Alignment of the CMS Tracker

Latest Results from LHC Run-II

Gregor Mittag
on behalf of the CMS Collaboration

Deutsches Elektronen-Synchrotron (DESY)

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Motivation

Precise tracking is key to CMS physics performance

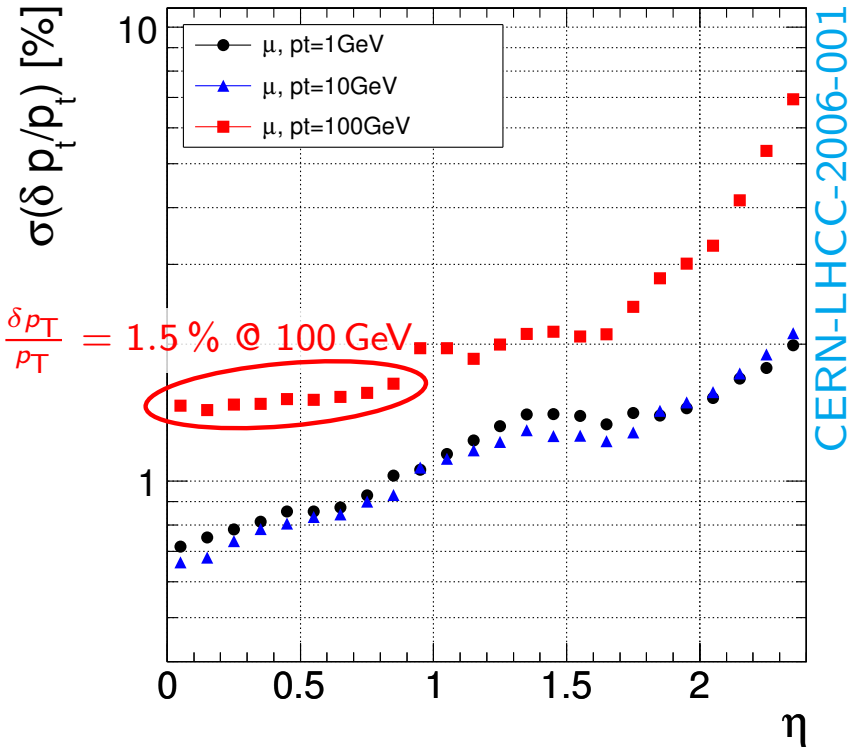
- What alignment precision is needed?
  - Track-p_T resolution

$$\frac{\delta p_T}{p_T} = \underbrace{C_1 \cdot p_T}_{\text{position res.}} \oplus \underbrace{C_2}_{\text{multiple scat.}}$$

$$\text{with } C_1 \propto \frac{\sigma_{\text{meas}}}{B \cdot L^2 \sqrt{N}}$$

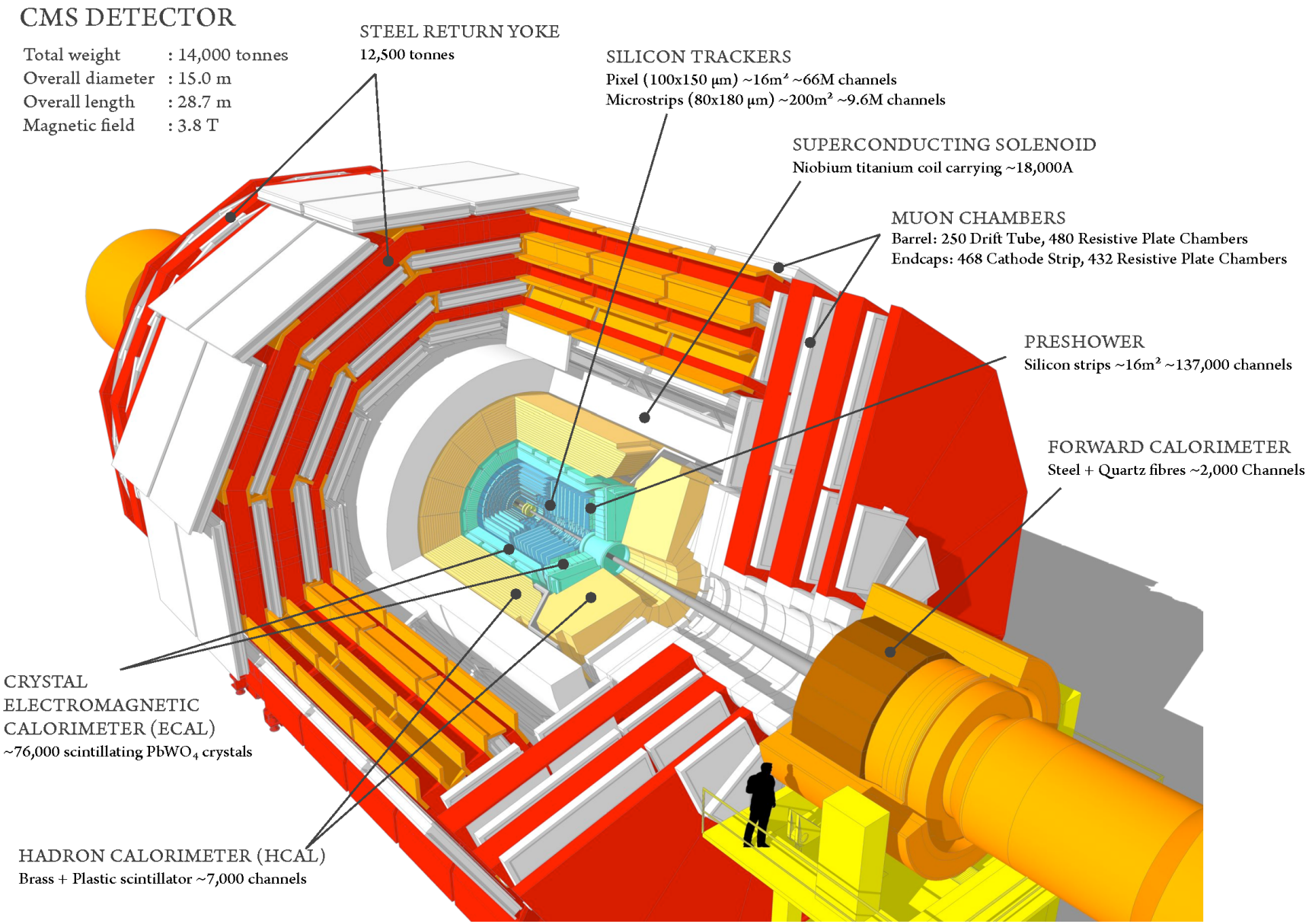
  - Effective position resolution
    - $\sigma_{\text{meas}} \propto \sigma_{\text{hit}} \oplus \sigma_{\text{align}}$
  - Intrinsic hit-position resolution
    - $\sigma_{\text{hit}} \approx 9\,\mu\text{m}$ (pixel)
    - $\sigma_{\text{hit}} \approx 20-60\,\mu\text{m}$ (strip)

