PIXEL 2018

10-14 December, 2018
Academia Sinica, Taipei

the 9th International workshop
on Semiconductor Pixel Detectors
for Particles and Imaging

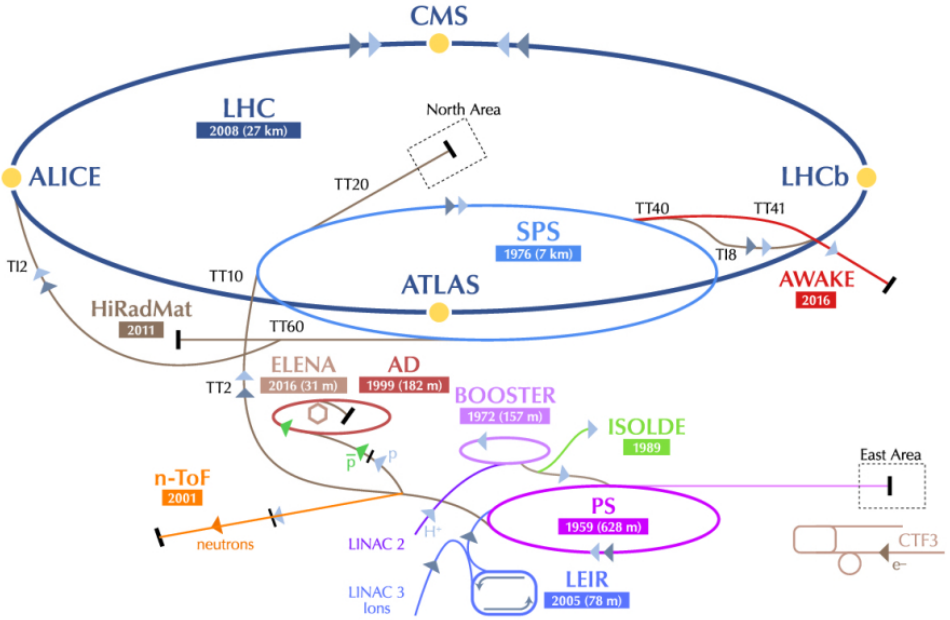
Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

M. Bomben, LPNHE & UPD – Paris
on behalf of the ATLAS collaboration

Outline

- Introduction
- ATLAS Radiation Damage Digitizer Goals
- Digitizer: implementation strategy and ingredients
- Validation
- Predictions
- Conclusion & Outlook

The CERN Large Hadron Collider (LHC)

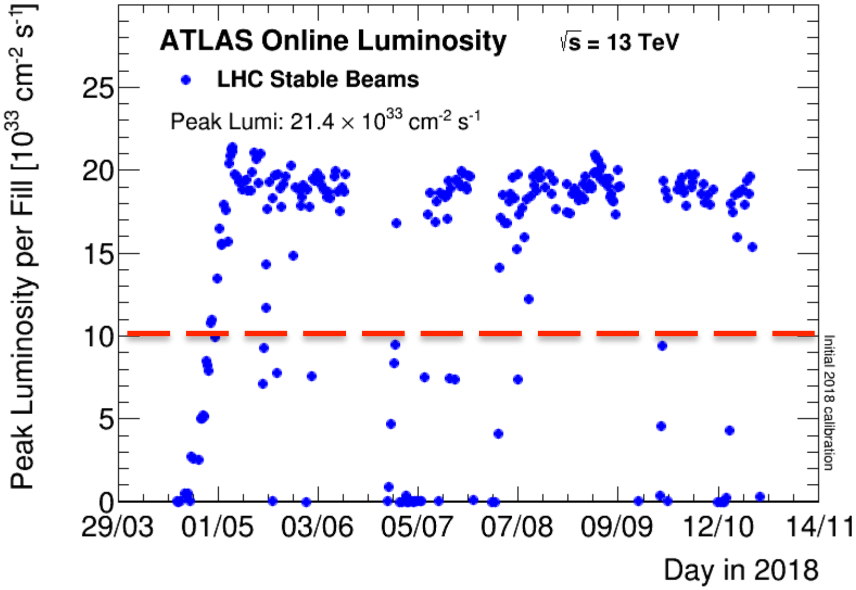


CERN LHC is the largest and most powerful particle accelerator ever built

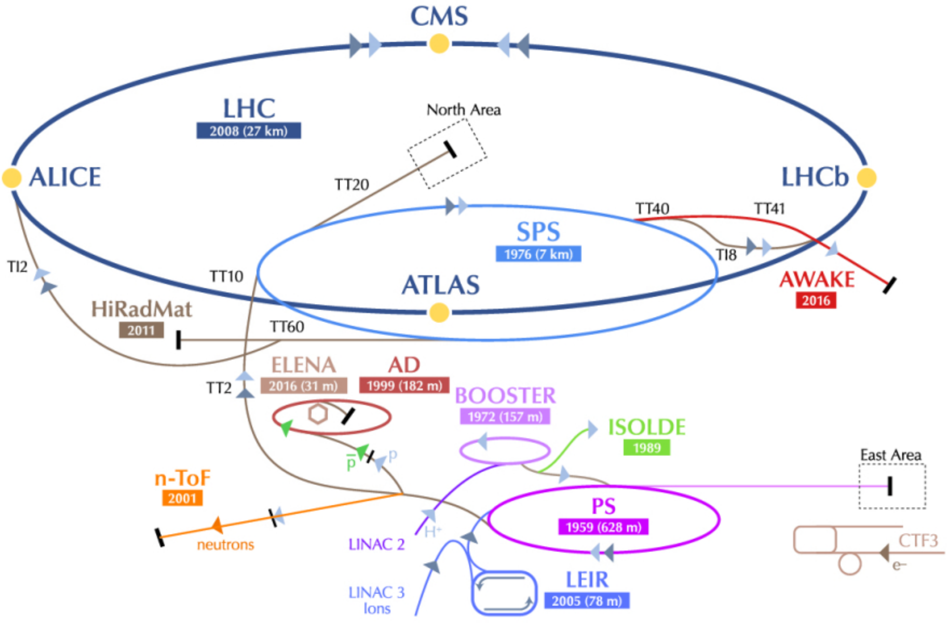
It provides proton-proton collisions at energies up to √s = 13 TeV

LHC design luminosity was 1×10^{34} cm^{-2}s^{-1}

Design value has been widely exceeded!

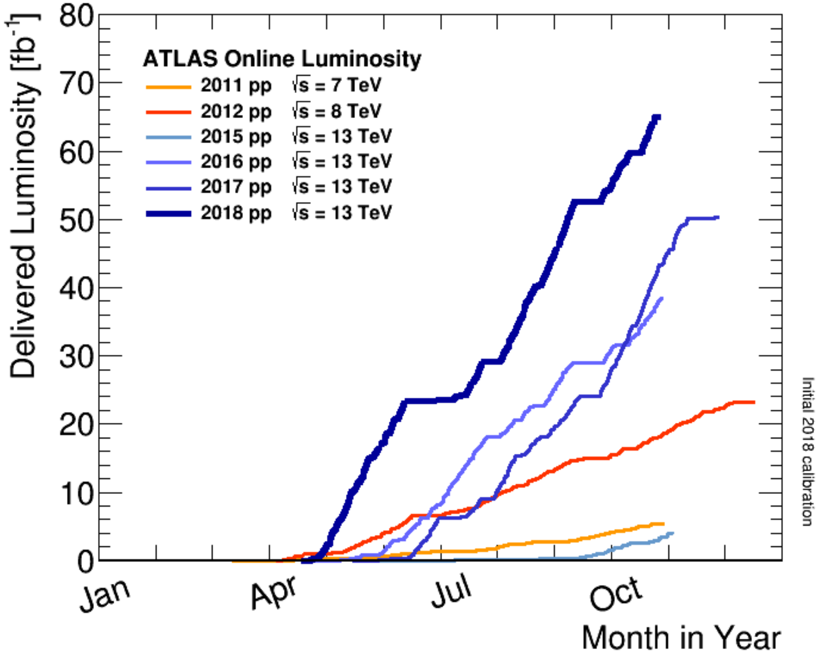


The CERN Large Hadron Collider (LHC)



CERN LHC is the largest and most powerful particle accelerator ever built

It provides proton-proton collisions at energies up to $\sqrt{s}$ = 13 TeV



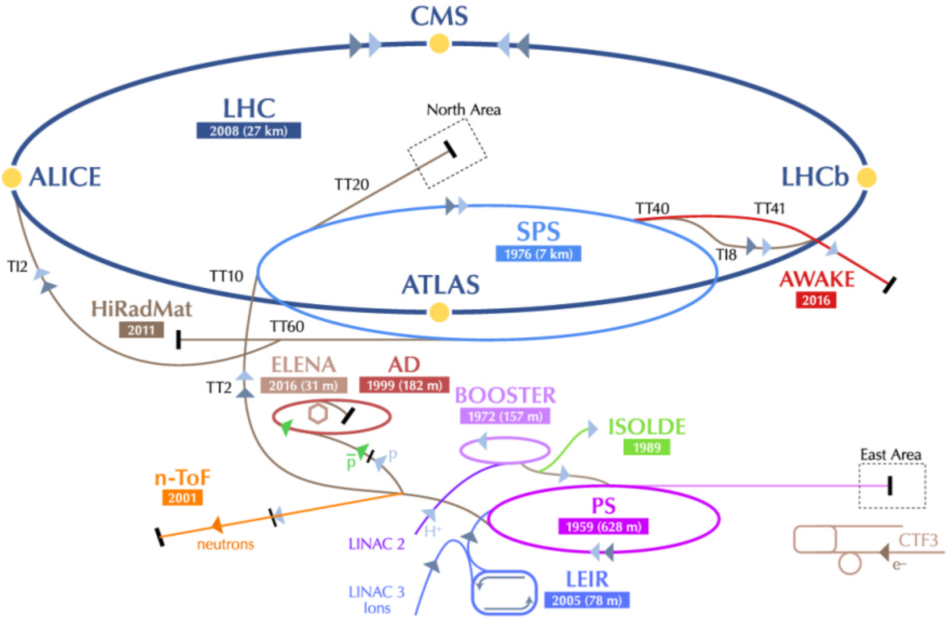
LHC design luminosity was 1×10^{34} cm^{-2}s^{-1}

Design value has been widely exceeded!

