CMS Tracker Status, Challenges, and Performance in Run 3

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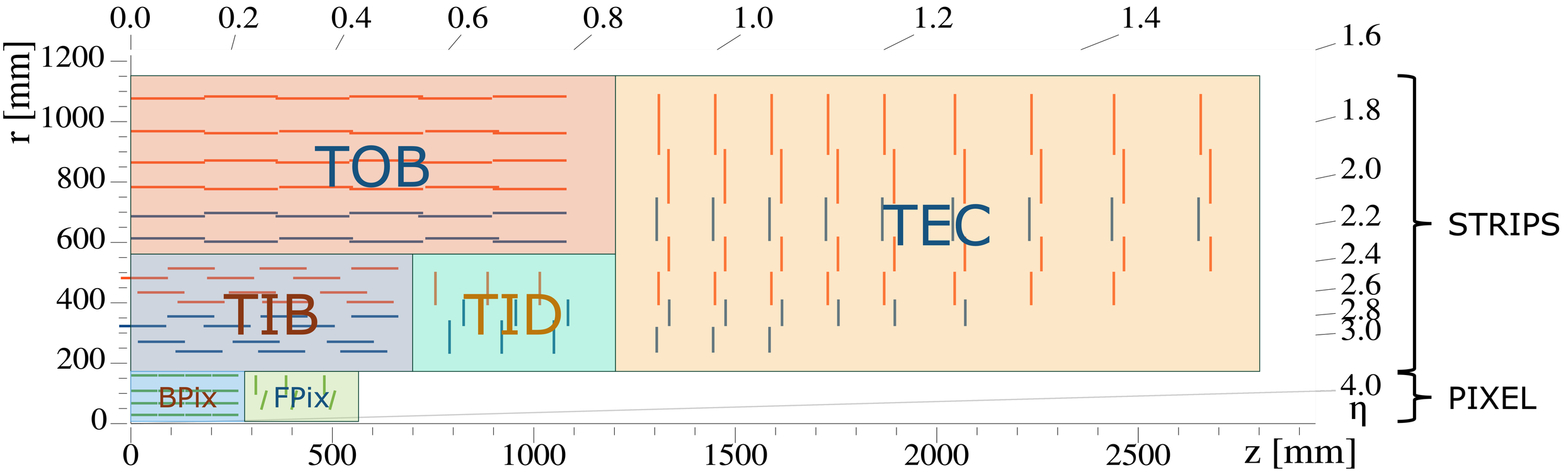
VERTEX 2025: 33rd International Workshop on Vertex Detectors
25 August 2025

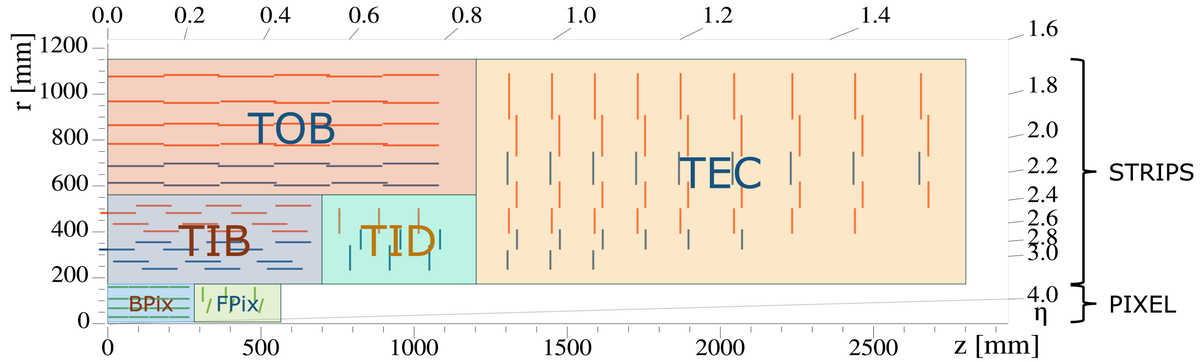
Tracking detectors of CMS

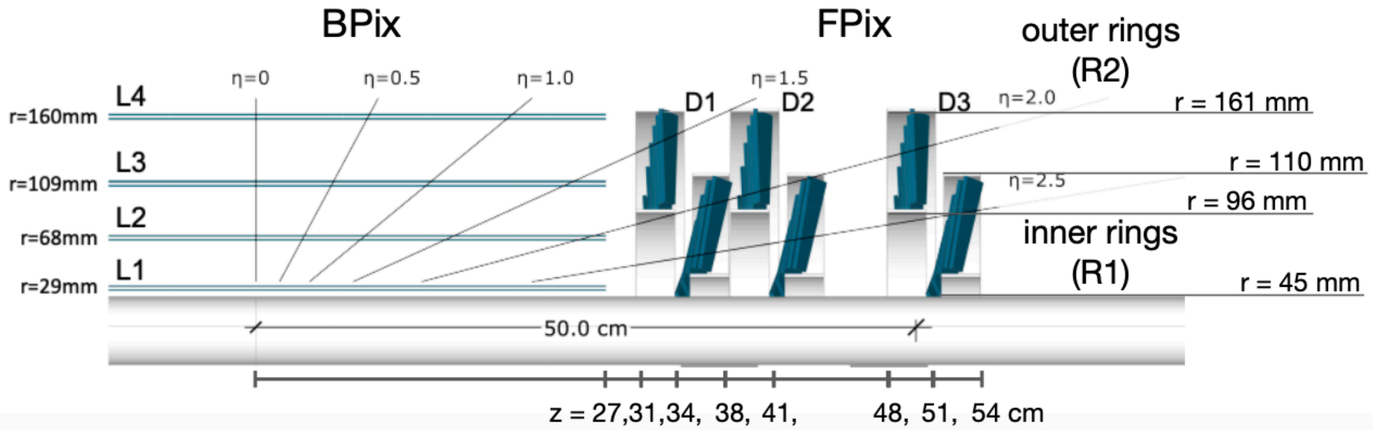


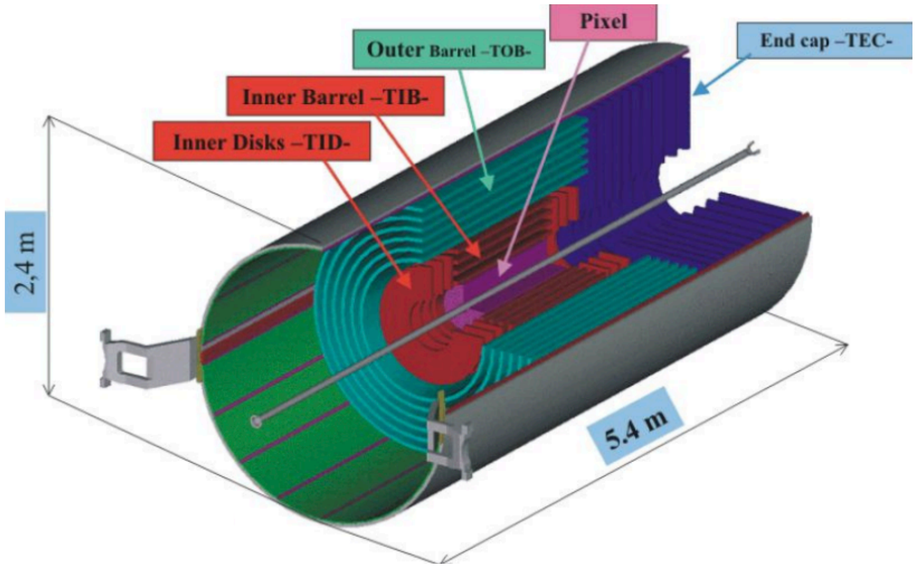
- **Silicon pixel tracker**
  Barrel Pixel (BPix) and Forward Pixel (FPix)

- **Silicon strip tracker**
  Tracker Inner Barrel (TIB), Tracker Inner Disk (TID),
  Tracker Outer Barrel (TOB), and Tracker Endcap (TEC)

Tracking detectors of CMS







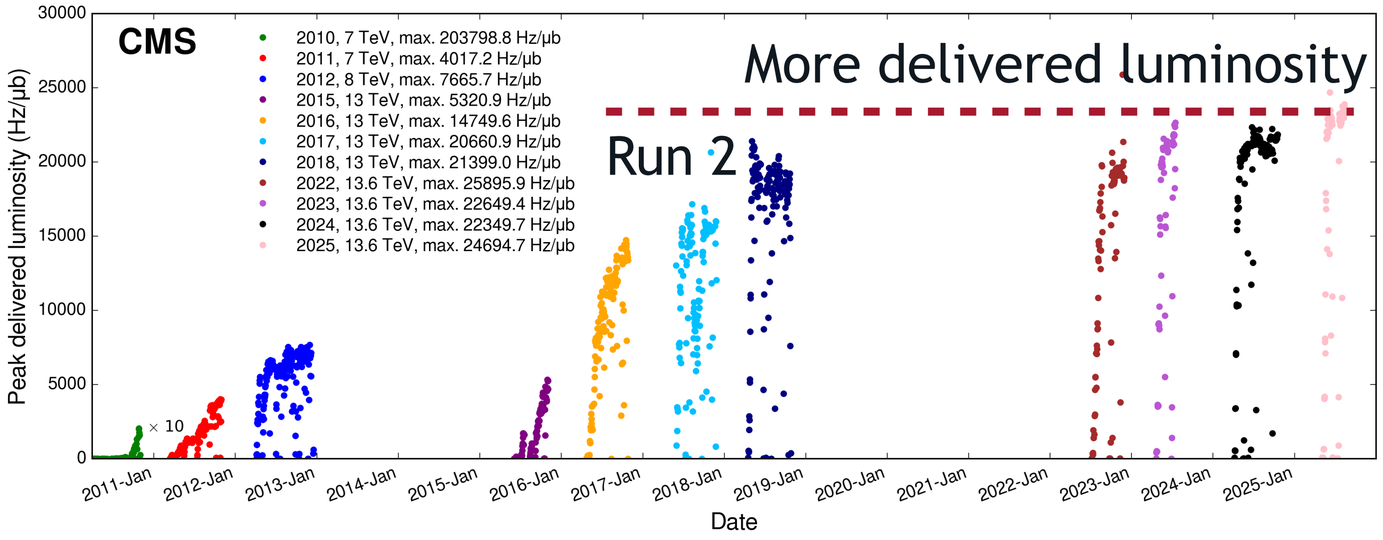
Barel pixels (BPix)
- 4 layers
- 1184 modules

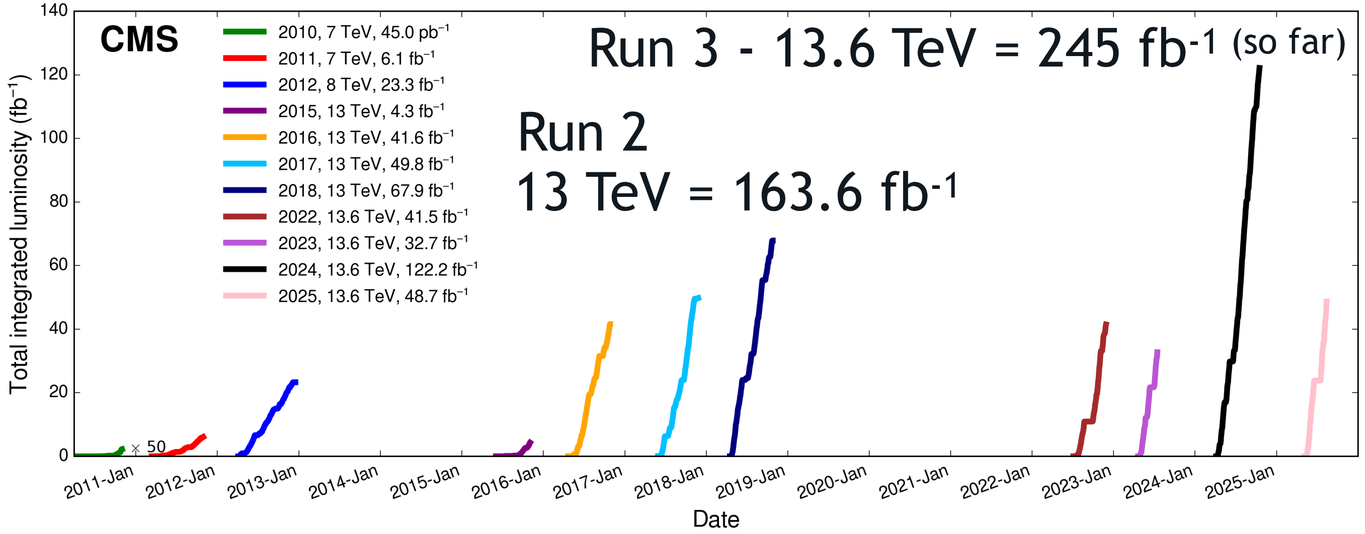
Forward pixels (FPix)
- 3 disks * 2 rings on each end
- 672 modules

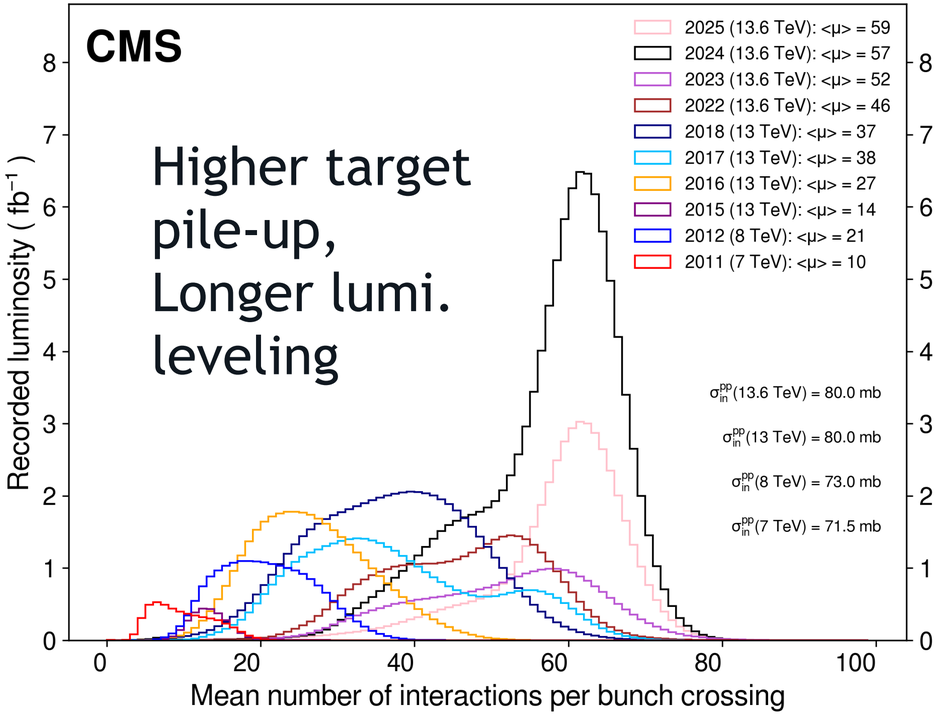
- 4 hit coverage up to $|\eta| < 2.5$

- 10 barrel layers: 4 in TIB, 6 in TOB
- 3 inner disk (TID) and 9 endcap disks (TEC)
- 15148 total modules, 198 m^2 of active silicon

