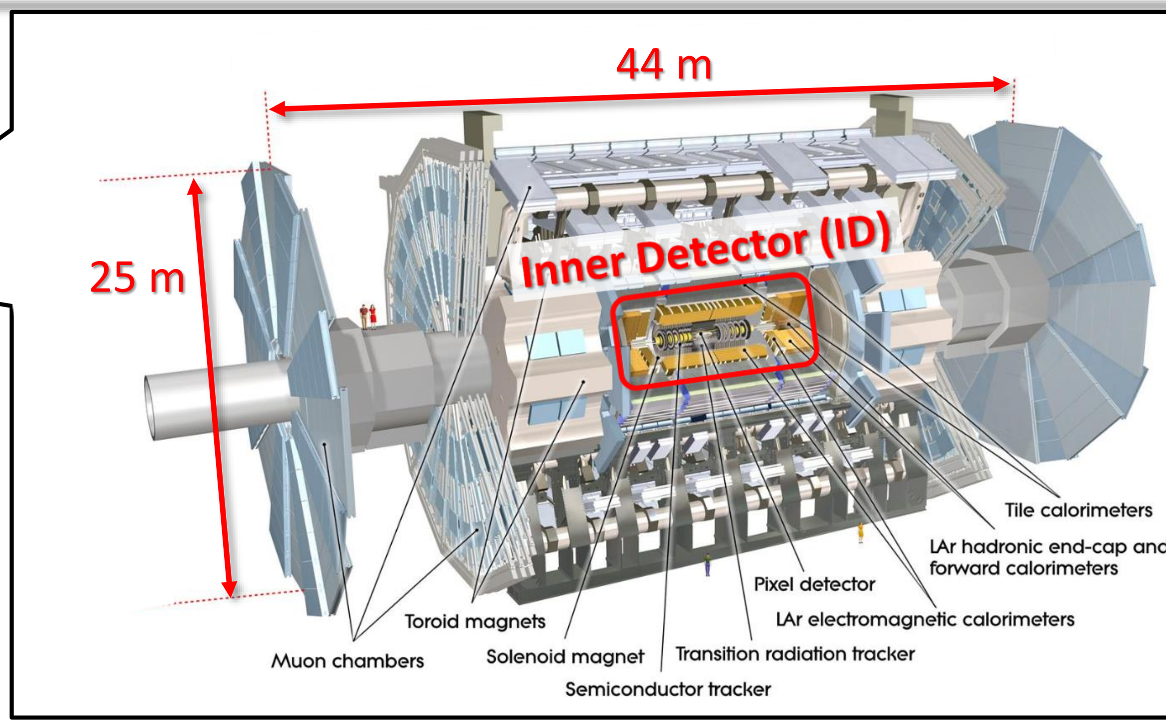
Performance and Radiation Damage of the ATLAS Semiconductor Tracker during LHC Run 2

26 December 2019, KEK seminar

Shigeki Hirose (Uni-Freiburg)

ATLAS Experiment

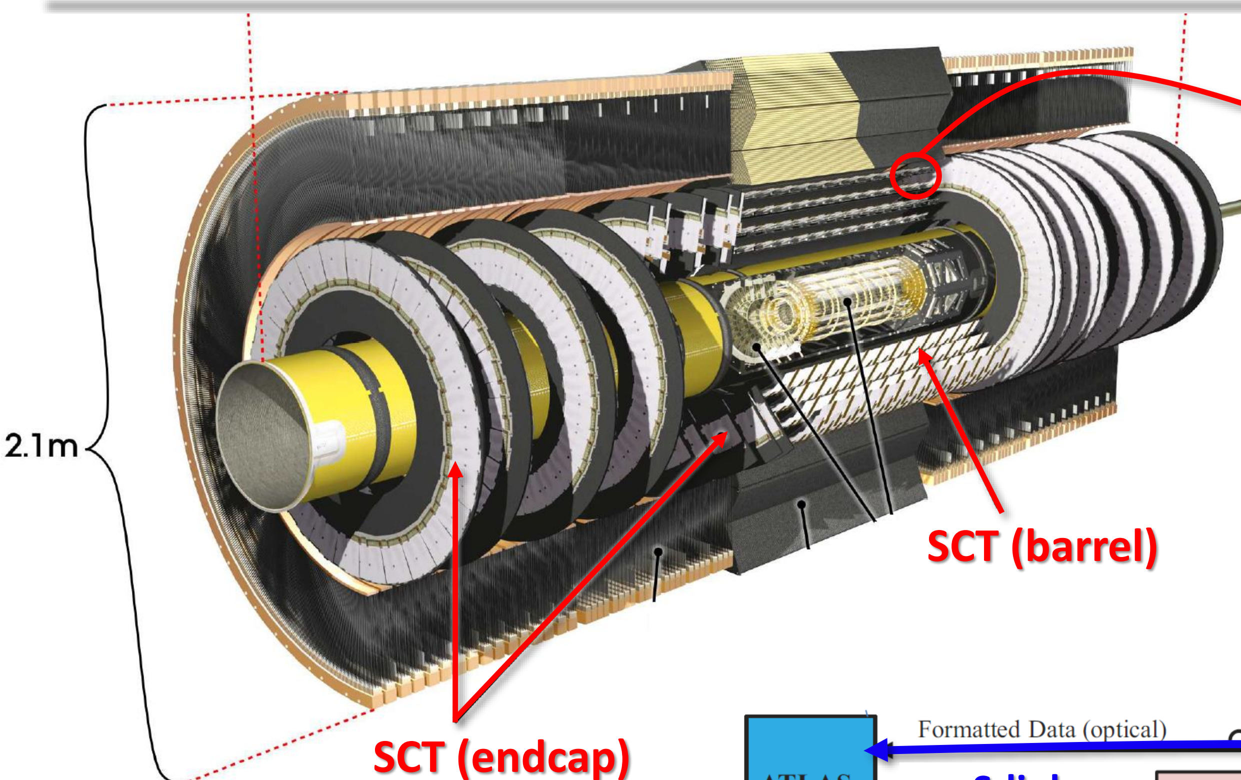
- Circumference = 27 km
- pp collision at $\sqrt{s}$ = 13 TeV
- Bunch per 25 ns

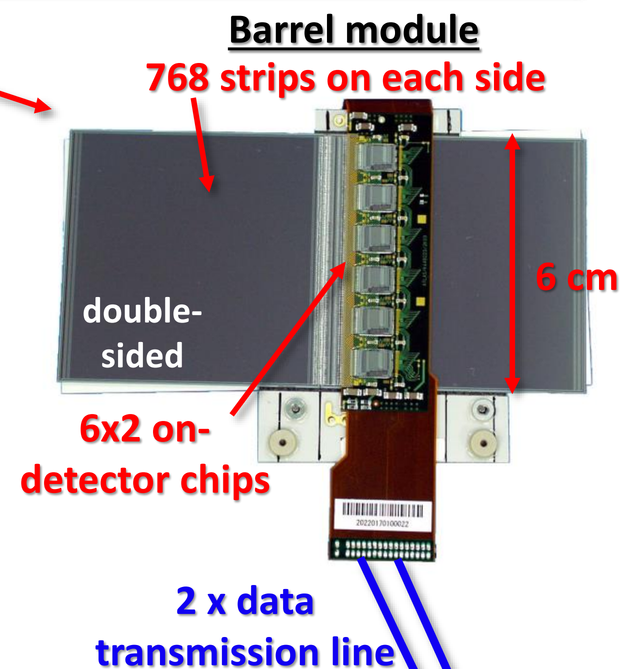


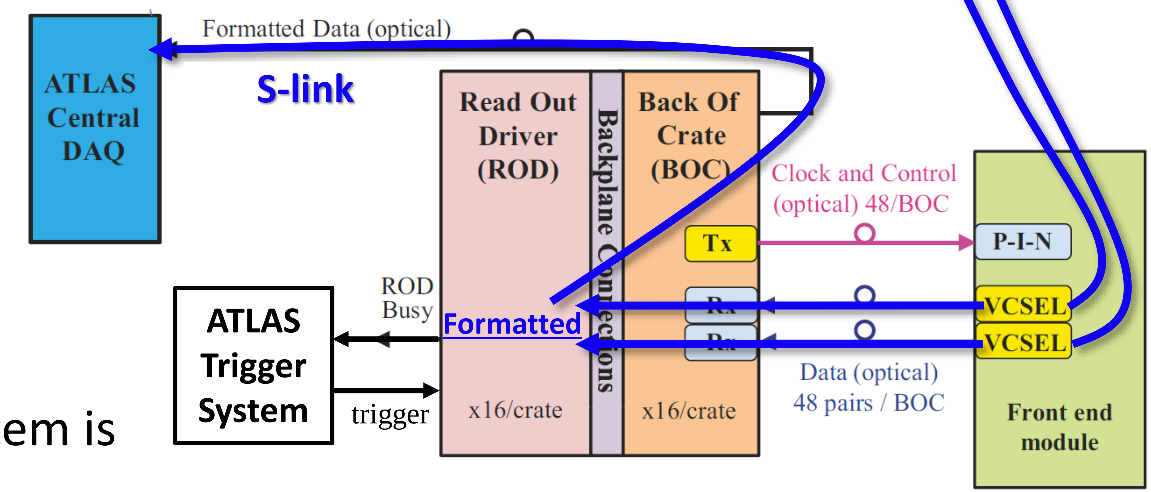
- ATLAS detector
  - Targets high-p_{T} objects from decays of massive particles
  - Messy environment of pp collisions due to QCD

    → Track finding performance of ID is essential for all physics analyses
- ID consists of three different subsystems

■ SemiConductor Tracker (SCT)

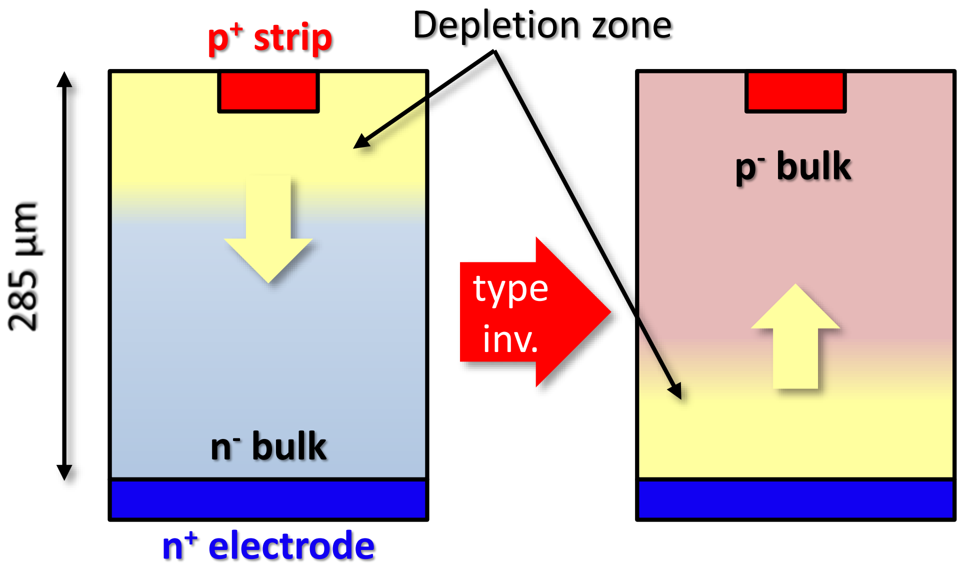


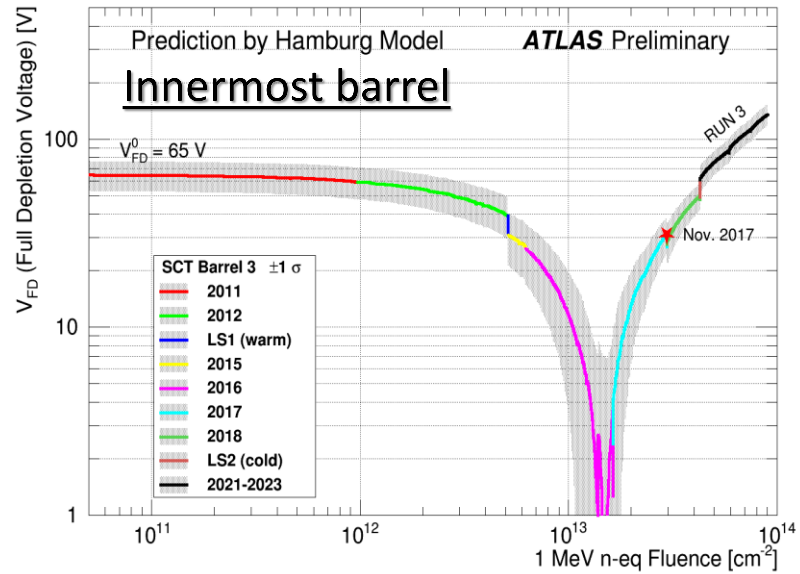




- 4 layers (barrel) and 9×2 disks (endcaps)
- > 6M channels
  - Maintaining a stable system is important

