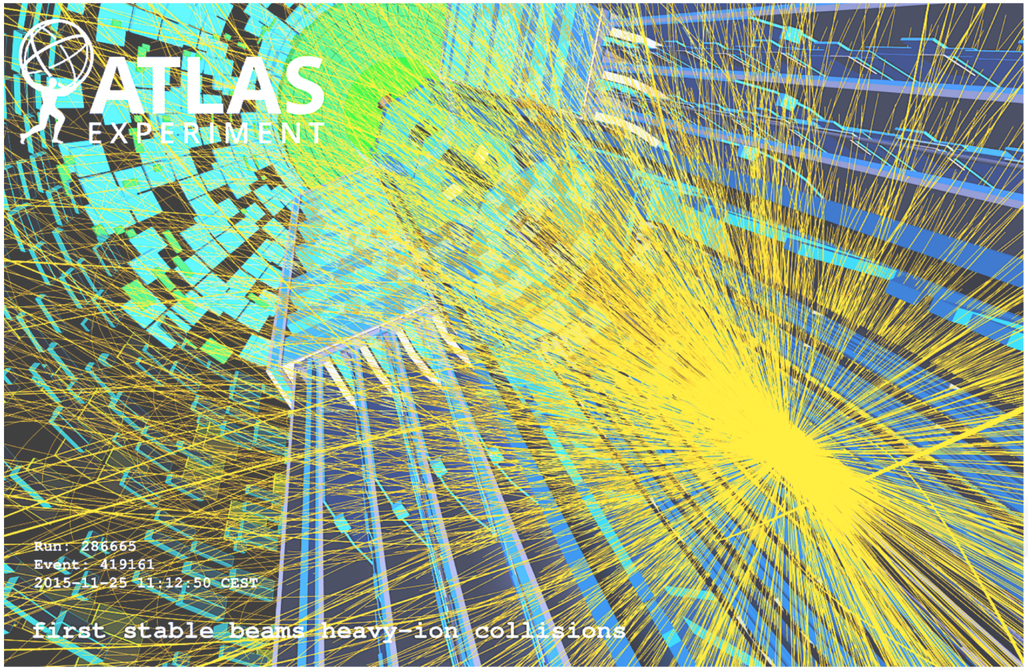
Operational Experience and Performance with the ATLAS Pixel detector at the LHC

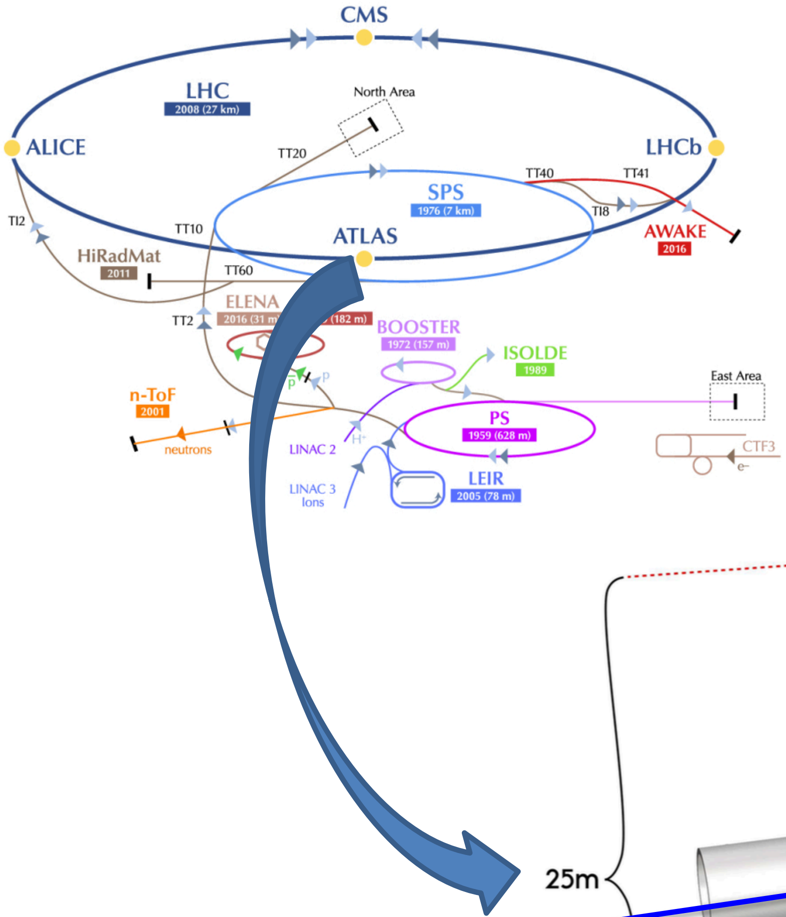


Marcello Bindi,

on behalf of the ATLAS Collaboration

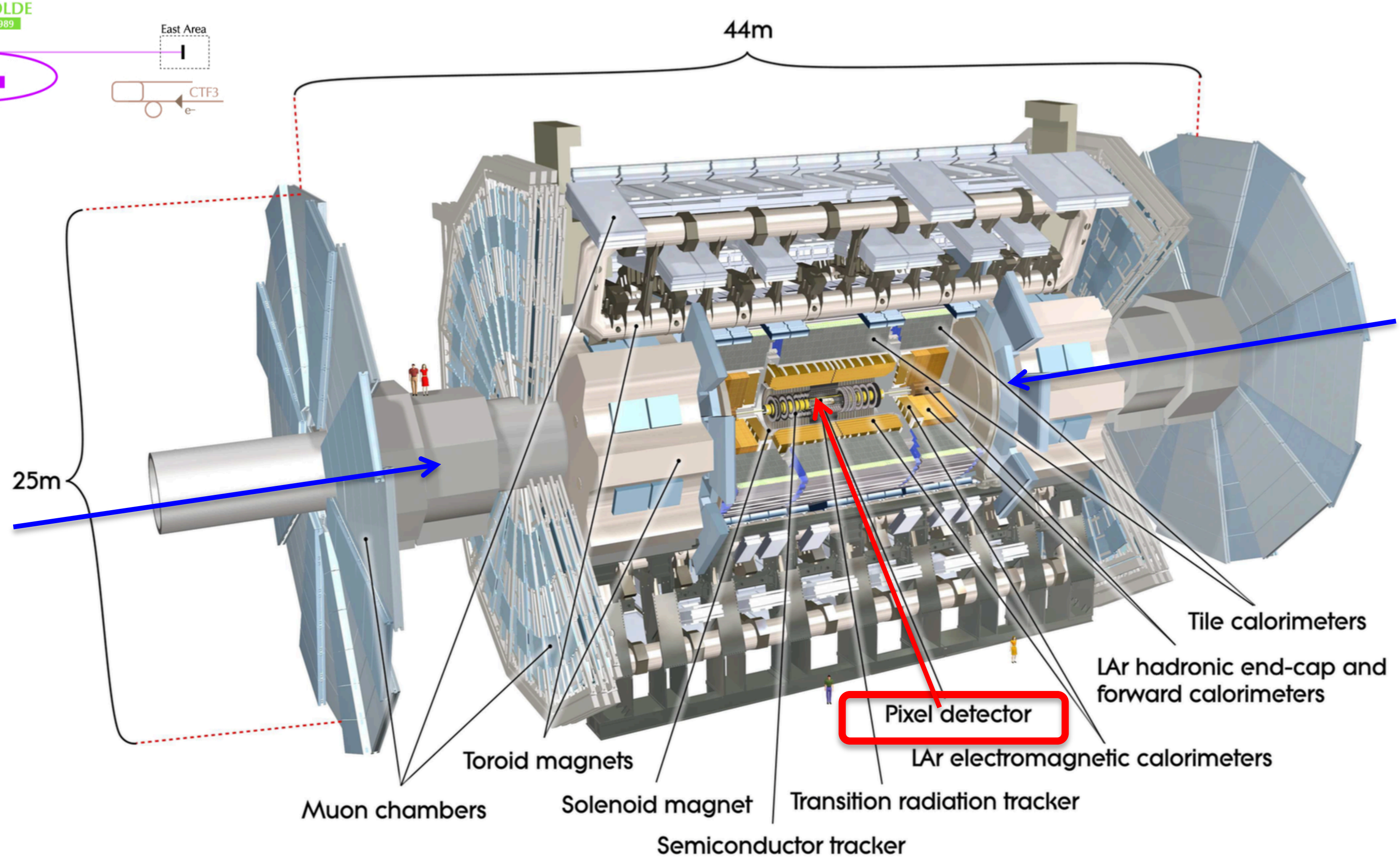
TREDI2020 – 15th Trento Workshop on Advanced Silicon Radiation Detectors
17-19 February – TU Wien - Austria

The ATLAS detector @ LHC



The ATLAS Inner Tracker

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

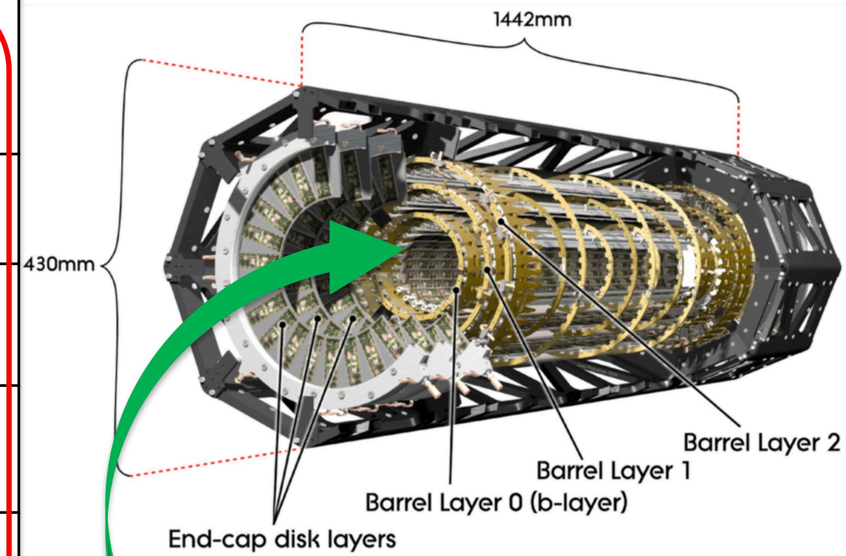


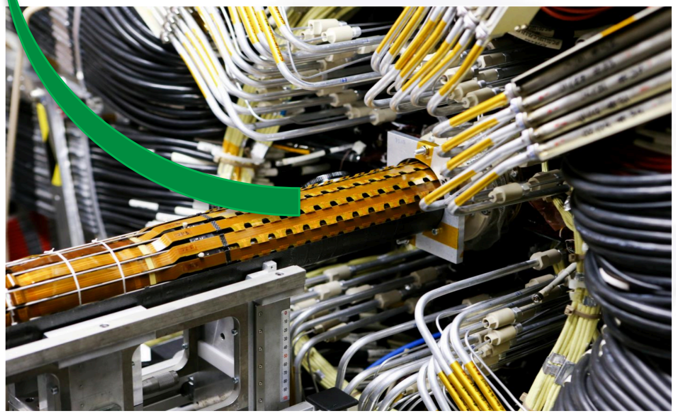
The Pixel (+IBL) Detector

	Pixel		**IBL**
Sensor Technology	*n*⁺-in-*n* (only planar) 1 mm inactive edge		*n*⁺-in-*n*/***n*⁺-in-*p*** (planar/**3D**) **~200 µm** inactive edge
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 Mrd** (500 kGy) ~ 1 x 10^{15} $n_{eq}\cdot cm^{-2}$		**250 Mrd** ~ 5 x 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

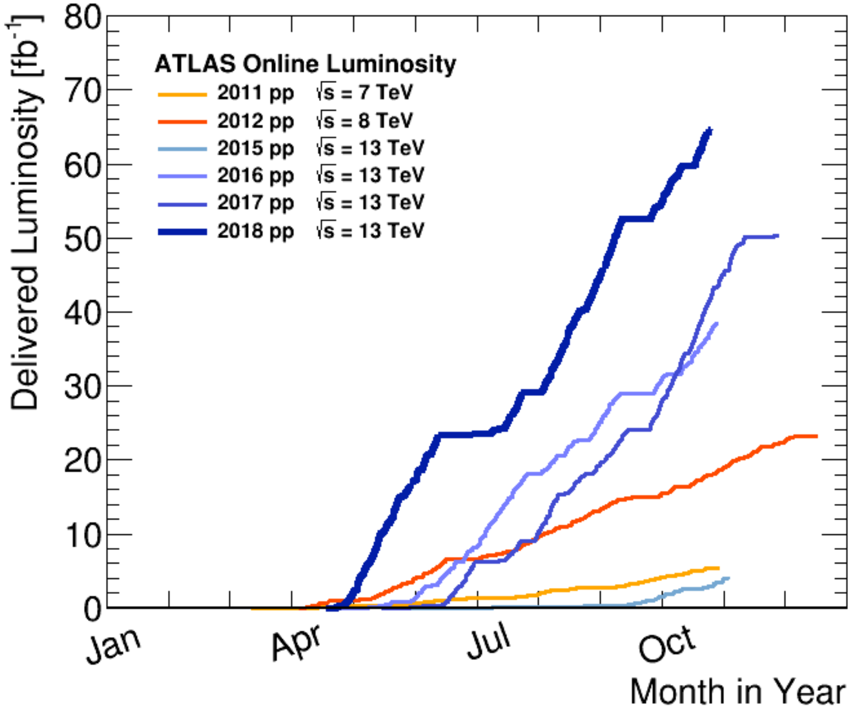
3 + 1 barrel pixels **layers**
3 + 3 pixels **endcaps**

