Tracker Alignment in CMS: interplay with pixel local reconstruction

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on behalf of the CMS Collaboration

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International Workshop on Pixel Detectors for Particles and Imaging
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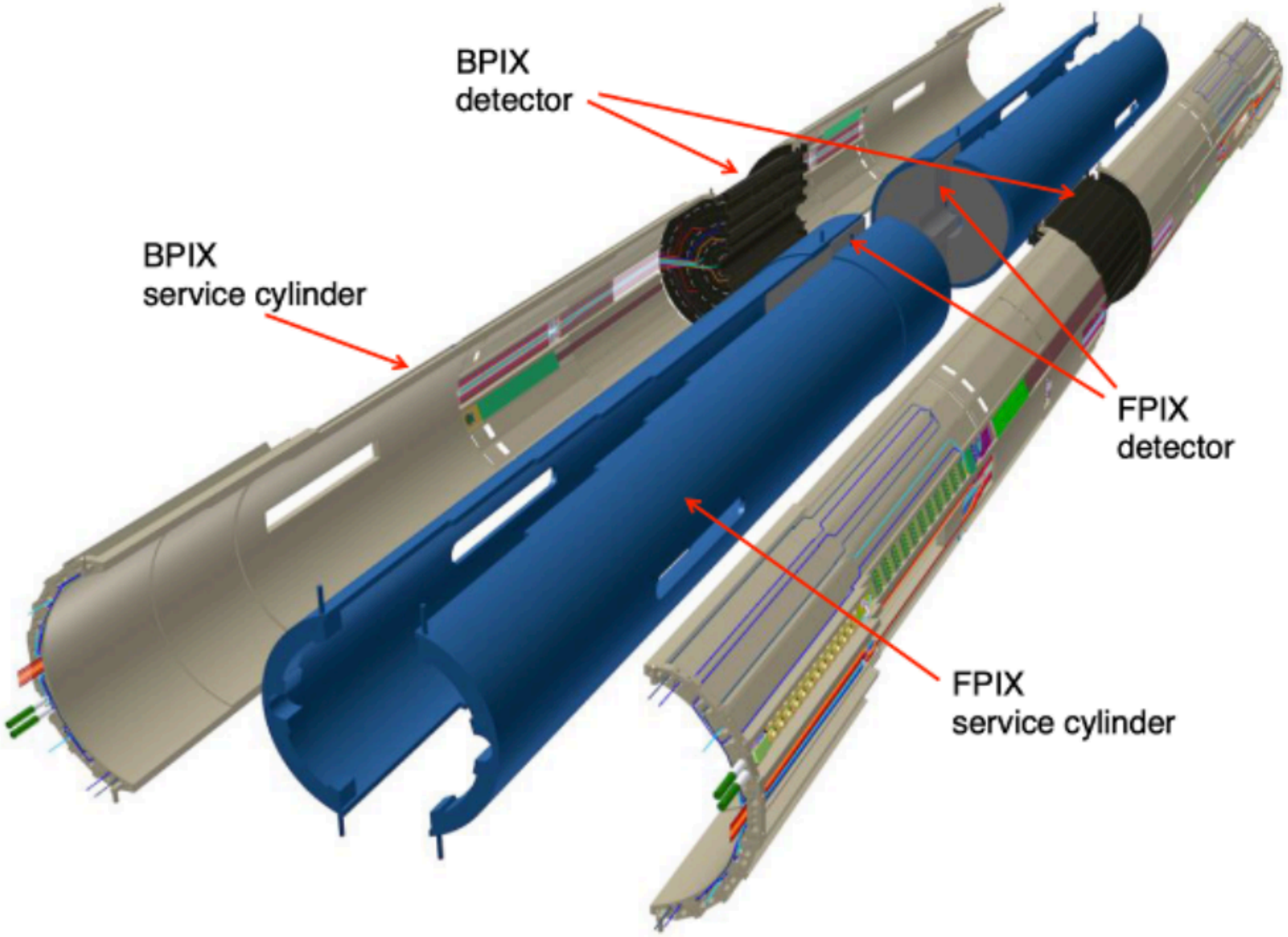
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

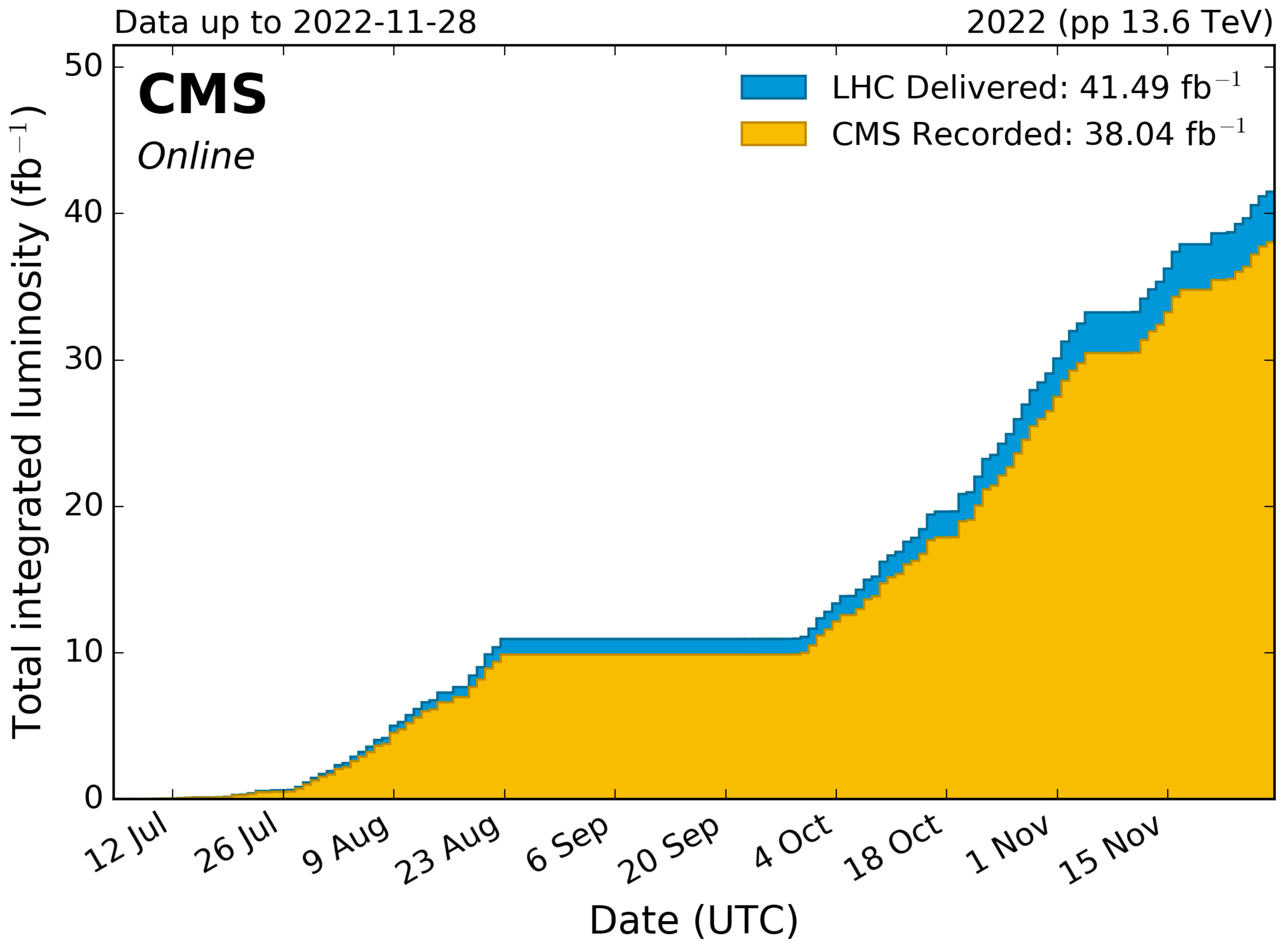
OVERVIEW

- The LHC and Run 3
- The CMS tracker
- Tracker alignment
- Interplay with pixel local reconstruction
- Alignment results
- Conclusions



INTRODUCTION

LARGE HADRON COLLIDER



CMS public data

LHC started Run 3 July 2022

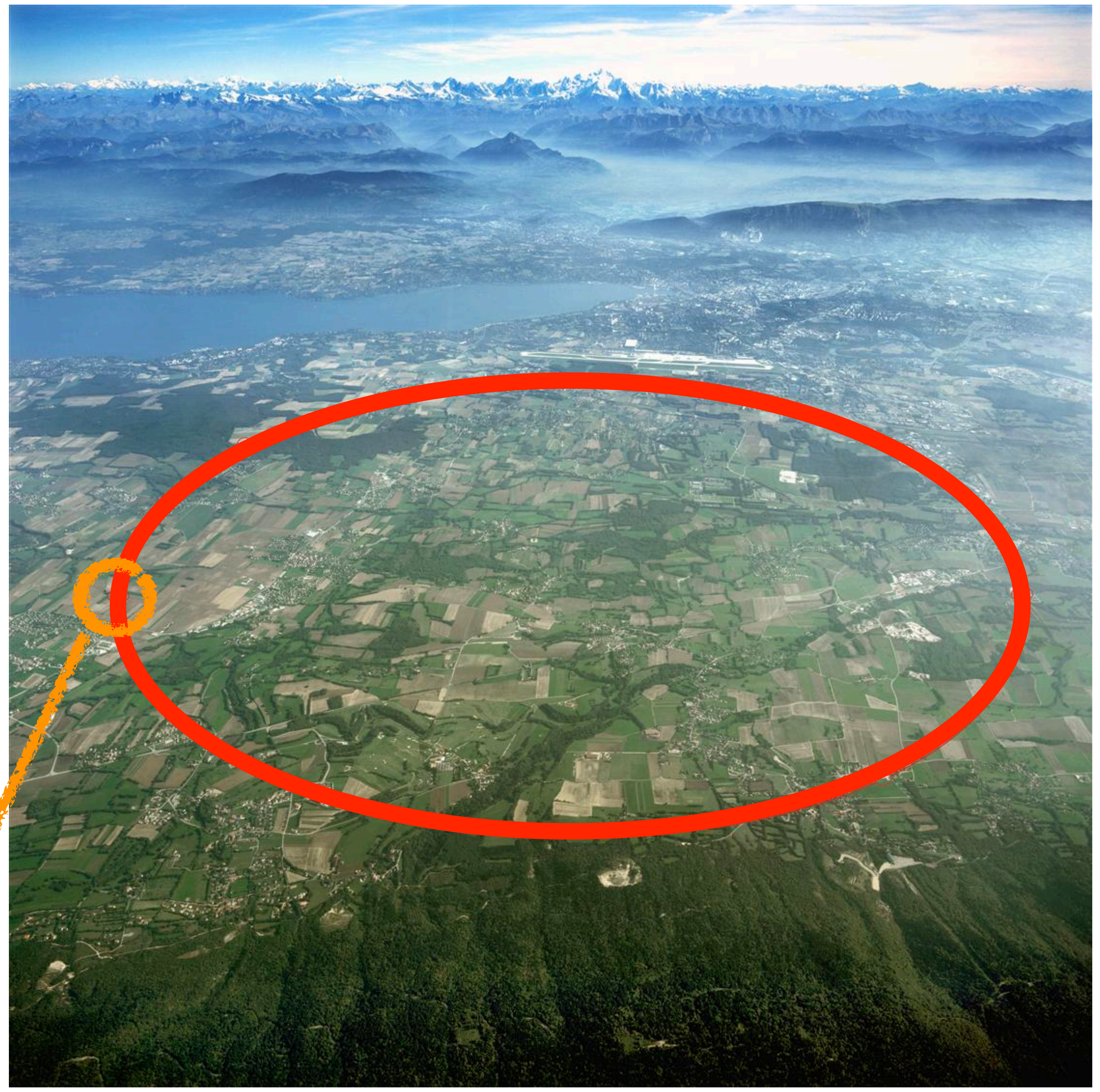
Proton-proton collisions at 13.6 TeV achieved

Finished data taking for 2022 on November

Compact Muon Solenoid experiment (CMS) is a general-purpose detector

Delivered integrated luminosity to CMS by the end of 2022 data taking

$41.49\ fb^{-1}$



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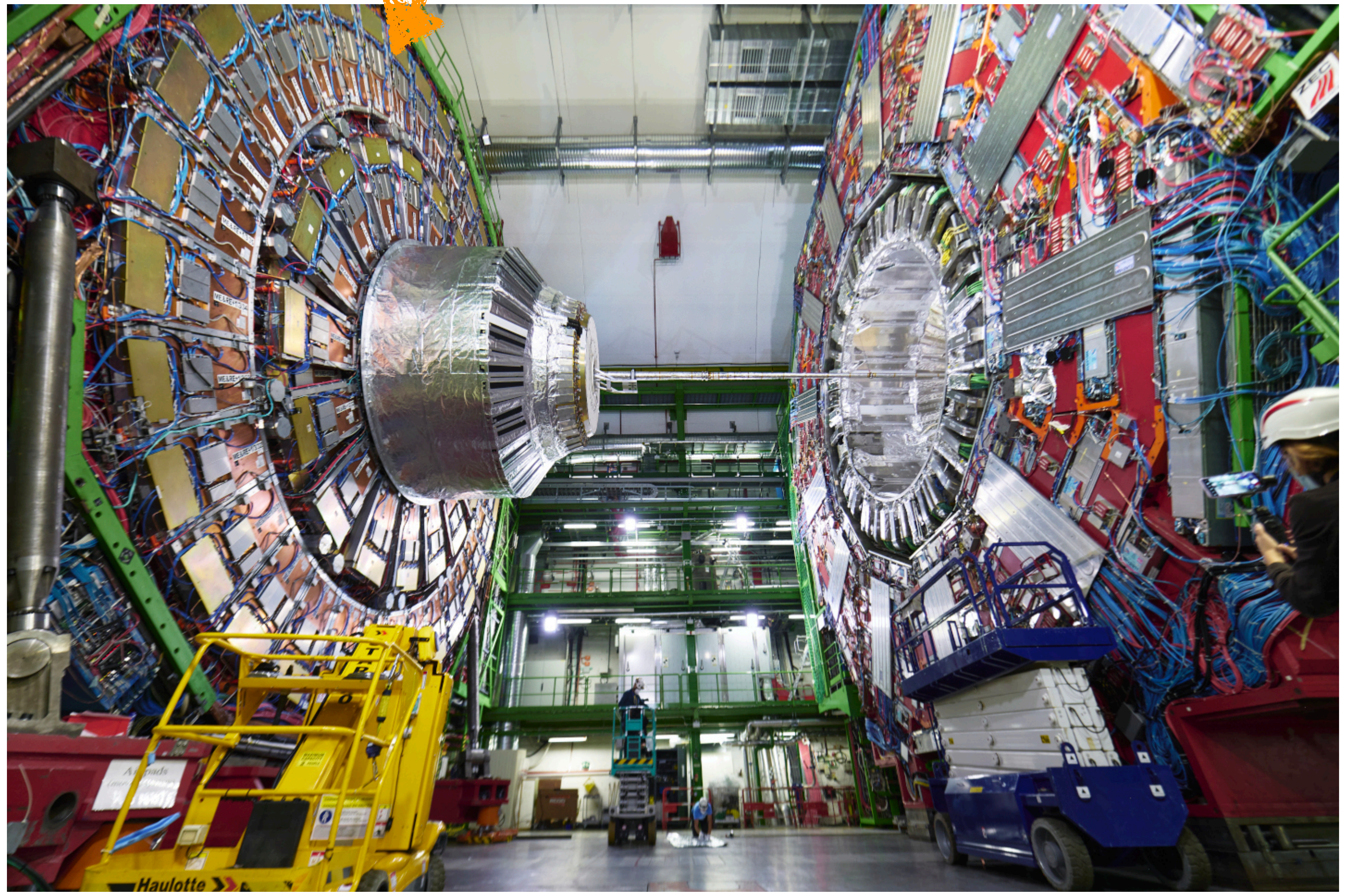

