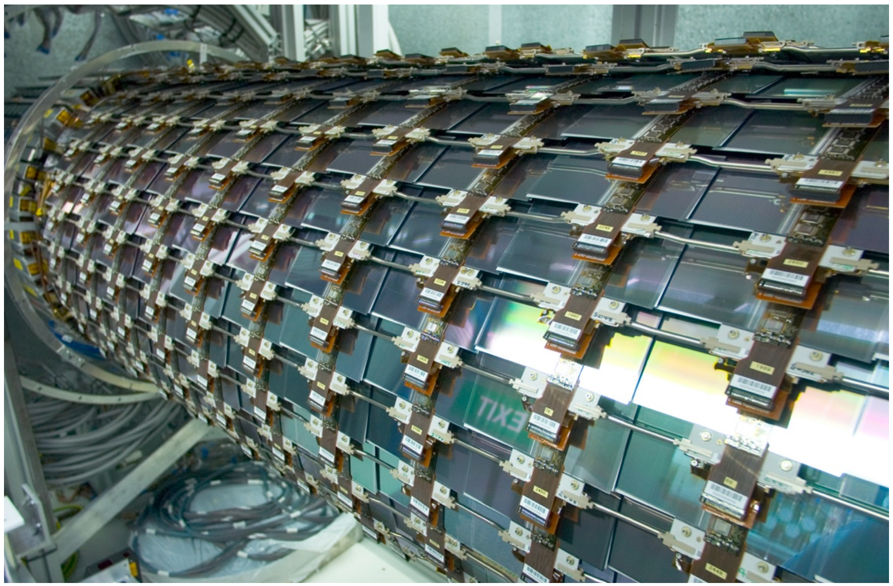


UNIVERSITY OF OXFORD

ATLAS SemiConductor Tracker:

Run 2 Performance and Run 3 Outlook

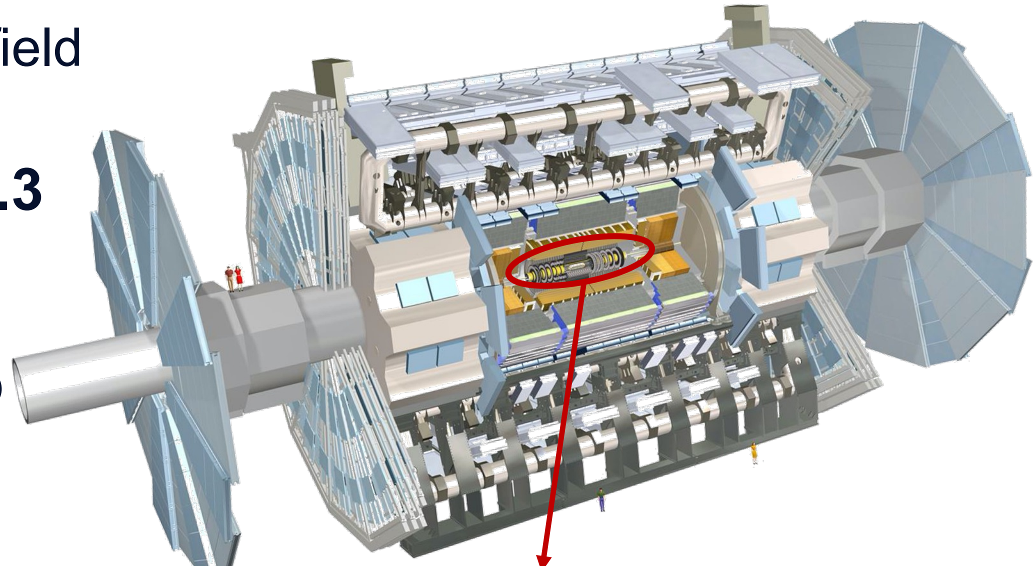
Elisabeth Schopf on behalf of the ATLAS Collaboration

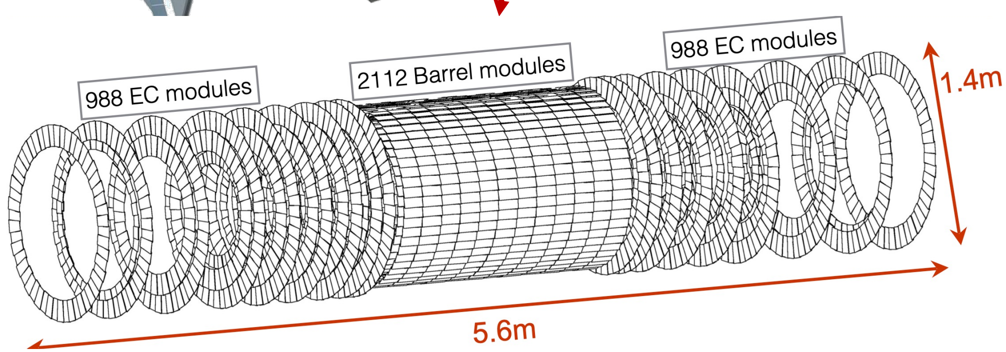
ATLAS EXPERIMENT

ICHEP 2022, Bologna

+ The ATLAS Semiconductor Tracker (SCT)

- Part of the inner detector
  - Located between silicon pixel detector and transition radiation tracker
  - Located inside a 2T magnetic field
- **Silicon strip detector with 6.3 million readout channels**
- 4 barrel layers and 18 endcap disks (4088 modules)
- Provides input to charged particle tracking and vertex reconstruction
  - Space point resolution rϕ~16μm



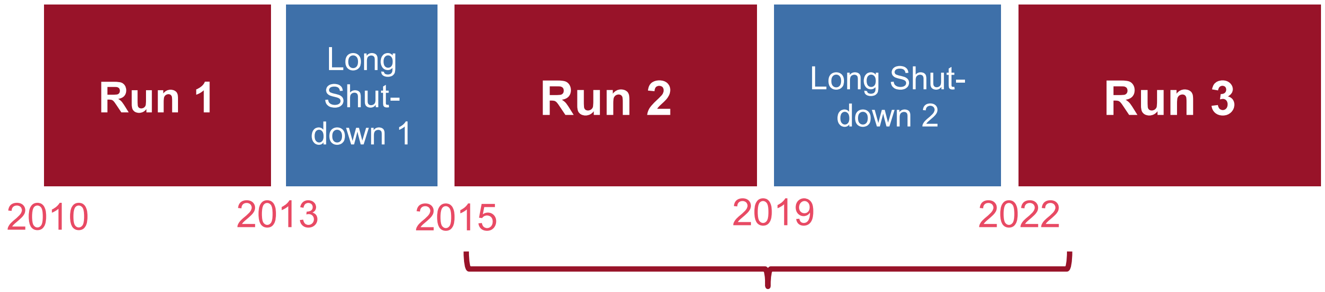


+ # SCT Roadmap

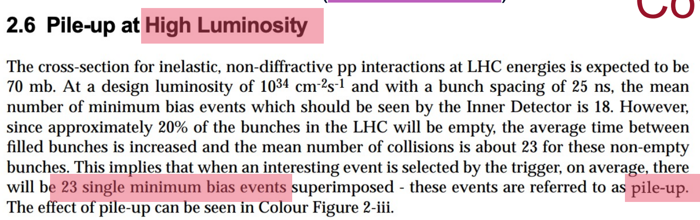
- Main operational aim: recording the Large Hadron Collider (**LHC**) **proton-proton and heavy ion collisions**
  - Collision energy up to 13.6 TeV, instantaneous luminosity $2{\cdot}10^{34}$ $cm^{-2}s^{-1}$

- SCT designed for data taking during all LHC run periods
  - Run 2 concluded end of 2018; Run 3 ramping up in 2022 (now!)
- **SCT is aging:** observed first serious effects of radiation damage and had to overcome bandwidth limitations during Run 2

+ Operation Conditions



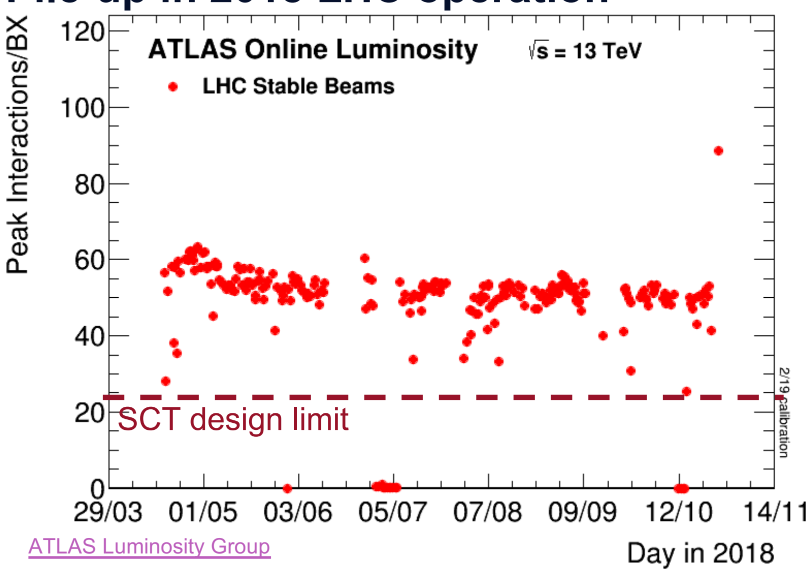
ATLAS inner detector TDR (ATLAS-TDR-4)



2.6 Pile-up at High Luminosity

The cross-section for inelastic, non-diffractive pp interactions at LHC energies is expected to be 70 mb. At a design luminosity of 10^{34} cm^{-2}s^{-1} and with a bunch spacing of 25 ns, the mean number of minimum bias events which should be seen by the Inner Detector is 18. However, since approximately 20% of the bunches in the LHC will be empty, the average time between filled bunches is increased and the mean number of collisions is about 23 for these non-empty bunches. This implies that when an interesting event is selected by the trigger, on average, there will be 23 single minimum bias events superimposed - these events are referred to as pile-up. The effect of pile-up can be seen in Colour Figure 2-iii.