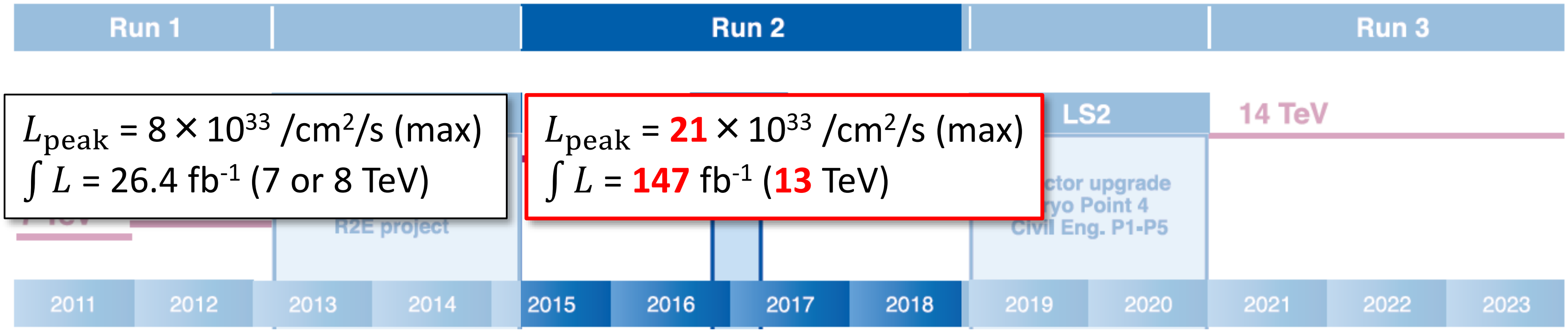
■ Silicon Sensor





- p^+-on-n type sensor
  - Depletion zone grows from p^+ side
  - Full-depletion voltage V_{FD} = 65 V without irradiation
- Type-inversion around 10^{13} 1-MeV n-eq/cm^2
  - Full depletion is necessary to keep good performance

■ LHC Run 2: 2015–2018



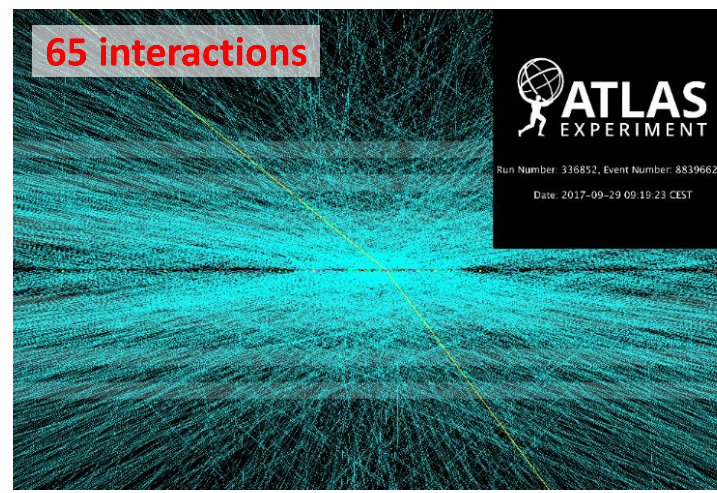
L_{peak} = 8 × 10^{33} /cm^2/s (max)
$\int L$ = 26.4 fb^{-1} (7 or 8 TeV)

L_{peak} = **21** × 10^{33} /cm^2/s (max)
$\int L$ = **147** fb^{-1} (**13** TeV)

- LHC Run 2 was a productive period
  - ×1.6-1.9 higher energy, ×5.6 more data than that in Run-1

    E.g. # of Higgs bosons: 5×10^5 → **80**×10^5
  - However, pileup (number of interactions per bunch crossing; μ) increased by 60%

Detectors had to endure high data rate and radiation!



■ Keys of SCT Run-2 Operation

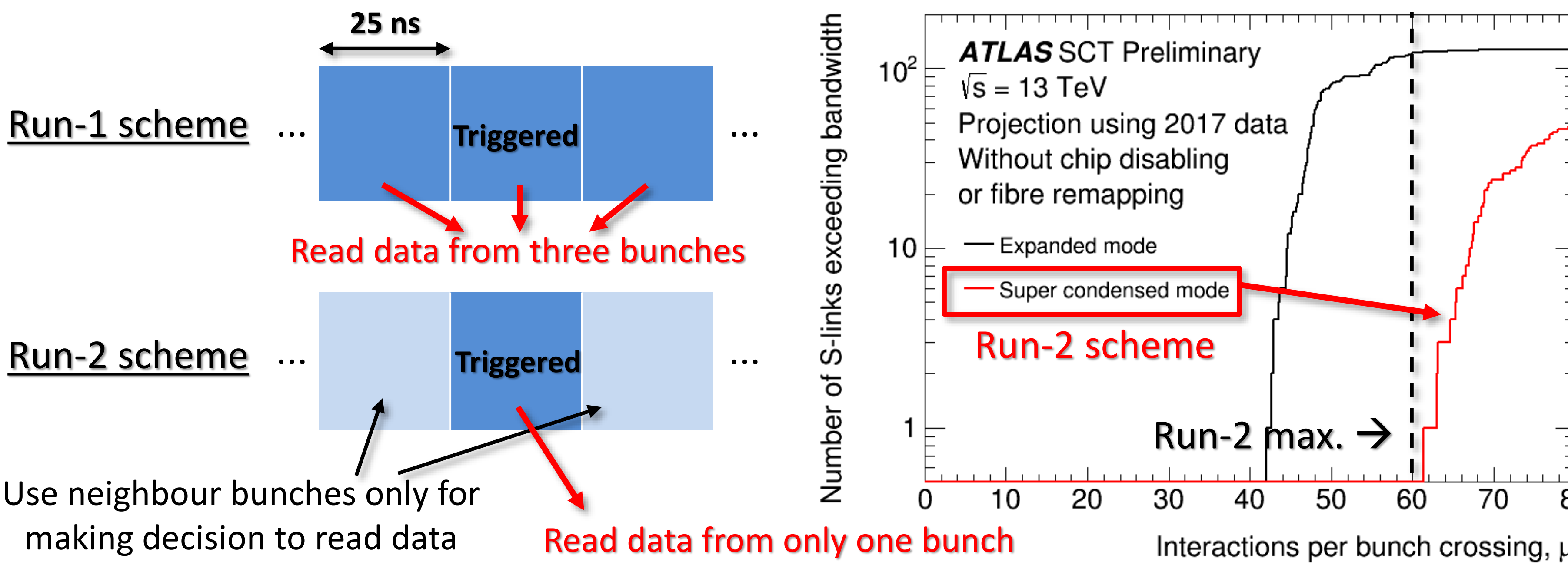
1. DAQ system
   - Enough data bandwidth
   - Tolerance to single event upsets
2. High hit efficiency and low noise
   - Low efficiency of SCT makes track finding difficult in high pileup events
   - Too many noise hits may cause
     - many fake tracks
     - busy on DAQ due to enlarged data size

- SCT performance in Run 2
  - SCT joined the ATLAS data-taking for **99.85%** of the stable beam time
  - **99.7%** of the SCT data was good quality for physics
  - As of end of Run 2, **98.6%** of elements are active

SCT has maintained high performance in the Run 2 condition!

Data Bandwidth

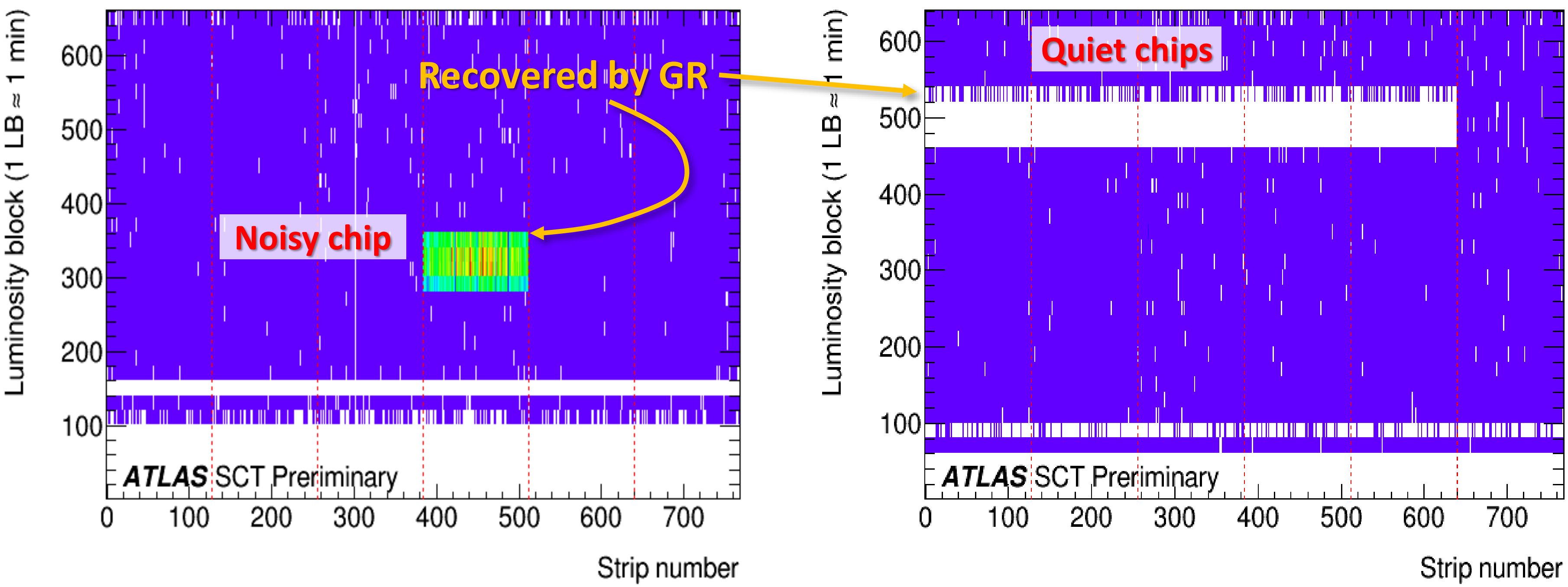
- Expanding bandwidth
  - Increased the readout drivers (90 → 128)
- Data size reduction
  - Read only one bit per strip ("no hit" is required on the previous bunch to avoid contributions from signal leakage)
  - Further reduction by more advanced data compression



All S-links are within the bandwidth up to μ = 60

Single Event Upset

Noise hit map (measured using empty bunch crossings)



- Single-event upsets can give rise to configuration bit-flips
  - Chips suddenly become noisy or quiet
- Global reconfiguration (GR)
  - Reconfigures all modules every 90 mins. (at cost of ~1 sec. deadtime)

GR is effective to clear problematic chips during a run

■ Hit Efficiency (1)

- SCT definition of hit efficiency

$$\varepsilon = \frac{N_{\mathrm{hit}}}{N_{\mathrm{hit}} + N_{\mathrm{hole}}}$$

A track creates a hit

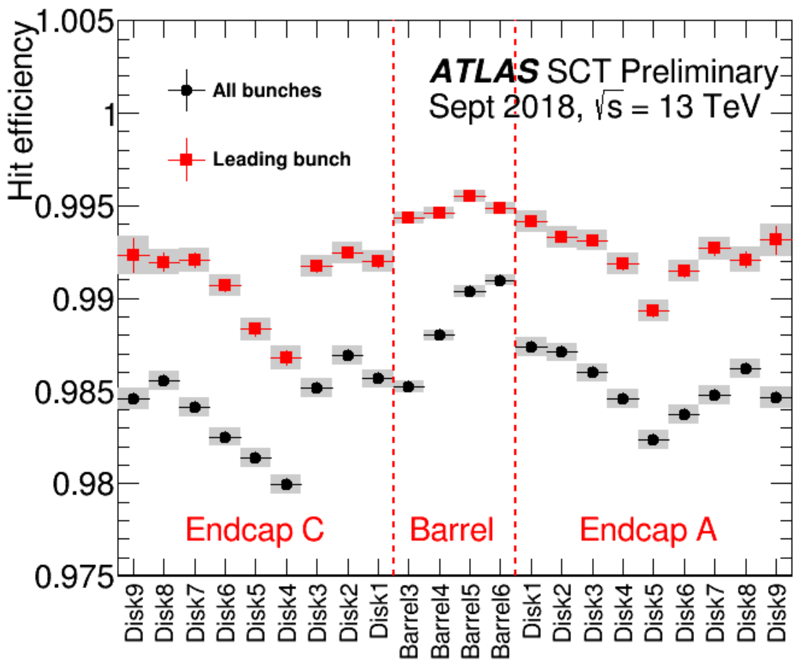
A track passes the sensor but no hit is found

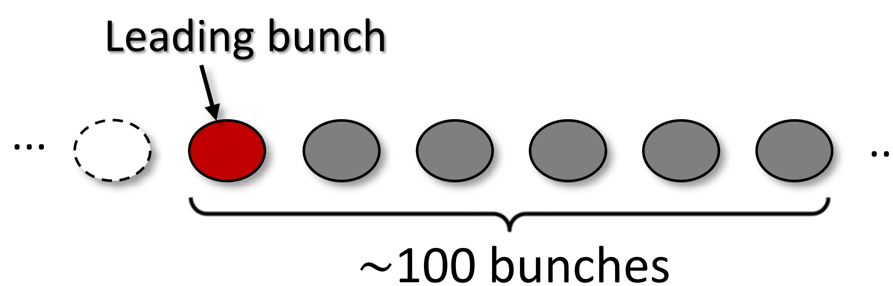
Dead modules and chips (~2%) are excluded (also from tracking)

- Typically the efficiency is > 99%
  - The intrinsic efficiency can be measured using the leading bunch
  - "No hit in the previous bunch" is required