Large dataset integrated over first 2 LHC Runs:

> 180 fb^{-1}

The CERN Large Hadron Collider (LHC)



CERN LHC is the largest and most powerful particle accelerator ever built

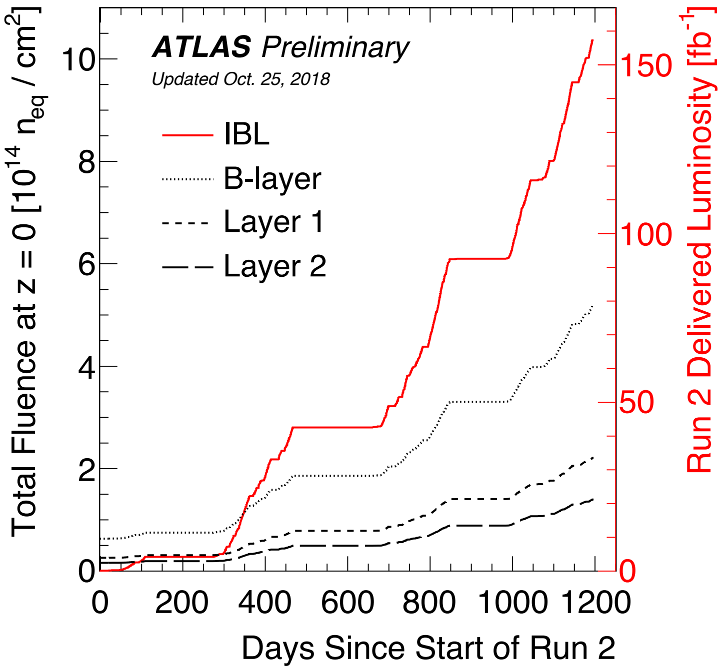
It provides proton-proton collisions at energies up to $\sqrt{s}$ = 13 TeV

LHC design luminosity was 1×10^{34} $cm^{-2}s^{-1}$

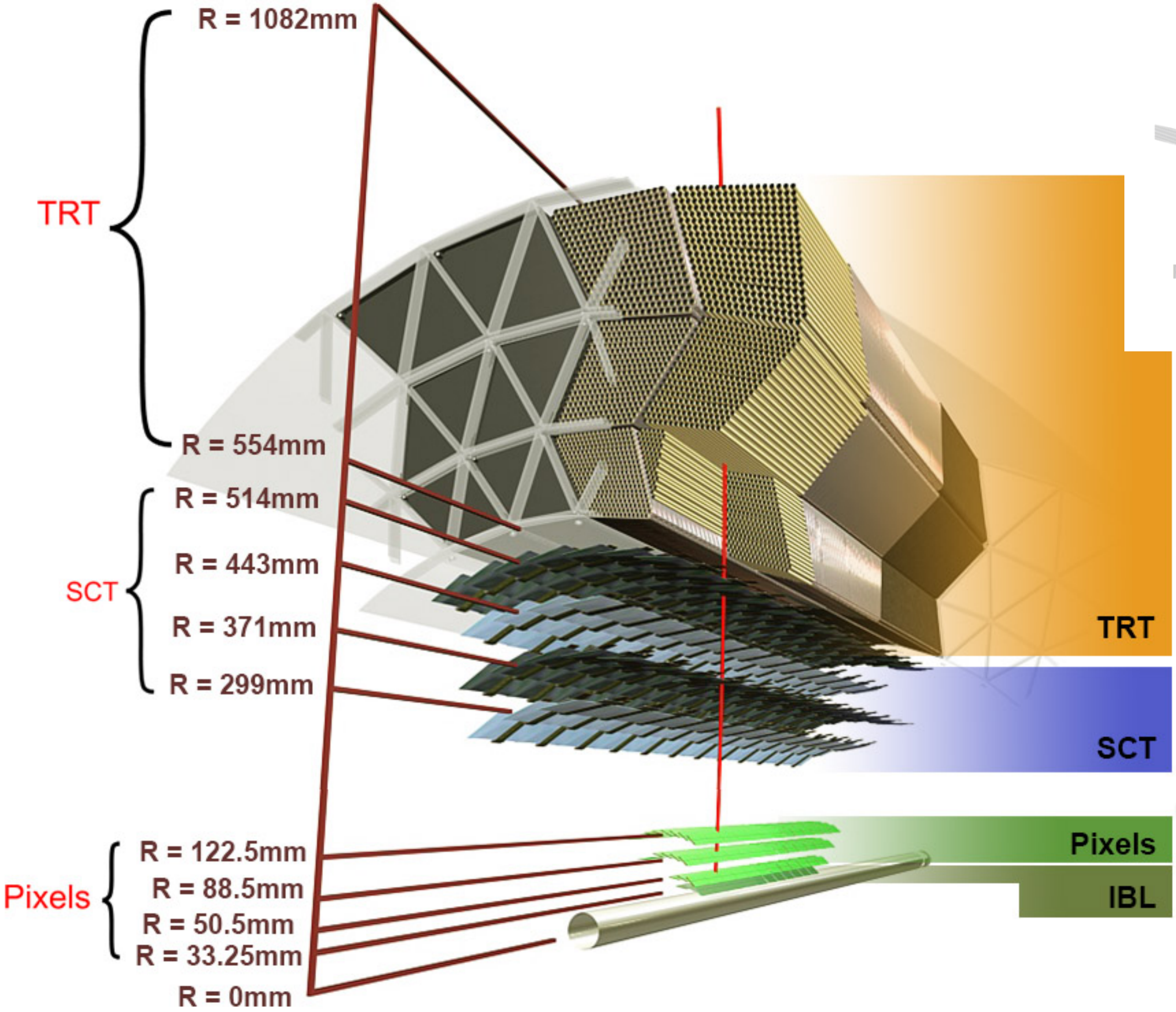
Design value has been widely exceeded!

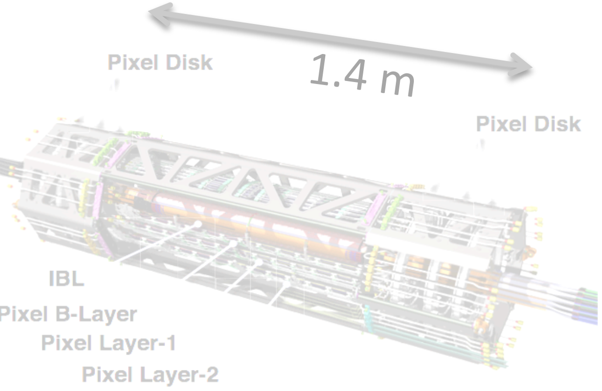
Large **fluence** integrated over first 2 LHC Runs:

> 9×10^{14} n_{eq}/cm^2 by the innermost pixel layer



ATLAS Inner Detector



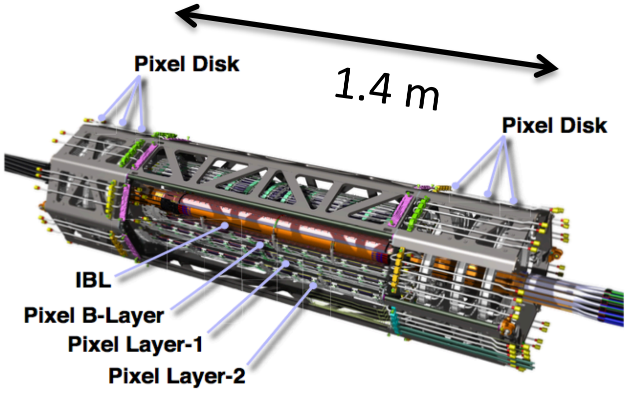


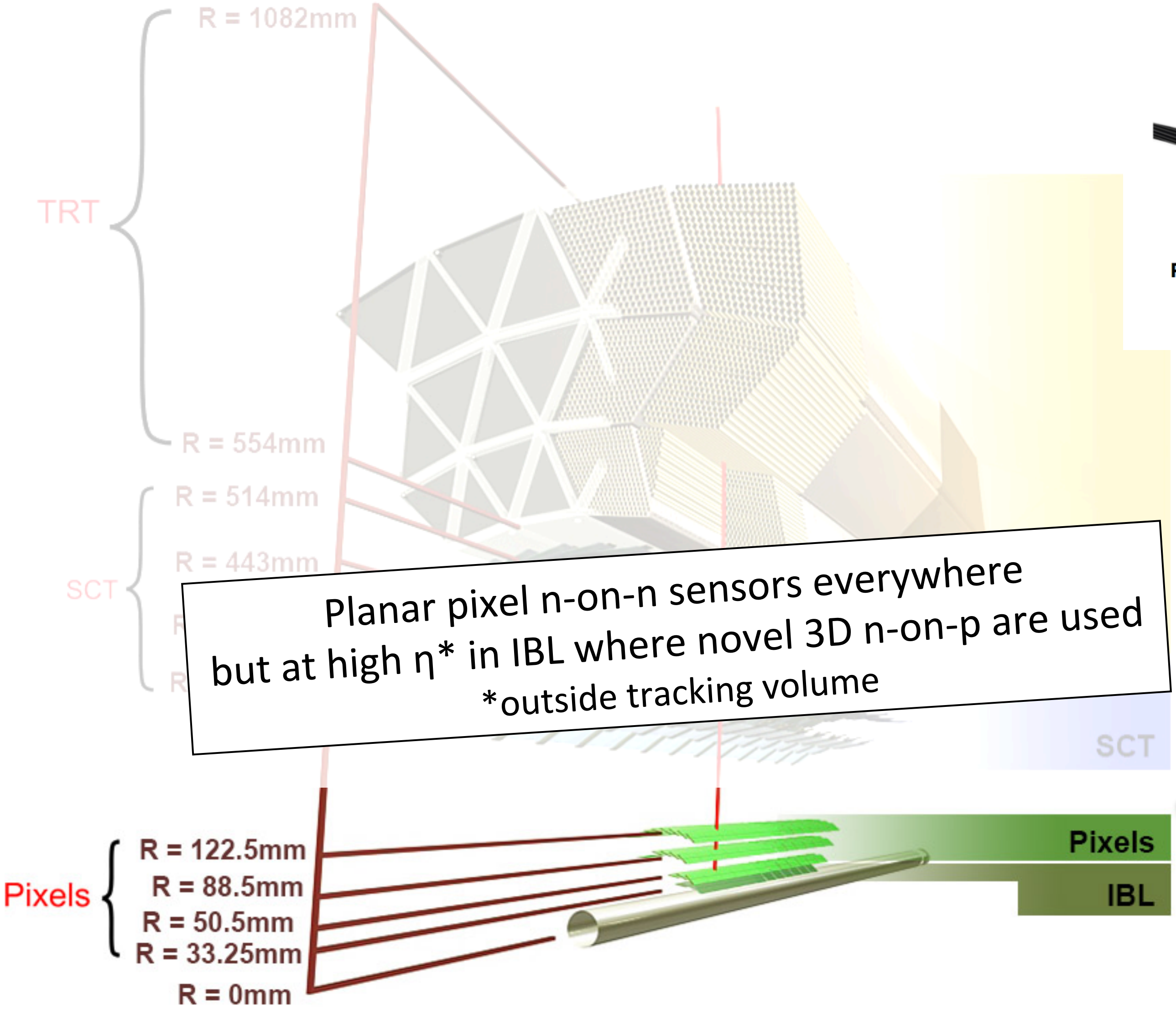
4 Pixel barrel layers

3 Outermost:
250 μm thick
50x400 μm^2 pitch

Innermost layer: IBL
Inserted in Run2
200 μm thick
50x250 μm^2 pitch

ATLAS Pixel Detector





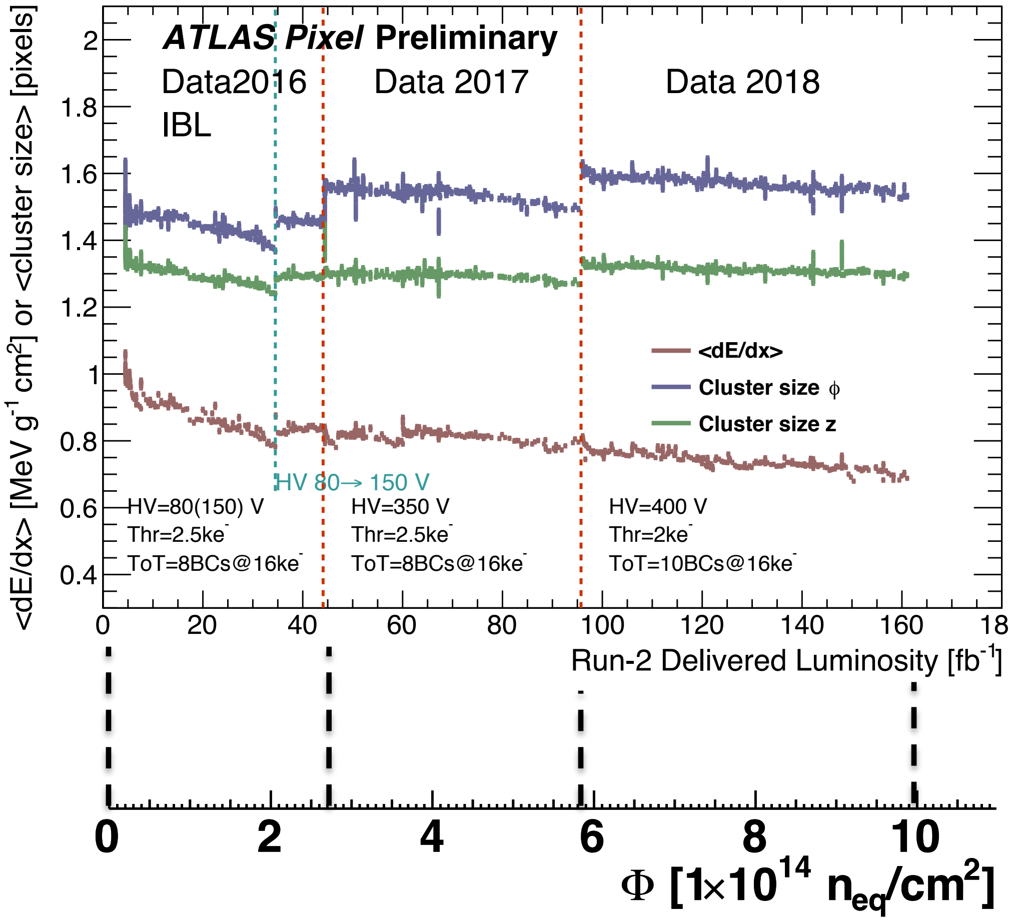
Planar pixel n-on-n sensors everywhere
but at high η* in IBL where novel 3D n-on-p are used
*outside tracking volume

4 Pixel barrel layers

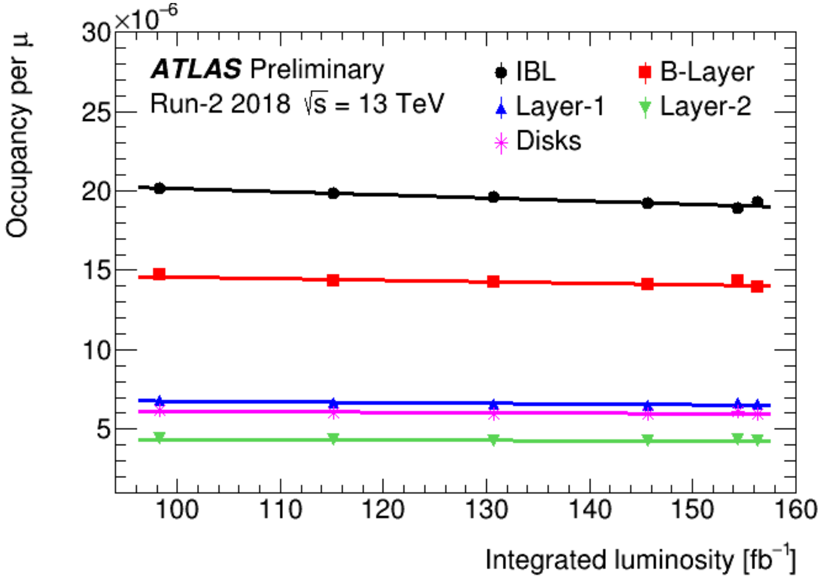
3 Outermost:
250 µm thick
$50 \times 400\ \mu m^2$ pitch

Innermost layer: IBL
Inserted in Run2
200 µm thick
$50 \times 250\ \mu m^2$ pitch

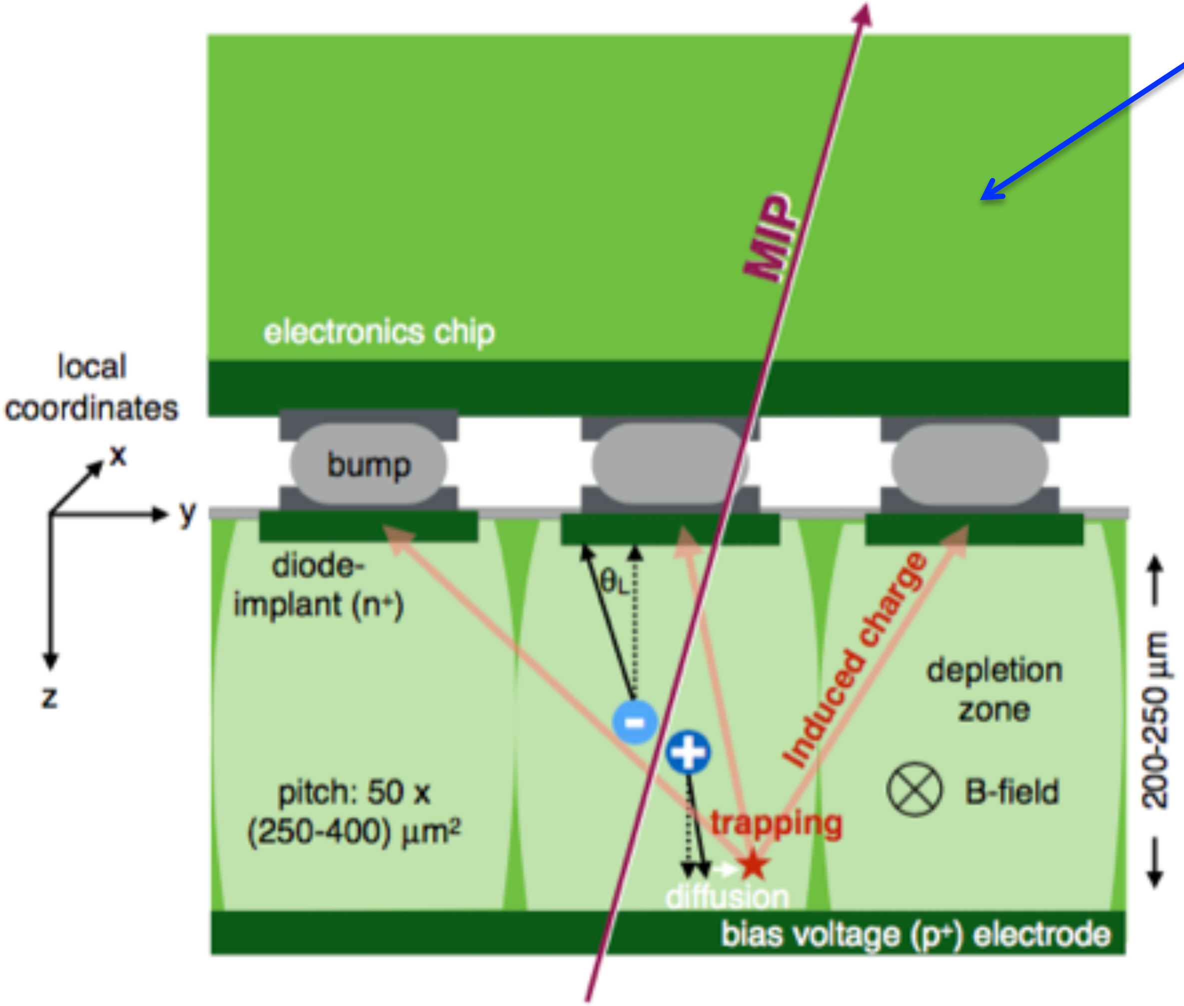
Pixel sensors: radiation damage effects



- Significant **decrease of dE/dx and cluster size for IBL**
    - Similar effect for B-Layer
- It was **necessary** to **increase** the **bias voltage** and **adjust threshold** to mitigate the negative trend
- Occupancy decreasing too



Pixel Radiation Damage Digitizer* Goals



Include all this in ATLAS MonteCarlo

Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage**.

