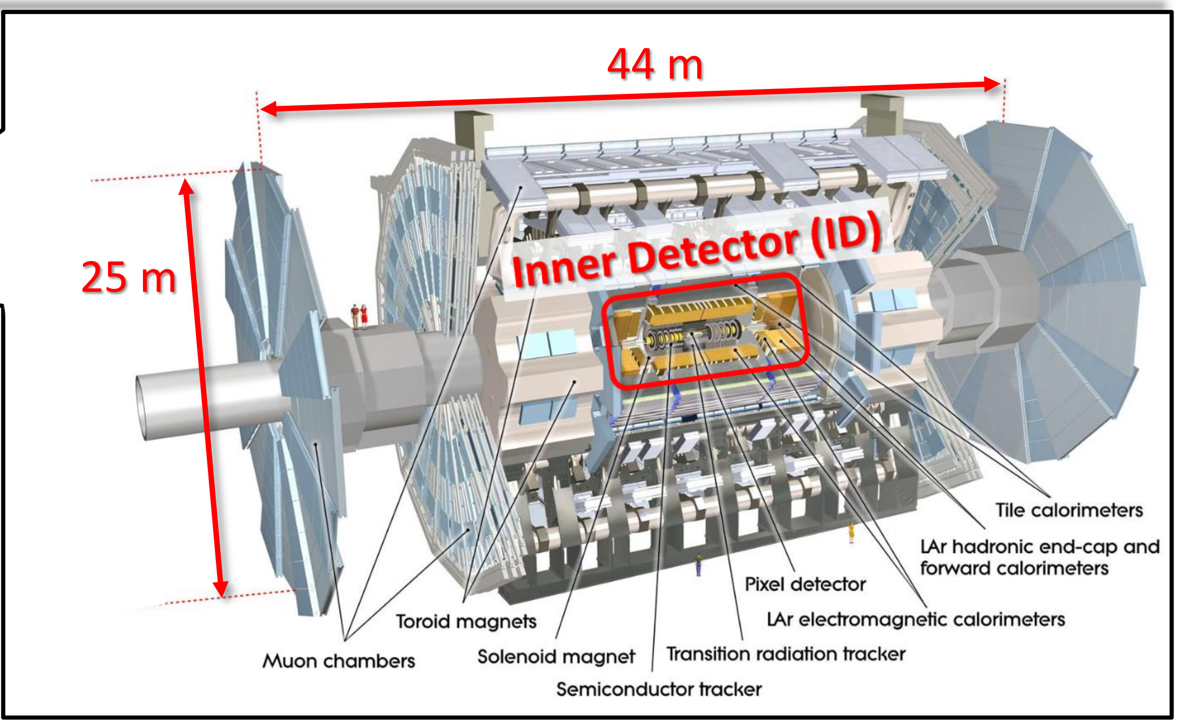
The operational experience, challenges and performance of the ATLAS SCT during LHC Run-2

14 October 2019, VERTEX 2019

Shigeki Hirose (Uni-Freiburg)

On behalf of the ATLAS Collaboration

ATLAS Experiment

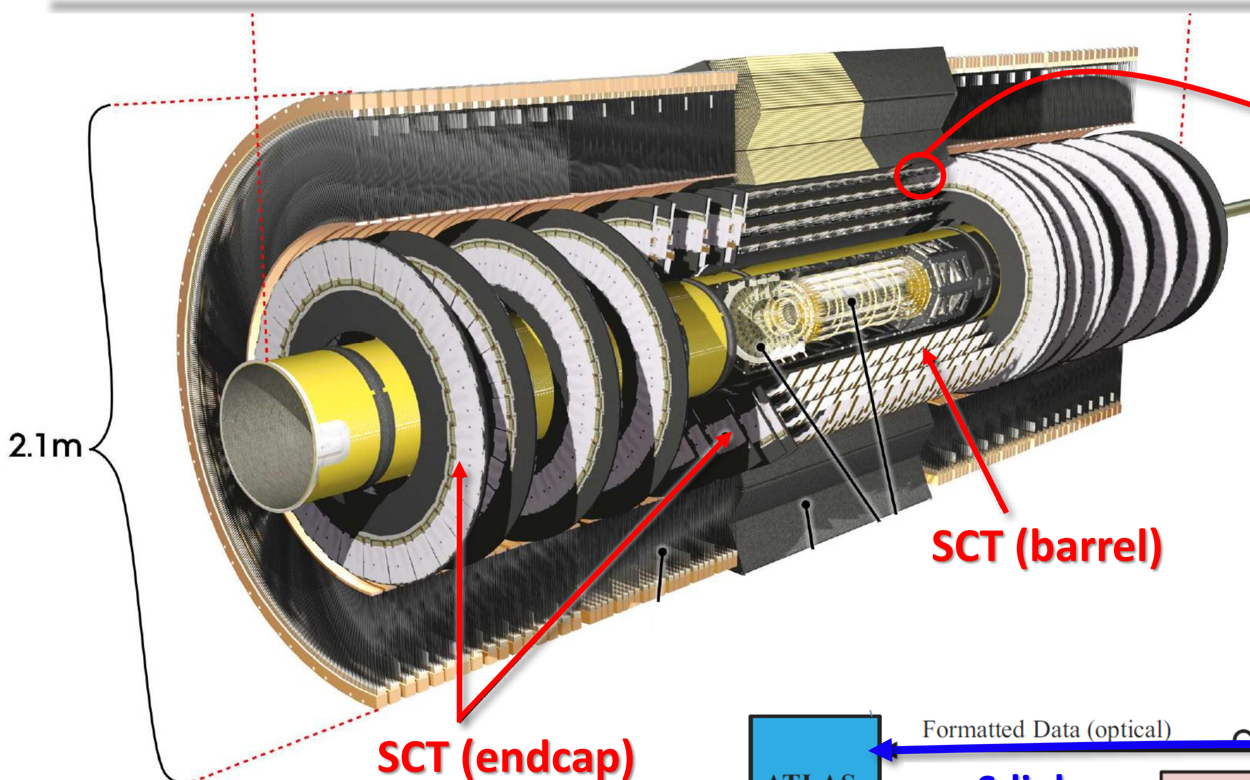


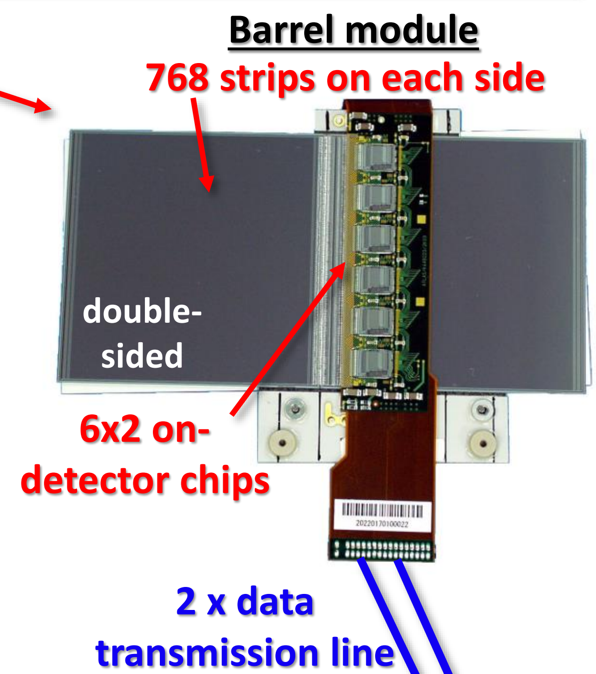
- Circumference = 27 km
- pp collision at $\sqrt{s}$ = 13 TeV
- Bunch per 25 ns

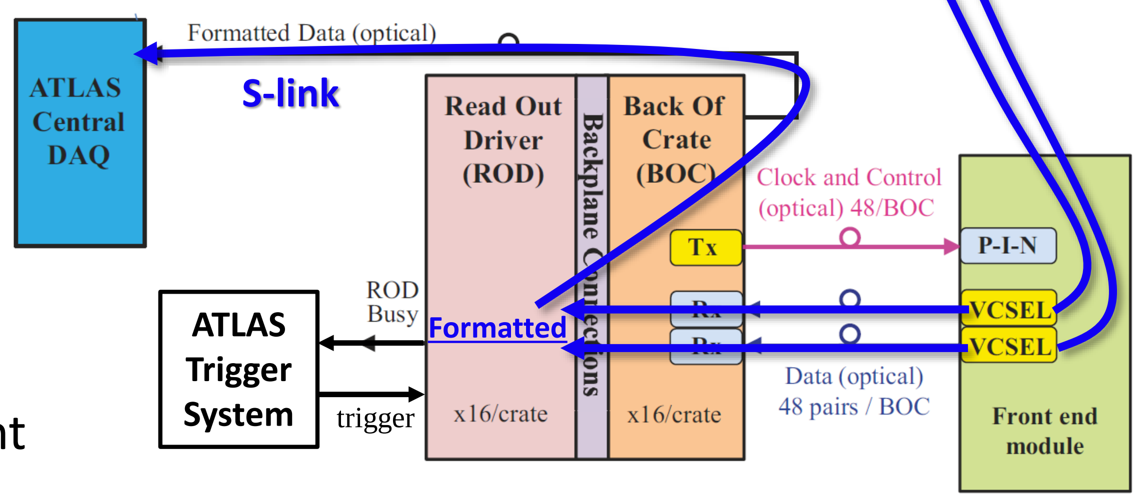
- ATLAS detector
  - Targets high-p_T objects from decays of massive particles
  - Messy environment of pp collisions due to QCD

    → Track finding performance of ID is essential for all physics analyses
- Semiconductor Tracker (SCT): one component of ID

SemiConductor Tracker (SCT)

