OPERATION AND PERFORMANCE OF THE ATLAS SEMI-CONDUCTOR TRACKER

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FOR THE ATLAS SCT COLLABORATION

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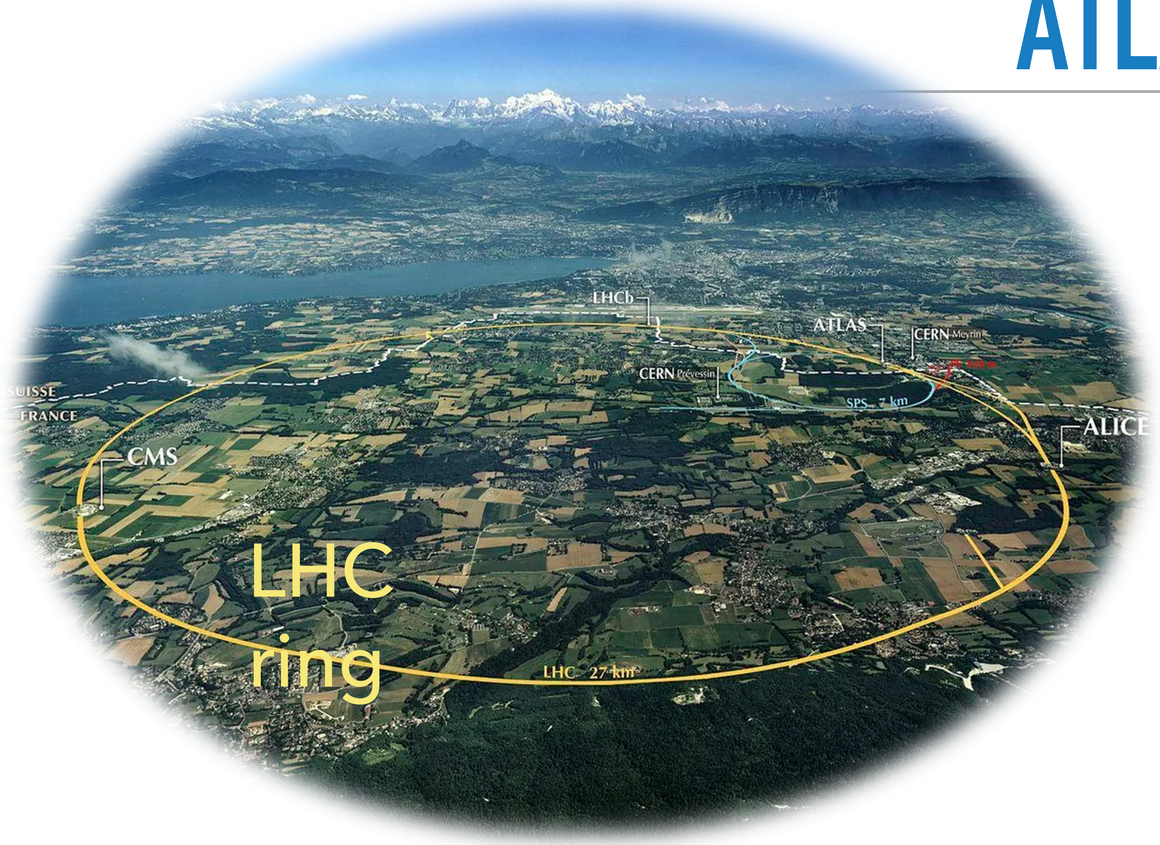
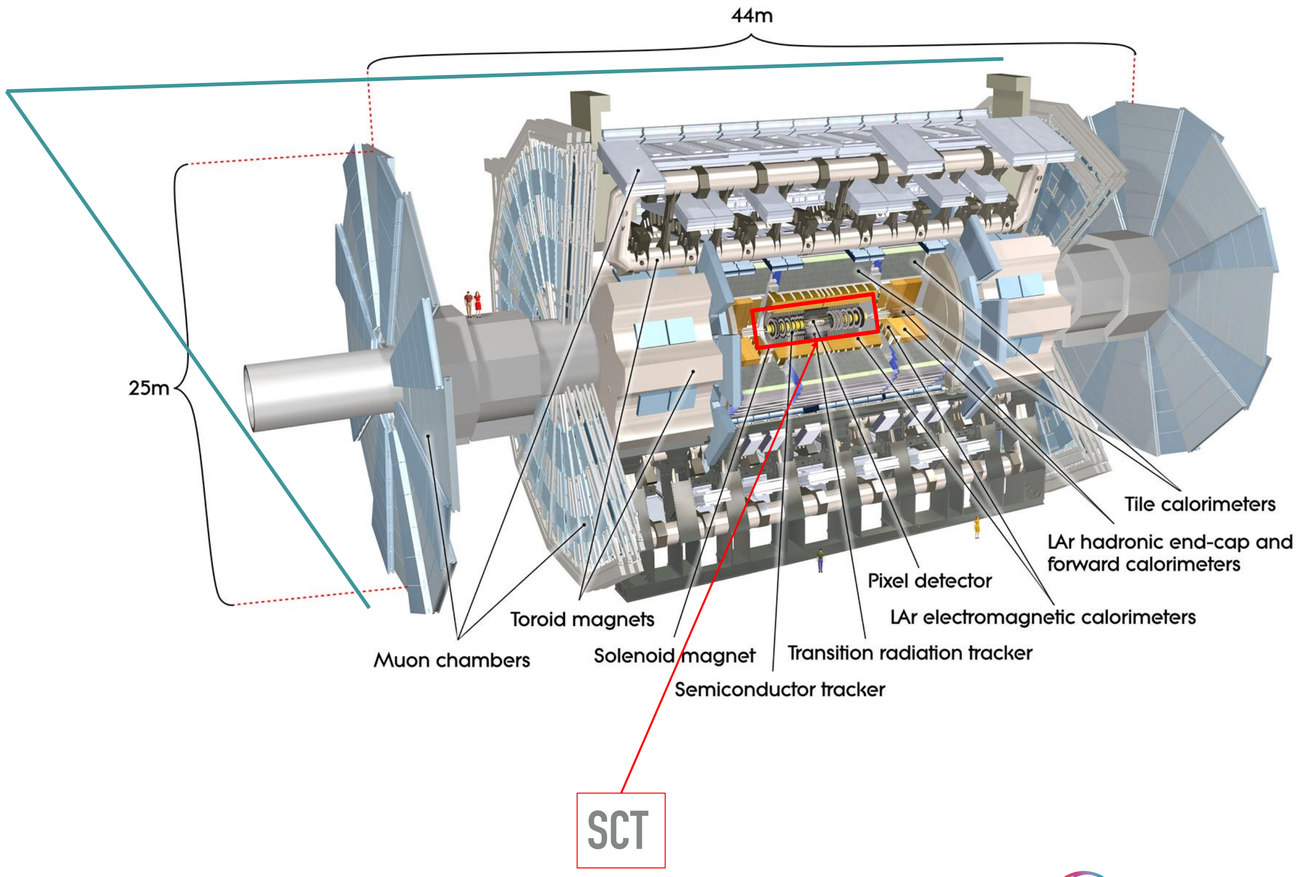
ATLAS AT THE LHC



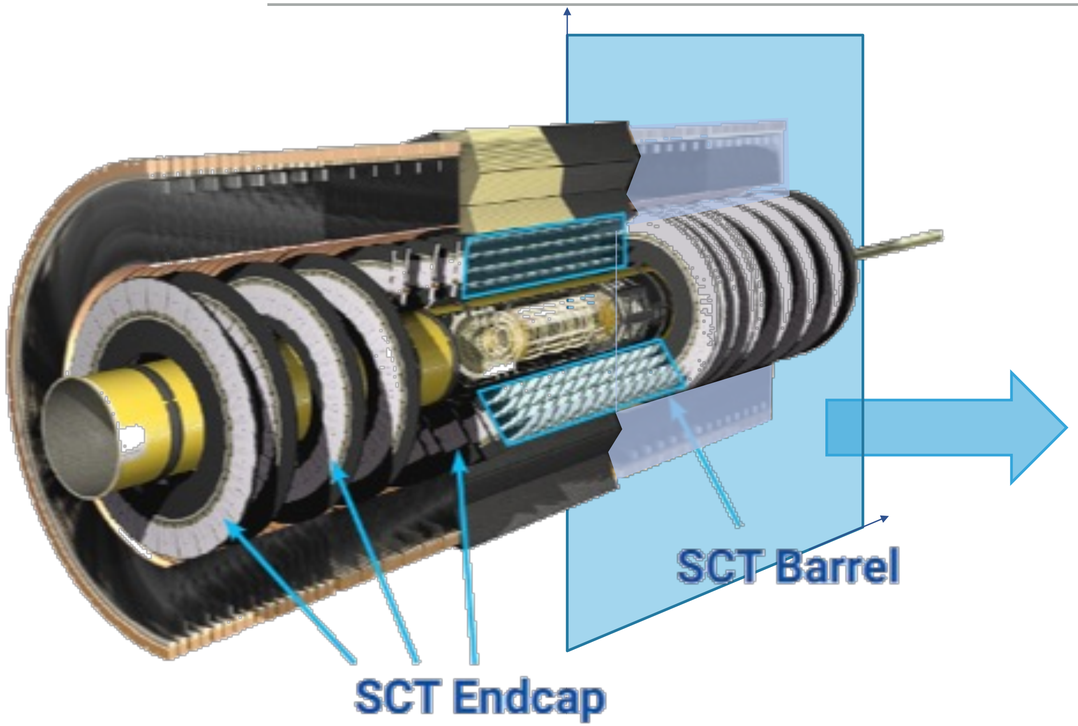


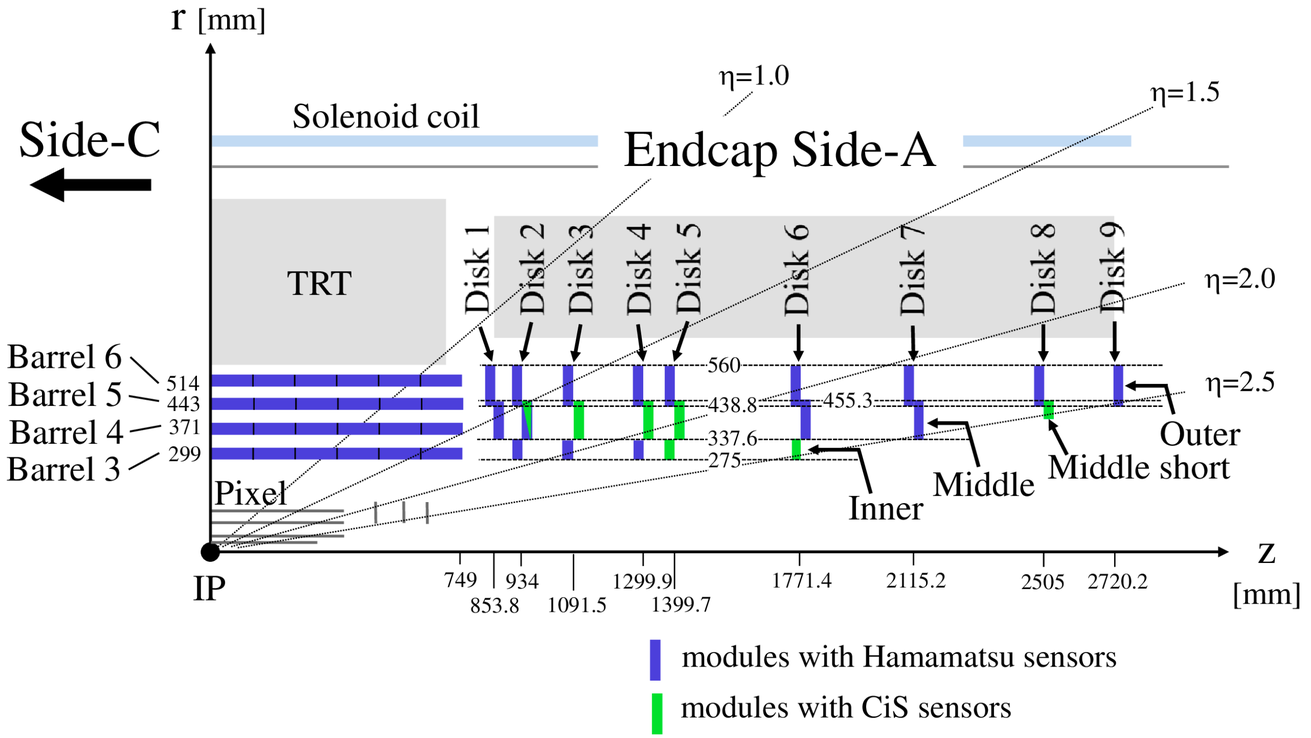
The ATLAS detector:

- Multipurpose detector
- Detect the particles coming from proton-proton interactions at the LHC at 25ns intervals
- Reconstruct the tracks and the energies of the particles
- Cylindrical shape with a layered structures

ATLAS EXPERIMENT

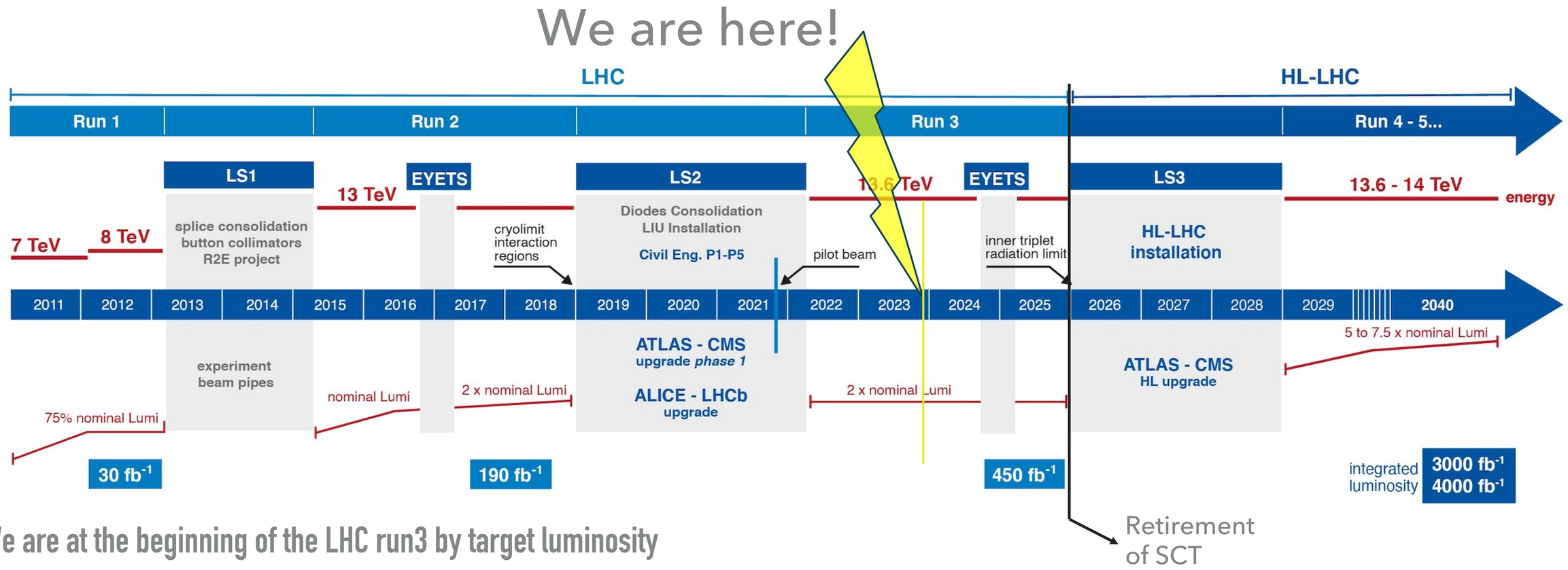
THE SEMI-CONDUCTOR TRACKER (SCT)





- SCT (Semi-Conductor Tracker): **4088 modules** organized in 4 barrel layers and 2 endcaps with 9 disks each
- A typical module consists of 4 silicon strip-sensors, two per side
  - The sides are glued back-to-back at 40mrad stereo angle
  - Silicon sensors are **p-on-n type**, 285μm thick, manufactured by Hamamatsu and CiS
- 786 strips per side per module with a strip pitch of 80μm and strip length of 12.8cm➔ $\sim 6 \cdot 10^6$ strips.

