FLORIDA STATE UNIVERSITY

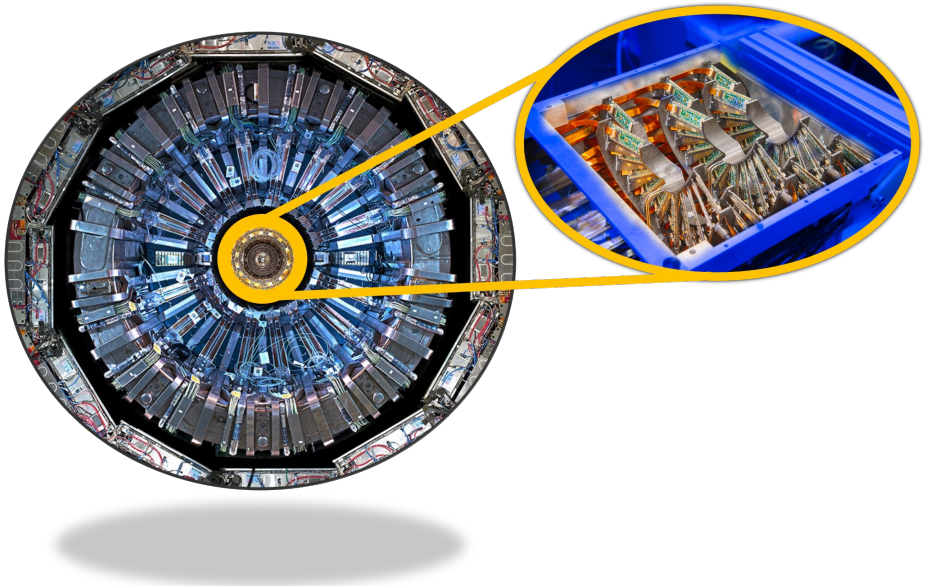
Operation and Performance of the CMS Pixel Detector

Steffi Bower (She/Her)

On Behalf of the CMS Collaboration

PIXEL2024: 18 Nov 2024

Pixel Tracker Overview



- Innermost subdetector in the CMS Experiment
- Provides track seeds, and determines primary and secondary vertex resolution
- Composed of 120 million 100 x 150 μm^2 pixels
- 280 μm thick n+-in-n Si sensors

Detector Geometry

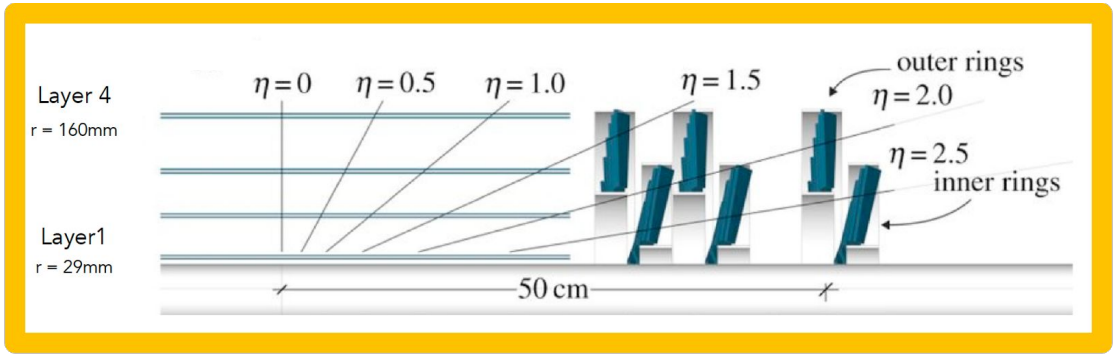
Tracker composed of 2 parts with 4 hit coverage out to |η|<3

Barrel Pixels (BPix)

0< |η| <1.5
4 layers
1184 total modules
Layer 1 was replaced during LS2

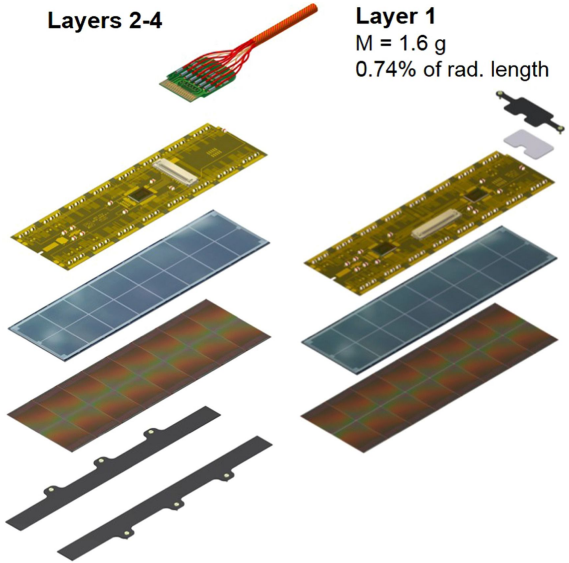
Forward Pixels (FPix)

1.5< |η| <3
3 disks × 2 rings on each end
672 total modules



Pixel Upgrades During LS 2

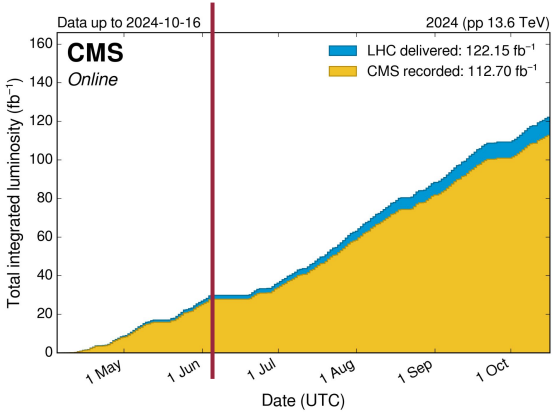
- Pixels refurbished and installed on June 2021
- Completely new Layer 1
  - New High Density Interface (HDI) with increased HV tolerance (up to 800V)
  - New readout chip
    - Reduce cross-talk
    - Decrease dynamic inefficiency
  - New Token Bit Managers (TBM)
    - Improved timing feature
    - Single Event Upset (SEU) resistance
    - New reset capabilities
- Maintenance work on Layer 2

