Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

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on behalf of the ATLAS Collaboration

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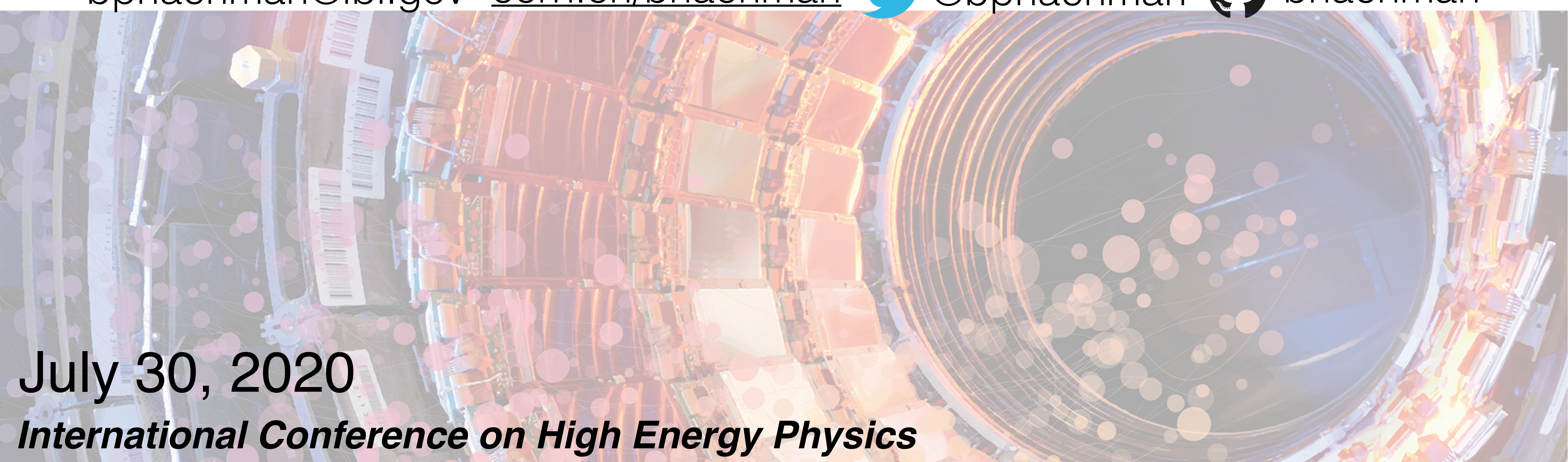

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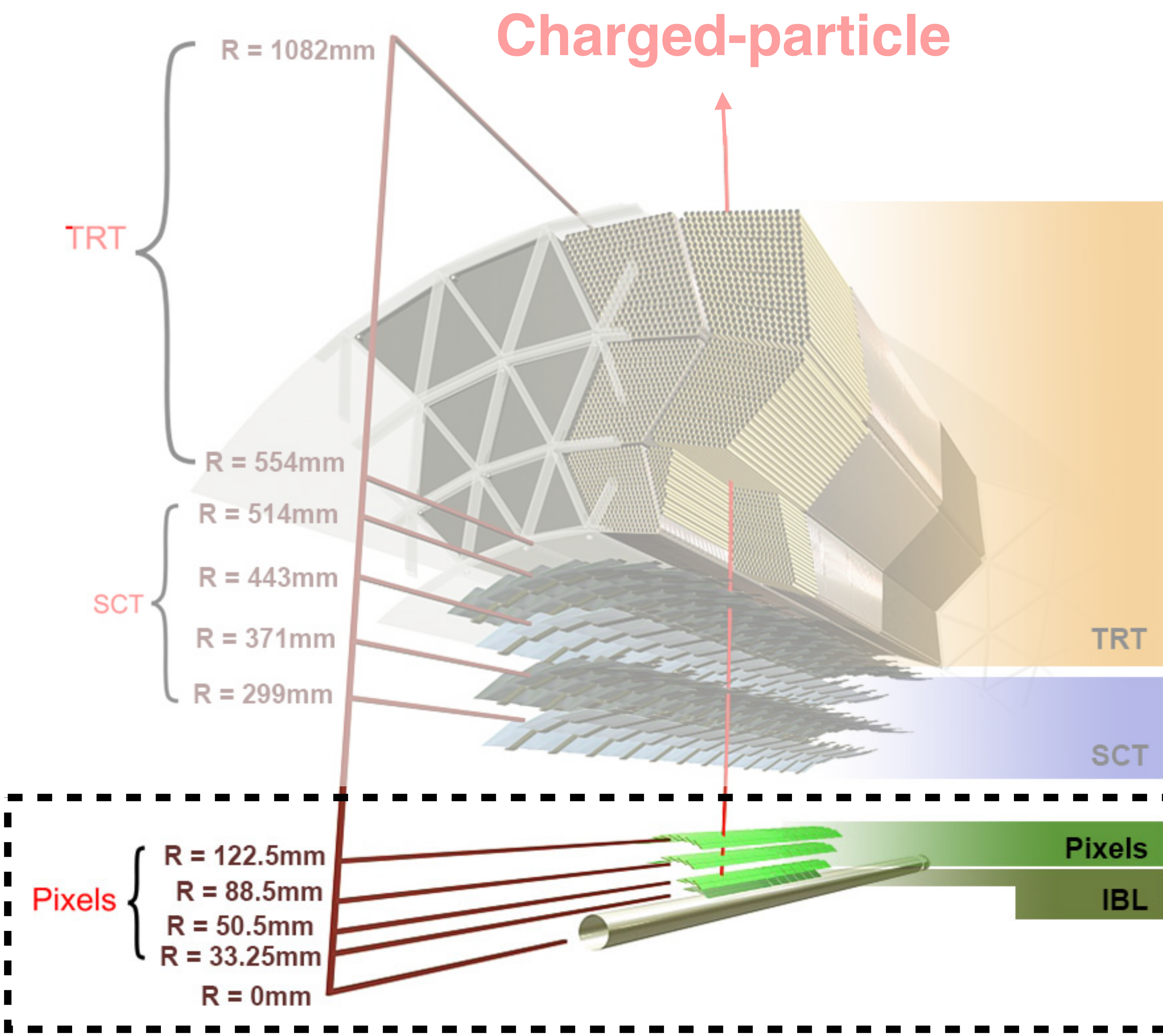
International Conference on High Energy Physics

At the heart of ATLAS: Silicon Pixels

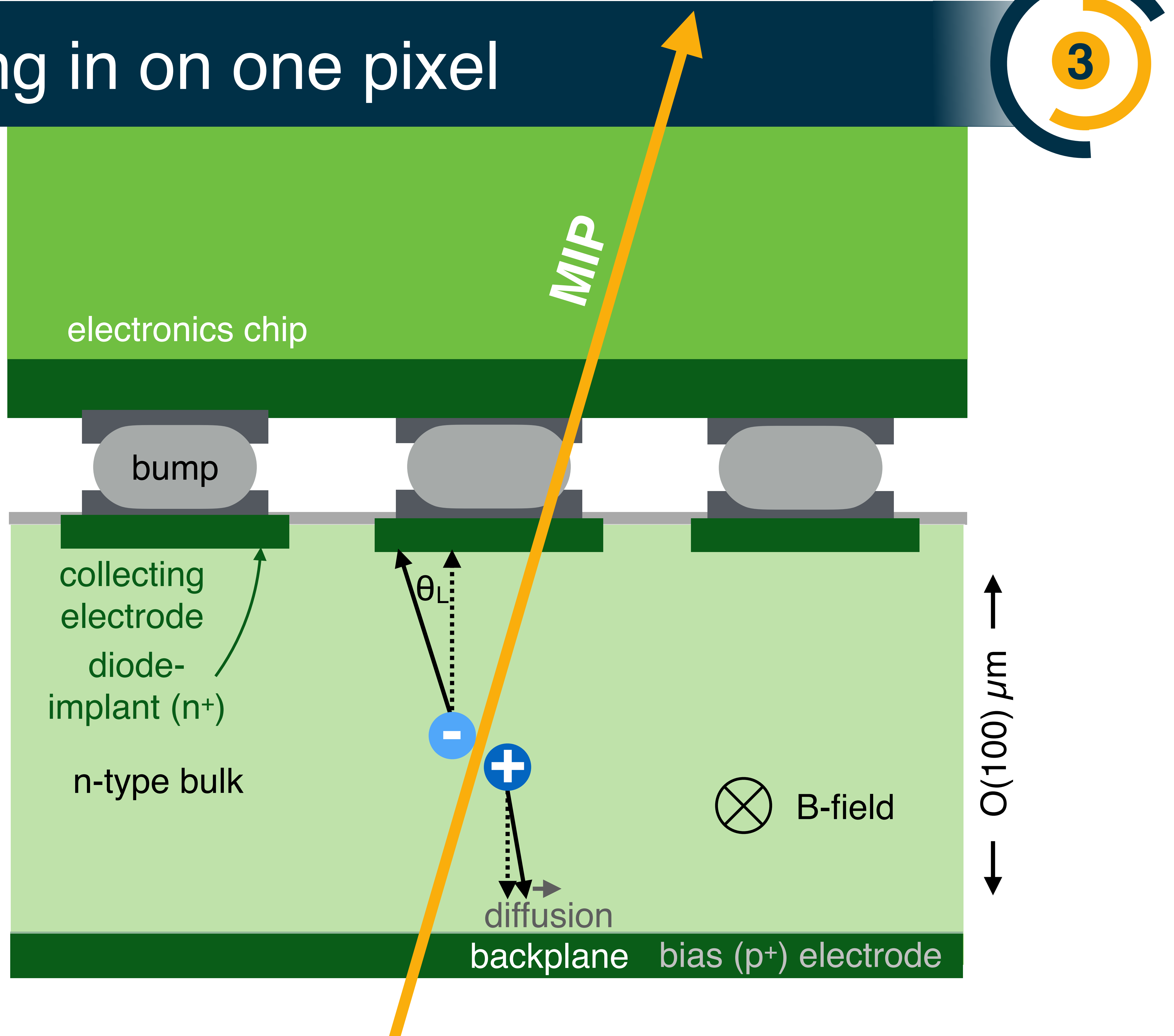
Closest to the interaction are finely segmented silicon pixels

