Karlsruhe Institute of Technology

Operation and performance of the CMS silicon tracker

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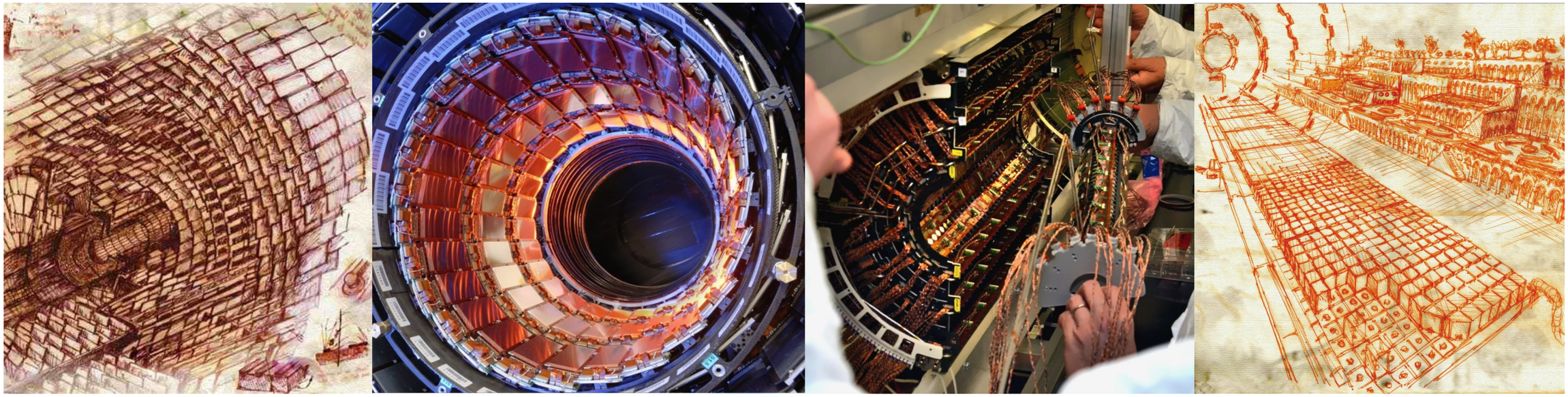
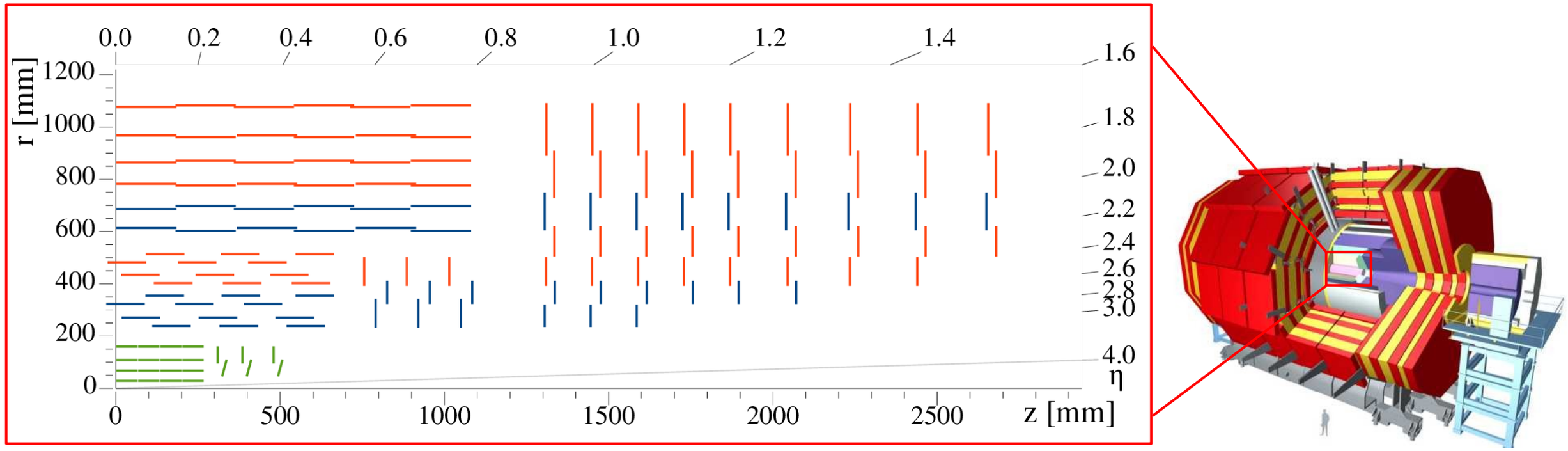


Overview of the CMS central silicon tracker



- **All-silicon** central tracking system
- 200 m^2 of active area, of which 1.75 m^2 pixel detector
- 5.6 m in length, 2.5 m diameter
- **Innermost layer at 2.9 cm** from beam line, **outermost layer at ~110 cm**
- Strip Tracker in place since end of 2007
- Pixel Detector completely replaced, **Phase-1 upgrade, in 2016/17**
  - Pixel detector designed to be removable and reinstallable quickly

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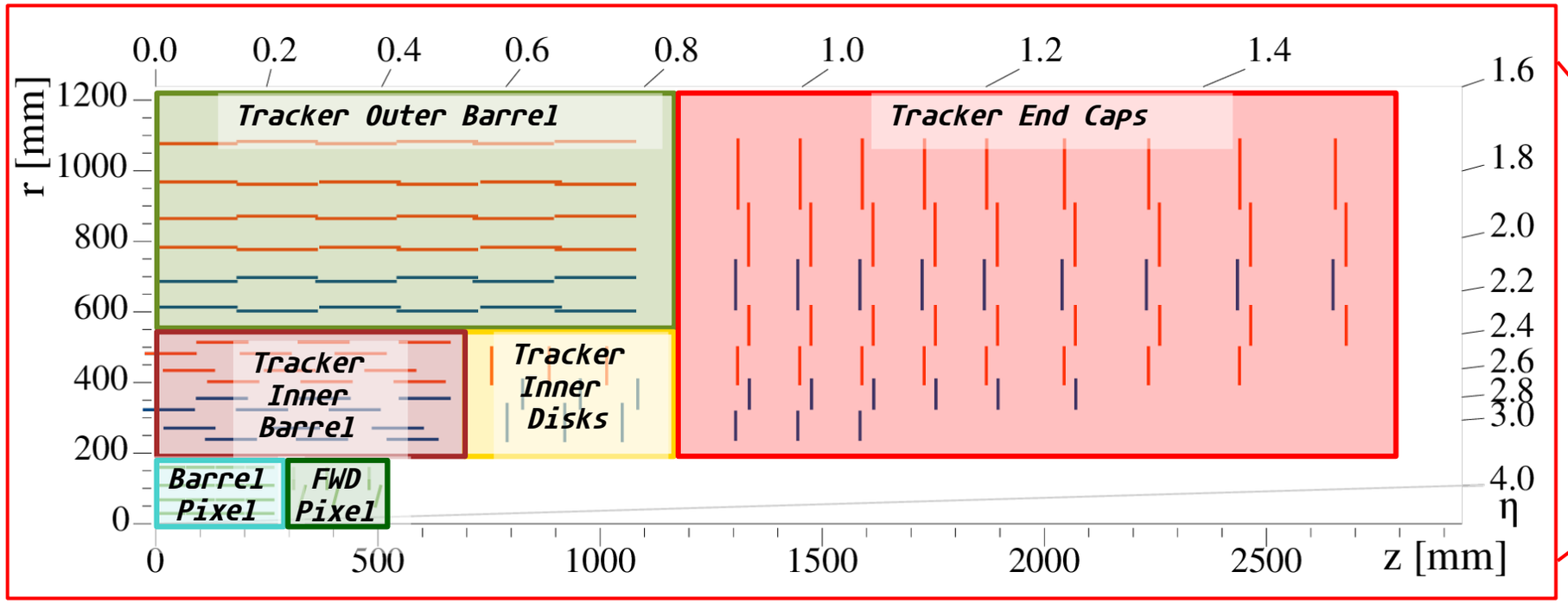

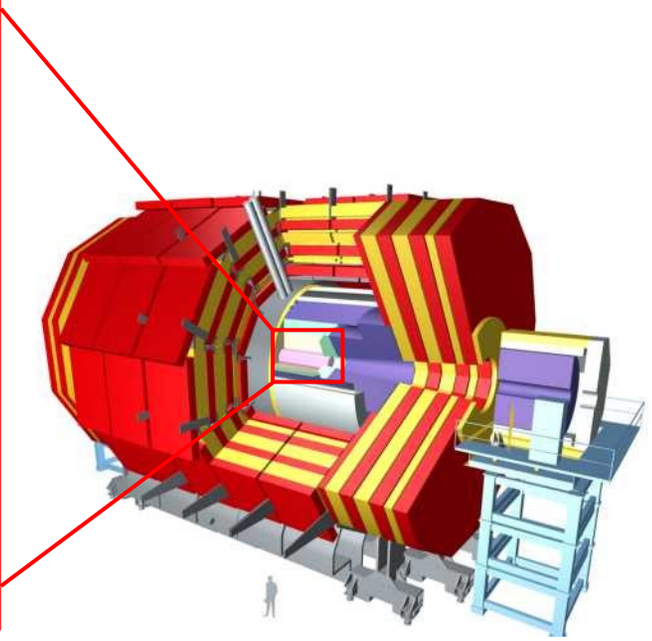

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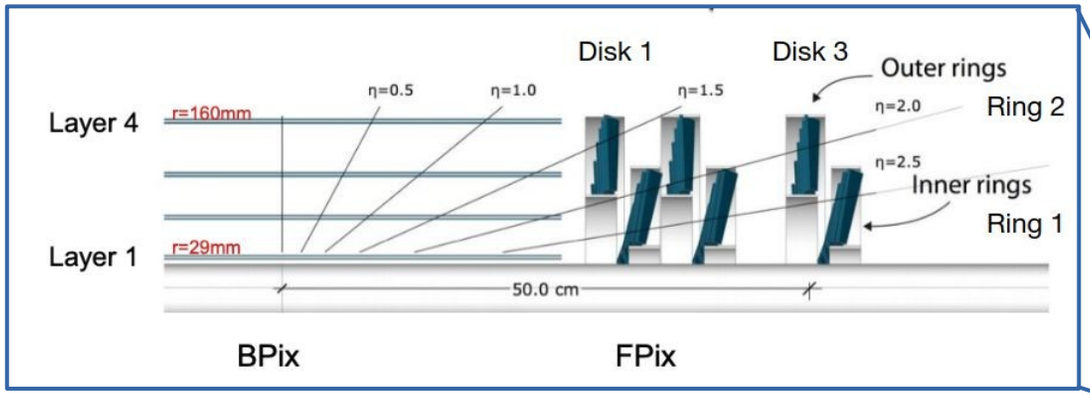
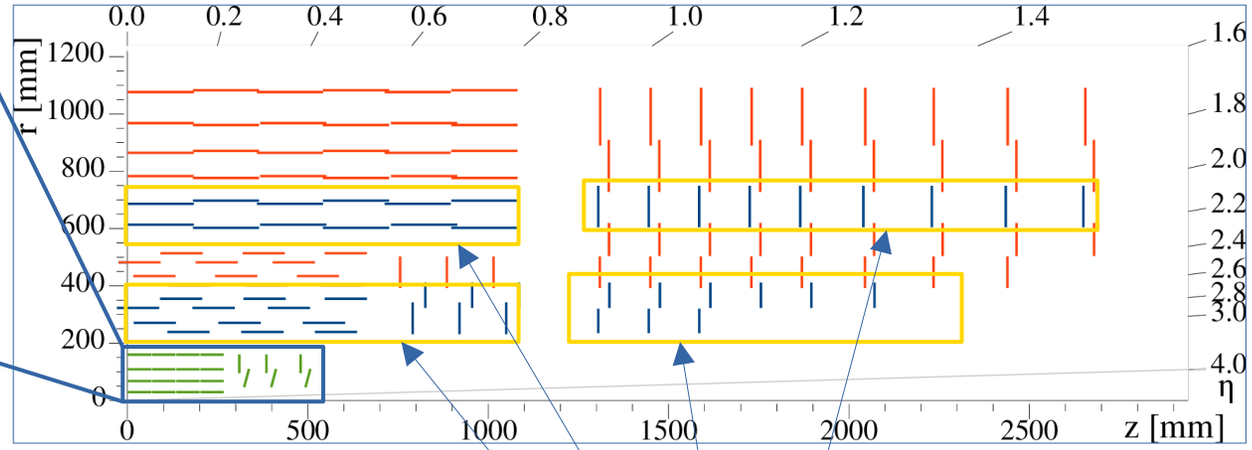
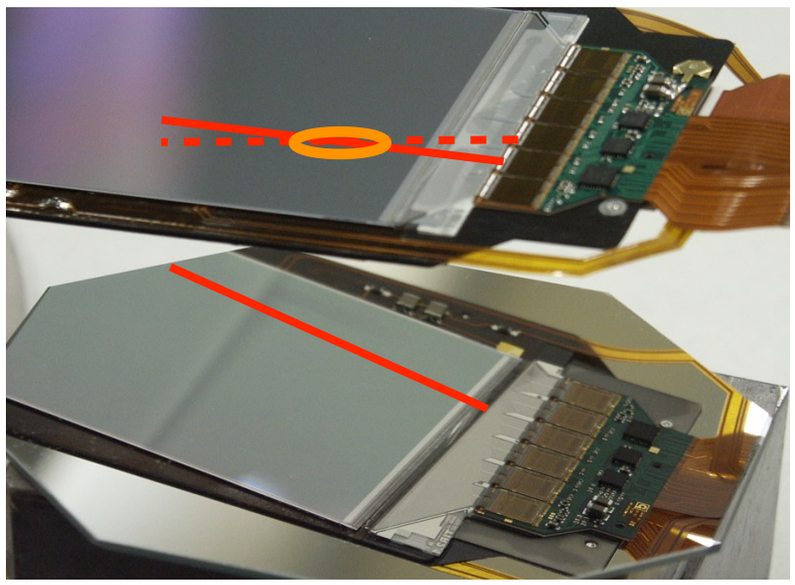
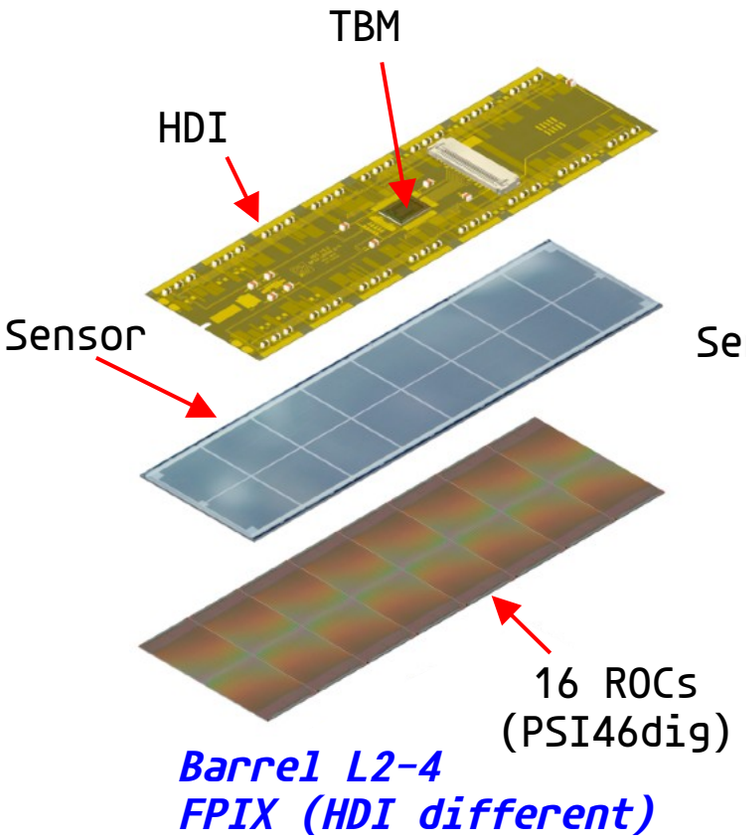




