TIPP2023

The CMS Tracker performance in Run 3

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on behalf of the **CMS Collaboration**

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In this talk

Part 1: The CMS Tracker

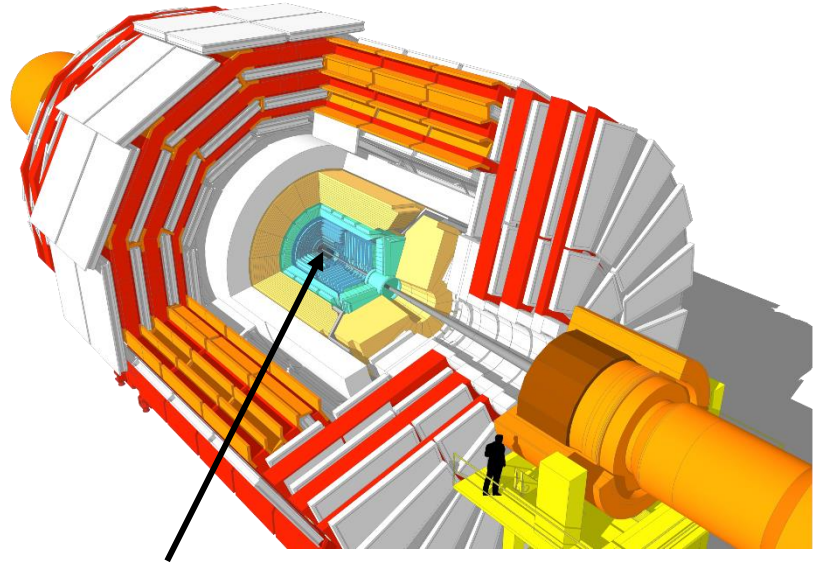
- Detector description
- Detector refurbishment during Long Shutdown 2 (LS2)

Part 2: Performance studies in Run 3

- Silicon Pixel performance [2] [3]
- Silicon Strip performance [4] [5]

Part 3: Tracker alignment and validation

- What is alignment and why it is needed?
- Alignment performance studies [6] [7]

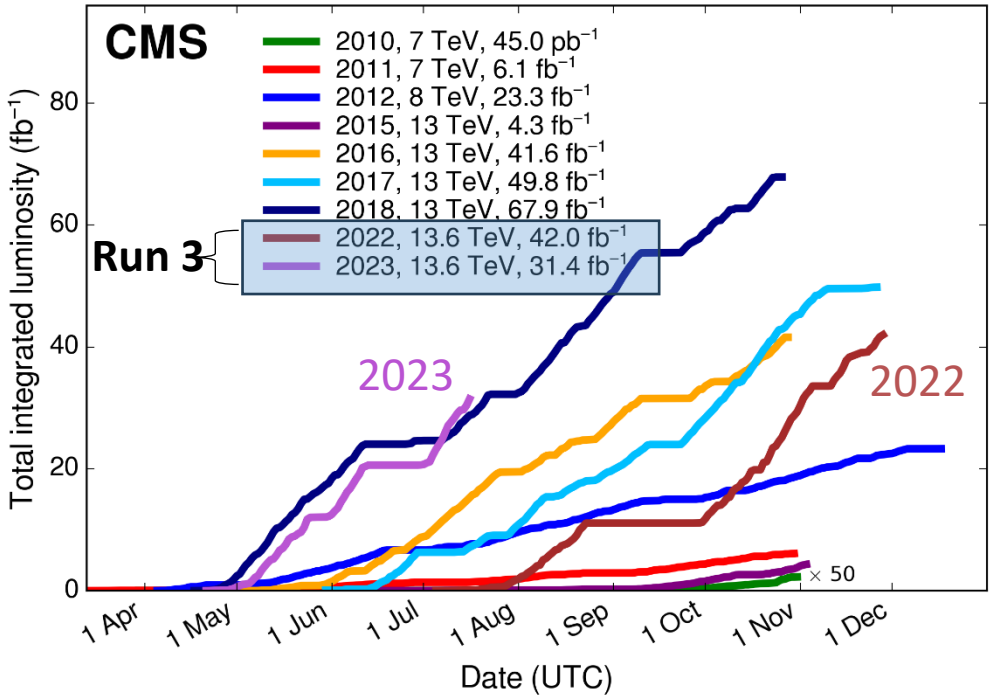


CMS Tracker
Visual from [1]

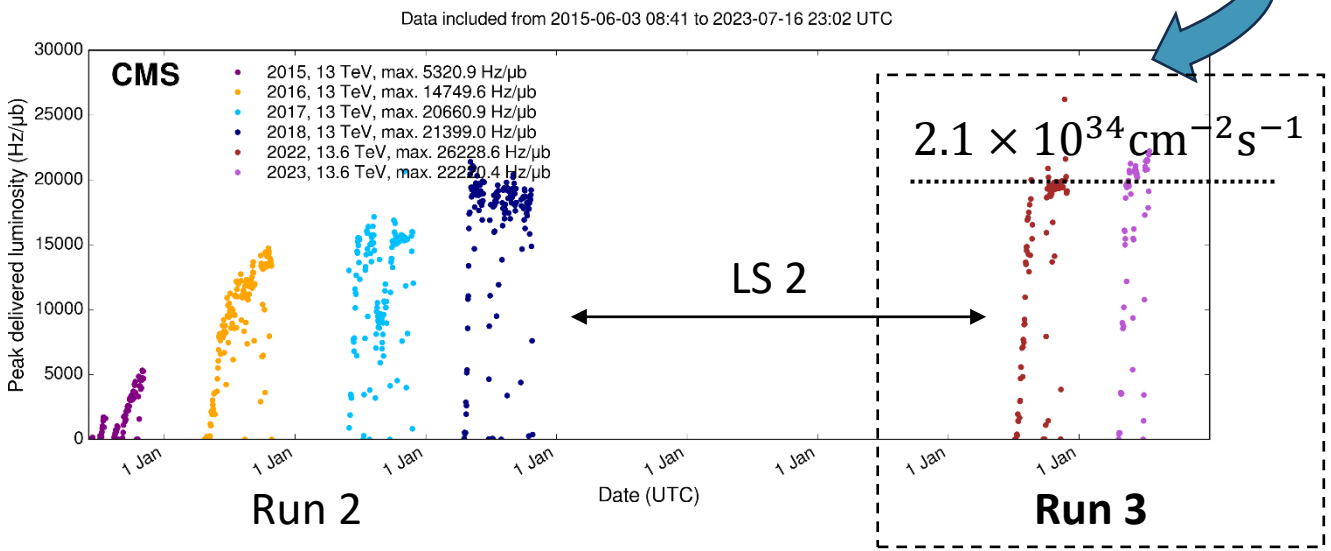
LHC Run 3

CMS delivered **integrated luminosity** [8]

- ❑ Run 1 (2010-12) + Run 2 (2015-18) ≈ 193 fb^{-1}
- ❑ **Run 1 + Run 2 + Run 3 (2022+) ≈ 265 fb^{-1}**



CMS **instantaneous** delivered luminosity



$3{,}6 \times 10^{15} n_{\mathrm{eq}}\mathrm{cm}^{-2}$ →expected particle fluence after $500\mathrm{fb}^{-1}$

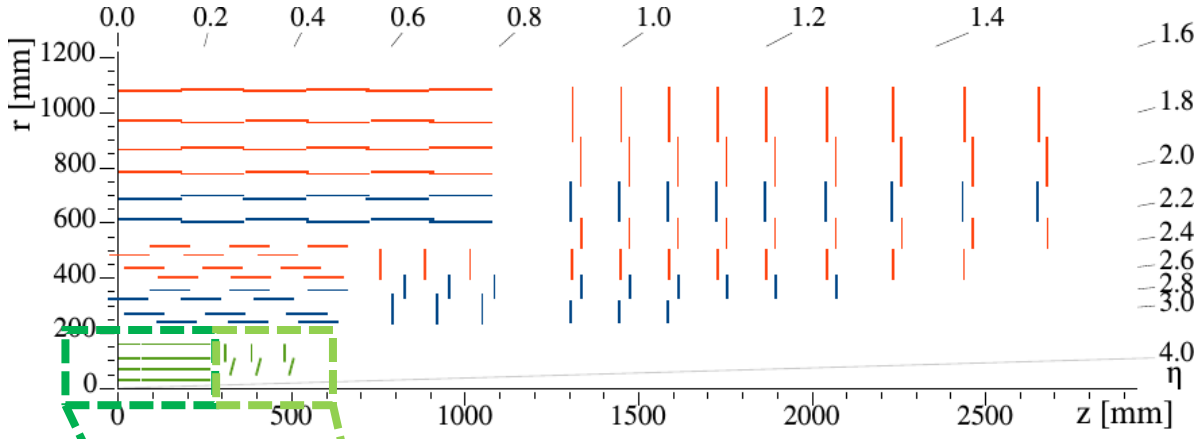
Year	Average pileup
2016	27
2017	38
2018	37
2022	46
2023	52

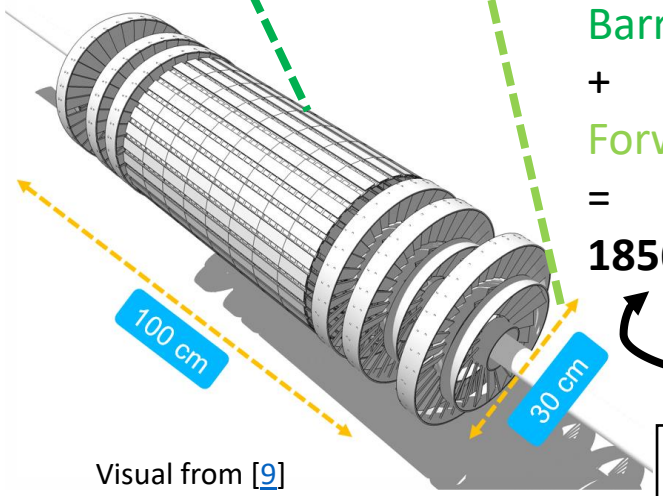
Mean number of interactions per bunch crossing (25ns)

Values at min bias cross section 80 mb

Part 1: The CMS Tracker

CMS Silicon Pixel detector





Visual from [9]

Barrel Pixel (BPIX) ↔ 4 layers

+

Forward Pixel (FPIX) ↔ 3 disks x 2 rings

=

1856 modules with $\approx 124\text{M}$ pixels ($100 \times 150\mu\text{m}^2$)

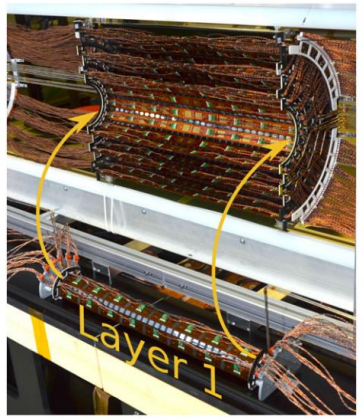
Each sensor connected to 16 readout chips (ROC)

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

- Phase-1 Pixel tracker in place since the end of 2016 (early 2017)
- The detector component **closest to the collision point**

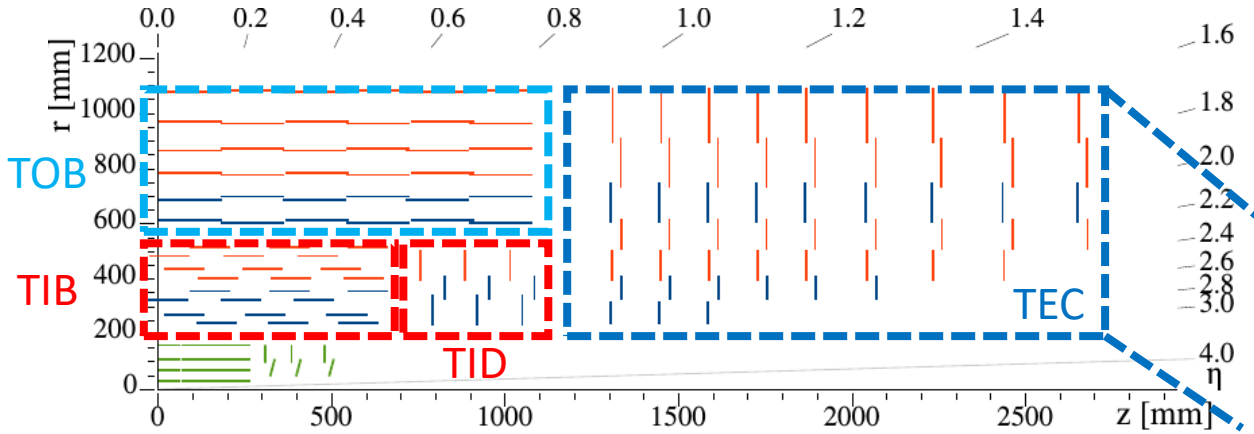
Particle-hit rate up to 600MHz/cm^2 (Layer 1)

