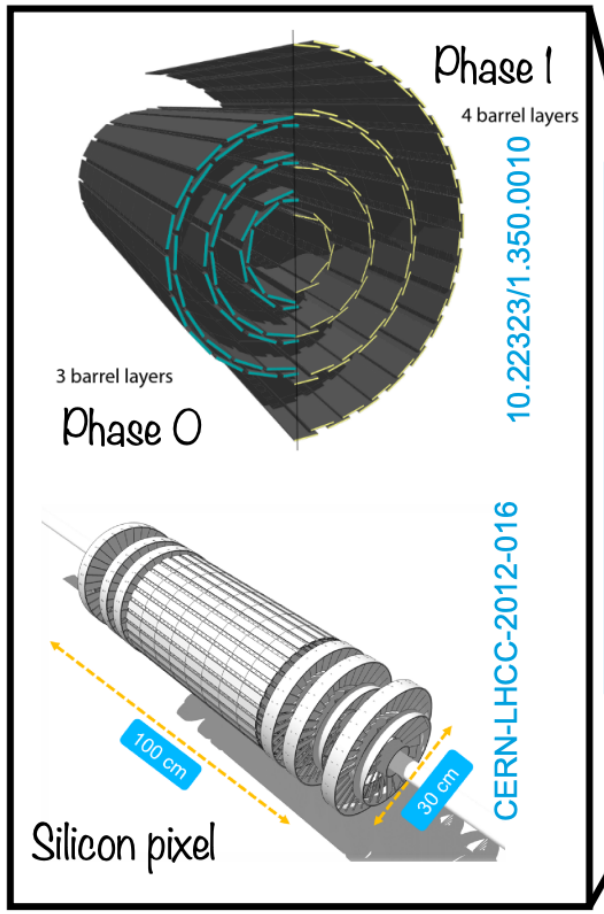
Temperature variations:

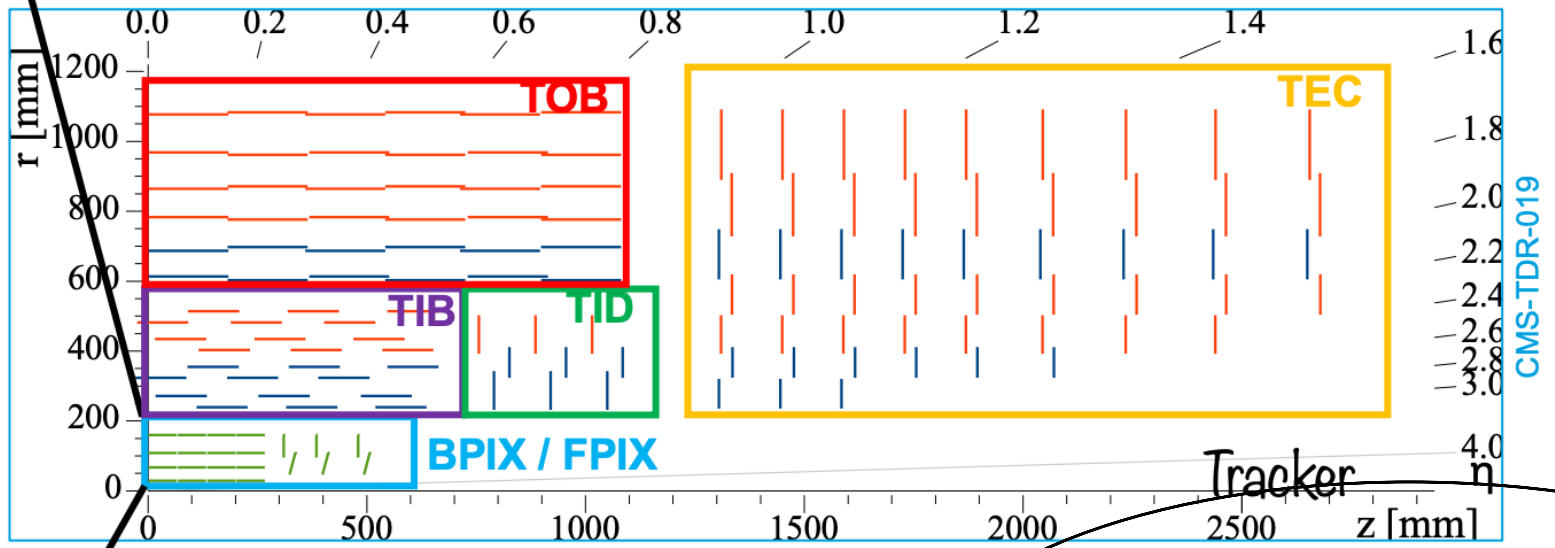
- Cooling operations after long shutdown periods (sensors – order of 10^{-1} mm).

