Performance of the CMS Tracker during LHC Run 3

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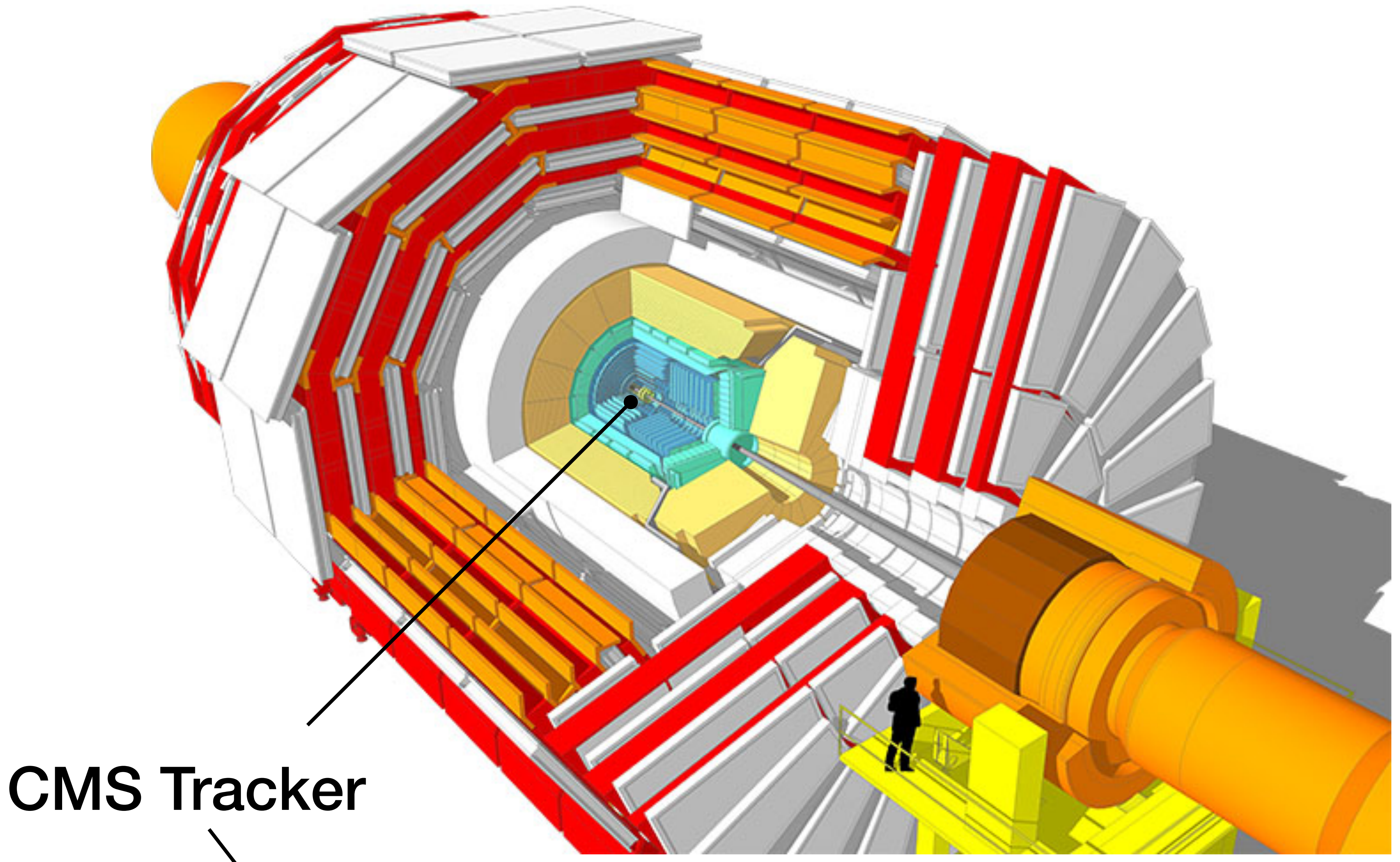
In this talk

- **CMS Tracker**
  - Silicon Pixel detector
  - Silicon Strip detector
- **Data taking conditions during Run 3**
- **Detector performance**
  - Pixel tracker performance
  - Strip tracker performance
  - Tracker alignment performance

The CMS Tracker

CMS Tracker

- **Largest silicon tracker in the world!**
  - ✦ ~200 m^2 area, ~135M electronic channels
- Innermost subdetector of CMS
- Crucial for particle identification, track and vertex reconstruction
- Comprised of
  - Pixel sub-detector
    - 4 layers in the barrel (BPIX) and 3 disks (FPIX) in the forward regions
  - Strip sub-detector
    - 10 layers in the barrel (TIB, TOB) and 12 forward disks (TID, TEC)



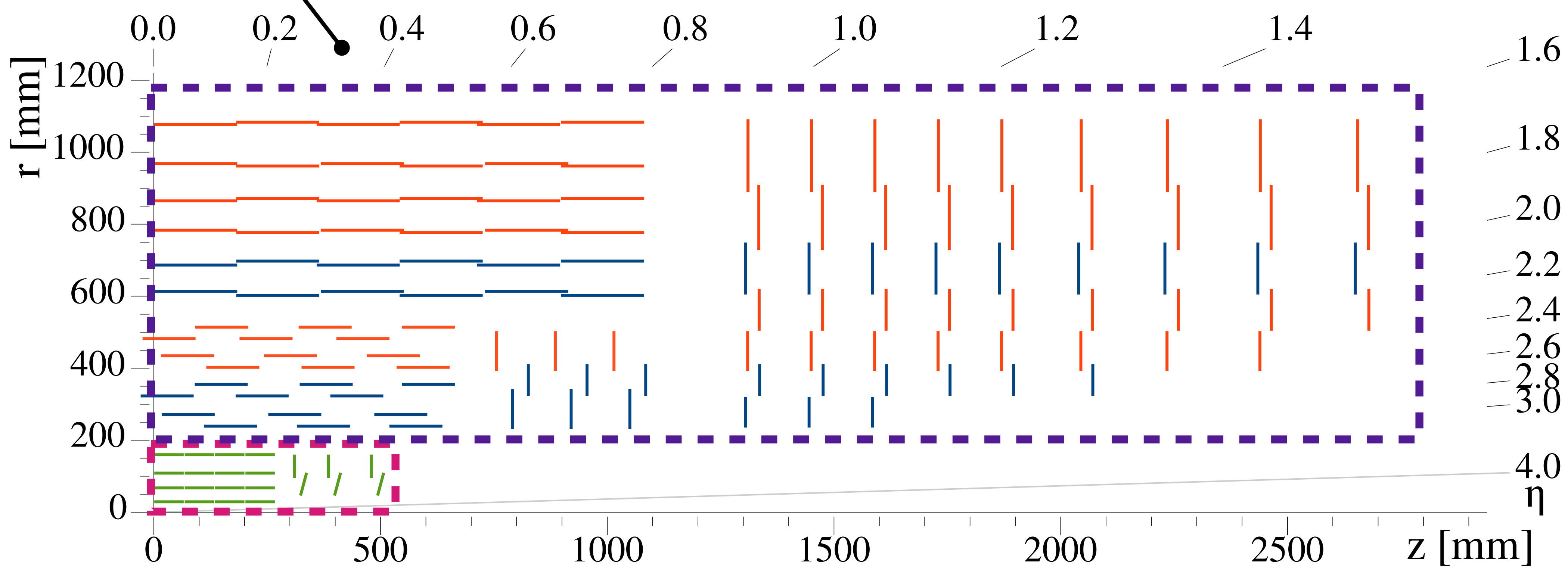
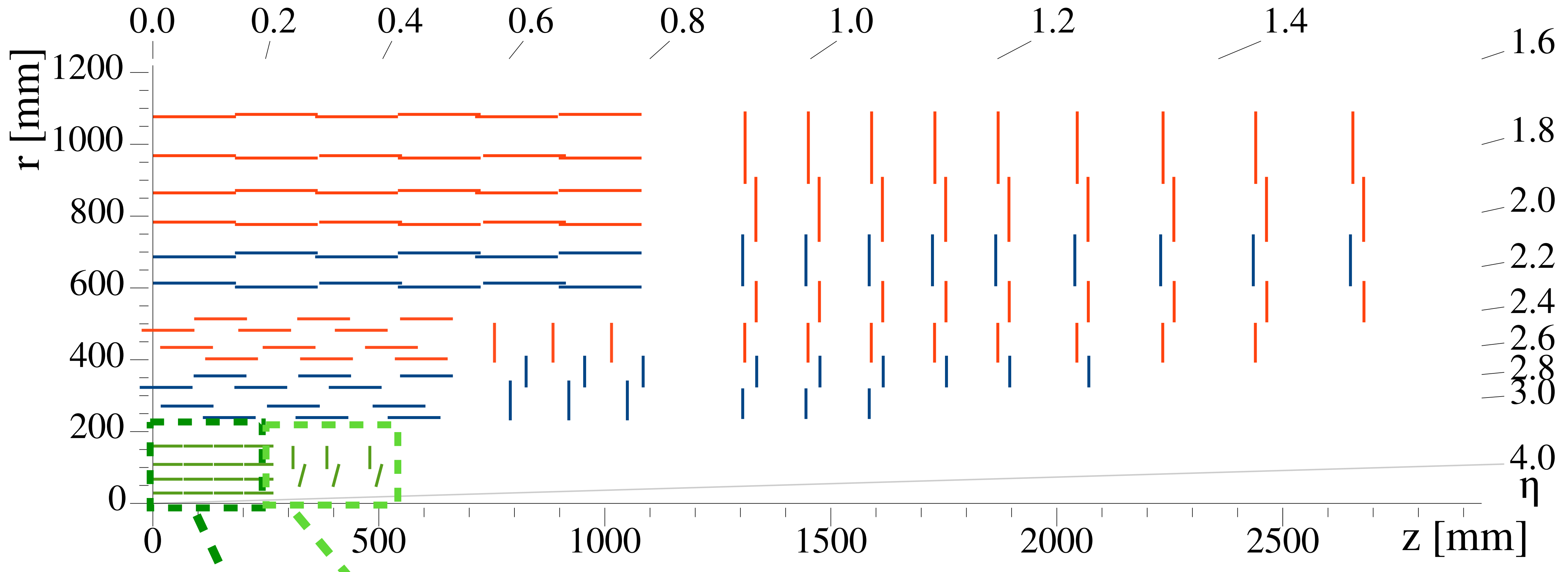


Image source: J.Phys.Conf.Ser. 513 (2014) 022032

CMS Silicon Pixel detector



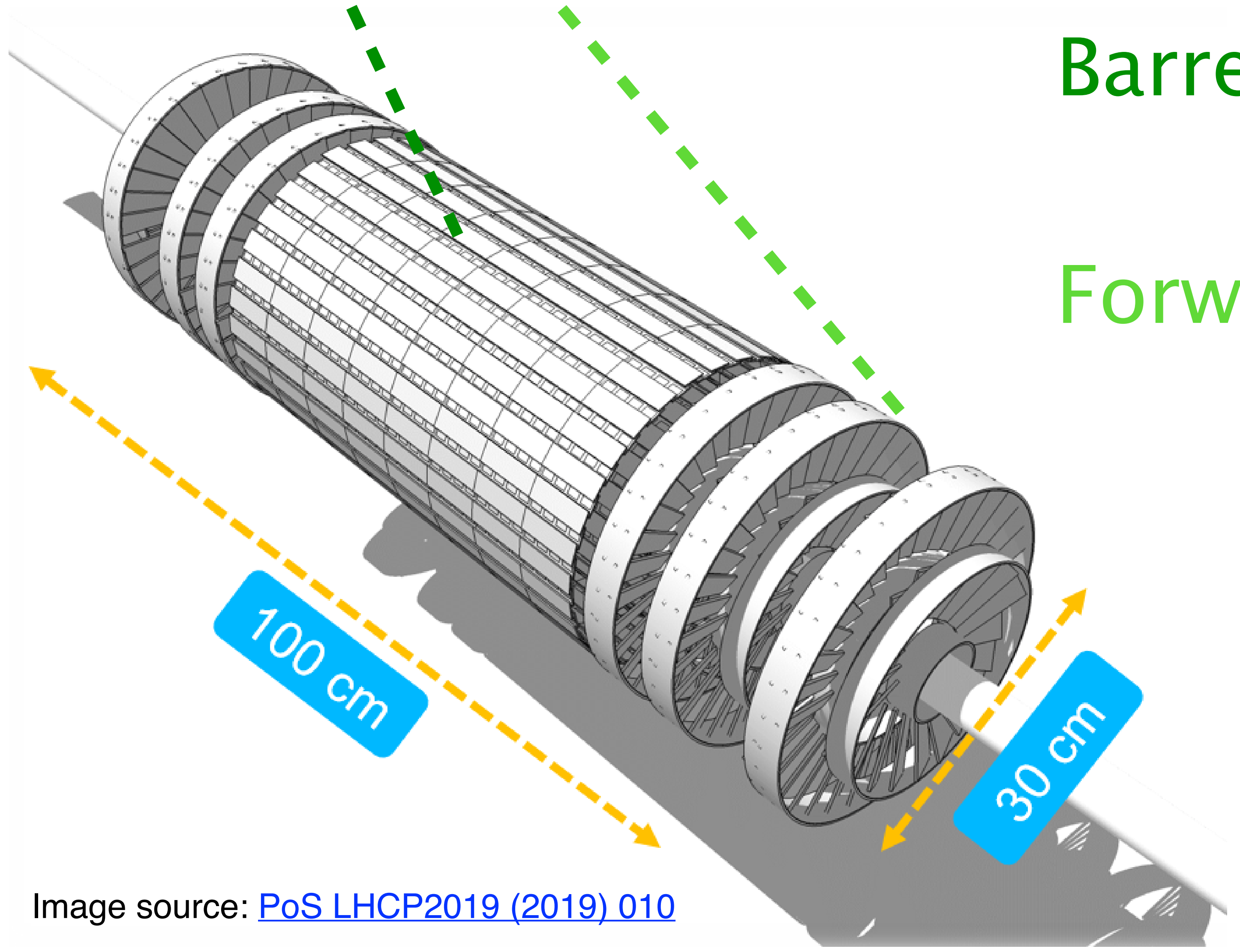


Image source: PoS LHCP2019 (2019) 010

Barrel Pixel (BPIX) ↔ 4 layers

+

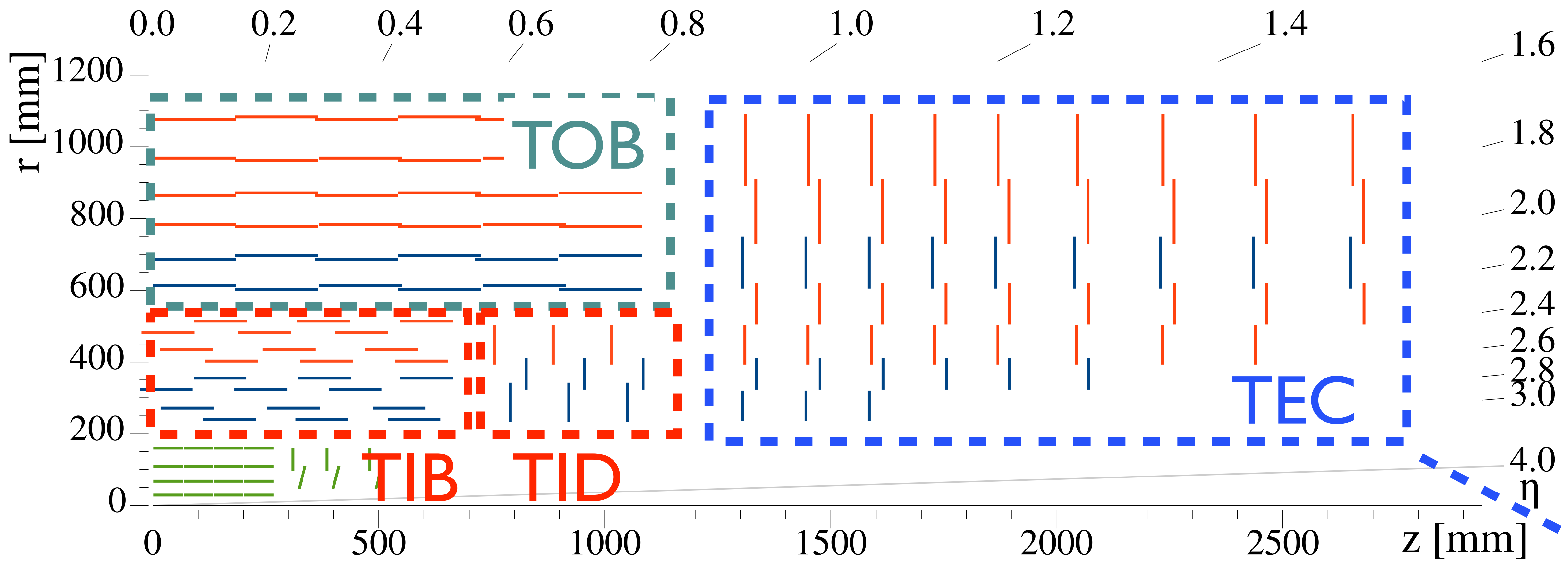
Forward Pixel (FPIX) ↔ 3 disks

1856 modules with
≈ 124M pixels
(100 × 150 μm²)

- Detector component **closest to the collision point**
  - BPIX Layer 1 only ~3 cm from beam pipe! → Particle-hit rate up to 600 MHz/cm²
- Phase-1 Pixel tracker in place since early 2017
- **Pixel refurbished** during LS2
  - Layer 1 fully replaced in 2022
    - Improved ROCs to cope with higher rates
    - Reverse bias up to 800V (compared to 600V before)

4-hit coverage in $|\eta| < 3.0$

CMS Silicon Strip detector



- **15148 modules**
- ≈ 9M analogue readout channels

9-hit coverage in $|\eta| < 2.4$

Thickness of silicon sensors

- TIB, TID, TEC – 320 μm
- TOB, TEC – 500 μm

Strip unchanged since Run 1!

