CMS tracker alignment with Run 3 data

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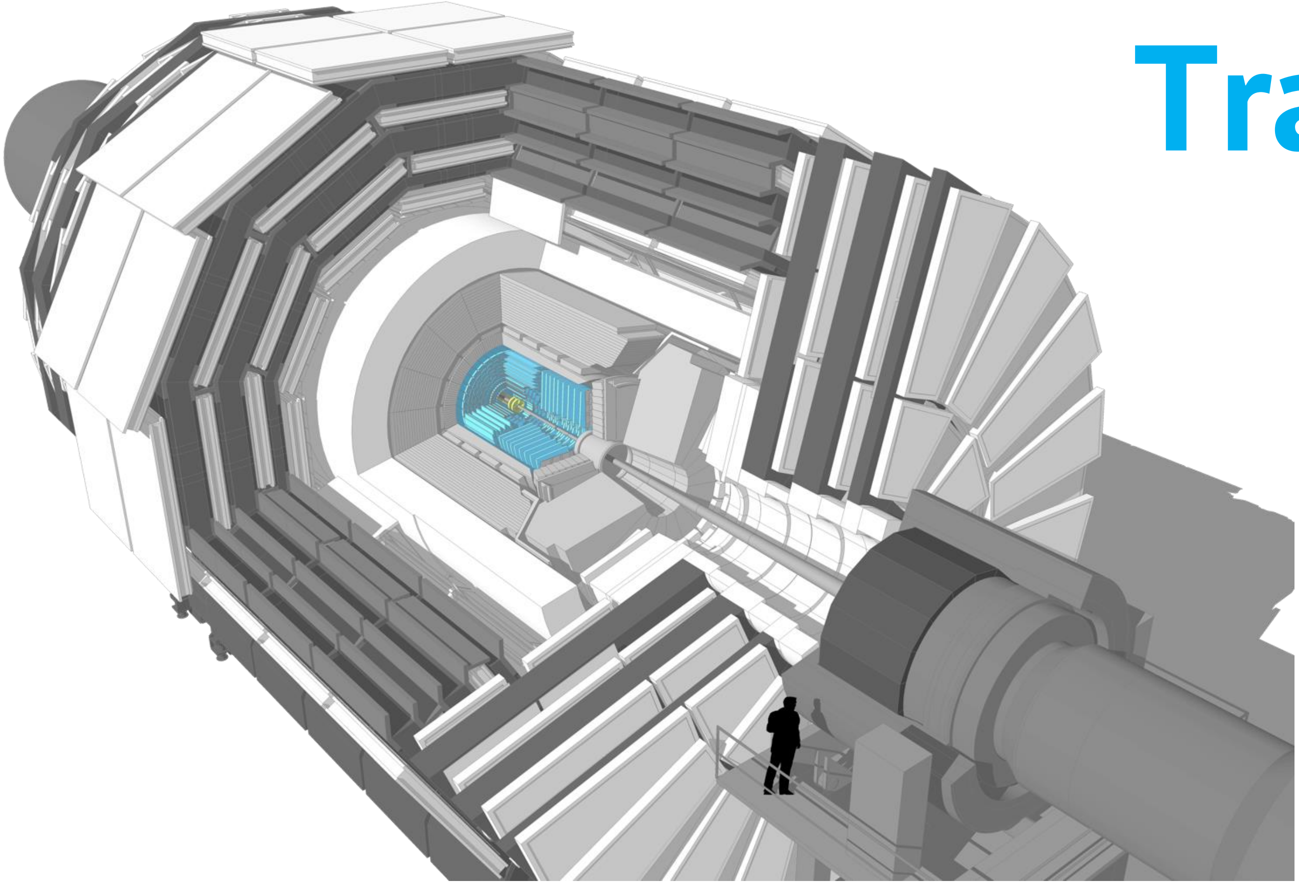
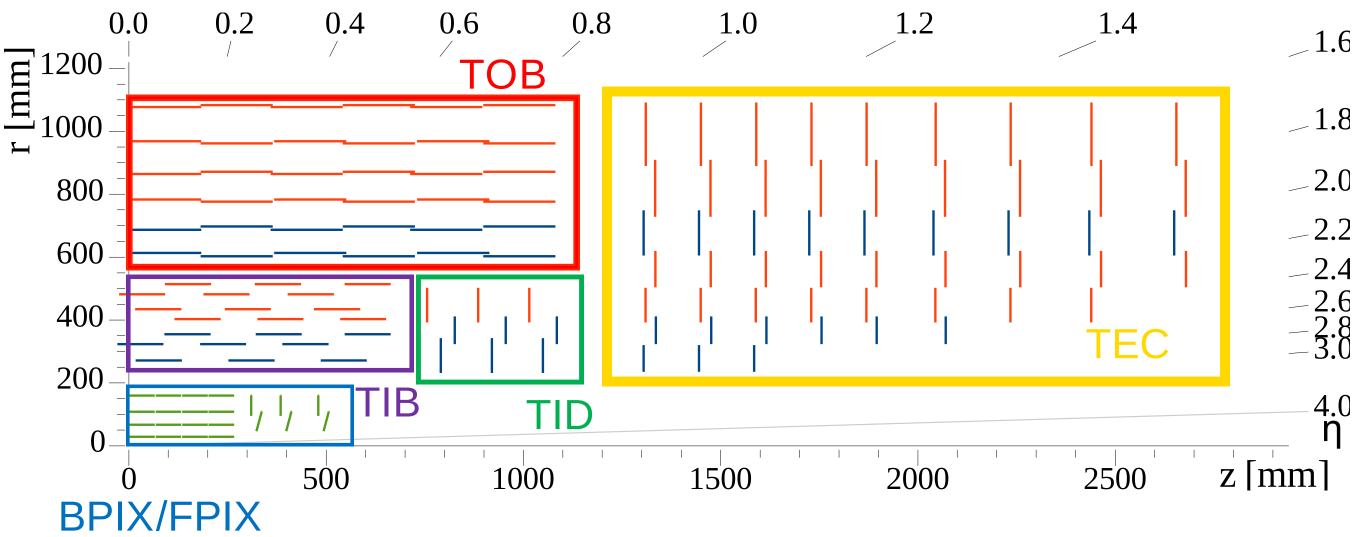
Tracker



- **It is no small feat to align the world's largest silicon tracker!**
- **Main objective of talk today:**
  - **Highlight the impressive performance** during Run 3 data taking (2022-present)
  - **Emphasize** the **challenges** as they appeared with a **focus on** the **mitigation strategies** put into place to address them
  - **Outlook for the remainer of Run 3 and HL-LHC – many challenges ahead!**

CMS tracker (Phase-I) and track-based alignment



Modified figure from [1]

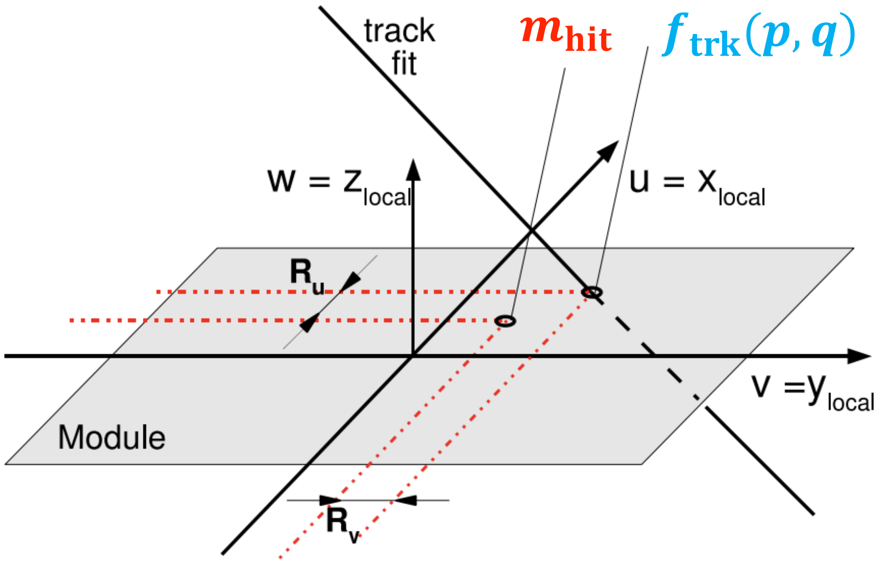
- New innermost layer of barrel pixel detector installed prior to Run 3
- Phase 1 modules:
  - Pixel: 1856
  - Strip: 15148