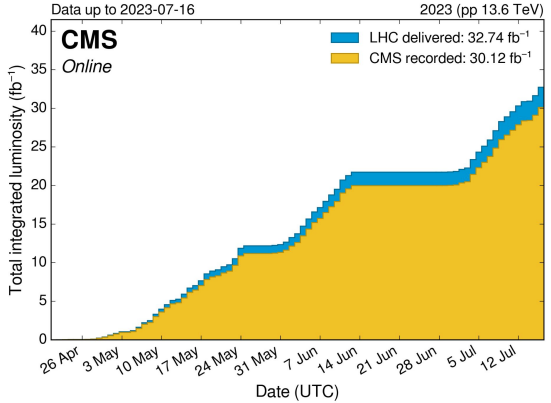


CMS Status

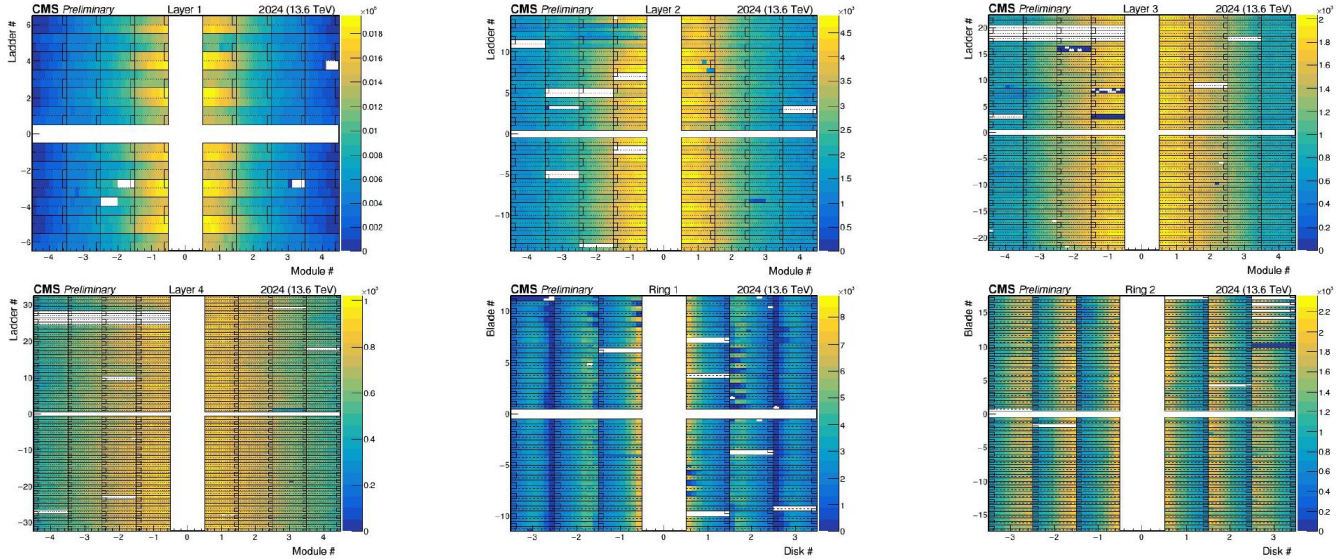
- Delivered pp lumi
  - 2023: 35 fb^{-1}
  - 2024: 122 fb^{-1}
  - 2025 projection: 120-160 fb^{-1}
- We are faced with unprecedented success in luminosity delivered and recorded
- This luminosity brings with it an intensive irradiation of our pixels and their components

