The CMS Pixel Detector for Run 3

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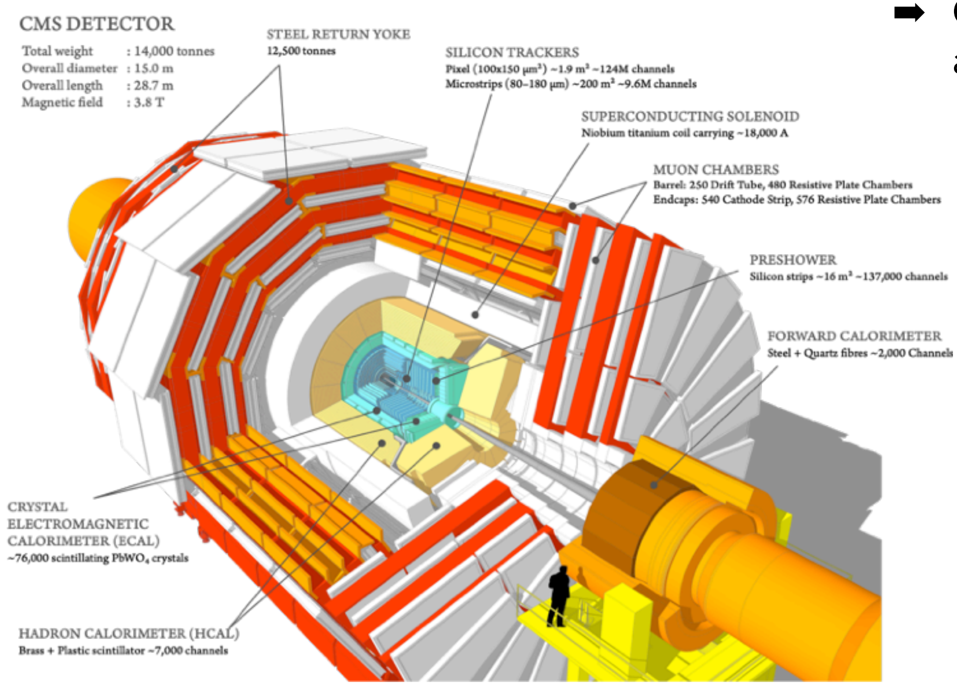
CERN Detector Seminar

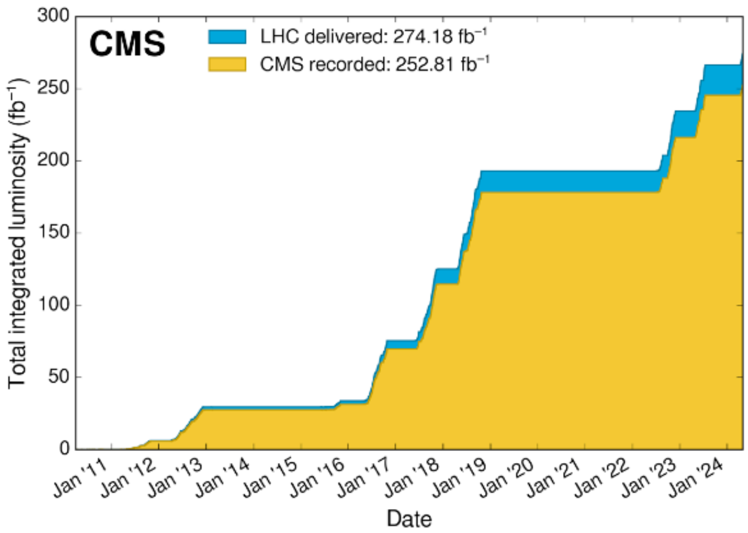
03 May 2024

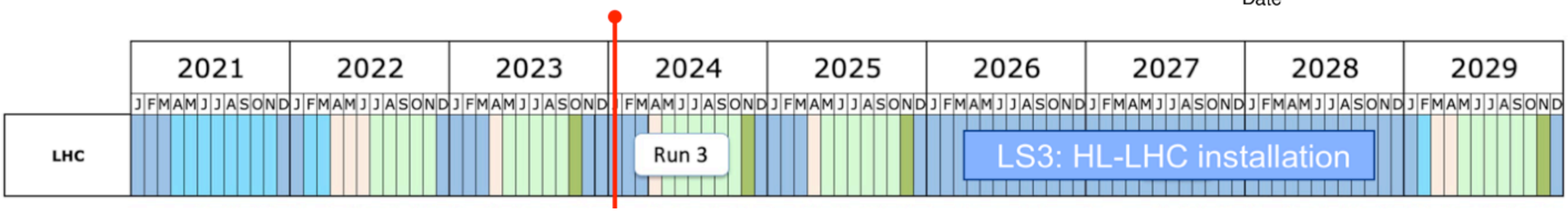
CMS for Run 3

The detector that will be with us for > 400 fb^{-1}

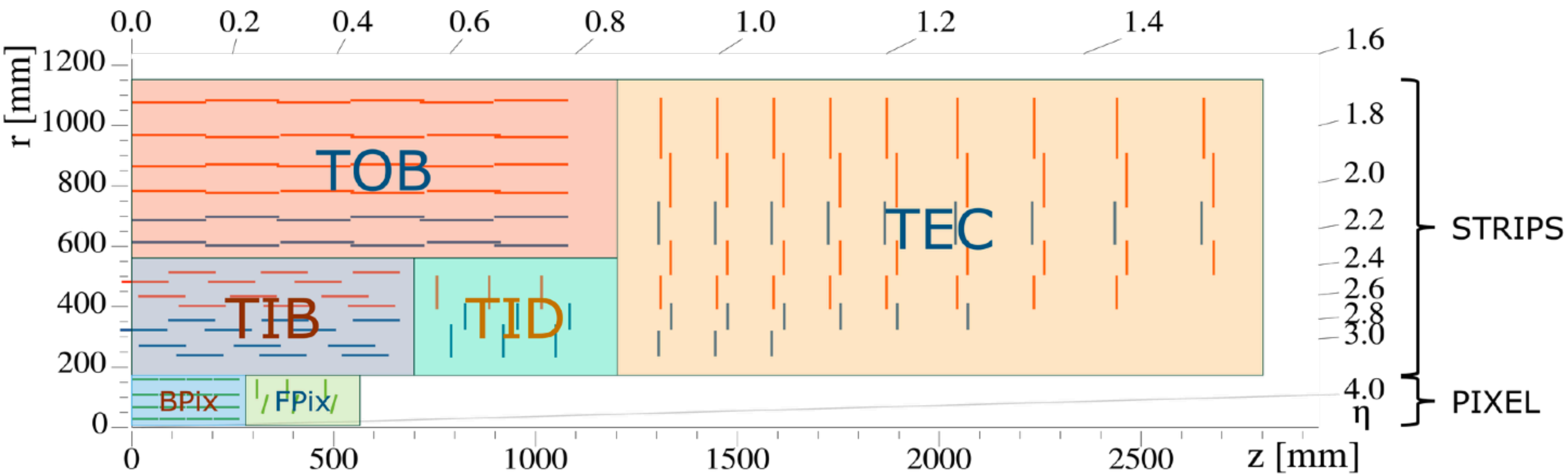
➡ Critical time ahead for data-taking before another Long Shutdown!







Tracking detectors of CMS



Silicon Pixel Tracker

➡ Barrel Pixels and Forward Pixels

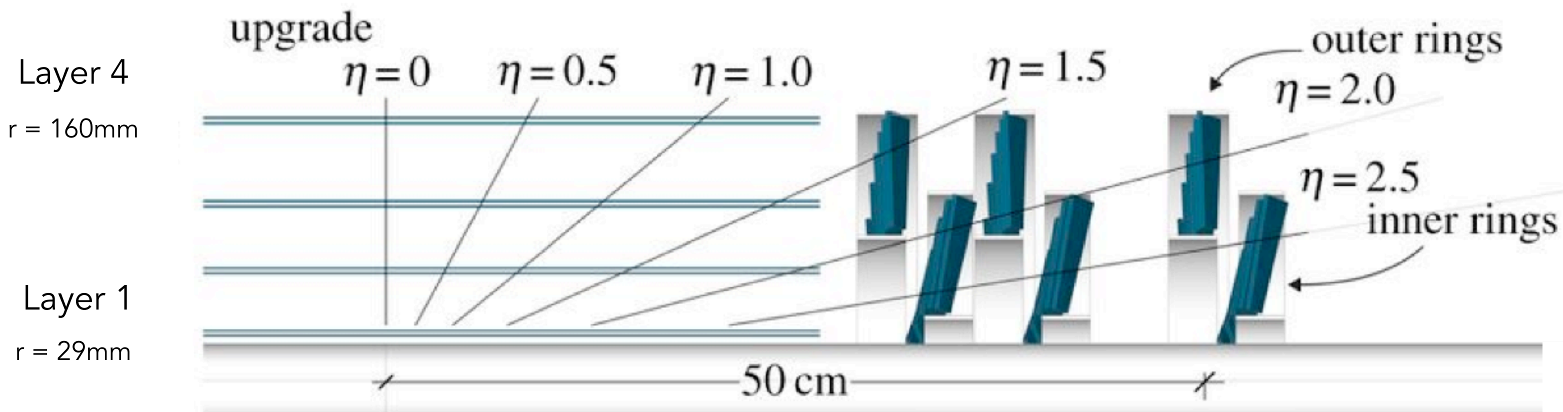
Silicon Strip Tracker

➡ Tracker Inner Barrel, Tracker Inner Disk, Tracker Outer Barrel, Tracker Endcap

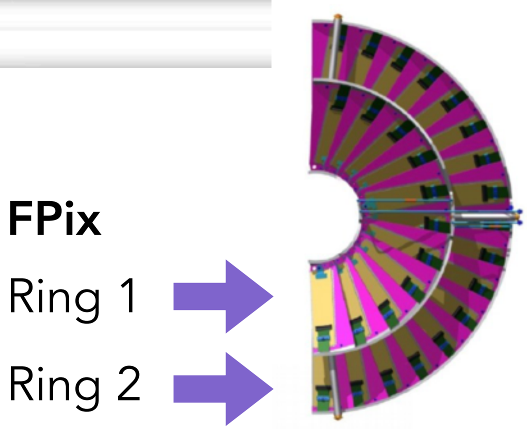
Pixel detector

Barrel pixels (BPix)
- 4 layers
- 1184 total modules

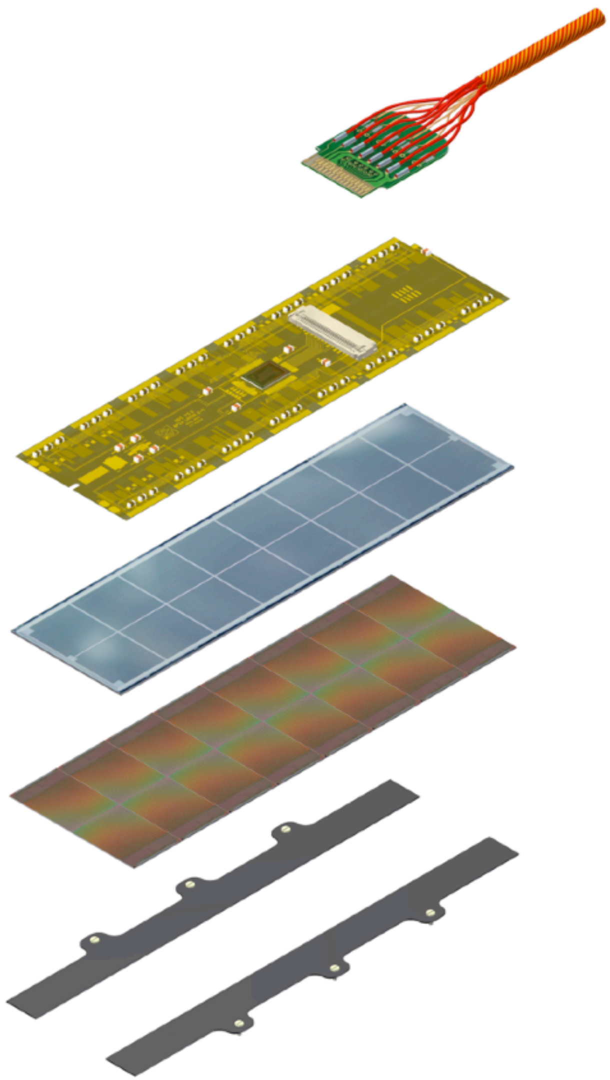
Forward pixels (FPix)
- 3 disks * 2 rings on each end
- 672 total modules



