# Pixel Sensors cluster property measurements and simulations in the ATLAS Detector

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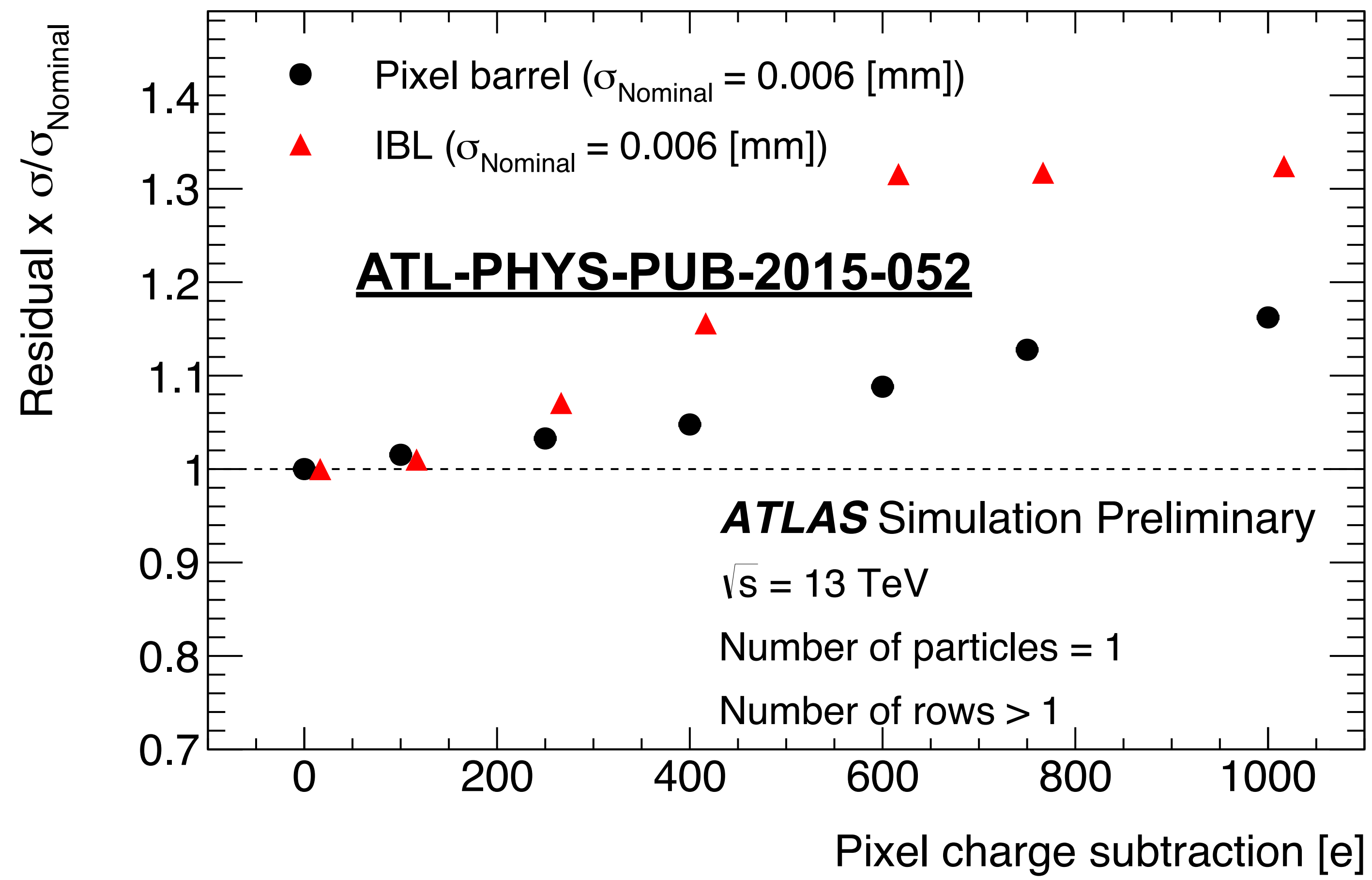
# Introduction - Radiation Damage

Leakage currents and depletion voltage have been monitored for a long time.

Less work on studies of cluster and track properties.

Different effects to account for:

- **reduced hit detection efficiency**
  - clusters are entirely lost if **all** pixel below threshold
- **reduced cluster size and worse resolution**
  - clusters are reduced in size if **some** pixel are below threshold



# Introduction - Radiation Damage

Tracking and pixel performance can directly impact physics analysis.

- Some analysis directly use clusters properties and are directly affected
- Many more analyses that use tracking, in the future will also be effected.

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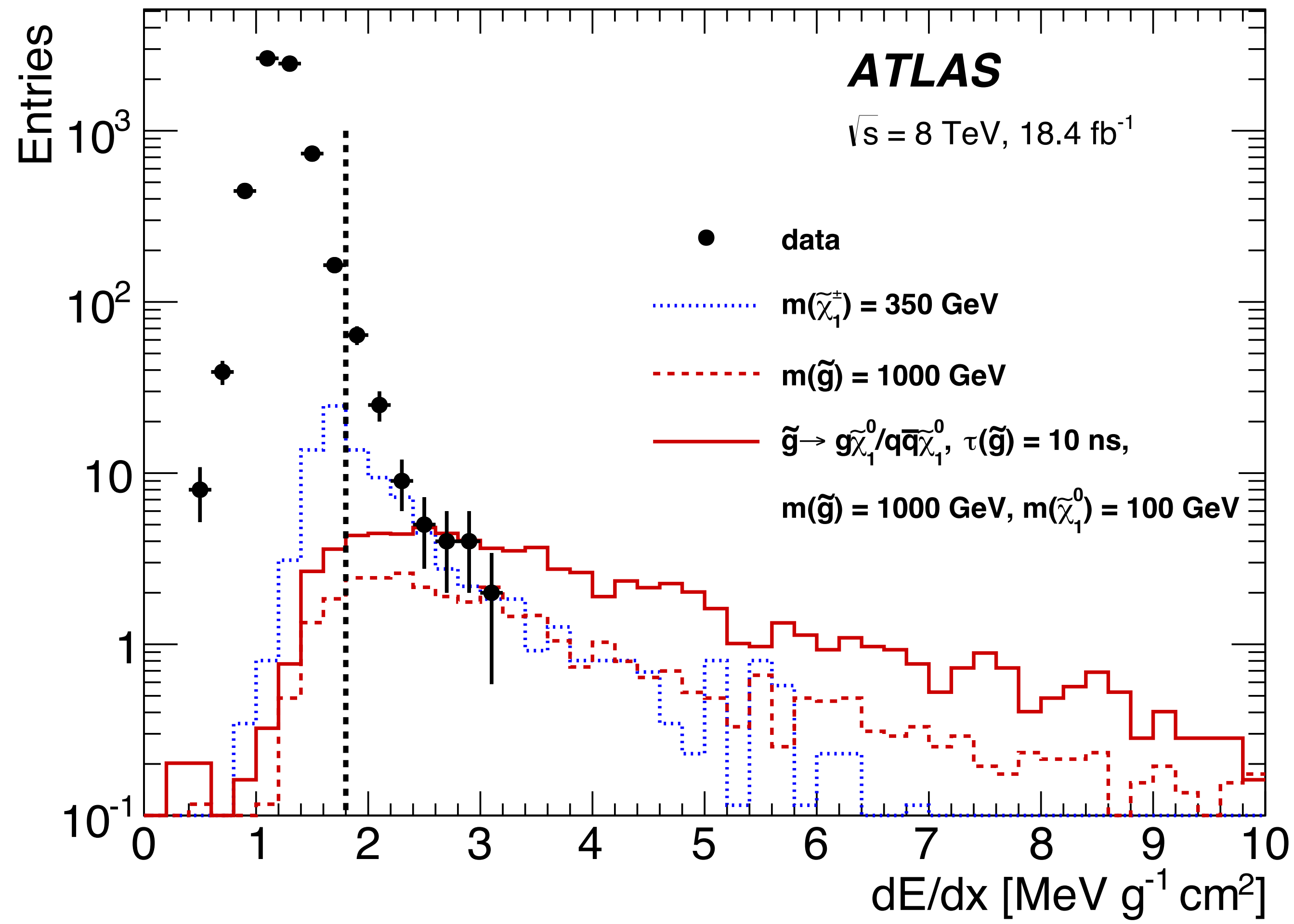



Important to account for these effects and have correct predictions

# Introduction - Prediction

Presenting results using a standalone tool (**Allpix**) based on Geant4 and the first full implementation in the ATLAS simulation framework (**Athena**).

