# ATLAS Pixel Detector Leakage Current

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# Introduction

- First report of leakage current data in the ATLAS Pixel Detector B-Layer, Layer-1, Layer-2 and the 2×3 Disks in LHC Run 2 through Nov. 2017
  - Also shown are the LHC Run 1 leakage current data
- Comparison of fluence predictions by Pythia8 and FLUKA to the fluence determined from leakage current data combined with the Hamburg Model* is made for B-Layer, Layer-1, and Layer-2
- Further investigations of fluence predictions for the IBL are made using various Pythia 8 minimum bias tunings combined with FLUKA and Geant 4

* M. Moll et al., Leakage Current of Hadron Irradiated Silicon Detectors - Material Dependence. Nucl. Instrum. Meth. A , 426(87), 1999.

# Introduction (II)

- Predictions have been made with the Hamburg Model and were found to underestimate the leakage current data throughout LHC Run 2 for B-Layer, Layer-1, and Layer-2
- Hamburg Model predictions were found to overestimate the leakage current data in the IBL

# Expectations of the Measurement

- Leakage current in silicon sensors is an indicator of received fluence and radiation damage

$$\Delta I = \alpha \cdot \Phi \cdot V$$

  - Here, $\Delta I$ is the difference in leakage current at fluence $\Phi$ relative to the value before irradiation of the physical volume V, and  is the current-related damage coefficient $\alpha$
- The ATLAS measured leakage current grows linearly with delivered luminosity and demonstrates various annealing responses to temperature changes as expected

# Measurement Procedure Details

- Measurements of Run 1 leakage current use the HVPP4 data collection subsystem as reported in the Run 1 ATLAS note*
- LHC run 2 leakage current measurements are made using HVPP4 data with power supply leakage current data to confirm and augment the measurement
- The leakage current data are restricted to when high voltage is applied across the silicon sensors and when the LHC beams are declared stable

* ATLAS Collaboration, A leakage current-based measurement of the radiation damage in the ATLAS Pixel Detector, 2015 JINST 10(04) C04024, http://cdsweb.cern.ch/record/1752122/files/ATL-INDET-PUB-2014-004.pdf

# Further Measurement Procedure Details

- For both data and the Hamburg Model prediction, the leakage current is corrected to 0°C using the equation:

$$I(T) = I(T_R)/R(T), \text{ where } R(T) = (T_R/T)^2 \cdot \exp\left( -\frac{E_{eff}}{2k_B}(1/T_R - 1/T)\right)$$

- The silicon activation energy is assumed to be $E_{eff} = 1.21$ eV [†]

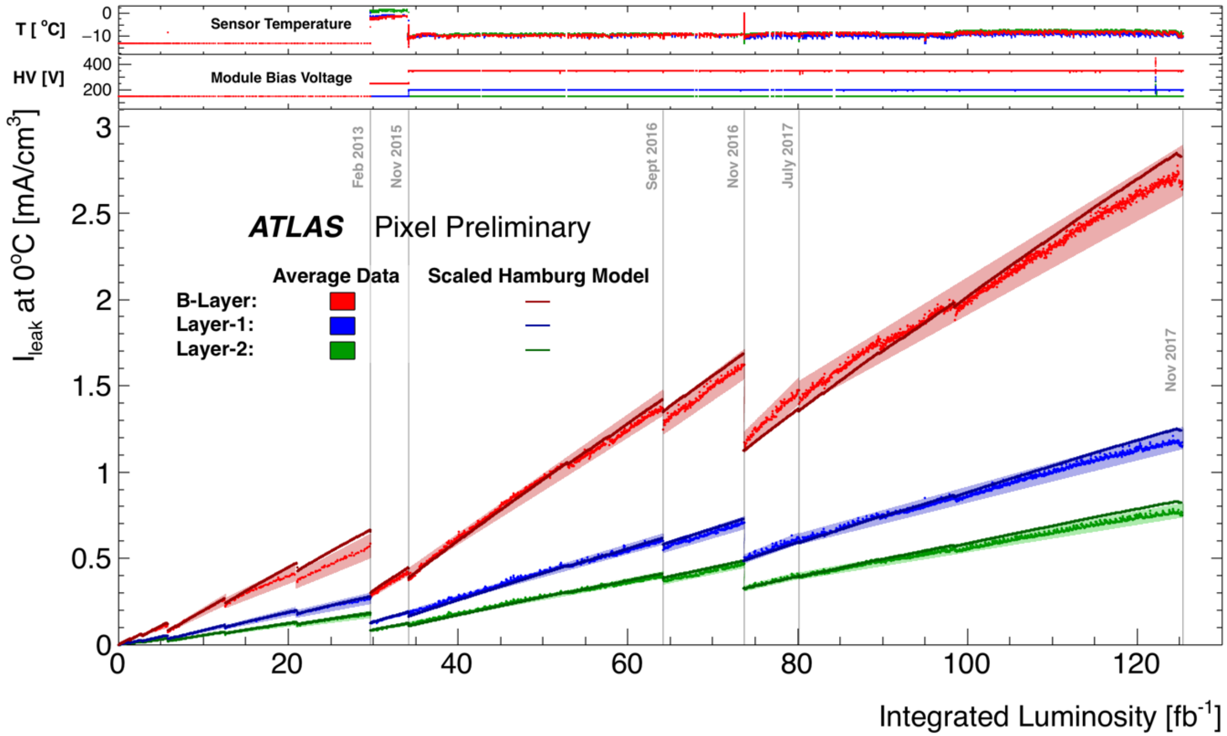
[†] A. Chilingarov, Temperature Dependence of the Current Generated in Si bulk, 2013 JINST 8(10) P1000, http://iopscience.iop.org/article/10.1088/1748-0221/8/10/P10003

