GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

ATLAS EXPERIMENT

Radiation damage effects in the ATLAS Pixel detector at the LHC:

(or how to face operation and performance challenges induced by high radiation)

Marcello Bindi

on behalf of the ATLAS Collaboration

IPRD2023

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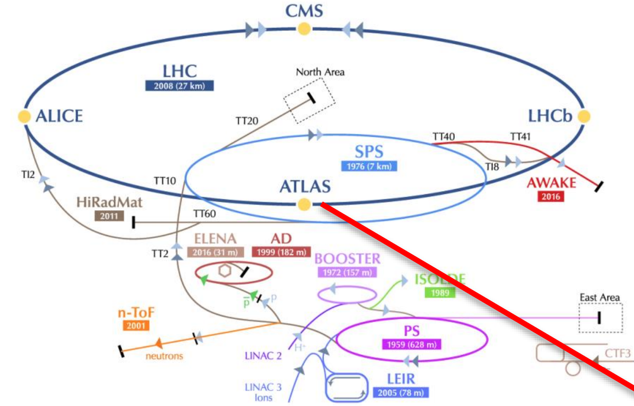
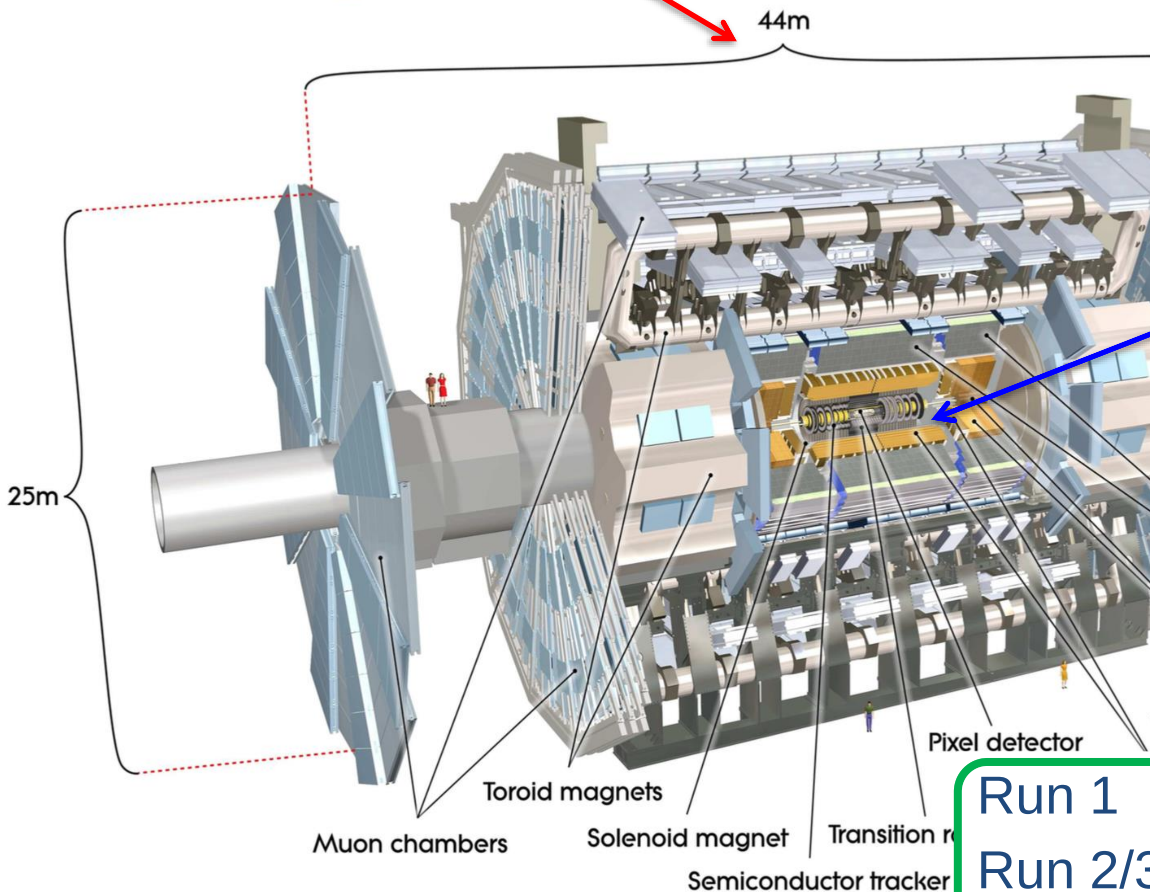
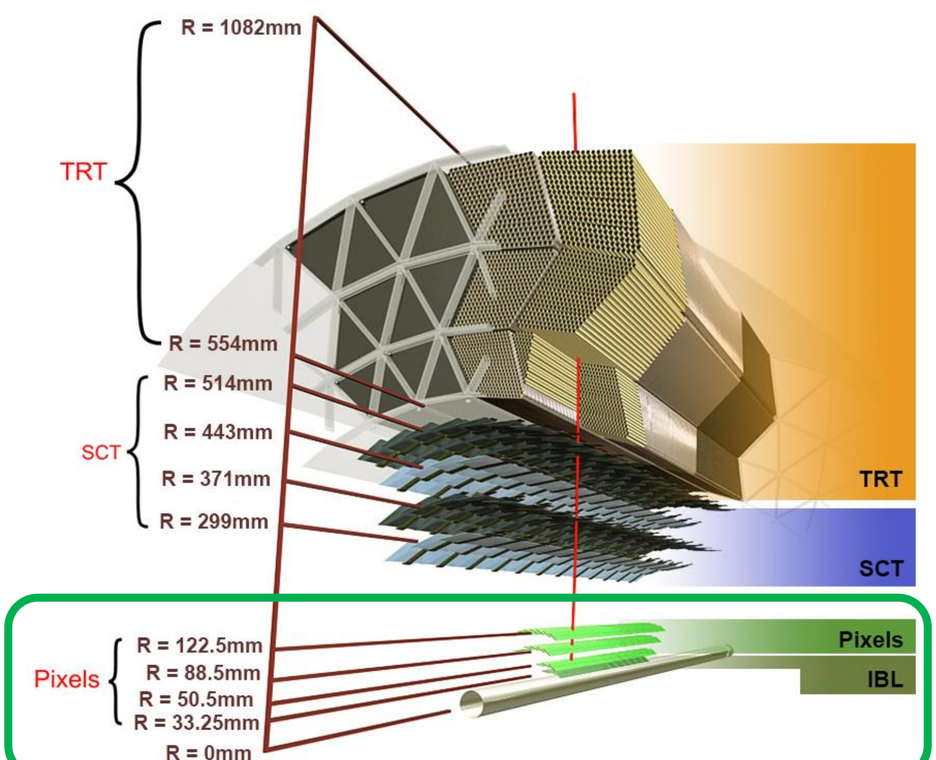
The ATLAS detector @ LHC





ATLAS **Inner Detector (ID)** tracker

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



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

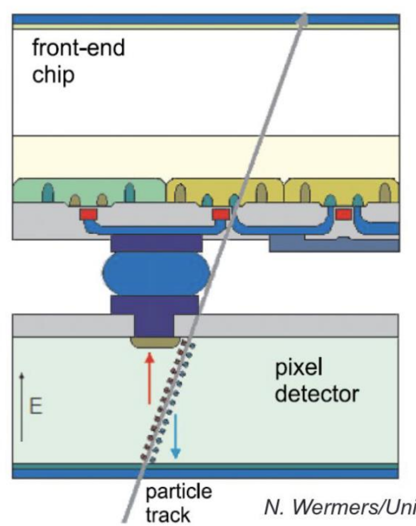
The Pixel (+ IBL) detector

	Pixel (3 layers)		IBL (1 layer)
Sensor Technology	n^+-in-n (only planar)		n^+-in-n and ***n*⁺-in-*p*** (planar and **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) ~ 1×10^{15} $n_{eq} \cdot cm^{-2}$		**250 Mrad** ~ 5×10^{15} $n_{eq} \cdot cm^{-2}$
Barrel <Radius> or EndCaps $Radius_{Min}$	**B-Layer**	**5.0 cm**	**3.3 cm**
	Layer 1	8.8 cm	
	Layer 2	12.2 cm	
	EndCaps	8.9 cm	

- **~ 2000** hybrid modules
- **~ 92 M** channels
- **~ 2 m²** of silicon

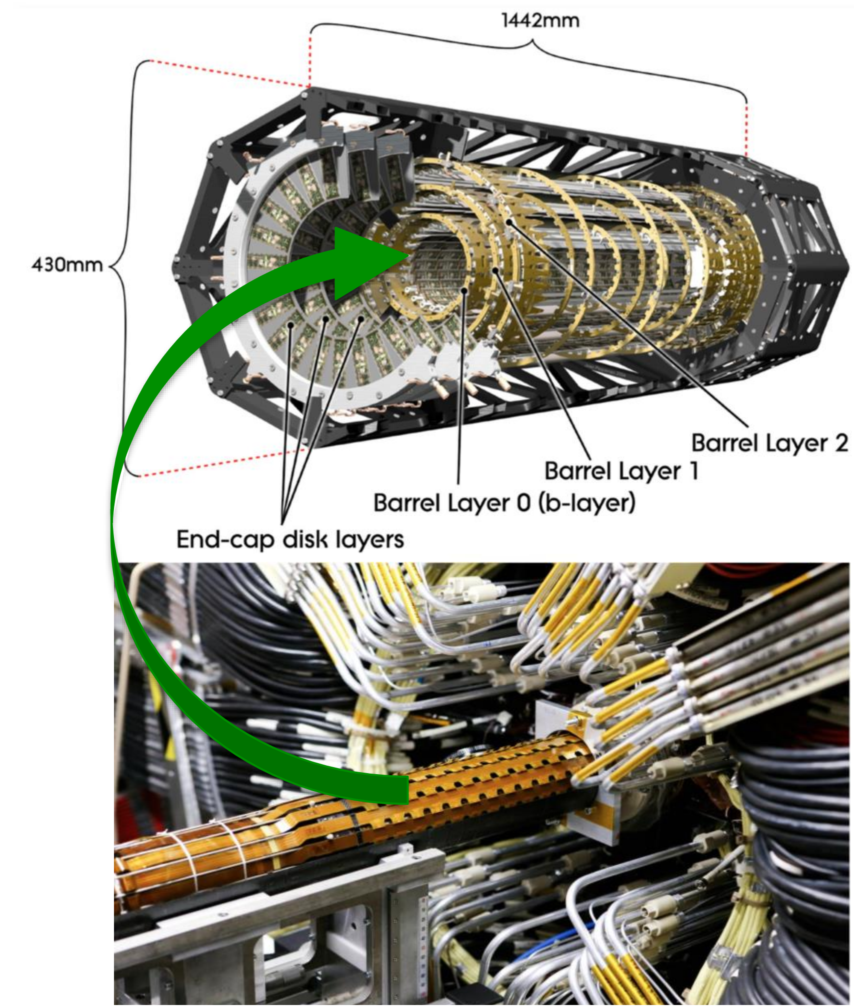
"ATLAS pixel detector electronics and sensors"

"Production and Integration of the ATLAS IBL"



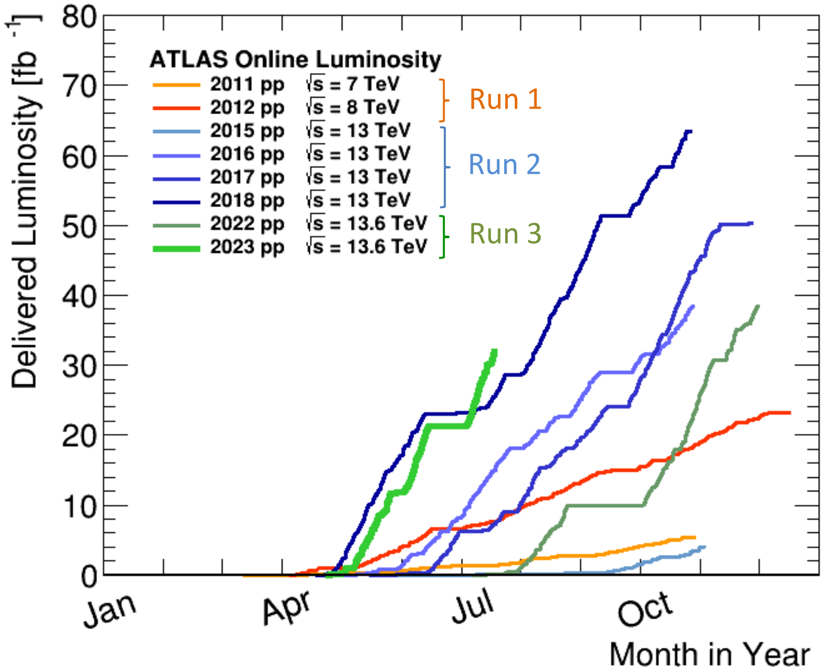
3 + 1 pixel **layers in barrel**

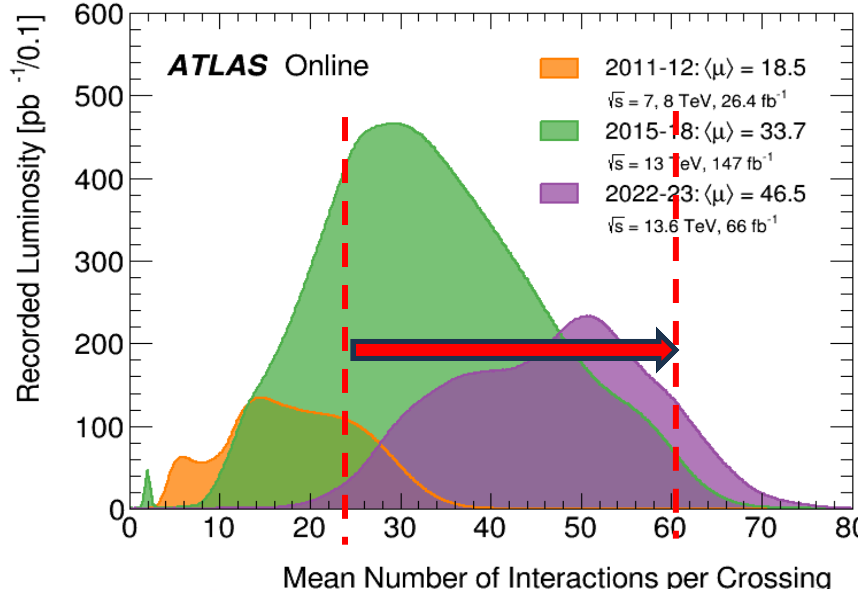
2 x 3 pixels **endcaps**



Insertable B-Layer (IBL) added before Run 2

LHC conditions: a long history.

