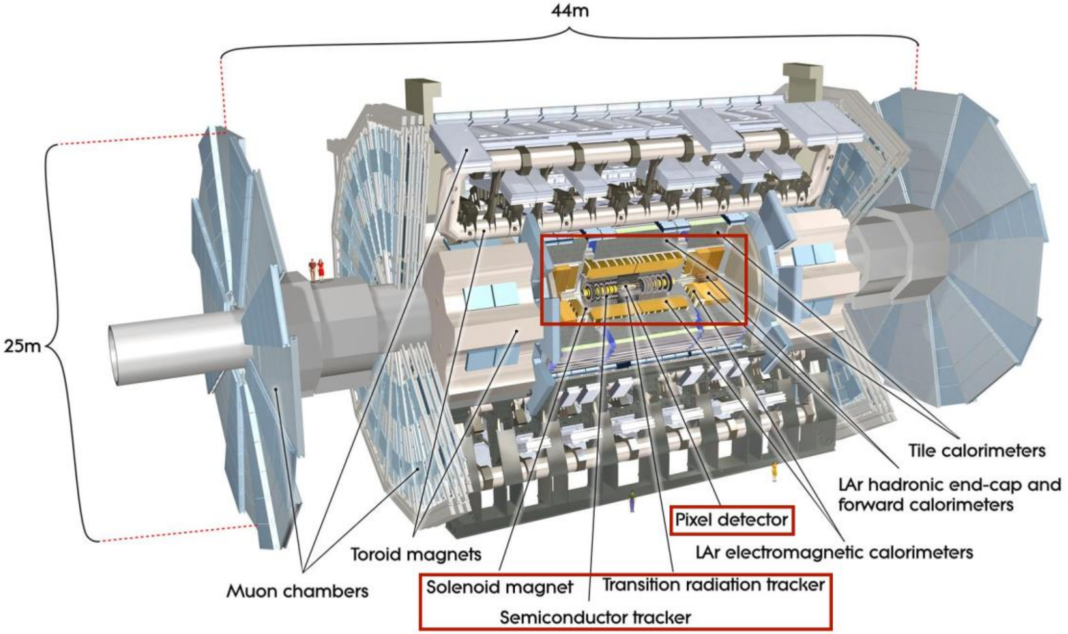
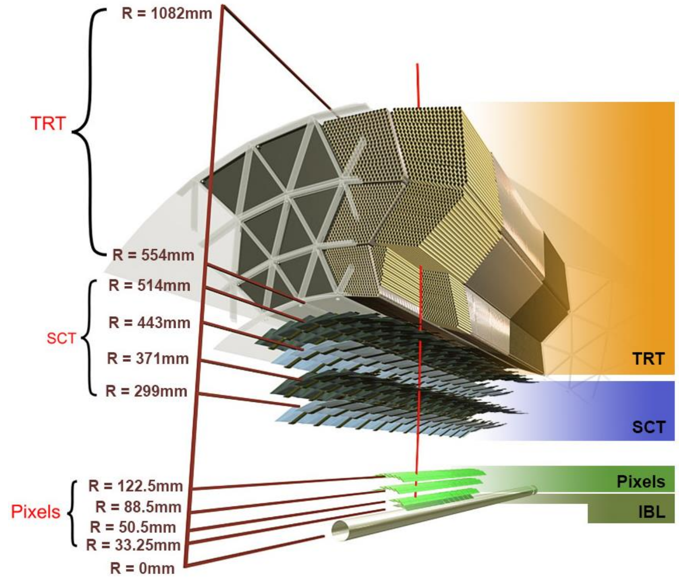
Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider at CERN

Tobias Bisanz (ATLAS Pixel Operation Team, CERN) *for the ATLAS Collaboration*

27.07.2021 [EPS-HEP2021 - T12: Detector R&D and Data Handling]

The ATLAS Detector





The ATLAS tracking detector, situated most closely to the interaction point, consists of:

- **the Transition Radiation Tracker (TRT)**
- **the Silicon Strip Detector (SCT)**
- **the Pixel Detector (PIX/IBL)**

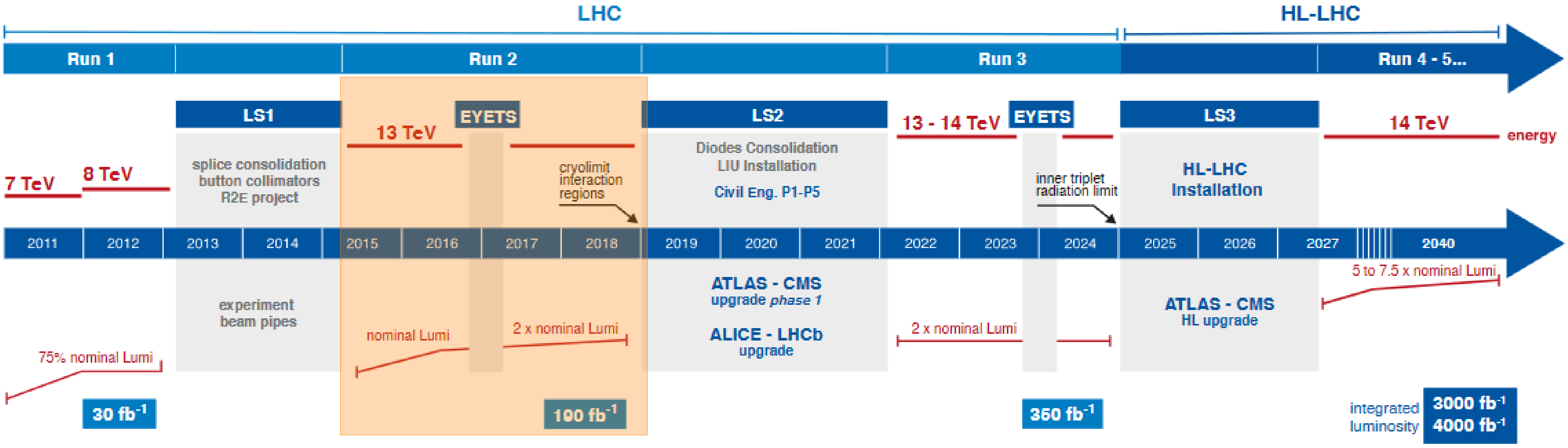
all situated within the ATLAS solenoid

Introduction: The ATLAS Pixel Detector

- **The initial pixel detector had three barrel layers (innermost: B-layer) and three disks on each side**
- **IBL upgrade inserted a fourth innermost layer of smaller pitched pixels (2013/14 shutdown)**
- **In total about 92 million channels**

