The CMS silicon tracker & performance

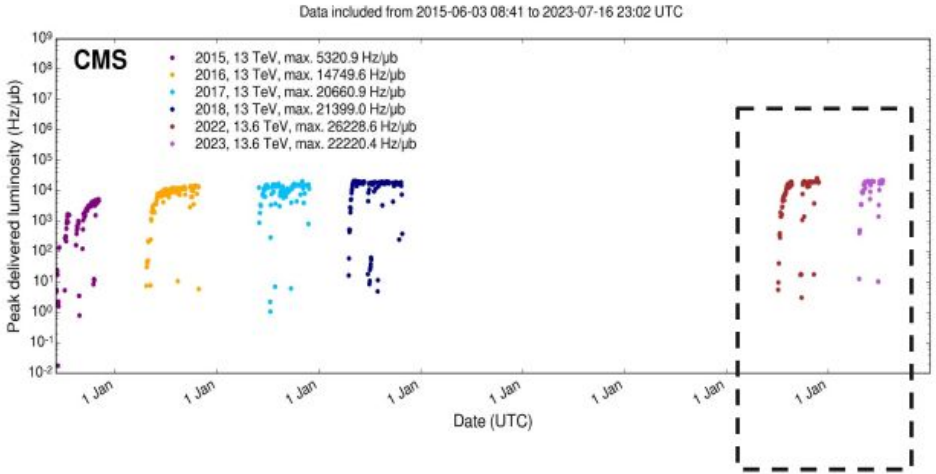
Suvankar Roy Chowdhury on behalf of the CMS Tracker group

Current and future tracking and vertexing detectors 2023

07.11.2023

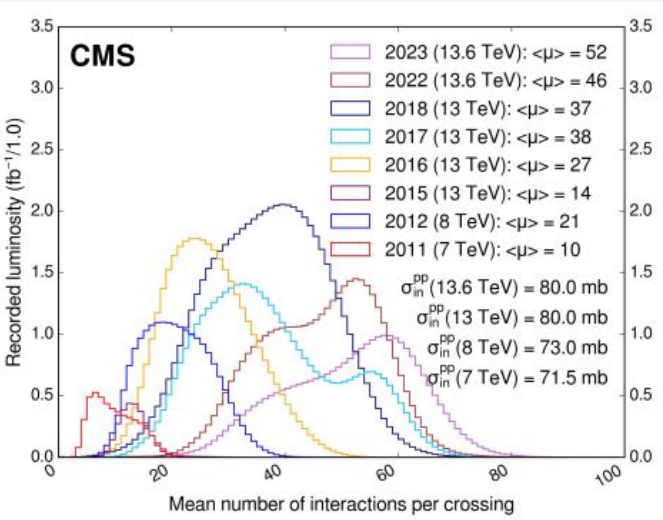
Data taking conditions

- Luminosity delivered to CMS
  - Run 1 + Run 2 is ~ 192 fb^{-1}
  - Run 1 + Run 2 + Run 3(till 2023) is 265 fb^{-1}



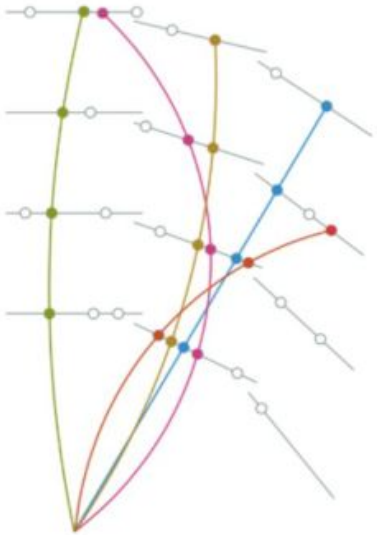
CMS instantaneous delivered luminosity

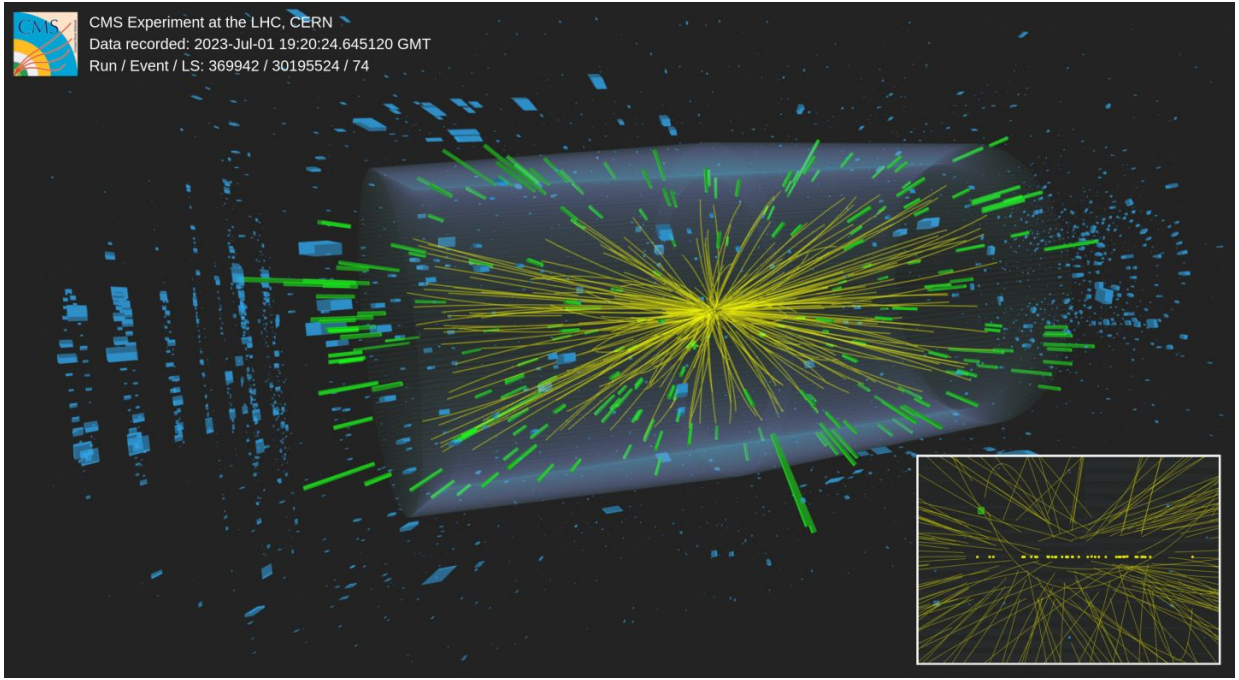
Run 3



- In Run 3, mean number of interactions per bunch crossing > 46
  - ~ 37 in 2017/2018
- LHC now stable ~ 2.1 x 10^{34} cm^{-2} s^{-1}
- CMS running at L1 trigger rate ~ 110 kHz.

Charged particle tracking

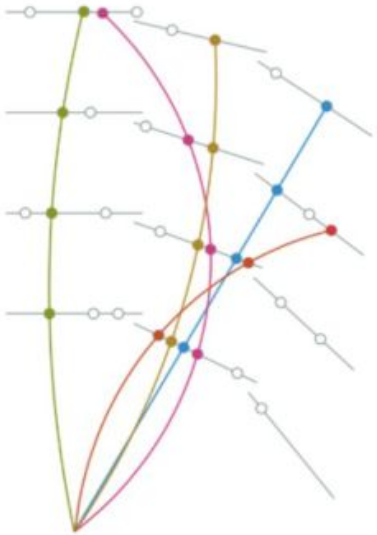


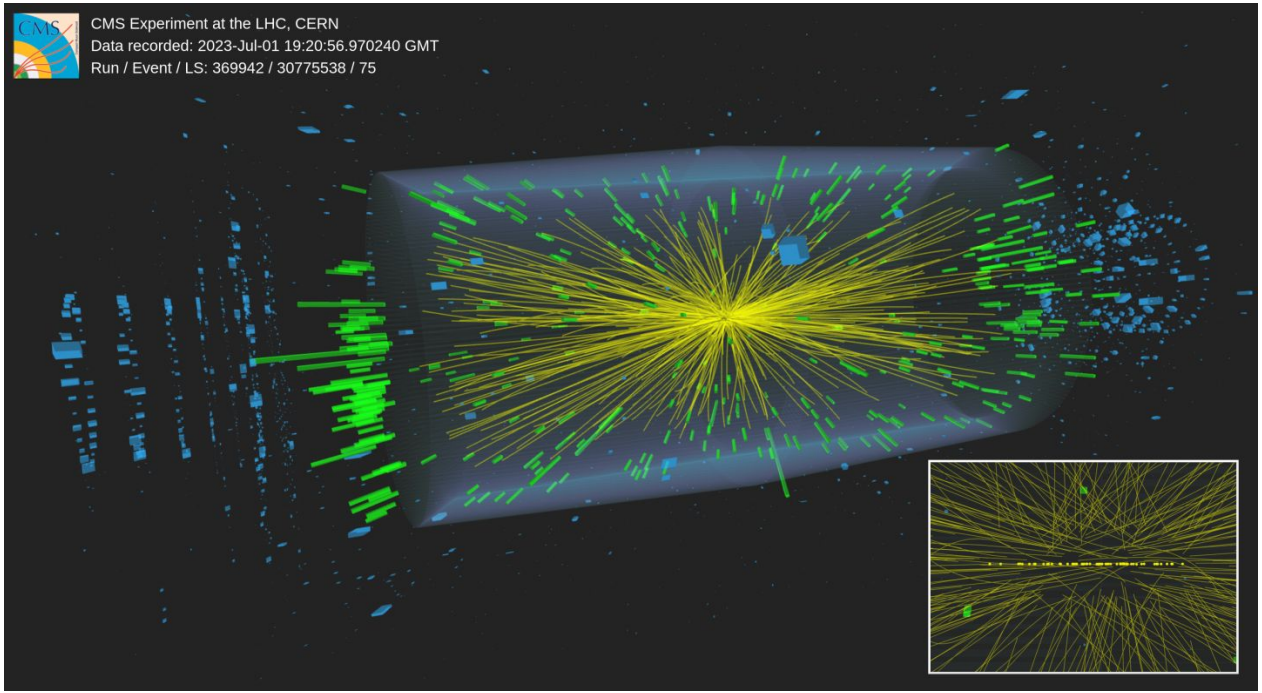


#PV - 39

- Hits from different layers used to build particle trajectories.
- Intersection of different trajectories correspond to either collision points (primary vertices) or displaced decays of long-lived particles (secondary vertices). Need good spatial resolution to separate different vertices
- **#vertices can go up to ~50 (Run 3) or more**