O(100^3) μm^3

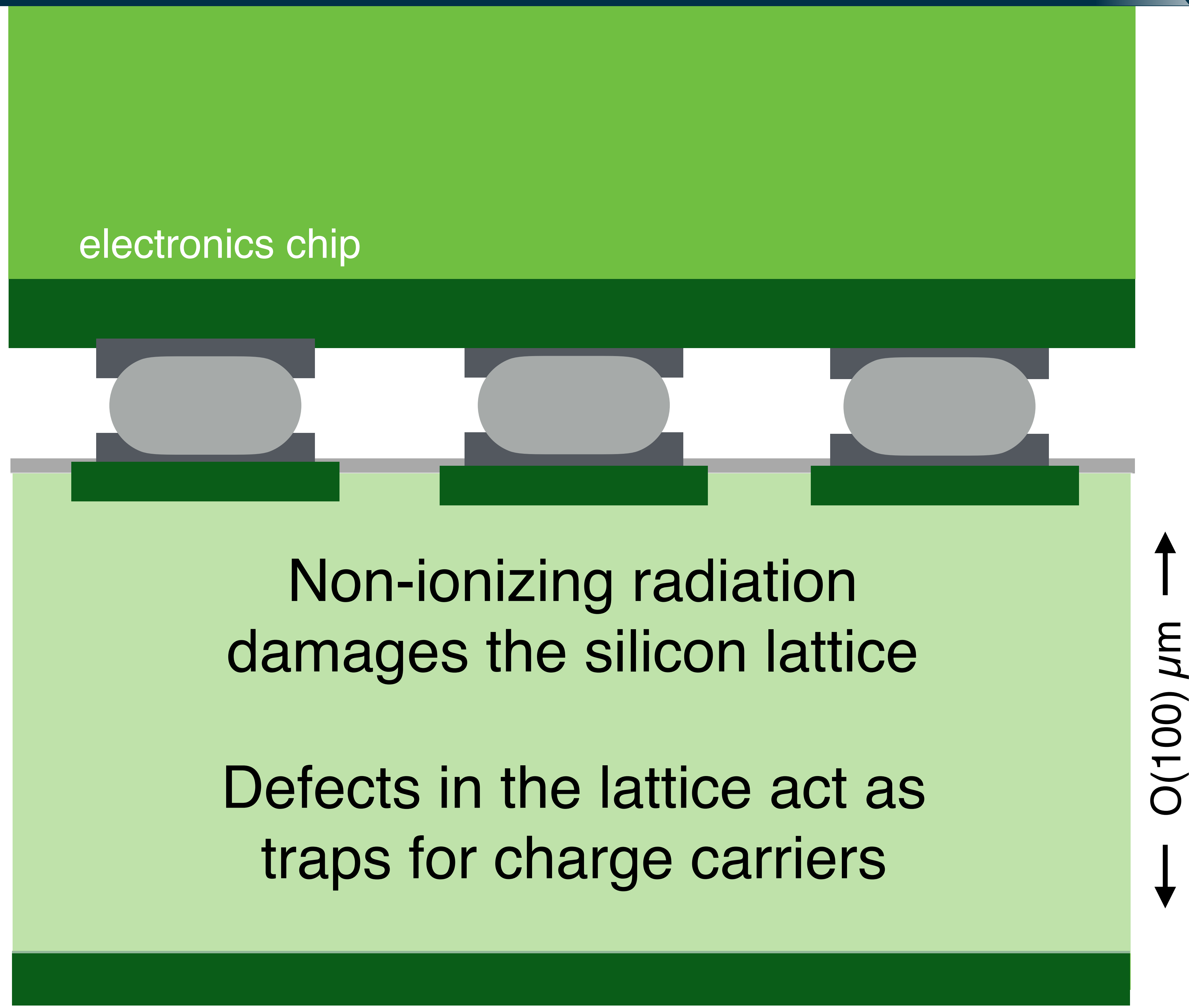
record (a digitized) charge for ionizing particles