	PIXEL (three outer layers + disks)	IBL (innermost layer)
Sensor Technology	n+-in-n (only planar)	n+-in-n/n+-in-p (planar/3D)
Sensor Thickness	250 µm	200/230 µm
Pixel Size	50x400 μm^2	50x250 μm^2
Front End Technology	250 nm CMOS	130 nm CMOS
Radiation Hardness	50 Mrad 10^{15} n_{eq}/cm^2	250 Mrad $5x10^{15}$ n_{eq}/cm^2
Radii	~5, 9, and 12 cm	3.3 cm

Run 2 Operational Experience



LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

EYETS

LS2

EYETS

LS3

7 TeV

8 TeV

13 TeV

13 - 14 TeV

14 TeV

energy

splice consolidation
button collimators
R2E project

cryolimit
interaction
regions

Diodes Consolidation
LIU Installation

Civil Eng. P1-P5

inner triplet
radiation limit

HL-LHC
Installation

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2040

experiment
beam pipes

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

ATLAS - CMS
HL upgrade

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

5 to 7.5 x nominal Lumi

30 fb^{-1}

100 fb^{-1}

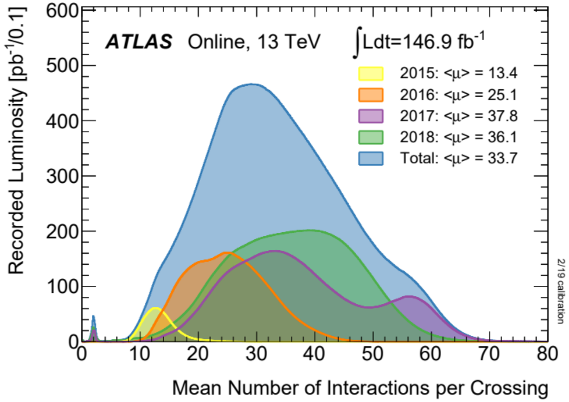
350 fb^{-1}

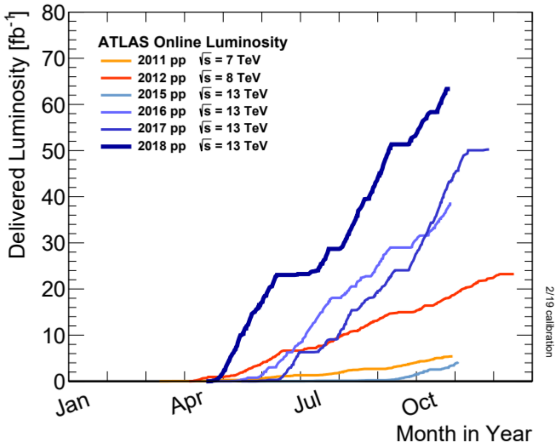
integrated
luminosity

3000 fb^{-1}
4000 fb^{-1}

Facing the Challenge: Run 2 Operational Conditions

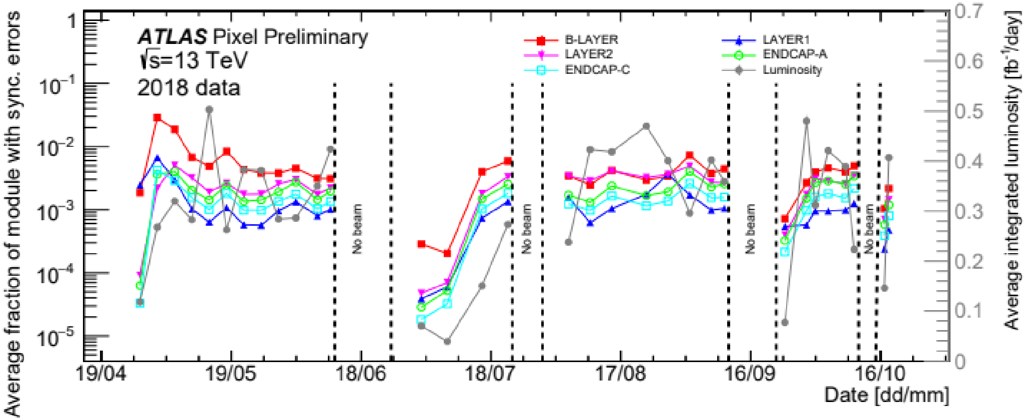
- For Run 2 the tails of average pile-up distributions extended to over 60 interactions (top)
- Instantaneous luminosity doubled w.r.t. specifications and reached 2x10^{34} cm^{2}s^{-1}
→ challenging conditions for Pixel modules designed for half this value
- Delivered up to 70 fb^{-1} per year and about 160 fb^{-1} in Run 2 overall (bottom)
- Level-1 trigger rate increased to about 85 kHz
- → keep read-out occupancy within margins and mitigate desynchronisation despite high pile-up events to ensure good data quality