Pile-up in 2018 LHC operation



ATLAS Luminosity Group

- **Run 2** (156 fb^{-1}): hugely successful data taking period for ATLAS but also **challenging for SCT**
  - Operation conditions far exceeding initial design limits
- Adjustments made in Run 2 to handle massive data flow and mitigate radiation damage impact

+ Operation Conditions

Run 1	Long Shut-down 1	Run 2	Long Shut-down 2	Run 3

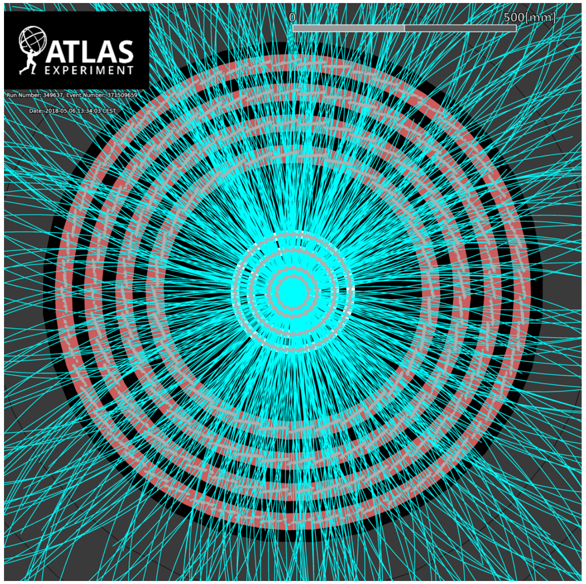
2010 2013 2015 2019 2022

Covered in this presentation

ATLAS inner detector TDR (ATLAS-TDR-4)

2.6 Pile-up at High Luminosity

The cross-section for inelastic, non-diffractive pp interactions at LHC energies is expected to be 70 mb. At a design luminosity of 10^{34} $cm^{-2}s^{-1}$ and with a bunch spacing of 25 ns, the mean number of minimum bias events which should be seen by the Inner Detector is 18. However, since approximately 20% of the bunches in the LHC will be empty, the average time between filled bunches is increased and the mean number of collisions is about 23 for these non-empty bunches. This implies that when an interesting event is selected by the trigger, on average, there will be 23 single minimum bias events superimposed - these events are referred to as pile-up. The effect of pile-up can be seen in Colour Figure 2-iii.



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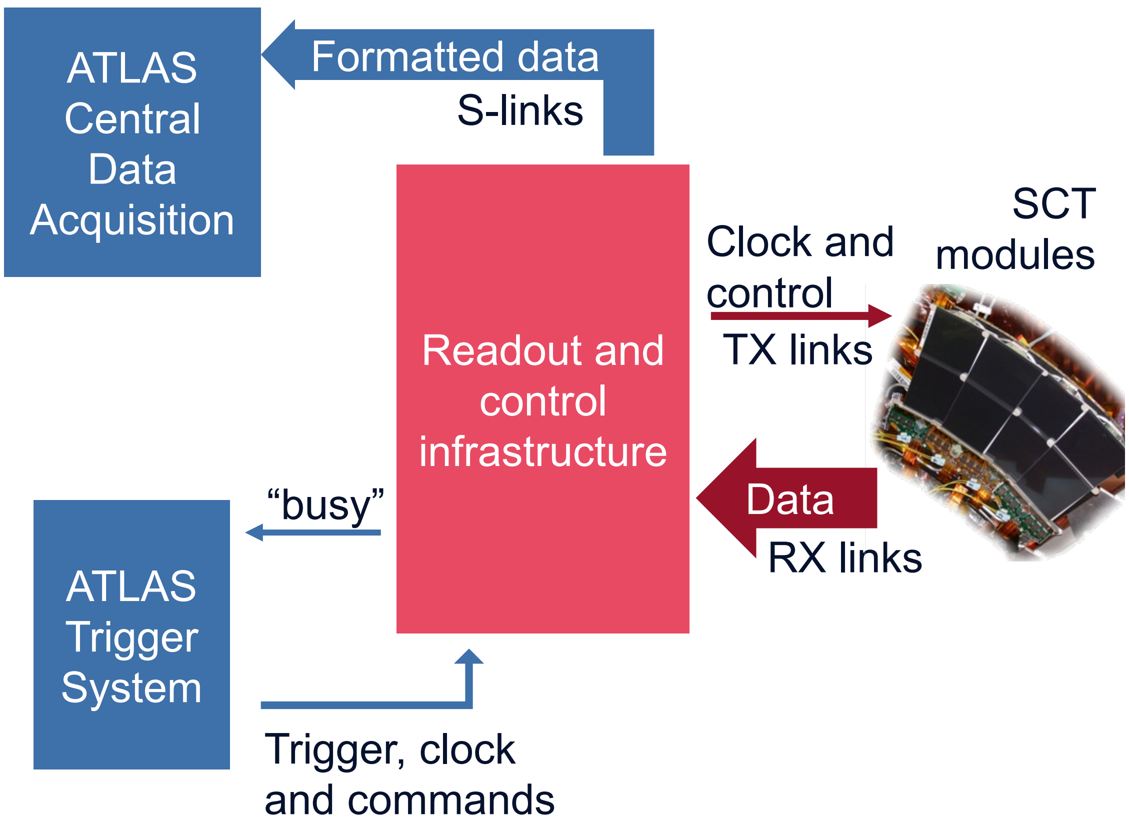
- **Run 2** (156 fb^{-1}): hugely successful data taking period for ATLAS but also **challenging for SCT**
  - Operation conditions far exceeding initial design limits
- Adjustments made in Run 2 to handle massive data flow and mitigate radiation damage impact

Data Acquisition Chain

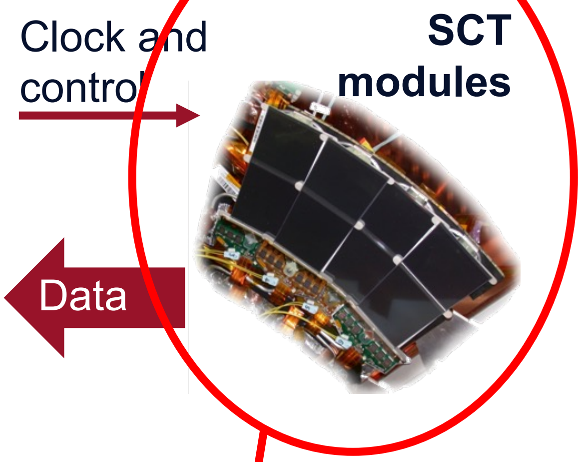


- SCT modules supplied with low voltage (=**LV, readout**) and high voltage (=**HV, sensor**)
- **Optical links** transmit data, clock and control
  - Build-in redundancy used for <2% of links
- Bandwidth limit reached **suspends data taking**
  - Errors from RX/TX links
  - "busy" signal from S-links
- SCT Run 2 data taking:
  - SCT availability 99.9%
  - 99.85% good data quality efficiency

SCT Components: Hardware

- >98% of strips still active today!
- In total only 46/4088 modules disabled today at the brink of Run 3

  → Modules disabled since start of Run 2: HV stability most common issue

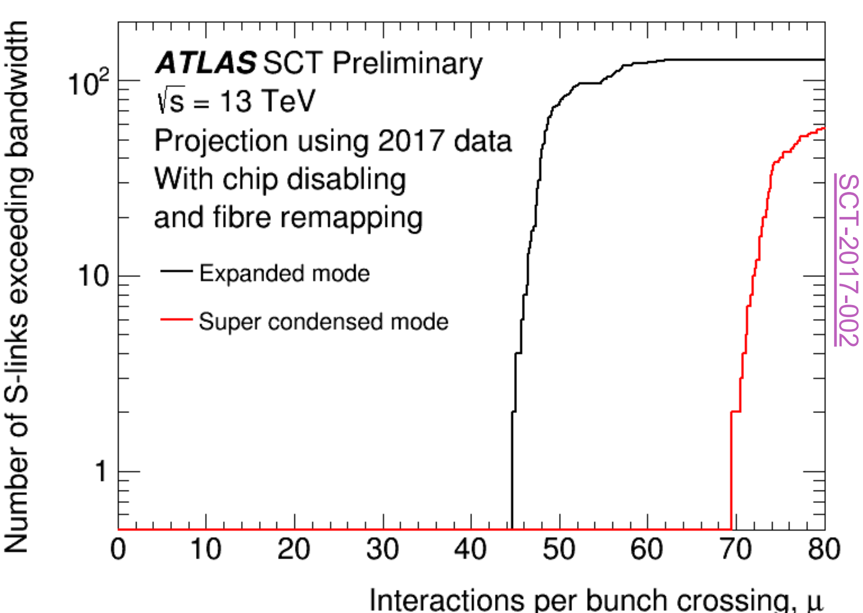


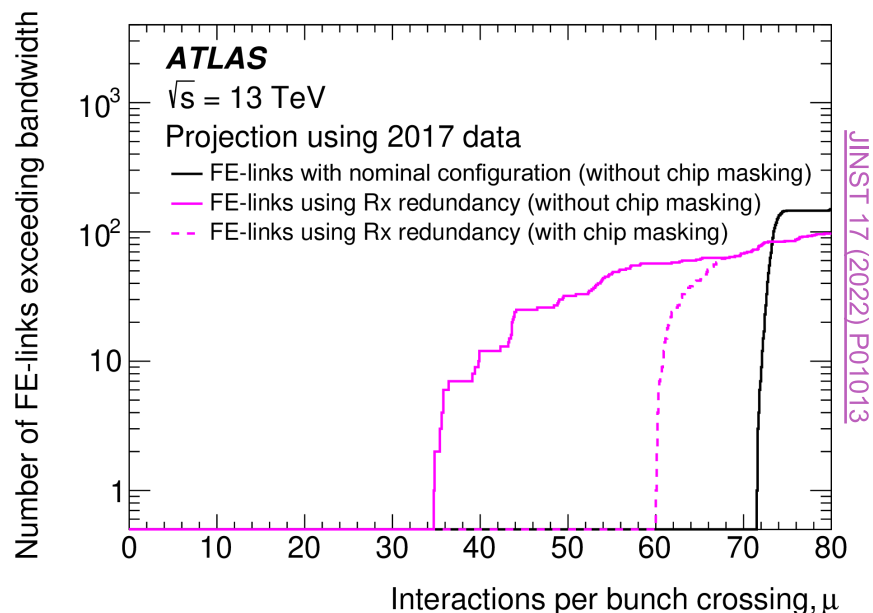
Disabled component	Start of Run 1 (2010)	End of Run 1 (2012)	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)
Modules	28	30	38	42	46
Chips	36	55	59	83	85
Strips	10795	11363	11452	14895	24071
fraction of active strips	99.1%	99.0%	98.8%	98.6%	98.3%

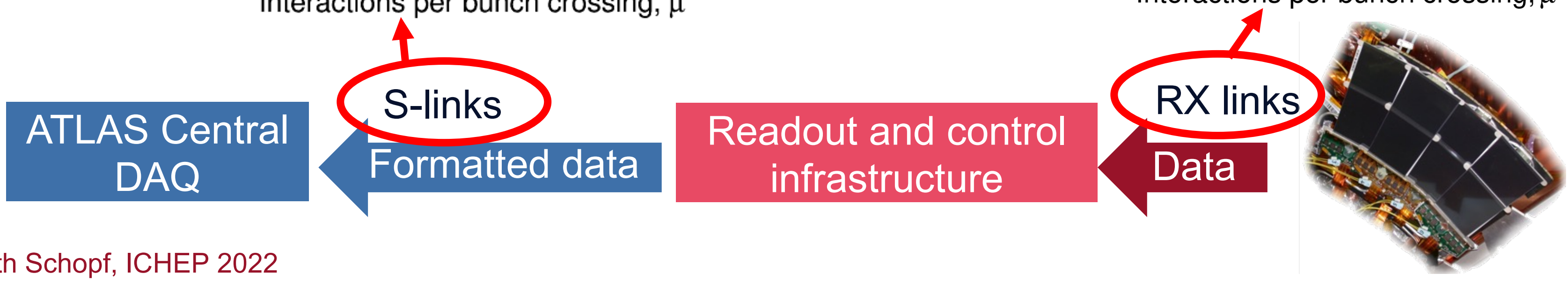
Bandwidth Limitations

- Due to high pile-up in **Run 2 improvements were necessary to avoid reaching bandwidth limitations** frequently
  → more S-links, better data compression, link re-mapping, masking noisy chips