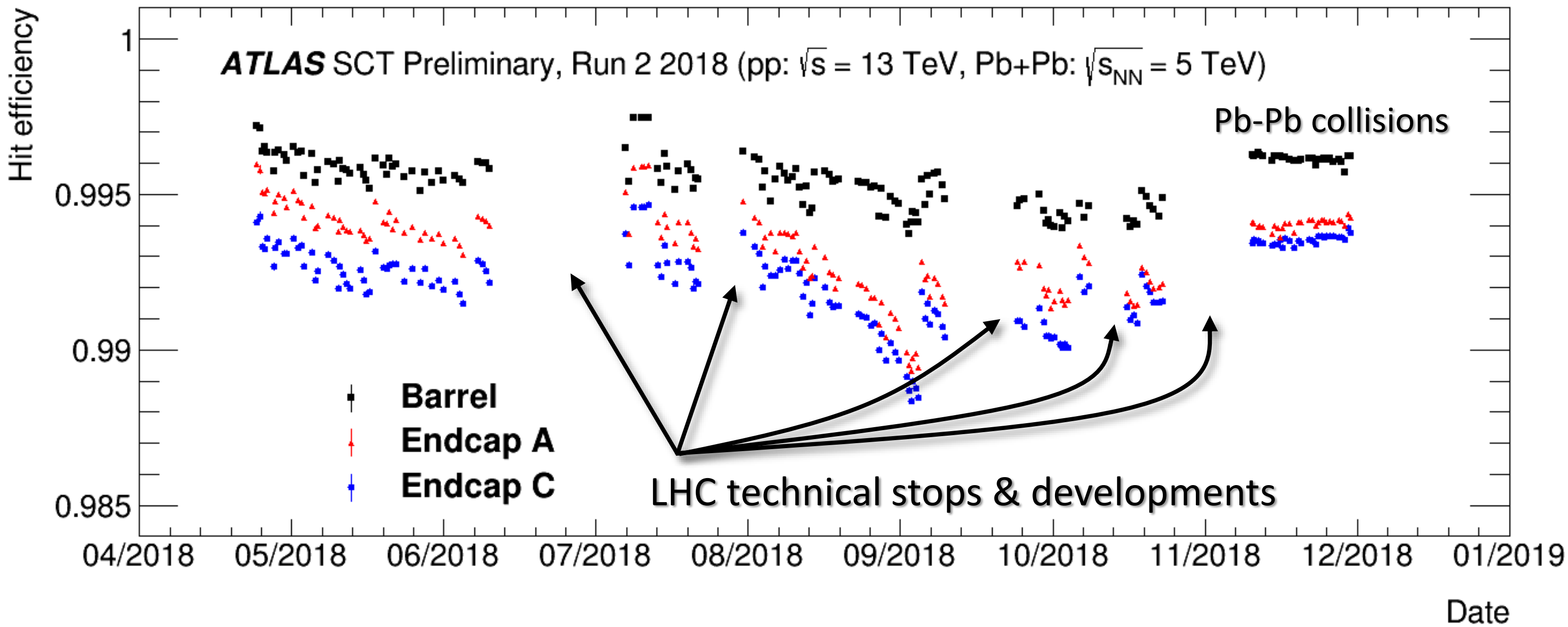
  → Efficiency from all bunches is lower by ~1%

(negligible impact for tracking)





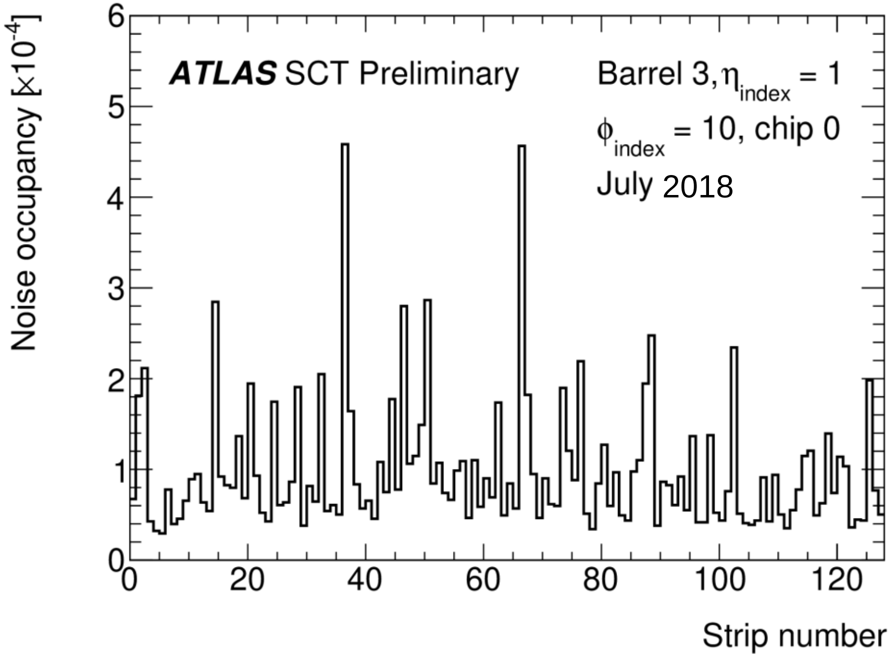
■ Hit Efficiency (2)

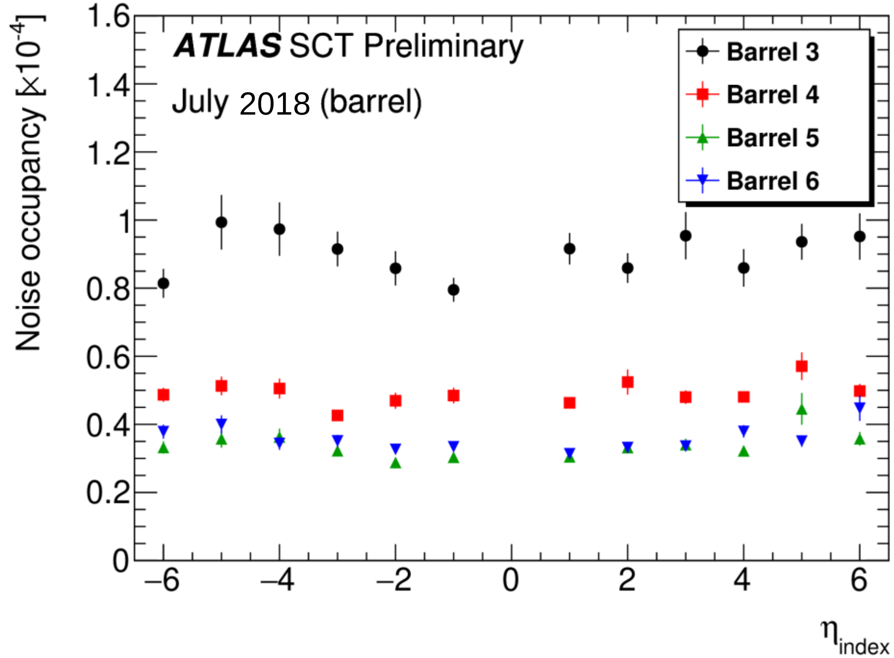


- Hit efficiency >99% was kept for almost entire Run 2
- Gradually drops over the time
  - Caused by baseline shift due to charge up from radiation effects
  - → Recovered by resetting the threshold

(More will be shown later)

■ Noise: Occupancy





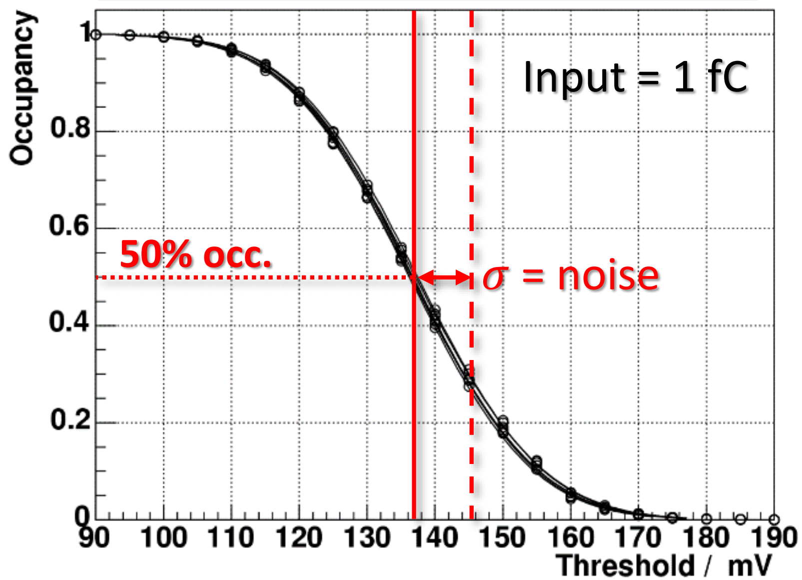
- NO: probability of noise hit with 1 fC = 6250 e^{-}
  - SCT is required to be < 5×10^{-4}
- Measurement from empty bunch crossings in a low-mu pp run
  - Strip-by-strip difference is large due to baseline shift

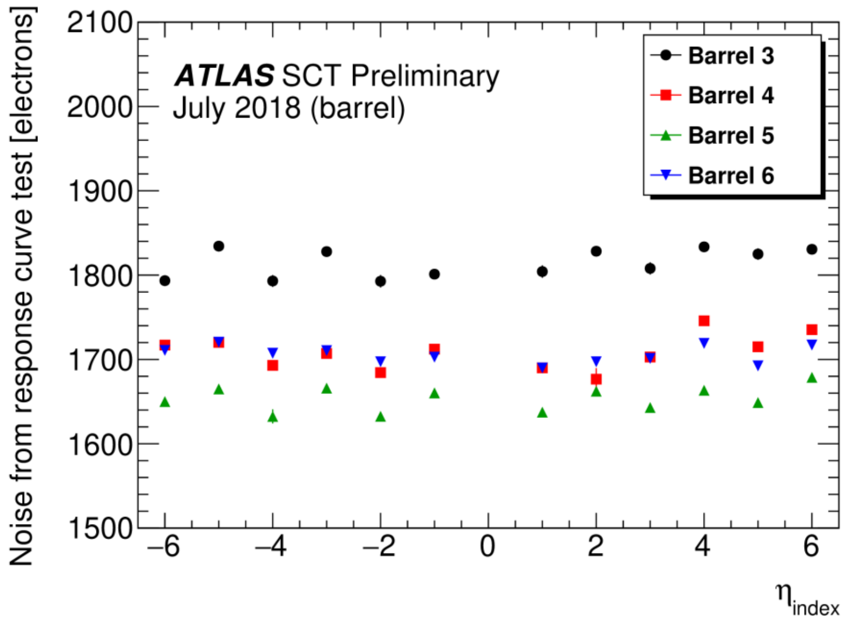
NO is sufficiently low in all barrel layers

(Similar results in endcaps)

■ Noise: Threshold Scan

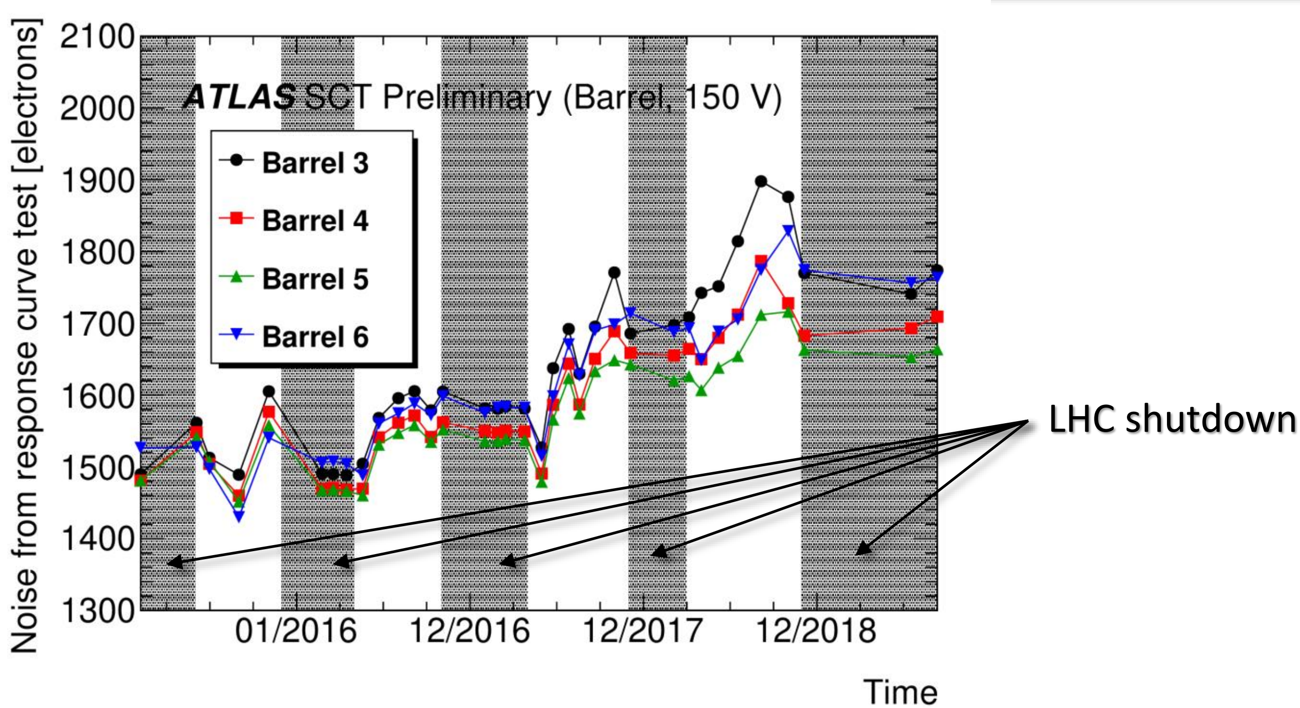
A. Abdesselam et al., JINST 3 P01003 (2008)





