Status of the ATLAS Pixel Detector

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on behalf of the ATLAS Collaboration

UNIVERSITY OF CALIFORNIA SANTA CRUZ

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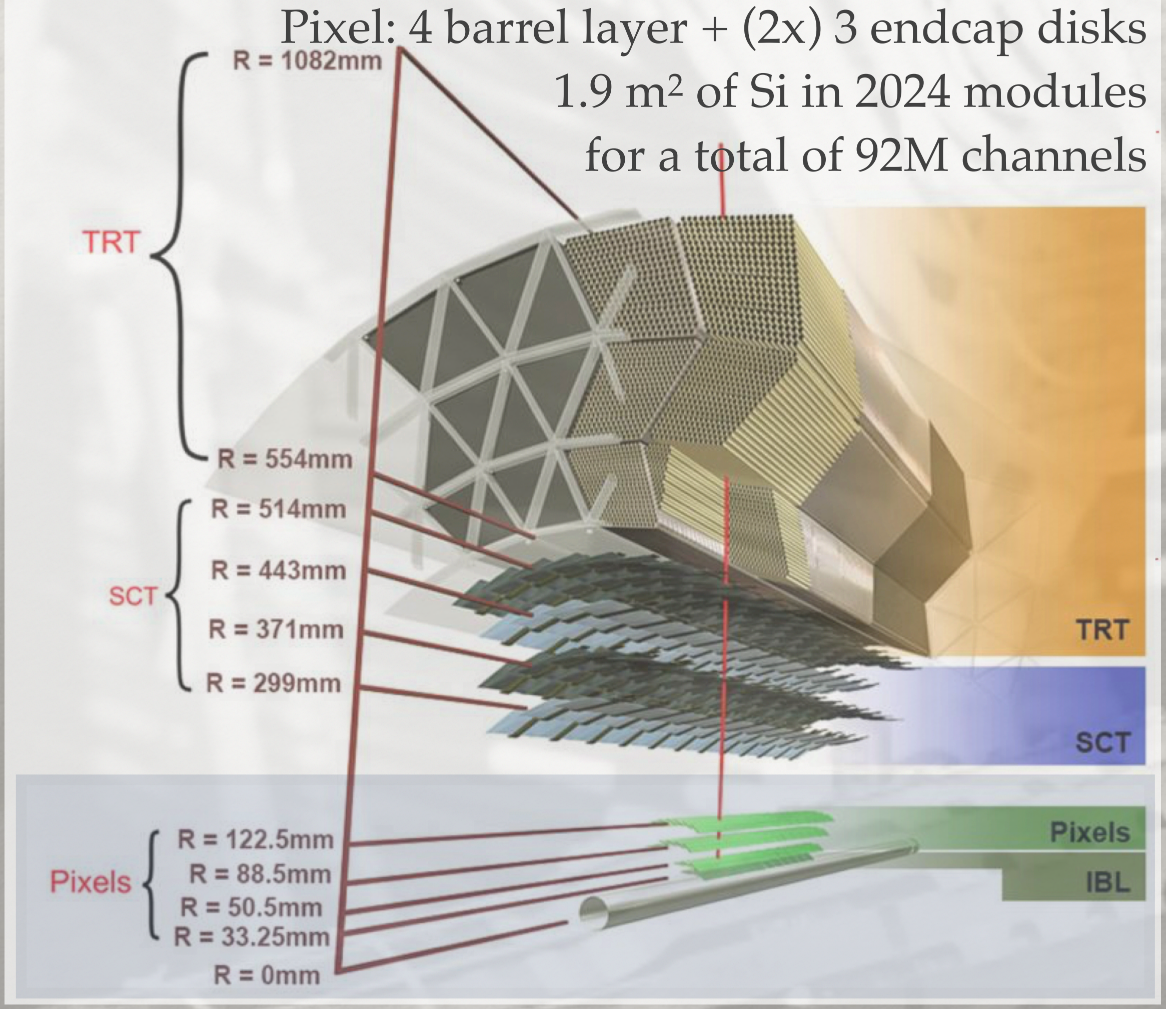
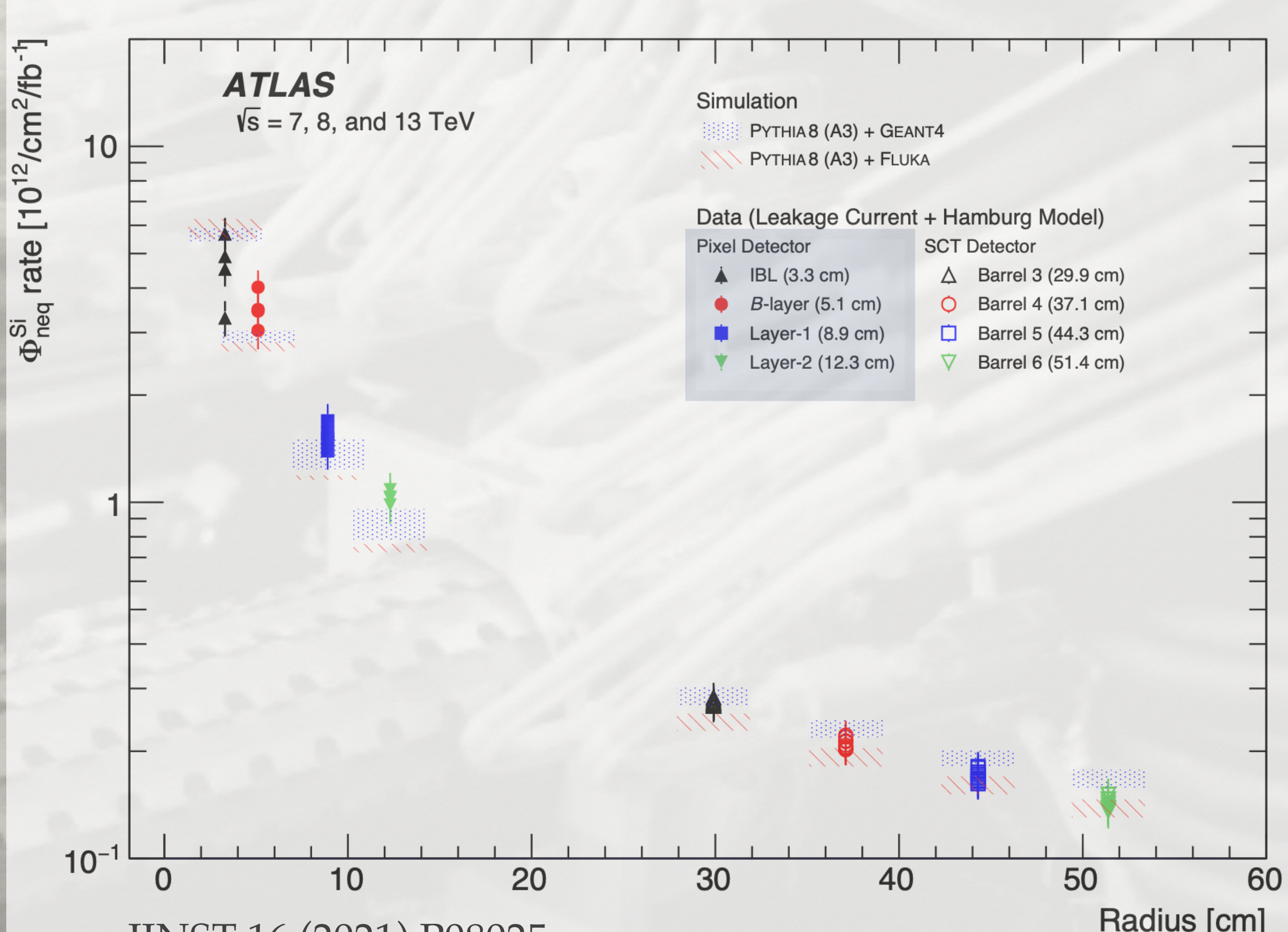
Santa Fe NM, December 12th, 2022

The ATLAS Pixel Detector

Pixel: 4 barrel layer + (2x) 3 endcap disks
1.9 m² of Si in 2024 modules
for a total of 92M channels





JINST 16 (2021) P08025

IBL n⁺-in-n planar + n⁺-in-p 3D sensors with 50x250 μm pitch read out by FEI4 chips in 130 nm CMOS with 4-bit time-over-threshold (ToT) analog information
Other pixel layers & disks n⁺-in-n planar sensors with 50x400 μm pitch readout by FEI3 chips in 0.25 μm CMOS with 8-bit ToT analog information

Pixel detector determines the accuracy of particle track extrapolation to their production vertex; provides space points for reconstructing very low momentum particle tracks and measures charged particle dE/dx important for searches of anomalously ionising new particles;

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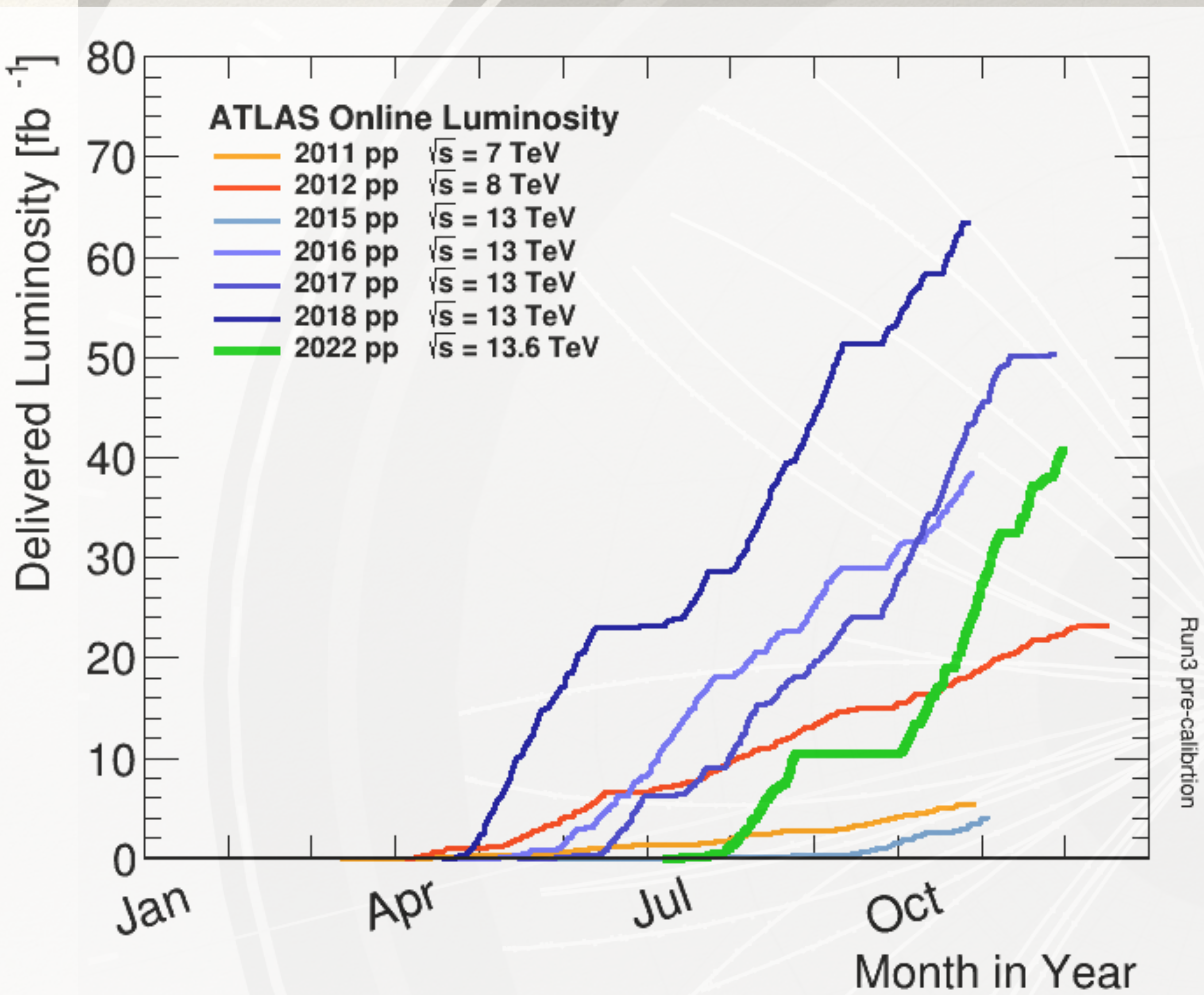
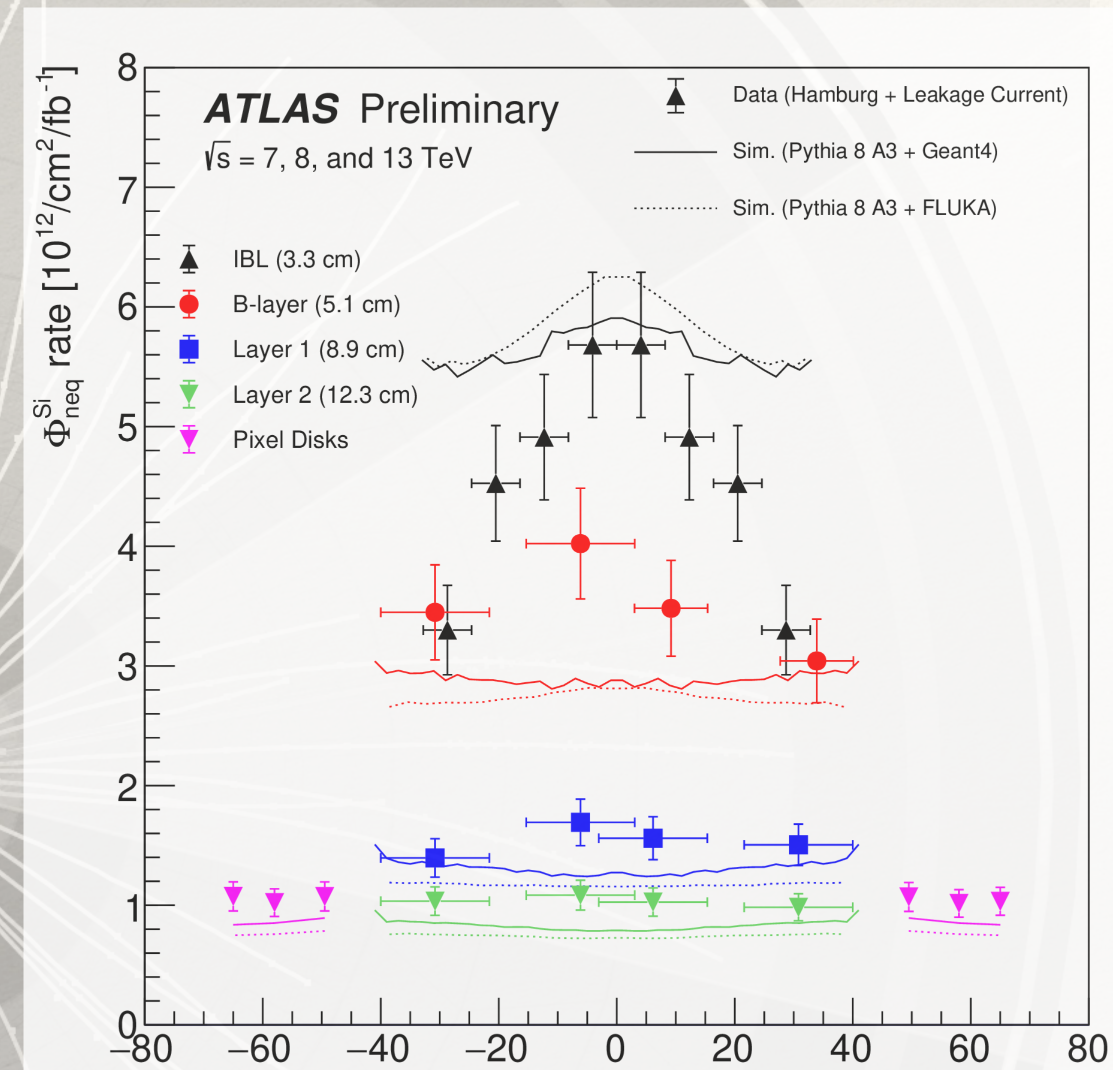
LHC Delivered Luminosity



