Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider at CERN

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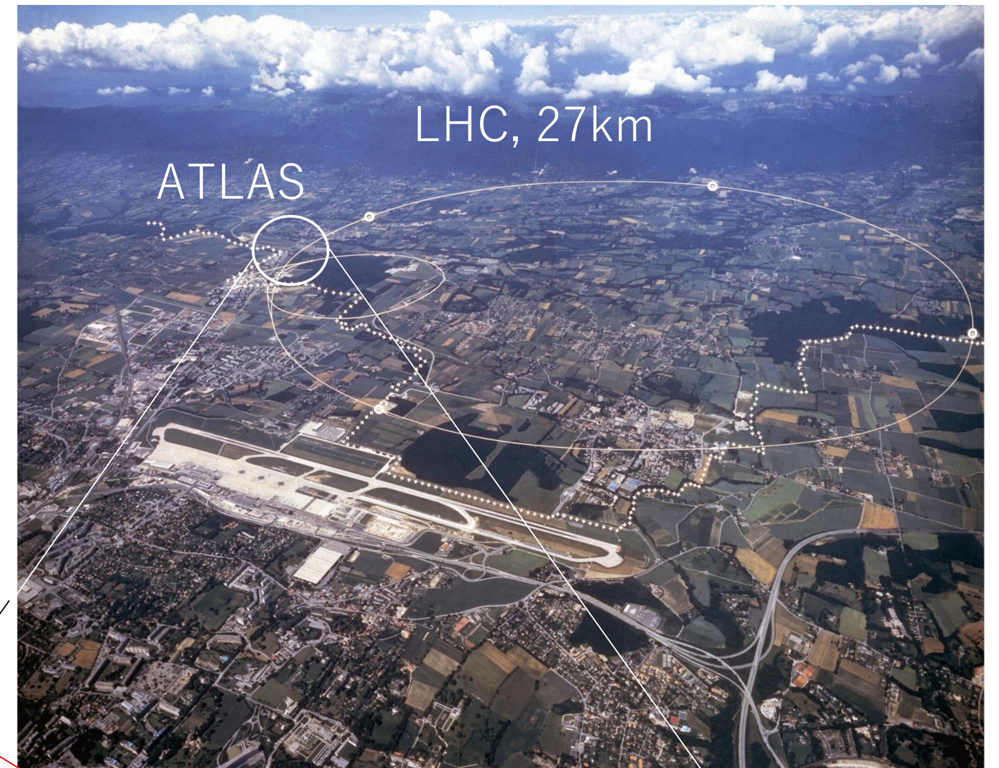
On behalf of the ATLAS Collaboration