design tracker p_T-resolution of single-μ

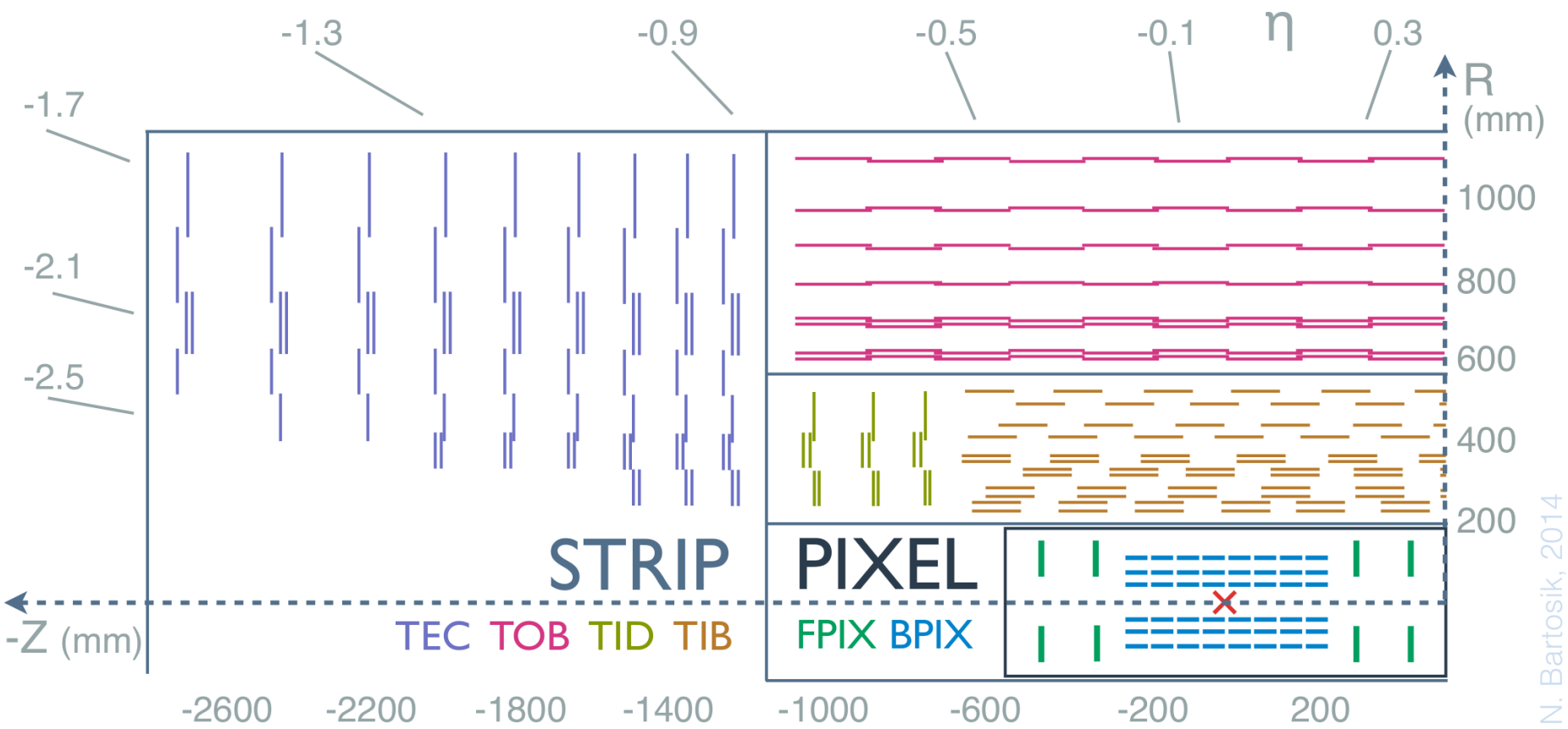


Need to keep $\sigma_{\text{align}} \ll \sigma_{\text{hit}}$

CMS experiment



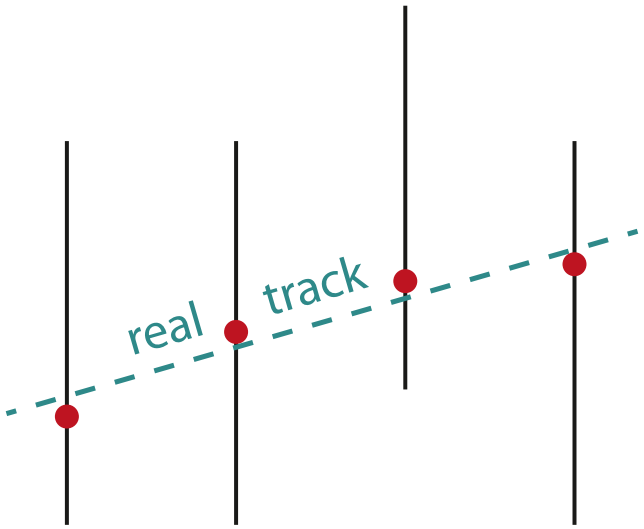
CMS tracker



- 1440 silicon pixel modules
  - 3D hit-position measurements
- 15 148 silicon strip modules (24 244 sensors)
  - 2D measurements ($r\phi$ direction)
  - In some layers: additional modules rotated by 100 mrad

Track-based alignment

- Difference between real and assumed geometry affects track measurement

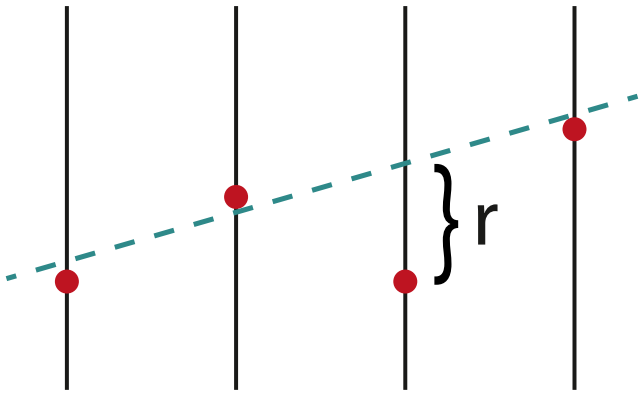


real geometry

- **Idea:** track-hit residuals r between predicted and measured hit positions as a measure of misalignment

Track-based alignment

- Difference between real and assumed geometry affects track measurement



assumed geometry

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Track-based alignment

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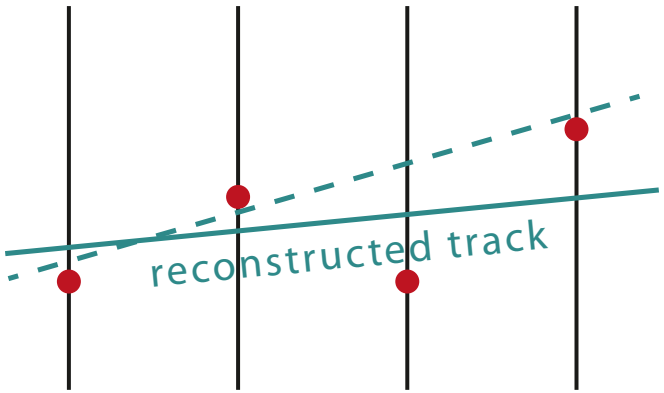
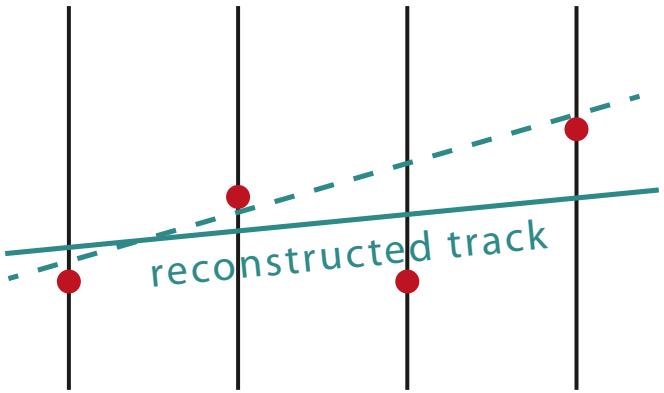


assumed geometry

- **Idea:** track-hit residuals r between predicted and measured hit positions as a measure of misalignment
- Simply moving module by $-r$ means
  - Change of position (alignment) parameters
  - Change of track parameters
  - Change of other residuals
- Tracks correlate alignment parameters
- Need many tracks to determine parameters for all tracker modules

Track-based alignment

- Difference between real and assumed geometry affects track measurement



assumed geometry

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Alignment challenge

- Deriving the optimal positions, orientations, and surface deformations that minimize residuals
- Two independent approaches in CMS complementing each other
  - HipPy (local fit)
  - MillePede-II (global fit)

CMS Tracker Alignment in 2016

EOY 2015

- Starting point for alignment
  - Only high-level-structure movements expected

- Start-up alignment
  - Using 0 T cosmics
  - Only high-level-structure alignment
  - Addresses effects accumulated during shut-down

Start of 2016 collisions

- Refined 2016 alignment
  - Alignment at module level
  - Take advantage of various 3.8 T data sets
    - Cosmics
    - Minimum bias
    - Isolated muons
    - $Z \to \mu\mu$ events $\to$ Use constraint on invariant di-muon mass

ICHEP

- Preparations for reprocessing of 2016 data

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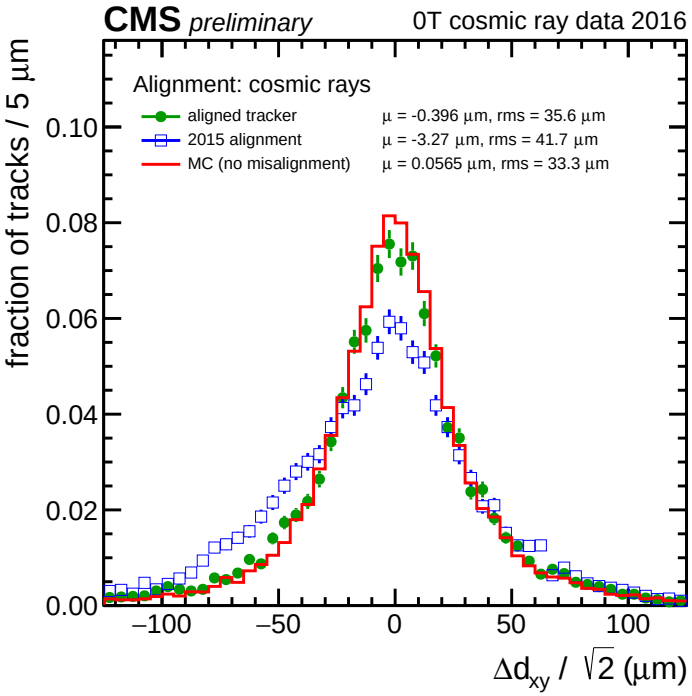
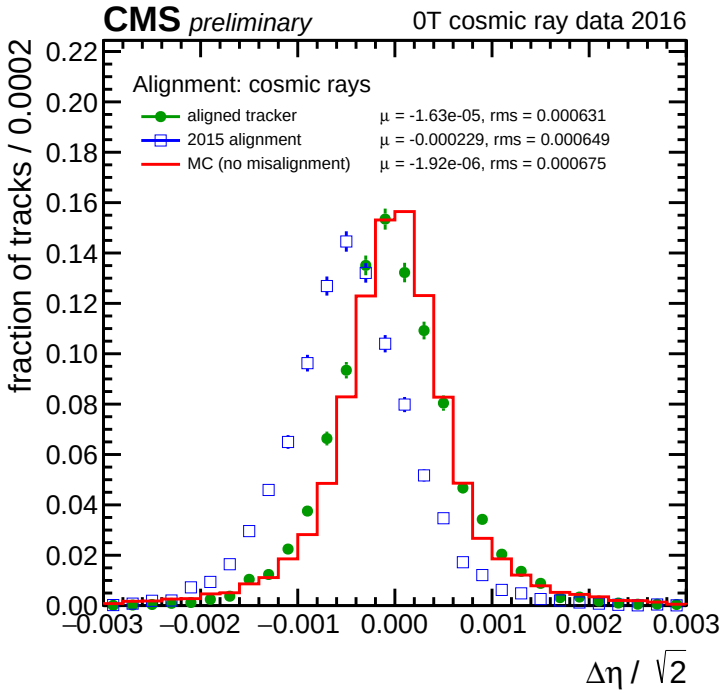
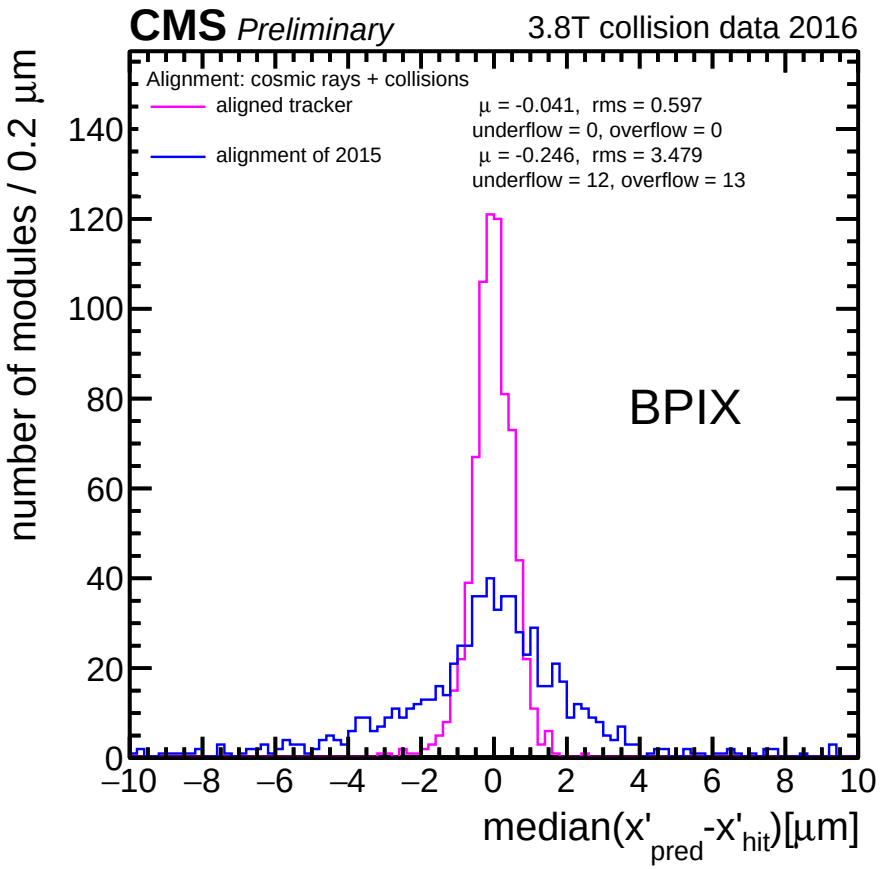
Cosmic track split validation





