ATLAS Inner Detector Operational Experience at the Large Hadron Collider at CERN

25/08/2025

VERTEX 2025

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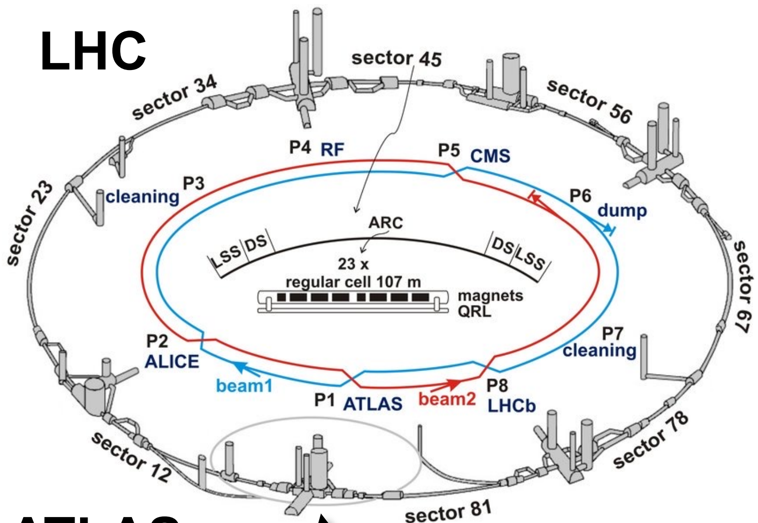
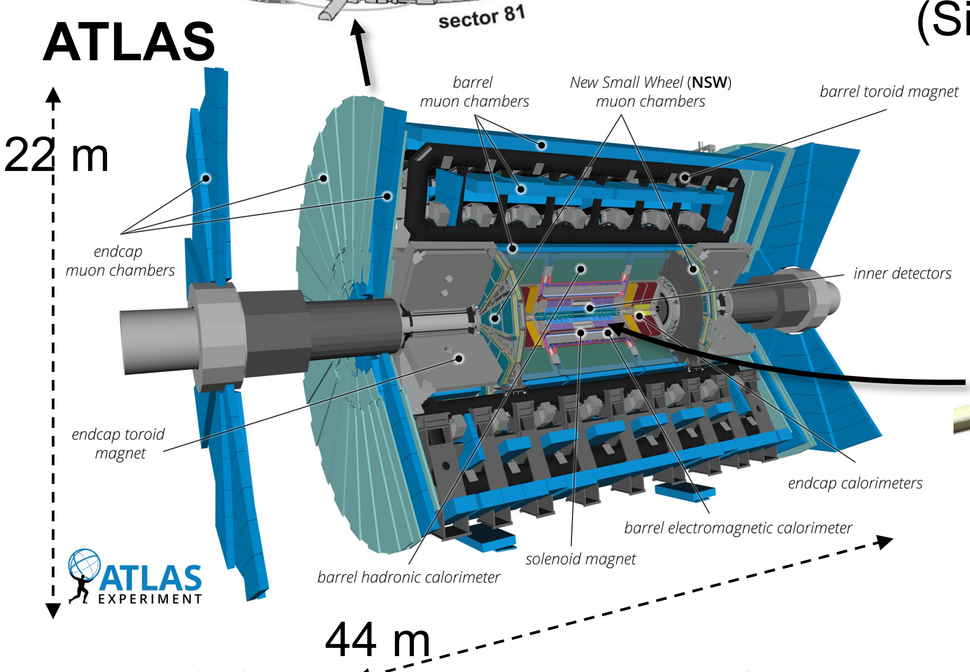
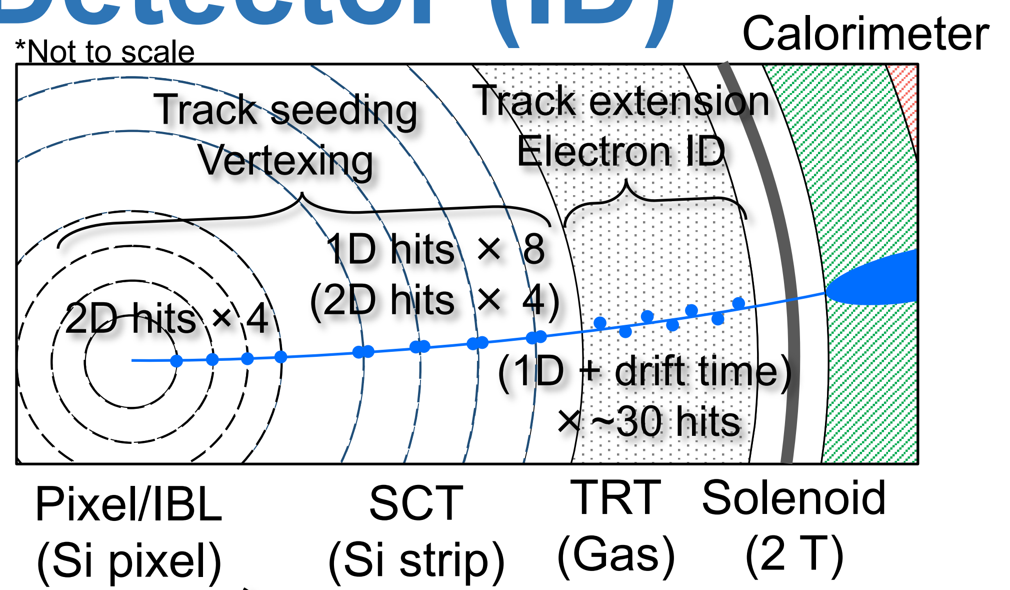
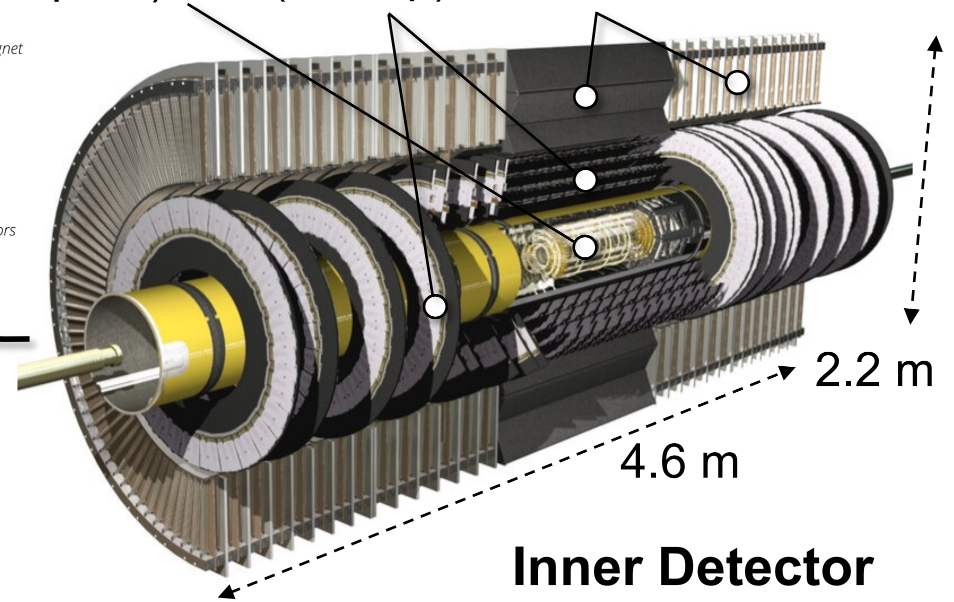
On behalf of the ATLAS Collaboration

ATLAS Inner Detector (ID)

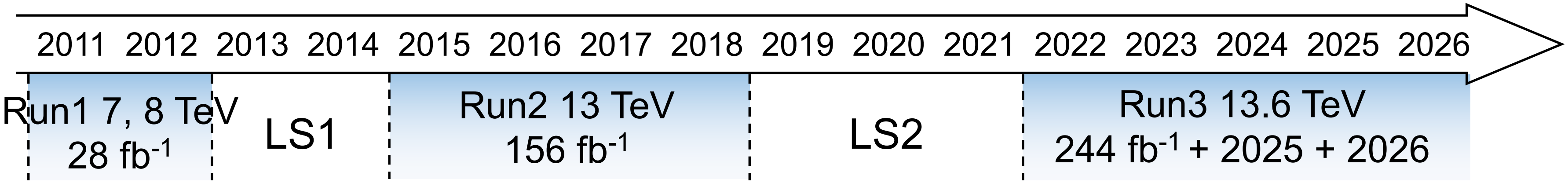




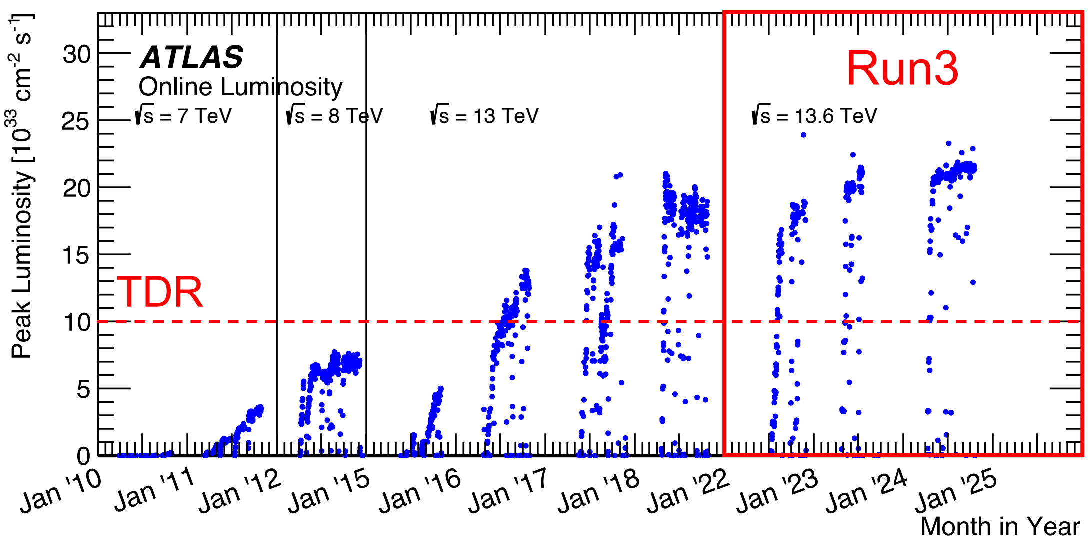


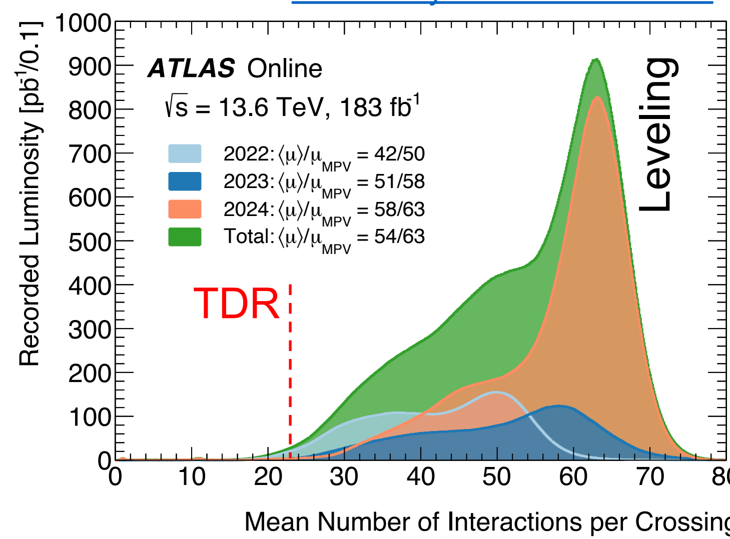


LHC Run 3 Performance



[LuminosityPublicResultsRun3]



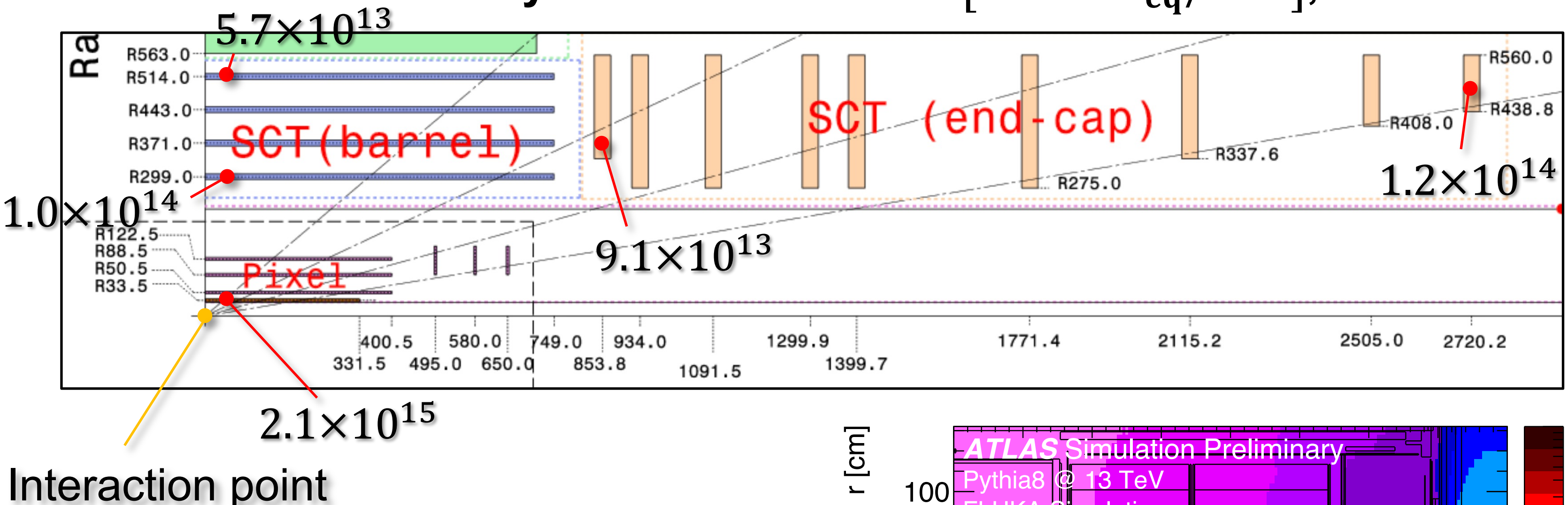


- Run 3 is ongoing with an excellent beam performance, thanks to the improved beam injector and the luminosity leveling scheme
- The luminosity and the pileup have exceeded the original design of ID since LHC Run 2* – Challenging environment for the DAQ
  - ATLAS Level 1 trigger rate has been keeping ~100 kHz