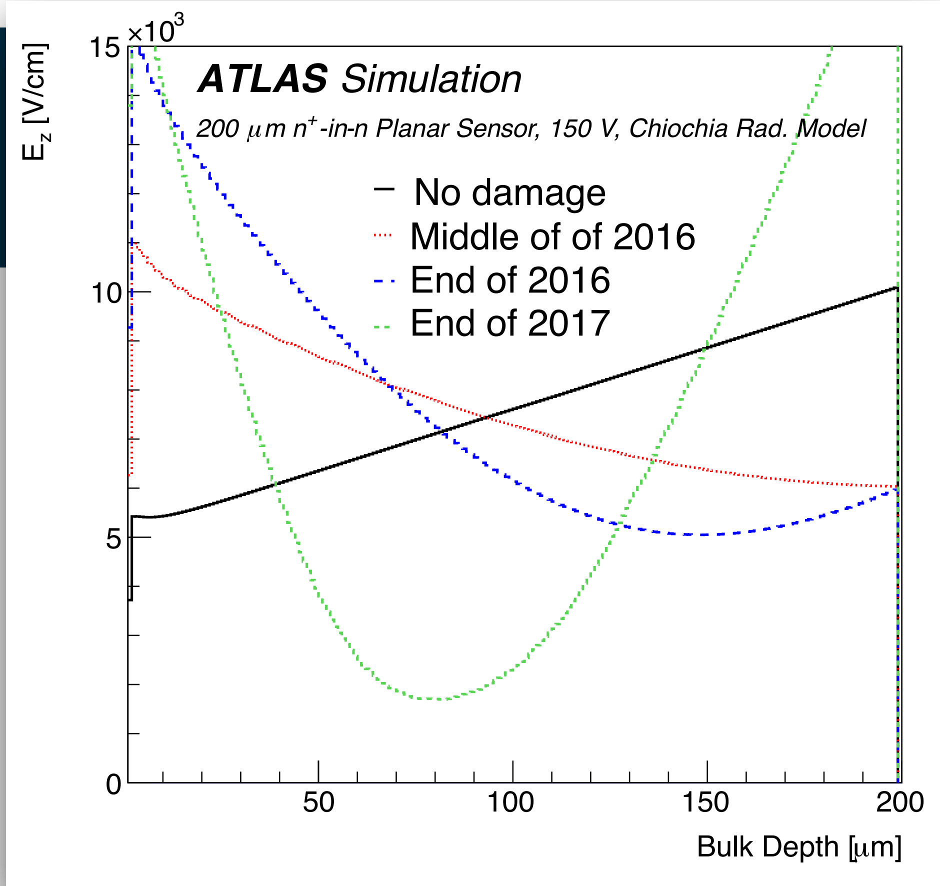
Zooming in on one pixel

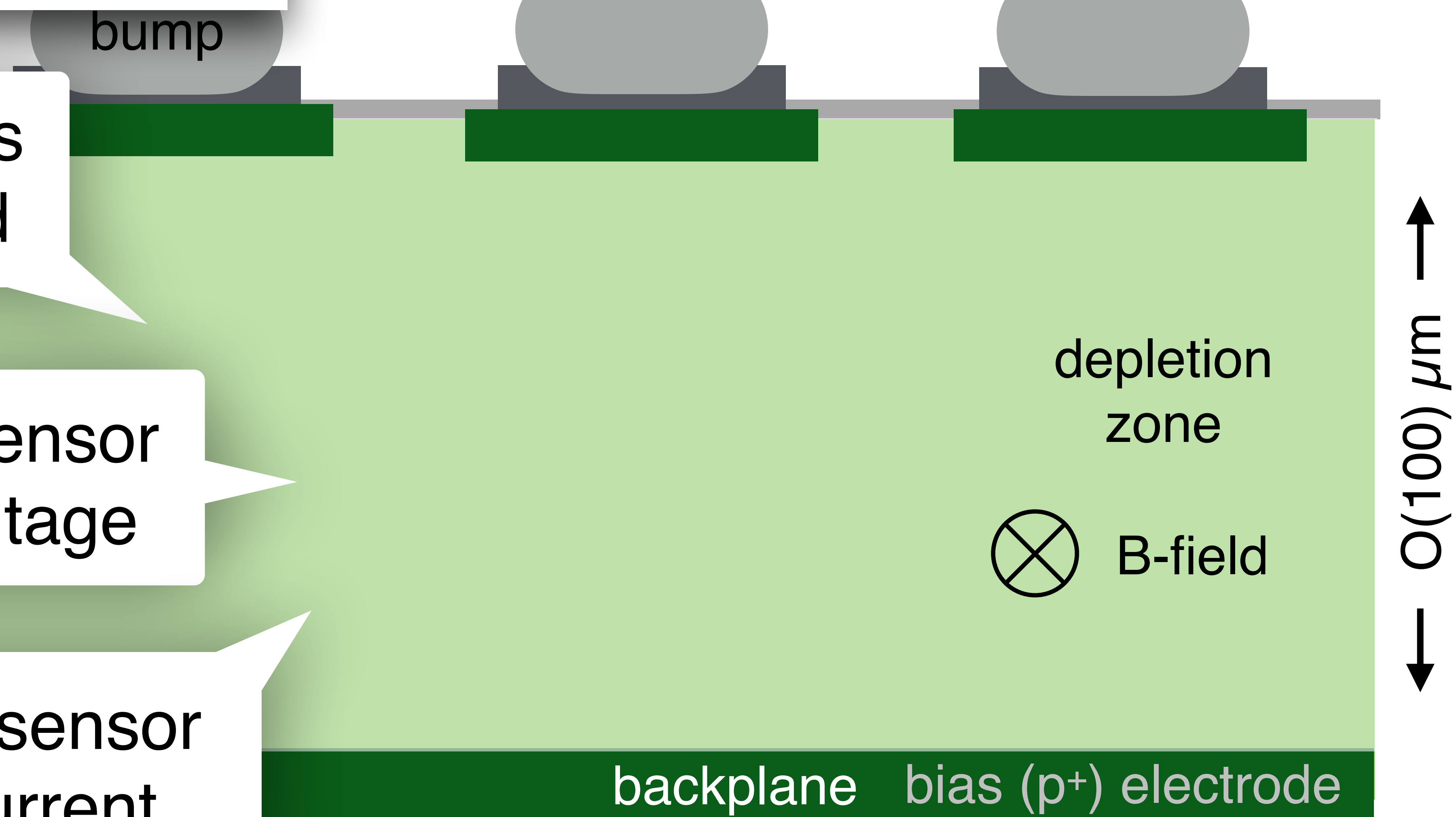


Silicon Radiation Damage



Signals after irradiation





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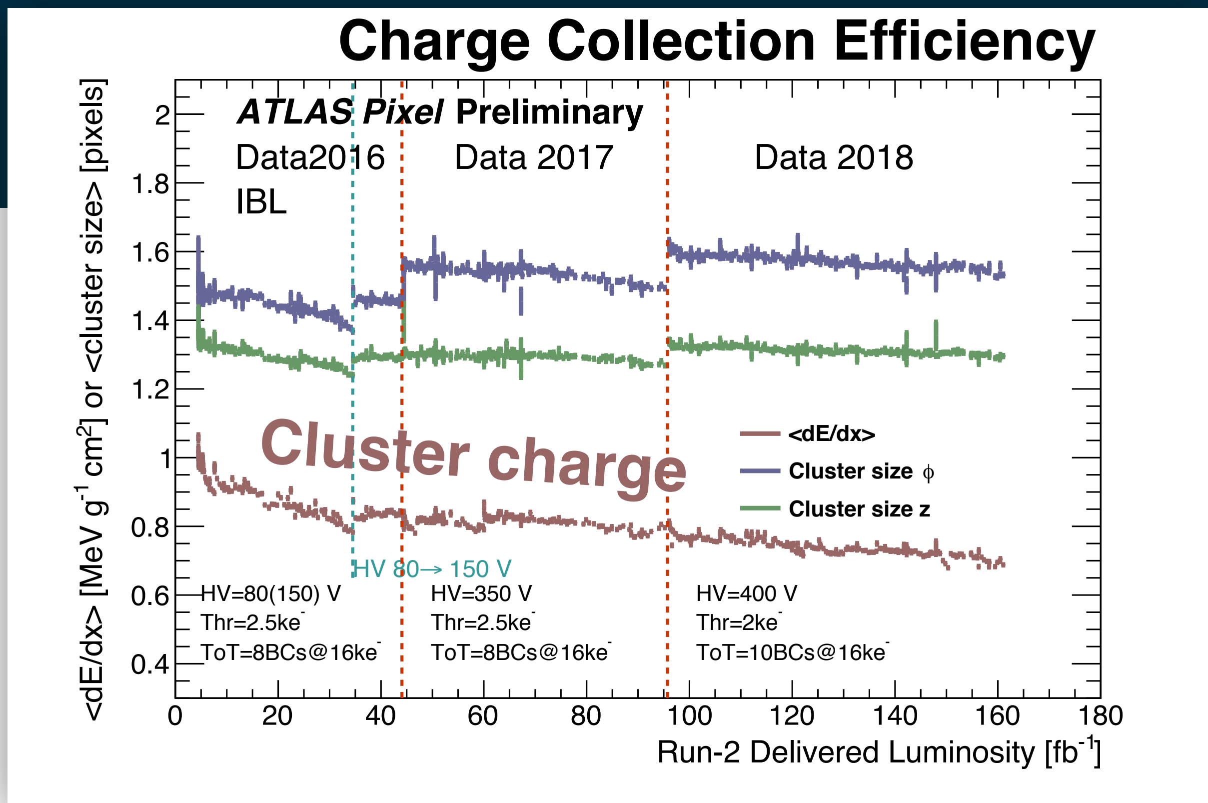
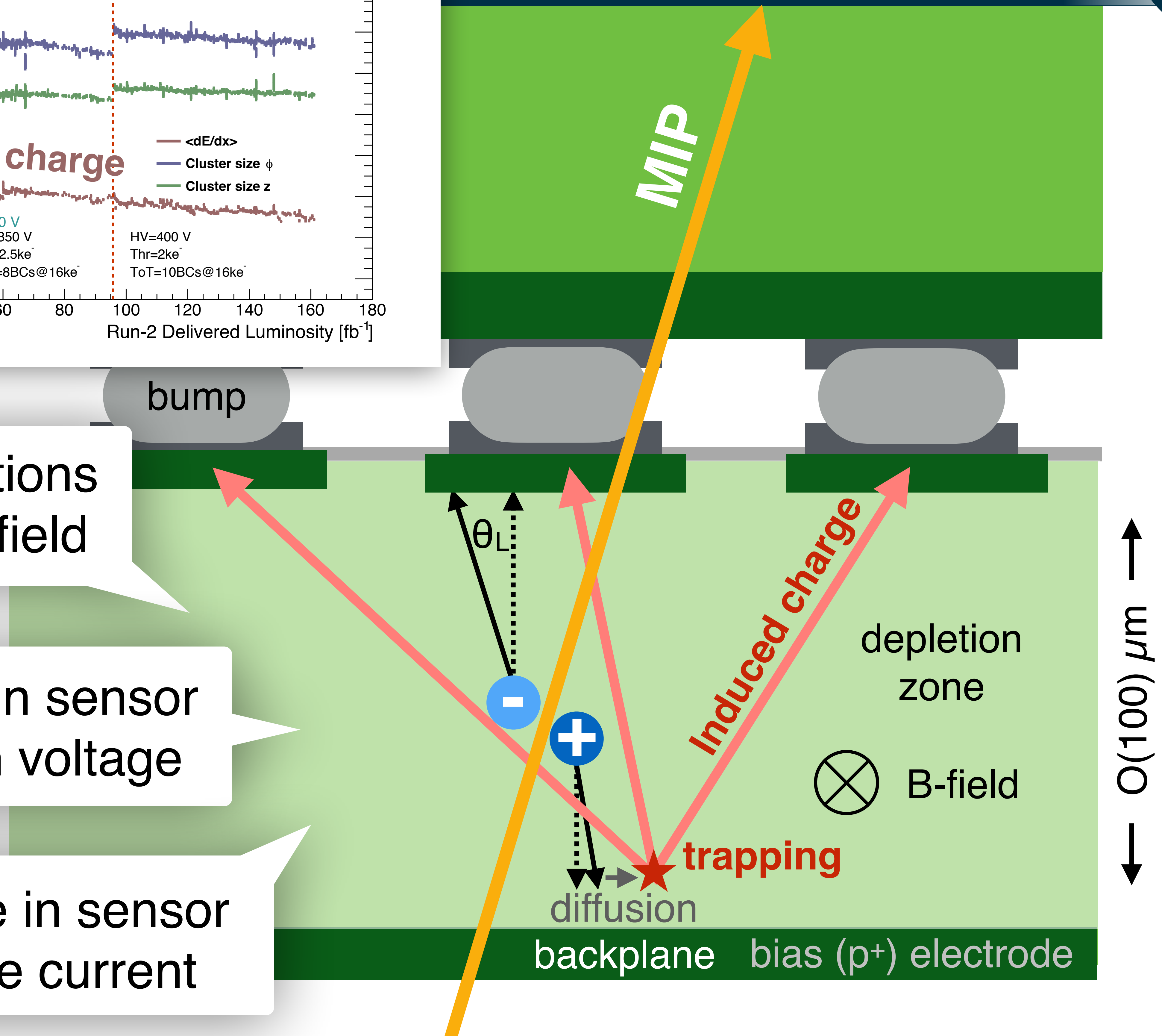