How does time dependence arise in the alignment?

Magnet cycles:

- Detector can be switched on and off for maintenance reasons
- Impacts large mechanical structures: barrel pixel/ forward pixel, tracker outer barrel, tracker inner barrel, tracker inner disks, tracker endcaps (order of a few mm).





Temperature variations:

- Cooling operations after long shutdown periods (sensors – order of 10^{-1} mm).

Age related factors:

- Irradiation and degradation with time (sensors – order of a few μm but changing rapidly).

New innermost layer added to the barrel pixel in phase 1

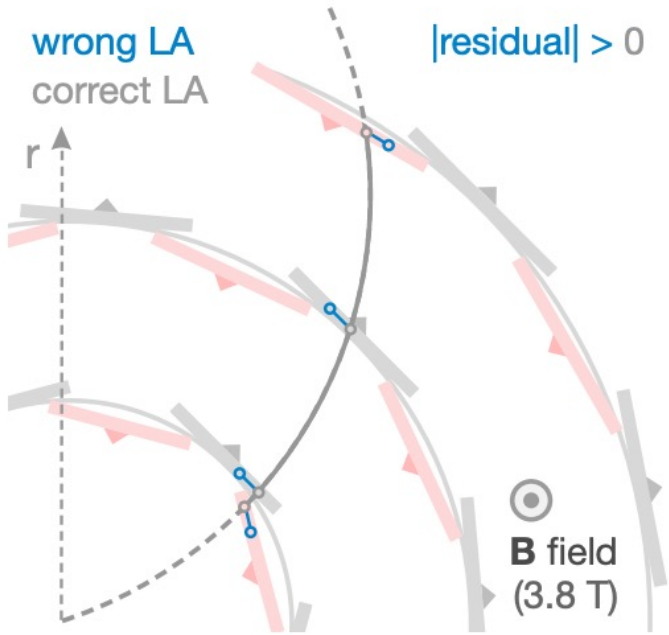
Ageing of silicon modules in the pixel detector

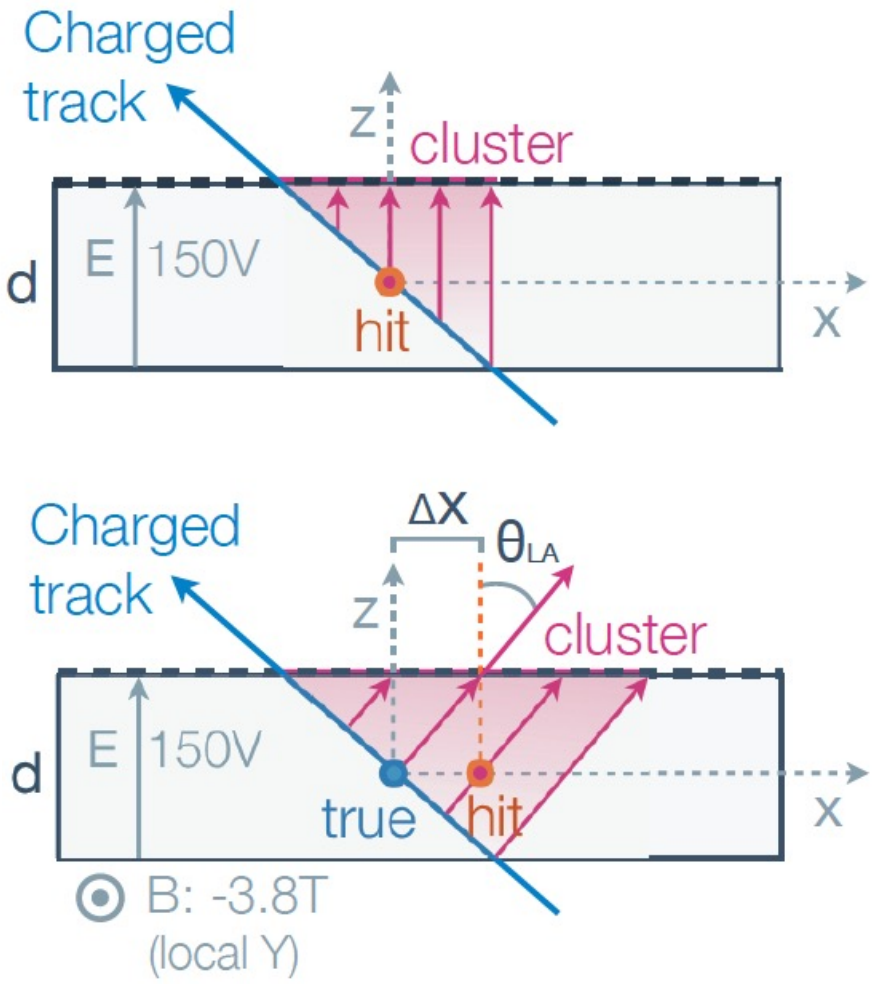
Lorentz drift in the silicon modules:

- Hit determined from barycentre of charge cluster.
- Hall effect leads to Lorentz drift.
  → Measured hit position shifts with respect to true hit (x-direction).

Inward and outward facing CMS tracker modules are affected by Lorentz drift in opposite ways!

Increased irradiation with increased luminosity.
→ more pronounced effect with age.

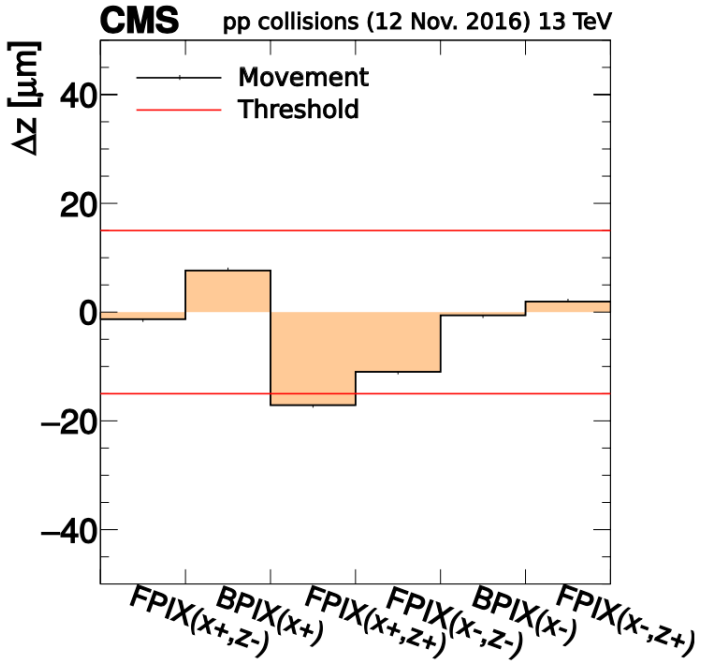




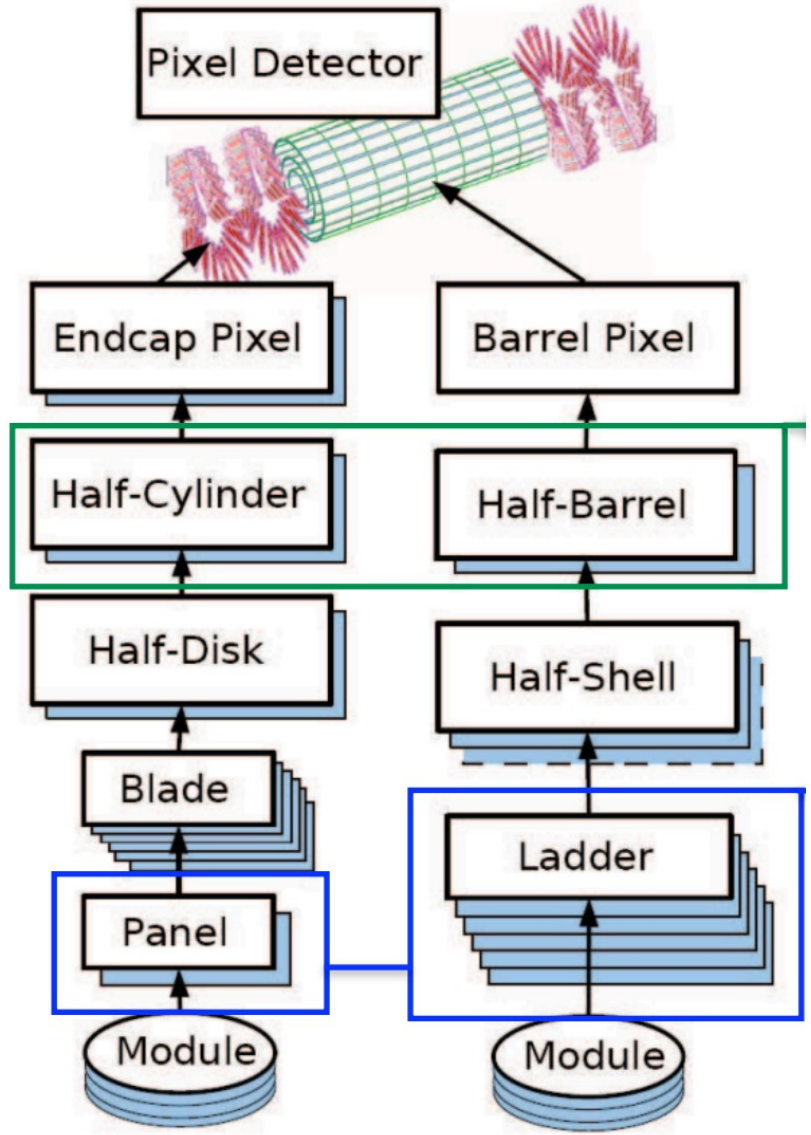
Sketch of Lorentz drift
(From N. Bartosik's thesis)