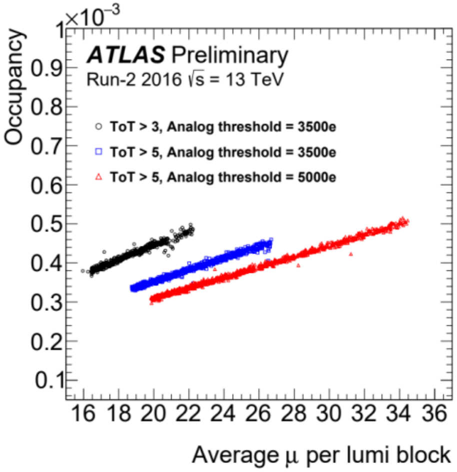


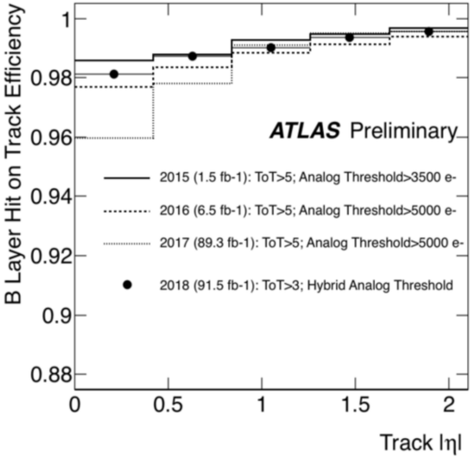


Detector Operation during Run 2

- **Desynchronisation errors below 1%, despite increasing luminosity (top)**
- **Increased thresholds to mitigate bandwidth saturation caused by higher pile-up (bottom left)**
- **Threshold modifications (eta dependent) closely monitored to ensure no deterioration of track efficiency (bottom right)**
- **Dead-time below 0.2% (2018), DQ efficiency at 99.5% (in 2018: 99.8%) and less than 5% non-operational modules → excellent performance despite age and radiation**

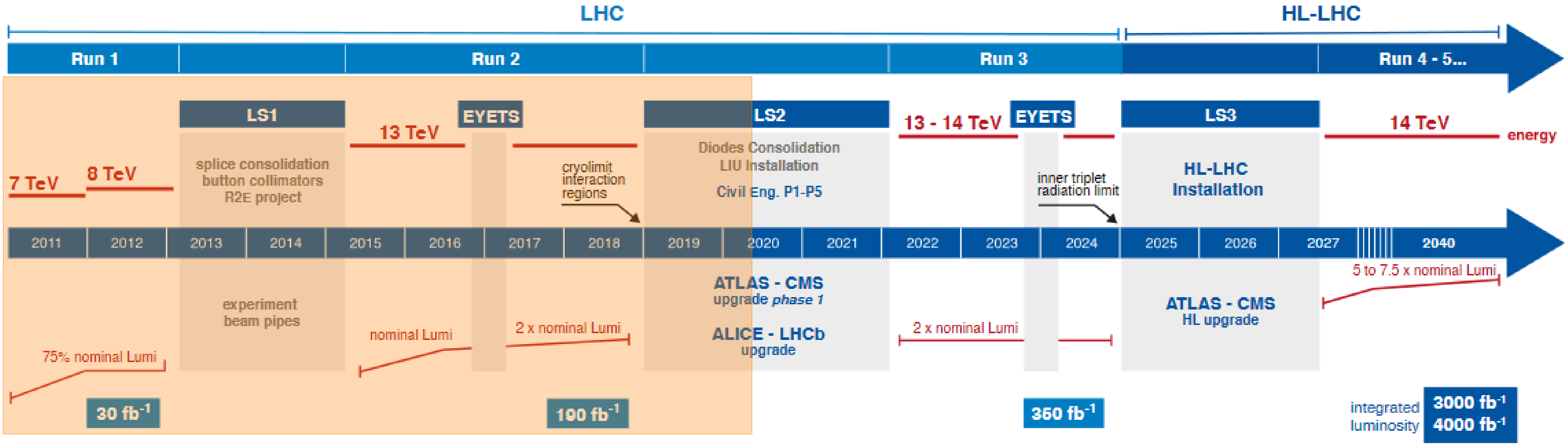






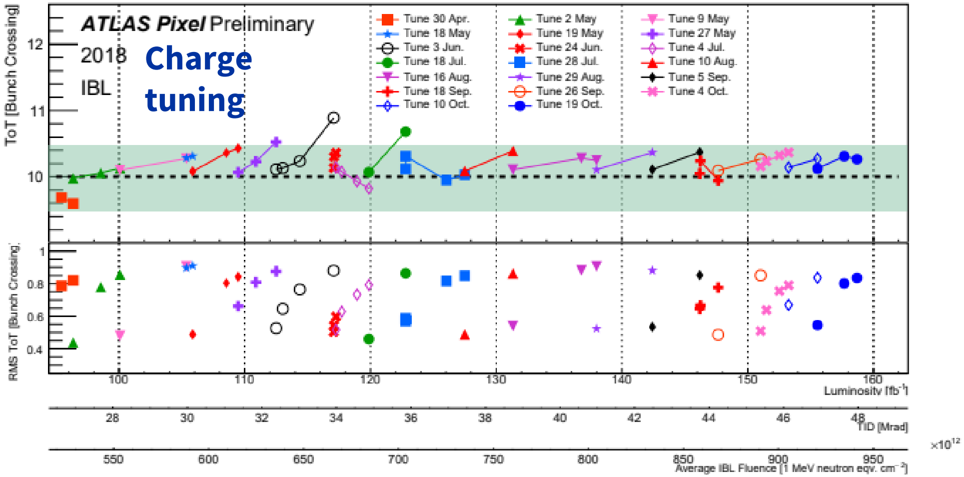
Radiation Damage and Modelling thereof

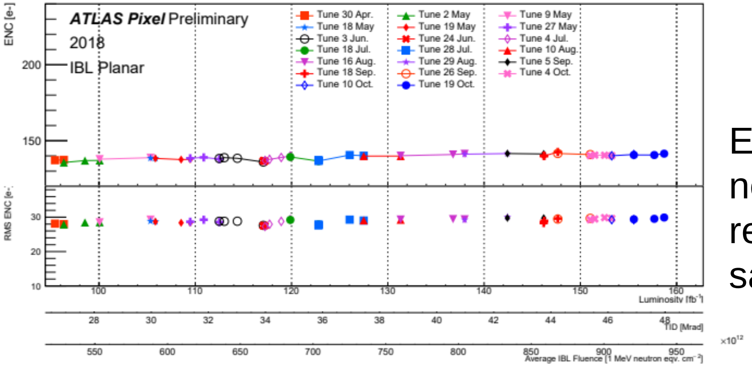
→ Also see recording of talk by T. Dado today morning in this session



