# ATLAS Pixel Detector Leakage Current

Sally Seidel
University of New Mexico

On behalf of the ATLAS Collaboration

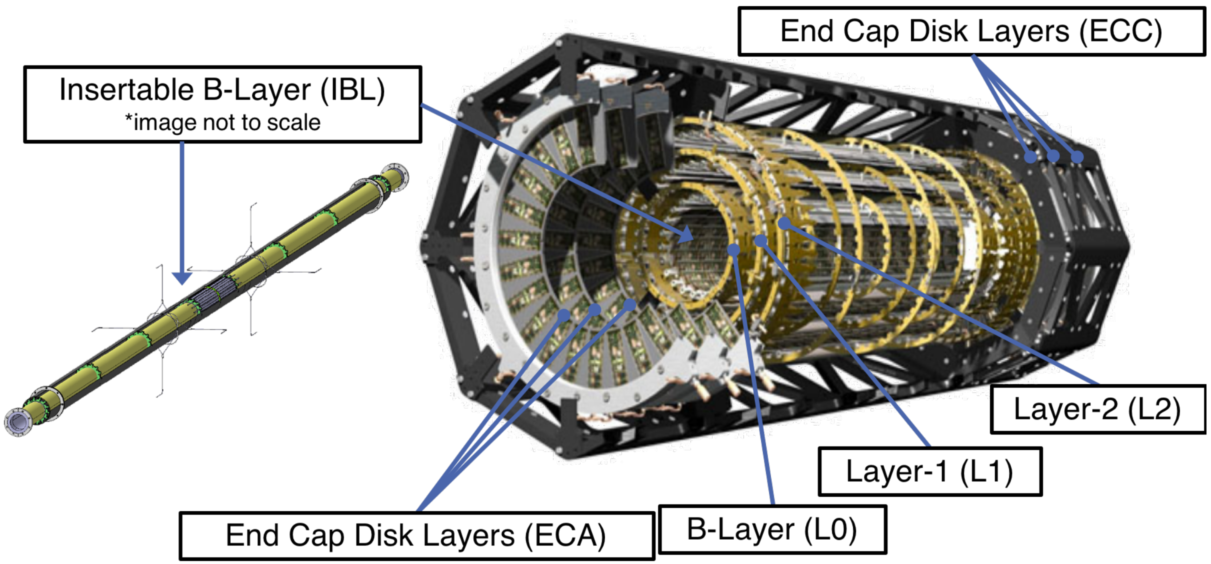
14th Trento Workshop on Advanced Silicon Radiation Detectors

25 February 2019

# Introduction-1

- Leakage current data in the ATLAS Pixel Detector – Insertable B-Layer (IBL), B-Layer, Layer-1, Layer-2, and Disks – is presented for the full period of operation through LHC Run 2

- Predictions have been made with the Hamburg Model* throughout LHC Run 2 for B-Layer, Layer-1, Layer-2, and Disks




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

# Introduction-2

- Comparison is made of fluence predictions by Pythia8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data
- A study of the optimal value of the effective band gap energy of irradiated silicon, $E_{eff}$, is performed with ATLAS data
  - This study indicates that a value of $E_{eff} < 1.21$ eV may be more appropriate for predicting and measuring leakage current

# Expectations of the Measurement

- Leakage current in silicon sensors is an indicator of received non-ionizing 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 depleted volume $V$, and $\alpha$ is the current-related damage coefficient
- 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*
- 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 times 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

** Iseg Spezialelektronik GmbH, High Voltage Power Supply EHQ F607n-F

# 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 study of the optimal $E_{eff}$ value for ATLAS data is presented later in these slides.

† 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

# Integrated Luminosity

- All fluence received by the pixel sensors impacts the leakage current
- The integrated luminosity used throughout this analysis includes the luminosity accumulated outside of the LHC stable beams declarations
- The total integrated luminosity seen by the B-Layer, Layer-1, Layer-2, and Disks for the full period of operation is 191.1 $fb^{-1}$

# Hamburg Model Predictions

- Hamburg Model predictions are made in four bins along the axis z for each barrel layer (a total of 12 predictions) and for each pair of Disks
- Luminosity to fluence conversions are made using the Pythia8 and FLUKA simulation and have a symmetric z-dependence around the interaction point
  - The predicted total fluence received by the B-Layer modules closest to the interaction point – calculated using the total integrated luminosity (191.1 $fb^{-1}$ ) – is $5.27 \times 10^{14}$ 1 MeV $n_{eq}$ / $cm^2$

# Scale Factor

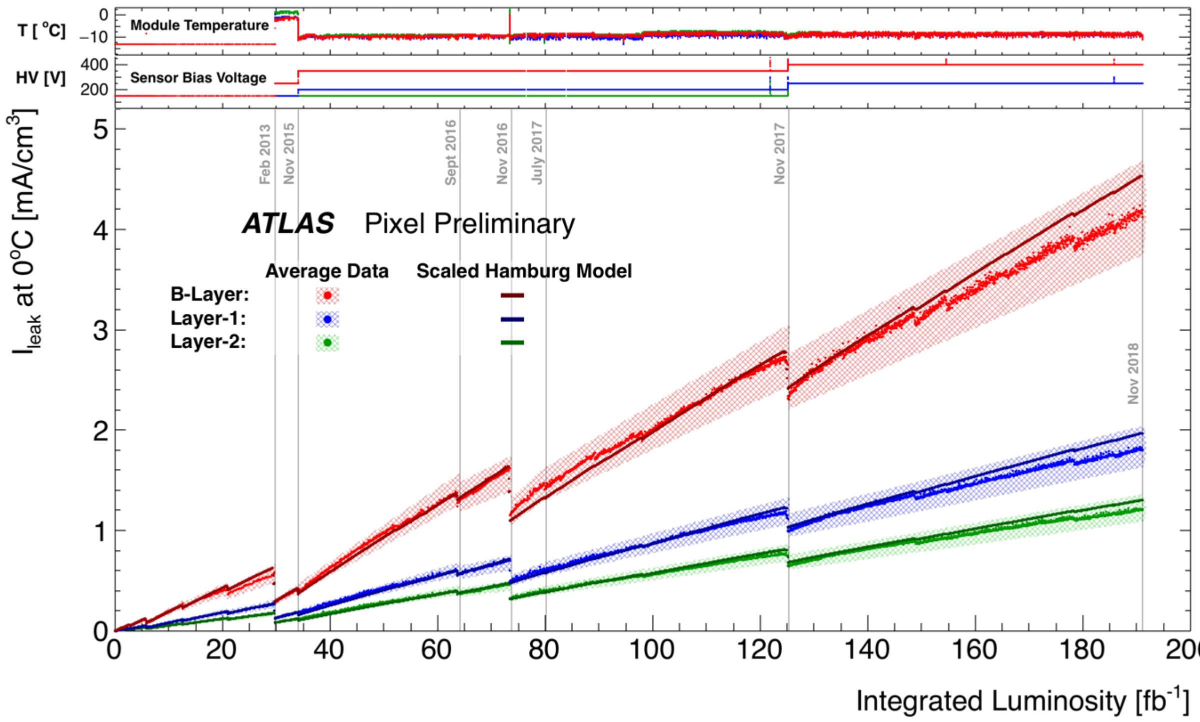
- The predictions (12 for the barrel layers and 3 for the pairs of disks) are fit to the data with a scale factor
  - Each scale factor is a constant given by the ratio of leakage current data to prediction
- For each barrel layer, the average of the scaled predictions associated with the four bins along the z axis is compared to the average leakage current data in the same four bins
- The scale factors* range from ~1.20 far from the interaction point in z to ~1.45 close to the interaction point in z