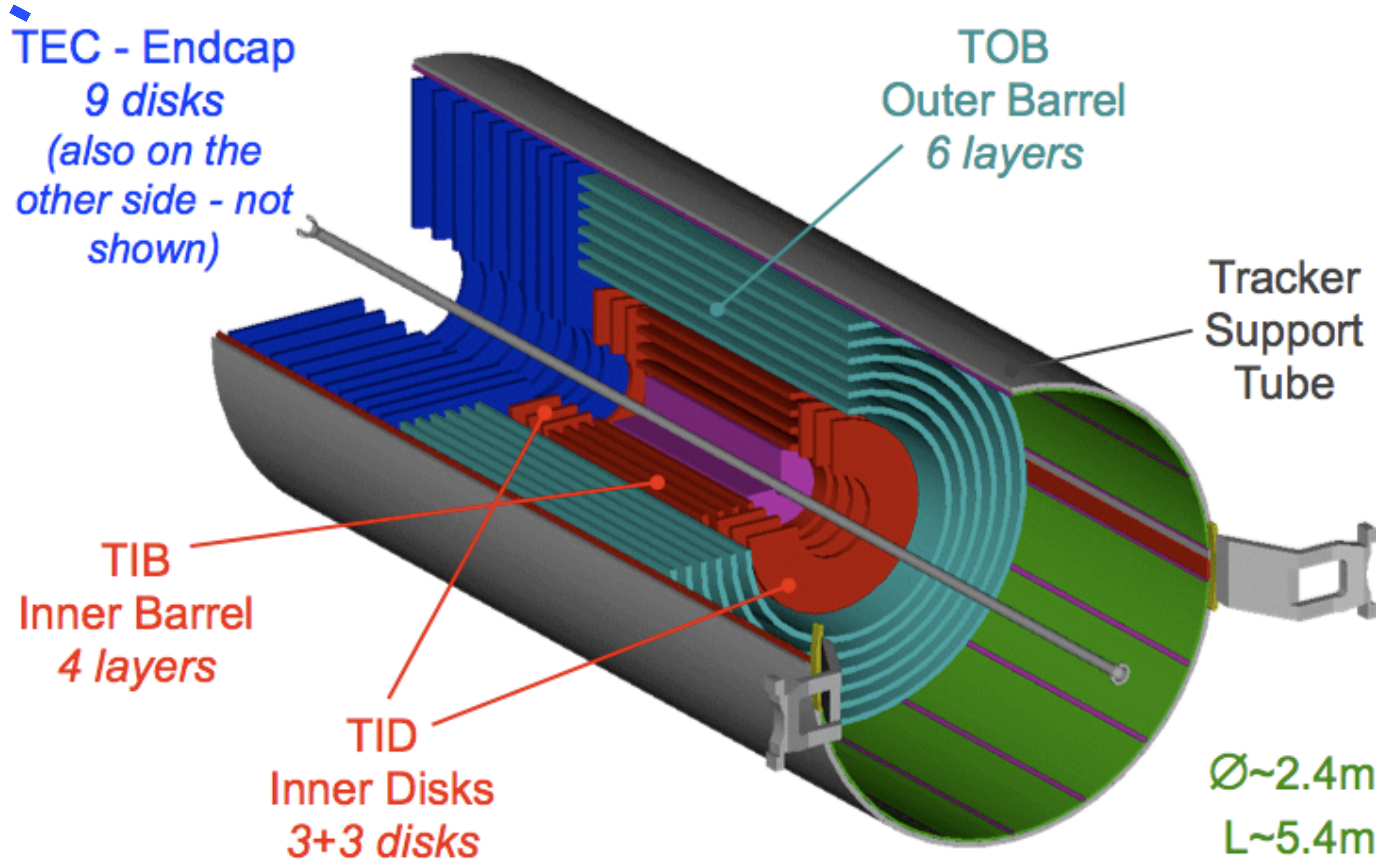
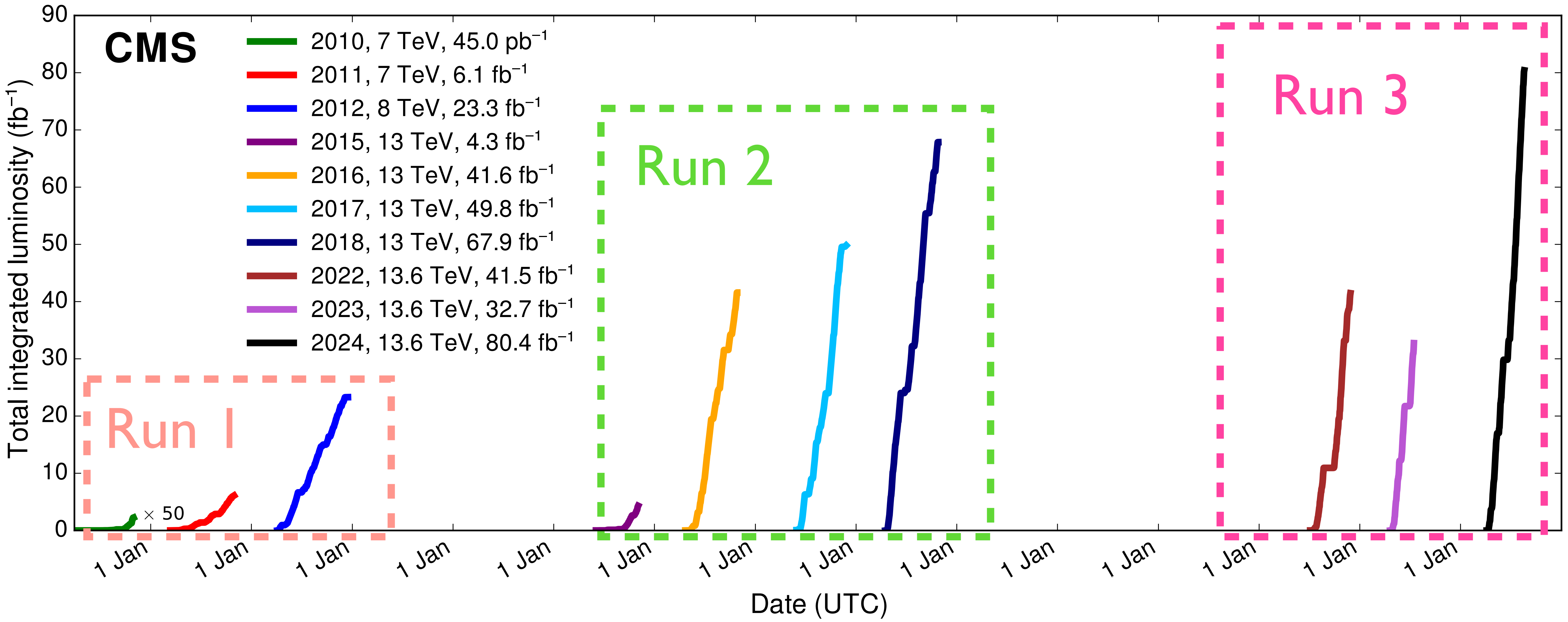


Image source: arXiv:0809.3344

Data taking conditions during Run 3

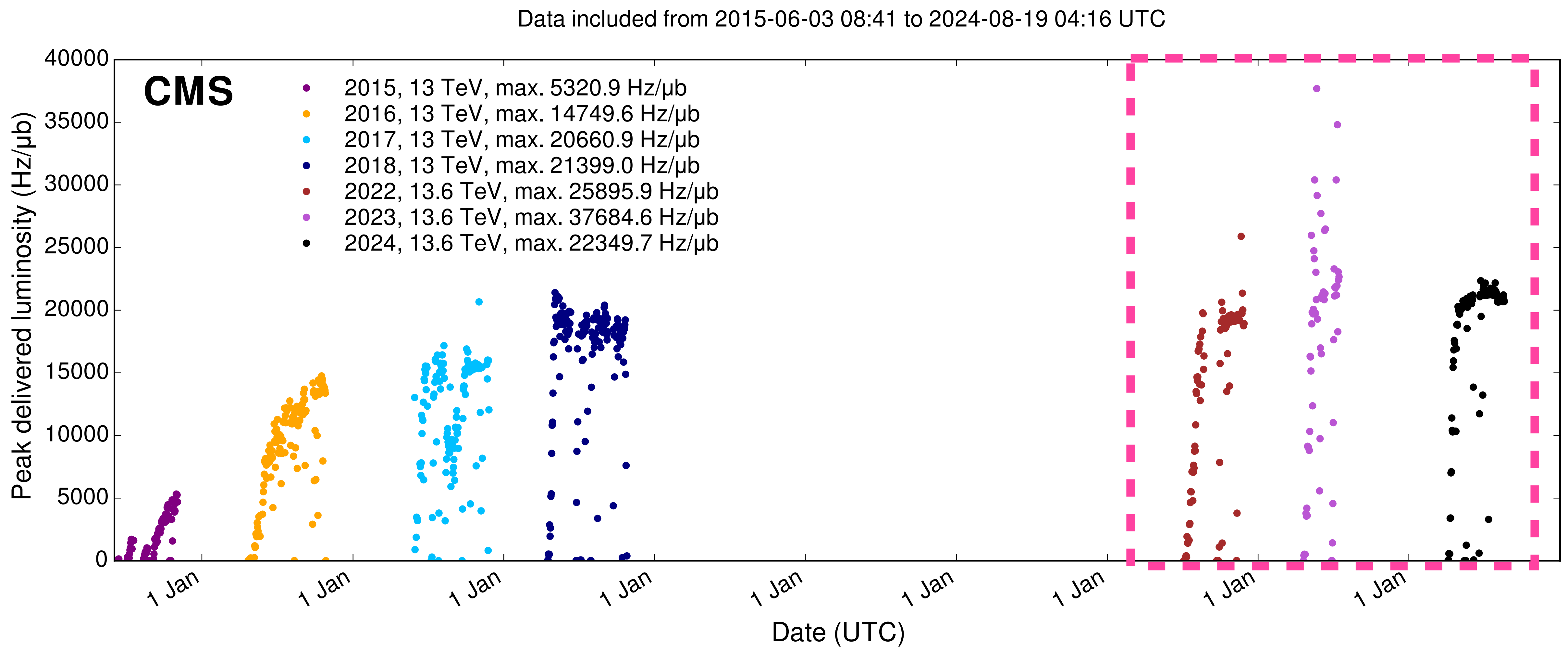
CMS data taking so far



- Luminosity delivered to CMS
  - Run1+Run2+Run3 ~ 318 fb^{-1}
  - Just in Run3 ~ 154.6 fb^{-1}

Data-taking still ongoing!

- CMS instantaneous luminosity ~ 2 x 10^{34} cm^{-2} s^{-1}
- Mean number of interactions per bunch crossing (25ns) in 2024 ~ 63!
- **Highly irradiated environment, challenging conditions for the tracker!**



Source: CMS Luminosity Results

Pixel Performance

Source

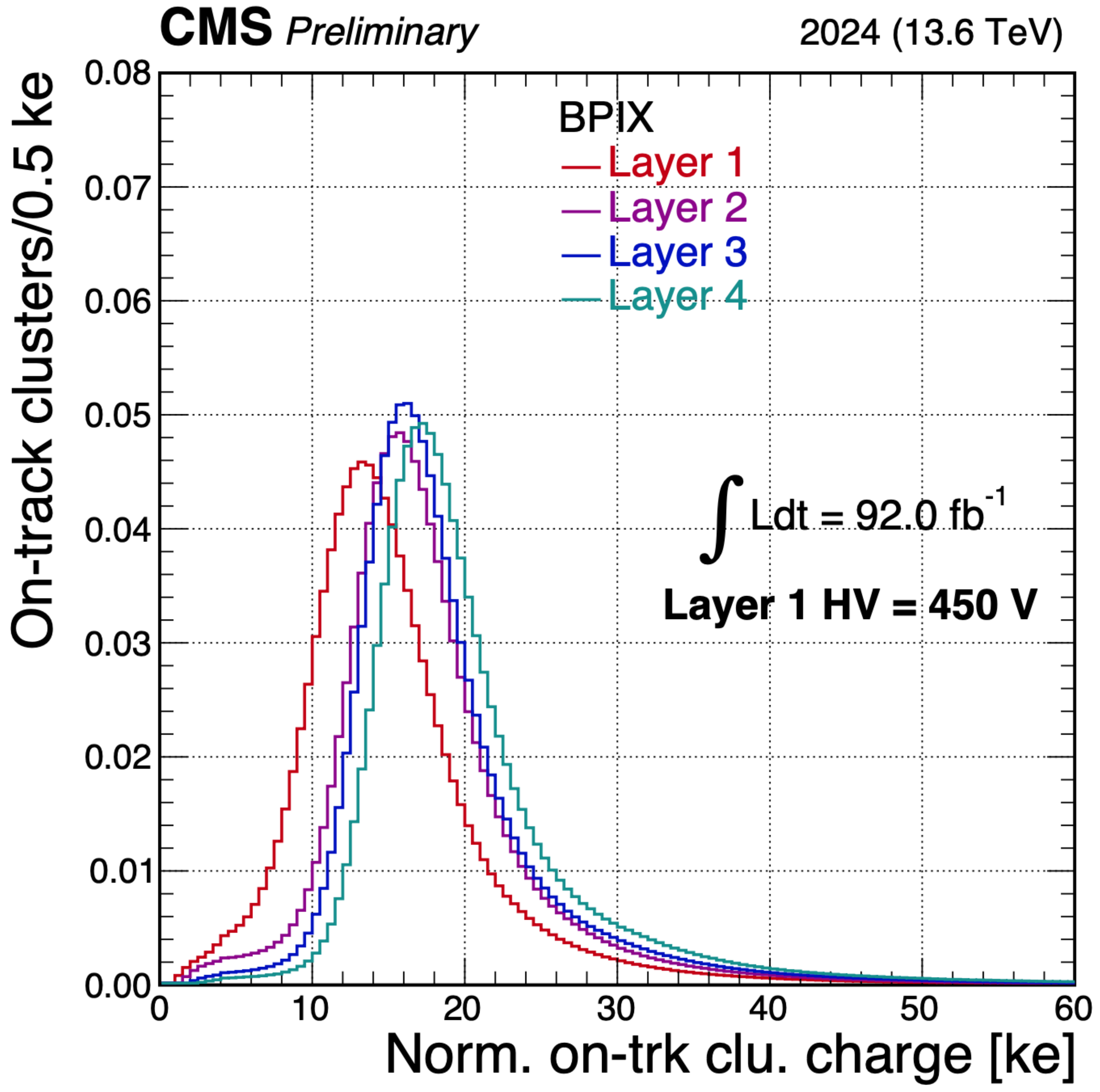
Pixel Performance - Cluster Charge

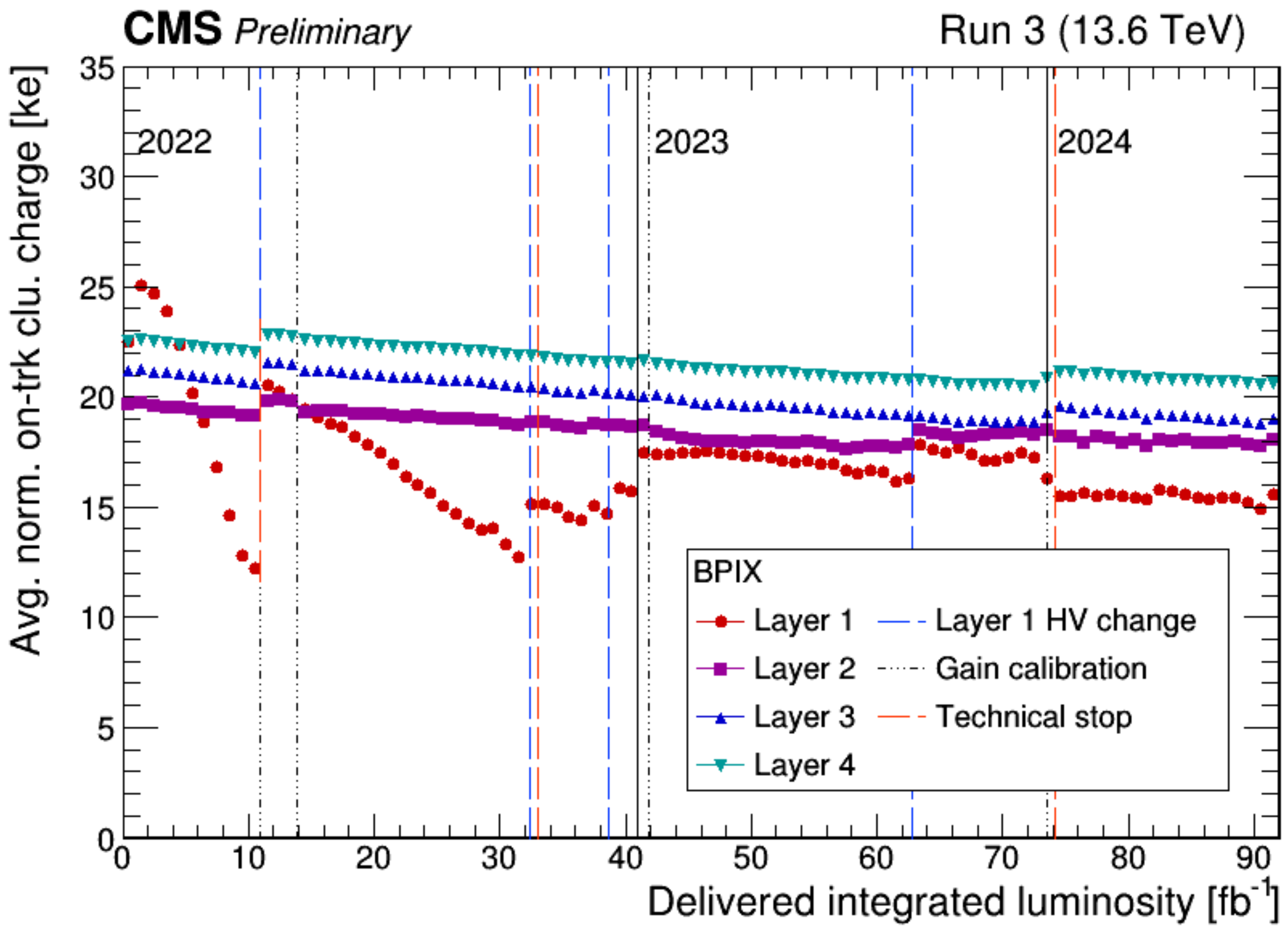
- Clusters formed of adjacent pixels with a charge above a certain threshold

Radiation damage → Loss in charge collection efficiency

Solution: Increase operational bias voltage (e.g. Layer 1 gradually from 150 → 500 V)

- Newly replaced Layer 1 (L1) rapidly changed with irradiation in 2022; with time became conditioned



