

Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

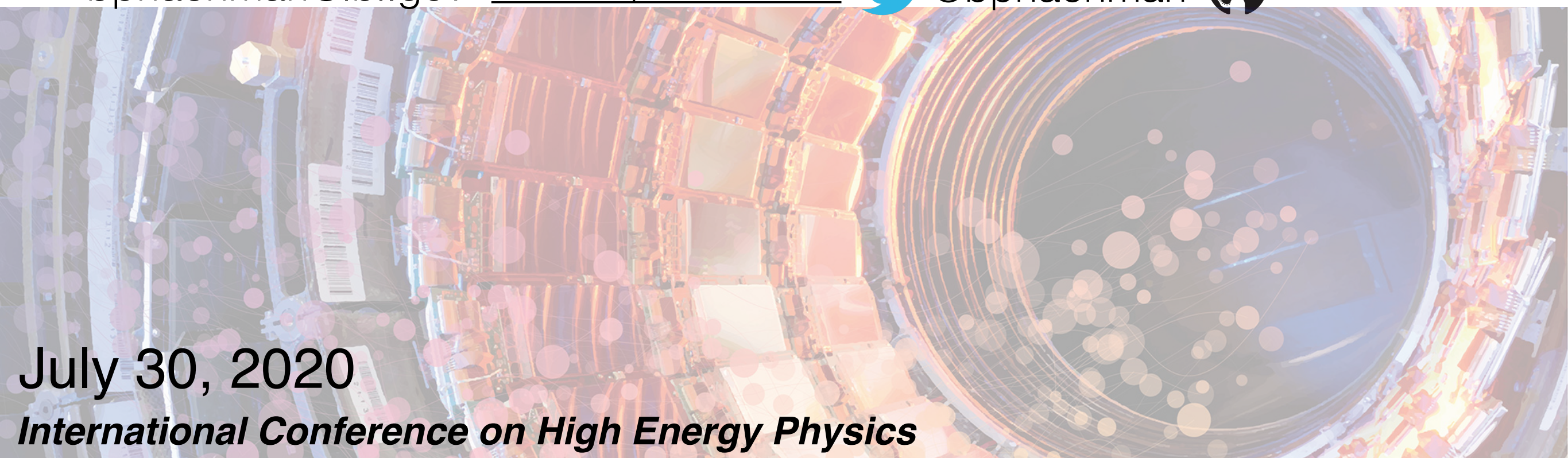


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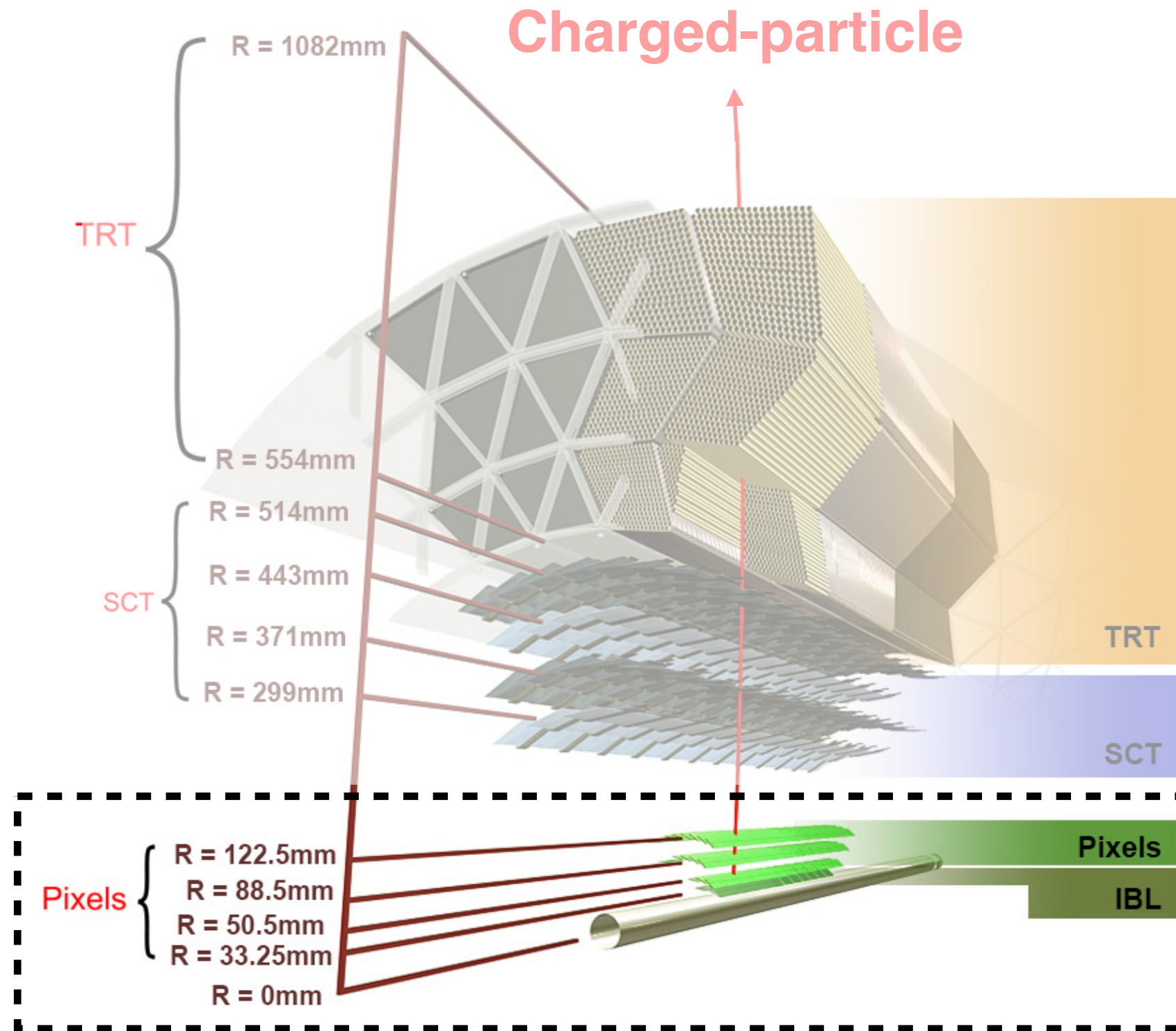
At the heart of ATLAS: Silicon Pixels

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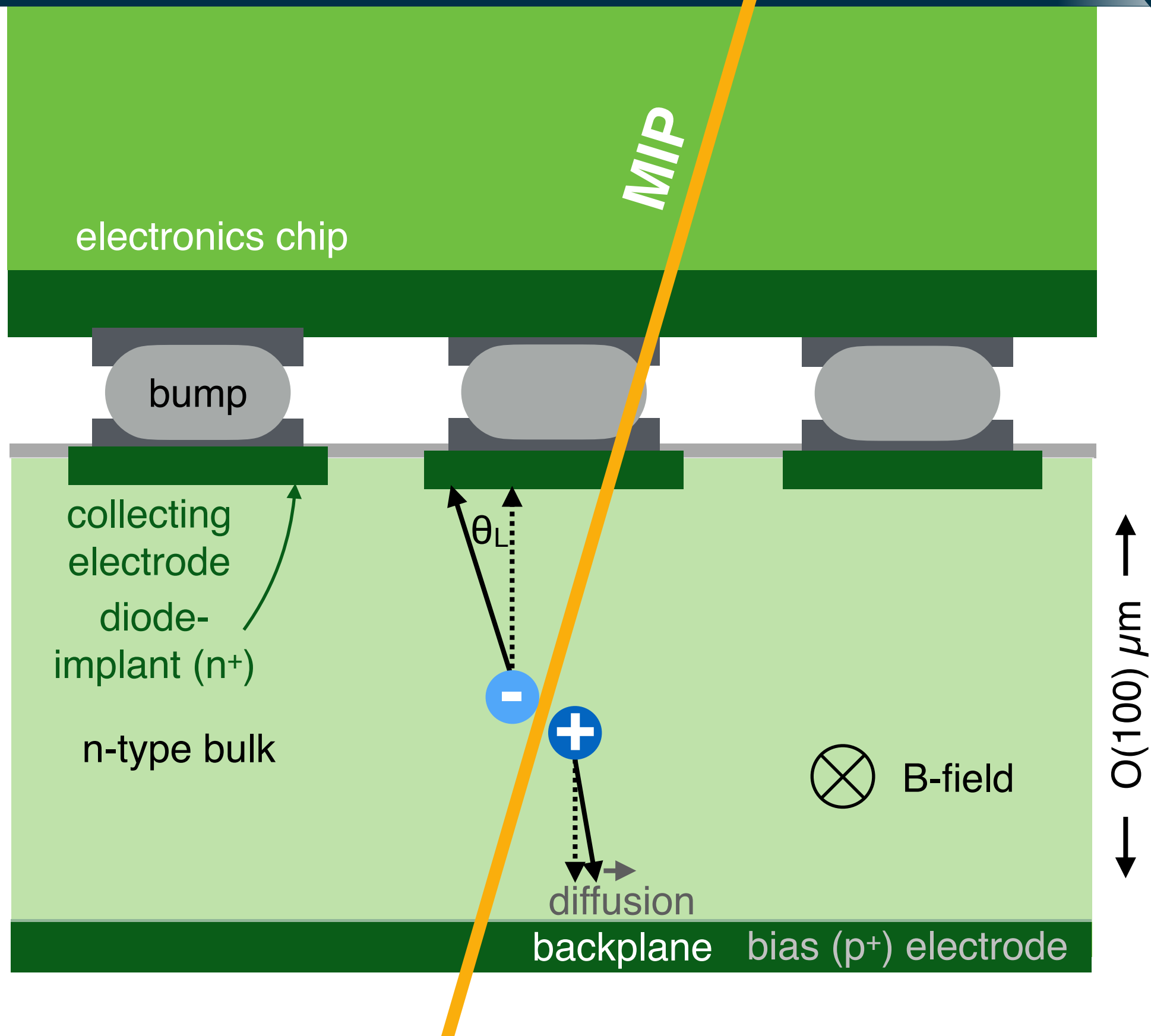
Closest to the interaction are finely segmented silicon pixels