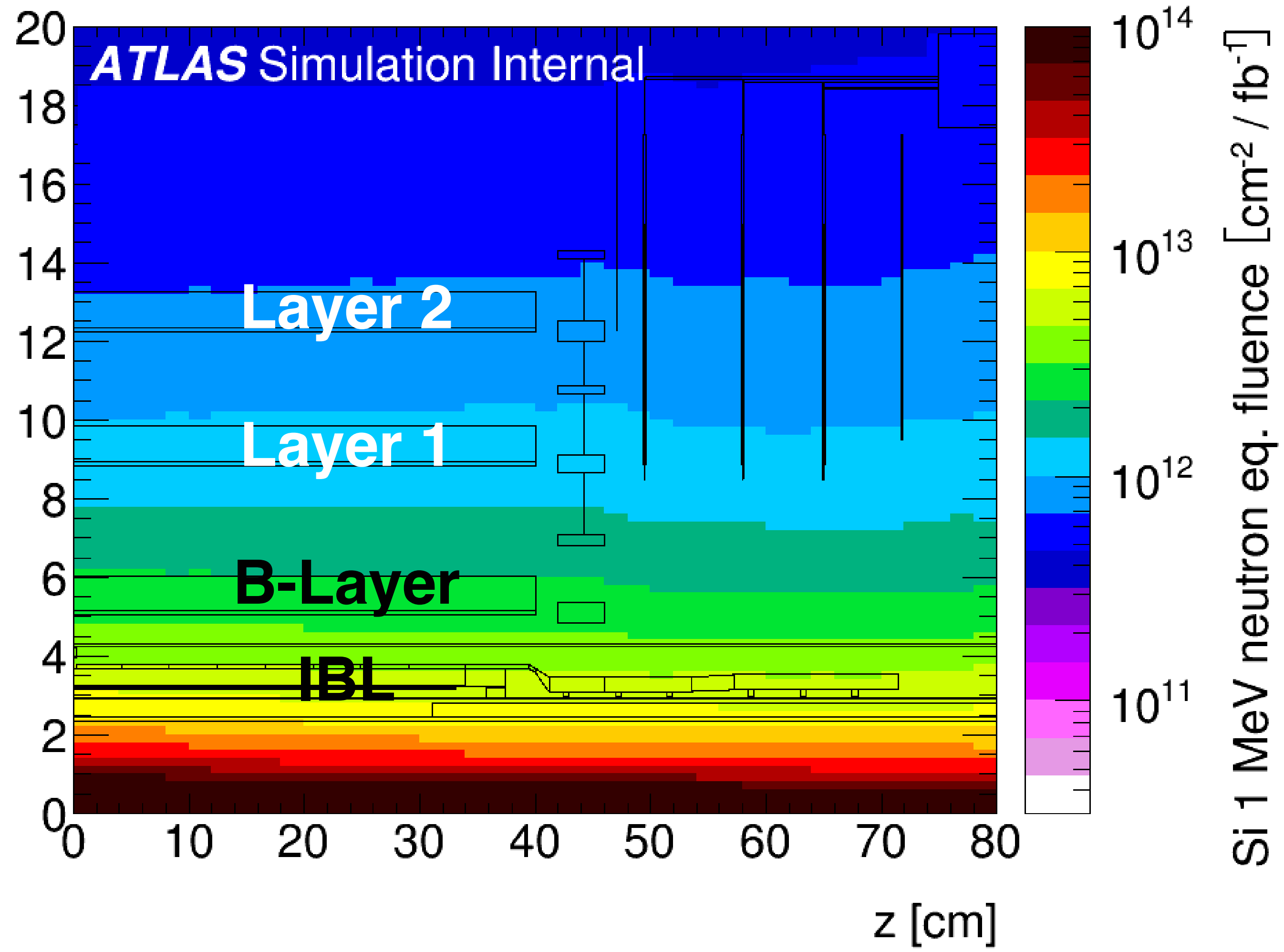
Deformations in the E-field

Increase in sensor depletion voltage

Increase in sensor leakage current

Radiation Environment at the LHC

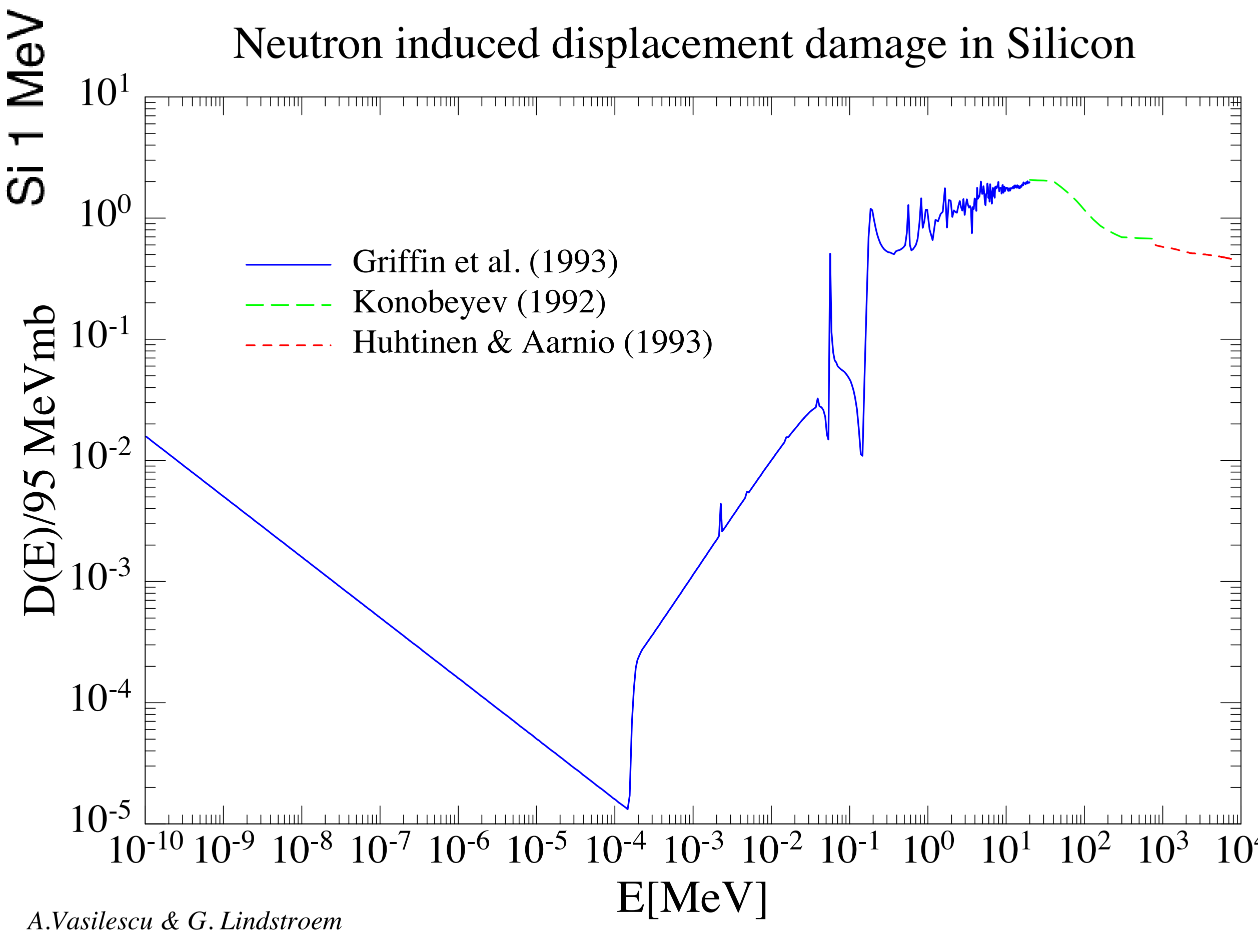
falls off as ~$1/r^2$



Units: we normalize damage to that of a 1 MeV neutron and the units are n_{eq}/cm^2

Fluence symbol: $\boldsymbol{\Phi}$

Most of the damage on the inner layers is from charged hadrons. Neutron damage is larger at higher radii (splash-back from calorimeters).

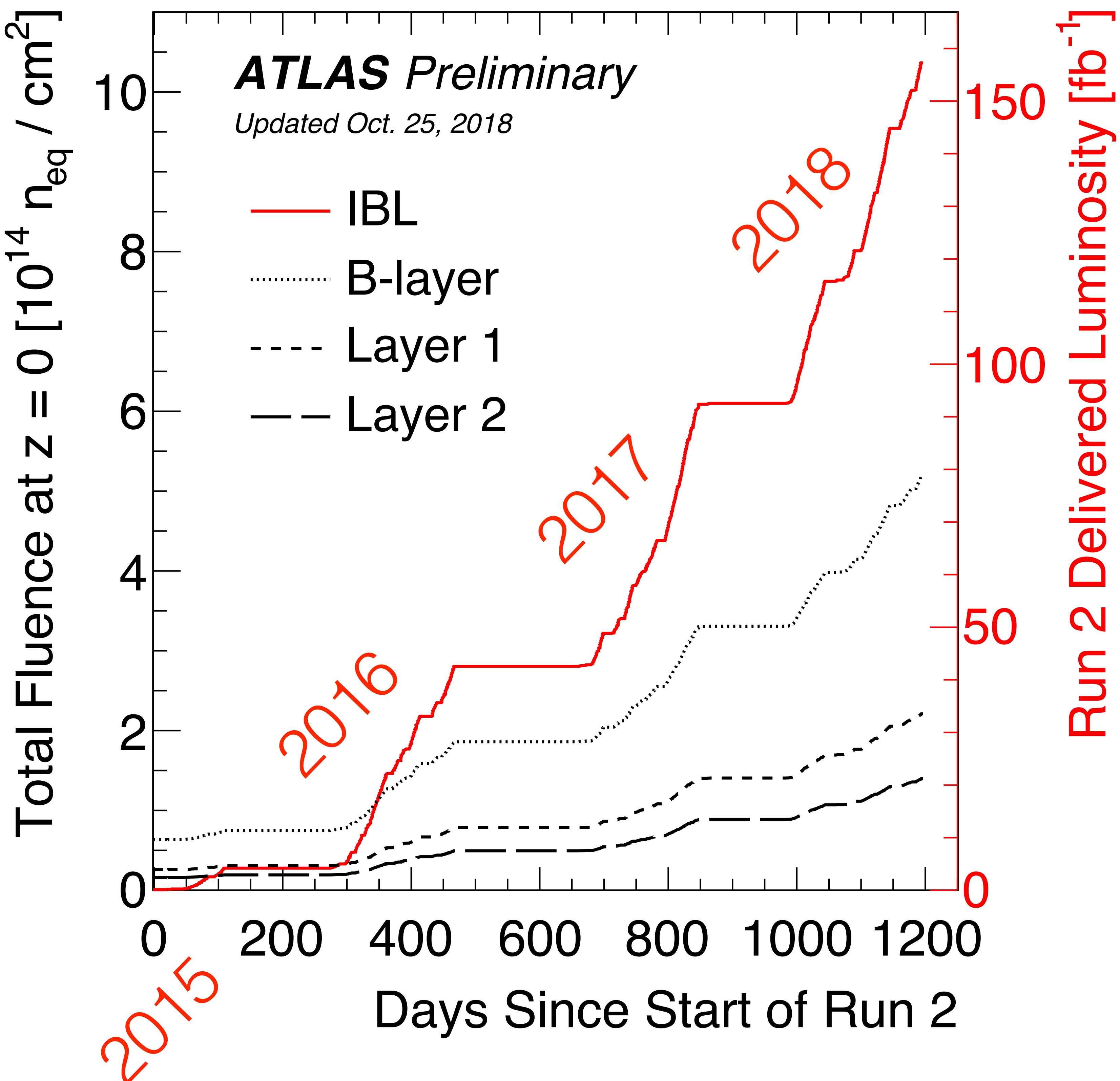


Radiation Environment at the LHC

Innermost layer
= more fluence

Even though the IBL was installed at the start of Run 2, it has surpassed the B-layer in fluence

It is imperative that radiation damage effects be quantified to inform **operations**, **offline analysis**, & **future detector design**!



Measuring the fluence

Most common method uses the leakage current, as $I_{\text{leak}} \propto \Phi$

Depleted volume

Caution: Model assumes uniform space-charge and a small number of effective defect states.

$$\Delta I = (\Phi_{\text{eq}}/L_{\text{int}}) \times V \cdot \sum_{i=1}^{n} L_{\text{int},i} \cdot \left[\alpha_{\text{I}} \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0}\right)\right]$$

"The Hamburg Model"