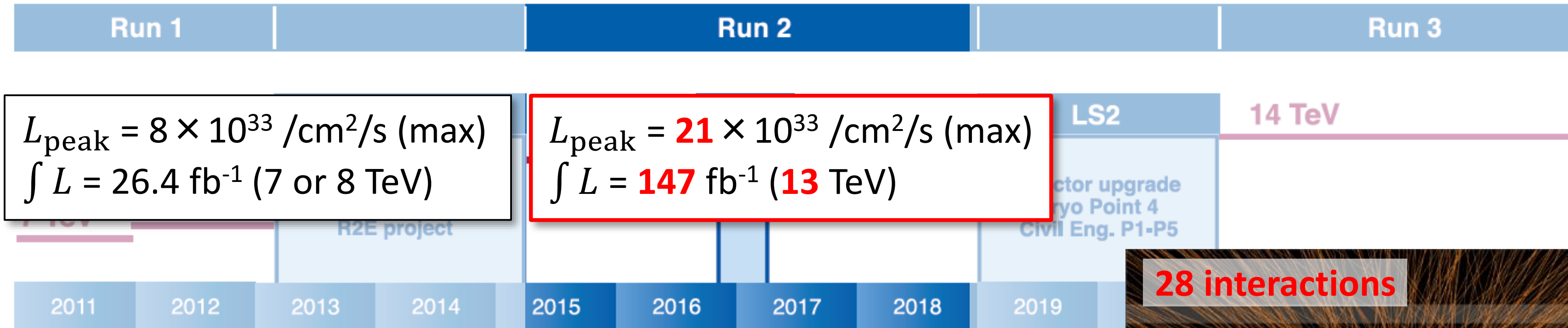






- 4 layers (barrel) and 9×2 disks (endcaps)
- > 6M channels
  - Stable system is important

■ LHC Run−2: 2015 – 2018

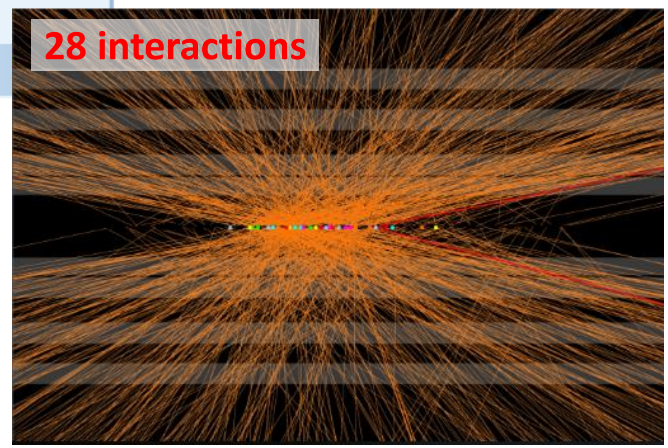


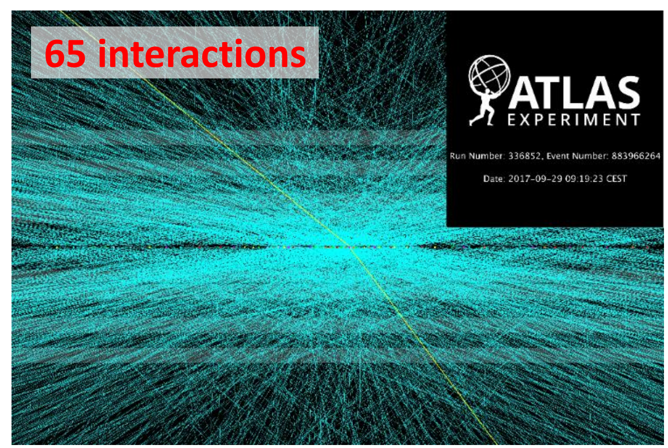
L_{peak} = 8 × 10^{33} /cm²/s (max)
$\int L$ = 26.4 fb^{-1} (7 or 8 TeV)

L_{peak} = **21** × 10^{33} /cm²/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: $5\times10^5 \rightarrow 8\times10^6$
  - 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. Hit efficiency
   - Low efficiency of SCT makes track finding difficult in high pileup events
3. Radiation hardness
   - Design: up to 700 fb^{-1} @ 14 TeV collision (currently 184 fb^{-1} @ $\leq$ 13 TeV)

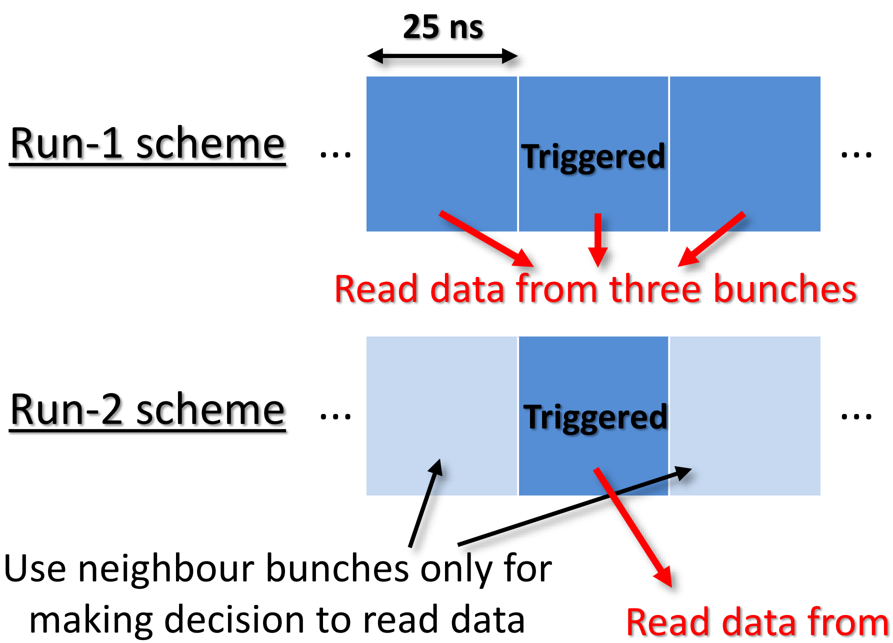
   → Enough margin, but the radiation damage was getting visible

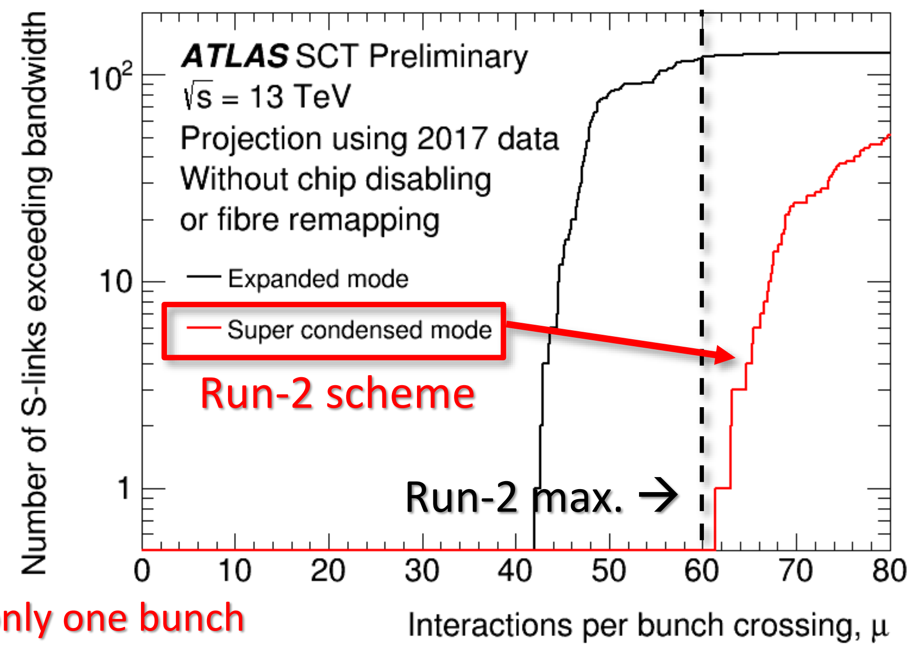
- Operation of SCT during Run-2
  - SCT joined the ATLAS data-taking for **99.85%** of the time
  - **99.7%** of the SCT data was good quality for physics
  - As of end of Run-2, **98.6%** of elements are active

SCT has maintained high performance in the severe Run-2 condition!

Data Bandwidth

- Expansion of 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

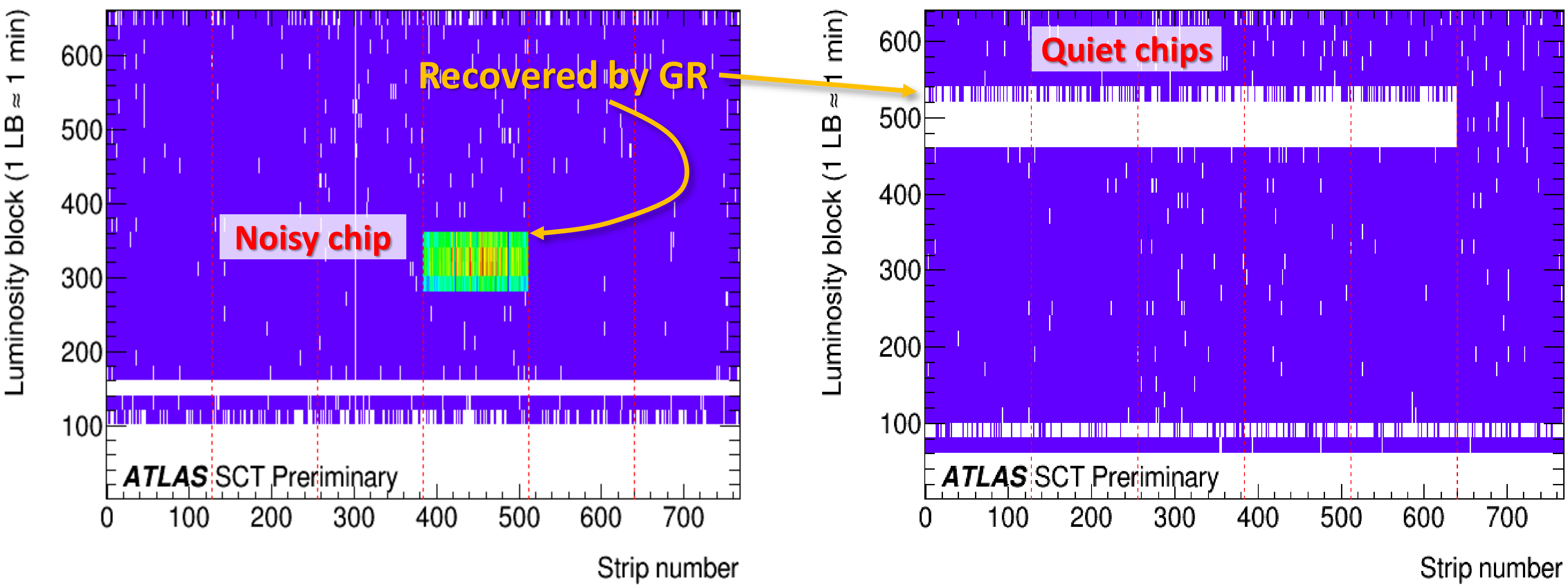




All S-links are within the bandwidth up to μ = 60

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 1.7 sec. deadtime)

