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

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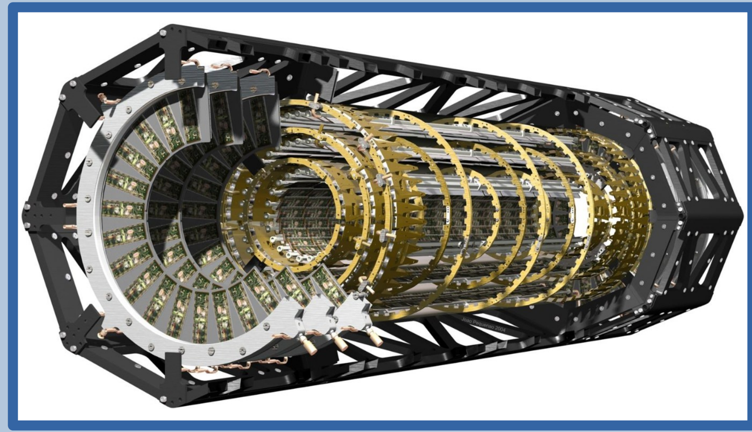
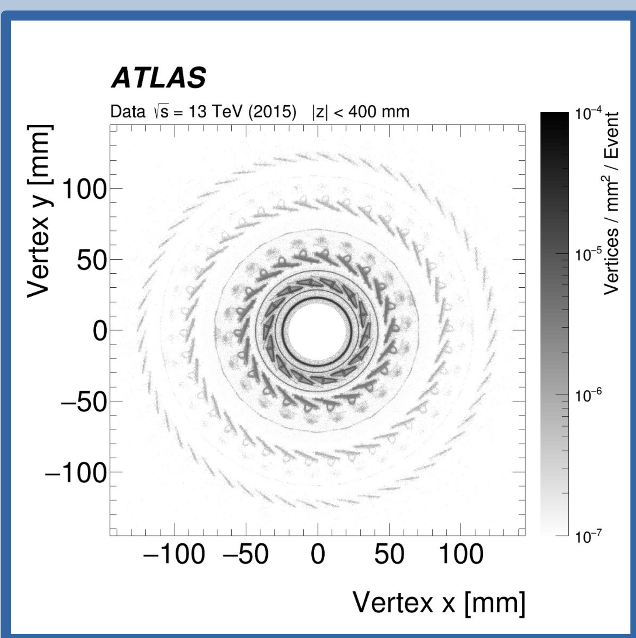
Introduction and Layout

- Four layers of silicon pixellated detector and 2x3 endcap disks in the ATLAS Inner Detector [1,2]
- Innermost layer (IBL) inserted in 2014 (planar & 3D sensors)
- First layer at 3.3 cm and outermost 12.3 cm away from interaction point
- Essential for tracking and vertexing (b-tagging)



Render image of the ATLAS Pixel Detector without the IBL

	Outer barrel & disks	IBL
Pixel size [μm x μm]	50 x 400	50 x 250
Resolution [μm x μm]	10 x 115	10 x 40
Channels	80 x 10^6	12 x 10^6
Design fluence [1 MeV n_{eq} cm^{-2}]	1 x 10^{15}	5 x 10^{15}
Design ionising dose [Mrad]	50	250
CMOS Technology	250 nm	IBL 130 nm
Pixel implants	n^+-in-n	n^+-in-n (planar) n^+-in-p (3D)

