The CMS Precision Proton Spectrometer in Run 3: upgrade and performance

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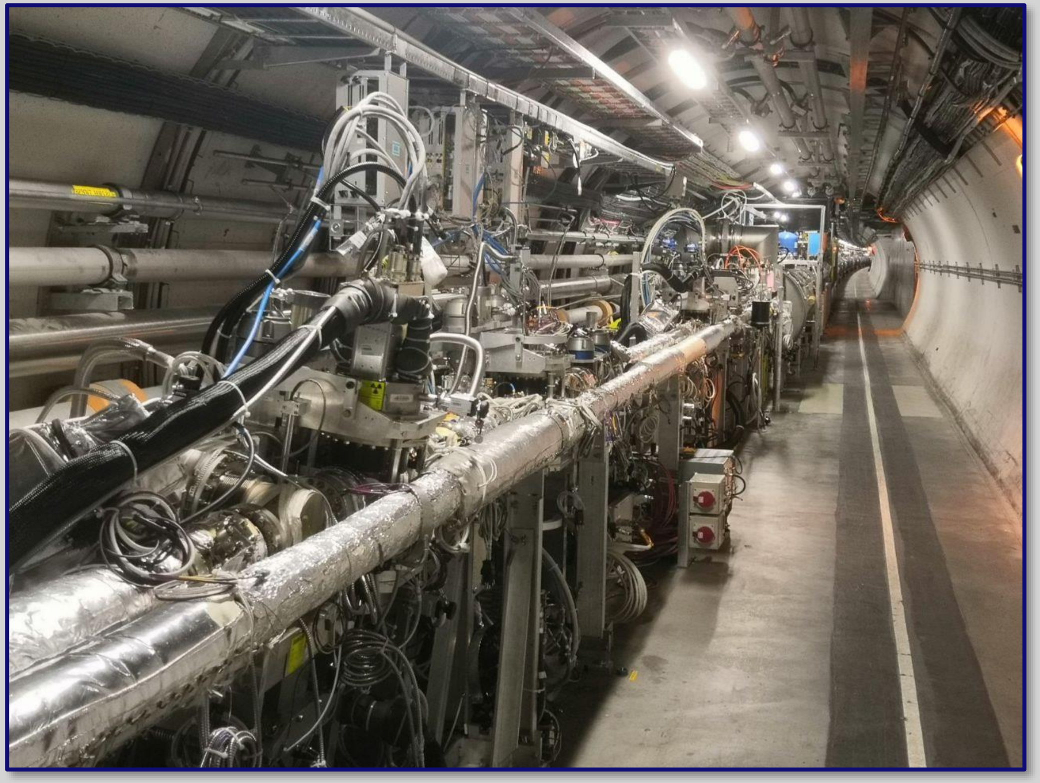
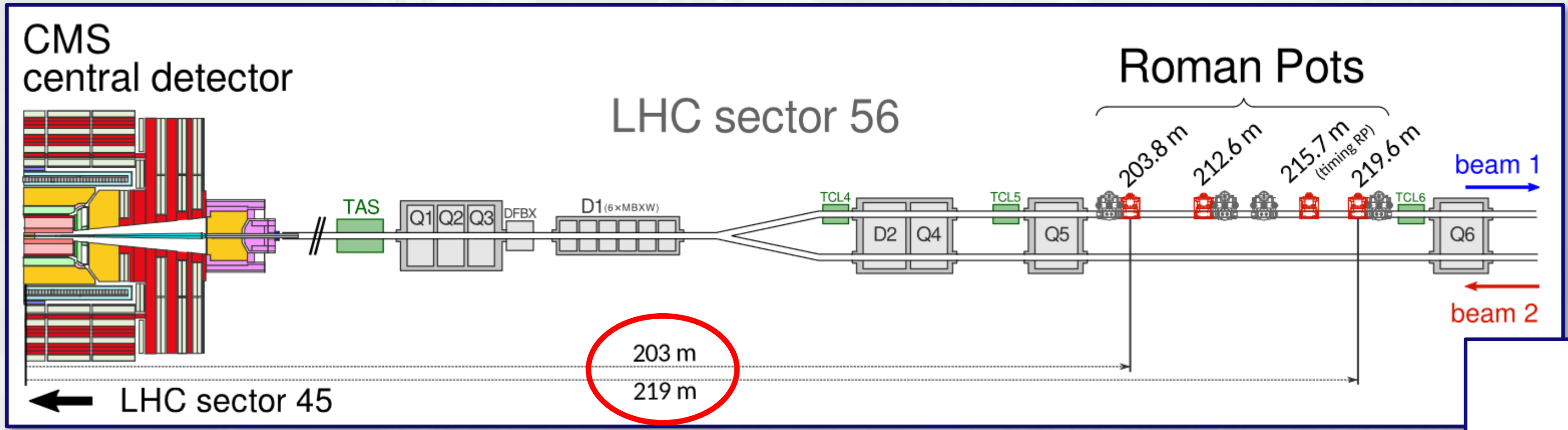
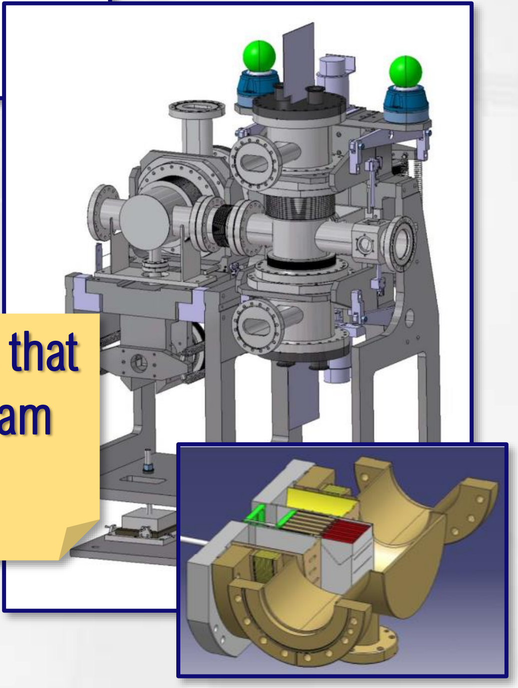


PPS: Run 3 setup and physics case



Detectors on both sides of CMS interaction point in Roman Pots (RPs):

- 4 horizontal RPs: physics data-taking
  - 2 **tracking** stations: 3D silicon pixels (6 planes each)
  - 1→2 **timing** stations: double scCVD diamonds (3/4 planes)
- 4 vertical RPs: alignment runs
- **Physics purpose:** measure protons surviving the interaction
  - Central exclusive production, BSM searches…