$$O(100^3) \mu\text{m}^3$$

record (a digitized) charge for ionizing particles

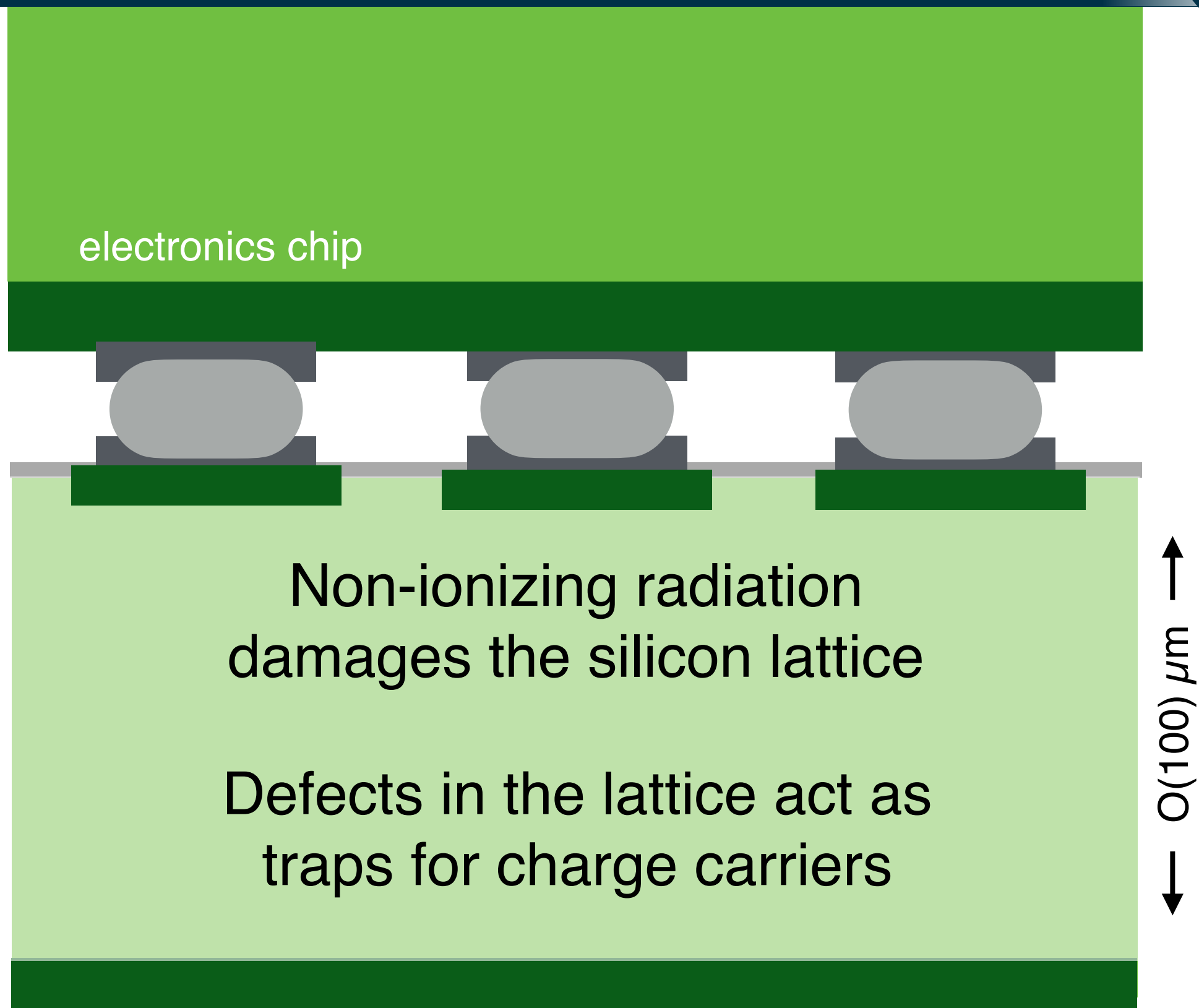


Zooming in on one pixel



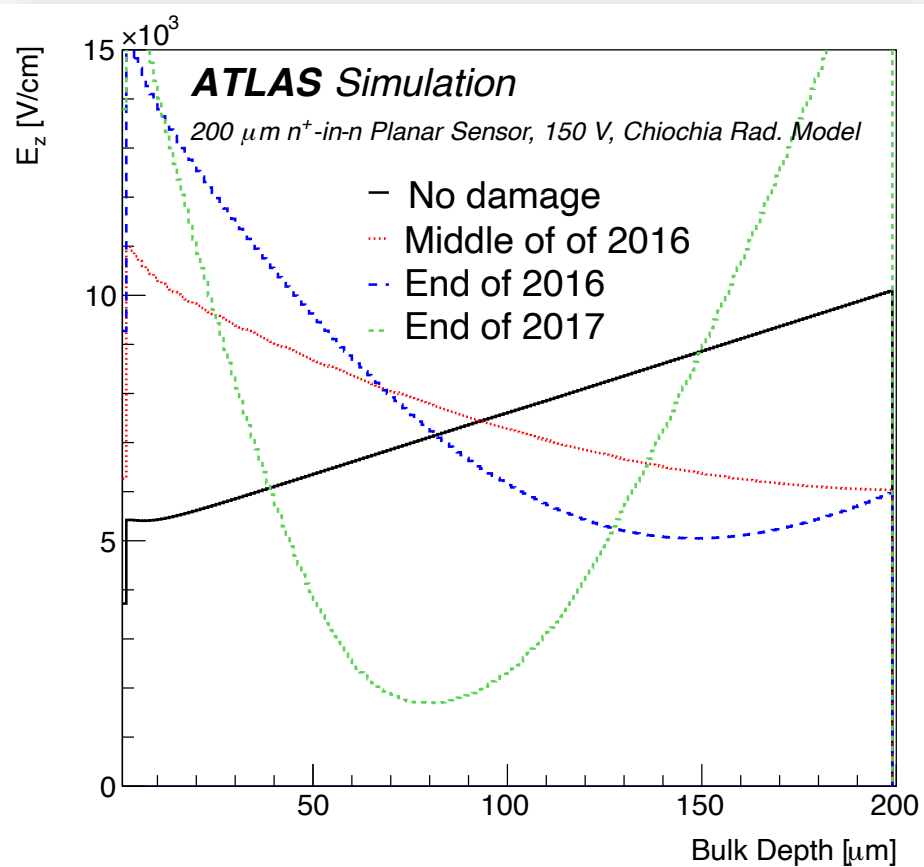
Silicon Radiation Damage

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Signals after irradiation

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Deformations
in the E-field


Increase in sensor
depletion voltage

Increase in sensor
