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ATLAS EXPERIMENT

Operational Experience and Performance with the ATLAS Pixel detector at the LHC

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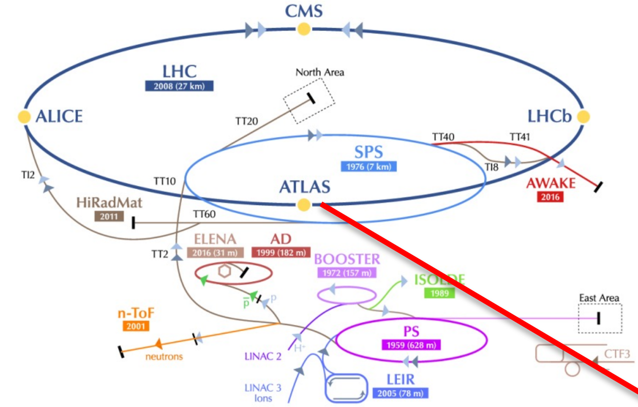
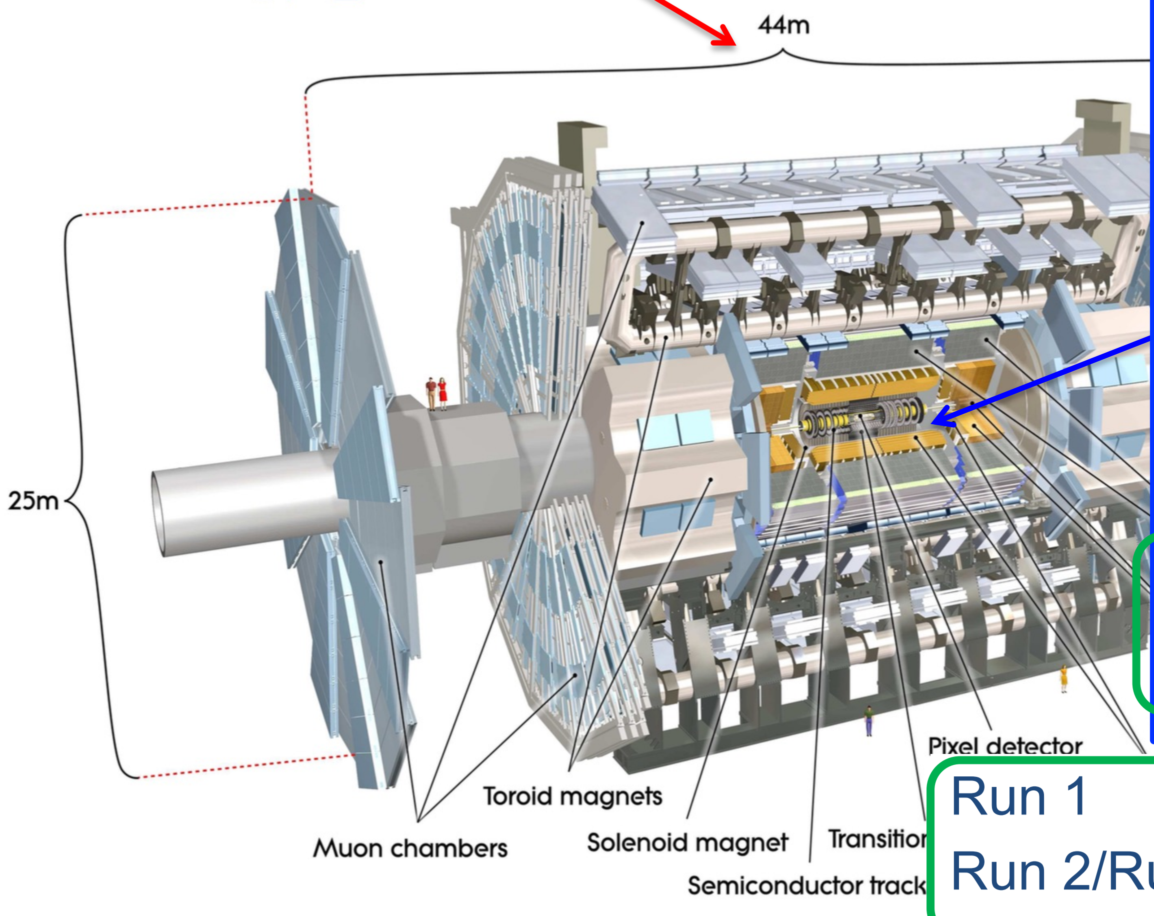
on behalf of the ATLAS Collaboration

11th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (Pixel 2024), 18th – 22nd November 2024,

Collège Doctoral Européen, University of Strasbourg, France.

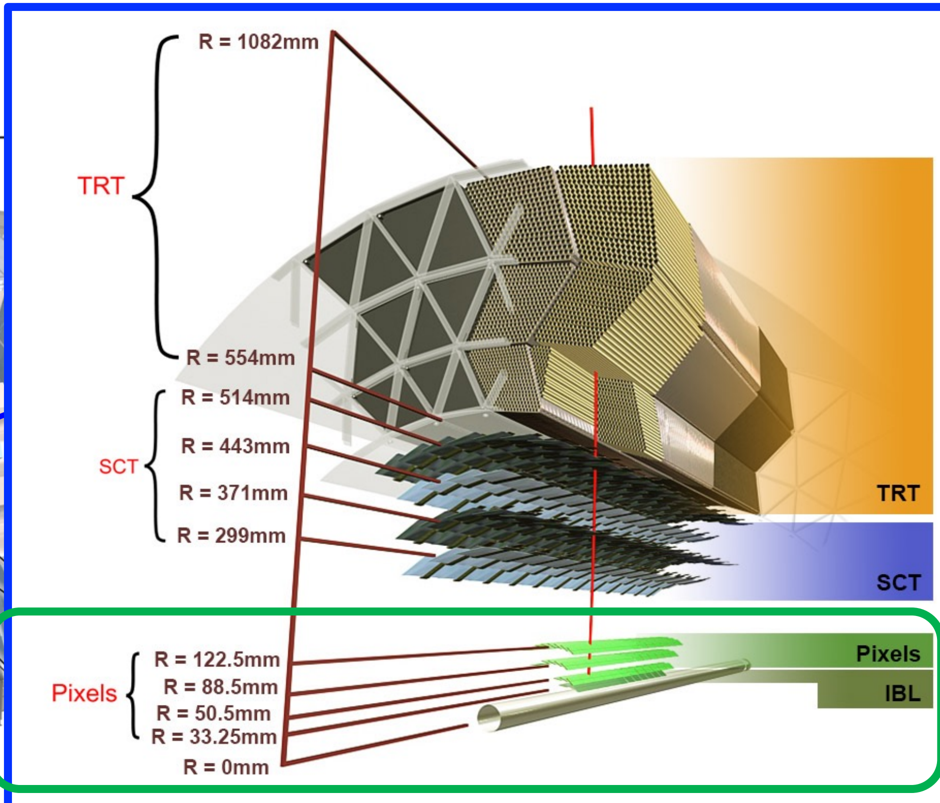
The ATLAS detector @ LHC





ATLAS **Inner Detector (ID)** tracker

- **Pixel Detector**
- Silicon Strip Detector (SCT)
- Transition Radiation Tracker (TRT)



Run 1 : 2010 - 2012 ➔ 3 pixel layers
Run 2/Run 3 : 2015 - 2024 ➔ 4 pixel layers

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The ATLAS Pixel (+ IBL) detector

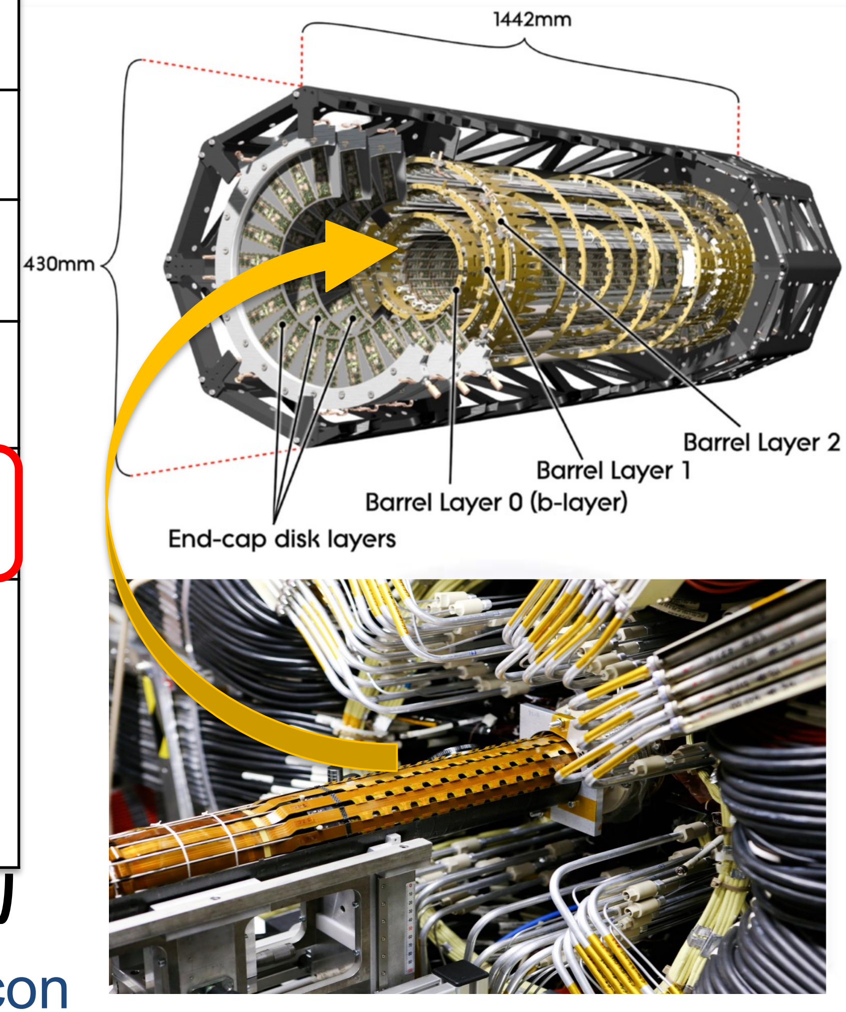
	Pixel (3 layers)		**IBL (1 layer)**
Sensor Technology	*n*⁺-in-*n* (only planar)		*n*⁺-in-*n*/***n*⁺-in-*p*** (planar/**3D**)
Sensor Thickness	**250** μm		**200/230** μm
Front End Technology	FE-I3 **250** nm CMOS		FE-I4 **130** nm CMOS
Pixel Size	50 x **400** μm^2 (short side along R-φ)		50 x **250** μm^2 (short side along R-φ)
Radiation Hardness	**50 Mrad** (500 kGy) ~ $1 \times 10^{15}\ n_{eq} \cdot cm^{-2}$		**250 Mrad** (2.5 MGy) ~ $5 \times 10^{15}\ n_{eq} \cdot cm^{-2}$
Barrel <Radius> or EndCaps $Radius_{Min}$	B-Layer	**5.05 cm**	**3.35 cm**
	Layer 1	8.85 cm	
	Layer 2	12.25 cm	
	EndCaps	8.88 cm	

2024 modules, **92 M** channels, **1.92 m²** of silicon

ATLAS pixel detector electronics and sensors, G Aad *et al* 2008 *JINST* **3** P07007

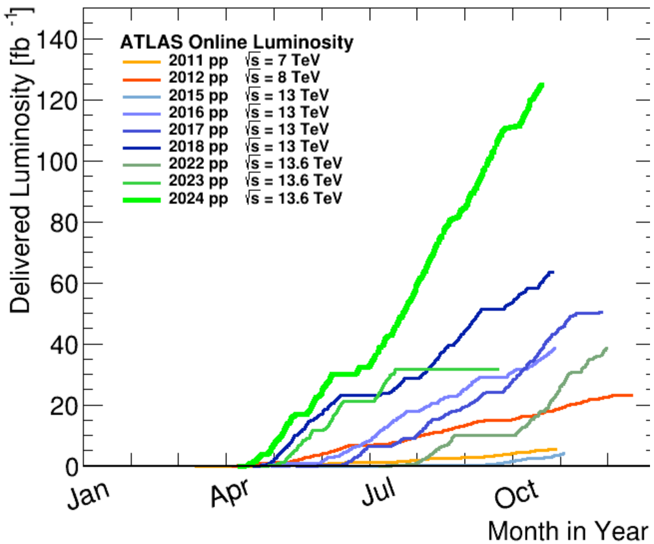
Production and Integration of the ATLAS Insertable B-Layer, B. Abbott et al 2018 JINST 13 T05008

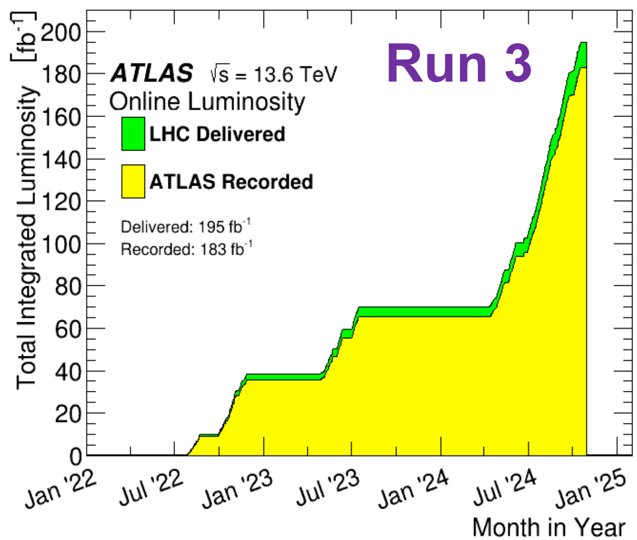
3 + 1 pixel **layers in barrel**
2 x 3 pixels **endcaps**



Insertable B-Layer (IBL) added in 2014 (Run 2)

LHC/ATLAS status at end of 2024

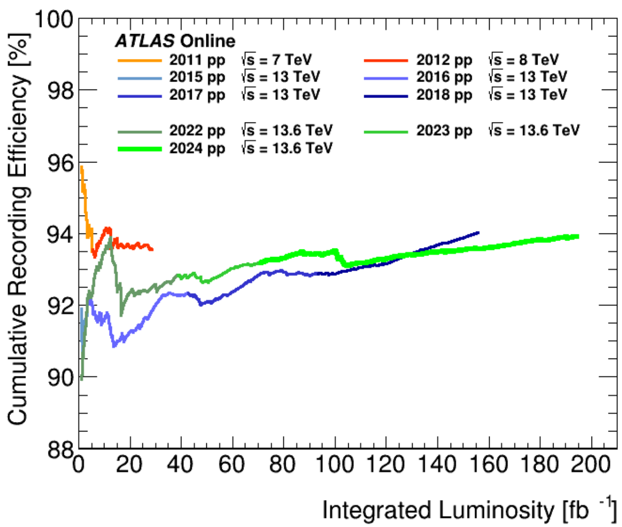


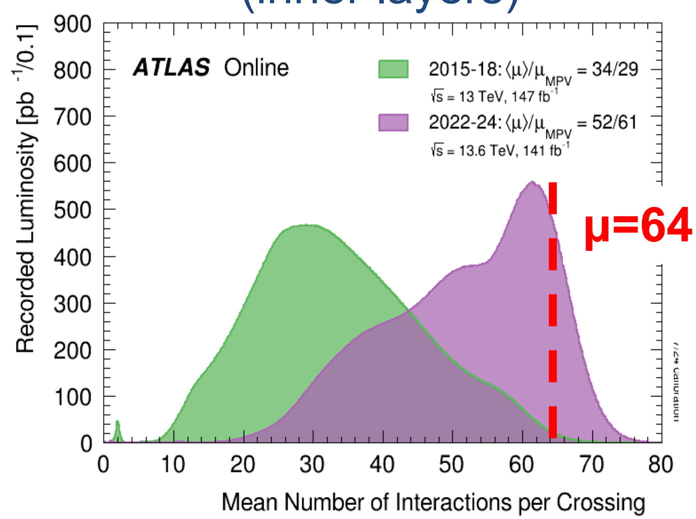


- LHC delivered **~380 fb^{-1}** (~350 fb^{-1} for IBL) over 16 years of operation (10 in IBL)
- Fluence received (inner layers):
  - ➔IBL 1.9 x 10^{15} n_{eq} cm^{-2}
  - ➔B-Layer 1.4 x 10^{15} n_{eq} cm^{-2}
- **200 fb^{-1}** more expected by mid-2026
  - ➔IBL ~ 3 x 10^{15} n-eq cm^{-2}
  - ➔B-Layer ~ 2 x 10^{15} n-eq cm^{-2}

ATLAS recording efficiency
94% (Run 3 cumulative)
with **L1 Trigger ~ 95 kHz**

Pile up (μ)
levelling target set to **64** (2024)
➔ up to 10^{-3} hit/pixel/event.
(inner layers)





Reminder:
Pixel outer layers designed for:

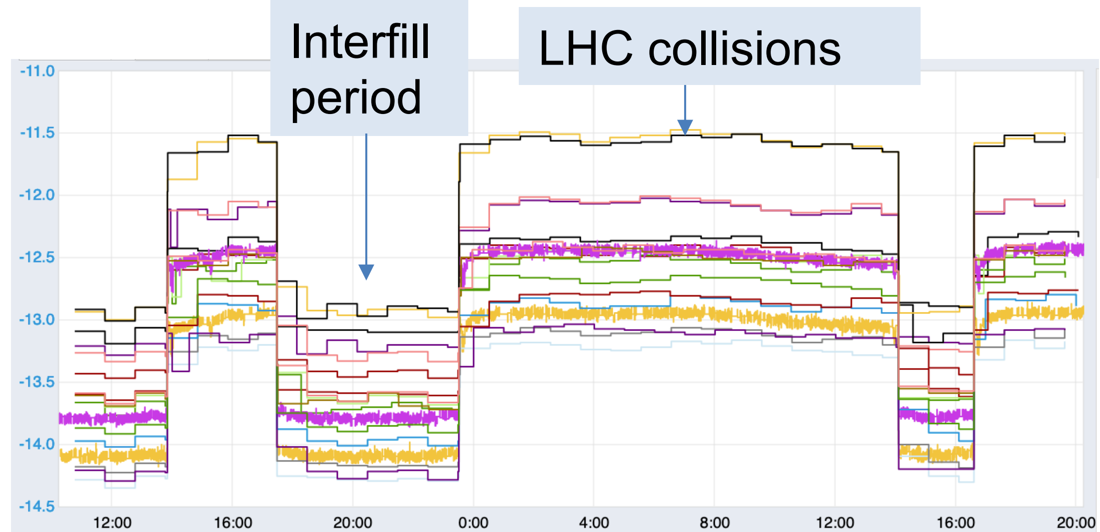
fluence ~ 1 x 10^{15} n_{eq}cm^{-2}
μ ~ 23

➔ Run 3 operation well beyond the detector design parameters (especially B-Layer)!