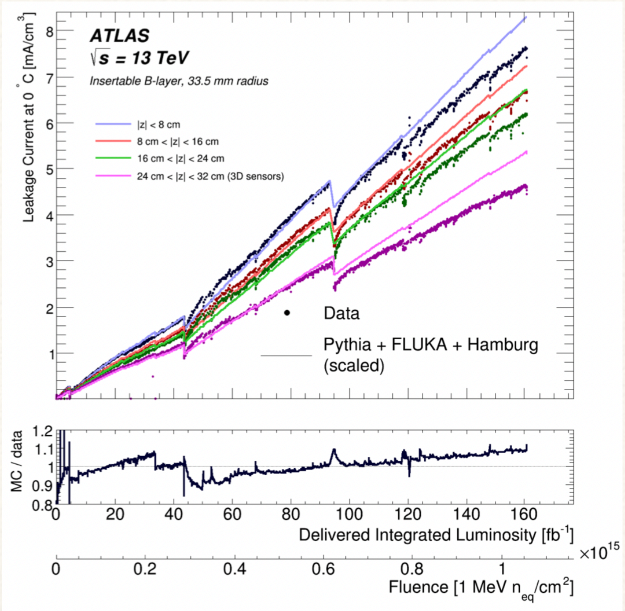
Integrated Luminosity to Fluence conversion for Pixel and SCT layers from Leakage Current Measurements



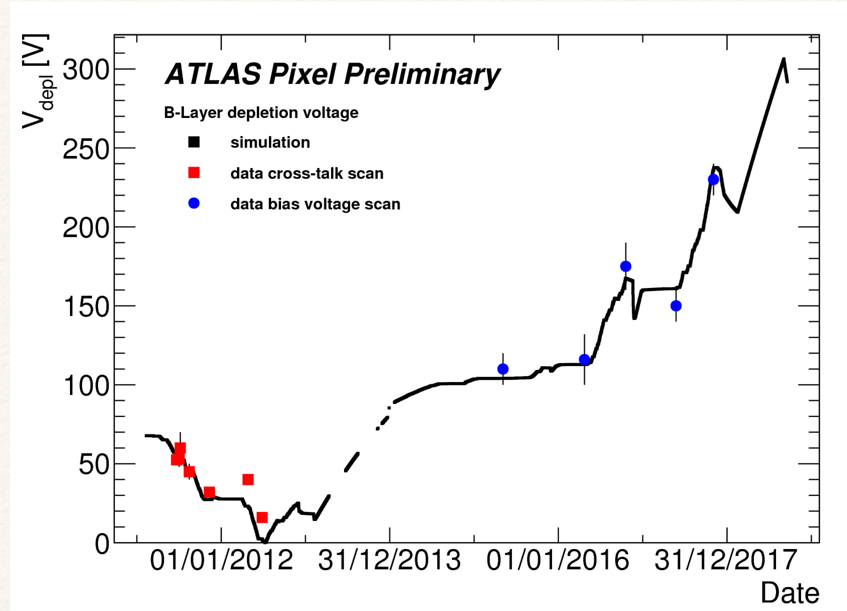
IDET-2020-001

With 200 fb^{-1} delivered since 2015, IBL received fluence > 10^{15} n-eq/cm^2, to increase by > 2 by end of Run 3 in 2025. Radiation damage has become parameter of relevance in evaluating performance of ATLAS Pixels and of derived physics objects (tracking and vertexing) in event reconstruction and analysis.

Sensor Bulk Damage



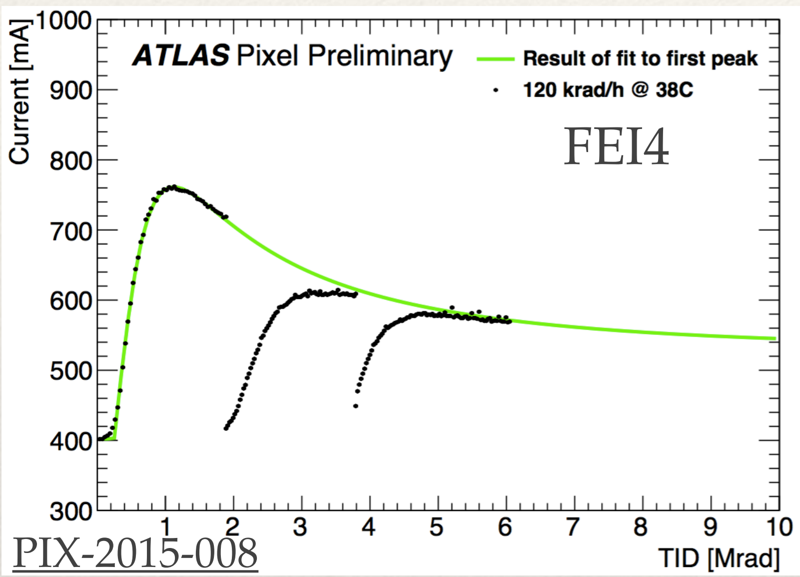
PIX-2019-001



PIX-2018-005

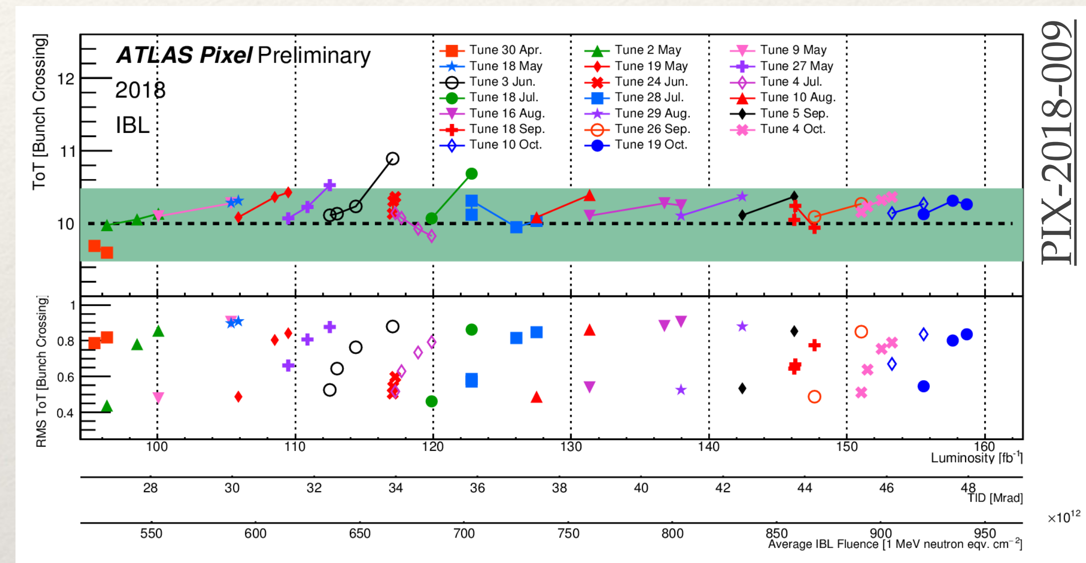
Damage to charge collection bulk responsible for decrease of charge yield, increase in leakage currents and depletion voltages;
Simulation of effects with radiation damage digitiser used in production of all ATLAS MC samples for Run 3 (discussed later).

Surface Effects



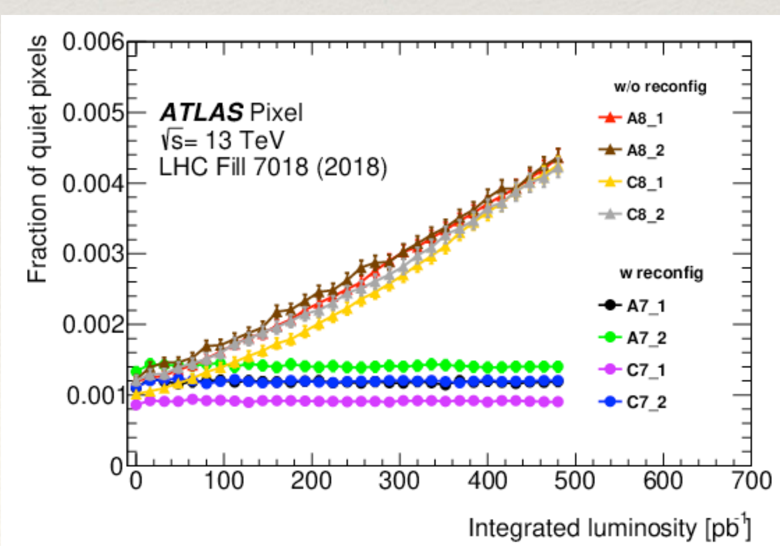
PIX-2015-008

Total Ionising Dose effect on FE chip induces transistor current variations (peaking at ~1MRad or ~3fb^{-1} for FEi4) impacting ToT and threshold tuning and need to be regularly monitored and re-calibrated.

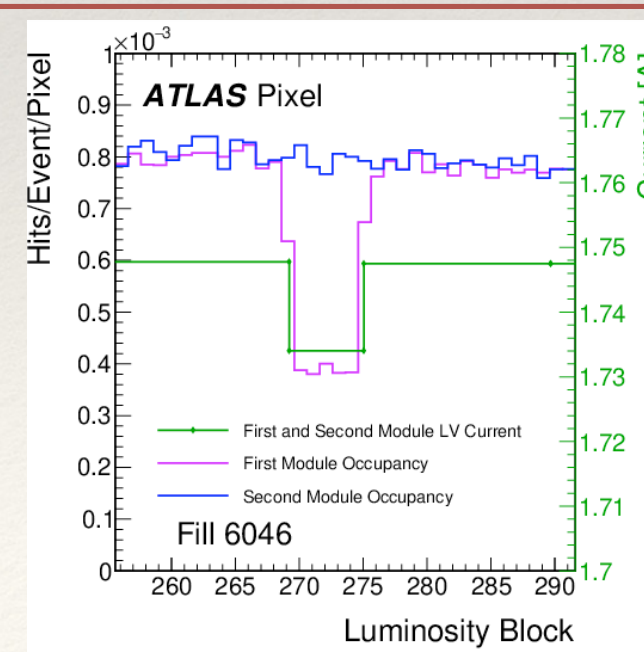


PIX-2018-009

Single Event Upset (SEU)



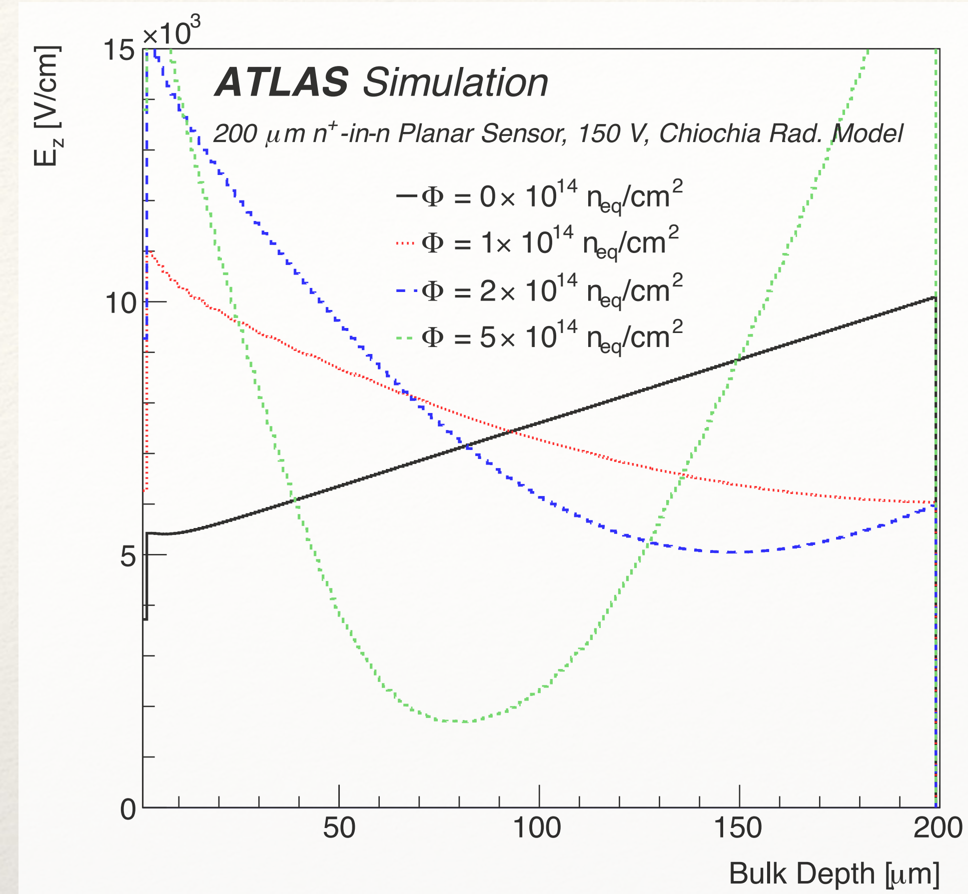
Single Event Upsets (SEU) and Single Event Transients (SET), studied in IBL FE-I4, affect FE global registers and settings for individual pixels, causing occupancy losses, drops in LV currents, noisy and silent pixels. Mitigation through single pixel reconfiguration during run have been applied in 2018. Regular full FE reconfiguration in Run 3.



