Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

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on behalf of the ATLAS Collaboration

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ATLAS Pixel Detector

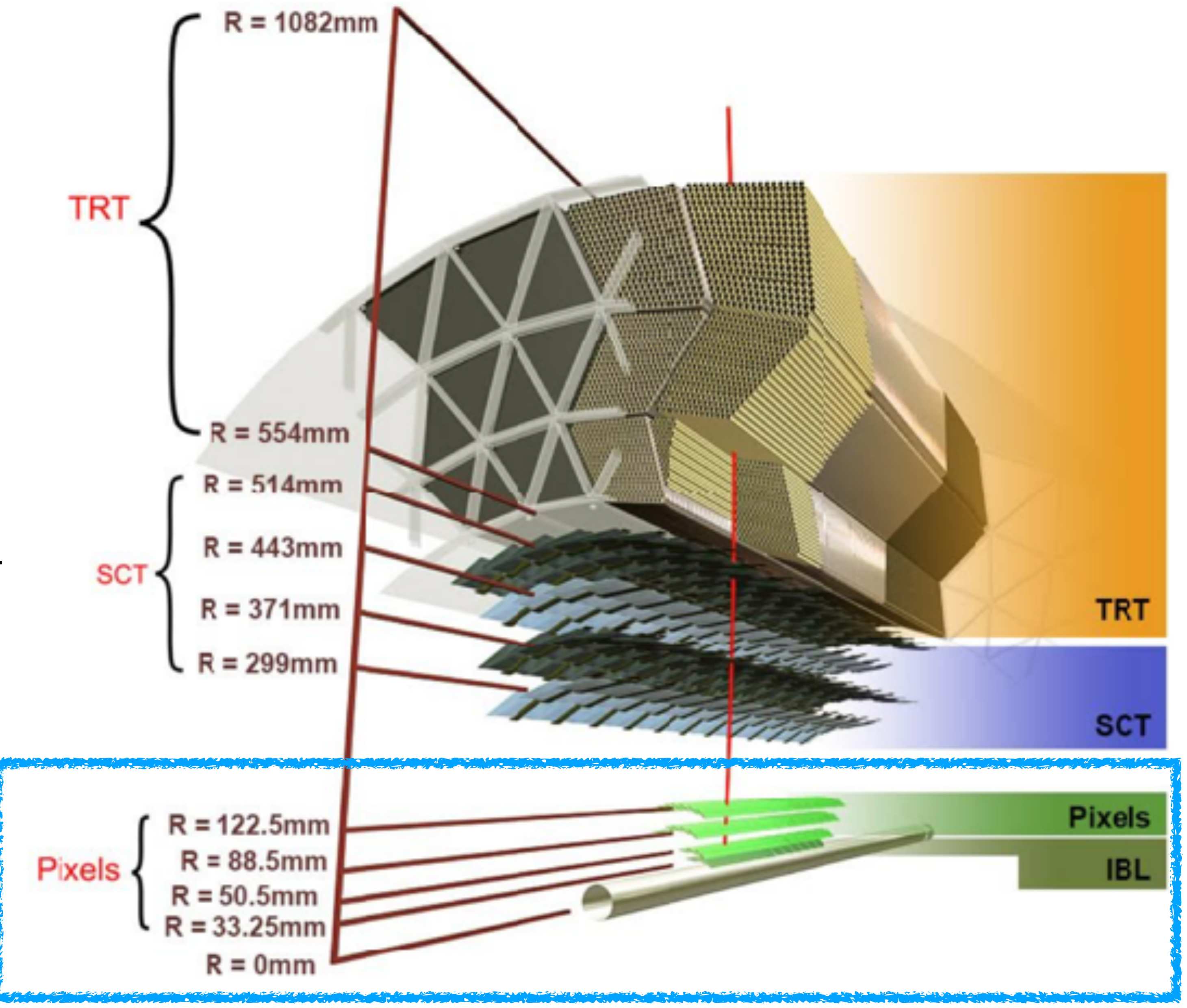
Pixel detector is the innermost layer of the ATLAS detector: High flux of particles!

4 Barrel layers + 6 Disk Layers (3 at each end) with different geometry and technology

n+ in n sensors technology

- Three outermost layers
  - B-Layer, Layer 1 and 2
  - 50 x 400 μm^2
  - 250 μm thickness
  - FEI3 readout - 8 bit ToT

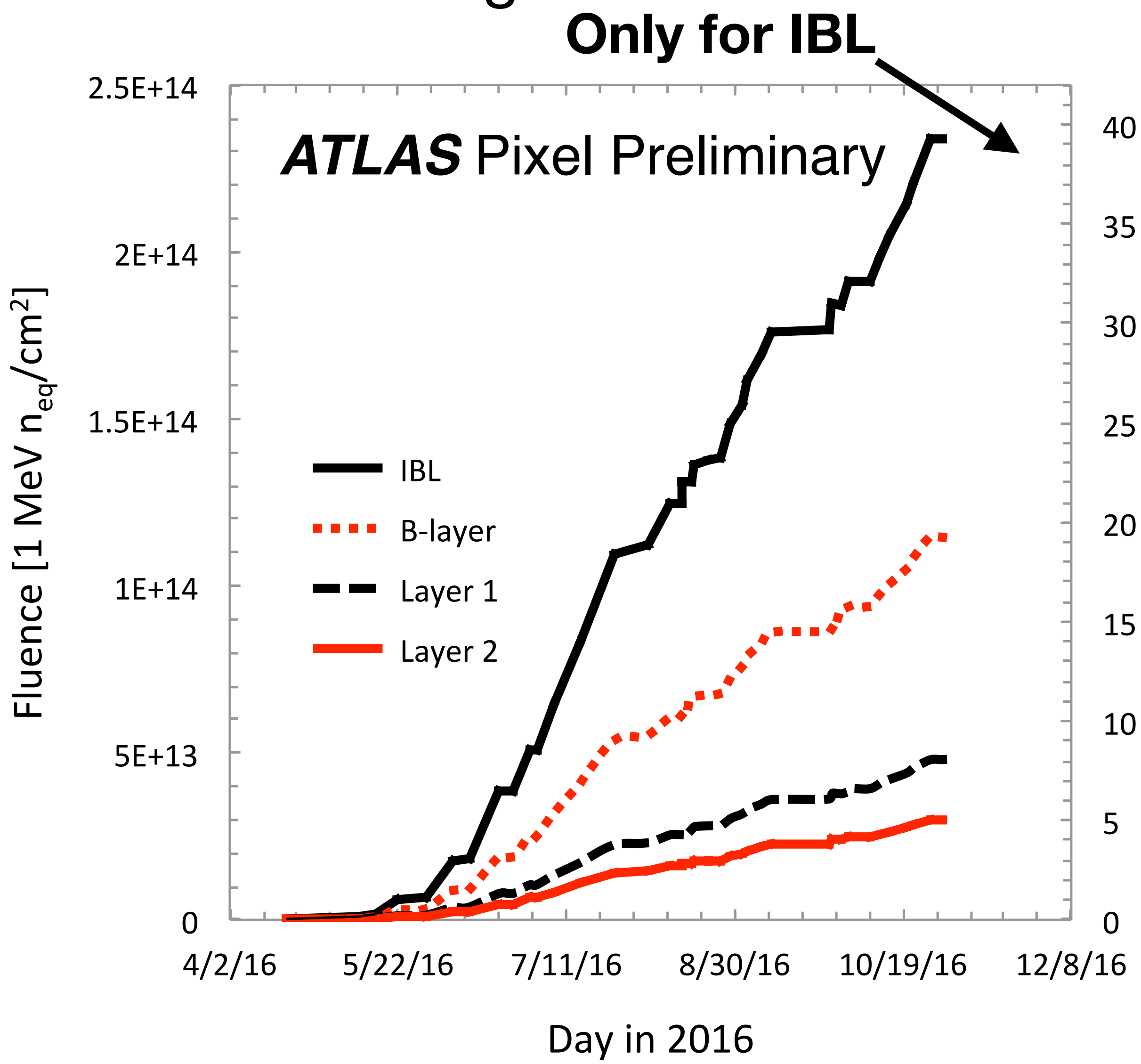
- Innermost Layer: **IBL** (planar and 3D)
  - 50 x 250 μm^2
  - planar: 200 μm thickness
  - 3D: 230 μm thickness (n-in-p)
  - FEI4 readout - 4 bit ToT
  - **3.3 cm from beam pipe!**