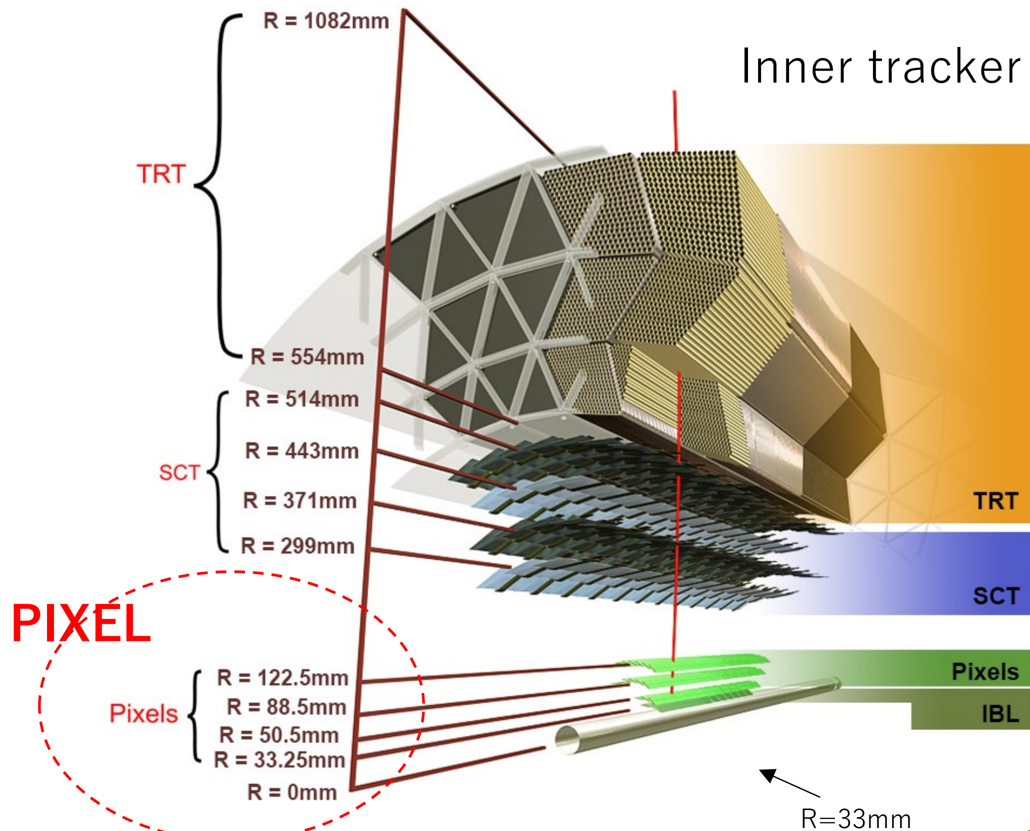
The ATLAS Pixel detector

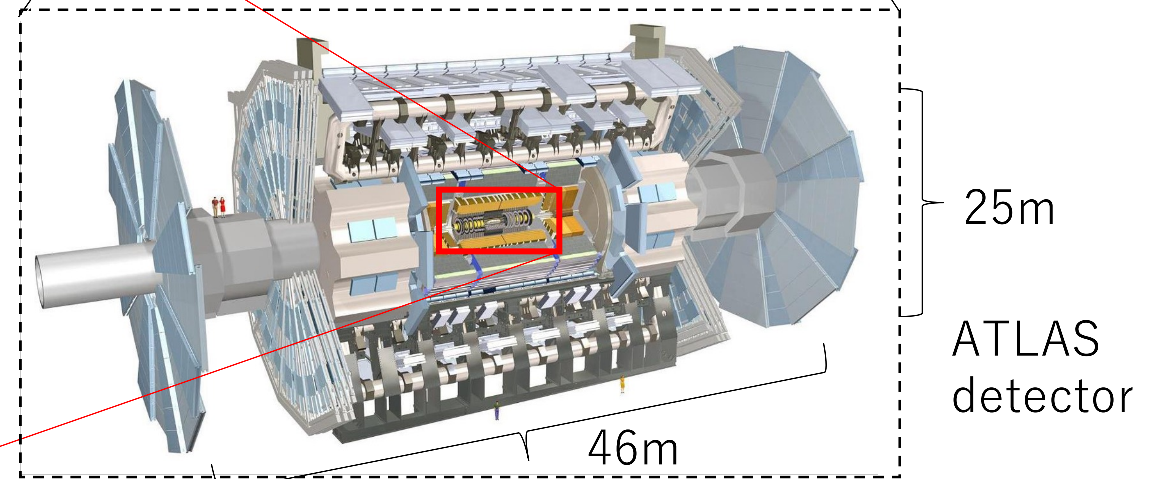
The ATLAS detector is located on the LHC ring.

The Pixel detector is the innermost silicon detector.

- 4 layers in the barrel + 3x2 endcap disks
- **NEW** innermost layer (**IBL**) newly used in RUN-2(2015).