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CMS

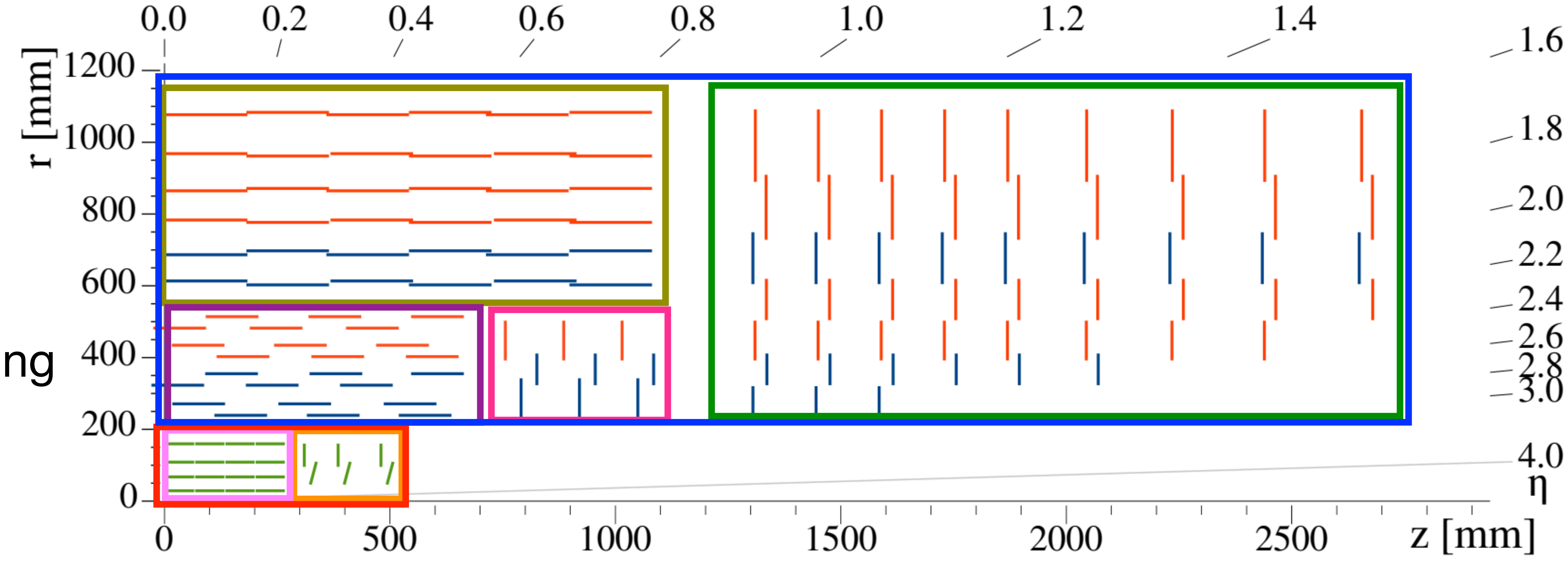
TRACKER DETECTOR

During the Long Shutdown period (2019 - 2022) CMS was refurbished and repaired

Largest fully sillicon-based detector

Pixel: 1856 modules → BPIX, FPIX

Strip: 15148 modules → TIB, TOB, TID, TEC

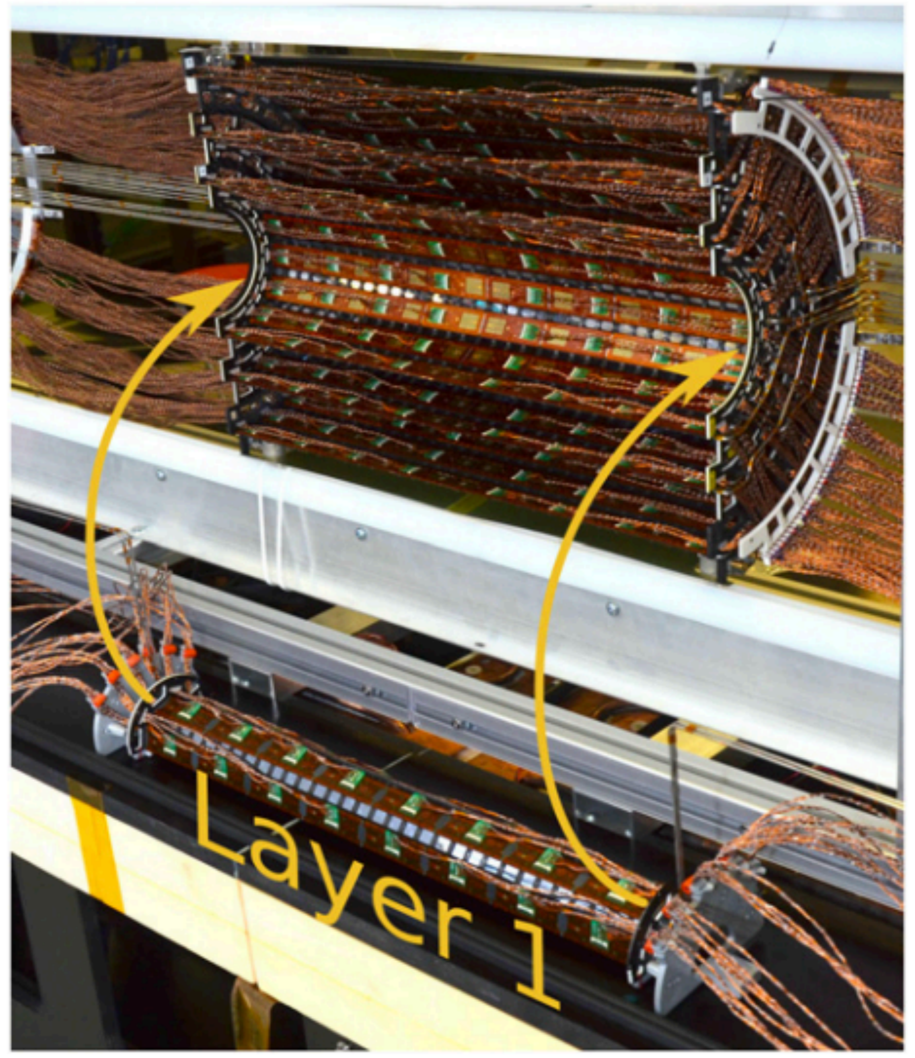


CMS-TDR-019

Why?

- Cope with radiation damages
- Perform in optimal conditions during Run 3 data taking

What?

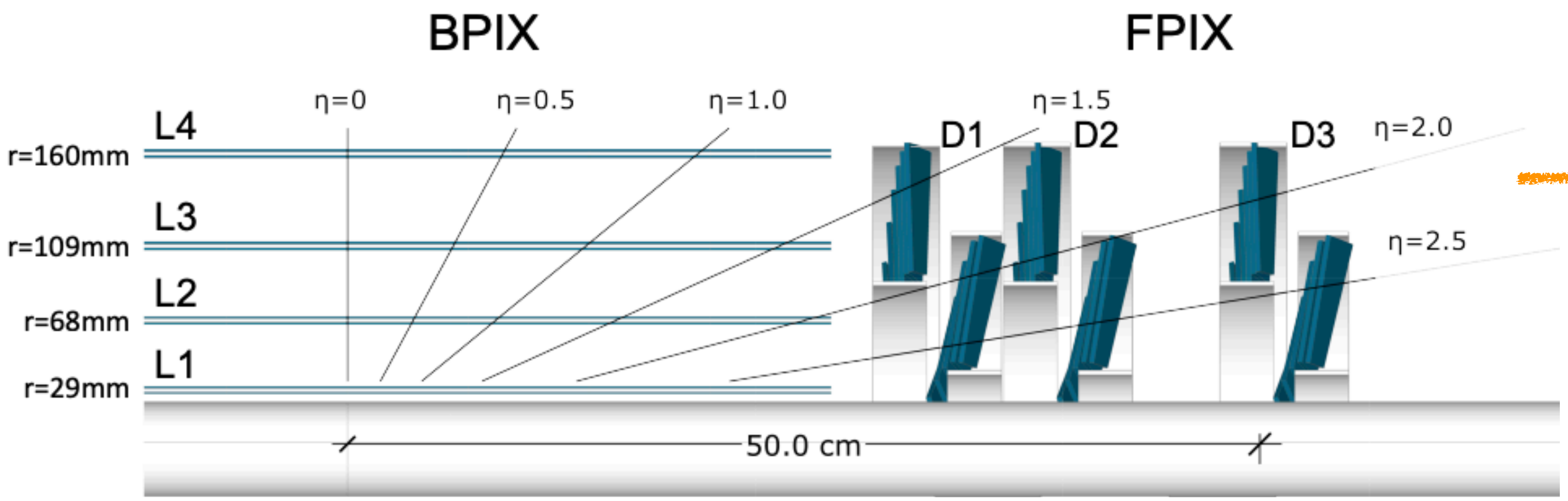


JINST 17 C09017

- PIXEL tracker extracted from CMS experimental cavern and kept cold
- Repaired (upgrade power supplies, replace damaged modules,…)
- Replacement of the innermost layer in BPIX
- Reinstalled in 2021

CMS

PIXEL TRACKER DETECTOR



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4 Barrel layers (BPIX) with 1184 modules
3 Forward disks (FPIX) with 672 modules

Tracker detector critical to correctly reconstruct tracks

Mechanical alignment precision of $O(0.1\ mm)$

Local hit reconstruction of the modules precision of $O(0.01\ mm)$

Local reconstruction

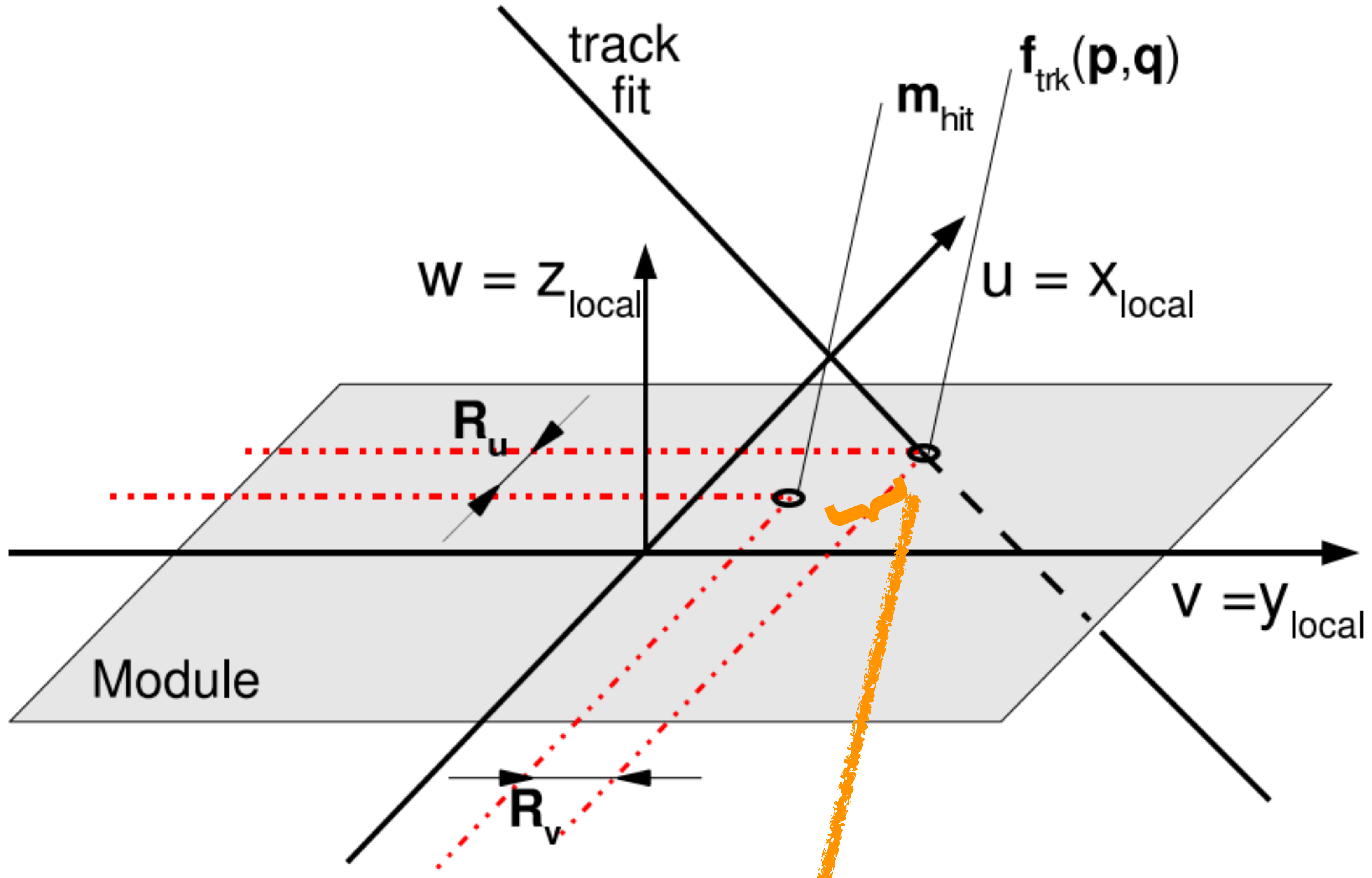
Tracker alignment

TRACKER ALIGNMENT

GOAL

Determine with enough precision the position and orientation of all the modules of the tracker (20k with 6 degrees of freedom), being of few μm in the pixel tracker

DESY-THESIS-2015-035



CMS-THESIS-2011-435

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

p : Global alignment parameters

q_j : Local track parameters

Usage of tracks to align the modules following a **Track-based alignment** approach

Global fit of all parameters → Minimisation of sum of squares of normalised track-hit residuals

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

TRACKER ALIGNMENT

TIME DEPENDENCE

Tracker needs to be realigned frequently

↓

Time variations

↓

half-barrels and half-disks (mm)

- **Magnet cycles**: Magnet switch on and off for maintenance reasons
- **Temperature variations**: Cooling operations after switching off and on the detector → Sensors ($10^{-1}mm$)
- **Ageing of the modules**: Change of the Lorentz drift due to high radiation environment

Sensors (few μm)