- **Pixel refurbished** during LS2 [10]
  - ❑ Layer 1 fully exchanged
    →Improved ROCs (reduced cross-talk noise…)
    →reverse bias up to 800V (compared to 450V before)
  - ❑ Defect Layer 2 modules were replaced



CMS Silicon Strip detector

with us since 2008



Thickness of silicon sensors

- 320 μm (TIB, TID, TEC)
- 500 μm (TOB, TEC)

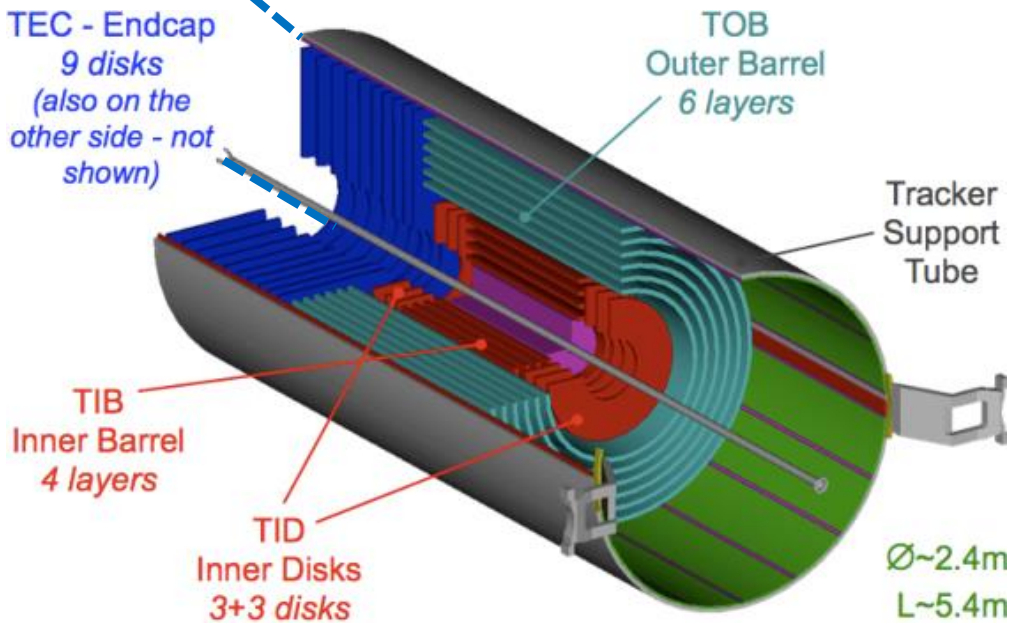
Double-sided stereo modules

- with a stereo angle of 100 mrad
- 2+2 layers (TIB and TOB)
- 3 rings (TID and TEC)
- allow to measure second dimension (z in barrel, r in endcaps)

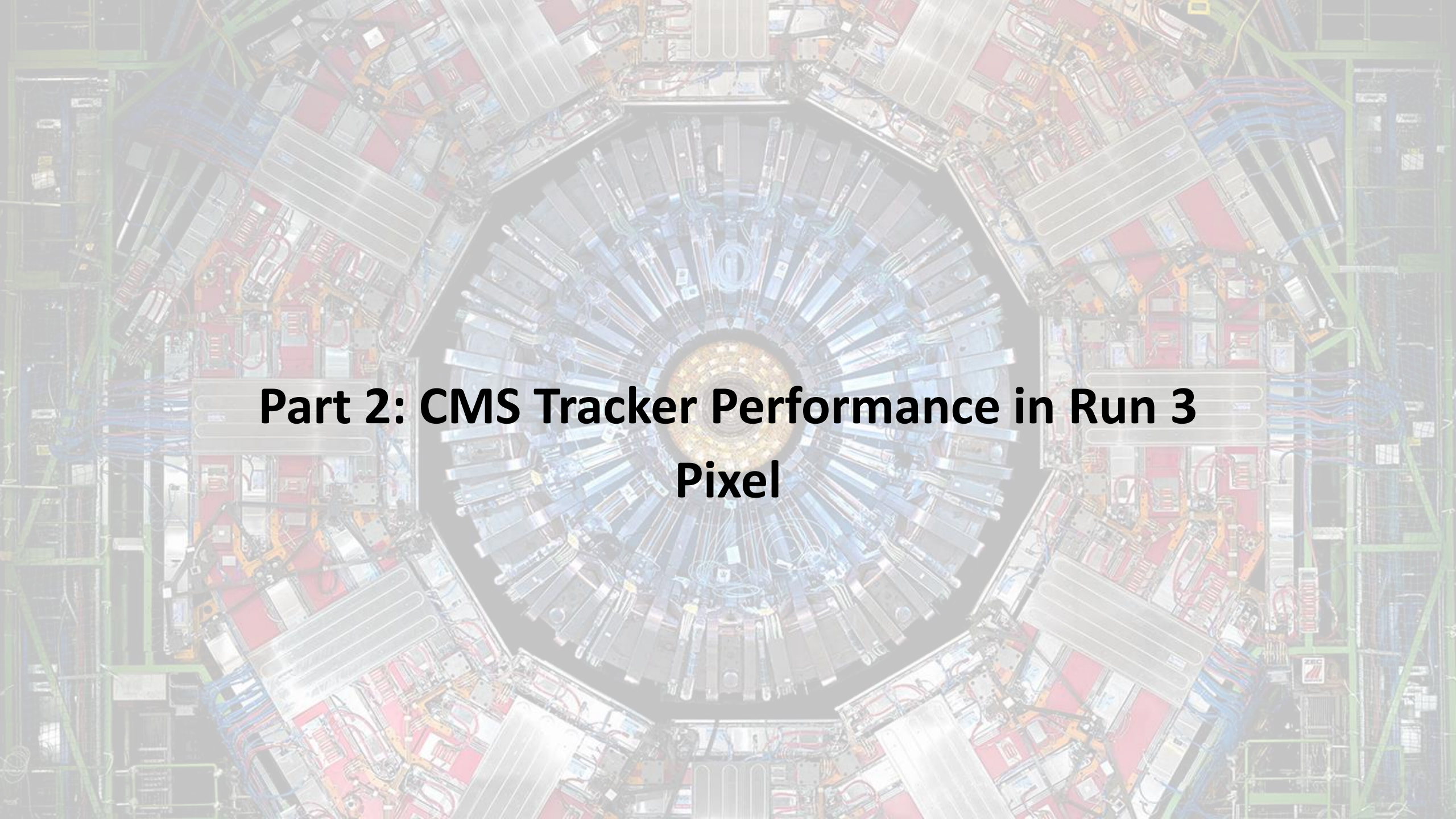
CMS Silicon Strip Tracker

- 15148 modules
- $\approx 200\ \mathrm{m}^2$ of active silicon area
- $\approx$ 9M analogue readout channels

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



Visual from [11]

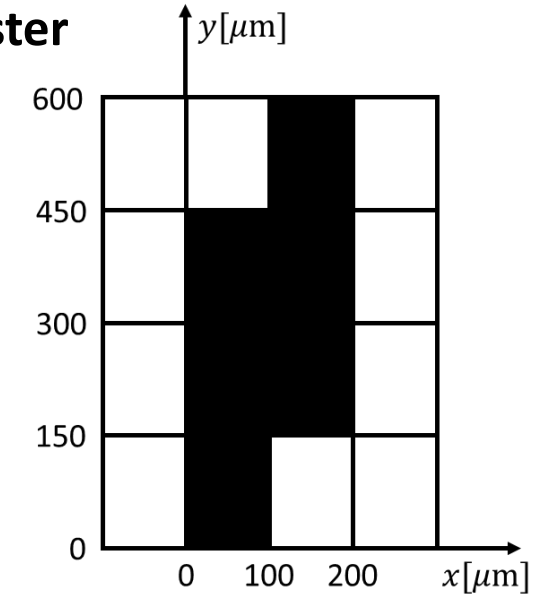


Part 2: CMS Tracker Performance in Run 3

Pixel

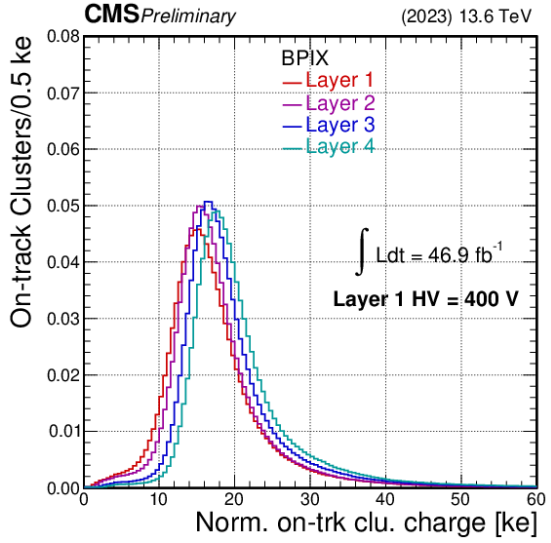
Pixel performance – cluster properties

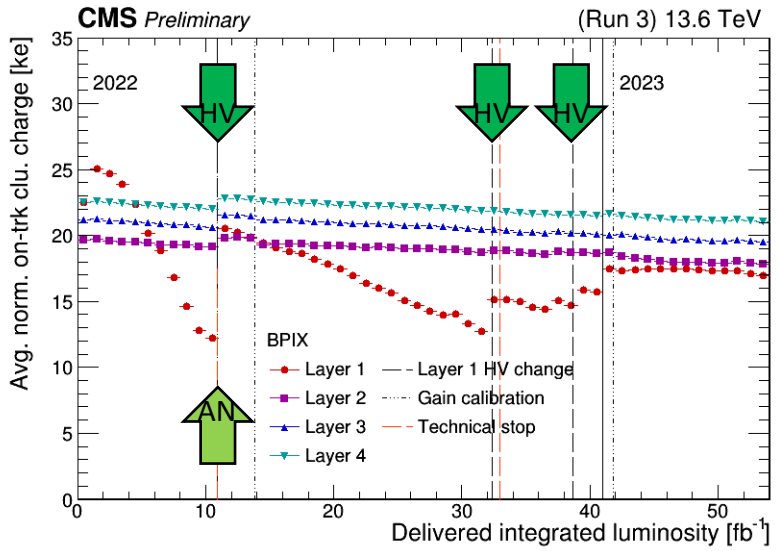
- **Hit position interpolated using** the charge information from all pixels in the **cluster**
- **Cluster is formed of adjacent pixels** with a charge above certain threshold



Radiation damage → Loss in charge collection efficiency

Cluster charge distribution in **BPIX**:





Note:

- ❑ Non-irradiated detector would exhibit flat charge trend in time
- ✓ **Solution:** increase operational bias voltage

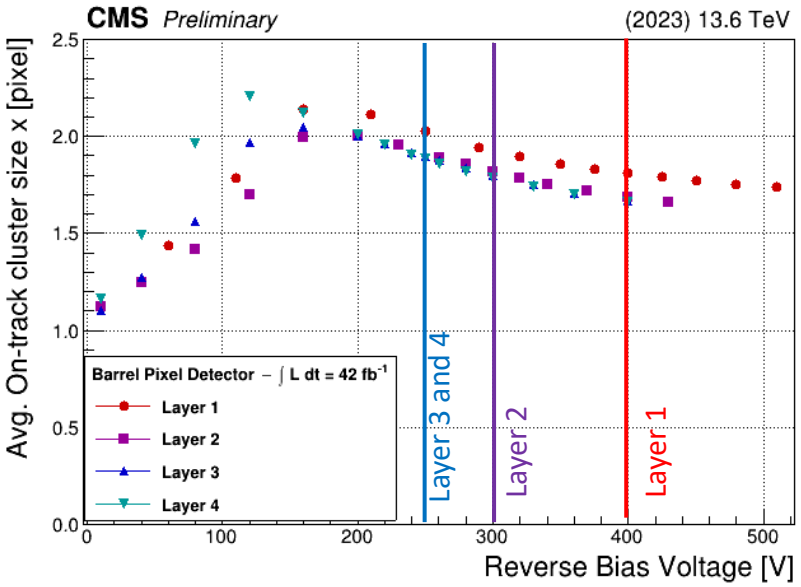
  Layer 1 gradually from 150 → 400 V
- ✓ **Solution:** annealing sensors when possible