Pixel detector status

- Cooling set points at **-25 °C/-20 °C** during LHC **collision** months (**-5 °C /-7.5 °C** during shutdowns**)**.
- **C_3F_8** evaporative in Pixel outer layers and **CO_2** bi-phase in IBL are **very stable.**

IBL Temperatures measured on the flex



% Disabled Modules

Layer	2018	2023	2024
Disks	5.2	4.5	5.5
B-Layer	6.2	5.2	7.3
Layer 1	5.8	4.4	3.6
Layer 2	4.8	6.3	7.4
IBL (Frontends)	0.7	0.9	0.9
Total	**4.5**	**4.4**	**5.0**

- Various **failure types** (NTC, Rx Plugin, HV open, module not configuring/sending data)
- Some failures are temporary, others are unrecoverable.
- **Number** of disabled modules **quite stable**:

➔recently 6 modules recovered in Layer 1 thanks to redundancy lines/fibers (readout speed reduced 160 Mbps →80 Mbps)

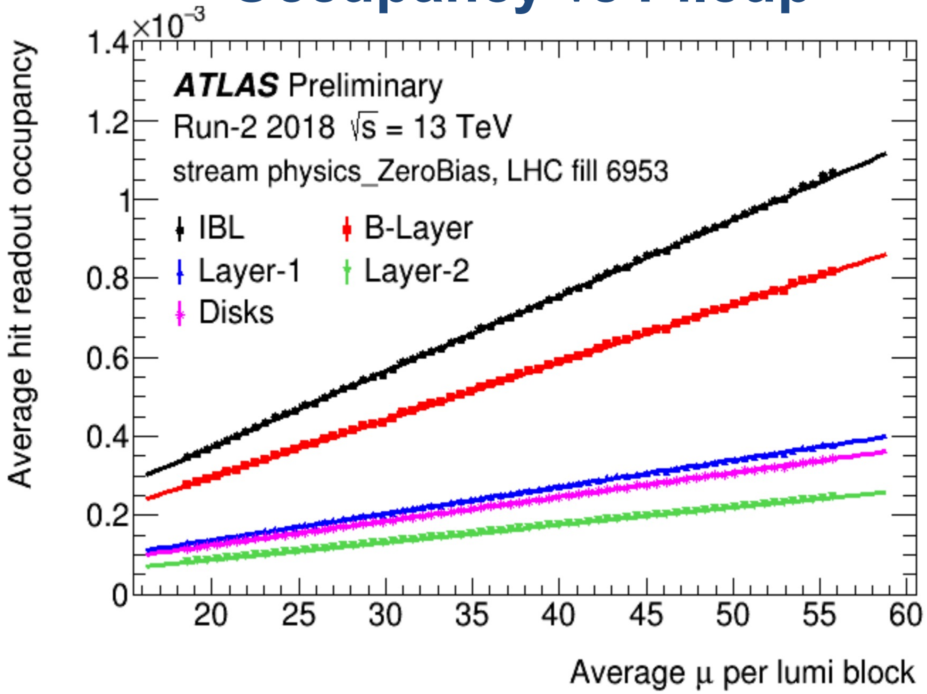
➔ **95% detector working fraction!**

Pixel operation: Deadtime and Occupancy

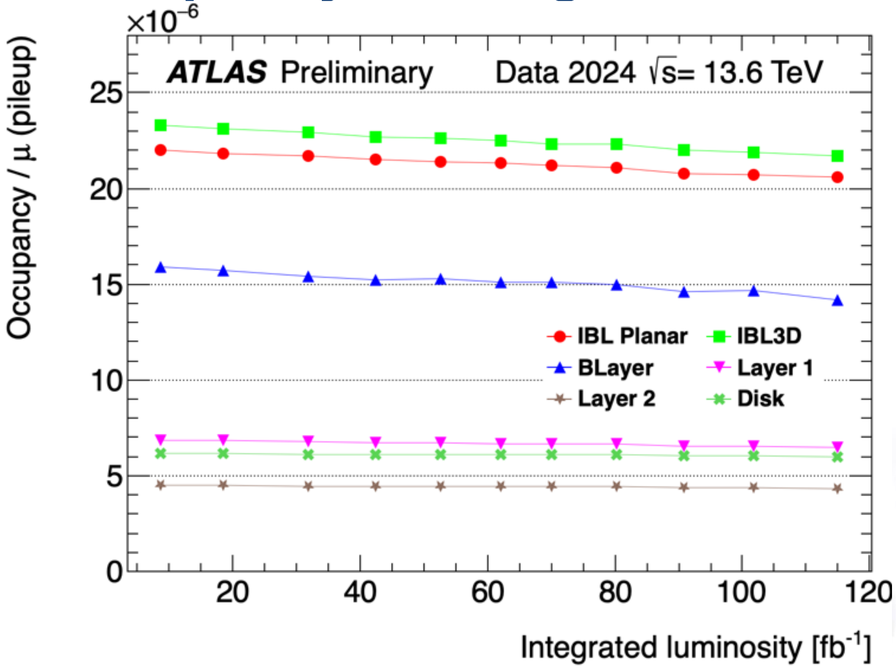
Deadtime

- After years of improvements on Sw/Fw ➔ **Pixel dead time < 0.1 % in 2024!**
- Recovery mechanism (module, ROD) very rare thanks to the periodic reconfiguration of front-end registers (see next slide).

Occupancy vs **Pileup**



Occupancy vs **Integrated Lumi**



- Pixel hit occupancy should scale linearly with μ (bandwidth extrapolations).
- Possible deviations from linearity occur during fills (**SEE**) or vs the integrated luminosity (**radiation damage**) ➔ good thermometer of the detector “health”!

Radiation on FE electronics: SEE

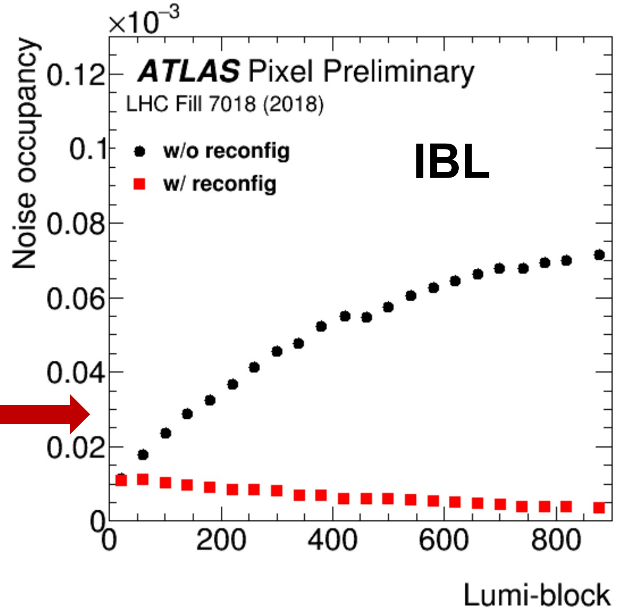
Big charge deposit in FE electronics can flip the state of **global/local memory cells**

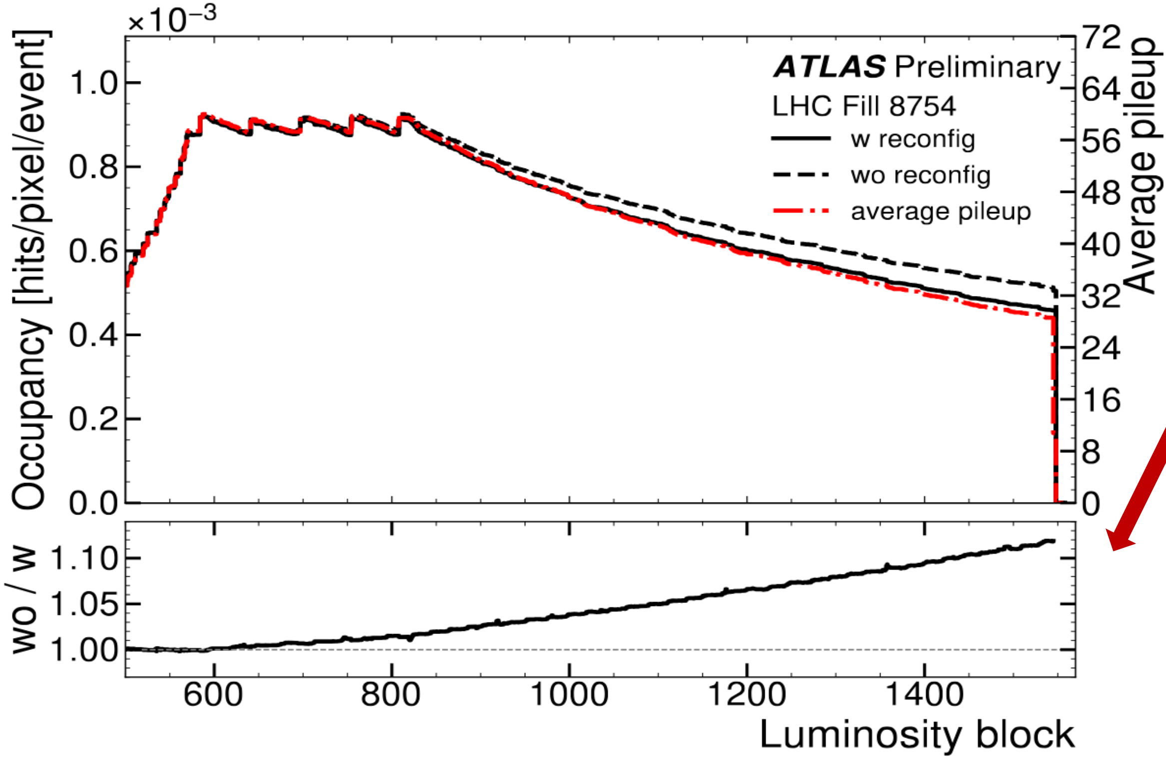
- IBL FE-I4 global registers affected by SEE already in 2017
  ➔ **periodical reconfiguration of FE global registers.**

Higher luminosity fills (up to 8 hours of leveling lumi)

- SEE becoming relevant for FE-I4 **single pixel registers**
  ➔ **periodical reconfiguration of single pixel registers**
  ➔ clear noise reduction observed during test (2018).

Measurements of Single Event Upset in ATLAS IBL





Occupancy increase (+15%) by end of fill (May 2023) in staves w/o reconfig. Staves w/ reconfig follow more closely the μ profile.

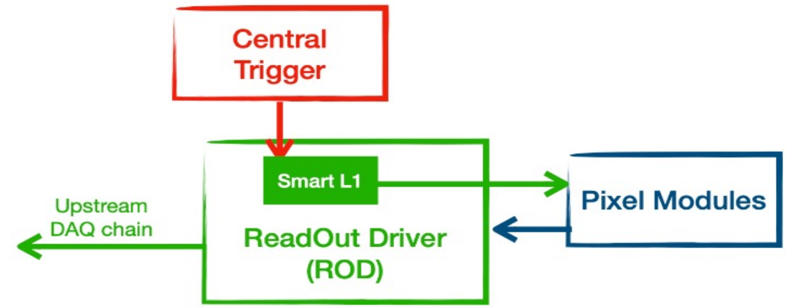
Run 3 strategy:
IBL full FE-I4 reconfiguration
(completed gradually in ~11 minutes, without adding extra dead time to ATLAS)

Pixel operation: ROD Desynch

ROD desynchronization (wrong assignment of event identification) has been **main source of inefficiency** in outer Pixel layers **(especially B-Layer)** until **June 2023**.

Introduction of ***"SmartL1 Fw"*** mechanism **reduced drastically (3 orders of magnitude)** the *"ROD desynchronization"* in outer pixel layers. How?

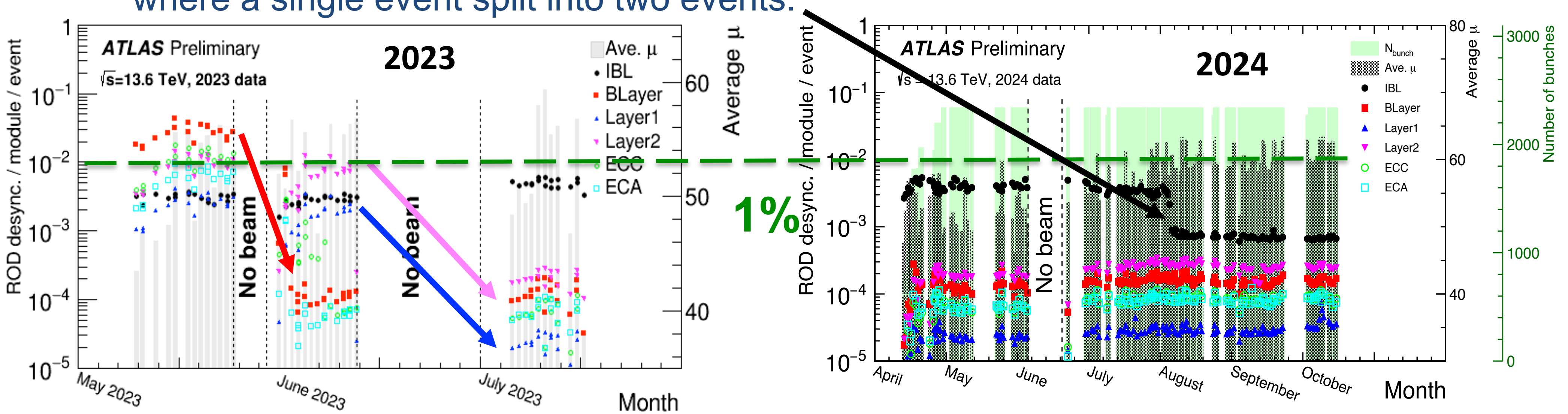
- Triggers not propagated whenever modules are late closing previous events .
- ROD keeps track of # "vetoed" triggers, maintaining data stream synchronization.



➔ *Preventing modules from getting desynchronized by introducing a known limited inefficiency.*

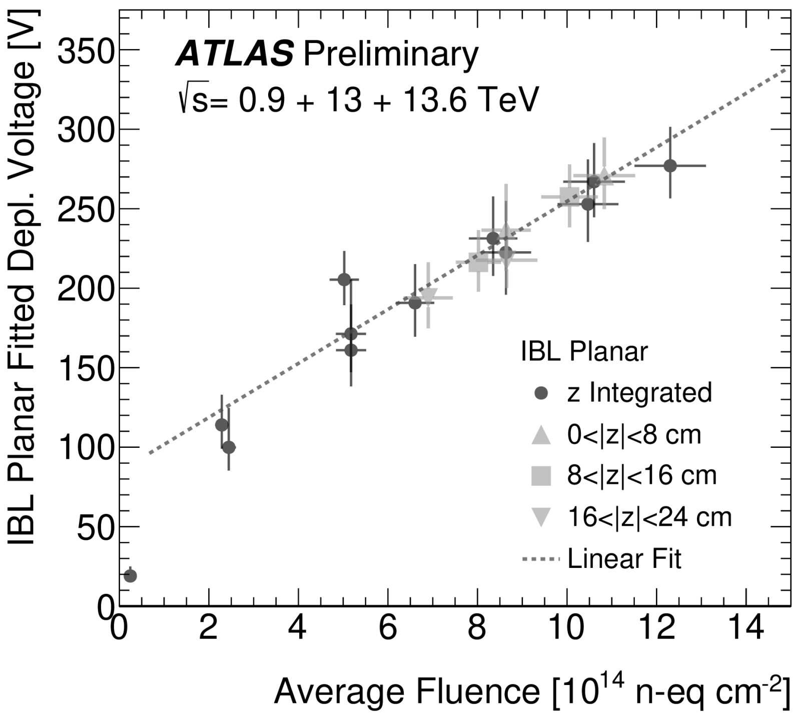
IBL not really affected by ROD desynchronization (FE-I4 chip optimized for higher data rate).

- Further improvements (August 2024) via Fw that compensates for a FE misbehaviour where a single event split into two events.

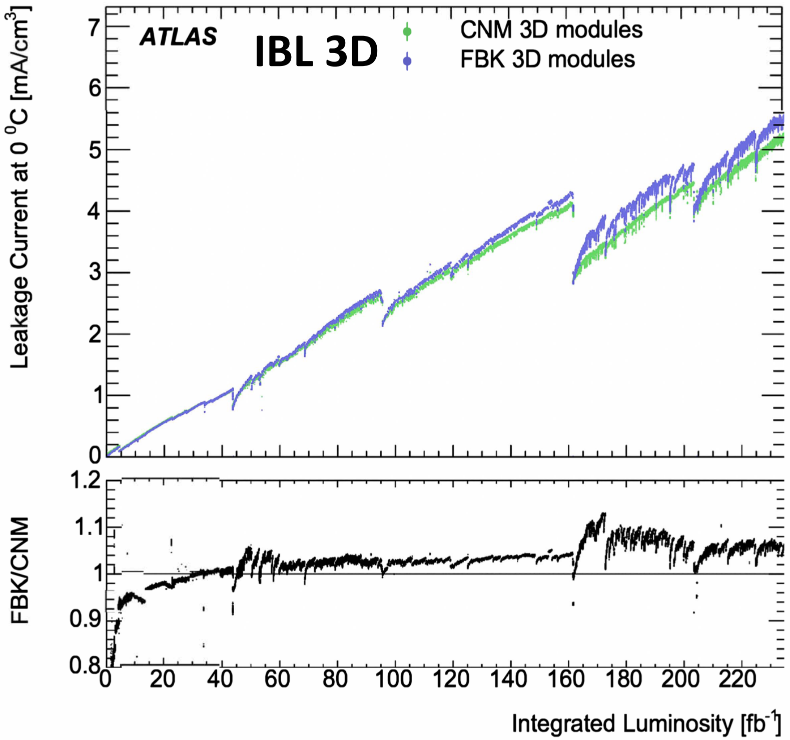


Depletion voltage/Leakage current

- **Depletion voltage** monitoring via **bias voltage (HV) scans** during collisions (begin/end of each year)
  ➔ decide the operating bias voltages for the year ahead.
- Depletion voltage in IBL scales linearly with fluence (cooling stability constrains any annealing).



- **Leakage current** monitoring **during fills** (and via **IV scans)**
  ➔ linear increase with integrated lumi.
- Making sure we have enough headroom till the end of Run 3.
- Leakage current data used to extract fluence seen by the detector.



Fighting radiation damage: configuration

- Module configuration initially used to accommodate for **readout problems**, typically correlated to bandwidth consumption.
  - Read out speed, Front-end latency, TOT target point for MIP ,Threshold modulation vs η, ..
- Impact of **radiation damage** on cluster charge becoming evident by end of 2017.
  ➔ ***Sensor bias voltage*** and ***analog thresholds*** updated yearly!

Bias Voltages

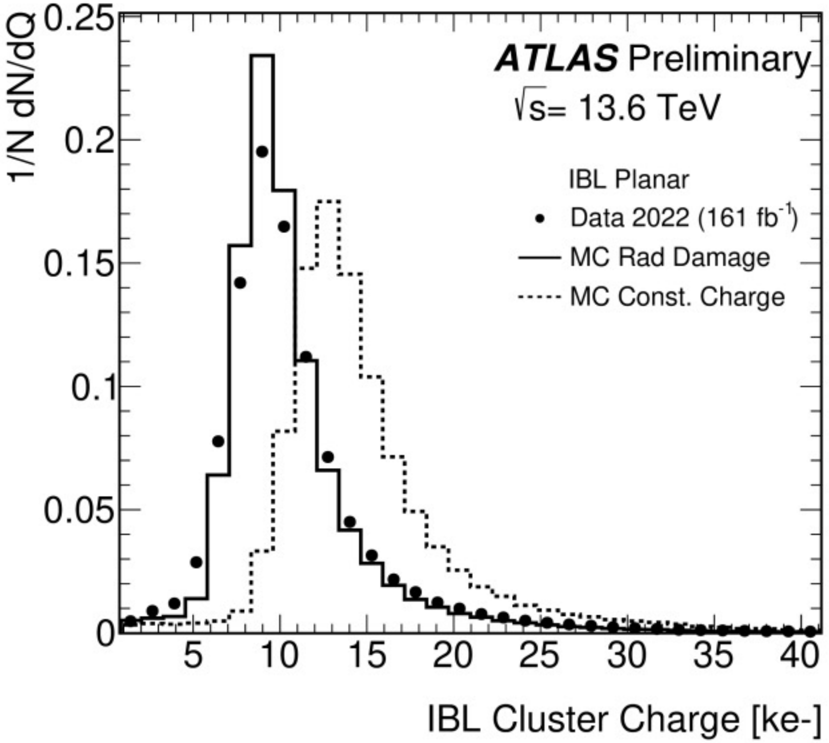
	2015		2024
IBL-Planar	80 V	..	450 V
IBL-3D	20 V	..	70
B-Layer	250 V	..	500 V
Layer 1	150 V	..	350 V
Layer 2	150 V	..	350 V
Disks	150 V	..	350 V

Gradually increased, typically at the begin of each year

Analog Thresholds

	2015		2024
IBL	2500e	..	1500e
B-Layer	3500e	..	4700e
Layer 1	3500e	..	4300e
Layer 2	3500e	..	4300e
Disks	3500e	..	4300e

Increasing or decreasing depending on readout limitations or radiation damage



Cluster charge from data doesn't match anymore the MC with constant charge..