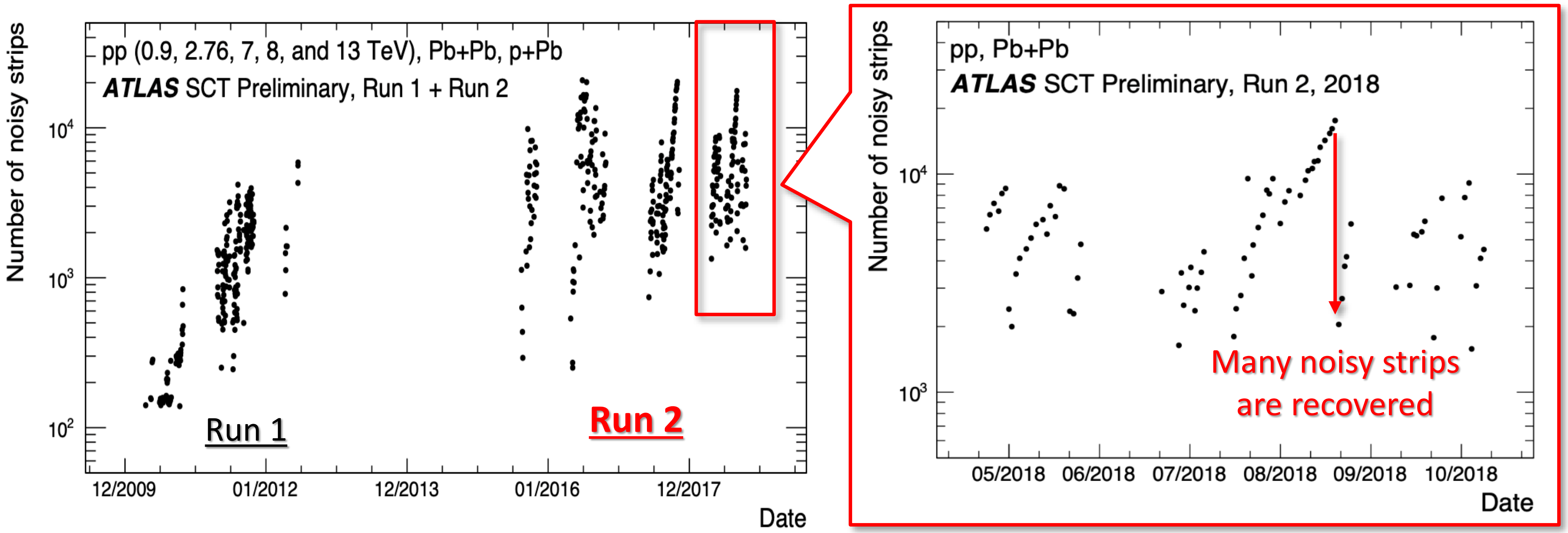
- Noise can be estimated from threshold scan with a fixed input charge
  - Extract noise from σ of an error function
  - More stable estimation → Better for monitoring time dependence
- 1600〜1800 e^- at the end of Run 2

■ Noise: Time Evolution



- Noise increased by 10-15% during Run 2
  - Doesn’t impact data quality (NO was low enough)
- Somewhat unstable during the data-taking periods
  - Under investigation

■ Detector Calibration

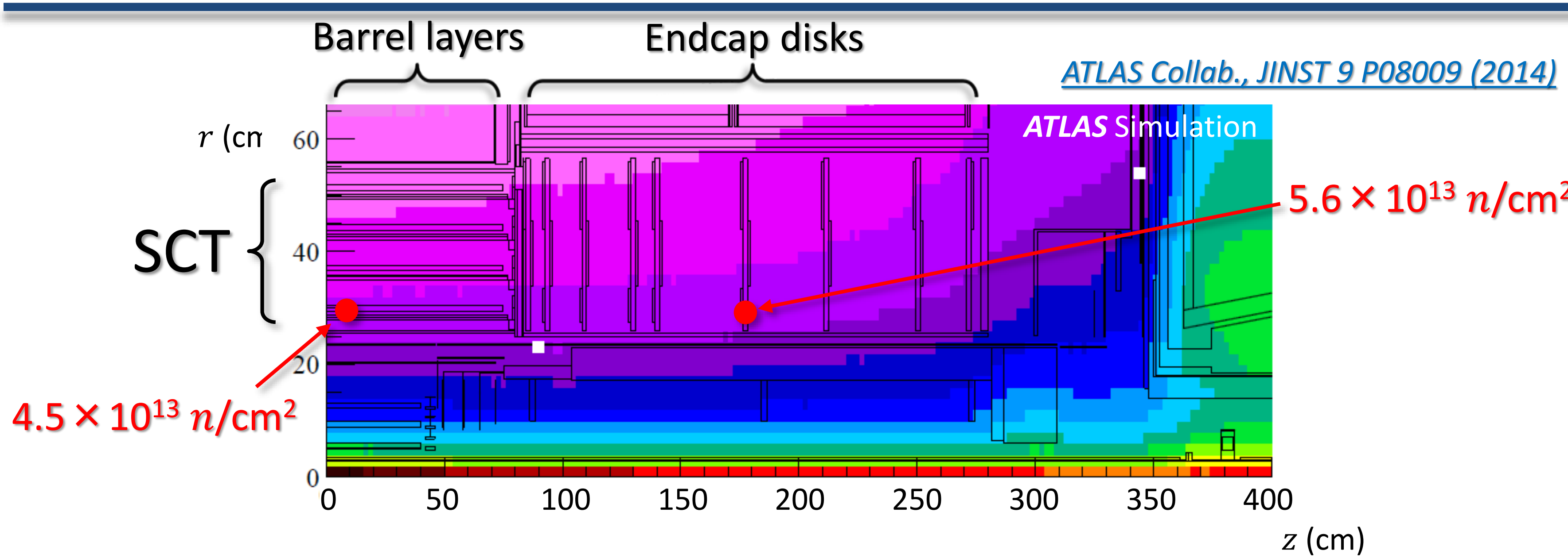


- Electrical calibration is performed every ~1 month
  - Reset threshold etc.
  - Disable too noisy elements
- E.g. number of noisy strips increases with accumulating radiation effects

  → Recovered by calibration

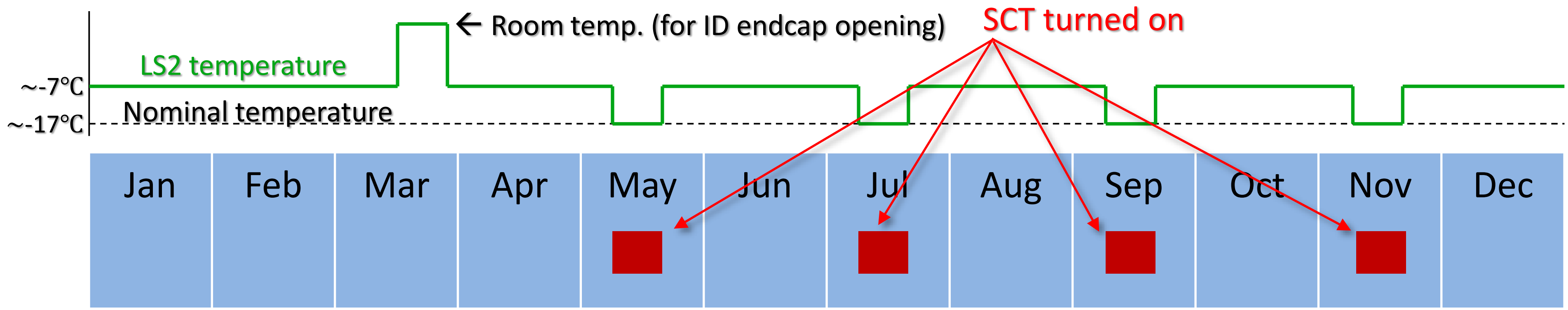
Periodical calibration is essential to maintain performance!

Radiation Damage on Sensors



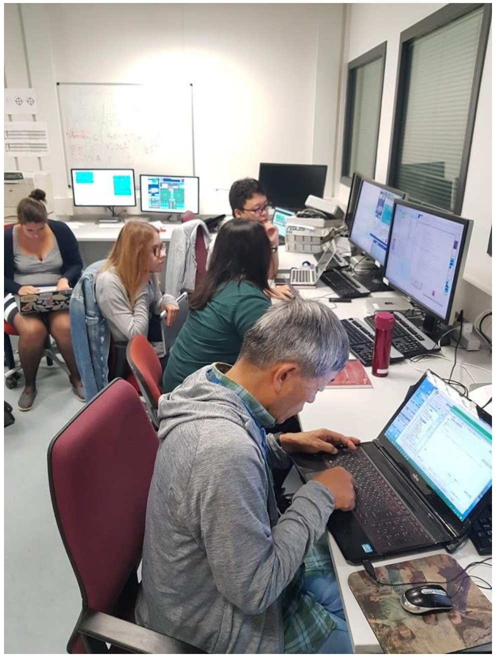
- SCT has been heavily damaged by radiation
  - Exposed up to 5.6×10^{13} 1-MeV n-eq/cm^2
- Potential crucial problems in Run-3 (2021 - 2023)
  - Too large leakage current (I_{leak})
  - Too high full-depletion voltage (V_{FD})
- Periodical measurements of I_{leak} and V_{FD}
  - Not only Run 2, but also during LS2 (2019-2020)

■ Measurements during LS2

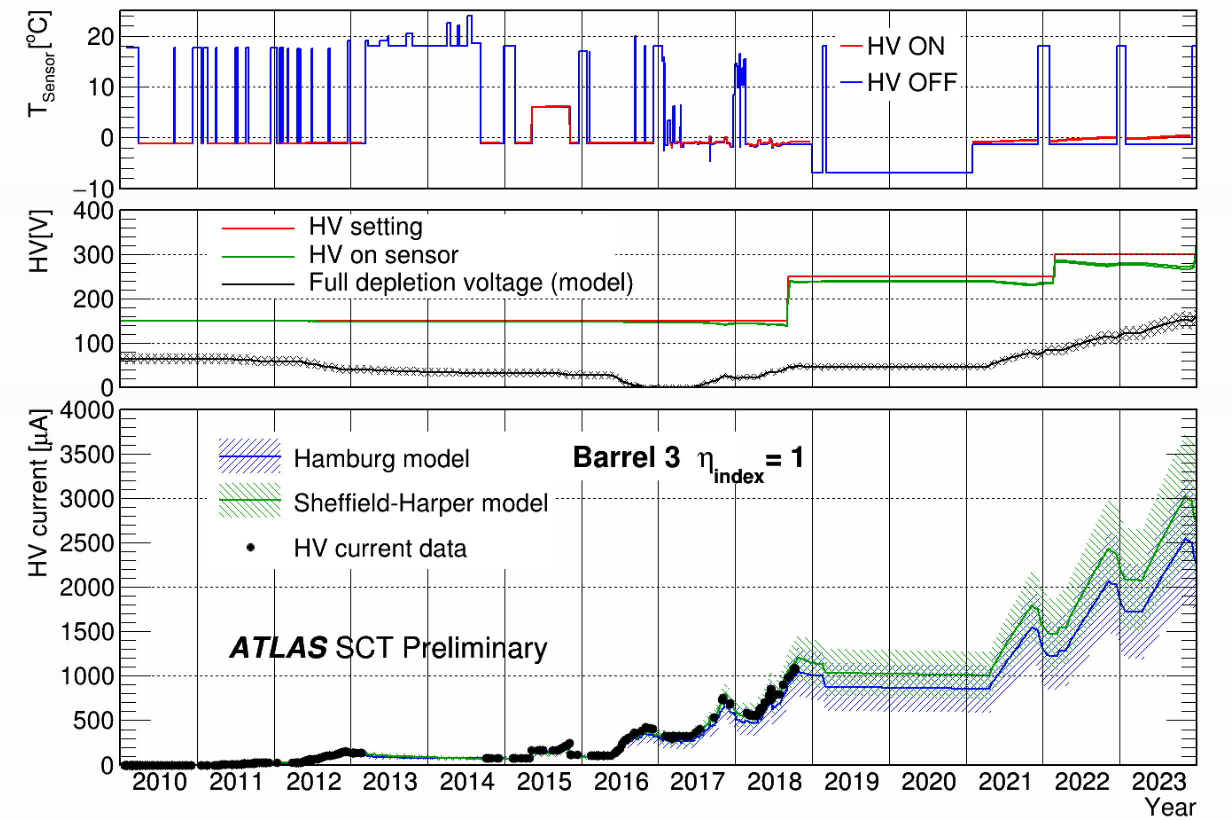


History of 2019

- Perform IV scan etc. every two months
  - 5-10 people staying at CERN contribute

