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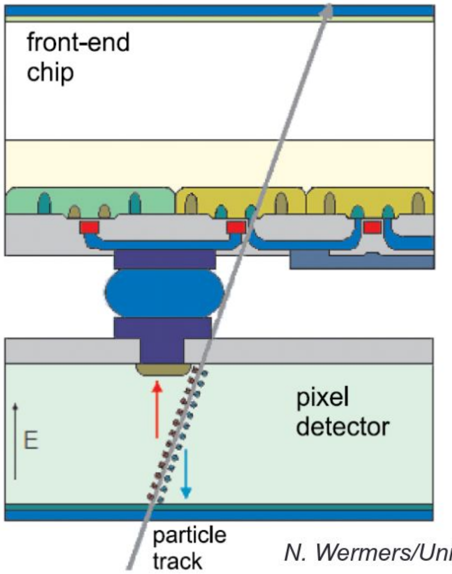
Including radiation damage effects in ATLAS Monte Carlo simulation: Status and perspectives

PSD13: The 13th International Conference of Position Sensitive Detectors

Oxford, 04.09.2023

Tobias Bisanz (TU Dortmund), on behalf of the
ATLAS Collaboration

Scope of this talk



In hybrid pixel modules:

- Radiation effects on readout chips
  - Single event upsets in digital parts of readout chip
  - TID effects on transistor leakage current
- Radiation effects on sensor bulk
  - Change of effective doping concentration → type inversion and change of depletion voltage
  - Loss of charge collection efficiency
  - Shift of Lorentz angle
  - In order to compensate: modify bias voltage and retuning
- Disclaimer: we will not talk about effects on the readout chip

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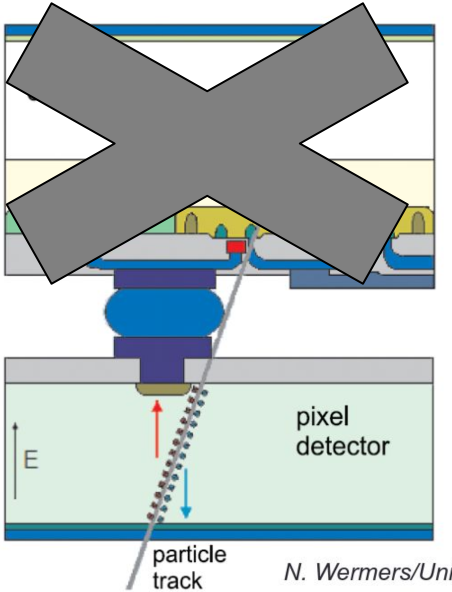

N. Wermers/Univ. of Bonn

In hybrid pixel modules:

- Radiation effec[illegible]n readout c[illegible]s
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  - In order to compensate: modify bias voltage and re[illegible]ing
- Disclaimer: we will not talk about effects on the readout chip → c.f. talk on Friday: **Operational Experience and Performance with the ATLAS Pixel Detector at the Large Hadron Collider**

The ATLAS Pixel Detector

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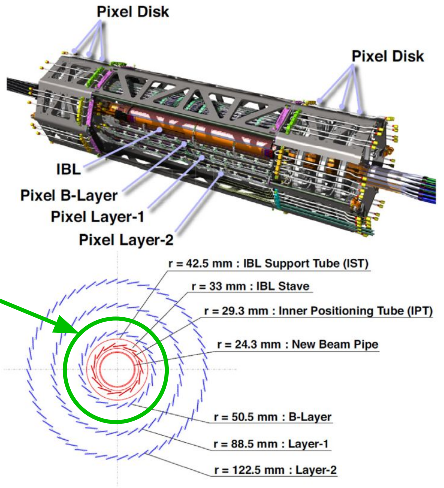
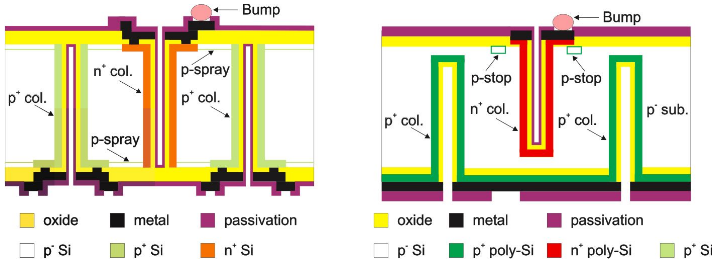
- Four layer pixelated detector with three end–caps on each side
- Inner layer (IBL) was inserted later at about 3 cm distance from interaction point
  - IBL uses planar **200 µm thick** sensors with 250 µm x 50 µm pixel pitch
  - Most modules are **planar n^+-in-n**
  - Forward modules are **n^+-in-p 3D sensors** (230 µm thick)
  - The innermost layer of the ATLAS Inner Tracker upgrade will use 3D sensors
- Other Pixel layers and disks
  - Innermost is the B-Layer at r = 5 cm
  - **250 µm thick n^+-in n-sensors**
  - 400 µm x 50 µm pixels

