INNOVATIVE PARTICLE AND RADIATION DETECTORS

SIENA, October 16th, 2019

MODELING RADIATION DAMAGE TO PIXEL SENSOR IN ATLAS DETECTOR

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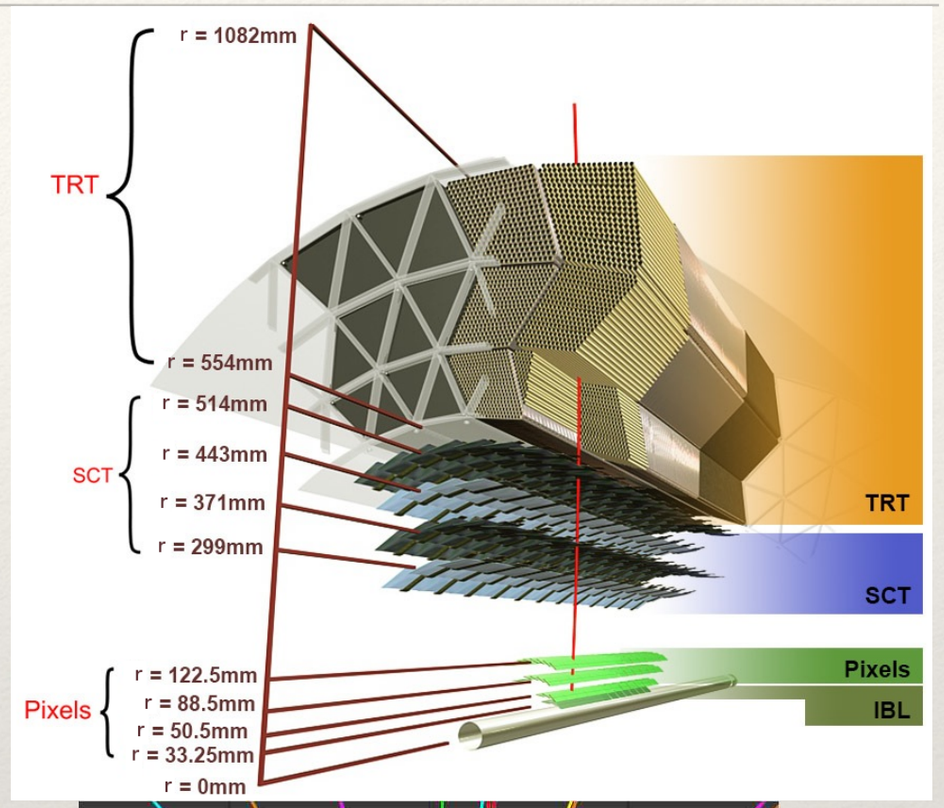
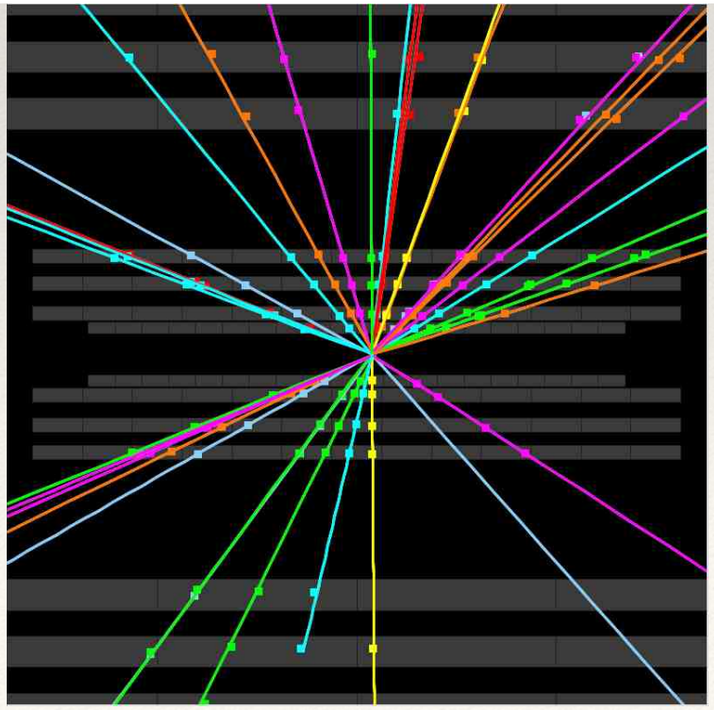
ON BEHALF OF THE ATLAS COLLABORATION

THE ATLAS PIXEL DETECTOR

- Innermost ATLAS detector => highest radiation levels !
- 4 barrel layers, 3 disks per side
- Innermost layer inserted before Run 2 (2015-2018) at 3.3 cm from beam



system	technology	pitch (μm x μm)	thickness (μm)	number of channels	Fluence ($n_{eq}cm^{-2}$)
Outer barrel	n-in-n planar	50 x 400	250	67.2 x 10^6	1.5 - 5.5 10^{14}
Disks	n-in-n planar	50 x 400	250	6.6 x 10^6	1.5 10^{14}
IBL	n-in-n planar, n-in-p 3D	50 x 250	200 or 230	12 x 10^6	10^{15}



EFFECTS OF RADIATION DAMAGE

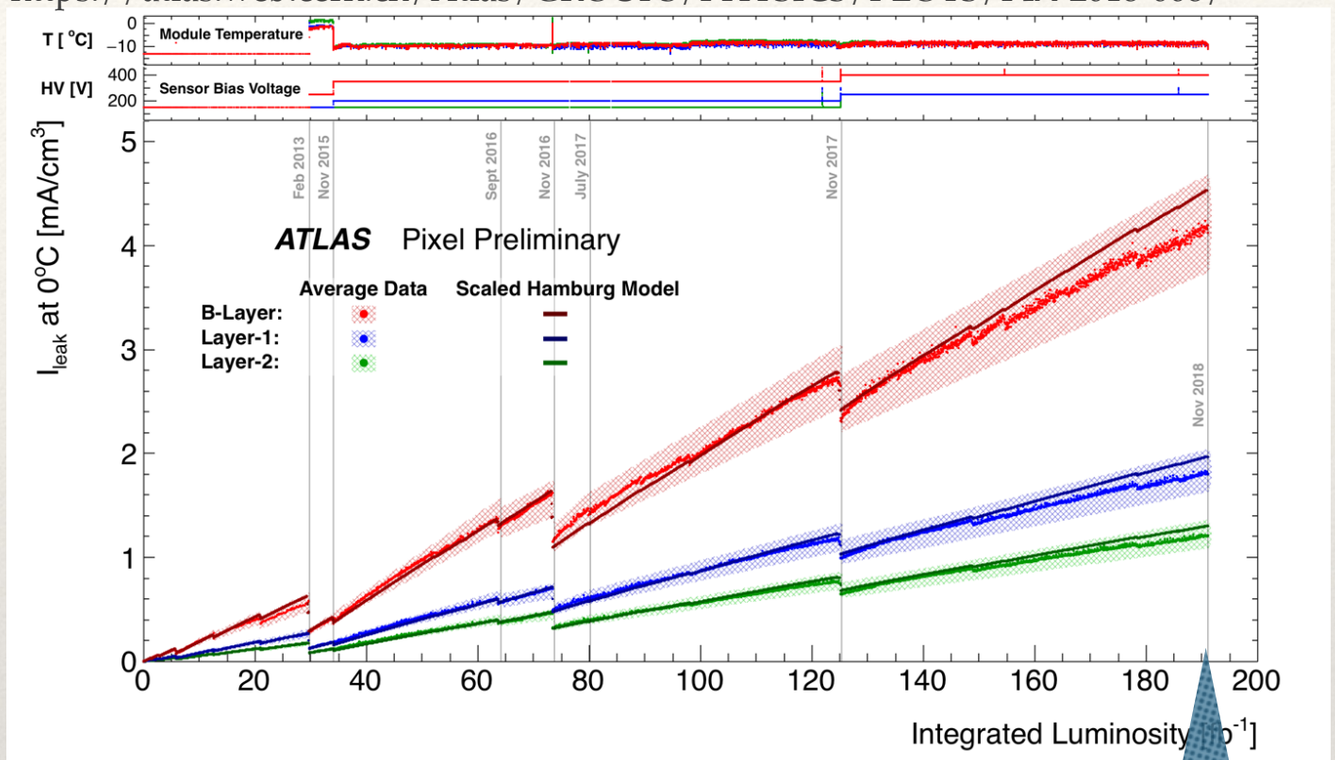
Defect introduced by not ionizing energy loss.

Their nature changes with time (**annealing**, strong dependence on temperature), described by Hamburg model [1].

Consequences :

1. **Increase in leakage current**

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-008/



Data vs Hamburg Model prediction
(normalized to data for each layer)

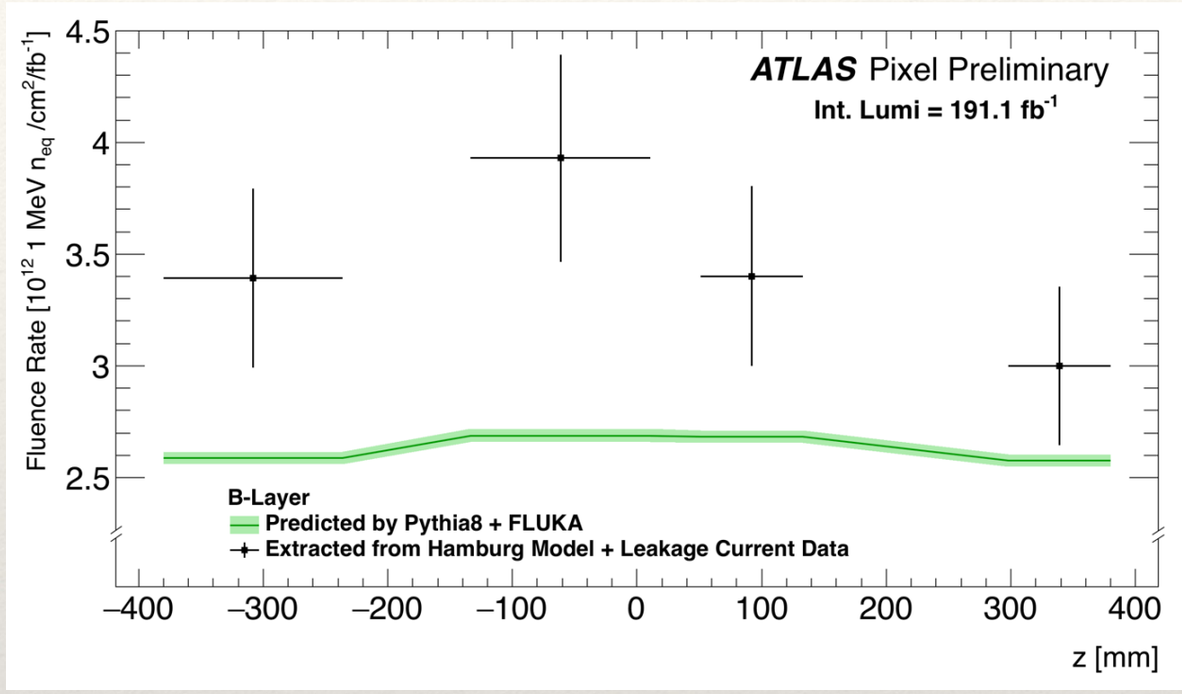
191 fb^{-1}
(includes non stable beam luminosity)