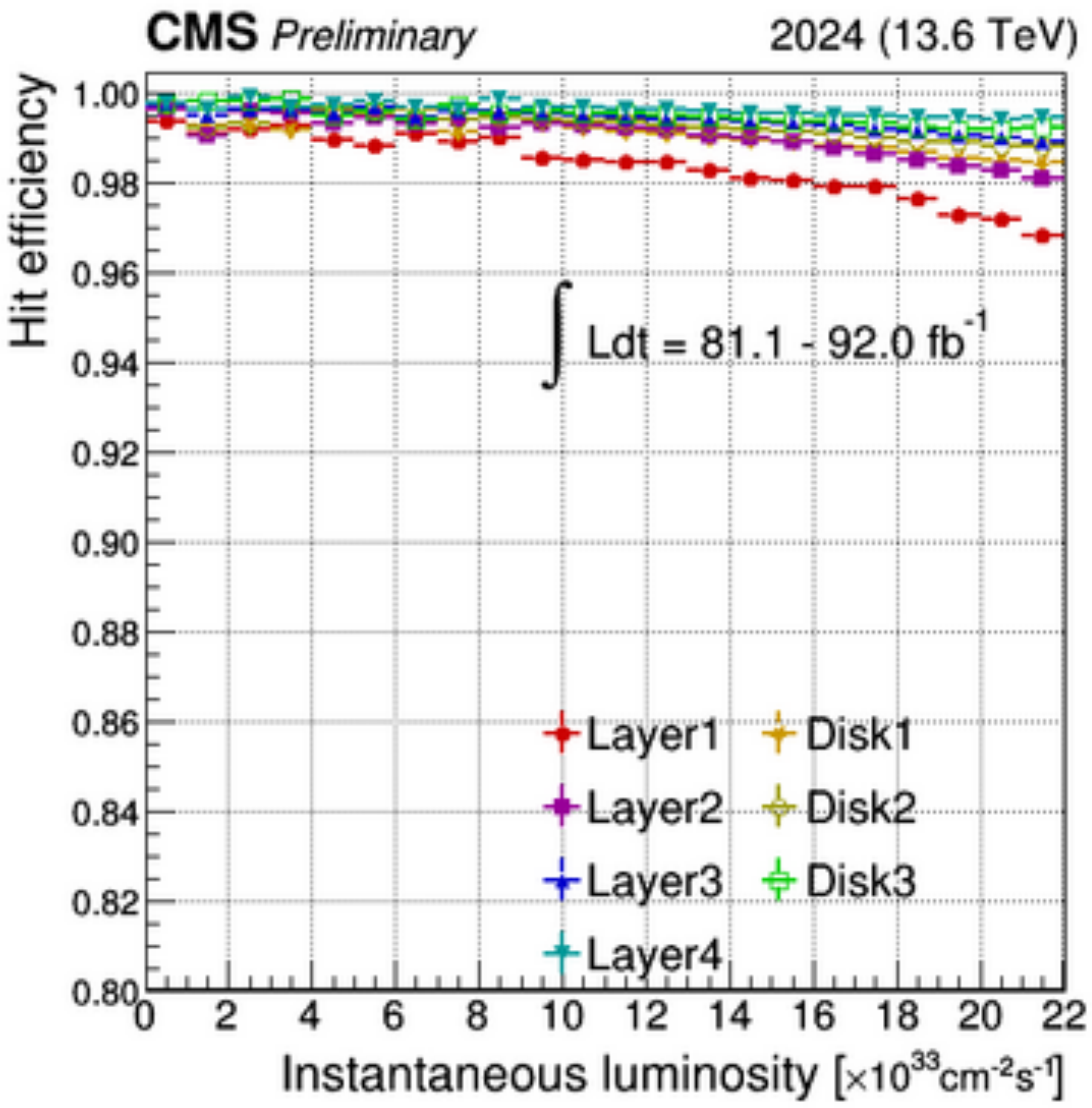


Pixel Performance - Hit Efficiency

- **Definition:** Probability to find any cluster within 1 mm around an expected hit (independent of the cluster quality)
- Bad components of pixel detector excluded from measurement; measured using muon tracks with $p_T > 2$ GeV

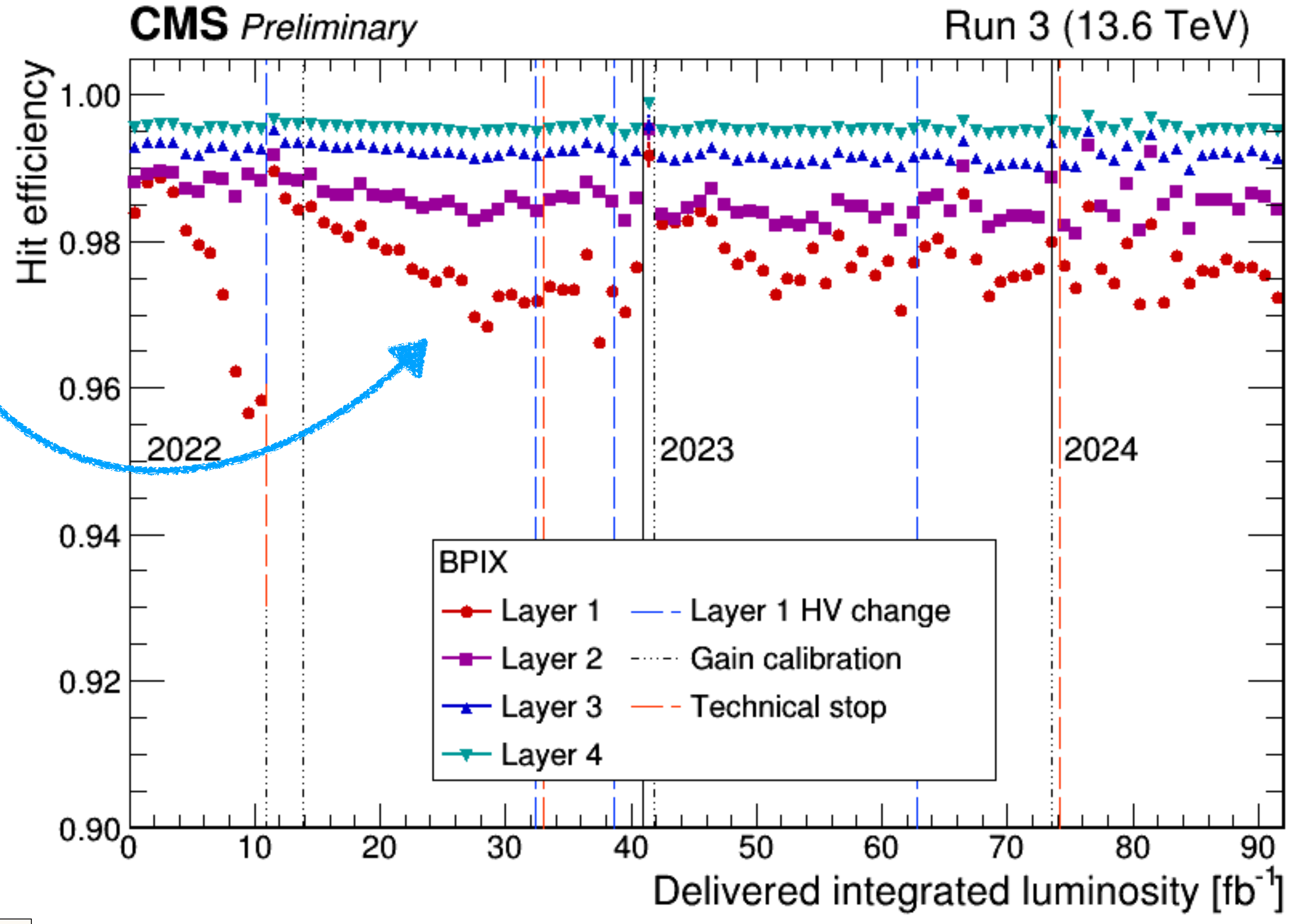
At an instantaneous lumi of ~ 2 x 10^{34} cm^{-2} s^{-1}

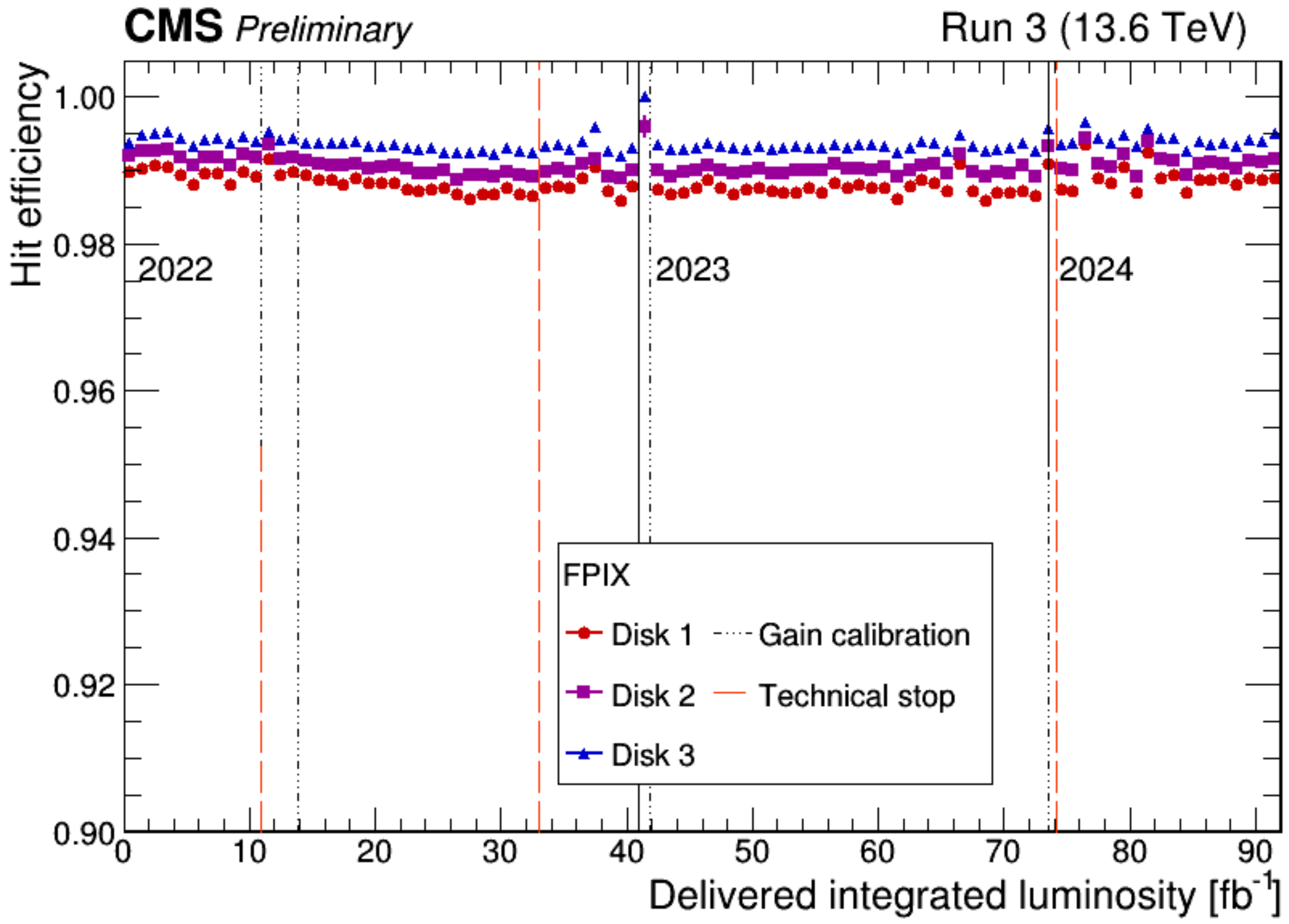
- ✦ **BPIX L1 can operate at > 96% hit efficiency**
- ✦ **BPIX L2-4 and FPIX > 98%**



Pixel Performance - Hit Efficiency

- Definition: Probability to find any cluster within 1 mm around an expected hit (independent of the cluster quality)
- **Degradation** in hit efficiency mostly for BPIX L1 due to **radiation damage** → Solution: Raise HV
- FPIX hit efficiency stable across years