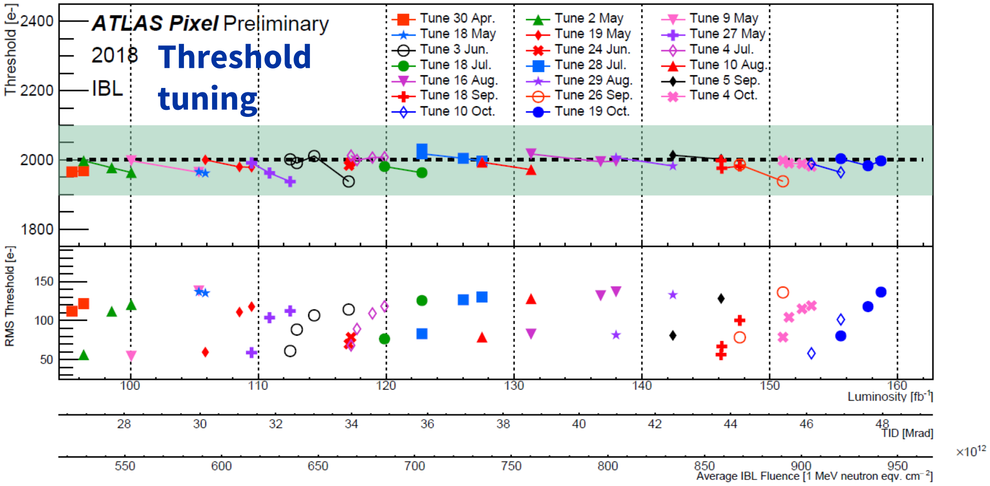
IBL Retuning

- **Change of transistor leakage current due to Total Ionising Dose (TID) known in IBM 130 nm CMOS technology → retuning of IBL charge response (ToT, top right) and threshold (bottom right) after irradiation**
- **By retuning every ~5 fb^{-1} the ToT mostly stays within 0.5 bunch crossings and the threshold within 100 electrons (green bands)**





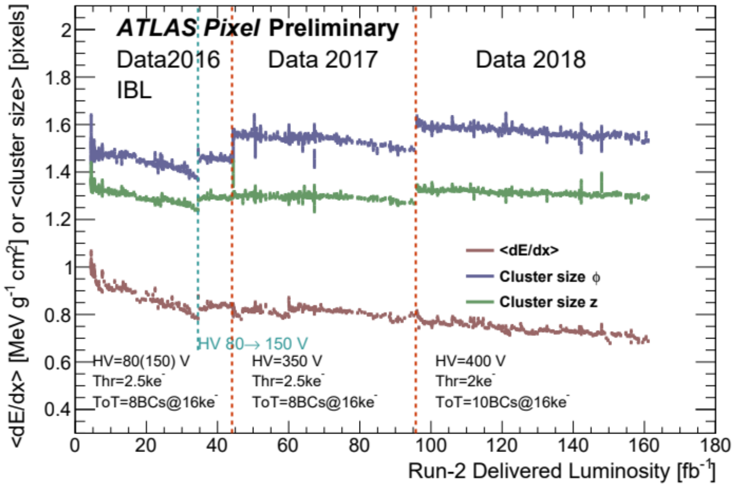
Equivalent noise charge remains the same (left)

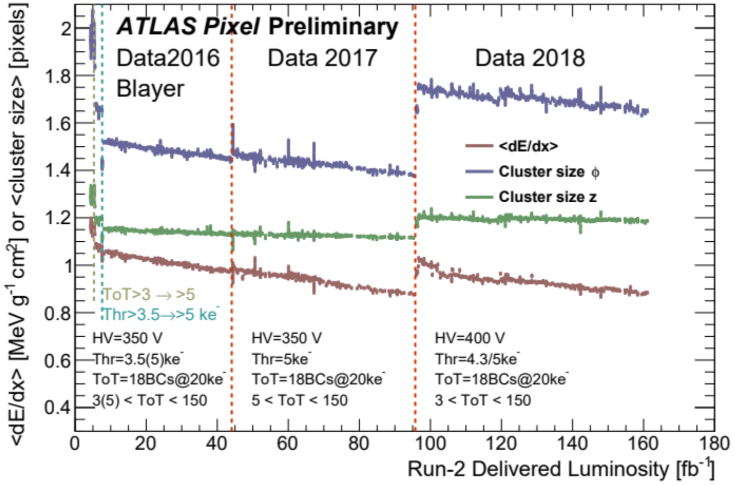


TID effect on electronics: CERN Yellow Reports: Monographs, CERN-2021-001 (CERN, Geneva, 2021)