Charged particle tracking





#PV - 55

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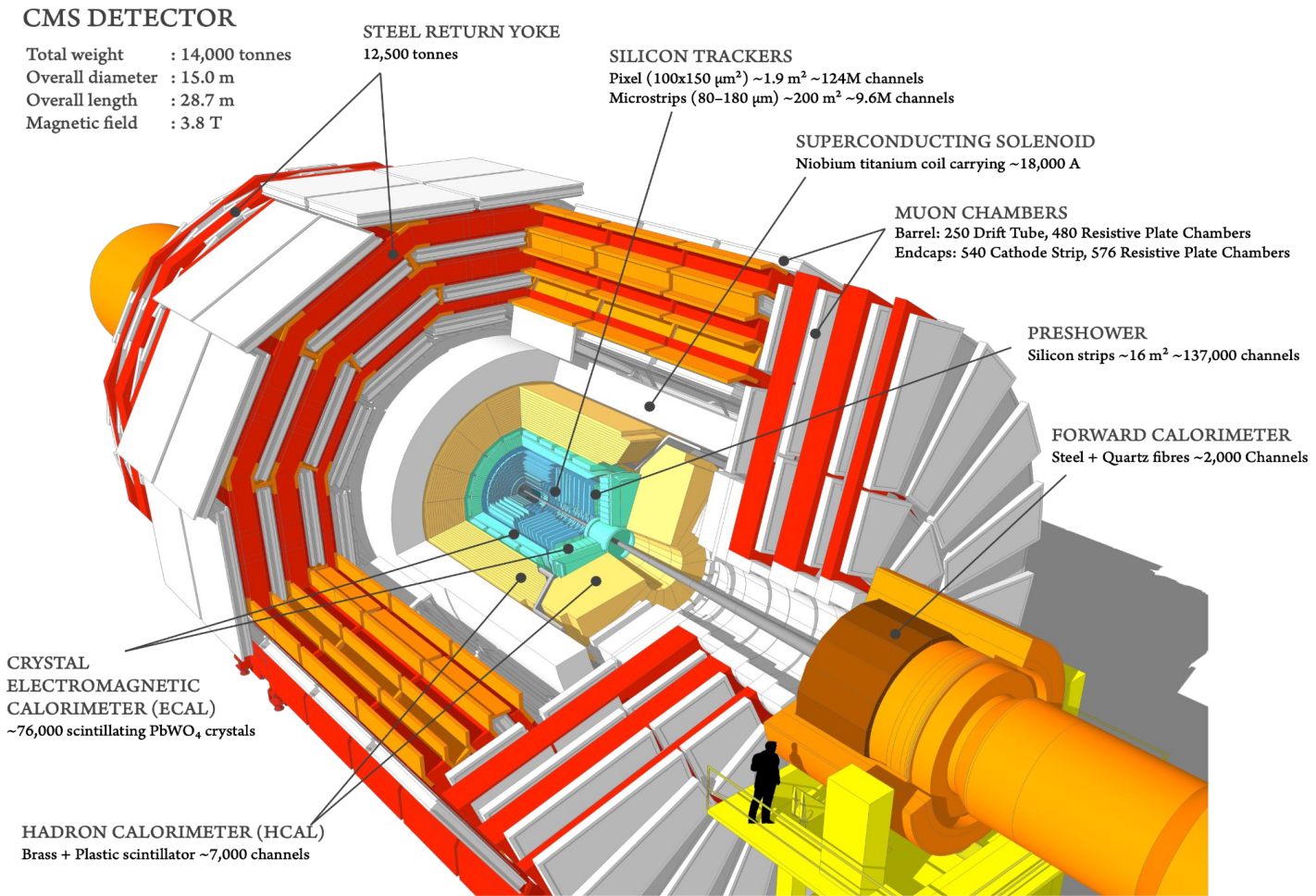
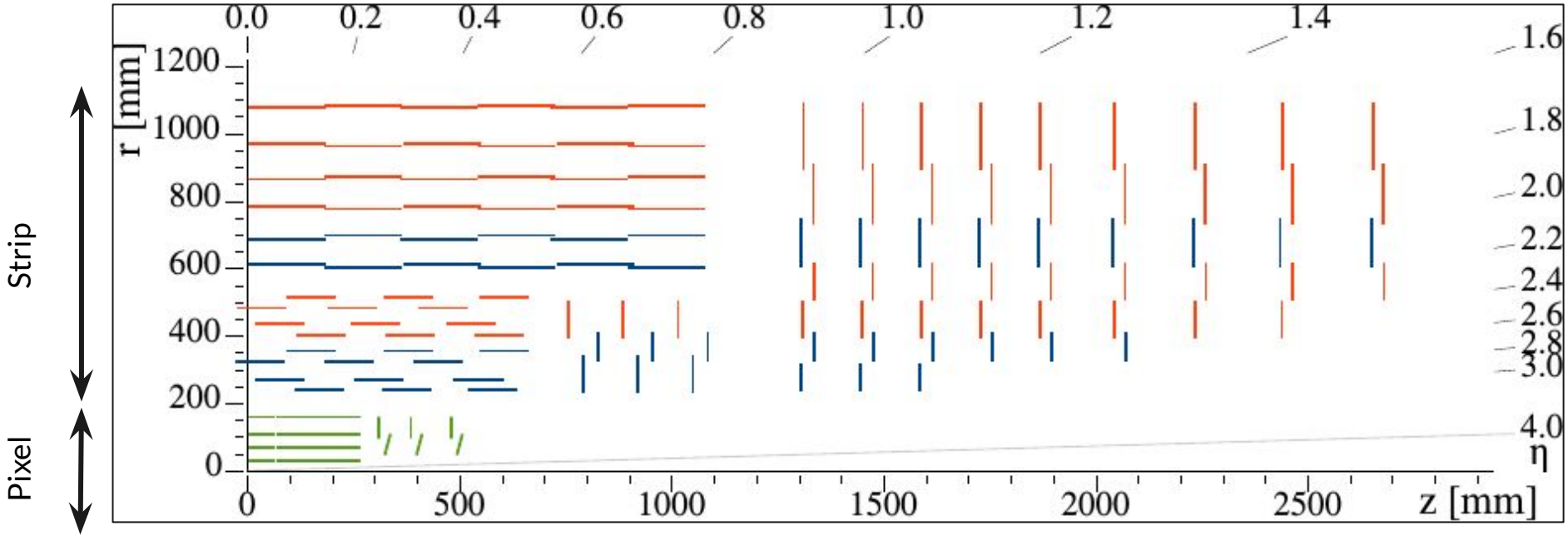
- Intersection of different trajectories correspond to either collision points (primary vertices) or displaced decays of long-lived particles (secondary vertices). Need good spatial resolution to separate different vertices
- **#vertices can go up to ~50 (Run 3) or more**

CMS Detector

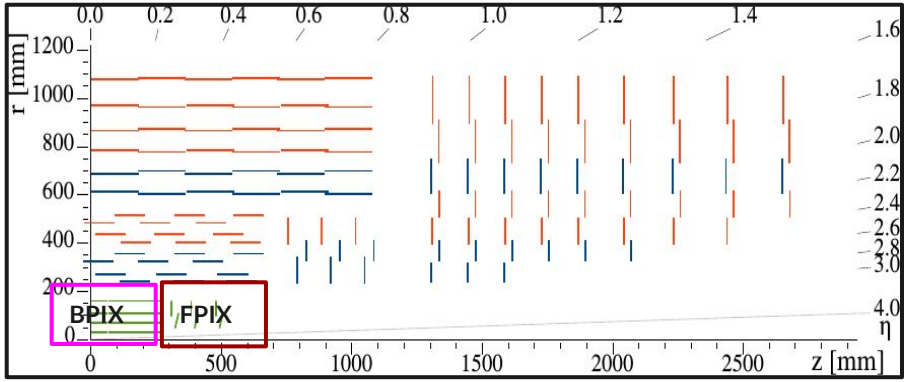


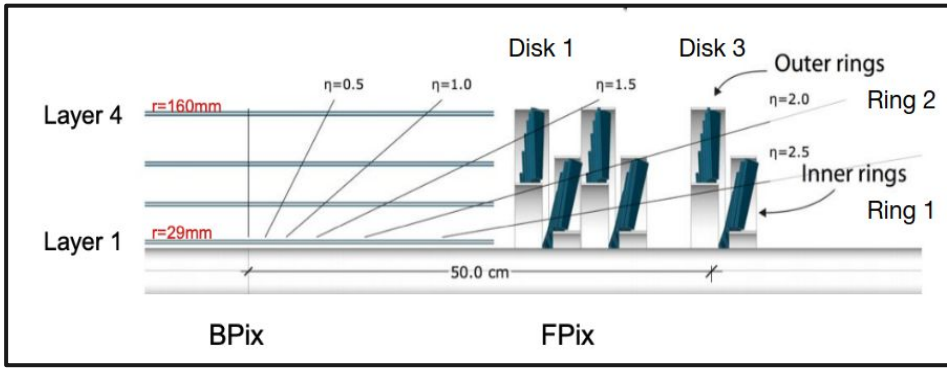
CMS Silicon Tracker



Pixel

CMS Tracker - Pixels





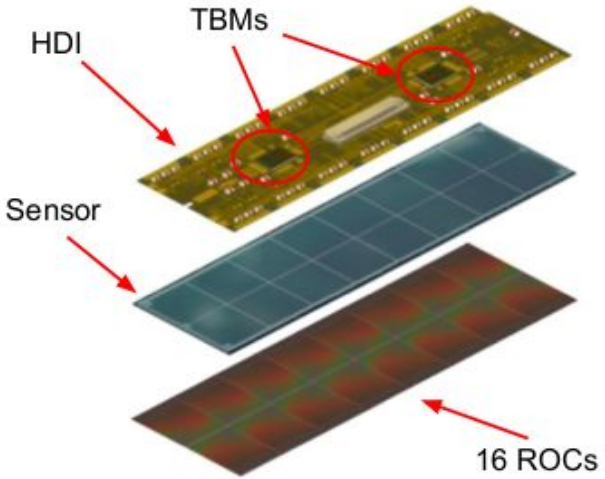
- Closest to the interaction point. Particle-hit rate up to 600MHz/cm^2 (Layer 1)
- Installed in end of year 2016- early 2017
- 1856 modules, ~124M channels, (100 × 150μm^2)
- **4 hit coverage up to |η| = 3**
- Barrel Pixel (**BPix**): 4 layers
- Forward Pixel (**FPix**): 3 disks arranged in 2 rings
- Refurbishment during the long shutdown after end of Run 2
- **Completely new BPix Layer 1 installed in 2022**
  - **New front-end readout chip** to be able to cope with higher rates
  - can operate upto 800 V (600 V during Run 2)