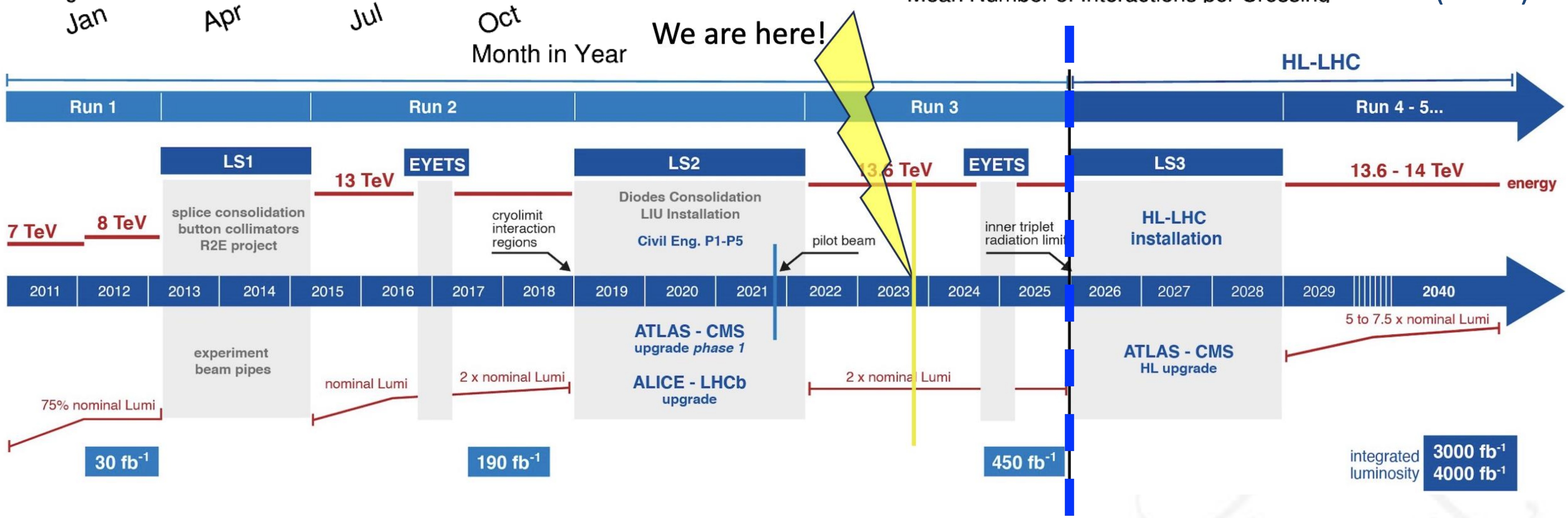




PILE UP
(p-p collisions/BX)

Design
μ = 23

Reality
Up to μ = 60
(2023)



The ATLAS ITk Pixel Detector: the biggest challenges from design to construction
The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

Decommissioning ATLAS ID → Installation ATLAS ITk

Pixel operation challenges at LHC

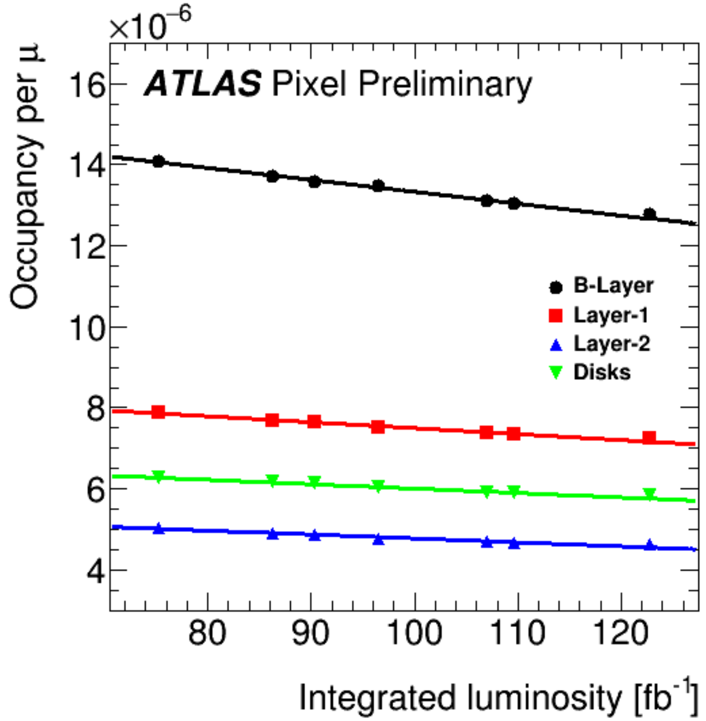
Accumulated radiation

driven by the integrated luminosity

Signal reduction is the most important radiation damage effect on silicon

➔ decrease of **charge collection efficiency**

➔ decrease of hit occupancy (2017)



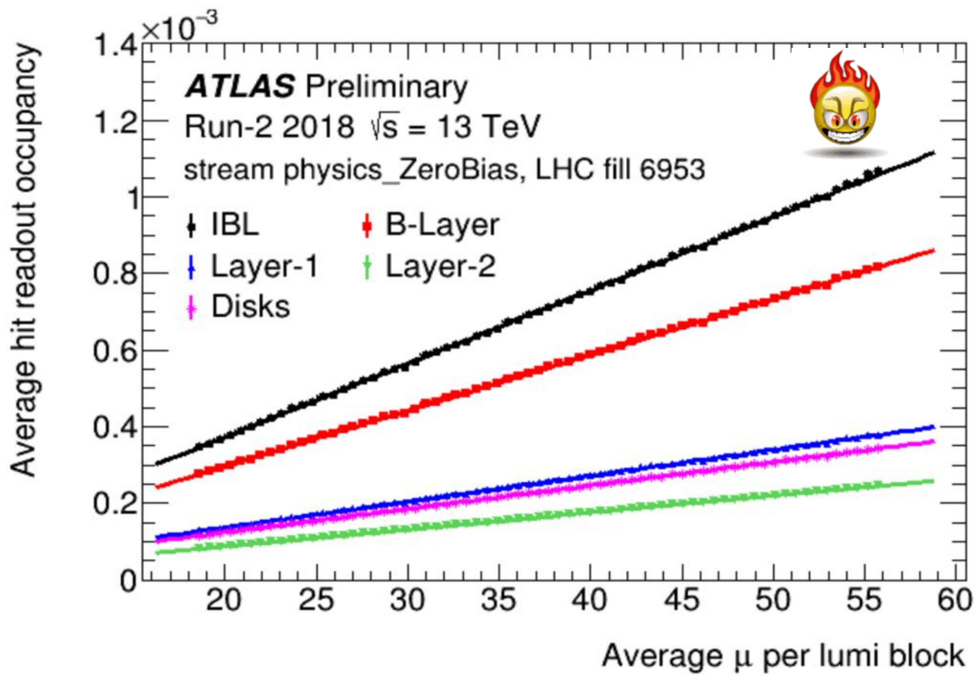
Particle hit rate

driven by high number of p-p collisions ***(pile up)*** *per time unit (25 ns bunch crossing)*

Occupancy (hit/pixel/event) scales linearly with pile up **(μ)**

➔ **big event size** and typically **high trigger rate (~100 kHz for high luminosity)**

➔ **high link bandwidth usage (~80%) !**



Accumulated Fluence and Dose

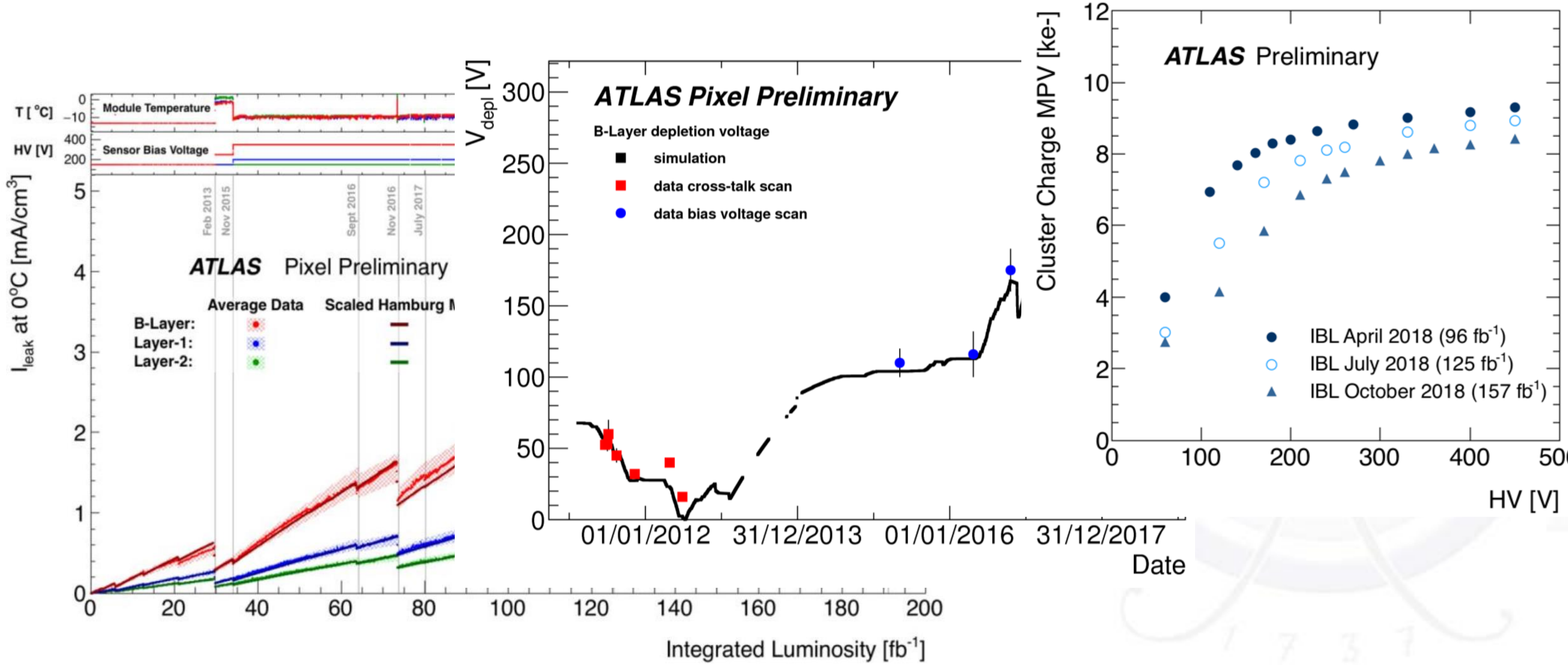
Integrated Luminosity for Pixel (all but innermost layer) : ~ 260 fb^{-1}
IBL (innermost layer since 2014): ~ 230 fb^{-1}
Run 3 plans (till end of 2025): + ~ 160 fb^{-1}

➔ Pixel B-Layer will exceed the design values for both sensor (Fluence) and Front-End electronics (Dose) !

Layer	IBL			B-Layer		
time	Int. Lumi [fb^{-1}]	Fluence [n_{eq}/cm^2]	Dose [Mrad]	Int. Lumi [fb^{-1}]	Fluence [n_{eq}/cm^2]	Dose [Mrad]
End of Run2	161	~ 9×10^{14}	~ 53	190	~ 7×10^{14}	~ 28
Till now	230	~ 12×10^{14}	~ 76	260	~ 10×10^{14}	~ 38
End Run3 (proj.)	395	~ 21×10^{14}	~ 130	425	~ 15×10^{14}	~ 63
Max by design	-	~ 50×10^{14}	~ 250	-	~ 10×10^{14}	~ 50

Impact of radiation on sensors

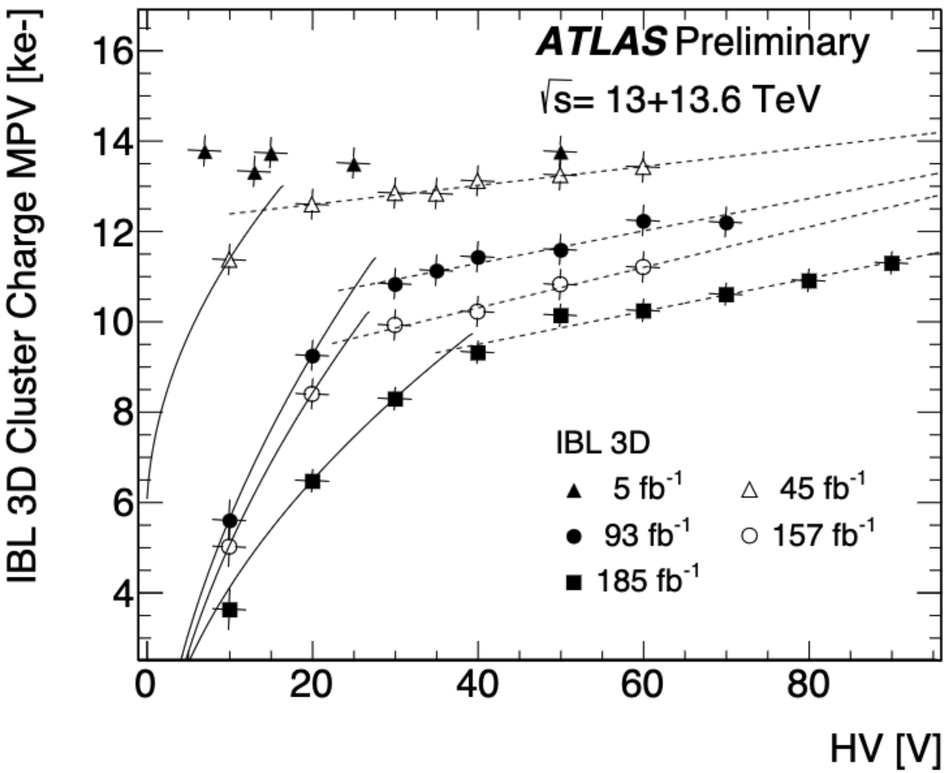
- Performance degradation mostly originating from non-ionizing energy loss (NIEL) → displacement damage in silicon bulk (defects with energy levels in the bandgap).
- Macroscopic effects:
  1. Increase of leakage current (Proportional to particle fluence)
  2. Change of depletion voltage (Change of space charge distribution)
  3. Decrease of charge collection efficiency (Signal reduction due to Trapping)

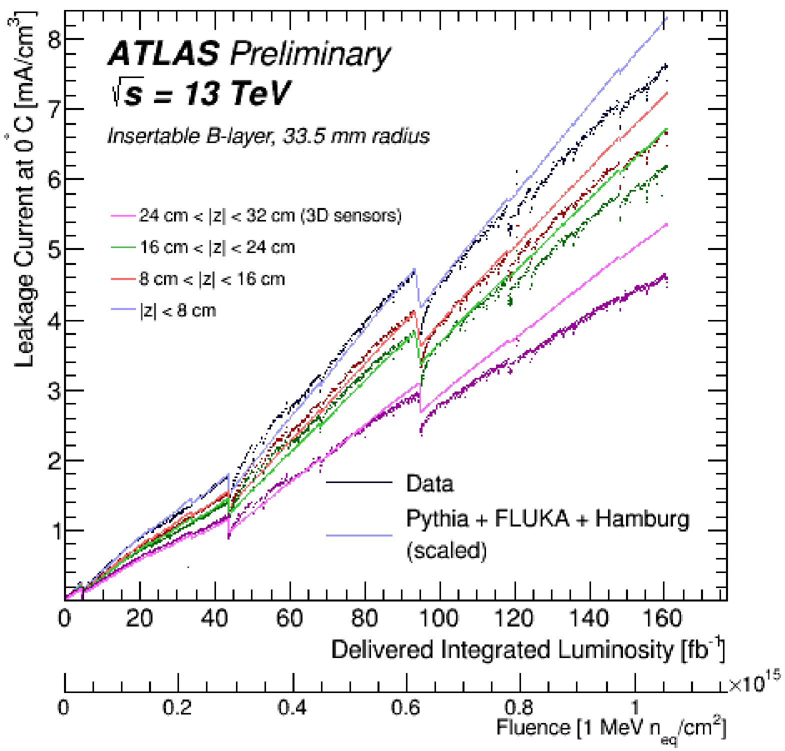


Depletion voltage/leakage current

- **Higher bias voltages needed** to guarantee a full depletion region.
- Bias voltage scans with collisions regularly performed at the begin/end of each year to confirm/prepare set points.
- **Keep the detector cold (also during shutdown)** to prevent reverse annealing.

- **Leakage currents** quite well described by Hamburg model (annealing, temperature)
  - slightly overestimated towards the end of Run 2.
- Extrapolation till end of Run 3 within the power supply limits.