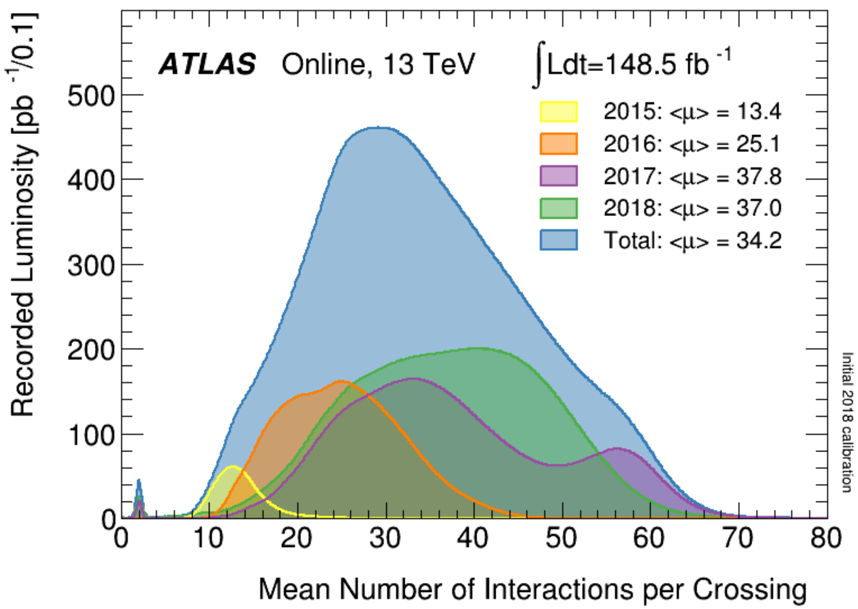




Insertable B-Layer (IBL) added in 2014 (Run 2)

Facing the unexpected @ LHC

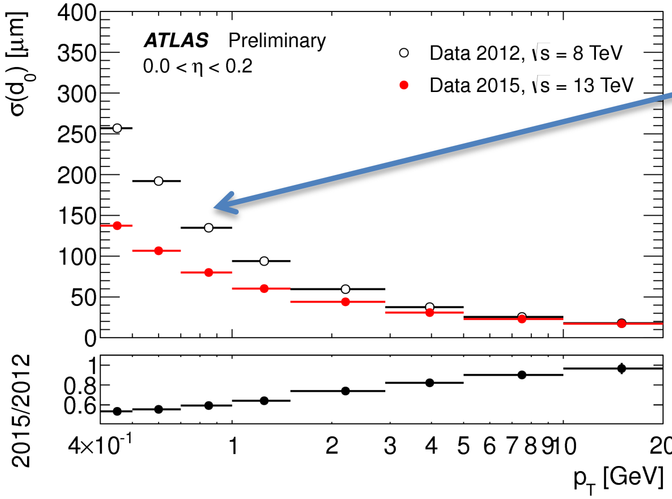




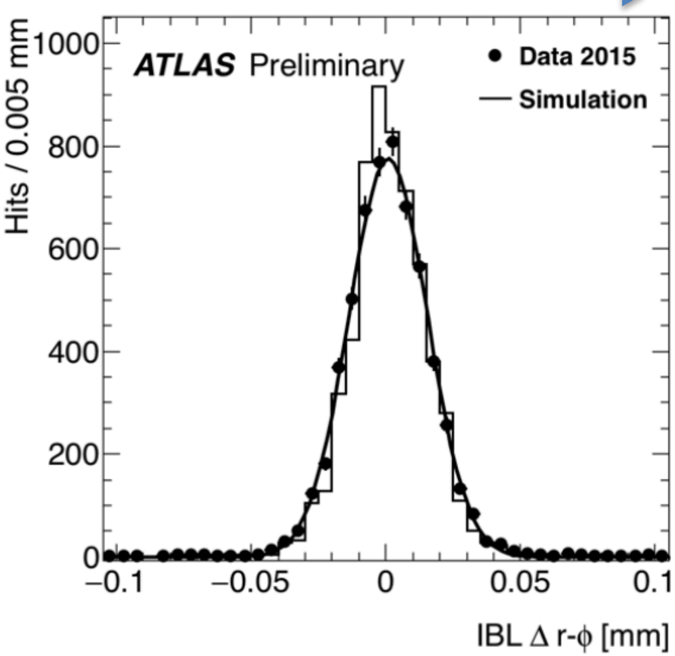
Run 1 vs Run 2 conditions for a typical fill:

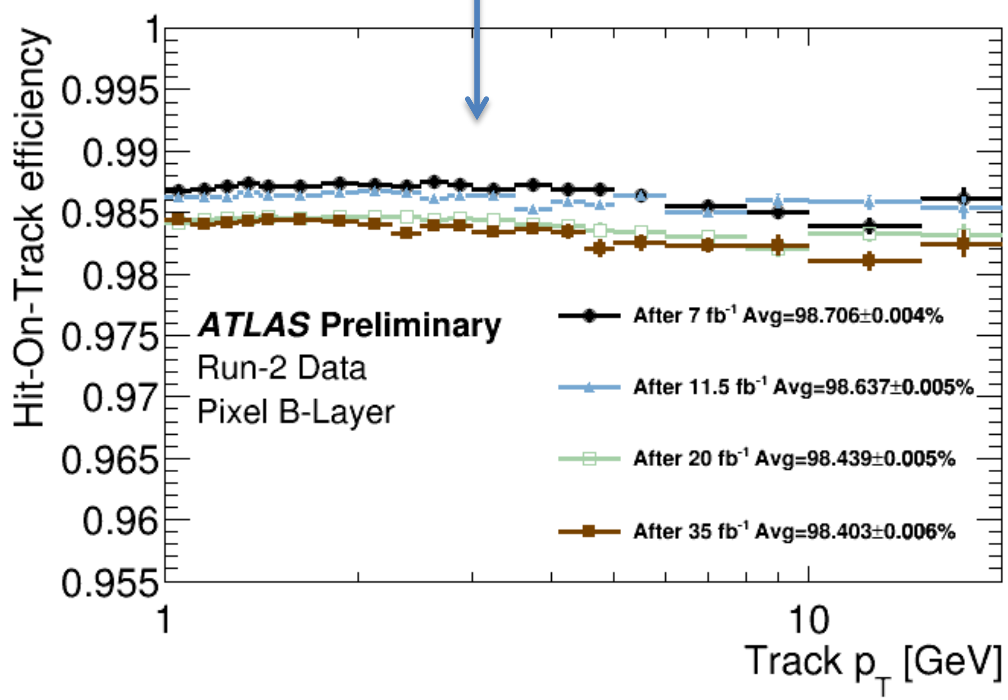
- Bunch crossing spacing or **BX** (ns)
  - **BX time 50 → 25**
- Pile-up or **μ** (# interactions per BX):
  - **Average ~20 → ~35**
  - **Peak ~40 → ~60**
- Instantaneous luminosity ($cm^2\ s^{-1}$):
  - **Peak ~7 x 10^{33} → ~2 x 10^{34}**
- Integrated luminosity (pb^{-1}):
  - **Average ~150 → ~500**
- Level 1 trigger rate (kHz):
  - **L1A Rate ~70 → ~100**

Pixel/IBL at the start of Run 2



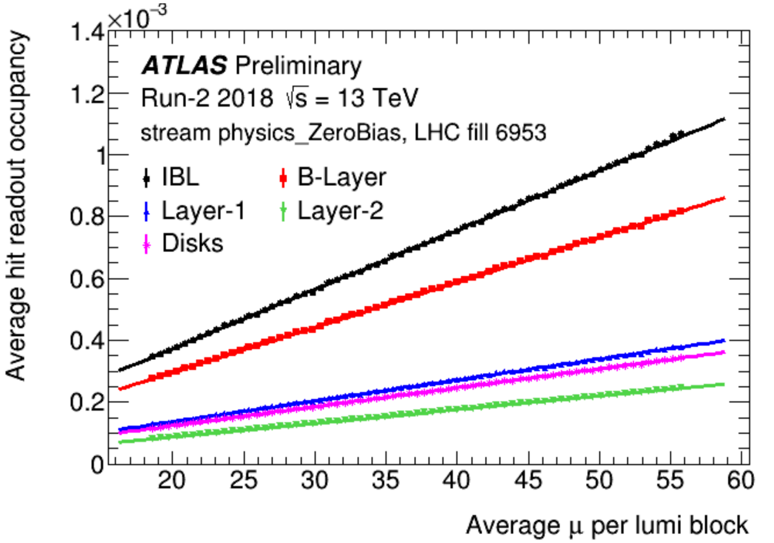
- **Impact parameter resolution** improvements after IBL insertion (2015)
- IBL spatial resolution **~ 10 μm** for the transverse R-φ plane (2015)
- B-Layer Hit-on-track efficiency **> 98%** (2016)





Detector operation in Run 2

OCCUPANCY vs PILE-UP

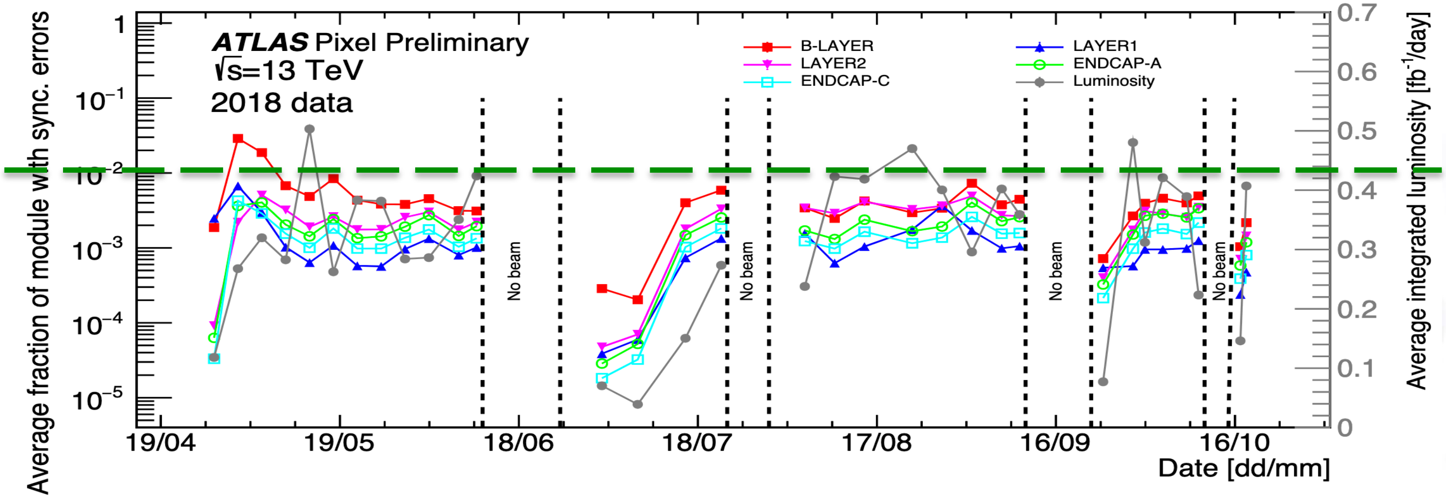


- Occupancy (hit/pixel/event) scales with pile-up
  - ➔ several challenges due to **big event size** joint to an **high trigger rate!**
    - ➔ **high link bandwidth usage <~70%**

DESYNCRONIZATION

- Desynchronization (event id. mismatch between Pixel modules and ATLAS) **within 1%** despite the increased luminosity along the years.

1%



DEADTIME

- Busy time in ATLAS further reduced in 2018 following previous year trends

Pixel and IBL dead time routinely <~ 0.2%

Fluence and Integrated Dose

	Pixel			IBL		
	Integrated Luminosity (fb^{-1})	Fluence B-Layer ($n_{eq} \cdot cm^{-2}$)	Dose B-Layer (Mrd)	Integrated Luminosity (fb^{-1})	Fluence @ Z=0 ($n_{eq} \cdot cm^{-2}$)	Dose @ Z=32 cm (Mrd)
Run 1	~30	$< 10^{14}$	~5	-	-	-
Run 1 + Run 2	~190	**$\sim 5 \cdot 10^{14}$**	~28*	~160	**$\sim 1.1 \cdot 10^{15}$**	~53
End of Run 3 (2024?)	**~450****	**$> 10^{15}$**	**>~ 50 Mrd**	**~420****	**$<\sim 3 \cdot 10^{15}$**	**~140**

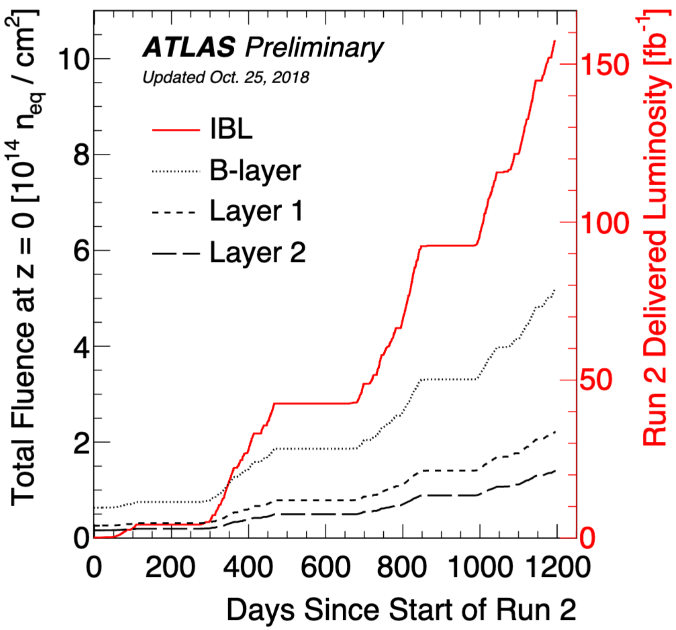
** Assuming the same Energy (13 TeV) in Run 1, Run 2, Run 3.*
*** Assuming an integrated lumi of **260 fb^{-1}** delivered in Run 3.*

Calculated using Pythia/Fluka to end of Run 3:

- IBL within specifications ($5 \cdot 10^{15}$ $n_{eq} \cdot cm^{-2}$ / 250 Mrd)
- B-Layer above specifications ($1 \cdot 10^{15}$ $n_{eq} \cdot cm^{-2}$ / 50 Mrd)