Performance plots taken from June 2024





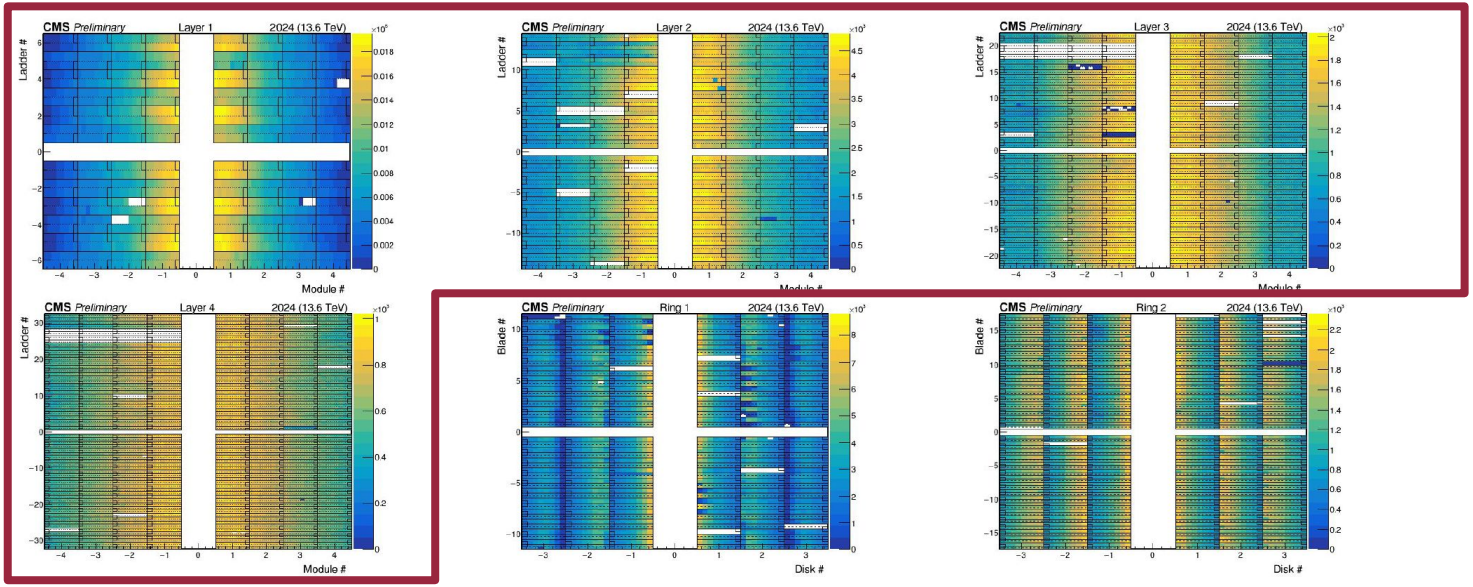
Active Detector Fraction



White sections at nonzero coordinates indicate permanently bad ROC that has been masked

ROCs with very low occupancy were *automasked* in the fill this was taken from

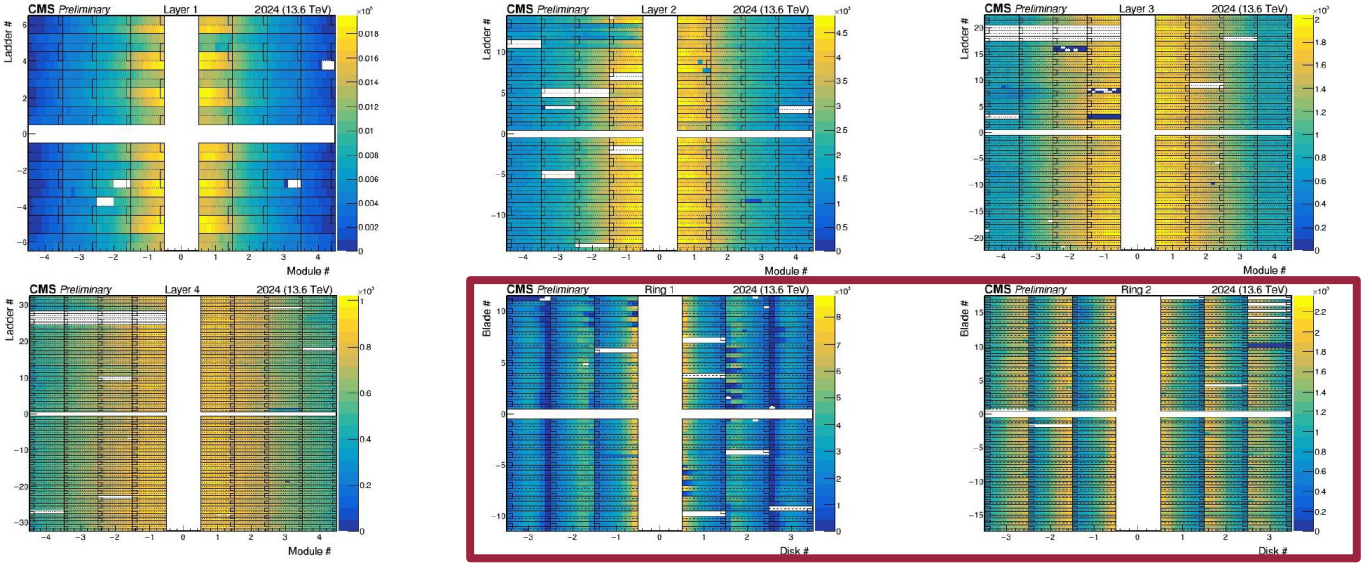
Active Detector Fraction



The on-track cluster occupancy maps for BPIX and FPIX detectors during 2024 data taking.

- Percentage of the non-functional ROCs masked at the detector level amounts to 3.2%:
  - BPIX: 96.1% Active (3.9% Masked)

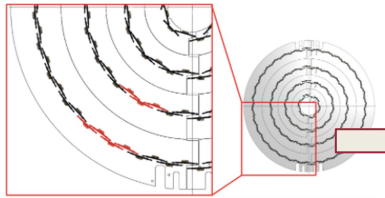
Active Detector Fraction

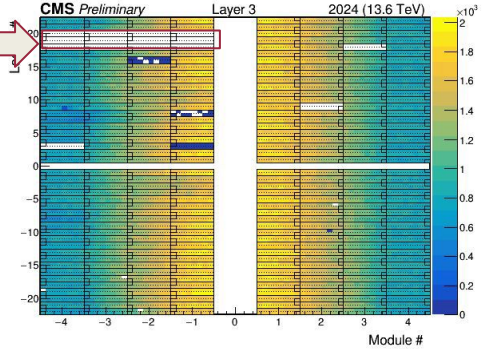


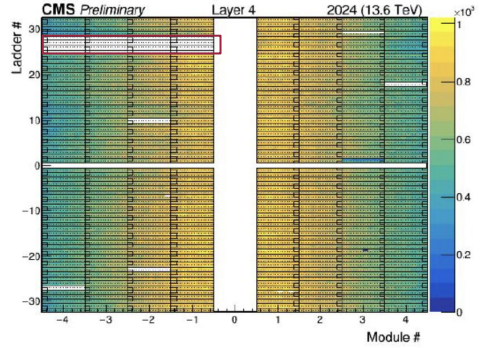
The on-track cluster occupancy maps for BPIX and FPIX detectors during 2024 data taking.