Operational conditions in Run 3







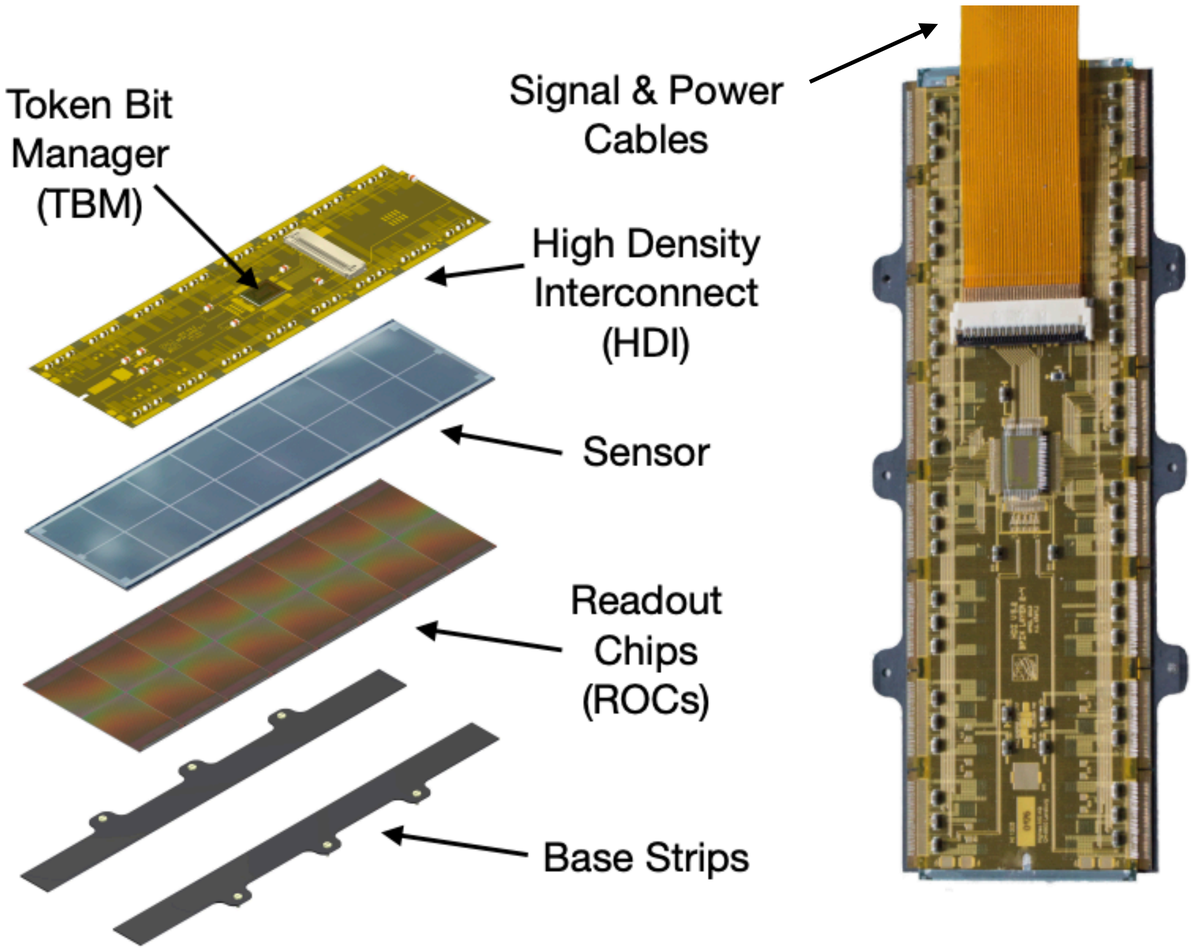
A much more demanding environment than Run 2

Silicon pixel tracker module design

Token Bit Manager (TBM)
- Controls readout of a group of ROCs
- 2 TBMs for Layer 1

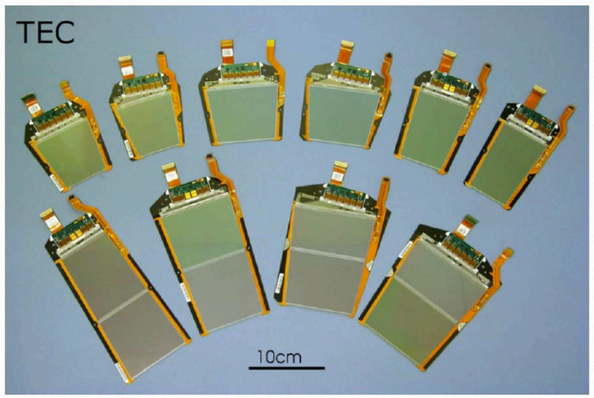
High-density interconnect (HDI)
- Routes high-voltage to the sensor

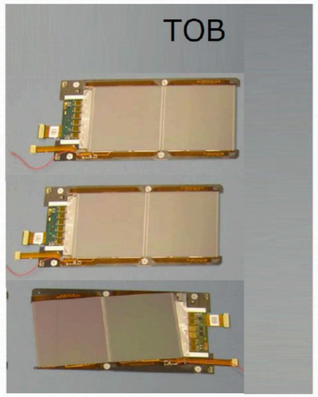
Planar n-in-n silicon sensor
- 280 μm thick
- 100x150 μm^2

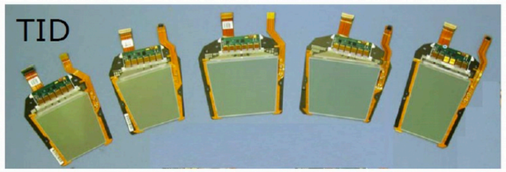


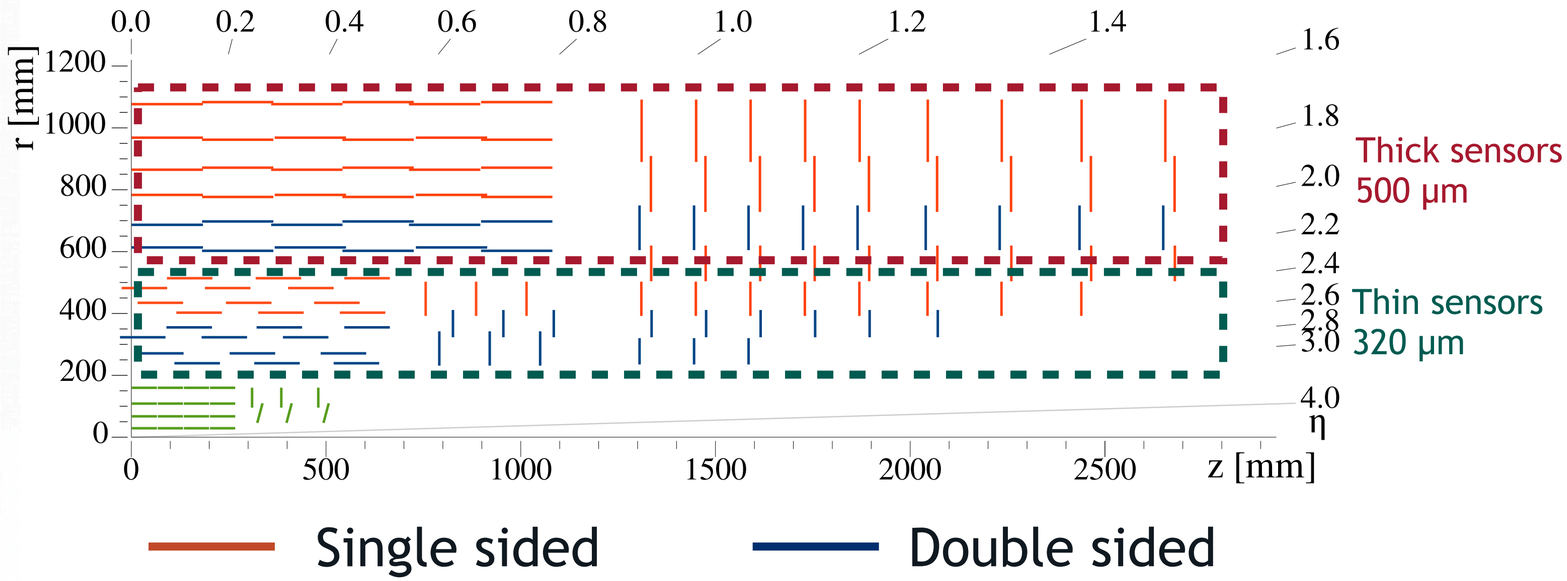
Read out chips (ROCs)
- PSI46dig >90% efficiency up to **200MHz/cm^2** hit rate (BPix Layer 2-4, FPix)
- PROC600 >90% efficiency up to **600MHz/cm^2** hit rate (Layer 1 only)

Silicon strip tracker module design



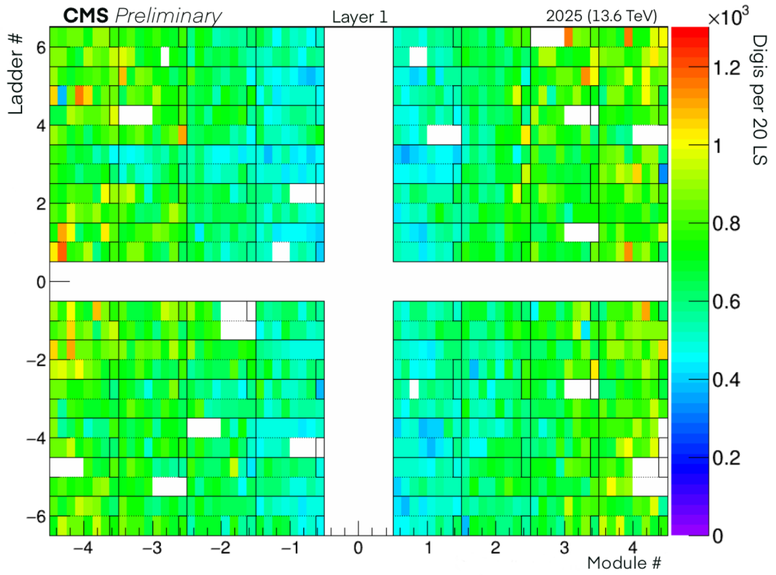


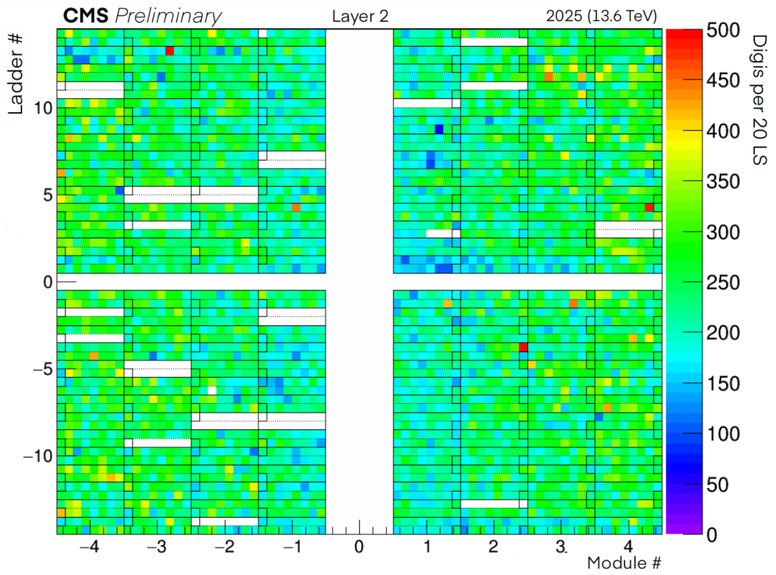


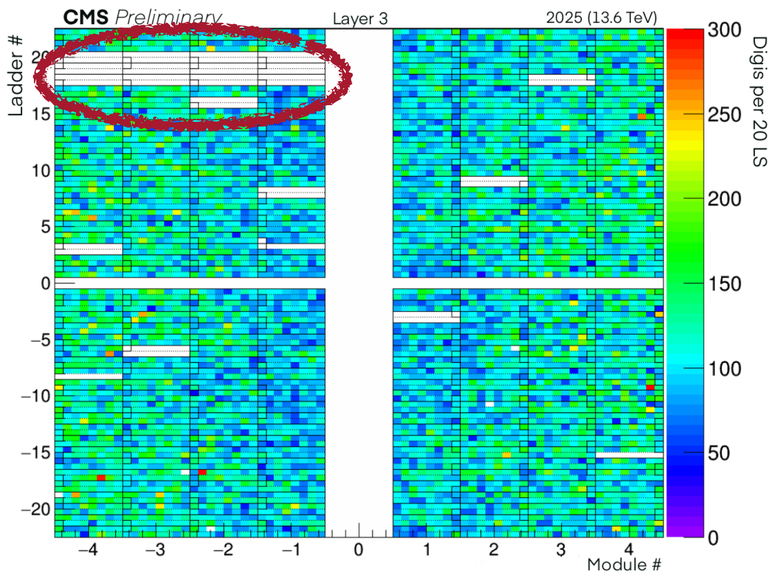


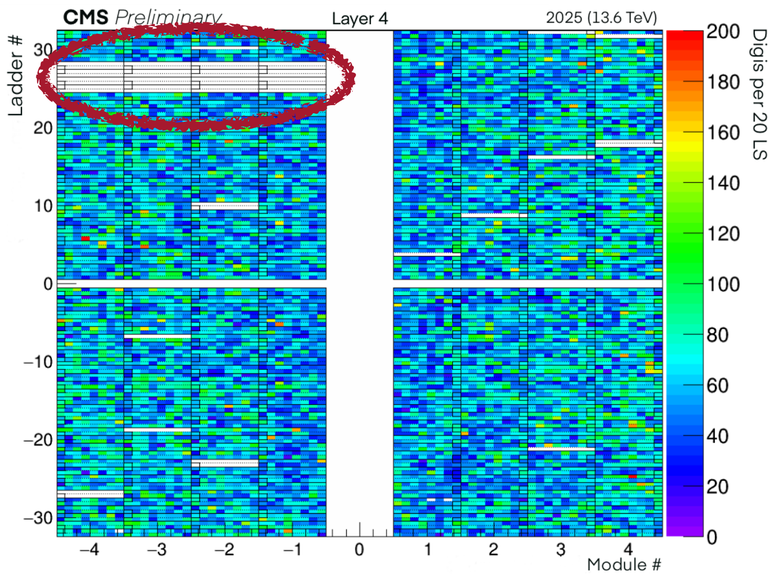
- p-in-n silicon sensors
- Two sensor thickness: 320 µm and 500 µm
- Various configurations of pitch, length, single/double sided depending on their distance from the interaction point
- Double sided modules: 2 modules with stereo angle of 100 rad

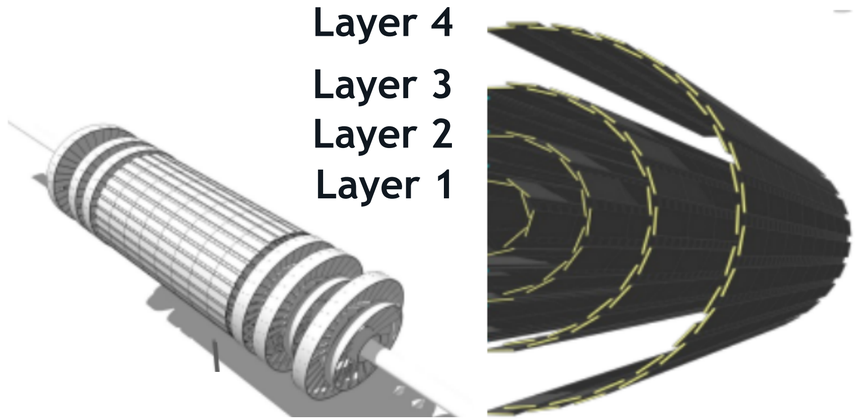
Detector status - Pixels BPix











Occupancy as of July 2025

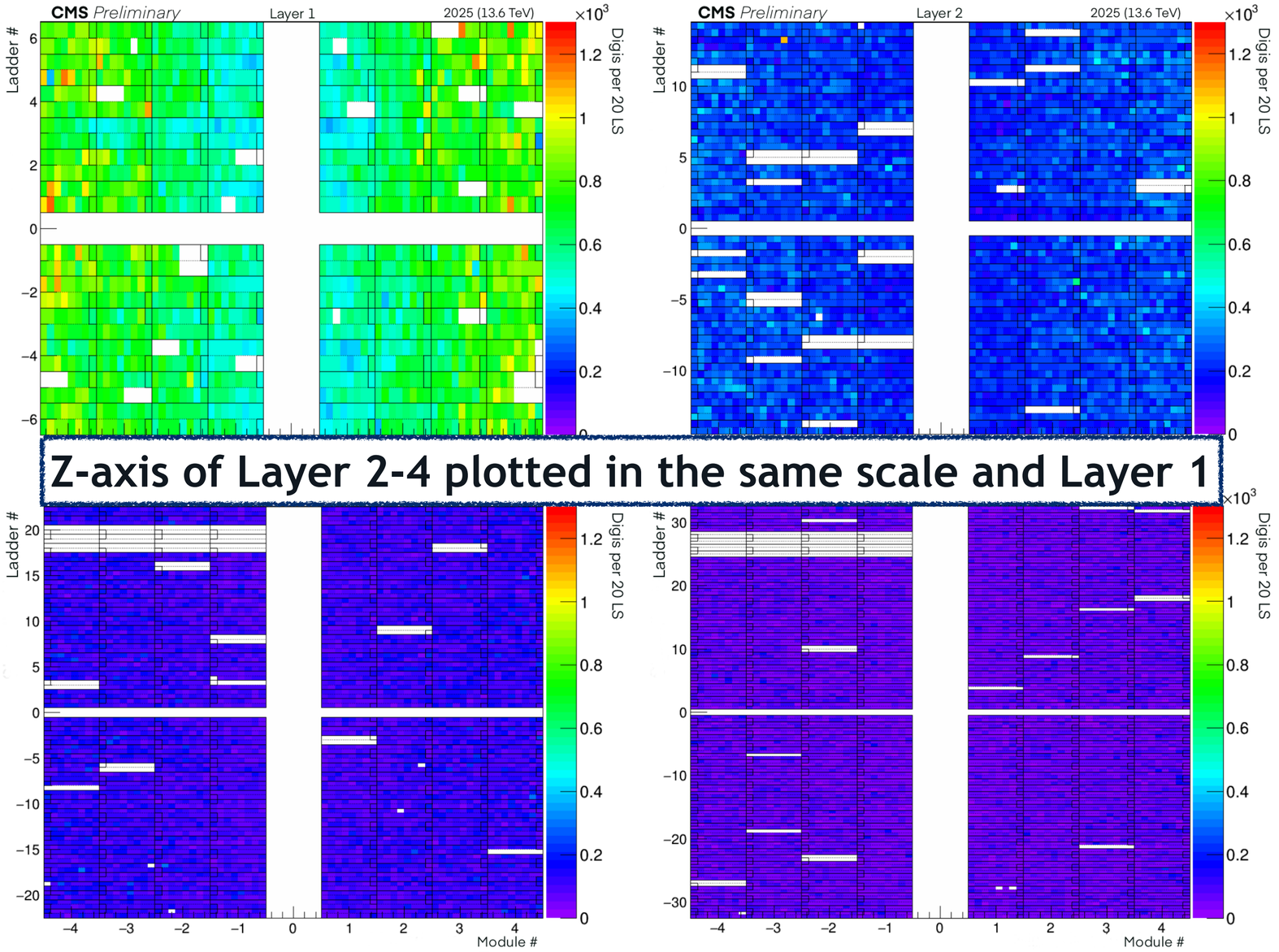
Active channels: ~96%

BmI SEC7 Layers 3/4:
Fails to lock to LHC clock

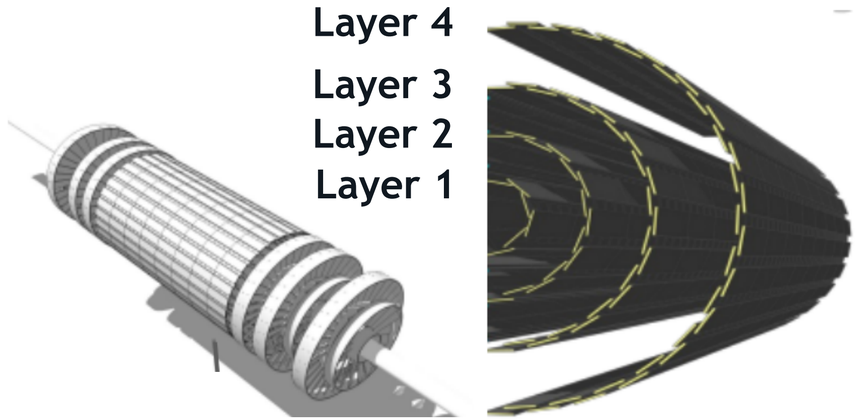
Temporary and permanently disabled modules are also visible