*See Slide 35 for all scale factors

# Leakage Current in the Barrel Layers

# Leakage Current in Pixel Barrel

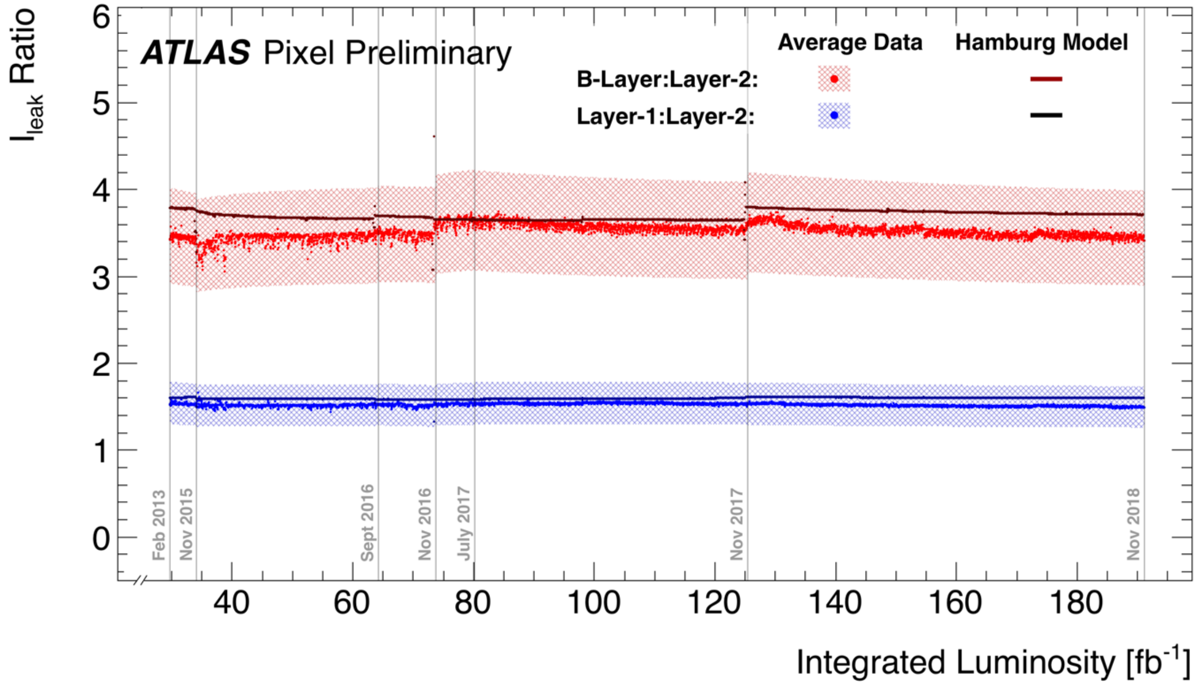
- Average leakage current data compared to the average scaled Hamburg Model predictions for each barrel layer through 2018
- The Hamburg Model predictions have been scaled to match the measured leakage current data




- 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 B-Layer is at r = 50.5 mm, Layer-1 at 88.5 mm, Layer-2 at 122.5 mm

# Ratios of Leakage Currents in Barrel Layers

- Ratios of the various Pixel Detector barrel layer leakage current data and (unscaled) Hamburg Model predictions for LHC Run 2

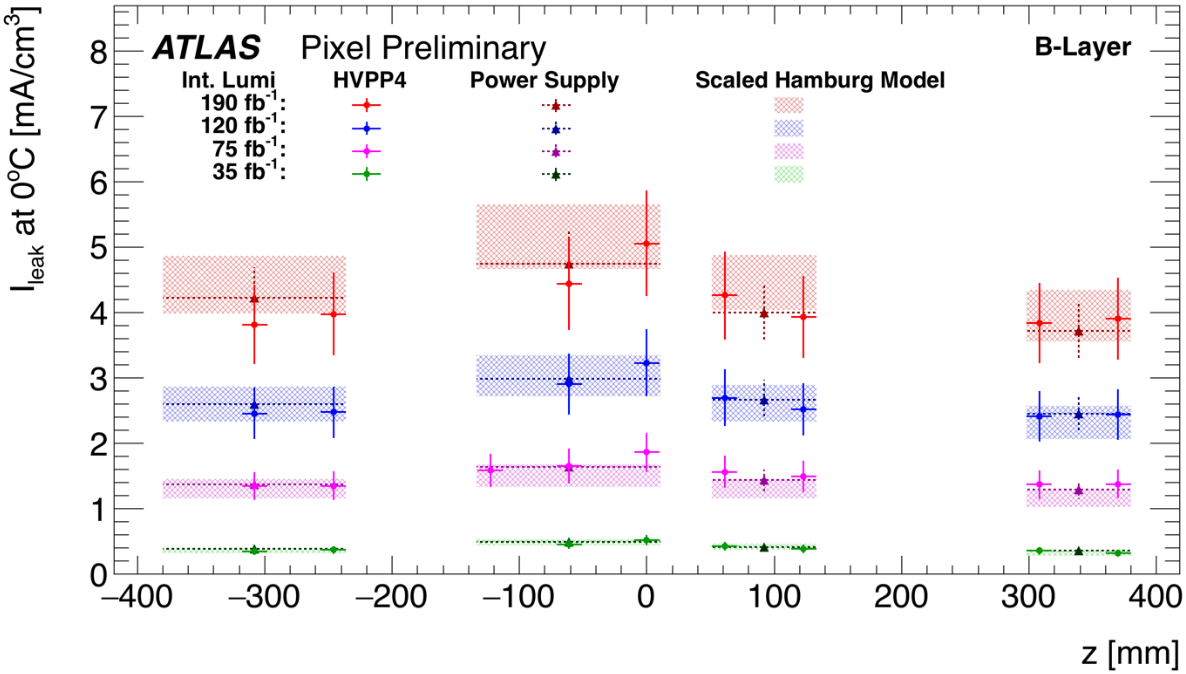



- The vertical axis is proportional to the ratio of the applied fluence
- The relative fluence between the layers is well predicted

# Leakage Current Dependence on z

# B-Layer Z-binned Leakage Current

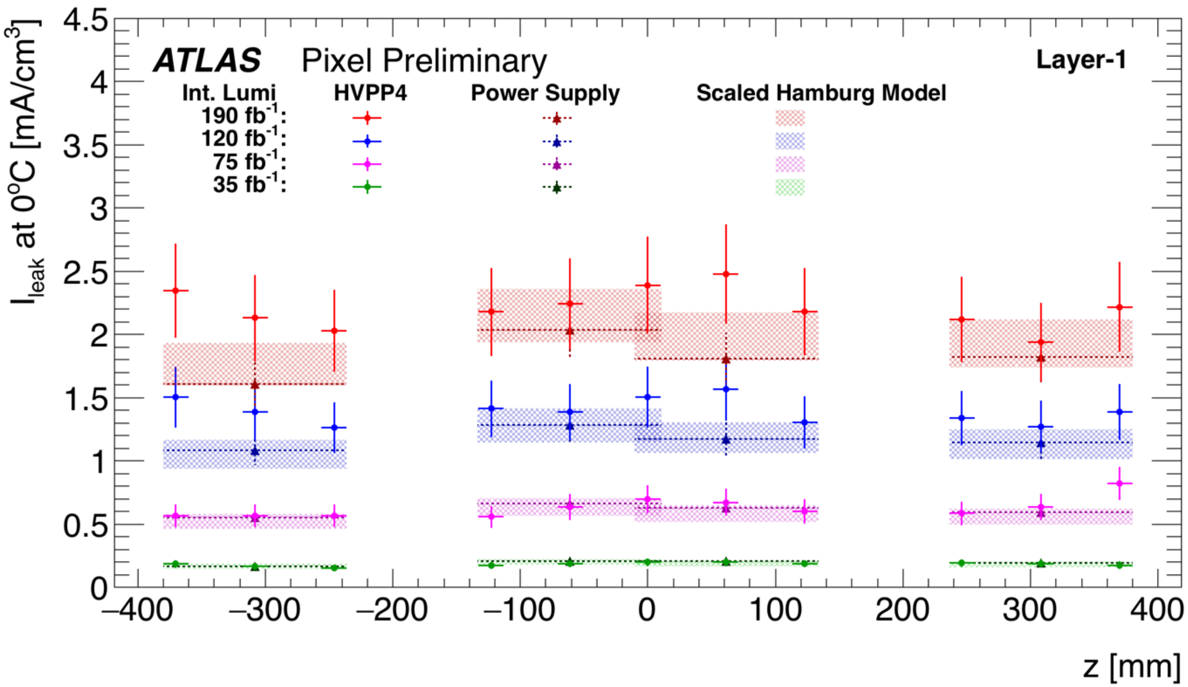
- Z-binned **B-Layer** leakage current data at four values of integrated luminosity.
- Single module precision is shown with HVPP4 data, and multiple module precision is shown with the power supply leakage current data