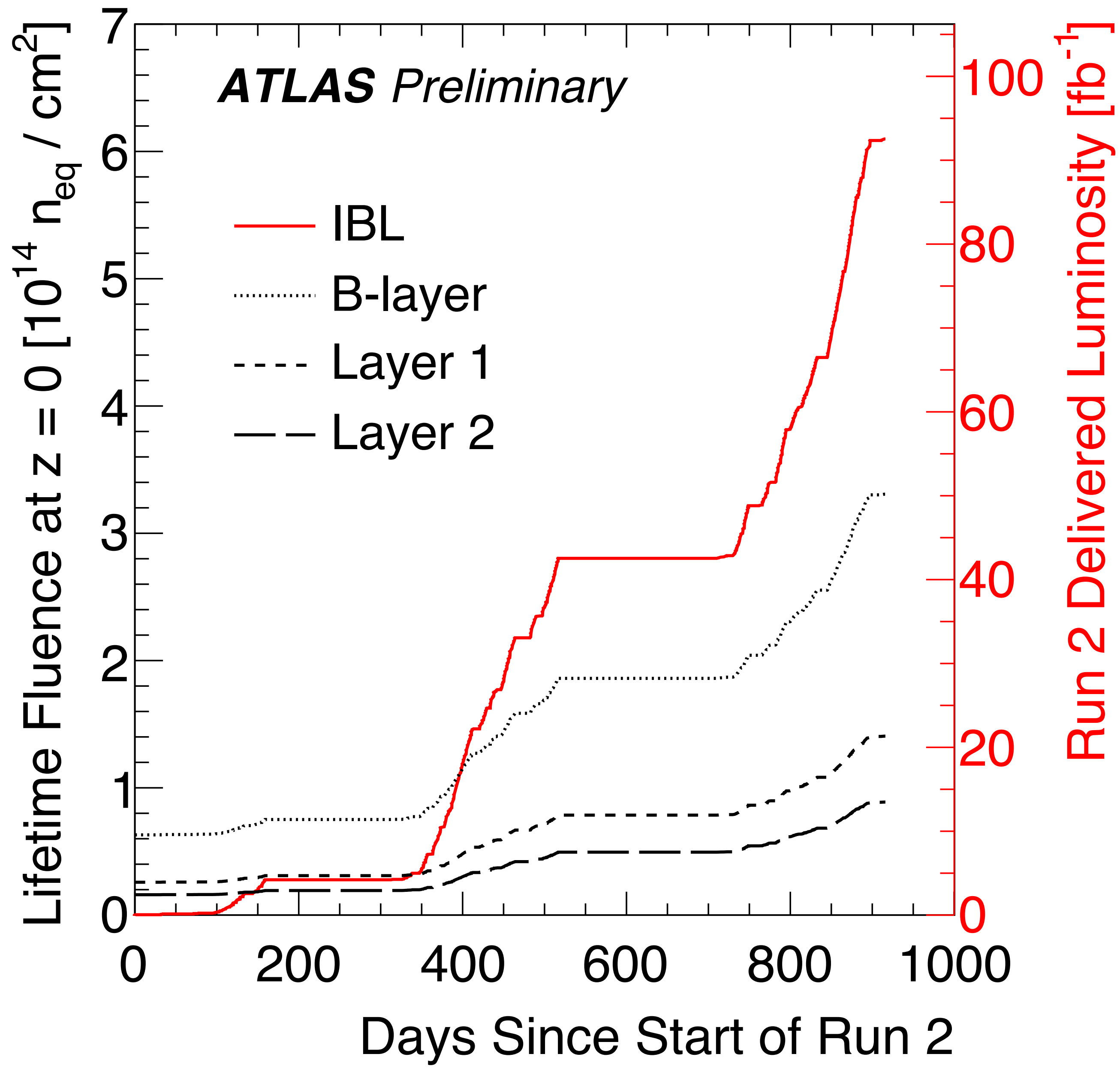
**Two important observable** sensitive to radiation damage:

- **Charge collection efficiency:** less charge collected due to trapping
  - MPV of fitted Landau
  - Normalized to 2015 data
  - sensors at $|\phi|=0$
- **Lorentz Angle:** radiation damage increase it
  - Function of incidence angle of the particles
  - Negligible for 3D sensors

# Fluence levels

High flux of particles means high radiation fluence on the sensor.

- Already enough fluence to study effects on sensors
- new IBL sensors are closer to the beam and already have much more fluence than the other layers that saw all of Run 1

