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

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on behalf of the ATLAS Collaboration

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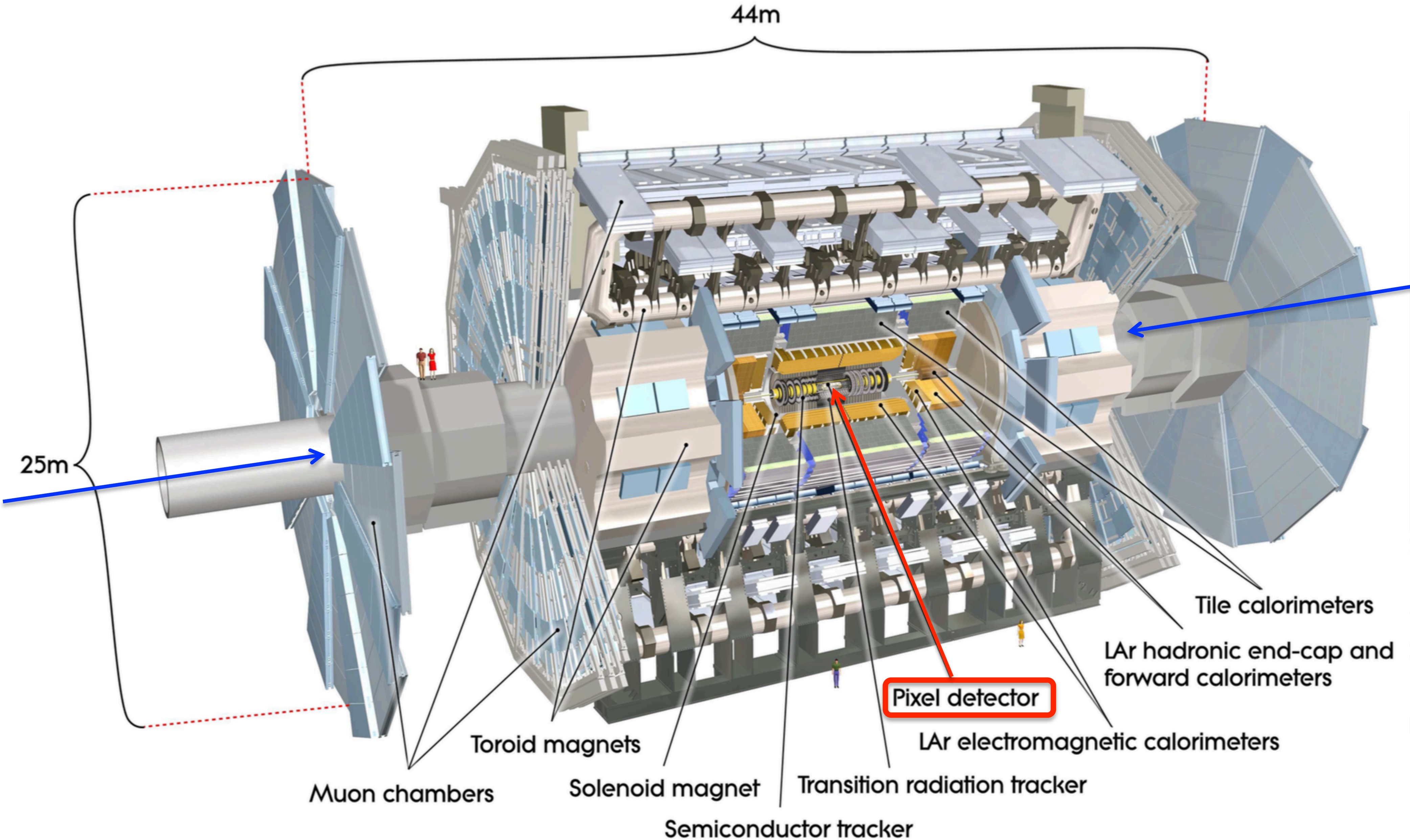
The ATLAS detector @ LHC



The Pixel (+IBL) Detector

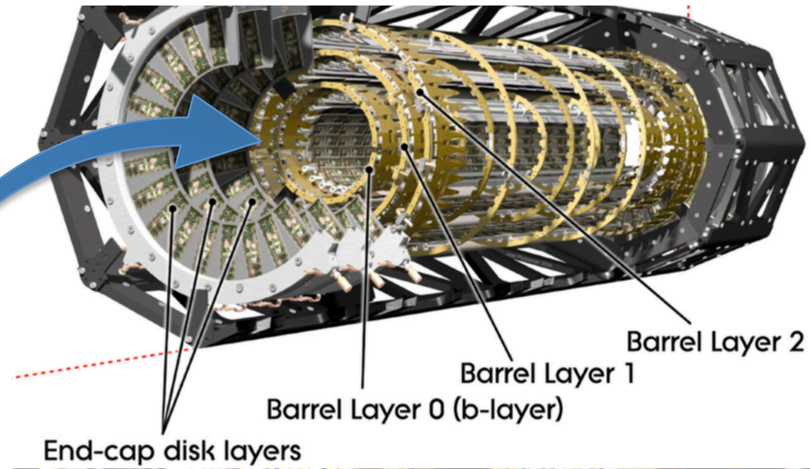
3 + 1 Barrel Layers and 3 Forward/Backward Disks

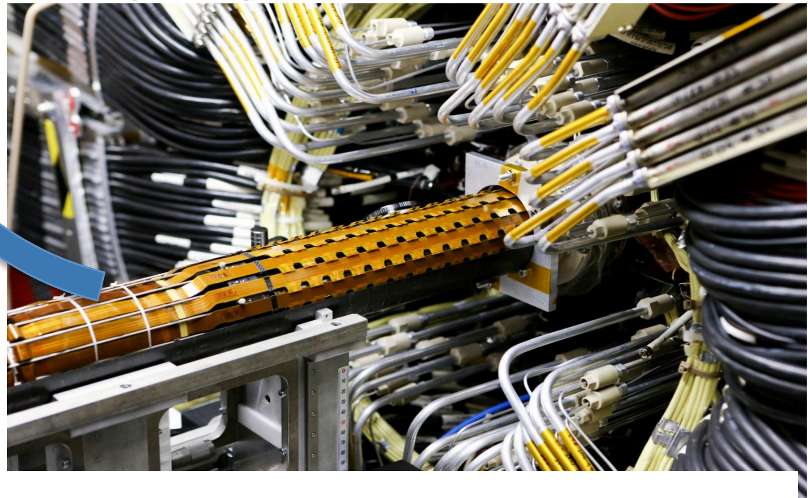
Layers	<Radius> (cm)
IBL	3.30
B-Layer	5.05
Layer 1	8.85
Layer 2	12.25

1744 + 280 modules
→ 80 + 12 million channels!!

	Pixel (Run 1 + Run 2)	IBL (Only Run 2)
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 ~ 1 x 10^{15} (1 MeV) $n_{eq}\cdot cm^{-2}$	250 Mrad ~ 5 x 10^{15} (1 MeV) $n_{eq}\cdot cm^{-2}$

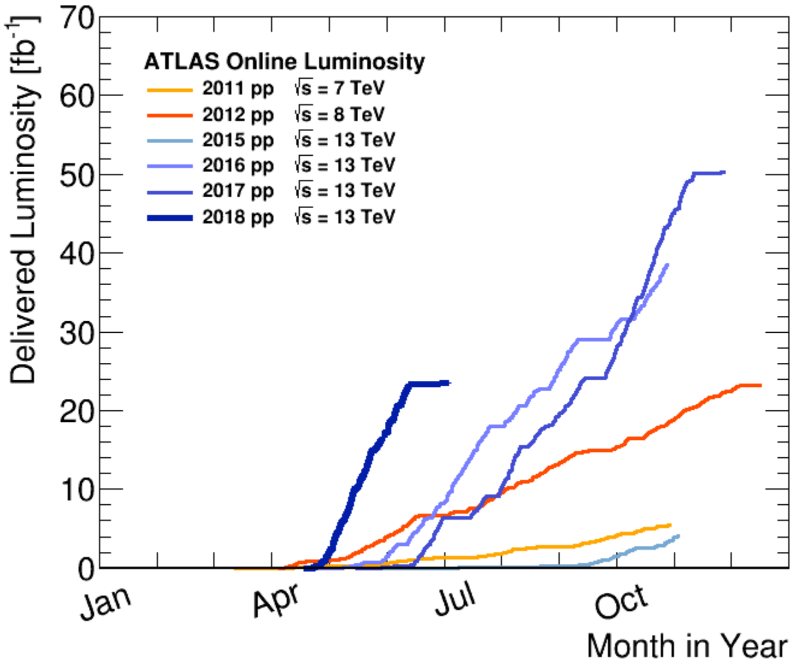
3 Layers Pixel Detector
in ATLAS since **RUN 1 (2010)**

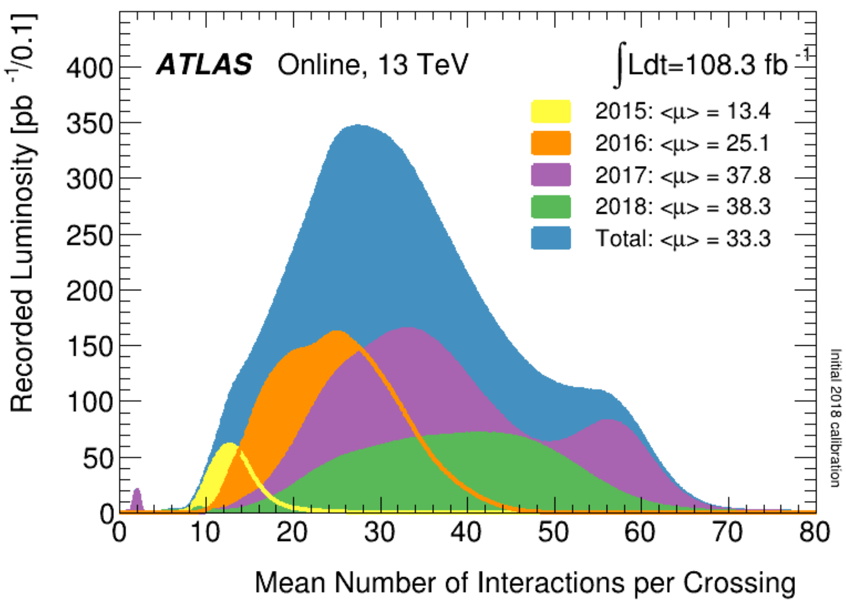




Insertable B-Layer (IBL)
added beginning **RUN 2 (2014)**

ATLAS and Pixel @ LHC





Integrated Luminosity	Pixel (fb^{-1})	IBL (fb^{-1})
Entire Run 1	~30	0
Run 2 (up to now)	~145	~115
By the end of Run 2 (2018)	~180	~150
By the end of Run 3 (2023)	**~480**	**~450**

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

- Big changes to Run 1/Run 2 running conditions:
  - Bunch crossing spacing
    - 50 ns ➔ **25 ns**
  - Pile up (**μ**) conditions:
    - 10 ➔**70** mean interactions/bunch crossing
  - Instantaneous luminosity:
    - Up to **~ 2,2 x 10^{34} cm^{-2} s^{-1}**
    - Level 1 Trigger (speed at which we read out the FEs) up to **100 kHz**.