~70 pile-up events is the absolute maximum SCT can handle







+ Radiation: 1 MeV neutron eq. fluence per fb^{-1} of int. luminosity (13 TeV pp)

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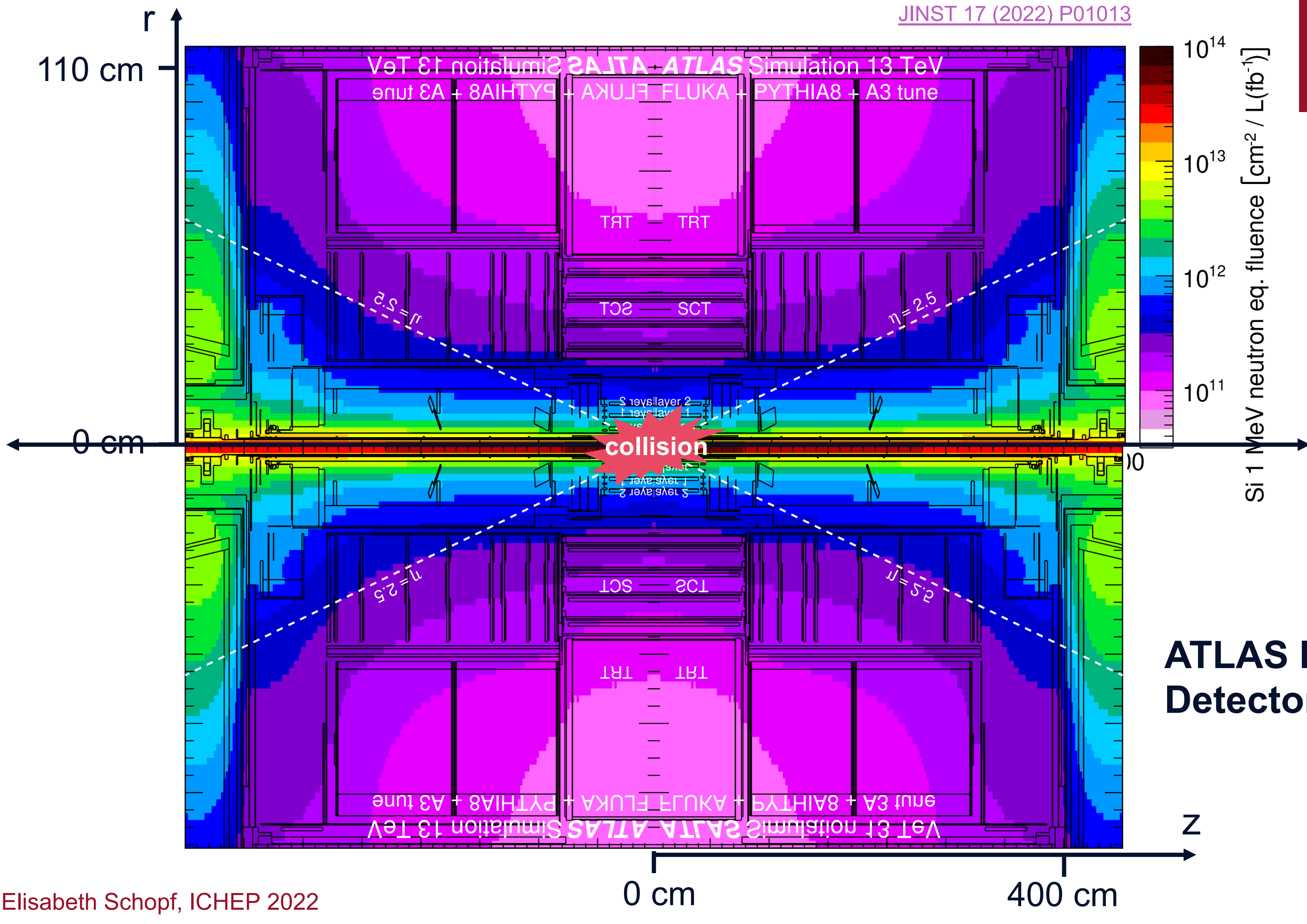

ATLAS Inner Detector

+ Radiation Dose

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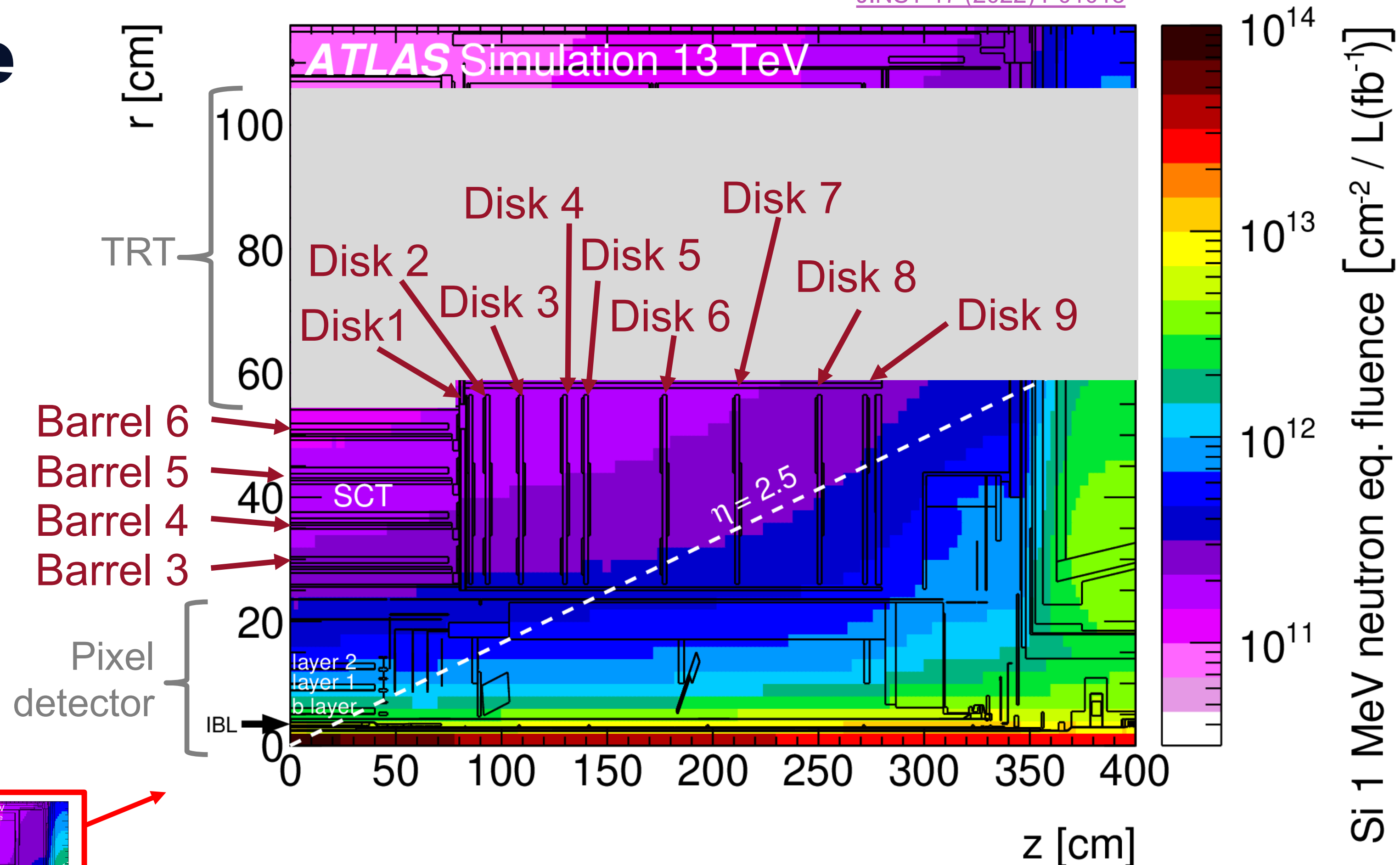