Evolution of <dE/dx> and Cluster Size

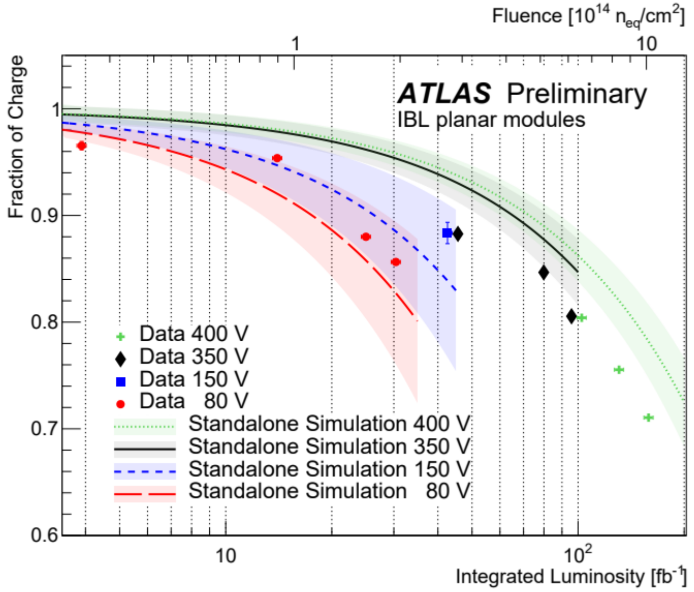
- Increased radiation damage → less collected charge (shallow downwards slope in <dE/dx>) and hence smaller cluster size (ϕ, z)
- Increase in HV → full depletion and reducing threshold to mitigate effect of less charge
- Increasing threshold (e.g. B-layer in 2016) due to limitation in bandwidth
- End of Run 2 → set lower thresholds and increase high voltage → mitigate effects of radiation damage

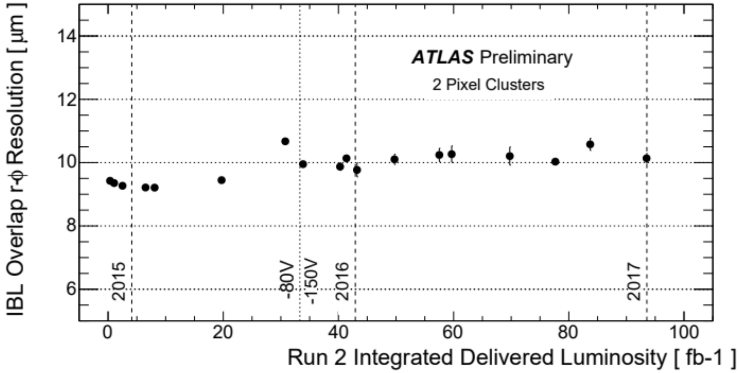




IBL: Charge Collection Efficiency (CCE)

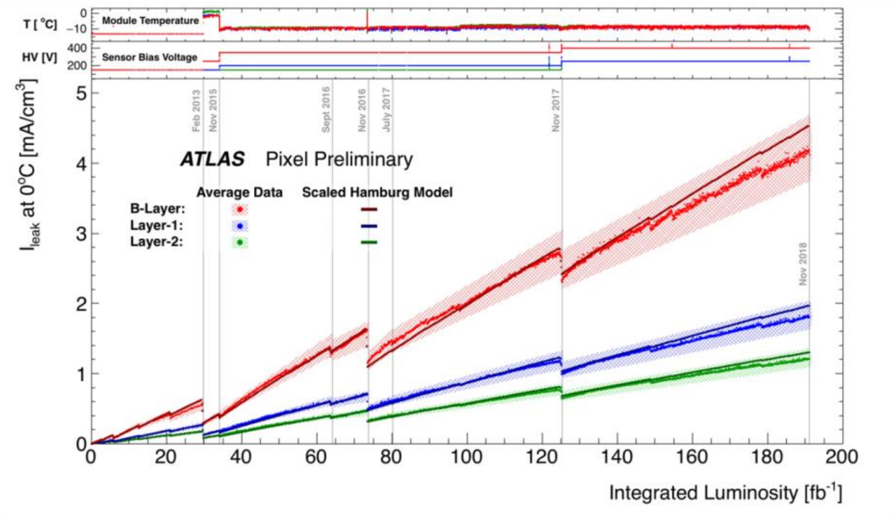
- **Increasing integrated luminosity → radiation damage to sensor bulk → reduction of collected charge (top)**
- **At 160 fb^{-1} only 70% of initial charge → very small impact also on tracking as can be seen in the evolution of two-cluster resolution (bottom)**
- **End of Run 2: at 70% CCE for IBL modules MPV is about 10 ke^{-} with a 2 ke^{-} threshold (tuning)**