  Visible at ~11fb^{-1} also for other layers

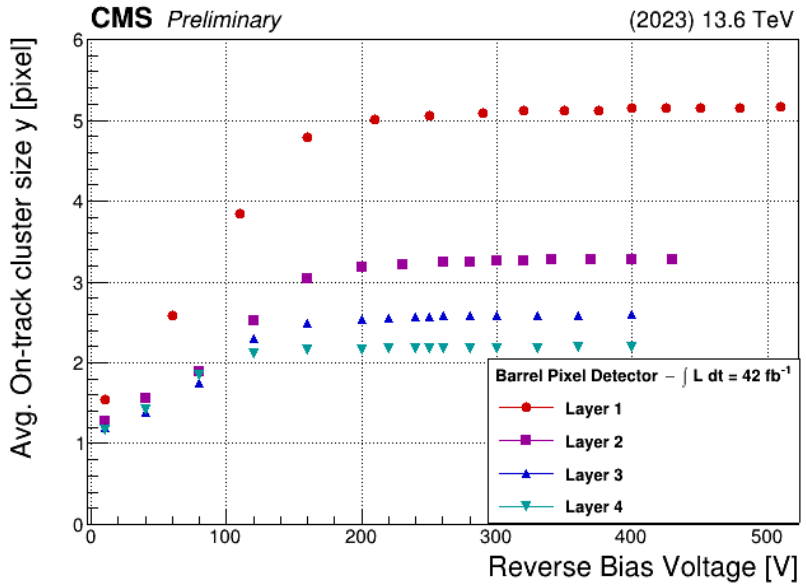
Pixel performance – HV bias scans

- **Target:** To determine operational bias voltage for pixel sensors
- **Monitored factors**: hit efficiency, **cluster size** & charge

Cluster size **in x-direction** (BPIX)



Cluster size **in y-direction** (BPIX)



Note:

- ❑ Trend change of the cluster size in **x-direction** comes from **2 competing effects:**

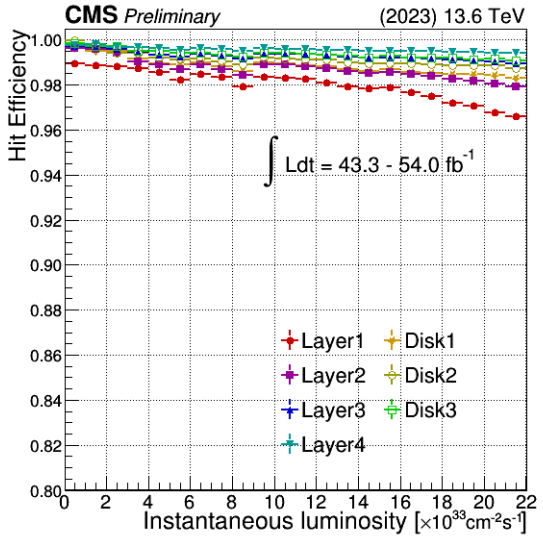
1. Volt. Bias ↑ ⟹ charge coll. ↑
2. Volt. Bias ↑ ⟹ charge sharing ↓

Pixel performance – hit efficiency

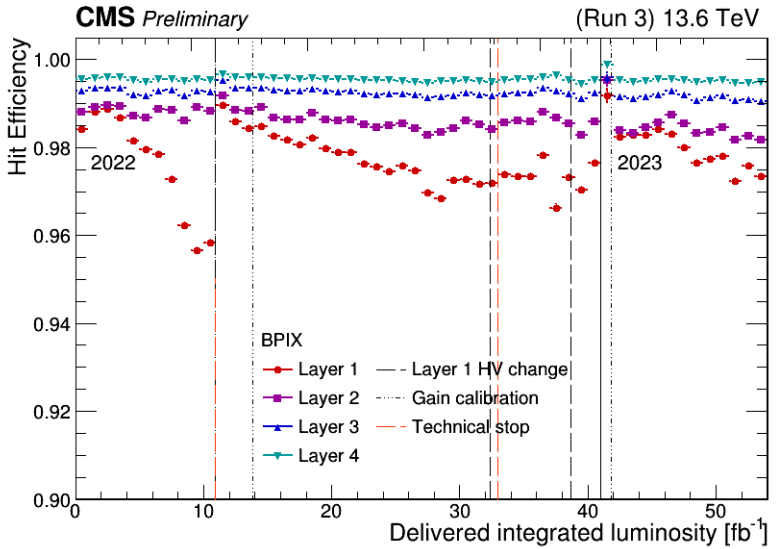
- **Definition:** Probability to find any cluster within $1\ \mathrm{mm}$ around an expected hit (independent of the cluster quality)
- **Bad components are excluded** from the measurements (~5%); measured using **muon tracks**

Run 3	**BPIX L1** can now operate at $> 96\%$ hit efficiency	At $2.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of inst. lumi
	BPIX L2-4 and FPIX $> 98\%$ hit efficiency	

BPIX+FPIX:



BPIX:

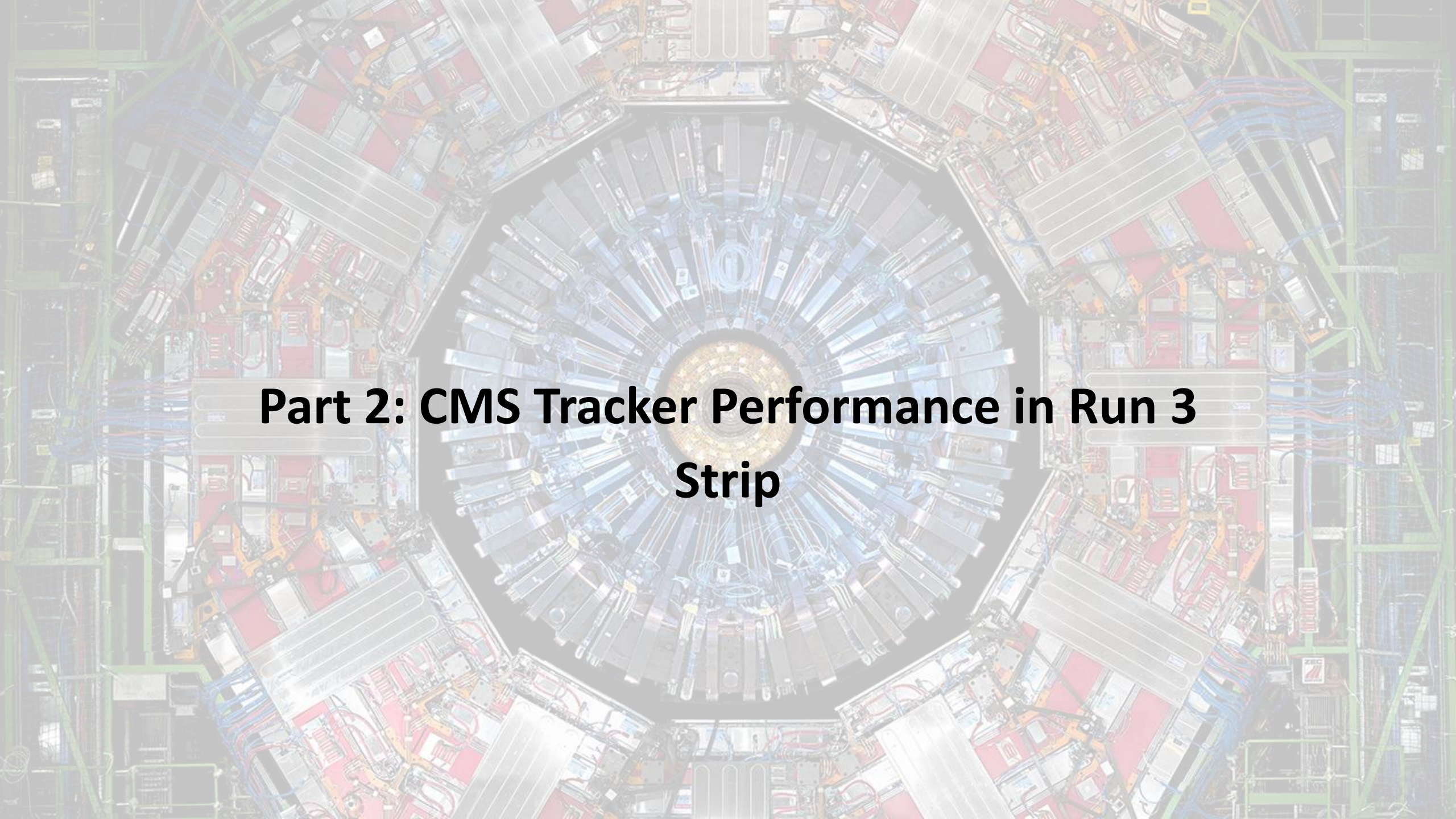


Note:

- ❑ Trend (mostly L1) shows degradation because of radiation
- ✓ Solution: HV increase and update of the Lorentz angle
- ❑ **LHC now stable at** inst. lumi = $2.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Similar performance as in Run 2 [11] ($1.8 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$):

$> 97\%$(BPIX L1); $> 99\%$ (BPIXL234+FPIX)



Part 2: CMS Tracker Performance in Run 3

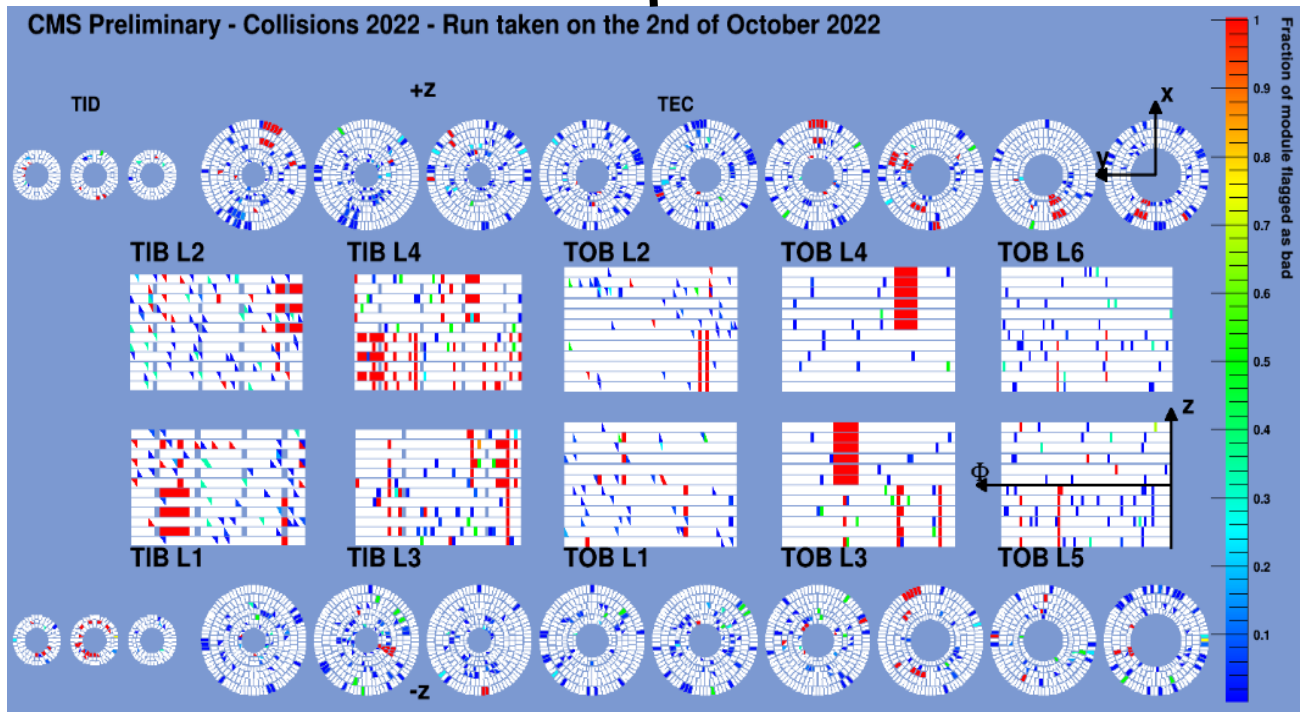
Strip

Strip performance – hit efficiency

- Trajectories passing near the edges of sensors are excluded from measurement
- **Known bad components are not used** in the measurement
- Using the 13.6 TeV data (2022) with a **standard/high lumi fills** for inst. lumi under/over $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

