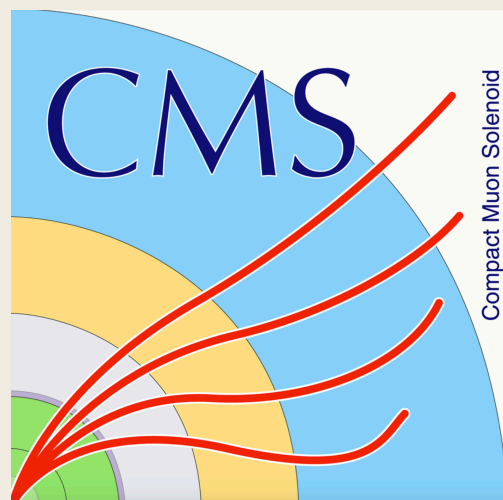
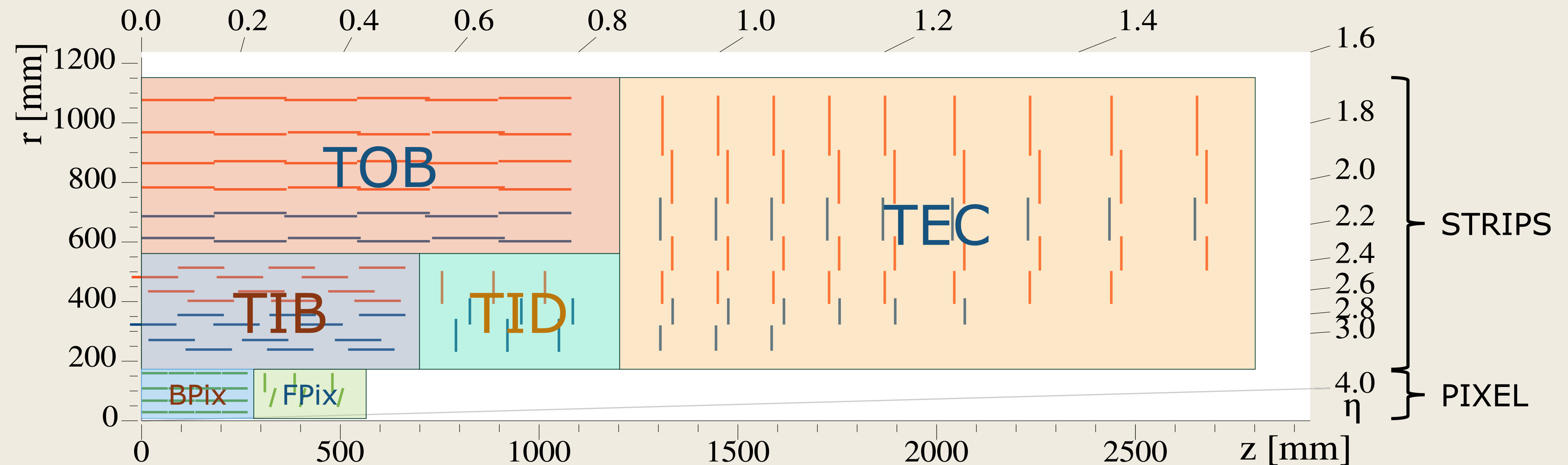

CMS Tracker Status, Challenges, and Performance in Run 3

Davide Zuolo - University of Colorado Boulder
On behalf of the CMS Collaboration Tracker Group



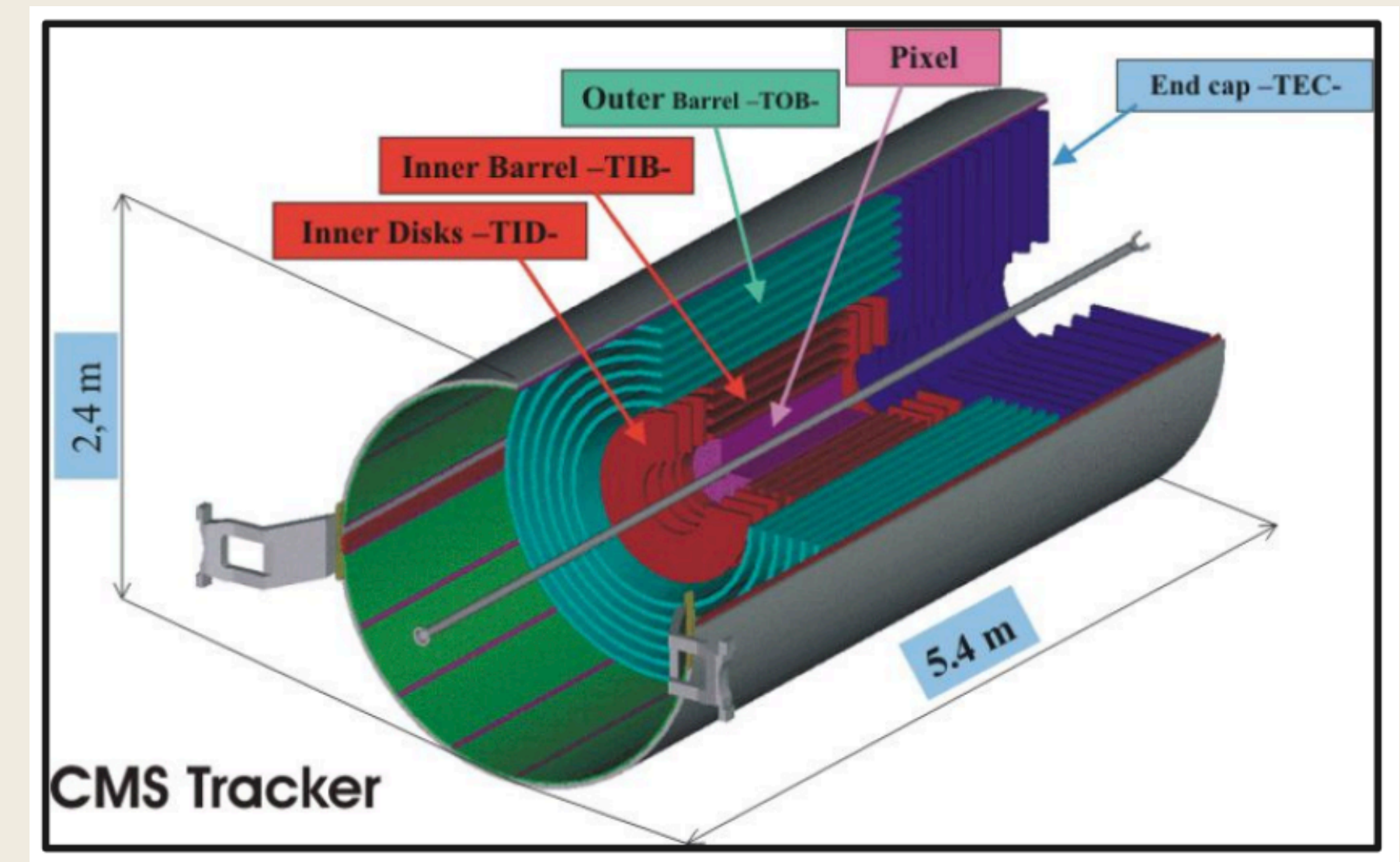
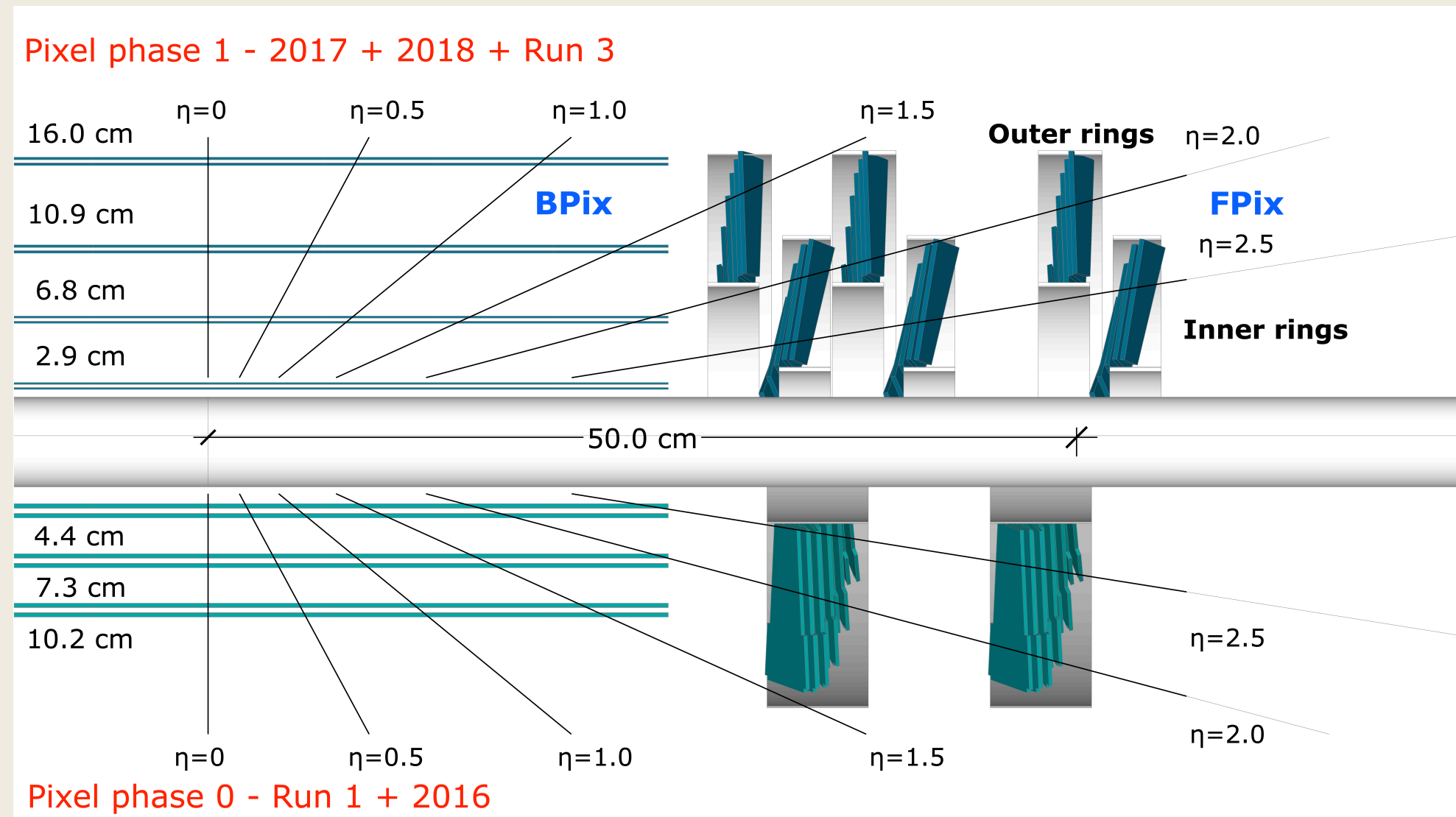
University of Colorado **Boulder**

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



Barrel pixels (BPix)

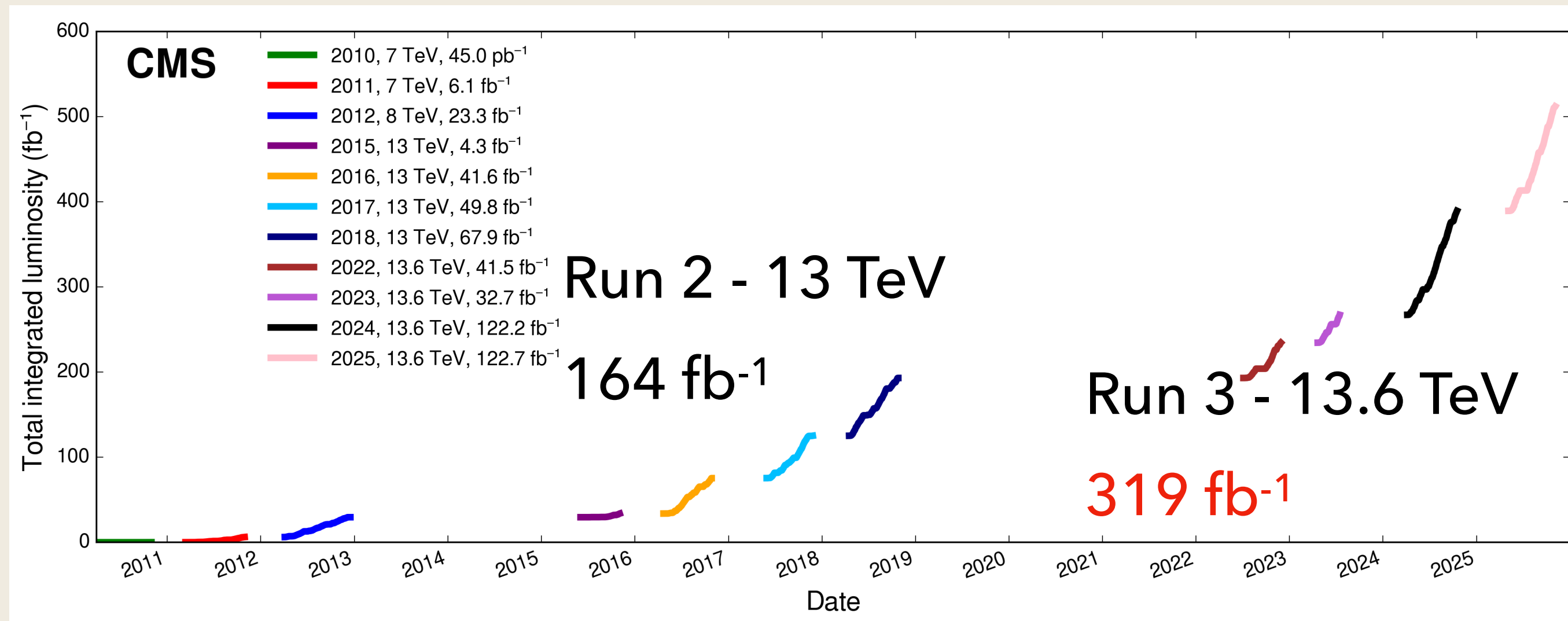
- 4 layers
- 1184 modules
- 4 hit coverage up to $|\eta| < 2.5$
- BPix Layer 1 replaced before the beginning of LHC Run 3

Forward pixels (FPix)

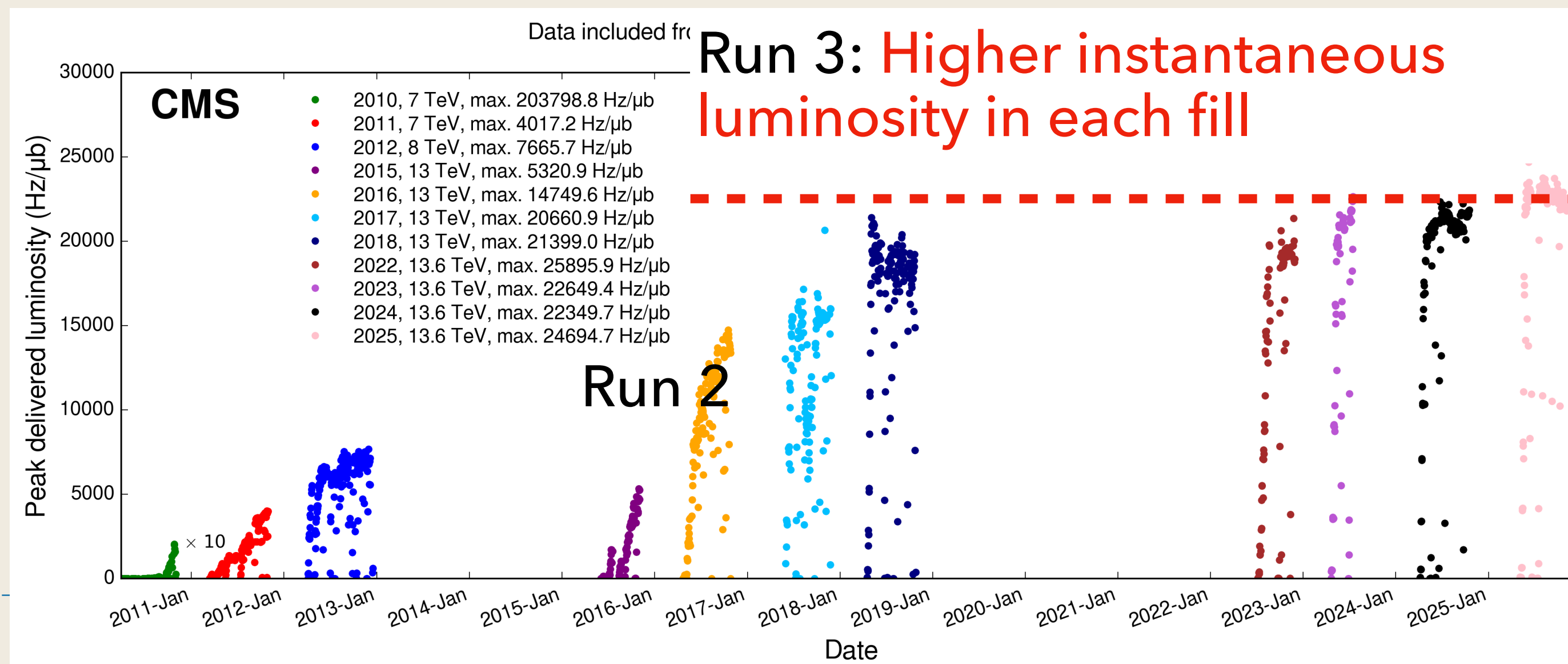
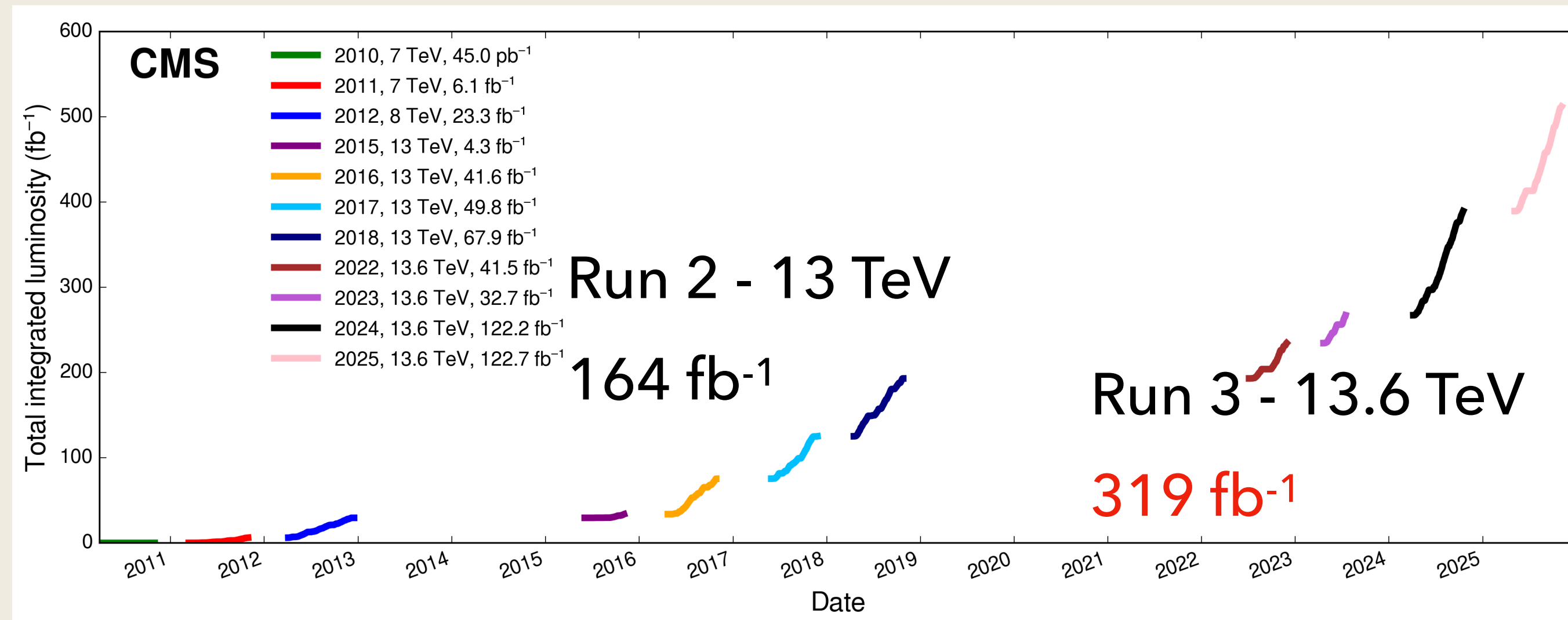
- 3 disks * 2 rings on each end
- 672 modules

- 10 barrel layers: 4 in TIB, 6 in TOB
- 3 inner disk (TID) and 9 endcap disks (TEC)
- 15148 total modules, 198 m² of active silicon

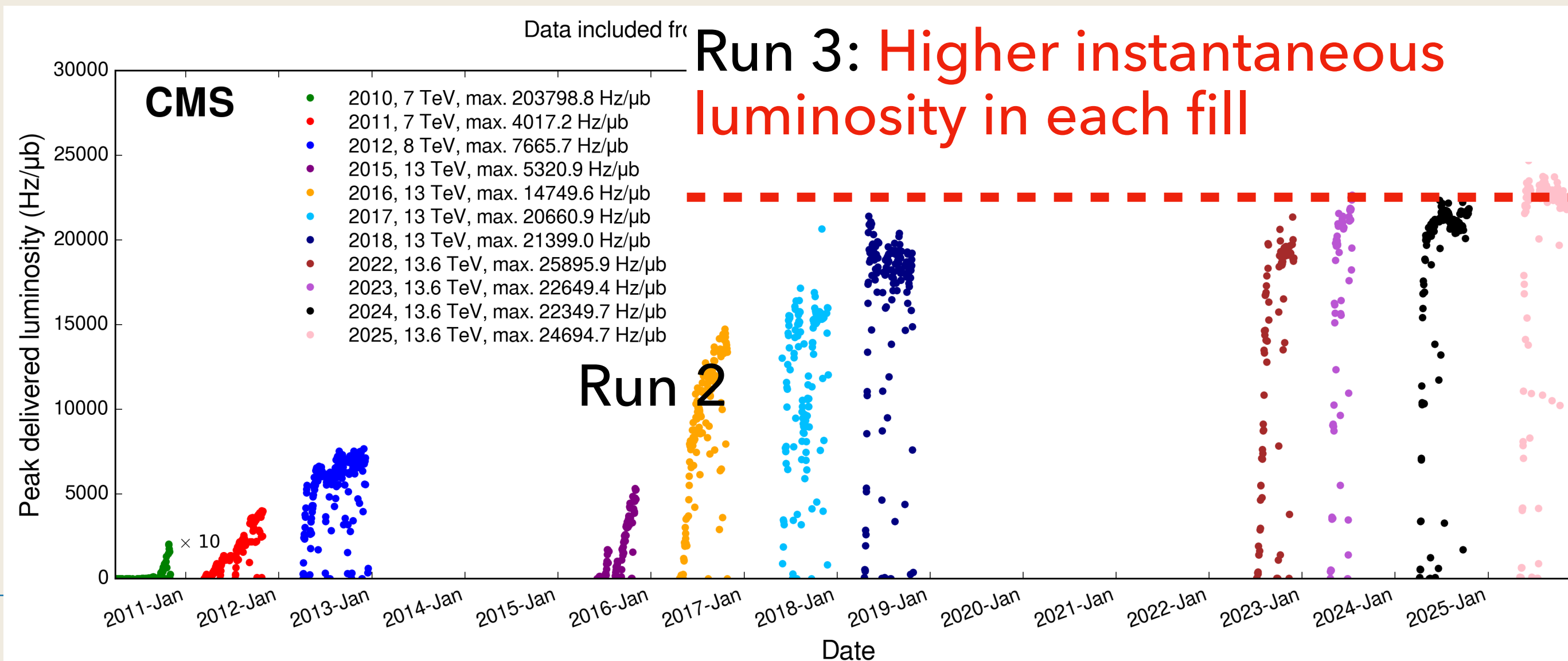
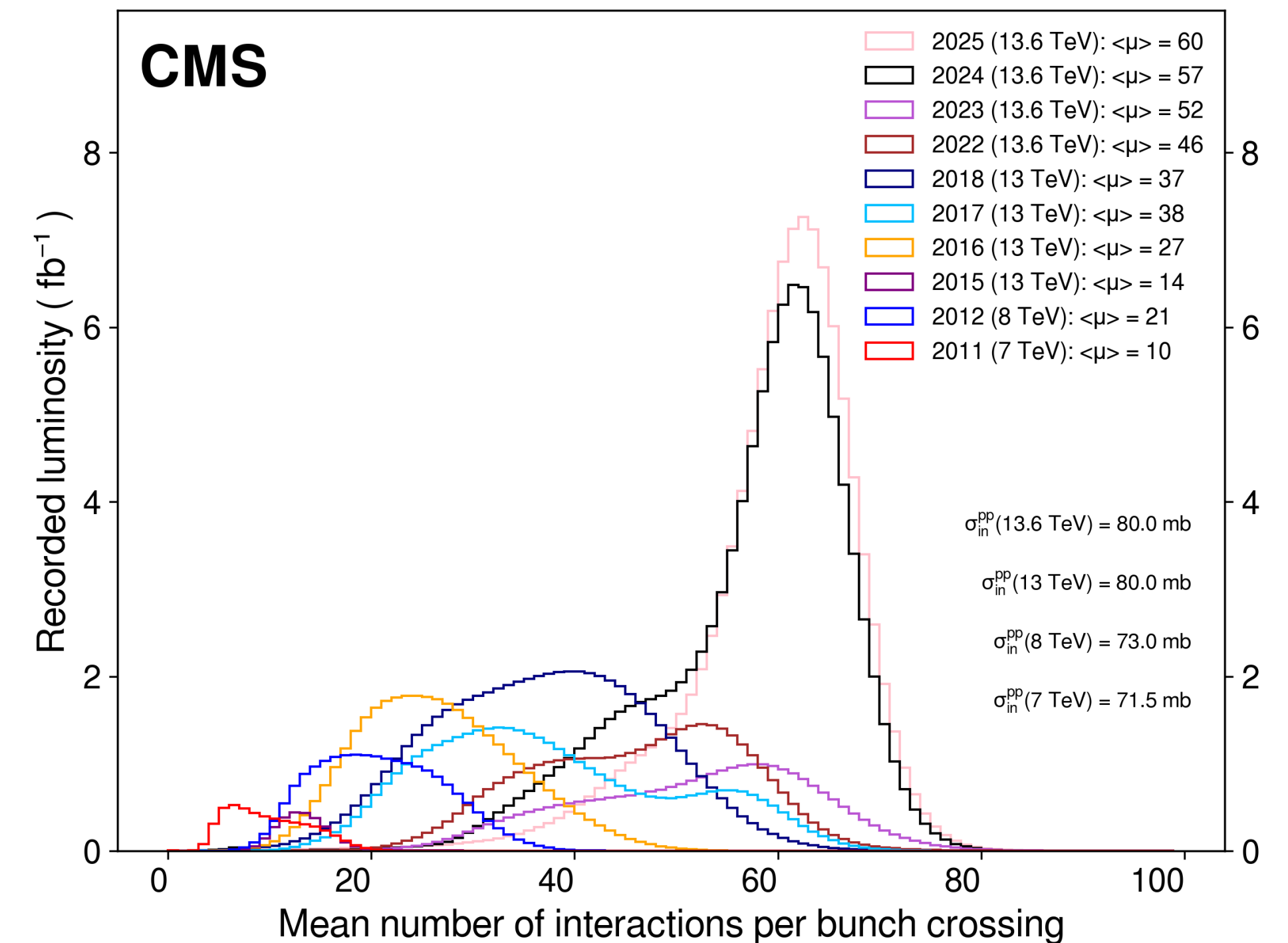
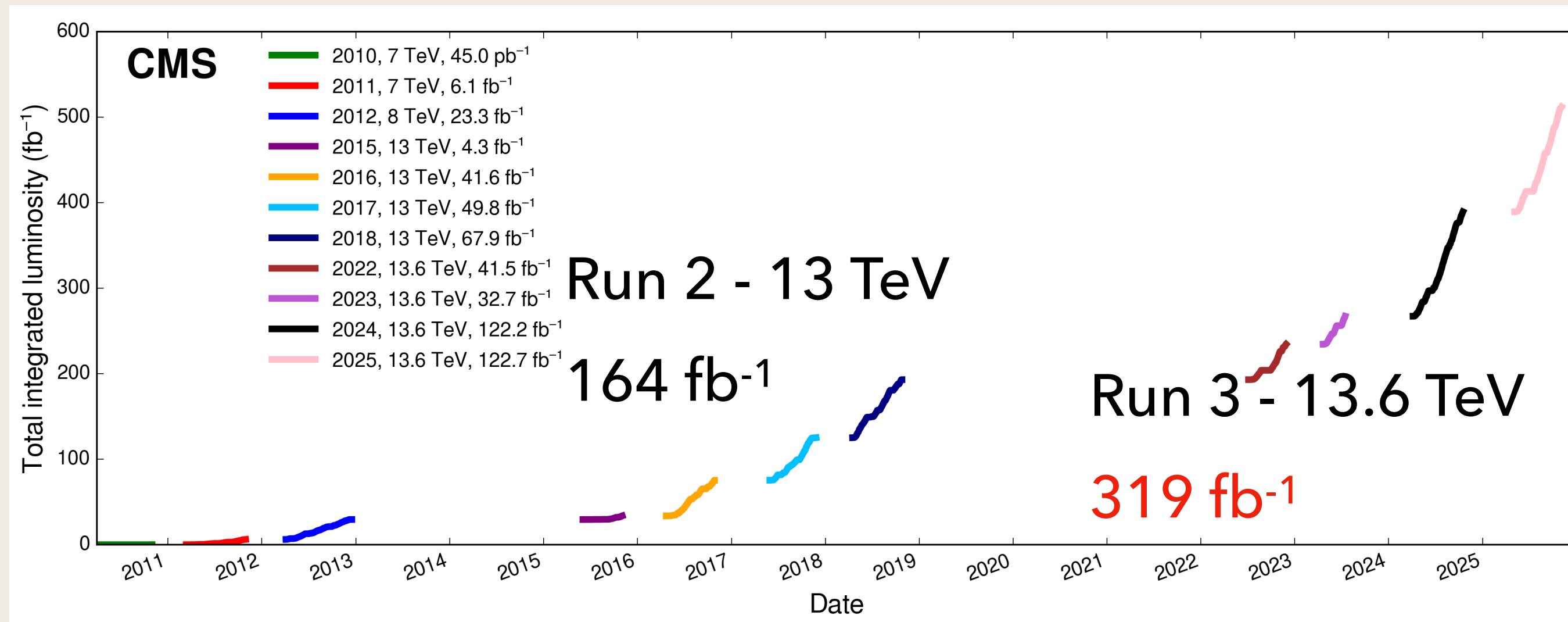
Operational conditions in Run 3



