Modeling Radiation Damage to Pixel Sensors in the *ATLAS* Detector

BERKELEY LAB

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on behalf of the ATLAS Collaboration

Lawrence Berkeley National Laboratory

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ATLAS Pixel Detector

4 pixel layers

<u>Outer three layers</u>

50 x 400 x 250 μm³

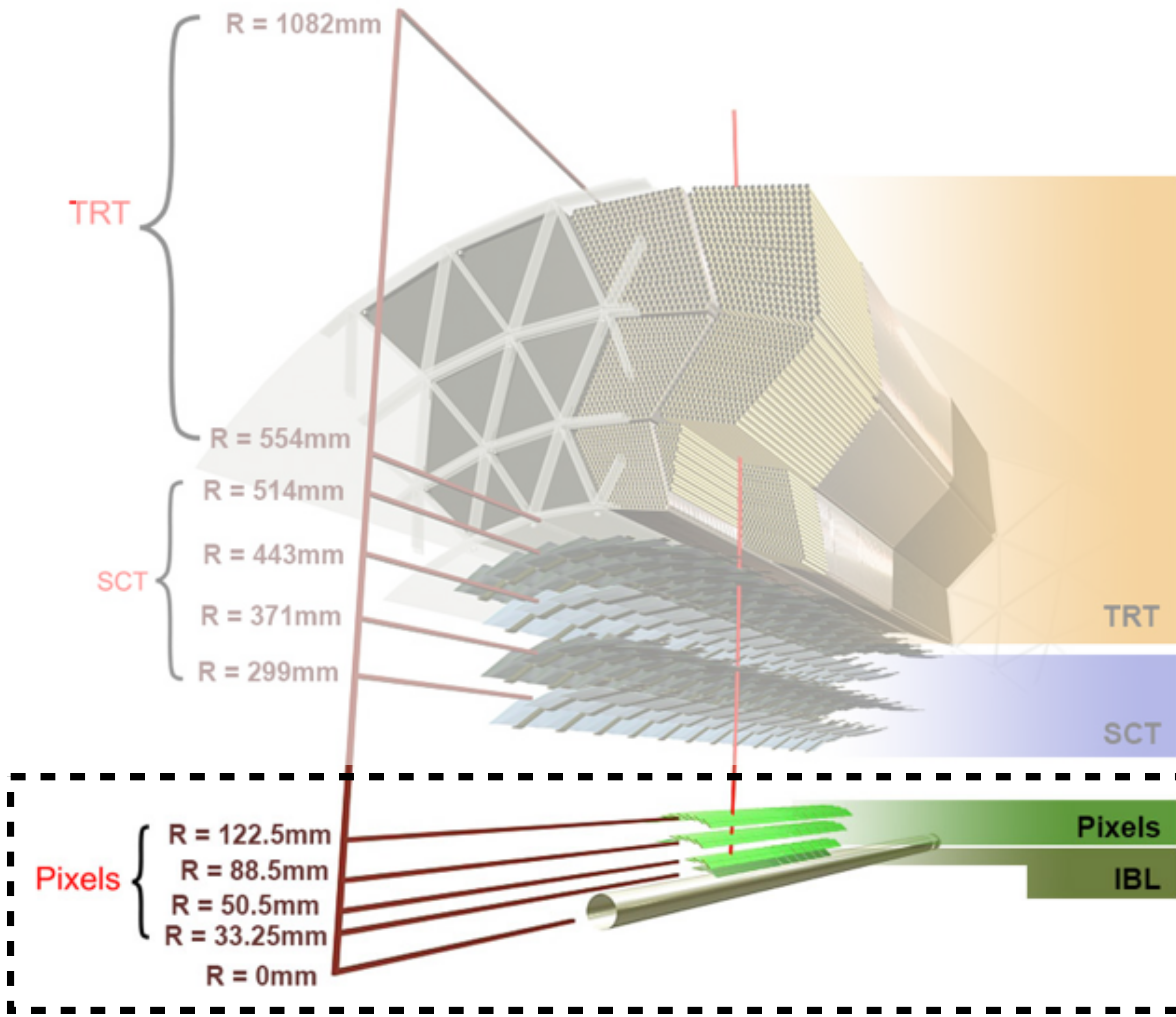
FEI3 readout chip (8 bit ToT)

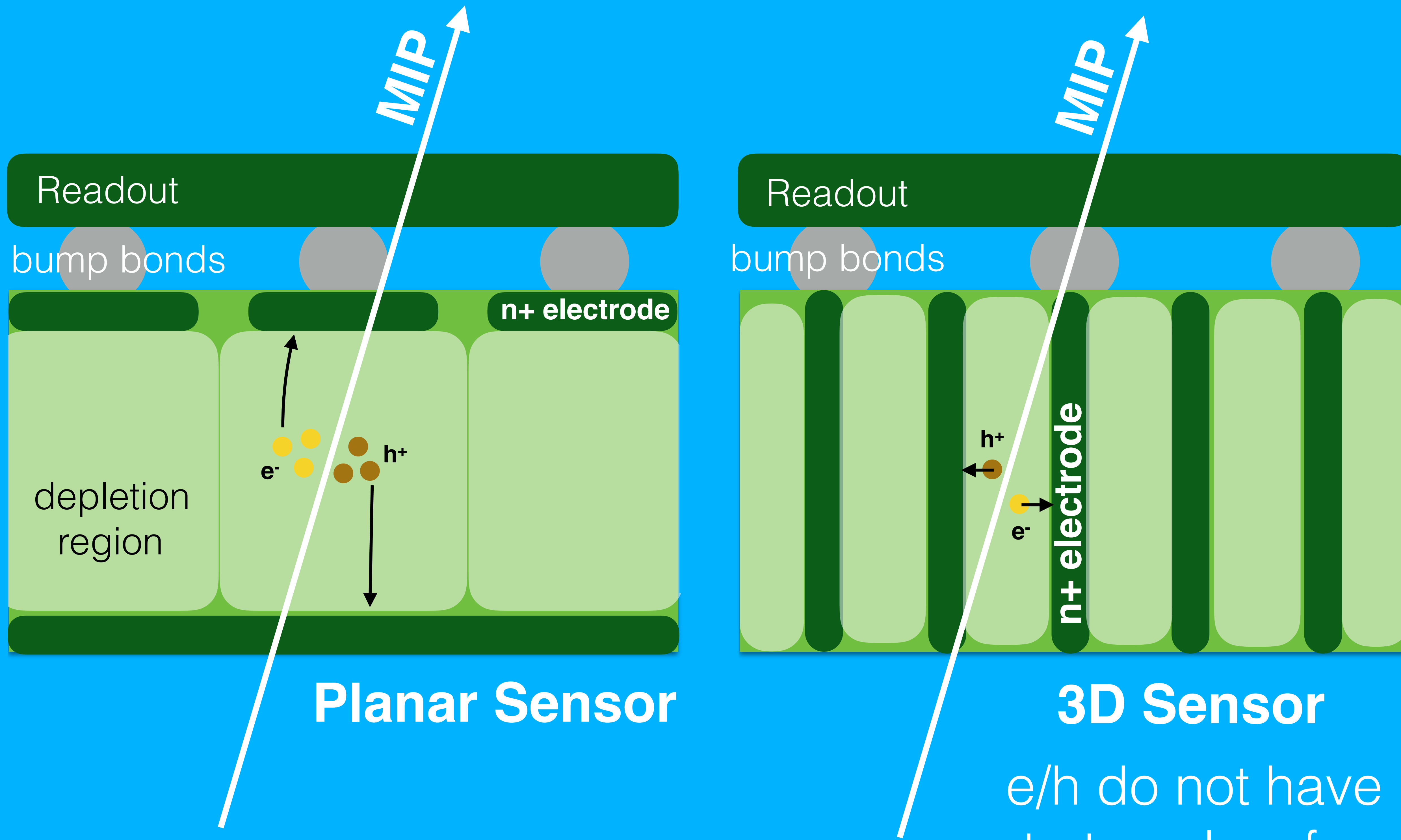
<u>Innermost layer</u>

50 x 250 x 200 μm³

FEI4 readout chip (4 bit ToT)

3.3 cm from interaction point; includes 3D sensors at high |z|.