leakage current

chip

bump

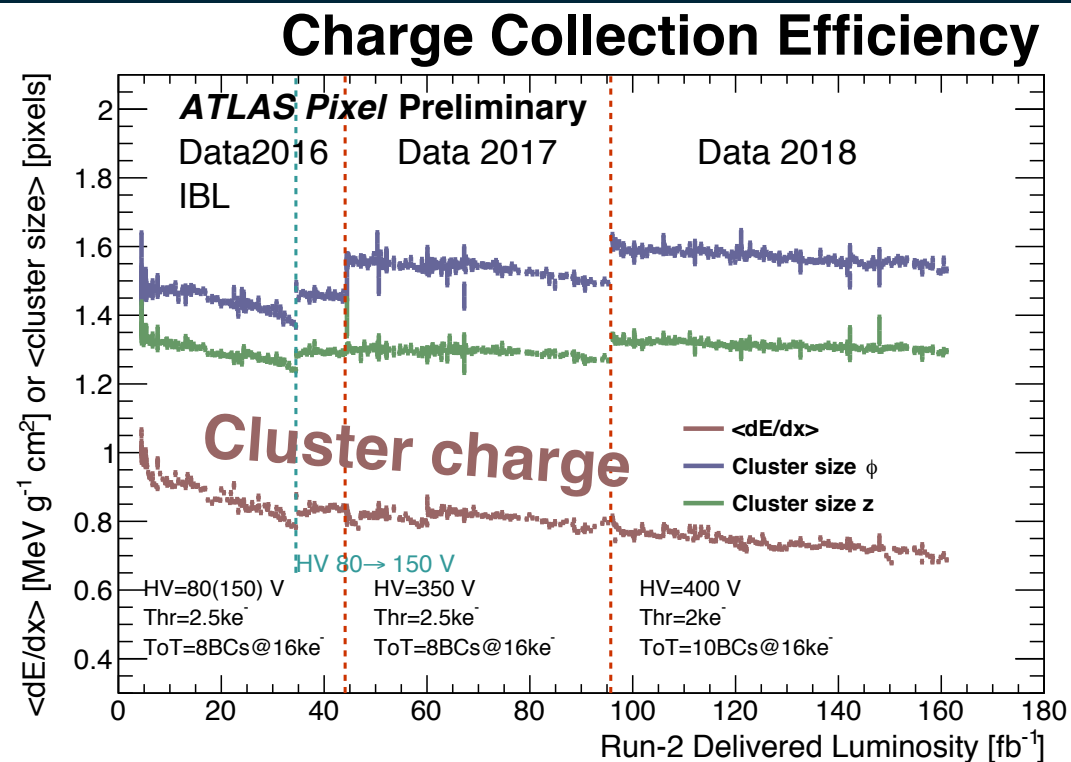
depletion
zone

 B-field

\uparrow
 \downarrow $O(100) \mu\text{m}$

backplane bias (p^+) electrode

signals after irradiation

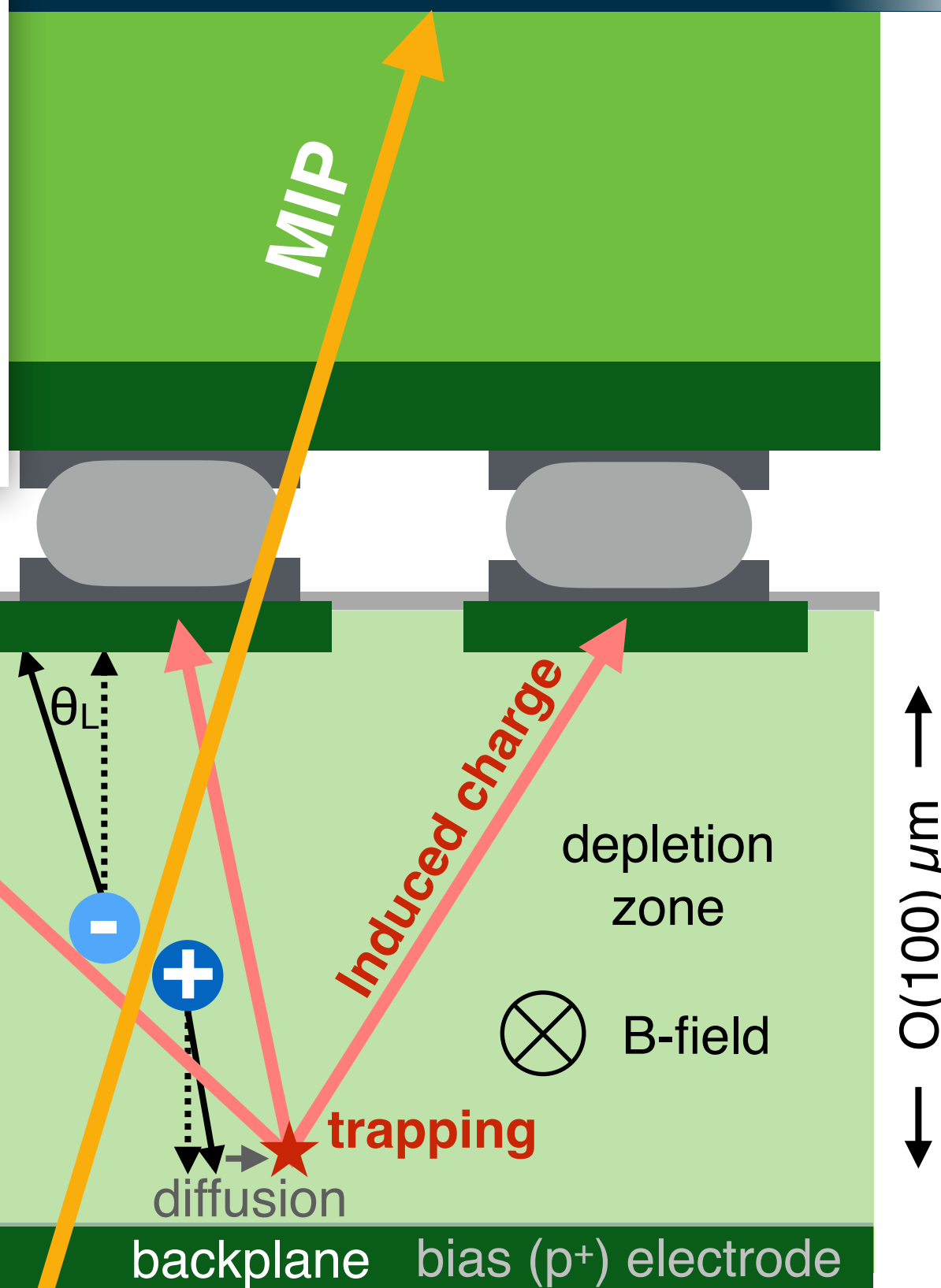


Deformations
in the E-field

Increase in sensor
depletion voltage

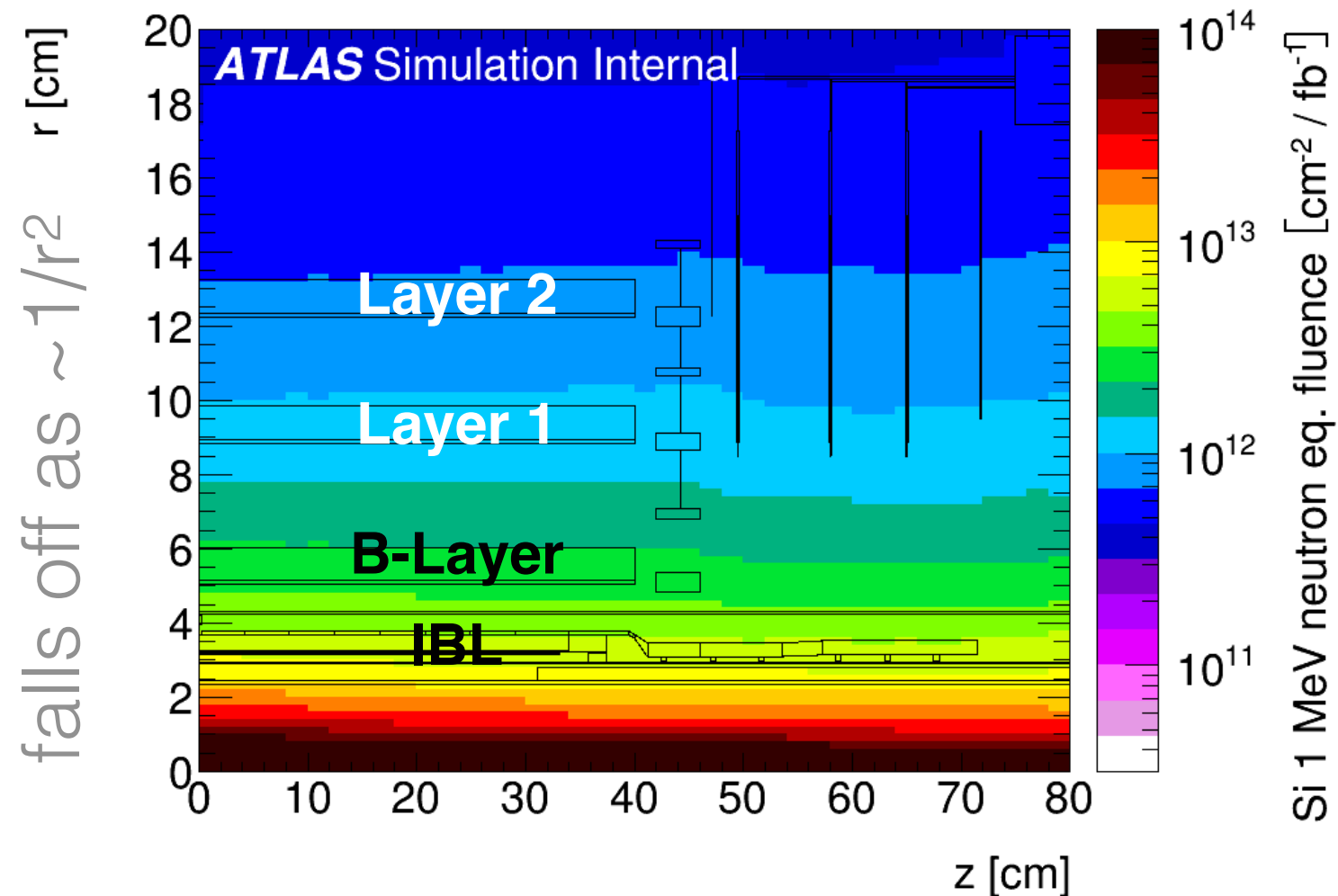
Increase in sensor
leakage current

bump



Radiation Environment at the LHC