# Hamburg Model Predictions

- Hamburg Model predictions are made in four bins in the barrel layers
- Luminosity to fluence conversions are made using the FLUKA simulation and have a symmetric z-dependence around the interaction point
- The predictions are fit to the data with a luminosity–to-fluence factor in each of the four bins and then averaged to compare to the average measurements.
  - Luminosity–to-fluence factors range from ~1.2 further from the interaction point in z to ~1.45 closer to the interaction point in z

# Leakage Current in Pixel Barrel

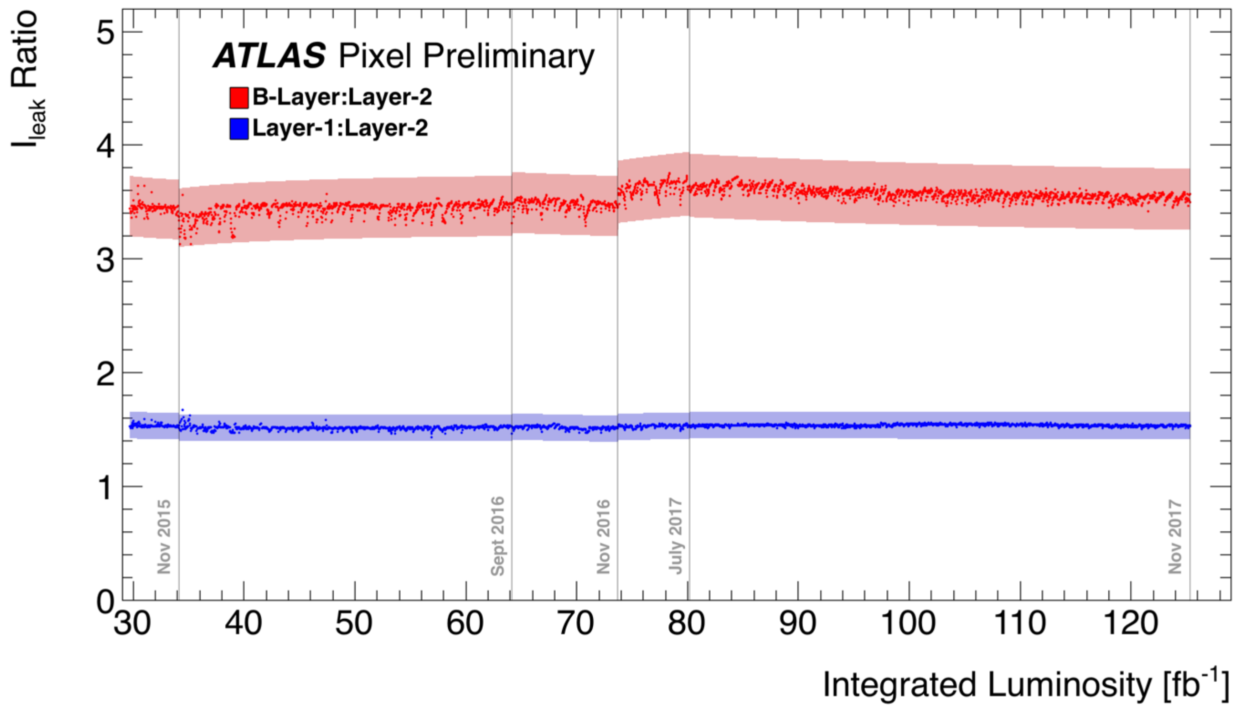
- Average leakage current data compared to the average scaled Hamburg Model predictions for each barrel layer through 2017
- The Hamburg Model predictions have been scaled to match the measured leakage current data




- Measurements on each layer are averaged over a representative sample of modules in η and $\phi$.
- The measurements are consistent with expected higher levels of radiation for sensors closer to the beam line.
- The Hamburg Model fit is qualitatively good over the entire range

# Ratios of Leakage Currents in Barrel Layers

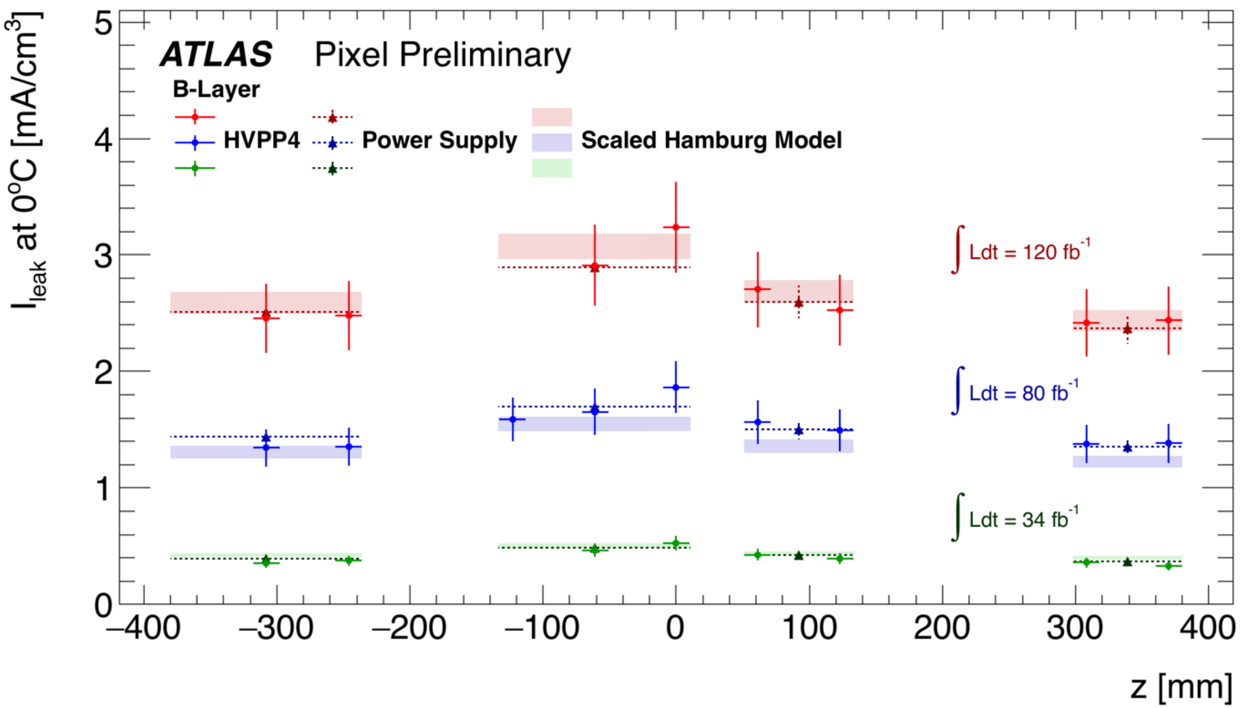
- Ratios of the various Pixel Detector barrel layer leakage current data for LHC Run 2
- Some dates corresponding to extended periods when the LHC beam was off are displayed for reference.




