Tracker alignment of the CMS detector with Run 3 data

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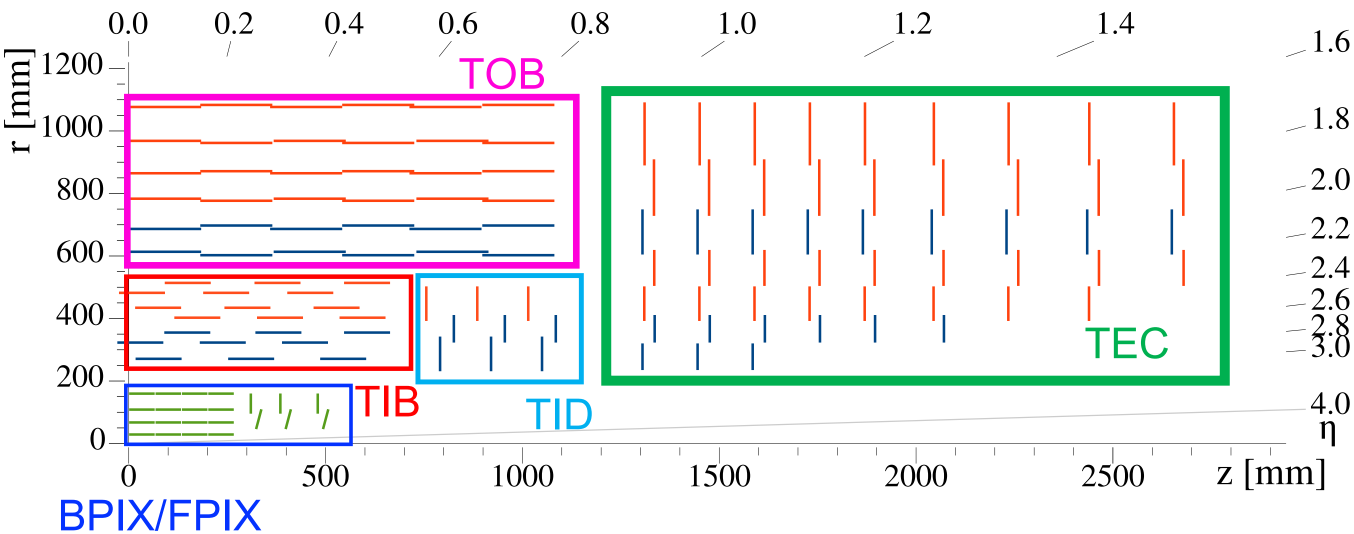
CMS tracker (Phase-I) and track-based alignment



Modified figure from [1]

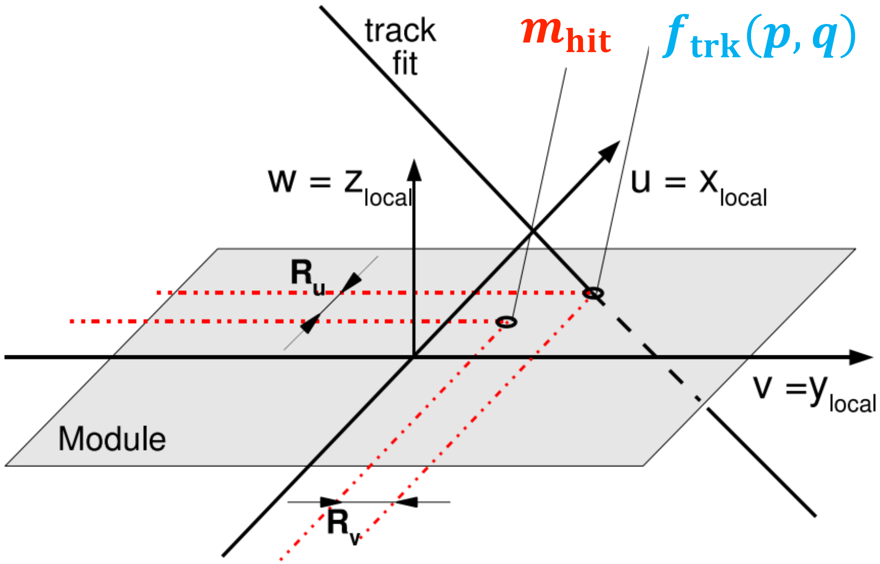
- New innermost layer of barrel pixel detector installed prior to Run 3
  - Phase 1 modules:
    Pixel: 1856
    Strip: 15148