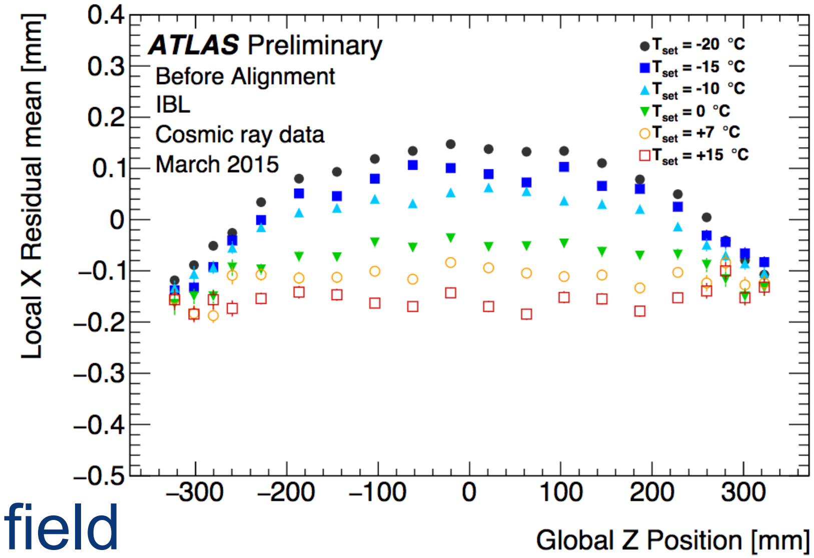
Pixel/IBL at the begin of Run2

- Extremely challenging years after the insertion of IBL:
  - maintenance of two different detectors/read-out systems
    - Pixel read out systems gradually upgraded with more modern IBL read out hardware during winter shutdowns..

      ➔ **fully unified in 2018!**

- Several issues were encountered and solved or mitigated:
  - IBL distortion due to different coefficients of thermal expansion on the stave flex)

    ➔ dynamic alignment to follow temperatures variation along the fill.

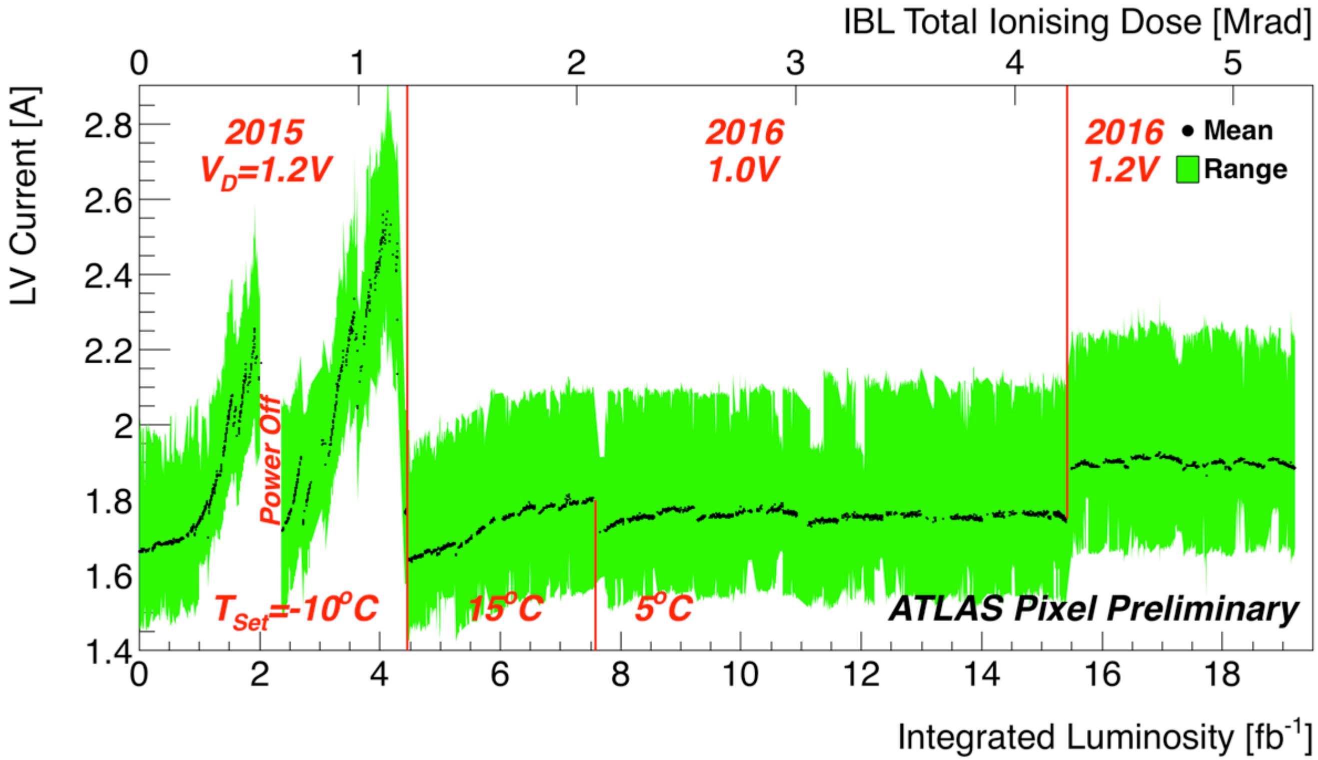


  - IBL wire bonds oscillation on magnetic field

    ➔ protection from trigger resonance frequencies

Pixel/IBL at the begin of Run2

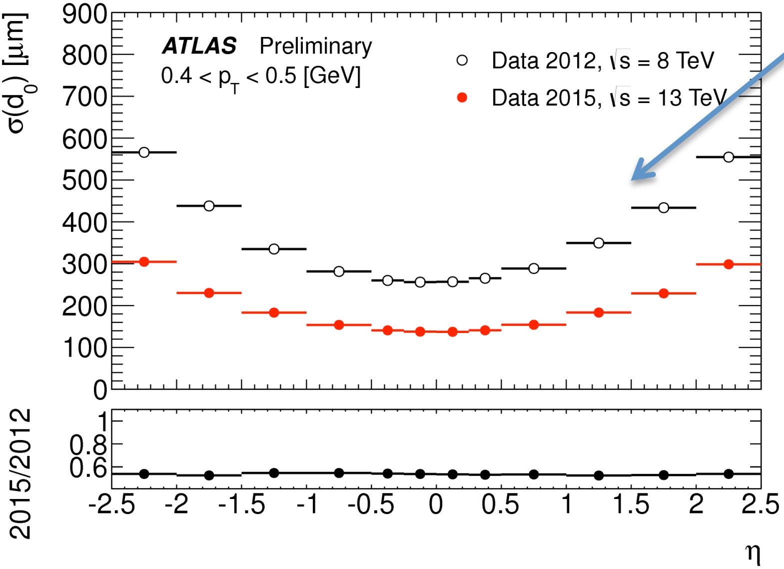
- IBL Total Ionizing Dose (TID) effect causing relevant increase of FE currents



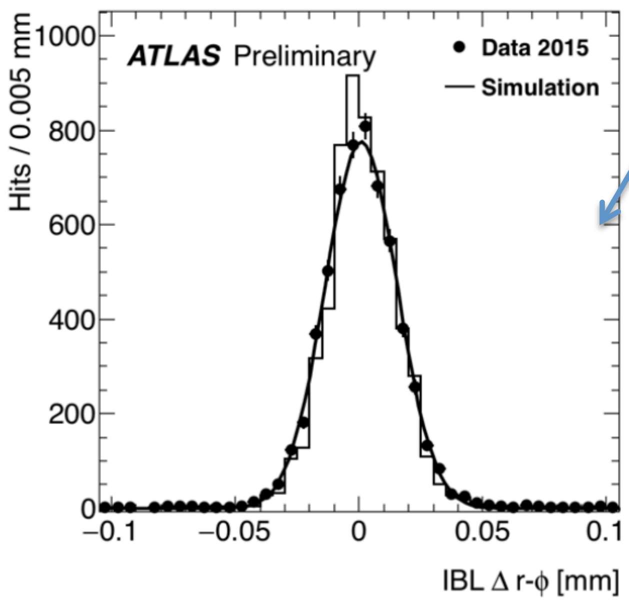
"Production and Integration of the ATLAS Insertable B-Layer" JINST paper for more info about IBL

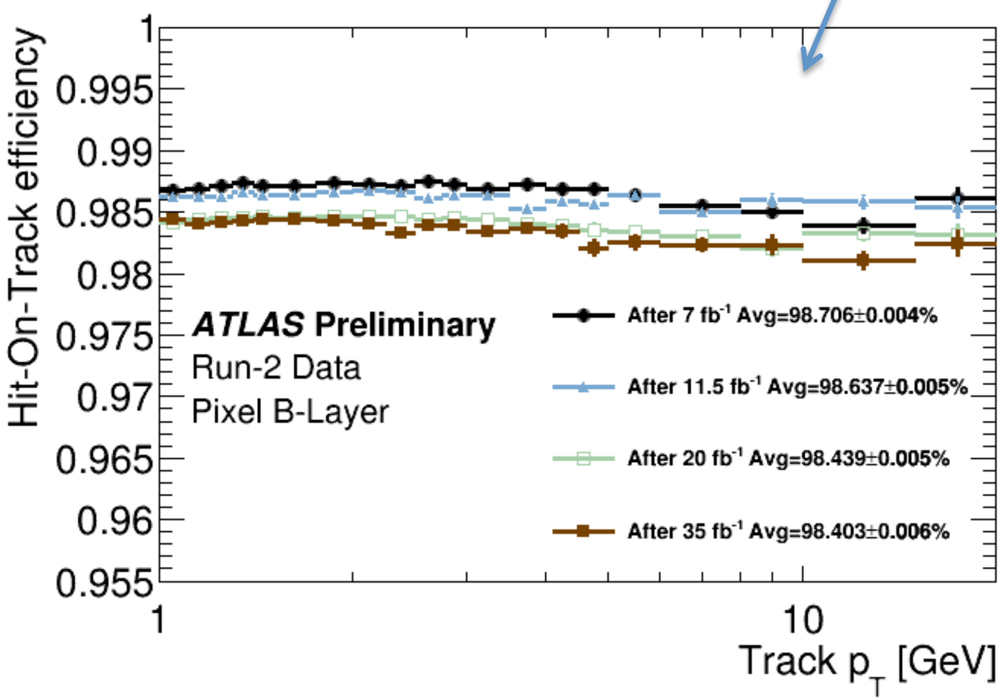
- Failures on both sides of the the Pixel on-detector ←→ off-detector communication (on-detector transmitters and off-detector receivers).