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

# Layer-1 Z-binned Leakage Current

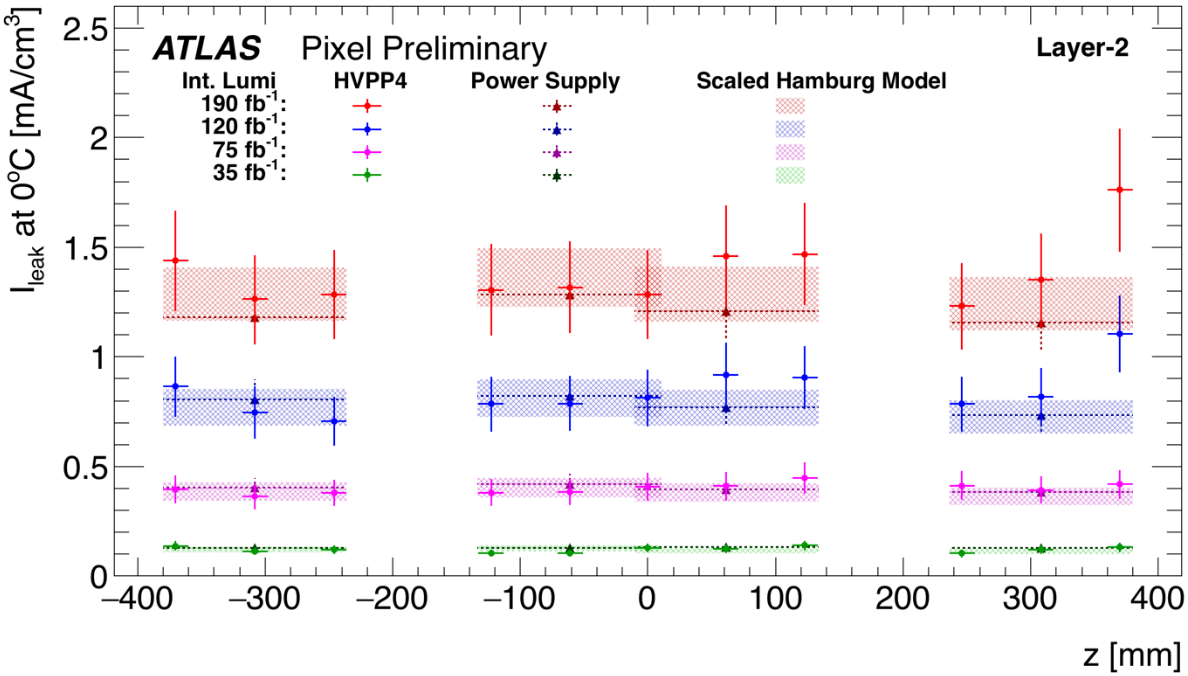
- Z-binned **Layer-1** leakage current data at four values of integrated luminosity.
- Single module precision is shown with HVPP4 data, and multiple module precision is shown with the power supply leakage current data




- 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 four 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



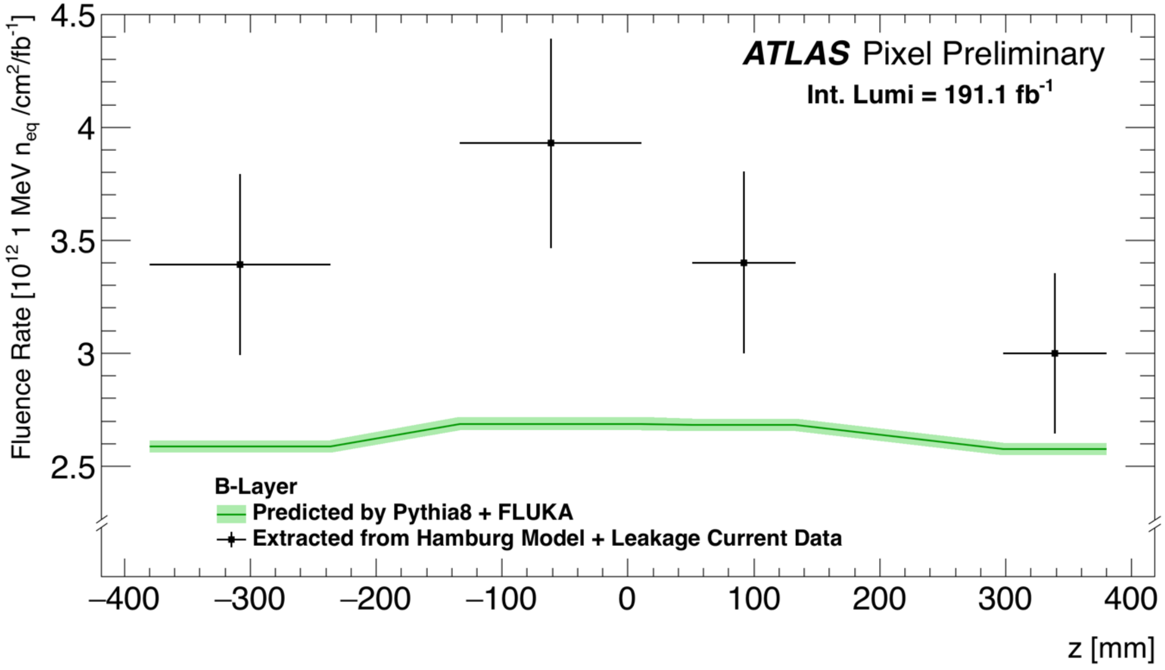

- The z-dependent scaled Hamburg Model predictions are also shown
- Overlapping bins are due to simultaneous module measurements by the power supply subsystem

# Comparison of Predicted Fluence and Extracted Fluence

# B-Layer Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data, for the **B-Layer**

- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at center of mass 7, 8, and 13 TeV
- Uncertainty on the fluence predicted by Pythia and FLUKA MC is 1% (statistical only)



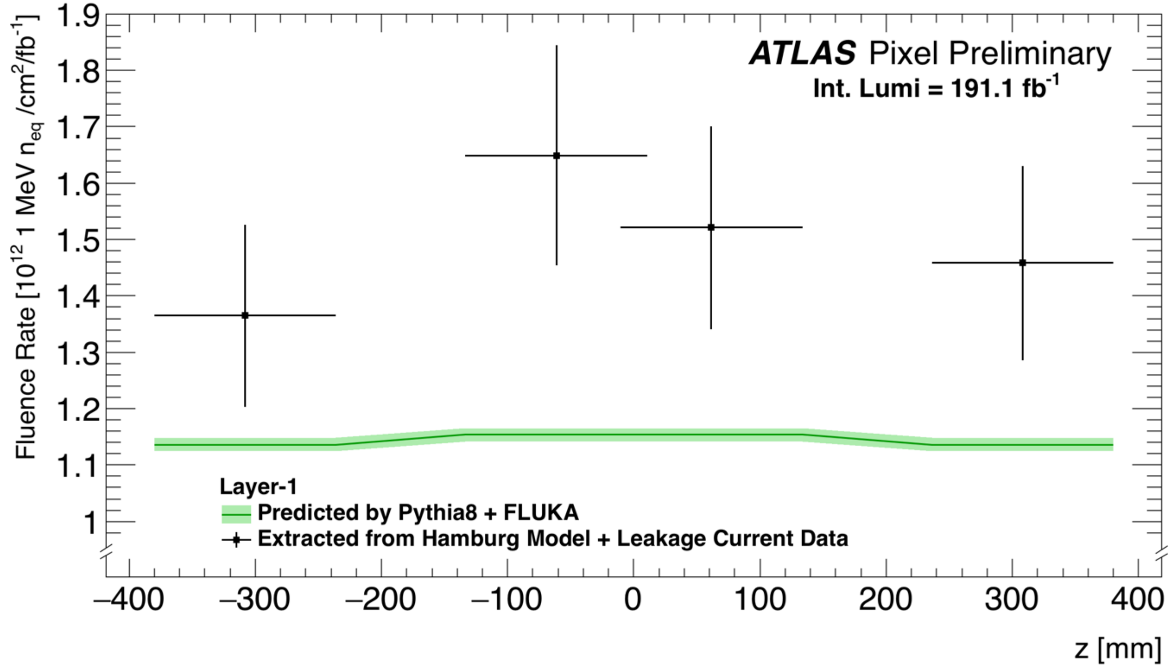

Pythia tuning: A2M_MSTW2008LO. See ref. on backup slide 41

# Layer-1 Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data, for the **Layer-1**

- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at center of mass energies 7, 8, and 13 TeV

- Uncertainty on the fluence predicted by Pythia and FLUKA MC is 1% (statistical only)

