Based in part on JINST 14 (2019) P06012 and ATL-INDET-PUB-2019-001

Mysterious trends in radiation measurements for the ATLAS pixel detector

Benjamin Nachman
Lawrence Berkeley National Laboratory

Brown bag instrumentation seminar

November 6, 2019

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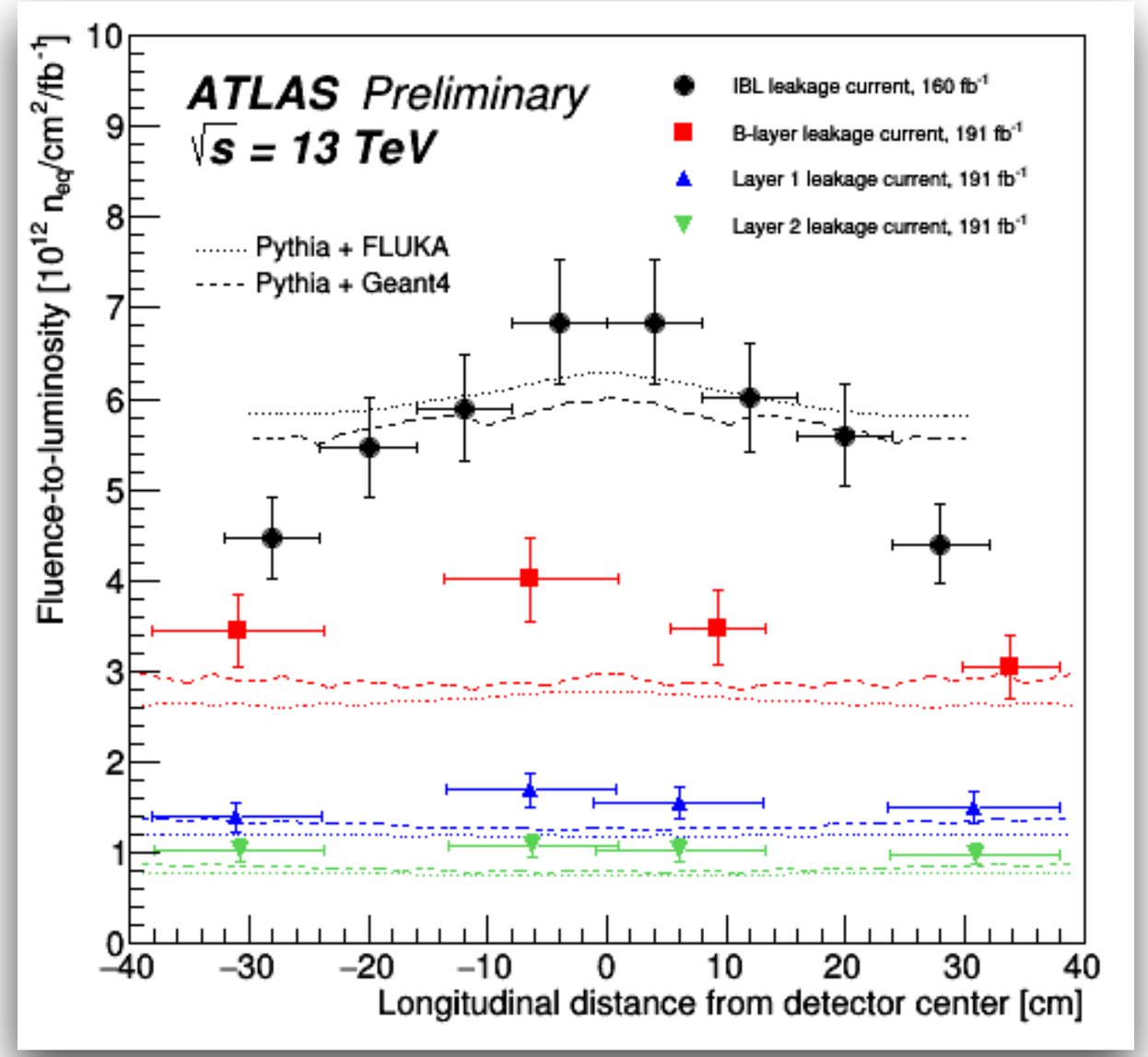
LBNL ATLAS radiation damage crew: Rebecca Carney (now at SLAC), Jennet Dickinson, Veronica Wallangen

Outline

- Silicon radiation damage at the LHC
- Mysterious trends in fluence measurements
  - ✦ Data
    - ▸Method biases
    - ▸Various measurements
  - ✦ Simulation
    - ▸Damage factors
    - ▸Transport models
    - ▸Physics models
- Outlook and future



Collisions in the ATLAS detector

p

Charged-particles from collision

p

ATLAS EXPERIMENT

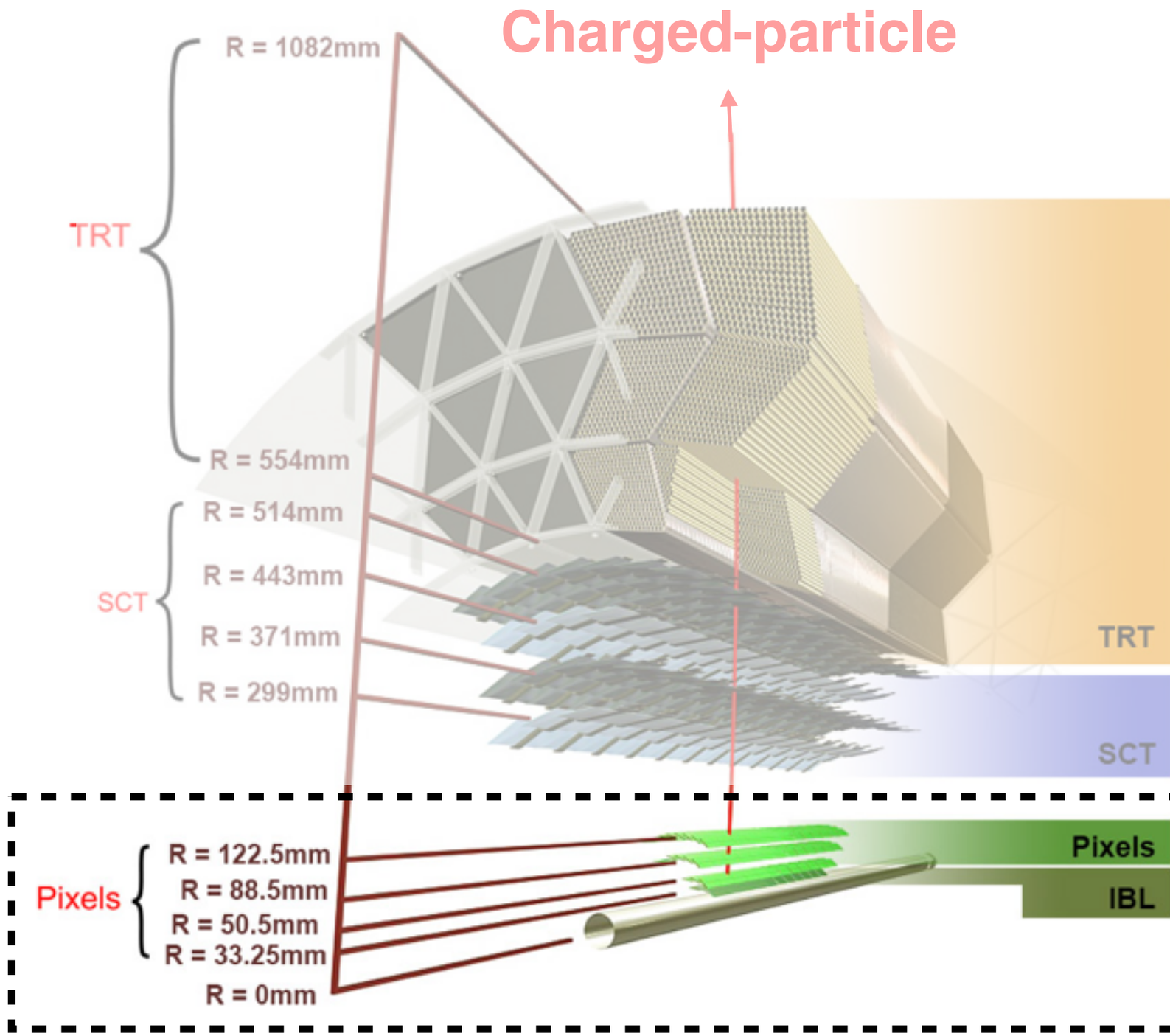
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

At the heart of ATLAS: Silicon Pixels

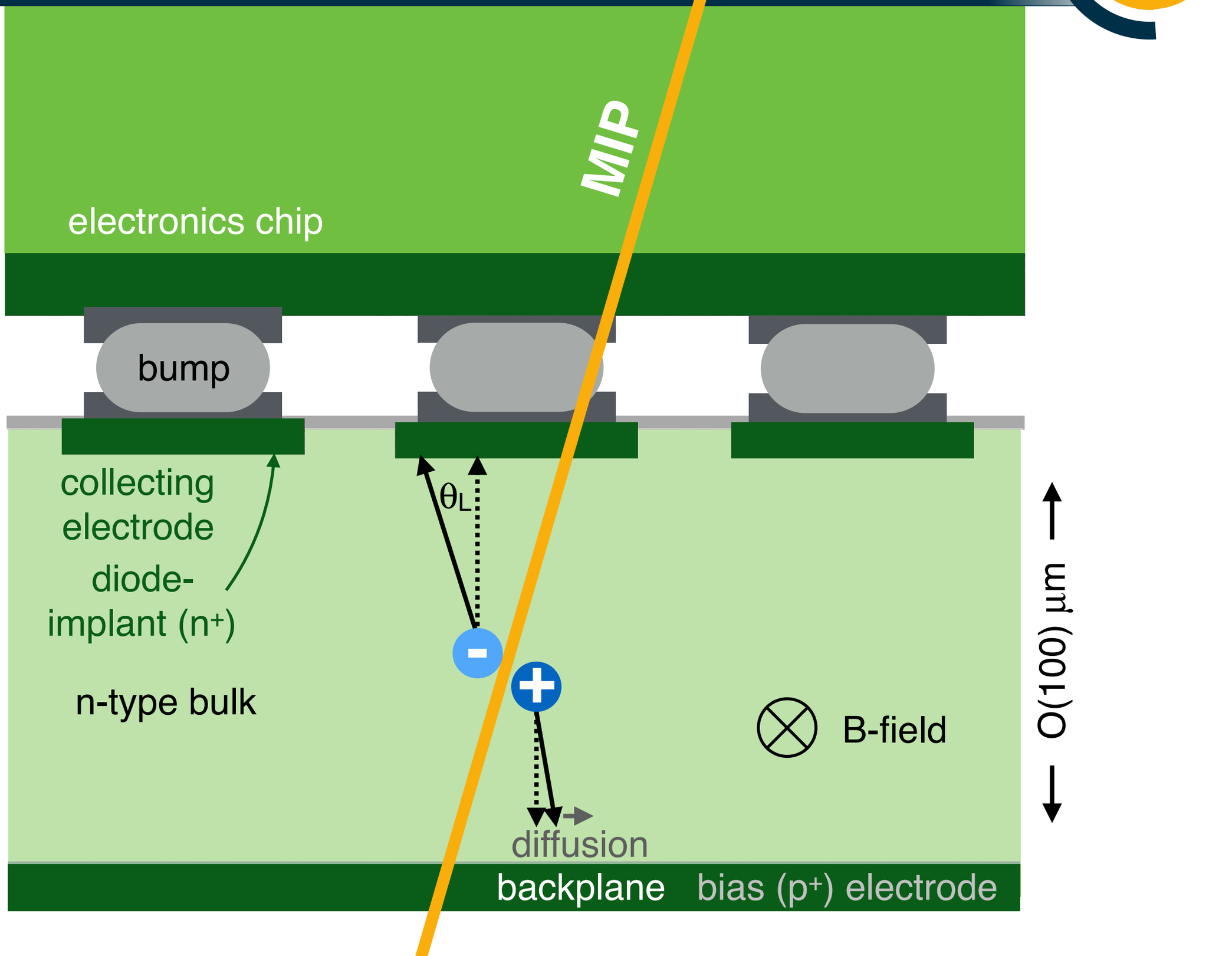
Closest to the interaction are finely segmented silicon pixels

$O(100^3)$ μm^3

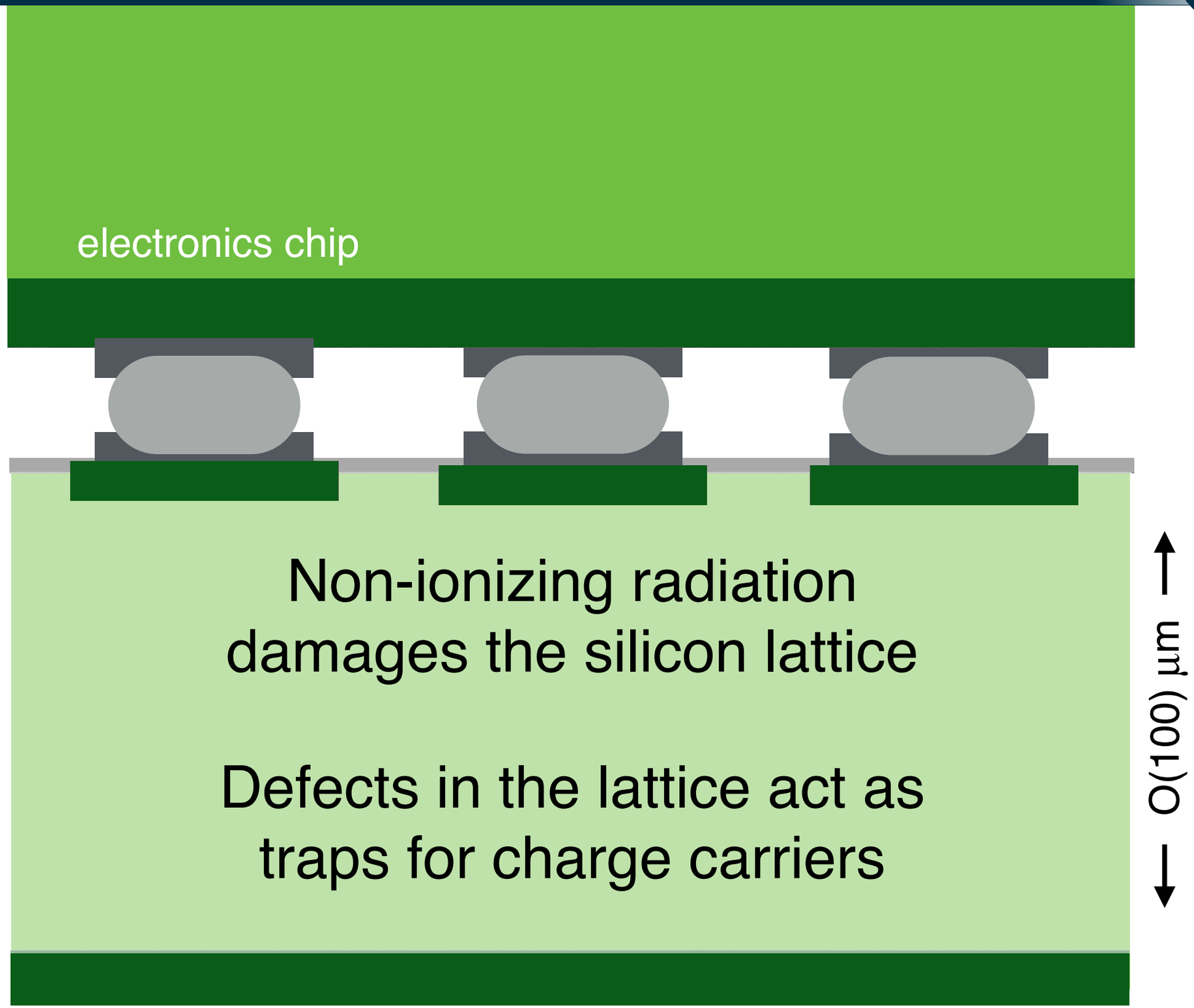
record (a digitized) charge for ionizing particles