≈ 96% of all components is functional in Run 3

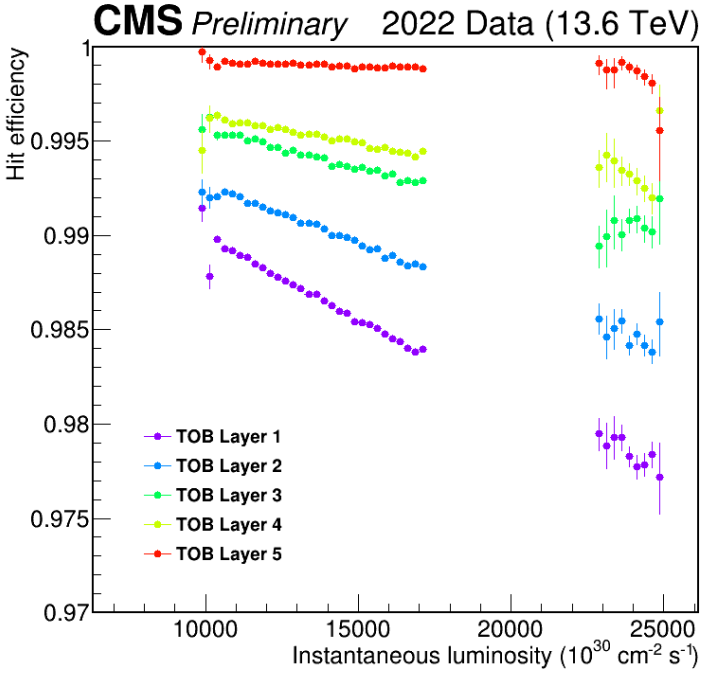
Bad-component situation in Run3 is similar to Run2



Hit eff. for 5 TOB layers:

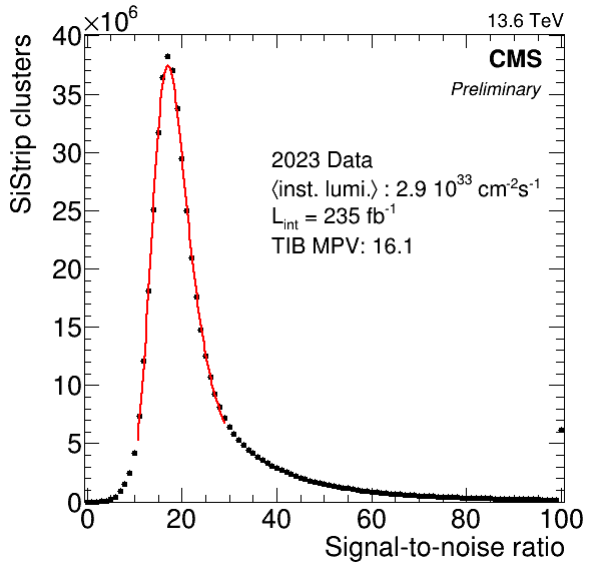
Excellent Run3 hit efficiency
TOB: $> 97.5\%$
TIB: $> 98.5\%$

Run 2 ($1.8 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
TOB: $> 98\%$
TIB: $> 99\%$

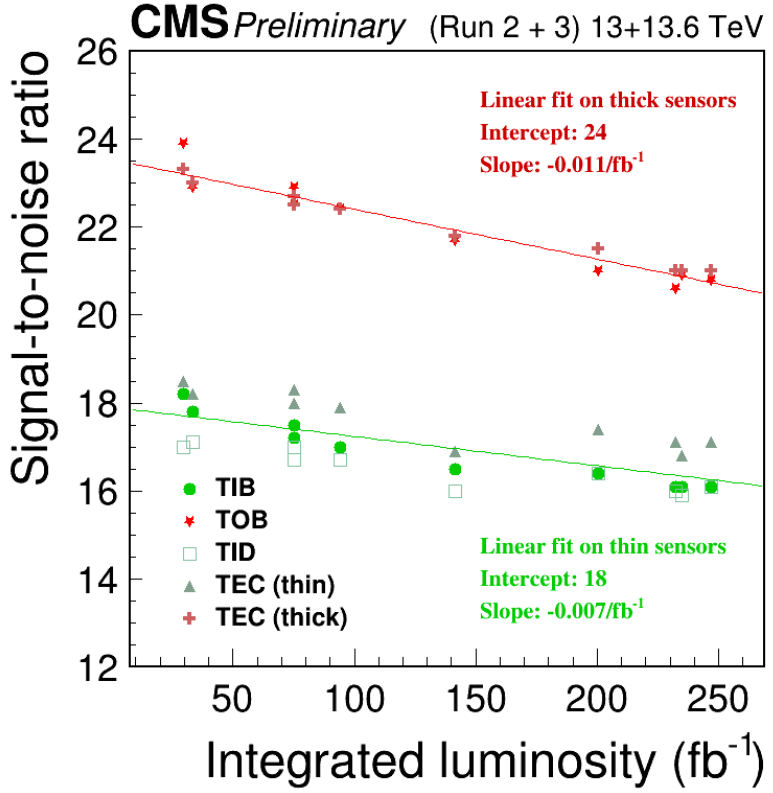


Strip performance – S/N ratio

- **Signal-to-noise ratio** measured regularly, including early 2023 13.6TeV data
- High S/N ratio ensures **better zero suppression and proper cluster buildup**



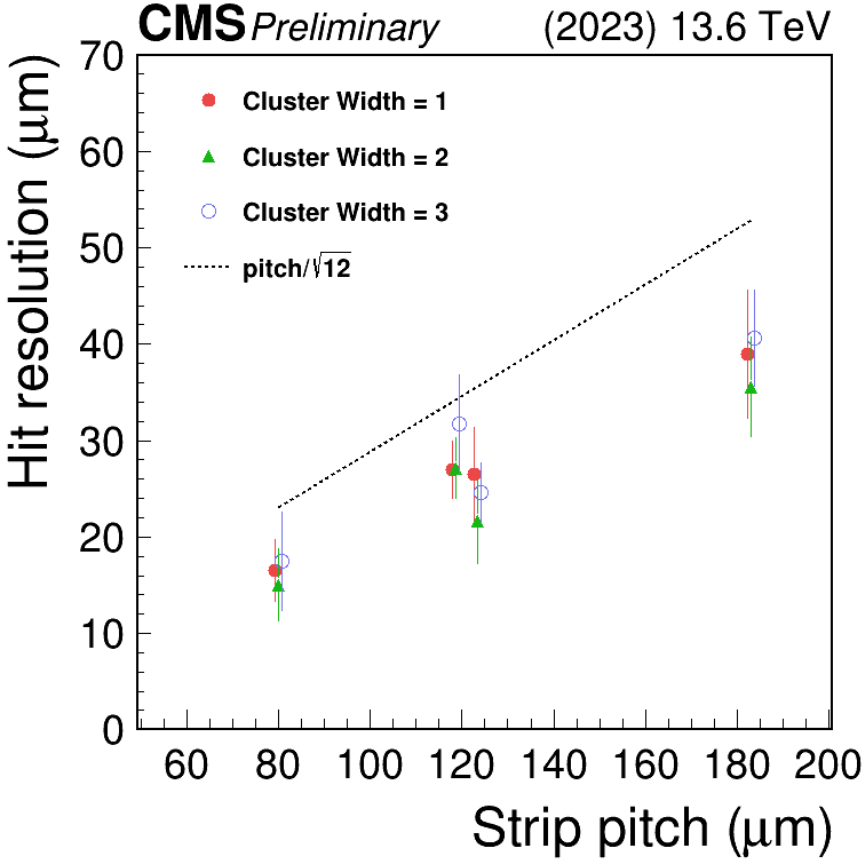
S/N ratio obtained for life-time integrated lumi of 235fb^{-1}



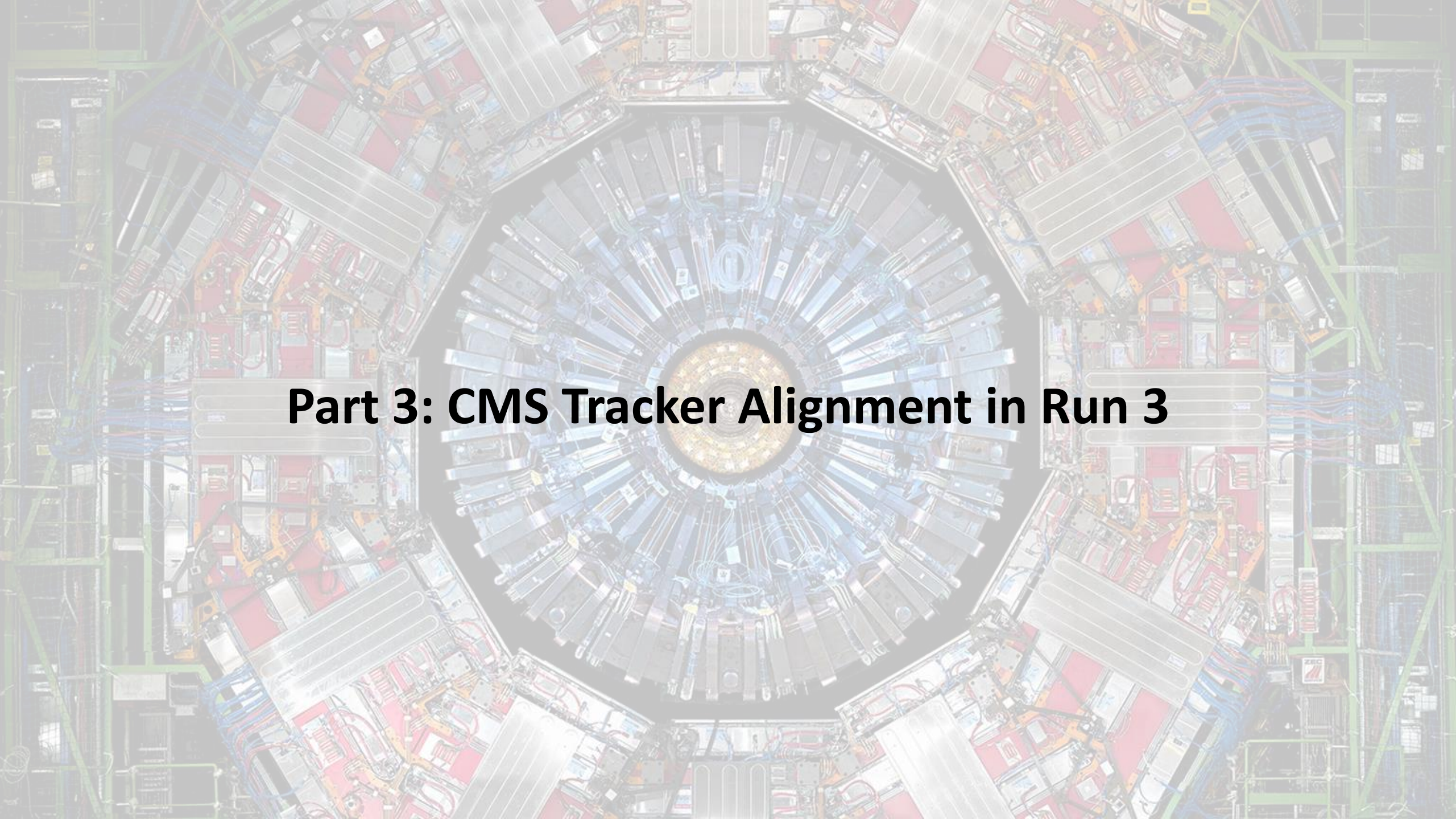
- Trend shows decreasing slope as expected from irradiation studies
- Measured separately for $320\ \mu\text{m}$ and $500\ \mu\text{m}$ sensor thickness
- Extrapolation at 500fb^{-1}:
  - ⇨ 18.5
  - ⇨ 14.5

Strip performance – hit resolution

- **Pair method:** 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 is better than expected resolution** for a pitch$/\sqrt{12}$
  - ✓ demonstrating benefits of the charge sharing



Part 3: CMS Tracker Alignment in Run 3

Tracker alignment

- Detector designed with excellent **hit resolution** $\sigma_{\text{hit}} \approx \mathcal{O}(10\mu\text{m})$
- But burdened by suboptimal **precision of mechanical alignment** $\sigma_{\text{align}} \approx \mathcal{O}(100\mu\text{m})$