* IBL: installed in LS1 is not outside the design parameter

Irradiation of ID Since Run 1

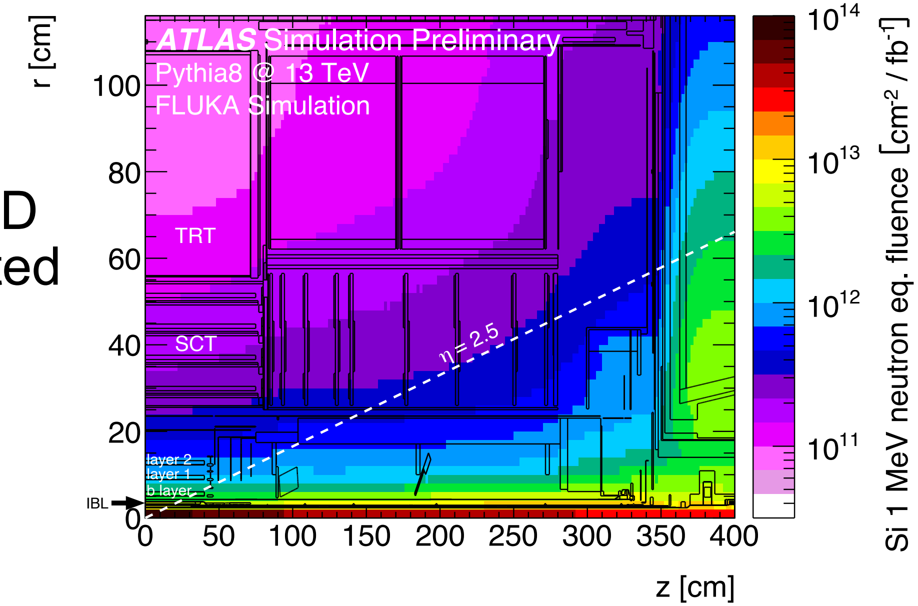
Radiation dose by FLUKA simulation $[1\ \mathrm{MeV}\ \mathrm{n_{eq}/cm^2}]$, 408 fb^{-1}



- The high luminosity and the extended Run 3 schedule give ID the irradiation more than expected

This talk focuses on…

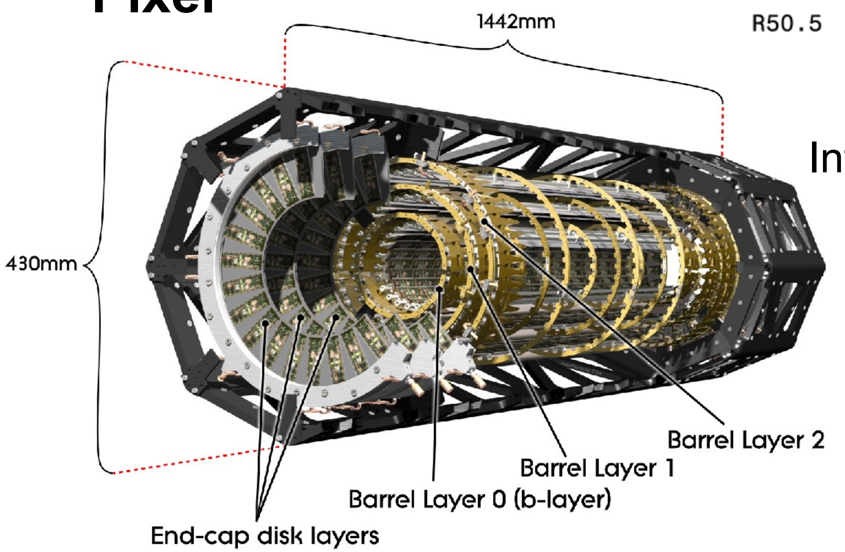
- Pixel & SCT DAQ in the high pileup condition
- Pixel & SCT performance with the high irradiation condition



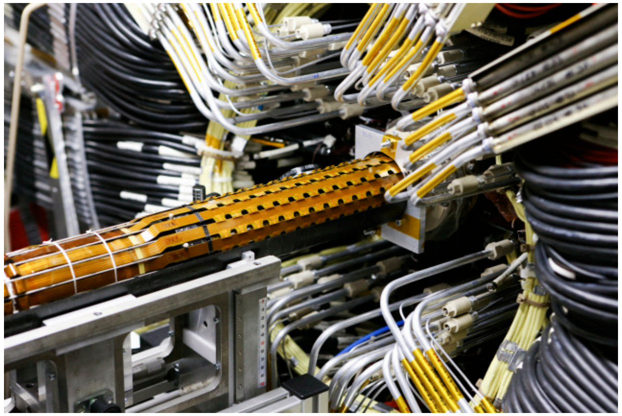
Pixel / IBL

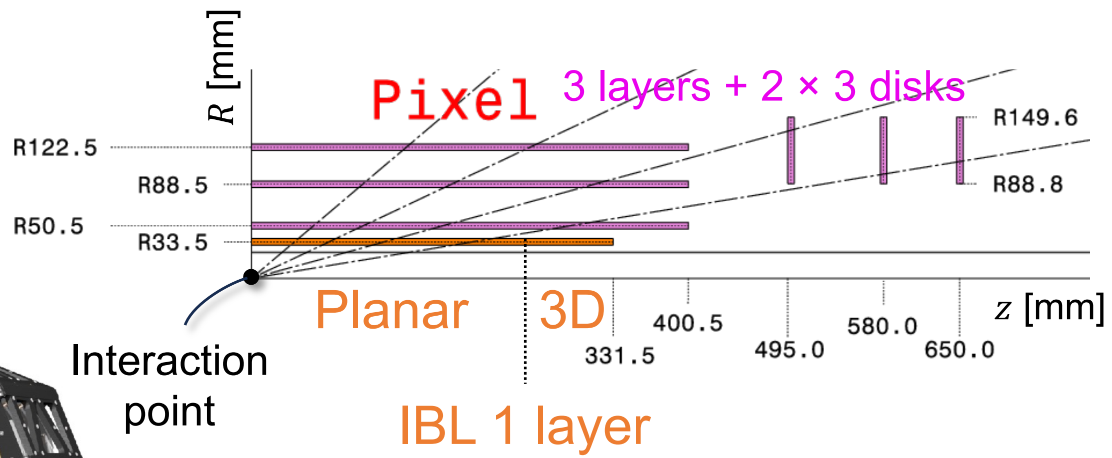
Pixel / IBL

Pixel



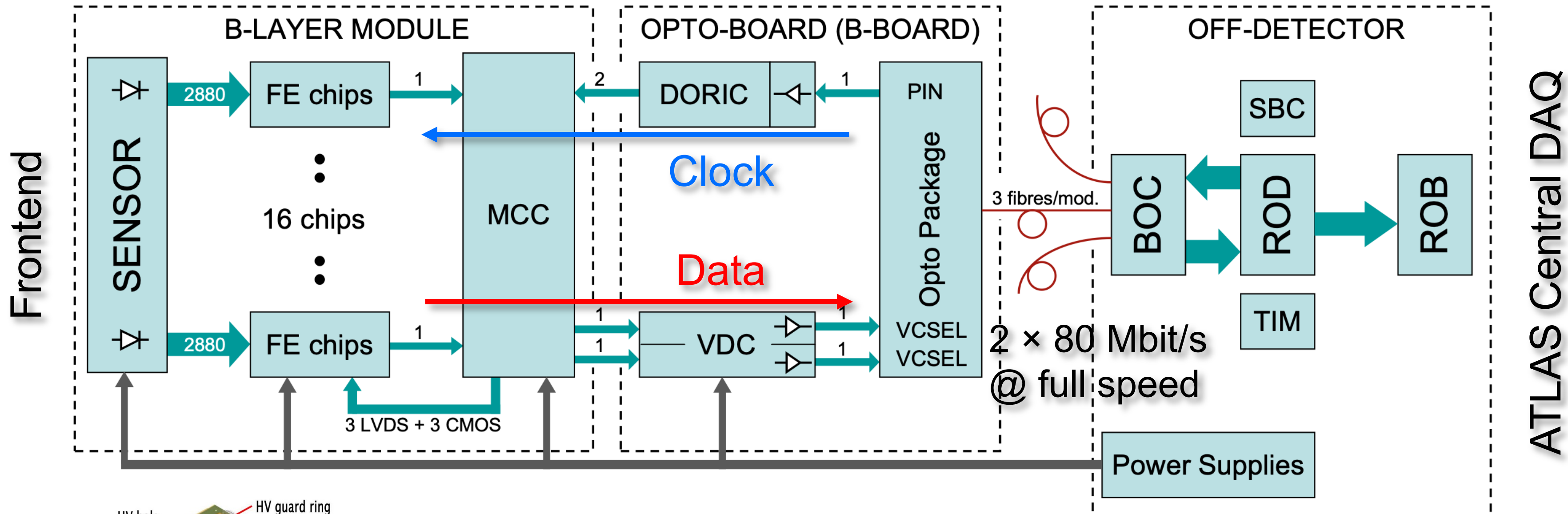
IBL (Installed after Run 1)

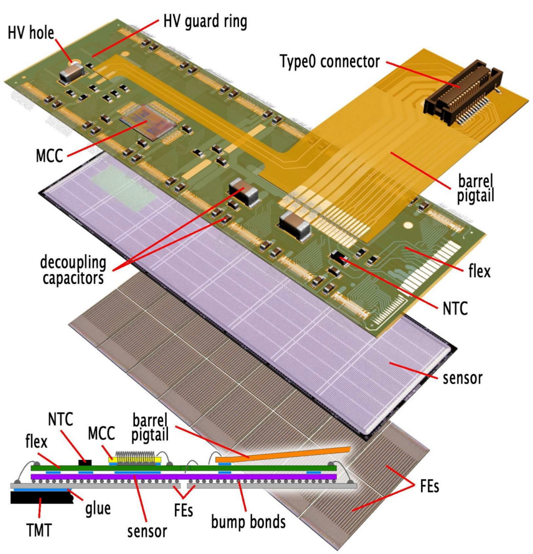




	Pixel	IBL (Planar/3D)
Sensor type	n+ in n	n+ in n / n+ in p
Sensor thickness	250 μm	200 / 230 μm
Front End	FE-I3 250 nm CMOS	FE-I4 130 nm CMOS
Pixel Size	$50 \times 400\ \mu m^2$	$50 \times 250\ \mu m^2$
Radiation Hardness	50 Mrad $\sim 1 \times 10^{15} n_{eq} cm^{-2}$	250 Mrad $\sim 5 \times 10^{15} n_{eq} cm^{-2}$
Charge	8 bit ToT	4 bit ToT
# channel	80M	12M

Pixel DAQ system





ATL-INDET-PROC-2010-028

- 16 FE chips are controlled by MCC (Module Control Chip)
- The data is sent via optoboard and the optics to ROD (Read Out Driver)
- No MCC and max 2 FEs in IBL

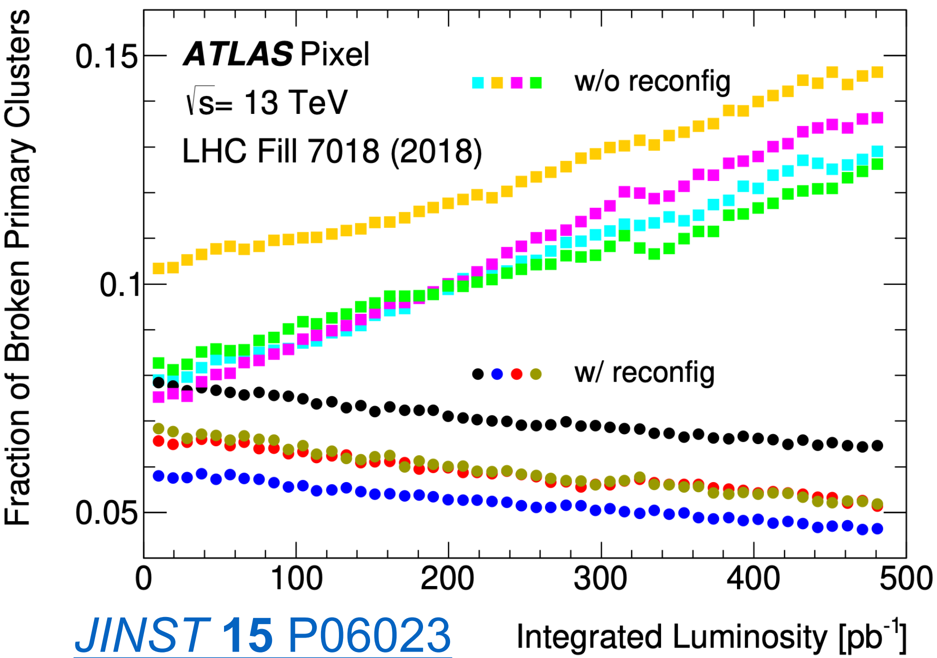
Detector Working Fraction

Disabled modules		2018		2024		2025	
		Disabled/Total	[%]	Disabled/Total	[%]	Disabled/Total	[%]
Pixel	B-Layer	18/286	6.2	21/286	7.3	22/286	**7.7**
	Layer 1	29/494	5.8	18/494	3.6	19/494	**3.8**
	Layer 2	33/676	4.8	50/676	7.4	61/676	**9.0**
	Disk	15/288	5.2	16/288	5.2	15/288	**5.2**
	Total	95/1744	5.4	105/1744	6.0	117/1744	**6.7**
IBL (Front End)		3/448	0.7	5/448	1.1	5/448	**1.1**
Total		98/2192	4.5	110/2192	5.0	122/2192	**5.6**