Operational conditions in Run 3



Operational conditions in Run 3



Instantaneous luminosity was kept constant at $2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for more than 7 hours → sharp pile-up profile, very high hit rate for long periods → **much more demanding environment than Run 2**

Radiation status

	BPix Layer 1	BPix Layer 2-4 FPix
End of 2025 (fb ⁻¹)	320	440
End of Run 3 (fb ⁻¹)	380	500

Table 2. Expected hit rate, fluence, and radiation dose for the BPIX layers and FPIX rings [7]. The hit rate corresponds to an instantaneous luminosity of $2.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [4]. The fluence and radiation dose are shown for integrated luminosities of 300 fb^{-1} for BPIX L1 and 500 fb^{-1} for the other BPIX layers and FPIX disks.

TDR Estimations	Pixel hit rate [MHz/cm ²]	Fluence [10 ¹⁵ n _{eq} /cm ²]	Dose [Mrad]
BPIX L1	580	2.2	100
BPIX L2	120	0.9	47
BPIX L3	58	0.4	22
BPIX L4	32	0.3	13
FPIX inner rings	56-260	0.4-2.0	21-106
FPIX outer rings	30-75	0.3-0.5	13-28

	Fluence [10 ¹⁵ n _{eq} /cm ²]	Dose [Mrad]
Layer 1	2.55	122
Layer 2	0.83	43
Layer 3	0.42	20
Layer 4	0.26	11
FPix - Ring 1 - low r	2.32	116
FPix - Ring 1 - mid r	0.44	23
FPix - Ring 2 - high r	0.22	12

Radiation status

BASICALLY... "THEY TRY TO BREAK US, LOOKS LIKE THEY'LL TRY AGAIN"

		Layer 1	2.55	122
End of 2025 (fb ⁻¹)	320		0.83	43
			0.42	20
			0.26	11
End of Run 3 (fb ⁻¹)	380		2.32	116
			0.44	23
			0.22	12

Table 2. Expected hit rate, fluence, and radiation dose for the BPIX. The hit rate corresponds to an instantaneous luminosity of 2.0×10^{34} cm⁻²s⁻¹ and radiation dose are shown for integrated luminosities of 300 fb⁻¹ for the other BPIX layers and FPIX disks.

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FPIX outer rings	30-75	0.3-0.5



Silicon pixel tracker module design

Token Bit Manager (TBM)

- Controls readout of a group of 16 ROCs (module)
- Newer version in BPix Layer 1 (SEU tolerant)

High-density interconnect (HDI)

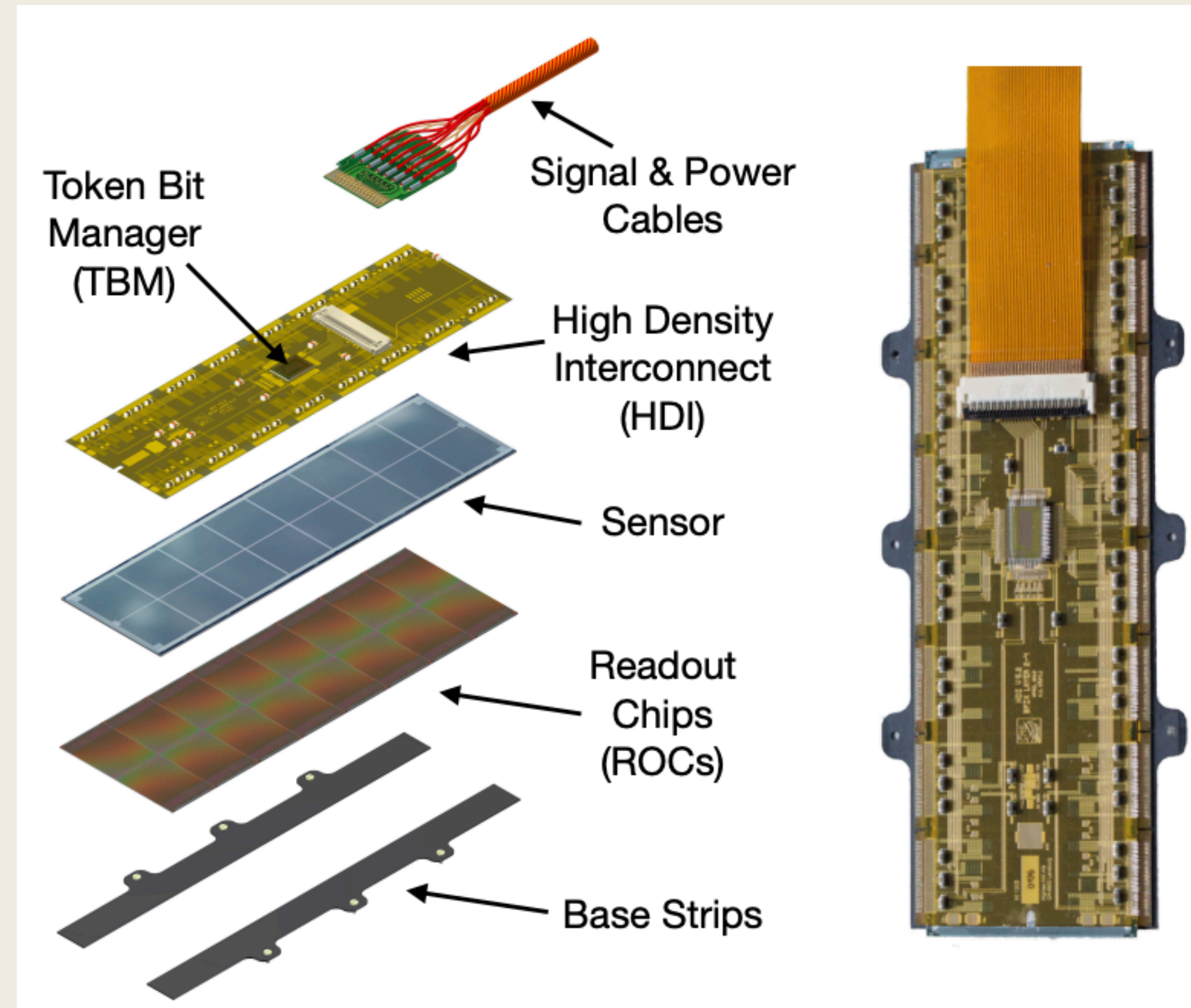
- Routes high-voltage to the sensor

Planar n-in-n silicon sensor

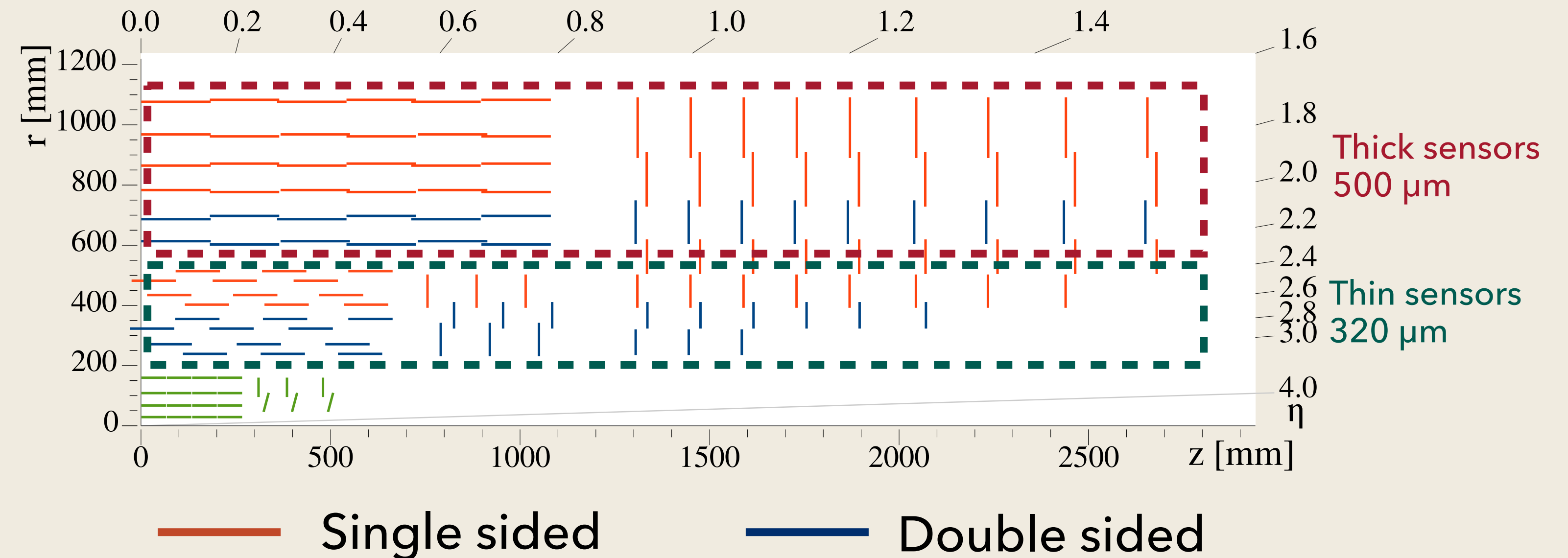
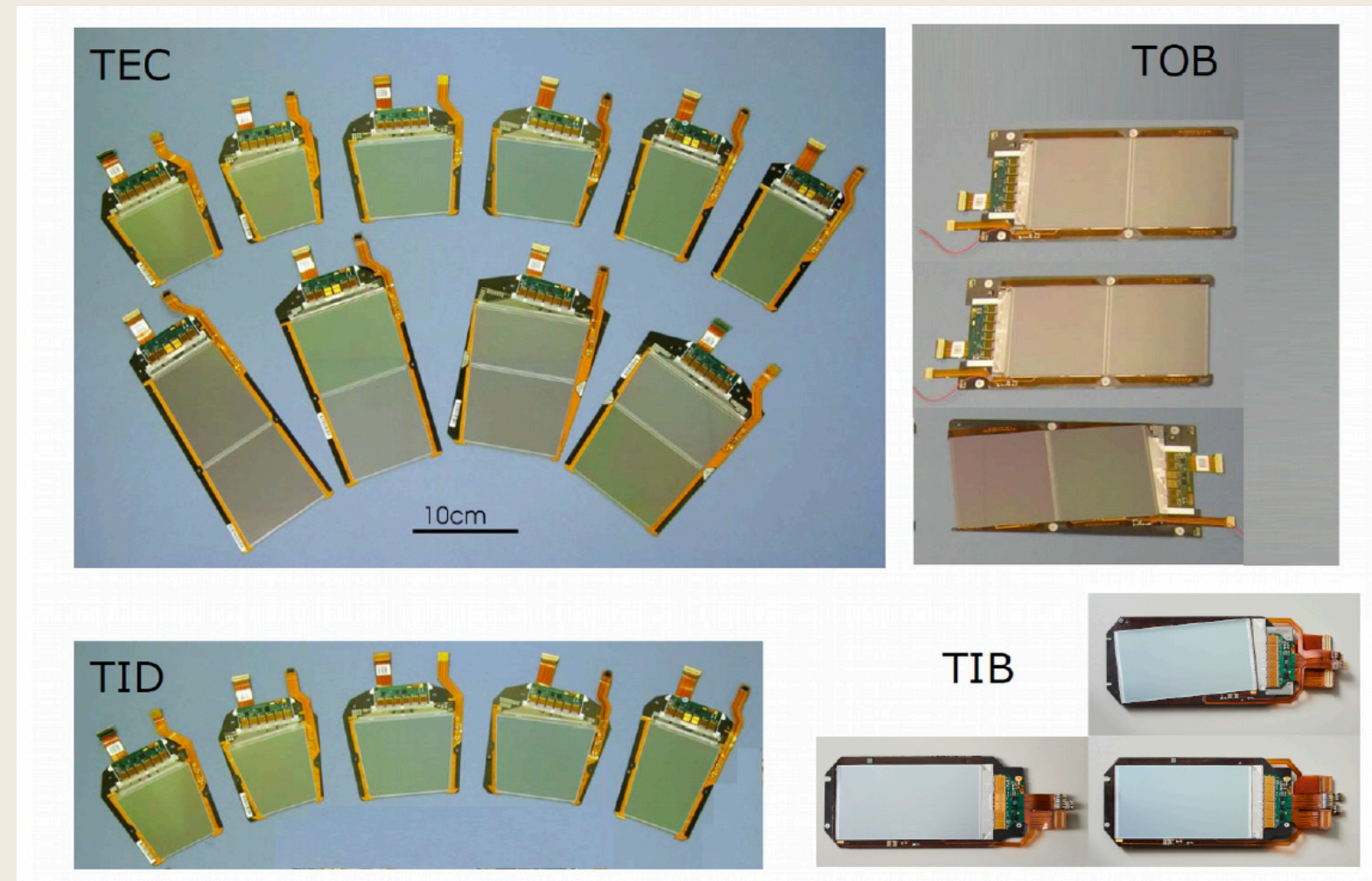
- 285 μm thick
- 100x150 μm^2 pixel cells

Read out chips (ROCs)

- PROC600 >90% efficiency up to **600MHz/cm²** hit rate (BPix Layer 1 only)
- PSI46dig >90% efficiency up to **200MHz/cm²** hit rate (BPix Layer 2-4, FPix)

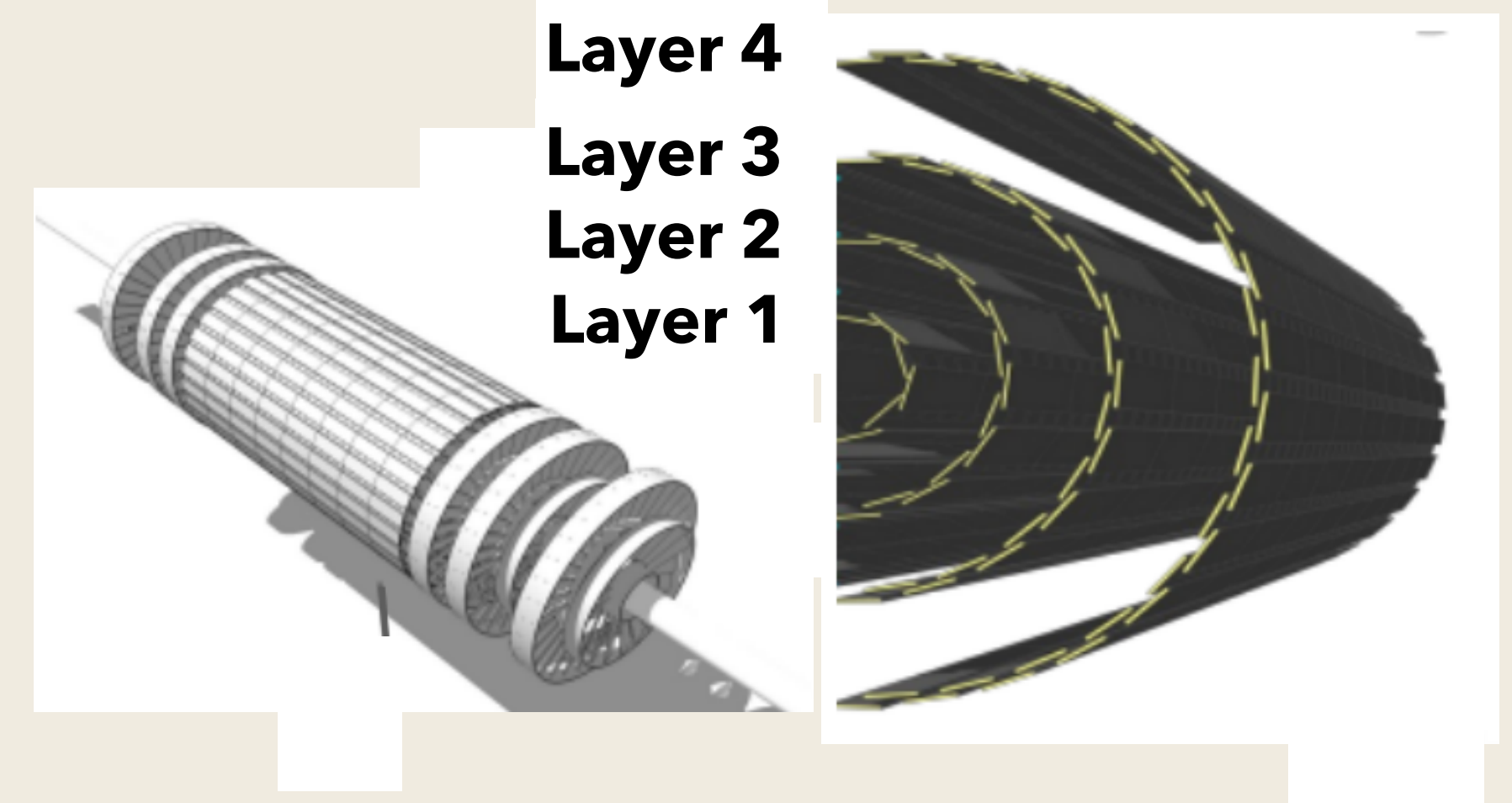
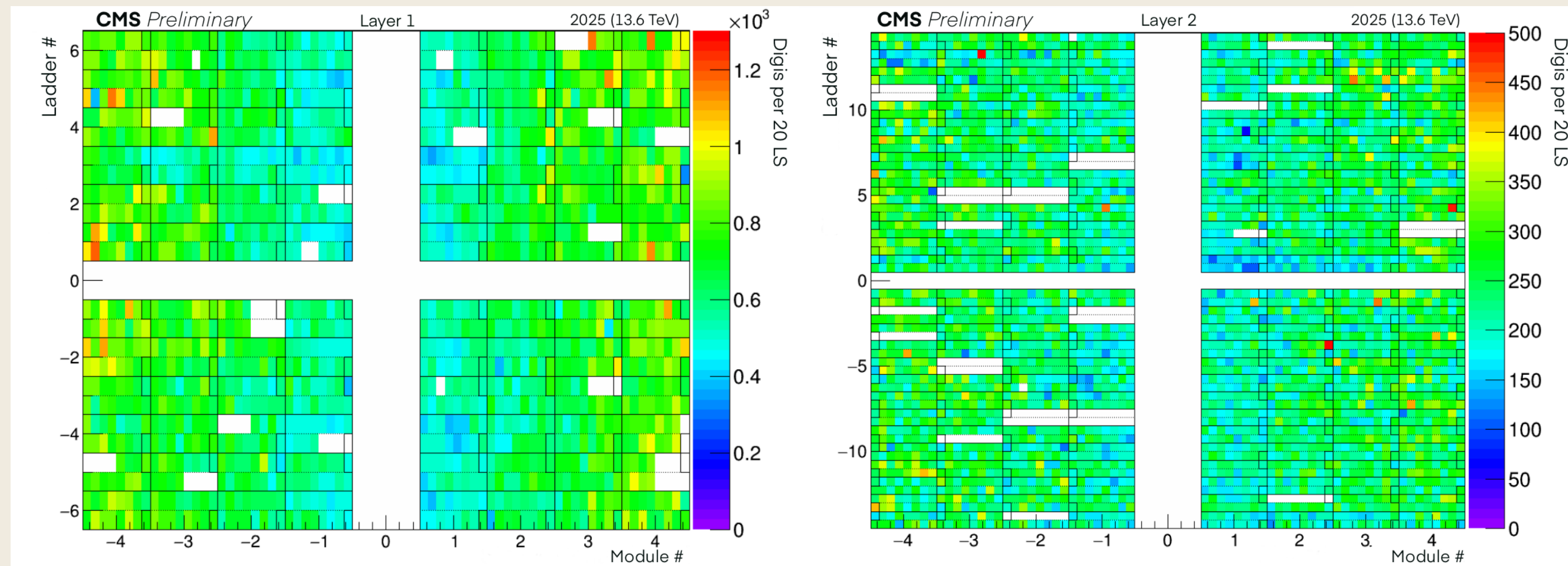


Silicon strip tracker module design



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

Detector status - Pixels BPix



Occupancy as of July 2025

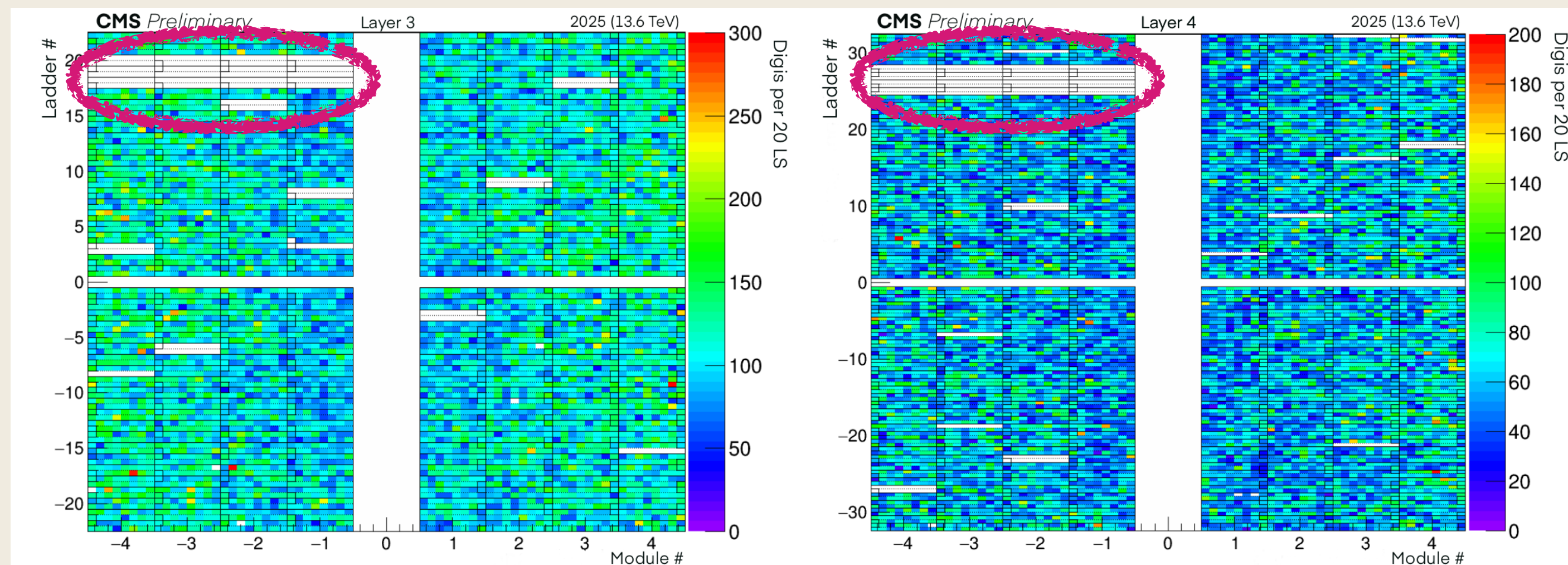
Active channels: ~96%

Bml SEC7 Layers 3/4:

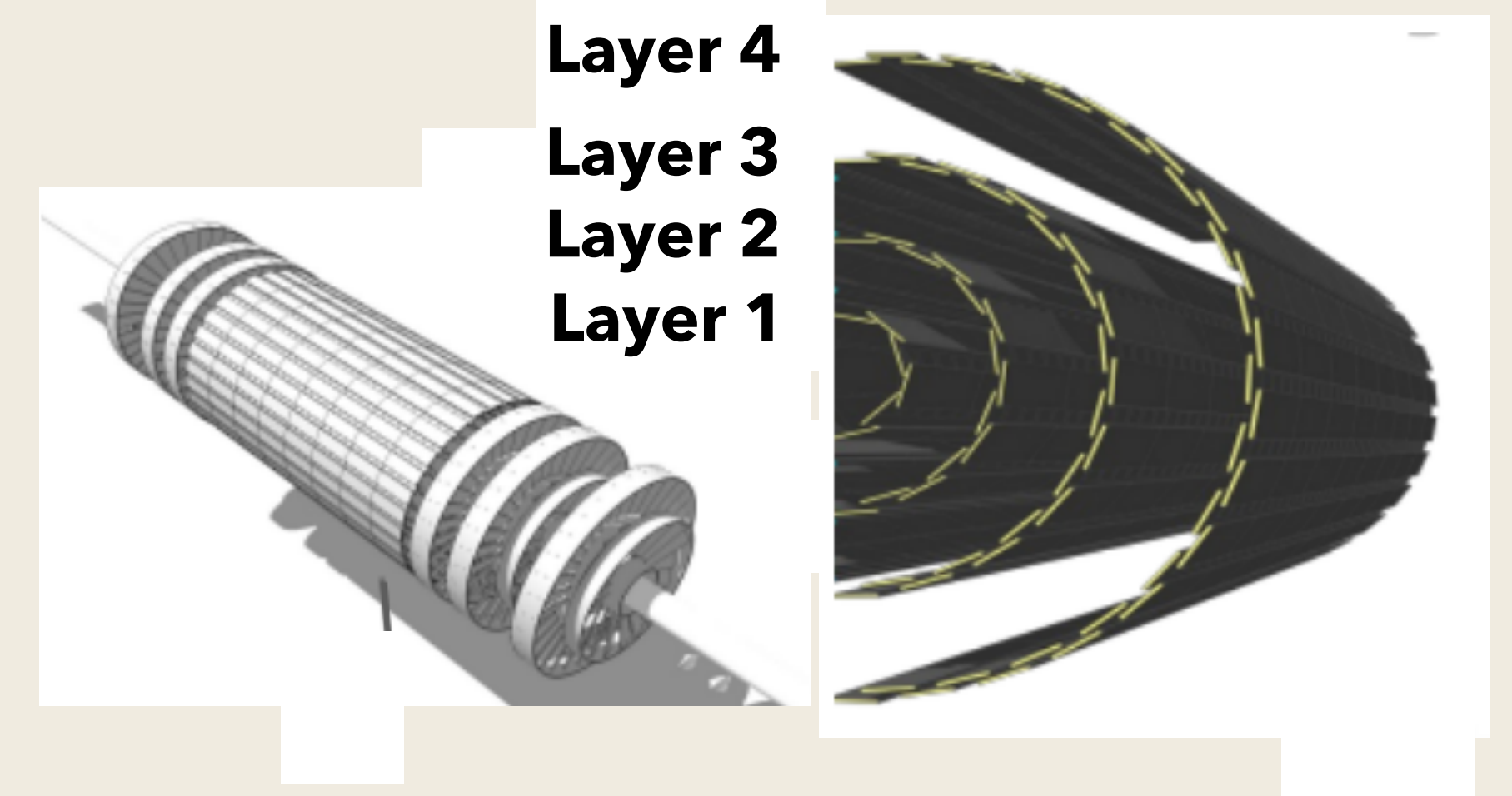
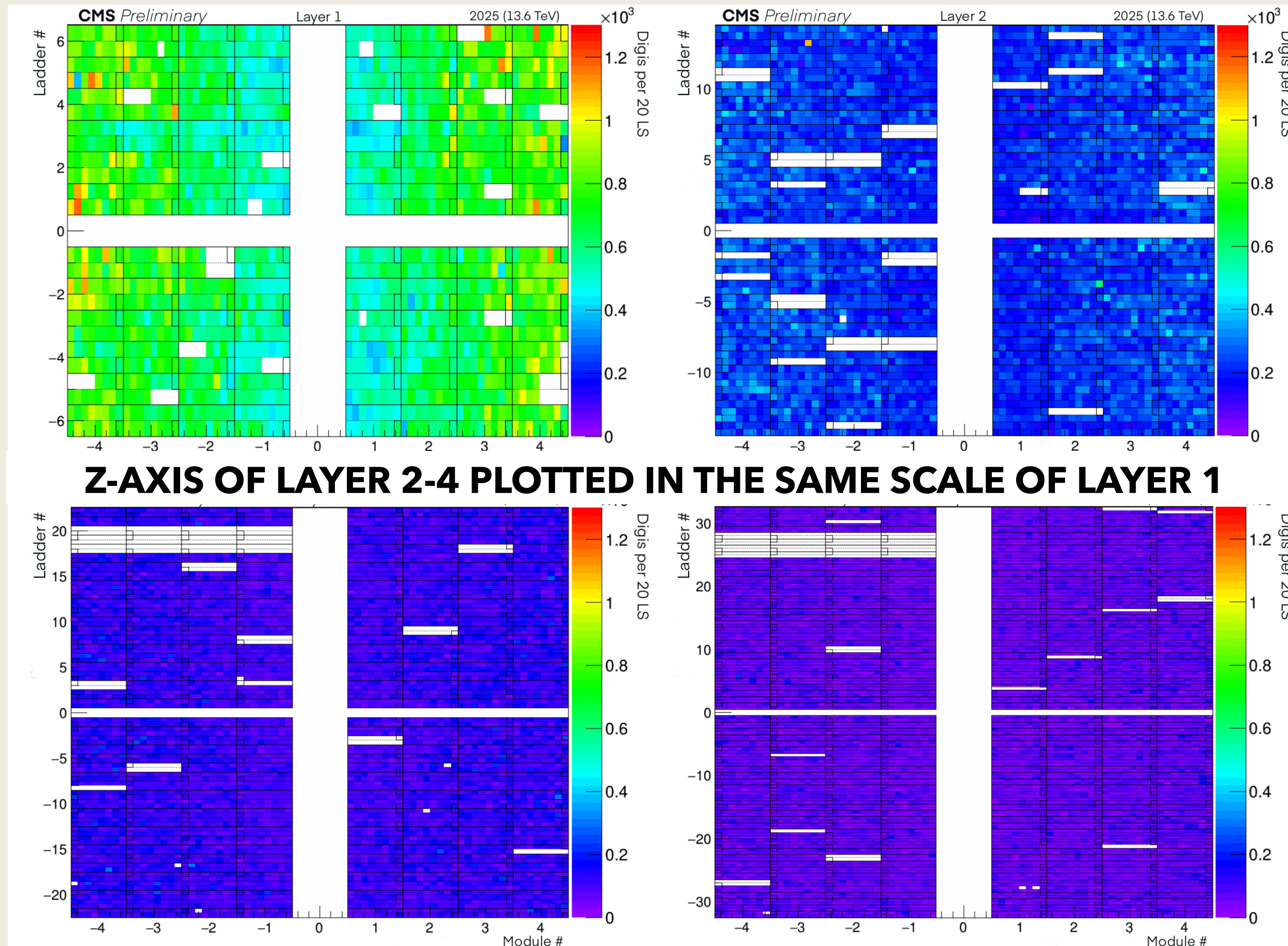
Fails to lock to LHC clock since the second half of 2023

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



Occupancy as of July 2025

Active channels: ~96%

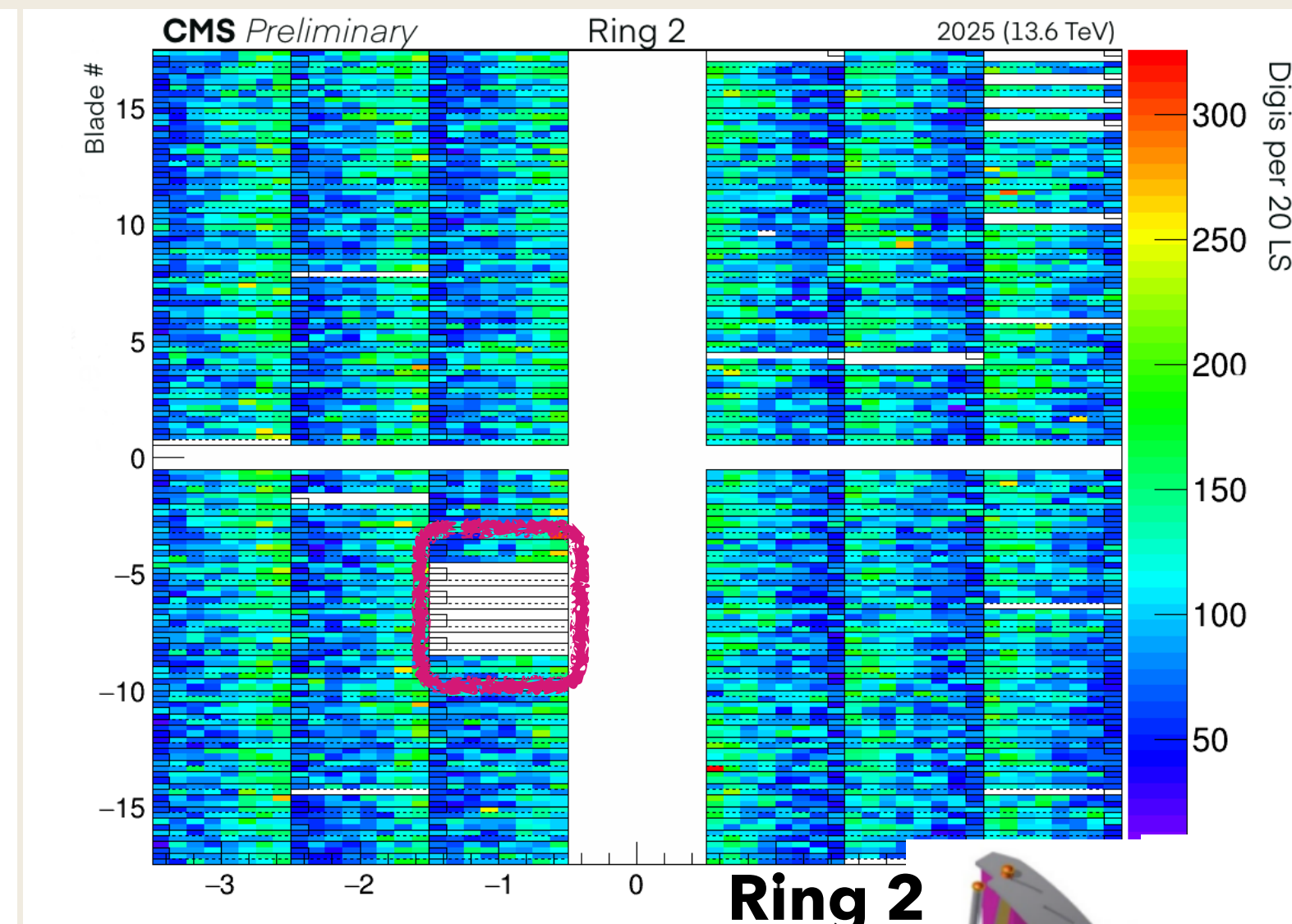
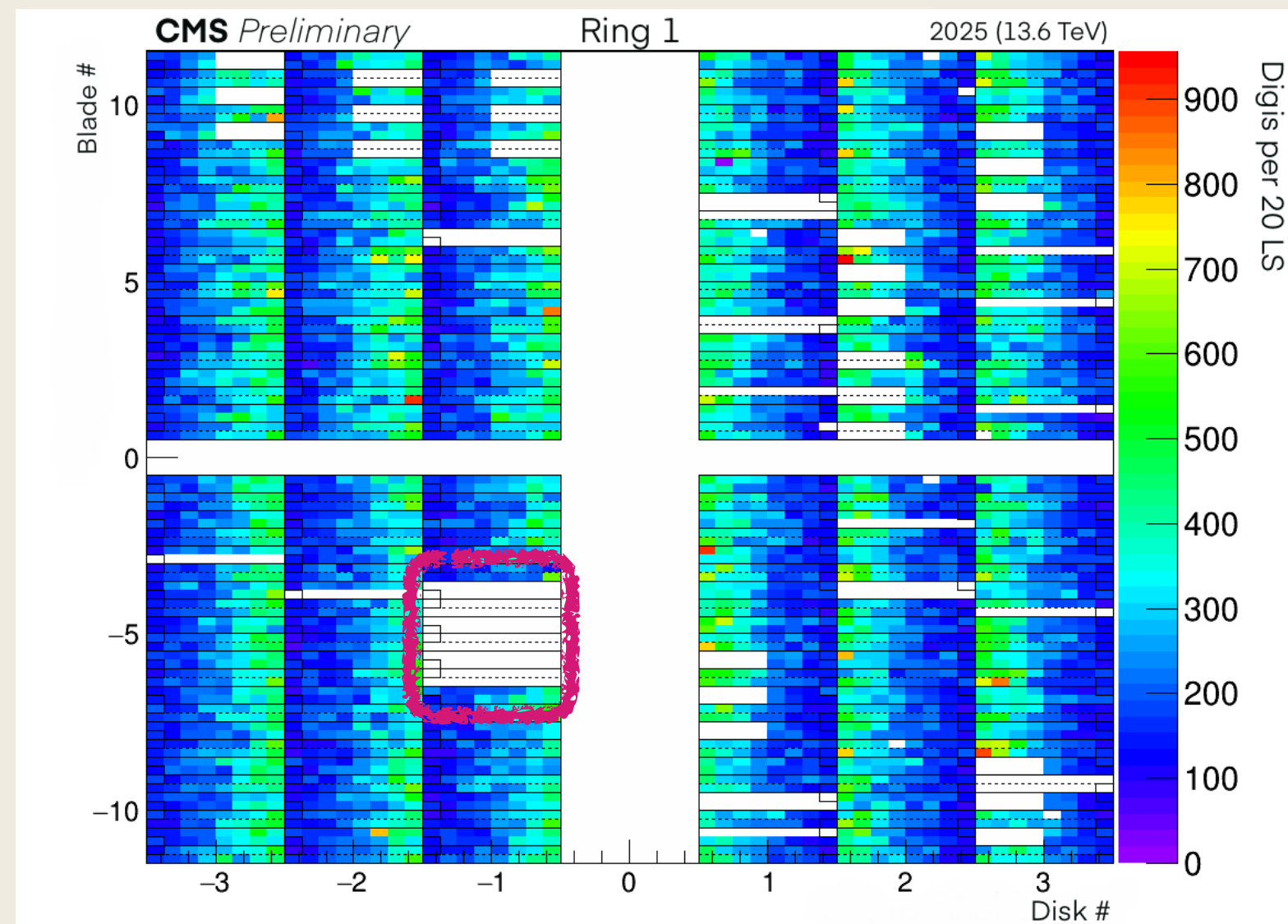
Bml SEC7 Layers 3/4:

Fails to lock to LHC clock since the second half of 2023

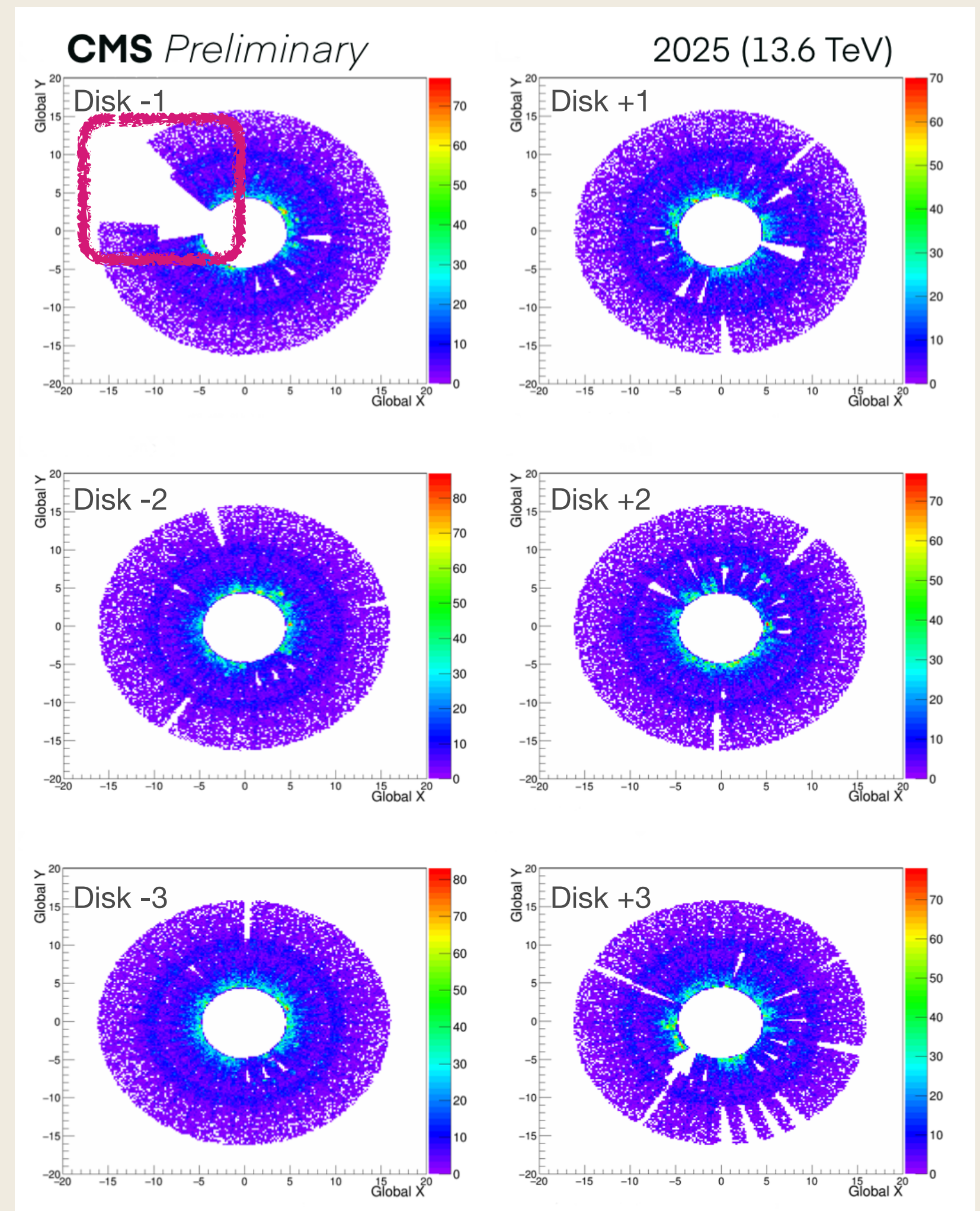
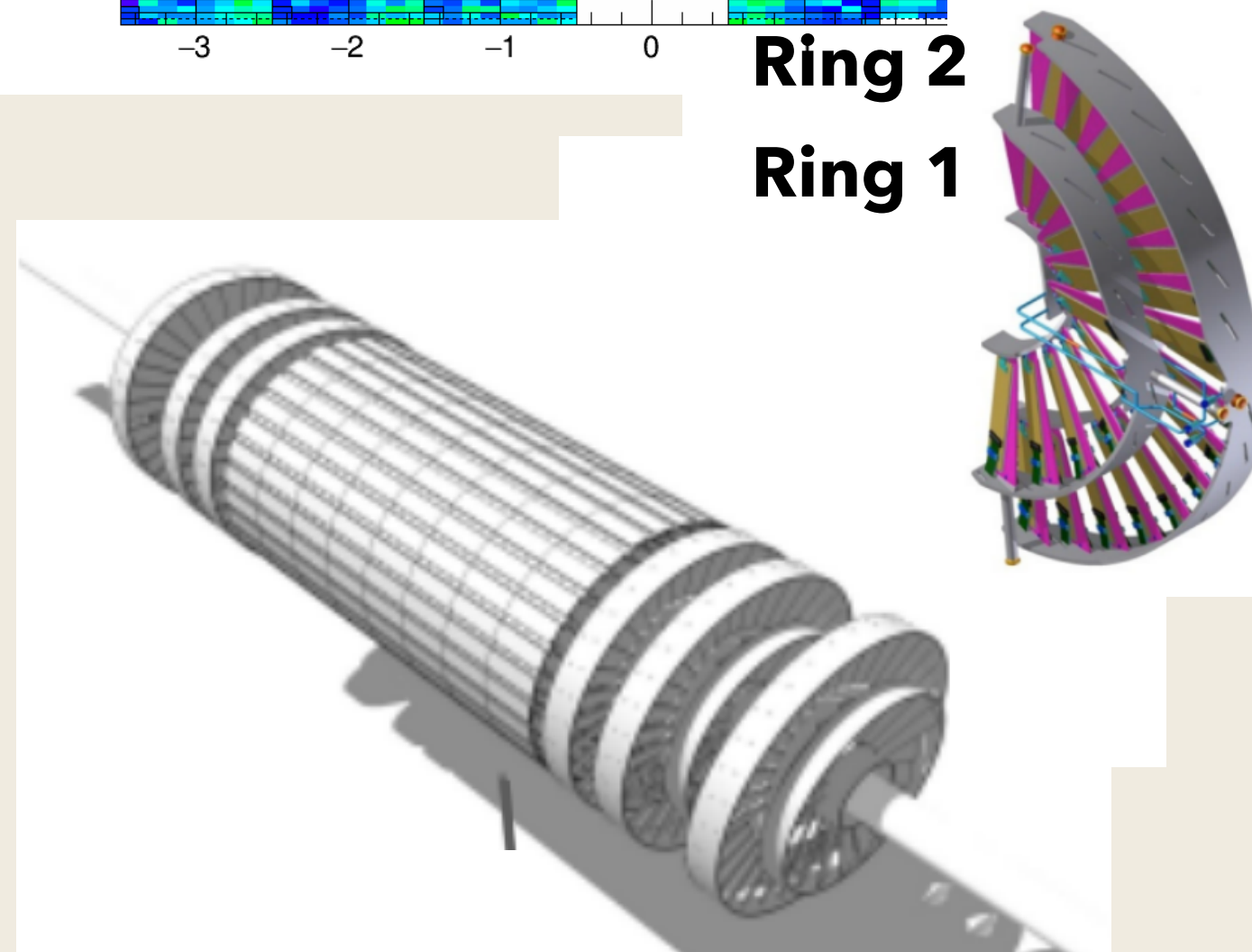
Temporary and permanently disabled modules are also visible

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

Detector status - Pixels FPix



Ring 2
Ring 1



Occupancy as of July 2025

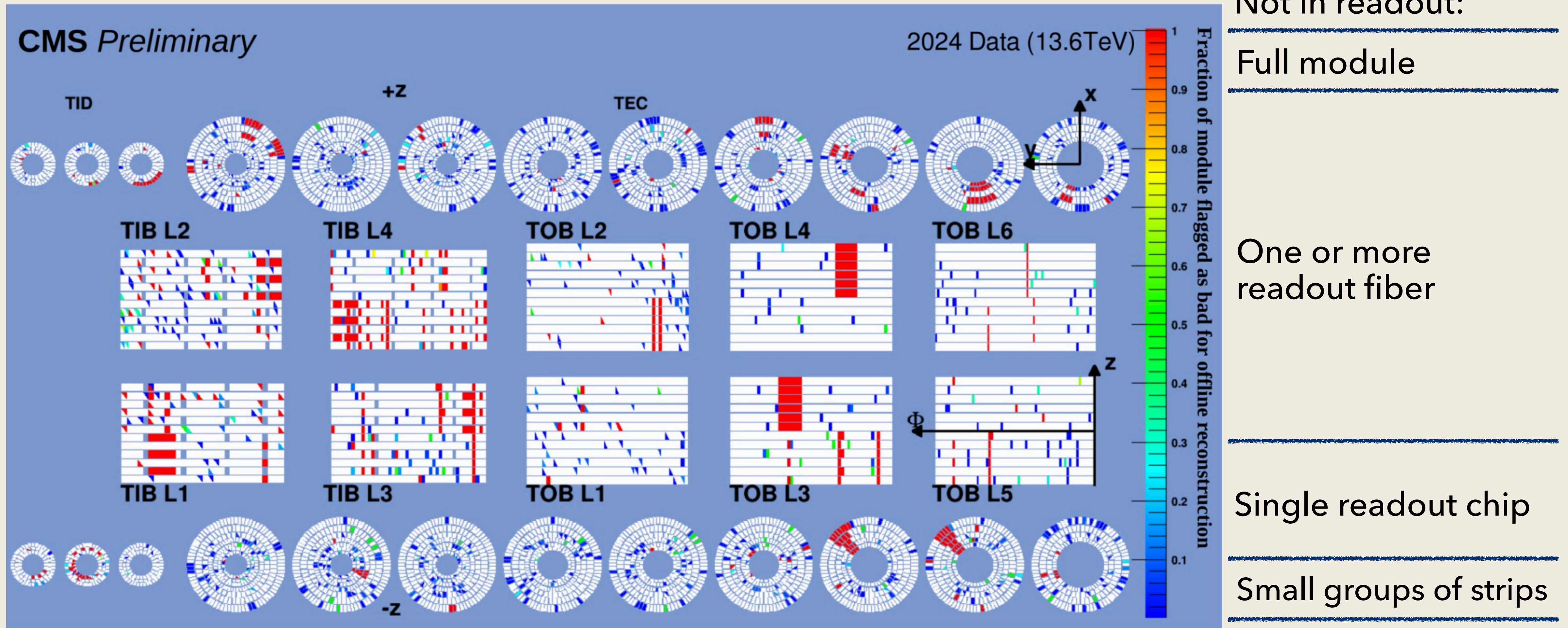
Active channels: ~94%

FPix BmO D1 ROG3:

Receives no triggers since the second half 2024

Temporary and permanently disabled modules are also visible

Detector status - Strips



Very high number of active channels: ~95% overall

Operational challenges in Run 3

Radiation effects

- Sensor degradation due to radiation damage (fluence)
 - increased leakage currents and noise
- Front-end electronics degradation due to radiation damage (dose)
- Single-event upsets (SEUs)