- Challenge of CMS tracker alignment: Largest silicon module tracker in the world!
  - Pixel detector: barrel (BPIX) and forward endcaps (FPIX)
  - Strip tracker: inner barrel (TIB), outer barrel (TOB), inner disks (TID), endcaps (TEC)
- Parameters to align: Position, rotation and curvature → $O(10^5)$ parameters!
- Goal is to find track-based alignment corrections to modules such that $\sigma_{\text{align}} \lesssim \sigma_{\text{hit}}$

Track-based alignment using MillePede-II

Simultaneous fit of all global alignment and local track parameters with MP-II [2]

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



Modified figure from [3]

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

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

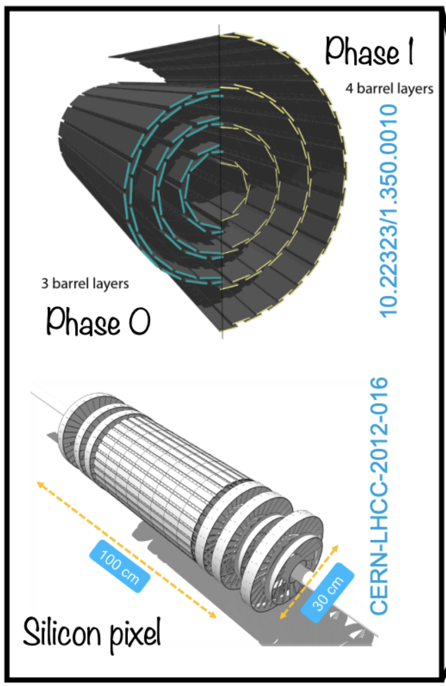
Ingredients:
p; global alignment parameters
q_j; local track parameters
m_{ij} $\pm\, \sigma_{ij}$; measured hit position
f_{ij}; predicted hit position

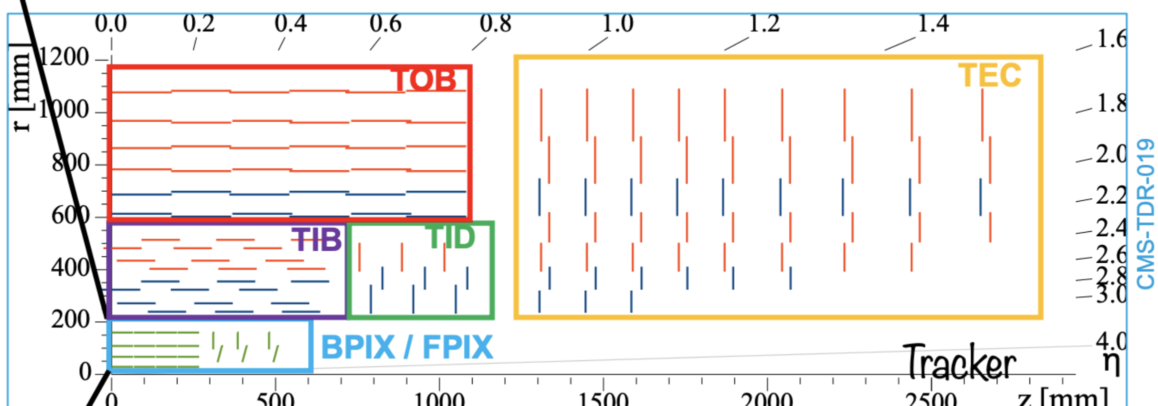
- The linear equation system (for χ^2 minimisation) is reduced to the number of global alignment parameters using block matrix algebra, keeping all correlations due to local track fits

- Solution methods employed to solve the equation system for pixel and strip modules in
  - **Run 2 (2016-2018, MINRES QLP): Approximate solution**
  - **Run 3 (2022-2026, LAPACK): Exact solution obtained using Cholesky decomposition**

How does time dependence arise in 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).





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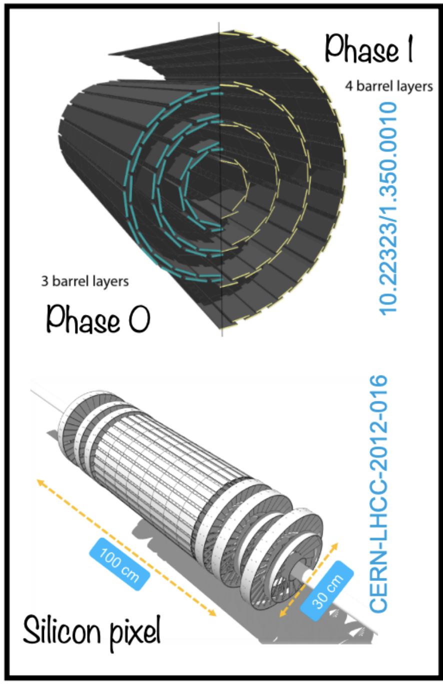

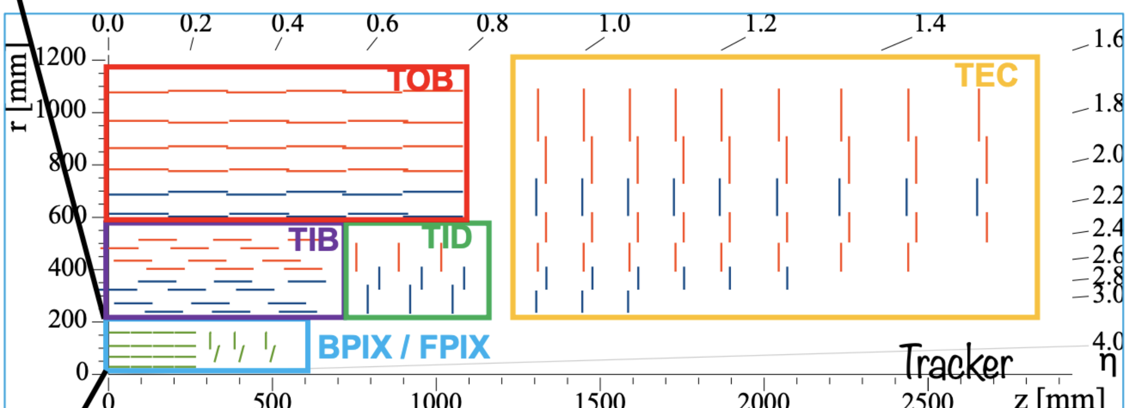

Modified figure from [1]

Temperature variations:

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

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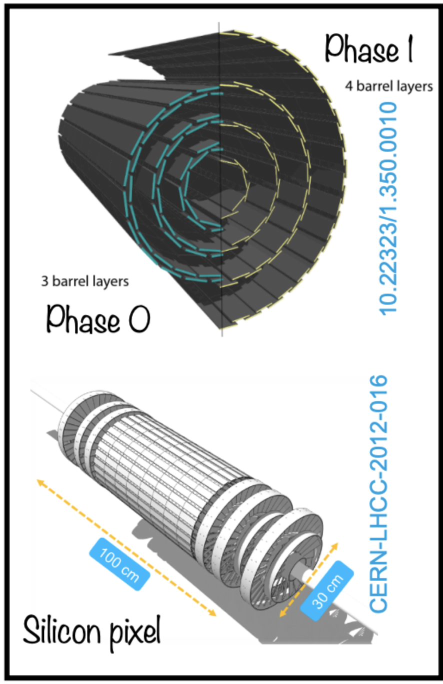
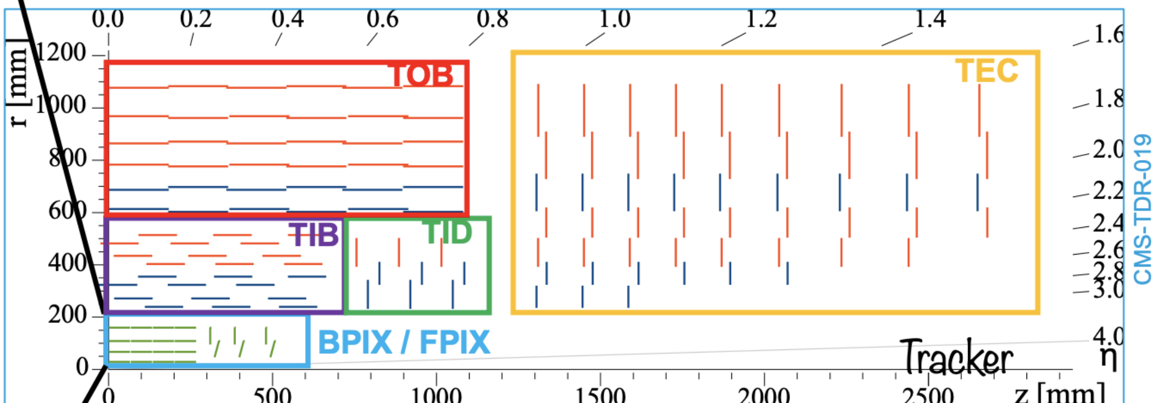