- 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 $\sigma_{\text{align}} \lesssim \sigma_{\text{hit}}$

MPII 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

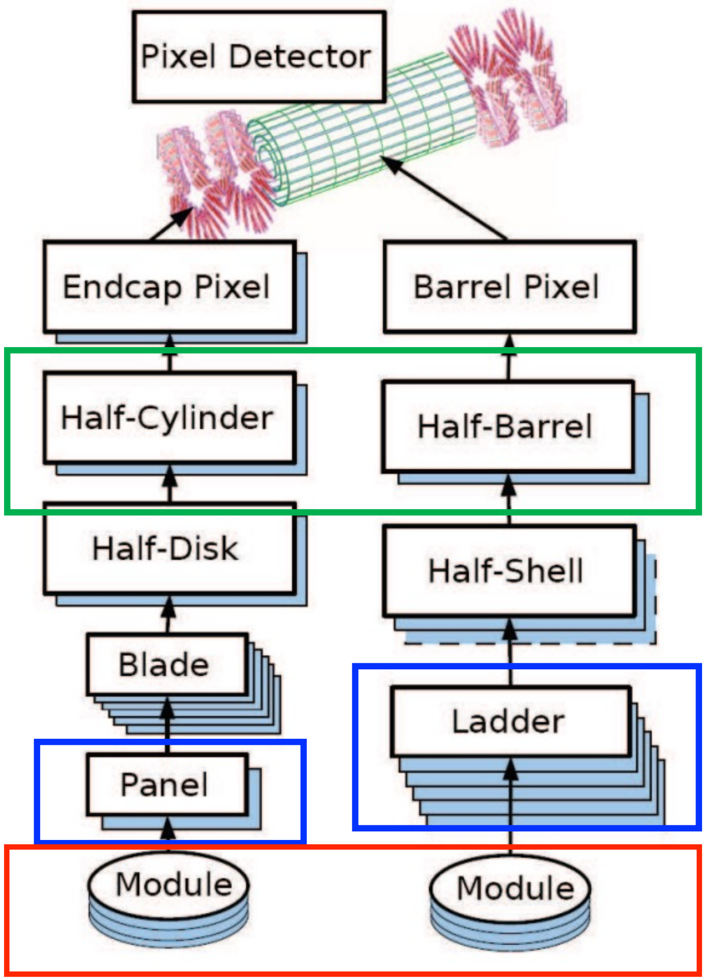
- Solution methods employed to solve the equation system for pixel and strip modules in
  - **Run 2 (MINRES QLP): Approximate solution**
  - **Run 3 (LAPACK): Exact solution obtained using Cholesky decomposition**

Tracker alignment strategy in Run 3

- Time dependence of alignment introduced by e.g.
  - Magnet cycles, temperature variations, irradiation effects

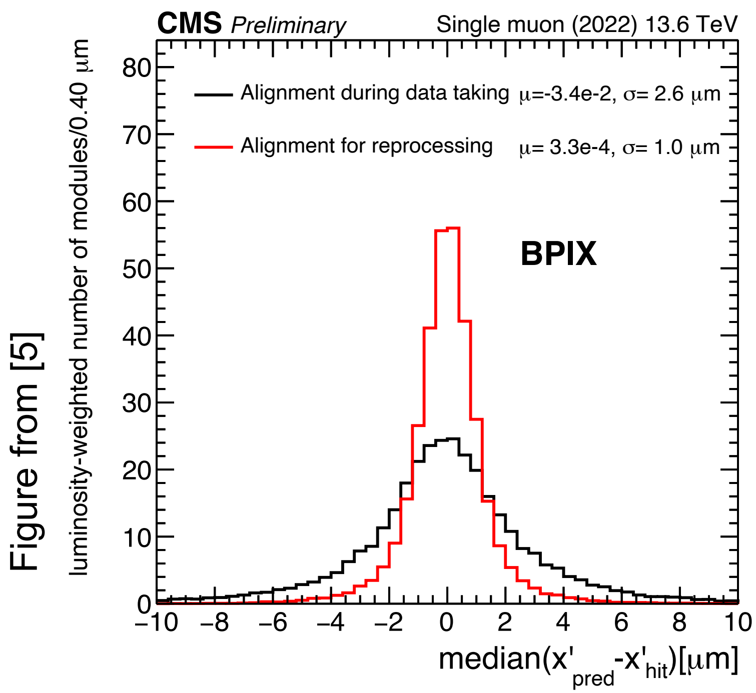
- **Alignment during data taking** mainly consists of an automated alignment performed in a Prompt calibration loop (PCL) if movements of the pixel detector are above a certain threshold
  - 2022:
    - The pixel detector was corrected at the half-barrel + half-cylinder level until the first technical 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