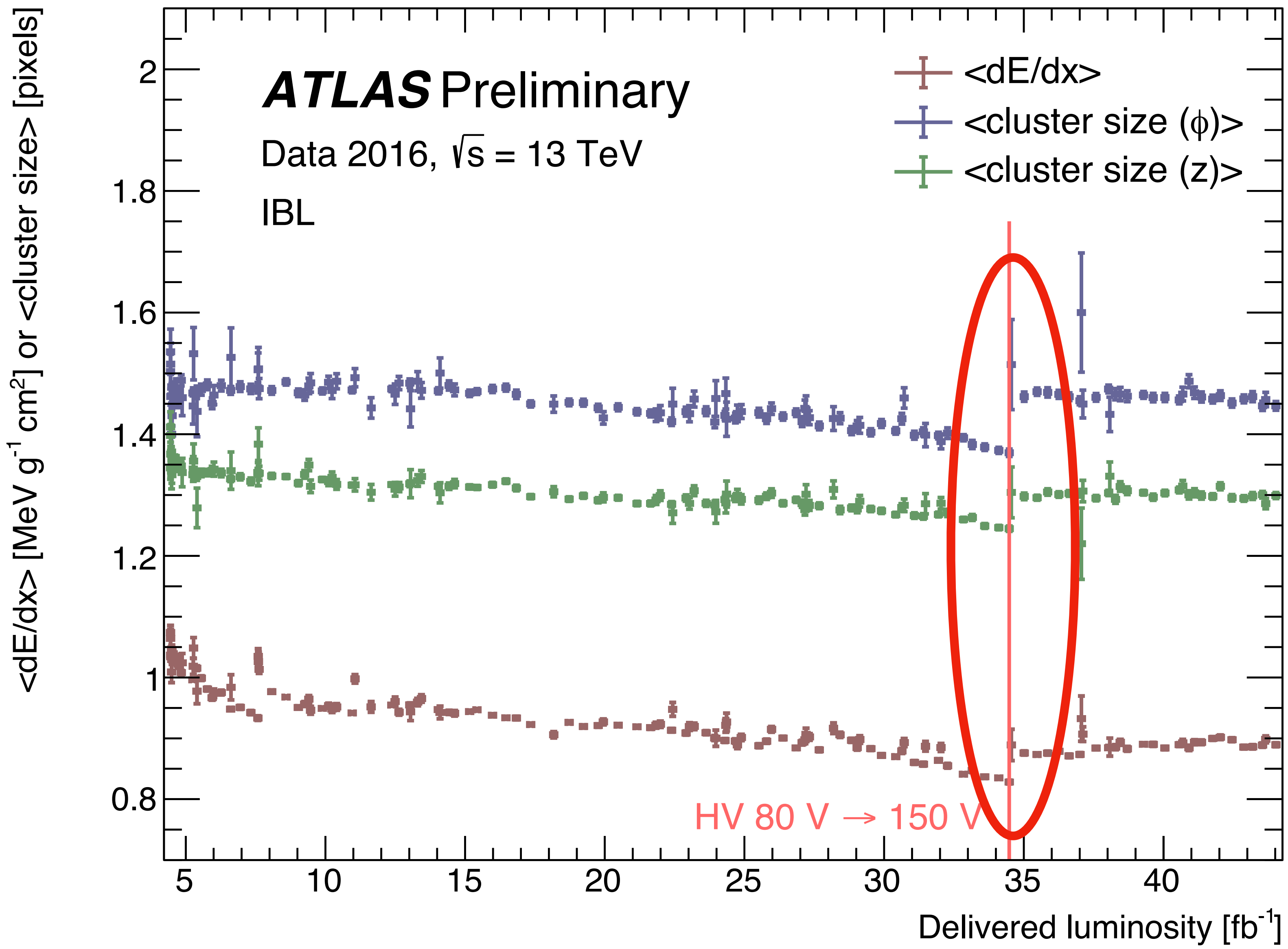


# ATLAS Pixel Detector Performance

Radiation damage effects in the sensor already visible

**Under Depletion**: average dE/dx and cluster size decrease and is recovered by increasing HV

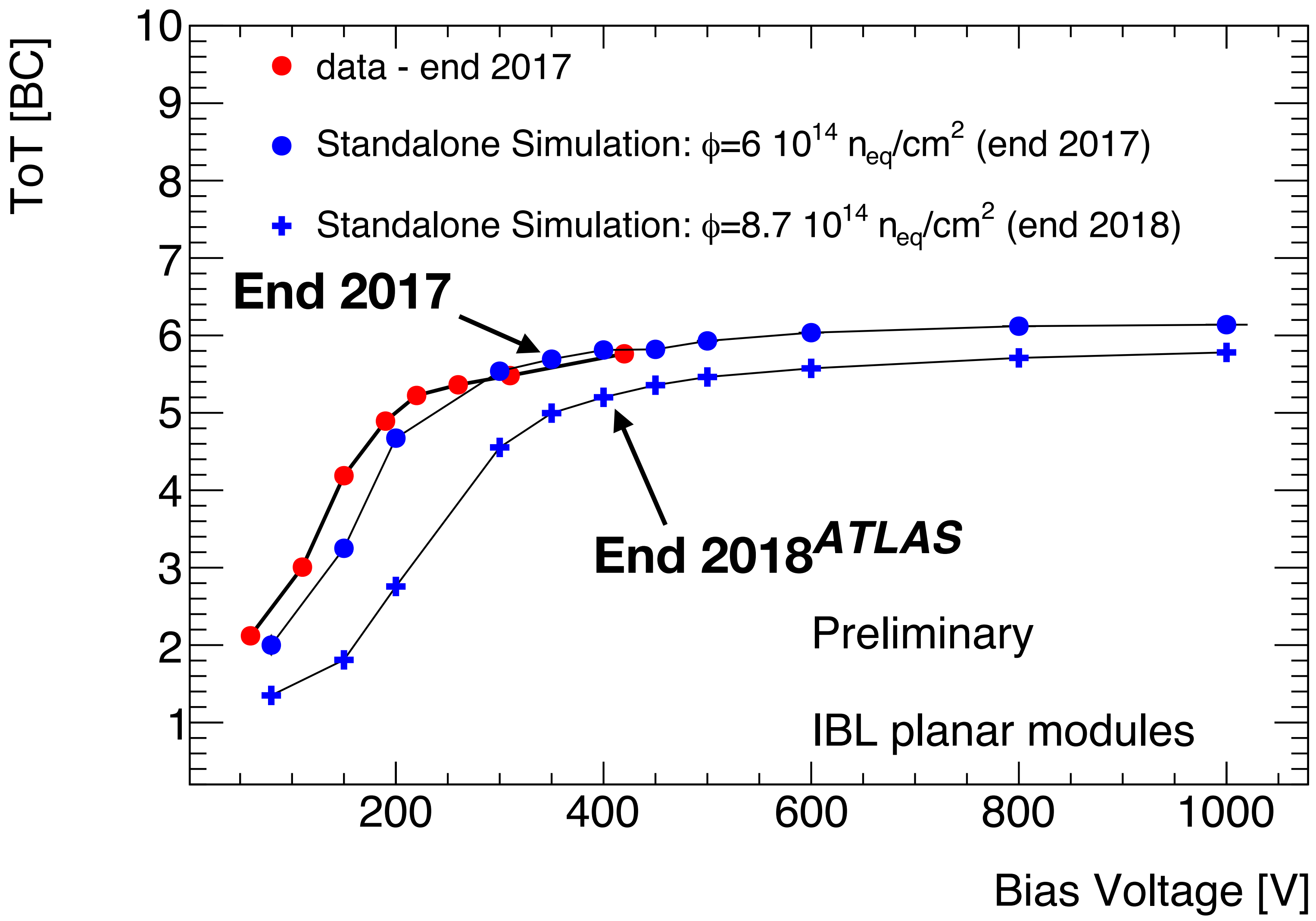
With our simulations we may be able to help predict it



# Bias Voltage Scan

Using standalone simulation (see slides from [Trento Workshop]) to predict MPV of the fitted landau distribution of the ToT as a function of bias voltage for fixed fluence.

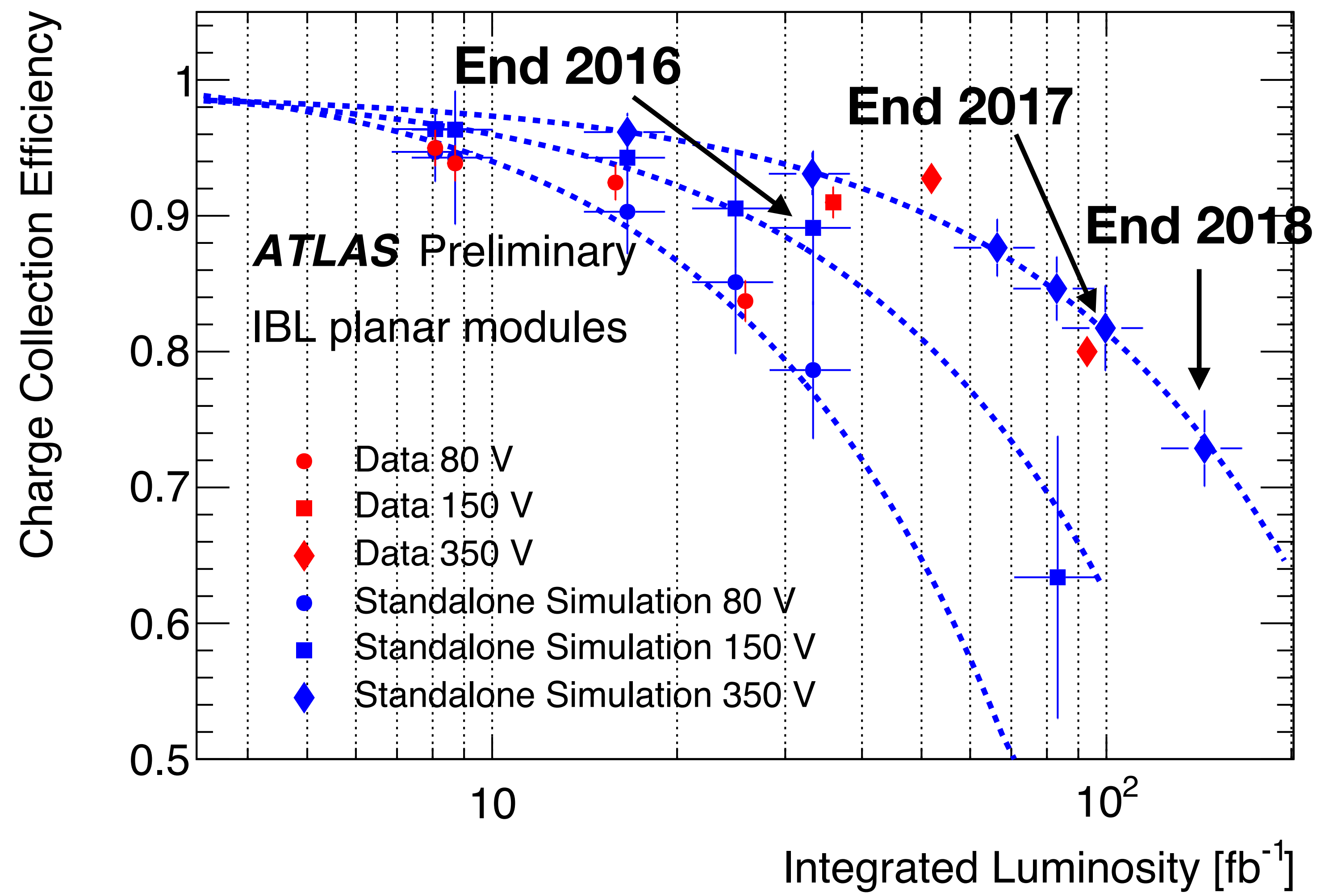
- Both data and simulation charge to ToT are tuned at the same value
- Good agreements in both shape and plateau position
- Correct Bias Voltage Working point to avoid under depletion



# Model Predictions and Data Comparison

Charge Collection Efficiency as a function of Luminosity for IBL with data from Run 2

- Using Trapping constant for electrons and holes:
  - $\beta_e = 4.5 \pm 1.0 \ 10^{-16} \text{cm}^2/\text{ns}$
  - $\beta_h = 6.5 \pm 1.5 \ 10^{-16} \text{cm}^2/\text{ns}$
- Simulation points error bars
  1. x: 15 % on fluence-to-luminosity conversion
  2. y: radiation damage parameter variations
- Data points error bars
  1. x: 2% on luminosity
  2. y: ToT-charge calibration drift