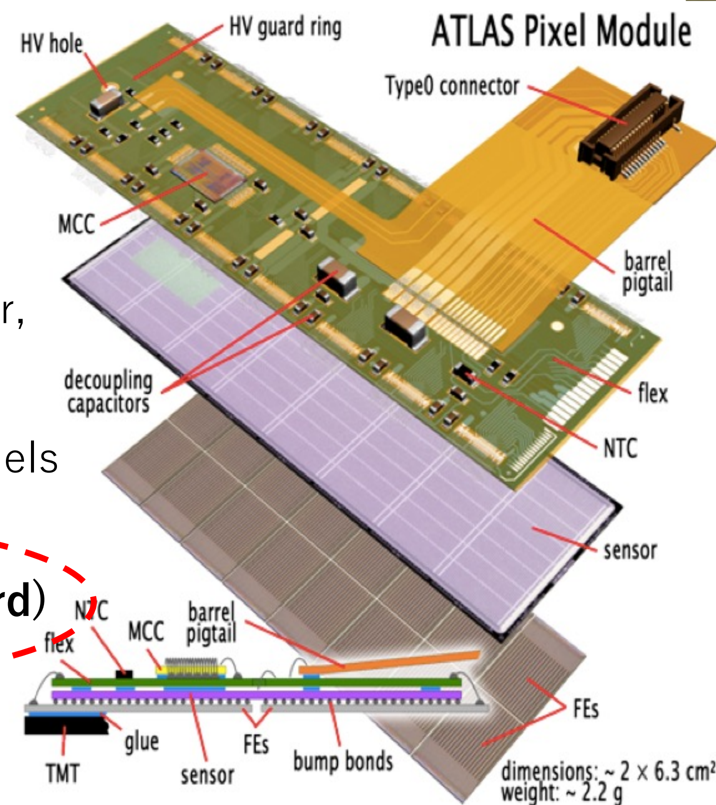
The Outer Pixel layer

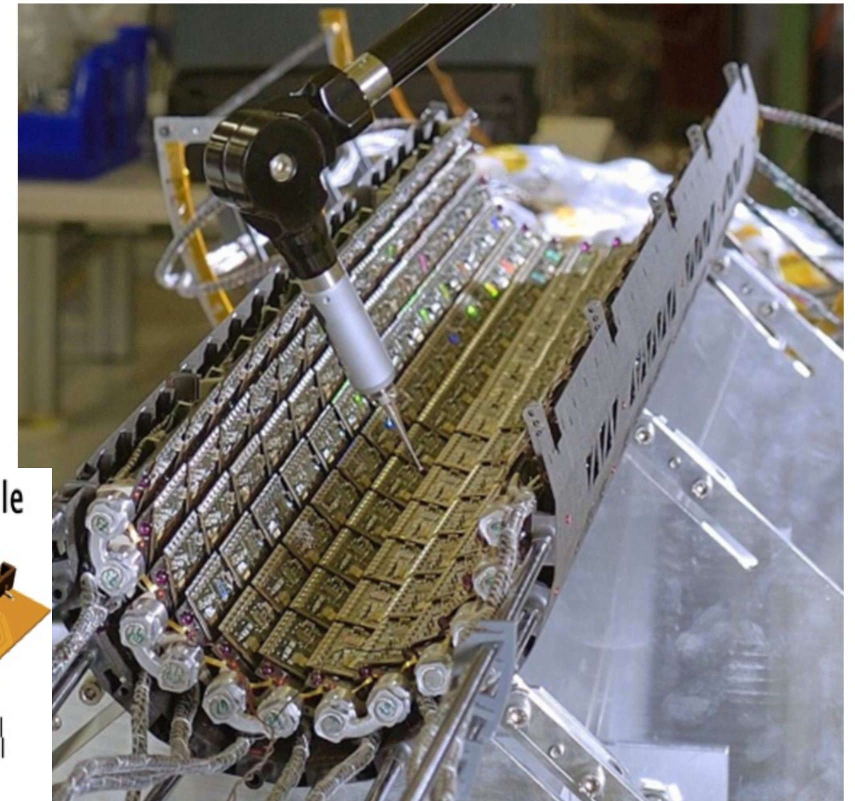
Three barrel layers, 2x3 endcap disks. (since RUN-1)