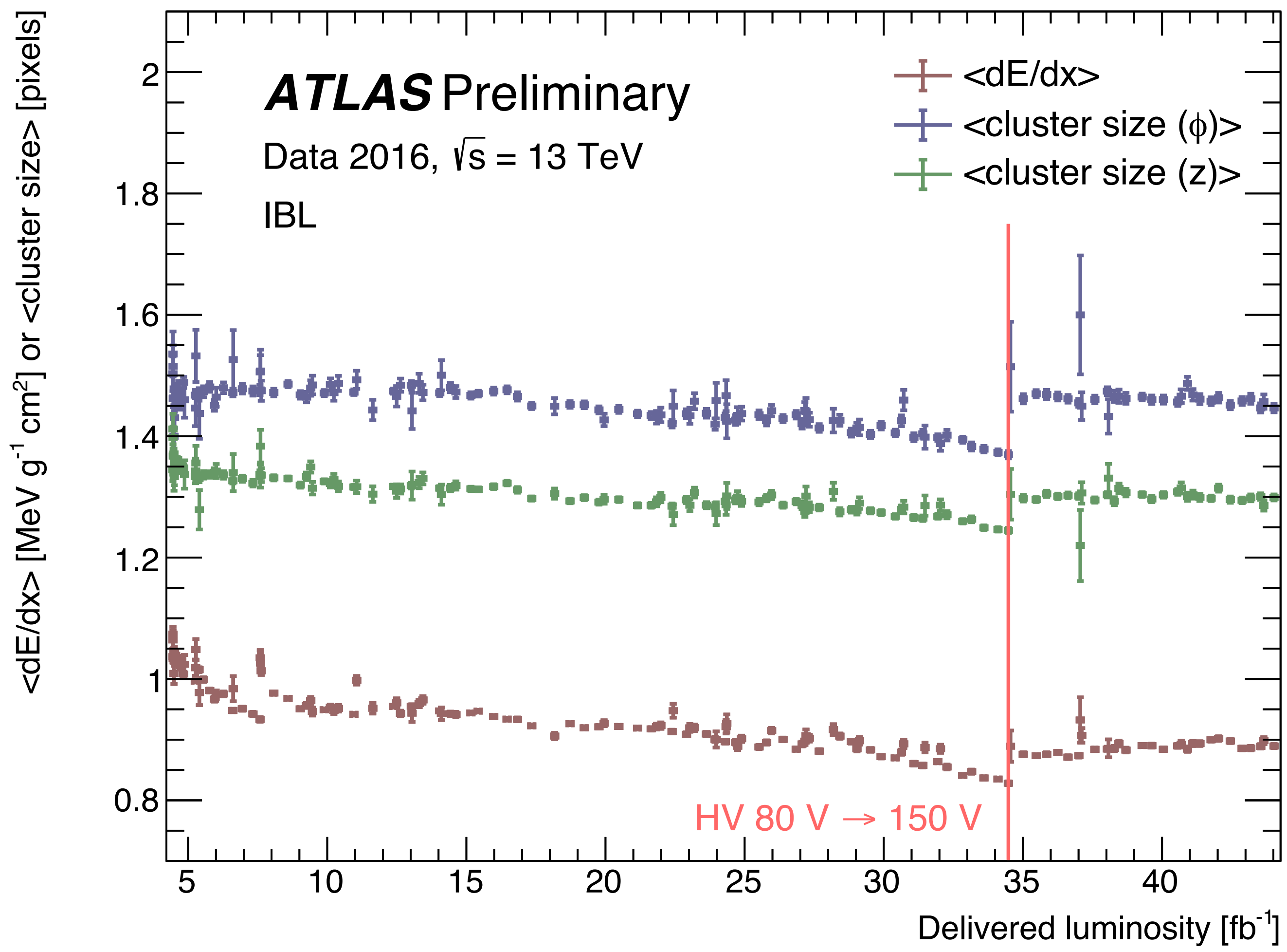


ATLAS Pixel Detector Performance

High flux of particles means high radiation dose on the sensor

Radiation damage effects in the sensor already visible! See also [Hongtao Yang talk]!





Correct Monte Carlo prediction that accounts for radiation damage is essential for physics

ATLAS Pixel Detector Performance

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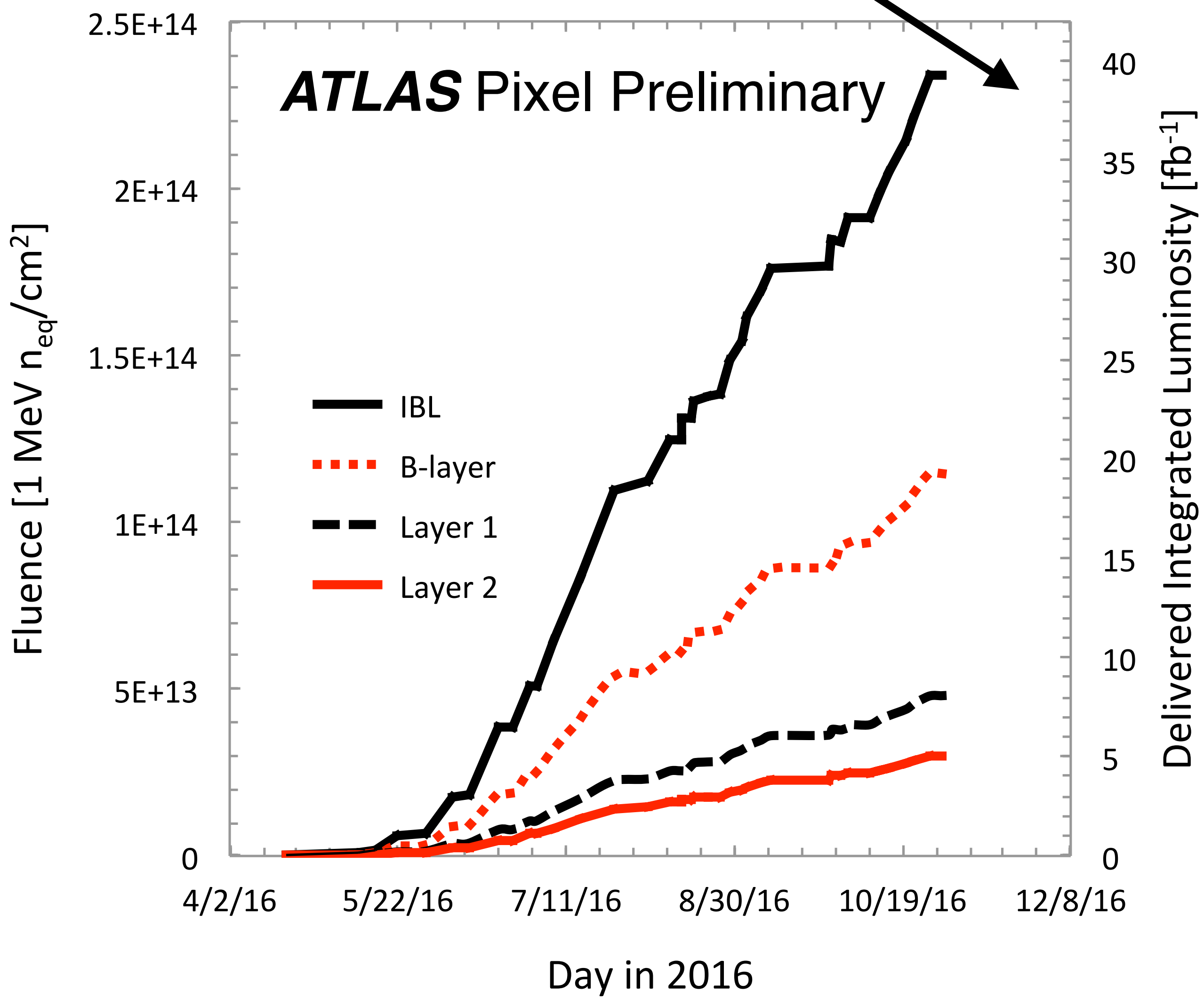
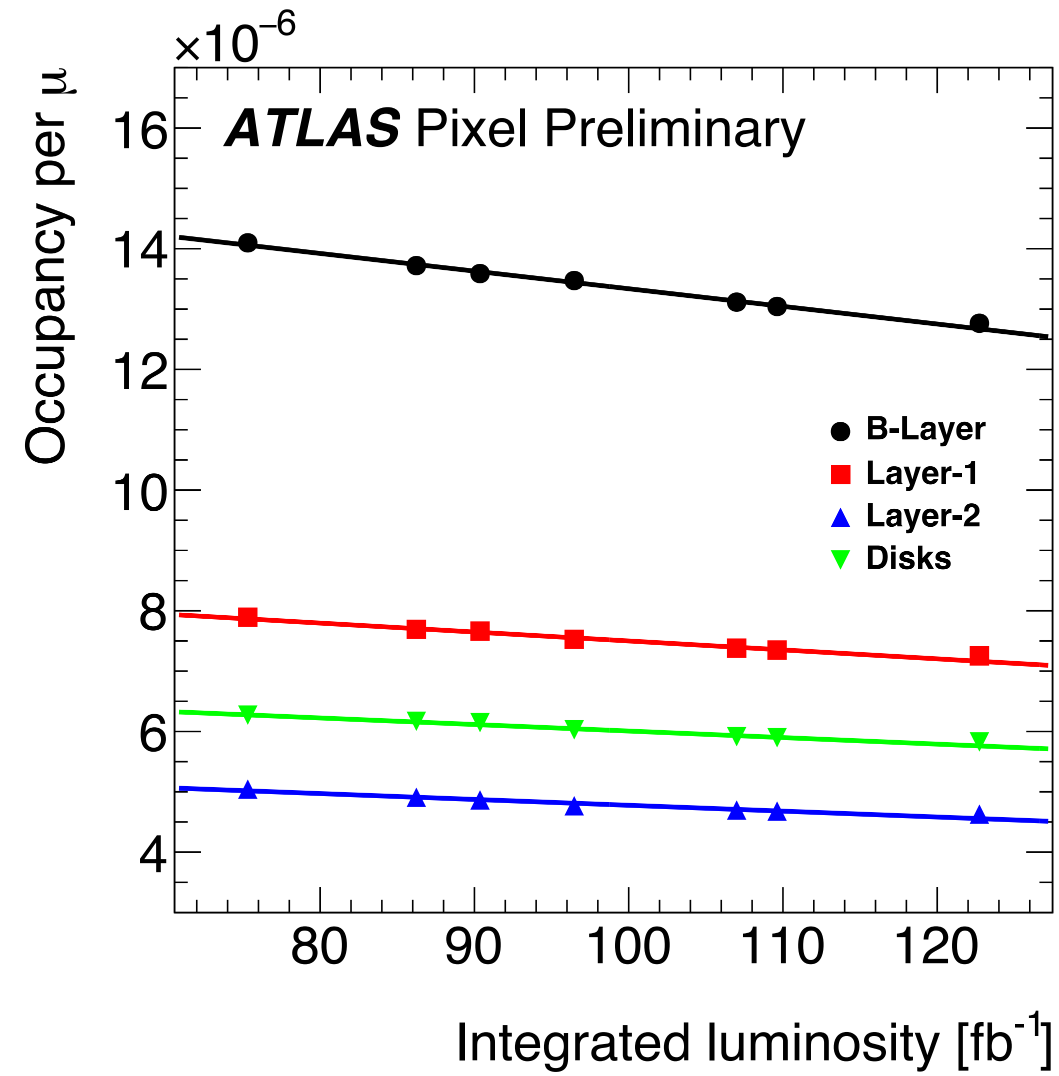
Only for IBL





Correct Monte Carlo prediction that accounts for radiation damage is essential for physics