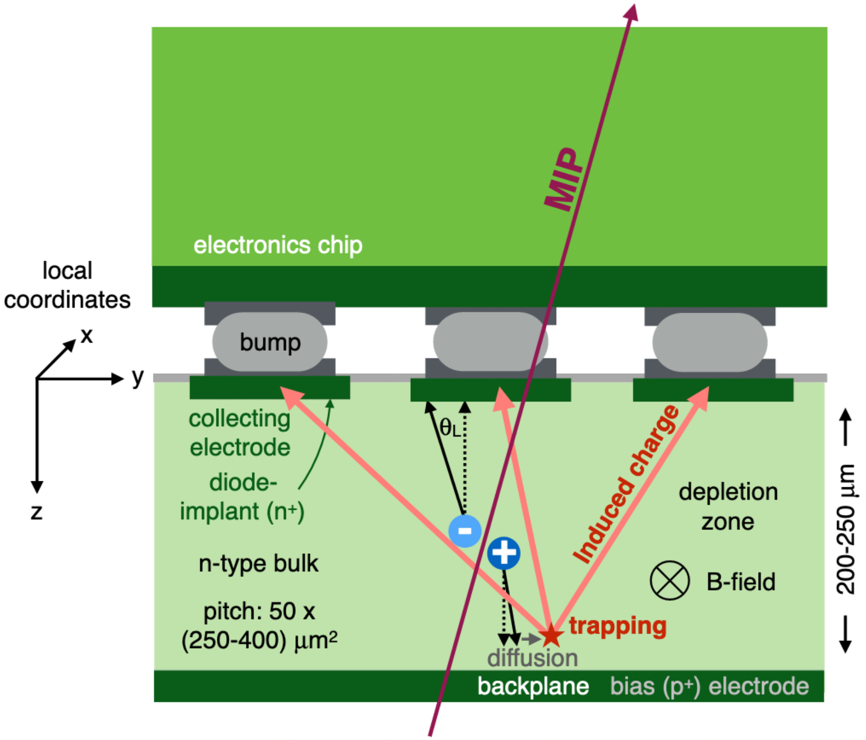




[Measurements of sensor radiation damage in the ATLAS inner detector using leakage currents]

Simulating radiation damage in MC

- Development of **new radiation damage (digitizer) MC.**
  - Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by radiation damage.
  - Their path will be deflected by **magnetic field** (Lorentz angle) and **diffusion**.
  - Due to radiation damage, they can be **trapped** and induce/screen a fraction of their charge (**Ramo potential**).
  - Total induced charge is then digitized and clustered.



Planar: Chiochia model 1,2,3,
(inspired by EVL 2-level model)

3D: LHCb/Perugia models

➔ *for details,* ***Modelling radiation damage to pixel sensors in the ATLAS detector***

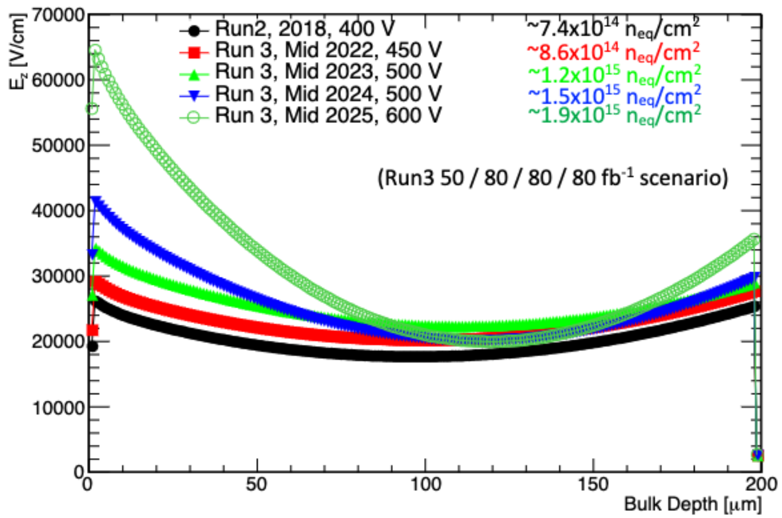
- Extensive validation of the new digitizer:

➔ now ***officially included in ATLAS MC as the new default for Run 3!***

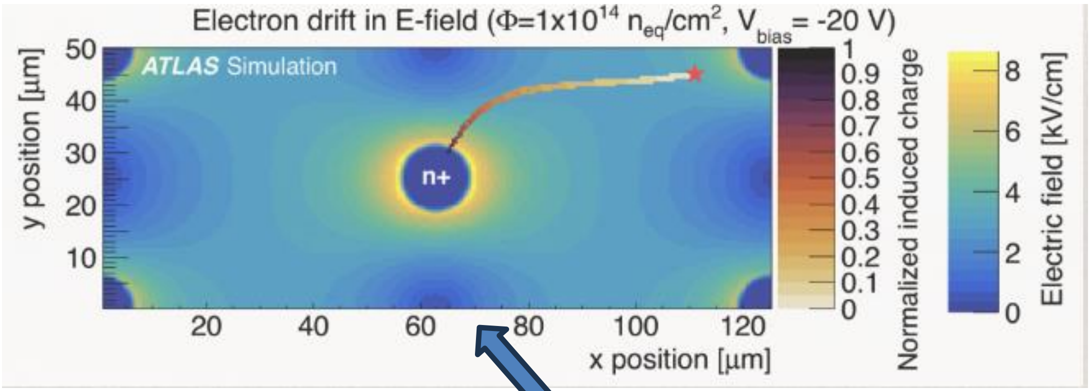
Input parameters for the digitizer

- Electric field map from TCAD simulations (Bias voltage, Fluence, Temperature)

IBL Planar E-Map

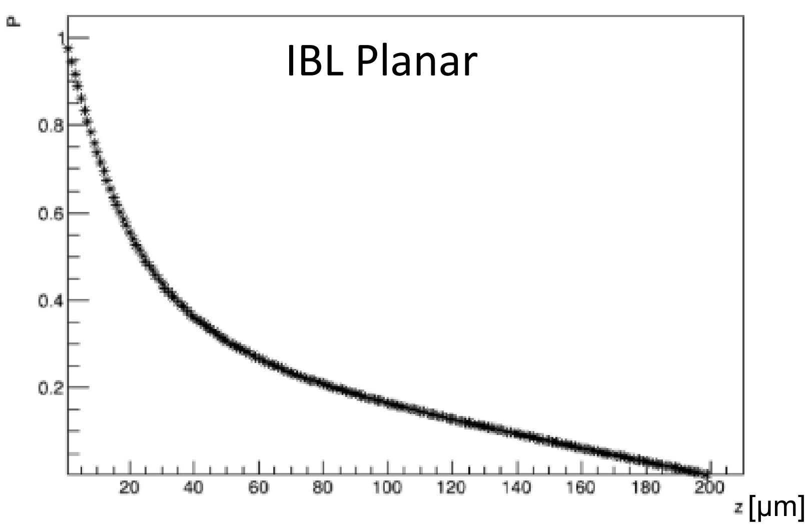


IBL 3D E-Map

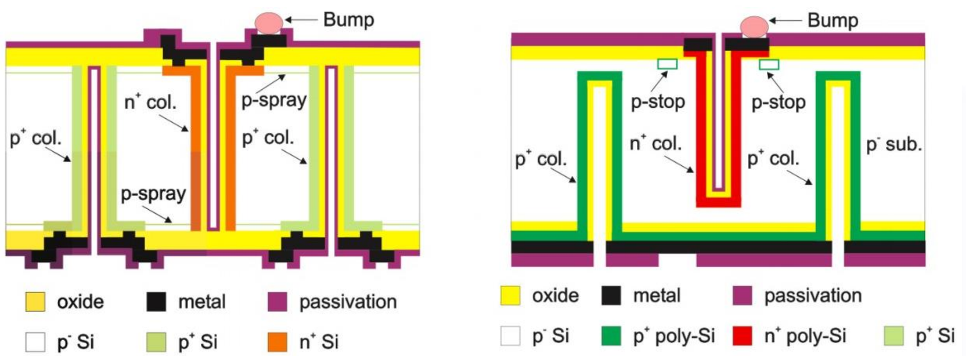


- Ramo potential from TCAD simulations

IBL Planar



IBL 3D geometry



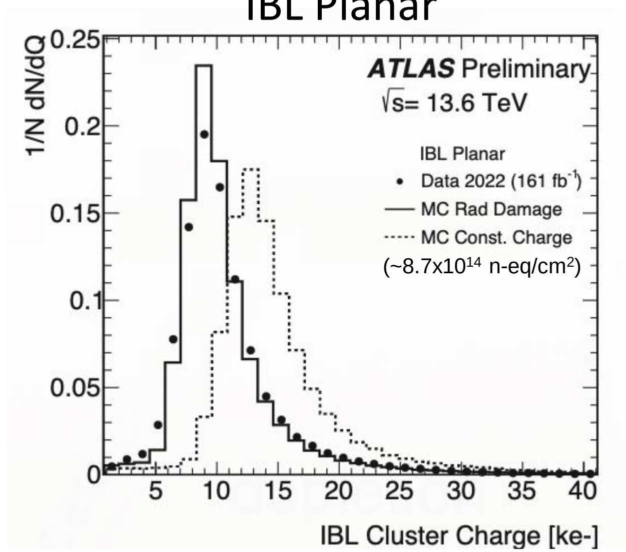
- Trapping rate interpolated from literature:

$$\beta_e = (4.5 \pm 1.5) \times 10^{-16}\ \text{cm}^2/\text{ns}$$

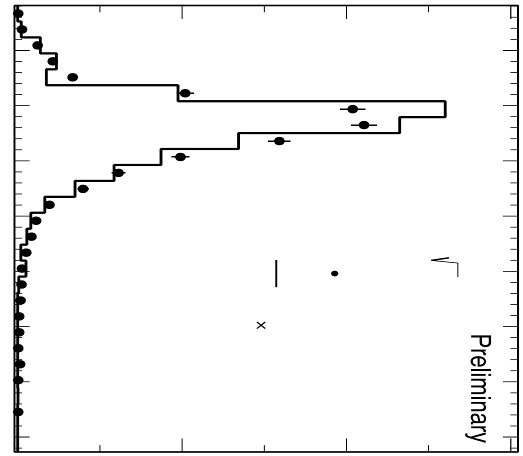
$$\beta_h = (6.5 \pm 1.5) \times 10^{-16}\ \text{cm}^2/\text{ns}$$

Cluster properties: data vs MC

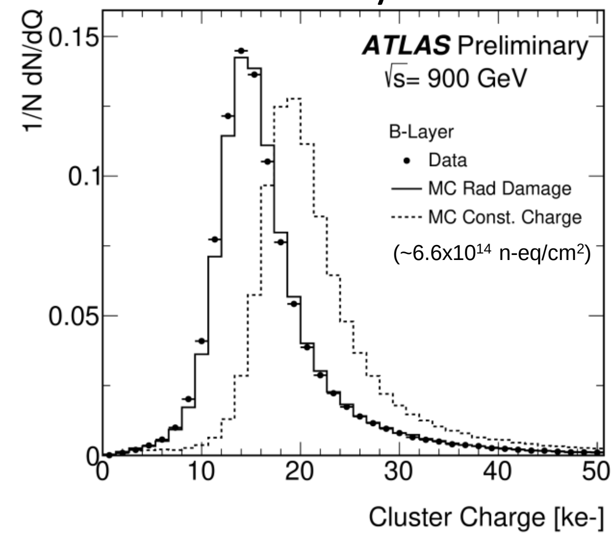
IBL Planar

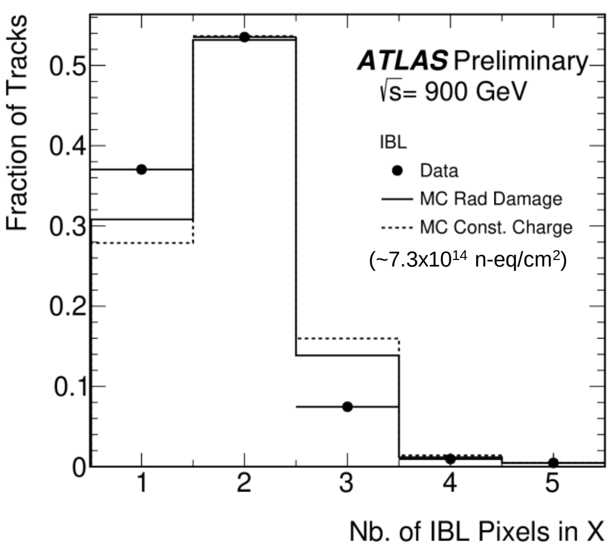


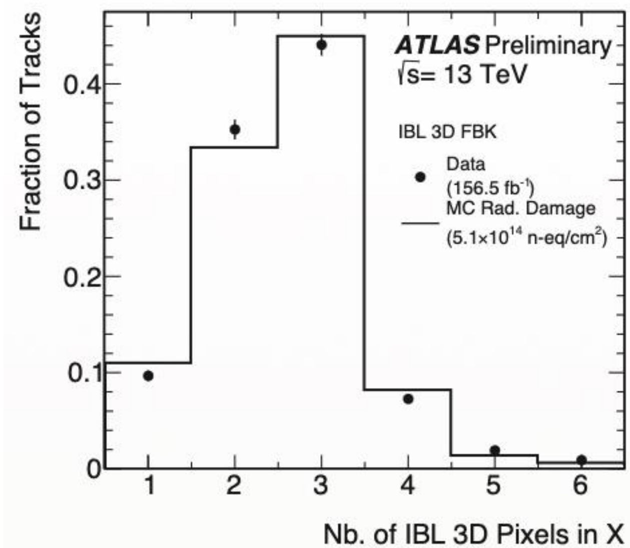
IBL 3D

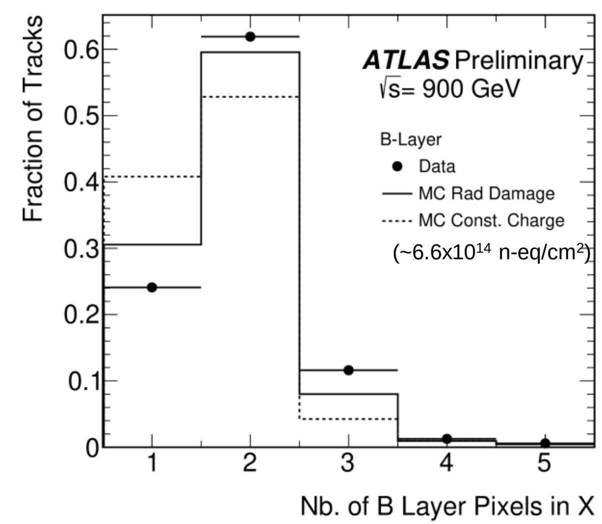


Pixel B-Layer



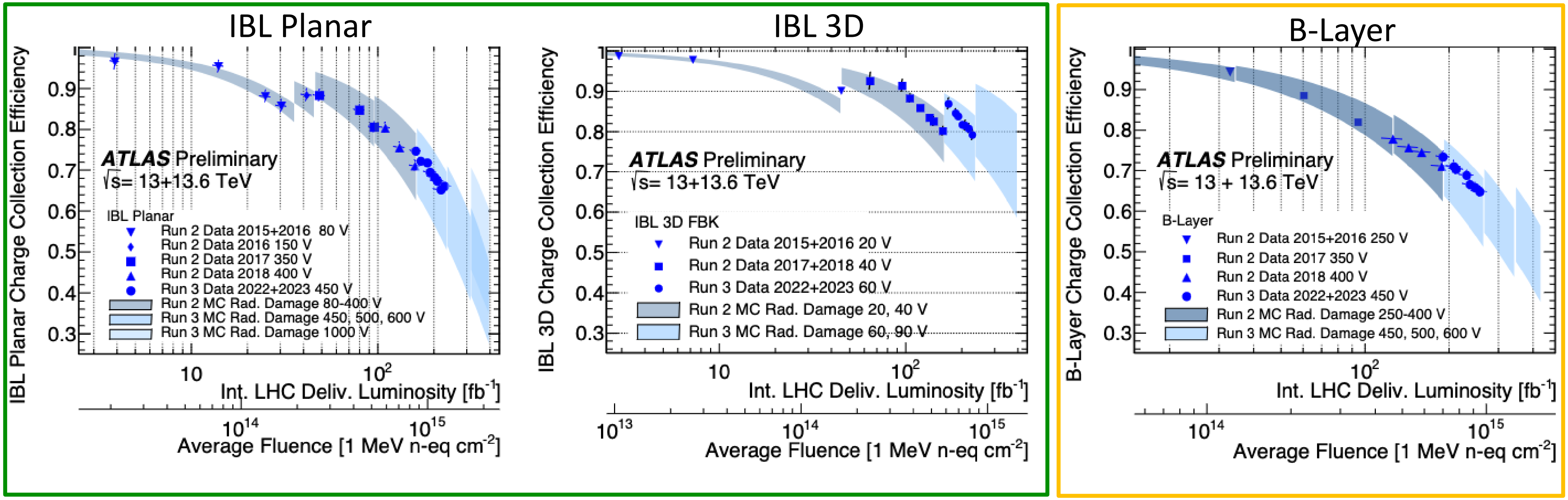






Effect of radiation damage on **cluster charge/cluster size** data **very well reproduced** by the **Radiation Damage MC ➔** Predicted MPV matches to 1%!