Measure this

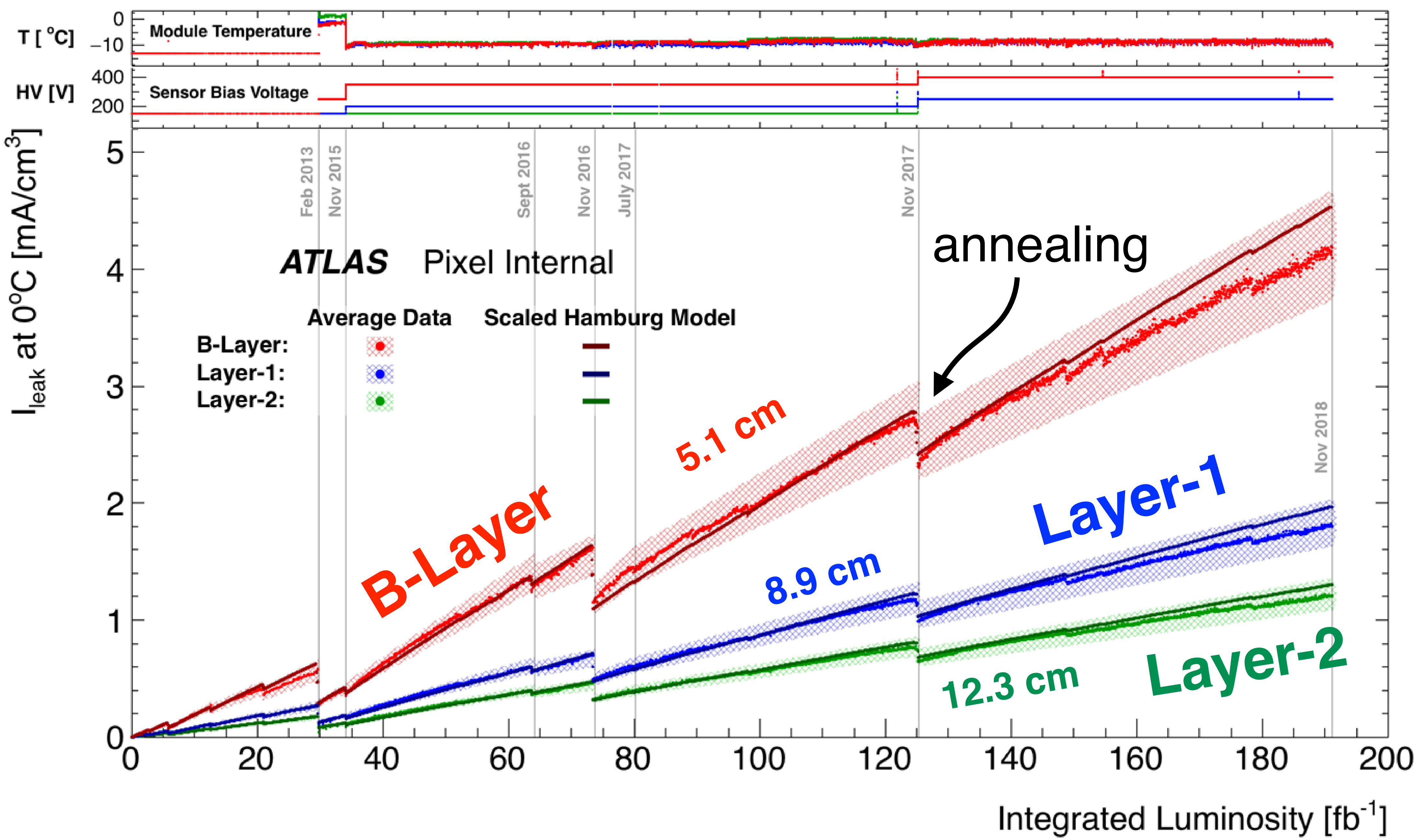
We want to know this

Annealing (depends on time ***t*** and temperature ***T***)

N.B. the coefficients are dimensionfull

Measuring the fluence

Most common method uses the leakage current, as $I_{\text{leak}} \propto \Phi$



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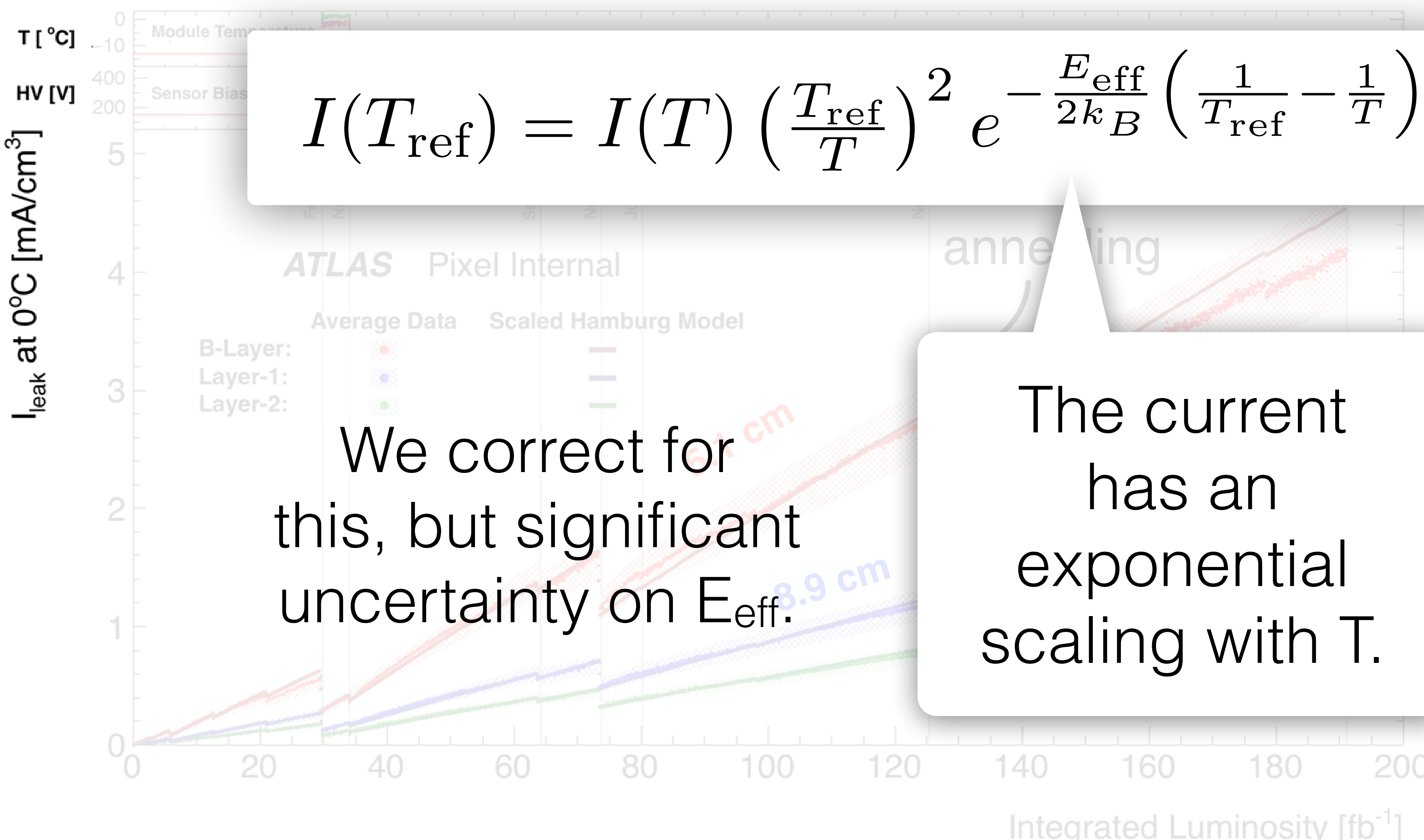
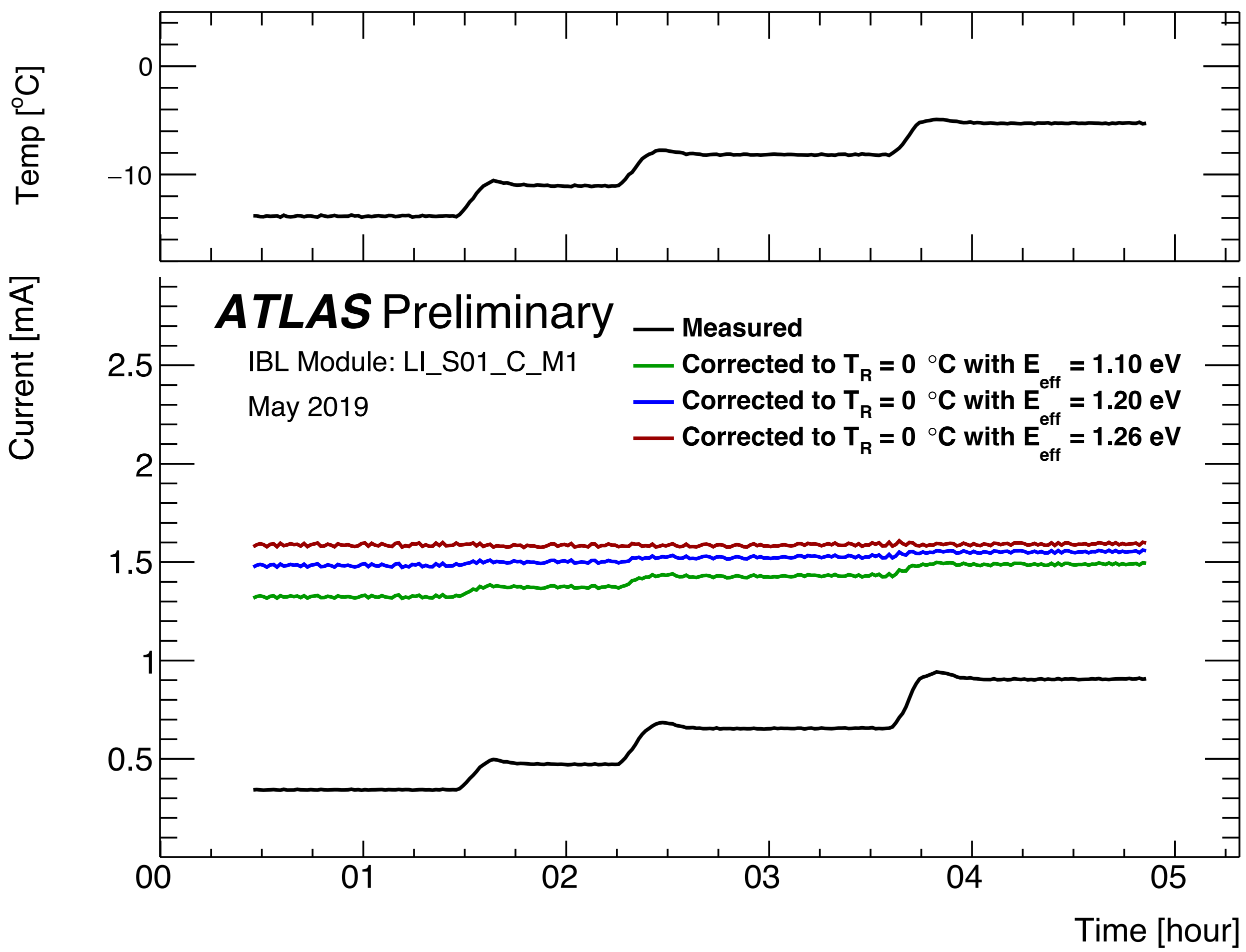