Modified figure from [1]

New innermost layer added to the barrel pixel in phase 1

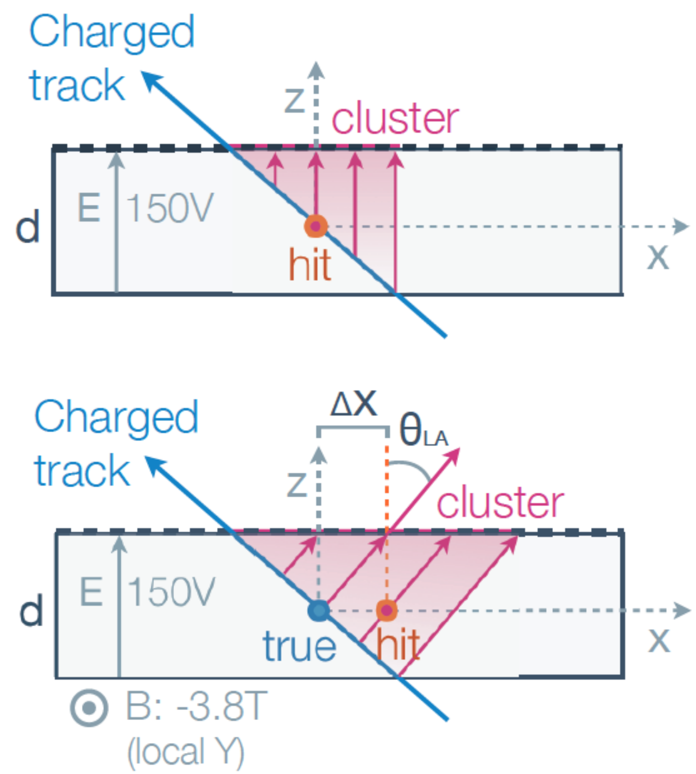
Temperature variations:
- Cooling operations after long shutdown periods
  (sensors – order of 10^{-1} mm).

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

Ageing of silicon modules in the pixel detector

Lorentz drift in the silicon modules:

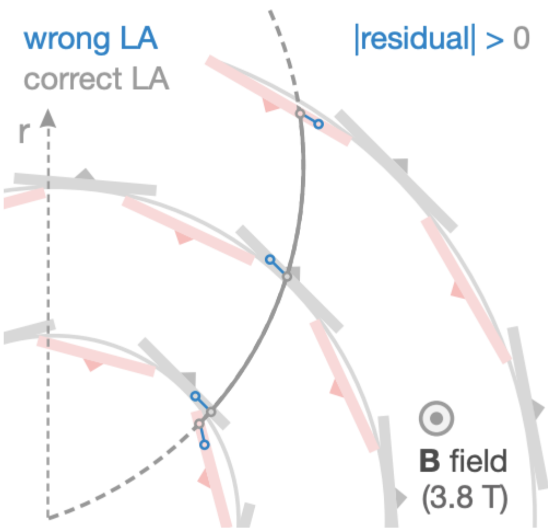
- Hit determined from barycentre of charge cluster.
- Hall effect leads to Lorentz drift.
  → Measured hit position shifts with respect to true hit (x-direction).



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

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

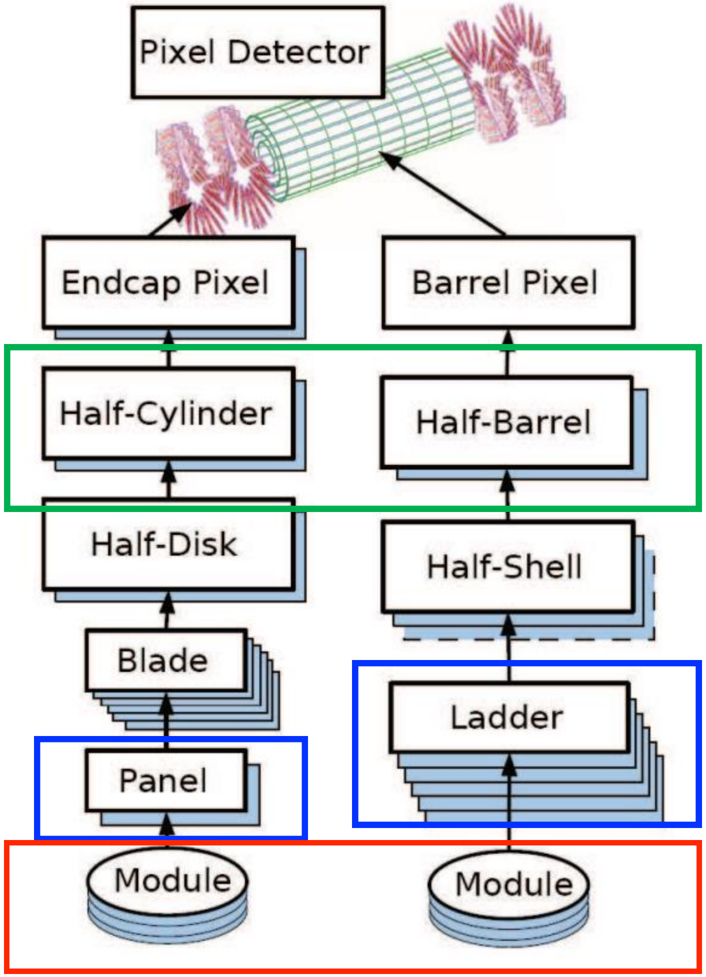
Increased irradiation with increased luminosity.
→ more pronounced effect with age.



Tracker alignment strategy in Run 3

- **Alignment during data taking** mainly consists of an automated alignment performed in a Prompt calibration loop (PCL) if movements of the pixel detector are above a certain threshold
  - 2022:
    - The pixel detector was corrected at the half-barrel + half-cylinder level until the first technical stop
    - A new high granularity alignment (HG PCL) at the ladder+panel level was active after the technical stop
  - 2023:
    - The HG PCL was predominantly active for the whole year

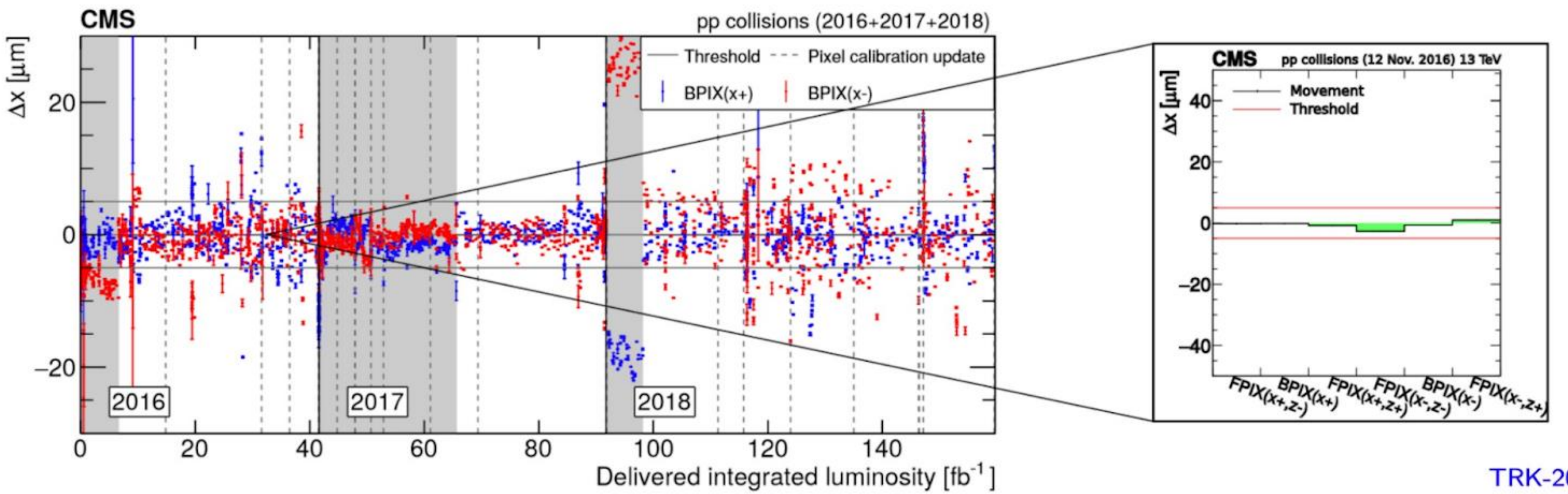
- Alignment for reprocessing
  - At the end of 2022 and 2023 data taking a full modular alignment of ***both*** the pixel and strip detector was done
  - For the first time in CMS an exact solution method was used