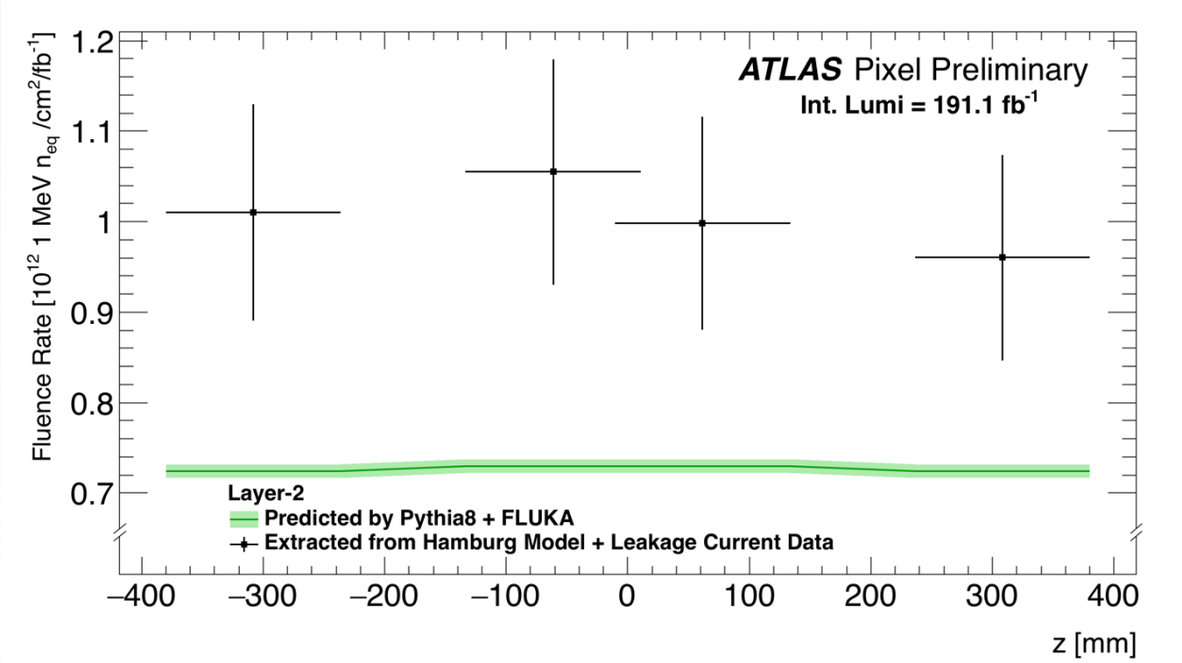
[1] M. Moll, PhD thesis: Hamburg U., 1999,
http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis99-040

FLUENCE AND LEAKAGE CURRENT

- Hamburg Model predictions, scaled to match the data for each layer and z-bin
- time evolution well modeled
- Fluence from leakage current 20-40% larger than Pythia+FLUKA calculation
  - z- and radius-dependence in agreement with calculation

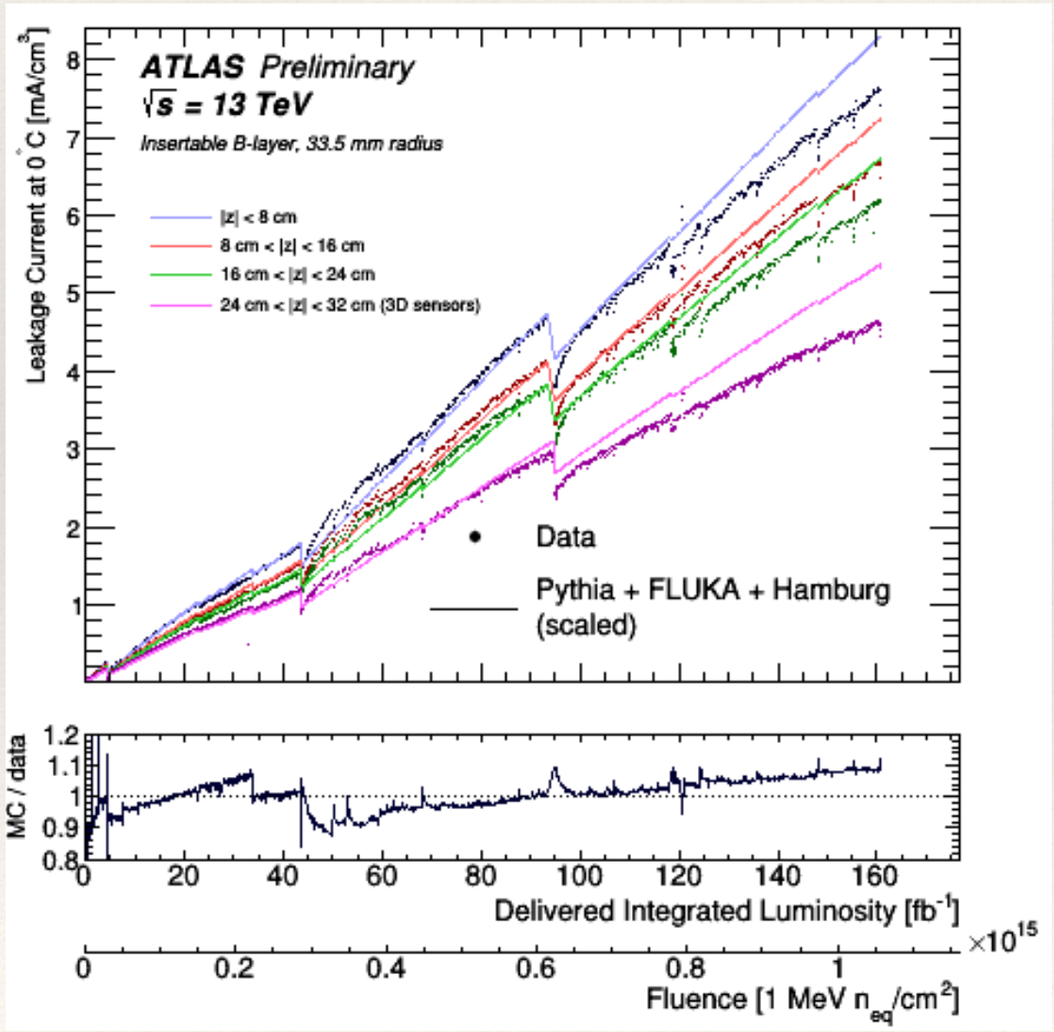
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-008/

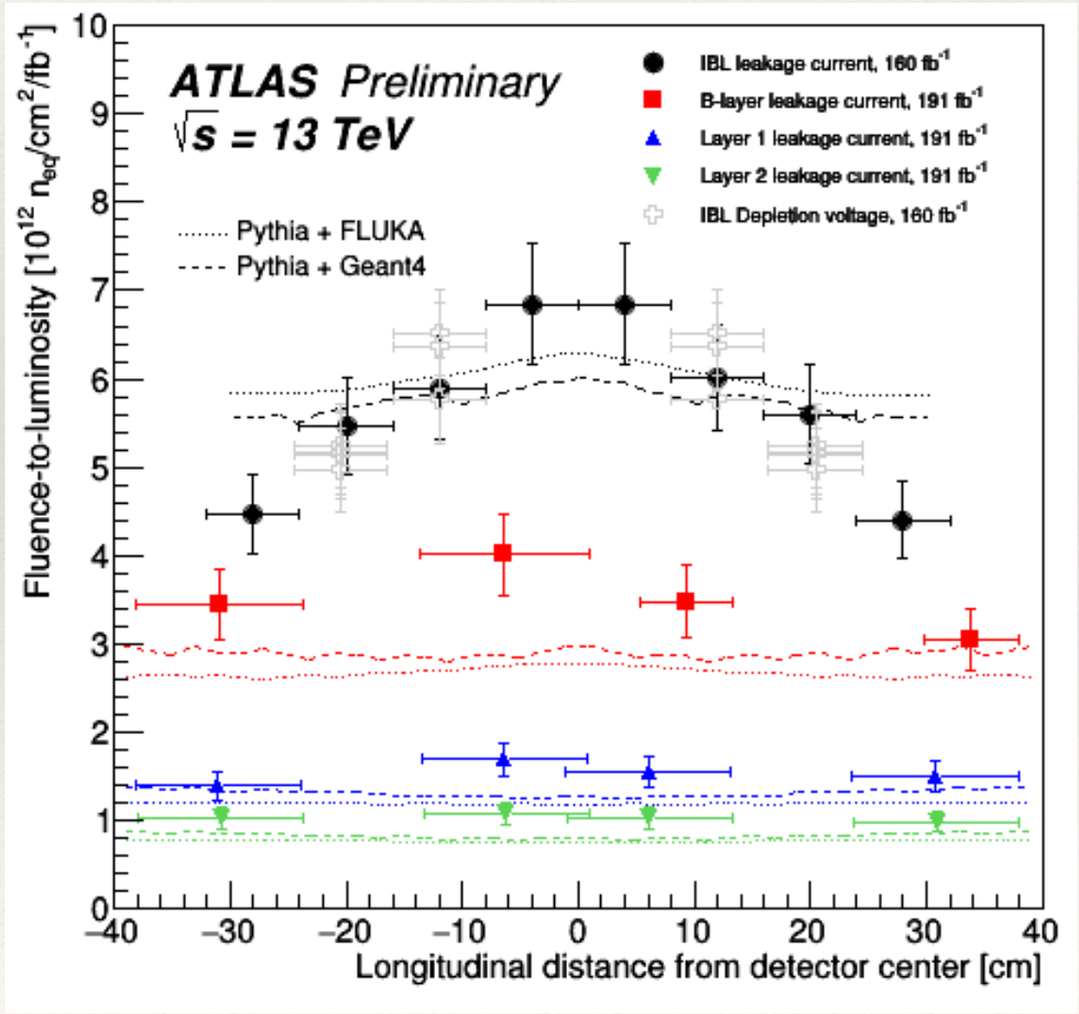




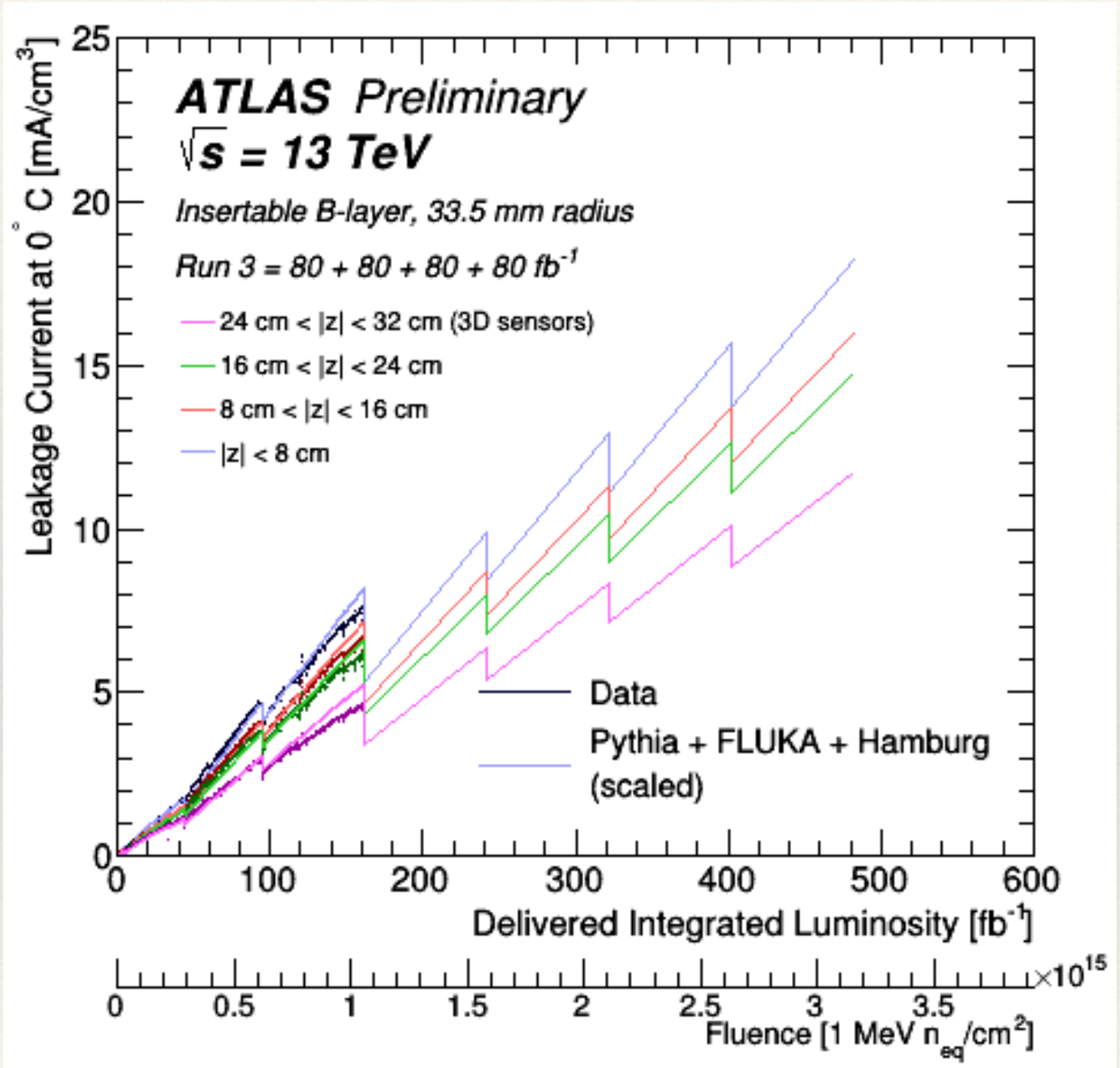
FLUENCE AND LEAKAGE CURRENT : IBL

- Time dependence also well modeled for IBL
- The z-dependence shows less fluence at high |z| than predicted by FLUKA+Pythia calculation. Supported by depletion voltage and Lorentz Angle measurements (see later)





IBL LEAKAGE CURRENT : RUN3 PROJECTIONS



- four year and 320 fb^{-1} for Run 3 considered as worst case (current plans are three years and 200 fb^{-1})
- up to 3 10^{15} n_{eq} cm^{-2} fluence by the end of Run 3

EFFECTS OF RADIATION DAMAGE

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-005/

Defect introduced by not ionizing energy loss.