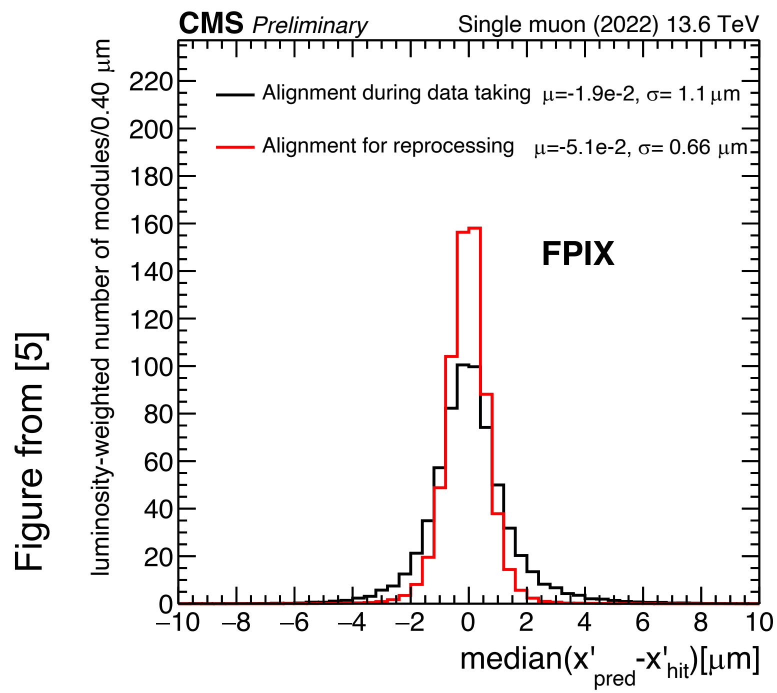
- Alignment for reprocessing
  - At the end of 2022 and 2023 data taking a full modular alignment of ***both*** the pixel and strip detector was done
  - For the first time in CMS an exact solution method was used



Modified figure from [4]

Distribution of median residuals (run-averaged)