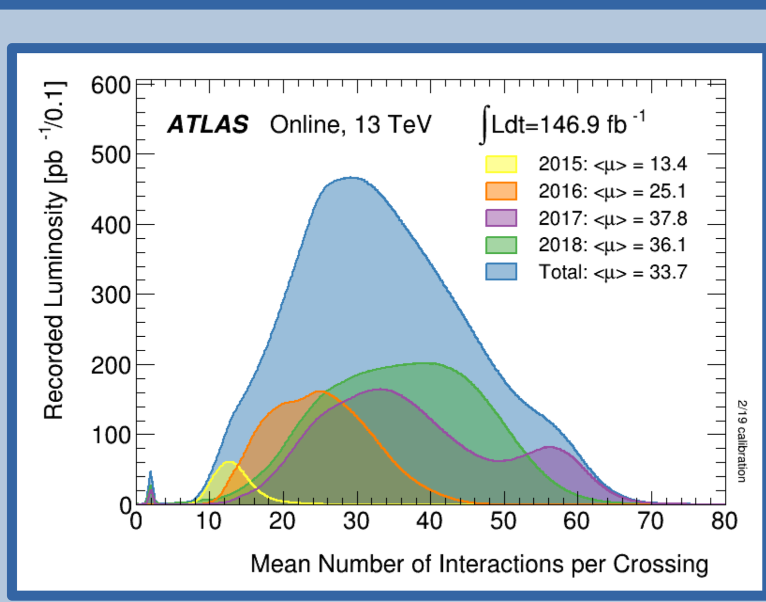


Vertices originating from interactions in the material of the Pixel detector

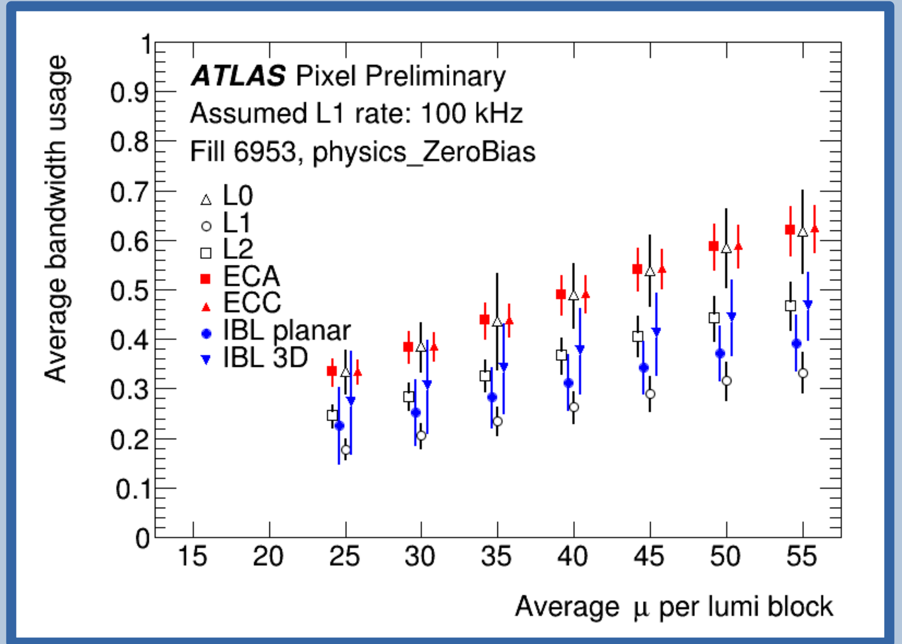
Detector Operation in Run 2

- Run 2 data taking period of LHC between 2015 and 2018
- Collision rate of 40 MHz
- LHC delivered instantaneous luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ – double with respect to LHC design (only IBL designed for those values)
- At the start of fill, the average pile-up (<μ>) extended to above 60
- Despite challenging conditions (bandwidth limitation & radiation effects), the detector performed well with a data-quality efficiency of 99.5%
- Dead-time contribution to ATLAS by Pixel only 0.2% (end of Run 2)
- Less than 5% of the modules not operational