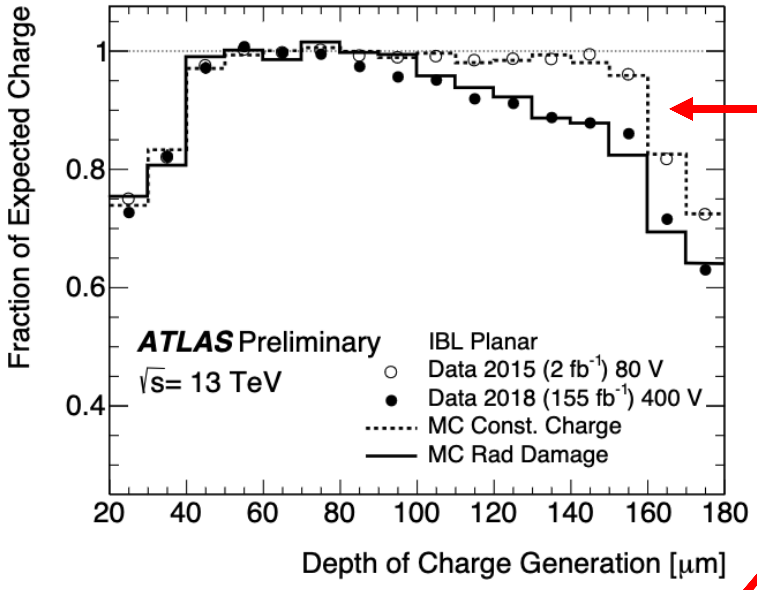
Charge collection efficiency: data vs MC



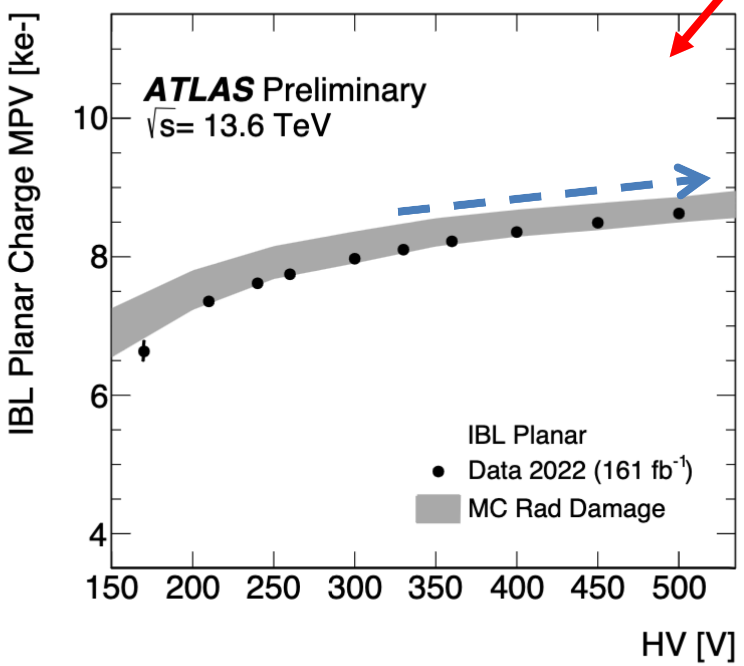
- Charge collection efficiency reduced by ~35% respect to the start of LHC in IBL Planar and B-Layer.
- IBL 3D shows a smaller reduction, ~20% (partially coming from lower fluence)
  - ➔ Excellent agreement over almost two order of magnitudes of fluence.
  - ➔ Different sensors type and rad damage models (Planar vs 3D) under test.
- Predictions indicates we still have a good margin for the end of Run 3.

N.B. Uncertainties in the input parameter (vertical band) dominated by the error on the trapping constants.

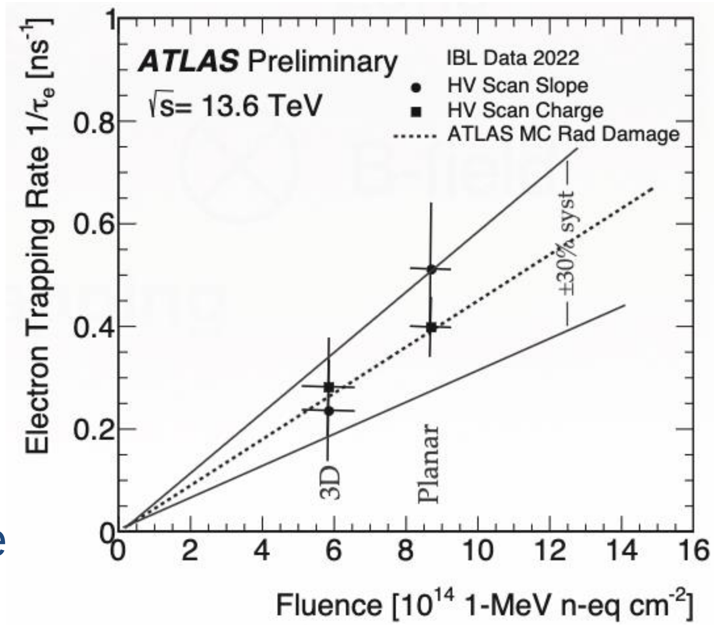
Modelling electric field and trapping



- Charge collection efficiency as a function of the estimated depth of charge generation in the bulk.
- Very strong test for the radiation damage model ➔ fully exploited by **training Neural Networks (used for cluster position determination) on radiation damage MC samples**.



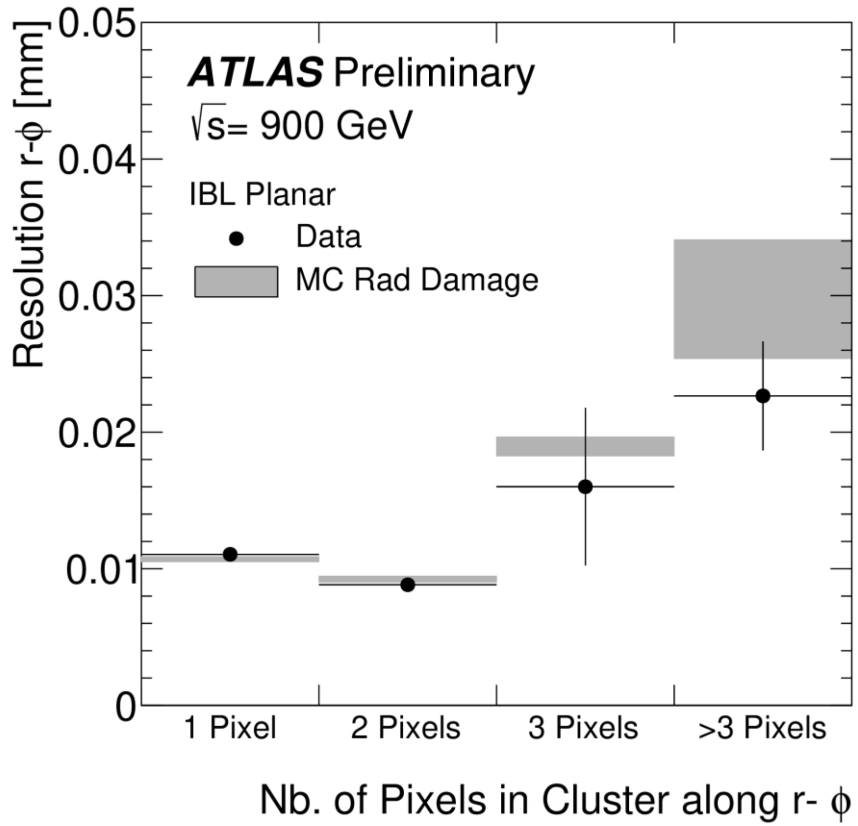
- Amount of collected charge increases also above the full depletion voltage ➔ reduction of the charge trapping effect with the increasing charge carrier velocity.
- Electron trapping rate extracted using the HV scan data from fits to the **cluster charge** or to the **slope** of the cluster charge increase above depletion



- Trapping value extracted consistent with input value (limited sensitivity).

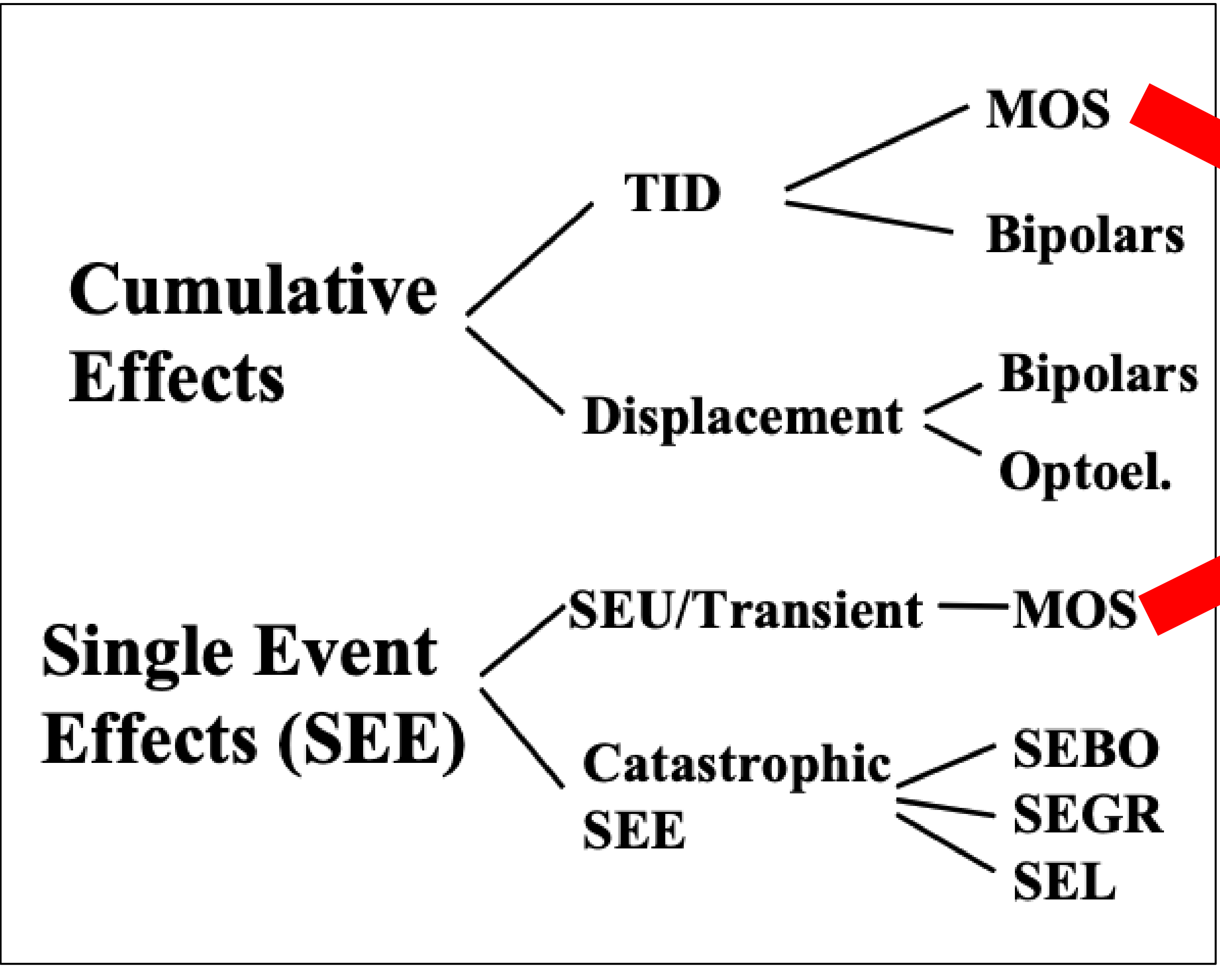
Radiation Damage MC performance

- 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.**
  - IBL spatial resolution for 50 μm pitch projection measured at 10 μm (Run 3 start)



[*Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run~3 in LHC Collisions at s√=900 \GeV*]

Impact of radiation on electronics



from F. Faccio, Cern

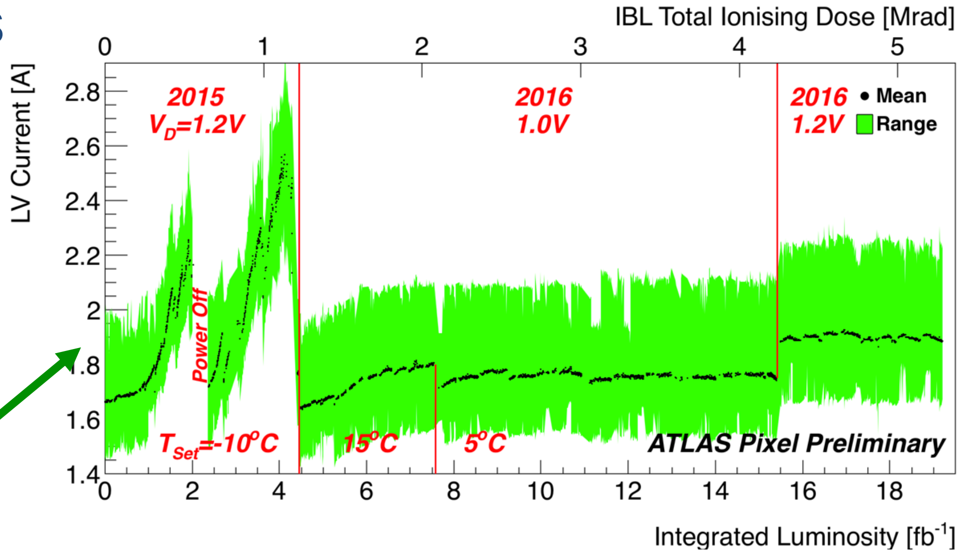
IBL front-end aka **FE-I4** (130 nm CMOS technology)

So far, these effects were only noticed (and quantified) in IBL front-end chip.

Outer Pixel layers (FE-I3 chip, 250 nm CMOS) don’t show the same symptoms.