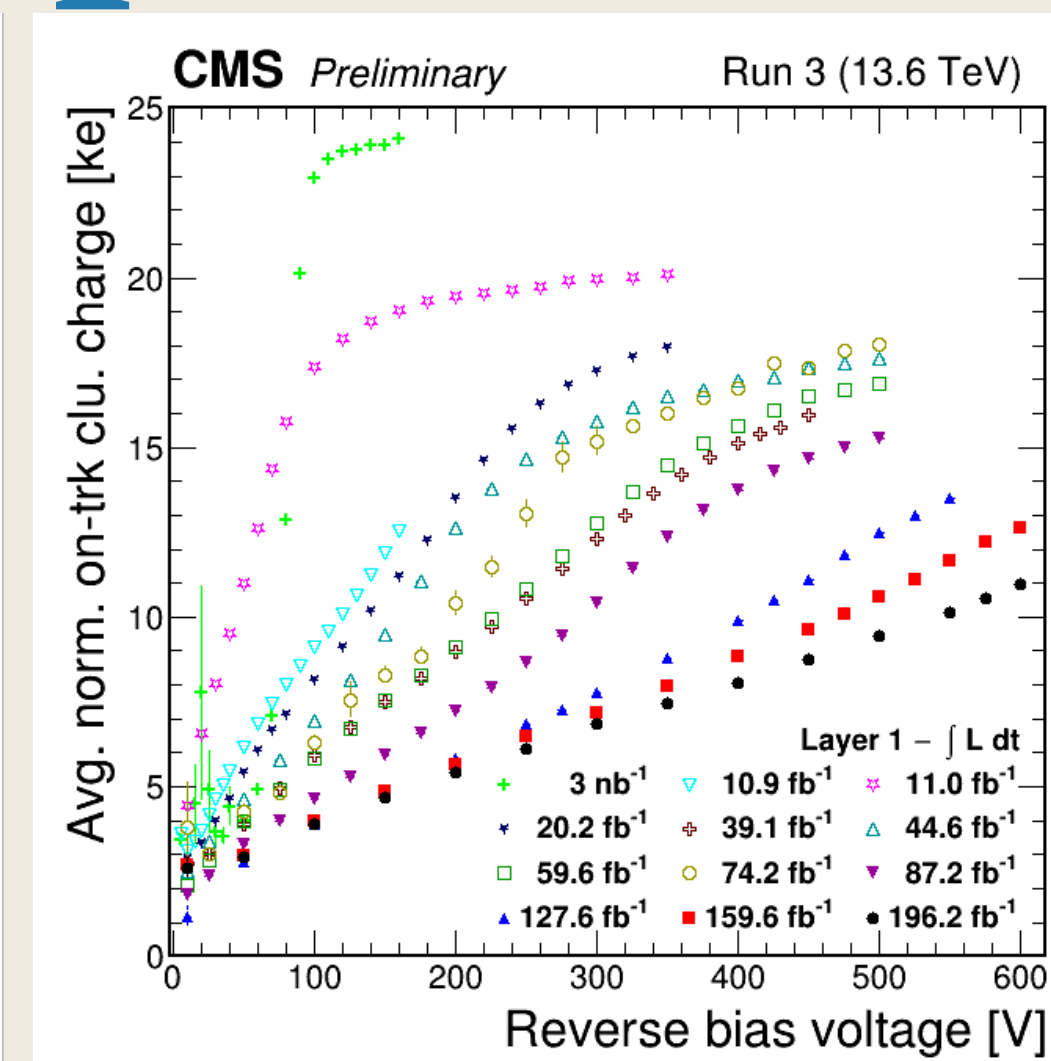
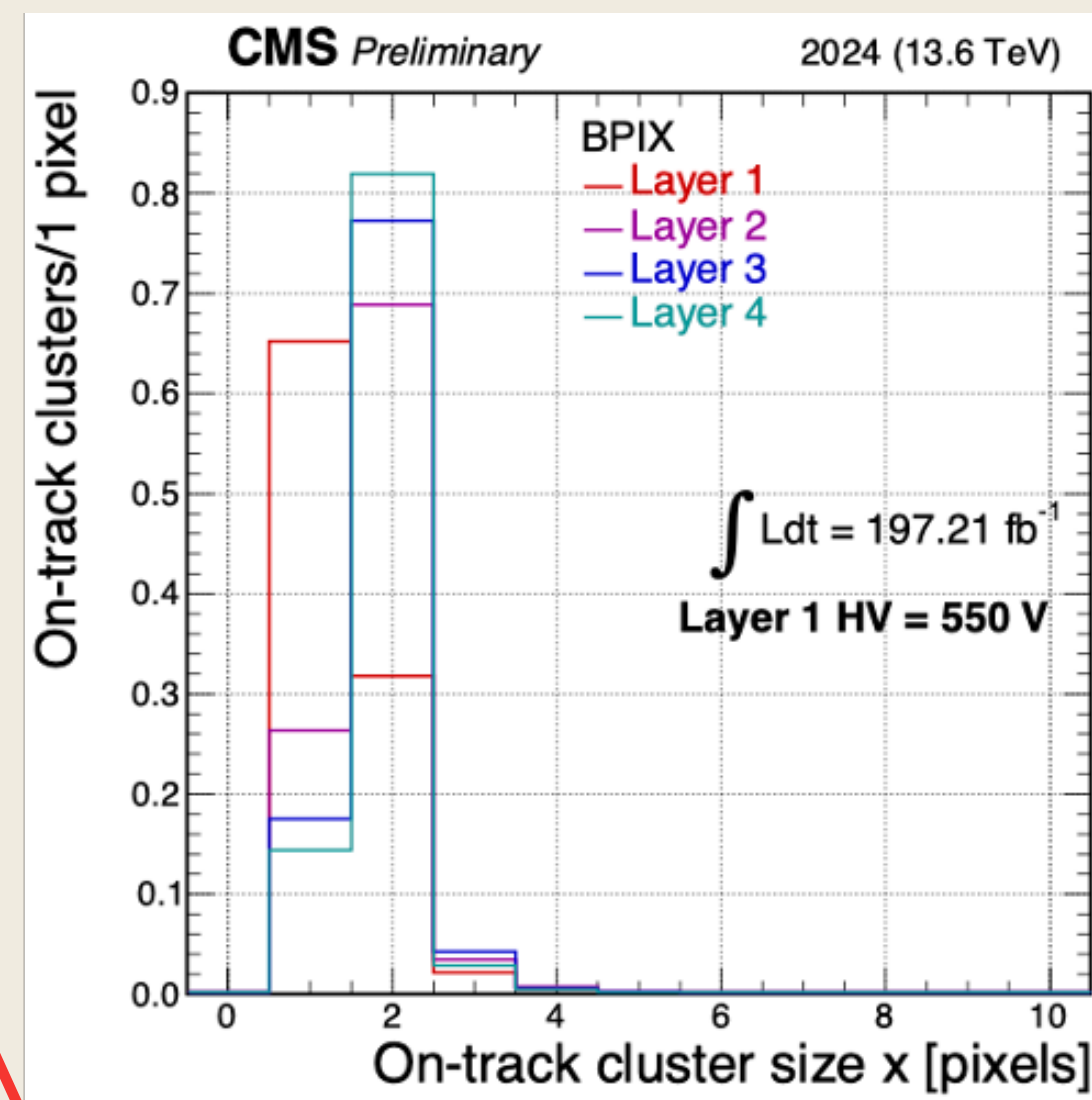
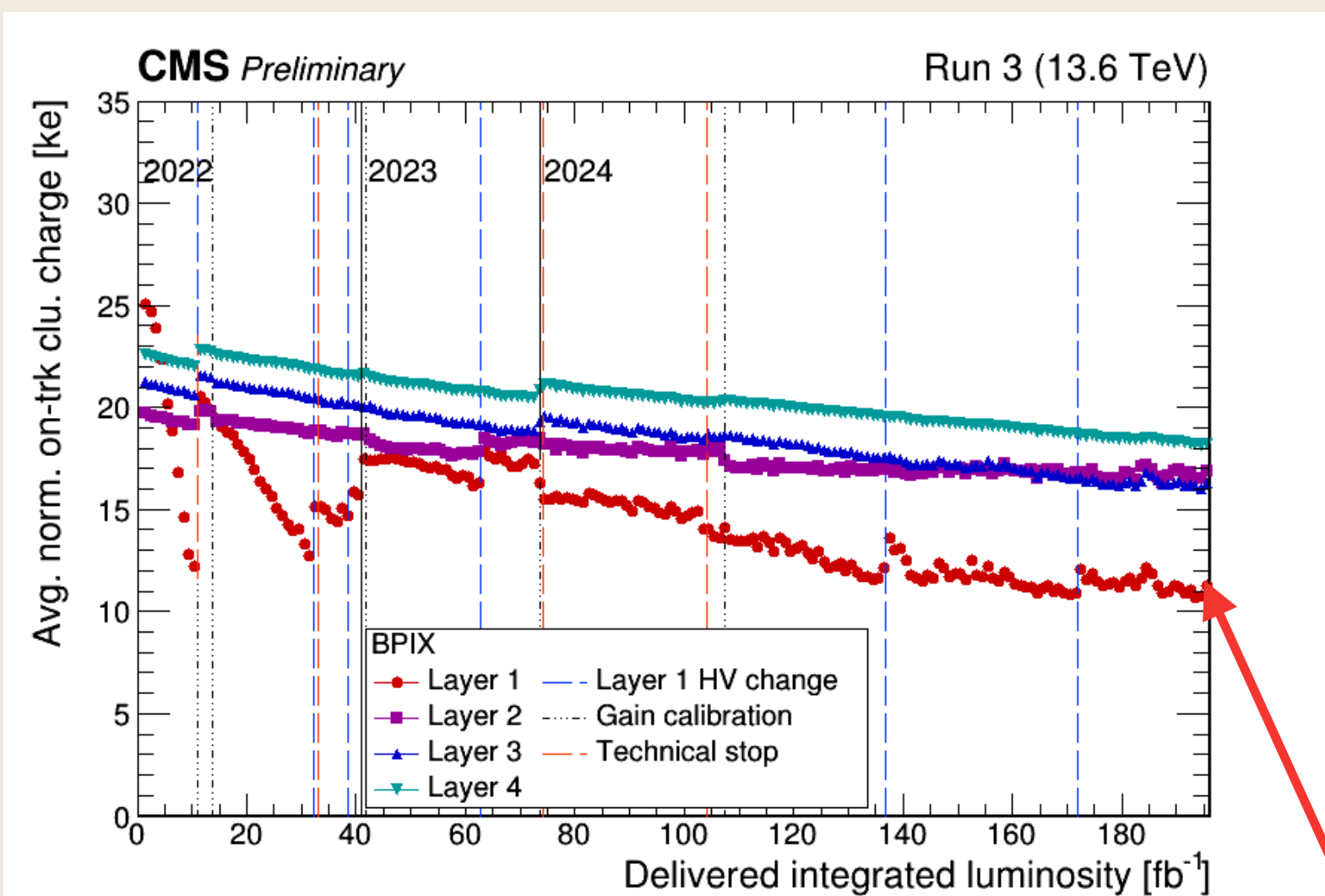
DRIVEN BY INTEGRATED
LUMINOSITY

DRIVEN BY INSTANTANEOUS
LUMINOSITY

Hardware reliability

- Connector/interconnect faults
- Auxiliary electronics failures (power/control) → see large inactive areas in occupancy maps
- Automatic masking of problematic channels → "The" issue since the beginning of Run 3

Radiation effects on pixel clusters



CURRENT SETTINGS:

LAYER 1: 650 V

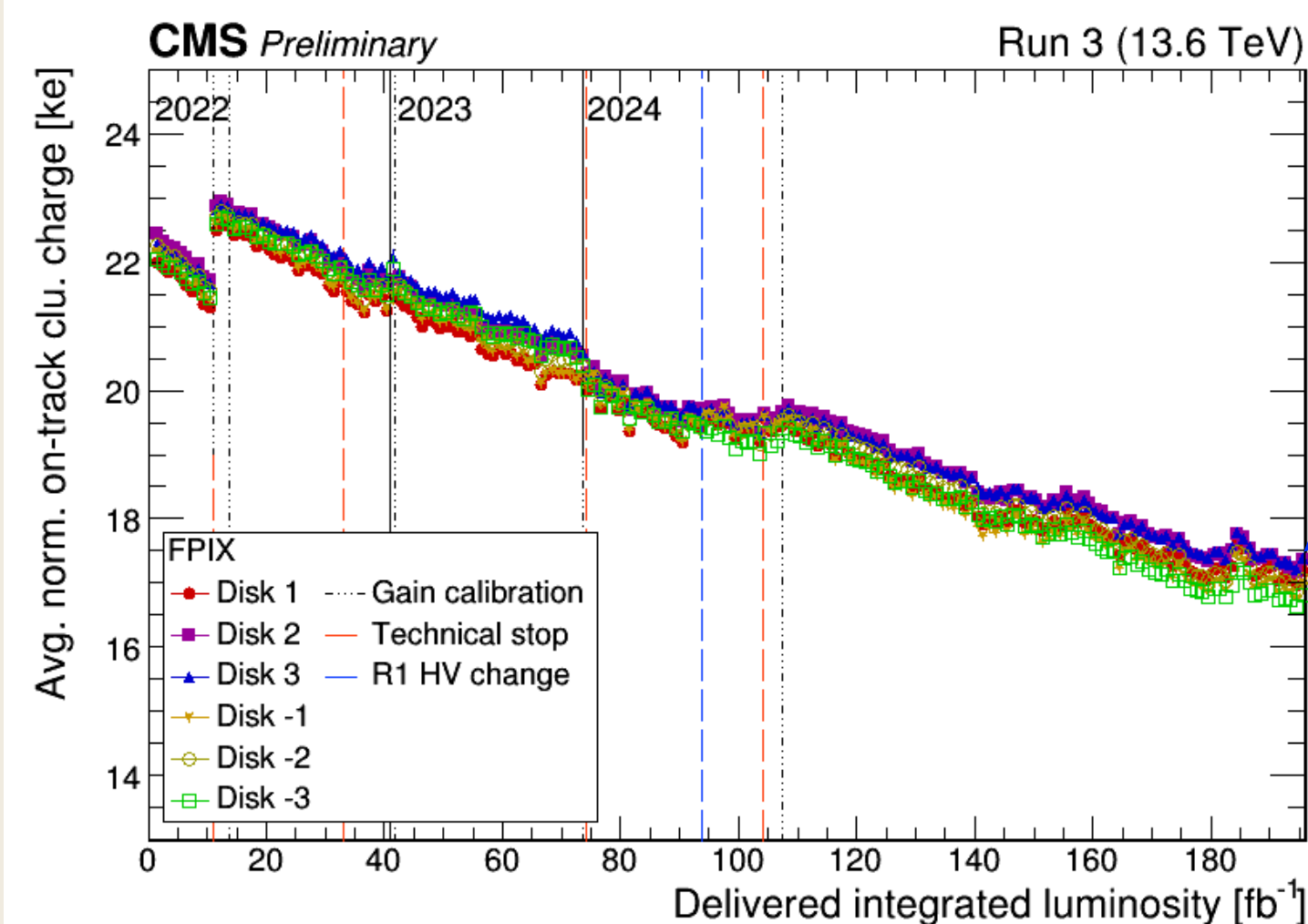
LAYER 2: 450 V

LAYER 3: 350 V

LAYER 4: 300 V

RING 1: 450 V

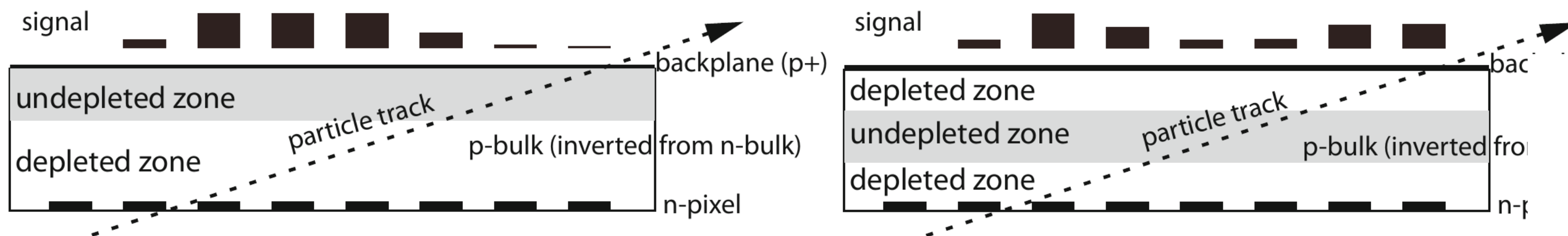
RING 2: 350 V



- Layer 1 currently collecting 50% of the charge compared to unirradiated sensors → mostly single hit clusters in X direction
- 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**

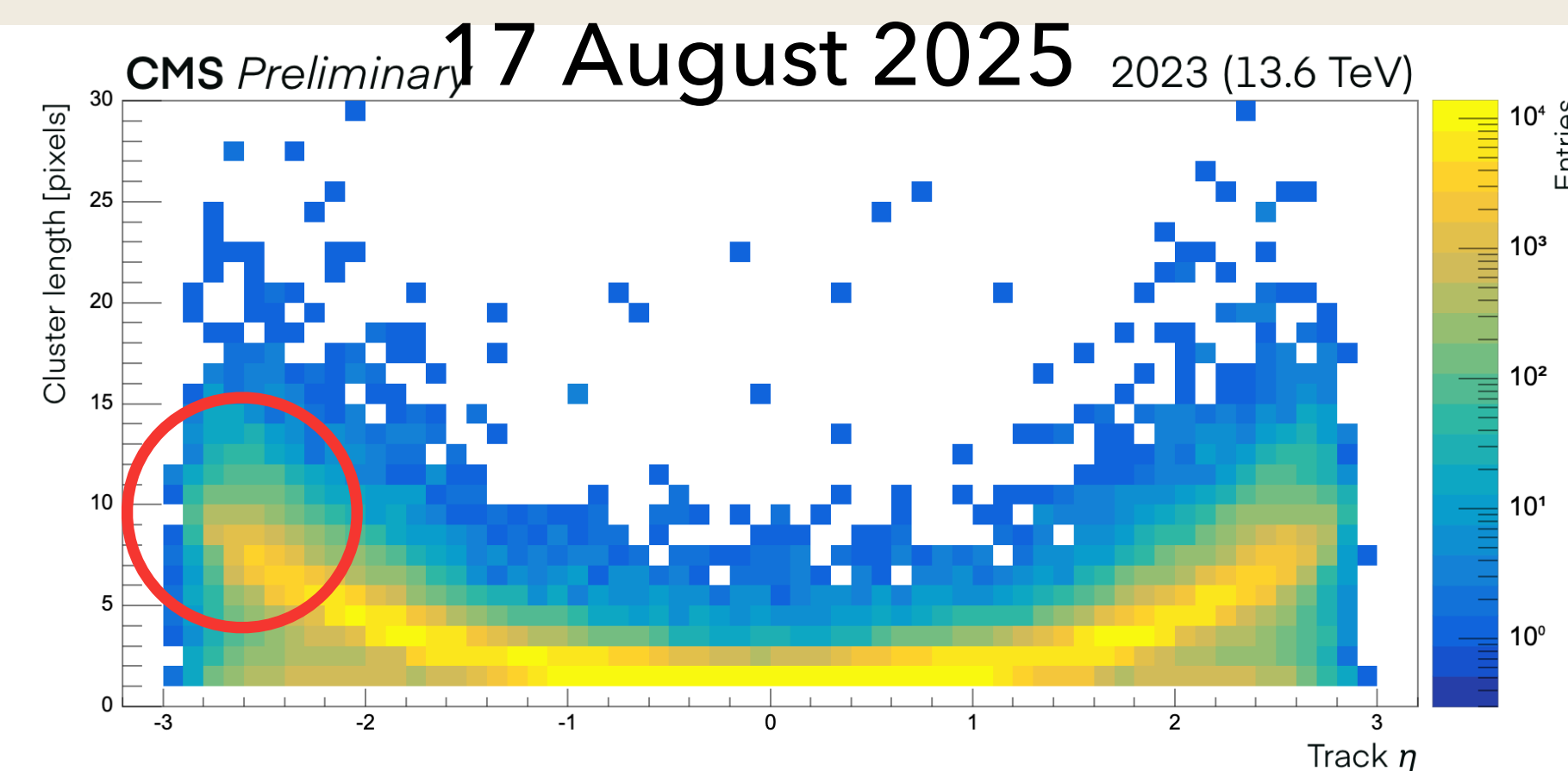
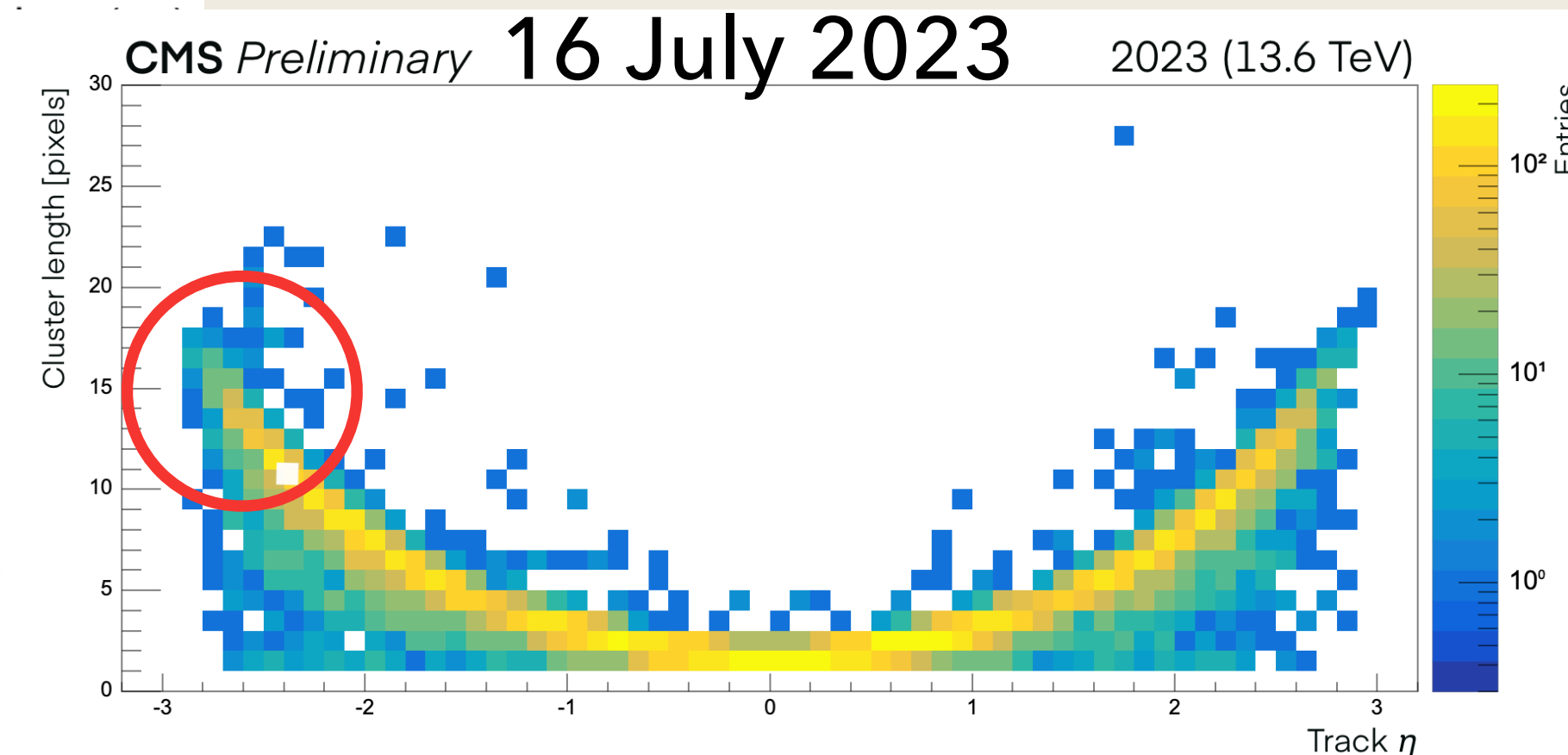
Pixel cluster breaking



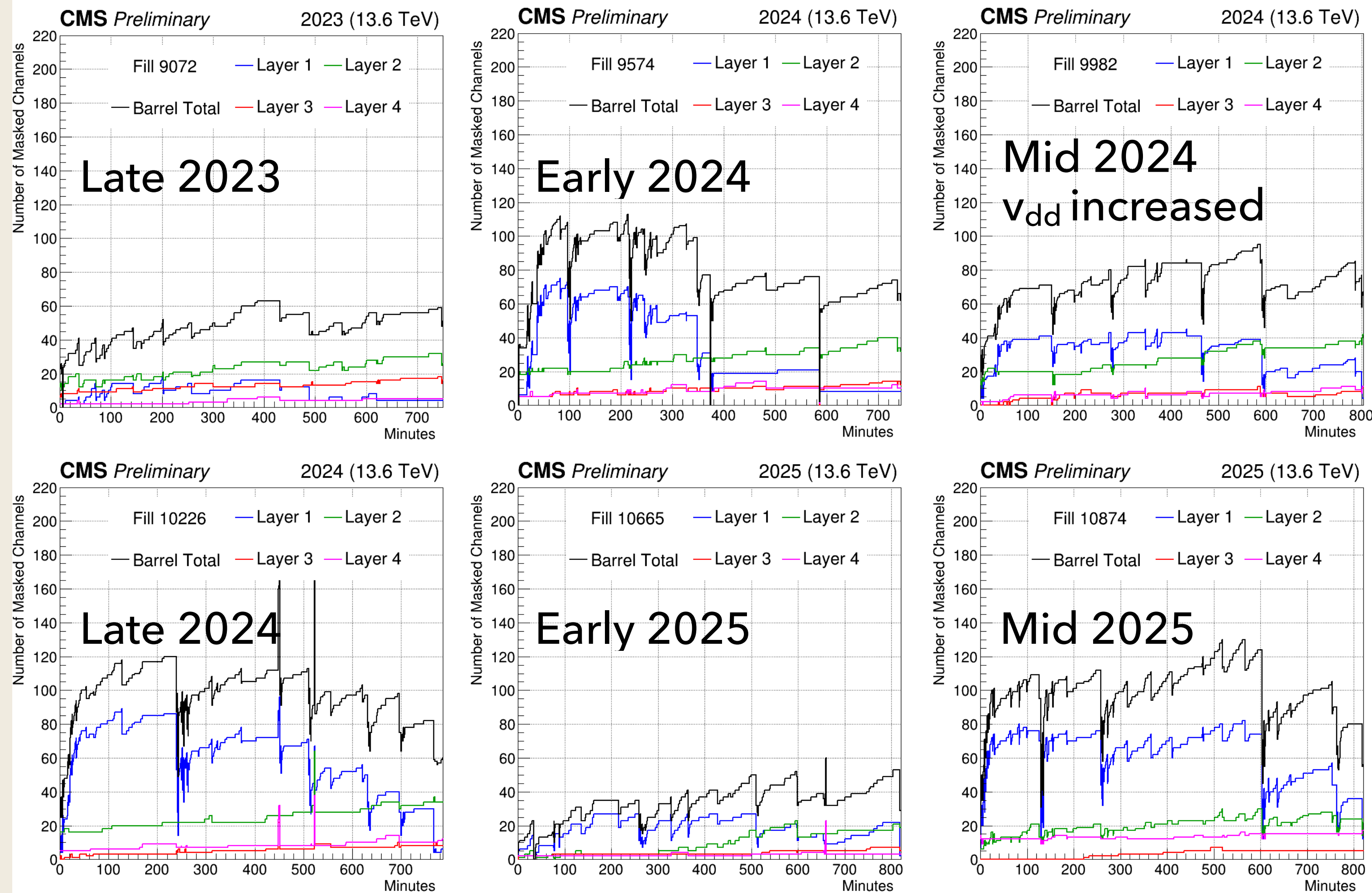
- Radiation damage reduces charge collection efficiency
 - Leads to split and shortened clusters, especially in the high η region
- Consequences: more off-track clusters, increased fake/duplicate tracks, reduced resolution, **especially at trigger level $\rightarrow$ impact on physics program!**
- On-track cluster size vs. η ("smiley plot"):
 - 2023: well-defined, pronounced "smiley" shape
 - 2025: more diffuse, shorter clusters especially at high $|\eta|$

A lot of efforts have been put in mitigation strategies

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



Auto-masked channels in pixel barrel



TBMs in Layers 2-4 get stuck following SEUs and stop sending data → need to be powercycled in interfills

TBMs in **Layer 1** (blue lines) are not affected by this issue but instead send many readout errors:

- The cause is not understood
- 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