Beam pipe insertions that approach the LHC beam down to ~1.5 mm

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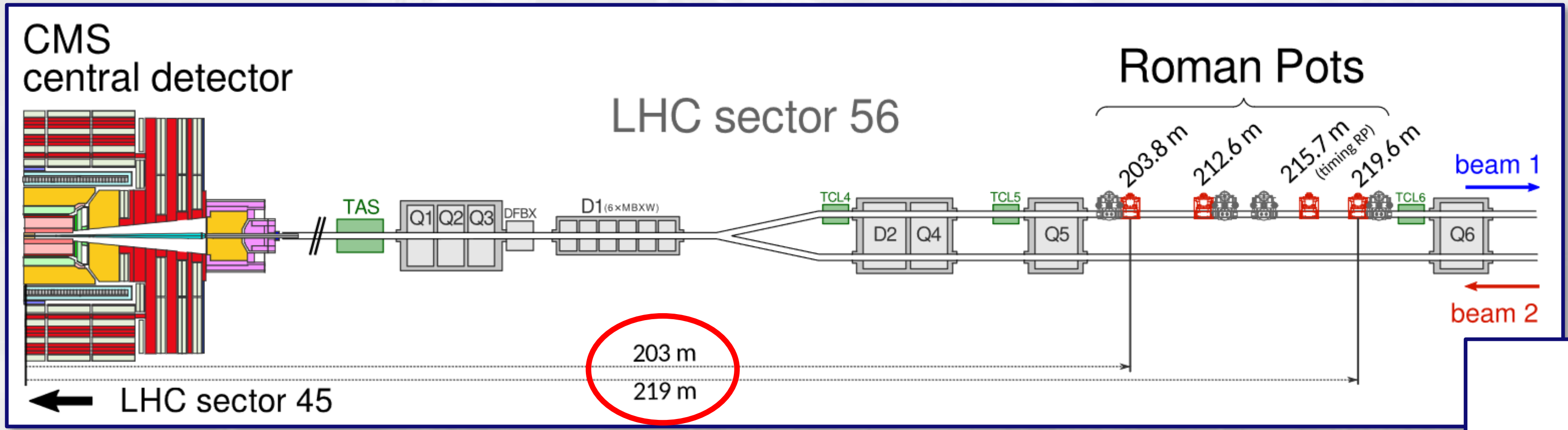

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- 4 verti…

More info in G. Gil Da Silveira talk!

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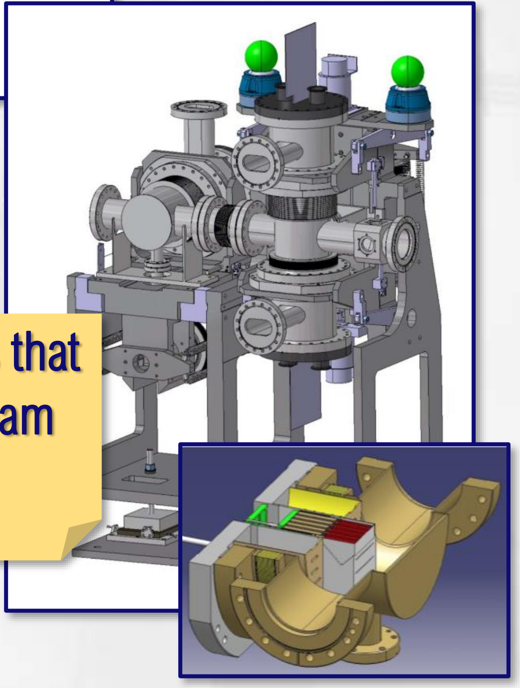

Beam pipe insertions that approach the LHC beam down to ∼1.5 mm

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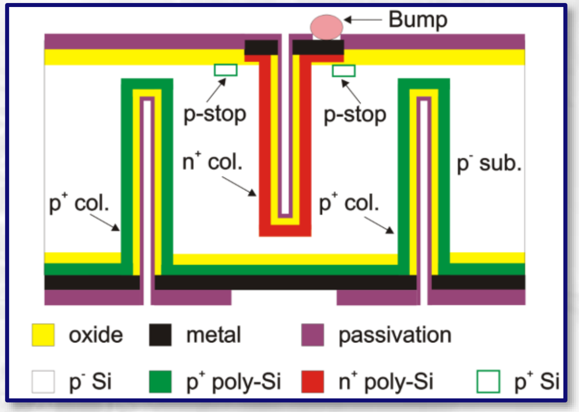
PPS tracker sensors

PPS took data in Run 2, collecting ~110 fb^{-1} of integrated luminosity

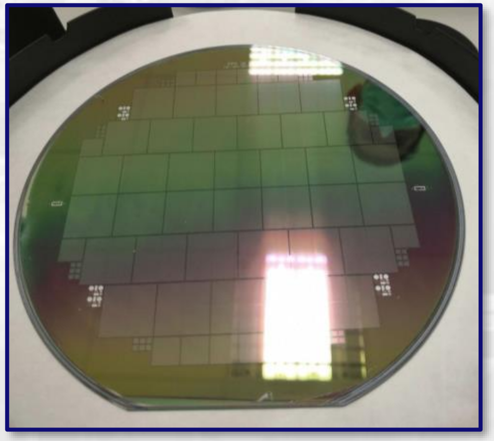
Run 2 silicon 3D pixel sensors:

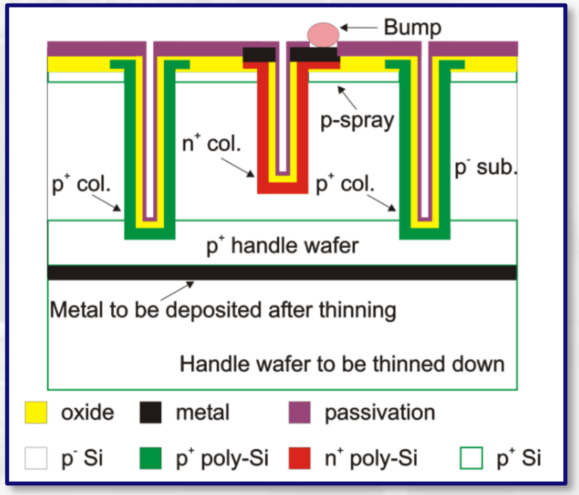
- Produced at CNM, double-sided process
- 230 μm-thick, 200 μm-deep and 10 μm-diameter columns
- 150x100 μm^2 pixels, 3x2 matrix of 52x80 pixels



New production of 3D pixels for Run 3:

- Made by FBK, single-sided process
- 150 μm-thick, 5 μm-diameter columns
- 80 μm-thick handle wafer, after thinning
- 150x100 μm^2 pixels, 2x2 matrix of 52x80 pixels
- 13 wafers, 36 2x2 sensors each





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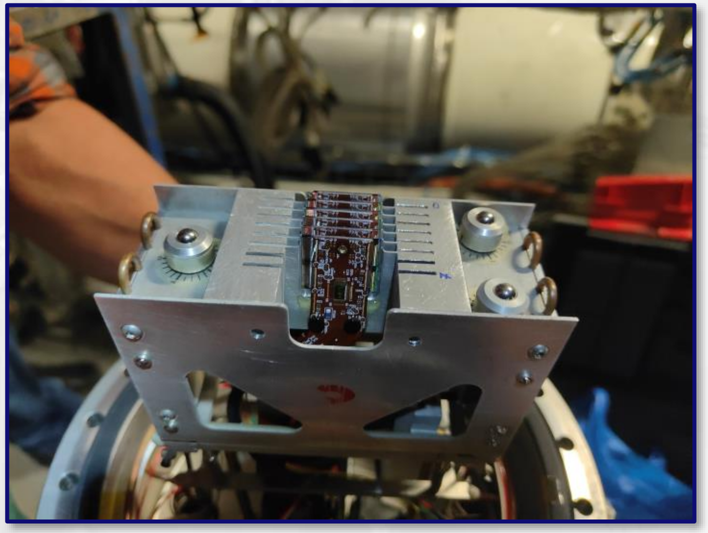
The PPS tracker readout

- Each sensor is read out by 4 PROC600 readout chips (ROCs)
  - Same ROC used for the first layer of the CMS pixel barrel
- Sensor+ROC glued to an aluminum plaquette and a flex hybrid forming a module
  - Flex hybrid hosts the Token Bit Manager (TBM10d) to coordinate the ROC data transfer to the back-end
- 6 modules are assembled in a detector package
  - 20° tilt w.r.t. incoming particles
- Each package is connected to a 'portcard'
  - Motherboard that distributes power, clock, trigger and receives/transmits optical signals from μTCA back-end
  - ~equivalent to the CMS pixel readout chain