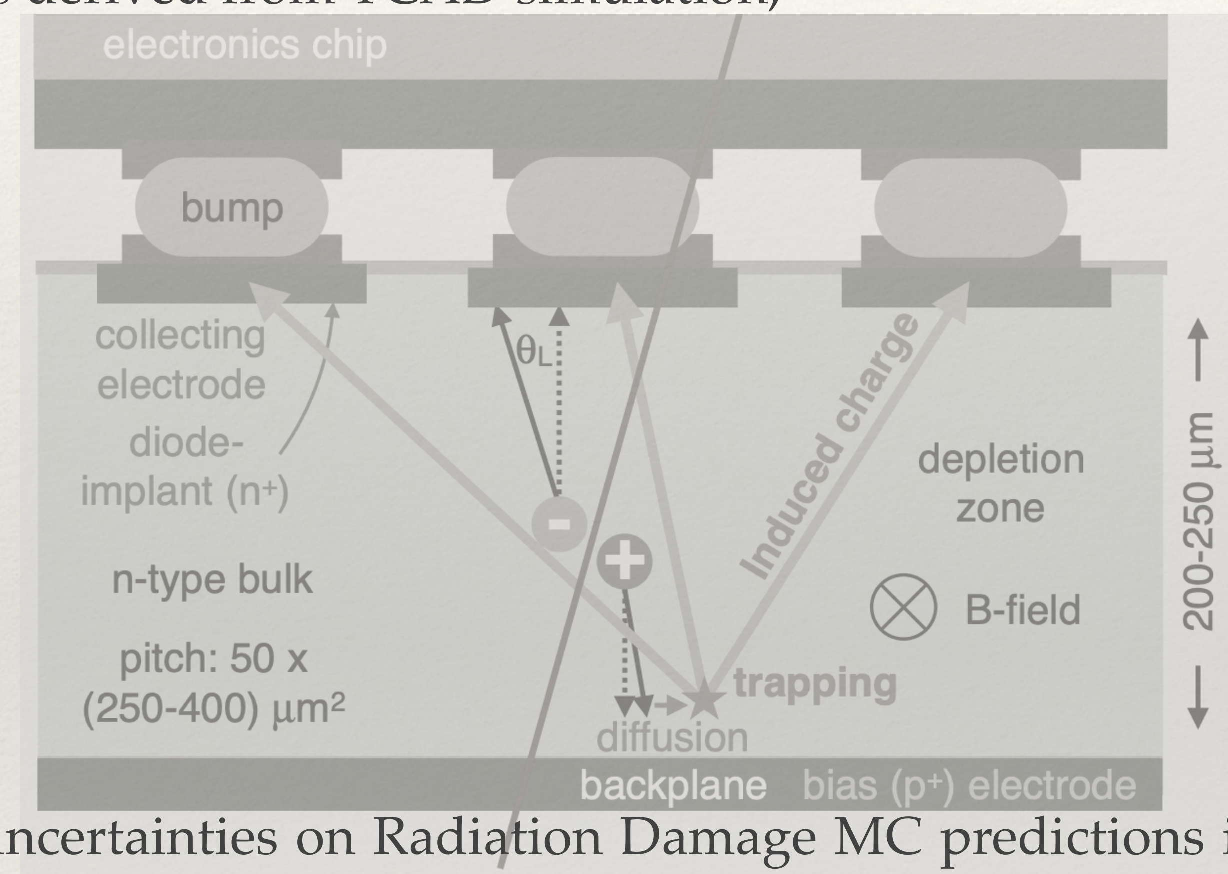
JINST 15 (2020) P06023

Pixel Radiation Damage Simulation in ATLAS

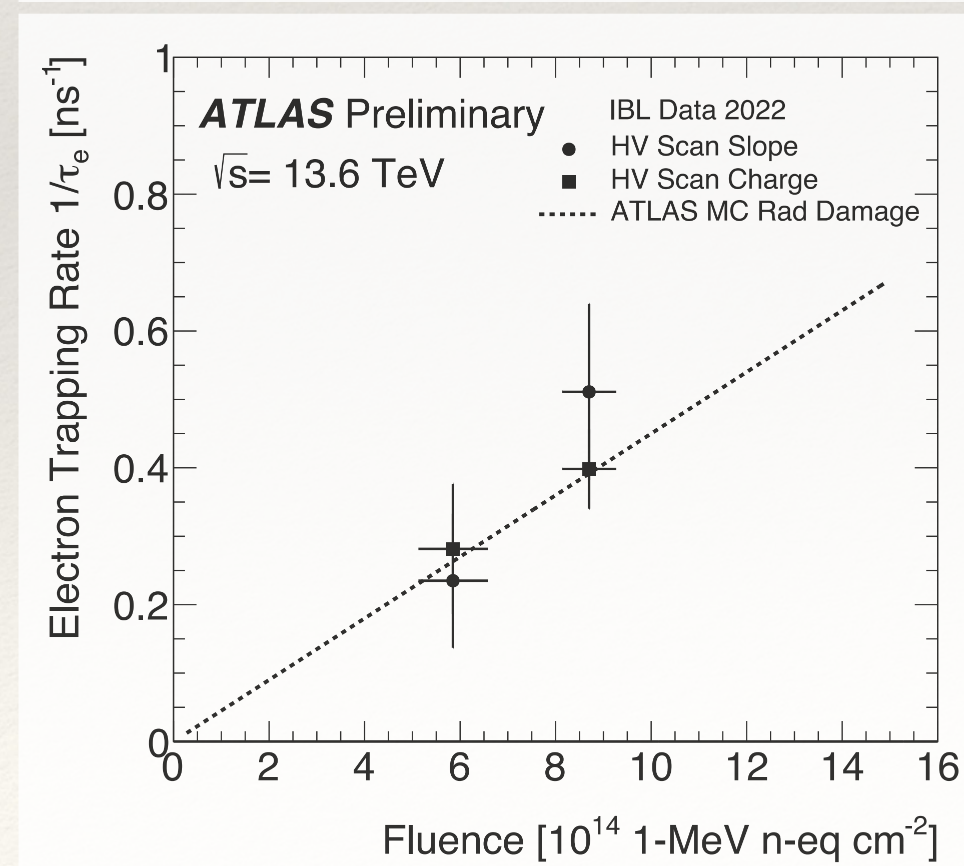
ATLAS developed radiation damage simulation based on realistic Si bulk E-field maps at different fluences and bias voltages adopted in official MC simulation;



Radiation damage digitiser calculates signal induced on read-out nodes by charge carriers produced by ionising particle energy losses modelled using Bichsel model;
E-field map, Lorentz angle and weighting potential based on inputs derived from TCAD simulation;



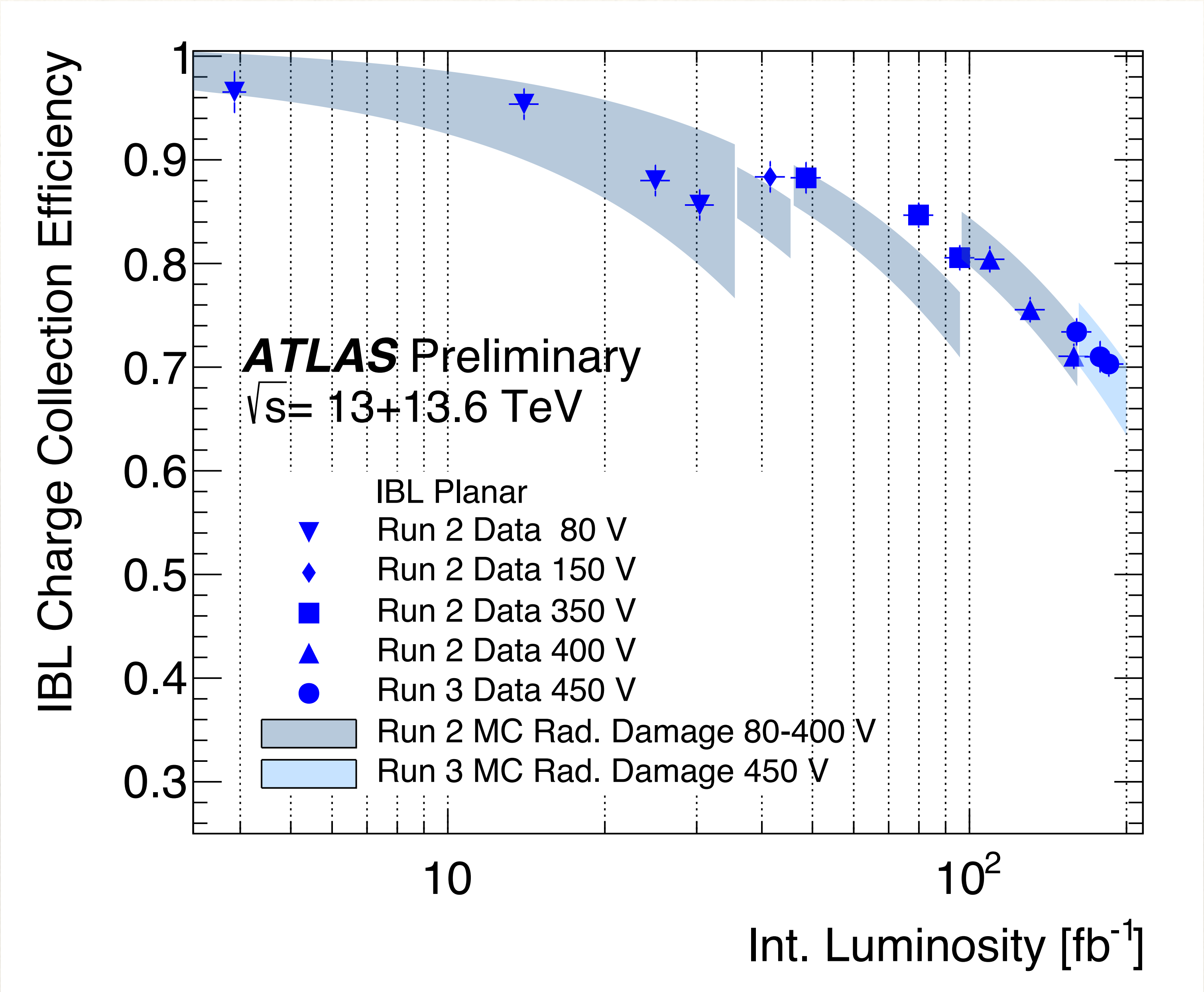
Main uncertainties on Radiation Damage MC predictions in terms of collected charge are due to conversion of integrated luminosity to n-eq fluence on sensor and electron trapping rate vs. fluence;



As fluence grows with delivered integrated luminosity,
E-field maps and predictions are updated:
Run 3 uses four different predictions corresponding to fluences at and pixel operating parameters for each data taking year;

Charge Collection Efficiency in Data and Radiation Damage MC: from Run 2 to Run 3

Charge collection efficiency as a function of integrated luminosity for IBL planar sensors for data and ATLAS radiation damage simulation since beginning of Run 2.



Degradation of performance is not only modelled but also mitigated by using radiation damage MC samples for training and tuning of pixel and track reconstruction algorithms.