Pixel (IBL) performance in Run 2



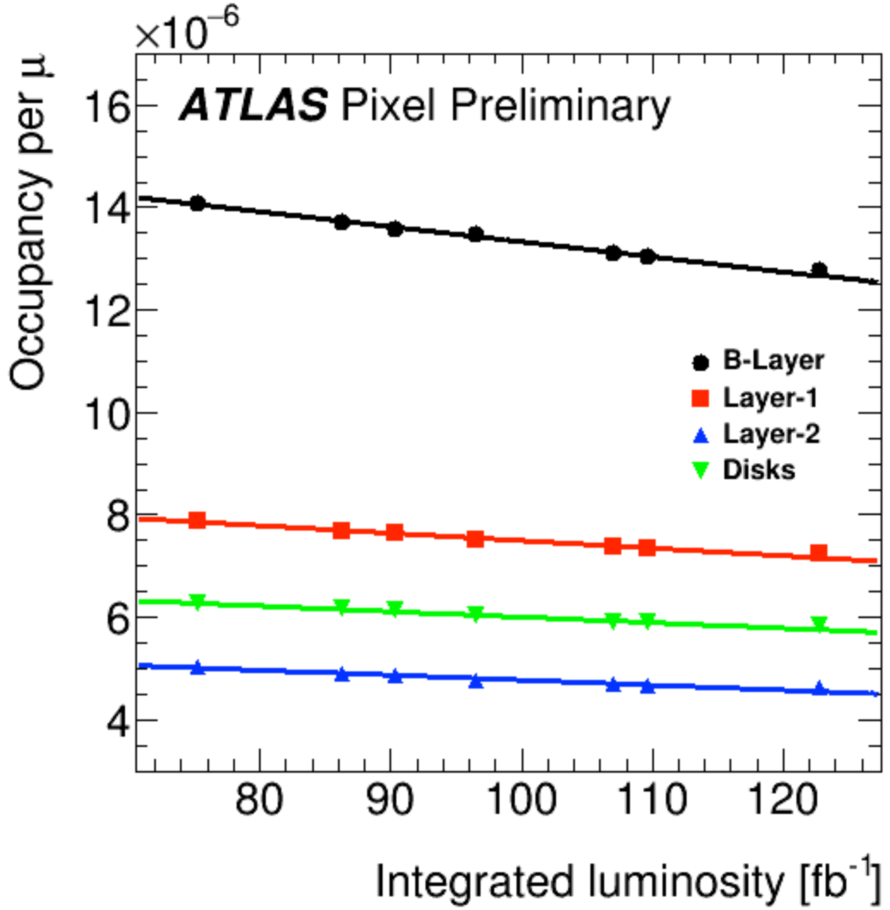
- Impact parameter resolution improvements after IBL insertion (2015 data)
- B-Layer Hit-on-track efficiency above 98% (2016 data)
- IBL spatial resolution ~ 10 μm for the transverse R-φ plane





Observations of radiation damage in 2017

- Observation of the radiation damage effect for Pixel:
  - **Pixel hit occupancy** (number of hits per pixel per event) **per unit of μ** decreases as a function of integrated luminosity (**~125 fb^{-1} by end 2017**).



➔ **Decrease the thresholds and increase the HV to compensate the lack of charge collection efficiency.**

➔ **Limitations on the read-out bandwidth if threshold decrease was too drastic!**

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**

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

Hybrid Analog Threshold Cut in B-Layer

Despite the increase of hit occupancy, Pixel is still within its specifications:

module to read-out system bandwidth usage < 80% if

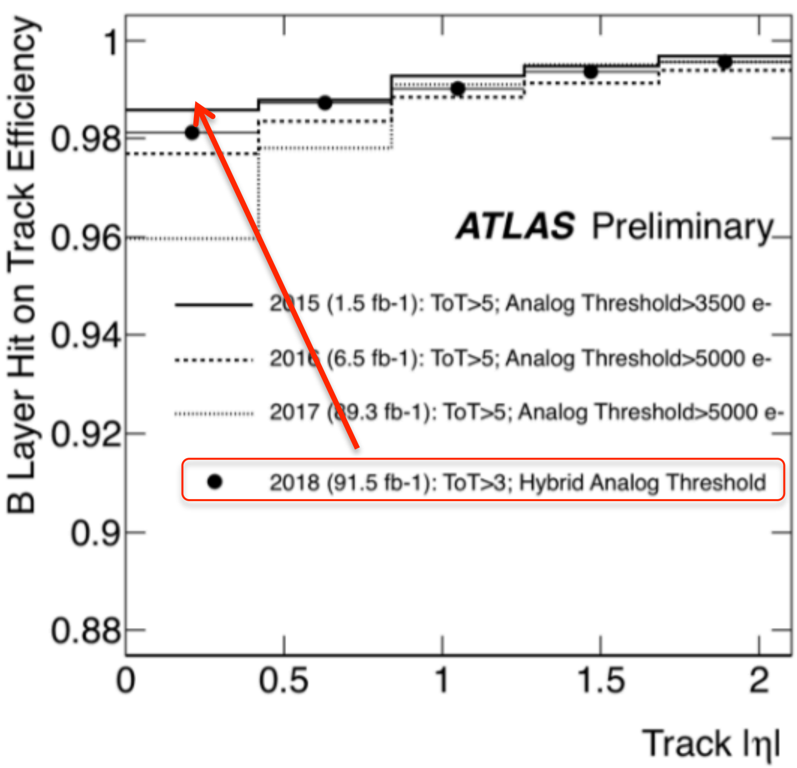
L1Trigger = 100 kHz
<μ> = 60
(ATLAS Run 2 benchmark)

Detector Performance in 2018

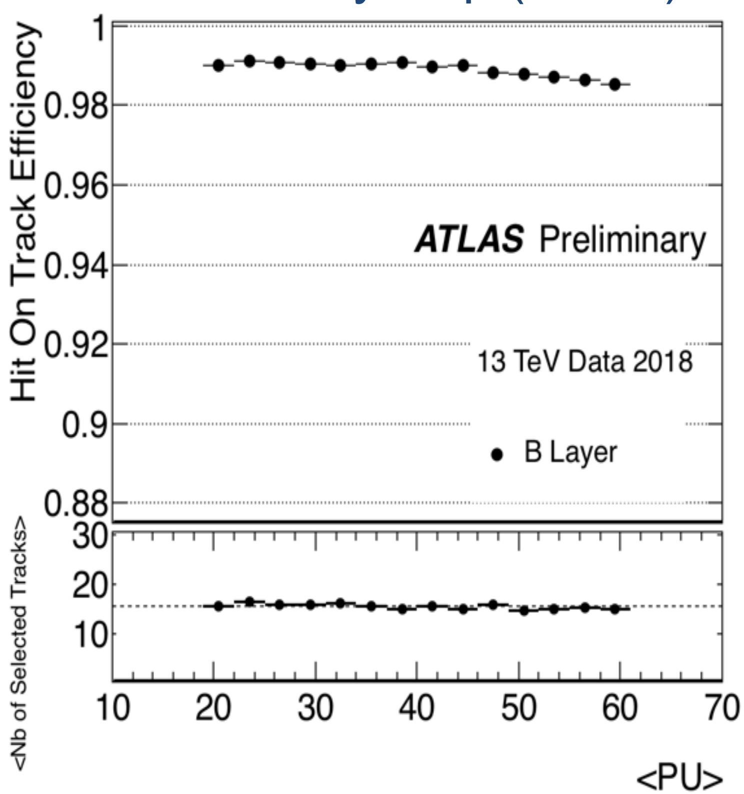
- Different analog thresholds within the same detector layer (B-Layer): **5000e** vs **4300e**
- Recovering hit on track efficiency in the central area without increasing the occupancy too much elsewhere.

➔ **recovered almost fully the 2015 efficiency!**

Time evolution vs 2018 config



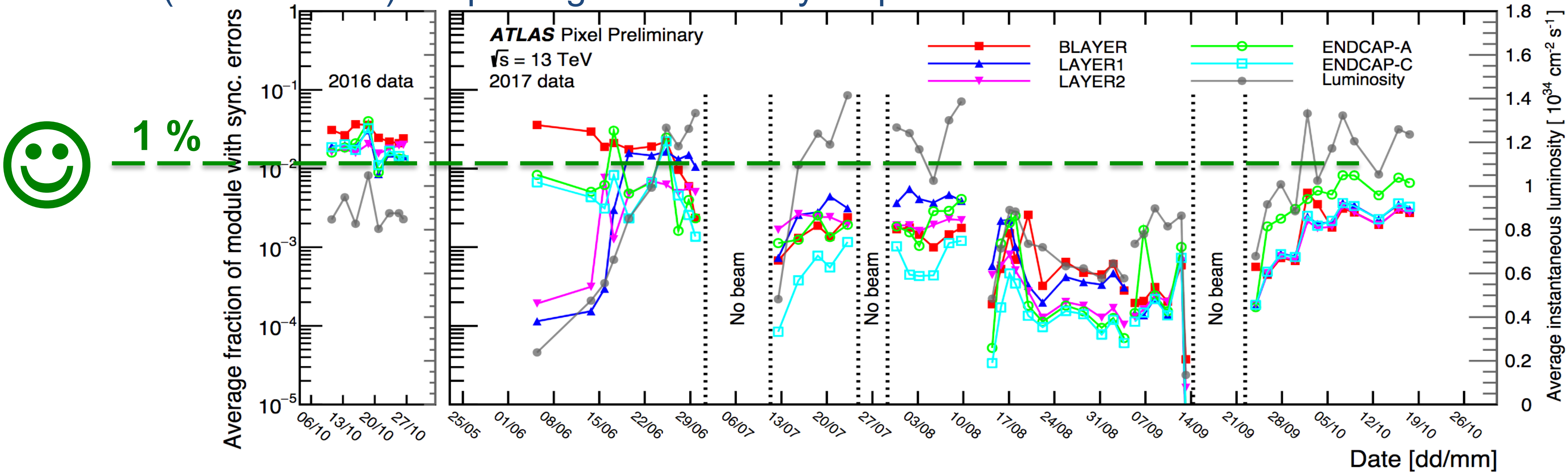
Good stability of the hit on track efficiency vs μ (**~99%**)



Detector Operation in 2018

DESYNCRONIZATION

- Desynchronization (mismatch in the event identifier between Pixel modules and ATLAS) under control (**<~ 1 % level**) despite higher luminosity respect to 2017.