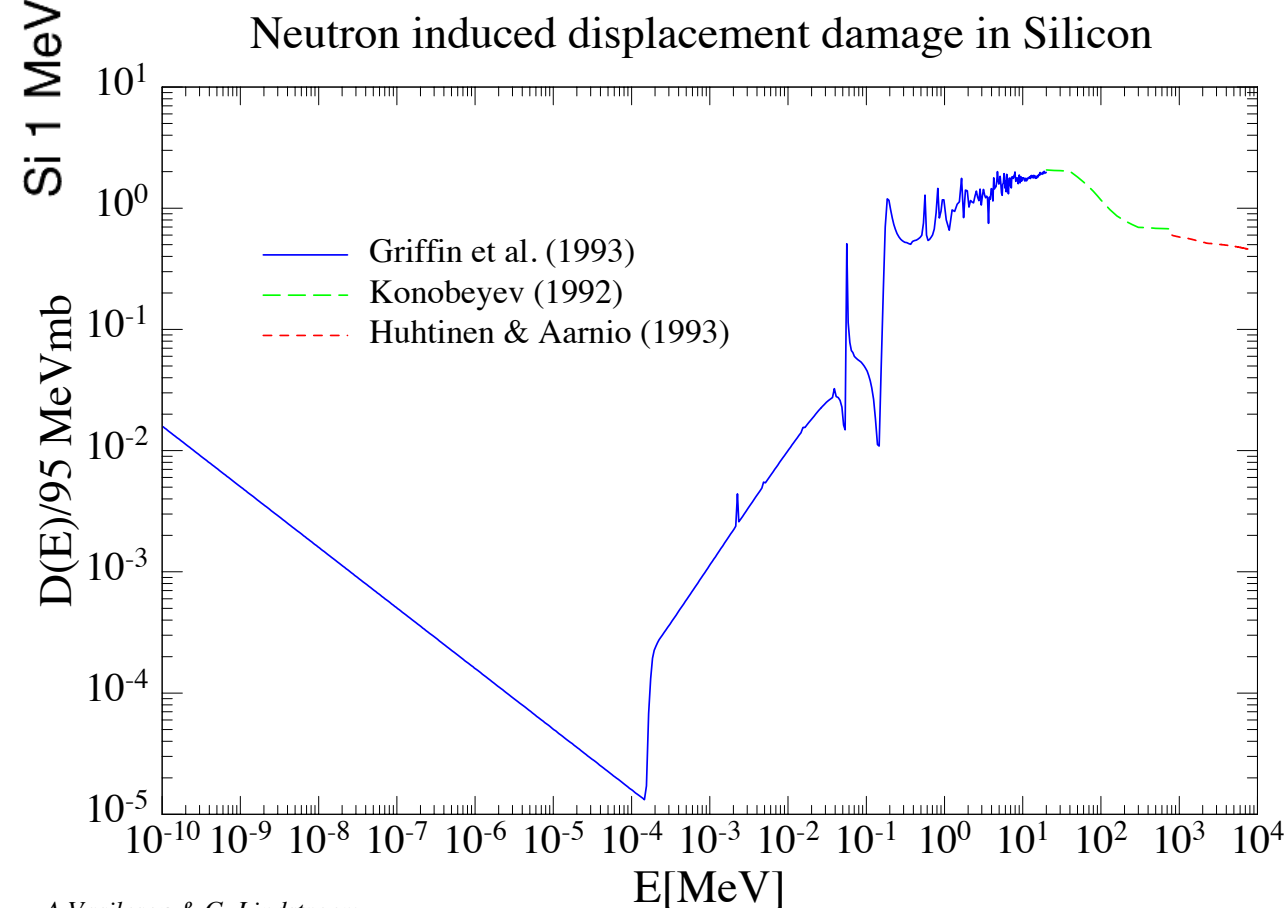
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Units: we normalize damage to that of a 1 MeV neutron and the units are $n_{\text{eq}}/\text{cm}^2$

Fluence symbol: Φ

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



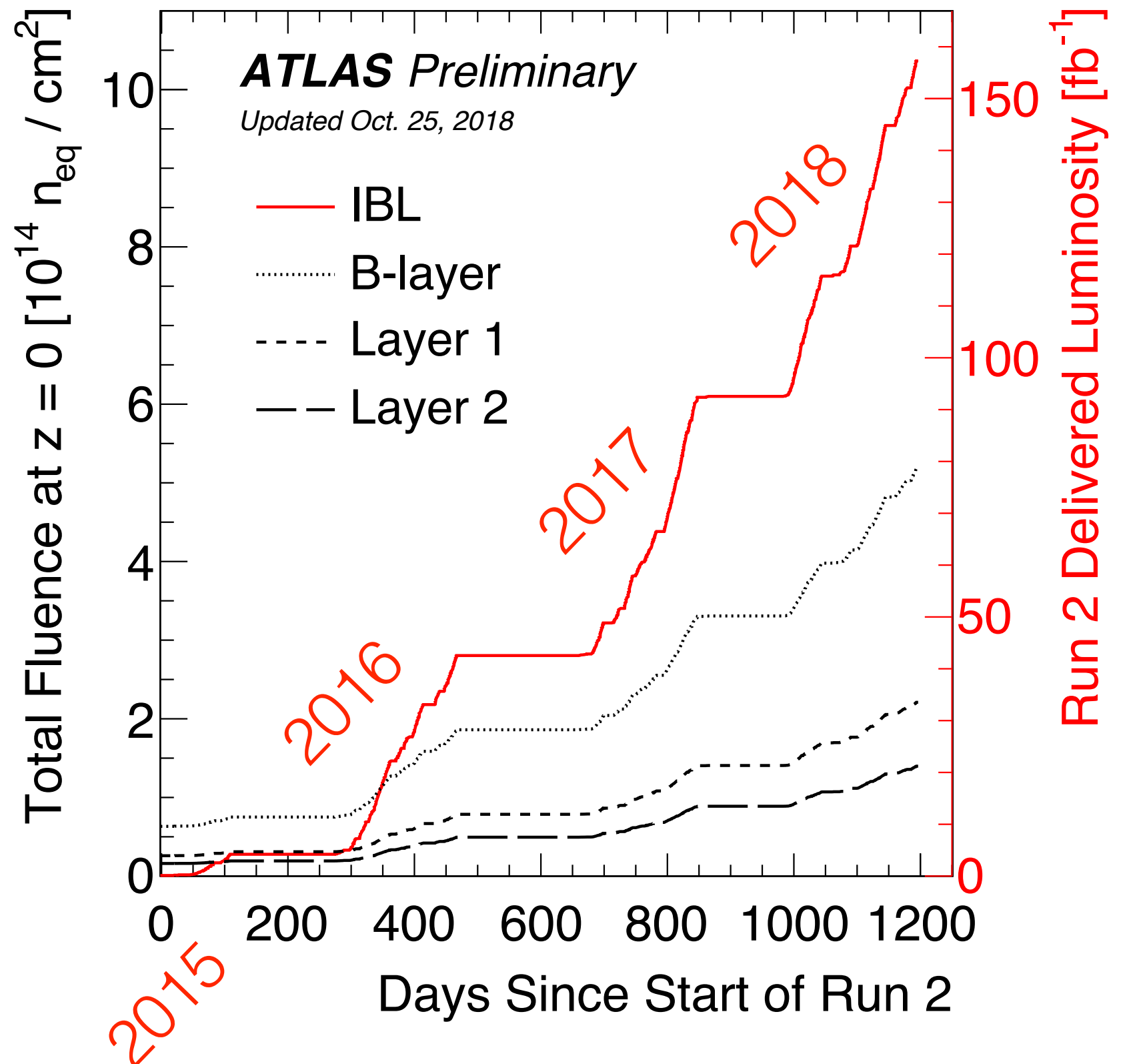
Radiation Environment at the LHC

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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.