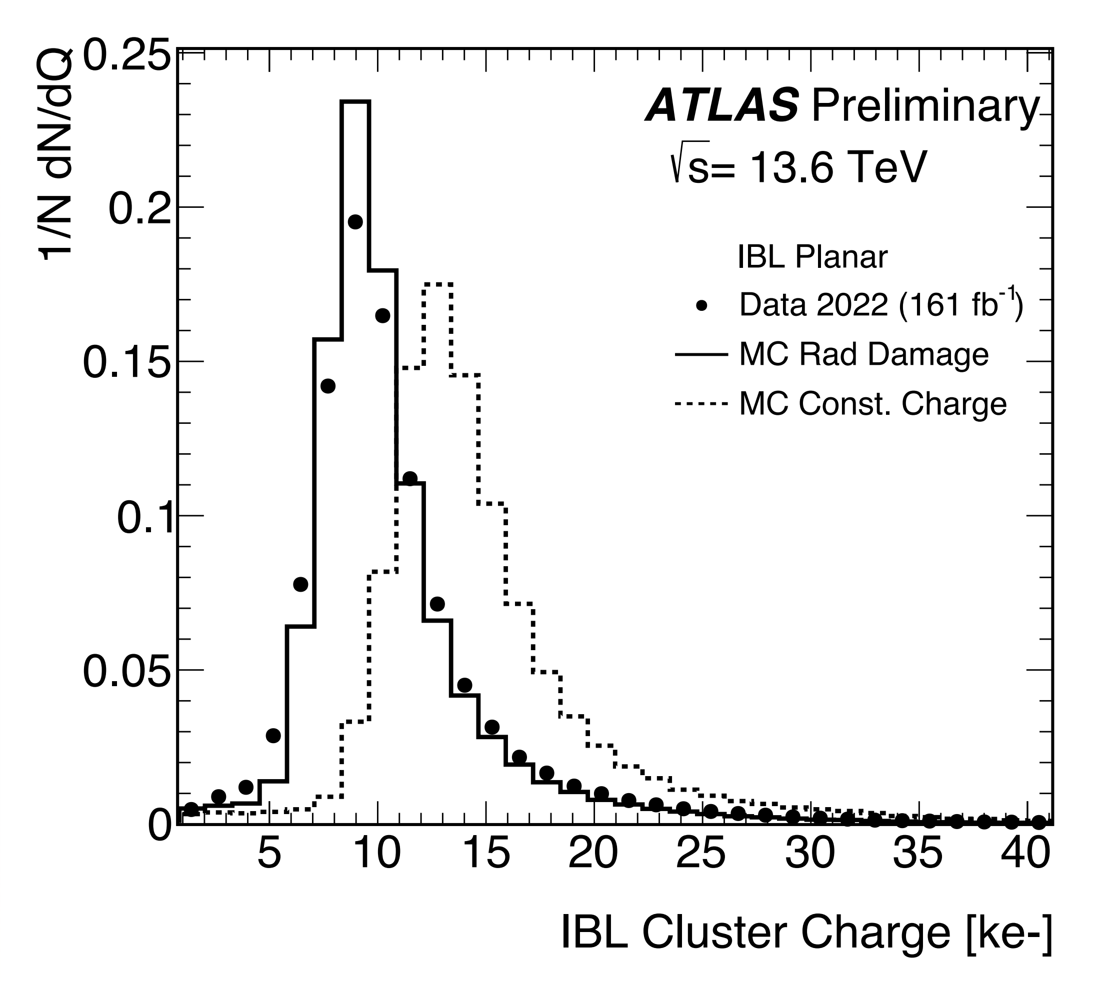
This partially recovers performance loss due to charge collection inefficiencies and corrects for distortions due to charge collection dishomogeneities.

ATLAS Pixels in Run 3: Charge Collection Properties

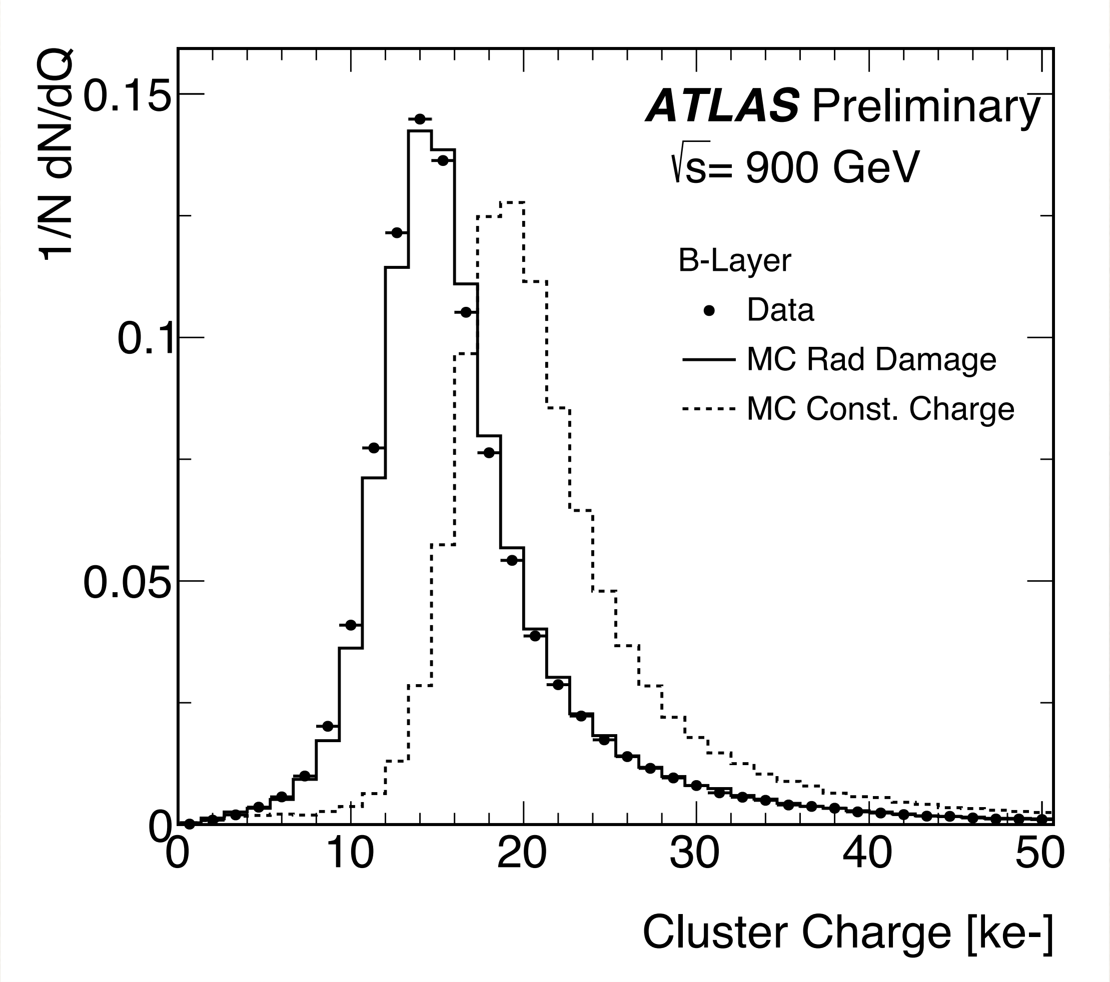
Modifications of charge collection properties are main effects of bulk radiation damage;

Radiation damage validation looks at detailed indicators of pixel response from cluster charge distribution and m.p.v. to their variation with HV bias voltage, charge collection efficiency as a function of depth and Lorentz angle of deflection of charge carriers drifted in the solenoidal field:

IBL Cluster charge corrected by particle path in Si



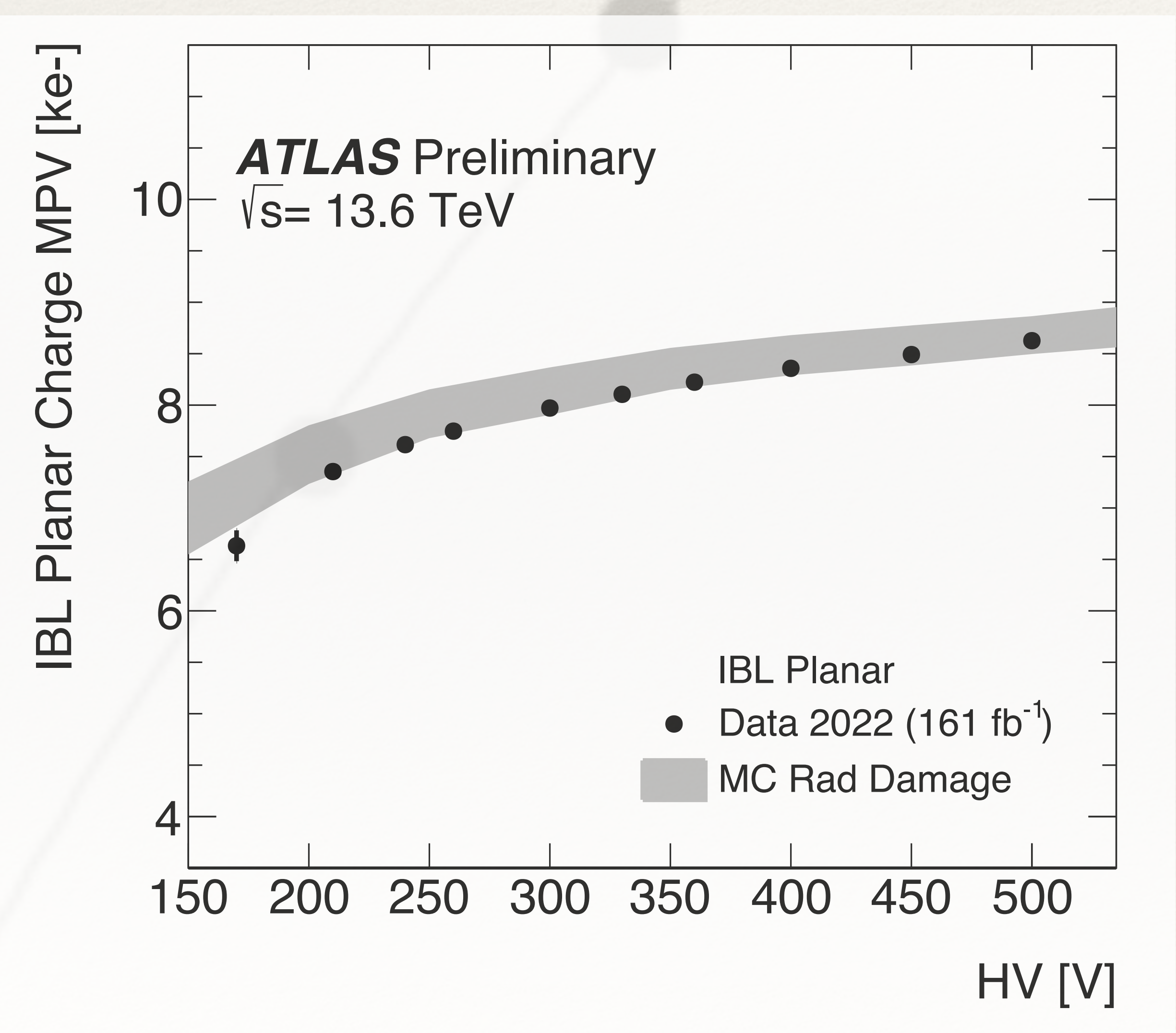
BL Cluster charge corrected by particle path in Si



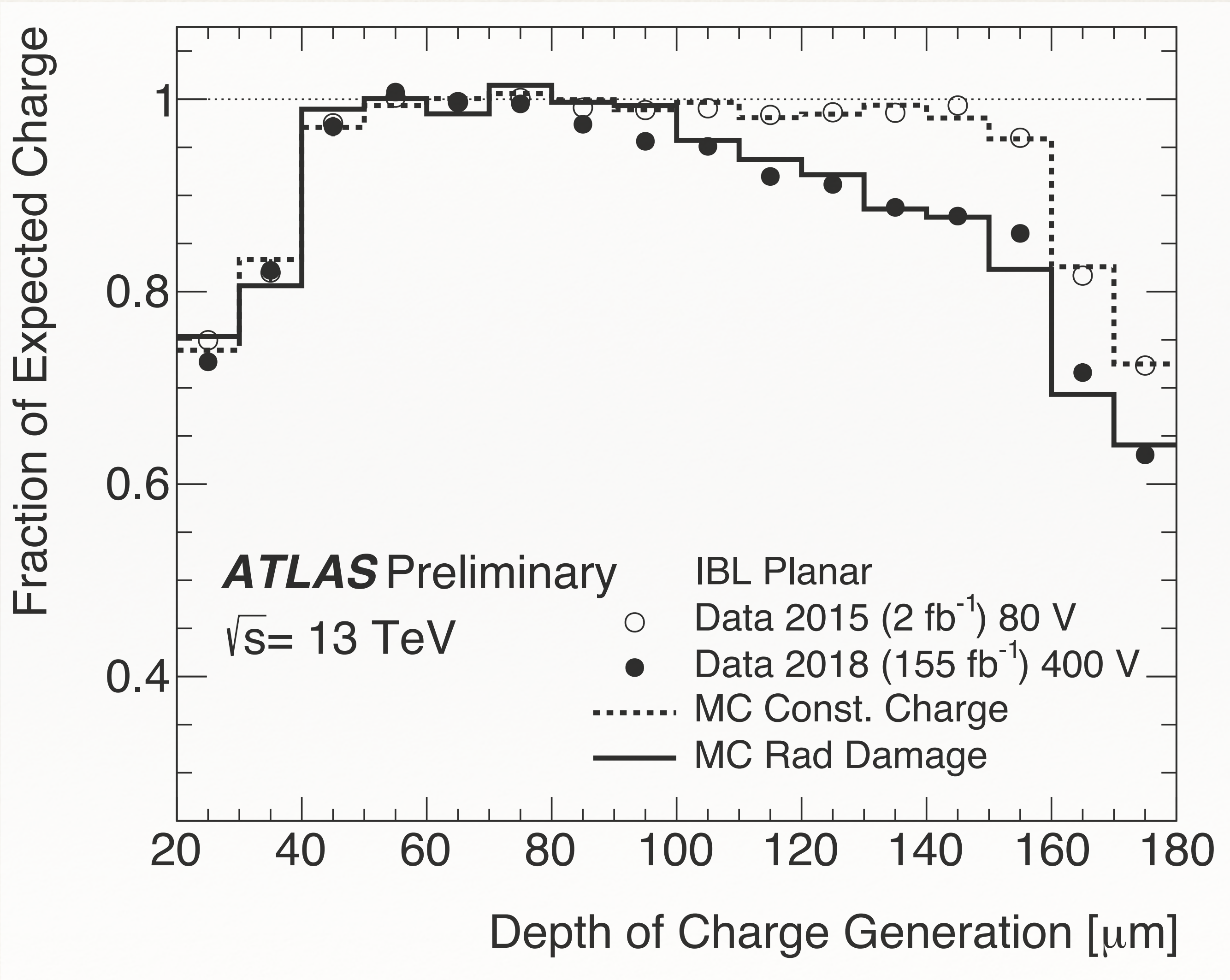
ATL-PHYS-PUB-2022-033

Indicators are important for determining performance in terms of pixel hit efficiency and spatial resolution.