- Pixel Phase 1 installed winter 2016/2017
- 4 hit coverage up to $|\eta| < 3$



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

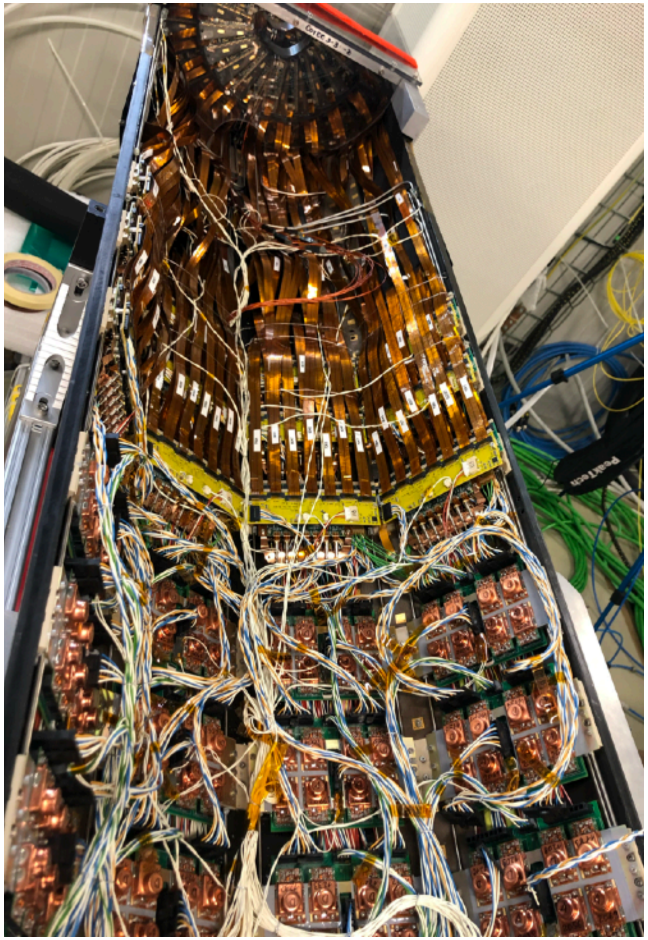
PROC600

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

Base strip

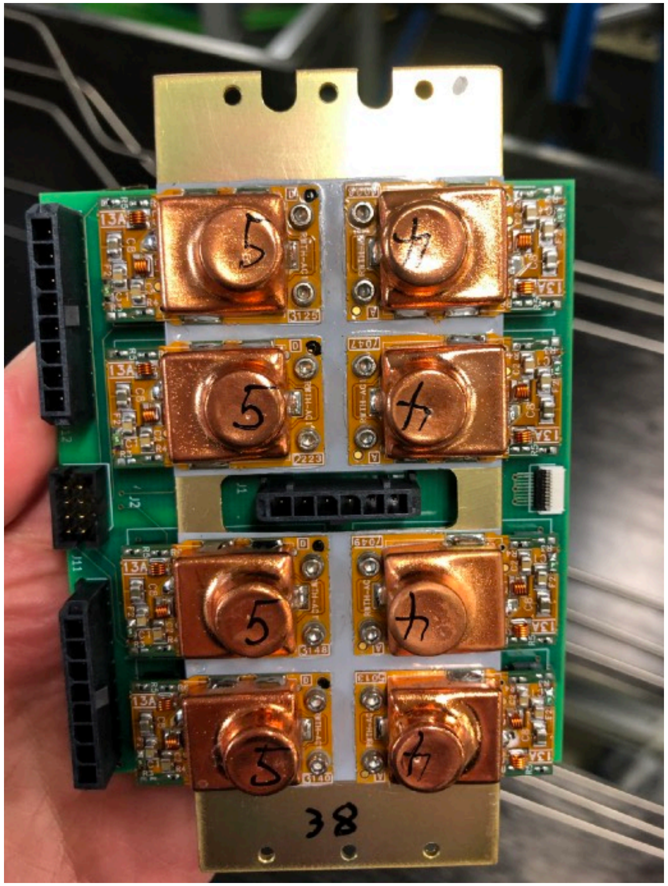
Transition from LS2 to Run 3

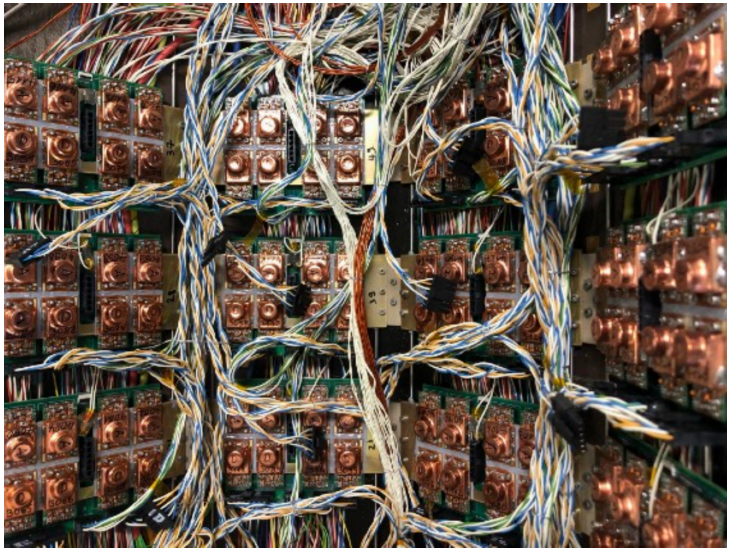
- Pixels extracted at the end of Run 2 and kept cold and dry in boxes in clean room at Point 5
- Refurbishment in Spring 2021
- Reinstallation in Summer 2021
- BPix stored in two halves and FPix stored in four quarters



New DCDC converters

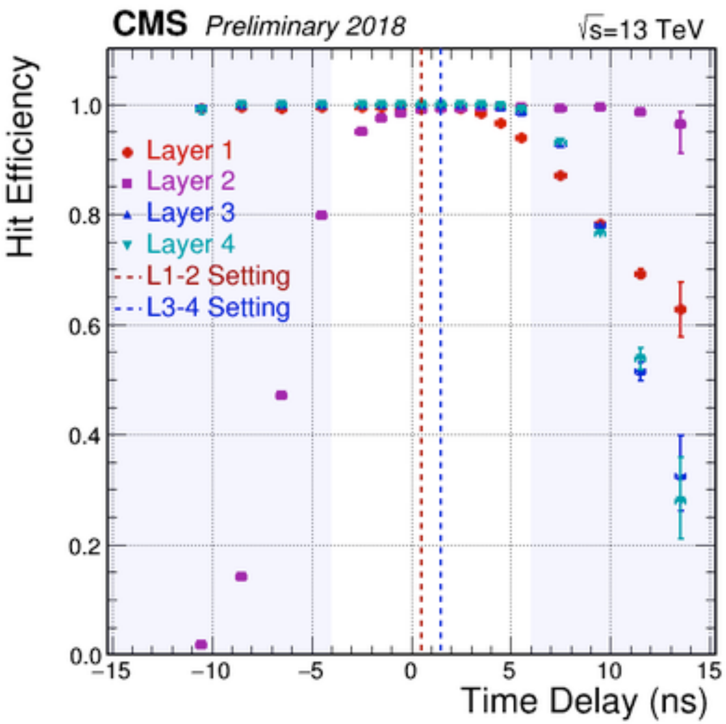
- Issue with DCDCs used in Run 2
  - ➡ Fault in FEAST chip design that led to unsafe charge buildup, breaking DCDC
  - ➡ Leakage current drained through preamplifier when ROC is not powered correctly
  - ➡ Problem only started after DCDC was irradiated
- DCDCs with new version of FEAST v2.3 chip eliminate this problem
- All DCDC converters of BPix and FPix replaced with this upgrade





BPix improvements

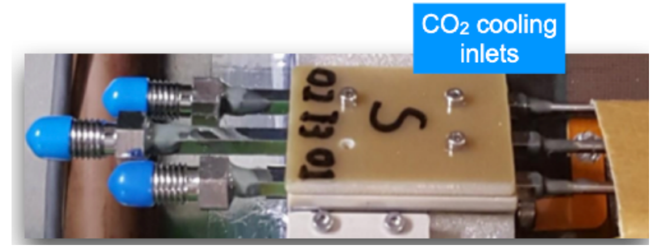
- **Completely new Layer 1** has significant improvements
  - ➡Readout chip decreased dynamic inefficiency and reduced crosstalk
  - ➡New TBM with additional delay option
  - ➡New high density interconnect for more robust HV operation
- Some (8 out of 10 damaged) Layer 2 modules replaced

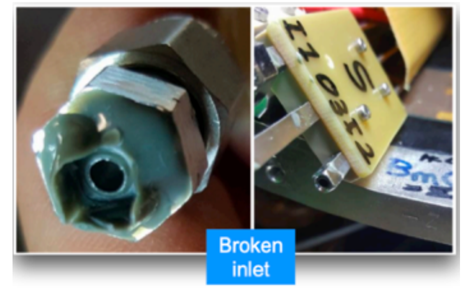


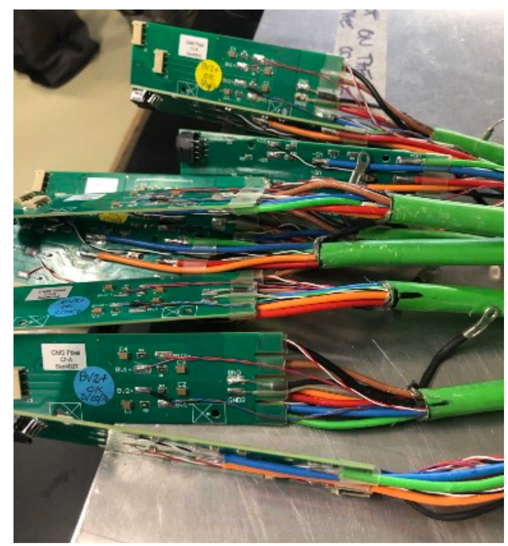
- **previous version of TBM:** compromise between Layers 1 and 2 for timing setting
- extra relative delay possible with new TBM