Pixel modules

BPIX L1

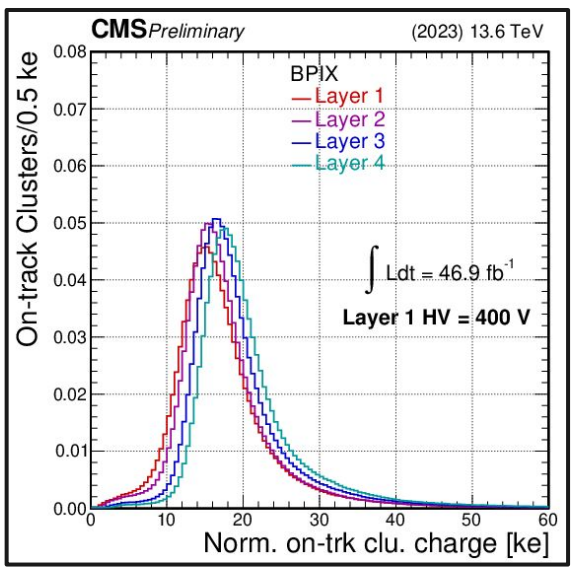
BPIX L2-L4

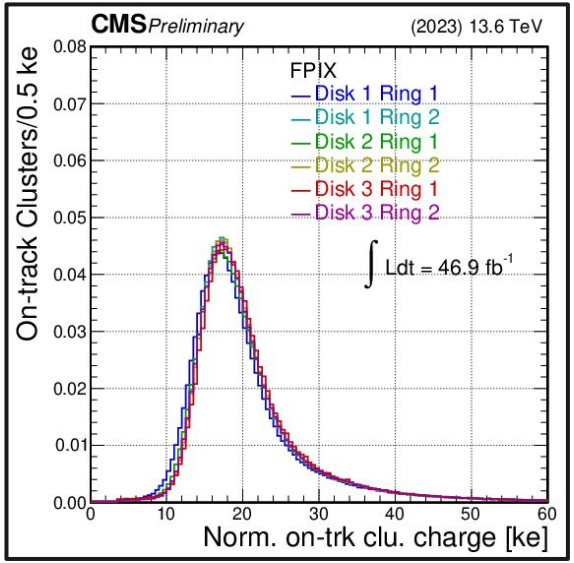
FPIX

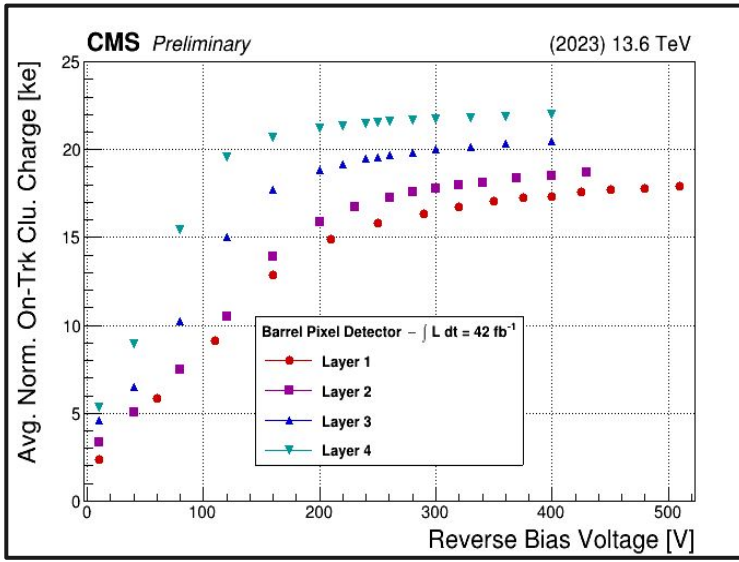


- Silicon sensor sandwiched between between high-density interconnect (HDI) flex printed circuit and 16 readout chips (**ROC**) organized in 2×8 matrix
- ROCs bump-bonded to sensor and wire-bonded to HDI
  - PSI46dig ROC in BPix L2-L4 and FPix
  - PROC600 ROC in BPix L1
- HDI contains Token Bit Manager (TBM) chip (2 in case of L1) that coordinates the readout of ROCs.
- Silicon sensor: n^+-in-n type, 285 μm thick, 16.2×64.8 mm^2 active area.

Pixel performance - Cluster charge

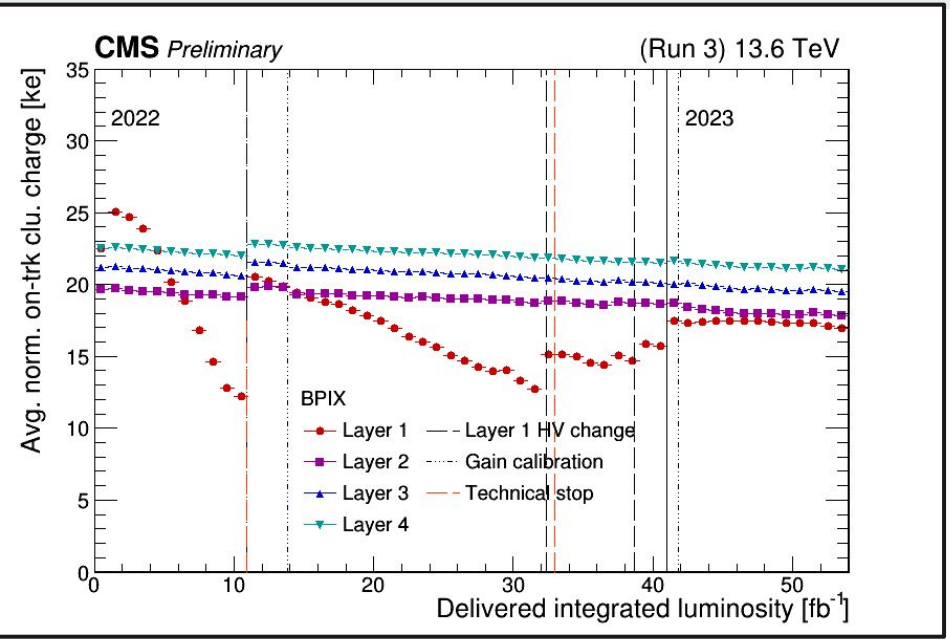


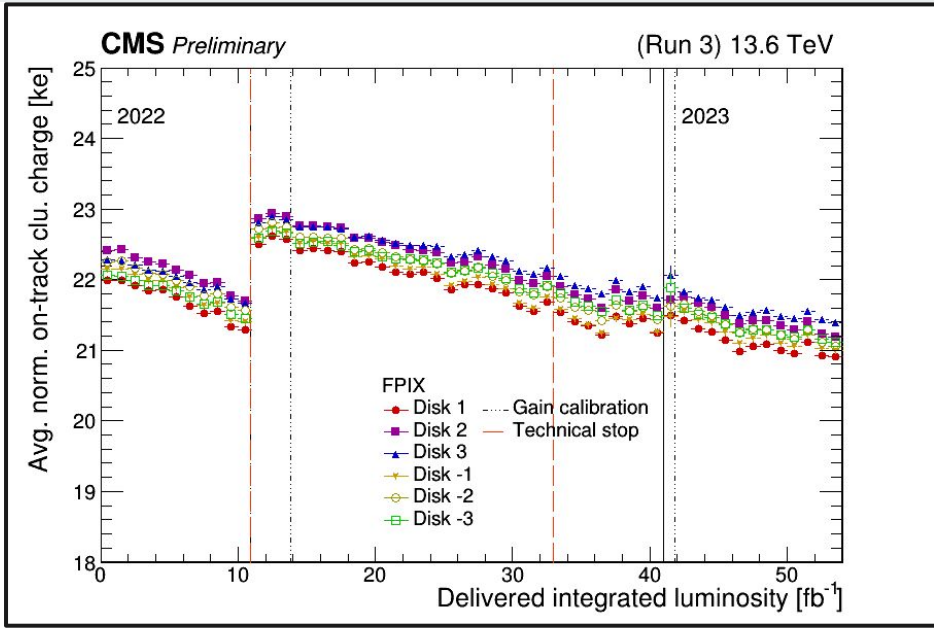




- Cluster charge on-track for BPix and FPix
  - Clusters are required to be attached to the tracks with p_T > 1 GeV
  - Radiation damage introduces the charge efficiency loss which is recovered by raising the HV.
- Regular bias scans are done during data taking to determine the best operating point of the detectors in various layers (more crucial for Layer 1).
- Current HV settings
  - BPix - Layer 1: 450V, Layer 2: 350V, Layer 3 & 4: 250V
  - FPix - Ring 1: 350V, Ring 2: 300V

Pixel performance - Cluster charge trend

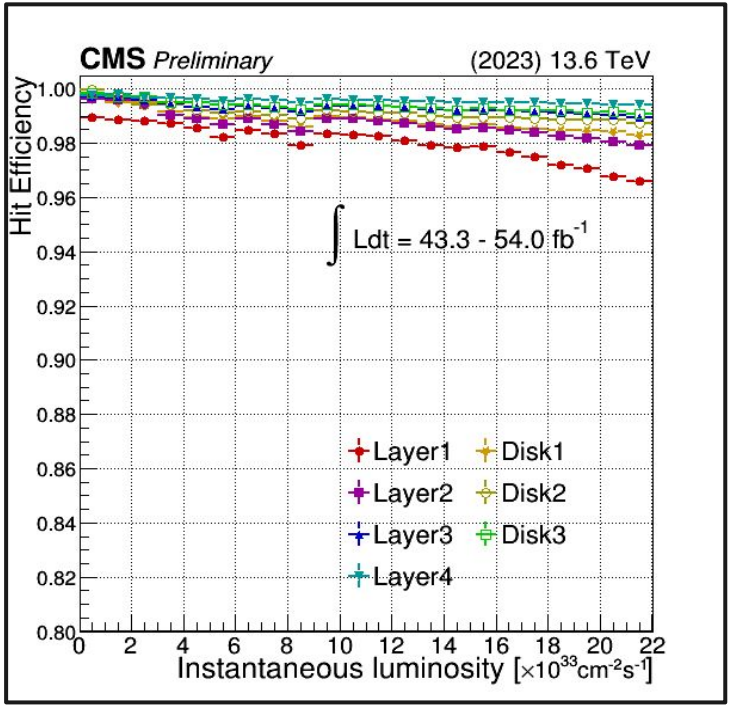




- Evolution of on-track cluster charge in BPix/FPix vs integrated lumi in Run 3
- Trend shows degradation of performance due to irradiation - esp in the BPix L1 which is ~ 3 cm away from beam-pipe
    - Mitigate by raising HV and updating Lorentz Angle

Pixel performance - Hit Efficiency

- Hit efficiency - the probability to find any cluster within 1mm around an expected hit
  - measured with muon tracks
  - bad components are excluded.
- At instantaneous lumi of ~ **2 E 34 cm^{-2} s^{-1}**
  - **BPix L1** can operate at **> 96%** hit efficiency
  - **BPIX L2-4** and **FPIX > 98%** hit efficiency



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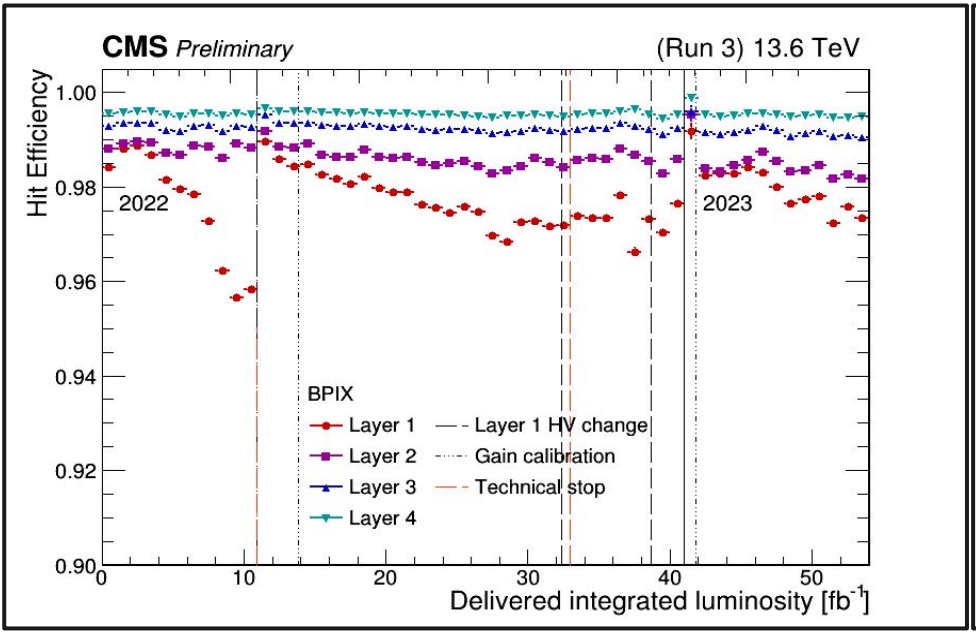