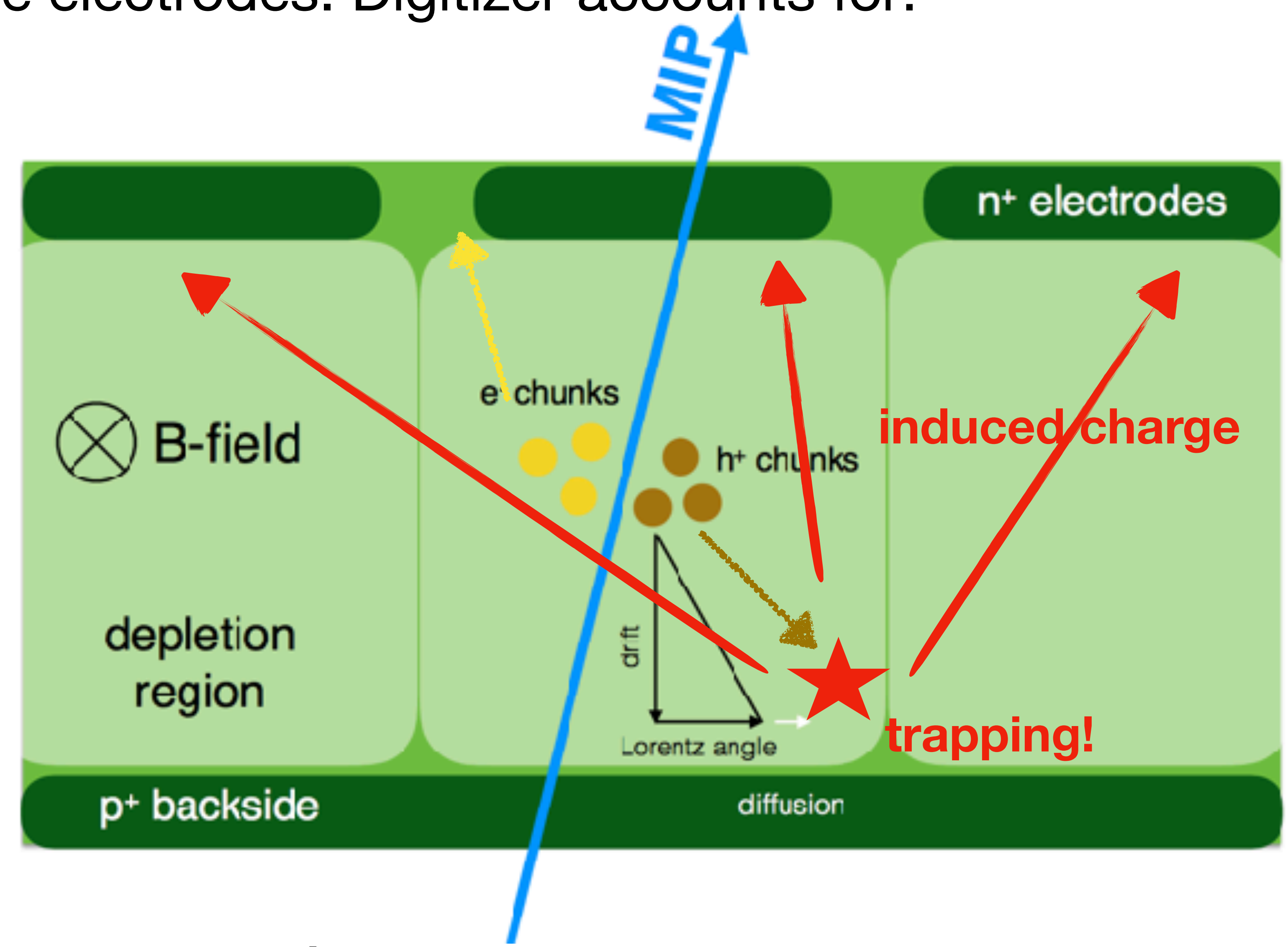
ATLAS Pixel Detector Digitizer

Digitization: the conversion from energy depositions of charged particles to digital signals sent from module front ends to the detector readout system

Develop digitizer that models inside effects of radiation damage

"Chunks" of charges are drifted to the electrodes. Digitizer accounts for:

- Charges drift
- E/B Field simulations from **TCAD**
- Lorentz Angle (function of E/B fields and distance in the detector)
- Trapping probability
- Ramo potential to account for induced charge
- Charge conversion to ToT

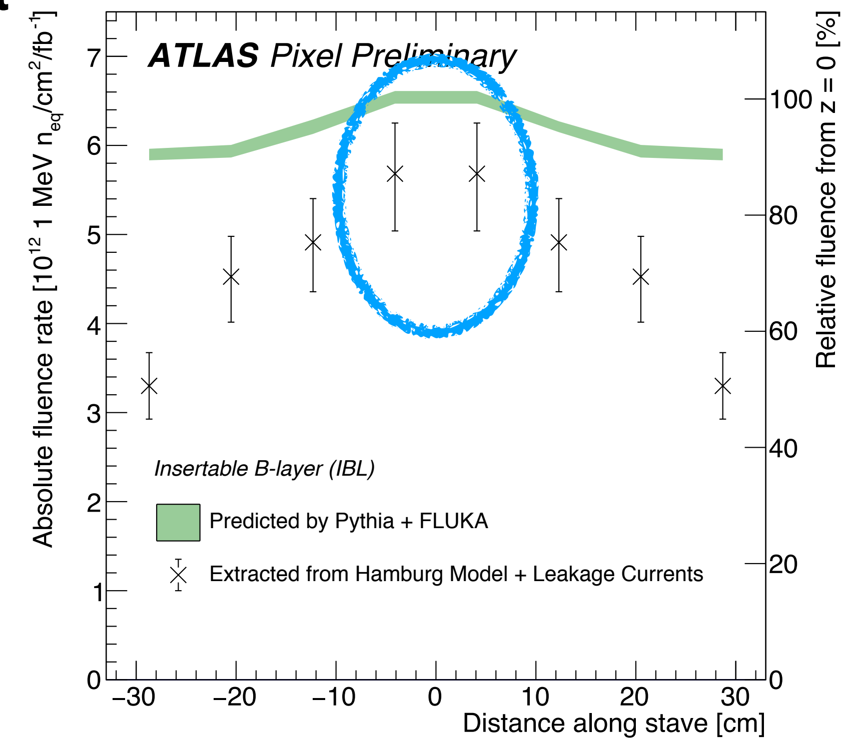


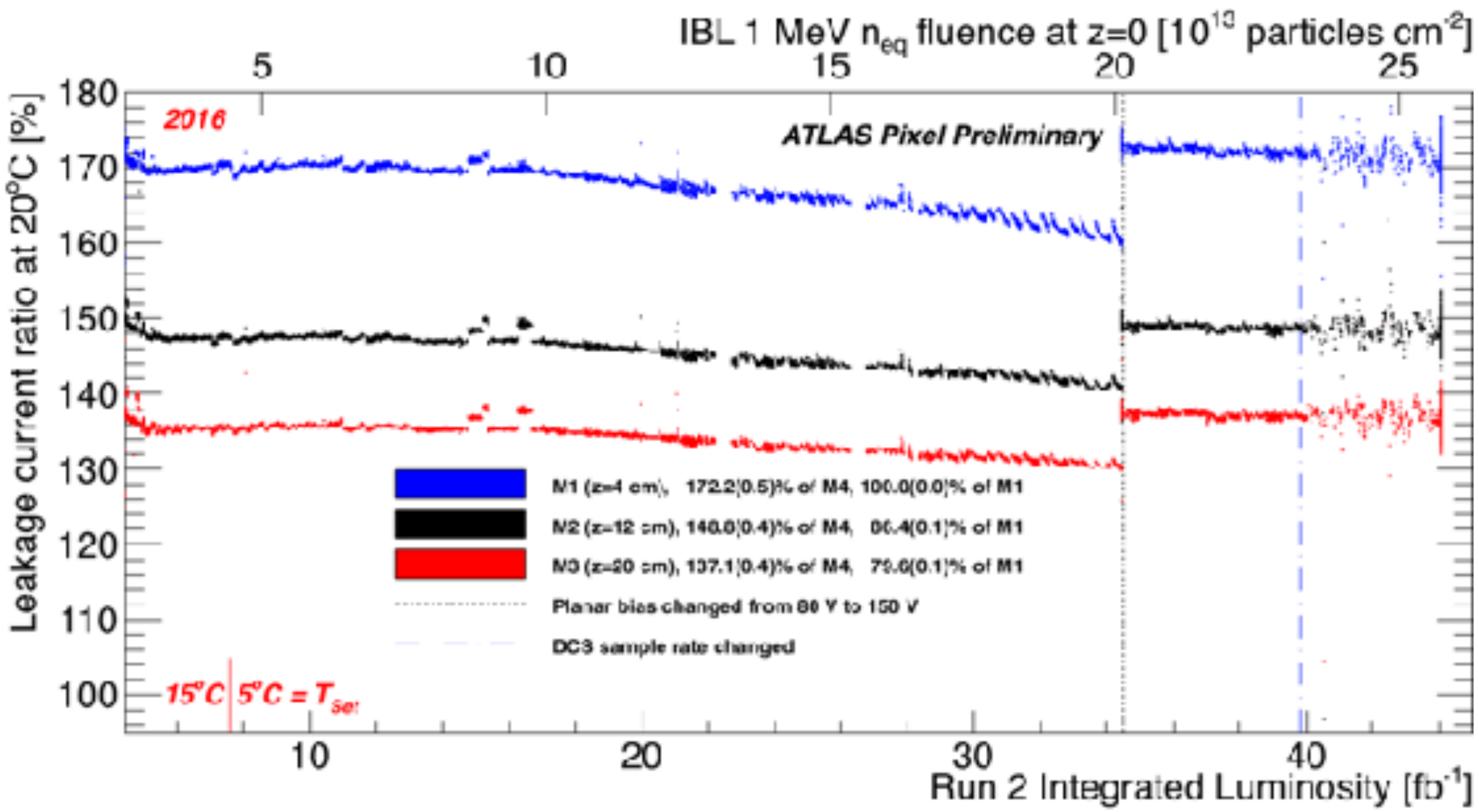
Digitizer for planar sensors! (3D in back up)