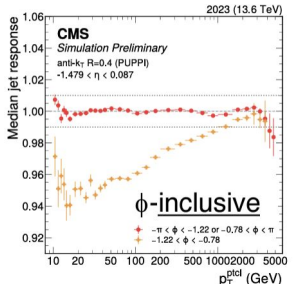
- Percentage of the non-functional ROCs masked at the detector level amounts to 3.2%:
  - FPIX: 97.2% Active (2.2% Masked)

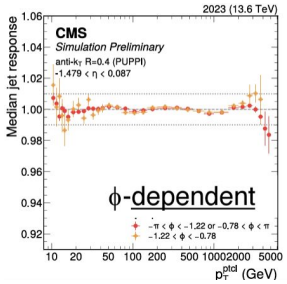
BPix BMI Sector 7











After TS 1 of 2023 (June 19-24), communication to 27 modules in the BPIX L3 and L4 was lost

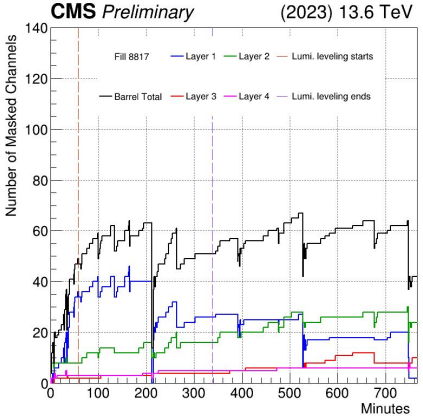
- Quartz Phase Locked Loop (QPLL) for this Readout Group is unable to lock to the LHC clock
- These modules have been masked and turned off
- 0.4 radians (~23 degrees) in phi at negative pseudo-rapidity

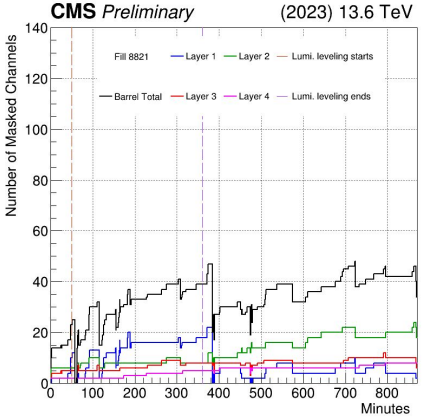
Offline Recovery:

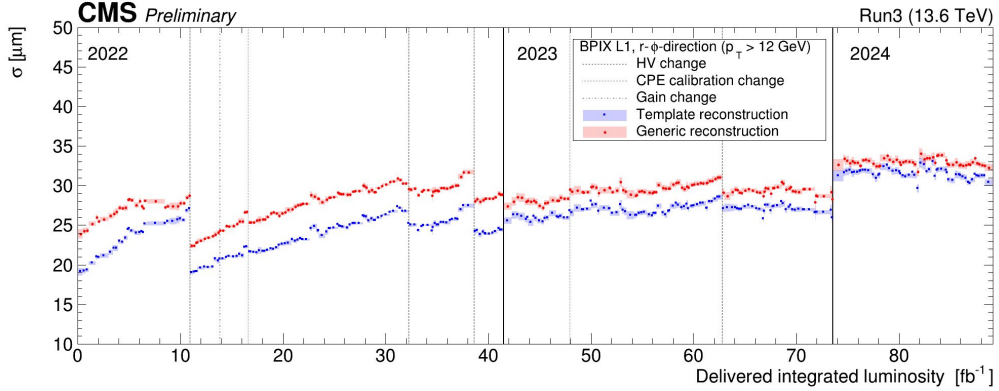
- Example: Applying a ϕ-η dependant correction to compensate from Track inefficiency and Jet energy scale shows efficacy
- An additional tracking sequence has been included in order to recover the HLT tracking efficiency

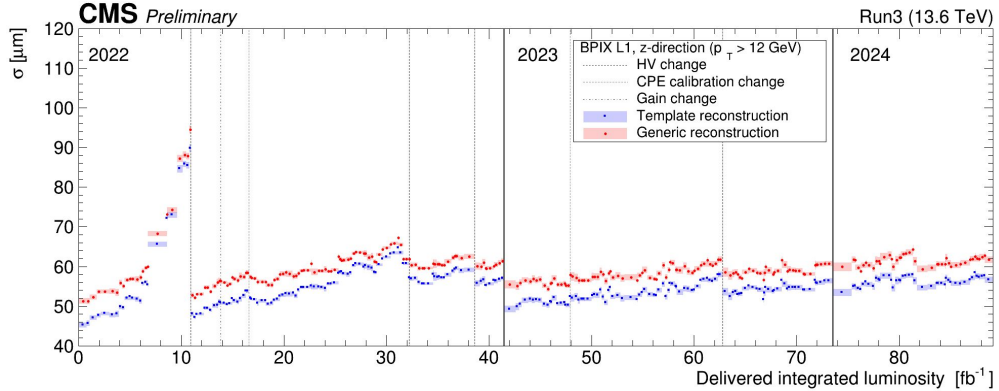
Automasking

- Channels masked during data taking due to repeated readout errors
- In 2022 we began to notice a stark accumulation of automasked channel particularly in the newly replaced layer 1
- Most effective recovery action was to adjust the clock phases within the TBM
- Frequently automasked channels continue to arise over the course of Run 3
  - Cause to be understood
  - Correlated with pileup