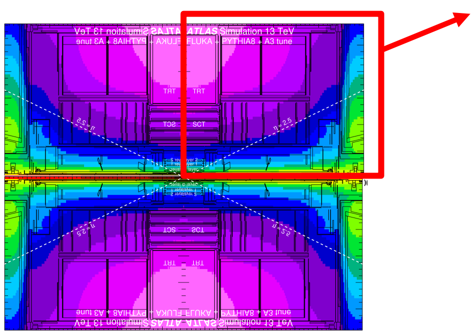

Elisabeth Schopf, ICHEP 2022

Radiation Dose

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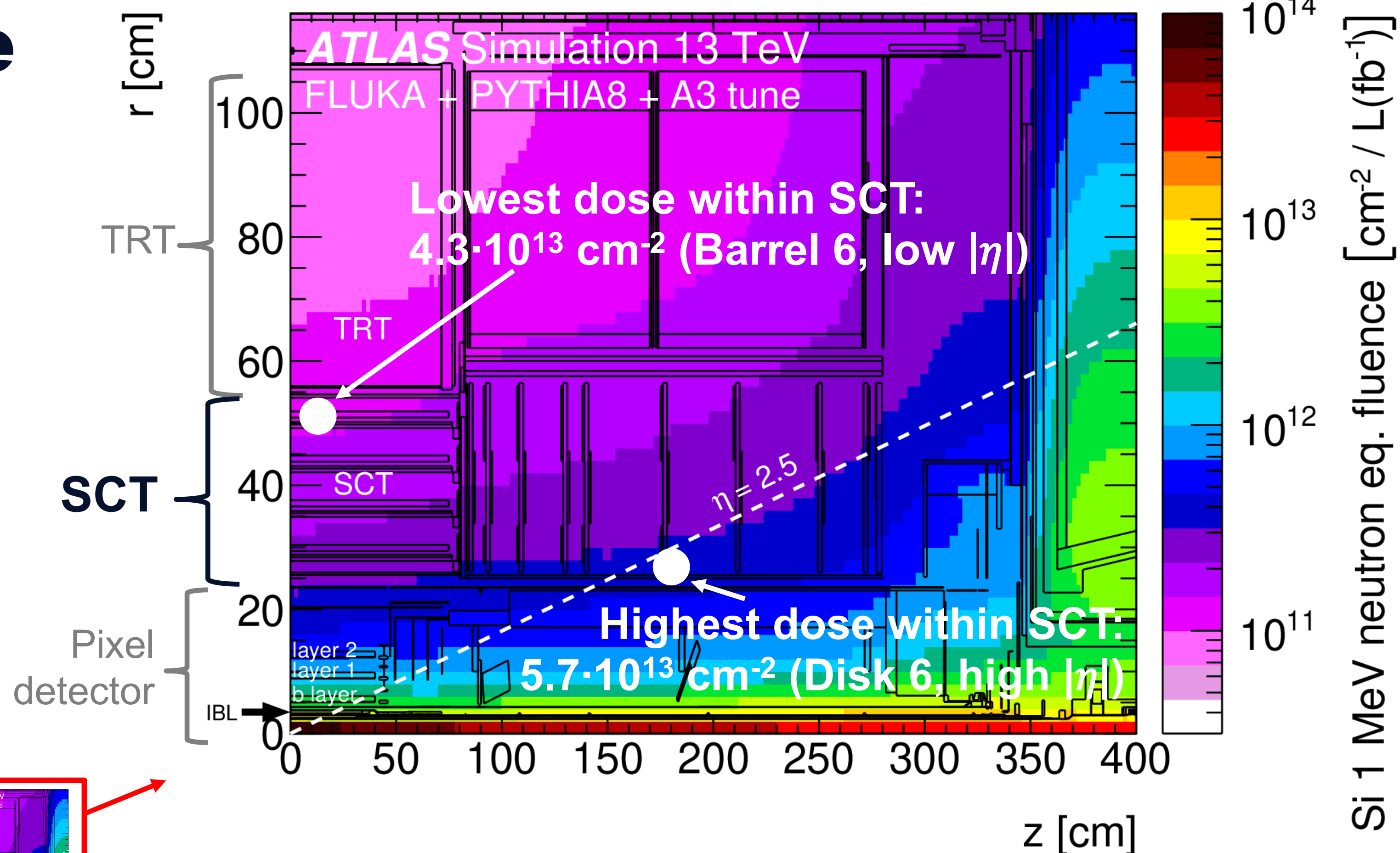

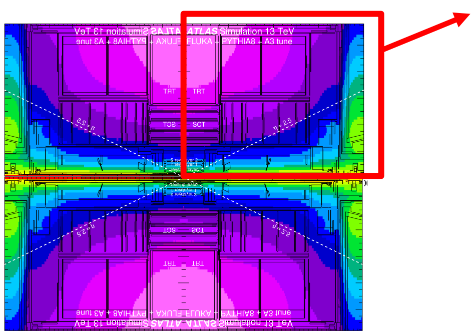

Highest doses for inner most barrel layer and high $|\eta|$ endcap disks

+ Leakage current in Run 2

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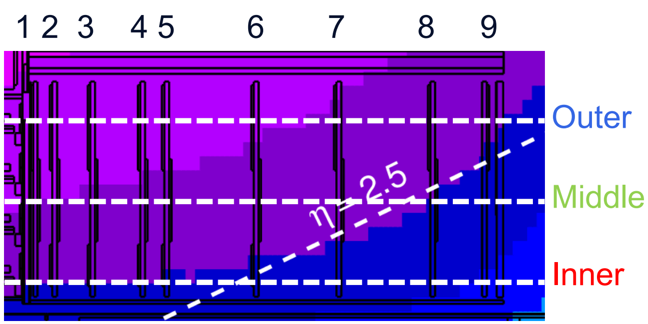
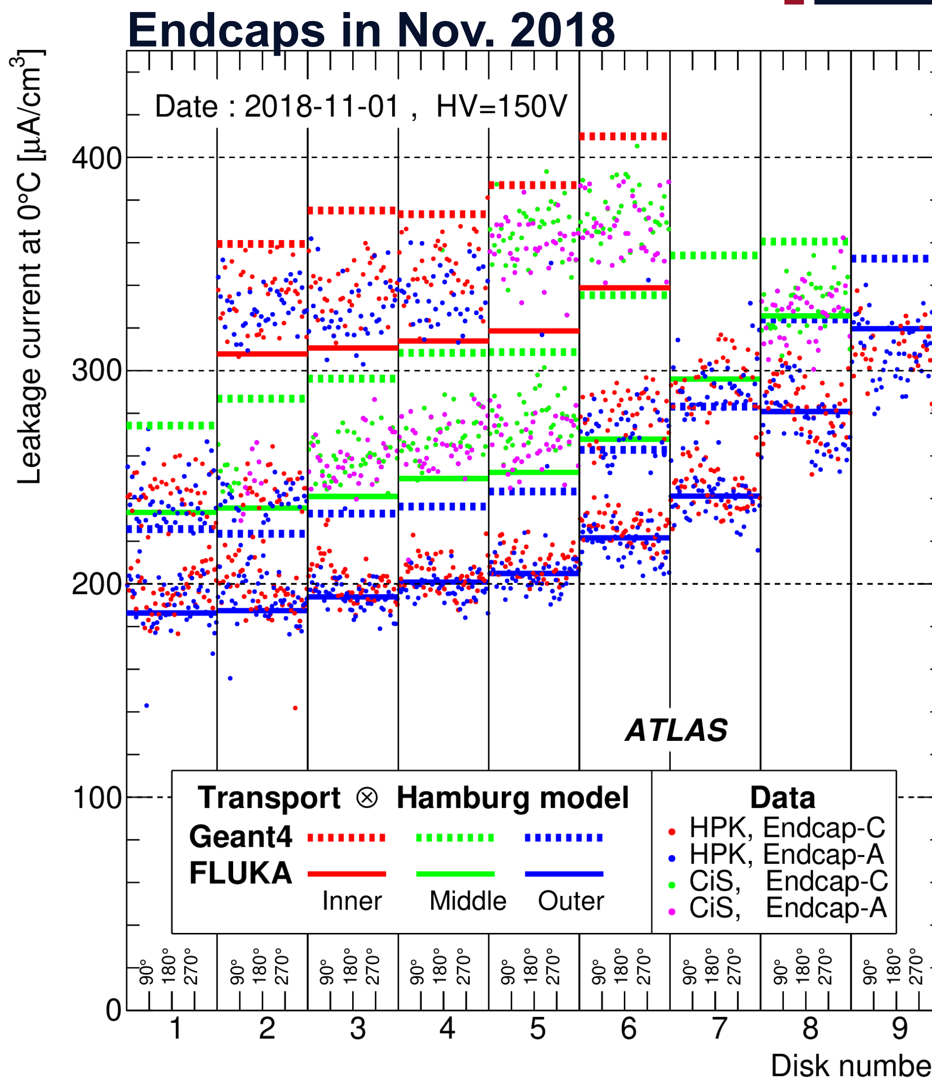
- Leakage current (I_L): thermally created electron-hole pairs
- I_L increases if radiation created additional energy levels in sensors

→ Leakage current follows radiation dose pattern

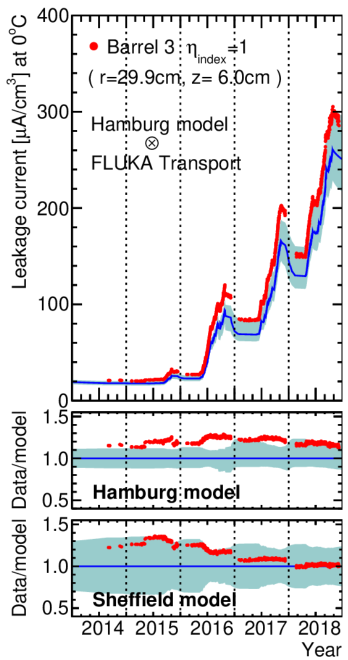




+ Thermal Runaway in Run 3?

- Heat generated by leakage current can lead to **self-enhancing loop** and eventually to fatal thermal runaway

I_L over time for inner most barrel layer during Run 2



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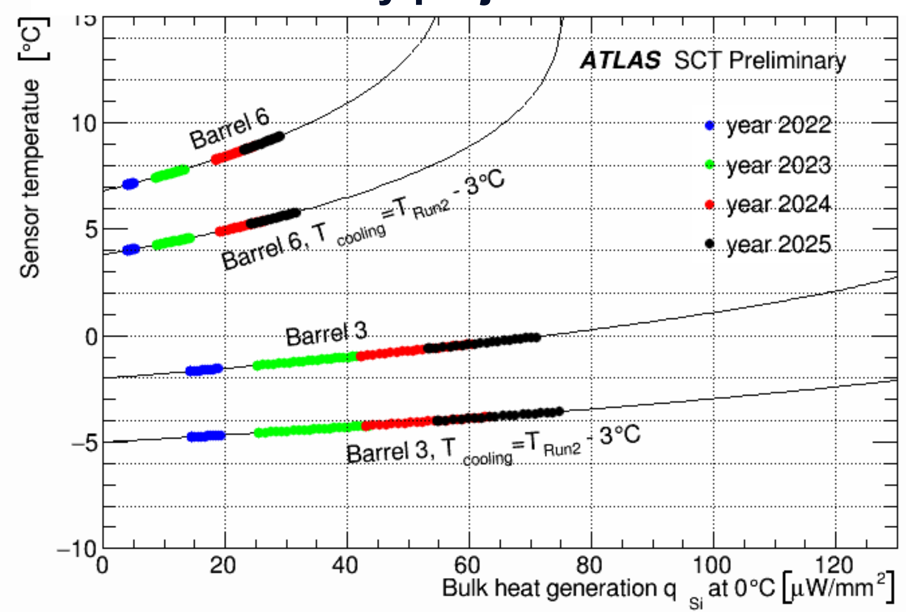
Thermal runaway projections for Run 3

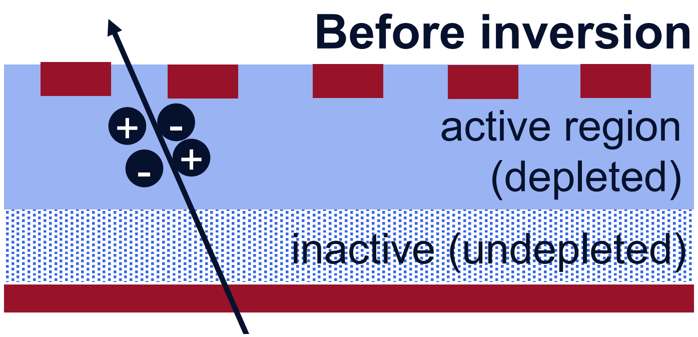


- Large increase of leakage current during Run 2 but still within safe levels for Run 3 for most at risk* barrel layers
  - Option of lower cooling temperature as an additional safety margin