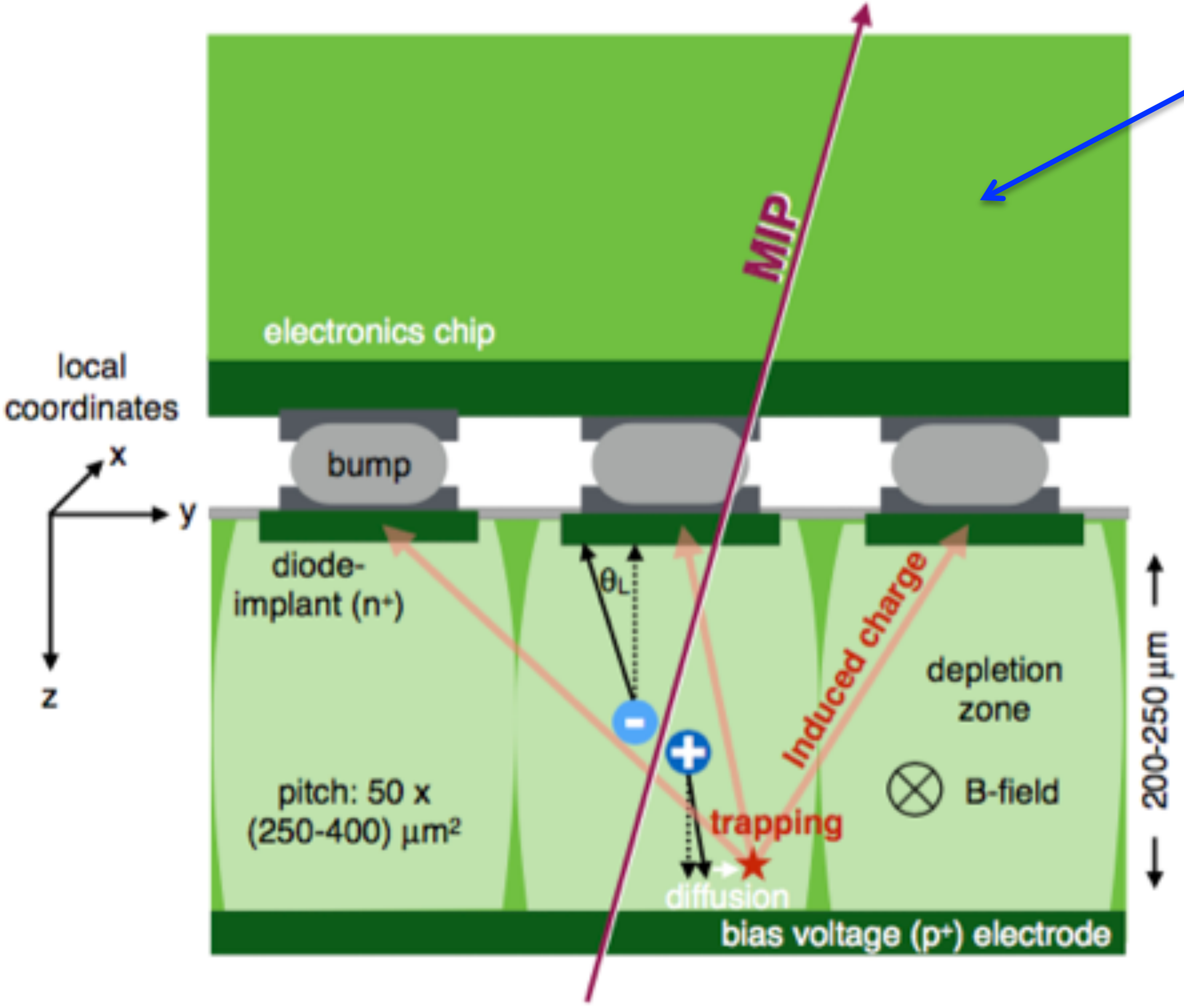
Their path will be deflected by magnetic field (**Lorentz angle**) and **diffusion**.

Due to **radiation damage** they can be **trapped** and induce/screen a fraction of their charge (**Ramo potential**).

Total induced charge is then digitized and clustered.

*Digitization happens after simulated charge deposition and before space point reconstruction

Pixel Radiation Damage Digitizer Goals



Include all this in
ATLAS MonteCarlo
Now ready!

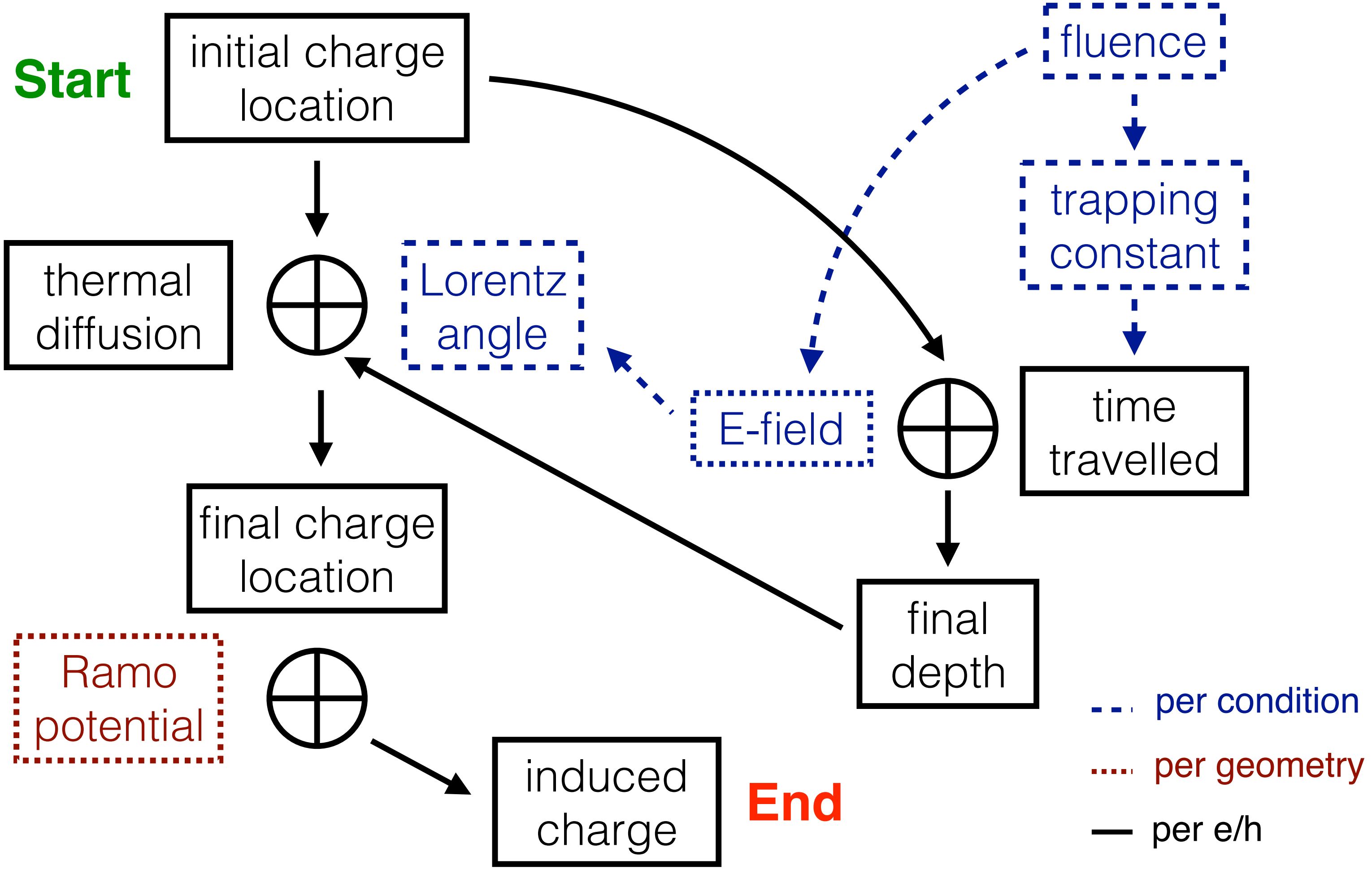
Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage**.

Their path will be deflected by magnetic field (**Lorentz angle**) and **diffusion**.

Due to **radiation damage** they can be **trapped** and induce/screen a fraction of their charge (**Ramo potential**).

Total induced charge is then digitized and clustered.