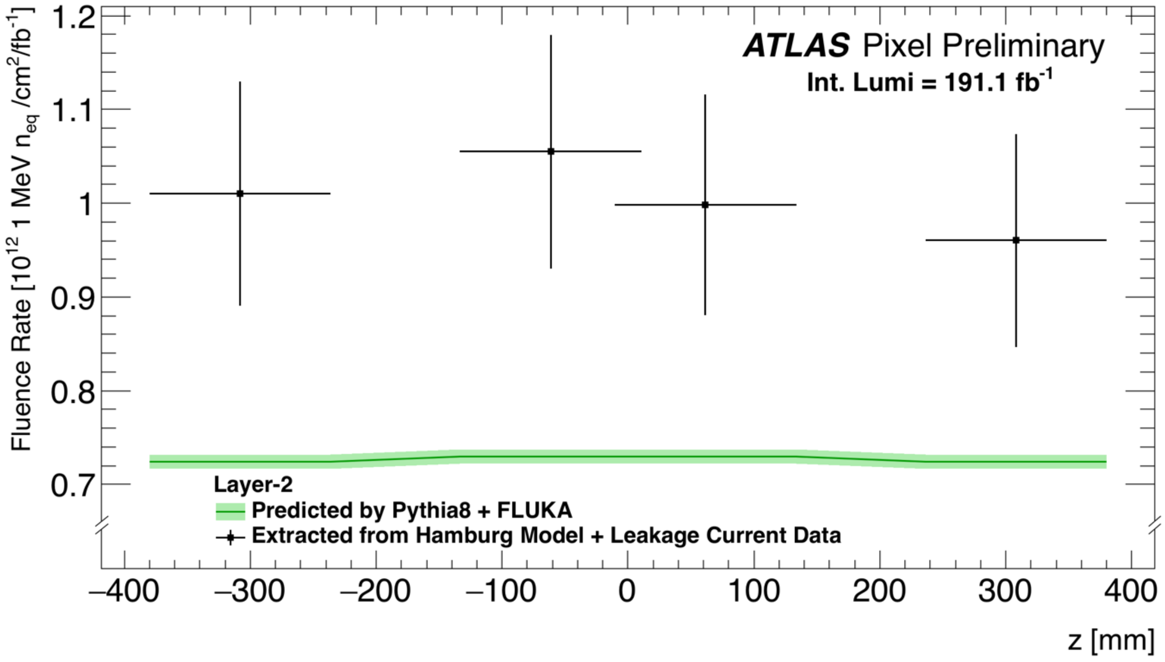



Pythia tuning: A2M_MSTW2008LO. See ref. on backup slide 41

# Layer-2 Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data, for the **Layer-2**

- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at center of mass energies 7, 8, and 13 TeV
- Uncertainty on the fluence predicted by Pythia and FLUKA MC is 1% (statistical only)

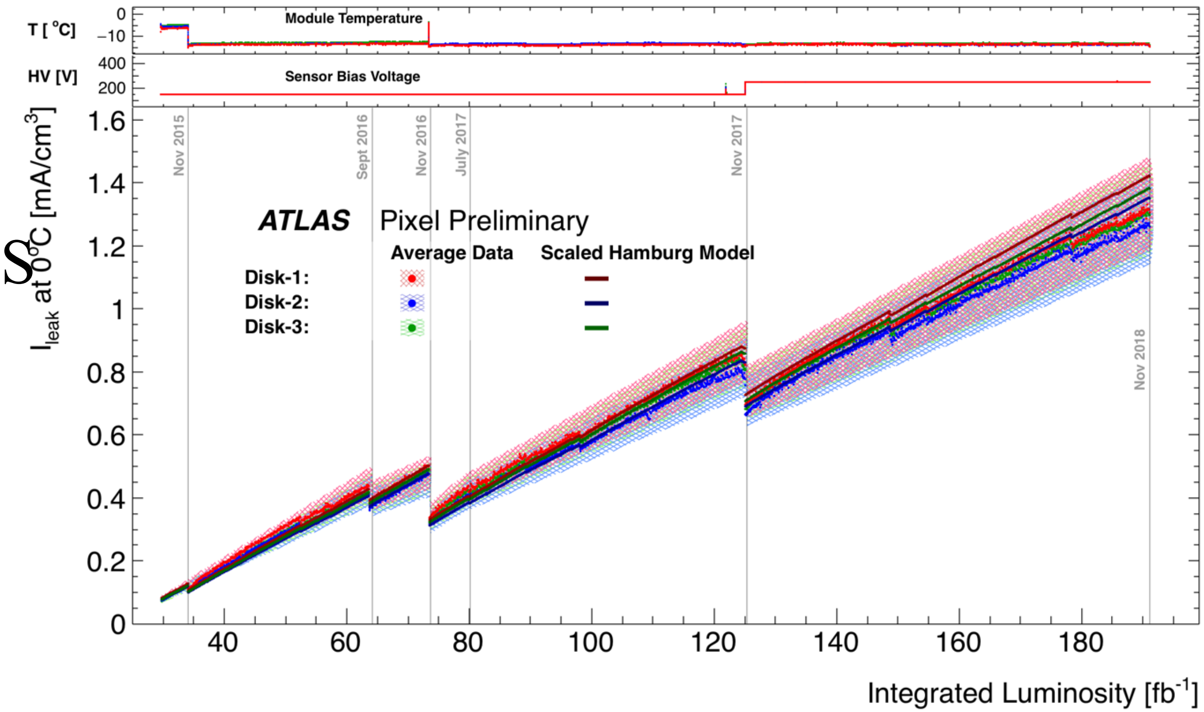



Pythia tuning: A2M_MSTW2008LO. See ref. on backup slide 41

# Leakage Current in the Disks

# Leakage Current in Disks

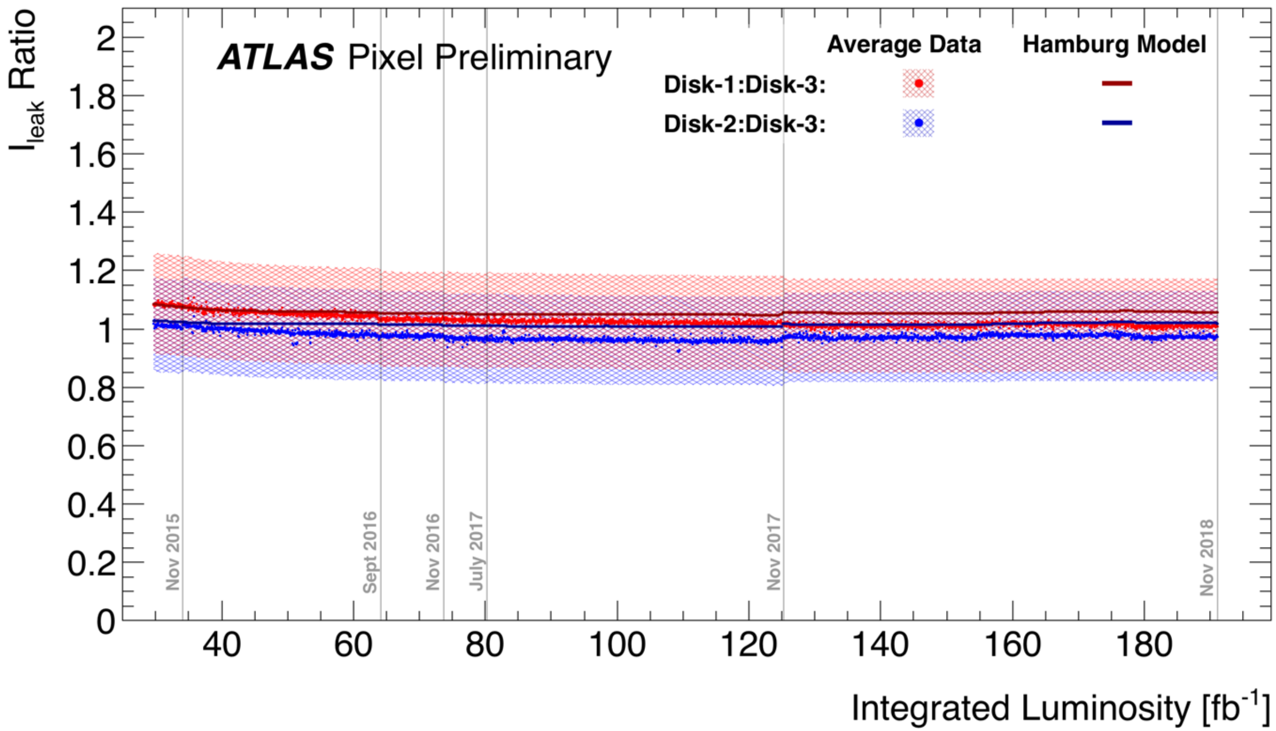
- Average measured leakage current and Hamburg Model predictions for a sample of modules in the ATLAS Pixel detector disks for LHC Run-2.
- Disk-1 (|z| = 495 mm), Disk-2 (|z| = 580 mm), and Disk-3 (|z| = 650 mm) show comparable values of leakage current.