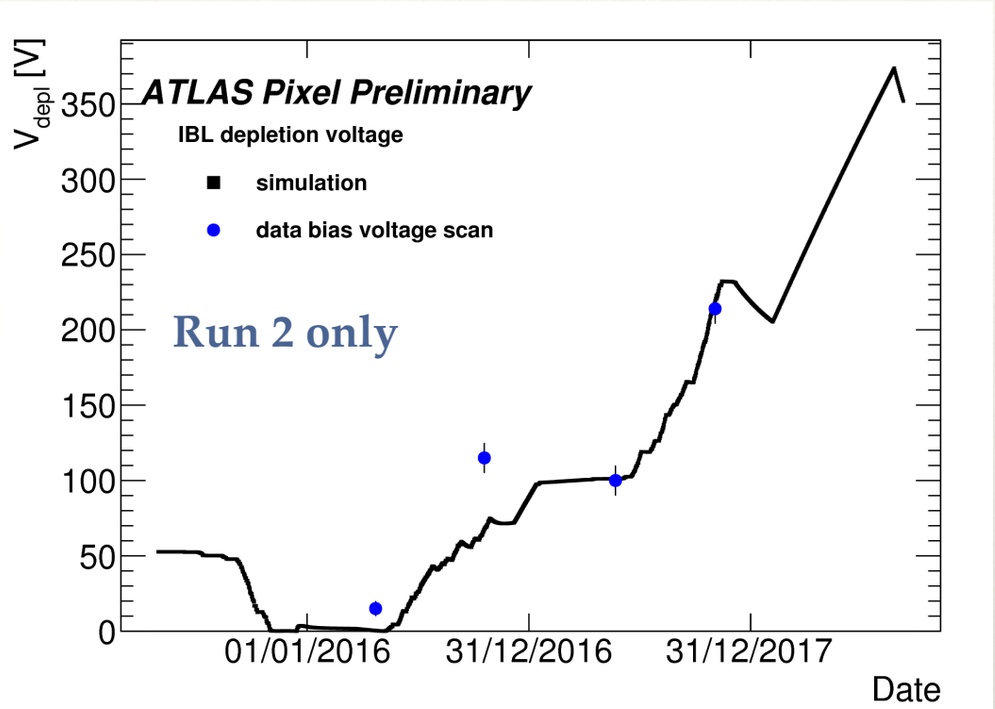
Their nature changes with time (**annealing**, strong dependence on temperature), described by Hamburg model.

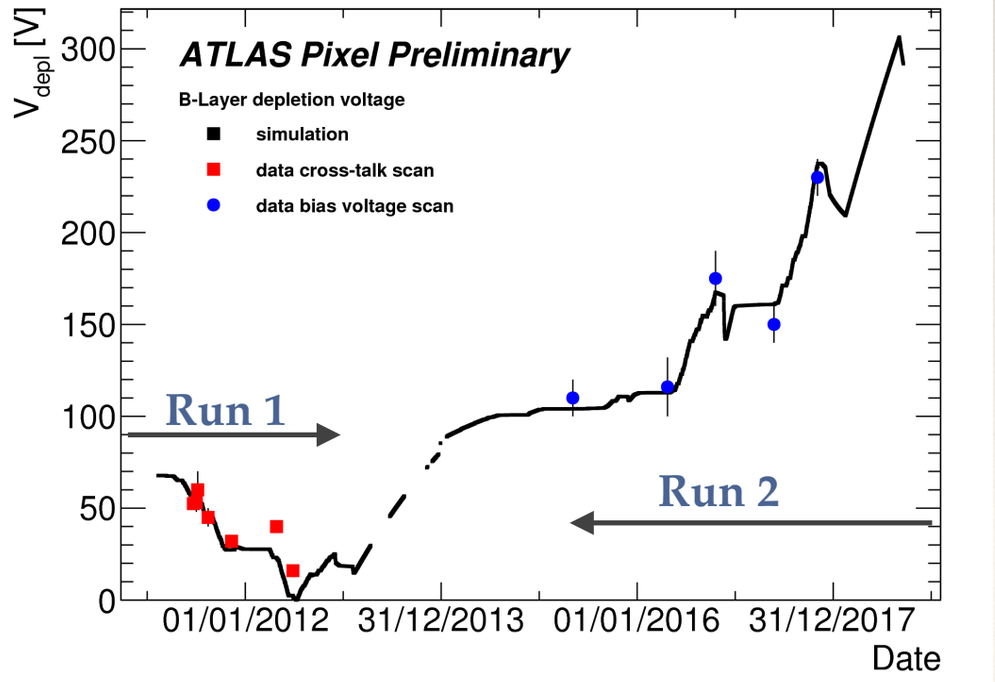
Consequences :

1. **Increase in leakage current**
2. **Higher bias voltage** needed for full depletion and efficient charge collection
   - Measurements compared with Hamburg model prediction, with defect introduction rates fitted to data

Parameter	IBL	B-Layer	Layer 1	Layer 2	ROSE values [2]	
g_A [cm^{-1}]	0.7 10^{-2}	0.6 10^{-2}	1.35 10^{-2}	1.35 10^{-2}	1.4 10^{-2}	beneficial annealing
g_Y [cm^{-1}]	6.0 10^{-2}	6.0 10^{-2}	6.0 10^{-2}	6.0 10^{-2}	n: 2.3 10^{-2} p: 4.8 10^{-2}	reverse annealing
g_C [cm^{-1}]	0.7 10^{-2}	0.43 10^{-2}	0.6 10^{-2}	0.9 10^{-2}	n: 0.53 10^{-2} p: 2.0 10^{-2}	stable damage

[2] G. Lindstrom et al., CERN-LHCC-2000-009, https://cds.cern.ch/record/421210





EFFECTS OF RADIATION DAMAGE

Defect introduced by not ionizing energy loss.

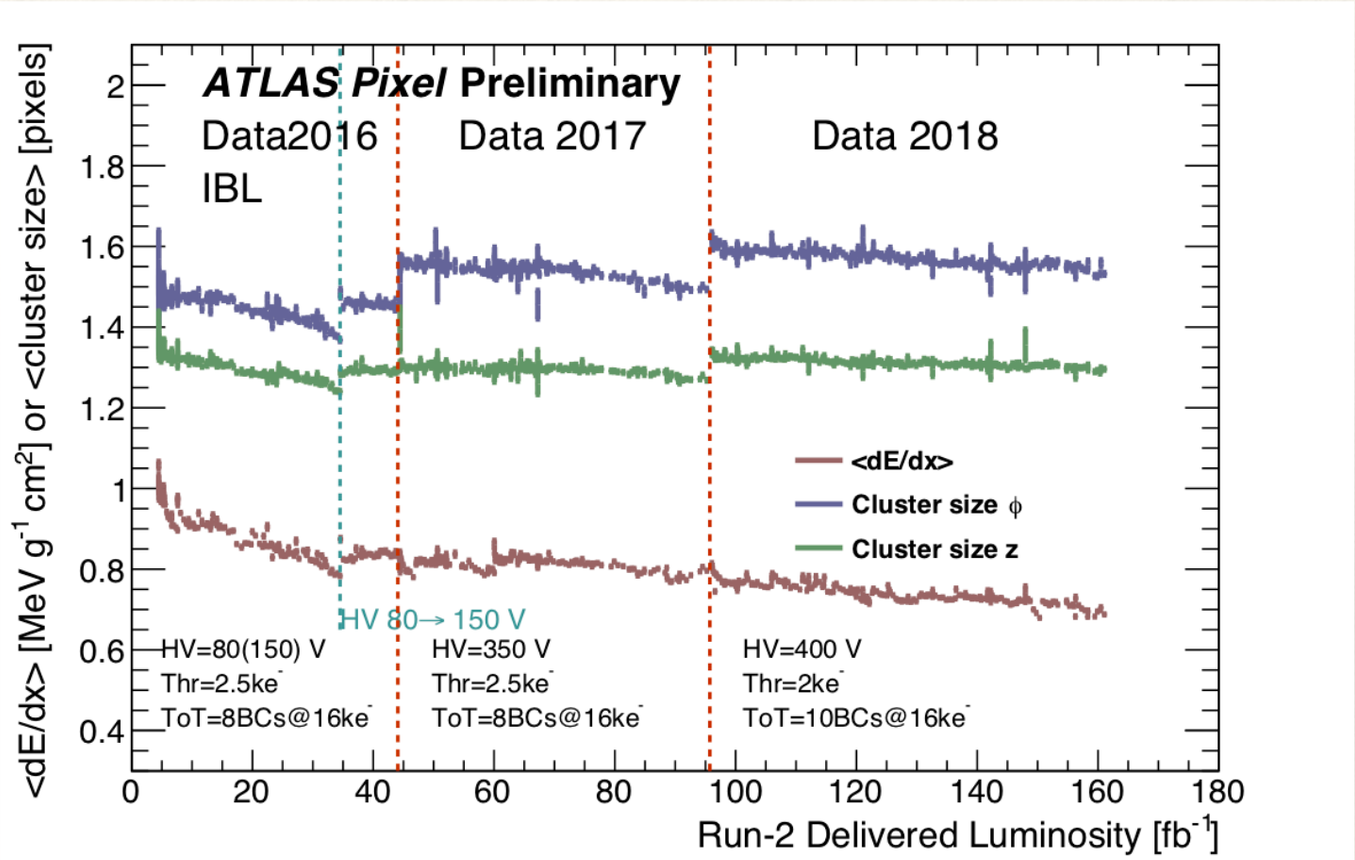
Their nature changes with time (**annealing**, strong dependence on temperature), described by Hamburg model.

Consequences :

1. **Increase in leakage current**
2. **Higher bias voltage** needed for full depletion and efficient charge collection
3. **Reduction of collected charge** (trapping [3,4,5])
   - cluster size, resolution etc. also affected

Need to include the radiation damage in detector response simulation - the rest of this talk

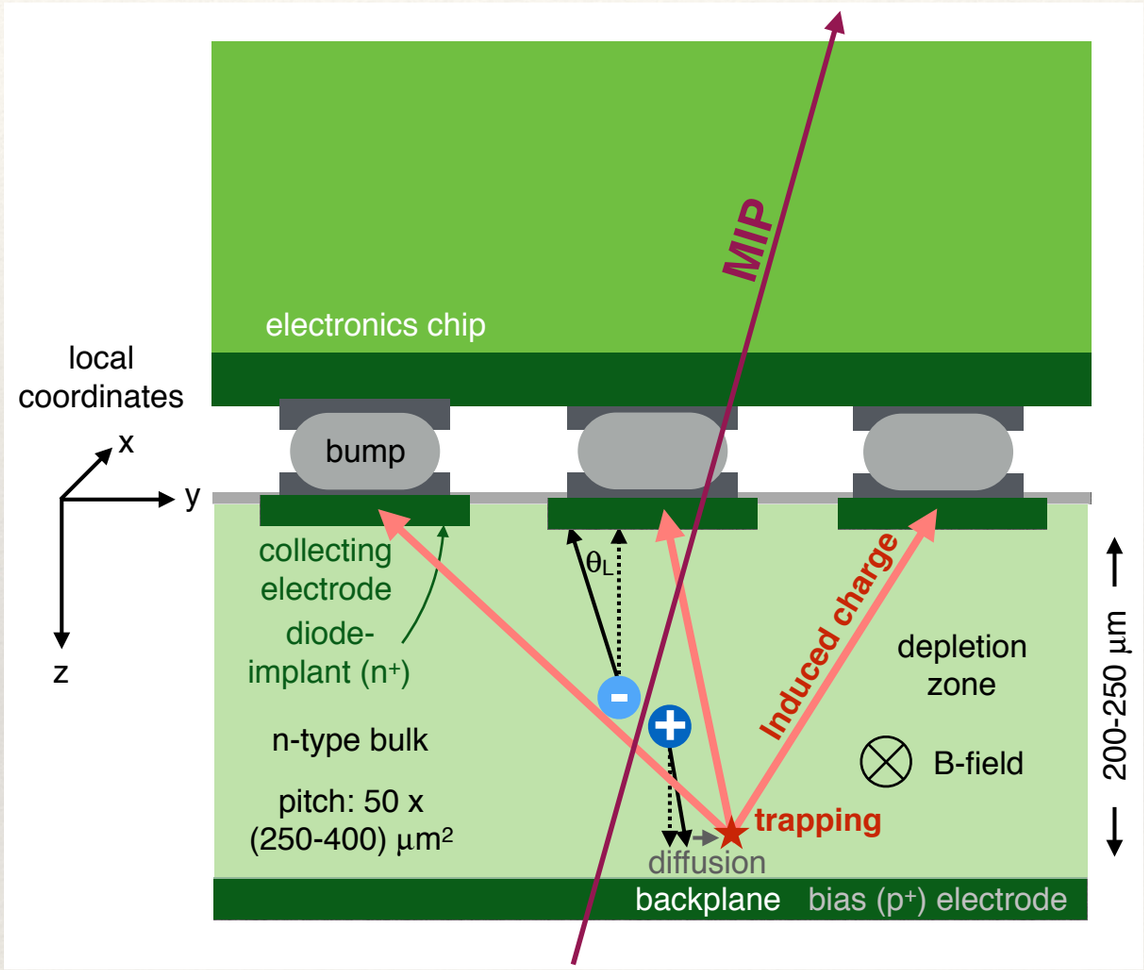
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-011/