- 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

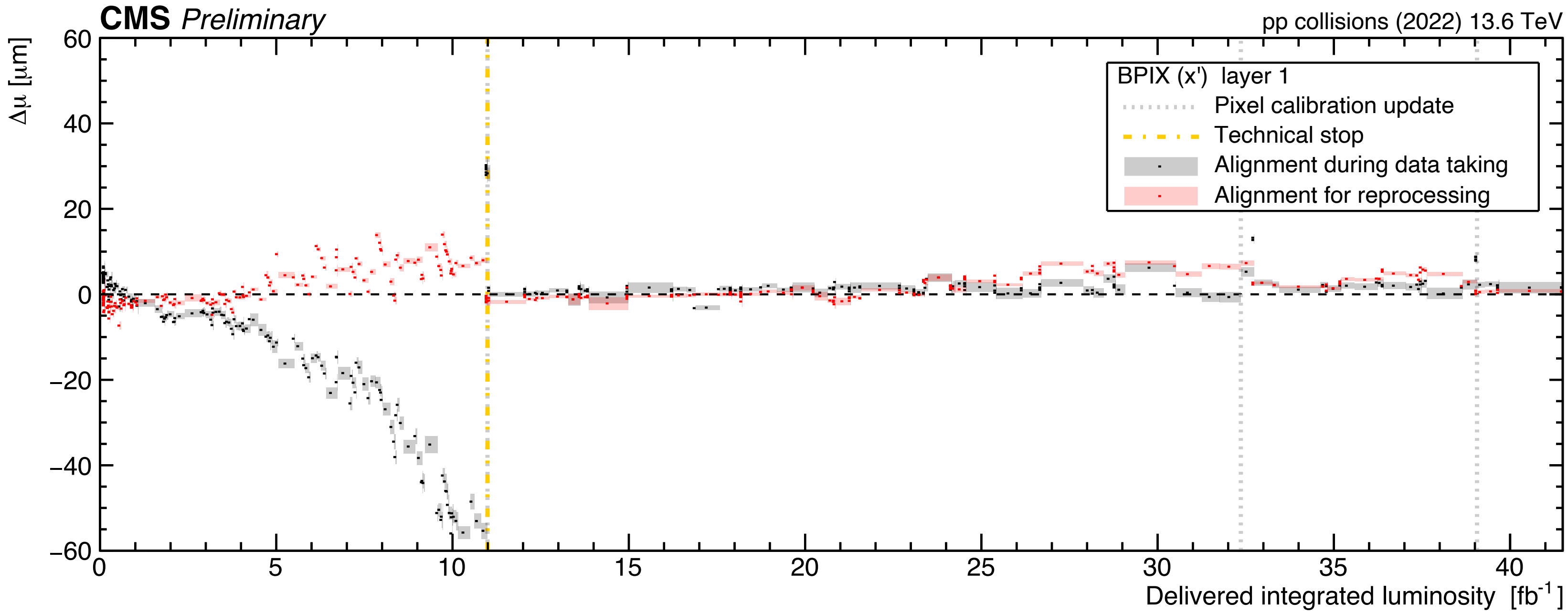


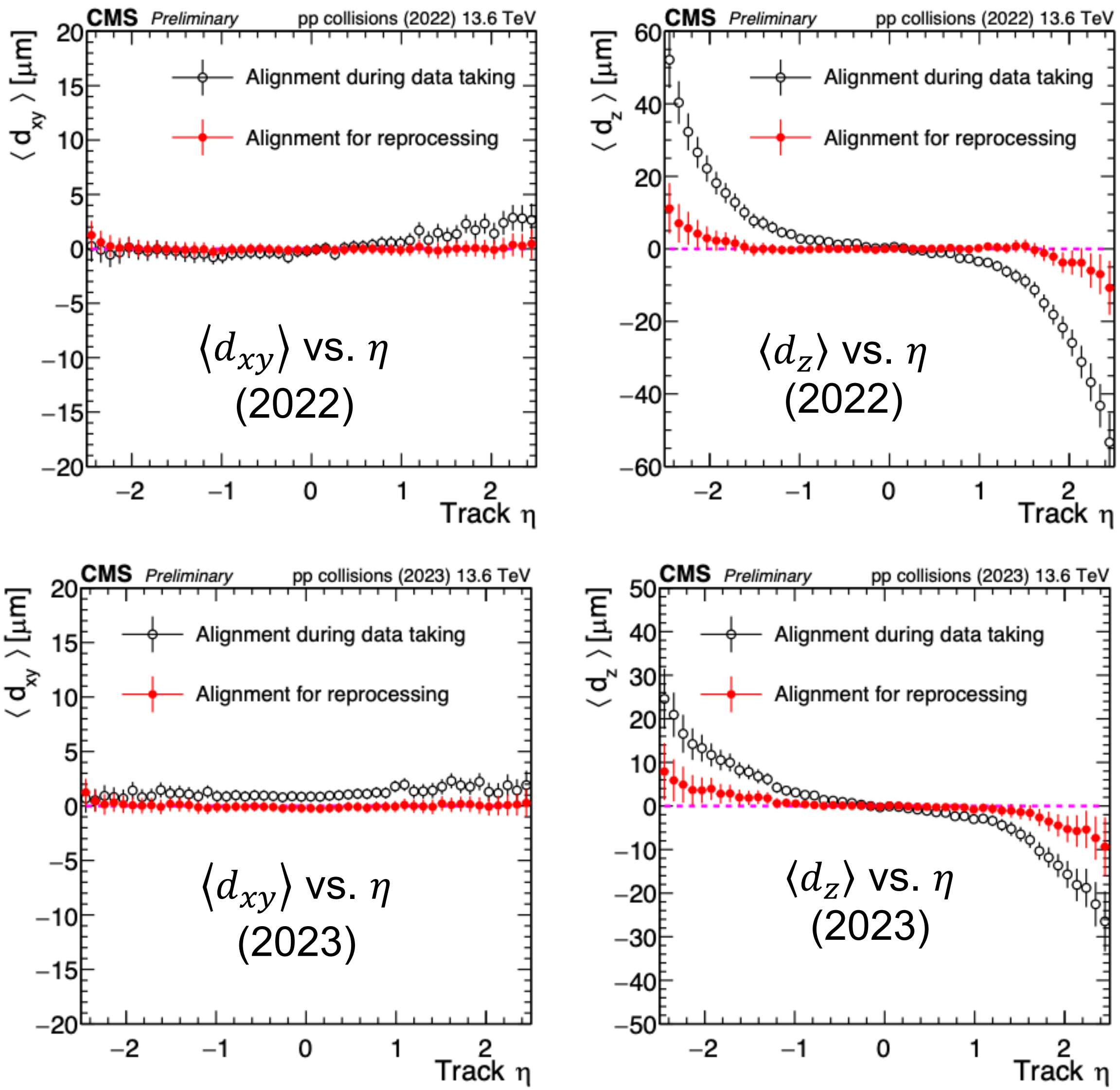
Figure from [5]