FPix improvements

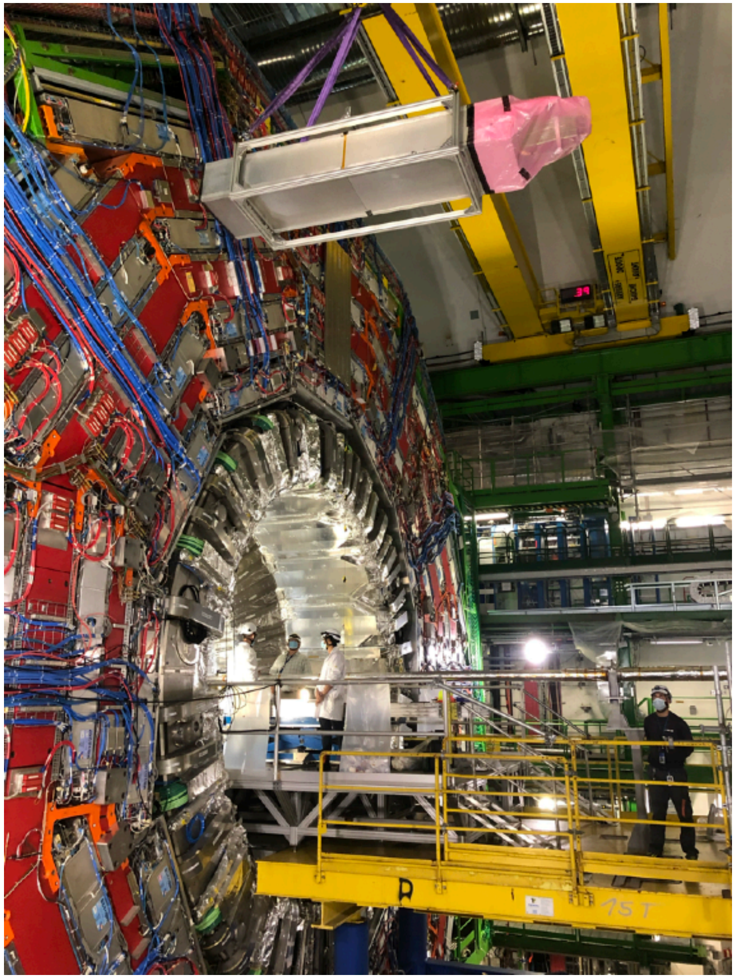
- Cooling connections
  - ➡Old version of inlet had nut directly welded to cooling pipes
  - ➡Little torque necessary to break connection
  - ➡New cooling connections made robust with rotating nut and custom fitting
- Filter boards
  - ➡Boards have 4 independent HV lines instead of 2
  - ➡Increase in HV granularity to match LV granularity