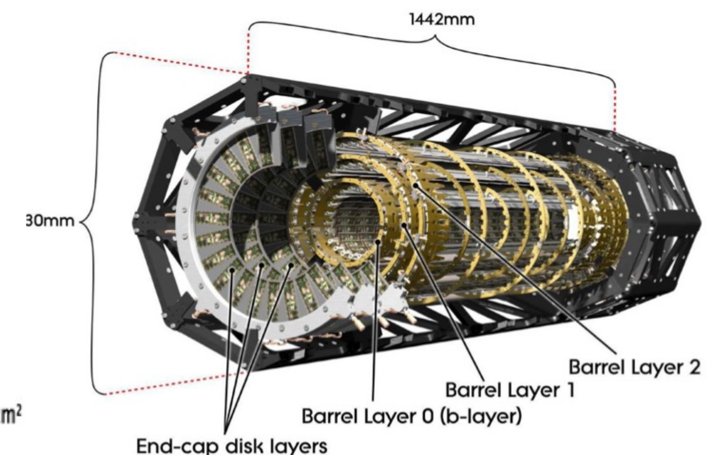
1744 modules ($1.7m^2$ surface), covering $|\eta| < 2.5$.

Pixel module:

- Planar n^+-in-n sensor,
- 60.8 x 16.4mm active area,
- 250 μm thickness,
- 16 FEI3 frontend bump-bonded on sensor,
- 50 x 400 μm^2 pixel size,
- Total 46080 pixels /module, ~80M channels
- 8-bit Time-over-threshold,
- Radiation hard to **$1 \times 10^{15}\ n_{eq}/cm^2$** **(50Mrd)**







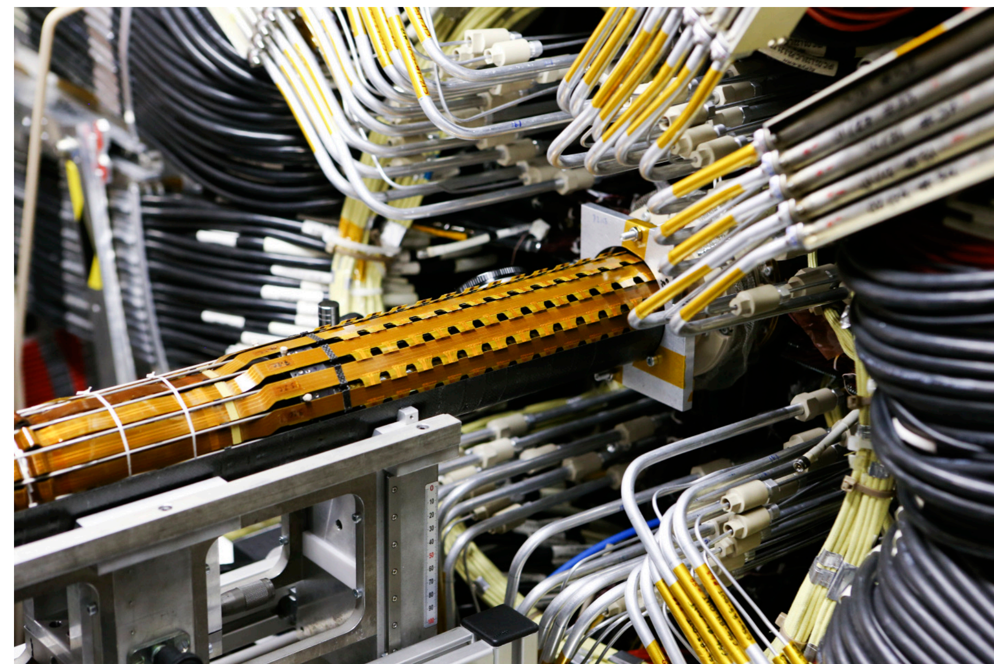
The IBL (Insertable B-layer)

New detector is used in RUN-2 (2015).

First time to use 3D sensor technology.

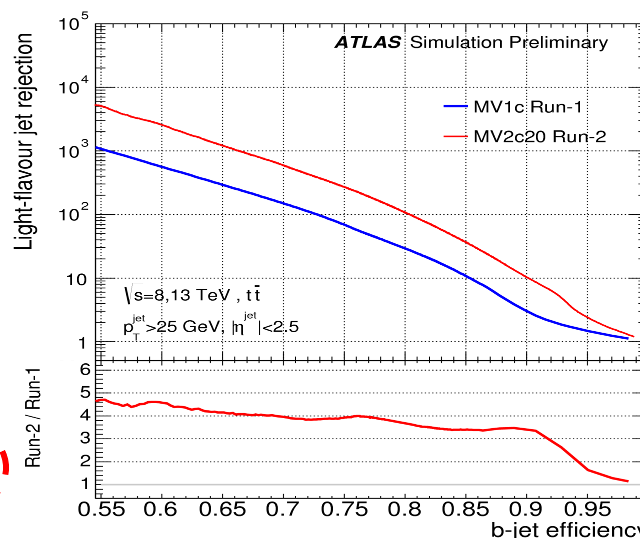
Located at R=33 mm (just outside of beampipe (28 mm)).