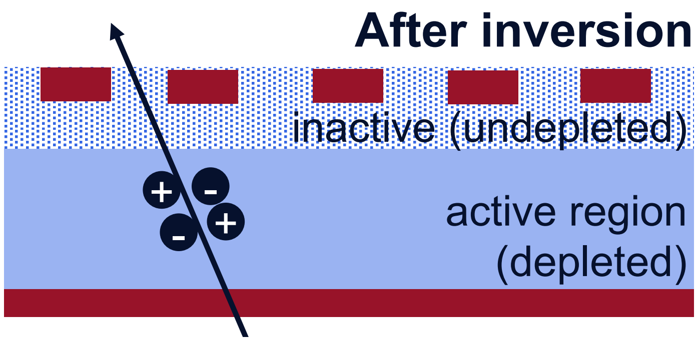
*Barrel 3: high radiation damage
Barrel 6: operates at higher temperatures (latter to protect TRT)

+ Type Inversion in Sensors with n-type Bulk

- During Run 2 modules **type inverted due to radiation damage**



Fully efficient (insensitive to undepleted region)



Partially inefficient (sensitive to undepleted region)

- Need to operate in fully depleted mode after type inversion → set HV >> full depletion voltage (V_{FD})
  - Generally SCT operated at HV>V_{FD} also before type inversion

Full Depletion Voltage

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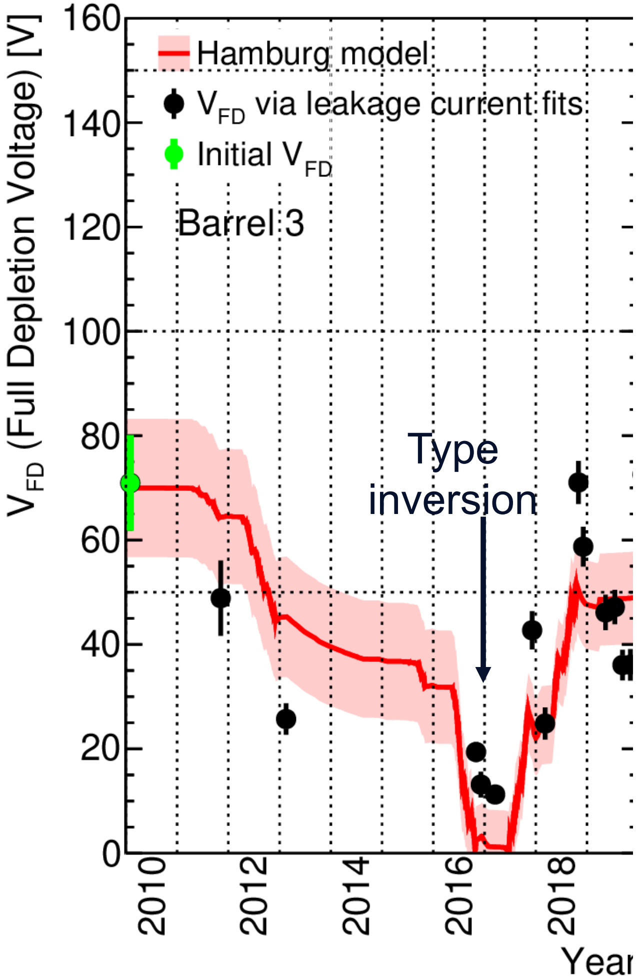
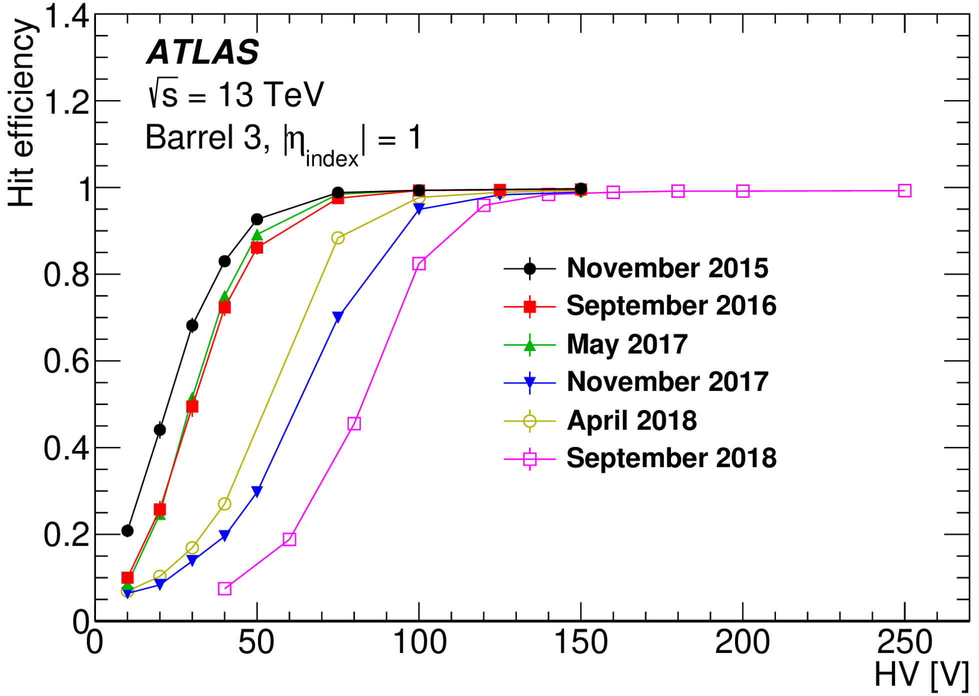
V_{FD} from measurements of I_L as function of HV

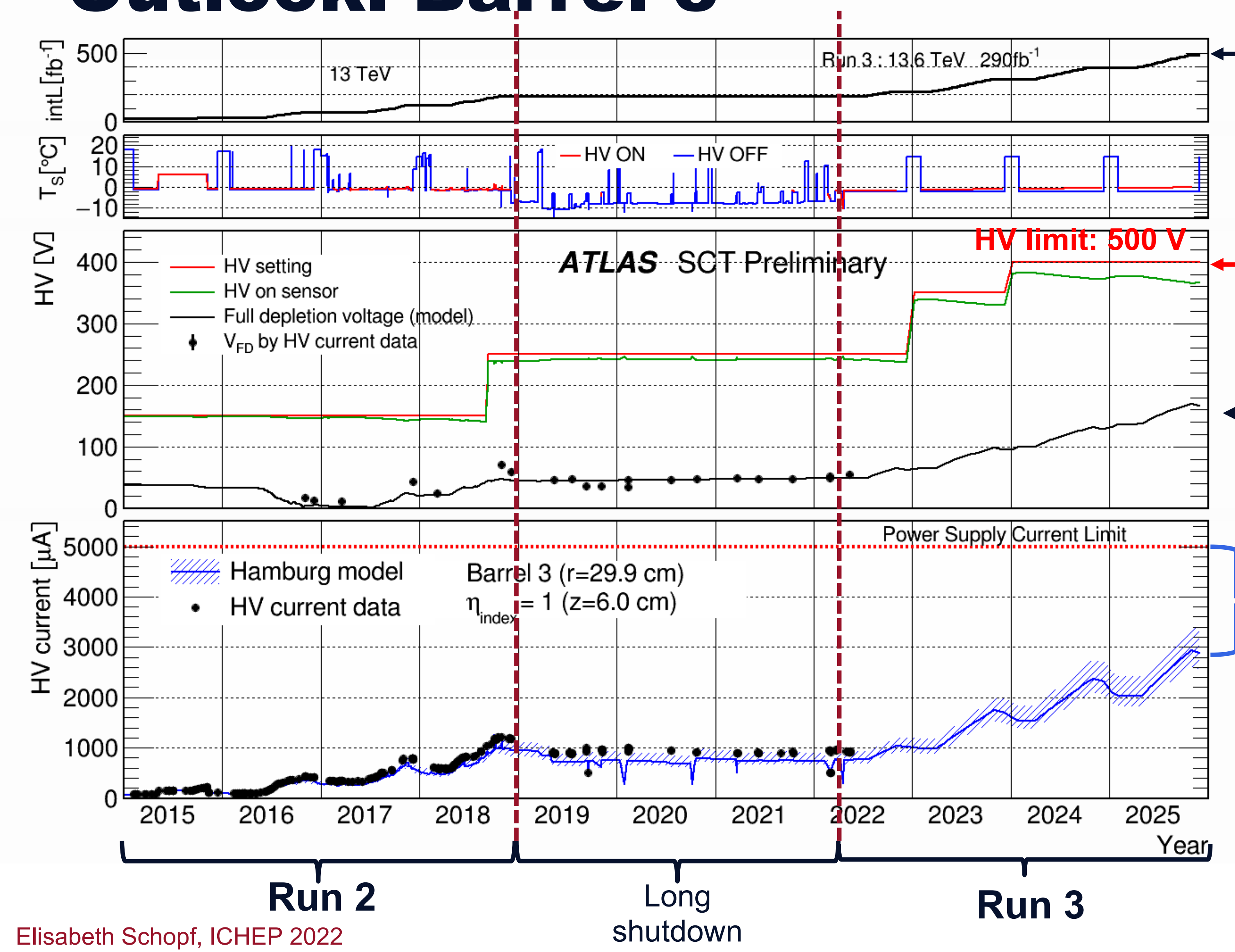


Hit efficiency vs. HV over time



- V_{FD} increased since type inversion
- HV was increased by 100 V towards end of Run 2 to maintain high hit efficiency