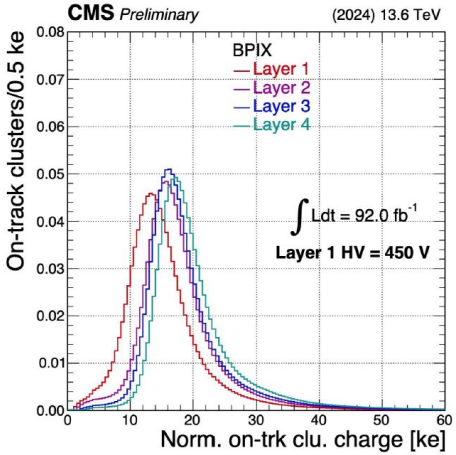


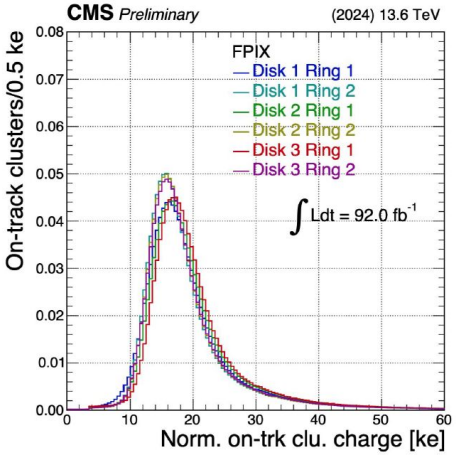


Residuals

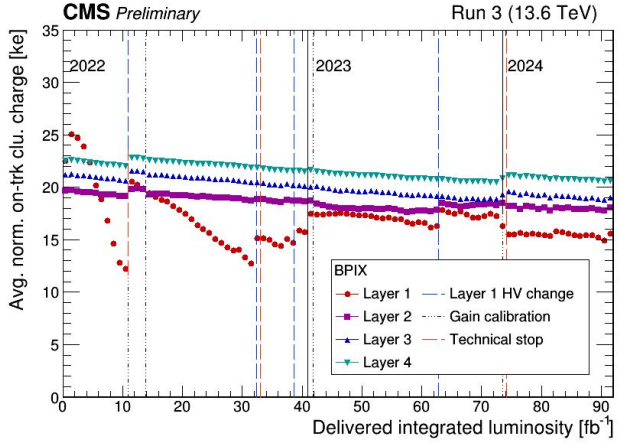
- Triplet method is used
- Positional resolution remains excellent and consistent
- Aligns well with predictions for evolution

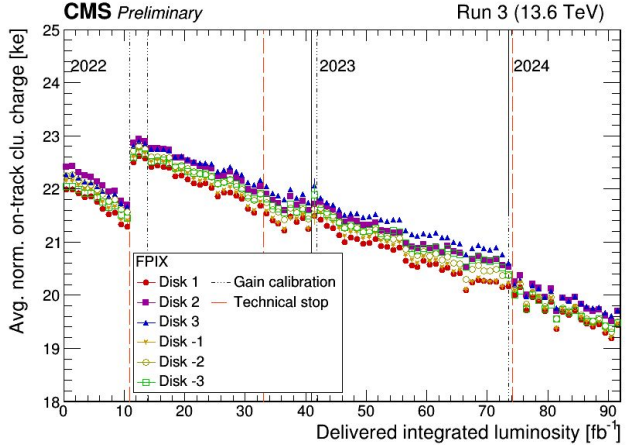
Cluster Charge





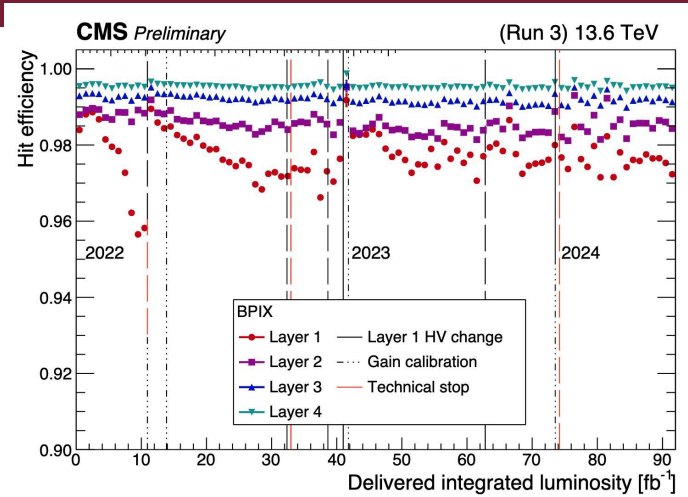
- Cluster charge normalized by incident angle
- Attached to a track of p_T>1 GeV
- Charge collection is consistent across the detector

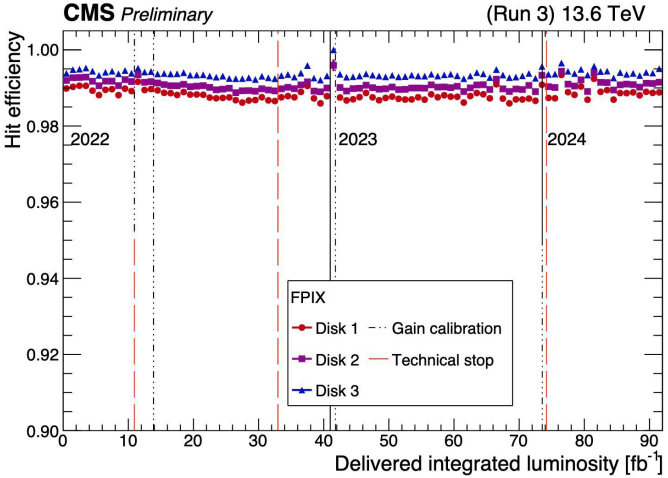




Hit Efficiency

- Probability to find any cluster within 1 mm of an expected hit
  - Measured using muon tracks with p_T>2 GeV
- Hit Efficiency remains excellent
- Primarily influenced by
  - Radiation damage
  - Annealing during technical stops
  - Gain calibrations
  - HV bias changes





HV Bias Scan

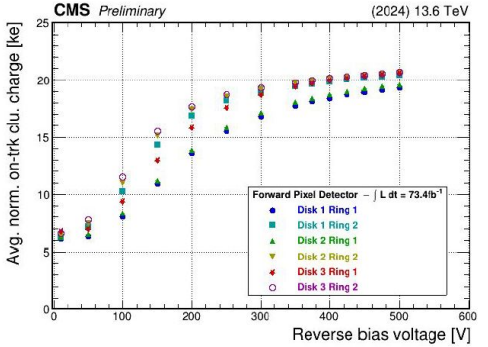
Bias voltage scans help us monitor effects of radiation on Si Bulk