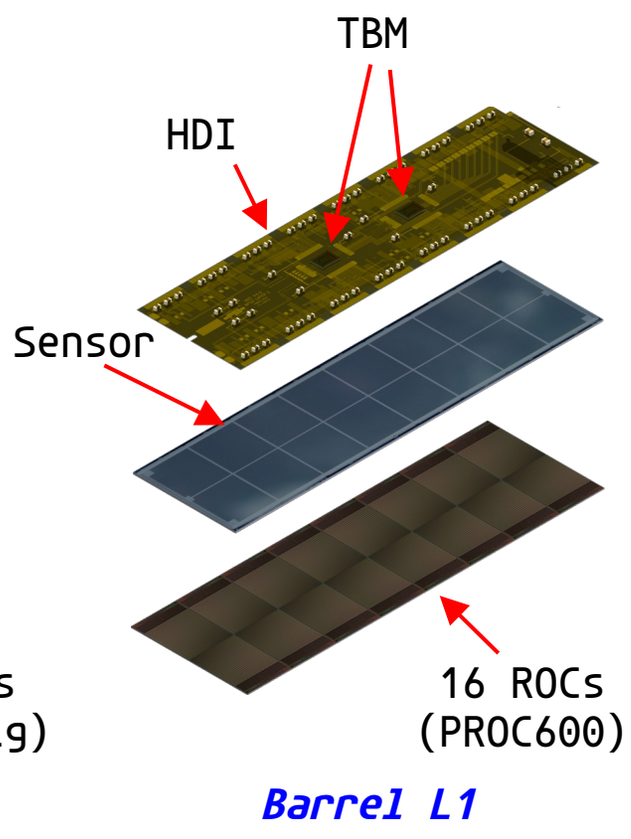
- 14 barrel layers: 4 pixel and 4+6 strip
- 15 forward disks: 3 pixel and 3+9 strip
- **1’856 pixel modules**
  - module size about 1.5x6 cm²
  - **124M pixels** with 100x150 µm² size
- **15’148 Silicon Strip Modules**
  - **9.3M microstrips**, pitch 80 µm to 205 µm, length: 10-20 cm
  - 4 strip layers/3 rings have “stereo modules”
    → modules mounted back-to-back with 100 mrad stereo angle



Pixel Detector – Modules



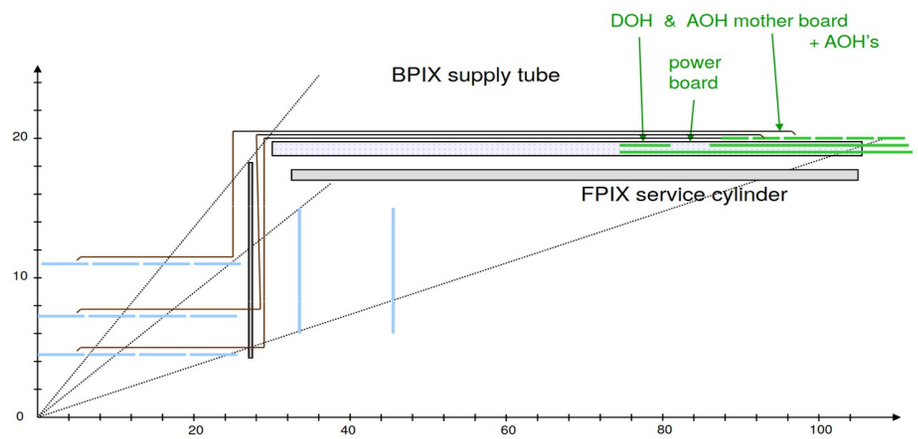
Barrel L2-4
FPIX (HDI different)



Barrel L1

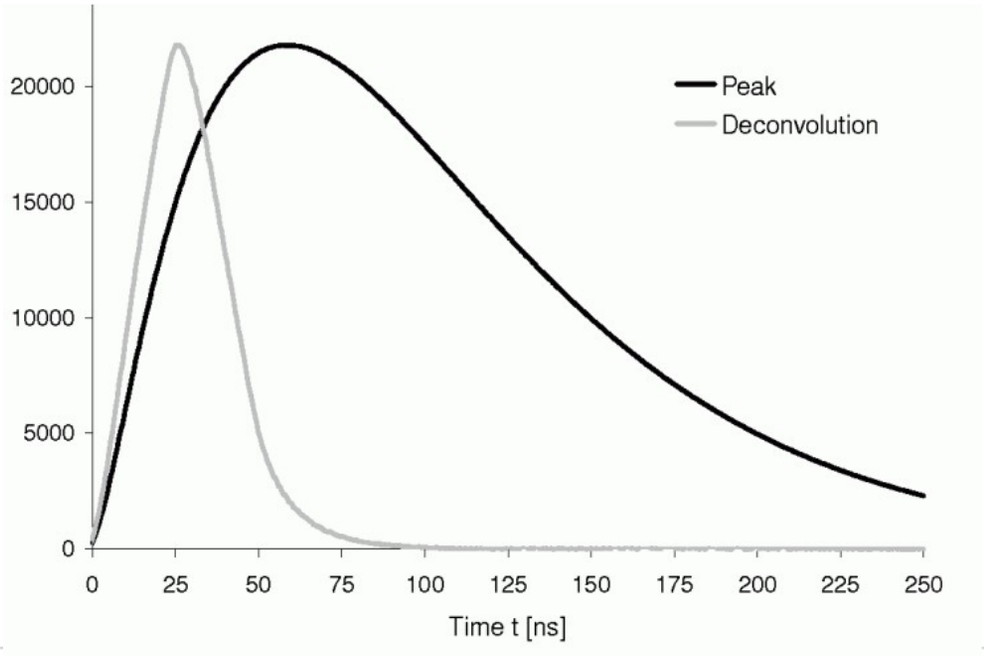
- **n-in-n silicon sensors**, double-sided processing, 285 µm active thickness
- Readout Chip (ROC):
  - **PSI46dig (BPIX L2–4, FPIX)**
    - Efficiency > 90% up to 200 MHz/cm²
  - **PROC600 (BPIX L1)**
    - Efficiency > 90% up to 600 MHz/cm²
- **Token-bit manager (TBM) ASIC** to orchestrate readout
  - 2 TBMs for Layer 1 modules to cope with very high data rates

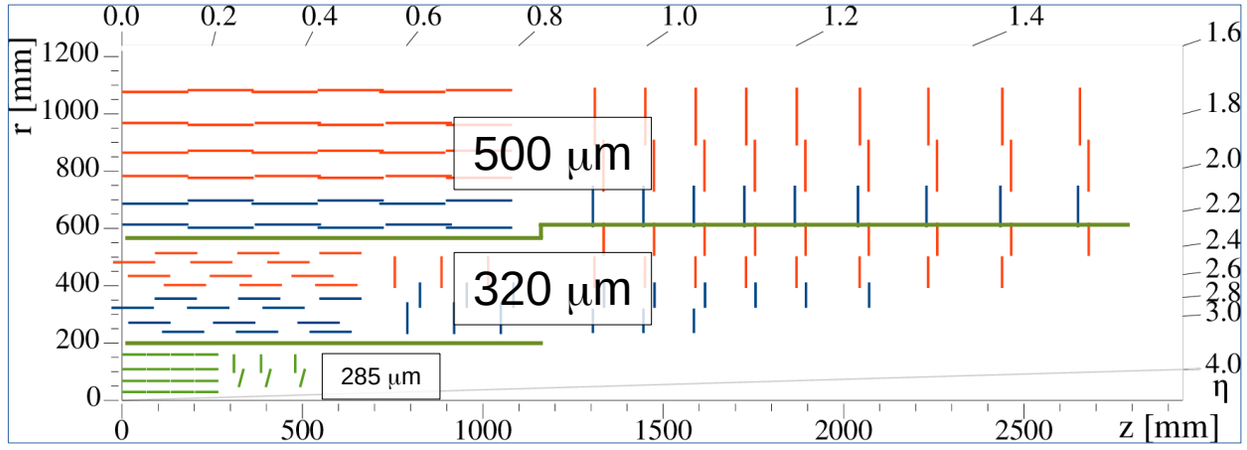
- Auxiliary electronics located **outside of tracking volume** on “service cylinder”
  - electro-opto conversion
  - DCDC converters
  - delay chips

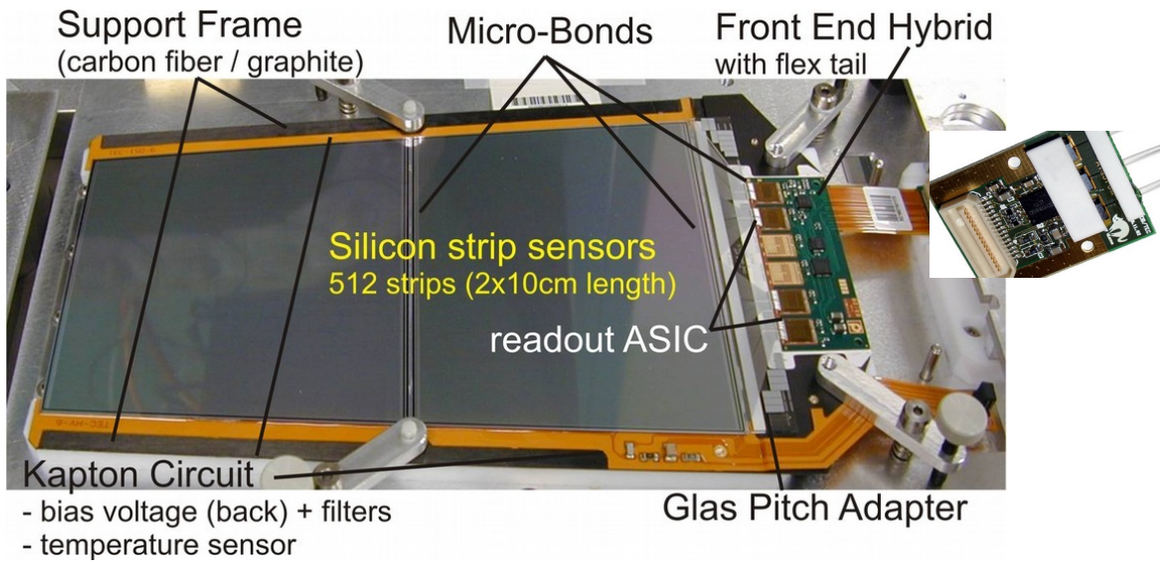


Strip Detector

- Strip Modules
  - **p-in-n sensors**, single-sided processing
    - 320 µm thickness in inner layers/rings
    - 500 µm thickness in outer layers/rings
      → compensate for longer strip length in outer layers → **two sensors daisy-chained**
  - analog opto-hybrid for electro-opto conversion in close proximity to individual modules
  - **APV25 readout chip**
    - Two readout modes:
      - Peak mode (1 sample from CR-RC shaper, slow shaper → **low power**)
      - **Deconvolution** (3 sample weighted average on-chip
        → **shorter effective pulse shape**)





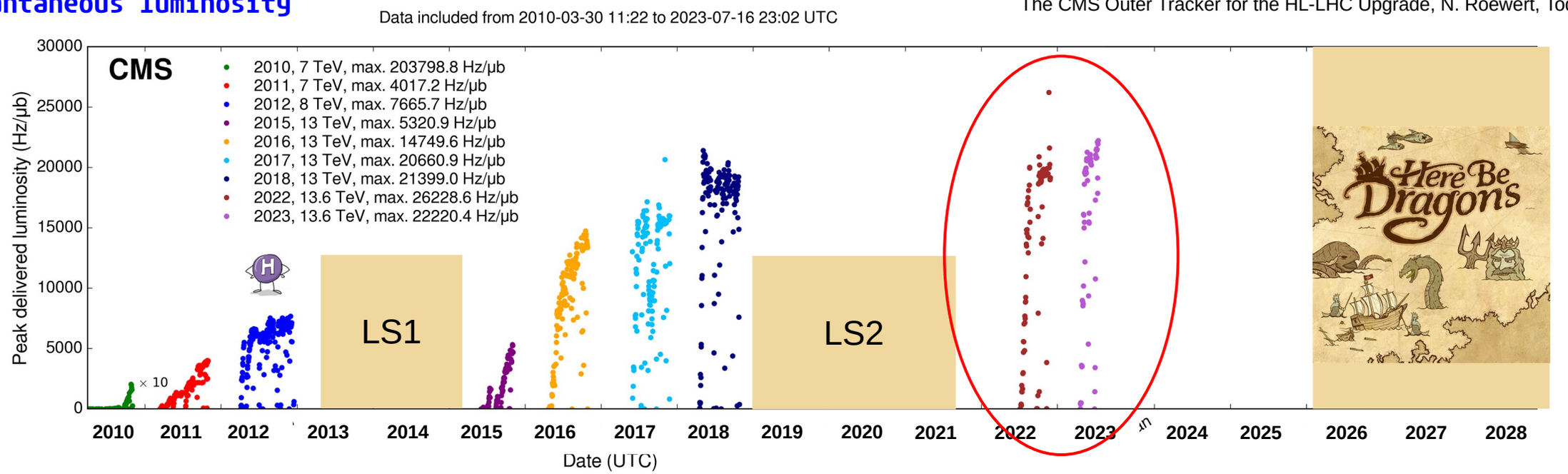


Detector Status

Data taking conditions in Run 3

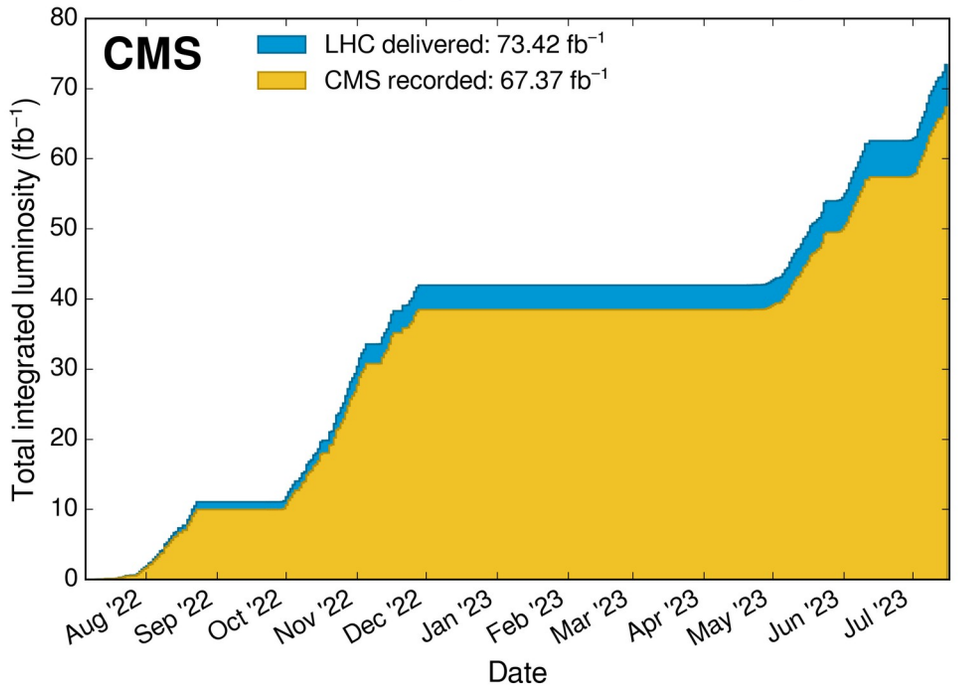
The CMS Inner Tracker for the HL-LHC Upgrade A. Papadopoulos, Today 17:20
The CMS Outer Tracker for the HL-LHC Upgrade, N. Roewert, Today 17:40