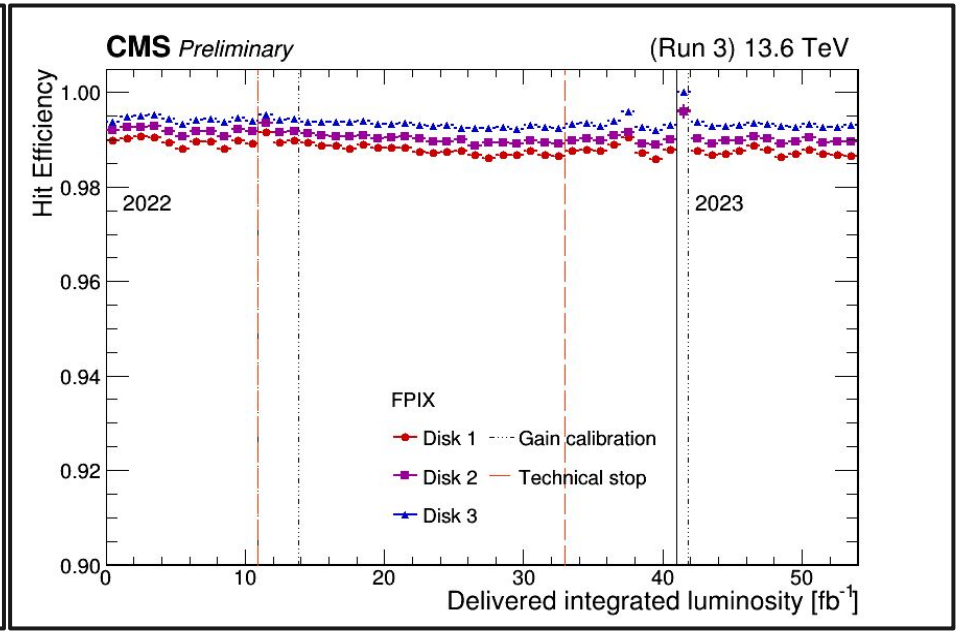

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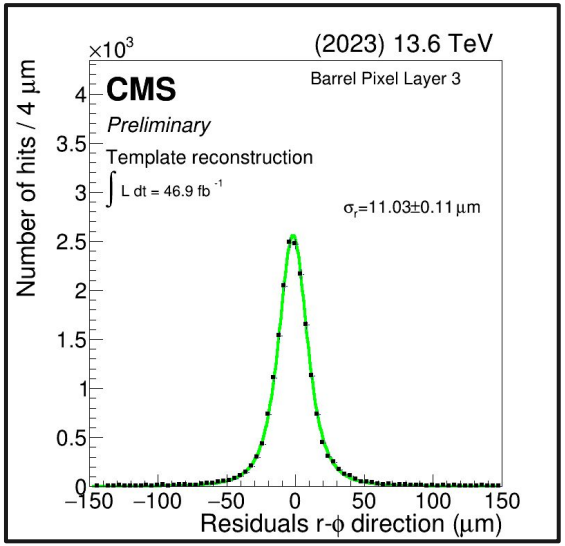
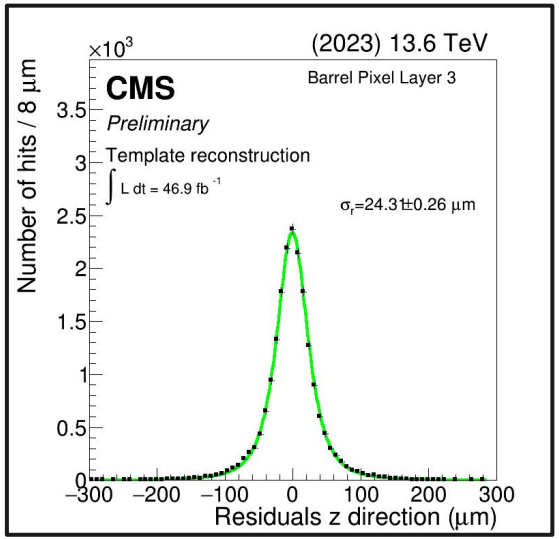
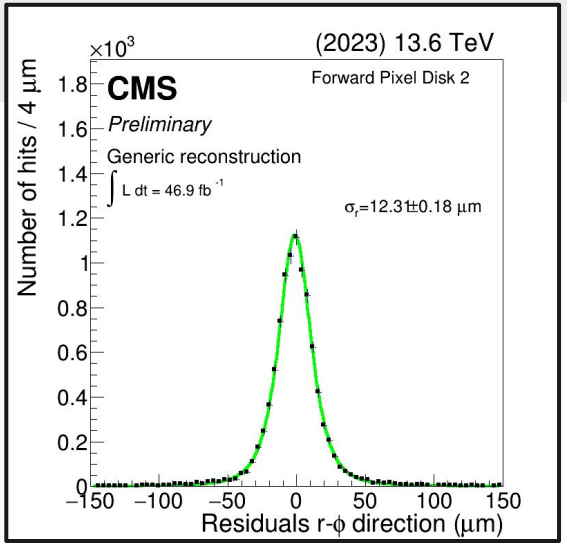
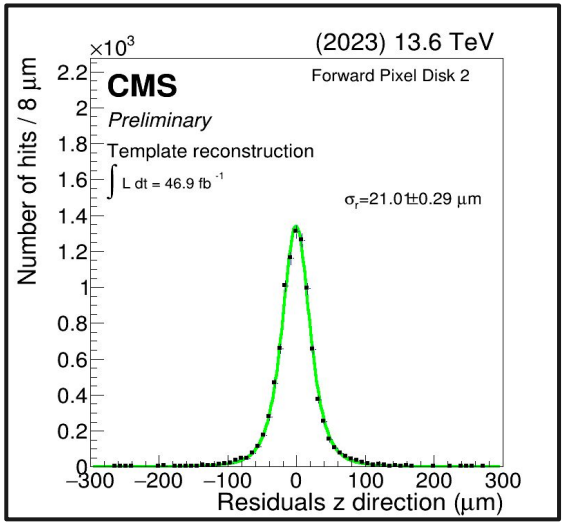
Pixel performance - Hit resolution



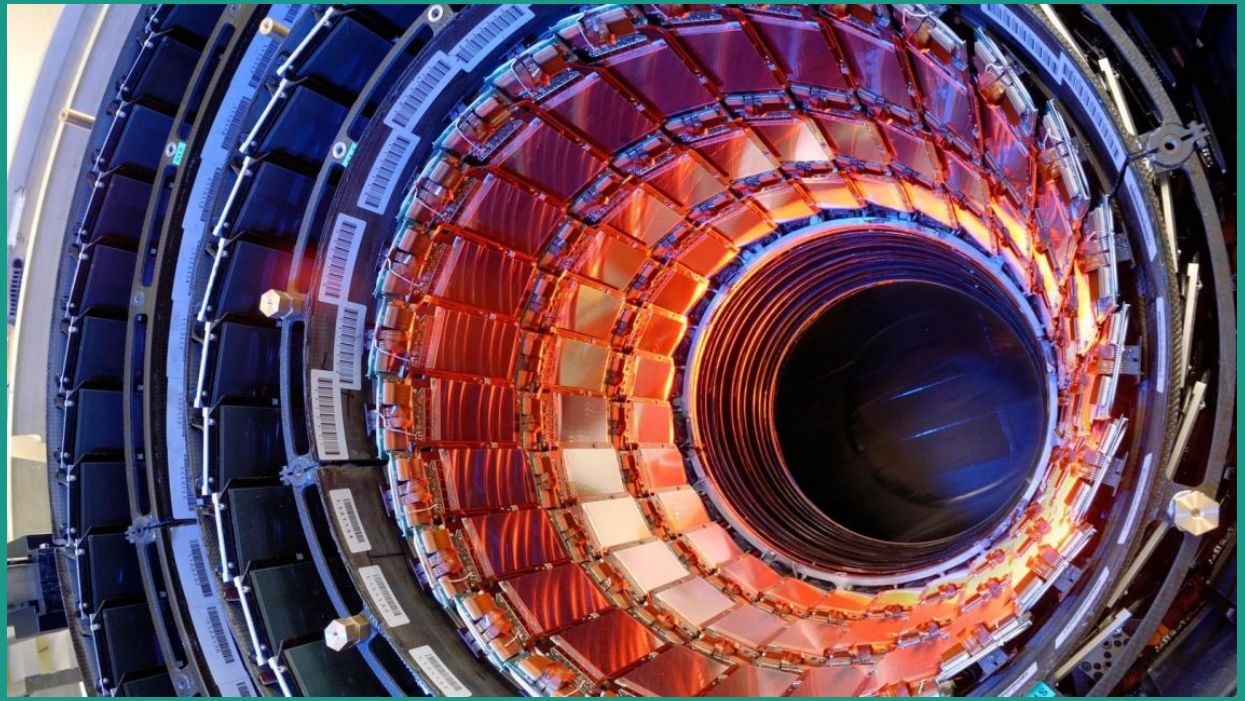




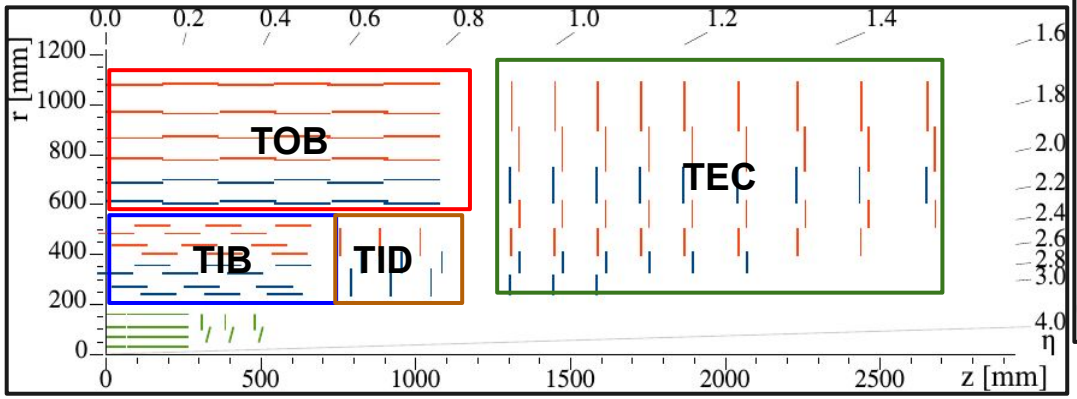


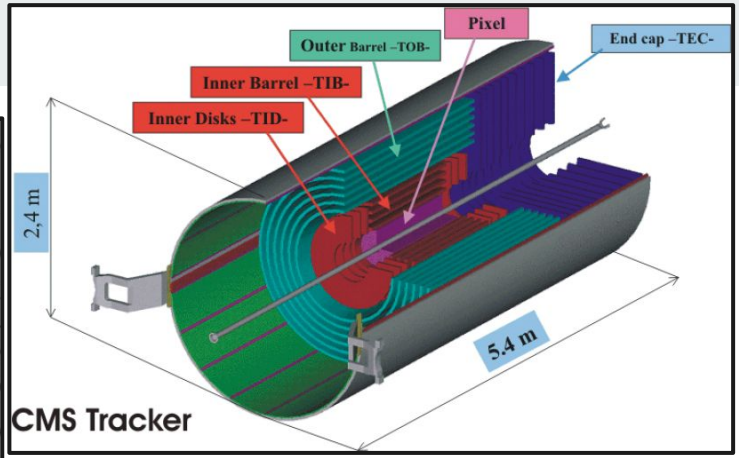
- Excellent hit resolution in r-phi and z direction
- Comparable to performance in Run 2