WHERE DO WE STAND TODAY?



We are at the beginning of the LHC run3 by target luminosity

Main goal:

- Take good quality data with the SCT detector until the detector is retired

We will show the **detector condition today** and **evolution of performance since LHC Run2** (Run2 performance)

98.4% ACTIVE STRIPS AFTER 13 YEARS OF OPERATION!

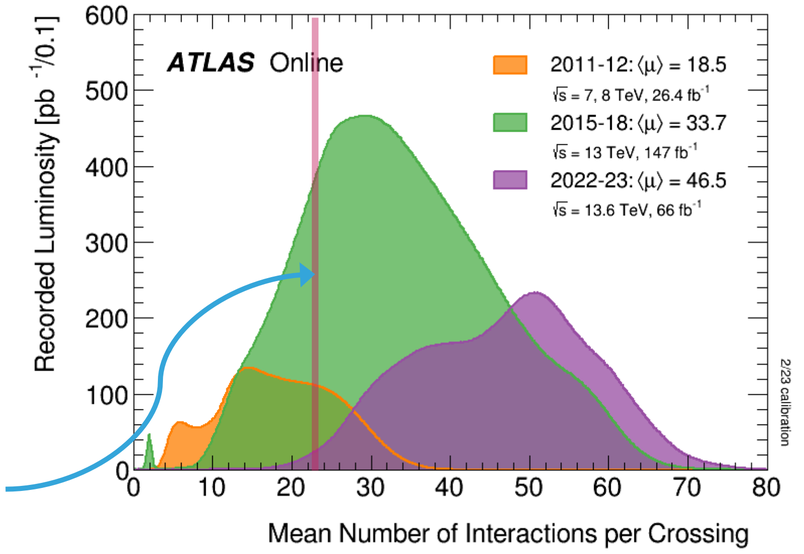
Disabled Components	Start of Run 2 (2015) ~185 fb^{-1}	End of Run 2 (2018) ~185 fb^{-1}	Start of Run 3 (2022)	End of 2022 ~194 fb^{-1}	End of TS (2023)	October 2023 ~224 fb^{-1}
Modules (12 chips)	38	42	46	47	49	49
Chips (128 strips)	59	83	85	81	82	88
Strips	11 452	14 895	24 071	24 454	15 558	15 574
% Active Strips	98.8	98.6	98.3	98.34	98.4	98.4

SCT designed for $700\ \mathrm{fb}^{-1}$ of $14\mathrm{TeV}\ p-p$ collisions

- $\sim 260\mathrm{fb}^{-1}$ luminosity collected so far
- $\sim 450\ \mathrm{fb}^{-1}$ luminosity expected by the end of Run 3
- **Safe margin for further operation in Run3…**

  ➔ challenging running conditions

  instantaneous Luminosity and μ much larger than design specification



Mitigation of Radiation Damage is increasingly important

➔ **Understand these effects for continuing safe and efficient SCT operation**

ATLAS EXPERIMENT

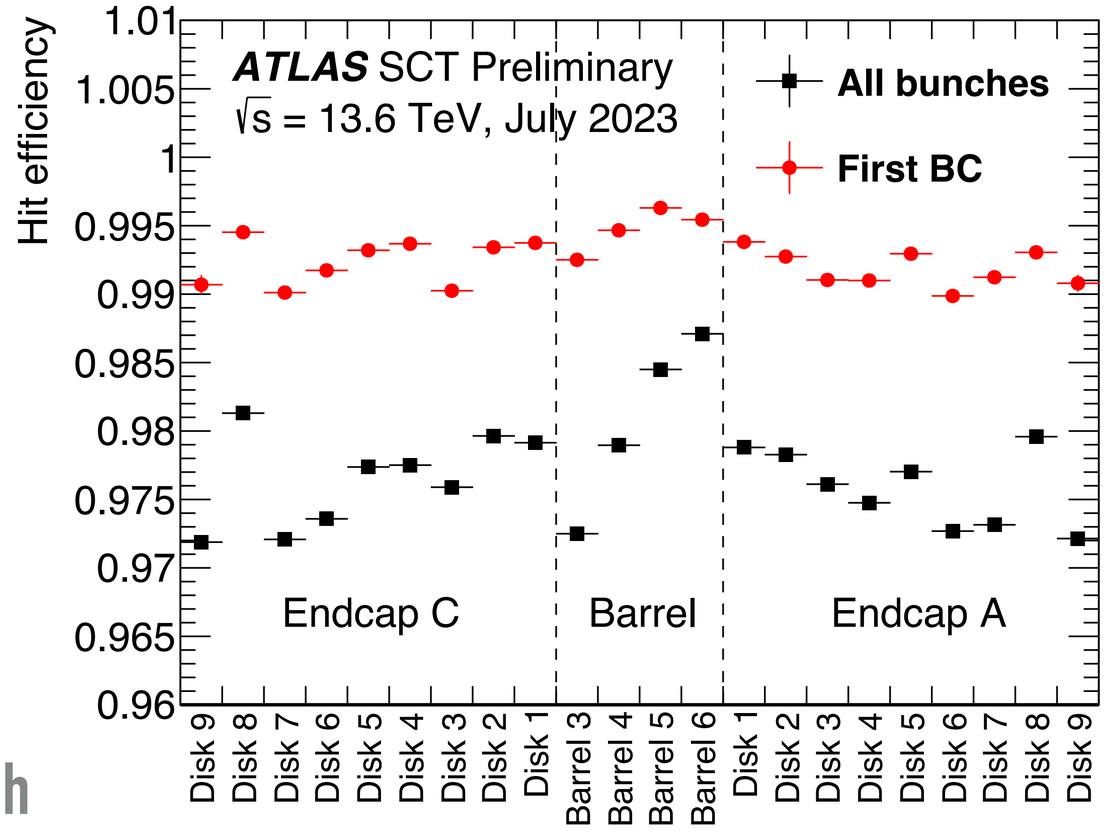
HIT EFFICIENCY

Hit efficiency per track:

$$\epsilon_{\text{hit}} = \frac{N_{\text{cluster}}}{N_{\text{cluster}} + N_{\text{hole}}}$$

- $\epsilon_{hit}^{1^{st}bc} \sim 99\ \%$
  - Within targeted performance
- Radiation damage results in increasing strip depletion voltage
  - hit efficiencies can drop below 0.99
  - Intrinsic hit efficiency is monitored, and the High Voltage (HV) increased when necessary.

All Bunches Efficiency is degraded by veto on energy detected in the period 17.5 to 12.5 ns before the pp collision



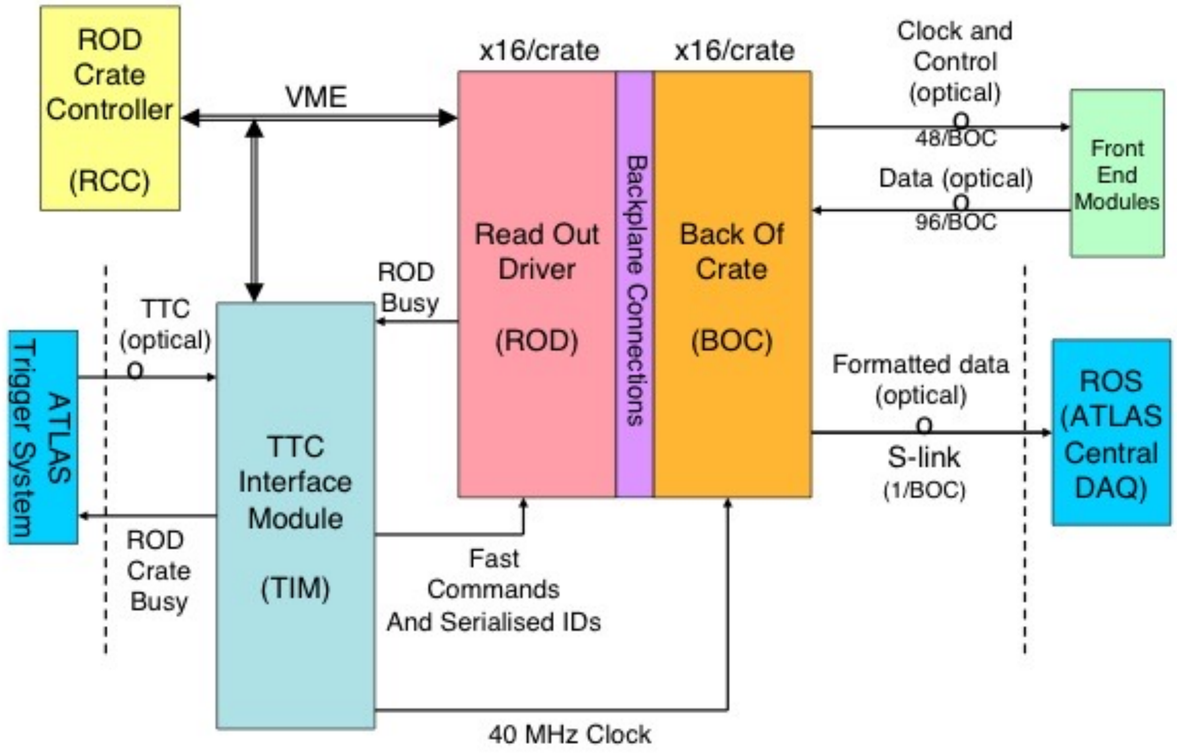
DETECTOR OPERATION

Targets: High hit efficiency (> 99%) ; Low Noise occupancy ($< 5\times10^{-4}$)

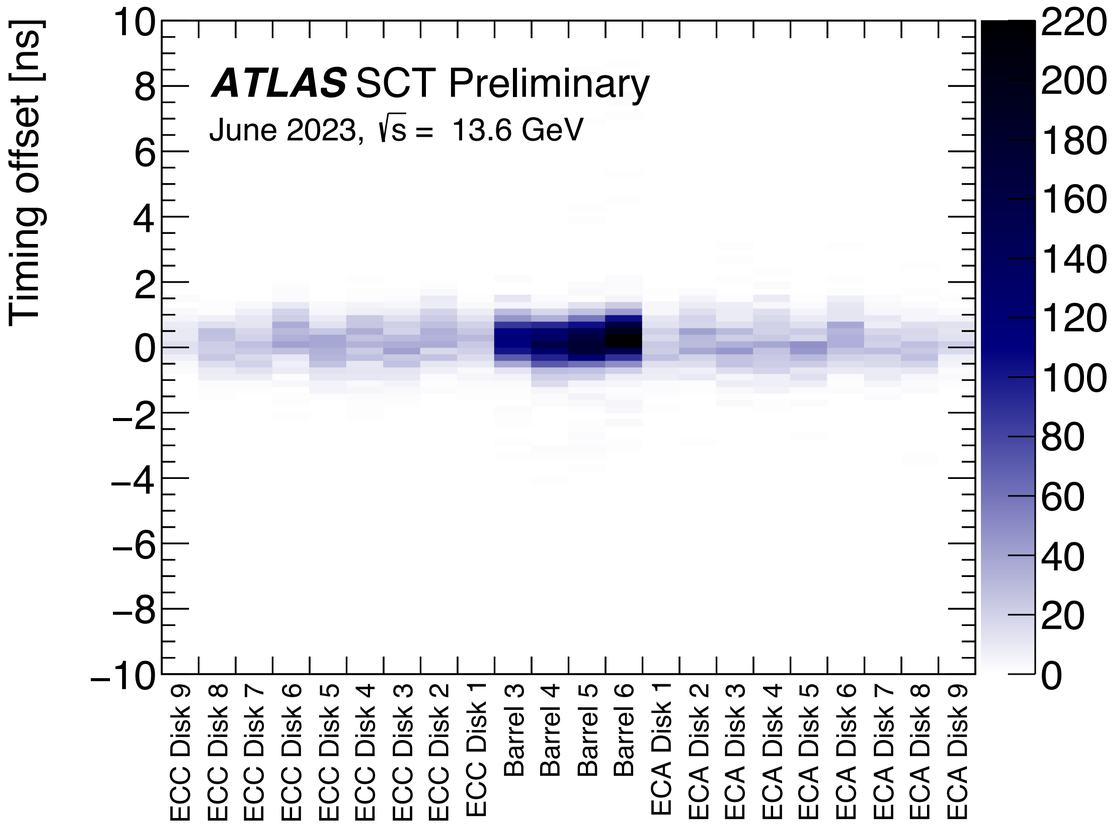
Calibration performed every few weeks between LHC beam fills

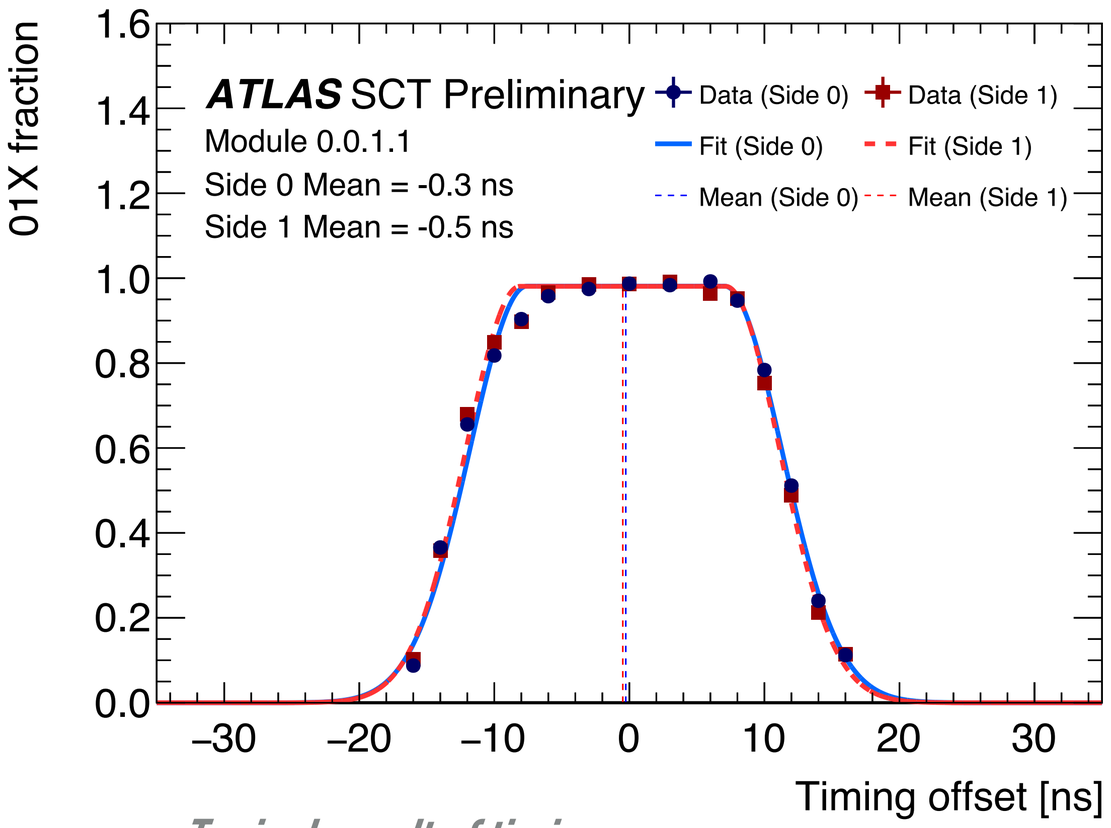
- Optimisation of channel variations in the DAC discriminator
- Gain, noise, and discriminator offset determination
- Defect identification
- Optical Receiver Threshold and Timing updates