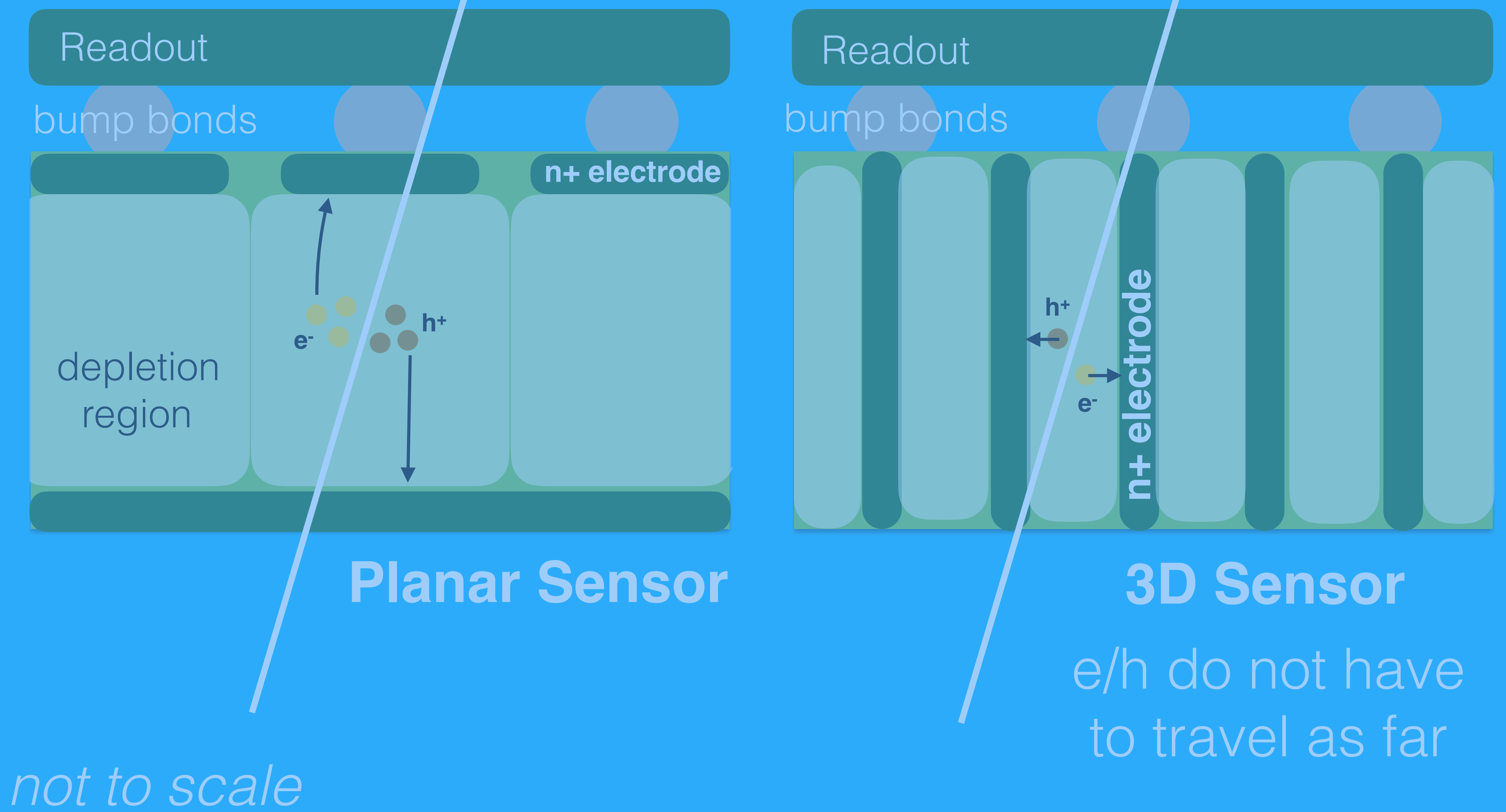


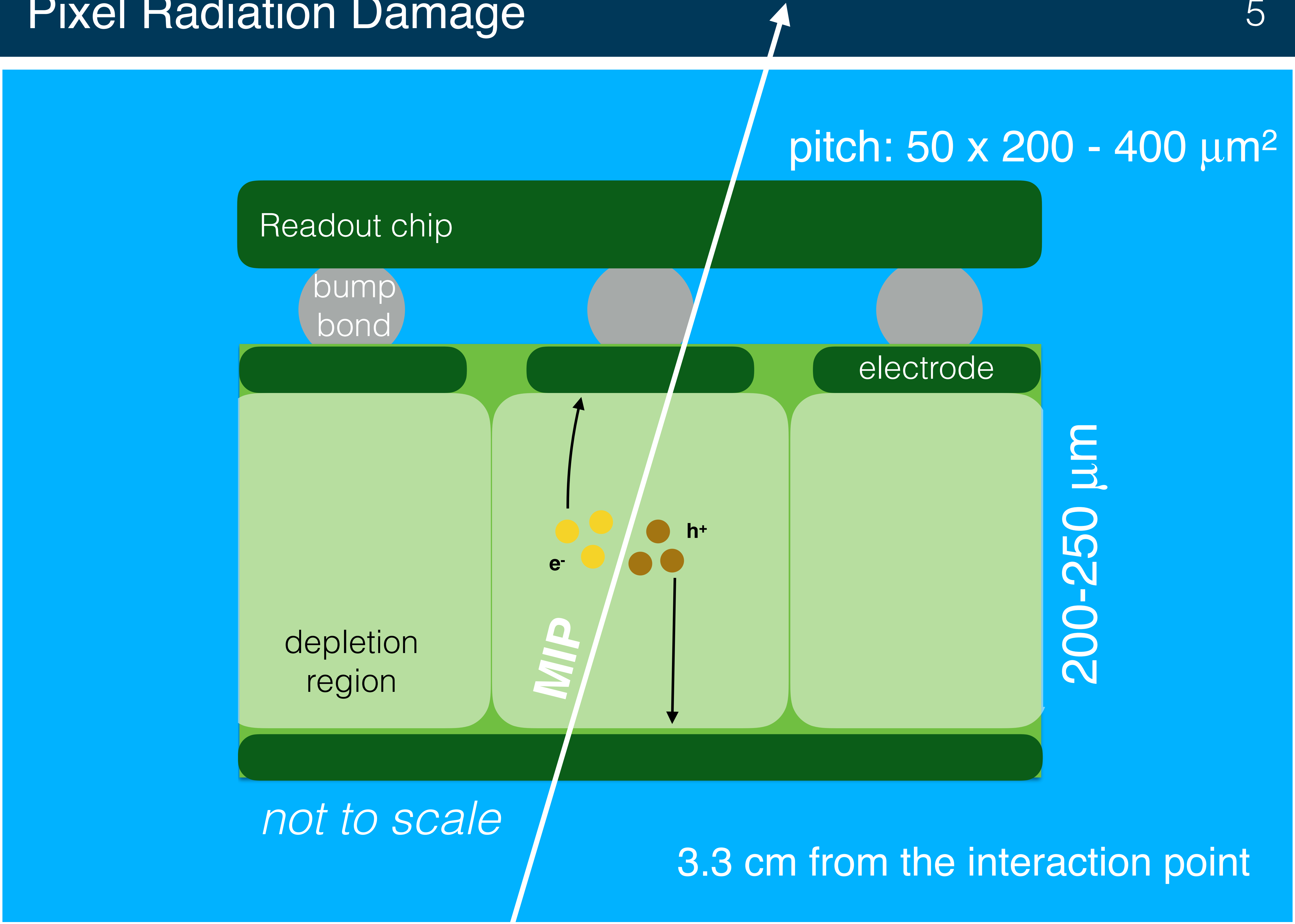
e/h do not have to travel as far

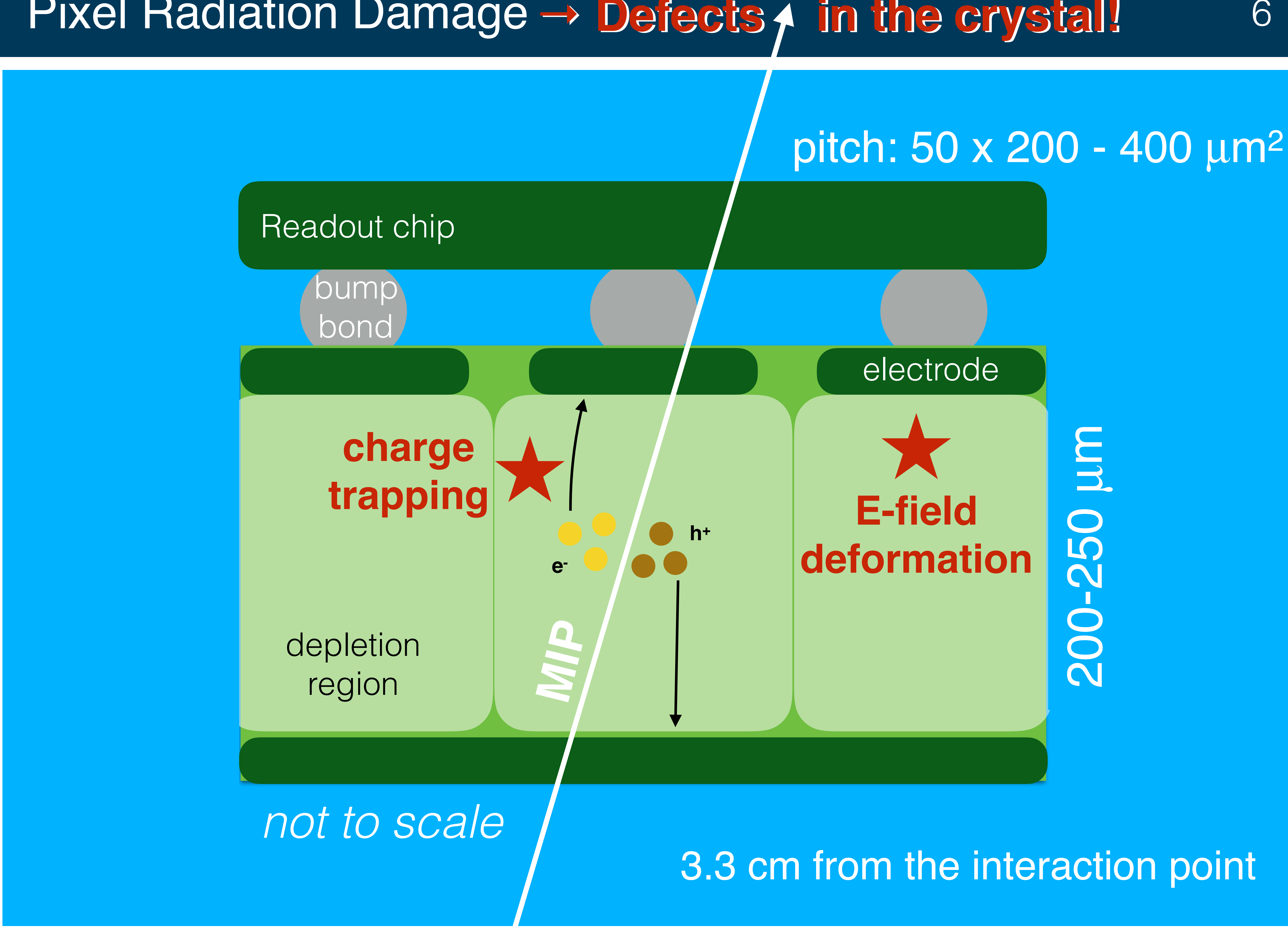
not to scale

Focus on planar for the rest of the talk

(3D's are outside tracking acceptance)

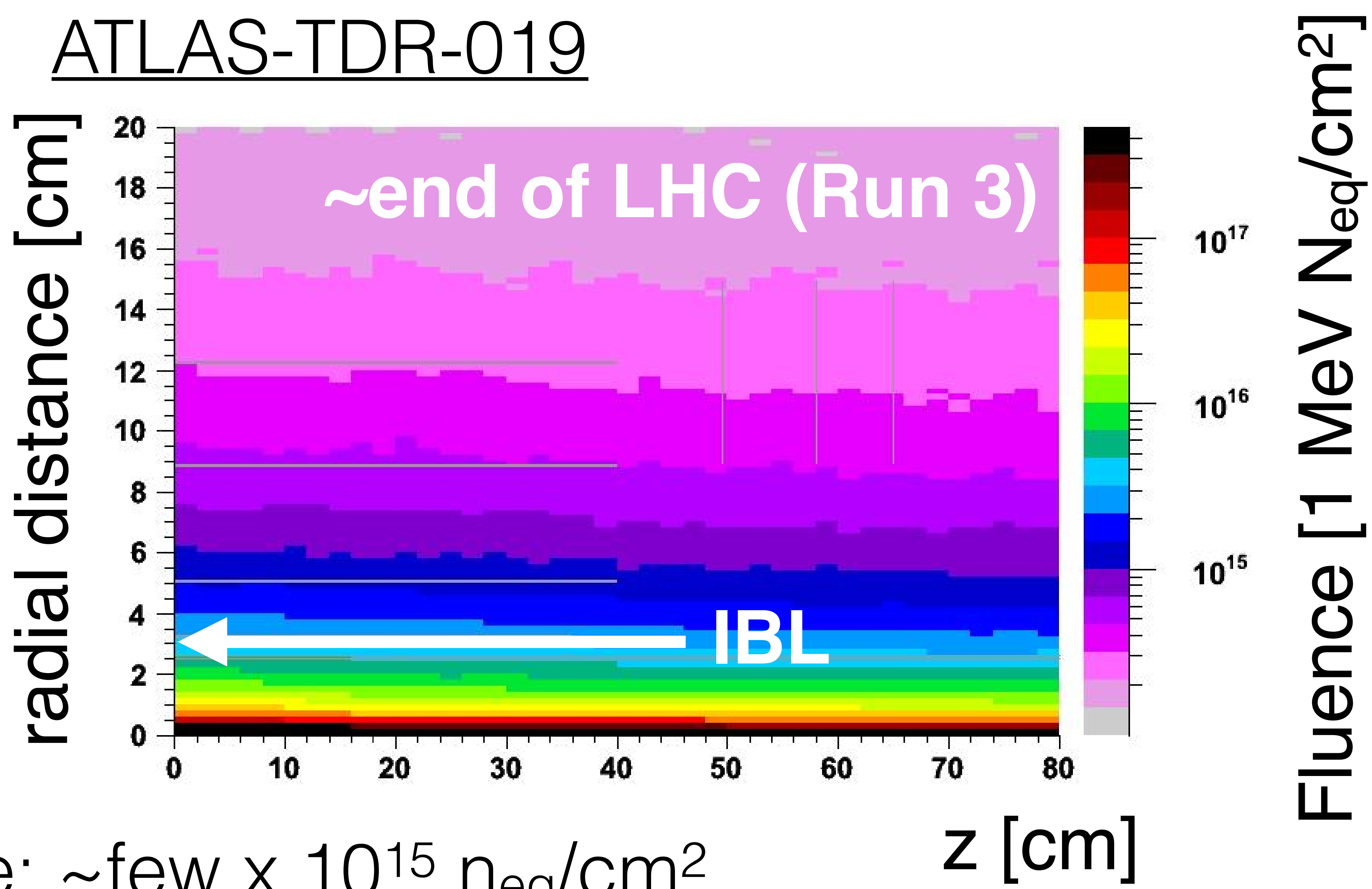



pitch: 50 x 200 - 400 μm²
Readout chip
bump bond
electrode
200-250 μm
h+
e-
MIP
depletion region
not to scale
3.3 cm from the interaction point


pitch: 50 x 200 - 400 μm²
Readout chip
bump bond
electrode
charge trapping
e⁻
h⁺
MIP
E-field deformation
depletion region
200-250 μm
not to scale
3.3 cm from the interaction point