focus on the IBL and B-Layer





FBK: pass-through columns, p-spray isolation

CNM: 210 µm columns, isolated with p-stop implants

Radiation: present and future

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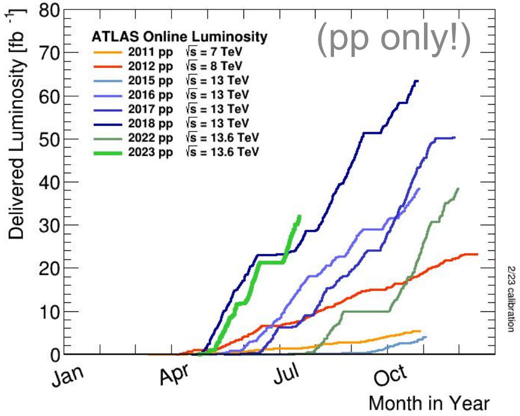
- About 290 fb^{-1} of collisions delivered to ATLAS so far
- To IBL about 30 fb^{-1} less due to later installation
- We aim at 160 fb^{-1} more for the rest of the project
- Innermost layers in the ATLAS Inner Tracker upgrade are targeted to withstand 2000 fb^{-1} of radiation
- Conversion from integrated luminosity to fluence?

	IBL		B-Layer	
	Fluence [1 MeV n_{eq}/cm^2]	**Int. Lumi** [fb^{-1}]	**Fluence** [1 MeV n_{eq}/cm^2]	**Int. Lumi** [fb^{-1}]
Current	~1.2 x 10^{15}	260	~0.9 x 10^{15}	290
Design	5 x 10^{15}		1 x 10^{15}	
EOL projection	2.1 x 10^{15}	395	1.5 x 10^{15}	425



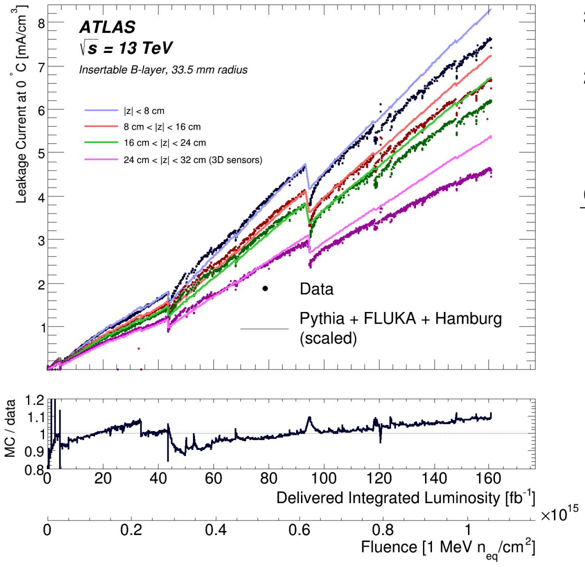
From luminosity to fluence

- No direct measurement of fluence
- Measurement of luminosity and extrapolation to fluence
  - Needs simulation of collisions (Pythia) and then transport code through the detector (FLUKA or Geant4)
  - Gives conversion from int. luminosity to fluence
- Indirect measurement of fluence by measurement of leakage current
  - Leakage current is proportional to fluence and voltage
  - Modelling of leakage current with Hamburg model

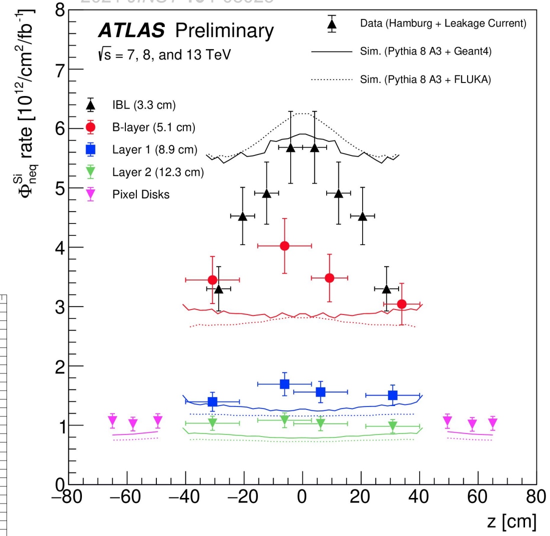
→ c.f. ATLAS Collaboration, 2021 *JINST* **16** P08025