Strip tracker

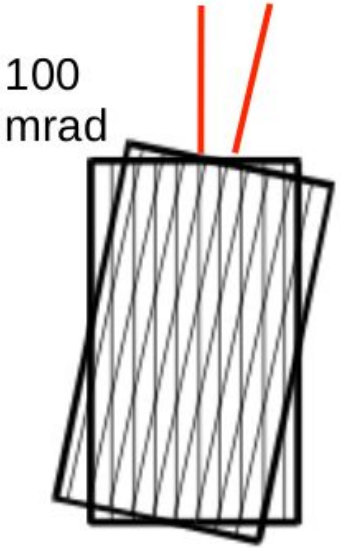


CMS Tracker - Strips



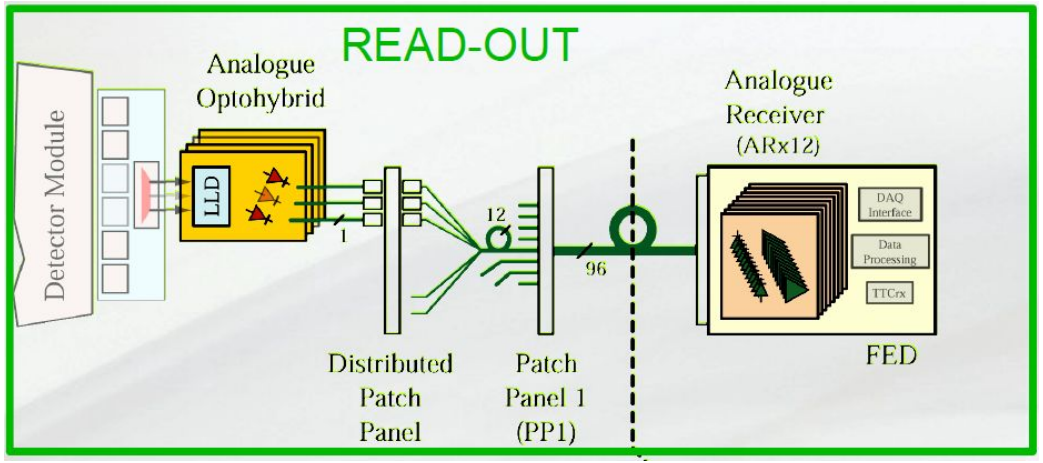


- Active area 200 m^2, 5.6 m long, 2.5 m diameter with 15148 silicon modules (p-in-n sensors), 9.6 million electronic channels.
- 10 layers in barrel region, 4 Inner Barrel (**TIB**), 6 Outer Barrel (**TOB**).
- 3+9 discs in the inner disks (**TID**) and endcaps (**TEC**)
- **Stereo modules** (two modules with 100 mrad stereo angle) in 4 layers in barrel & 3 rings in endcap. → 2D hits from 1D strips
- 320 µm Si in inner layers (TIB, TID, TEC ring 1-4), 500 µm Si in outer layers (TOB, TEC ring 5-7)
- Analog readout.



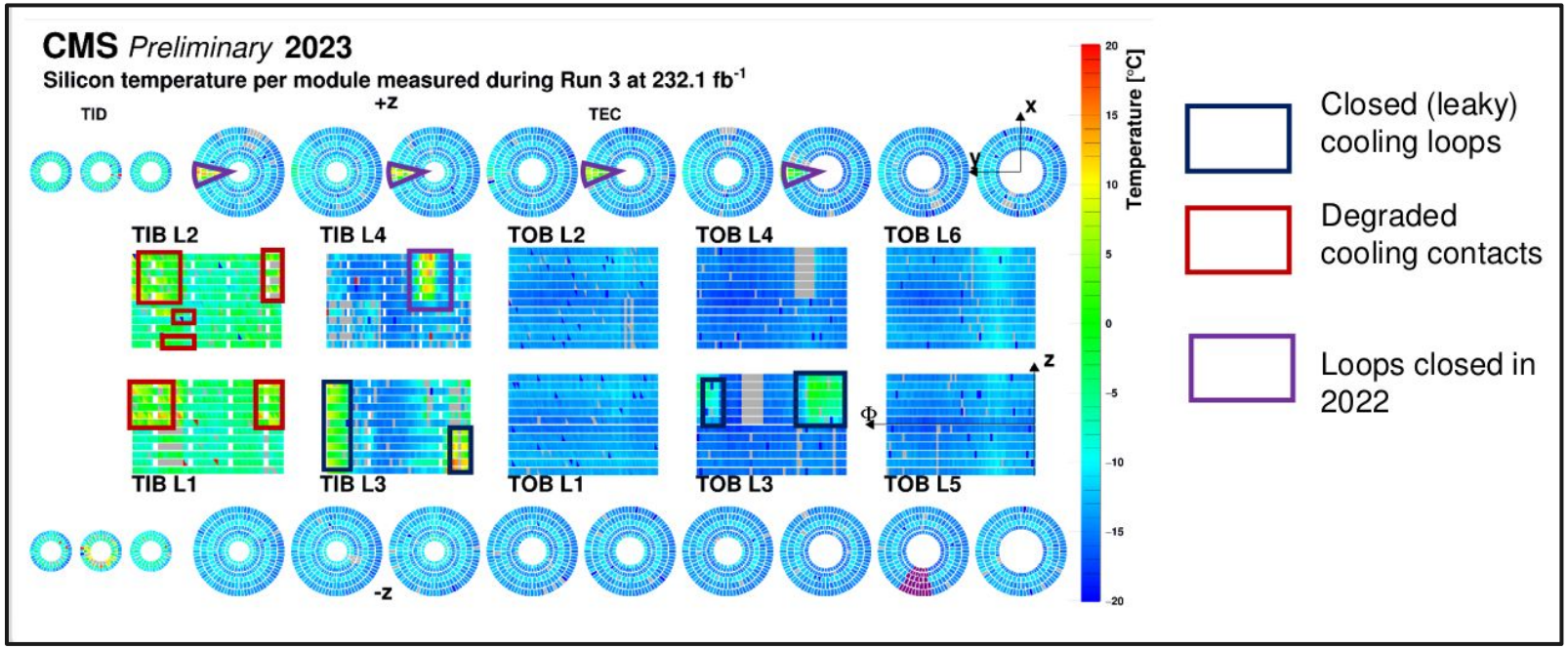
Readout Strip modules

- Analogue readout with APV25 chip.
- Each chip has 128 channels.
- Tracker module have 4 or 6 APV chips.
- Two modes of operation:-
  - Peak mode - single sample - corresponds to the peak voltage of the signal.
  - Deconvolution mode - three-sample weighted sum.
- Signal from 2 chips multiplexed to a Laser Driver.
- Signal from APV25 chips converted to optical signal on Analog-opto-hybrid (AOH).



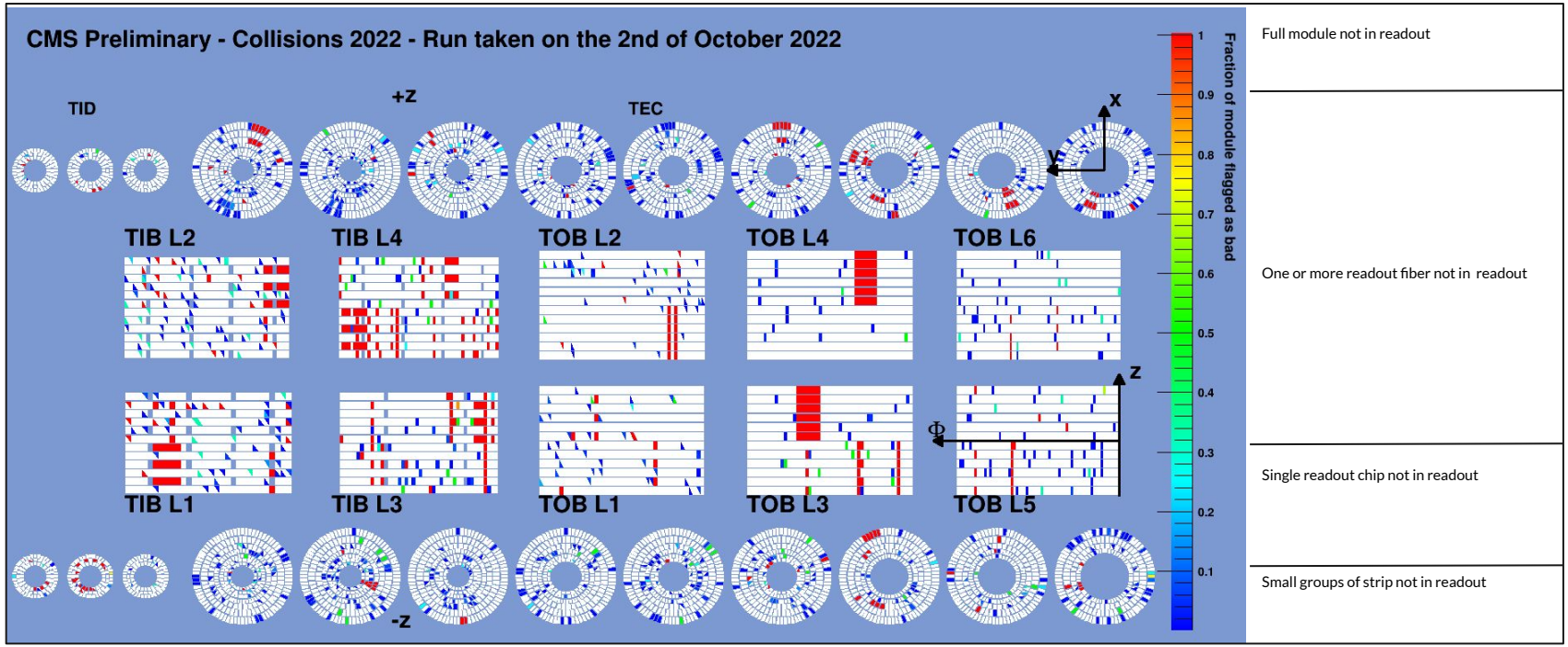
FED → Front End Driver

Strips - Silicon temperature



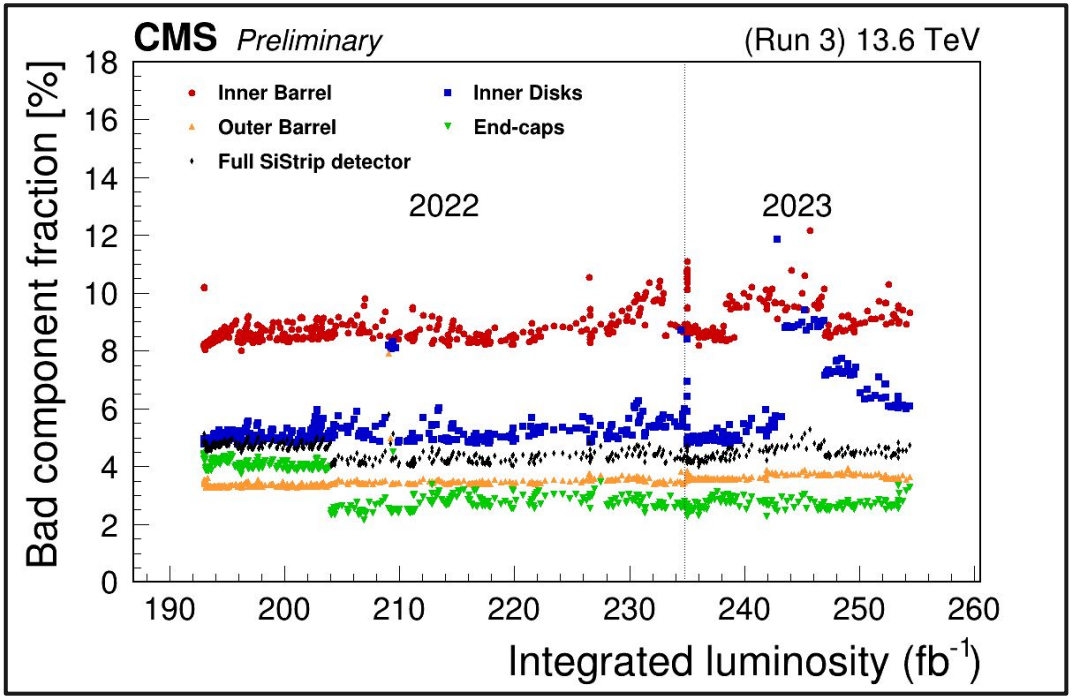
- Detector is currently operated at -22℃ (since June 2023)
- Grey regions = modules excluded from data-taking
- Purple regions = modules with DCU data missing

Strips - Good detector fraction in Run 3



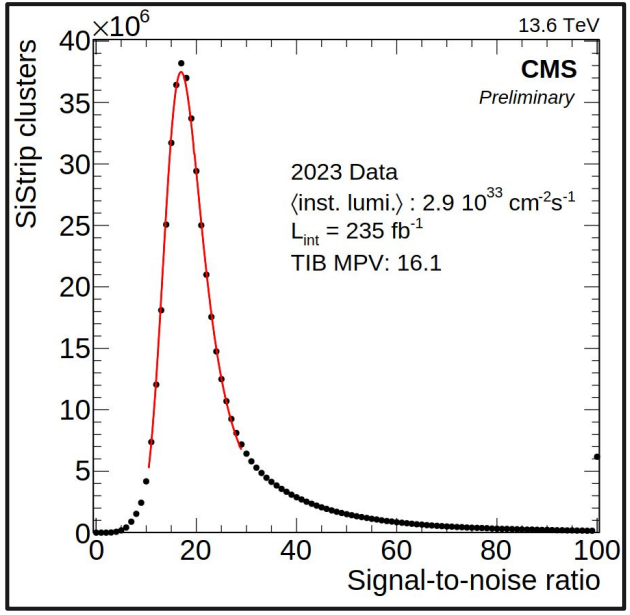
- Knowledge of bad components crucial for tracking
- **Fraction of active channels during Run 3 ~ 96** %
  - Similar to Run 2.