- The ratios are expected to be flat
- The vertical axis is proportional to the ratio of the applied fluence

# B-Layer Z-binned Leakage Current

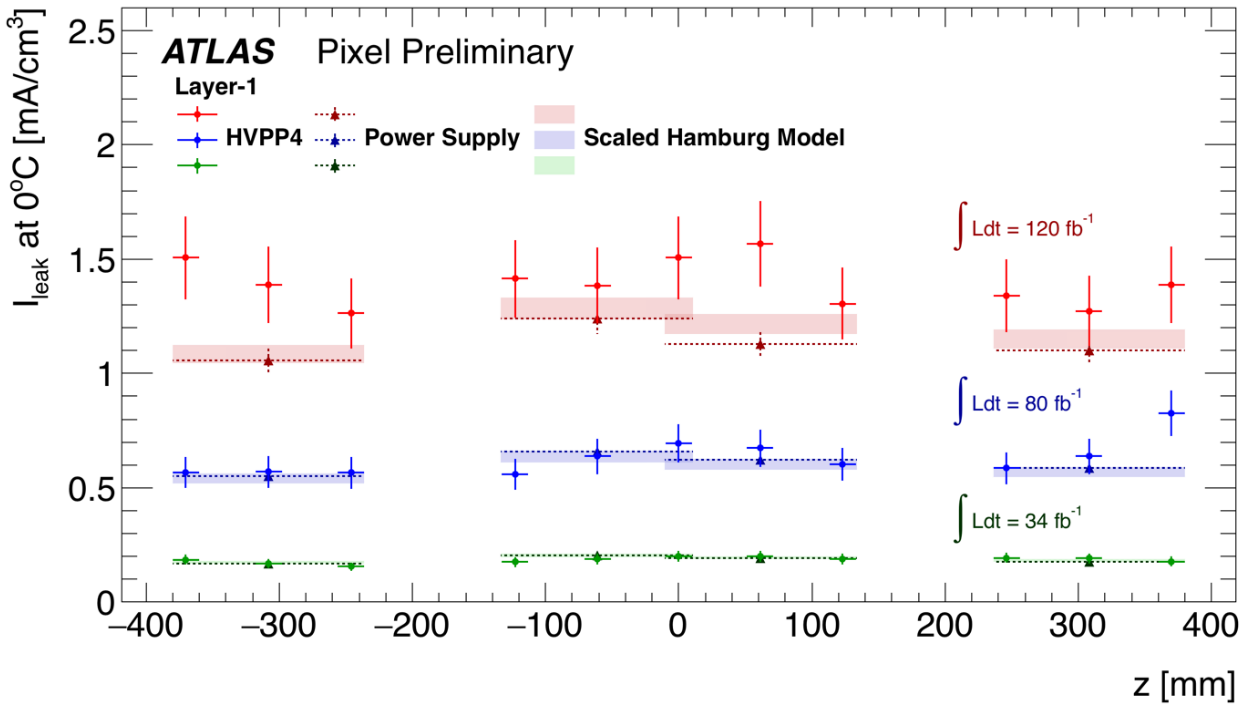
- Z-binned **B-Layer** leakage current data at three values of integrated luminosity.
- Single module precision is shown with HVPP4 data and multiple module precision is shown with the power supply leakage current data




- The z-dependent scaled Hamburg Model predictions are also shown
- We see agreement and consistency between measurement methods