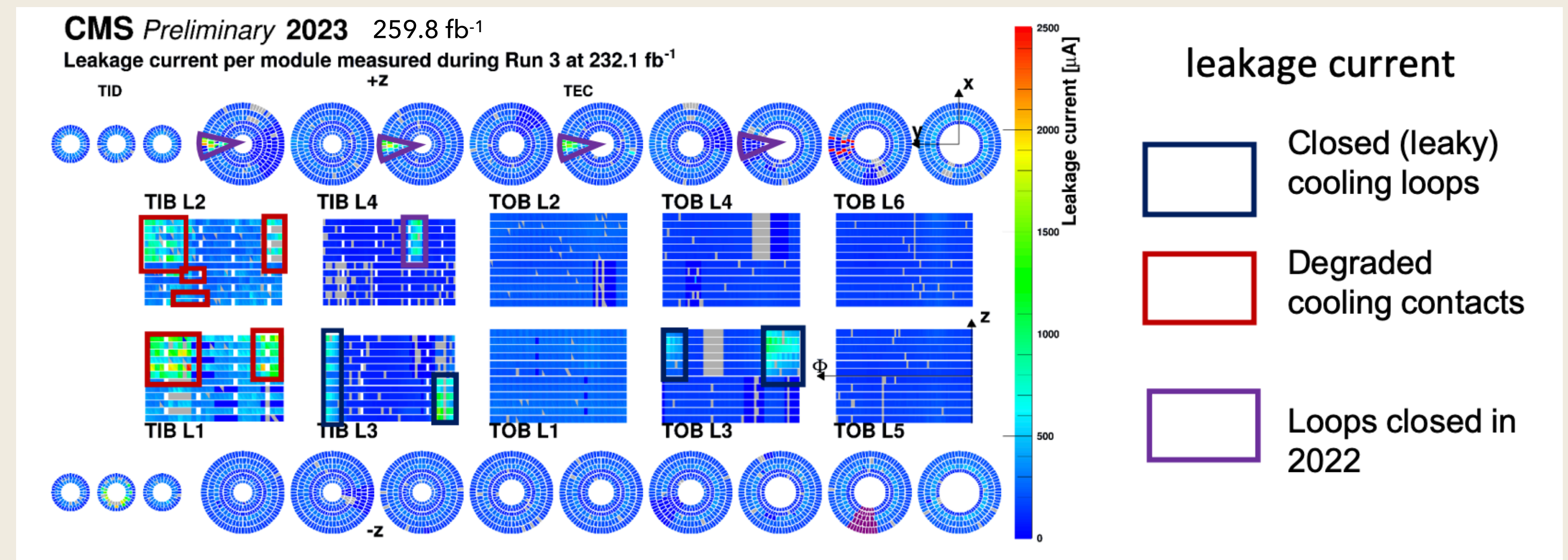
Strips depletion voltage

- 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:
 - Baseline is 300 V
 - TEC disks 5-9 and TOB L1 and L2 increased to 500 V in July 2025
 - TEC disks 1-4 and TOB L3 and L4 also increased to 500 V in October 2025
- More frequent HV bias increases are foreseen till the end of Run 3 (June 2026)

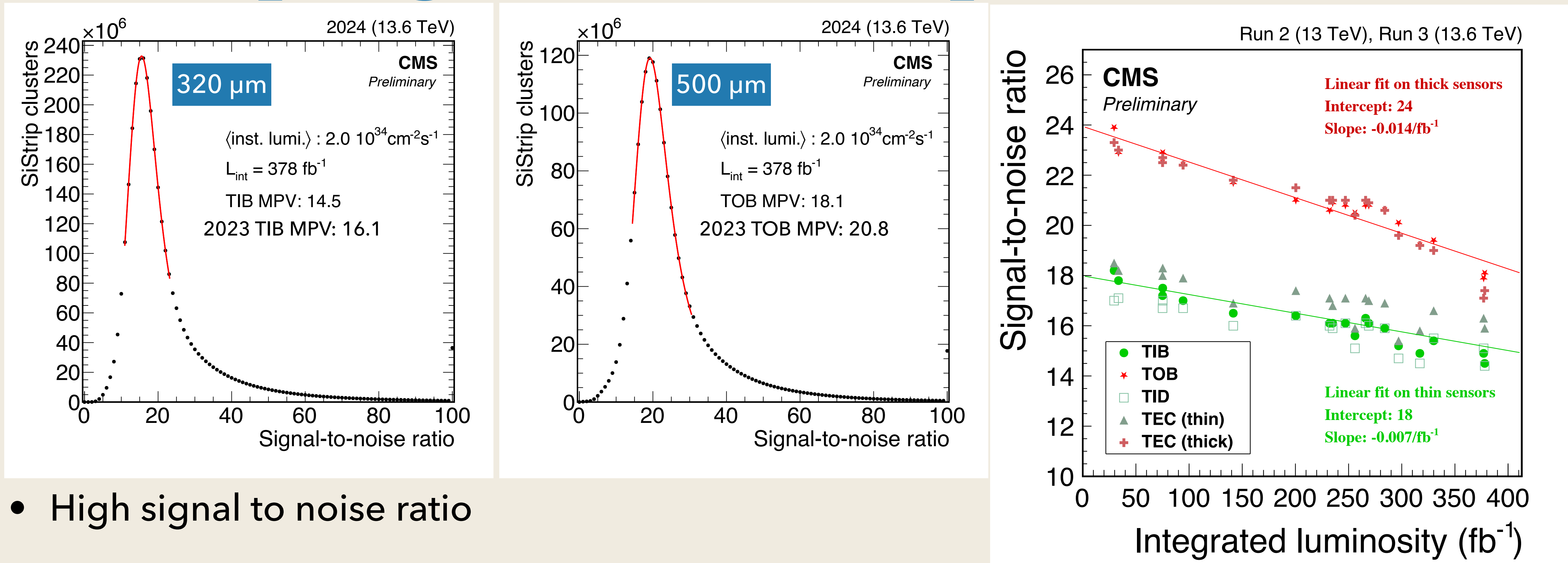
Strips leakage current

- Leakage current per module map from 2023. Current profile is similar, except the blue-green regions are now 1000-2500 μA
- Modules in uncooled regions show large leakage currents
- Cooling temperature was lowered from -20 degC to -25 degC in June 2024
- Few HV channels per week reaching the power supply limit of 12 mA are excluded from readout

1 power supply unit supplies between 2 and 12 modules



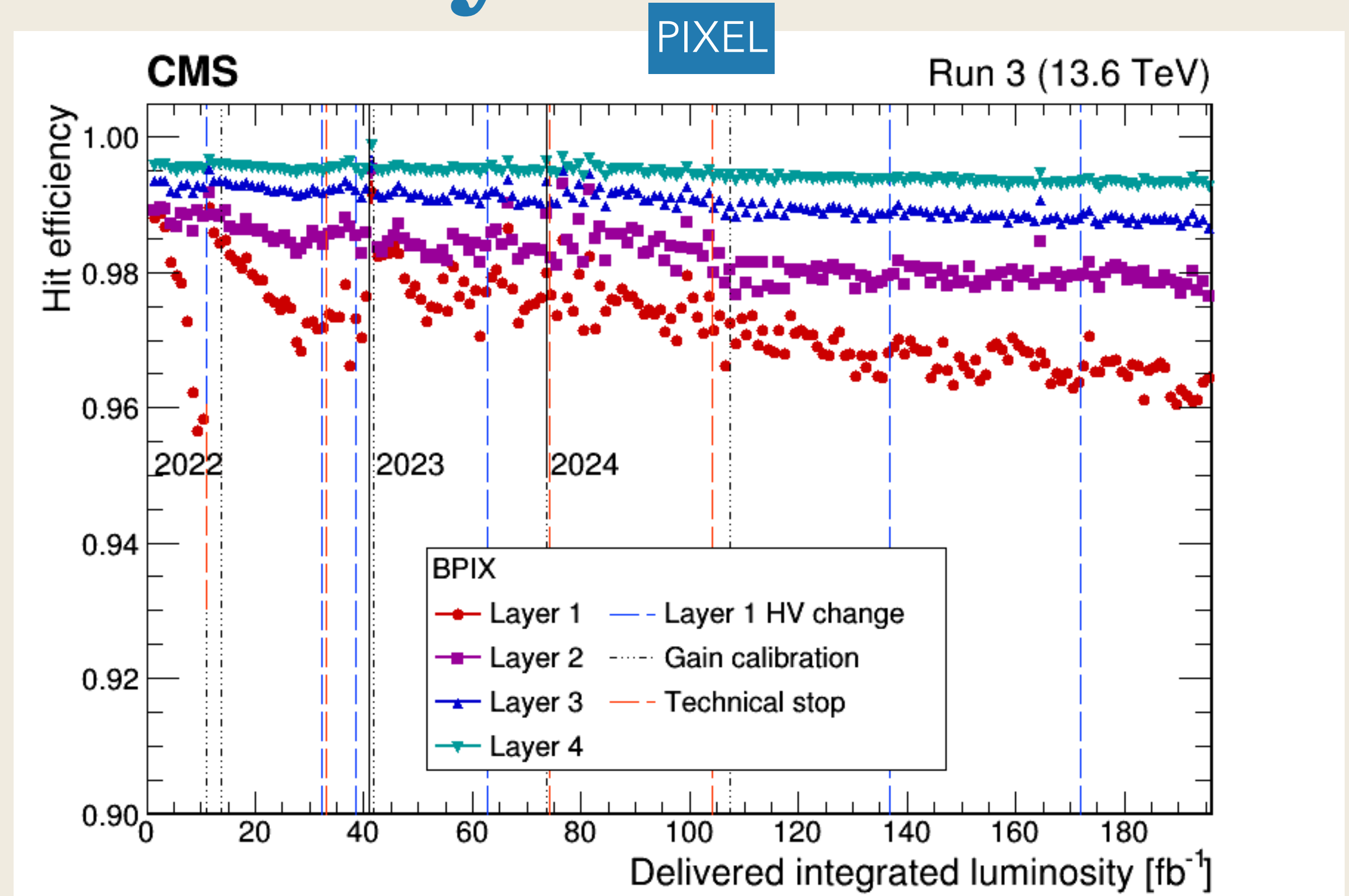
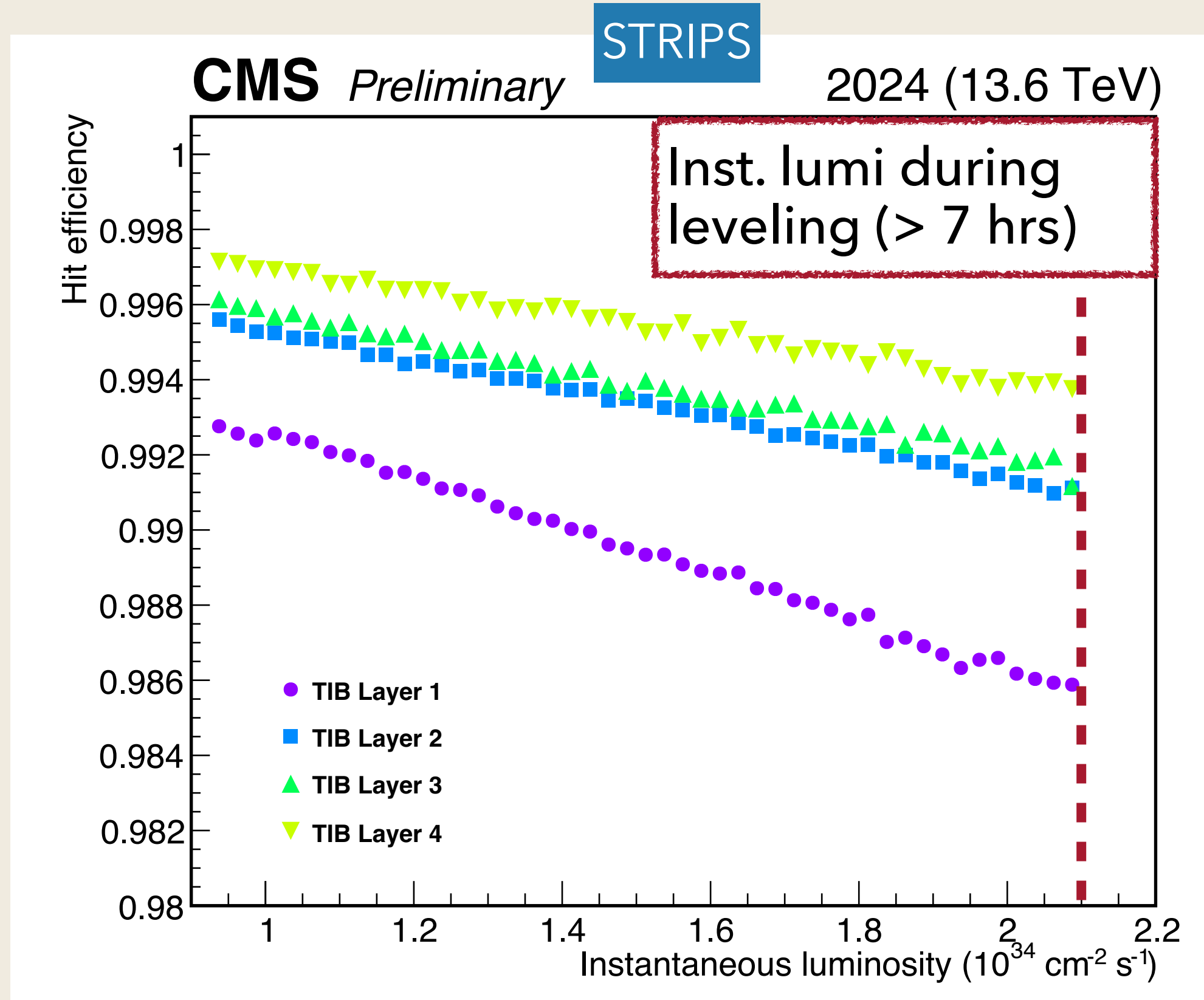
Strips signal over noise performance



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

Expected to remain sufficiently high until the end of Run 3

Hit efficiency

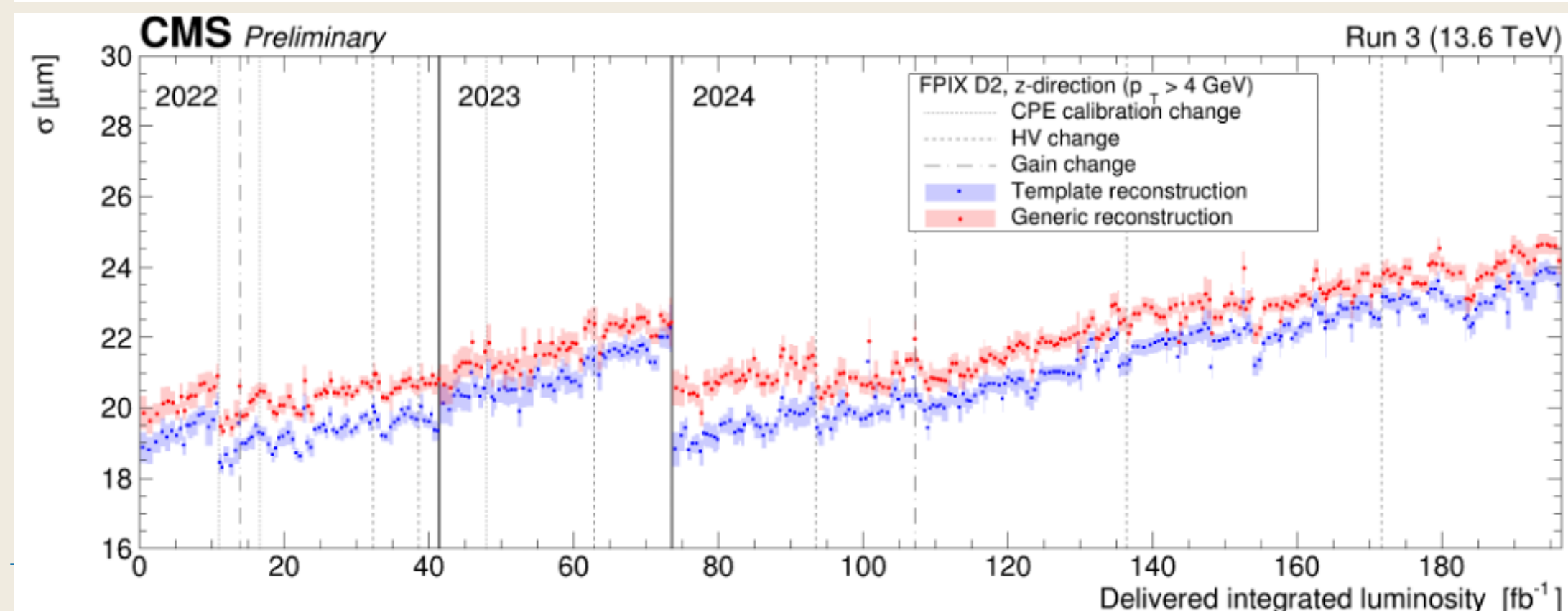
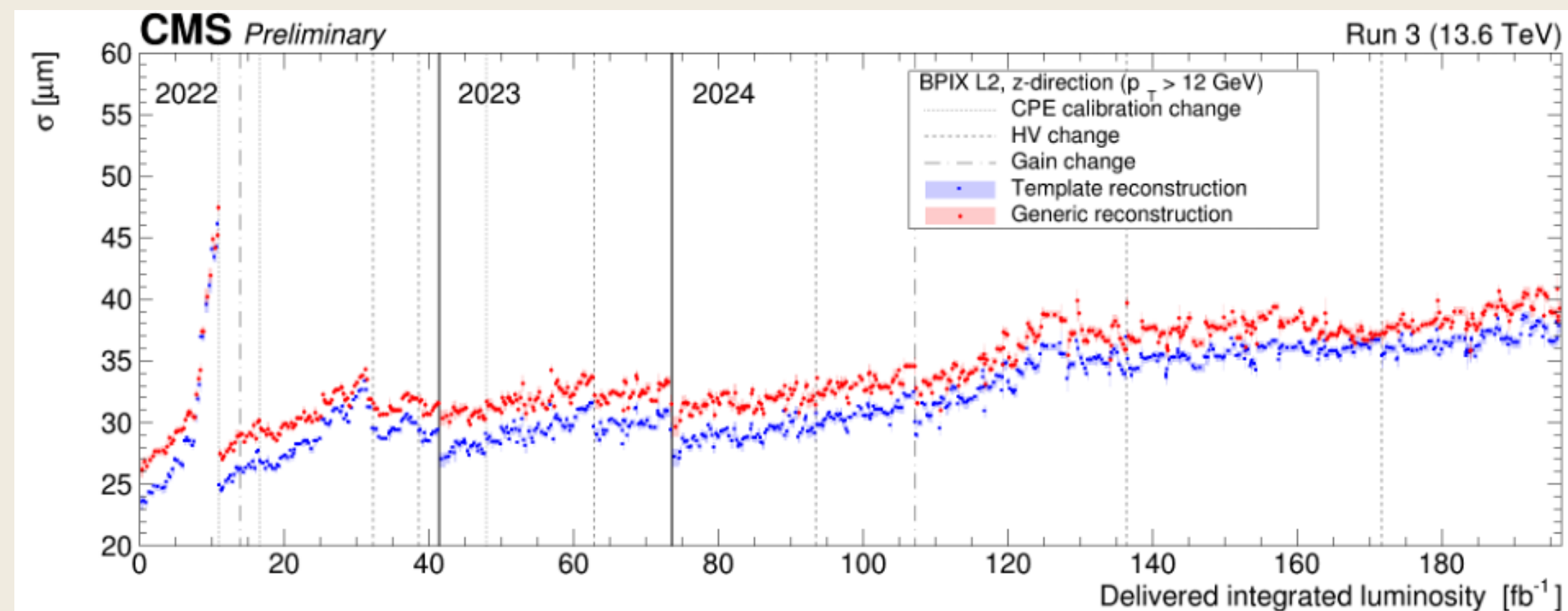


- High hit efficiency >98% for strips, scales linearly with instantaneous luminosity (hit rate)
- Pixels hit efficiency also shows inst. lumi (hit rate) dependence, degrades with integrated luminosity, recovered by annealing, gain calibrations, and HV bias increase

Resolution

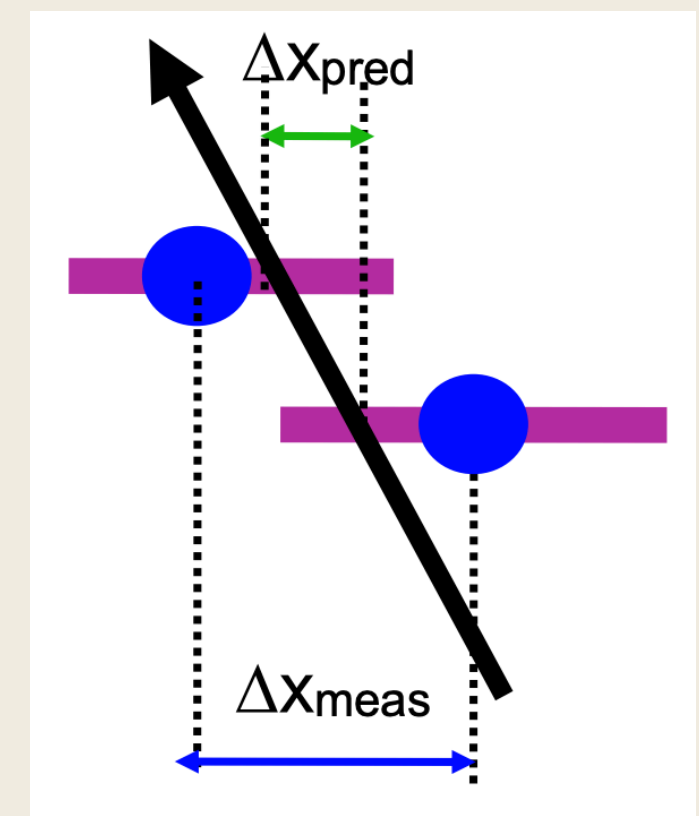
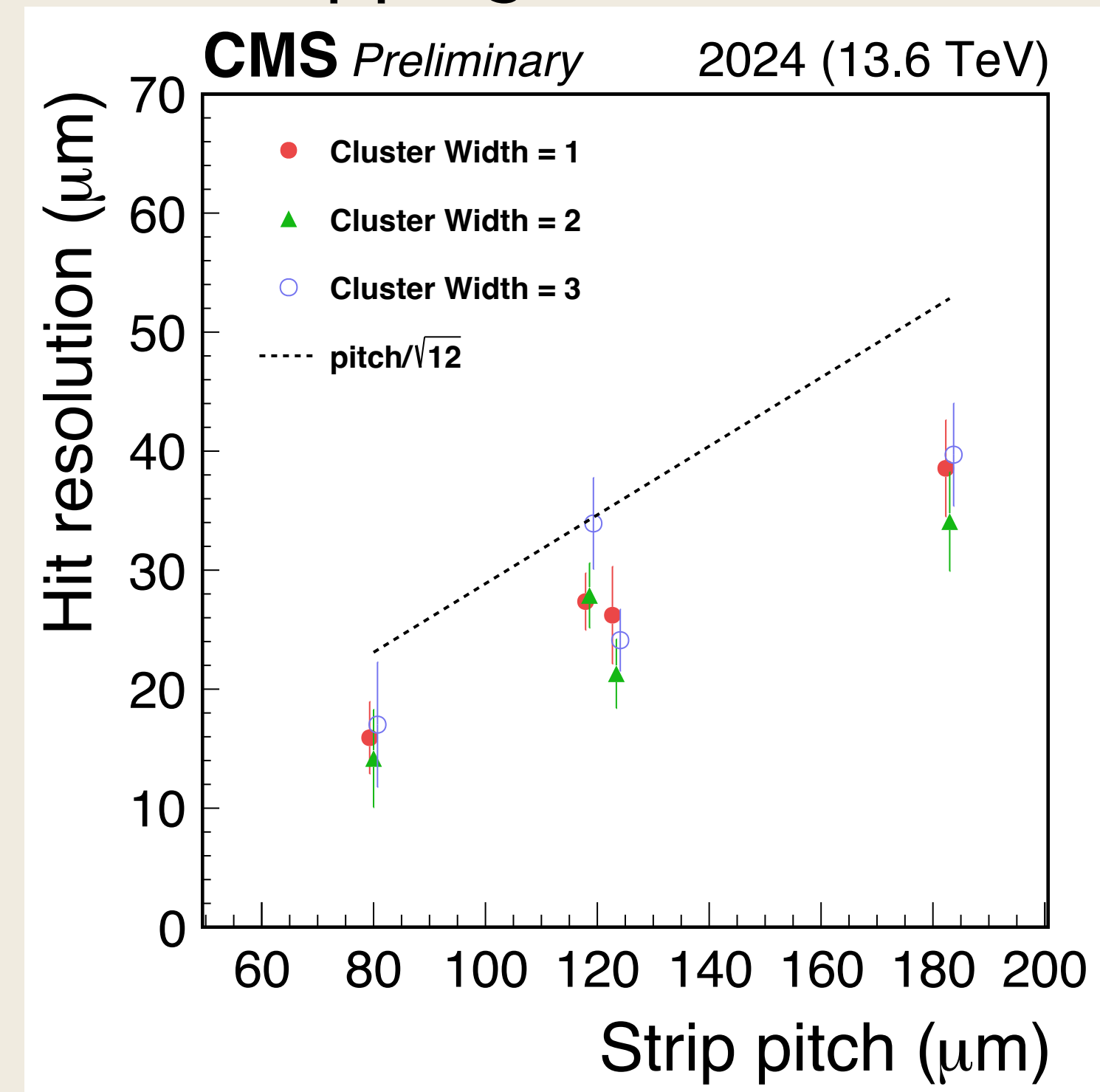
Pixels