[3] O. Krasel et al., IEEE Trans on Nucl. Sci. 51 (2004) 3055
[4] G. Kramberger et al., Nucl. Instr. and Meth. A481 (2002) 297
[5] G. Alimonti et al., ATL-INDET-2003-014

DIGITIZER

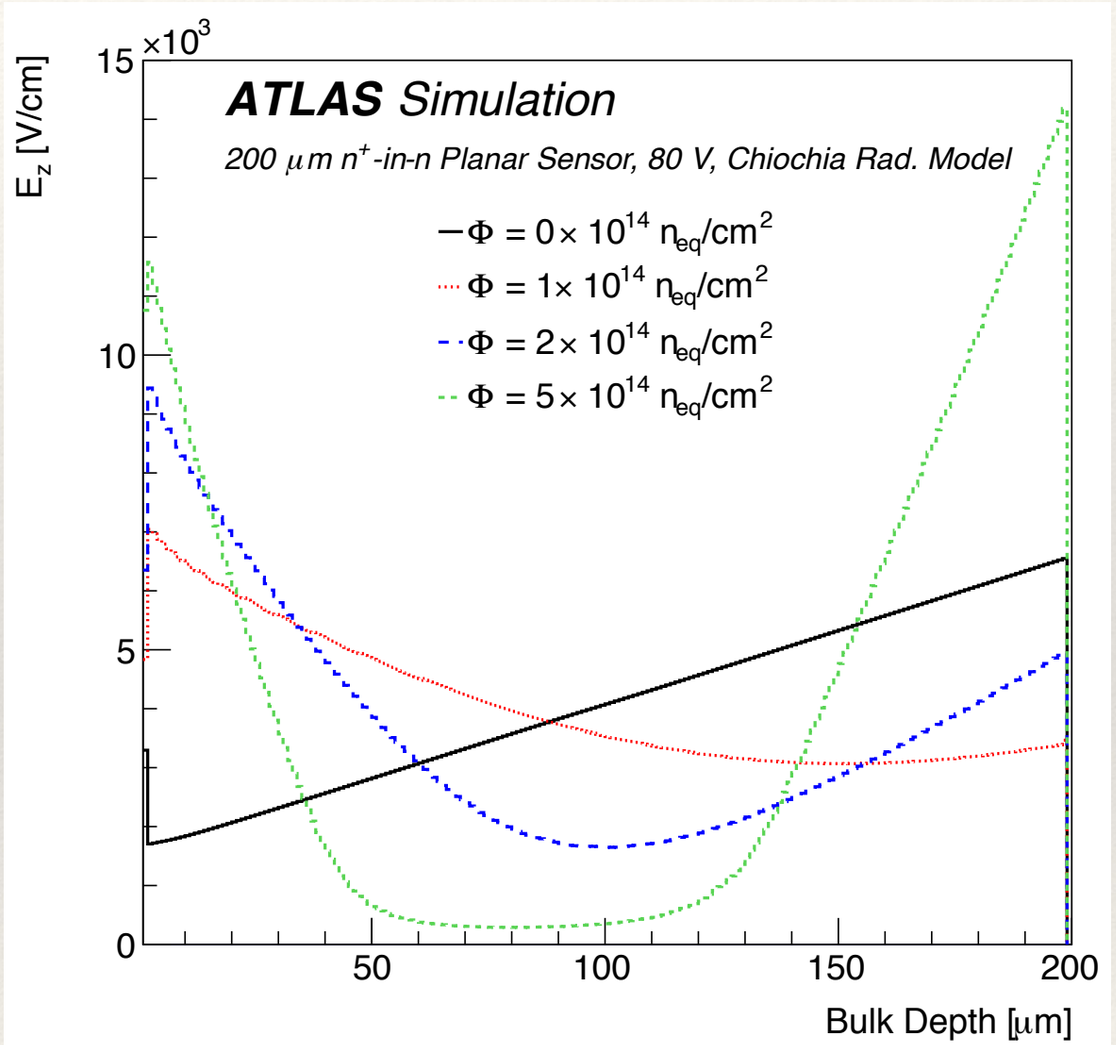
- From particles energy deposits (Geant4 hits) to the Front-End signal in RAW data format
- Elements :
  - Calculation of electric field inside the sensor
  - Charge trapping
  - Drift, diffusion, signal formation
- Used in standalone simulator
- Being implemented for the first time in the ATLAS official simulation (under validation)



ELECTRIC FIELD

- Bulk defects model based on [6]
- Electric field calculated with TCAD
- This describes space charge variation with position inside the sensor (double peak field) but not for defect annealing
  - Hamburg model instead describe annealing but not the position dependence
  - We rescale the space charge to the value predicted by Hamburg model

JINST 14 (2019) 06 P06012 (arXiv:1905.03739)

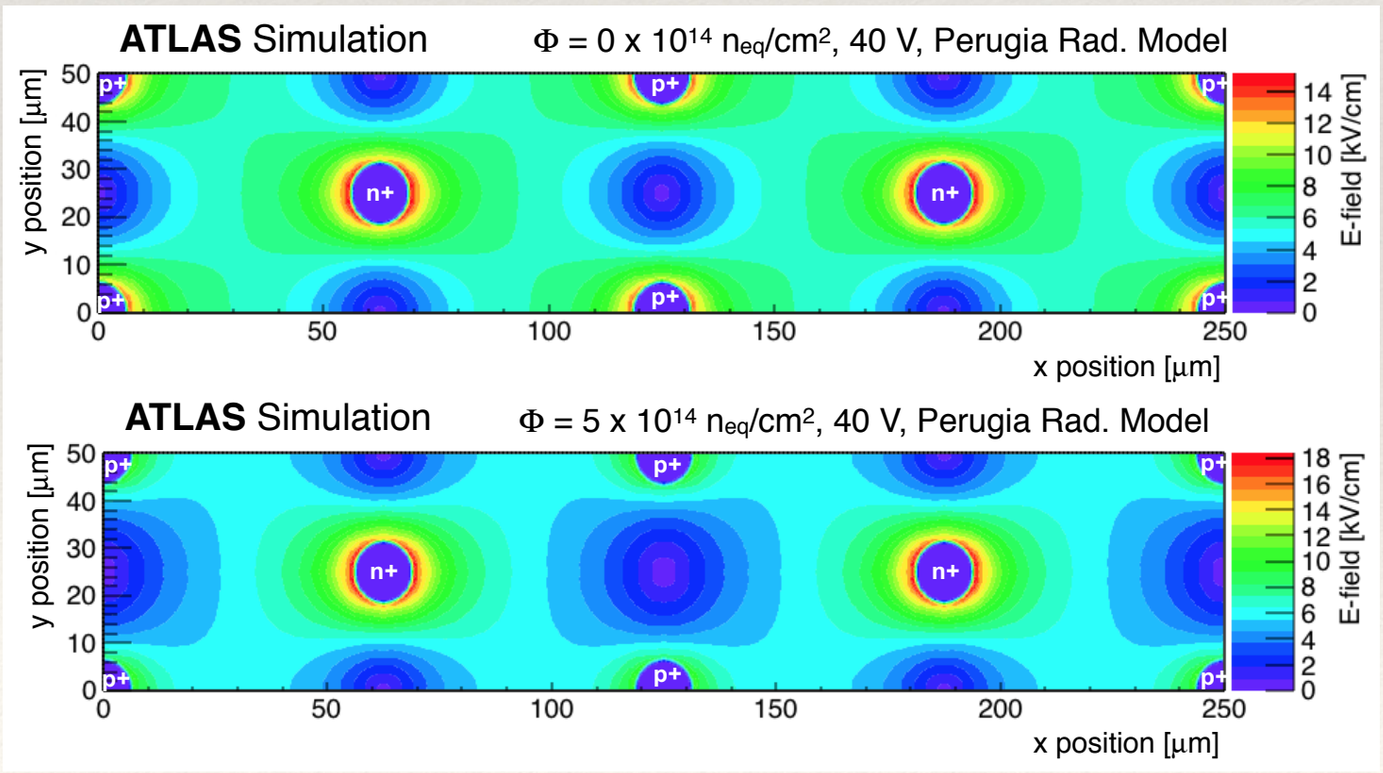


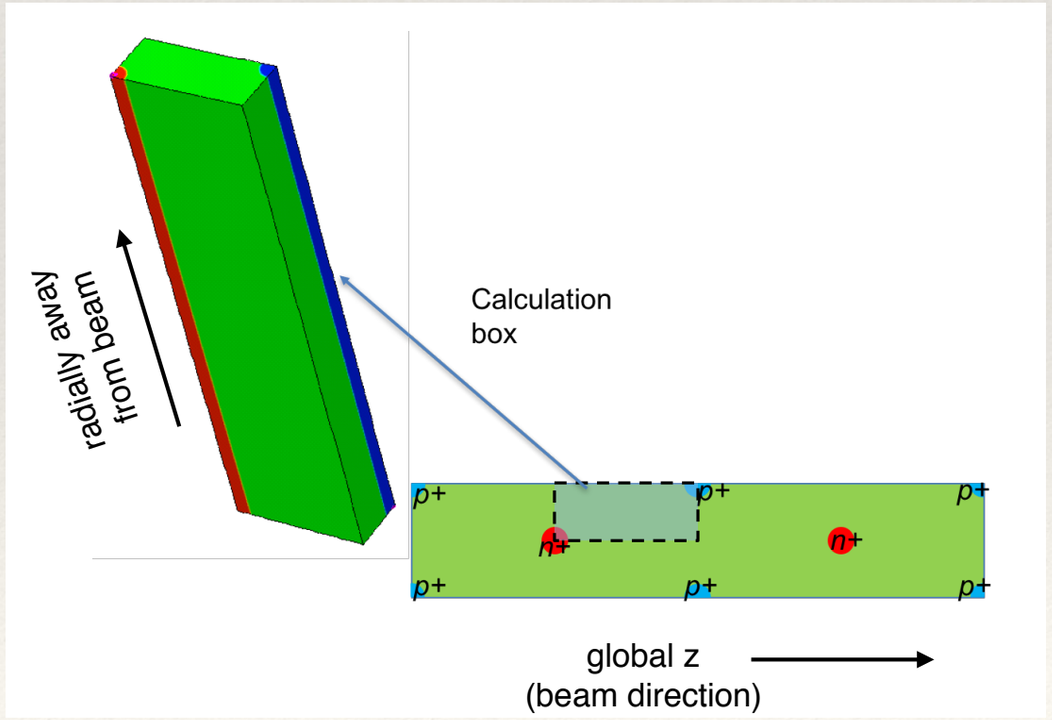
[6] V. Chiochia et al., Nucl. Inst. and Meth. A 568 (2006) 51