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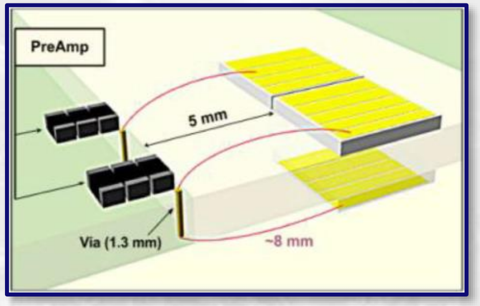
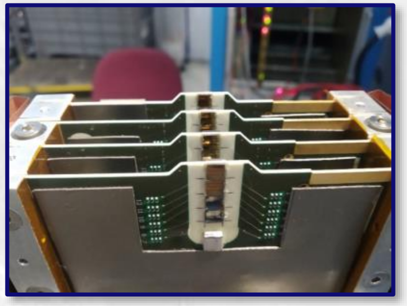
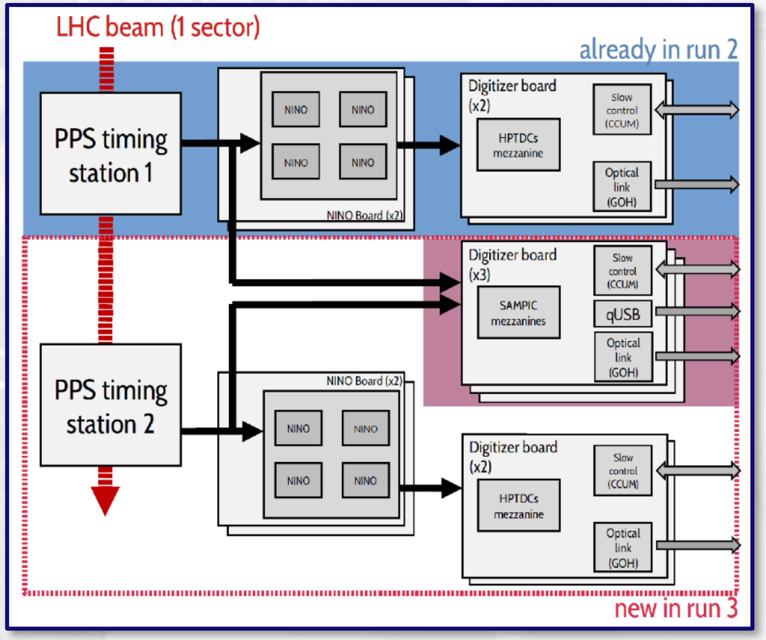
Timing detectors

- 500 μm-thick scCVD diamond sensors
  - Double-diamond (DD) layout to improve signal to noise ratio
  - Crystals horizontally segmented in 2/4 channels
    - 10-12 total channels per plane
- New production at Element Six launched for Run 3
  - 2022: one station per sector equipped with a mix of Run 2 and Run 3 crystals on new hybrids
  - 2023: one station per side added with new modules only
- Readout chain based on NINO+HPTDC revised and optimized for Run 3
  - Added SAMPIC readout for commissioning and calibration







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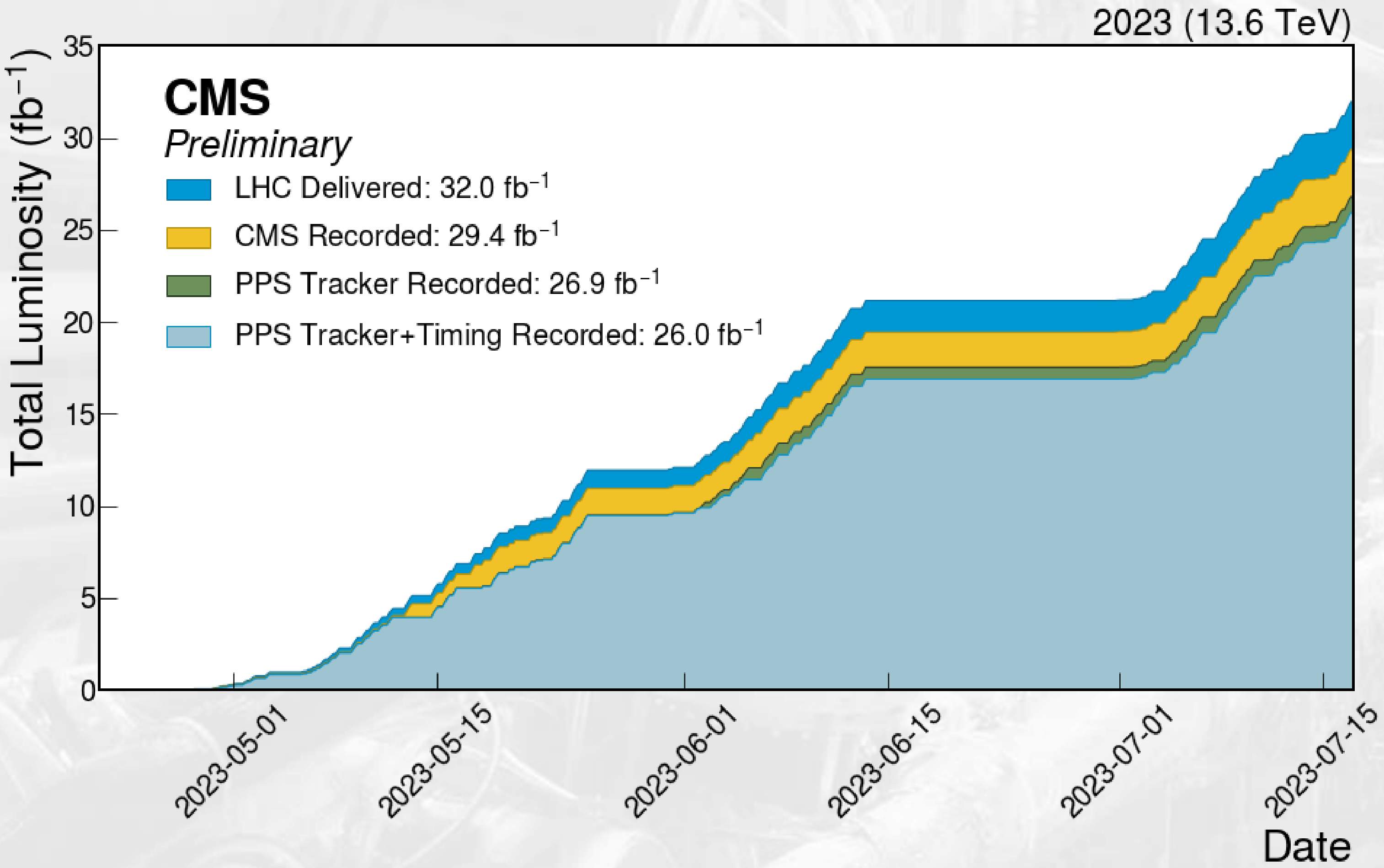
2023 data-taking



PPS tracker recorded ~26.9 fb^{-1} of data in 2023:

- 84% of total luminosity delivered by LHC
  - Losses mainly caused by the nominal RP insertion delay + 1 LHC fill for testing

> 30 fb^{-1} already collected in 2024

Very stable operation!