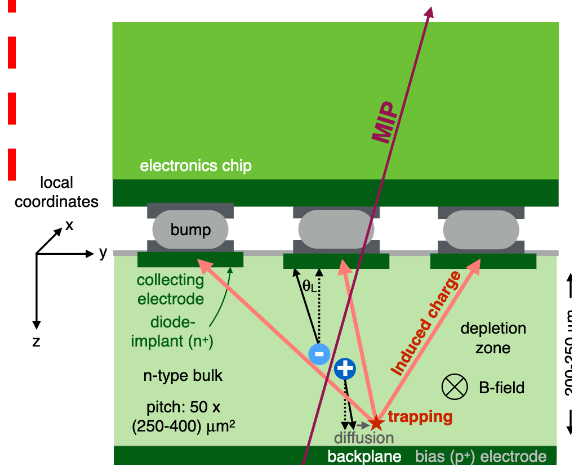
Modeling the radiation damage: MC

Development of **new radiation damage (digitizer) MC.**

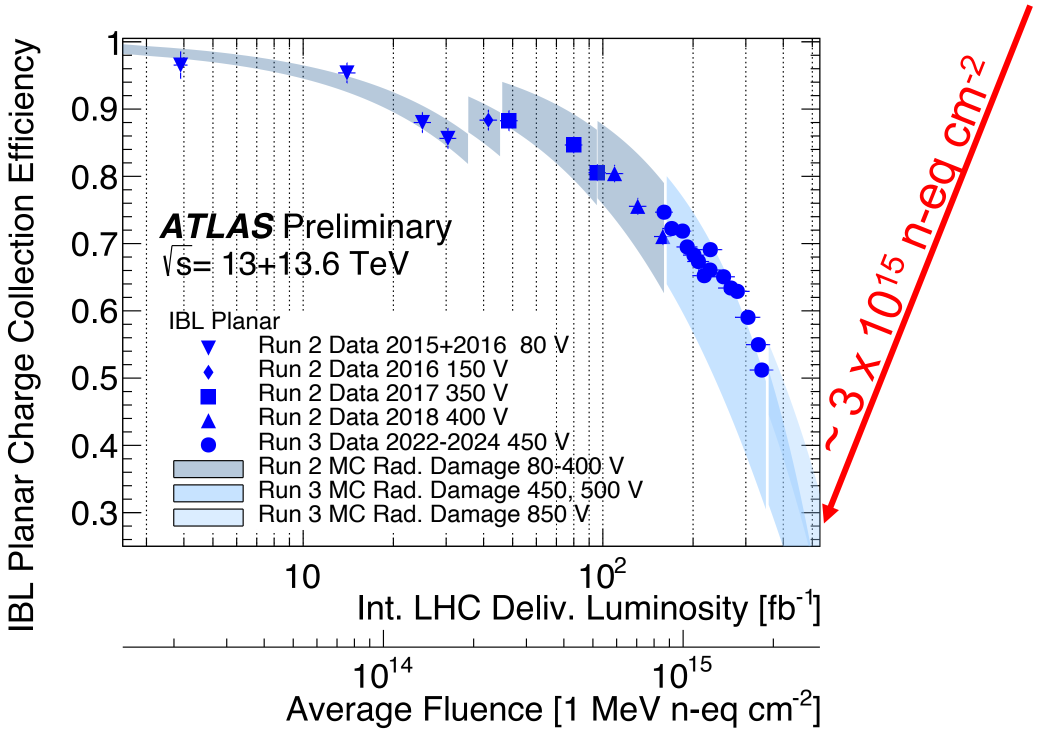
- Extensive validation of the new digitizer ➔ **official ATLAS Run 3 MC.**
- Exploit the radiation damage MC to train our clustering/tracking algorithms (**NN**).
- Extrapolate **CCE/depletion voltage** to the end of Run 3, providing guidance for detector operation (HV, thresholds, tunings points, ..)

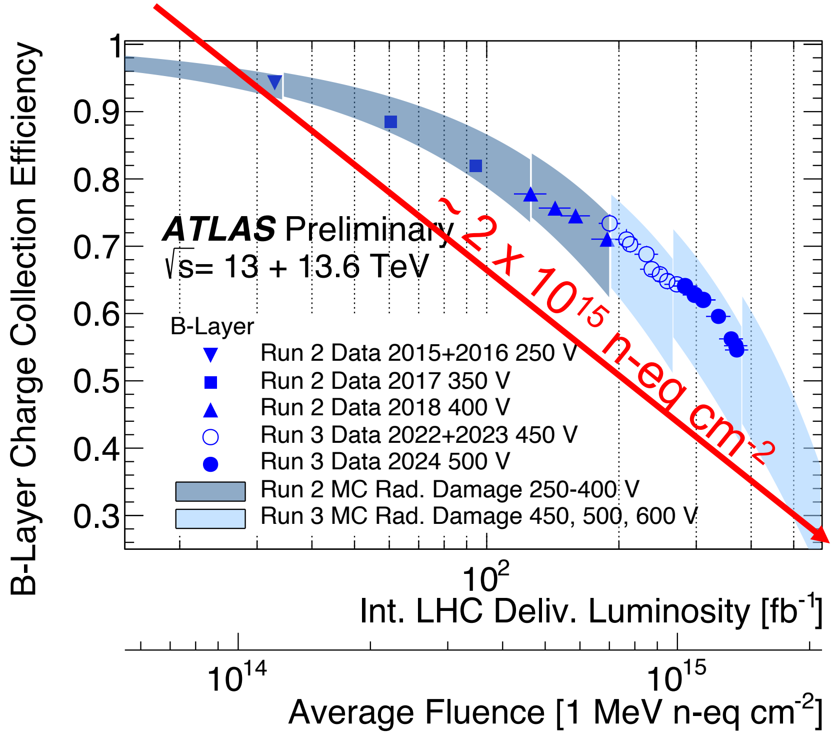
See poster on Rad. Damage MC from ***M. Bomben***

[*Modelling radiation damage to pixel sensors in the ATLAS detector*]



➔ **CCE ~ 30% at end of Run 3, for both IBL and B-Layer!**

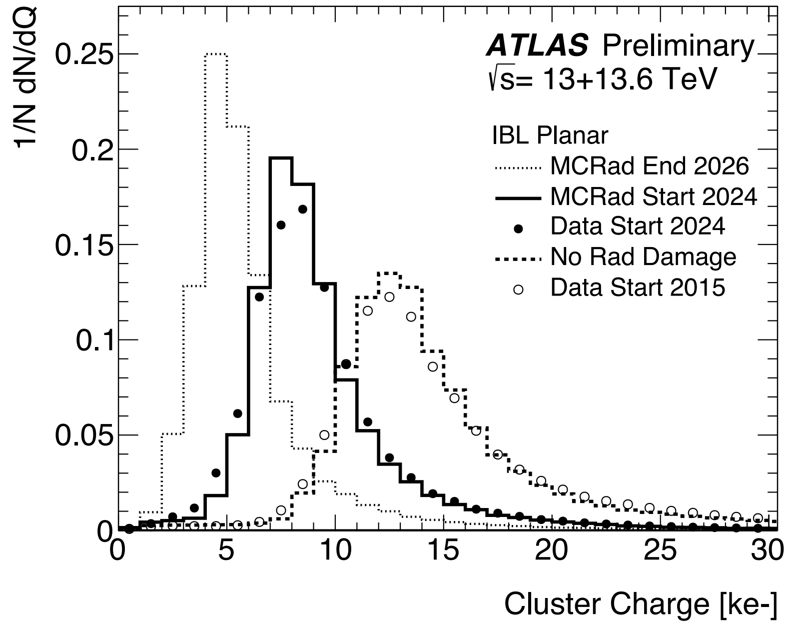


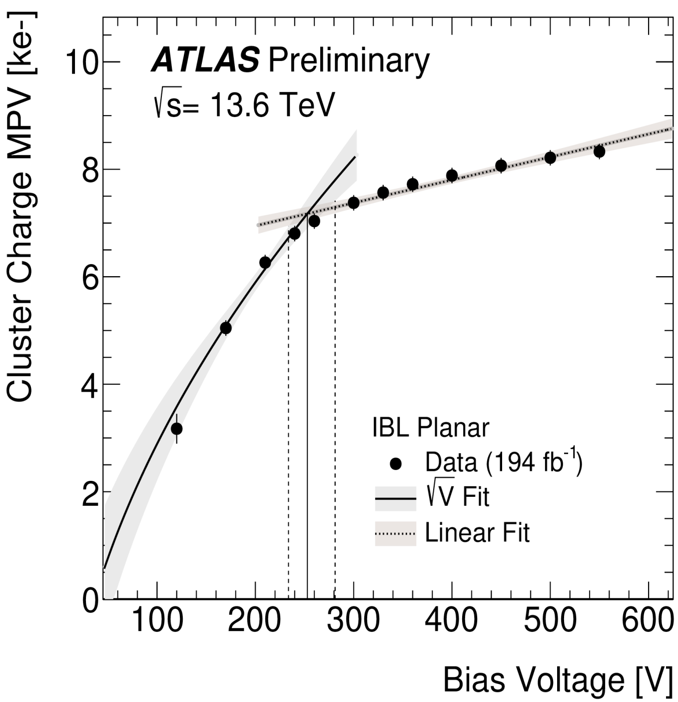


Cluster charge/Depletion voltage

- Cluster charge (corrected for Si path) very well reproduced by Radiation Damage MC.

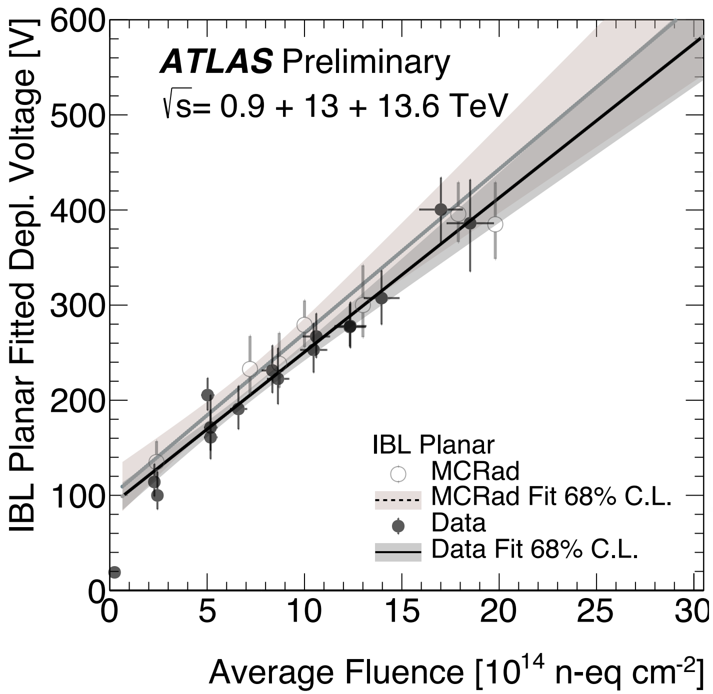
- Exploiting the predictive power to check the cluster charge/shape at the end of Run 3.





- Extraction of depletion voltage from HV scan during LHC fills.

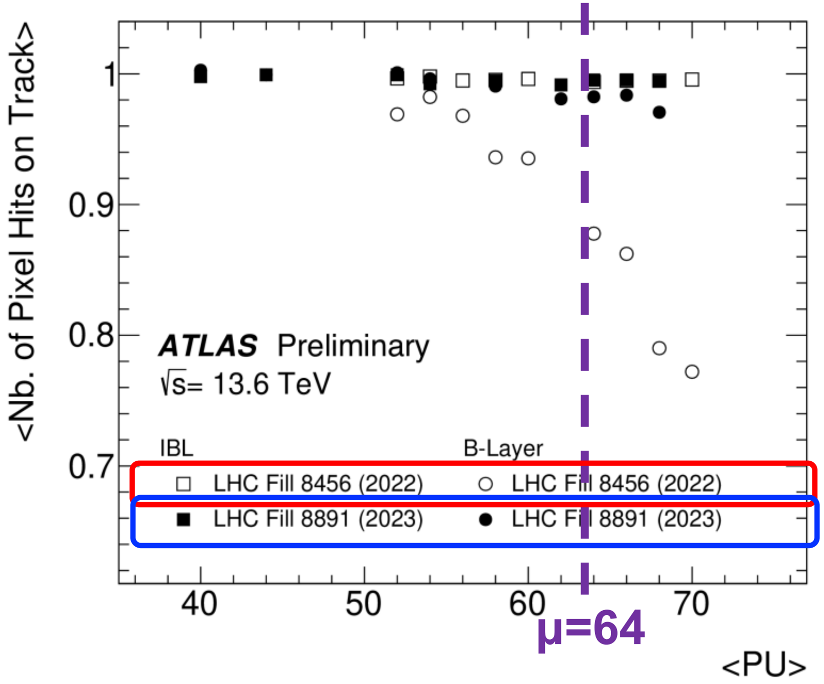
- Good agreement between data and MC (biggest uncertainties from fluence and electron trapping rate).



Hits on track efficiency

Run 2: Readout error age

Most of the hit-on-track inefficiencies driven by readout problems (desynch): particularly relevant for the B-Layer and Endcap, minor for IBL.



Run 3: Radiation damage era

Predicting the hit-on-track efficiency by considering the radiation damage on the sensor via cluster charge shrinking below threshold.

Extrapolating # Hits-on-track from **average 2024 ➔ end of Run 3** (based on LHC "optimistic" scenario, **580 fb^{-1}** at the end of Run 3):

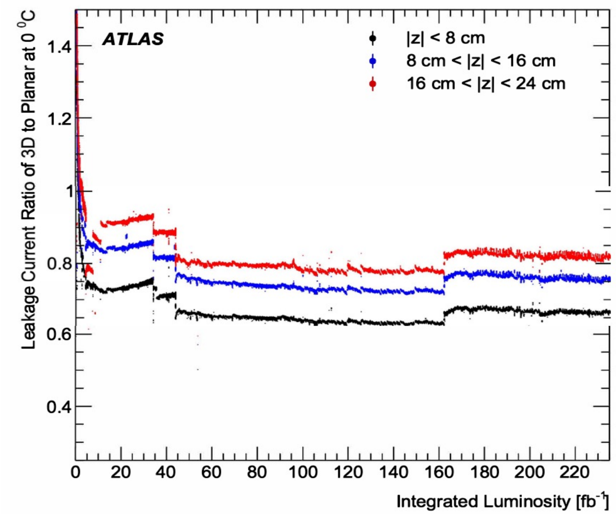
- **B-Layer 0.97** (2024) ➔ **0.95** (2026)
- **IBL 0.99** (2024) ➔ **0.96** (2026)

IBL 3D.. or the "ITk inner layer precursor"

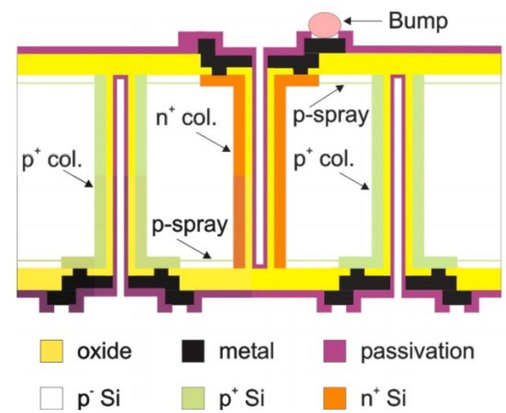
- 3D pixel sensors located at outer ends of IBL staves ($245<|z|<335$ mm or $1.90<|\eta|<2.55$), accounting for LHC beam spot length in z.

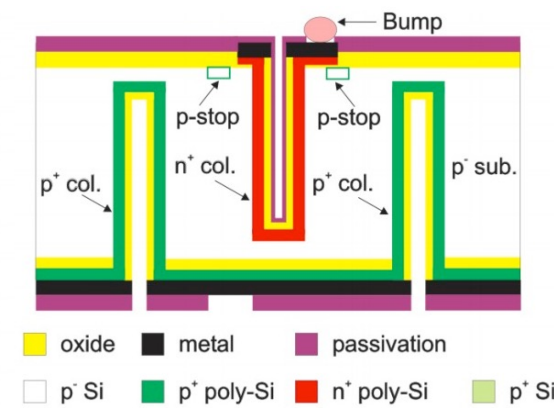
➔ The **first large scale 3D pixel detector** (0.5 m^2) installed at LHC!

- Two different designs adopted: **full-column (FBK)** vs **partial (CNM)** pass through + other differences like guard rings vs fences or p-stop vs p-spray



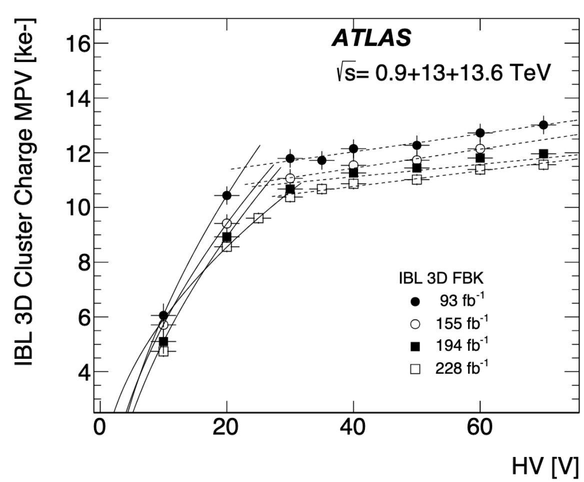
Leakage current (for fluence extraction)

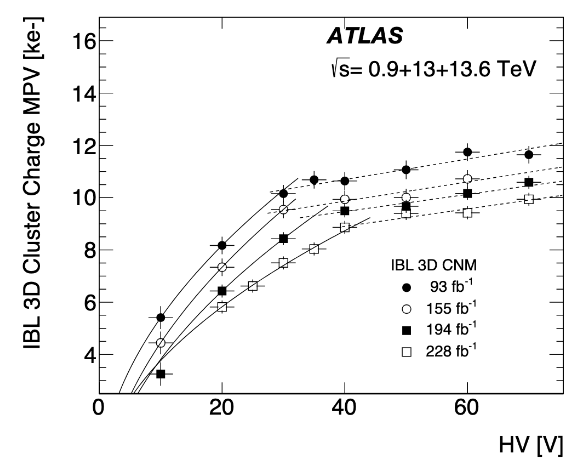




- **HV scans with collisions to monitor the depletion voltage.**

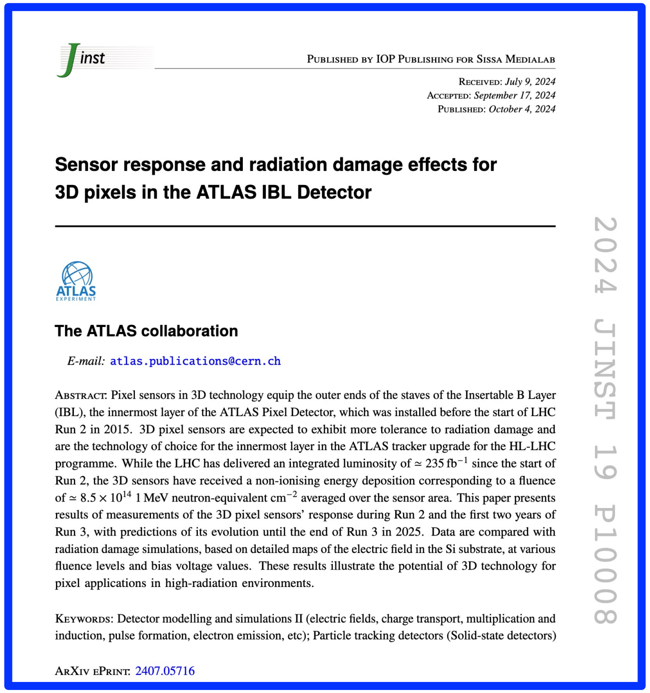
- **Rad Damage model** also implemented for **3D sensor** (FBK design only).