- Each disk corresponds to both side A and side C of the Pixel Detector. Disk modules are at radius 119.2 cm.
- The average module temperature and average sensor bias voltage are shown in the top panels

# Ratios of Leakage Currents in Disks

- Ratios of Disk-1 and Disk-2 to Disk-3 leakage current data and (unscaled) Hamburg Model predictions for the LHC Run 2 period of operation.



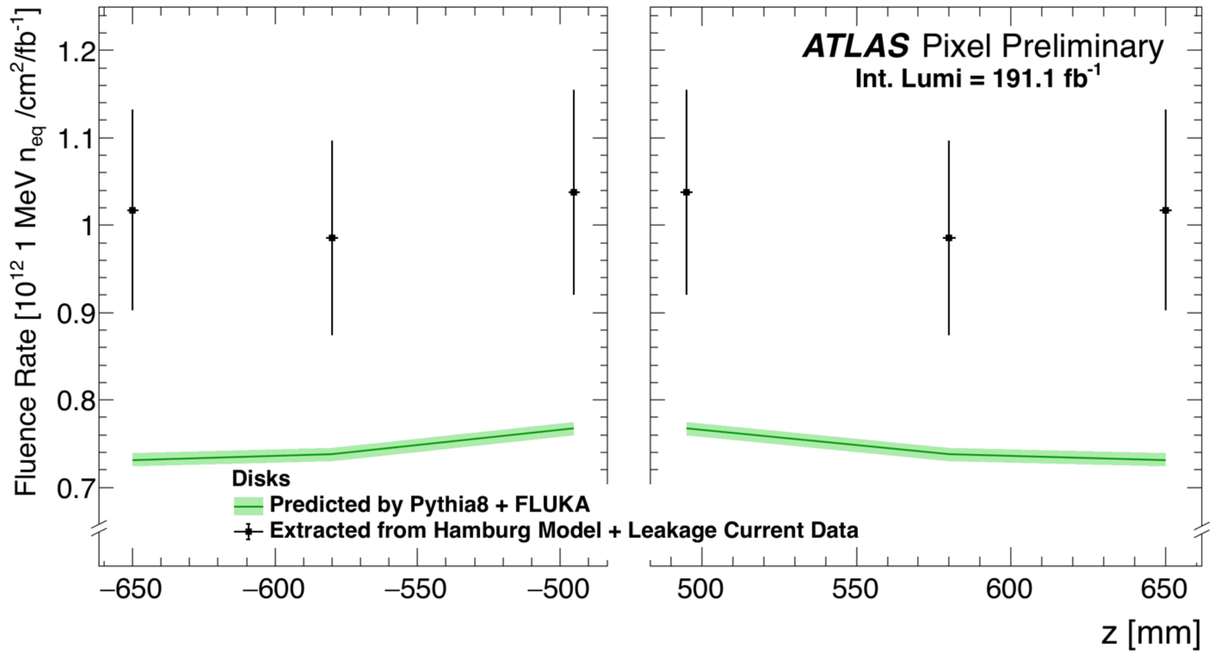

- The vertical axis is proportional to the ratio of the applied fluence
- The relative fluence between the disks is well predicted

# Disk Fluence Comparisons

- Comparison of fluence predictions by Pythia 8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data, for the **Disks**

- Fluence predictions by Pythia8 and FLUKA are weighted averages of the fluence predicted at center of mass energies 7, 8, and 13 TeV

- Uncertainty on the fluence predicted by Pythia and FLUKA MC is 1% (statistical only)

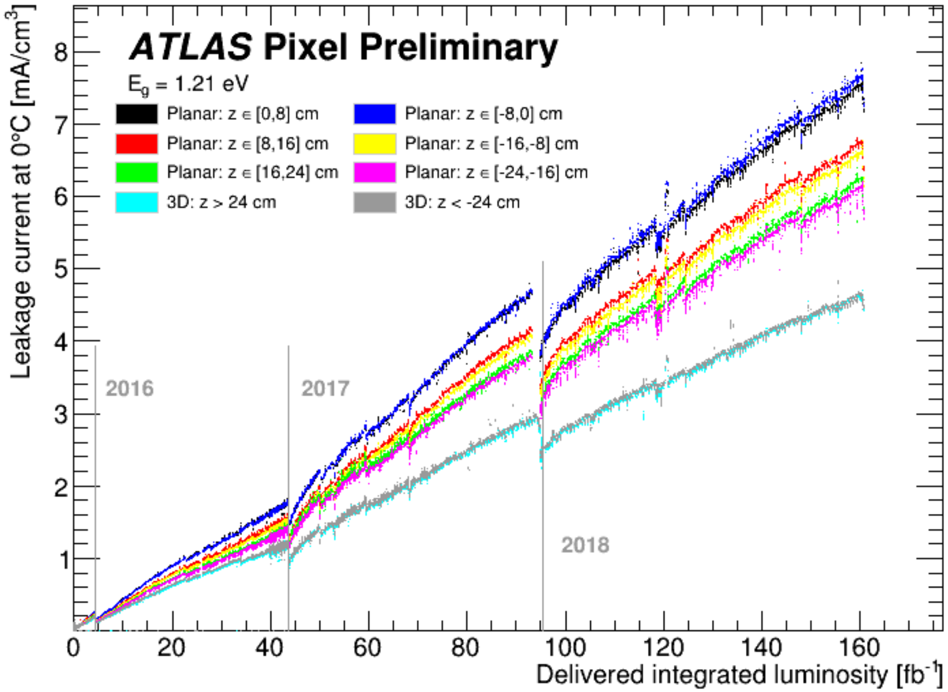



Pythia tuning: A2M_MSTW2008LO. See ref. on backup slide 41

# Leakage Current
# in the Insertable B-Layer (IBL)

# IBL Leakage Currents

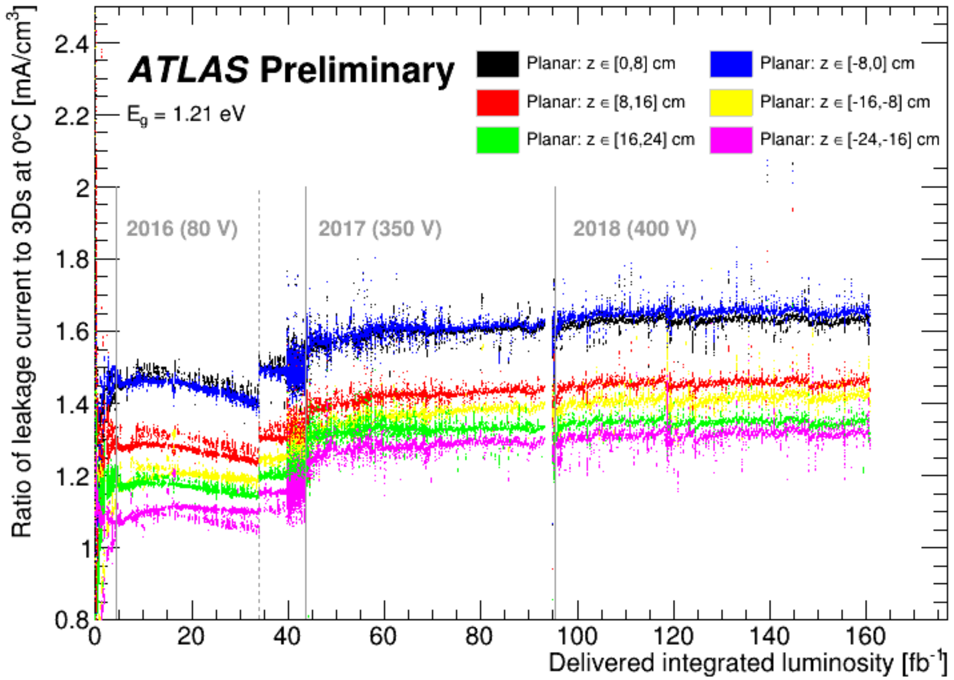
- The measured leakage current in modules from the Insertable B-layer (IBL) as a function of integrated luminosity during the LHC Run 2
- The current is averaged over ϕ and also averaged over modules with a similar z




- Both planar and 3D sensors are measured and shown in the figure
- The high voltage on the planar sensors was changed during 2016 from 80 V to 150 V, then to 300 V at the start of 2017 and then to 400 V at the start of 2018
- The high voltage of the 3D sensors was 20 V in 2015 and 2016, and increased to 40 V for the remainder of the run

# IBL Leakage Current Ratios

- The ratio of the measured leakage currents* on planar sensors to the 3D sensors is shown in the figure
- The 3D sensors are expected to be the least affected by radiation damage
- The leakage current ratio is predicted to be the ratio of the fluence multiplied by the depleted volume.