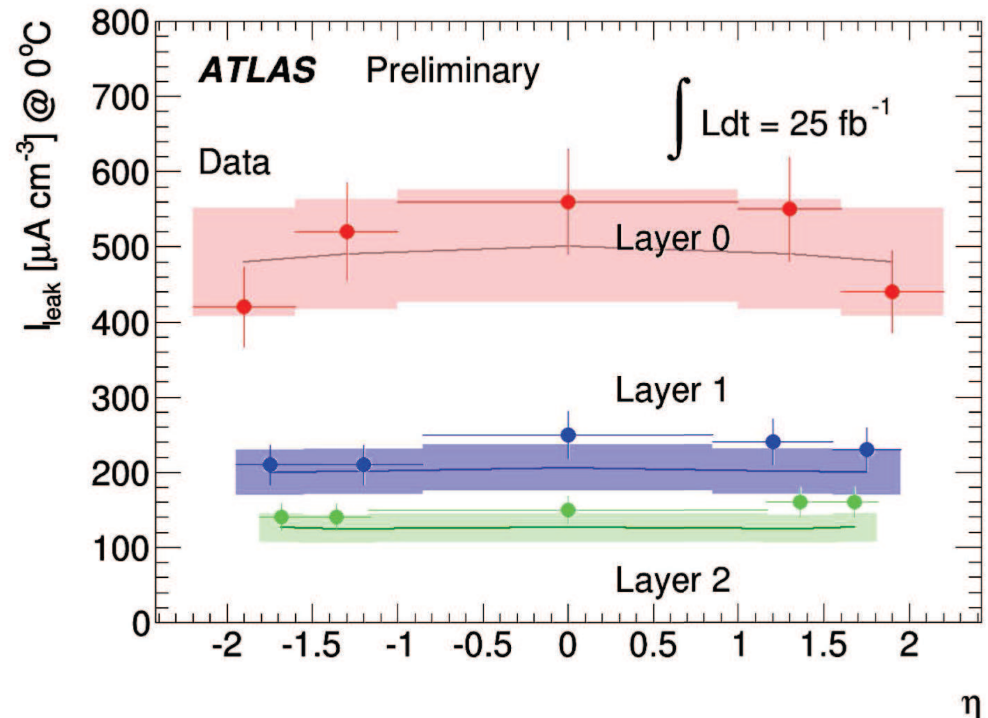
Fluence

Fluence prediction taken from FLUKA + Pythia

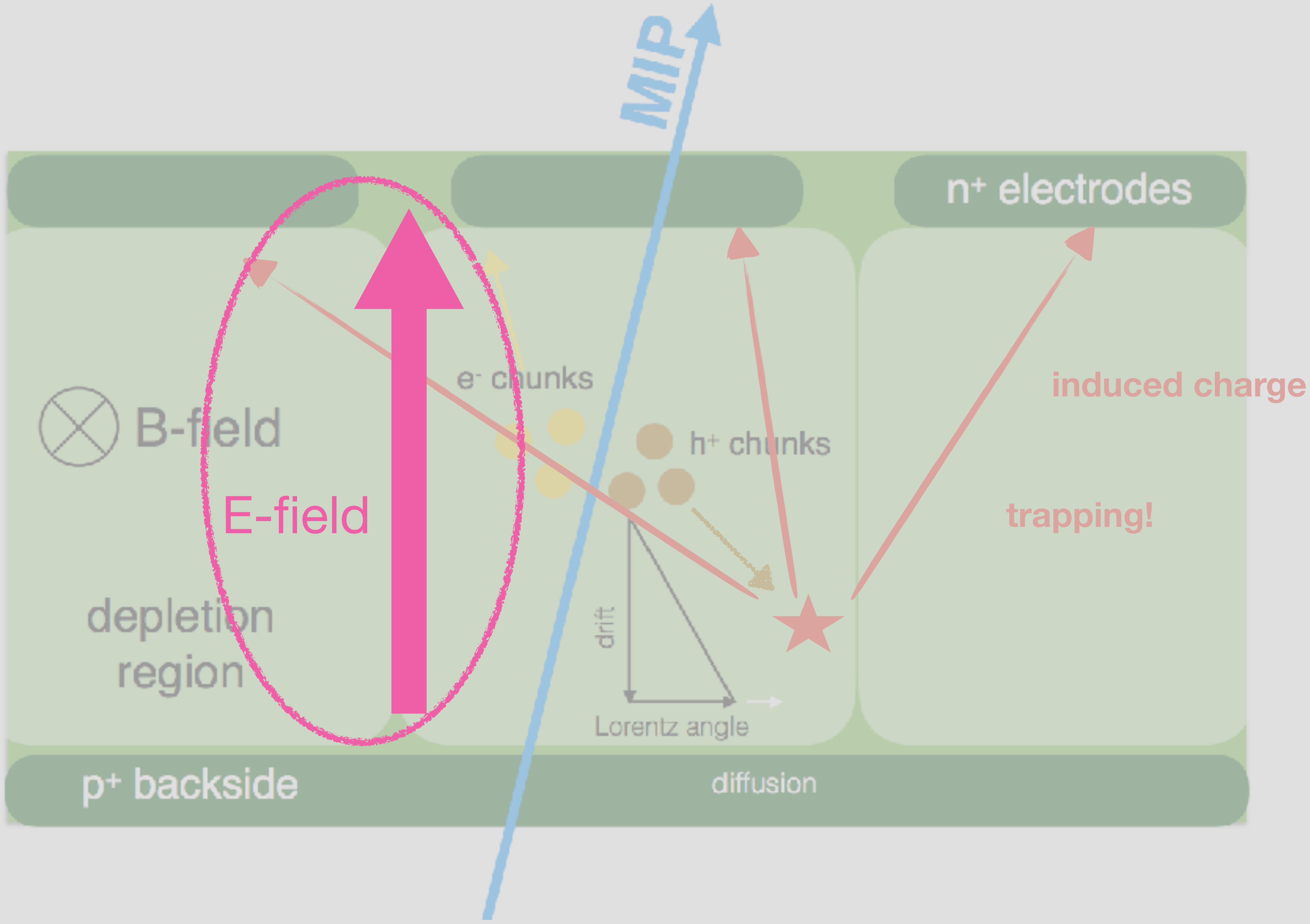
- FLUKA prediction validated with leakage current and Hamburg model:
  - Assign 15% uncertainties in the central region (|z|~0)







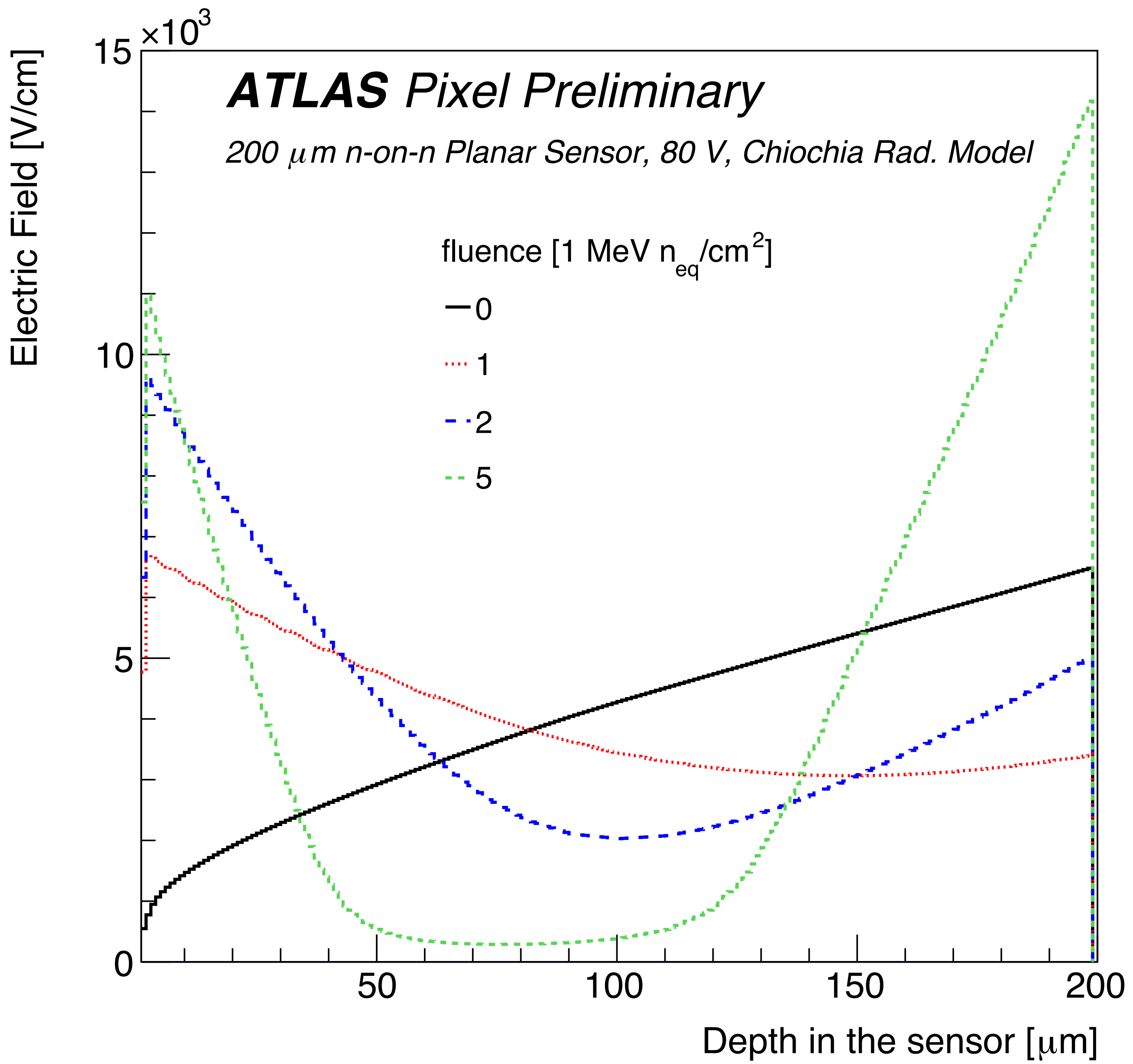
ATLAS Pixel Detector Digitizer: E-field



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
  - more information in Marco Bomben talk
  - **TCAD first step on which build the simulations**
- Typical double junction effect well described →"U" shaped E-Field