Pixels in BPix Layer 1 record more than twice as many hits compared to the other layers

Detector status - Pixels BPix



Z-axis of Layer 2-4 plotted in the same scale and Layer 1



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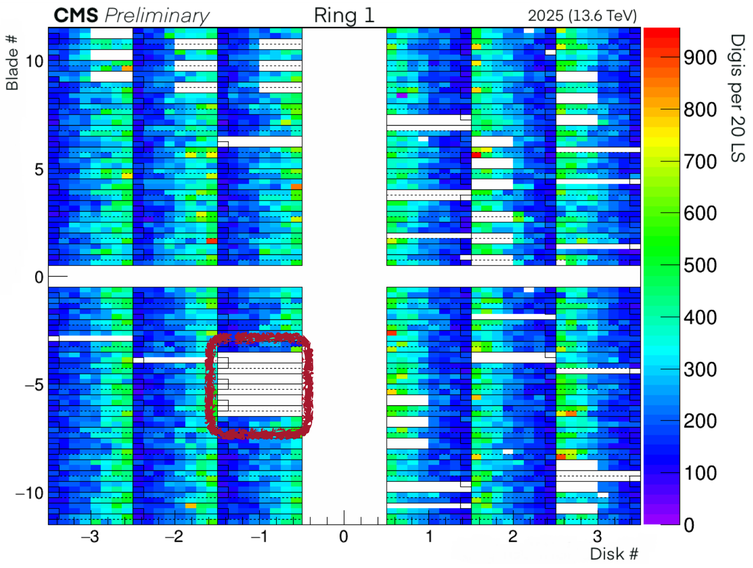
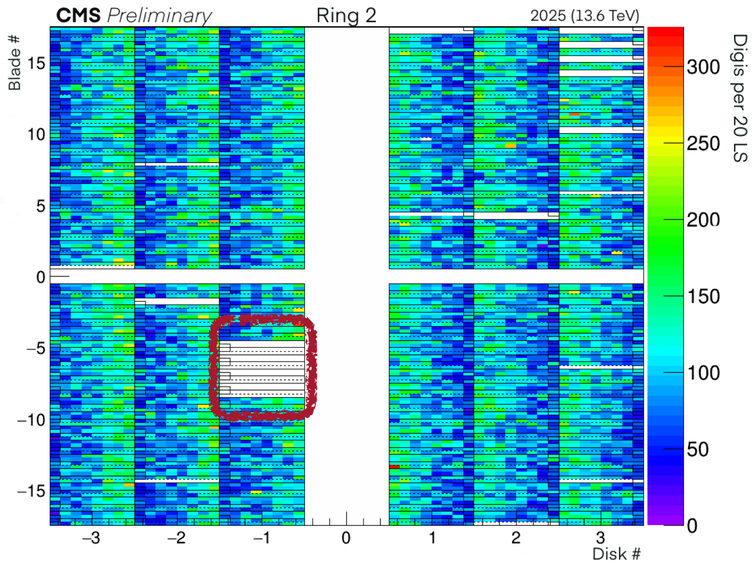
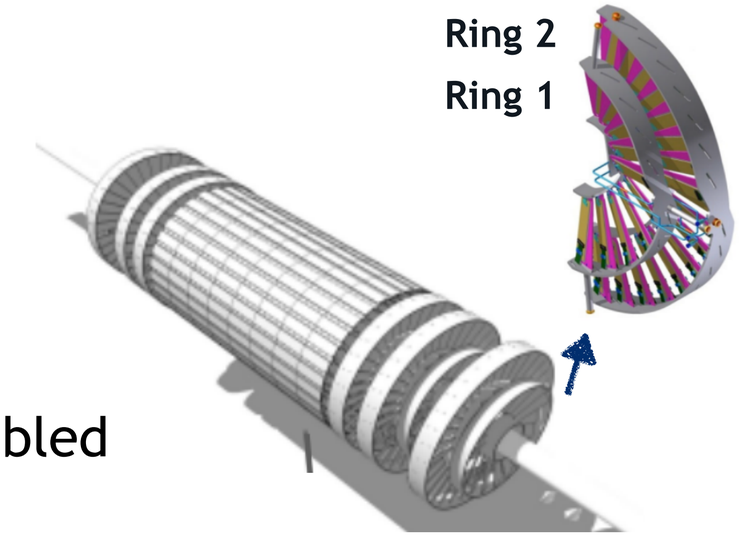
Detector status - Pixels FPix





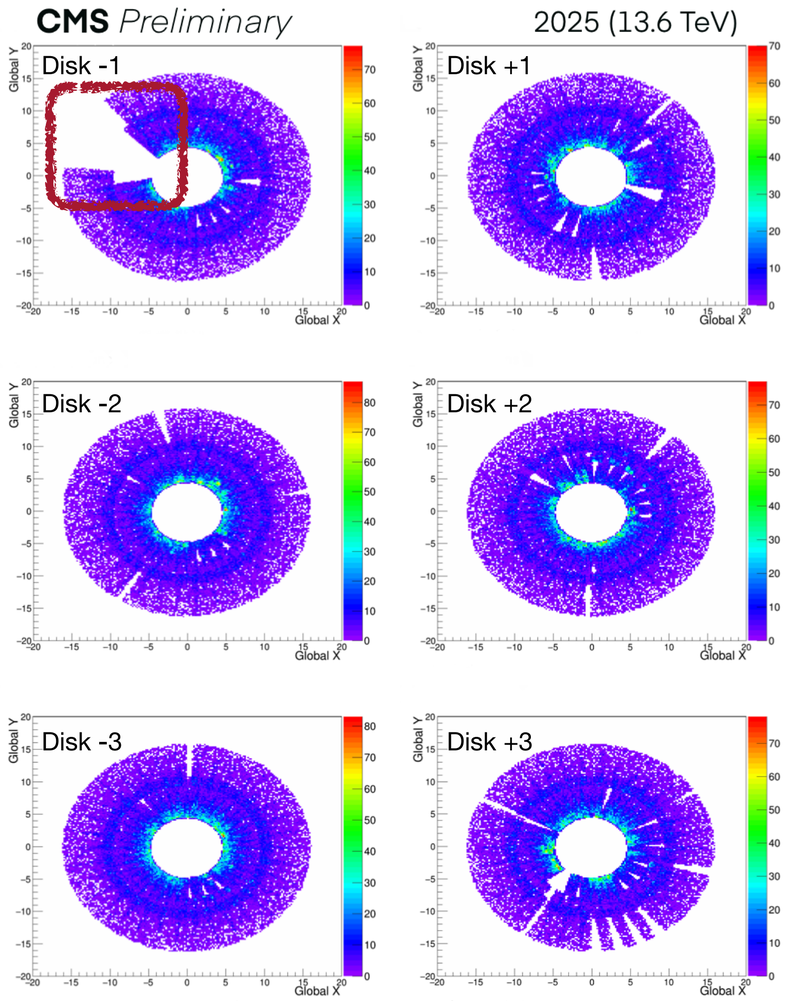


Occupancy as of July 2025

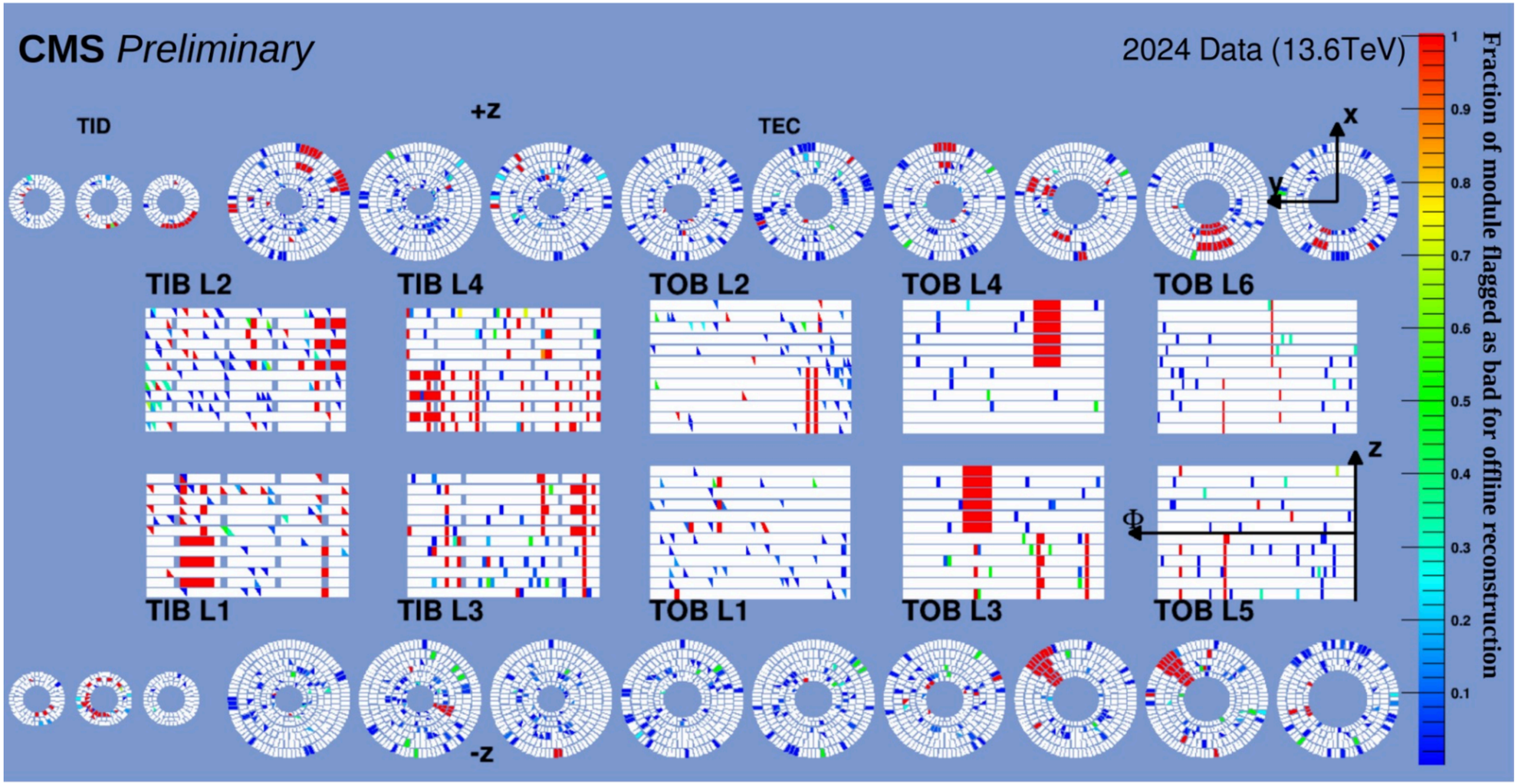
Active channels: ~94%

FPix BmO D1 ROG3:
Receives no triggers

Temporary and permanently disabled modules are also visible



Detector status - Strips



Not in readout:

Full module

One or more readout fiber

Single readout chip

Small groups of strips

Very high number of active channels: ~95% overall

Operational challenges in Run 3

Radiation effects

- Sensor degradation due to radiation
  - e.g. increased leakage currents, higher depletion voltages
- Irradiation impacts on front-end electronics

Driven by integrated luminosity

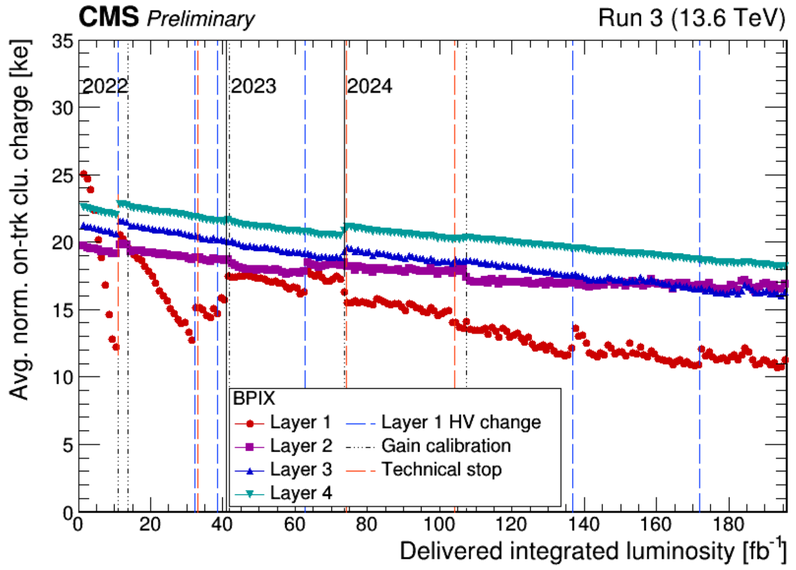
- Single-event upsets (SEUs)