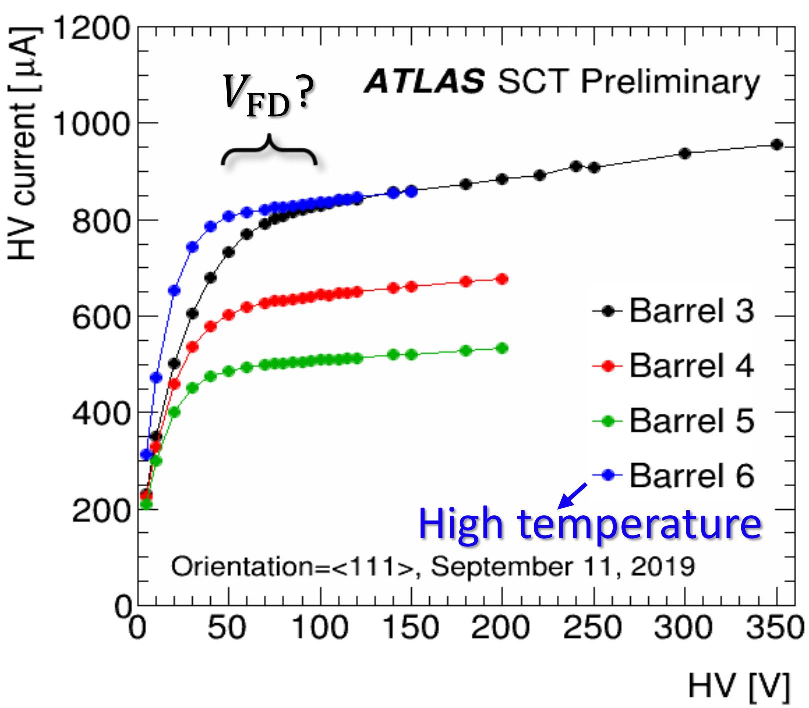


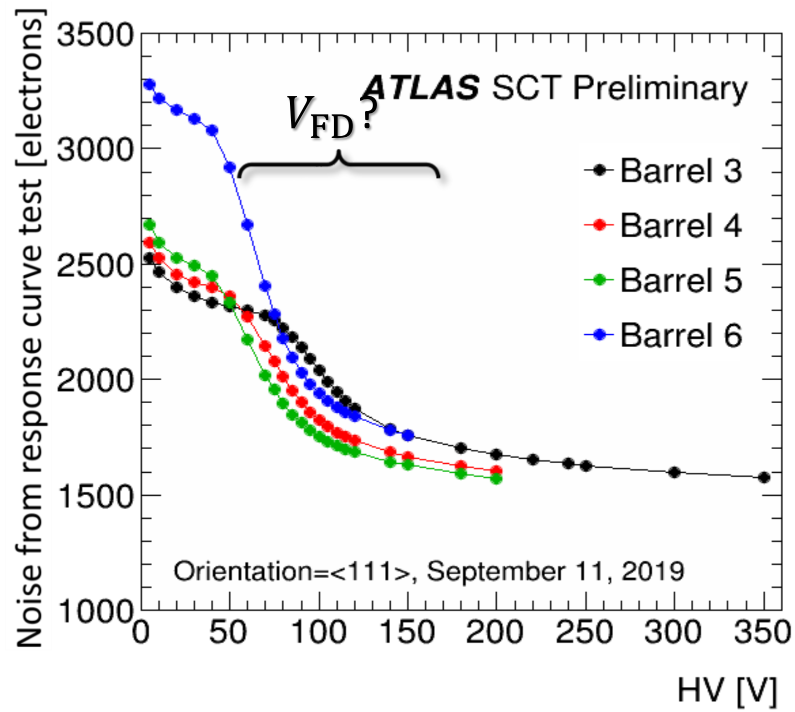
■ Leakage Current



- I_{leak} is monitored since 2010
  - It increased by a factor of 10^6!
  - Annealing is very visible every year-end
- Our measurement agrees with the models
  - Radiation flux is well understood

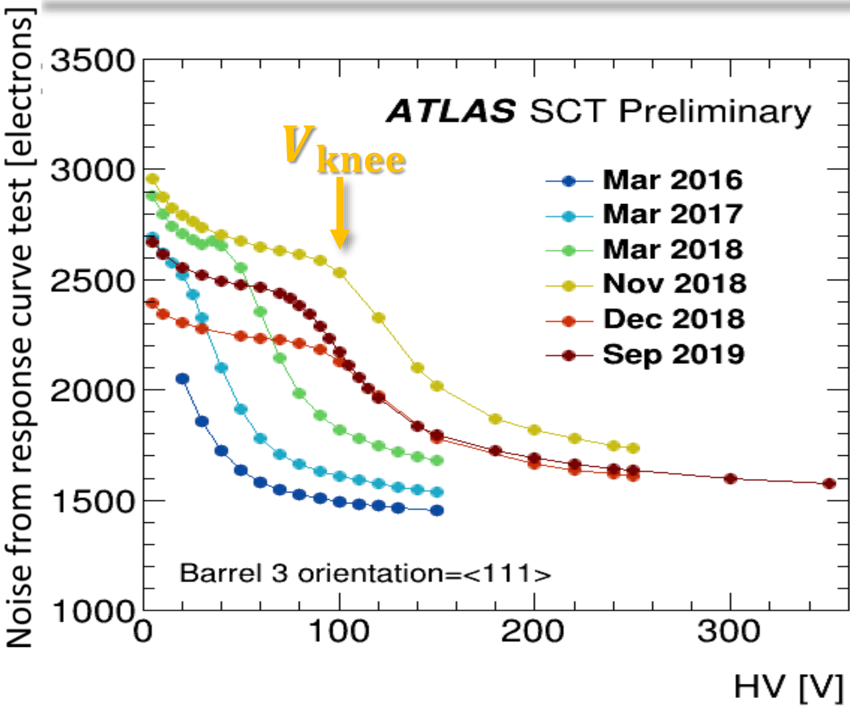
I–V Measurement

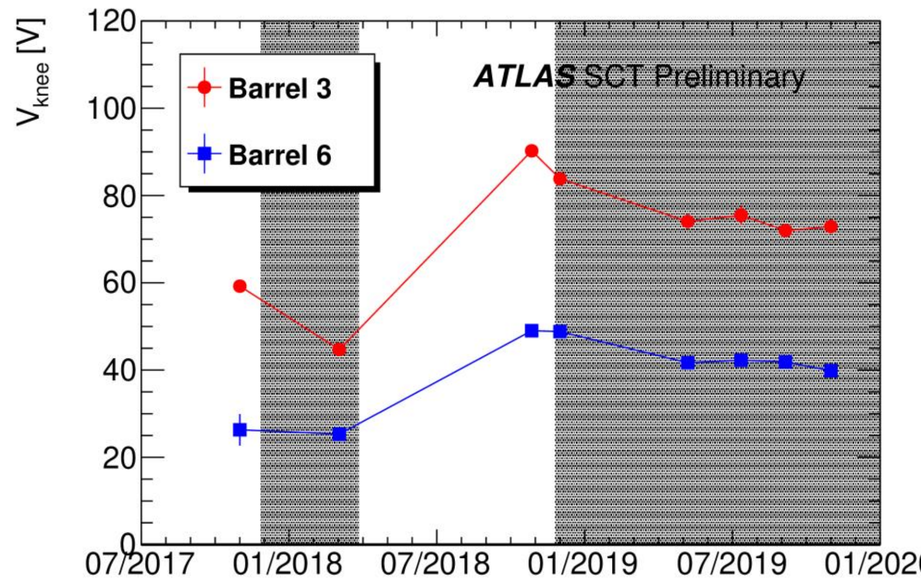




- Measure leakage current and noise vs HV
  - After reaching HV = V_{FD}, leakage current and noise become plateau
  - However the transition is not very sharp
- V_{FD} estimation from the I-V measurement
  - Rough estimate is 50-100 V

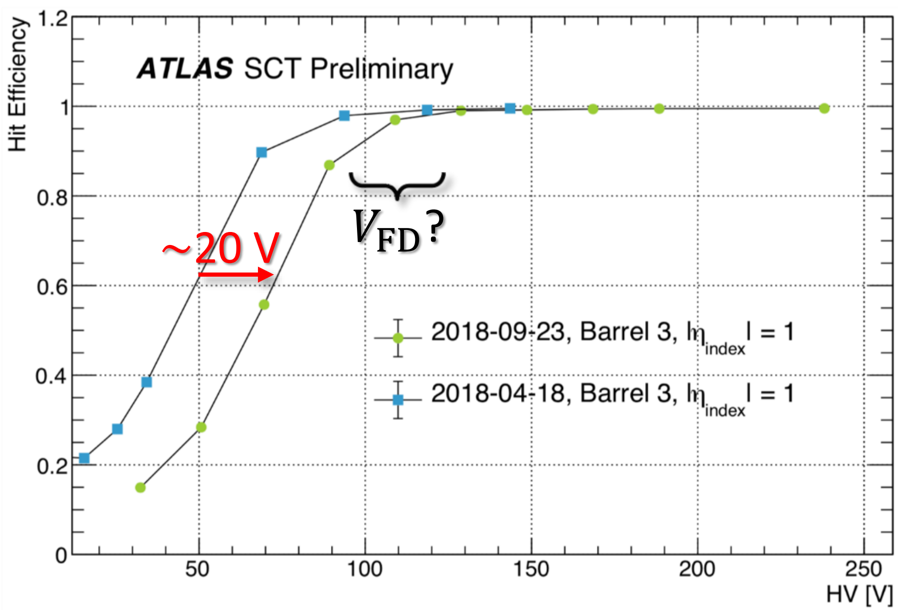
Evolution of V_{FD}

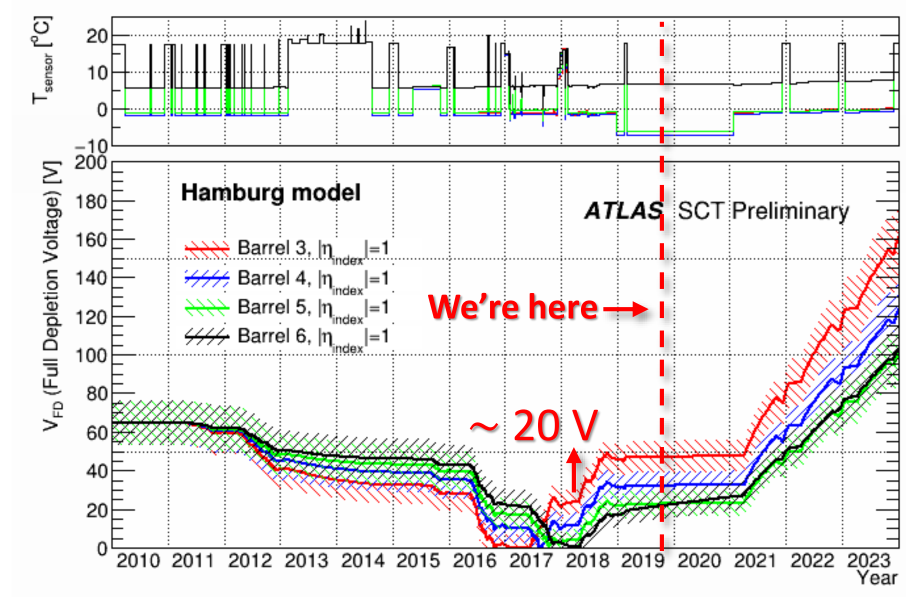




- The “knee” structure appears after type-inversion
  - All modules have been type-inverted
- Evolution of V_{FD} can be tracked using V_{knee}
  - Annealing is very clear in 2019
  - Reverse annealing is suppressed thanks to cooling

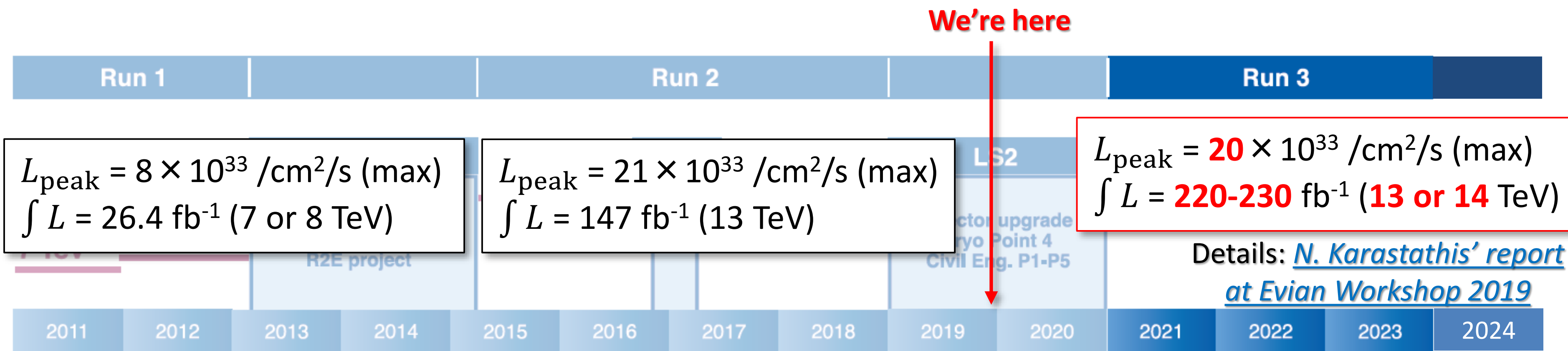
■ Efficiency vs HV





- Efficiency curve is another measure of V_{FD}
  - Efficiency is significantly lower if HV < V_{FD}
  - But the transition is not sharp...
- Model prediction with the Hamburg model
  - Currently V_{FD} = 50 V → Will be up to 150 V
  - All measurements consistently indicate much higher V_{FD}...
  - Even +50 V is not worrisome; the system limit is 480 V

■ Towards Run 3: 2021–2024



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L_{peak} = 21 × 10^{33} /cm^2/s (max)
$\int L$ = 147 fb^{-1} (13 TeV)