- Observe stronger z-dependence in data from leakage current
- In forward region, leakage current lower than expected

2021 *JINST* **16** P08025



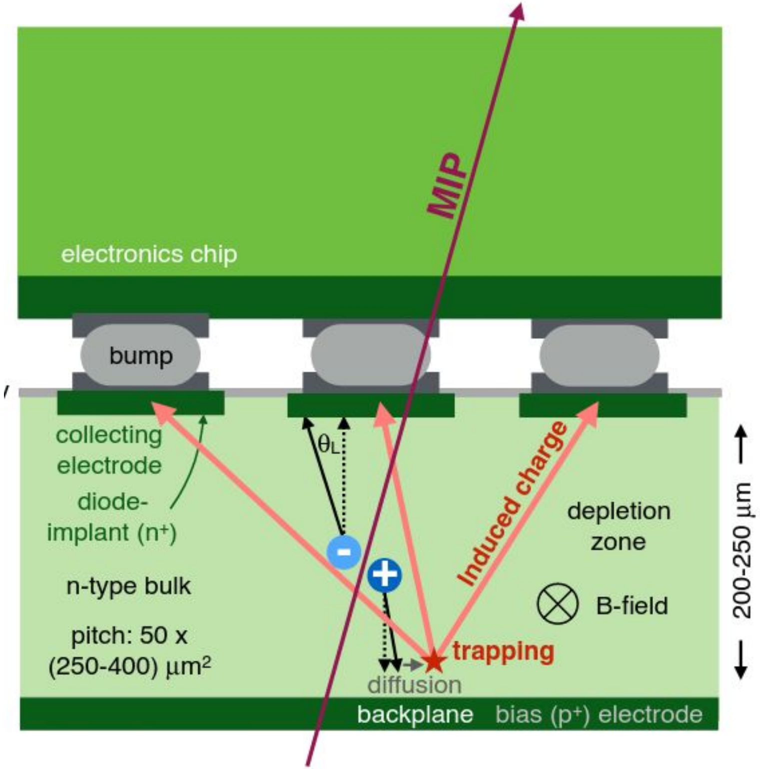
2021 *JINST* **16** P08025



z Bin	Mean SF
32 cm > |z| > 24 cm	0.56 ± 0.06
24 cm > |z| > 16 cm	0.77 ± 0.08
16 cm > |z| > 8 cm	0.84 ± 0.09
8 cm > |z| > 0 cm	0.97 ± 0.10

- → scale factors for IBL in z-bins
- (other layers are also scaled)
- **large uncertainty due to this**

Modelling radiation damage

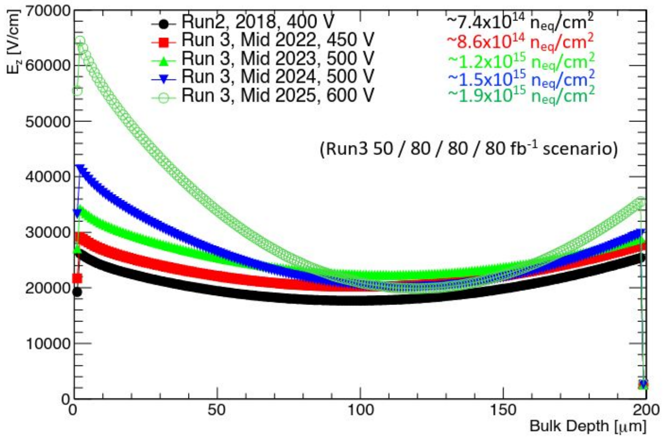


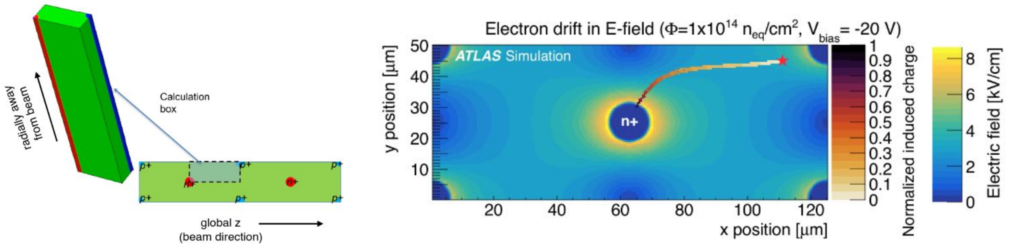
- Deposited charged by MIP in the sensor bulk drift to the electrodes due to electric field
  - Field is modified by radiation damage
- Path is deflected by magnetic field of 2 T solenoid + diffusion
  - Lorentz angle
- Charges can be trapped and only induce a fraction of signal
  - Ramo potential
- Digitisation step is used in many ATLAS Monte Carlo physics samples