→ *good performance in Run 2*



Average pile-up for the different years in Run 2

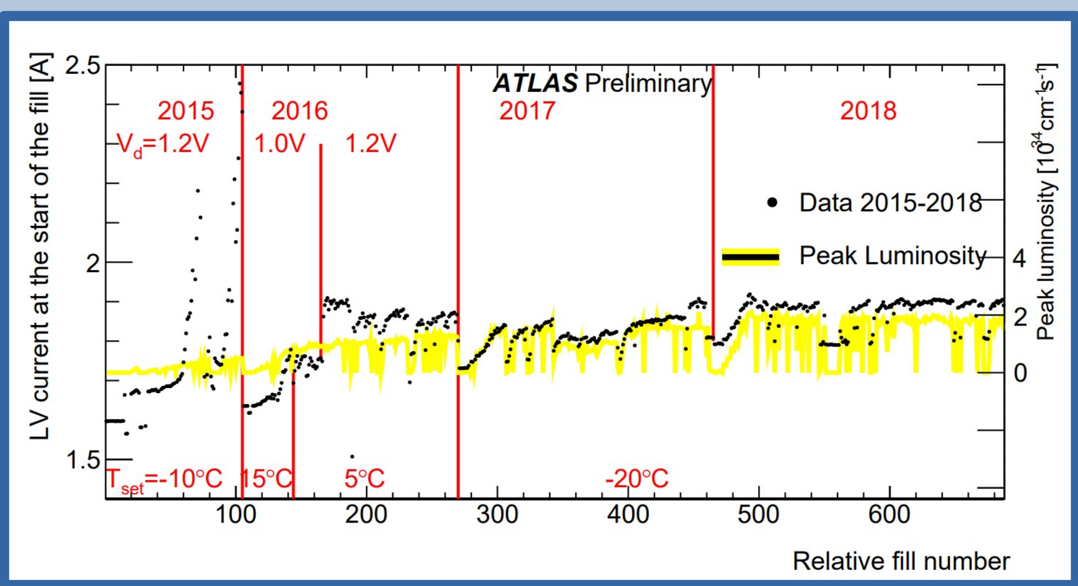


Bandwidth usage as a function of <μ> for the different layers

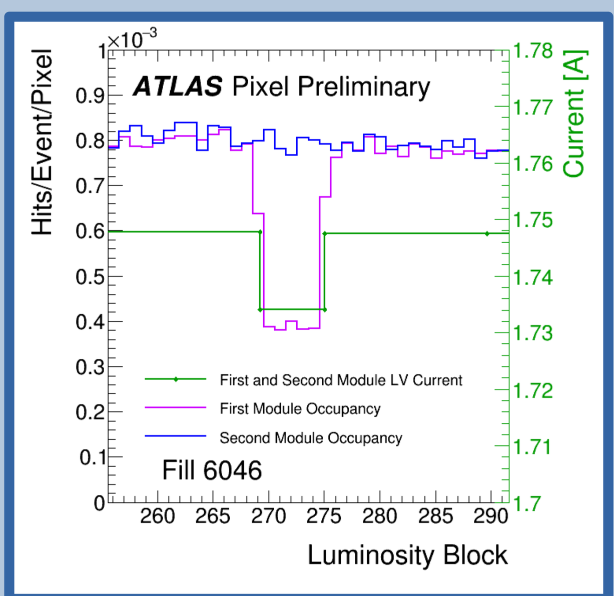
Radiation Effects on the Front-End

- Early IBL LV current increase due to low TID effect [3]
- Counteract this beginning of Run 2 by changing operating temperatures and voltages
- At higher instantaneous luminosities, single event effects (SEEs) became an issue for the IBL [4]
- SEEs cause bit-flips in front-end registers and can make pixels get noisy or become silent → reflected in LV
- Mitigation strategies to reconfigure global front-end registers without dead-time were introduced

→ *if not counter-acted, radiation effects will become more of an issue in Run 3 because of the higher integrated luminosity LHC fills*