- Degradation overtime expected
- Worsened by cluster breaking



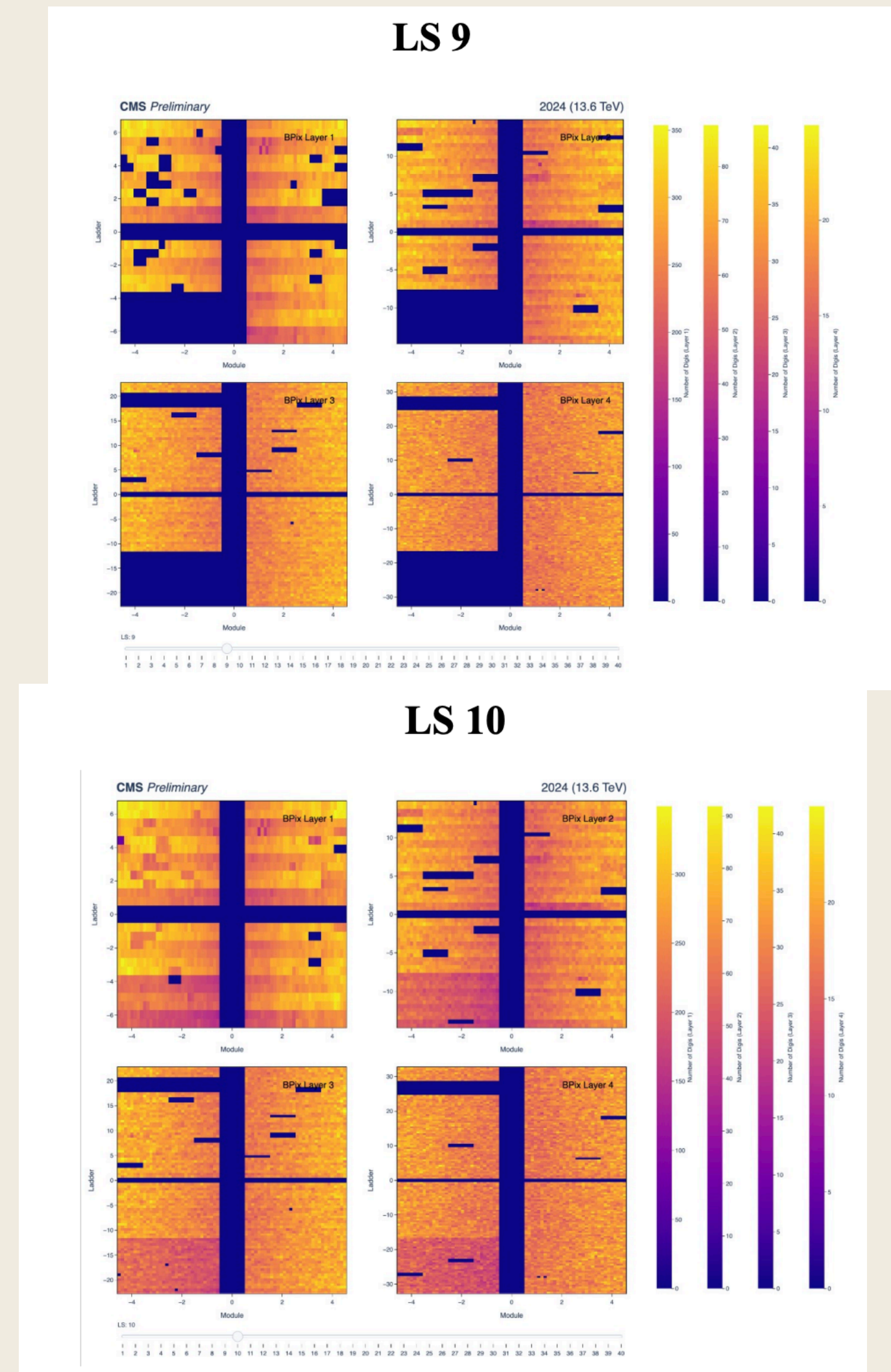
Strips

- Scales with pitch size
- Computed by using hits from overlapping modules



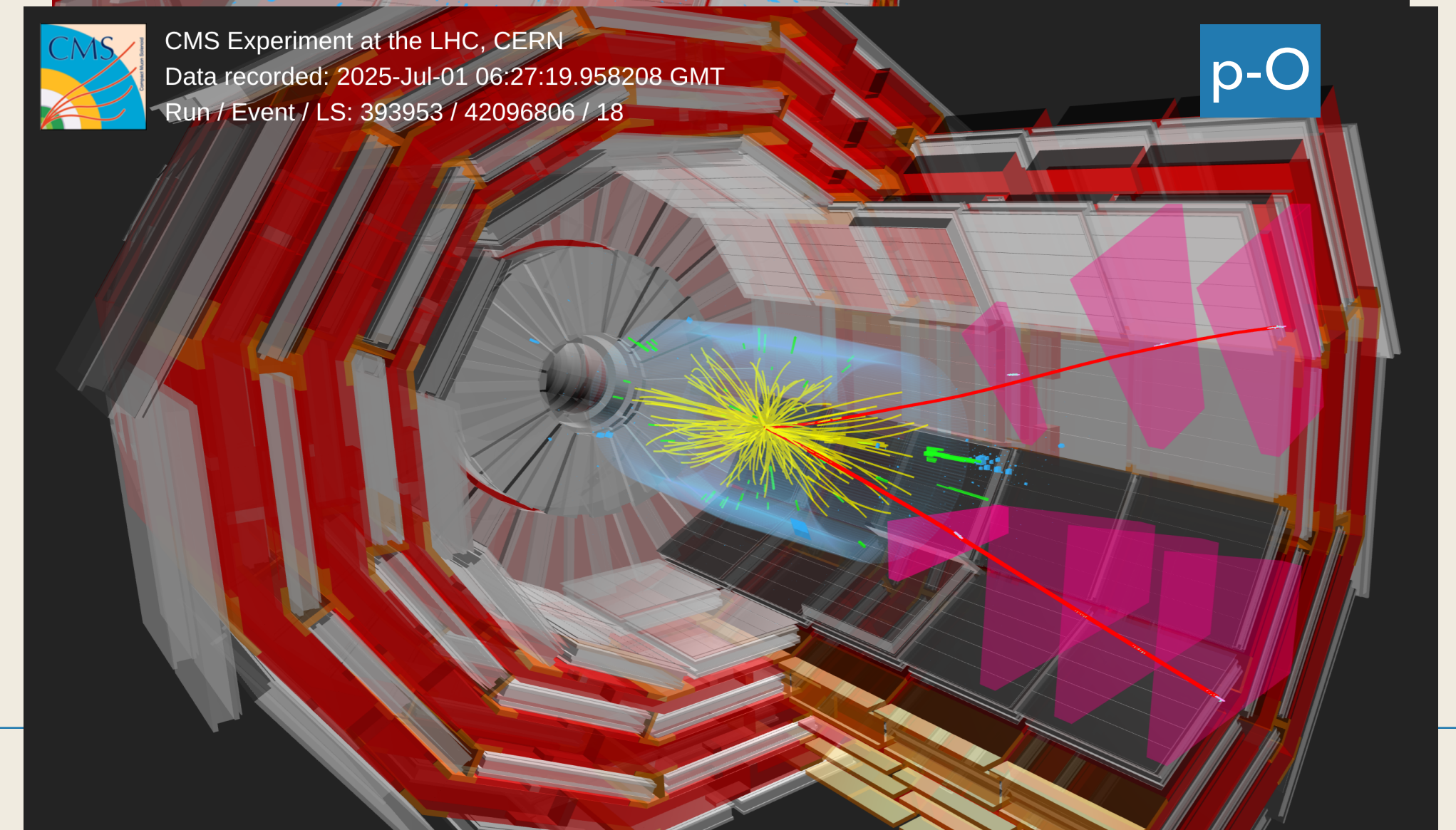
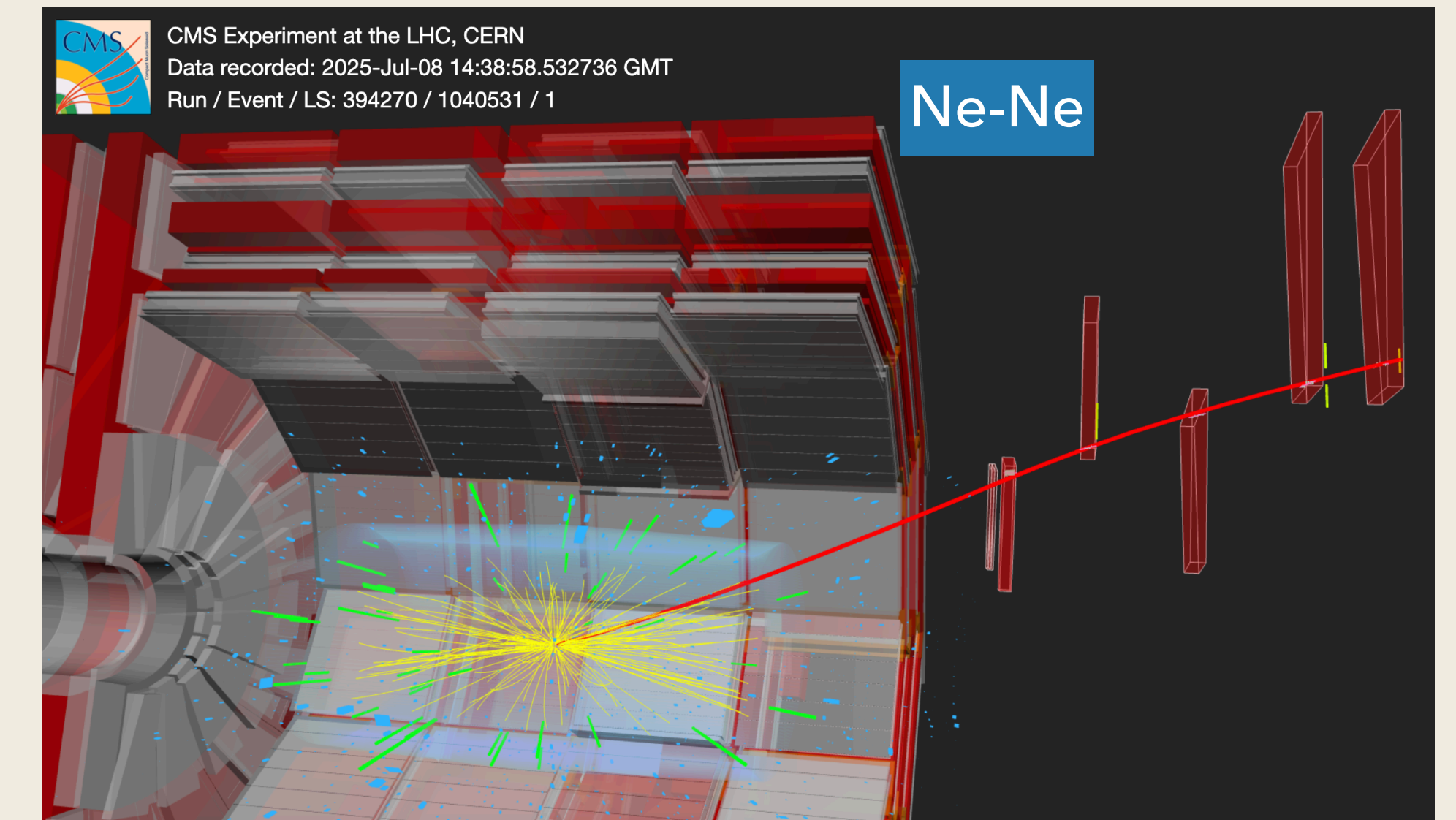
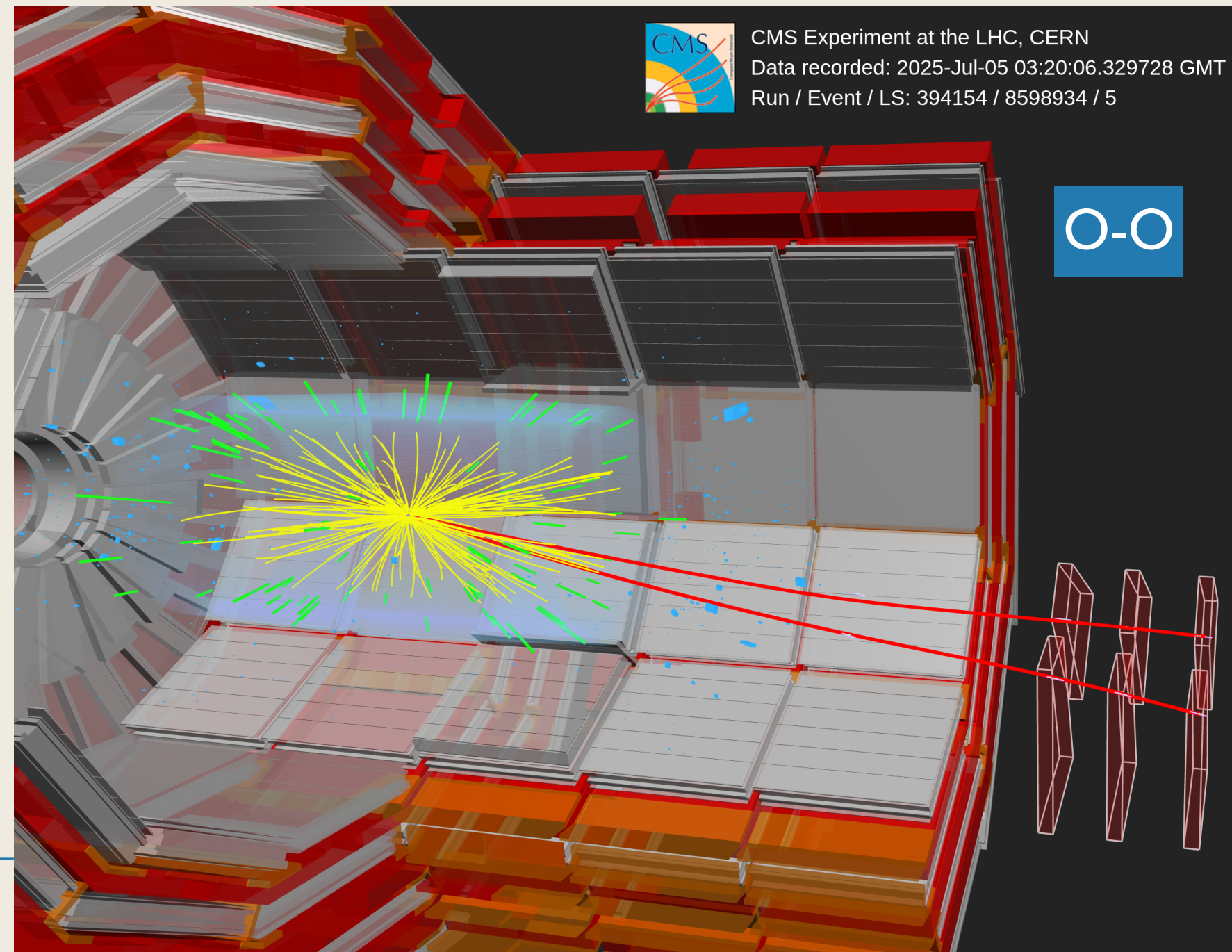
Automatic anomaly detection

- The pixel detector is prone to short (a few LS) anomalies (1 LS = 23 seconds), **mainly originating from automatic recovery processes of service components**
- 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 luminosity
- ML models (AutoEncoder, NMF) are being developed to aid automatization



Light ion collisions

- In July 2025, for the first time, LHC has been able to collide light (Oxygen and Neon) ions in the form of Ne-Ne, O-O, and p-O collisions
- CMS Tracker performed well during these light ions collisions



Summary and outlook

- No major failures in the last years for strips.
- Pixels lost a few components due to connector/auxiliary electronics faults
- Leakage current in strip detector is increasing but no major difference in profile 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

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

Summary and outlook

- No major failures in the last years for strips.
- Pixel Barrel Layer 1 evolves rapidly

ALL IN ALL... "I'M STILL STANDING"

- Pixels lost a few components connector/auxiliary electronics
 - Leakage current in strip detector increasing but no major difference in profile compared to earlier in
 - Good overall hit efficiency, rate and signal-to-noise ratio
- Increased charge collection efficiency
 - Layer breaking
 - Masked channels
 - Such as automatic anomaly
 - on helps ensure high data



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

References

CMS Collaboration, *Pixel Auto-masked Channels*, CMS-DP-2023-080, 2023, <https://cds.cern.ch/record/2876547>

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

CMS Collaboration, *CMS tracker data quality certification with new machine learning tools*, 2024, <https://cds.cern.ch/record/2905834>

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

Backup

PSI46dig and PROC600

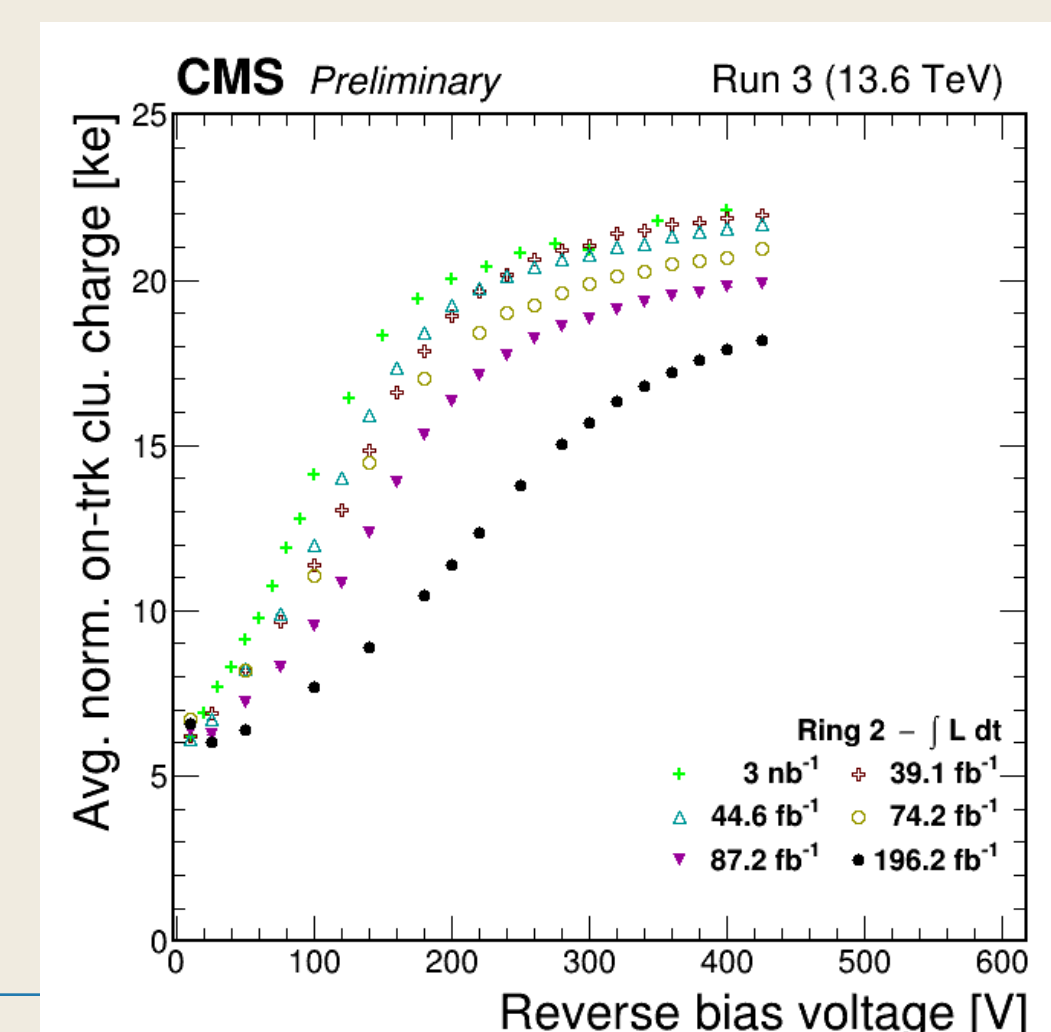
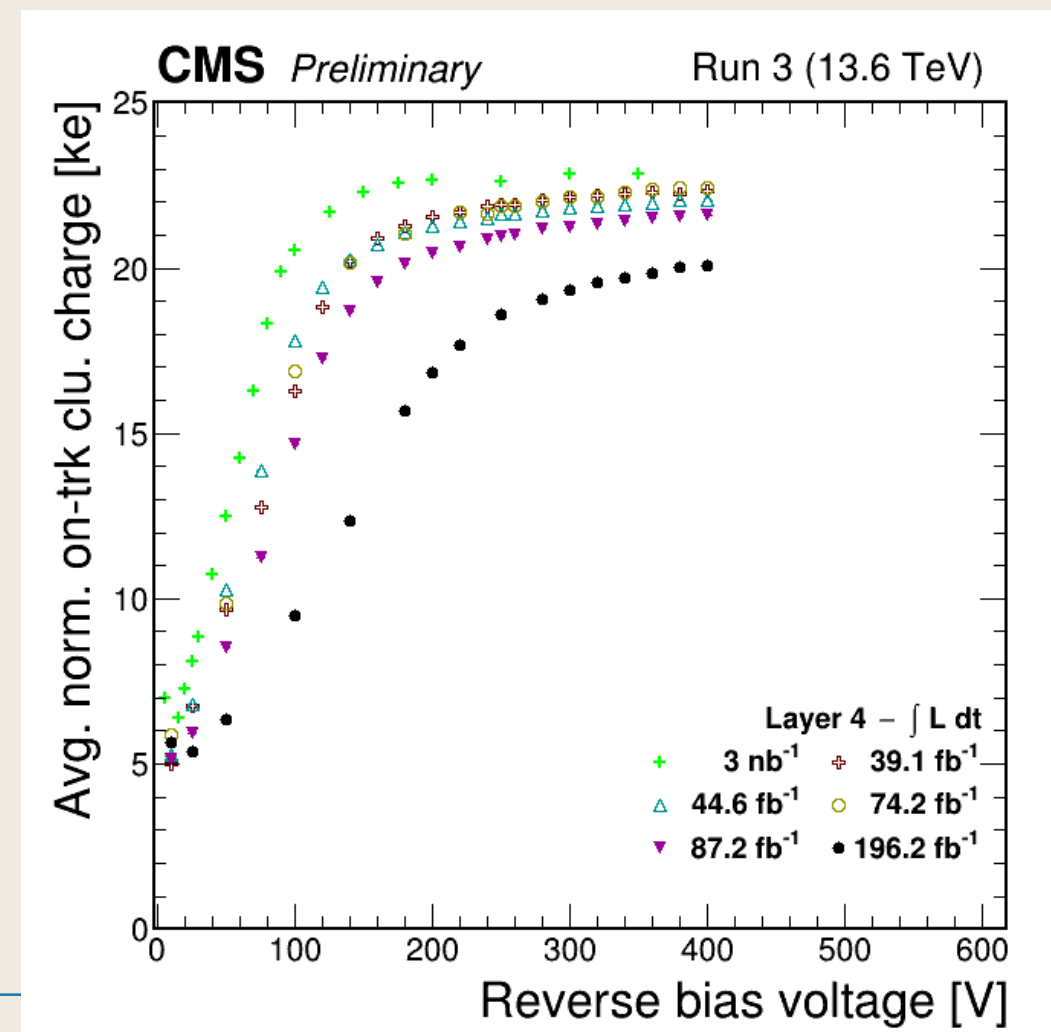
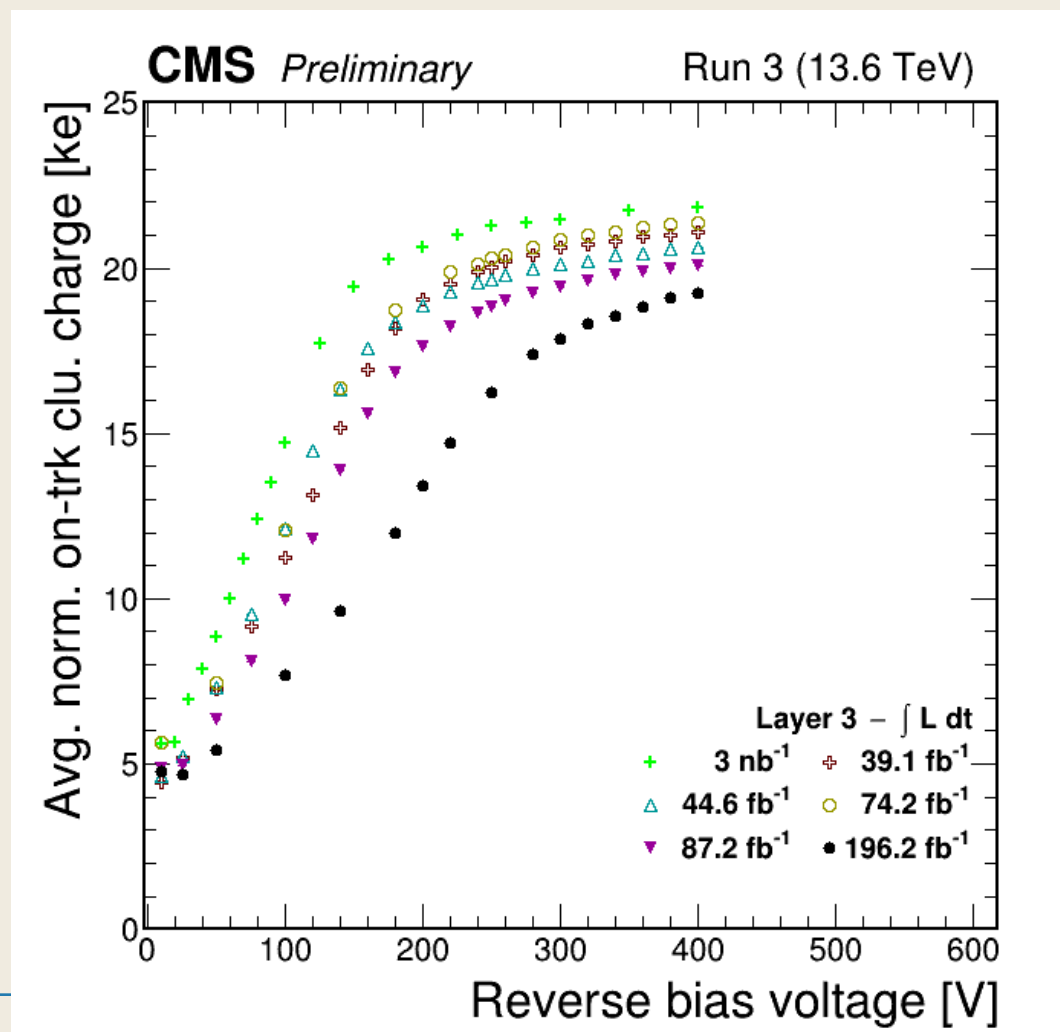
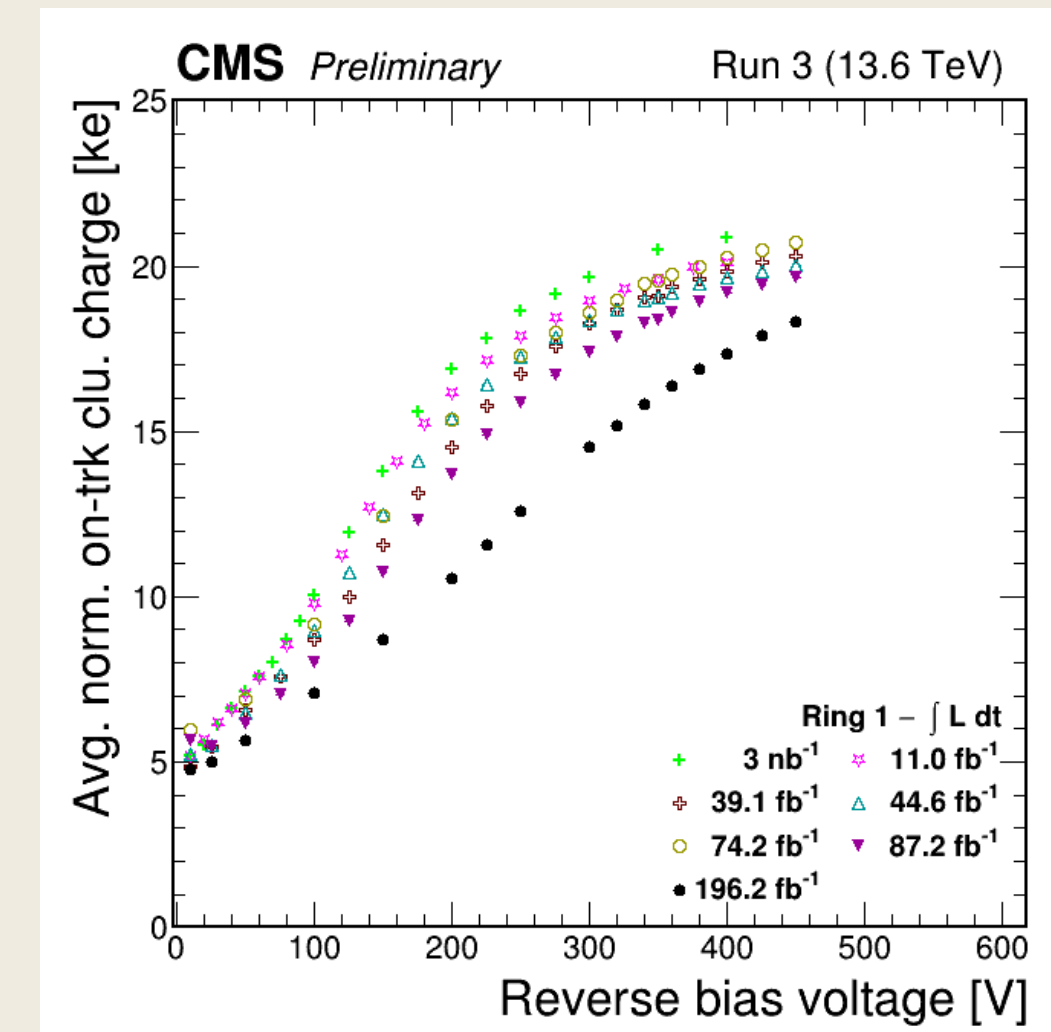
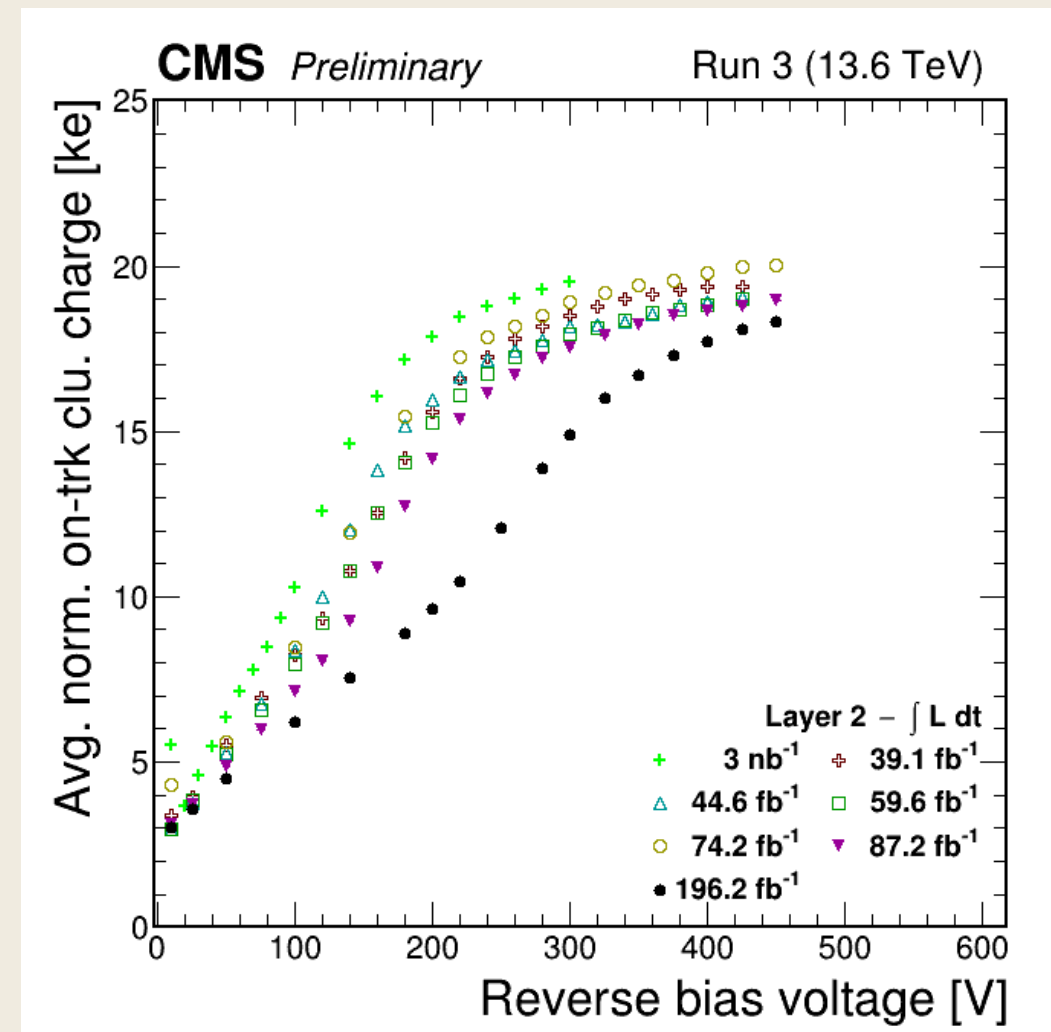
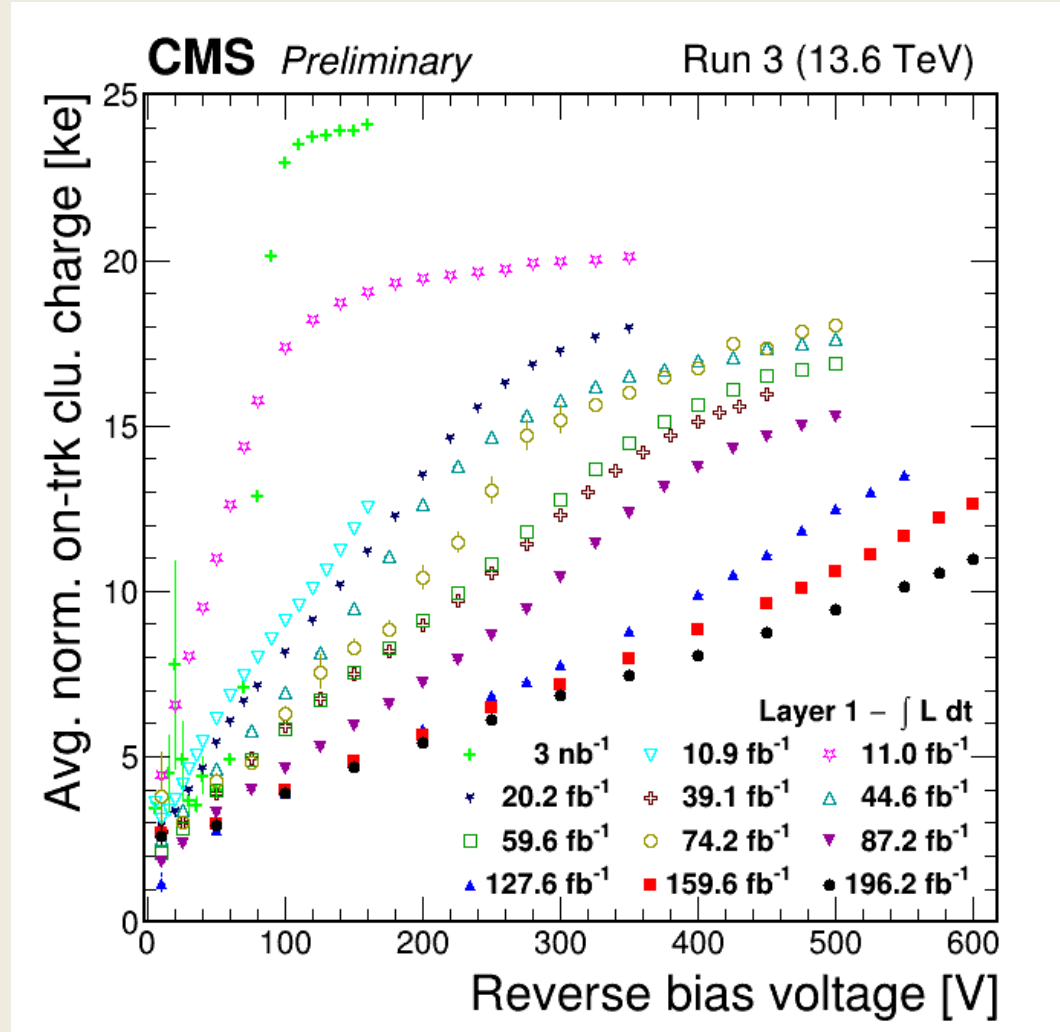
PSI46dig