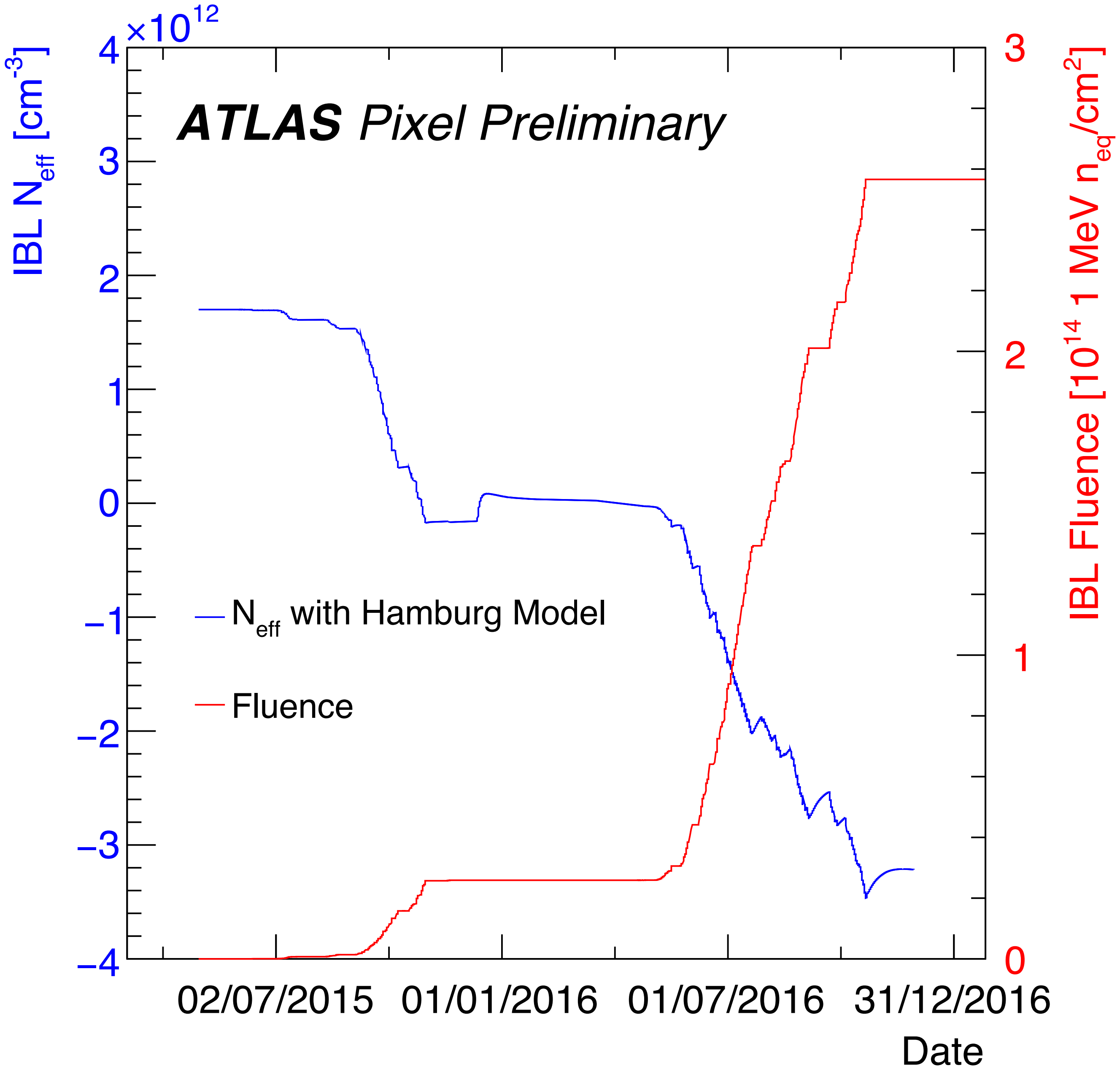
Radiation Damage model from: V. Chiochia et al., Nucl. Instr. and Meth A 568 (2006) 51-55

Annealing

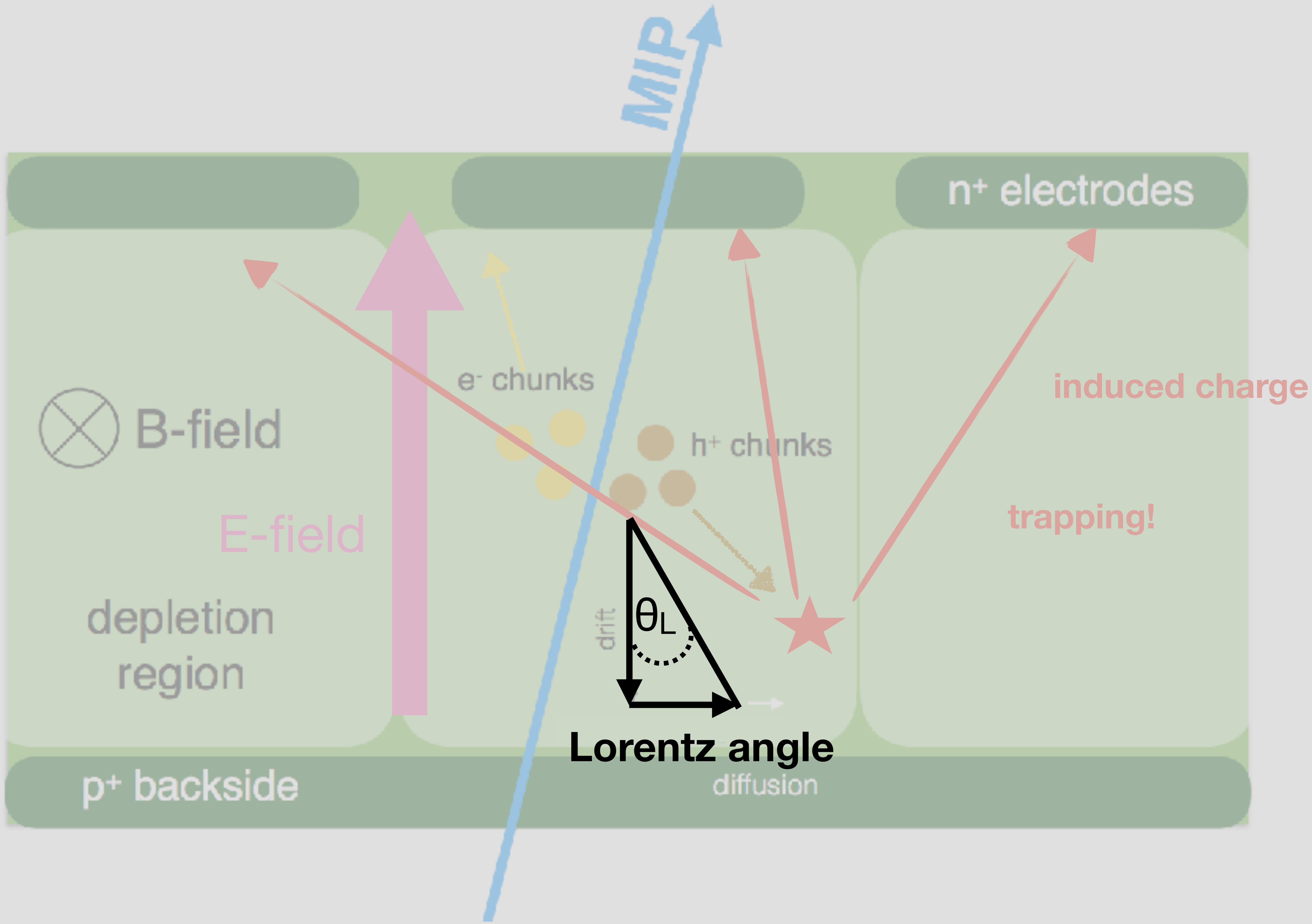
TCAD simulation doesn't account for thermal history: no annealing effects included

Use Hamburg Model to model annealing

- Set the average charge distribution in the sensor to match the N_{eff} concentration predicted by Hamburg model
- No 1-1 correspondence between TCAD and Hamburg model
    - We only match the total effective concentration