- 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

Track-vertex impact parameters (run-averaged)



Figures from [5]

- Impact parameters are obtained by recalculating the vertex position after removing the track being studied from it and considering the impact parameter of this removed track
- Mean track-vertex impact parameter in the transverse plane d_{xy} (left) and in the longitudinal direction d_z (right) are shown as a function of track pseudorapidity η
- Distributions shown here are averaged over all processed runs of 2022 (top) and 2023 (bottom), after scaling them with the corresponding luminosity for each run.
- *Exploiting $Z \rightarrow \mu\mu$ events with mass and vertex constraints* in the alignment for reprocessing helps to reduce the bias in d_z vs η significantly

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

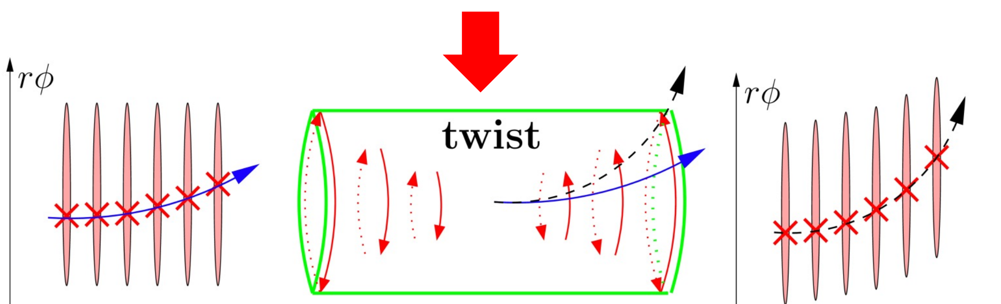


Figure from [7]