Trigger synchronisation (~once a year)



TRIGGER SYNCHRONISATION





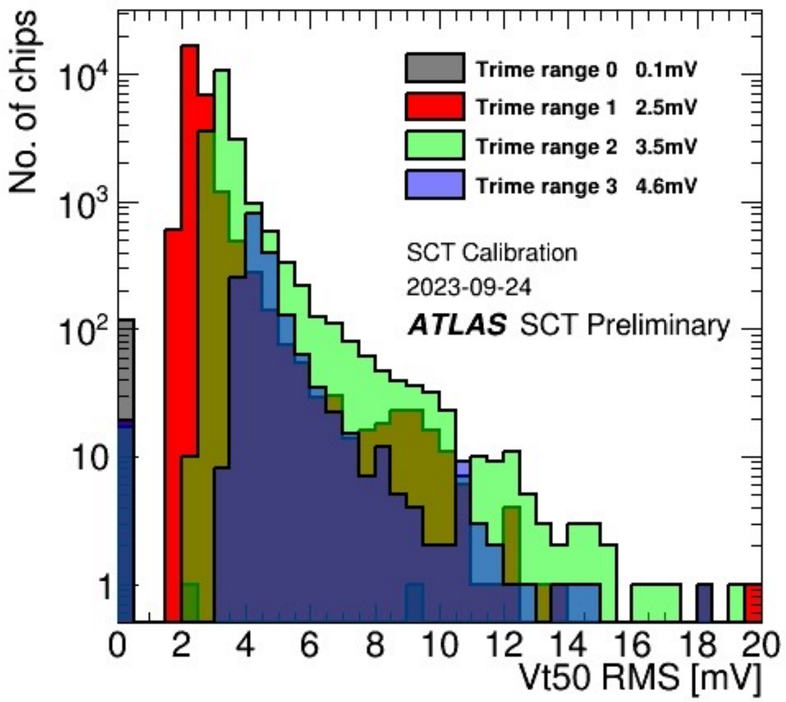
Typical result of timing scan

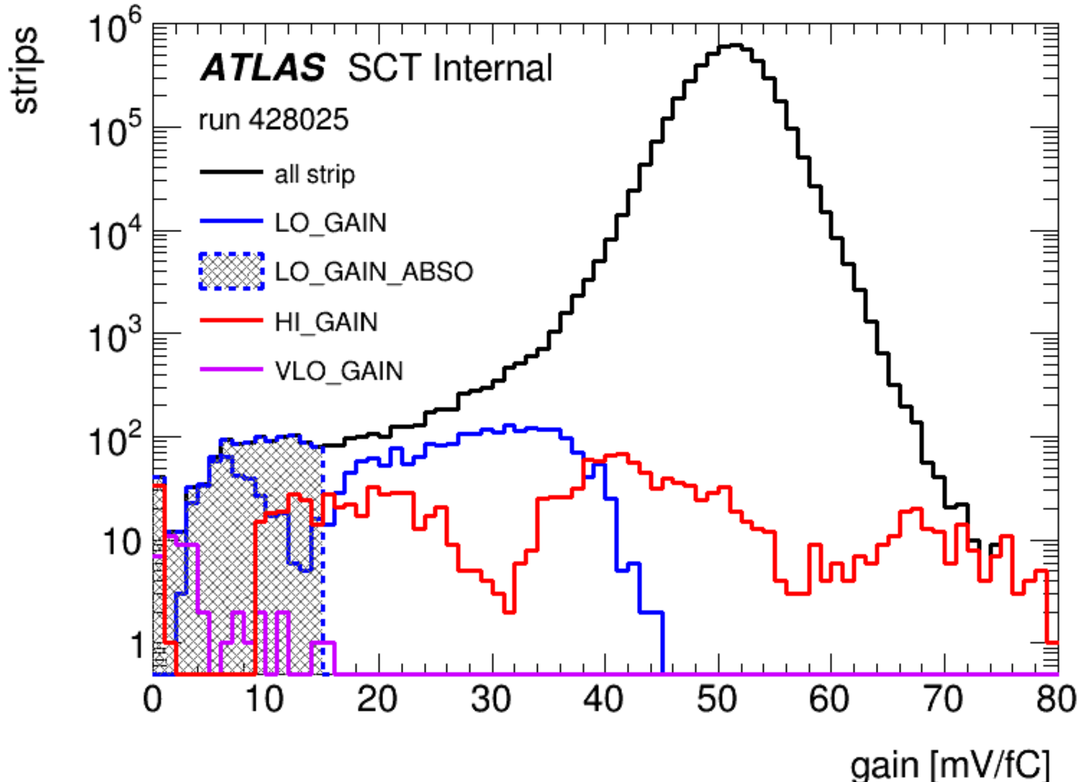
Timing offset are applied to compensate length of optical fibres (for trigger signal) and delay of trigger electronics

Note: The SCT is read out in 25 ns time bins – these are (mostly) inconsequential corrections

ANALOGUE CALIBRATION / NOISE AND DEFECT ESTIMATION

- DAC threshold determined per chip based on a threshold scan with 1 fC injected charge
  - A per channel calibration across a chip accounts for variations due to manufacturing and radiation damage via 16 available trimDAC settings and sets the discriminator thresholds
- Response Curve
  - Calibration between threshold (mV) and input charge (fC), Gain and Noise Measurement, Defect Identification





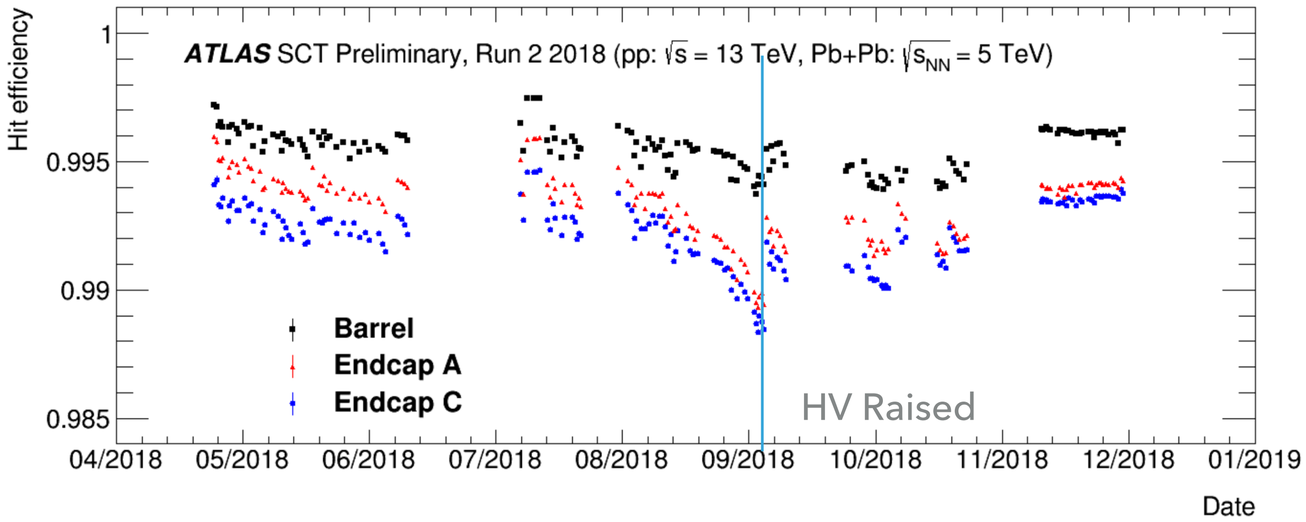
DETECTOR MONITORING

SCT operation targets: High hit efficiency (> 99%) ; Low Noise occupancy ($< 5\times10^{-4}$)

The performance and radiation effects are monitored, and mitigated through periodic scans and changes to the operating HV

- HV scan
- Threshold scan
- IV scan
- Noise measurement

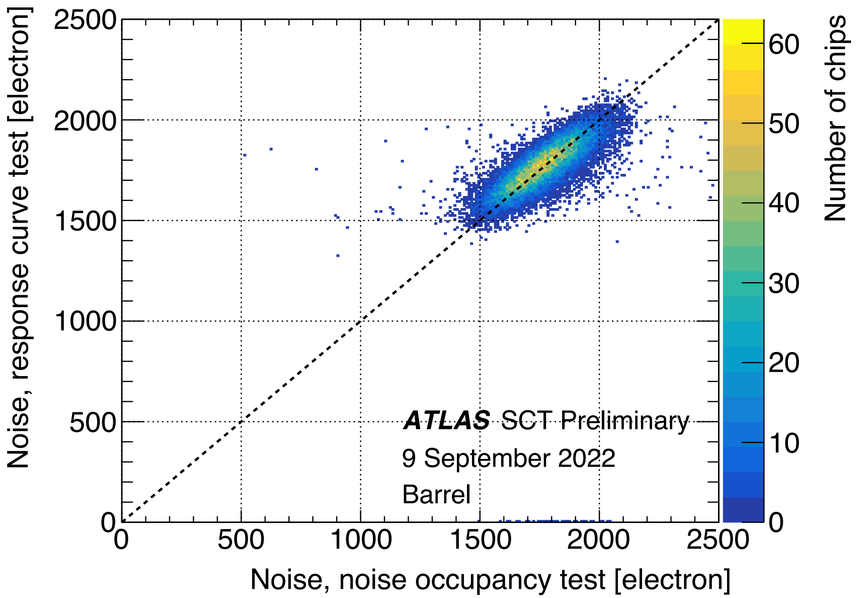
- We will see **ageing of the sensor due to radiation damage…**
- … but also **confirm good performance**, well within the limits for safe operation

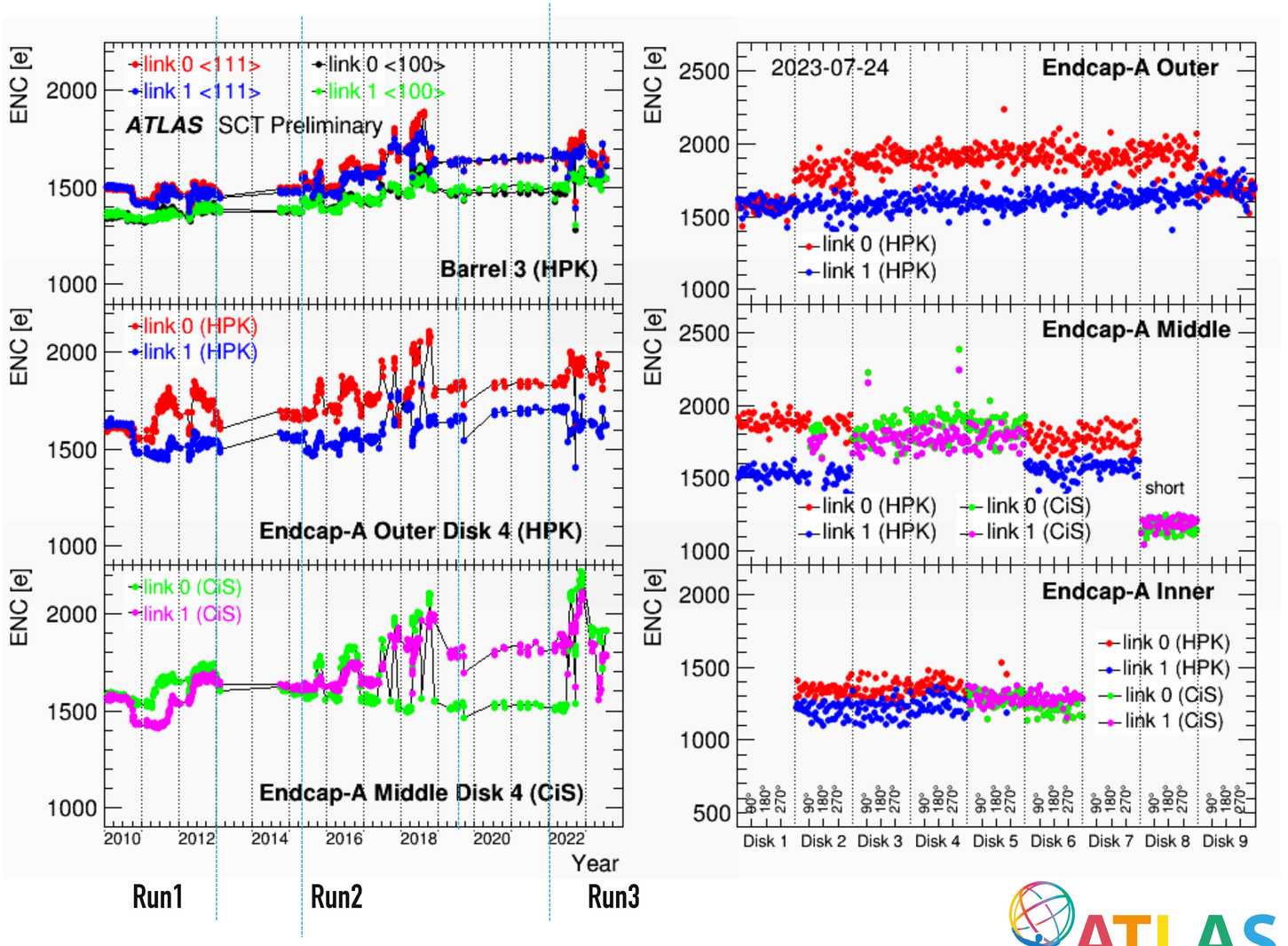


ATLAS EXPERIMENT

NOISE MEASUREMENT

- Noise constantly monitored
- Noise at most 2300e (0.37 fC) much lower than the 1 fC hit threshold
- Two ways of determining noise
  - From response curve test
  - From a threshold scan with no injected charge