→ c.f. ATLAS Collaboration, 2019 *JINST* **14** P06012

Input: electric field maps

- Electric non-linear fields are simulated in TCAD for different fluences and bias voltages
  - Radiation damage modelled via **Chiochia model** for planar n-in-n sensors
  - For p-type bulk in 3D sensors, 3-level models (**Perugia*, LHCb****)
- *: F. Moscatelli et al., IEEE Trans. Nucl. Sci. 63 (2016) 2716
- **: A. Folkestad et al., NIM A874 (2017) 94-102

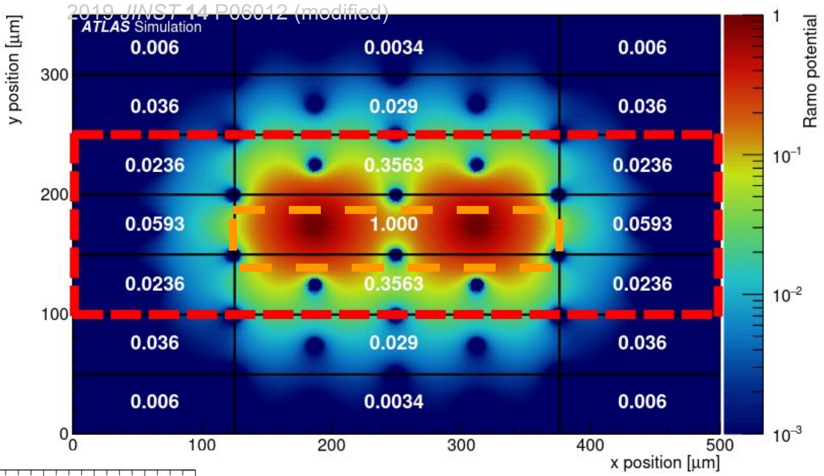


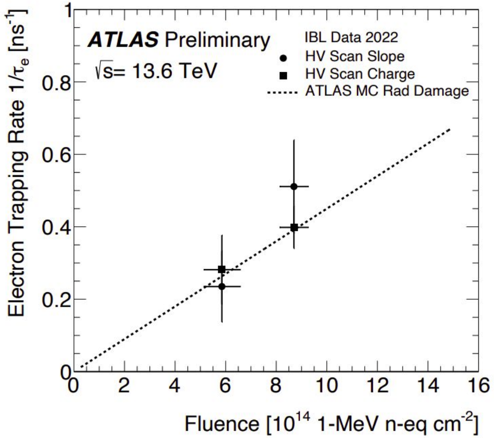


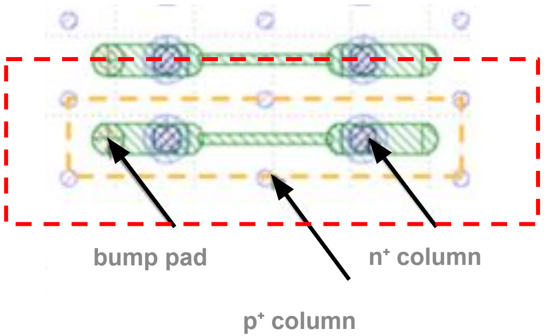
2019 *JINST* **14** P06012

Input: ramo potential and charge trapping

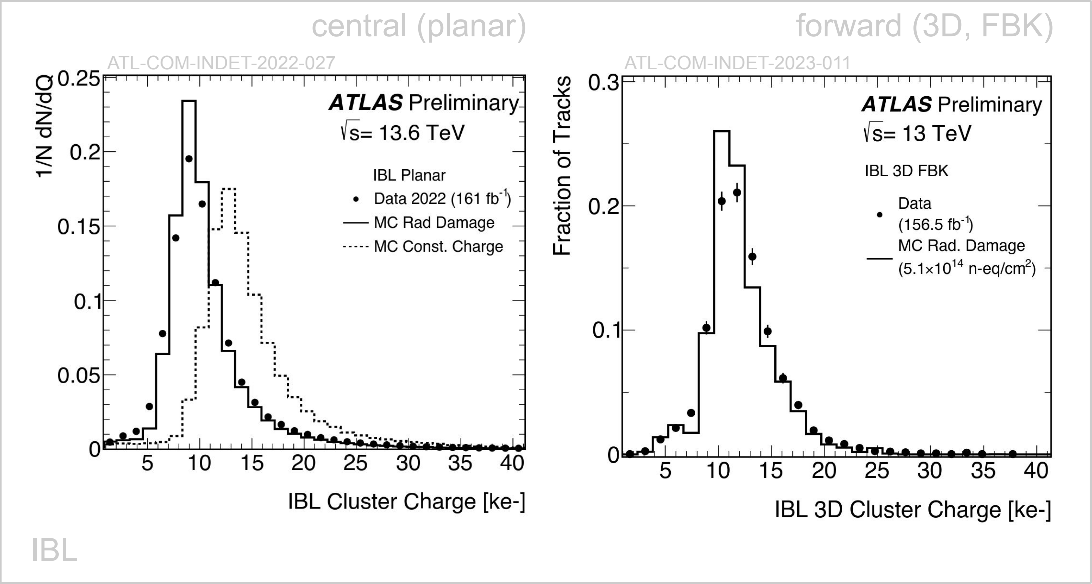
- Ramo potential solved in TCAD
  - Only signal induced in adjacent pixels is considered (red box)
  - More complex potential for 3D sensors as the two n^+-columns are electrically connected