# Layer-1 Z-binned Leakage Current

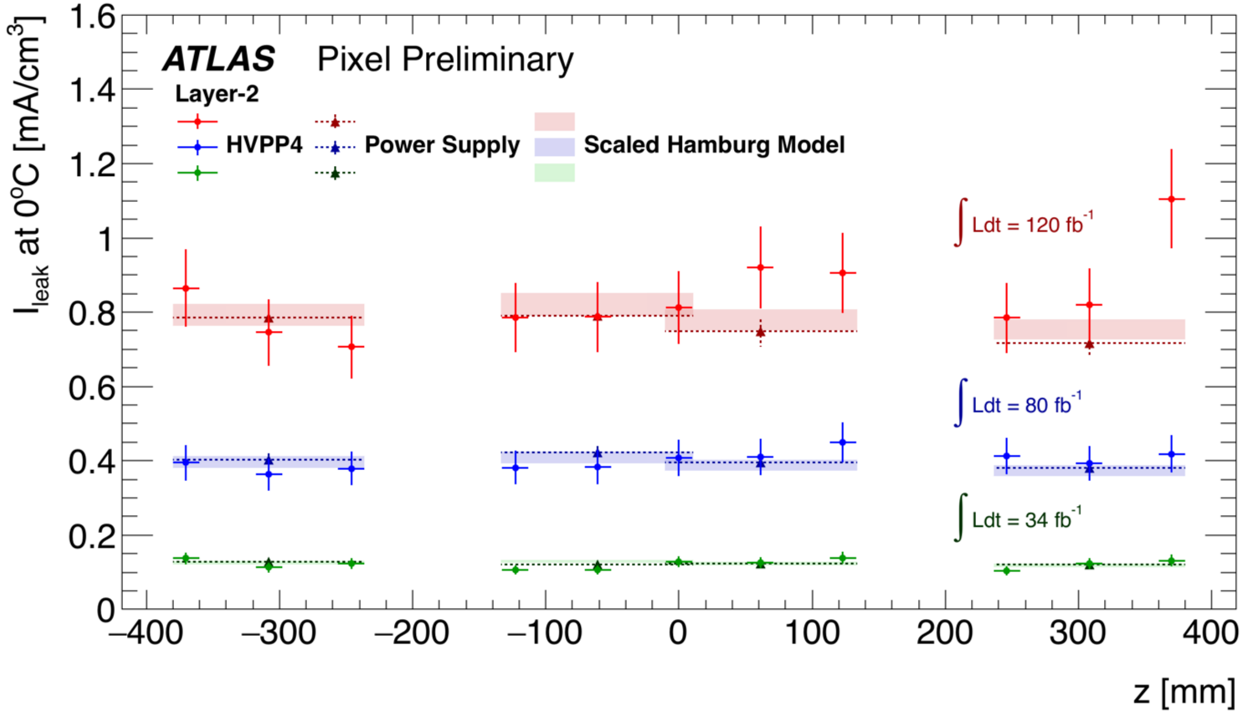
- Z-binned **Layer-1** leakage current data at three values of integrated luminosity.
- Single module precision is shown with HVPP4 data and multiple module precision is shown with the power supply leakage current data




- The z-dependent scaled Hamburg Model predictions are also shown
- Overlapping bins are due to simultaneous module measurements by the power supply subsystem

# Layer-2 Z-binned Leakage Current

- Z-binned **Layer-2** leakage current data at three values of integrated luminosity.
- Single module precision is shown with HVPP4 data and multiple module precision is shown with the power supply leakage current data

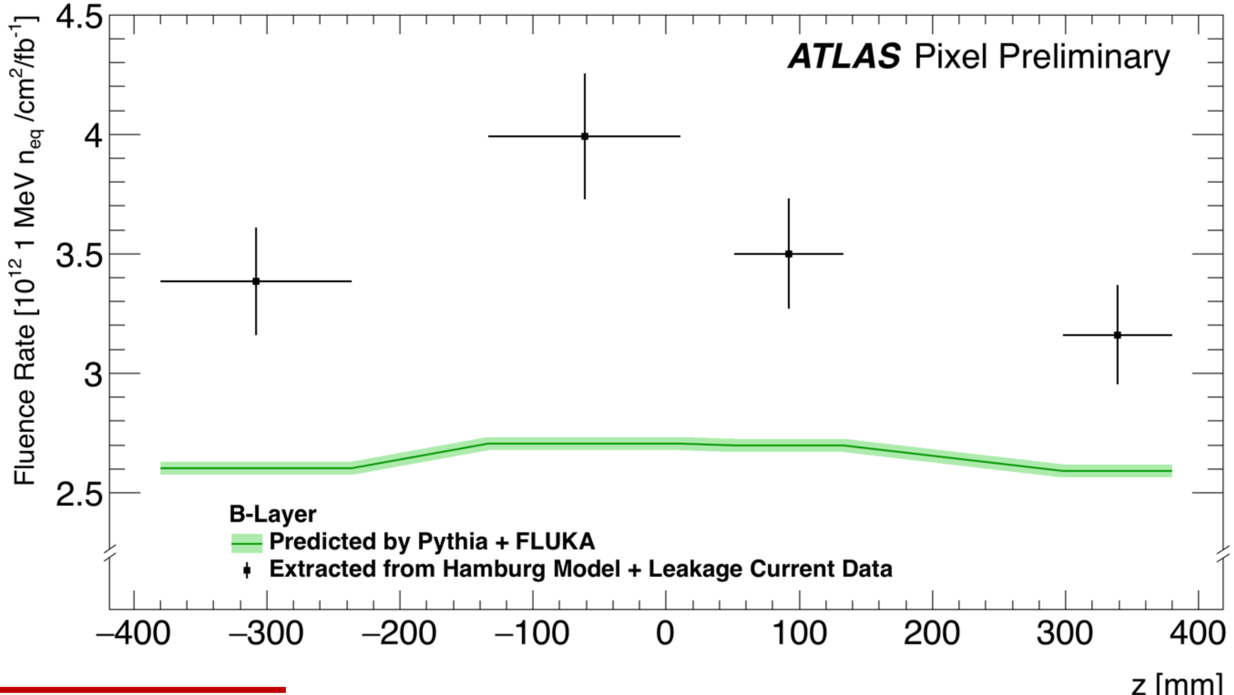



- The z-dependent scaled Hamburg Model predictions are also shown
- Overlapping bins are due to simultaneous module measurements by the power supply subsystem

# B-Layer Fluence Comparison

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from leakage current data combined with the Hamburg Model, for the **B-Layer**
- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at three energy levels throughout the full period of operation as of November 2017.