IBL 3D: new Performance Paper

New paper published recently about IBL 3D performance



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Sensor response and radiation damage effects for 3D pixels in the ATLAS IBL Detector

The ATLAS collaboration

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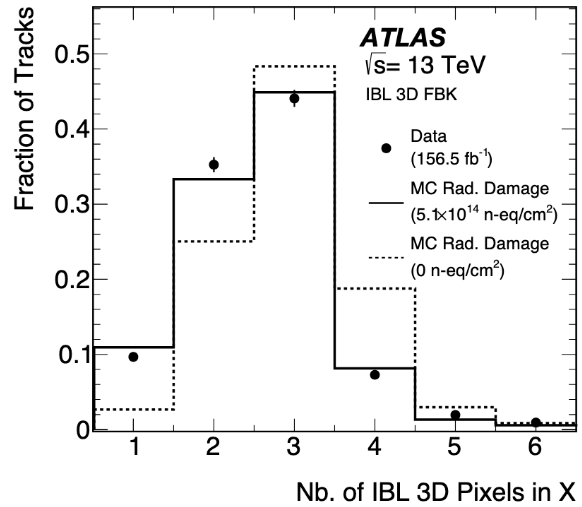
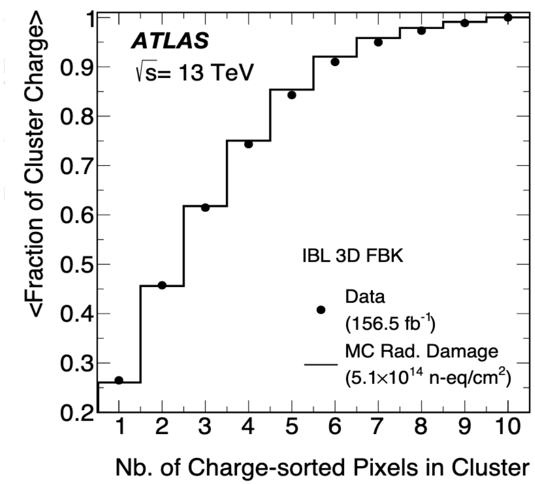
Abstract: Pixel sensors in 3D technology equip the outer ends of the staves of the Insertable B Layer (IBL), the innermost layer of the ATLAS Pixel Detector, which was installed before the start of LHC Run 2 in 2015. 3D pixel sensors are expected to exhibit more tolerance to radiation damage and are the technology of choice for the innermost layer in the ATLAS tracker upgrade for the HL-LHC programme. While the LHC has delivered an integrated luminosity of $\simeq 235$ fb^{-1} since the start of Run 2, the 3D sensors have received a non-ionising energy deposition corresponding to a fluence of $\simeq 8.5 \times 10^{14}$ 1 MeV neutron-equivalent cm^{-2} averaged over the sensor area. This paper presents results of measurements of the 3D pixel sensors' response during Run 2 and the first two years of Run 3, with predictions of its evolution until the end of Run 3 in 2025. Data are compared with radiation damage simulations, based on detailed maps of the electric field in the Si substrate, at various fluence levels and bias voltage values. These results illustrate the potential of 3D technology for pixel applications in high-radiation environments.

Keywords: Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Particle tracking detectors (Solid-state detectors)

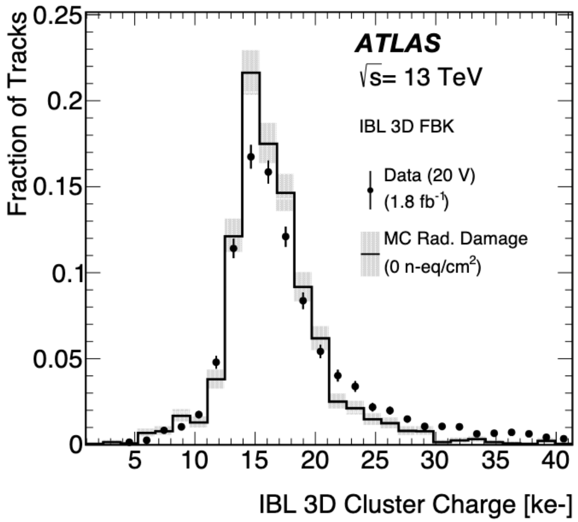
ArXiv ePrint: 2407.05716

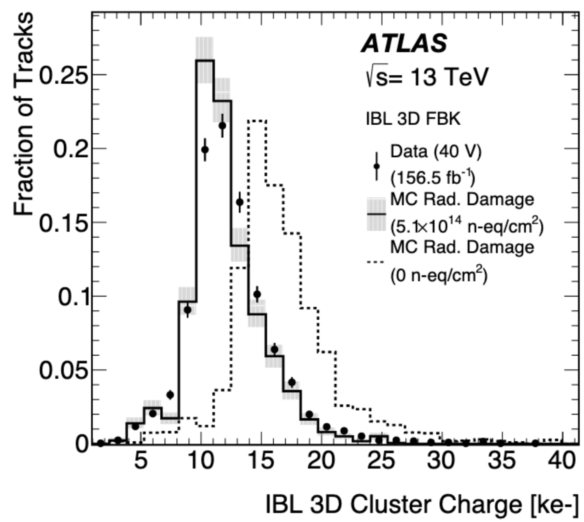
2024 JINST 19 P10008

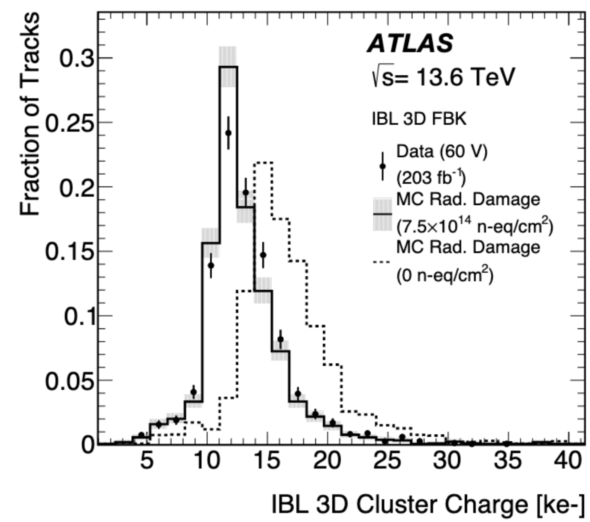




- Good agreement between data and Rad Damage MC that describes well the **clusters size** (including charge sharing) and the **MPV of the cluster charge** vs integrated luminosity.



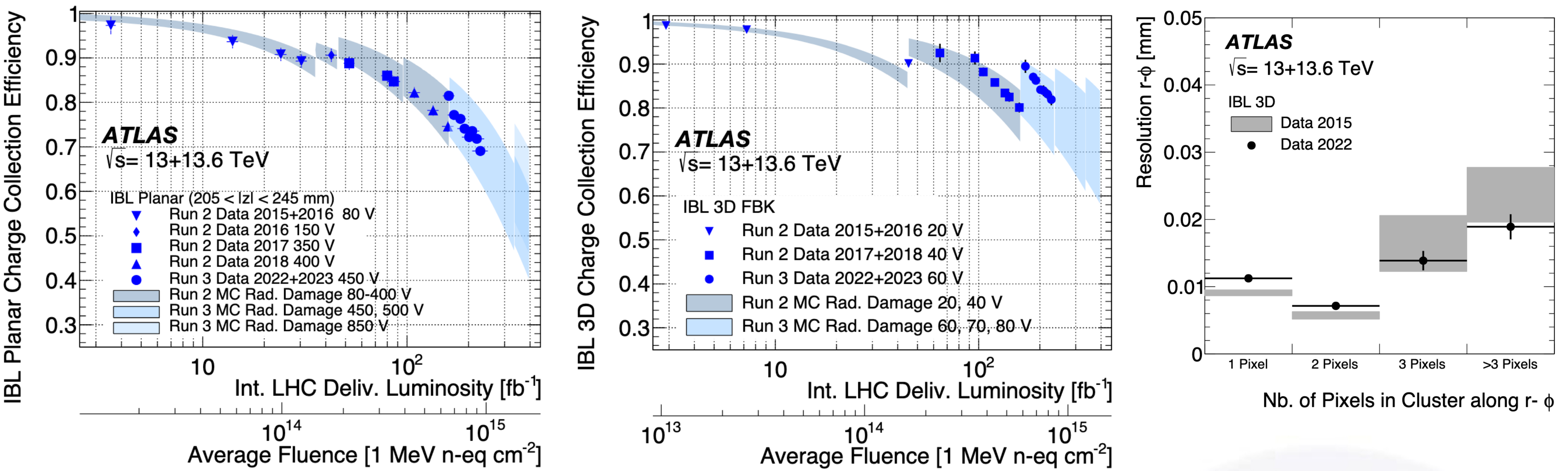




Integrated Luminosity

IBL 3D: new Performance Paper

New paper published recently about IBL 3D performance



- IBL 3D showing better CCE respect to IBL planar sensors for the same fluence
  ➔ **~15%** less reduction in the CCE at the **end of 2023** (~8.3 ×10^{14} n_{eq}/cm^2).
  ➔ difference expected to grow to ~**25%** at the **end of Run 3** (~1.5 × n_{eq}/cm^2).
- Resolution in r-Φ (using overlap method) averaged over all cluster:
  - 2015 data (8.6 ± 0.4) vs (8.1 ± 0.3) MC
  - 2022 data (9.7 ± 0.4) vs (9.1 ± 0.4) MC
- Large pixel multiplicity (small incidence angle in longitudinal projections) → the total 3D pixel cluster charge is large → radiation damage effects on resolution are limited.

Conclusion and outlook

- ATLAS Pixel detector is operating in Run 3 under very challenging conditions (well beyond the design): **$\mu \gtrsim 60$, trigger rate ~ 100 kHz,** fluence **$\gtrsim 10^{15}$ n_{eq} cm^{-2}** in the innermost layers.
- Detector **cooling** is very stable, and **hardware** failures are under control. **DAQ and DQ efficiencies** (historically affected by **dead time** and **desynchronization)** have reached their **peak values**.
- Tremendous efforts on **operation (detector configuration optimization)** and on **DAQ (stabilize/streamline the system)**, culminated with the deployment of **SmartL1 Fw:**

  ➔ **Pixel (ATLAS) benchmark** for **max. operational μ (→ max. instantaneous luminosity → max. integrate luminosity) increased considerably**.

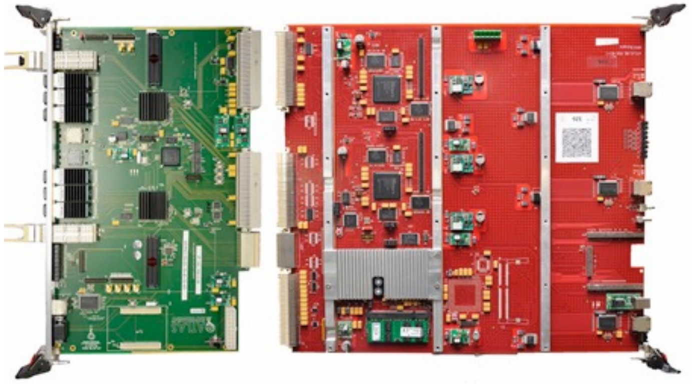
- Radiation damage became a fundamental aspects of the detector performance. **New radiation damage digitiser** developed/included in ATLAS Run 3 MC.
- **CCE** vs fluence for data and radiation damage simulation show good agreement, allowing extrapolations to the end of Run 3. Despite **30% CCE expected at the end Run 3, hits-on-track will remain high ($\gtrsim$ 95%)** thanks to detector parameter optimization (HV, Threshold).
- **New Paper on IBL 3D senso**r published: improved response of 3D pixels after 10^{15} n_{eq} cm^{-2} of fluence, with ~25 % gain in CCE compared to planar sensors at the end of Run 3. Cluster properties well described; 3D sensor spatial resolution not much affected by radiation.
- **Outlook**: Very important experience for HL-LHC tracker upgrades, giving insight about future detector operation, supporting choices for next upgrade phases.

Ready to face more radiation till mid 2026 and test the ultimate conditions!

Back-up

Pixel Detector Read Out Upgrades

- The Run 1 Pixel read-out system went through a series of upgrades using the new IBL read-out:
  - Layer2 (2015/2016 Winter Shutdown)
  - Layer1 (2016/2017 Winter Shutdown)
  - B-Layer/Disks (2017/2018 Winter Shutdown)



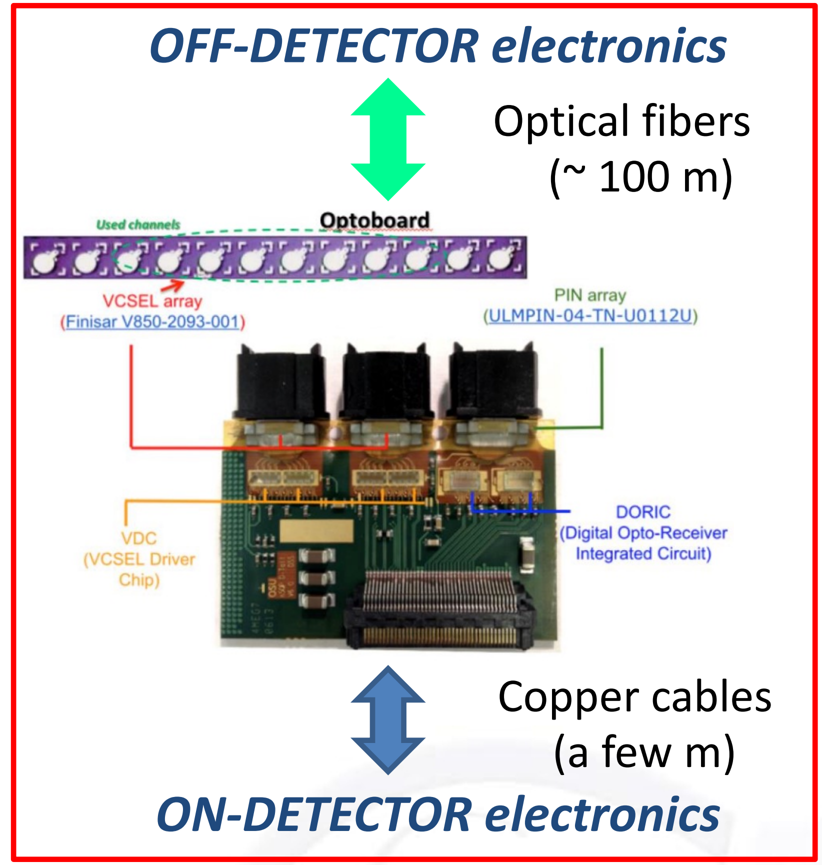
a) b)

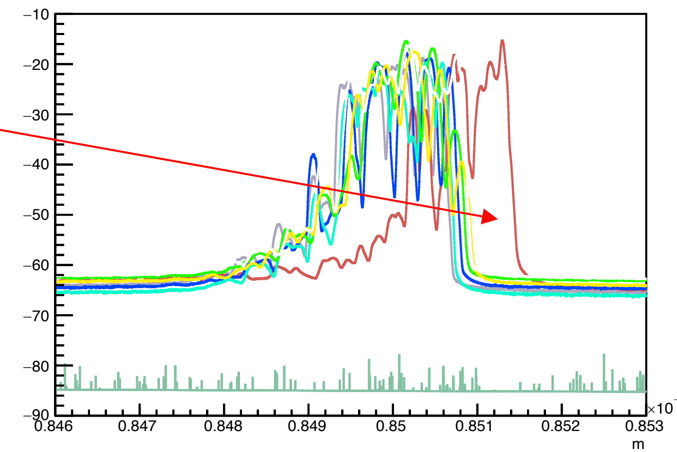
- Overcome bandwidth limitations but also enhance debugging capability and Sw/Fw flexibility.
- Finally in 2018, one unified read-out system that brought Pixel many advantages:
  - the operation of different type of FEs will always be there but…transparent for most of the operations!

Opto-Board replacement during LS2

- Relevant number of VCSEL (laser array) failures during Run 2 (**~3%**).
  - humidity being the main suspect.
- New **O**pto-**B**oard production (with new VCSELs) ➔ **>400** qualified.
- Selective replacement done (**178 OBs**) in February 2021.
  - replacement of OBs hosting dead VCSELs (**25 modules recovered**) or VCSEL alive with a shifted optical spectrum.
- Sealing of Optoboxes (hosting OBs) to keep the boards dry (humidity concern).

➔ no failures observed so far!