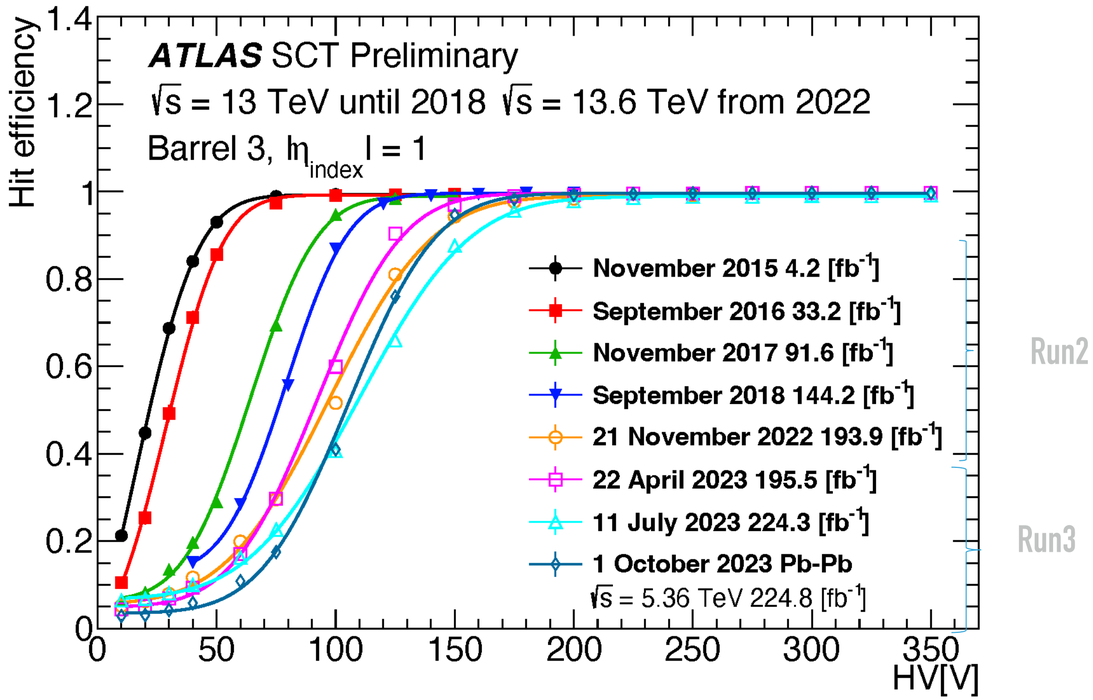




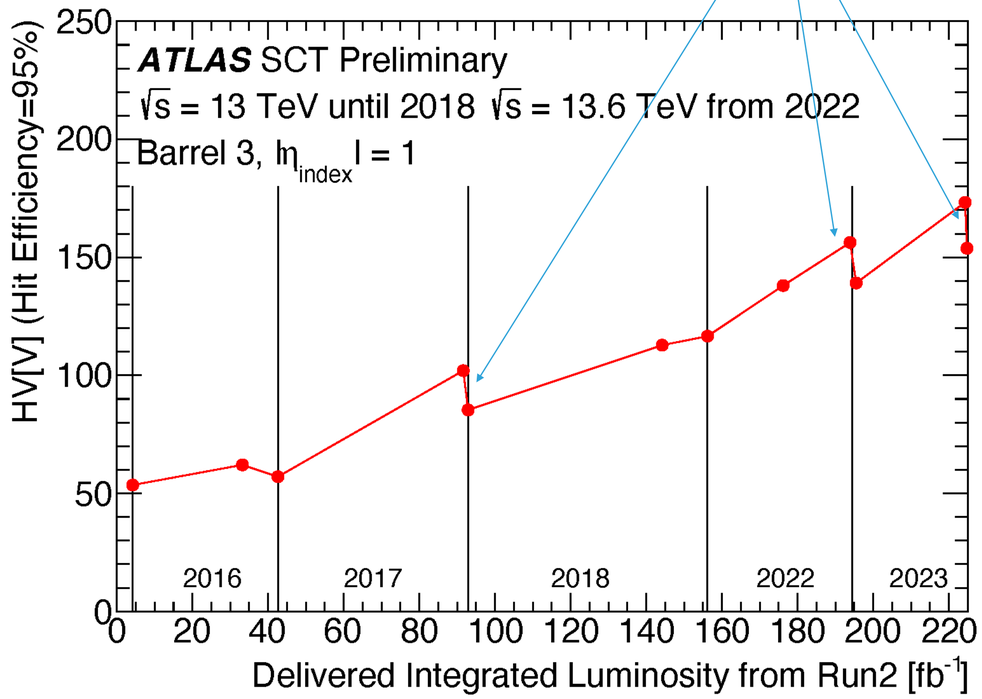
HV SCAN

After type inversion the HV needed to have full depletion can be considerably higher than V_{FD} from IV scan.

- Hit efficiency is monitored through HV scans



Annealing effects



- HV Scan results from beginning of Run1 to October 2023
- $HV(\text{hit efficiency} = 95\%)$ decreased by 20V wrt end of 2022 (annealing effect after end of the year shutdown)

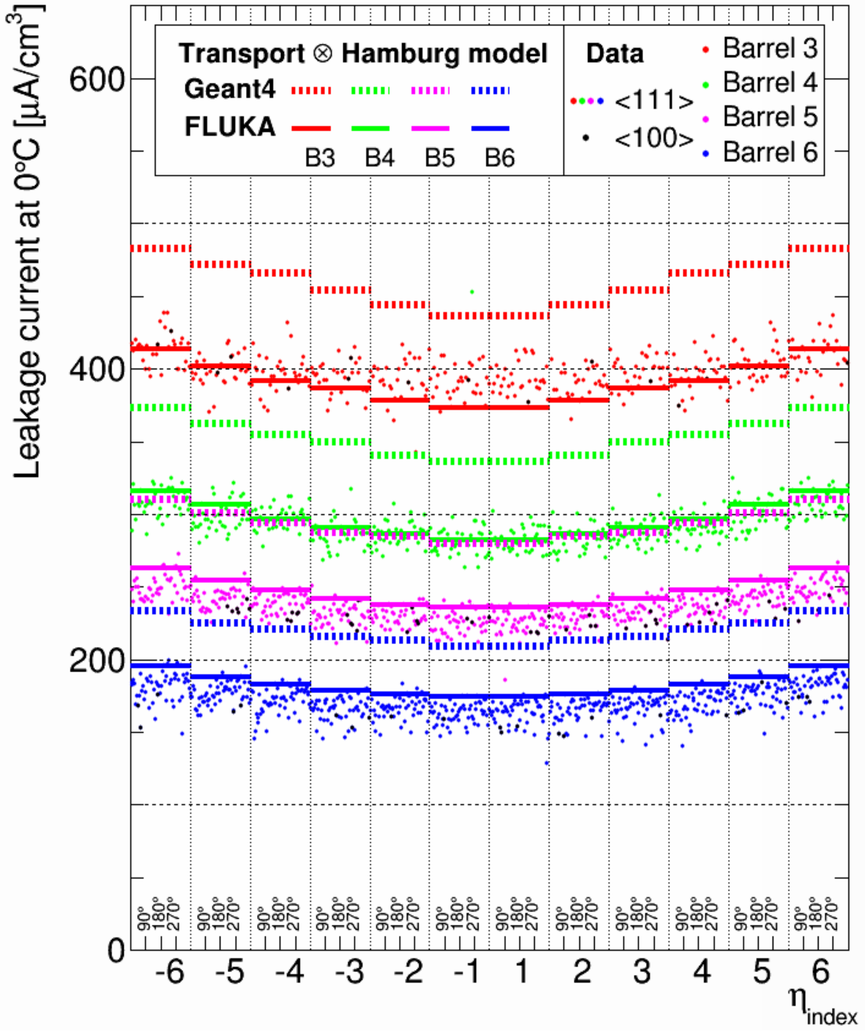
LEAKAGE CURRENT

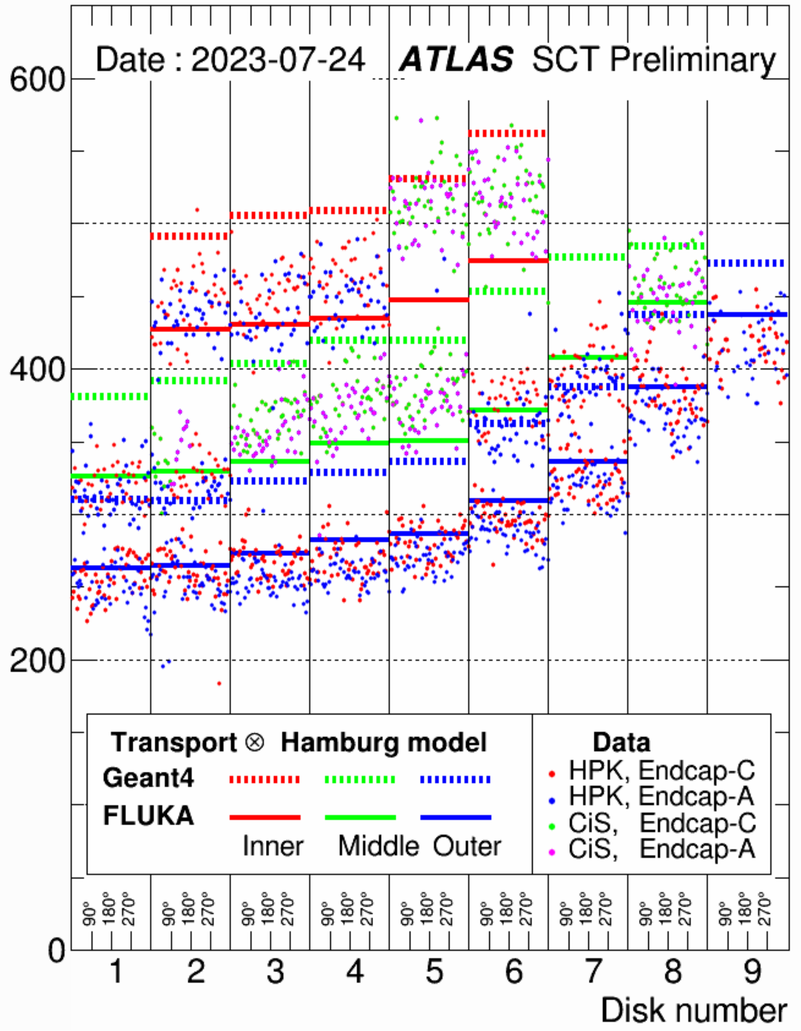
'Snapshot' of latest detector conditions

- leakage current for all module in SCT as of July 2023
- Values are 'normalized' to $T = 0°C$

Leakage current increases with radiation damage

- Clearly higher for layers closer to the interaction point

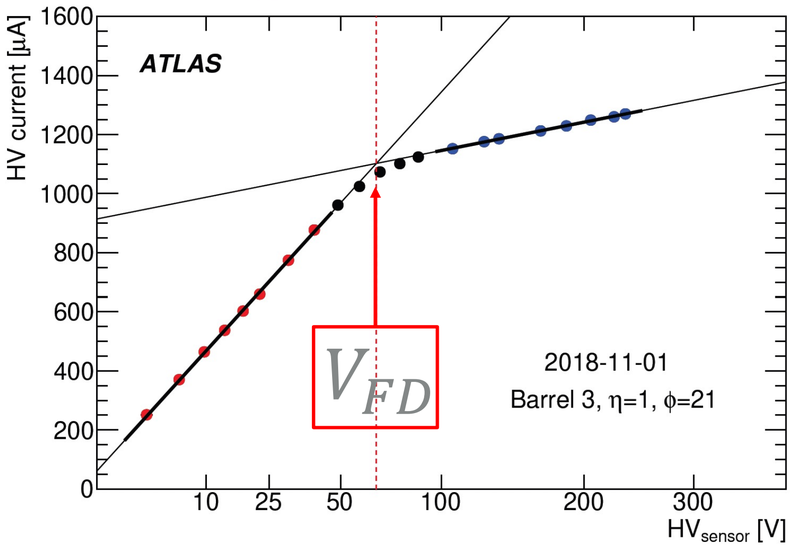




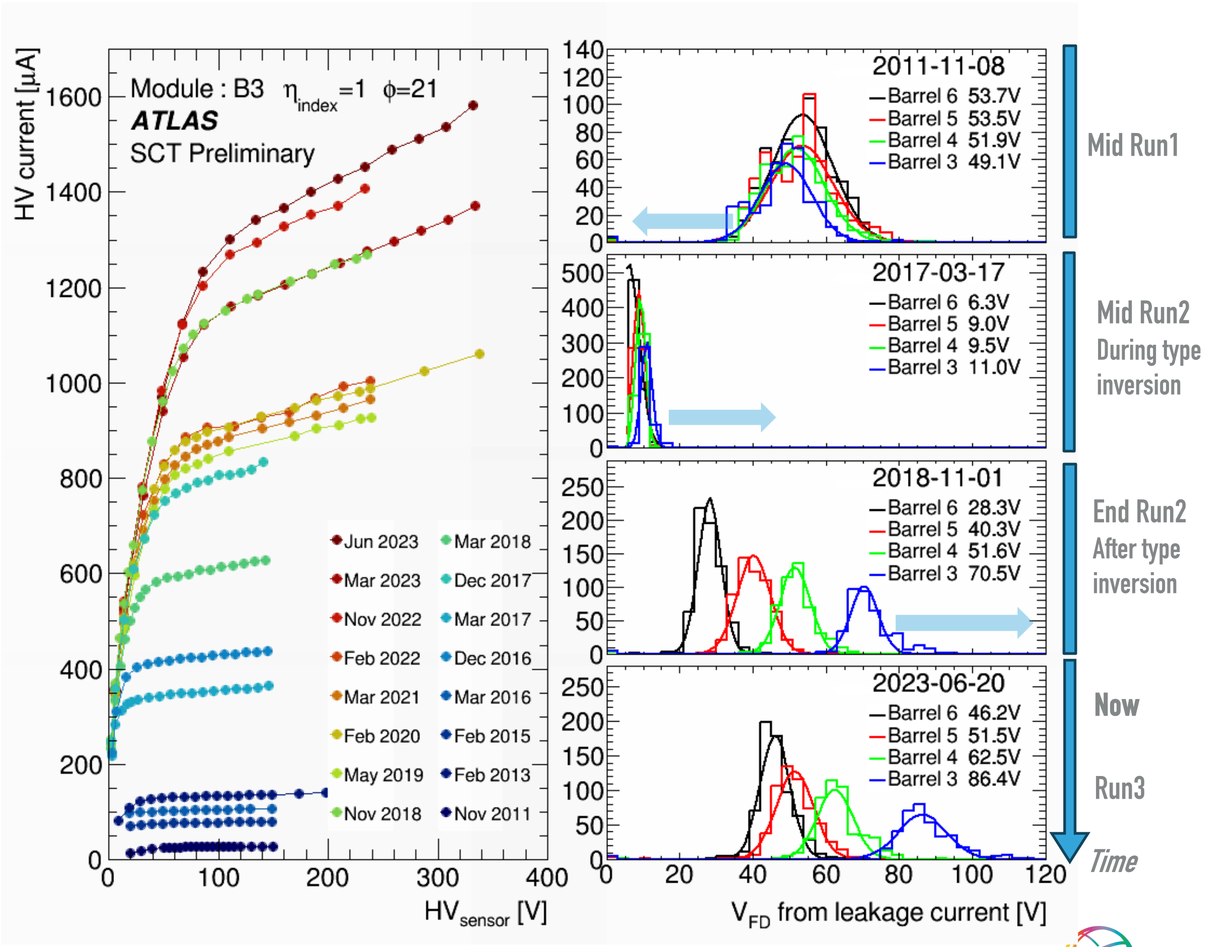
FULL DEPLETION VOLTAGE (V_{FD})

V_{FD} can be determined from kink in *leakage Current-vs-HV* lines:

- Leakage current is proportional to depletion volume.
- At full depletion the leakage current should be constant.
- Depletion Volume is proportional to $\sqrt{V}$.
- **Change in behaviour of $I_{leakage}$ vs HV indicates V_{FD}**