TRACKER ALIGNMENT
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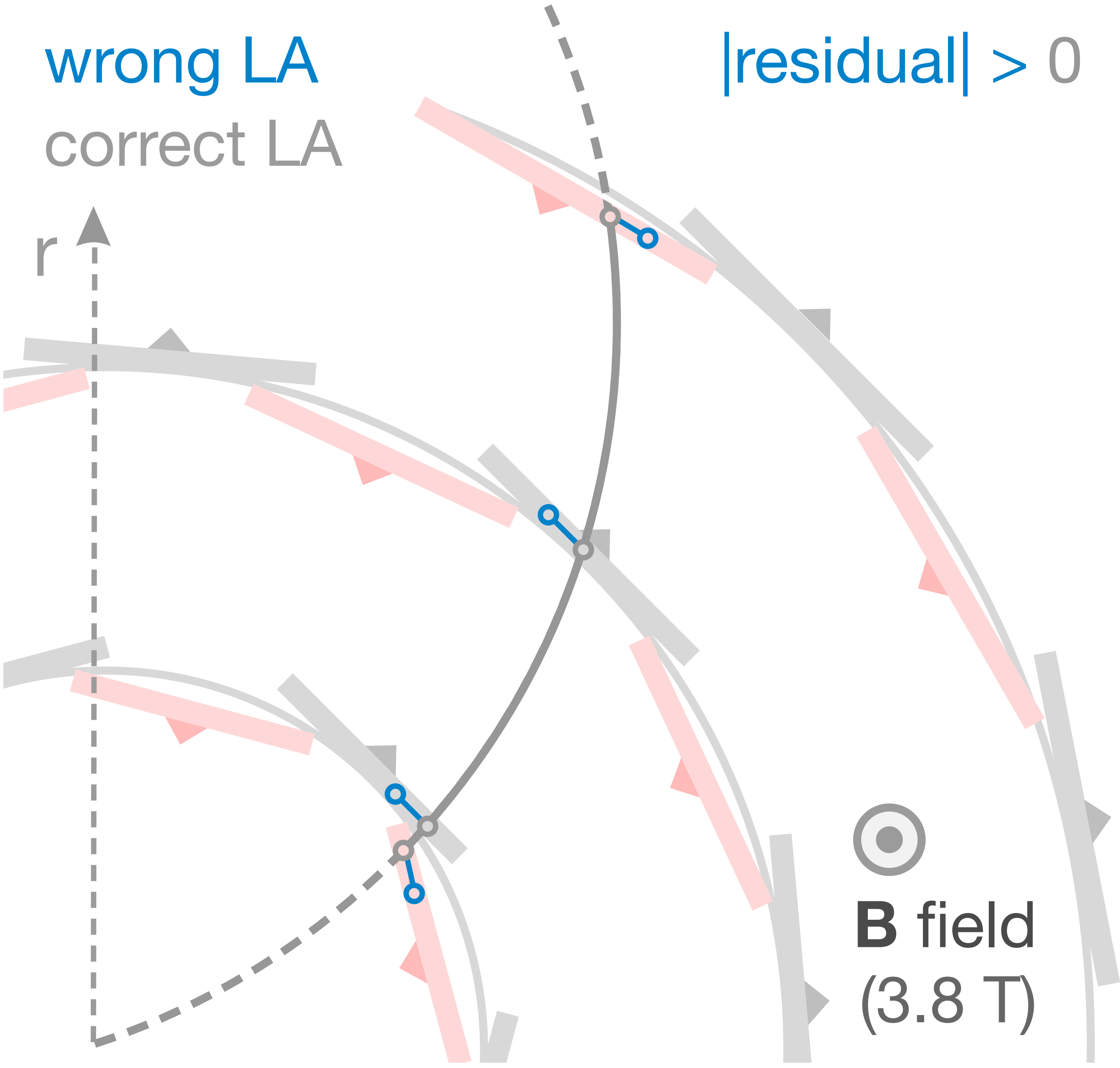


10.1016/j.nima.2022.166795

RADIATION DAMAGE

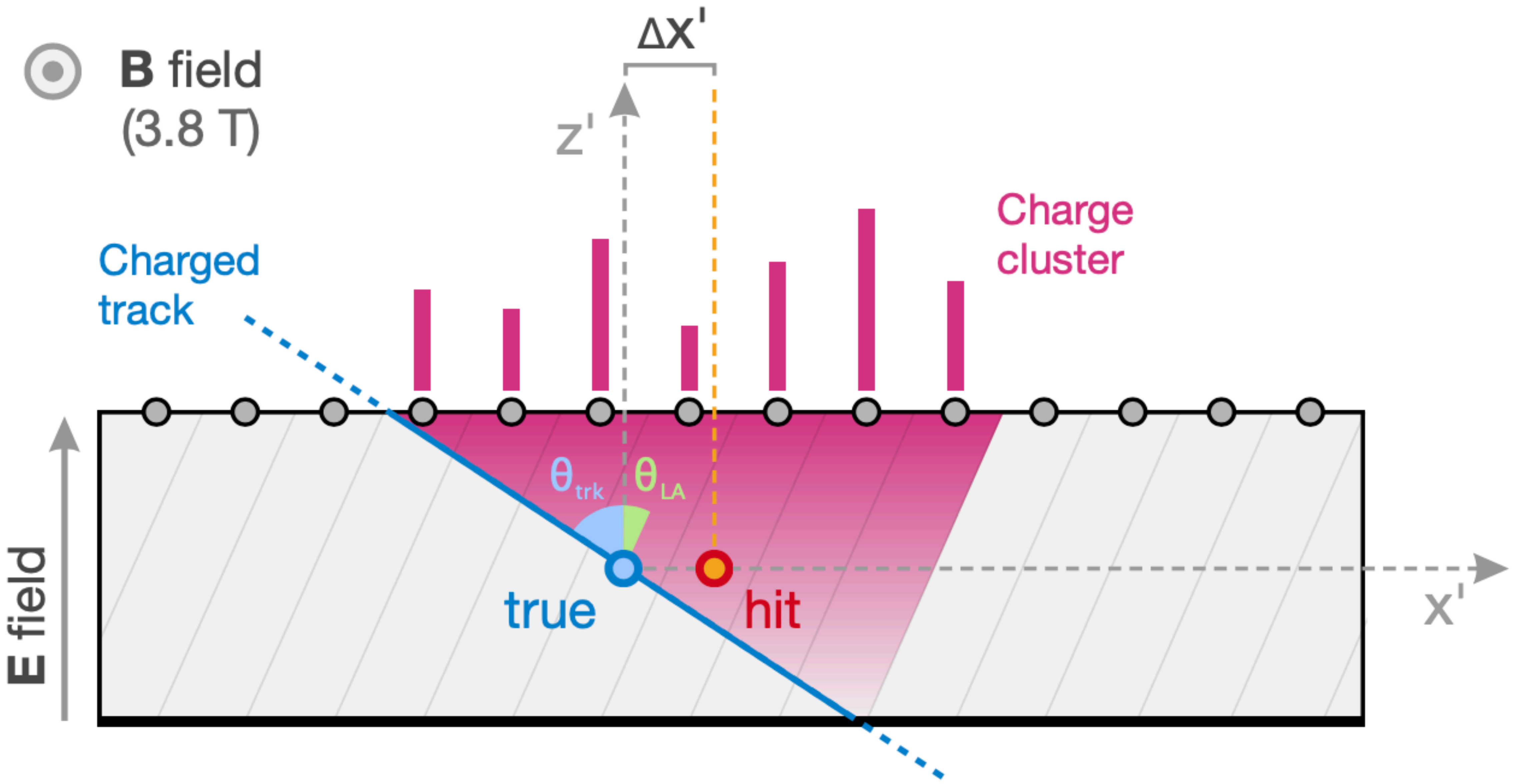
LORENTZ DRIFT

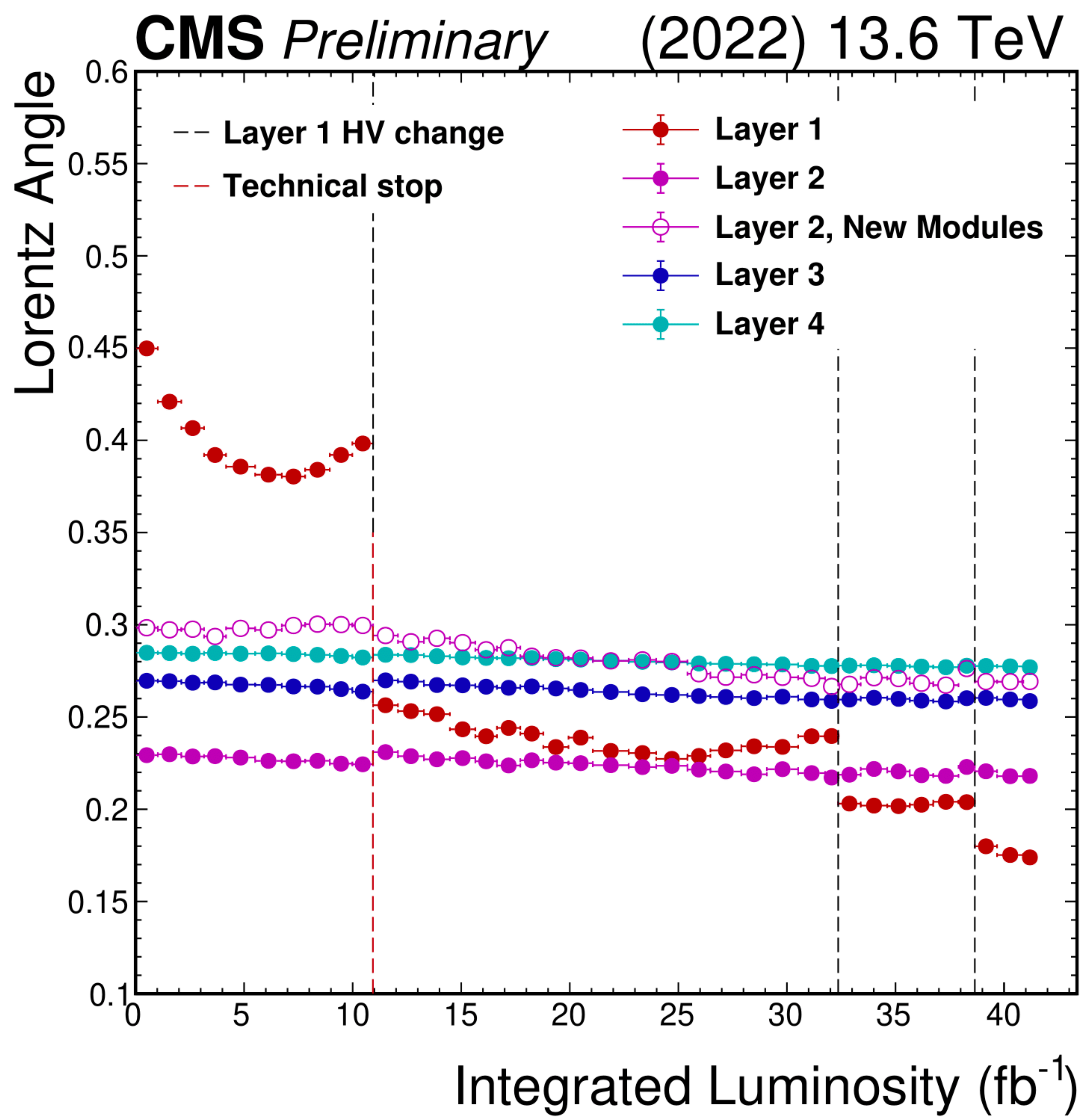
Lorentz angle (θ_{LA})

- Electric field
- Mobility of the charge carriers
- Thickness of active area

Not constant

Radiation damage!





During the track reconstruction, the Lorentz angle has to be taken into account to properly estimate the hit position