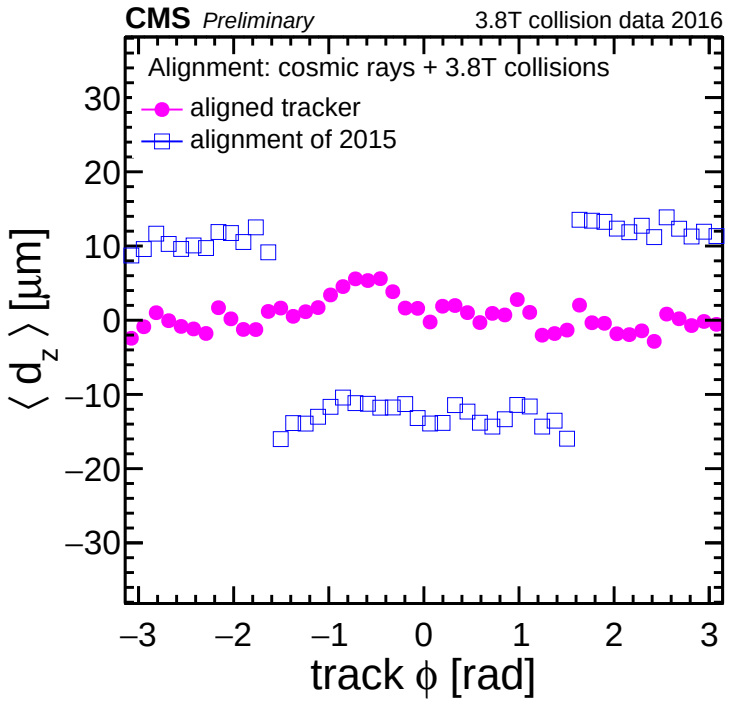
- Cosmic tracks are split at point of closest approach to the interaction region
- Differences in track quantities between the two parts indicate misalignment
- Derived updated alignment with 0 T cosmic data prior to 2016 data-taking start-up
- Mean & RMS values show reduced bias of updated alignment wrt. 2015 geometry
  - 2015-EOY geometry no longer valid due to temperature and magnetic field changes
  - Performance of updated geometry very close to ideal Monte Carlo

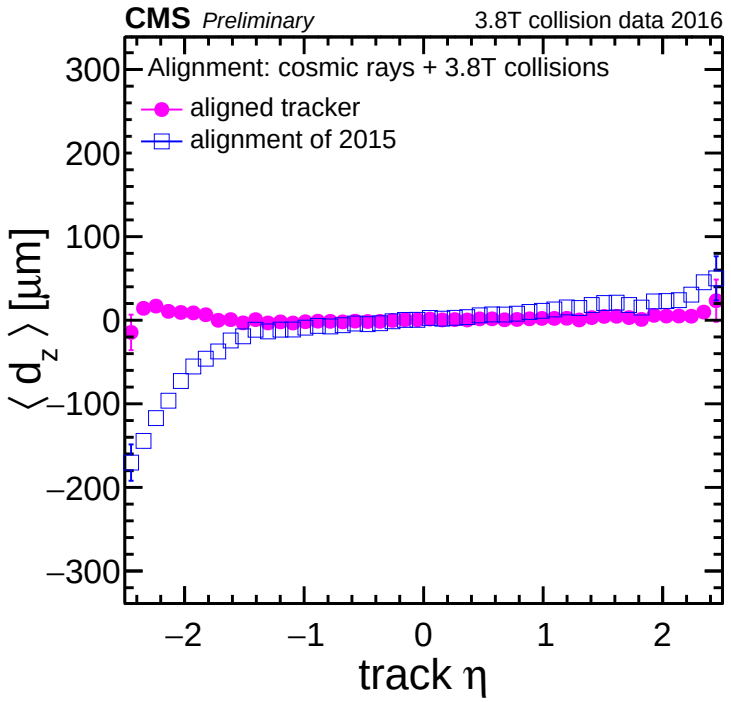
Distribution of median residuals (DMR)



- Unbiased track-hit residuals of 1 M collision events @ 3.8 T
- Pixel-detector position known to be very sensitive to condition changes
- Updated alignment produced using 3.8T cosmic-ray and collision data
- EOY-2015 no longer valid for 2016 data, mainly due to temperature and magnetic field changes
- RMS values show improvement over the 2015 geometry by a factor of 5

Primary vertex validation

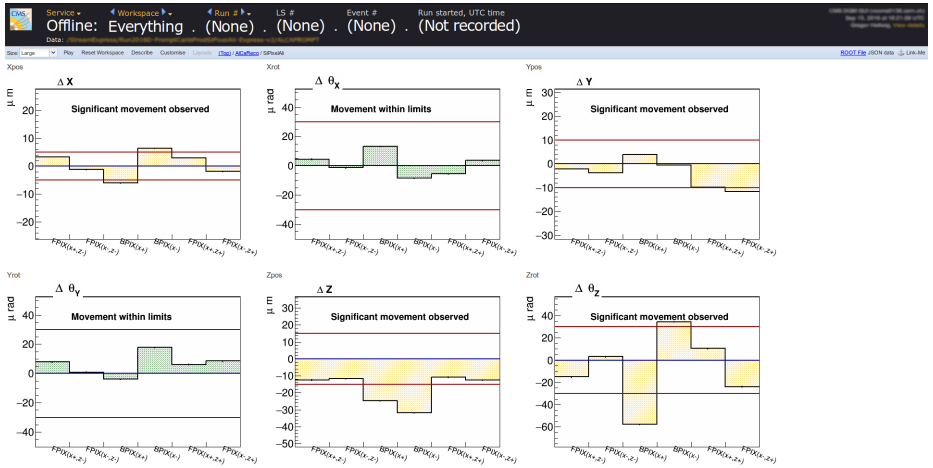




- Unbiased residuals between tracks and primary vertices are studied
  - In the longitudinal and transverse plane
  - In bins of η and ϕ
- Cosmic-ray and collision data @ 3.8 T are used for alignment
- Sample of 1 M events collected through minimum bias triggers @ 3.8 T used for validation
- Systematic z-offset of the pixel half-shells is corrected by the updated alignment