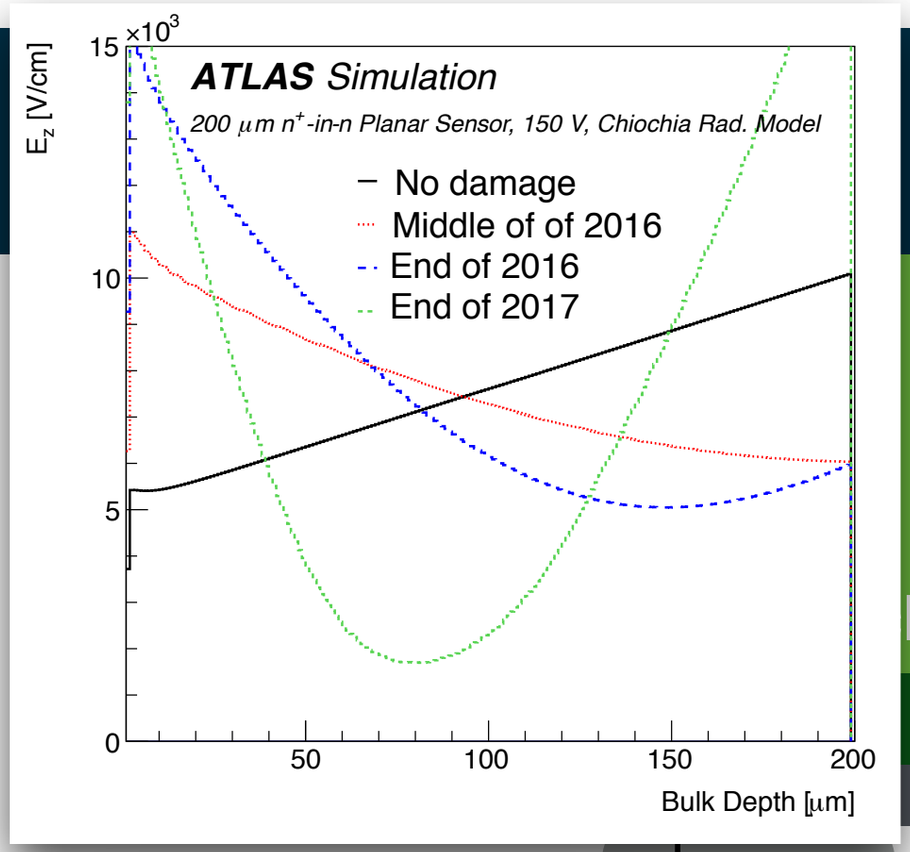
Zooming in on one pixel

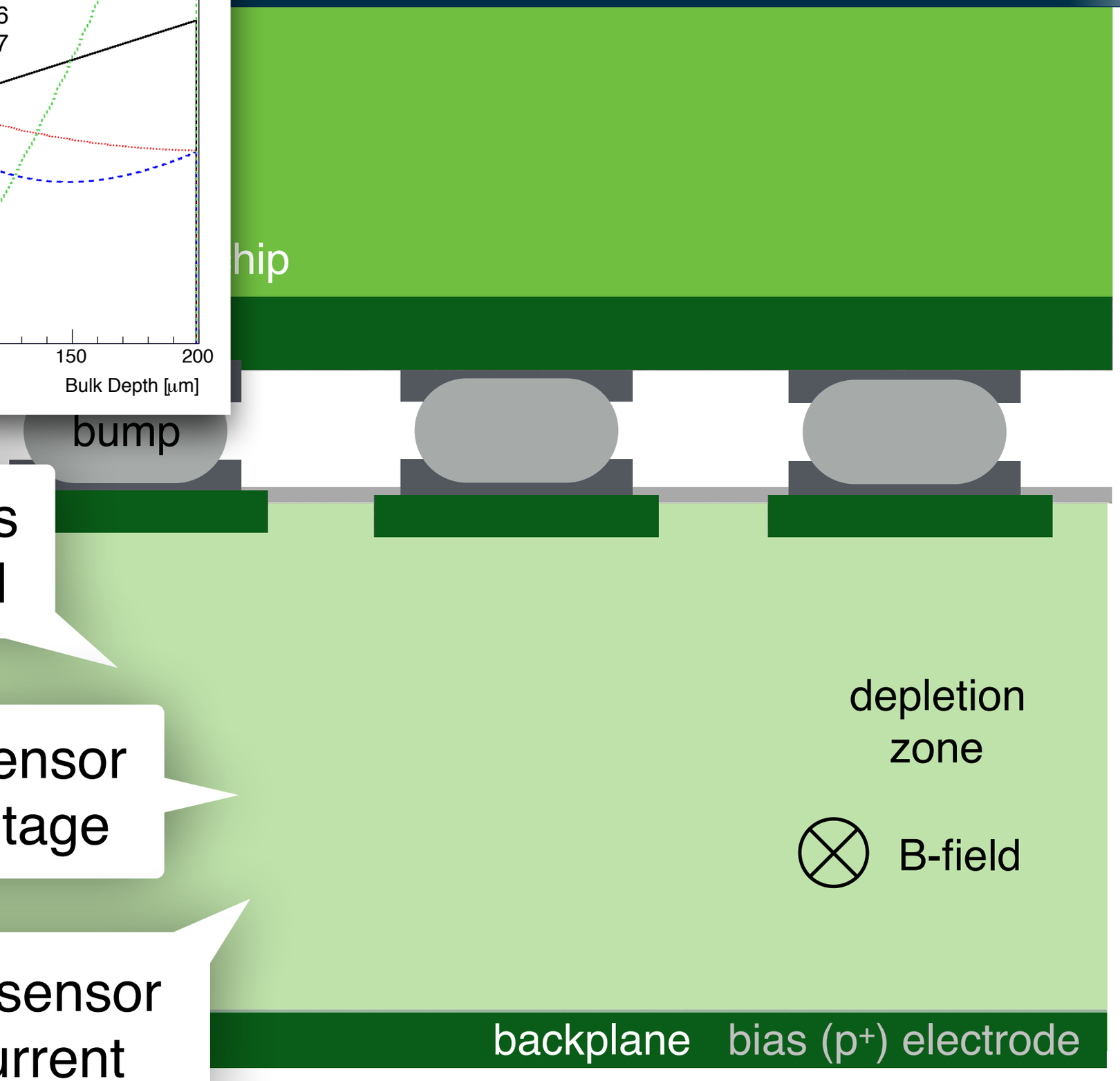


Silicon Radiation Damage



Signals after irradiation



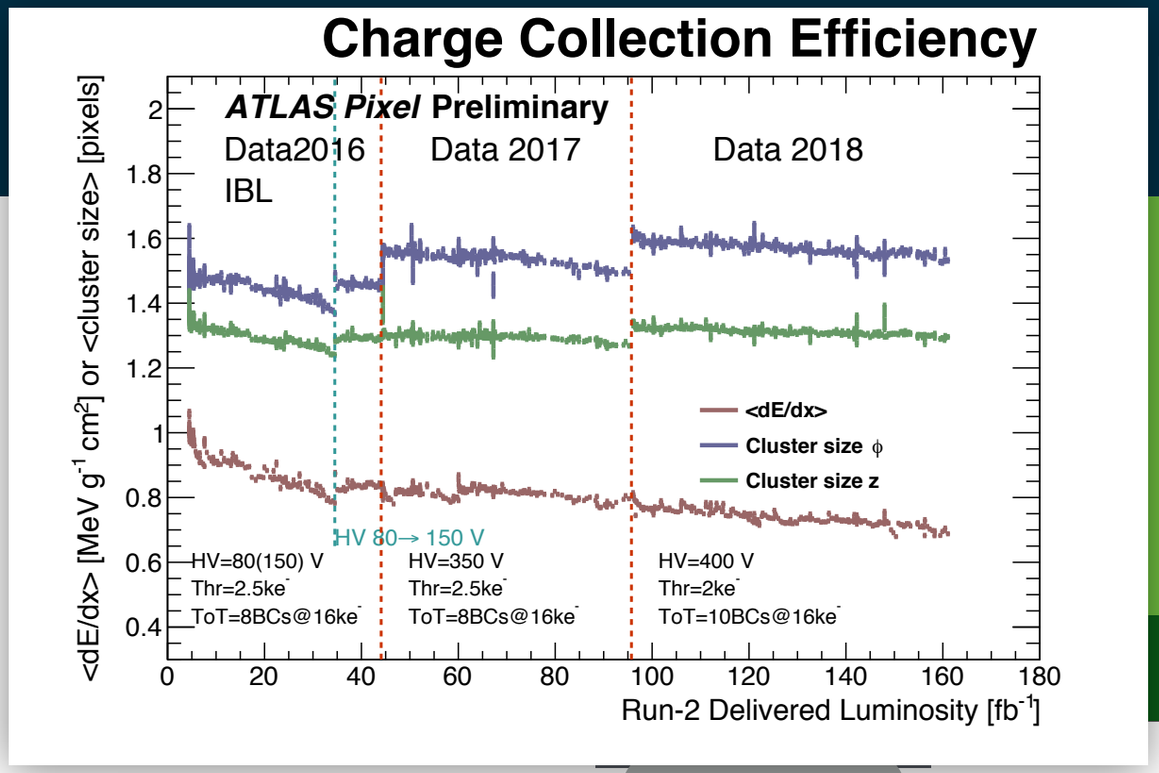


Deformations in the E-field

Increase in sensor depletion voltage

Increase in sensor leakage current

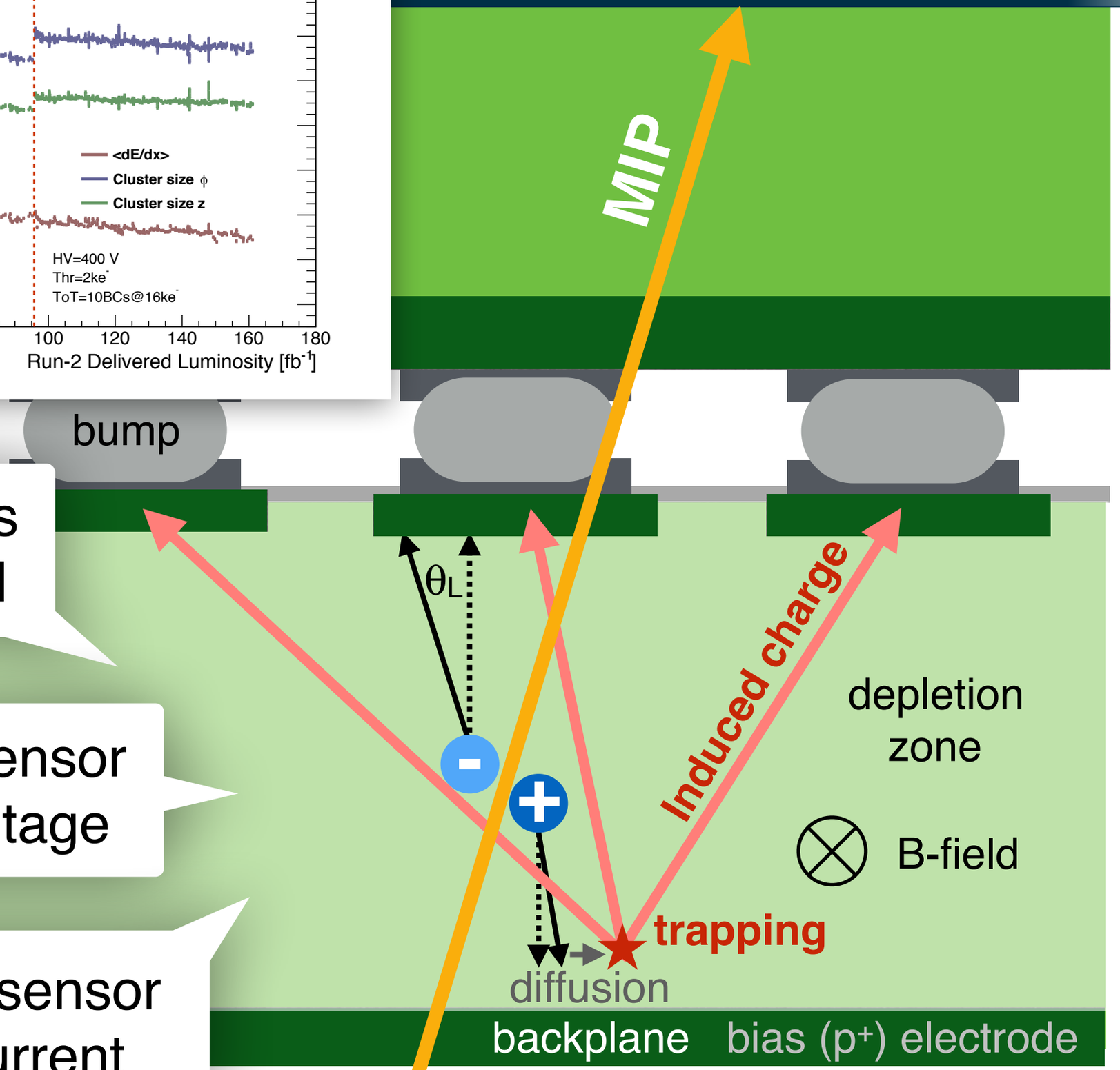
nals after irradiation



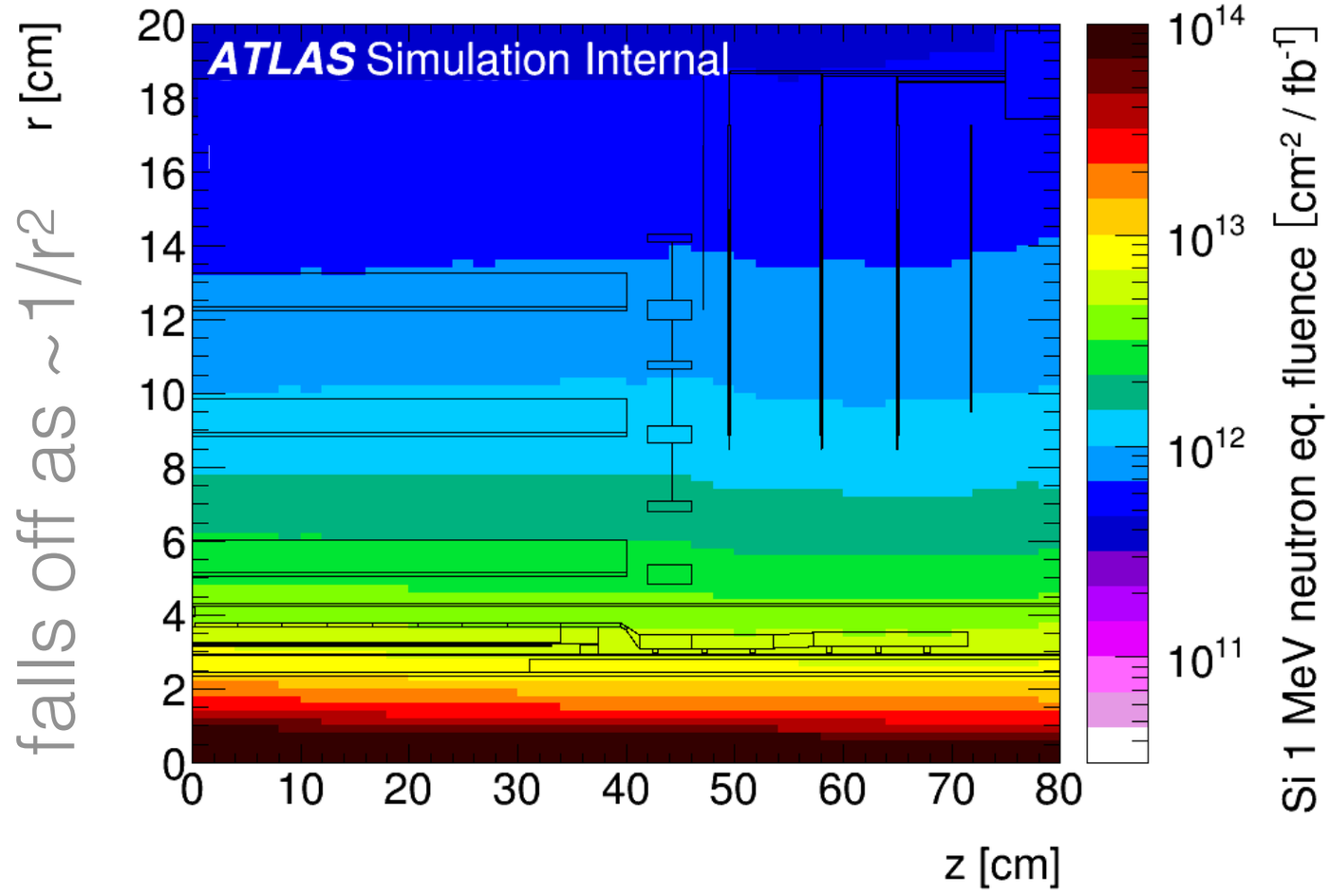
Deformations in the E-field

Increase in sensor depletion voltage

Increase in sensor leakage current



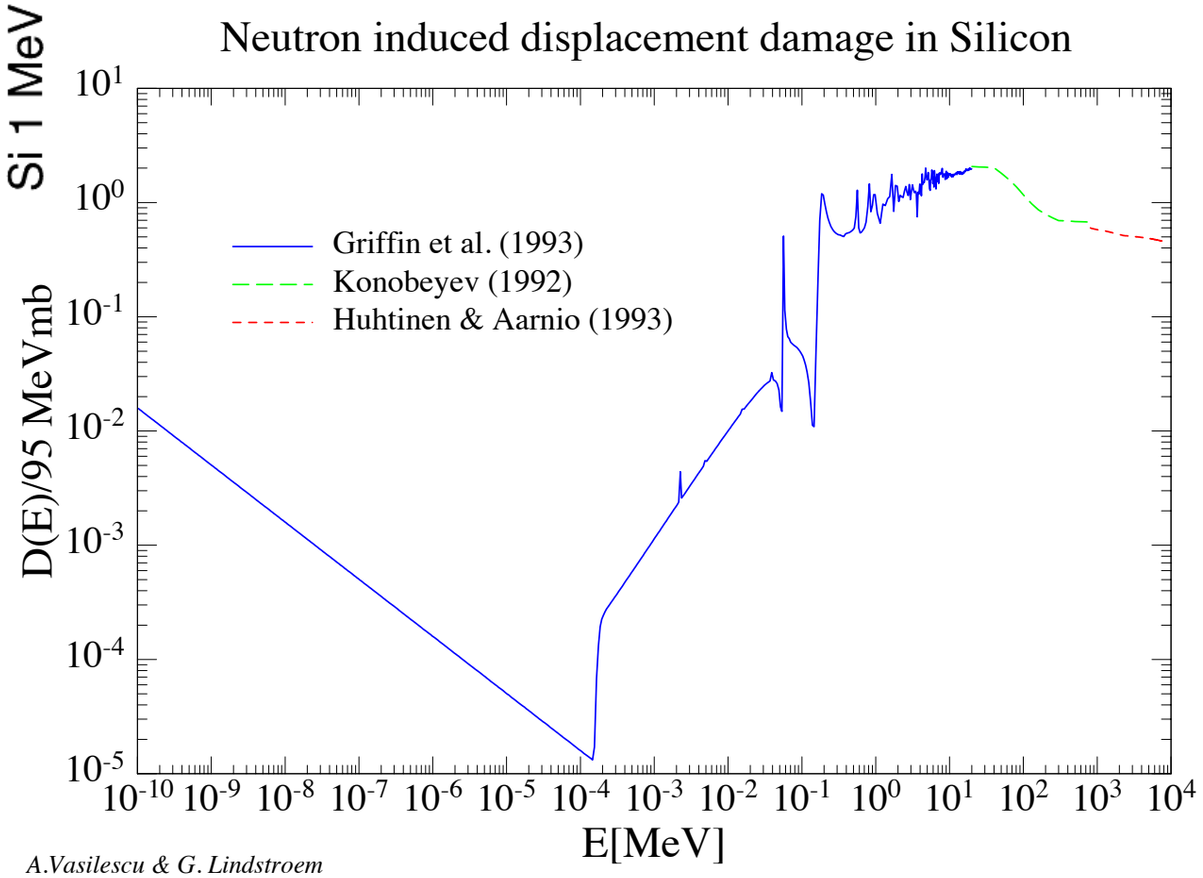
Radiation Environment at the LHC



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

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

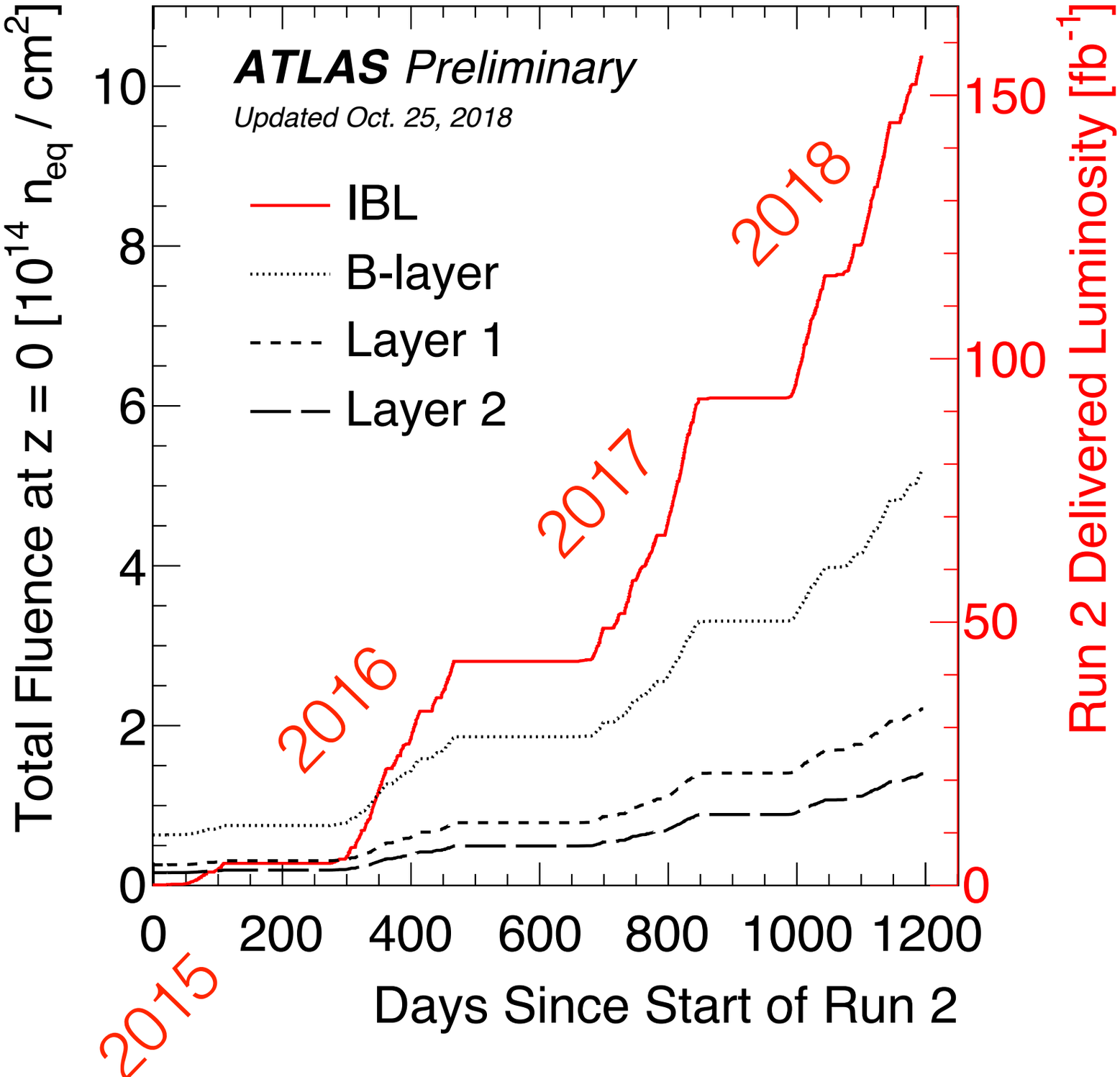
Fluence symbol: Φ



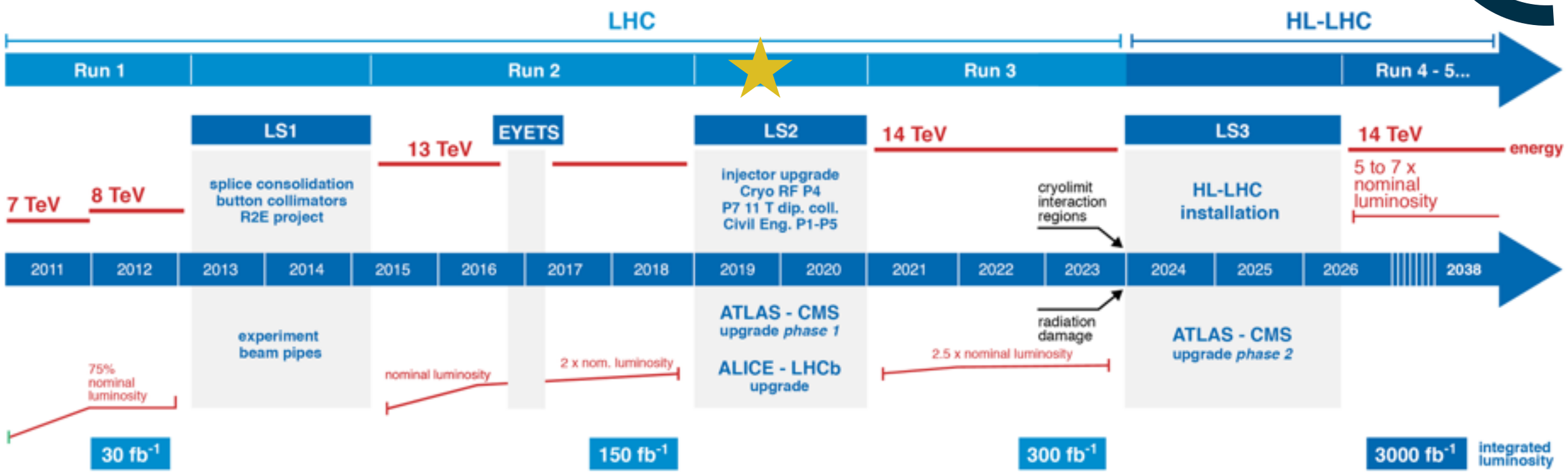
Radiation Environment at the LHC

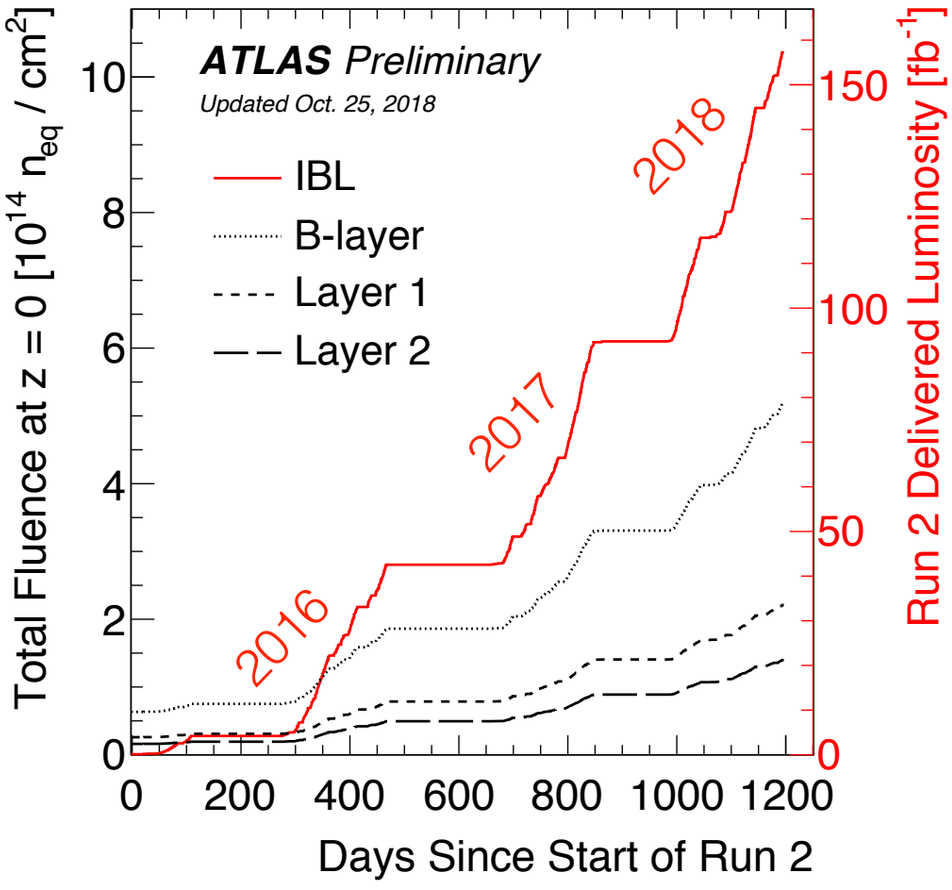
Innermost layer = more fluence

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



Current detector irradiation





We have now (★) passed
$\Phi = 10^{15}$ 1 MeV n_{eq}/cm^2 !

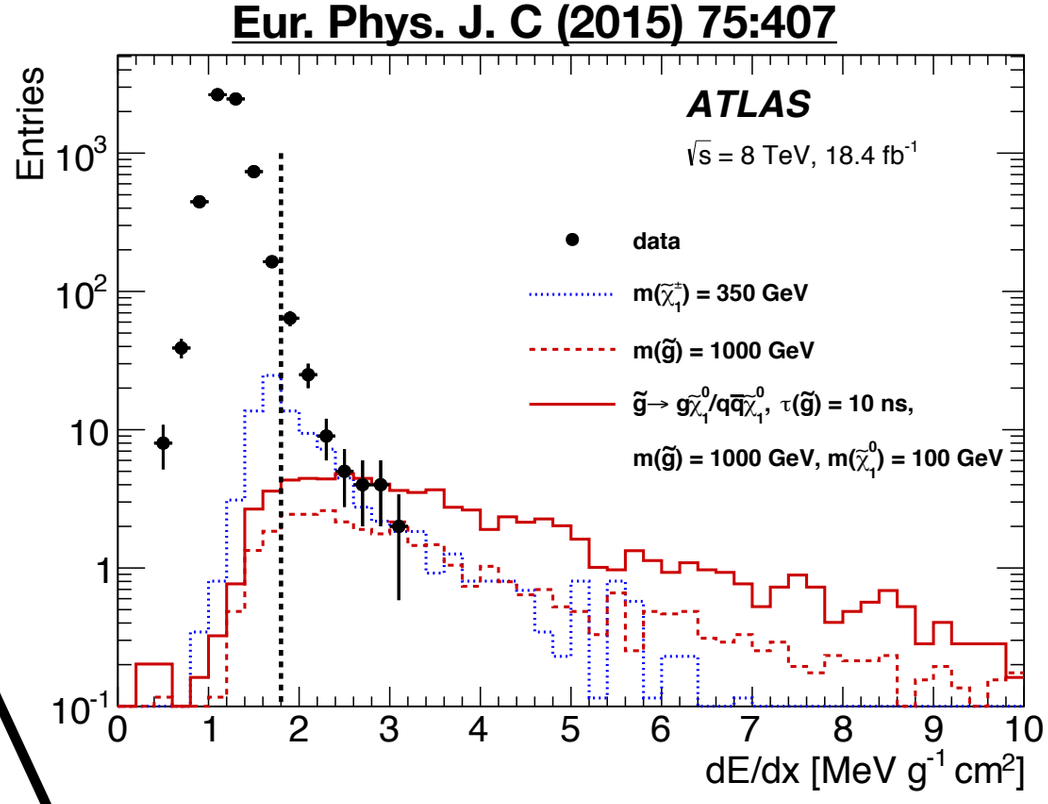
We have huge, irradiated detectors to inform Run 3 / HL-LHC.

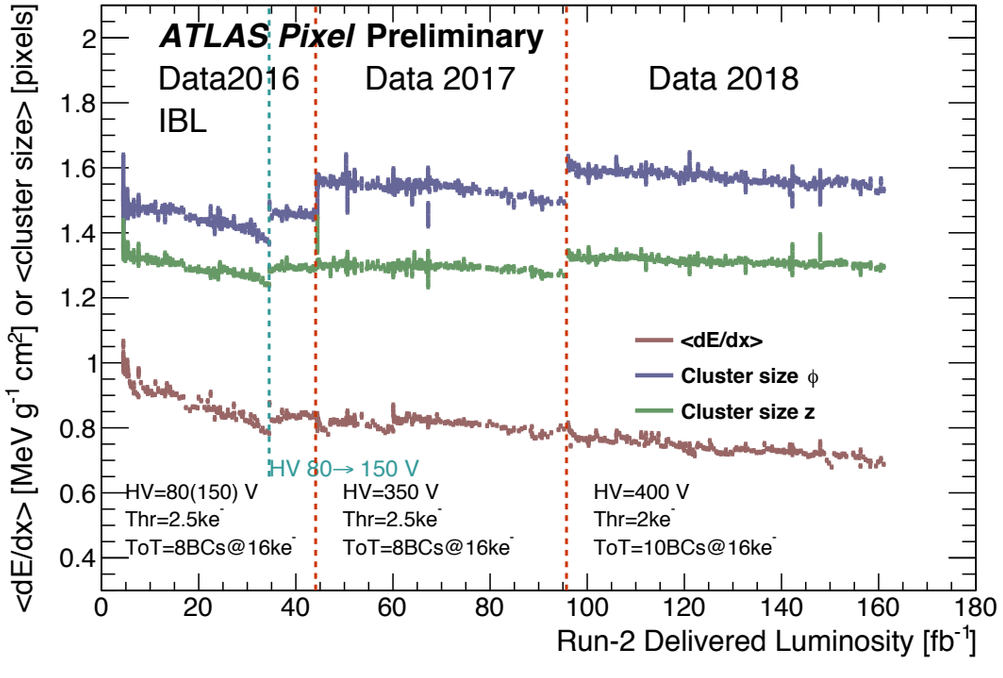
Impact on Physics and Performance

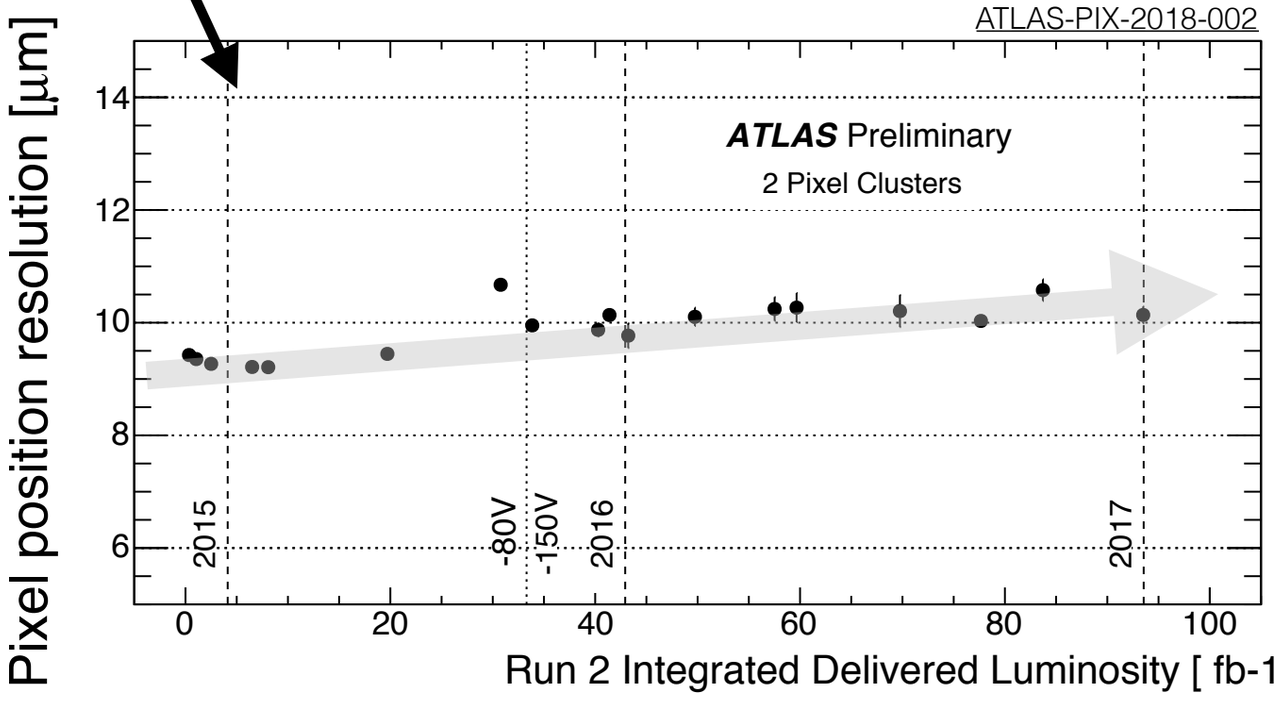
Charge loss directly effects searches for new highly ionizing particles →

We may be seeing a degradation in position resolution.