➔ *Full ATLAS tracker will be replaced at HL-LHC!*

➔ *See Q. Buat and J. Lange talks later.*



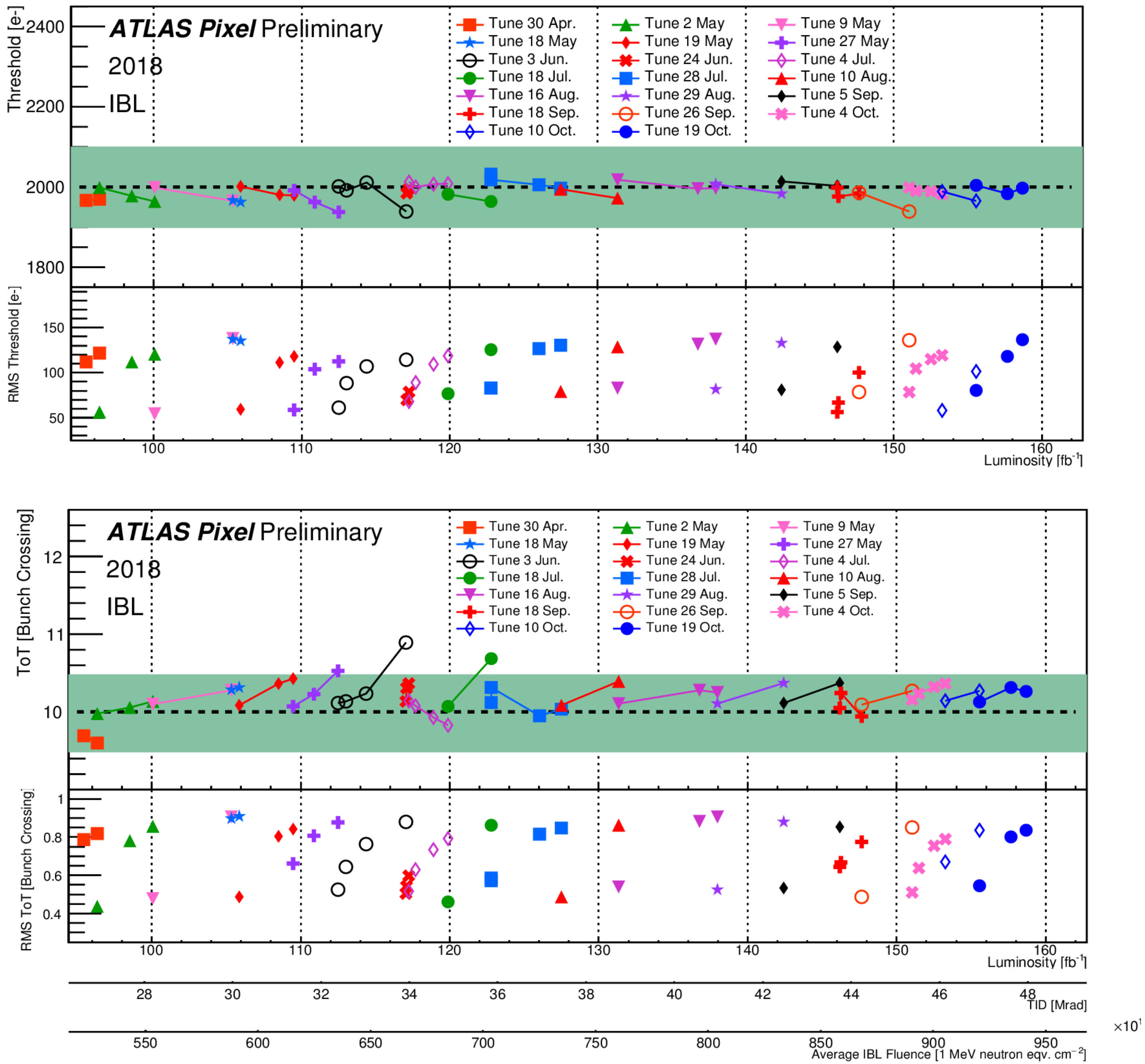
Evolution of detector parameters

Thresholds

Evolution of FE-I4 parameters in IBL due to known TID effect on transistor leakage currents (130 nm IBM):

➔ regular retuning needed!

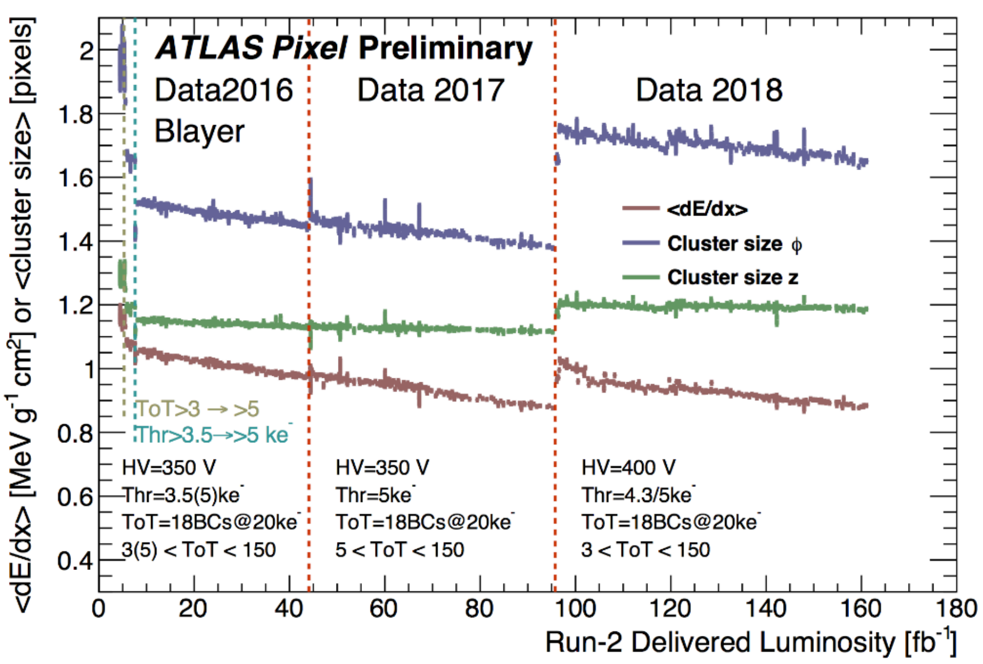
Time over Threshold (ToT)

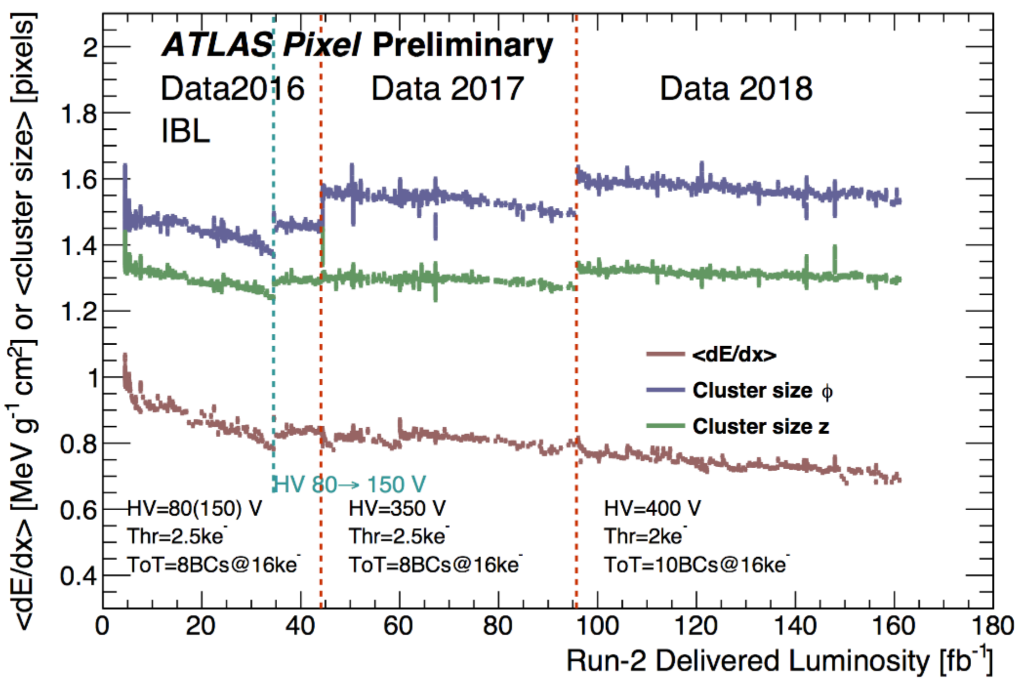


Effects of radiation damage

- **dE/dx and cluster size decrease** due to the decreased charge collected (slow slope).
- **HV increased** to assure the detector was fully depleted.
- **Threshold changes** show up (as steps) in dE/dx since hits below threshold do not get recorded

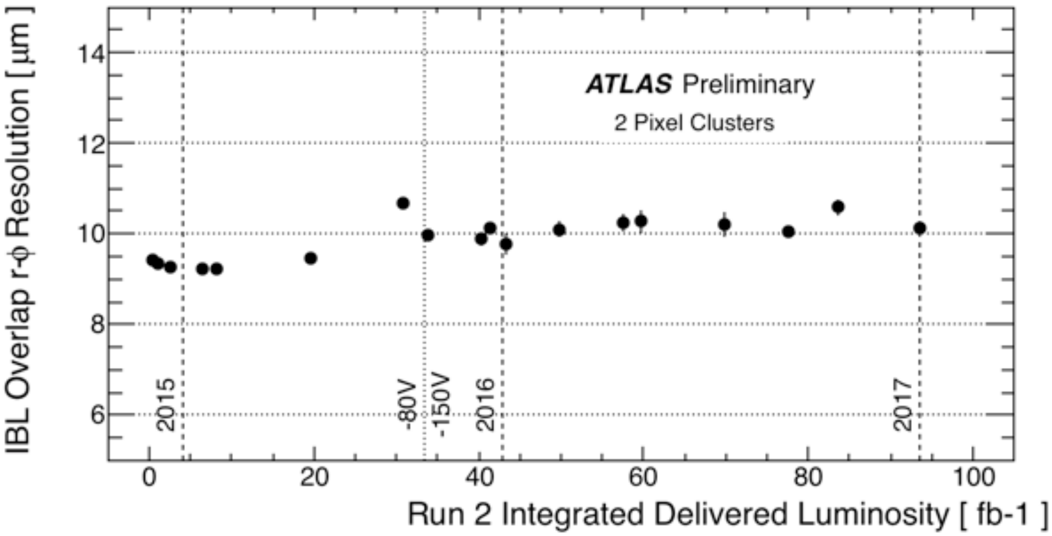
➔ thresholds increased in B-Layer (2016) and Disk (2017) due to limitations on the read-out bandwidth between modules and off-detector electronics.



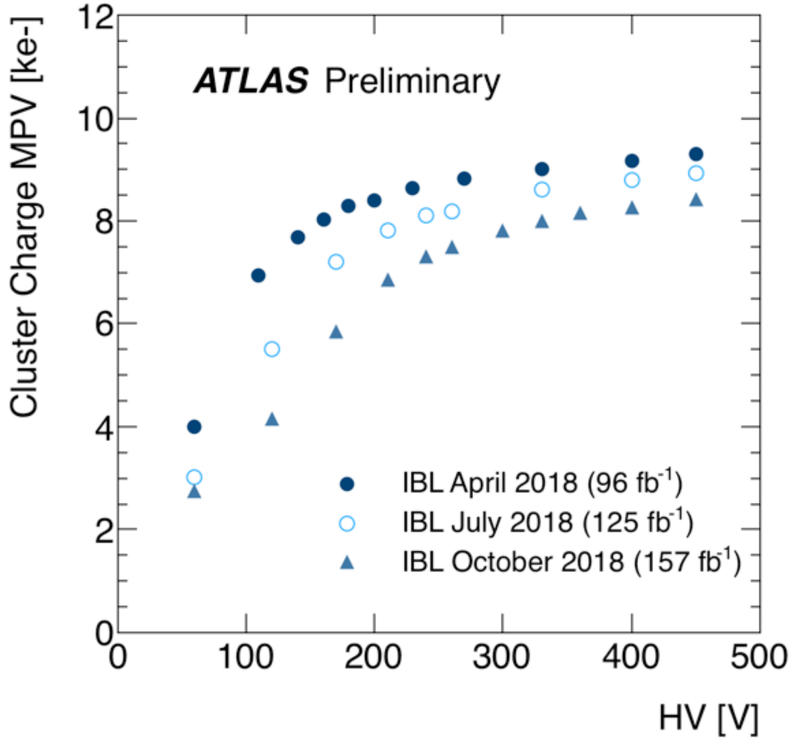


Effects of radiation damage/1

- **IBL hit spatial resolution quite stable:**
  - used only clusters with two pixels in the overlap region
  - small degradation observed by the end of 2017 (~ 95 pb^{-1}).

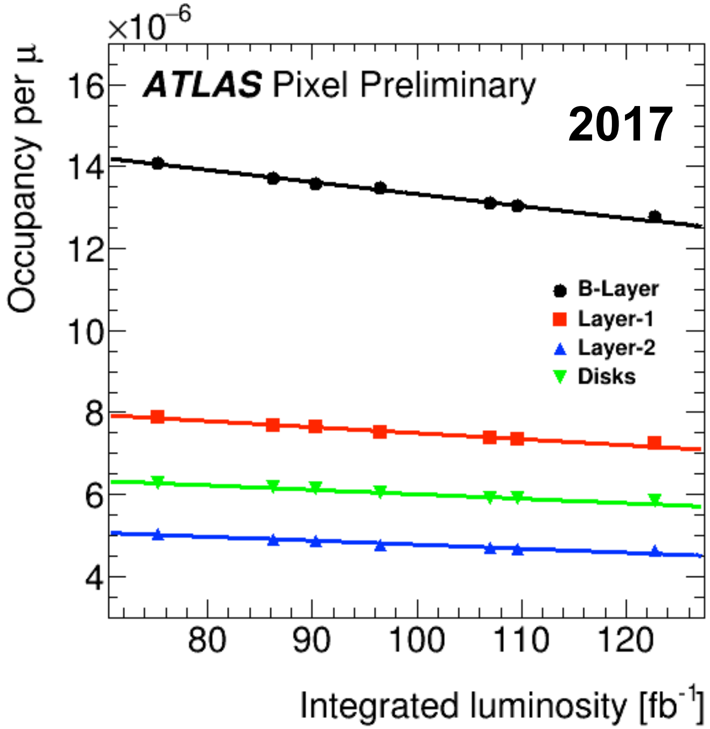


- Charge collection constantly measured via **bias voltage scans** performed for different integrated luminosity
  - MPV of the fitted Landau distribution of TOT clearly affected
    - **decrease of plateau values associated to shape changes.**



Effects of radiation damage/2

- **Hit occupancy per μ** decreases with integrated luminosity (2017).