Part I: Monitoring Radiation Damage Effects

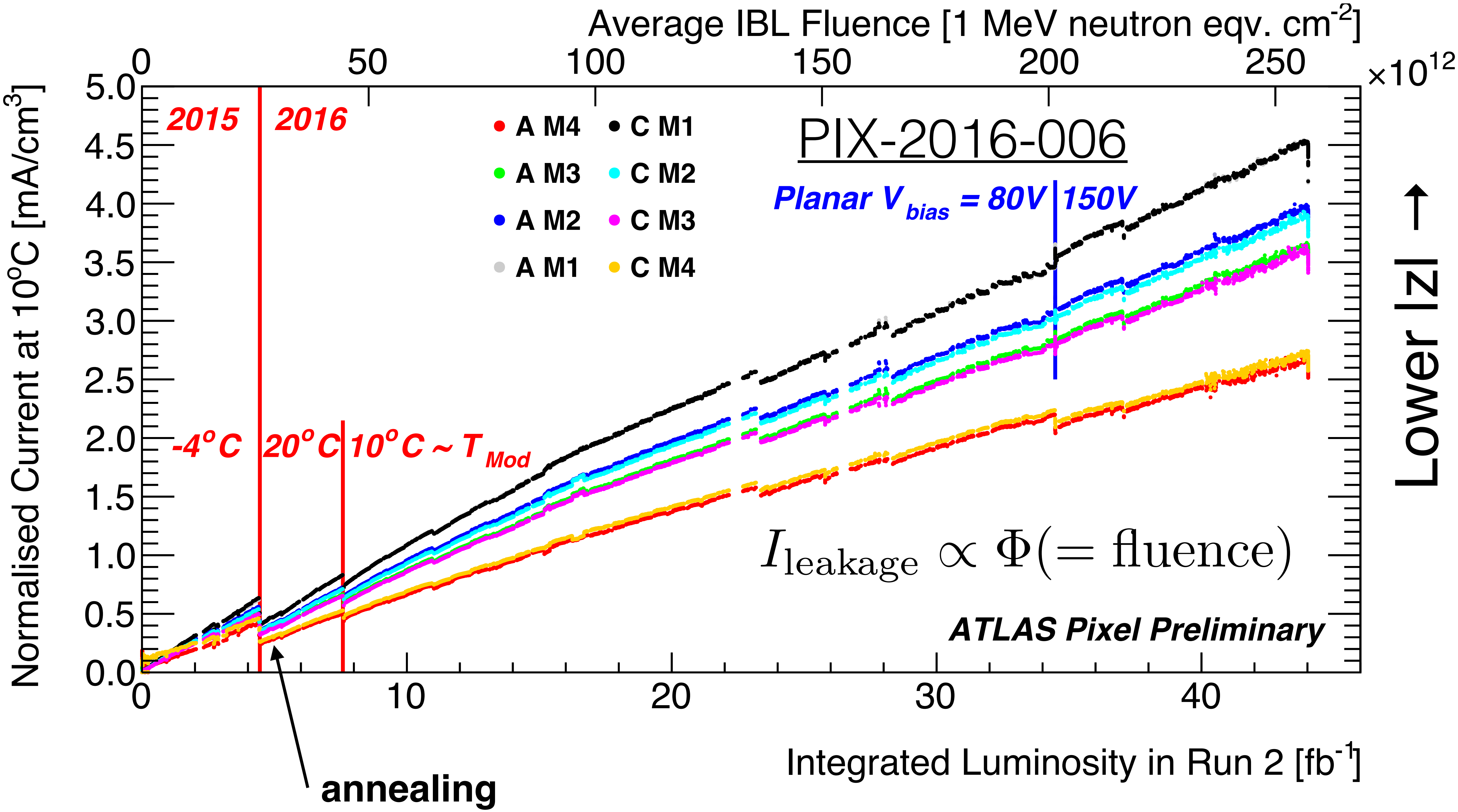
ATLAS-TDR-019



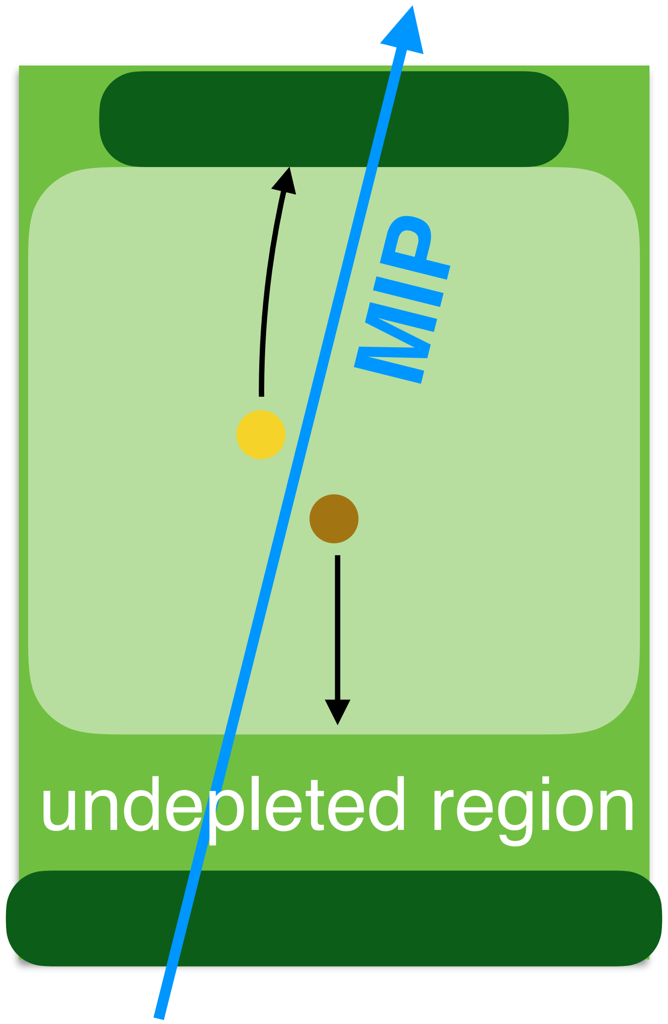
IBL lifetime: ~few x 10^{15} n_{eq}/cm^2

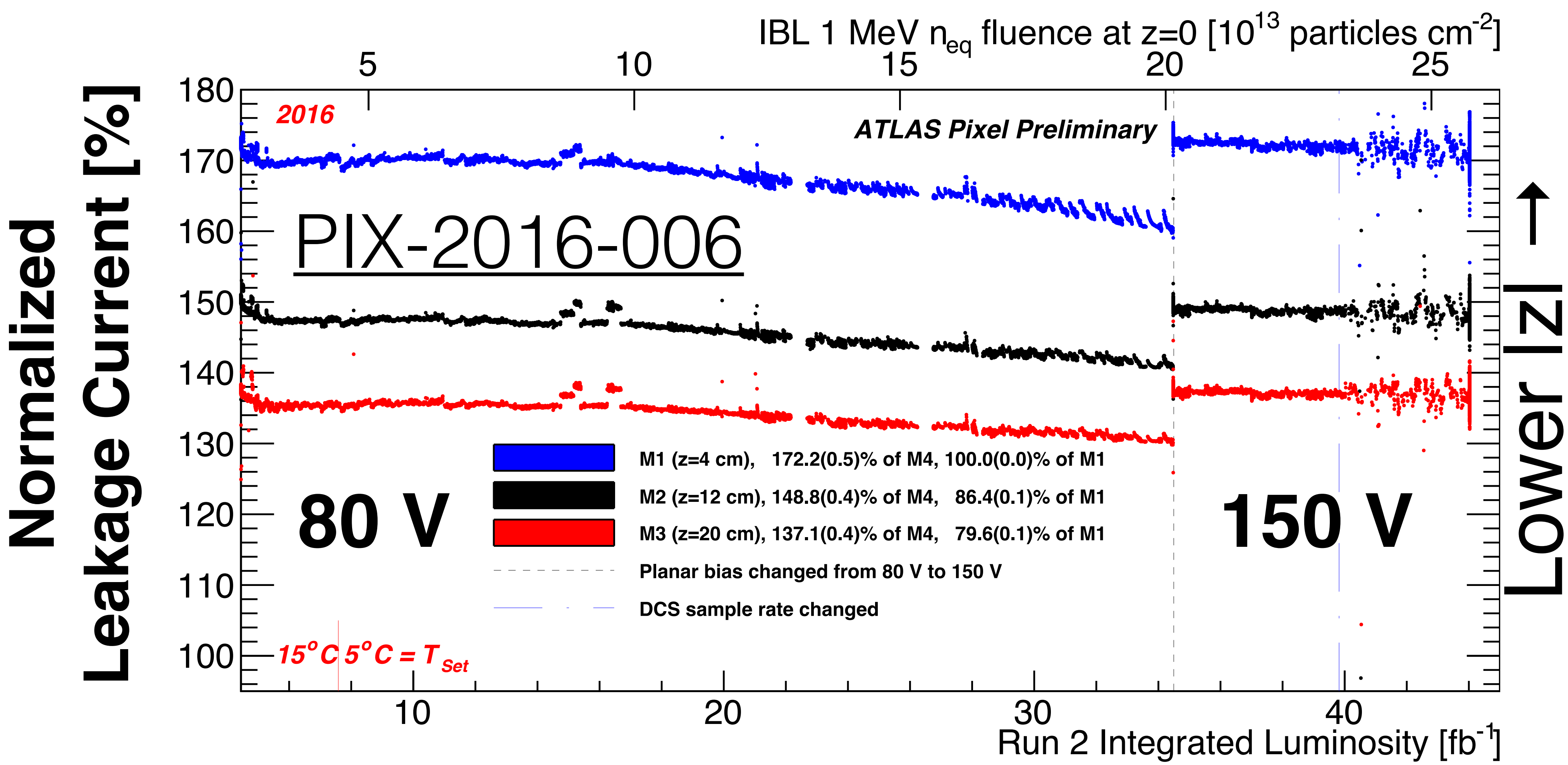
Leakage Current

Crystal defects are energy levels in the band gap
→ More defects = more thermal charges = **leakage current**



Depletion Voltage and Leakage Current



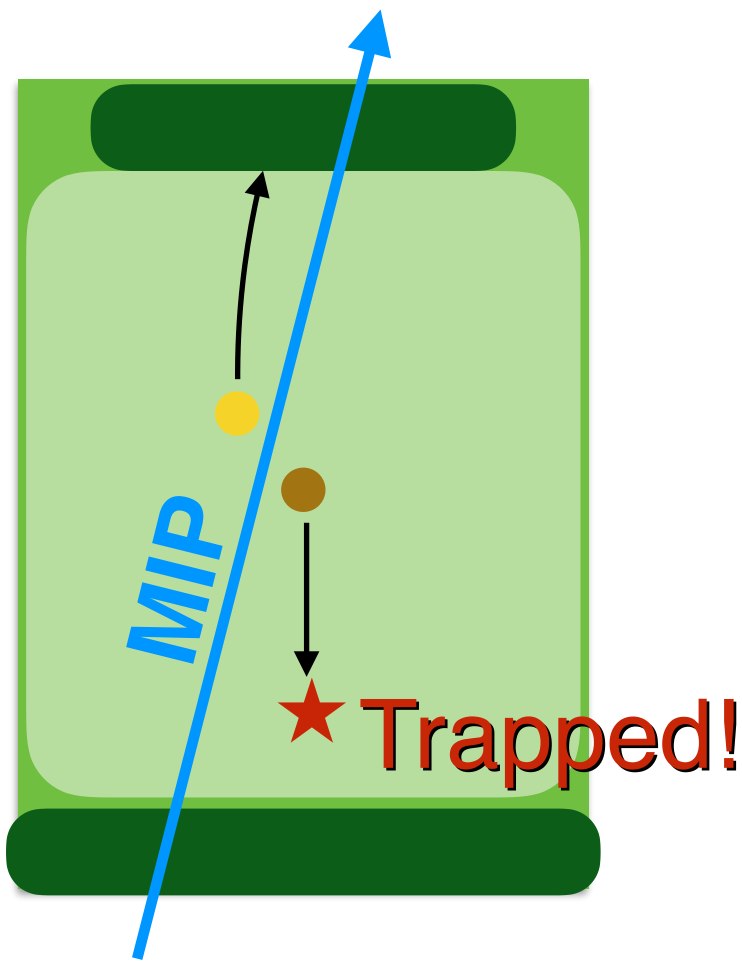


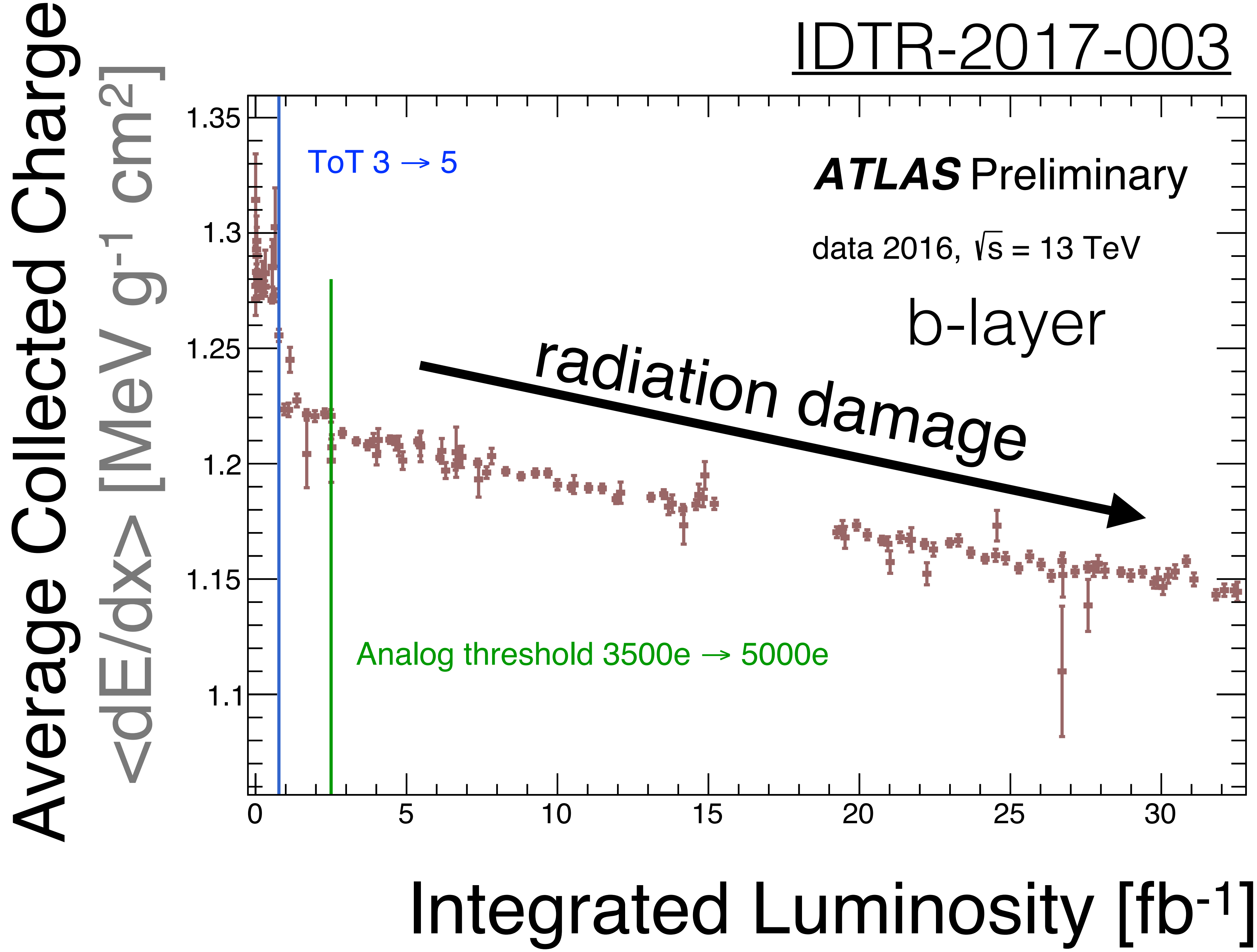
Leakage current proportional to fluence;
proportionally constant is independent of |z|.