Automatic alignment workflows (running during data-taking)

- Prompt calibration loop (PCL)
- Run2: Corrections of the half-cylinder and half-barrel at low granularity (LG PCL)
- Run 3: High granularity alignment (HG PCL) is a refined online alignment at the level of ladders and panels.



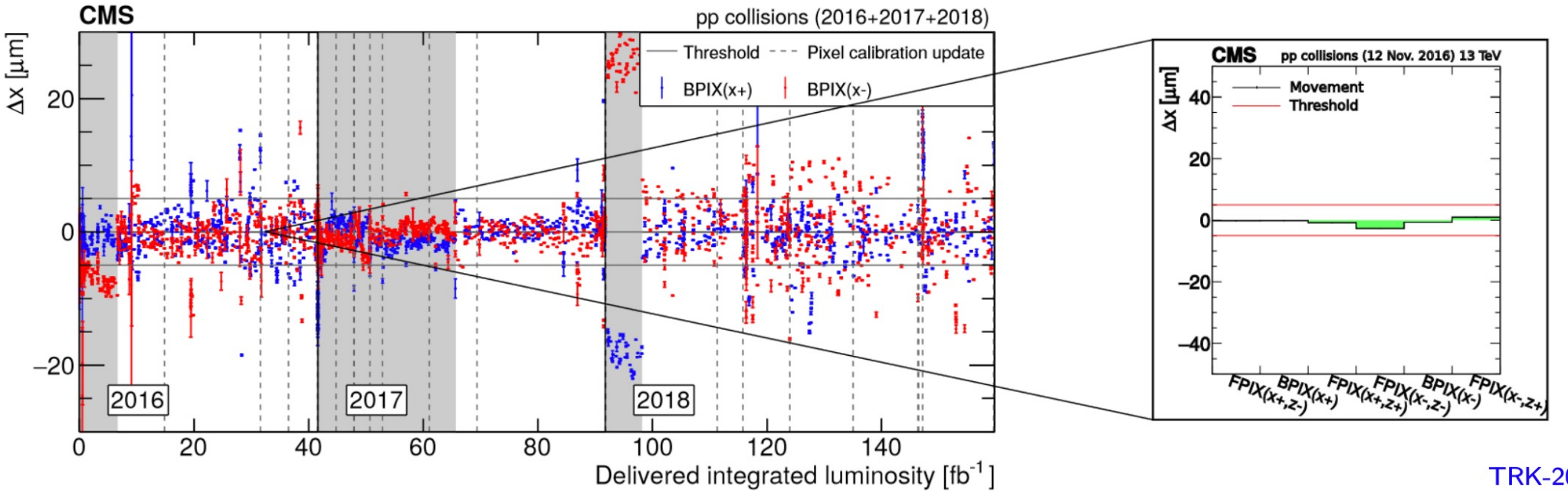
- Alignment automatically updated for production if movement above certain threshold
  - For small significance or too large movements, alignment is vetoed