- Planar sensor volume: 1.5378 cm$^3$; 3D sensor volume: 0.8774 cm$^3$.
- After the high voltage change in 2016, the ratio is nearly flat as the sensors were fully depleted.

*B. Abbott et al., "Production and integration of the ATLAS Insertable B-Layer, 2018 JINST 13 T05008.

# Investigation of the Optimal $E_{eff}$ Value

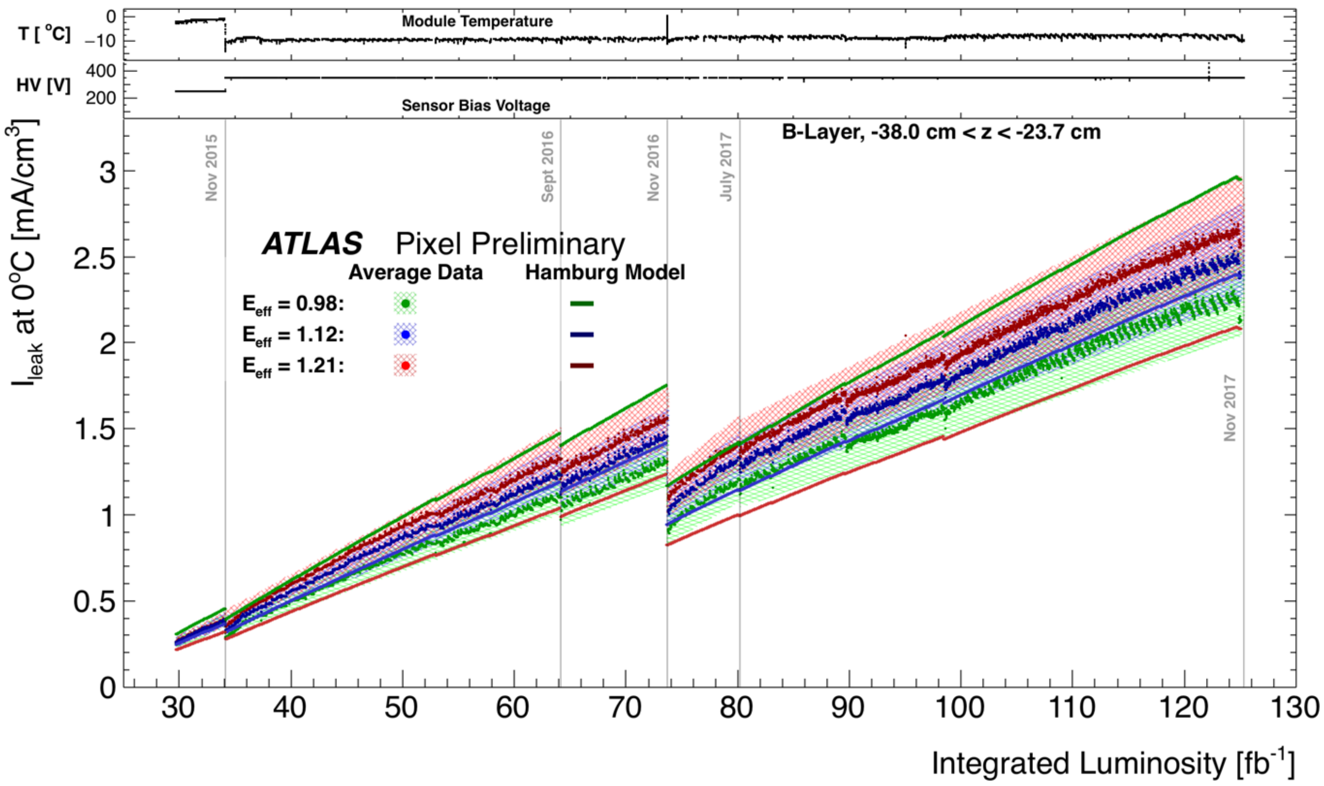
# Study of $E_{eff}$ and the Scale Factor

- A study was performed to find the best combination of $E_{eff}$ (which is input to the Hamburg Model) and the scale factor which brings the magnitude of leakage current predicted by the model into agreement with the average magnitude of the leakage current data.
- The study used currents recorded in modules located in the range ($-38.0 < z < -23.7$) cm on the B-Layer

# Setup of the Investigation

- Several predictions were generated, all normalized to 0 $^{o}$C, each using a different value of $E_{eff}$
- The leakage current data were also normalized to 0 $^{o}$C and analyzed once with each unique value of $E_{eff}$
  - Note that the value of $E_{eff}$ is used in the temperature normalization step

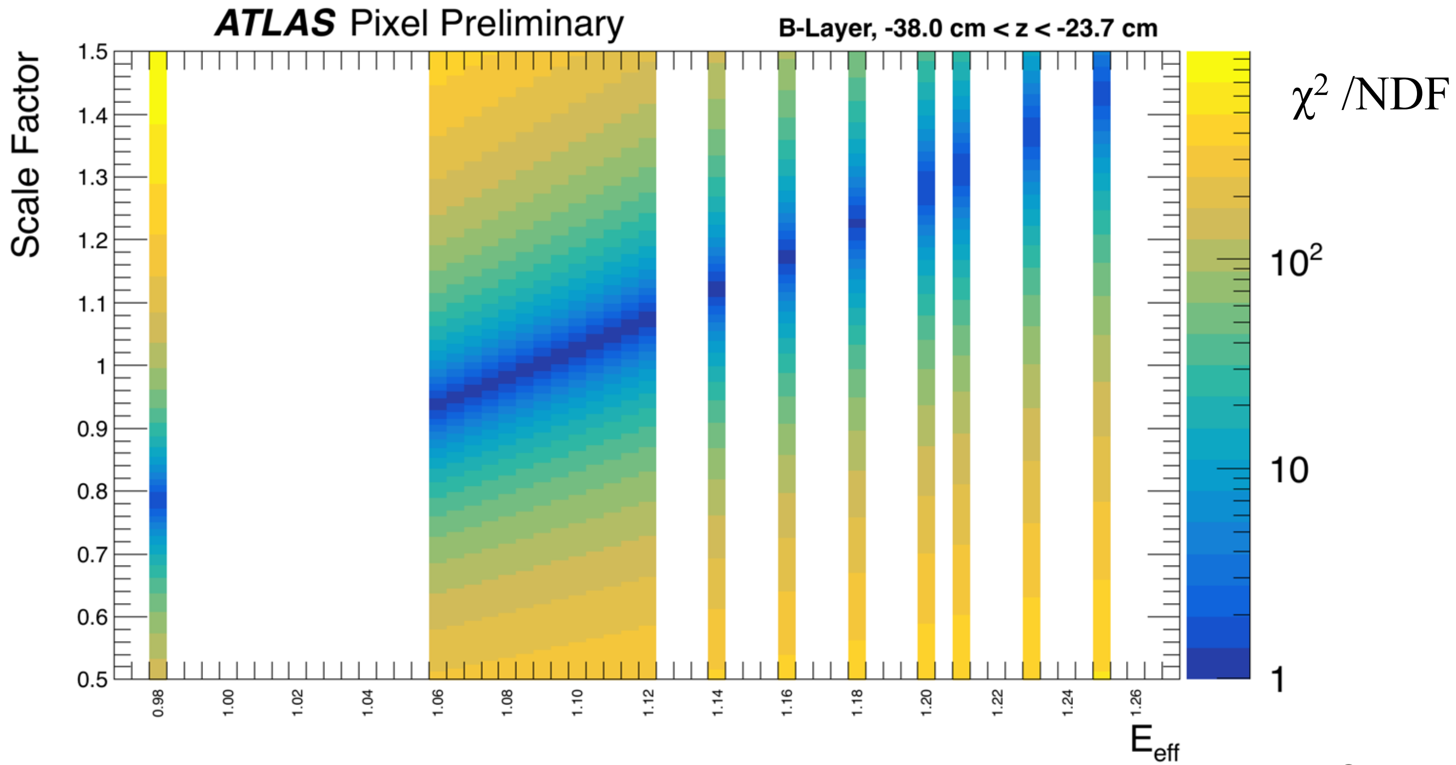
# Impact of $E_{eff}$




- Three pairs of leakage current data and predictions with the Hamburg Model, with three $E_{eff}$ values used to analyze them, are shown here before a scale factor is applied