- Uncertainty on the fluence predicted by Pythia and FLUKA MC statistical only
- Uncertainty on the fluence determined by the leakage current data and the Hamburg Model excludes temperature offset uncertainty

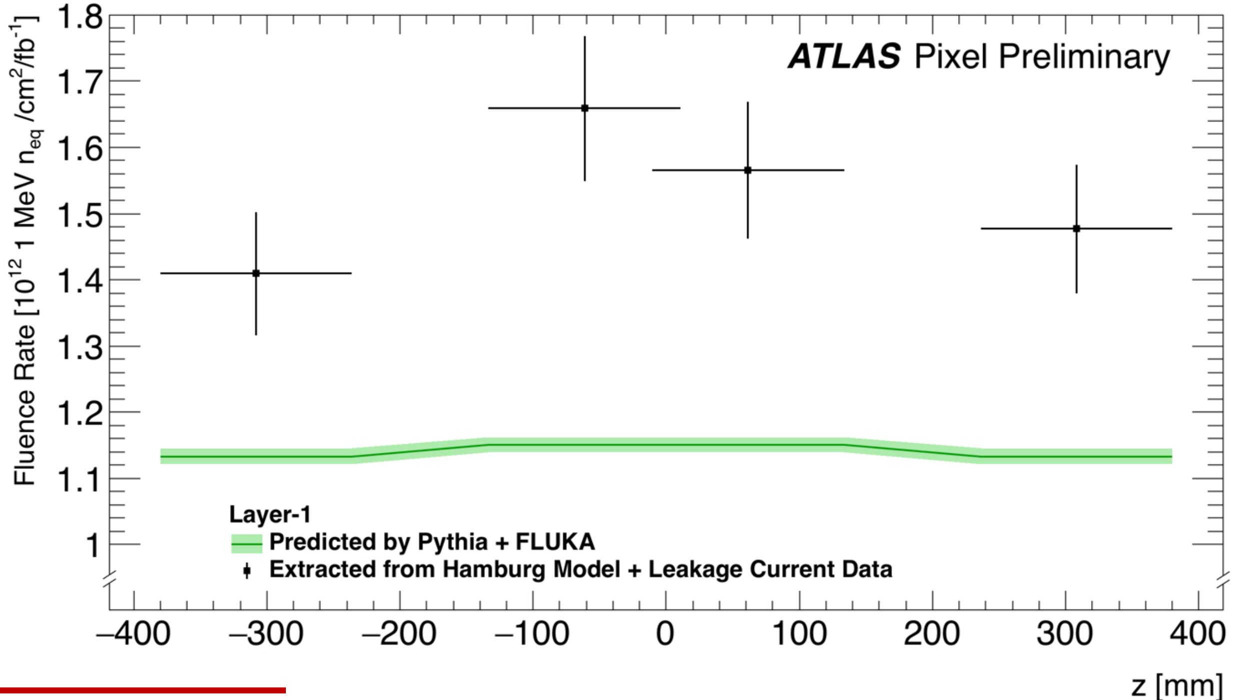



Pythia tuning: A2M_MSTW2008LO. See ref. on slide 19

# Layer-1 Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from leakage current data combined with the Hamburg Model, for the **Layer-1**
- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at three energy levels throughout the full period of operation as of November 2017.

- Uncertainty on the fluence predicted by Pythia and FLUKA MC statistical only
- Uncertainty on the fluence determined by the leakage current data and the Hamburg Model excludes temperature offset uncertainty