➔ **Increase HV** to fully deplete the sensors and **decrease the thresholds** to recover from the loss of charge collection efficiency

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

- However, **bandwidth limitations from module to off-detector electronics** appear if thresholds too low!

ATLAS Run2 benchmark

L1Trigger = 100 kHz
<μ> = 60

Detector Performance in 2018

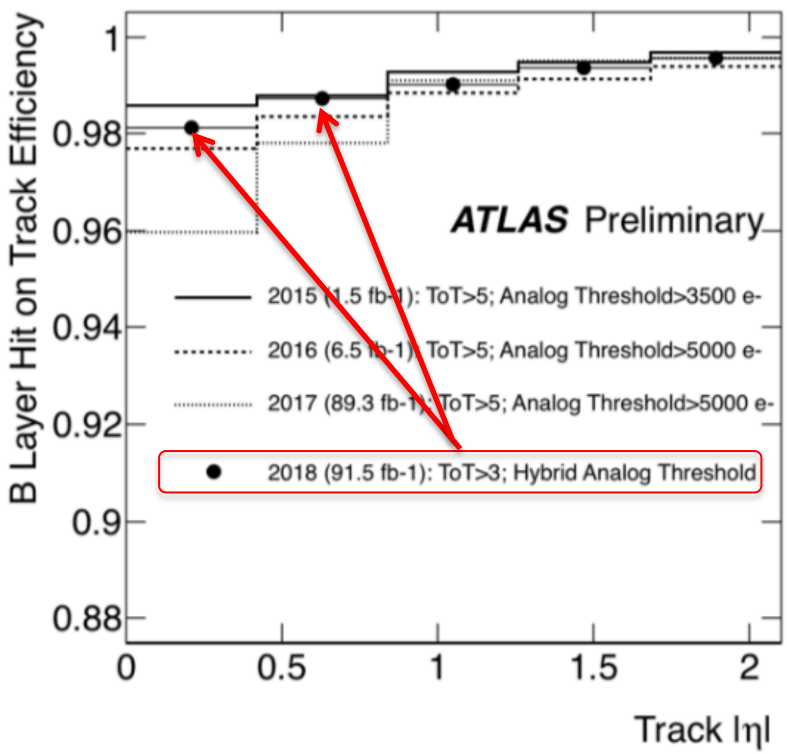
- Different thresholds within the same detector layer (B-Layer) were explored:

5000e (high |η| modules)
vs
4300e (low |η| modules)

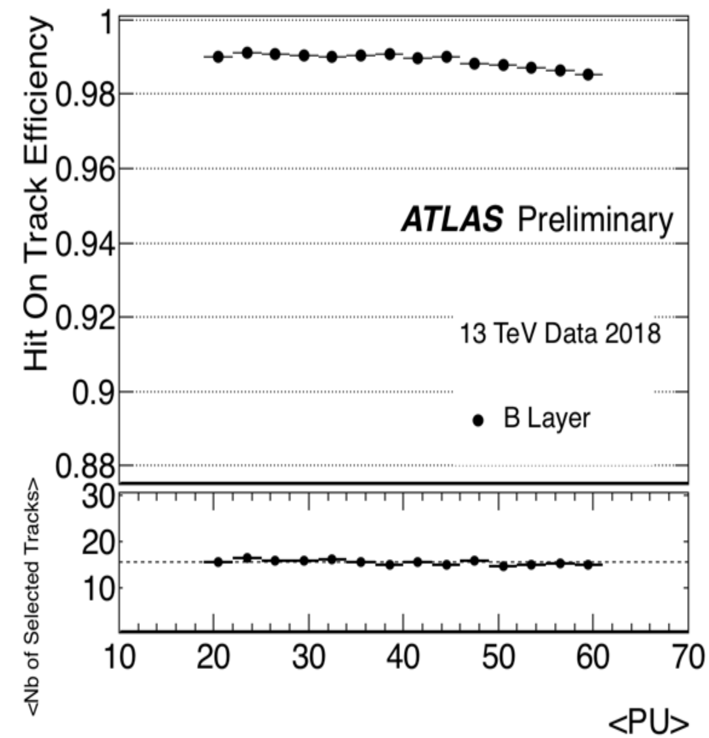
Hybrid analog threshold configuration in B-Layer

- Recovering hit on track efficiency in the central area (more affected by radiation damaged) without increasing too much the occupancy elsewhere.

Recovered the 2015 efficiency!



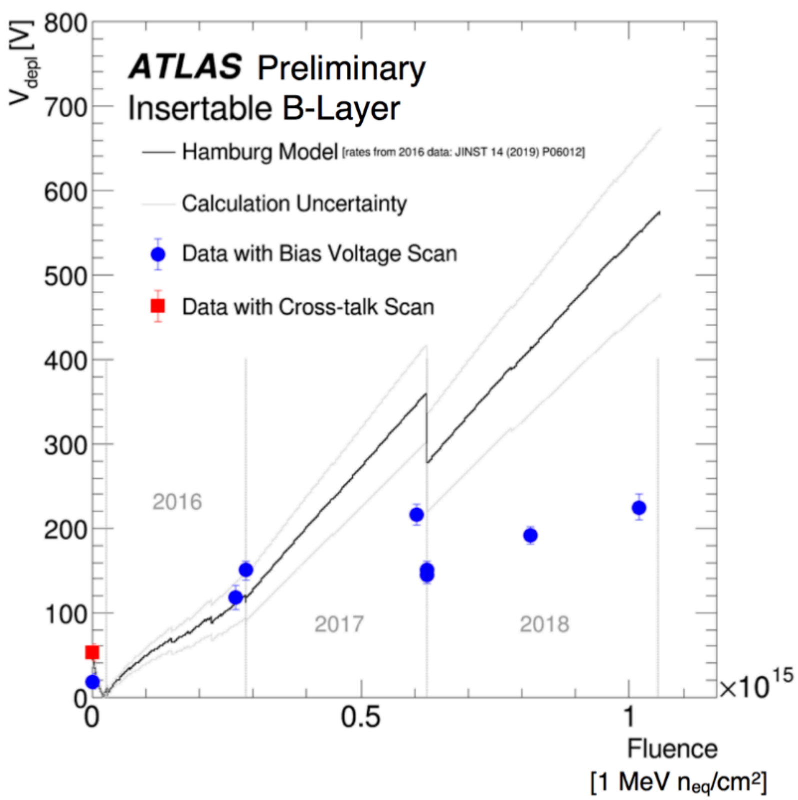
Hit on track efficiency vs μ at **~99%**

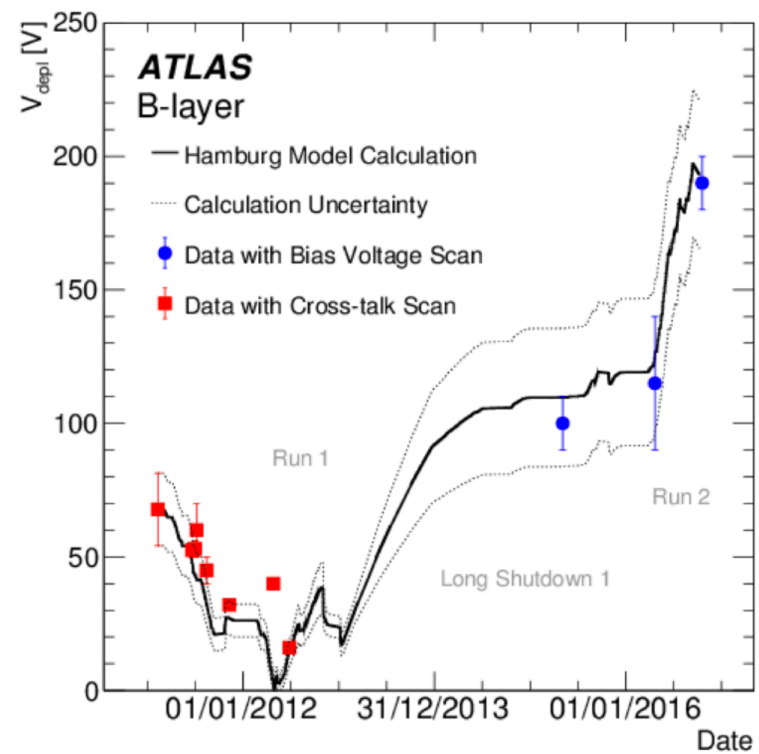


Depletion voltage

Higher bias voltage needed for full depletion and efficient charge collection:

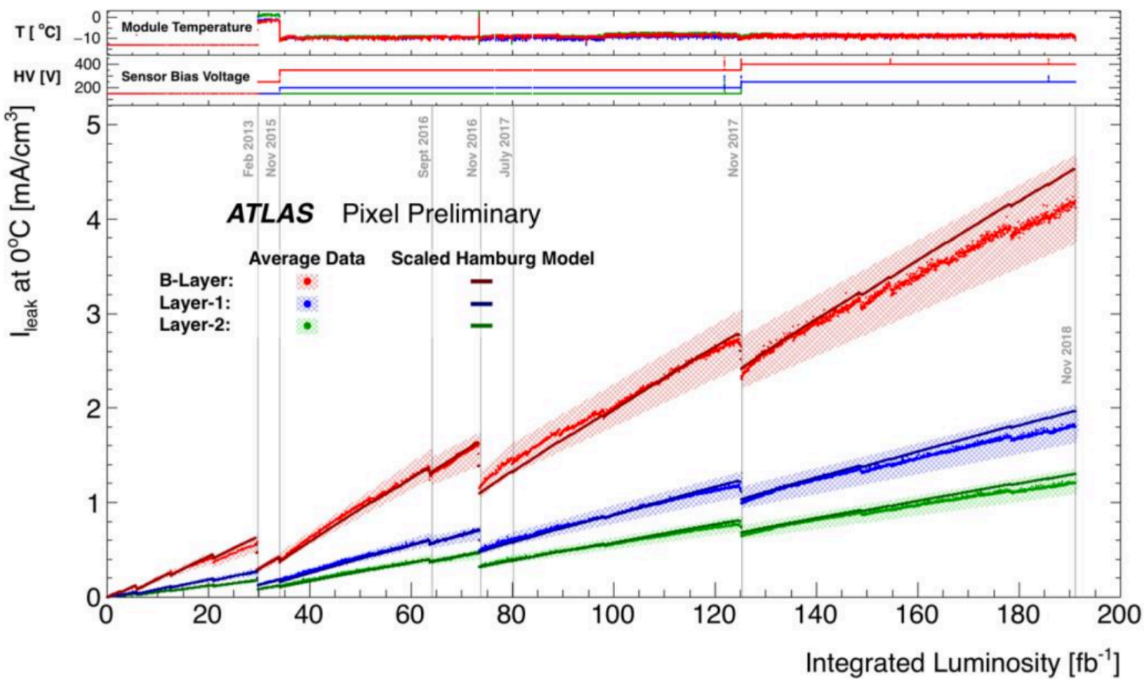
- Hamburg model predictions vs data from bias voltage scan (or cross talk scan before type inversion)
- Full depletion is well predicted by the Hamburg Model at lower fluences and over predicted at higher fluences.