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

Measure
this

We want to
know this

“The Hamburg Model”

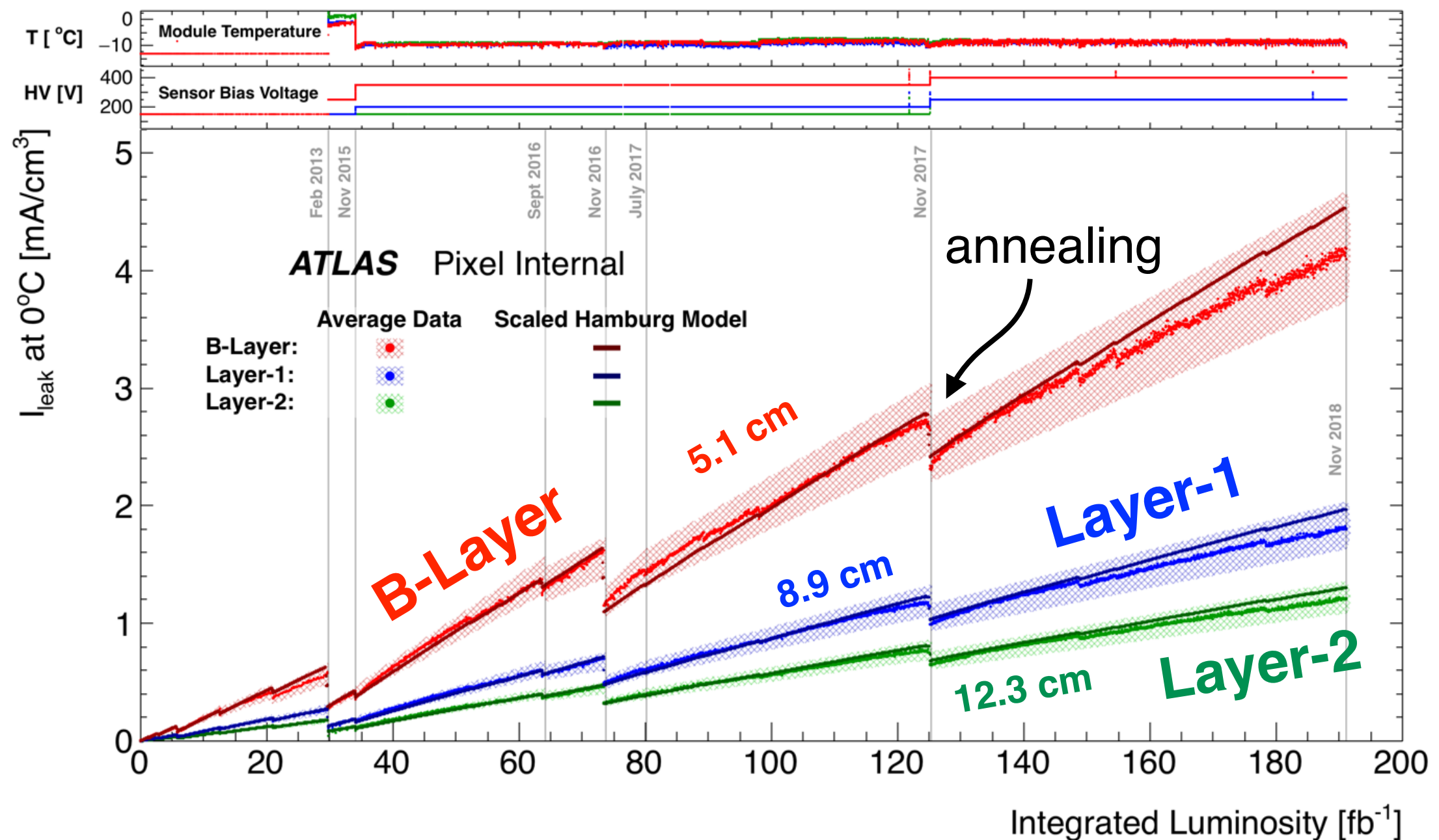
Annealing (depends on
time ***t*** and temperature ***T***)

*N.B. the coefficients are
dimensionfull*

Measuring the fluence

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



Measuring the fluence

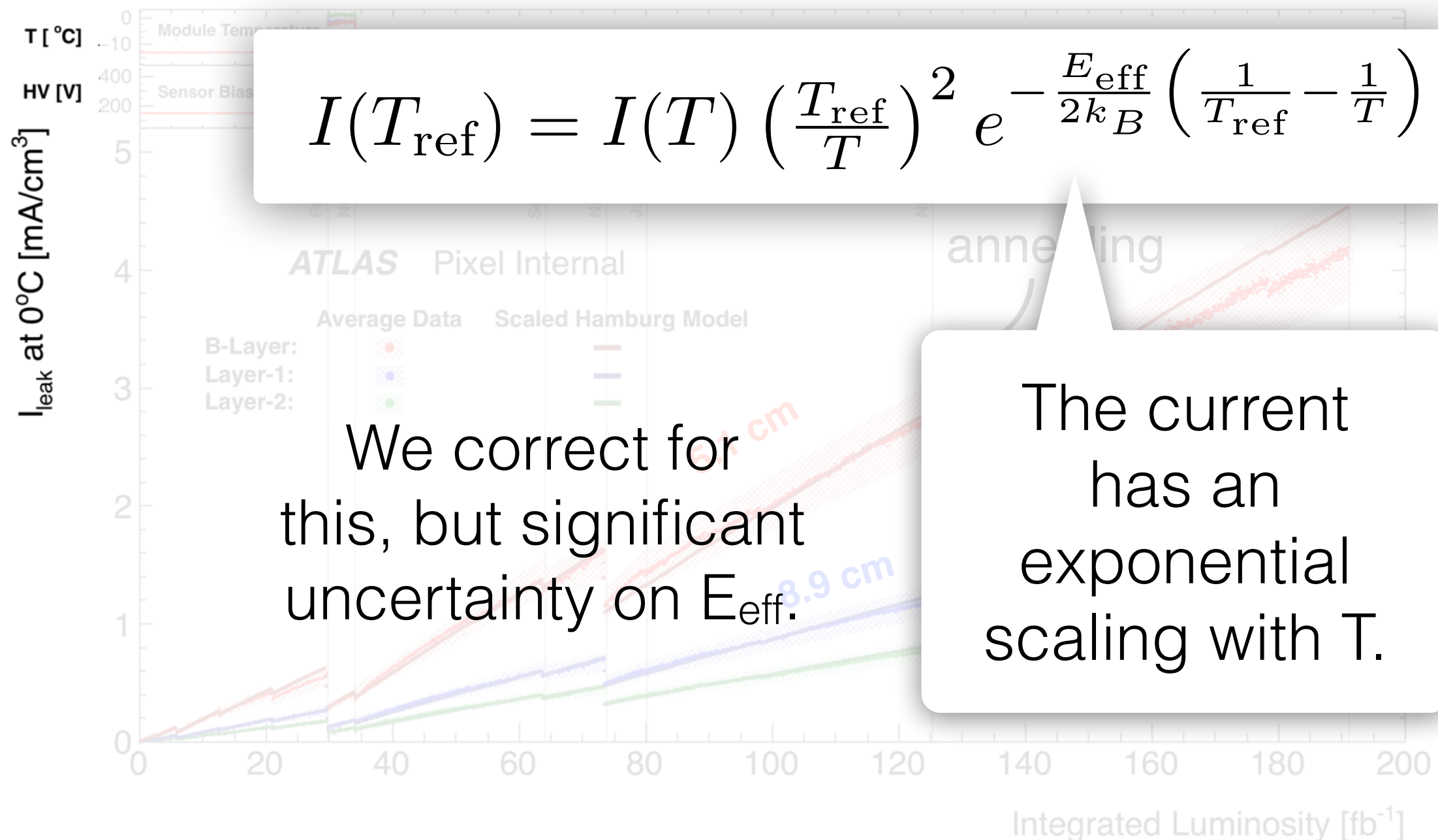
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Most common method uses the leakage current, as $I_{\text{leak}} \propto \Phi$