Instantaneous luminosity



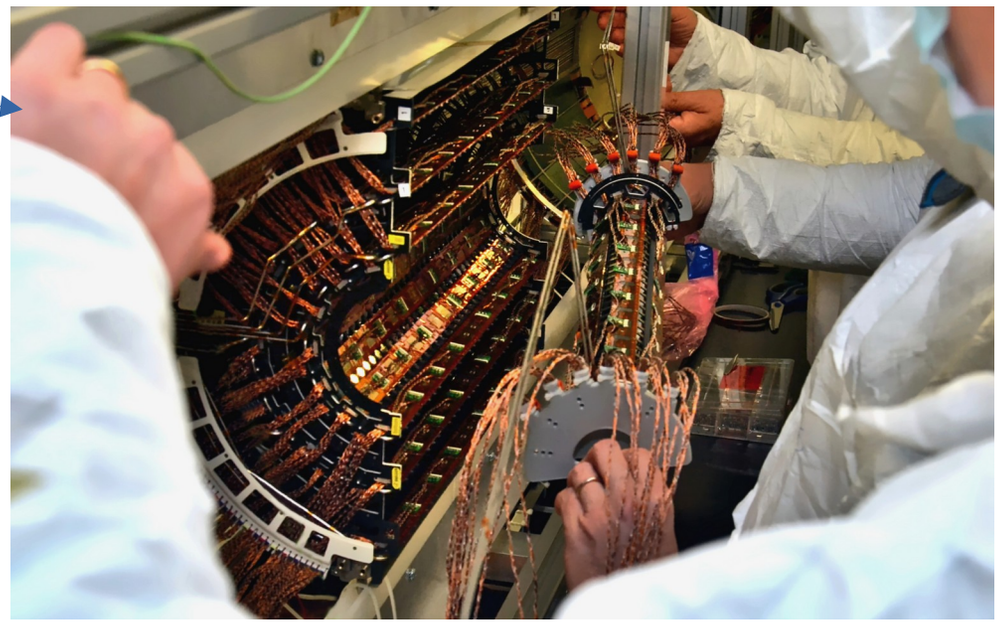
- In 2022/2023 LHC running routinely at luminosities around $2x10^{34}\,cm^{-1}s^{-1}$
- Pile-up reaching up to 65 overlapping collisions at the start of LHC fills
- CMS recording data with around 92% efficiency
- Level-1 trigger rate up to 110 kHz

Run 3 integrated luminosity



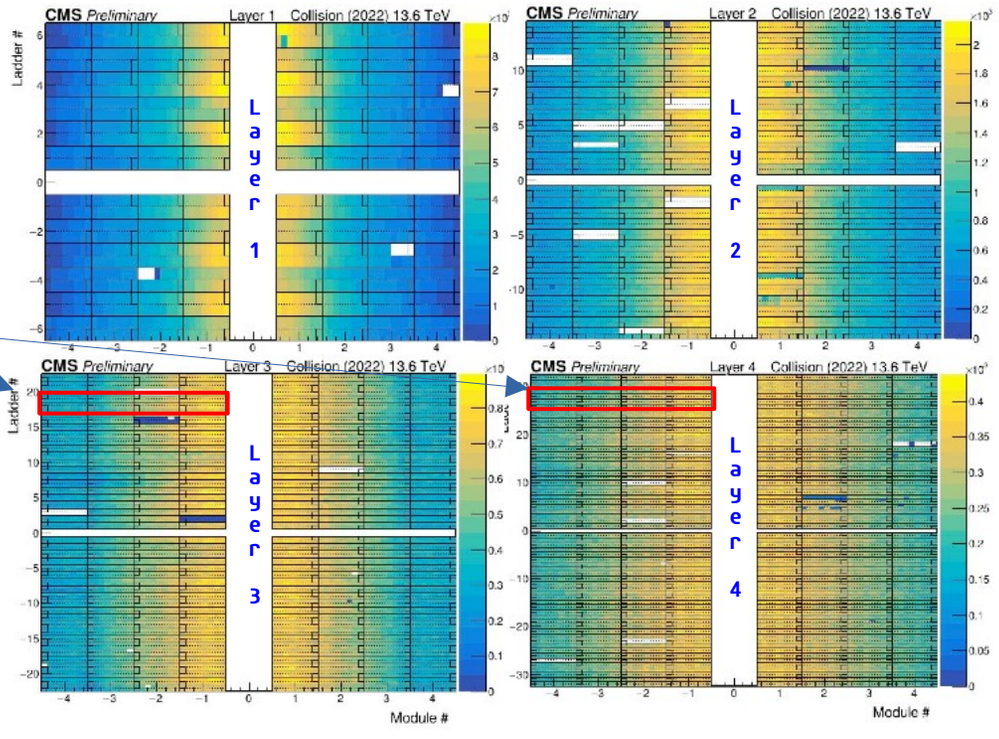
Pixel Detector – Operational Status

- Refurbishments during LS2
  - Completely new BPIX Layer 1 (exchange planned in any case due to radiation damage)
    - Opportunity used to develop and deploy **improved version of ASICs (TBM and PROC600)**
  - Full set of new DCDC converters
  - Other work during LS2
    - Replacement of few non-working modules in BPIX Layer 2
    - Rework of cooling connections on FPIX
    - Change of low and high voltage distribution for FPIX
    - Upgrade of power supplies



Installation of new BPIX Layer 1

- Active fraction at beginning of June 2023
  - 98.4 % of Barrel Pixels
  - 97.9 % of Forward Pixels
- New failure in June 2023: group of 27 modules in Barrel layers 3/4 with problem in clock distribution
  - Excluded from data taking
    → Barrel Pixel ~96% active channels



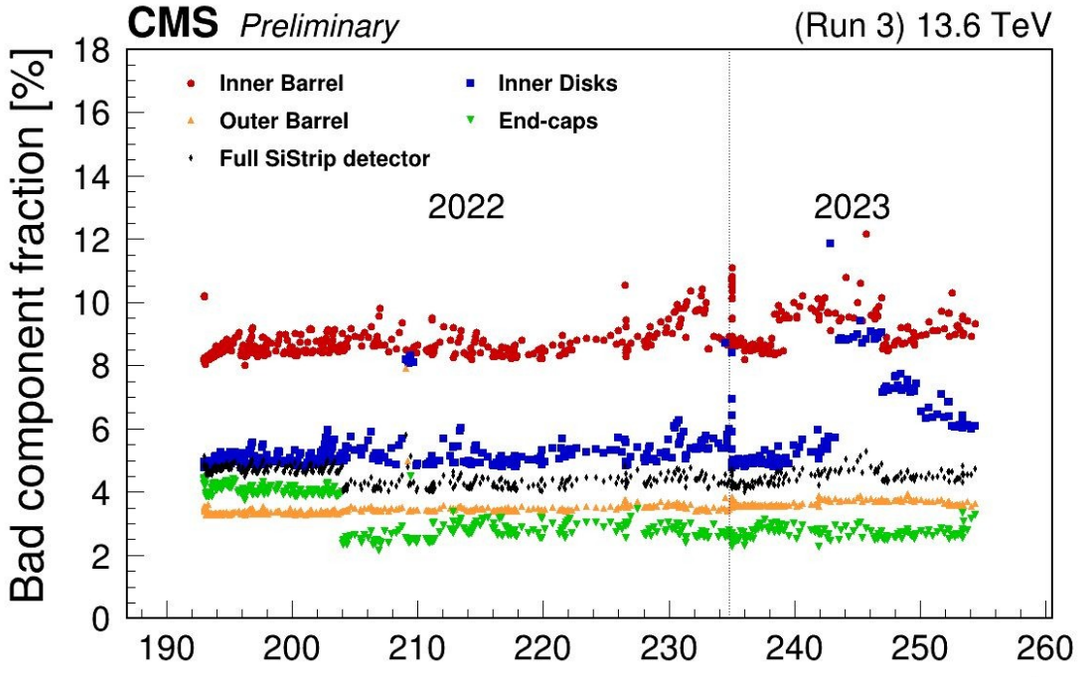
Hit map for barrel layers

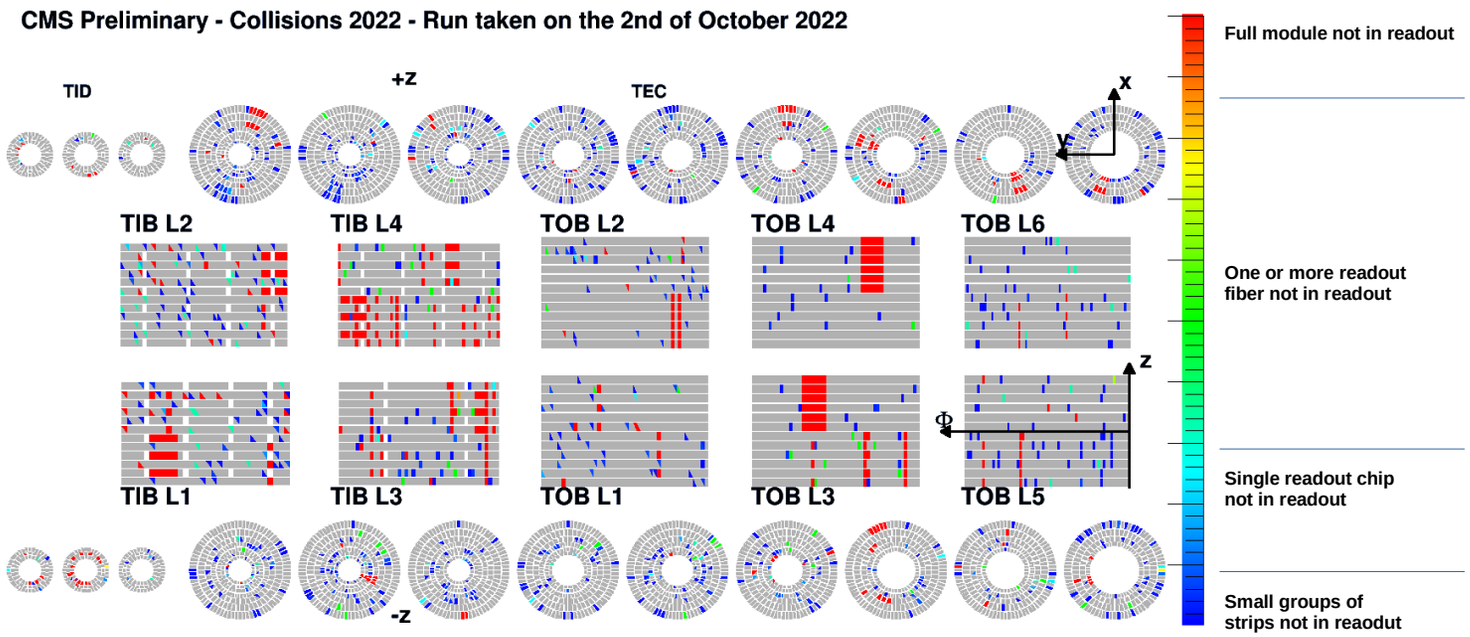
Strip Detector – Operational Status

- System hardware is ~unchanged since start of operation in 2009
- Coolant set point gradually lowered to counter radiation effects

+4°C (‘09-’12) → -15°C (‘15-’17) → -20°C (‘18,’22) → -22°C (‘23)

Run 1 Run 2 Run 3

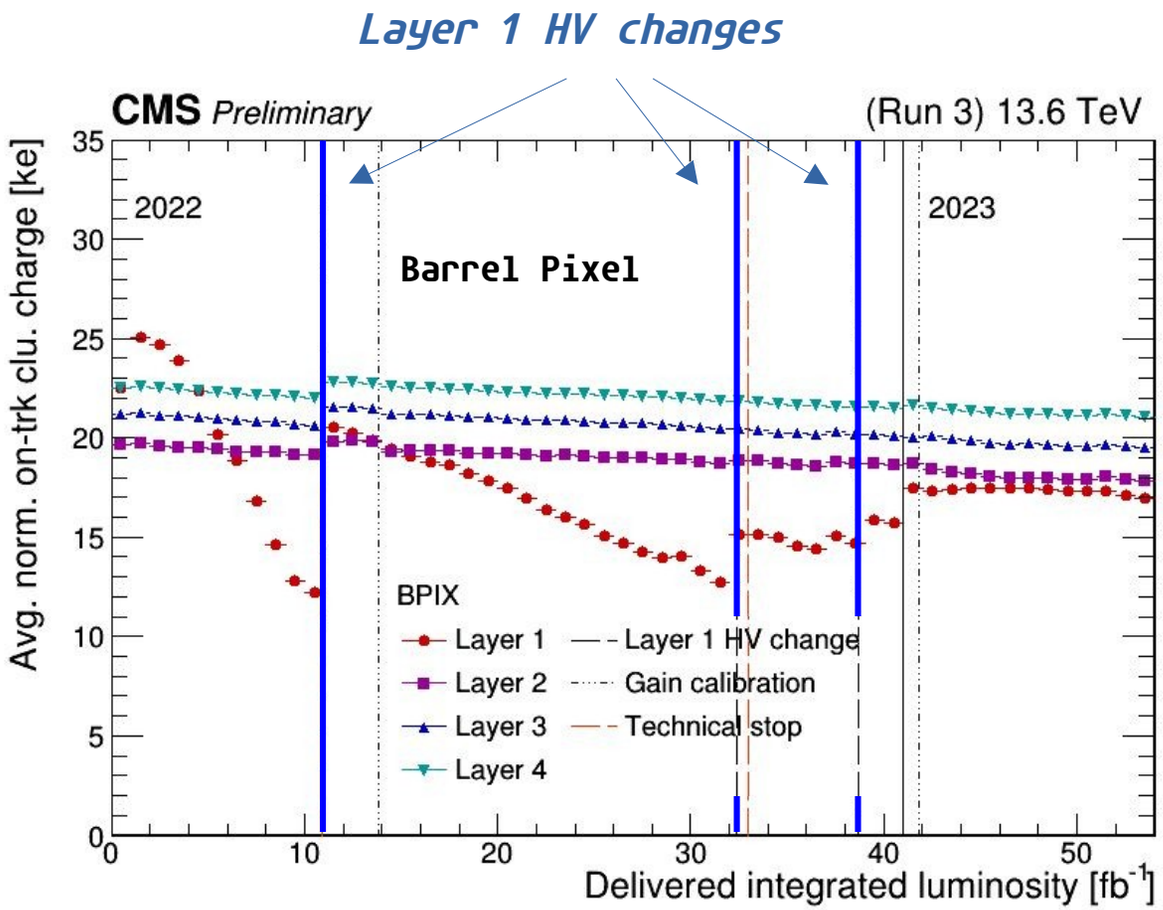


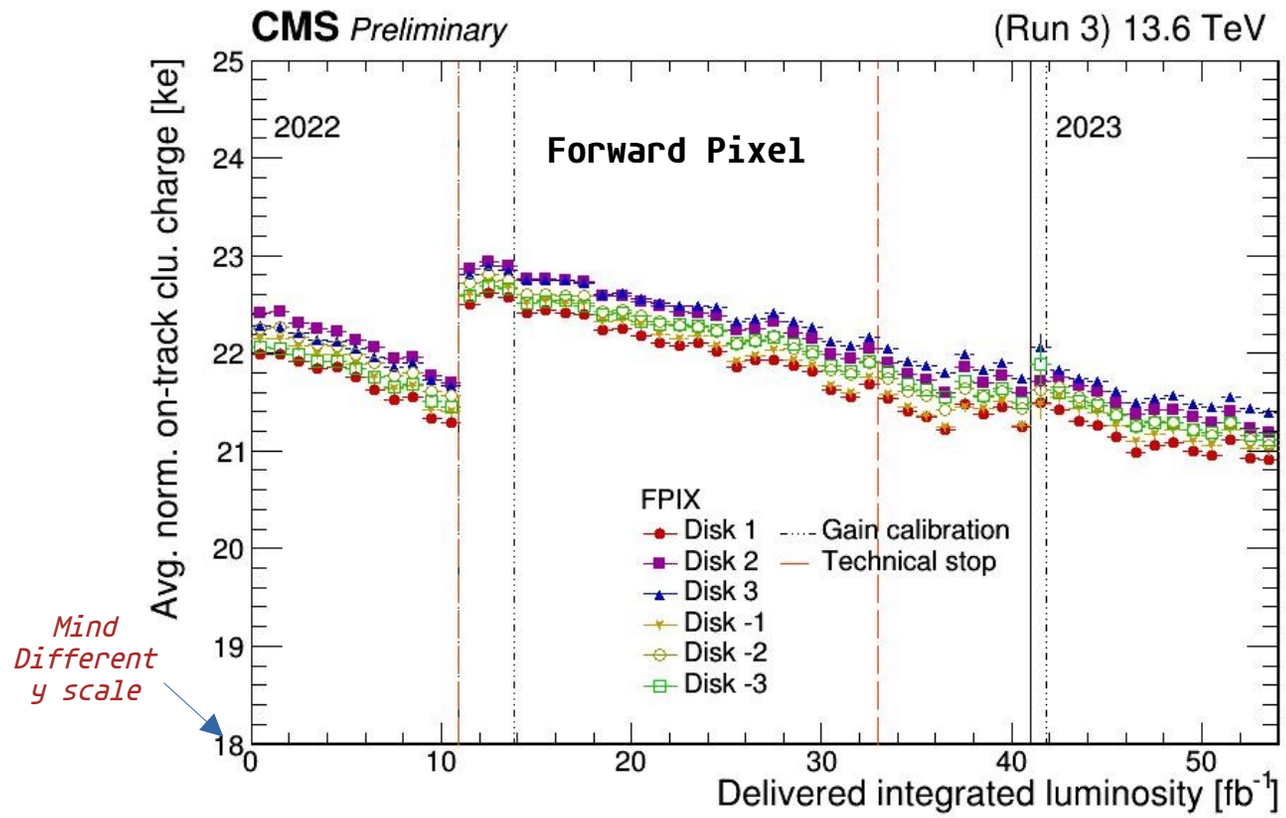


- Number of active channels quite **stable at around 96%**
- Some fluctuations during Run 3
  - End-caps → modules on a closed cooling loop in operation again
  - Inner disk → small total number of modules, few modules result in large fluctuations