GR is effective to clear problematic chips during a run

Hit Efficiency (1)

- SCT definition of hit efficiency

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

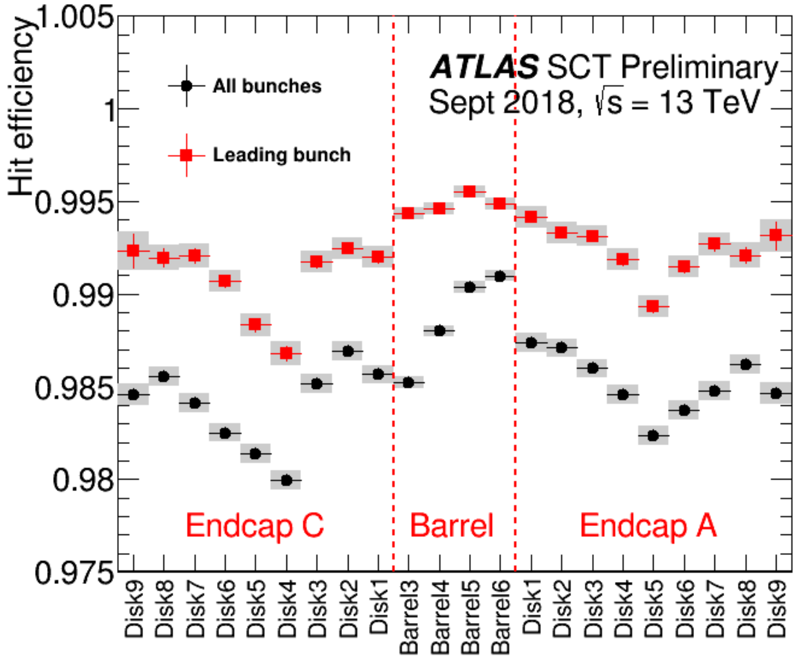
A track creates a hit

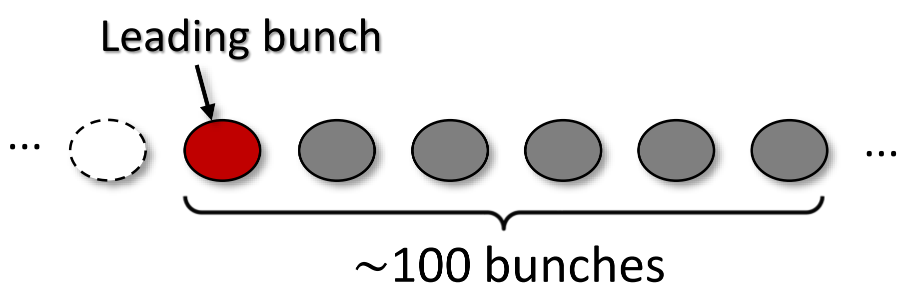
A track passes the sensor but no hit is found

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

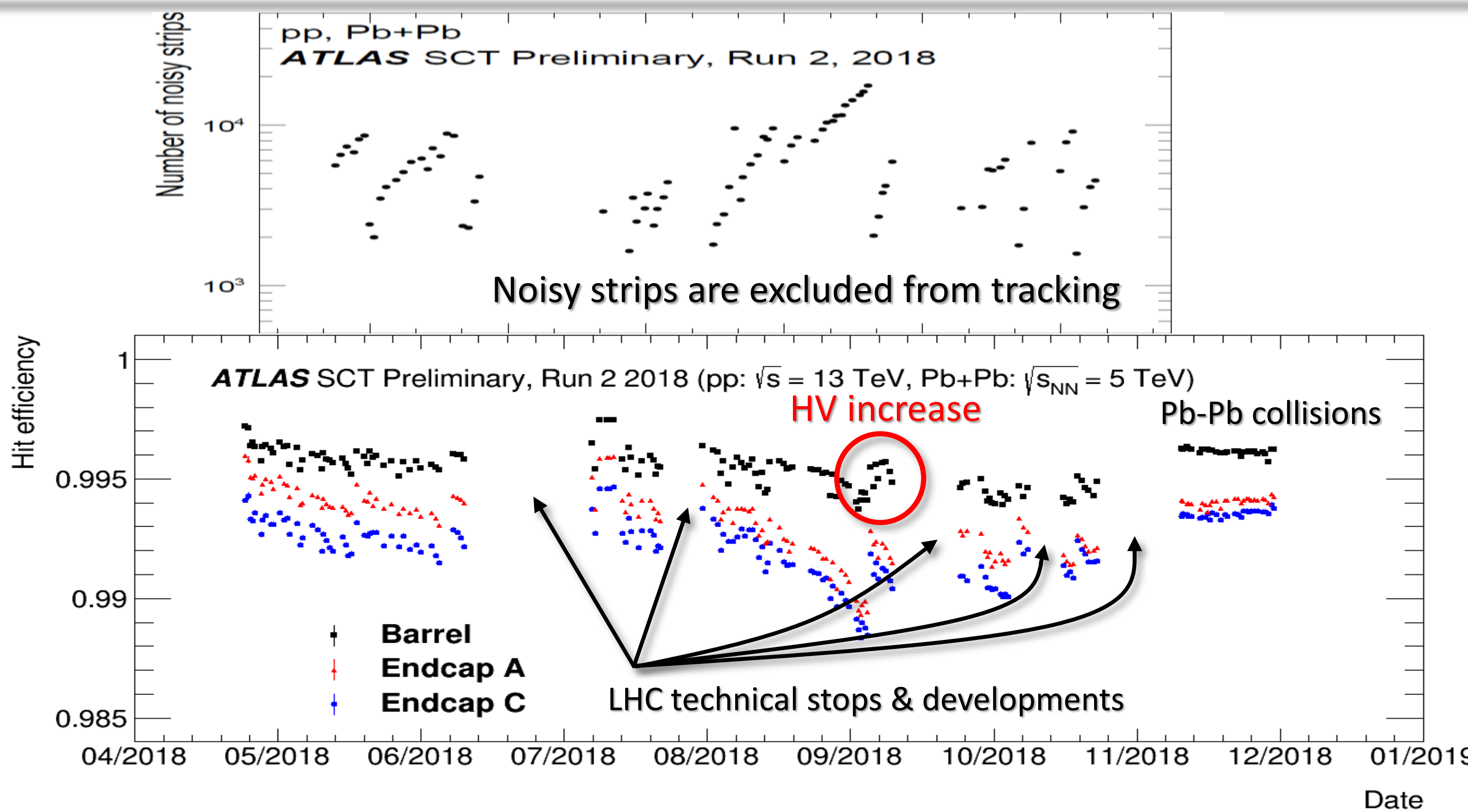
- Typically the efficiency is > 99%
  - The intrinsic efficiency can be measured using the leading bunch
  - "No hit in the previous bunch" is required

  → Efficiency from all bunches is lower by ~1% (negligible impact for tracking)





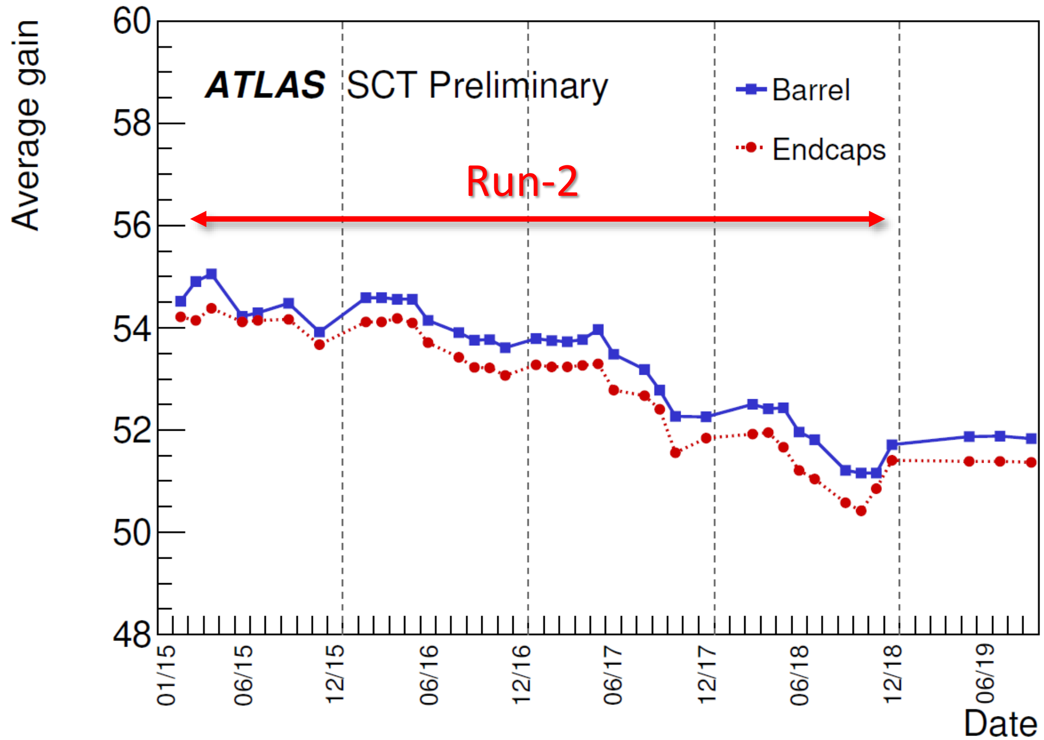
■ Hit Efficiency (2)



- Hit efficiency >99% was kept for almost entire Run-2
  - Gradually drops due to threshold shifts by radiation
  - → Periodical calibration to reset threshold is very important!
- In 2018, HV was partly increased: 150 V → Up to 250 V

■ Detector Calibration

- Detector calibration is periodically performed
  - Reset settings such as threshold
  - Understand the sensor condition
  - Disable bad elements etc.
- Effects of radiation and aging gradually appear
  - Preamp gain decreased by ~5%