Cumulative effects on IBL front-end

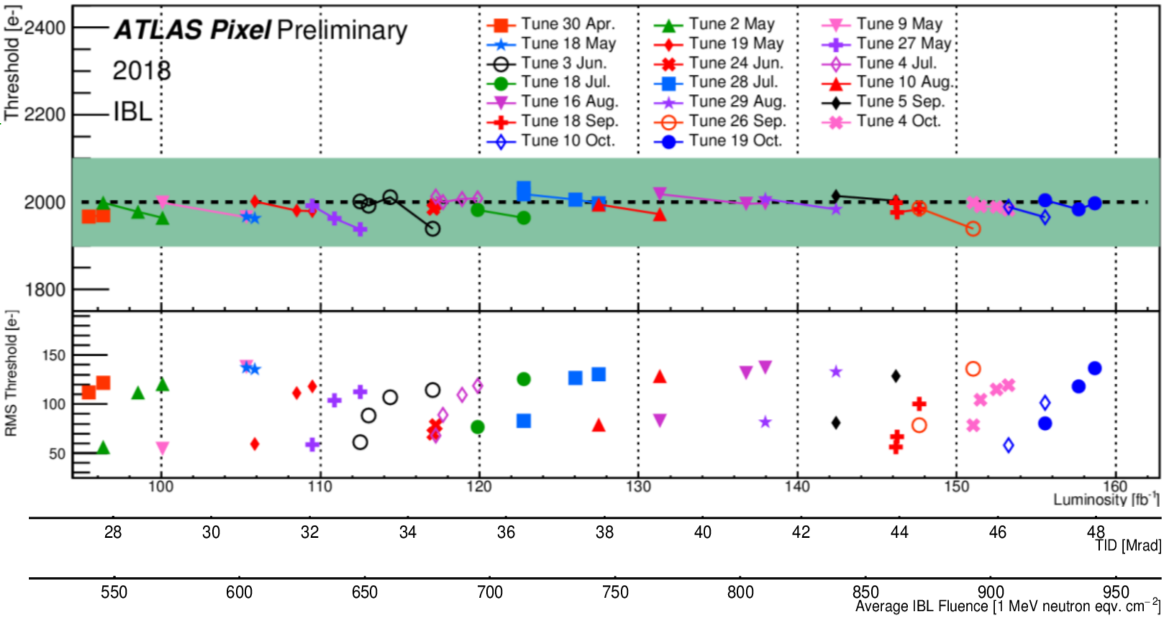
- Total Ionising Dose (TID) effect in front-end electronics (FE-I4)
- Mostly due to charged hadrons/electrons deposing energy and ionizing SiO_2
  - charge/defects build up inducing a current variations in MOS transistors (peak at ~1MRad or ~3fb^{-1} for FE-I4).



Macroscopic observations:

1. Huge drift of **front-end LV currents**
   ➔ power off, increase temperature, reduce bias!

2. Drift of **Thresholds** and **Time-Over-Threshold (TOT)**
   ➔ regular (~weekly) re-tuning!

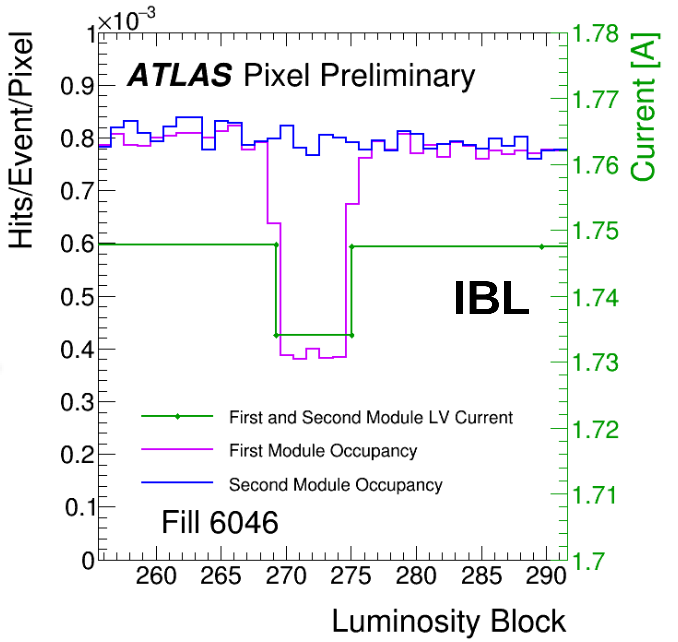


Luckily, the size of the effect decreased with time but still present after 230 fb^{-1}!

SEE in IBL front-end

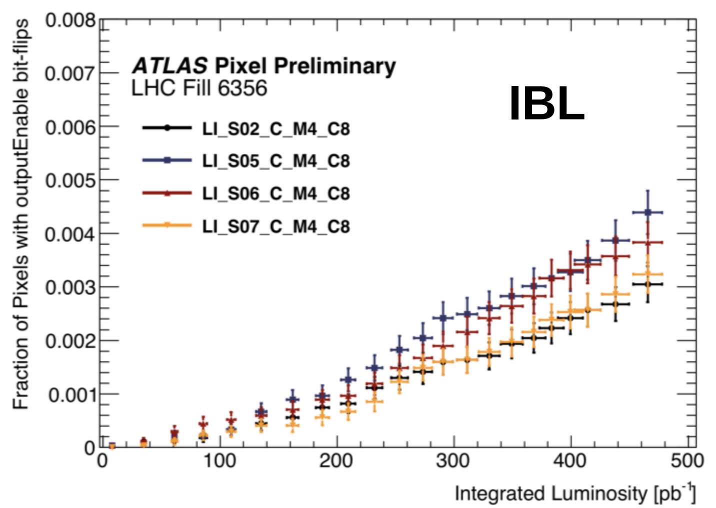
Big charge deposit (heavy particles recoil) in FE electronics can flip the state of **global/local memory cells**

- IBL FE global registers affected by SEE (2017)
  ➔ **periodical reconfiguration of FE global registers** improved the operation stability/data quality.



- As LHC started delivering fills with higher integrated luminosity (2018):
  - **noisy pixels** (pixels firing in the empty bunches)
  - **quiet pixel** (pixels not firing in colliding bunches)

  ➔ due to SEE in **local pixel latches!**

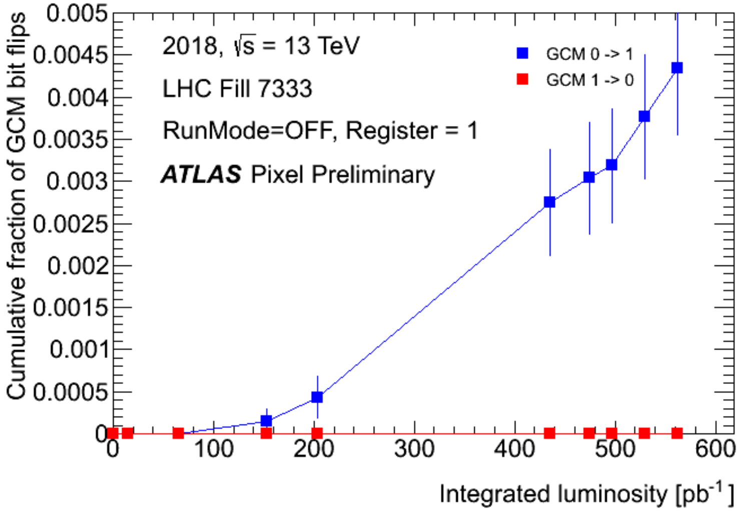


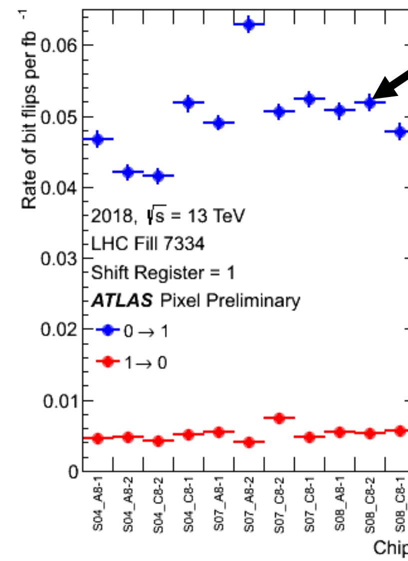
- Both **Single Event Upset (SEU),** errors overwriting information stored by the circuit, and **Single Event Transient (SET),** spurious signals propagating in the circuit, were observed and quantified.

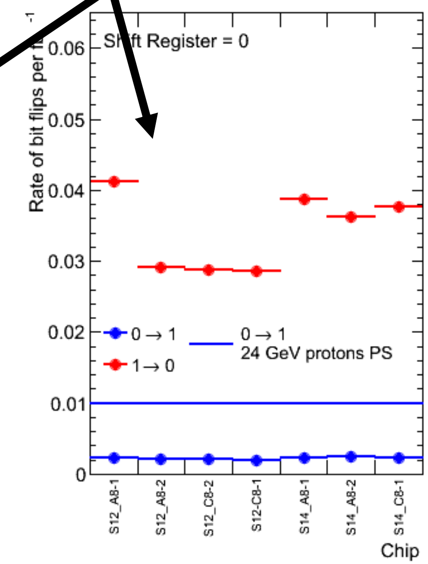
For details see paper → [***Measurements of Single Event Upset in ATLAS IBL***]

Results of FE-I4 SEE studies

- Cross section calculations for both front-end (global) and single pixel registers (local)

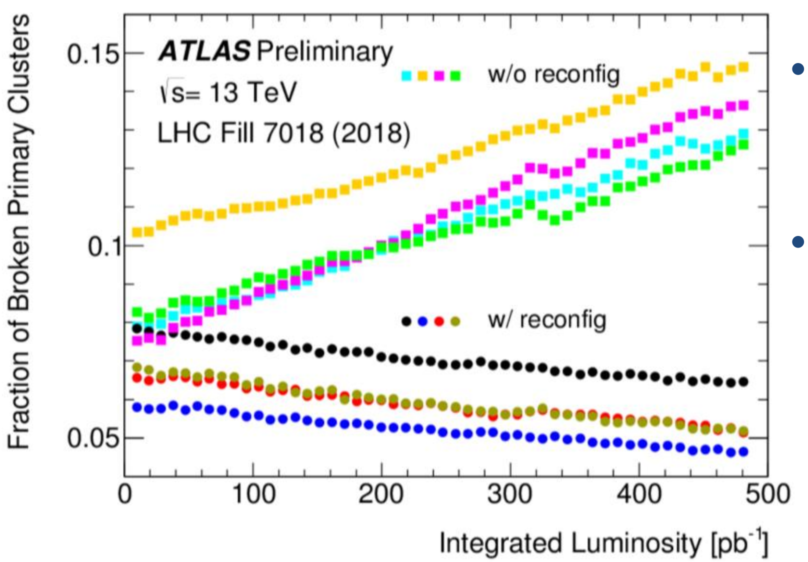




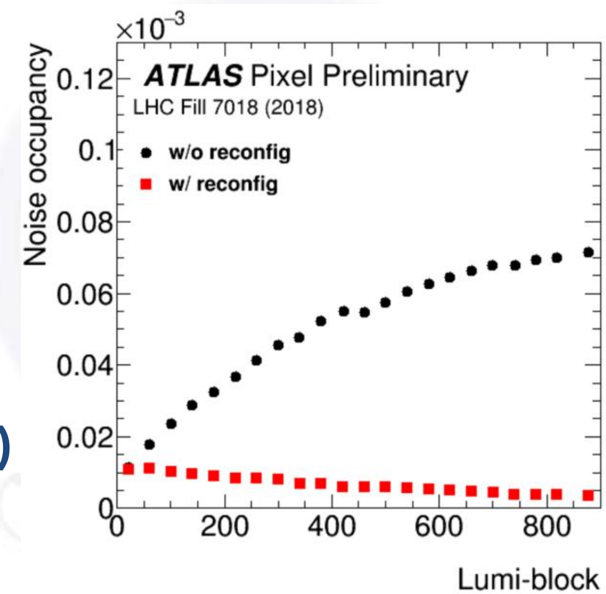


- Solved by adding the periodical reconfiguration of the **single pixel latches**

N.B. 12 Mpixel x 13 latches, reconfigured completely every ~10 minutes without extra deadtime!



- Clear gain observed during test run in 2018.
- Fully deployed in Run 3 (complex Sw/Fw task):
  ➔ Very important due to the **higher radiation (luminosity) per fill in Run 3 vs Run 2.**



Conclusion and outlook

- ATLAS Pixel inherited several challenges from Run 2:
  - strong effort (a few years) to consolidate the detector stability (Sw, Fw) to operate in difficult conditions (high accumulated radiation and hit rate)
    - **FE thresholds and bias voltages** adjusted almost yearly
    - **FE regular reconfiguration** during data taking is the default mode
- So far, Run 3 was the harvest time for Pixel: **data taking efficiency/data quality** reached the best values despite the LHC conditions/detector aging.

Clear impact of radiation in innermost layers even if with small implications for **tracking/vertexing**.

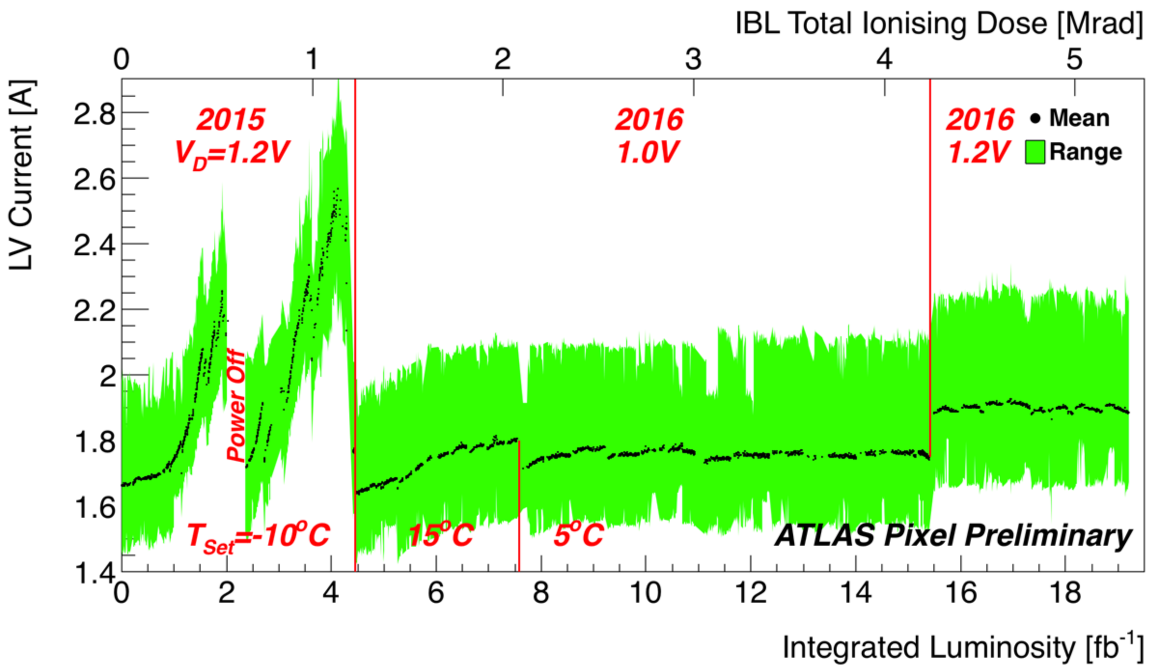
- Vital to forecast (when possible) and mitigate (when needed) the effects of radiation on sensors and electronics :
  - **new digitization model developed (default in ATLAS Run 3 MC)**
    - **~% agreement reached with data for various layers/sensor type**
  - **SEE mitigation with continuous reconfiguration of FE electronics.**

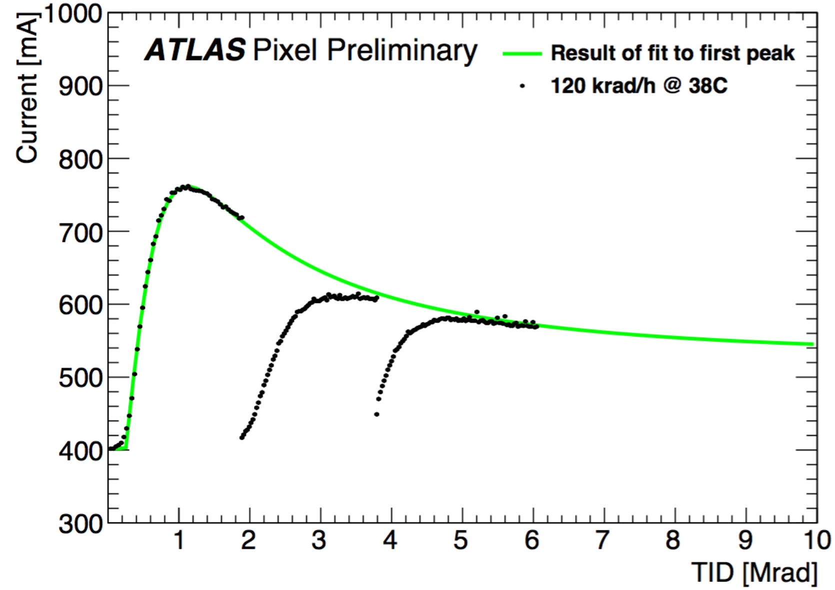
➔ Radiation damage became a key ingredient to operate the present silicon detectors (Run 3) and will be essential for the trackers upgrades at HL-LHC.