Evolution of cluster charge m.p.v. vs. bias voltage on data collected in HV scan and rad damage MC. Operating in regime above depletion allows to gain charge collection efficiency, since higher electric field reduces charge trapping effects in damaged Si bulk. Data to radiation damage MC shows good agreement also below depletion voltage (~260 V):



Dependance of collected charge with depth of charge generation important for Lorentz angle and uniformity of hit position with particle angle of incidence. Measurement performed by comparing fraction of cluster charge deposited on pixels ordered from point of track entrance to exit from Si substrate to fraction of track segment below corresponding pixels to total track length in Si:

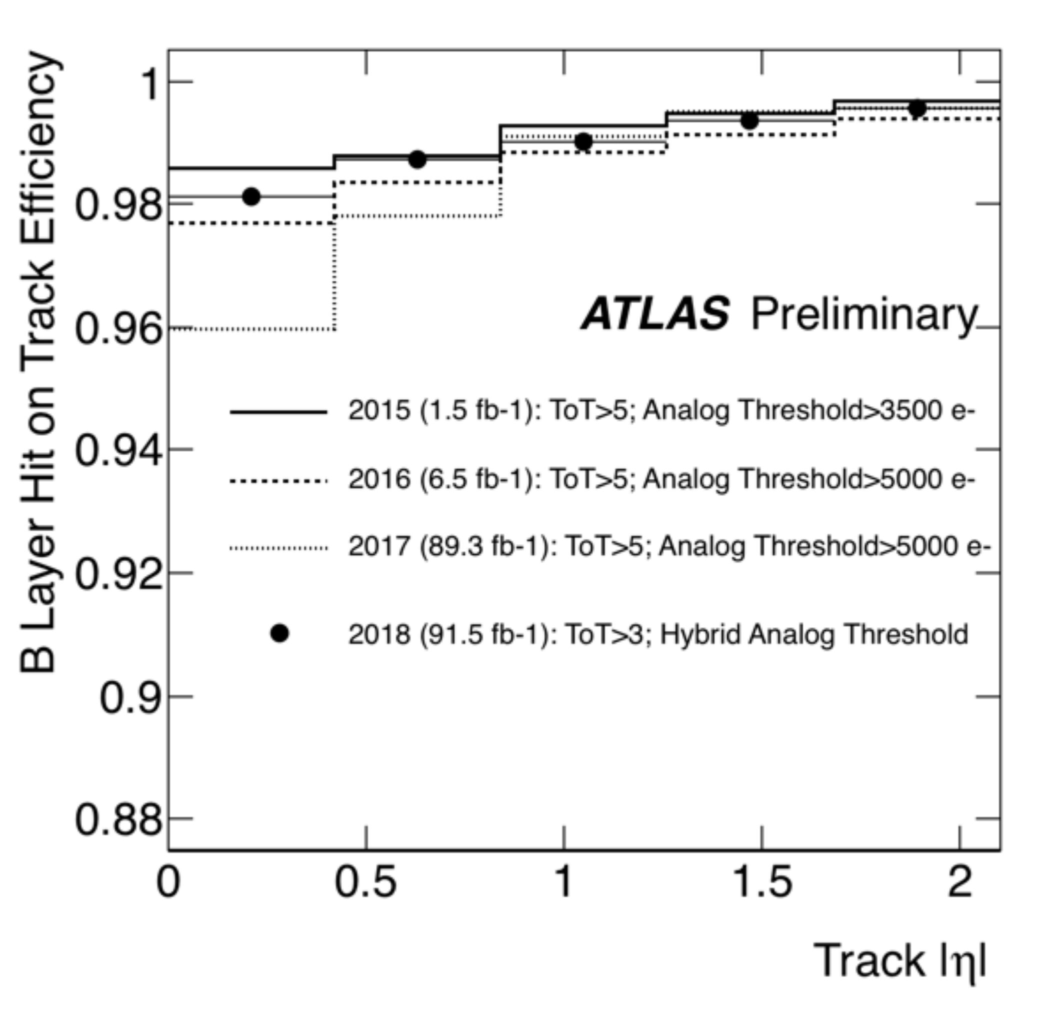


ATLAS Pixels Performance: Hit on Track Efficiency

Hit-on-track efficiency drives uniformity of performance of tracking and derived physics objects in time;

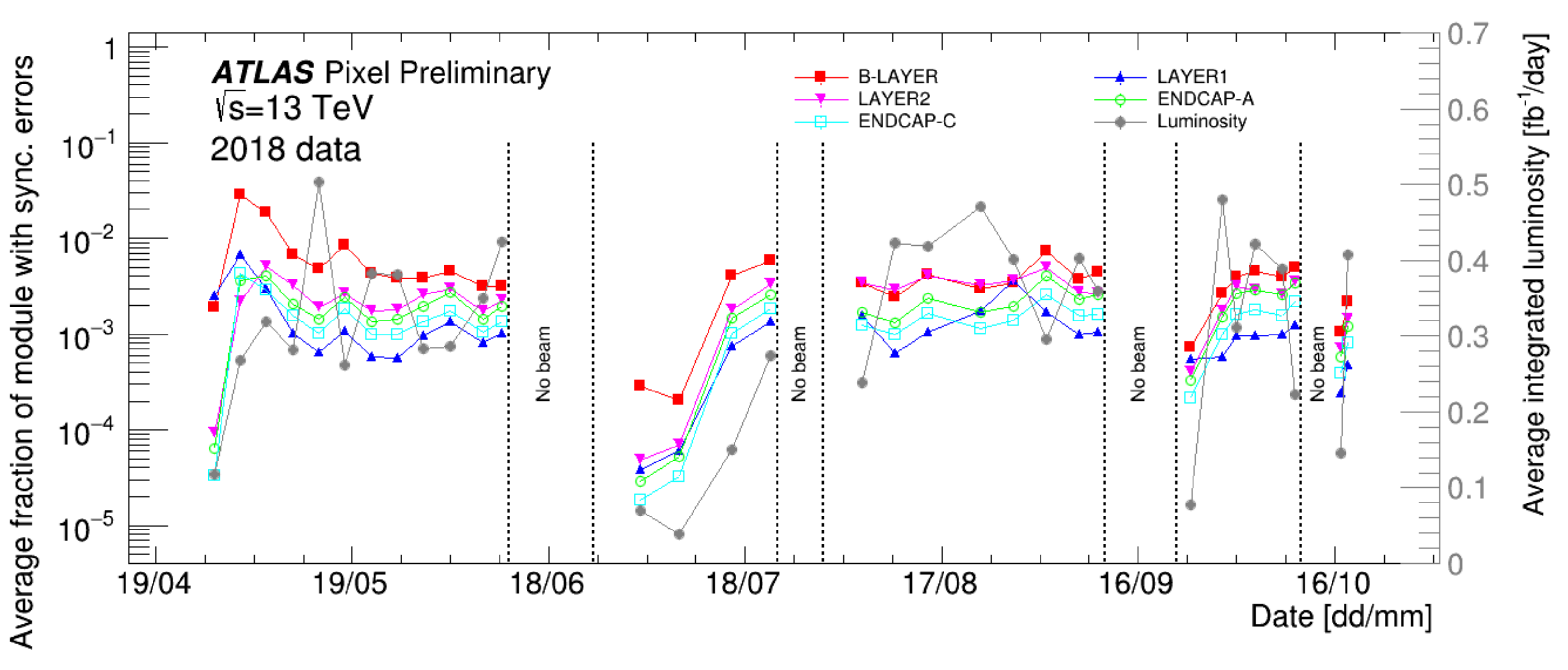
Regular optimisation of operating bias voltage and thresholds ensures uniform response of pixel clusters in terms of hit on track efficiency;

Drop in efficiency from start to end of Run 2 measured to be below 1% on all layers (see PIX-2020-003)



PIX-2016-012 (updated 2018)

Hit-on-track efficiency must be preserved in pixel operations under challenging LHC conditions inducing effects related to module de-syncronisation, bandwidth limitations, etc



PIX-2015-003 (updated 2018)

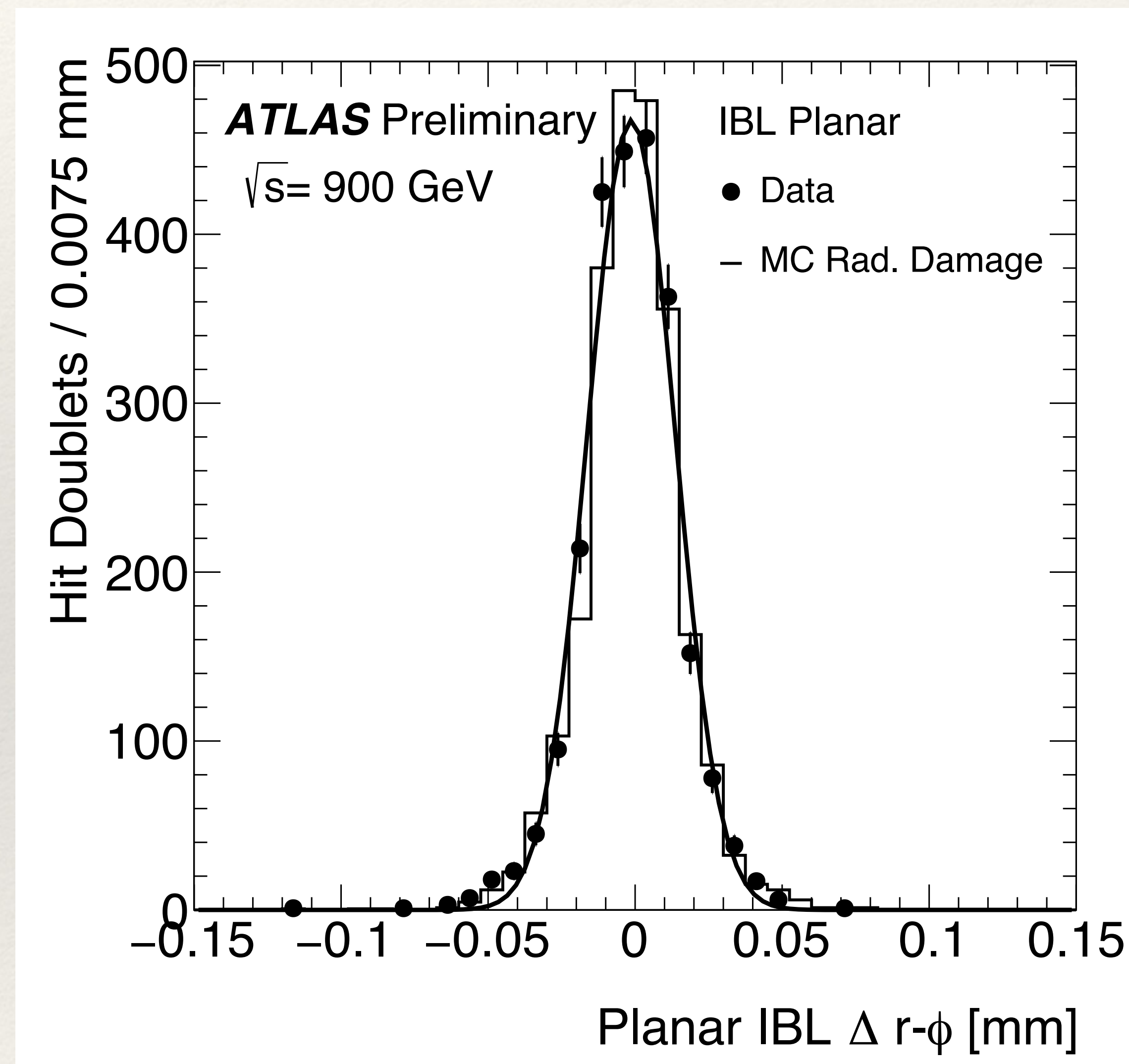
ATLAS Pixels Performance: IBL Hit Spatial Resolution

Spatial resolution extracted in active region of adjacent module overlaps in ϕ where particles generate hits on the two neighbouring modules. Distributions of corrected difference Δr-ϕ and Δz have widths is proportional to resolutions $\sigma_{r\text{-}\phi}$ and σ_z and depend only weakly on reconstructed track parameters and detector alignment:

Particle track traversing IBL overlaps

ATL-INDET-PUB-2016-001

IBL Hit Position Difference on Module Overlaps
2022 Data (161 fb^{-1})



ATL-PHYS-PUB-2022-033

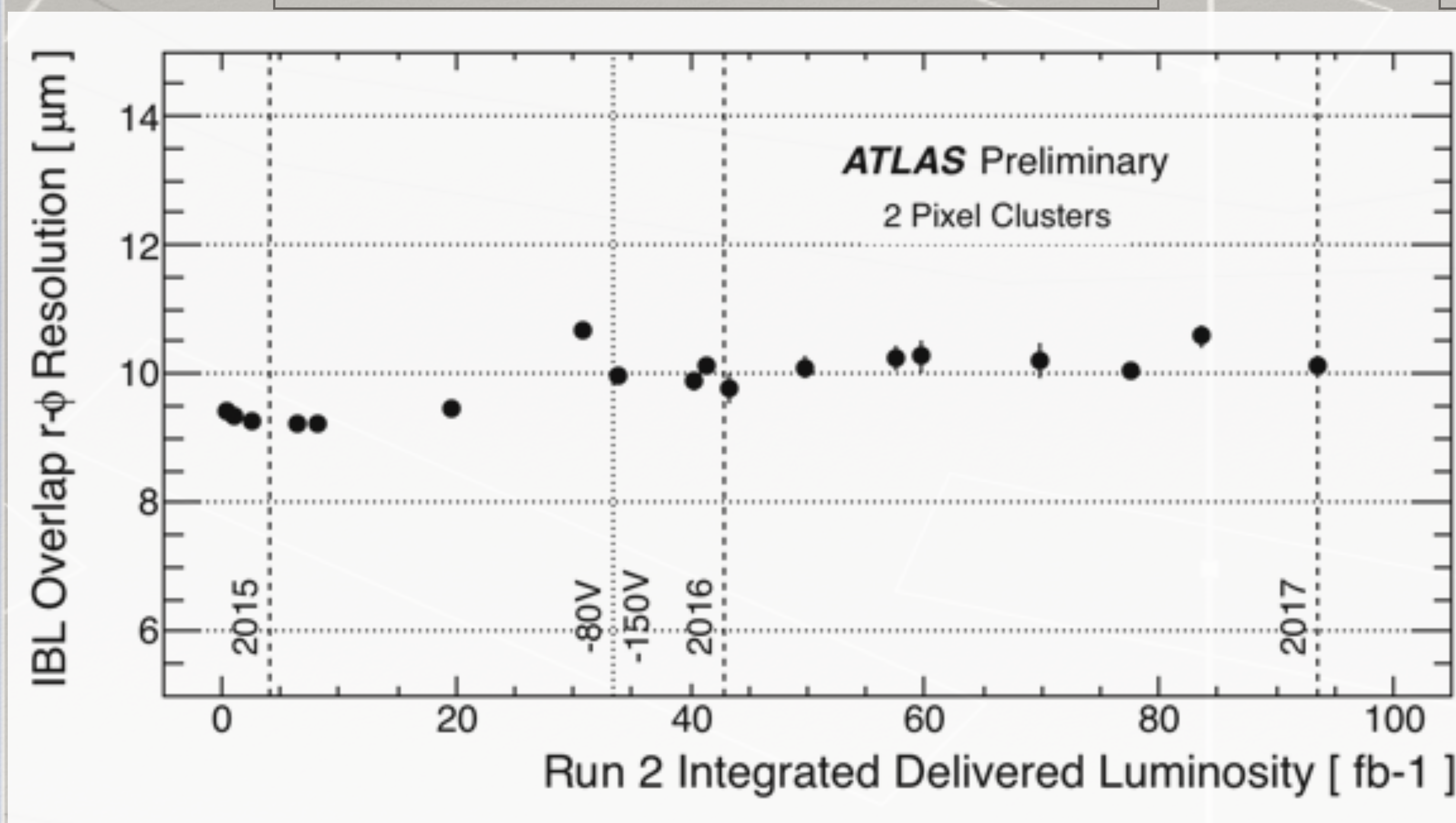
ATLAS Pixels Performance: IBL Hit Spatial Resolution

Pixel detector spatial resolution evolves with collected charge loss due to radiation damage effects. Impact on resolution is modest since pixel hit position in multi-pixel clusters depends on relative quantities (fraction of cluster charge shared between neighbouring pixels).