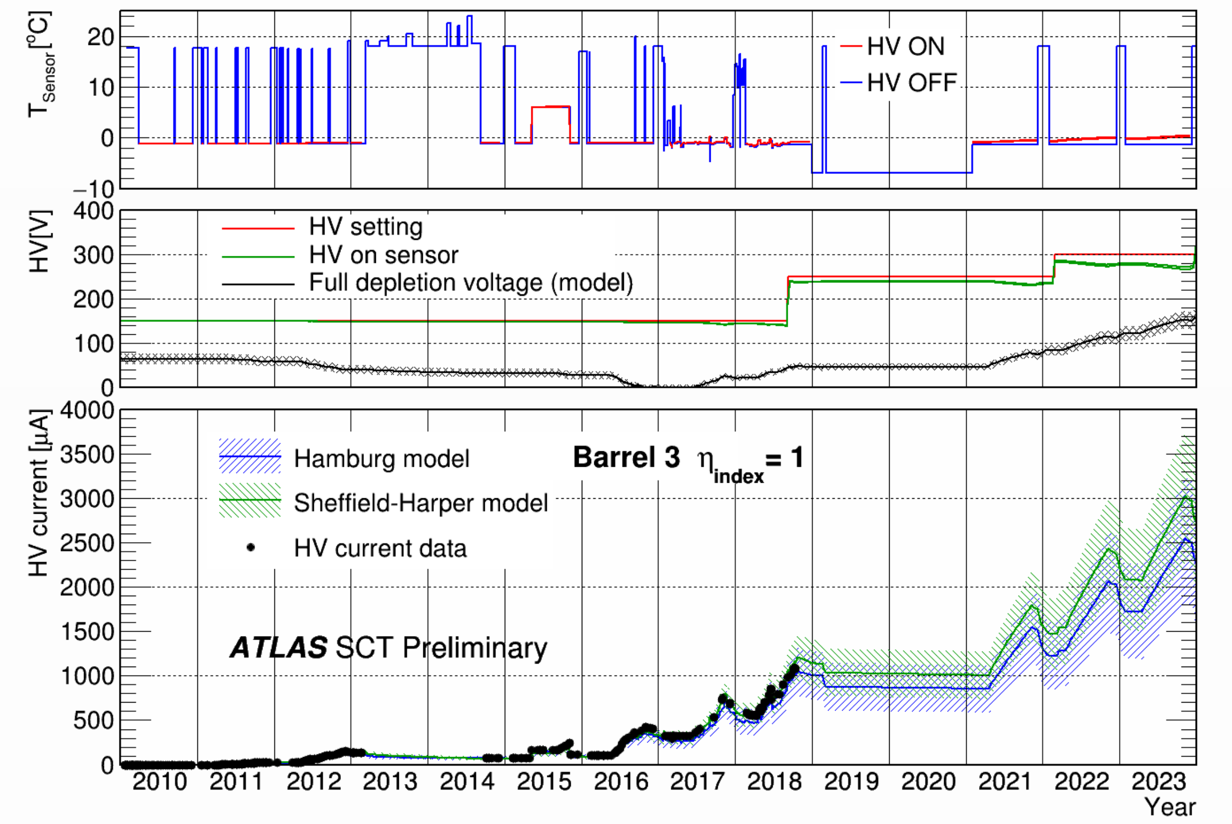
■ Radiation Damage on Sensors

- The SCT performance was kept high over Run-2
  - Impact of radiation damage on data quality was minor
    (More careful monitoring procedure is needed in future)

- Potential crucial problems in Run-3 (2021 - 2023)
  - Larger leakage current (I_{leak})
  → Much power dissipation, that may finally cause thermal runaway
  - Higher full-depletion voltage (V_{FD})
  → If V_{FD} exceeds maximum allowed HV, full depletion cannot be achieved anymore

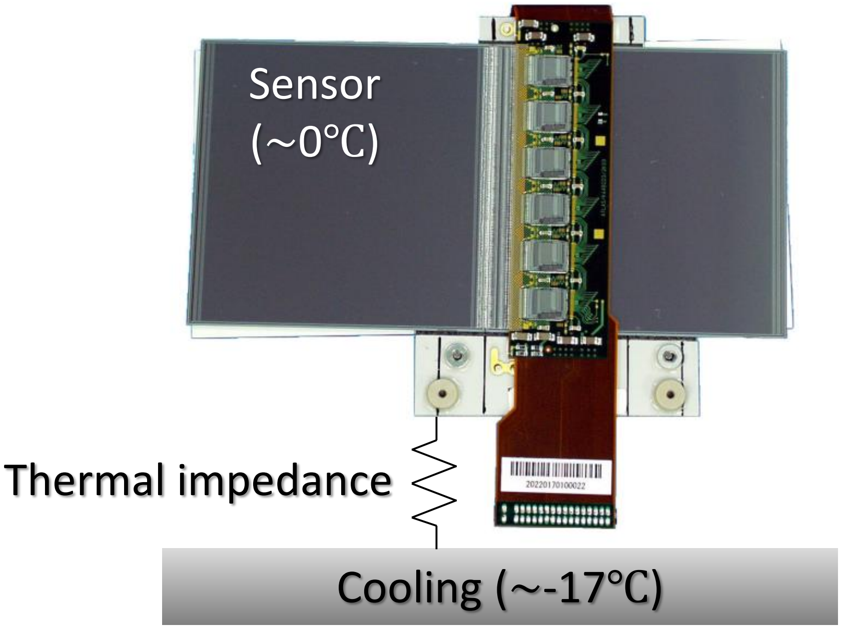
- Dedicated measurements to understand the radiation damage
  - I_{leak} monitoring
  - HV dependence of various quantities such as noise, efficiency, ...
    → Estimate V_{FD}

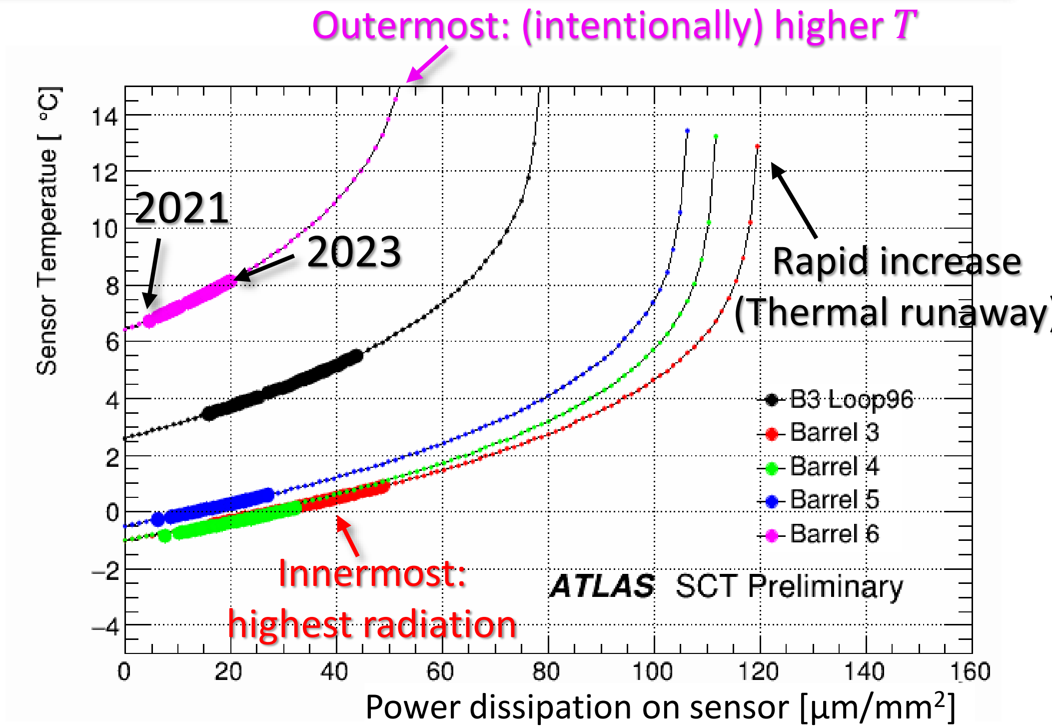
■ Leakage Current



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

■ Thermal Performance



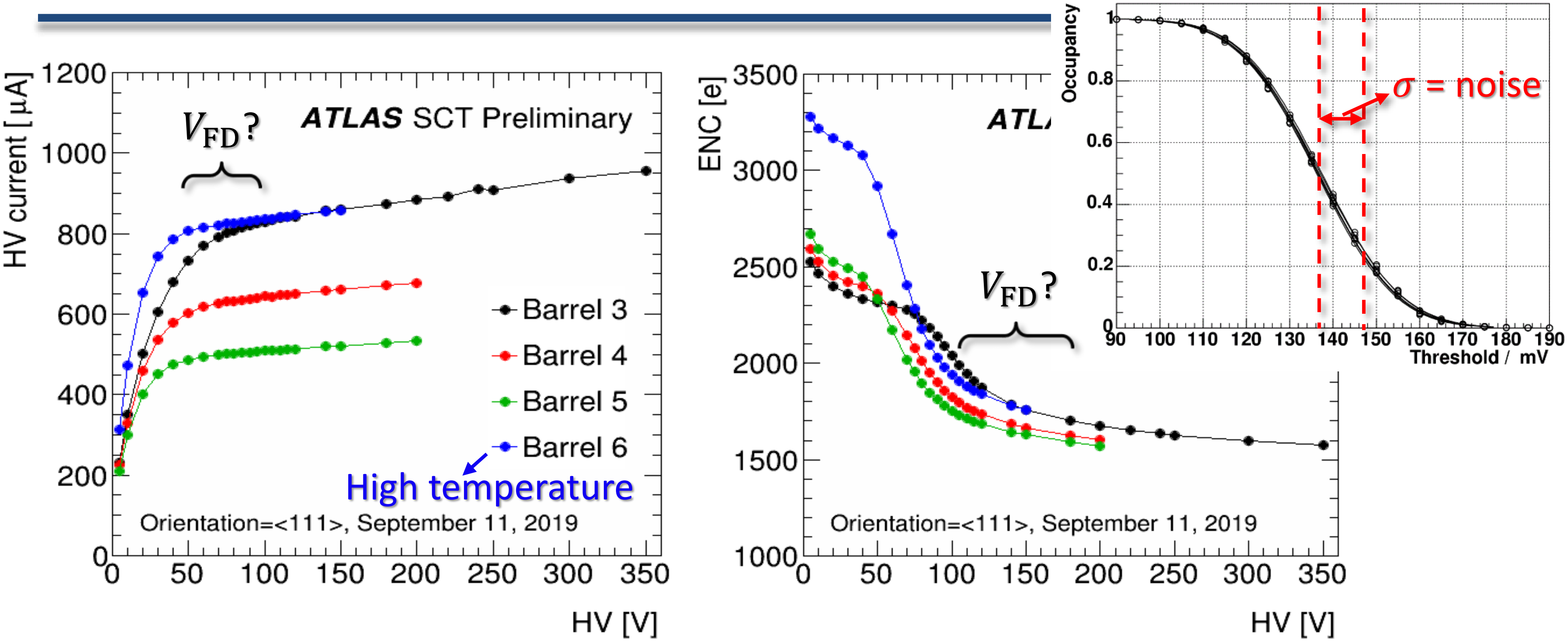


- Sensor temperature evolution
  - Higher I_{leak} → More heat generation → Further I_{leak} → ...
- Predicted sensor temperature indicates enough headroom
  - Realistic operation strategy for Run-3 was assumed