$$\Delta x' \propto \tan \theta_{LA}$$

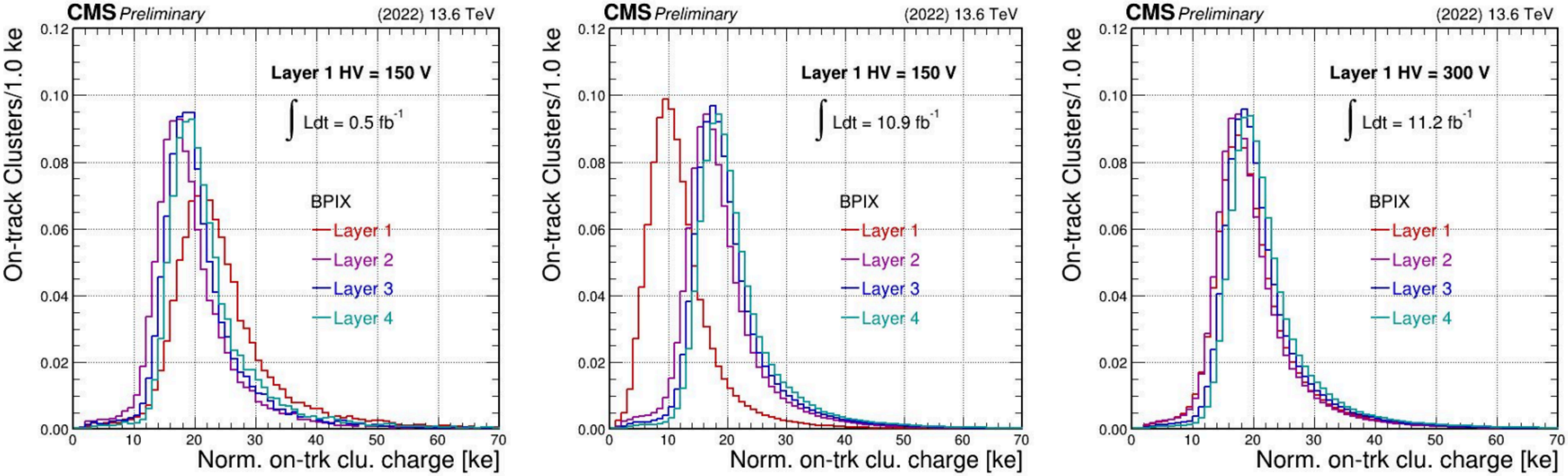
10.1016/j.nima.2022.166795

CMS DP -2022/047

RADIATION DAMAGE

CLUSTER PROPERTIES IN BARREL PIXEL

Radiation damage introduces charge efficiency loss



150V 150V 300V

CMS DP -2022/047

Recovered by raising the bias voltage

RADIATION DAMAGE

CLUSTER PROPERTIES IN BARREL PIXEL

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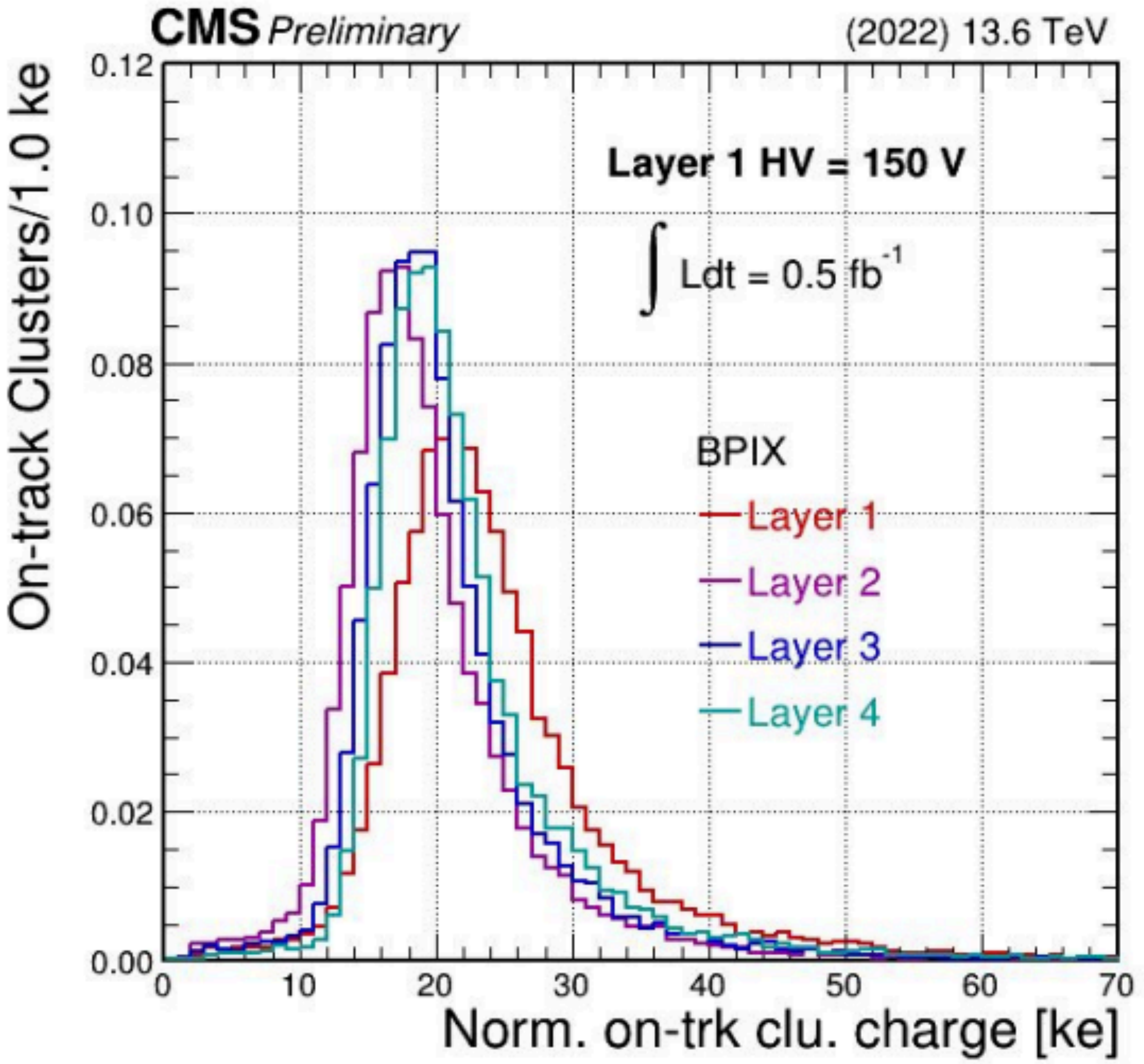
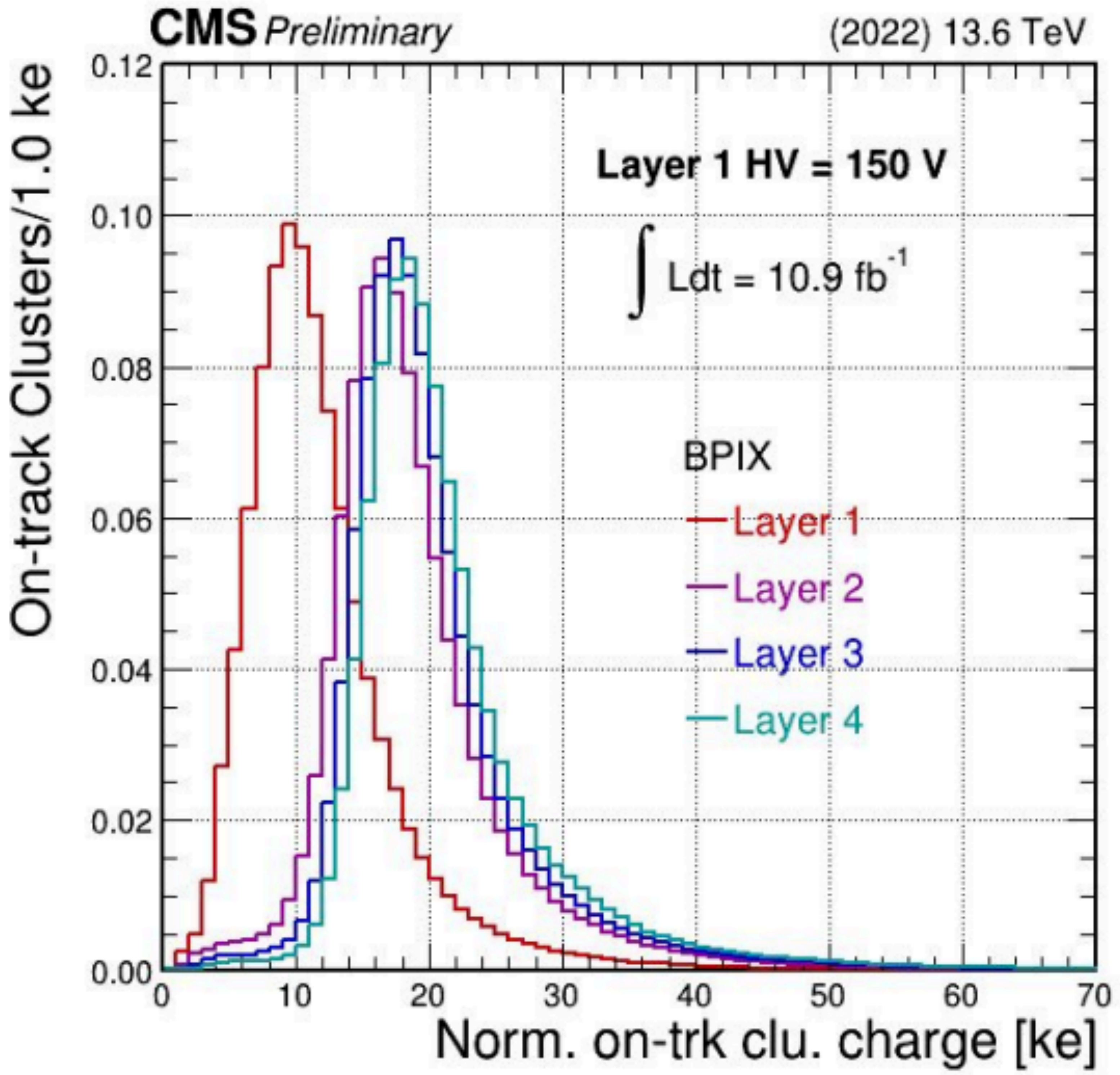
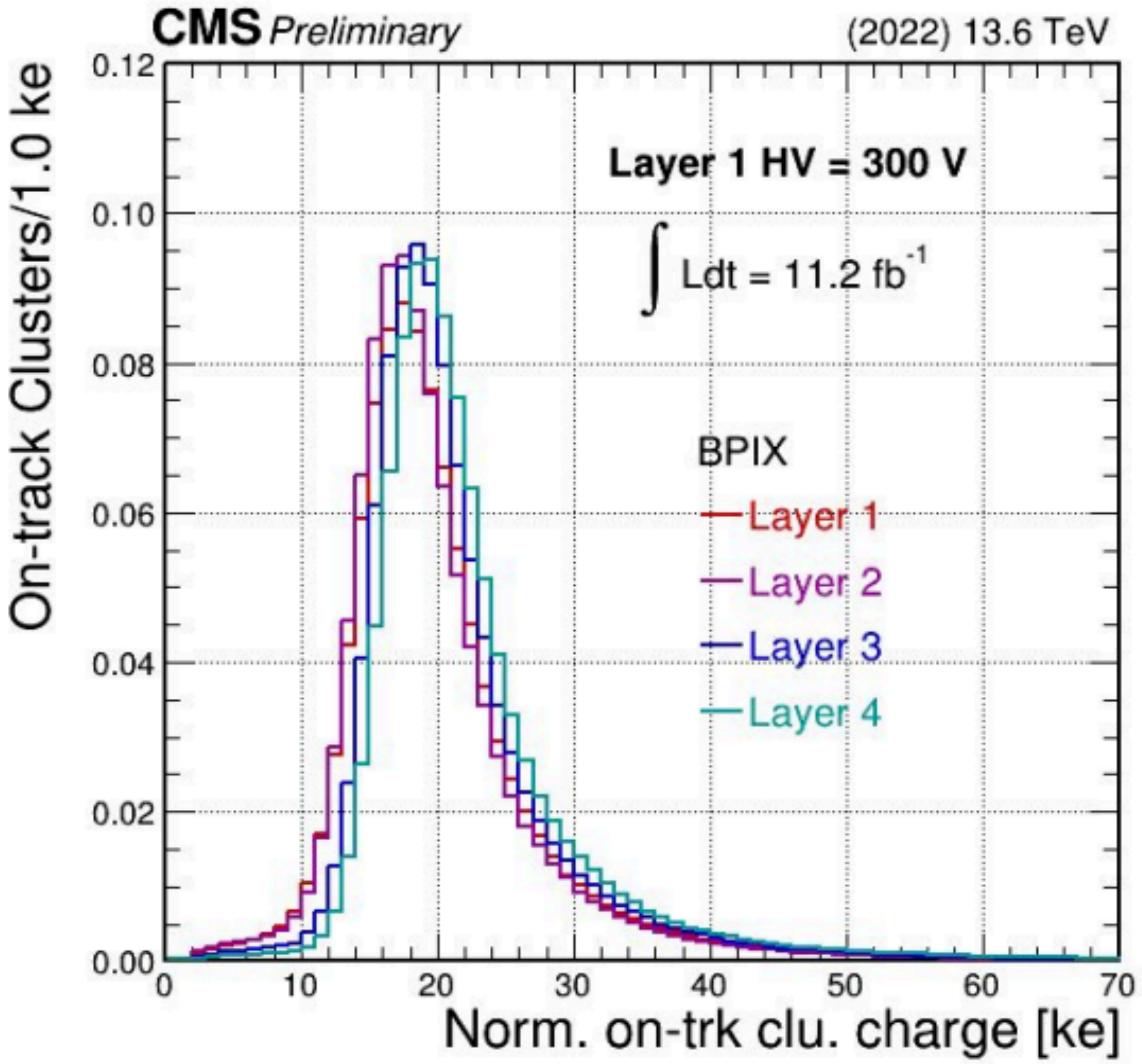


150V



150V



300V

CMS DP -2022/047

Recovered by raising the bias voltage

Not completely

→

Re-alignment as often as possible
Higher granularity

MONITORING TRACKING PERFORMANCE

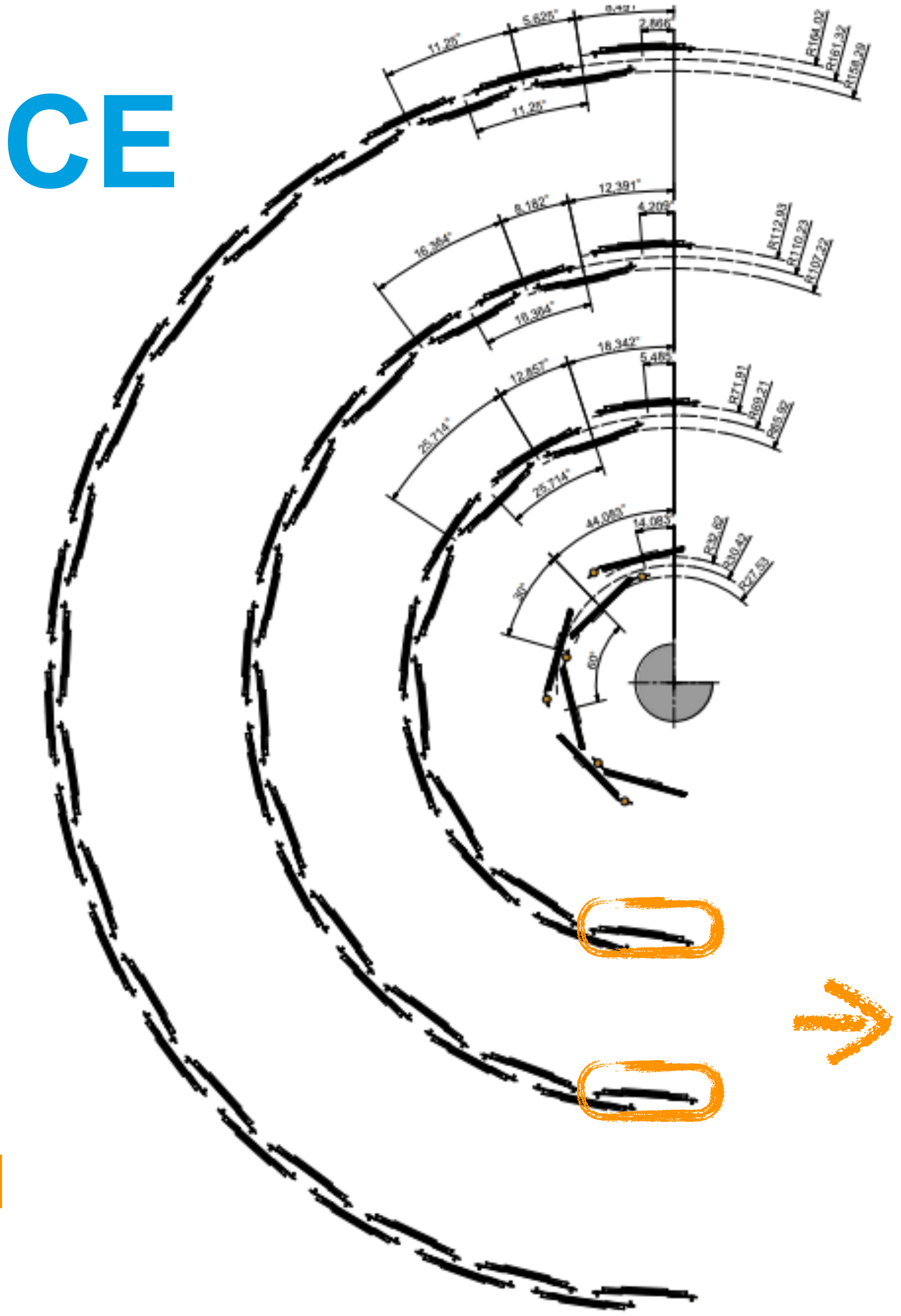
PROMPT CALIBRATION LOOP

To account for shifts in the different components of the pixel detector during data taking

↓

Automated alignment workflow that provides an update of the alignment parameters within 48 hours

Runs at Tier-0



→ ladders

Alignment of the pixel while the strip is fixed

Low Granularity Prompt Calibration Loop (**LG PCL**)

↓

Track-based alignment at the level of half barrels and cylinders

36 alignment parameters

→

High Granularity Prompt Calibration Loop (**HG PCL**)

↓

Track-based alignment at the level of ladders and panels

5k alignment parameters

Replace some of the manual HG alignments after new pixel calibrations

MONITORING TRACKING PERFORMANCE

ALIGNMENTS GEOMETRY

Alignment during data taking (black)

- Automated online alignment
- LG PCL

Mid-year re-reconstruction (red)

- Offline alignment with 120M collision tracks during pp collisions at $\sqrt{s}$ = 13.6 TeV and 8.5M cosmic rays at 3.8T magnetic field
- First period of data taking (up to $\sim 8\ fb^{-1}$) derived at level of single modules
- Second period (from $\sim 8\ fb^{-1}$ to $\sim 11\ fb^{-1}$) HG PCL

End-of-the year re-reconstruction (blue)