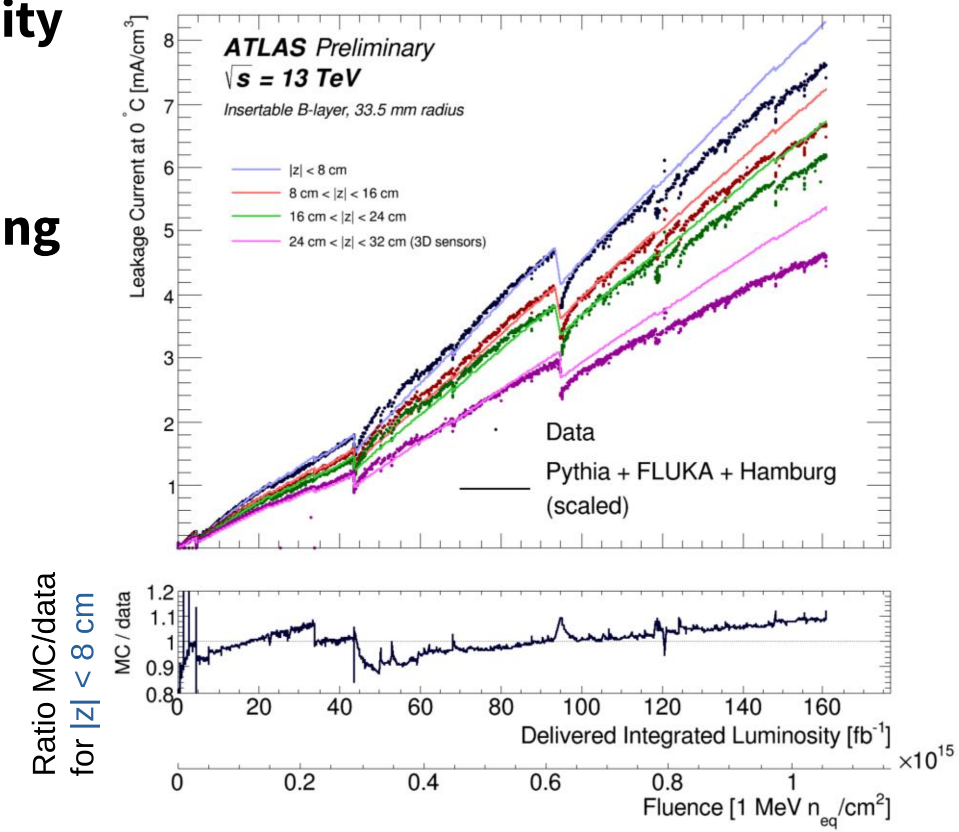




Modelling Radiation Damage: Leakage Currents

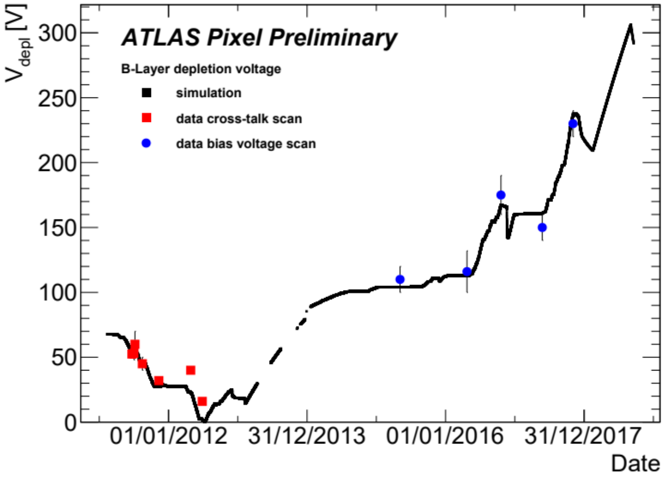
- **Leakage current easily accessible quantity to monitor radiation damage**
- **Modelled by Hamburg Model (input: temperature, annealing) with reweighting**
- **Slight over prediction at high fluences**

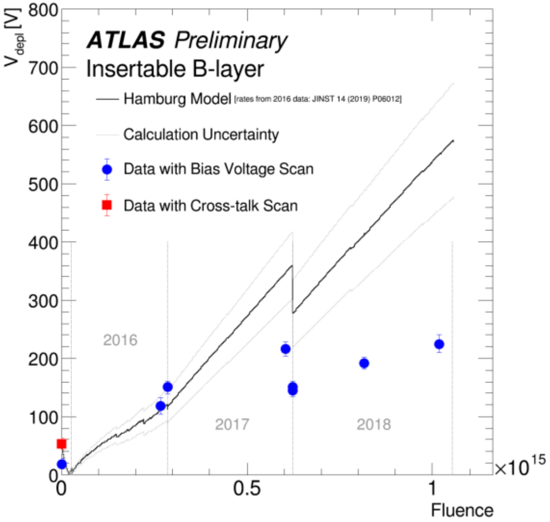




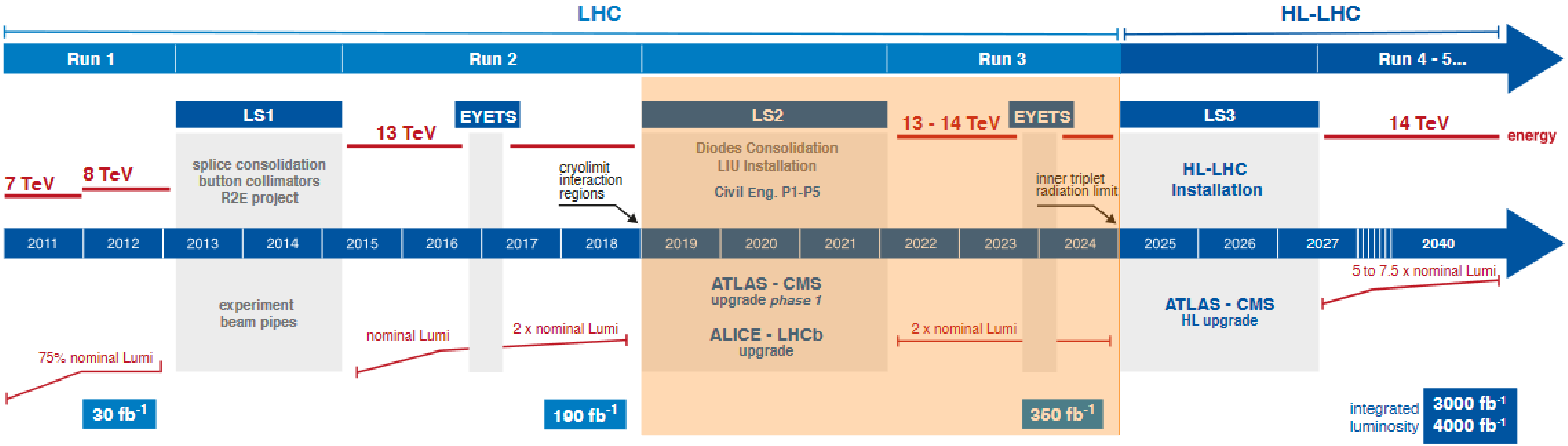
Depletion Voltage

- **Depletion voltage measured via cross-talk scans (before type inversion) and bias-voltage scans (after)**
- **B-layer (top) in good agreement with prediction at low fluences**
- **For IBL (bottom), the Hamburg model slightly overpredicts the depletion voltage for low fluences and underpredicts it for high fluences**