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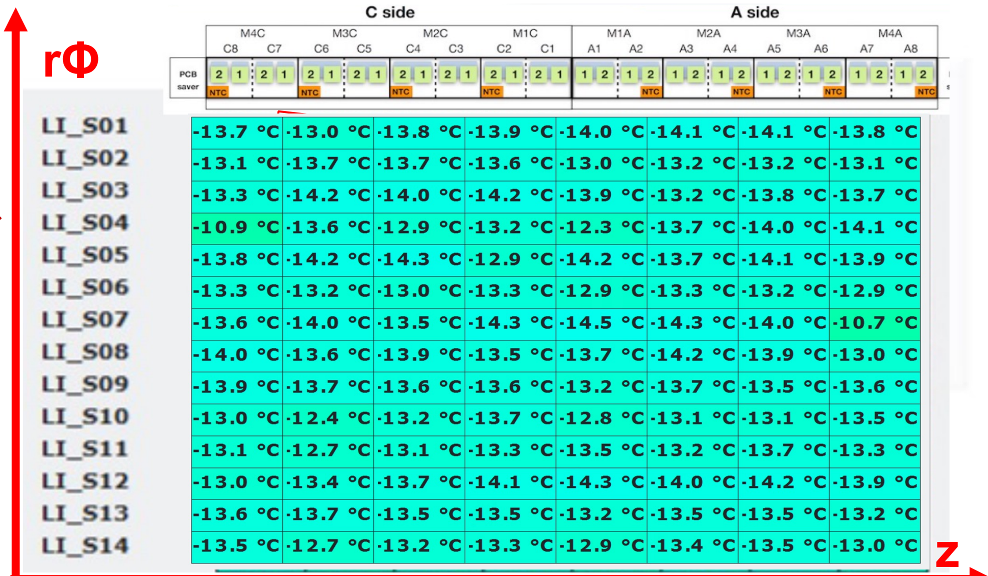
Pixel detector status: Cooling

- Detector kept **cold** most of the time.
  - Pixel (and strips) uses C_3F_8 evaporative whilst IBL uses CO_2 bi-phase cooling ➔ very stable so far.
- A new **thermosiphon** system (instead of standard compressors) was developed and **used in Run 3 (shared between Pixel and strips).**

Typical temperature set points	PIXEL	IBL
Detector ON	-20 °C /-25 °C	-20 °C
Detector OFF (winter shutdowns)	-5 °C	-7.5 °C

IBL Temperatures measured on module flex (NTC)



	M4C	M3C	M2C	M1C	M1A	M2A	M3A	M4A
LI_S01	-13.7 °C	-13.0 °C	-13.8 °C	-13.9 °C	-14.0 °C	-14.1 °C	-14.1 °C	-13.8 °C
LI_S02	-13.1 °C	-13.7 °C	-13.7 °C	-13.6 °C	-13.0 °C	-13.2 °C	-13.2 °C	-13.1 °C
LI_S03	-13.3 °C	-14.2 °C	-14.0 °C	-14.2 °C	-13.9 °C	-13.2 °C	-13.8 °C	-13.7 °C
LI_S04	-10.9 °C	-13.6 °C	-12.9 °C	-13.2 °C	-12.3 °C	-13.7 °C	-14.0 °C	-14.1 °C
LI_S05	-13.8 °C	-14.2 °C	-14.3 °C	-12.9 °C	-14.2 °C	-13.7 °C	-14.1 °C	-13.9 °C
LI_S06	-13.3 °C	-13.2 °C	-13.0 °C	-13.3 °C	-12.9 °C	-13.3 °C	-13.2 °C	-12.9 °C
LI_S07	-13.6 °C	-14.0 °C	-13.5 °C	-14.3 °C	-14.5 °C	-14.3 °C	-14.0 °C	-10.7 °C
LI_S08	-14.0 °C	-13.6 °C	-13.9 °C	-13.5 °C	-13.7 °C	-14.2 °C	-13.9 °C	-13.0 °C
LI_S09	-13.9 °C	-13.7 °C	-13.6 °C	-13.6 °C	-13.2 °C	-13.7 °C	-13.5 °C	-13.6 °C
LI_S10	-13.0 °C	-12.4 °C	-13.2 °C	-13.7 °C	-12.8 °C	-13.1 °C	-13.1 °C	-13.5 °C
LI_S11	-13.1 °C	-12.7 °C	-13.1 °C	-13.3 °C	-13.5 °C	-13.2 °C	-13.7 °C	-13.3 °C
LI_S12	-13.0 °C	-13.4 °C	-13.7 °C	-14.1 °C	-14.3 °C	-14.0 °C	-14.2 °C	-13.9 °C
LI_S13	-13.6 °C	-13.7 °C	-13.5 °C	-13.5 °C	-13.2 °C	-13.5 °C	-13.5 °C	-13.2 °C
LI_S14	-13.5 °C	-12.7 °C	-13.2 °C	-13.3 °C	-12.9 °C	-13.4 °C	-13.5 °C	-13.0 °C

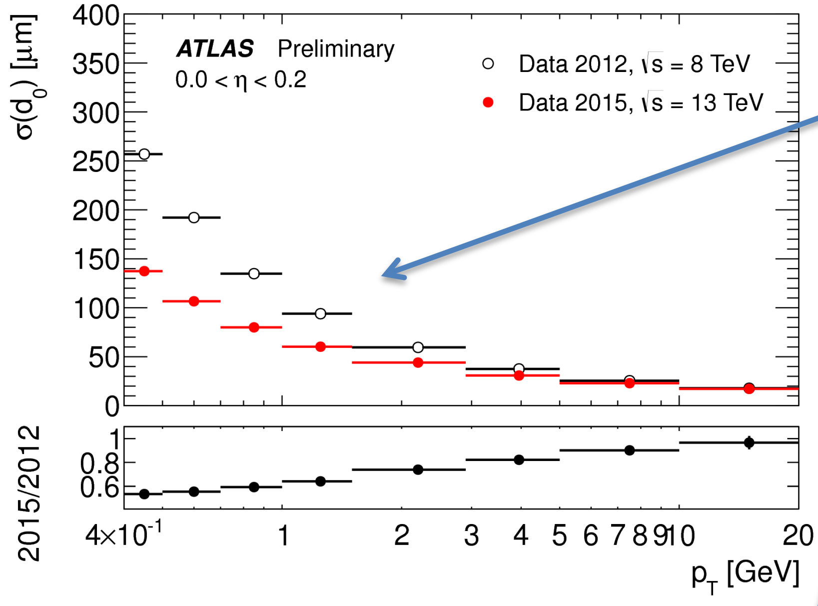
Pixel detector status

- **Rx Plugins** failures (off-detector electronics, receiving data from modules)
  ➔ not fully understood but easily replaceable and relatively small fraction.
- **NTC** failures (increasing with accumulated radiation)
  ➔ causing temperature interlock, loosing temp. readout in single modules.
- **Other module** failures (HV open, not configuring, no data..) under control:
  ➔ a few modules (6) recently recovered in Ly1 using redundancy lines/fibers (readout speed had to be reduced from 160 mbps to 80 mbps).

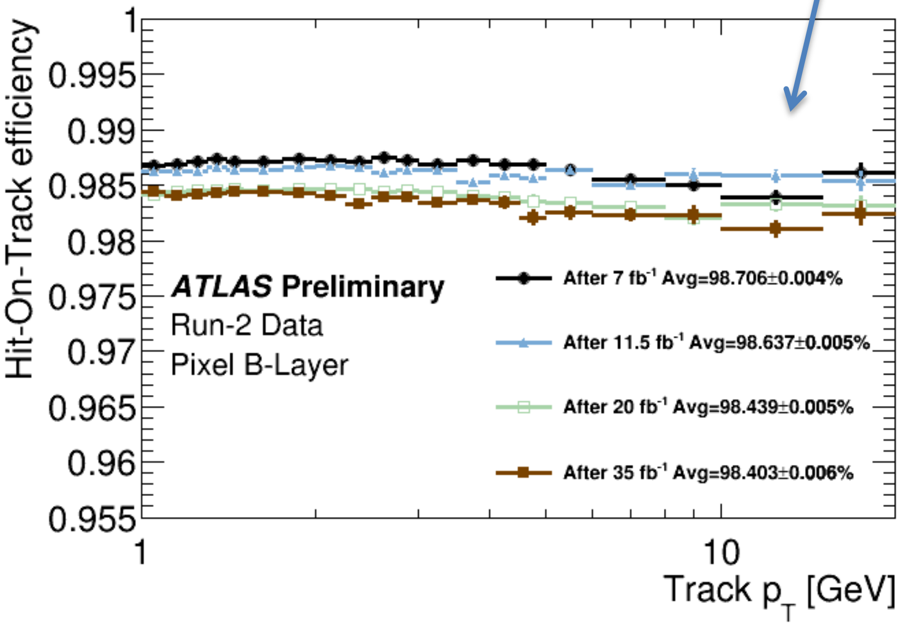
Layer	2018		2023		2024	
	Disabled/Total	%	Disabled/Total	%	Disabled/Total	%
Disks	15/288	5.2	13/288	4.5	16/288	5.5
B-Layer	18/286	6.2	15/286	5.2	21/286	7.3
Layer 1	29/494	5.8	22/494	4.4	18/494	3.6
Layer 2	33/676	4.8	43/676	6.3	50/676	7.4
Total (Pixel)	**95/1744**	**5.4**	**93/1744**	**5.3**	**105/1744**	**6.0**
IBL (Frontends)	3/448	0.7	4/448	0.9	4/448	0.9
Total	**98/2192**	**4.5**	**97/2192**	**4.4**	**109/2192**	**5.0**

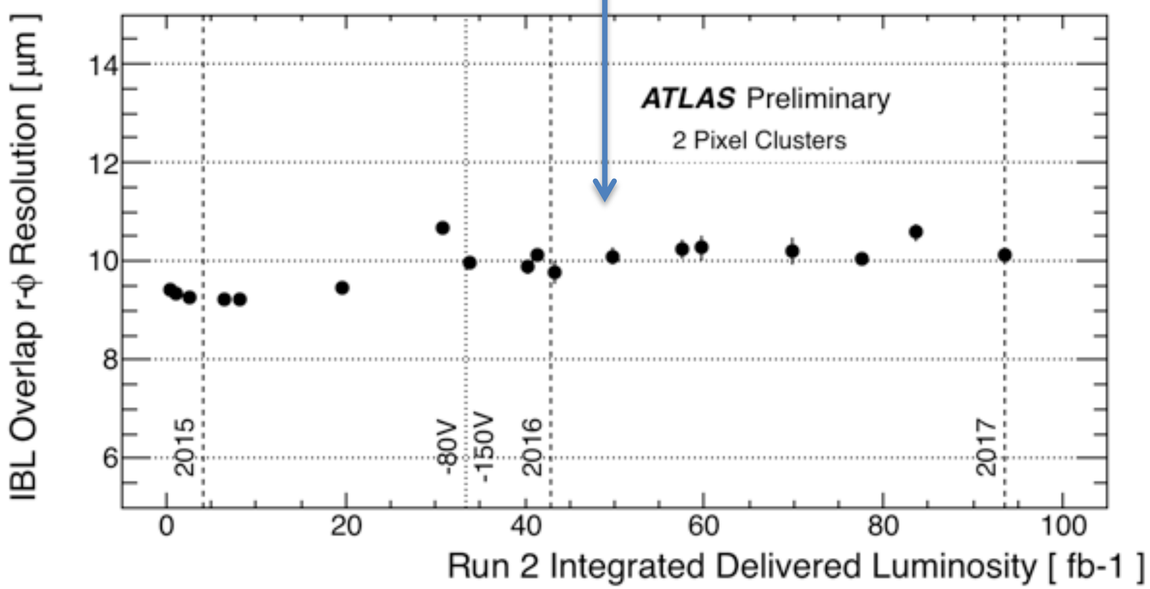
95% detector working fraction!

Pixel performance in Run 2



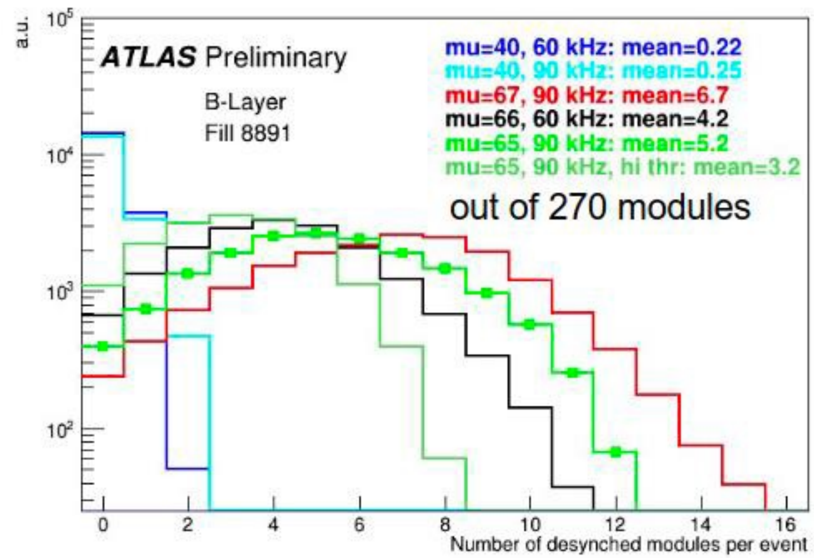
- **Impact parameter resolution** improvements after IBL insertion (2015)
- B-Layer **Hit-on-track efficiency > 98%** (2016)
- IBL **spatial resolution** (transverse R-φ plane) **~< 10 μm** over Run 2.

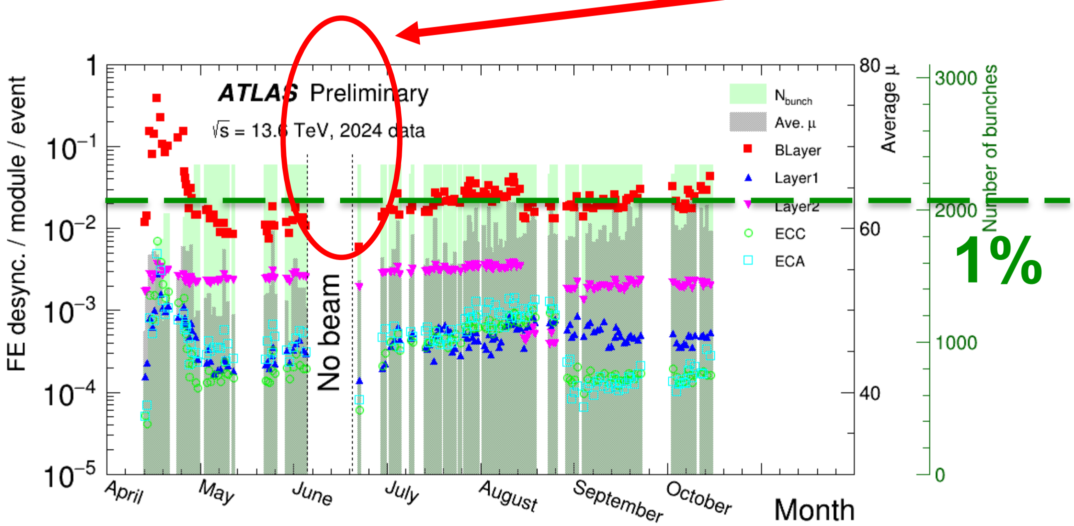


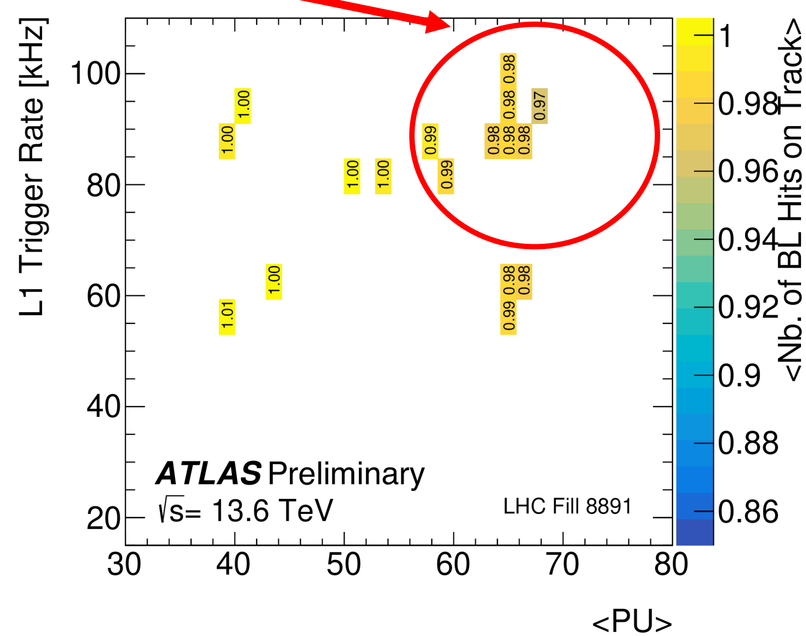


Pixel operation: FE Desynch

- Remaining de-synchronization is internal to the modules (16 FEs sharing the same micro-controller chip - MCC)
- Single FE can desynchronize, until next ATLAS Event Counter Reset (ECR), issued every 5 seconds.
- Increasing thresholds can mitigate the desync, as far as don't impact cluster properties/hits-on-track efficiency.
- Direct relation between desynchronization and lack of hits-on-track
  - Problem typically correlated <u>with high-rate/mu</u> ➔ high bandwidth consumption.
  - Present also in fills with <u>low #bunches and high mu</u> ➔ related to spacing of triggers.

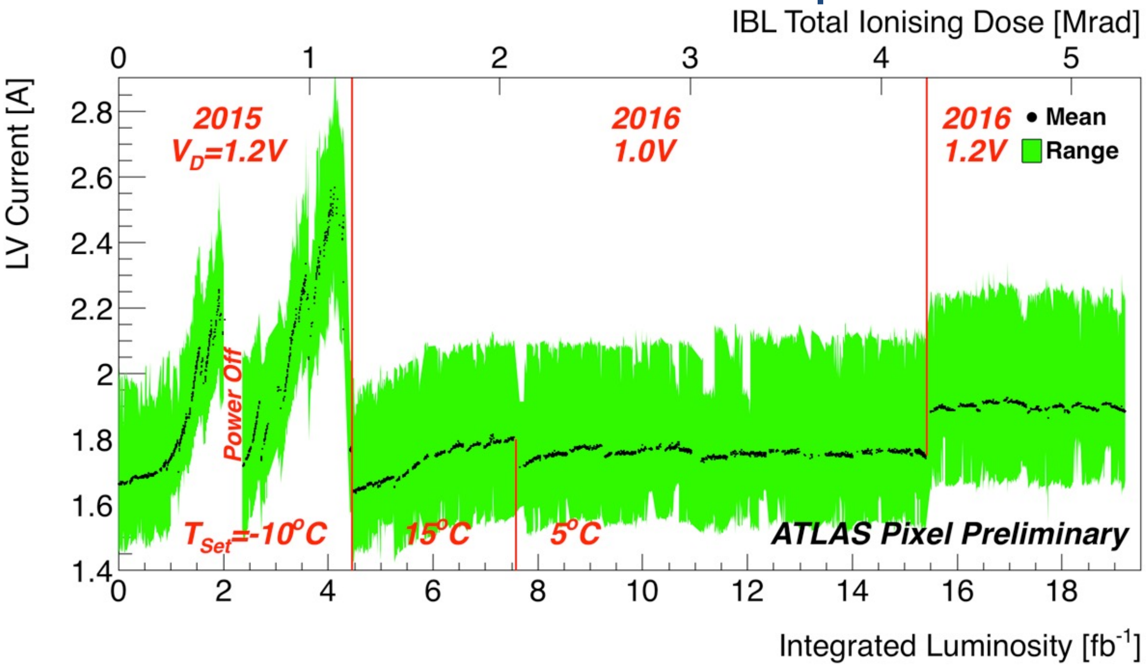


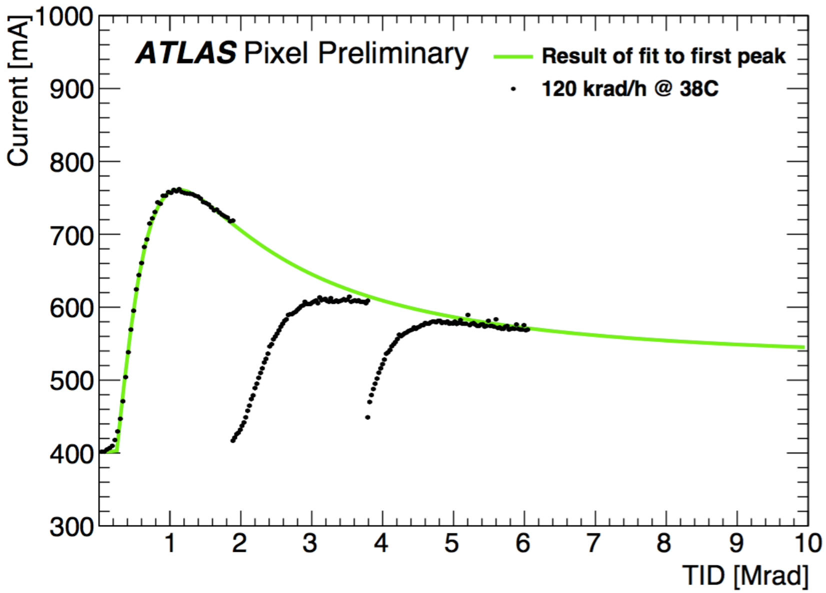




IBL TID at the begin of Run2

- IBL Total Ionizing Dose (TID) effect causing relevant increase of FE-I4 currents
  - Induced by the usage (~Millions) of 130 nm IBM transistor technology
    - Known to have a special leakage current evolution