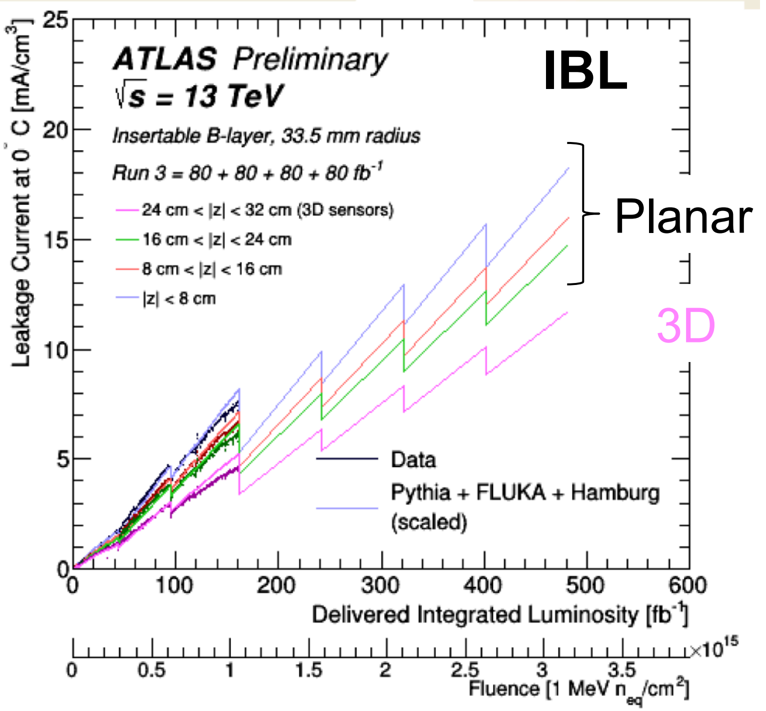




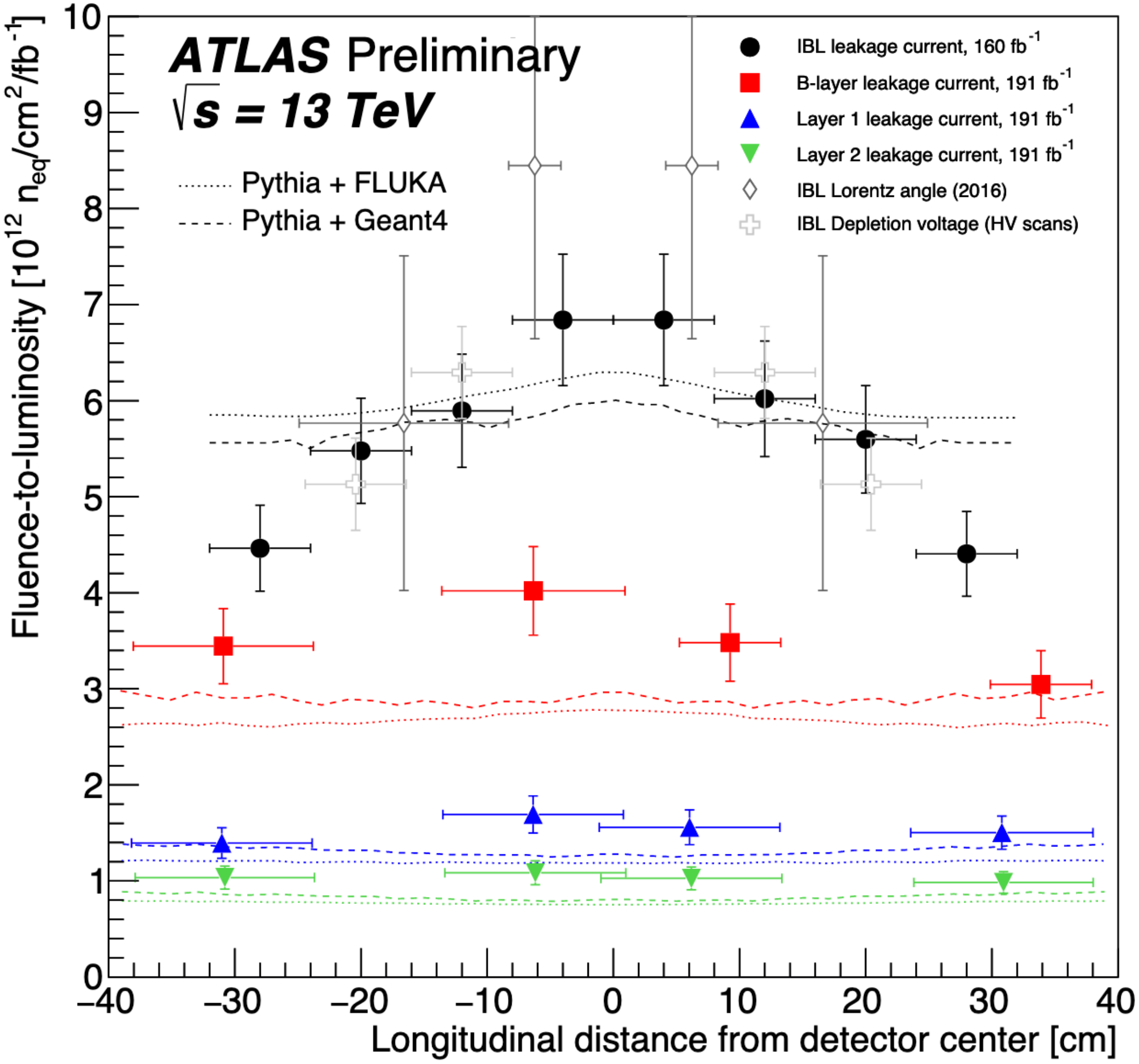
Leakage currents

- 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).
- **IBL:** Leakage current per module expected at the end of Run 3 within the power supply limitation (< 5 mA per sensor).





z-dependence comparisons

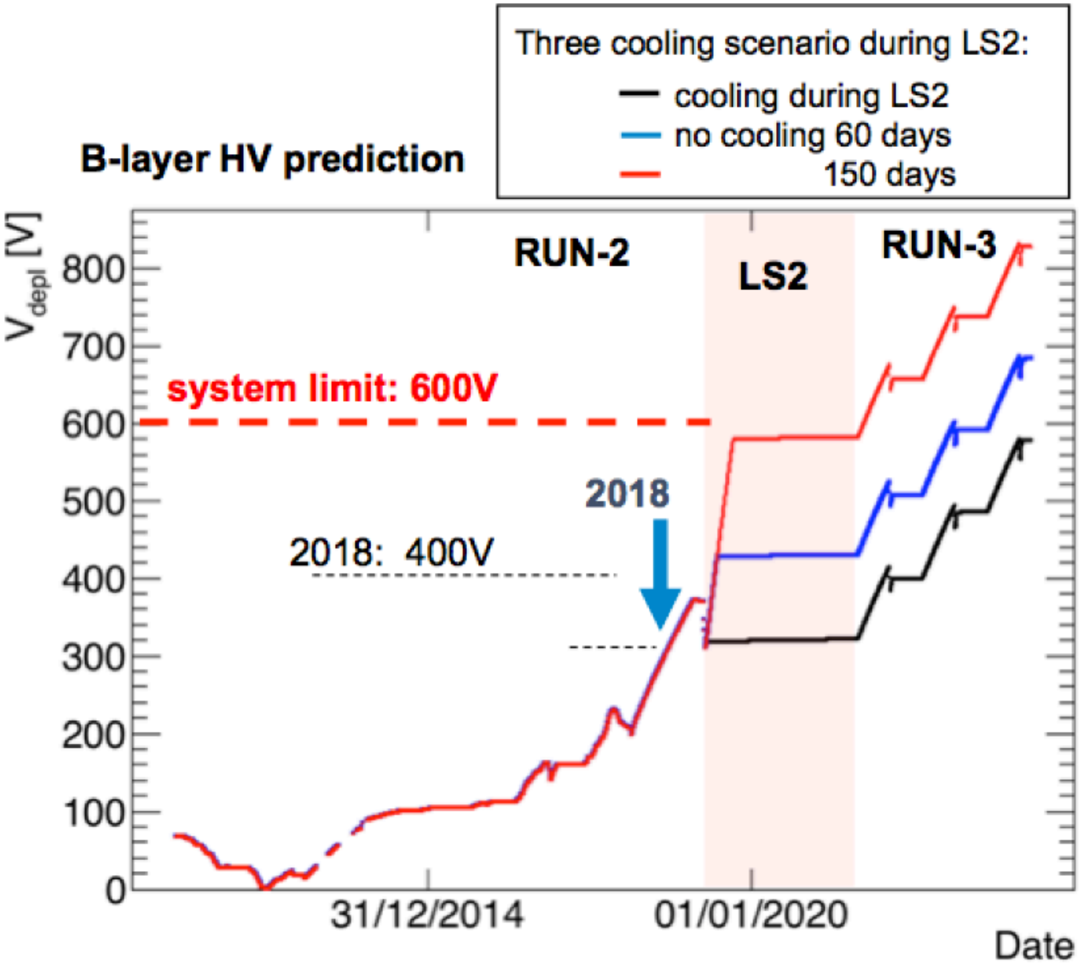


Fluence-to-luminosity conversion factors extracted from the leakage current, Lorentz angle and Depletion Voltage measurements:

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

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 **17 days up to now.**
- Expecting about 2 more weeks
  ➔ **total of 31 days.**



- Exploring colder operating set points in these days (-25°C/-30°C).

Temp set point during LS2	PIXEL	IBL
Detector Unpowered	-5 °C	-5°C
Detector Powered (Cosmics)	-20 °C	-20°C

Radiation damage studies

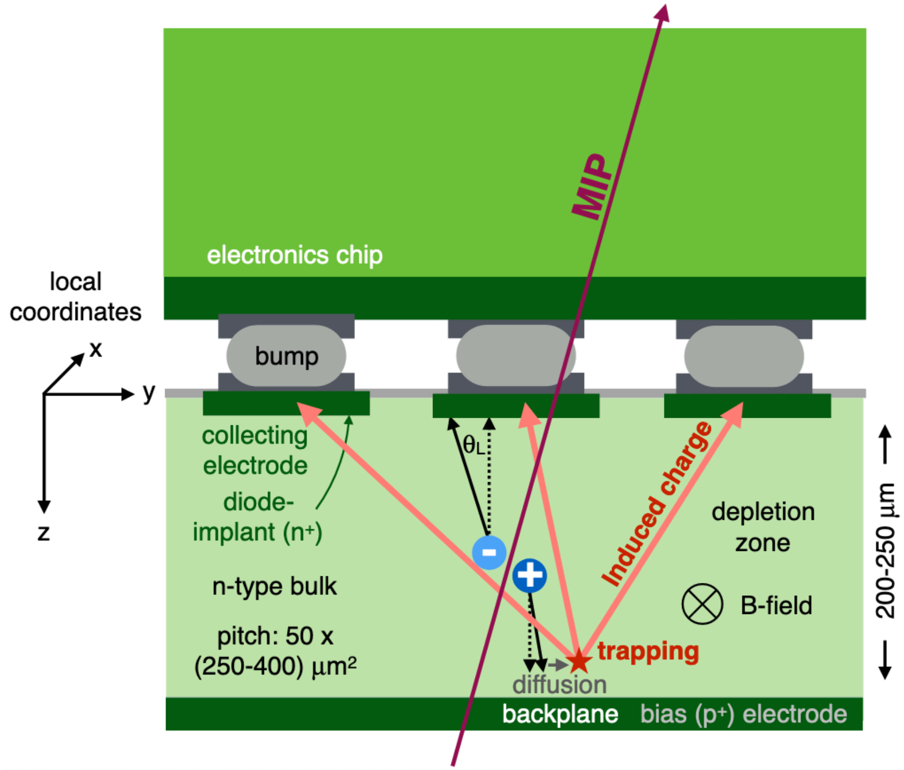
- New Pixel digitization model was developed and is now under validation before entering the official ATLAS simulation

  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.

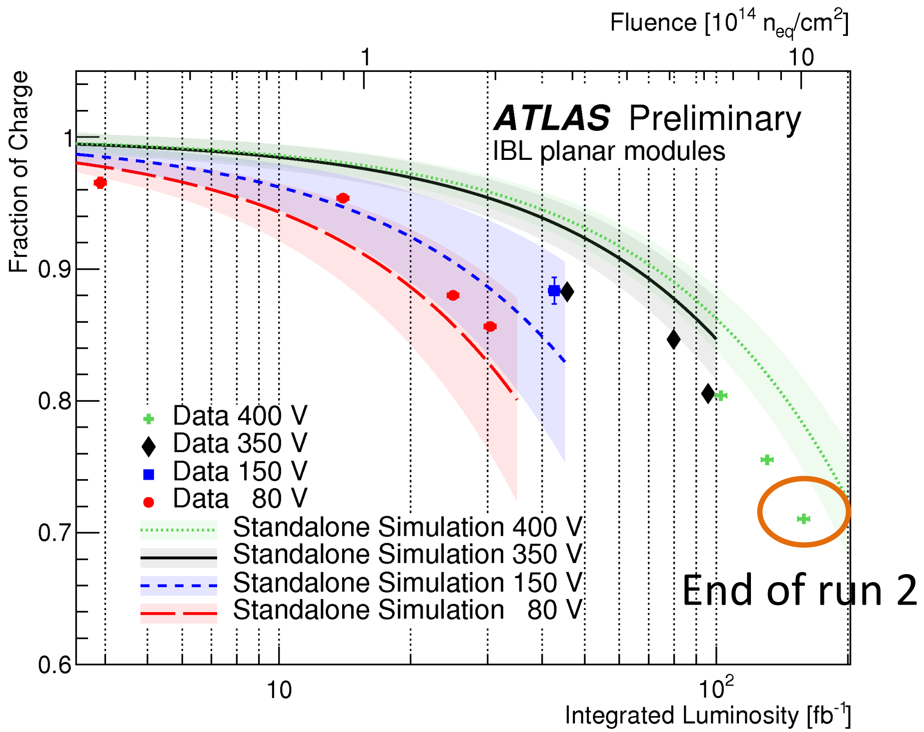


- Available for both **Planar** and **3D** sensors.

Modeling the radiation damage

Charge Collection Efficiency (CCE) for IBL modules with $|\eta|<0.2$ at the end of Run 2 is **~70%**

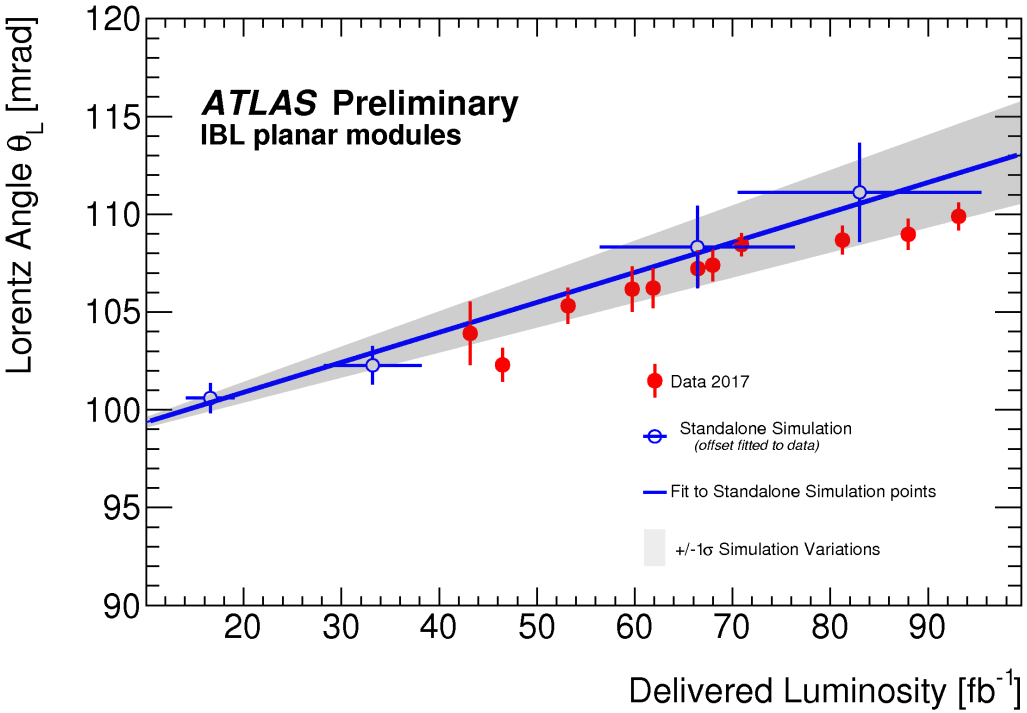
- MPV at the end of Run 2 **~10 ke**, with a front-end threshold of **2 ke.**



Lorentz Angle extracted from a fit to the cluster size vs track incident angle:

- big variations when bias voltage or temperature change
- further changes due to changing electric field shape inside the sensor

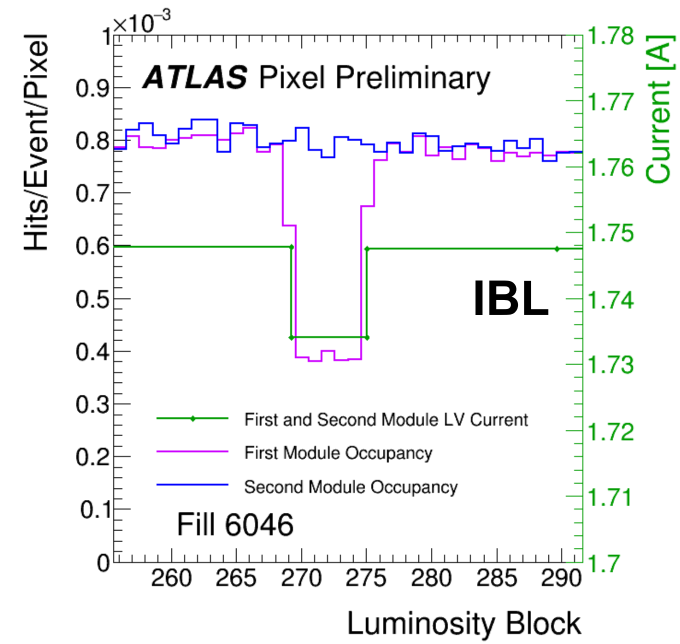
➔ probing the electric field profile.