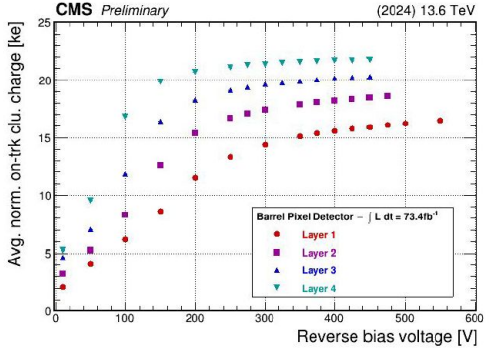
- Scan over bias voltage and adjust values to ensure we are maximizing charge collection

Current Settings

FPix
Ring 1:400V
Ring 2:350V

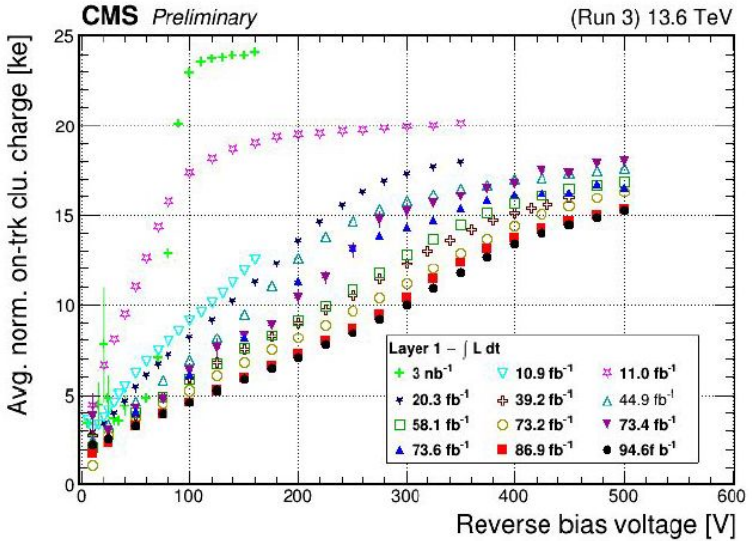
BPix
Layer 1: 450V
Layer 2: 350V
Layer 3-4: 250V





Layer 1 Irradiation

- The new BPix layer 1 evolves rapidly
- We began with HV=150V and have since increased it to 450V*

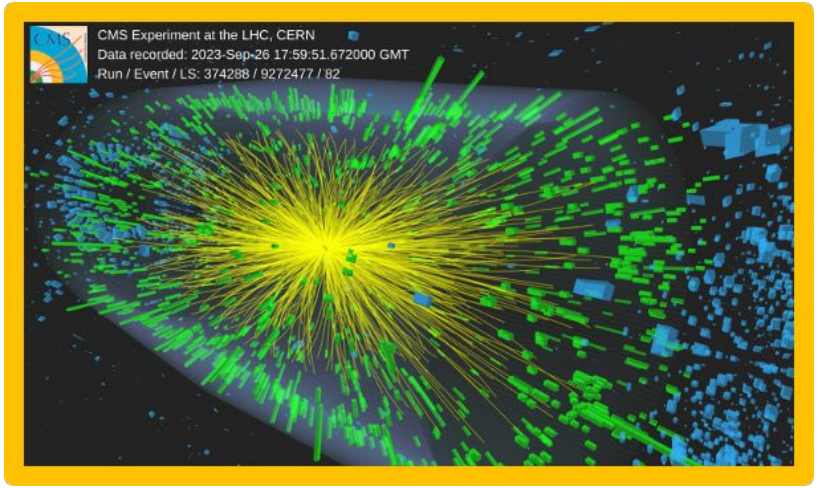


*At the time of plotting. The level has since been raised to 550V

Heavy Ions

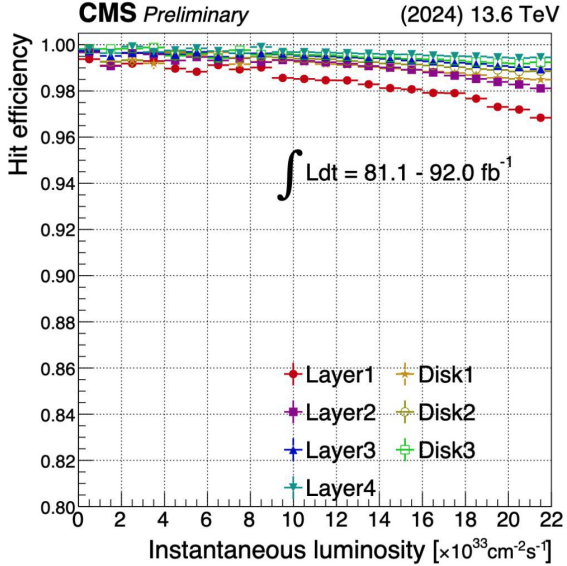
Pixels performing well during heavy ion collisions

- Buffers increased to allow for larger event sizes in readout
- Low luminosity leads to virtually no SEUs



Outlook and Summary

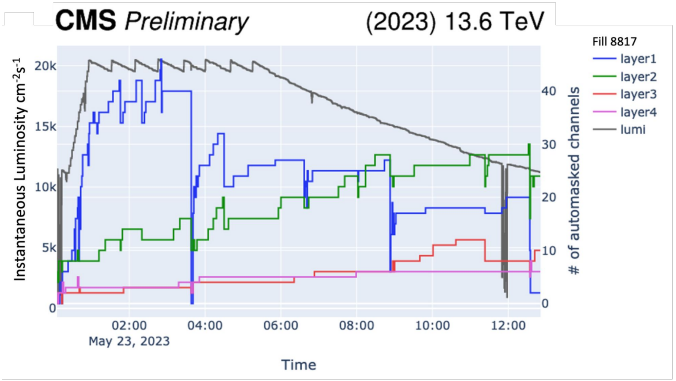
- Pixel data quality and performance remains excellent
- We are prepared for the extent of Run 3



Backup

Automasked Channels

- Right number of automasked channel over time with inst. Lumi



Triplet method

Disk hit residuals measurement: ▪ Triplet method ▪ pT > 4 GeV tracks with hits in 3 disks are selected and refitted using hits in

Disks 1 and 3.