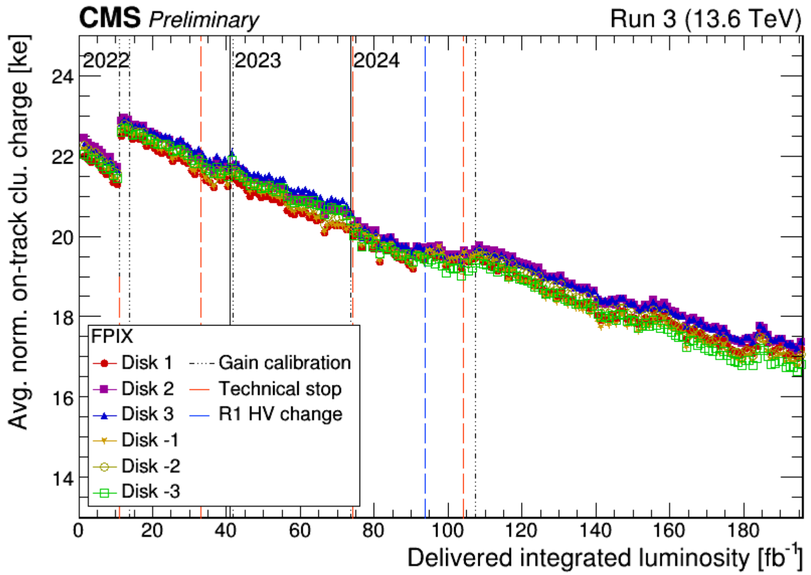
Driven by instantaneous luminosity

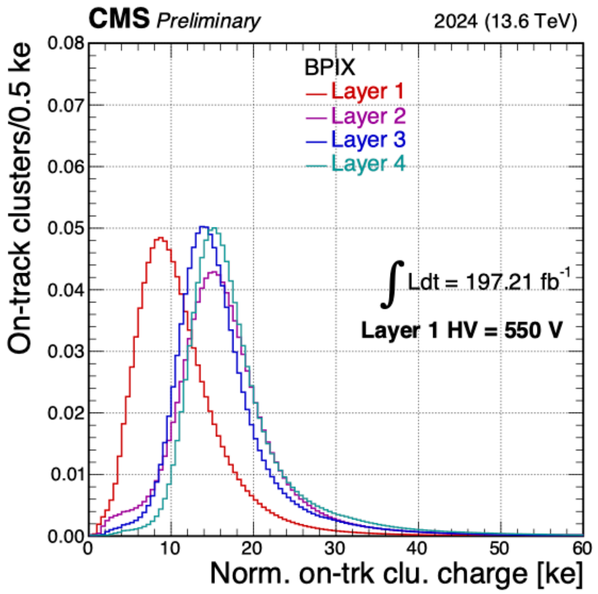
Hardware reliability

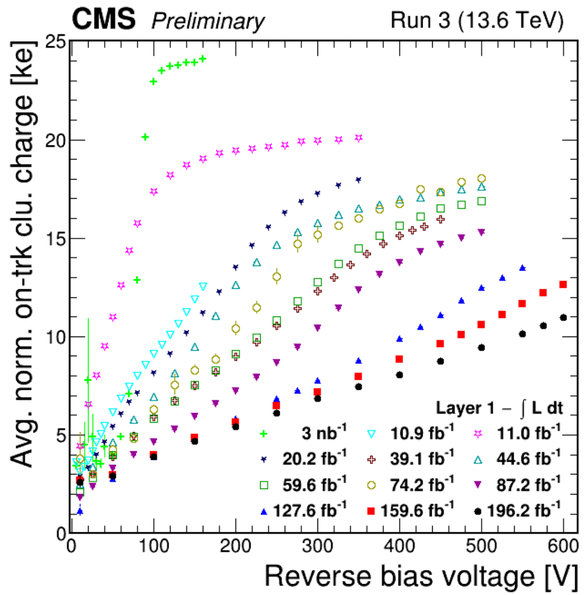
- Connector/interconnect faults
- Auxiliary electronics failures (power/control)
- Automatic masking of problematic channels

Radiation effects on pixels cluster charge









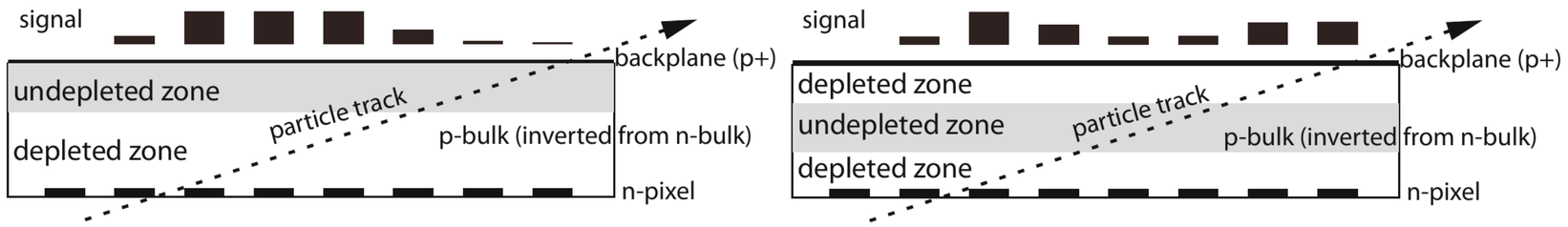
Current settings:
Layer 1: 600 V
Layer 2: 450 V
Layer 3: 350 V
Layer 4: 300 V

Ring 1: 450 V
Ring 2: 350 V

- Layer 1 currently collecting 50% of the charge compared to unirradiated sensors
- Charge collection in FPix is also degrading, but more slowly
- Improvements come from beneficial annealing, increase of HV bias, updated gain calibrations
- HV bias scan performed regularly to monitor performance
  → **Layer 1 evolves rapidly**

Cluster breaking

- Radiation damage reduces charge collection efficiency
  - Leads to split and shortened clusters especially in the high η region



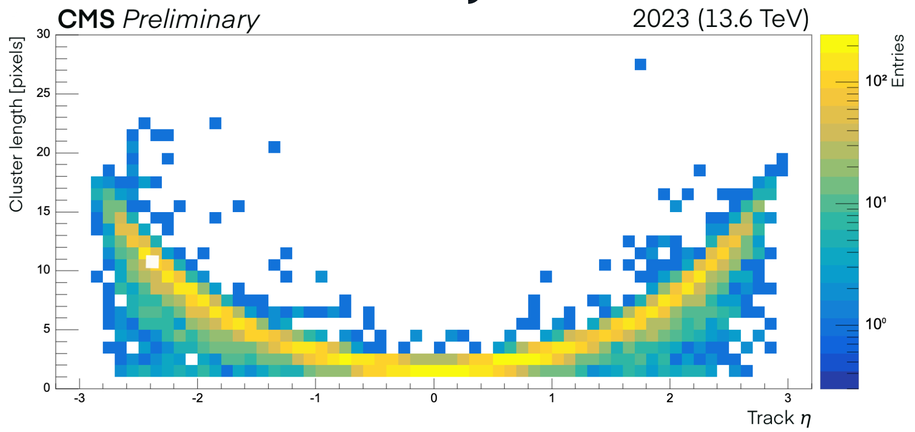
- Consequences: more off-track clusters, increased fake/ duplicate tracks, reduced resolution

- On-track cluster size vs. η (“smiley plot”):
  - 2023: well-defined, pronounced “smiley” shape
  - 2025: more diffuse, shorter clusters especially at high |η|

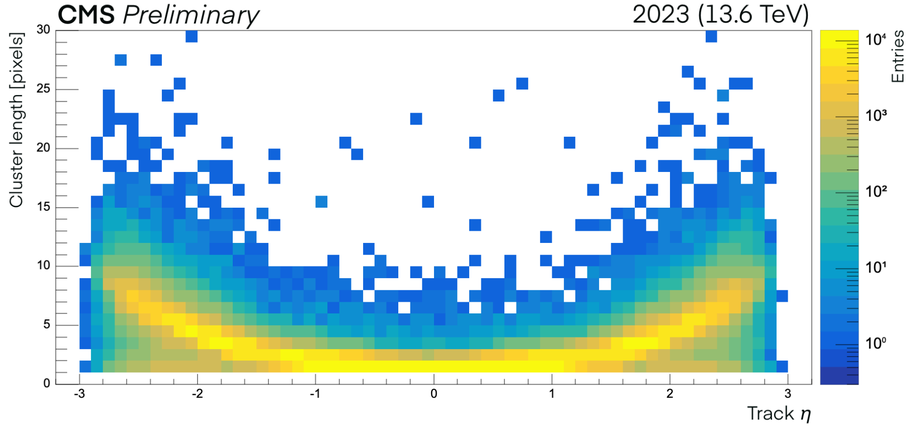
A lot of efforts have been put in mitigation strategies

Pixel Barrel Layer 1
on-track cluster size vs. eta

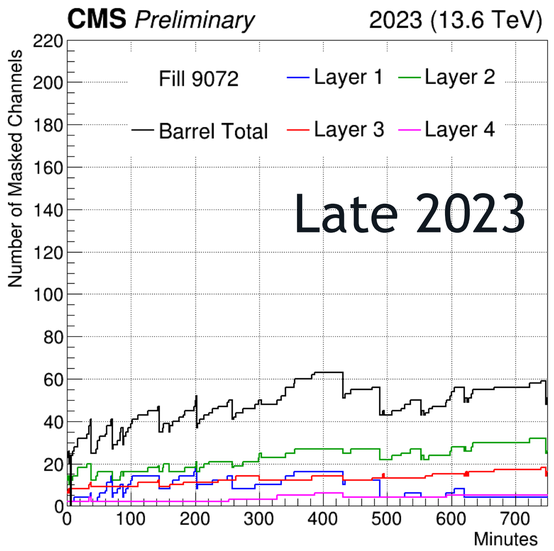
16 July 2023

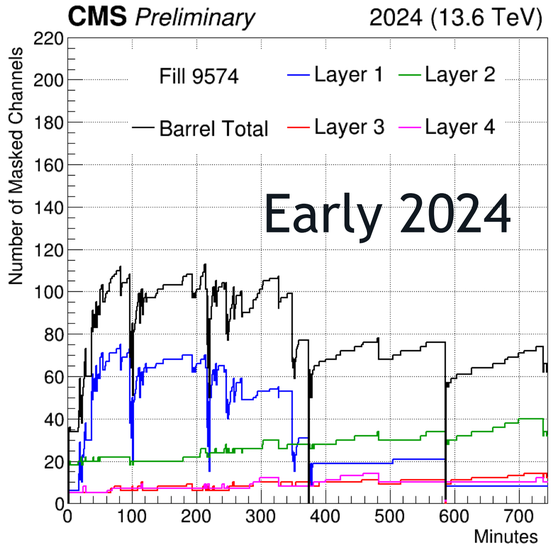


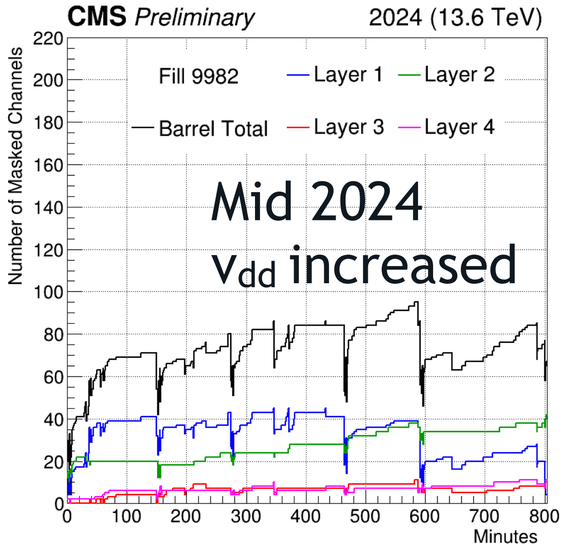
17 August 2025

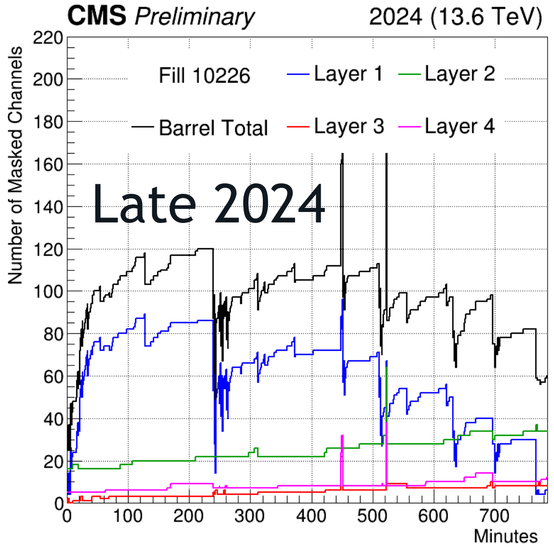


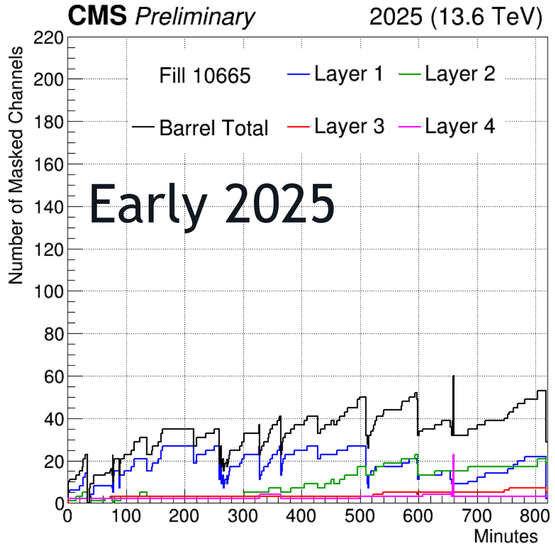
High auto-masked channels in pixel barrel layer 1

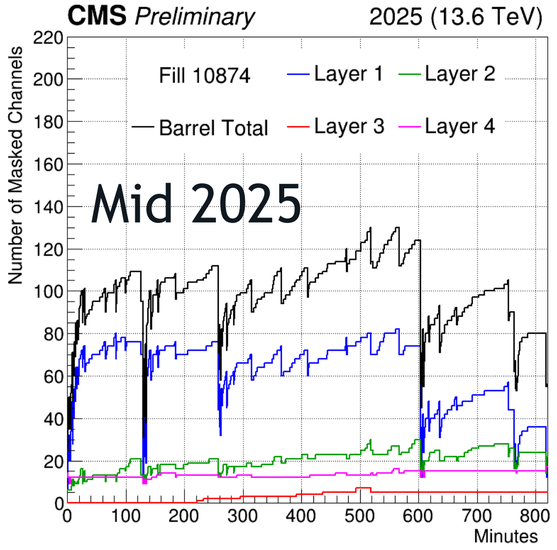












Channels are masked during data-taking due to readout errors

Layer 1 (blue lines):

- Auto-masking rate grows overtime
- Increasing the power to the digital electronics of the ROCs (v_{dd}) helps mitigate this

Data quality remained good for CMS

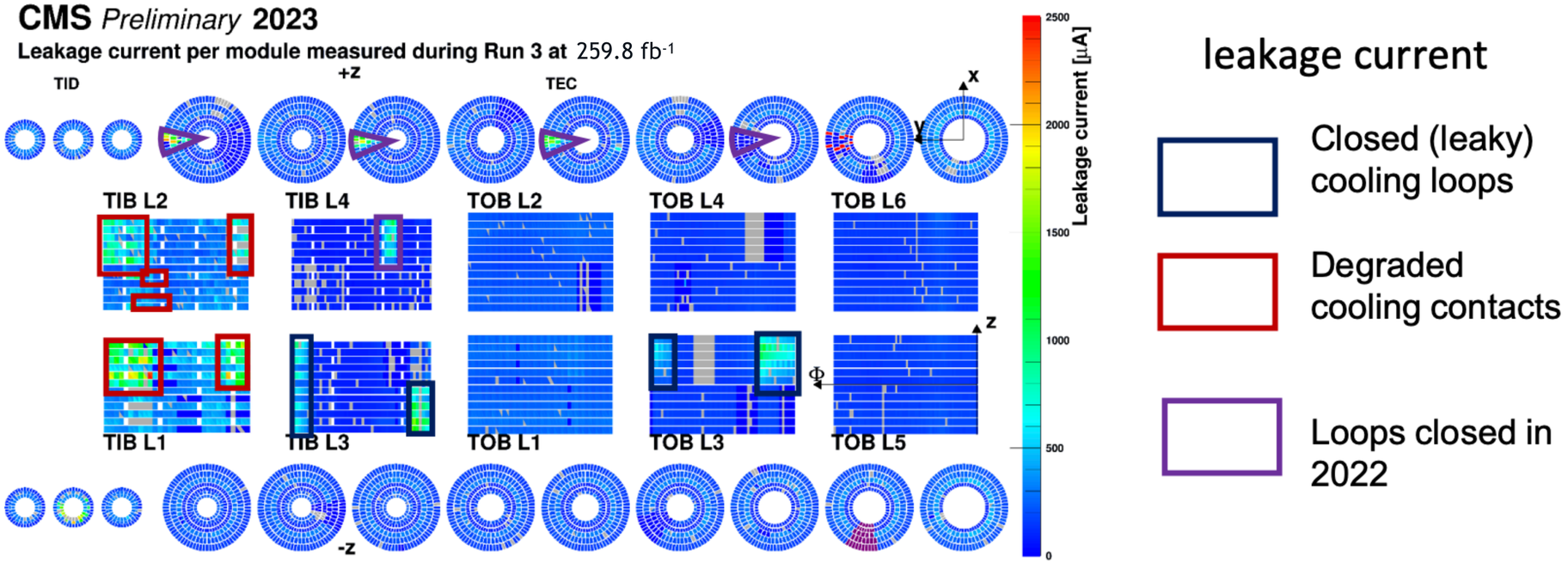
Strips depletion voltage

- Approximately 245 fb-1 have been delivered in Run 3 (~500 fb^{-1} since Run 1)
- Recall: strips tracker sensors are p-in-n strips
  → depends on running over-depleted
- Depletion voltage is monitored: bias scan on full detector twice a year and on representative group once a month
- HV bias settings:
  - TEC disks 5-9 and TOB L1 and L2: 500 V (changed this year)
  - The rest of the detector: 300 V