Effect of radiation on IBL electronics

SEE: **big charge deposit** in FE electronics can **flip** the state of a **global** or **local memory cell**.

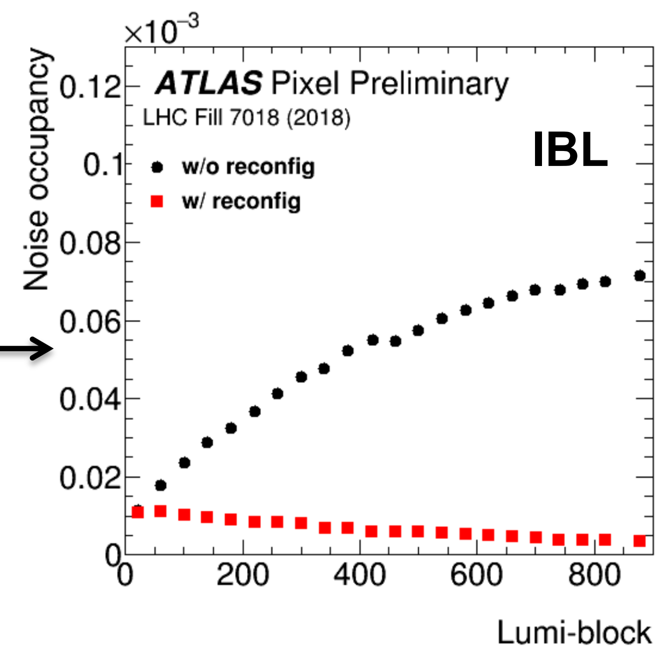
- IBL FEs started being affected by SEE in 2017 → **periodical reconfiguration of FE global registers**.



- However, increase of :
  - **noisy pixels** (pixels firing in the empty bunches)
  - **quiet pixel** (pixels not firing in colliding bunches)

  due to **SEE in single pixel latches** that modify:
  - **local threshold DAC (TDAC)**
  - **return to baseline DAC (FDAC)**
  - **enable bit**.

- Solved by a periodical reconfiguration of the **FE global register + single pixel latches** → clear gain from reconfiguration in test run in 2018.



- The fully FE reconfiguration every few minutes will be the **default approach in Run 3**!

Conclusion and future plans

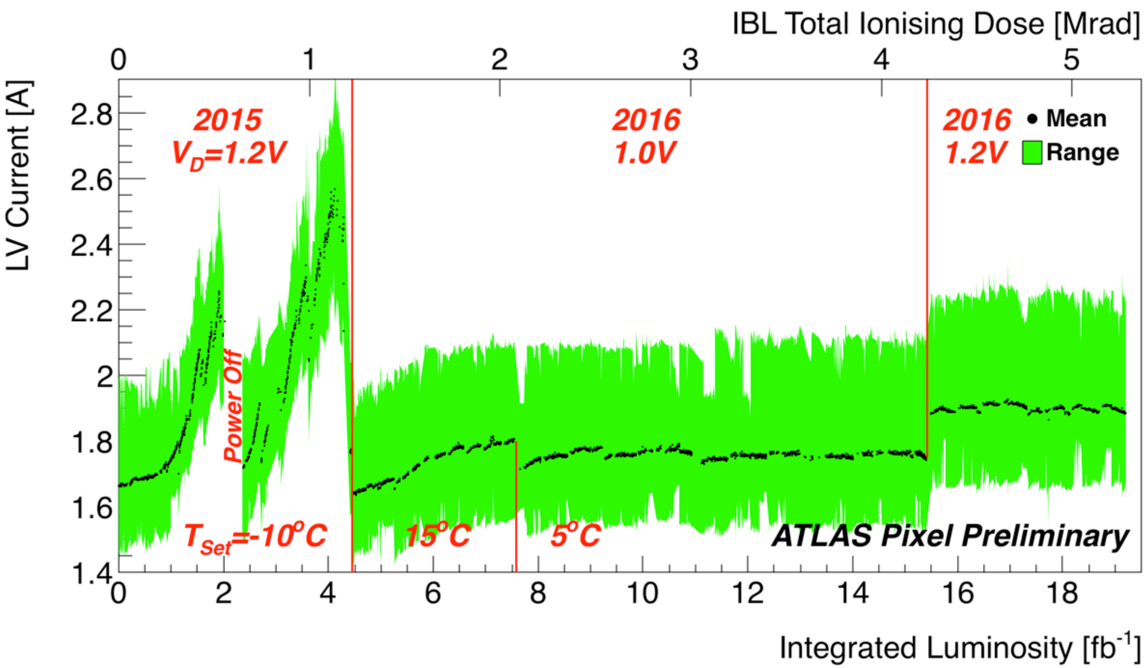
- Several operational challenges/adjustments since beginning of Run 2:
  - **lowered thresholds** for **IBL, B-Layer** and **Disk**
  - **increased bias voltage** for **all the layers.**

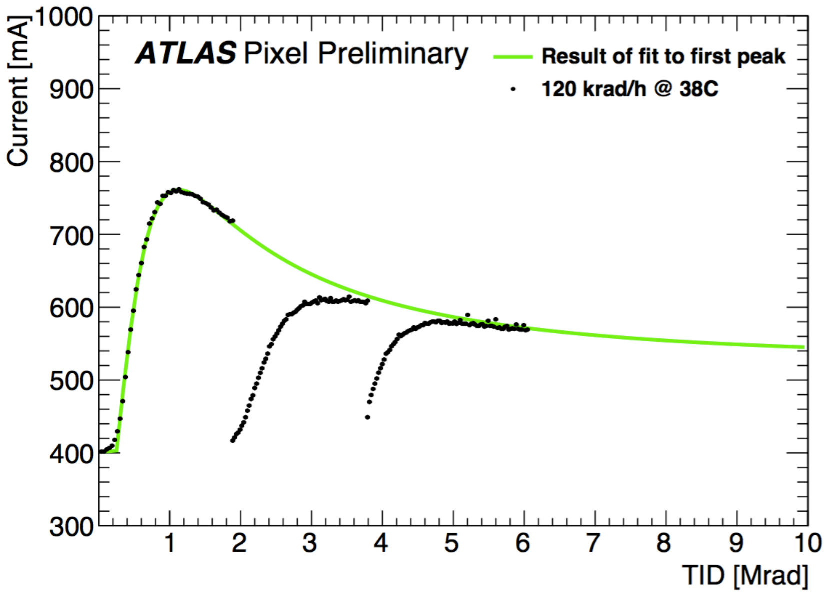
  ➔ time for **consolidation, automatization and optimizations**!
- Pixel/IBL **dead time** reached **minimal** values (~0.2%), with an **excellent data quality** (99.5%) despite the high pile-up/luminosity.
- Reliable and efficient operation of **planar sensors** (small inactive edge) at full depletion voltage (400 V).
- Novel **3D technology** used successfully for the first time in HEP, operating **at lower HV** (40 V)**.**
- Fundamental to **understand and forecast the effects of radiation:**
  - **validate the new digitization model** available for the **MC**
  - **mitigate the radiation damage** (Vth, HV, Cooling)
    - **keep the detector cold** (**-5°C**)
    - **decrease** the operating **temperature** (**< -20°C)**
  - **enhance the FE reconfiguration** operation to limit the impact of SEE.

Back-up

Pixel/IBL at the begin of Run2

- IBL Total Ionizing Dose (TID) effect causing relevant increase of FE currents



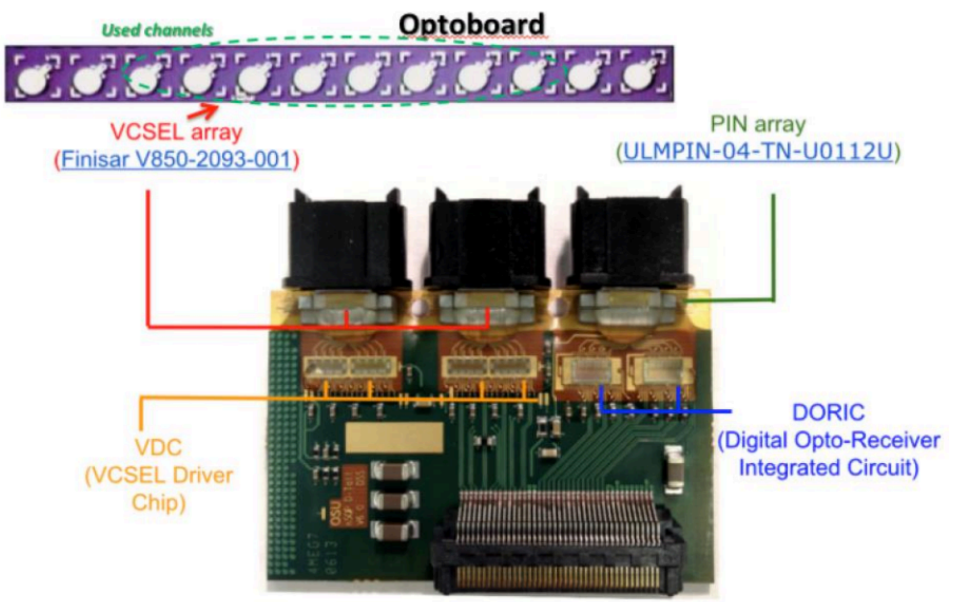


"Production and Integration of the ATLAS Insertable B-Layer"
JINST paper for more info about IBL

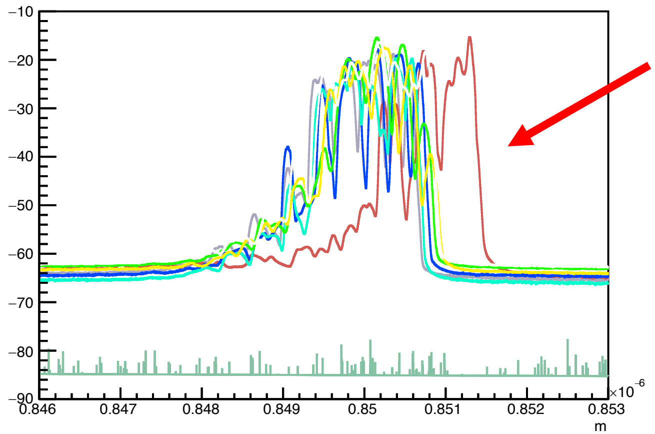
Opto-board failures during LS2

- **High failure rate of VCSELs** since start of Run 2 (on-detector data transmission).
- Cause of the failures not fully understood:
  - **humidity**
  - thermal cycling of VCSELs due to non-DC-balanced transmission.
- About **30 boards** were already **replaced** before the start of 2018 run
  - **20 new** VCSELs died in 2018/2019

    ➔ 20 modules not operational.
- Failed (or suspected to fail) optoboards will be **replaced next summer**
  - better sealing planned to decrease humidity.



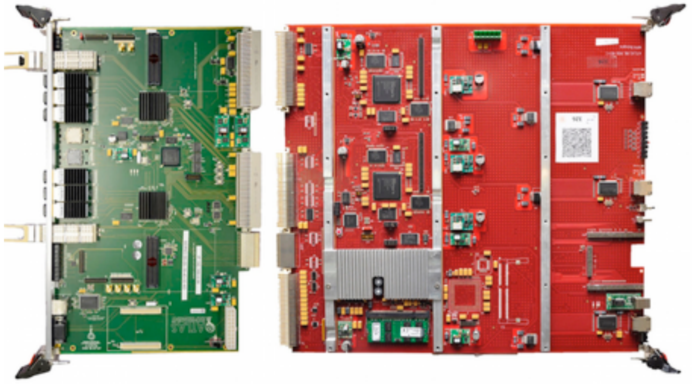
Possible to predict the failure



Shifted spectra of the single VCSEL respect to the rest of the channels in the array.

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 should bring 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!

Pixel status at the end of 2017

Expectations for 2017 were:
Limitations to be expected in module to read-out system bandwidth
➔Pixel high lumi task force recommended an occupancy reduction in Disk.