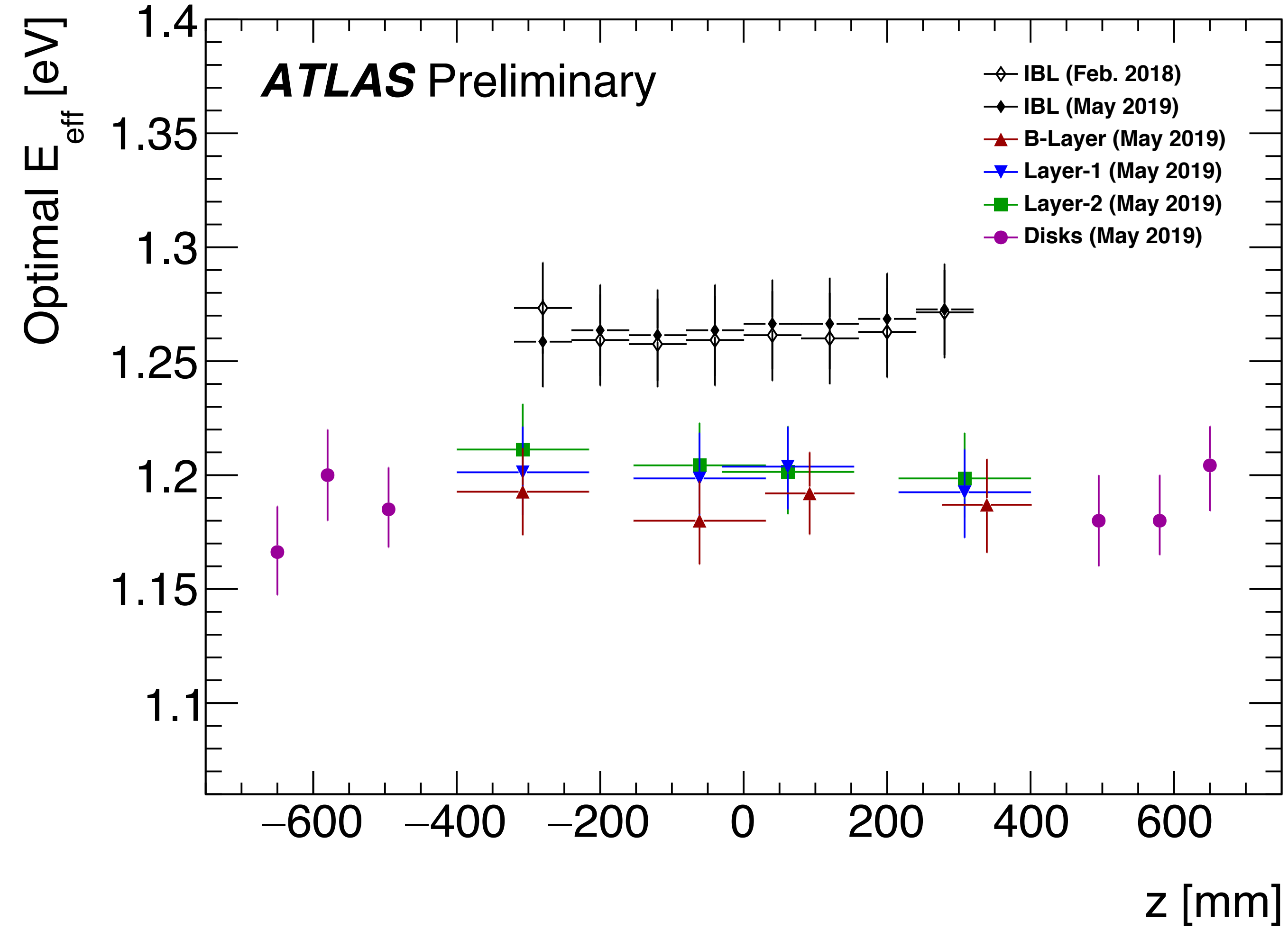
$$I(T_{\text{ref}}) = I(T)\left(\frac{T_{\text{ref}}}{T}\right)^2 e^{-\frac{E_{\text{eff}}}{2k_B}\left(\frac{1}{T_{\text{ref}}}-\frac{1}{T}\right)}$$

The current has an exponential scaling with T.

We correct for this, but significant uncertainty on E_{eff}.

Temperature corrections



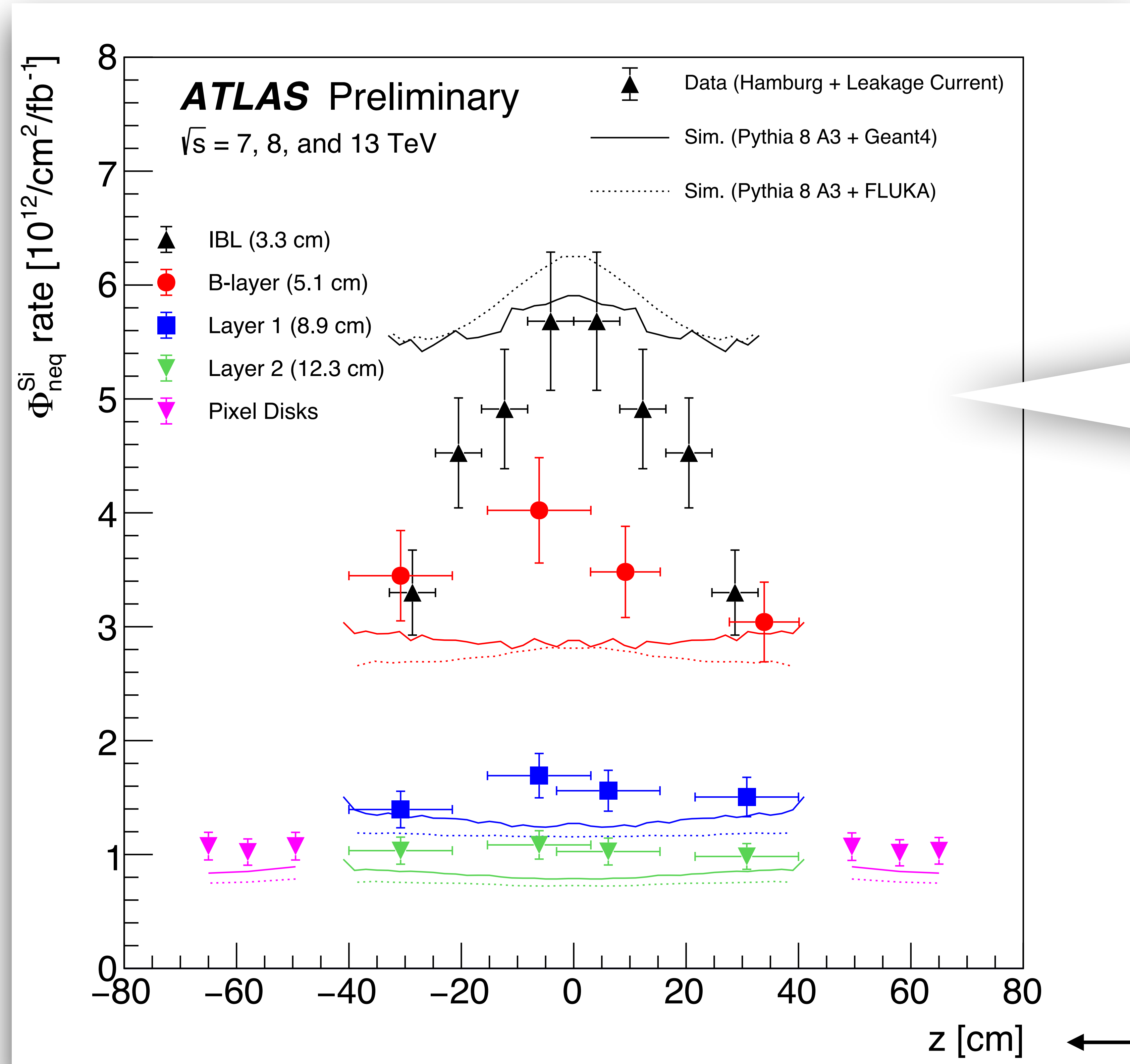


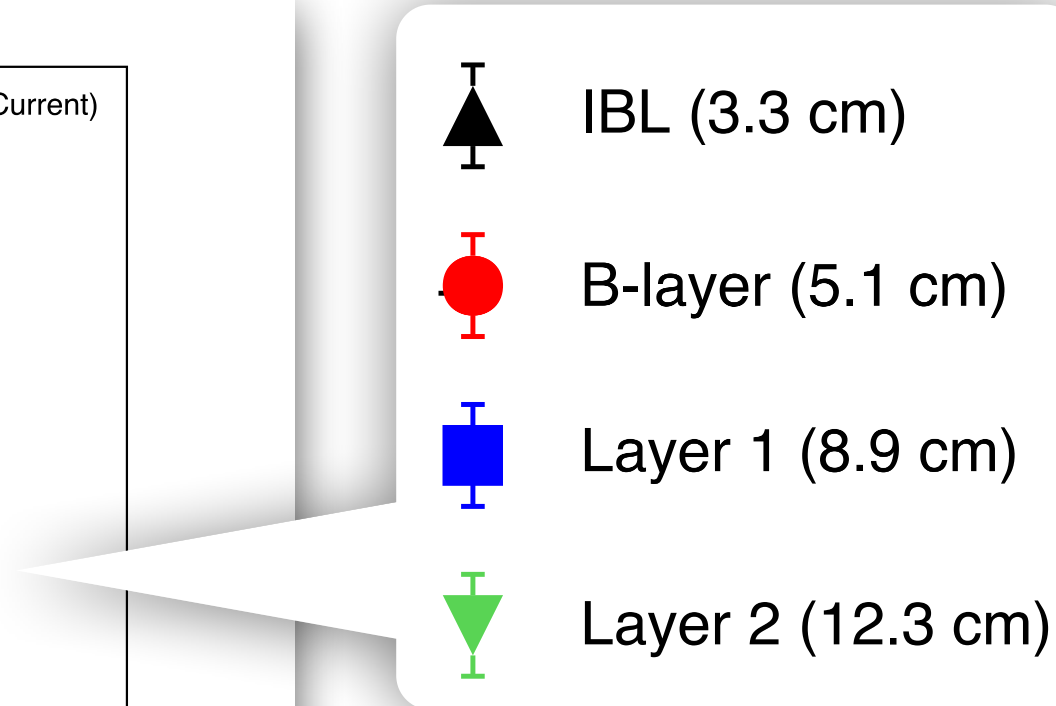
We have **measured E_{eff}** using **dedicated temperature scans**!