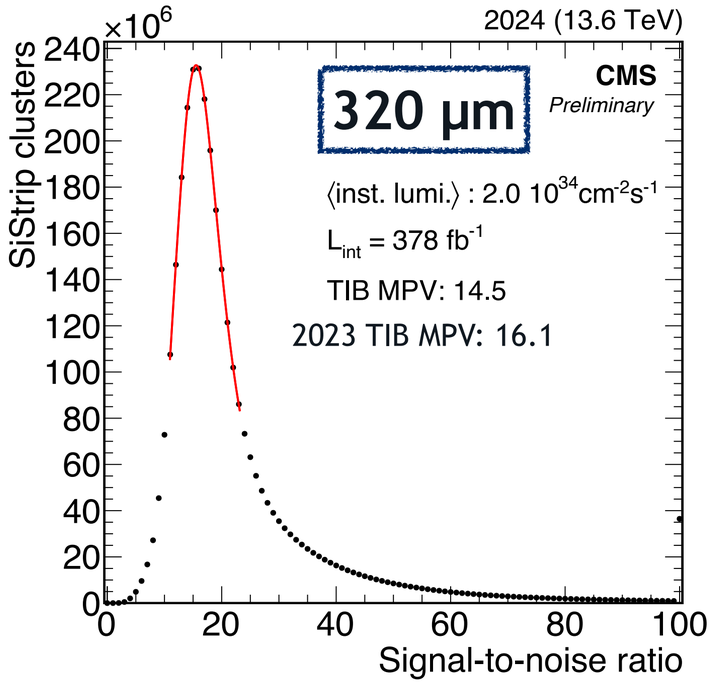
Strips leakage current

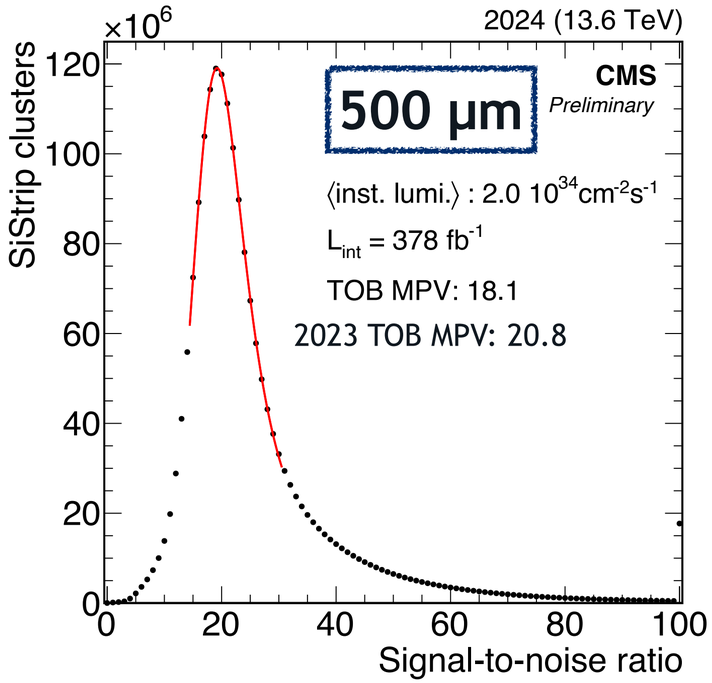
- Leakage current per module map from 2023. Profile is similar, except the blue-green regions are now 1000-2500 μA
- Modules in uncooled regions show elevated leakage currents
- Cooling was lowered from -20 degC to -25 degC in June 2024
- A few HV channels on poorly cooled parts have reached the power supply limit of 12 mA

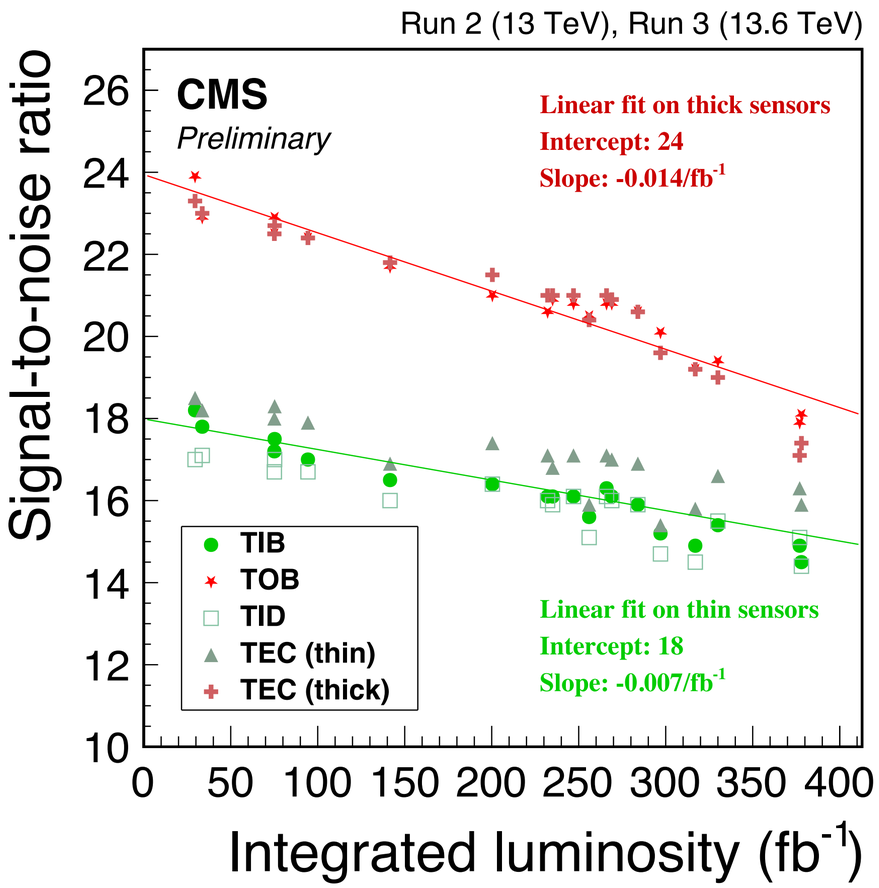
1 power supply unit supplies between 2 and 12 modules



Strips signal over noise performance



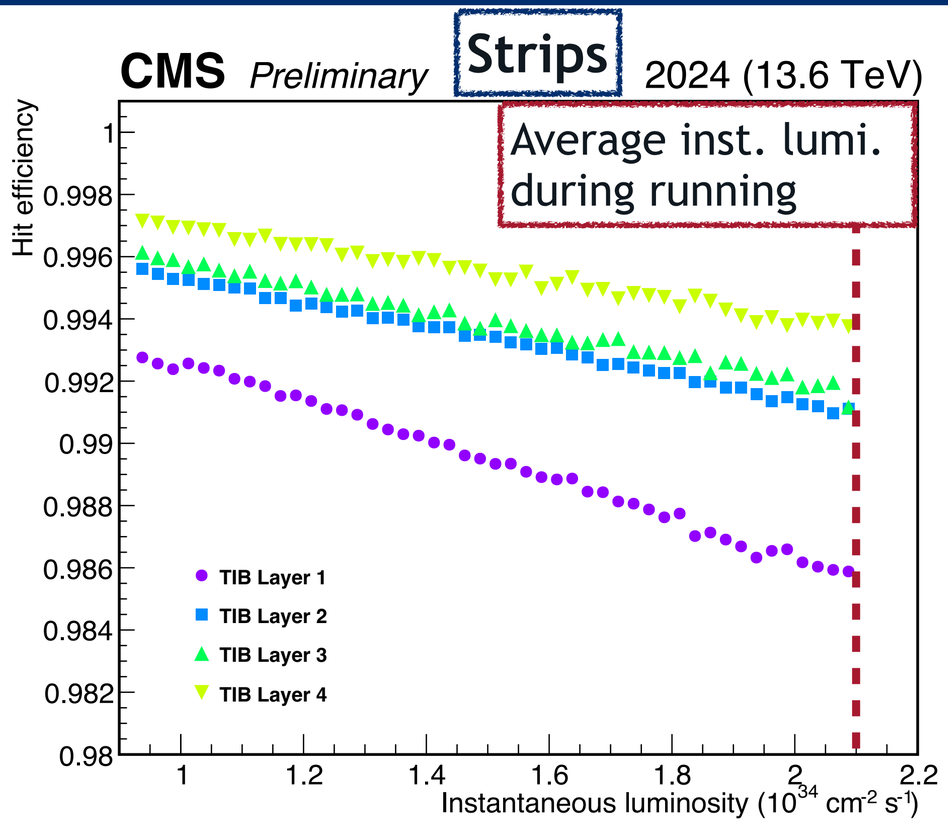


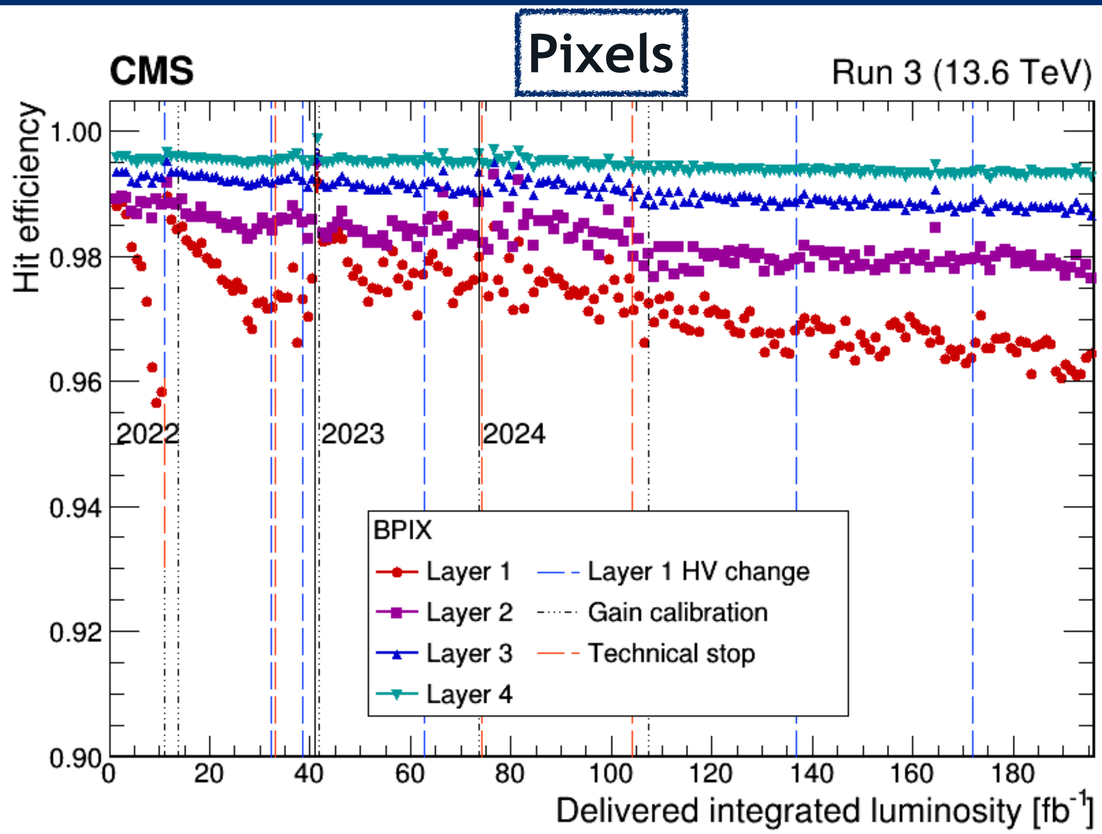


- High signal to noise ratio
  - Expected to decrease with irradiation

Expected to remain sufficiently high until the end of Run 3

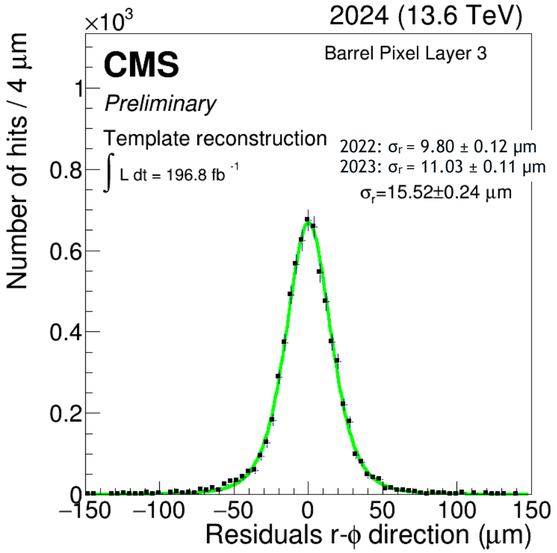
Hit efficiencies

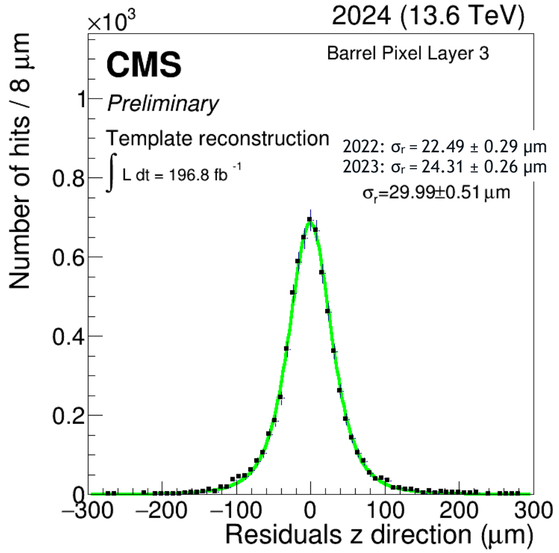


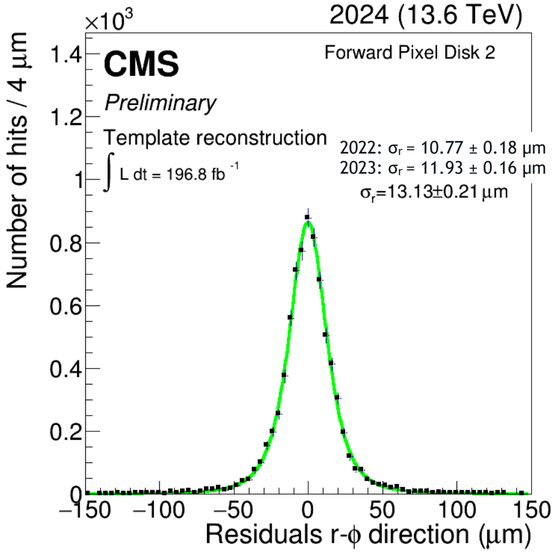


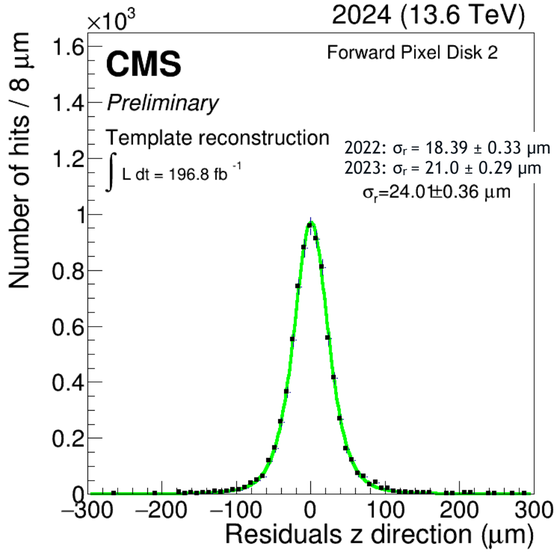
- High hit efficiency >98% for strips, scales linearly with instantaneous luminosity
- Pixels hit efficiency degrades with integrated luminosity, recovered by annealing, gain calibrations, and HV bias increase