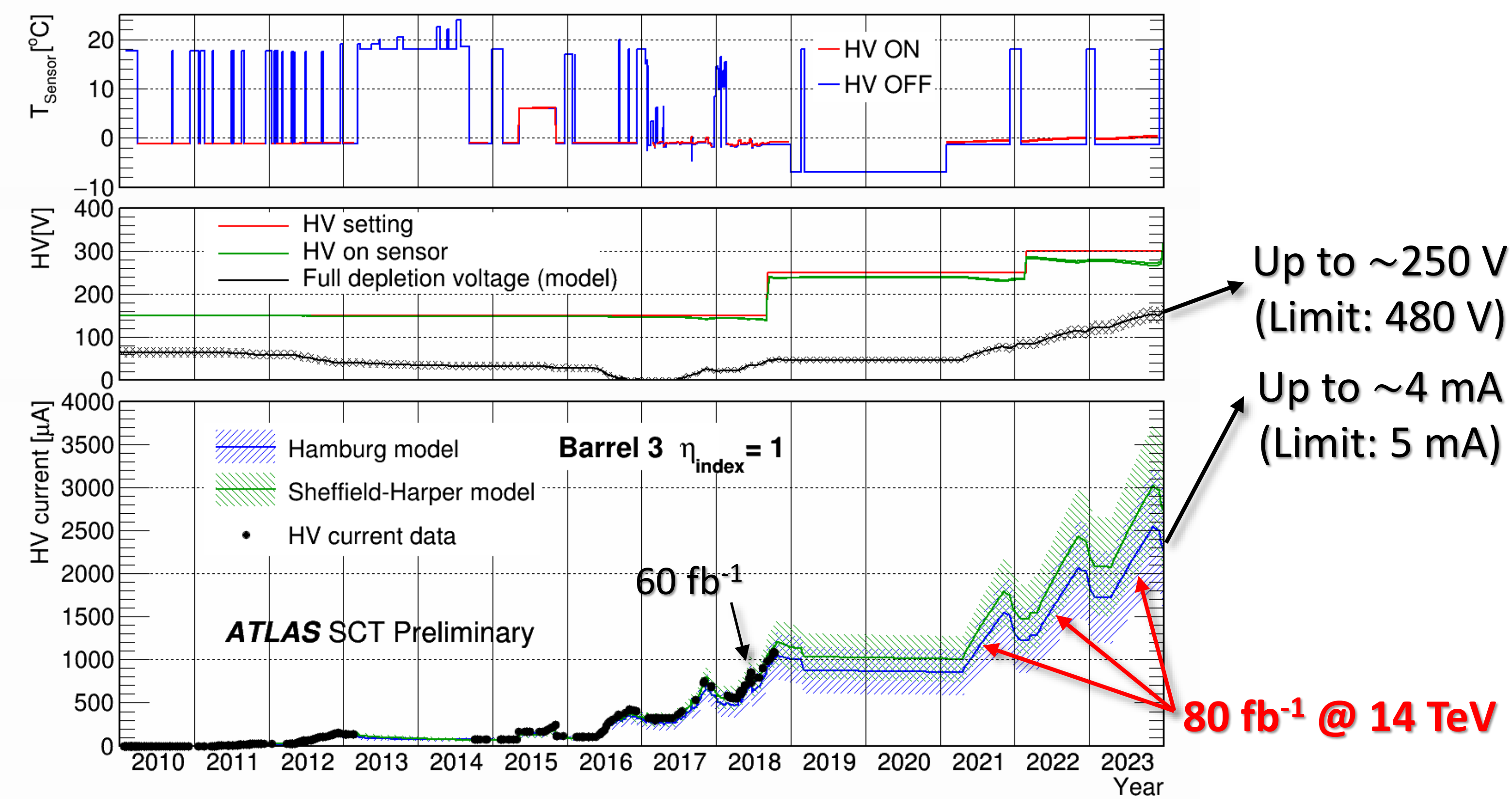
L_{peak} = **20** × 10^{33} /cm^2/s (max)
$\int L$ = **220-230** fb^{-1} (**13 or 14** TeV)

Details: *N. Karastathis' report at Evian Workshop 2019*

One-year extension was recently decided:
https://home.cern/news/news/accelerators/new-schedule-lhc-and-its-successor

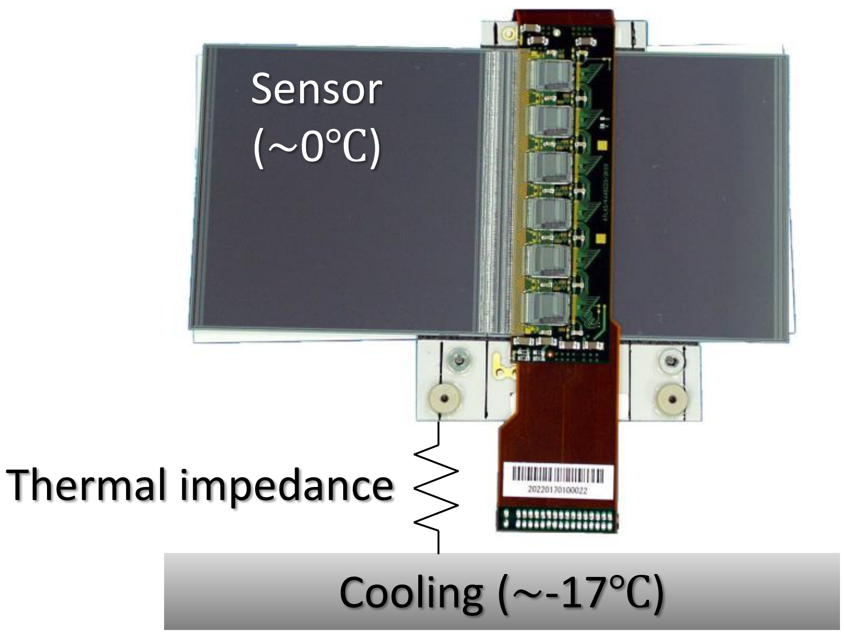
- Conditions will be similar to Run 2
- No major upgrade is planned for SCT
  - The very robust and stable system has been already established because of a number of improvements
  - Need a solid prediction for Run 3 operation

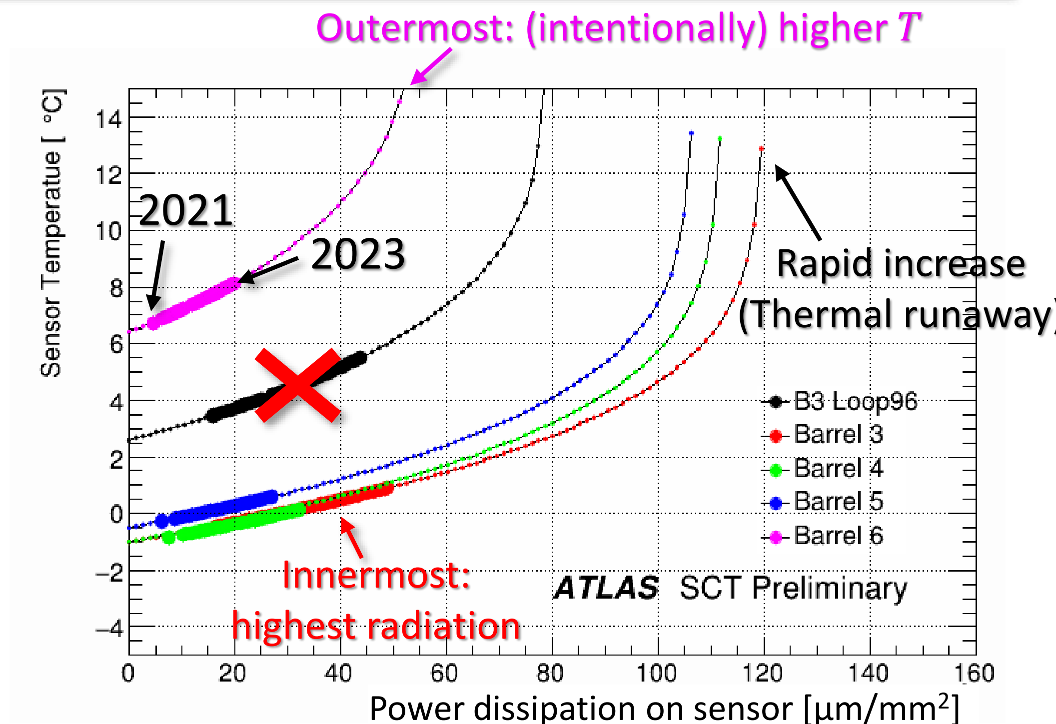
Projection to Run 3



- Projection until the end of Run 3
  - V_{FD}: enough headroom until it reaches 480 V
  - I_{leak}: safety margin of only 1 mA is a little worrisome?
    - → I_{leak} can be further suppressed by lowering temperature

■ Thermal Performance

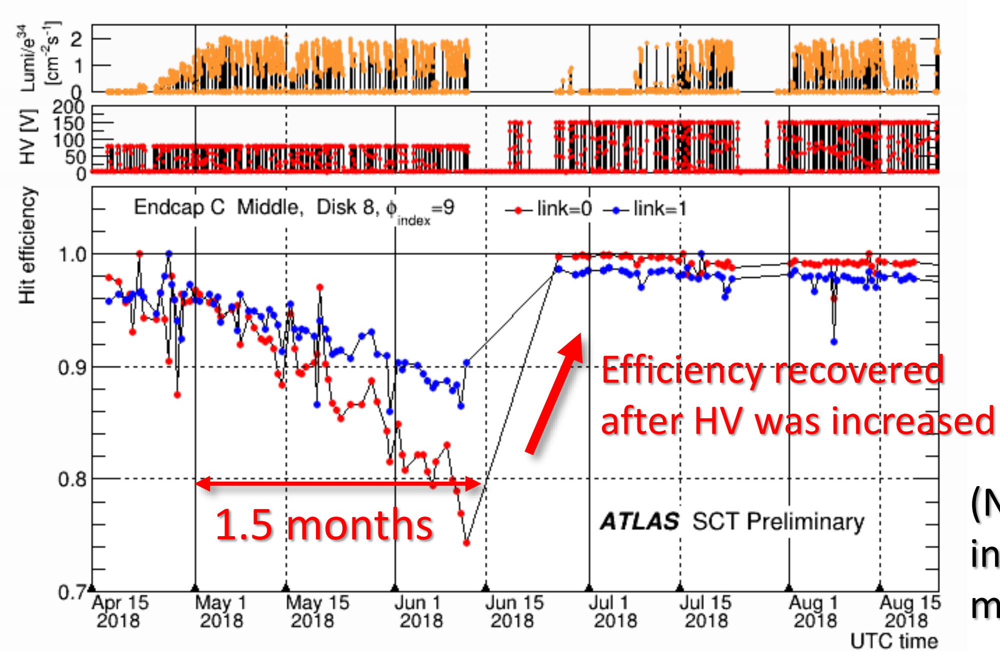




- Sensor temperature evolution
  - Higher I_{leak} → More heat generation → Further I_{leak} → ...
- Predicted sensor temperature indicates enough headroom
- Uncertainty on the thermal impedance

  → Important to carefully monitor sensor temperature in the first half of Run 3

■ Preparation for DQ in Run 3



(N.B. lower HV was intentionally applied to this module)

- Radiation damage will be more severe
  - Catch DQ degradation before it becomes intolerant
- Efficiency rapidly drops within ~1 month
  - However, it’s too slow to be caught by run-by-run comparisons

→Sophisticated monitoring & quick diagnosis tool is being developed

Summary

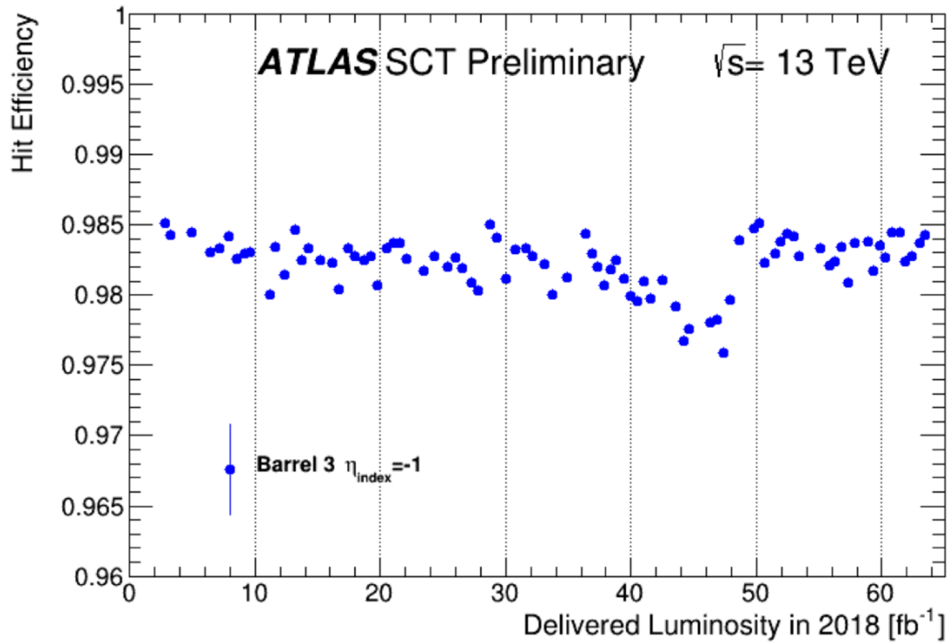
- ATLAS SCT has been operated since 2010
  - Successful operation with high efficiency + low noise in Run 2
- SCT provides interesting opportunities to study radiation-damaged silicon sensors
  - Leakage current well agrees with model predictions
  - Full depletion voltage may be ~50 V higher than the prediction
    → Complicated to predict V_{FD} with the Hamburg model...
- For Run 3 in 2021-2024
  - No critical operational problems are foreseen
  - Total radiation dose will be more by a factor of ~2
    → More careful performance monitoring will be important