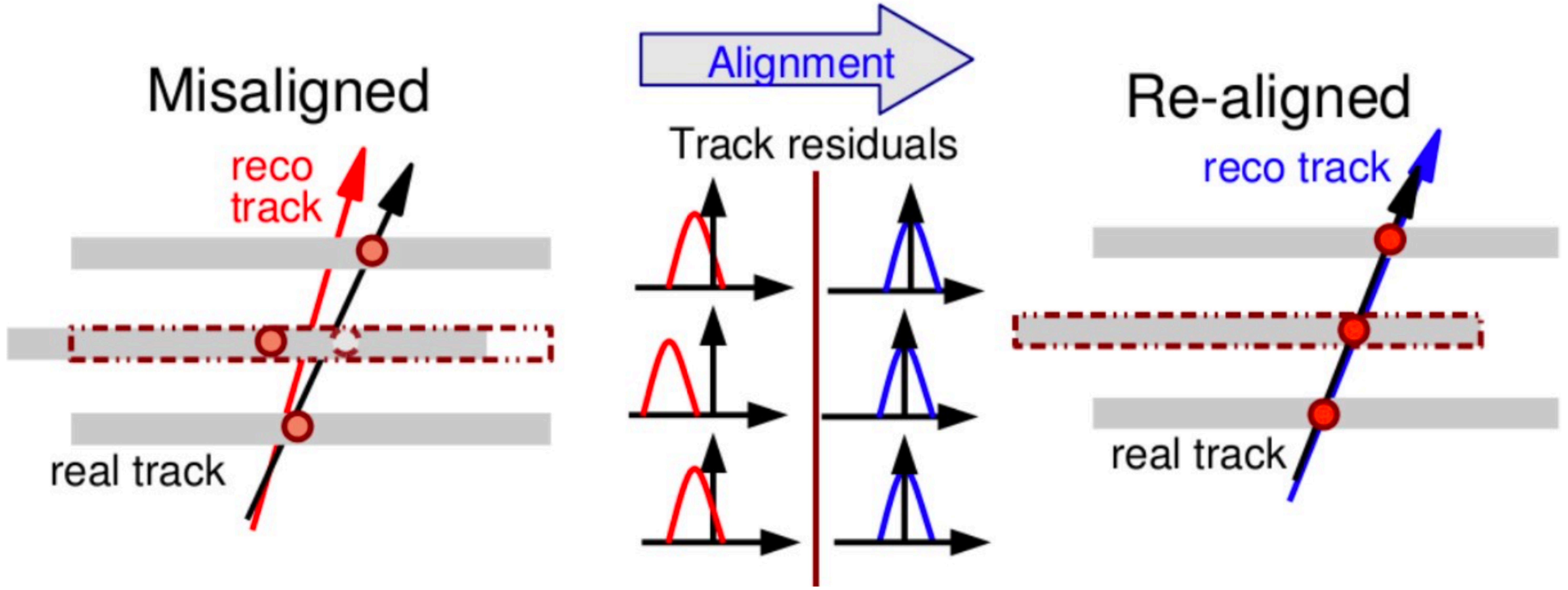
- Automated online alignment
- HG PCL

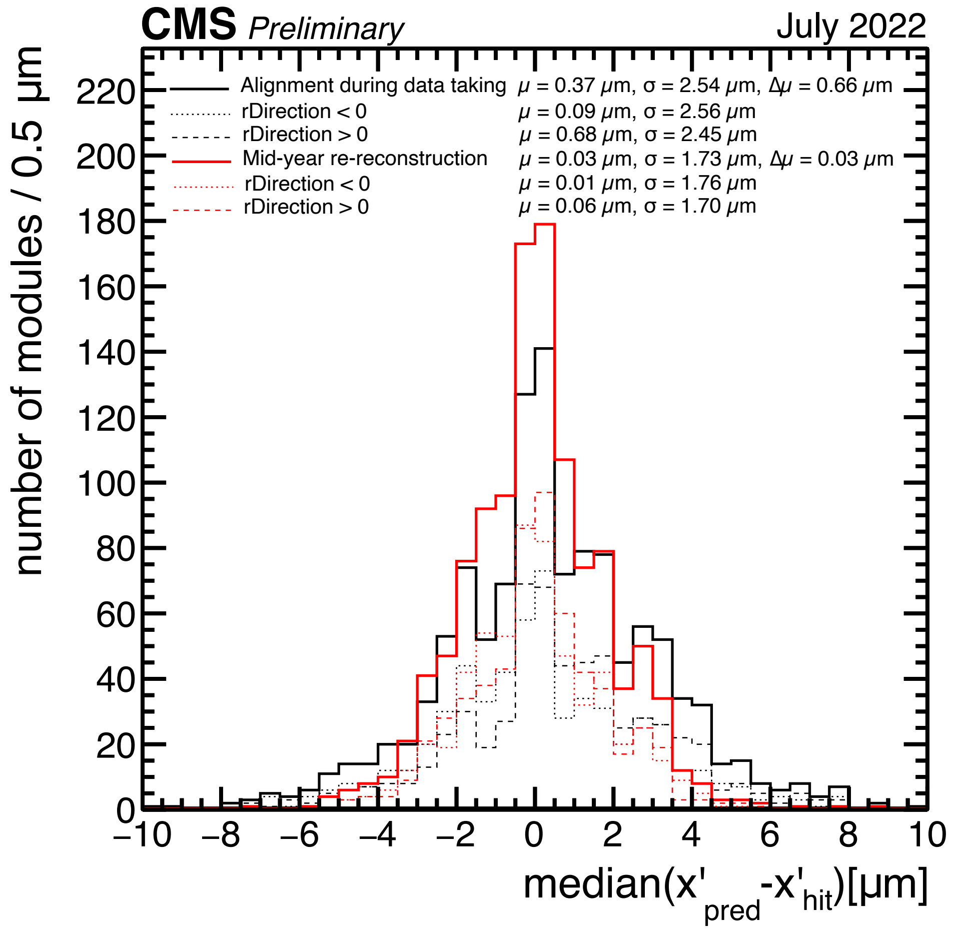
MONITORING TRACKING PERFORMANCE

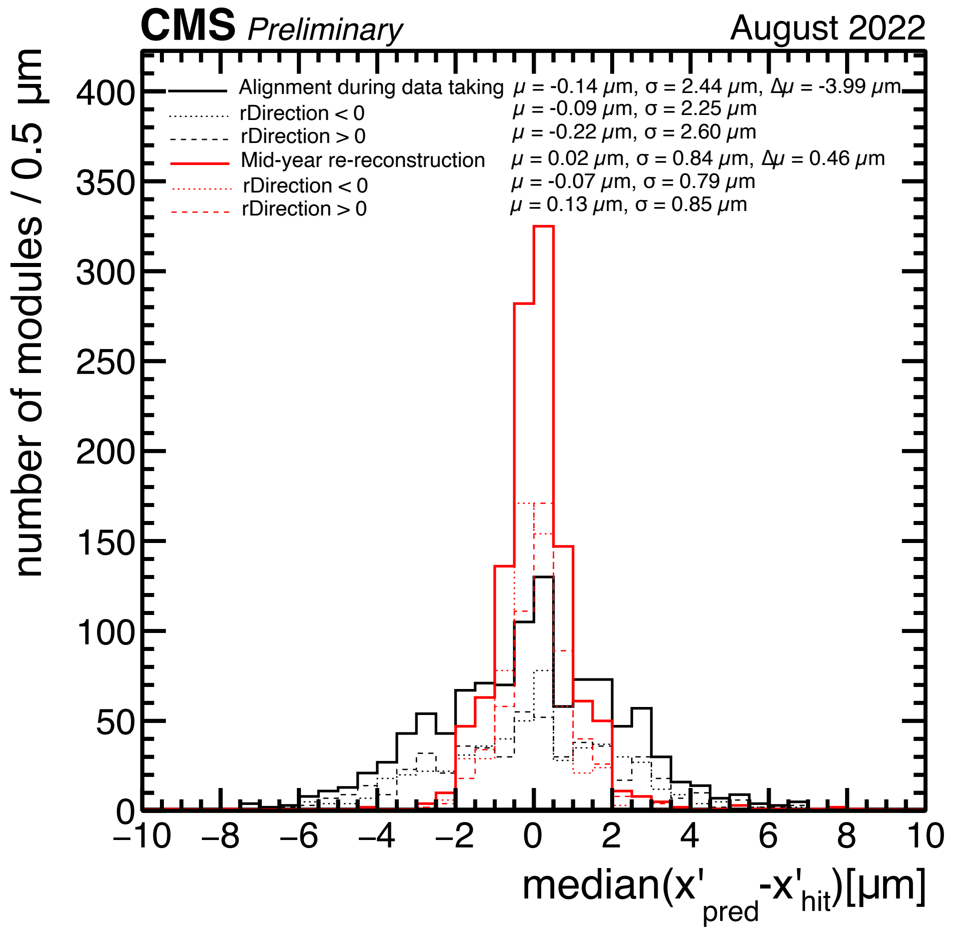
DISTRIBUTION OF MEDIAN RESIDUALS

Hit prediction obtained by fitting the track from all hits except the one under study → Obtain track-hit residual → Histogram of the median of the distribution

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







Width

measure of the local precision of the alignment results

Mean

deviations from zero indicate possible bias due to change of conditions

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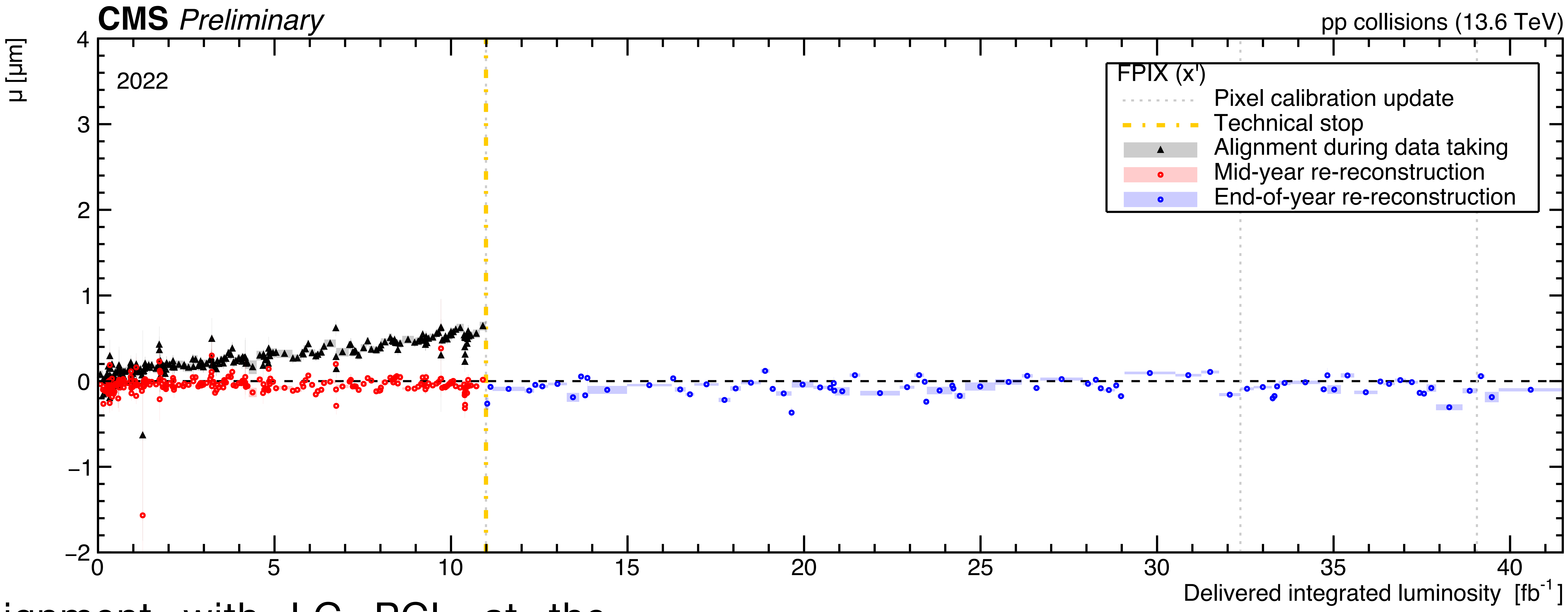
MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS



Online alignment with LG PCL at the beginning of data taking (black)

Deviation from zero

Change of conditions

Corrected by the offline alignment after reprocessing (red)

Higher granularity alignment (blue) deployed for online alignment

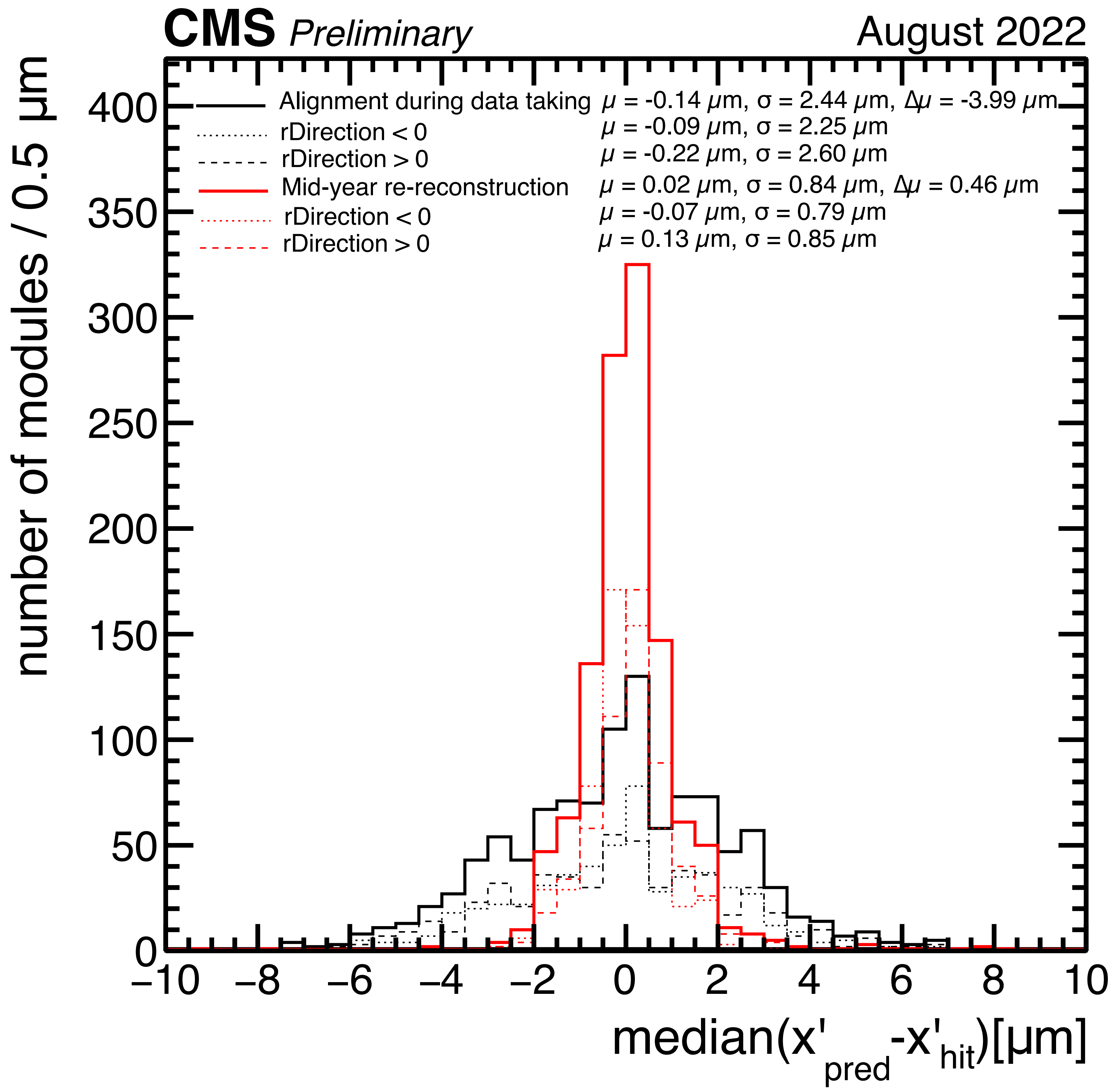
HG PCL + Pixel calibration updates recover from the change of conditions during data taking

TRACKER ALIGNMENT

SENSITIVITY TO LORENTZ DRIFT

Sign of the Lorentz Angle (LA) shift depends on the orientation of the E field

BPIX modules arranged in ladders → Facing inward / Facing outward → Opposite shift in the hit position for inward and outward modules



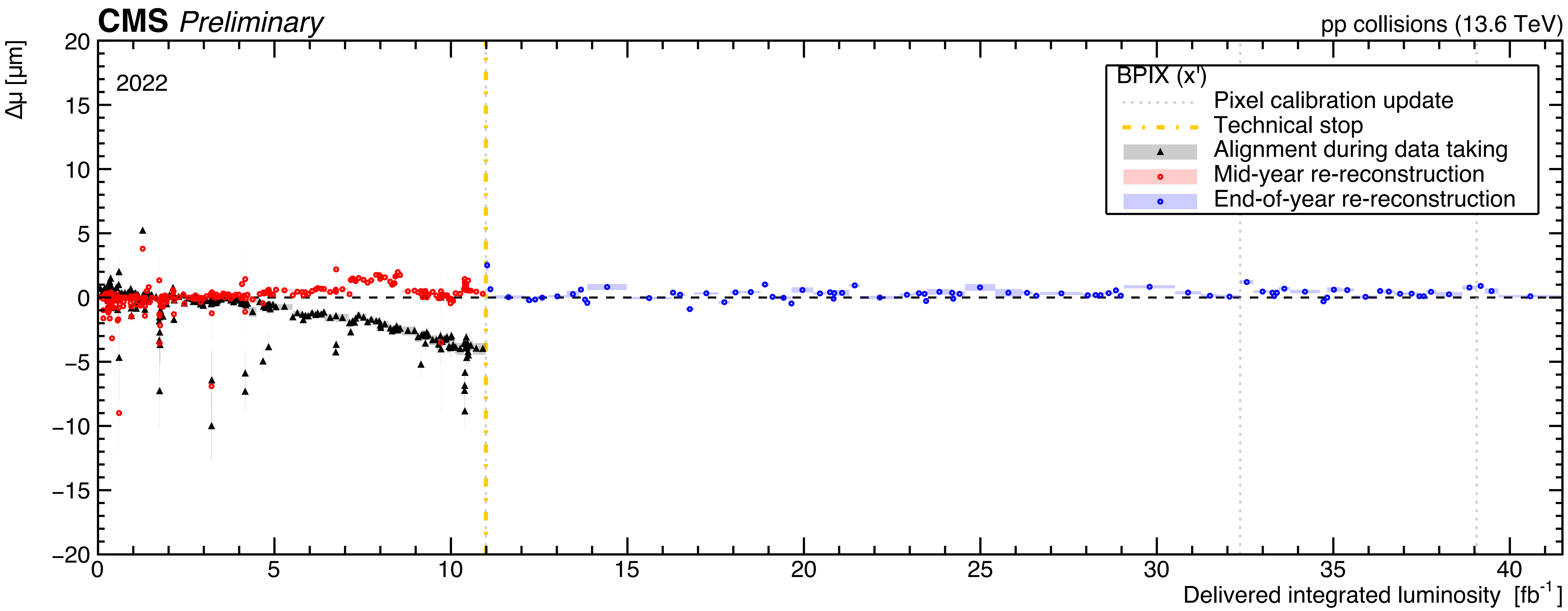
$\Delta\mu$ = difference in the mean of the inward and outward residuals distributions