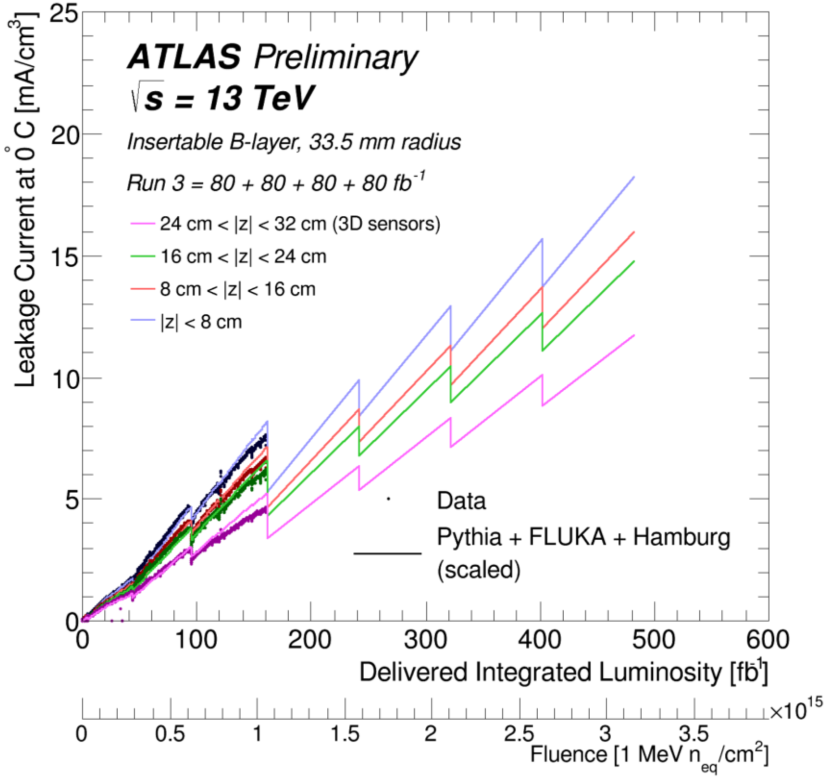


Towards and into Run 3



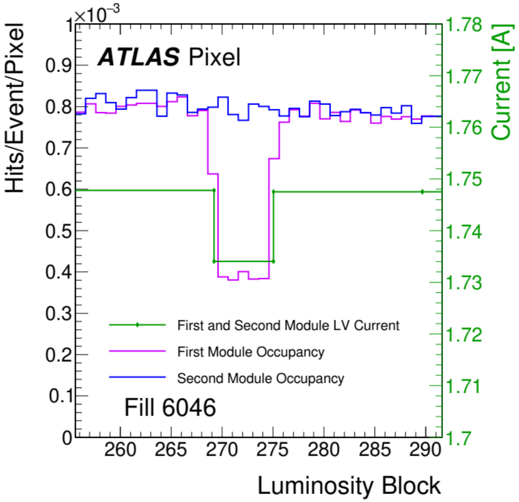
Towards Run 3

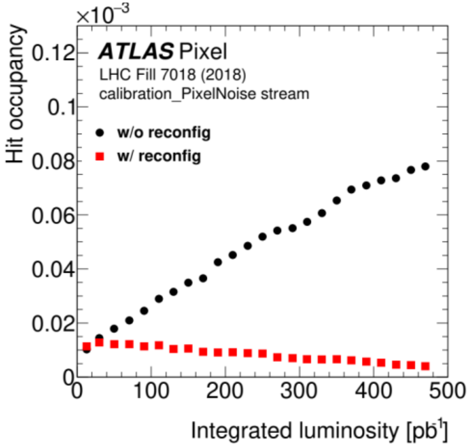
- **Detector is being kept cold during Long Shutdown 2 (LS2) in order to reduce reverse annealing → keep voltage required for full depletion as low as possible for B-layer and IBL**
- **For operations: the goal is to set the HV high enough to stay fully depleted for one year**
- **Leakage current prediction for IBL (right) and Pixel (not shown) are within power supply limits**
- **Additionally, we are investigating to what extent it is possible to increase the cooling and reduce the module temperatures**



Single Event Upsets in IBL

- **Charged particles crossing front-end can corrupt registers → detune module (make them noisy or silence them) and change module low voltage (top)**
- **Mechanism to retune the IBL global registers w/o introducing any additional busy-time implemented during Run 2**
- **For Run 3: also IBL pixel level registers will be reconfigured which has been briefly tested previously (bottom)**
- **Moreover, reconfiguration of Pixel (in contrast to IBL) modules was implemented**
- **→ mitigate effects of radiation to front-end (increasing integrated luminosity per fill in Run 3)**