Implementation Strategy

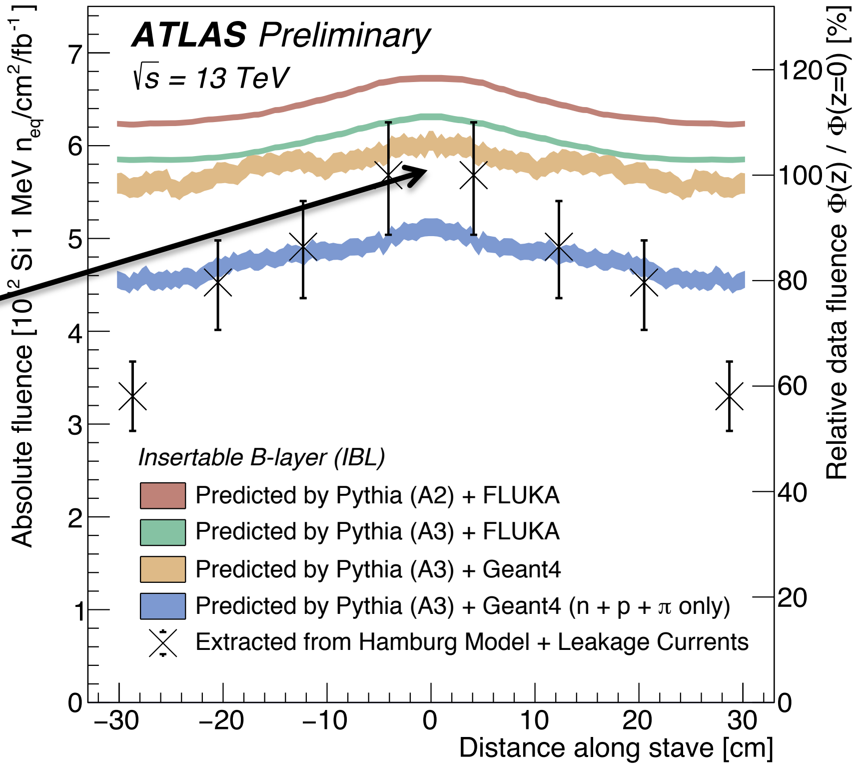


Ingredients: fluence and trapping time

Fluence prediction taken from FLUKA & Pythia

FLUKA prediction validated with leakage current and Hamburg model* simulation

- ➢ 15% difference in the central region



Trapping constants from literature**:

- ➢ $\beta_e = (4.5 \pm 1.5) \times 10^{-16}$ cm^2/ns
- ➢ $\beta_h = (6.5 \pm 1.5) \times 10^{-16}$ cm^2/ns

** *ATLAS pixel coll.*, JINST 3 (2008) P07007
G. Kramberger et al., Nucl. Instrum. Meth. A481 (2002) 297
O. Krasel et al., IEEE Trans. on Nucl. Sci. 51 (2004) 3055.
G. Alimonti et al., ATL-INDET-2003-014 (2003)

* M. Moll, DESY-THESIS-1999-040

Ingredients: electric field (planar sensors)

Radiation damage induced defects deform the electric field distribution in the bulk

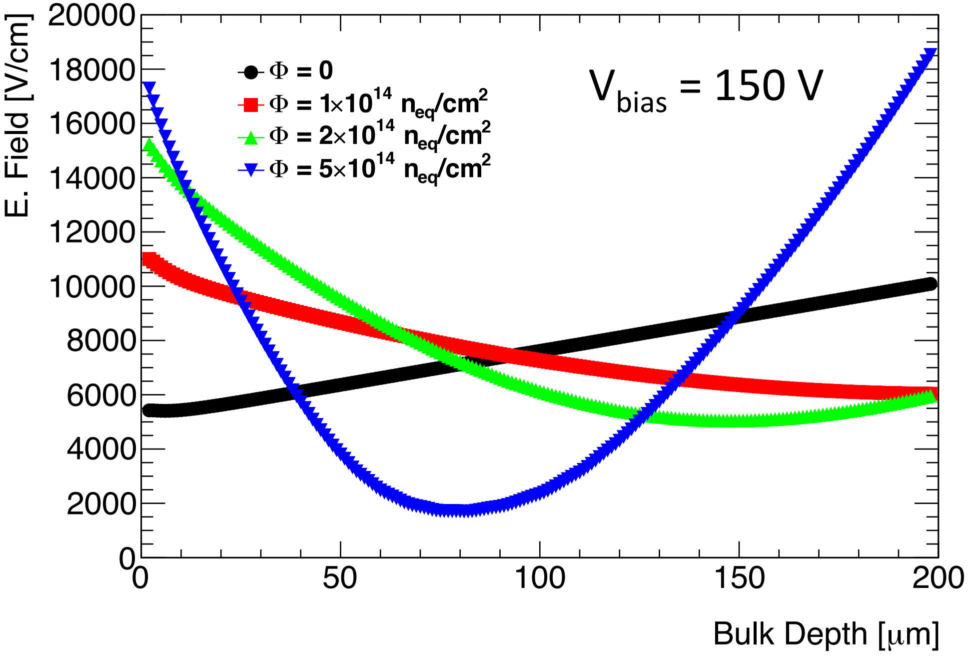
We use TCAD simulation tools to make predictions of electric field in the bulk

A 2 trap model due to CMS collaborators* has been used with Silvaco tools**

Model chosen because:

- developed on n-on-n pixels
- irradiated at CERN w/ 24 GeV/c p
- built on testbeam data
- predicts type inversion at right fluence

Main feature: double peak electric field



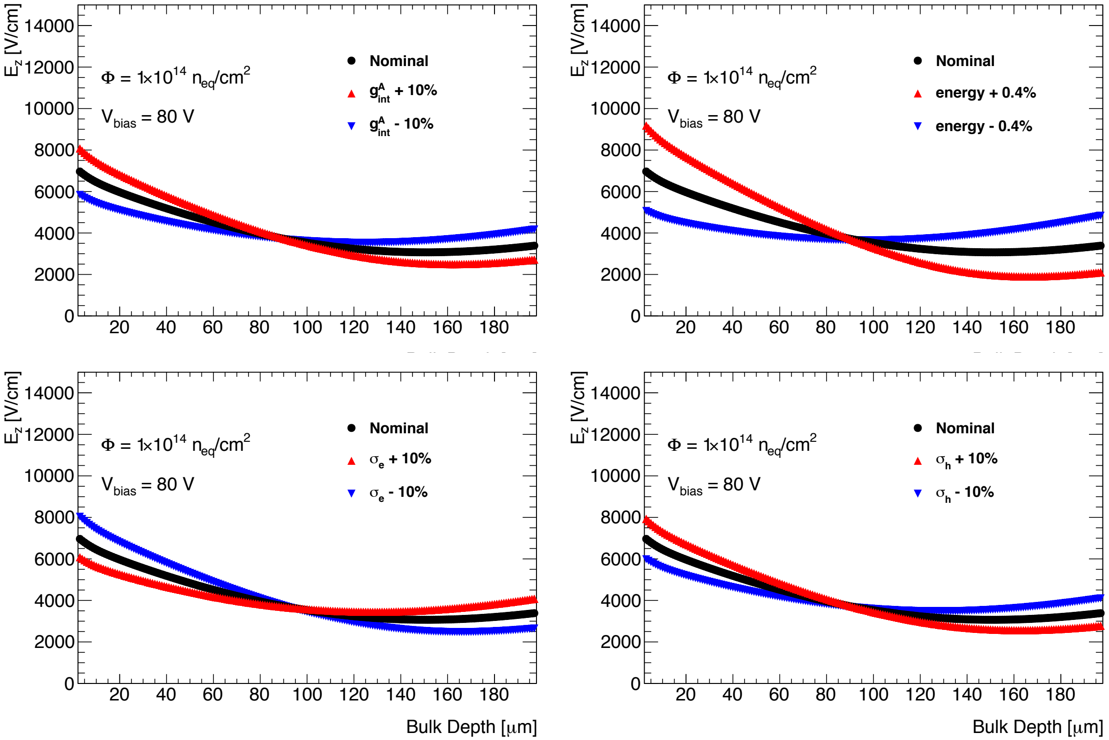
*V. Chiochia et al., Nucl. Instr. and Meth A 568 (2006) 51-55

** https://www.silvaco.com/products/tcad.html

Ingredients: electric field mod. uncertainties

TCAD radiation damage model parameters come with no uncertainties

Fluence (10^{14} $\mathbf{n_{eq}/cm^2}$)	E_T^A (eV) ±0.4%	E_T^D (eV) ± 0.4%	N_A (10^{14} cm^{-3}) ± 10%	N_D (10^{14} cm^{-3}) ± 10%	$\sigma_e^{A,D}$ & σ_h^D (10^{-15} cm^2) ± 10%	σ_h^A (10^{-15} cm^2) ± 10%
1	E_C-0.52eV	E_V+0.48eV	3.6	5	6.60	1.65
2			6.8	10		
5			14	34		



So we had to explore the sensitivity of electric field on each defect parameter:

- concentration
- energy
- electron and hole capture cross sections

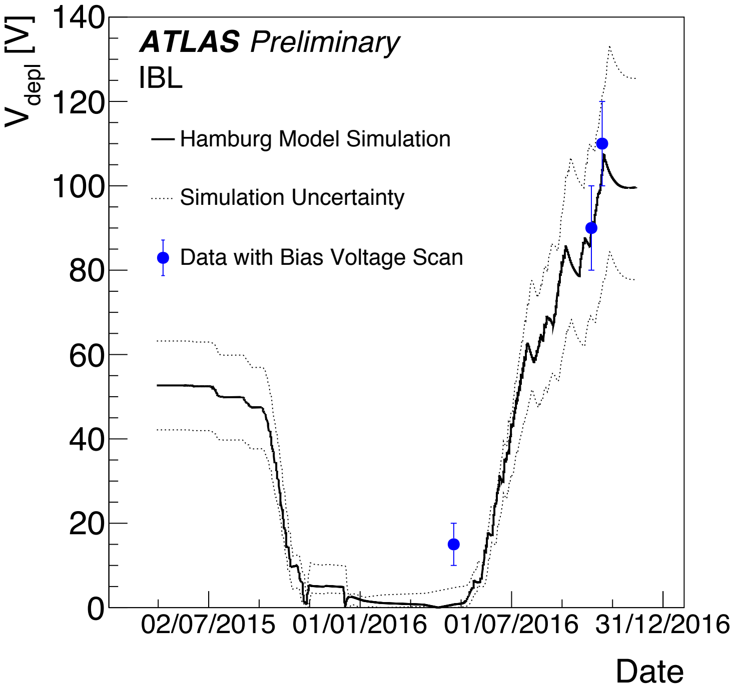
Trends are compatible with expectations

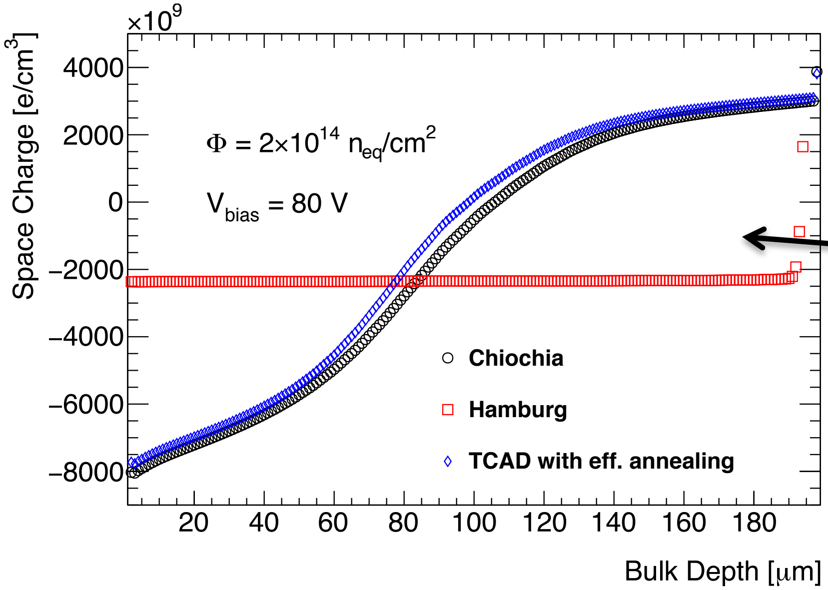
Ingredients: annealing

Annealing not modeled in TCAD

Effective correction to TCAD: rescale defects concentration in TCAD to match the average (constant) space charge concentration predicted by Hamburg Model