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

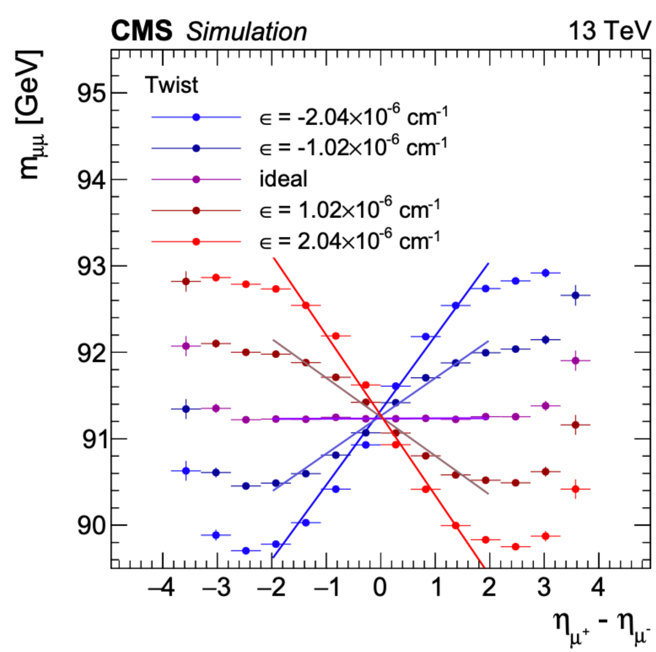
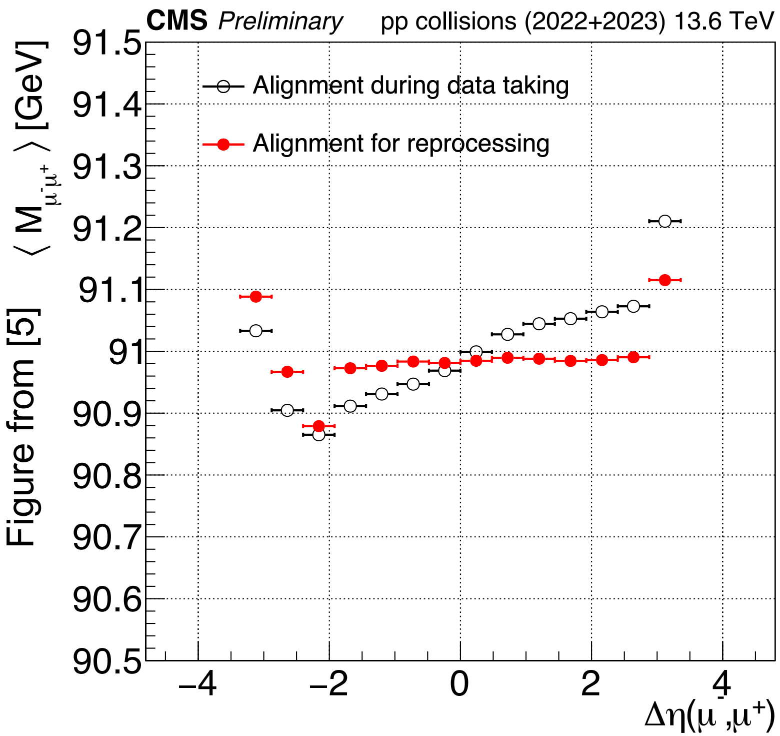


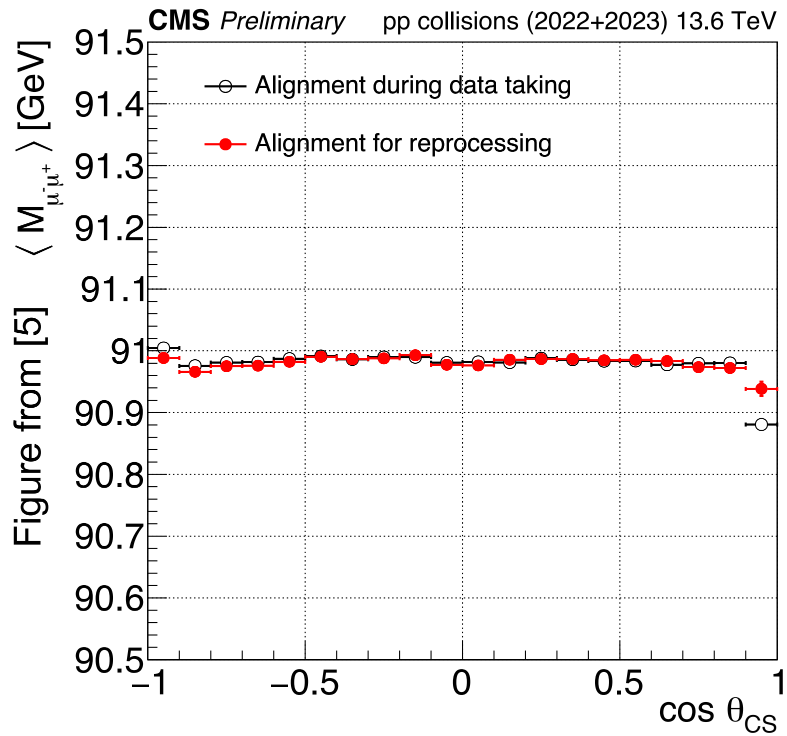
Figure from [8]