ATLAS Pixel Detector Digitizer: Lorentz Angle

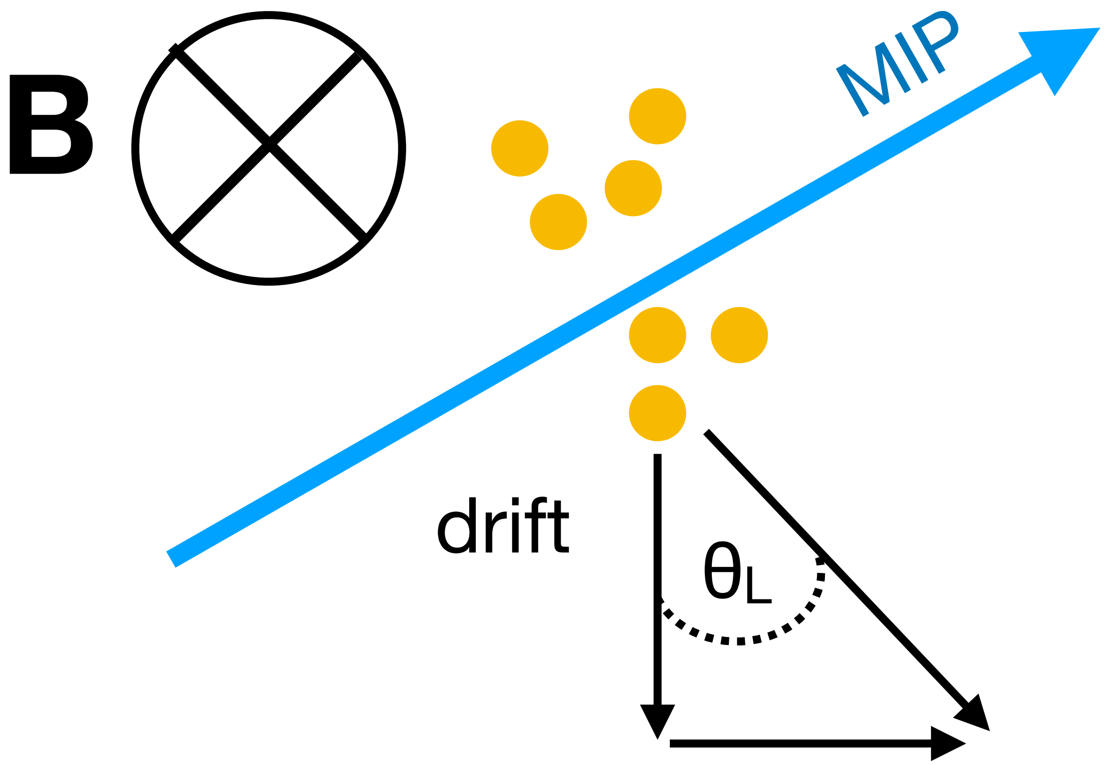


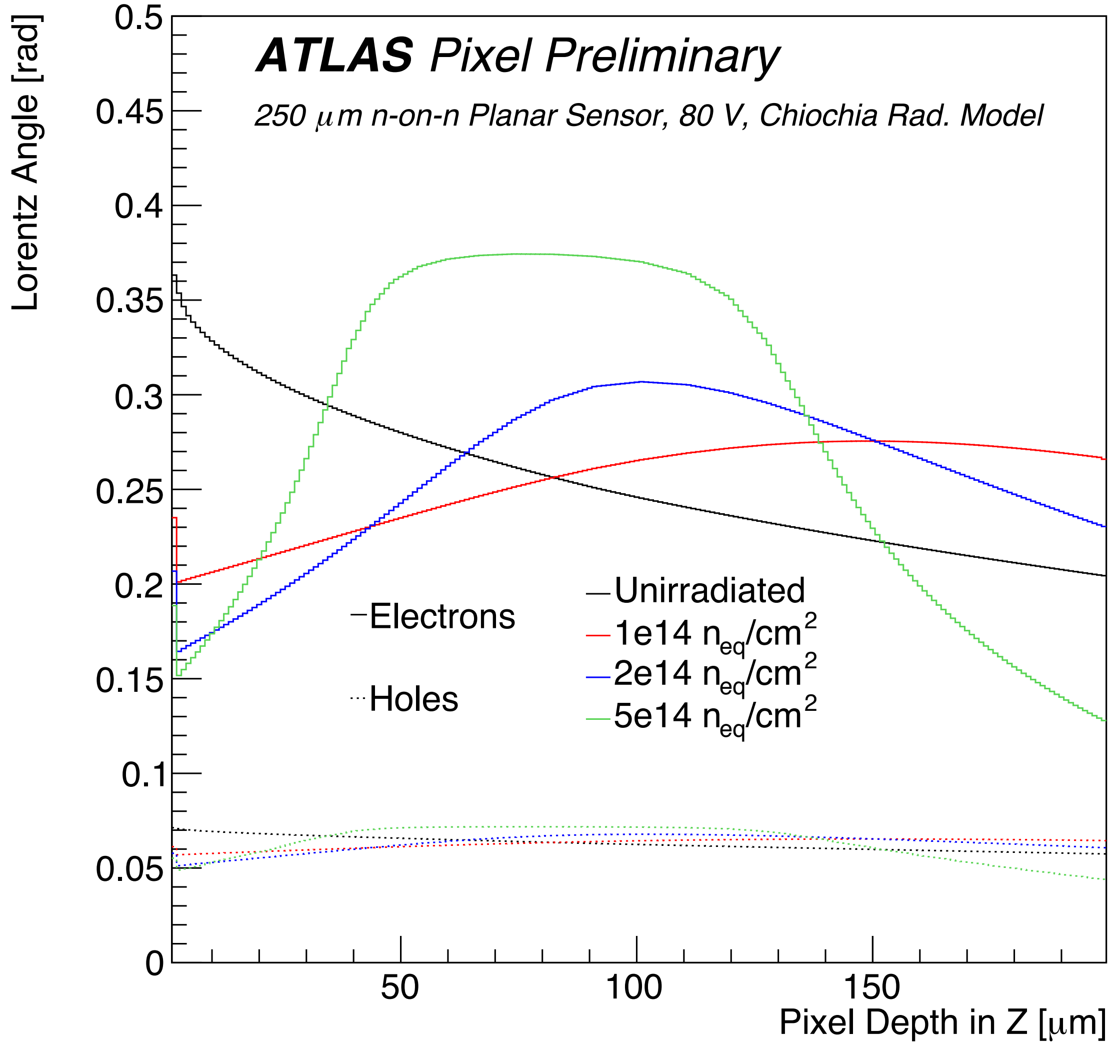
Lorentz angle

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

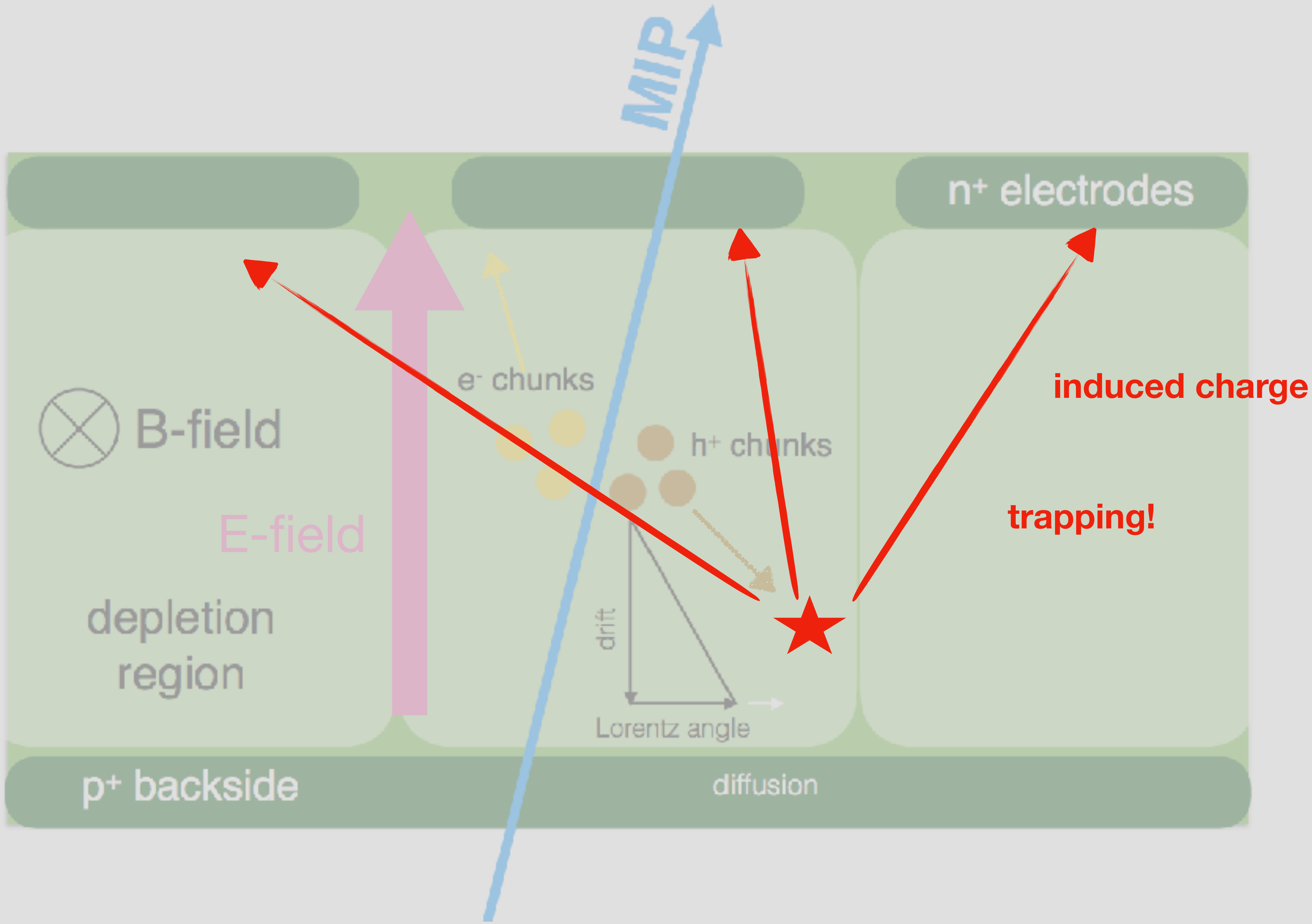
Hall scattering factor (r); Mobility (μ)

- Intrinsic dependence on the E field
- Radiation damage modifies E field shape and therefore θ_L
  - depends on final and initial positions
  - integrate over path





ATLAS Pixel Detector Digitizer: Trapping Probability



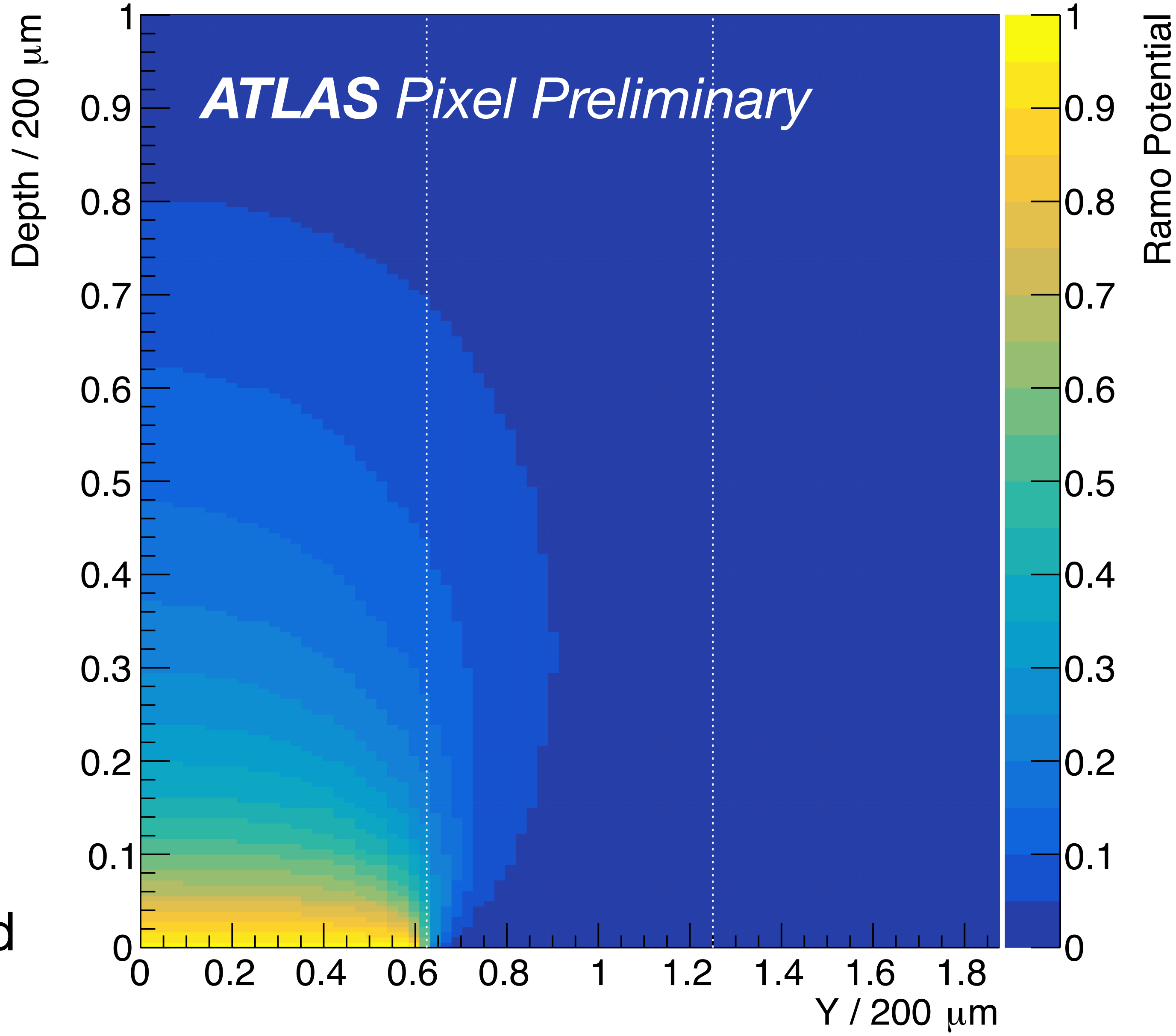
Trapping probability

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 τ

- τ is a random variable exponentially distributed with mean value $1/(\beta_{h/e}\phi)$
  - ϕ is the fluence
  - $\beta_{h/e}$ is the trapping constant: different for electrons and holes
  - $\beta_e = 4.5 \pm 1.0 \ \ 10^{-16}\ \mathrm{cm^2/ns}$
  - $\beta_h = 6.5 \pm 1.5 \ \ 10^{-16}\ \mathrm{cm^2/ns}$
  - 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