- Charged are trapped (drawn from exponential distribution) and their induced charge at final position is computed
  - Mean of exponential distribution $1/(\beta\Phi)$ with Φ the fluence
  - $\beta_e = 4.5 \times 10^{-16}\ cm^2ns^{-1}$
  - $\beta_h = 6.5 \times 10^{-16}\ cm^2ns^{-1}$

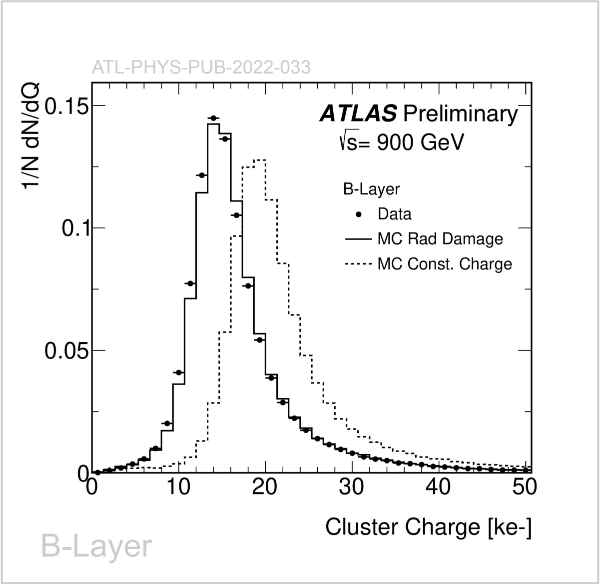






Cluster charge





- Cluster charge as measured in end of Run 2/early Run 3 data
- Comparison with radiation damage digitiser (and constant charge digitiser)
- **Radiation damage digitiser replaces constant charge digitiser as ATLAS default since Run 3**
- **Predicted most probable values match to 1%**

Charge collection efficiency

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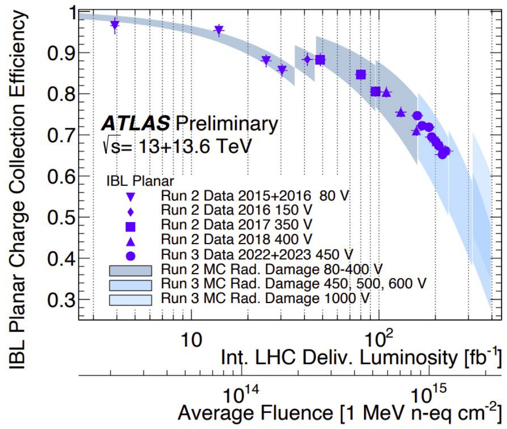
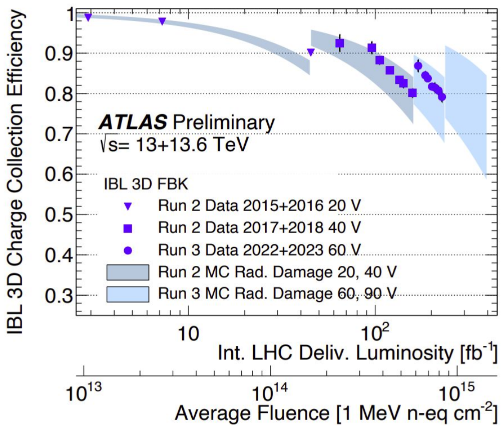
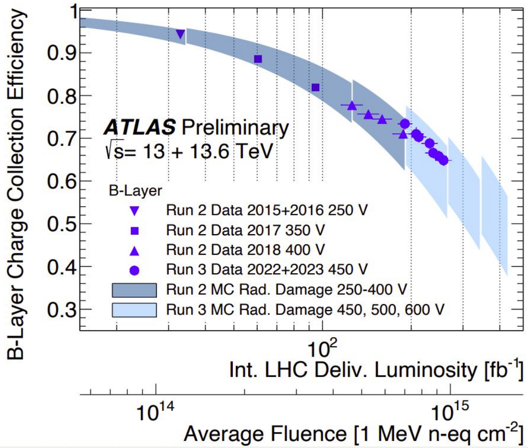
central (planar) | forward (3D, FBK)