Back-up

Pixel/IBL 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

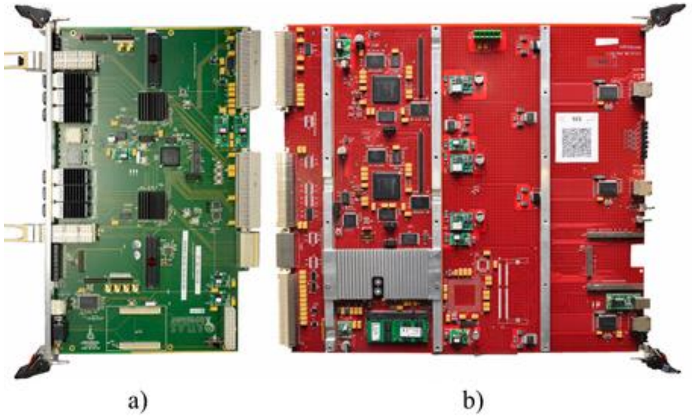




"Production and Integration of the ATLAS Insertable B-Layer"
JINST paper for more info about IBL

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)



- 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 on a longer term:
  - the operation of different type of FEs will always be there but…transparent for most of the operations!

The Pixel metamorphosis

- Readout electronics upgrades and changes of the configuration parameters to accommodate for **bandwidth limitations** and **radiation damage**.
  - ***Sensor bias voltage (HV)***
  - ***FE Analog/Digital thresholds***
  - *Read out speed*
  - *Front-end latency*
  - *TOT target point for a MIP*
  - *Threshold modulation vs eta*
  - ..

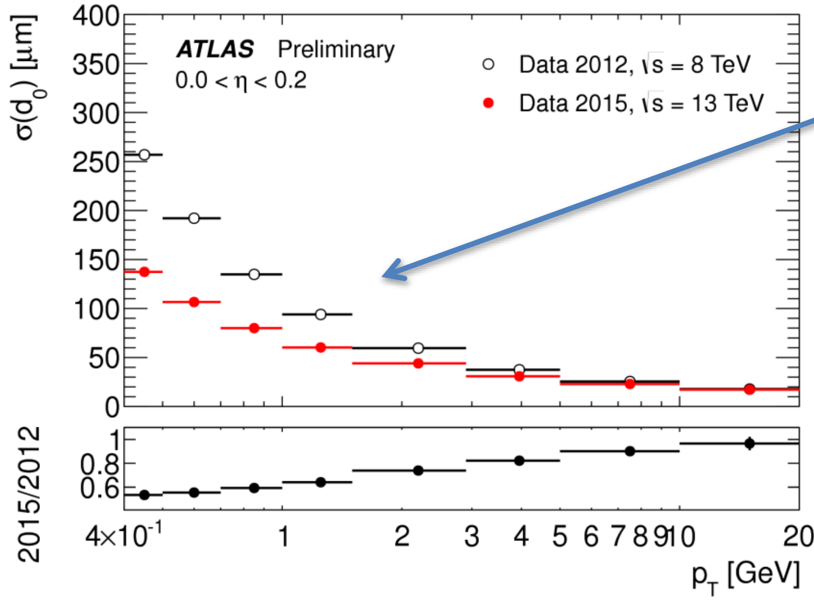
Sensor Bias Voltage (HV)

	Run 2				Run 3	
Layer\Year	**2015**	**2016**	**2017**	**2018**	**2022**	**2023**
IBL Planar	80 V	150 V	350 V	400 V	450 V	450 V
IBL 3D	20 V	20 V	40 V	40 V	60 V	60 V
B-Layer	250 V	350 V	350 V	400 V	450 V	450 V
Layer1	150 V	200 V	200 V	250 V	300 V	350 V
Layer 2	150 V	150 V	150 V	250 V	300 V	350 V
EndCaps	150 V	150 V	150 V	250 V	300 V	350 V

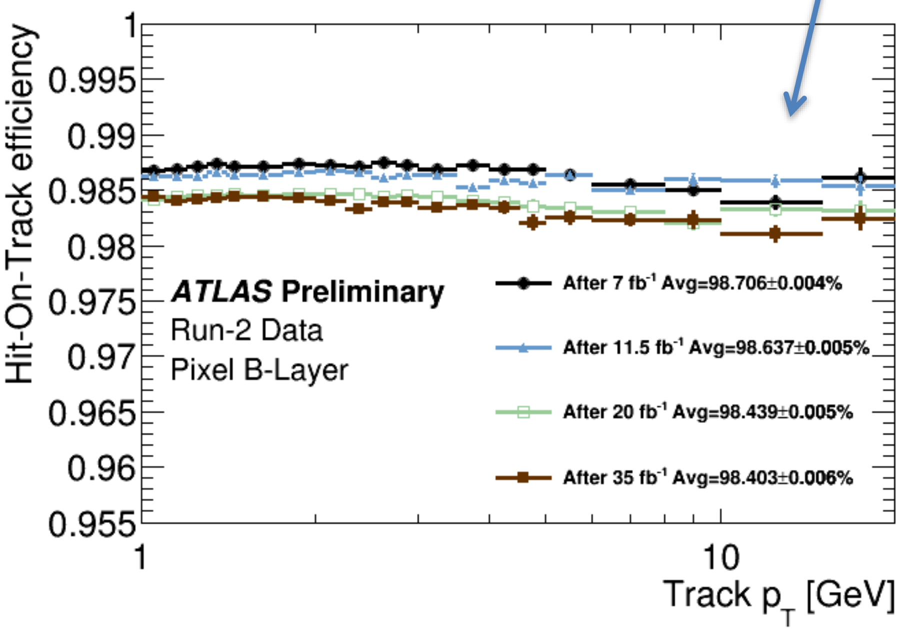
Front End Analog/Digital thresholds

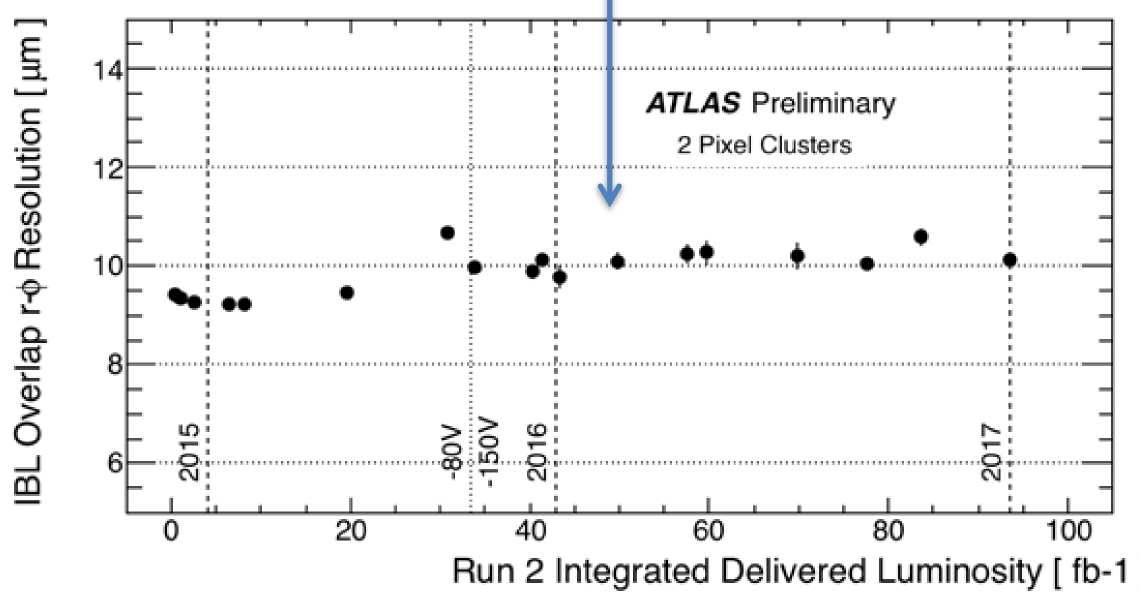
	Run 2				Run 3	
Layer\Year	**2015**	**2016**	**2017**	**2018**	**2022**	**2023**
IBL	2500e	2500e	2500e	2000e	1500e	1500e
B-Layer	3500e TOT>3	3500e-5000e TOT>3-5	5000e TOT>5	4300e/5000e TOT>3	3500e/4300e TOT>3	4700e TOT>3
Layer 1	3500e TOT>3	3500e TOT>5	3500e TOT>5	3500e TOT>5	3500e TOT>5	4300e TOT>5
Layer 2	3500e TOT>3	3500 TOT>5	3500e TOT>5	3500e TOT>5	3500e TOT>5	4300e TOT>5
Endcaps	3500e TOT>3	3500e TOT>5	4500e TOT>8	3500e TOT>5	3500e TOT>5	4300e TOT>5

Pixel performance in Run 2



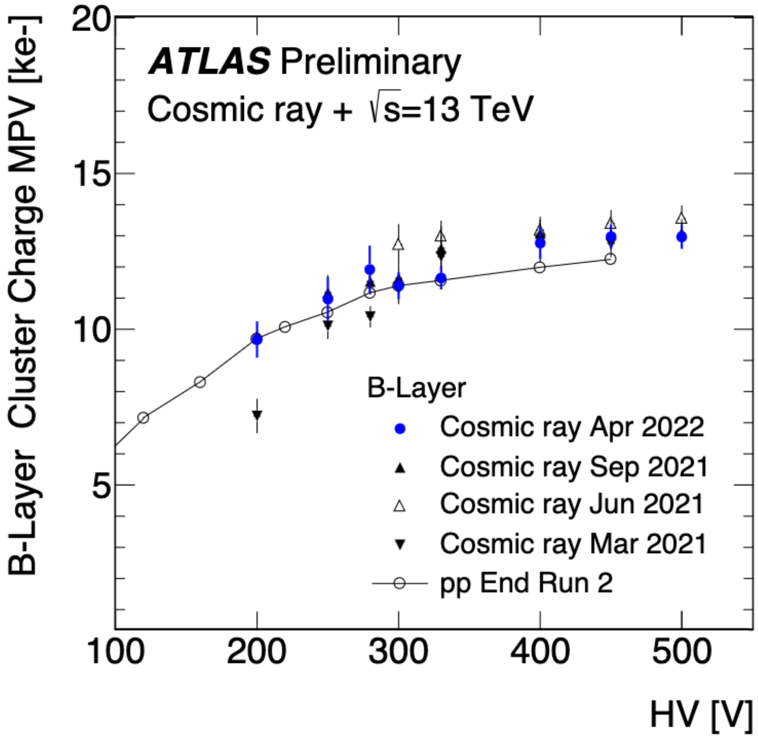
- **Impact parameter resolution** improvements after IBL insertion (2015)
- B-Layer **Hit-on-track efficiency > 98%** (2016)
- IBL **spatial resolution** (transverse R-φ plane) **~< 10 μm** over Run 2.

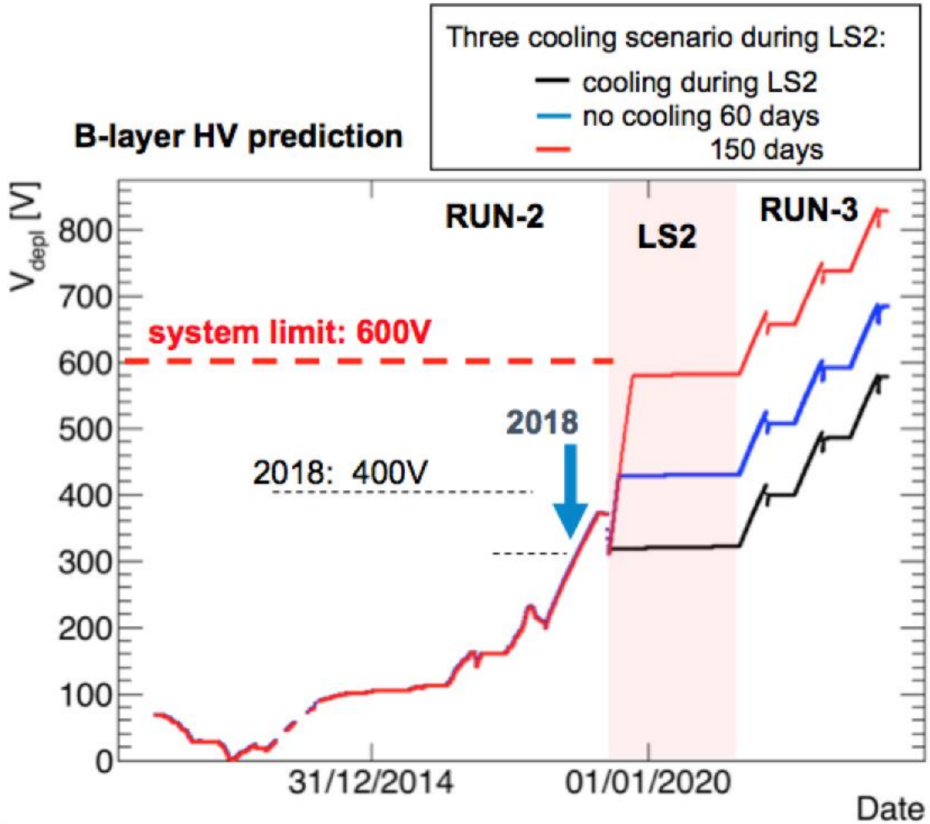




Fighting the reverse annealing

- **Keeping the detector cold during LS2** to prevent reverse annealing, despite the warm periods due to the ID maintenance.
  ➔ keep the depletion voltage under control, mostly a concern for B-layer and IBL.
- Target to be **warm for < 60 days** during LS2.
  - Warm for **43 (23) days** in Pixel (IBL)