Safe operation is expected until the end of Run-3

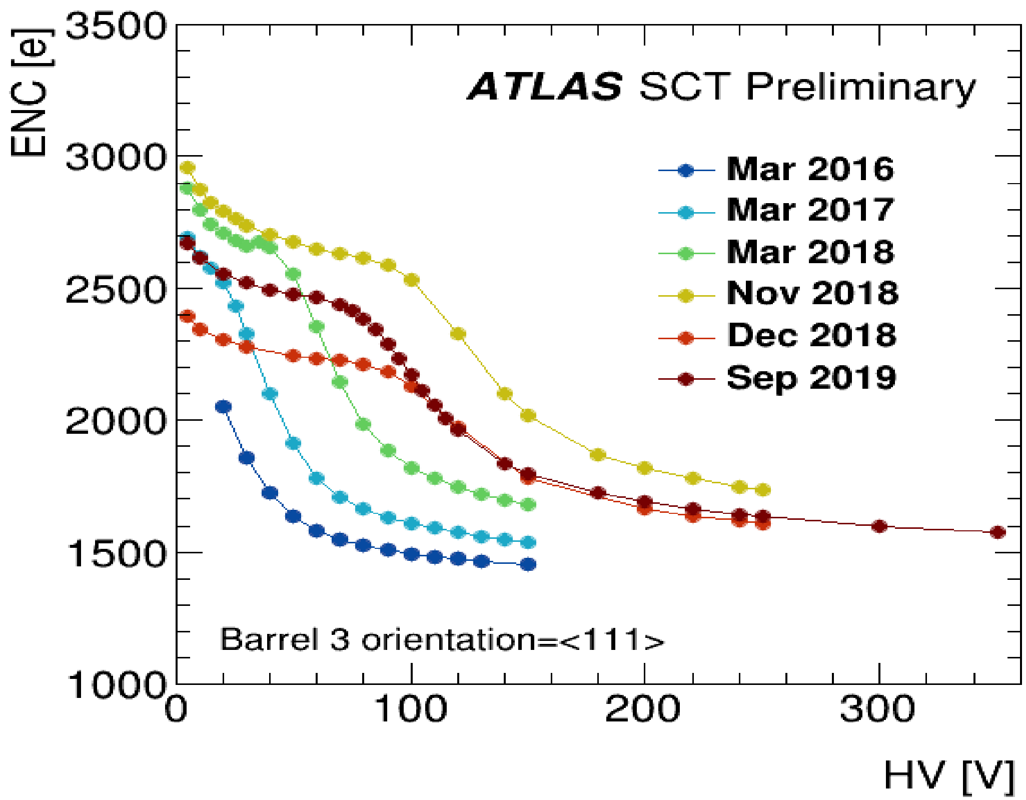
■ I–V Measurement

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



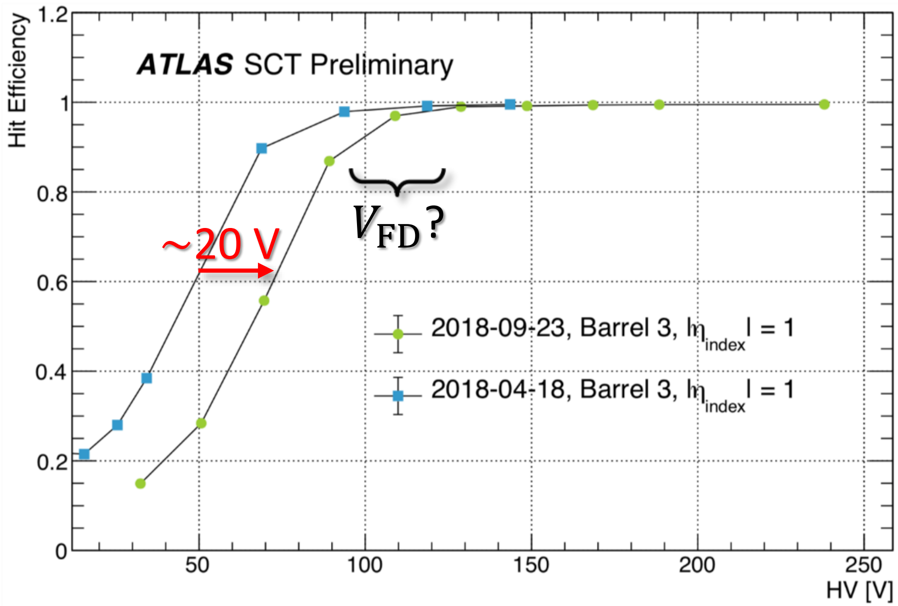
- Measure leakage current and noise vs HV
  - After reaching HV = V_{FD}, leakage current and noise become plateau
  - However the transition is not very sharp
- V_{FD} estimation from the I-V measurement
  - Rough estimate is 50-100 V

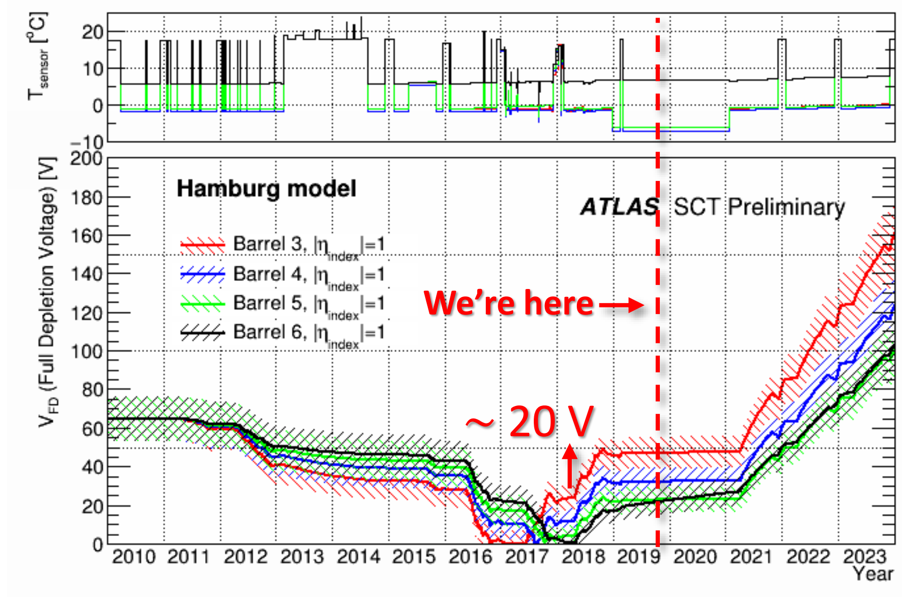
■ Evolution of Noise and Type-Inversion



- The knee structure appears after type inversion
  - SCT uses p^+-on-n sensor; becomes p^+-on-p after type inversion
- All modules have been type-inverted
- $V_{\mathrm{knee}} \propto V_{\mathrm{FD}}$ → Annealing is very clear after the end of Run-2

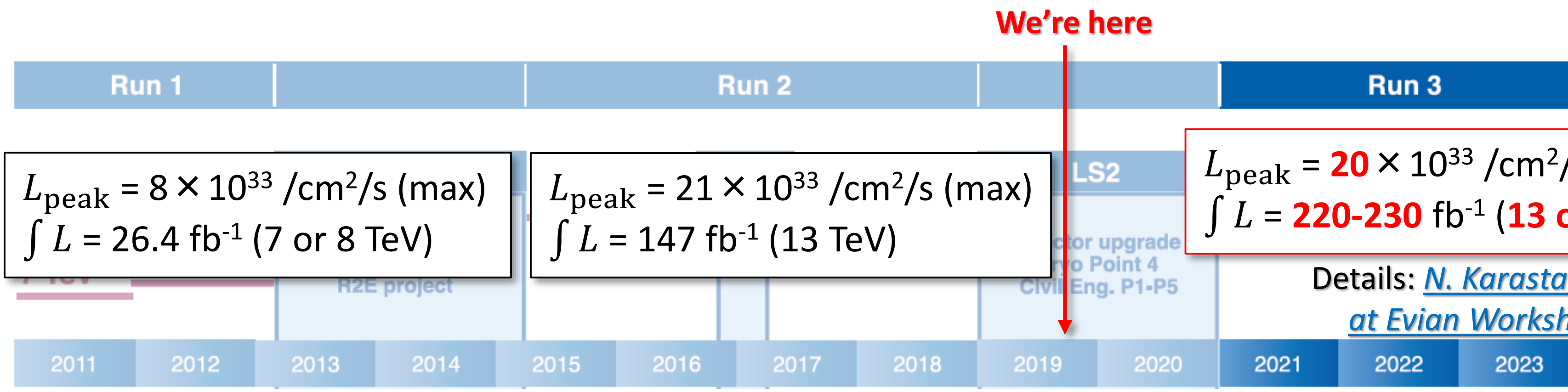
■ Efficiency vs HV





- 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; all modules were tested up to 500 V in QA