Resolution



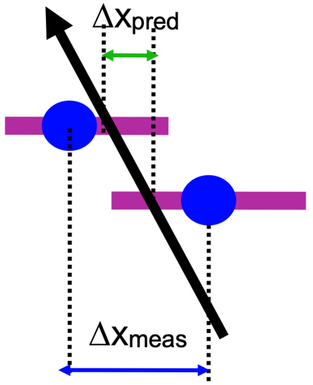




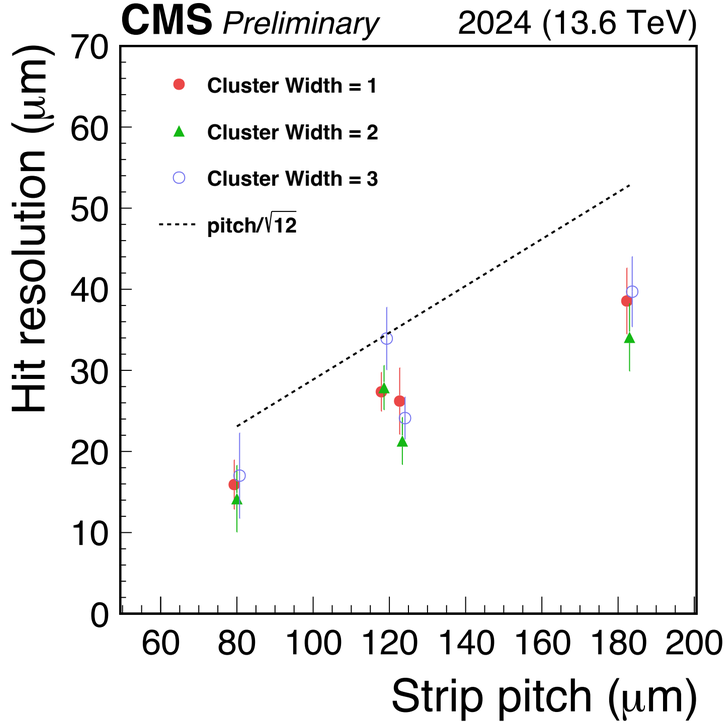


Pixels

- Degradation overtime expected
- Worsen by cluster breaking



Computed by using hits from overlapping modules



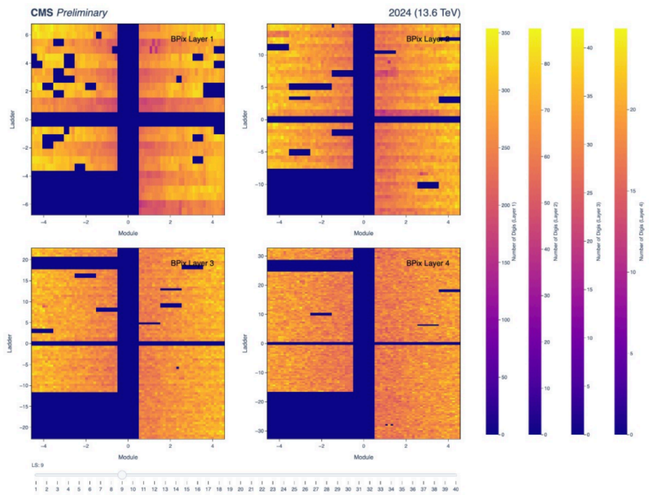
Strips

- Scales with pitch size

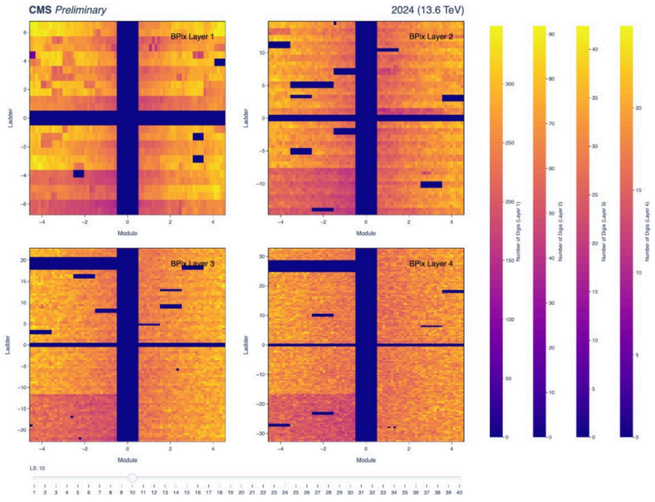
Automatic anomaly detection

- The pixel detector is prone to short (a few LS) anomalies (1 LS = 23 seconds)
- Spotting them is not the easiest task: runs can last 100-1000 LS
- Anomalies:
  - One layer/disk: low impact on tracking
  - Overlapping layers/disks: tracking is affected
    → LS certified bad
- Improves overall data quality, minimal effect on integrated lumi.
- ML models (AutoEncoder, NMF) are being developed to aid automatization

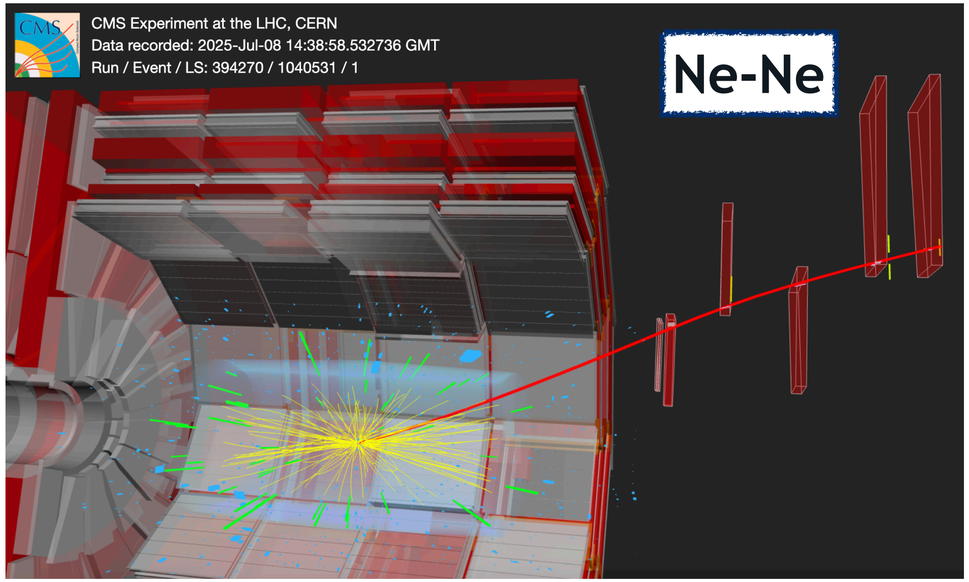
LS 9

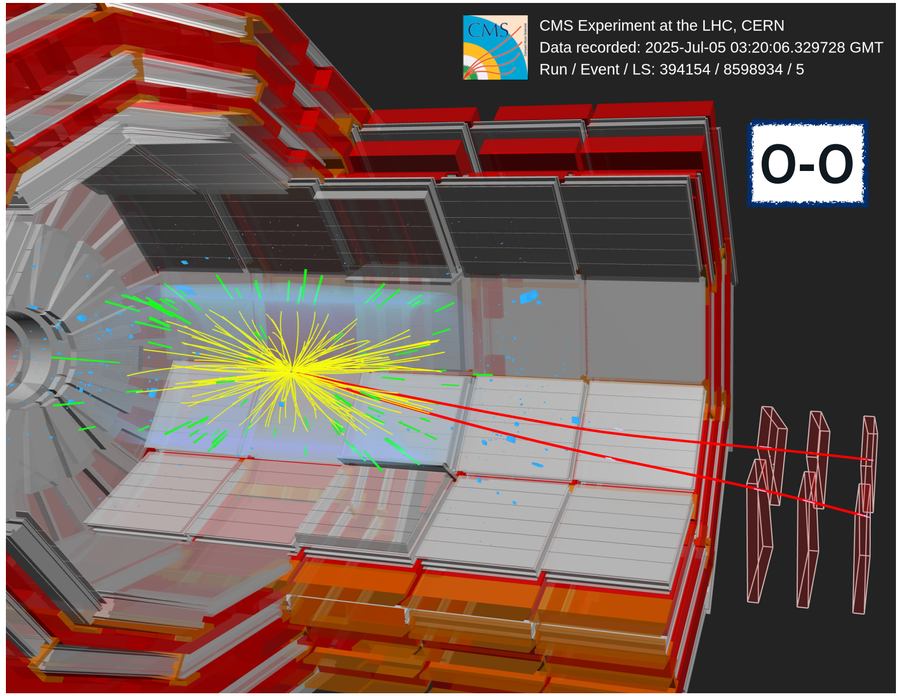


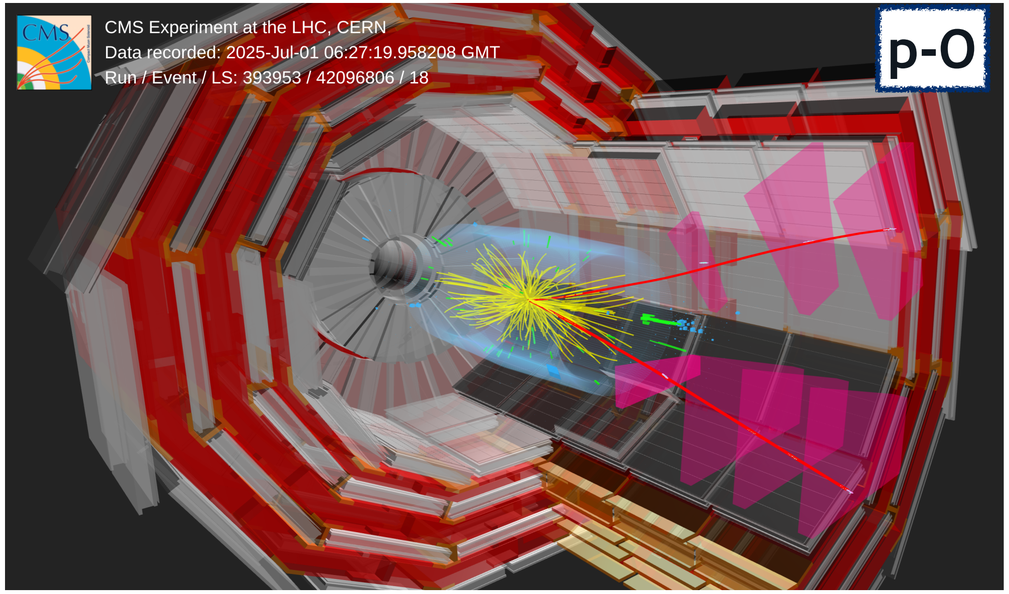
LS 10



Heavy ion collisions







- For the first time, CMS had Ne-Ne, O-O, and p-O collisions
- Tracker performed well during these heavy ion collisions

Summary and outlook

- No major failures in the last years for strips. Pixels lost a few components due to connector/ auxiliary electronics faults
- Higher leakage current, but no major difference in profile for strips compared to earlier in Run 3
- Good overall hit efficiency, resolution and signal-to-noise ratio
- Pixel Barrel Layer 1 evolves rapidly with radiation
  - Decreased charge collection efficiency
  - Cluster breaking
  - Auto-masked channels
- Tools such as automatic anomaly detection helps ensure high data quality

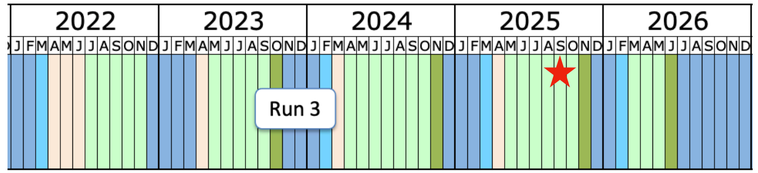
Publication available (Run 2):
Operation and performance of the CMS silicon strip tracker with proton-proton collisions at the CERN LHC

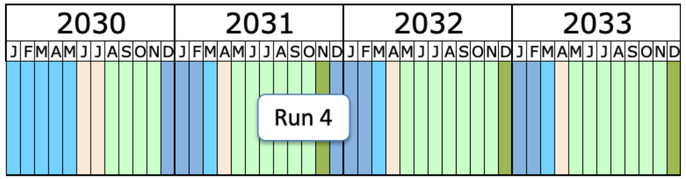
Pixel and Strips Tracker continue to deliver high quality tracks to CMS

Summary and outlook

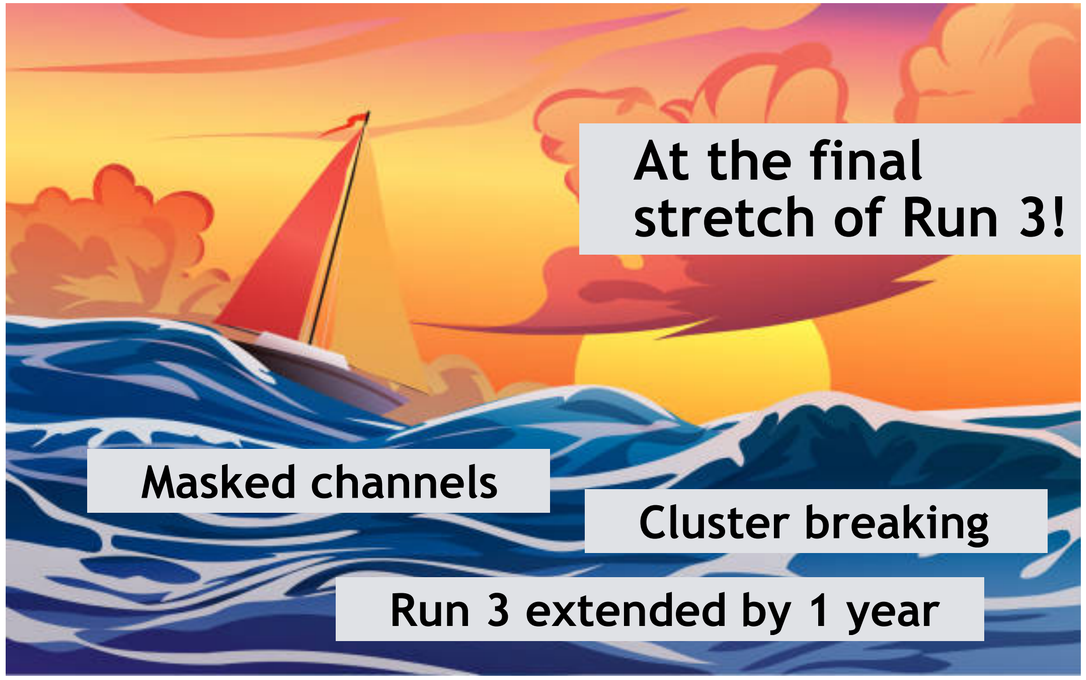
Keeping the ship afloat

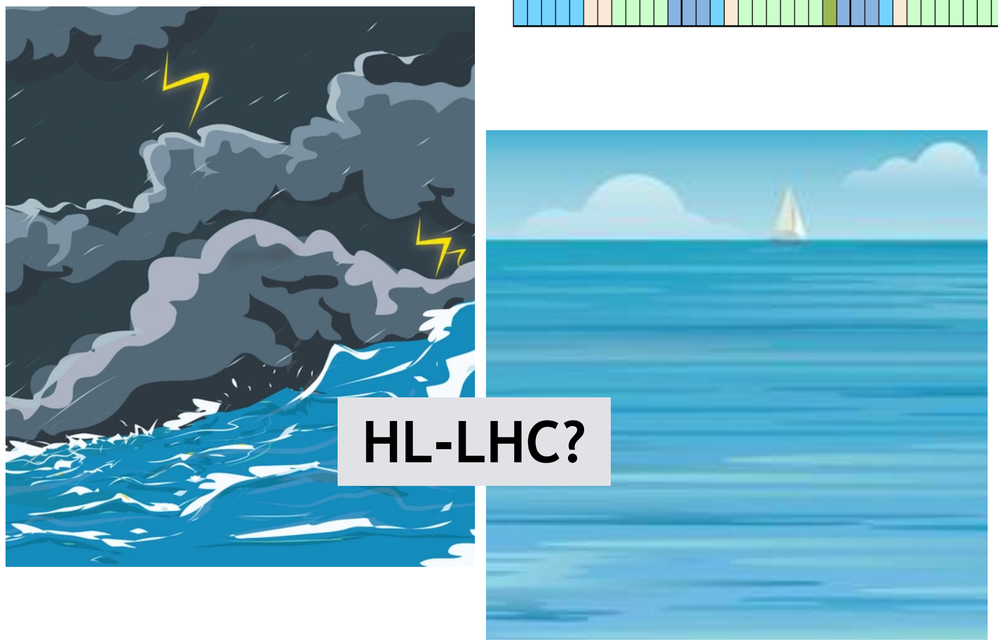
Continuous calibrations of the detector
Radiation effects are being monitored and studied closely
Various mitigation strategies





Navigating uncharted waters





Valuable experience for HL-LHC upgrades!