↓

Monitor Lorentz drift

MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS



Online alignment with LG PCL at the beginning of data taking (black) and offline alignment after reprocessing (red)

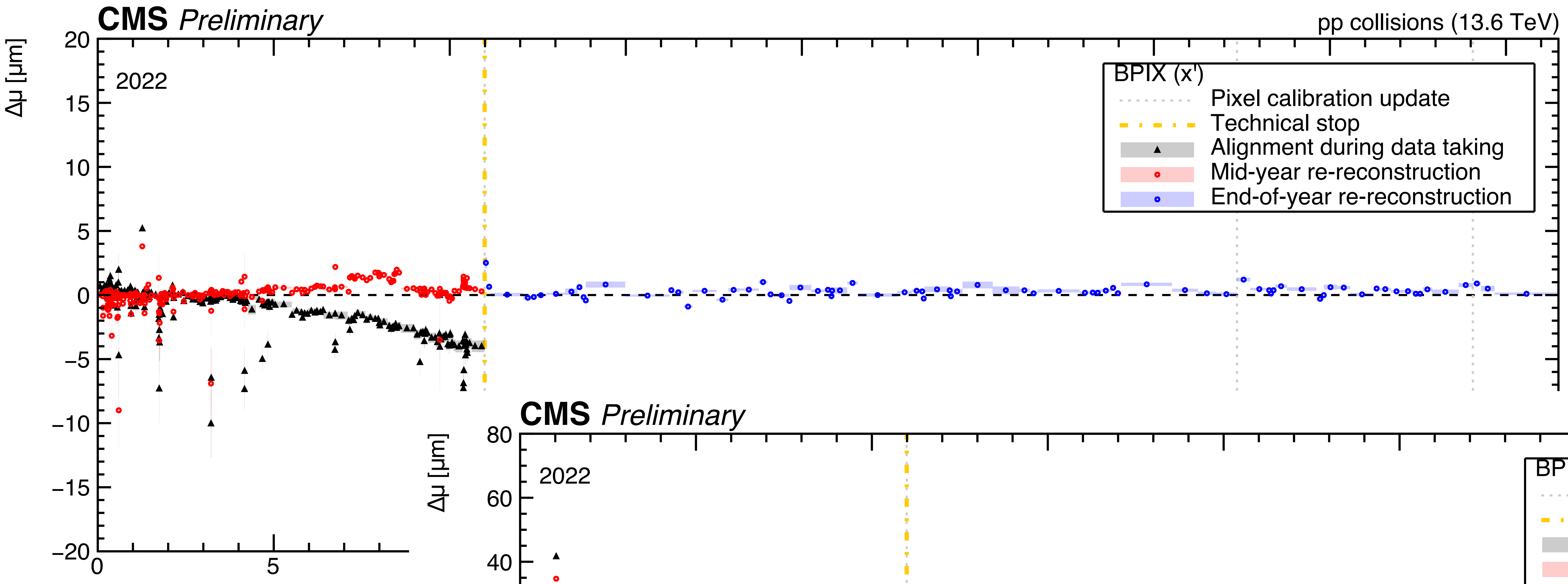
Deviation from zero

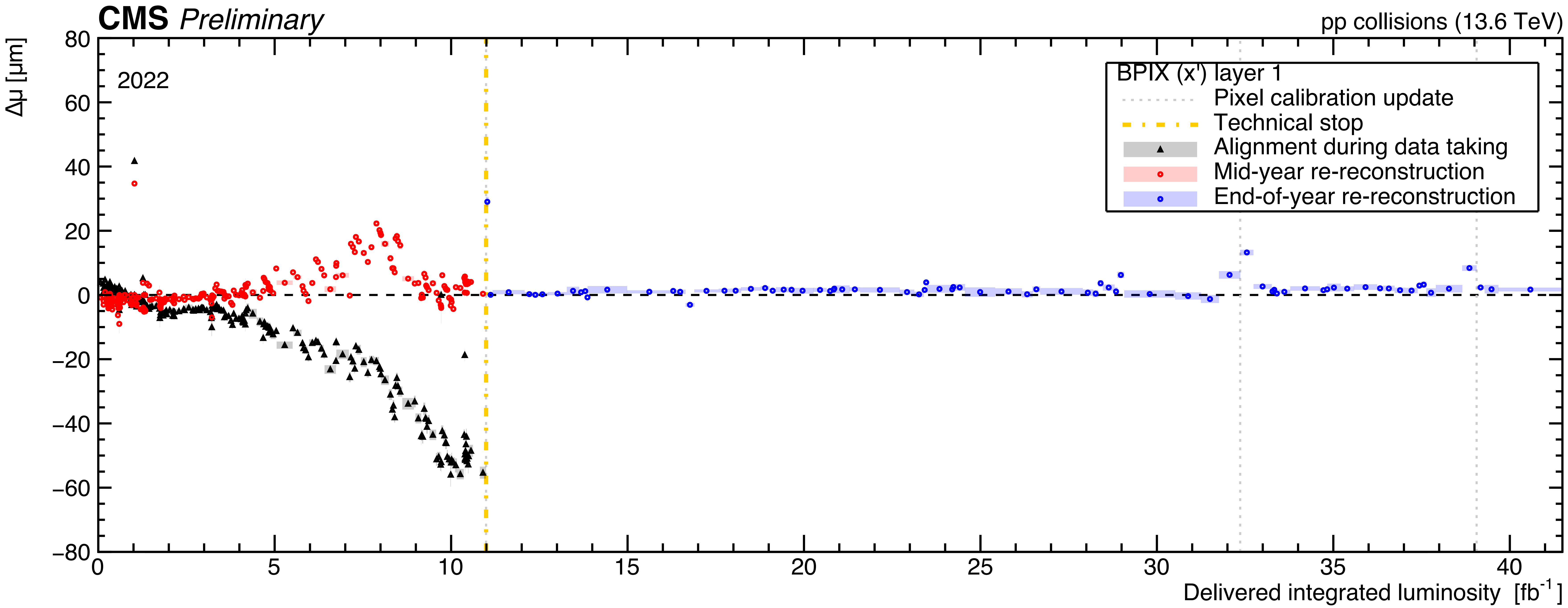
Shift on LA → Radiation damage

Online HG PCL corrects position bias developed during data-taking and uncorrected by local reconstruction

MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS





BPIX layer 1 more affected

Closer to the interaction point

Online alignment with LG beginning of data taking (blac alignment after reprocessing (re

Deviation from zero

Shift on LA → Ra

CONCLUSIONS

Relevance of the Interplay between pixel local reconstruction and tracker alignment

Ageing and Lorentz angle effect in silicon modules is monitored as a function of time using trends of distributions of the median of the residuals

The HG PCL has shown as being extremely efficient at absorbing effect of radiation damage reducing the need for manual updates of the alignment conditions and improving the quality of the alignment in the prompt reconstruction

HG PCL online shows stable performance in Run 3

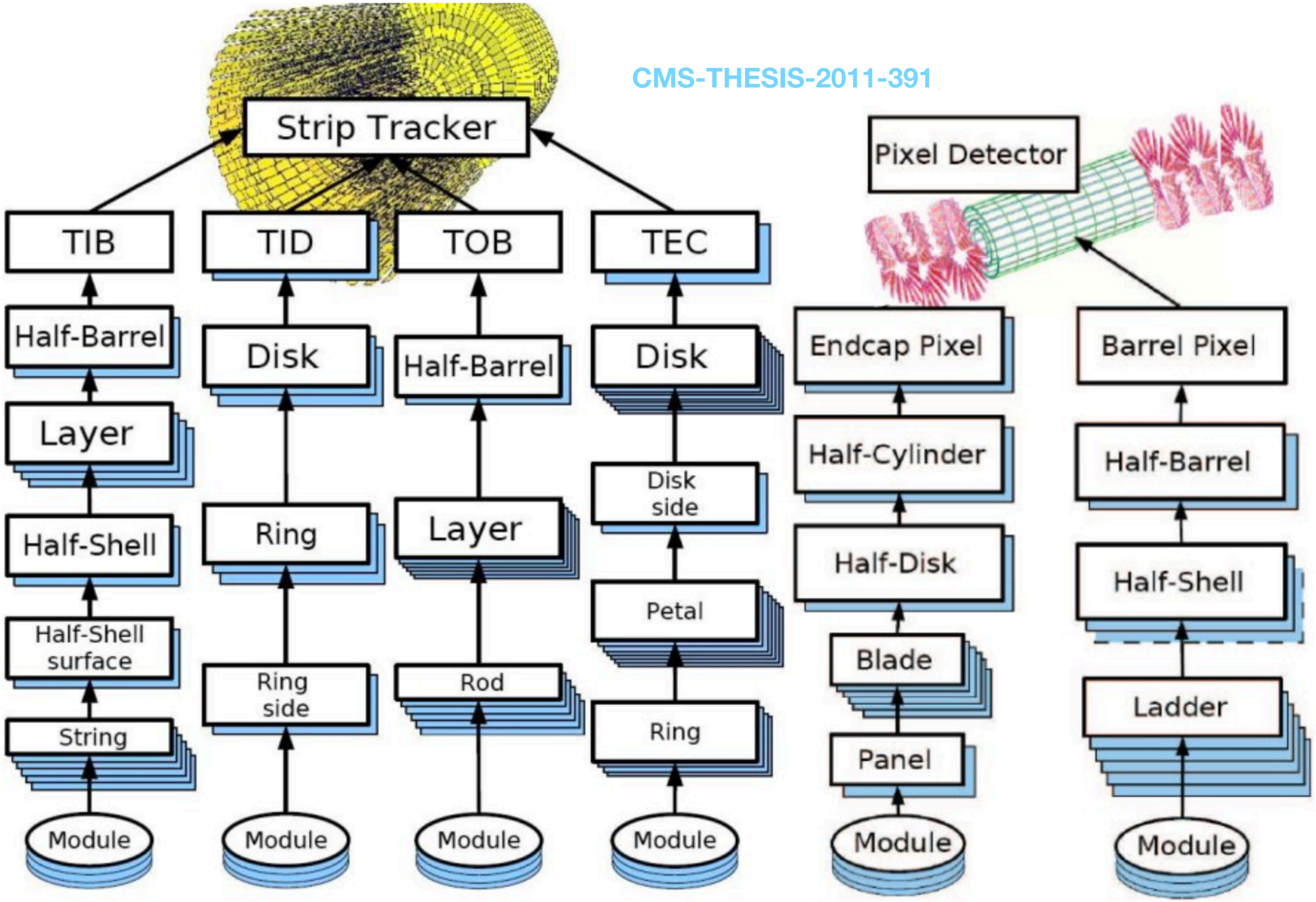
THANK YOU FOR YOUR ATTENTION!

BACK-UP

BACK-UP

HIERARCHY

CMS-THESIS-2011-391



BACK-UP

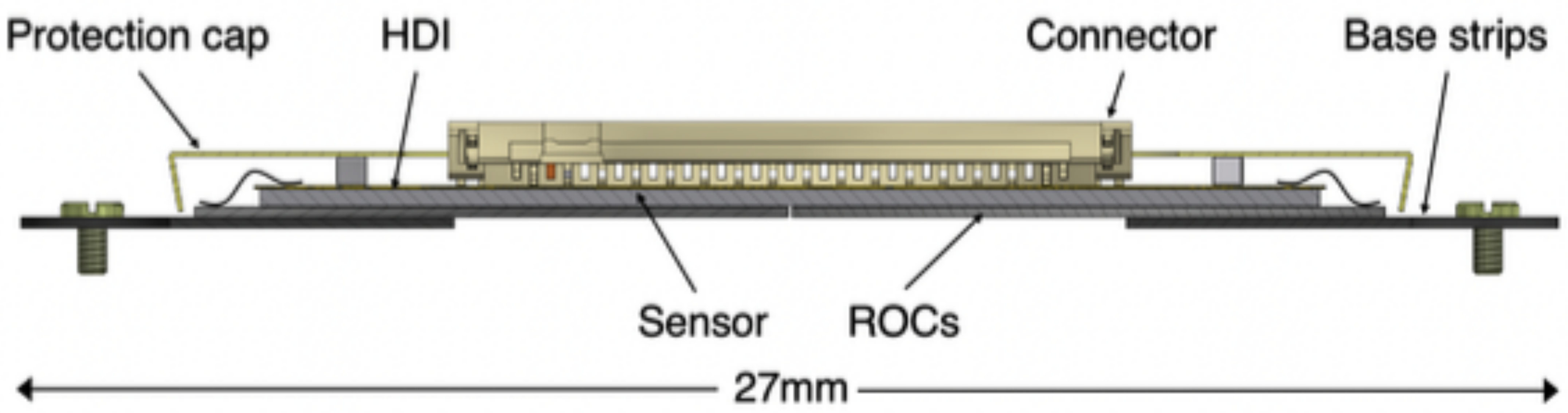
CMS PIXEL SENSOR

Particle hit rate up to $600\ MHz/cm^2$

Module consists of a sensor connected to 16 front-end readout chips (ROCs) → Data routed on a High Density Interconnect (HID), glued to the sensor and wire-bonded to the ROCs → Managed by an ASIC, Token Bit Manager (TBM)

n-in-n planar silicon sensors

Active are of 16.2x64.8mm2



Cross section of a pixel detector module for BPIX L2–4 cut along the short side of the module

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BACK-UP

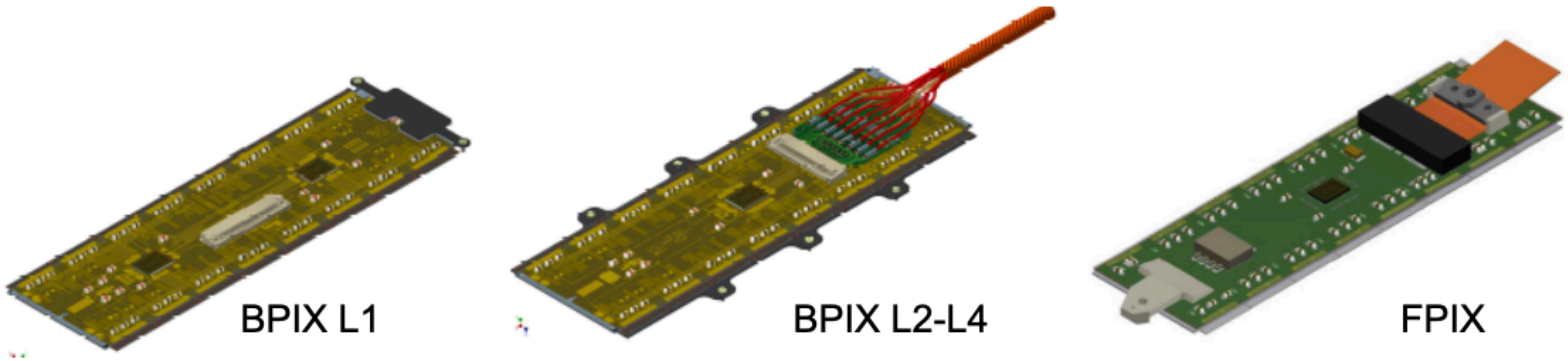
TACKER DETECTOR UPDATES DURING LS2

General detector maintenance

- Replace DCDCs with fixed version
- Fix problematic connections
- Replace damaged modules (mostly BPIX layer 2)
- Re-evaluate HV granularity in FPIX
- Upgrade power supplies from 600V to 800V