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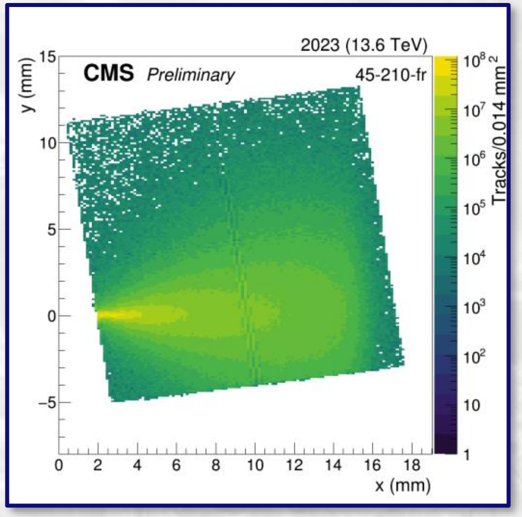
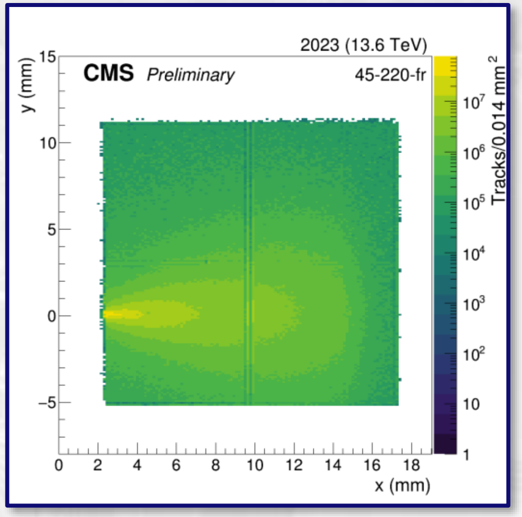
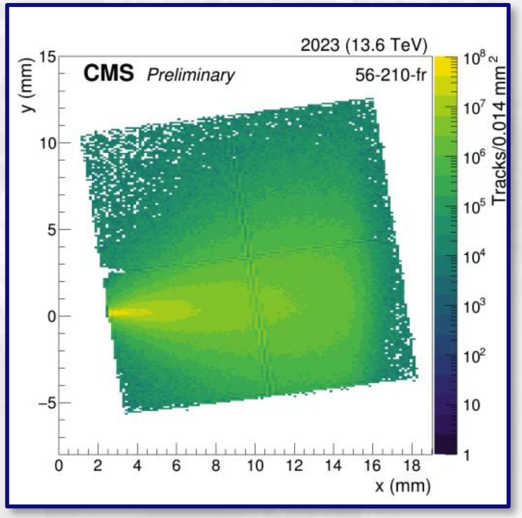
Tracker performance in 2023

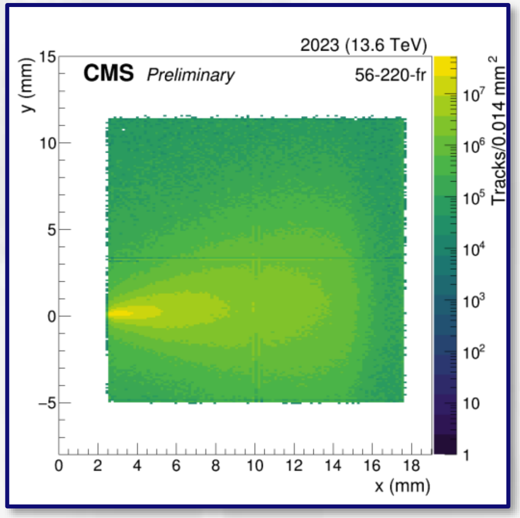
Preliminary look at the collected data:

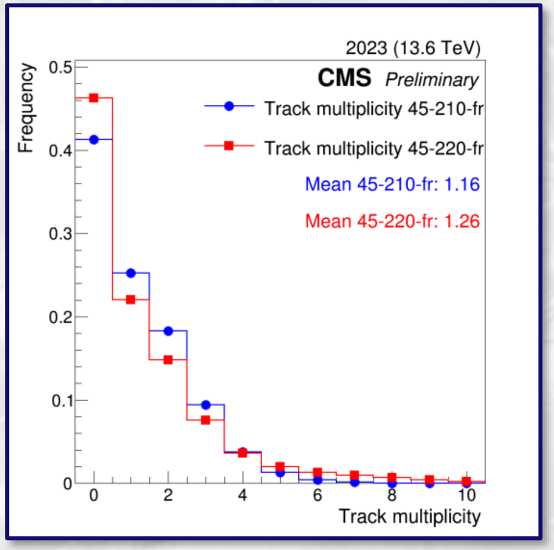
- Non-uniform irradiation visible in the track hit distribution
  - Mainly concentrated close to the beam – at (0,0)
- Higher track multiplicity observed in far stations
  - Protons reaching 220 stations have a higher chance of producing secondary particles











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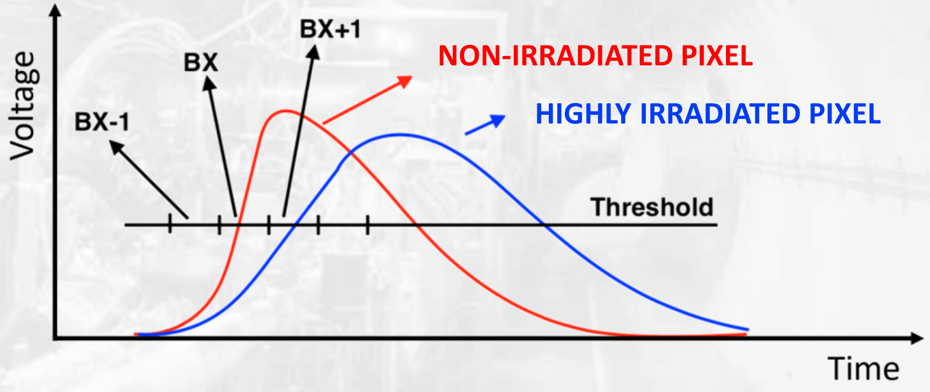
Radiation effects on the PPS tracker

The irradiation effects on the PPS tracker were studied in Run 2:

- Main effect: non-uniform irradiation of the ROC causes efficiency loss
  - Front-end amplifiers damaged by radiation
  - Irradiated pixels cross the threshold in the clock window (BX) following the correct one
  - Per-pixel timing adjustment is not possible



Efficiency loss foreseen to start at $\mathcal{L}_{INT} \simeq 8\ \mathrm{fb}^{-1}$

- Studied on PSI46dig ROCs (Run 2), but equivalent for PROC600 (Run 3)
- Sensor radiation damage found negligible up to ~1.5E15 p/cm^2

Impact on Run 2 data quality mitigated by manually shifting the detector stations during LHC technical stops (TS) in the vertical direction