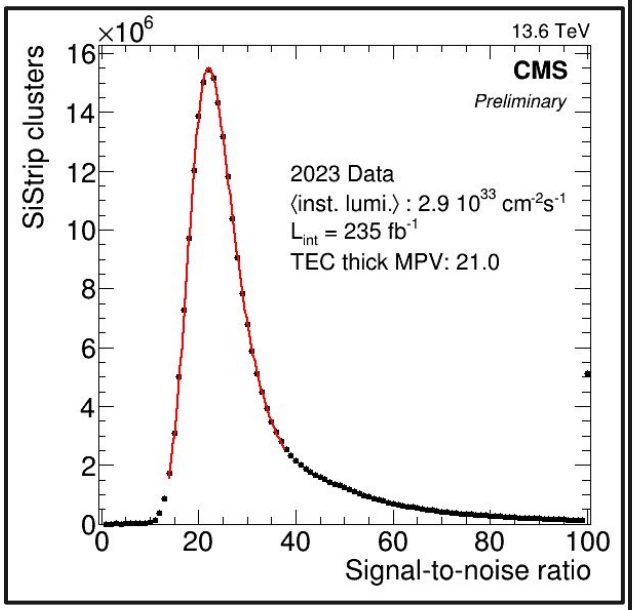
Strips - Evolution of bad components in Run 3

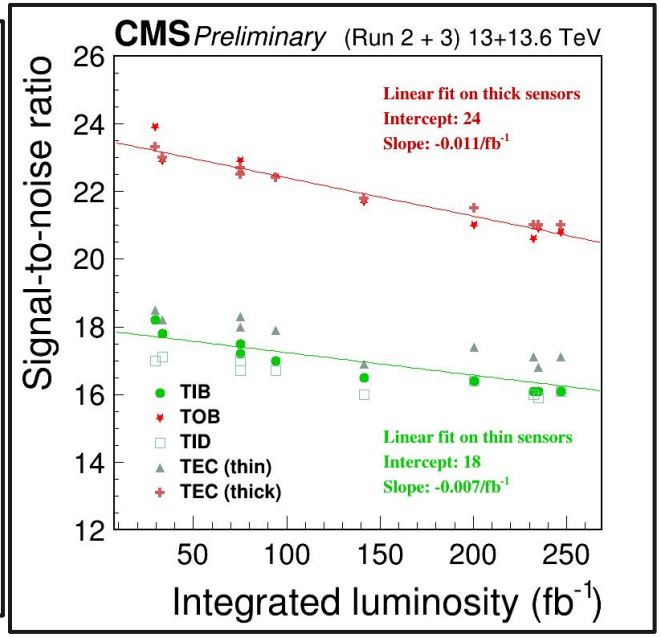


- Knowledge of bad components crucial for tracking
- **Fraction of active channels during Run 3 ~ 96** %
  - Similar to Run 2.
- The drop in TEC is related to recovery of uncooled modules

Strips - Signal over Noise

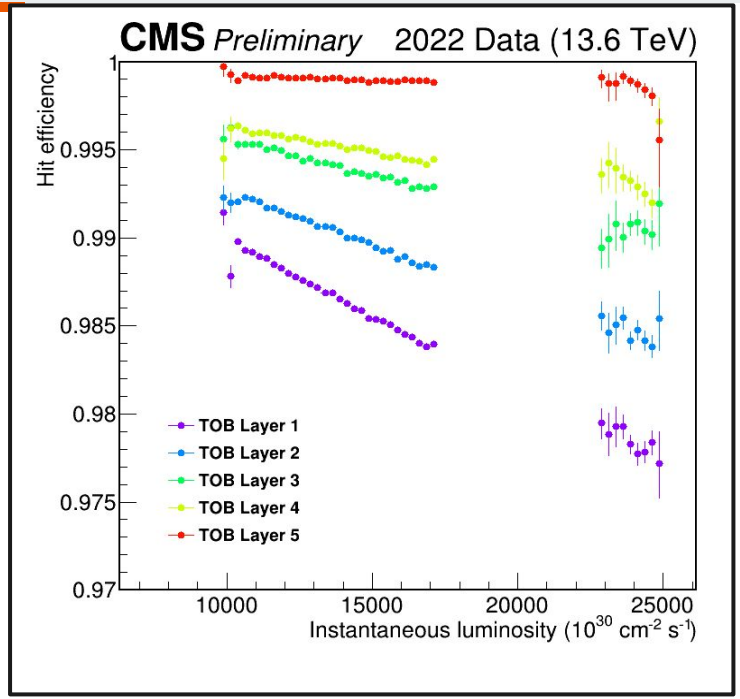


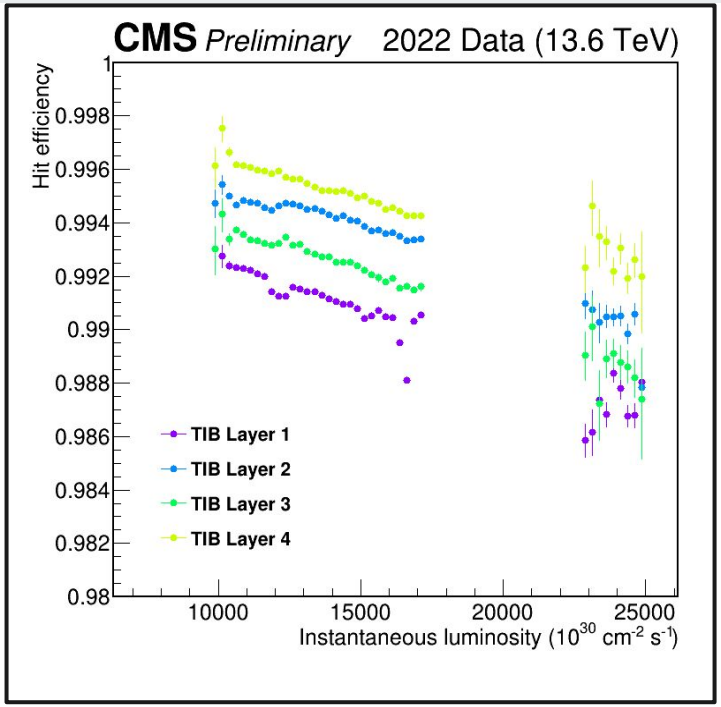




- **Signal Over Noise** for a run taken in 2023 (left)
- **High S/N** means better **zero suppression** and **cluster building**.
- As expected, a decrease is observed with time (center).
- Expected S/N ratio at the end of Run 3 (~500/fb).
  - Thin sensor - 14.5
  - Thick sensor - 18.5.

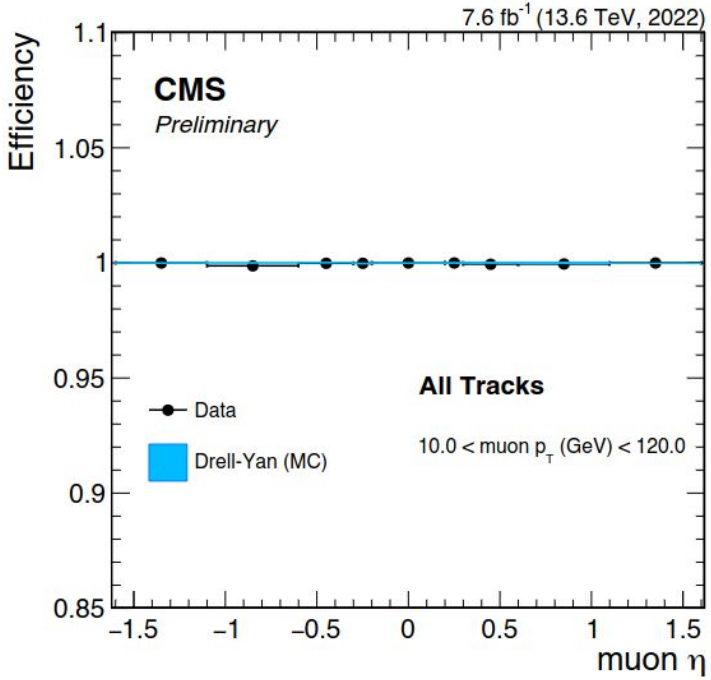
Strips - Hit efficiency

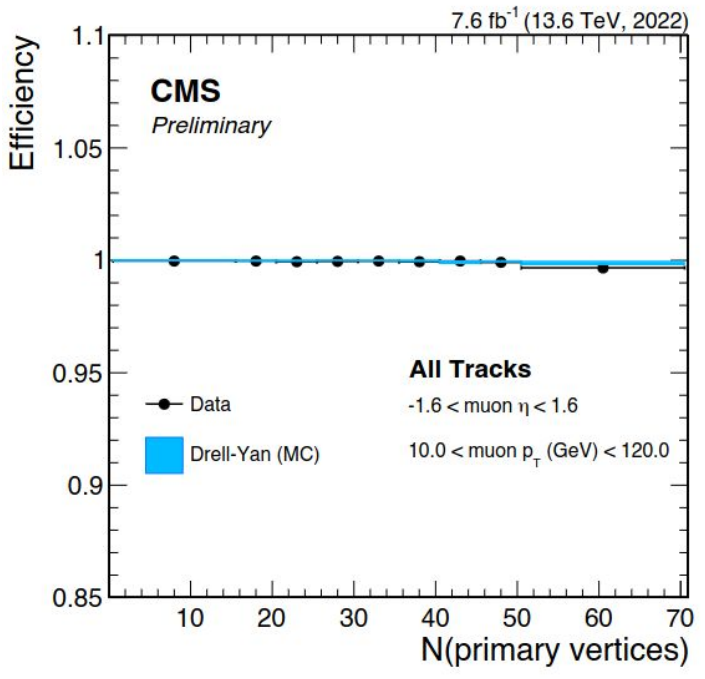




- Hit efficiency vs instantaneous
- Data used from a normal/very high lumi fills to compute hit efficiency..
- Hit Efficiency in
  - **TOB**: > **97. 5%**, **TIB**: > **98. 5%**
- Run 2 eff at **1.8 E 34 cm^{-2} s^{-1}**
  - **TOB: > 98%, TIB: > 99%**

Tracking performance





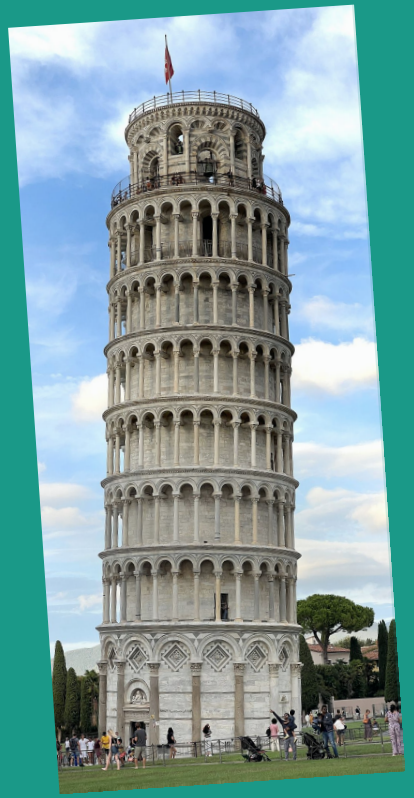
- Efficiencies are calculated using the tag-and-probe method exploiting the Z -> μμ decays
- Data used from early Run 3. Excellent tracking performance is observed.
- Efficiency is stable as a function of muon η (left) & number of primary vertices (right)

Conclusion

- The CMS Tracker operational since the beginning of Run 3 and took part in all periods of pp collision data taking
- Detector in good condition
  - Continuous monitoring
  - Calibrations
- Successful performance in data collection with proton-proton collisions with inst. lumi up to 2.1 x 10^{34} $cm^{-2}s^{-1}$, L1 trigger rate ~ 110 kHz.