# Fitting $E_{eff}$ and the Scale Factor

- The level of agreement provided by each scale factor is characterized by a $\chi^2$ figure of merit




- The $E_{eff}$ value and scale factor with the minimum $\chi^2$/NDF is:
  $E_{eff}$ = 1.11 with a scale factor = 1.05

  ($E_{eff}$ = 1.210 is paired with a scale factor = 1.312)

# Final Comments

- Leakage current data in the ATLAS Pixel Detector through LHC Run 2 are reported
  - Including all barrel layers and Disks
- Comparisons of fluence predictions by Pythia8 and FLUKA to the fluence determined from the Hamburg Model scaled to agree with the leakage current data show tension
  - The relative fluence between the layers is well predicted
  - The magnitude of the tension may be improved with an re-optimized value of $E_{eff}$
  - The tension in the z-dependence allows us to probe the quality of fluence predictions by Pythia8 and FLUKA

# Additional Slides

# Scale Factors

- The following scale factors are applied to the Hamburg Model prediction in each corresponding z-bin
- The average of the scaled predictions is used to compare to the average leakage current data for each layer

| | Z Bin | | Scale Factor |
|---|---|---|---|
| B-Layer | "-38.0 cm < z < -23.7 cm" | | 1.312 |
| | "-13.3 cm < z < 1.0 cm" | | 1.461 |
| | "5.17 cm < z < 13.3 cm" | | 1.268 |
| | "29.9 cm < z < 38.0 cm" | | 1.164 |
| | | | |
| Layer-1 | "-38.0 cm < z < -23.7 cm" | | 1.201 |
| | "-13.3 cm < z < 1.0 cm" | | 1.429 |
| | "-1.0 cm < z < 13.3 cm" | | 1.318 |
| | "23.7 cm < z < 38.0 cm" | | 1.296 |
| | | | |
| Layer-2 | "-38.0 cm < z < -23.7 cm" | | 1.395 |
| | "-13.3 cm < z < 1.0 cm" | | 1.445 |
| | "-1.0 cm < z < 13.3 cm" | | 1.368 |
| | "23.7 cm < z < 38.0 cm" | | 1.326 |

| | Scale Factor |
|---|---|
| Disk-1 | 1.353 |
| Disk-2 | 1.335 |
| Disk-3 | 1.391 |

# Measurement Uncertainty

- The measurement uncertainty for HVPP4 is 15.9%*
- The uncertainty on measured leakage current for LHC Run 2 Power Supply modules is 11.2%, calculated by adding the following uncertainties in quadrature:

| | Hardware | Current Precision | Temperature Precision | Temperature Offset | Total |
|---|---|---|---|---|---|
| HVPP4 | 12.0 | 0.5 | 2.9 | 10.0 | 15.9 |
| Power Supply | 4.0 | 0.5 | 2.9 | 10.0 | 11.2 |

* ATL-INDET-PUB-2014-004
** https://twiki.cern.ch/twiki/bin/view/Atlas/LuminosityForPhysics

# Other Uncertainties

- The uncertainty for the scaled Hamburg Model is given by the table below:

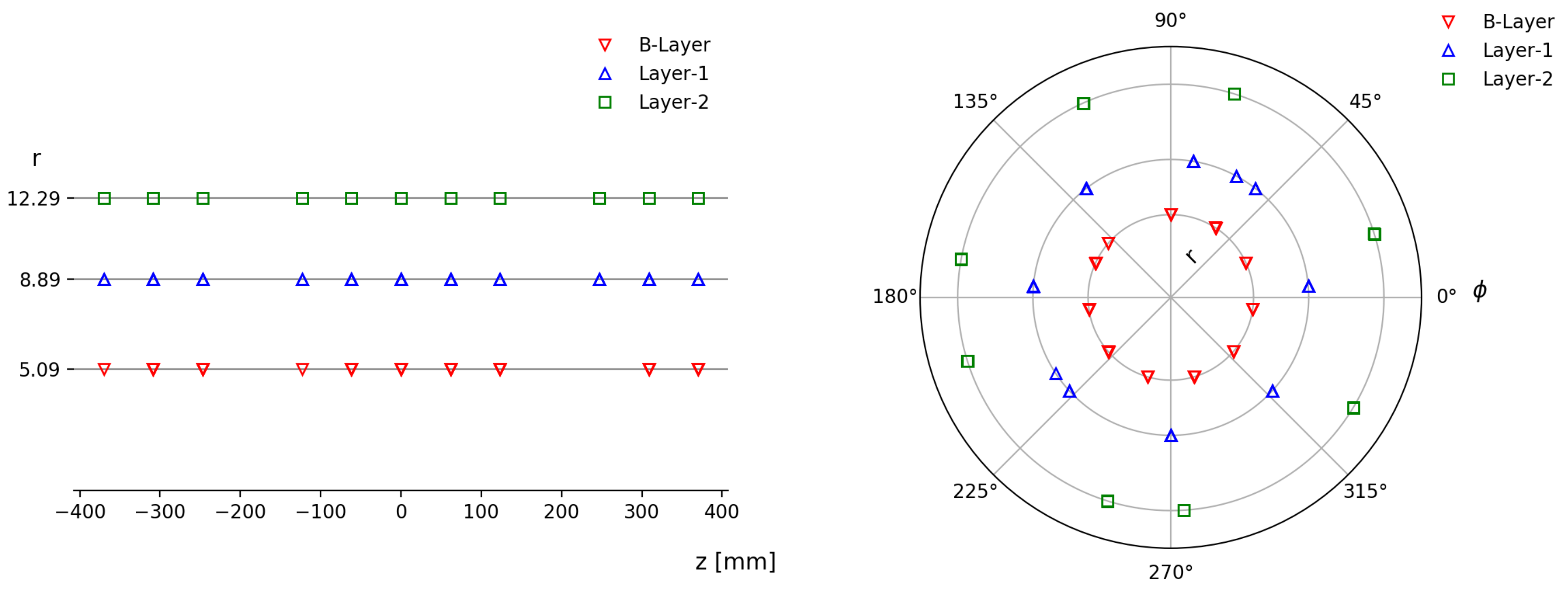
The Scale Factor uncertainty is obtained from the fitting procedure output from ROOT. The fit finds a constant that best fits the ratio of the data to the model, and this function includes an uncertainty.

| | Scale Factor | Temperature Precision | Temperature Offset | Total |
|---|---|---|---|---|
| Scaled Hamburg Model | 1.6% | 2.9% | 10.0% | 10.5% |

- The Pythia8 + FLUKA predicted fluence uncertainty is 1.0% (statistical only)
- The uncertainty for the fluence obtained from the Hamburg Model scaled to the leakage current