The low TID effect impacting the IBL operation in 2015 and 2016

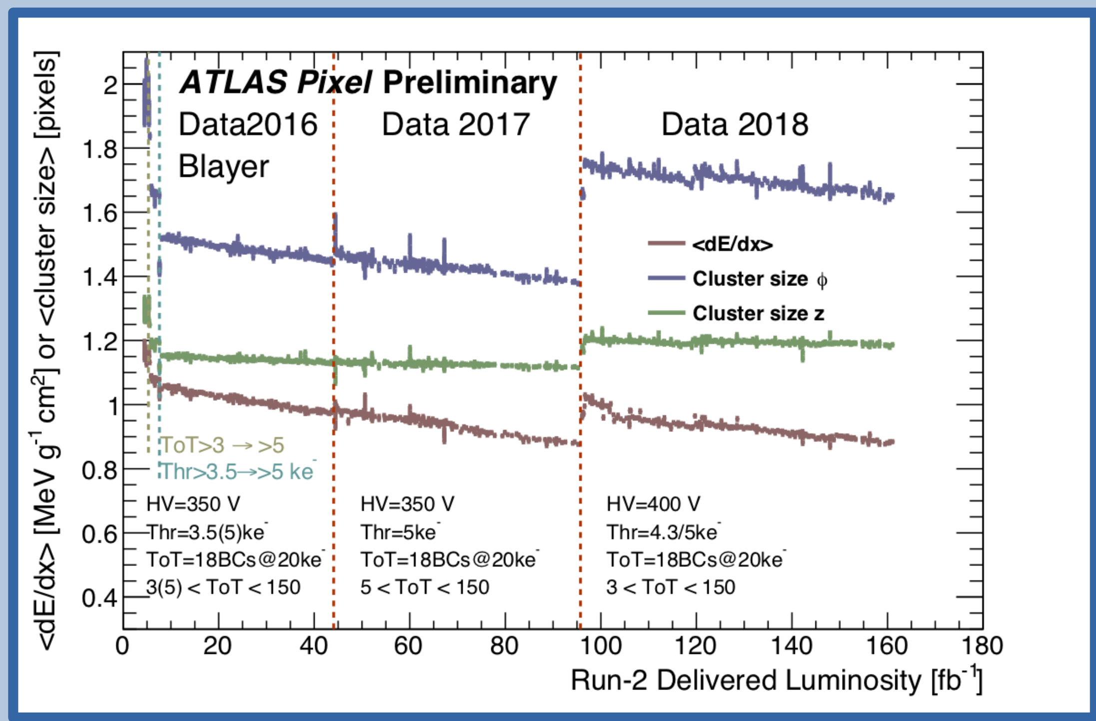


SEE and reconfiguration of an IBL module

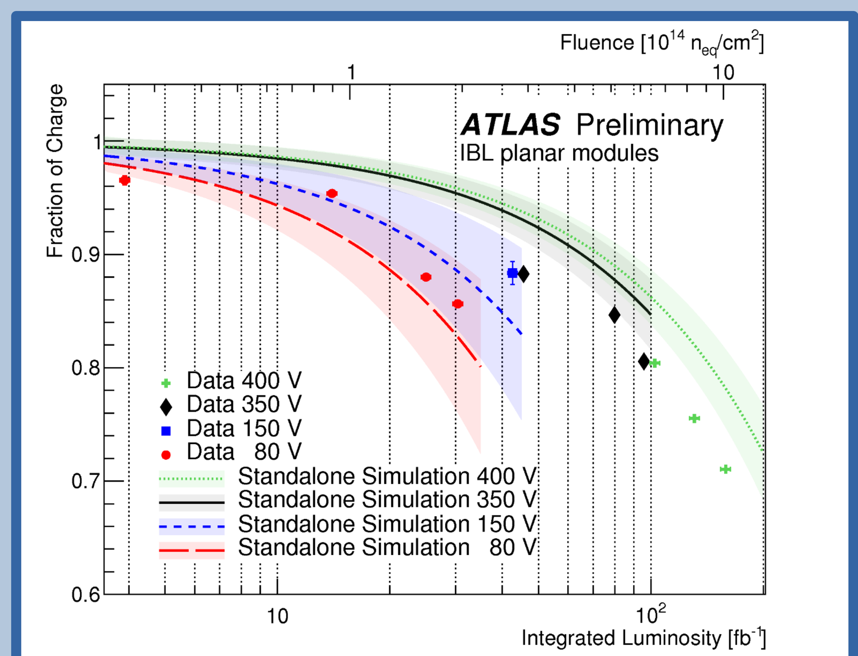
Radiation Damage on the Silicon Sensors

- IBL received fluence up to 10^{15} 1 MeV n_{eq} cm^{-2}
- Charge trapping due to introduced defects → less charge
- Counteract this by decreasing thresholds
- HV increase to ensure full depletion
- Regularly perform HV scans to derive depletion voltage. Is input for radiation damage modelling → predict HV needed for full depletion and expected leakage currents
- Predicted leakage currents at the end of Run 3 within design limits
- Developed and deployed radiation damage modelling for Run 3 Monte Carlo simulation [5]

→ *constant monitoring of radiation damage → predictions for operational parameters throughout Run 3*