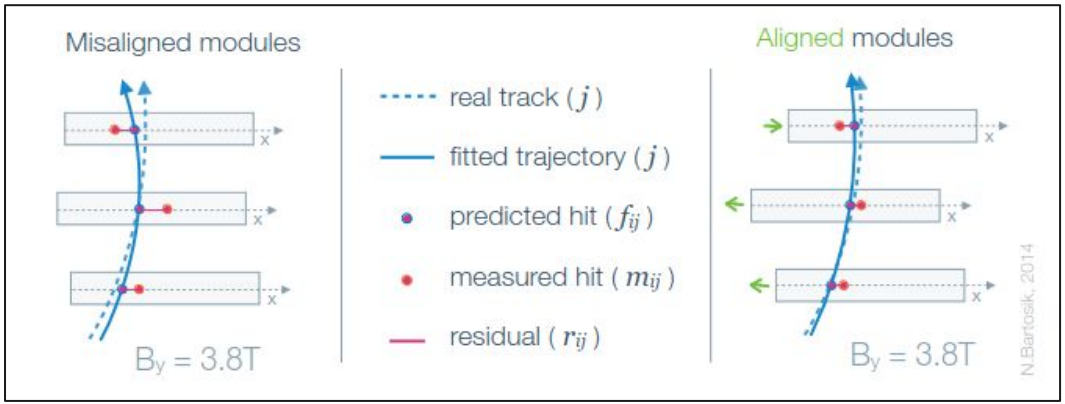
Backup

Alignment

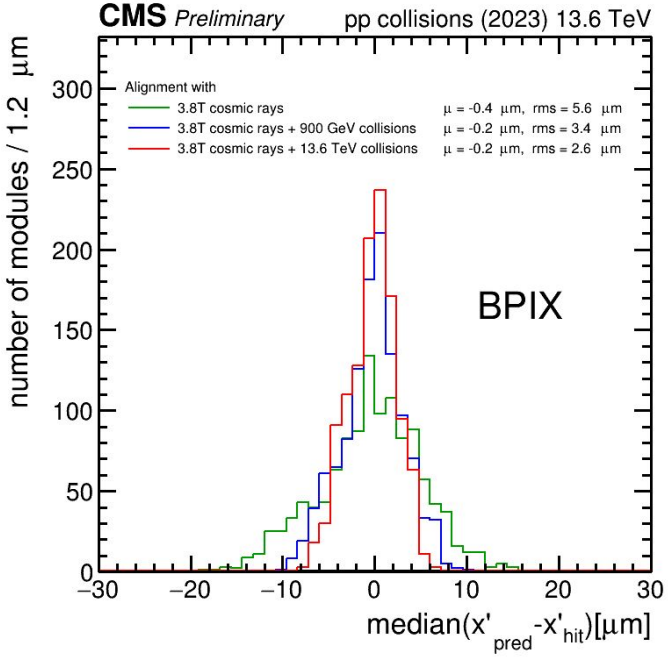


Alignment

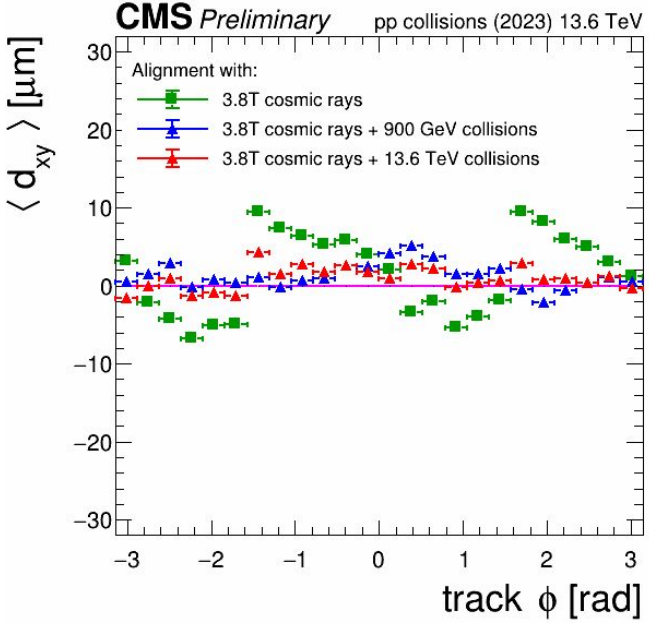
- Main aim - determine with enough precision the position and orientation of tracker modules such that the **alignment precision ~ intrinsic hit resolution** (~10 μm).
  - Minimization of track-hit residuals
- **Automated alignment - prompt alignment**
  - Continuous monitoring of tracker high level structures
  - System in place to correct the geometry as soon as movement increases above certain thresholds
  - Similar precision (compared to offline) can be achieved in a short amount of time (put plot in backup)
- **Offline alignment**
  - track-based alignment run offline for refinement of online calibration,
  - uses increased track kinematic variety and statistics
  - Higher granularity



Alignment observables



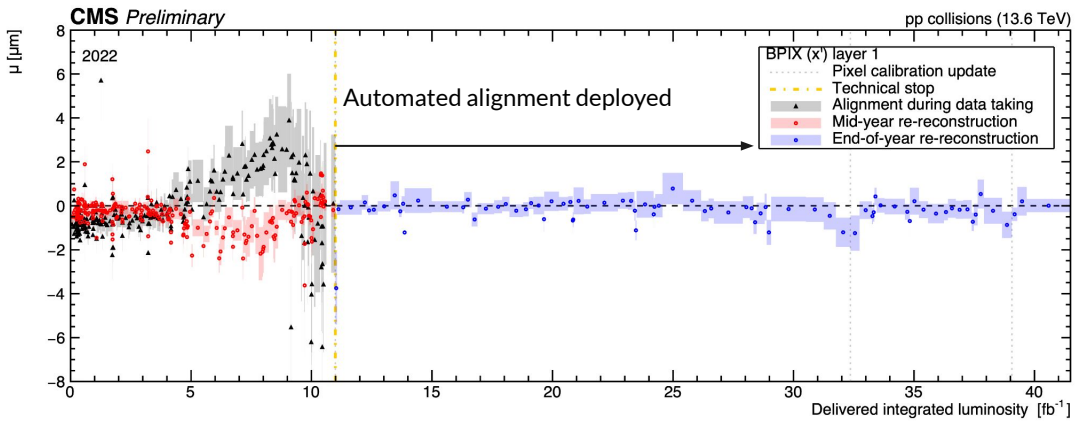
- **Median residual in X** - The width of this distribution of the **median of residuals (DMR)** constitutes a measure of the local precision of the alignment results - **deviations from zero** indicate possible biases.

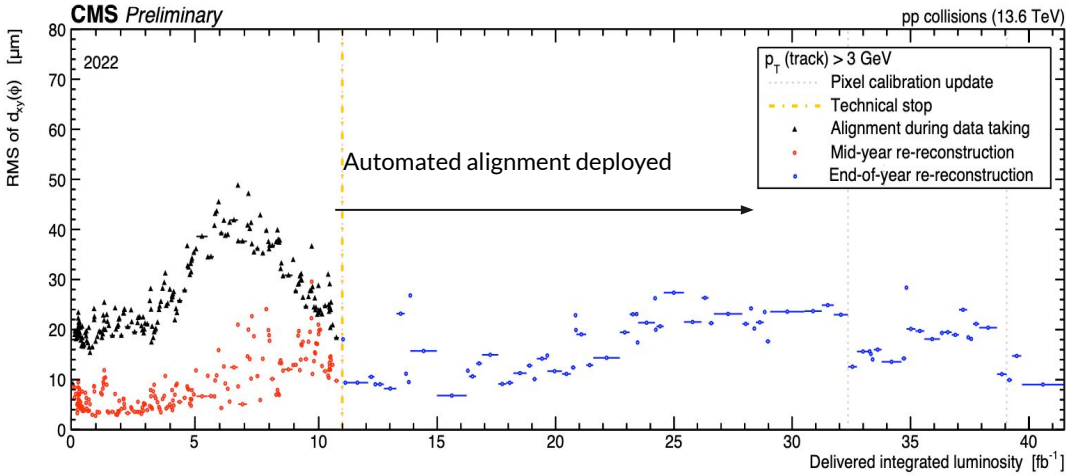


- PV are first refitted removing the track under scrutiny
- Performance improves with higher statistics

- **Primary vertex validation**- distributions of track-vertex residuals (impact parameters)
- Indicates possible bias in Pixel
- Perfect alignment ⇨ flat distribution around 0.

Alignment - trends

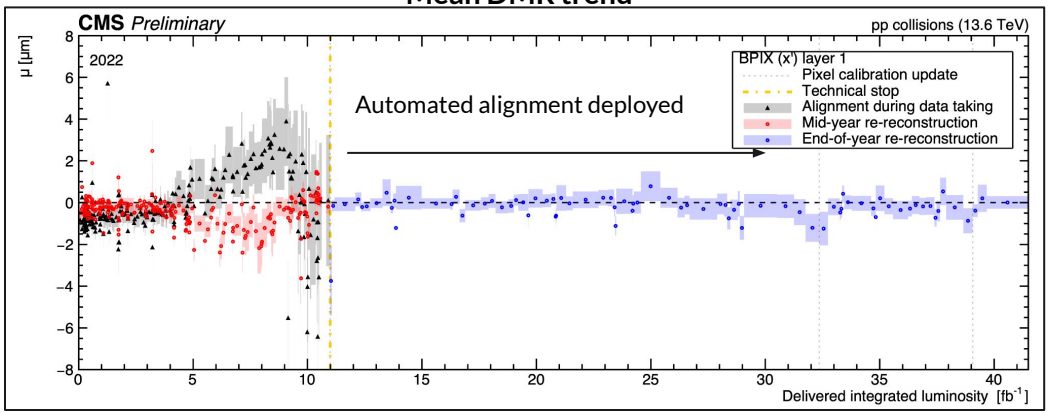




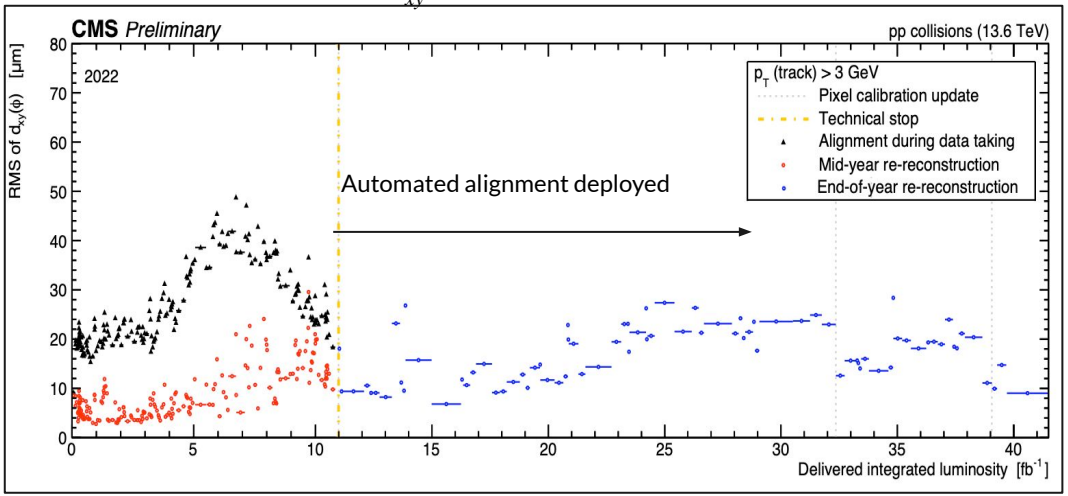
- **Black**: automated (online) Low Granularity alignment (high level structures)
- **Red**: refined offline + High Granularity automated alignment (last 2 fb^{-1} before Technical stop)
- **Blue**: High Granularity alignment for remaining 30 fb^{-1} of 2022 (level of ladders and panels)