Problem leading to limited performance

Figure from [13]

$\sigma_{\text{align}} \gg \sigma_{\text{hit}}$

Alignment narrowed down to minimization problem

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

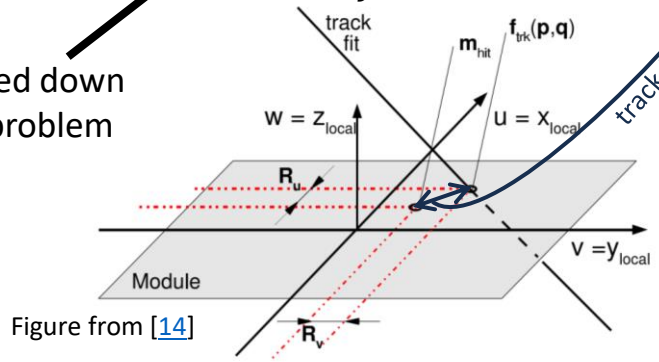


Figure from [14]

Parameter space

Module p + Track q
$\sim\mathcal{O}(1\text{M})$

$\sigma_{\text{align}} \approx \sigma_{\text{hit}}$

Alignment is time-dependent:

- ❑ Magnet cycle $\mathcal{O}(1\text{mm})$
- ❑ Cooling cycle $\mathcal{O}(10\mu\text{m})$
- ❑ Irradiation $\mathcal{O}(1\mu\text{m})$

Solved by track-based alignment

Online
Automated alignment
Higher-level structures

Offline
Higher track statistics
Superior granularity

Primary Vertex validation (2023)

- Performance measured by a quality of **PV reconstruction**
- **Target:** distributions of **track-vertex residuals** (i.e. impact parameters)
- Indicates **physics object performance in the Pixel**

Which 2023 alignment conditions?

Time order:

Granularity:

BPIX (FPIX): ladders (half-cylinders)
Strip: half-barrels and half-cylinders

Pixel: single modules
Strip: fixed in the fit

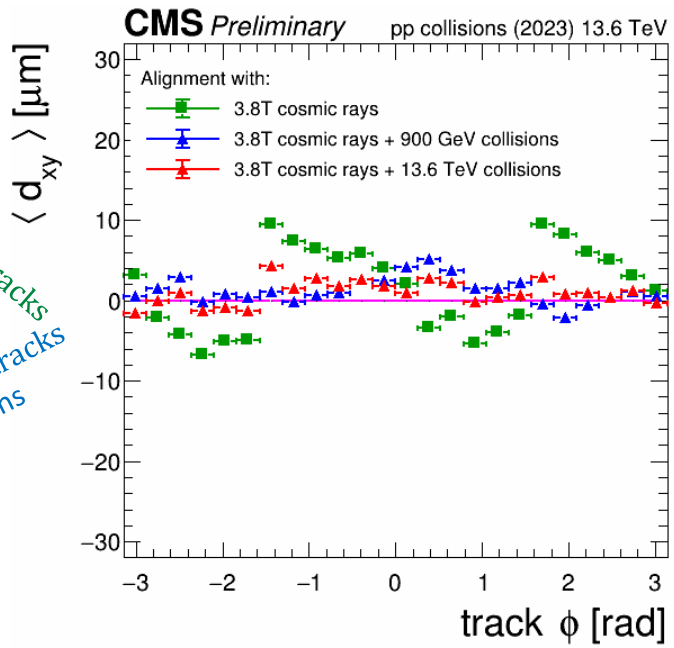
BPIX (FPIX): ladders (panels)
Strip: fixed in the fit

Statistics:

≈ 187k cosmic ray tracks

≈ 71k cosmic ray tracks
≈ 4.5M pp collisions

≈ 295k cosmic ray tracks
≈ 16M pp collisions

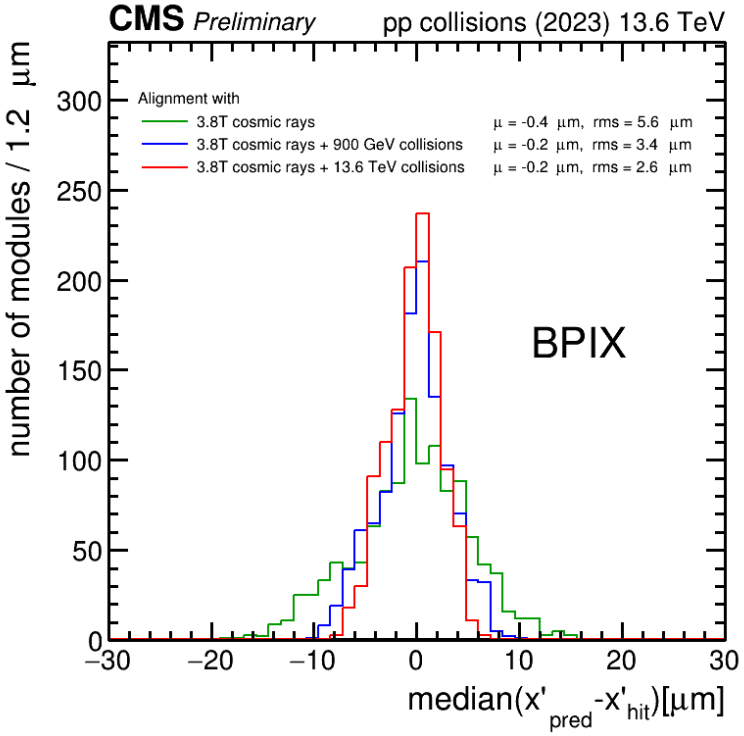


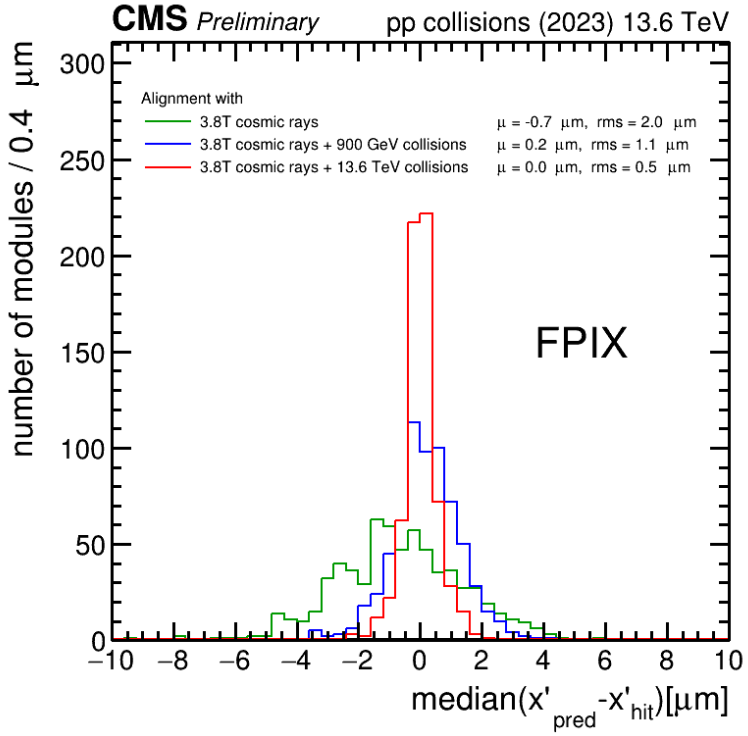
Note:

- ❑ **PV are first refitted** removing the track under scrutiny
- ❑ Perfectly aligned detector would show flat distribution centred at zero
- ❑ Improvement visible for alignment at higher granularity and using higher statistics

Distribution of median residuals (2023)

- Median of **track-hit residuals** $x'_{\mathrm{pred}} - x'_{\mathrm{hit}}$ is determined for a given number of tracks
- Tracker geometry in 2022 → starting geometry in 2023





Note:

- ❑ **Tracks are first refitted** removing the hit under scrutiny
- ❑ Perfectly aligned detector would show **DMR centred at zero**
- ❑ **Width** of DMR indicates **local alignment precision**

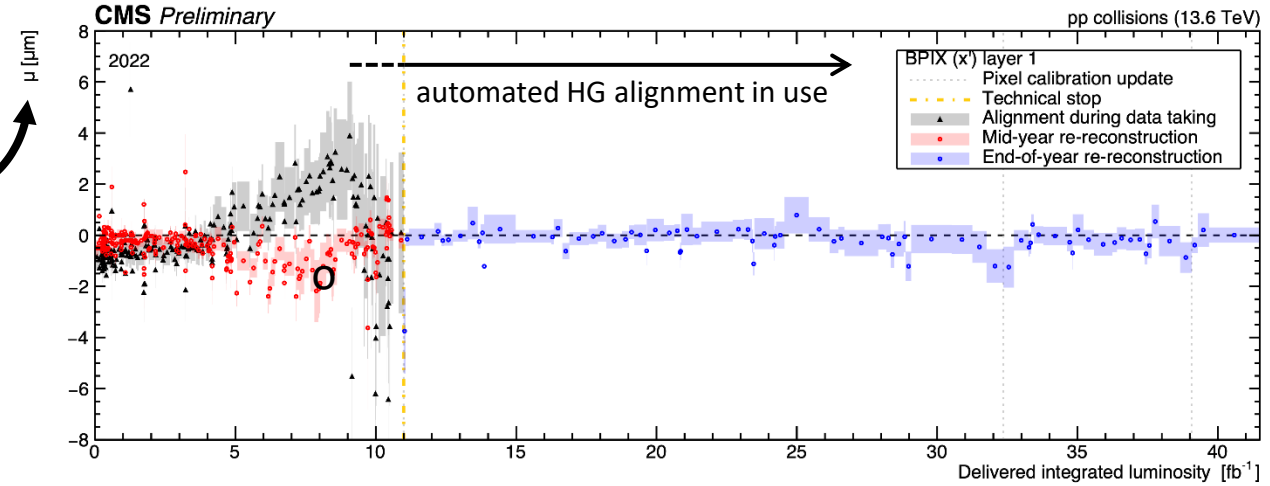
Alignment validation in 2022 - trends

Black: automated (online) Low Granularity alignment (high level structures)

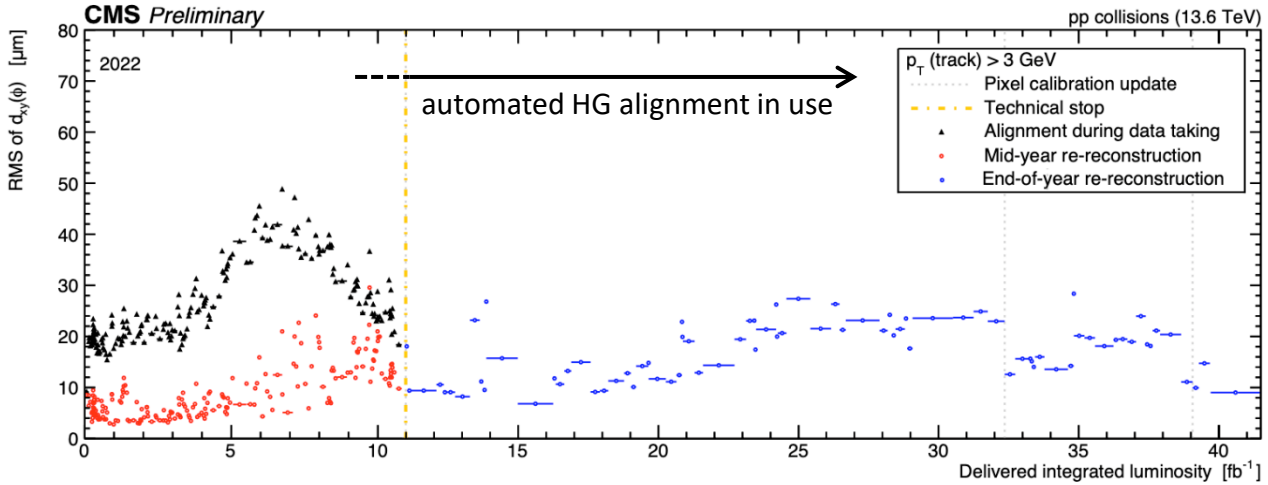
Red: refined offline + High Granularity automated alignment (last 2 fb^{-1} before Technical stop)

Blue: High Granularity alignment for remaining 30 fb^{-1} of 2022 (level of ladders and panels)