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. $\cos\,\theta_{CS}$

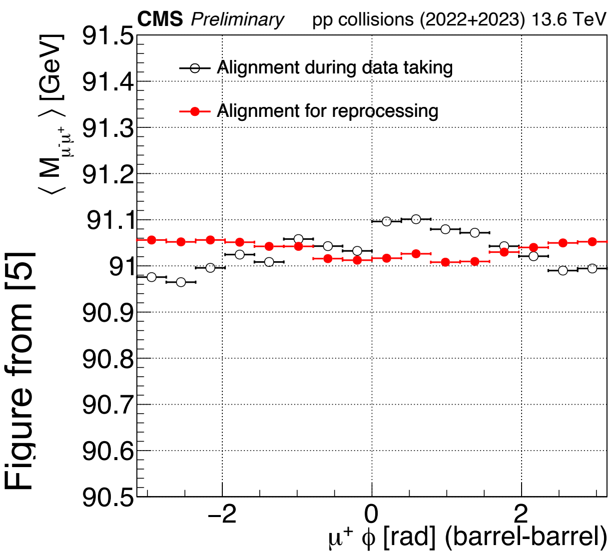


- Reconstructed Z → μμ mass as a function of the difference in η between the negatively and positively charged muons (left) and as a function of the angle $\cos\theta_{CS}$ in the Collins-Soper frame of the reconstructed Z boson (right)

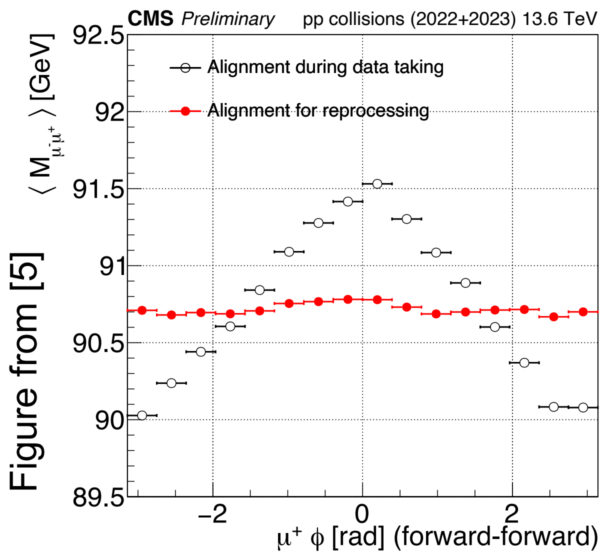
- The alignment for reprocessing shows an improvement in the uniformity of the reconstructed Z → μμ mass

Minimizing the spatial dependence of the Z boson mass

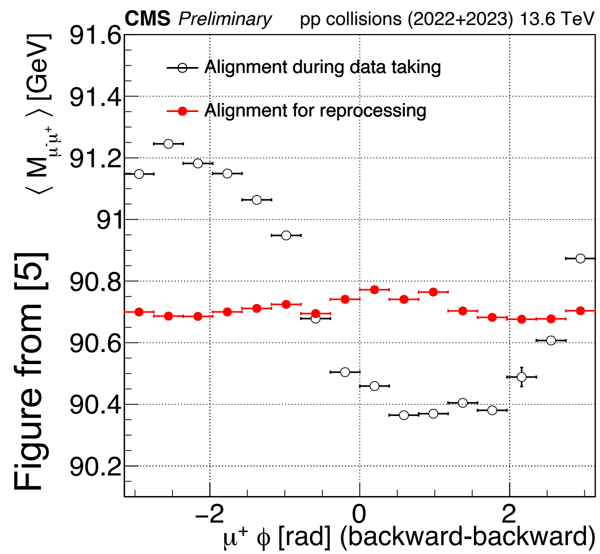
$\langle M_{\mu^-\mu^+} \rangle$ vs. $\mu^+ \phi$
(both muons within barrel)



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



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



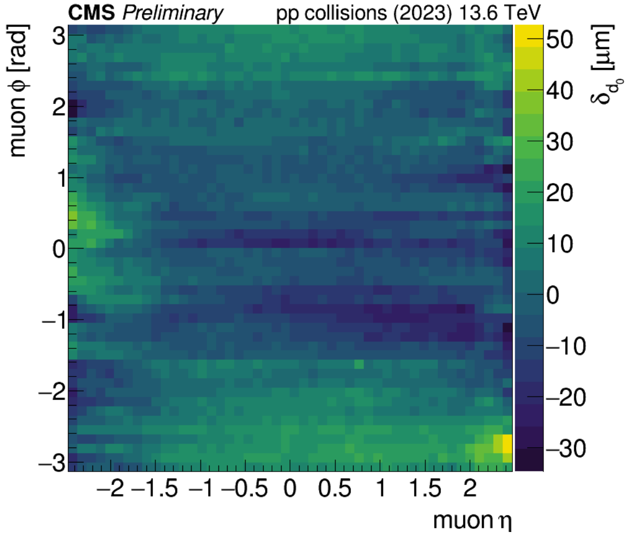
- Reconstructed Z → μμ mass as a function of the azimuth angle ϕ of positively charged muons shown for the η region when both muons are within the barrel i.e. $|\eta| \leq 1.5$ (left), when both muons are forward i.e. $\eta > 1.5$ (middle) and when both muons are backward i.e. $\eta < -1.5$ (right)