3D sensor simulations

- Similar to planar simulation but
  - Using Perugia model [7] of defect creation (Chiochia not applicable for p-in-n).
  - Different boundary conditions (3D electrodes)
- Region of low electric field between the electrodes gets larger with irradiation

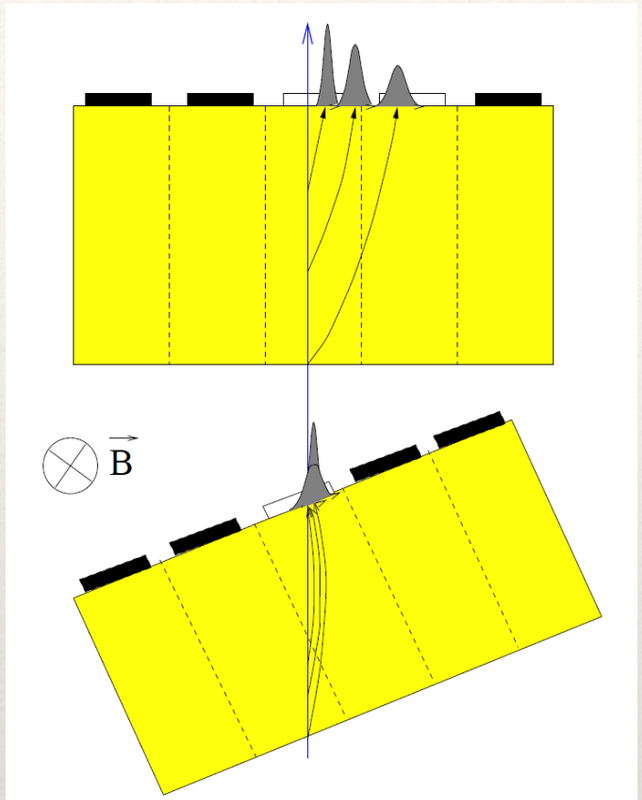
JINST 14 (2019) 06 P06012 (arXiv:1905.03739)





[7] F. Moscatelli et al., IEEE Trans. on Nucl. Sci. 63 (2016) 2716

CHARGE DRIFT

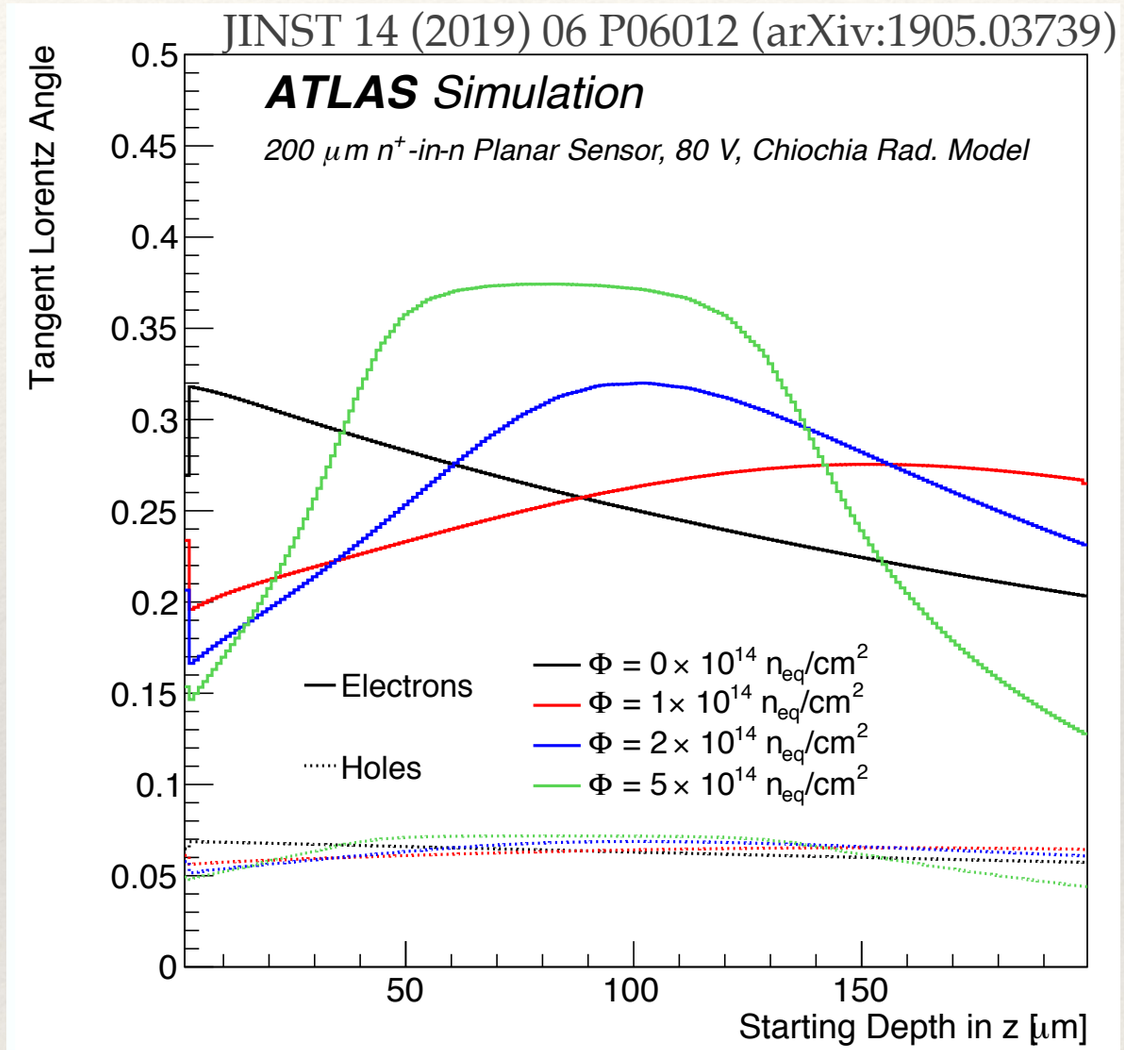


$$\tan\theta_L^{integrated}(z_{initial}, z_{final}) = \frac{rB}{|z_{final} - z_{initial}|}\int_{z_{initial}}^{z_{final}} \mu(E(z))dz$$

Hall scattering factor

Mobility

JINST 14 (2019) 06 P06012 (arXiv:1905.03739)



- Electric field => Lorentz angle variation inside the sensor
- Drift along electric field and diffusion

CHARGE TRAPPING

- Electron and hole lifetime inversely proportional to fluence

$$\tau = 1/\beta\Phi$$

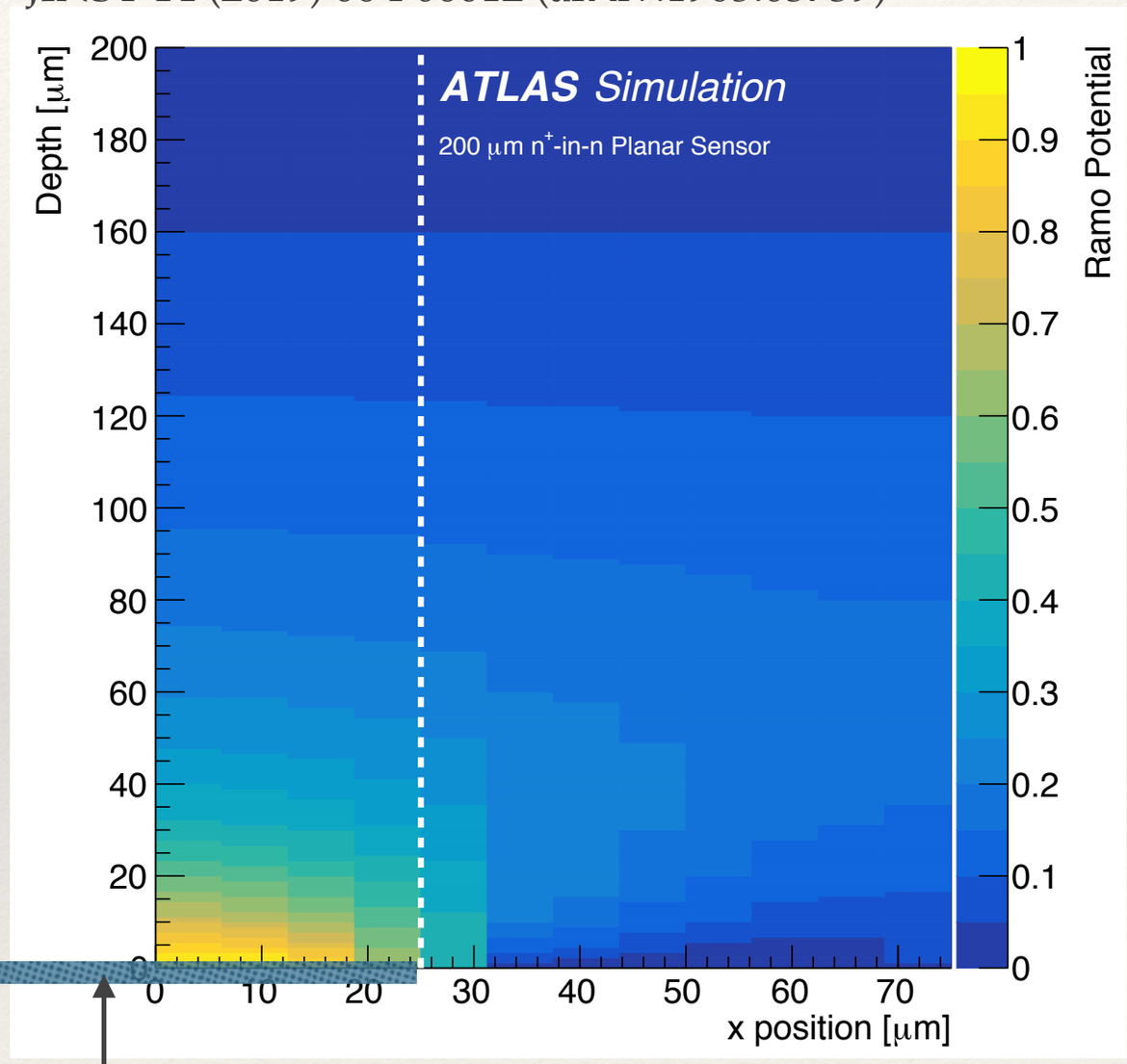
- Use β values measured in literature

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

the error covers difference between different measurements [3,4,5], between neutral and charged irradiation, and the dependence on annealing

- Charges trapped before reaching the electrodes still induce a signal, calculated with the Ramo potential

JINST 14 (2019) 06 P06012 (arXiv:1905.03739)



pixel electrode (-25 to 25 micrometers) at potential 1

Use symmetry : map only for x > 0

[3] O. Krasel et al., IEEE Trans on Nucl. Sci. 51 (2004) 3055
[4] G. Kramberger et al., Nucl. Instr. and Meth. A481 (2002) 297
[5] G. Alimonti et al., ATL-INDET-2003-014