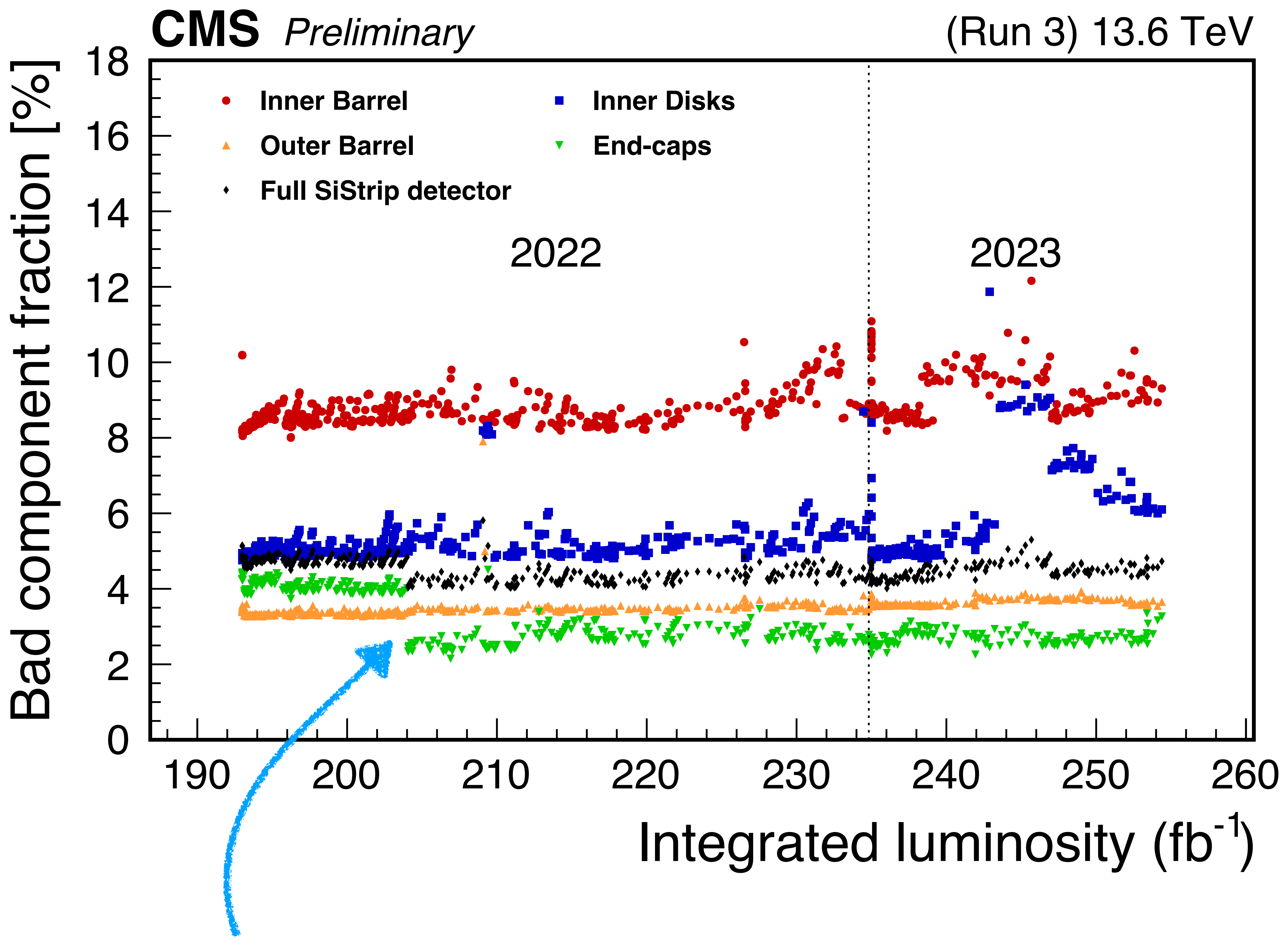




Strip Performance

CMS-DP-2023-030, CMS-DP-2023-040

Strip Performance - Bad Components

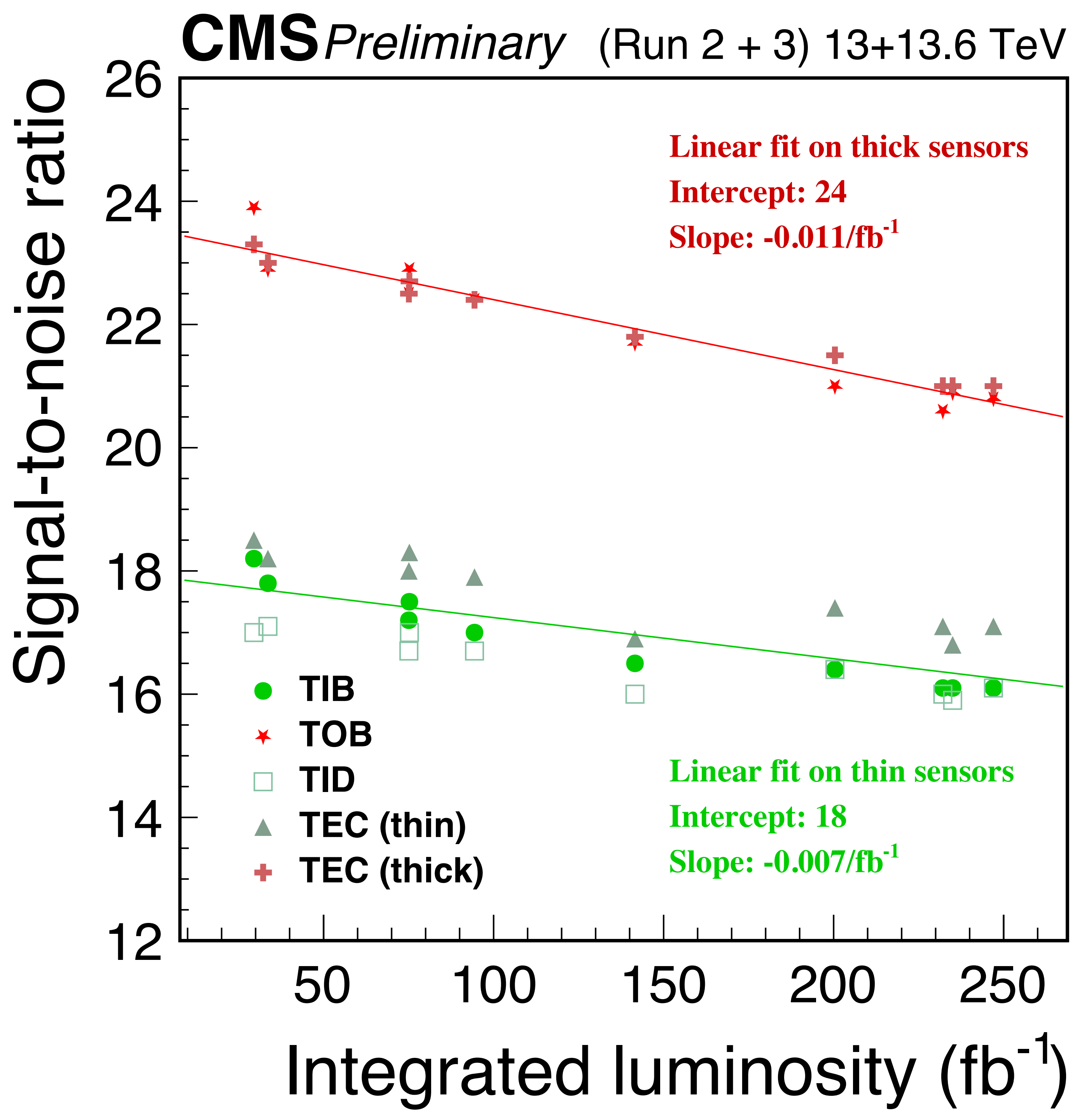


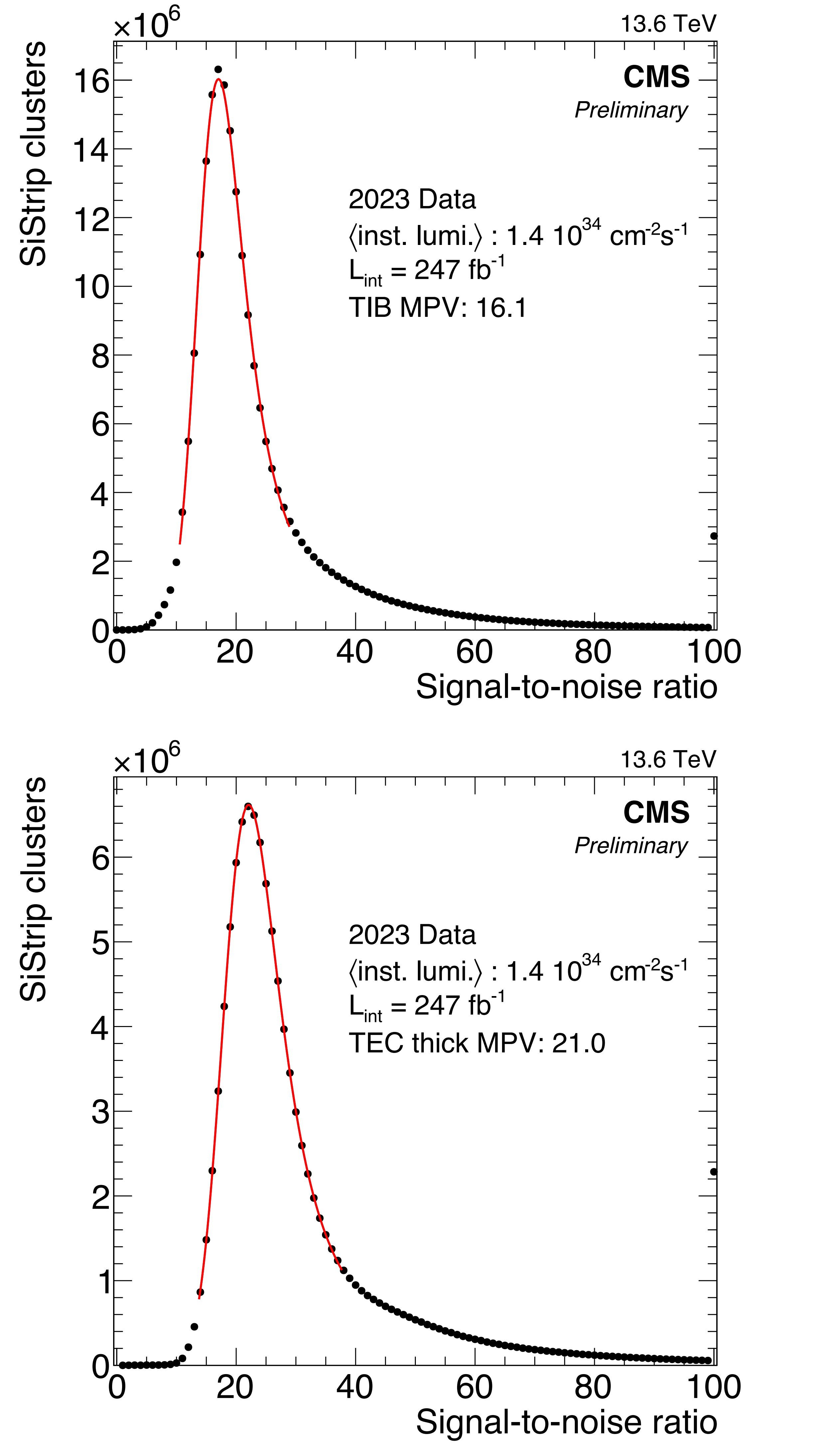
Fraction of active channels during Run 3 ~ 96 %

- Drop in bad module fraction around 205 fb^{-1} due to the recovery of a cooling loop in TEC+
- Fraction seen to increase for a handful of runs due to some (promptly recovered) issues in either data-taking or in powering

Strip Performance - Signal-to-noise Ratio

- Signal-to-noise ratio measured regularly throughout the year
  - Measured separately for 320 µm and 500 µm sensors in tracker endcaps
  - **High S/N ratio → better** zero suppression and cluster building
  - Decreasing ratio with time (as expected from irradiation studies)
  - **Expected S/N at the end of Run 3 (~500/fb)**
    - ✦ Thin sensor – 14.5
    - ✦ Thick sensor – 18.5

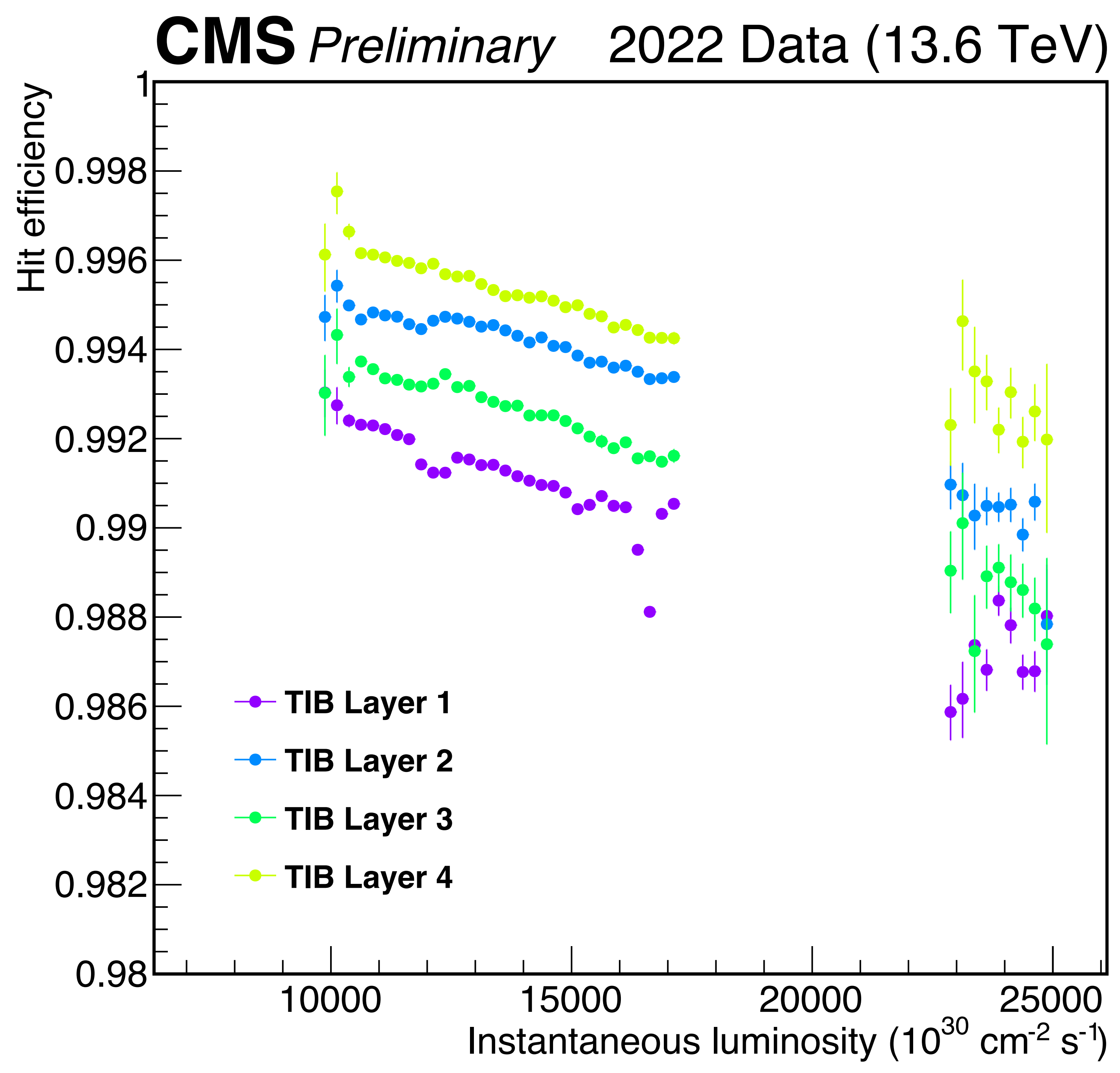


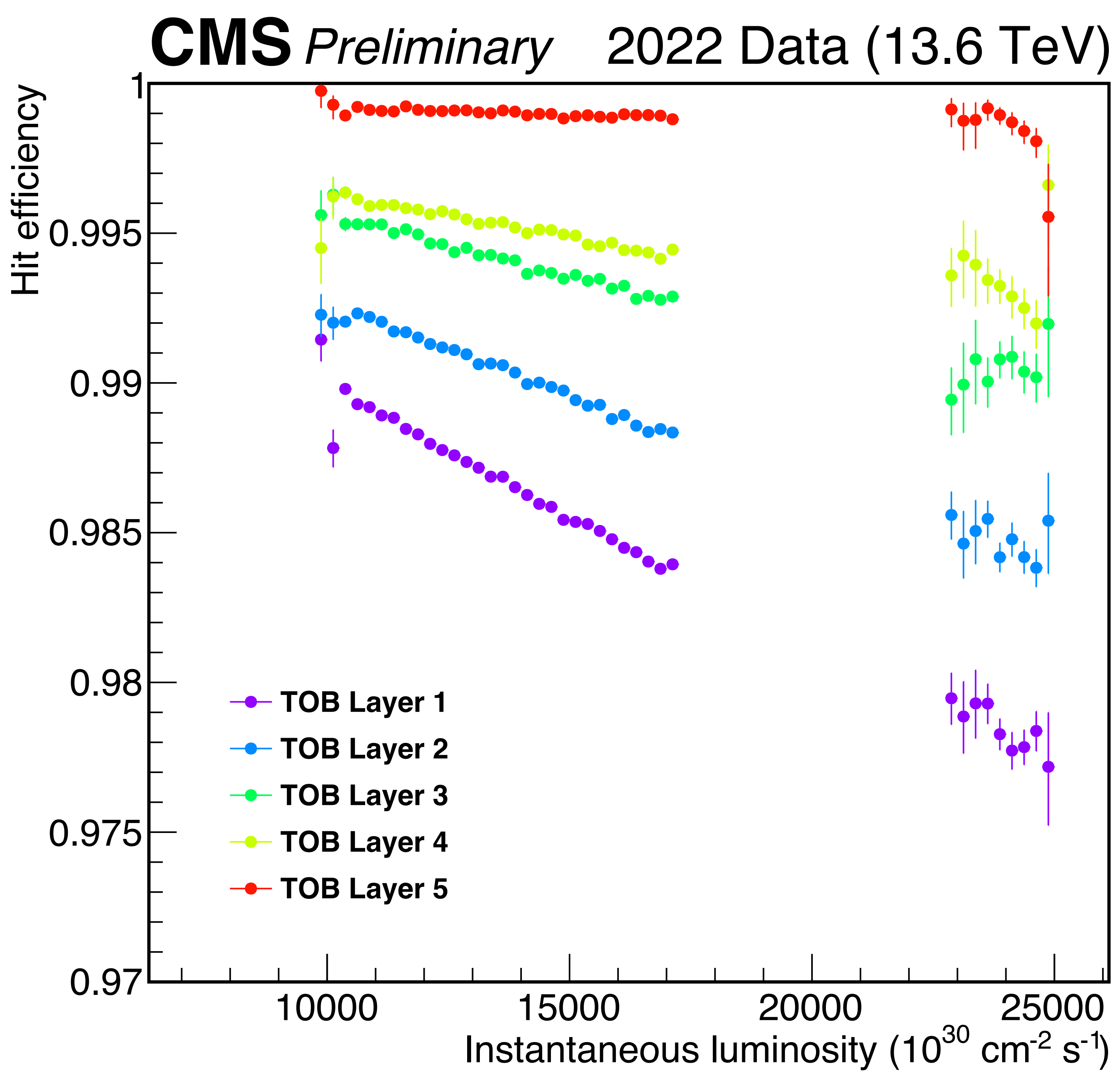


S/N for a run taken in 2023

Strip Performance - Hit Efficiency

- Definition: Fraction of traversing tracks with a hit anywhere within a range of 15 strips
- Measured using high purity tracks; modules flagged as bad not used in measurement
- Data used from normal/very high lumi fills to compute hit efficiency





Hit efficiency in

✦ TOB > 97.5%

✦ TIB > 98.5%

even at high lumi!

Tracker Alignment Performance

CMS-DP-2024-071

Track-based Alignment of the CMS Tracker

- **Goal:** Determine corrections to the position and orientation of all modules of the tracker such that $\sigma_{\text{align}} \lesssim \sigma_{\text{hit}}$ ($\sigma_{\text{hit}} \rightarrow$ intrinsic hit resolution ~10μm)

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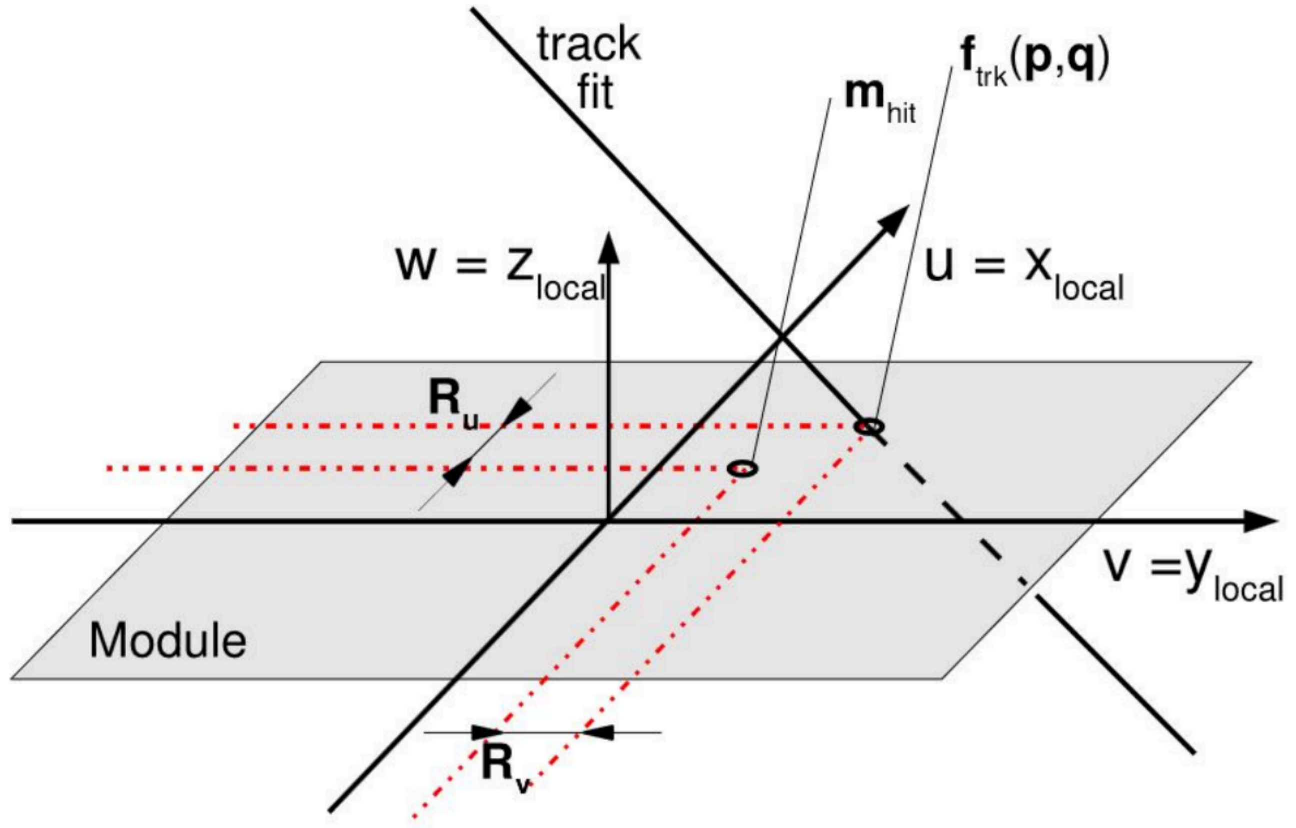
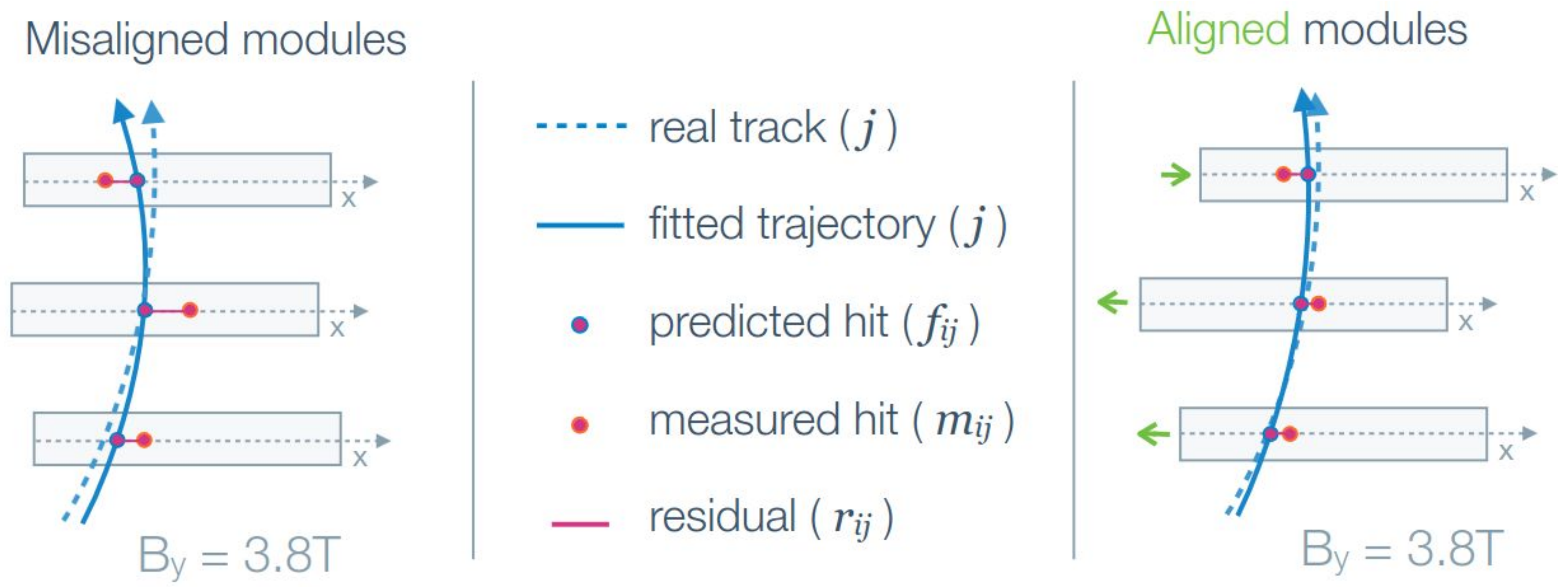


$\mathcal{O}(10^5)$ parameters to align!