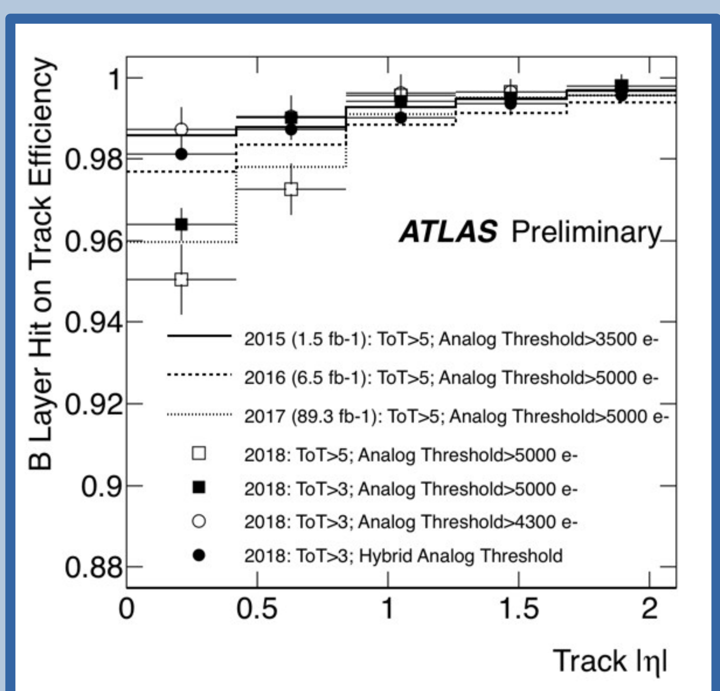
<dE/dx> and <cluster size> over time for B-Layer throughout Run 2



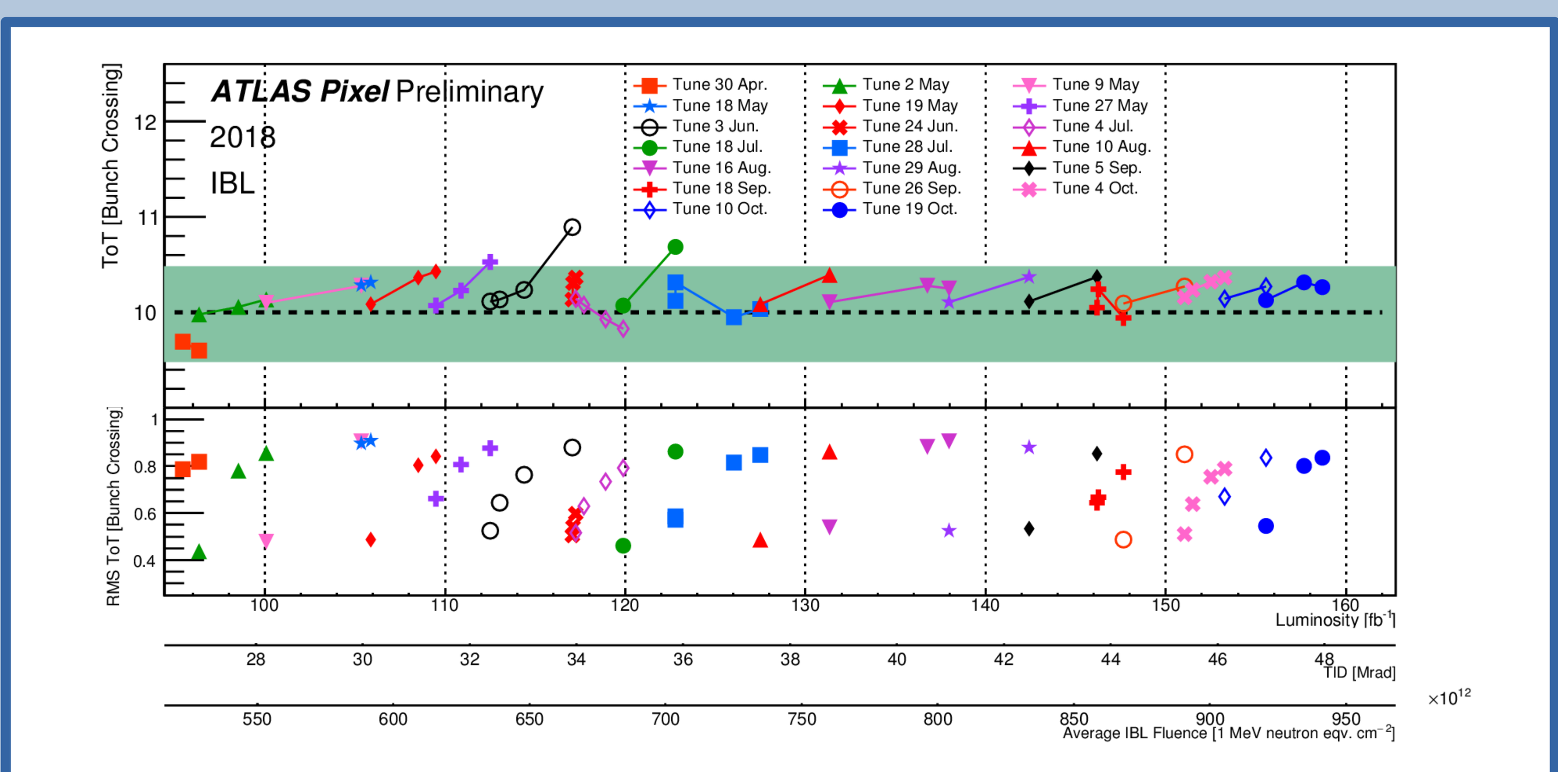
Charge for the IBL versus int. Luminosity for different HV settings