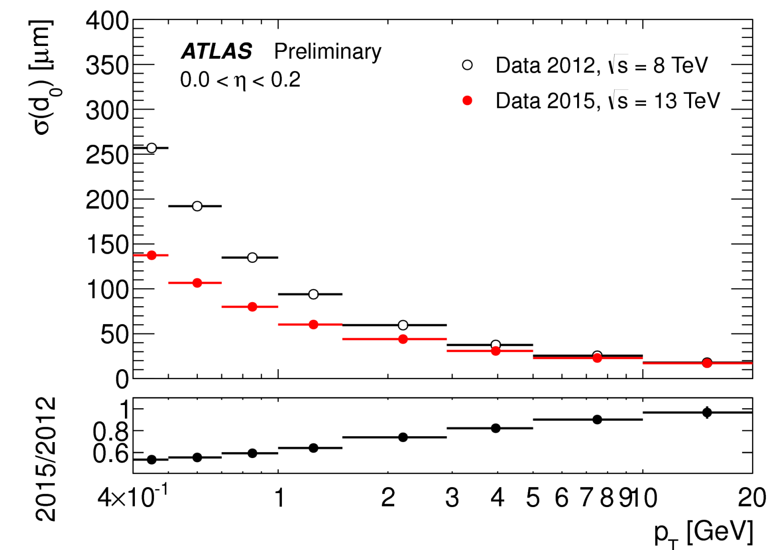
5 times better rejection of b-tagging from RUN-1.



IBL module:

- Planar n^+-in-n / 3D n^+-in-p sensor,
- 41.3(20.5) x 18.6 mm active area,
- 200(230) μm thickness (Planar/3D),
- 2(1) FEI4 chip on sensor (Planar/3D),
- 50 x 250 μm^2 pixel size,
- Total 26880 pixels / chip, ~12M channels,
- 4-bit Time-over-threshold,
- Radiation hard to **5x10^{15} n$_{eq}$/cm^2 (250Mrd)**





Major changes in RUN3

Optoboard replacement:

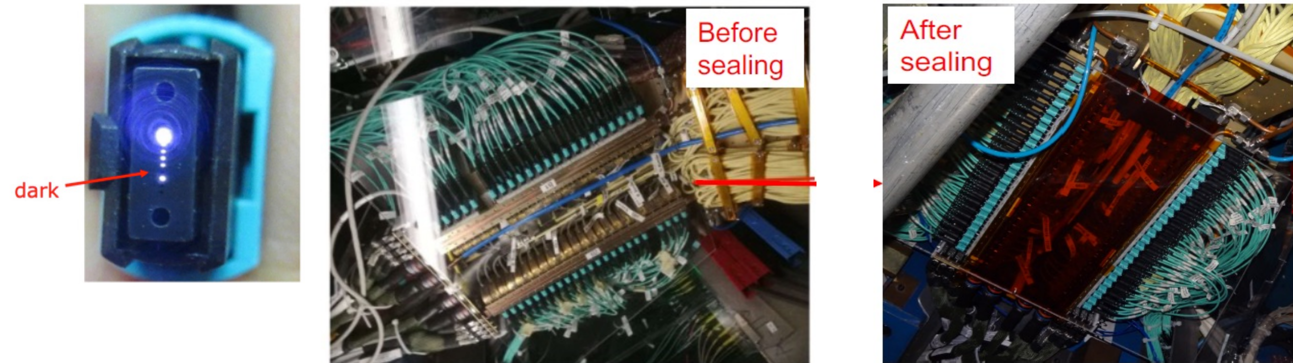
During RUN2, number of disabled modules were increased due to optboard failure.