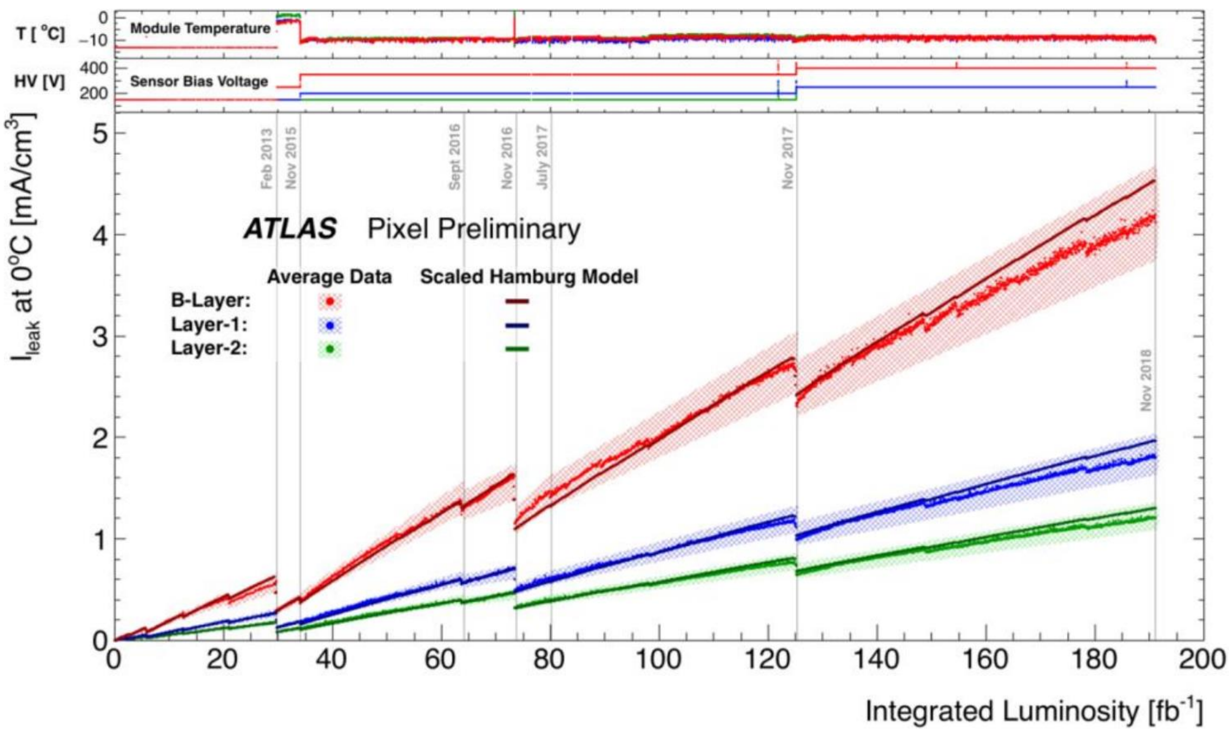


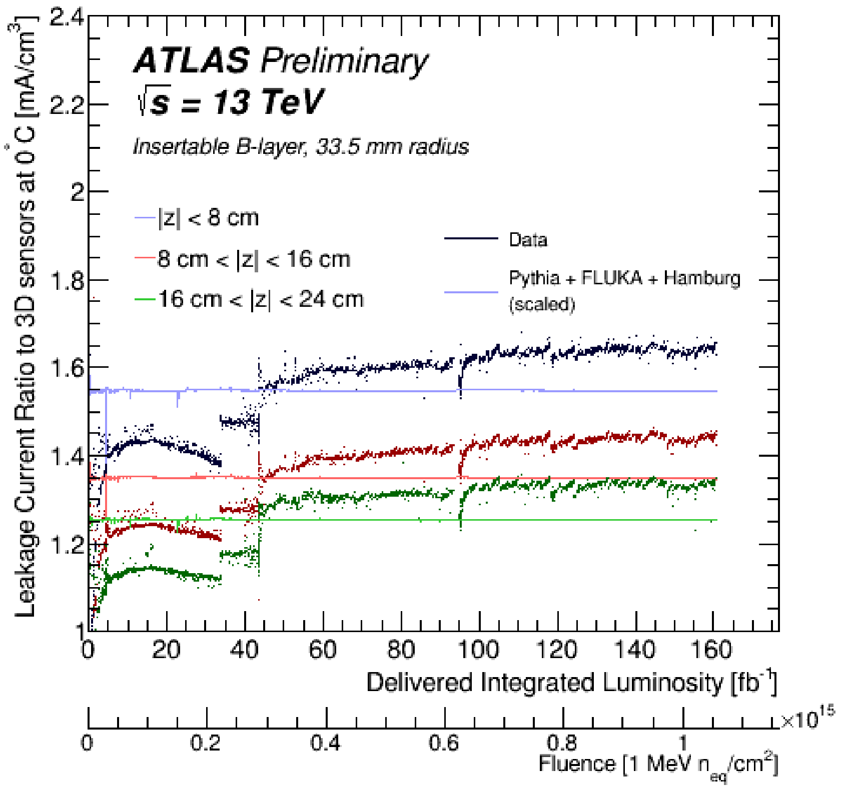


- Exploring colder operating set points (-25°C/-30°C) for last years of Run 3 if needed.

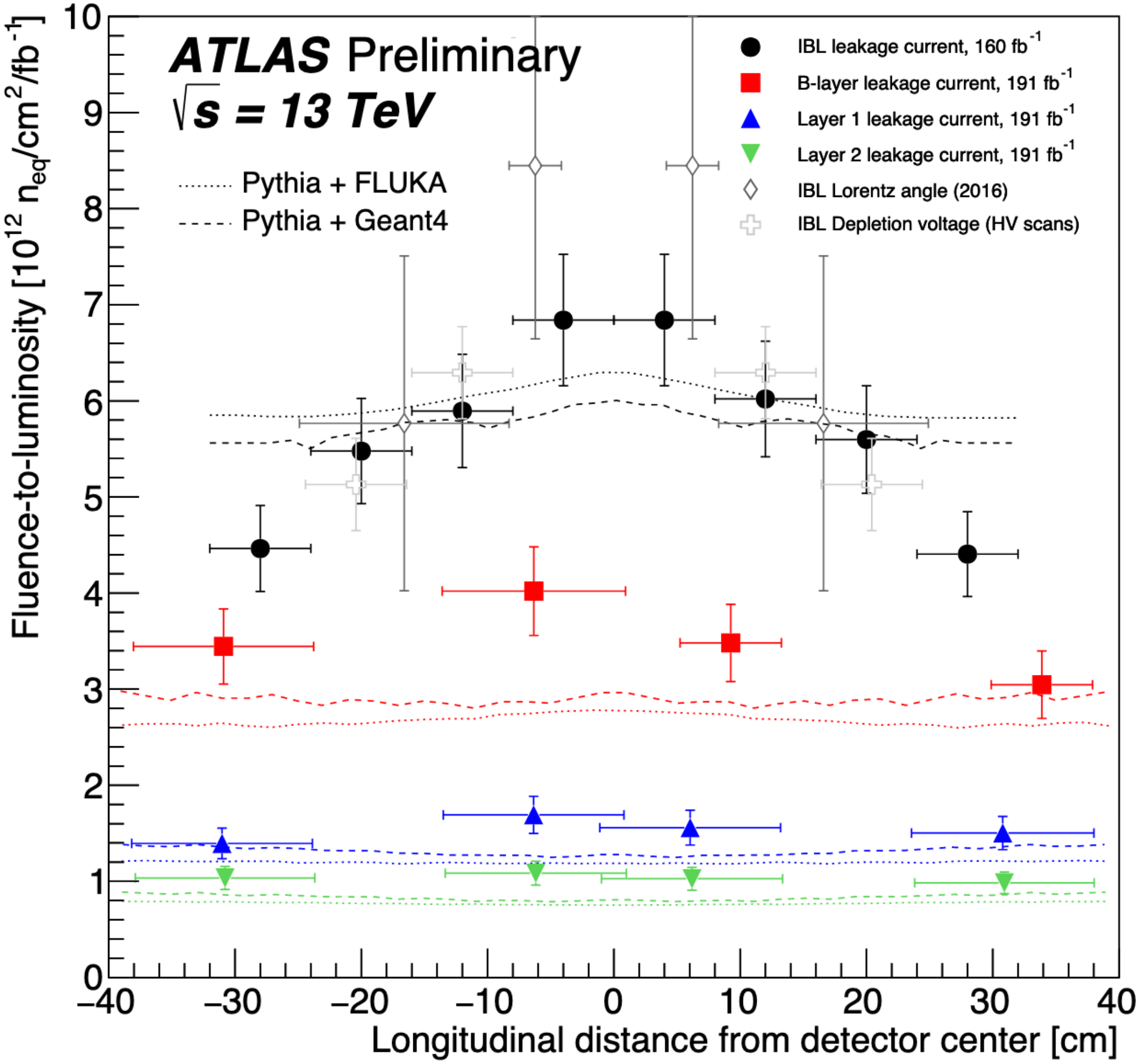
Pixel Leakage currents

- 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).





z-dependence comparisons



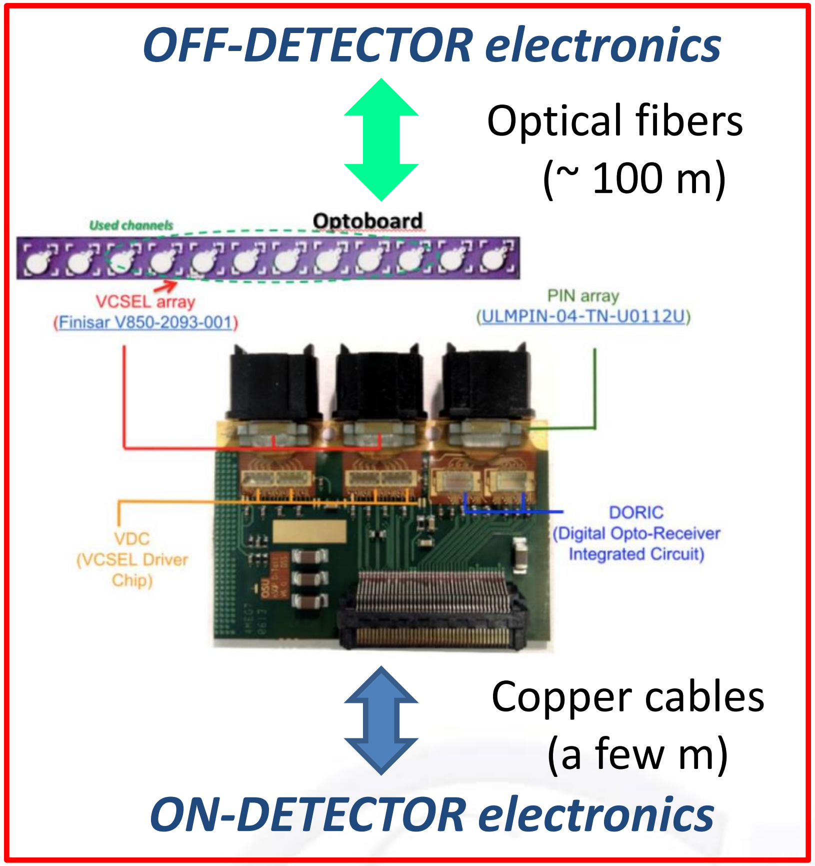
Fluence-to-luminosity conversion factors extracted from the leakage current, Lorentz angle and Depletion Voltage measurements:

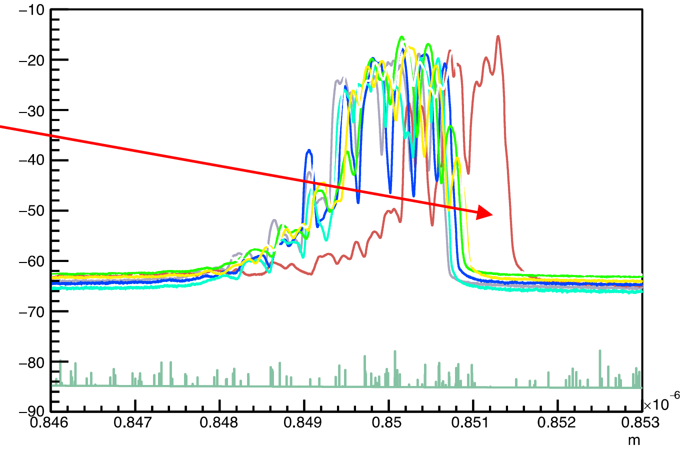
- **less fluence at at high |z| on IBL data** respect to Pythia + FLUKA/Geant4 predictions
- more flat distributions for outer Pixel layers.

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!





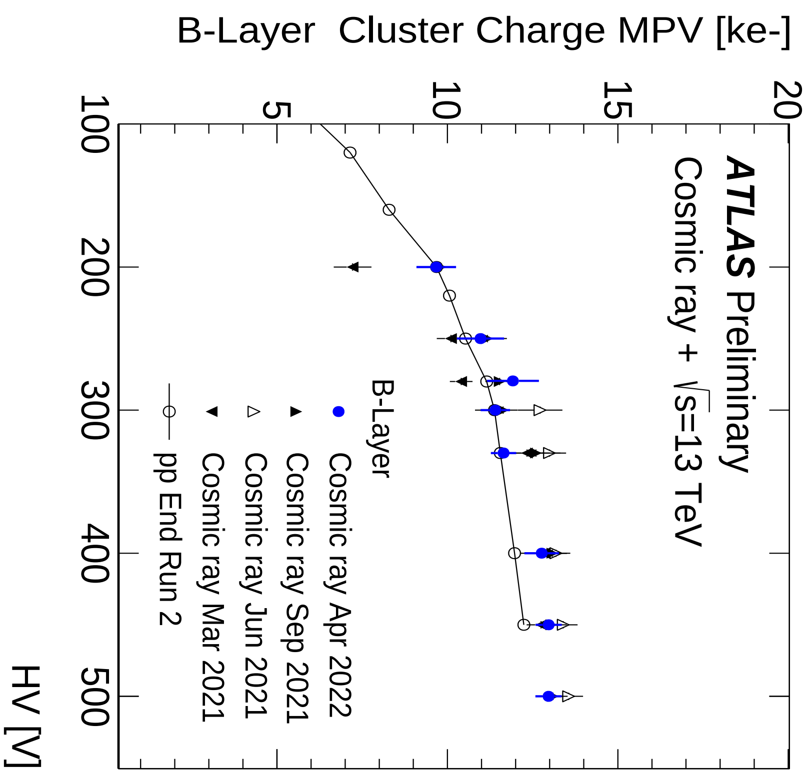
Detector status during LS2

- Detector kept **OFF (and cold)** most of the time.
  - Pixel (C_3F_8 evaporative) and IBL (CO_2 bi-phase) cooling very stable.
- Successful yearly maintenance of cooling systems
  - a few weeks at room temperature, **43 (23) days** in Pixel (IBL).
- A new thermosiphon system will serve as ID **Run 3 official cooling.**

Temp set point (LS2)	PIXEL	IBL
Detector OFF	-5 ºC	-7.5ºC
Detector ON (Cosmics)	-20 ºC	-20ºC

- Turn ON **two weeks every two months**
  - Calibrations and cosmic data taking
  - Monitoring noise and depletion voltage (annealing negligible)
  - Test of Run 3 configs

Vth	Run 2 (End Of)	Run 3 (Start of)
IBL	2000 e	1500 e
B-Layer	4300 e/ 5000 e	3500 e/ 4300 e
Layer 1	3500 e	3500 e
Layer 2	3500 e	3500 e
Disks	3500 e	3500 e



Radiation damage studies

- 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:

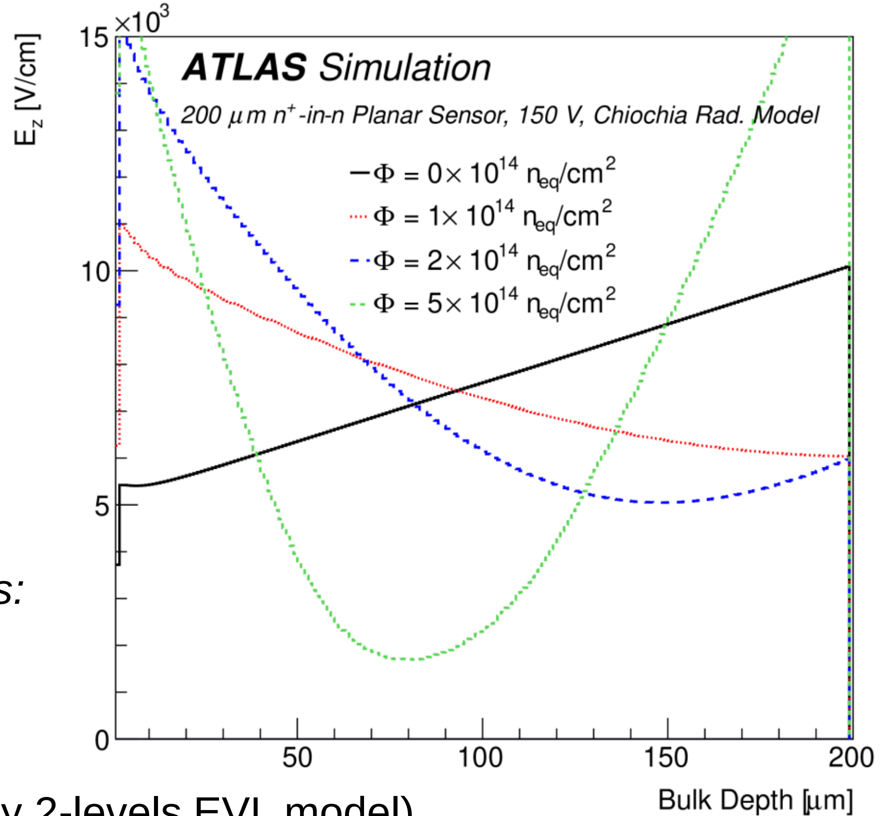
➔ **charge trapping**

➔ 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



***Planar* ➔** 2-levels models used

***Chiochia** model, maps from interpolation between publications:*
TNS, VOL. 52, NO. 4, AUGUST 2005
NIM A 568 (2006) 51–55
W. Adam et al 2016 JINST 11 P04023