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

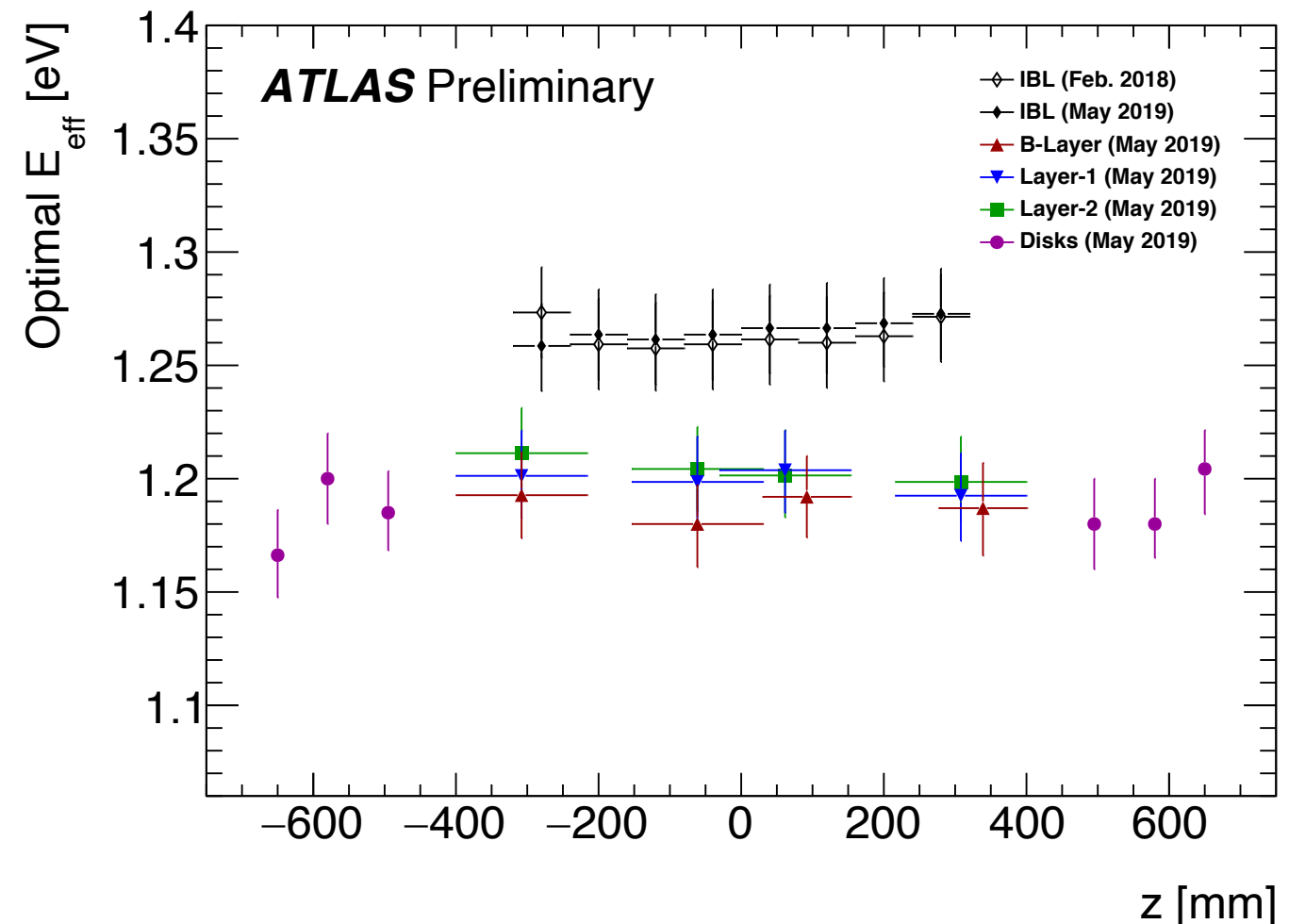
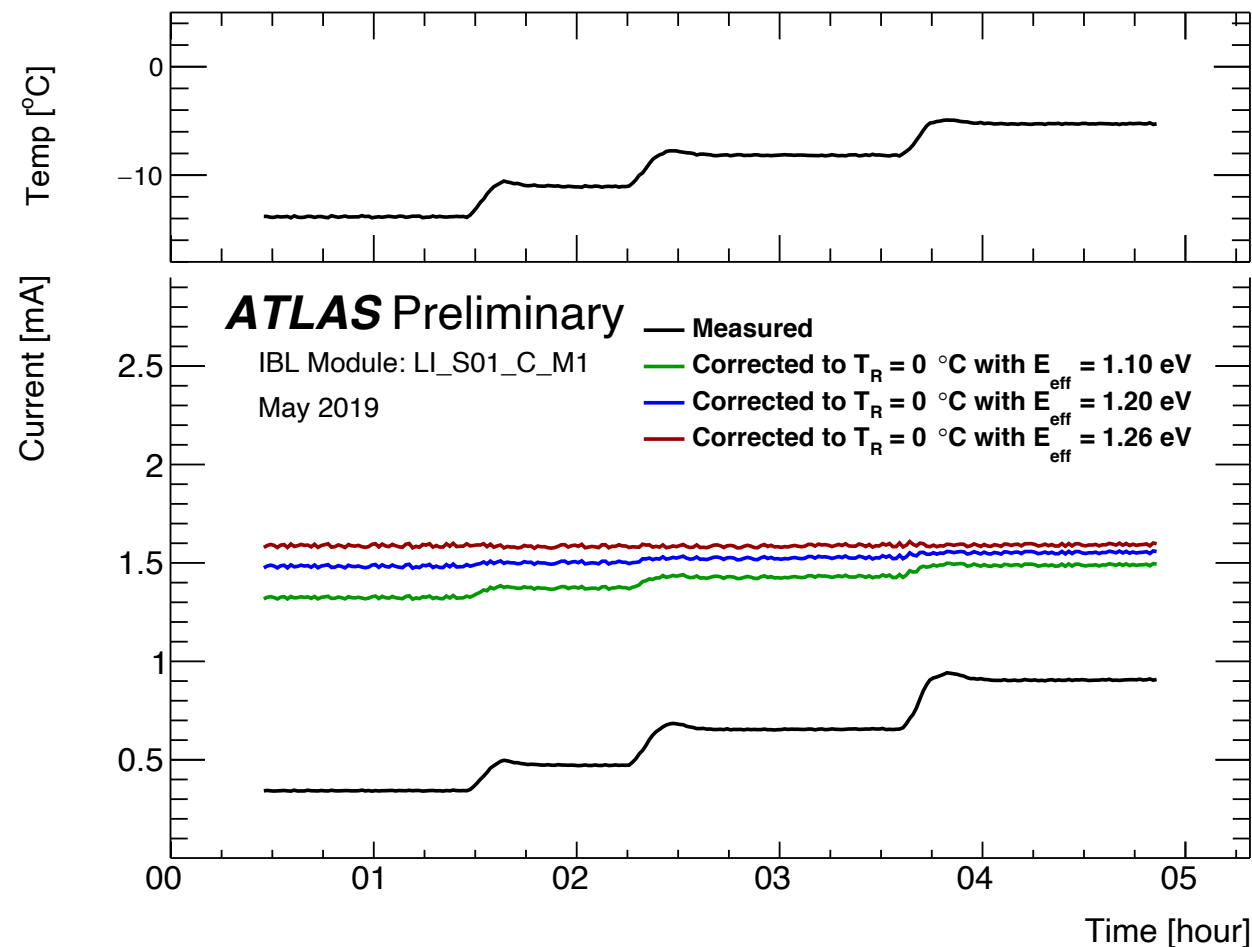
The current has an exponential scaling with T .

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



Temperature corrections

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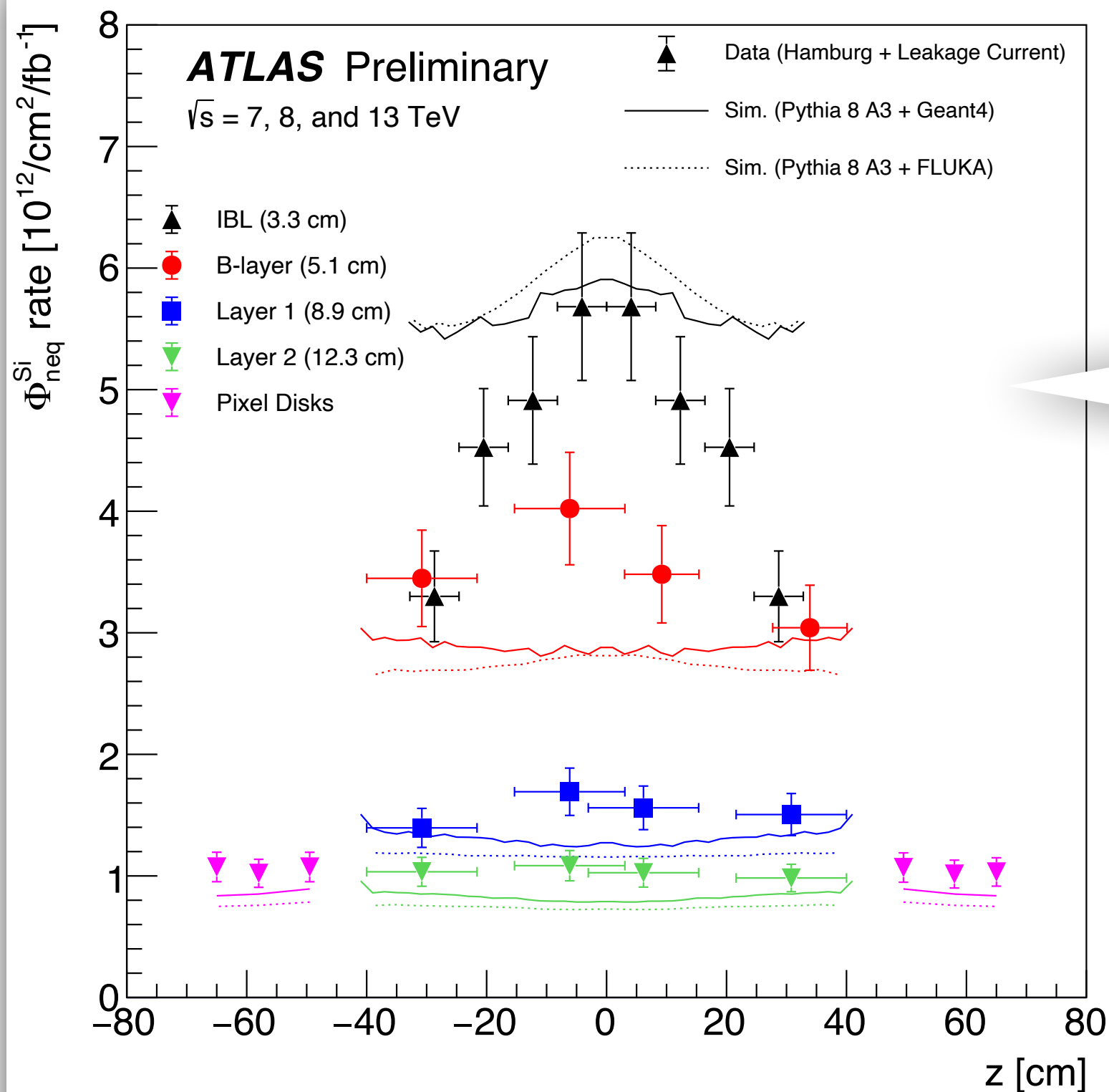
We have **measured E_{eff}** using **dedicated temperature scans!**

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

See [this talk](#) for more details.