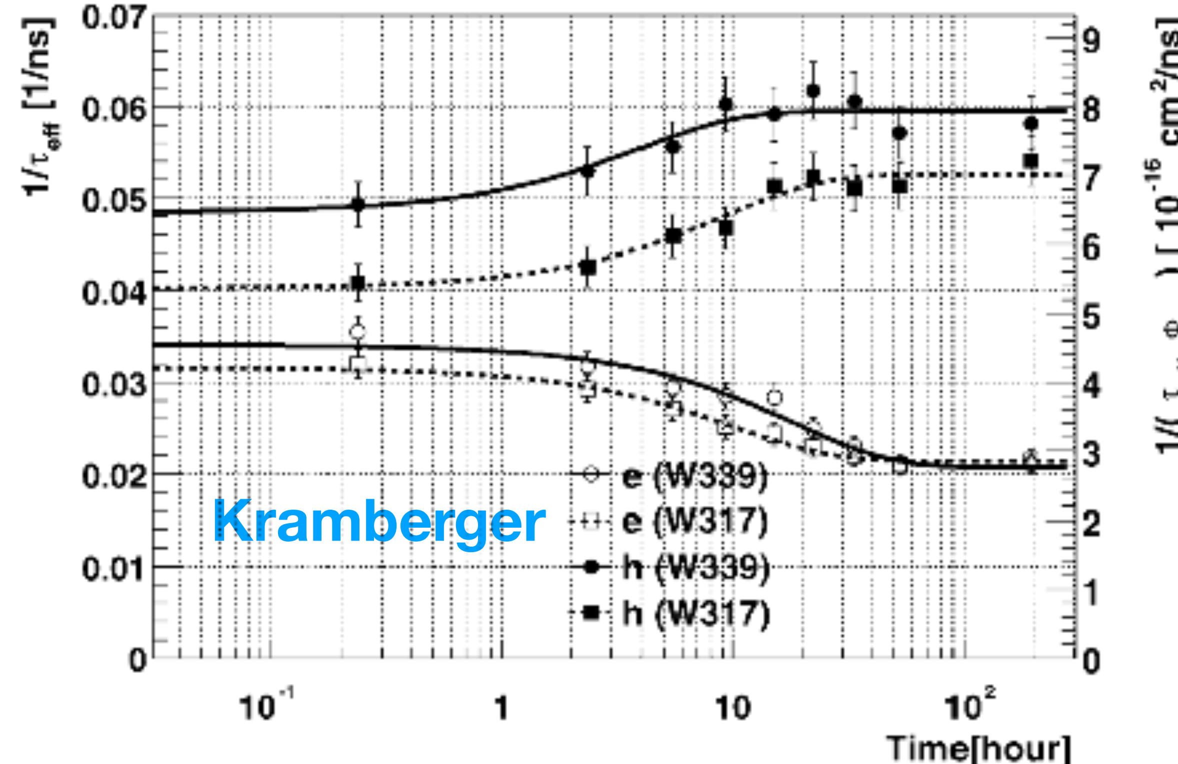
TCAD model of an ATLAS IBL module

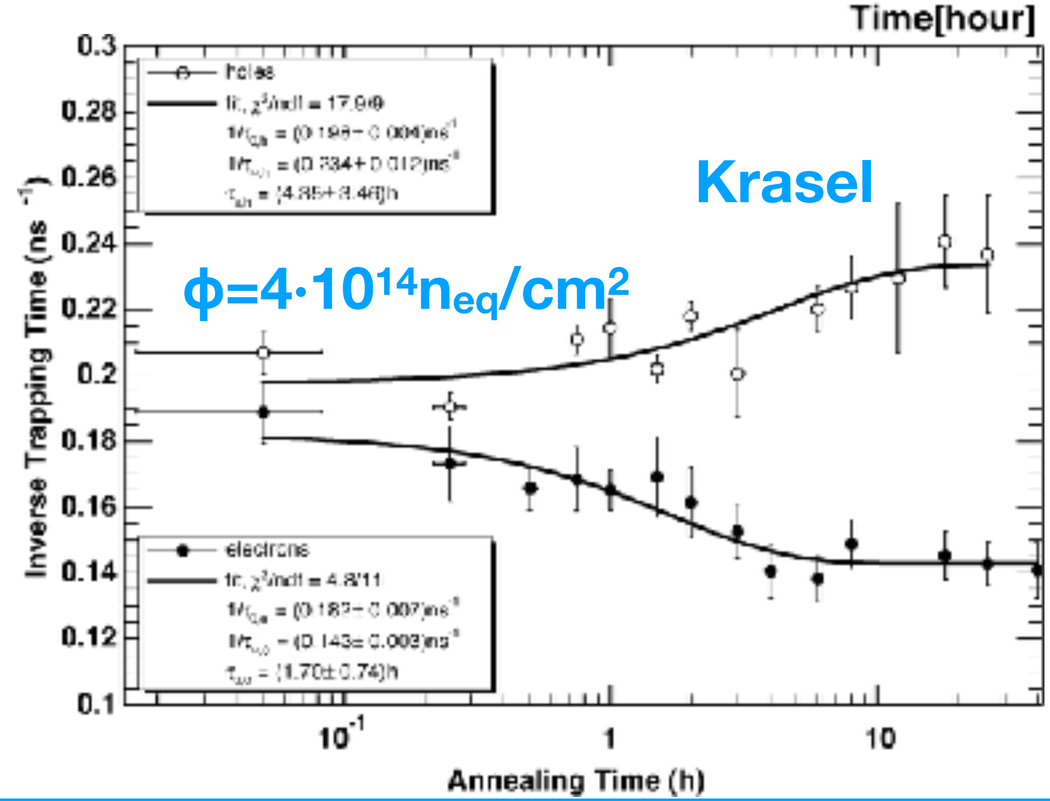


Trapping probability

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

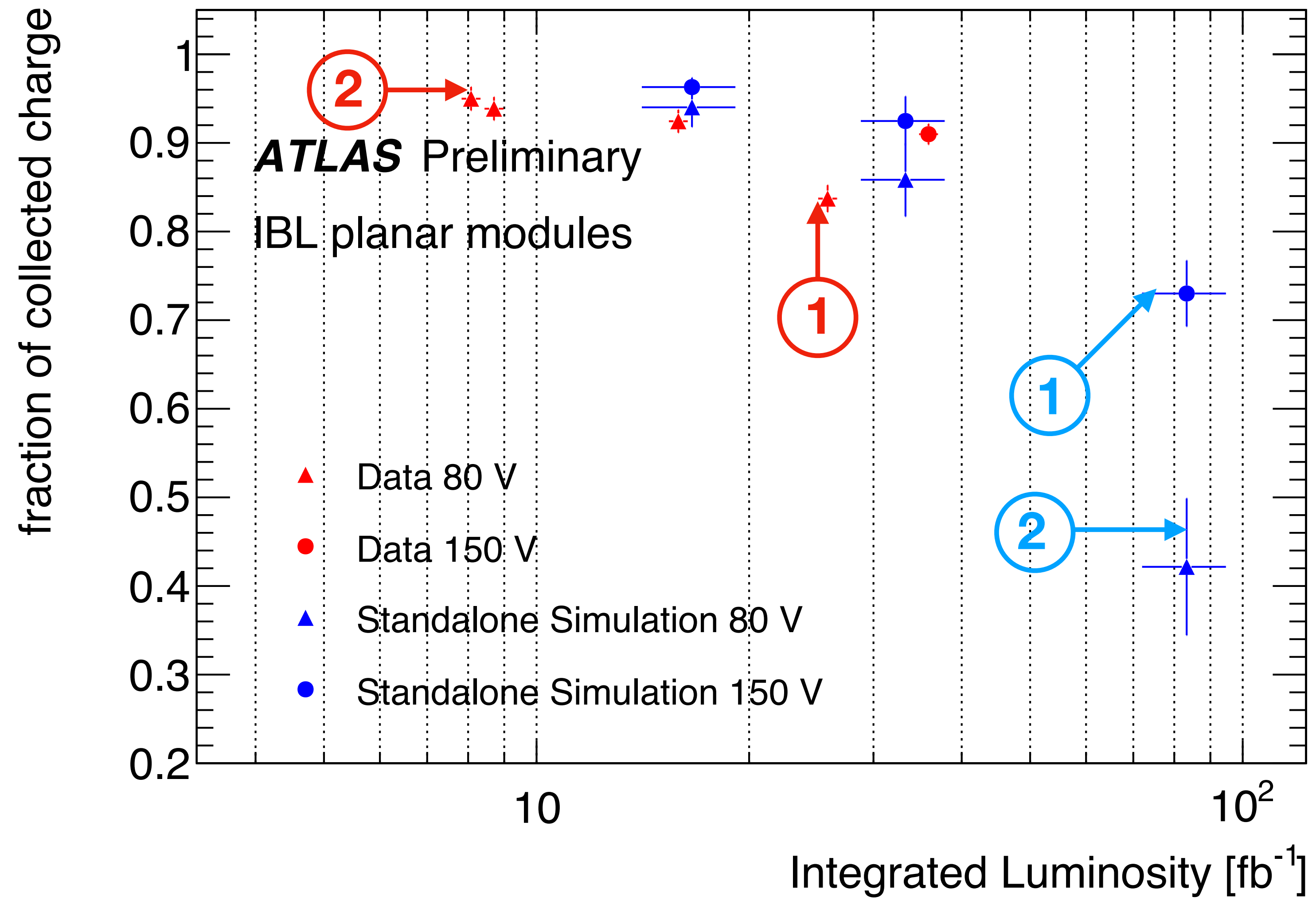




Model Prediction and Data Comparison

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

- 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

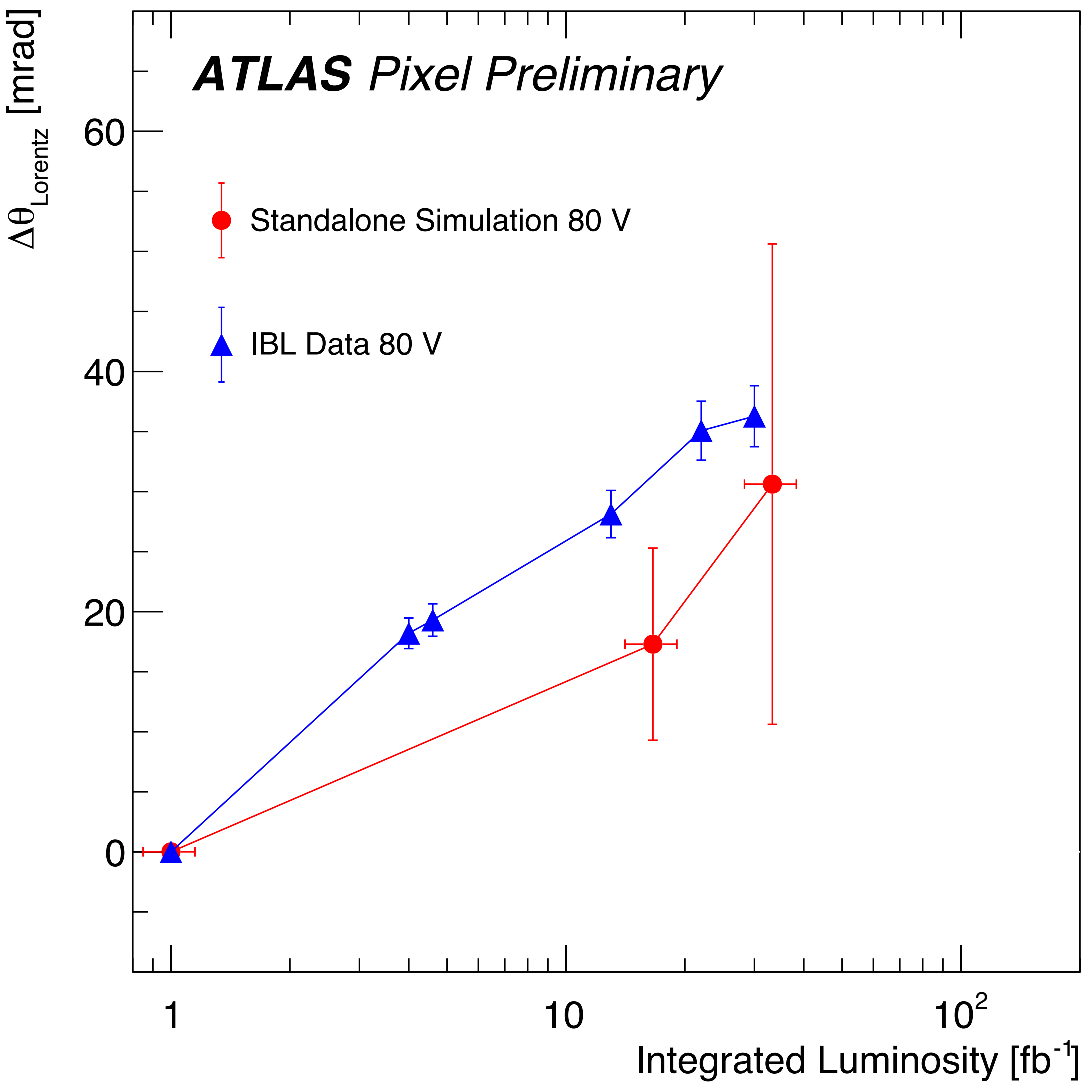


Good agreement with data!

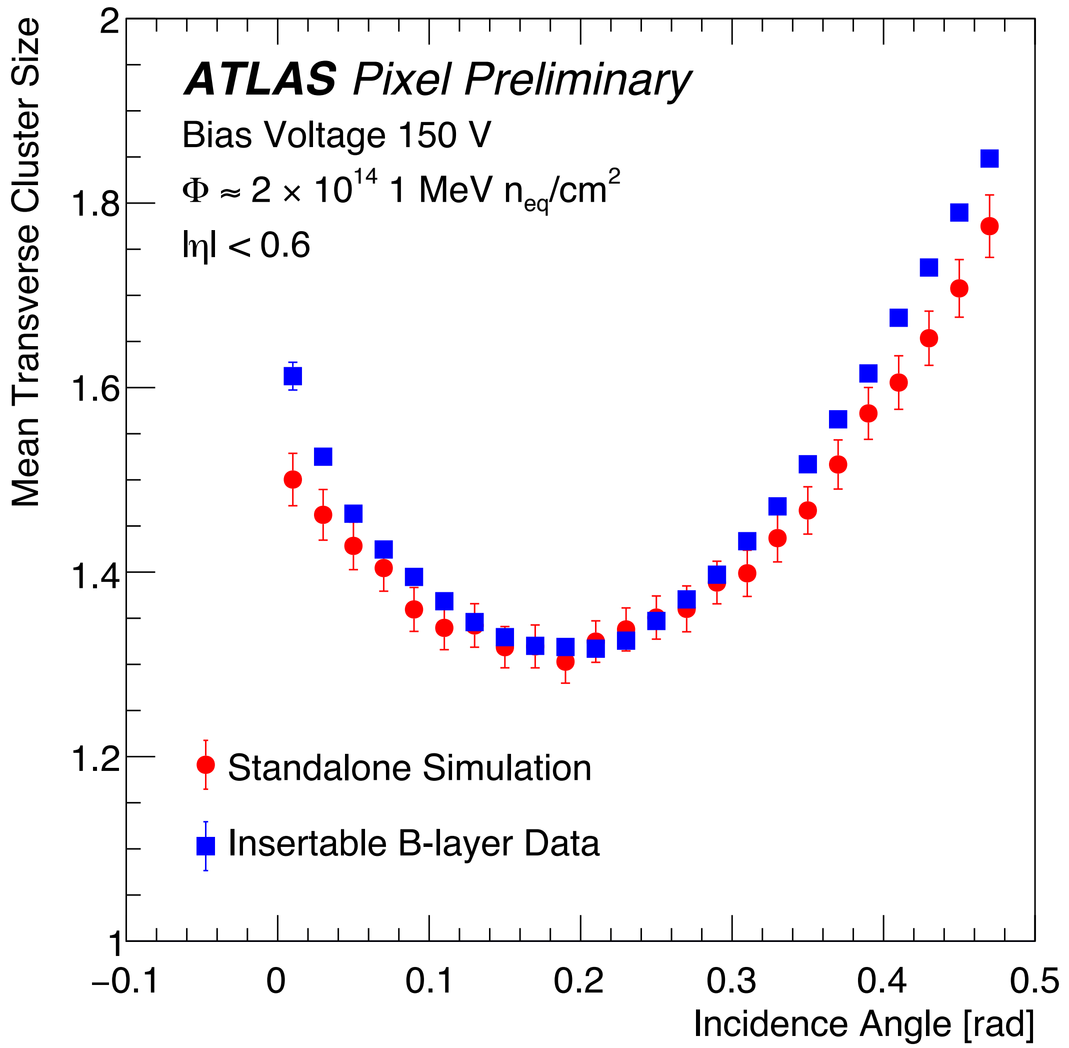
Essential to understand what operational condition to use in the future

Model Prediction and Data Comparison

Lorentz Angle depends on the fluence