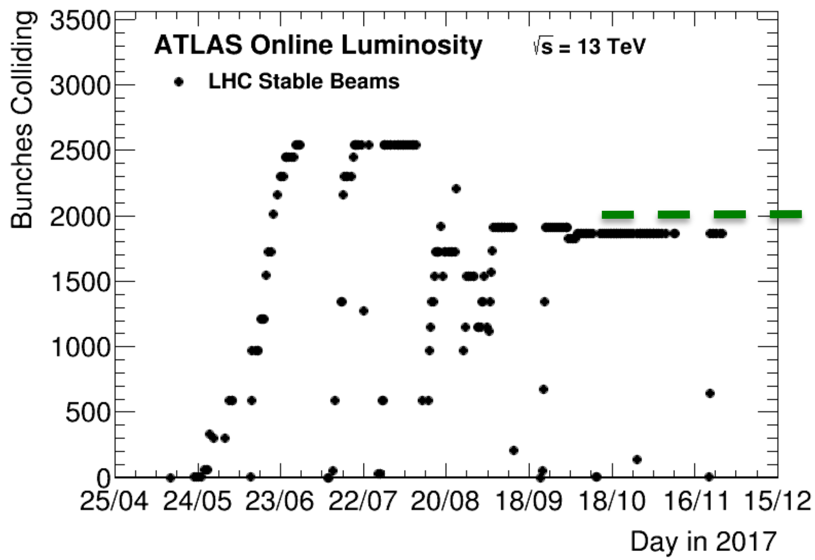
Hit occupancy in disks was reduced by ~20% to maintain sustainable operation:
- increase analog threshold: 3500 e- → 4500 e-
- increase digital threshold : 5 (TOT) → 8 (TOT)

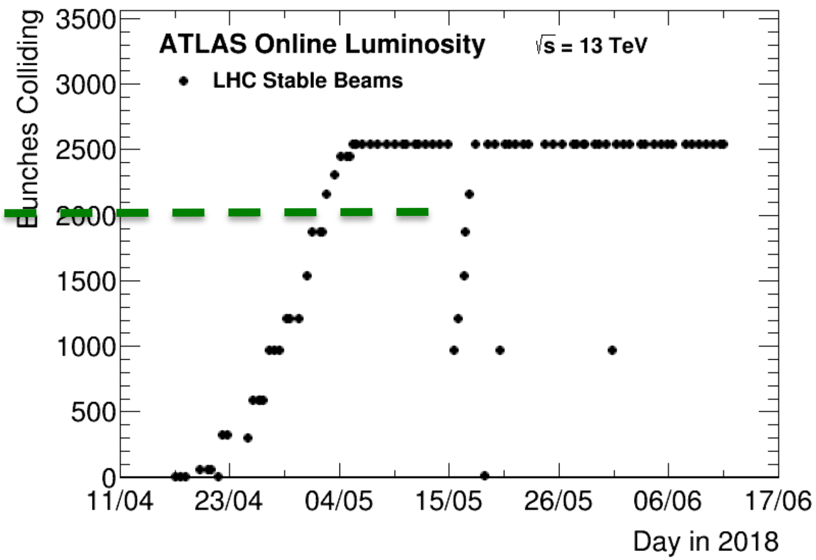
Layer	Analog Threshold [e-]	Digital ToT cut [BC]	Latency [BC]	Tuning
B-layer	5000	5	150	ToT = 18 @ 20,000 e-
Layer 1	3500	5	255	ToT = 30 @ 20,000 e-
Layer 2	3500	5	255	ToT = 30 @ 20,000 e-
Disks	**4500**	**8**	255	ToT = 30 @ 20,000 e-
IBL	2500	n/a	255	ToT = 8 @ 16,000 e-

Frist clear effects of the radiation damage:
- after accumulating ~ 45 fb^{-1}, a decrease of charge collection efficiency (trapping) was observed:
  ➔ plan to increase HV in 2018 and possibly reduce the thresholds if bandwidth allows!

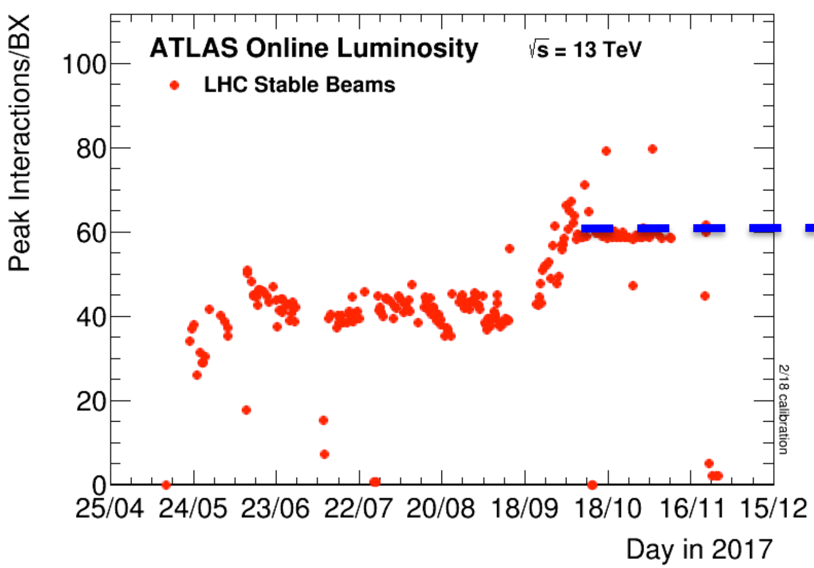
What has changed in 2018? LHC

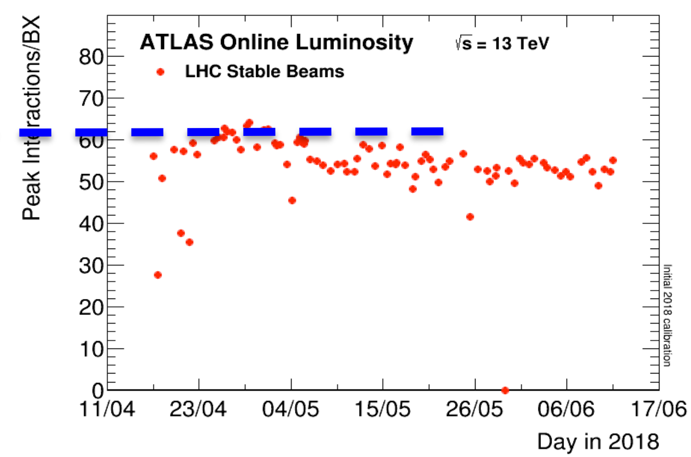
- More colliding bunches in the ring…..from ~2000 to 2544





- Pile-up always below 60 due to bunch intensity limitations





Pixel operational parameters in 2018

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**

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

Run 2 Bias Voltage Evolution

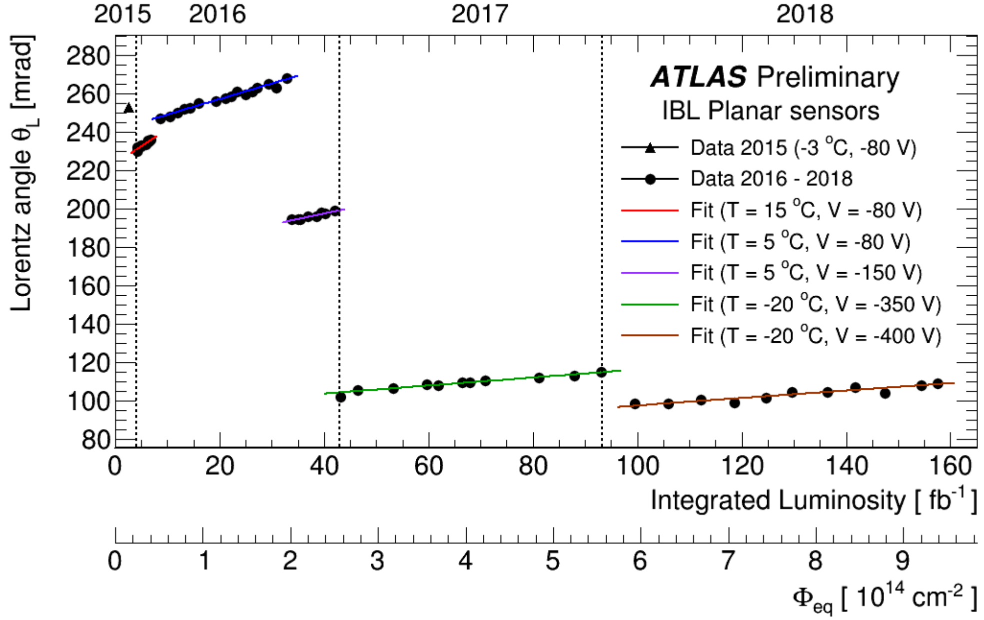
HV	2015	2016	2017	2018
IBL	80V →	150V →	350V →	400V
B-layer	250V	350V	350V	400V
Layer-1	150V	200V	200V	250V
Layer-2	150V	150V	150V	250V
Endcap	150V	150V	150V	250V

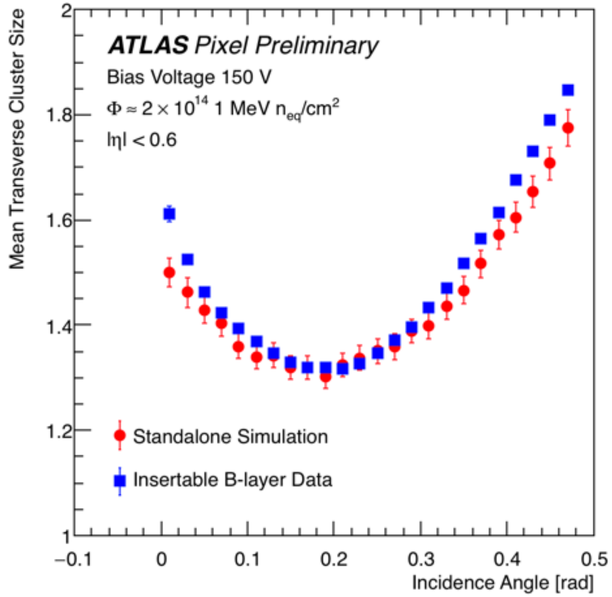
ATLAS Run2 benchmark

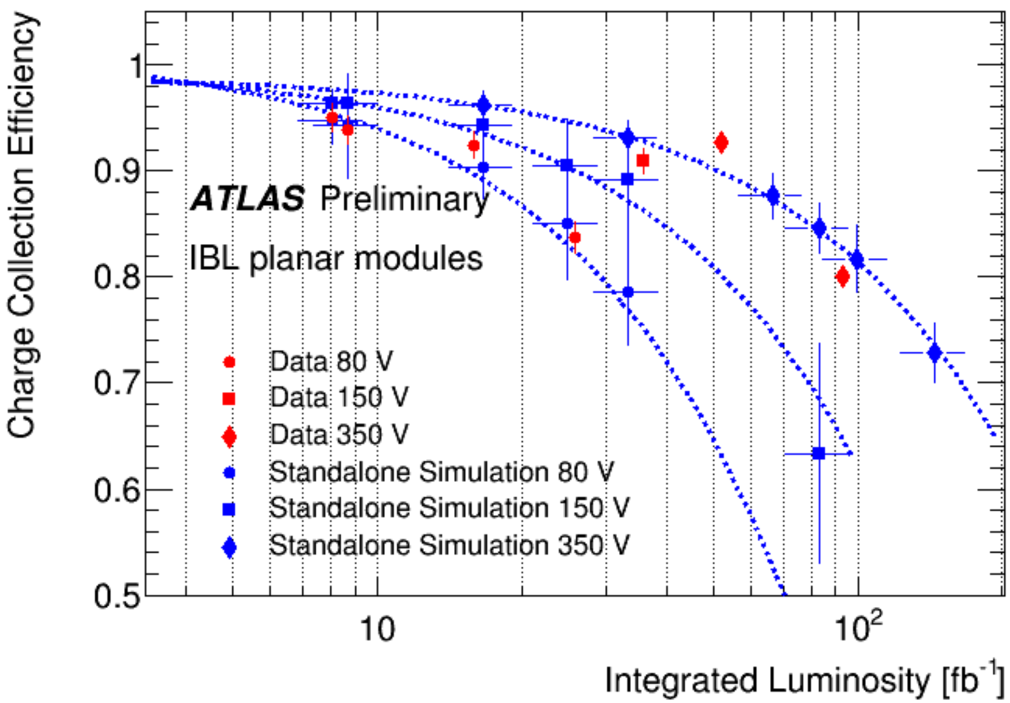
L1Trigger = 100 kHz
<μ> = 60

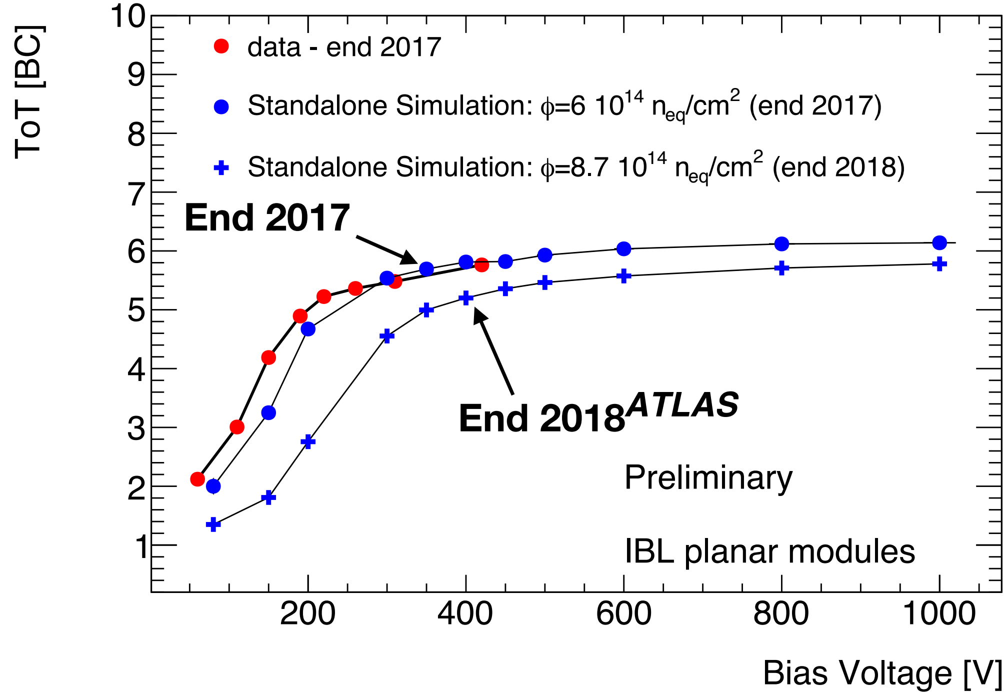
➔Module to read-out system bandwidth usage needs to stay within 80%