IV scans in run2 ➔ deduce type inversion



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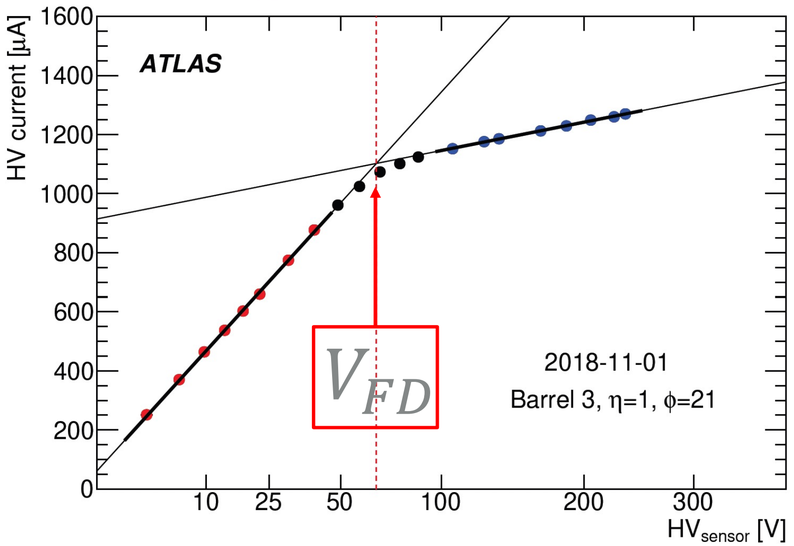
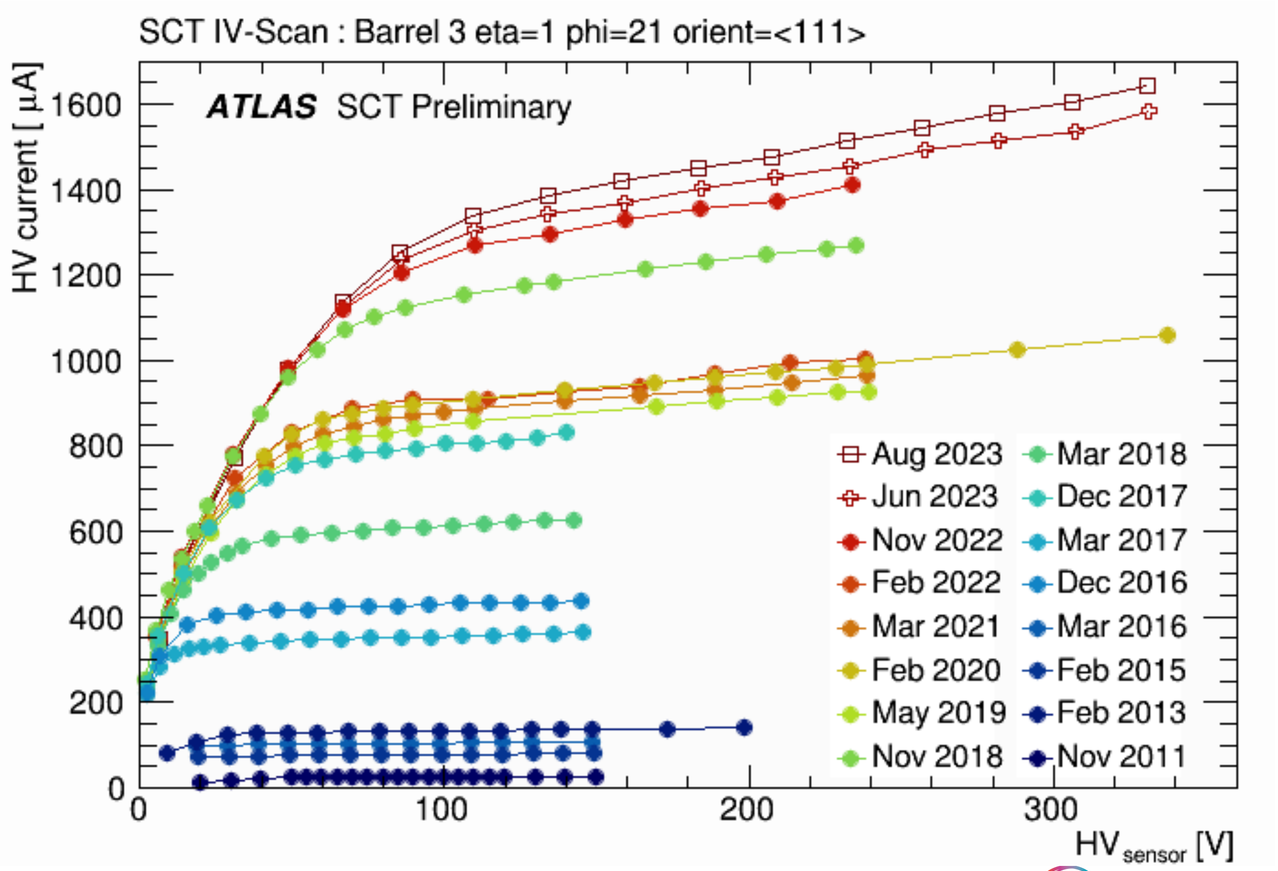


Latest IV Scan



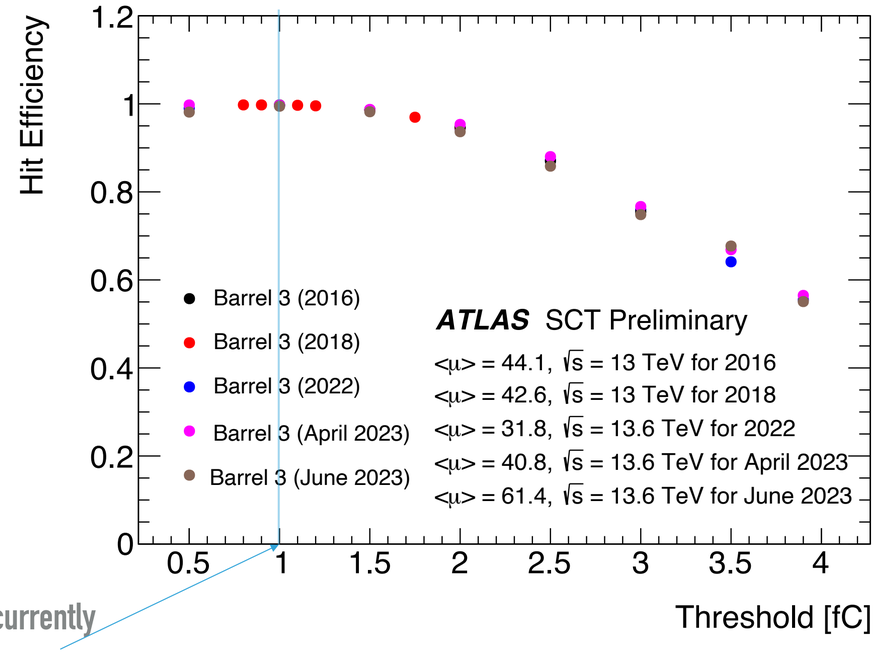
ATLAS EXPERIMENT

NOISE – THRESHOLD SCAN

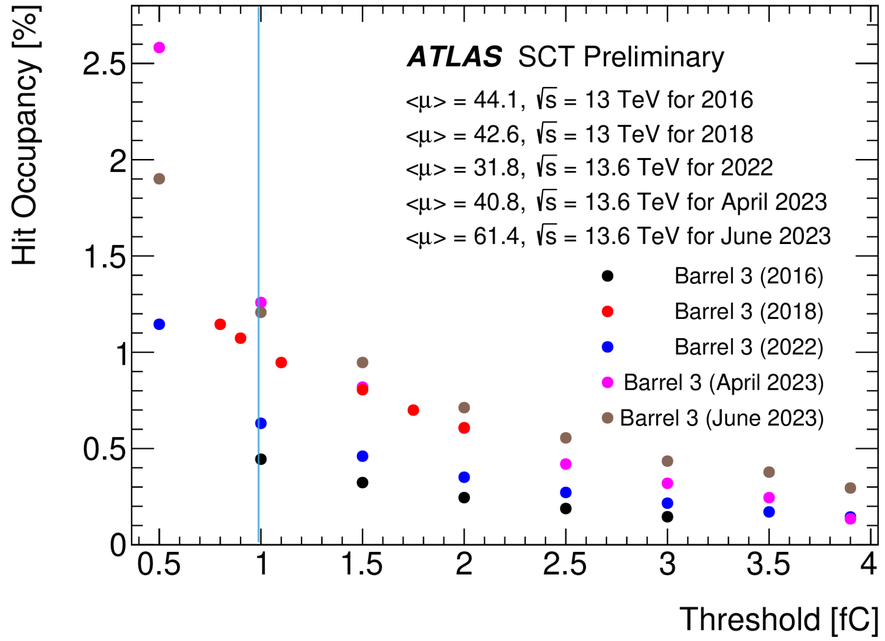
- To keep high efficiency need to set threshold as low as possible
  - Possible only if noise is low

$$Occupancy = \frac{N\ module\ above\ threshold\ per\ event}{Total\ N\ modules}$$

- Optimal threshold parameter can change because of radiation
  - Threshold scans in 2023 shows that $1\ \mathrm{fC}$ is still a good range

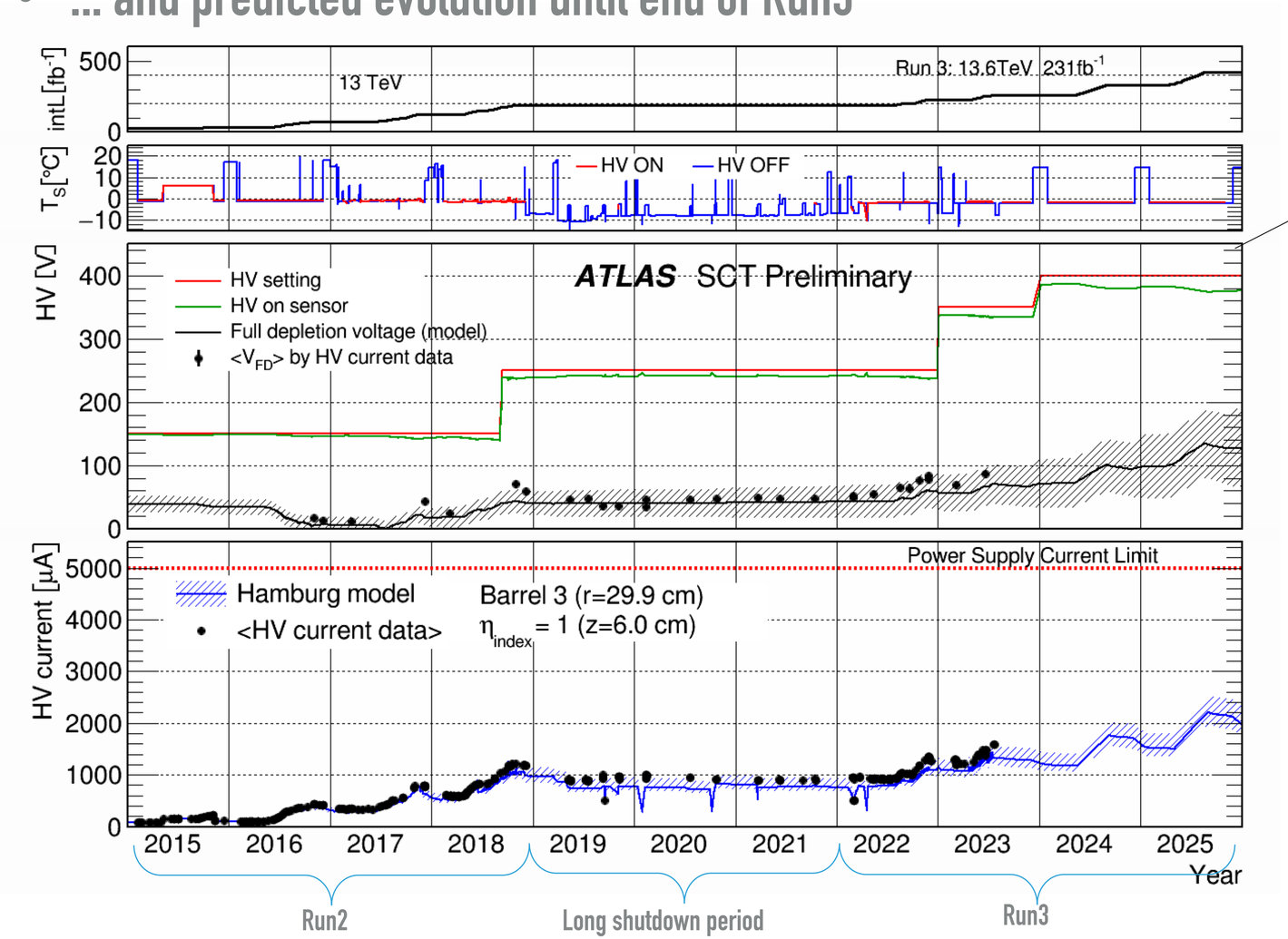


Threshold value currently used



HV & LEAK. CURRENT PREDICTIONS (BARREL3)

- Evolution of detector condition since Run2…
- … and predicted evolution until end of Run3



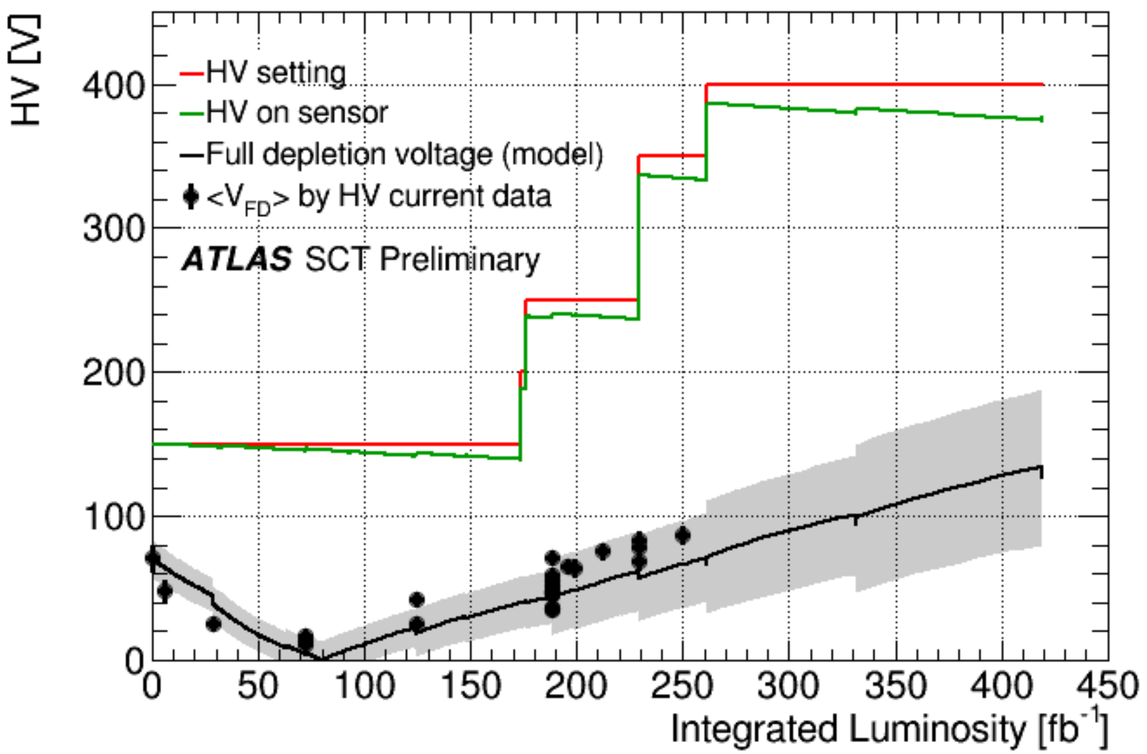
HV limit on sensor is 500V

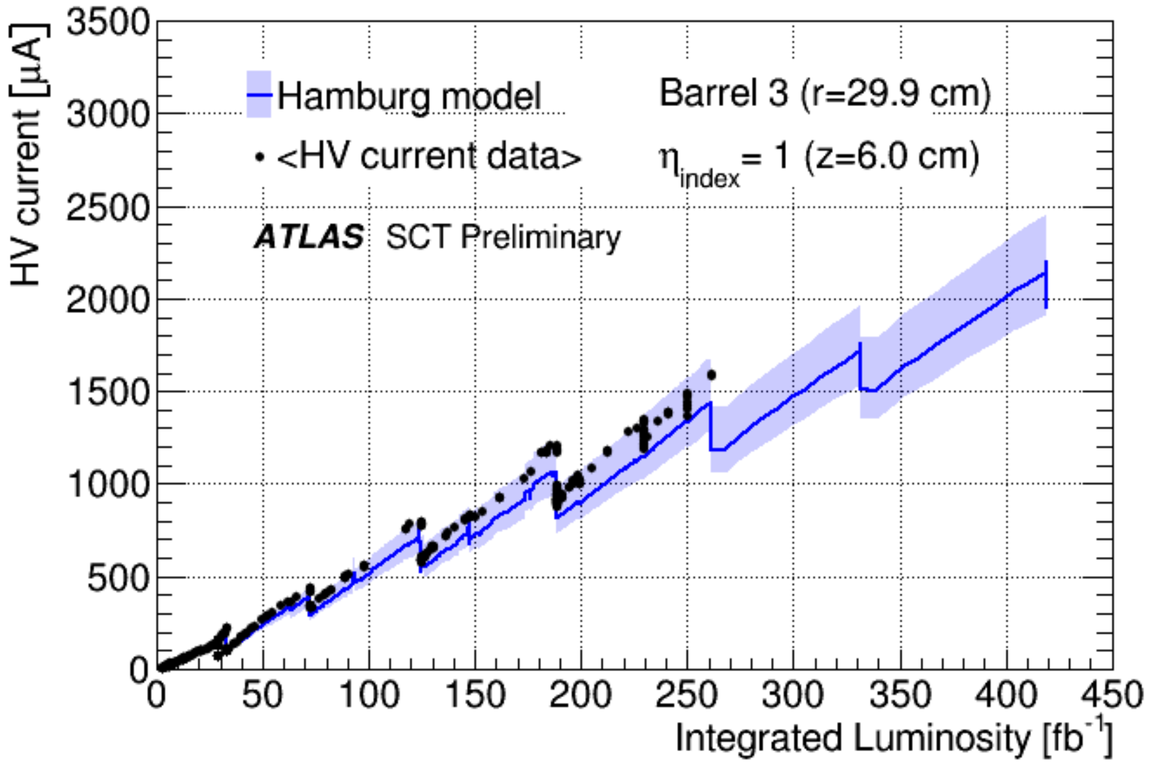
- Measured V_{FD} agrees well with model prediction and continues to increase since type inversion in 2016 (but should not exceed 180V)
- Leakage current < PS Limit

Enough margin for Run3 operation in both HV and HV current.