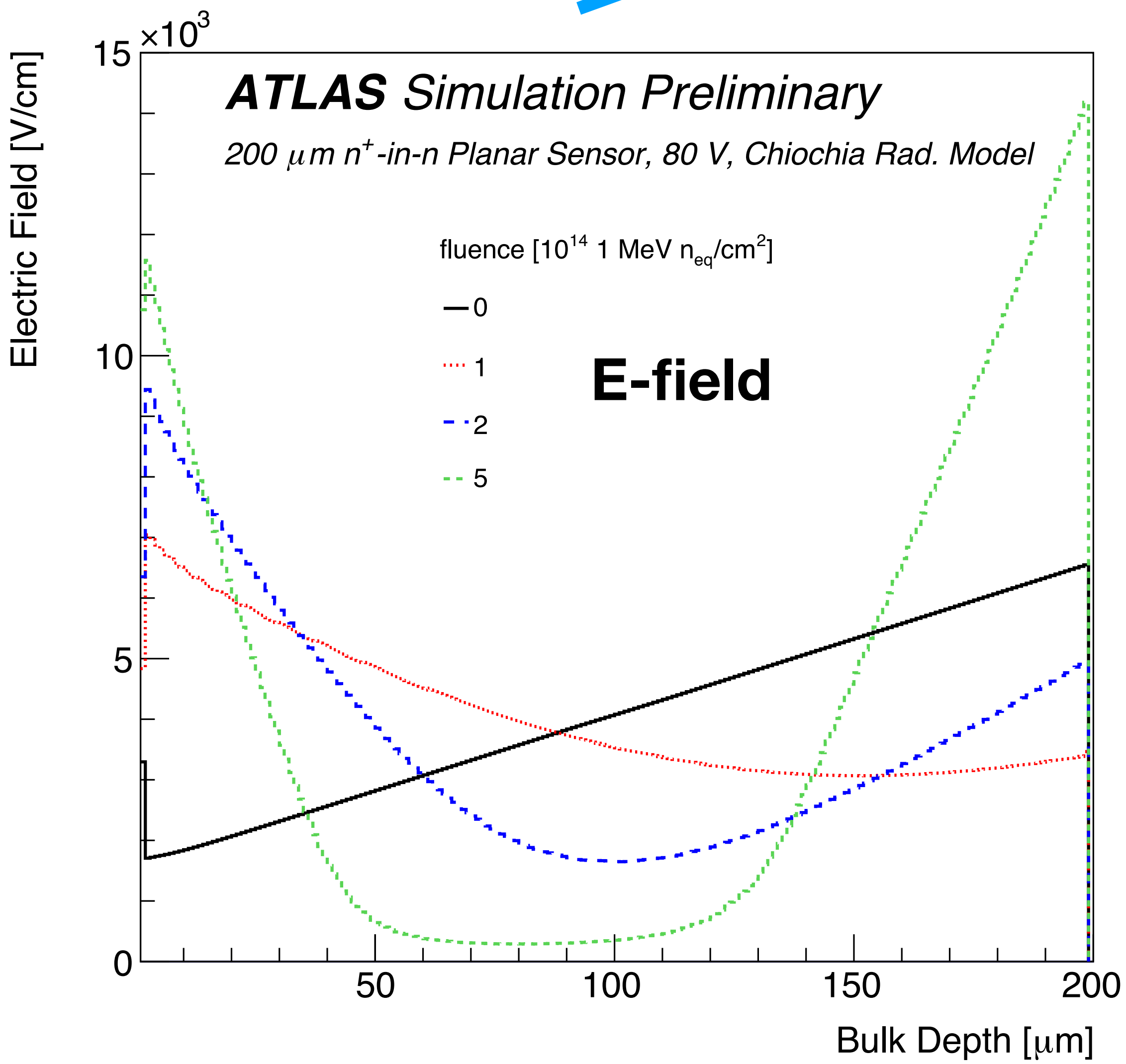

Good agreement with data, but very large uncertainties
Essential to understand what operational condition to use in the future

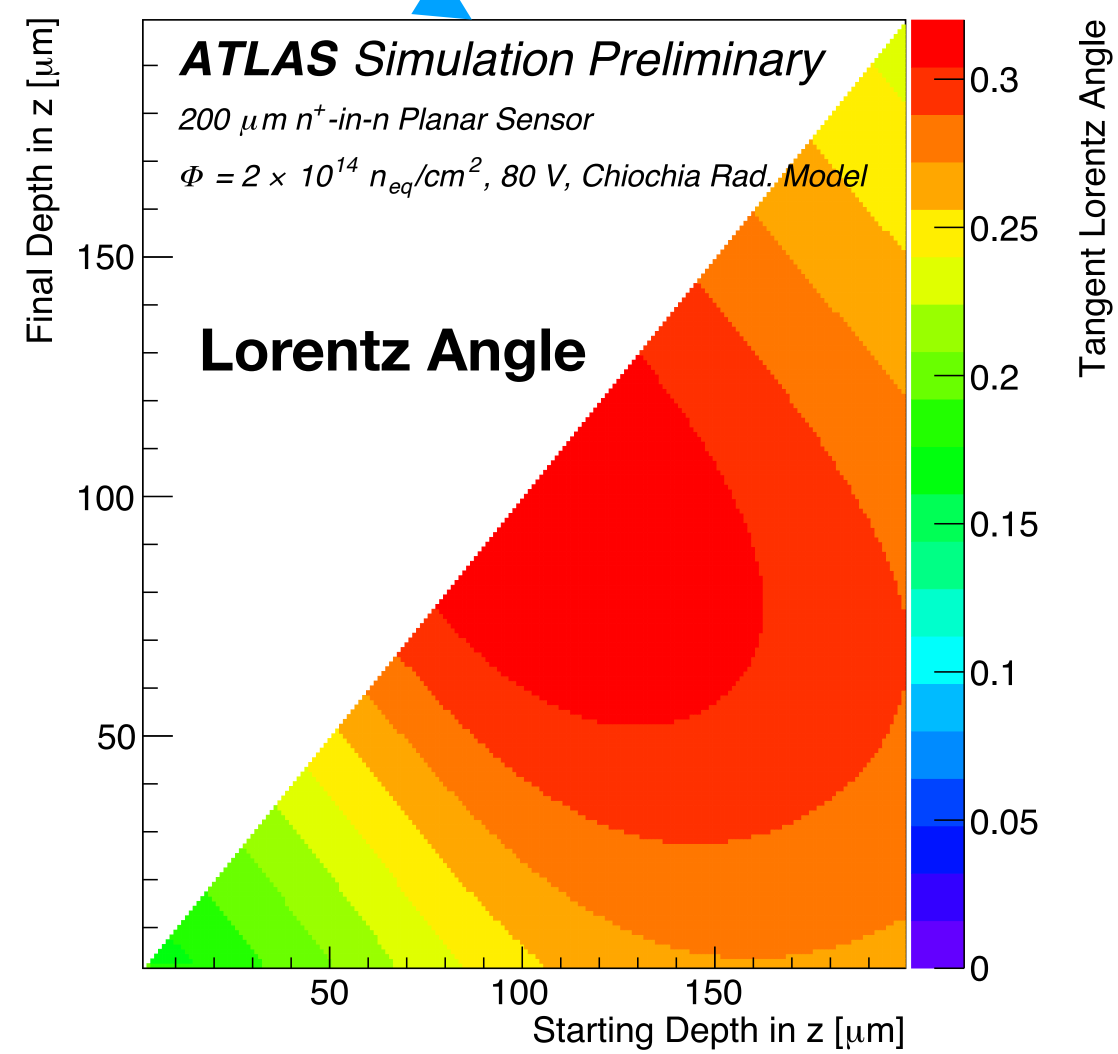
# Lorentz angle

Hall scattering factor

Lorentz Angle: $$\tan\theta_L^{integrated}(z_{initial}, z_{final}) = \frac{rB}{|z_{final} - z_{initial}|}\int_{z_{initial}}^{z_{final}} \mu(E(z))dz$$

Mobility




**Intrinsic dependence on the E field and final and initial position**

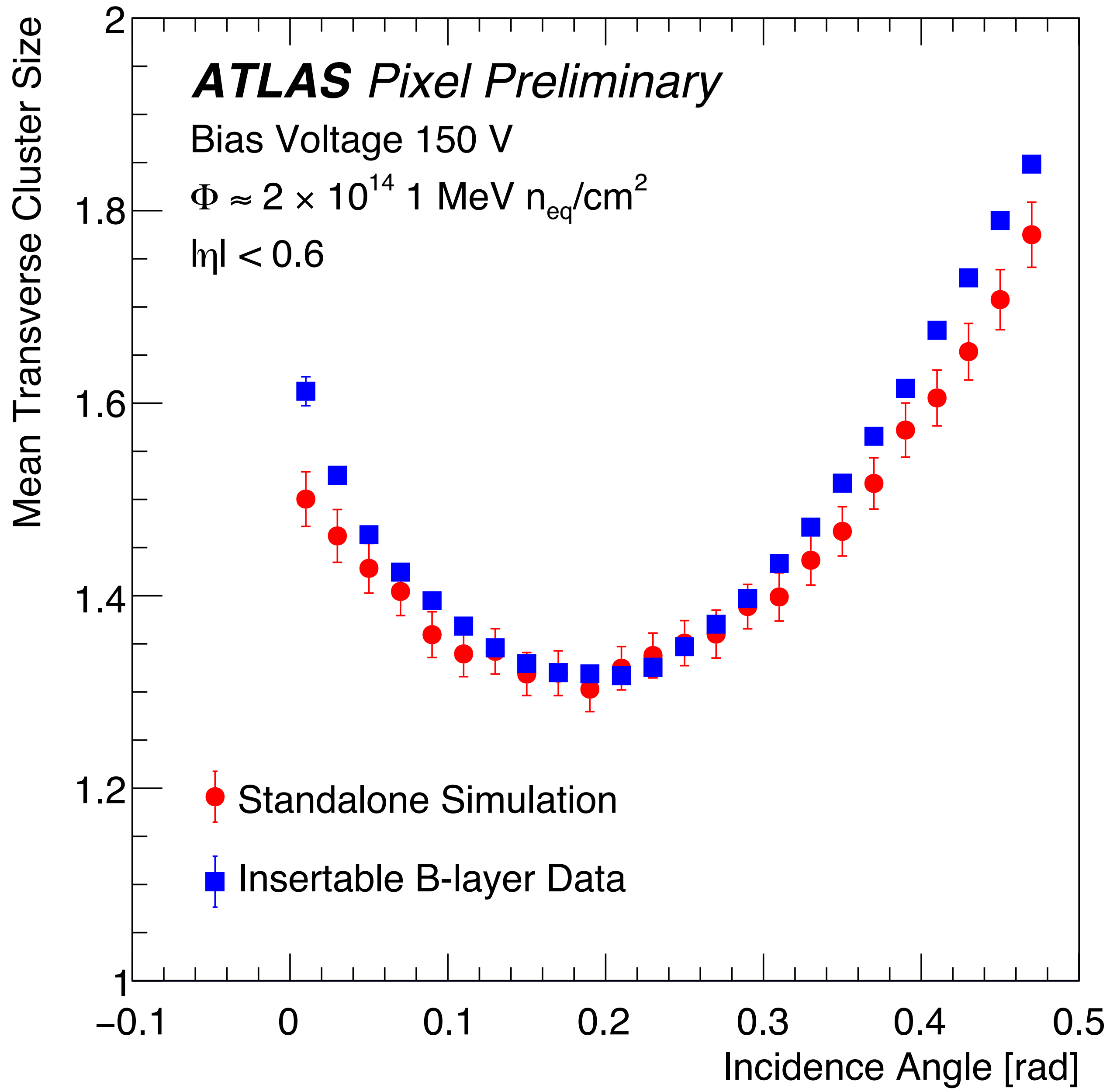
# Lorentz Angle

Mean transverse cluster size distribution as a function of incidence angle on the module