Modified figure from [4]

Low Granularity Prompt Calibration Loop (PCL) alignment

- Alignment of large structures (HLS) of the pixel detector ⇒ low granularity (LG)
  - 2 BPIX half-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 express minimum bias data
- Alignment automatically updated, if movements within set requirements
- Due to low granularity cannot account for some effects like radiation damage



TRK-20-001

Distribution of median residuals (run-averaged)

Figure from [5]

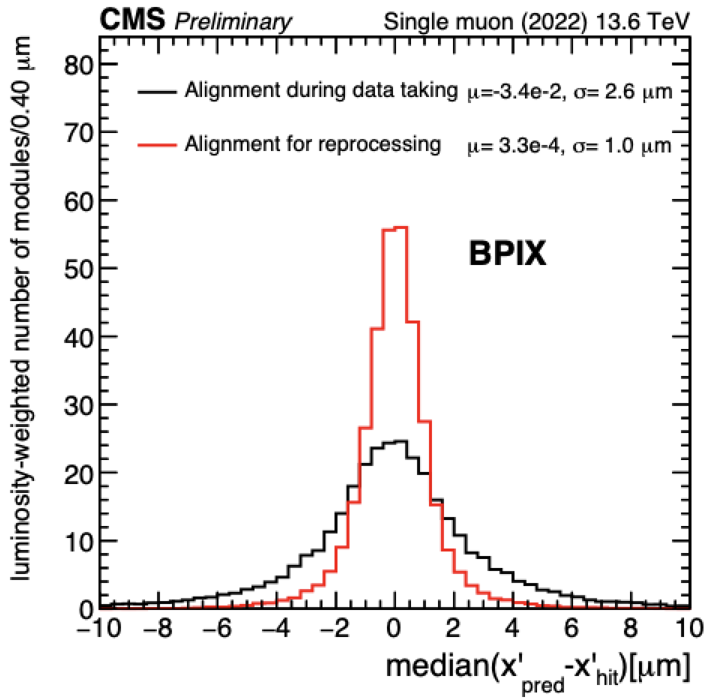
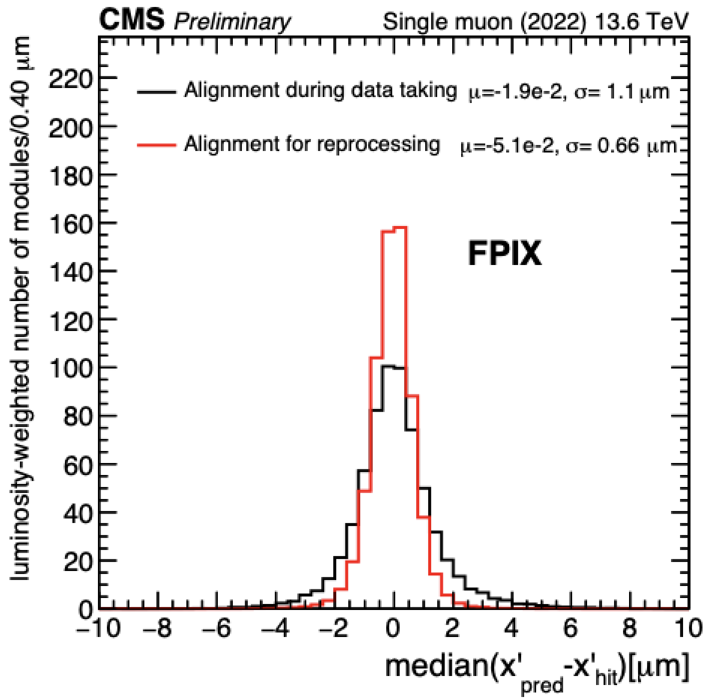


Figure from [5]



- Distributions of the median track hit residuals (DMRs) are shown for all modules in the barrel (left) and forward endcaps (right) of the pixel detector in the local x (x') direction
- Distributions shown here are averaged over all processed runs of 2022, after scaling them with the corresponding luminosity for each run
- The alignment for reprocessing has a smaller mean deviation away from zero and a better width indicating less misalignment due to changing conditions and a higher precision of the calibration

Trends of Distribution Median Residuals

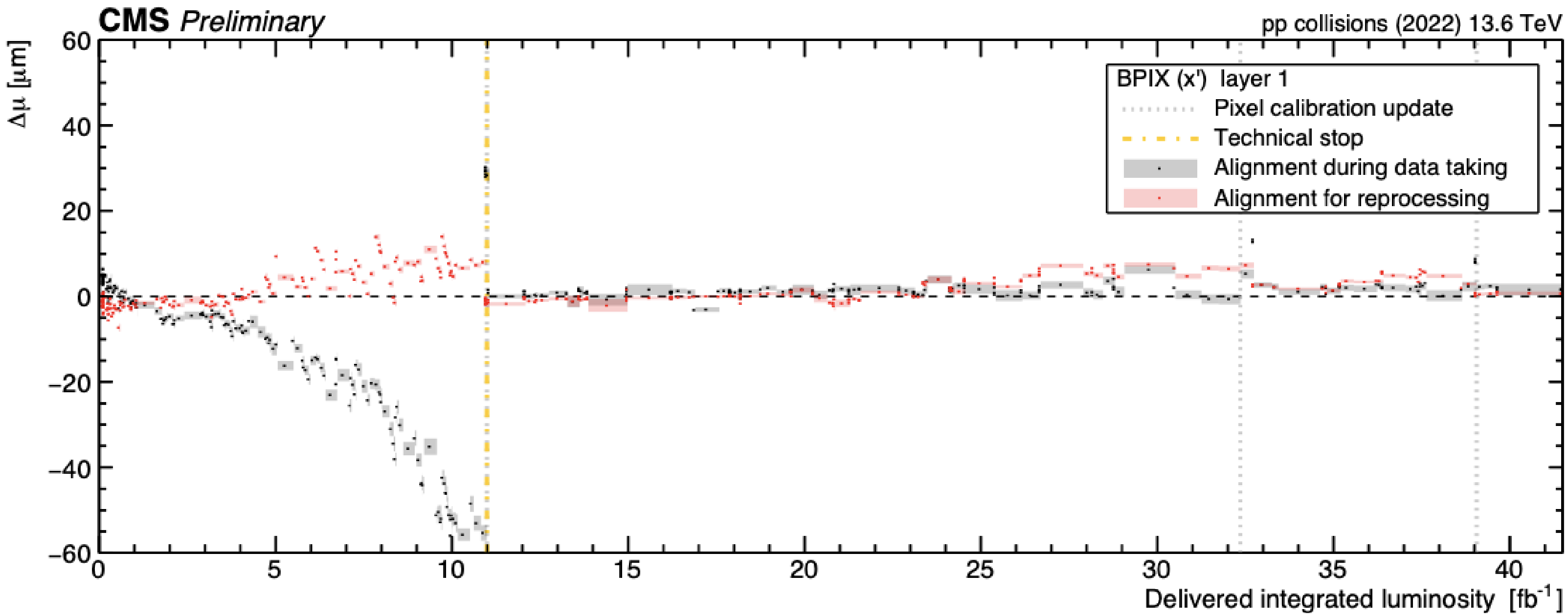


Figure from [5]

- Difference in DMR mean values ($\Delta\mu$) for modules with electric field pointing radially inwards or outwards in the local x (x') direction shown for layer 1 of the barrel pixel detector in 2022

- **$\Delta\mu$ is sensitive to Lorentz angle effects**
  - Measured hit position shifts with respect to true hit (x-direction)
  - Inward and outward facing tracker modules are affected by Lorentz drift in opposite ways!