- Minimisation of sum of squares of normalised track-hit residuals

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

track-hit residual

Alignment is time dependent due to:

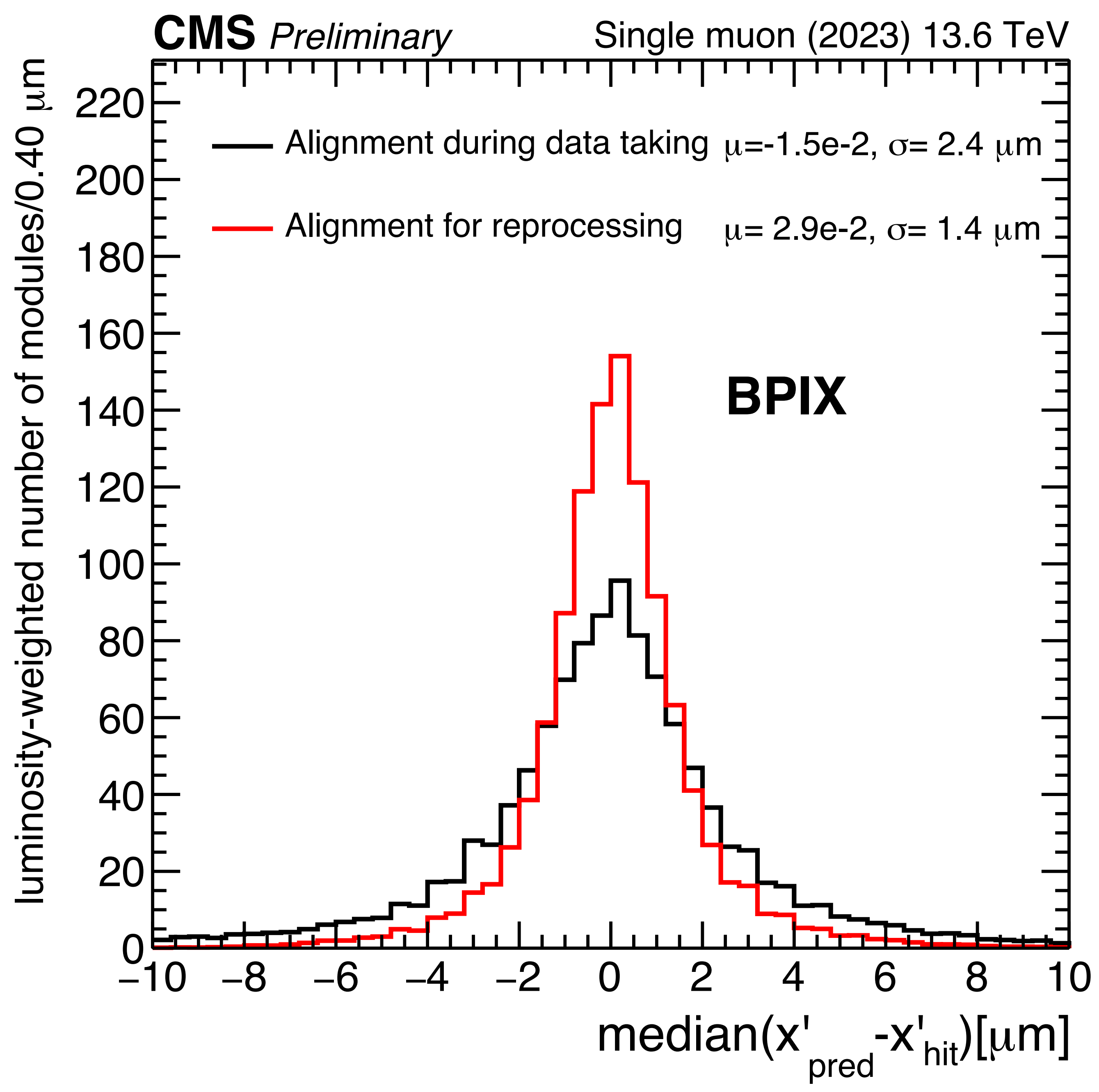
- Cooling cycle – $\mathcal{O}$(10μm)
- Magnet cycle – $\mathcal{O}$(1mm)
- Irradiation – $\mathcal{O}$(1μm)

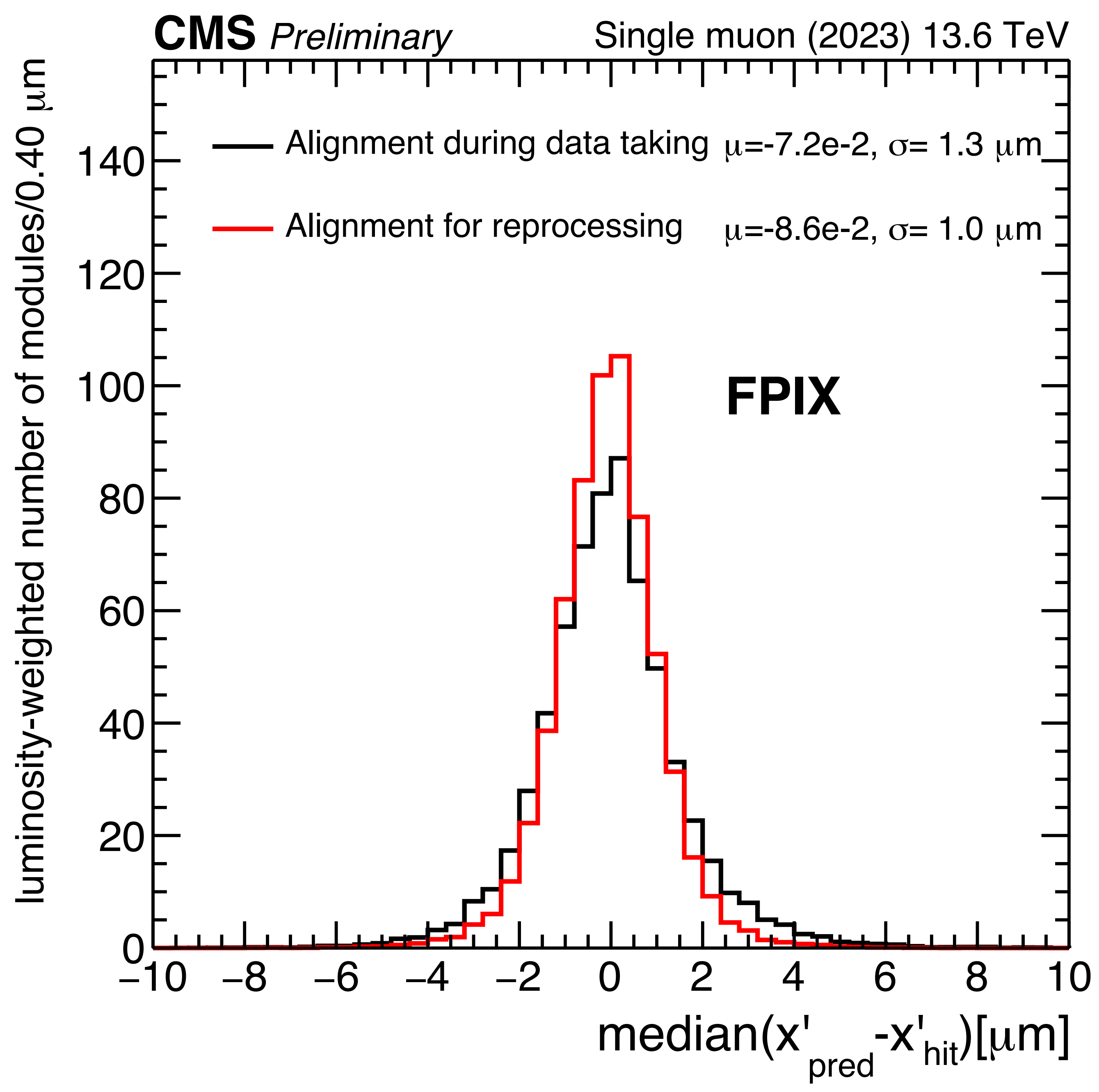
Strategy:

- **Alignment during data taking** → mainly consists of an automated alignment performed in a Prompt calibration loop (PCL)
- **Alignment for reprocessing** → At the end of 2022 and 2023 data taking, a full modular alignment of both pixel and strip

Tracker Alignment Performance - Distribution of median residuals

- Distribution of median of **track-hit residuals** $x'_{pred} - x'_{hit}$ (DMRs) determined for a given no. of tracks
- Tracks first refitted removing the hit under scrutiny to avoid any bias
- For a perfectly aligned detector, distributions expected to be centred at zero
- Width of distribution indicates local alignment precision



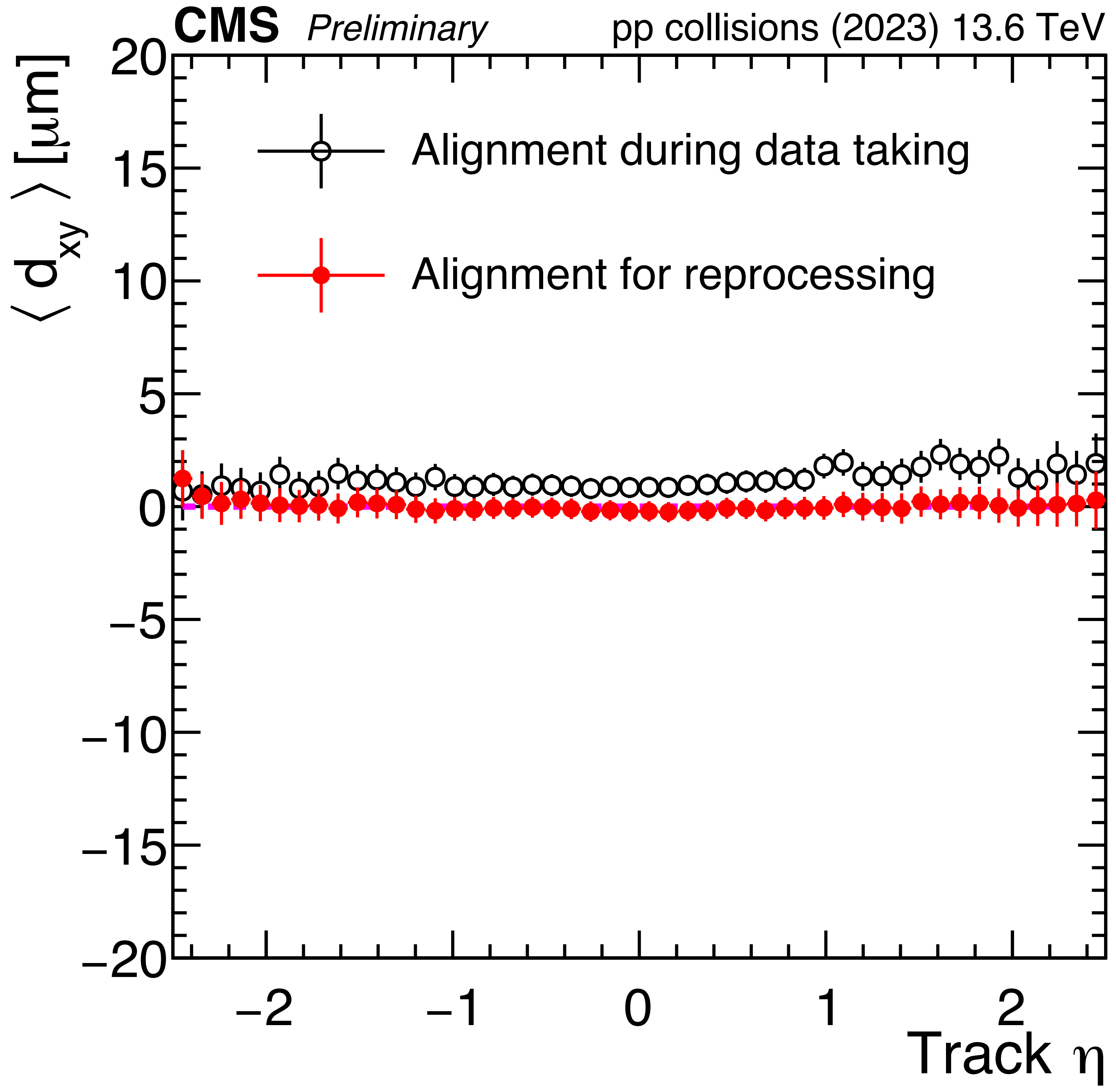


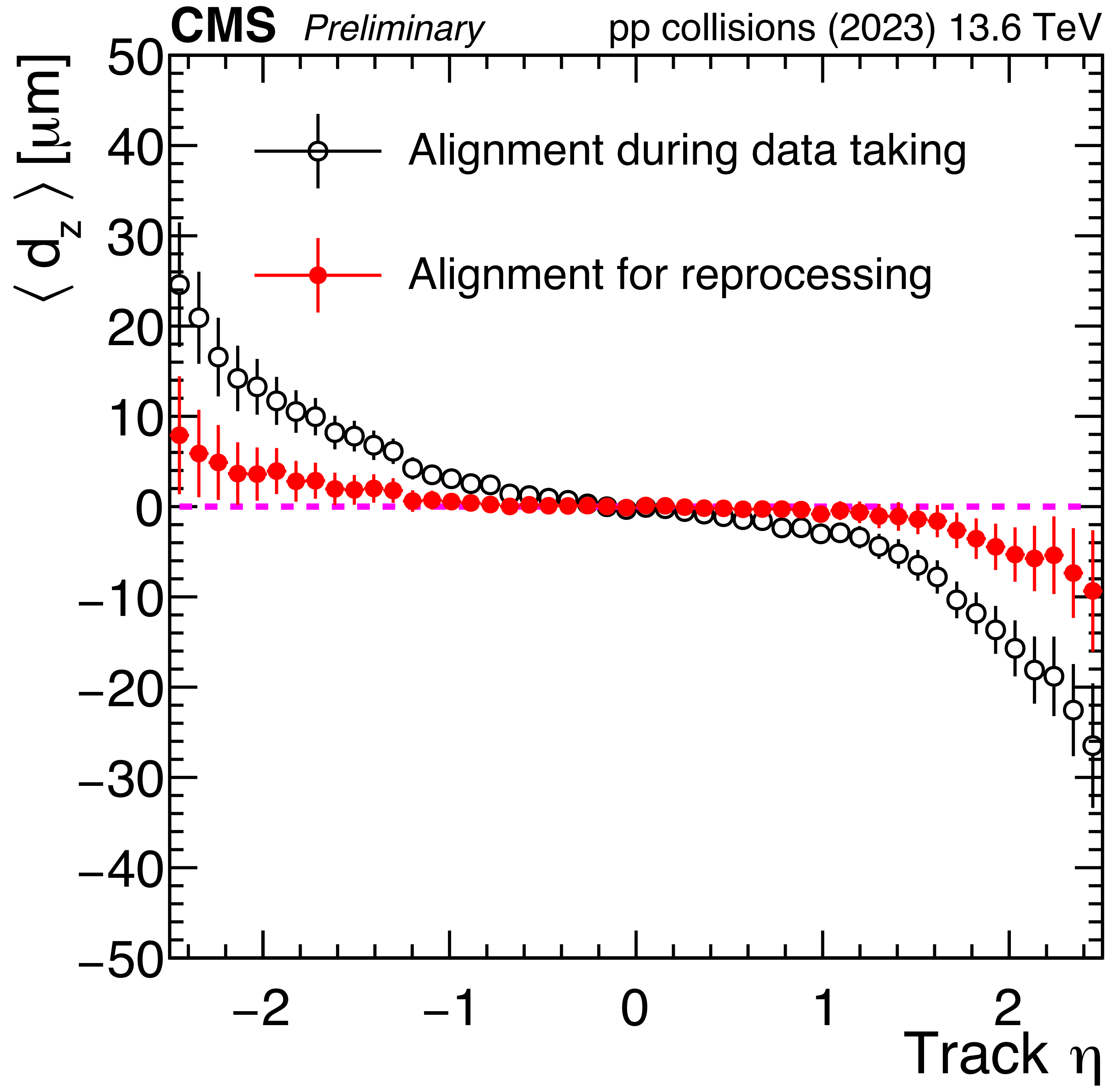
- Alignment for reprocessing → Smaller mean deviation away from zero and better width
  - ➡ Indicating less misalignment due to changing conditions and a higher precision of the calibration

Tracker Alignment Performance - Track-vertex Impact Parameters

- Impact parameters obtained by recalculating the primary vertex position after removing the track being studied from it and considering the impact parameter of this removed track

- Perfectly aligned detector → flat distribution centred at zero





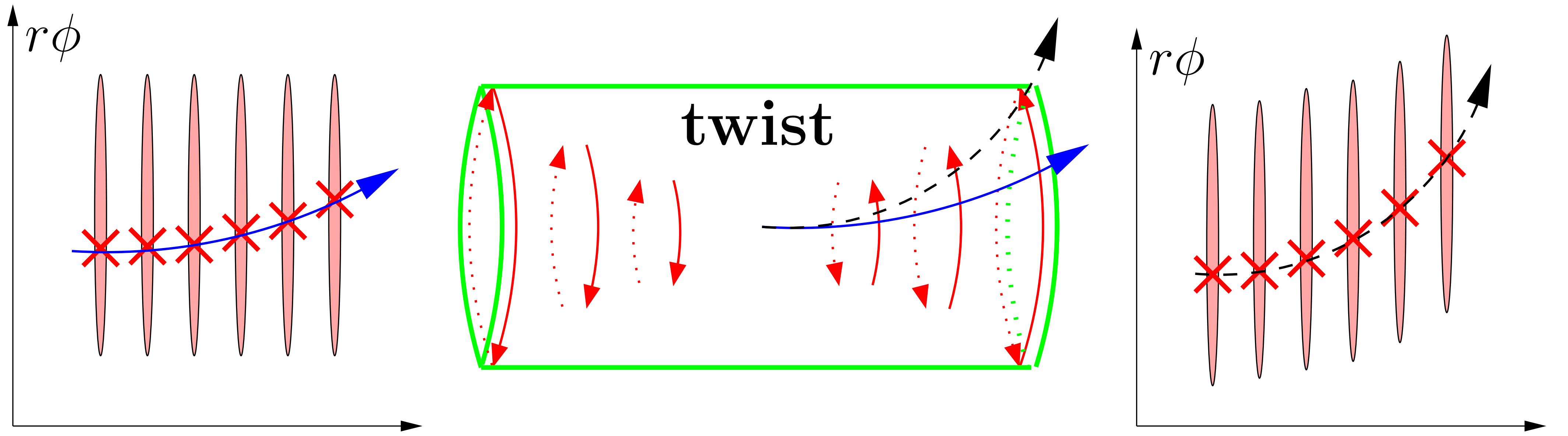
Exploiting $Z \to \mu\mu$ events with mass and vertex constraints in alignment for reprocessing helps to reduce the bias in d_z vs η significantly

Tracker Alignment - Weak Modes

- Weak modes → Unphysical distortions of the detector that don't impact the track fit, but introduce biases in measurements

- Dataset variety of utmost importance for controlling various biases and weak modes
  - ✦ Cosmics and Z → μμ events **critical** and therefore exploited in the alignment for reprocessing