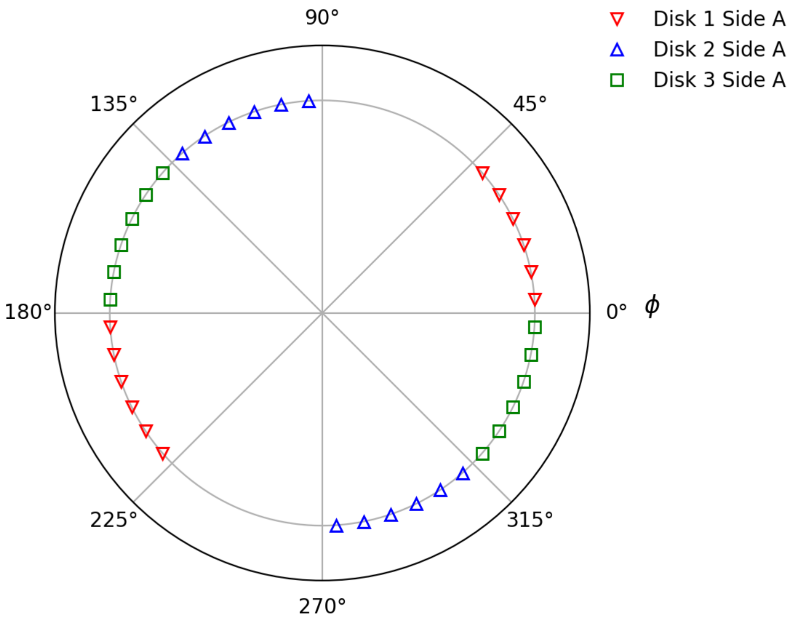
| | Scale Factor | Hardware | Temp. Precision | Temp. Offset | Predicted Fluence | Total |
|---|---|---|---|---|---|---|
| Extracted Fluence | 1.6% | 4.0% | 2.9% | 10.0% | 1.0% | 11.3% |

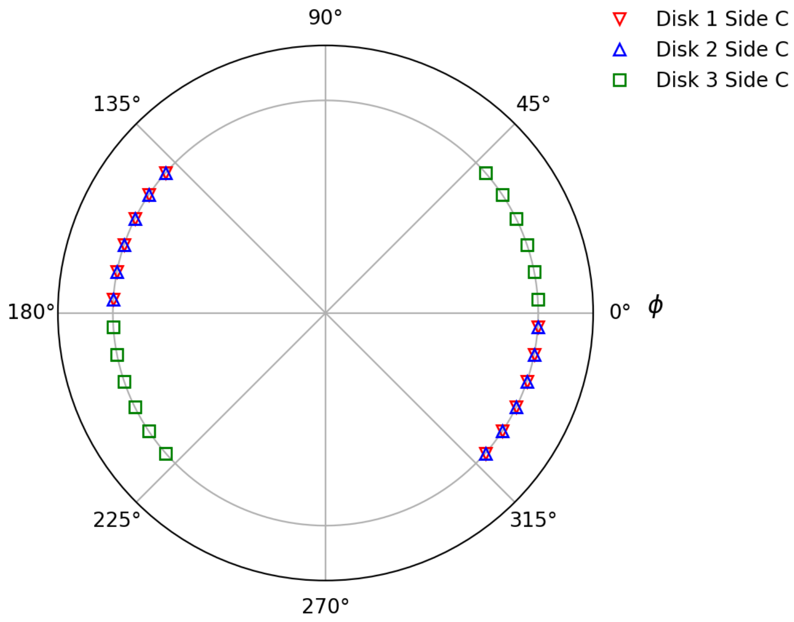
# Barrel Module Locations




- The positions of modules in φ and r on the barrel layers

# Disk Module Locations




- The positions of modules in φ on the disks on side A (left) and side C (right). The modules on each disk are centered at a radial distance of 119.2 mm.

# 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

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

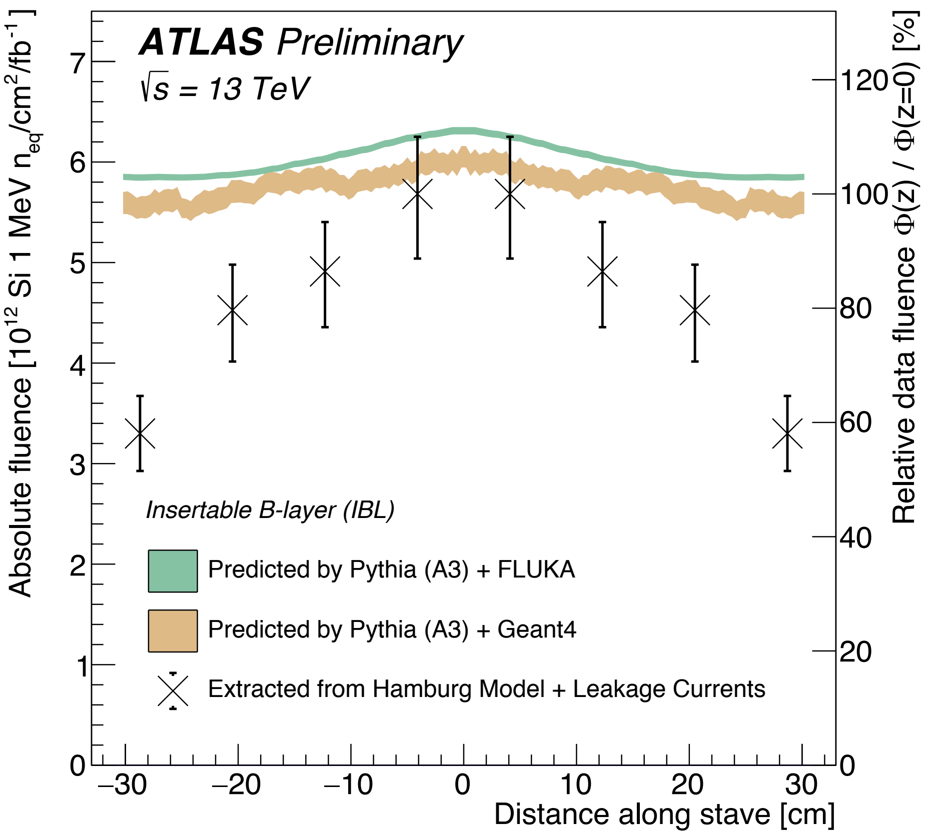
** S. Baranov et al., Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS, (2005), http://inspirehep.net/record/1196420/

† 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)




* 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

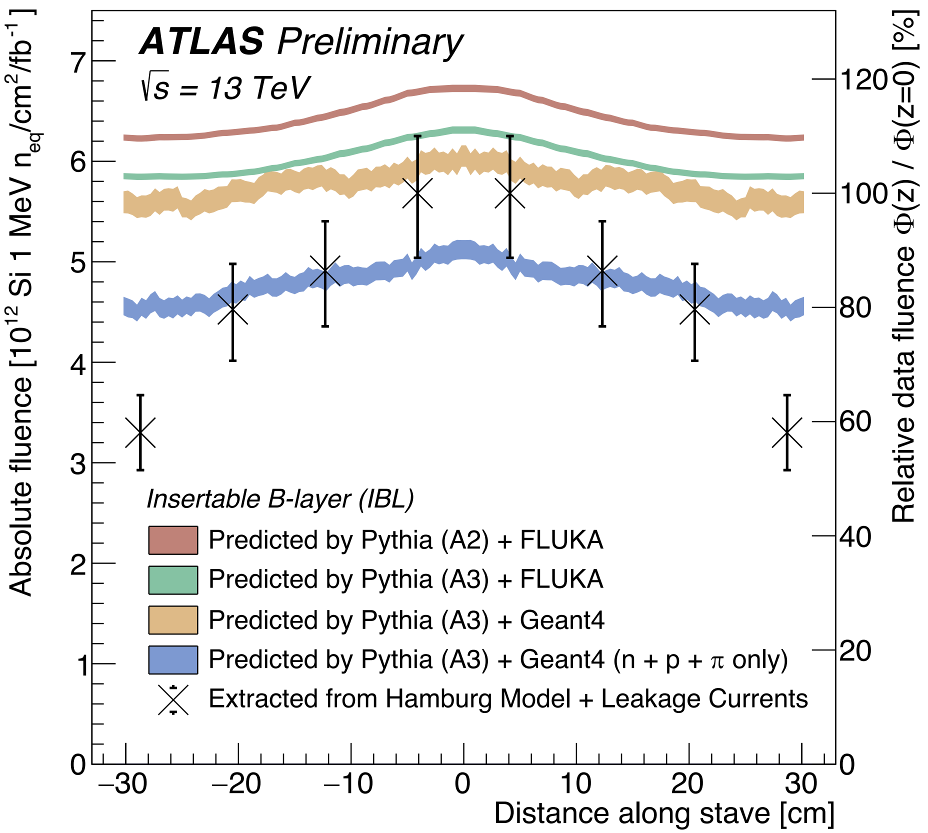
† ATLAS Collaboration, Summary of ATLAS Pythia 8 Tunes, ATL-PHYS-PUB-2012-003, https://cds.cern.ch/record/2206965

‡ 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/

# 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 backup slide 41