Mean of DMR trend



RMS of the average d_{xy} in bins of the track azimuth



- Milestone reached of adding HG automated alignment
- Both DMR mean and width increasingly improved
- Comparable physics performance achieved for automated alignment

Conclusions

- **Challenging conditions** ↔ LHC is stable at providing inst. luminosity of $2.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (expected value till the end of Run 3)
- **The CMS Tracker is in the excellent state,** behaved properly from the beginning of Run-3 and is expected to continue doing so till the end of Run 3
  - ❑ BPIX Layer 1 fully exchanged (new readout chip) during LS2
  - ❑ Excellent hit efficiency/resolution, minimum of bad components …
- Ageing/Irradiation effects visible ↔ successful attempts to mitigate them
  - ❑ Robust monitoring of the Tracker allows for the active intervention
- Excellent results with offline/automated Tracker Alignment in 2022/23 → more dedicated campaigns yet to come

References:

[1] Tai Sakuma and Thomas McCauley 2014 *J. Phys.: Conf. Ser.* **513** 022032. URL: Detector and Event Visualization with SketchUp at the CMS Experiment – IOPscience

[2] CMS Collaboration. Performance of the CMS phase-1 pixel detector with Run 3 data. URL: https://cds.cern.ch/record/2839741?ln=en

[3] CMS Collaboration. Pixel Detector Performance in early 2023. URL: http://cds.cern.ch/record/2865842/files/DP2023_041.pdf

[4] CMS Collaboration. CMS Silicon Strip Tracker Performance Results in 2022. URL: https://cds.cern.ch/record/2860872?ln=en

[5] CMS Collaboration. CMS Silicon Strip Tracker Performance in 2023. URL: https://cds.cern.ch/record/2865841/files/DP2023_040.pdf

[6] CMS Collaboration. Tracker alignment performance in 2022. URL: http://cds.cern.ch/record/2845618/

[7] CMS Collaboration. Tracker alignment performance in early 2023. URL: http://cds.cern.ch/record/2865840

[8] CMS Luminosity public results. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Run_3_charts_of_luminosity

[9] Tamas Almos Vami for the CMS Collaboration. Calibration and performance of the CMS pixel detector in LHC Run 2. arXiv:1909.12920v1

[10] Lars O. S. Noehte for the CMS Collaboration. CMS Phase-1 pixel detector refurbishment during LS2 and readiness towards the LHC Run 3. https://iopscience.iop.org/article/10.1088/1748-0221/17/09/C09017/pdf

[11] Giacomo Sguazzoni for the CMS Collaboration. The construction of the CMS Silicon Strip Tracker. URL: https://arxiv.org/pdf/0801.2468.pdf

[12] CMS Collaboration. The Performance plots for Phase 1 Pixel Detector, August 2018. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsAugust2018

[13] Bartosik N. Associated top-quark-pair and b-jet production in the dilepton channel at s√ = 8 TeV as test of QCD and background to tt+Higgs production. URL: https://bib-pubdb1.desy.de/record/222384

[14] Musich M. The Alignment of the CMS Tracker and its Impact on the early Quarkonium Physics URL: http://musich.web.cern.ch/musich/PhDThesis_Musich.pdf

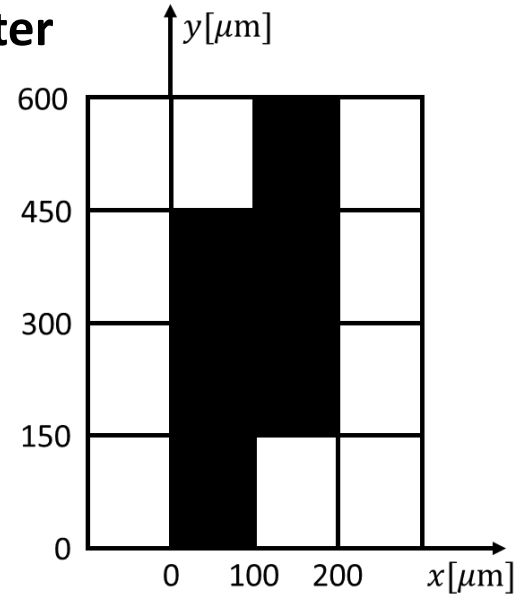
Thank you for your attention!

Contact: tomas.kello@cern.ch

BACKUP

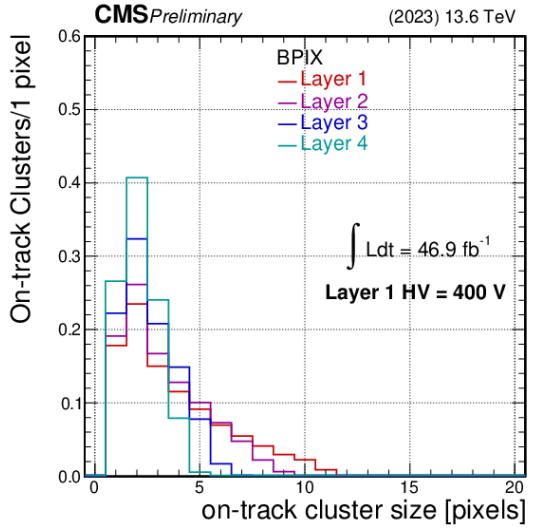
Pixel performance – cluster properties

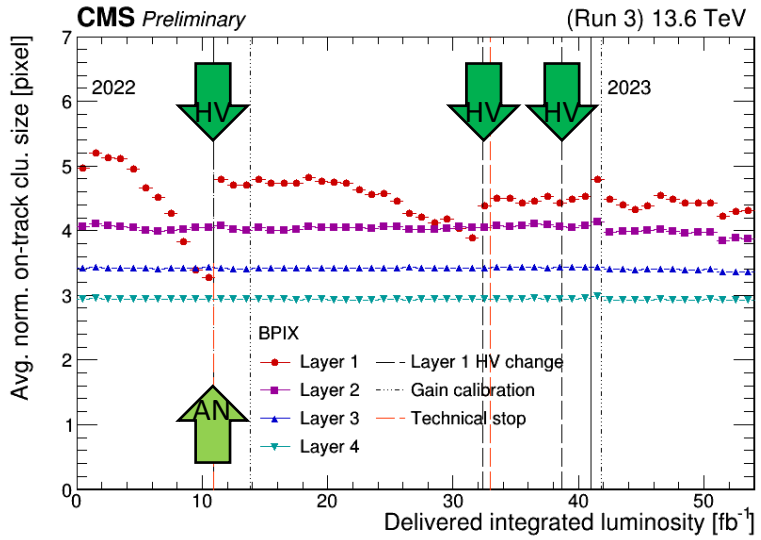
- **Hit position interpolated using** the charge information from all pixels in the **cluster**
- **Cluster is formed of adjacent pixels** with a charge above certain threshold



Radiation damage → Loss in charge efficiency ↔ Cluster size defined by charge distribution

Cluster **size in y-direction in BPIX**:





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- ✓ **Solution:** increase operational bias voltage

  Layer 1 gradually from 150 → 400 V
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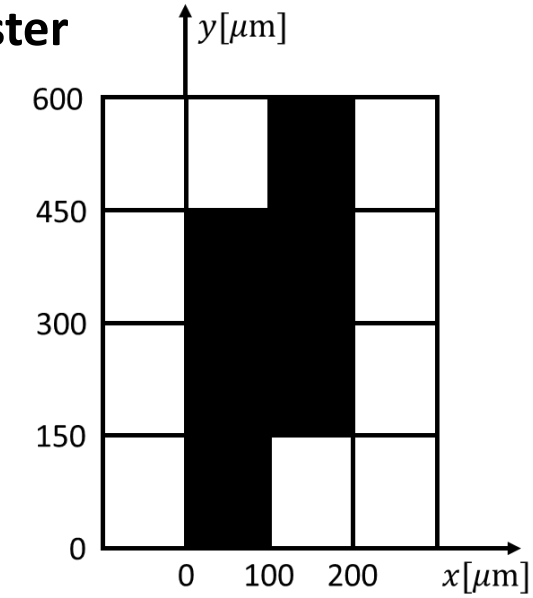
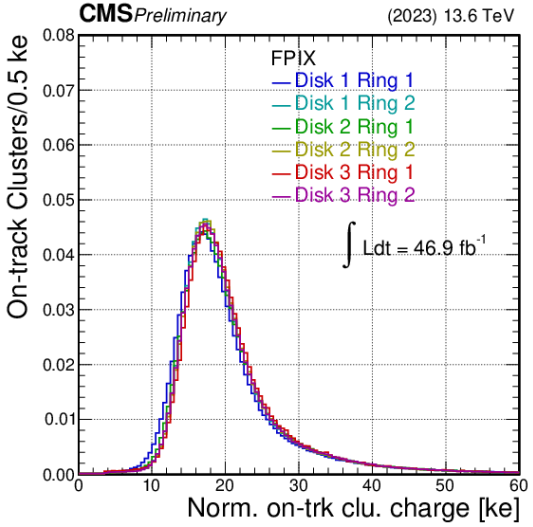
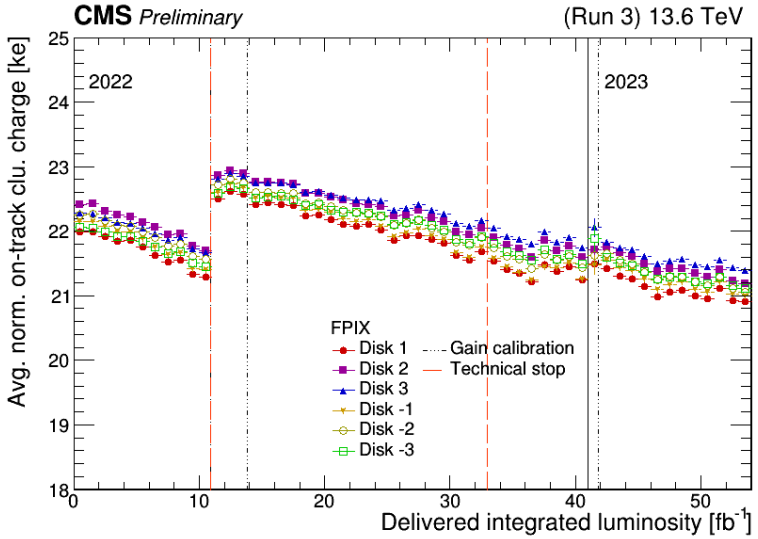


Radiation damage → Loss in charge collection efficiency

Cluster charge distribution in **FPIX**:





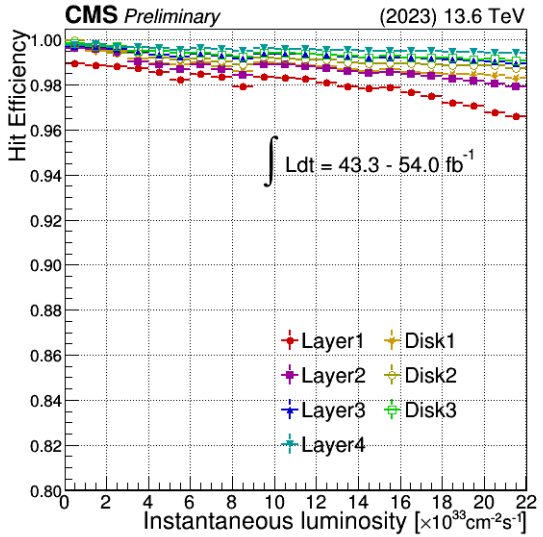
- ❑ Non-irradiated detector would exhibit flat charge profile in time
- ❑ Increase in charge during technical stop due to the new gain calibration
- ❑ Much narrower y-axis range compared to BPIX

Pixel performance – hit efficiency

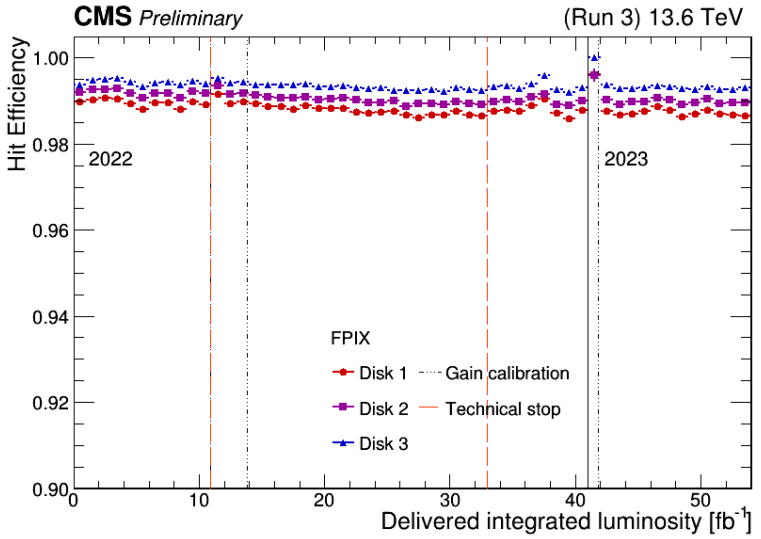
- **Definition:** Probability to find any cluster within $1\ \mathrm{mm}$ around an expected hit (independent of the cluster quality)
- **Bad components are excluded** from the measurements; measured using **muon tracks**