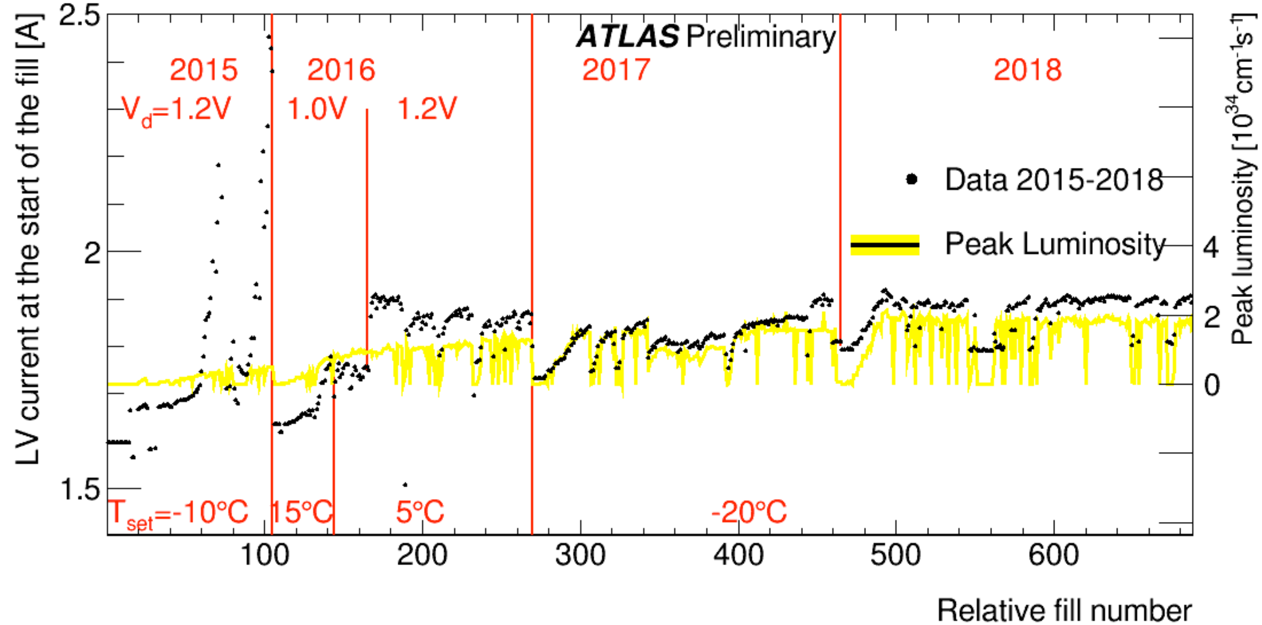


["Production and Integration of the ATLAS Insertable B-Layer"](#) JINST paper for more info about IBL

Impact of radiation on FE electronics: TID

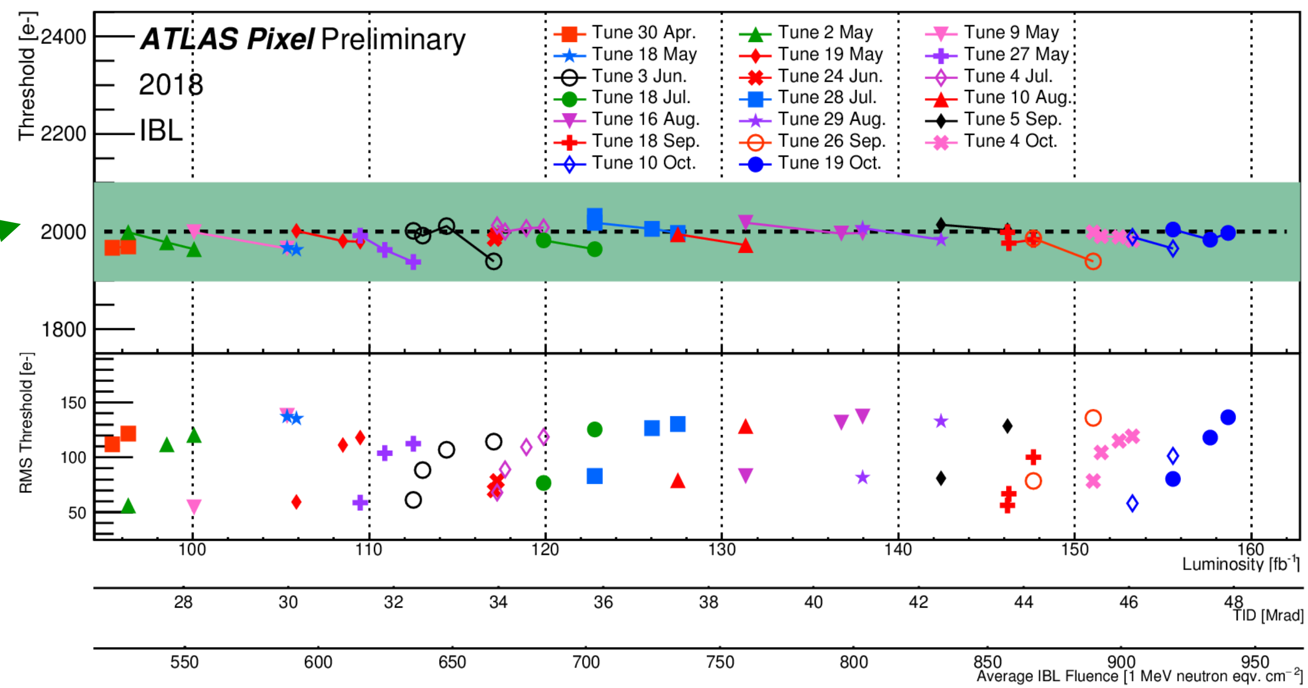
LV power system

- ➔ Low voltage current consumption heavily affected (2015-2016)
- ➔ under control by 2017, when correlation with Inst Luminosity become finally visible (digital activity in the chip)



FE-I4 (De)Tuning

- ➔ drift of **Thresholds** and **Time-Over -Threshold (TOT)**
- ➔ regular (~weekly) re-tuning needed during Run 2!

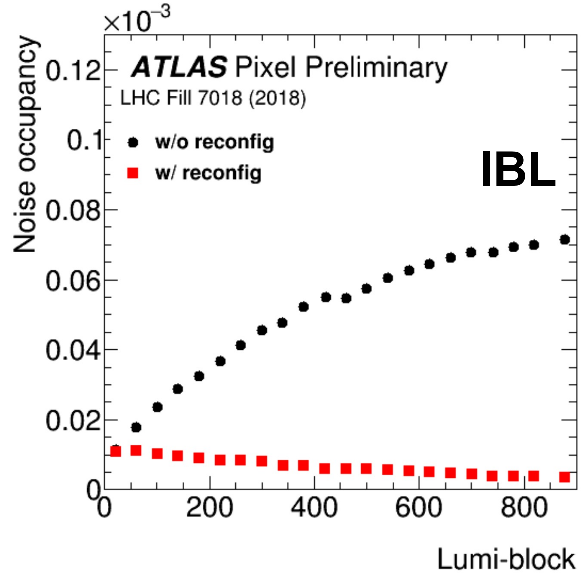


Radiation on FE electronics: SEE

Big charge deposit in FE electronics can flip the state of **global/local memory cells**

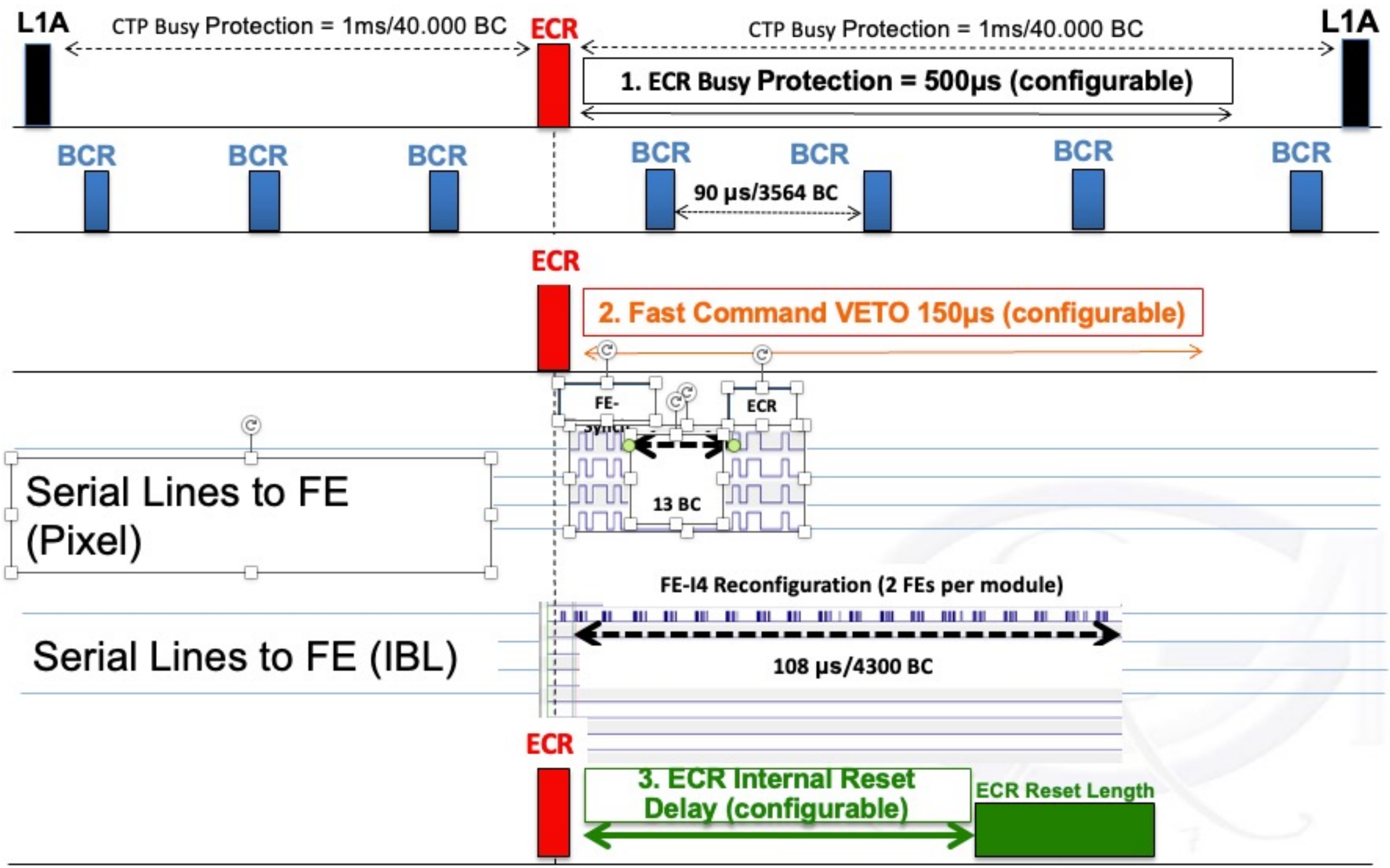
- IBL FE-I4 affected by SEE already in 2017
  ➔ **periodical reconfiguration of FE global registers.**
- Higher luminosity fill in Run 3
  ➔ SEE becoming relevant in **single pixel latches!**
  - **noisy pixels ..**firing whilst they should be masked.
  - **quiet pixel ..**stop firing during a fill.
- Solution: periodical reconfiguration of **single pixel registers** ➔ clear gain observed during test run (2018).

Measurements of Single Event Upset in ATLAS IBL

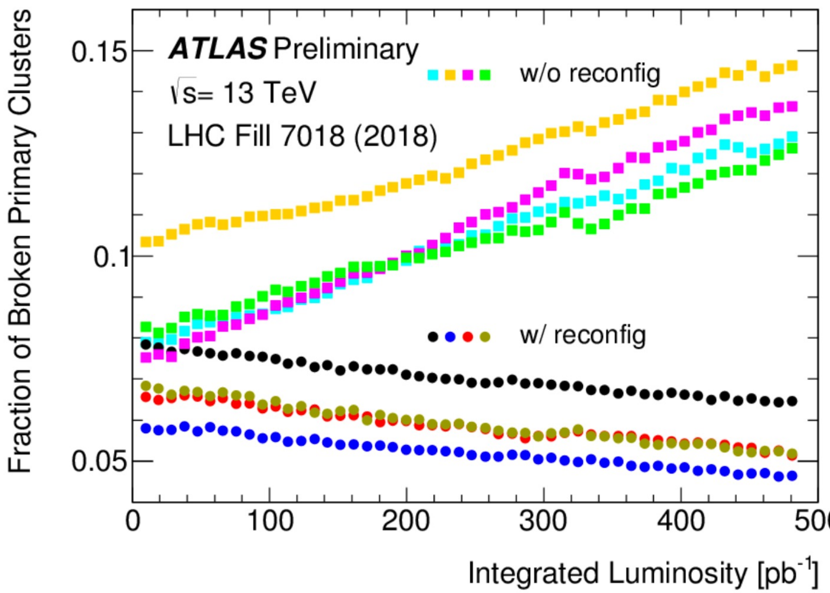


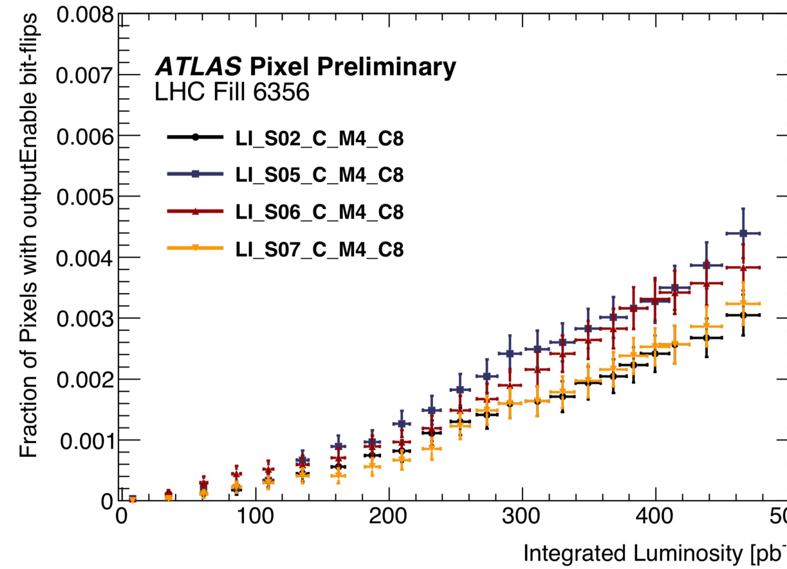
Run 3 strategy:
full FE reconfiguration
(completed gradually in ~11 minutes, without adding extra dead time to ATLAS)