- 94% is active in pixel even for 17 years since the commissioning
- 99% of IBL is working since the installation in 2014
- Two major recoveries
  - ~30 modules recovered in LS2 by replacing optoboards
  - 6 Layer 1 modules with one problematic readout link recovered in 2024 by going to half readout speed (i.e. from 2 to 1 link)

Pixel Register Reconfiguration

Test in 2018



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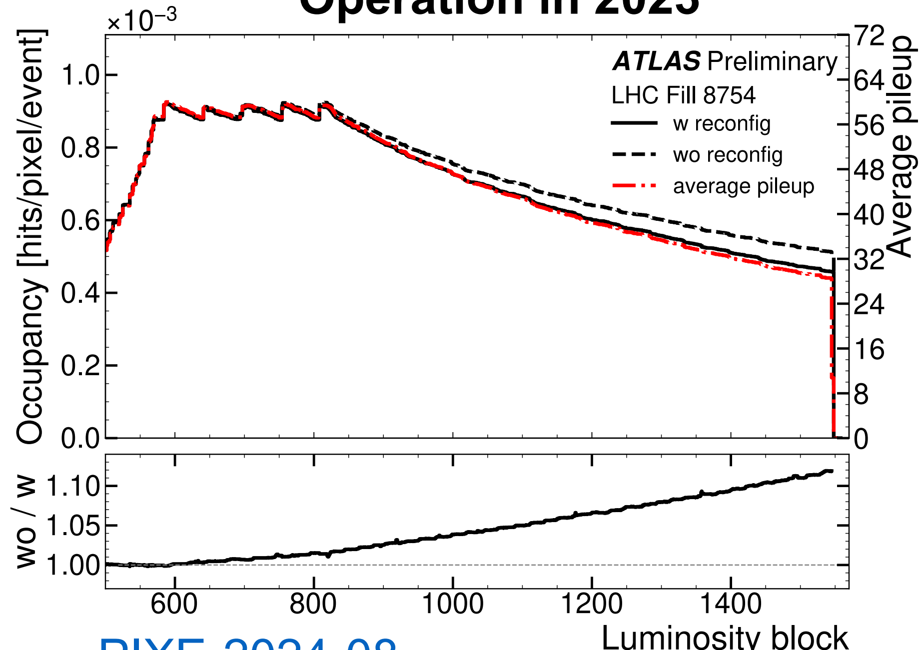
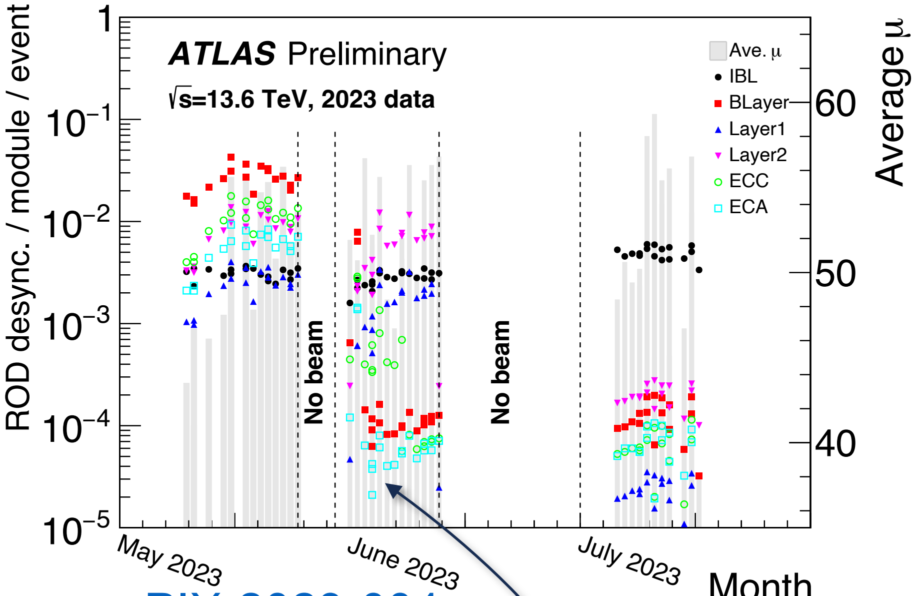
Operation in 2023



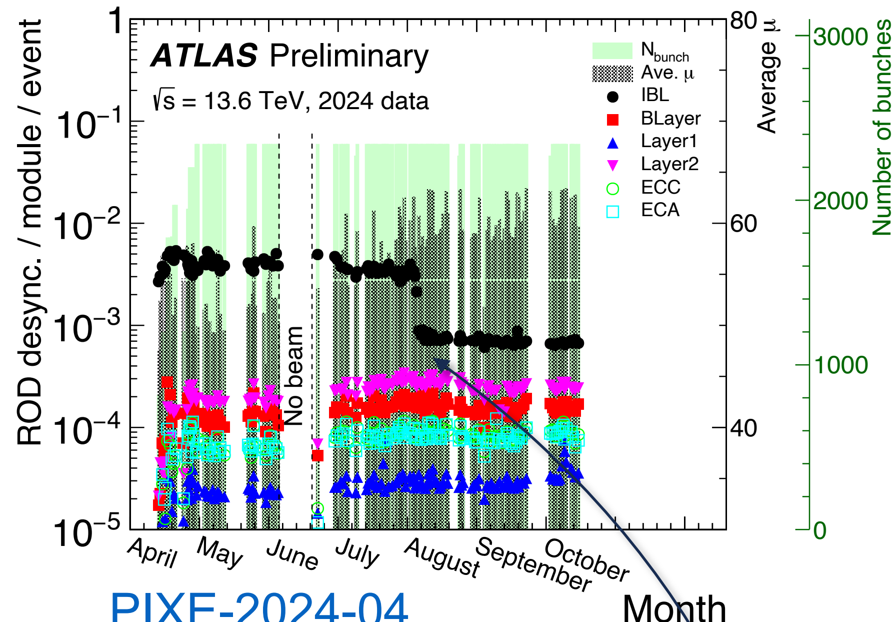
PIXE-2024-08

- Reconfiguration of every pixel register on the front-end chip every 11 min to recover them from the single event effect is introduced
  - The reconfiguration can be done within the ATLAS global event counter reset
- Significantly reduced the noise and broken clusters in IBL

Desynchronization



[PIX-2023-004](#)

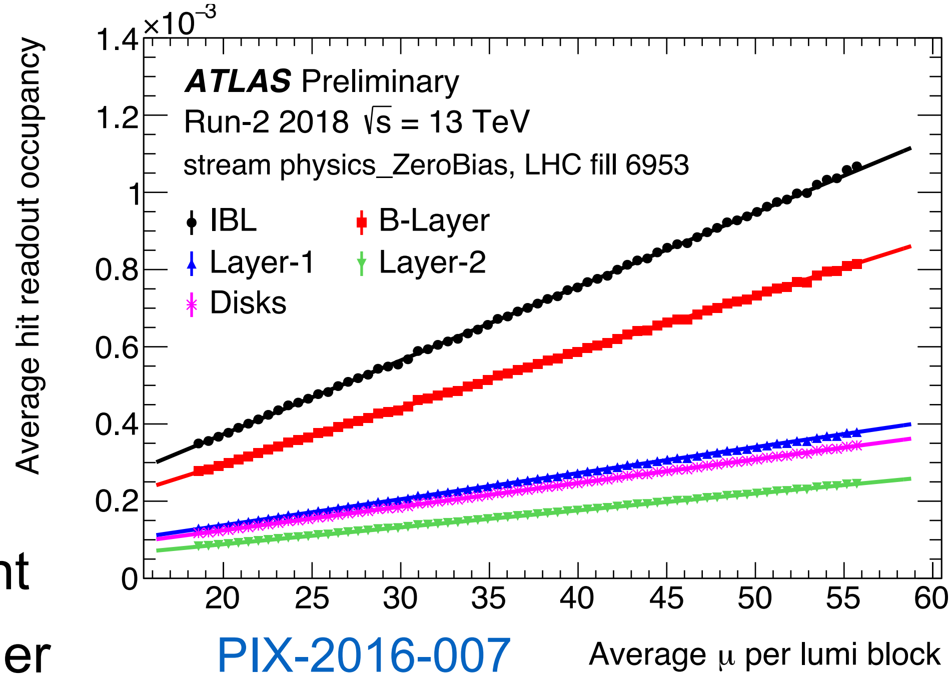


[PIXE-2024-04](#)

- Exceeding the bandwidth led to desynchronization between the ATLAS central DAQ and a module, causing data loss from that module for up to 5 seconds
- Smart L1 forwarding logic was introduced in the ROD firmware
  - Send the dummy data if the module buffer is full, and keep tracking the trigger
- The misbehavior of a single event, splitting into two events, was fixed

Threshold

- The threshold is decided by the readout occupancy
  - The balance between Pileup vs Radiation Damage
  (occupancy↑) (occupancy↓)
- The thresholds of some parts are lowered in 2018 and 2022, thanks to the DAQ improvement
- However, they are back to higher threshold due to the LHC performance

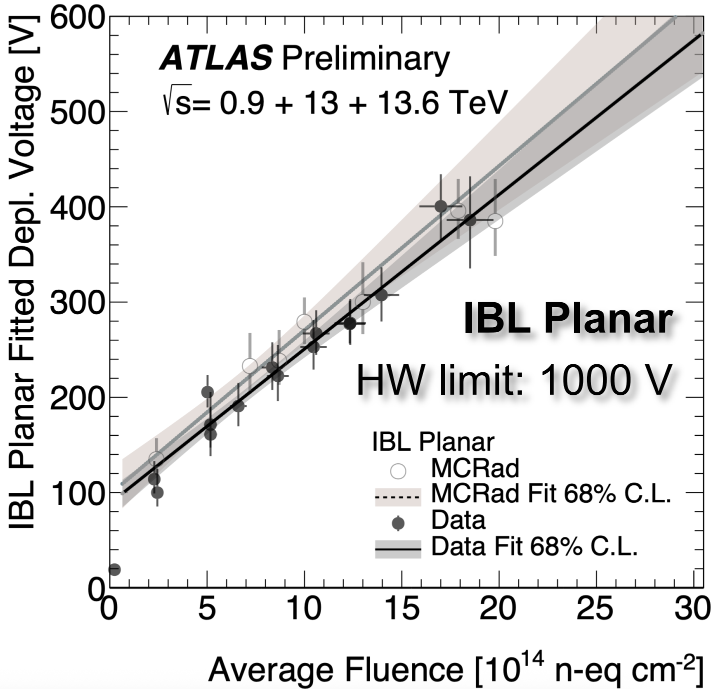


PIX-2016-007

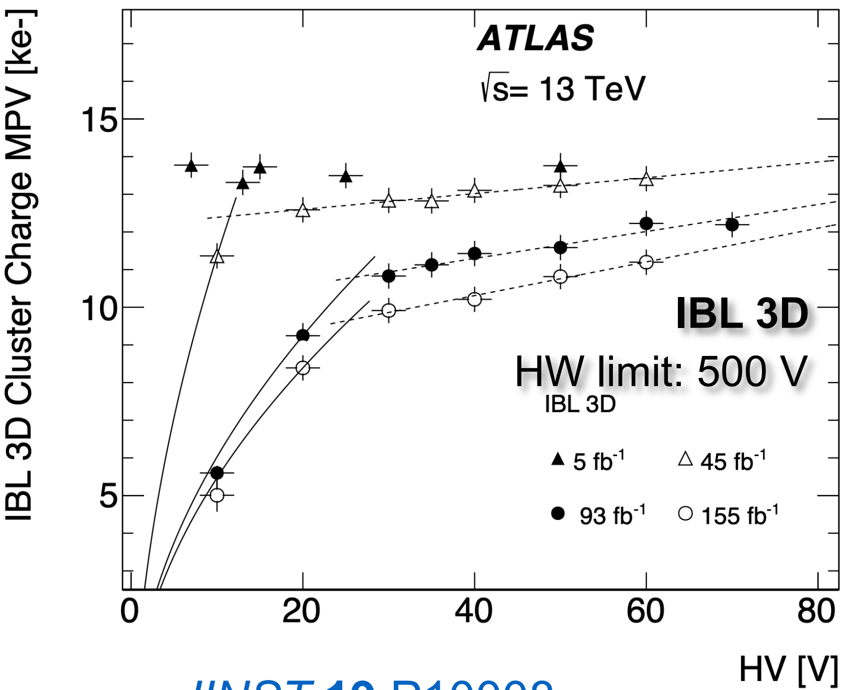
Threshold [e]	2015	2016	2017	2018	2022	2023
IBL	2500	2500	2500	2000	1500	1500
B-Layer	3500	5000	5000	4300*	3500*	4700
Layer 1, Layer 2	3500	3500	3500	3500	3500	4300
Disks	3500	3500	4500	3500	3500	4300