- Irradiation effects from the newly installed innermost layer of the barrel pixel detector are visible prior to the technical stop (yellow line) for the **alignment during data taking**
  - After the technical stop the high voltage was raised and corresponding updates were done in pixel local reconstruction (grey lines) [6]. The high granularity automated alignment helped to mitigate remaining irradiation effects
  - Irradiation effects before and after the technical stop are mitigated in the alignment for reprocessing

High Granularity Prompt Calibration Loop (PCL) alignment

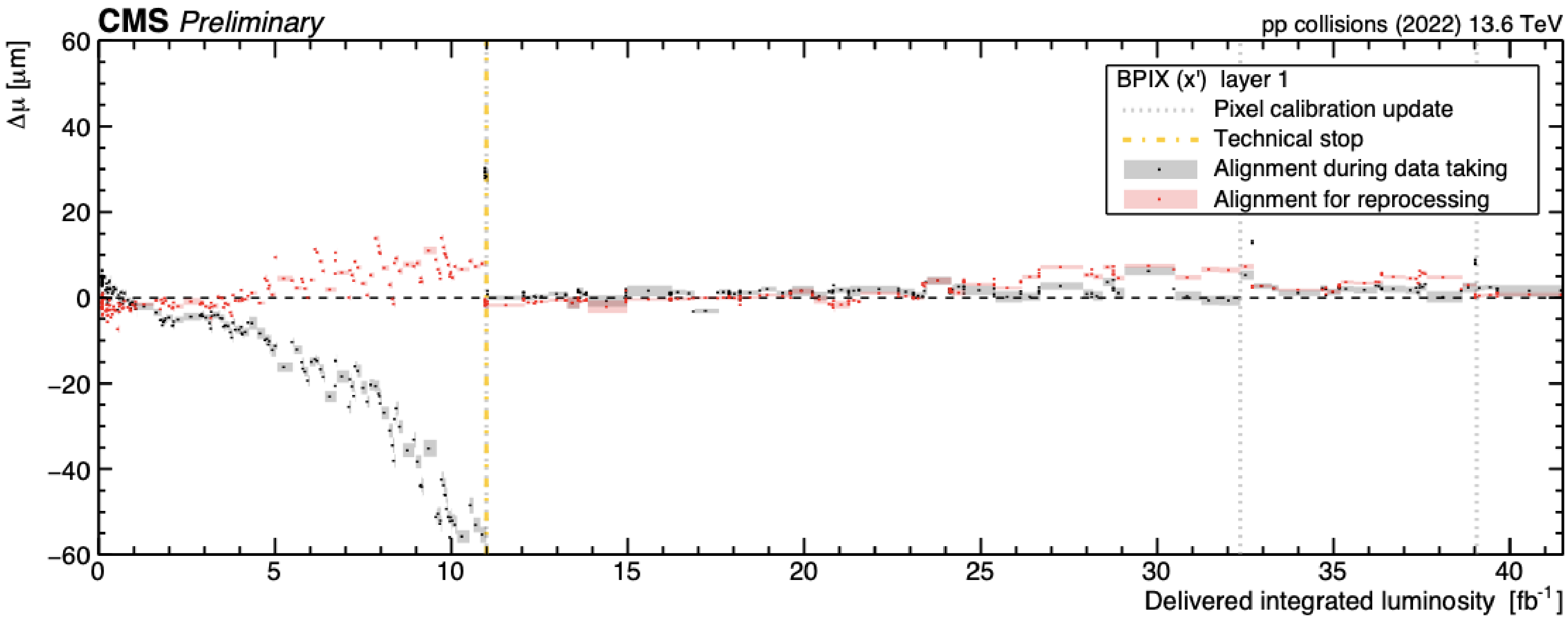
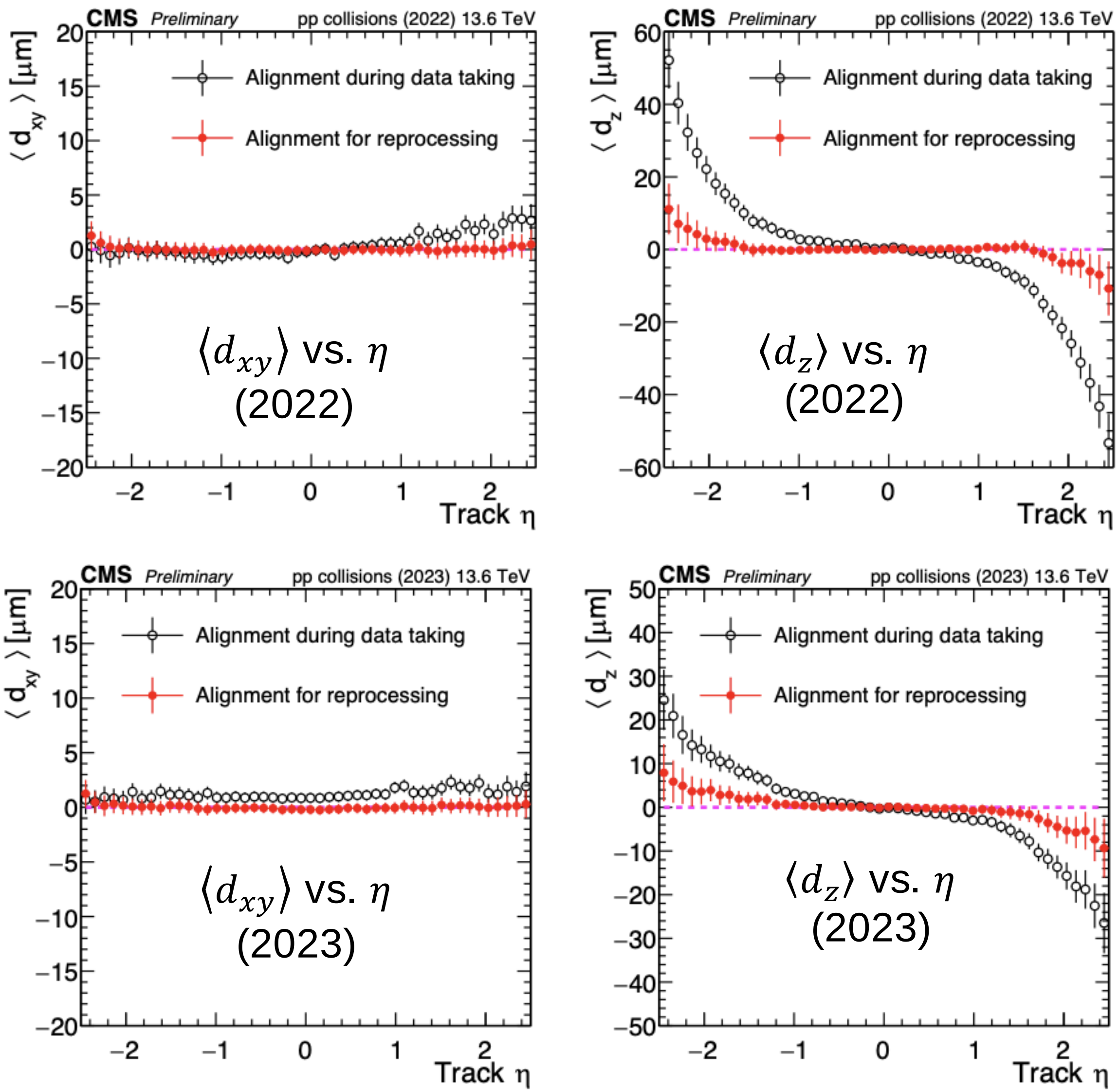


Figure from [5]

- Change from HLS-based to ladder/panel-based alignment
  - Increase number of parameters from 36 to ~ 5000
- Improved performance w.r.t. LG PCL alignment
  - Uses express minimum bias data

- But: <u>More parameters ⇒ Cannot be fully constrained by MinBias</u>
  - **can be seen through relatively large bias in longitudinal impact parameter vs. Pseudorapidity (next slide)!**

Track-vertex impact parameters (run-averaged)



Figures from [5]

- **Impact parameters are obtained by recalculating the vertex position**
  - Remove the track being studied from it
  - considering the impact parameter of this removed track to the recomputed vertex
- **Left: Mean track-vertex impact parameter in the transverse plane d_{xy}**
- **Right: Longitudinal direction d_z**
- Distributions shown here are averaged over all processed runs of 2022 (top) and 2023 (bottom),
  - Scaled with the corresponding luminosity for each run.