- Used in BPix 2-4 and FPix
- Column-drain readout architecture, 160 Mb/s digital readout, enhanced charge discriminator
- >90% efficiency up to 200MHz/cm² hit rate
- Radiation tested up to 150 Mrad

PROC600

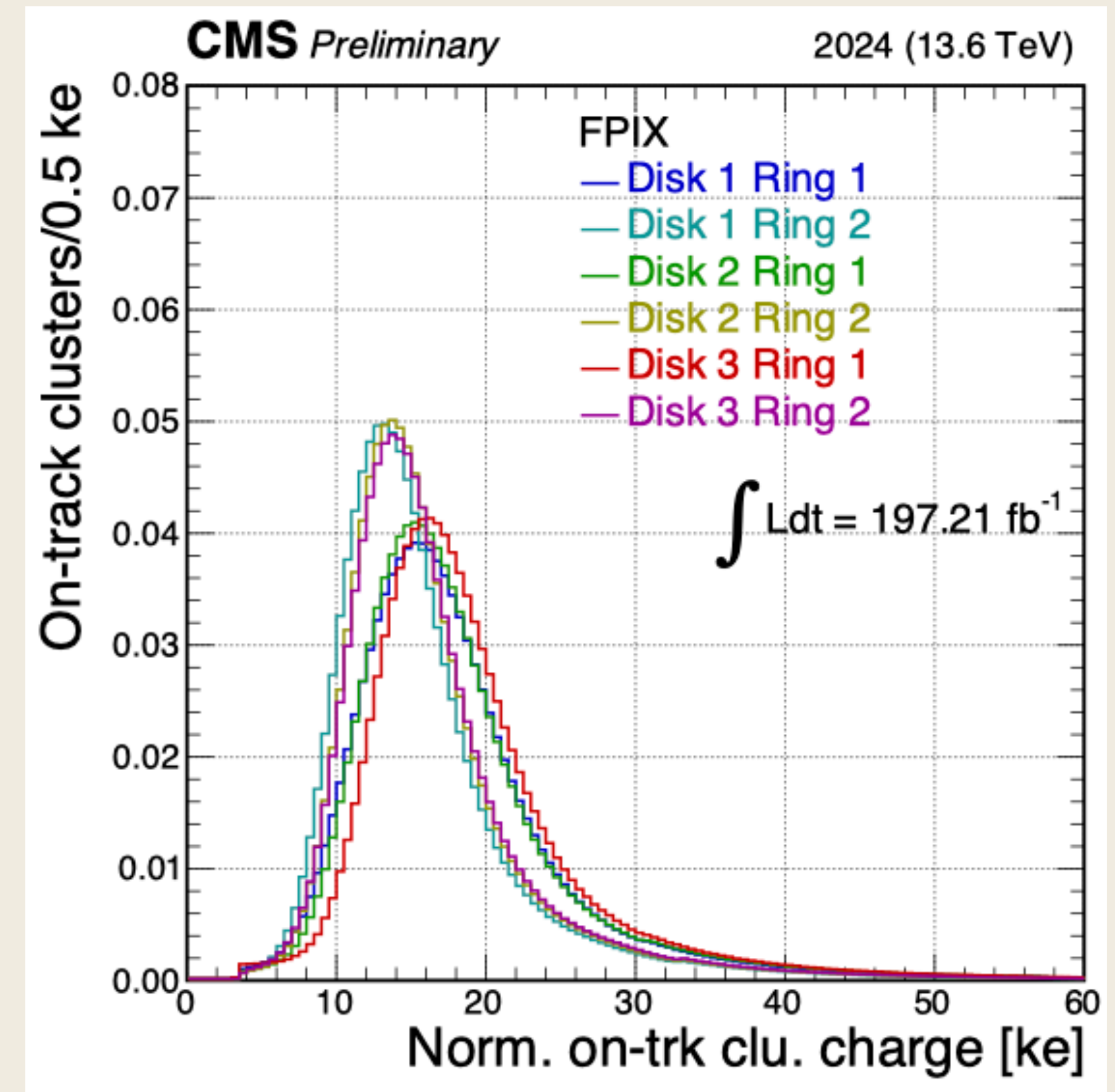
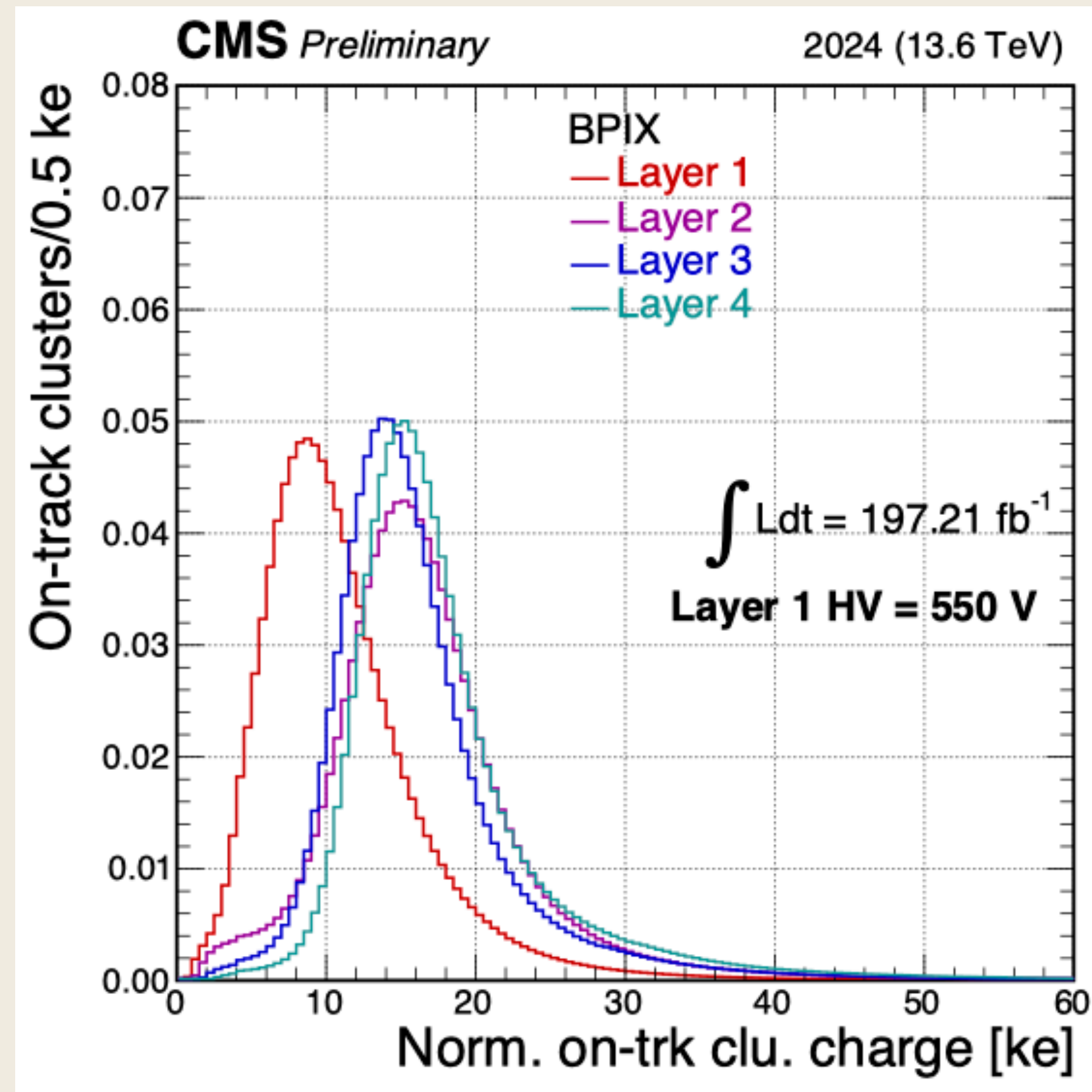
- Specifically designed for BPix Layer 1
- Faster hit transfer by grouping pixels into clusters of four for simultaneous readout
- >90% efficiency up to 600MHz/cm² hit rate
- Radiation tolerance tested up to 480 Mrad, with full functionality at doses up to 120 Mrad