■ Towards Run–3: 2021 – 2023



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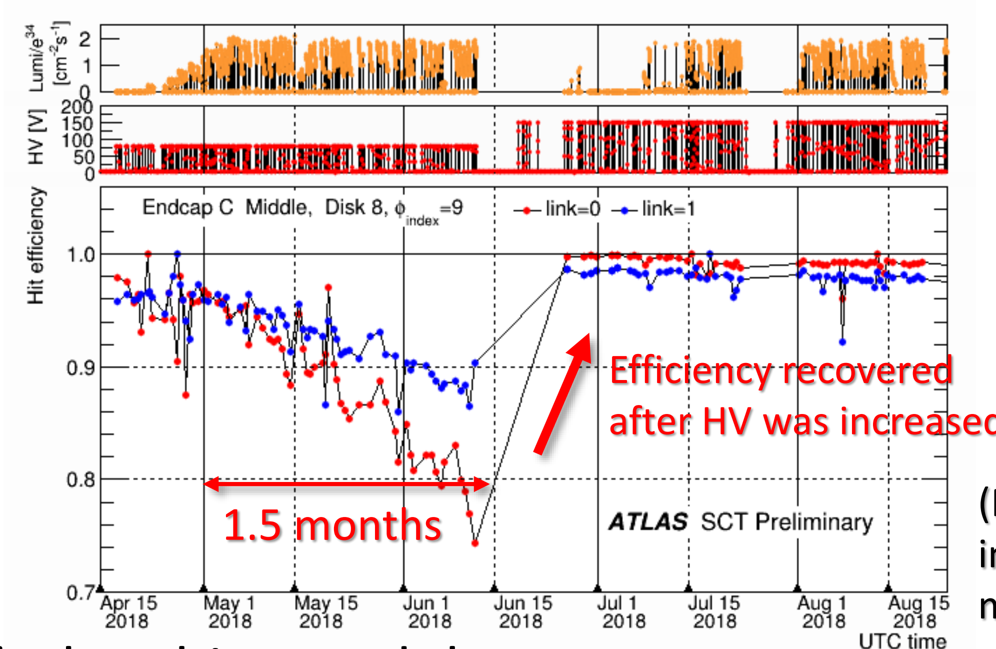
$\int L$ = 147 fb^{-1} (13 TeV)

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*

- Conditions will be similar to Run-2
- No major upgrade on SCT
  - The very robust and stable system has been already established because of a number of improvements
  - Performance monitoring will be more important

■ Preparation for Run-3



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

- One case of a low-bias module
  - Efficiency was slowly dropping (recovered after increase of HV)
- Important lesson: efficiency drop may happen in the time scale of O(months)
  - Slow enough to make it difficult to catch, but fast enough to possibly impact on Run-3 operation
  - Sophisticated monitoring & quick diagnostics tools are under development

■ Summary

- ATLAS SCT operation in Run-2: 2015 - 2018
  - Successful operation with high performance
  - Effects from radiation damage were getting important; we increased the operational HV for the first time (150 V → up to 250 V)
  - SCT provides an interesting opportunity for various studies on radiation-damaged silicon sensors

    → More results will be published soon

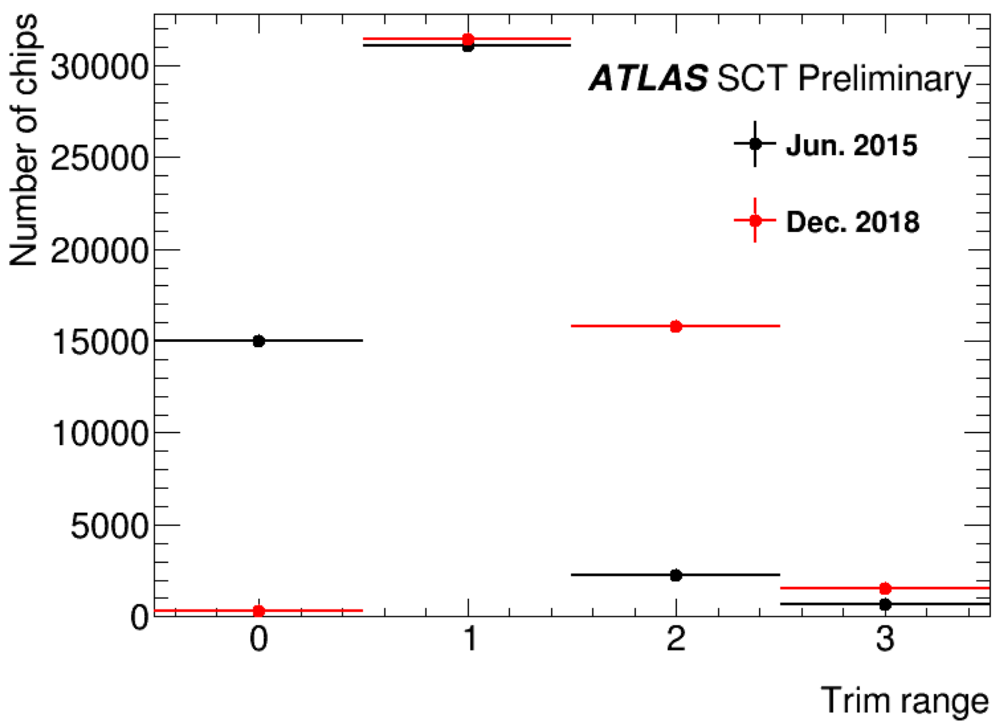
- For Run-3: 2021 - 2023
  - No serious operational problems are foreseen
  - Total radiation dose will be more by a factor of ~2

    → More detailed performance monitoring will be important

SCT will continue providing high quality data in ATLAS Run-3

■ Other Indicator of Aging

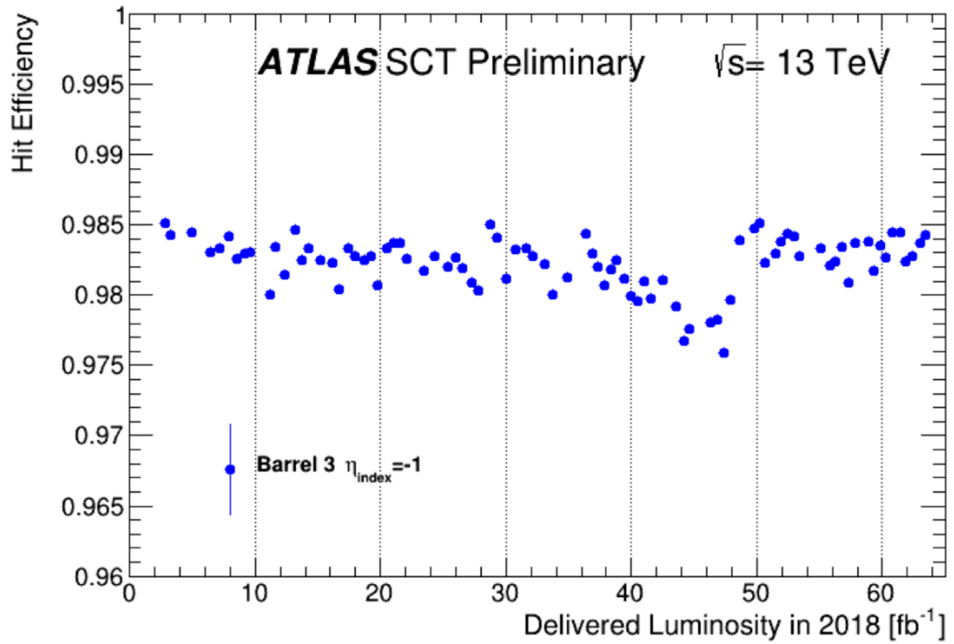
- Threshold setting
  - Overall threshold is set by 8-bit DAQ (common for 128 strips in a chip)
  - 4-bit Trim DAQ finely adjusts the strip-by-strip variation (independent for strips)
  - 2-bit trim range determines the step size of Trim DAQ (0 for 4 mV, 1 for 8 mV, ...)



Higher trim range in 2018 indicates larger strip-dependent variations due to radiation damage