Example of a weak mode



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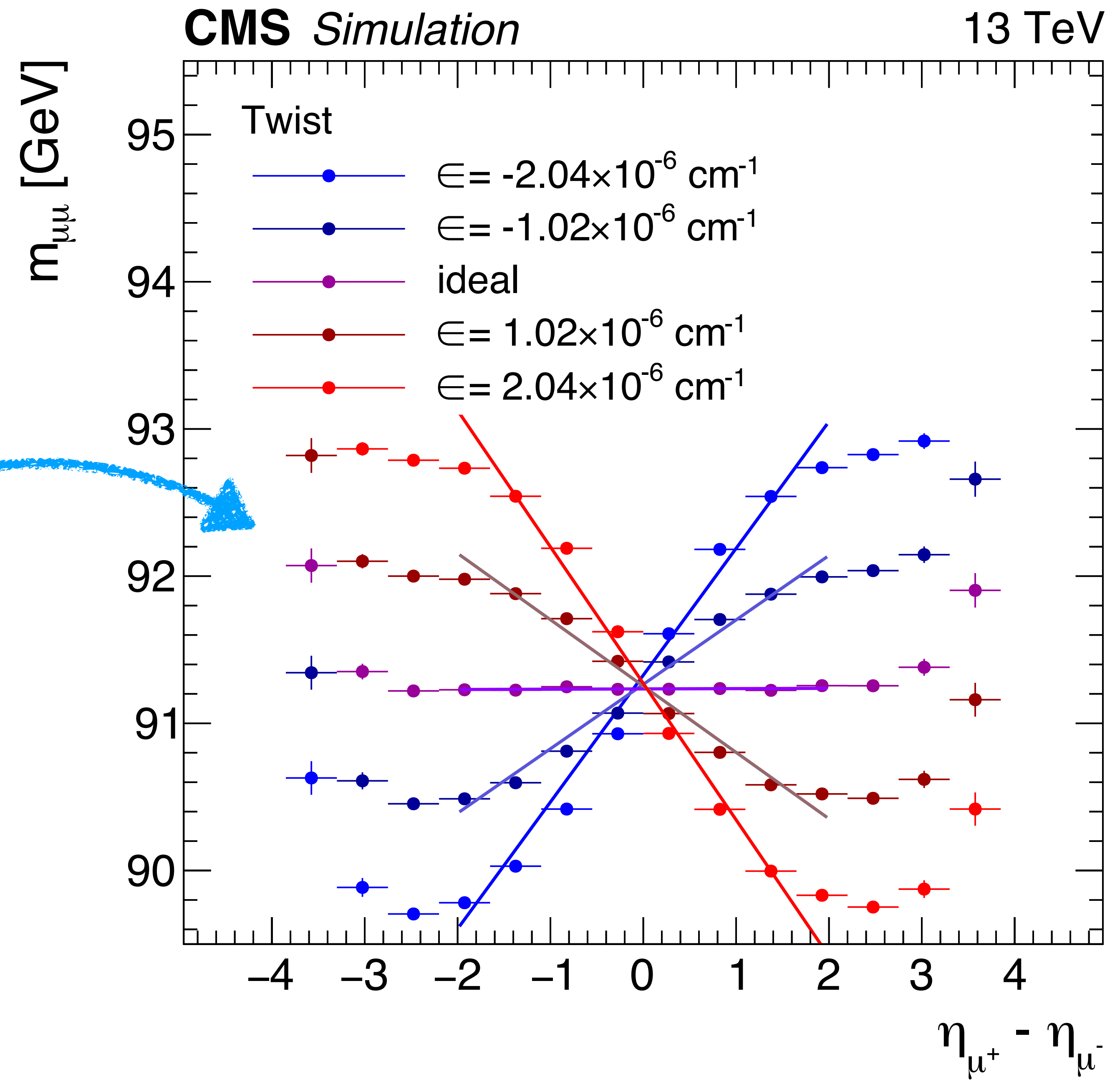
What it'll do to the data



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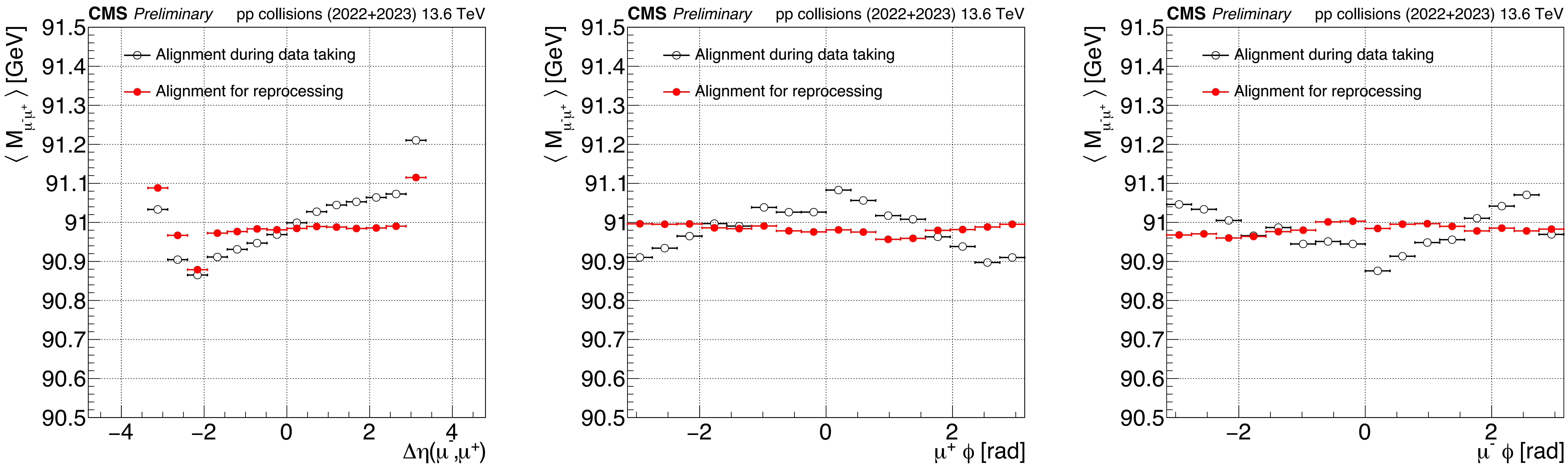
Minimising the spatial dependence of the Z boson mass



- Reconstructed Z → μμ mass as a function of
  - Difference in eta between the negatively and positively charged muons (left)
  - Azimuthal angle phi of the positively charged muon (middle) and negatively charged muon (right)
- Alignment for reprocessing shows an improvement in the uniformity of reconstructed Z → μμ mass

Summary

- The CMS Tracker in good condition, successfully delivering high quality data in Run 3
  - The Pixel tracker after refurbishment with a new Layer 1 operating well
  - The Strip tracker performing excellent, well after ~13 years of operation
  - Ultimate physics precision achieved in the alignment of the tracker via reprocessing the data
- Performance of the detector constantly monitored and frequent calibrations performed
  - Ageing/irradiation effects visible → Efforts made timely to mitigate them
- Studies ongoing with data collected (and to be collected during the remaining year). So many more interesting results expected. **Stay tuned!**

Backup

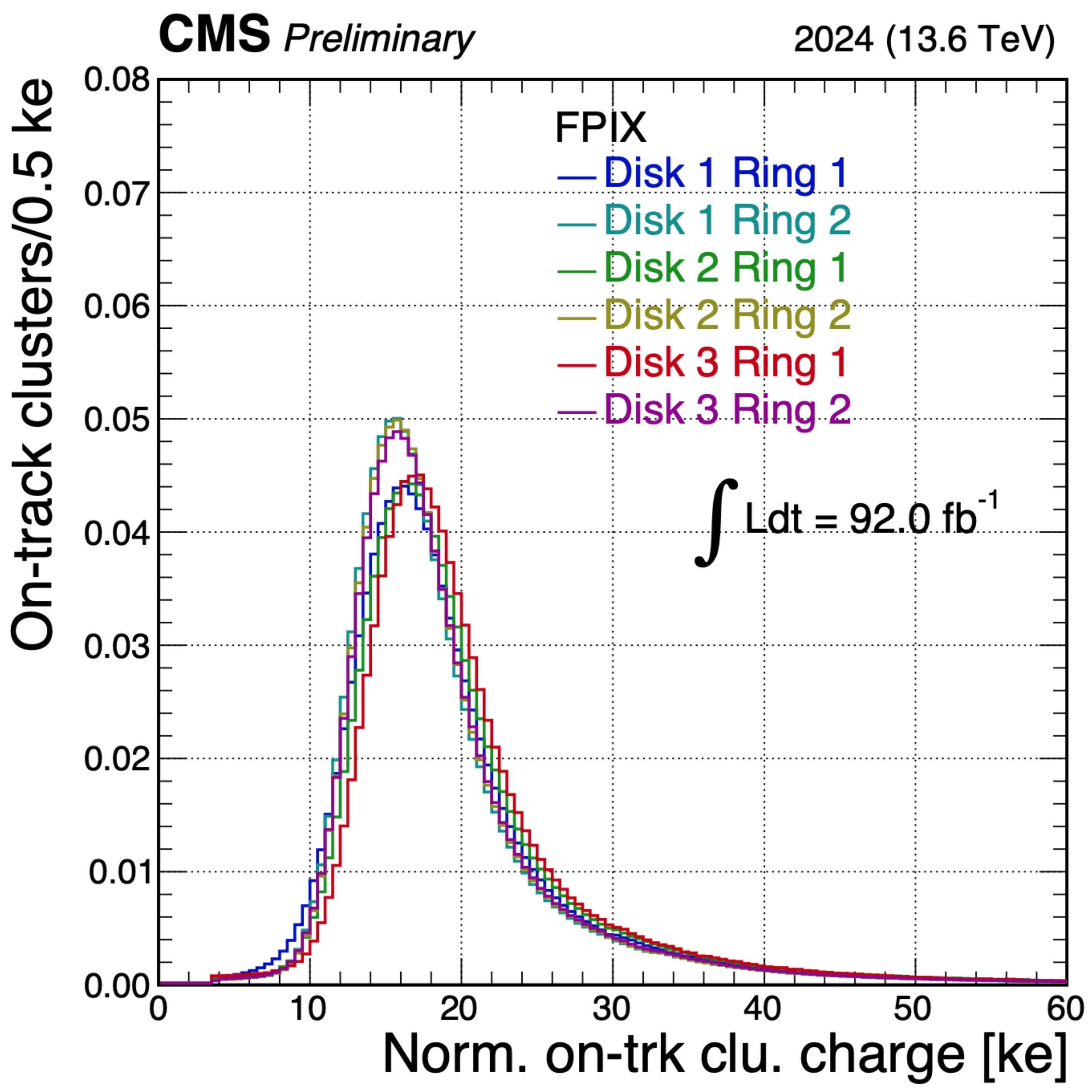
Pixel Performance - Cluster Charge

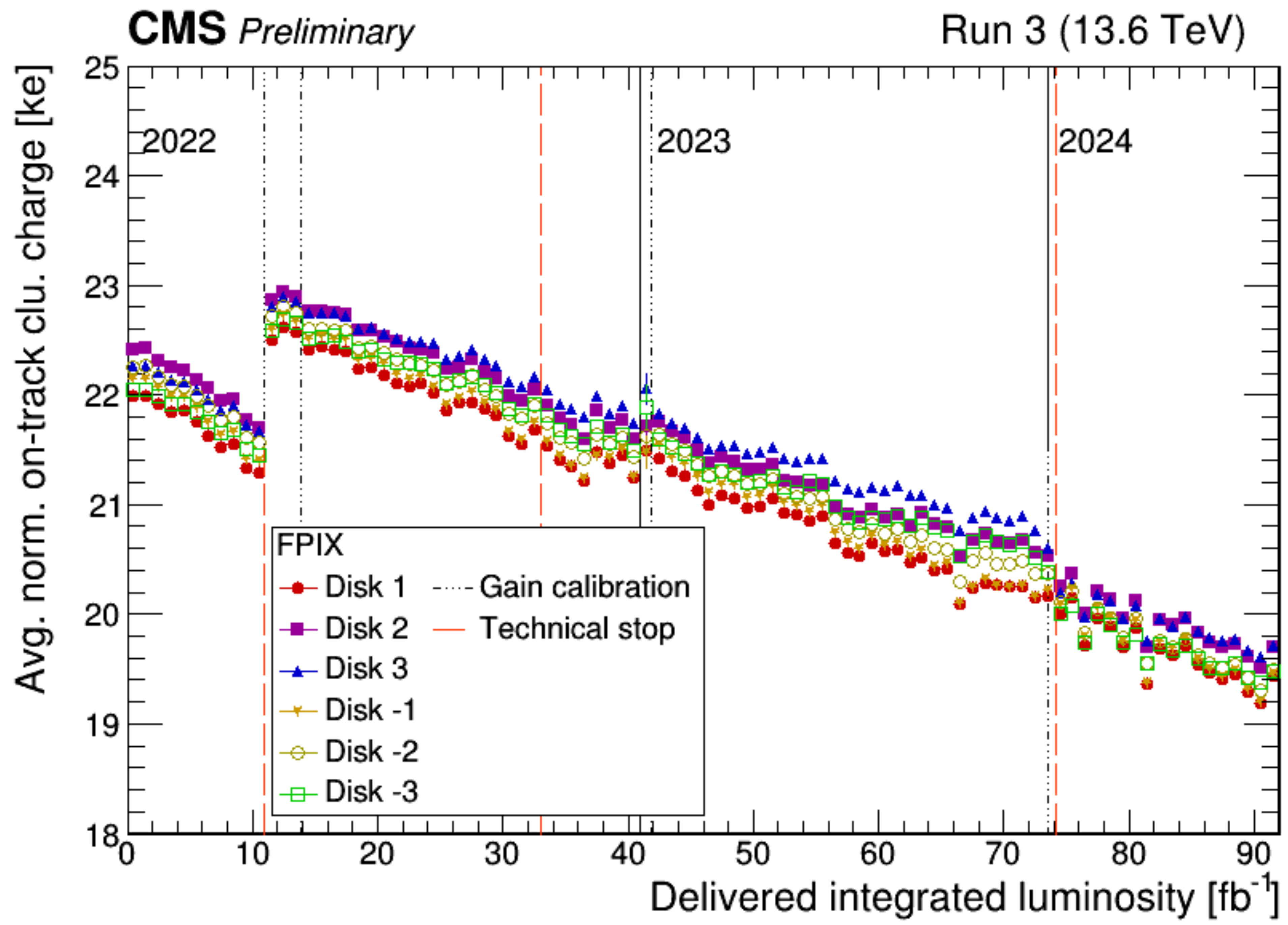
- Clusters formed of adjacent pixels with a charge above a certain threshold

Radiation damage → Loss in charge collection efficiency

Solution: Increase operational bias voltage (e.g. Layer 1 gradually from 150 → 500 V)

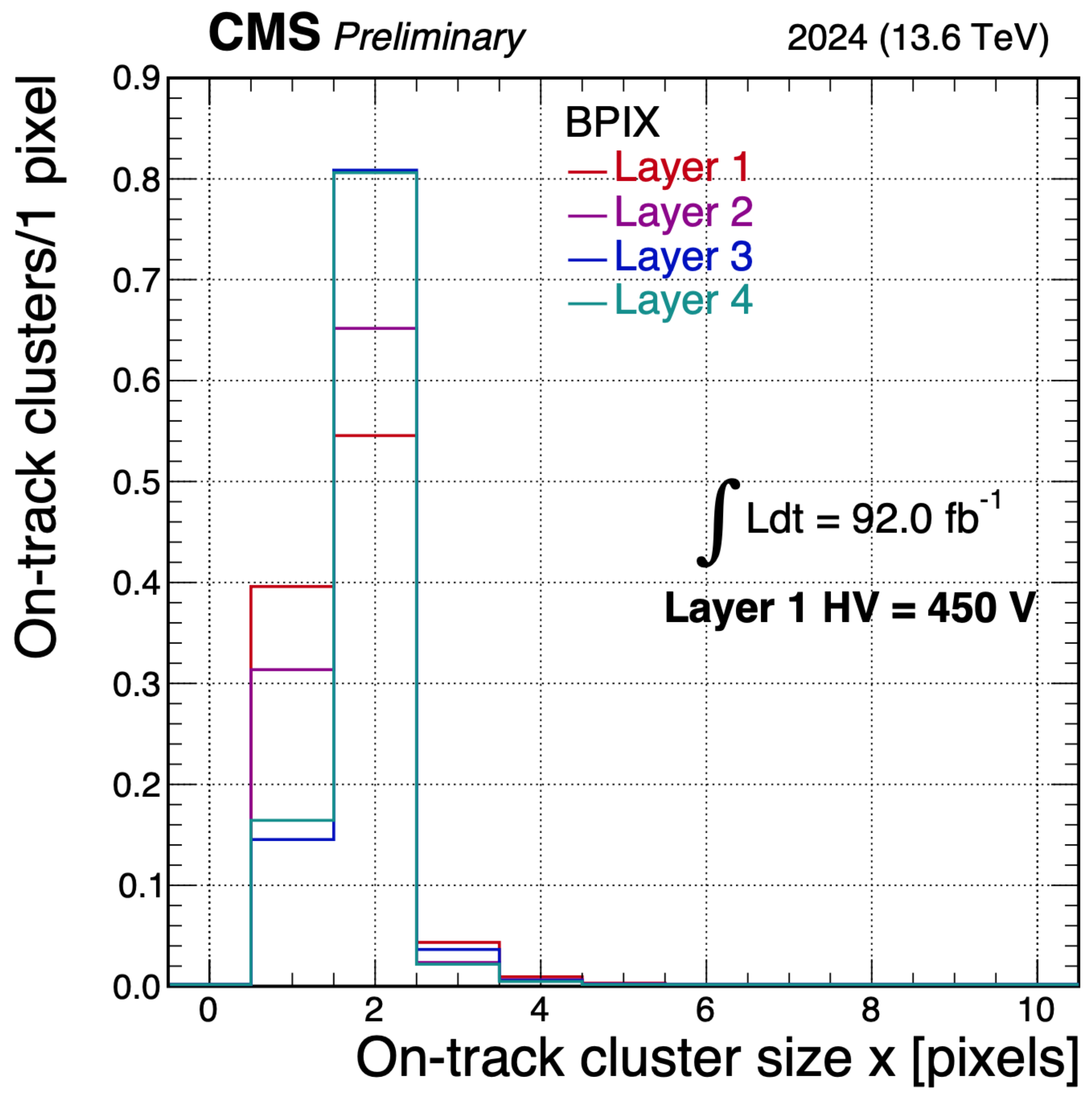
- Newly replaced Layer 1 (L1) rapidly changed with irradiation in 2022; with time became conditioned