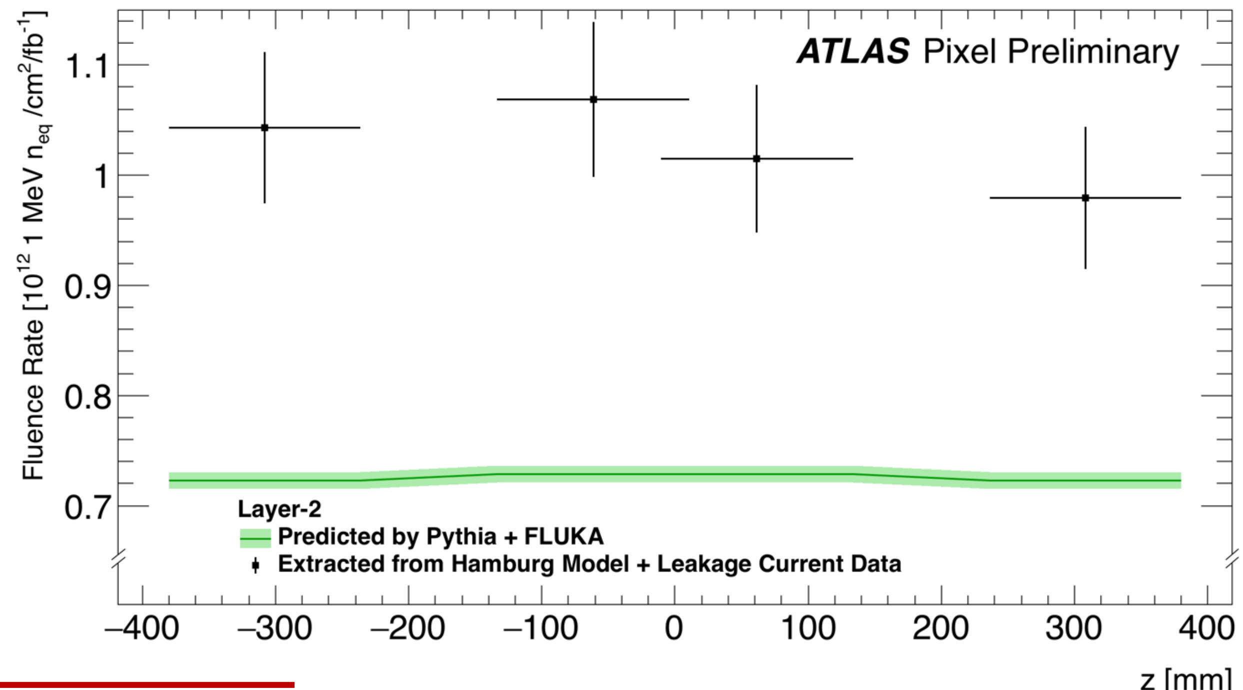



Pythia tuning: A2M_MSTW2008LO. See ref. on slide 19

# Layer-2 Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from leakage current data combined with the Hamburg Model, for the **Layer-2**
- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at three energy levels throughout the full period of operation as of November 2017.

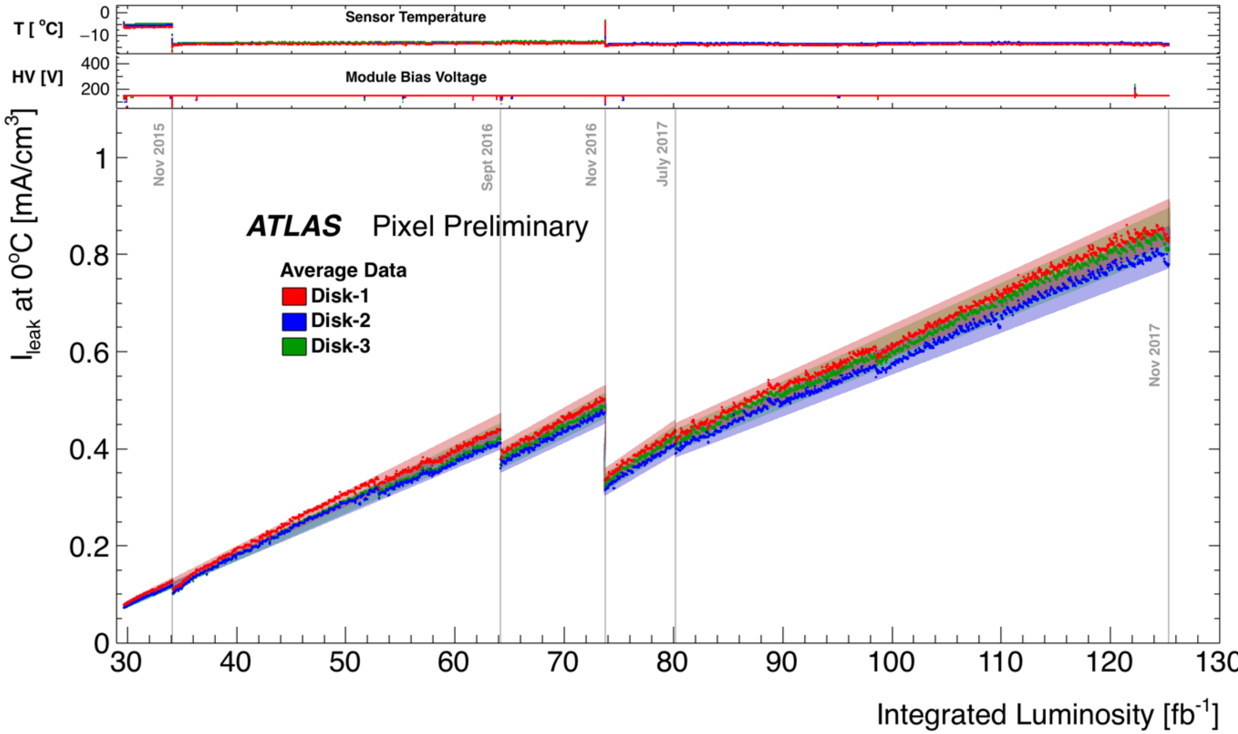
- Uncertainty on the fluence predicted by Pythia and FLUKA MC statistical only
- Uncertainty on the fluence determined by the leakage current data and the Hamburg Model excludes temperature offset uncertainty