+ Run 2 Evolution and Run 3 Outlook: Barrel 3



~500 fb^{-1} across SCT's lifetime

HV increase up to 400 V during Run 3

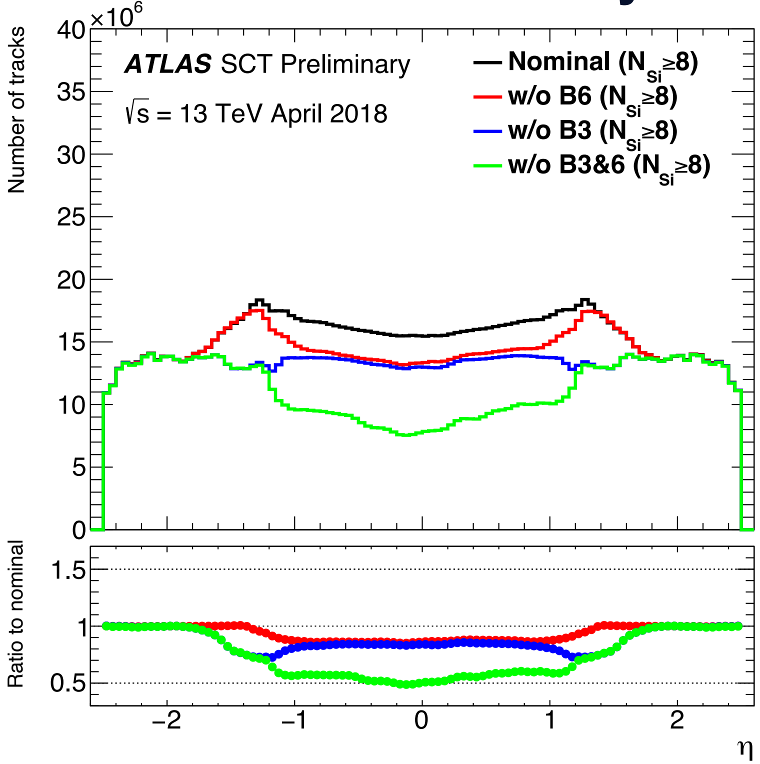
V_{FD} >150V

Enough margin

…Barrel 6 in backup

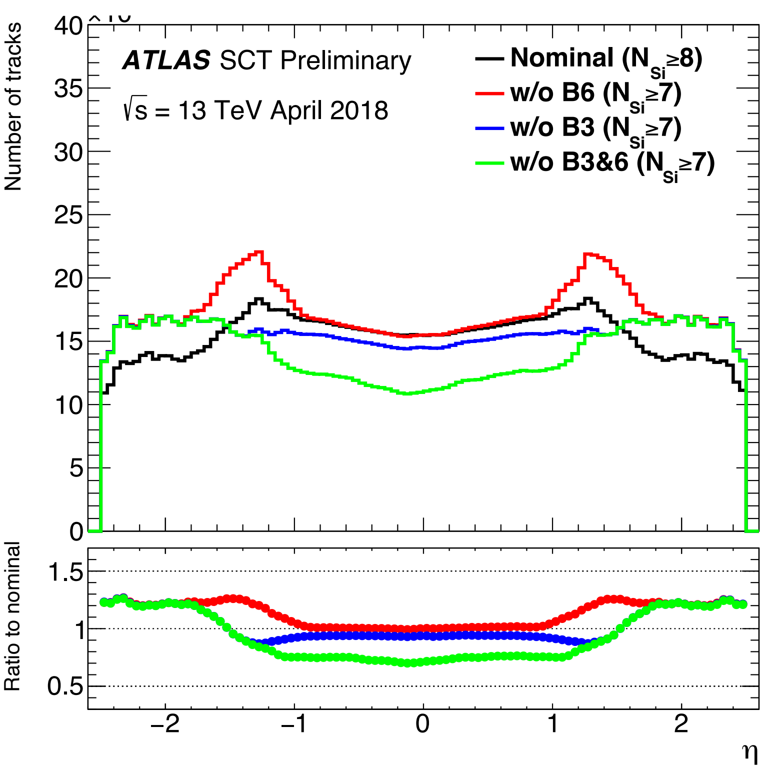
What happens if we lose Barrel 3 or Barrel 6?

Decrease in track reconstruction efficiency



or

Increase in "fake" tracks if reconstruction criteria loosened



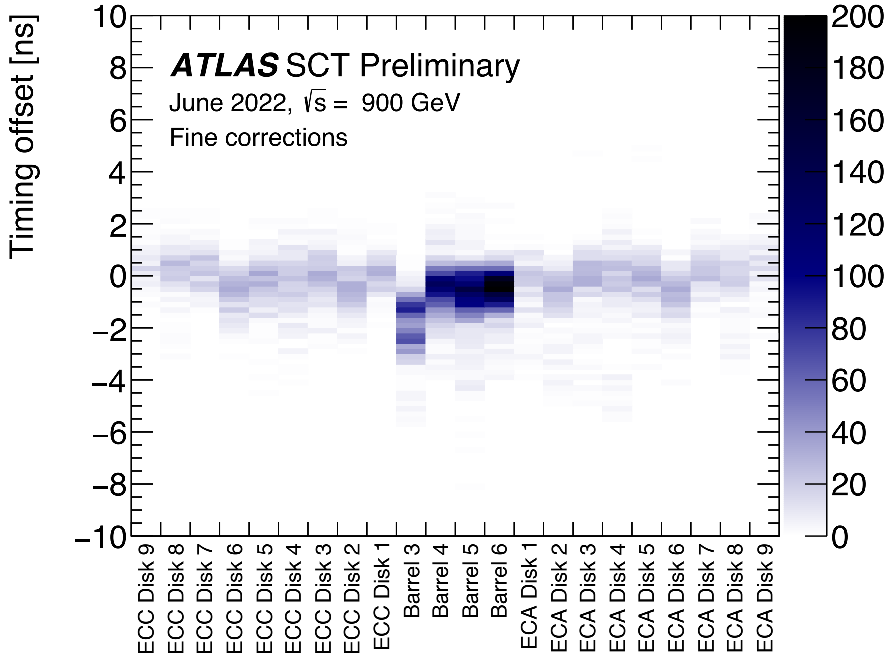
→ However, based on projections it is unlikely we will need to operate without Barrel 3 or Barrel 6

Preparing for Run 3: Timing

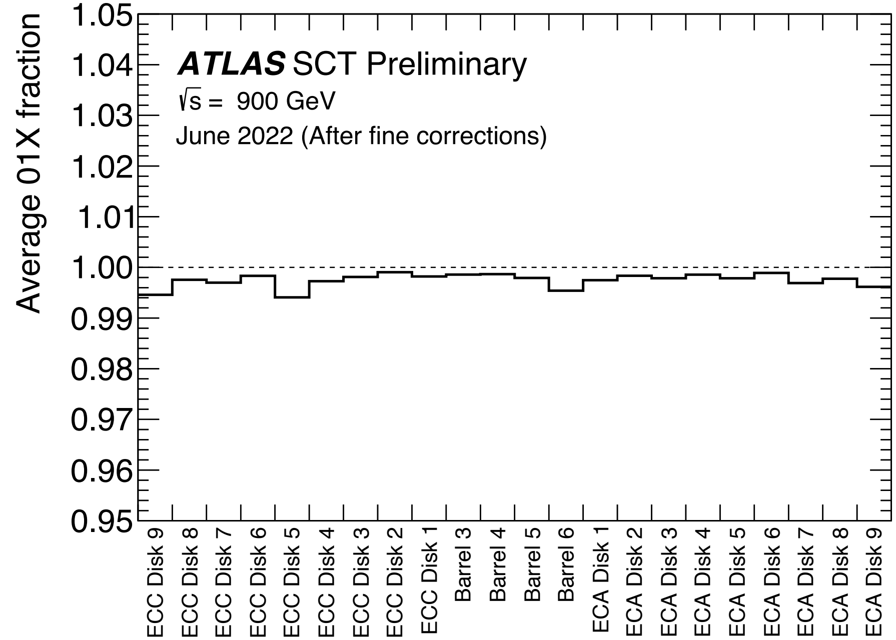
- Delays to trigger signal needed to compensate for length of optical fibres, delay in electronics and time-of-flight of particles

→ SCT ”timed in” for Run 3 operations

Timing corrections for start of Run 3

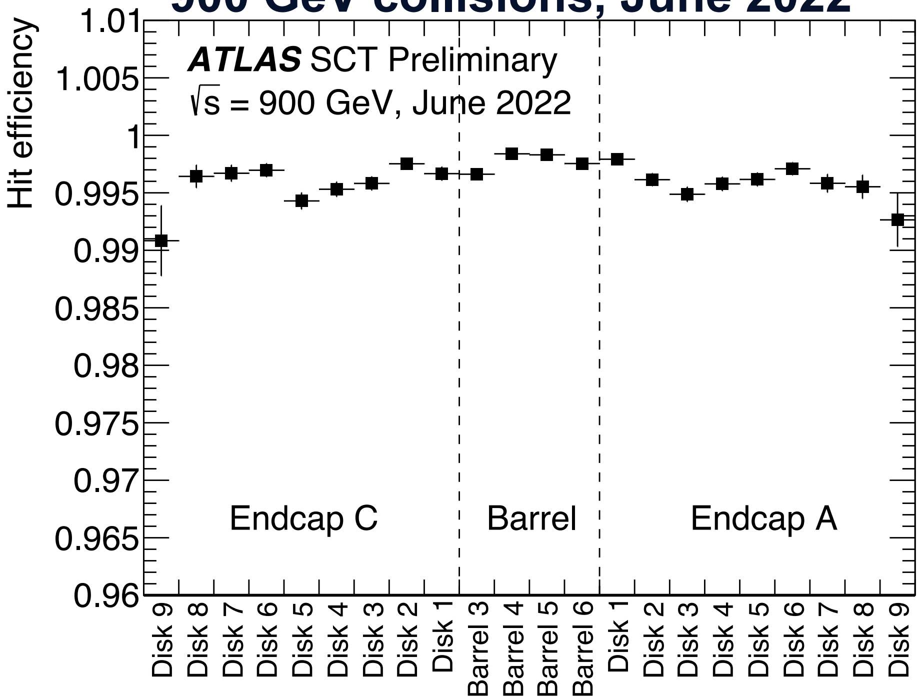


Average fraction of hits following nominal read-out pattern at beginning of Run3



Run 3 Operations Teaser

900 GeV collisions, June 2022



- Very good hit efficiency (comparable to Run 2)
- SCT is ready for 13.6 TeV data taking!

For comparison: hit efficiency towards end of Run 2 in low pile-up run

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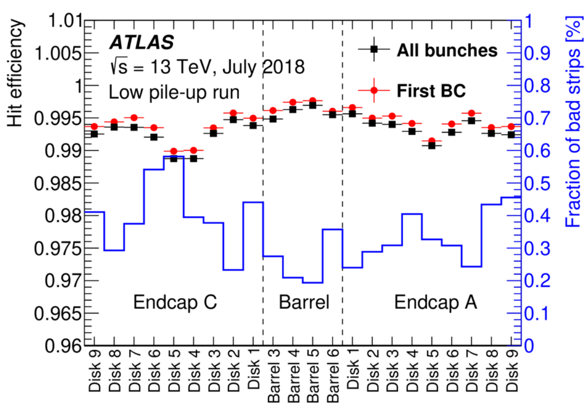
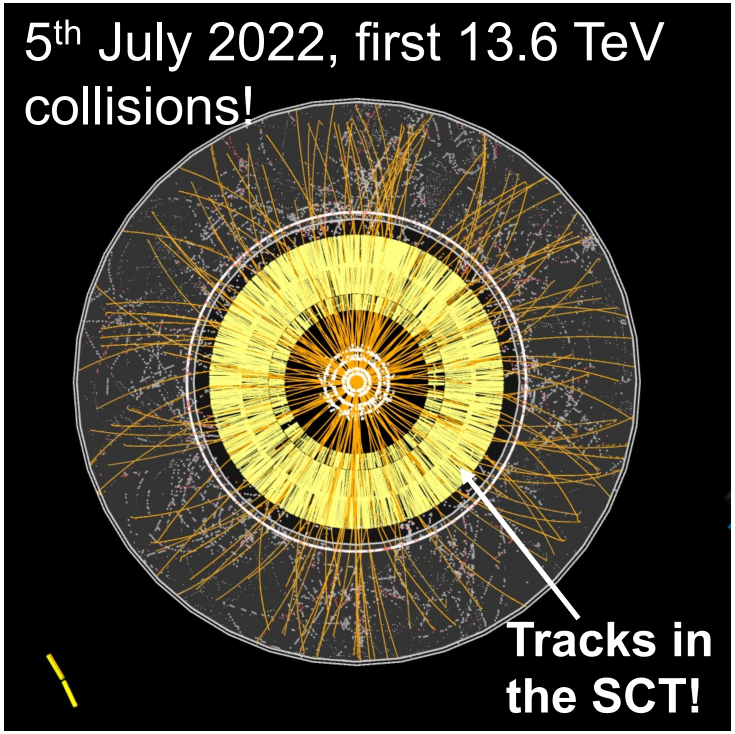
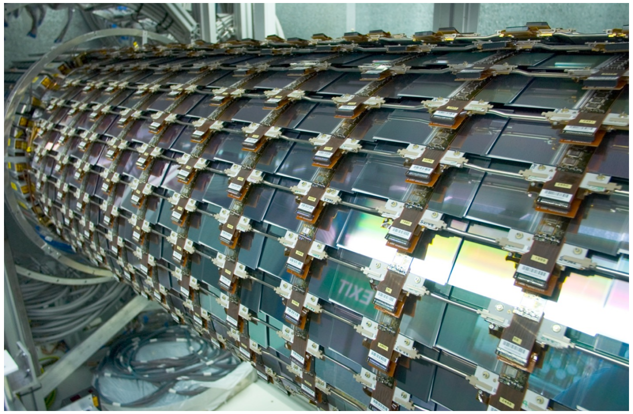