→ **leakage current ratios tell us about the depleted volume**
(normalized to 3D sensors that are always depleted here)

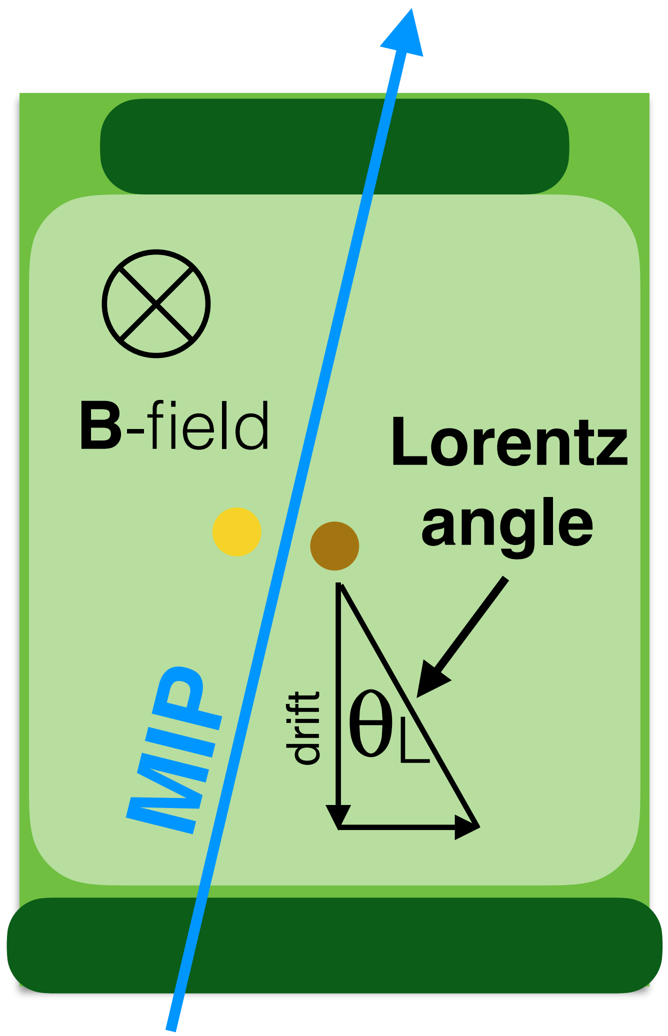
Charge Collection Efficiency

Average charge collected from MIPs decreased due to charge trapping





Lorentz Angle



$$\tan(\theta_{\mathrm{L}}) \propto \mu(E)B$$

Mobility
~ 1/E for high E

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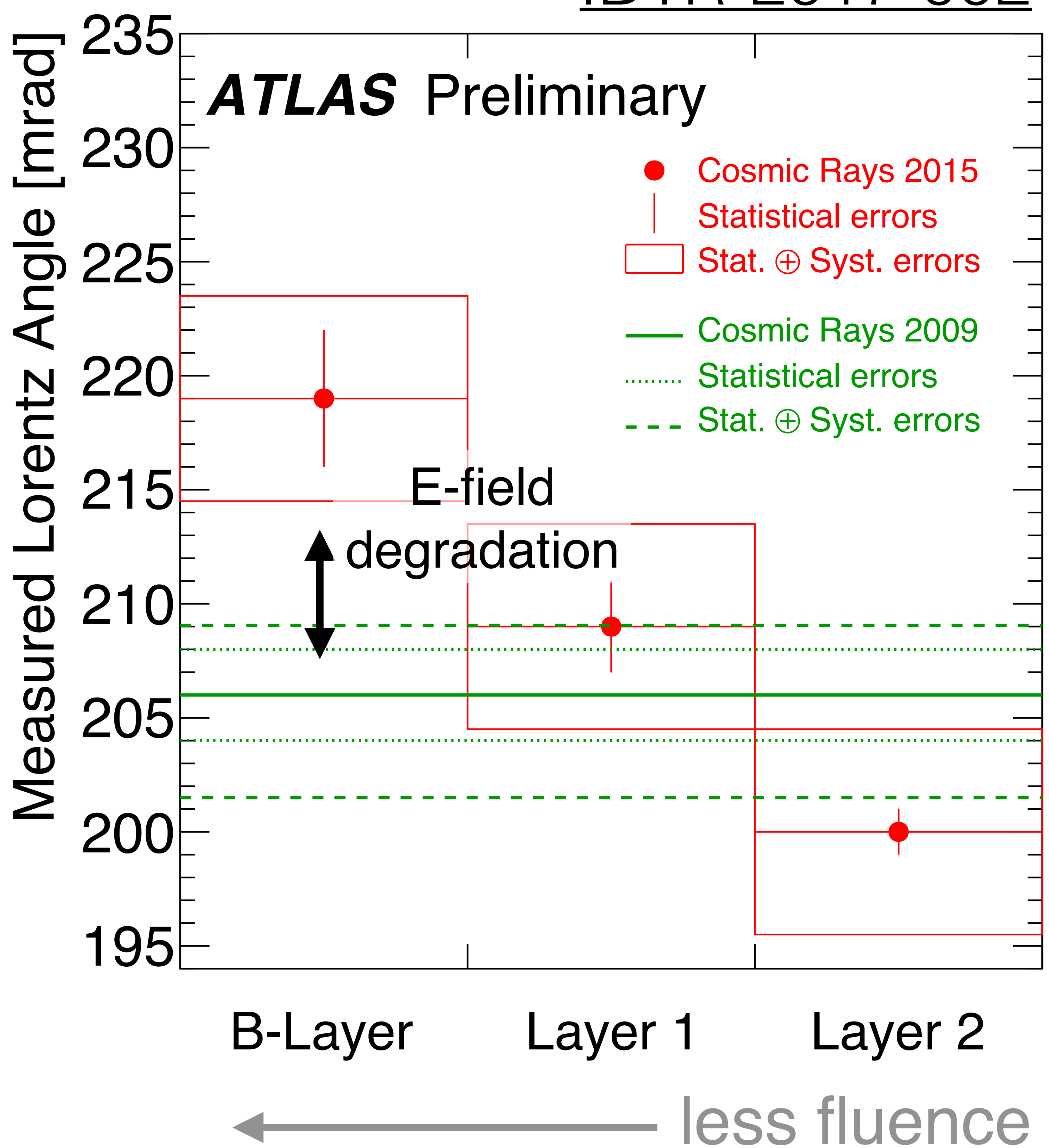


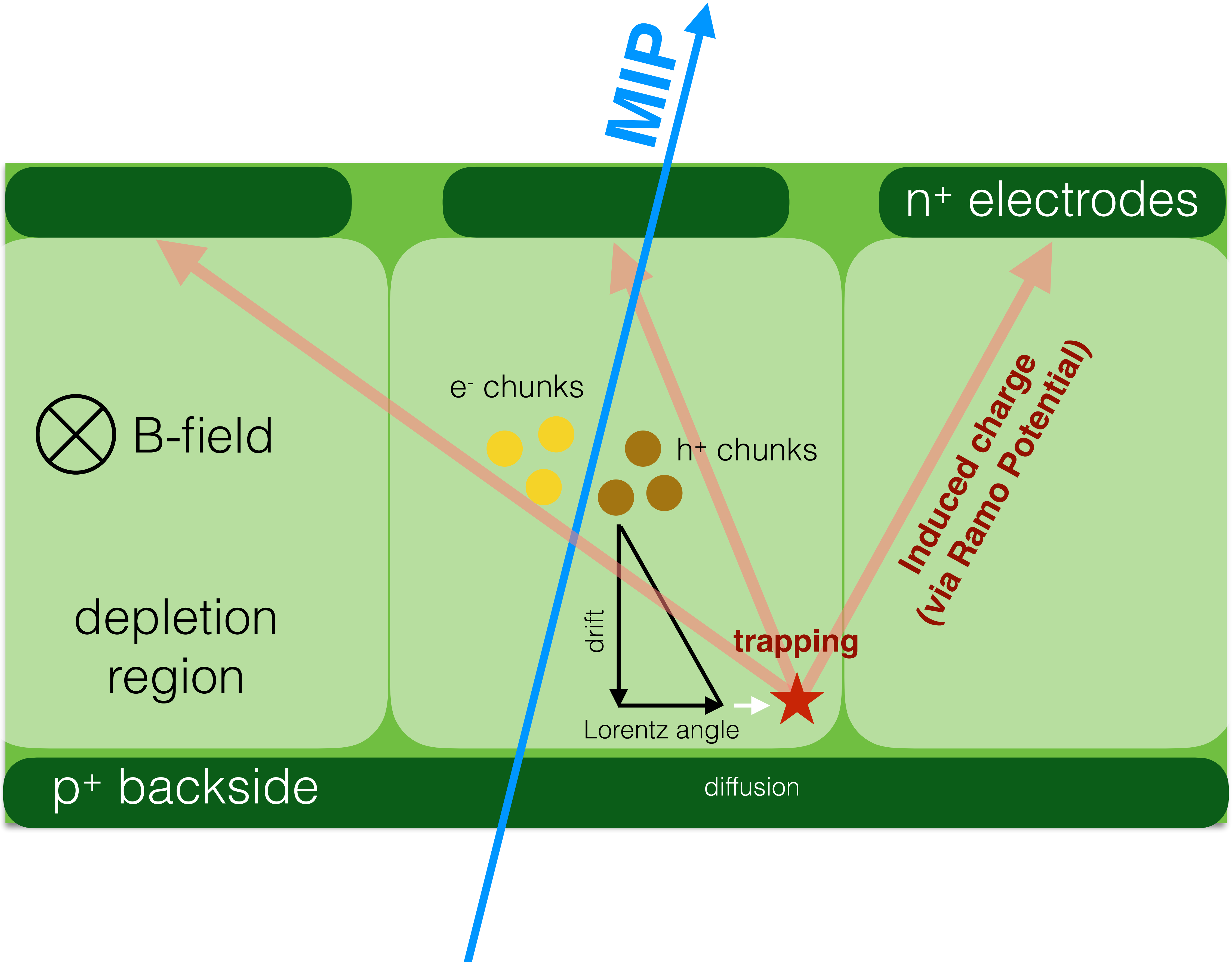
Part II: Modeling Radiation Damage Effects

Radiation damage is already producing measurable effects; this will only continue to be more important.

→ **Need to include radiation damage in our simulation!**

This is currently not done by default for the current or HL-LHC ATLAS simulations !