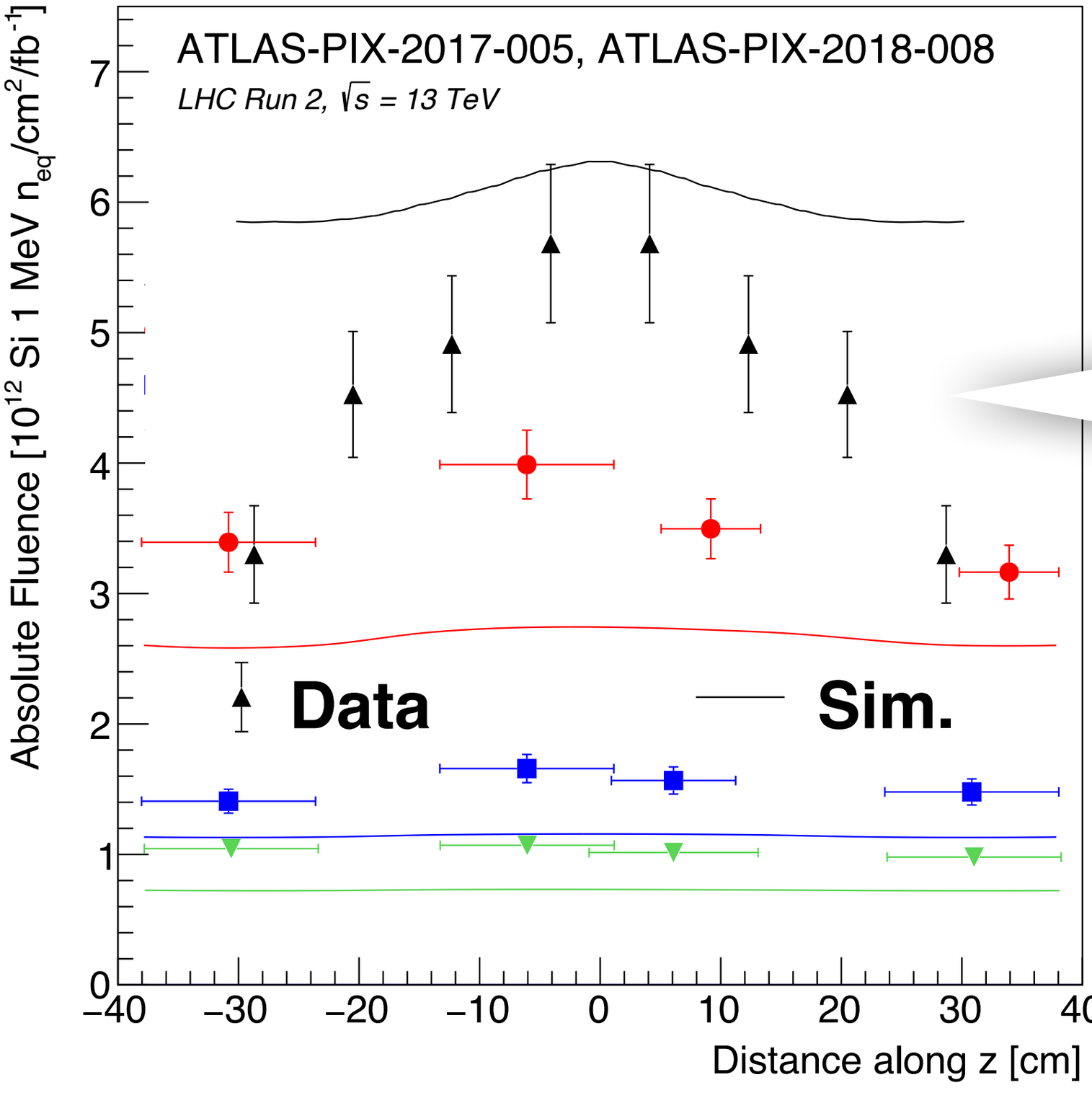
It is imperative that radiation damage effects be quantified to inform **operations**, **offline analysis**, and **future detector design**!







The mysteries



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

(2) data > simulation past innermost layer

Road map

Is it a problem with …?

- **Data**
  - Method biases
    - Try multiple methods!
  - Model biases
- **Simulation**
  - Physics modeling
  - Transport model
  - Damage factors

Road map

Is it a problem with …?

Data

- Method biases
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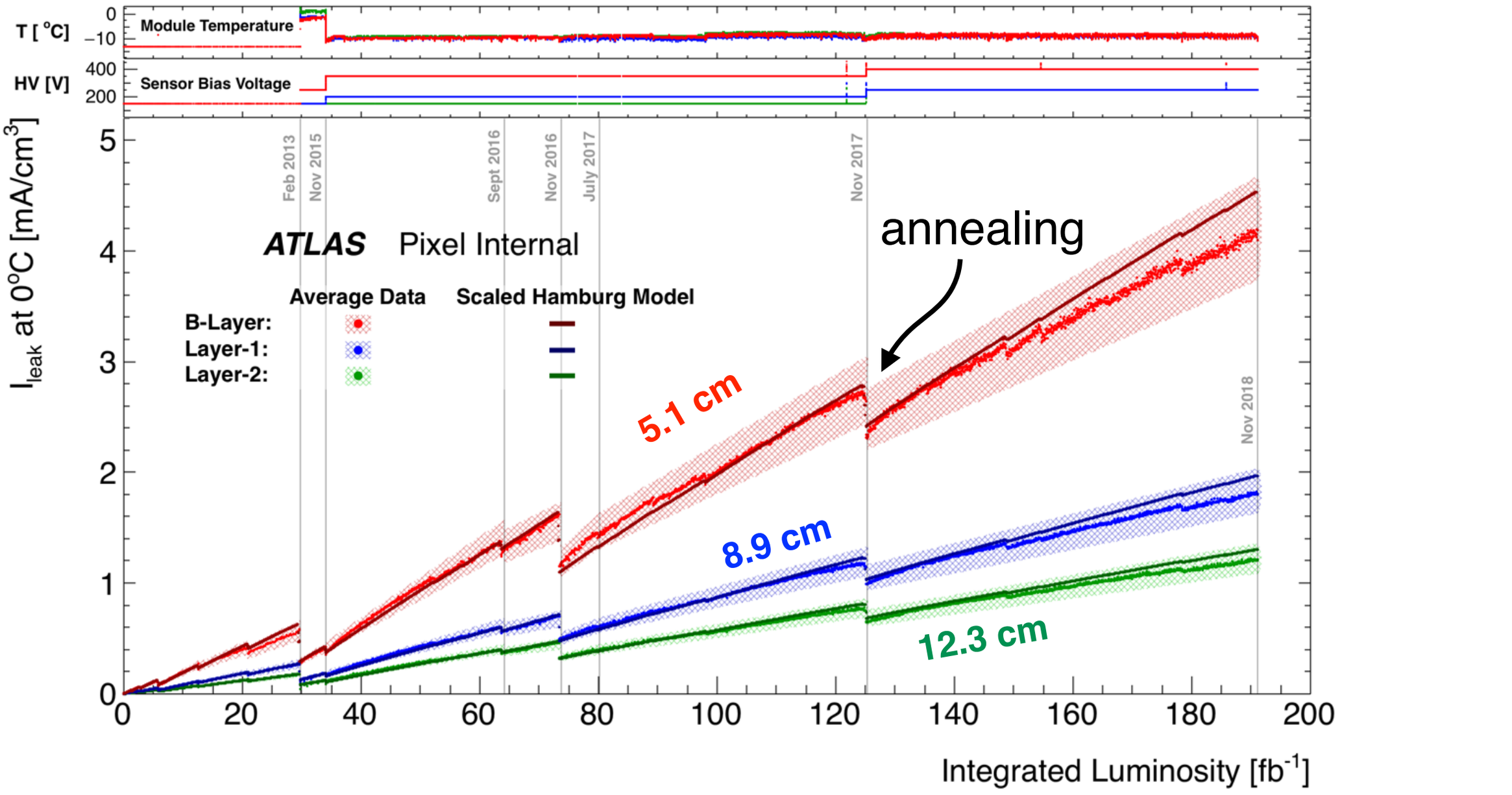
Simulation

- Physics modeling
- Transport model
- Damage factors

Measuring the fluence

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



Measuring the fluence

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

Depleted volume

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

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

"The Hamburg Model"

Measure this

We want to know this

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

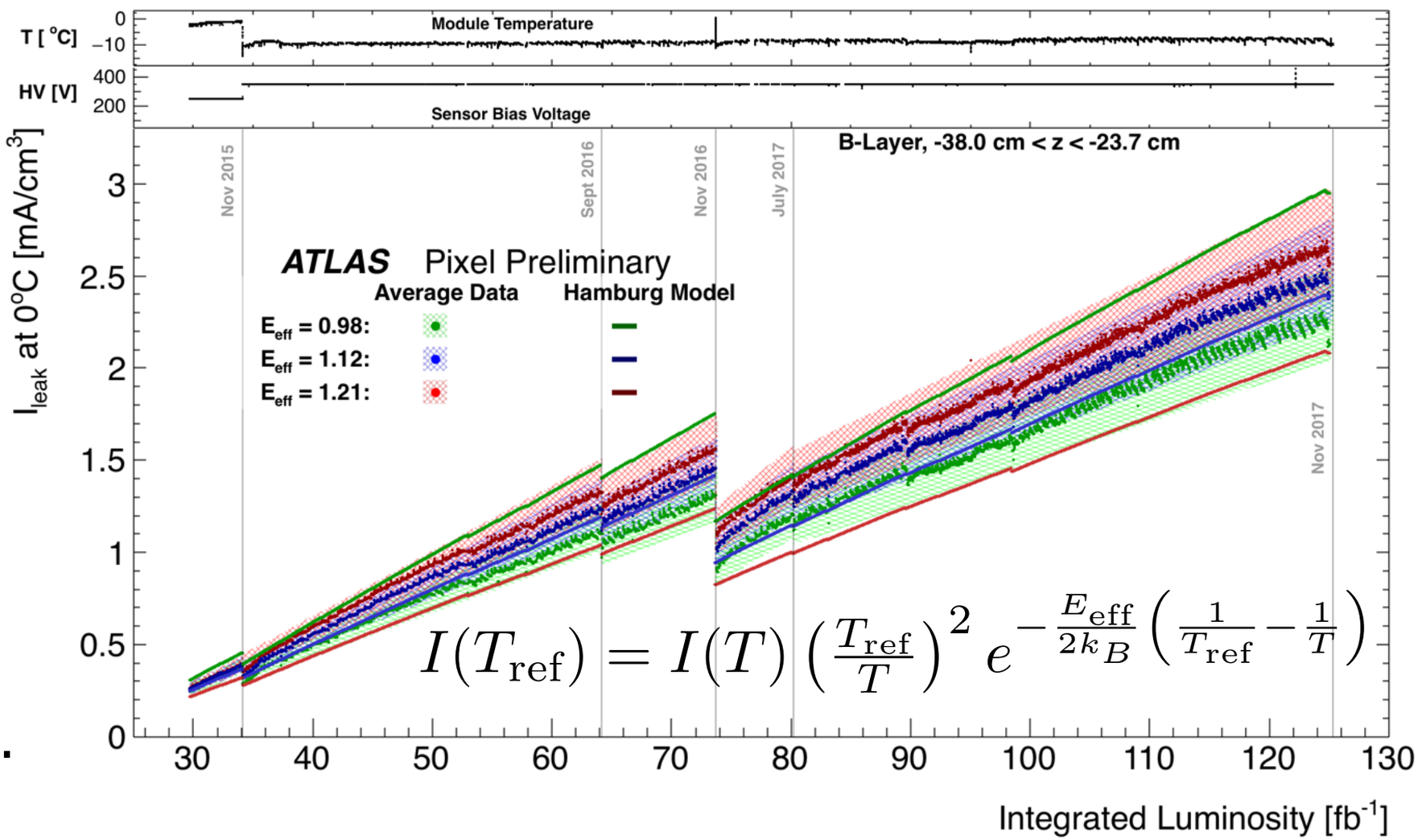
N.B. the coefficients are dimensionfull

Challenges with leakage measurement

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

The current has an exponential scaling with T.

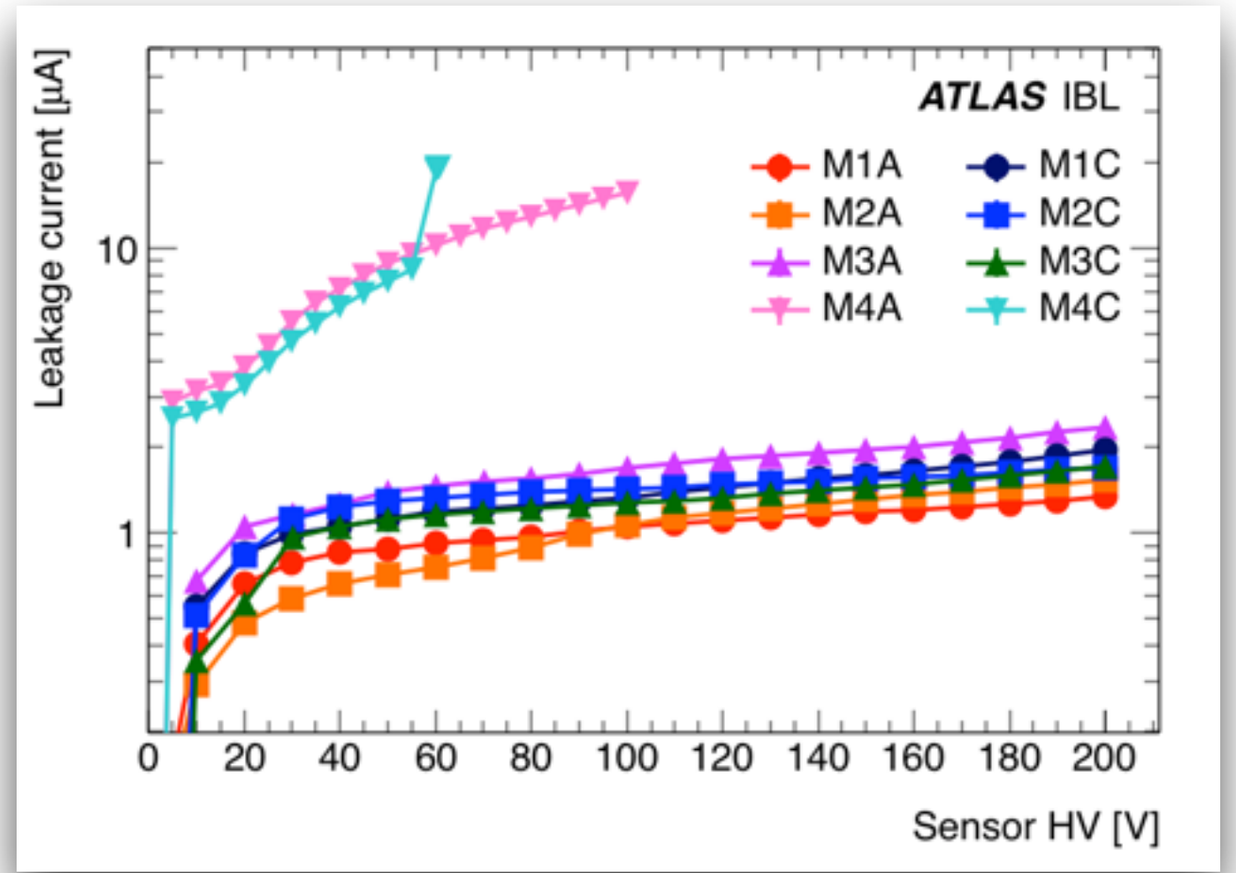
We correct for this, but no consensus on E_{eff}.



Challenges with leakage measurement

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

JINST 13 T05008 (2018), 1803.00844



The current is not constant - have to make a choice about what we call “the” leakage current.

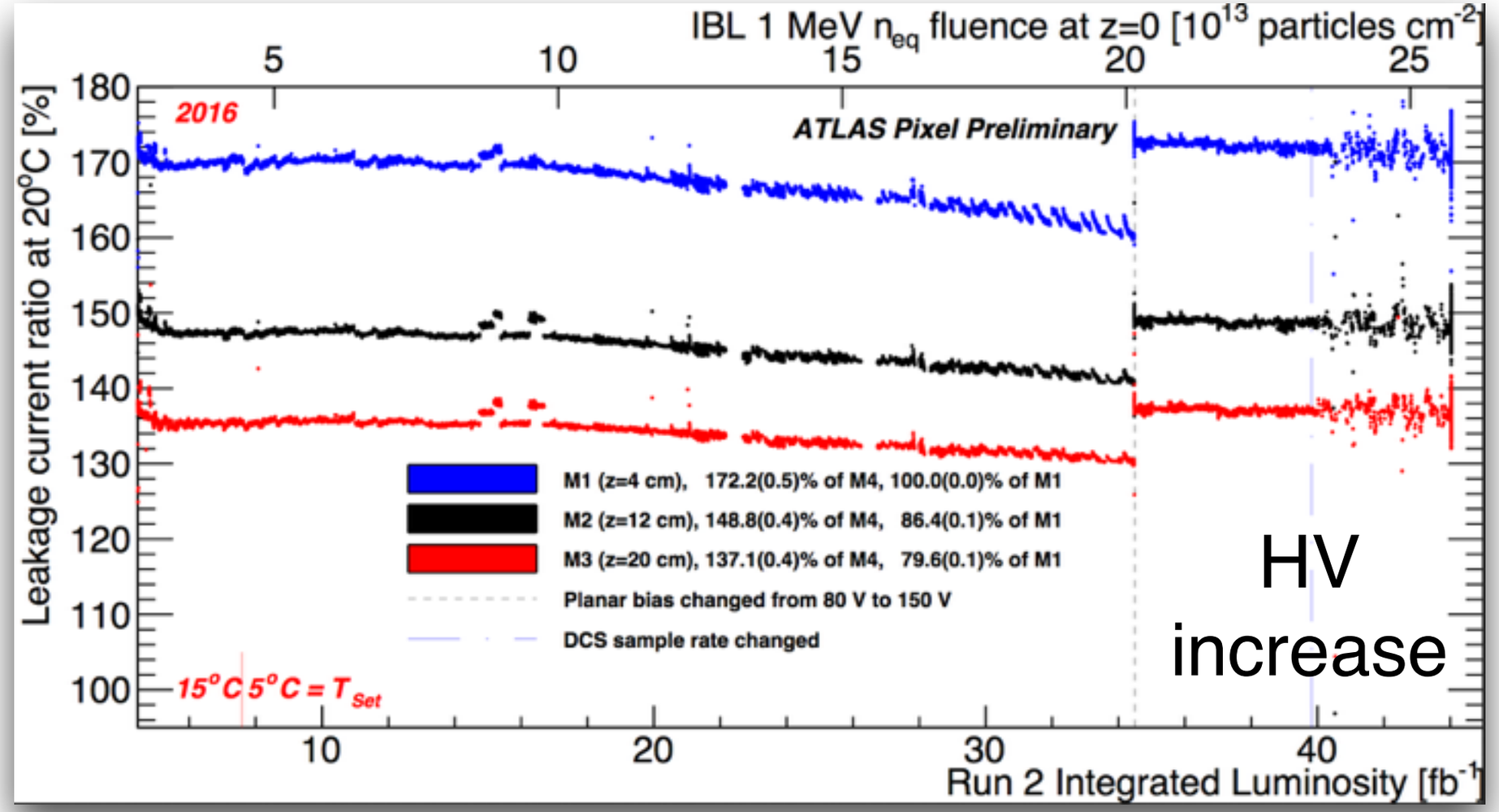
Challenges with leakage measurement

Depleted volume

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

Ratios between layers should be constant

2016 we were underdepleted!



Challenges with leakage measurement

Depleted volume

$$\Delta I = (\Phi_{eq}/L_{int}) \times V \cdot \sum_{i=1}^{n} L_{int,}$$

Ratios between layers should be constant

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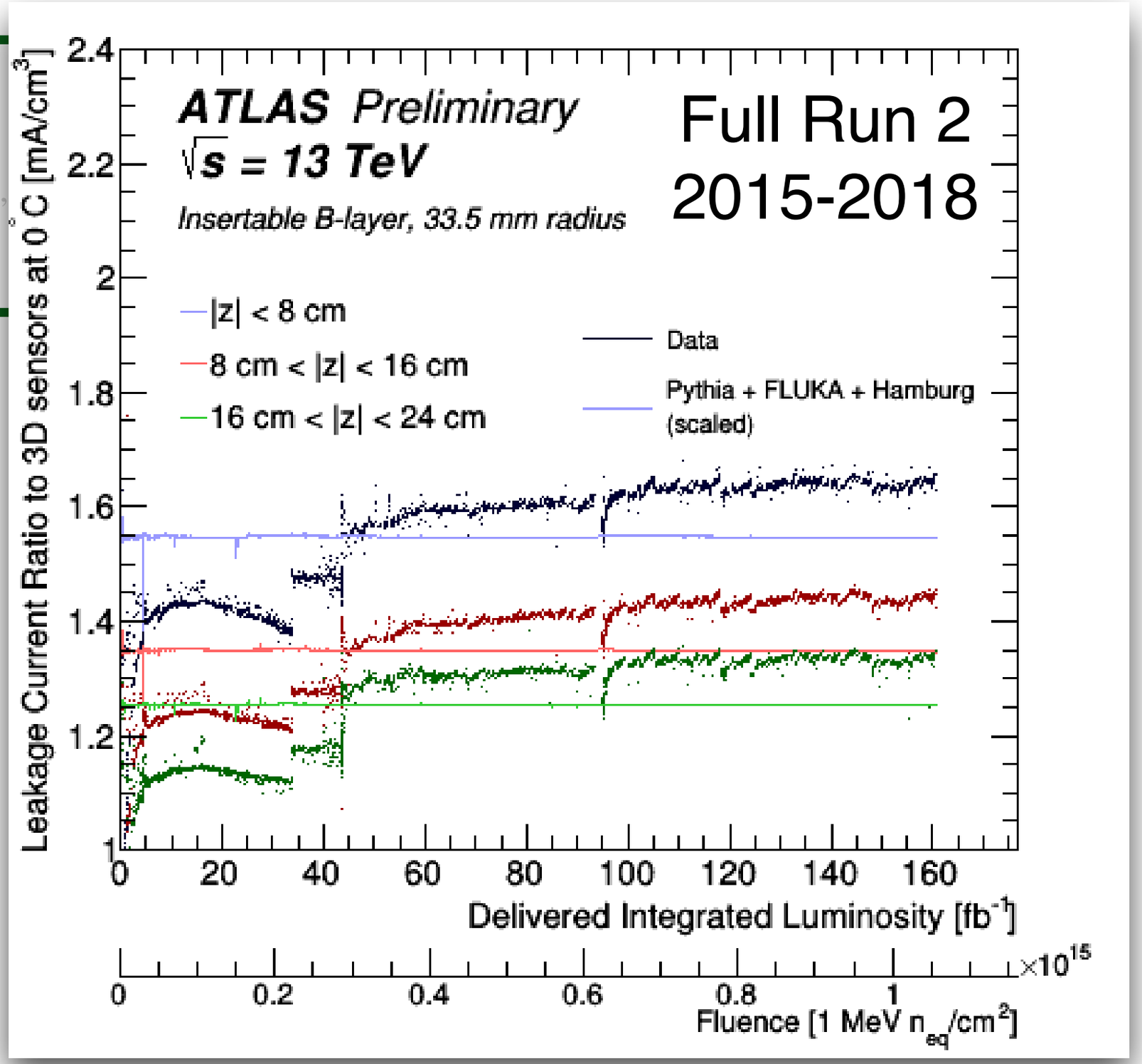