***3D* ➔** 3-levels models used (inspired by 2-levels EVL model)

***PERUGIA** model : * F. Moscatelli et al.,, IEEE Trans. Nucl. Sci. 63 (2016) 2716.*
***LHCb** model ** A. Folkestad et al., NIM A874 (2017) 94-102*

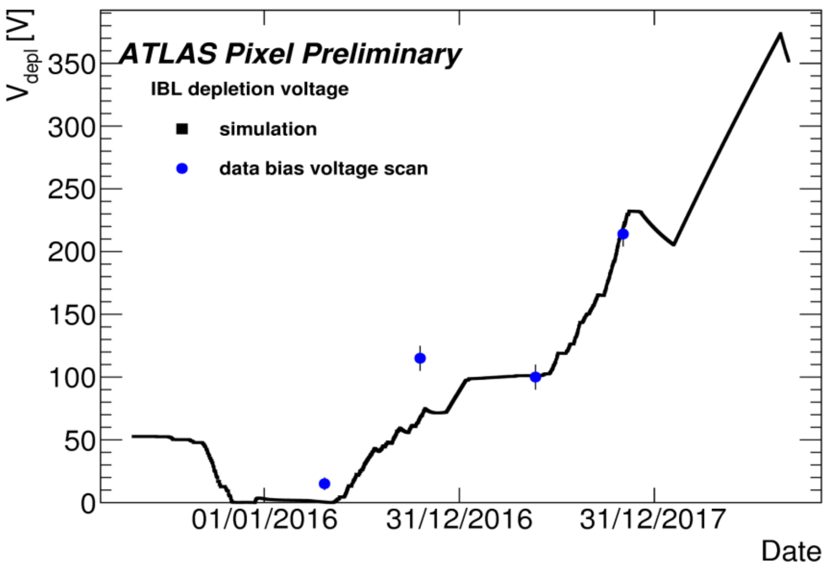
HV evolution

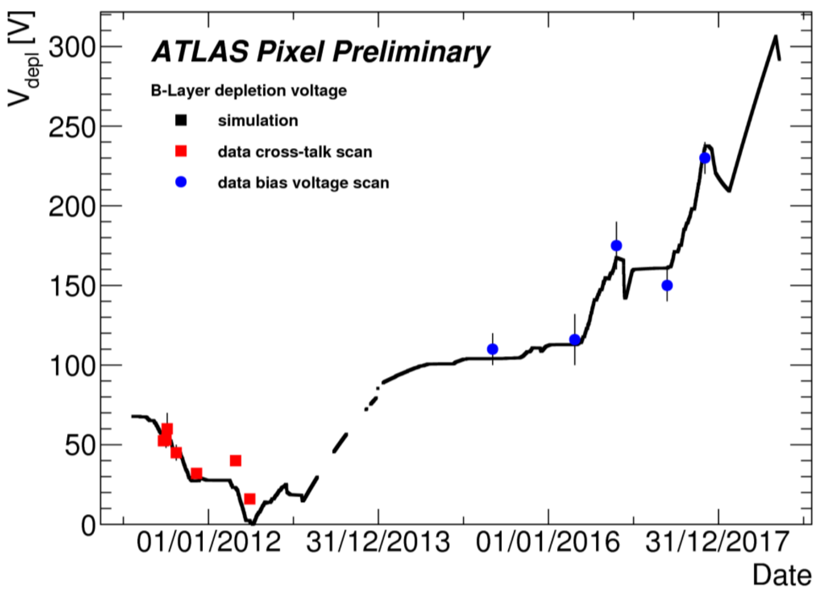
- HV settings have been adjusted to ensure a well depleted sensor:

RUN-2 HV

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

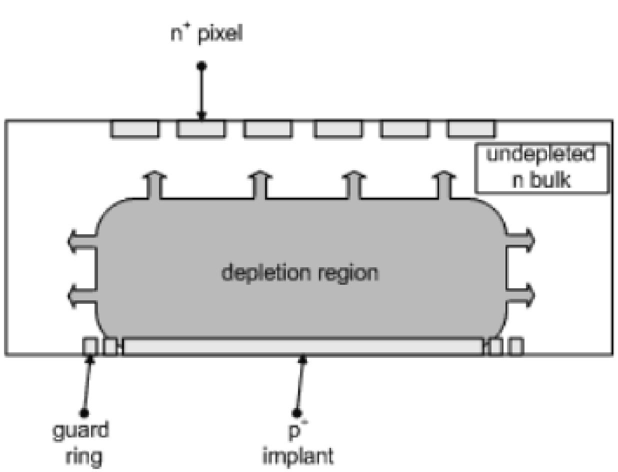
- To avoid to run with an under depleted detector, Pixel should be kept cooled as long as possible during the LS2 (2 years long).

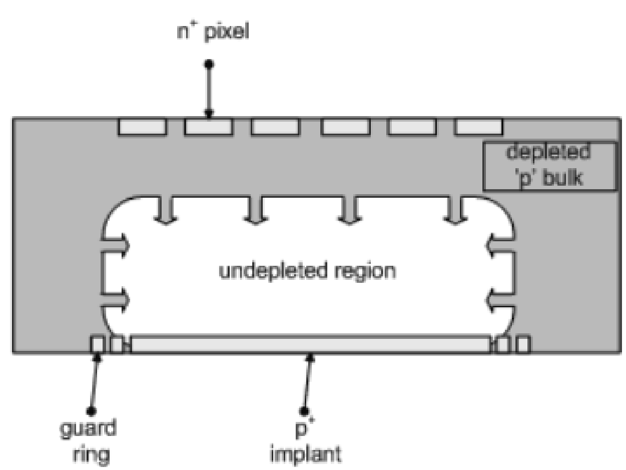


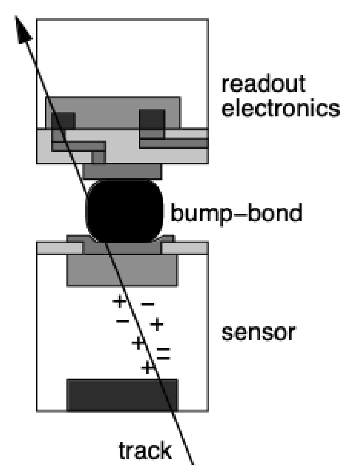


Sensor type inversion

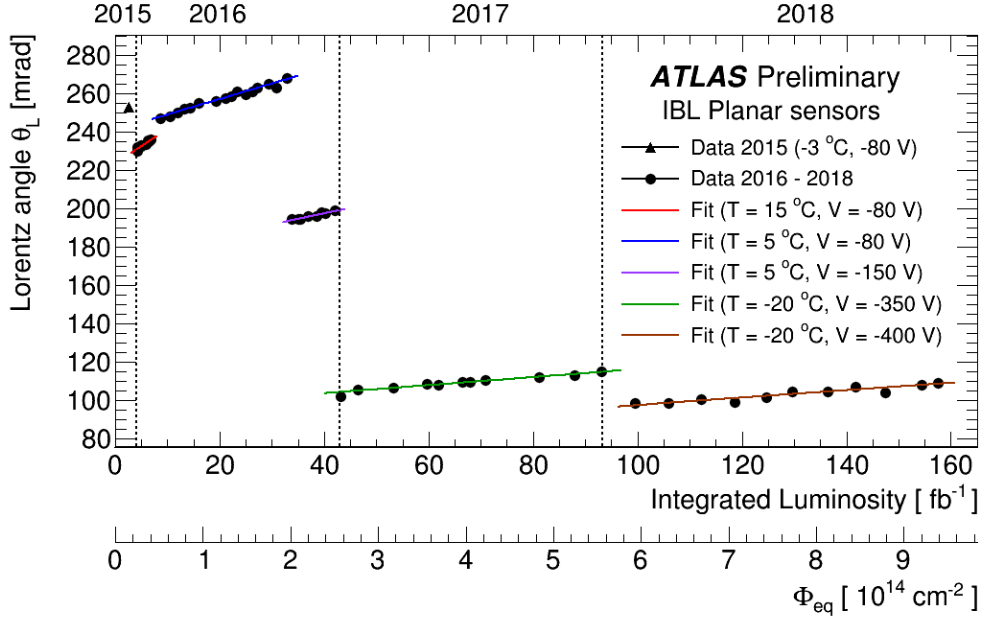
- 18 mm × 62 mm tile of diffusion oxygenated float-zone silicon.
- High-resistivity n-type bulk material with an array of 47232 implanted diodes: n+ implantations on the readout side; back-plane of the sensor tile highly p+ doped to form the *pn*-junction needed for sensor depletion .
- The ***n^+-in-n sensor*** has the depleted region forming on the sensor backside before the radiation-damage induced type-inversion of the bulk material.
- After a non-ionizing dose of ~**$3 \cdot 10^{13}$ n_{eq}/cm^2**, concentration of acceptor-like defects exceeds the donor concentration in the bulk (effectively **p-type)**.
- After type inversion, depleted region forms at pixel implantation (readout side).

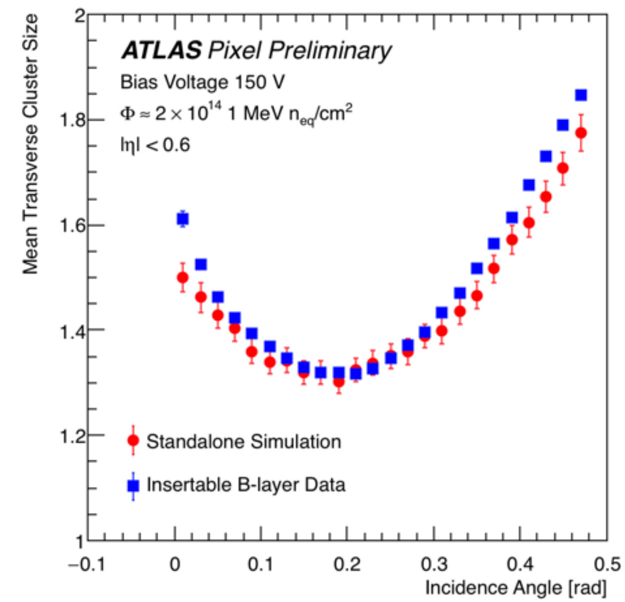


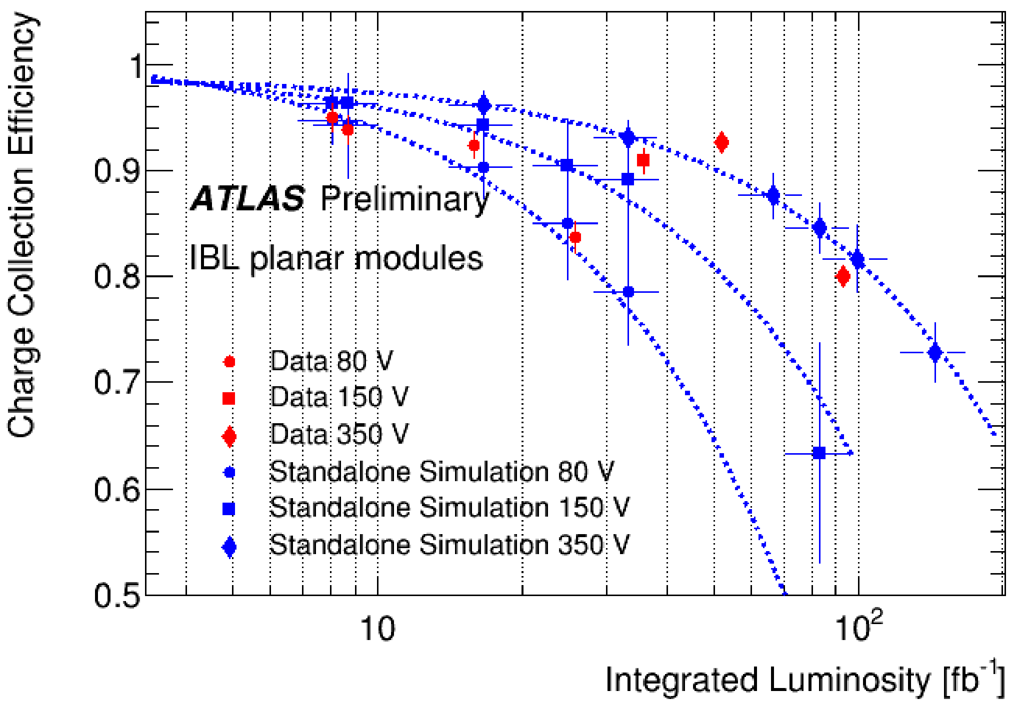


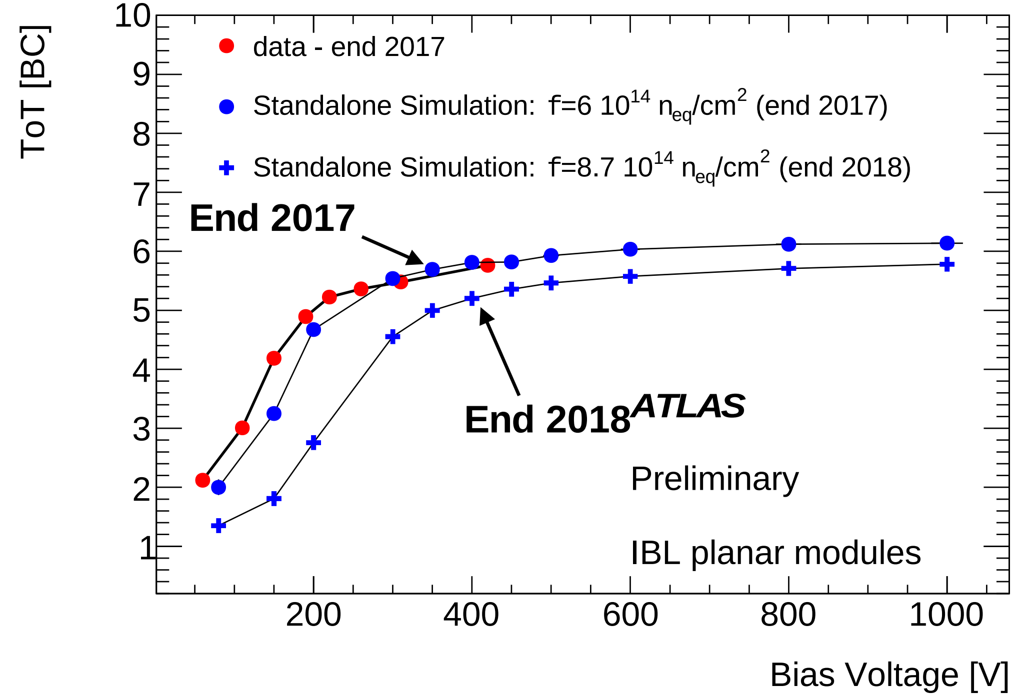


Modelling the radiation damage in the sensor









Luminosity-to-Fluence