IBL



B-Layer

- Good prediction of charge collection efficiency for a large range of fluence
- Comparison of planar IBL and 3D IBL (difference fluence due to position) → different radiation models, still good agreement
- Prediction within what we can deal with loss of CCE until end-of-life

Charge collection efficiency

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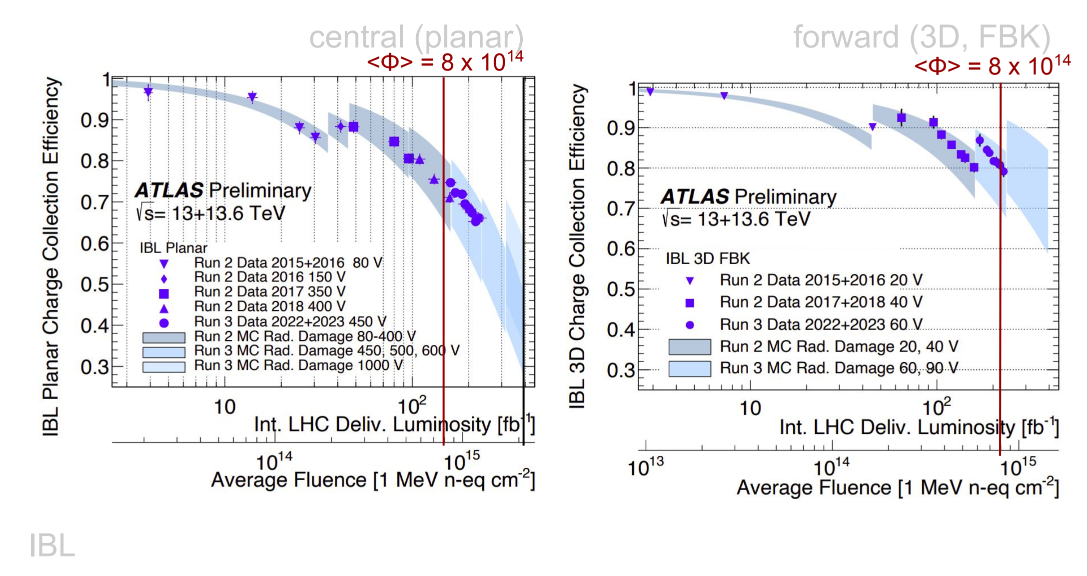