▪ Trajectory extrapolated to the disk 2, residuals with the actual hit are calculated

▪ Residual distribution fitted with the Student-t function

▪ Residual offset (mean) and resolution are obtained from the fit

▪ Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated

Reconstruction:

▪ Positions are reconstructed with two algorithms: generic and template

Barrel hit residuals measurement:

▪ Triplet method:

▪ pT > 12 GeV tracks with hits in 3 layers are selected and refitted using hits in two of three layers.

▪ Trajectory extrapolated to remaining layer, residuals with the actual hit are calculated

▪ Residual distribution fitted with the Student-t function

▪ Residual offset (mean) and resolution are obtained from the fit

▪ Triplets considered:

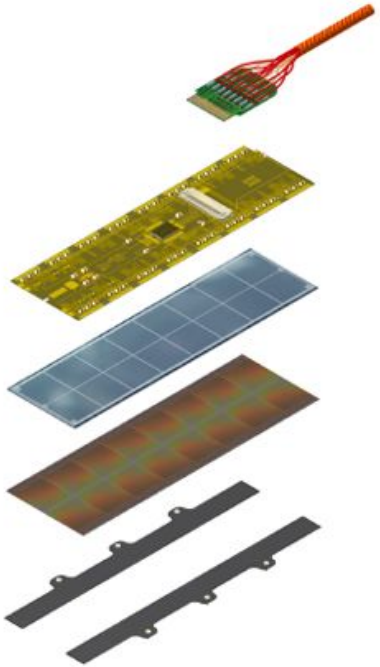
▪ L3: propagate from hits on L2 and L4

▪ Integrated delivered luminosity since the beginning of Run 3 until the data-taking run used to produce the figures is indicated

Rec

Positions are reconstructed with two algorithms:
▪ Generic: a simple algorithm based on track position and angle [2]. Used in our High Level Triggers (HLT) and early track iterations offline.
▪ Template: an algorithm based on detailed cluster shape simulations predicted by PixelAv [3][4]. Used in the final fit of each track in the offline reconstruction.

Module design



Signal and power cables

Token bit manager (TBM) chip
- Receives clock, level 1 trigger accept, configuration data
- Orchestrates readout
- 2 TBM/module in layer 1

Silicon sensor
- (150x100) μm^2
- 280 μm n-in-n

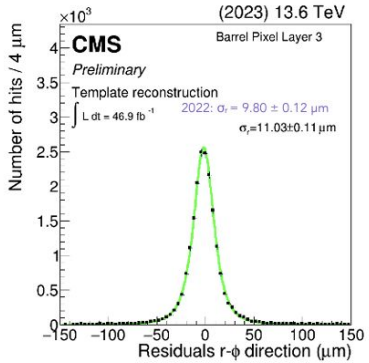
Read out chips

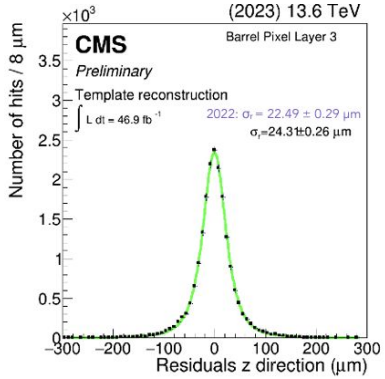
PSI46dig
- Digital readout
- Double column drain
- > 90% efficiency up to 200MHz/cm^2 hit rate

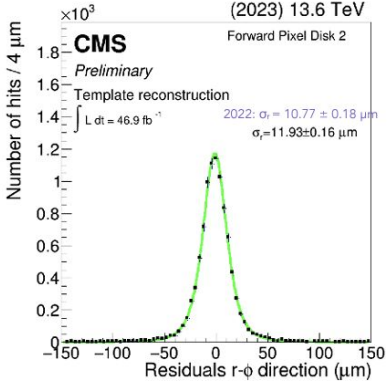
PROC600
- Specialized for layer 1
- Dynamic cluster drain
- > 90% efficiency up to 600MHz/cm^2 hit rate