ATLAS Pixel Digitization Simulation



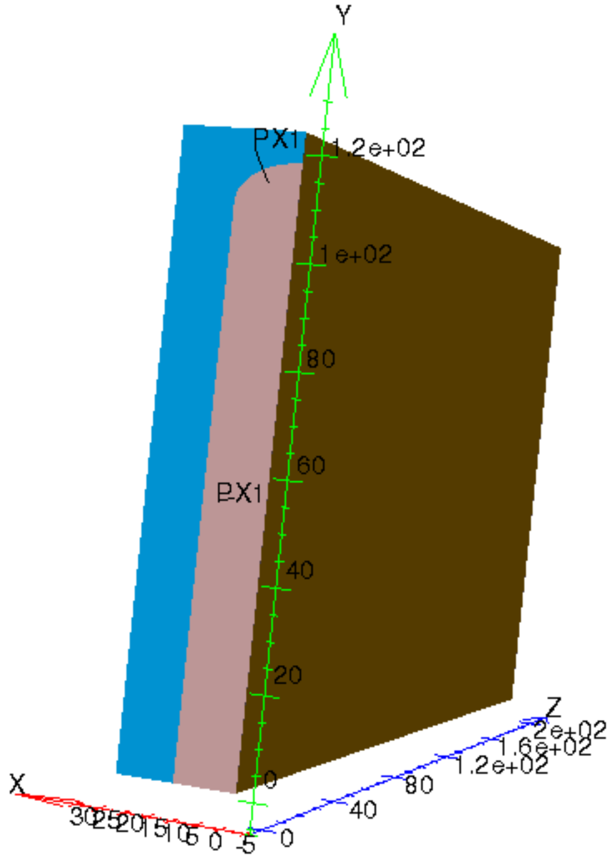
Modeling Electric Field Deformations

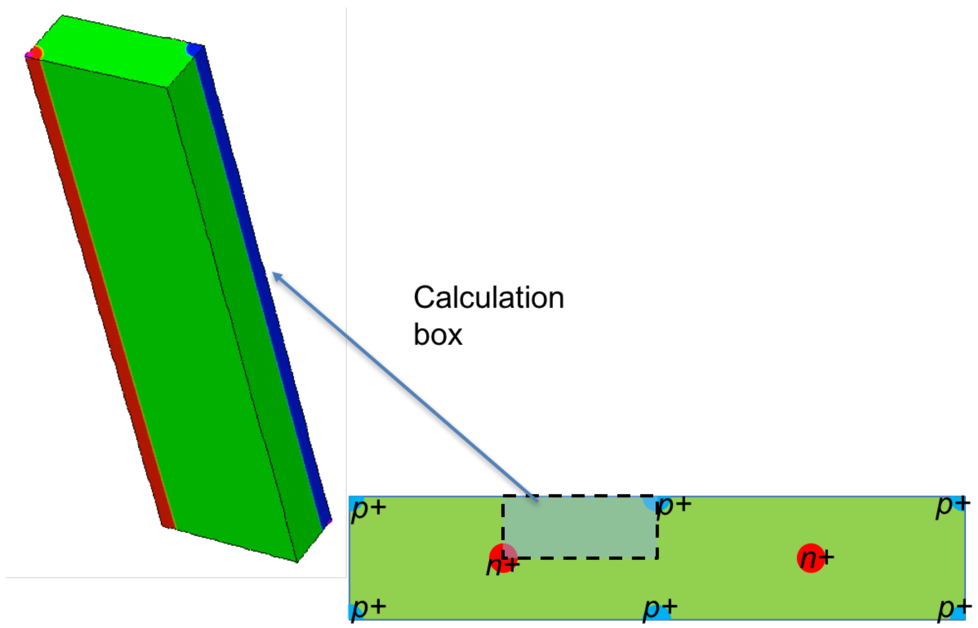
Use TCAD to calculate the E-field

2-trap (Chiochia model) for planar and 3-trap (Perugia model) for 3D

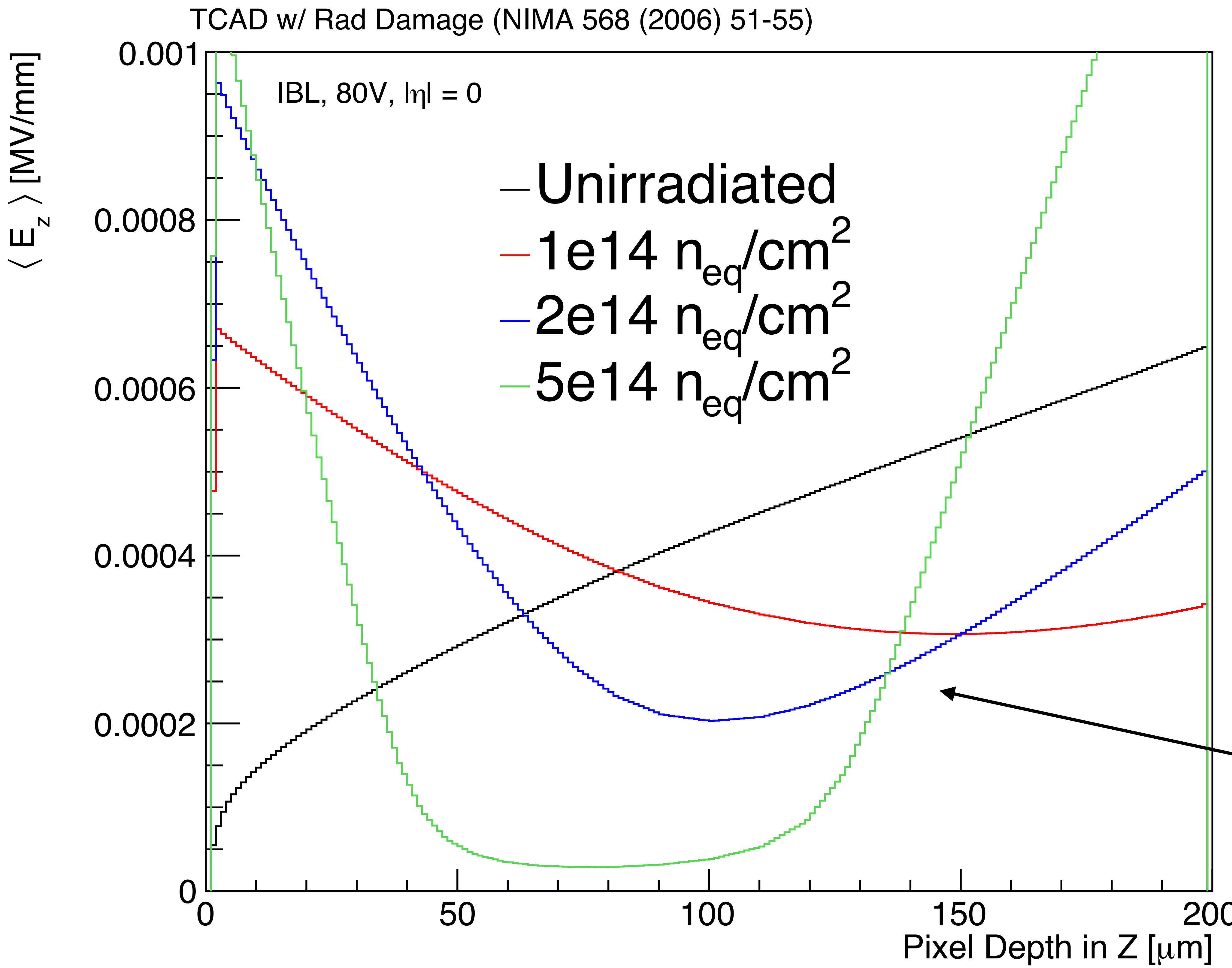
traps are $O(k_B T)$ from the intrinsic energy level

additional parameters: e/h capture cross sections and introduction rates





references in backup

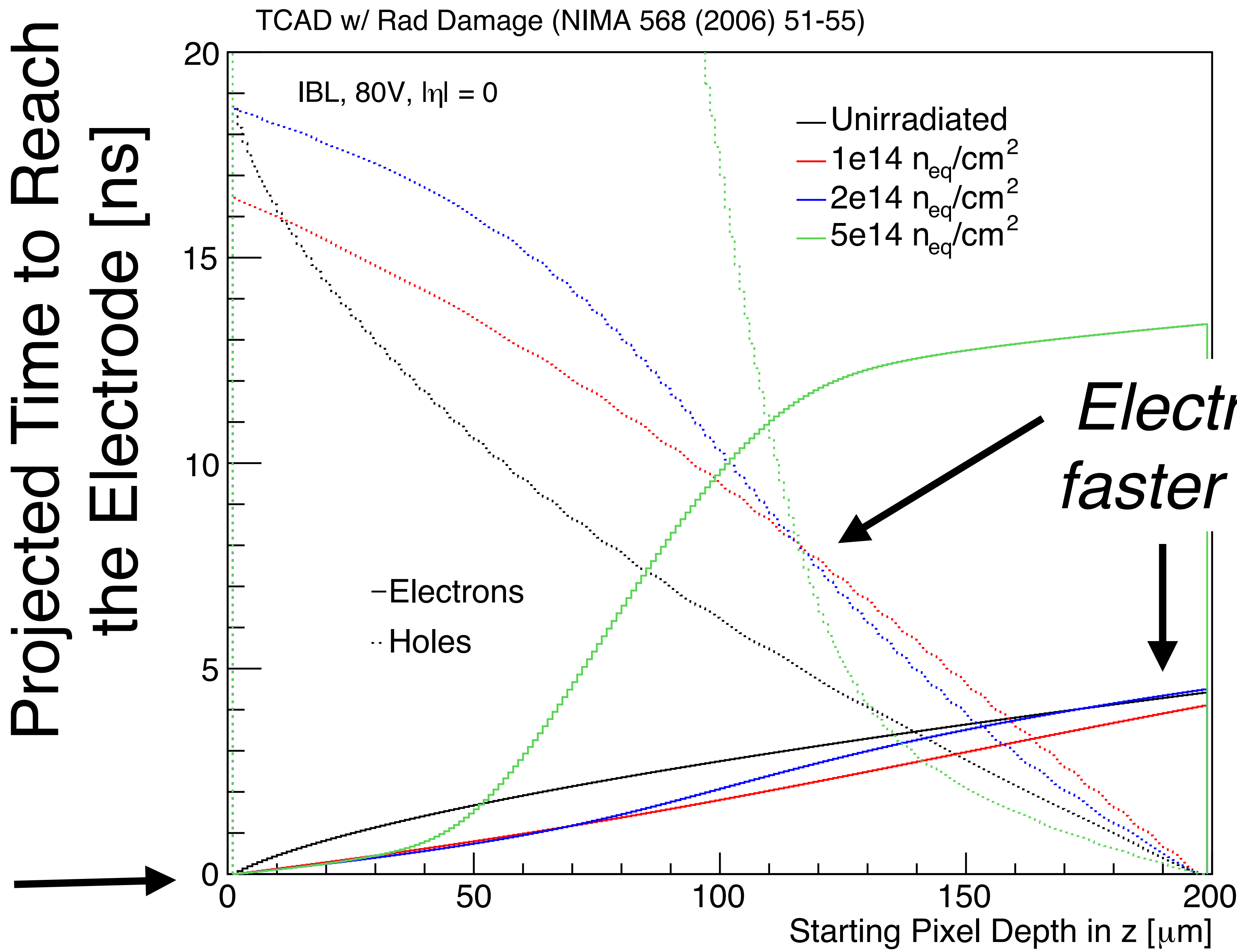


before space-charge sign ("type") inversion

characteristic double-peak

pixel implant **backside**

To save time, we pre-compute ('maps') all the quantities derived from the E-field.



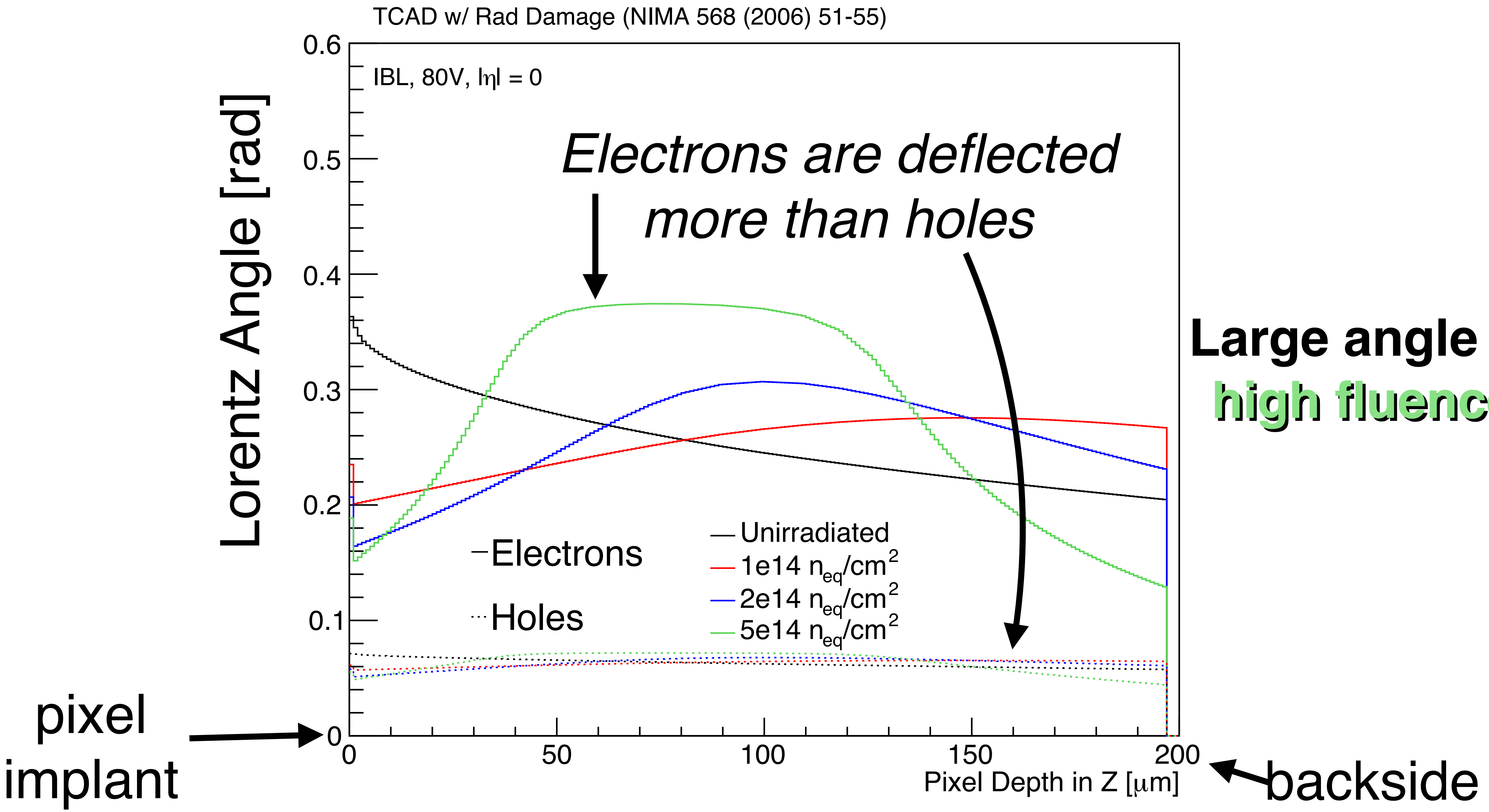
pixel implant

backside

Small field = long time at high fluence

Electrons move faster than holes

The Lorentz angle also changes with depth because of the non-uniform field: $\tan(\theta_{\mathrm{L}}) \propto \mu(E)E$