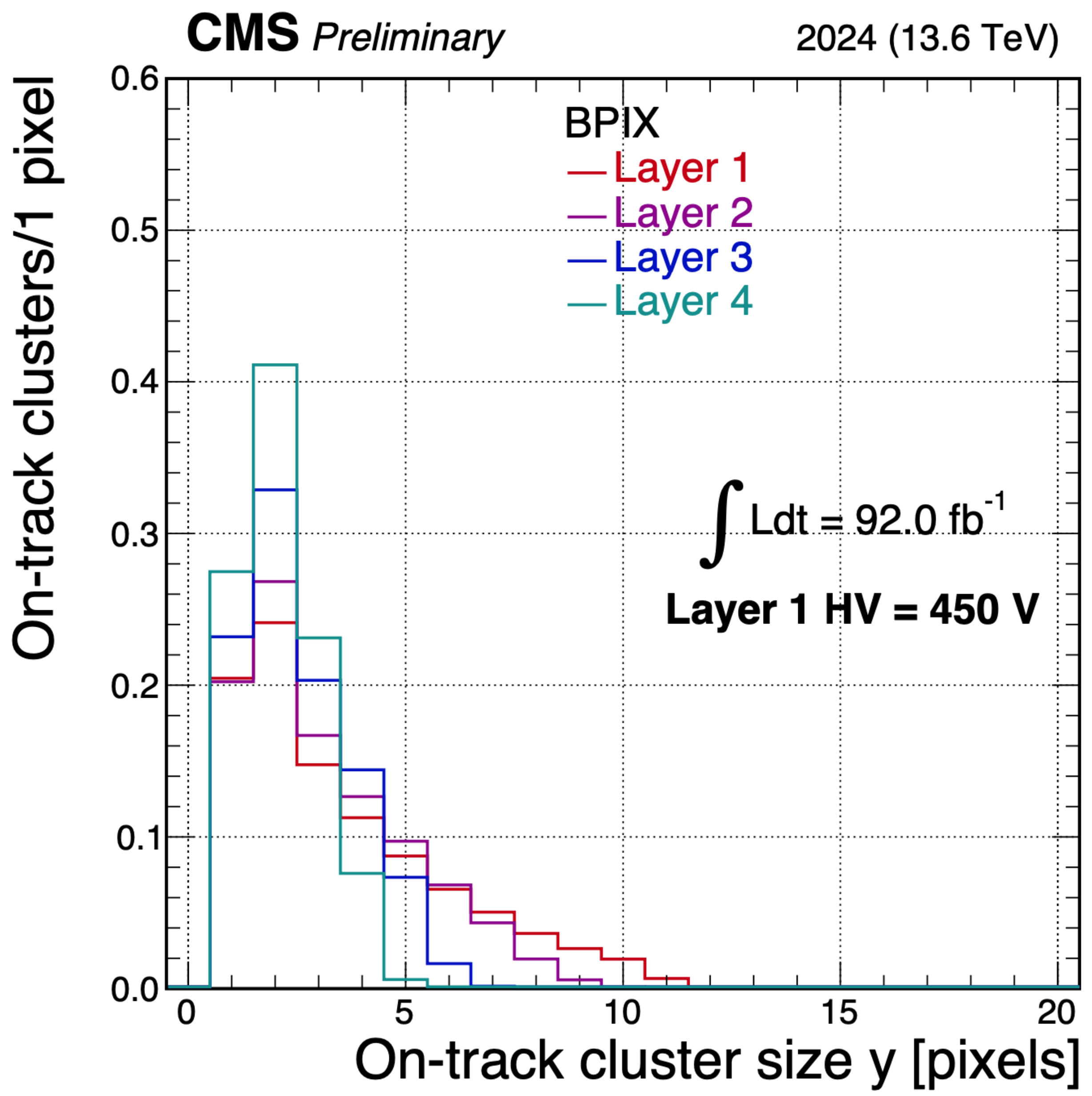




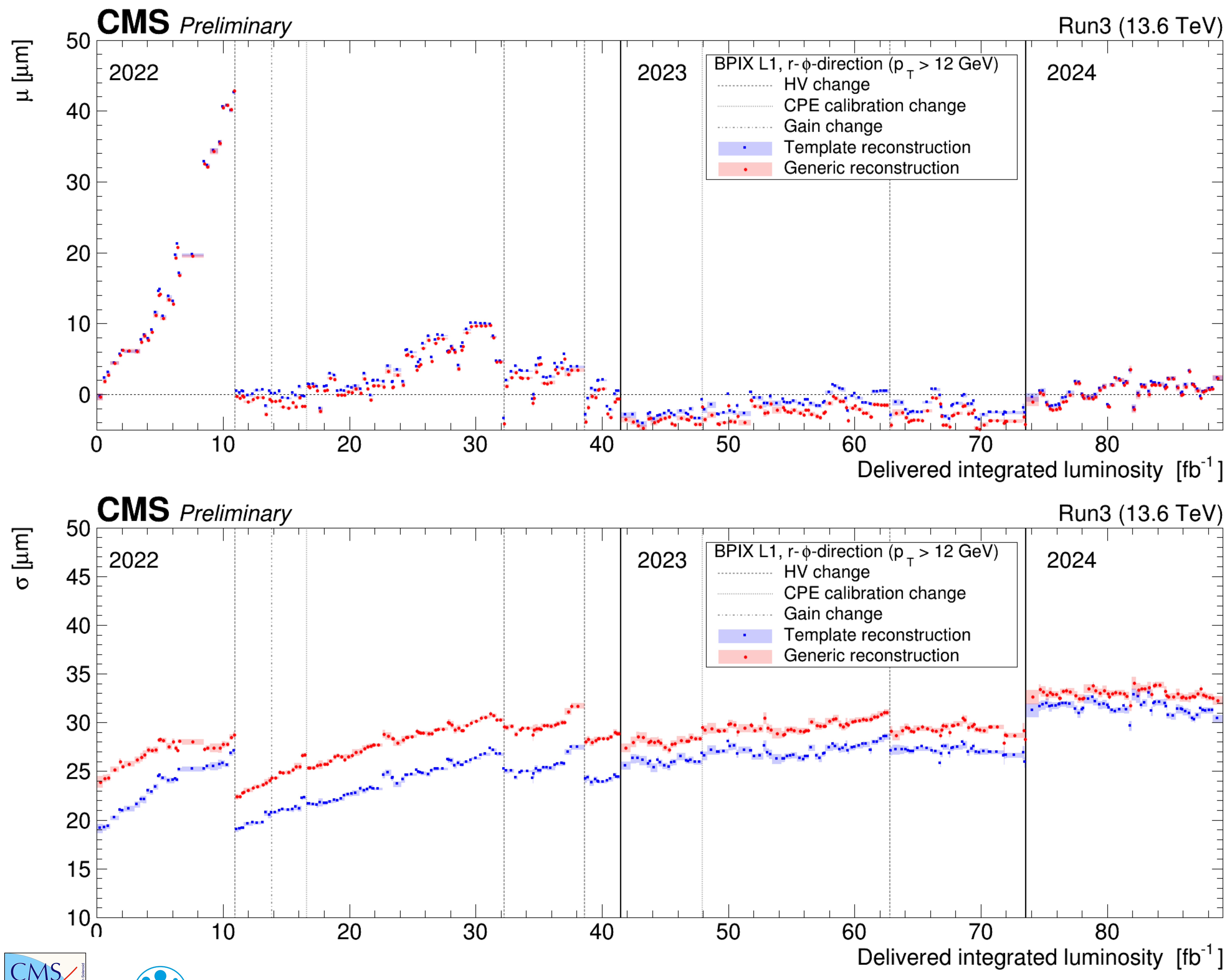
Pixel Performance - Cluster Size

- Cluster Size in X direction (global r– Φ)
  - Determined mostly by the Lorentz charge sharing and also the geometry of the detector
  - The difference between layers in BPIX expected due to the different bias voltages and consequently different Lorentz charge
- Cluster Size in Y direction (global z on the barrel)
  - Determined by the geometry of the detector: the layers closer to the beam see more shallow tracks therefore longer clusters are expected





Pixel Performance - Hit Resolution



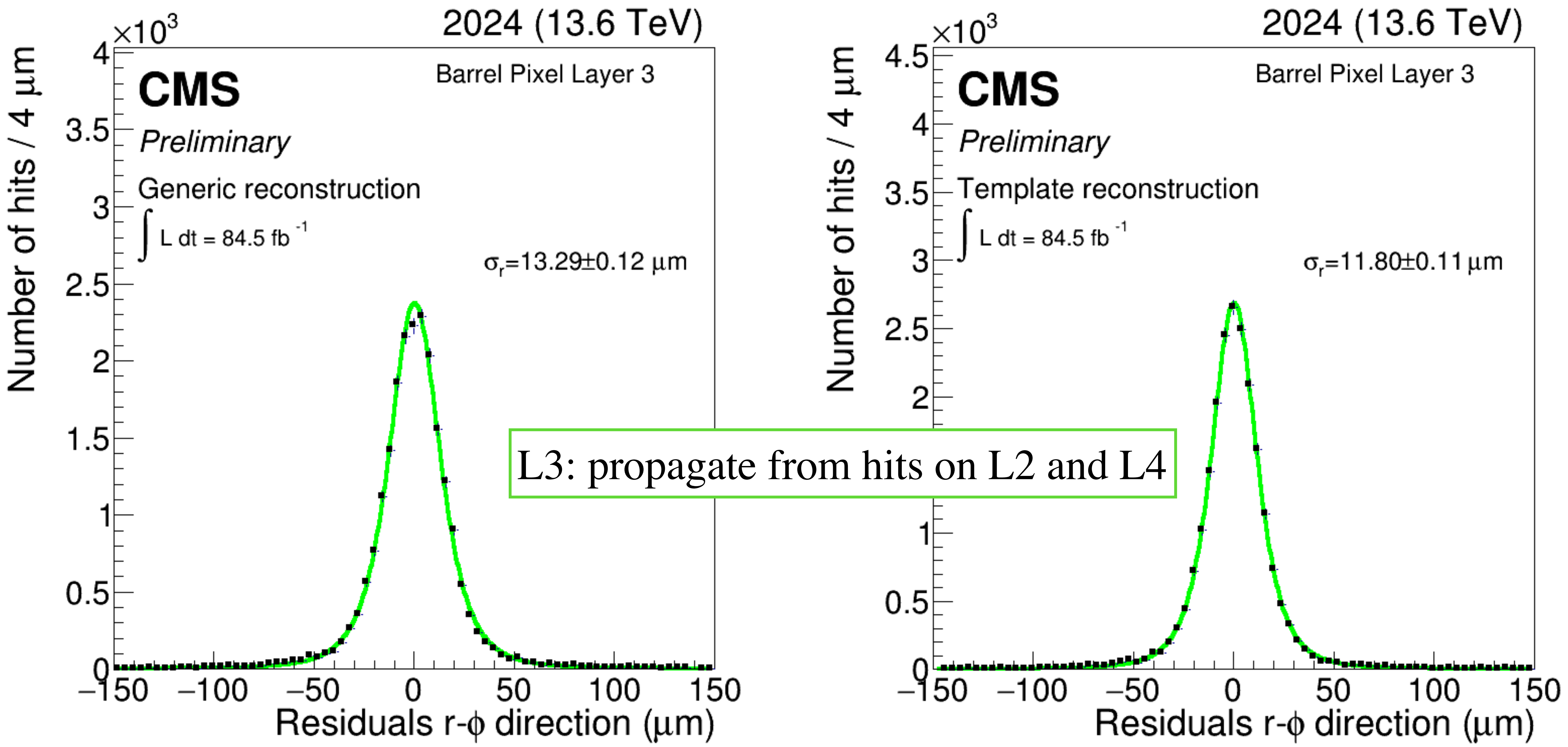
- **BPIX residual offset and resolution trends for L1**
- **Increase** in offset and the degradation of resolution caused by **radiation damage**
  - ✦ Recovered by the increase in sensor high voltage bias and the update of the Lorentz angle
- Performance of template algorithm better than generic algorithm

Pixel Performance - Hit Resolution

- Barrel hit residual calculation (Triplet method)

Select tracks with p_T > 12 GeV & 3 hits → Refit using 2 hits → Extrapolate to 3rd layer → Calculate residuals with the actual hit

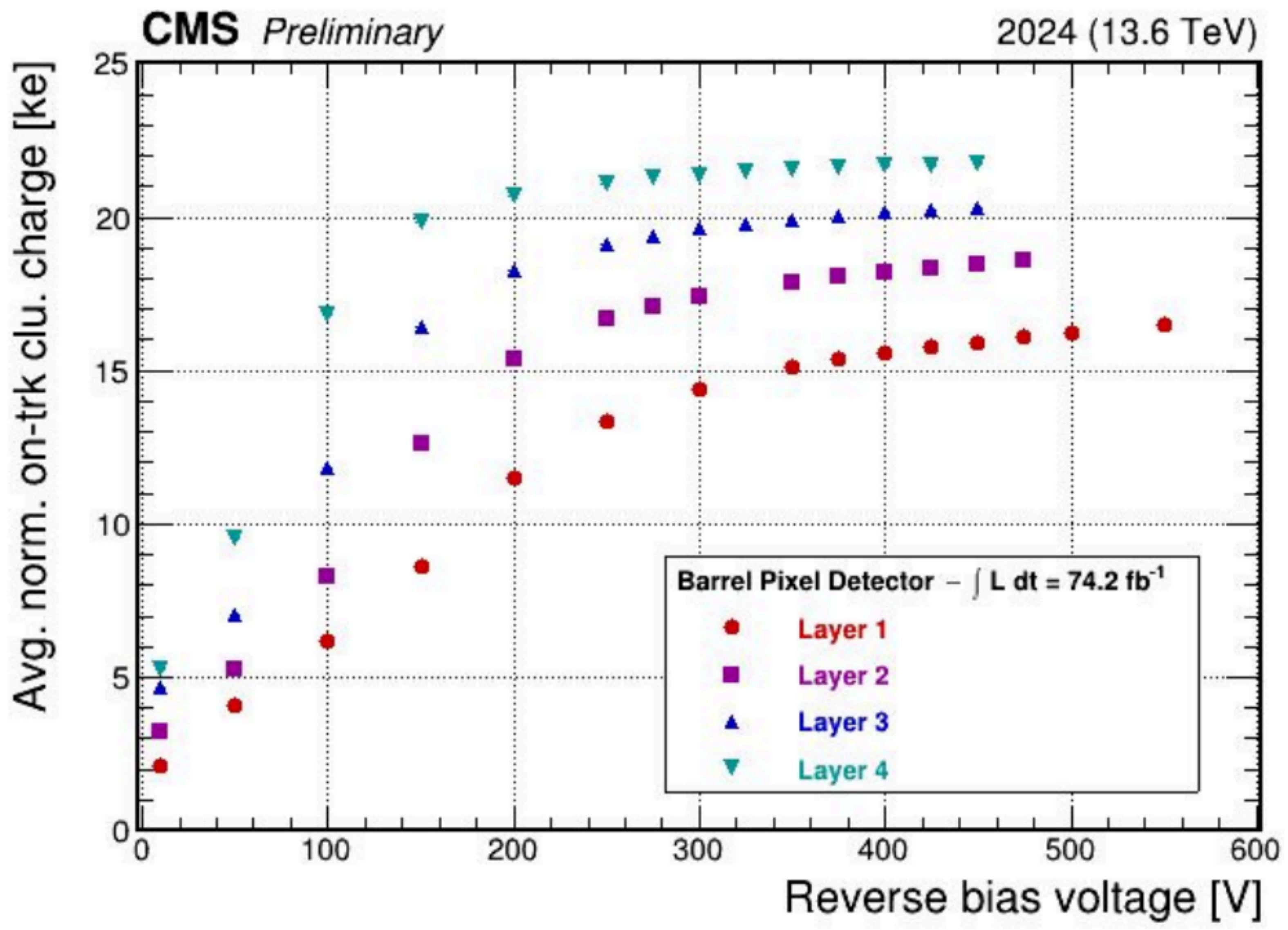
- Fit residuals with Student–t function for offset (mean) and resolution

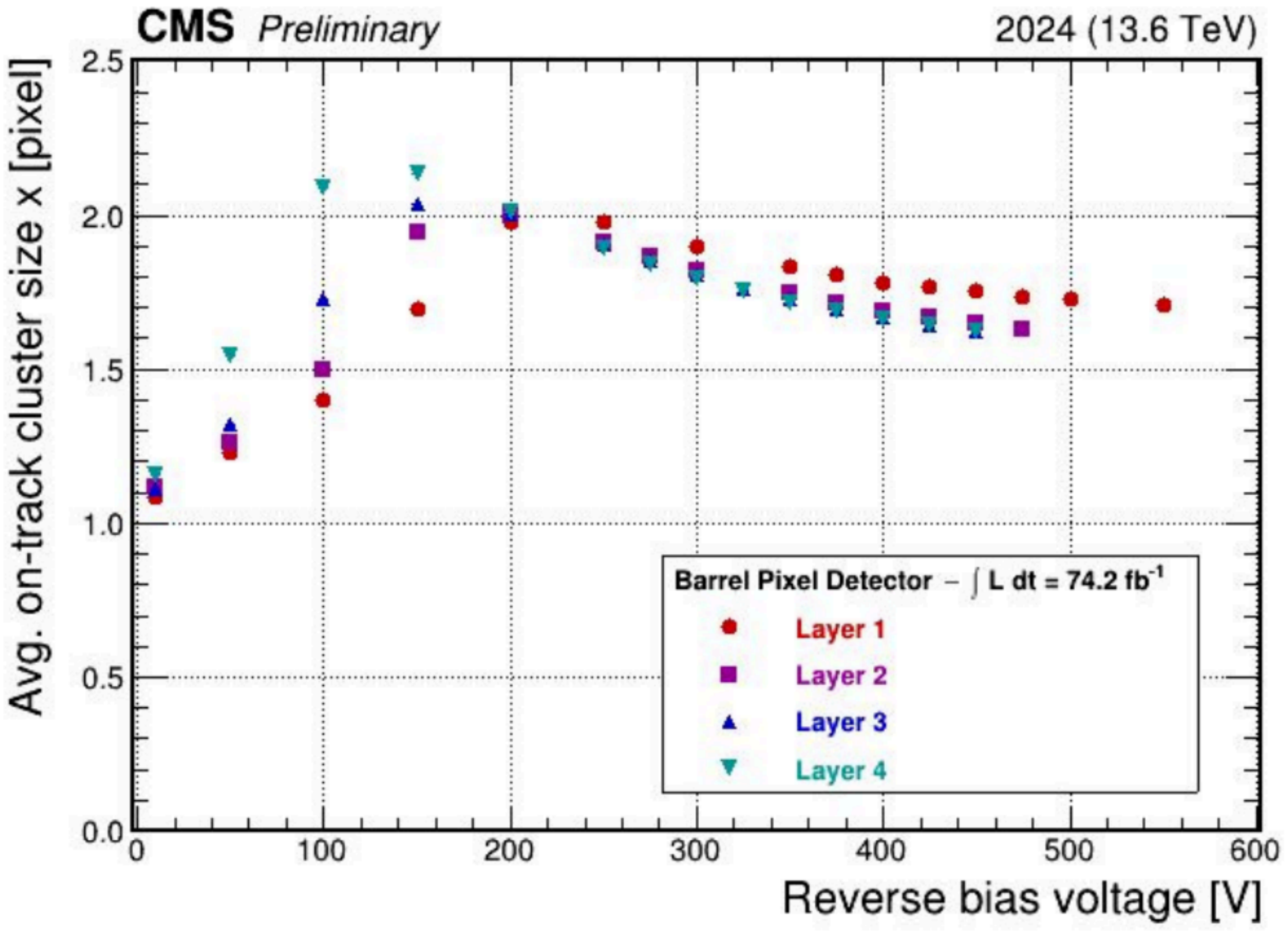


- Cluster position estimated with two reco algorithms
  - Generic: Simple; based on track position and angle; used in HLT
  - Template: Based on detailed cluster shape simulations; used in final track fitting offline.
- Template algo performs better