CONDITIONS DURING RUN2

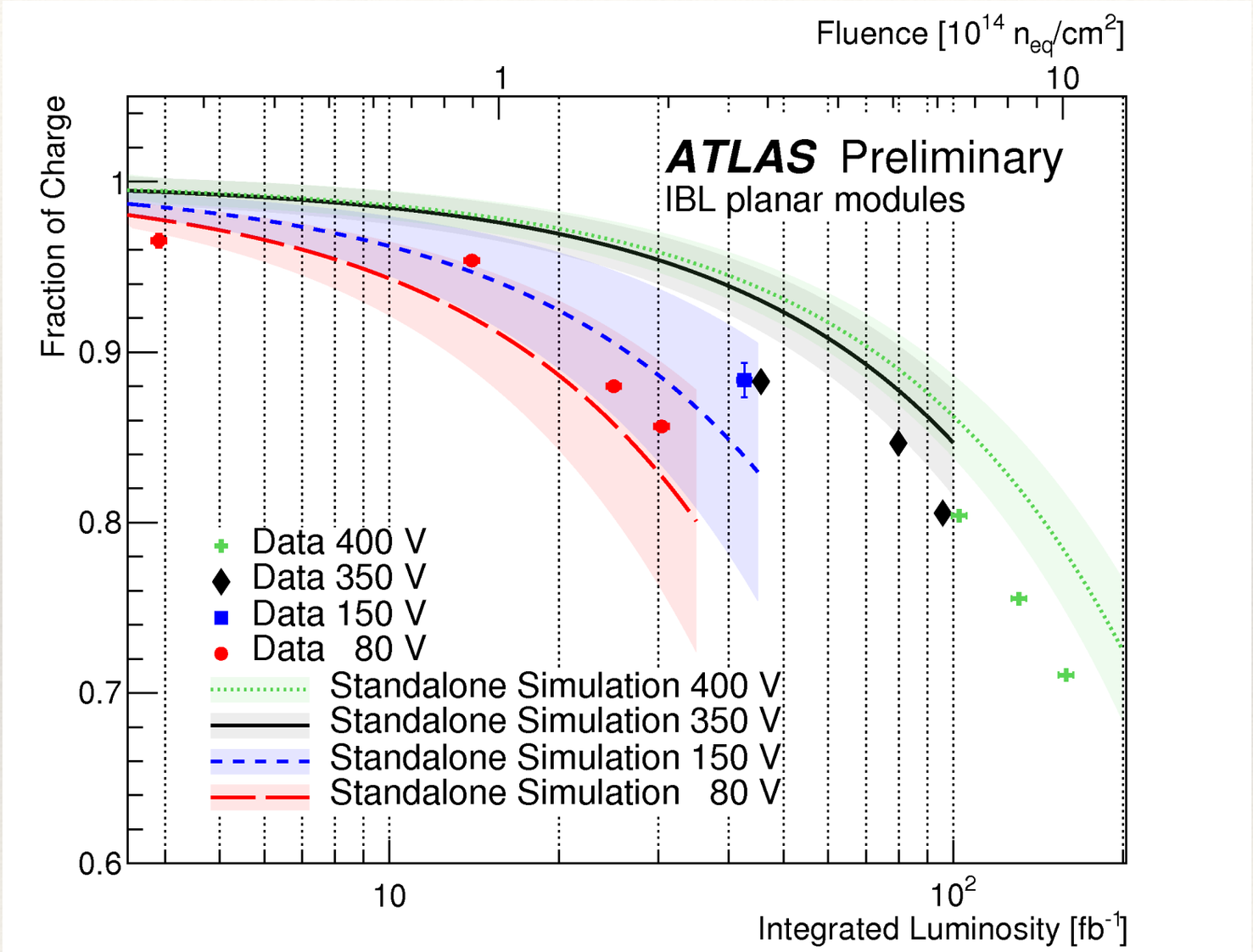
- Measurements with run2 data used to validate the digitizer predictions
- Conditions : bias voltage gradually increased to maintain good charge collection efficiency

Bias voltage	2015	2016	2017	2018	maximum allowed value
IBL	80 V	80 V	350 V	400 V	1000 V
B-layer	250 V	350 V	350 V	400 V	600 V
Layer 1	150 V	200 V	200 V	250 V	600 V
Layer 2	150 V	150 V	150 V	250 V	600 V

CHARGE COLLECTION EFFICIENCY

- Fair agreement of measurements and standalone simulation
- CCE at the end of Run2 is 70%
  - MPV at the end of Run2 10 ke, detection threshold 2 ke

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-004/



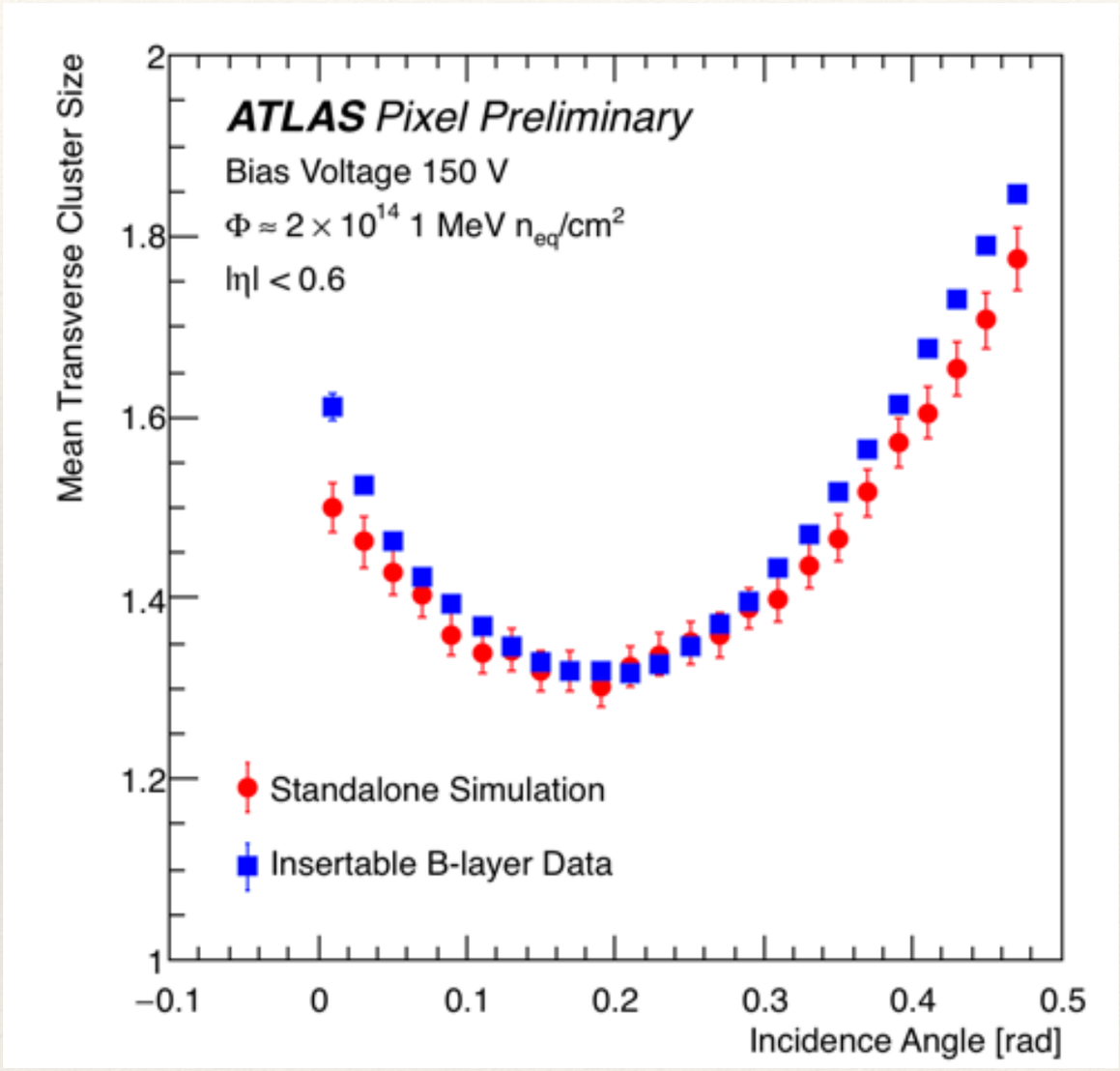
Error band includes :

- Uncertainty on fluence to luminosity conversion
- Variation of radiation damage parameters

LORENTZ ANGLE

- Measured as minimum of cluster size vs angle

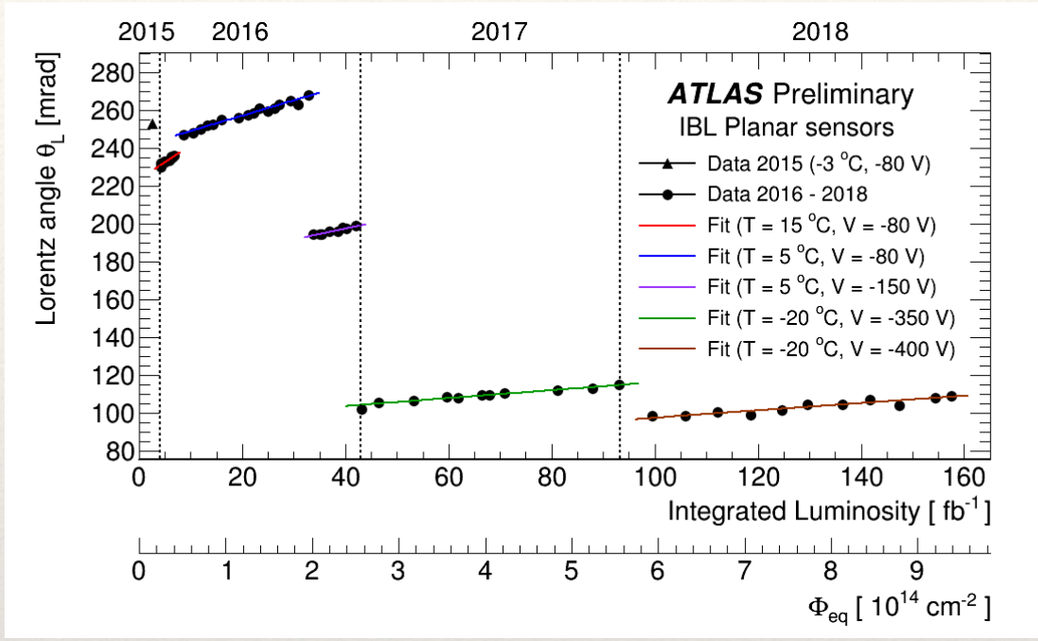
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-005/

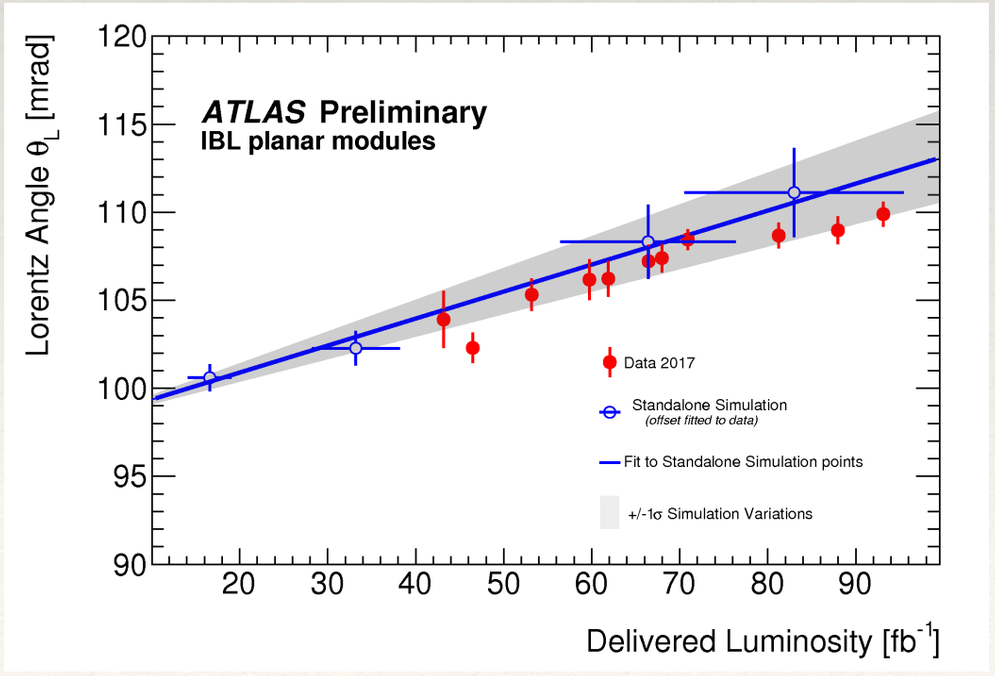


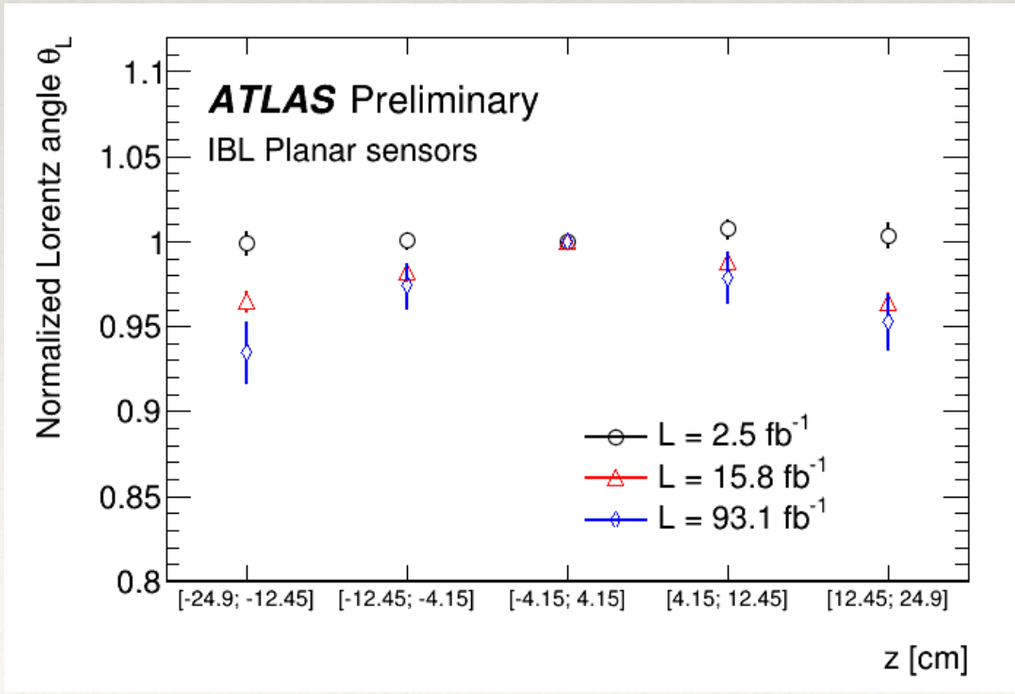
LORENTZ ANGLE

- Big jumps when bias voltage is changed
- At fixed bias voltage, Lorentz angle changes because of changing electric field shape inside the sensor - **probing modeling of electric field profile**
- Lorentz angle vs z measurement supports decrease of fluence along longitudinal coordinate