ATLAS Run 3 event displays



+ Summary

- **Excellent SCT performance during Run 2** in (pile-up) conditions exceeding initial design limits
  - 98.3% of strips remained active
  - 99.9% data taking efficiency and only 0.15% loss in DQ efficiency
- **Effects of radiation damage** start to become apparent
  - Increasing leakage current
  - Operation at HV well above full depletion voltage necessary
- We are confident SCT will perform well until end of Run 3
  - **Continued careful monitoring and tweaking of operational settings**
    → lowering temperature, increasing HV?



Thank you for your attention!

Detailed studies of SCT Run 2 performance documented in:
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SCT DQ Defects During Run 2

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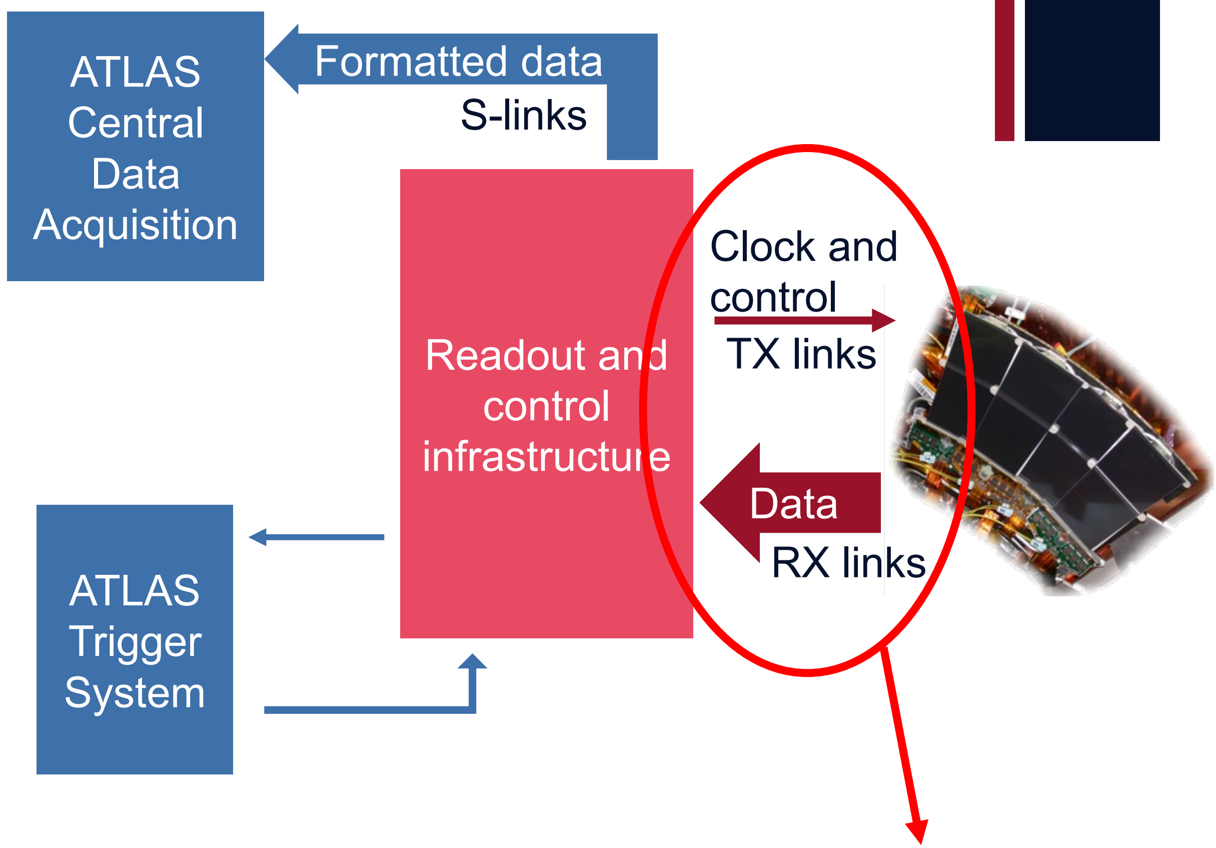
Table 4: SCT DQ defect summary in Run 2.

Year	2015	2016	2017	2018	Total
Luminosity recorded by ATLAS (fb^{-1})	3.6	35.5	46.5	60.2	145.8
Defect description	Fraction of luminosity affected (%)				
Intolerable defect					
SCT simulation data flag activated	0.00	0.0	0.0	0.21	0.09
SCT bias voltage not ready	0.01	0.10	0.04	0.01	0.04
Major acceptance loss due to ROD exclusion	0.22	0.0	0.01	0.0	0.01
Crate(s) excluded from readout	0.0	0.01	0.01	0.0	0.01
Tolerable defect					
$>$ 40 modules noisy	6.0	13	20	51	31
Minor acceptance loss due to ROD exclusion	14	5.1	0.68	0.55	2.0
Low efficiency	4.3	0.0	1.4	1.6	1.2
$>$ 40 modules with link errors	2.4	1.6	0.34	0.0	0.57
SCT not at standard HV	0.58	0.08	0.08	1.2	0.54
Trip of one PS crate	0.0	0.0	0.0	0.06	0.03

+ SCT Components: Optical Links

- Redundancies built in in case of single link failures
- **Only <2% links rely on redundancy**
- Before Run 2 all TX links were replaced



Redundancies used	Start of Run 1 (2010)	End of Run 1 (2012)	Start of Run 2 (2015)	End of Run 2 (2018)	Start of Run 3 (2022)
RX links	108	132	136	153	155
TX links	126	up to 240 →	20	55	58

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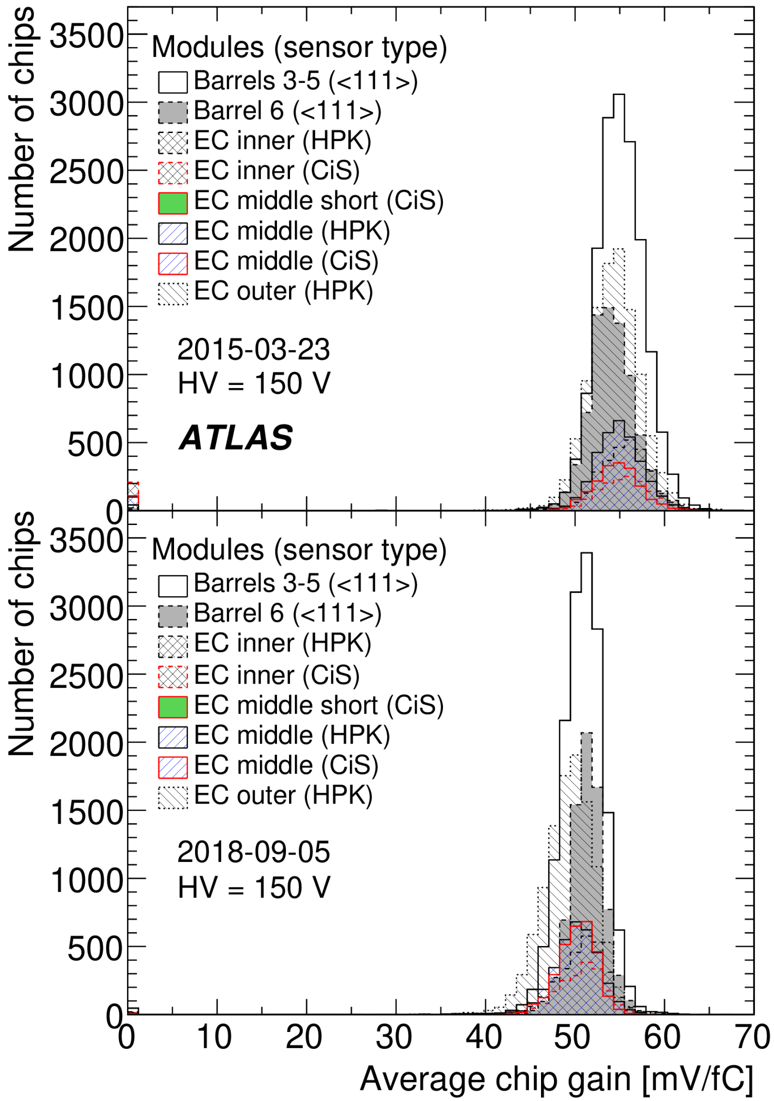
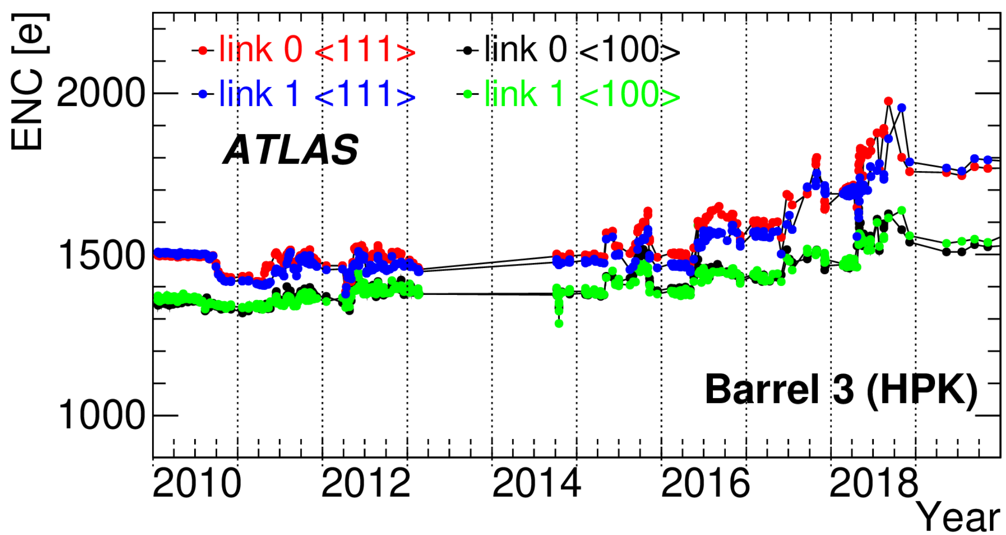
Gain and Noise





