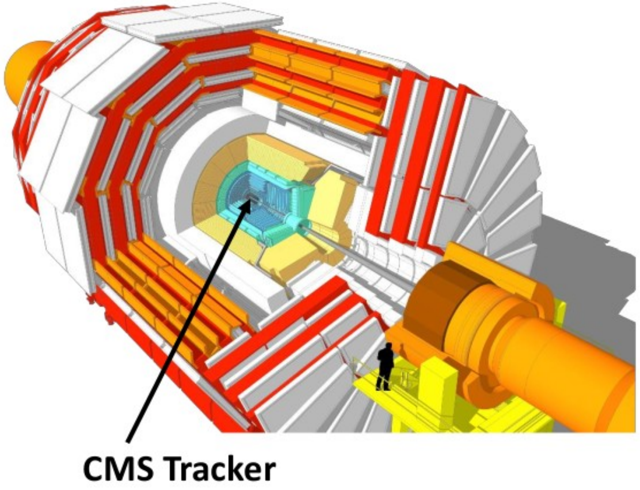
Alignment of the CMS tracker

with Run 3 data



Lucia Coll Saravia on behalf of the DESY-CMS group for Tracker Alignment
Karlsruhe, 04.03.2024

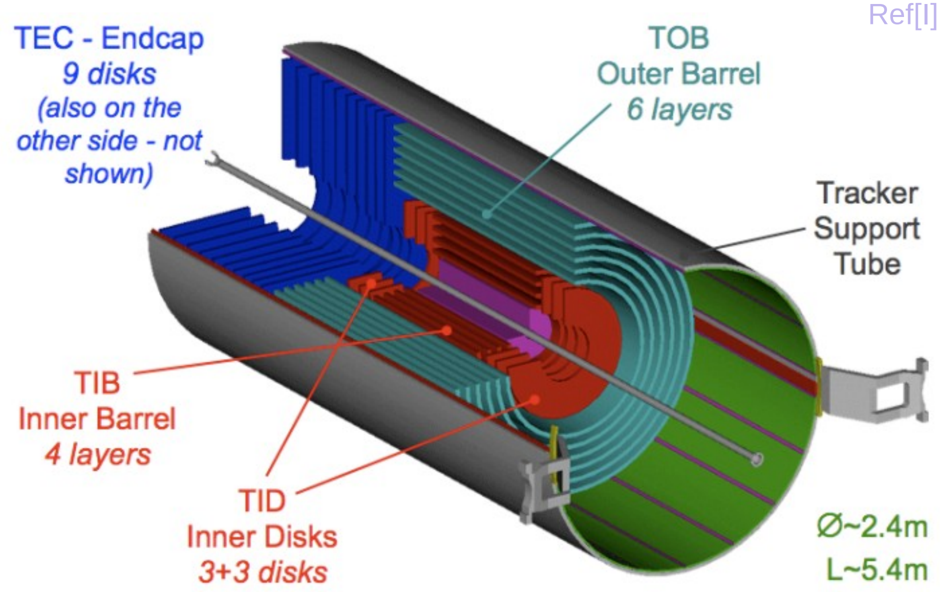
HELMHOLTZ

CMS Tracker detector

Largest silicon module tracker in the world!

Silicon tracker:

- 1856 pixel modules for phase 1
- 15148 strip modules



Goal of track based alignment:

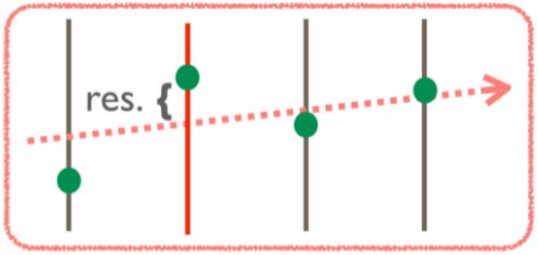
- Find corrections to modules such that at least:

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

Parameters aligned:

- Position
- Rotation
- Curvature
- $O(10^5)$ parameters!

- pp collisions at 13.6 TeV and cosmics at 0T and 3.8T are used to minimize the differences between measured and predicted hits (residuals)



MillePede-II:

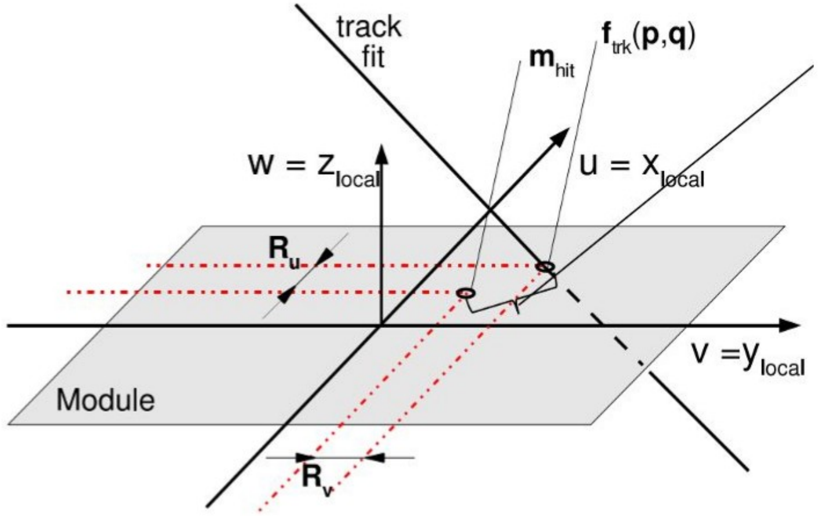
The algorithm

Goal:

- Simultaneous fit of all track and alignment parameters (correlations taken into account).
- Least-square minimization of sum of squares of normalized track-hit residuals

Minimize:

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



Ref[III]

CERN-THESIS-2011-435

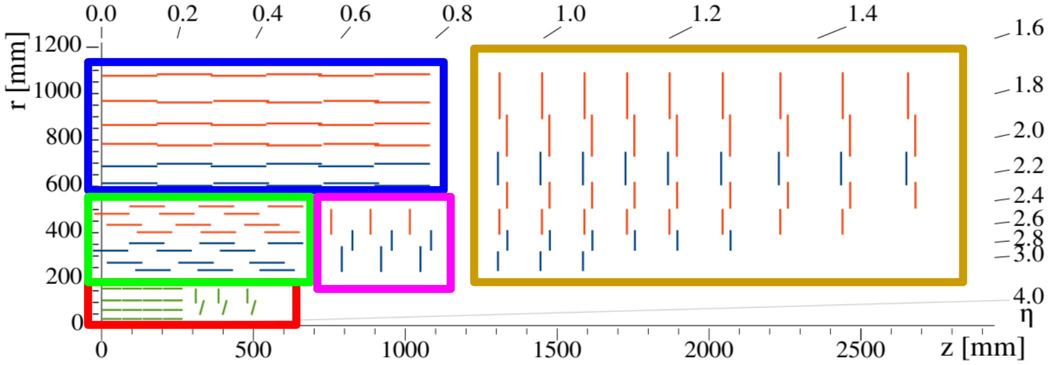
p : alignment parameters
q : track parameters
m : measurements
f : predictions
σ : uncertainties

Ref[IV]

Challenges in alignment

Time dependence

Ref[II]



We need continuous alignment throughout the year

- Magnet cycles:

  Magnets switched off and on (e.g. for maintenance reasons). Impacts large mechanical structures: barrel pixel/ forward pixel, tracker outer barrel, tracker inner barrel, tracker inner disks, tracker endcaps.

  Changes in the order of few mm

Year:	2016	2017	2018	2021	2022	2023
N (total)	8	4	4	2	2	8
On request	3	3	4	2	1	1
Fault	5	1	0	0	1	7

Large number of magnet cycles in 2023

Challenges in alignment

Time dependence – sensor level movements

- Temperature variations

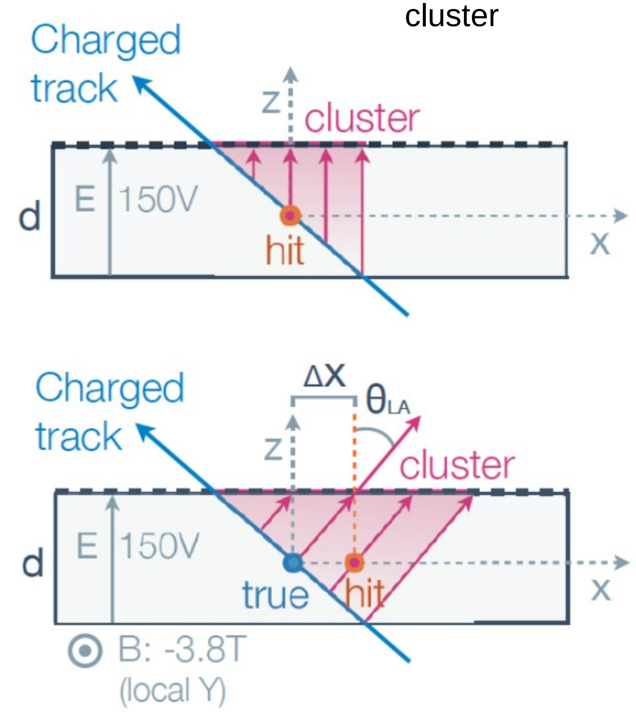
  e.g. cooling operations after long shutdown periods.
  (order of 0.1 mm)

- Age related factors

  i.e. hall effect leads to Lorentz drift

  - Measured hit drifts with respect to true hit (order of a few µm but changing rapidly)
  - miscalibration due to irradiation effects can be absorbed in the alignment