*Threshold only lowered in the central region, higher at high eta

Full Depletion Voltage



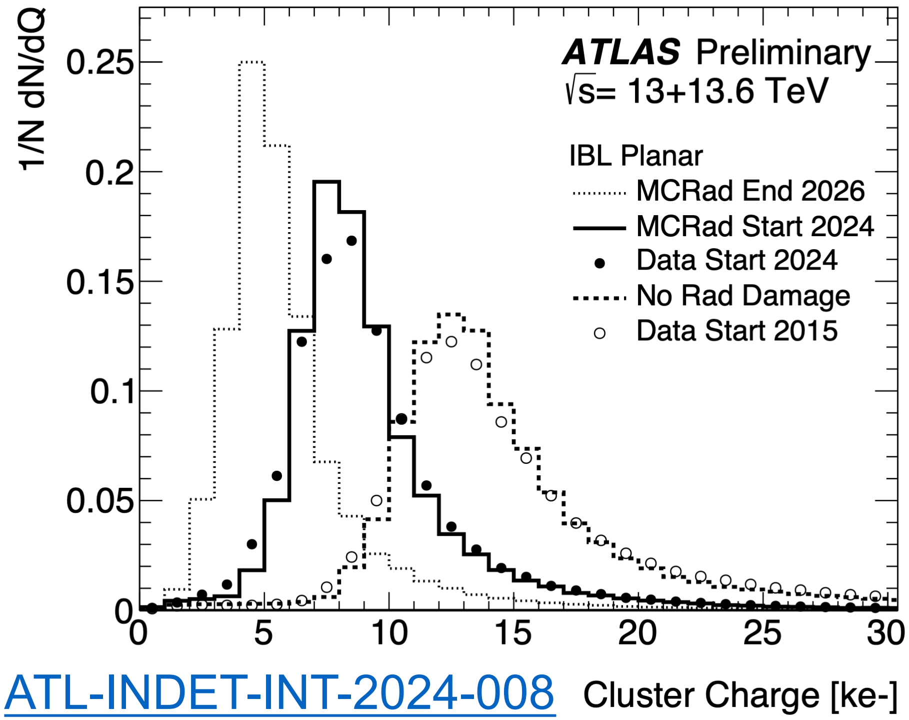
ATL-INDET-INT-2024-007



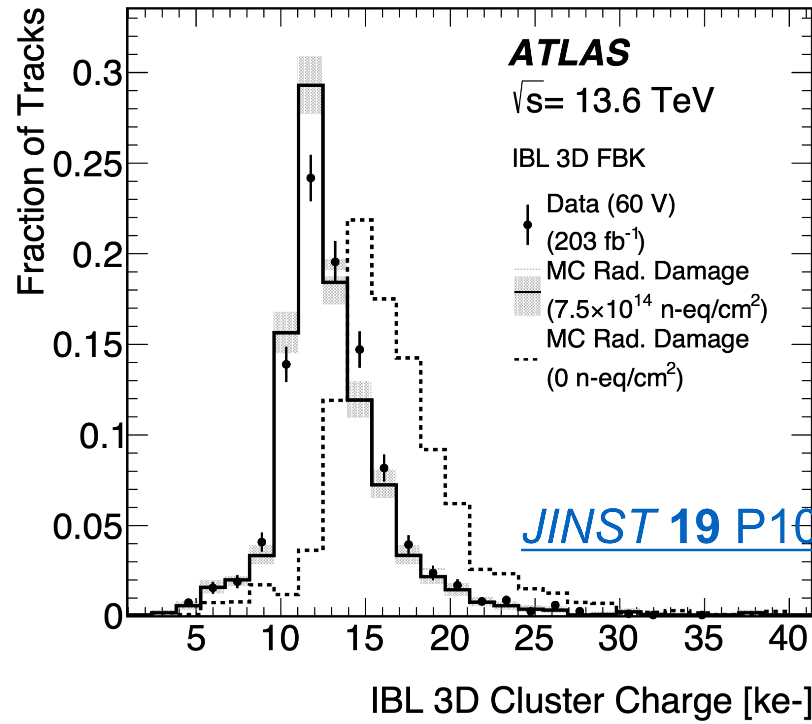
JINST **19** P10008

- The full depletion voltage increases due to the irradiation
- Measured by the cluster charge dependency of the bias voltage
- The bias voltage is adjusted at the beginning of each year to achieve the full depletion
- Enough margin to the hardware limit

Radiation Damage Digitizer



ATL-INDET-INT-2024-008



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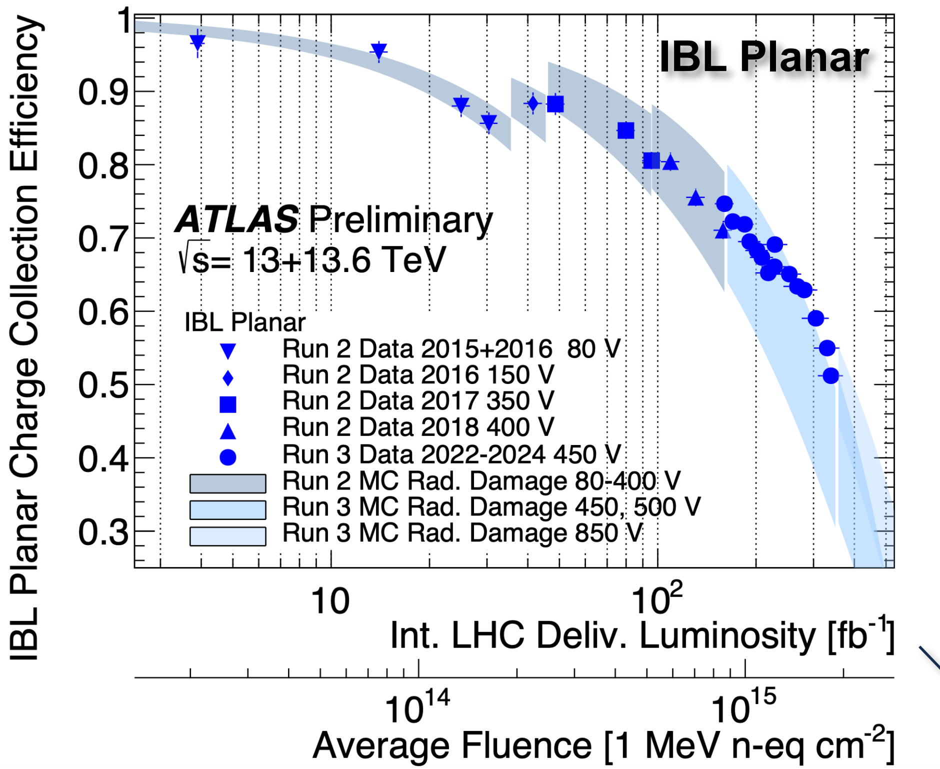
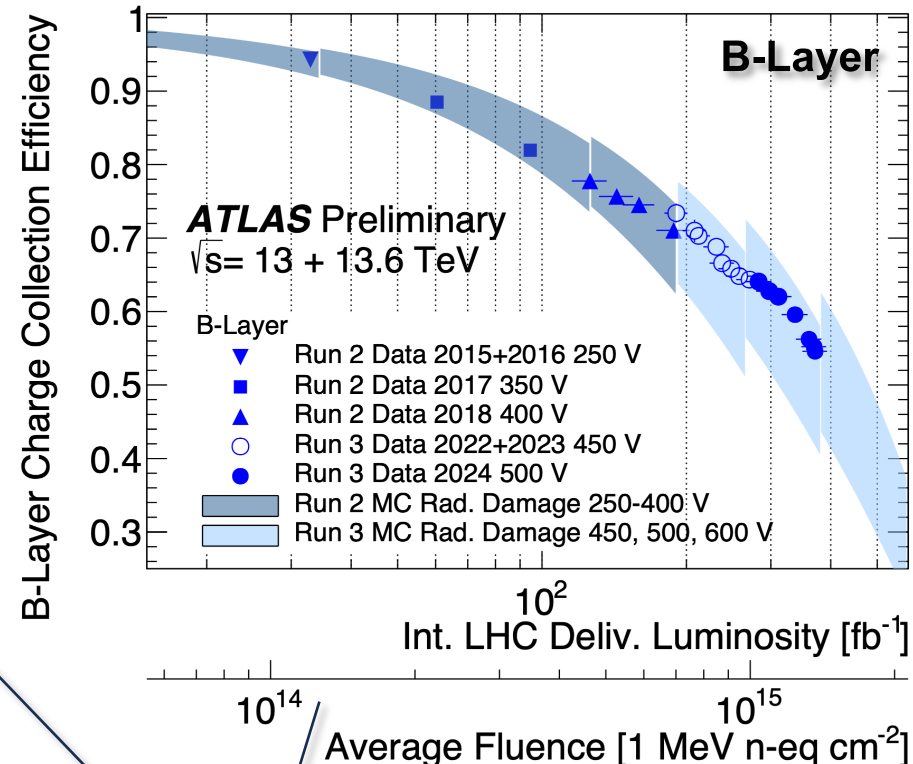
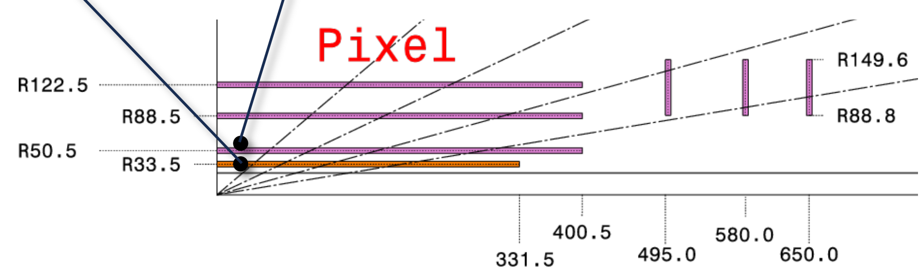
- The new digitizer was validated with data and implemented in the ATLAS official MC samples since Run 3
- The signal is calculated using the electric field, Lorentz angle, and weighting potential maps, taking into account carrier trapping and diffusion effects

Charge Collection Efficiency





ATL-INDET-INT-2024-008



- About 30% charge collection in IBL Planar and B-Layer at the end of Run 3
- Hits on track efficiency have been kept > 98% in IBL Planar

3D Sensor Performance

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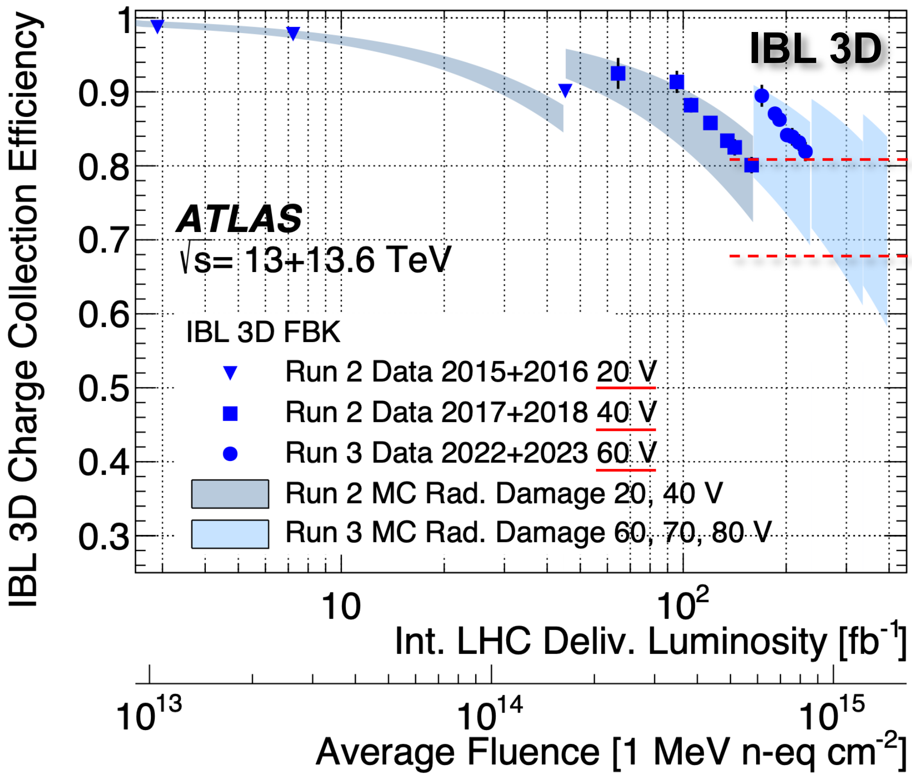
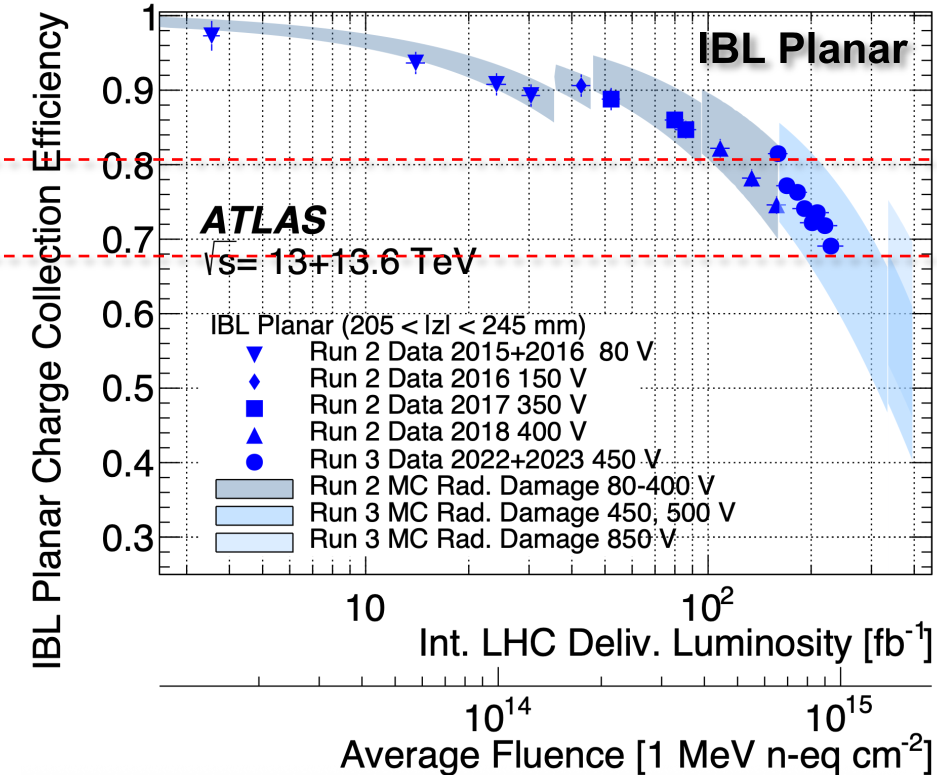
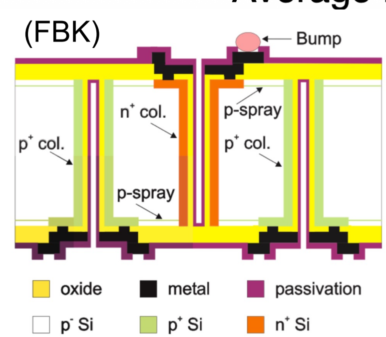
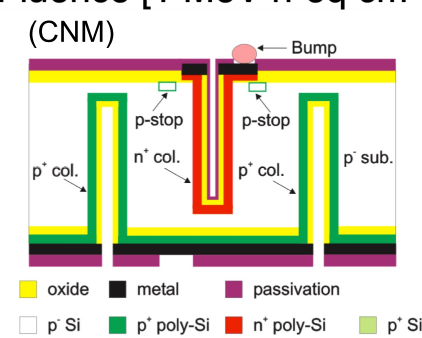