- The IBL was operated at -150 V in 2016
- Fit distribution with:

$$F(\alpha) = [a \times (\tan\alpha - \tan\theta_L) + b/\sqrt{\cos\alpha}] \oplus G(\alpha)$$

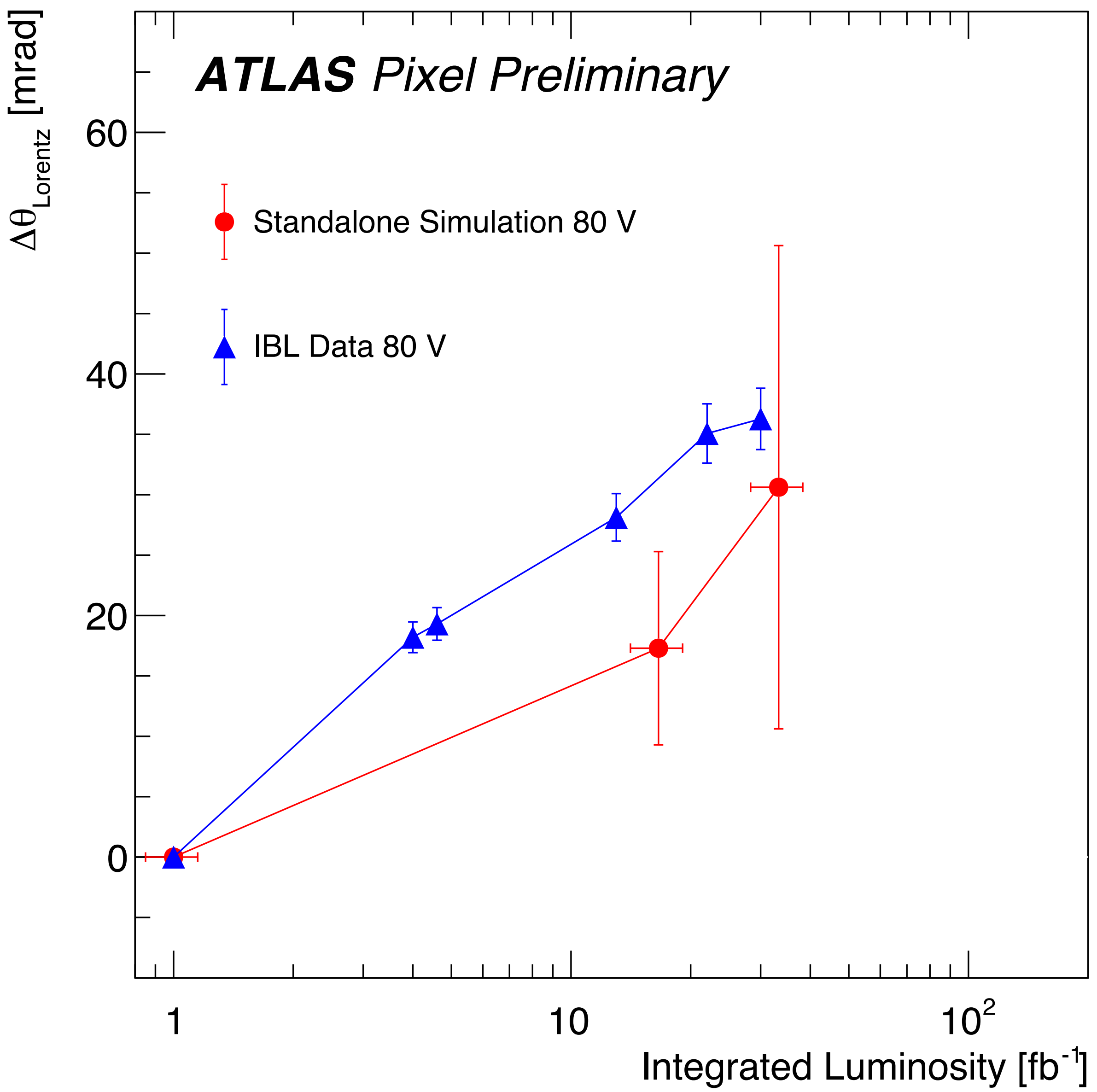
  - $\alpha$ is the incidence angle
  - $G(\alpha)$ a gaussian function
  - $\theta_L$ is the Lorentz Angle



# Lorentz angle

Fit Lorentz Angle from data and simulation. Plot as a function of integrated luminosity

- Lorentz Angle not sensitive to trapping, so it provides orthogonal information to CCE.
- Difference of Lorentz angle from first point
- Errors include variations of the radiation damage parameters




Trend is robust but we can’t make precise predictions yet (very sensitive to radiation model parameter variations)

# Spatial resolution

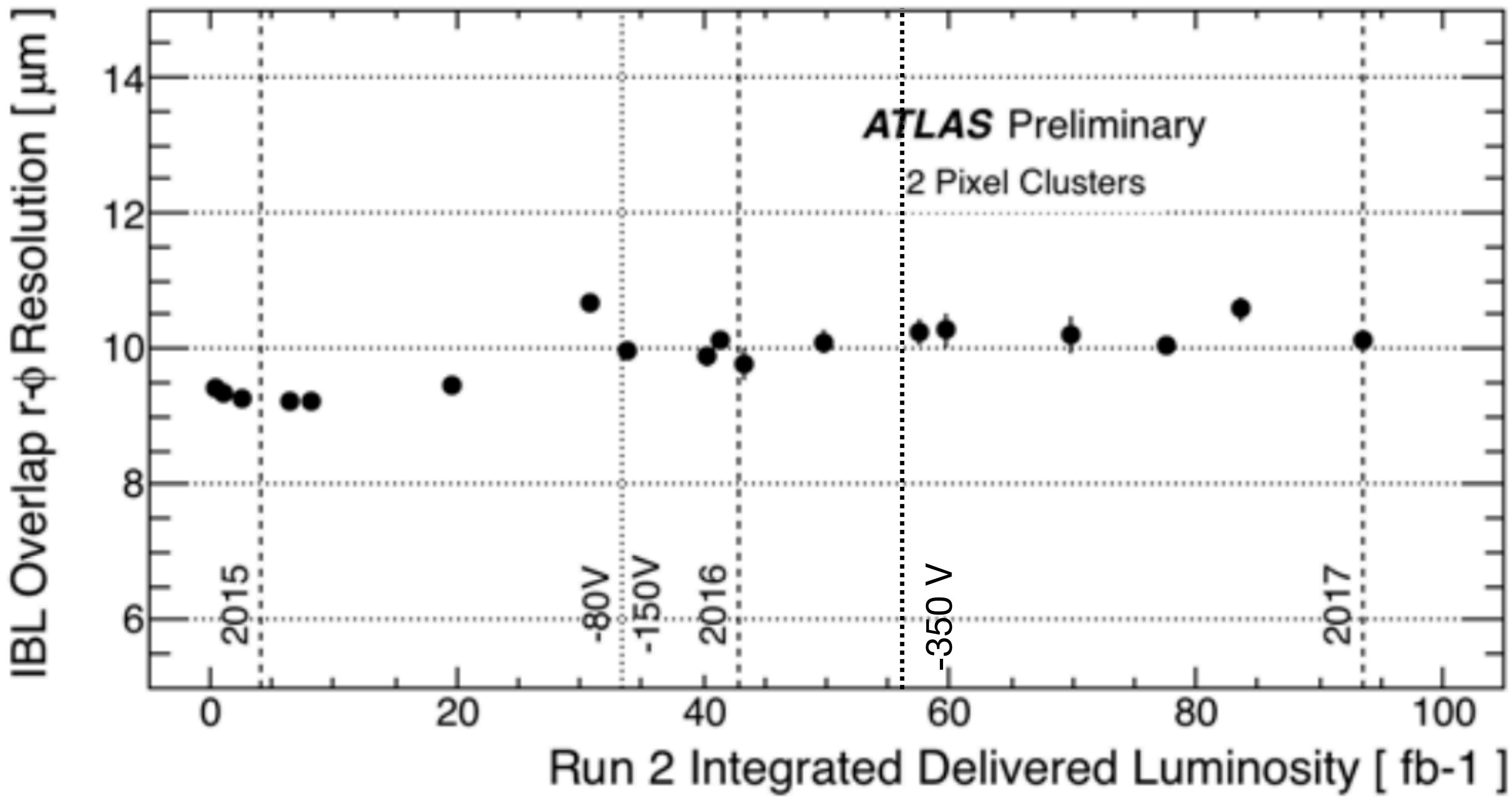
Not yet a huge impact on spatial resolution.