New mitigation strategy in data taking: High Granularity Combined PCL

- Very significant improvement can be seen in the alignment for reprocessing
  - bias in d_z vs η greatly reduced
- Exploiting Z → μμ events with mass and vertex constraints is key!
- Introduction of High Granularity Tracker Alignment Prompt Calibration Loop with Z → μμ data (HG PCL combined)
- **Effective strategy but there are limitations!**

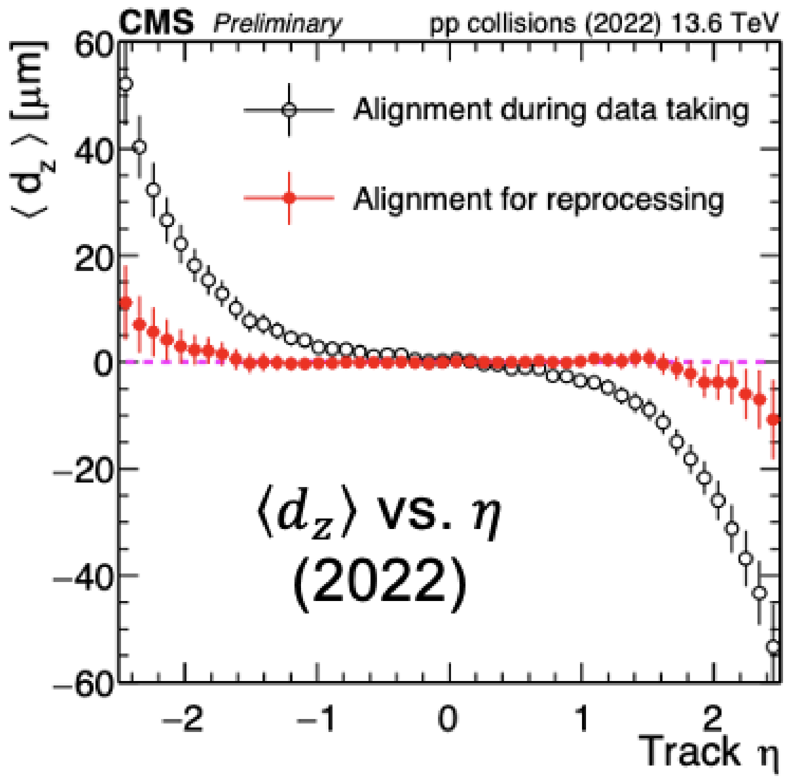


Figure from [5]

Weak modes in track-based alignment

- **Prompt calibration loops (PCL) in 2022 and 2023 lacked dataset variety** and **manuel updates** could only be done with a **limited frequency** during data taking
- **Dataset variety** is of utmost importance for **controlling various biases and weak modes** (unphysical distortions of the detector that don't impact the track fit).
- **Nine basic systematic distortions** in the cylindrical system can occur!
  - **Cosmics and Zmumu data are critical** to control those and are therefore exploited in the alignment for reprocessing

Example of a weak mode

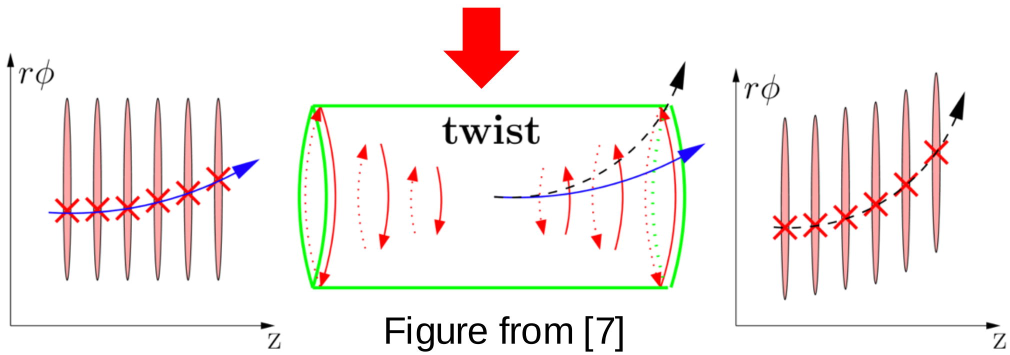


Figure from [7]

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

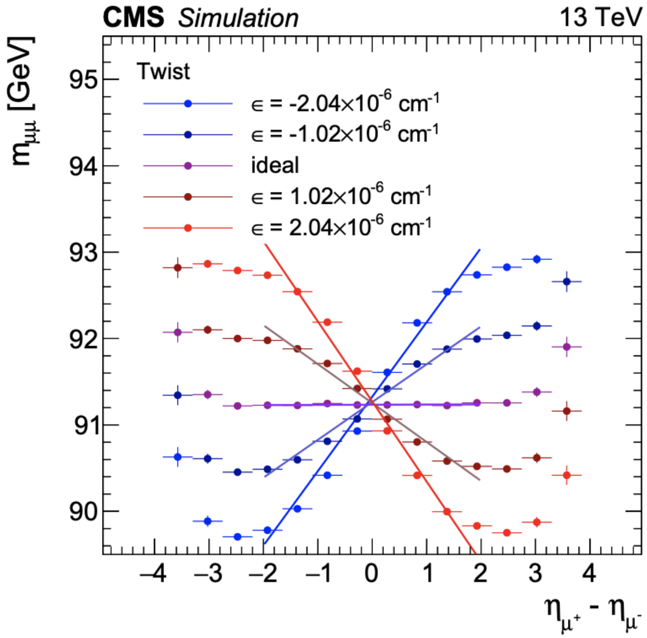
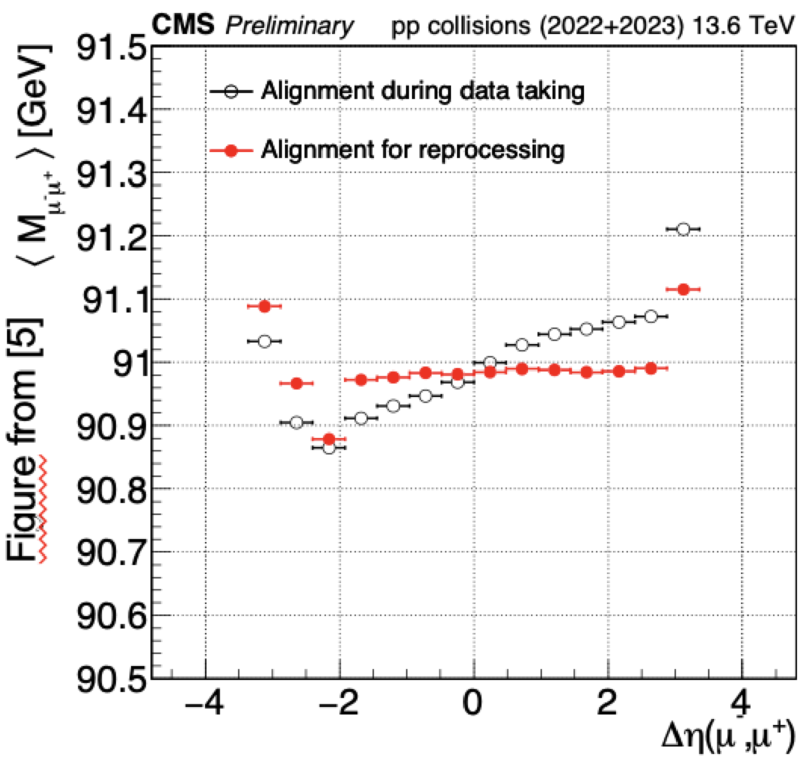


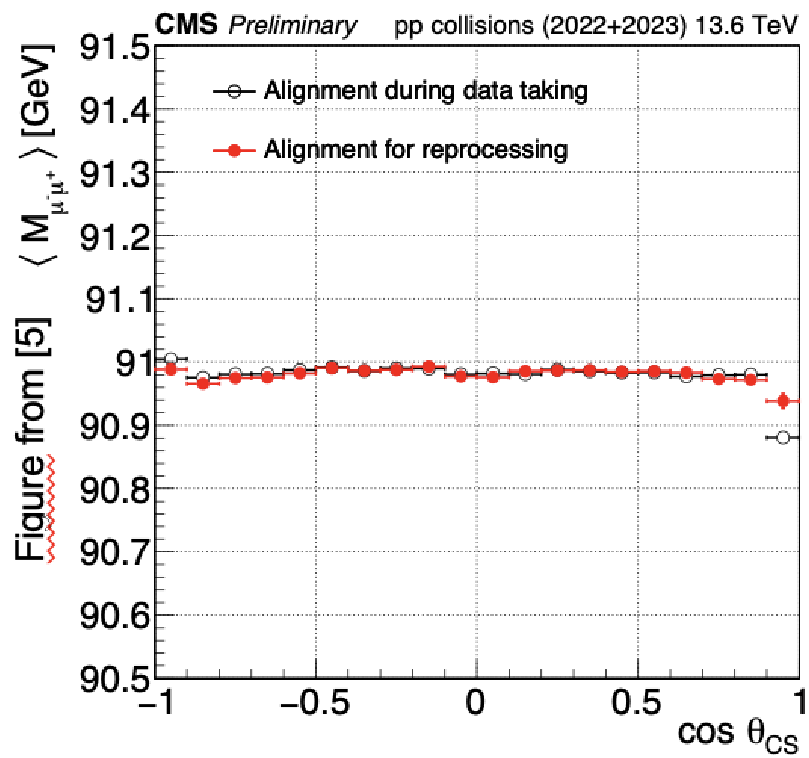
Figure from [8]