Detector Performance

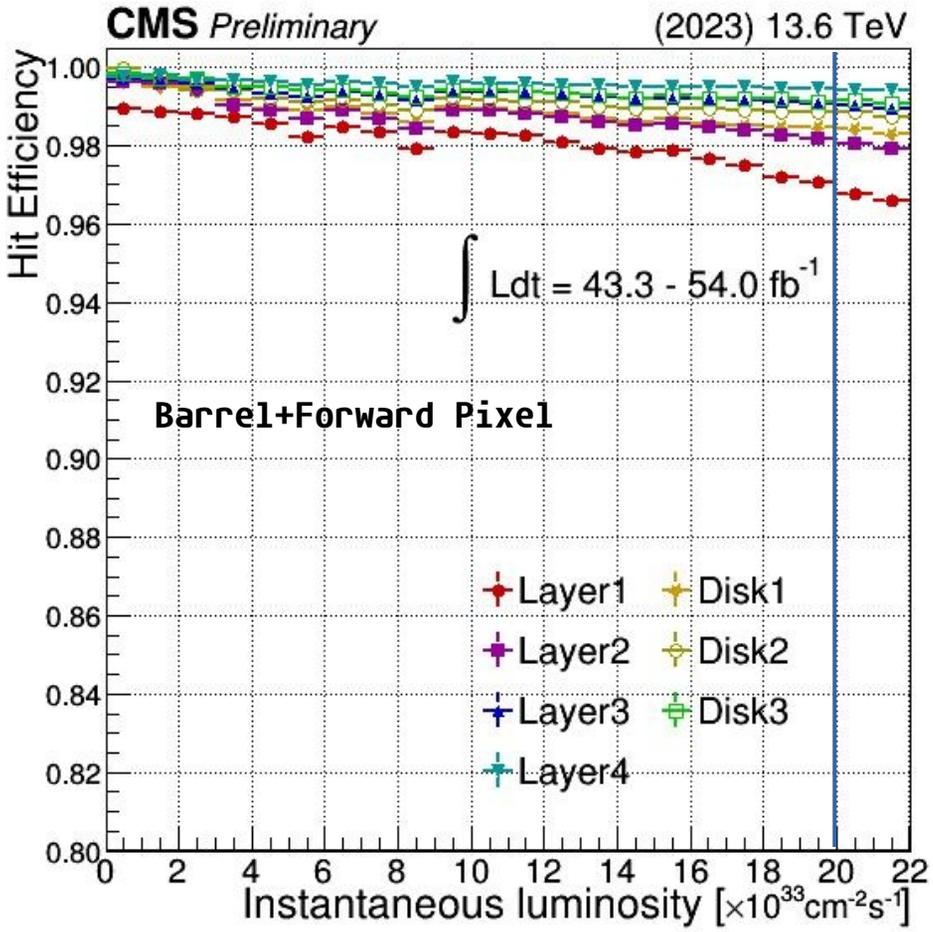
Pixel – Cluster Charge

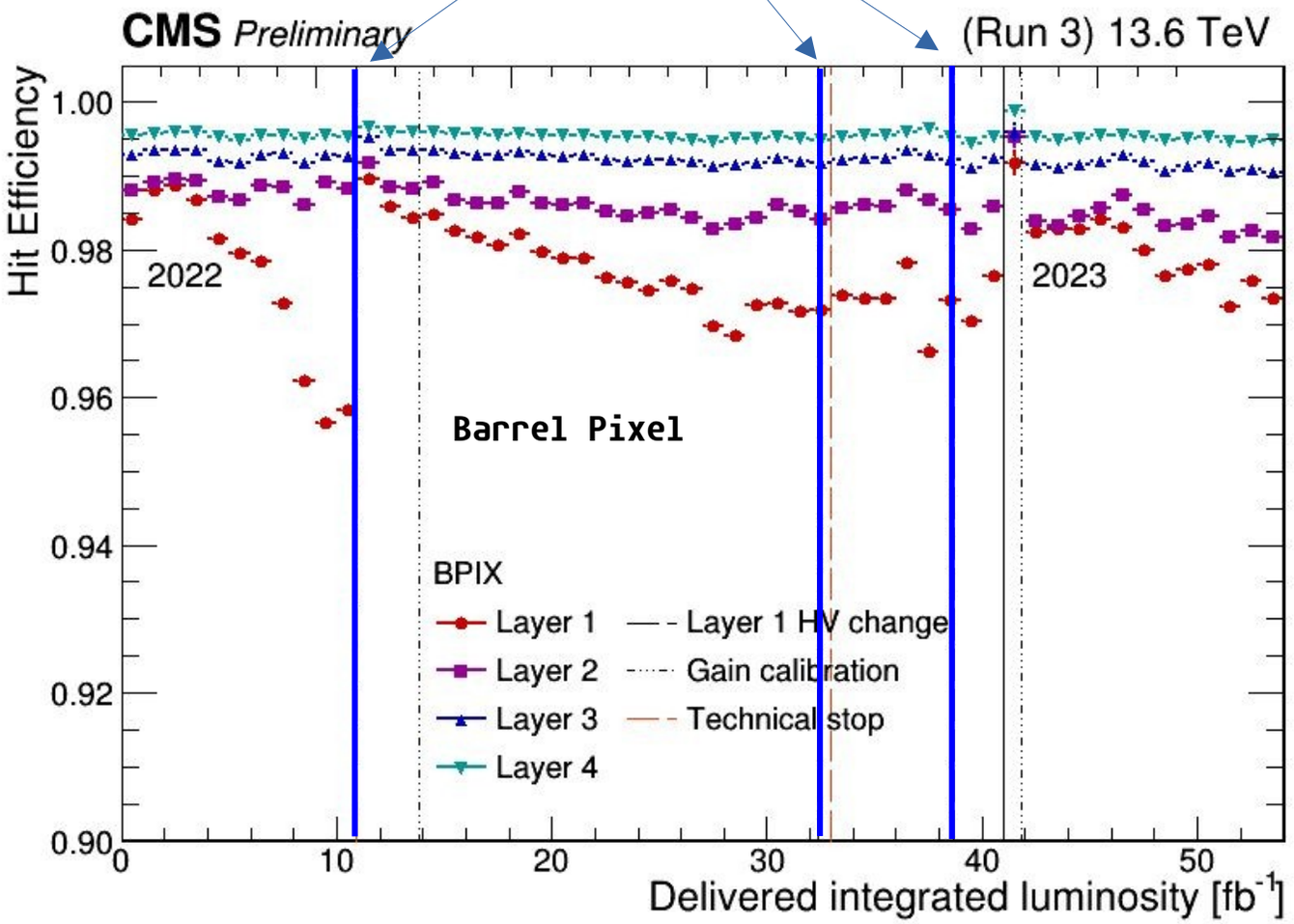




- Rapid change of conditions in new BPIX layer 1 → expected
  - Now pace of change has slowed, in line with other layers (see also later)
- Steep reduction initially for new layer 1 before HV change around 11 fb^{-1} → luminosity accumulated in short time

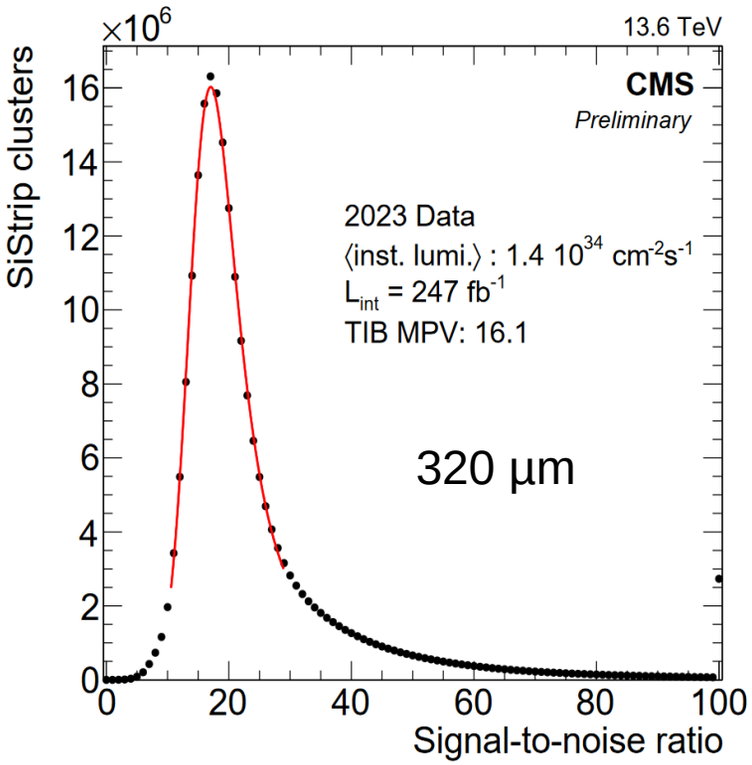
Pixel – Hit efficiency

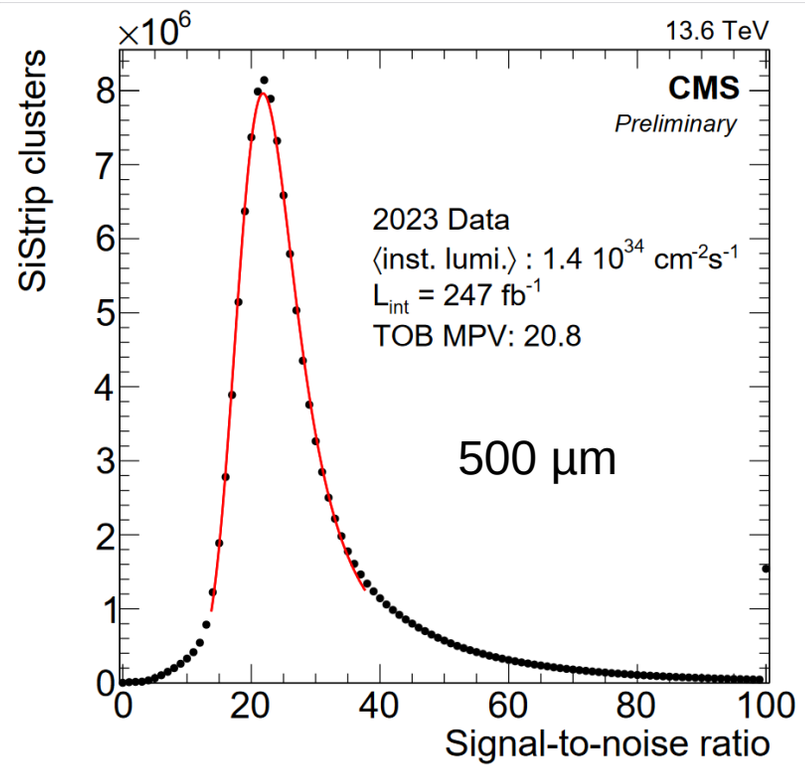


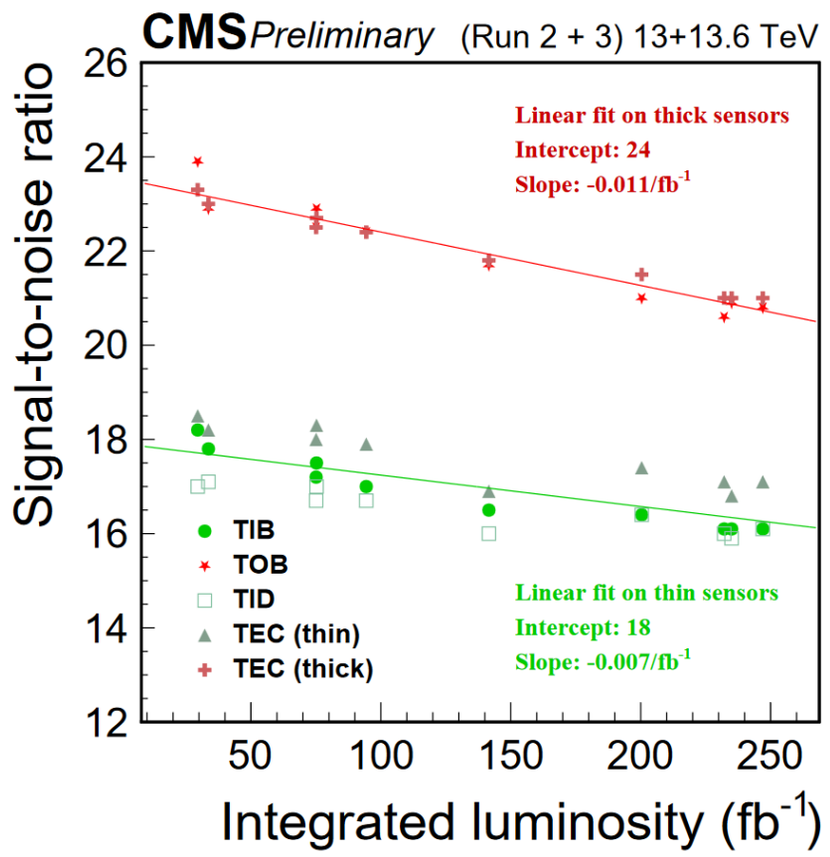


- As function of instantaneous luminosity and integrated luminosity
- Hit efficiency **at $2\times10^{34}cm^{-1}s^{-1}$**
  - above 98% for all BPIX L2-4 and FPIX,
  - BPIX L1 efficiency around 97%
- Sharp drop seen in cluster charge also seen in hit efficiency
  - Fully recovered after HV adjustment