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-005/







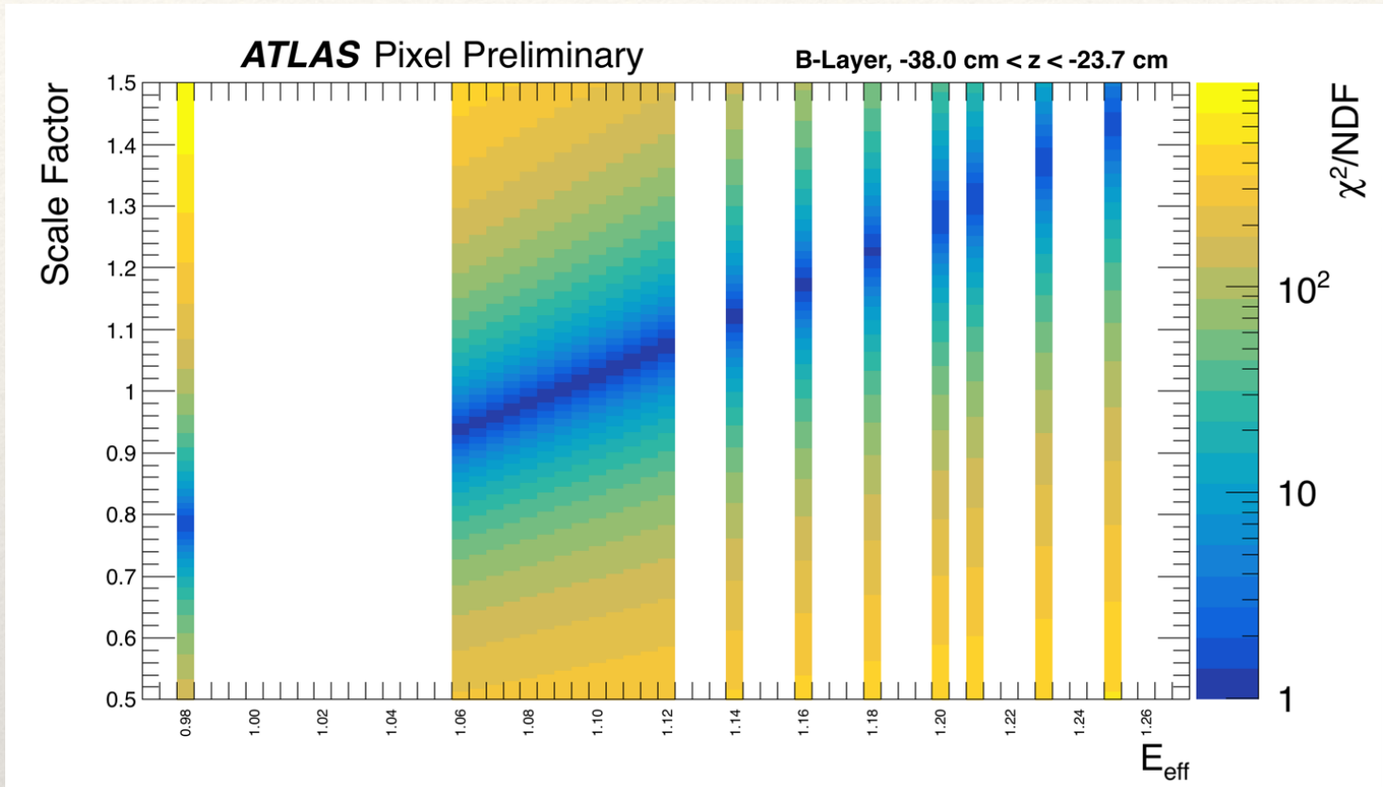
CONCLUSIONS

- Radiation damage effects are increasingly important for the vertex detectors at the LHC
- ATLAS has a very active group to monitor radiation damage effects and implement them in the detector simulation
- Leakage current well modeled but requiring lower fluence than calculations at small radius and large |z|
- Space Charge density also well modeled, but requiring custom values for defect introduction rates.
- Charge Collection Efficiency modeled by a digitizer based on TCAD calculation of electric field inside the sensor (JINST 14 (2019) 06 P06012). Lorentz angle measurements probing the electric field shape and in agreement with the calculation
- We are not done yet ! Still working on improving the model, more measurements, etc.

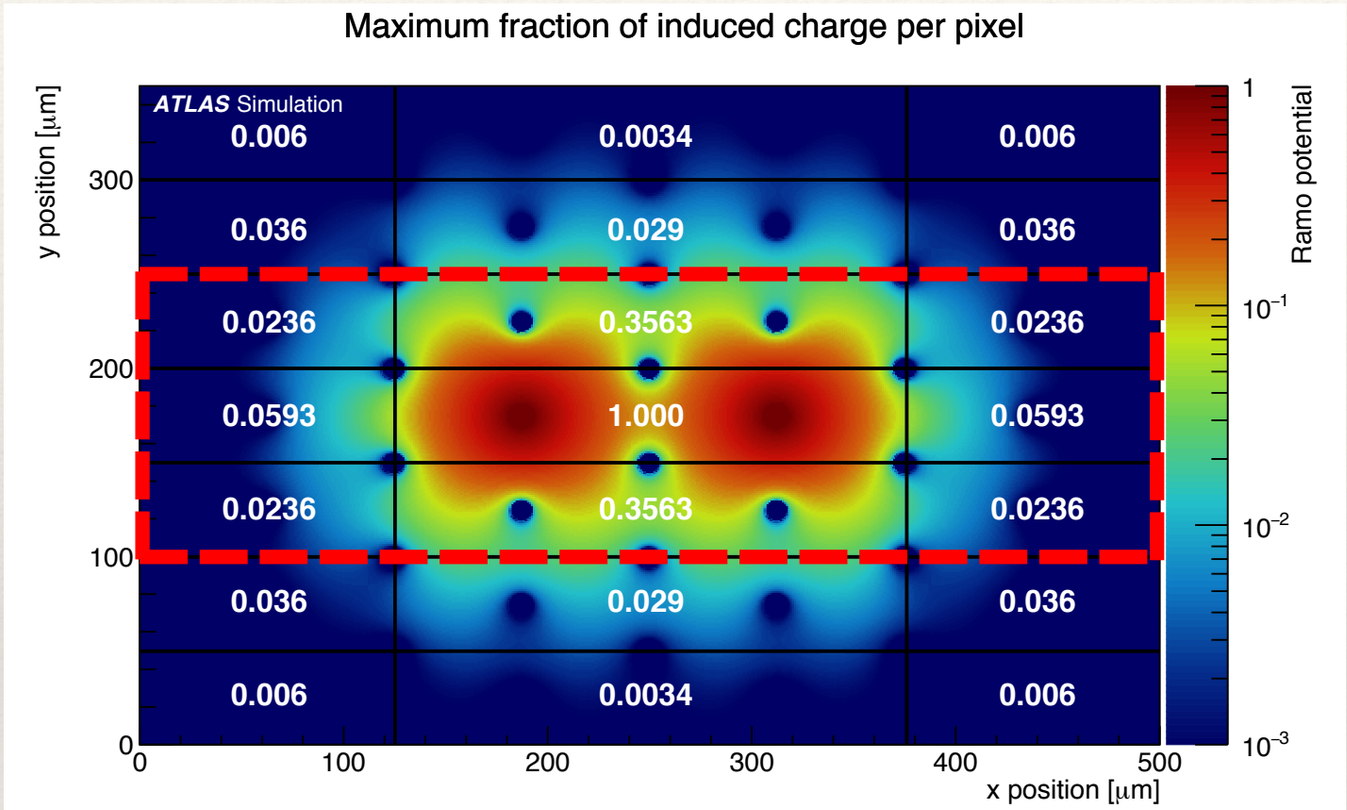
BACKUP

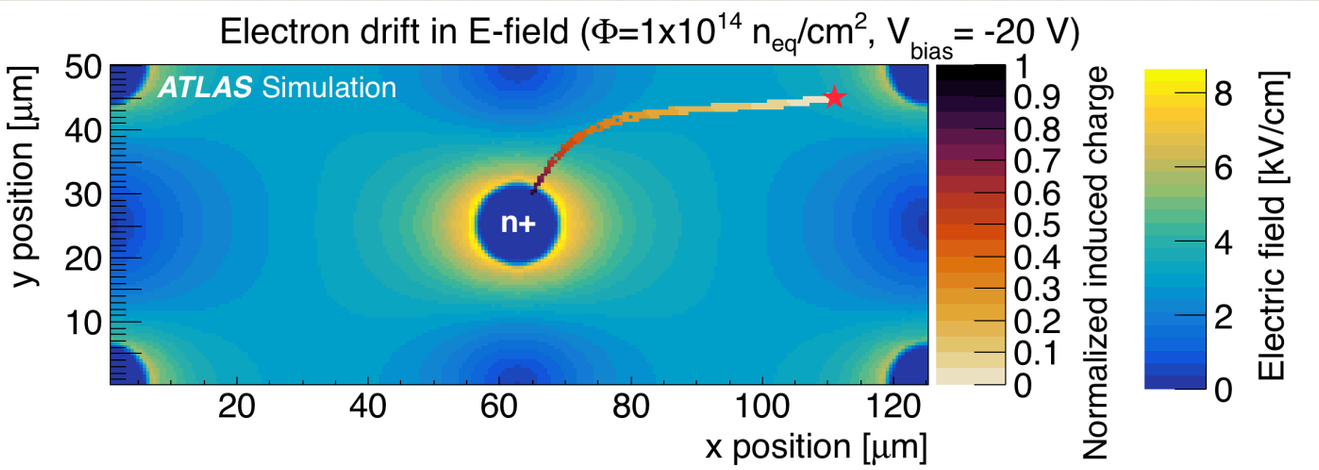
LEAKAGE CURRENT SCALE FACTORS

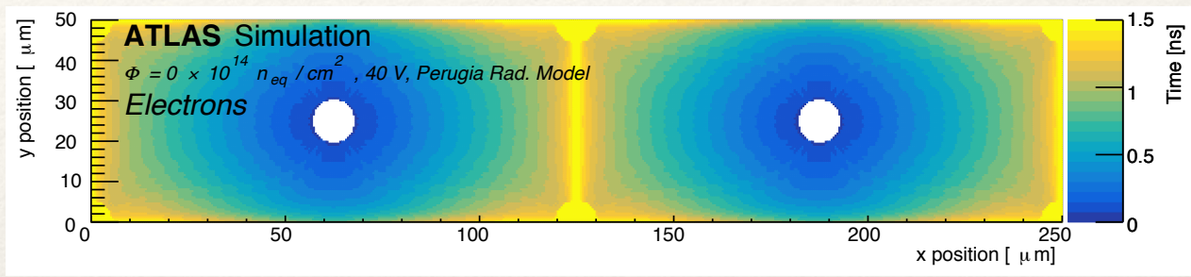
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-008/