Fluence measurement overview

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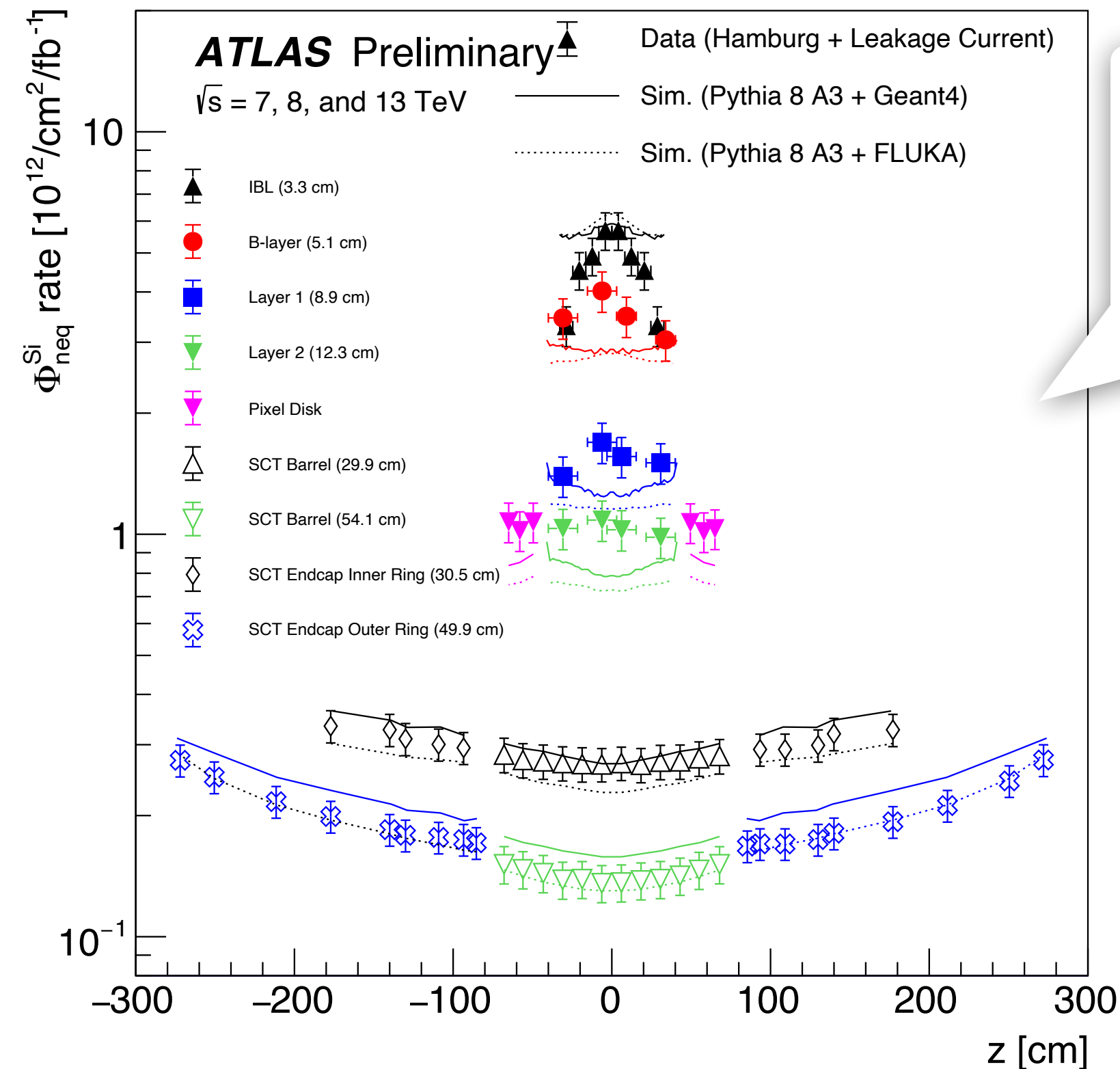
**(1) $|z|$ -dependence
much stronger in data**

**(2) data > simulation
past innermost layer**

← Beam direction

A global picture: pixels and strips

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data ~ sim. for innermost
data ~ 1.5 x sim. for other pixels