Strips – Signal to Noise ratio

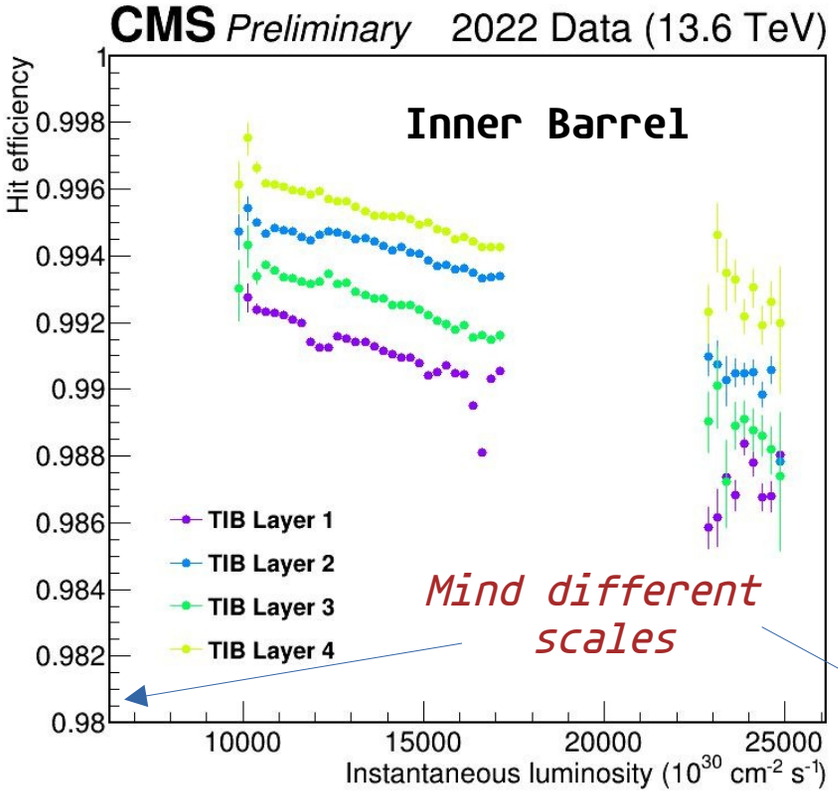




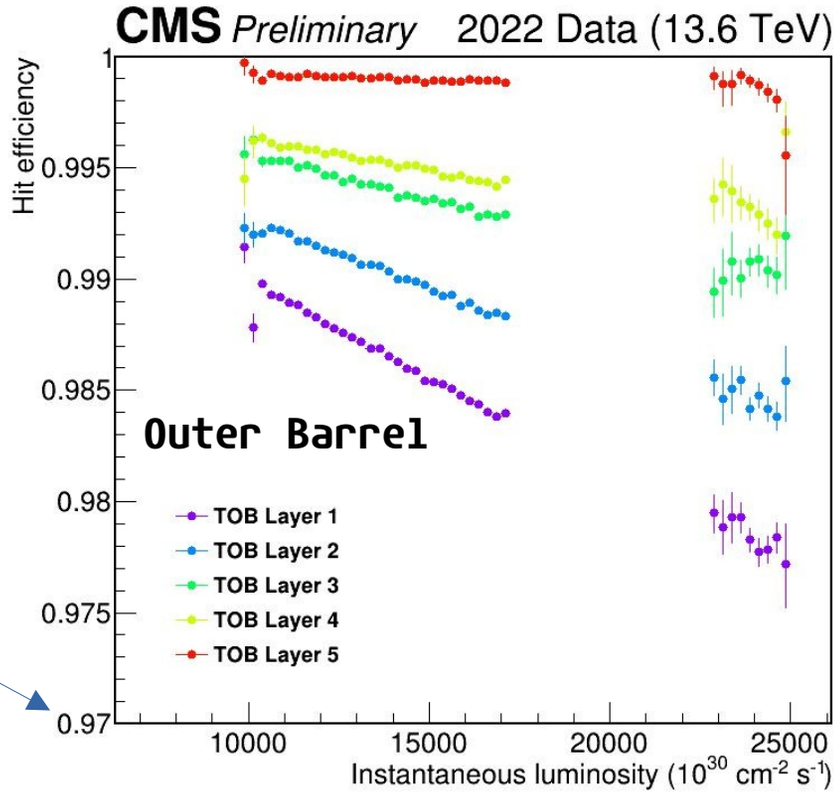


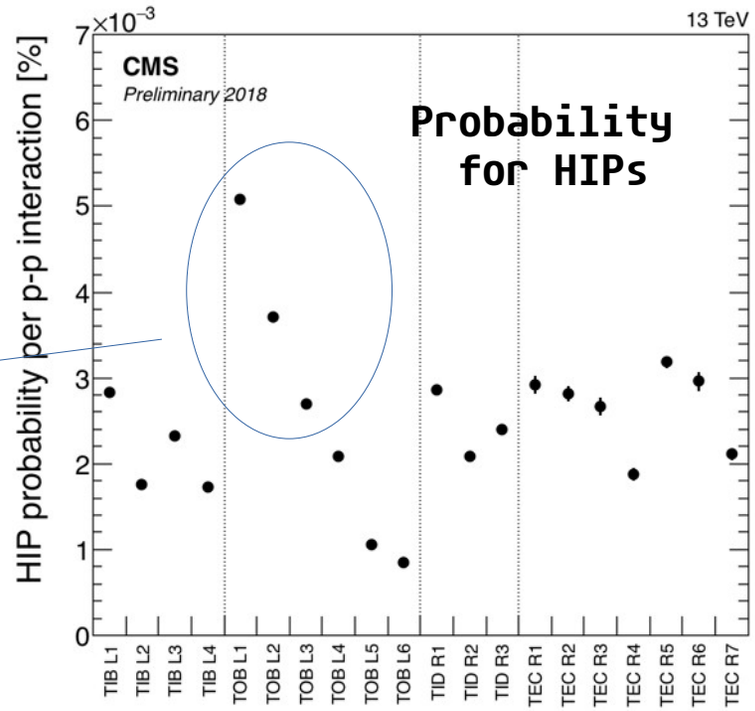
- Good signal-to-noise ratio crucial to performance; used in
  - Zero-suppression in readout electronics
  - Offline cluster reconstruction
- Extrapolation to **500 fb-1 yields S/N > 14 (18) for thin (thick) sensors** → excellent result
  - Design specification of **S/N > 10** after 10 years and 500 fb-1

Strips – Hit Efficiency

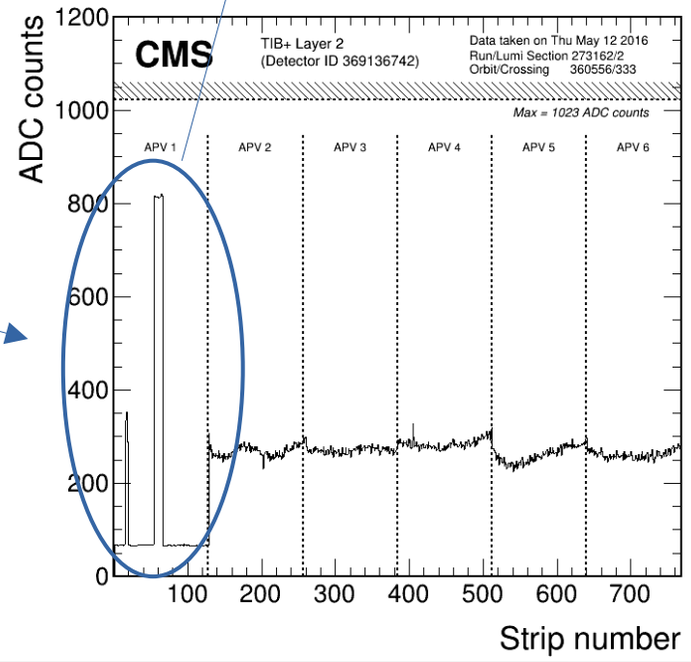


Mind different scales

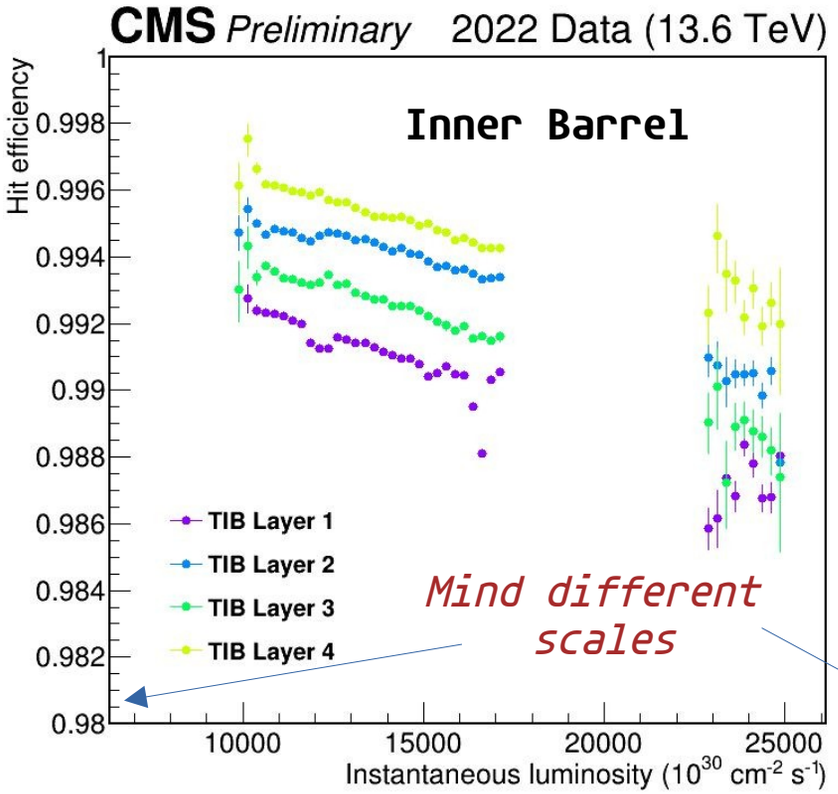




- Hit efficiency **> 98%** up to instantaneous luminosities of $2x10^{34}cm^{-2}s^{-1}$
  - Inner barrel layers **>~99%** efficient
  - Residual inefficiency caused by heavily ionizing particles
    - Probability for outer barrel higher because of larger modules (daisy-chained sensors) and thicker silicon bulk (500 vs 320 μm)



Strips – Hit Efficiency



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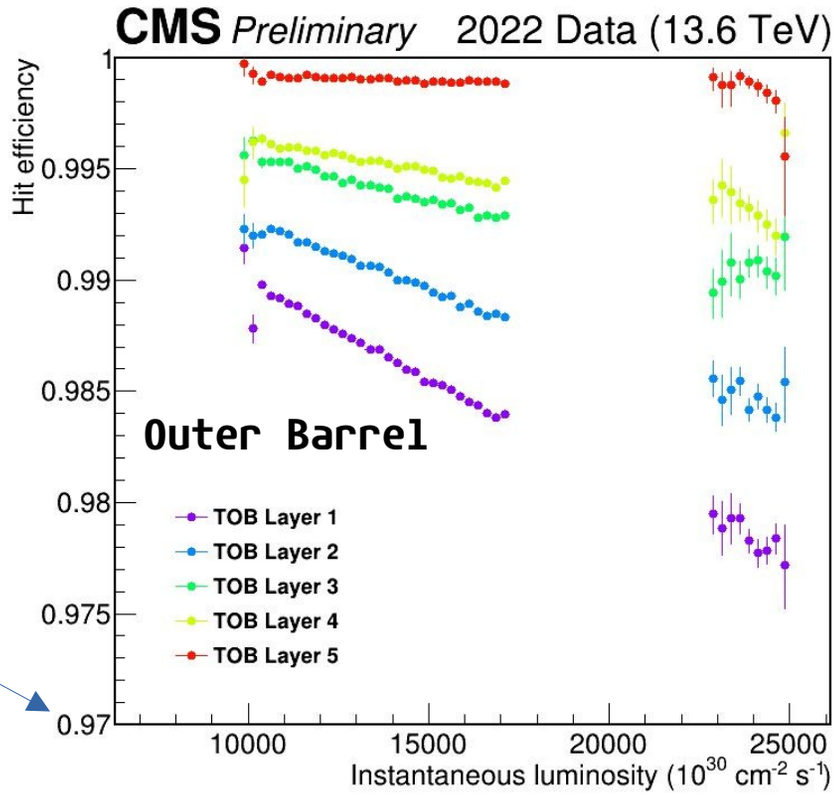

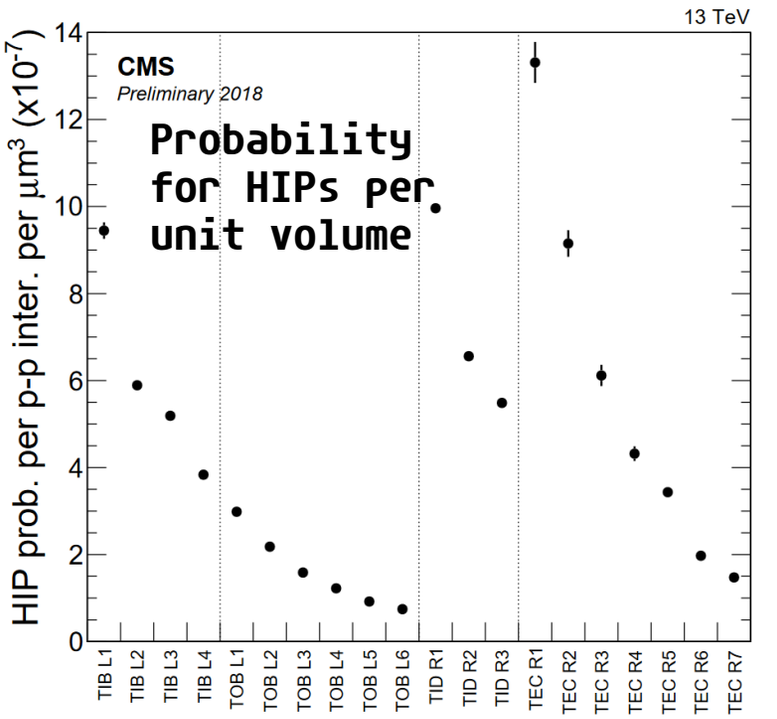

Expected 1/r2 scaling when normalized to unit volume in silicon

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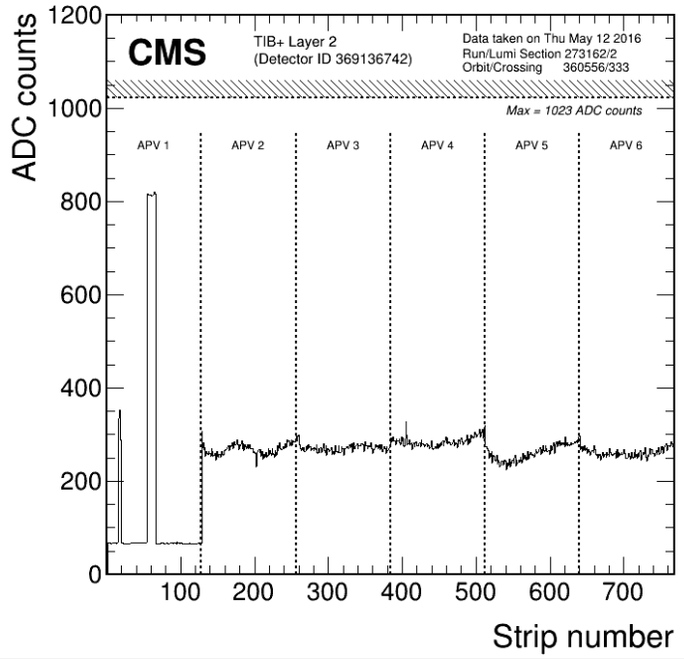
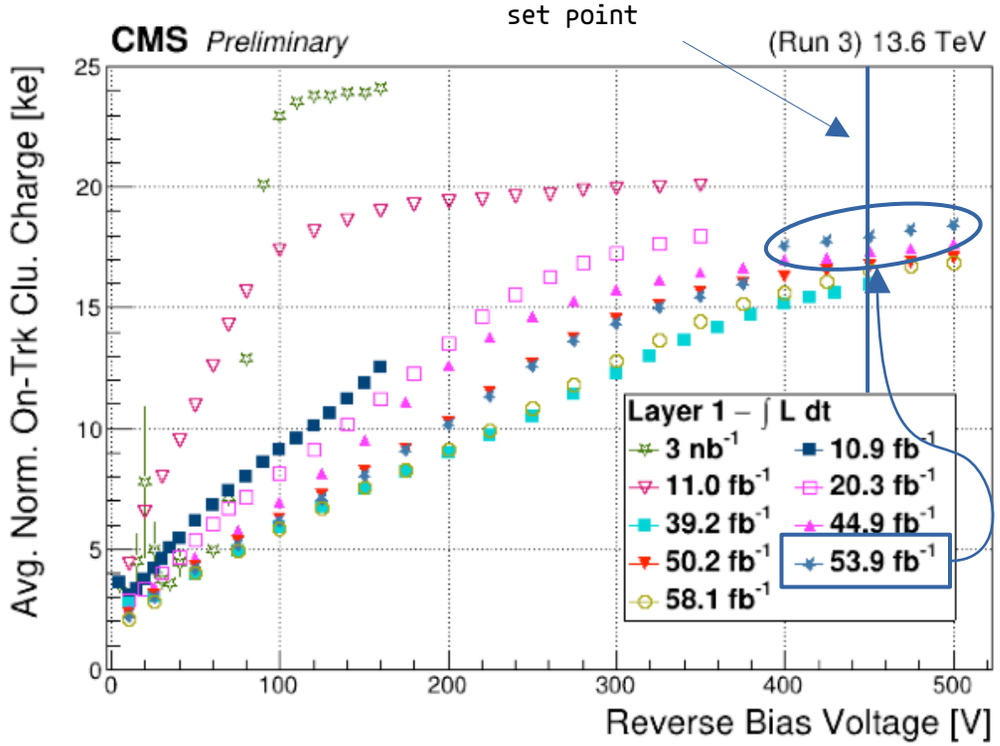
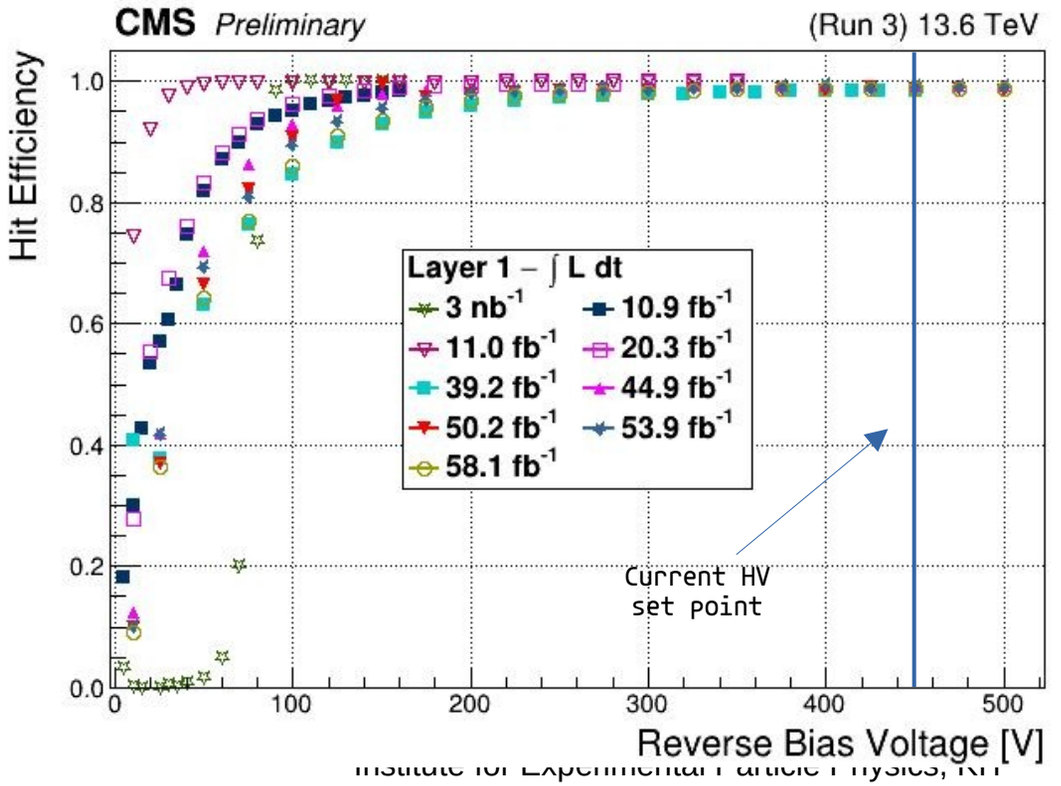