Hamburg model predictions based on bias voltage scans





IBL stayed cold most of the time
➔ small correction

More important effect for B-Layer

Ingredients: signal from trapped carriers

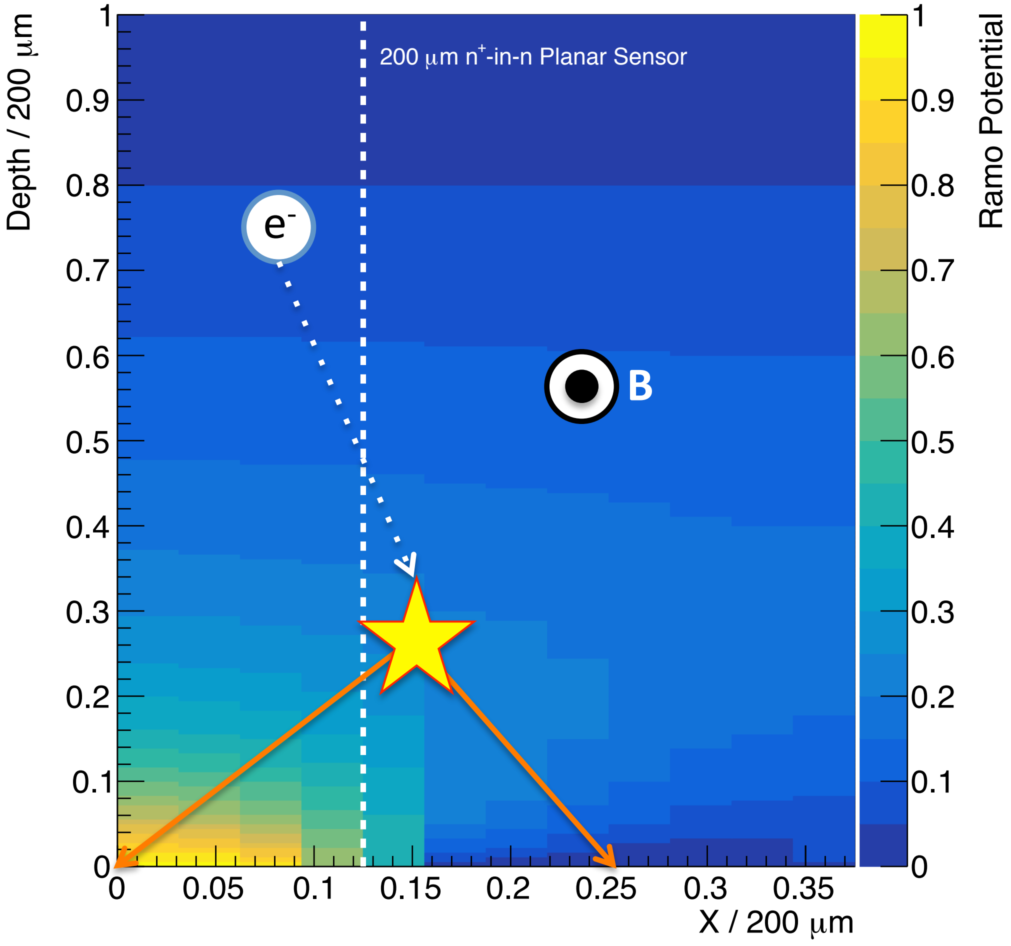
Charge drift towards collecting electrode

They induce larger and larger current the closer they get to the electrode

If **trapped** only a fraction of the total charge will be induced

Trapping position is **stochastically** determined, based on **fluence** and **voltage** conditions

The **final signal** is calculated in a **3x3 pixels matrix** thanks to the **Ramo potential**



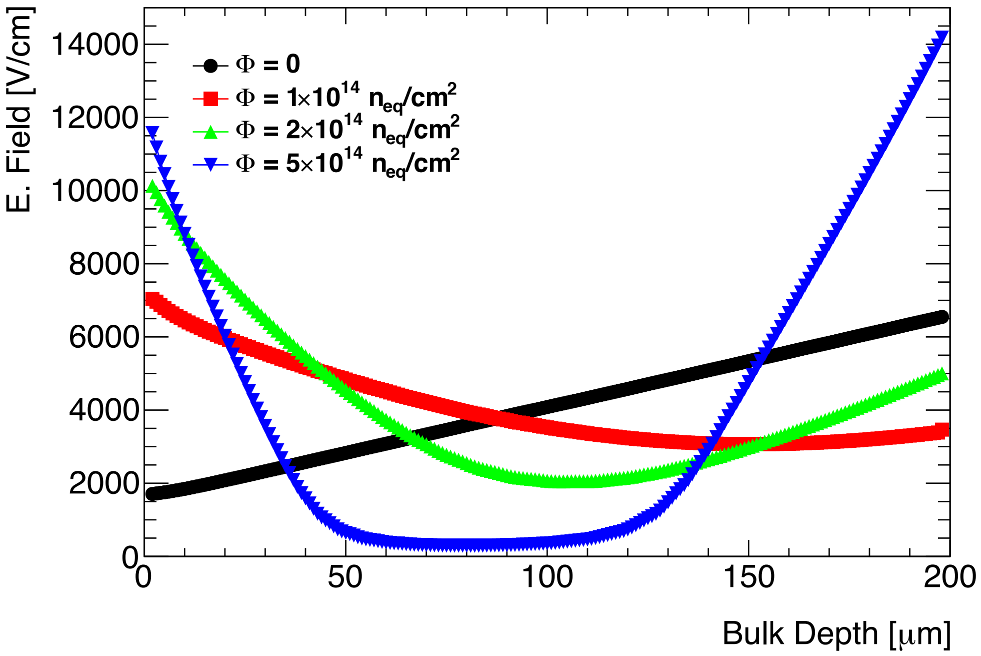
2D slice of 3D Ramo potential calculated using TCAD simulations

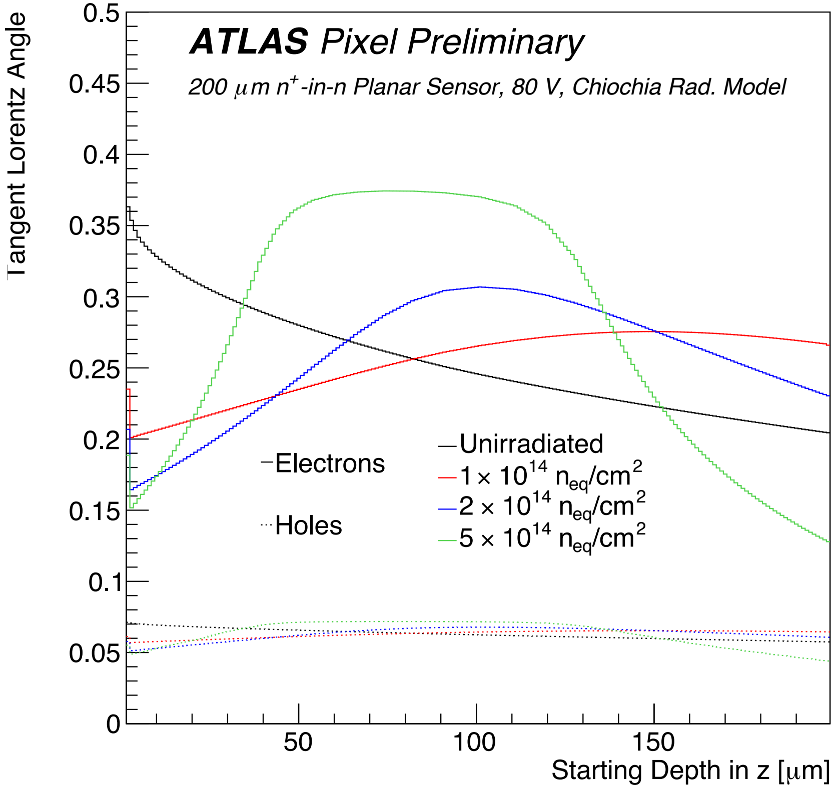
Ingredients: Lorentz angle deflection

$$< \tan\theta_L(z_{\text{initial}}, z_{\text{final}}) >= \frac{rB}{|z_{\text{final}} - z_{\text{initial}}|}\int_{z_{\text{initial}}}^{z_{\text{final}}} \mu(E(z))dz$$

Electric field profile no longer shows linear dependence on bulk depth

It is now even more important to model the Lorentz angle depth-dependence





Validation: Charge Collection Efficiency (CCE)

CCE for IBL across its lifetime

Simulation uncertainties:

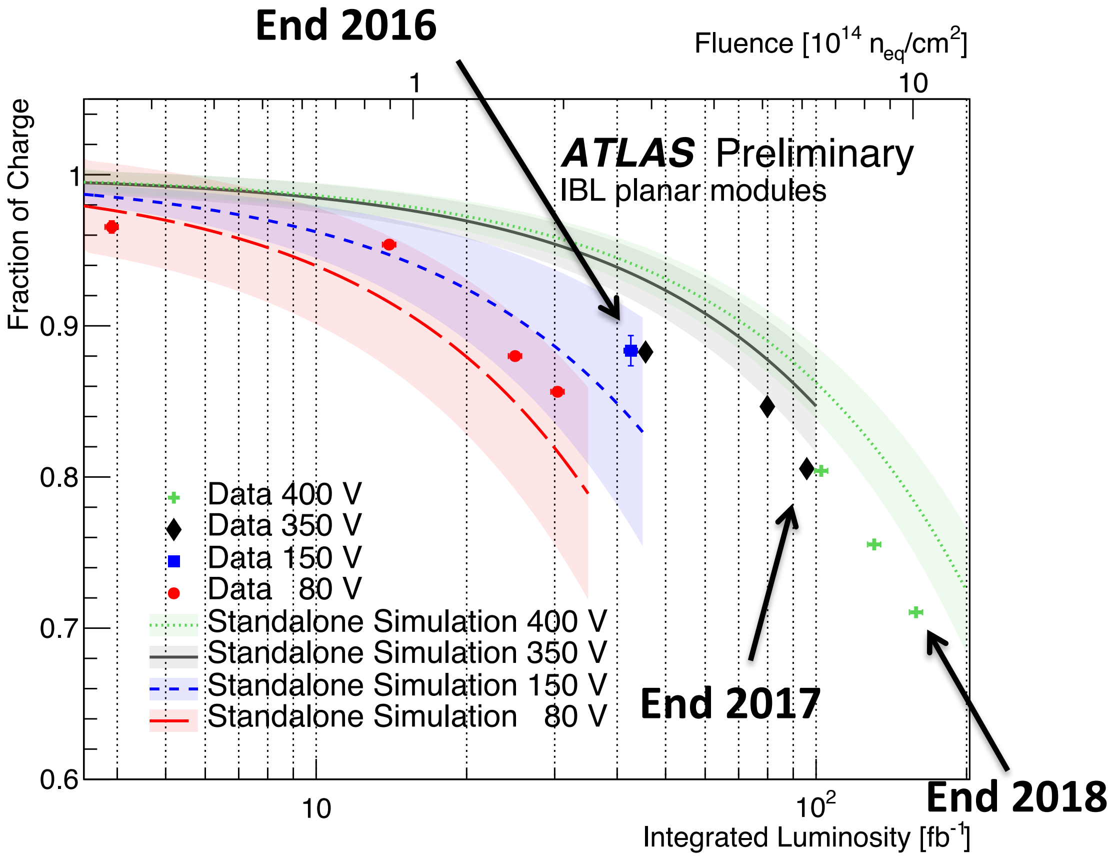
Horizontal error bars include uncertainties on **luminosity to fluence** conversion (15%)

Vertical error bars include uncertainties from **the TCAD radiation damage model**

Data uncertainties

Horizontal error bars include luminosity unc. (2%)

Vertical error bars include calibration drift effects

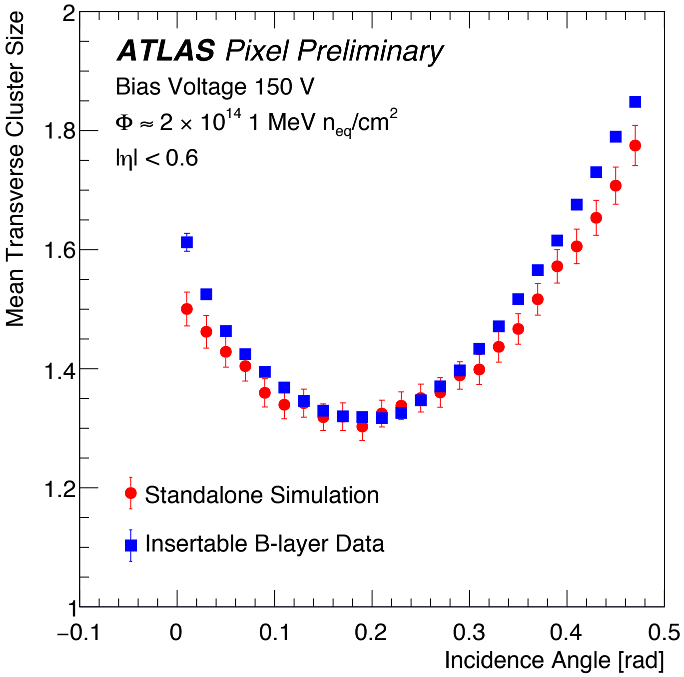


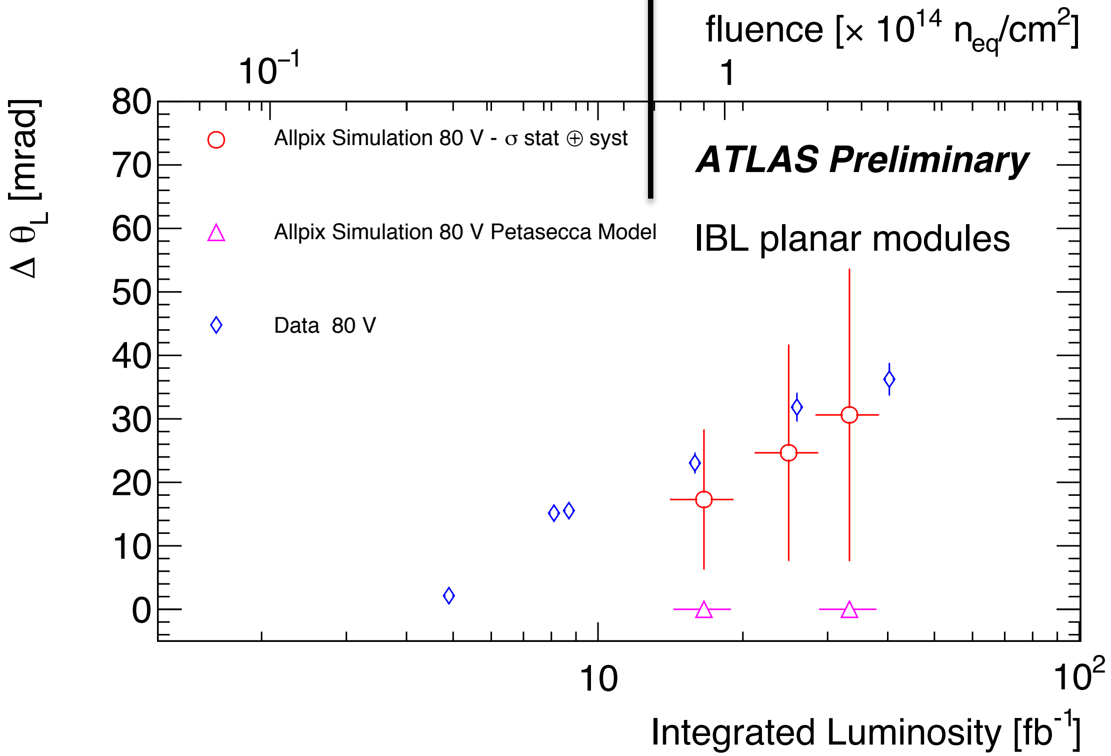
Good agreement with data but large uncertainties

In the **future collision data** can be used to **further constrain** the **radiation damage model**

Validation: Lorentz angle

Petasecca *et. al*,
IEEE TNS 53 (2006) 2971





Lorentz angle is extracted from a fit to the cluster size vs track incident angle

$$F(\alpha) = [a \times (\tan\alpha - \tan\theta_L) + b/\sqrt{\cos\alpha}] \otimes G(\alpha)$$

The trend of increase of Lorentz angle with luminosity is robust

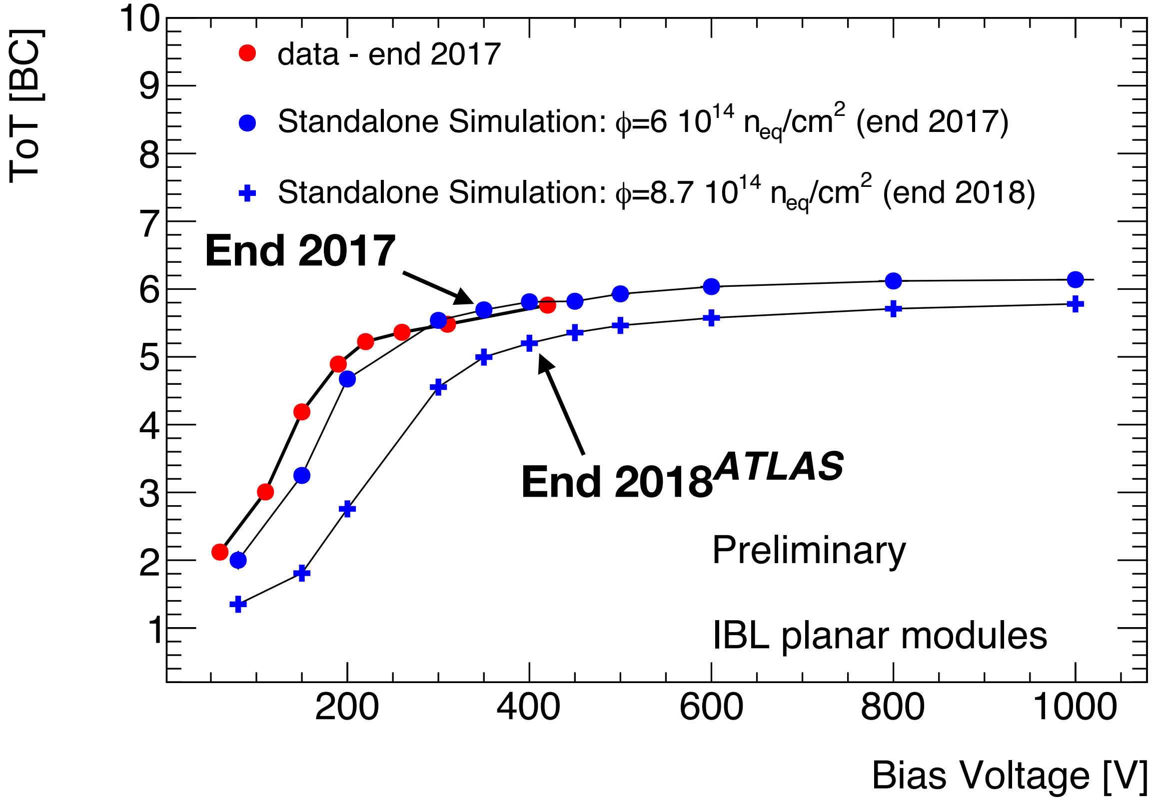
Models predicting no double peak in electric field fail at reproducing increase of L.A. with luminosity

Validation and predictions: HV scans

Standalone simulation to predict MPV of the fitted Landau distribution of the ToT as a function of bias voltage for fixed fluence

Good agreements in both shape and plateau position

This confirms that both the **electric field** and the **trapping time** are correctly reproduced in our modeling!