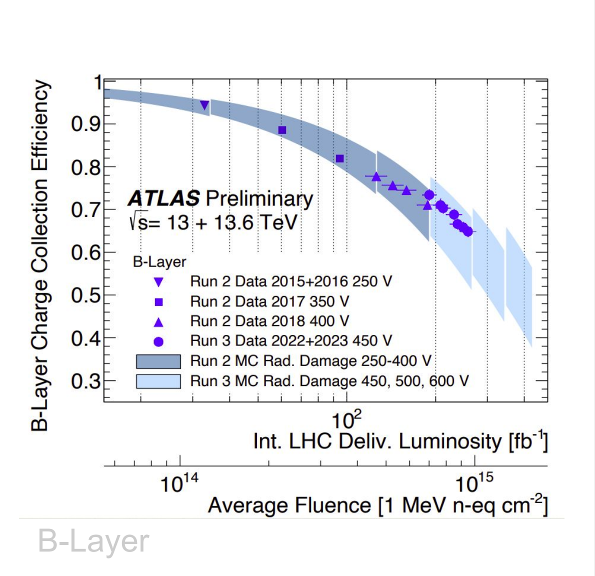

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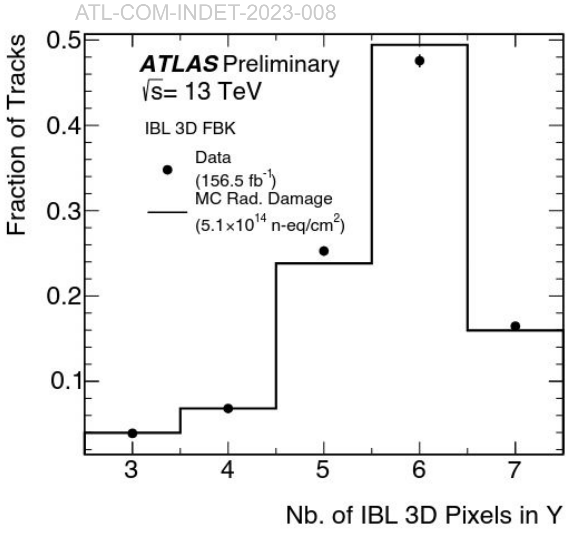
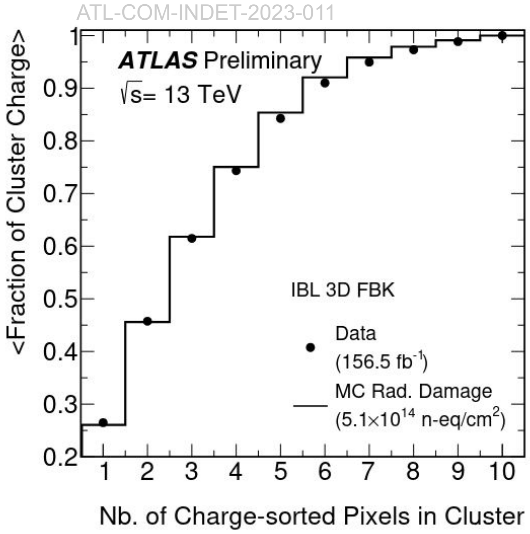
IBL 3D damage modelling

- Charge sharing also well modelled by radiation damage digitiser
- High number of pixels in a cluster in longitudinal direction because of forward position of 3D modules
- Even cumulative distribution of fraction of charge versus number of highest charge-pixels shows very good agreement

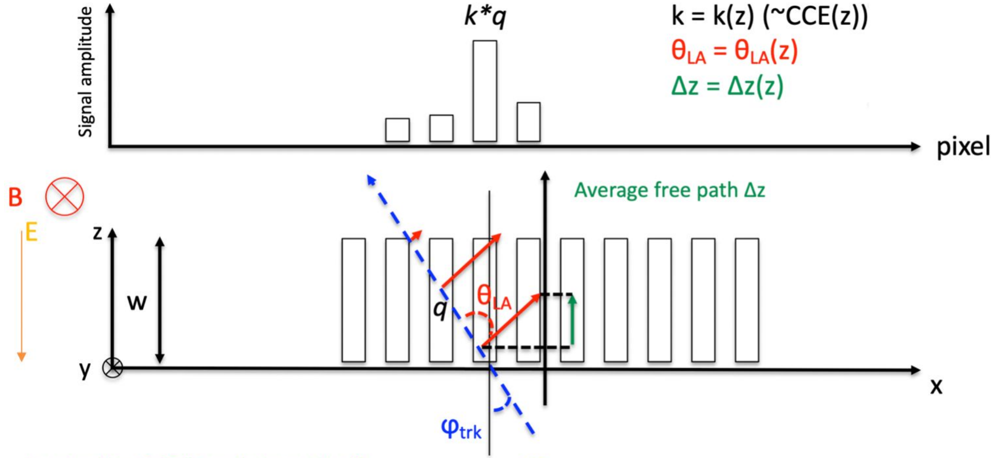




Digitiser: now and future

- Novel radiation damage digitiser used in ATLAS Monte Carlo production since Run 3
- Excellent agreement between data and MC predictions (w.r.t. large deviations with constant charge digitiser)
- For the ATLAS Inner Tracker (ITk) most inner layers: (1 to 2) x 10^{16} 1 MeV n_{eq}/cm^2 after 2000 fb^{-1}
- current digitiser is unfortunately too slow
- → need other approach for ITk

- ITk digitiser inspired by CMS template method → c.f. 2007 *PoS* **Vertex 2007** 035
- Lookup tables (LUTs) to determine how much charge induction is where and by how much it is reduced



Inspired by CMS “template method”