Challenges with leakage measurement

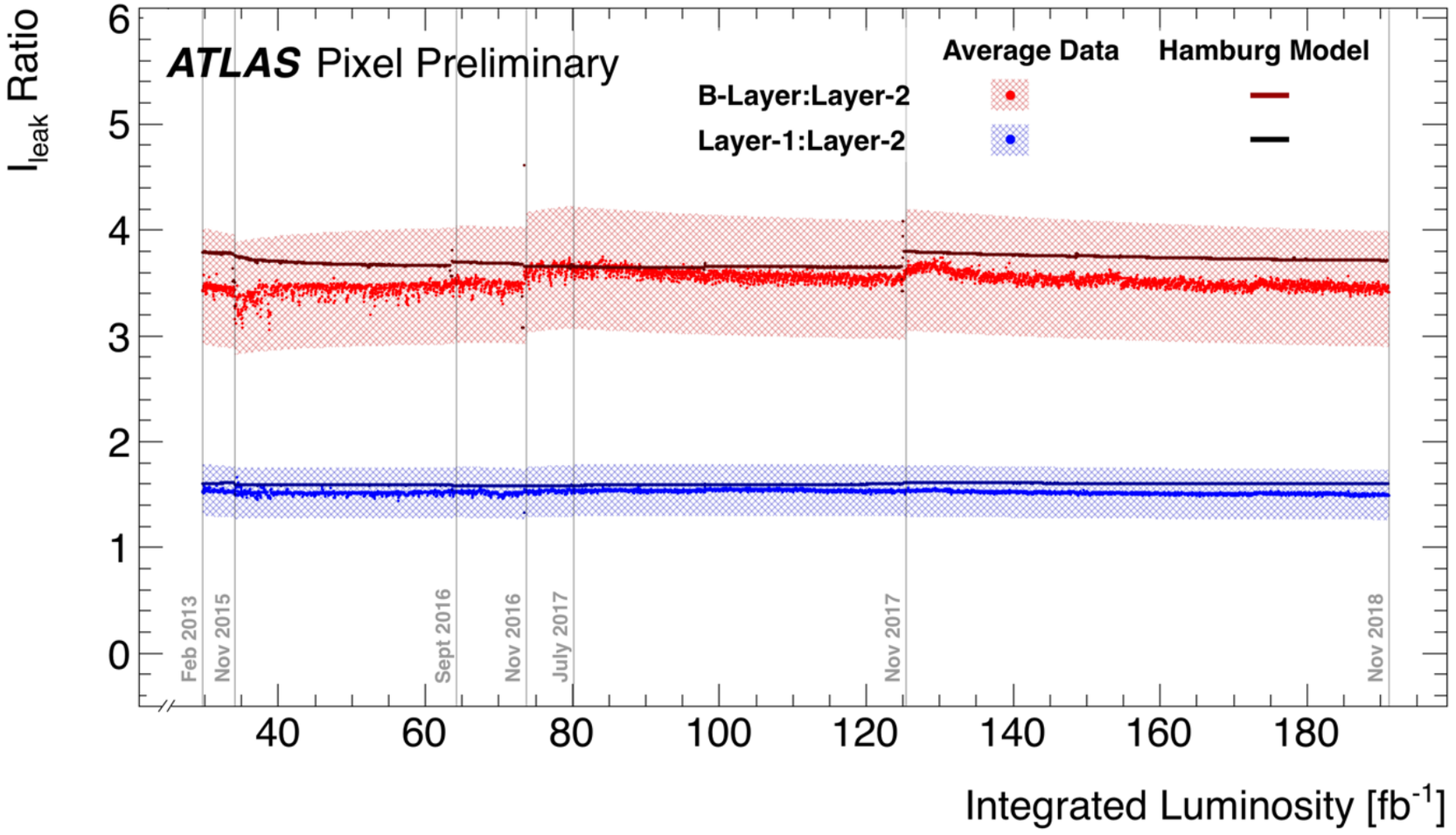
Depleted volume

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

Ratios between layers should be constant

for the three outer layers, remarkably stable

(probably not stable enough to be useful to constrain the luminosity, unfortunately)

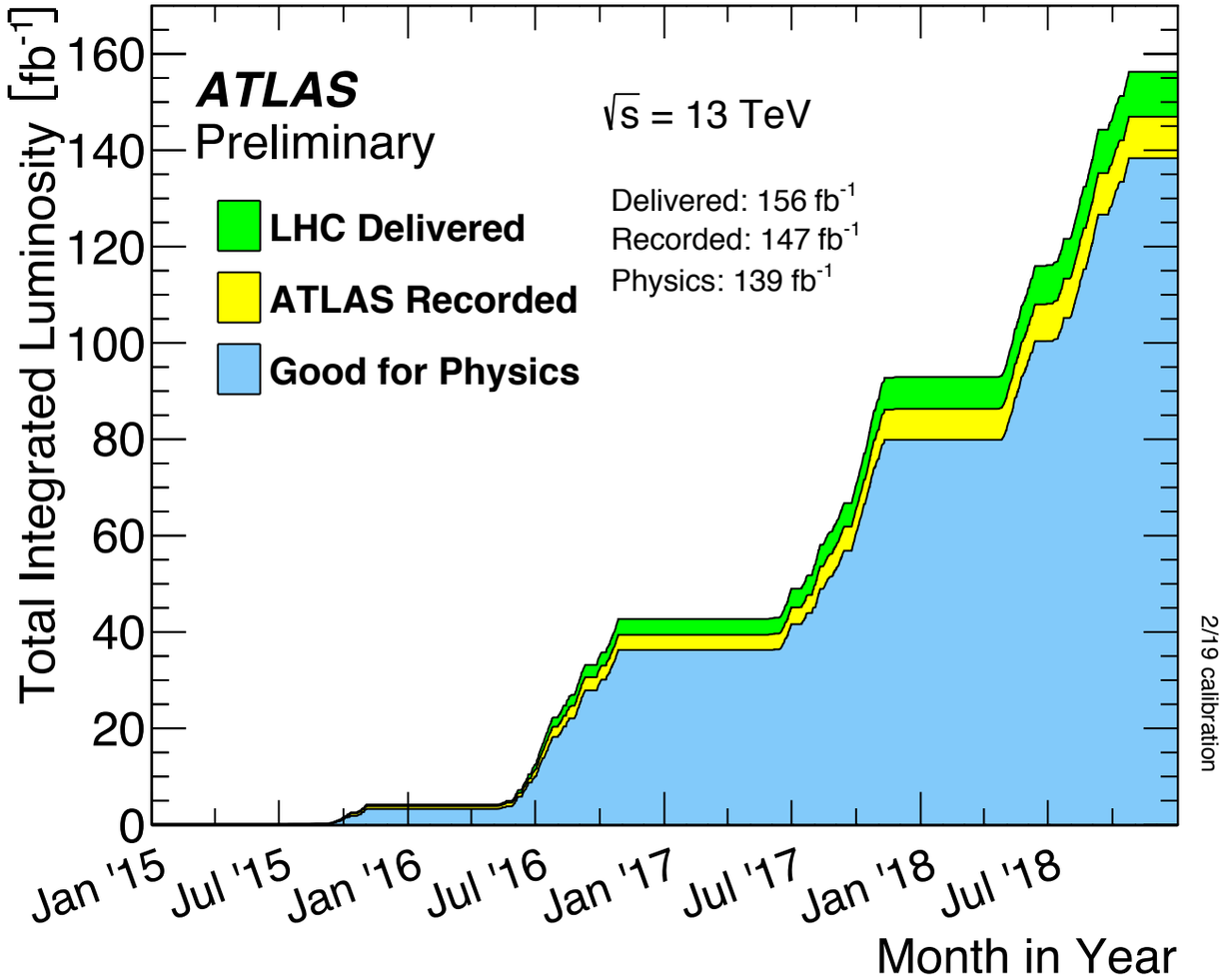


Challenges with leakage measurement

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

We care about the fluence that the detector saw, not the fluence that was good for physics!

…non-trivial to ensure we have all the right conditions information.



Challenges with leakage measurement

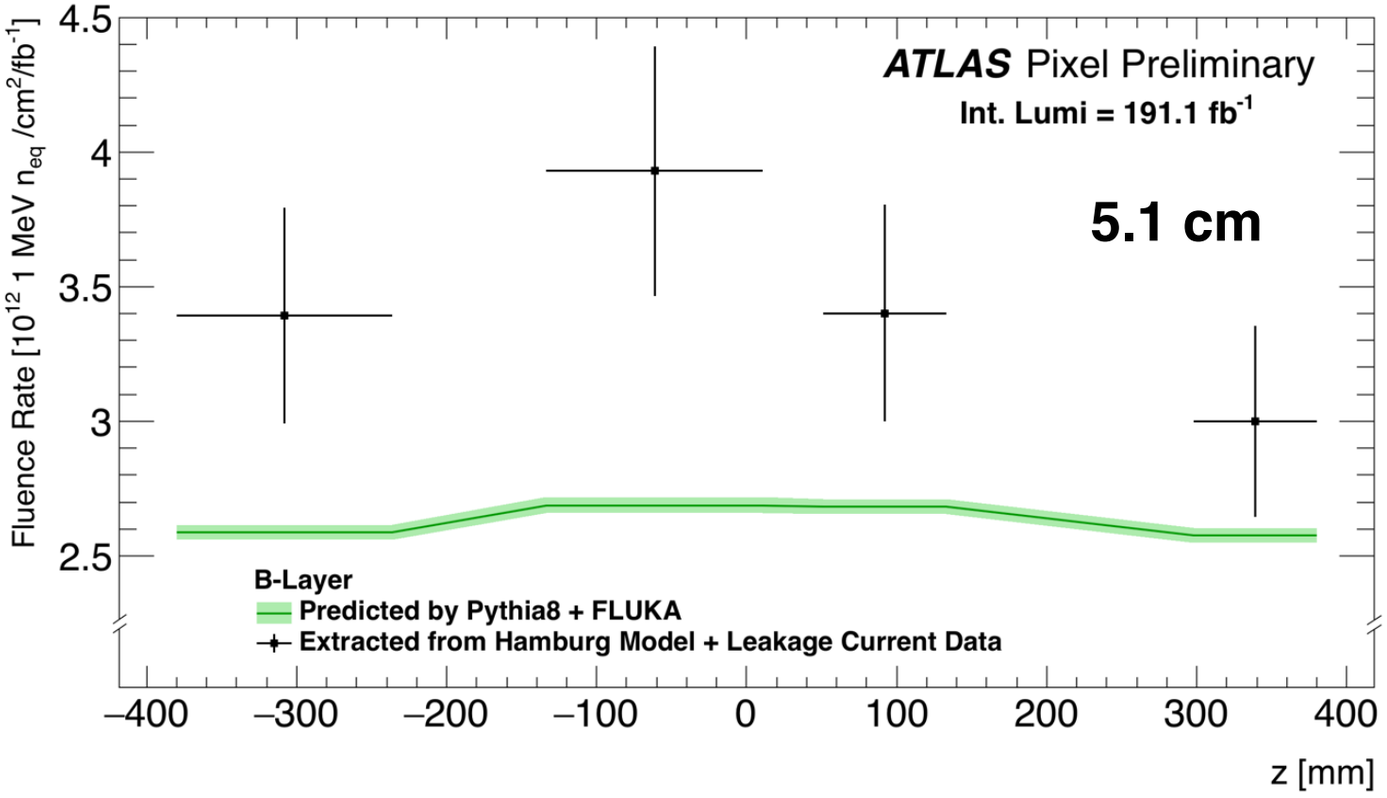
$$\Delta I = (\Phi_{\mathrm{eq}}/L_{\mathrm{int}}) \times V \cdot \sum_{i=1}^{n} L_{\mathrm{int},i} \cdot \left[\alpha_{\mathrm{I}} \exp\left(- \sum_{j=i}^{n} \frac{t_j}{\tau(T_j)} \right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0} \right) \right]$$

This is the largest source of uncertainty from the measurement.

These coefficients are “known” from various laboratory measurements, but there is a hidden & largely unknown damage factor conversion (more on this later).

(you know how many e.g. protons hit your detector, but not their 1 MeV n_{eq}!)

Leakage current data summary

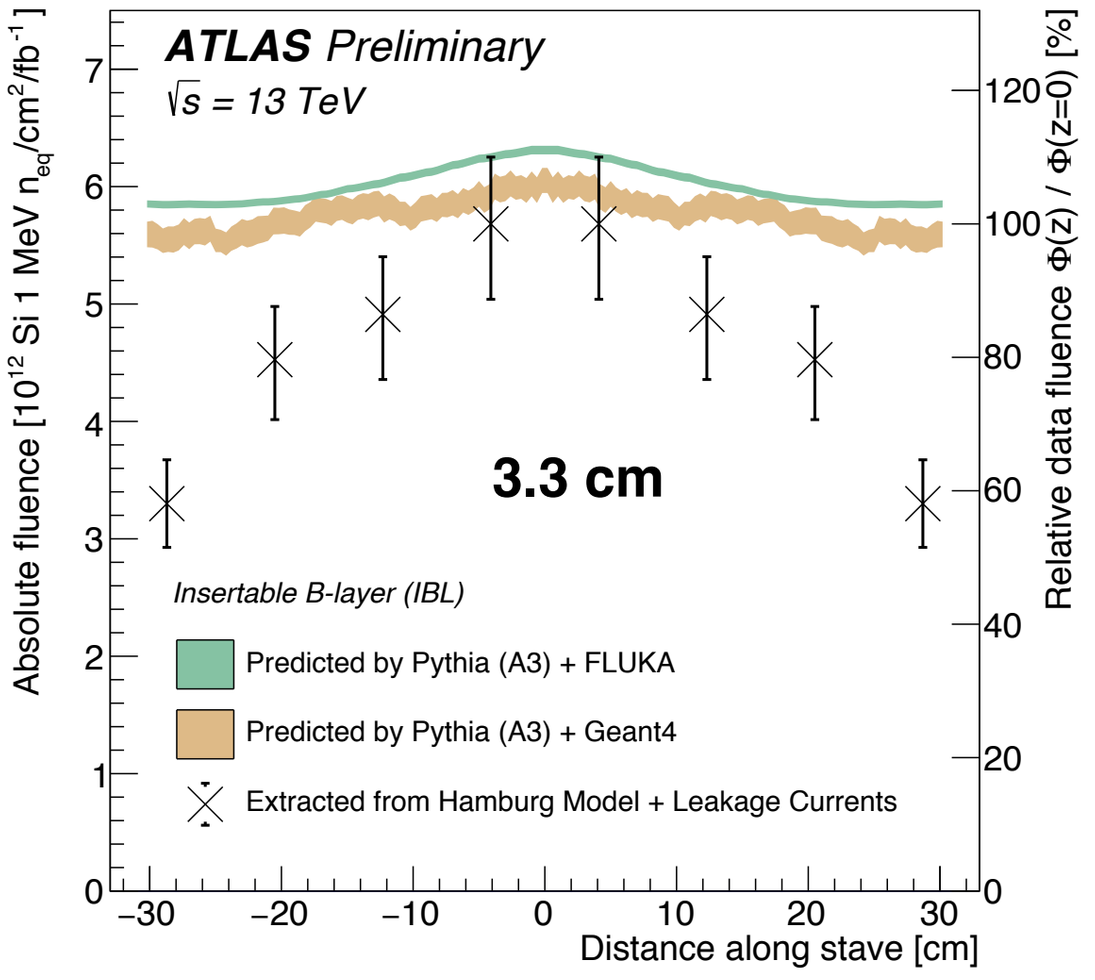


data ~ sim. for innermost

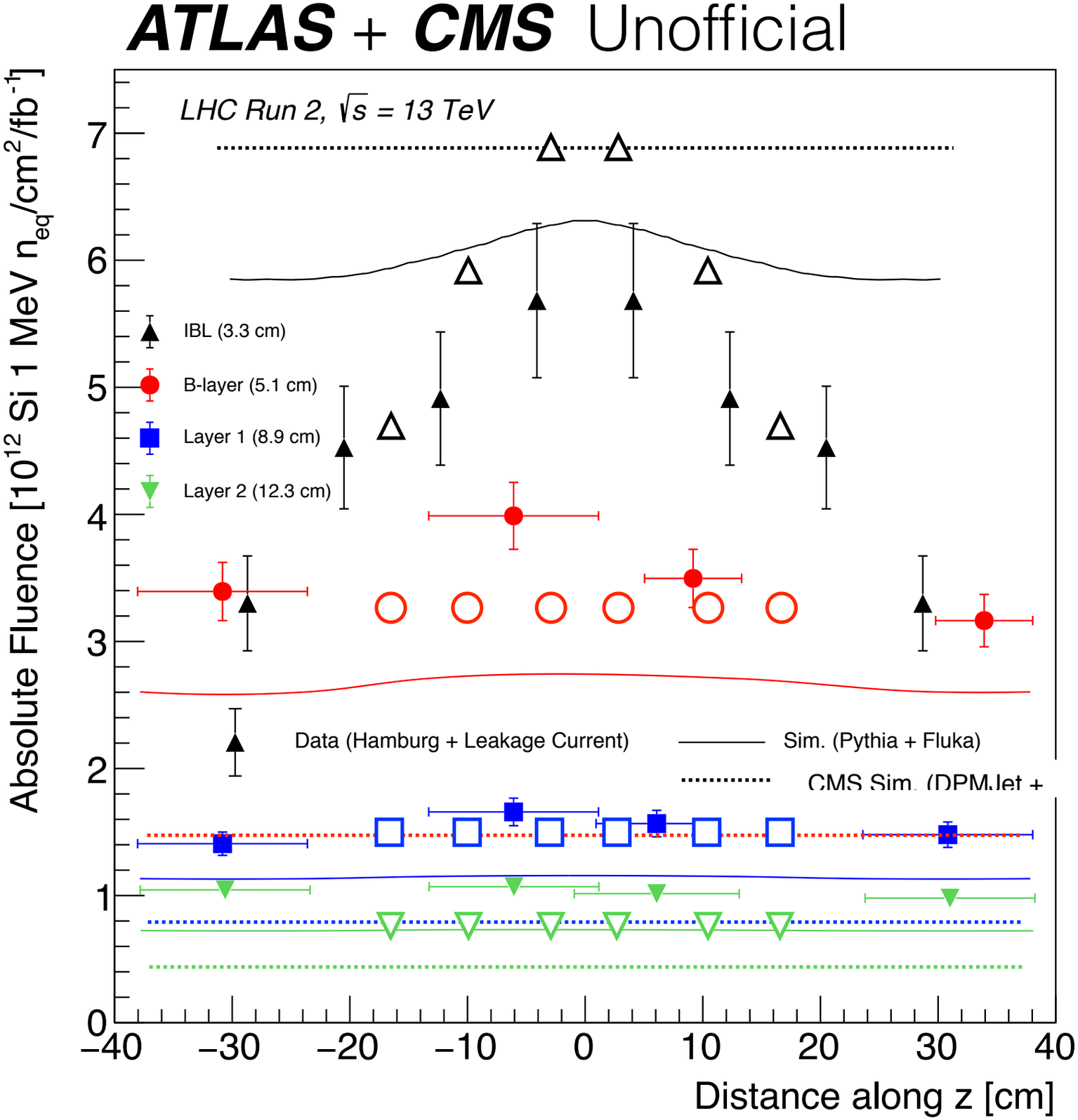
data ~ 1.5 x sim. for other pixels

data ~ sim. for strips

N.B. data > prediction … important to take note for safety factors !



What about CMS?



also seen by CMS!

2nd workshop on radiation effects in the LHC experiments: impact on operation and performance

a post run 2 review, with focus on inner detector systems

11-12 Feb 2019 at CERN: indico.cern.ch/event/769192

Sessions on: sensor measurements & simulations; radiation background simulation & benchmarking; effects on electronics/optoelectronics

Organising Committee: E.Butz (KIT), M.van Beuzekom (Nikhef), J.Buytaert (CERN), M.Bomben (LPNHE), P.Collins (CERN), I.Dawson (Sheffield), S.Mallows (KIT), M.Moll (CERN), A.Mucha (AGH UST), B.Nachman (LBNL), D.Robinson (Cambridge), A.Rozanov (CPPM-IN2P3-CNRS)

ALICE ATLAS EXPERIMENT CMS LHCb RD50

△ CMS layer 1 (2.9 cm)

○ CMS layer 2 (6.8 cm)

□ CMS layer 3 (10.9 cm)

▽ CMS layer 4 (16.0 cm)

Road map

Is it a problem with …?

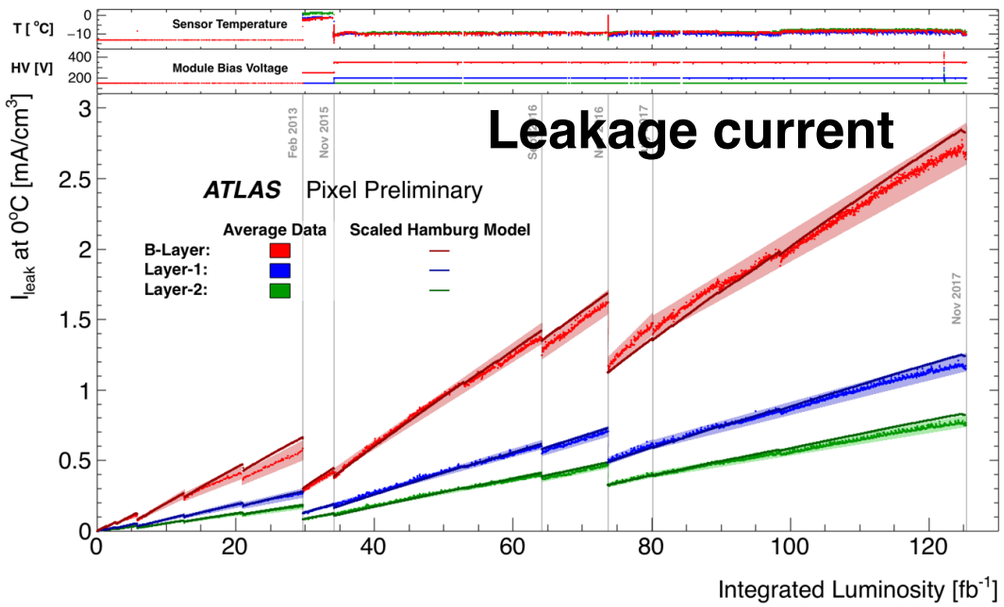
Data

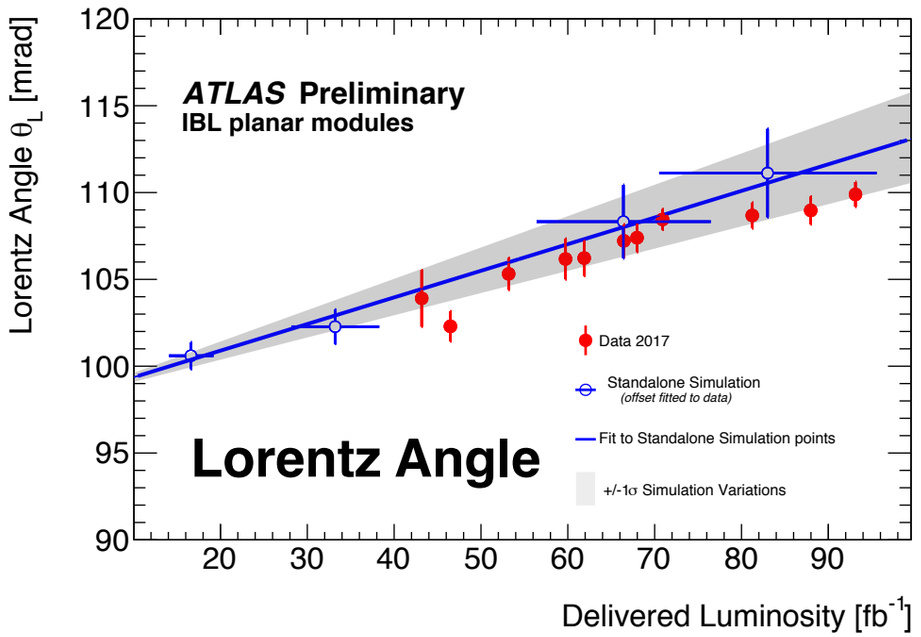
- Method biases
  - Try multiple methods!
- Model biases