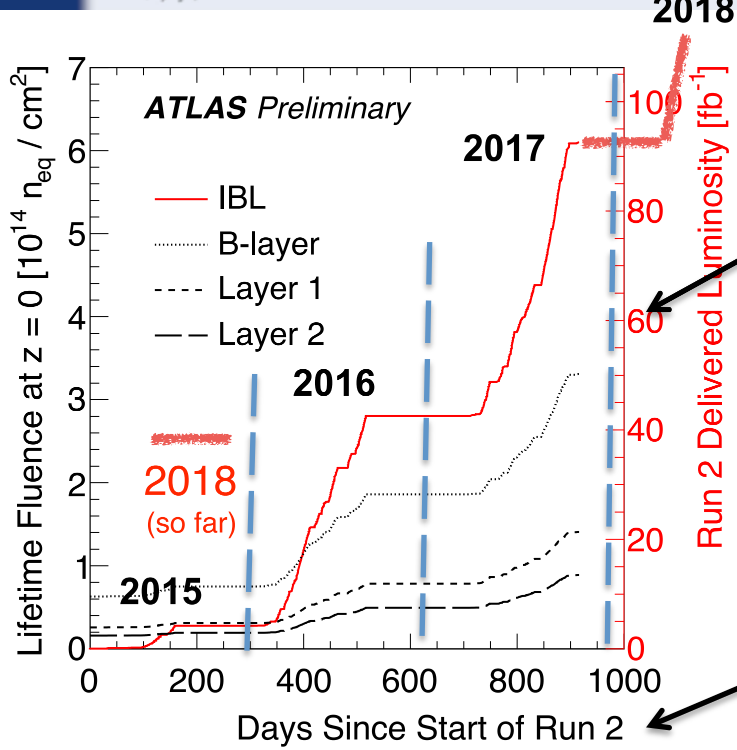
- New mechanism (under test) to avoid sending triggers to modules that are particularly "late" ➔ **prevent de-synchronization instead of trying to cure it!**

DEADTIME

- Dead time further reduced following previous year trends:
  - further optimization still possible…

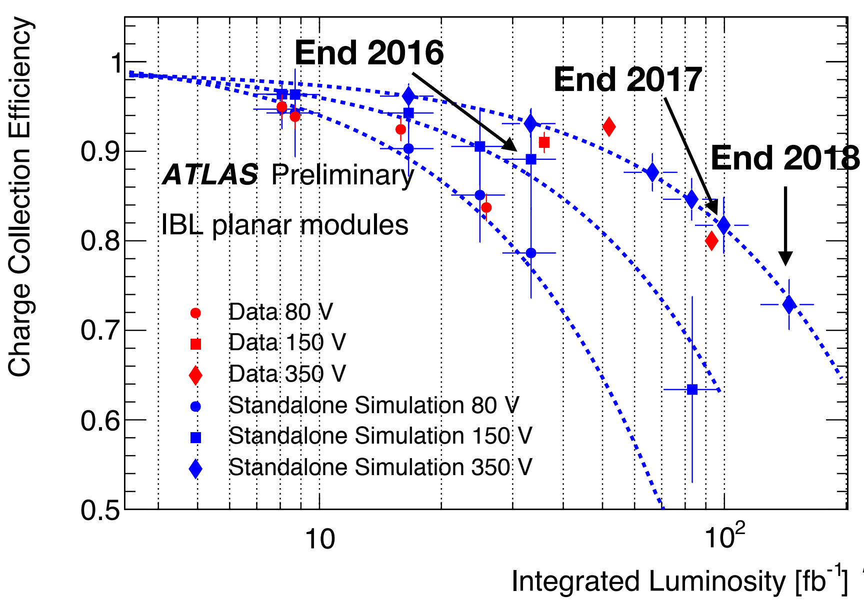
2018 Pixel dead time routinely below 0.2%

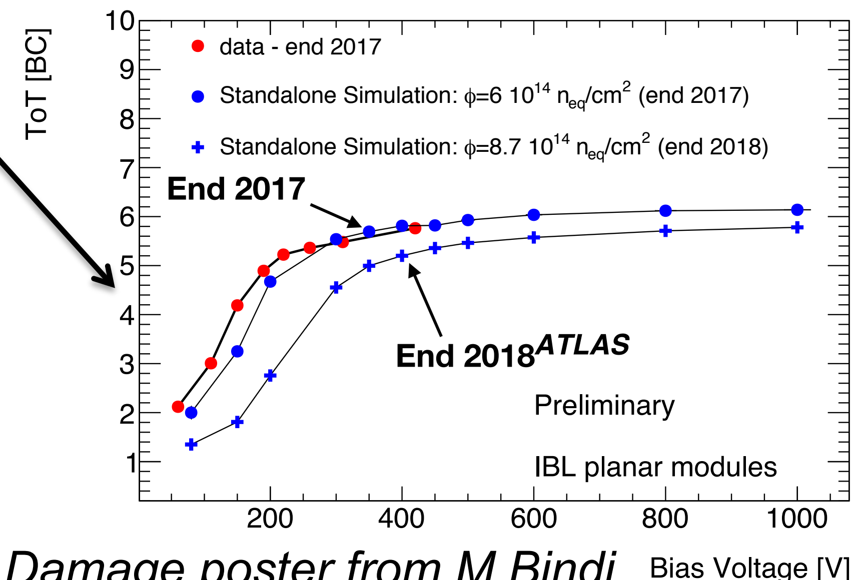
Modeling the radiation damage



New Pixel Digitization model developed for next MC releases:

- conversion between integrated luminosity and fluence computed using FLUKA 2011
  - **IBL will reach ~ 10^{15} n_{eq}/cm^2 by end of 2018**
  - compared with leakage current measurements.
- Most Probable Value of the fitted Landau distribution of the Time Over Threshold (TOT):
  - **ratio between non-irradiated and irradiated sensor as a function of bias voltage**
  - **bias voltage scans**

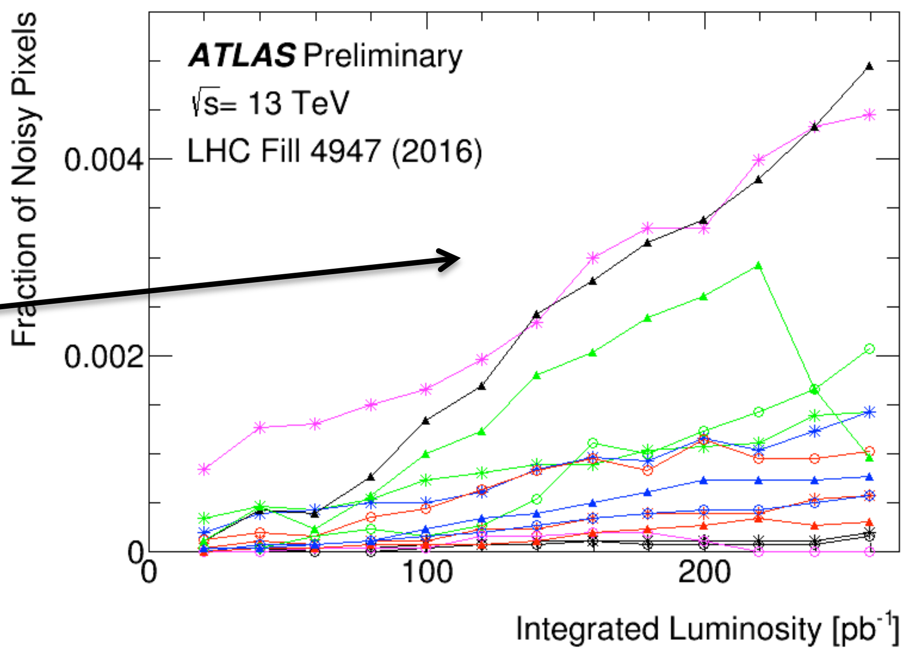




➔ *See Radiation Damage poster from M.Bindi*

Single Events Upset in IBL

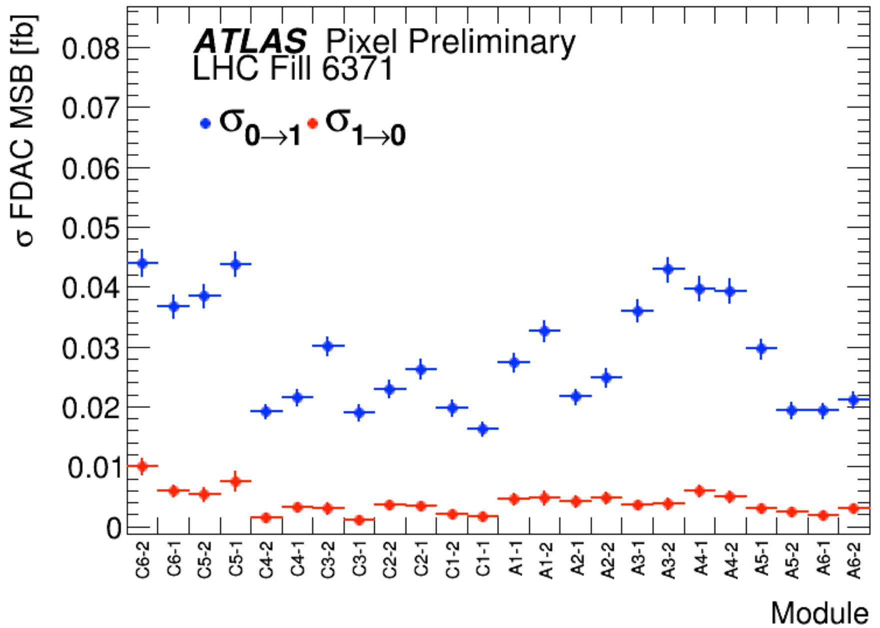
- IBL FEs affected by SEU with increasing radiation/luminosity already in 2017
  ➔ **continuous reconfiguration of FE global registers every ~ 5 s**
  ➔ **no extra dead time introduced!**



- However, increase of **noisy pixels** (up to +20% occupancy) or **quiet pixels** (up to 1% of pixels disabled) during the fill.

  ➔ *See SEU poster from P. Liu*

- Problem due to SEU in single pixel latches
  ➔ it can be solved by **a full (including pixel single registers) and periodical (every few minutes) reconfiguration!**



- Deploying new Sw/Fw implementation to fully reconfigure the FEs every few minutes (no extra dead time)..
  … similar to ATLAS ITK future strategy:

  ➔ *See SEU poster from P.Butti*

Conclusion and future plans

- Several challenges/upgrades since beginning of Run 2:
  ➔ now fully unified read out system,
  ➔ time for **consolidation, automatization and other optimizations**!

- Some adjustments of the detector operational parameters needed at the begin of 2018:
  ➔ **lowering thresholds for IBL, B-Layer and Disk and increasing bias voltage for all the layers.**

- **Pixel/IBL dead time is now minimal** (~0.2%) with an excellent data quality despite the high pile-up and luminosity in ATLAS.

- Key component in the next years will be to **understand the radiation damage of the detector:**
  - **new digitization model** available for the **MC** ➔ promising results.