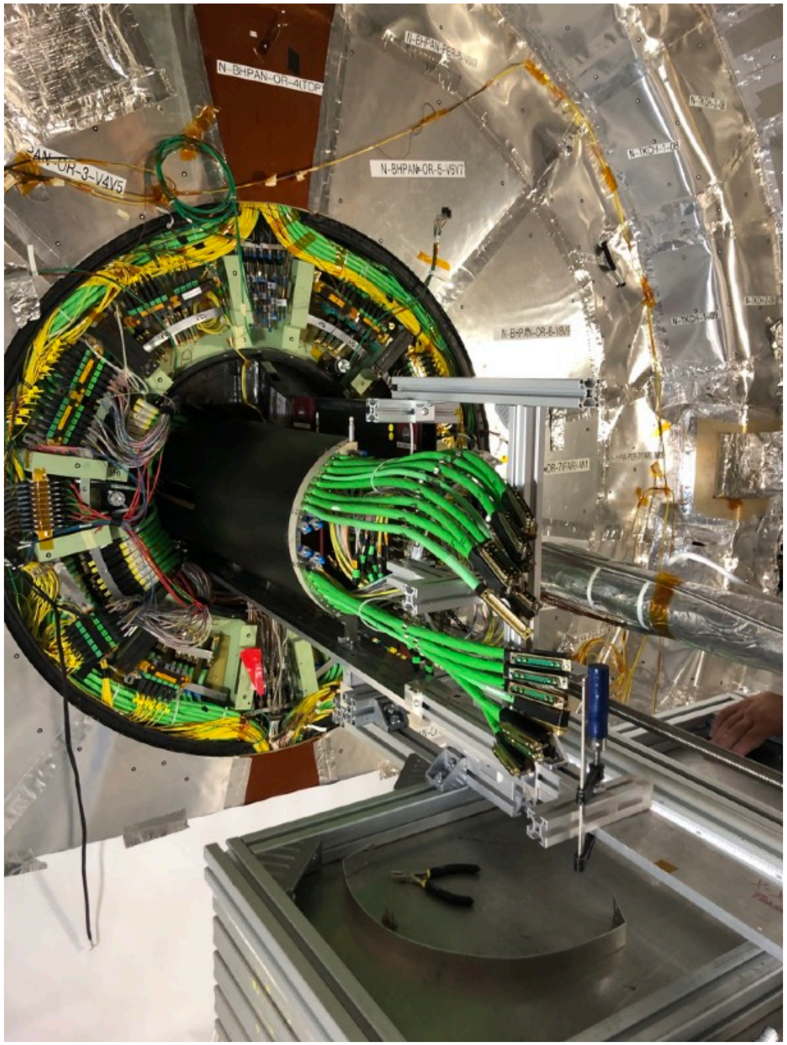


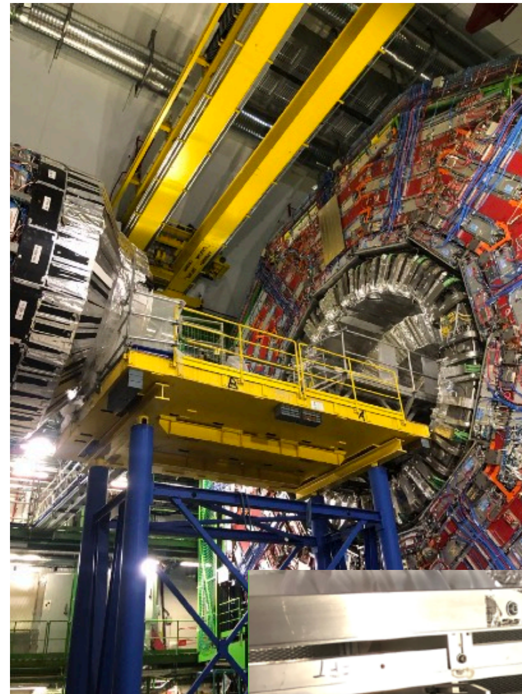


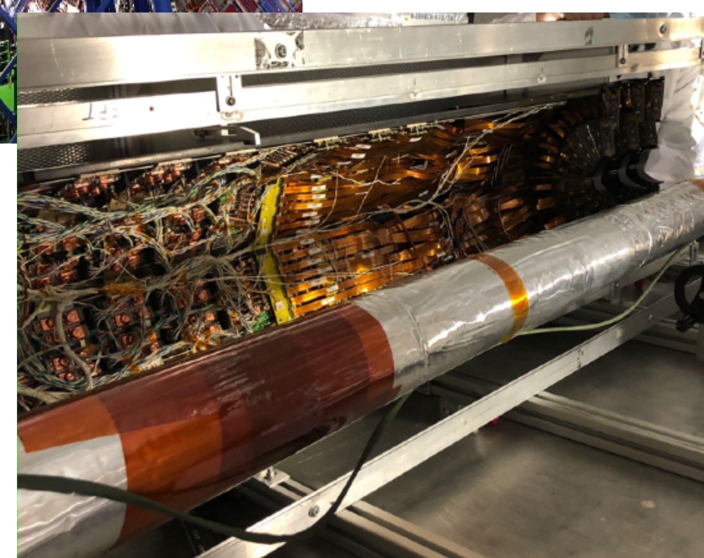
Moved underground…



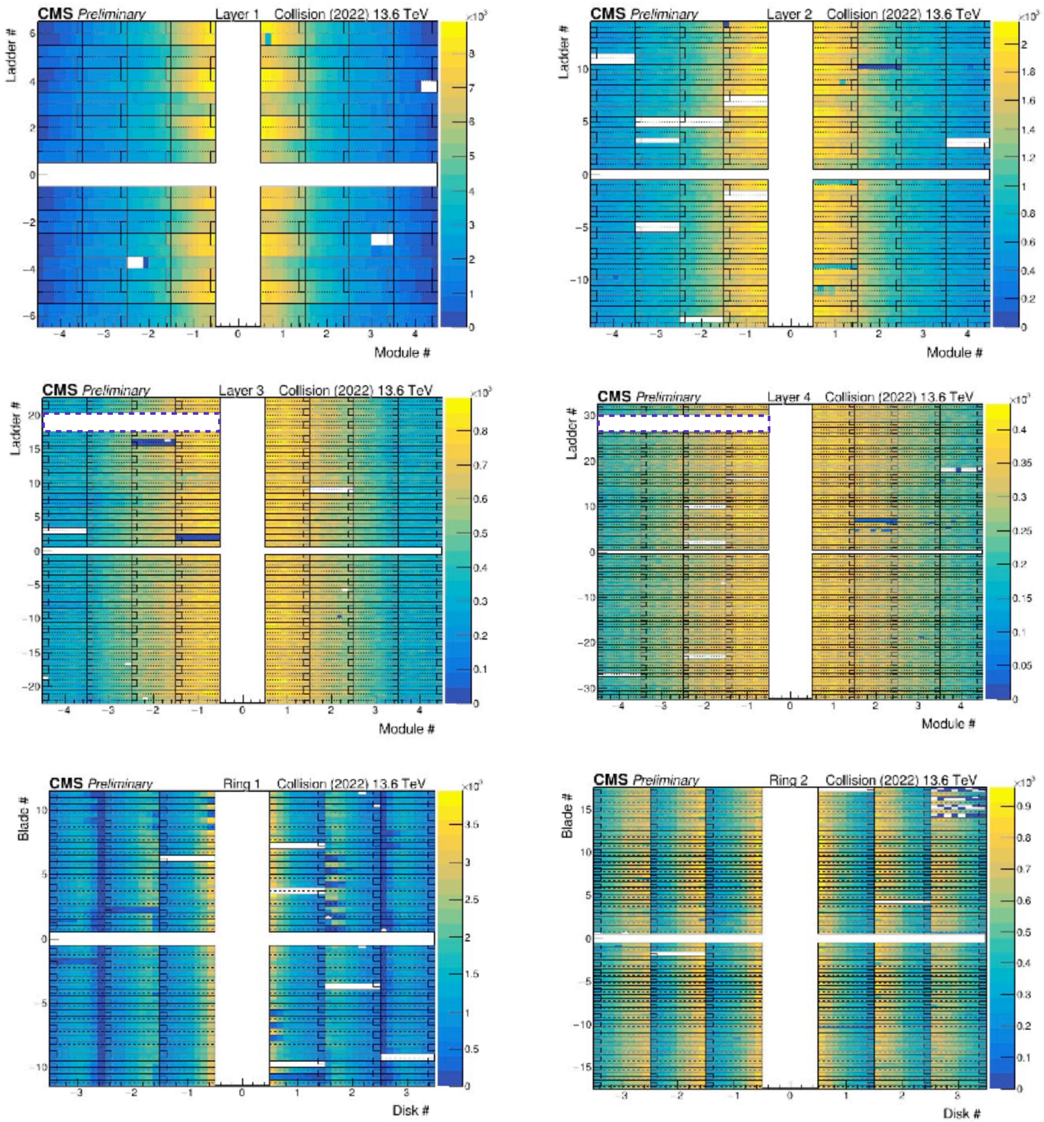
...and installed in center of CMS







Active detector fraction

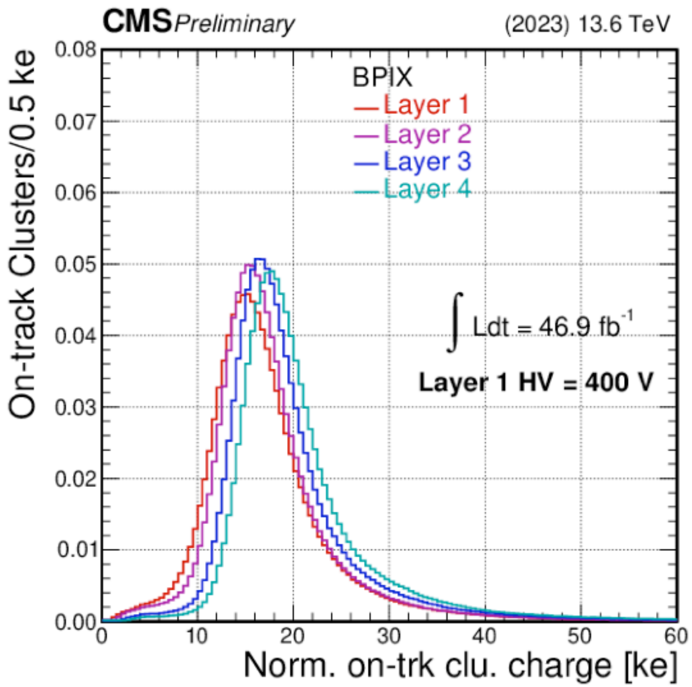


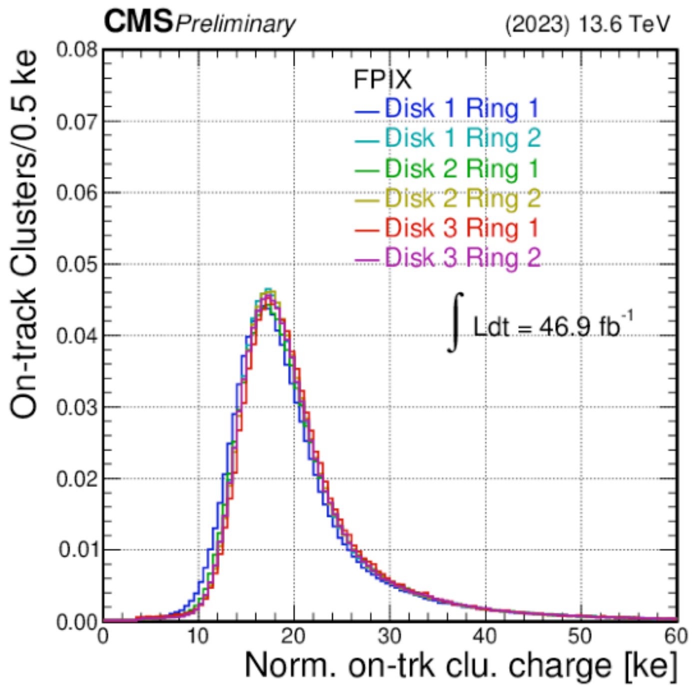
BPix : 96.2 %

FPix : 97.9 %

QPLL of BPix Sector 7 Layers 3 & 4 fails to lock to LHC clock

Cluster charge distributions





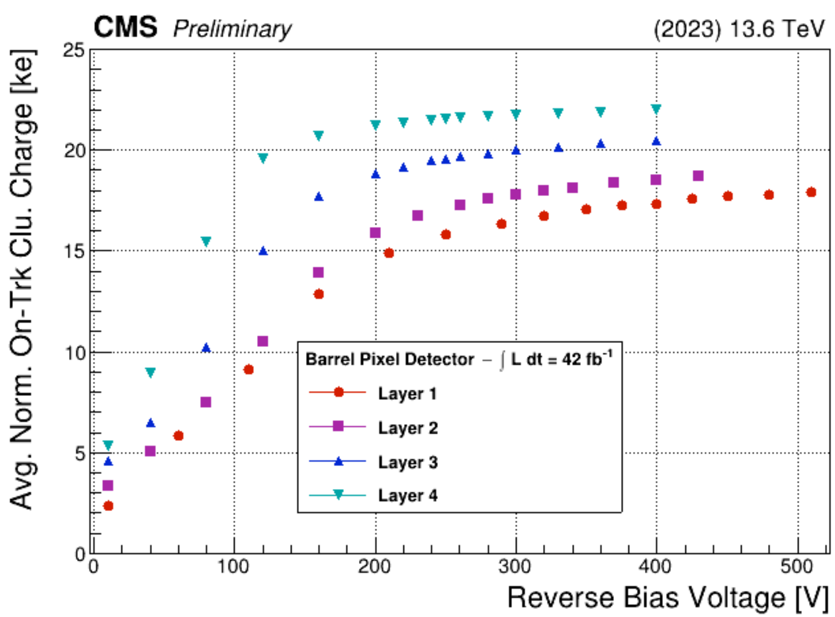
On-track cluster charge consistent across detector

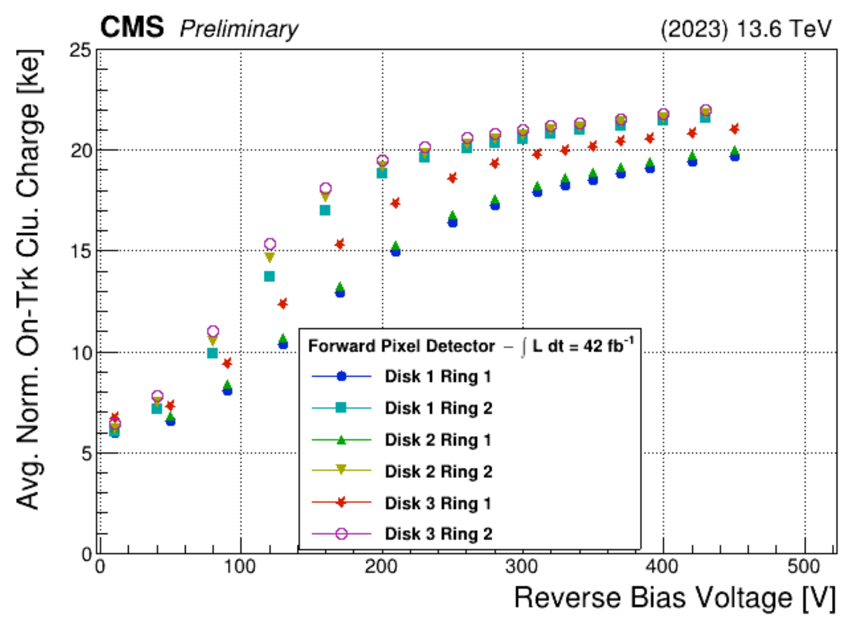
Cluster charge measurement

Cluster charge measured as function of bias voltage to determine when settings should be adjusted

Current settings

- Layer 1: 450V
- Layer 2: 350V
- Layer 3 & 4: 250V
- Ring 1: 350V
- Ring 2: 300V