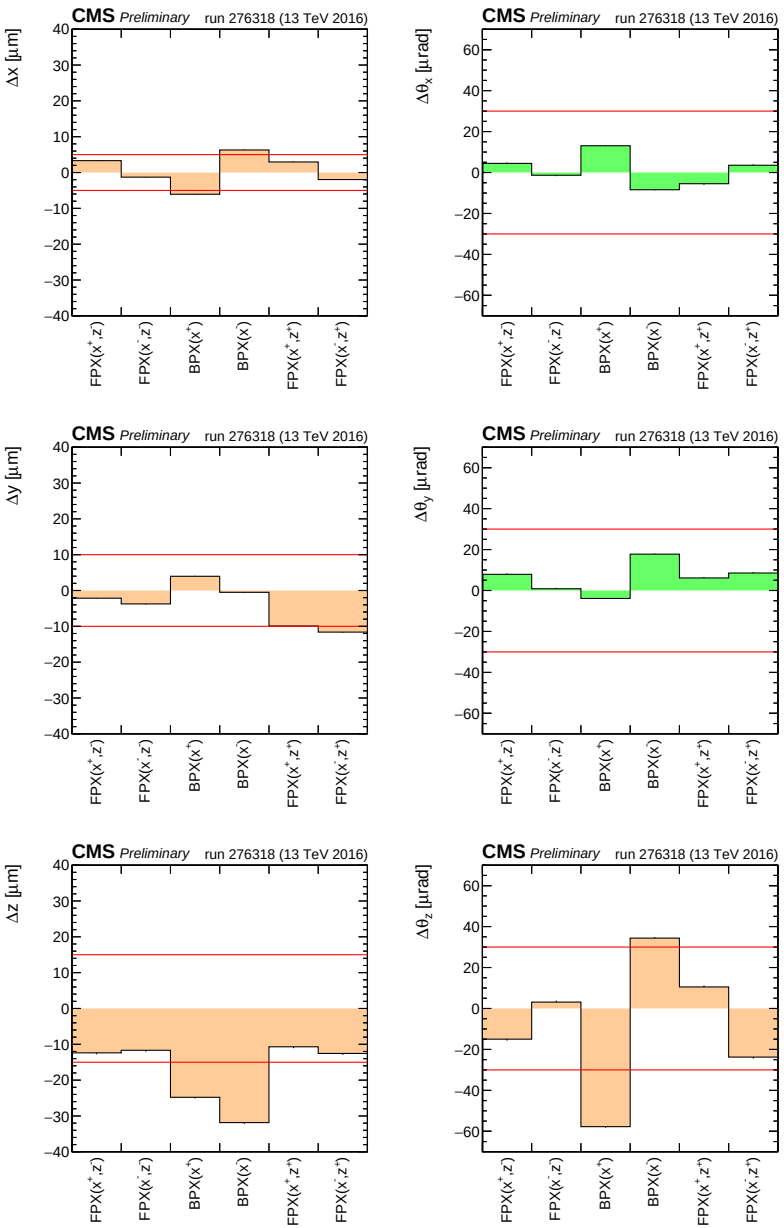
Prompt Calibration Loop

- Since this year, CMS employs an automatic procedure to continuously monitor movements of the high-level structures of the pixel tracker
  - Occur for example due to temperature changes or changes of the magnetic field



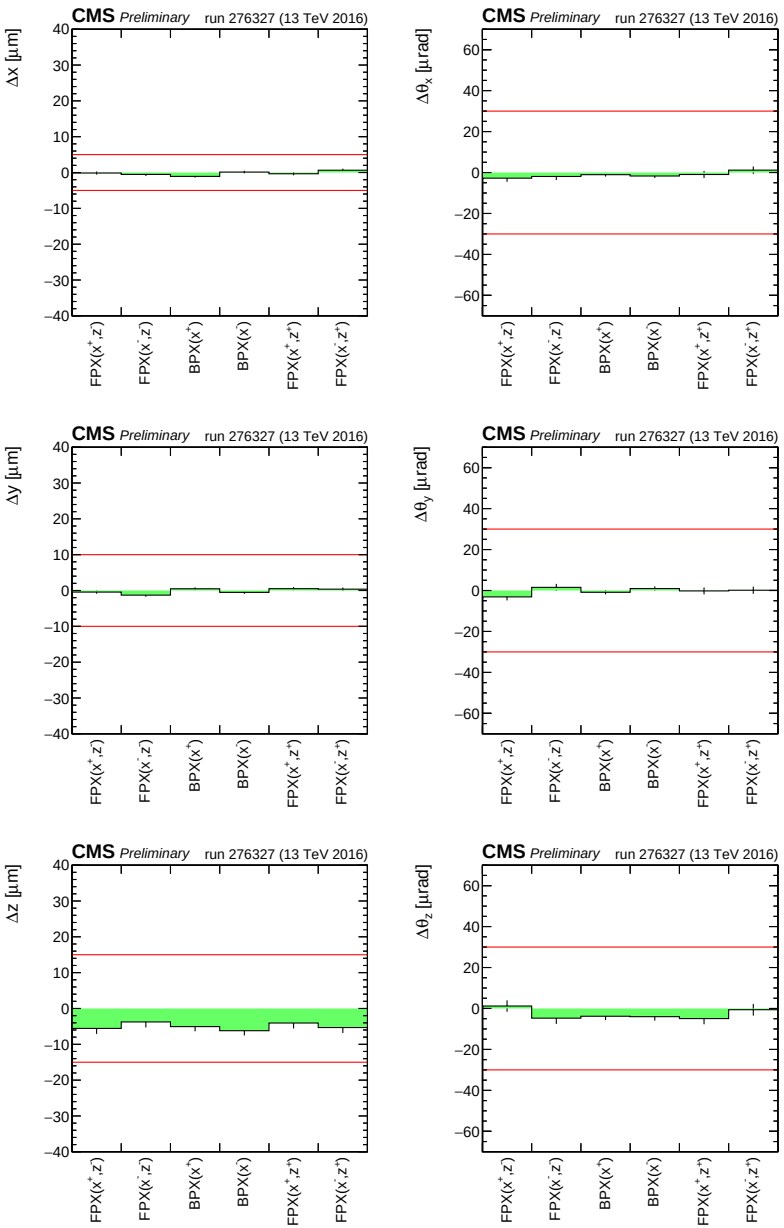
- For each run with more than 20 000 events, an alignment of the high-level structures is performed online, measuring the movements relative to the geometry used in data processing
- When appropriate, the geometry is updated with the results of this online alignment

Prompt Calibration Loop



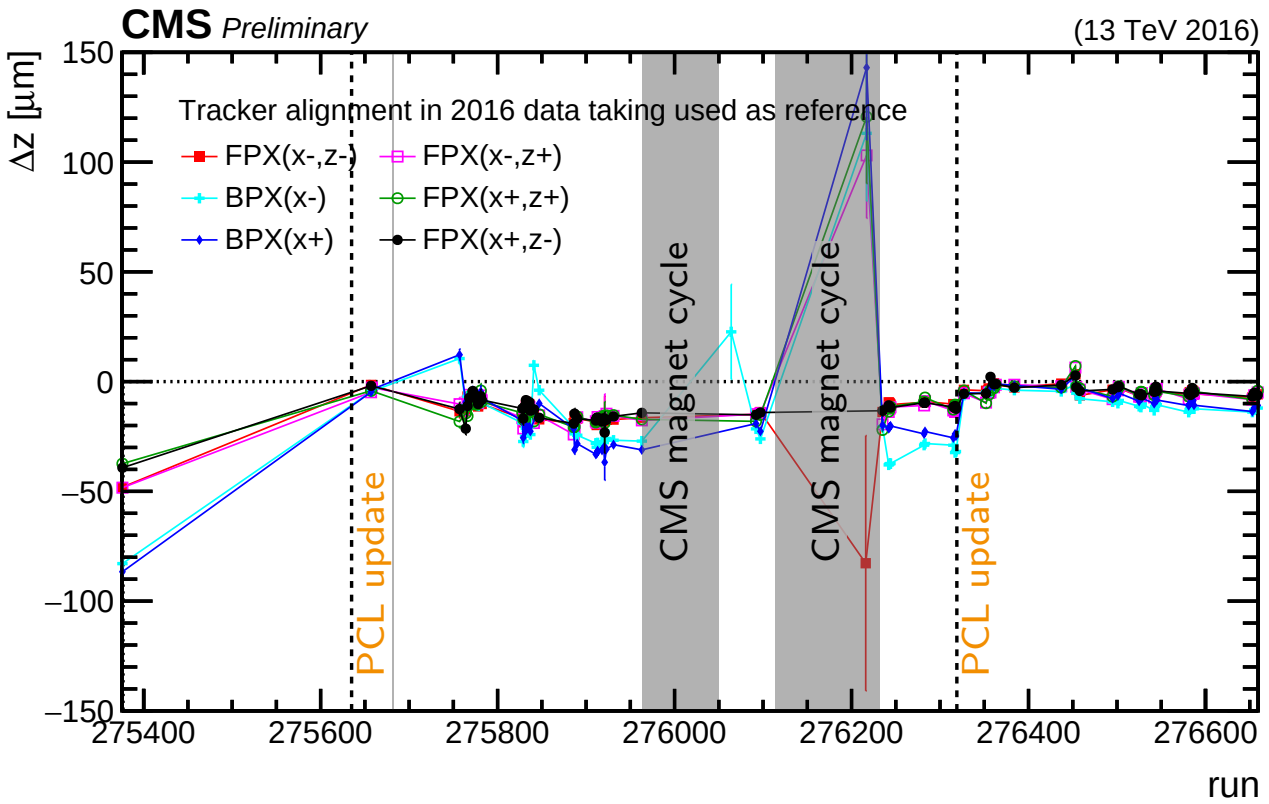
- Run 276318 was taken shortly after a magnet ramp during July 4 2016
  - Resulted in movements of the pixel detector structures up to 30 µm wrt. the geometry used in data processing
- Red horizontal lines indicate the thresholds to trigger updates
  - Histogram color changes from green to orange if limit is exceeded

Prompt Calibration Loop



- Geometry was updated afterwards
  - Much improved performance during run 276327
  - Only small residual movements below 2 μm in x and y, and below 10 μm in z direction
- Such plots are routinely produced per run as part of the data-quality monitoring CMS