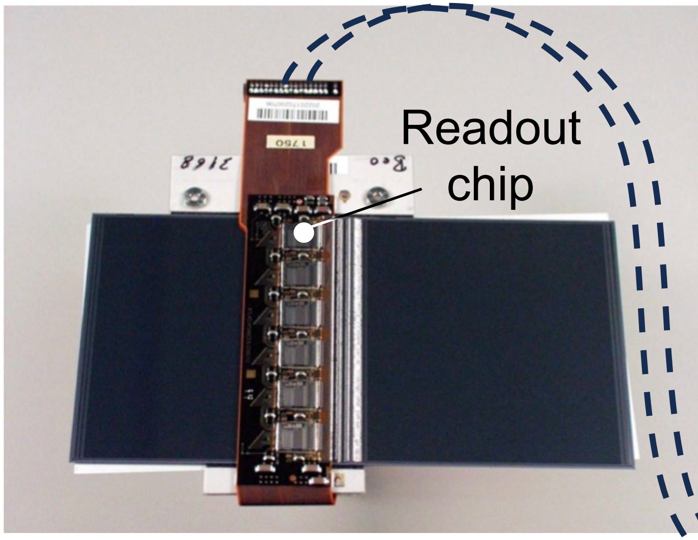
- The 3D sensor is fully depleted by a lower supplied voltage than the planar
- The 3D sensor shows better performance at the same fluence in terms of CCE



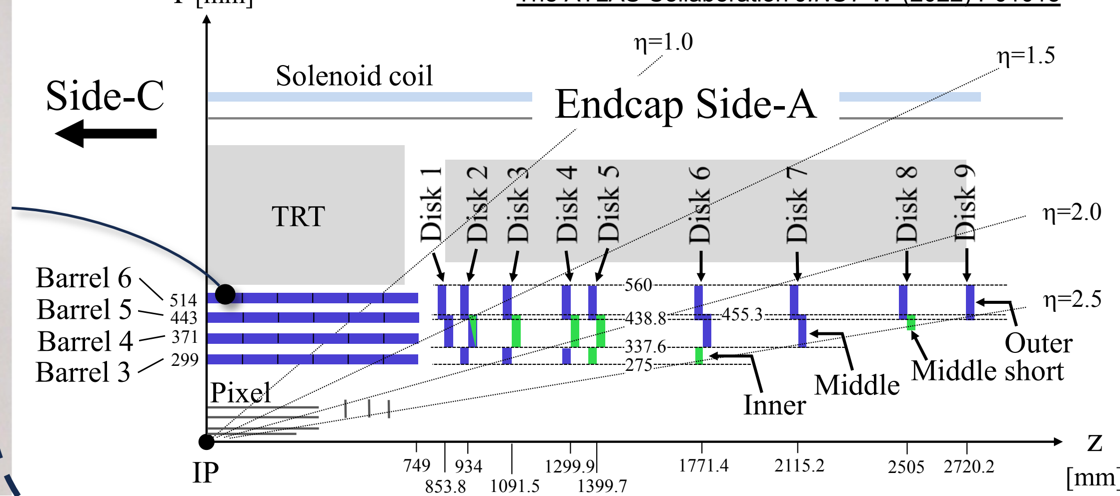


SCT

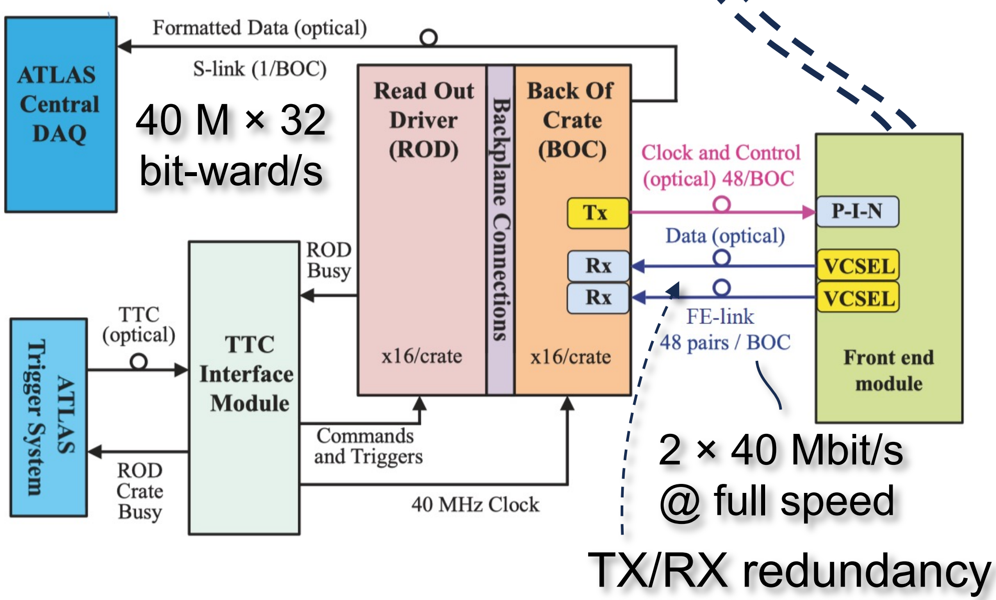
SemiConductor Tracker (SCT)



The ATLAS Collaboration *et al* 2008 *JINST* **3** S08003



The ATLAS Collaboration *JINST* **17** (2022) P01013



- p-in-n Si strip sensor
  - 80 µm pitch
- 4088 modules × 1536 strips = 6.3 M channels
- Binary read-out (1 fC threshold)
- 12 ABCD read-out chip
  - Includes amplifier, shaper, and discriminator

Detector Working Fraction

ATLAS SCT Preliminary ↙ Start of Run 3 SCTD-2025-02

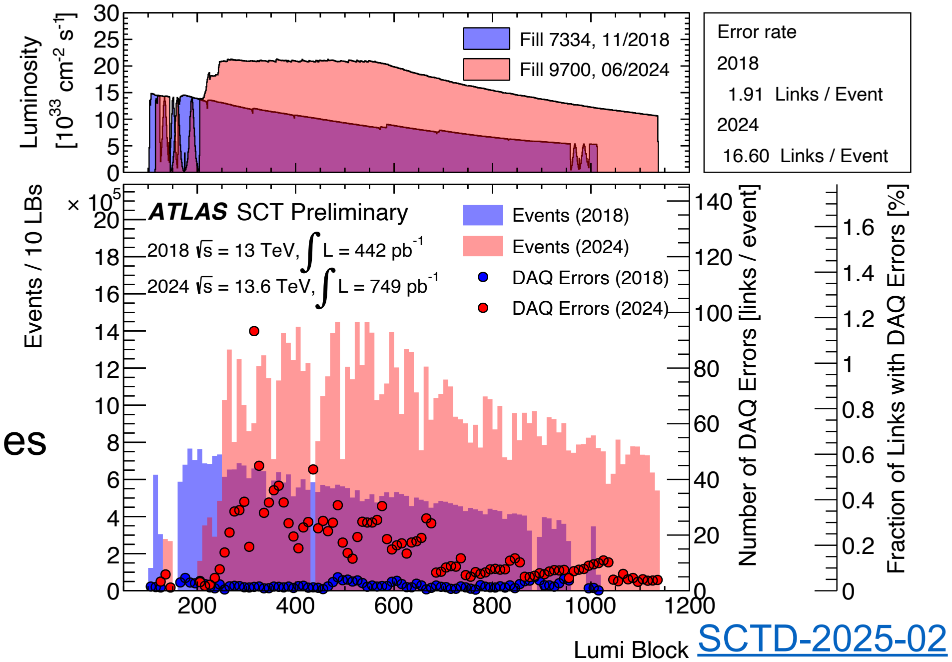
Disabled component	05/2022	12/2022	11/2023	12/2024	08/2025
Modules	46	47	49	51	**57**
Chips	85	81	88	171	**183**
Strips	24071	15310	15574	12738	**13314**
TX Redundancy	58	59	50	51	**53**
RX Redundancy	155	156	159	171	**171**
Active Strips	98.3 %	98.4 %	98.4 %	98.2 %	**98.0 %**

- A highly active strip fraction has been kept since the commissioning (17 years ago)
- Redundancy recovers the partially inactive modules well, and is applied in 5.5% of SCT
- Replacement of the hardware in the DAQ and the power supplies in the off-detector, the continual optimization of the calibration software and the operational parameters have all been vital in keeping the active strips

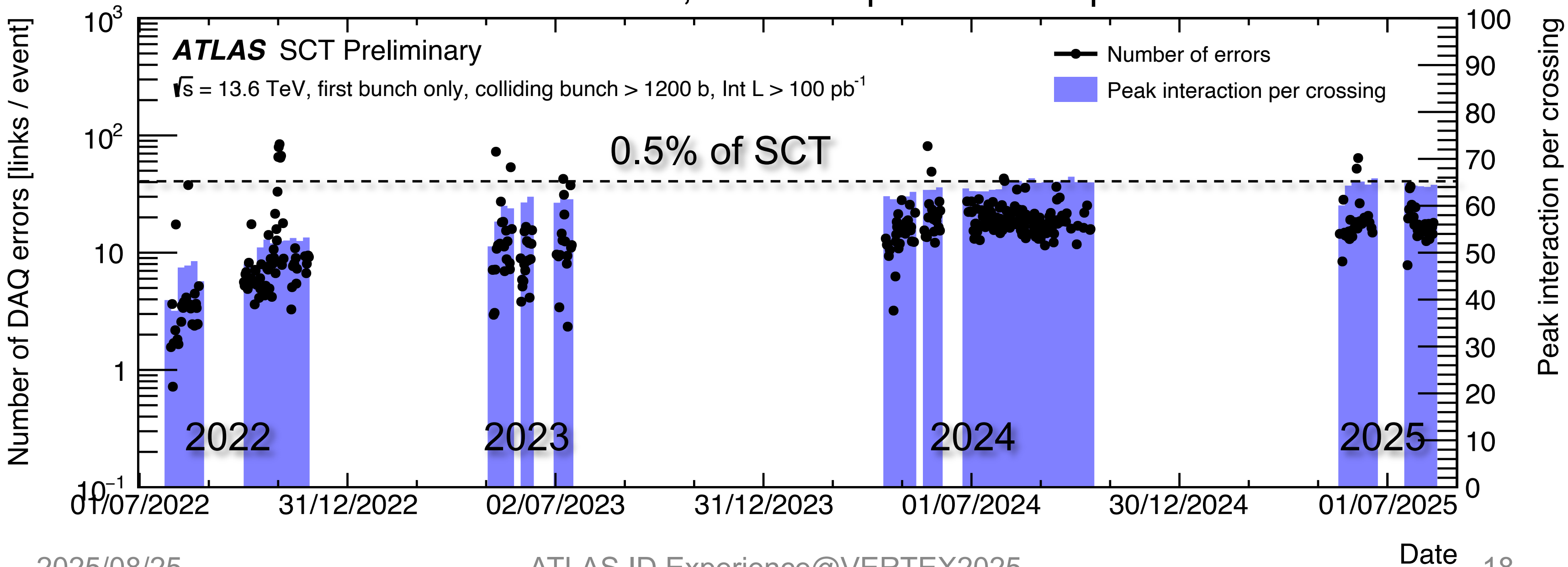
RX plugin replacement in the service cavern

DAQ Errors

- Increased from Run 2 due to the high luminosity (pileup)
  - DAQ errors are catalyzed by exceeding the data link bandwidth, SEU, and the data processing issues resulting the power supply failure
- However, the rate has kept low level (< 0.5% of SCT)
  - Thanks to the automatic recovery, the DAQ fiber remap to equalize the amount of the data to each link in LS2, and the operational experience of the team