Minimizing the spatial dependence of the Z boson mass

$\langle M_{\mu^-\mu^+} \rangle$ vs. $\Delta\eta(\mu^-, \mu^+)$

$\langle M_{\mu^-\mu^+} \rangle$ vs. $\cos\theta_{CS}$

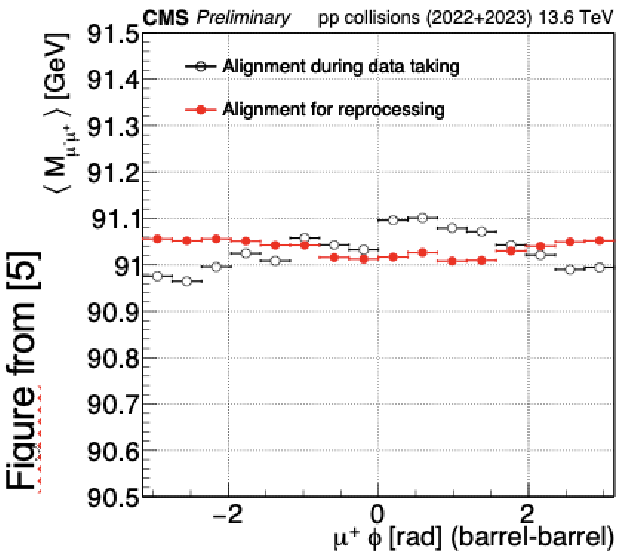




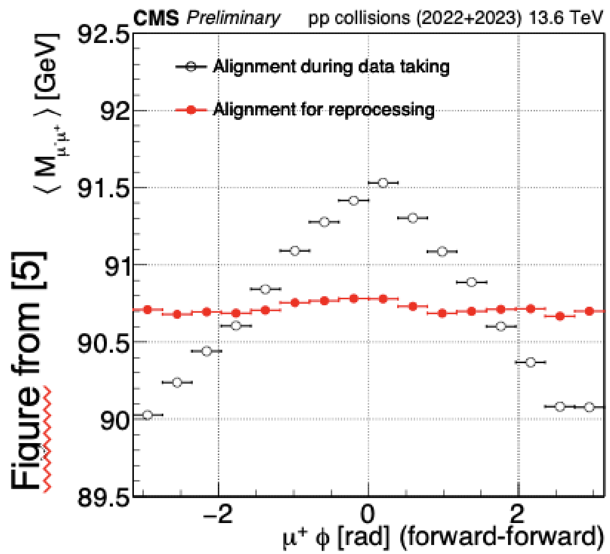
- Reconstructed Z → μμ mass as a function of the difference in η between the negatively and positively charged muons (left) and as a function of the angle $\cos\theta_{CS}$ in the Collins-Soper frame of the reconstructed Z boson (right)
- The alignment for reprocessing shows an improvement in the uniformity of the reconstructed Z → μμ mass

Minimizing the spatial dependence of the Z boson mass

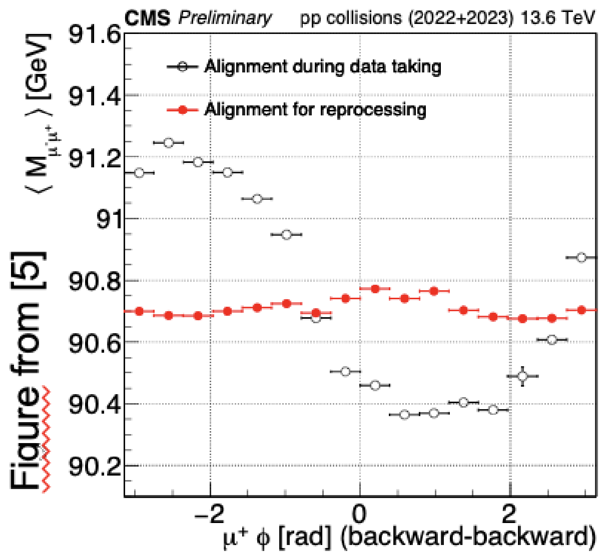
$\langle M_{\mu^-\mu^+} \rangle$ vs. $\mu^+ \ \phi$
(both muons within barrel)



$\langle M_{\mu^-\mu^+} \rangle$ vs. $\mu^+ \ \phi$
(both muons forward)



$\langle M_{\mu^-\mu^+} \rangle$ vs. $\mu^+ \ \phi$
(both muons backward)



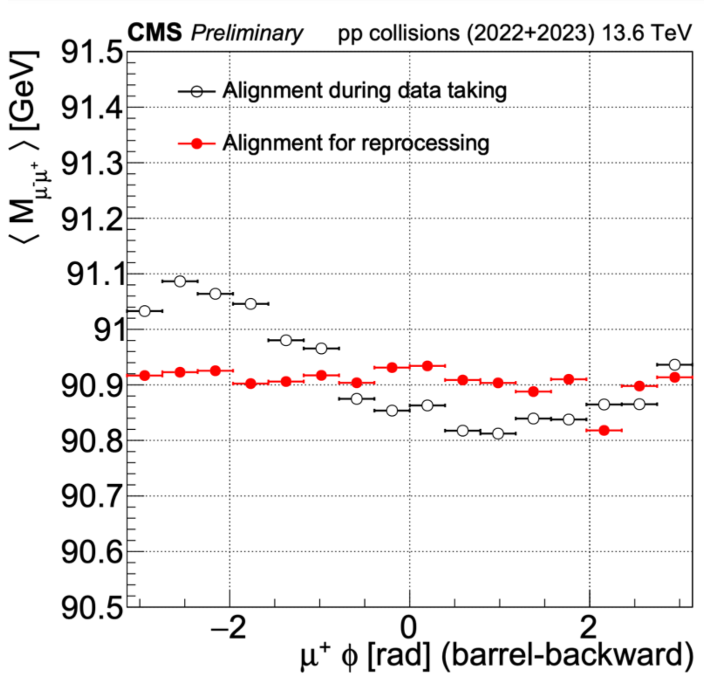
- Reconstructed Z → μμ mass as a function of the azimuth angle ϕ of positively charged muons shown for the η region when both muons are within the barrel i.e. $|\eta| \leq 1.5$ (left), when both muons are forward i.e. $\eta > 1.5$ (middle) and when both muons are backward i.e. $\eta < -1.5$ (right)

- Alignment for reprocessing shows an improvement in the uniformity of the reconstructed Z → μμ mass

Minimizing the spatial dependence of the Z boson mass

$\langle M_{\mu^-\mu^+} \rangle$ vs. $\mu^+\ \phi$
(one muon within the barrel,
other muon backward)

Figure from [5]



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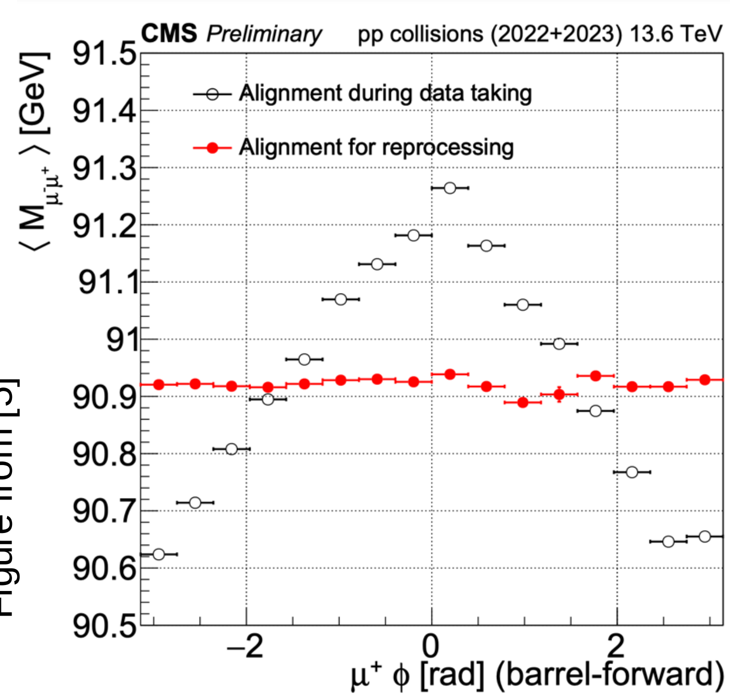
(one muon within the barrel,
other muon forward)

Figure from [5]