Prompt Calibration Loop



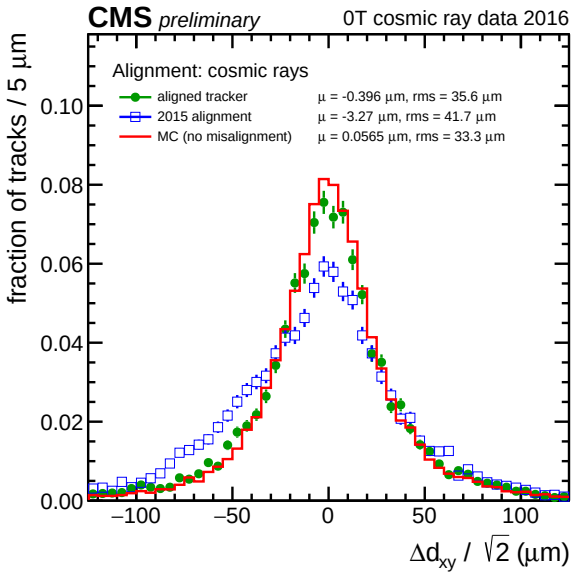
- Evolution of the pixel's high-level-structure movements
  - Covers the time from June 21 to July 12 2016, corresponding to 7 fb^{-1}
  - Error bars represent the statistical uncertainties
  - Grey bands represent runs during which CMS magnet was not at 3.8 T
  - Vertical dashed lines illustrate updates of the alignment
- Typical movements during magnet-cycles are smaller than 50 µm in x and y, and smaller than 150 µm in z

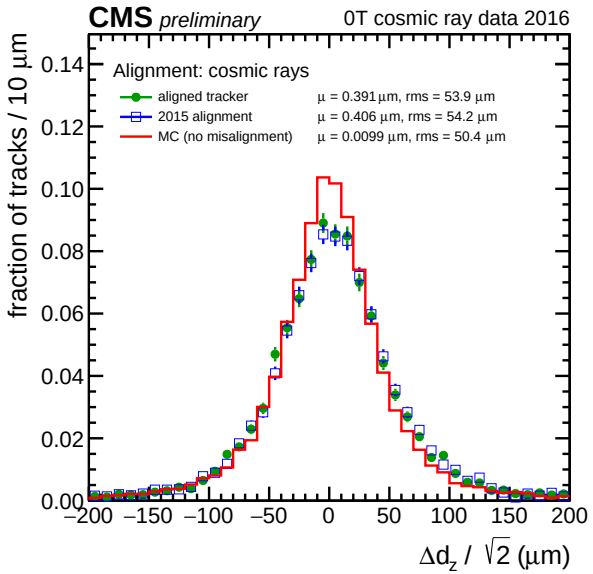
Summary

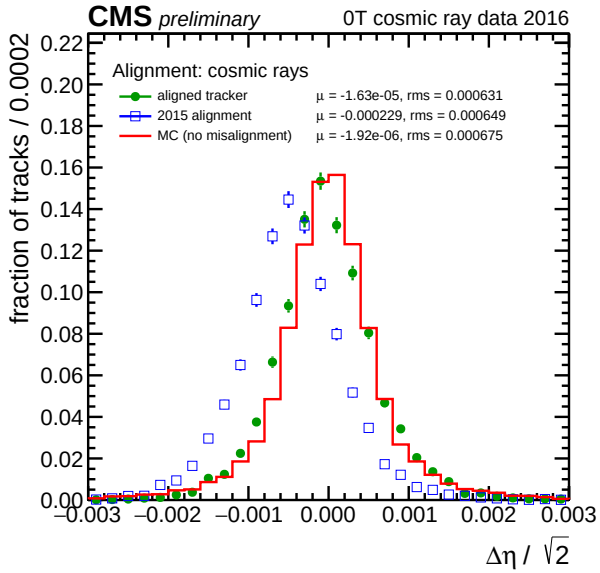
- CMS has two independent algorithms in place to solve the highly non-trivial alignment task
- Tracker-alignment updates in 2016 significantly improved the performance at start-up and during data taking
- Geometry changes due to temperature and magnetic-field changes are nicely compensated
- An automatic online calibration workflow successfully put in place
  - Clear improvement of the prompt reconstruction
- References
  - *CMS Tracker Alignment Performance Results Summer 2016*, https://twiki.cern.ch/twiki/bin/view/CMSPublic/TkAlignmentPerformanceICHEP2016
  - *Alignment of the CMS tracker with LHC and cosmic ray data*, 2014 JINST 9 P06009, doi:10.1088/1748-0221/9/06/P06009
  - *Alignment of the CMS silicon tracker during commissioning with cosmic rays*, 2010 JINST 5 T03009, doi:10.1088/1748-0221/5/03/T03009