Pixels HV bias scan

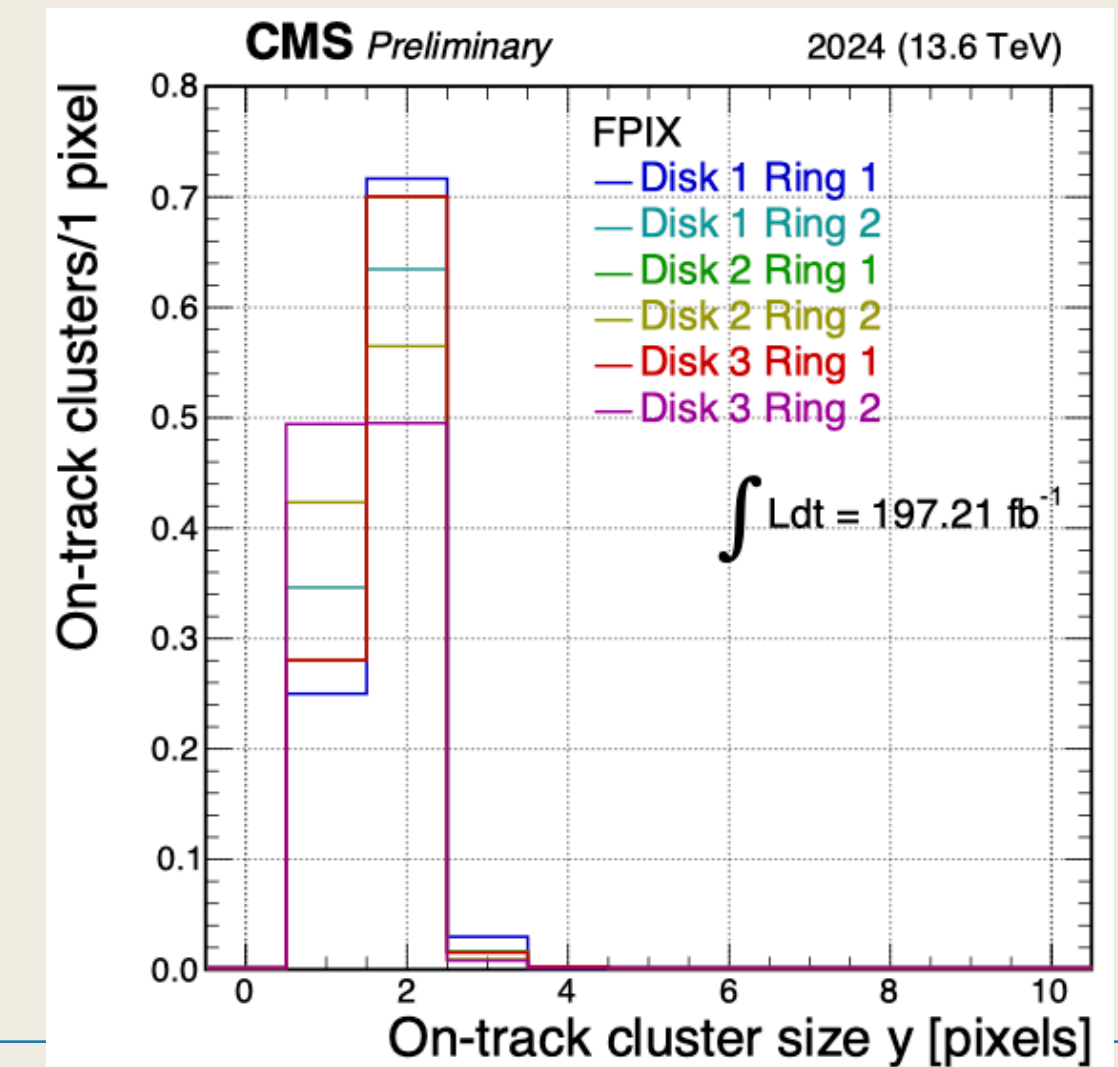
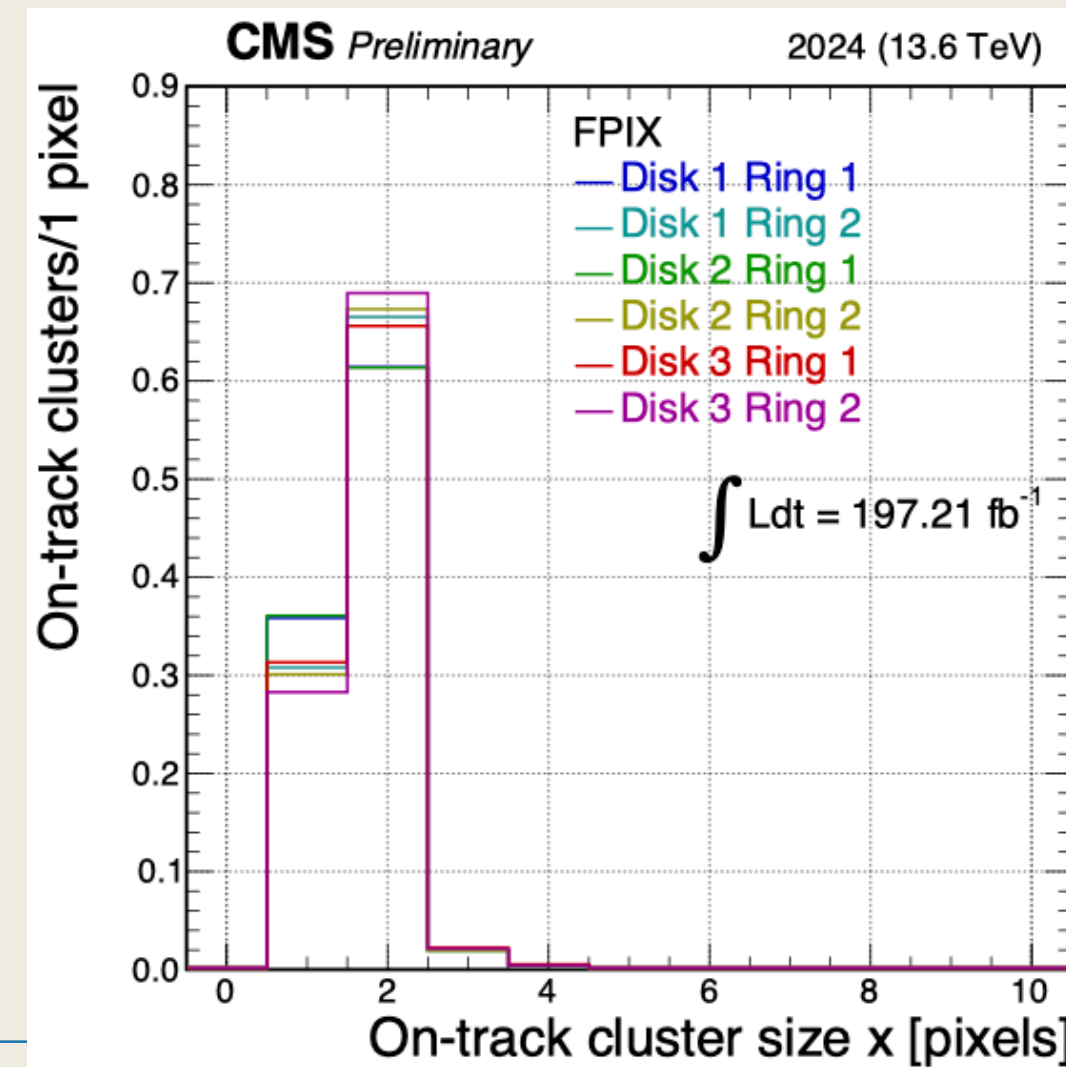
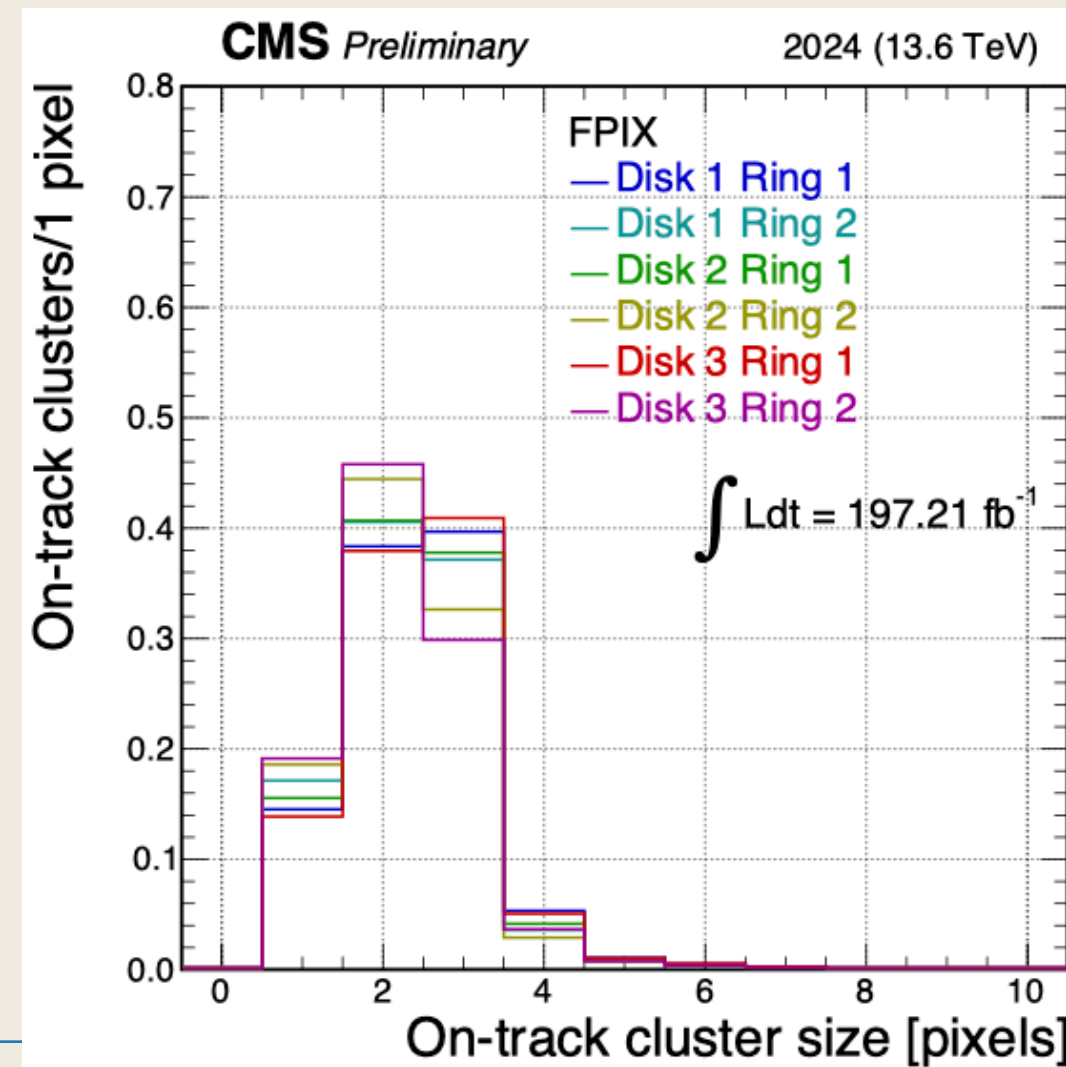
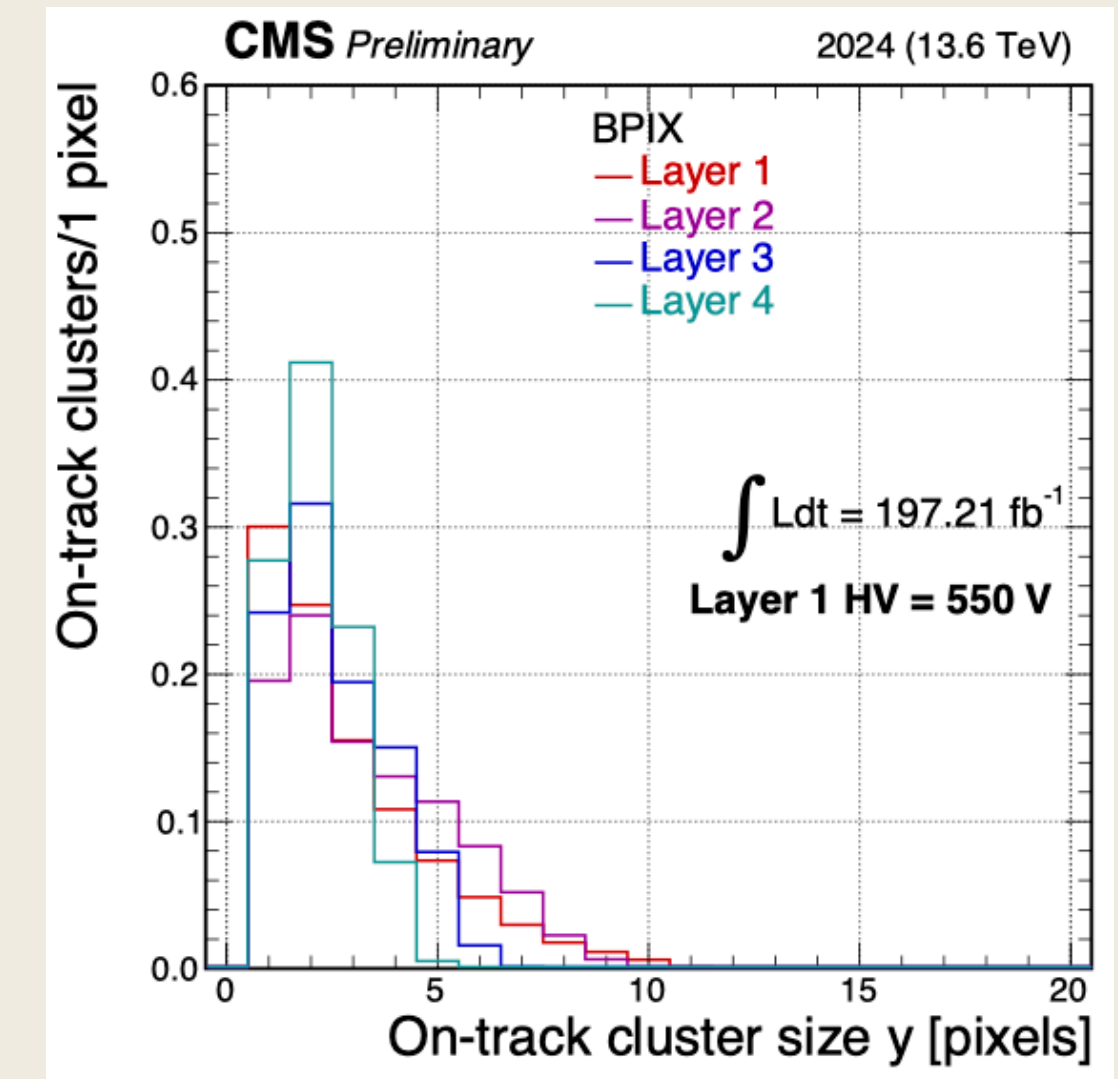
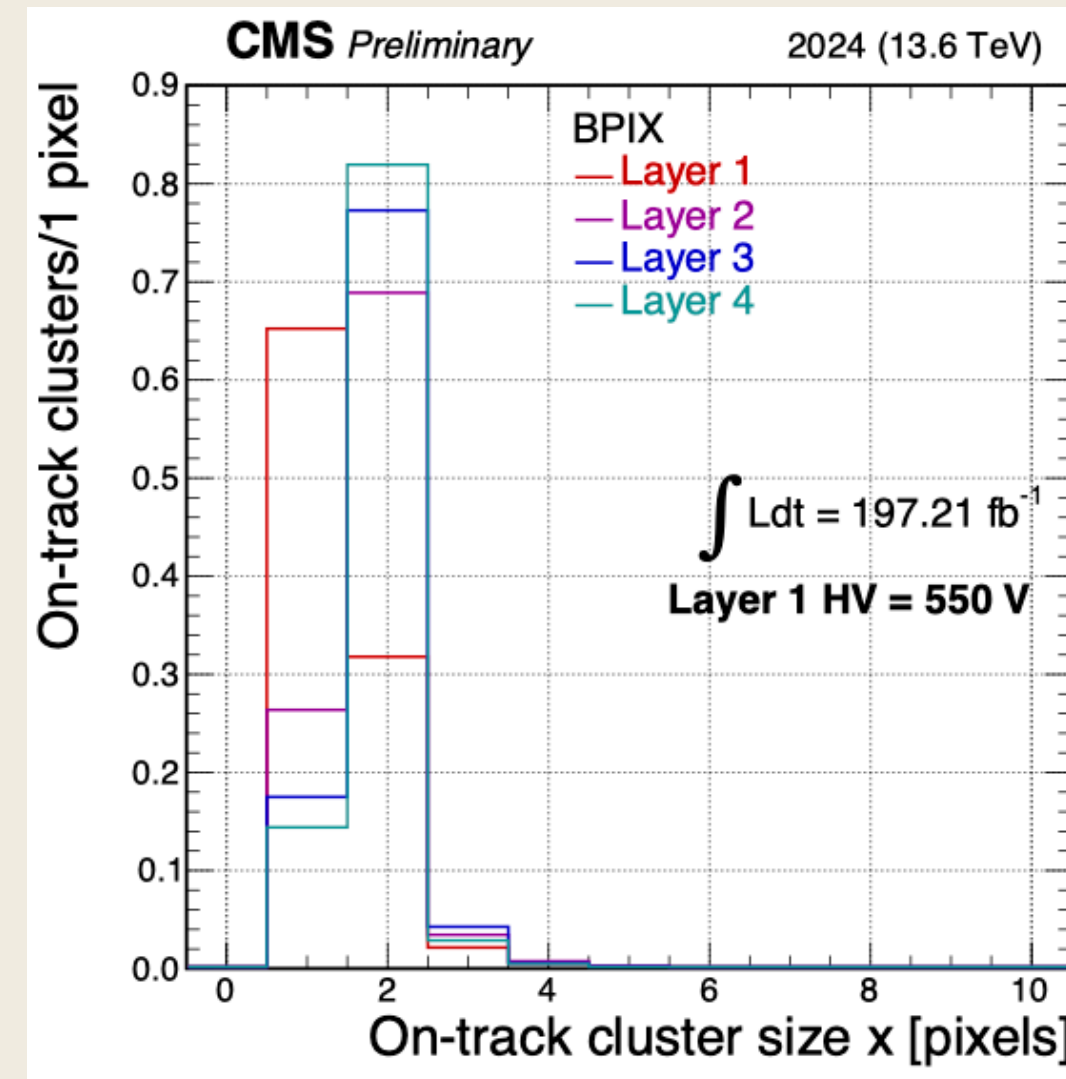
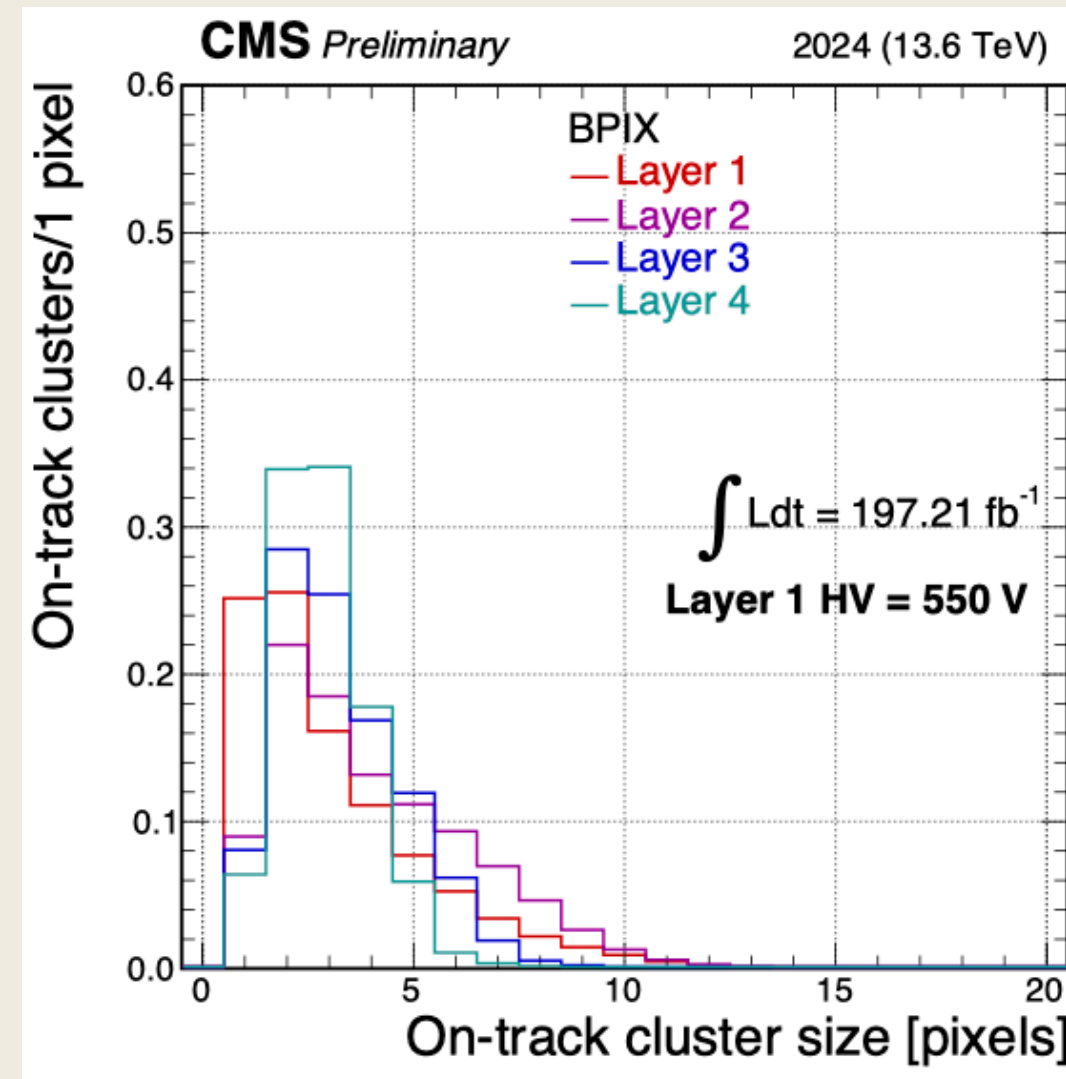


Pixels cluster properties

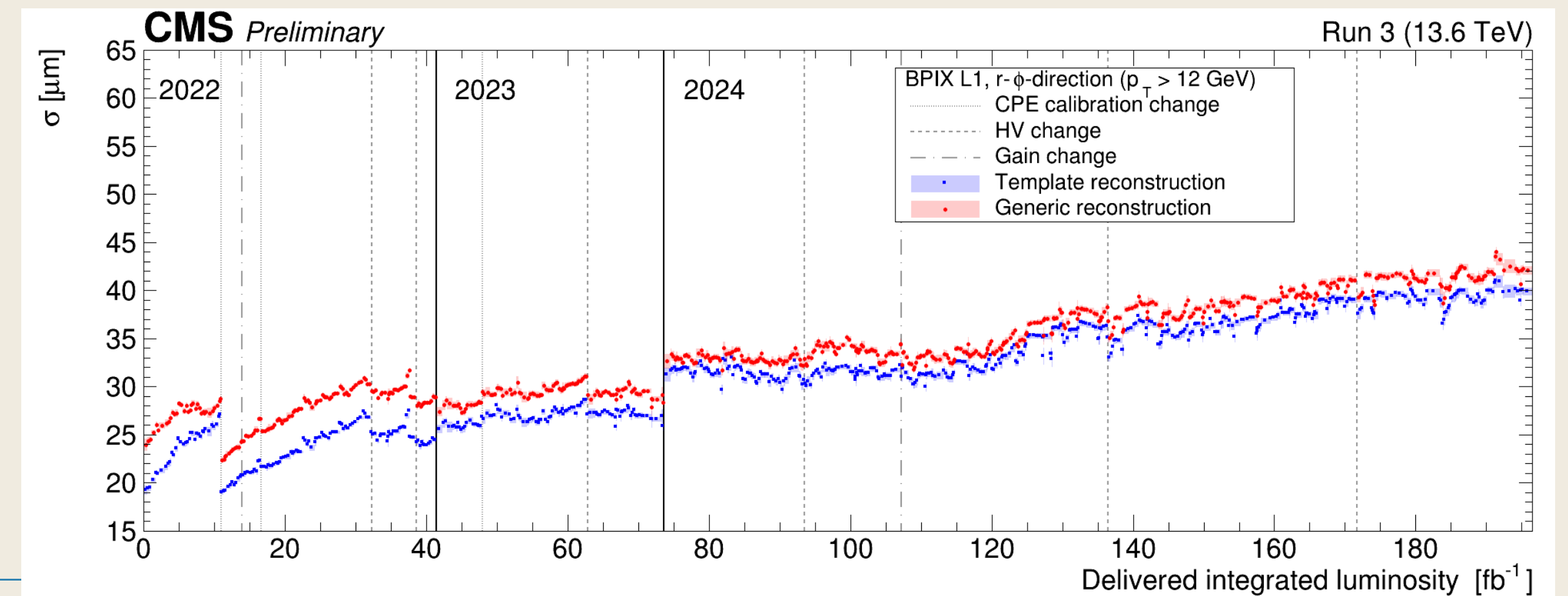
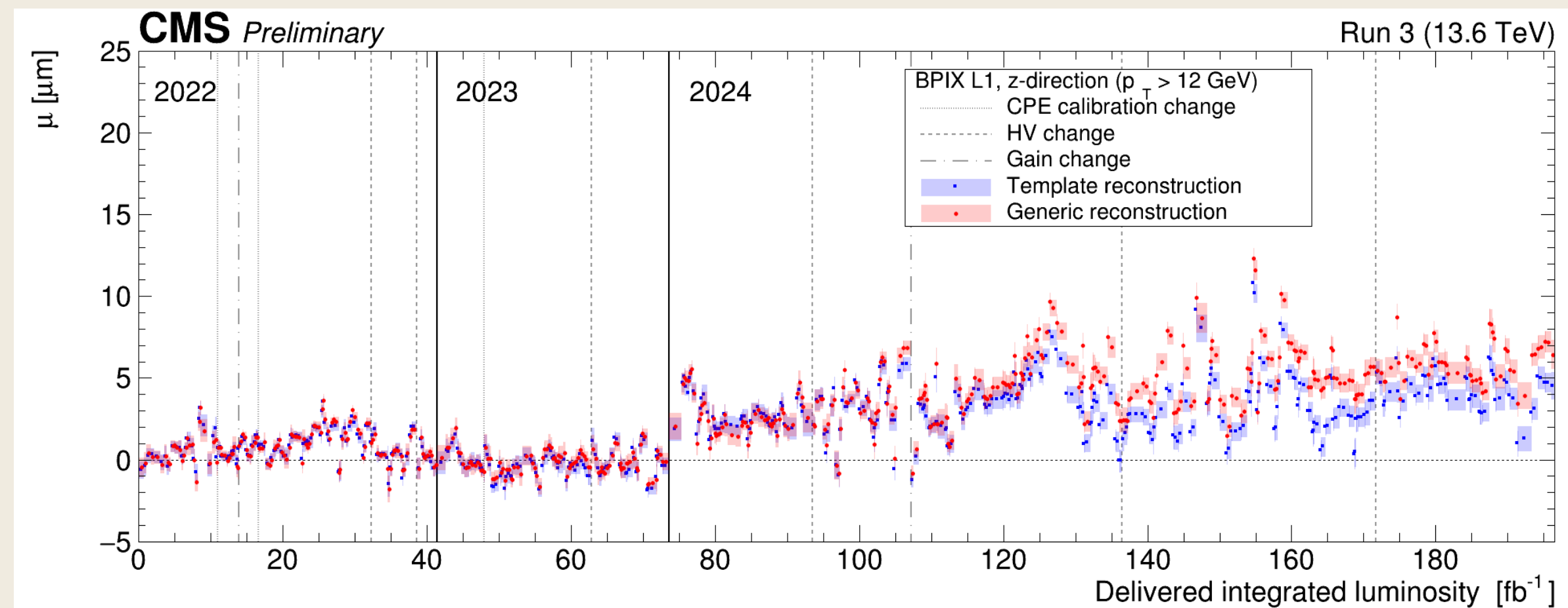
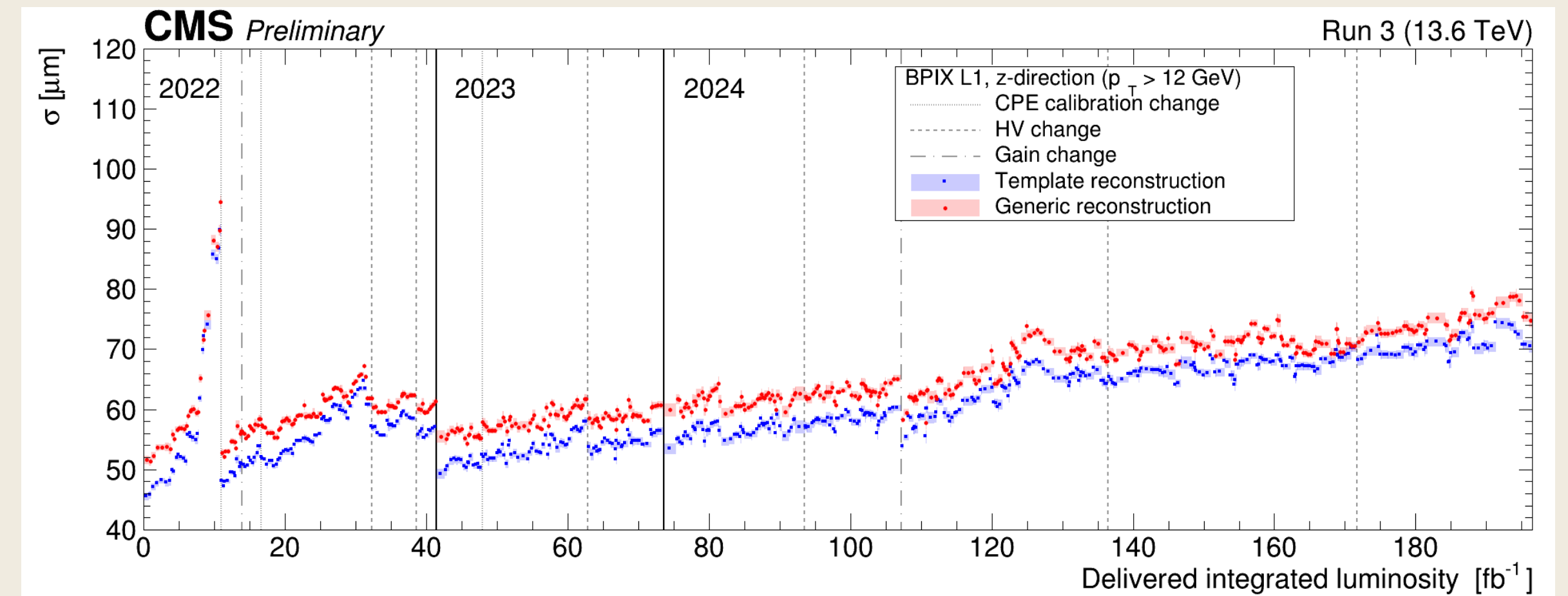
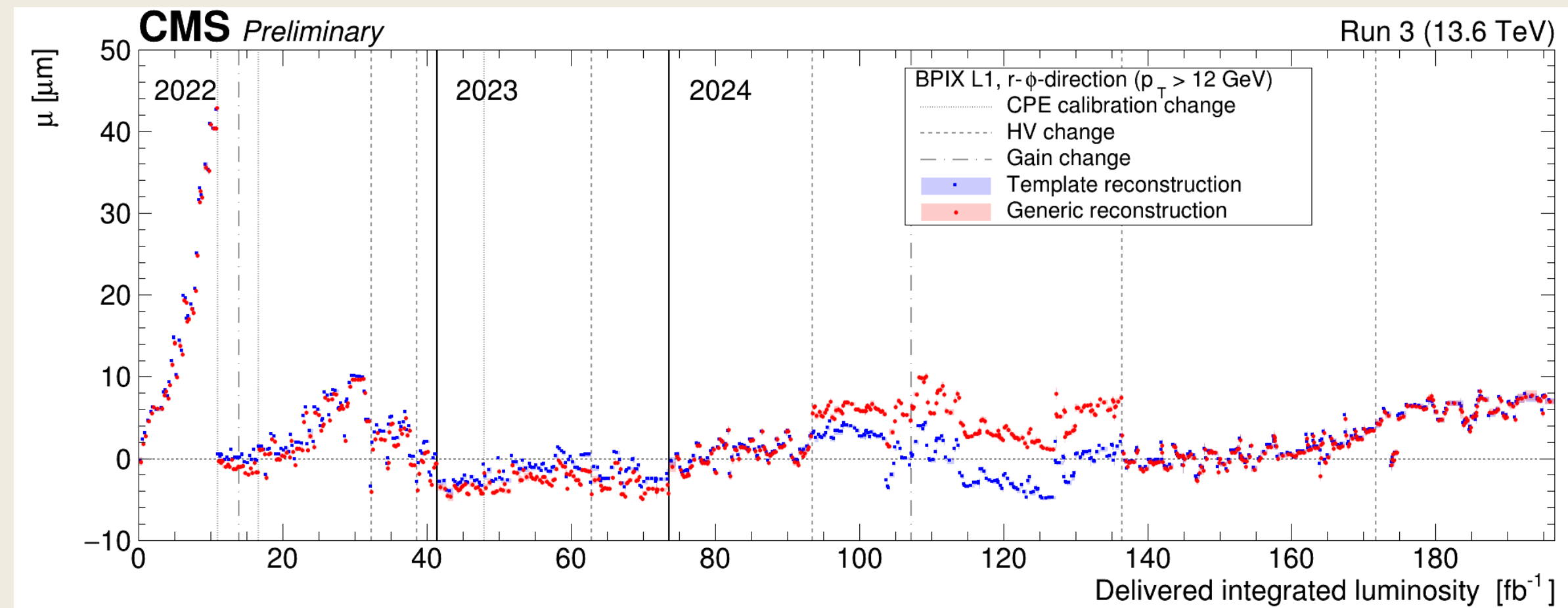
- Cluster charge normalized by incidence angle
- HV: BPix L2: 350V, L3&L4: 250V, FPix R1: 400V, FPix R2: 300V



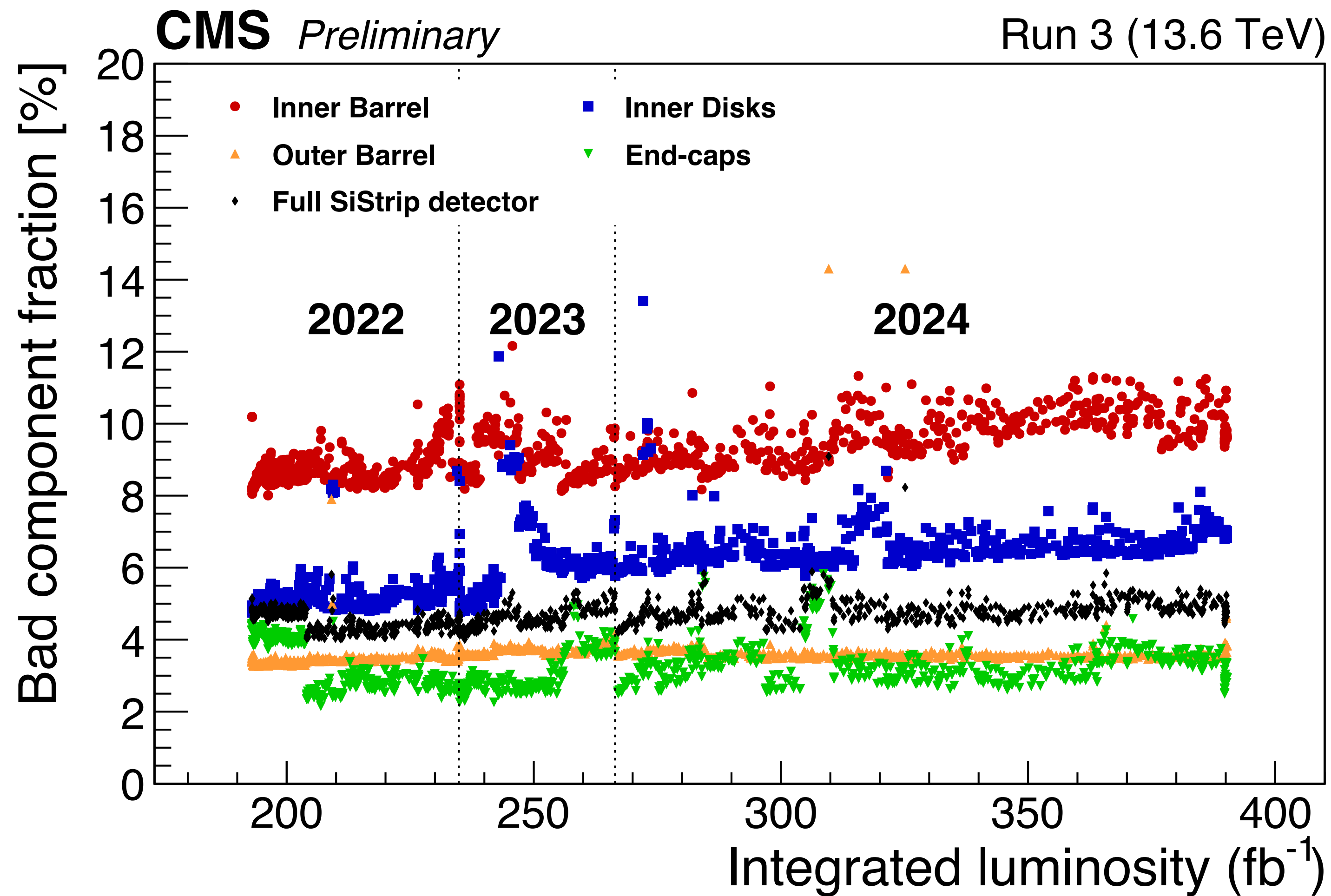
Pixel on-track cluster size



Pixels barrel layer 1 residual offset and resolution



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