ATLAS EXPERIMENT

HV & LEAK. CURRENT PREDICTIONS VS LUMINOSITY





Enough margin for Run3 operation in both HV and HV current.

CONCLUSION

- SCT is in good condition with 98.4% of active strips
- Efficient data-taking and monitoring of ageing due to regular calibrations and special tests
- Radiation Damage is apparent
- Operations team continually adding incrimental improvements to maintain high standards
- But safe margin for efficient operation until the end of Run3 (in 2025)...

... when SCT will reach end of duty!

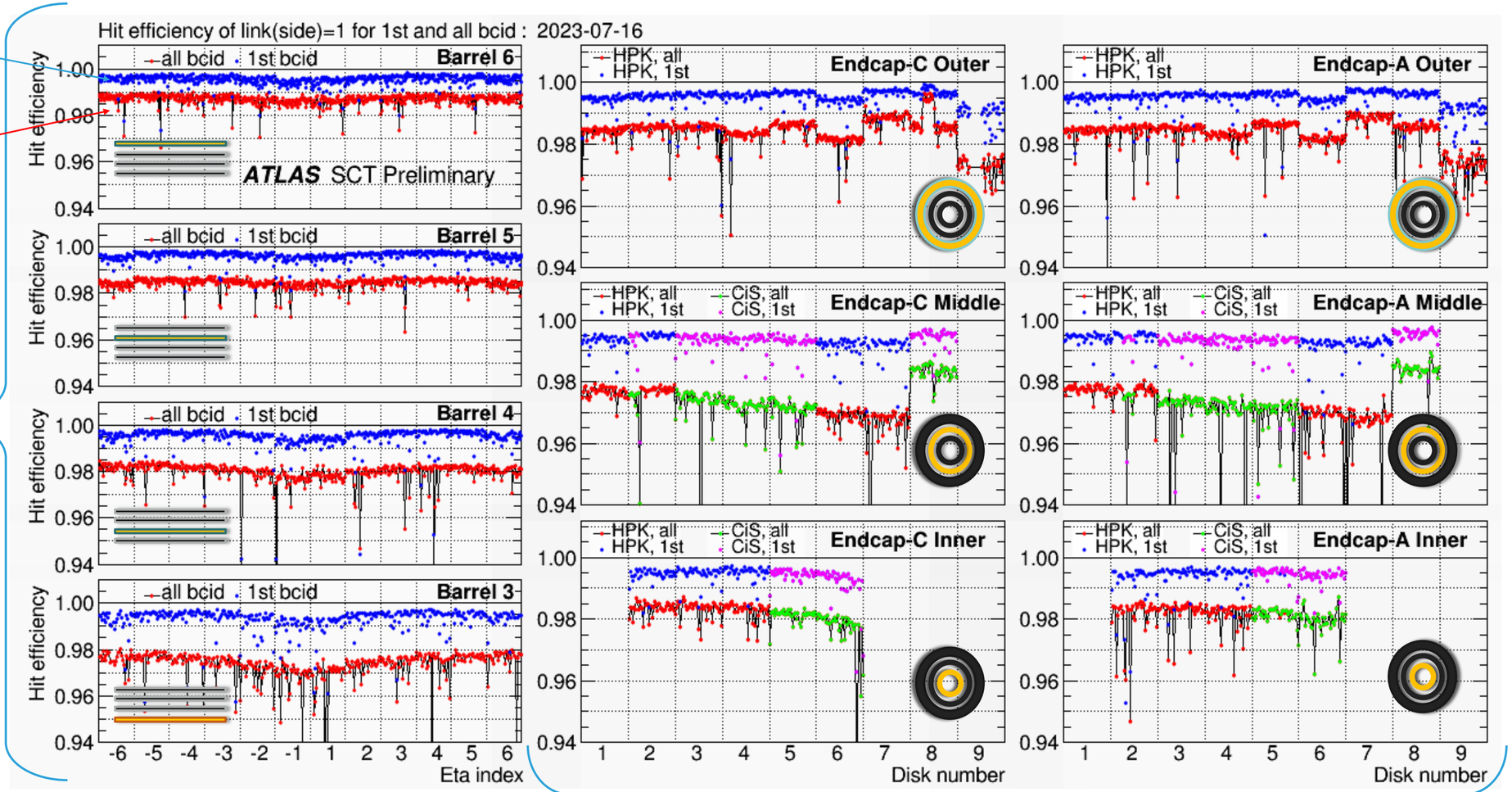
BACKUP

MODULE HIT EFFICIENCY – JULY 2023

First bunch crossing eff.

All bunch crossing eff.

Barrel



EndCaps

Need to reach full depletion voltage in modules to reach high efficiency

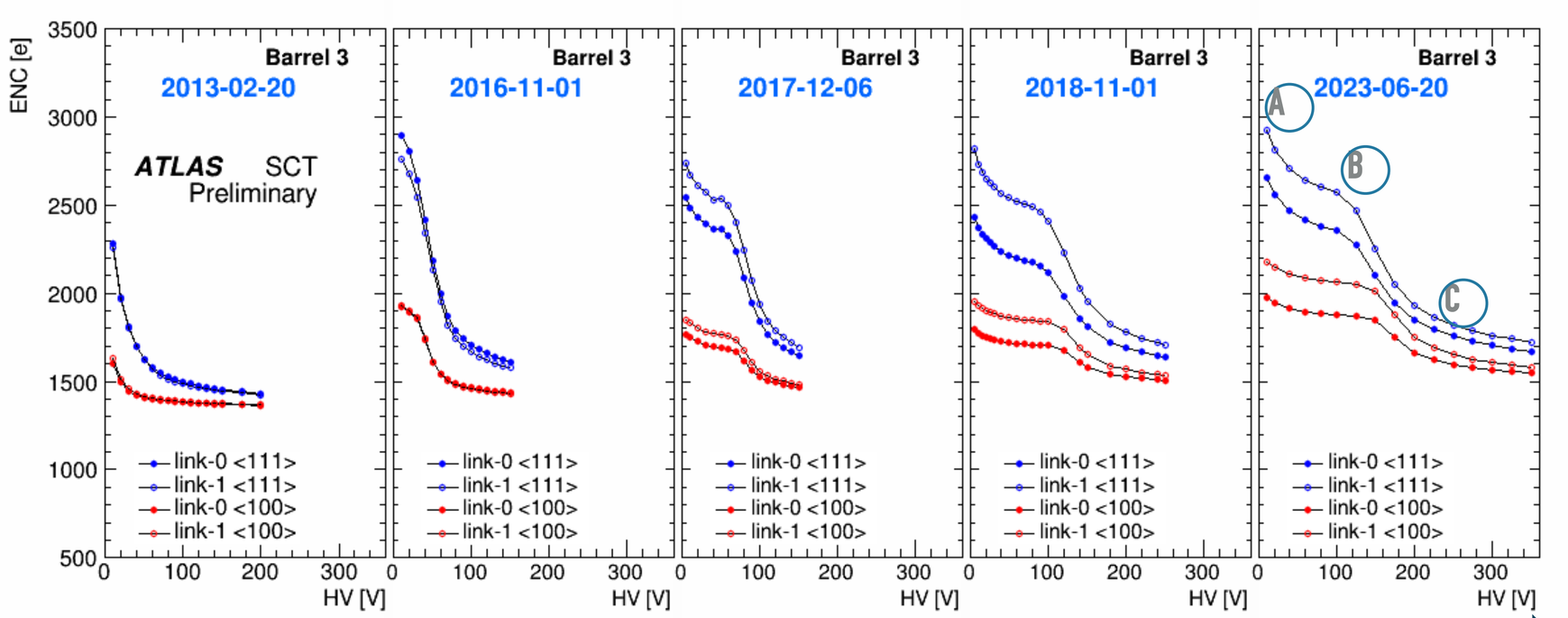
Monitored through IV scans and HV scans…

ATLAS EXPERIMENT

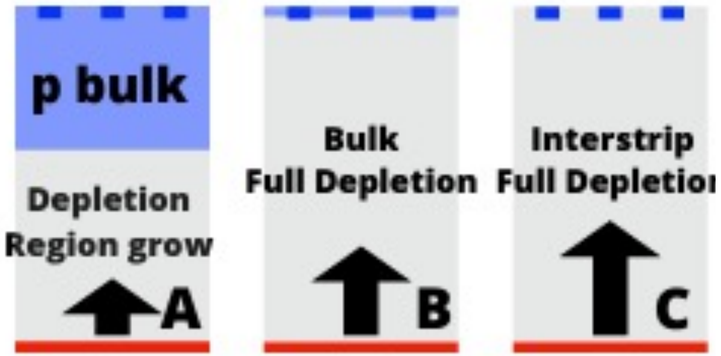
NOISE & HV

Noise was measured periodically in a series of response curve scans or noise occupancy scans performed while varying HV

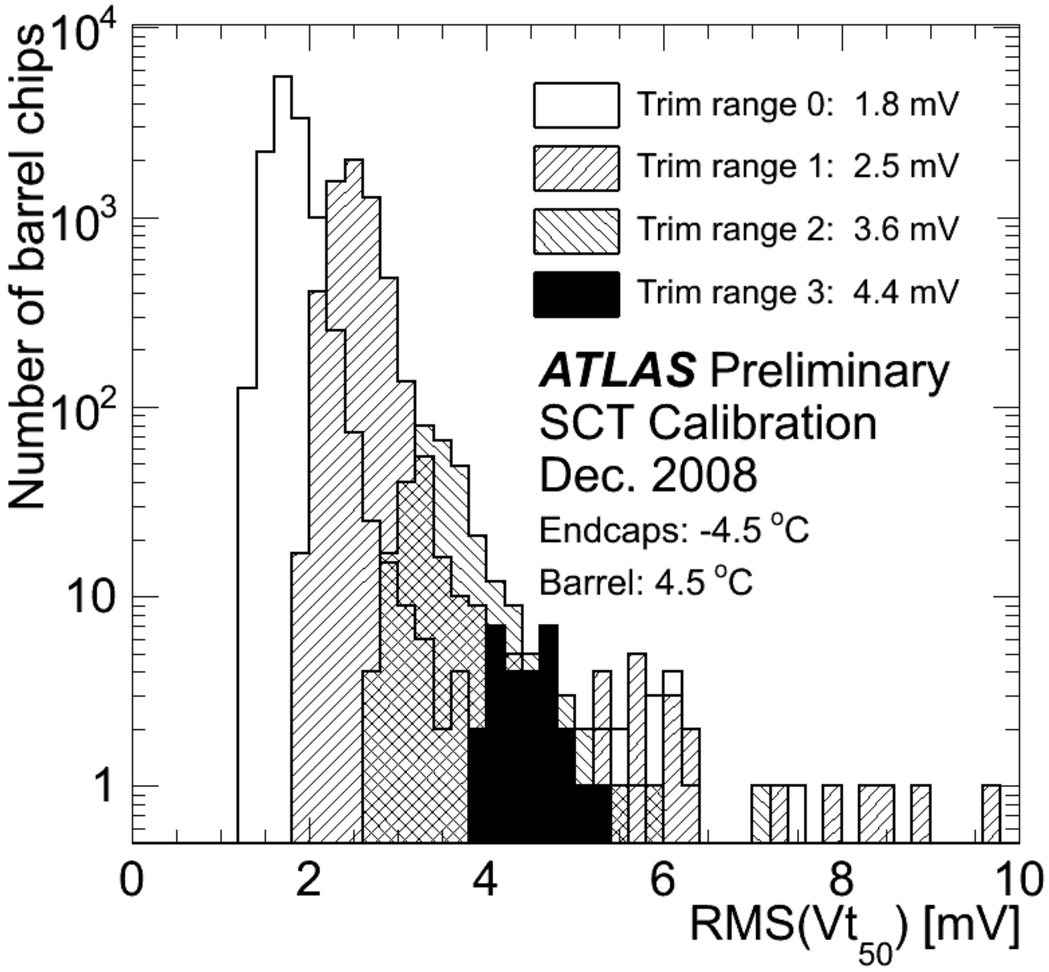
- A knee-like structure appeared after type inversion and its evolution results from changes in full depletion voltage