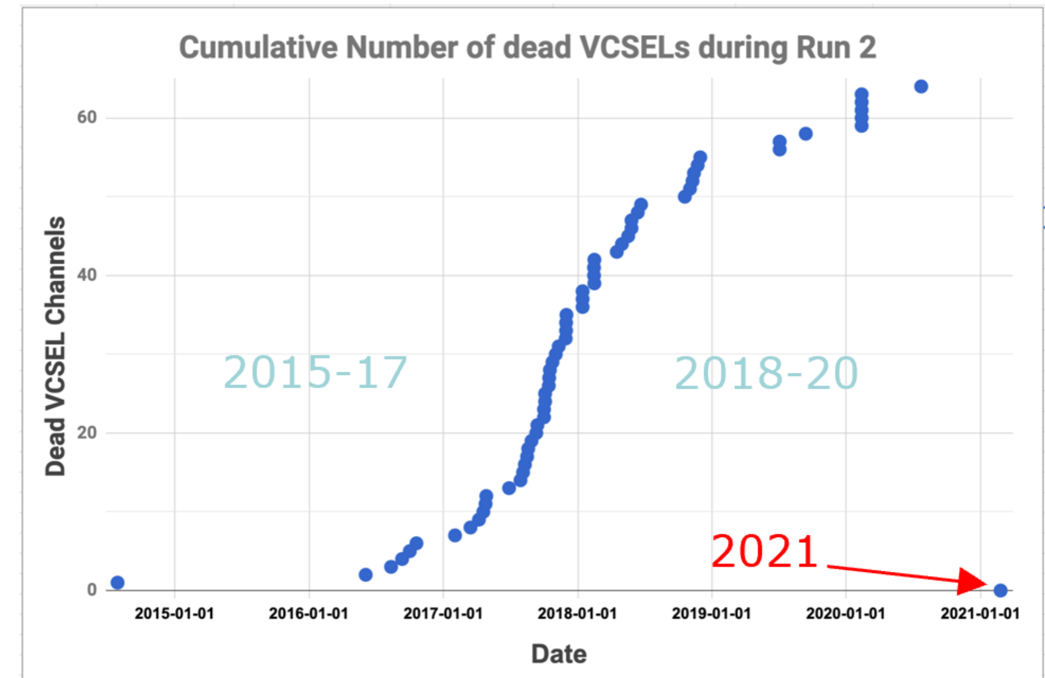
~50% disabled modules were caused by this.

Suspect humidity.

Most of optoboards were replaced during LS2.

No new failure is seen since then (RUN3).





Major changes in RUN3

Software upgrade:

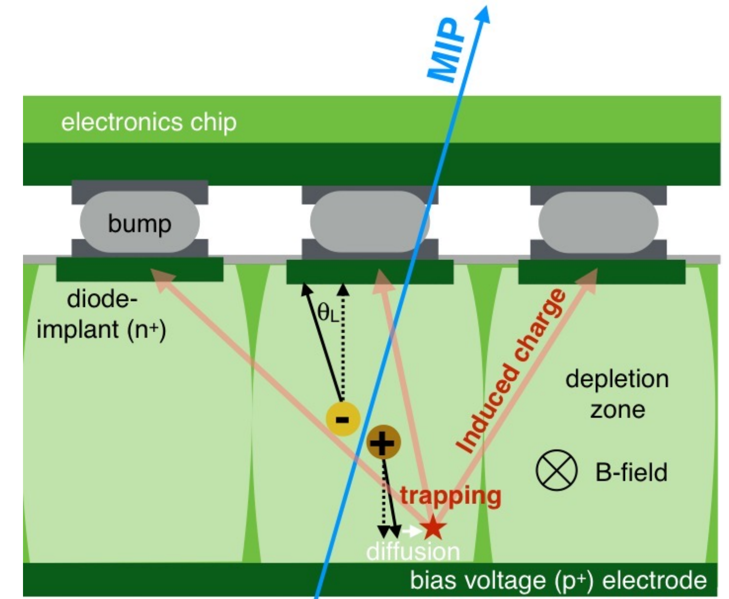
Employ radiation damage simulation.