Modelling the radiation damage in the sensor

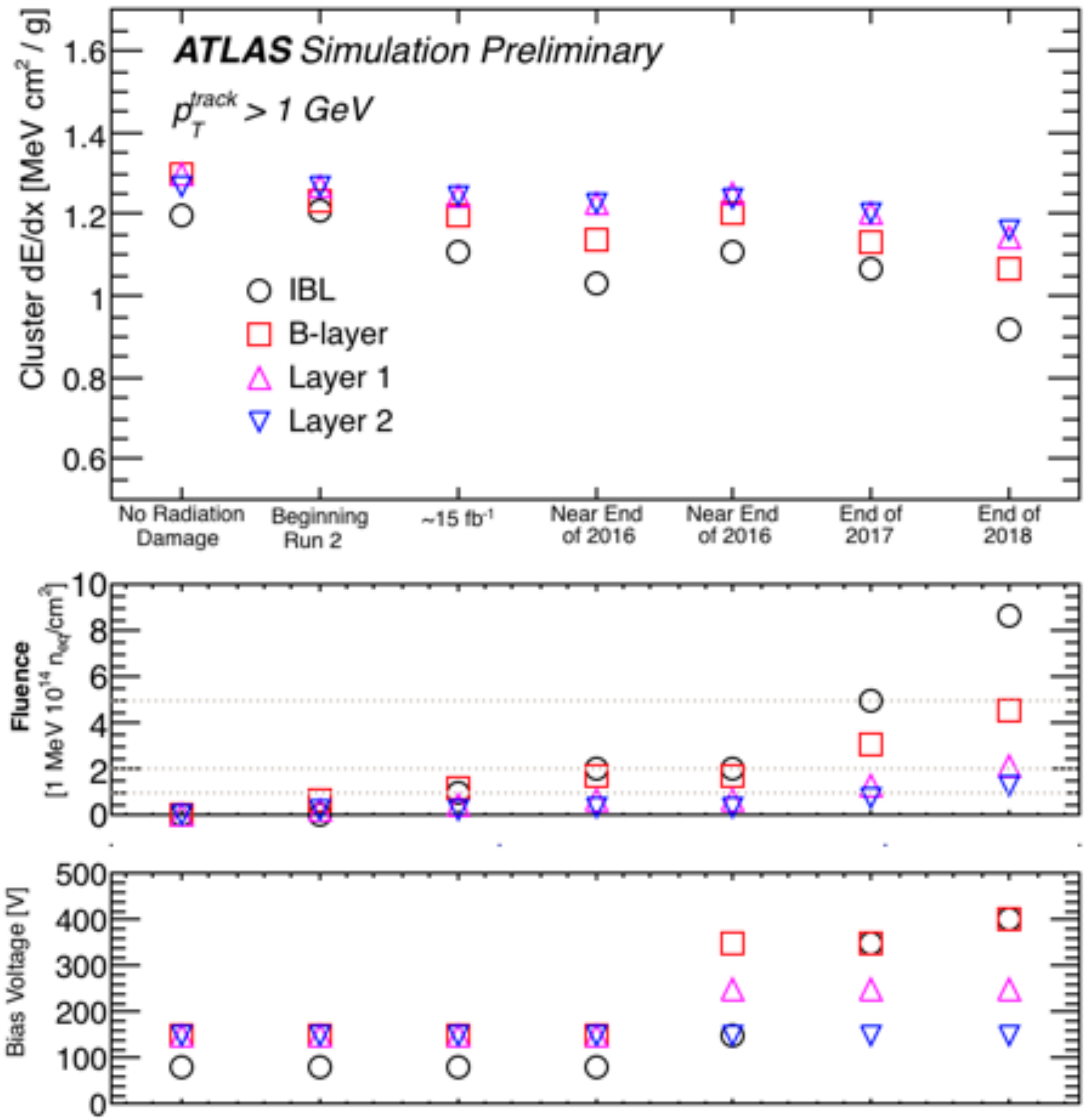




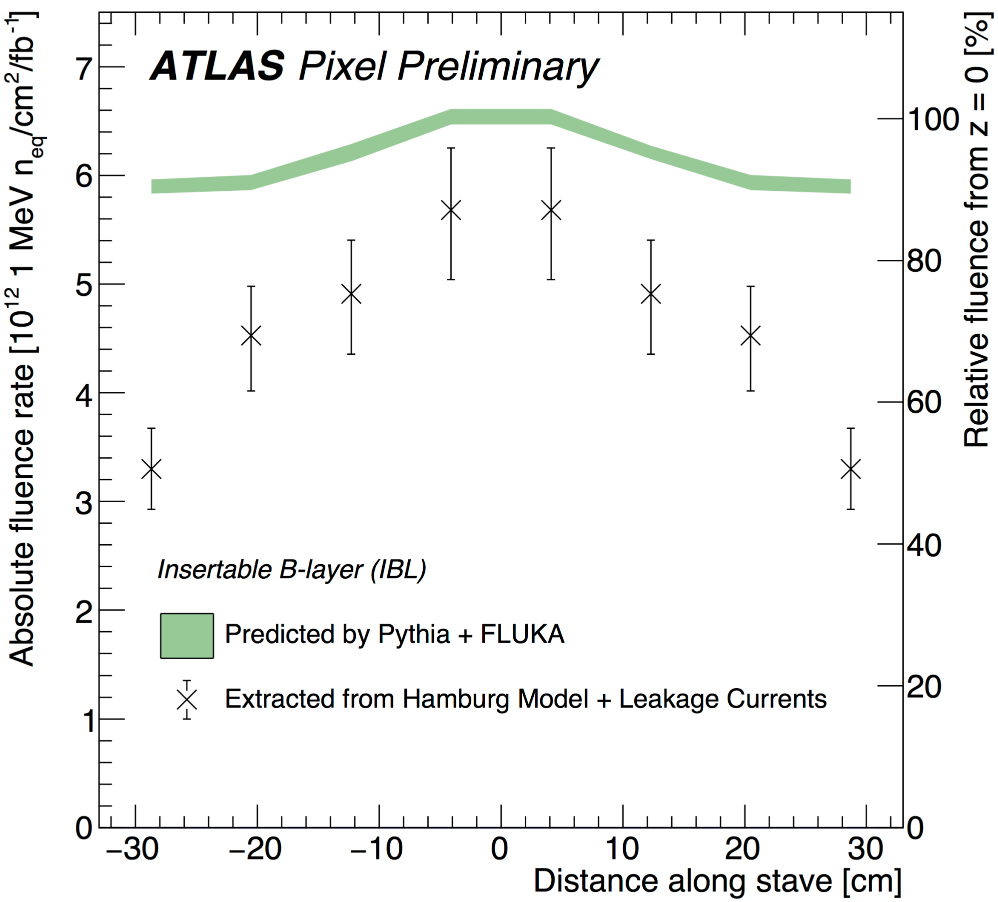


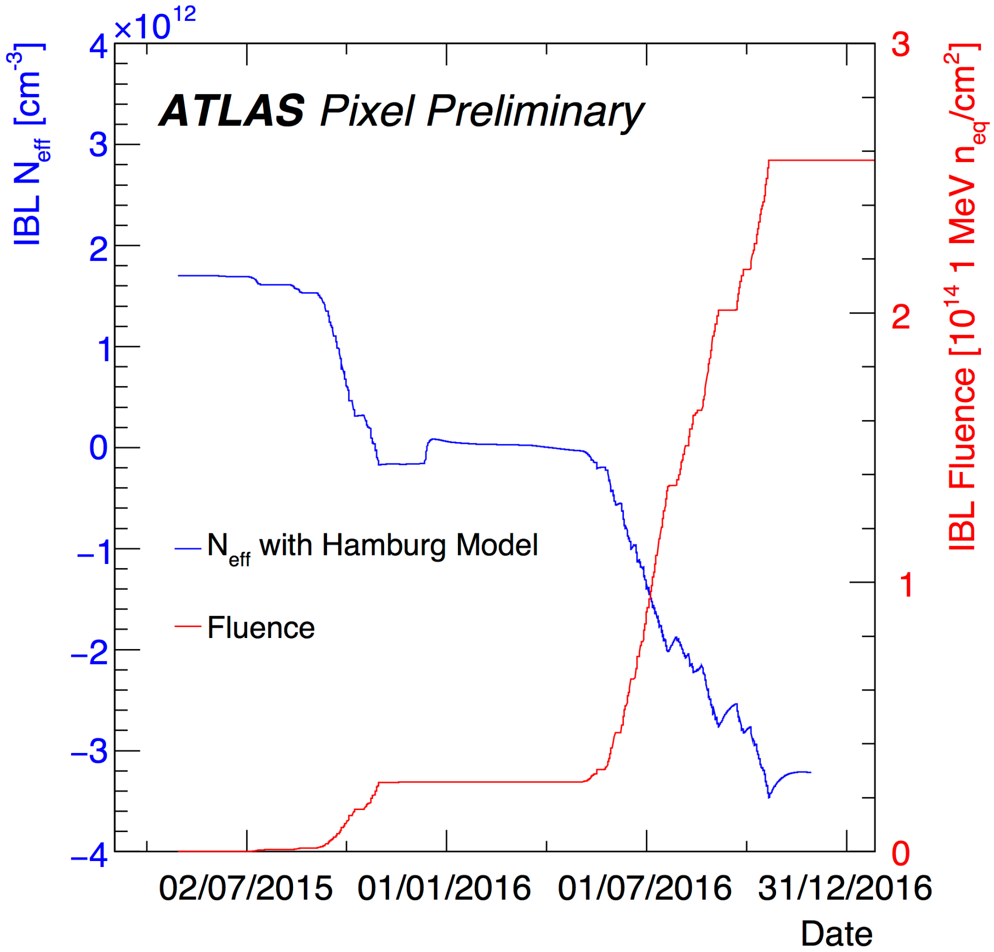


dE/dx in simulation



IBL Fluence z-dependence





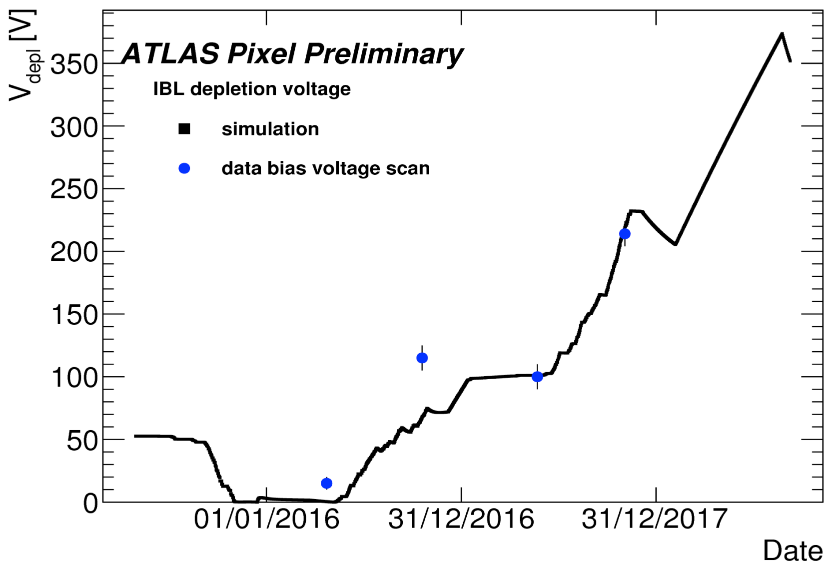
HV evolution

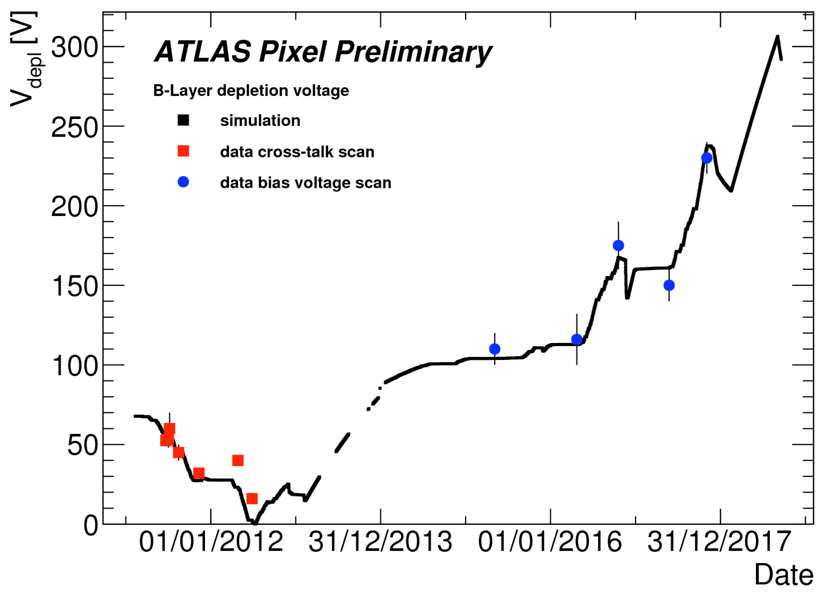
- HV settings have been adjusted to ensure a well depleted sensor:

  ➔ **HV increase in all the layers in 2018!**

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





- Radiation damage will be particularly severe in Run 3.
- In order to avoid to run with the detector not fully depleted, Pixel should be kept cooled as long as possible during the LS2 (2 years long).

FE-I4 SEU studies