Hit determined from barycenter of charge cluster

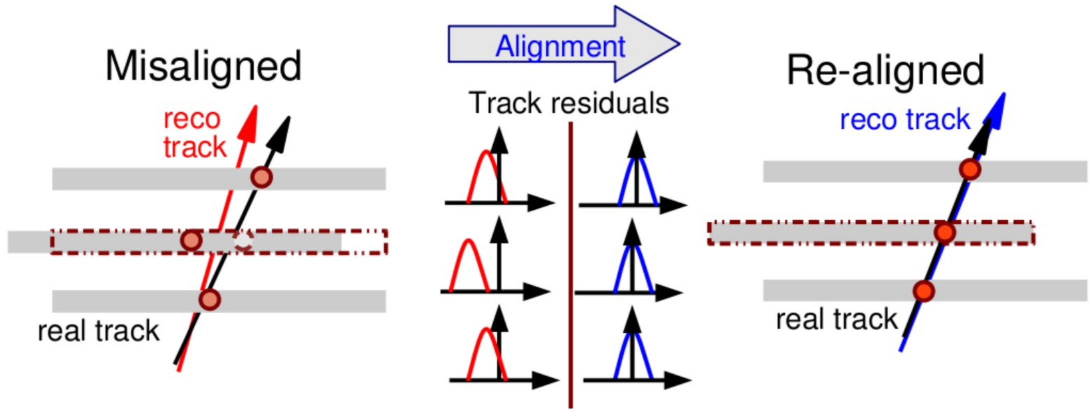


Sketch of Lorentz drift
(From N. Bartosik's thesis) Ref[V]

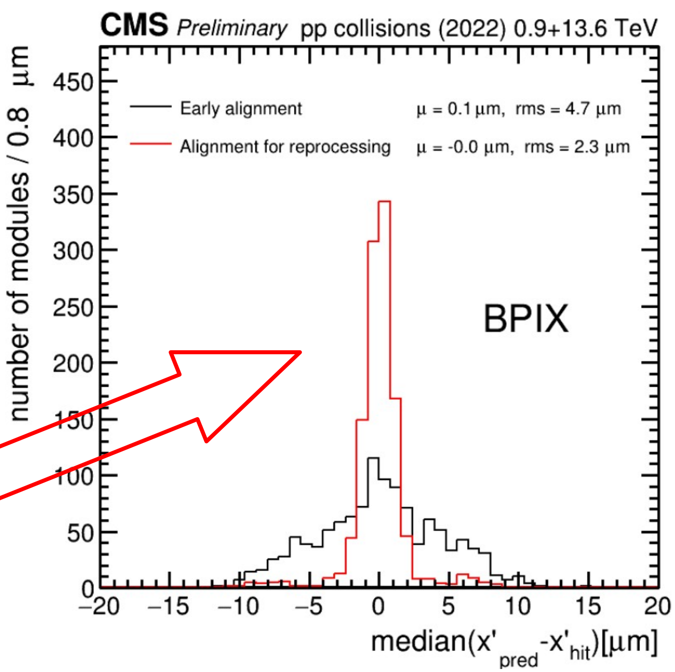
Barrel pixel detector received new innermost layer after LHC Long Shutdown 2

→ increased irradiation effects in beginning of Run 3 (2022).

Distributions of median residuals - DMR (2022)



Ref[III]



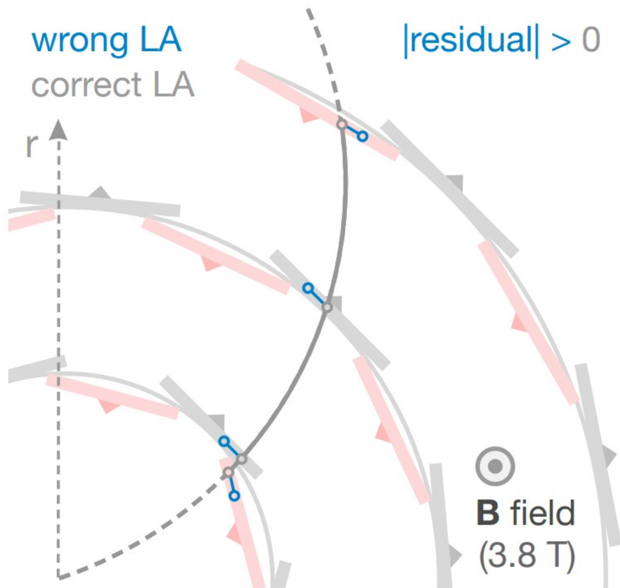
Ref[VI]