Degradation modelled by radiation damage MC predicts ~25% increase over a decade of operations, from Run 2 start to Run 3 end.

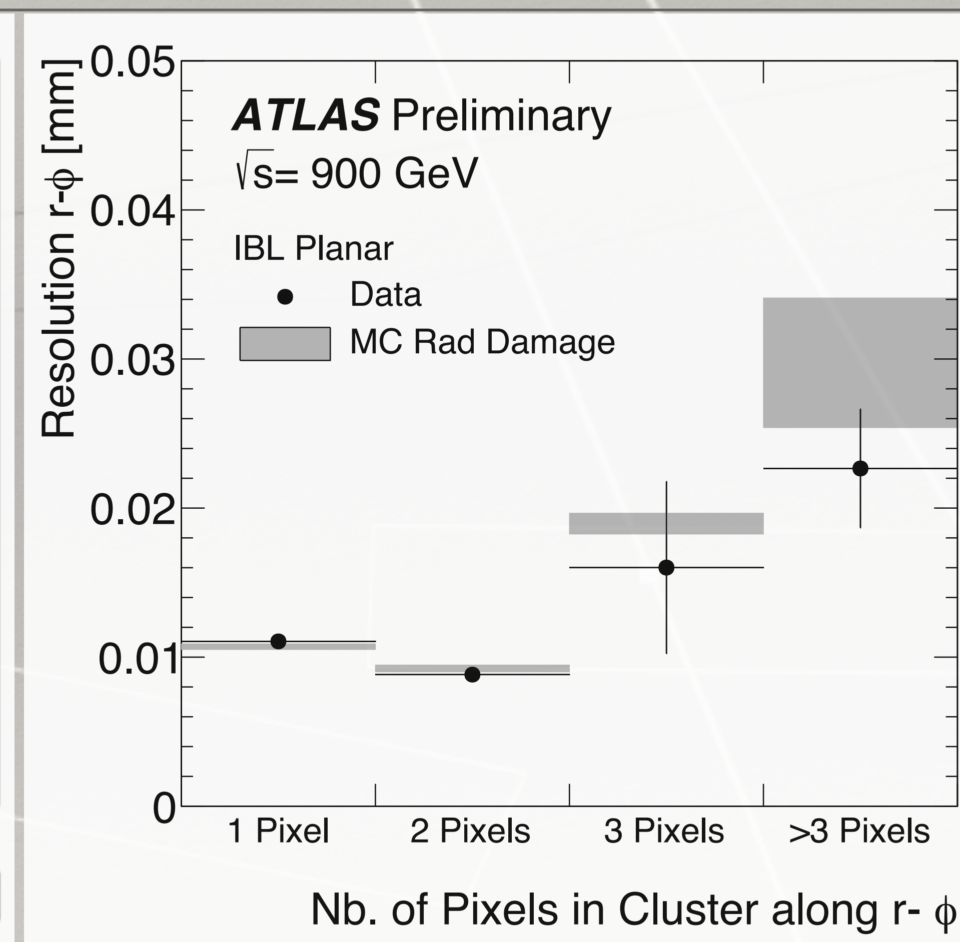
Further mitigated by improvement in resolution using Mixed Density Network trained on radiation damage MC (radiation-aware NN training).

IBL Hit Spatial Resolution in r-ϕ (50 μm pitch)
vs. Integrated Delivered Luminosity
2015-2017 Data



PIX-2018-002

IBL Hit Spatial Resolution in r-ϕ (50 μm pitch)
vs. nb of pixels in cluster along r-ϕ
2022 Data (161 fb^{-1})

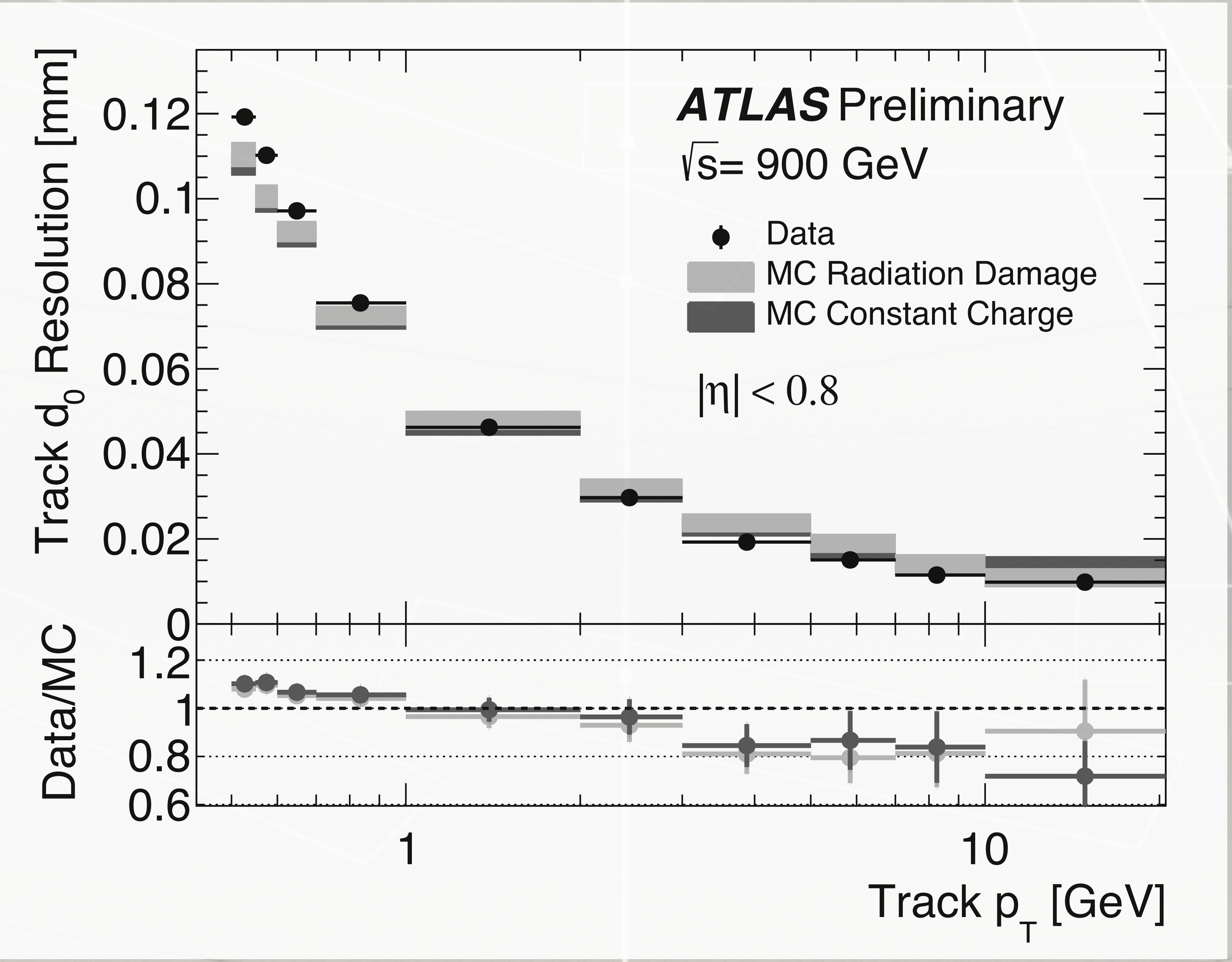


ATL-PHYS-PUB-2022-033

ATLAS Pixels Performance:
from IBL Hit Spatial Resolution to Track Extrapolation Resolution

Owing to its position closest to IP and 250 μm pitch in z (compared to 400 μm), IBL carries largest weight in determining extrapolation to PV for particles of low-to-moderate p_T tracks;

Impact of radiation damage of track extrapolation resolution still marginal:



ATL-PHYS-PUB-2022-033

ATLAS pixels started operating in Run 3 with parameters optimised to mitigate effects of radiation damage and boost tracking performance.

ATLAS simulation includes by default new radiation damage pixel digitiser accounting for detailed radiation effects in Si bulk. This simulation is used both to understand and predict impact of radiation damage on pixel response and to understand their effect on physics objects (tracks, secondary vertices, …);

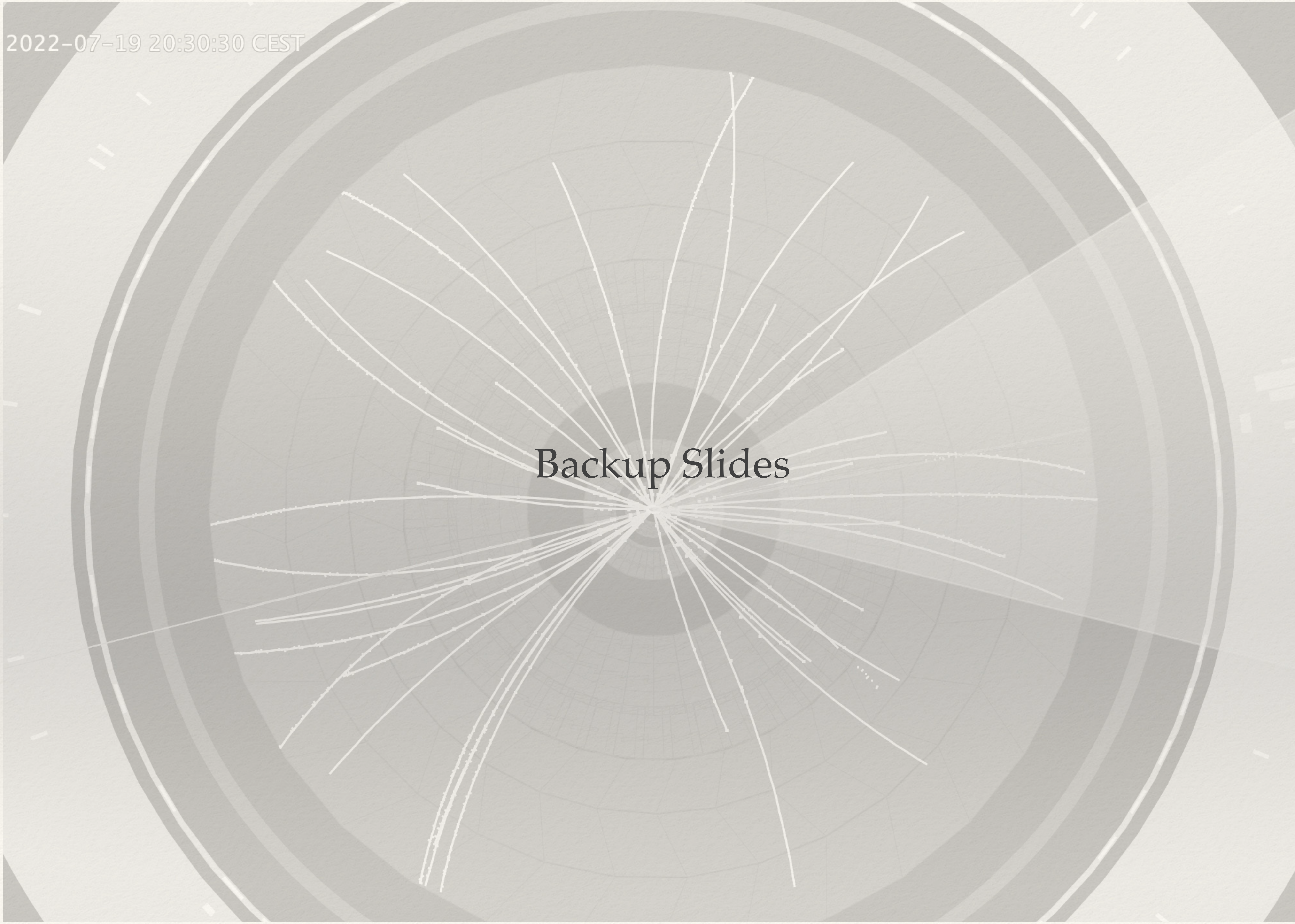
New radiation damage MC gives very good description of the pixel response down to details of charge collection properties;

Efficiency for pixel hit on track kept constant thanks to increase of bias voltage and decrease of analog thresholds on innermost layers;

Mixture Density Network trained on simulated samples generated with radiation damage MC and used for determining spatial position of pixel hits and their resolution in track reconstruction provides improved performance compared to NN used in Run 2, offsetting radiation damage effects on resolution;

In track reconstruction, where radiation damage effects are still tiny, new Run 3 pixel operational parameters and adoption of new MDN has made it possible to achieve performance improvements compared to end of Run 2.