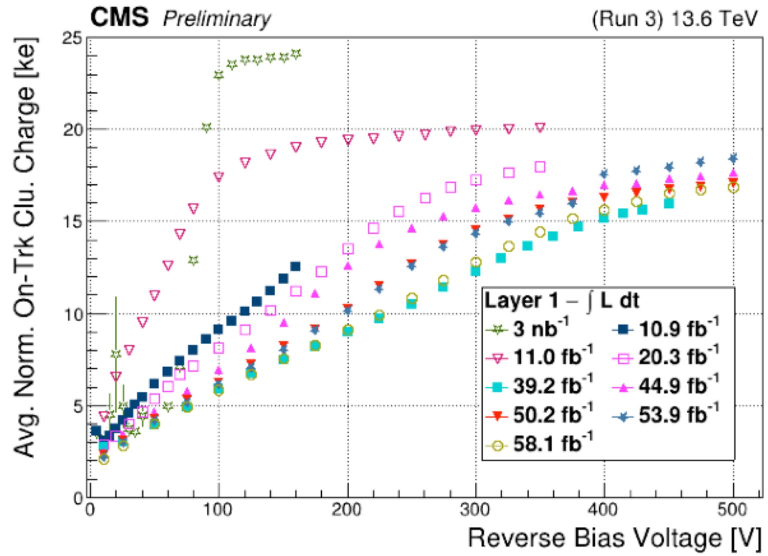


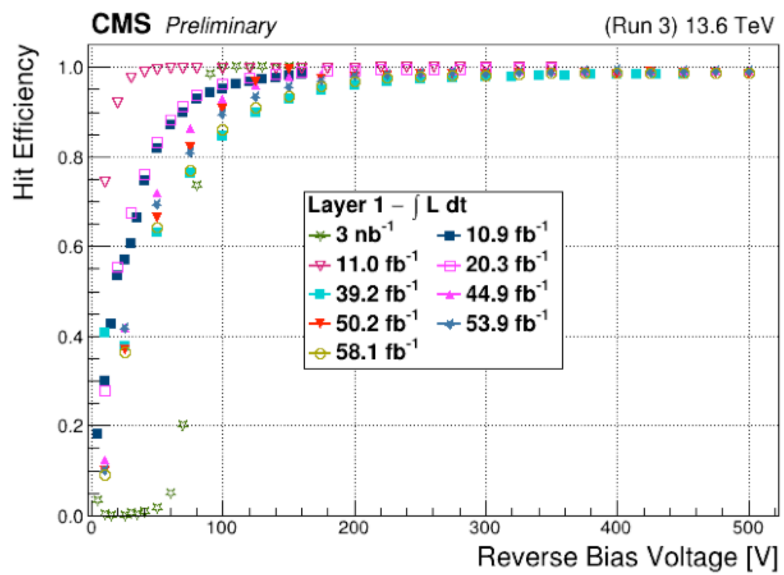


Layer 1 radiation damage

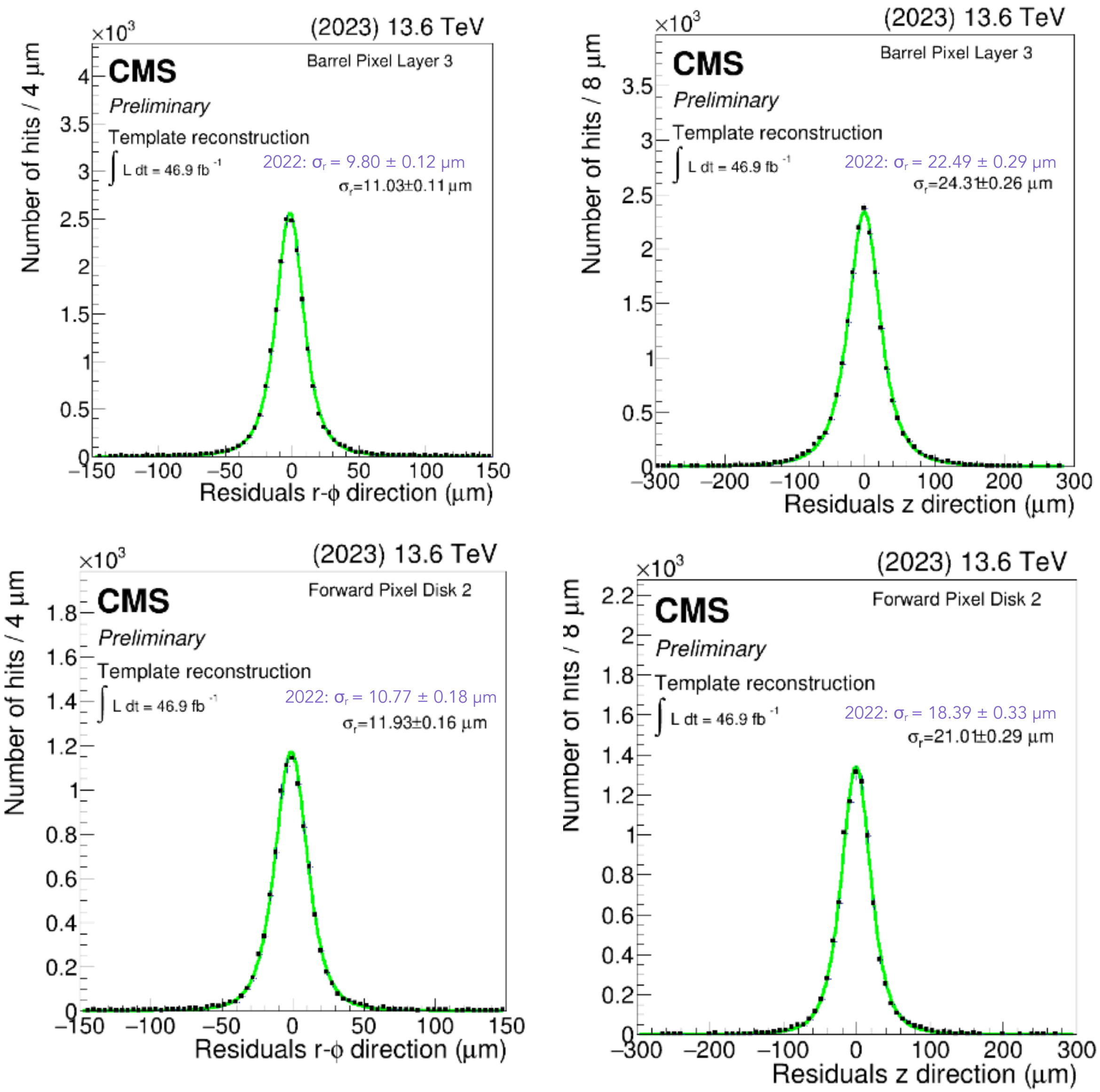
Layer 1 evolving rapidly

- ➡ HV bias scans performed regularly to monitor performance
- ➡ Layer 1 began Run 3 with HV bias of 150V, now at 450V





Resolution



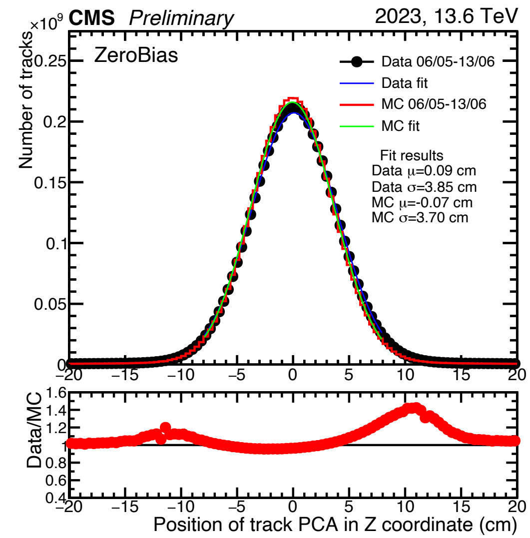
Great position resolution

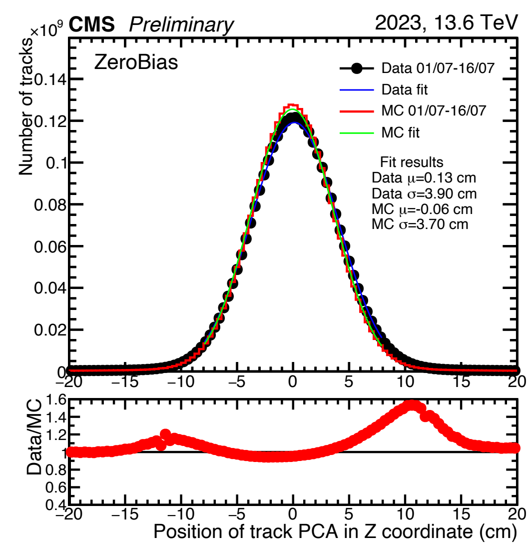
- ➡ Performance consistent with expected evolution
- ➡ Comparable to performance seen in 2022 and Run 2

Tracking performance: Point of closest approach

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

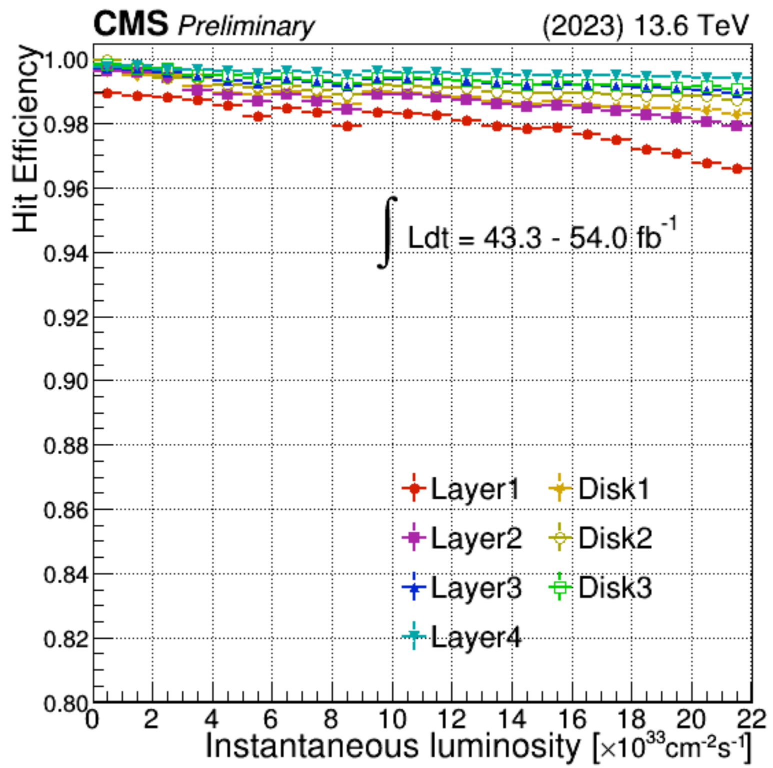
- ➡ Good data and MC agreement
- ➡ Z coordinate is wrt pixel detector barycenter
- ➡ Simulation set to approx. match position of beam in data wrt pixel barycenter
- ➡ MC distributions narrower and a single Gaussian
- ➡ Spread of Z coordinate in data distributions affected by lumi leveling





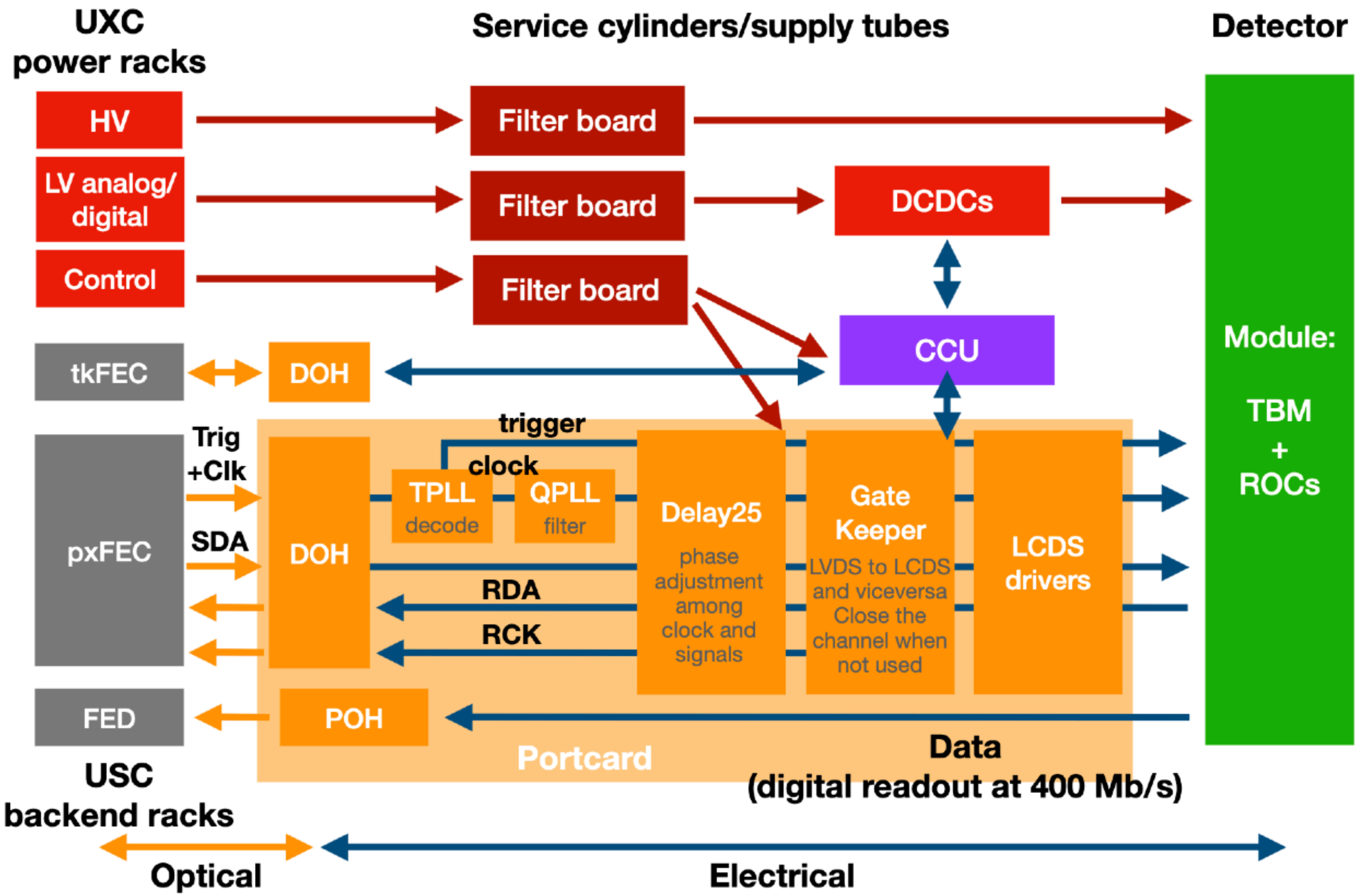
Summary

- Detector refurbished with several improvements for Run 3
- Smooth installation and commissioning
- Detector in good health with continuous monitoring and calibrations
- **Overall successful performance** in data collection with proton-proton collisions with inst. lumi up to $2.1*10^{34}$ $cm^{-2}s^{-1}$ and heavy ion collisions
- Looking forward to the rest of Run 3!