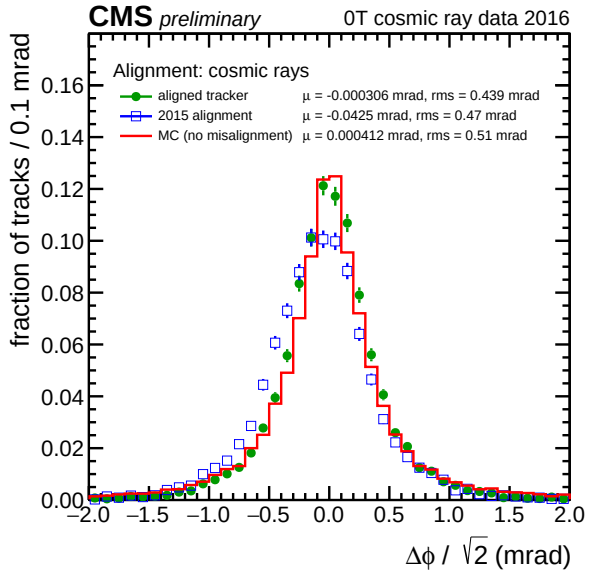
Back-Up

Cosmic track split validation

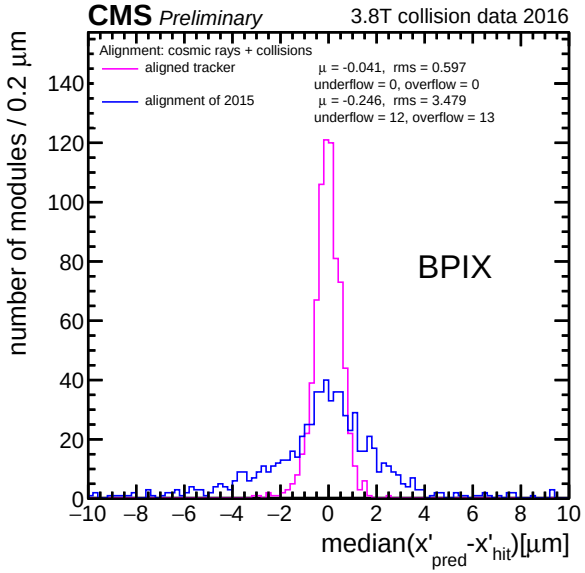


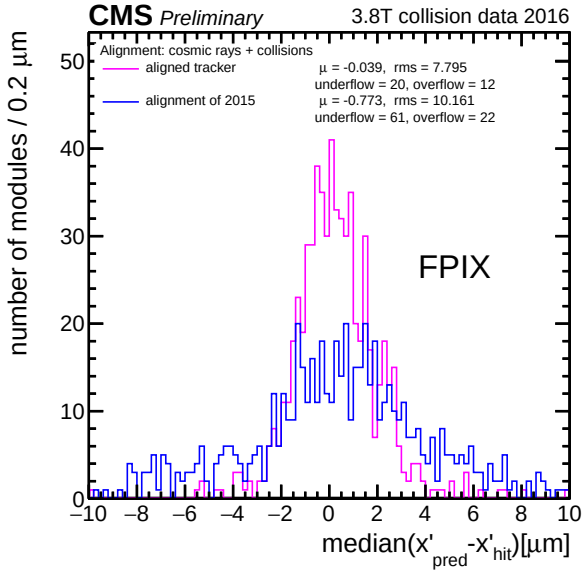


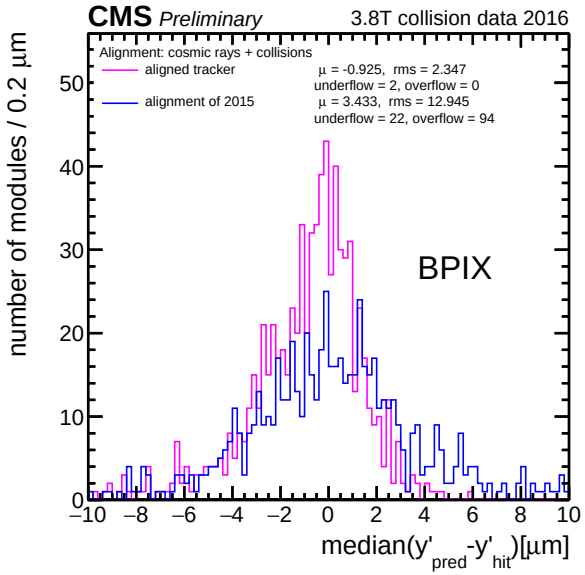


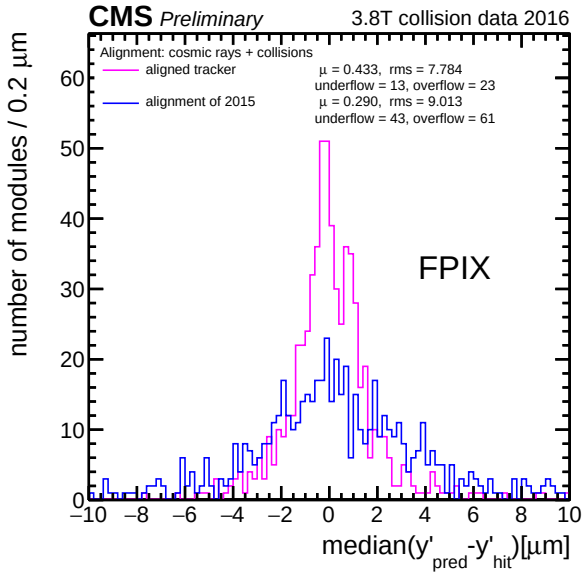


Distribution of median residuals (DMR) – Pixel

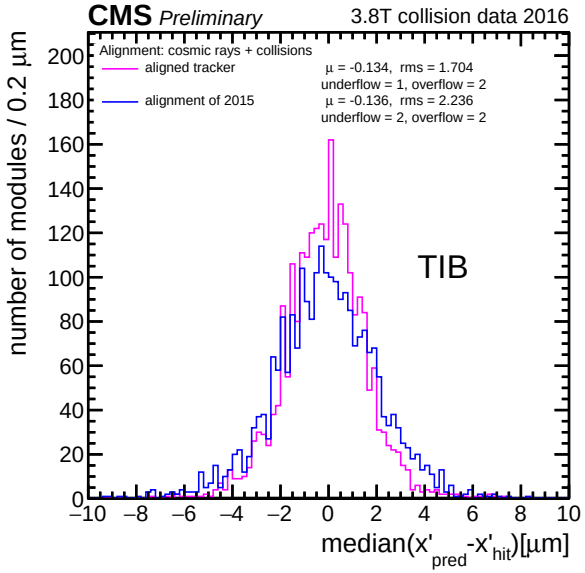


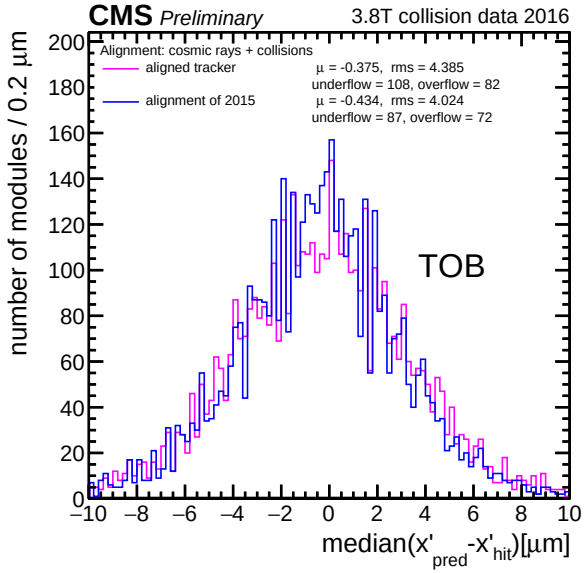


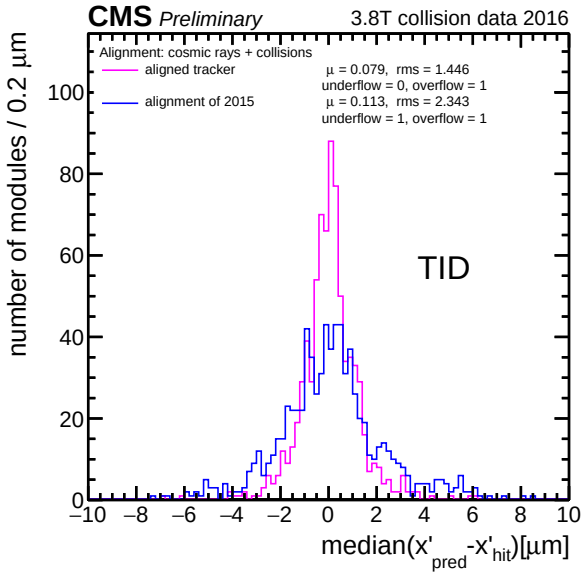