Pixel Performance - High Voltage Bias Scans

- **Target:** To determine operational bias voltage for pixel sensors
- Monitored quantities: Hit efficiency, average normalized on-track cluster charge and average on-track cluster size
- Operating voltage – 450 V in BPIX L1, 350 V in L2 and 250 V in L3 & 4

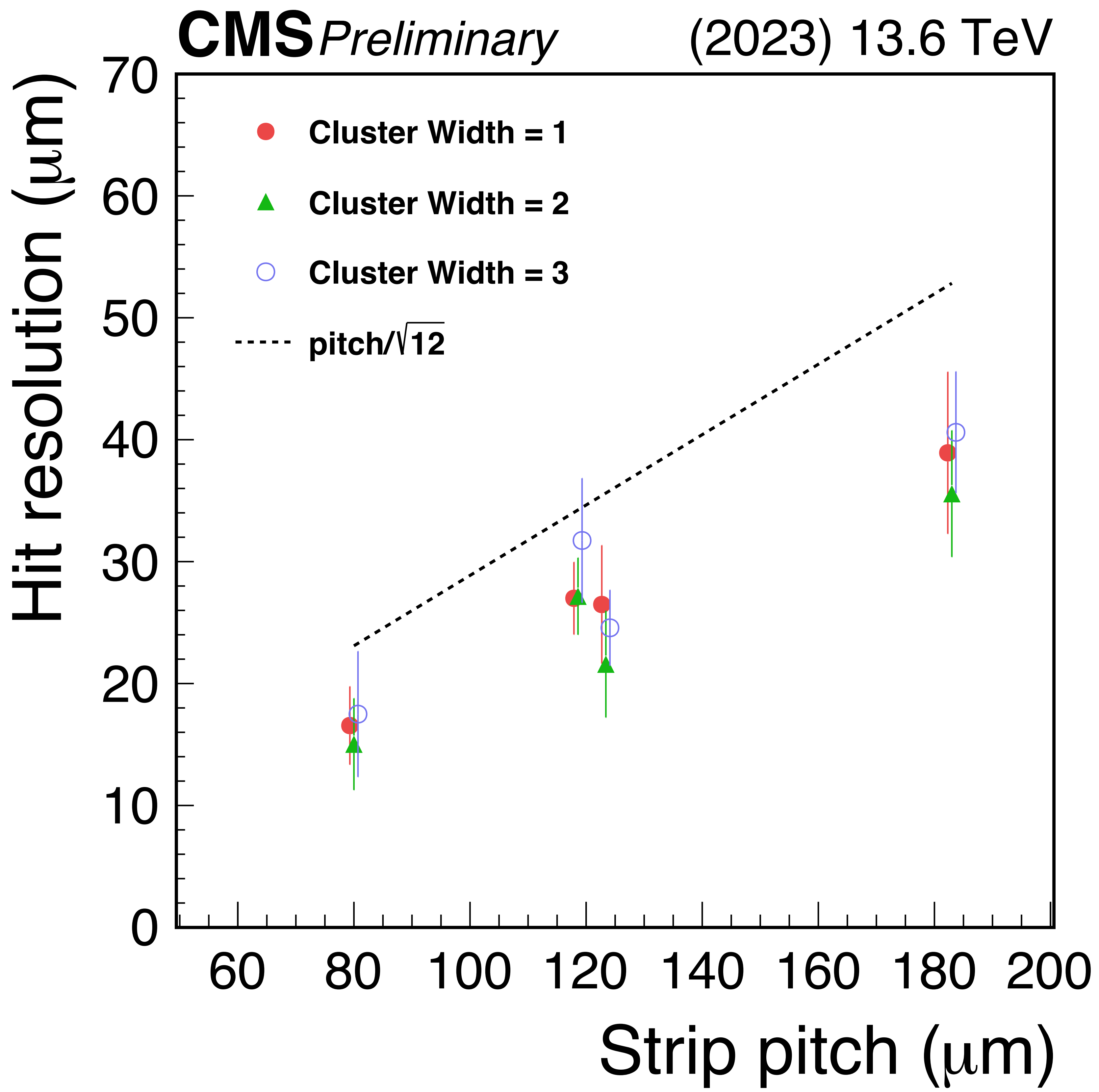




- Trend change of the cluster size in x-direction comes from 2 competing effects:
  - ✦ Bias Volt. ↑ → Charge collection ↑
  - ✦ Bias Volt. ↑ → charge sharing ↓

Strip Performance - Hit Resolution

- Resolution computed using hits in overlapping modules of the same layer
- Hit pairs selected requiring various quality conditions on strip-clusters (e.g. at most 4 strips per cluster)

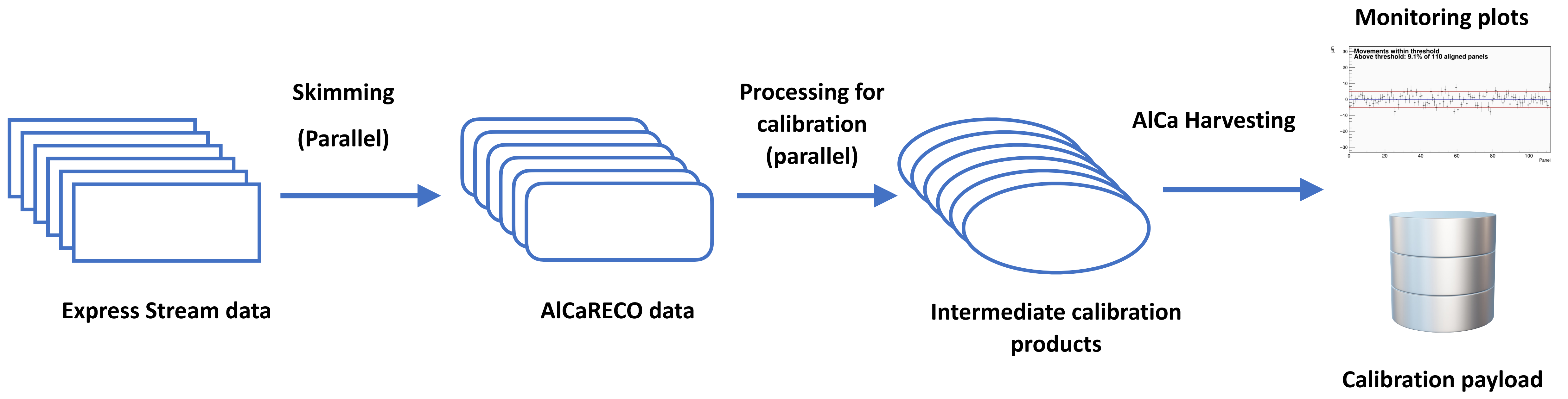


Hit resolution **measured for different widths** of strip-clusters as a function of the strip pitch

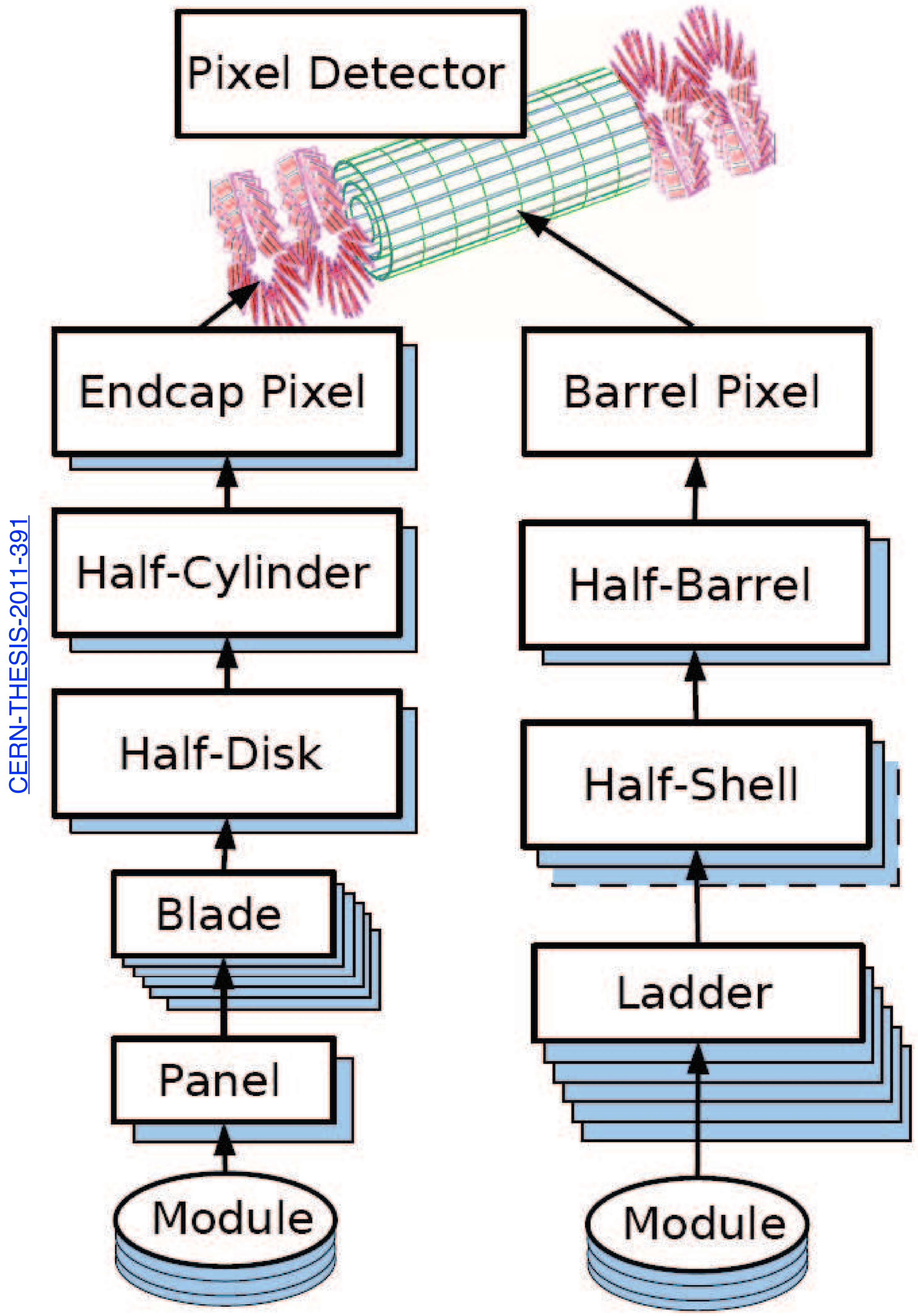
✦ **Measured resolution better than expected resolution** for a pitch/$\sqrt{12}$

✓ Demonstrating benefits of charge sharing

Automated Tracker Alignment



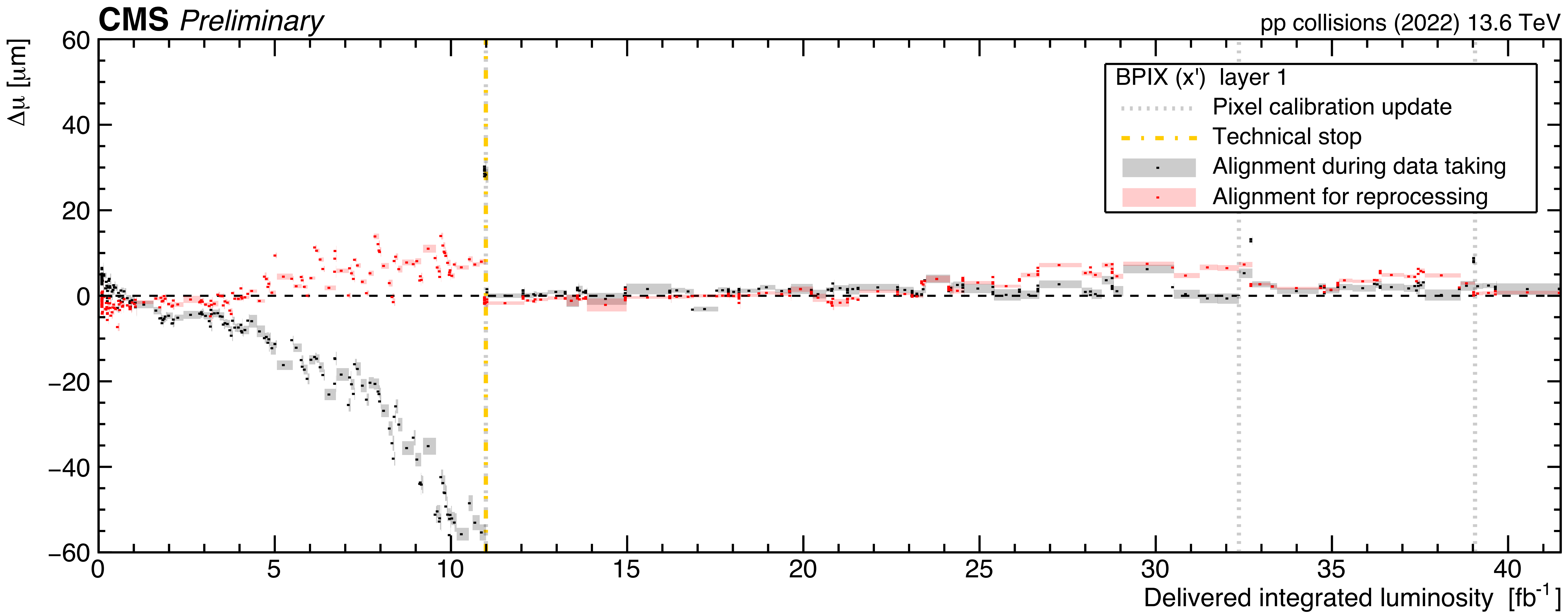
- Automated alignment workflow that provides an update of the alignment parameters within 48 hours
- Alignment of the pixel while the strip is fixed
  - 2022: The pixel detector corrected at the **half-barrel** + **half-cylinder** level until the first technical stop (36. d.o.f). A new high granularity alignment **(HG PCL)** at the **ladder+panel** level active after the technical stop (~5k parameters)
  - 2023: The HG PCL predominantly active for the whole year



Tracker Alignment Performance - Distribution of median residuals

Sensitivity to Lorentz drift

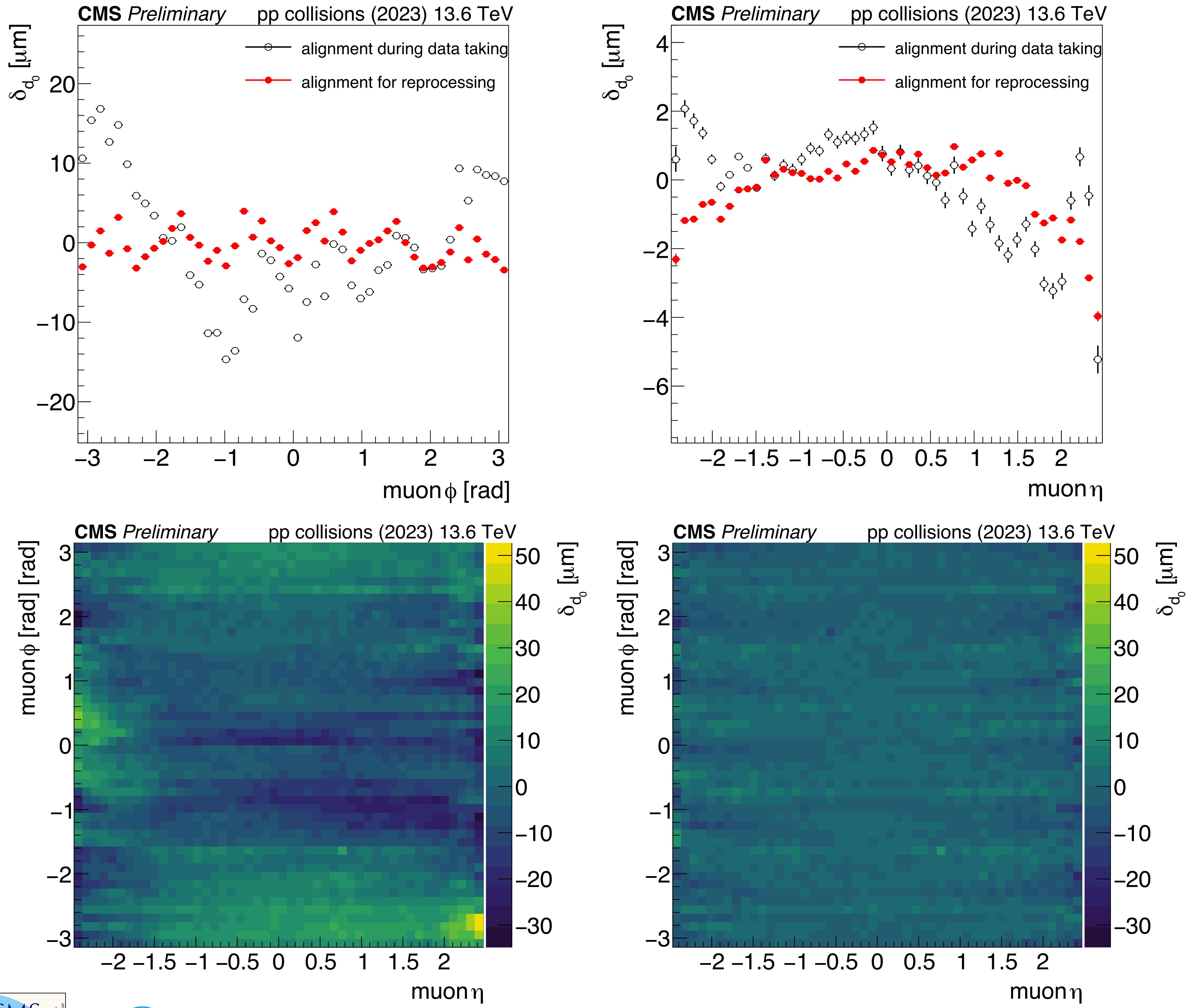
- Ageing of modules due to **high radiation environments** causes changes in the **Lorentz drift**
- Sign of the Lorentz Angle (LA) shift depends on the orientation of the E field
- BPIX modules arranged in ladders (alternatively facing inward or outward w.r.t to the beamline)
  - Inward and outward facing tracker modules affected by Lorentz drift in opposite ways



Monitoring difference in DMR mean values (Δμ) for inwards and outward facing modules allows to monitor the Lorentz drift

- ✦ Deviation from zero → Shift in LA → indication of radiation damage
- ✦ BPIX layer 1 most affected due to proximity to the interaction point

Tracker Alignment - Impact Parameter Bias in Z → μμ events



- 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 and
- Mean corrections are smaller and show an improved uniformity with the alignment for reprocessing
- The alignment during data taking (left) is shown in comparison to the alignment for reprocessing (right) for 2023 data