Backup

Hardware connections



Radiation environment for BPix Layer 1

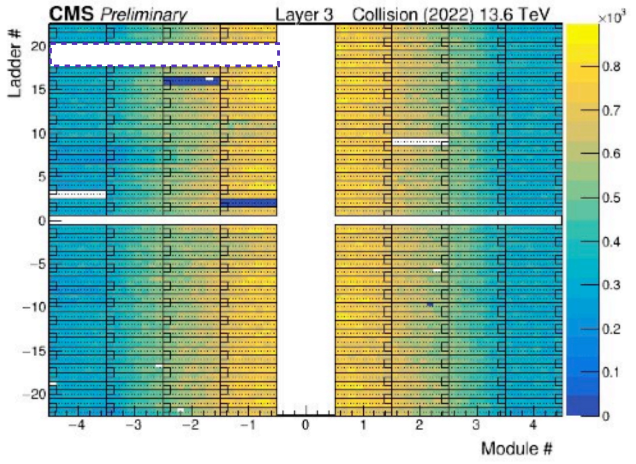
2021-2023: CMS/ATLAS collected an integrated luminosity of about 73 fb^{-1}

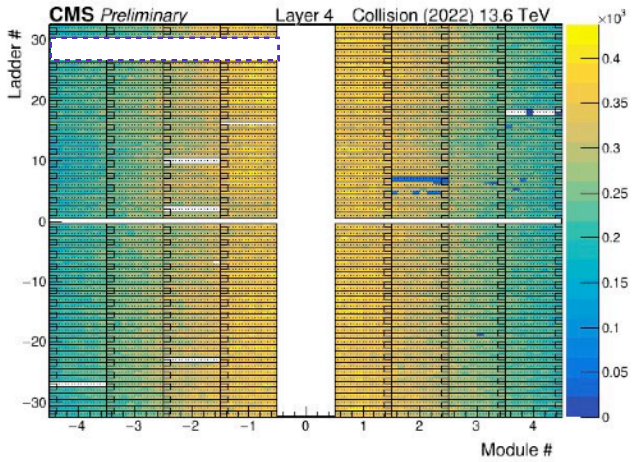
- **Particle fluence/flux = 8.4 * 10^{14} - particles/cm^2** (1MeV neutron equivalent/cm^2)
- **Dose = 280 kGray (28 Mrad)**

At the end of LHC Run 3, estimating integrated luminosity of 230 fb^{-1}

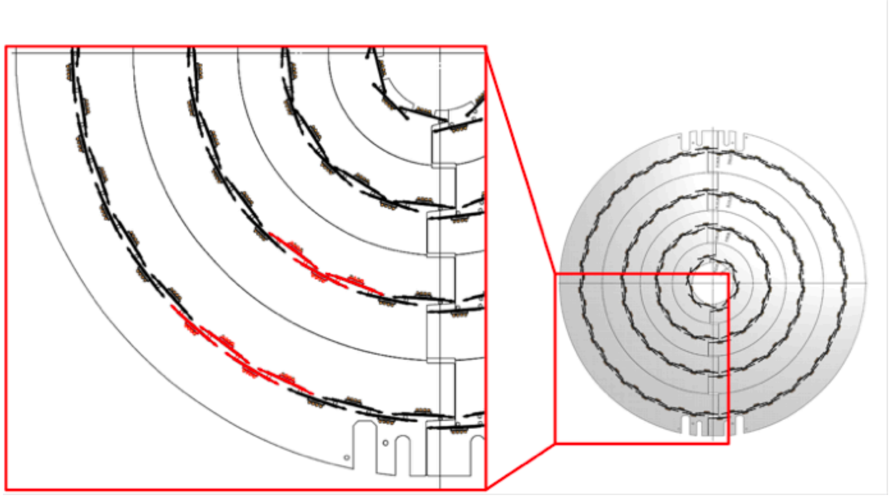
- **Particle fluence/flux = 2.3 * 10^{15} - particles/cm^2** (1MeV neutron equivalent/cm^2)
- **Dose = 93 Mrad**

QPLL issue





- Quartz controlled PLL circuit does not lock to LHC clock
- Layers 3 and 4 of one sector of barrel pixels affected
- Modules are not currently read out
    - ➡ Fixing the issue would require extracting and reinstalling pixel detector



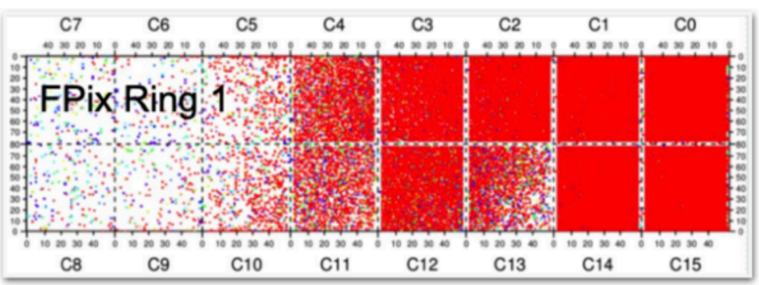
DCDC issue in Run 2

- Flaw in FEAST chip design
- When DCDC disabled, charge build up on circuit due to irradiation, causing DCDC to break
- Impact:
  - converters not used to power cycle modules
  - powercycling needed for stuck TBMs
  - reduced power supply voltage to 9V
  - high current trips in power groups with higher number of modules
  - disabled a few DCDC converters to prevent trips
  - no broken DCDC converters in 2018

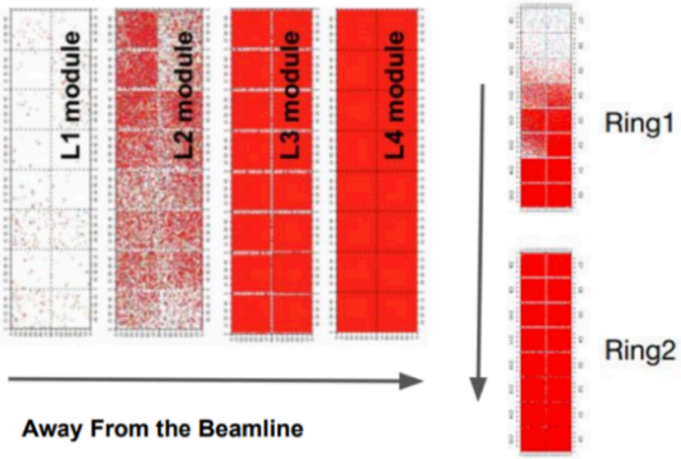
DCDC damaged modules

DCDC damaged modules not correctly powered

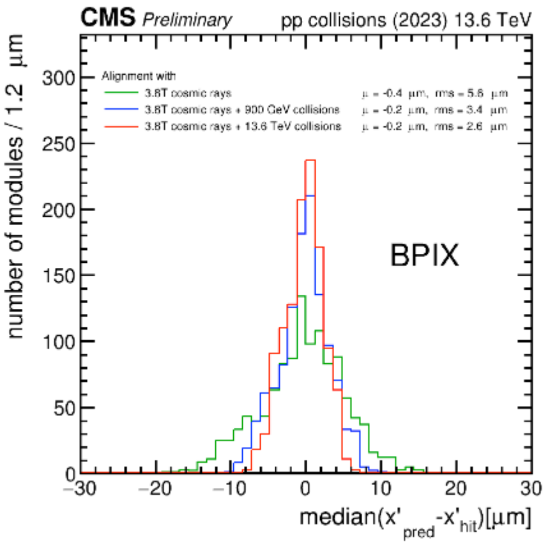
- Sensor leakage current cannot be drained efficiently if the ROC is not powered
- Bias voltage (HV) ON and module power (LV) OFF leads to bad grounding
- Leakage current is drained through the pre-amplifier, damaging the pre-amplifier and the module
- Damage seems to accumulate with radiation and distance from beamline
- 6 (accessible) Layer 1 modules replaced during 2017-18 YETS out of total 8 damaged modules in Layer 1
- Accessible DCDC-damaged modules in Layer 2 were replaced during LS2