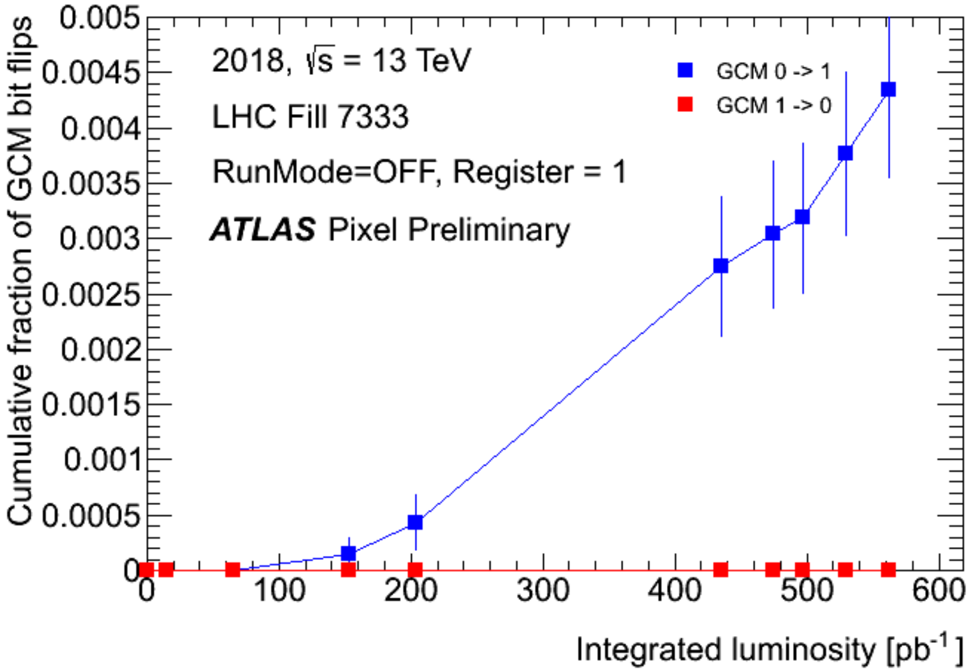
IBL register reconfiguration @ECR

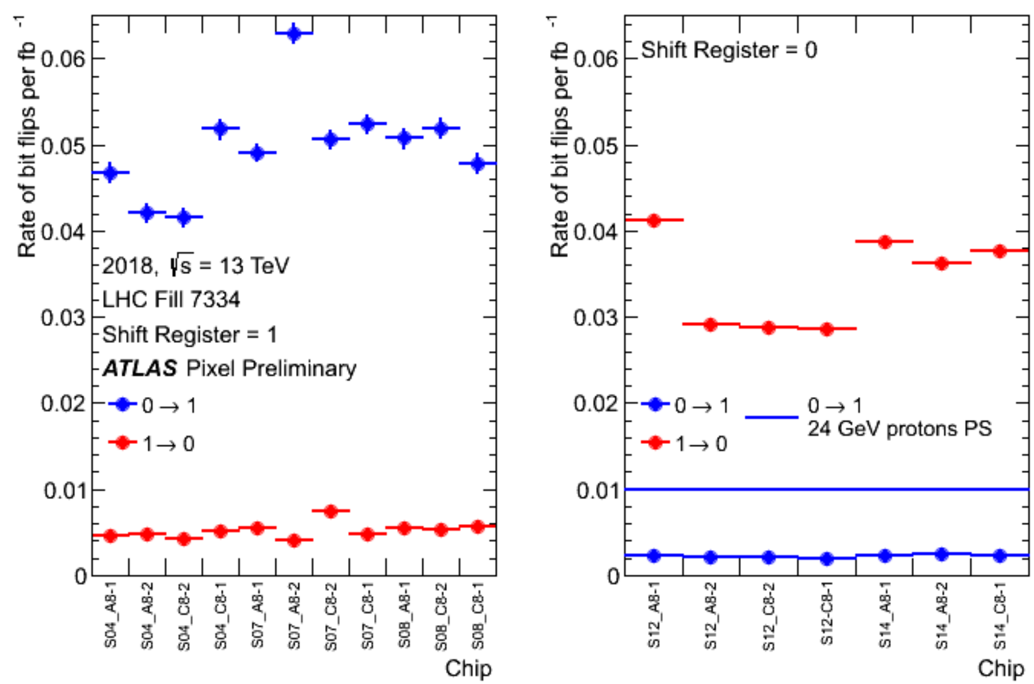


FE-I4 SEU studies



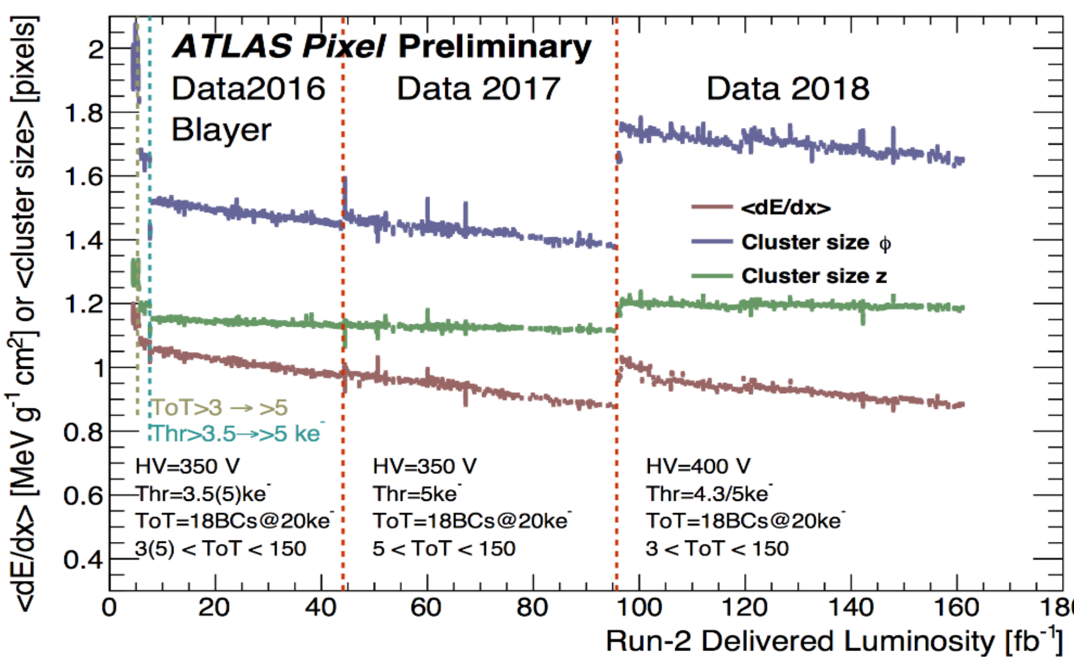


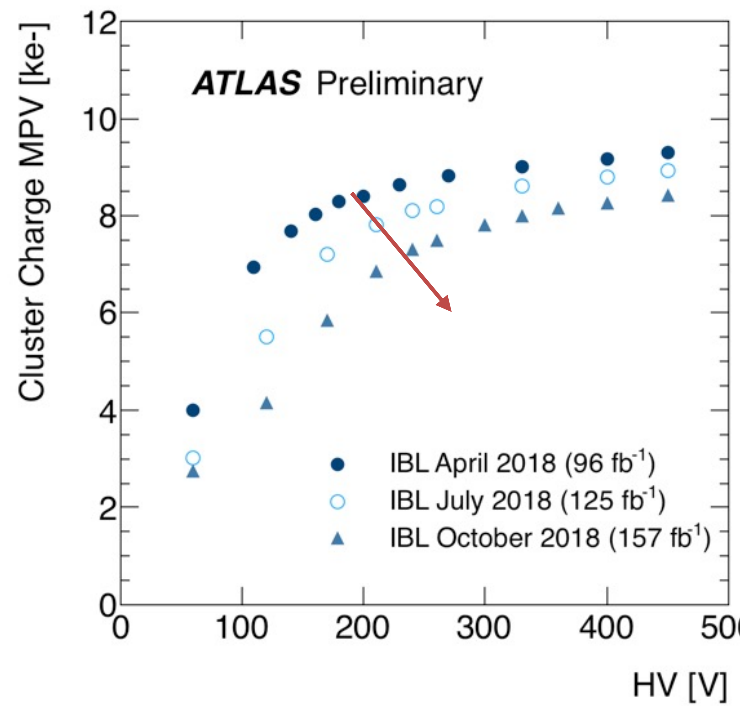




Impact of radiation on sensor

- **dE/dx and cluster size decrease** due to the decreased charge collection efficiency (slow slope).
- **HV (threshold) increase (decrease)** shows gain in dE/dx.
  - however, thresholds increased in 2016 due to bandwidth limitations (B-Layer).
- Charge collection constantly measured via **HV scans**
  - MPV of the fitted Landau cluster charge affected ➔ **decrease of plateau.**





Fighting radiation damage: configuration

- Readout electronics/services/module configuration were upgraded/replaced/changed to accommodate for **bandwidth limitations, hardware failures, radiation damage**.
  - Read out speed, Front-end latency, TOT target point for MIP ,Threshold modulation vs η, ..
- ***Sensor bias voltage (HV)*** and ***analog thresholds*** updated yearly!

Run 2 (2015–2018) | Run 3 (2022–2024)

Bias Voltages

	2015	2016	2016	2017	2018	2022	2023	2024
IBL-Planar	80 V	80 V	150 V	350 V	400 V	450 V	450 V	450 V
IBL-3D	20 V	20 V	20 V	40 V	40 V	60	60	70
B-Layer	250 V	350 V		350 V	400 V	450 V	450 V	500 V
Layer 1	150 V	200 V		200 V	250 V	300 V	350 V	350 V
Layer 2	150 V	150 V		150 V	250 V	300 V	350 V	350 V
Disks	150 V	150 V		150 V	250 V	300 V	350 V	350 V

Analog Thresholds

	2015	2016	2016	2017	2018	2022	2023	2024
IBL	2500e	2500e		2500e	2000e	1500e	1500e	1500e
B-Layer	3500e	3500e/5000e		5000e	5000/ 4300e	4300/ 3500e	4700e	4700e
Layer 1	3500e	3500e		3500e	3500e	3500e	4300e	4300e
Layer 2	3500e	3500e		3500e	3500e	3500e	4300e	4300e
Disks	3500e	3500e		3500e	3500e	3500e	4300e	4300e

Pixel "Hybrid" threshold

Threshold	2017	2018
IBL	2500e, ToT>0	**2000e**, ToT>0
B-layer	5000e, ToT>5	**4300e(*), ToT>3**
Layer-1	3500e, ToT>5	3500e, ToT>5
Layer-2	3500e, ToT>5	3500e, ToT>5
Endcap	4500e, ToT>5	**3500e**, ToT>5

*** central Eta: 4300e   high Eta: 5000e**

Run 2 Bias Voltage Evolution

HV	2015	2016	2017	2018
IBL	80V ⇨	150V ⇨	350V ⇨	400V
B-layer	250V	350V	350V	400V
Layer-1	150V	200V	200V	250V
Layer-2	150V	150V	150V	250V
Endcap	150V	150V	150V	250V

Keep adjusting threshold and HV but… **limitations on the read-out bandwidth** if thresholds decreased too much!

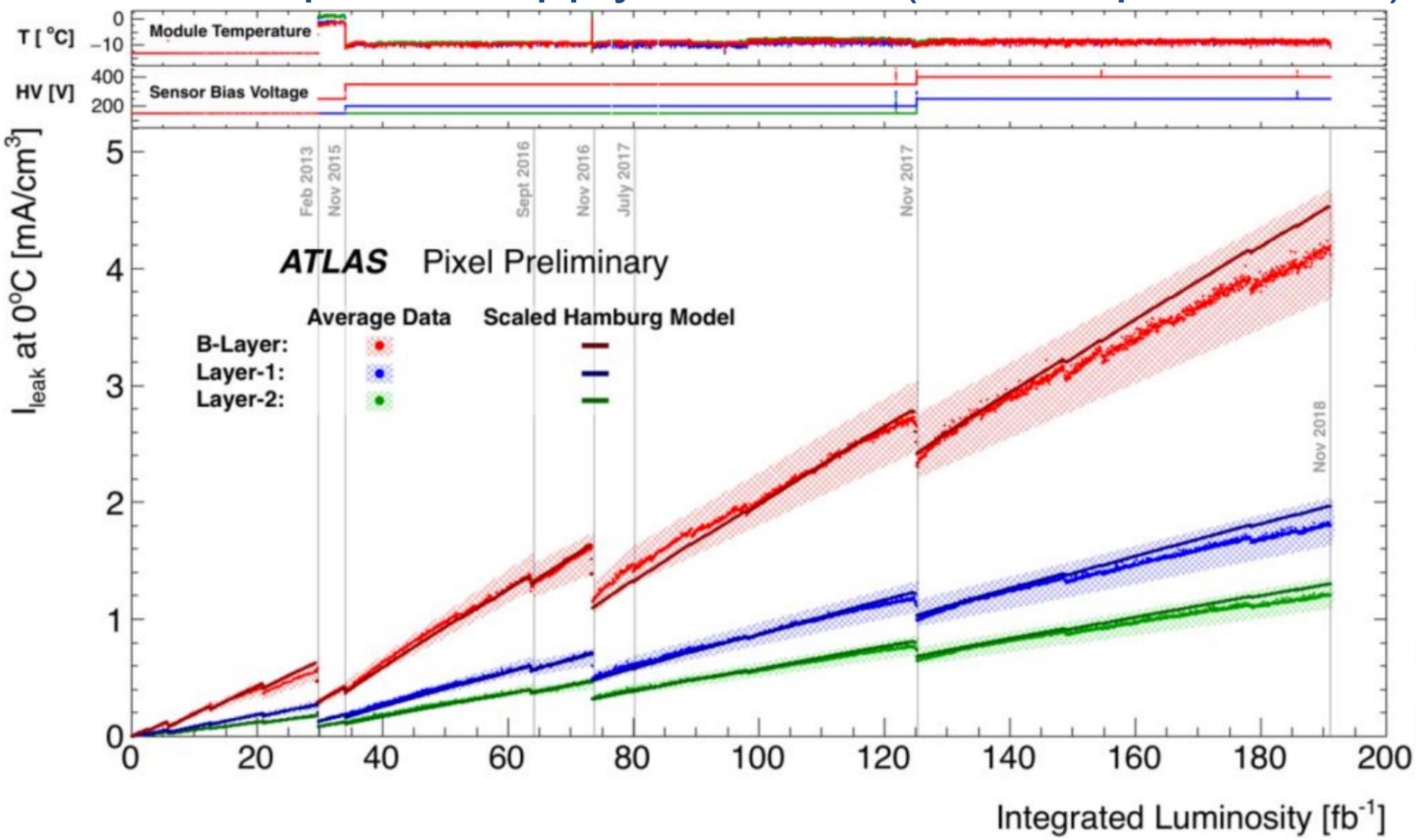
ATLAS Run2 benchmark

L1Trigger = 100 kHz
<μ> = 60

➔Module to read-out system bandwidth usage needs to stay within 80%

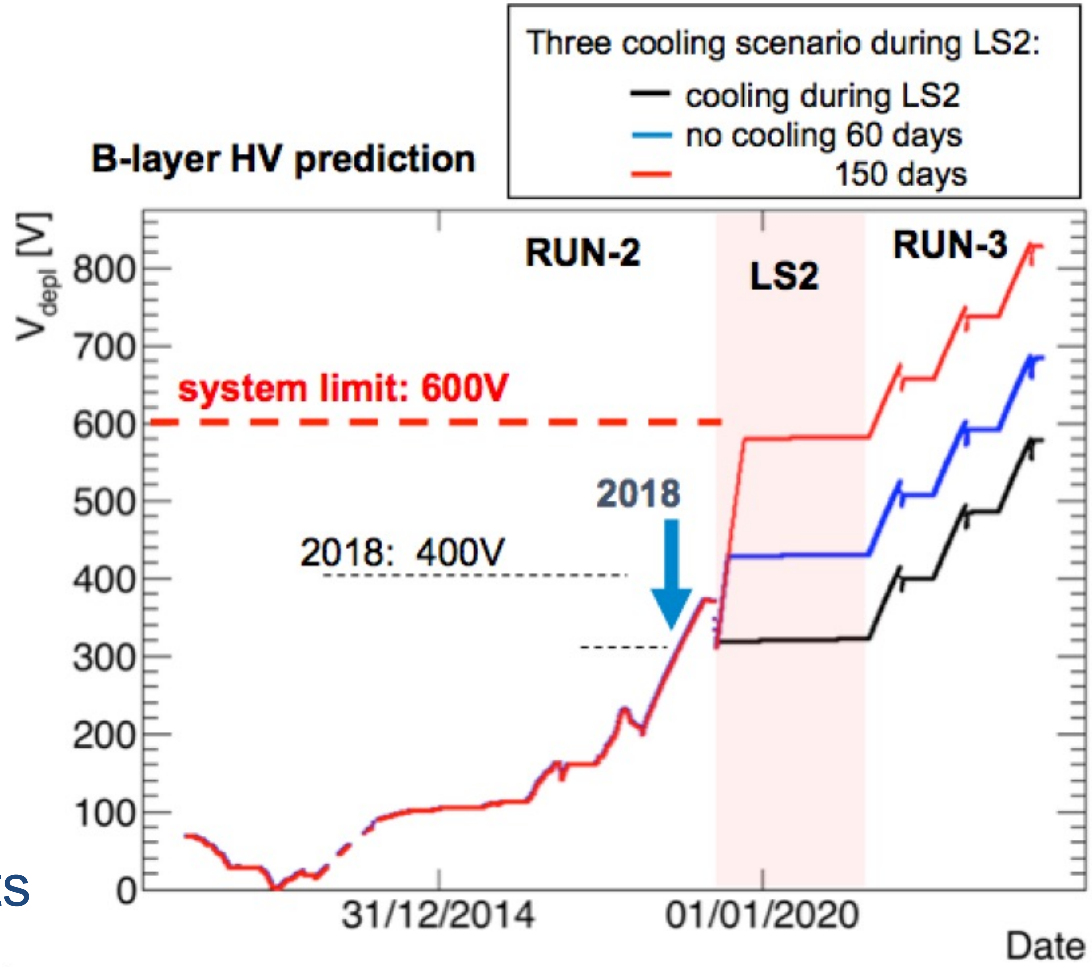
Pixel Leakage currents

- Measured leakage currents quite well described (annealing, temperature dependence) by the Hamburg Model but:
  - scaling factor per layer and z bin is required
  - towards the end of Run 2, the leakage currents seem overestimated.
- **Pixel:** Leakage current per module expected at the end of Run 3 within the power supply limitation (< 2 mA per sensor).



Fighting the reverse annealing

- **Keeping the detector cold during LS2** to prevent reverse annealing
  ➔ keep the depletion voltage under control (B-layer, IBL).
- Warm up periods unavoidable due to the ID maintenance during LS2
- Target to stay **warm for < 60 days** during the LS2.
- Detector warm for **43 (23) days** in Pixel (IBL)
- Exploring colder operating set points (-25^{o}C/-30^{o}C).for late Run 3.



Radiation damage MC

- New Pixel digitization model was developed and is now under validation before entering the official ATLAS simulation

  Recent paper available here: JINST 14 (2019) 06 P06012

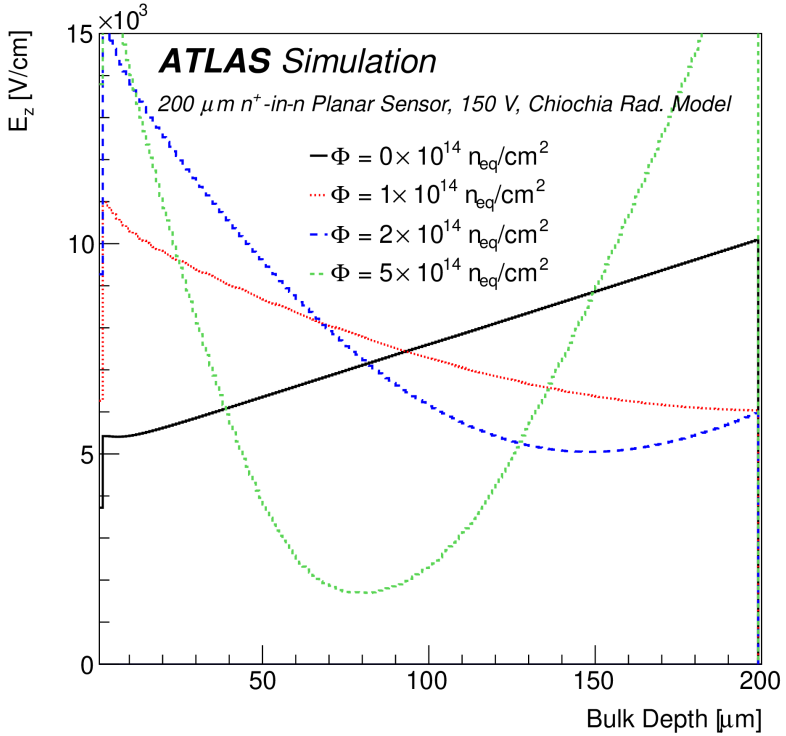
- Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage (double peak)**.
- Their path will be deflected by magnetic field (Lorentz angle) and diffusion.
- Electron and hole lifetime inversely proportional to fluence:

  ➔ **charge trapping**,

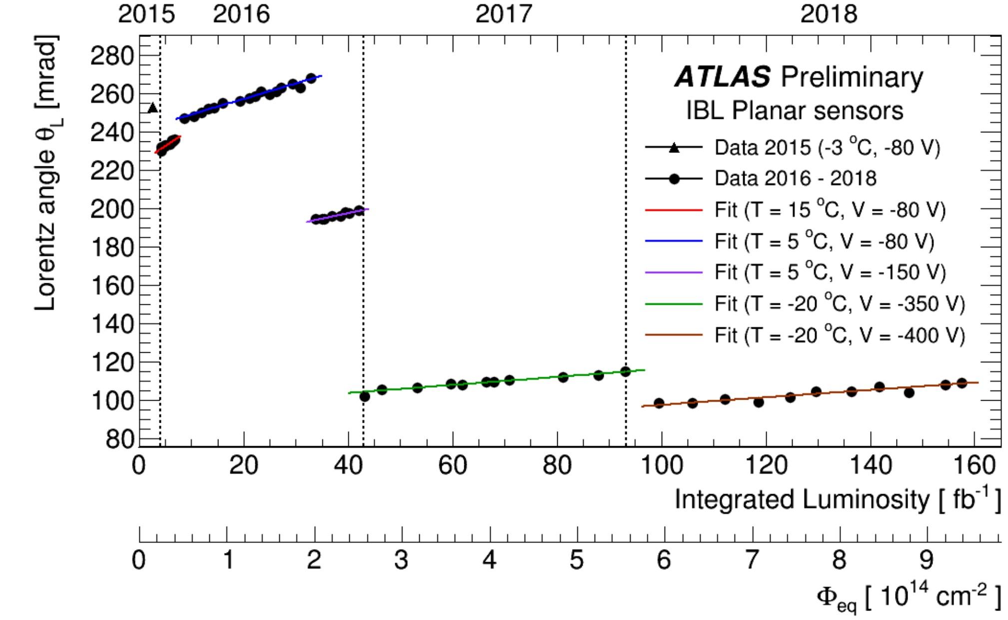
  ➔ reduction of the collected charge.

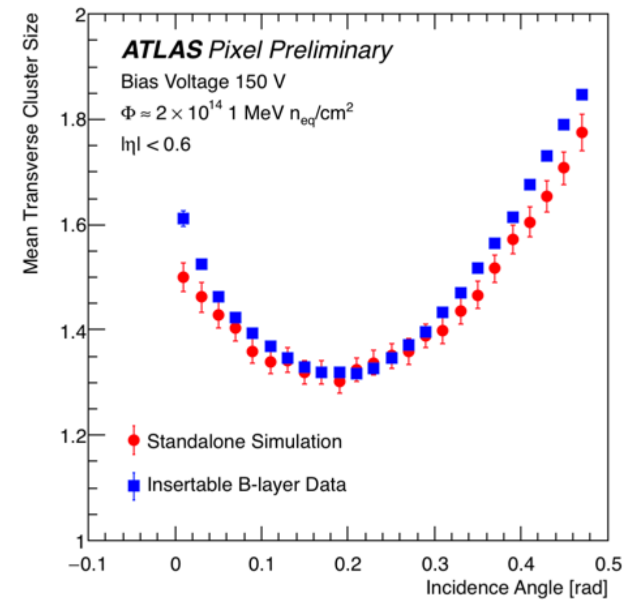
- Available for both **Planar** and **3D** sensors.