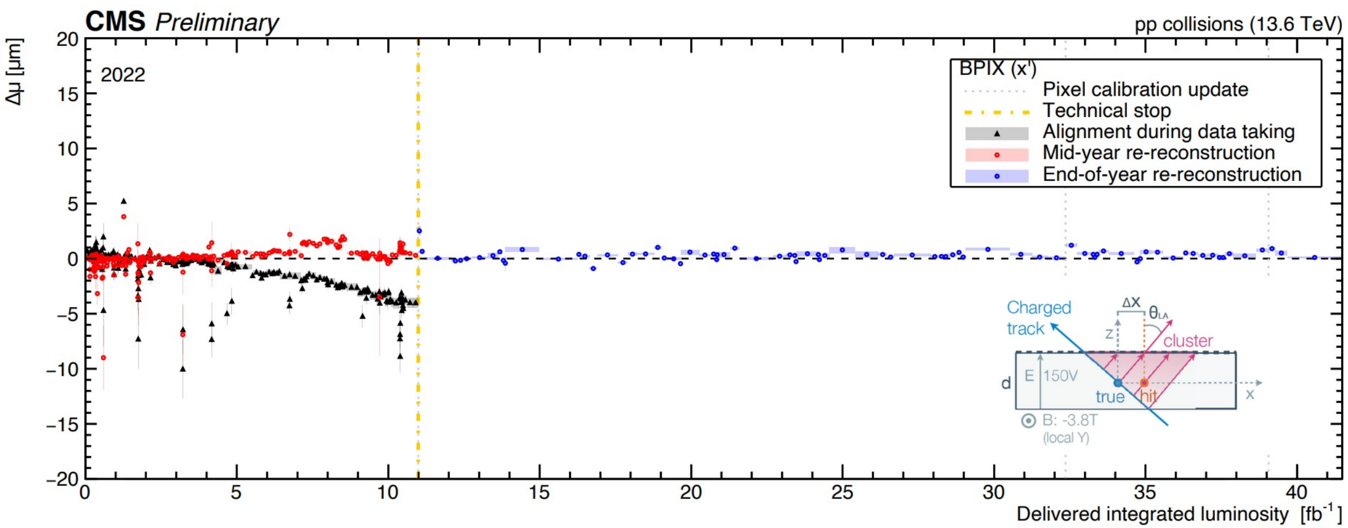
- Median of residuals per module in a given detector section
- Correction of misalignment centered distribution with smaller width

Trends in distributions of median residuals (2022)

- Inward and outward-pointing modules are affected by Lorentz drift in opposite ways
  - ➔ by moving ladders and panels alignment will absorb miscalibration
- Sensitive observable: $\Delta\mu$ = difference in DMR mean between inward and outward-pointing modules

Ref[VII]





Ref[VI]

→ Automated (online) Low Granularity alignment (high level structures)

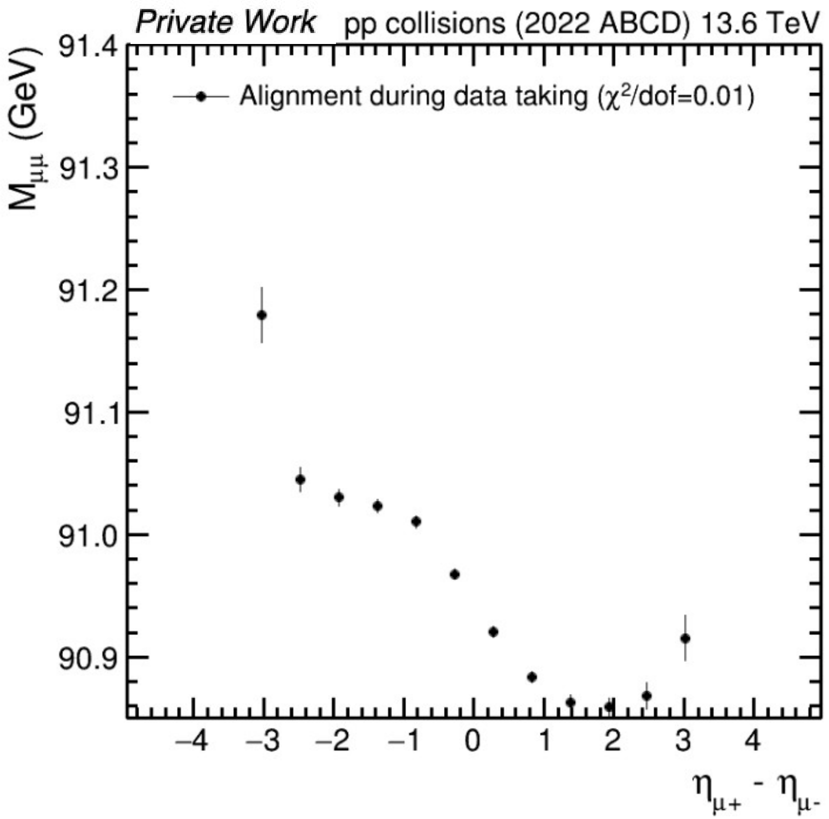
→ Refined offline + High Granularity automated alignment (last 2 fb^{-1} before Technical stop)

→ High Granularity automated alignment for remaining 30 fb^{-1} of 2022 (level of ladders and panels)

Dimuon resonance validation (2022)

Goal:

- Minimized kinematic dependence of dimuon mass on difference in pseudorapidity between positive and negative muon