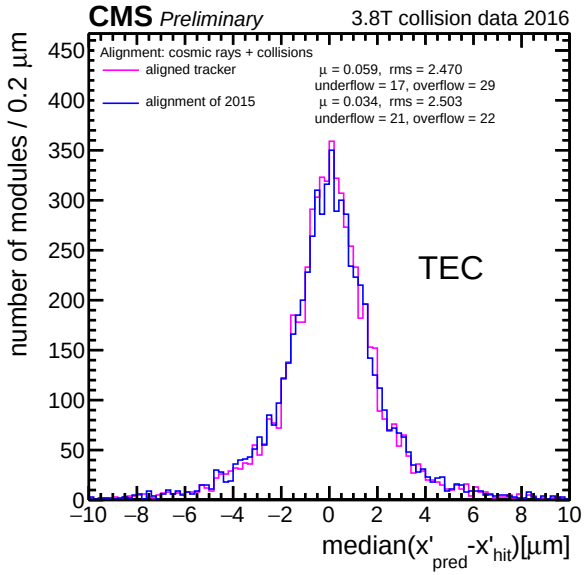


Distribution of median residuals (DMR) – Strip

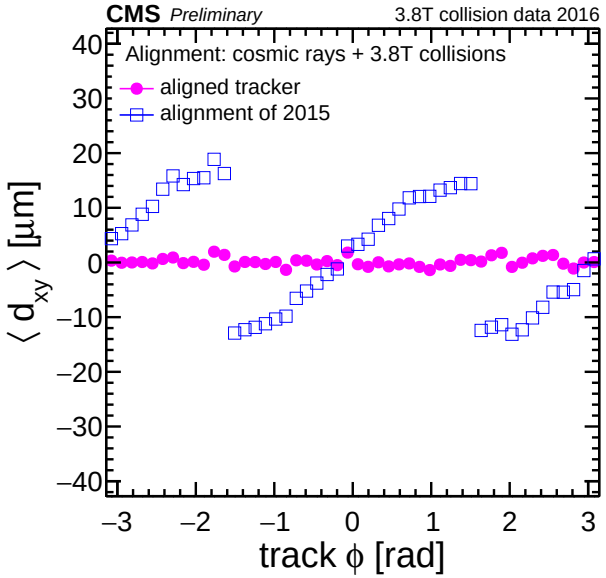


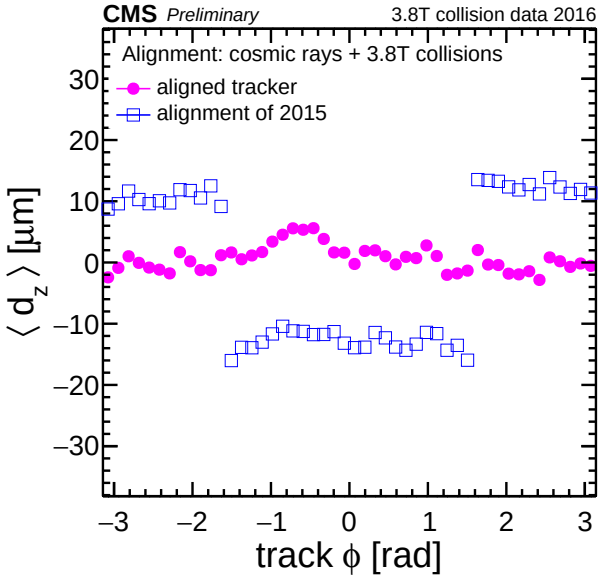


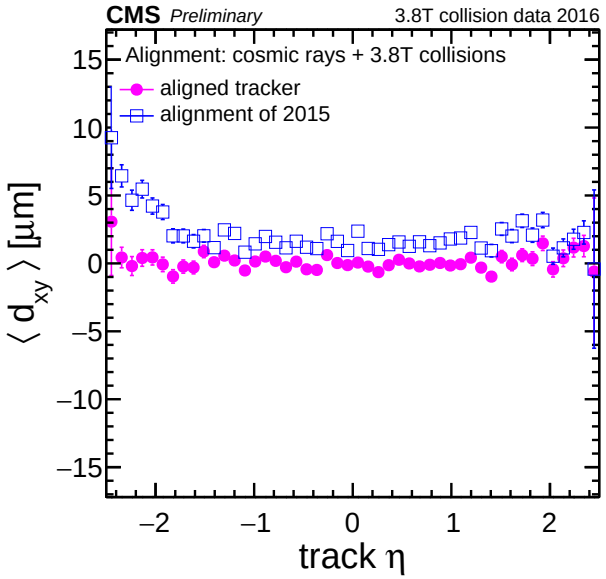


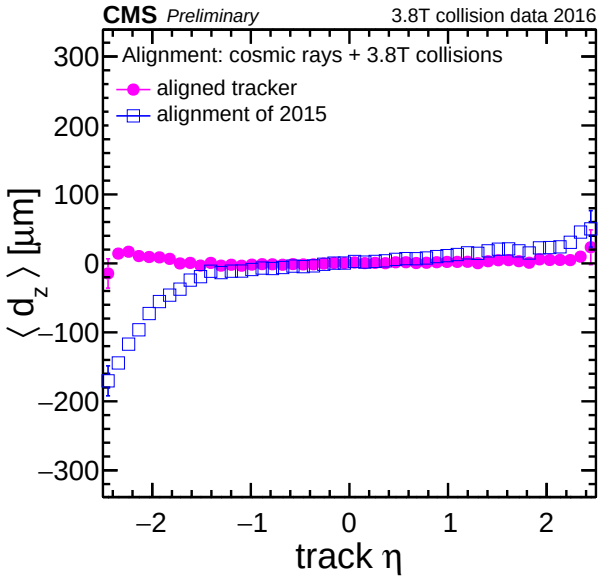


Primary vertex validation

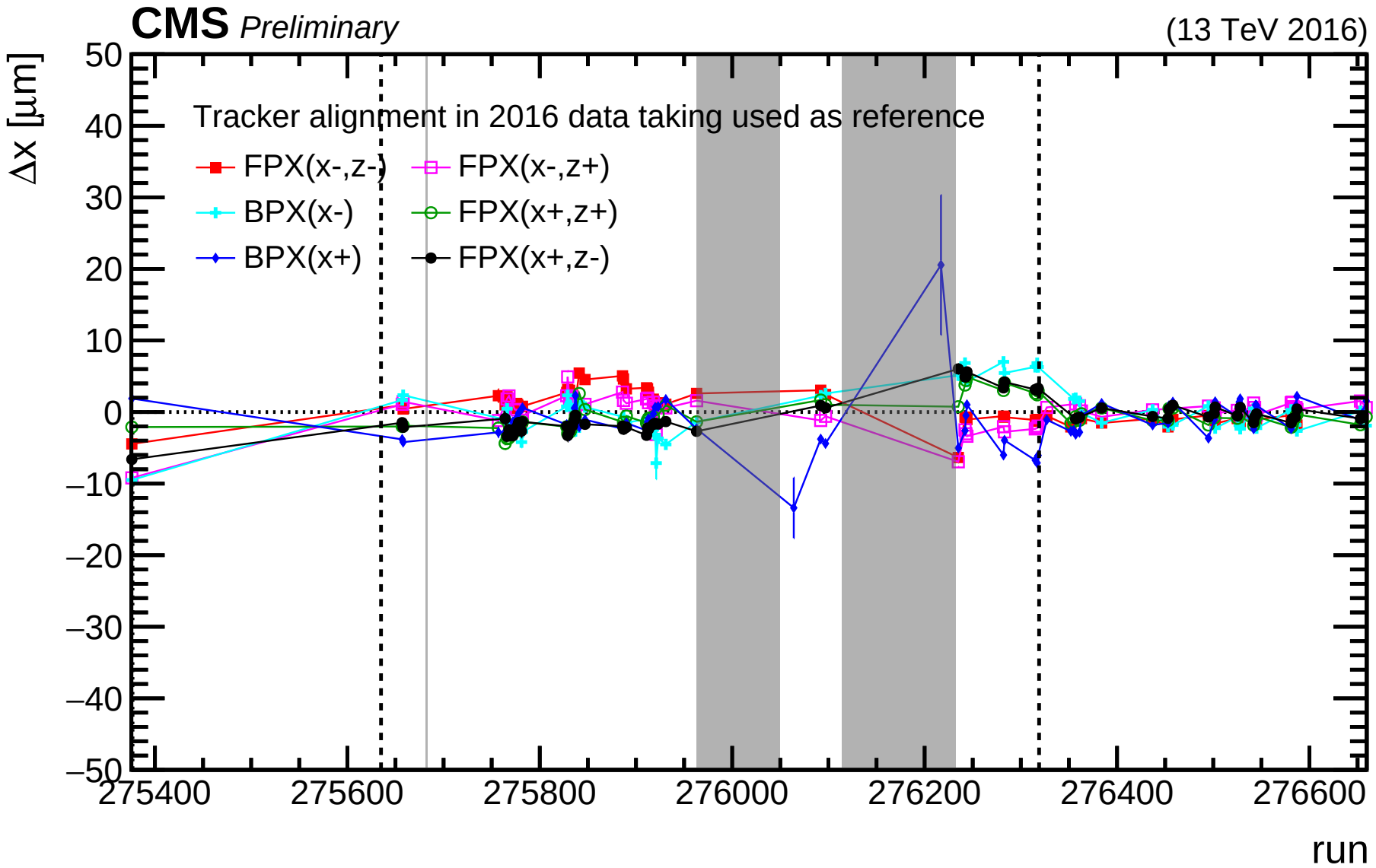








Prompt Calibration Loop



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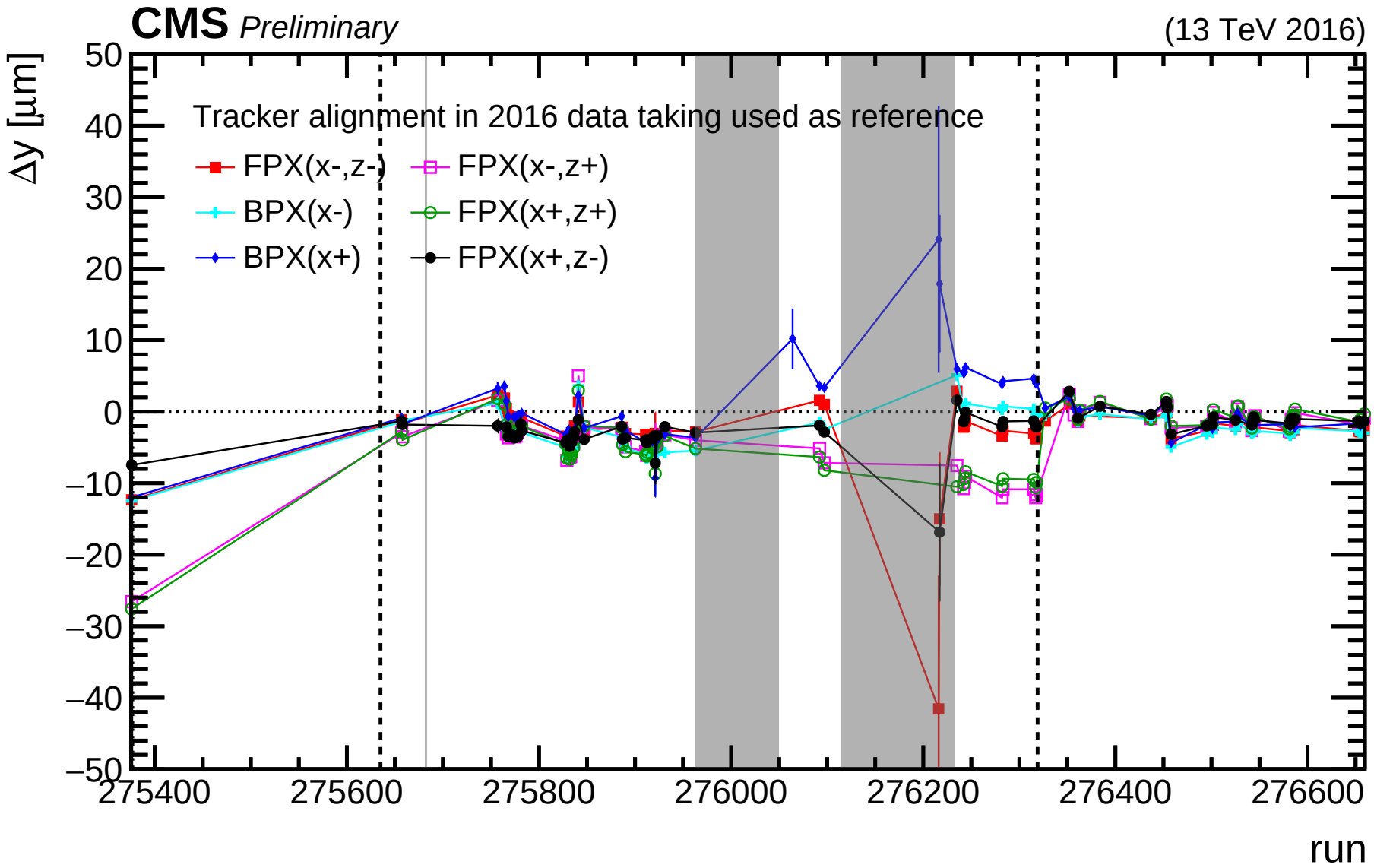