Effects from different sources: Change in HV, temperature and tuning.

Determined by the corrected transverse positions of the two reconstructed IBL clusters associated to a charged particle track in the regions where the IBL modules overlap.
See: **ATL-INDET-PUB-2016-001**.

Using only clusters with two pixels in the transverse coordinate.

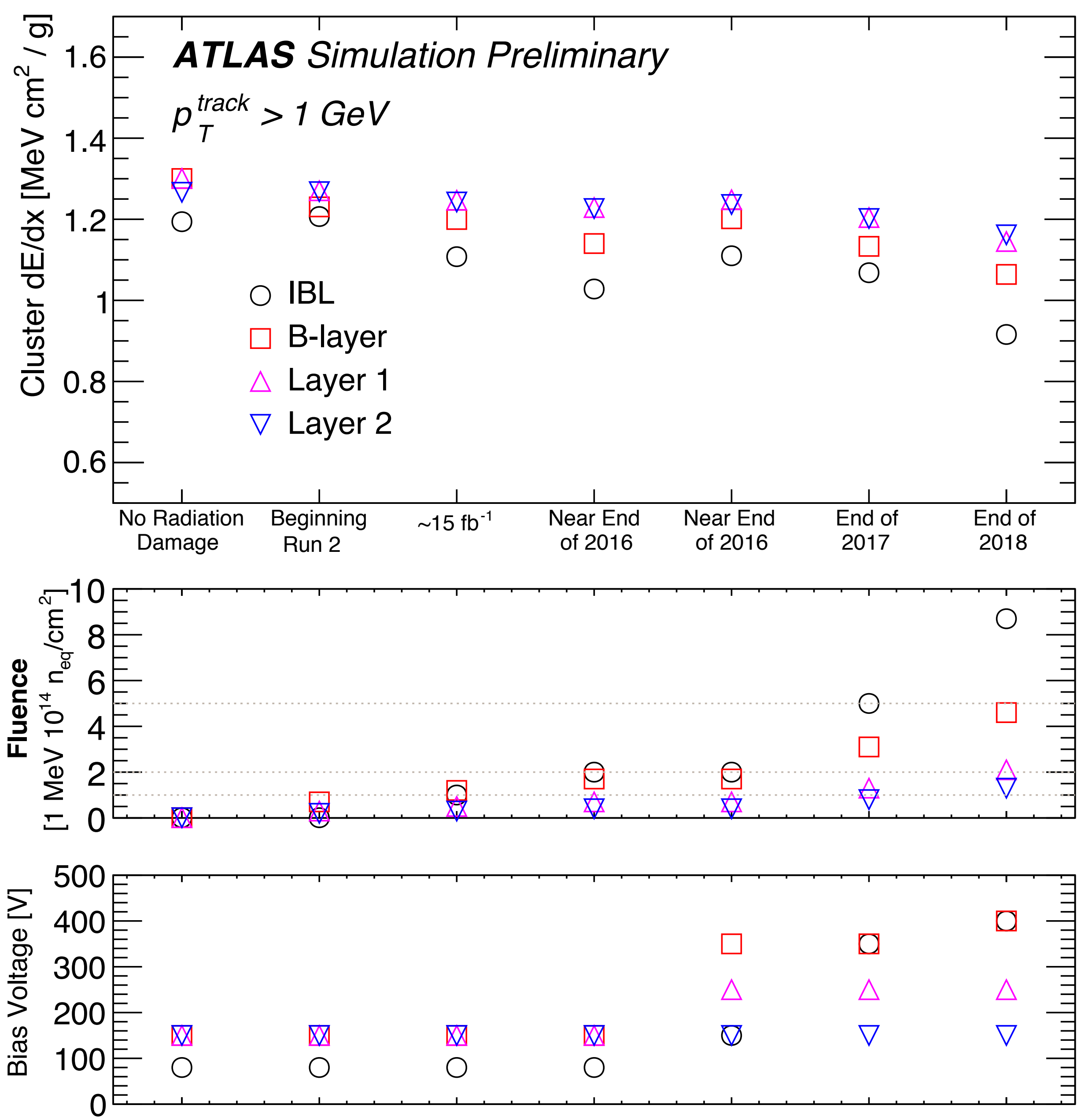
Reweighting run-by-run to ensure that their |η| distribution is constant for the dataset



# Outlooks: Full ATHENA simulation

Simulations now integrated in the ATLAS Simulation framework.
First results to use for predictions for operations

- Average of cluster dE/dx for tracks with $p_T$>1 GeV
- Only some “benchmark” point to summarize detector behavior.
- Lower boxes indicate:
  - corresponding fluence
  - corresponding bias voltage

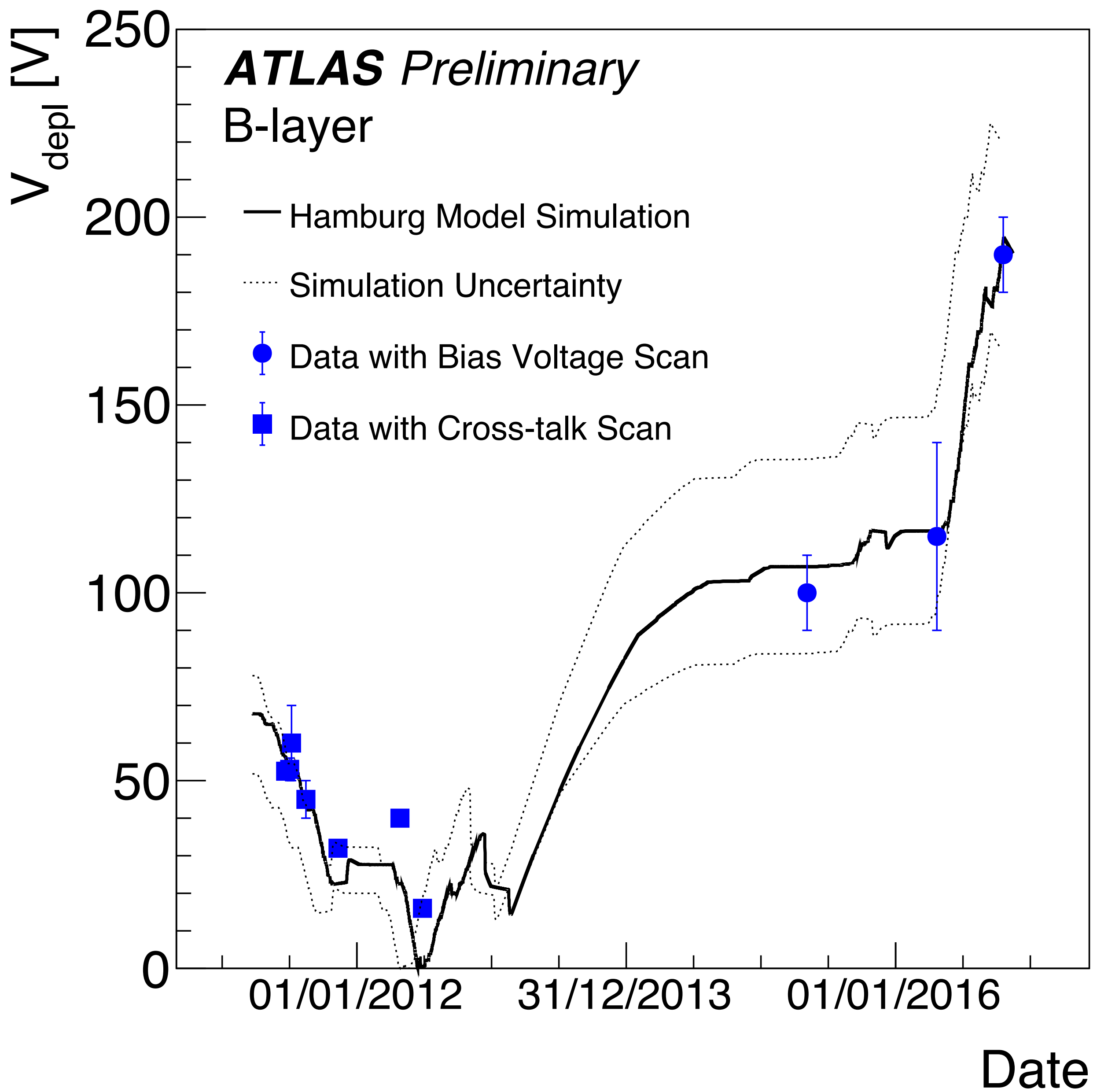


# Outlooks: Annealing

TCAD simulation doesn't account for thermal history: no annealing effects included

Use Hamburg Model to model annealing:

- set the average charge distribution in the sensor to match the $N_{eff}$ concentration predicted by Hamburg model.
- Hamburg model fitted to data.
- See talk from Julien: [here]
- Ad hoc correction. Will probably not work on the long term




Need more viable solutions when annealing is very important and Hamburg model assumptions (uniform space charge) break down