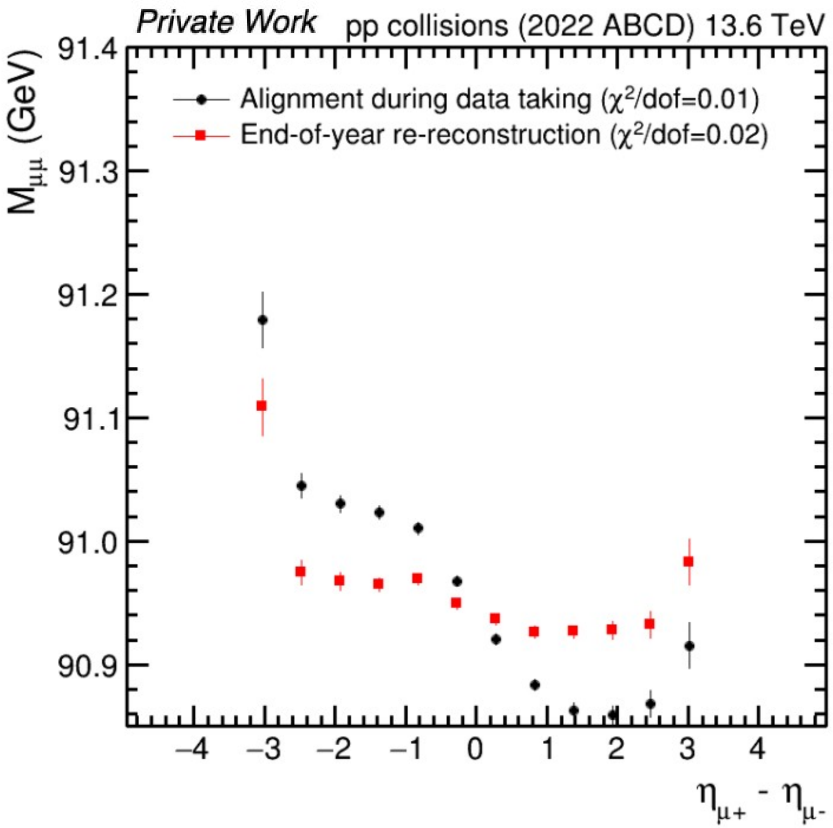


Dimuon resonance validation (2022)

Goal:

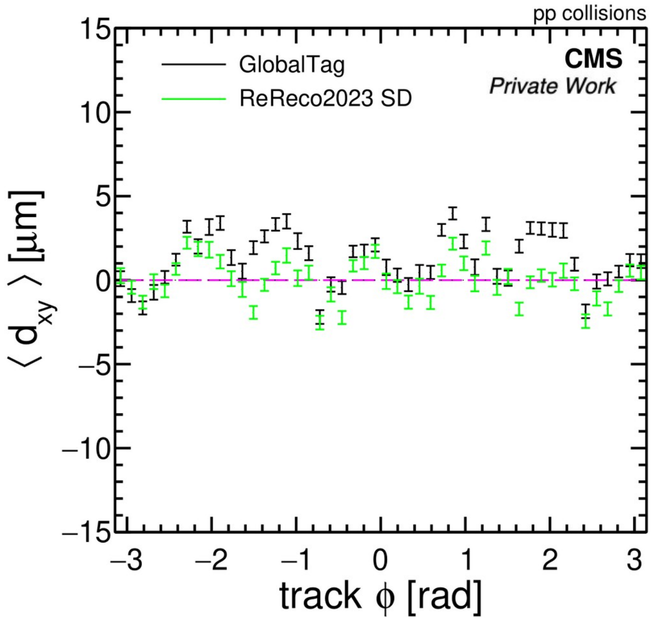
- Minimized kinematic dependence of dimuon mass on difference in pseudorapidity between positive and negative muon

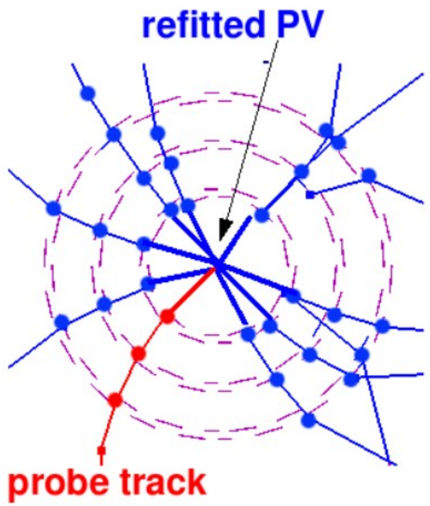
- Improvement achieved by using $Z\mu\mu$ resonance date in the alignment calibrations:
  - ➔ application of mass and vertex constraints.

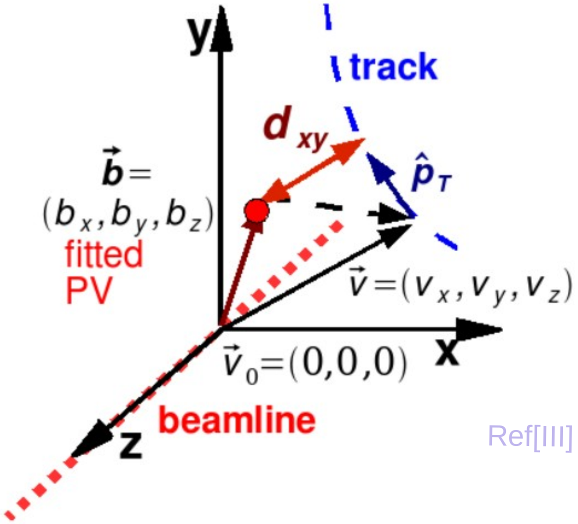


Primary vertex validation (2023)

- A probe track is removed from a primary vertex (PV) with N tracks, the PV is then refitted from the N-1 tracks
- Average transverse (d_{xy}) and longitudinal (d_z) impact parameters are calculated from the probe track to the refitted PV.
- PV validation is sensitive to random misalignment. Improvement seen below for the 2023 End-of-year re-reconstruction.