Lorentz angle as a function of integrated Luminosity



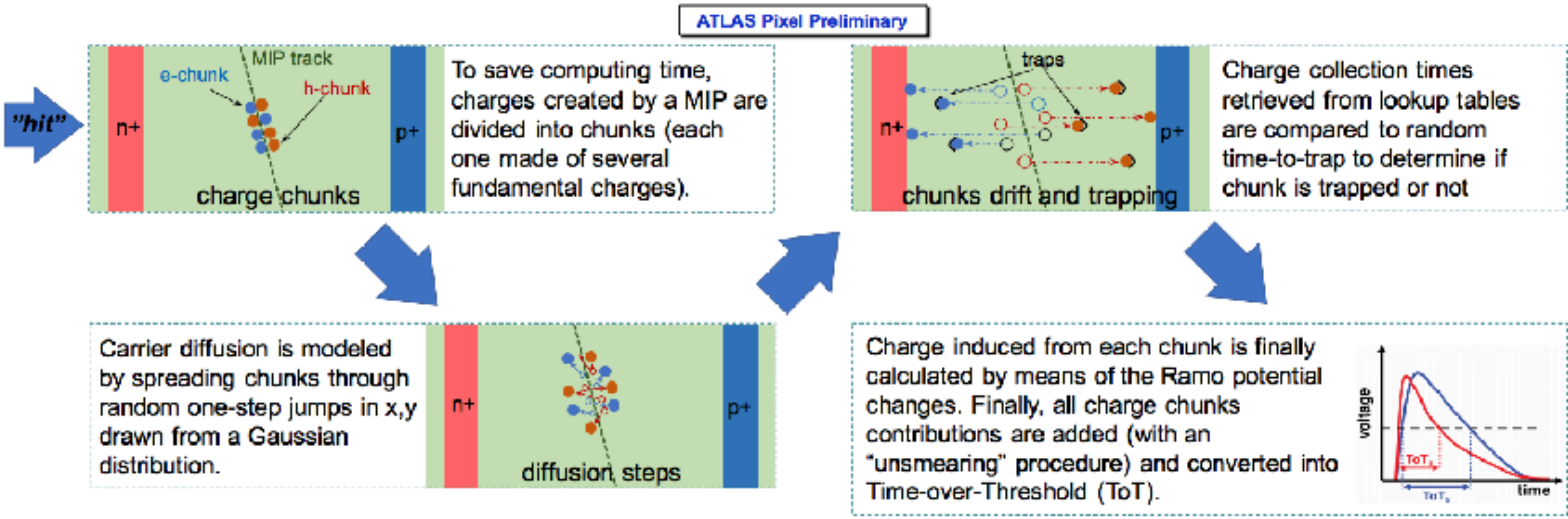
Mean cluster size as a function of particle incident angle

Conclusions

- A new digitizer for the ATLAS pixel detector has been presented
  - Many features that account for most of the effects involving radiation damage
  - Based on TCAD maps for E-fields
- 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

BACK UP

ATLAS 3D Detector Digitizer



- Similar approach of digitizer
  - Charges are drifted towards electrodes
- Charge collection efficiency
  - Only simulation results
  - higher fluences than IBL results