evolution

RUN1 (2010-2012) : Default G4 (conventional energy loss)

RUN2 (2015-2018) : Introduction of Nuclei interaction in sensor (Bichsel model Nucl.Instrum.Meth. **A899** (2018) 1)

RUN3 (2022 --) : Introduction of Ramo potential (trapping of electron/hole during drift JINST 14 (2019) P06012)



Radiation damage:

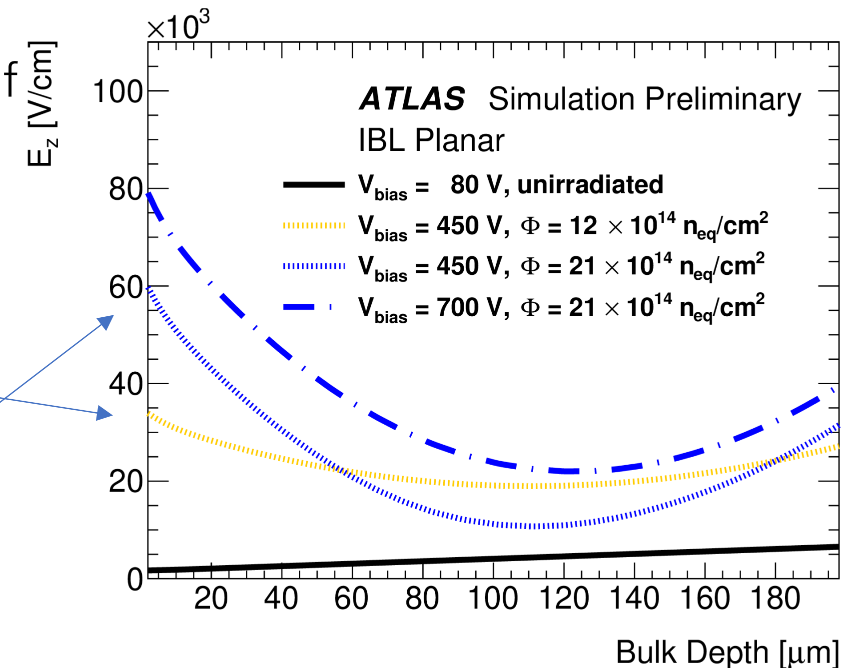
IBL : ~1.2×10^{15} n_{eq}/cm^2 (current, 2024)

2.1×10^{15} n_{eq}/cm^2 (expected in end of RUN3 (2025))

ITk L0 : 18×10^{15} n_{eq}/cm^2@2000fb^{-1}

ITk L2-4 : $1 \sim 4 \times 10^{15}$ n_{eq}/cm^2@4000fb^{-1}

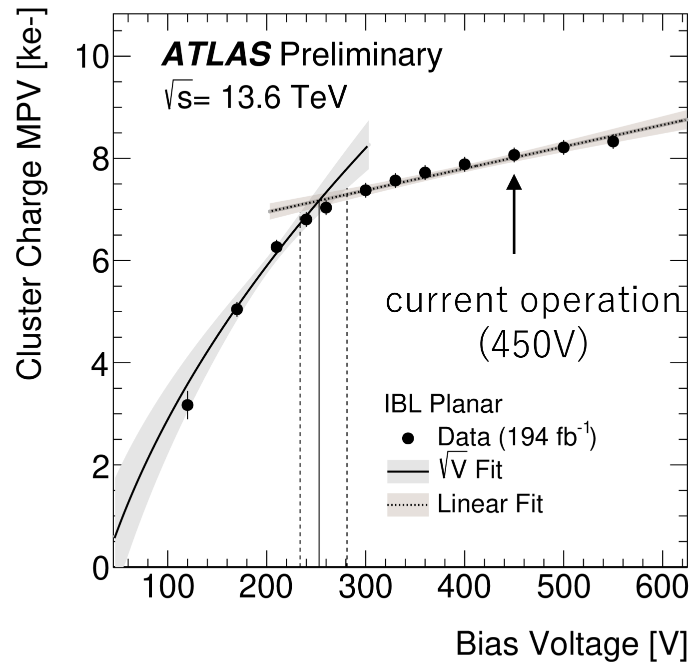
Same order of the ITk Outer barrel



HV and threshold tuning

Keep high hit-on-track efficiency:

- HV needs to be **increased** to operate at full-depletion voltage.
- Threshold could be **lowered**, but trade-off by the **readout error rate**.