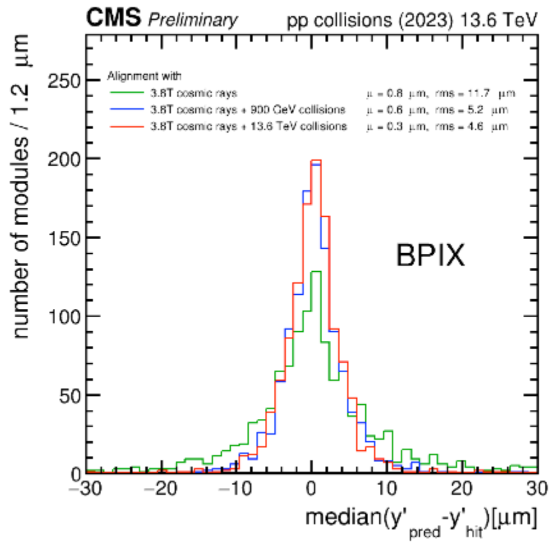


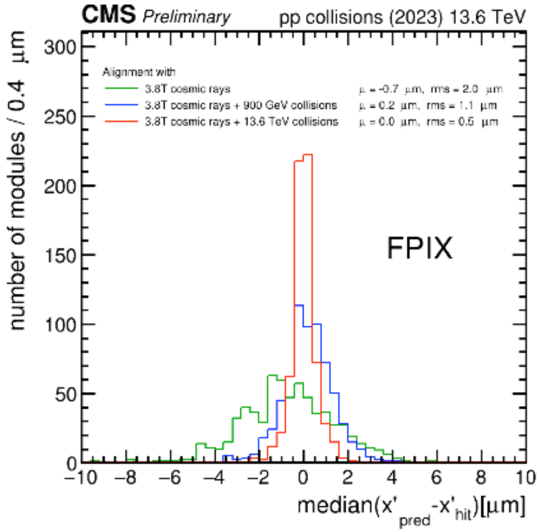
Damages due to HV on and LV off

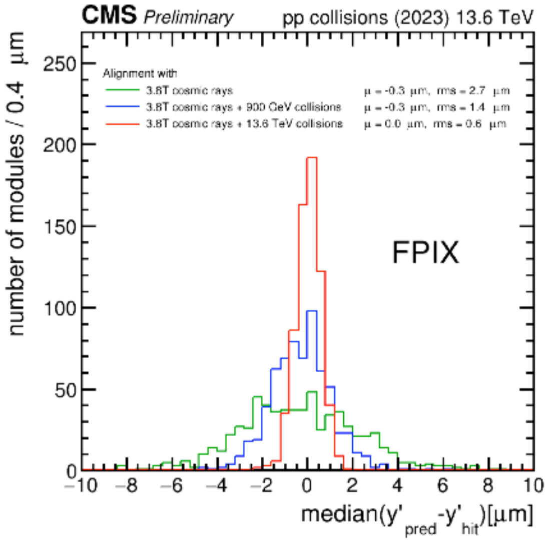


Alignment



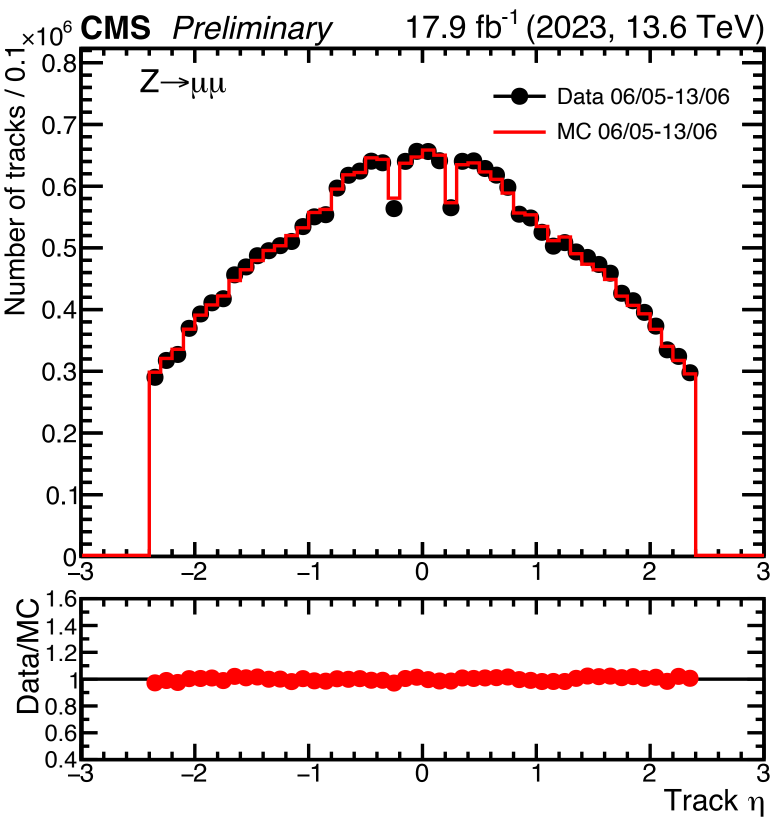


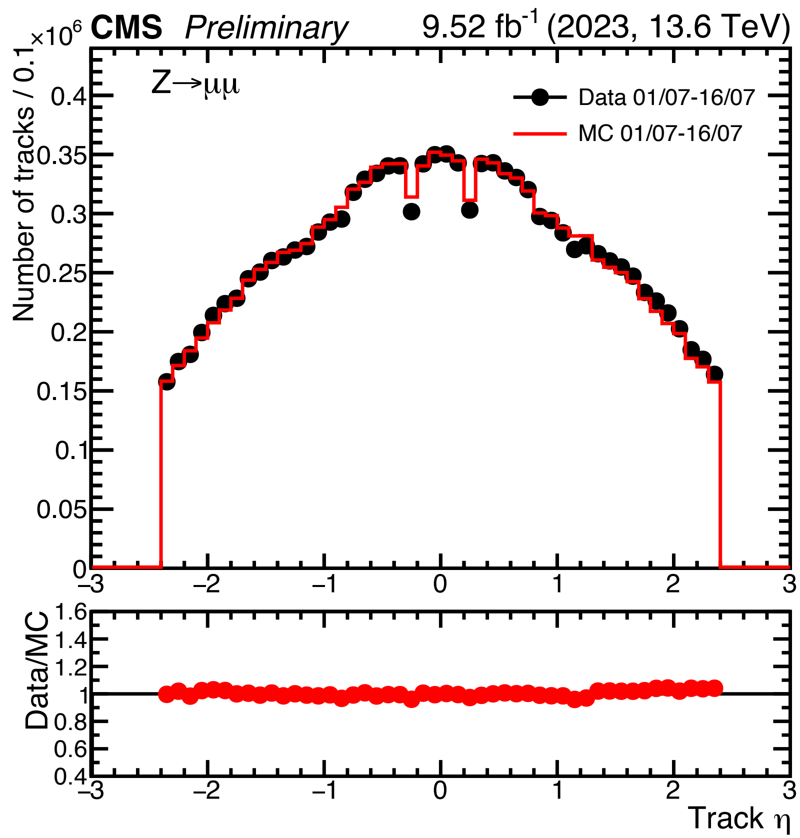




- Alignment performed with cosmic rays, 900GeV collisions, 13.6TeV collisions
- Distributions are medians of track-hit residuals
- Hit prediction obtained from all other track hits
- Median of distribution taken for each module
- Width of this distribution constitutes a measure of the local precision of the alignment results
- Deviations from zero indicate possible biases

Tracking performance: Z→mu mu





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

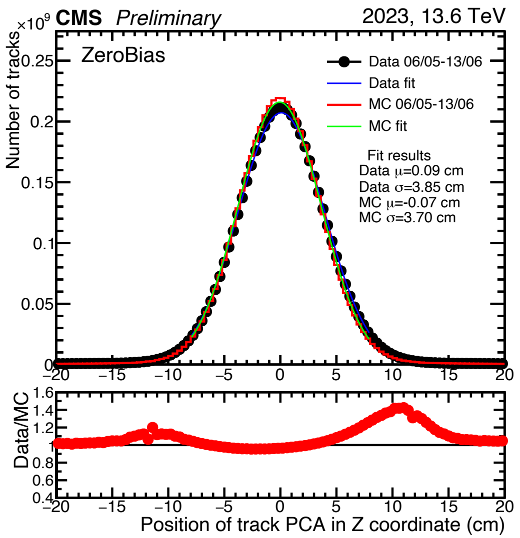
➡ Good data and MC agreement

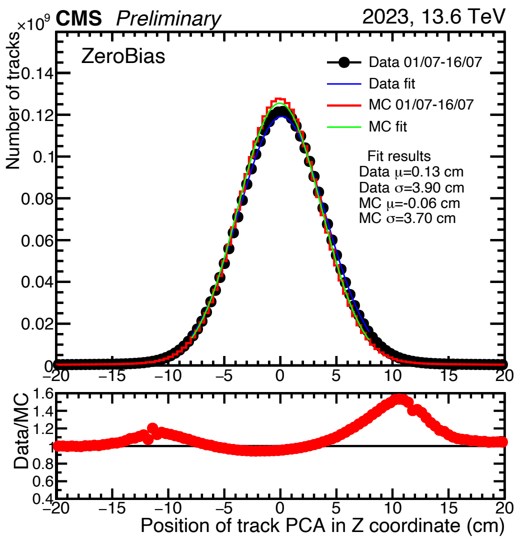
Tracking performance: Z→mu mu

- MC simulation for $Z \rightarrow \mu\mu$ is Pythia 8 Drell-Yan to $\mu\mu$ with Tune CP5 for the underlying event
- MC distributions are normalized to reproduce the number of reconstructed vertices in data
- Tracks with requirements:
    - Global Particle Flow muons
    - $\eta| < 2.4$, $p_T > 5$ GeV
    - χ^2/nDOF < 10, impact parameter in the transverse plane with respect to the beamspot |dxy, BS| < 0.02 cm, and in the longitudinal plane with respect to the beamspot |dZ, BS| < 20 cm
    - at least one valid hit in the pixel detector, at least 8 valid hits in the strip detector, has hits in at least 2 muon stations
    - relative isolation within a cone of radius $\Delta R = 0.4$ less than 0.3
    - two highest p_T tracks must have 75 GeV < $m_{\mu\mu}$ < 105 GeV

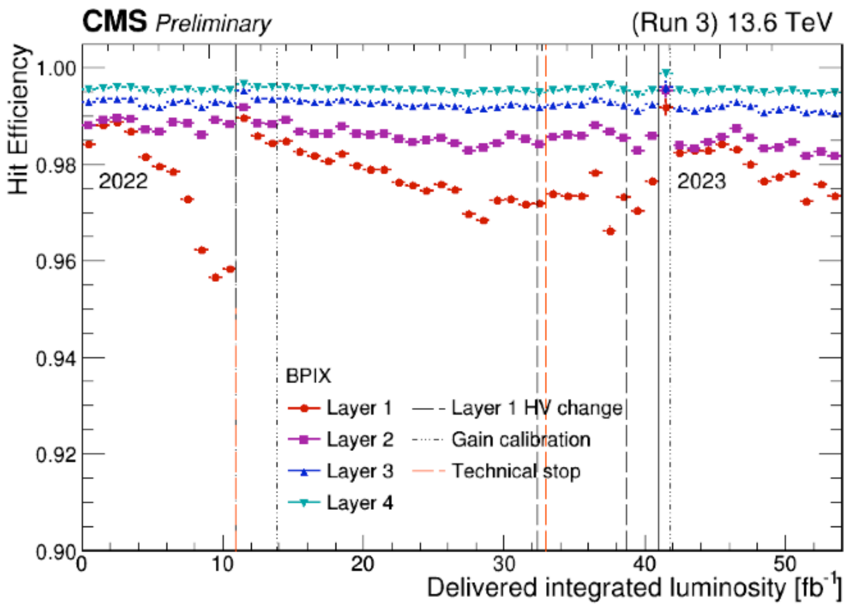
Tracking performance: Point of closest approach

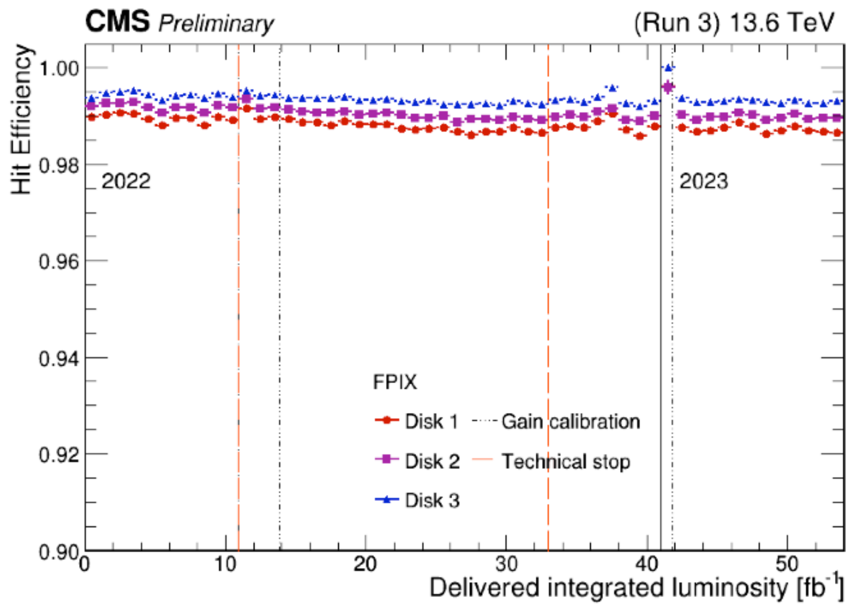
- ZeroBias events
- selected using only the information on the beam-beam coincidence
- highPurity tracks with $p_T > 1$ GeV
- MC simulation for the ZeroBias events is a Pythia 8 generic QCD with Tune CP5 for the underlying event
- MC distributions normalized to reproduce the number of reconstructed vertices in data





Hit efficiency





- Hit efficiency affected by gain calibration, HV setting, and annealing during technical stops

➡ High hit efficiencies for all layers and disks

Hit efficiency and hit residuals measurement

Hit efficiency is the probability to find any cluster within 1mm around an expected hit independent of the cluster quality