Simulation

- Physics modeling
- Transport model
- Damage factors

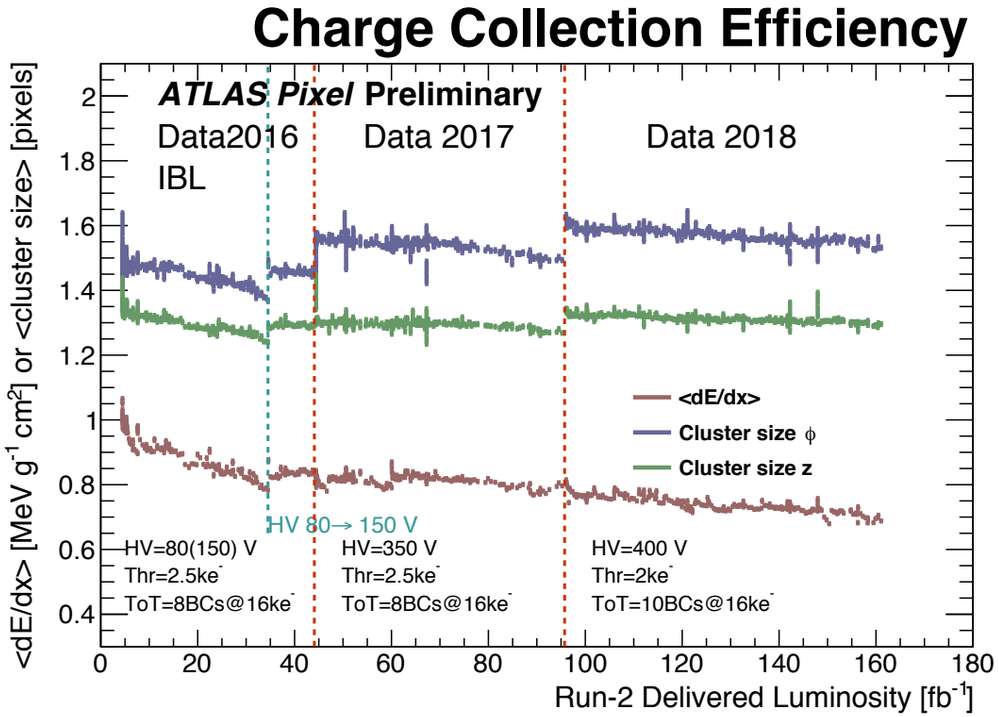
Fluence Measurements

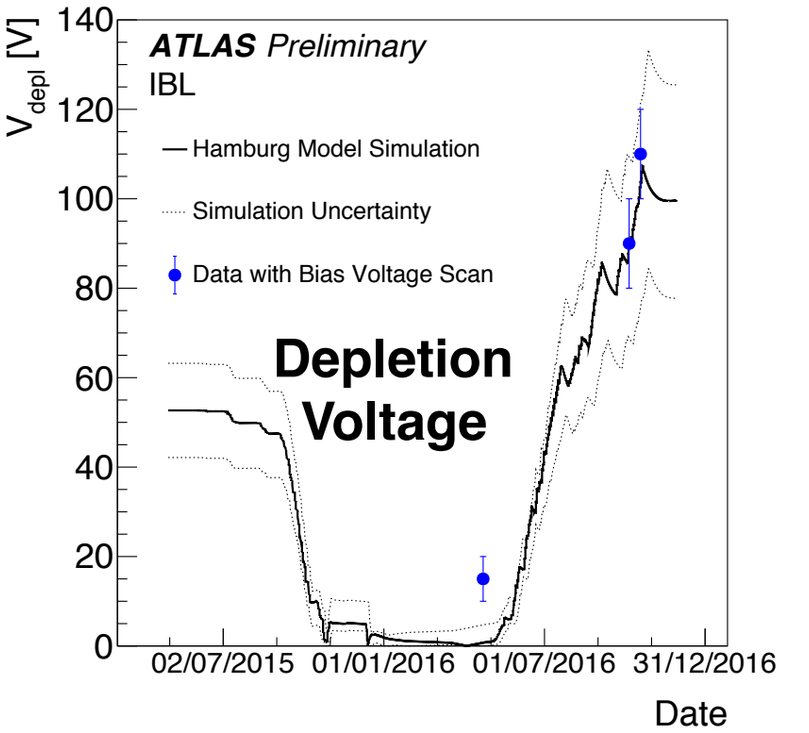




Many sensor properties are proportional to Φ

can use these for calibration and validation

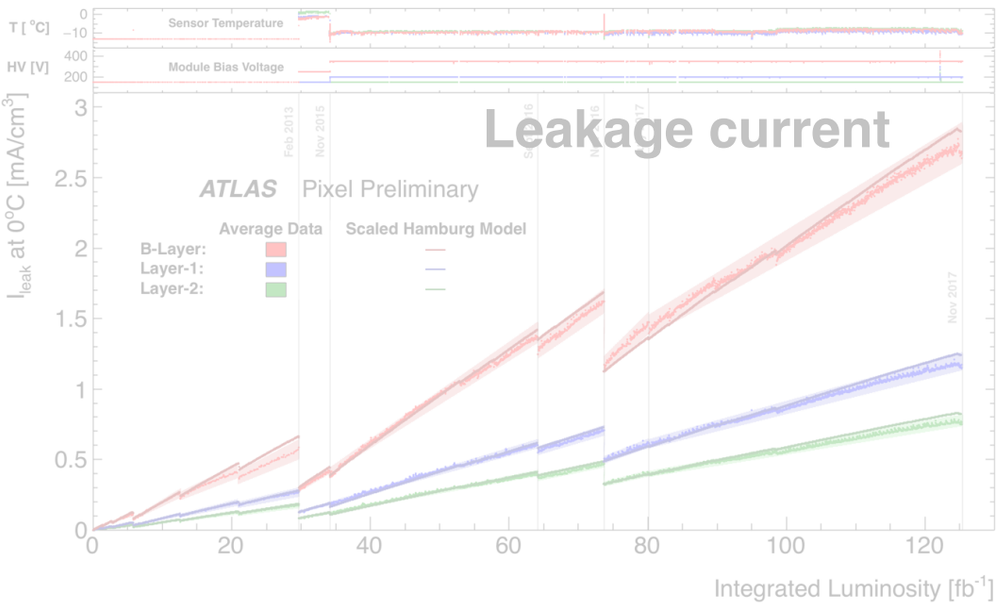


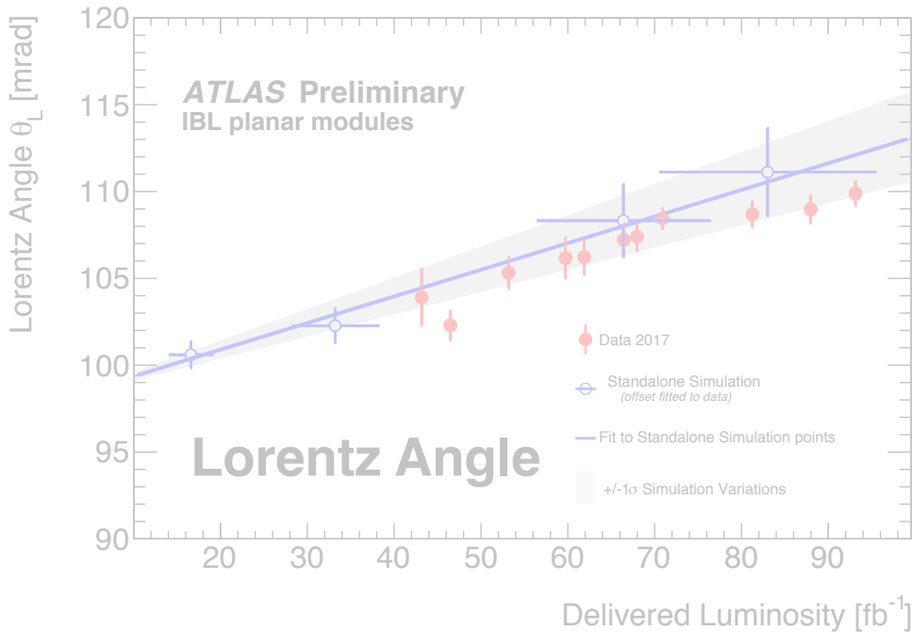


Caution:

Annealing can affect in different ways!

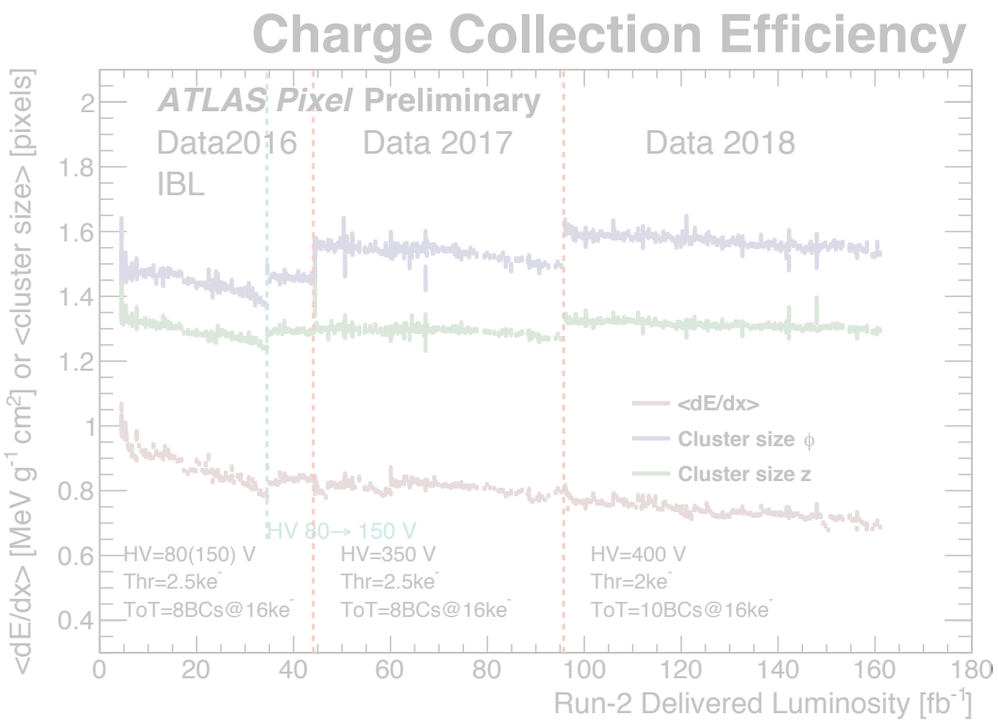
Fluence Measurements

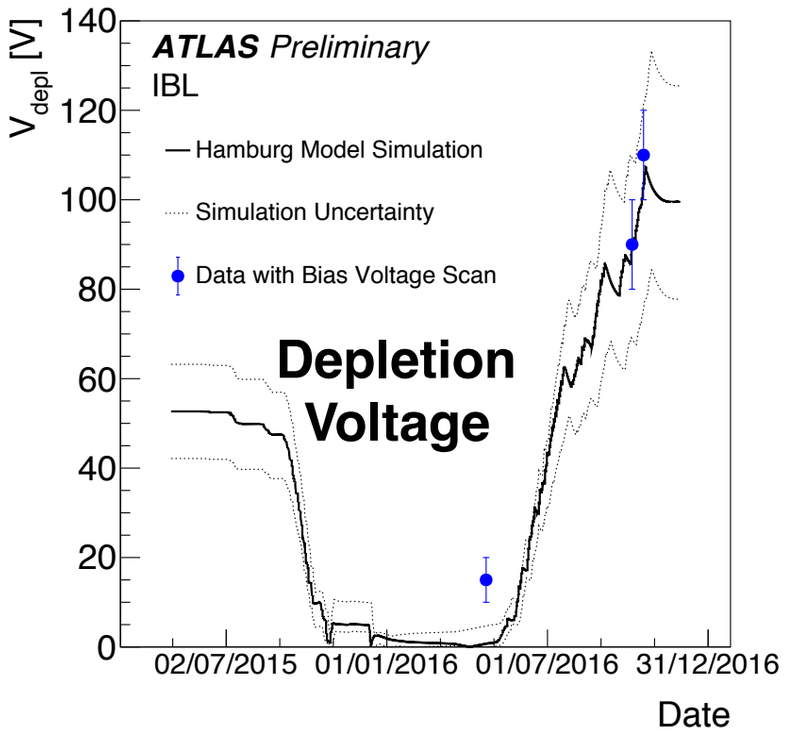




Many sensor properties are proportional to Φ

can use these for calibration and validation





Caution:

Annealing can affect in different ways!

Depletion voltage

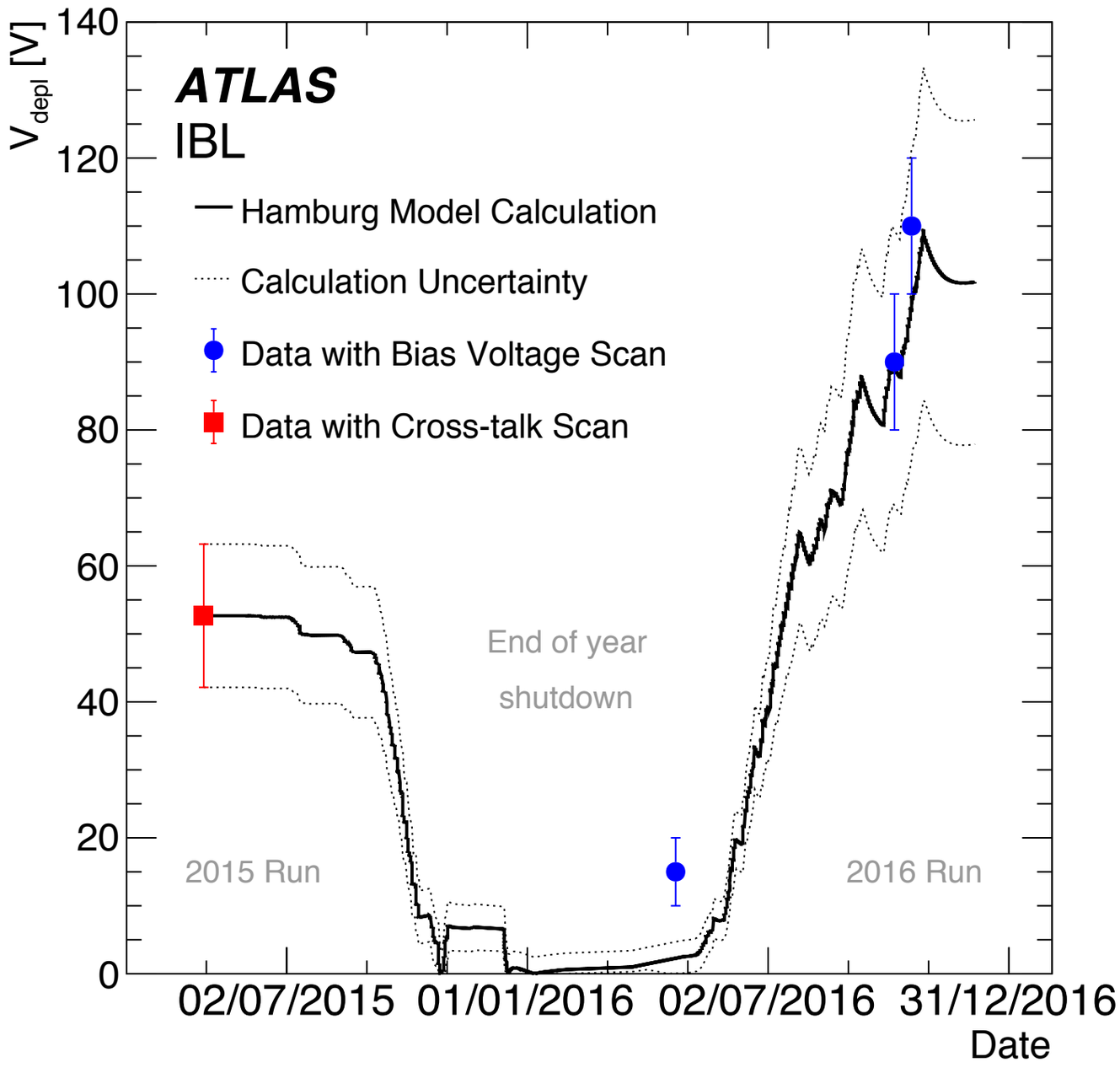
$$V_{\text{dep.}} = |N_{\text{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

$$N_{\text{eff}}(t) = N_0(t) - N_A^{\text{stable}}(t) + N^{\text{annealing}}(t)$$

$$dN_A^{\text{stable}}/dt \propto \Phi(t)$$

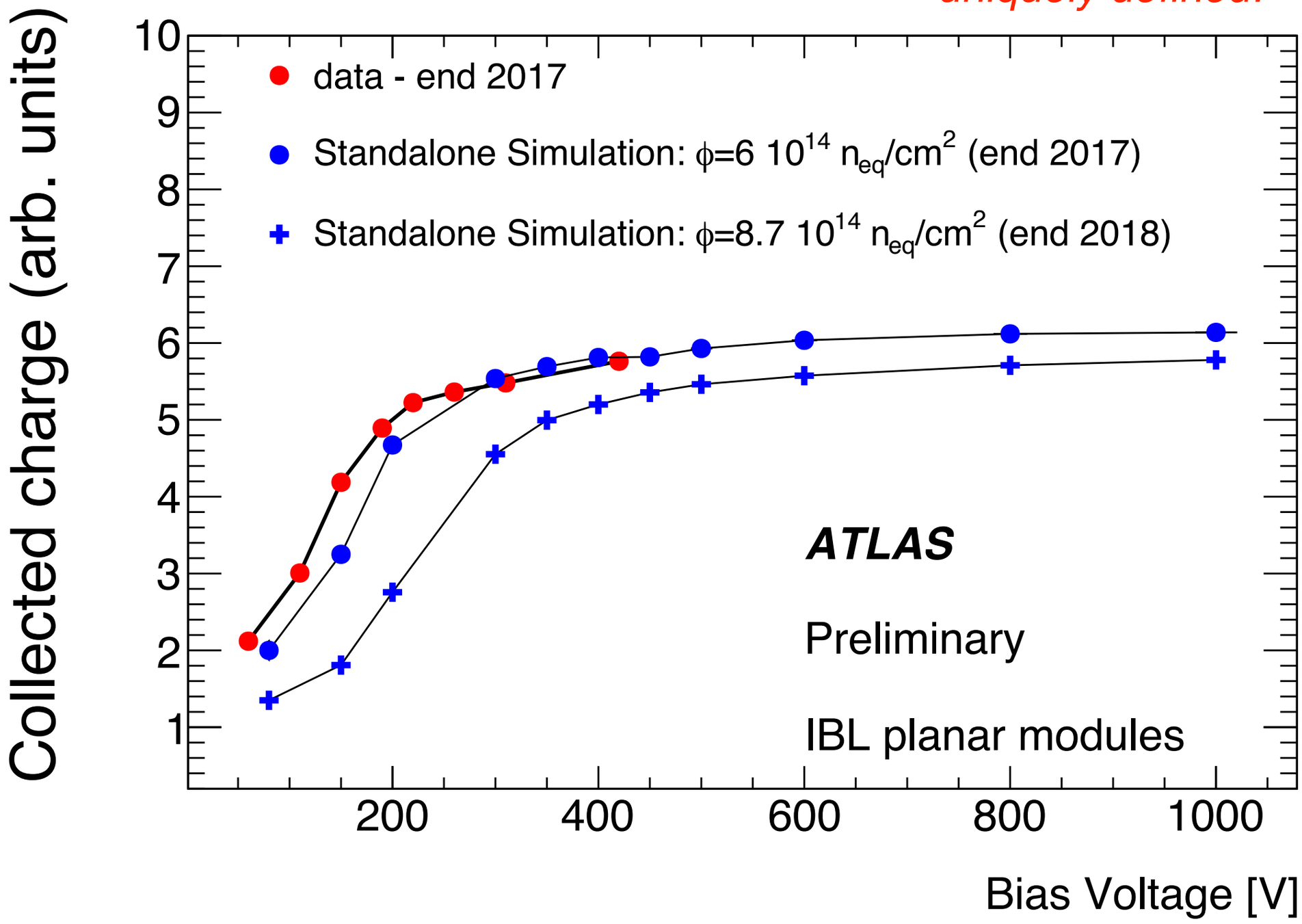
"Hamburg Model"

The depletion voltage is approximately proportional to fluence.

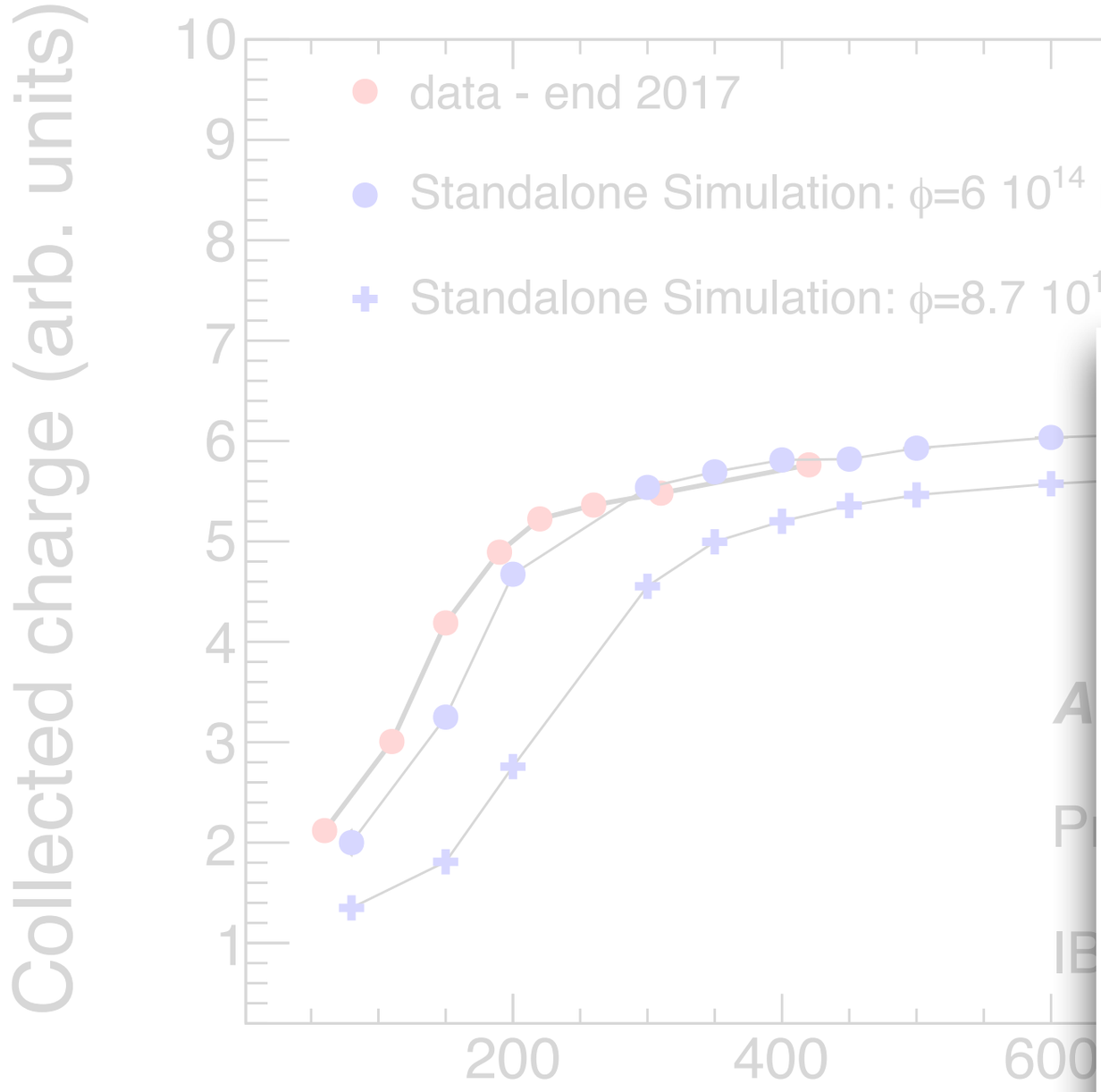


Caveats with depletion voltage

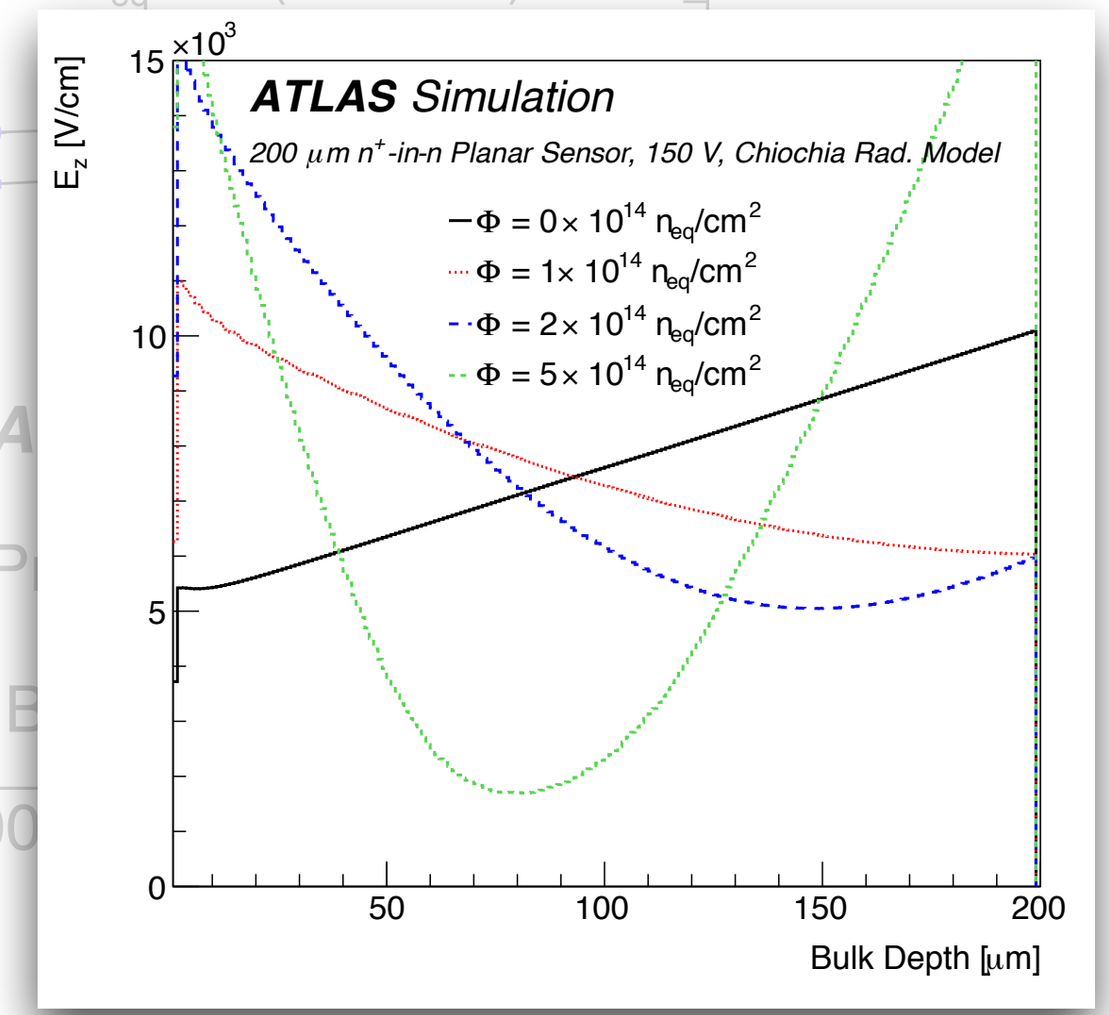
The kink is not uniquely defined!