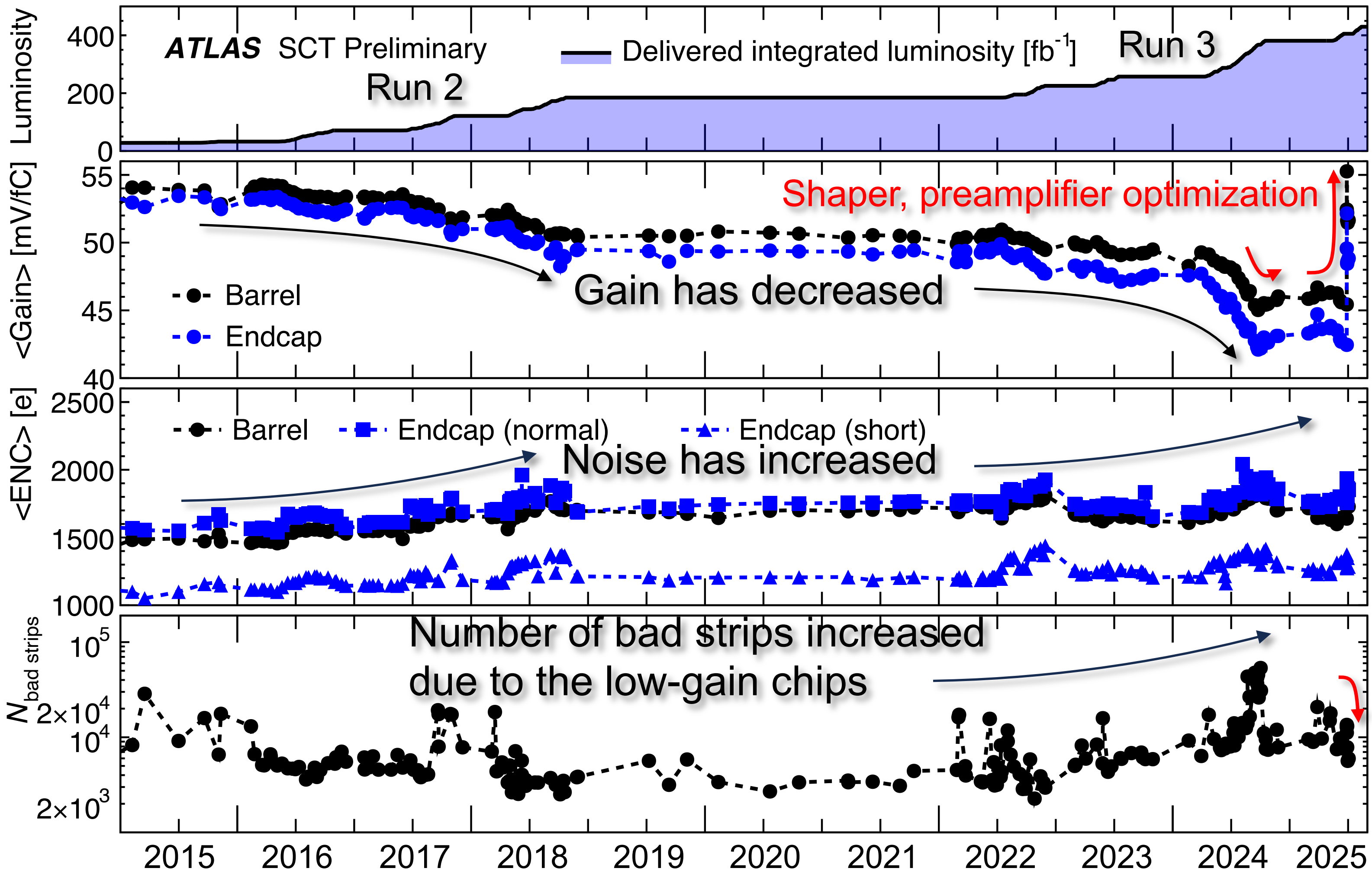


SCTD-2025-02



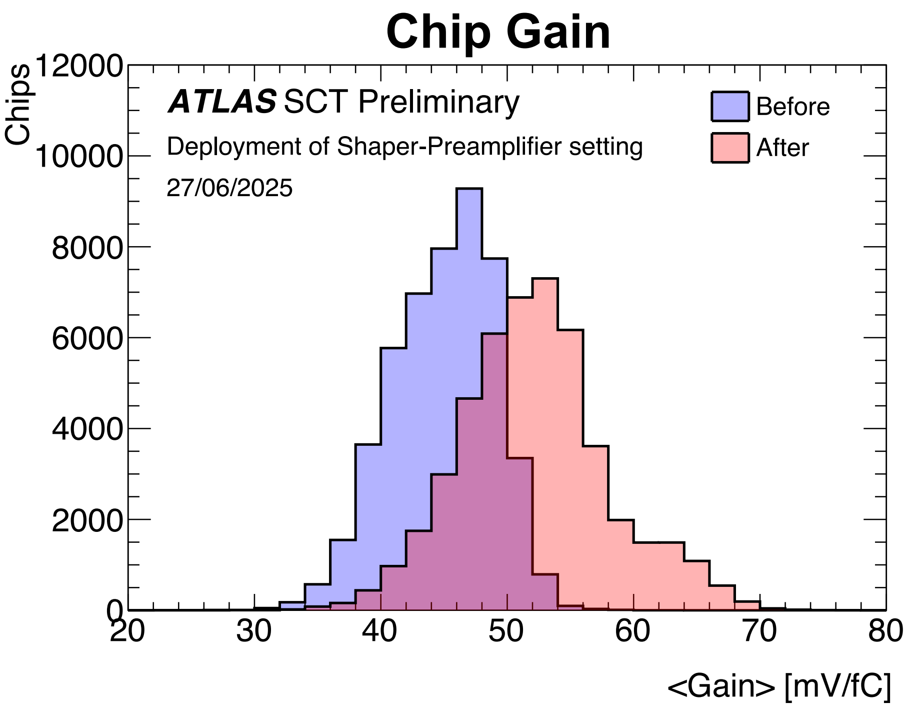
Gain & Noise Monitoring

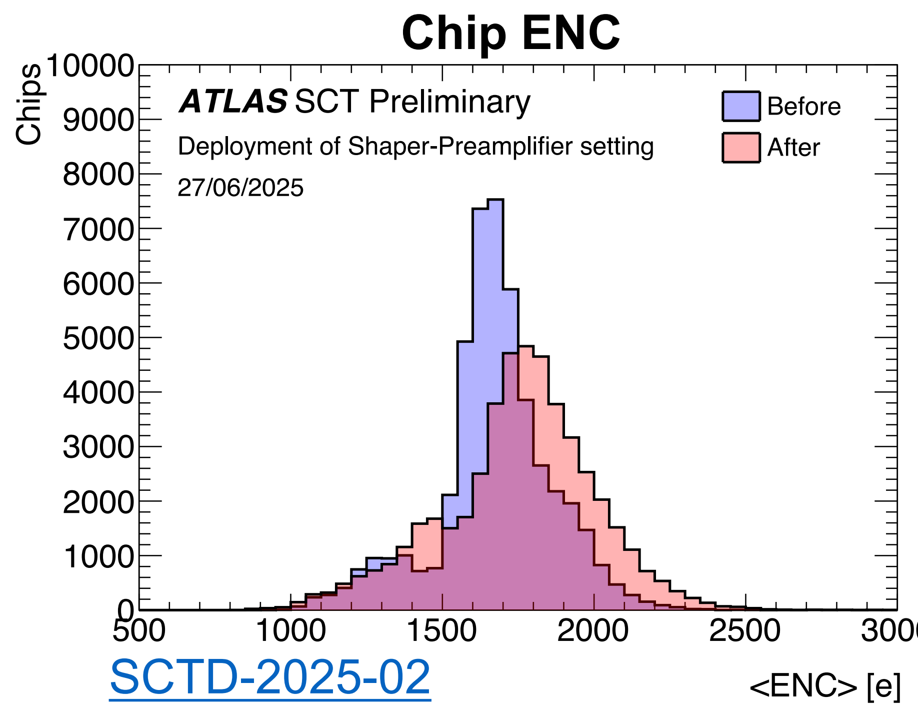
SCTD-2025-02



- Performance degradation is seen, and recovery actions were applied

Shaper & Preamp Optimization

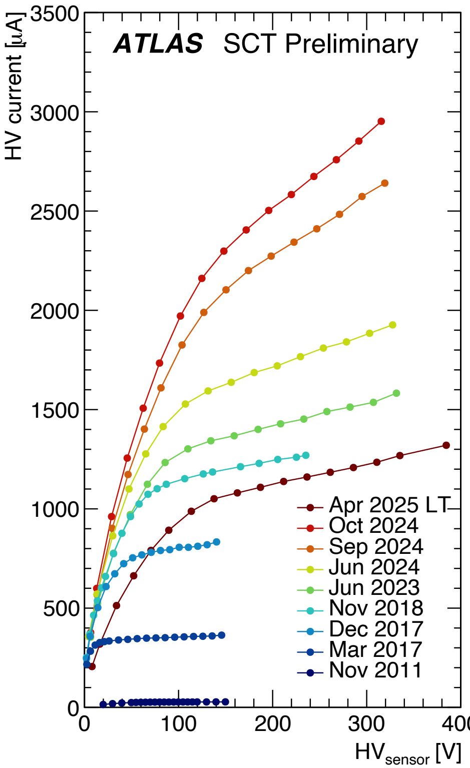


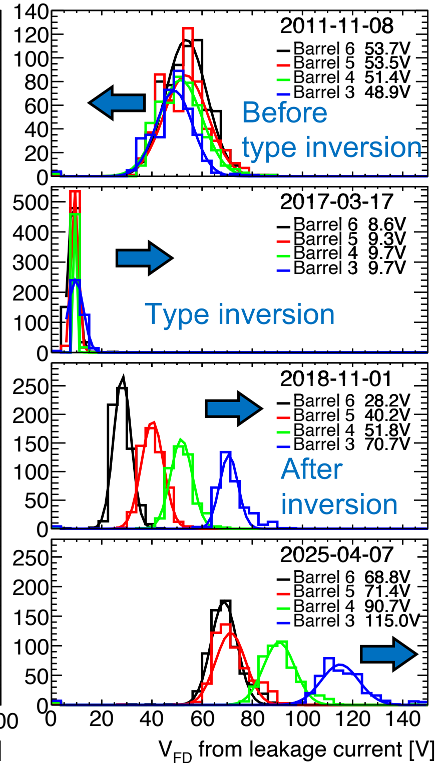


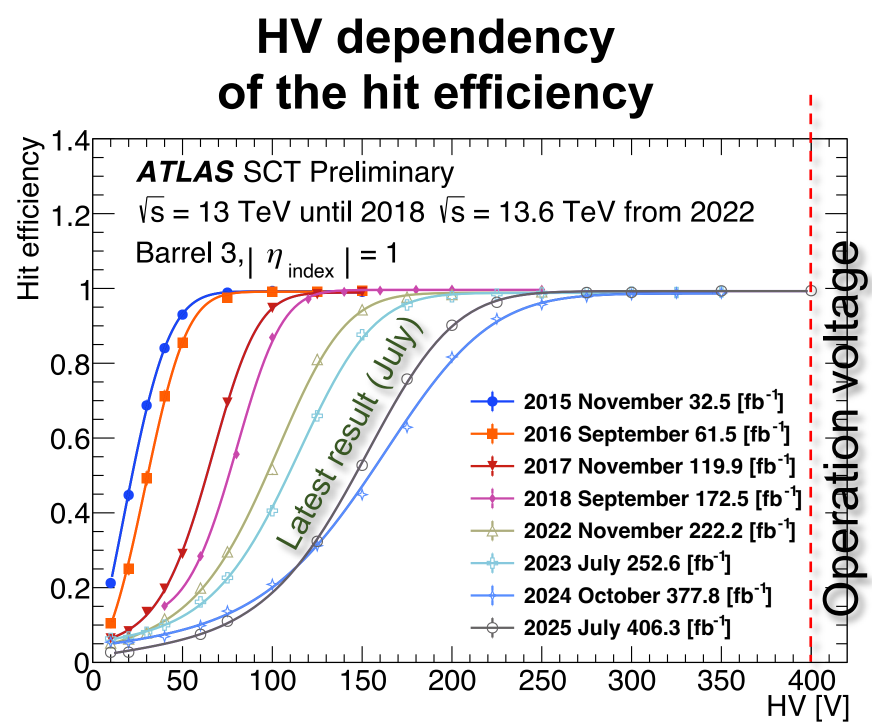
[SCTD-2025-02]

- The bias current of the shaper and preamplifier changes the signal shape and the amount of the signals before the discriminator
- The settings were optimized with a day-long scan in a long no-beam period to increase the gain while keeping the noise level
- The combination of the increase in the shaper bias current and the decrease in the preamplifier bias current improved the gain

Full Depletion Voltage





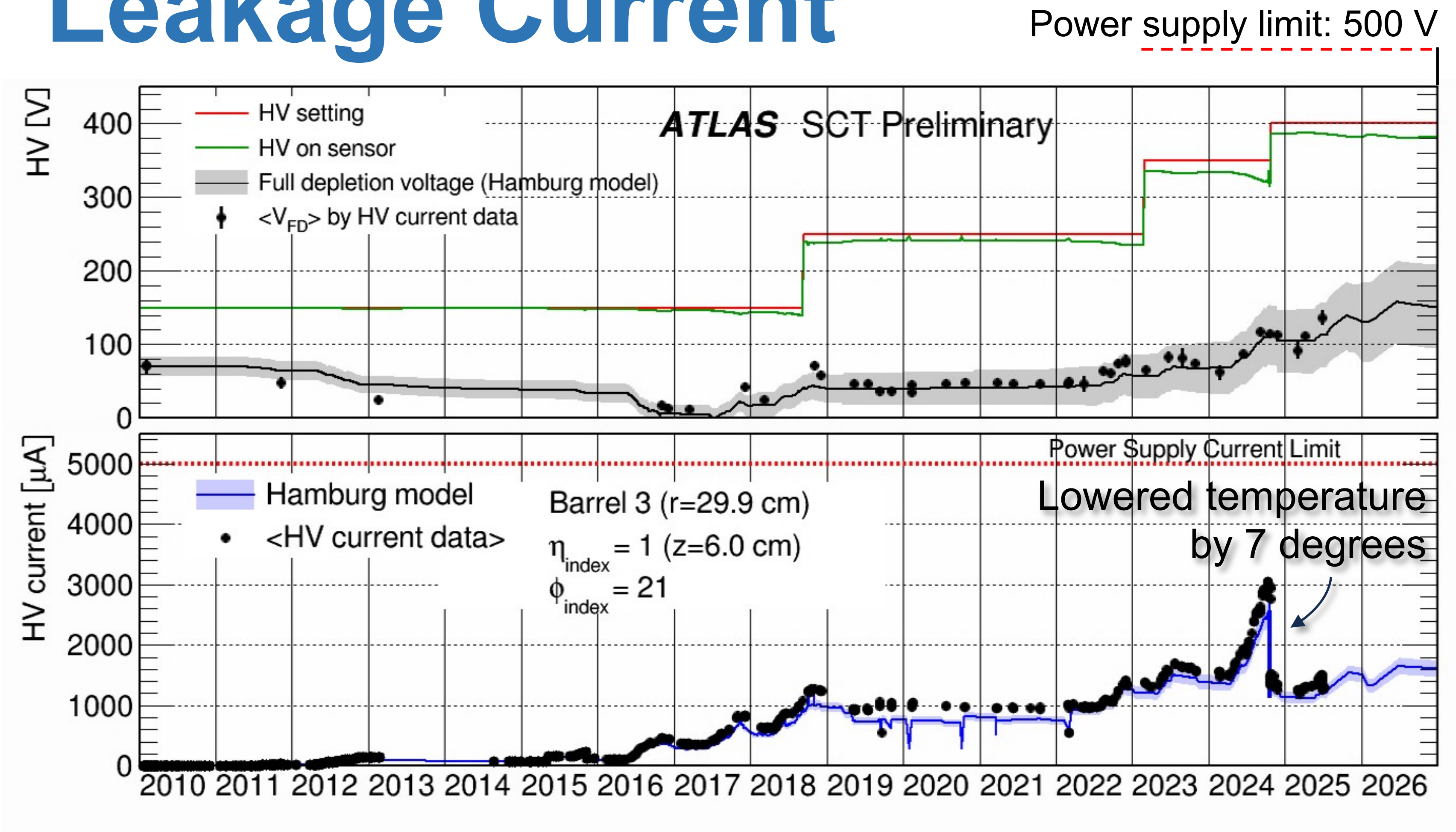


SCTD-2025-02

- Full depletion voltage V_{FD} is estimated by the I-V curve
- V_{FD} has been increasing due to the radiation damage since the type inversion in 2017
- The HV setting is adjusted once or twice per year by the continual hit efficiency monitoring