# Conclusions

- Effects of radiation damage are already visible
  - Charge loss (dE/dx)
- Not a huge impact on spatial resolution
- We produced simulations that are in good agreement with Run 2 data, in terms of
  - Charge collection efficiency
  - Lorentz angle
- Predictions useful for:
  - Decide pixel detector operation condition
  - Improve our modeling of data for physics analysis
- We are now prepared to model the radiation degradation for Run 2+3 and for HL-LHC

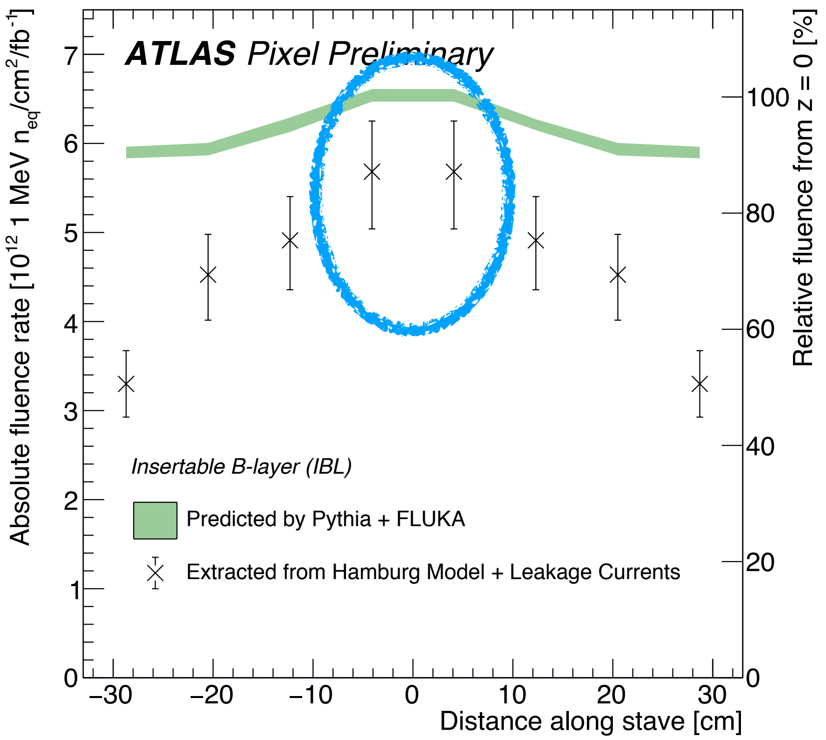
# Conclusions

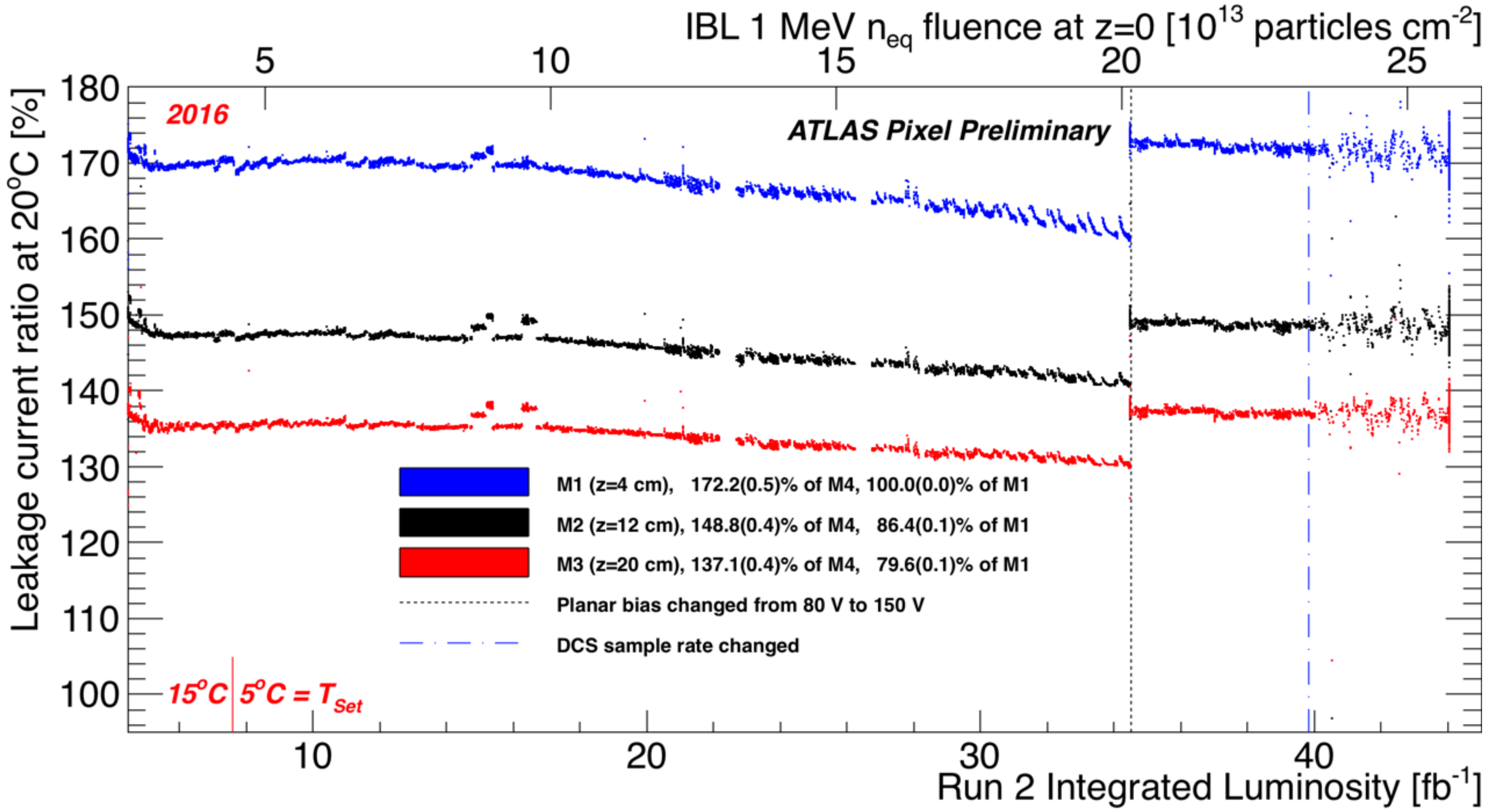
**BACK UP**

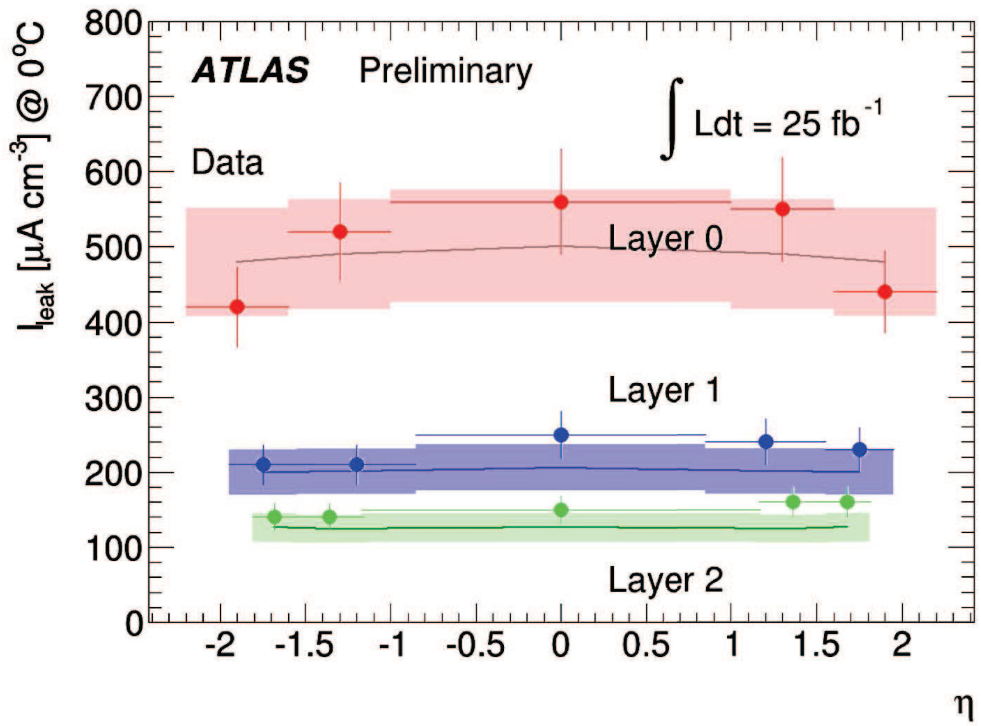
# Fluence

Fluence prediction taken from FLUKA + Pythia

- FLUKA prediction validated with leakage current and Hamburg model:
  - Assign 15% uncertainties in the central region (|z|~0)