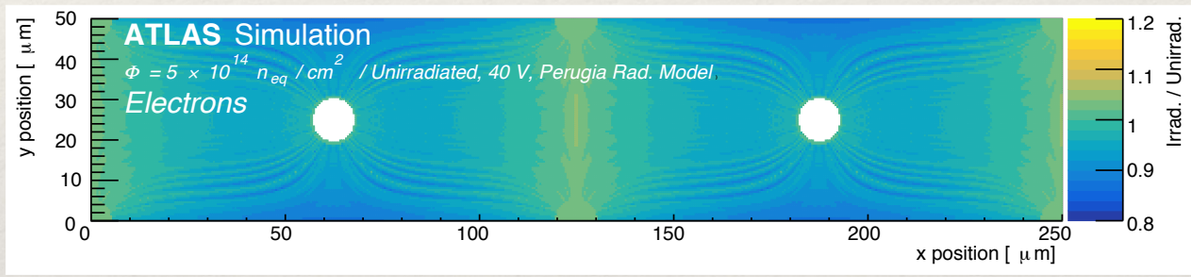
3D sensors



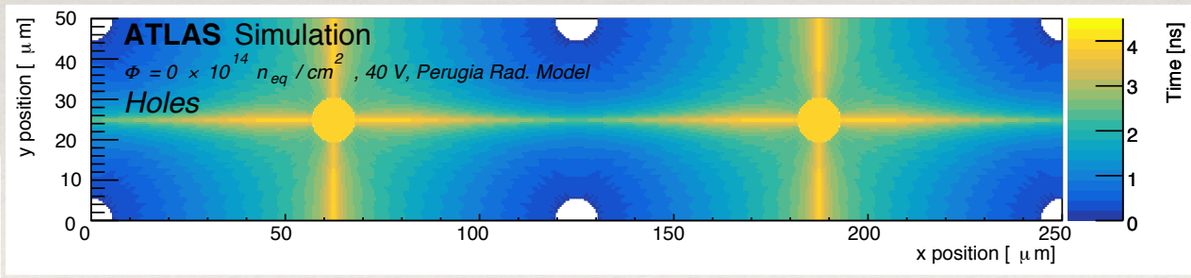




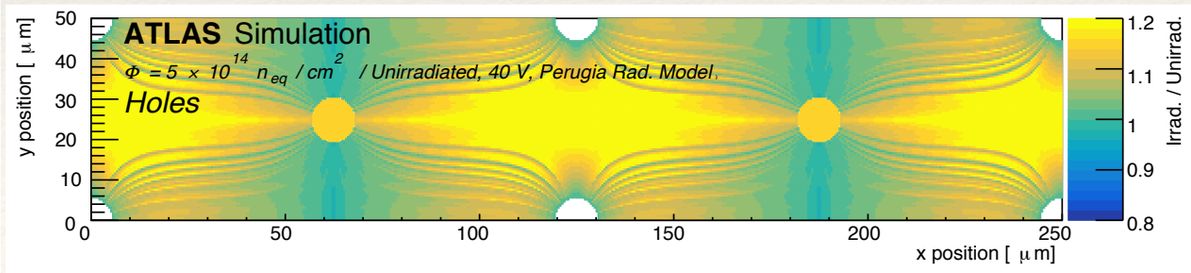
(a)



(b)



(c)

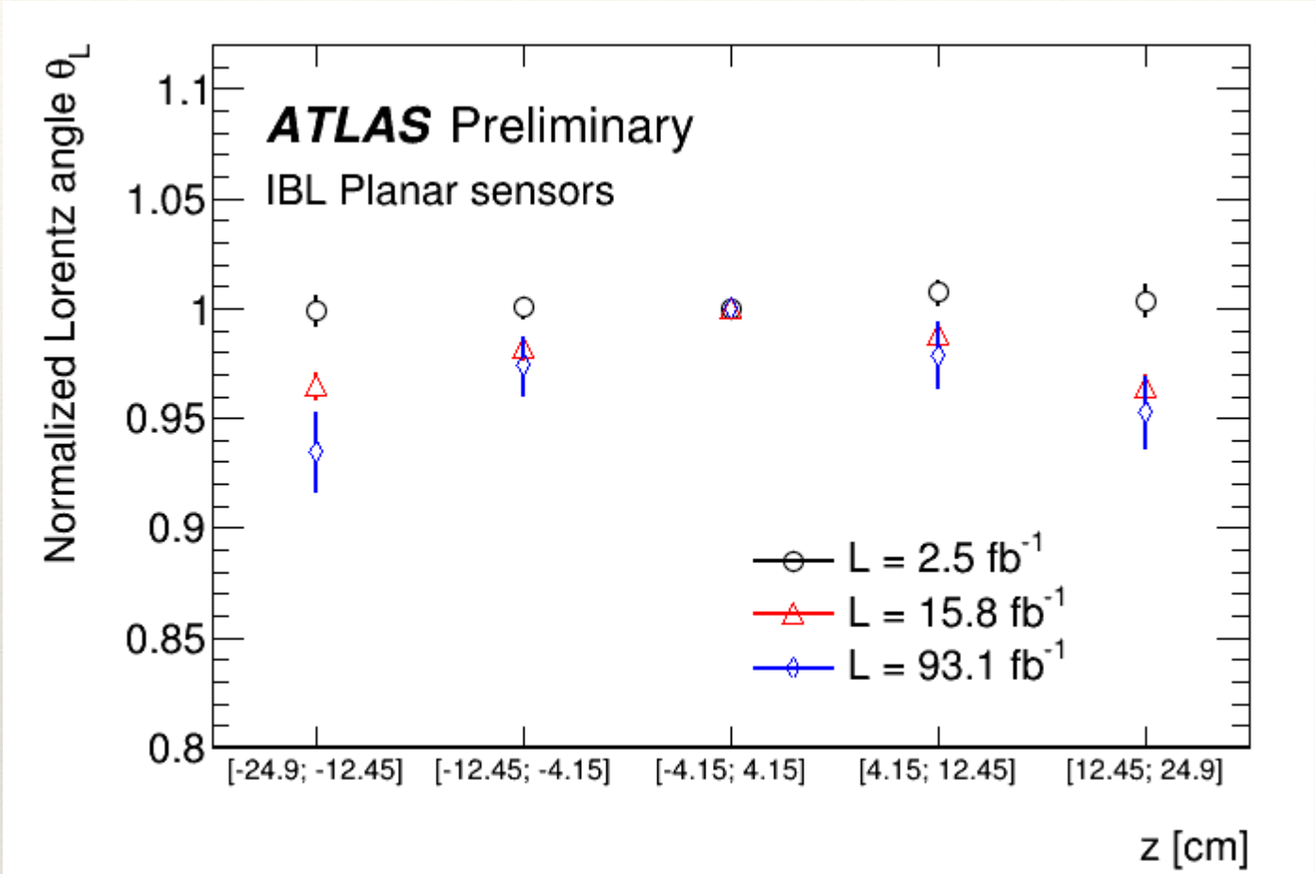


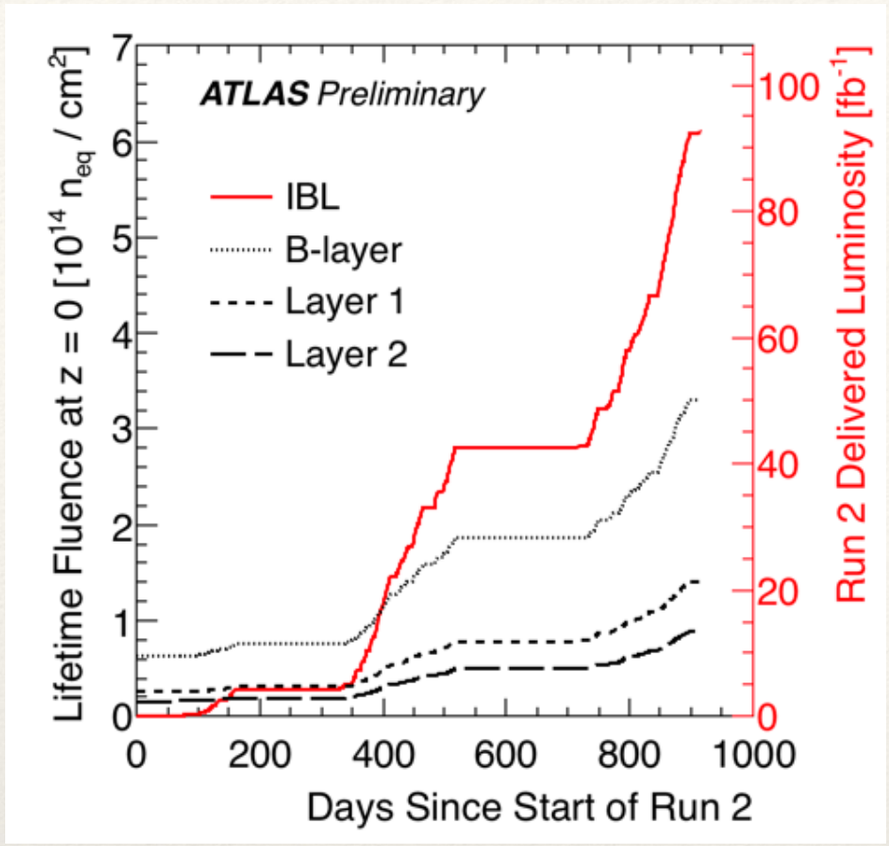
(d)

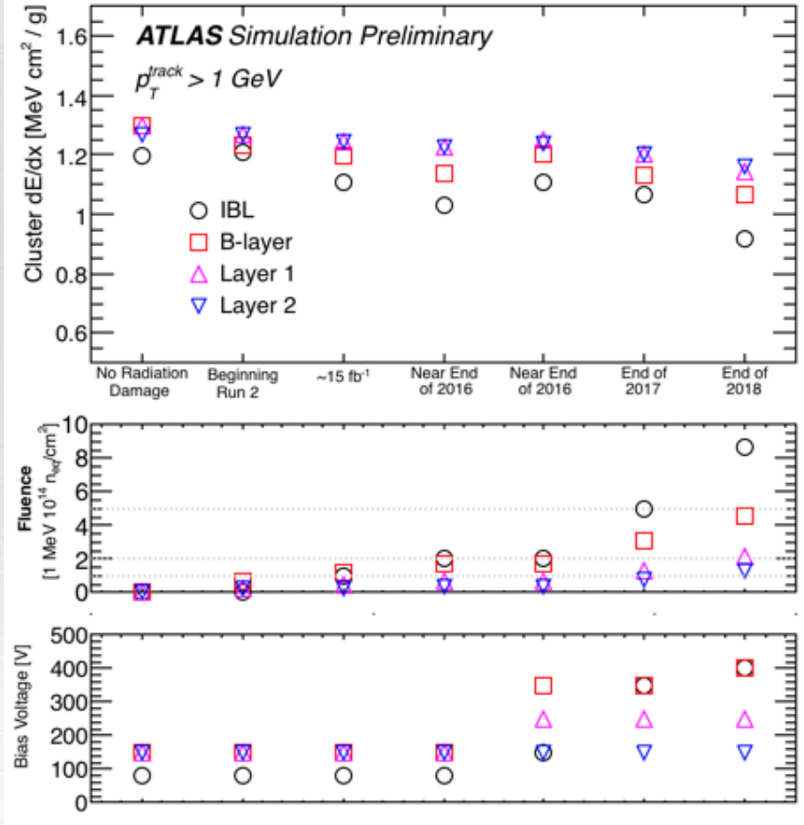
LORENTZ ANGLE

Also, Lorentz angle decreases with z - supporting leakage current based inference of lower fluence at large |z|

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-005/




ATLAS Preliminary
IBL
B-layer
Layer 1
Layer 2
Lifetime Fluence at z = 0 [10^14 n_eq / cm^2]
Run 2 Delivered Luminosity [fb^-1]
Days Since Start of Run 2


ATLAS Simulation Preliminary
p_T^track > 1 GeV
IBL
B-layer
Layer 1
Layer 2
Cluster dE/dx [MeV cm^2 / g]
No Radiation Damage
Beginning Run 2
~15 fb^-1
Near End of 2016
Near End of 2016
End of 2017
End of 2018
Fluence [1 MeV 10^14 n_eq/cm^2]
Bias Voltage [V]

Data - 4/11/2017
Data - 16/10/2018
Standalone Simulation: ϕ=5.5 10^14 n_eq/cm^2 (end 2017) - TCAD high fl. setup
Standalone Simulation: ϕ=8.7 10^14 n_eq/cm^2 (end 2018) - TCAD high fl. setup
ATLAS
Preliminary
IBL planar modules
Fraction of Collected Charge
Bias Voltage [V]