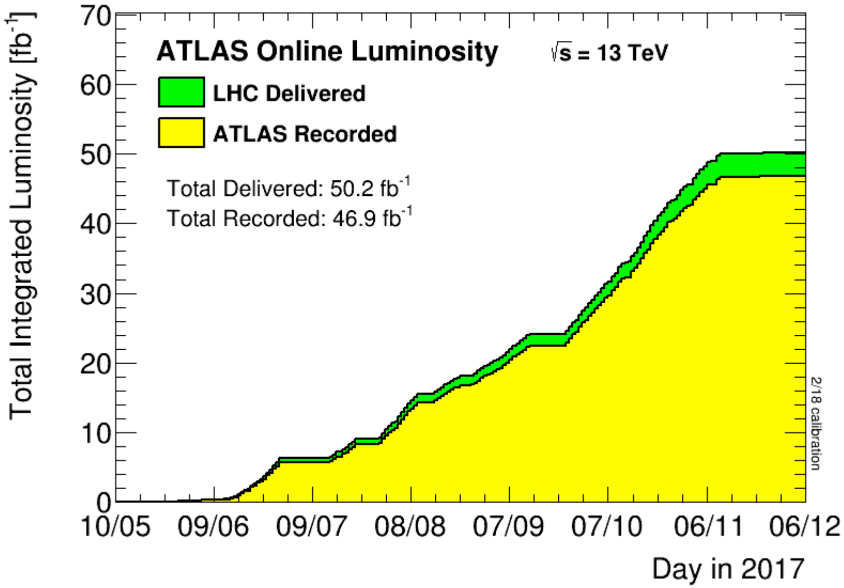
Back-up

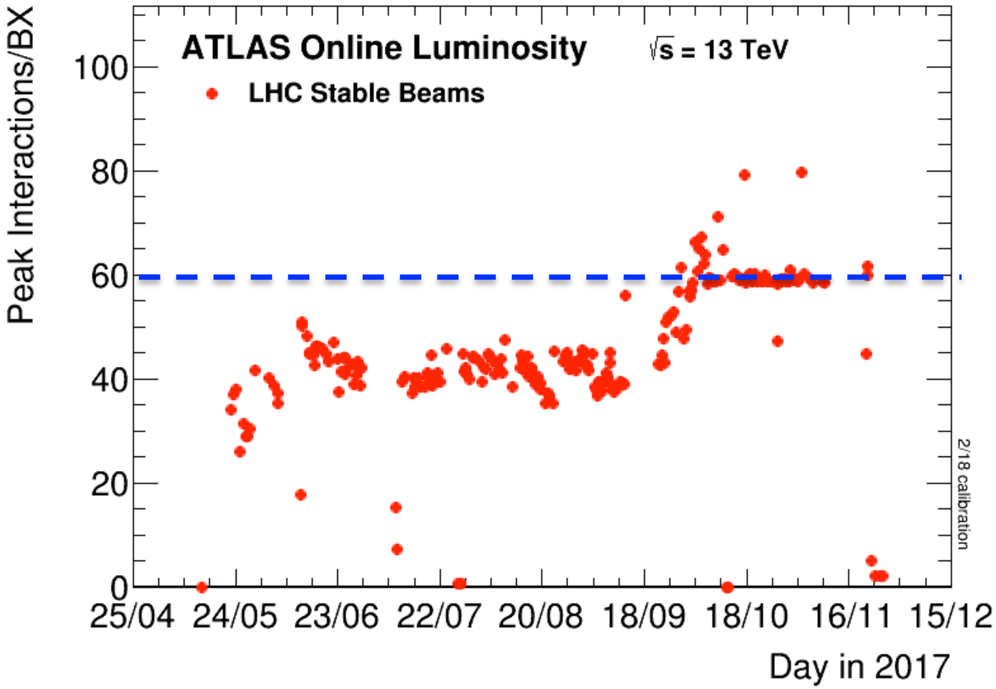
LHC Status at the end of 2017

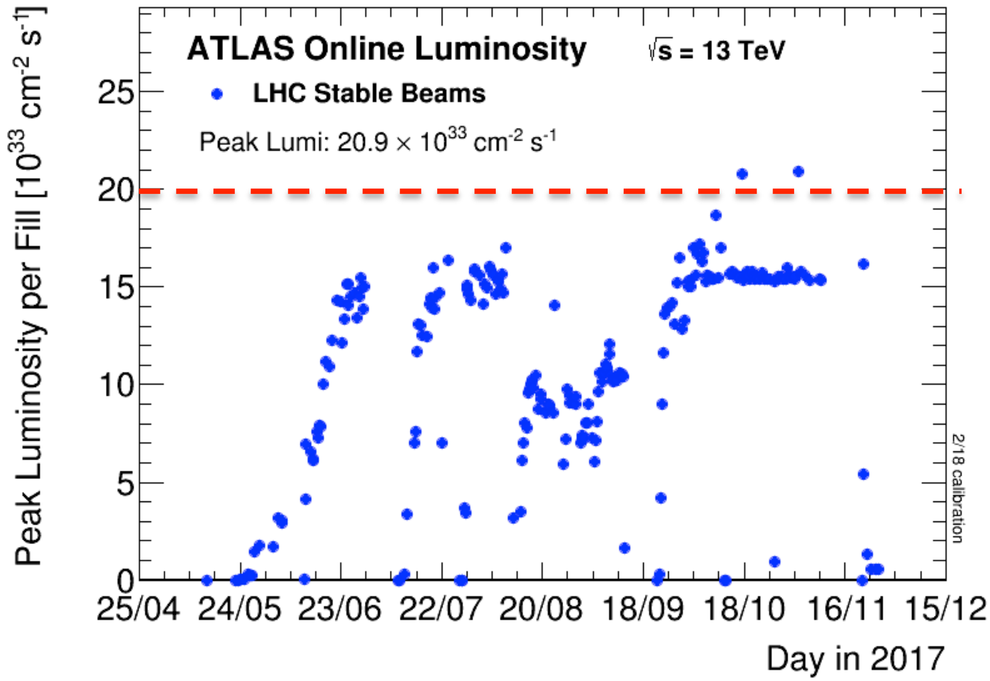
Expectations for 2017 were:
- Pile-Up of ~60
- Peak luminosity up to 2×10^{34} cm^{-2} s^{-1}

  → Challenging year for Pixel

- **Max peak lumi.: ~2.1×10^{34} cm^{-2}s^{-1}**
- **Max PU: 78.1**
- **Exceeded 2016 integrated luminosity**







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.

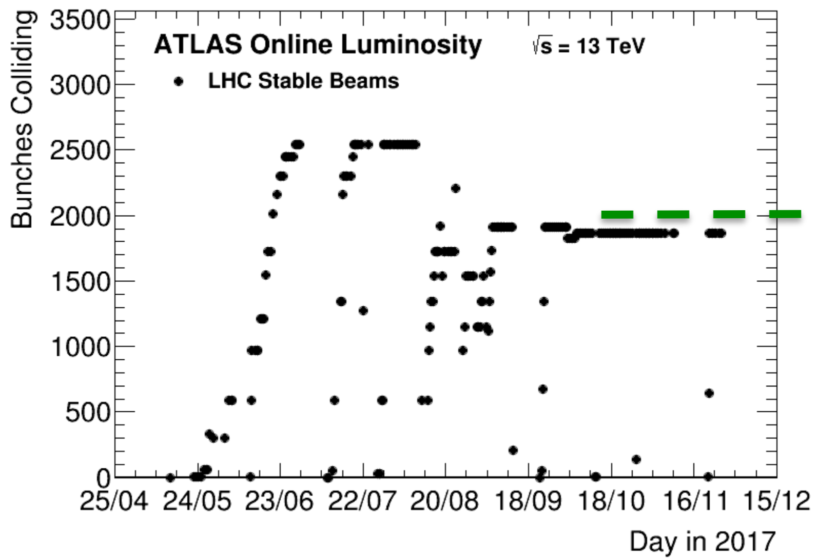
Hit occupancy in disks was reduced by ~20% to maintain sustainable operation:
- increase analog threshold: 3500 e- → 4500 e-
- increase digital threshold : 5 (TOT) → 8 (TOT)

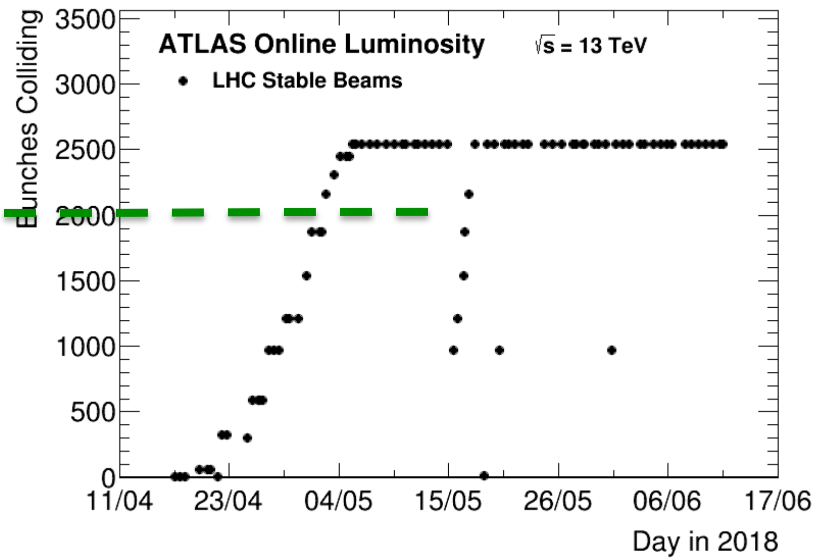
Layer	Analog Threshold [e-]	Digital ToT cut [BC]	Latency [BC]	Tuning
B-layer	5000	5	150	ToT = 18 @ 20,000 e-
Layer 1	3500	5	255	ToT = 30 @ 20,000 e-
Layer 2	3500	5	255	ToT = 30 @ 20,000 e-
Disks	**4500**	**8**	255	ToT = 30 @ 20,000 e-
IBL	2500	n/a	255	ToT = 8 @ 16,000 e-

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!