SCT will continue providing high quality data in ATLAS Run 3

...and will be replaced by a new tracker for HL-LHC

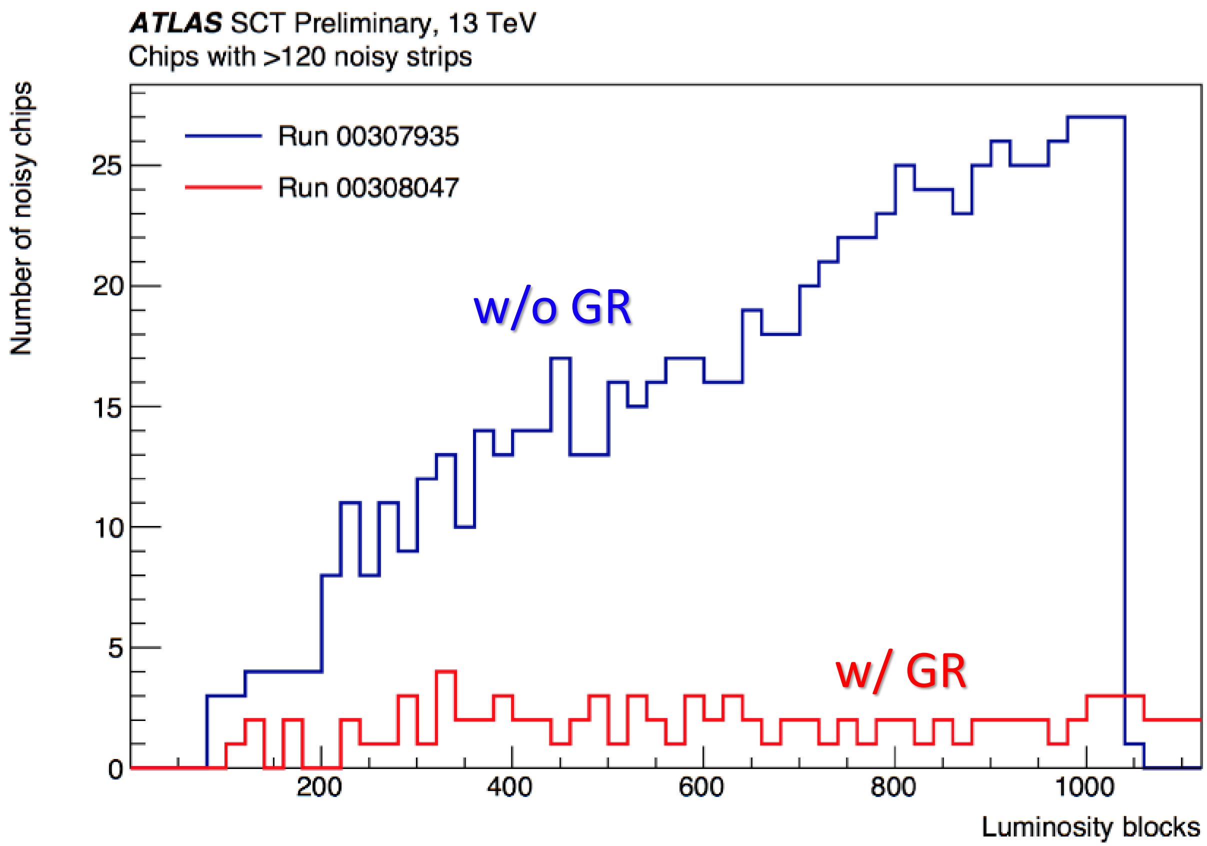
■ Efficiency Drop in 2018

- Overall efficiency drop was observed on Barrel 3 (innermost layer)
  - This wasn't specific to some modules, so couldn't be attributed to too many noisy strips
- Increase of HV helped recovering the efficiency
  - Clearly indicates the lower efficiency was due to radiation damage



■ Global reconfiguration

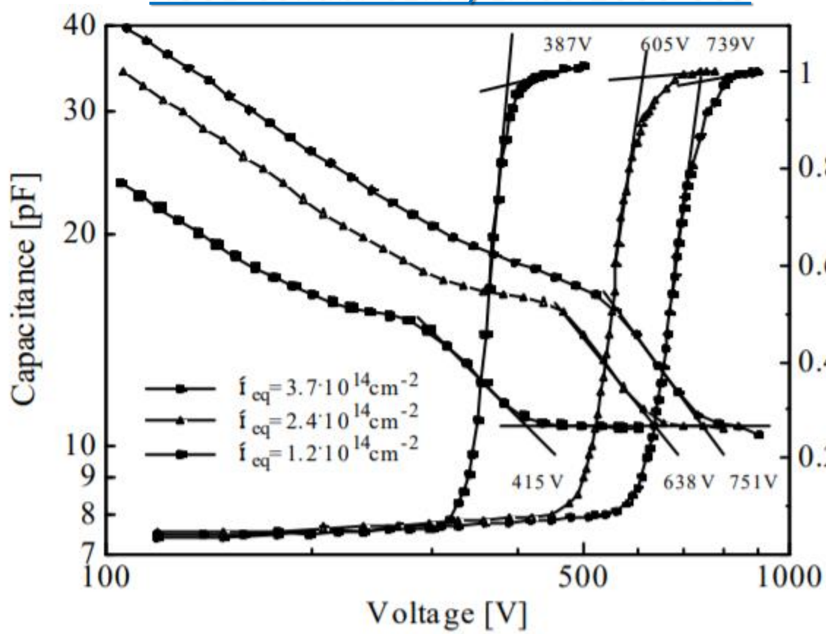
- Introduction of GR was effective to reduce the number of problematic chips
  - This is important not only in terms of data quality (efficiency etc.), but also of DAQ; too many noisy chips may interrupt DAQ due to too high data transmission rate

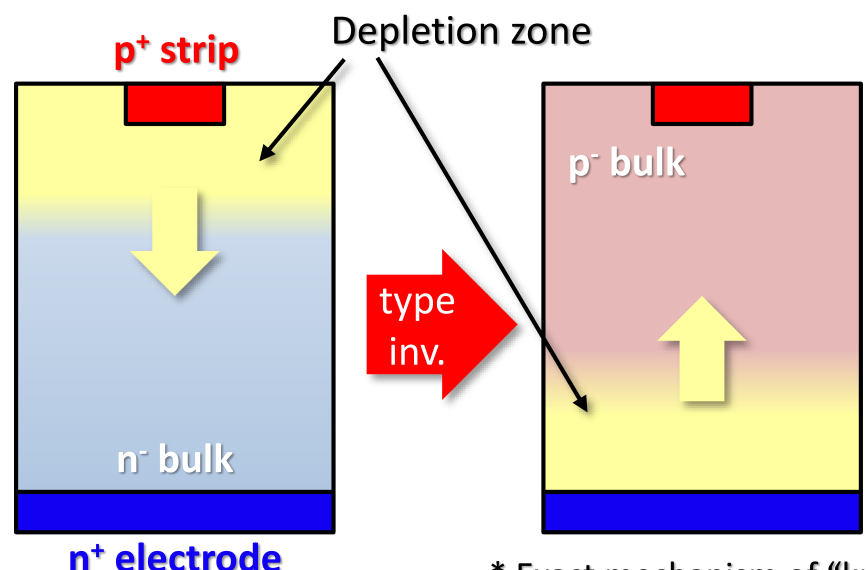


■ Type–inversion and “knee”

- After type-inversion, the depletion zone grows from the back electrode
  - – Depletion zone doesn’t contact with strips before full depletion
  - → This may be a cause of “two-step” structure of noise (or capacitance)
- The knee was reported by RD48 project in 1999

ROSE Collab. CERN/LHCC 2000-009

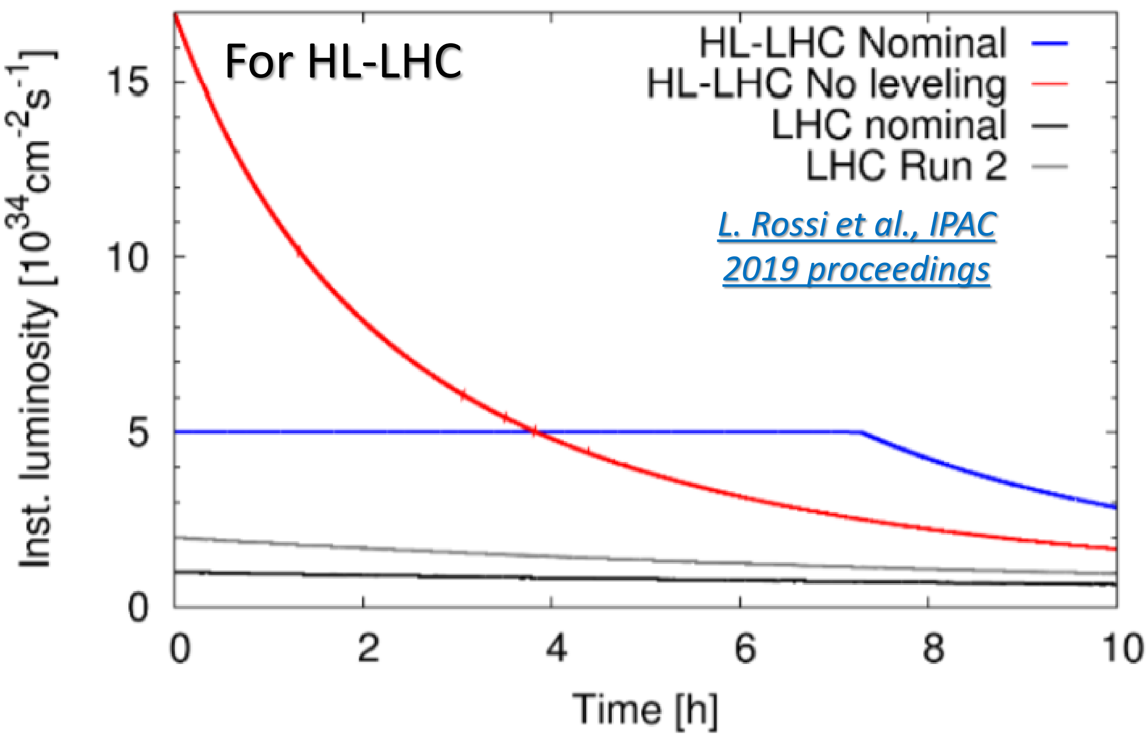




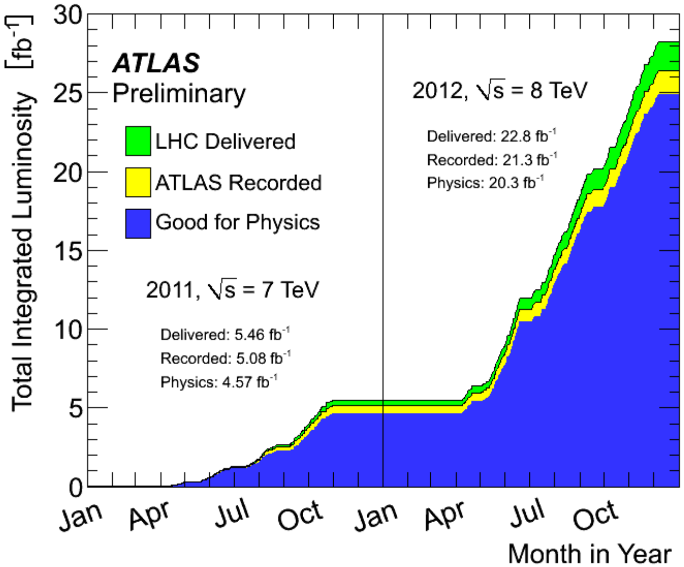
* Exact mechanism of “knee” is still under investigation

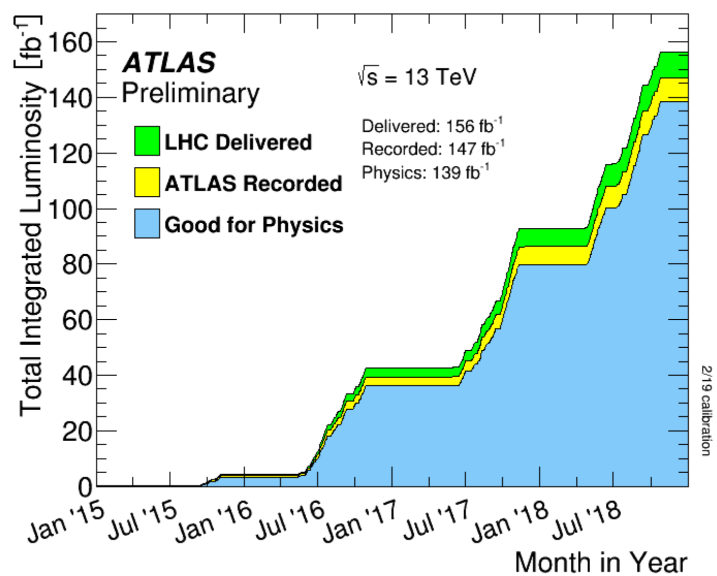
■ Luminosity Levelling

- Too high instantaneous luminosity is harmful...
  - Detector: too high data rate
- The luminosity is intentionally reduced to the maximum allowed range
  - Beam lifetime is extended



■ Number of Higgs Bosons





	7 TeV [1]	8 TeV	13 TeV [3]
ATLAS lumi.	4.57 fb^{-1}	20.3 fb^{-1}	139 fb^{-1}
ggF	15.11	19.24	48.52
VBF	1.222	1.579	3.779
WH	0.5770	0.7027	1.369
ZH	0.3341	0.4142	0.9404
ttH	0.08611	0.1290	0.5065
bbH	0.1555	0.2030	0.4863
Total	17.49	22.27	55.60
# of Higgs bosons	79,906	452,040	7,728,539

[1]:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt7TeV

[2]:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV

[3]:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV

Run-2 Summary

ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collision physics runs with 25 ns bunch-spacing at $\sqrt{s}$=13 TeV for the full Run-2 period (between July 2015 – October 2018), corresponding to a delivered integrated luminosity of 153 fb^{-1} and a recorded integrated luminosity of 146 fb^{-1}. Runs with specialized physics goals are not included. Dedicated luminosity calibration activities during LHC fills used 0.6% of recorded data in 2018 and are included in the inefficiency. Trigger-specific data quality problems (0.4% inefficiency at Level-1) are included in the overall inefficiency. When the stable beam flag is raised, the tracking detectors undergo a so-called "warm start", which includes a ramp of the high-voltage and turning on the pre-amplifiers for the Pixel system. The inefficiency due to this, as well as the DAQ inefficiency, are not included in the table above, but accounted for in the ATLAS data taking efficiency.