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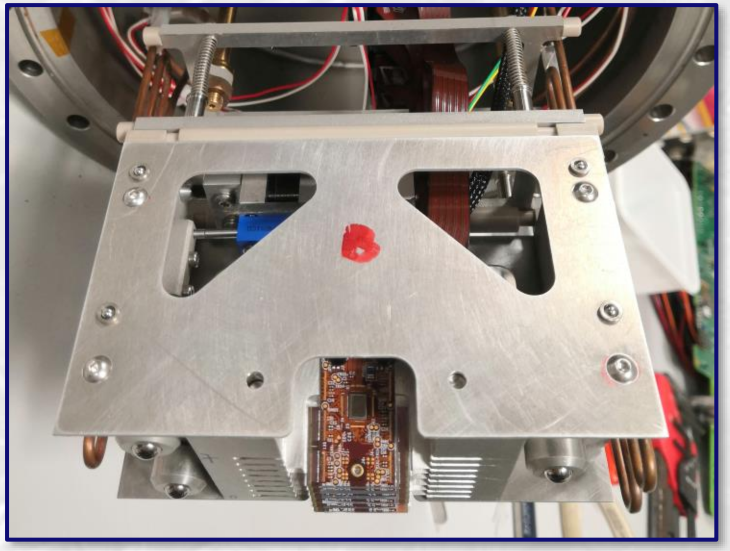
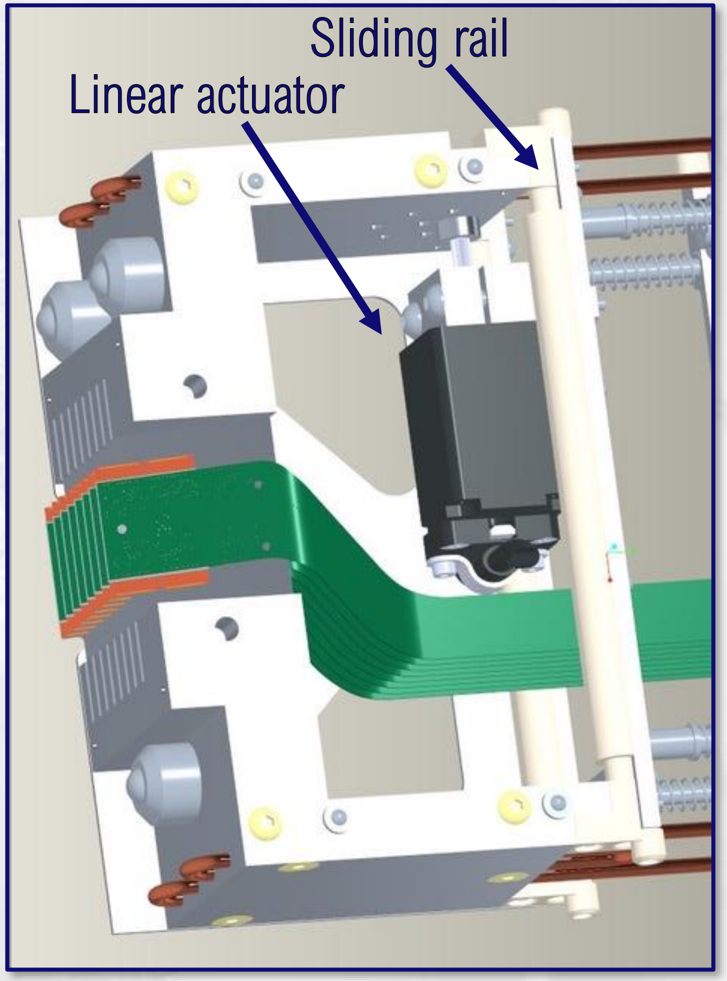
Movement system for the Run 3 tracker

Run 3 detector package heavily re-designed:

- Sliding rails to allow 'vertical' movement
  - ~6 mm range
  - The package moves rigidly within the RP vessel
- Stepping linear actuator + resistive position sensor
  - Precise movement (resolution <10 μm)

Vertical movements to be performed during inter-fills





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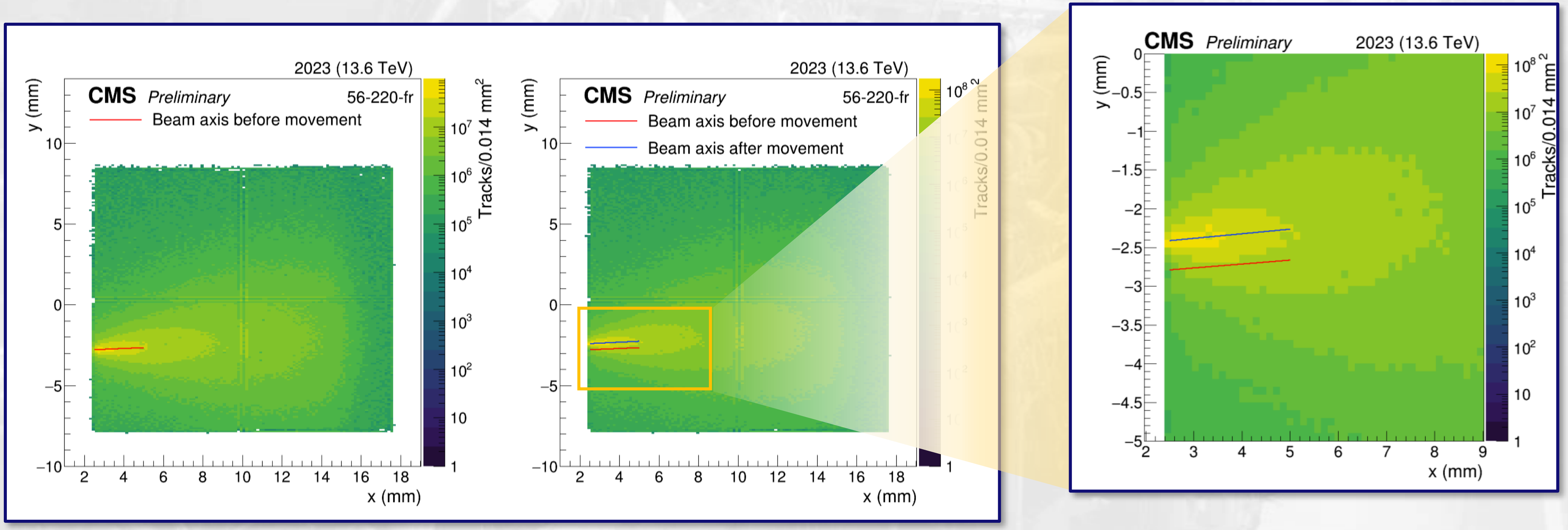
Operation of the movement system

Initial movement strategy: move all stations every ~10 fb^{-1} by ~500 μm

- Two movements performed in 2023 after ~8.8 fb^{-1} and 18.5 fb^{-1}

Vertical shift verified and confirmed using the track hit distribution in physics runs



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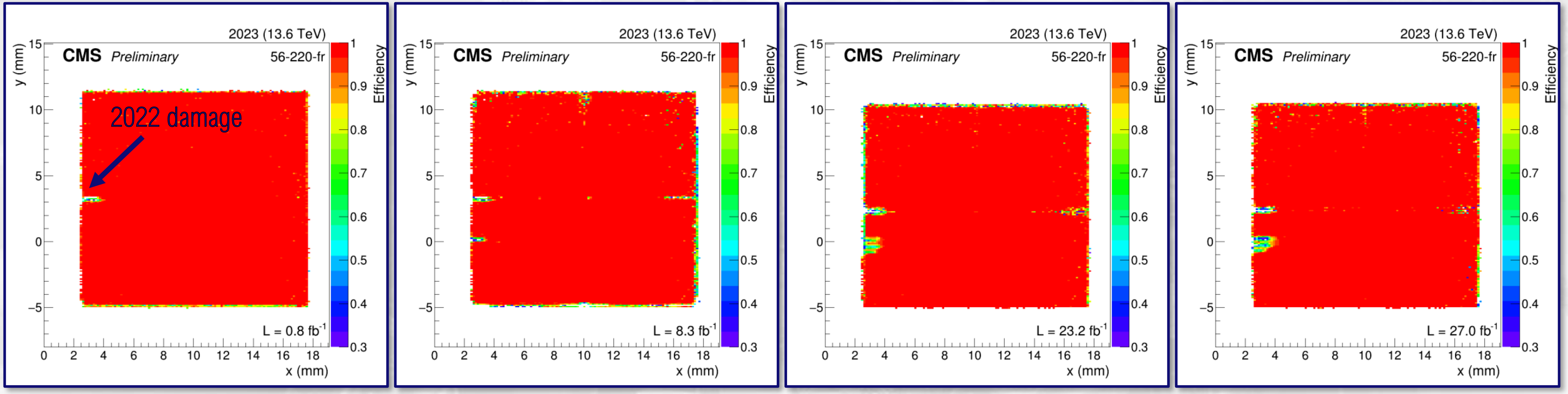
Tracker efficiency in 2023