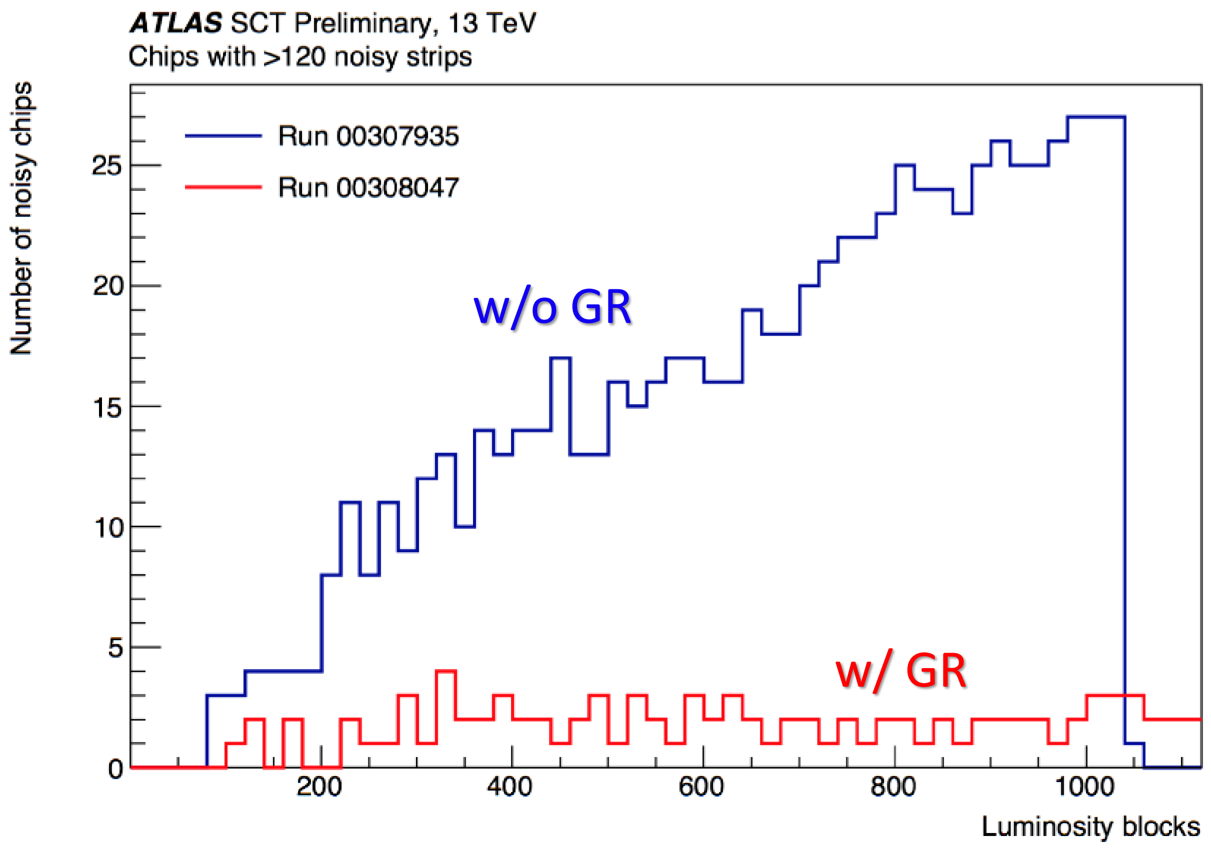
■ Efficiency Drop in 2018

- 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

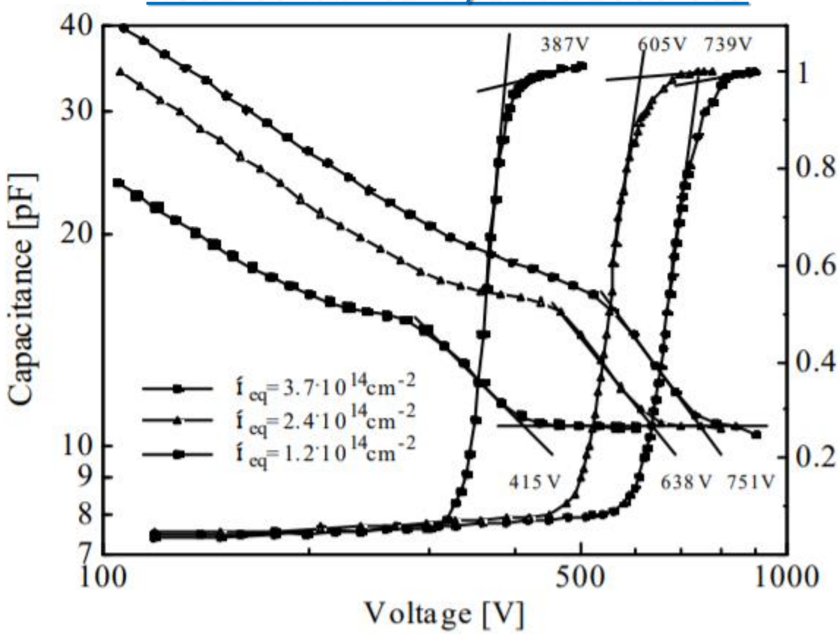


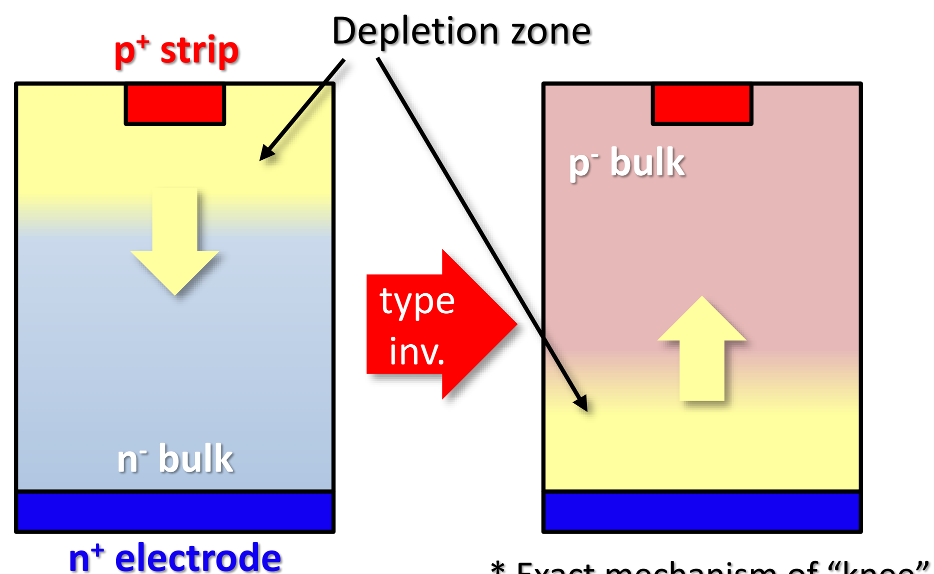
■ Type-inversion and "knee"

- 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

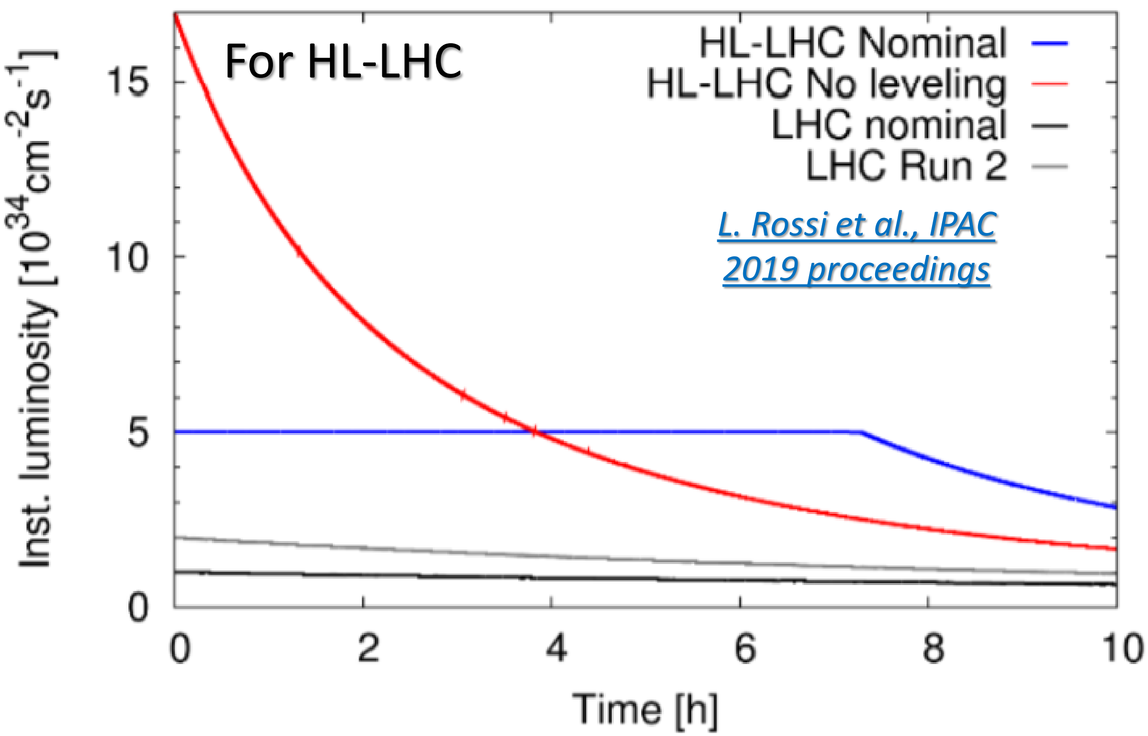




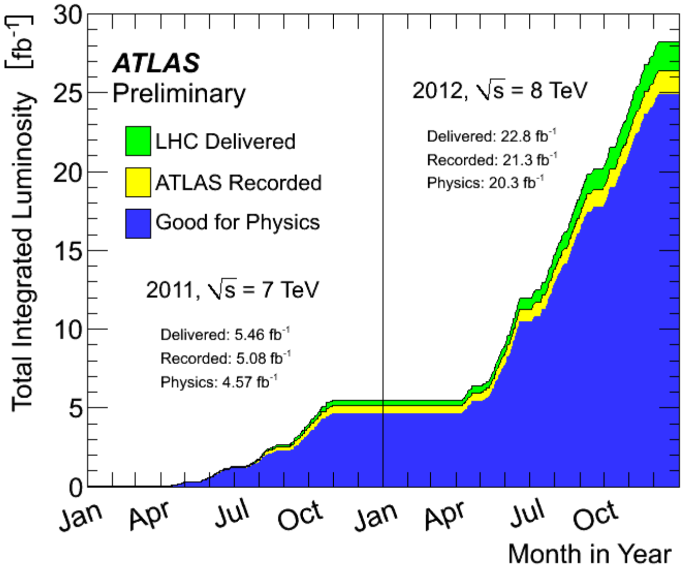
* Exact mechanism of "knee" is still under investigation