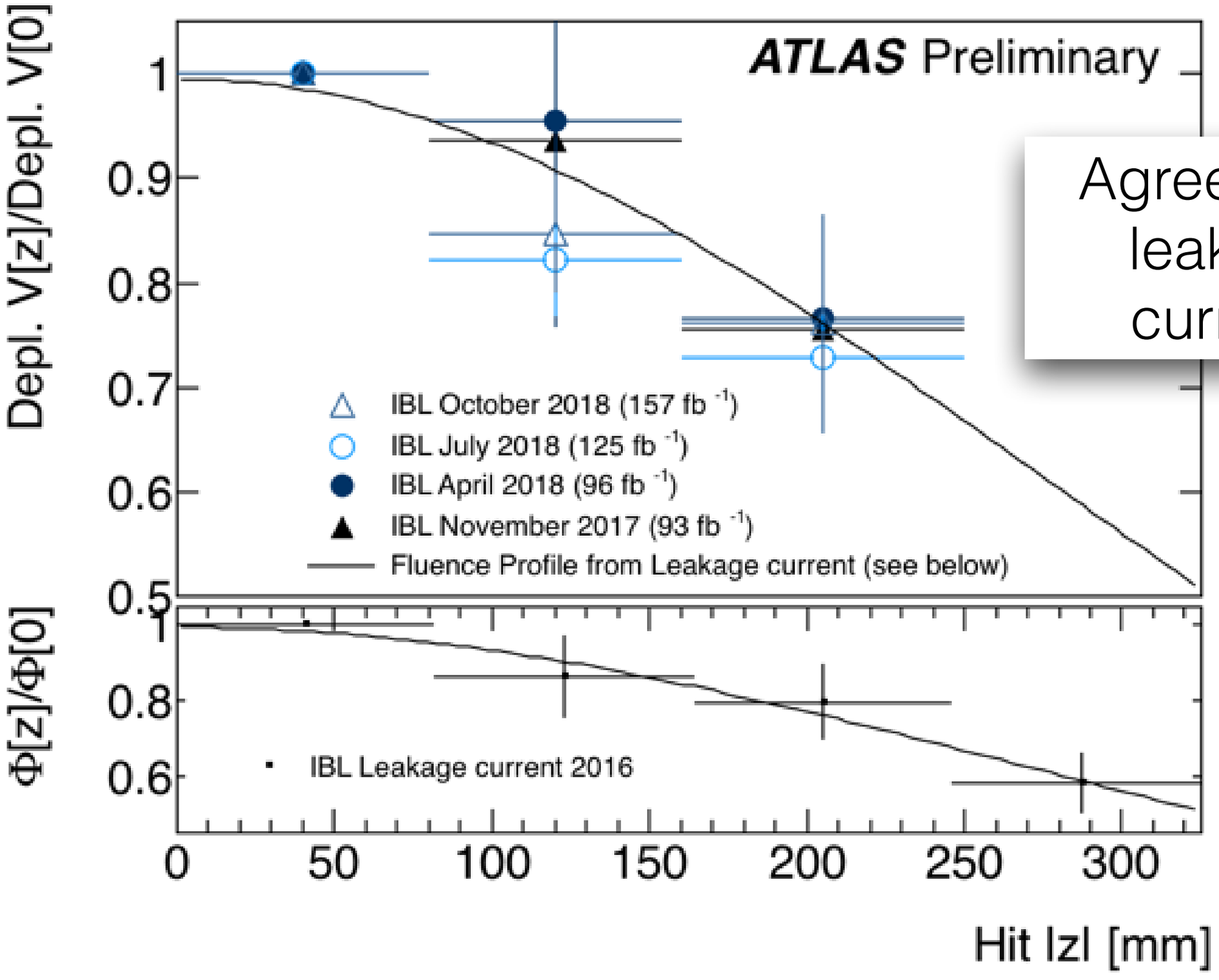
Caveats with depletion voltage



What does full depletion mean for highly irradiated sensors?

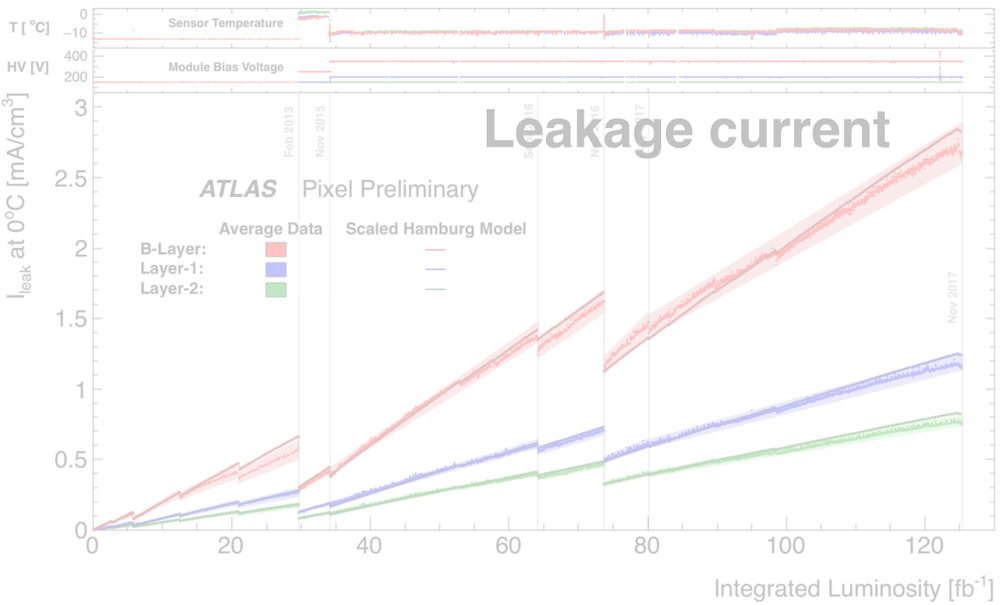


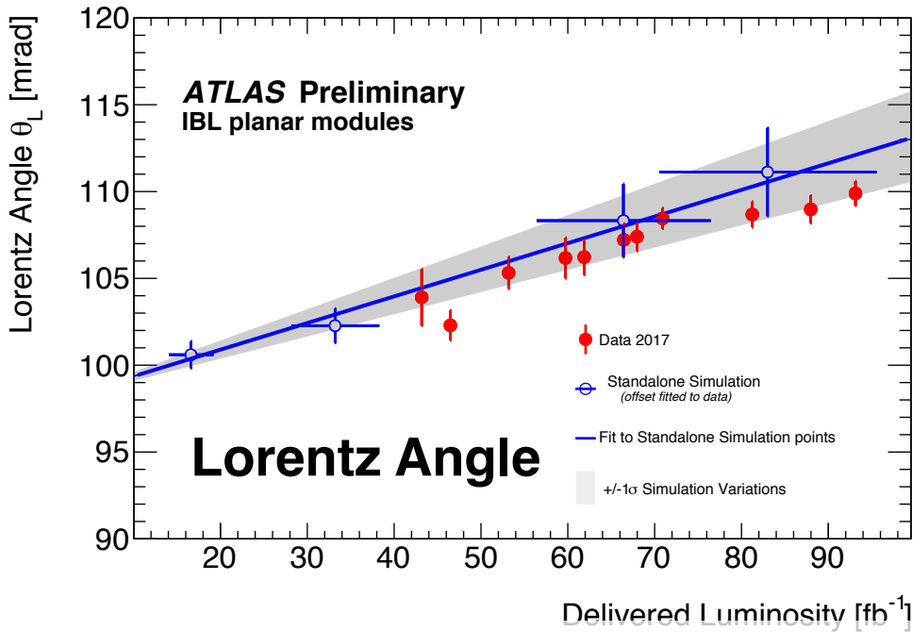
Relative fluence with depletion voltage



Agrees with leakage current!

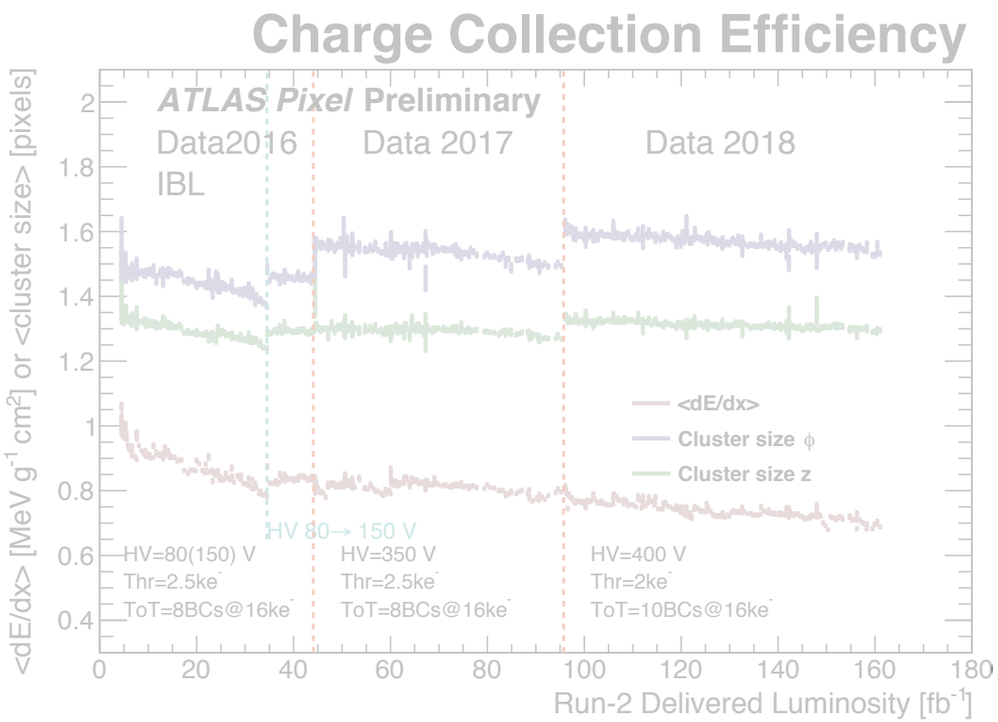
Fluence Measurements

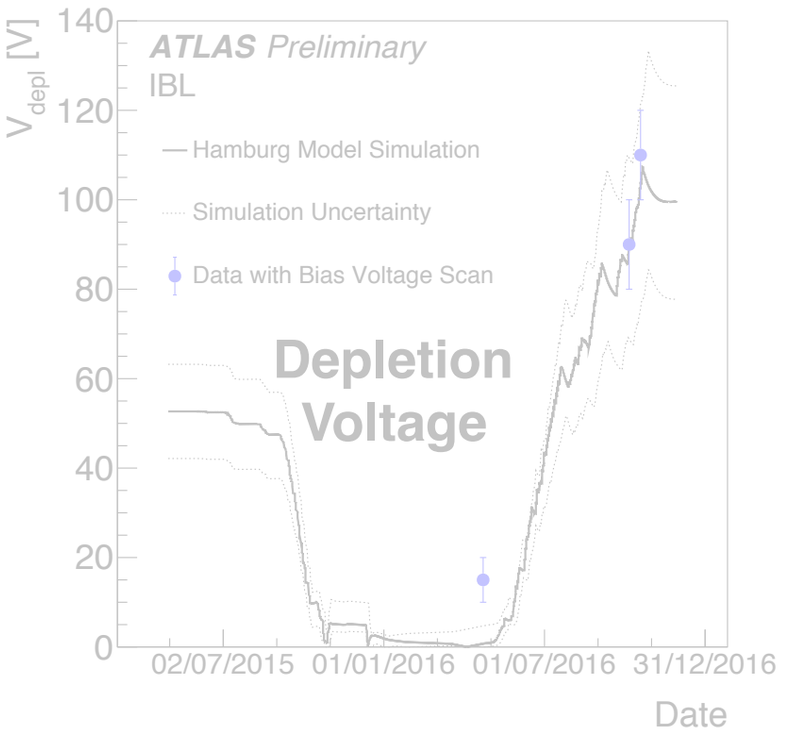




Many sensor properties are proportional to Φ

can use these for calibration and validation

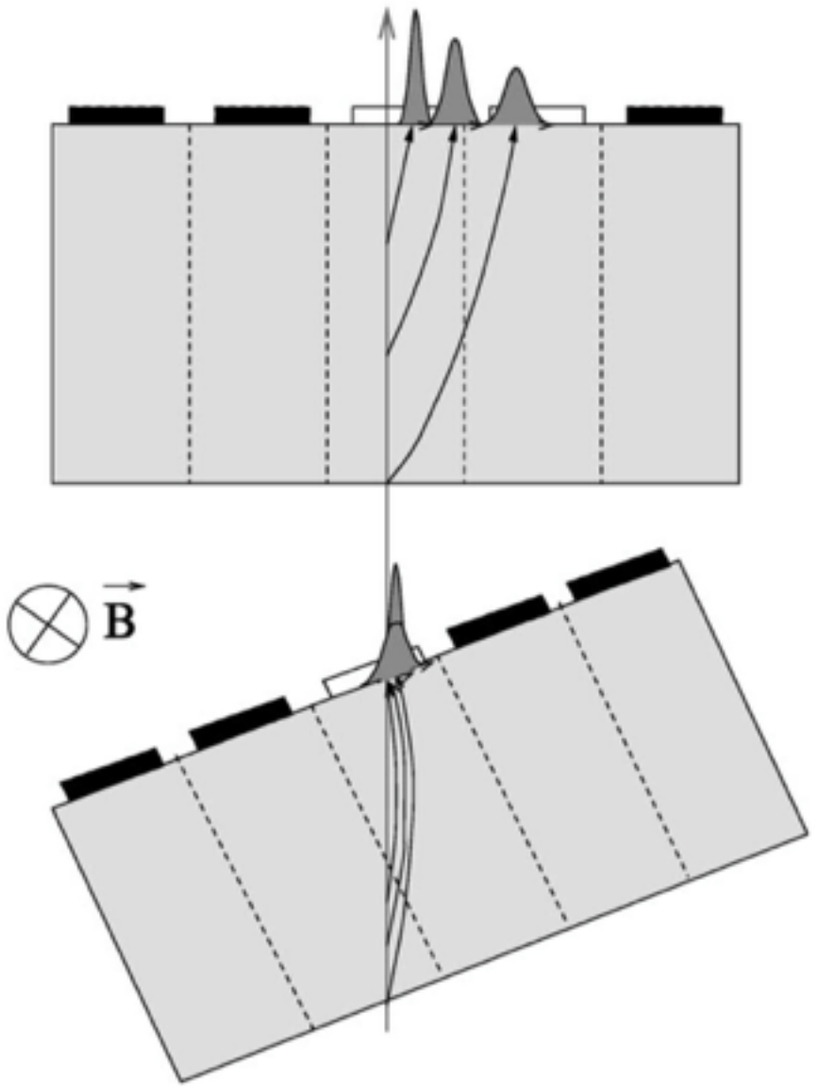




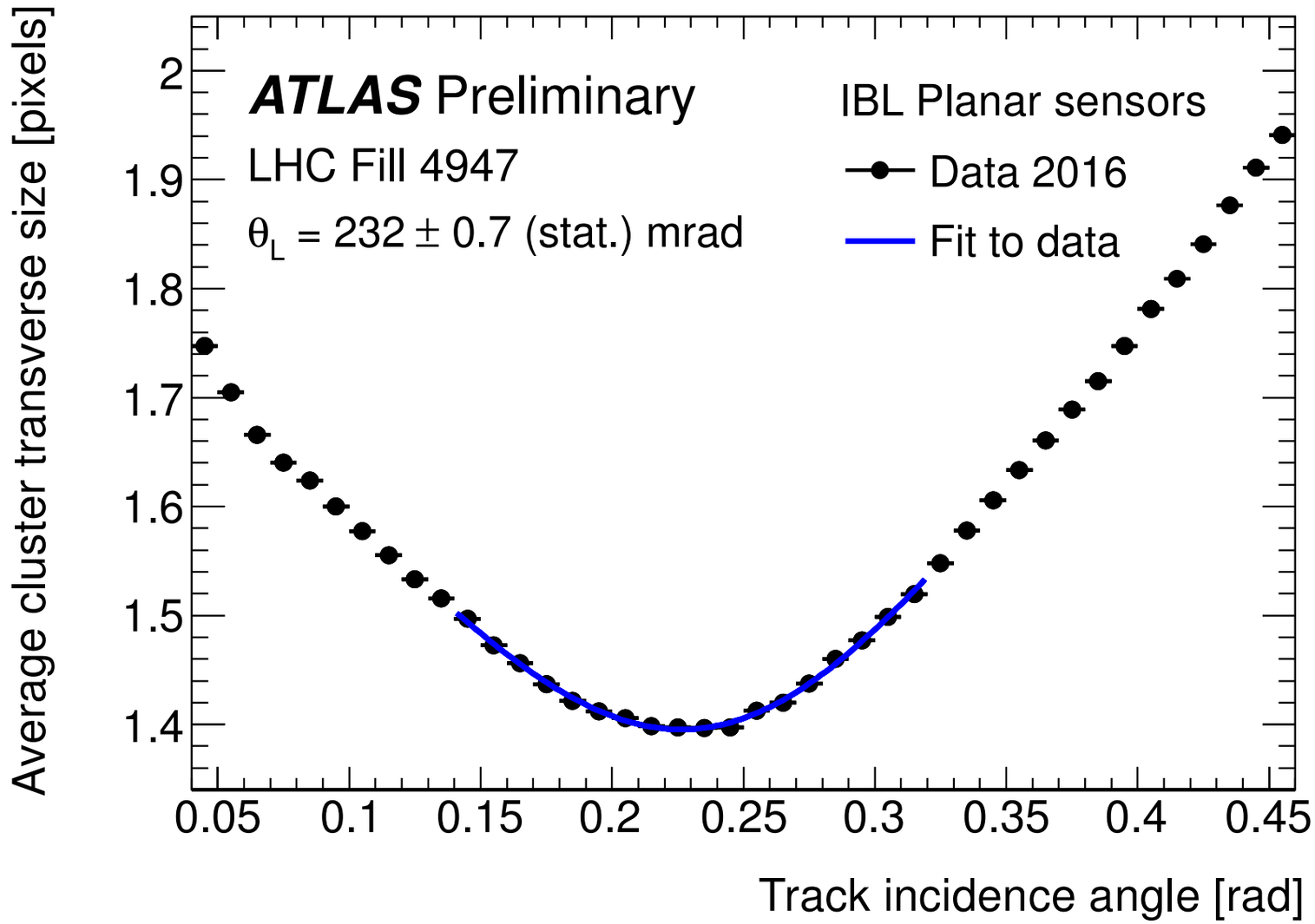
Caution:

Annealing can affect in different ways!

Internal consistency: Lorentz angle



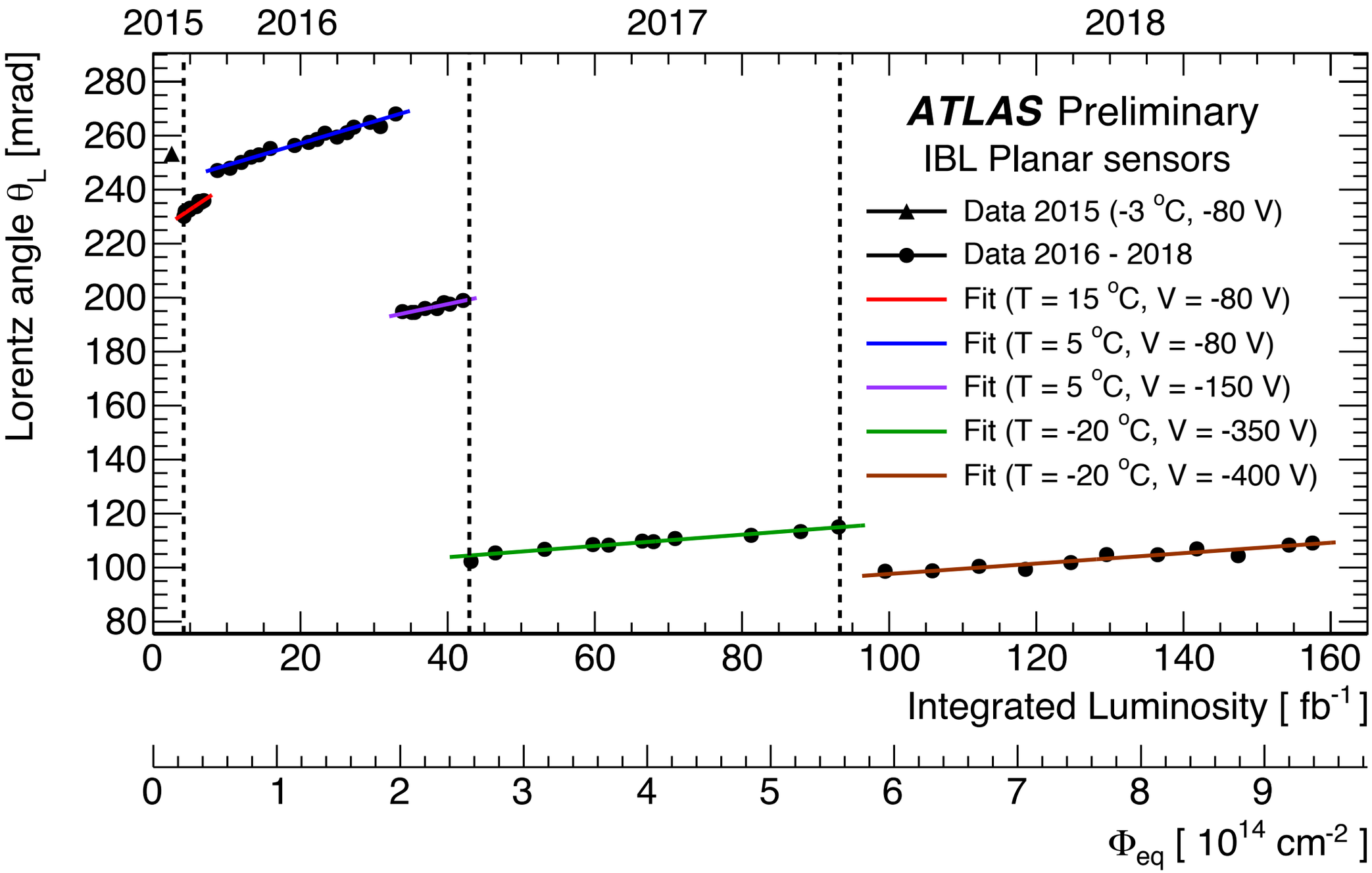
I. Gorelov et al. NIMA (2002)



Since we apply both E and B fields, the charges drift at an angle. The sensors are tilted and there is an angle that minimizes the cluster size.