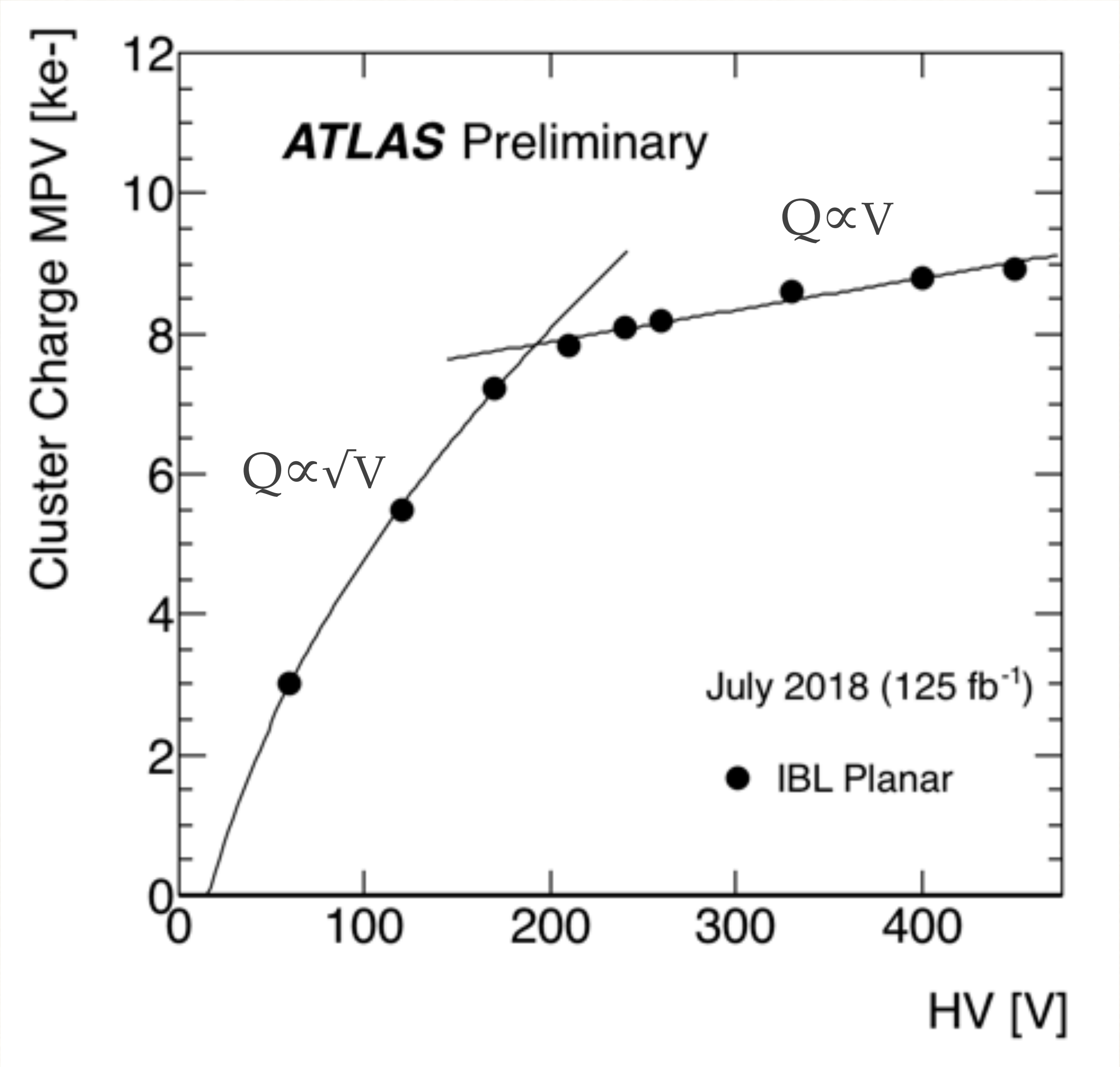
ATLAS Pixels have just concluded a successful run of operation both in terms of performance for physics and of understanding and modelling of radiation damage effects.

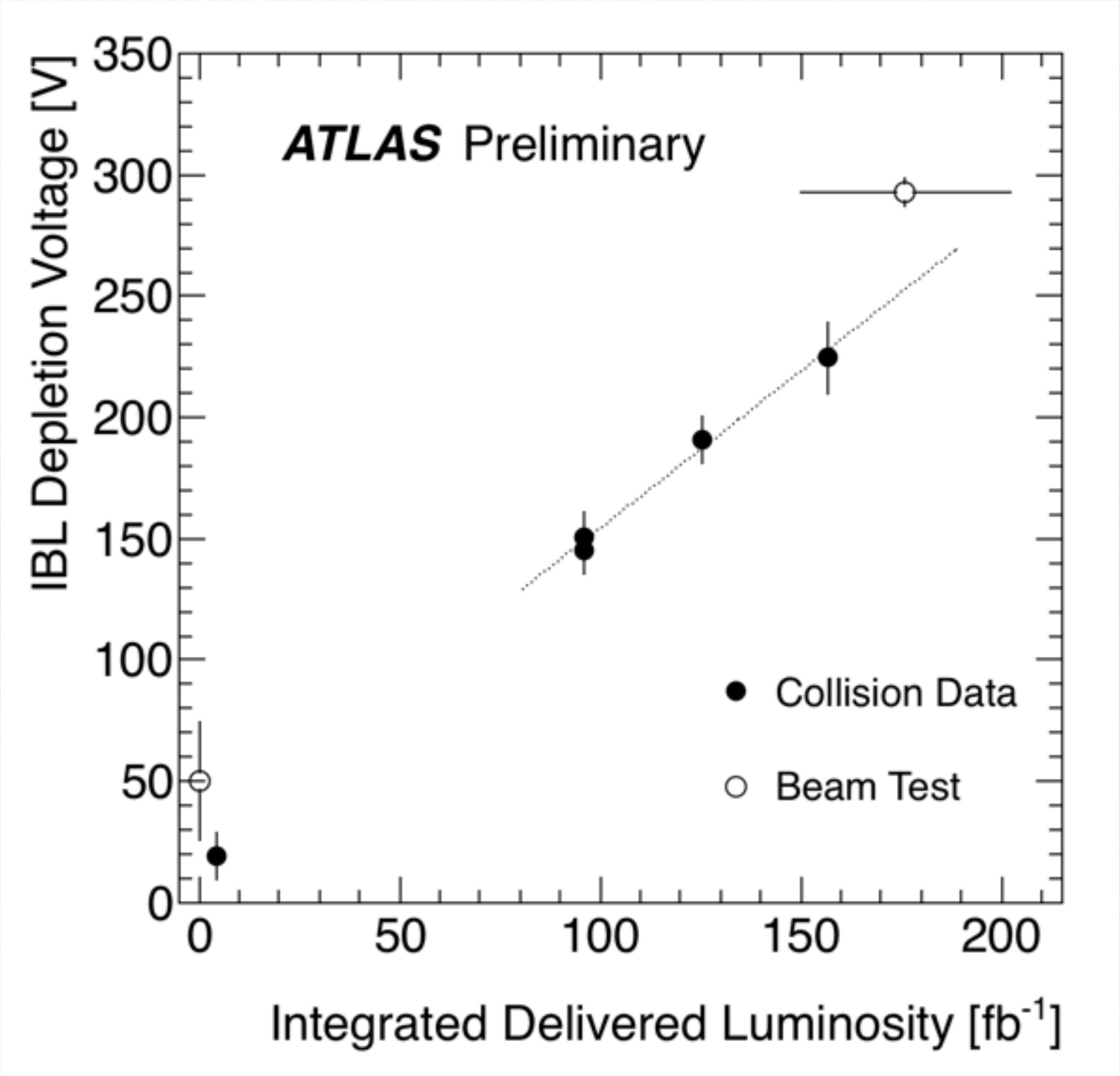


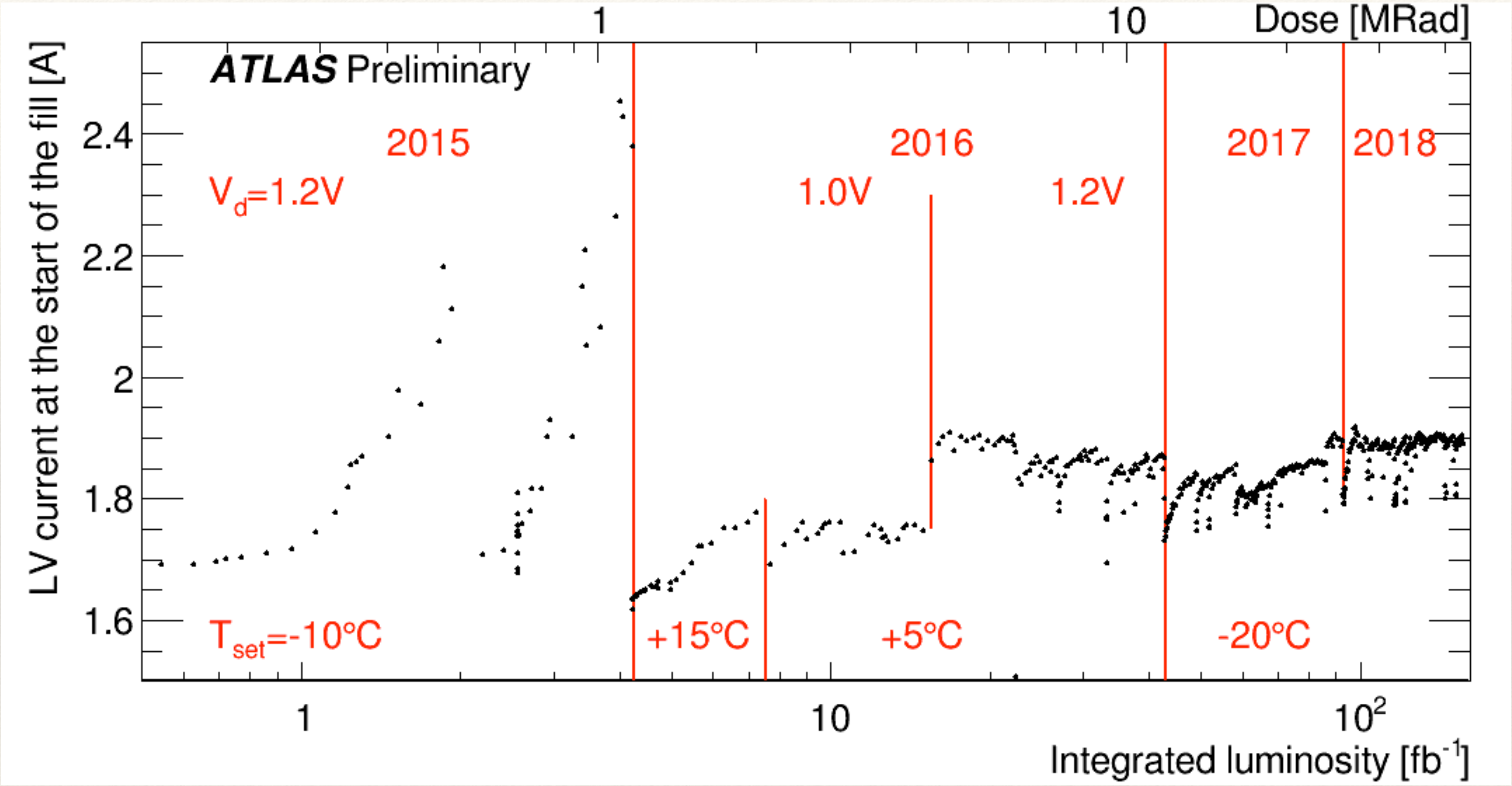
Backup Slides

ATLAS Pixels in Run 3:
Charge Collection Properties vs. Bias Voltage

For undamaged detectors collected charge increases ∝√V until Si bulk is fully depleted
In damaged Si bulk, amount of collected charge continues to increase ∝V above point of full Si depletion due to reduction of charge trapping effects with increasing charge carrier velocity.
Depletion voltage defined as voltage value at the transition between the ∝√V and ∝V regimes:

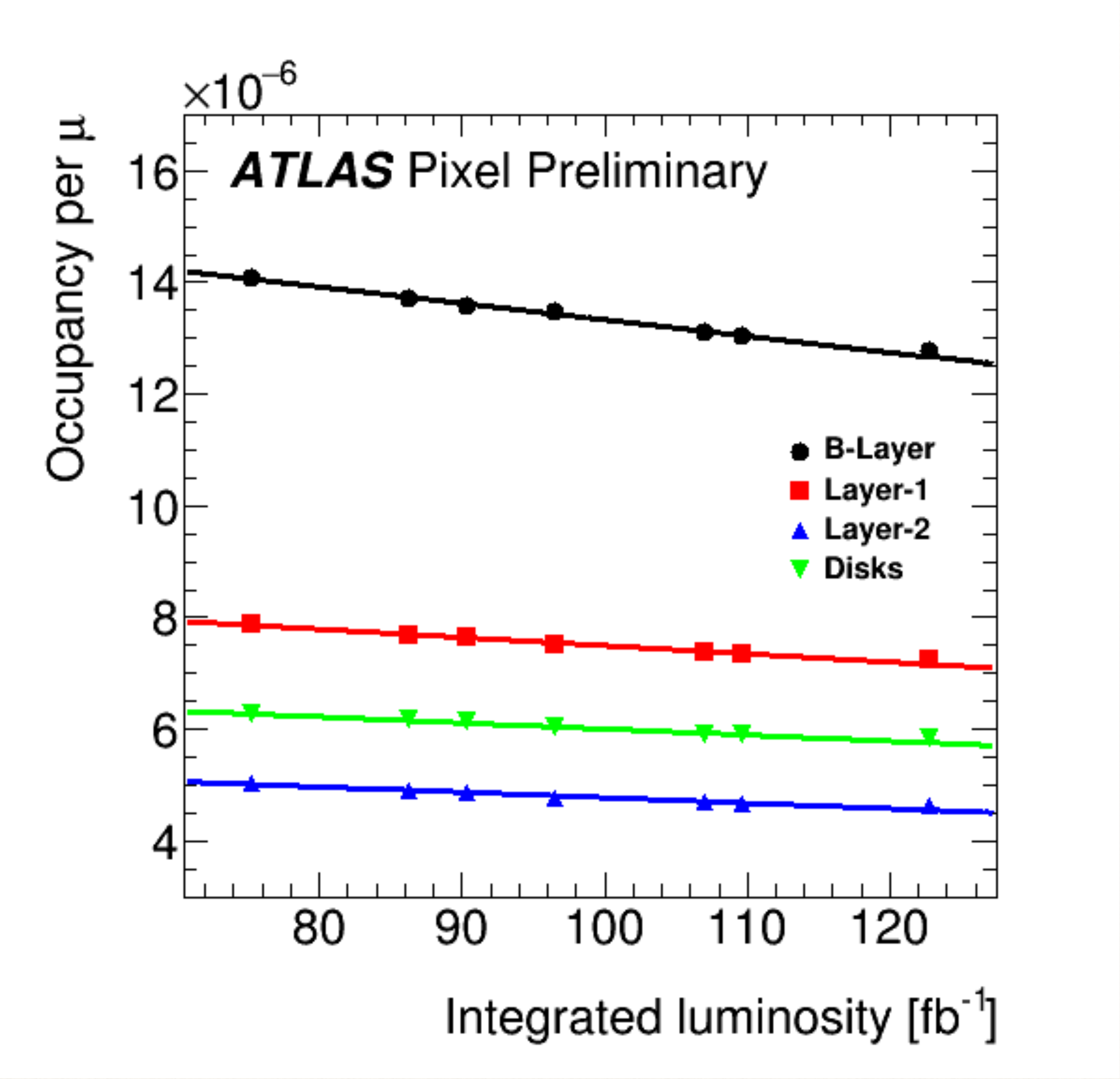




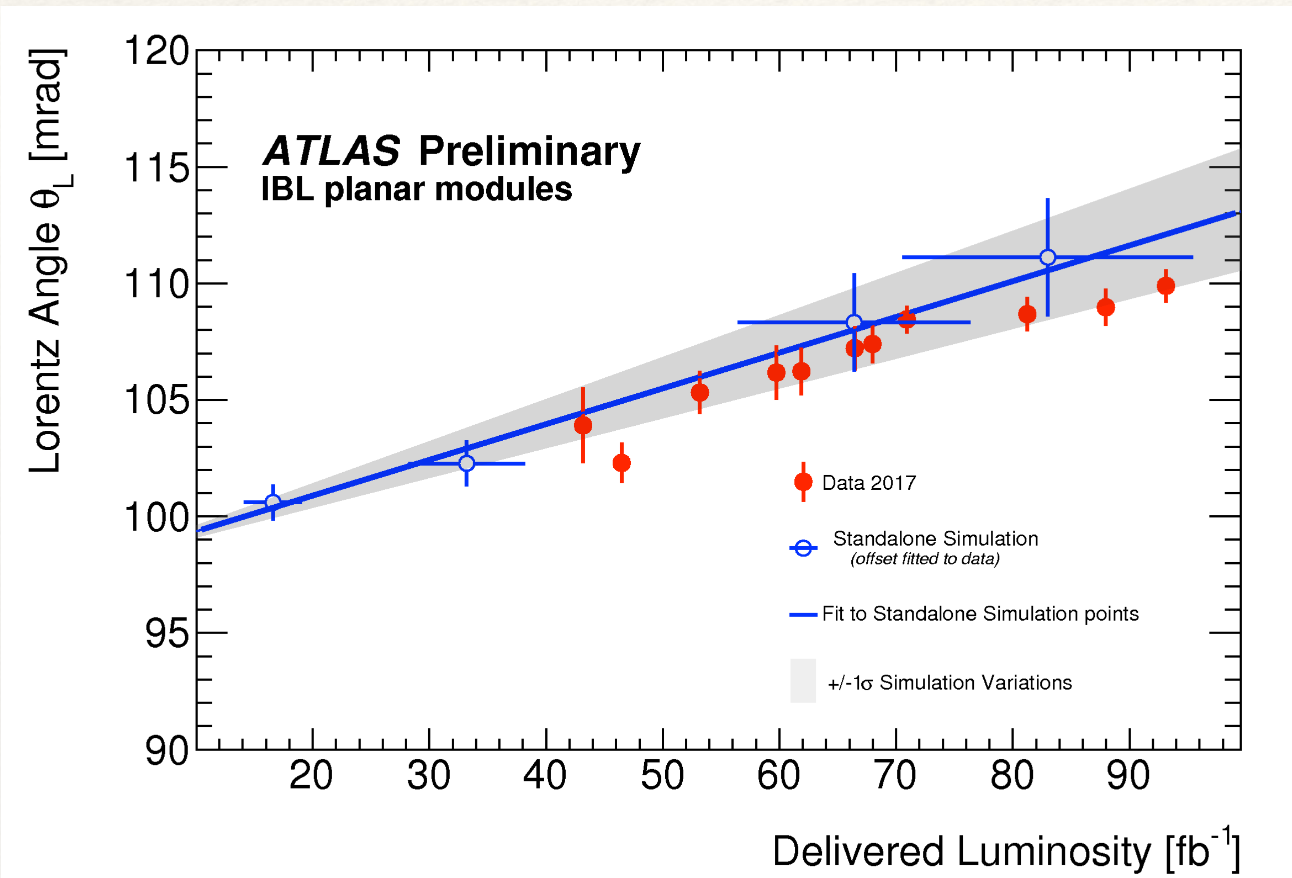


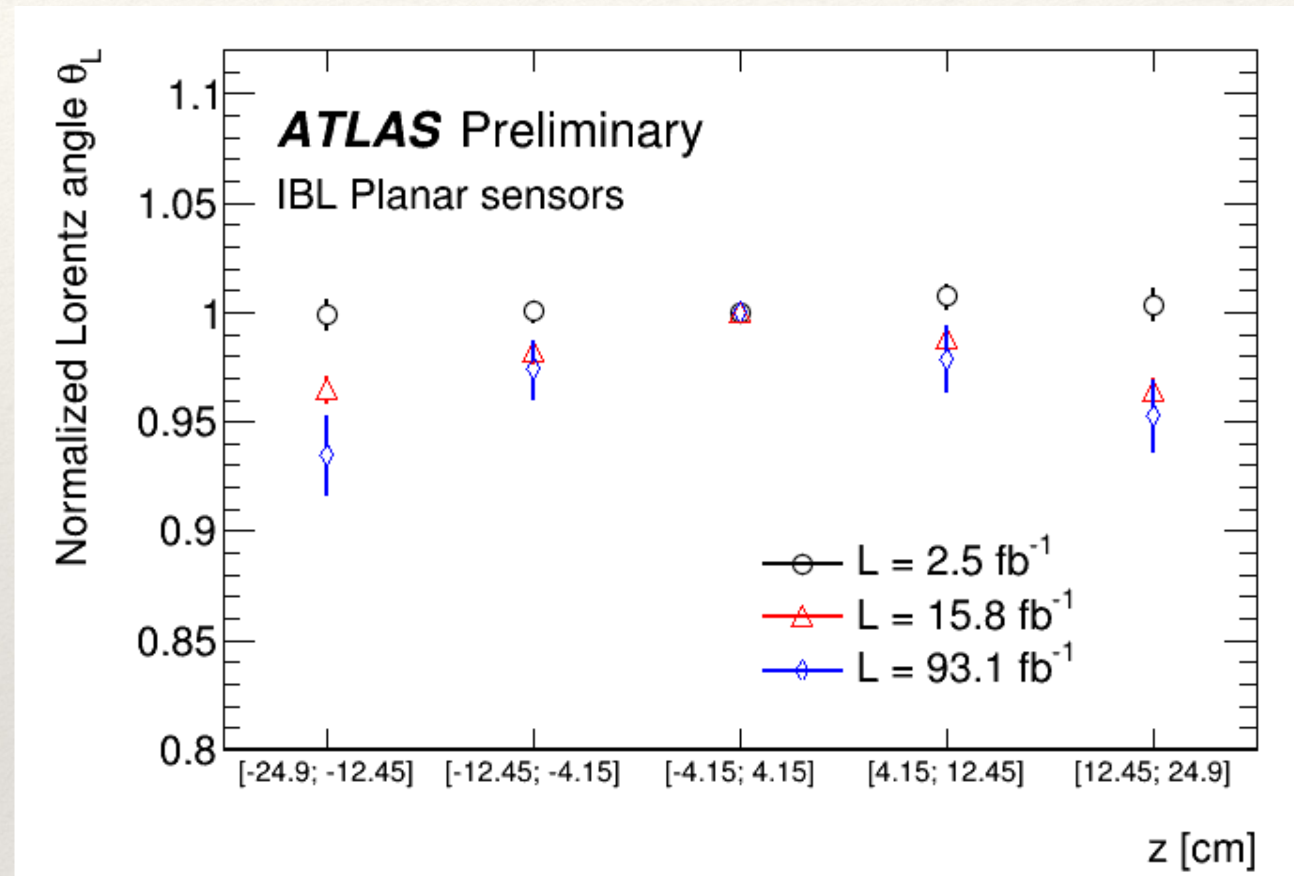
Dose [MRad]
1
10
ATLAS Preliminary
LV current at the start of the fill [A]
2.4
2.2
2
1.8
1.6
2015
2016
2017
2018
V$_d$=1.2V
1.0V
1.2V
T$_{set}$=-10°C
+15°C
+5°C
-20°C
1
10
10^2
Integrated luminosity [fb^{-1}]

PIX-2020-004

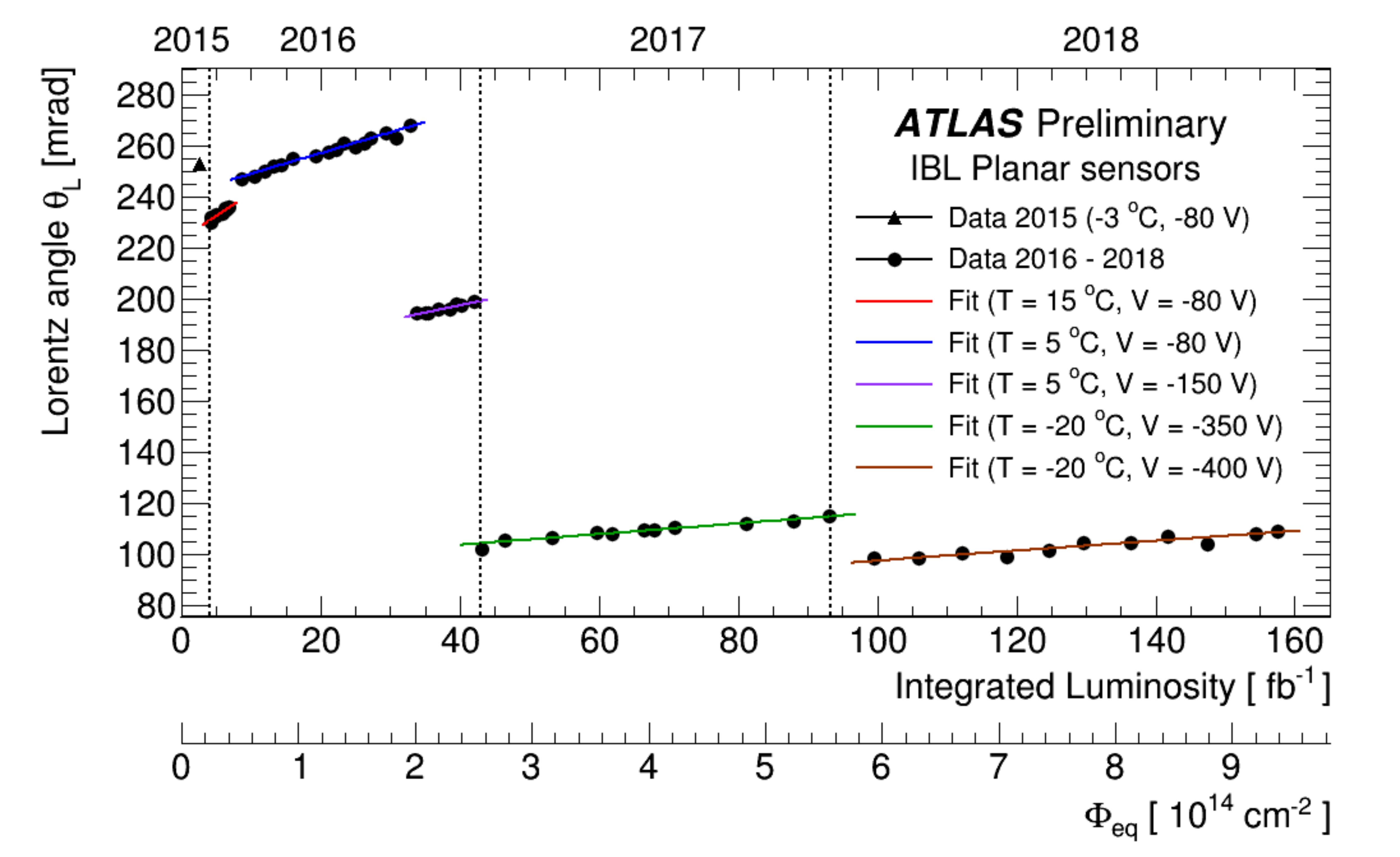

×10⁻⁶
ATLAS Pixel Preliminary
Occupancy per μ
16
14
12
10
8
6
4
B-Layer
Layer-1
Layer-2
Disks
80
90
100
110
120
Integrated luminosity [fb⁻¹]

PIX-2017-008





ATL-PIX-2017-005



ATL-PIX-2017-005