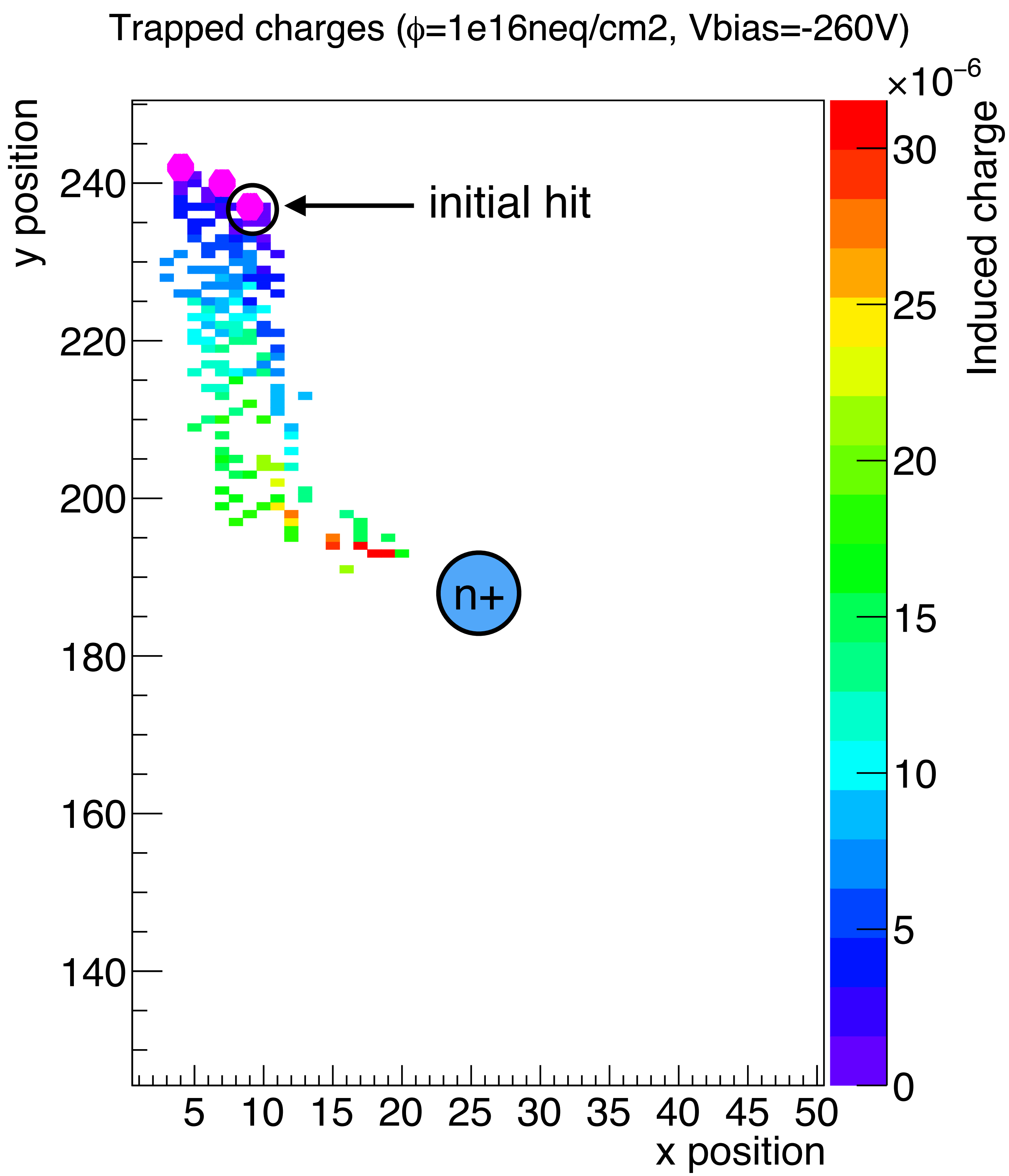
Large angle at high fluence

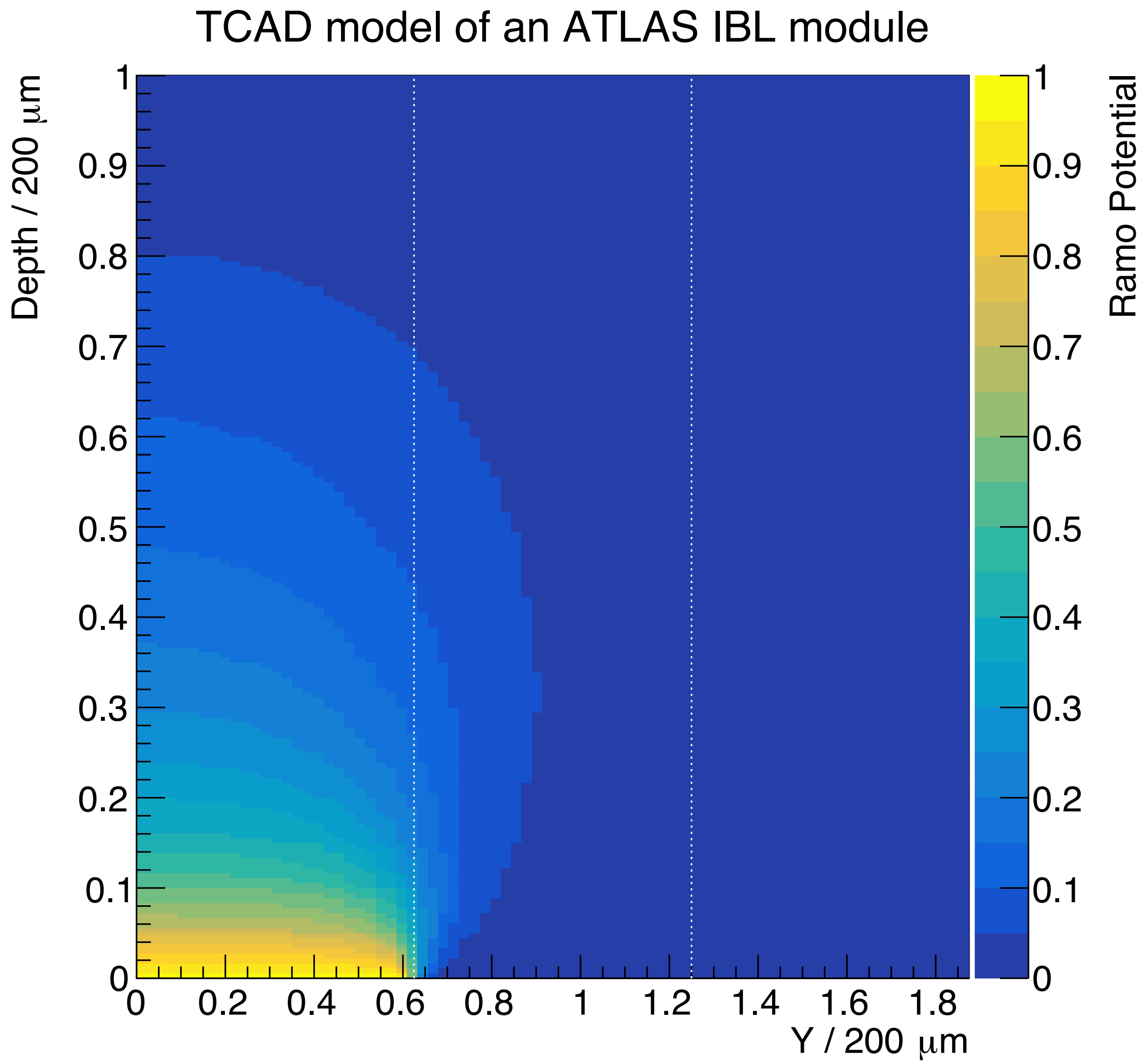
Trapping

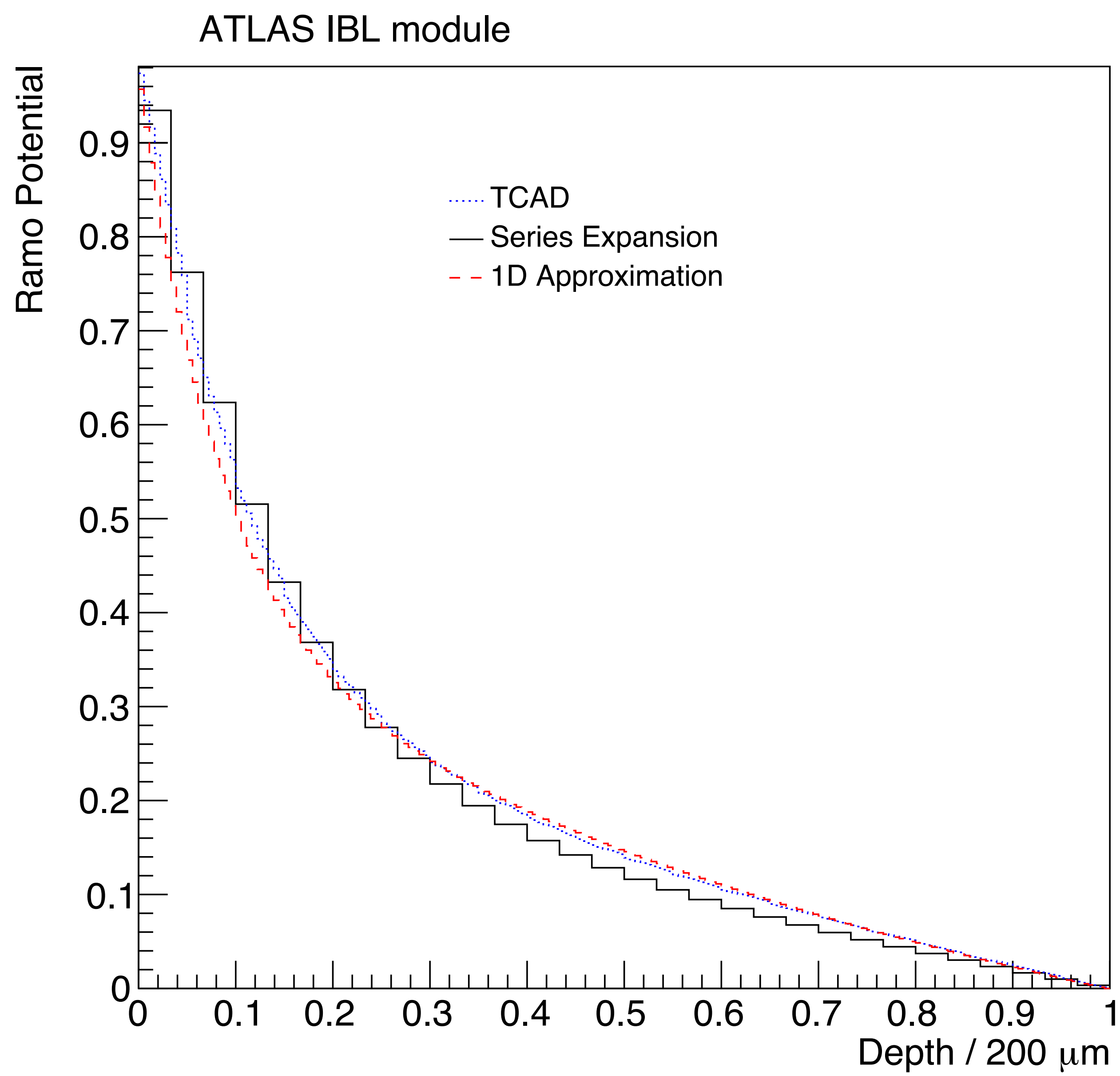
Charged get trapped with a time constant
$\tau \sim 1$ ns @ 3 x 10^{15} n_{eq}/cm^2

Even trapped charges contribute to the signal, calculated with the Ramo potential (ϕ)

$$Q_{\text{induced}} = -Q[\phi(\vec{x}_{\text{end}}) - \phi(\vec{x}_{\text{start}})].$$