- Gain decreased over time and noise increased
- Corrected for by regular calibrations

→ Negligible impact on performance

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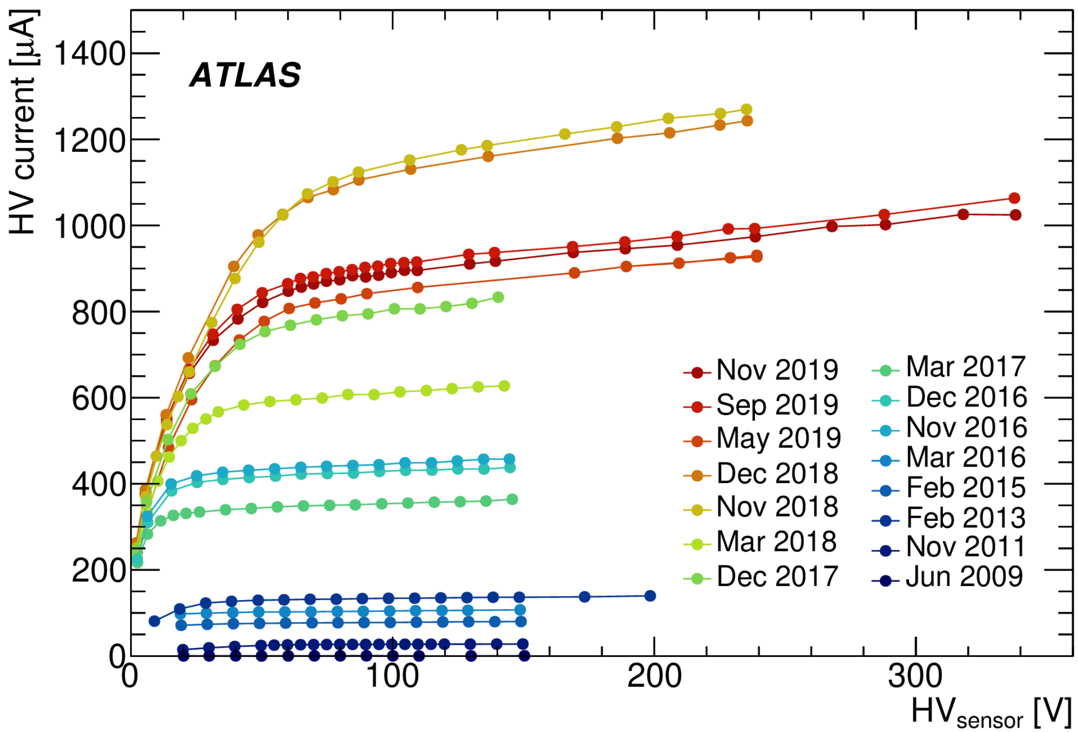
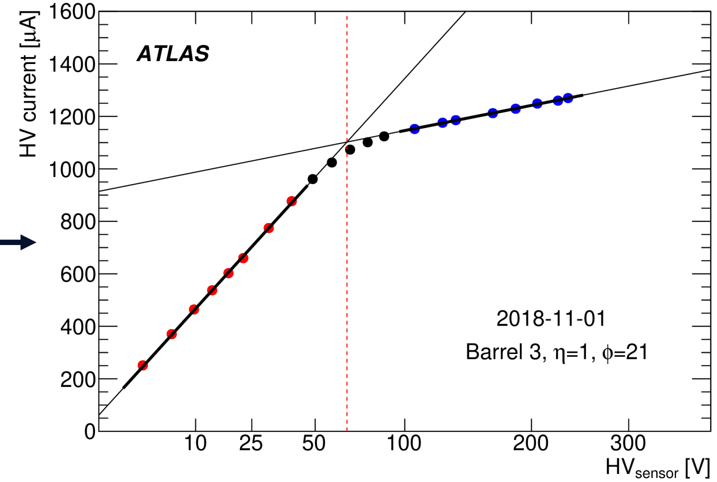
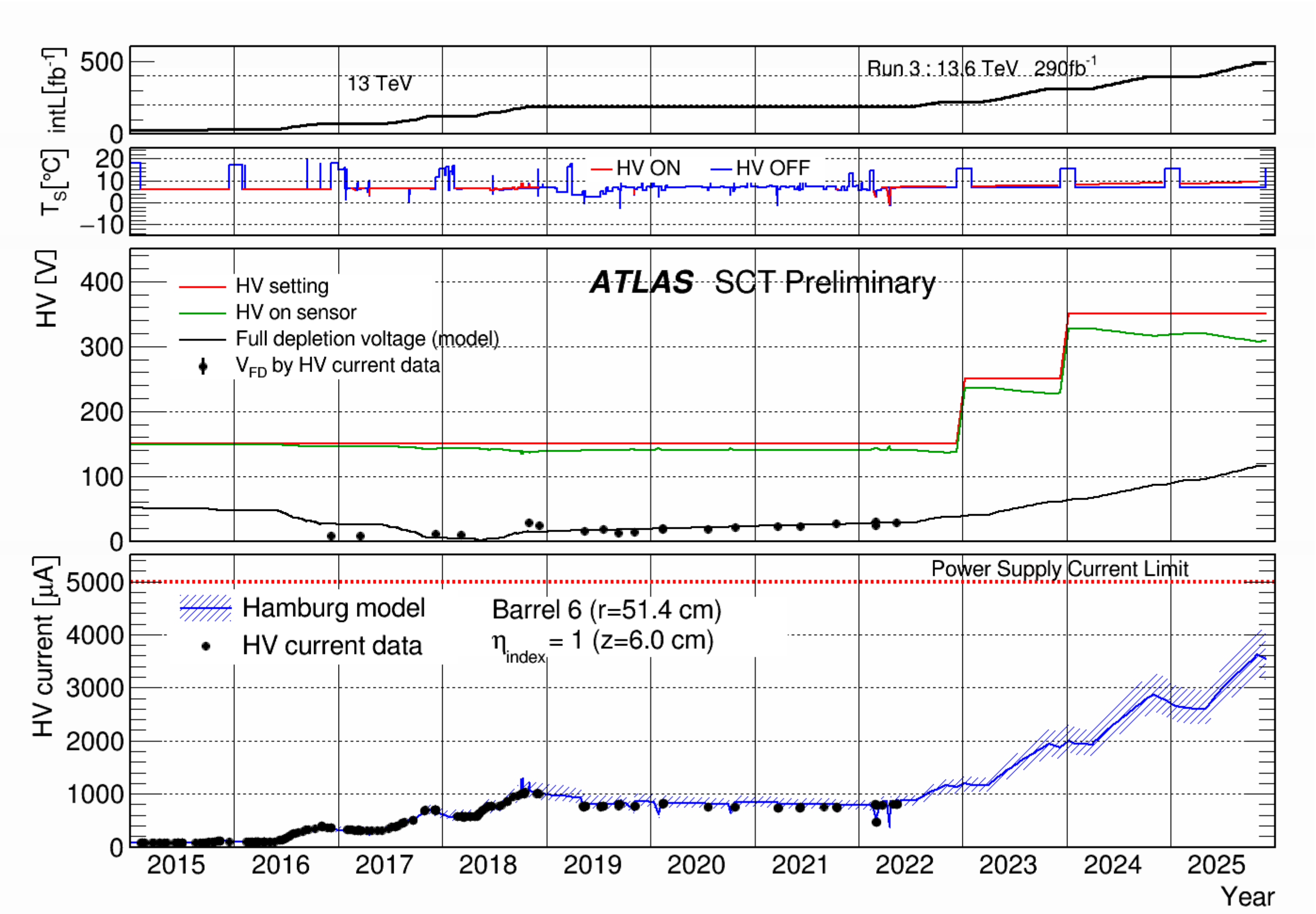
I-V Scans



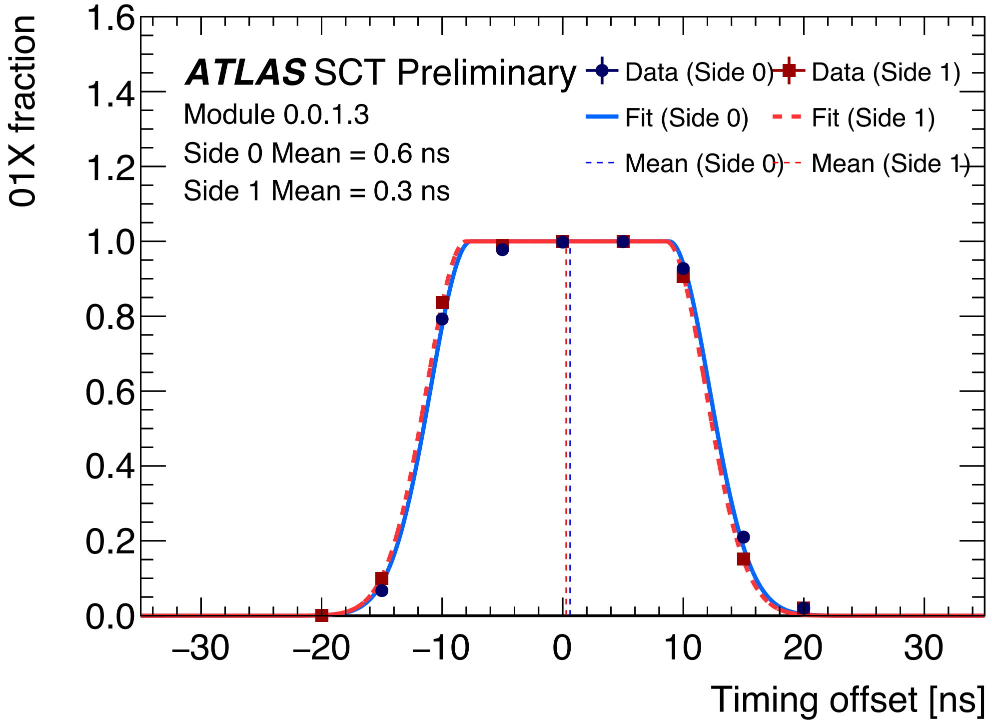
Example of V_{FD} extraction from an I-V scan



Run 2 Evolution and Run 3 Outlook: Barrel 6



Timing Scan: one example module



Scan in steps of 5 ns and measure fraction of hits on tracks that fulfil 01X pattern

01X pattern = readout three bins of 25 ns each

- 0 = nothing in first bin
- 1 = something in second bin
- X = no requirement on third bin

Mean of distribution = timing correction to be applied