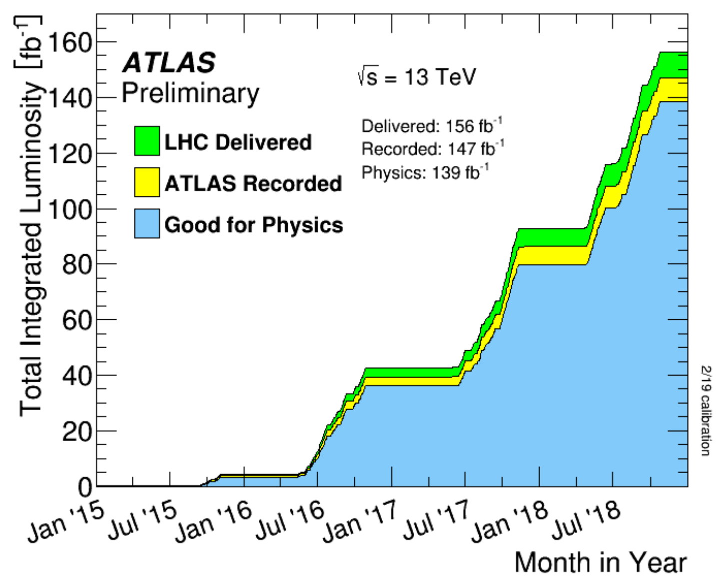
■ Luminosity Levelling

- 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**

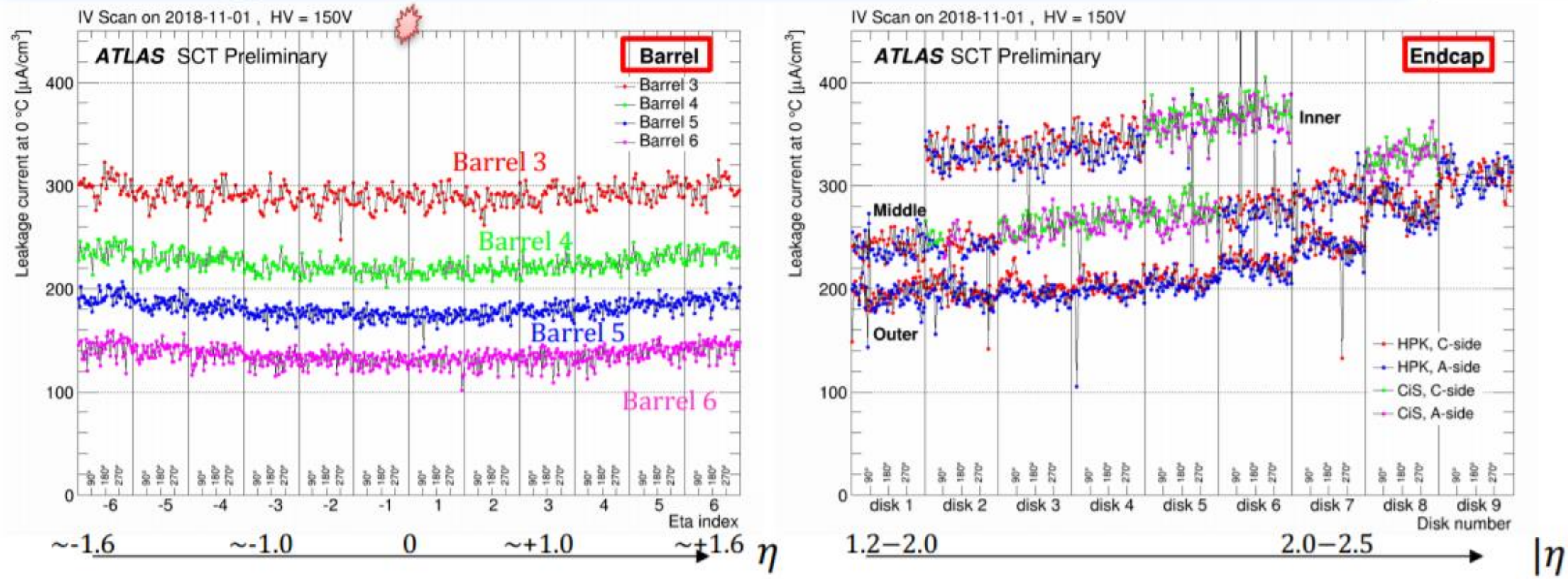
← SCT today > 98% active!!

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

■ Leakage current

Leakage current

Université de Montréal



Kazuya Mochizuki 11 February 2019

- ➢ 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

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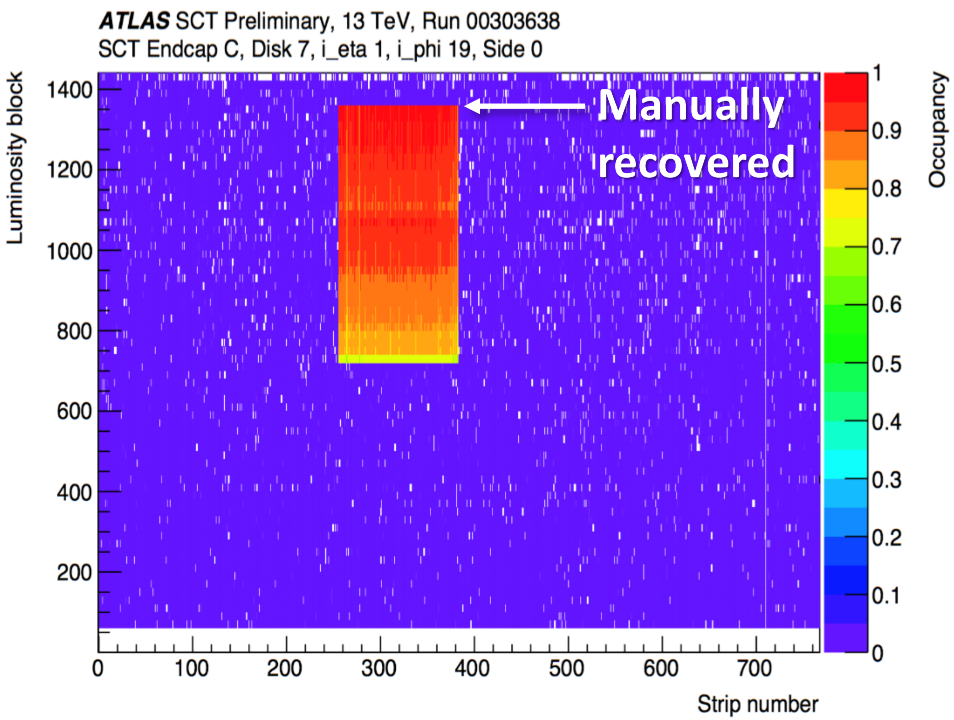
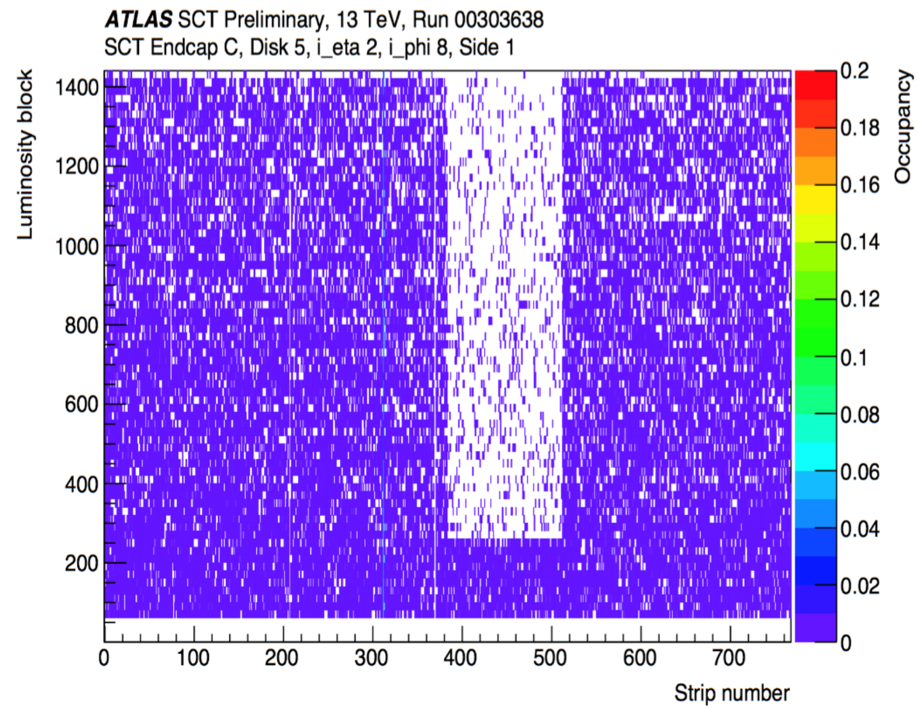
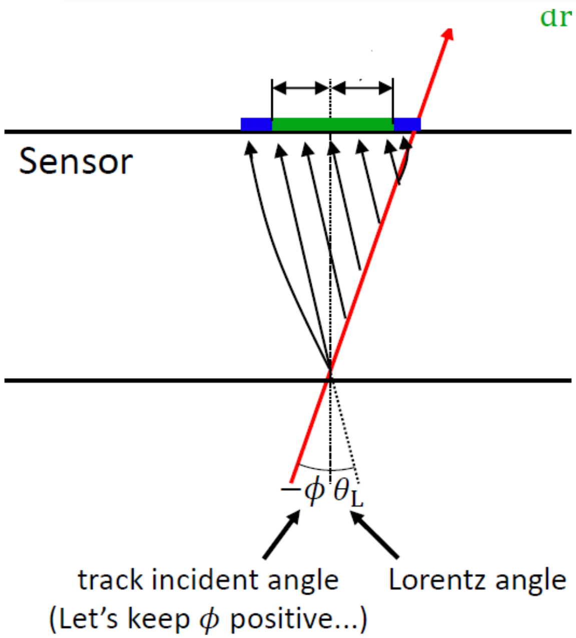
K. Mochizuki, presented at workshop for radiation effects in the LHC experiments

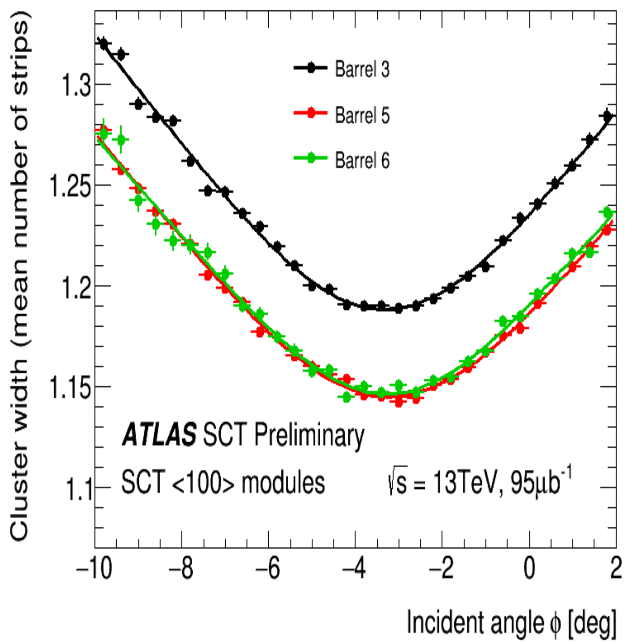
■ SEU without GR

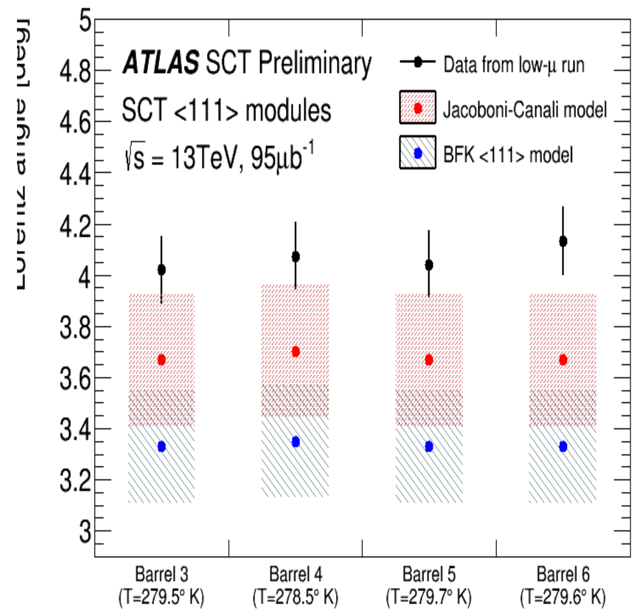




Lorentz Angle







- 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