Predictions now used to **determine** desired **bias voltage** during LHC Run3 for all pixel layers

Predictions: energy loss

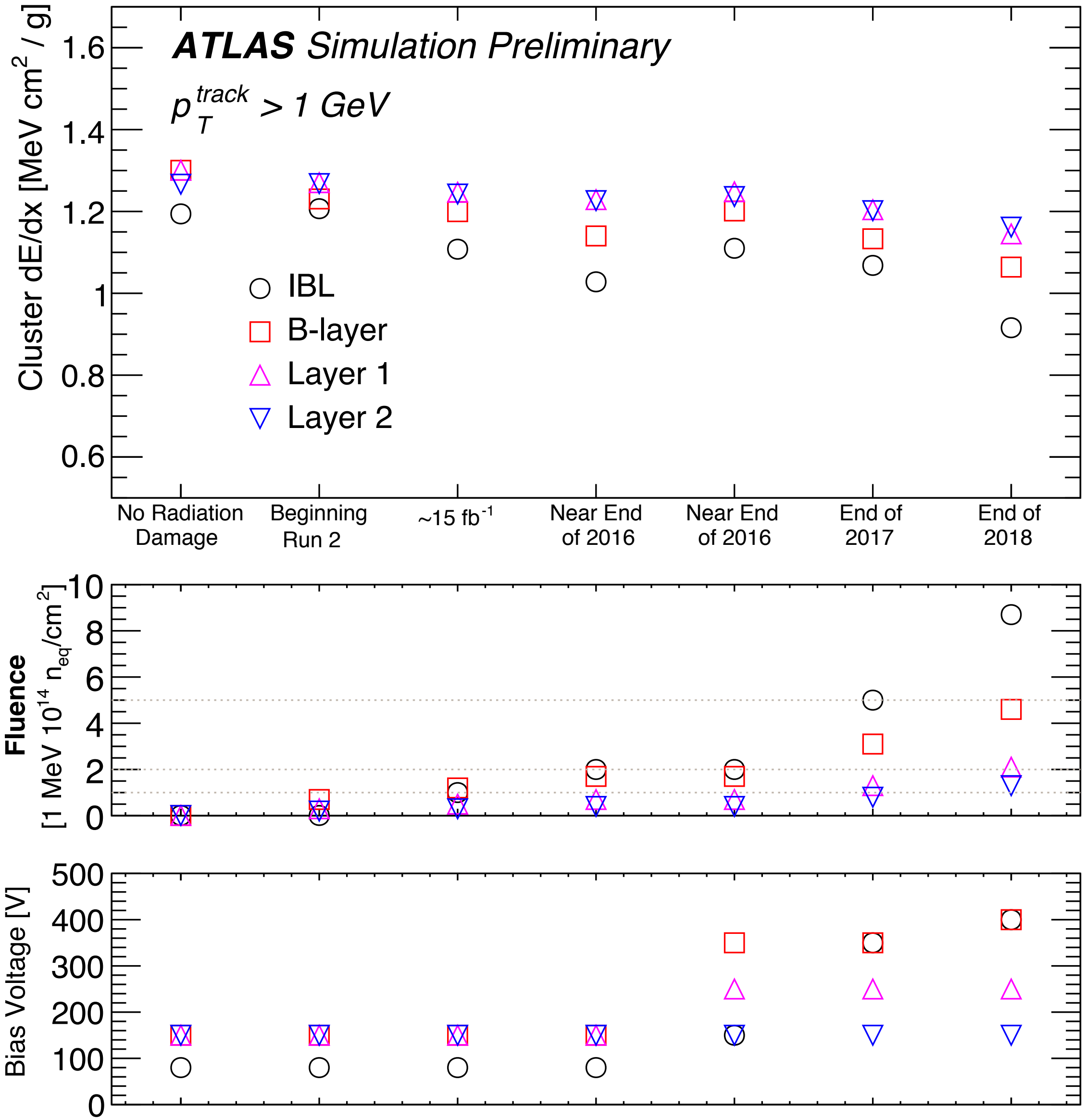
Digitizer can be used to make predictions on fundamental observables

Energy loss per layer for tracks with $p_T > 1$ GeV

Several scenarios considered, in terms of

- fluence
- bias voltage
- different layer by layer

N.B. other parameters (thr., tuning) fixed



Conclusions and outlook

- Effects of **radiation damage to silicon** sensor bulk are **already visible** in the **ATLAS pixel** detector
- Increasing bias voltage helps mitigating the main effect (signal loss)

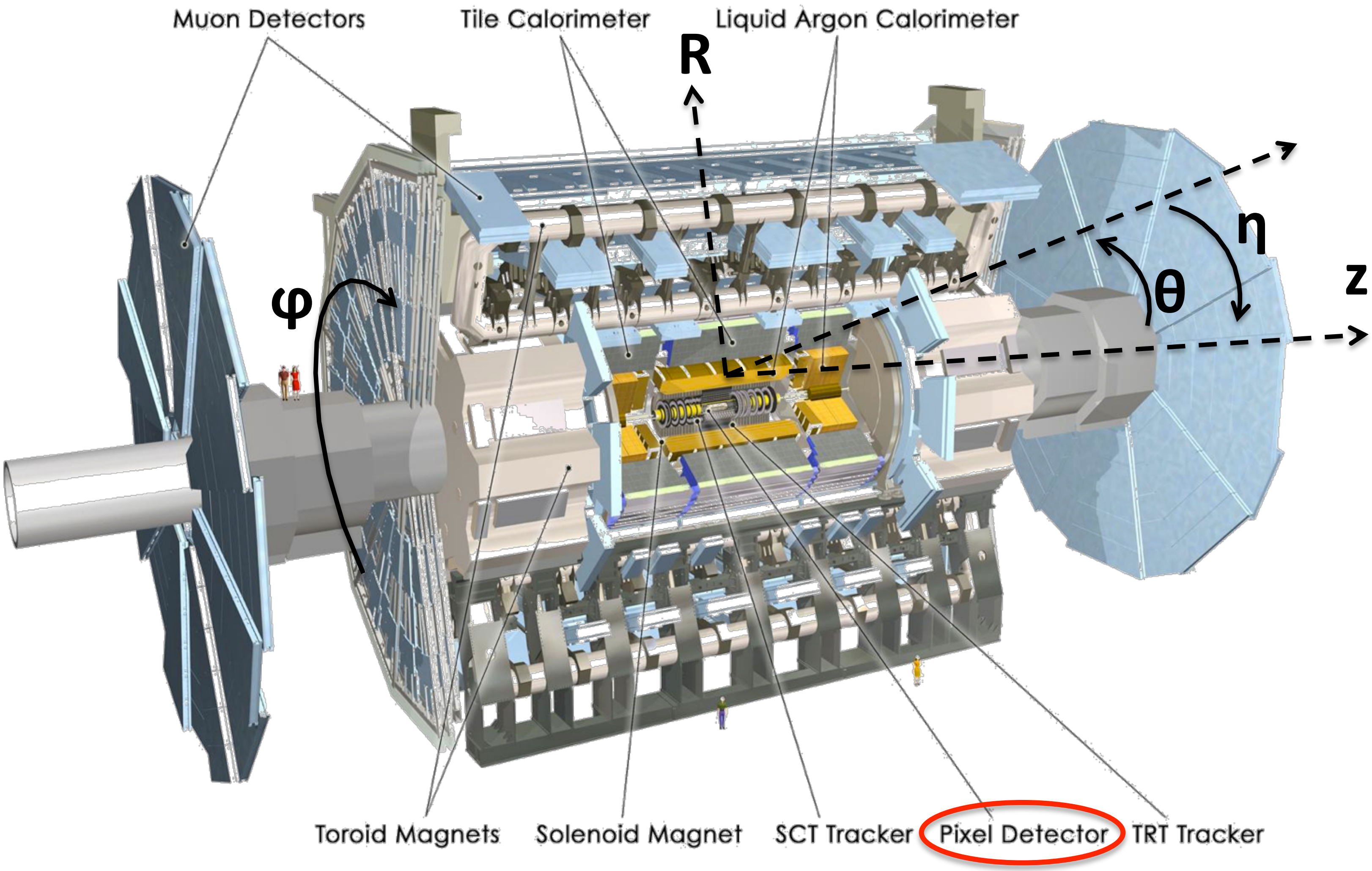
- **Fundamental** to **reproduce** these **effects** in **simulations**
- The **new ATLAS digitizer includes radiation damage effects**
- First **comparison with** collision **data** are **promising**

- The **new digitizer** is an essential tool **to determine ATLAS Pixel detector** data taking **future conditions**
- Work is **ongoing** to **include 3D** modeling and **extend predictions** to **High Luminosity LHC** fluence for the new **ATLAS Inner Tracker**

THANK YOU
FOR YOUR ATTENTION

Backup

ATLAS Detector



Run2 Pixel data taking conditions

RUN-2 HV

HV	2015	2016	2017	2018
IBL	80V	⇨ 150V	⇨ 350V	⇨ 400V
B-layer	250V	350V	350V	400V
Layer-1	150V	200V	200V	250V
Layer-2	150V	150V	150V	250V
Endcap	150V	150V	150V	250V

Threshold	2017	2018
IBL	2500e, ToT>0	**2000e**, ToT>0
B-layer	5000e, ToT>5	**4300e(*), ToT>3**
Layer-1	3500e, ToT>5	3500e, ToT>5
Layer-2	3500e, ToT>5	3500e, ToT>5
Endcap	4500e, ToT>5	**3500e**, ToT>5

(*) M1A/M0/M1C : 4300e, otherwise : 5000e