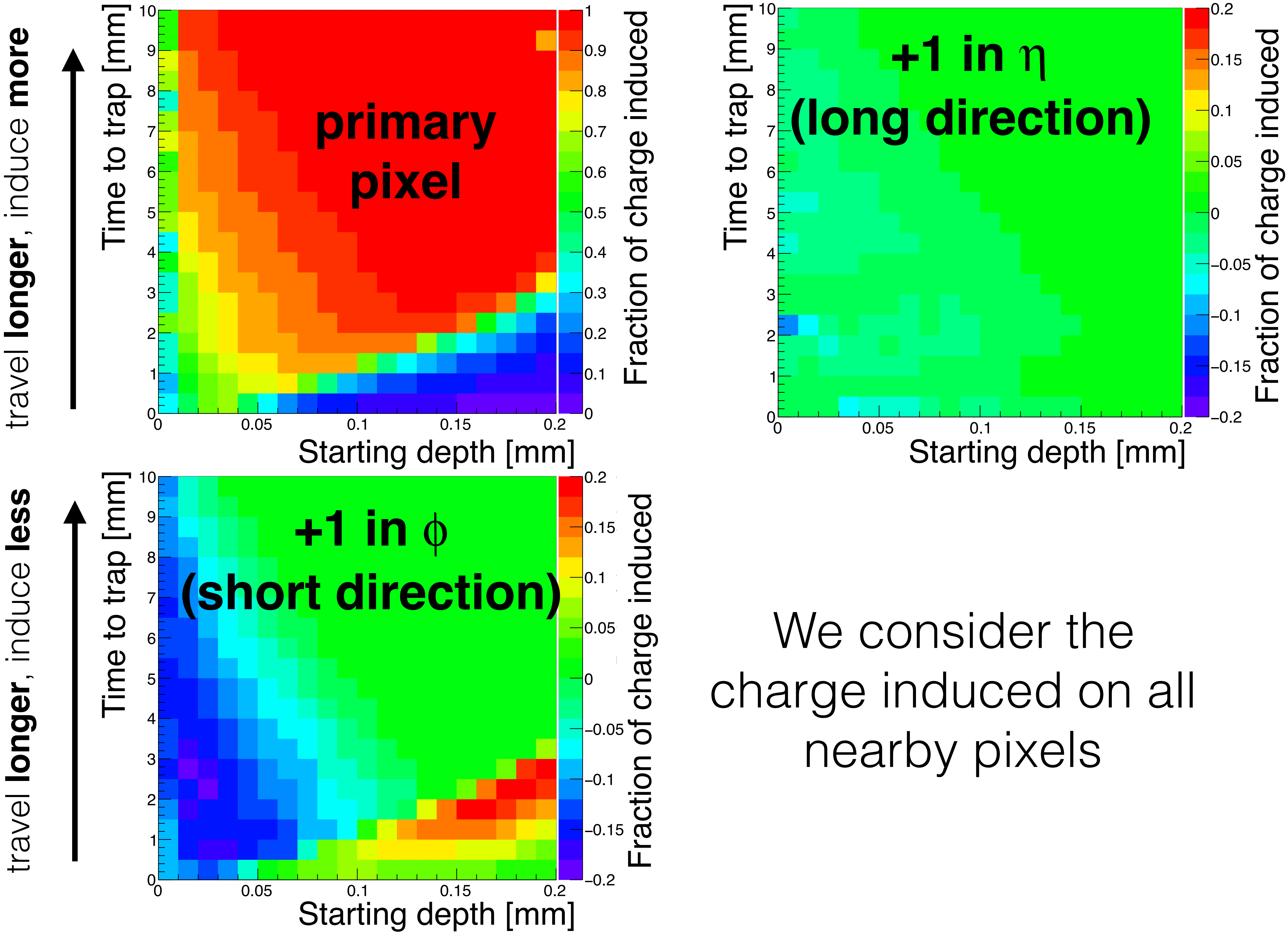






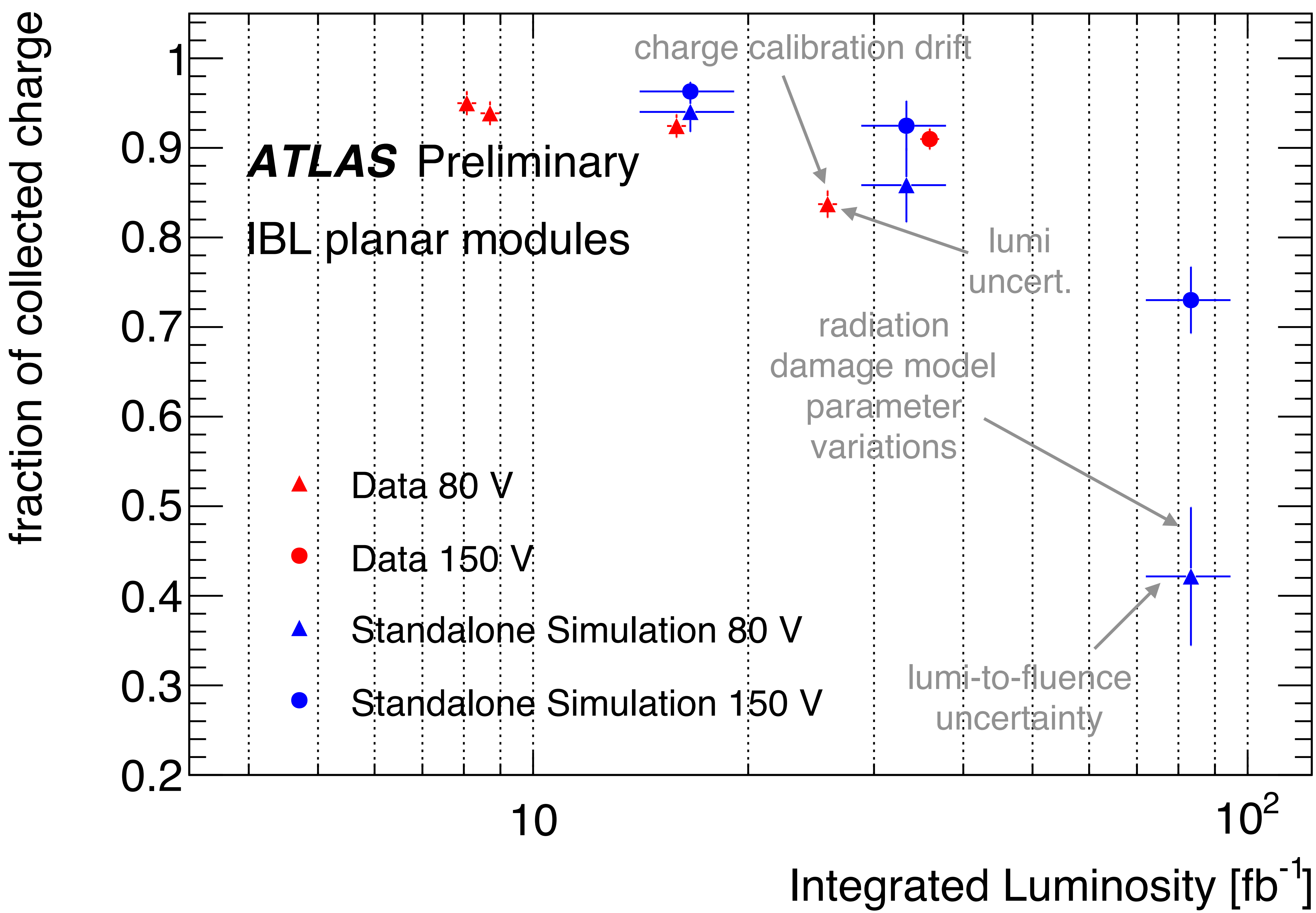
1 @ electrode, 0 @ far away

Ramo Potential - Induced Charge *IBL planar modules*



We consider the charge induced on all nearby pixels

Model Prediction and Comparison with Data



Conclusions and Future Outlook

We have developed pixel digitization model with radiation damage effects.

Tracking performance seems insensitive to the present fluence levels, but **degradation is inevitable**

We are now prepared to model the degradation for Run 2+3 and for the HL-LHC

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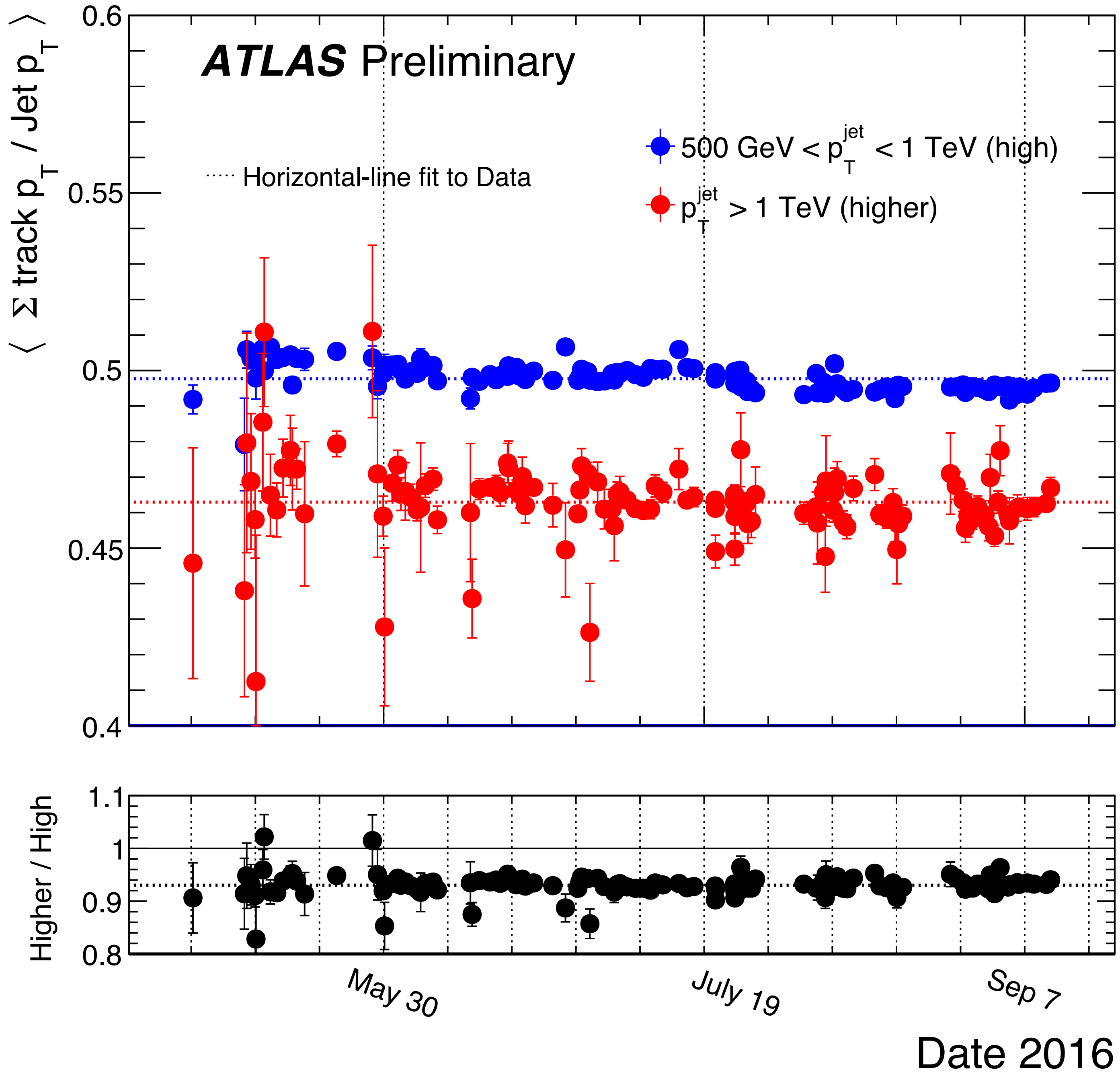
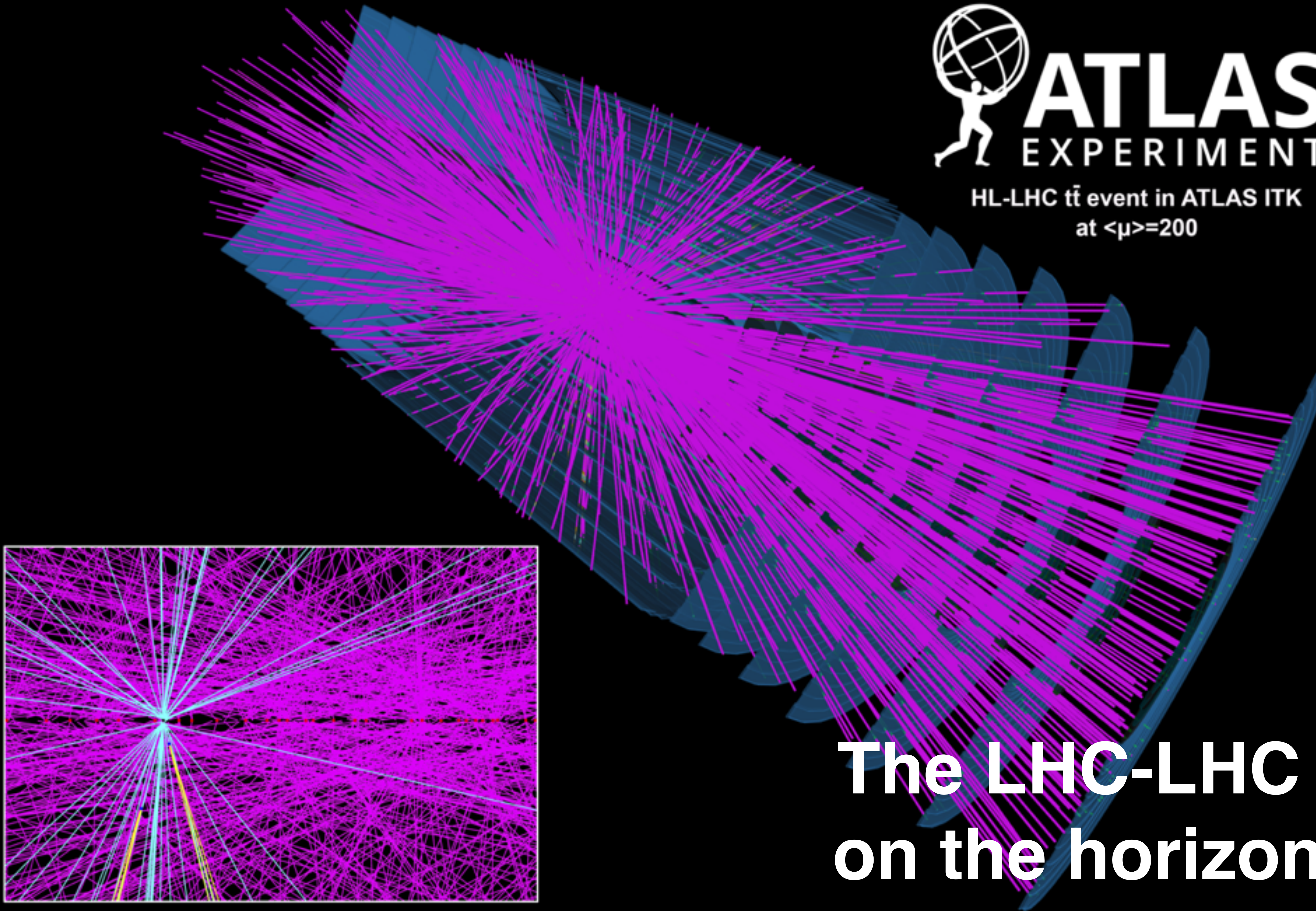