Noise related to interstrip capacitance



TRIM RANGE

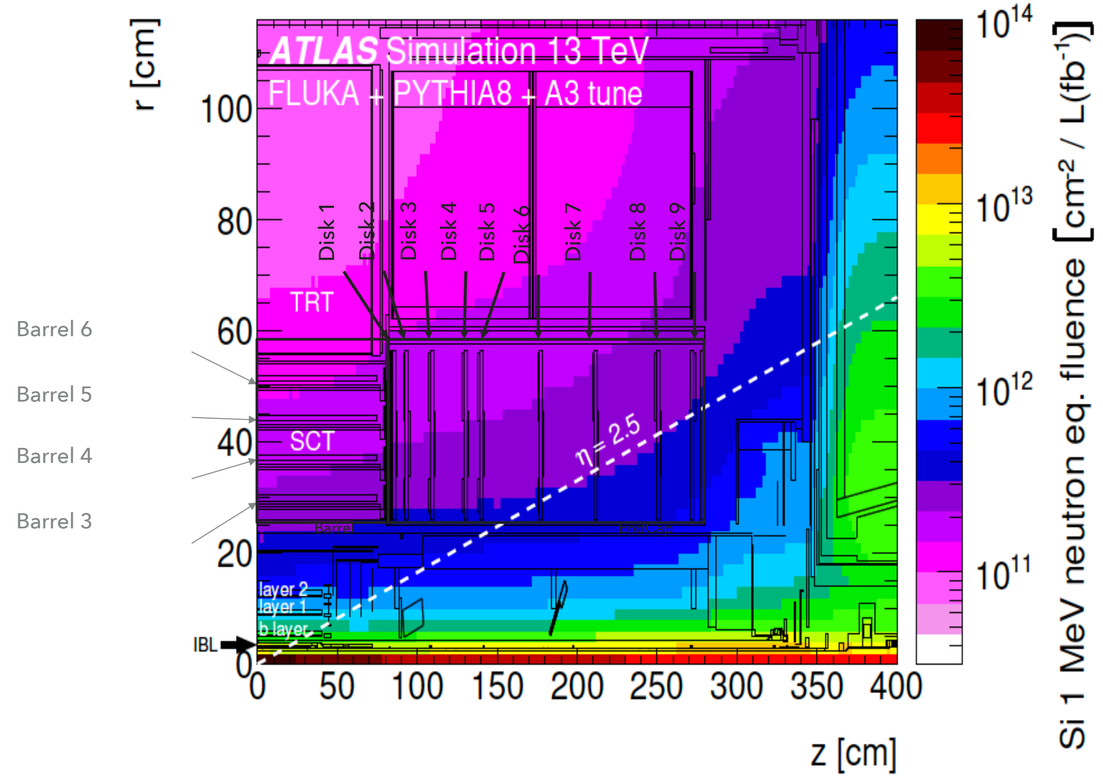

Number of barrel chips
10^4
10^3
10^2
10
1
0
2
4
6
8
10
RMS(Vt_{50}) [mV]
Trim range 0: 1.8 mV
Trim range 1: 2.5 mV
Trim range 2: 3.6 mV
Trim range 3: 4.4 mV
ATLAS Preliminary
SCT Calibration
Dec. 2008
Endcaps: -4.5 °C
Barrel: 4.5 °C

FLUENCE ESTIMATE

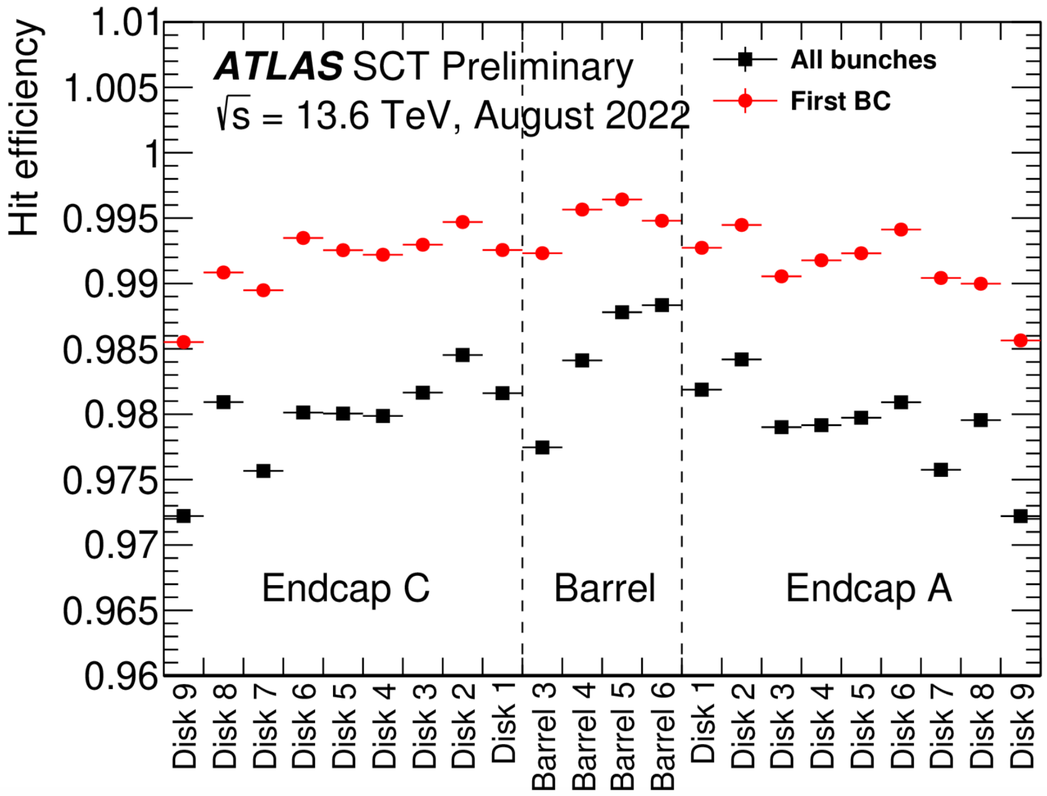
Some numbers (from FLUKA+PYTHIA8) about radiation…

1MeV n-eq. fluence $[\mathrm{cm}^{-2}]$ for total Luminosity ($\sim 260\mathrm{fb}^{-1}$)

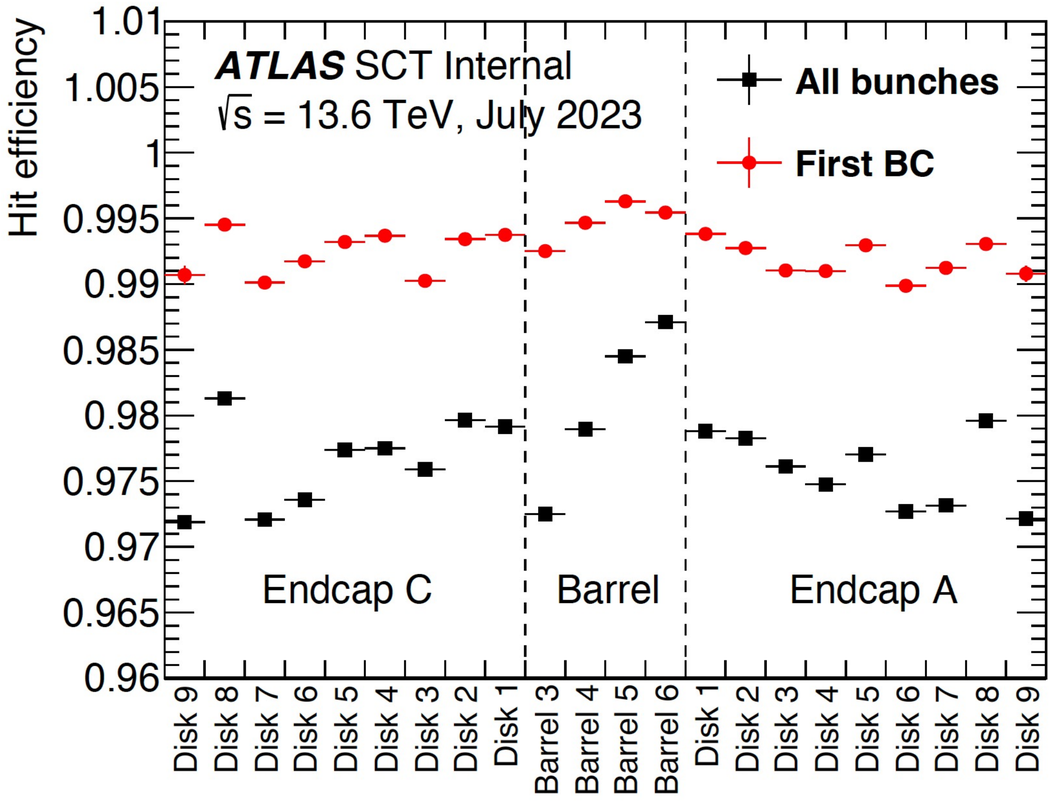
- Barrel3 ➔ $6.3 \cdot 10^{13}$
- Barrel6 ➔ $3.6 \cdot 10^{13}$