Biggest source of uncertainty is the absolute temperature of our sensors.

See <u>this talk</u> for more details.

Fluence measurement overview



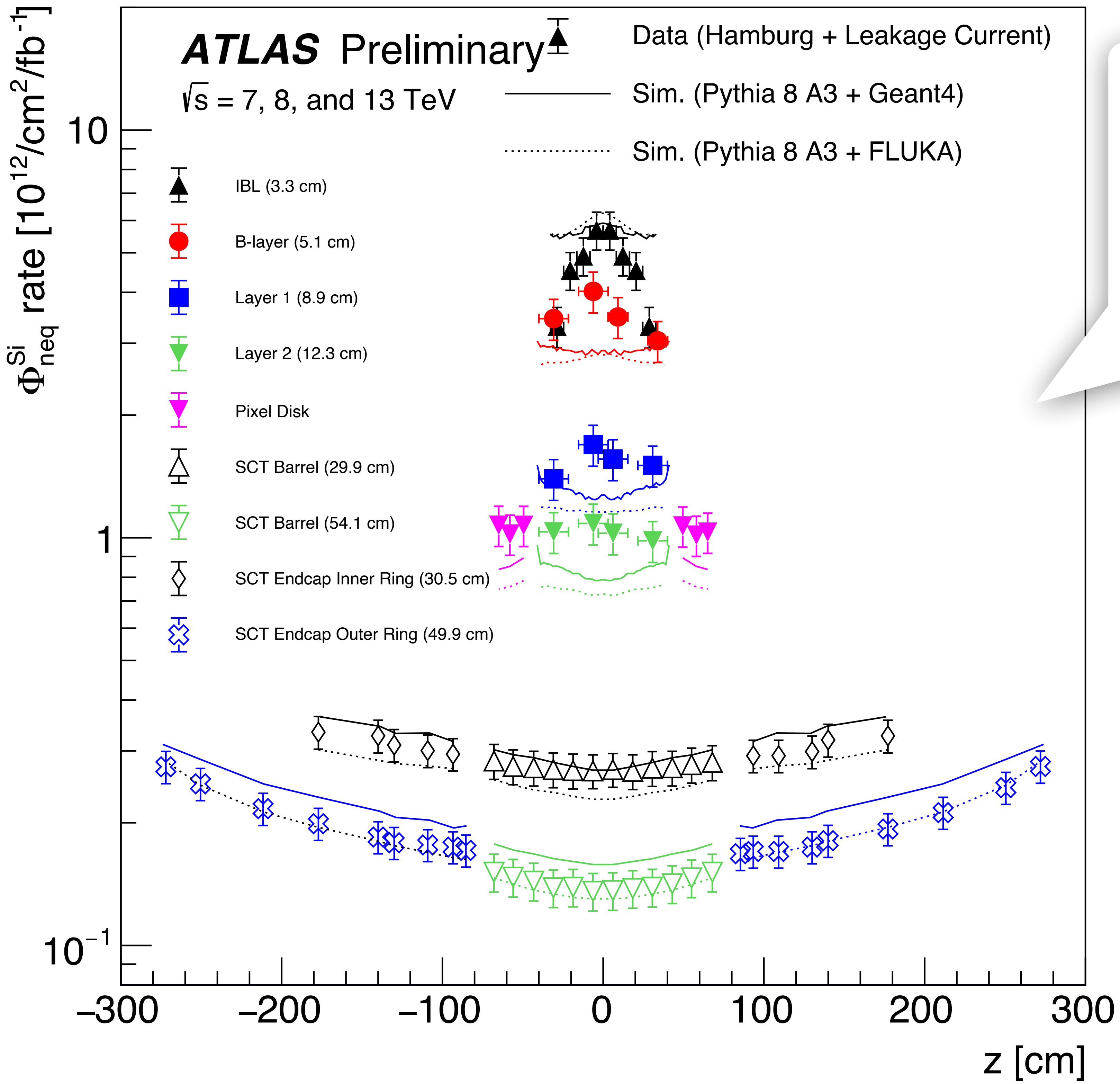


(1) |z|-dependence much stronger in data

(2) data > simulation past innermost layer

← Beam direction

A global picture: pixels and strips



data ~ sim. for innermost

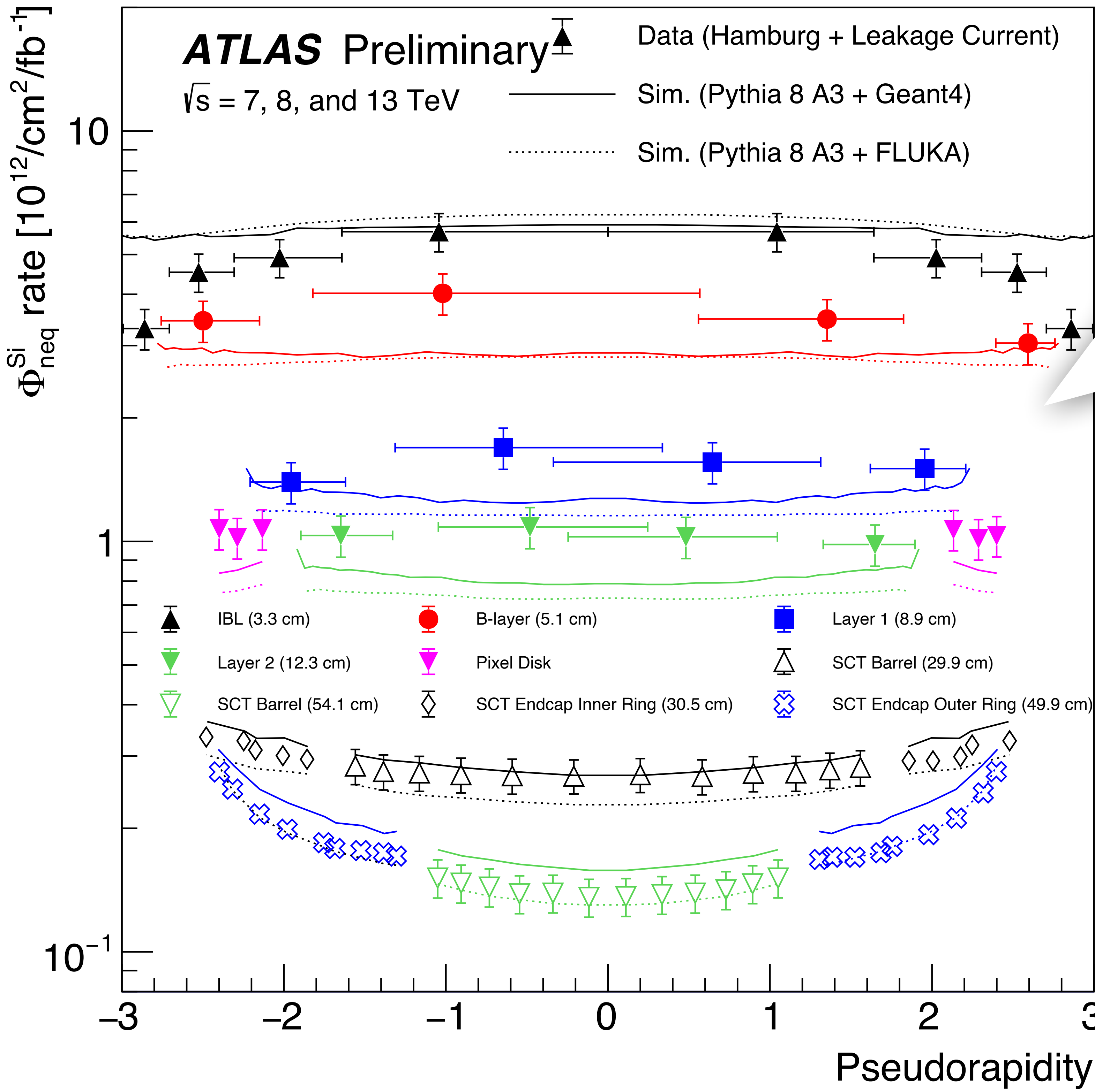
data ~ 1.5 x sim. for other pixels

data ~ sim. for strips

Stronger |z| dependence in data on inner layers - present with Geant4 and FLUKA

(and for various tunes of Pythia, not shown)