The LHC-LHC is on the horizon .. are you ready?

References

[1] Marco Bomben et al., Planar TCAD Simulation Details

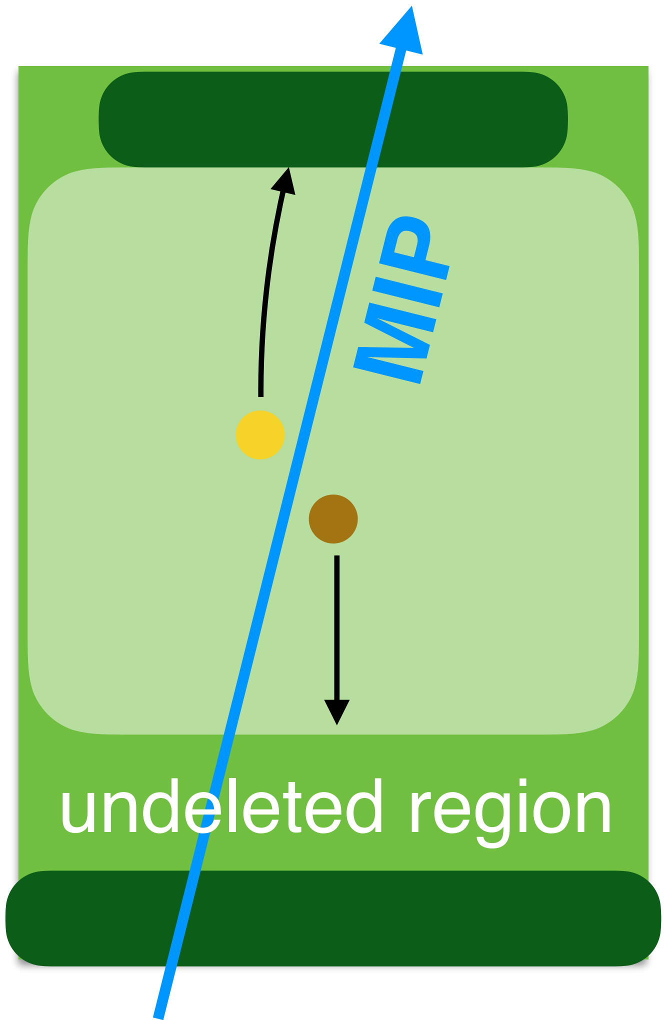
[2] Gilberto Giugliarelli et al., 3D TCAD Simulation Details

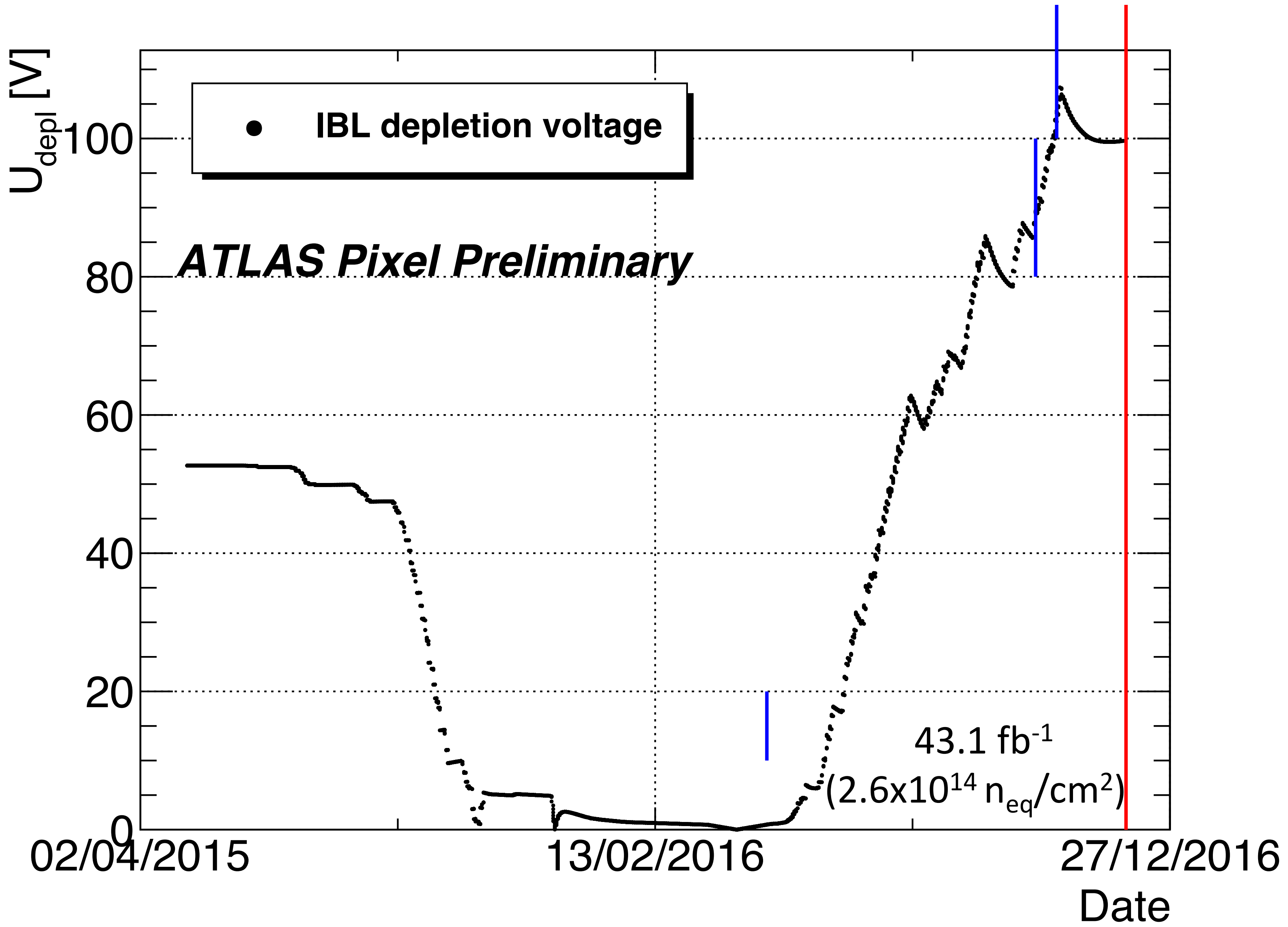
Backup

Slide Change After Presentation

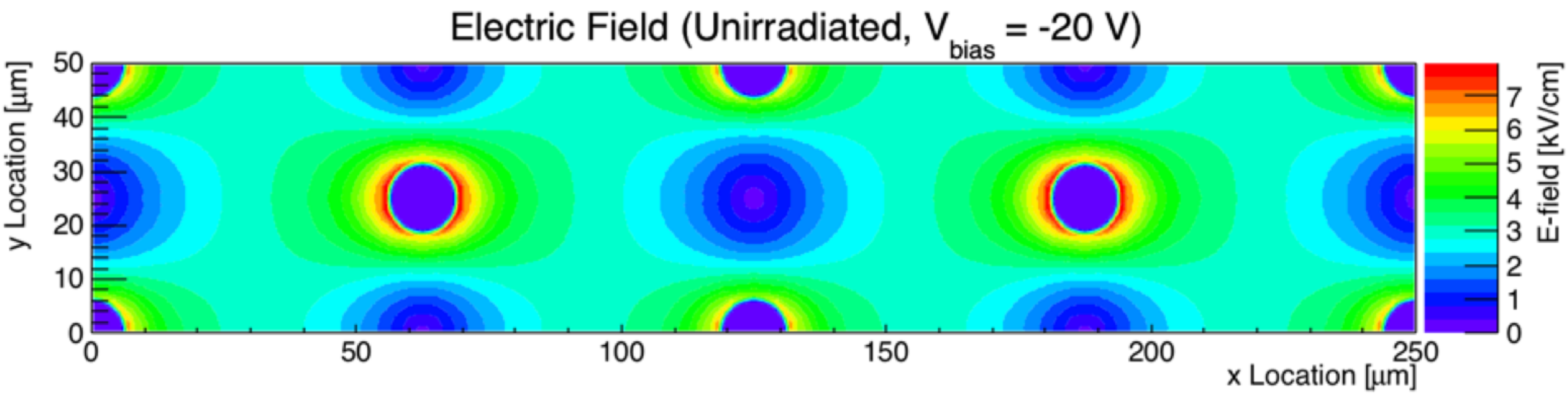
p10 was slightly modified to reflect the fact that the HV was changed in the IBL and not the b-layer towards the end of the run. The b-layer was fully depleted during all of 2016.

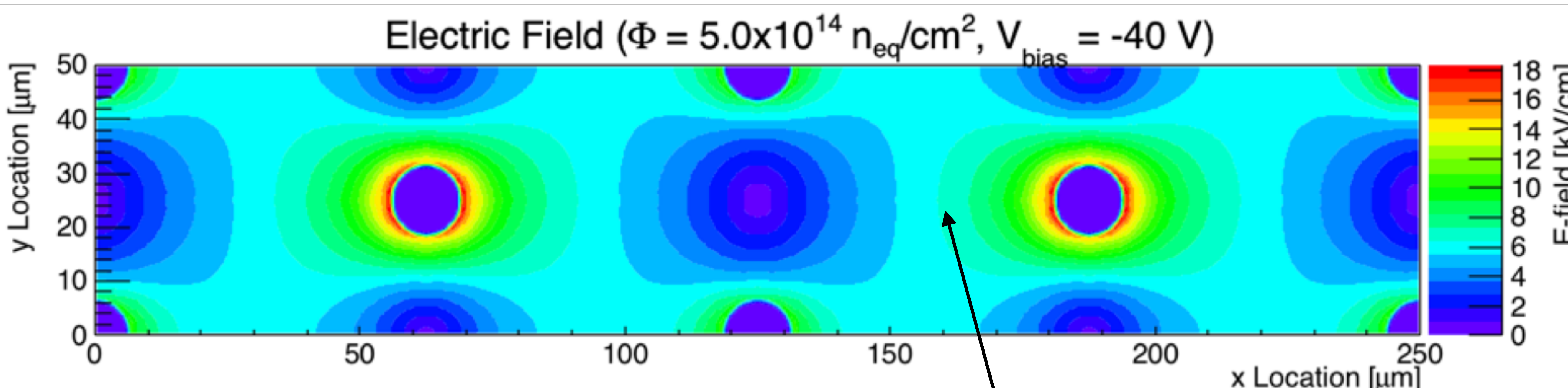
Depletion Voltage - Predictions





Electric Field: Field Profiles





no double peak, but field is weaker