Layer 1 replacement

- New TBM version
- New ROC version



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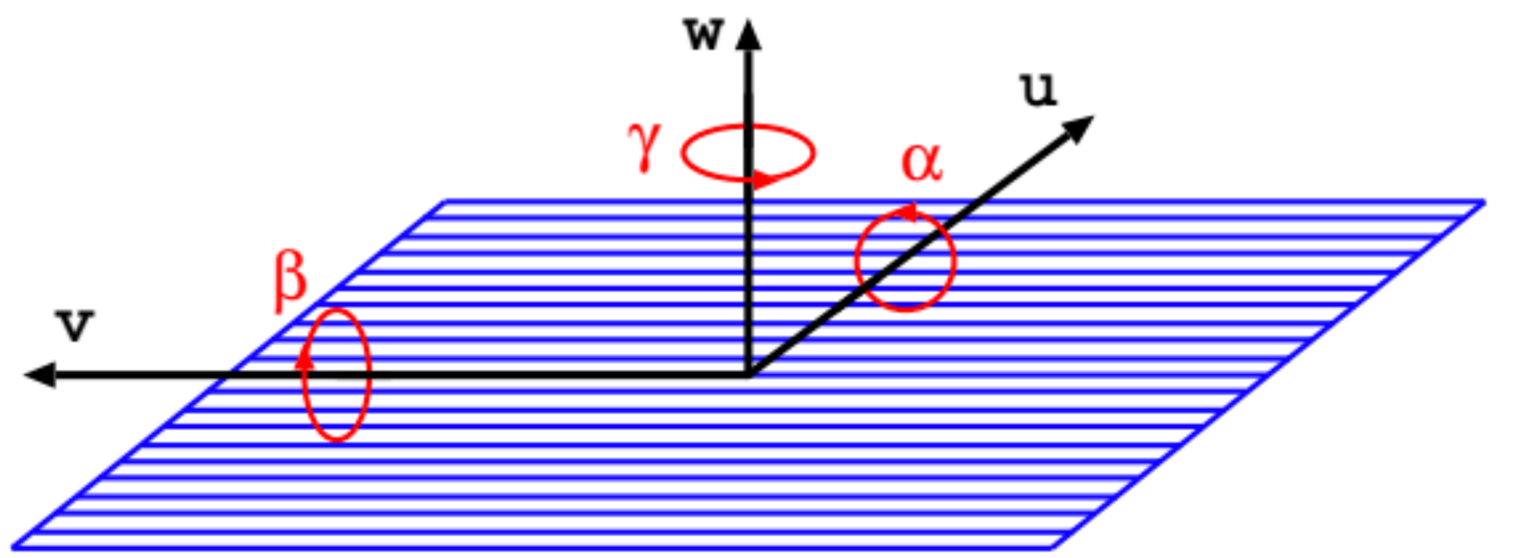
RECONSTRUCTION

LOCAL AND GLOBAL RECONSTRUCTION



CMS-TRK-11-002

Local reconstruction

Using detector readout information to reconstruct local hit candidates

- Digitization of signals generated by charged particles traversing the pixel detector
- Select signal, pixel with a charge above the signal-over-noise threshold
- Neighbouring signals are grouped together forming clusters
- The shape of the clusters and the signal charge determine the hit position and its uncertainty in the local coordinate system of each module

Position and orientation of each module must be precisely measured

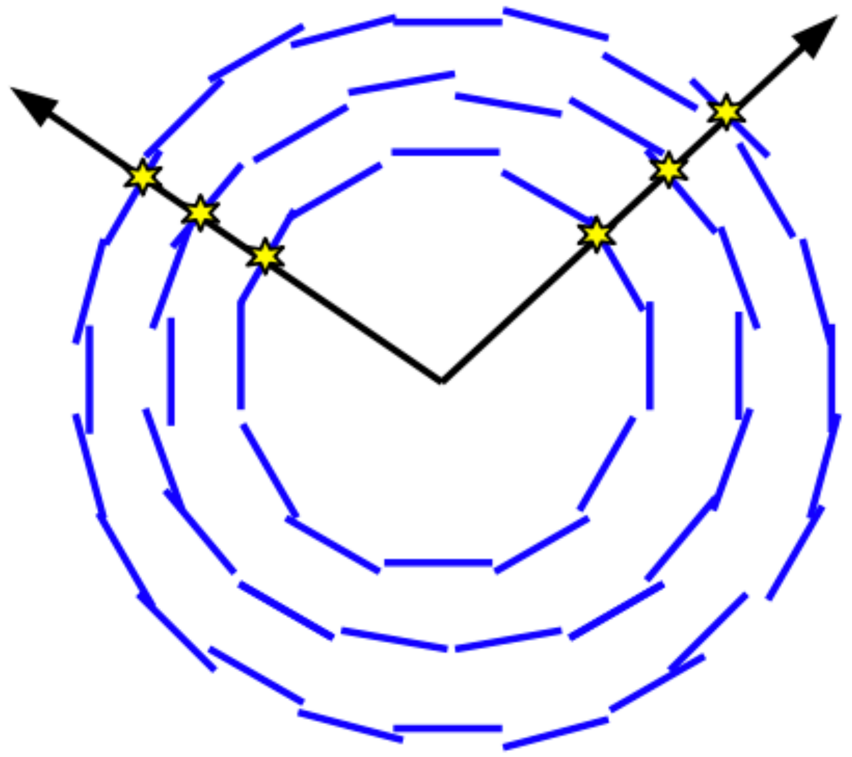
Global reconstruction

Combining hits produced from the local reconstruction to form tracks

- Seed generation
- Track finding
- Track fitting
- Track selection

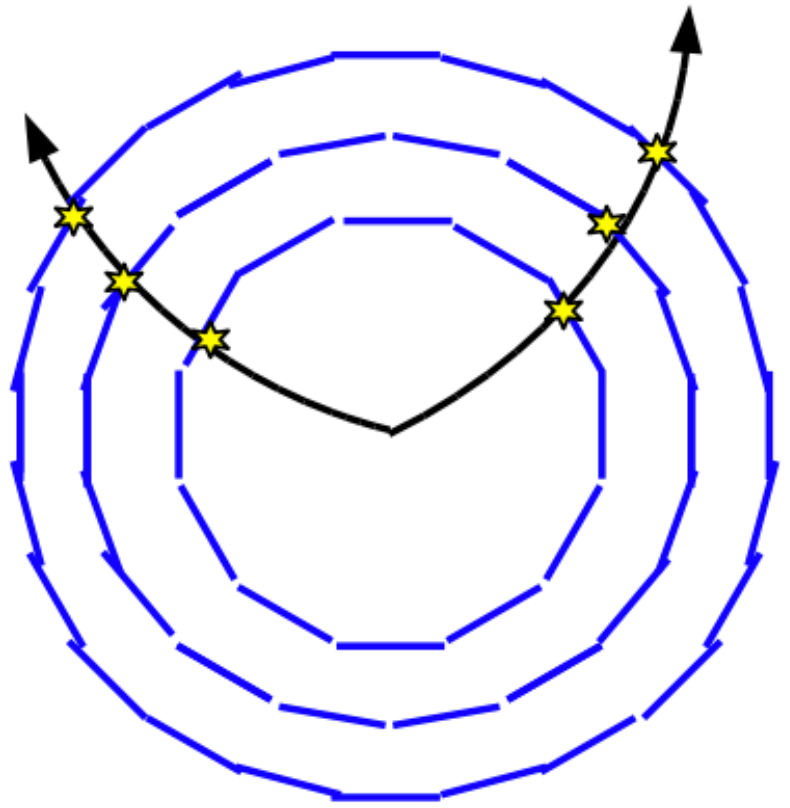
TRACKER ALIGNMENT

GOAL



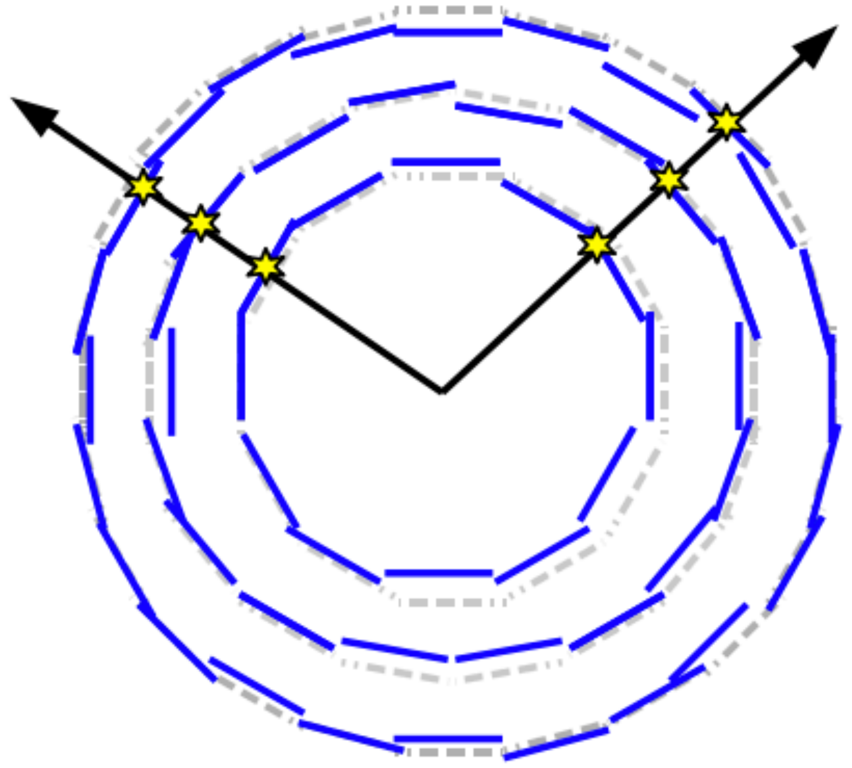
Charged particles cross the tacker

Produce tracks



Ideal geometry assumed

Wrong estimation



Modules position corrected after alignment

Correct estimation

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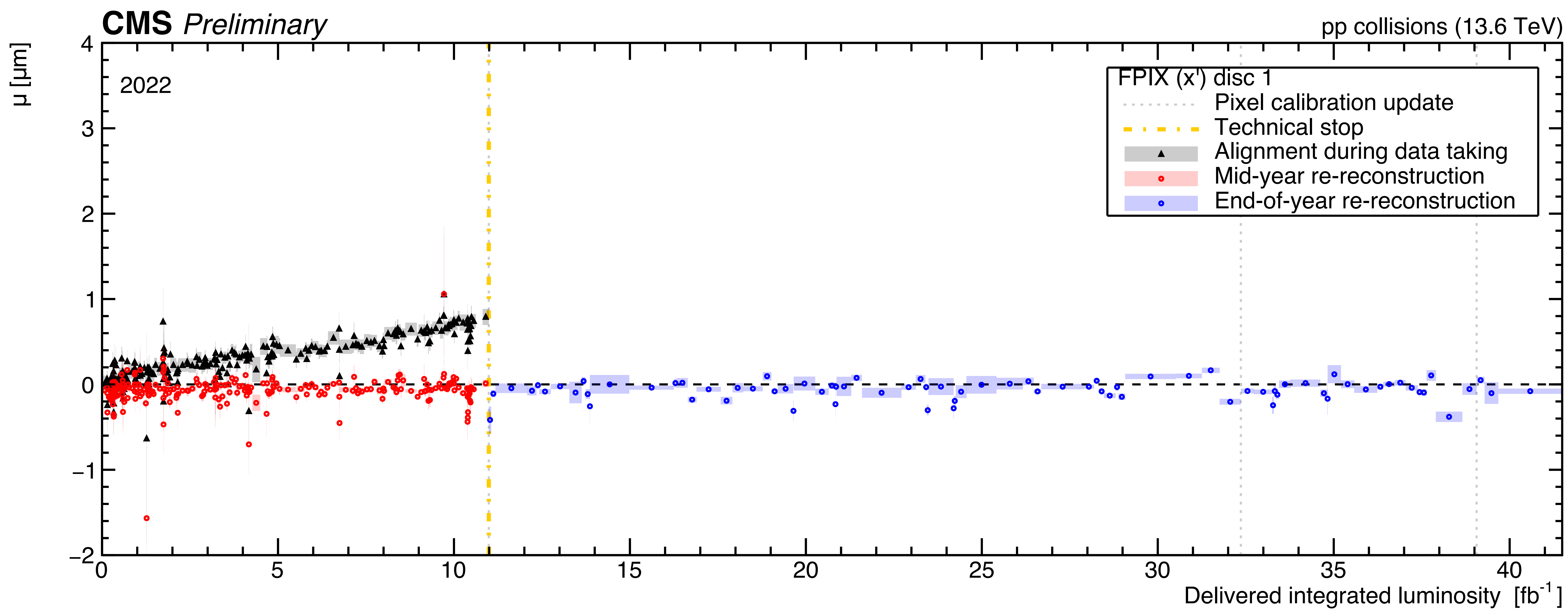
MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS

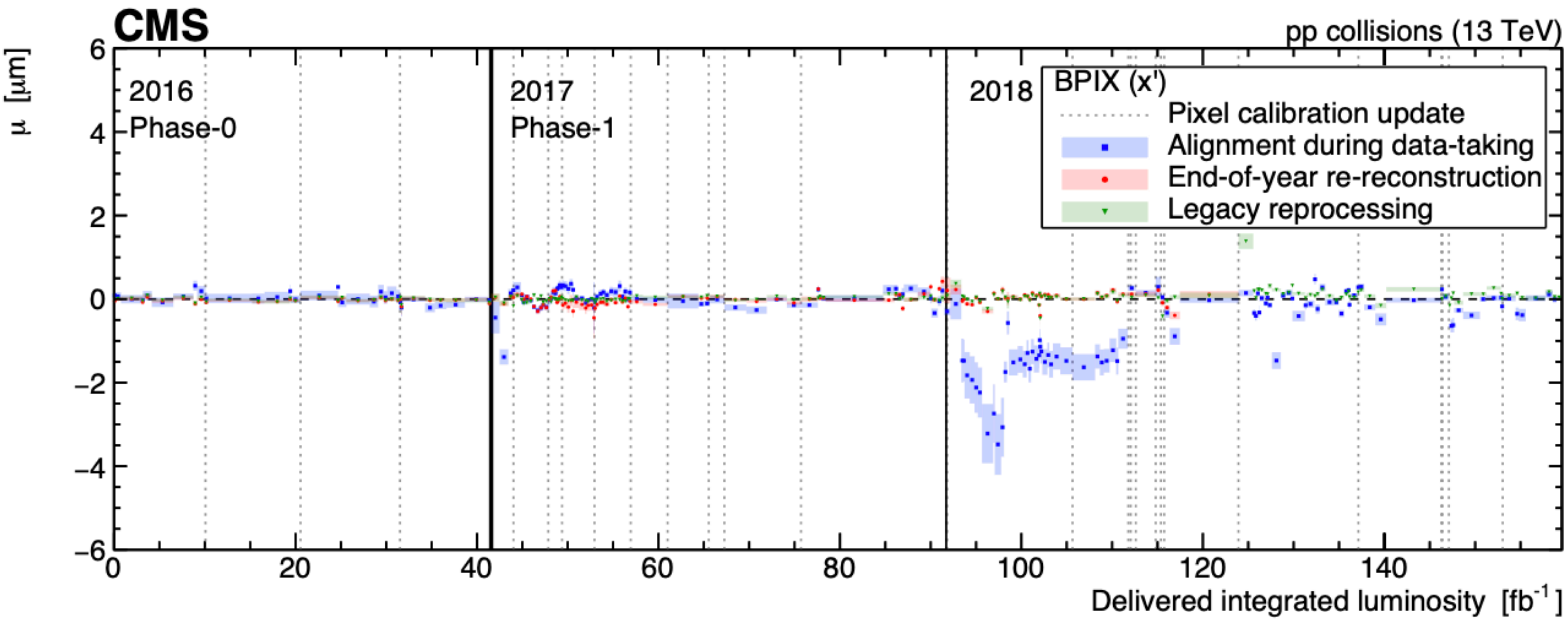


FPIX disc 1 more affected

Closer to the interaction point

MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS



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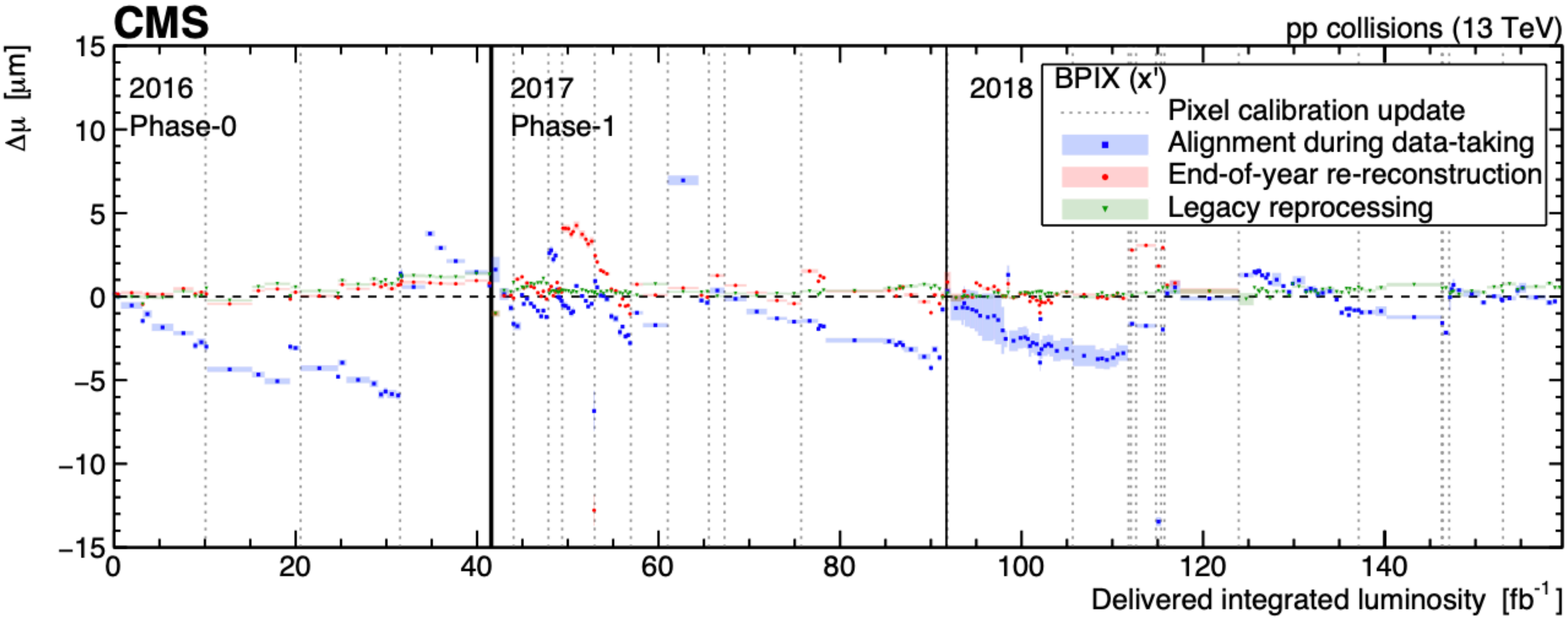


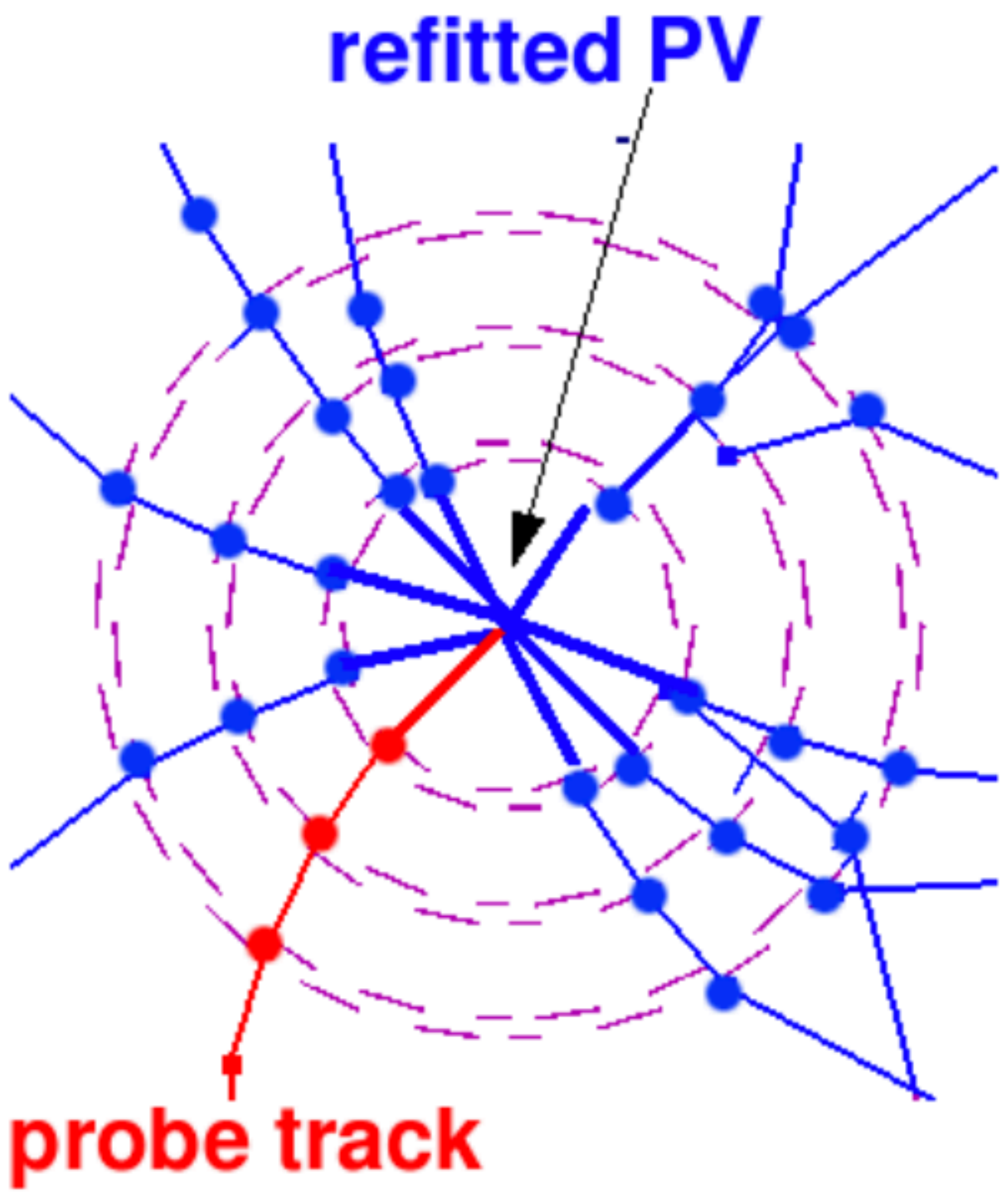
FPIX disc 1 more affected

Closer to the interaction point

MONITORING TRACKING PERFORMANCE

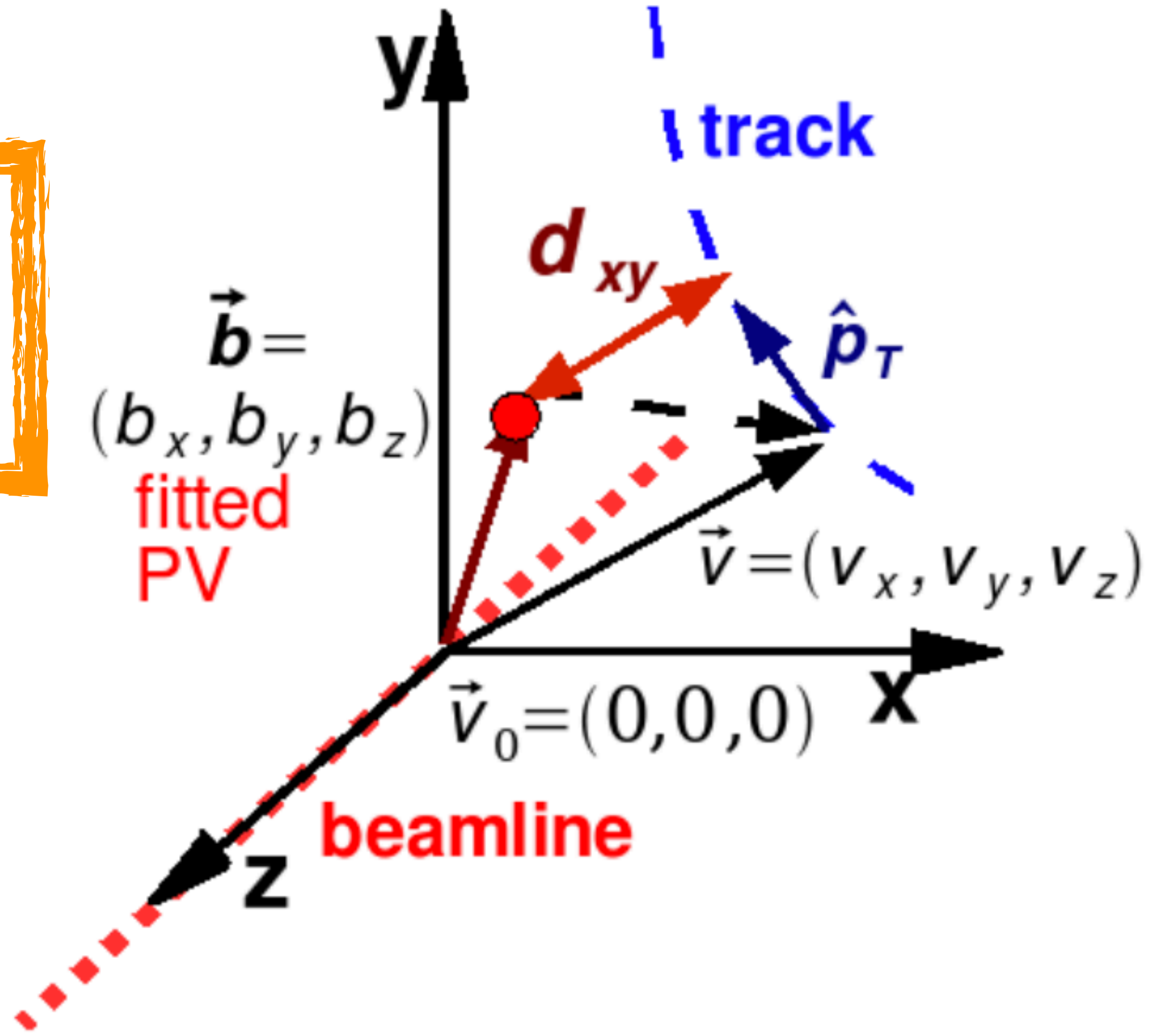
PRIMARY VERTEX RECONSTRUCTION

Primary vertex position reconstructed excluding the track under study from a sample of tracks → Calculate the unbiased track residual in the transverse (d_{xy}) and longitudinal (d_z) planes



$$d_{xy}(PV) = [(b - v) \times \hat{p}_T] \cdot \hat{z}$$

$$d_z(PV) = \left[\left(\frac{(b - v) \times \hat{p}_T}{p_T} p \right) - (b - v) \right] \cdot \hat{z}$$

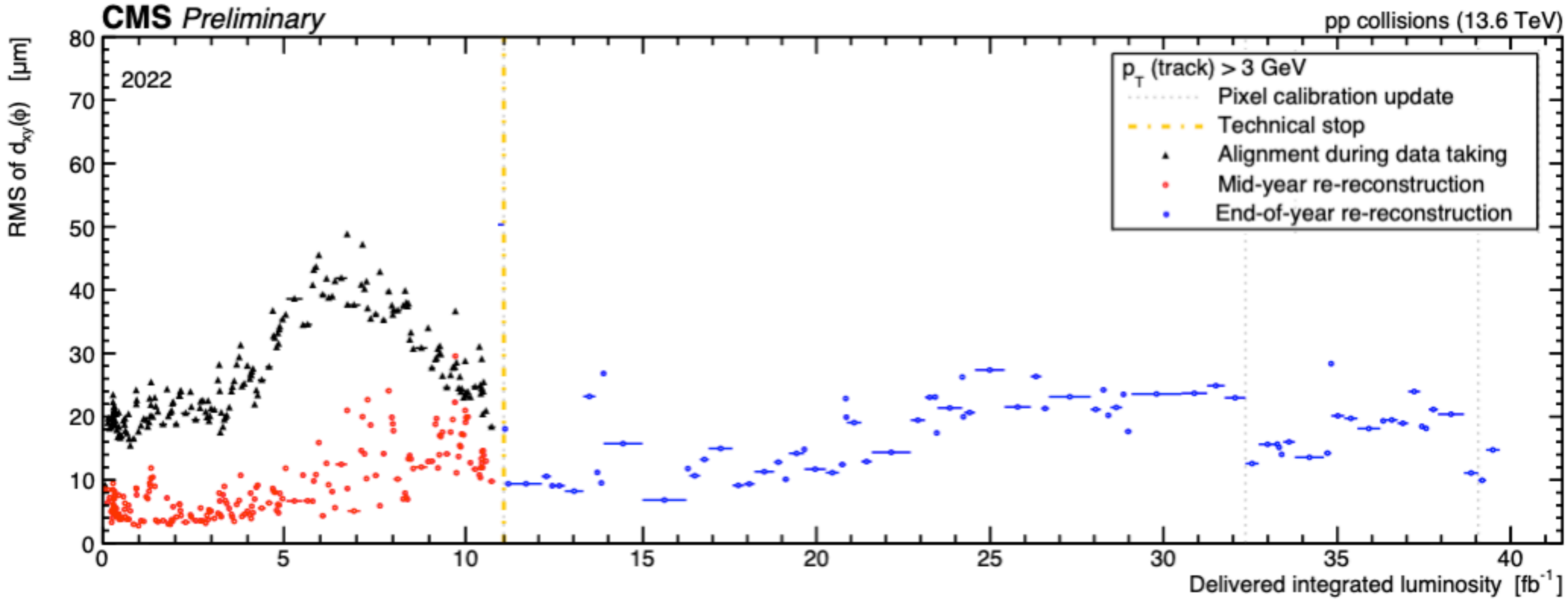


CMS-THESIS-2011-435

Distributions are expected to be flat and compatible with zero for an ideally aligned tracker

MONITORING TRACKING PERFORMANCE

DISTRIBUTION OF MEDIAN RESIDUALS



Online alignment with LG PCL at the beginning of data taking (black)

↓

Deviation from zero

↓

Shift on LA → Residual effect corrected by aligning with a finer granularity → Higher granularity alignment (blue) deployed for online alignment

HG PCL + Pixel calibration updates recover from radiation damage