CERN-THESIS-2011-391

Run 2: Low Granularity PCL alignment

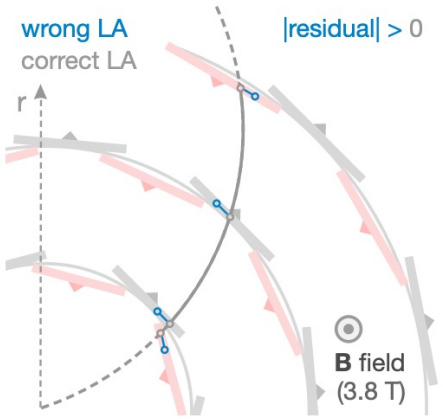
- Alignment of large structures (HLS) of the pixel detector (⇒ LG)
  - 2 BPIX barrels, 4 FPIX half-cylinders, 6 dof per structure → 6 × 6 = 36 parameters
- MillePede 2 algorithm runs in the Prompt Calibration Loop (PCL) at Tier-0
- Uses minimum bias data from first (express) reconstruction
- Alignment automatically updated, if movements within set requirements



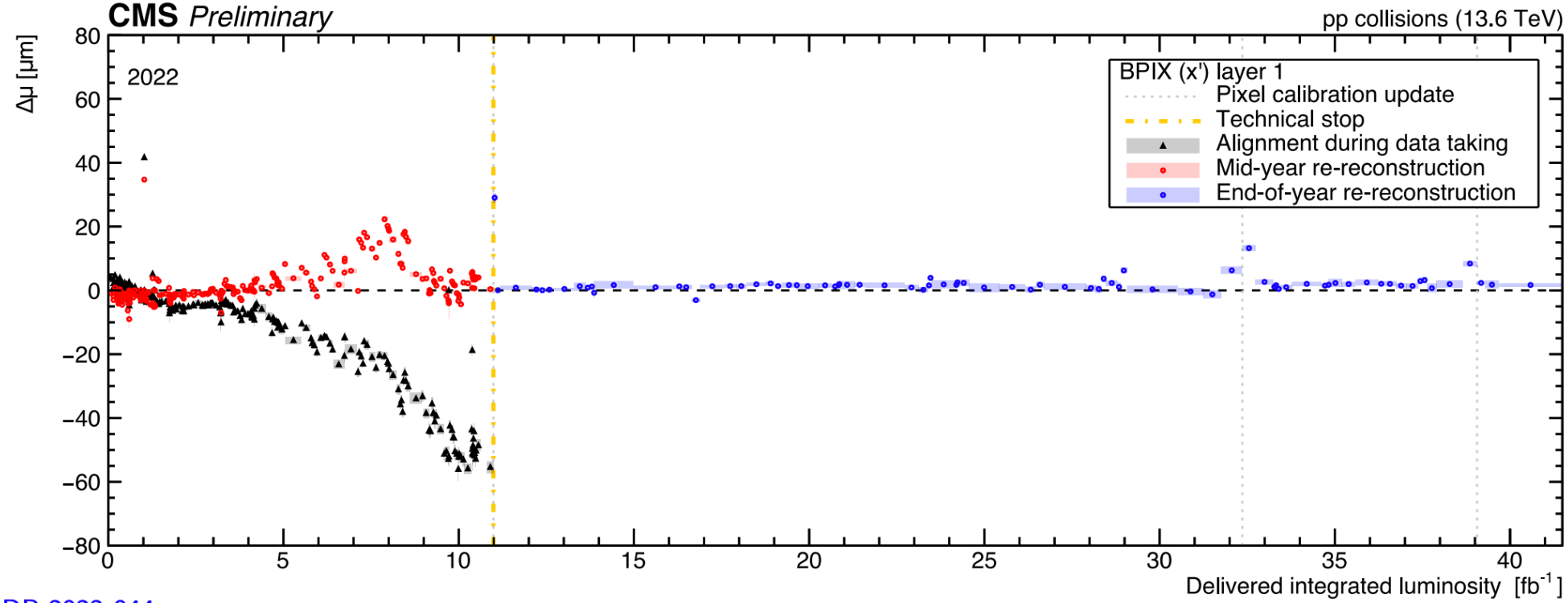
TRK-20-001

Slide taken from talk by P. Nattland

Run 3: High Granularity PCL alignment



- Change from HLS-based to ladder/panel-based alignment
  - Increase number of parameters from 36 to ~ 5000
- Improved performance wrt LG PCL alignment
- Uses express MinBias data
- But: More parameters ⇒ Cannot be fully constrained by minimum bias data set