HIT EFFICIENCY 2022-VS-2023



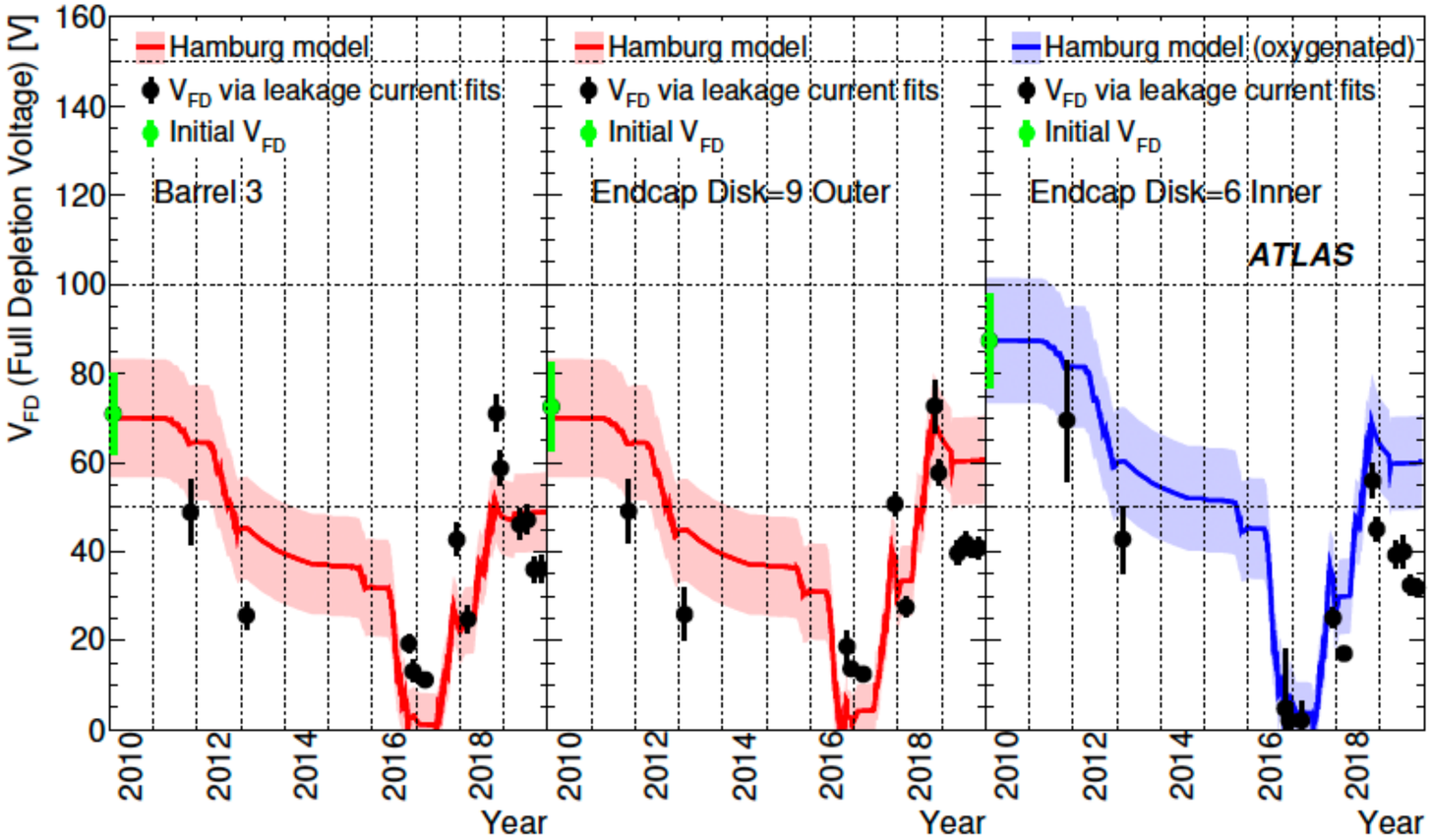
Last year hit efficiency



This year hit efficiency

ATLAS EXPERIMENT

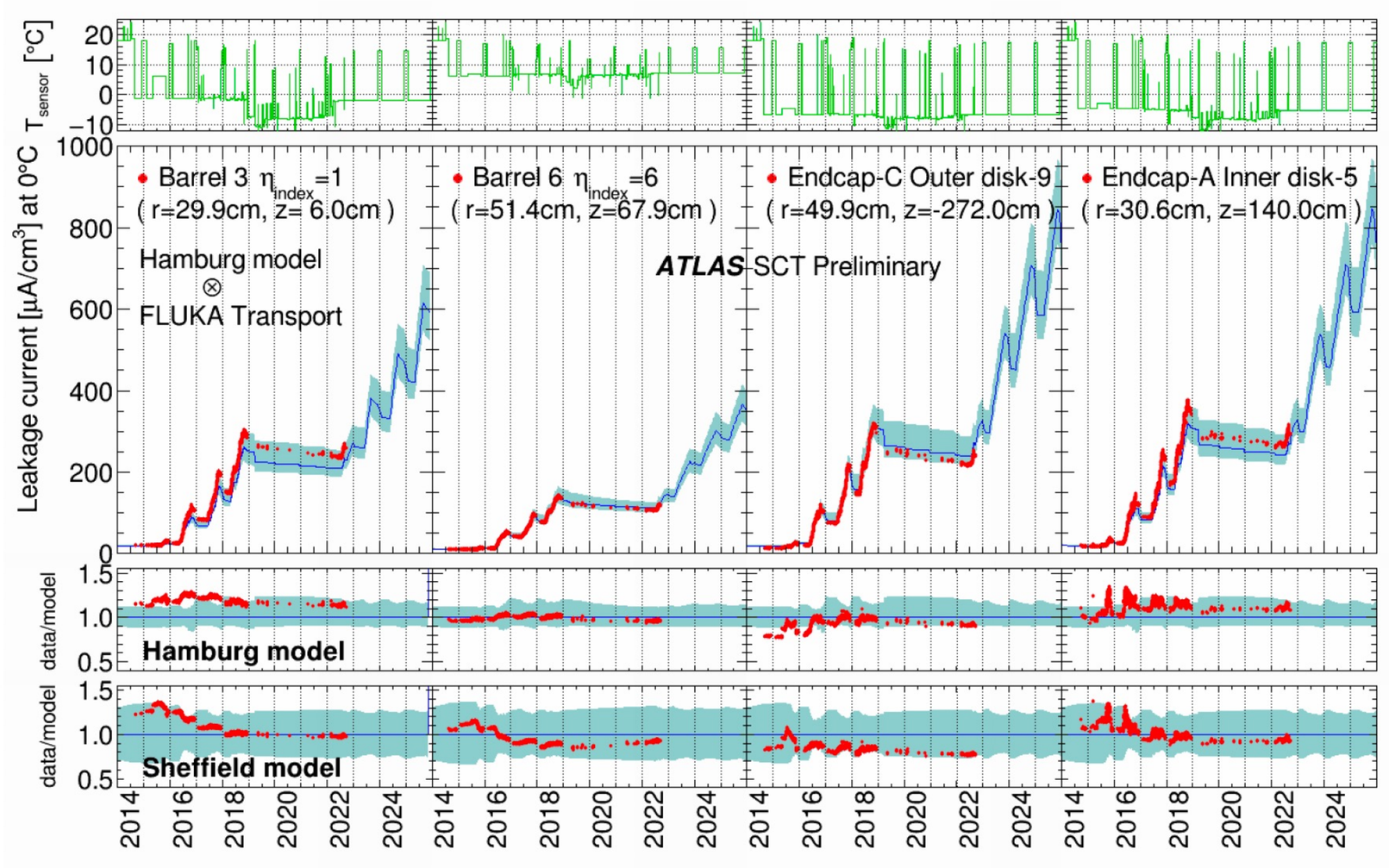
V_{FD} AND TYPE INVERSION



Depletion Voltage as measured in IV scans from Run1 till end of Run2

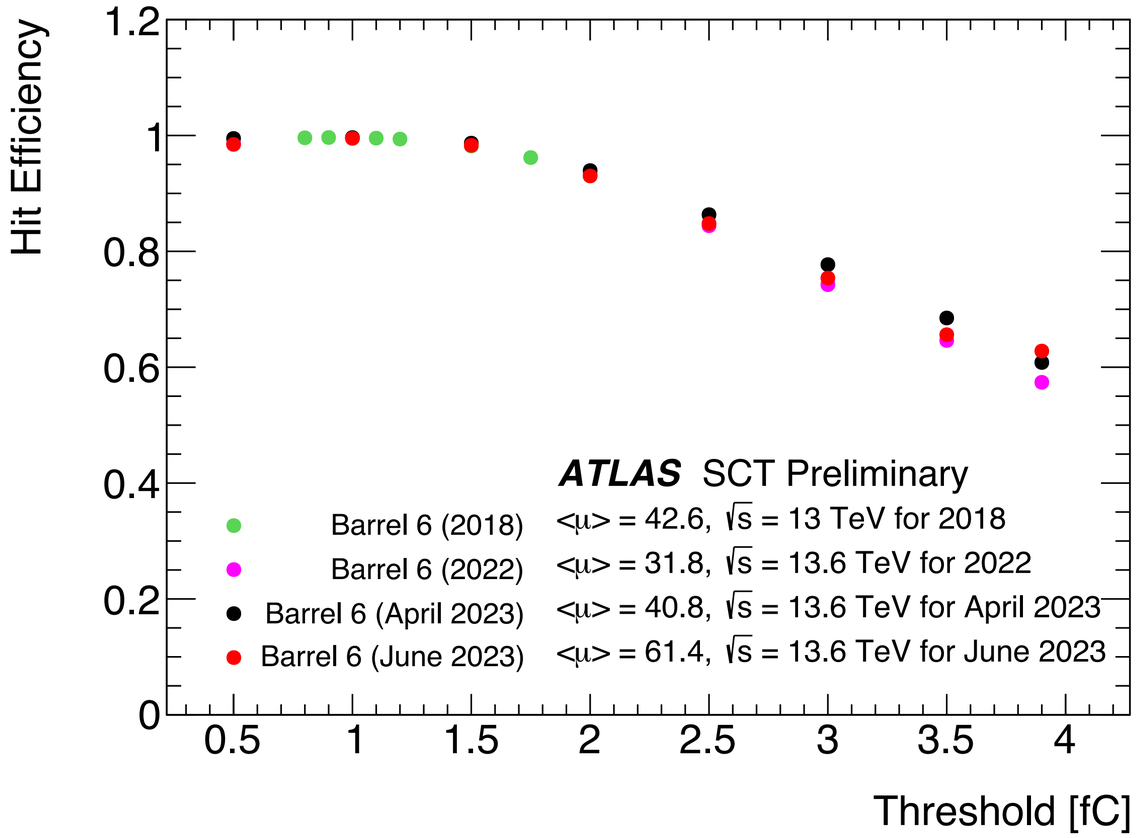
- Type inversion visible between 2016-2017

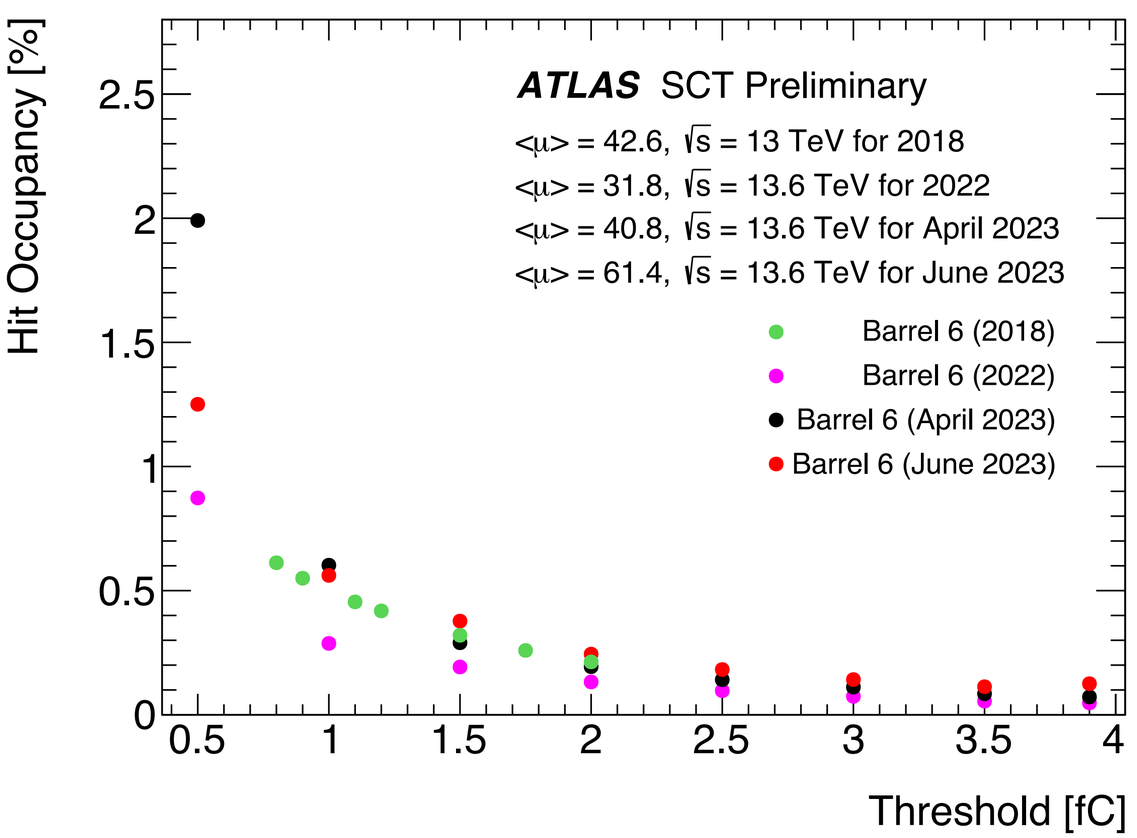
LEAKAGE CURRENT



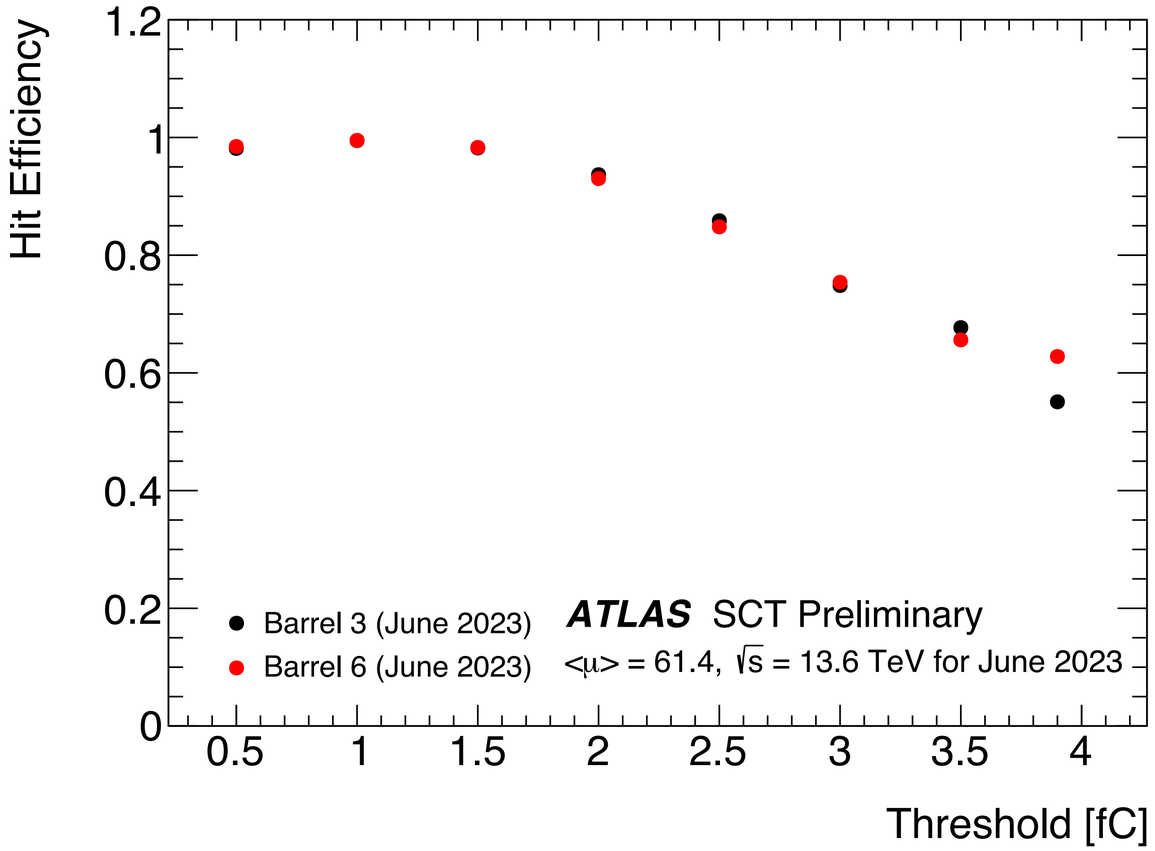
Evolution of the leakage current between Run2 and beginning of Run3

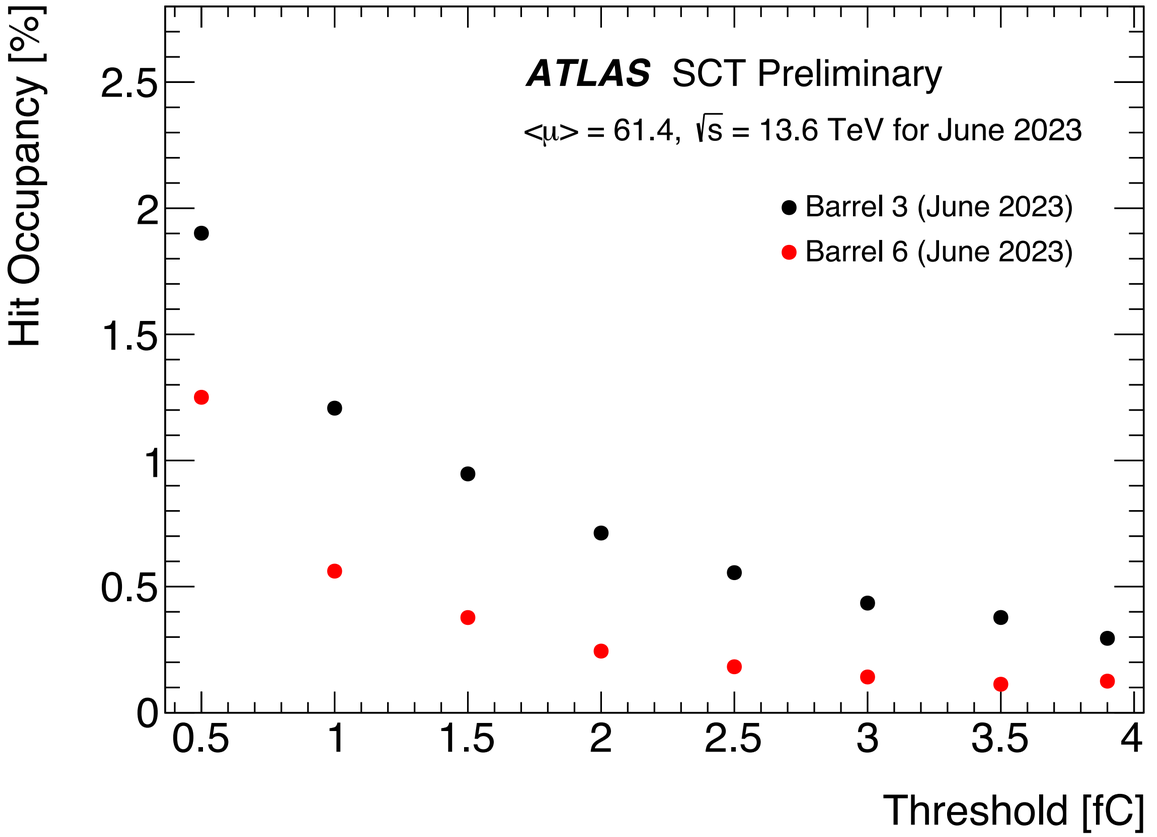
THRESHOLD SCAN



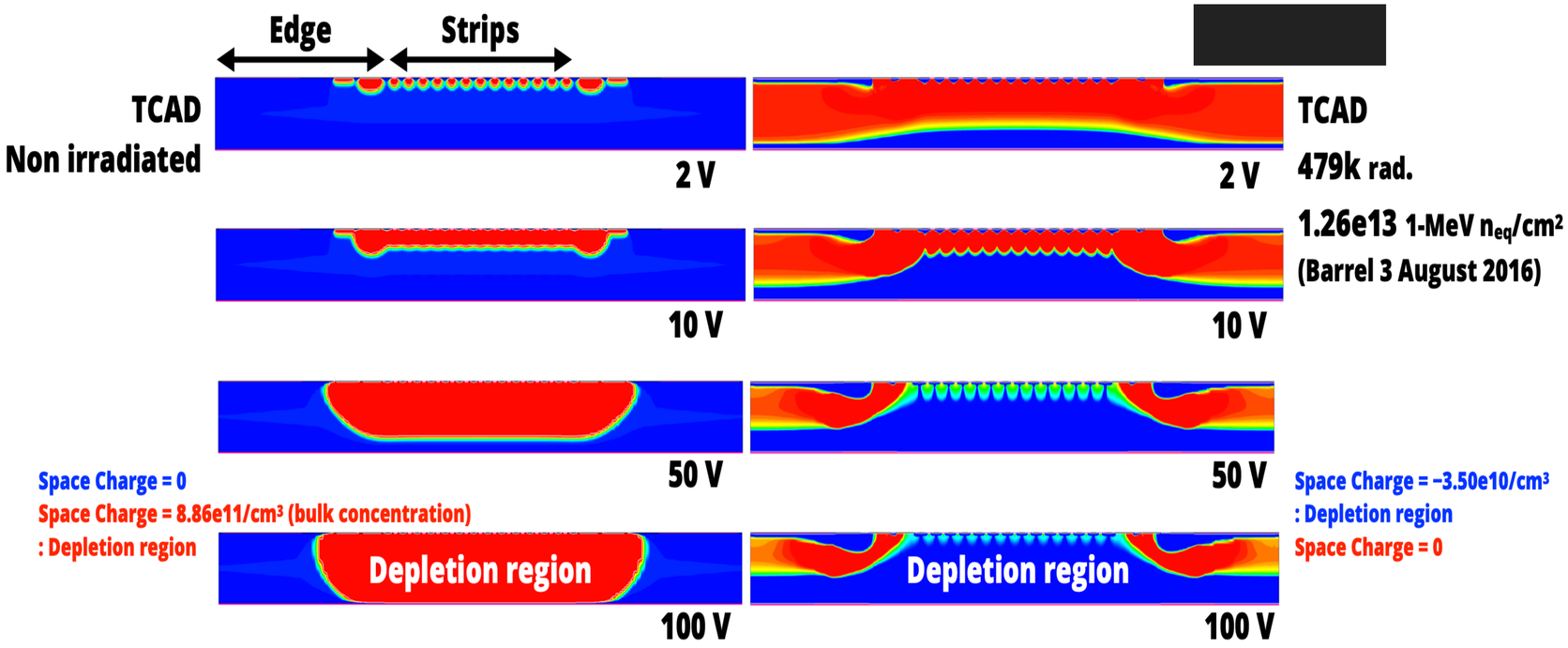


THRESHOLD SCAN





TYPE INVERSION



TCAD simulation of irradiated and non -- irradiated sensor