Radiation Effects

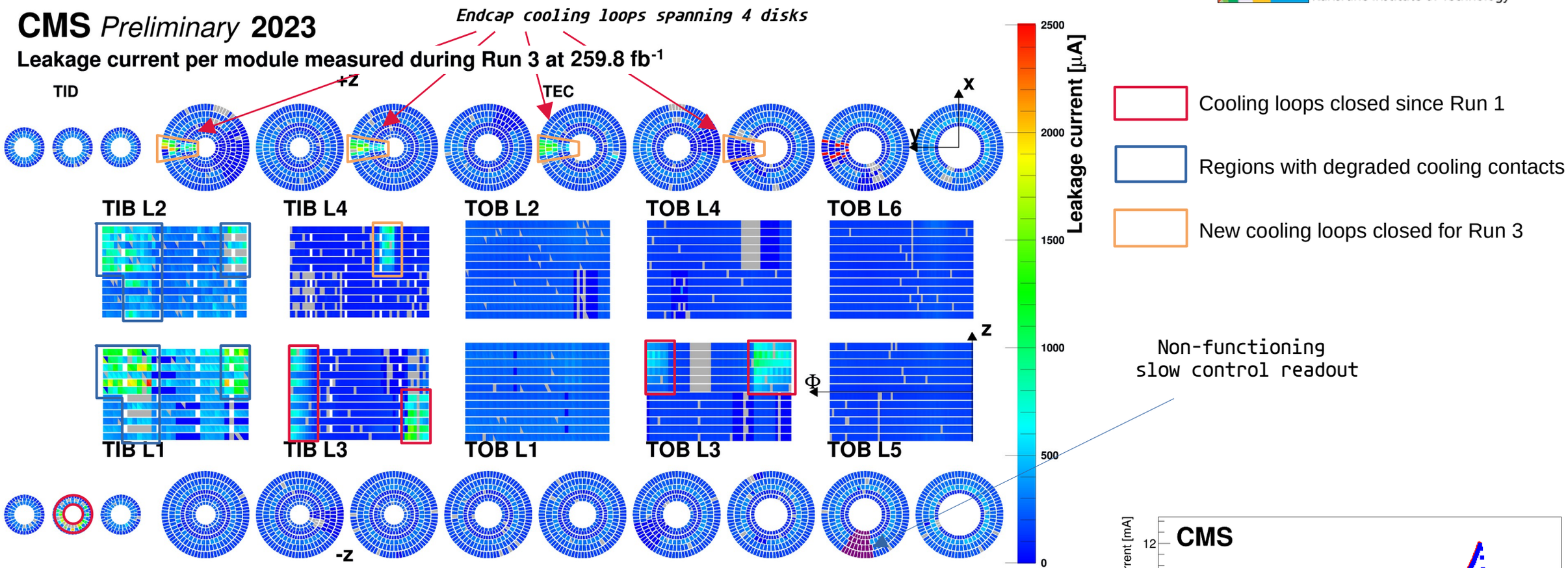
Barrel Pixel Layer 1 – Radiation effects

- Unirradiated sensors operated at 150 V
- n-in-n sensors went through type inversion very early in Run 3
- HV settings raised to keep efficiency and spatial resolution optimal
  - **Current set point: 450 V**
    - Maximum 800 V
  - **underdepleted operation possible**

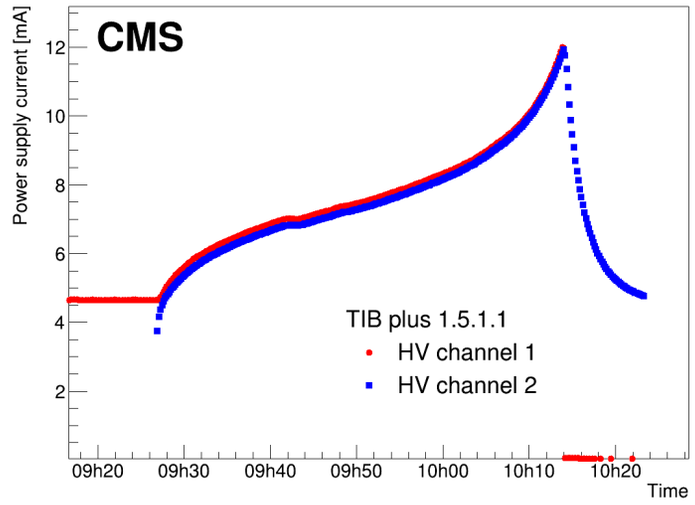




Strips – Sensor Leakage current

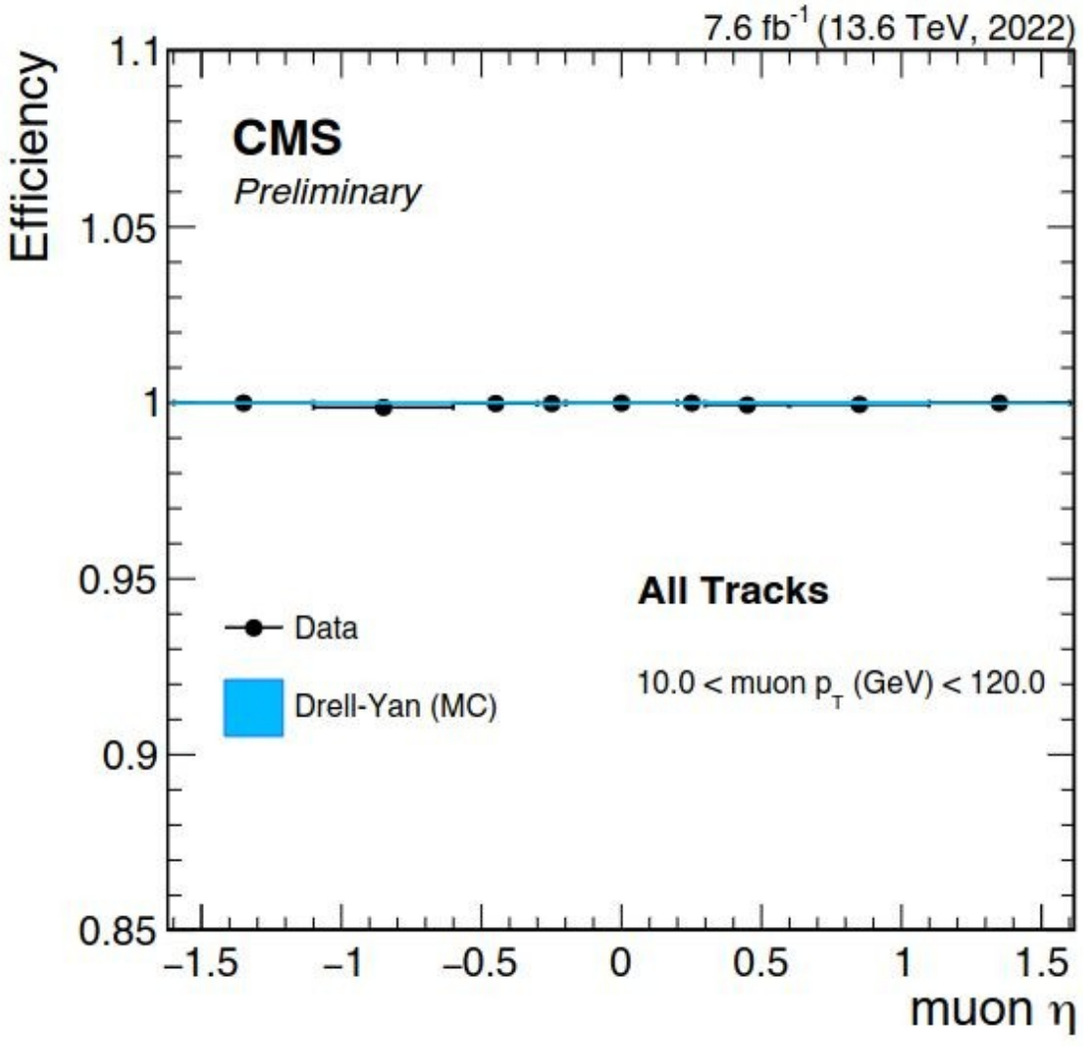


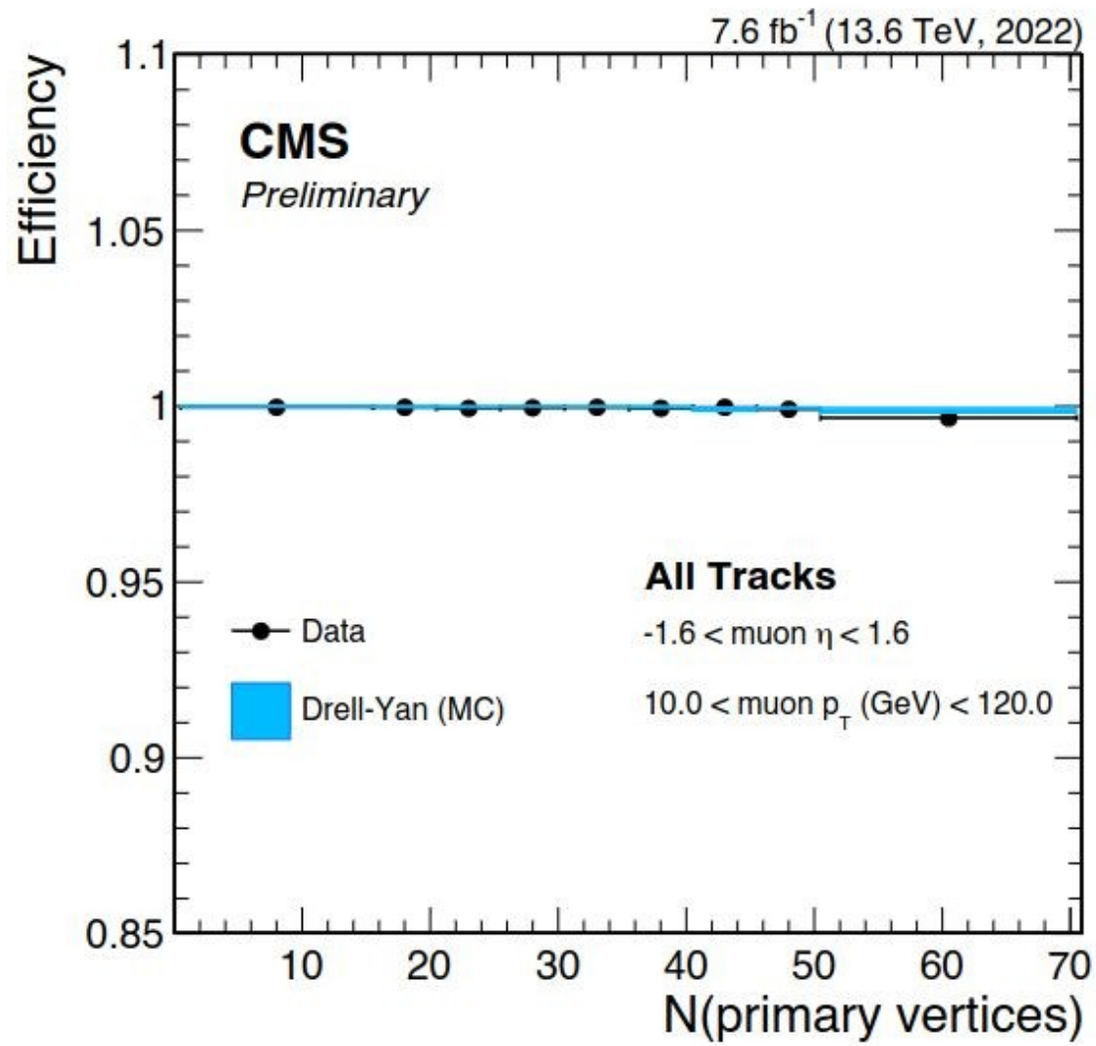
- Regions of high temperature directly correspond to regions of high leakage current
  - Individual modules in TIB layer 1 and 3 above 1 mA per module
  - Before end of Run 3 will hit power supply limit or thermal runaway on some detector parts
    - Mitigation possible through partial switch-off or lowering of bias voltage
- Vast majority of strip tracker at very low leakage currents



For illustration: thermal runaway observed in 2017

Summary (sort of...actually tracking performance)





N.B. effect of BPIX L3/4 failure not in here but effect on efficiency small (but small increase in fake rate)

- Efficiency measured with a tag-and-probe in $Z \rightarrow \mu\mu$
  - Uses data from early Run 3
- Excellent tracking efficiency as function of η and #primary vertices

Summary and Outlook

- CMS all-silicon tracker continues to perform very well also after many years of operation
  - Active detector fraction above 95% for all detector parts
  - New failures in pixel (Layer 3 and 4 in one sector) and strips (2 additional closed cooling loops) have been encountered after LS2
    - Mitigation has been put in place where possible
- Performance parameters like signal height/signal-to-noise ratio, hit efficiency and hit resolution continue to be excellent
- Outlook until end-of-life at start of LS3 indicates good margin for excellent performance for both systems