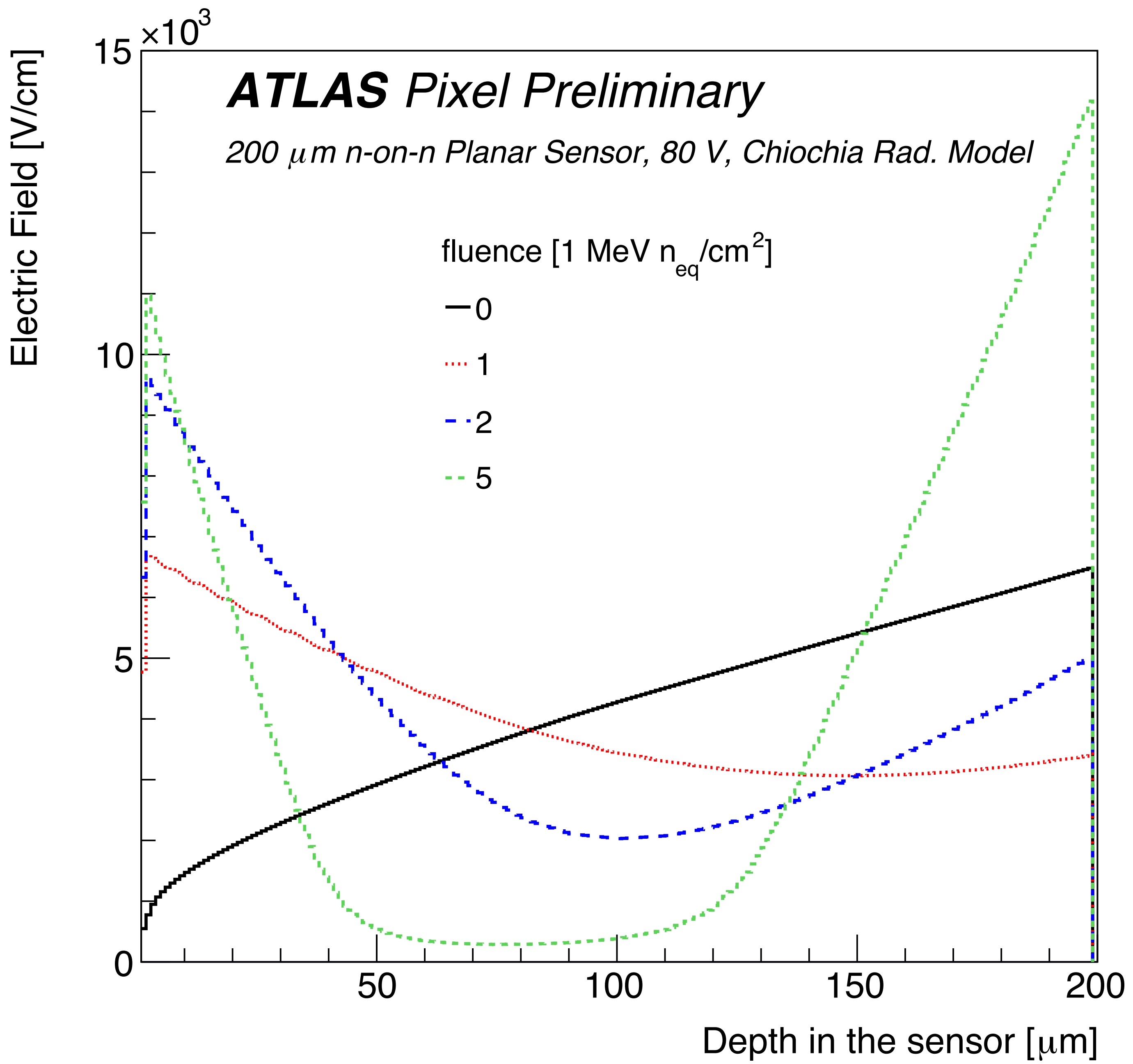



# Electric Field simulations

Radiation damage produces defects in the sensor that change the effective doping concentration

- Depletion voltage and Electric Field profile depends on:
  - Fluence
  - Type of irradiation
  - Temperature during and after irradiation (annealing)
- Electric Field is simulated with **TCAD** technology
  - **TCAD first step on which build the simulations**
- Typical double junction effect well described →"U" shaped E-Field




Radiation Damage model from: V. Chiochia et al., Nucl. Instr. and Meth A 568 (2006) 51-55

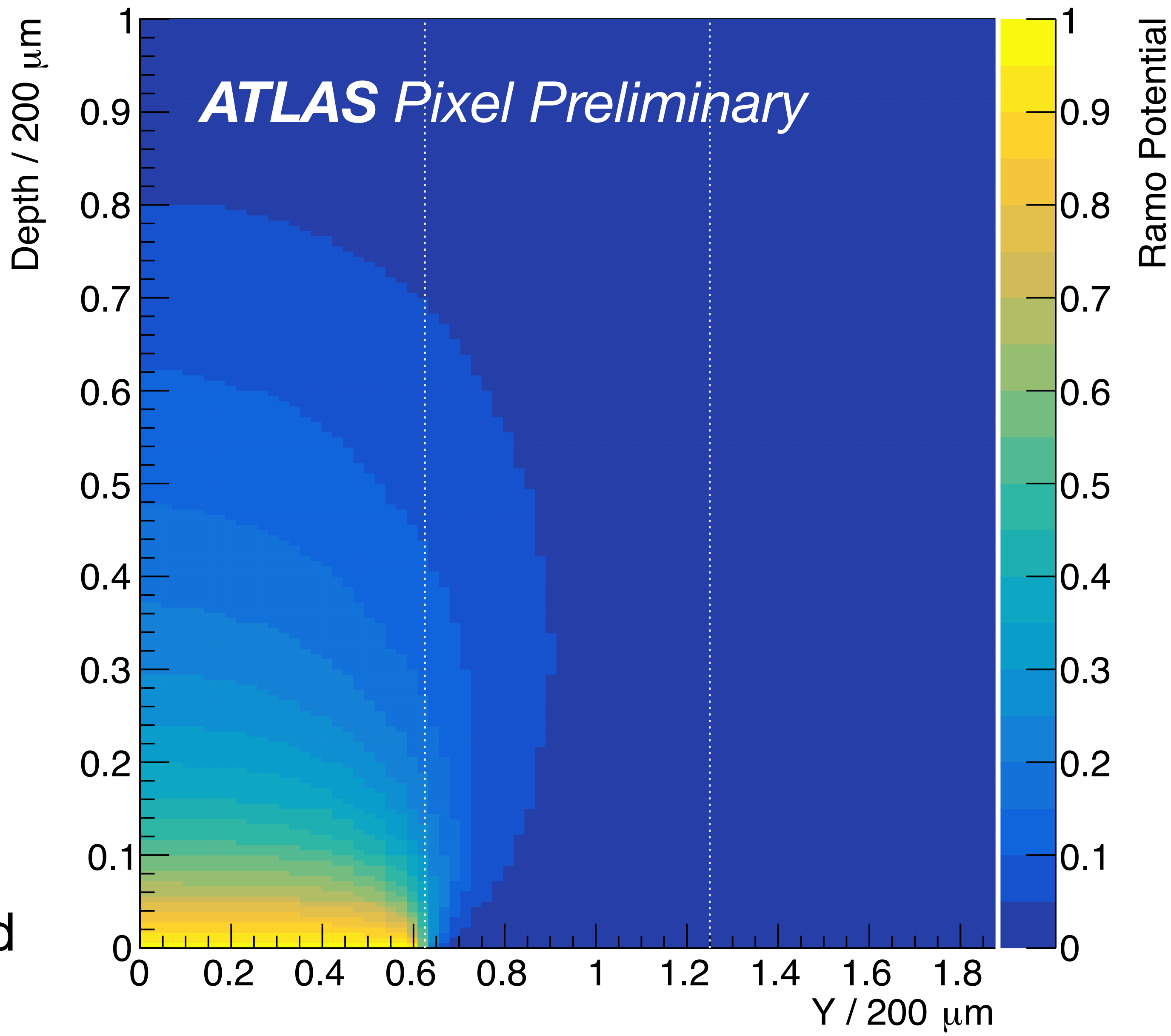
# Trapping probability

Defects form in the silicon and are sites for charge trapping

Charges are trapped if the time to reach the electrode is larger than a trapping time $\tau$

- $\tau$ is a random variable exponentially distributed with mean value $1/(\beta_{h/e}\phi)$
  - $\phi$ is the fluence
  - $\beta_{h/e}$ is the trapping constant: different for electrons and holes
  - $\beta_e = 4.5 \pm 1.0 \;\; 10^{-16}\, cm^2/ns$
  - $\beta_h = 6.5 \pm 1.5 \;\; 10^{-16}\, cm^2/ns$
  - Average of neutron and proton irradiation studies
- Trapped charges induce a partial signal on the electrode, given by:
  - $-q(R_f - R_i)$:
- $R_f$ and $R_i$ are the Ramo potential in final and initial positions

TCAD model of an ATLAS IBL module



# Trapping probability

Different trapping constant for electrons and holes

- Trapping probability depends on time of annealing
- Different results for type of irradiation (protons vs neutrons) and temperature
- Two main sources for these values
  - G. **Kramberger** et al., NIM A481 (2002) 297. Plot: trapping constant as a function of annealing time
  - O. **Krasel** et al., IEEE Trans. Nuc. Sci. 51 (2004) 3055. Plot: mean half life for $\phi=4\cdot10^{14} n_{eq}/cm^2$
- In simulation use average of two values
- Errors account for:
  - differences between two groups
  - annealing effects
  - measures uncertainties