SCTD-2025-02

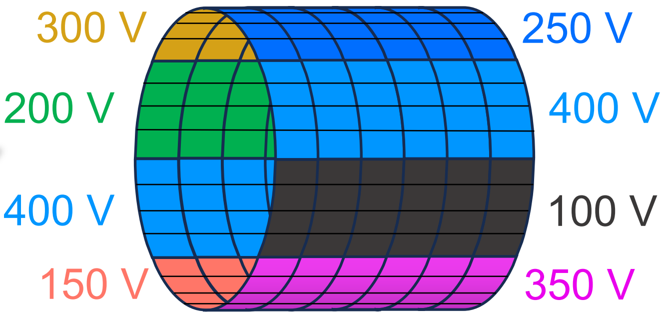
Leakage Current

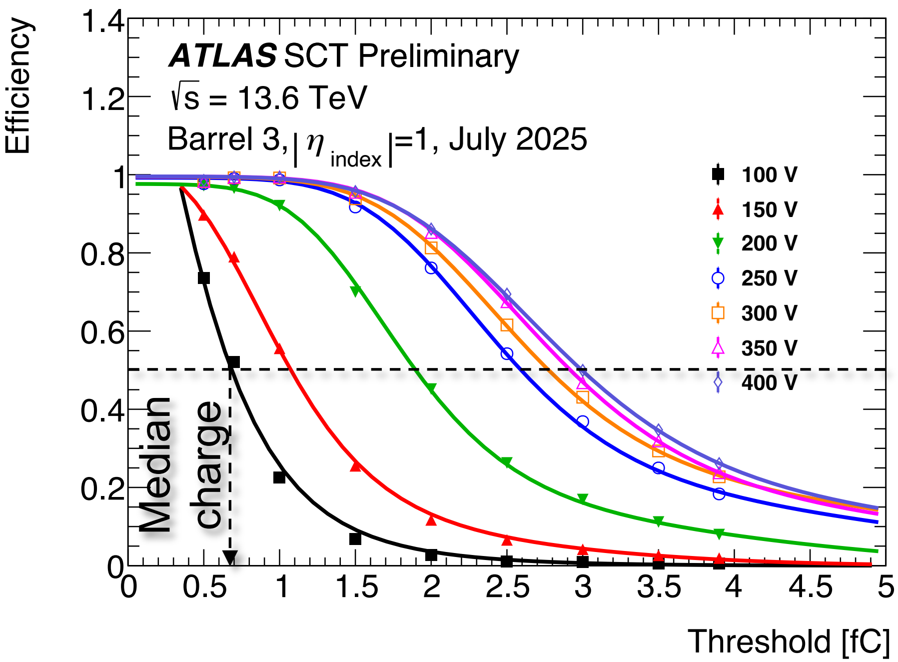


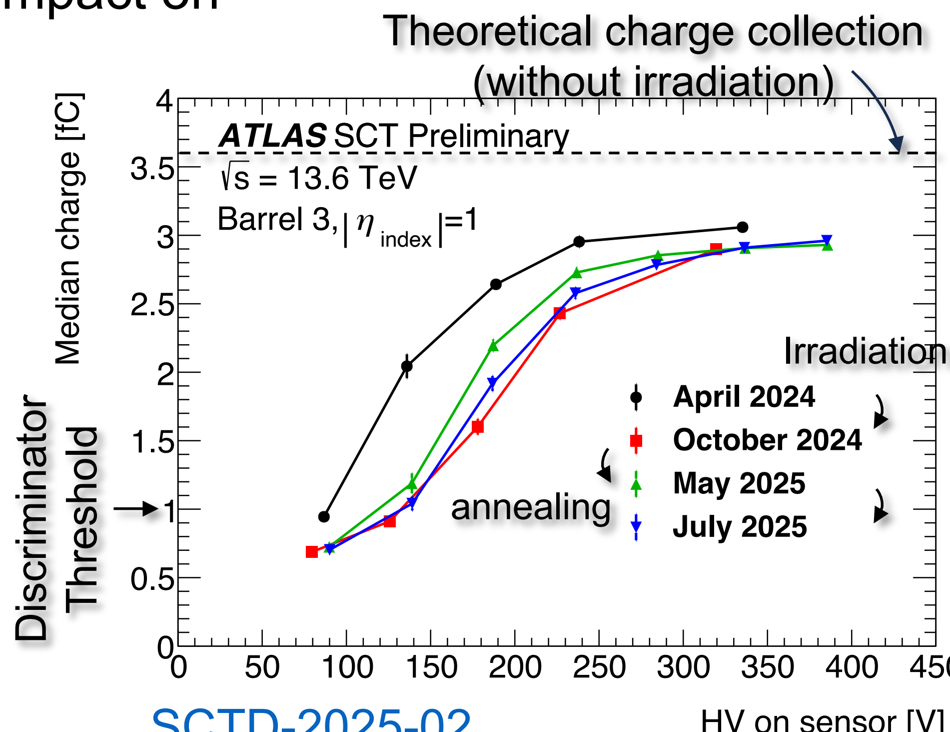
- HV setting has been increased, corresponding to the increase in V_{FD}
  - The high hit efficiency will be kept until 2026 with the HV below the system limit
- The reduced cooling temperatures are expected to be sufficient to maintain the leakage current within the system limit

Charge Collection Efficiency

- Hit efficiency scanned over a discriminator threshold provides the median charge
  - The idea for extracting the amount of charge in the binary readout was tried
- HV dependency was measured with a special setting to minimize the impact on the physics data



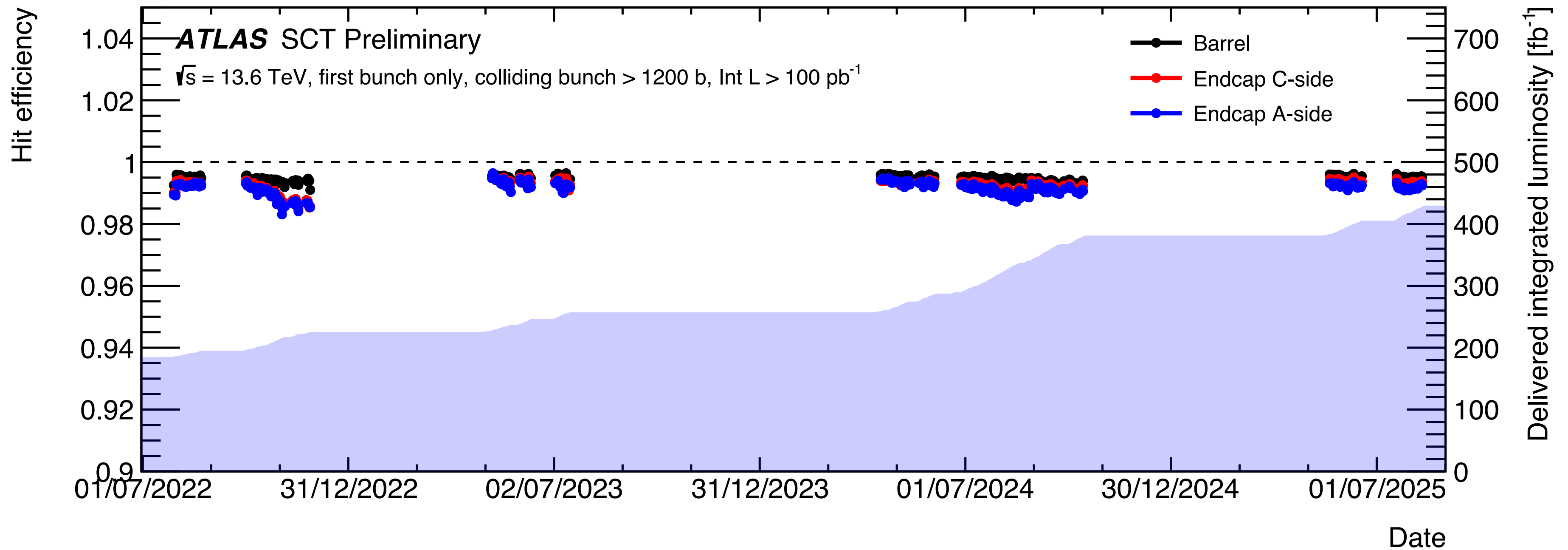




SCTD-2025-02

Hit Efficiency

SCTD-2025-02



- SCT has maintained very good efficiency since its commissioning 17 years ago, thanks to the HV and the other operational parameter optimization
- The preventive increase in the HV was deployed at the beginning of 2025, and the efficiency will be monitored periodically

Summary

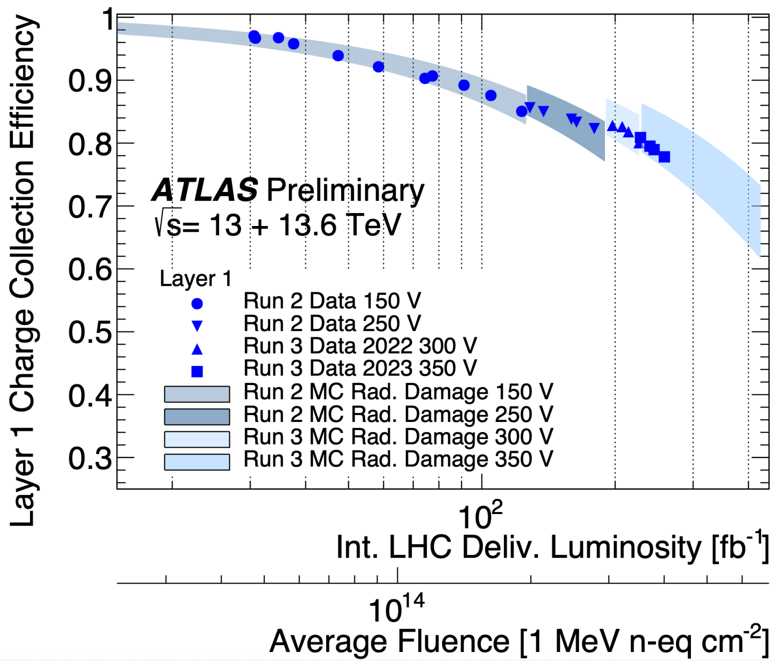
Data quality efficiency in 2024

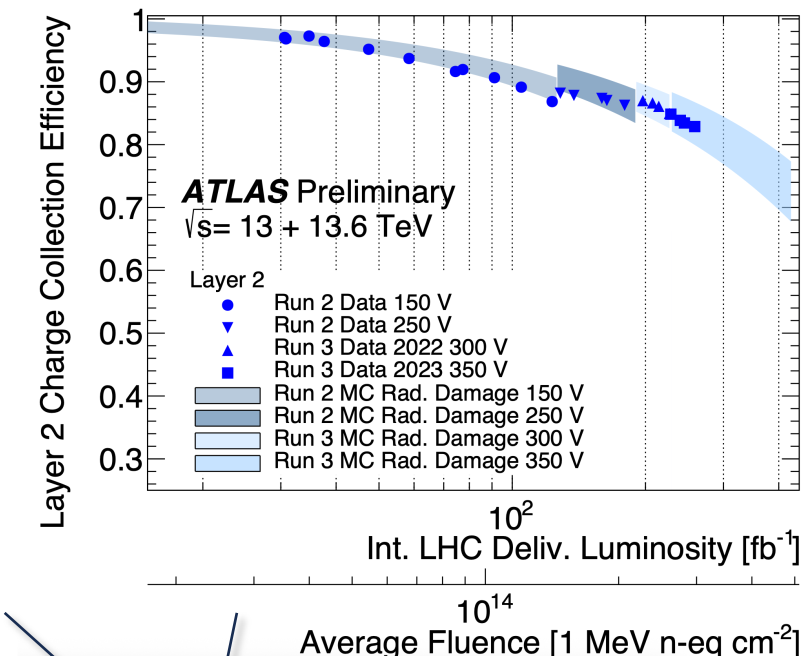
ATLAS pp Run-3: 2024														
Trigger	Inner Tracker			Calorimeters		Muon Spectrometer					Magnets		Global	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	MM	sTGC	Solenoid	Toroid	Lumi. calib.	Other
99.7	99.7	99.8	99.9	99.8	99.3	100	99.8	99.8	100	100	98.3	96.6	99.6	99.9
Good for physics: 93.8% (110 fb^{-1})														

- Pixel and SCT in the ATLAS Inner Detector have delivered excellent performance in Run 3 so far
- The high performance of LHC in Run 3 is challenging in terms of the DAQ and the irradiation
- The continual improvement in the firmware, the optimization of the operational parameters, and the experience of the operation team led to the stable, high-efficiency operation
- The simulation and the observation show good agreement, and tell us a promising performance that can be kept until the end of Run 3