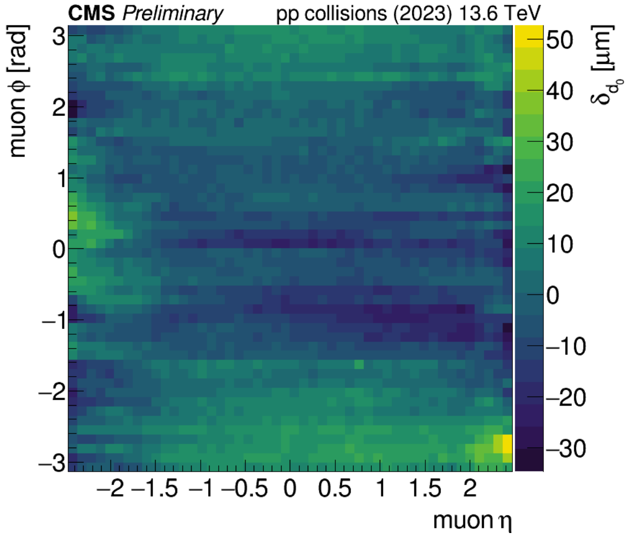
- Reconstructed $Z \rightarrow \mu\mu$ mass as a function of the azimuth angle ϕ of positively charged muons shown for the η region when one muon is within the barrel i.e. $|\eta| \leq 1.5$ and the
  - other muon is backward i.e. $\eta < -1.5$ (left)
  - other muon is forward i.e. $\eta > 1.5$ (right)

- Alignment for reprocessing shows an improvement in the uniformity of the reconstructed $Z \rightarrow \mu\mu$ mass

2023 Impact Parameter Bias in Z → μμ events

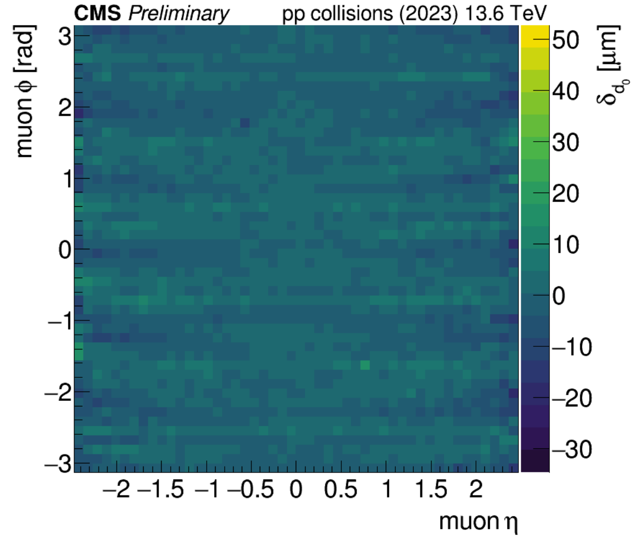
Alignment during data taking

δ_{d_0} in bins of ϕ and η



Alignment for reprocessing

δ_{d_0} in bins of ϕ and η



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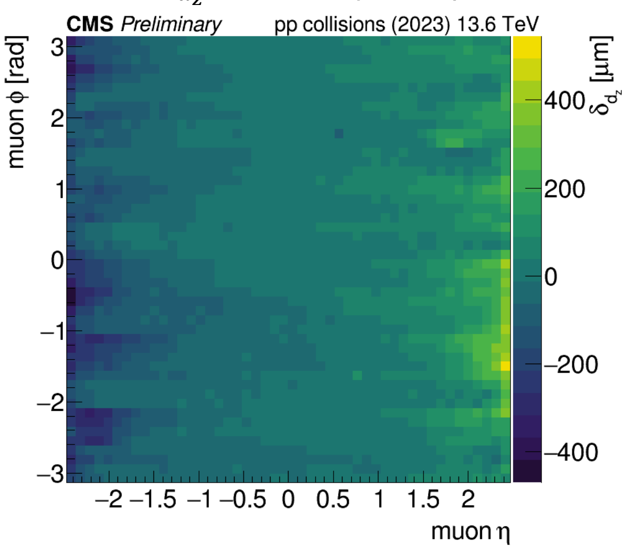
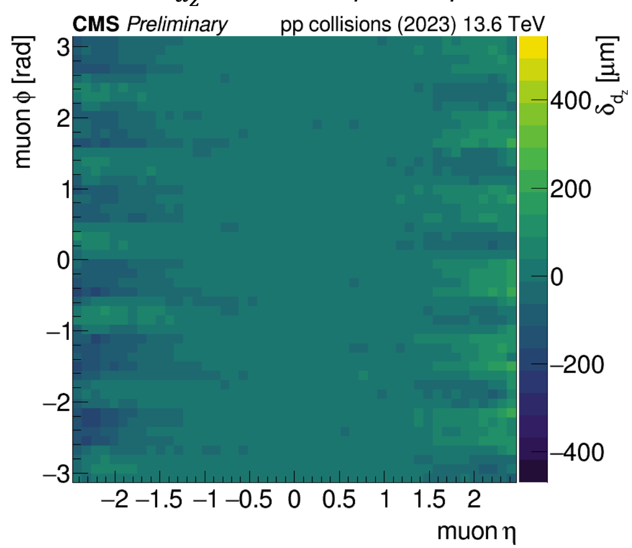


Alignment for reprocessing

δ_{d_z} in bins of ϕ and η



- Mean correction to the measured transverse (top) and longitudinal (bottom) impact parameter estimated to satisfy on-average-zero difference between the impact parameters of the two muons originating from the Z boson is shown in bins of track ϕ and η
- The **alignment during data taking** (left) is shown in comparison to the alignment for reprocessing (right) for 2023 data
- Mean corrections are smaller and show an improved uniformity with the alignment for reprocessing

Figures from [5]

What's next on the horizon?
Run 3 + Hl-LHC - New automated "rolling calibration" workflows

- Fast accumulation of integrated luminosity brings many challenges!

- <u>High quality and speedy calibrations needed very frequently</u> - already quite challenging in Run 3….
  - Not sustainable due to several reasons incl. person power

- **In Run 4 and 5 of the HL-LHC data reprocessing schedule will need to change. Why?**
  - Demands on computing from sheer volume of data
  - On demand high precision needed for physics analyses in timely manner

- **What must be done?**
  - Goal: <u>approximate ultimate precision in prompt</u> through the use of automated rolling calibration workflows

- **What is a "rolling calibration"?**
  - Hypothesis that resetting the starting geometry online several times with "ultimate precision" like updates will lead to "ultimate precision" like data quality. Trick is to do updates frequently enough and maintain performance inbetween…
  - Easier said than done but…
  - Efforts in Run 3 supports the hypothesis that it's probably feasible to the extent required

Summary

- The challenges in aligning the CMS tracker were presented in the context of the alignment strategy for Run 3

- The performance of the alignment derived to achieve ultimate physics precision in the reprocessing of 2022 and 2023 data was shown and compared to the alignment during data taking

- For the first time in CMS an exact solution method was employed in deriving corrections to the pixel and strip modules

- Significant improvements seen in
  - Distributions of median track hit residuals
  - Track vertex impact parameter validation
  - Uniformity of $Z \rightarrow \mu\mu$ mass dependence on η and ϕ
  - Track impact parameter bias in $Z \rightarrow \mu\mu$ events

Thank you!

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References

[1] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK

[2] V. Blobel and C. Kleinwort, “A new method for the high precision alignment of track detectors”, in Conference on Advanced Statistical Techniques in Particle Physics. 2002. arXiv:hep-ex/0208021

[3] M. Musich, ”The Alignment of the CMS Tracker and its Impact on the Early Quarkonium Physics”, Ph. D. Thesis, University of Turin. 2011.
https://cds.cern.ch/record/2636097

[4] J. Draeger, ”Track based alignment of the CMS silicon tracker and its implication on physics performance”, Ph. D. Thesis, University of Hamburg. 2011.
https://cds.cern.ch/record/2283085

[5] CMS Collaboration,
https://twiki.cern.ch/twiki/bin/view/CMSPublic/TkAlignmentPerformanceRun3Reprocessing

[6] CMS Collaboration, "Pixel Detector Performance in Run 3”. 2022.
https://cds.cern.ch/record/2844889

[7] H. Enderle, ”Momentum bias determination in the tracker alignment and first differential $t\bar{t}$ cross section measurement at CMS”, Ph. D. Thesis, University of Hamburg. 2012.
https://cds.cern.ch/record/1513691

[8] CMS Collaboration "Strategies and performance of the CMS silicon tracker alignment during LHC Run 2" 2022 Nucl. Instrum. Meth. A 1037 166795
doi:10.1016/j.nima.2022.166795