A global picture: pixels and strips



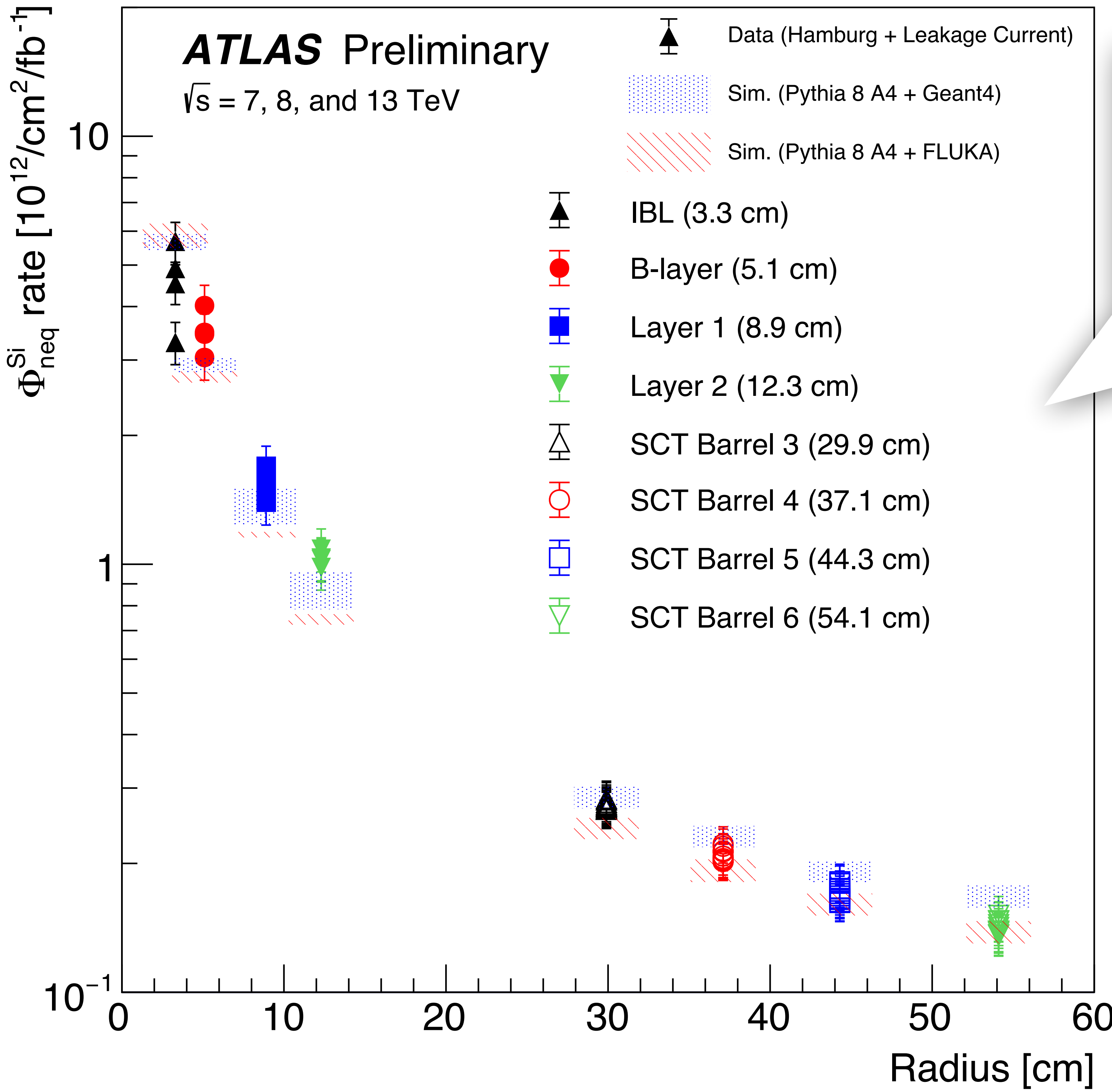
data ~ sim. for innermost

data ~ 1.5 x sim. for other pixels

data ~ sim. for strips

Same data as previous slide, but ID acceptance to |η|=2.5 is clear

A global picture: pixels and strips



data ~ sim. for innermost

data ~ 1.5 x sim. for other pixels

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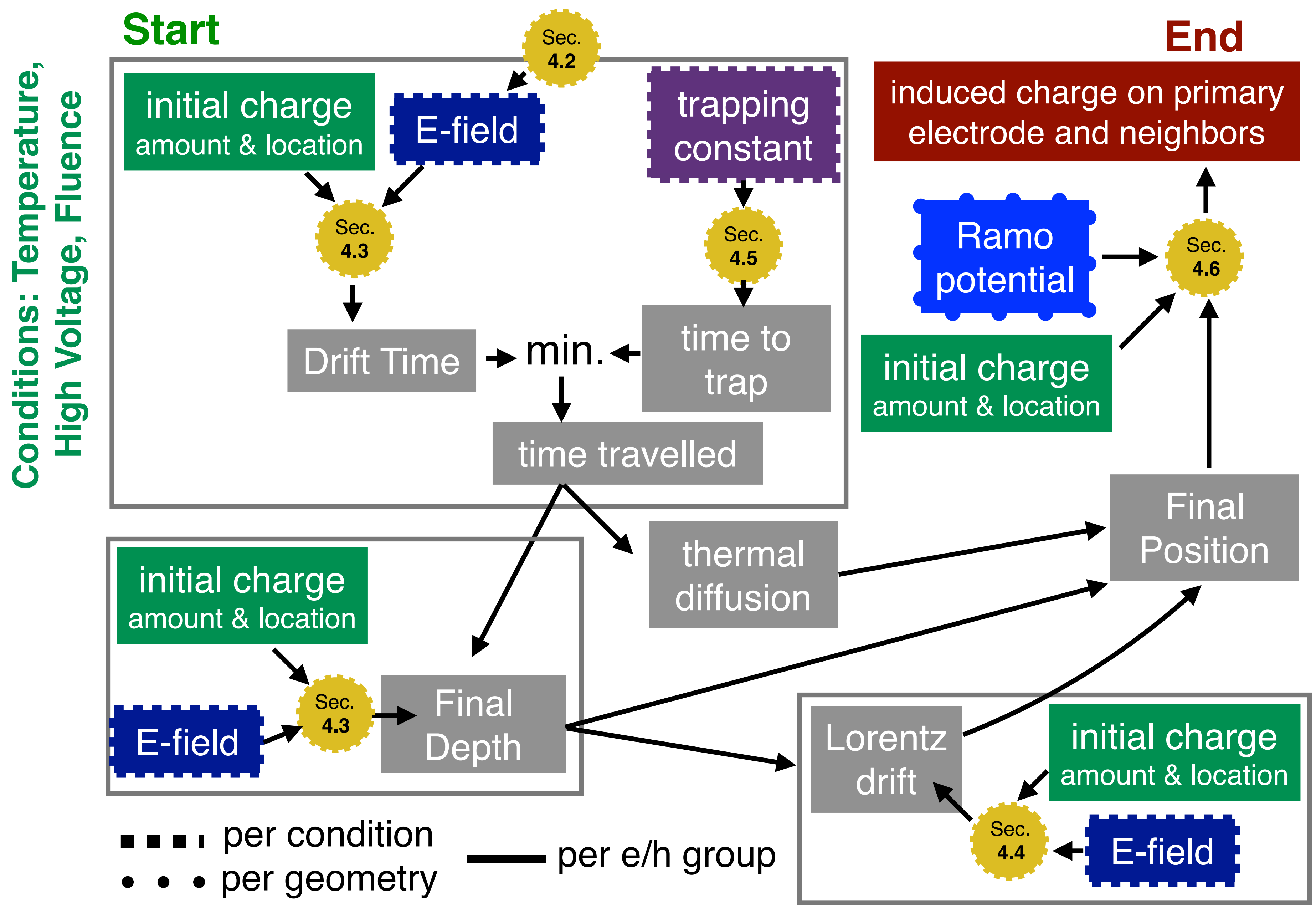
The fluence falls off roughly as $1/r^2$

Integrating fluence into digitization

In parallel, we have integrated the fluence modeling into ATLAS simulation - default for Run 3.



JINST 14 (2019) P06012

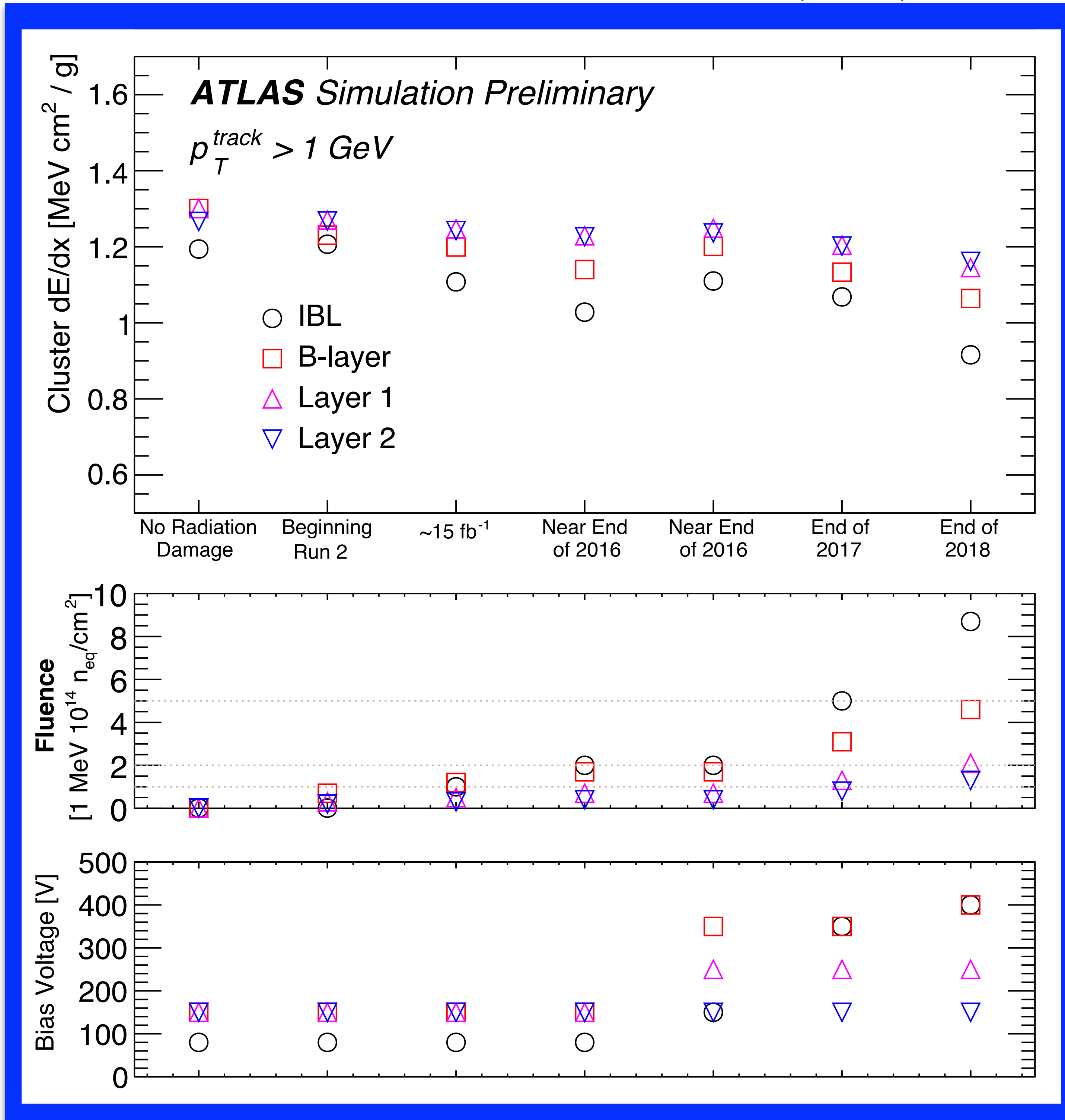
Conclusions and outlook

The fluence is the key ingredient to radiation damage modeling.

We have performed a detailed measurement using leakage currents. In parallel, we **have integrated radiation damage into the ATLAS simulation**.

This is allowing us to improve our data analysis and plan for Run 3 and the HL-LHC!

For details, see JINST 14 (2019) P06012



Backup