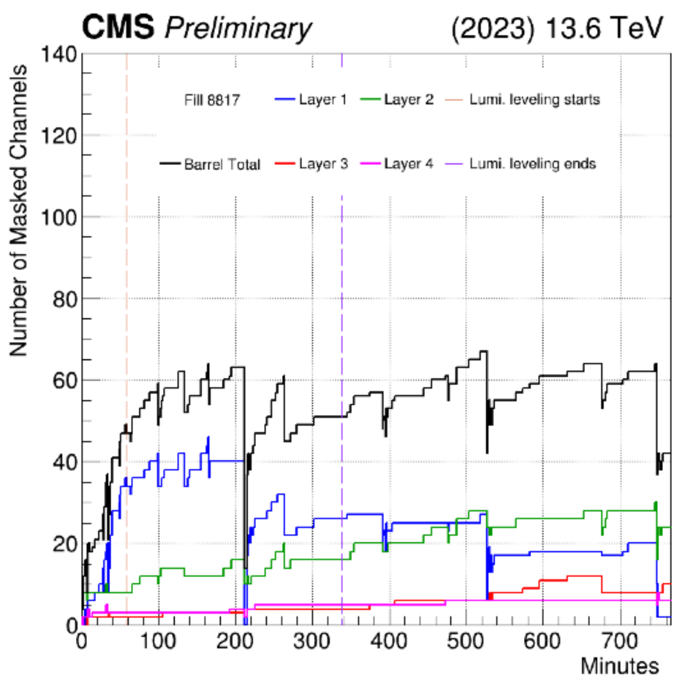
- Measured using muon tracks with pT > 2 GeV
- Bad components of the pixel detector are excluded from the measurement

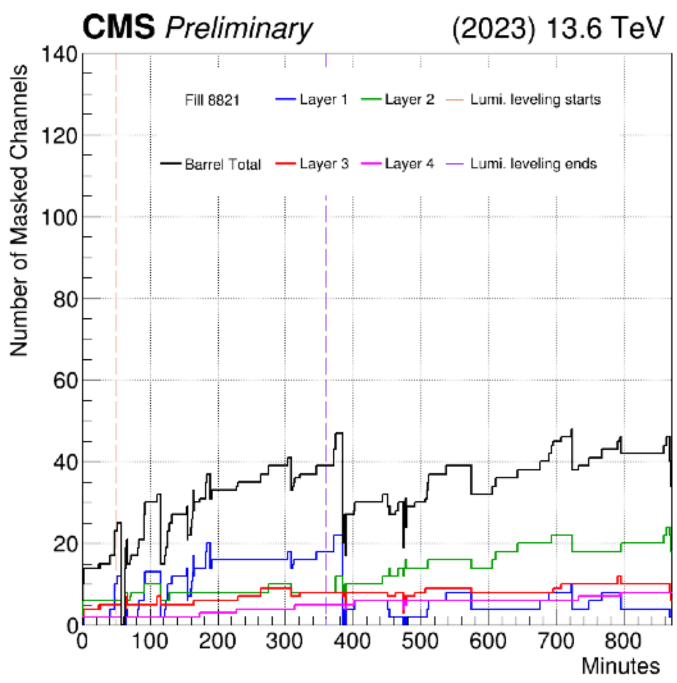
Hit residuals measurement:

- Triplet method
  - p_T > 12 (4) GeV tracks with hits in 3 layers (disks) are selected and refitted using hits in two of three layers (disks) for the BPIX (FPIX).
  - Trajectory is extrapolated to remaining layer (disk) and residuals with the actual hit are calculated for the BPIX (FPIX)
  - Residual distribution fitted with the Student-t function to obtain the mean offset (μ) and resolution (σ)
    - Residual offset (mean) and resolution are obtained from the fit
  - Triplets considered:
    - Layer 3: propagate from hits on Layer 2 and 4
    - Disk 2: propagate from hits on Disks 1 and 3
- Reconstruction:
  - Generic:
    - Simple algorithm based on track position and angle
    - Used in our High Level Triggers (HLT) and early track iterations offline
  - Template:
    - Algorithm based on detailed cluster shape simulations
    - Used in the final fit of each track in the offline reconstruction

Automasked channels

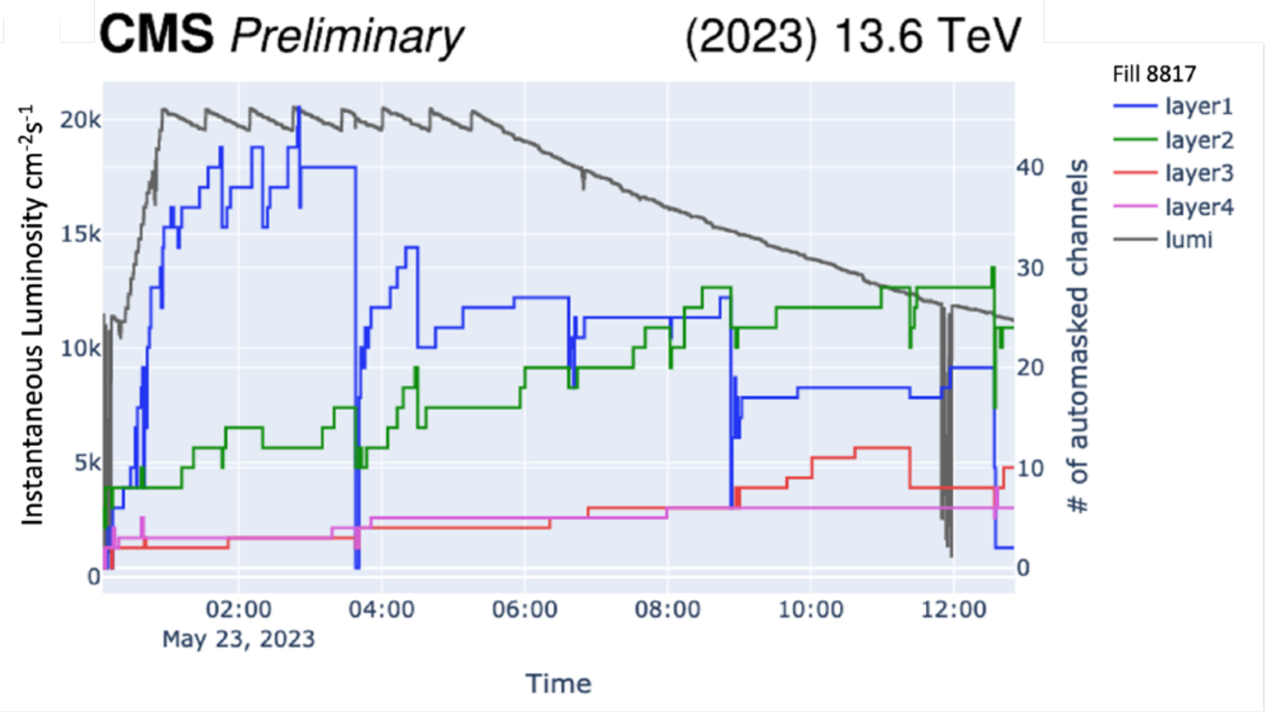
- Problem greatly mitigated by adjusting phases of the 400MHz data transmission (relative phase of readout chip and TBM)
  - ➡ Calibrations do not not always predict a good setting for high rate data transfer
- Automasking of Layer 1 modules now very low, usually 1% of channels





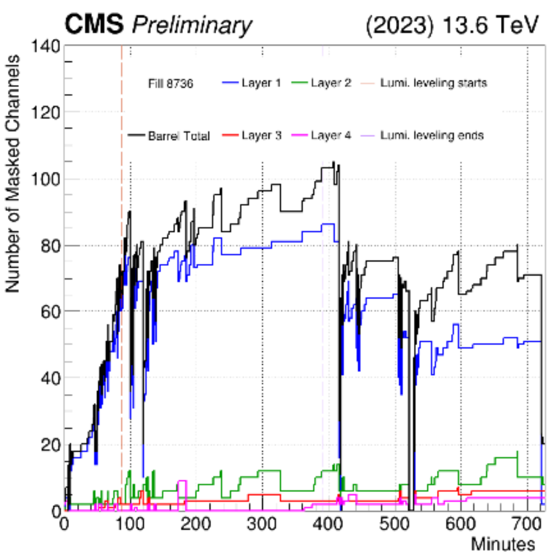
Automasked channels

- Channels masked during data-taking due to readout errors
  - ➡ **Layer 1:** operational problem first mitigated by increasing number of allowed readout errors before channel masking
  - ➡ **Layer 2-4:** unrecoverable SEUs accumulate over a fill
- Recovery action at certain pile up
- Data quality remained good for CMS

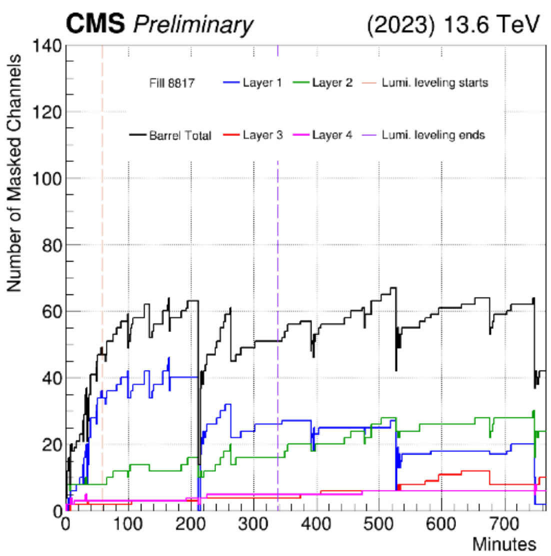


Automasked channels

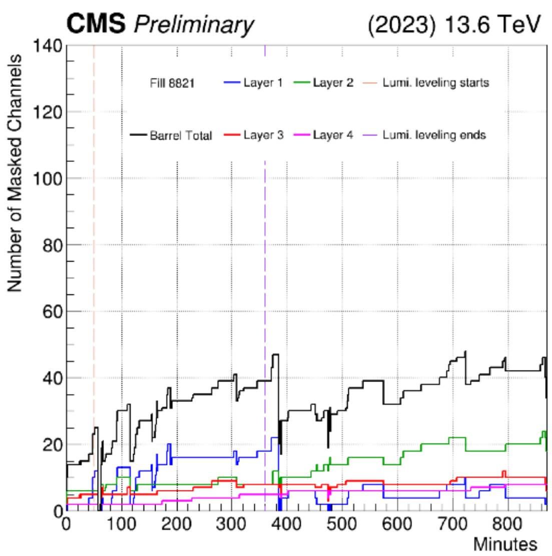
- **Fill 8736:** Channel auto-masked if there are 30 Out-of-Sync (OOS) errors seen in one minute in the channel
- **Fill 8817:** OOS setting was changed from 30 OOS/minute to 63 OOS/minute
- **Fill 8821:** The Token Bit Manager phase settings of several modules in BPix Layer 1 were changed



Fill 8736



Fill 8817



Fill 8821

Automasked channels: fill details

Fill 8736 (8 May 2023):

- Number of bunches: 1805
- Peak instantaneous luminosity: 1.56×10^{34} cm^{-2} s^{-1}
- Peak PU: 61.401

Fill 8817 (24 May 2023):

- Number of bunches: 2345
- Peak instantaneous luminosity: 2.05×10^{34} cm^{-2} s^{-1}
- Peak PU: 62.299

Fill 8821 (25 May 2023):

- Number of bunches: 2345
- Peak instantaneous luminosity: 2.12×10^{34} cm^{-2} s^{-1}
- Peak PU: 64.316

- All fills have the same trigger rate