Pythia tuning: A2M_MSTW2008LO. See ref. on slide 19

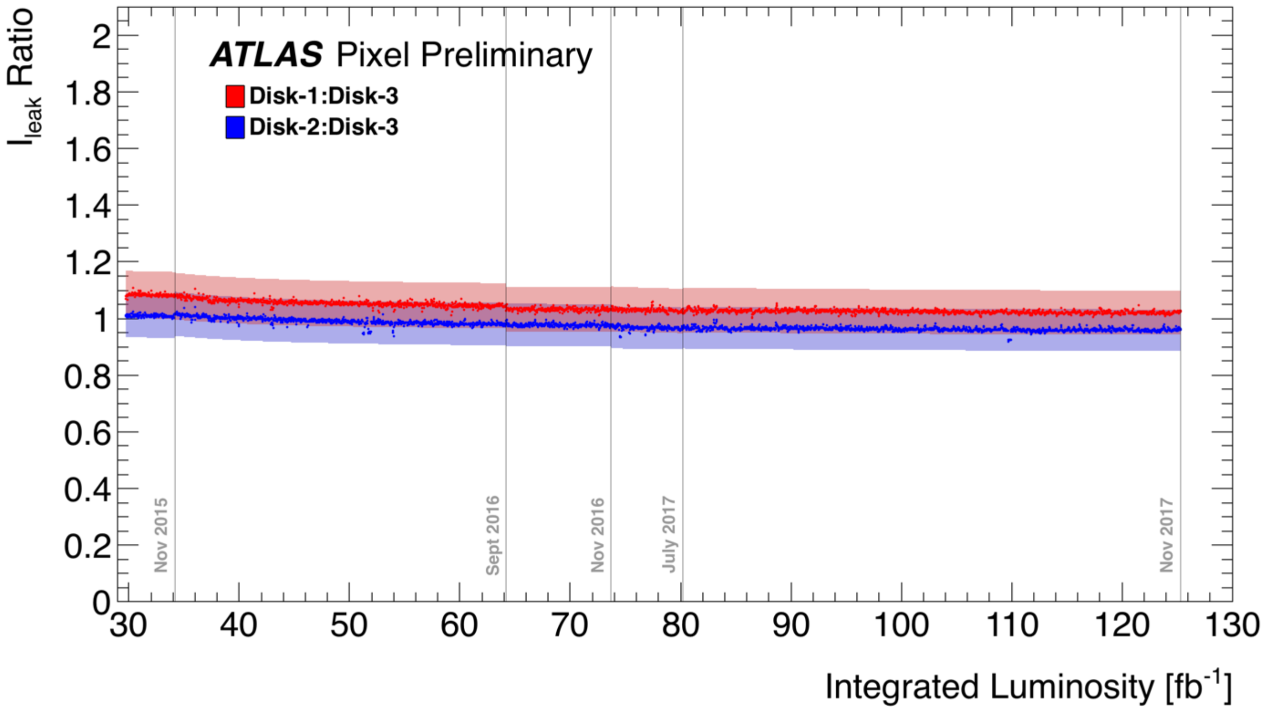
# Average Measured Disk Leakage Current

- Average measured leakage current data of a representative sample of modules in the ATLAS Pixel detector disks for the LHC Run 2 period of operation.
- Disk-1, Disk-2, and Disk-3 show comparable values of leakage current.




- Each disk corresponds to both side A and side C of the Pixel Detector.
- The average module sensor temperature is shown in the top panel.
- The average module bias voltage is shown in the middle panel.

# Ratios of Leakage Currents in Disks




- Ratios of Disk-1 and Disk-2 leakage current data to Disk-3 leakage current data for the LHC Run 2 period of operation.
- The ratios are expected to be flat
- The vertical axis is proportional to the ratio of the applied fluence

# IBL Fluence

- The IBL leakage current data were reported at the RD50 meeting in November 2017*
- Hamburg Model predictions were found to overestimate the leakage current data for the IBL
- Dedicated studies of fluence simulation using FLUKA** and Geant 4 † ‡ are ongoing and will be discussed later in the workshop.

* Nick Dann, ATLAS pixel and strip rad damage measurements, RD50 Workshop https://indico.cern.ch/event/663851/contributions/2711512/

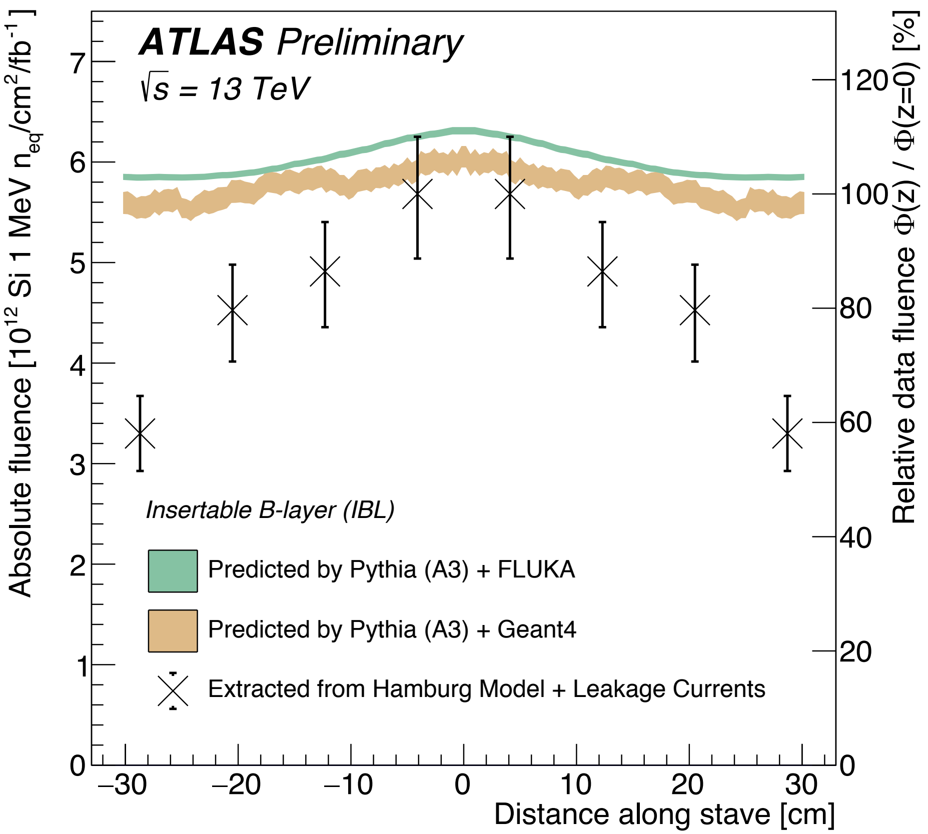
** S. Baranov et al., Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS, (2005), http://inspirehep.net/record/1196420/

† GEANT4 Collaboration, GEANT4: a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250.