Run 3	**BPIX L1** can now operate at $> 96\%$ hit efficiency **BPIX L2-4 and FPIX** $> 98\%$ hit efficiency	At $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of inst. lumi

BPIX+FPIX:



FPIX:



Note:

- ❑ Trend (mostly L1) shows degradation because of radiation
- ✓ Solution: HV increase and update of the Lorentz angle
- ❑ **LHC now stable at** inst. lumi = $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

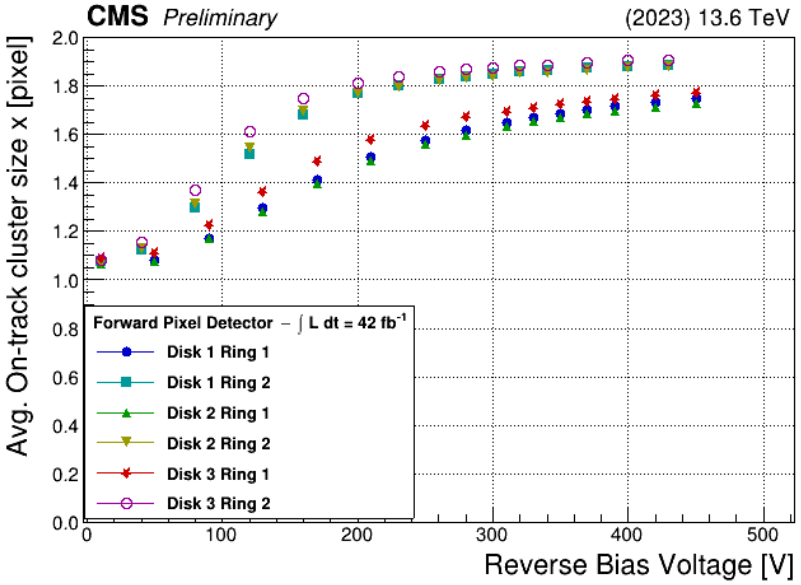
Similar performance as in Run 2 [10]

$> 97\%$(BPIX L1); $> 99\%$ (BPIXL234+FPIX)

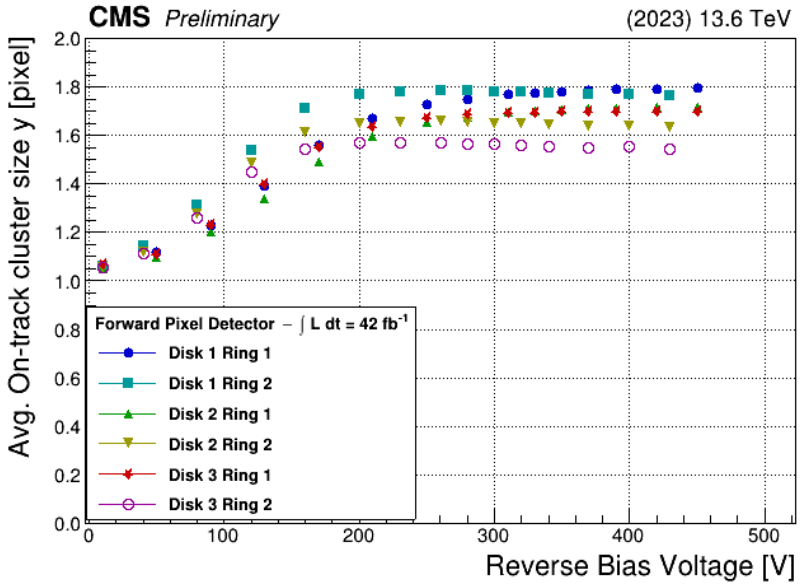
Pixel performance – HV bias scans

- **Target:** To determine operational bias voltage for pixel sensors
- **Monitored factors**: hit efficiency, **cluster size** & charge

Cluster size in x-direction (FPIX)



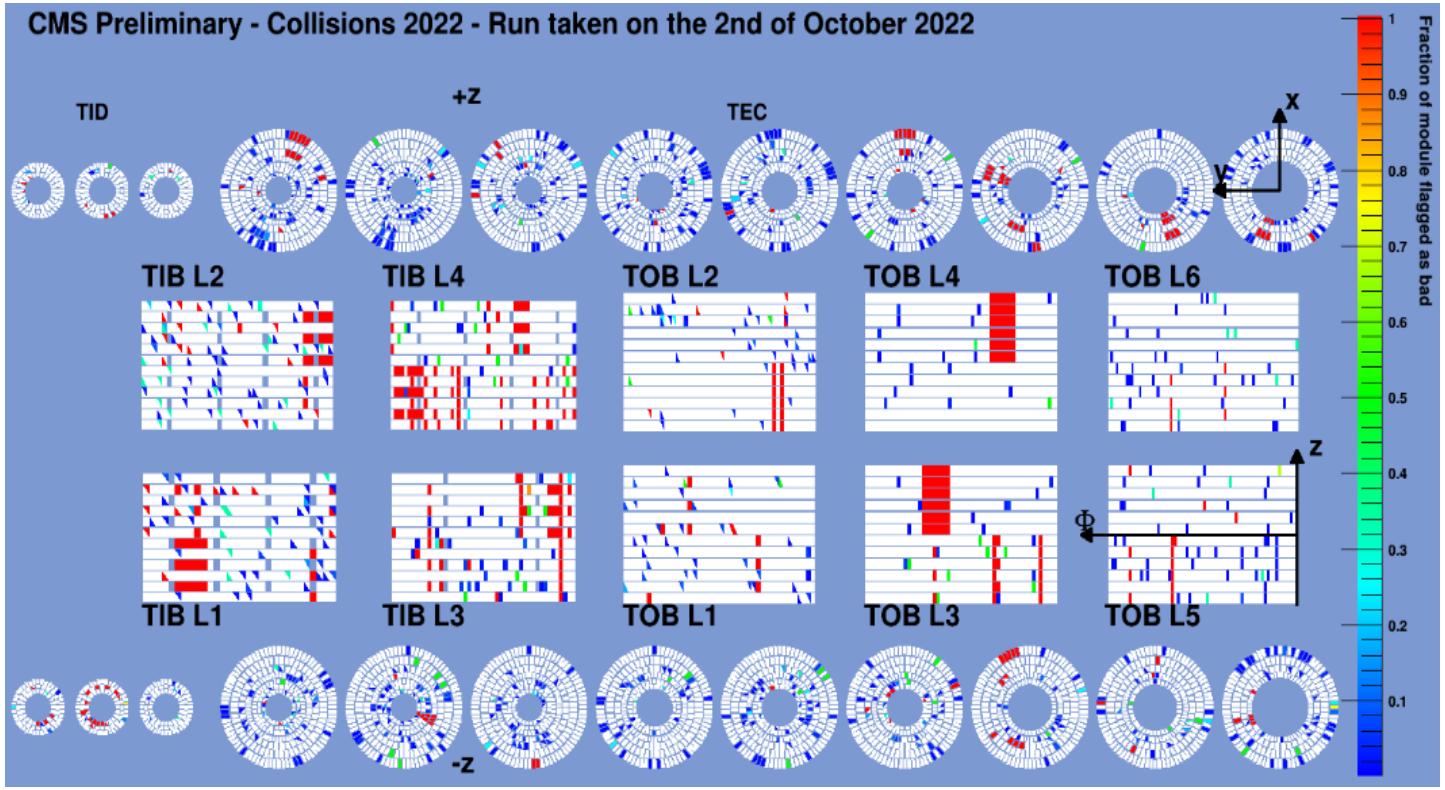
Cluster size in y-direction (FPIX)



Note:

- Operational bias: **350V (Ring 1), 300V (Ring 2)**

Strip performance – bad components



Red: full module not in readout

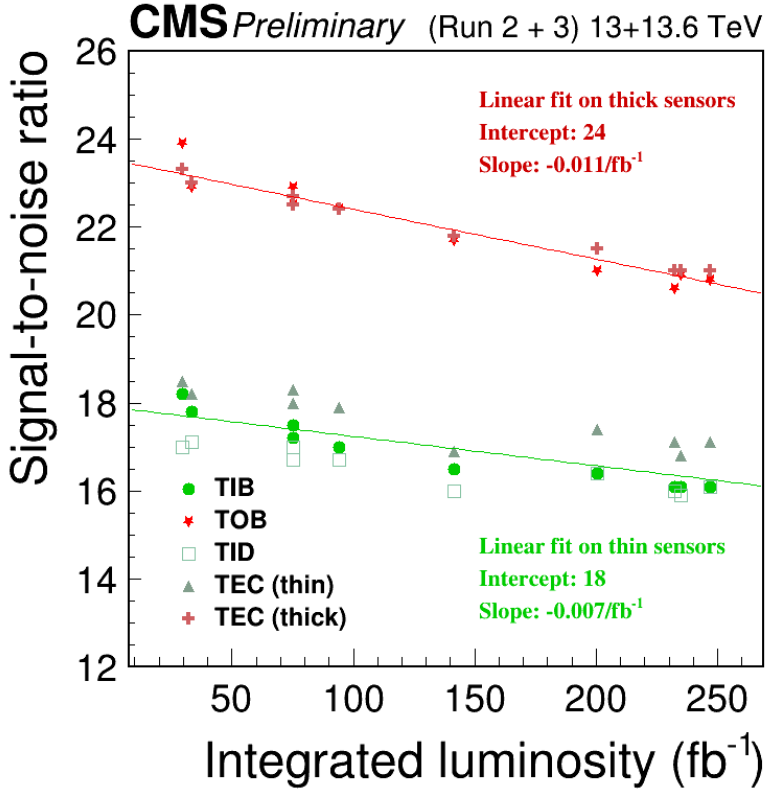
Orange to green: one or more readout fibers not in readout

Light blue: single readout chip not in readout

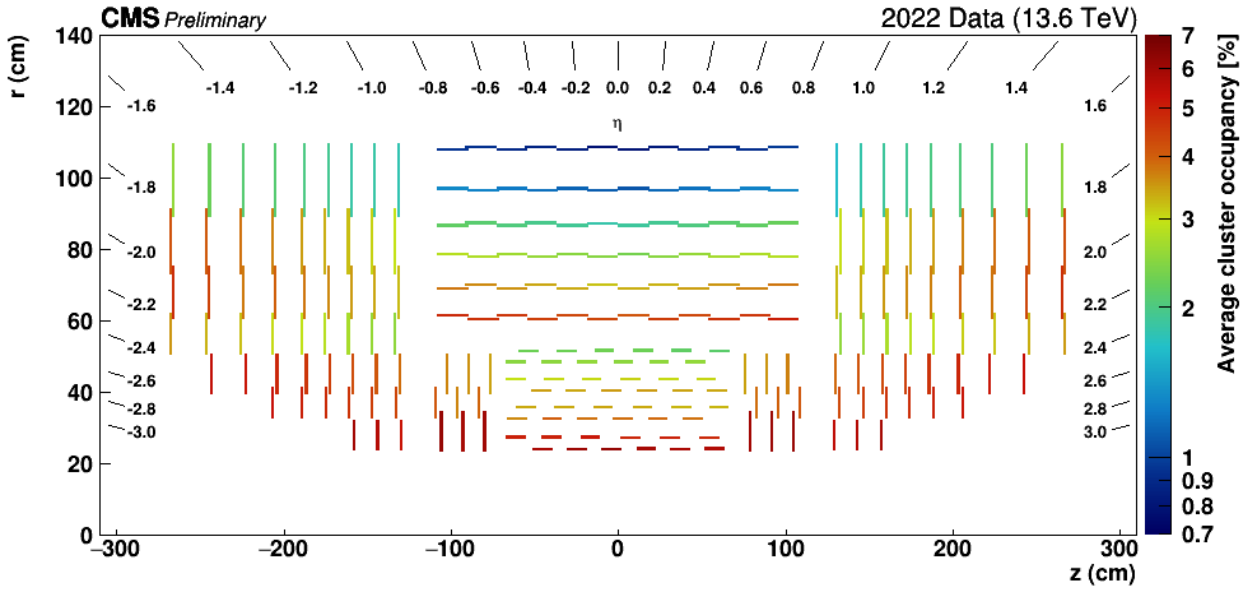
Dark blue: small group of strip not in readout