Alignment - trends

Mean DMR trend



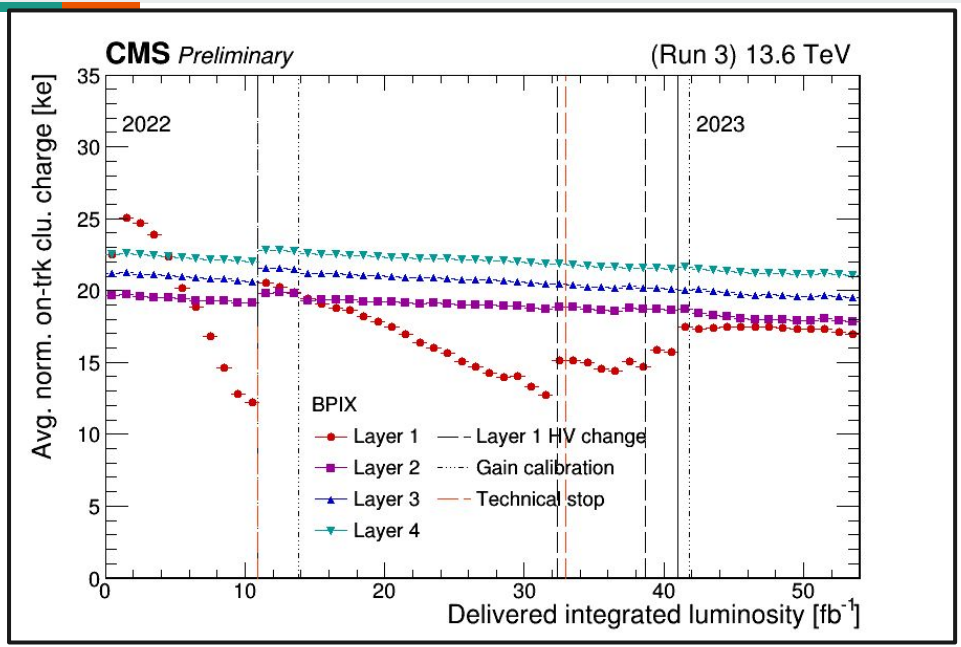
RMS of the average d_{xy} in bins of the track azimuth

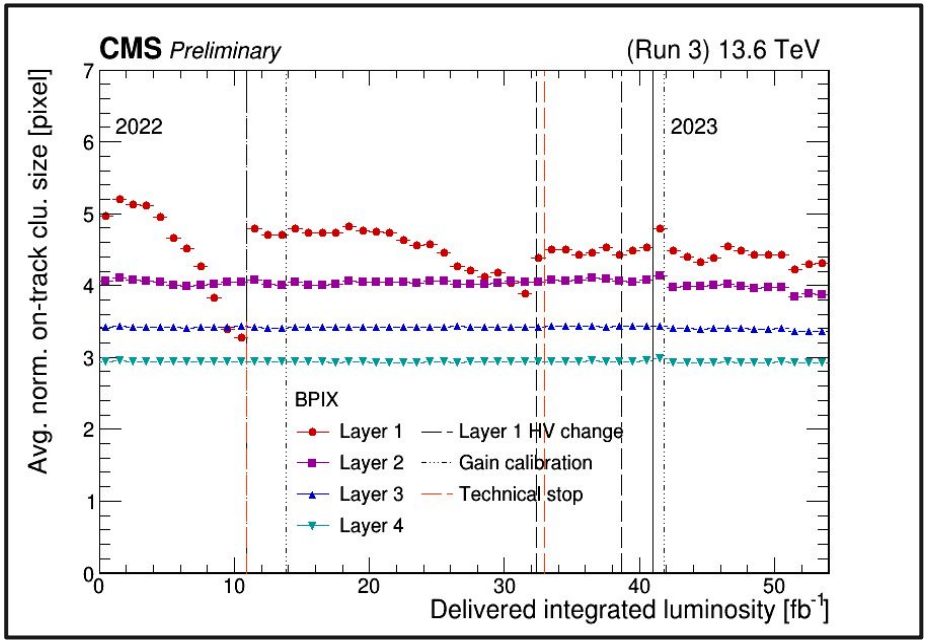


- **Black**: automated (online) Low Granularity alignment (high level structures)
- **Red**: refined offline + High Granularity automated alignment (last 2 fb^{-1} before Technical stop)
- **Blue**: High Granularity alignment for remaining 30 fb^{-1} of 2022 (level of ladders and panels)

- Good stability of trends after deploying automated alignment
- Comparable physics performance achieved by the automated alignment

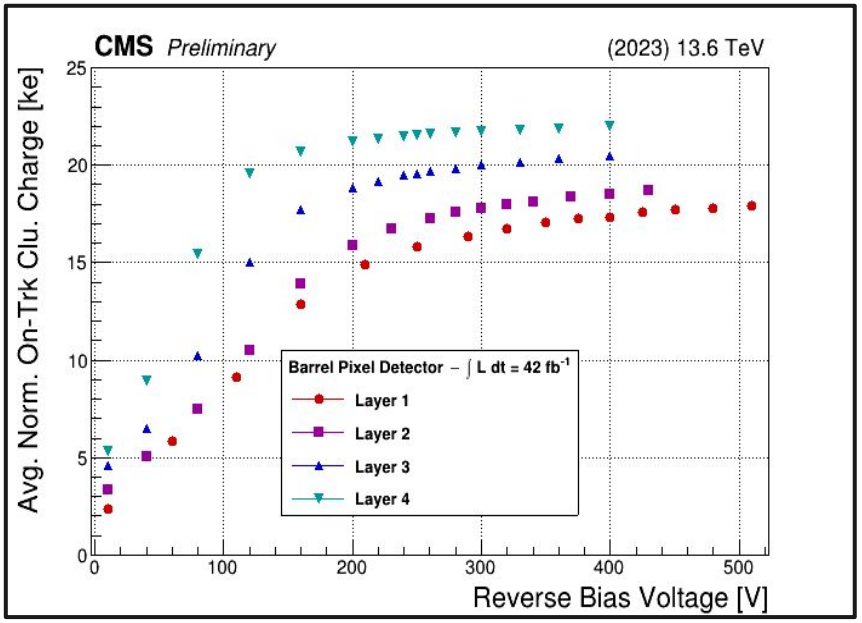
Pixel Cluster properties - Charge & size

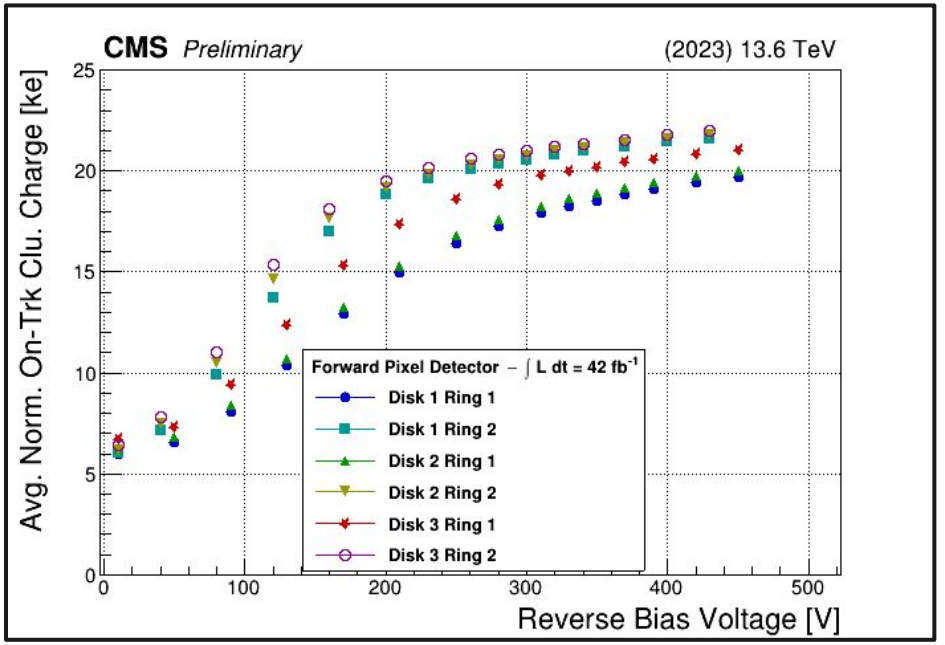




- Trend of on-track cluster charge (left) and size (right) in BPix
- Trend shows degradation of performance due to radiation - esp in the BPix L1 which is ~ 3 cm away from beam-pipe
  - To cope with irradiation, the HV of L1 was raised - after which a recovery can be seen
  - Effects of beneficial annealing during technical stops are also seen.
- Regular bias scans are done during data taking to determine the best operating point of the detectors in various layers (more crucial for Layer 1).

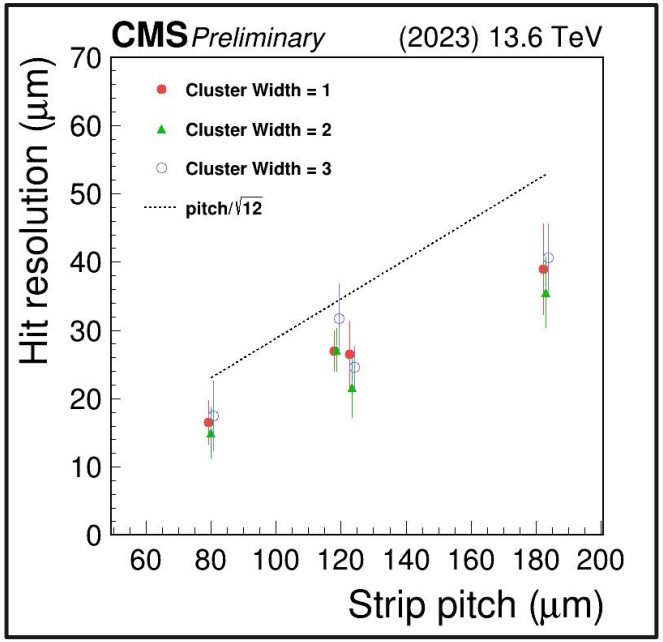
Cluster properties - Bias scans





- Several Bias scans performed throughout the year
- Plots show the results of bias scans performed after an integrated lumi of 42 /fb during Run 3
- Current operating points
  - BPix: 400 V in Layer 1, 300 V in Layer 2 and 250 V in Layer 3 & 4
  - FPix: 350 V in Ring 1 and 300 V in Ring 2

Hit resolution



- The strip hit resolution is computed by using hits in overlapping modules of the same layer ("pair method").