CMS-DP-2022-044

Slide taken from talk by P. Nattland

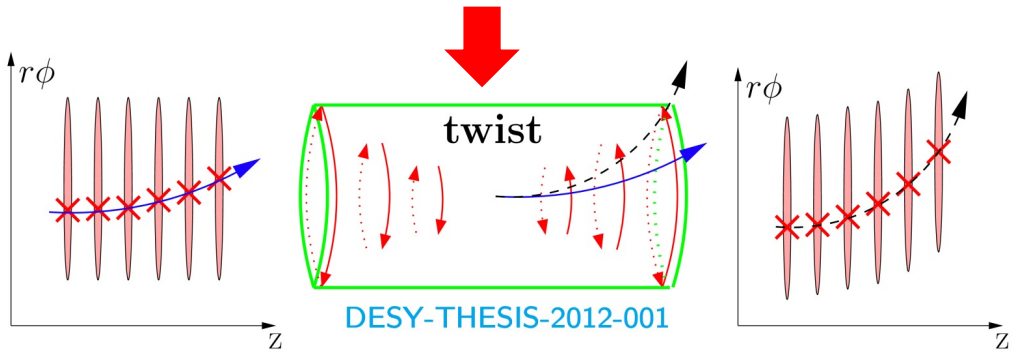
Run 3: Developments of High Granularity PCL alignment

- **Prompt calibration loops (PCL) lack dataset variety** and **offline updates** can only be done with a **limited frequency**

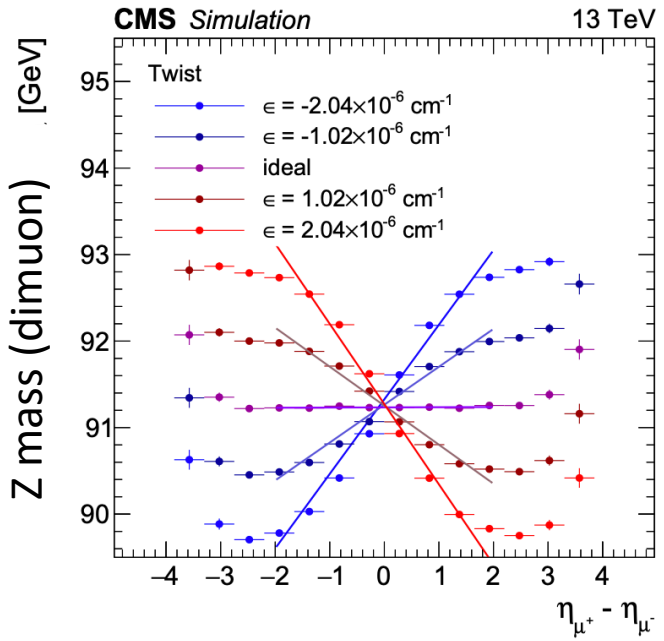
- **Dataset variety** is of utmost importance for **controlling various biases and weak modes** (unphysical distortions of the detector that doesn't impact the track fit).

- **Nine basic systematic distortions** in the cylindrical system can occur!
  - **Cosmics and Z $\longrightarrow$ $\mu\mu$ data are critical** to control those – only the latter is now incorporated into a combined High Granularity PCL workflow exploiting both minimum bias and Z $\longrightarrow$ $\mu\mu$ data (***new***)

Example of a weak mode



What it will do to the data
(among other bad things)



Plans in view of the remainer of Run 3 and HL-LHC

- **Phase 2** will make **frequent reprocessing of data difficult/impossible** due to sheer volume

- Idea is to move towards **manual rolling calibrations** to improve quality in active data-taking:

- Hypothesis: resetting the starting geometry online several times with reprocessing-like quality will lead to reprocessing quality *during* data-taking

- Possible workflow

  1. Accumulate X fb-1 of statistics of critical datasets: cosmics and $Z \longrightarrow \mu\mu$. Re-do alignment in a PCL-like workflow that aligns at the finest granularity (modular level for pixel and strip).
     - Frequency of this PCL-alignment can be several days / weeks

  2.—> Introduce time-dependence in strip detector through occasional manual input to the otherwise automatic workflow
     - i.e. make intervals of validity where the detector physically changes (magnet cycle, temperature variations etc.)

  3. repeat the accumulation of X fb-1 of statistics and re-do alignment to boot strap the regular ”high granularity” PCL alignment.

Summary

- An overview was given of the tracker alignment algorithms and procedures

- Described how the Prompt calibration loop was modified to deal with irradiation effects in the newly installed (prior to Run 3) innermost layer of the barrel pixel

- New major development done to include dataset variety in the High Granularity prompt calibration loop
  - $Z \longrightarrow \mu\mu$ data for now but plans for cosmics (during collisions) in the future

- The challenges in terms of reprocessing for phase 2 were outlined along with the preliminary plans of how we plan to adapt our calibration procedures.