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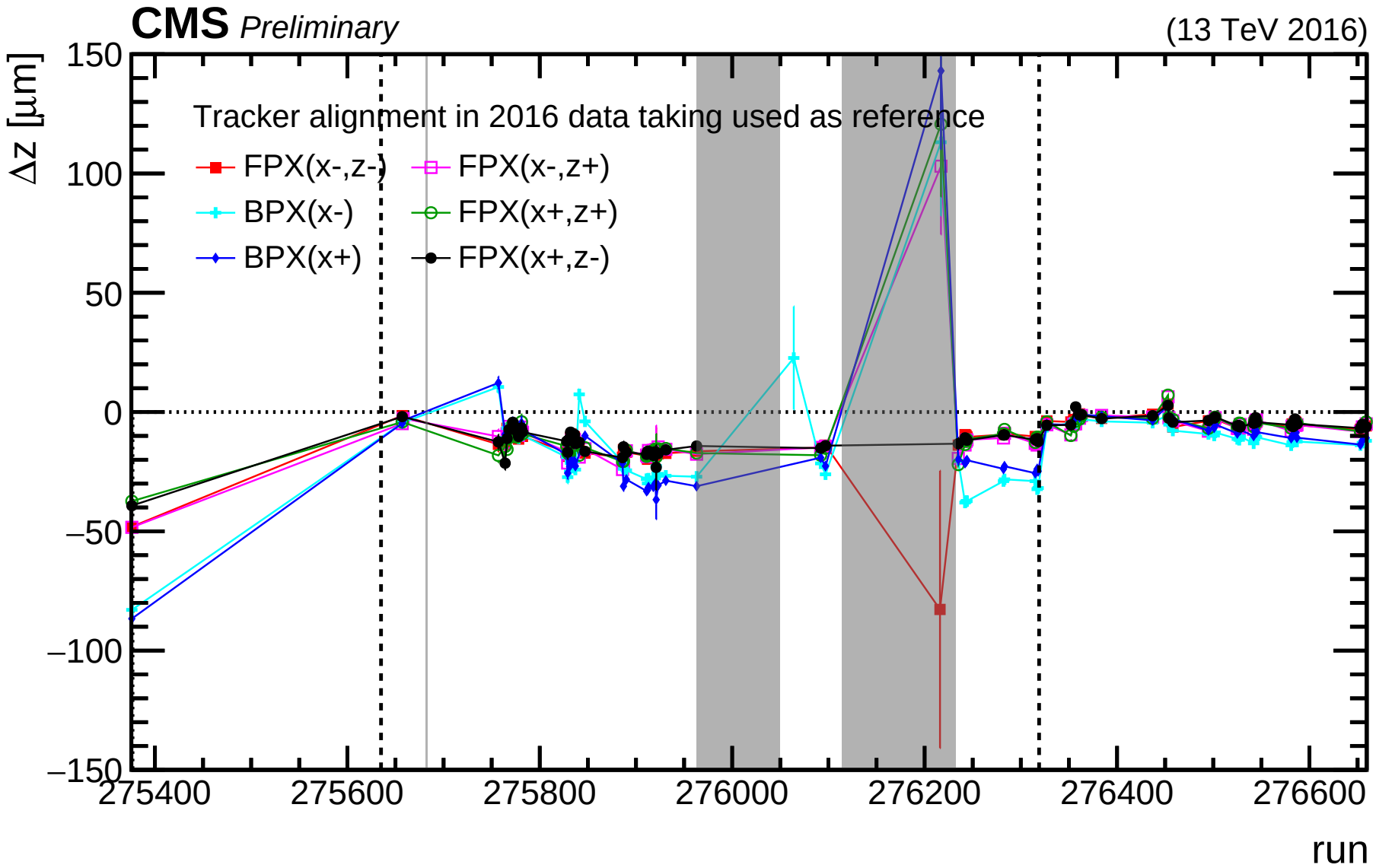

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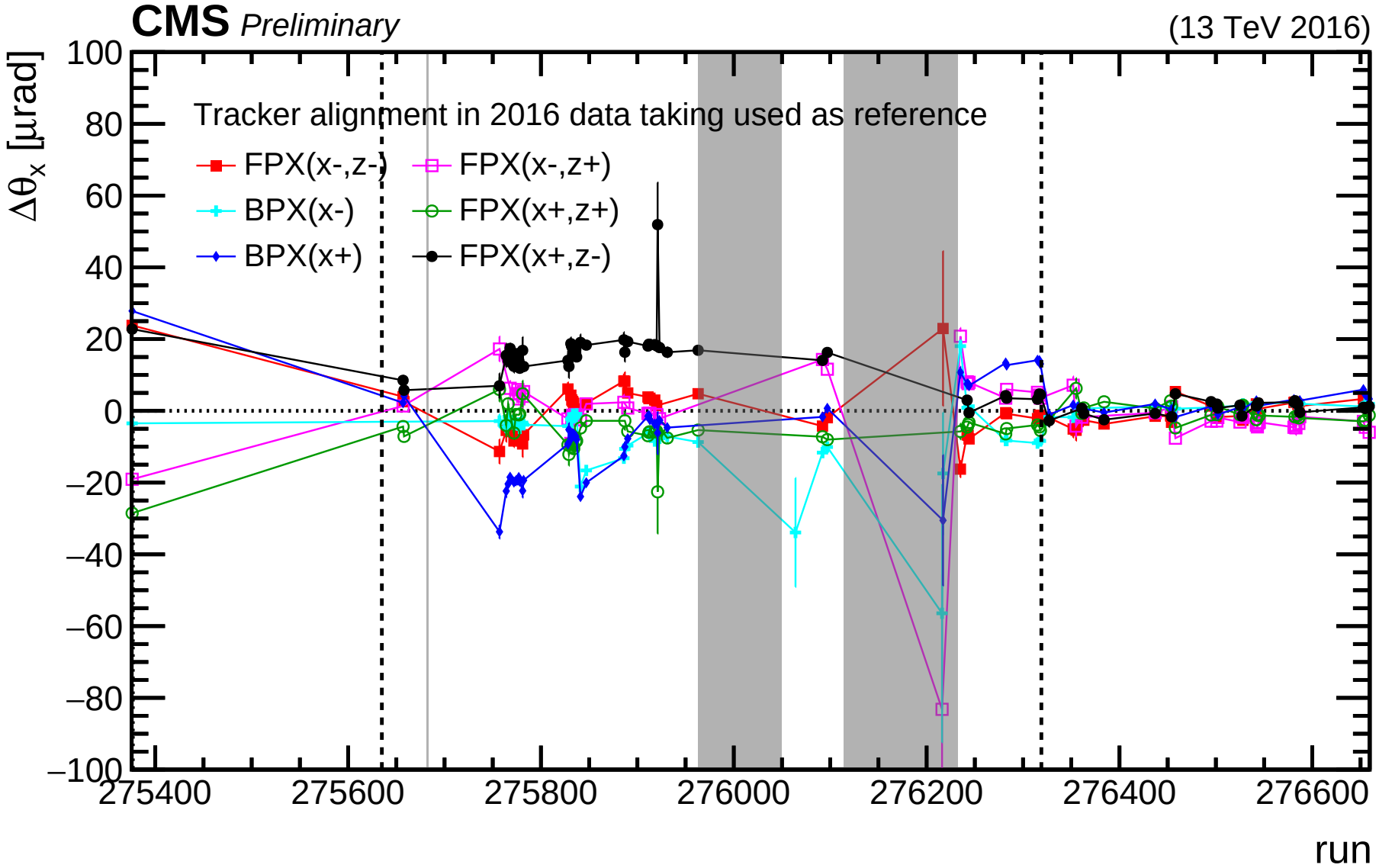

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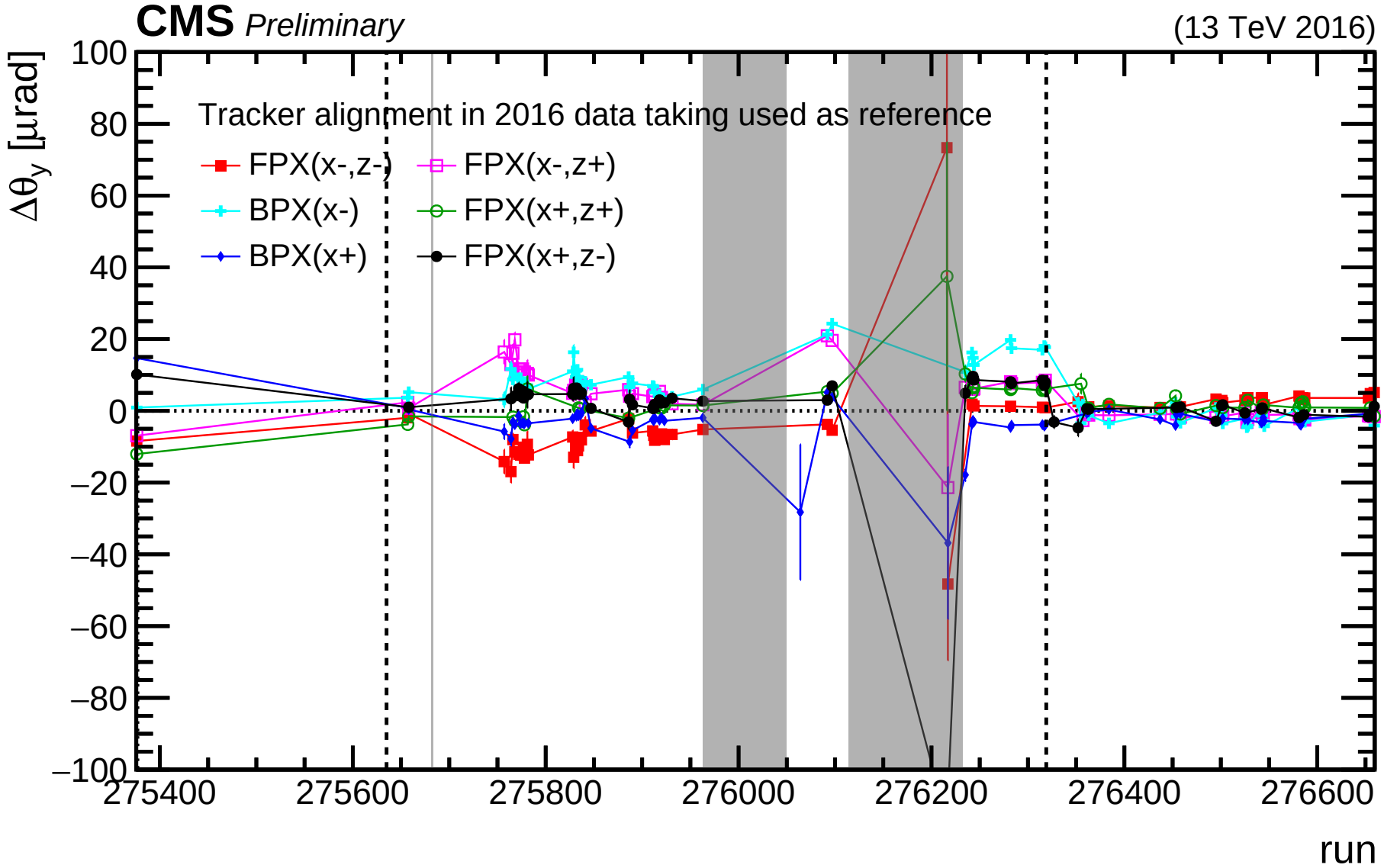

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