‡ ATLAS Collaboration, The ATLAS Simulation Infrastructure, Eur. Phys. J. C 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].

# Comparison of FLUKA and Geant 4

- Fluence predictions made with Pythia 8 + FLUKA and Pythia 8 + Geant 4 are compared to the fluence determined with the leakage current data and Hamburg Model.
- Both FLUKA and Geant 4 use the Pythia 8 simulation tuned with MSTW2008LO PDF with A3* minimum bias (in place of the previously studied A2† minimum bias)
- See presentations by Paul Miyagawa ‡ and Sven Menke** later in the workshop




* ATLAS Collaboration, A study of the Pythia 8 description of ATLAS minimum bias measurements with the Donnachie-Landshoff diffractive model, ATL-PHYS-PUB-2016-017, https://cds.cern.ch/record/1474107

† ATLAS Collaboration, Summary of ATLAS Pythia 8 Tunes, ATL-PHYS-PUB-2012-003, https://cds.cern.ch/record/2206965

‡ Paul Miyagawa, ATLAS simulation overview, https://indico.cern.ch/event/695271/contributions/2942436/

** Sven Menke, ATLAS radiation background studies using GEANT4 & GRID https://indico.cern.ch/event/695271/contributions/2942614/

# Final Comments

- This was a first report of the leakage current data in the ATLAS Pixel Detector B-Layer, Layer-1, and Layer-2 and Disks through LHC Run 2
- We saw that the Hamburg Model predictions underestimate the leakage current data for B-Layer, Layer-1, and Layer-2 while they overestimate the leakage current data on the IBL
- There is a strong z-dependence on the fluence in the IBL leakage current data and a significant z-dependence on the B-Layer
- Studies of various fluence simulations have been shown in an effort to improve the comparison with the fluence determined from the leakage current data and Hamburg Model

# Backup Slides

# Measurement Uncertainty

- The measurement uncertainty for HVPP4 in Run 1 was found to be 12.5% *
- The uncertainty on measured leakage current for LHC Run 2 Power Supply modules is 5.4%, calculated by adding the following uncertainties in quadrature:
  - Power Supply precision on current measurements contributing 4% uncertainty
  - Current measurements made approximately once per minute contributing 0.5%
  - Uncertainty on the luminosity is 2.4% **
  - Uncertainty on temperature measurements contributing 2.9% (do not include uncertainty in temperature offset)

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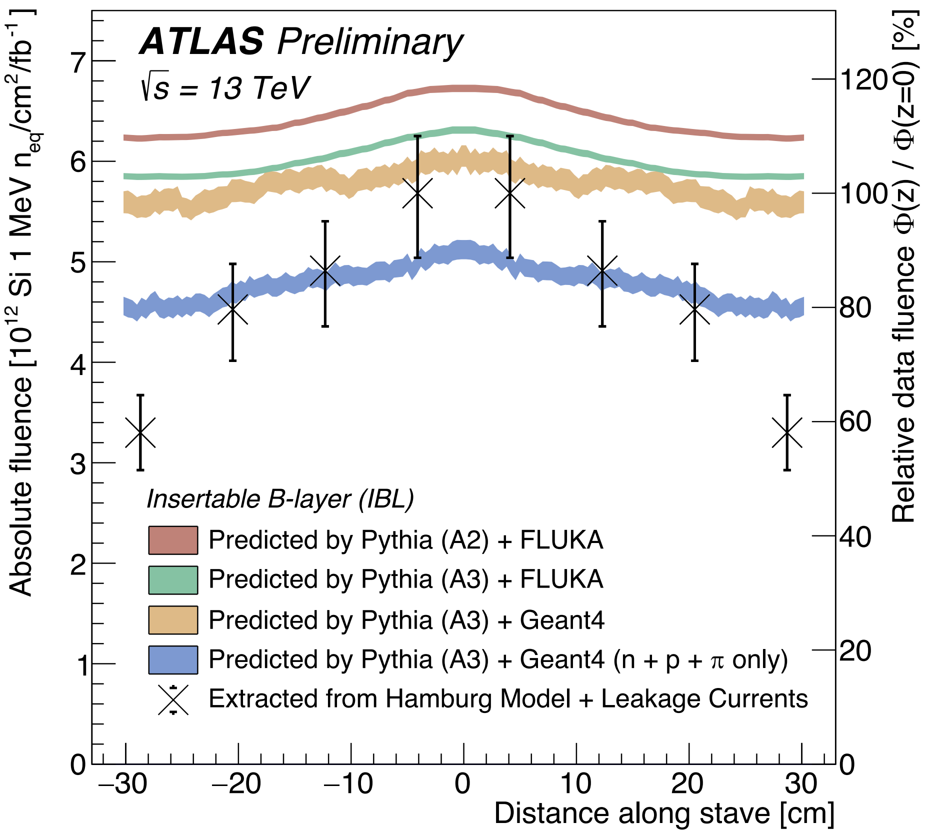
* ATL-INDET-PUB-2014-004

** https://twiki.cern.ch/twiki/bin/view/Atlas/LuminosityForPhysics

# Fluence Simulation Comparisons

- A comparison of fluence predictions made with FLUKA and Geant4 are compared to the fluence determined with the leakage current data and Hamburg Model.
- The Pythia 8* simulation tuned with A2 minimum bias and Geant 4 accounting for neutrons, protons and pions only are also compared.




*See references on slides 18 and 19