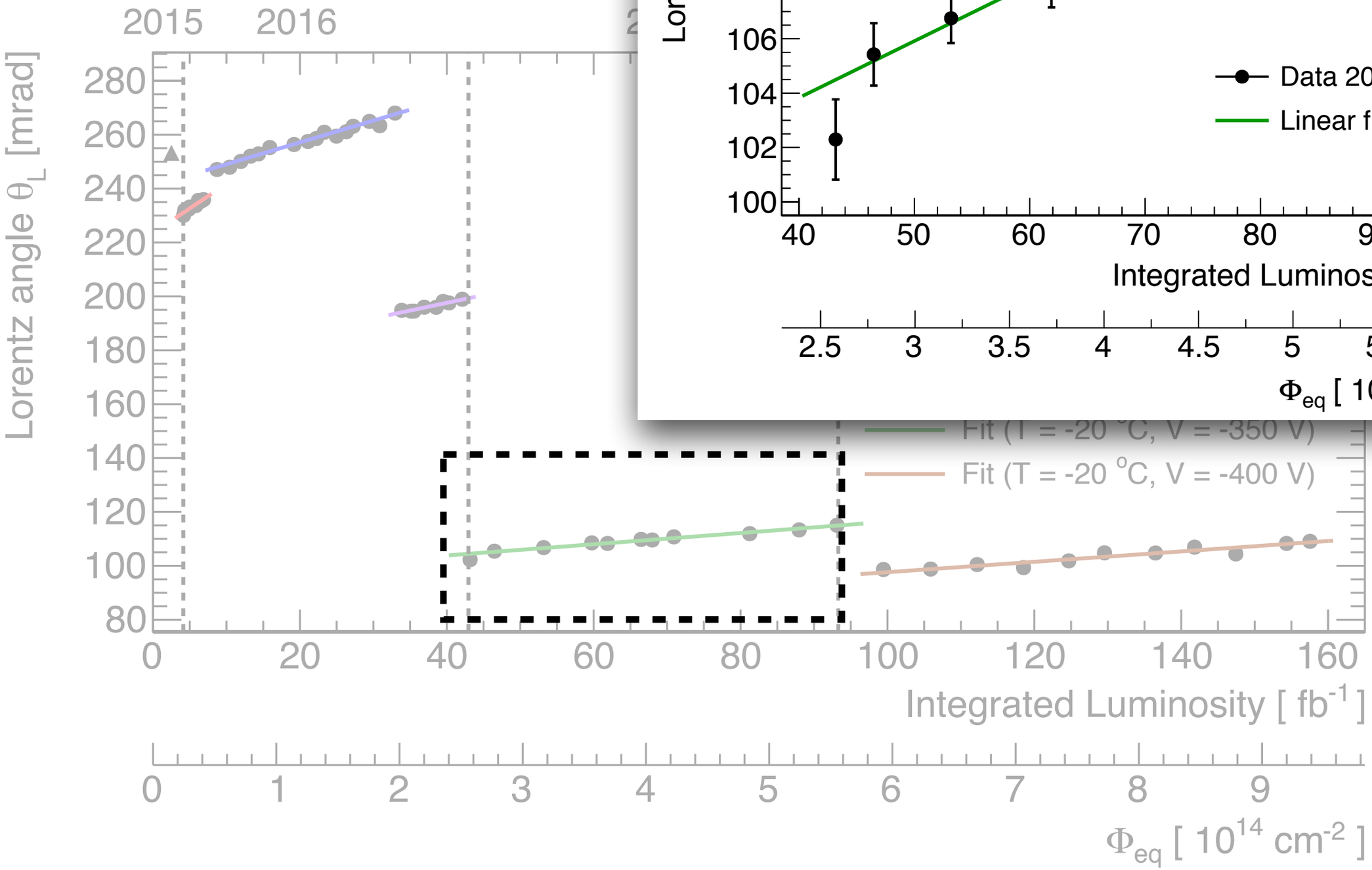
Internal consistency: Lorentz angle

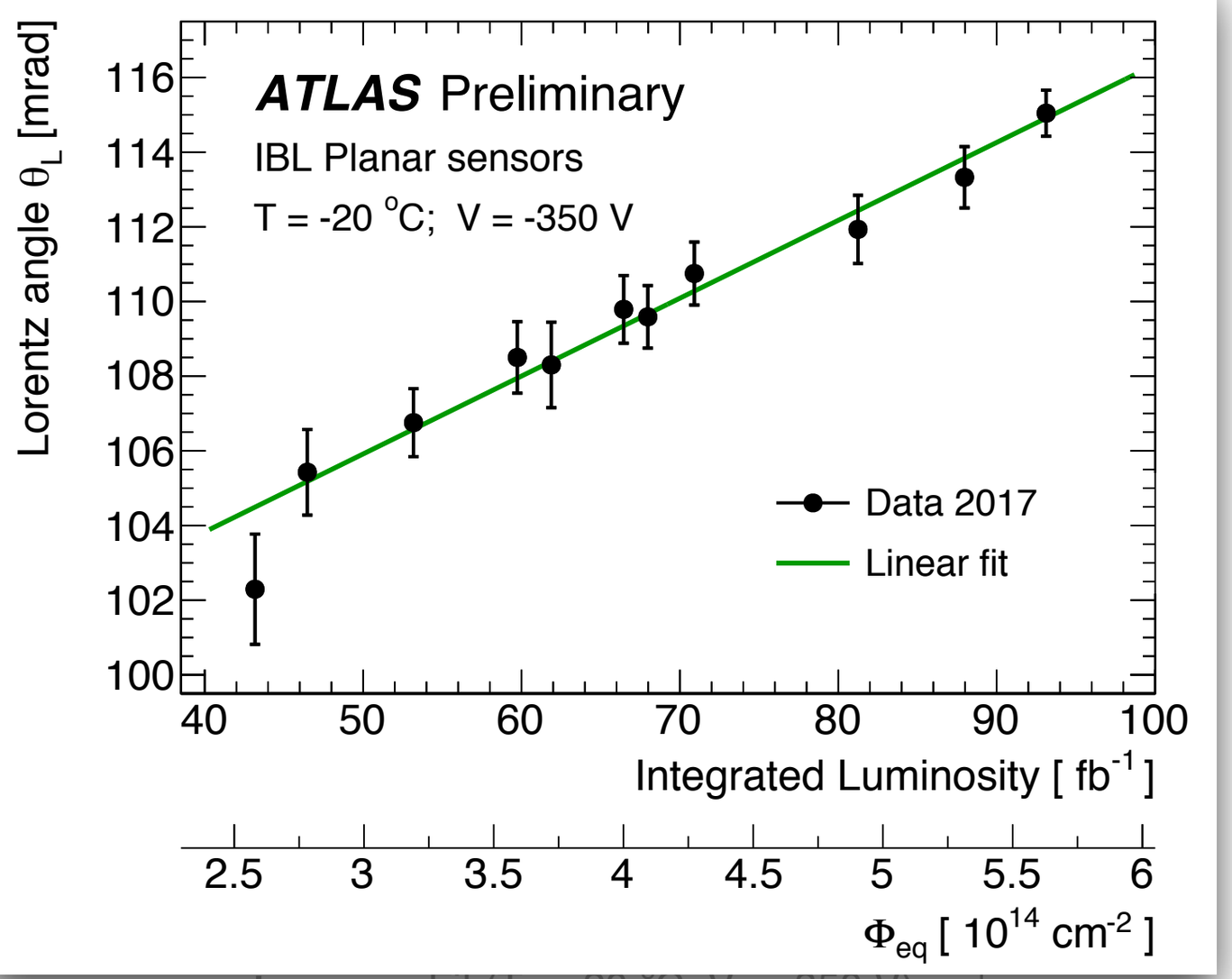
Given temperature, Lorentz angle is proportional to fluence.



Internal consistency:

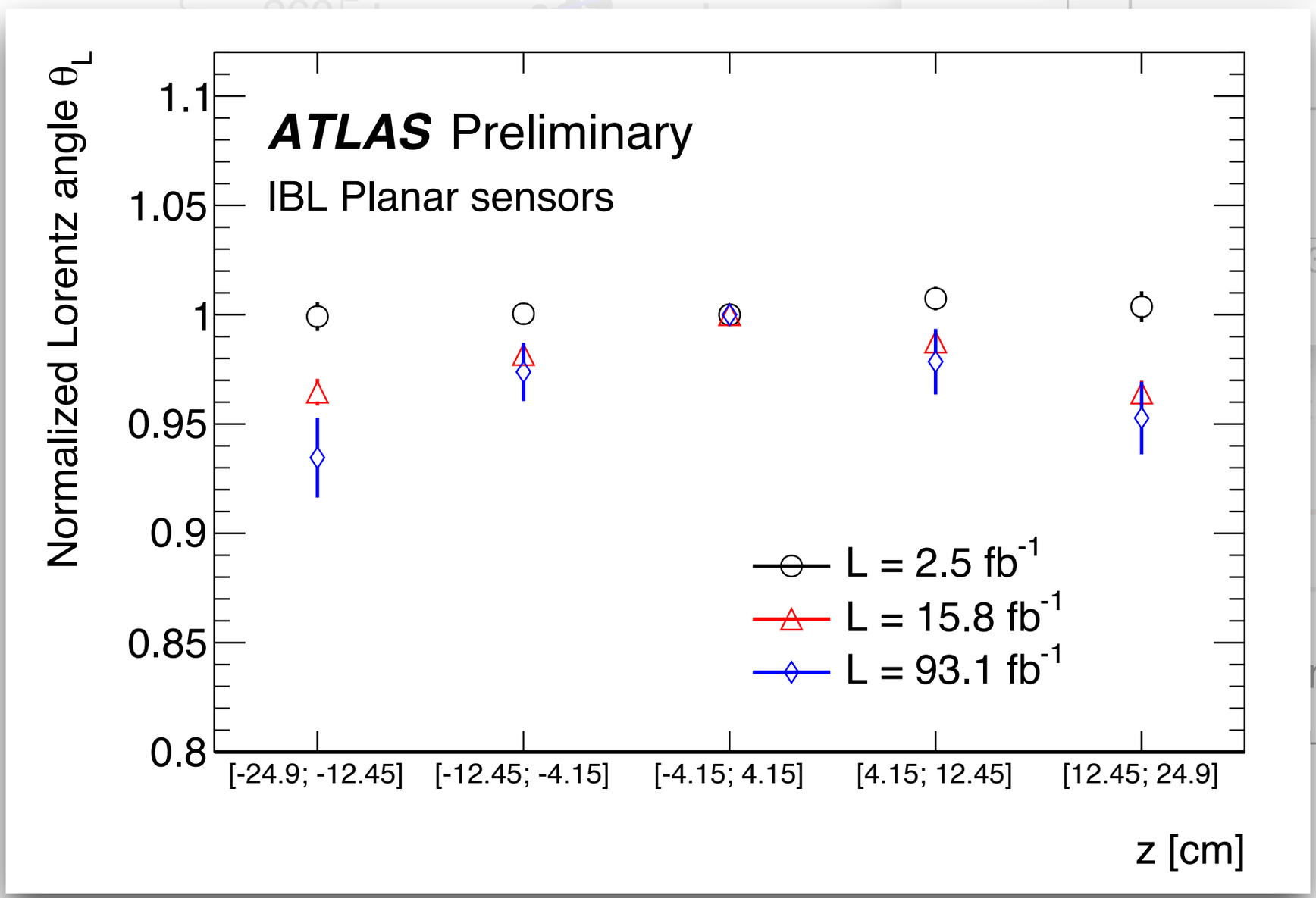
Given temperature, Lorentz

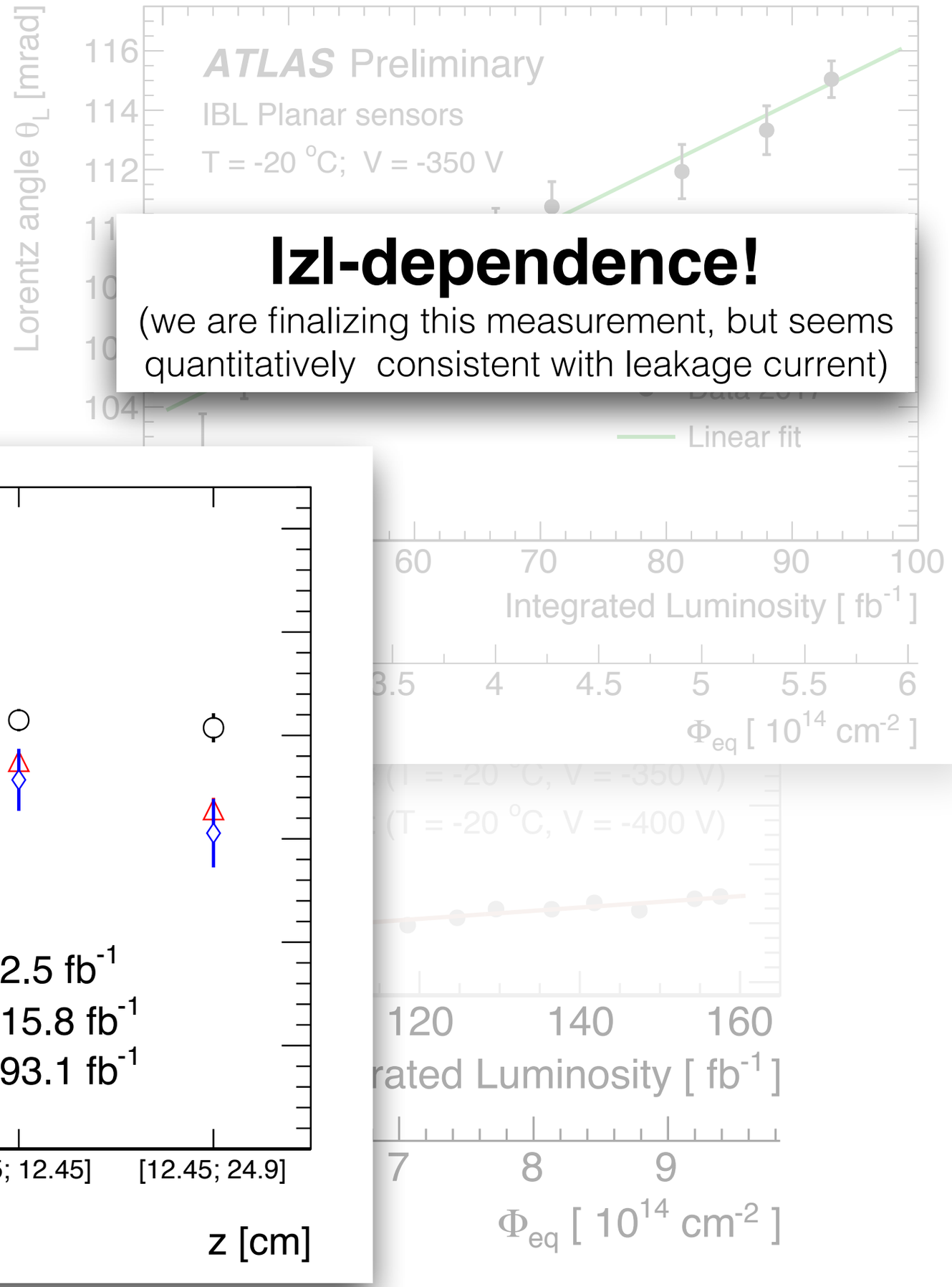




Internal consistency:

Given temperature, Lorentz





|z|-dependence!

(we are finalizing this measurement, but seems quantitatively consistent with leakage current)

Road map

Is it a problem with …?

- **Data**
  - Method biases
    - Try multiple methods!
  - Model biases
- **Simulation**
  - Physics modeling
  - Transport model
  - Damage factors

So the data seem real … maybe the source is on the prediction side?

Predicting the absolute fluence

Physics modeling

Particle multiplicity, energy, composition

↓ *Pythia*

Transport model

Geometry and Particle transport

↓ *FLUKA or Geant4*

Damage factors

Non-ionizing damage

↓ *RD50 damage factors*

Predicted Φ

Caution:

Tuned to data, but still significant uncertainty (PDFs, MEs, frag., etc.)

Caution:

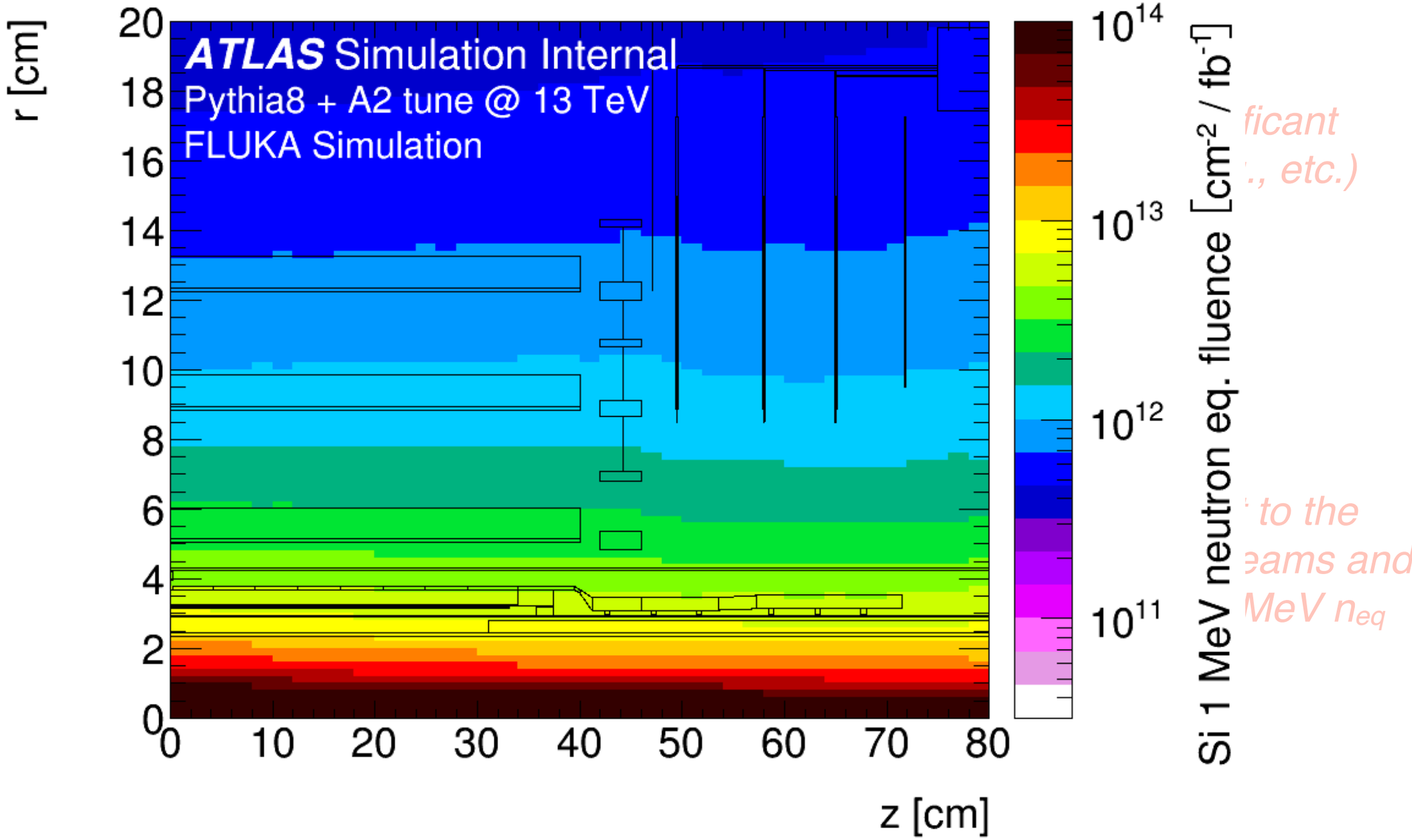
Largely unknown due in part to the availability of monochromatic beams and uncertainty in converting to 1 MeV n_{eq}

Predicting the absolute fluence

Phys
mode

Trans
mod

Dama
facto



ficant
., etc.)

to the
eams and
MeV n_{eq}

Road map

Is it a problem with …?

Data

Method biases

Model biases

Try multiple methods!

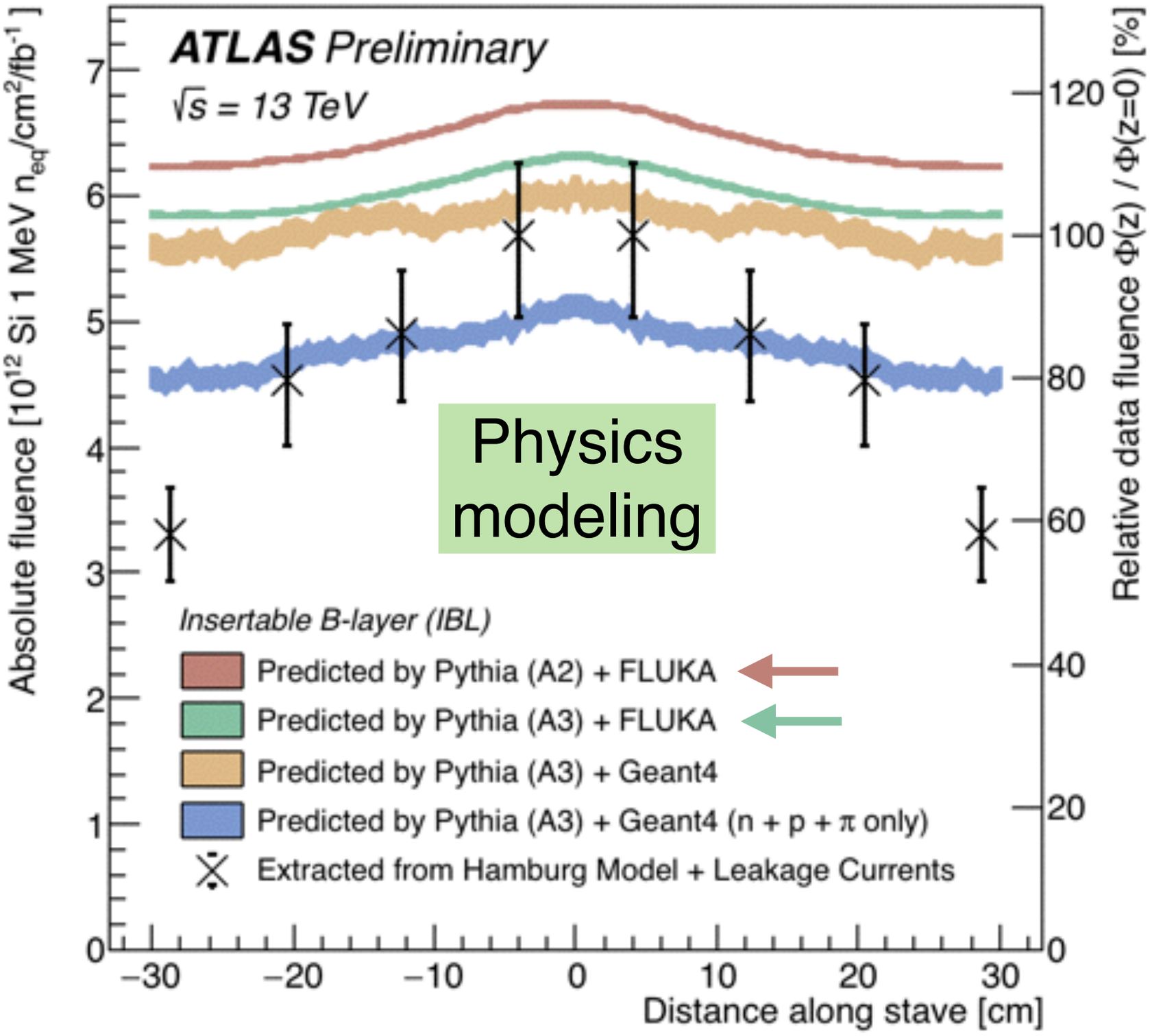
Simulation

Physics modeling

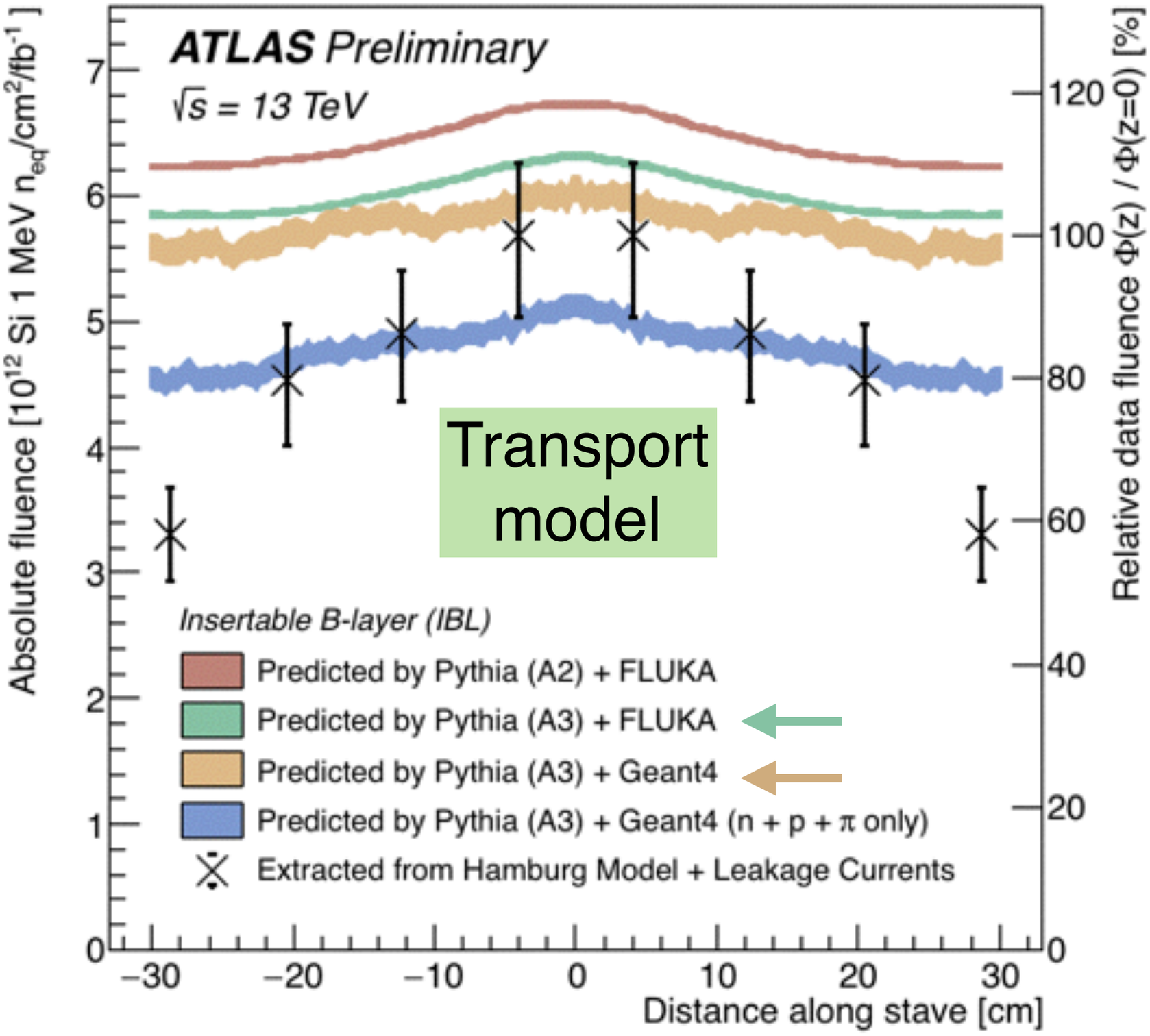
Transport model

Damage factors

Comparing to Simulations



Comparing to Simulations



Road map

Is it a problem with …?