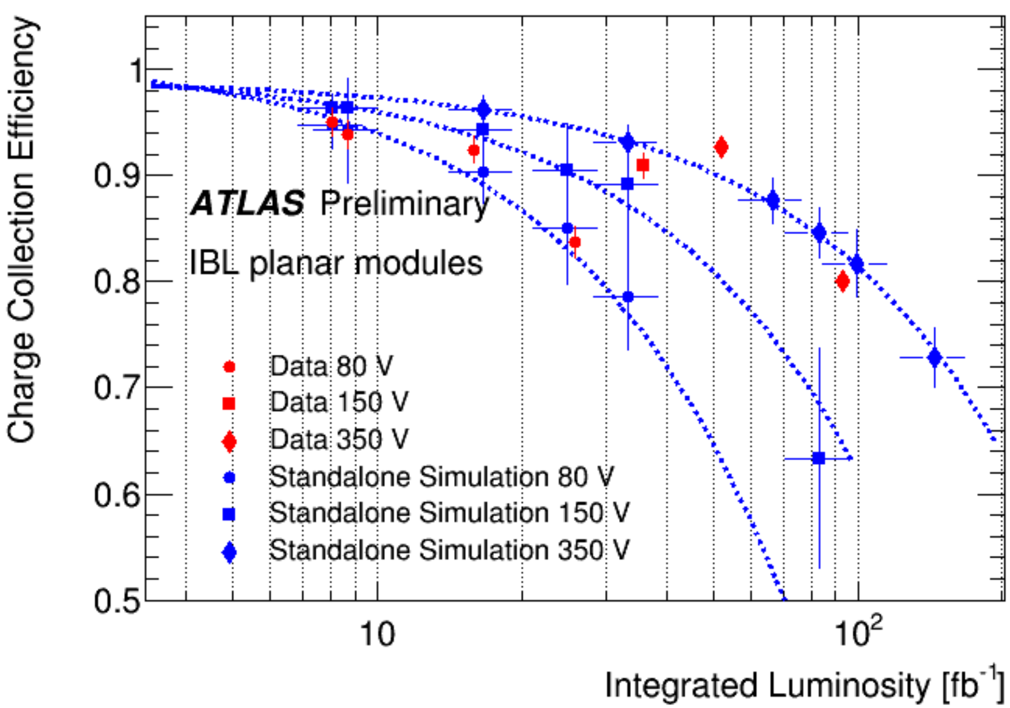
  ➔ due to performance constraints (CPU), not used in IBL 3D and Pixel Disks

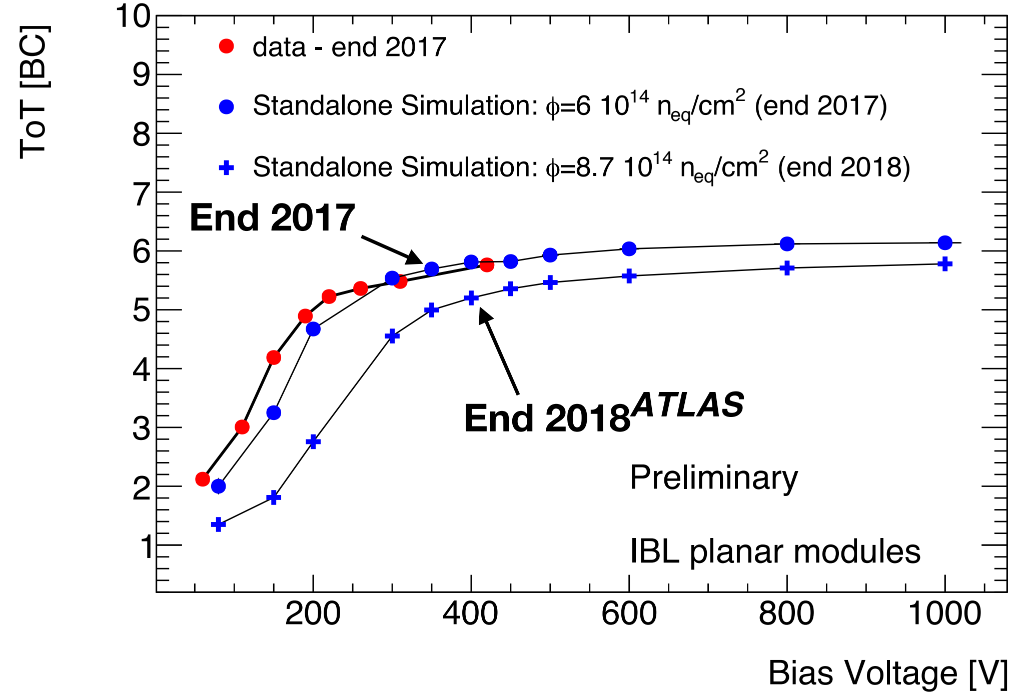


Modelling the radiation damage in the sensor

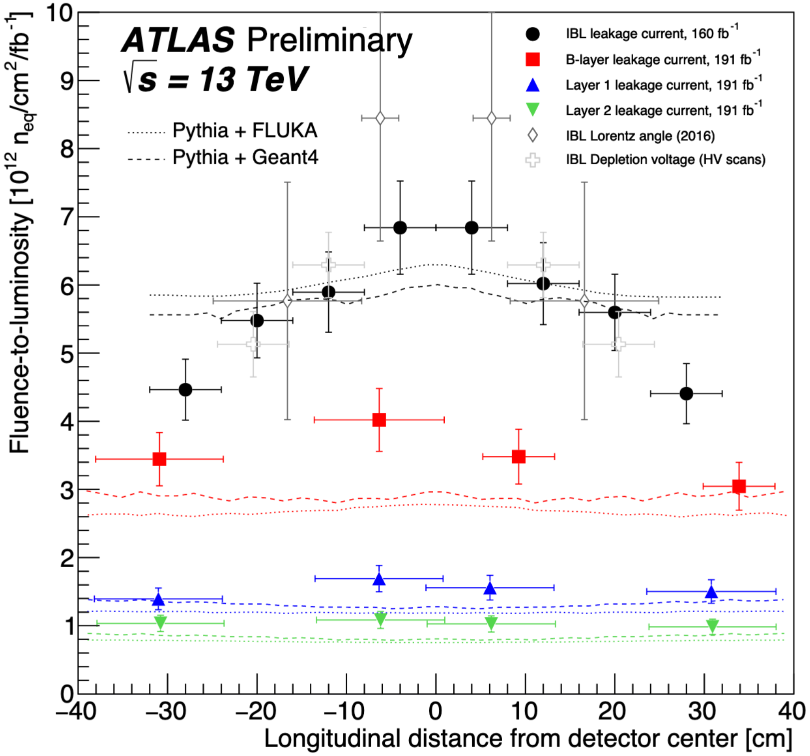






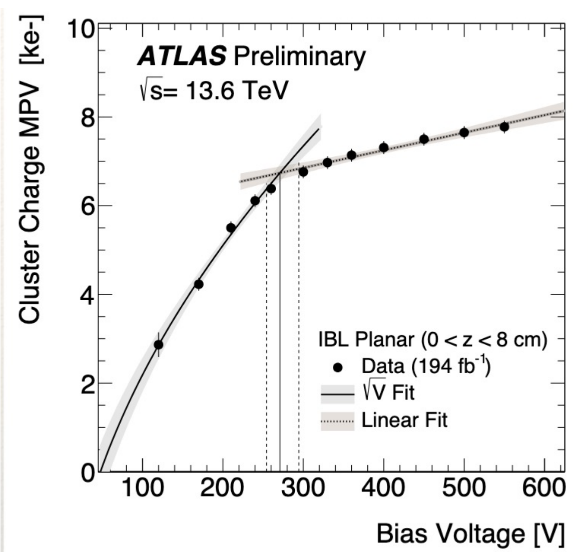


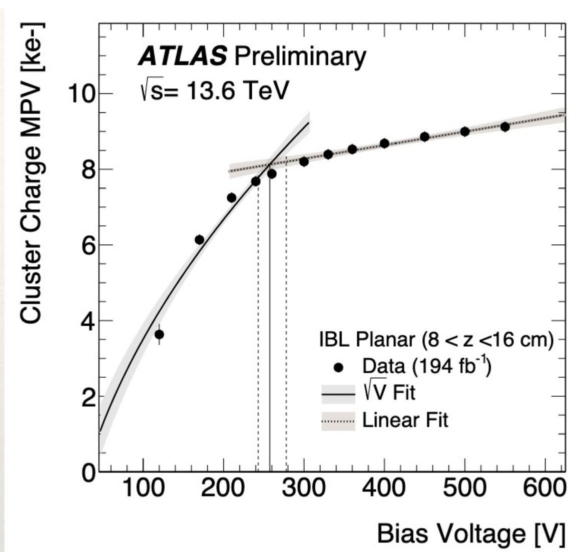
z-dependence comparisons

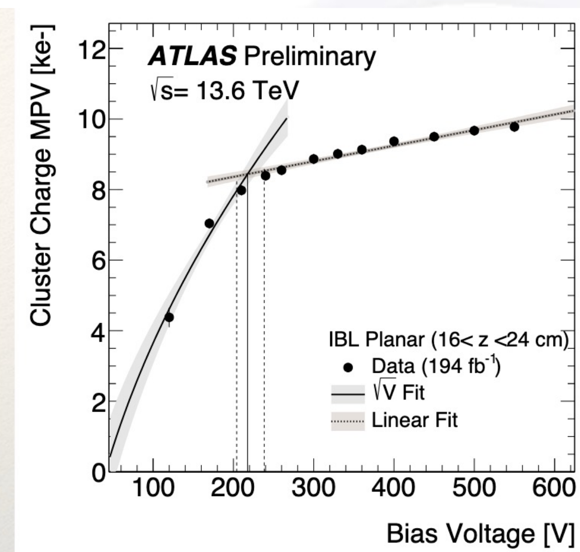


Fluence-to-luminosity conversion factors extracted from the leakage current, Lorentz angle and Depletion Voltage measurements:

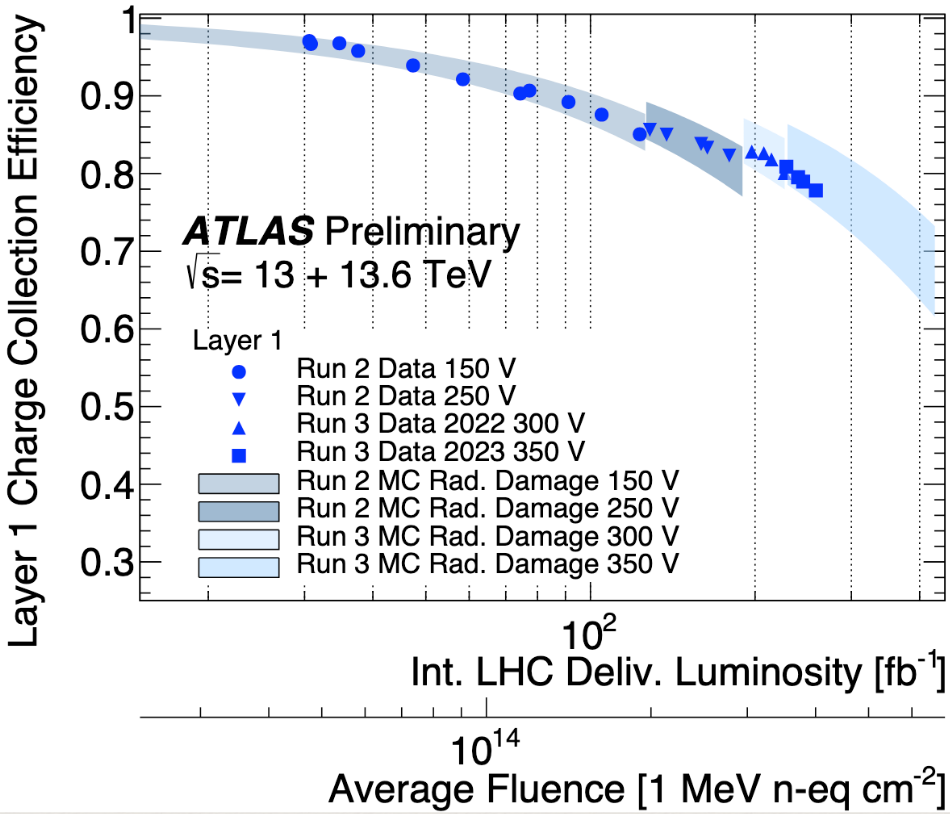
- **less fluence at at high |z| on IBL data** respect to Pythia + FLUKA/Geant4 predictions
- more flat distributions in outer Pixel layers.

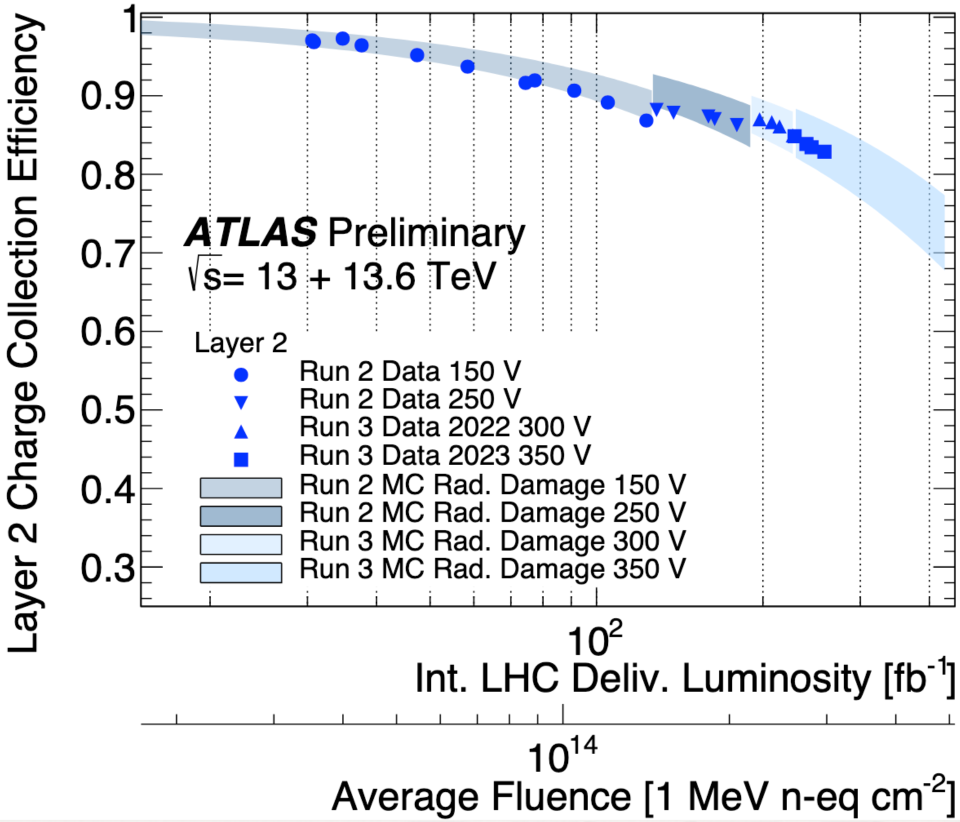






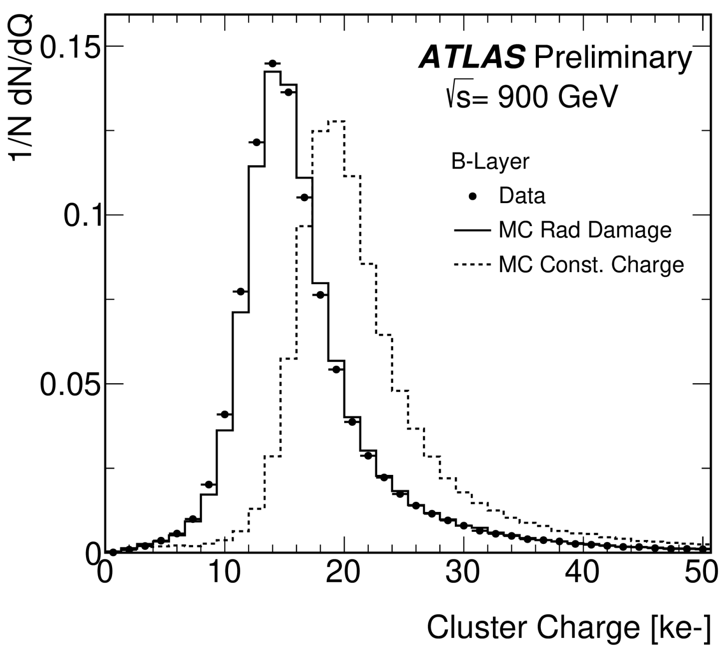
Outer Pixel layers



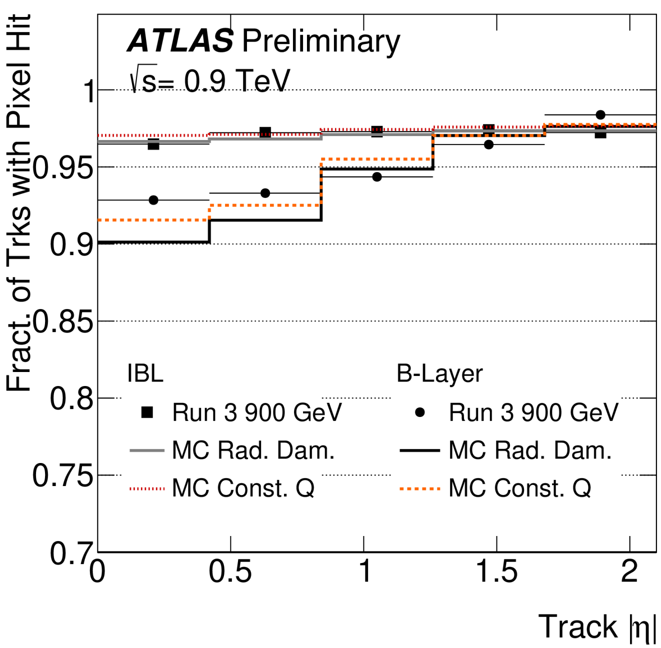


PUB Note on first Run 3 collisions

- End of LS2 (cosmics) and begin of Run 3 (900 GeV collisions) used to test new configurations with **increased HV** and **lowered thresholds**.
- Effect of radiation damage on cluster charge data, **very well reproduced** by new **Radiation Damage MC!**
- Fraction of tracks with Pixel hits slightly affected in the central part of the detector (short silicon path traversed and higher radiation damage).



HV	Run 2 (End Of)	Run 3 (Start of)
IBL Planar IBL 3D	400 V 40 V	450 V 60 V
B-Layer	400 V	450 V
Layer 1	250 V	300 V
Layer 2	250 V	300 V
Disks	250 V	300 V



Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at 900 Gev

Spatial resolution

- Spatial resolution (r-phi and z) computed using the overlap region:
  - **well reproduced** by new **Radiation Damage MC.**
  - **data improvements by using NN training on Rad. Dam. MC samples.**
- Limited effect of radiation damage on the tracking performance for the Run 2 fluence: impact parameter $\mathbf{d_0}$ resolution **well reproduced** by both MC.