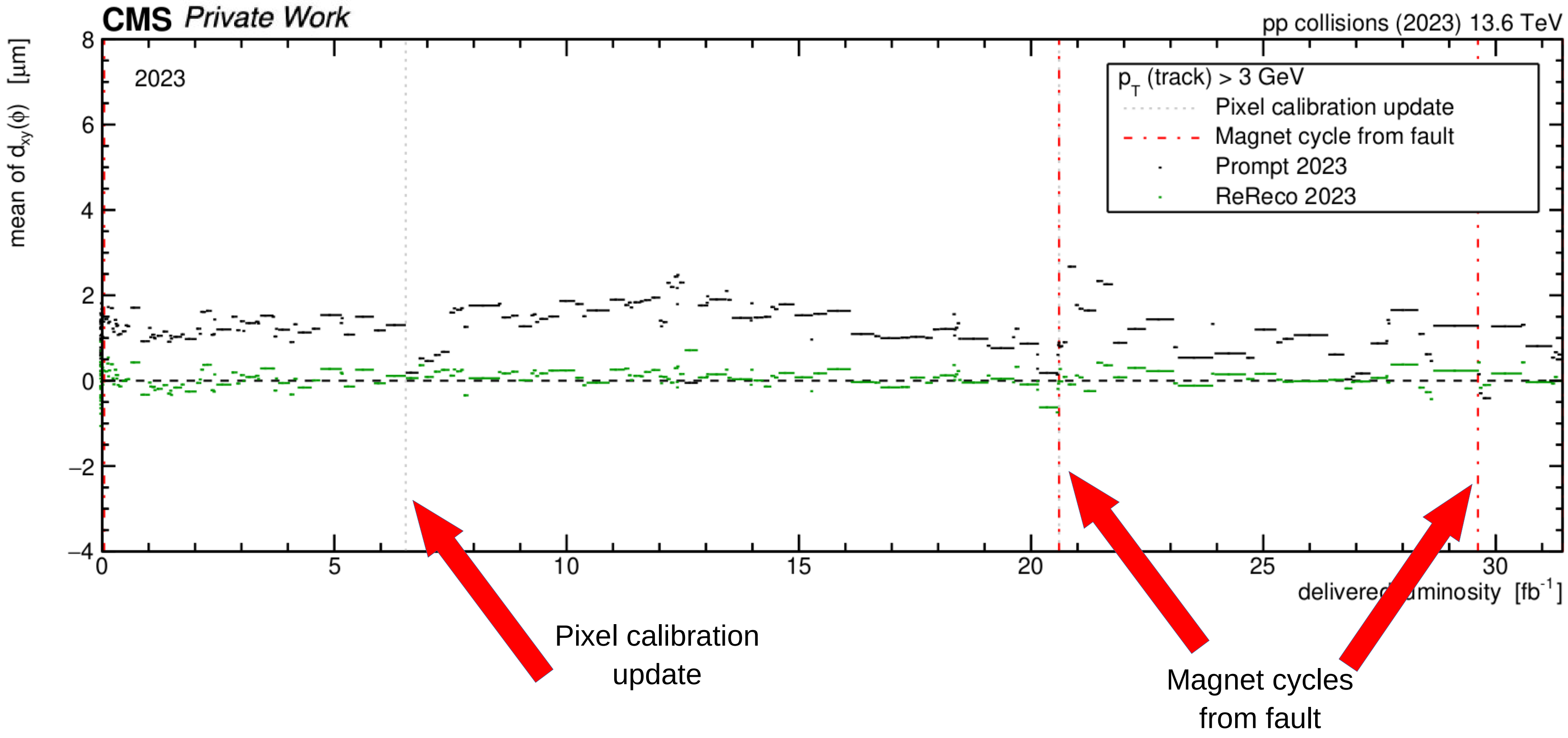


Ref[III]