References and acknowledgments

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CMS Collaboration, *Pixel Detector Performance in Run 3 (December 2024)*, 2025, https://cds.cern.ch/record/2923949

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CMS Collaboration, *Operation and performance of the CMS silicon strip tracker with proton-proton collisions at the CERN LHC*, 2025, https://arxiv.org/abs/2506.17195

CMS Collaboration, *The CMS Phase-1 Pixel Detector Upgrade*, 2020, https://arxiv.org/abs/2012.14304

V. Chiochia et al., *A double junction model of irradiated silicon pixel sensors for LHC*, Nucl. Instrum. Meth. A 568 (2006) 51–55, [arXiv:physics/0506228], doi:10.1016/j.nima.2006.05.199

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Backup

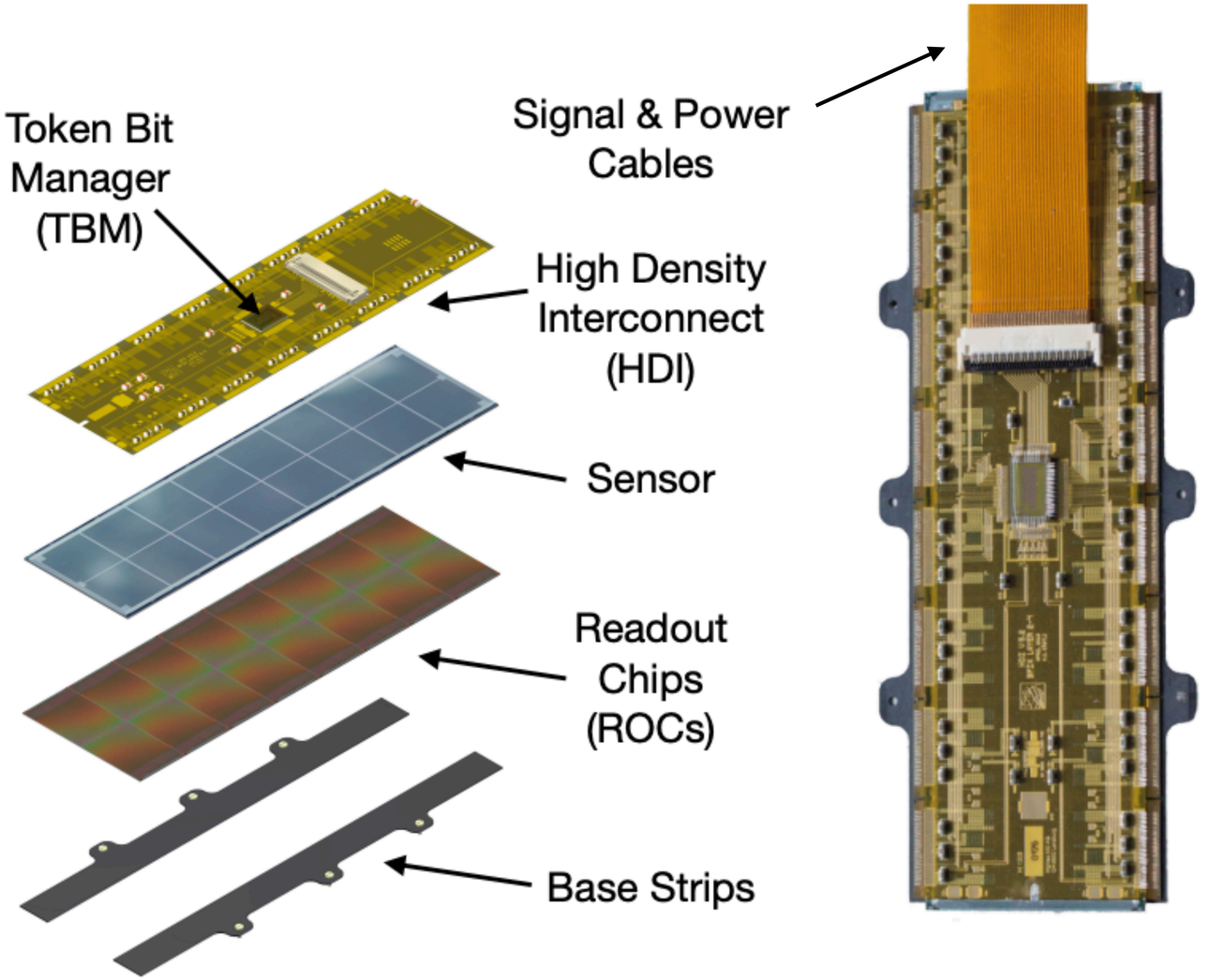
Silicon pixel tracker module design

Token Bit Manager (TBM)
- Receives clock, trigger, configuration data
- Controls readout of a group of ROCs
- 2 TBMs for Layer 1

High-density interconnect (HDI)
- Flex printed circuit glued on top of the sensor and wire-bonded to ROCs
- Routes control and data signals between ROCs and TMBs
- Routes high-voltage to the sensor

Planar n-in-n silicon sensor
- 280 μm thick
- 100x150 μm^2
- Bump-bonded to array of 2x8 ROCs

Read out chips (ROCs)
- PSI46dig > 90% efficiency up to 200MHz/cm^2 hit rate
- PROC600 > 90% efficiency up to 600MHz/cm^2 hit rate



PSI46dig and PROC600

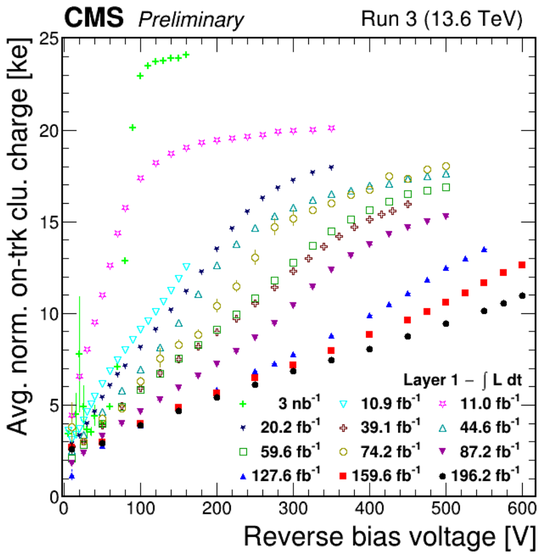
PSI46dig

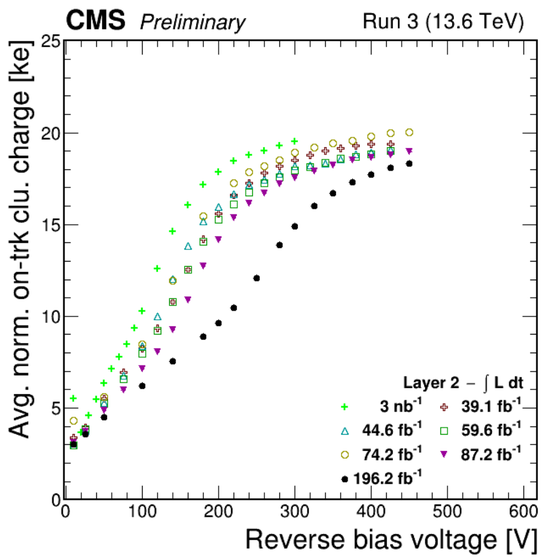
- Used in BPix 2-4 and FPix
- Column-drain readout architecture, 160 Mb/s digital readout, enhanced charge discriminator
- >90% efficiency up to 200MHz/cm^2 hit rate
- Radiation tested up to 150 Mrad

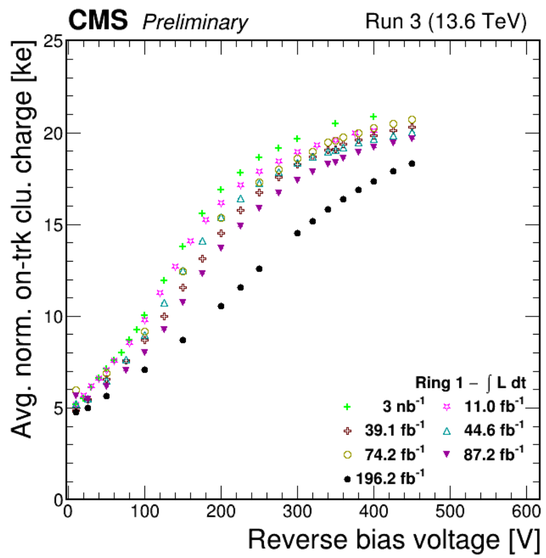
PROC600

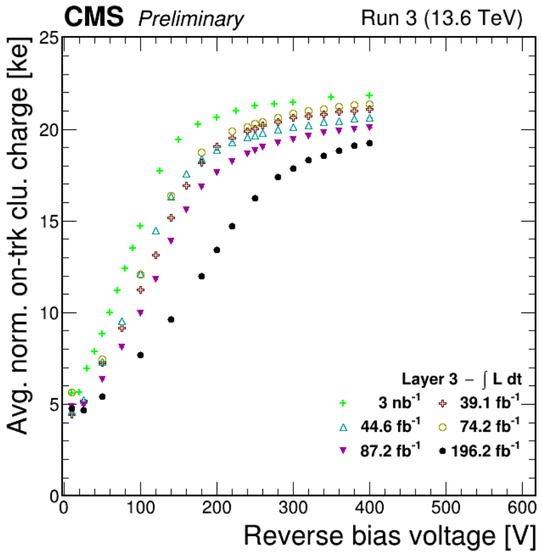
- Specifically designed for BPix Layer 1
- Faster hit transfer by grouping pixels into clusters of four for simultaneous readout
- >90% efficiency up to 600MHz/cm^2 hit rate
- Radiation tolerance tested up to 480 Mrad, with full functionality at doses up to 120 Mrad

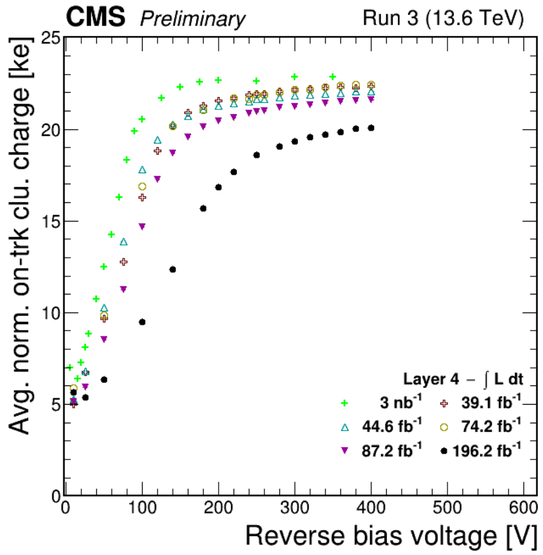
Pixels HV bias scan

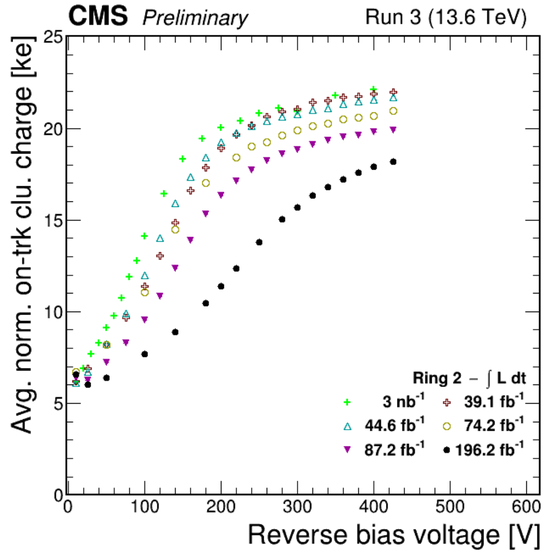






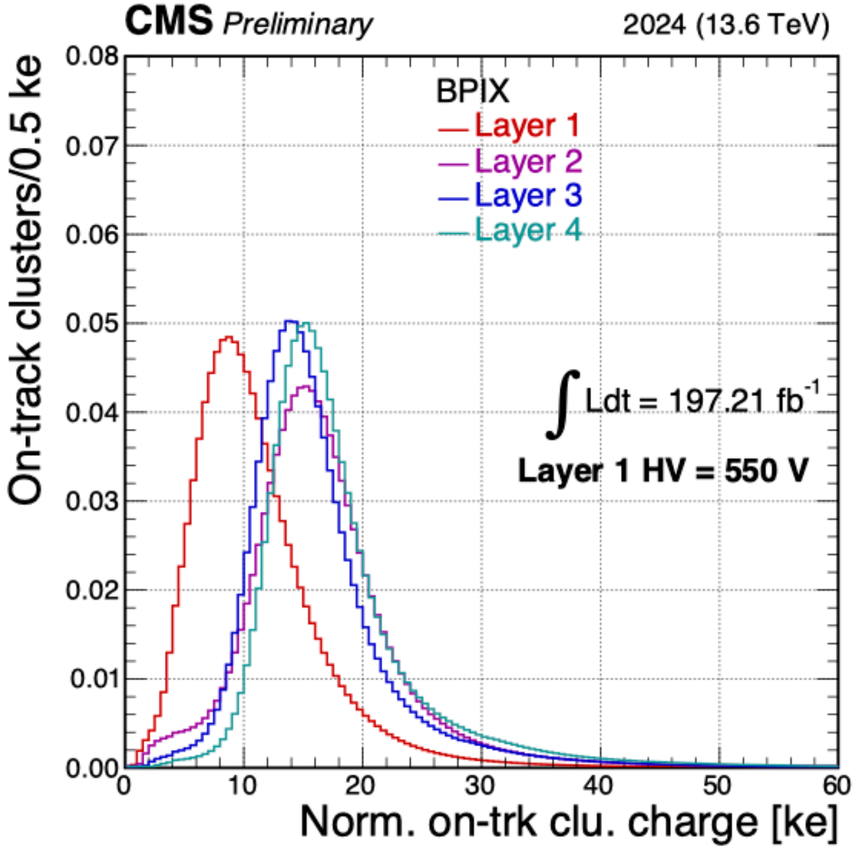


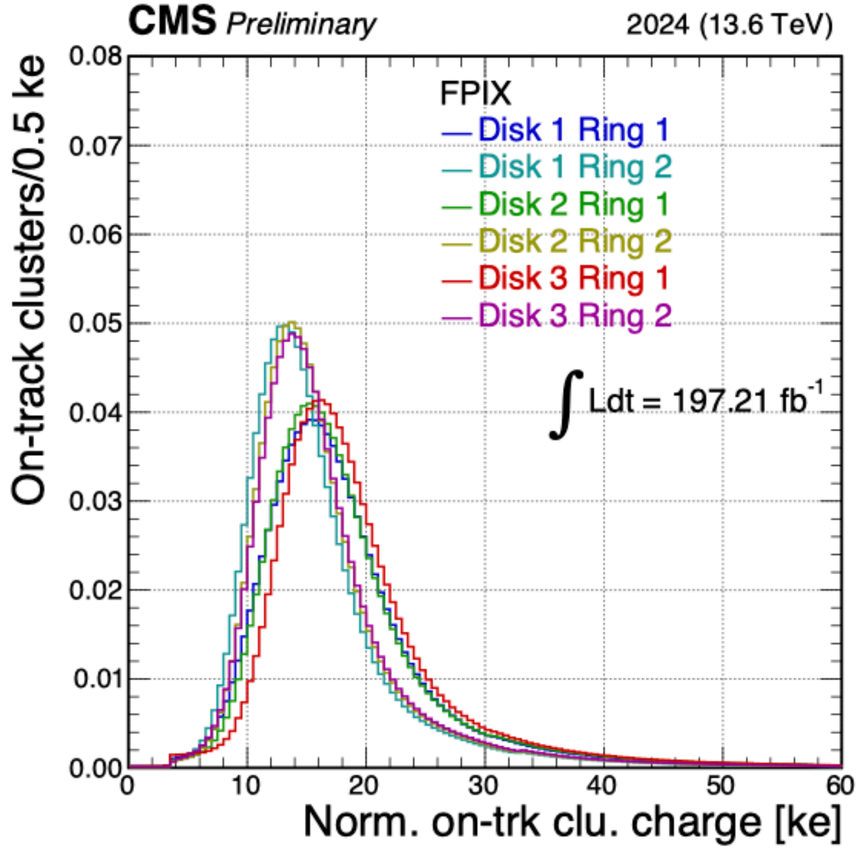




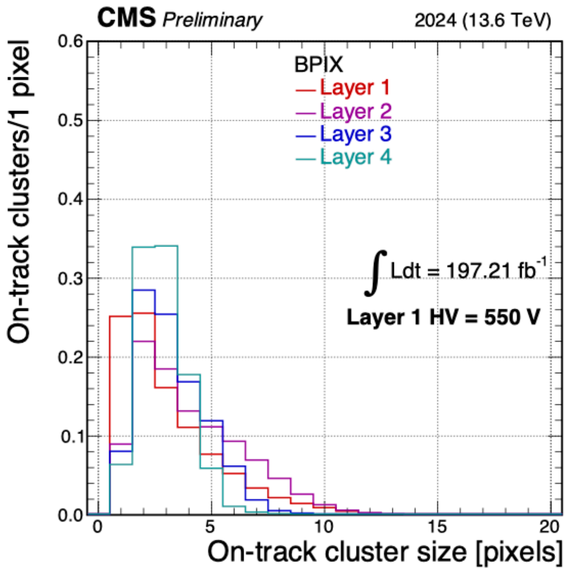
Pixels cluster properties

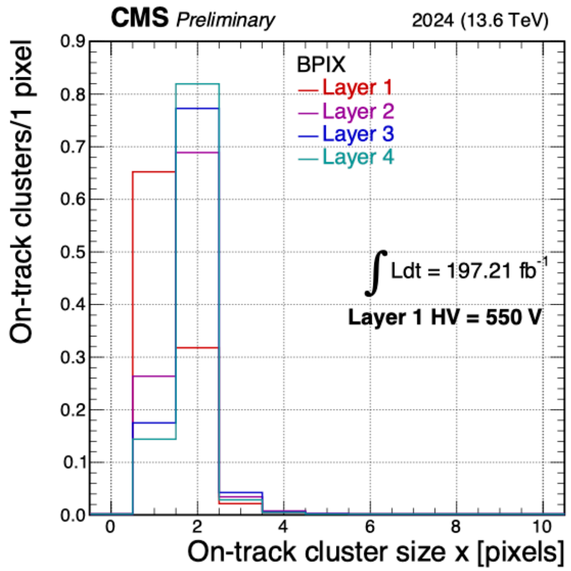
- Cluster charge normalized by incidence angle
- HV: BPix L2: 350V, L3&L4: 250V, FPix R1: 400V, FPix R2: 300V