Before first movement

After second movement

Overall, **optimal efficiency:** >98% average on the full detector area

Radiation damage forms in the region closest to the beam – at (0,0) – as expected:

- Some of these sensors had already collected ~10 fb^{-1} in 2022 (previous damage is visible)
- Different damaged regions are quite separated vertically

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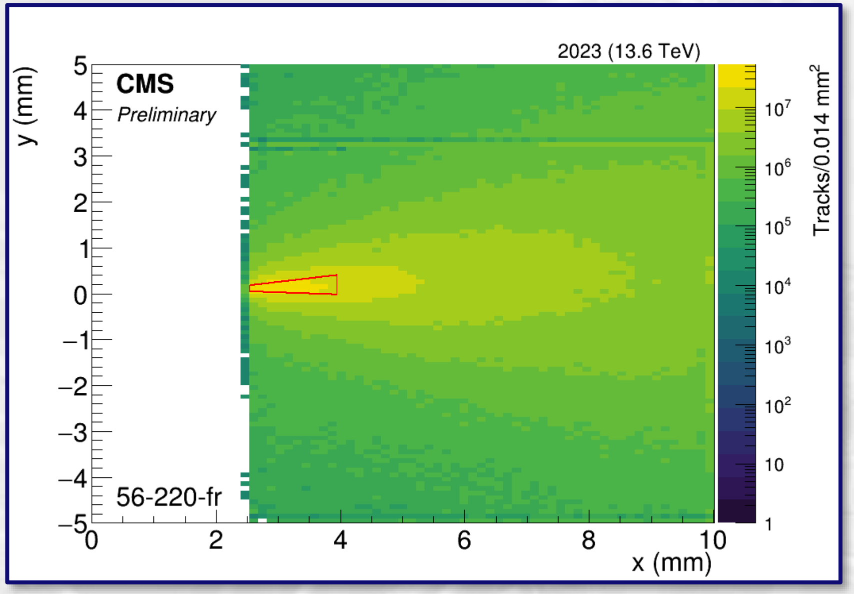
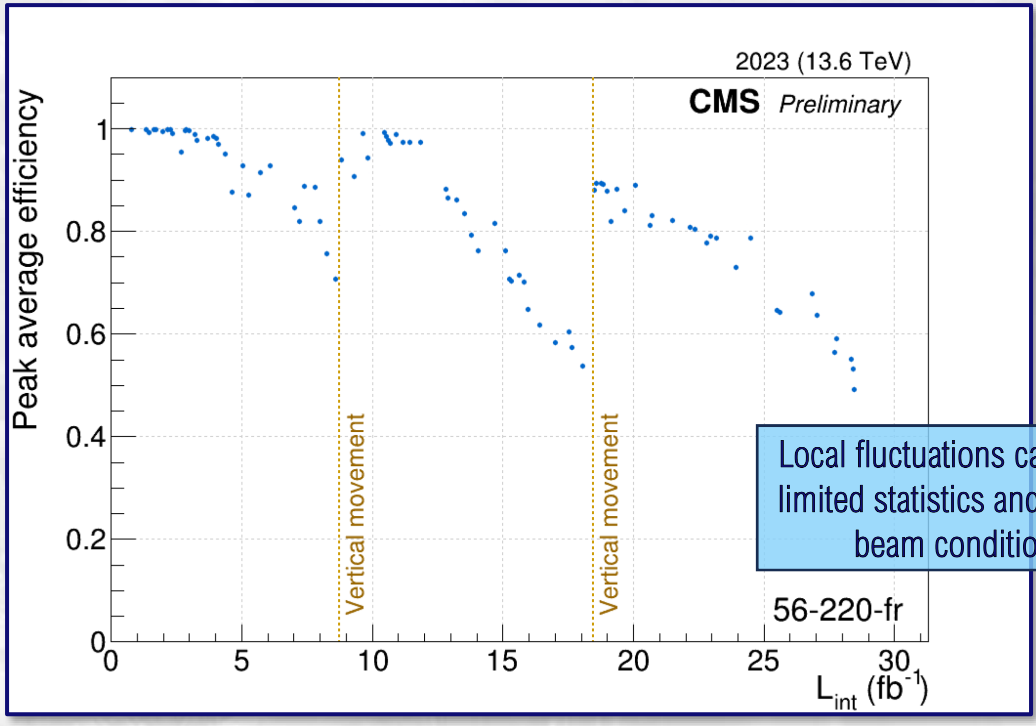
Tracker efficiency in 2023





Local fluctuations caused by limited statistics and varying beam conditions

Preliminary results on the average efficiency in the irradiation peak region:

- The movement assures the recovery of the detector performance
  - Incomplete recovery after the second movement due to the damage still overlapping with the most irradiated region, movement strategy being optimized

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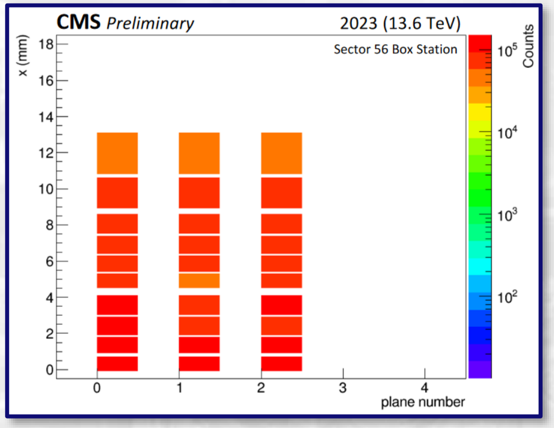
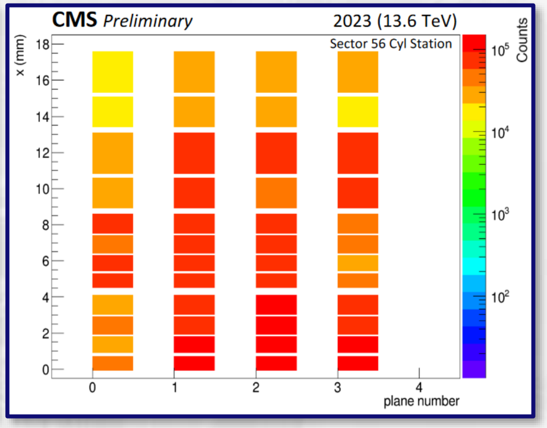
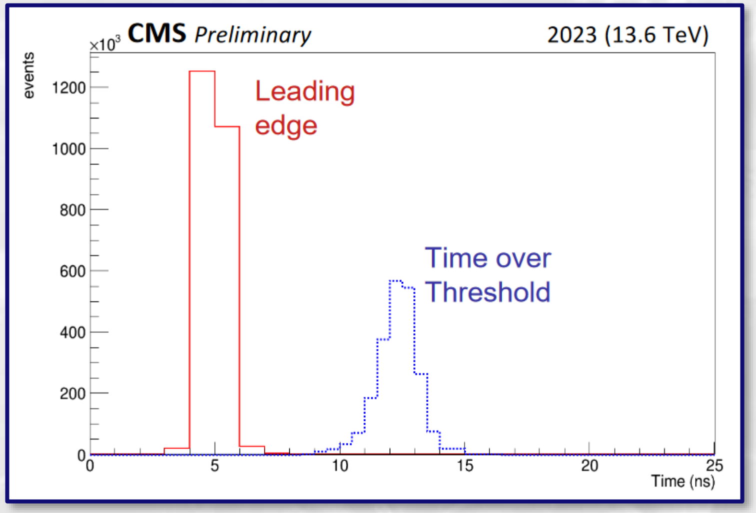
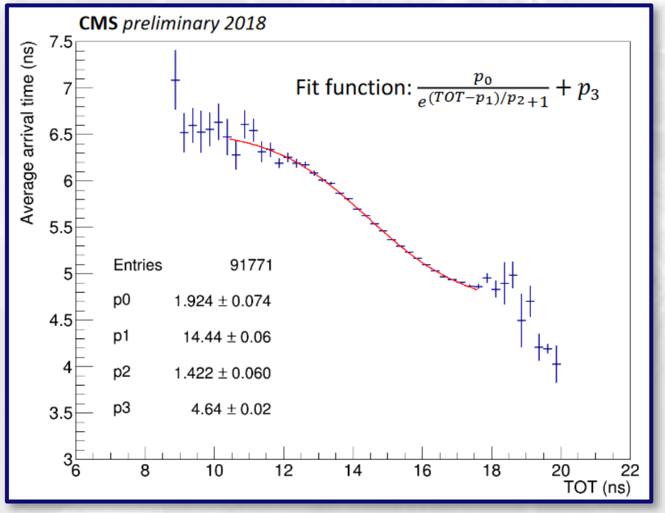
Timing detectors operation