Trends in primary vertex validation

Mean of d_{xy} vs. ϕ

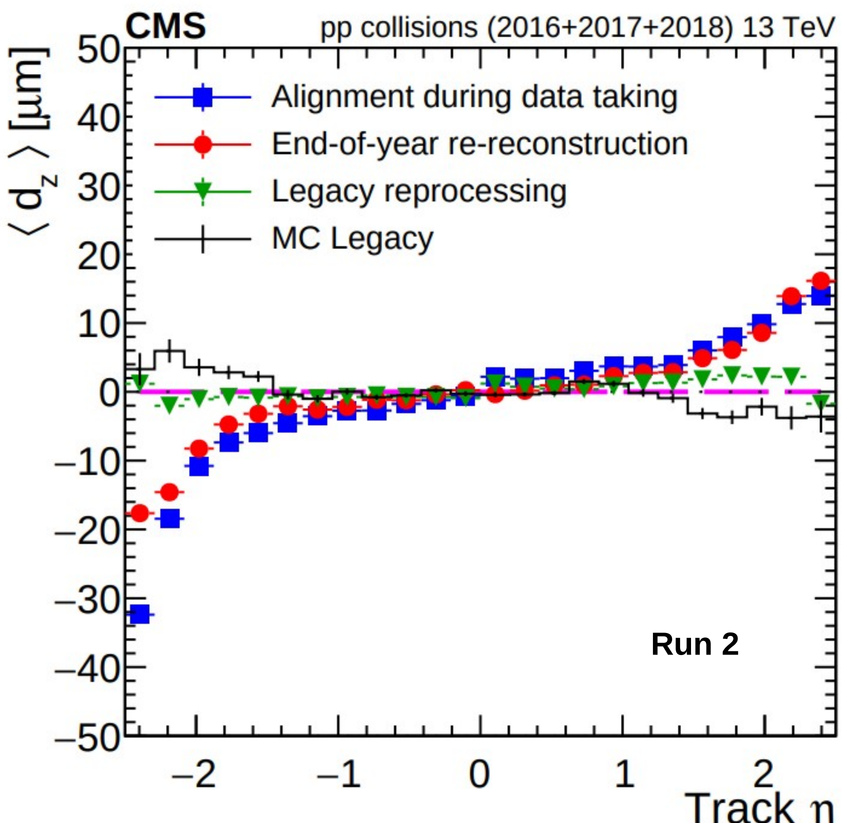
- Significant improvement in mean transverse impact parameter mismodelling



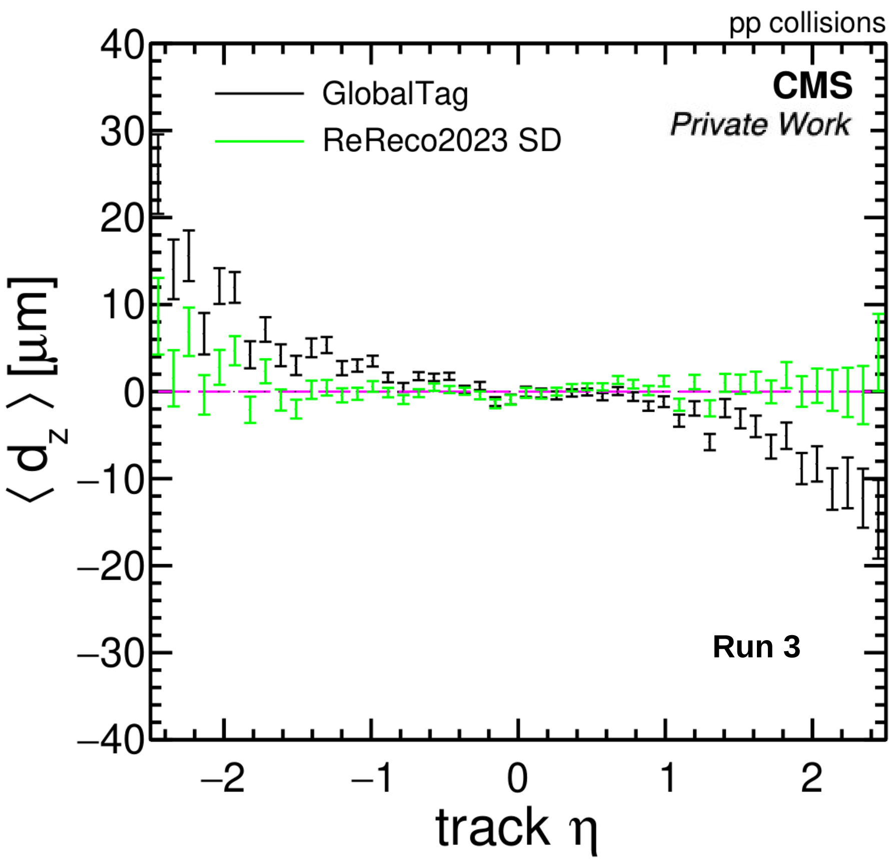
Primary vertex validation (d_z)

Comparison of Run 2 with 2023

- Significant reduction of d_z vs η bias in 2023
- 2023 End-of-year re-reconstruction is comparable to Run 2 ultra legacy alignment



Ref[VII]



Summary

- An overview was given of track-based alignment in CMS with an emphasis on the challenges faced during active data-taking
  - ➔ e.g. magnet cycles, temperature variations and irradiation effects
- The current status of alignment calibrations to be used for data reprocessing were shown, highlighting (for either 2022 or 2023)
  - ➔ better mean and RMS of track-hit residuals
  - ➔ compensation in the alignment procedure of the increased pixel irradiation (from newly installed innermost layer of the barrel pixel)
  - ➔ reduced kinematic dependence of the Z boson mass
  - ➔ improved impact parameter performance
- Extensive list of first results available for 2022 in CMS-DP-2022-044
  - ➔ ongoing work on 2022 and 2023 end-of-year alignment calibrations will be finalized and summarized in a DP note later this year