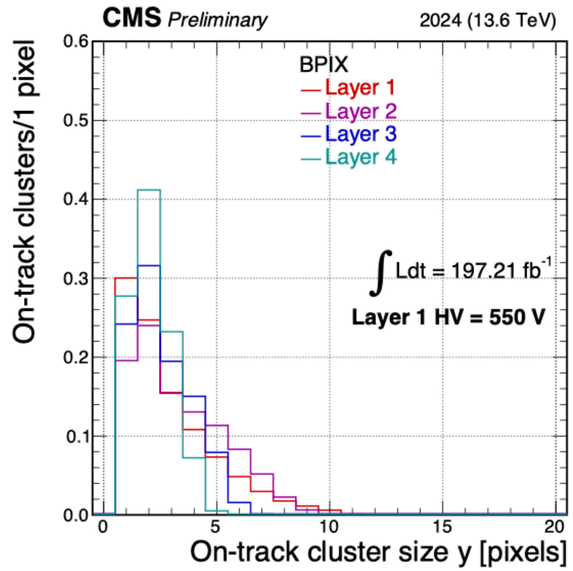


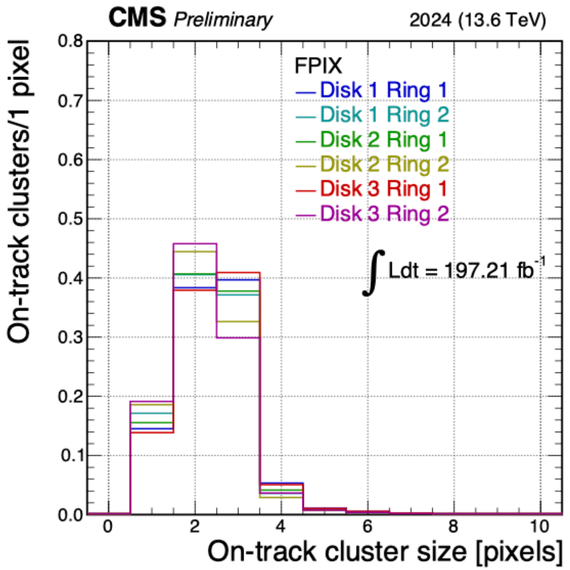


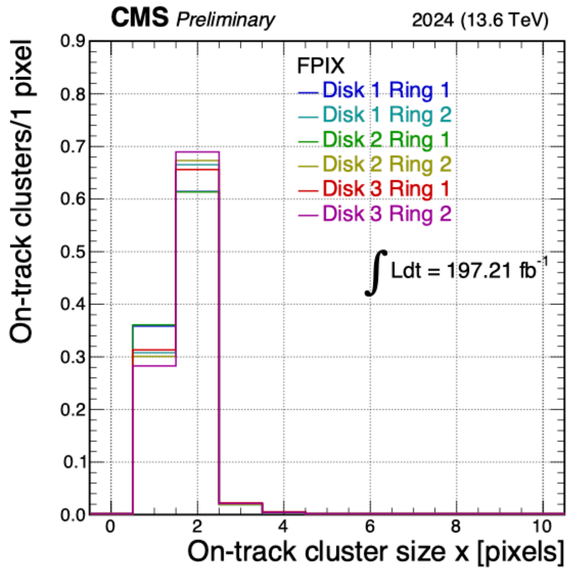
Pixel on-track cluster size

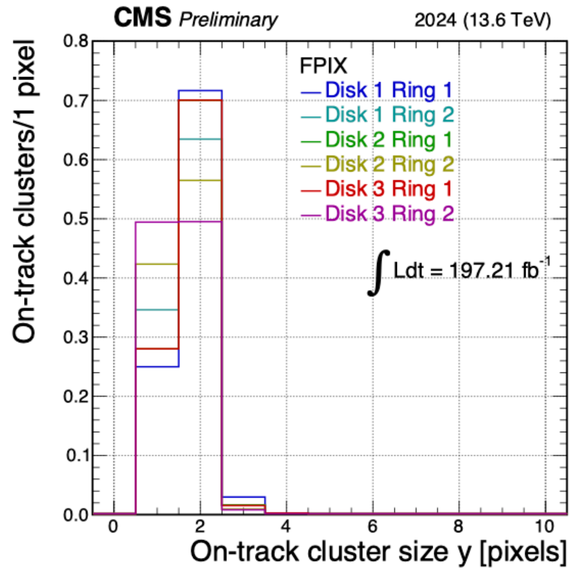






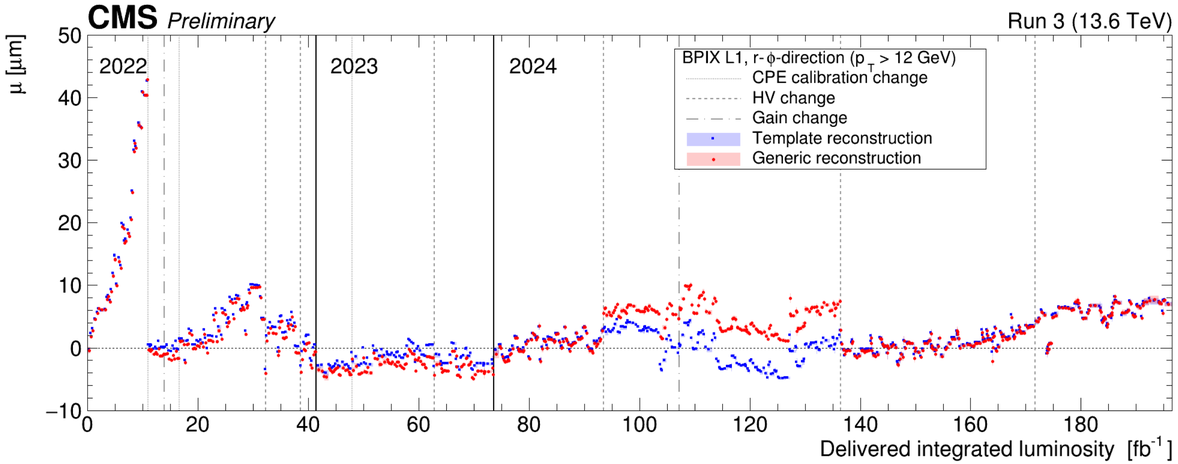


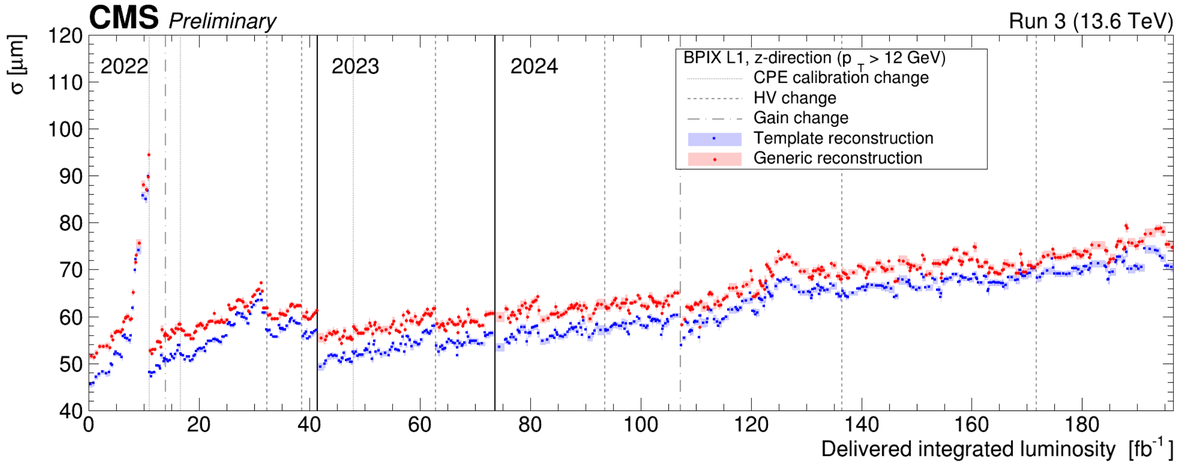


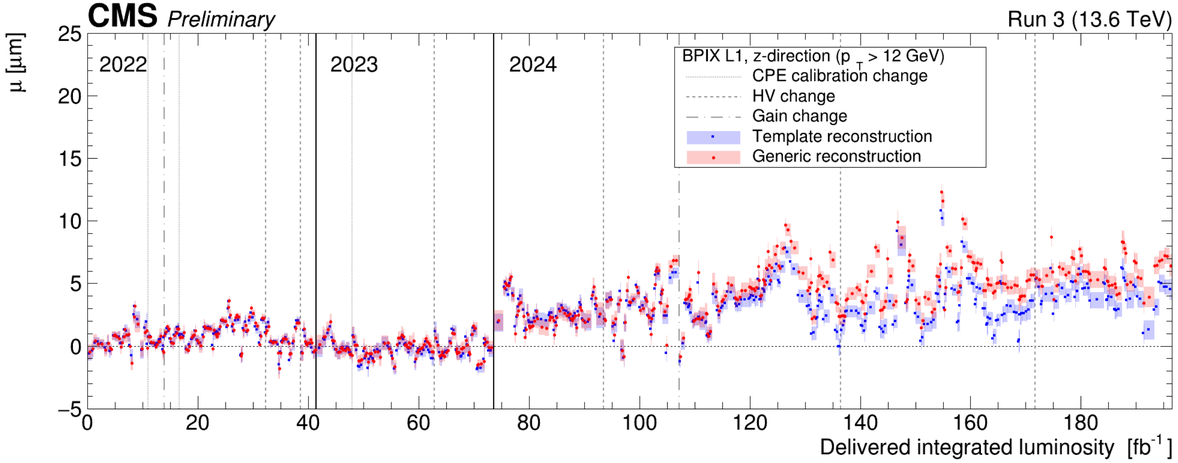


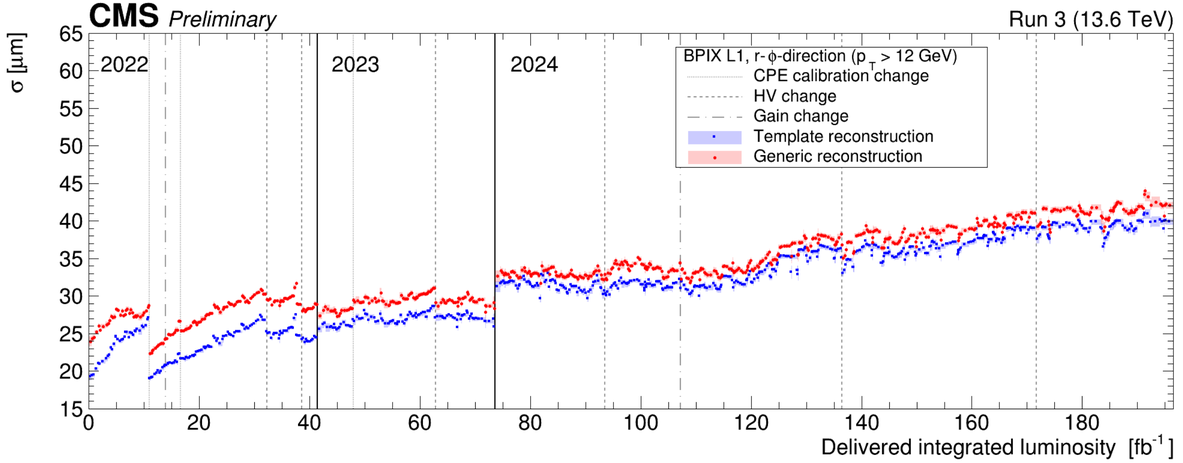
Pixels barrel layer 1 residual offset and resolution

Hit residuals in Layer 1 are not equivalent to the intrinsic hit resolution due to sizable extrapolation uncertainty that is folded in







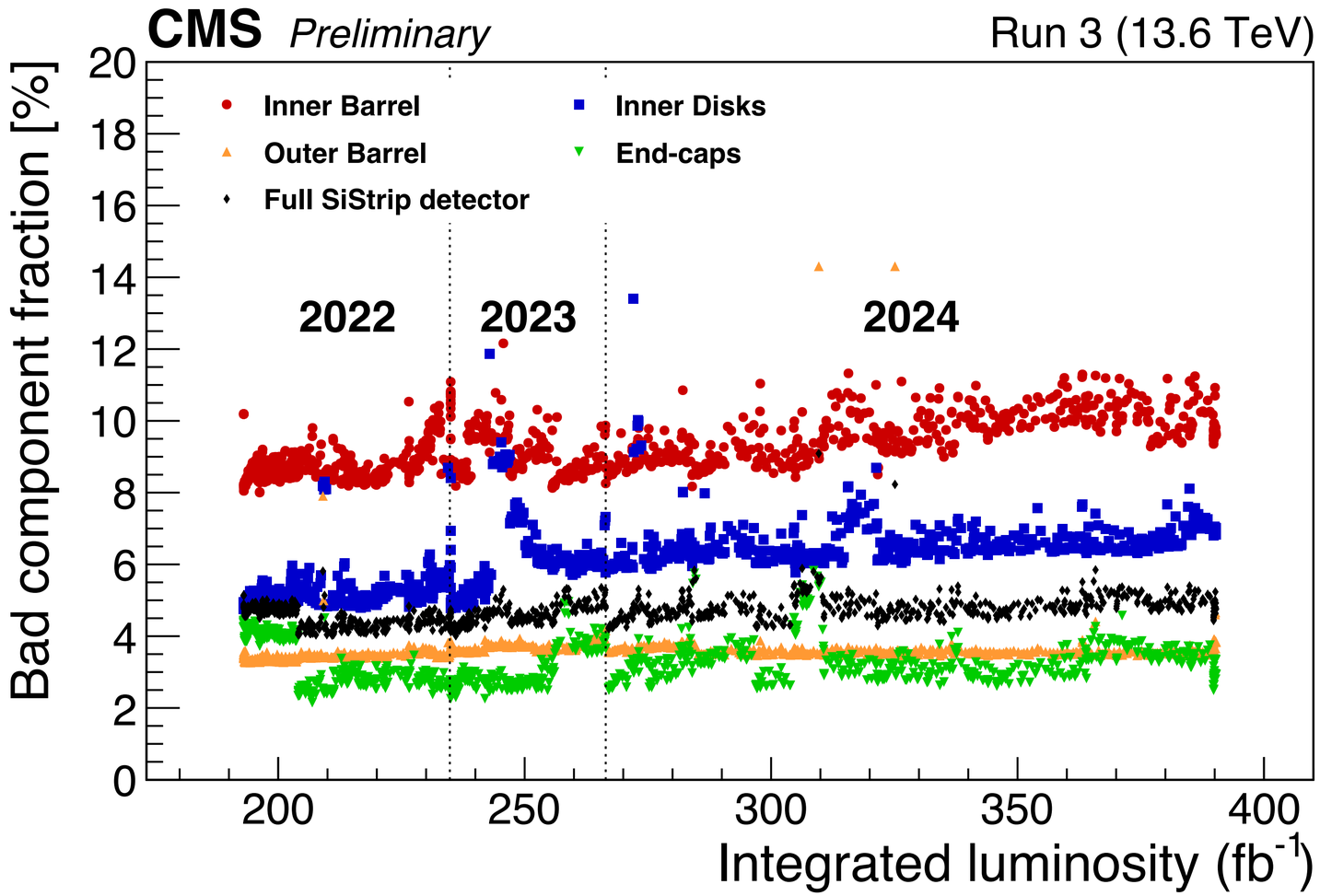


Summary of strip pitch range

Sub-detector	Layer	Pitch
TIB	1, 2	80
TIB	3, 4	120
TOB	1-4	183
TOB	5, 6	122

Sub-detector	Layer	Pitch
TID	1	80.5-119
TEC	1	81-112
TID/TEC	2	113-143
TED/TEC	3	123-158
TEC	4	113-139
TEC	5	126-156
TEC	6	163-205
TEC	7	140-172

Detector status - Strips



Each point represents a single run

Fraction of active channels:

Global: 95%

TEC: 97%

TOB: 96%

TID: 93%

TIB: 90%

Very high number of active channels

Radiation status

	BPix Layer 1	BPix Layer 2-4 FPix
Present (fb^{-1})	250	366
End of 2025 (fb^{-1})	320	435
End of Run 3 (fb^{-1})	380	495

	Fluence [10^{14} N-eq/cm^2]	Dose [Mrad]
Layer 1	20	94
Layer 2	6.9	36
Layer 3	3.5	17
Layer 4	2.1	9.2
FPix	3.7	19.3