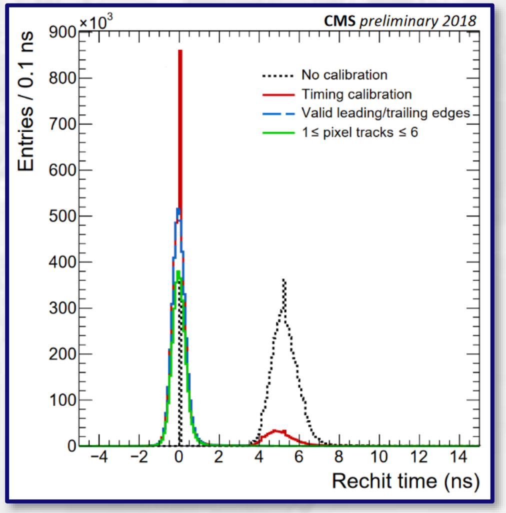
- Detectors operated smoothly in Run 3
- Automation framework developed for calibrations
  1. Correction and alignment of the time of arrival with time over threshold (TOT)
  2. Measurement of the resolution of each channel via inter-calibration procedure

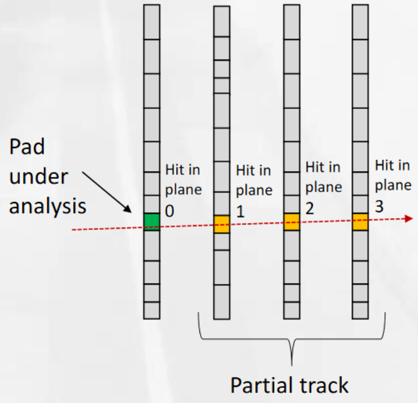












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Timing detectors performance

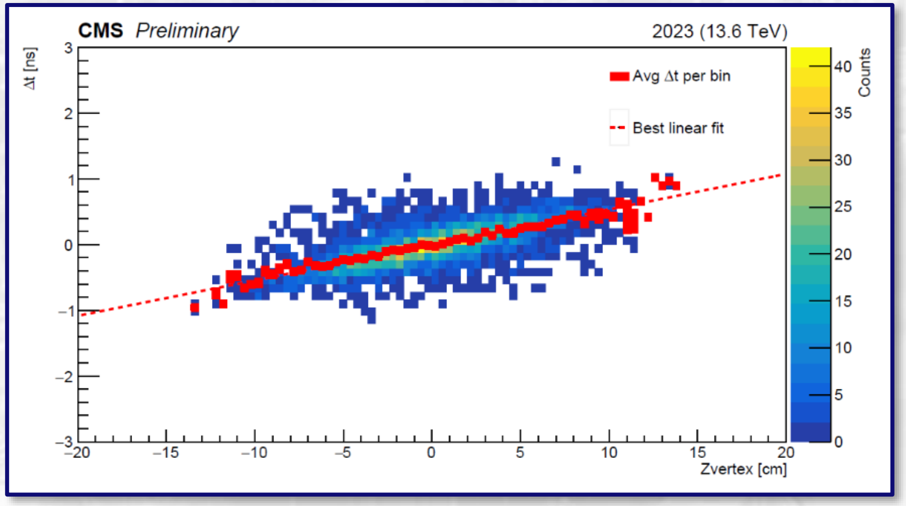
- **Low-PU ($\langle\mu\rangle$=1) ZeroBias data** used to correlate PPS vertex from timing with CMS

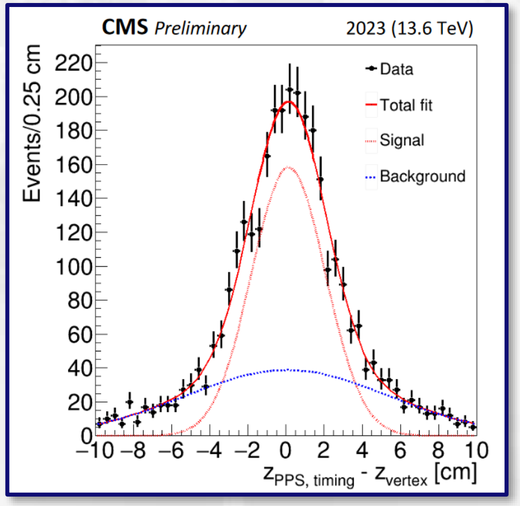
$$z_{\mathrm{PPS,\,timing}} - z_{\mathrm{vertex}} = (c/2 \cdot \Delta t) - z_{\mathrm{vertex}}$$

- Selection: 1 good vertex in CMS and 1 multiRP proton per sector of PPS
- TOT correction applied, but no hit-weighting on the resolution
  - Results are expected to improve once this is finalized

Preliminary results show:

- Good correlation between Δt and z_{vertex}
  - Slope = 0.048 $\pm$ 0.003 ns/cm
  - Expected to be c/2 (0.066 ns/cm) for signal-only events
- 1.9 cm vertex resolution
  - Improvement w.r.t. Run 2 measurement of 2.77 cm





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Summary

The PPS data-taking in CMS Run 3 is ongoing:

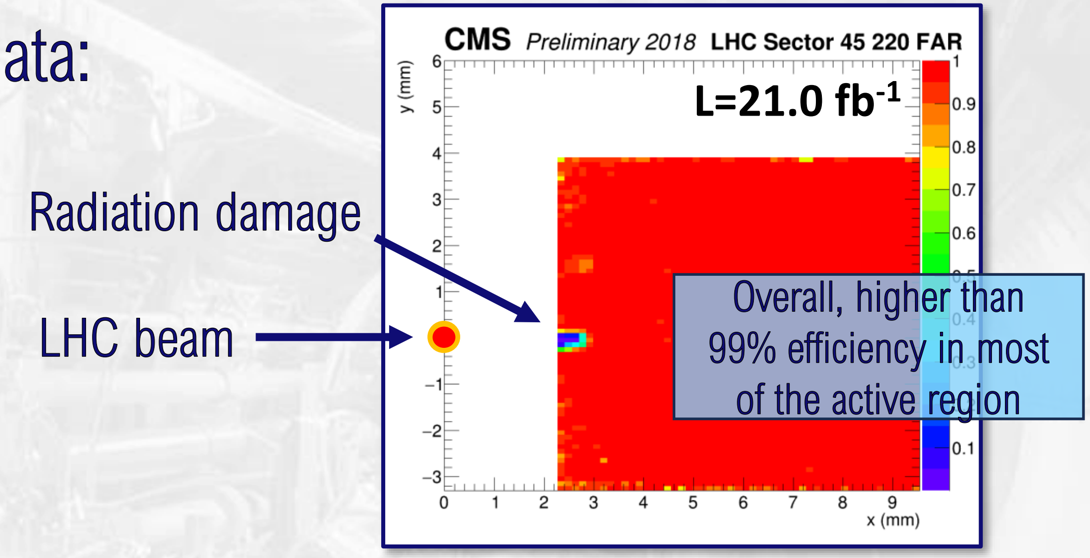
- Preliminary results on the tracking efficiency
  - The detectors are >99% efficient in most of the active region
  - The movement system is effective at maintaining high performance in the most irradiated region
- Preliminary results on the diamond timing detectors
  - Good correlation of the time difference with the vertex longitudinal coordinate
  - Observed vertex z resolution: 1.9 cm – improved w.r.t. Run 2

Backup

Tracker efficiency measurement

Tracker efficiency monitored using LHC data:

- Developed for Run 2 data-taking
- Automated for Run 3



2-step procedure:

1. Estimate the efficiency of each detector plane in a chosen data-taking run
2. Convolve the efficiency of the 6 planes in the detector package to obtain a global track efficiency for the pixel unit, as a function of the track coordinates
   - Proton tracks are mostly parallel, no strong dependence on their angle is observed

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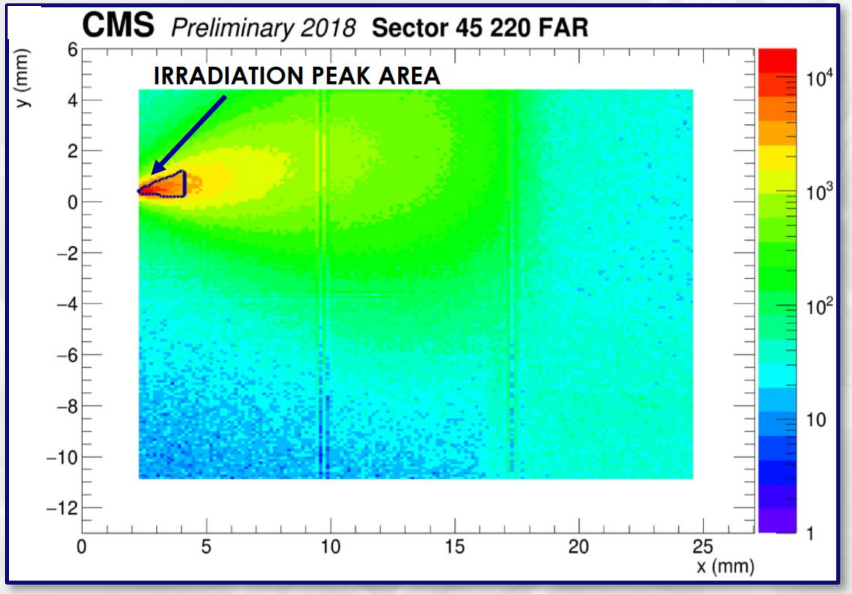
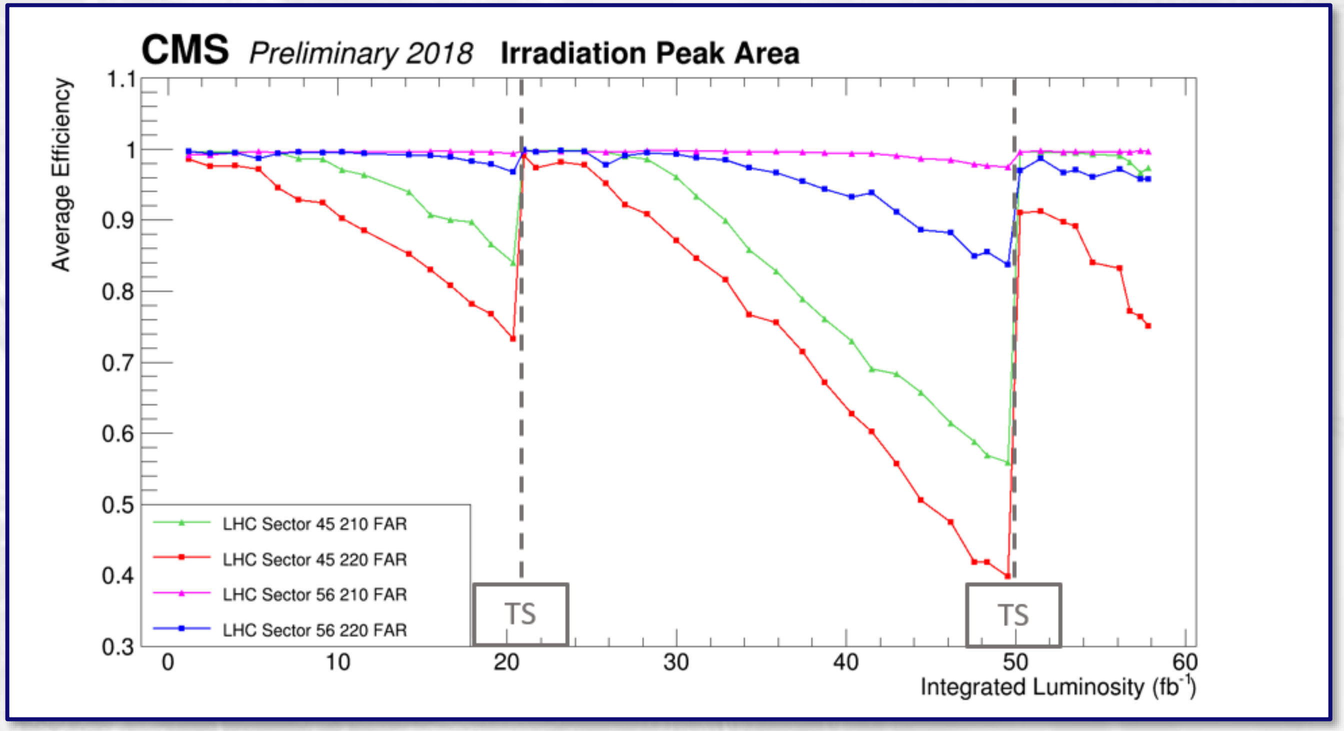
Tracker radiation damage in Run 2





Average efficiency in the irradiation peak studied in Run 2 (2018):

- Differences in efficiency loss mainly due to different irradiation profiles in the stations
- Proved that the manual vertical shift effectively mitigated the loss of performance

PPS opted for more frequent movement strategy for Run 3, not relying on technical stops…

CMS DP-2019/036

Sensor production for Run 3

Specifications:

- Wafer bow < 200 μm
- Depletion voltage $V_{depl} < 10\ V$
- Breakdown voltage $V_{bd} > 50\ V$
- Class A sensors:
  I($V_{op} = V_{depl} + 20\ V$) < 16 μA (@ room temp.)
- $I(x + 2V)/I(x) < 2$

3 wafers bump bonded to PROC600 chips at IZM

- IV measurement repeated after bump-bonding

24 quad modules installed for data-taking

- One sensor per detector plane
- 22 worked well (2 mechanically damaged during assembly)

468 sensors produced

Yield: 50.9 % (all Class A)

Relaxing requirement: $I(x + 2V)/I(x) < 4$

→Yield: 70%