Thank you

Contact

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I. G. Sguazzoni, The construction of the CMS Silicon Strip Tracker, INFN Sezione di Firenze (January 2008). [arXiv:0801.2468]

II. The Phase-2 Upgrade of the CMS Tracker: CMS-TDR-014

III. The Alignment of the CMS Tracker and its Impact on the Early Quarkonium Physics: CERN-Thesis-2011-435

IV. 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].

V. N. Bartosik, Associated top-quark-pair and b-jet production in the dilepton channel at 8 TeV as test of QCD and background tt+Higgs productio, UHH (July, 2015). [DOI: 10.3204/DESY-THESIS-2015-035]

VI. Tracker Alignment Performance – Twiki

VII. The CMS Collaboration. Strategies and performance of the CMS silicon tracker alignment during LHC Run 2. [CMS-TRK-20-001].

Backup

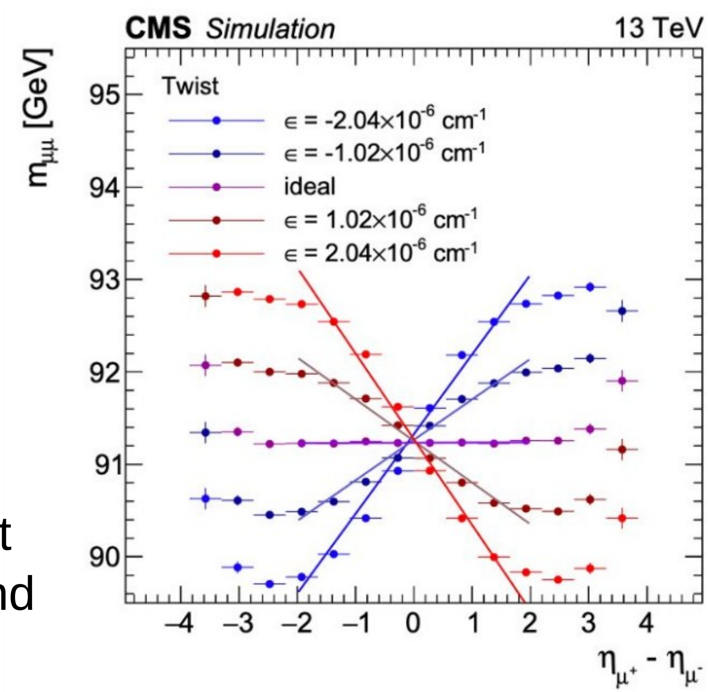
Challenges in alignment

Weak modes

- Non-physical geometrical transformations:

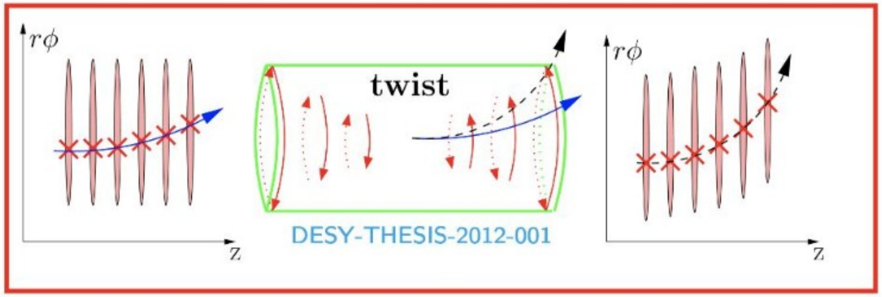
$$\Delta\chi^2 \sim 0$$

- Valid tracks turn into other valid tracks
- Key to treating weak modes is using dataset variety in alignment calibrations: cosmics and resonance data



Nine basic systematic distortions in the cylindrical system

	Δz	Δr	$\Delta\phi$
vs. z	*z expansion* $\Delta z = \epsilon z$ overlap	*bowing* $\Delta r = \epsilon r(z_0^2 - z^2)$ overlap	*twist* $\Delta\phi = \epsilon z$ $Z \to \mu\mu$
vs. r	*telescope* $\Delta z = \epsilon r$ cosmics	*radial* $\Delta r = \epsilon r$ overlap	*layer rotation* $\Delta\phi = \epsilon r$ cosmics
vs. ϕ	*skew* $\Delta z = \epsilon\cos(\phi + \phi_0)$ cosmics	*elliptical* $\Delta r = \epsilon r\cos(2\phi + 2\phi_0)$ cosmics	*sagitta* $\Delta\phi = \epsilon\cos(\phi + \phi_0)$ cosmics



Trends in primary vertex validation

RMS of d_z vs. η

- Clear improvement in the RMS of the longitudinal impact parameter → significant reduction of d_z vs η bias across the whole data-taking period