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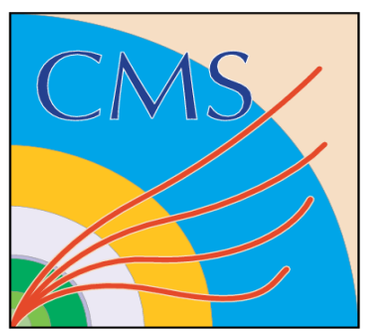
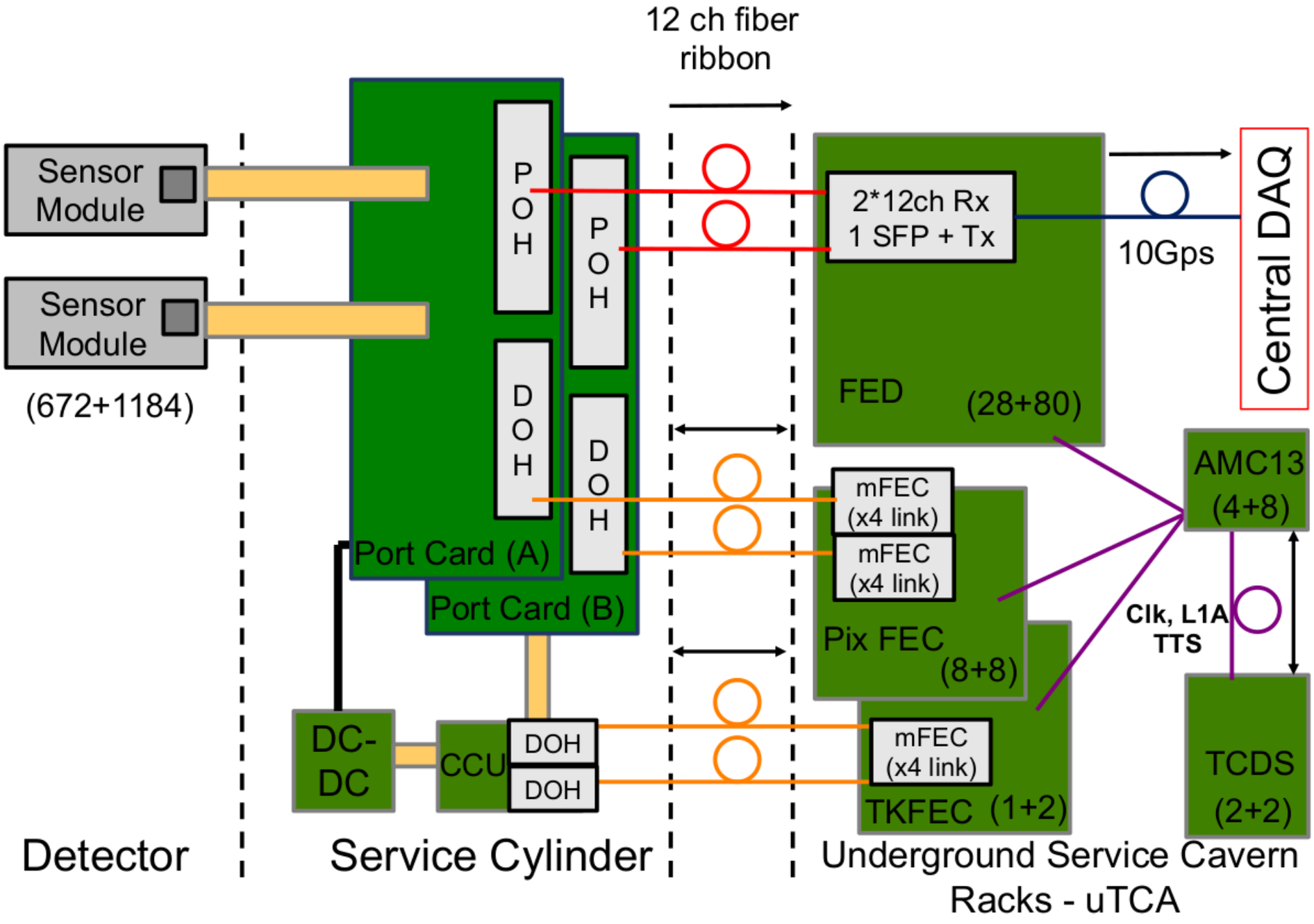
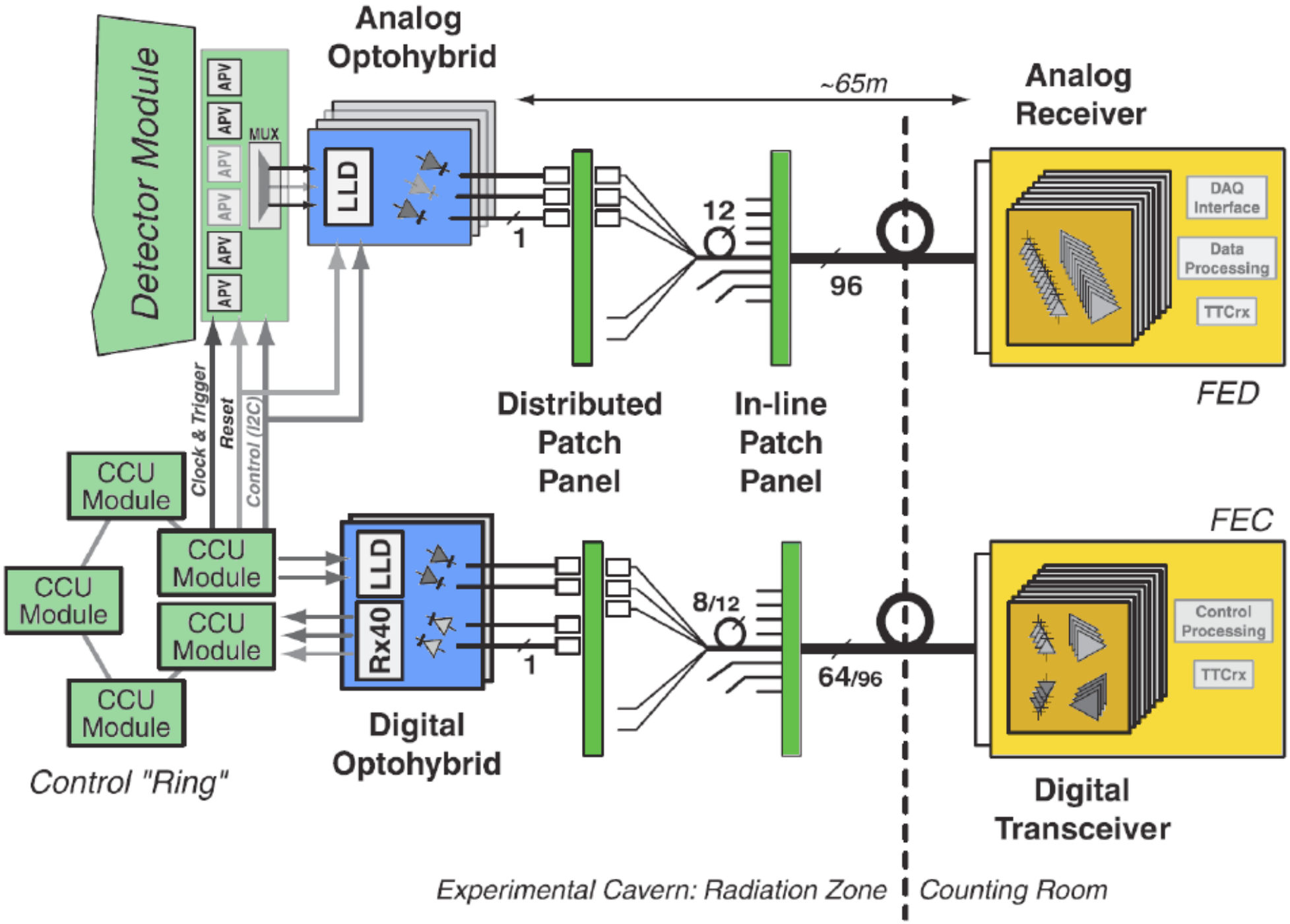


Backup

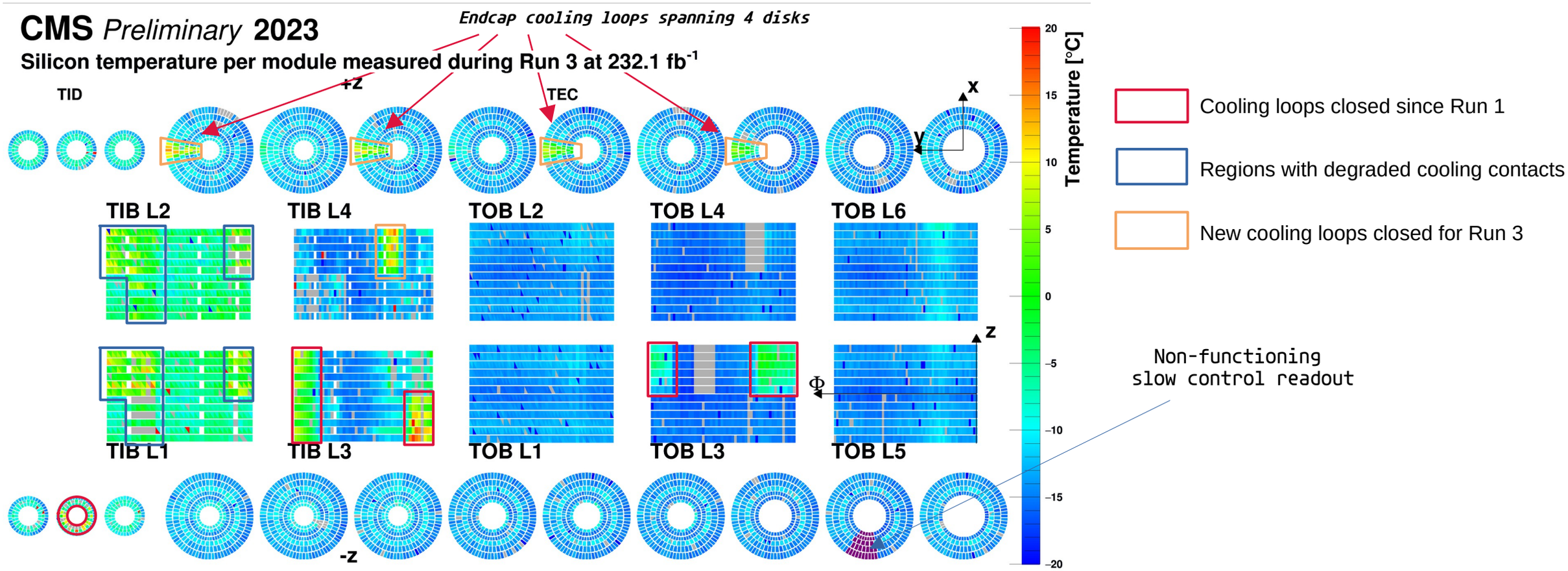
Pixel DAQ and Control Overview



Strips DAQ and Control Overview

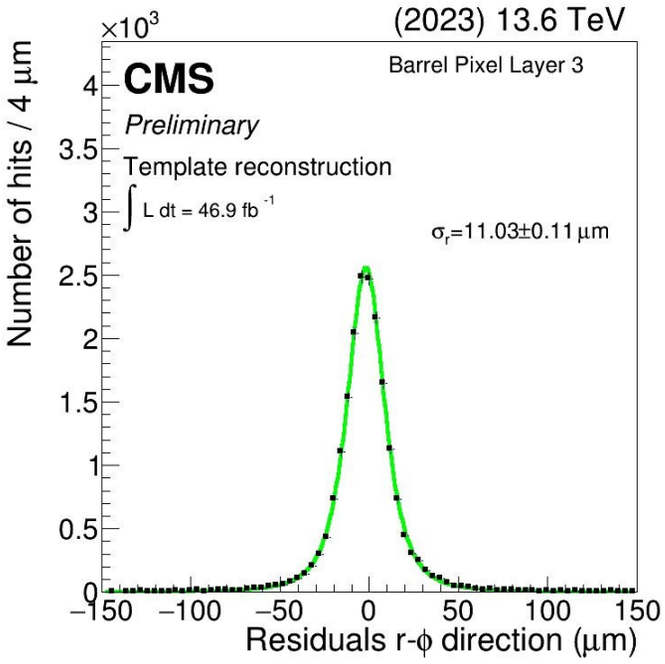


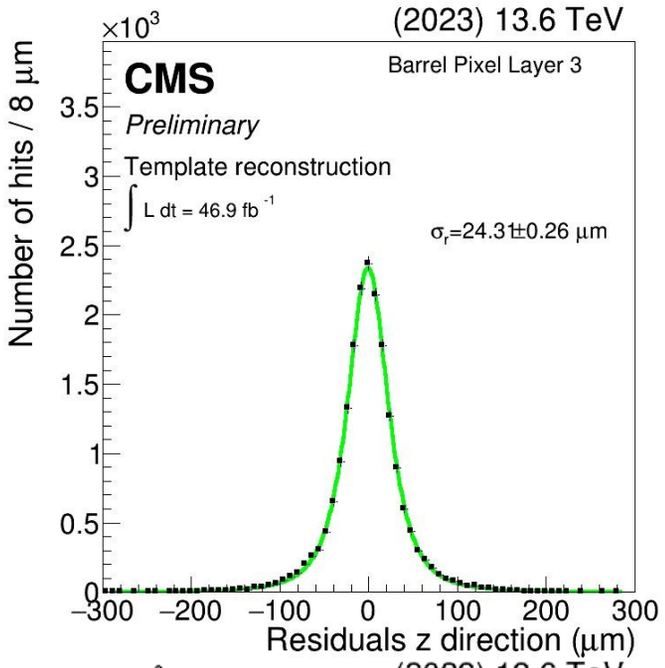
Strip Detector – Operational Status

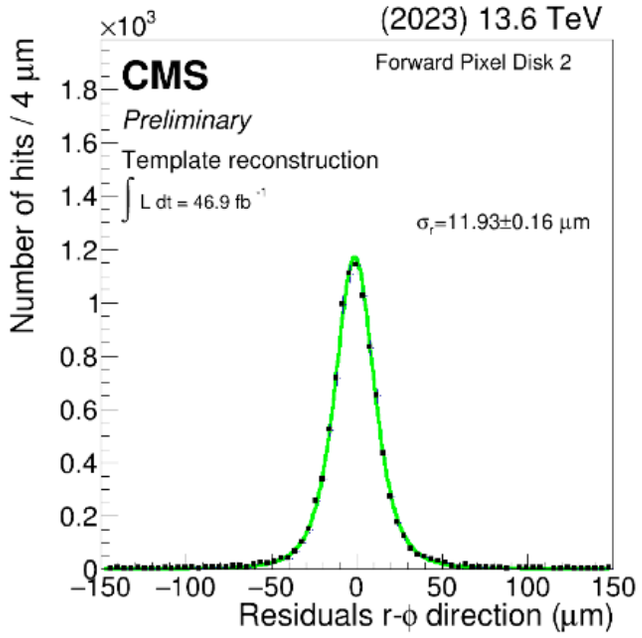


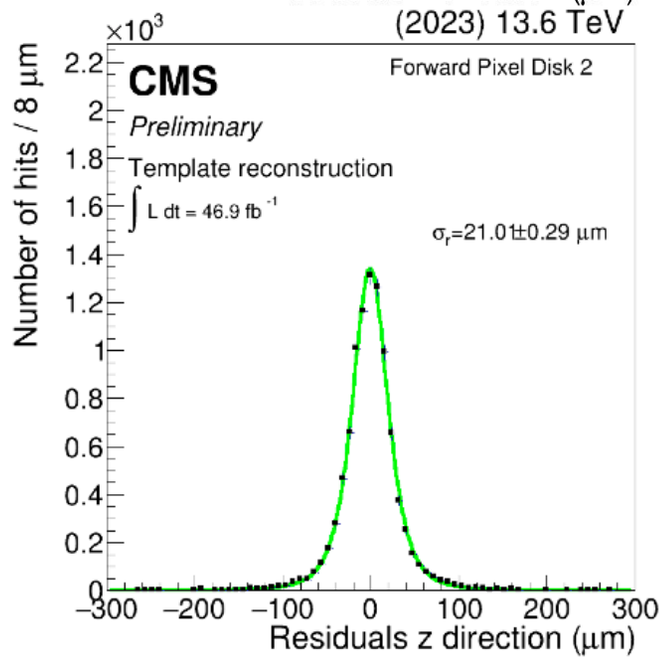
- Rather inhomogeneous temperature distribution to a number of (unfortunately well-known) issues
  - 5 out of 180 cooling loops closed since Run 1 (closed between 2009 and 2011)
  - Regions with degraded cooling contacts since 2009 overpressure incident especially in TIB layers 1 and 2
- 2 more cooling loops had to be closed towards the end of LS2