Todays count of disabled elements

		ECC	Barrel	ECA	Total
# of disabled	Modules	21	12	9	42
	Chips	11	60	12	83
	Strips	4854	5927	4114	14895
	Active(%)	**97.46**	**99.01**	**98.72**	**98.57**

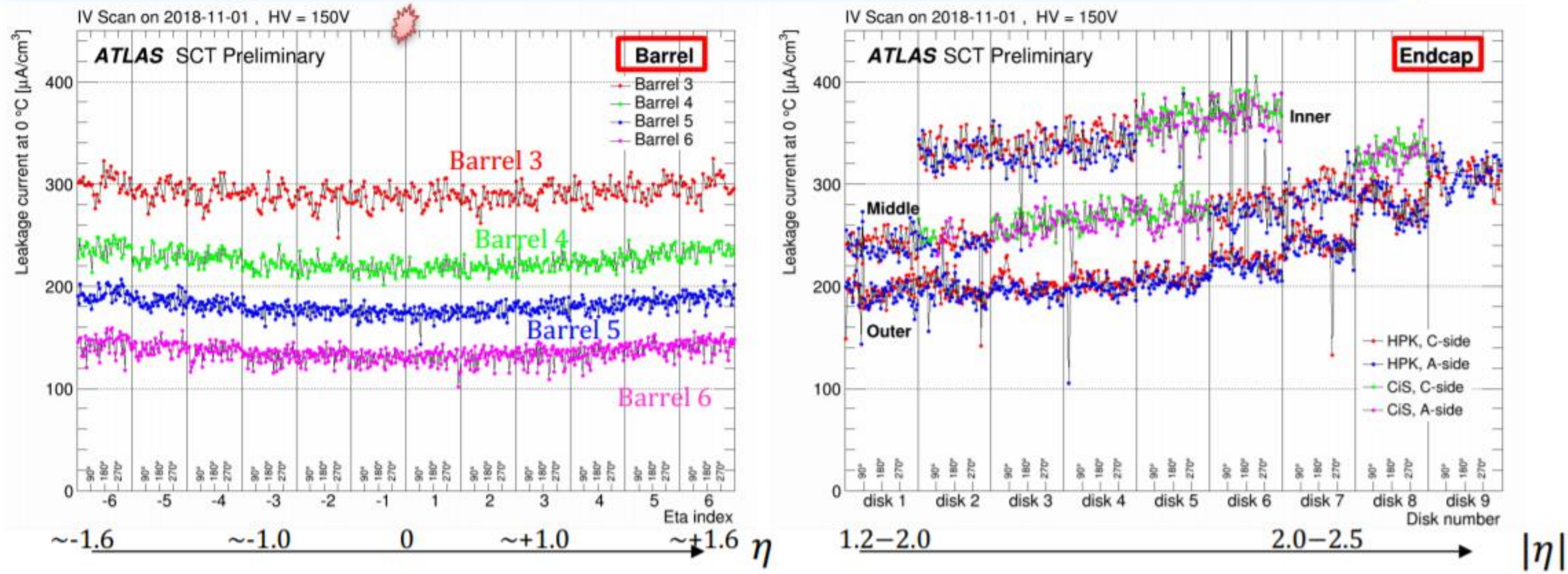
← SCT today > 98% active!!

[K. Mochizuki, presented at workshop for radiation effects in the LHC experiments]

■ Leakage current

Leakage current

Université de Montréal



- ➢ Normalized leakage current in barrel (left) and endcaps (right)
- ➢ Problem of temperature normalization now overcome in the endcaps
  → good agreement of leakage current distribution between A & C endcaps
- ➢ Quite uniform distribution
  Higher leakage current in higher eta

Kazuya Mochizuki 11 February 2019

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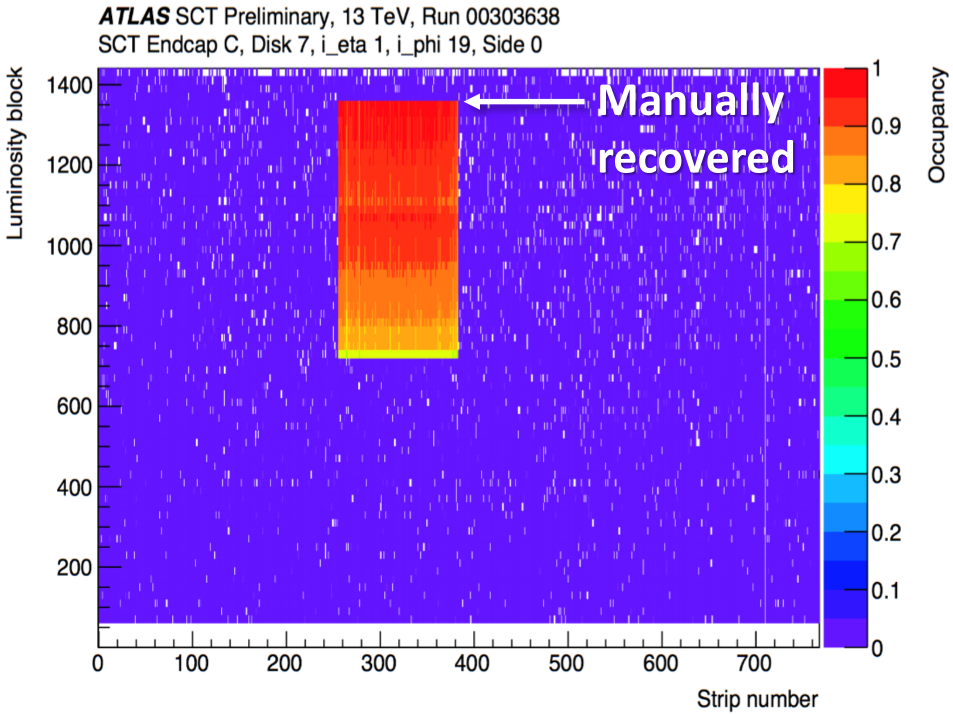
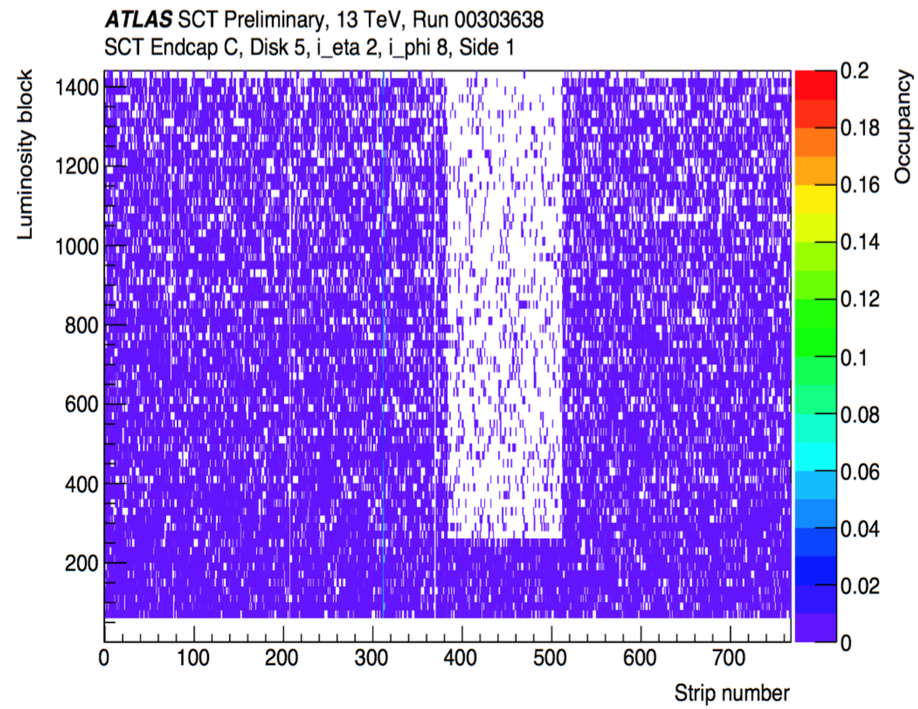
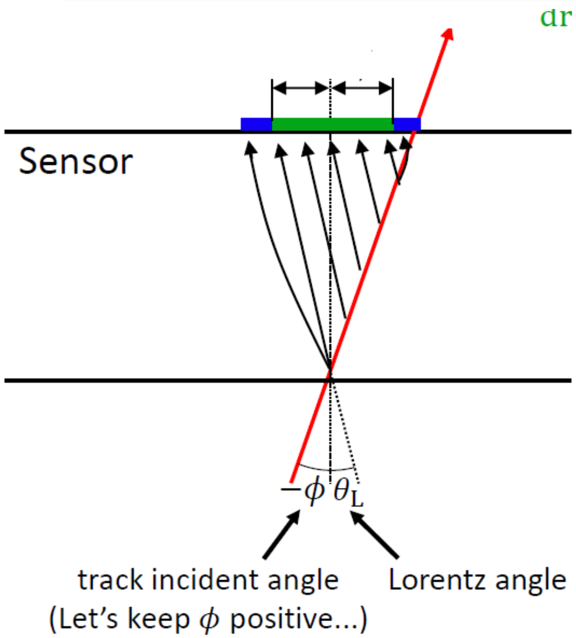
[K. Mochizuki, presented at workshop for radiation effects in the LHC experiments]

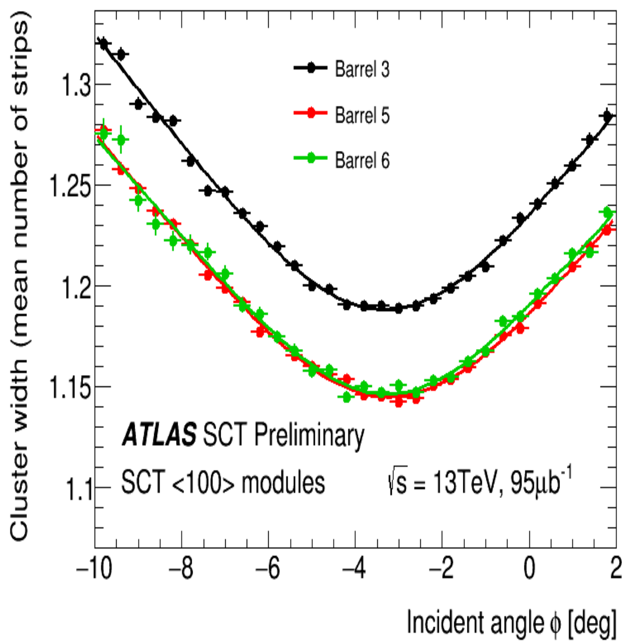
■ SEU without GR

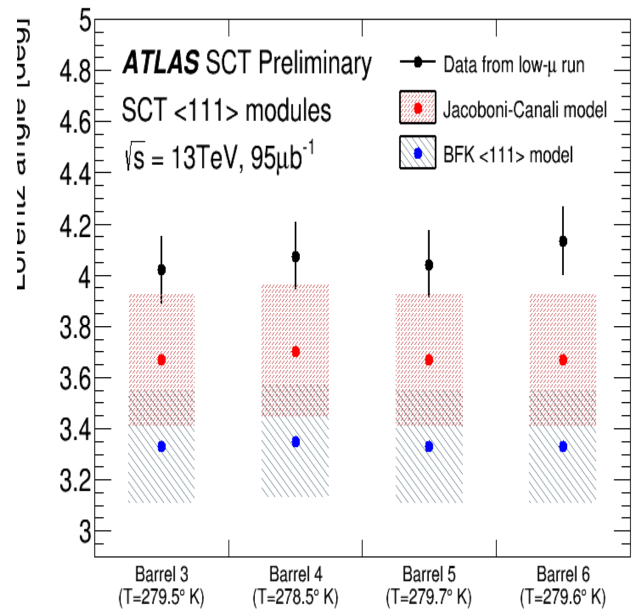




Lorentz Angle







- Deflection of charge drift due to the Lorentz force
- Important to correct in order to obtain precise points of charged tracks
- Also a good indicator of the inner electric field
- Study using 2018 is ongoing