Mitigating Effects of Radiation Damage

- Detector kept cold (also in periods of shutdown) to minimise reverse annealing
- Frequent retuning (about every 5 fb^{-1}) of IBL to ensure uniform detector response
- Hybrid threshold tuning (η-dependent) in second pixel layer (B-Layer) to balance charge loss and bandwidth usage
- Threshold decrease necessary to retain tracking performance



Decrease of hit on track efficiency on the B-Layer due to charge loss

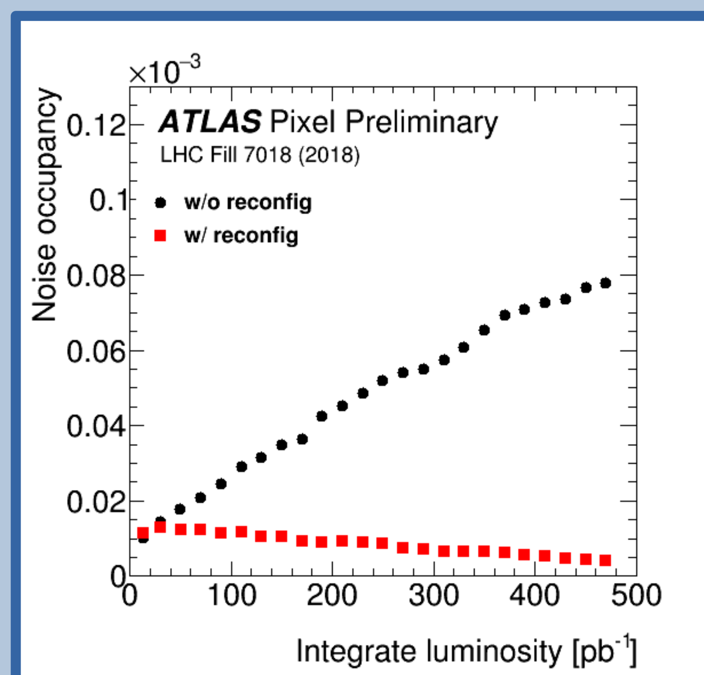


The time-over-threshold (ToT) tuning for the IBL. The ToT corresponds to the deposited charge

Conclusion and Outlook

- Good performance of the ATLAS Pixel Detector throughout Run 2, despite increasingly harsh conditions and radiation damage
- Radiation damage had measureable impact on the collected charge, but could be mitigated by lowering the thresholds → challenge with increased hit rates
- Extension of Run 3 poses challenges to Pixel, with the risk of having to run the B-Layer underdepleted
- Constant monitoring of the detector provides good modelling for the future
- For Run 3, additional pixel level register reconfiguration has been put in place to mitigate SEEs

→ *Pixels ready for Run 3 and LHC intensity ramp-up*



Pixel level reconfiguration of IBL prevents the increase of noisy pixels due to SEEs

[1] G. Aad et al., *ATLAS pixel detector electronics and sensors*, 2008 JINST 3 (P07007)
[2] B. Abbott et al., *Production and Integration of the ATLAS Insertable B-Layer*, 2018 JINST 13 (T05008)
[3] I. Dawson (ed.), *Radiation effects in the LHC experiments: Impact on detector performance and operation*, CERN Yellow Reports: Monographs, CERN-2021-001, Geneva, 2021
[4] G. Balbi et al., *Measurements of Single Event Upset in ATLAS IBL*, 2020 JINST 15 (P06023)
[5] ATLAS Collaboration, *Modelling radiation damage to pixel sensors in the ATLAS detector*, 2019 JINST 14 (P06012)