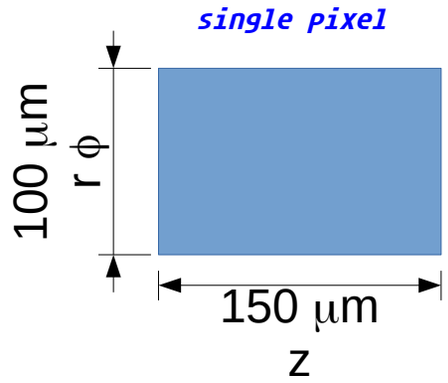
Pixel – Hit resolution





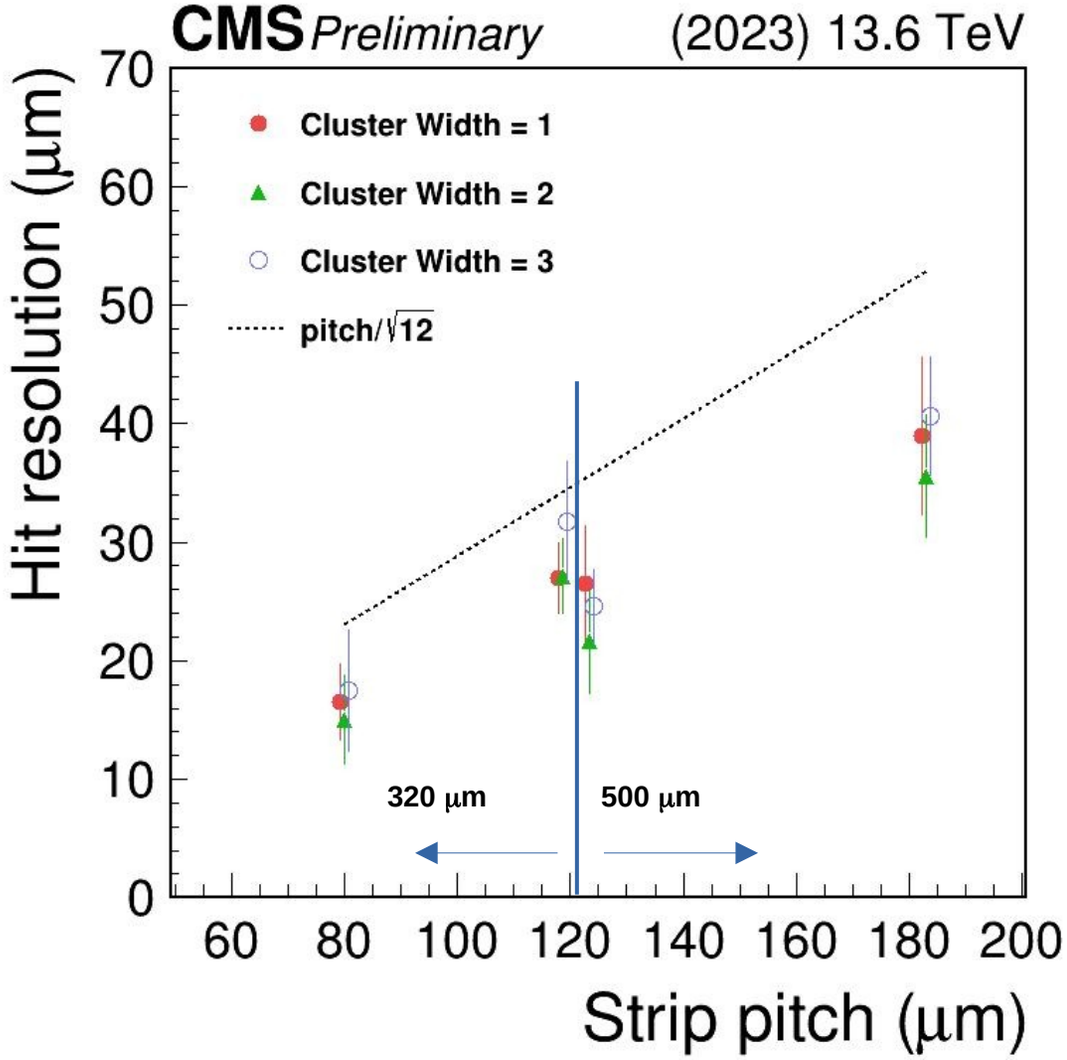


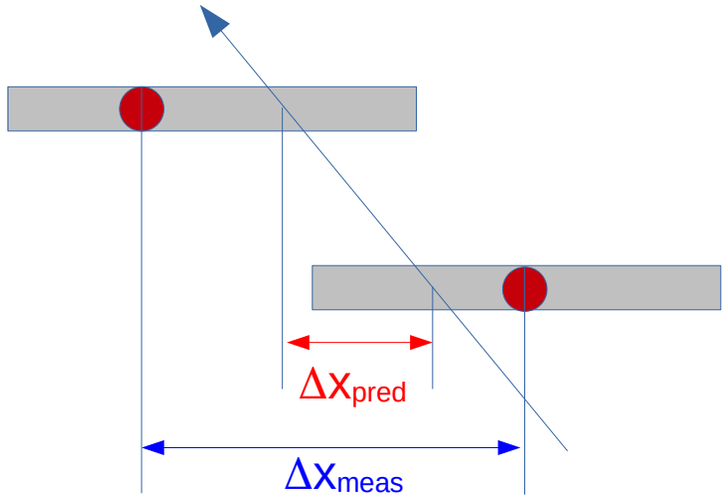




- Hit resolution measured for layers other than layer 1 and 4 (disks 1 and 3) to have good pointing resolution from surrounding layers
- Position estimate via “template” method → precise simulation of charge distribution inside sensitive volume and readout response
  - Excellent resolution in both rϕ and z

Strips – Hit Resolution

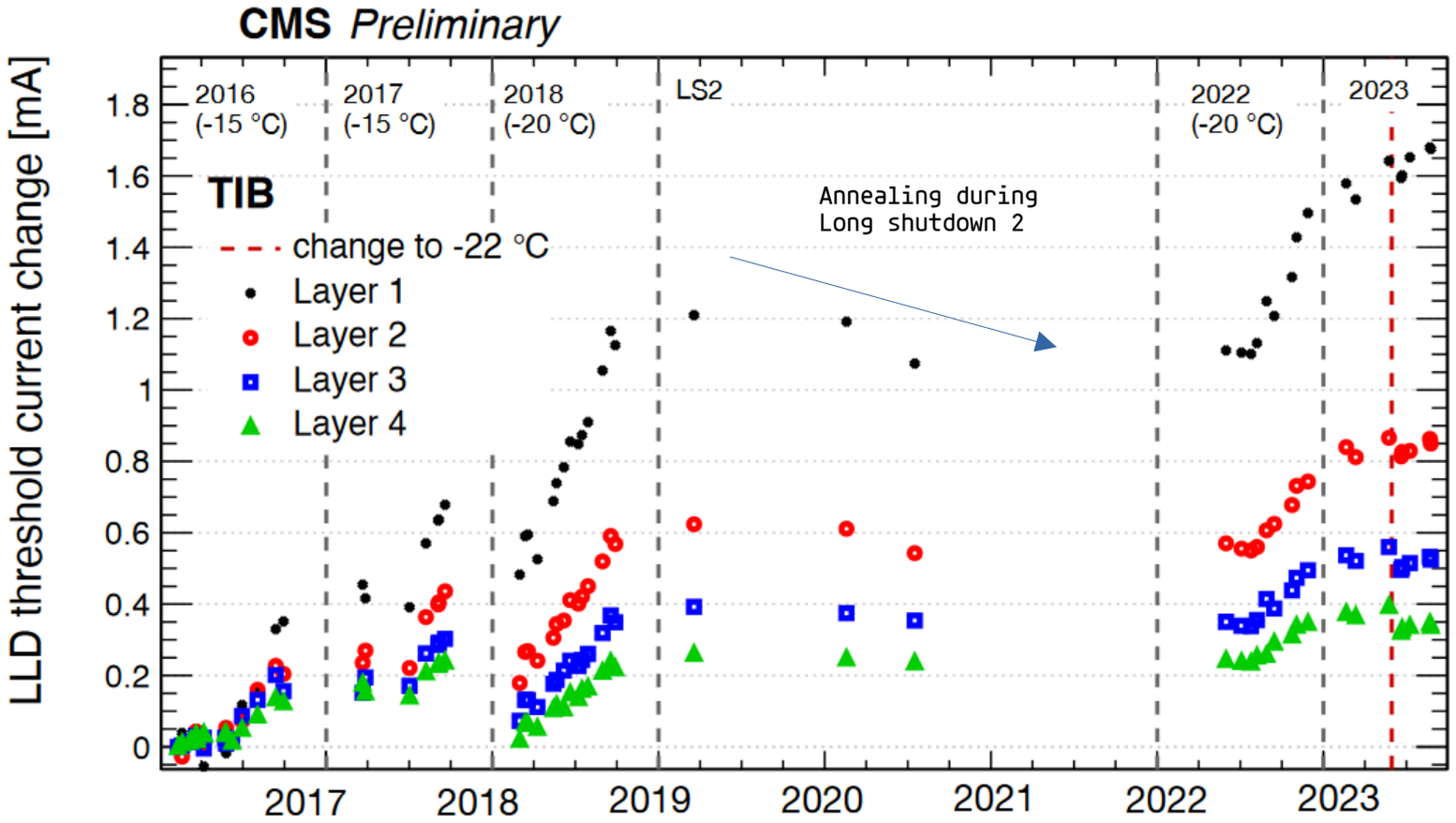


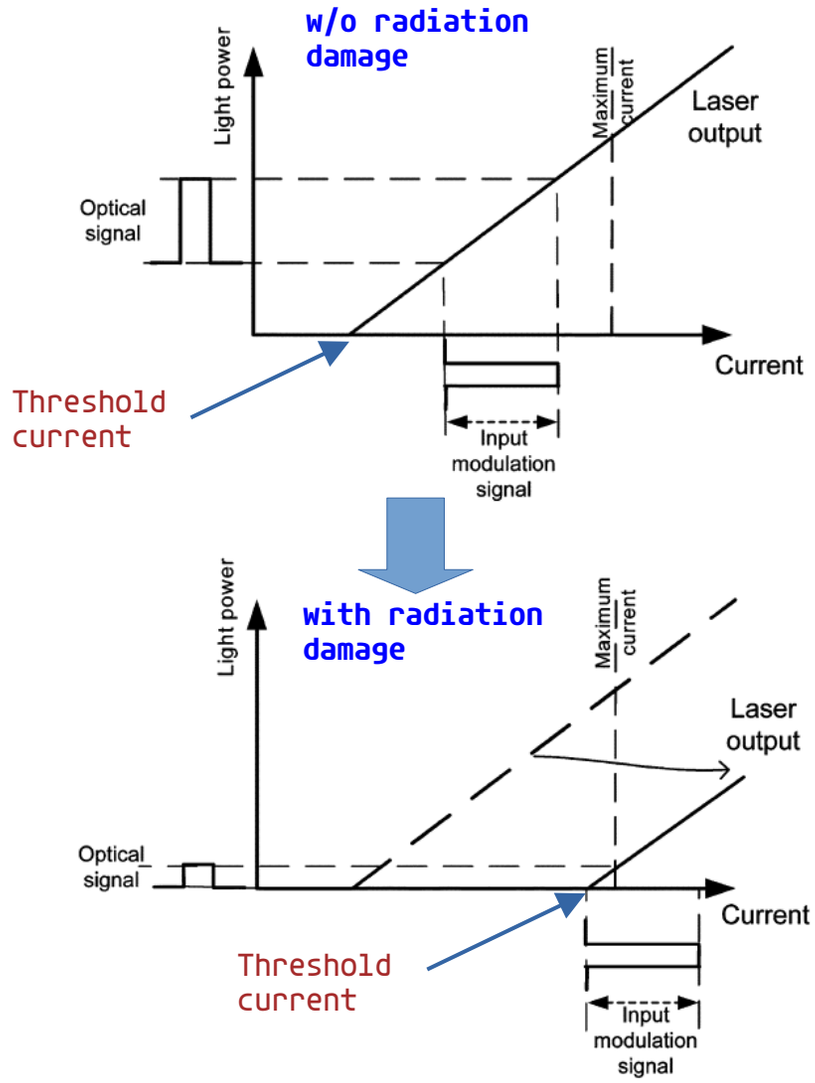


$$\sigma_{hit} = \frac{\sqrt{\sigma(meas-pred)^2 - \sigma^2_{meas}}}{\sqrt{2}}$$

- Measured in with “pair method” by using hits from overlapping modules in the same layer
  - Significantly better than binary resolution in all layers
  - N.B. strip reconstruction only uses center-of-gravity, not charge (sharing) templates

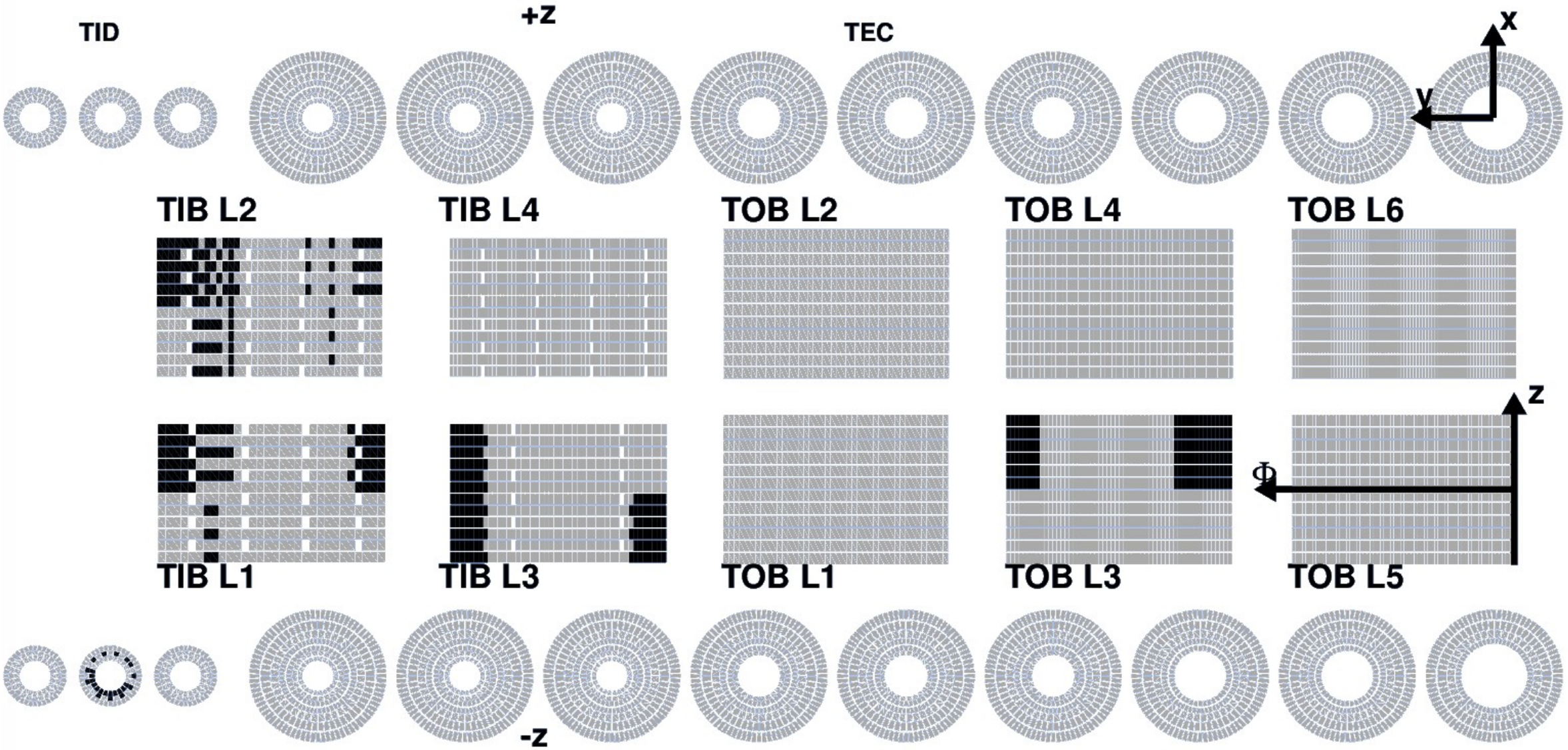
Strips Laser Driver Threshold Currents





- Laser driver threshold current monitored regularly
  - Affected by radiation damage and annealing but also temperature
- Clear dependence on radius can be seen
- Temperature set point changes manifest as drops in the distribution
- Ample margin until end-of-life of Strip Tracker

Strips Bad Components – Expectation from 2012



TDR of Phase-1 Pixel Detector, 2012: modules in black that are expected to degrade in performance in the future