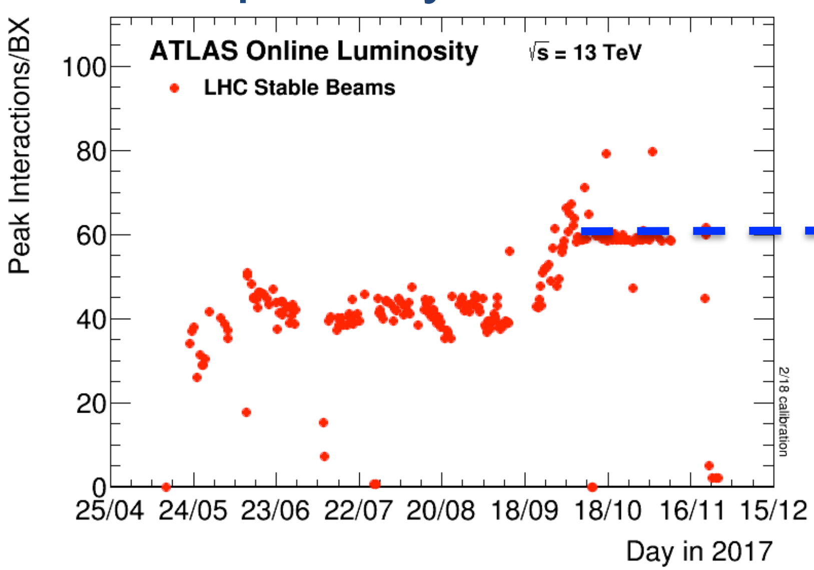
What has changed in 2018? LHC

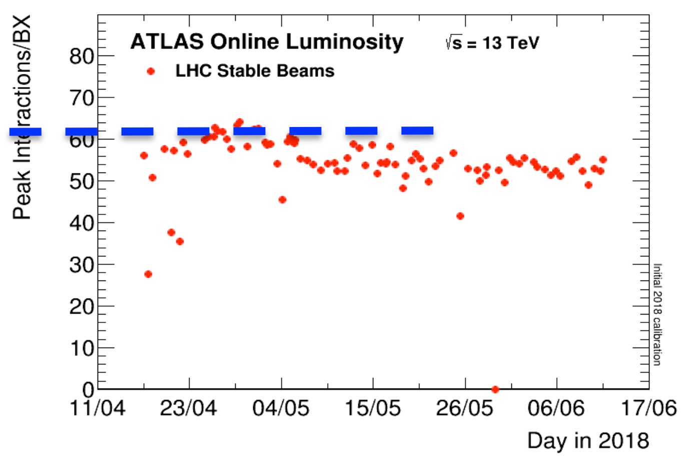
- More colliding bunches in the ring…..from ~2000 to 2544





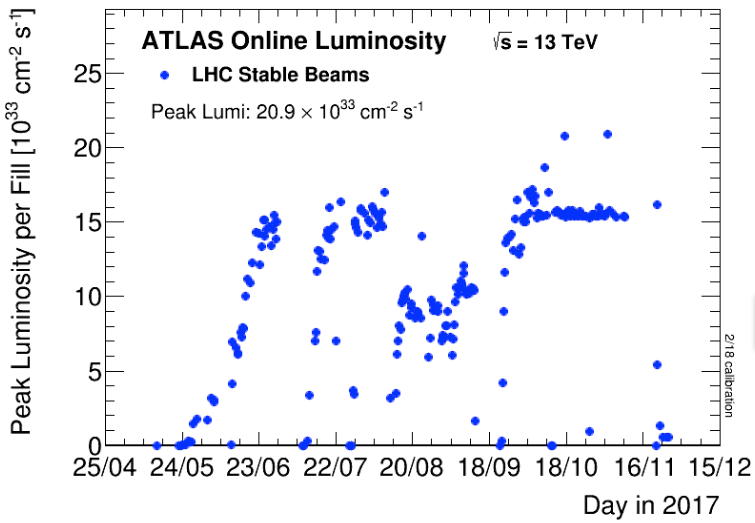
- Pile-up always below 60 due to bunch intensity limitations

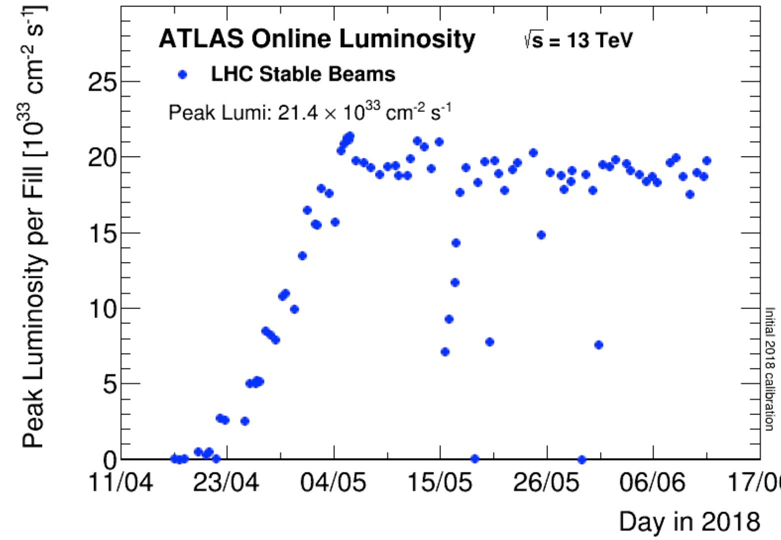




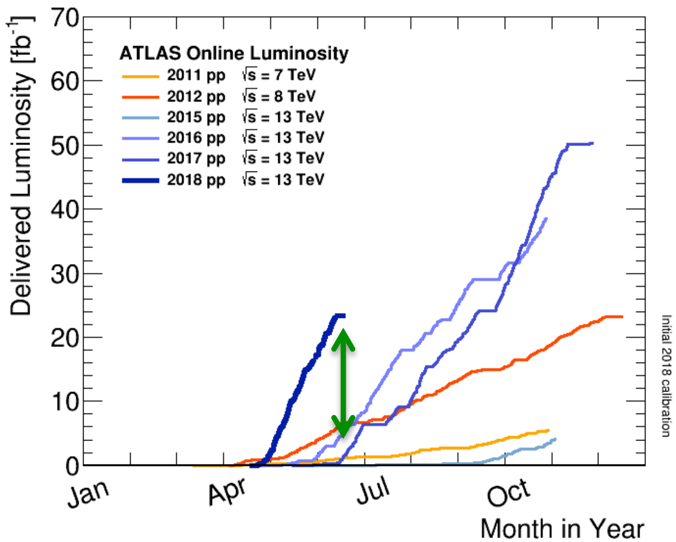
2018 vs 2017

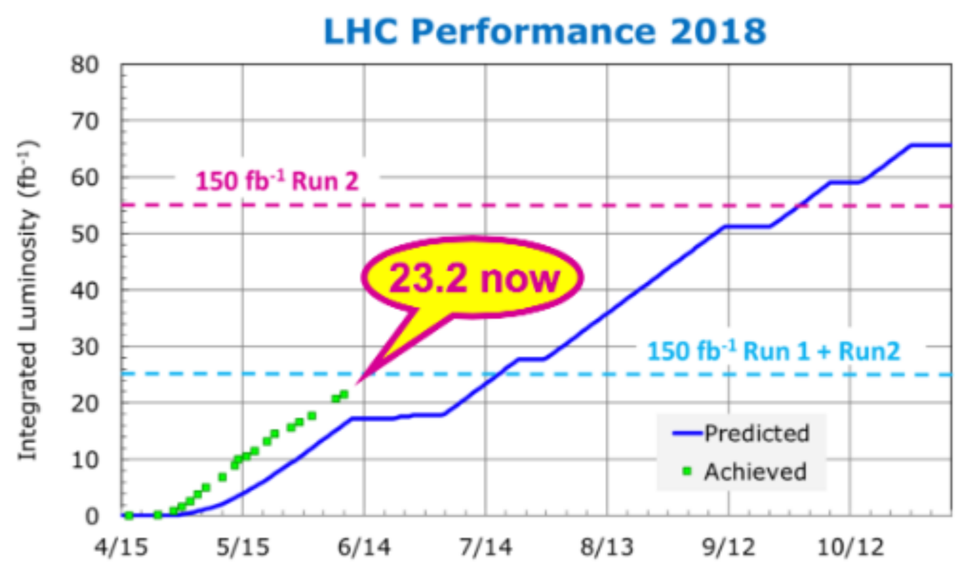
Inst. Luminosity constantly higher than 2017 (similar/lower pile-up)!





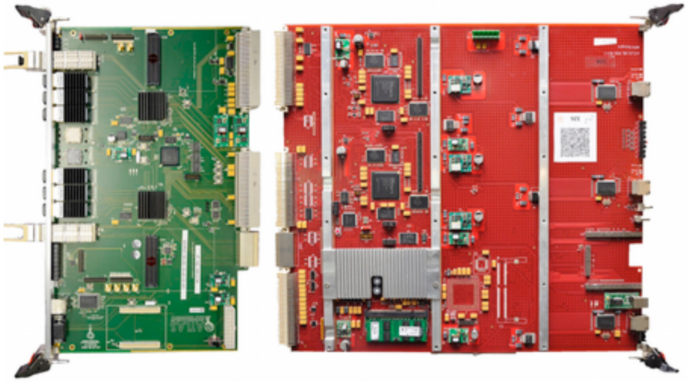
60-70 fb^{-1} expected in 2018 ➔ 150 fb^{-1} Total RUN2 Lumi!





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)



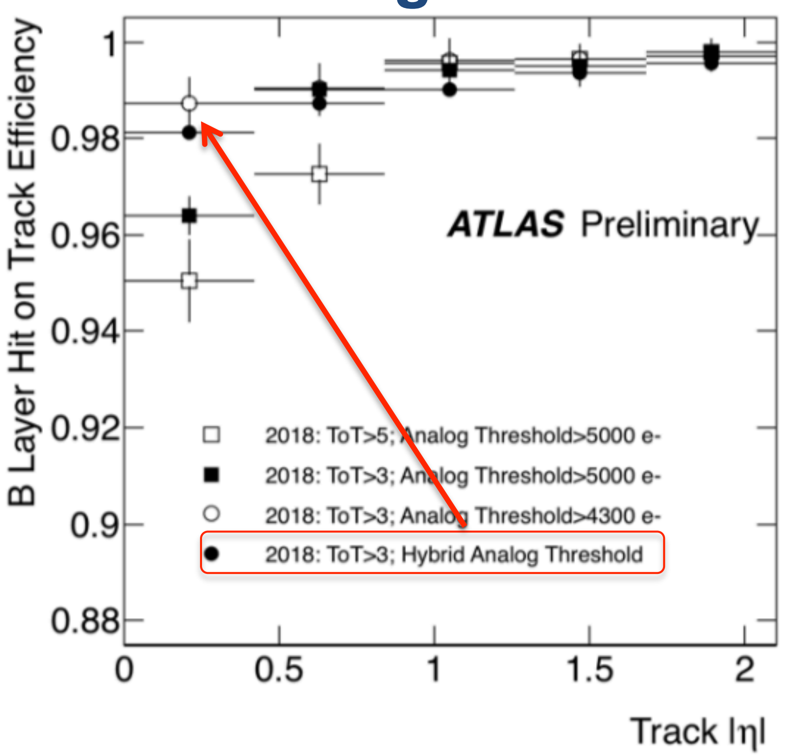
a) b)