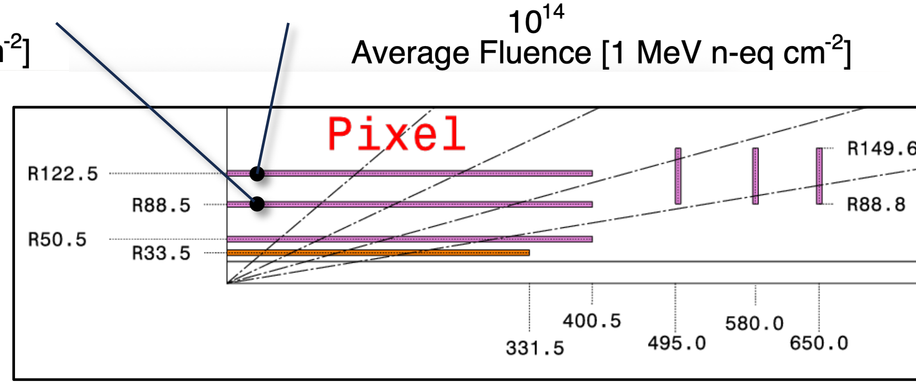
backup

Charge Collection Efficiency

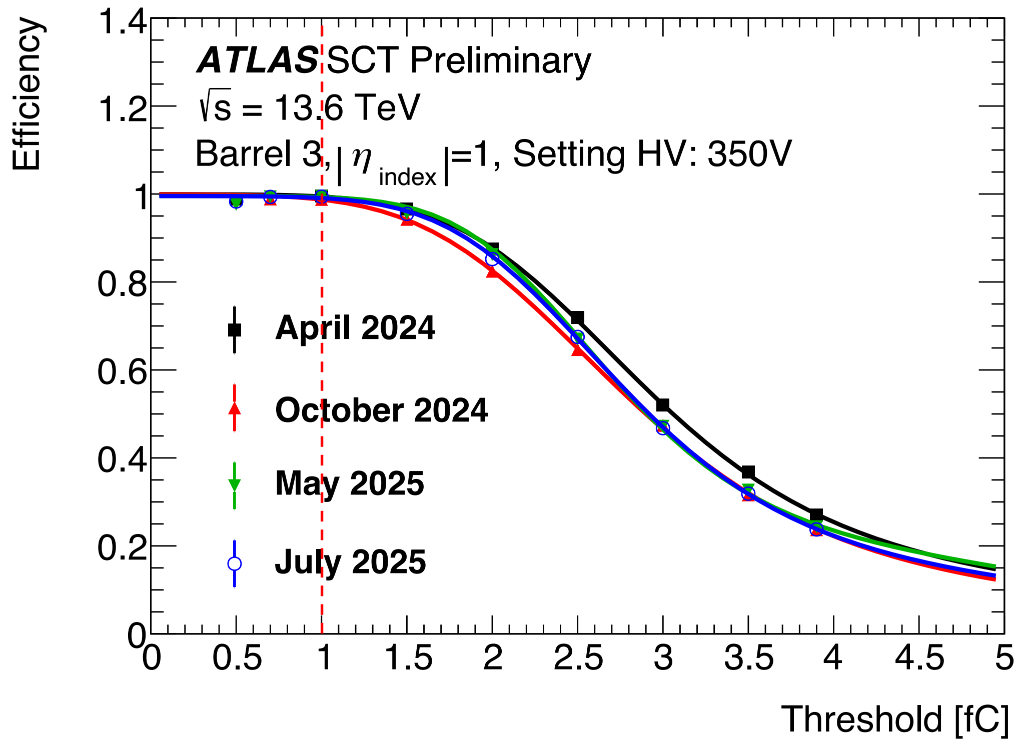




- CCE in the outer layer about 70% at the end of Run 3

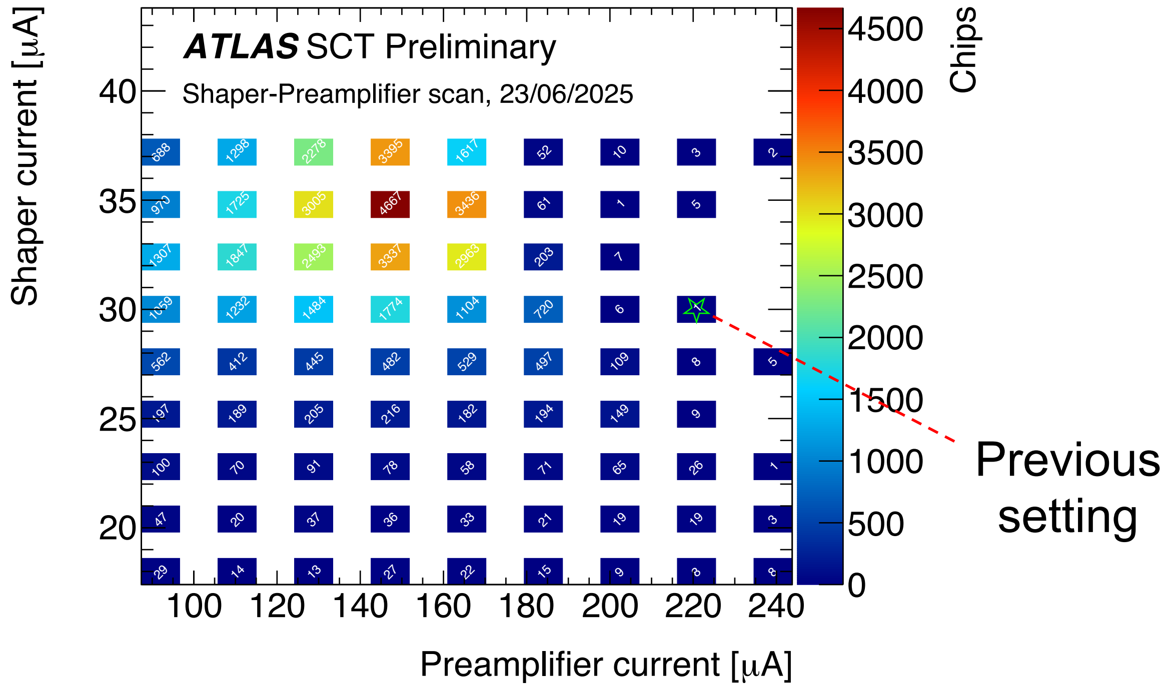


SCT Threshold Scan



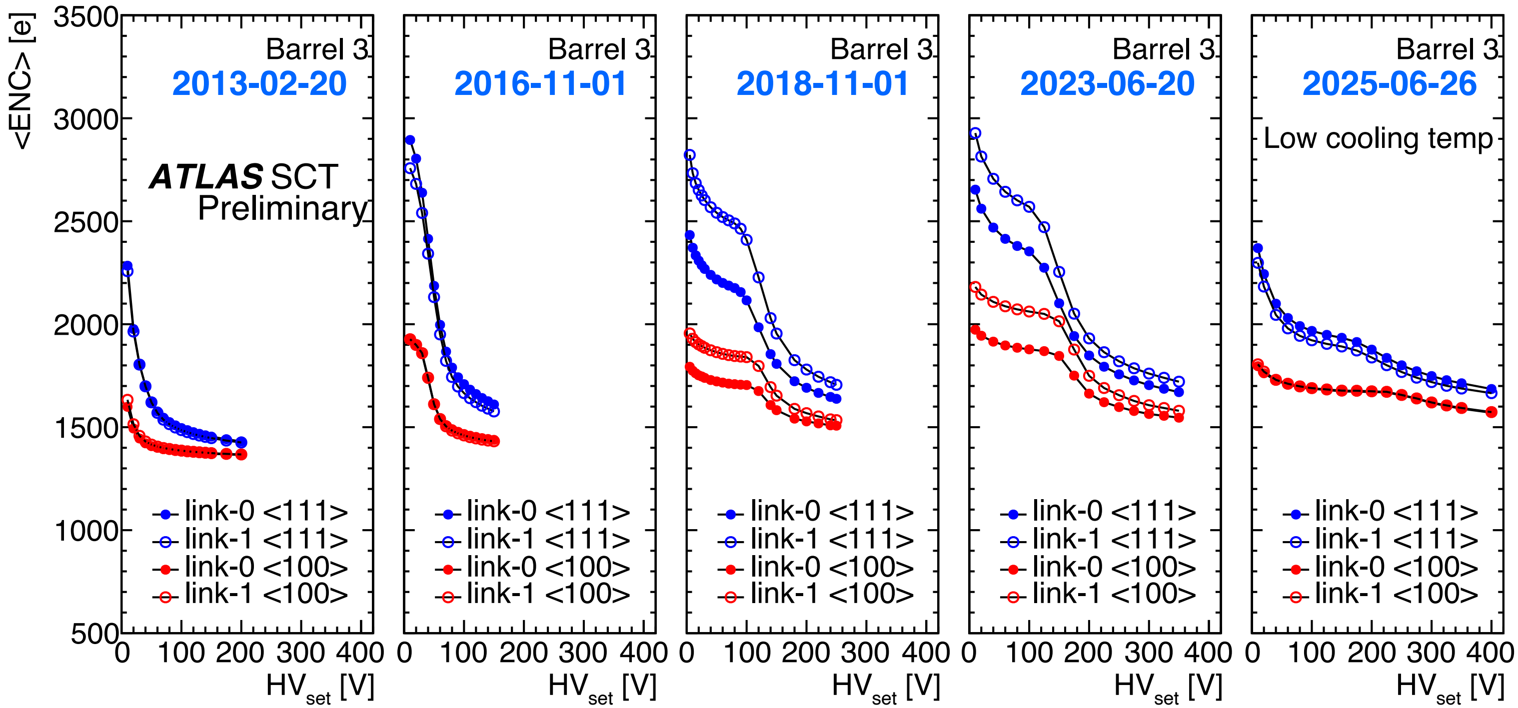
- Hit efficiency above the full depletion voltage has been kept > 99% at the nominal discriminator threshold

SCT Shaper Preamp Setting

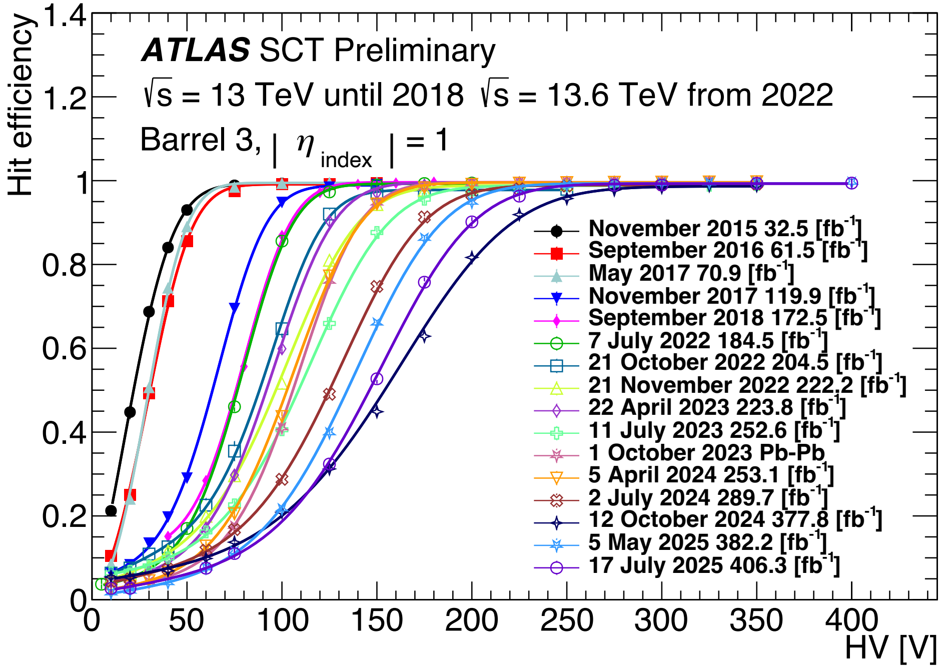


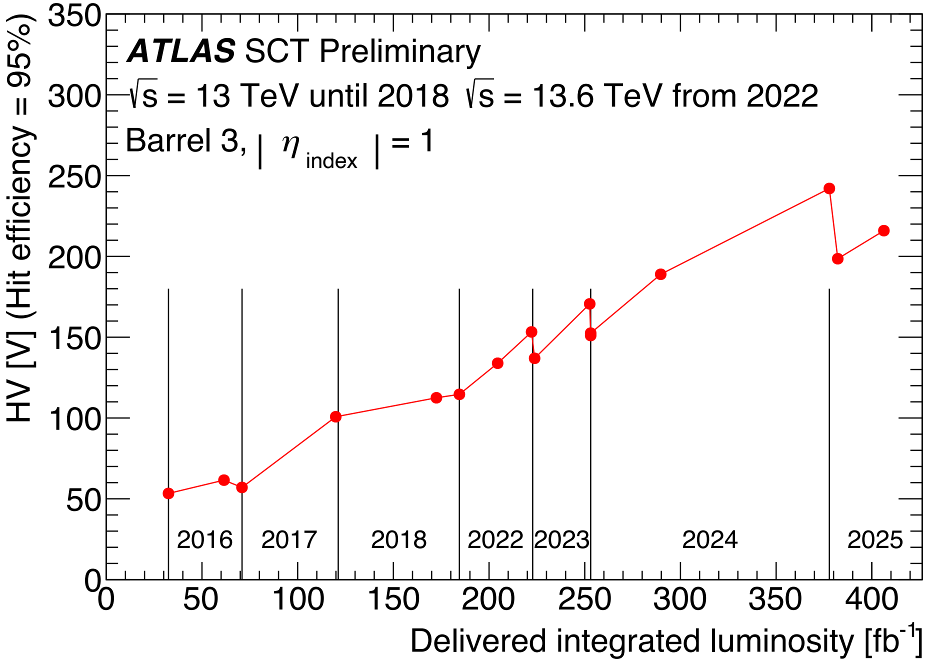
- 9*9 points were scanned and optimized to maximize the gain without the dramatic noise increase

SCT HV dependency of ENC



SCT HV Scan





- HV for keeping 95% hit efficiency increases roughly following the rate 1 V/1 fC