Strip performance – S/N ratio

- **Signal-to-noise ratio** measured regularly, including early 2023 13.6TeV data
- High S/N ratio ensures **better zero suppression and proper cluster buildup**

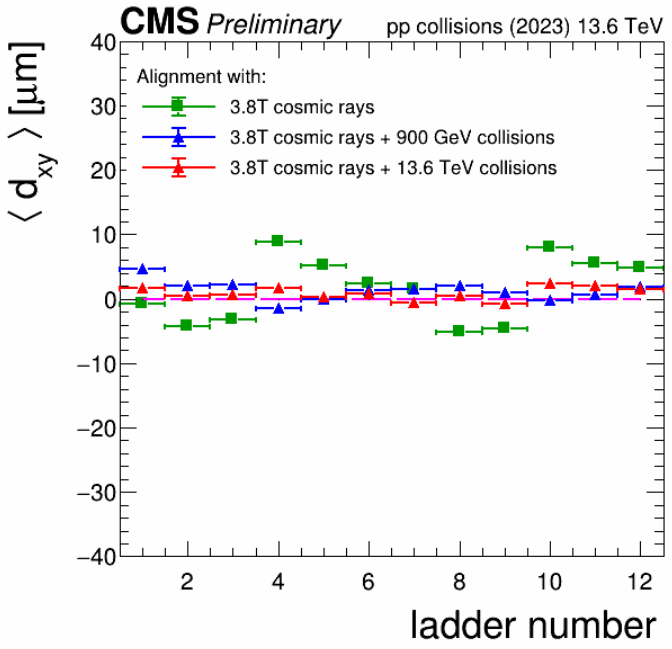


Average cluster occupancy per strip and per event (2022)



Primary Vertex validation (2023)

- Performance measured by a quality of **PV reconstruction**
- **Target:** distributions of **track-vertex residuals** (i.e. impact parameters)
- Indicates **physics object performance in the Pixel**



Note:

- ❑ **PV are first refitted** removing the track under scrutiny
- ❑ Perfectly aligned detector would show flat distribution centred at zero
- ❑ Improvement visible for alignment at higher granularity and using better statistics

Which 2023 alignment conditions?

Granularity:

BPIX (FPIX): ladders (half-cylinders)
Strip: half-barrels and half-cylinders
≈ 187k cosmic ray tracks

Pixel: single modules
Strip: fixed in the fit
≈ 71k cosmic ray tracks
≈ 4.5M pp collisions

BPIX (FPIX): ladders (panels)
Strip: fixed in the fit
≈ 295k cosmic ray tracks
≈ 16M pp collisions

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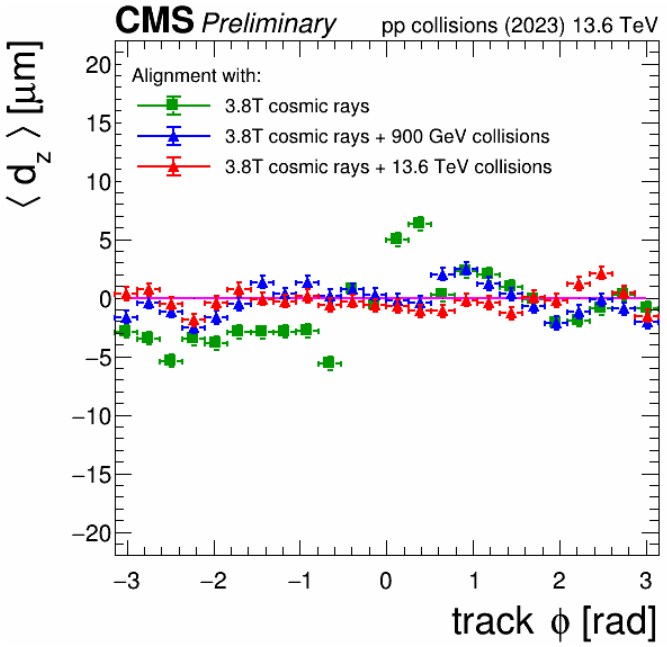

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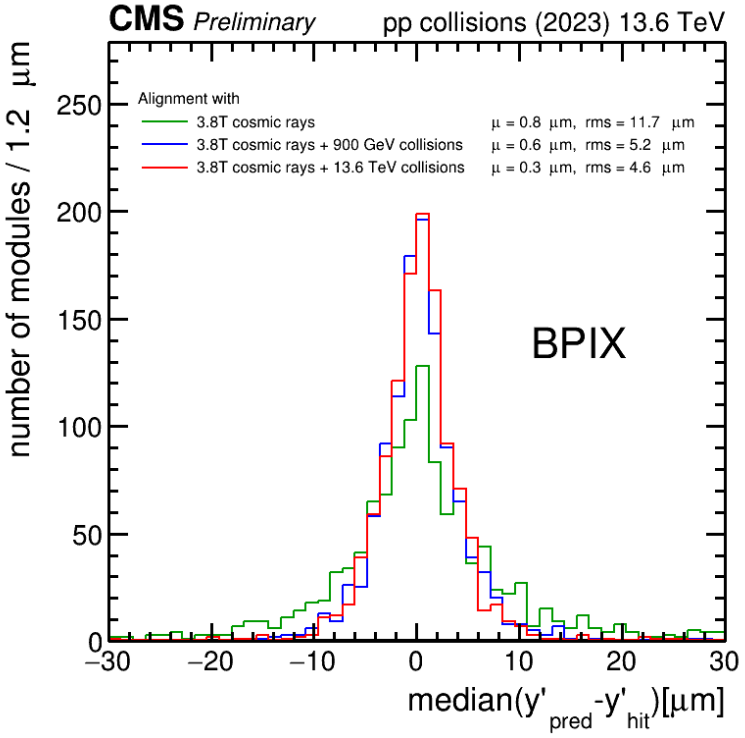
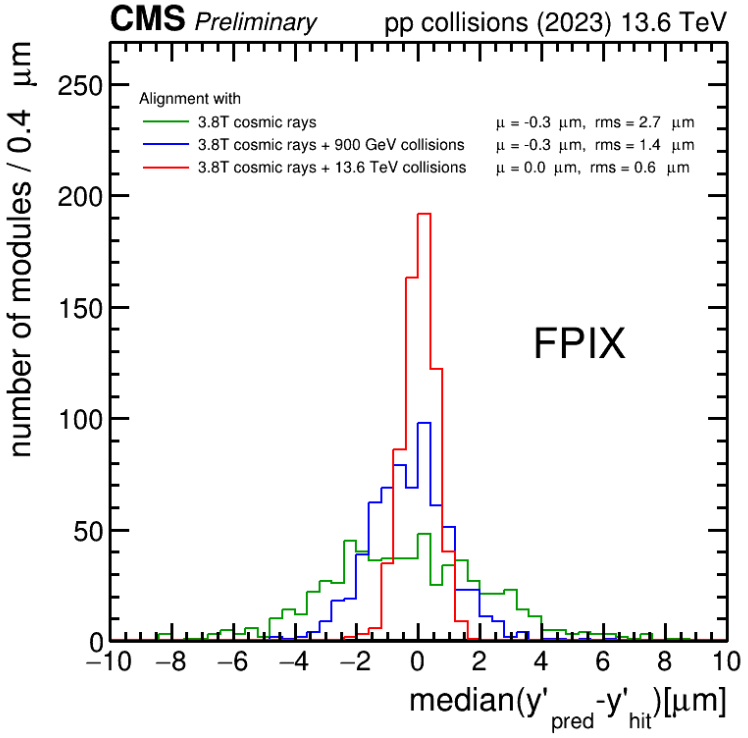
Distribution of median residuals (2023)

- Median of **track-hit residuals** $x'_{\mathrm{pred}} - x'_{\mathrm{hit}}$ is determined for a given number of tracks
- Tracker geometry in 2022 → starting geometry in 2023



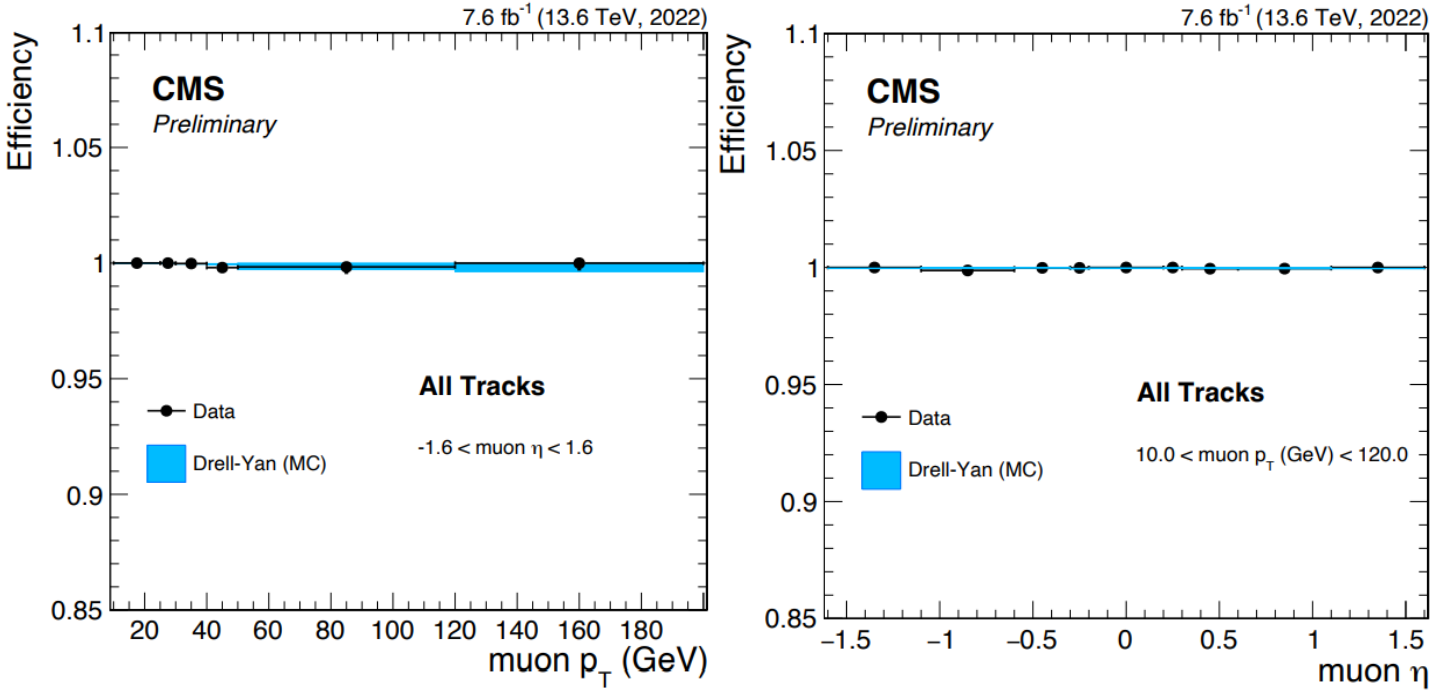


Note:

- ❑ **Tracks are first refitted** removing the hit under scrutiny
- ❑ Perfectly aligned detector would show **DMR centred at zero**
- ❑ **Width** of DMR indicates **local alignment precision**

Tracking efficiency

- Measured by means of the **Tag&Probe** method exploiting $\boldsymbol{Z \rightarrow \mu\mu}$ **resonance**
- Early 2022 data (7.6fb^{-1}) and LO DY simulation (matching the PU distribution in data)
- **Tag muon:** tight identification/isolation criteria, $p_{\mathrm{T}} > 27\mathrm{GeV}$, …
- **Probe muon:** any standalone muon with at least 1 hit in the CMS Muon system, …



Note:

- ❑ **Passing probe criteria:** The standalone muon is matched in $(\Delta R < 0.3, \Delta\eta < 0.3)$ with tracks having $p_{\mathrm{T}} > 10\mathrm{GeV}$
- ❑ Z mass window [70-115 GeV]