- **Data**
  - Method biases
    - Try multiple methods!
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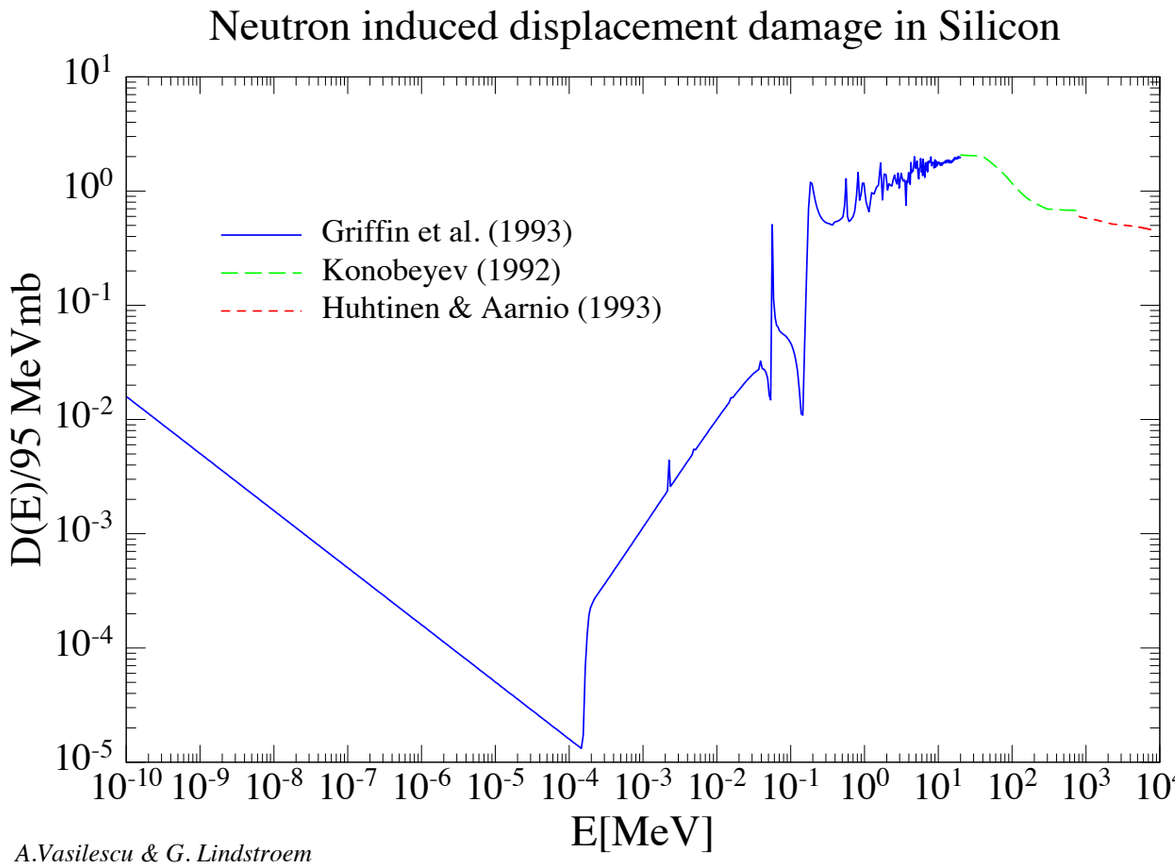
- **Simulation**
  - Physics modeling
  - Transport model
  - Damage factors

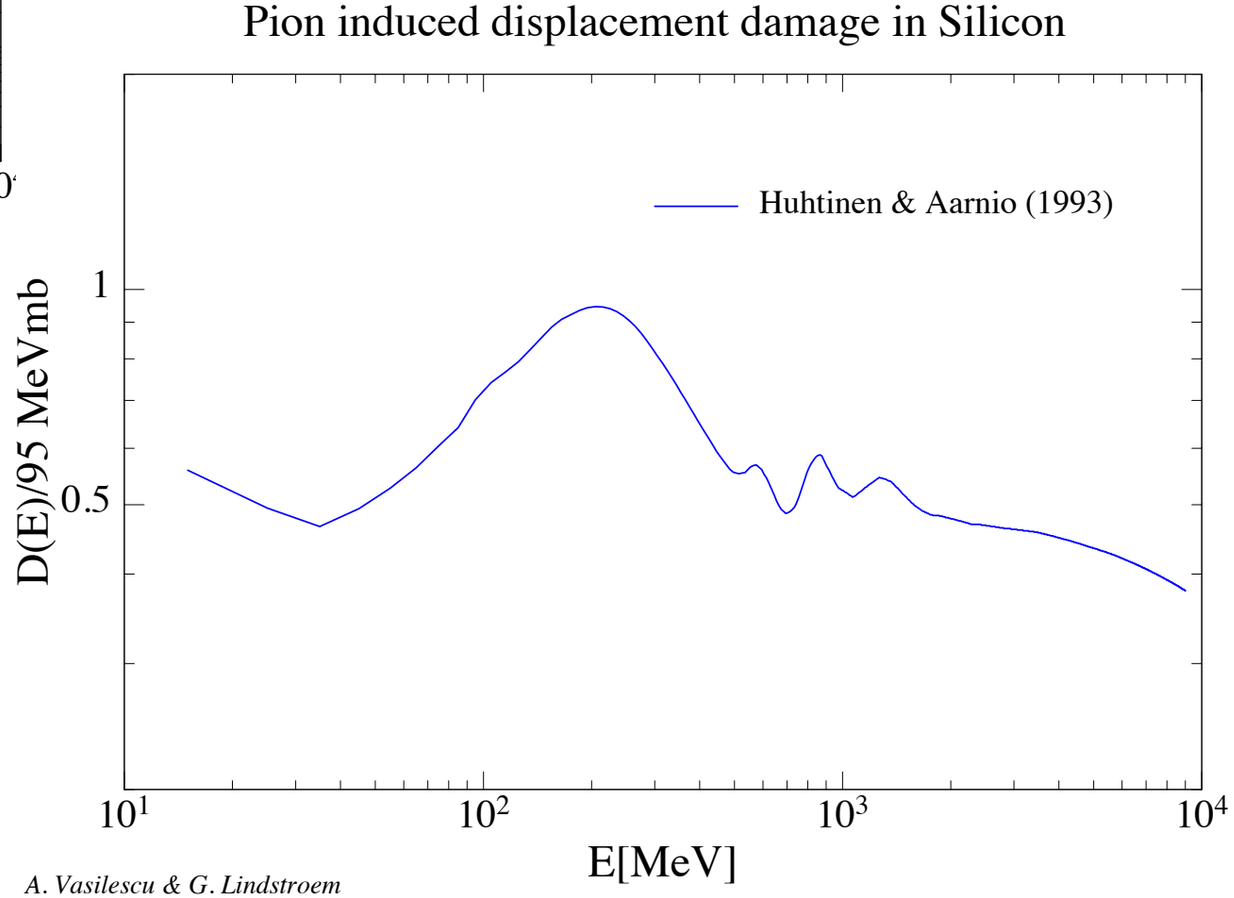
Damage factors



A.Vasilescu & G. Lindstroem

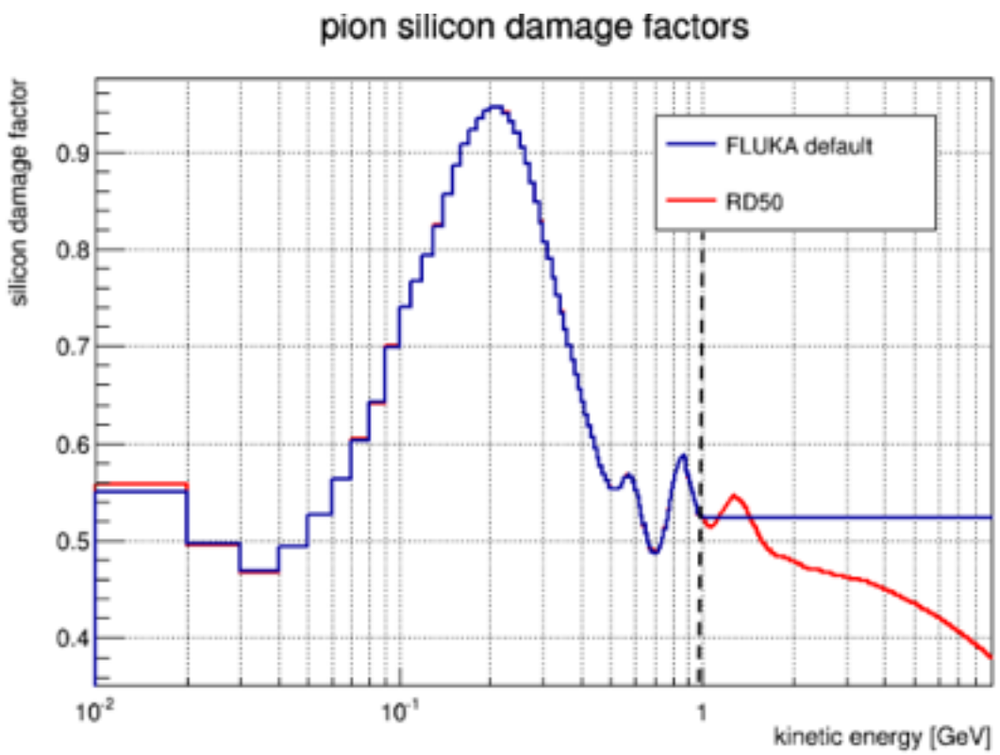
Community repository of damage factors:

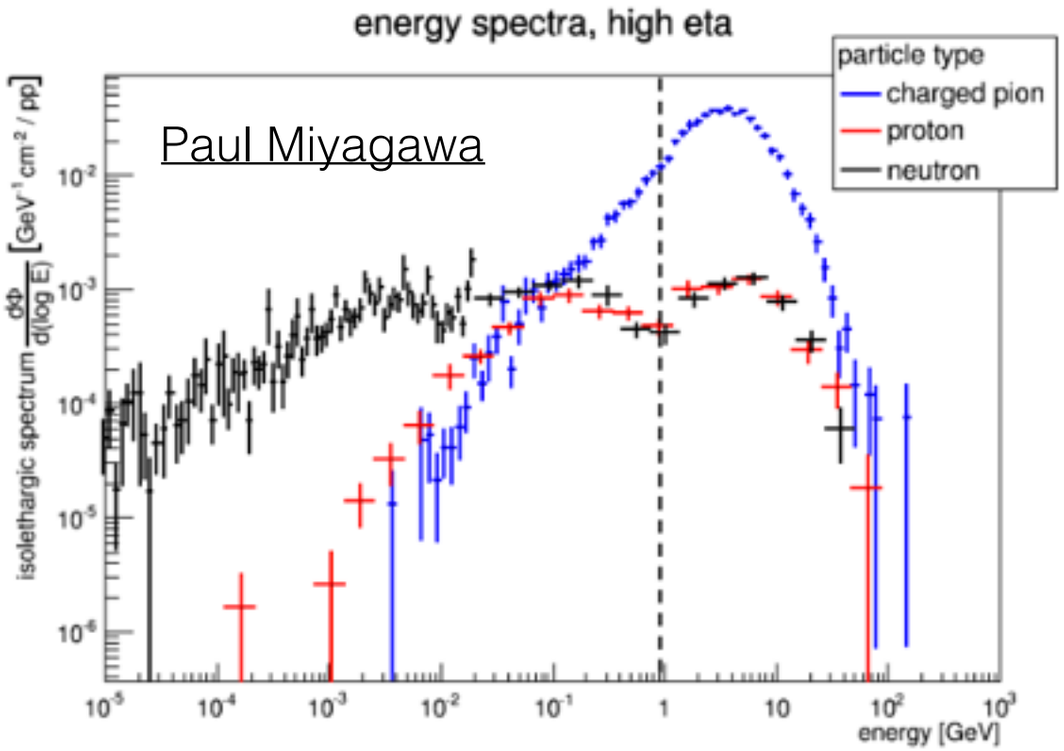
rd50.web.cern.ch/rd50/NIEL



A. Vasilescu & G. Lindstroem

…and now the caveats





Not all transport codes use the full range of damage factors.

Here is a 10% effect from truncating the pion damage factors

(no, it does not induce a 50% shift for the IBL fluence at high |z|!)

Damage factors

IBL damage with uncertainties

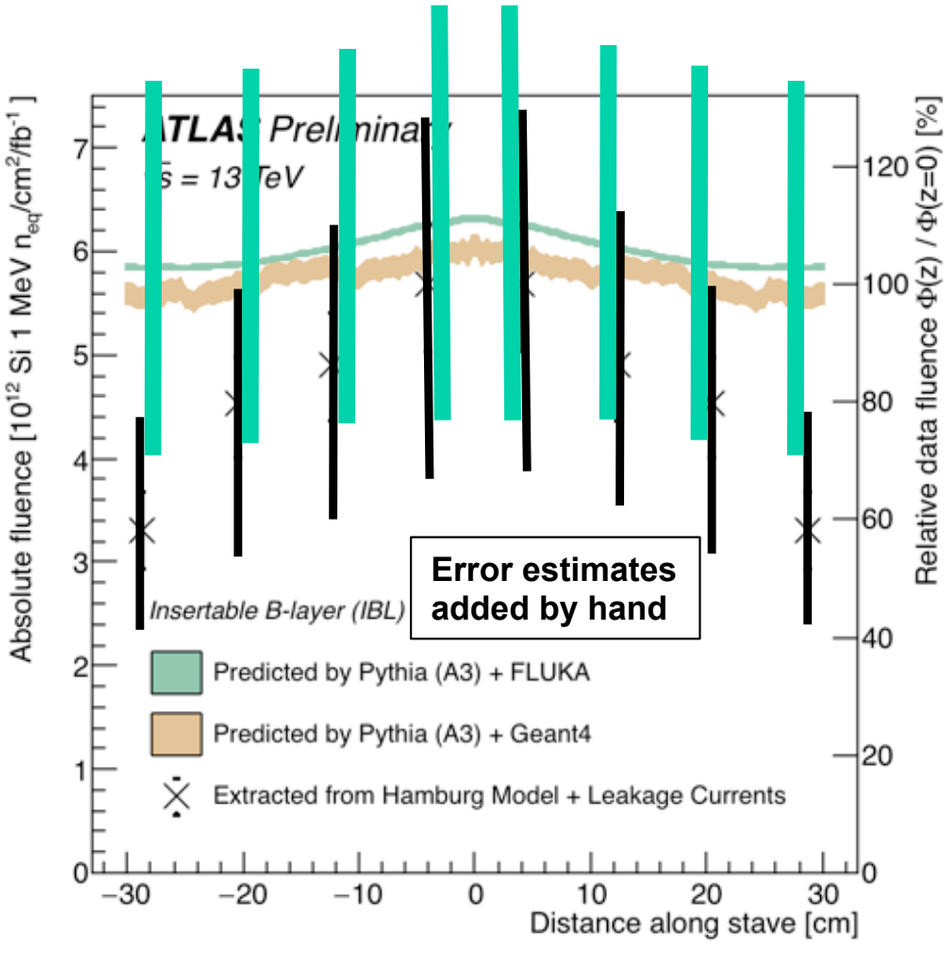
Now, let's look again at the ATLAS IBL damage prediction vs data plot:

Both simulations use the RD50 damage constants.

- **about 60% of the damage is due to pions**
- **these pion damage constants have ~30%, mostly correlated, uncertainty**
- **Kaon damage (~15%) is pure guess**

The measured leakage current is translated to 1 MeV n Eq. Φ using an α measured in some neutron spectrum, folded with the (RD50) neutron damage curve

- **these also have ~30%, fully correlated, uncertainty**



→ the comparison suggests a difference in z-dependence, but it is inconclusive if the center is underestimated or the large-z region overestimated, or both

Road map

Is it a problem with …?

- **Data**
  - Method biases
    - Try multiple methods!
  - Model biases
- **Simulation**
  - Physics modeling
  - Transport model
  - Damage factors

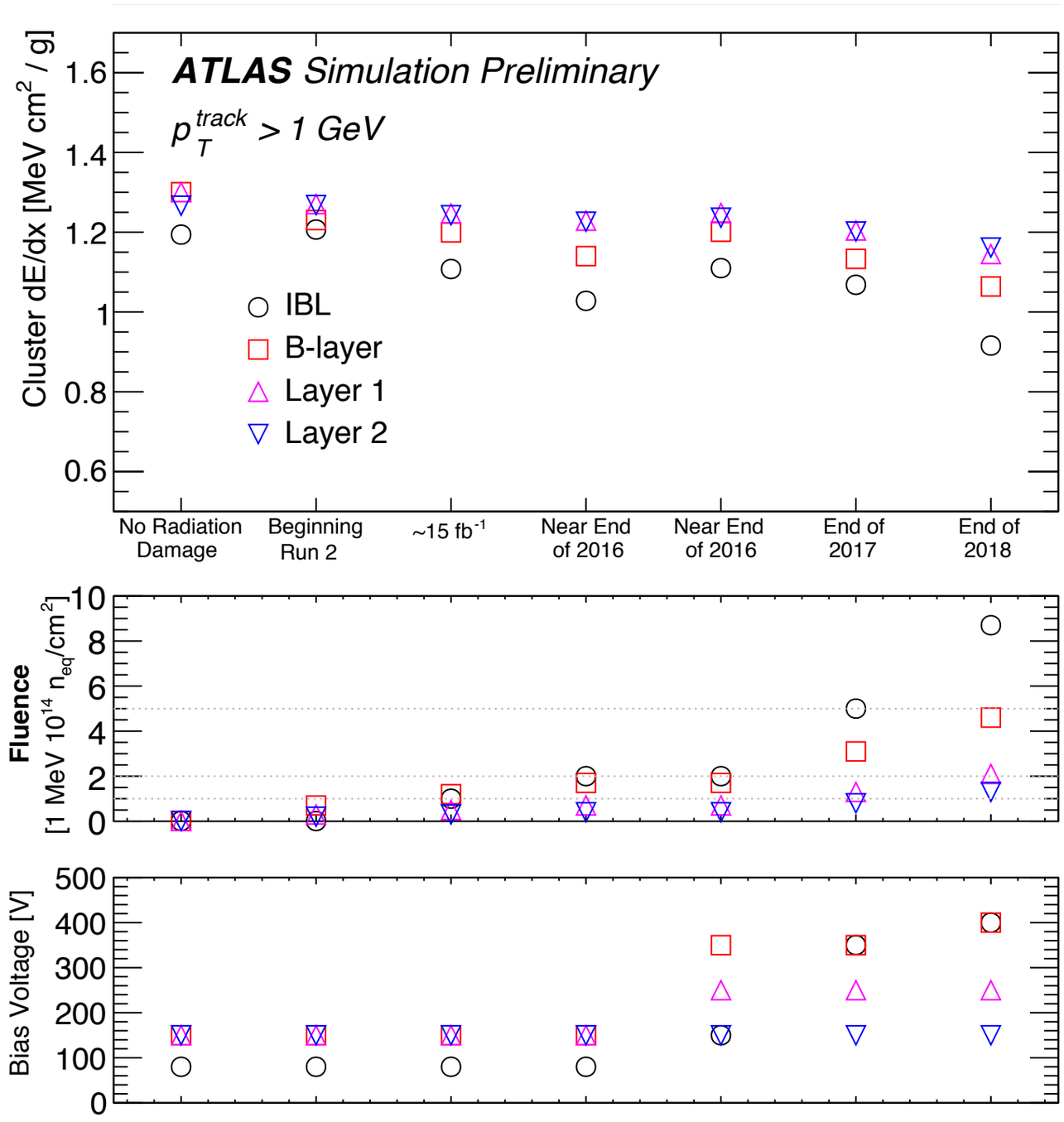
Most likely candidate(s)? I'd put my money on physics modeling or damage factors. The latter are quite uncertain, but hard to make a big Izl-dependence.

Conclusions and outlook

The fluence is the key ingredient to radiation damage modeling.

We are still investigating, but in the mean time **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!



Backup

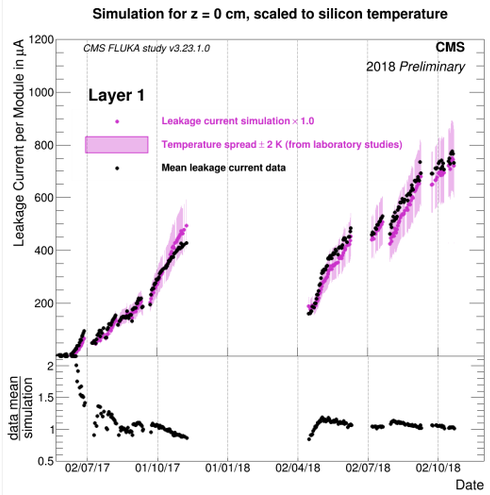
Results from CMS pixels

...confirm our strong radius dependence

Simulation vs. Measurements – Leakage Current Layer 1

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

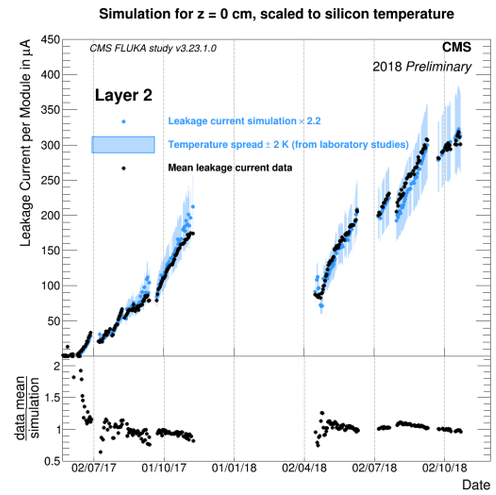
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^{\circ}\mathrm{C}$
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -8.5 $\pm$ 2 °C
- Leakage current simulations are corrected by a factor of 1.0
- Final fluence from FLUKA: $\approx 7.9 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$



Simulation vs. Measurements – Leakage Current Layer 2

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

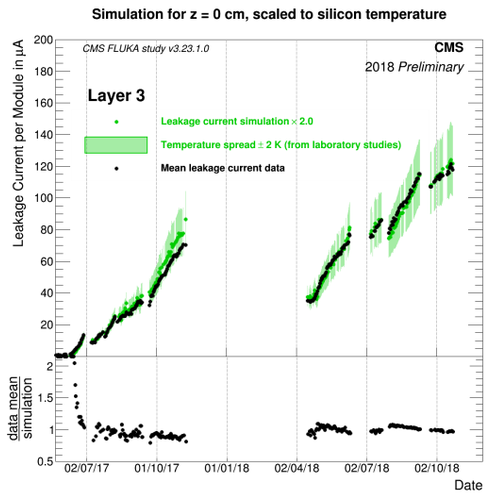
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^{\circ}\mathrm{C}$
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -8.5 $\pm$ 2 °C
- Leakage current simulations are corrected by a factor of 2.2
- Final fluence from FLUKA: $\approx 1.8 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$



Simulation vs. Measurements – Leakage Current Layer 3

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

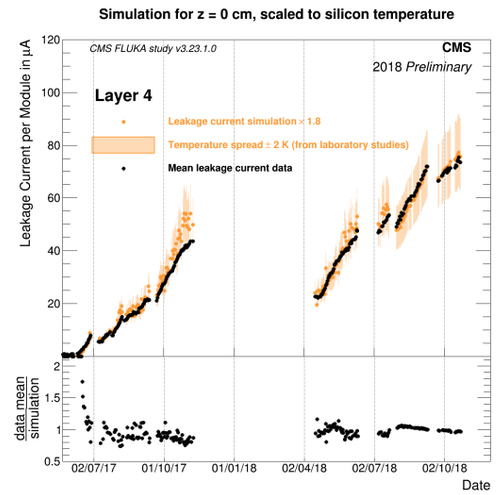
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^{\circ}\mathrm{C}$
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -8.5 $\pm$ 2 °C
- Leakage current simulations are corrected by a factor of 2.0
- Final fluence from FLUKA: $\approx 9 \times 10^{13}\ \mathrm{n_{eq}/cm^2}$



Simulation vs. Measurements – Leakage Current Layer 4

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^{\circ}\mathrm{C}$
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -7.5 $\pm$ 2 °C
- Leakage current simulations are corrected by a factor of 1.8
- Final fluence from FLUKA: $\approx 5 \times 10^{13}\ \mathrm{n_{eq}/cm^2}$



Results from CMS pixels

…and confirm our strong z dependence!

Z-Dependence of Leakage Current – Measurements

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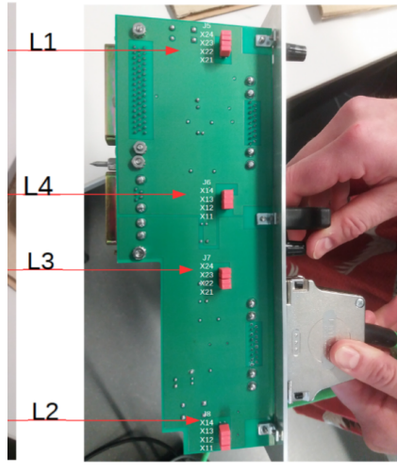
- HV channels group modules with the same ϕ region in the detector. Individual cables group modules in z. By disconnecting cables from power supply backplanes in the CMS experimental cavern it was possible to isolate individual (layer 1) and groups of modules on same z-positions.
- The detector was at nominal operating temperature with a CO_2 set point of $-22\,°C$.
- The measurements were taken after the end of the 2018 heavy ion run.



Z-Dependence of Leakage Current – Layer 1 - I

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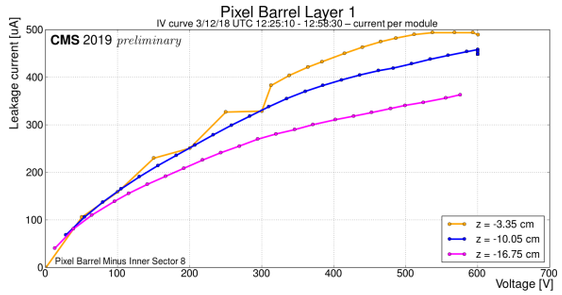
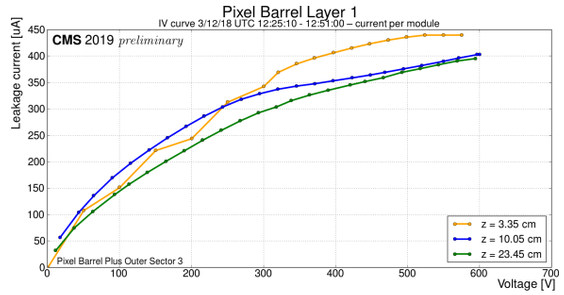


- Z-position measured mid of each module
- Measured volume $0.299\,cm^3$ (16 ROCs)
- Fluence $7.9 \times 10^{14}\,n_{eq}/cm^2$ (FLUKA, at z=0)
  Dose 41 Mrad (from occupancies)



- Different z, I_{leak} differs up to $\approx 150\,\mu A$
- Between sectors I_{leak} differs up to $\approx 50\,\mu A$
- Larger leakage currents towards smaller z, not fully consistent between all measured sectors (one outlier)