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

2023 Impact Parameter Bias in Z → μμ events

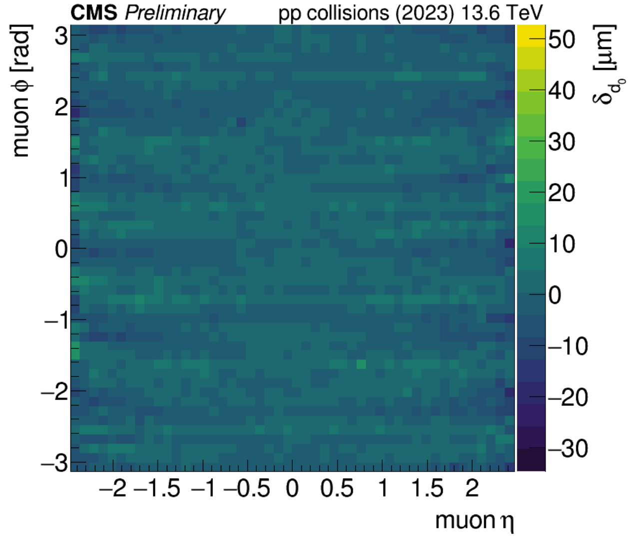
Alignment during data taking

δ_{d_0} in bins of ϕ and η



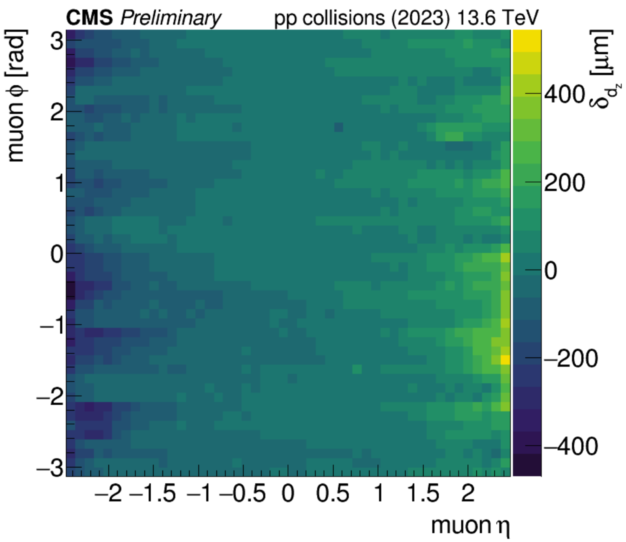
Alignment for reprocessing

δ_{d_0} in bins of ϕ and η



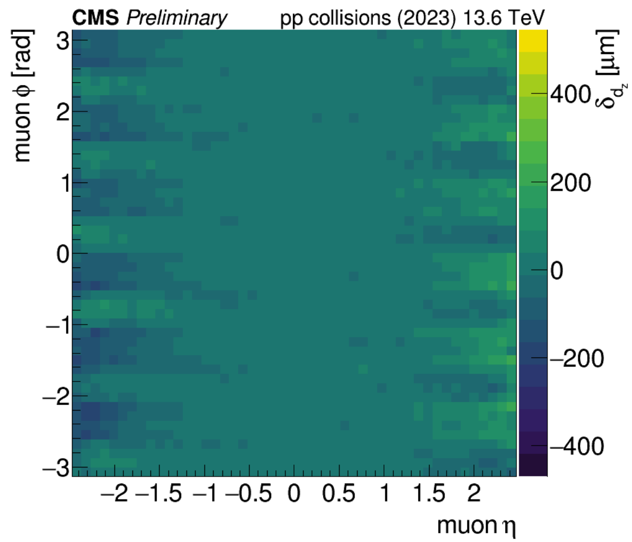
Alignment during data taking

δ_{d_z} in bins of ϕ and η



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]

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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[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

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[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

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[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