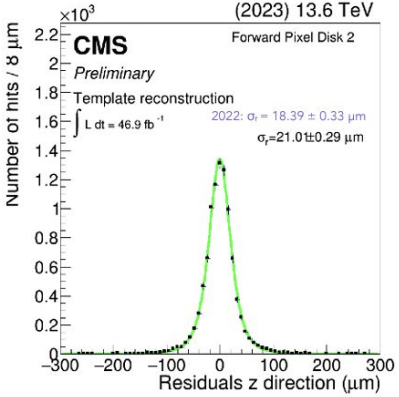
Base strip

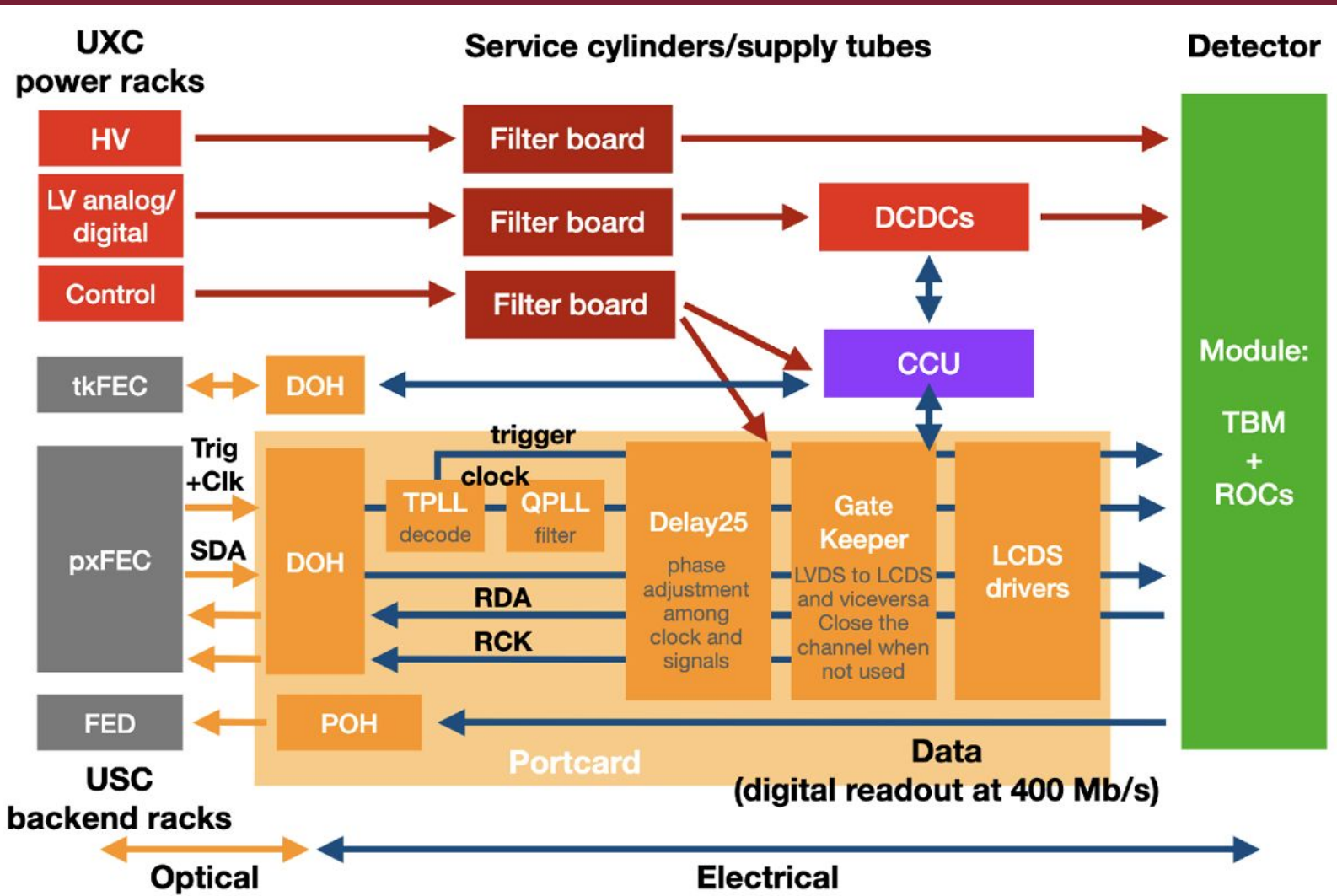
Historic Residuals










UXC
power racks
Service cylinders/supply tubes
Detector
HV
LV analog/
digital
Control
Filter board
Filter board
Filter board
DCDCs
CCU
tkFEC
DOH
Module:
TBM
+
ROCs
trigger
clock
Trig
+Clk
SDA
pxFEC
DOH
TPLL
decode
QPLL
filter
Delay25
phase
adjustment
among
clock and
signals
Gate
Keeper
LVDS to LCDS
and viceversa
Close the
channel when
not used
LCDS
drivers
RDA
RCK
FED
POH
Portcard
Data
(digital readout at 400 Mb/s)
USC
backend racks
Optical
Electrical

Hi girls, please let me know when you have time for an extra practice talk today?

Tracking performance: Point of closest approach

Before and after issue in BPix Sector 7 Layers 3 and 4

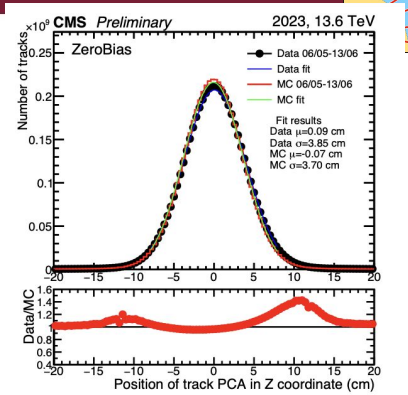
➡ Good data and MC agreement

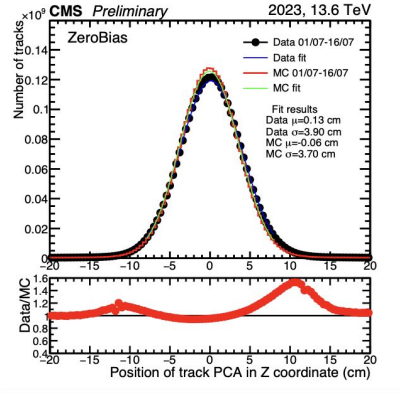
➡ Z coordinate is wrt pixel detector barycenter

➡ Simulation set to approx. match position of beam in data wrt pixel barycenter

➡ MC distributions narrower and a single Gaussian

➡ Spread of Z coordinate in data distributions affected by lumi leveling





Doublet Method

- Reco technique under BPix BMI Sector 7
- Initial issue caused a loss in HLT tracking efficiency of about 40%.
  - Additional sequence added to
- Tracks seeded by doublets
  - To prevent duplicates we only use pixel hits not associared to tracks already to triplet methodethod
  - Doublets are only considered in triplet tracks underneath sector 7

New Sequene preformance