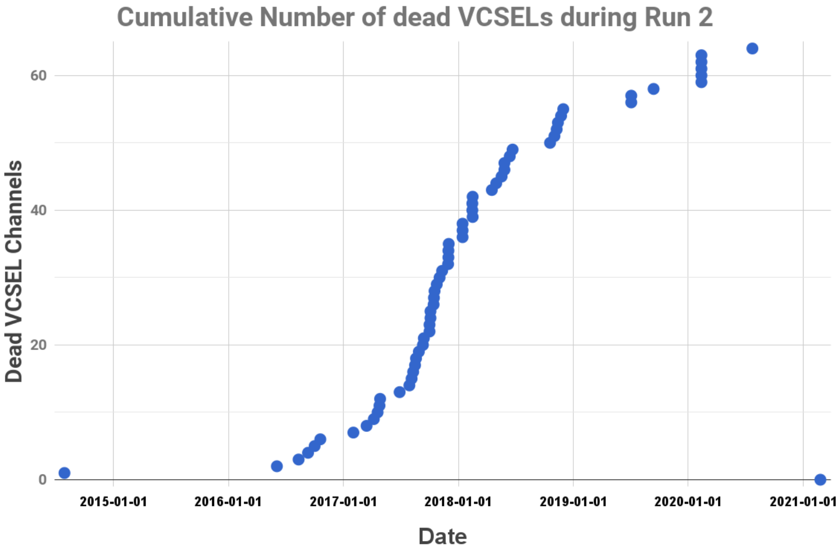


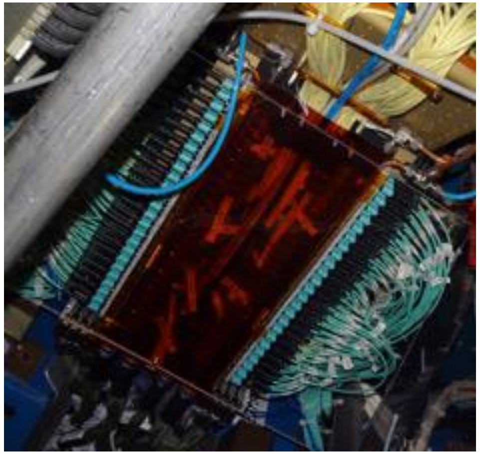


G. Balbi et al., Measurements of Single Event Upset in ATLAS IBL, 2020 JINST 15 P06023

Optoboard Replacement

- Opto-electrical conversion between read-out equipment and modules done by optoboards
- Optoboards have laser diode arrays (VCSELs) and PIN diode arrays
- Failure of VCSELs about 2 years after installation → exact failure mode unknown but possibly linked to humidity
- First optoboard replacement before 2018 run and a replacement of all broken, suspicious, and B-layer optoboards was done in early 2021 to prevent failures in Run 3
- Additional sealing of the opto-boxes to shield optoboards against humidity (bottom)





Summary

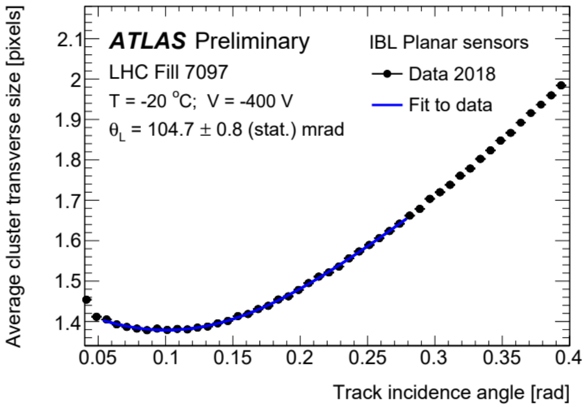
- **Despite the radiation damage and age, the ATLAS Pixel detector has delivered excellent performance**
- **We kept (and keep) the detector cold to prevent reverse annealing, ensuring that we can achieve full depletion throughout Run 3**
- **During LS2 we have taken actions to recover modules which have previously failed due to a broken optical connection and hope to have mitigated this issue for Run 3**
- **Radiation damage is closely being monitored and modelled and the results are vital input for decisions on Run 3 operational parameters**
- **Radiation damage results are also of interest for upgrade (ITk) and research (RD50) projects**
- **Ready for the LHC commissioning phase (pilot beams) and Run 3 (2022)**

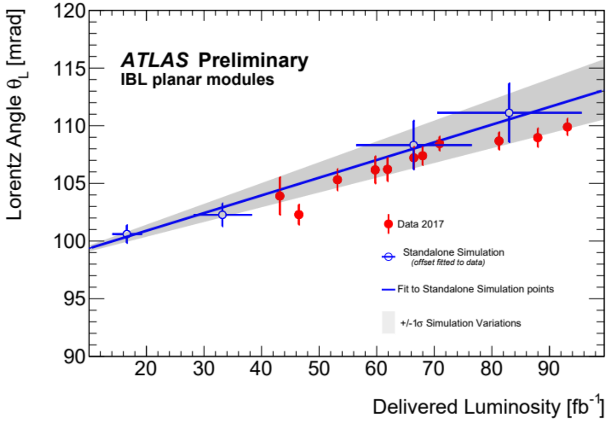
Thank you for your attention!

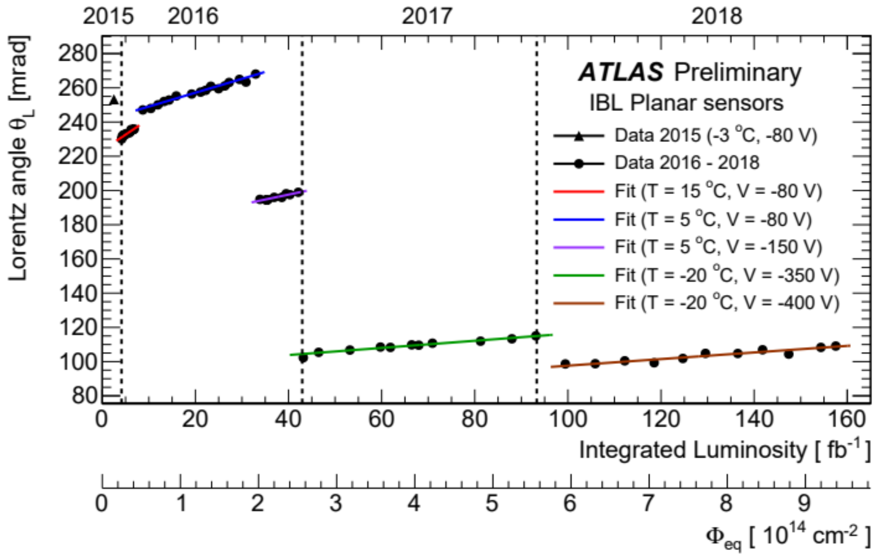
home.cern

Lorentz Angle Measurements

- **Magnetic field deflects charges propagating in sensor → Lorentz angle**
- **Lorentz angle can be measured by studying cluster size vs. track incidence angle (top left)**
- **Simulation input: TCAD electric field maps (Chiochia model, top right)**
- **Lorentz angle changes with temperature, bias voltage, and fluence (bottom)**
- **Sensitivity to electric field → measure Lorentz angle and study electric field**







Fluence-to-Luminosity Factors

- **Deriving the fluence-to-luminosity conversion factors in z-dependence**
- **Exploiting the various measurements: leakage current, Lorentz angle, and depletion voltage**
- **For IBL, the z-dependance is predicted (Pythia + FLUKA/Geant4) to be shallower than measured**