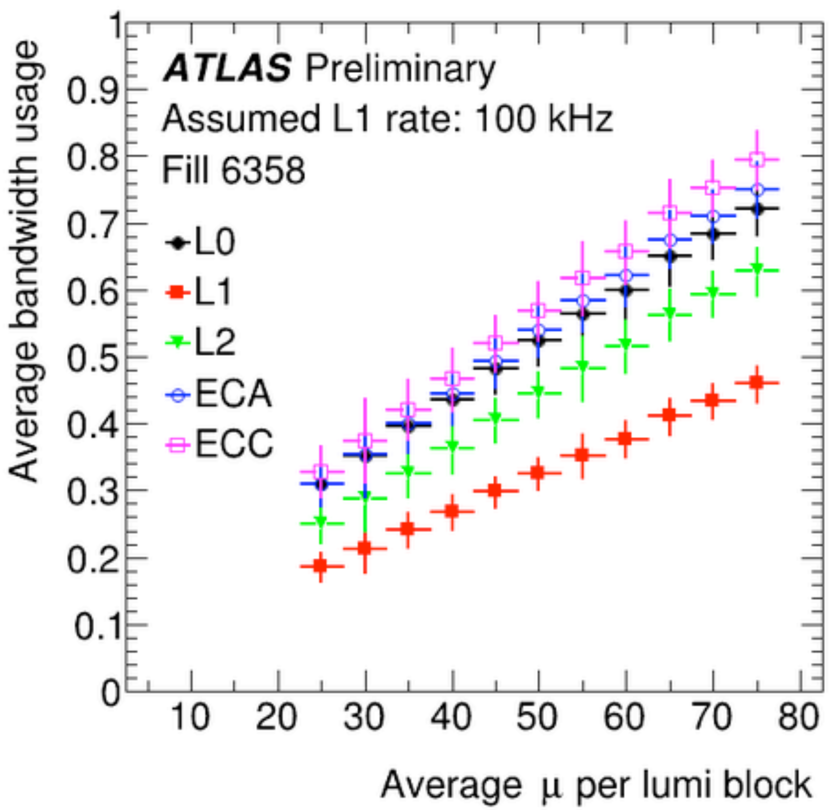
- Overcome bandwidth limitations but also enhance debugging capability and Sw/Fw flexibility.
- Finally in 2018, one unified read-out system that should bring Pixel many advantages on a longer term:
  - the operation of different type of FEs will always be there but… transparent for most of the operations!

Occupancy increase in 2018

Detector Layer	Occupancy Increase 2018/2017
IBL	+5%
B-Layer	+26% (central Eta); +15% (high Eta)
Layer1/2	~stable
Disk	+14%

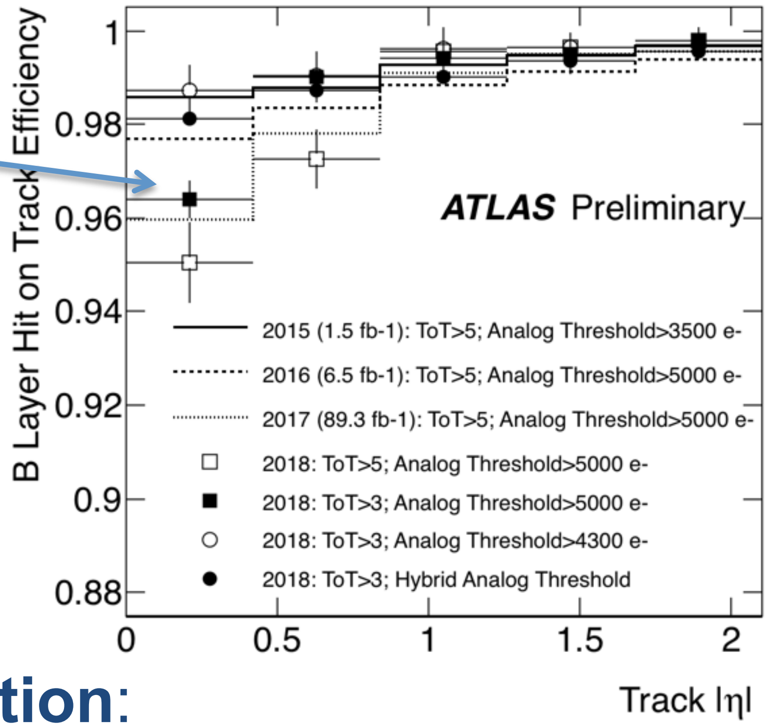
2018 configuration tests



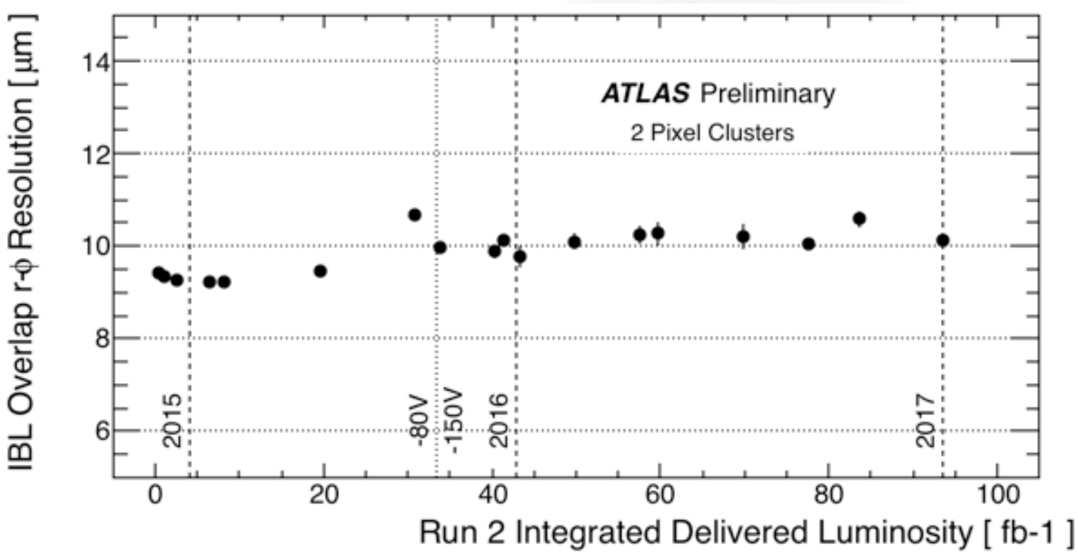


More Pixel performances

- Hits- on track efficiency clearly related to eta of the modules
- Reduction of the threshold particularly important to recover efficiency in the central area…the most important for the Physics.



- Effect visible also in **IBL hit spatial resolution**:
  - slightly degradation as a function of integrated luminosity (**~95 fb^{-1} by end of 2017**)
  - only clusters with two pixels in the overlap region
  - effect correlated with reduction of charge collection efficiency.



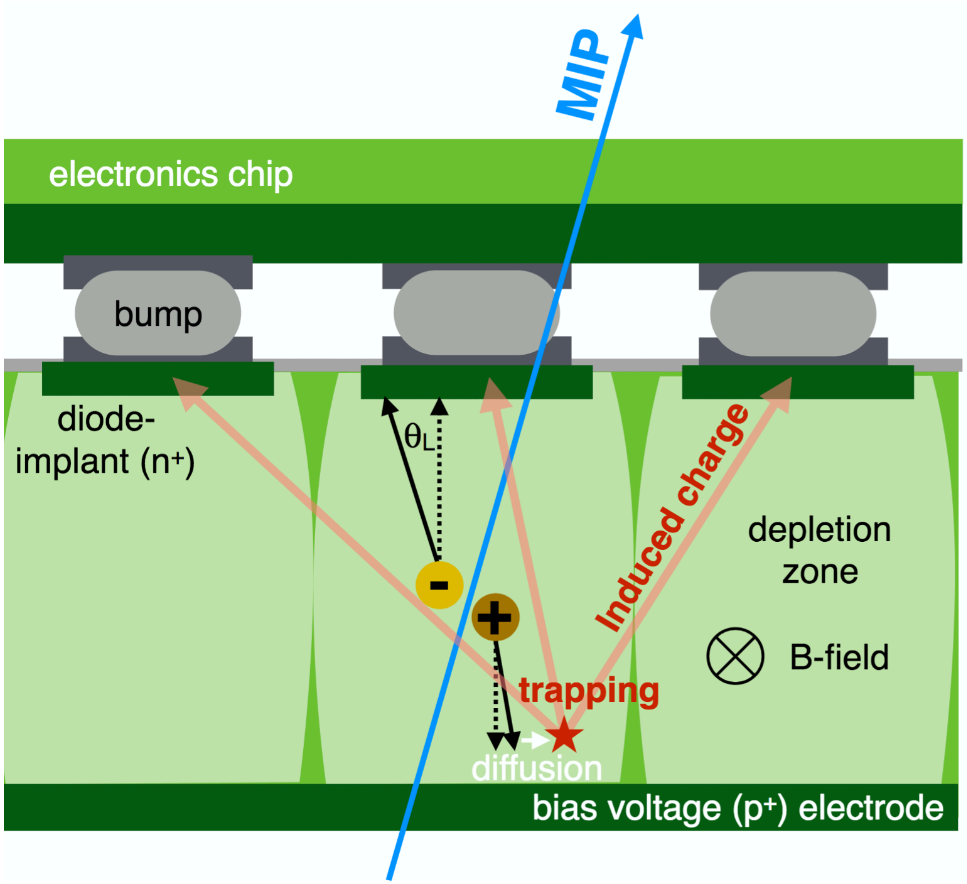
Radiation damage studies

- New Pixel digitization model is ready to be included in release 22.

  https://twiki.cern.ch/twiki/bin/viewauth/Atlas/PixelDigitizationRadDamage

- Paper expected by the end of the year.

  https://cds.cern.ch/record/2255825



Radiation damage introduces defects into the sensor bulk

→ increases the leakage current

→ increases the "depletion voltage"

→ decreases the collected charge

→ deforms the E-field (double-peak)

HV evolution

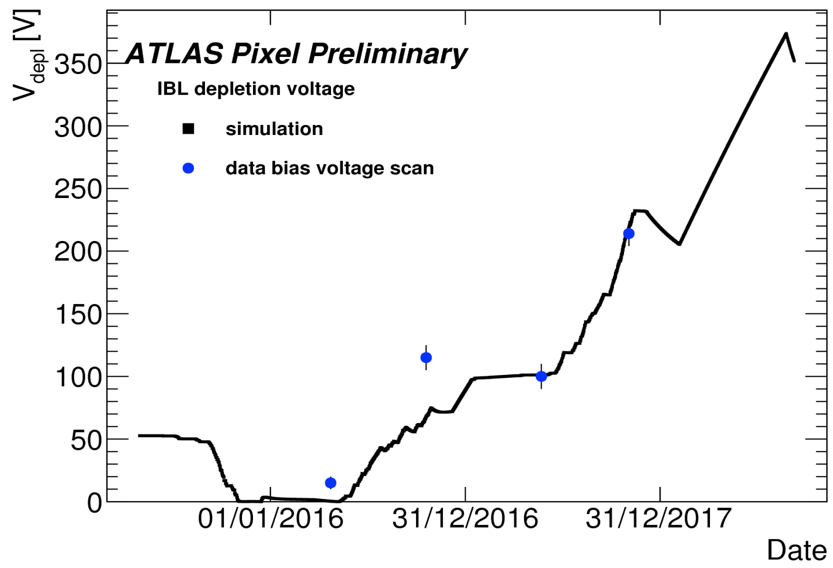
- HV settings have been adjusted to ensure a well depleted sensor:

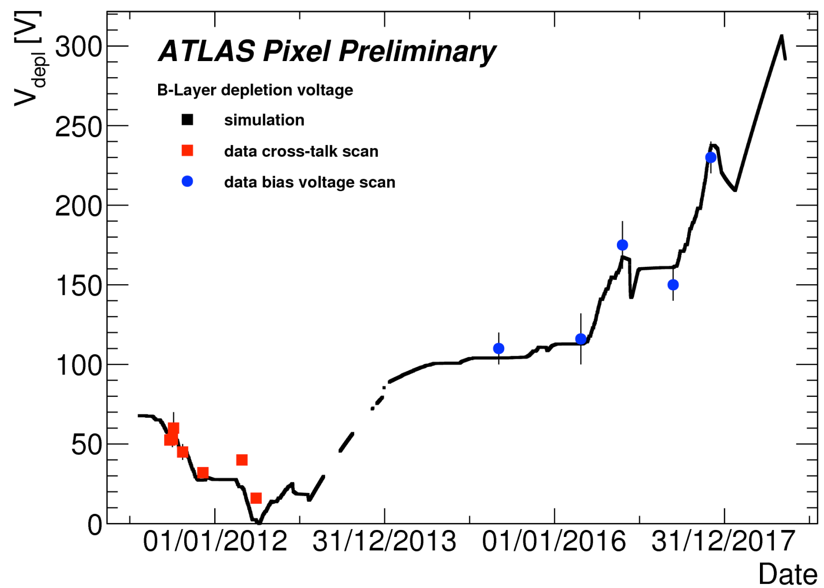
  ➔ **HV increase in all the layers in 2018!**

- Radiation damage will be particularly severe in RUN3.

- 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)

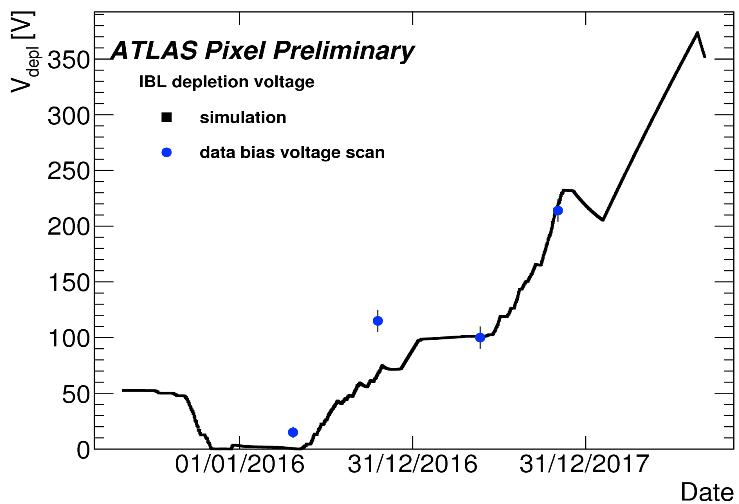
  ➔ **discussions on-going with the ATLAS Technical coordination and the Pixel Cooling experts.**

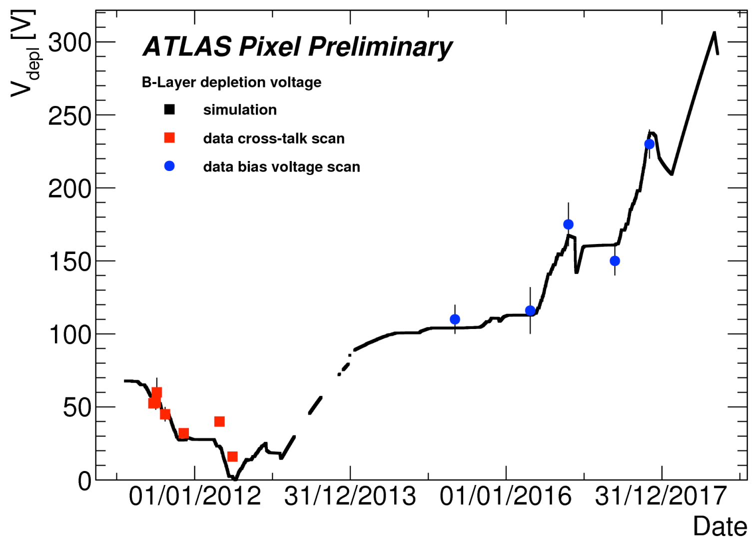




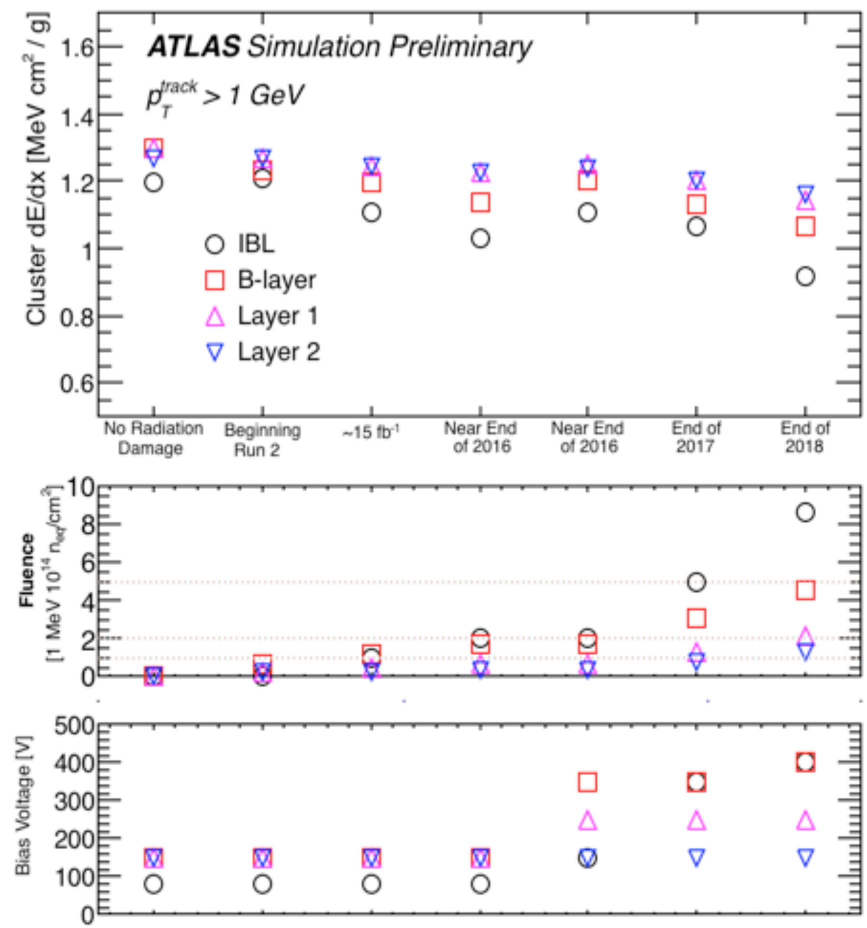
Modeling the radiation damage/2

- Simulated full depletion voltage of the **IBL** and **B-Layer** according to the Hamburg model.
- The prediction for 2018 assumes 70 fb^{-1} of integrated luminosity to be delivered to ATLAS.

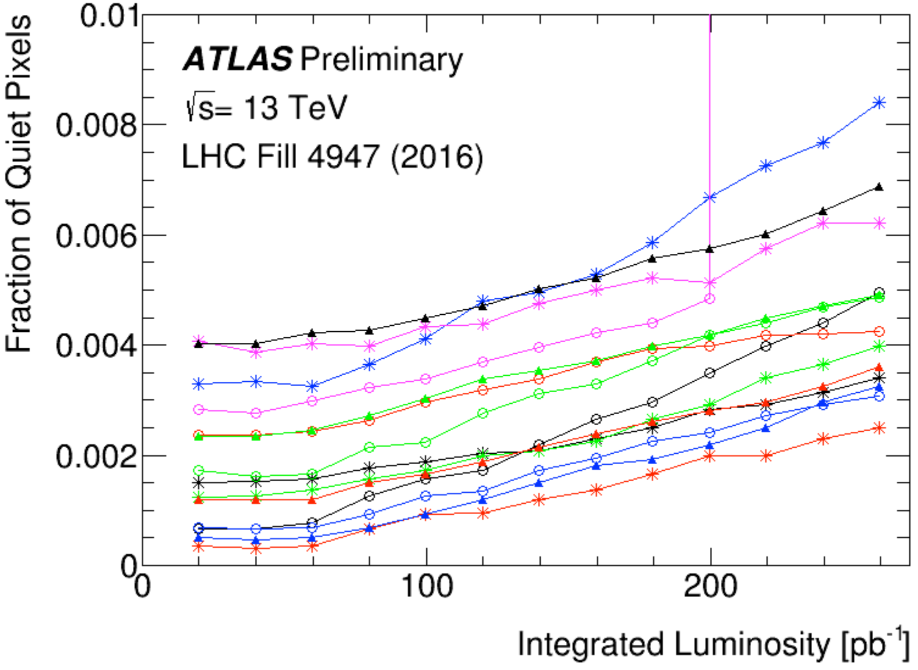




- Predictions for cluster dE/dx during different points of Run 2, taking into account charge loss from radiation damage.
- The average dE/dx per pixel layer is estimated from reconstructed tracks with transverse momenta greater than 1 GeV.



SEU mitigation strategies



- Thread on the PPC Sw (ROD FPGA embedded system) that fills the BOC Tx FIFOs (1 per each module) with different content at each ECR.
- The content will depend on the ECR number ➔ configuring the corresponding FE-I4 Double Column (1 out of 40 DCs)
- Reconfigure only part of the latches (Threshold/Feedback current and Hit Enable) if not enough time during ECR (1 ms time window available)

- We should have the full detector reconfigured after 40 ECRs…→ 200 seconds ➔ trying to anticipate the ITK reconfiguration concepts ;-)
- Sets of measurement with current probe is on-going in SR1 to establish the intensity and frequency of the current spikes induced by the reconfiguration commands
  - Standard trigger and Calibration commands are also under observation….