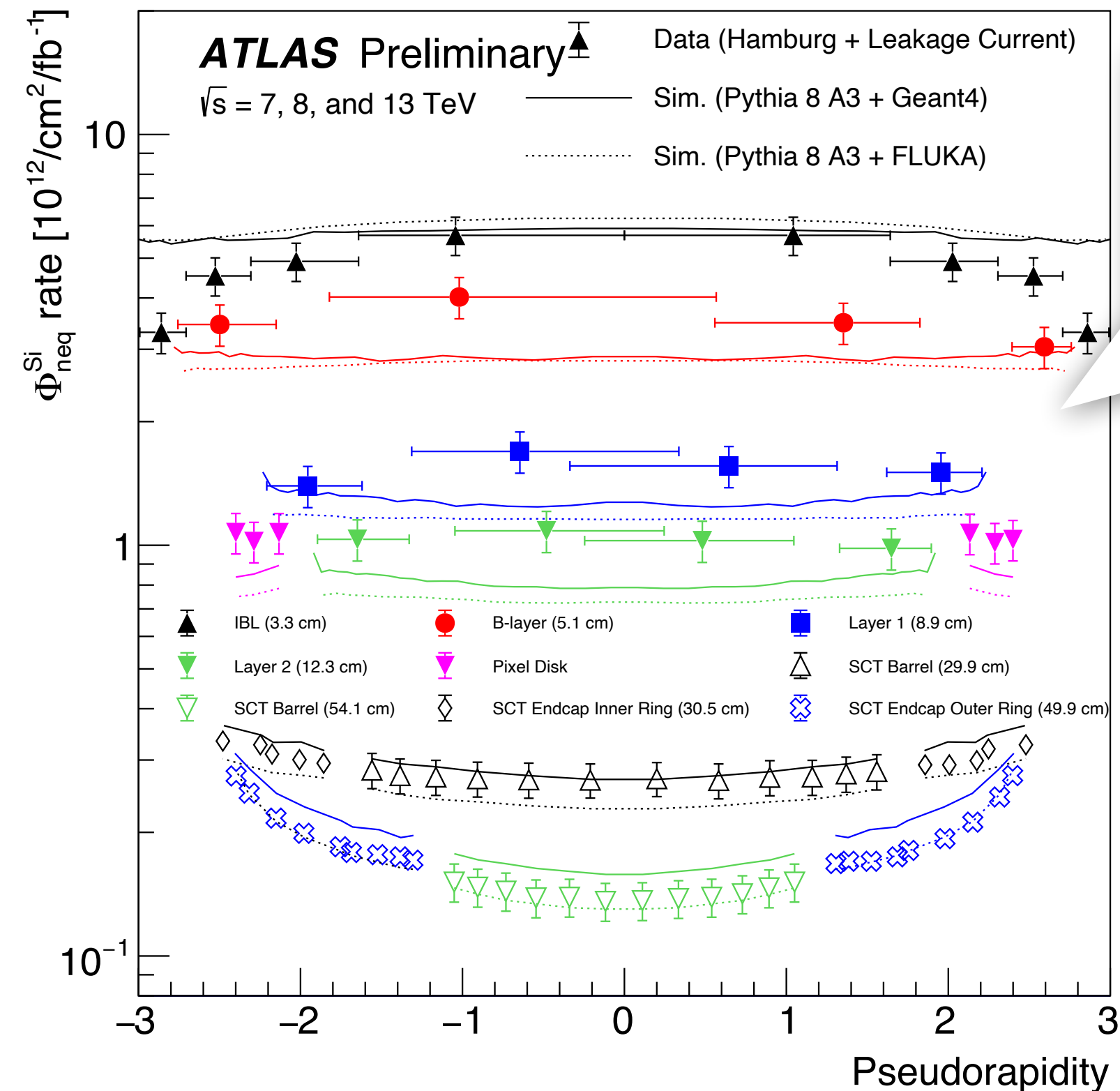
data ~ sim. for strips

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

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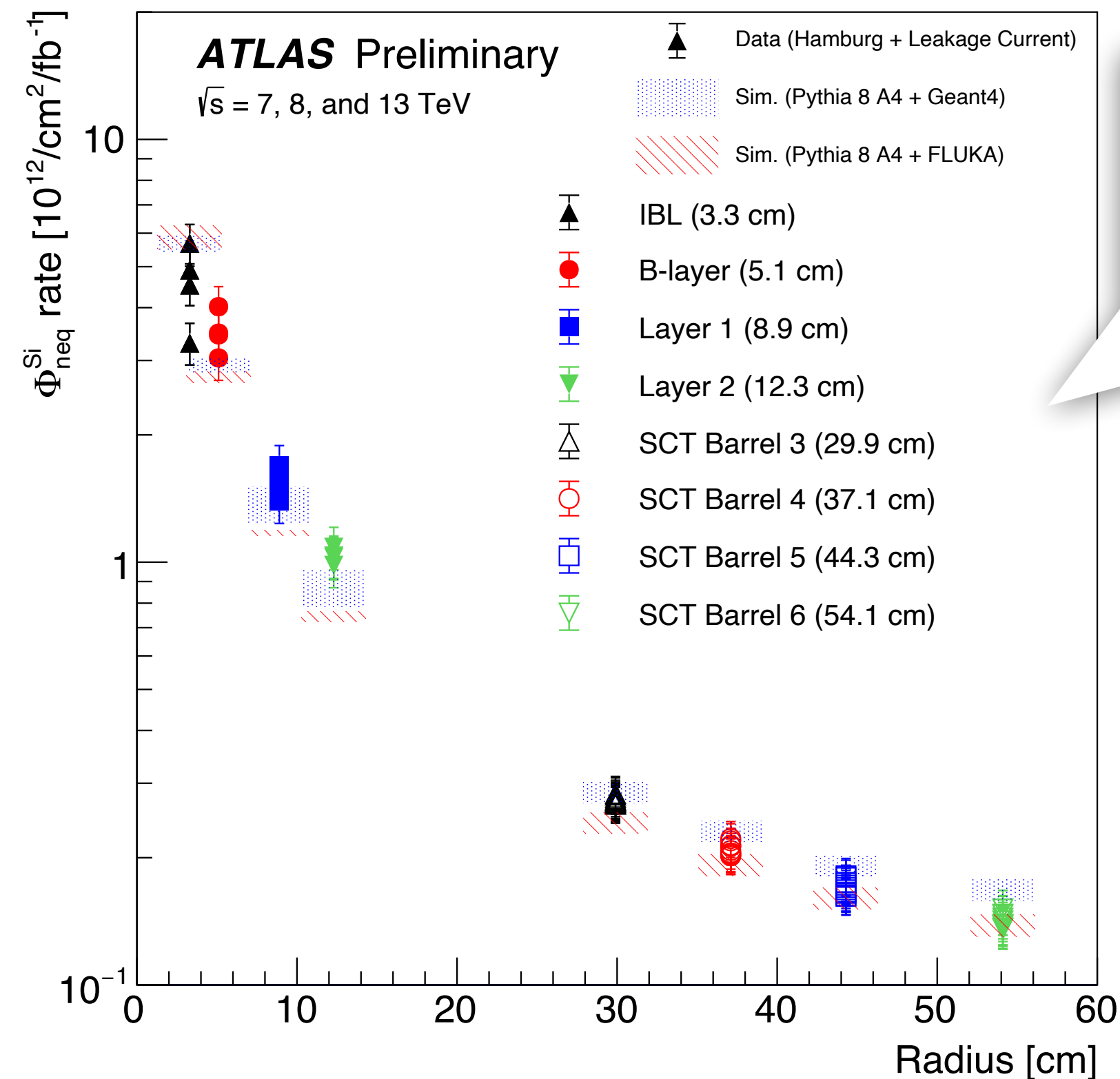
data ~ sim. for innermost
data ~ 1.5 x sim. for other pixels

data ~ sim. for strips

Same data as
previous slide, but
ID acceptance to
 $|\eta|=2.5$ is clear

A global picture: pixels and strips

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data ~ sim. for innermost
data ~ 1.5 x sim. for other pixels
data ~ sim. for strips

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

Conditions: Temperature, High Voltage, Fluence

Start

initial charge amount & location (green box) → Sec. 4.3 (yellow dashed box) → Drift Time (grey box)

E-field (blue dashed box) → Sec. 4.2 (yellow dashed box) → trapping constant (purple dashed box) → Sec. 4.5 (yellow dashed box) → time to trap (grey box)

Drift Time → min. → time travelled (grey box)

time to trap → min. → time travelled

End

induced charge on primary electrode and neighbors (red box)

Ramo potential (blue dashed box) → Sec. 4.6 (yellow dashed box) → induced charge on primary electrode and neighbors

initial charge amount & location (green box) → Sec. 4.6

Final Position (grey box) → induced charge on primary electrode and neighbors

Process Blocks

Block 1: initial charge amount & location (green box) → Sec. 4.3 (yellow dashed box) → Final Depth (grey box)

E-field (blue dashed box) → Sec. 4.3

Block 2: Lorentz drift (grey box) → Final Position

initial charge amount & location (green box) → Sec. 4.4 (yellow dashed box) → E-field (blue dashed box) → Sec. 4.4

Block 3: thermal diffusion (grey box) → Final Position

Final Depth → Final Position

Legend

- ■ ■ per condition
- • • per geometry
- per e/h group

Conclusions and outlook

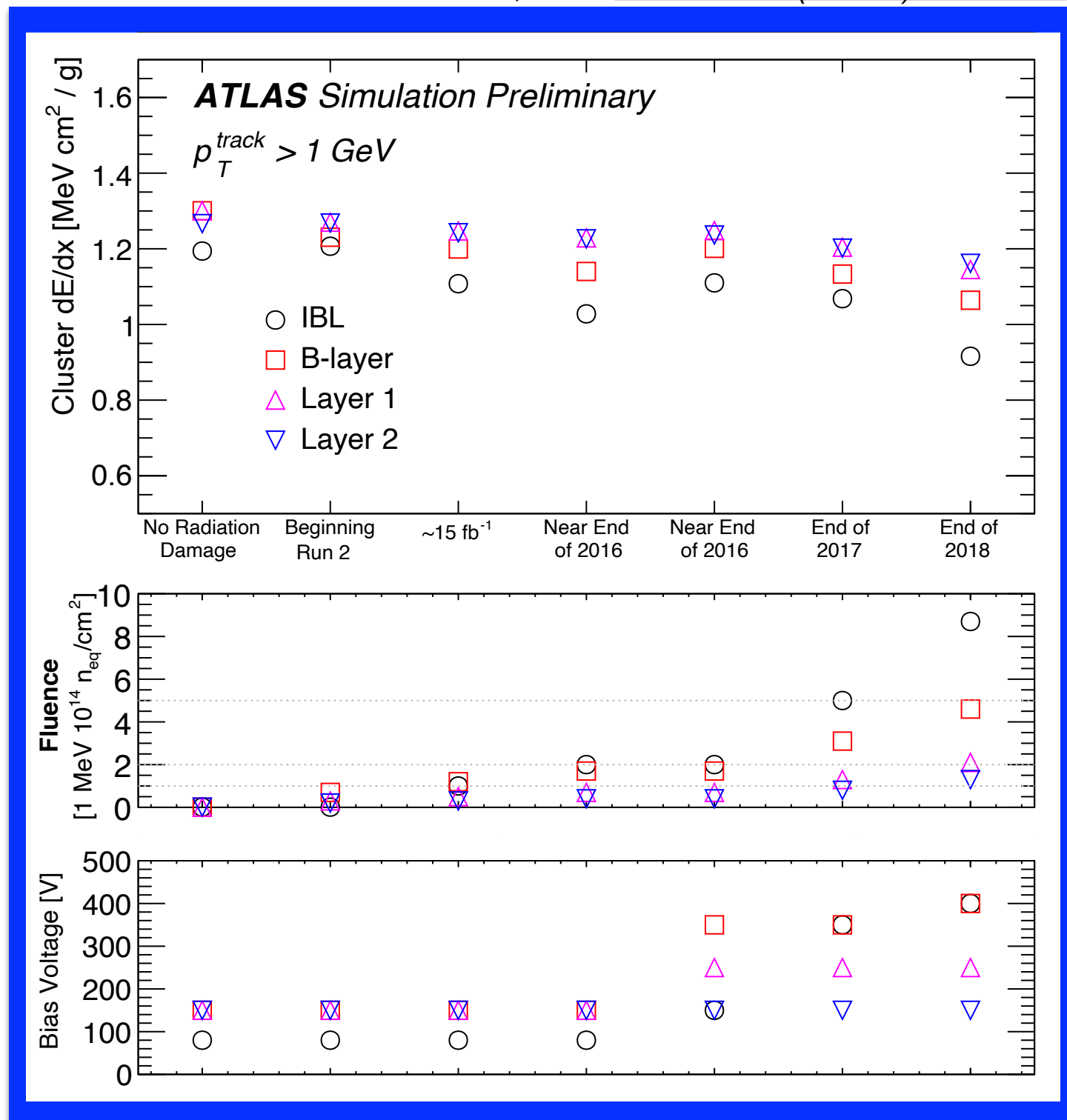
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The fluence is the key ingredient to radiation damage modeling.

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