Template method: allpix²

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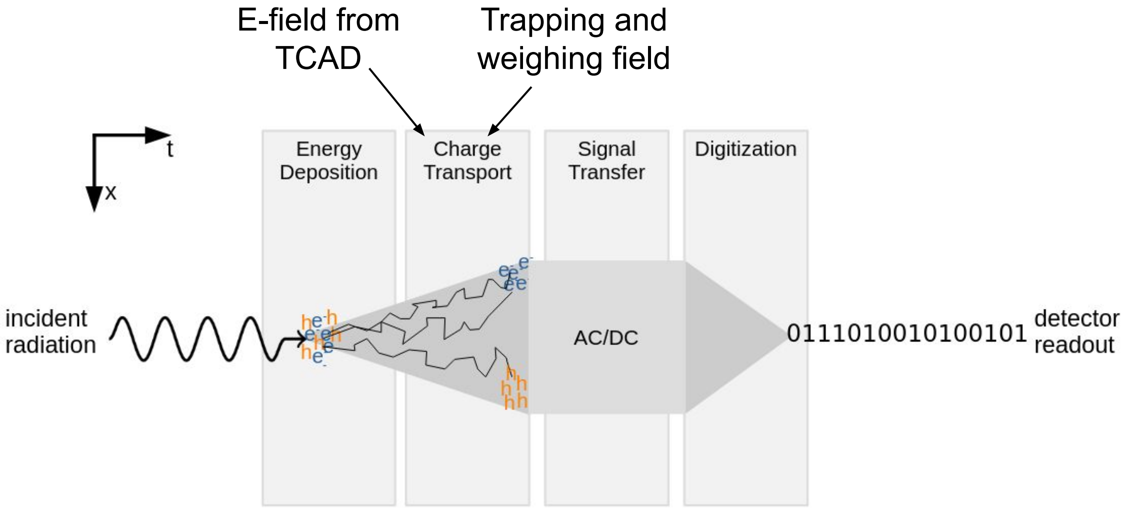
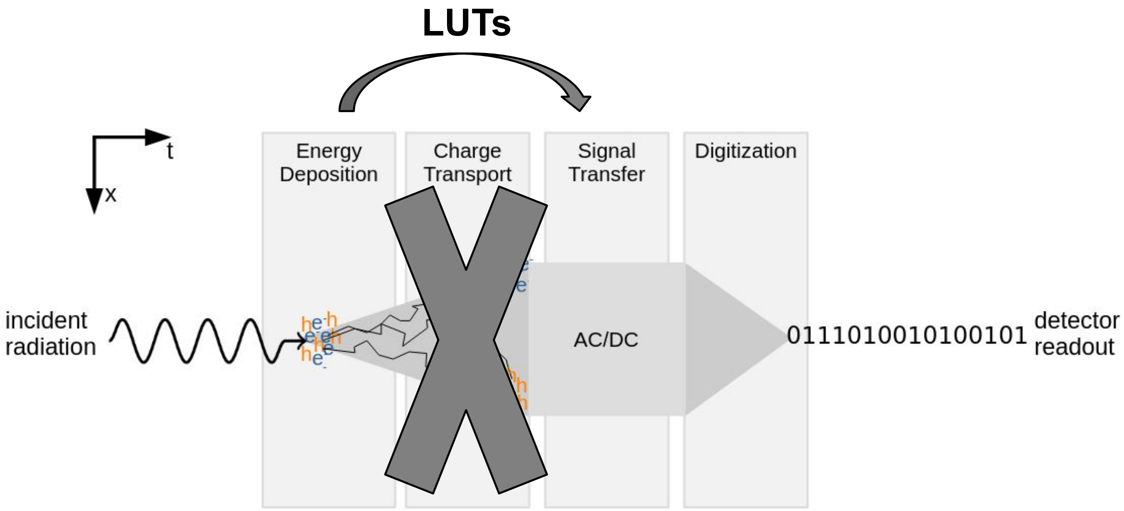


- Using the allpix² framework, the templates for the ITk digitiser are derived
- allpix² is a full Geant4 based detector simulation which simulates the propagation of charges in sensor bulk + further steps

- A LUT-based propagator based on the ITk digitiser approach has been implemented and is used to compare the "full" simulation vs. LUT approach

Template method: allpix²



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Conclusion

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- The new Run 3 radiation damage digiters performs well and is currently used in ATLAS MC production
- The agreement with Run 3 data is impressive
  - Also for the 3D n^+-in-p pixel sensor
- Despite that, need for faster approach in the future → ITk template approach
- This is currently under development and validation

Backup

IBL 3D performance

- HV scans used to monitor depletion voltage with irradiation
- Shown are the data for the IBL 3Ds
- Increase MPV of cluster charge even above full depletion observed due to reduction of charge trapping
- Range between 0.2 to 6 x 10^{14} 1 MeV n_{eq}/cm^2 for given fluences

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