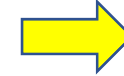


		IBL	B-layer	Layer-1	Layer-2	Disks
Run-2	2015	80V/2500e	250V/3500e	150V/3500e	150V/3500e	150V/3500e
	2016	80V/2500e	350V/3500e	200V/3500e	150V/3500e	150V/3500e
	2017	350V/2500e	350V/3500e	200V/3500e	150V/3500e	150V/4500e
	2018	400V/2000e	400V/4300e	250V/3500e	250V/3500e	250V/3500e
Run-3	2022	450V/1500e	450V/3500e	300V/3500e	300V/3500e	300V/3500e
	2023	450V/1500e	450V/4700e	350V/4300e	350V/4300e	350V/4300e
	2024	450V/1500e	500V/4700e	350V/4300e	350V/4300e	350V/4300e

Operation highlight

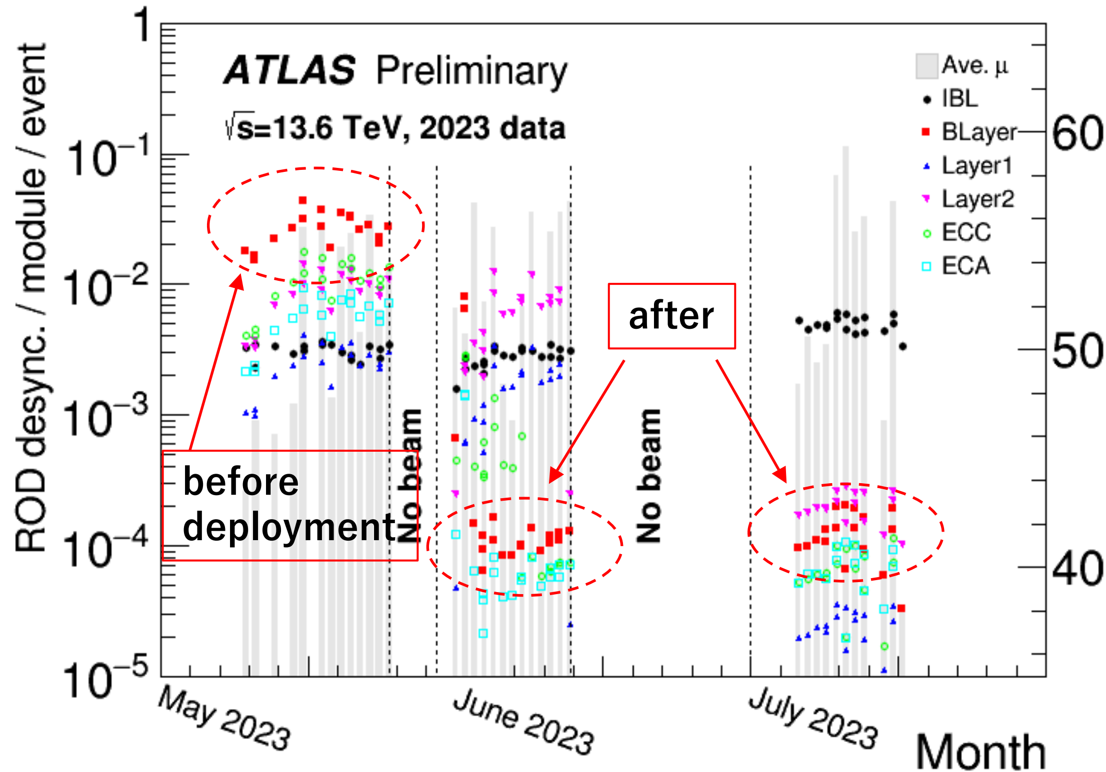
Desynchronization error:

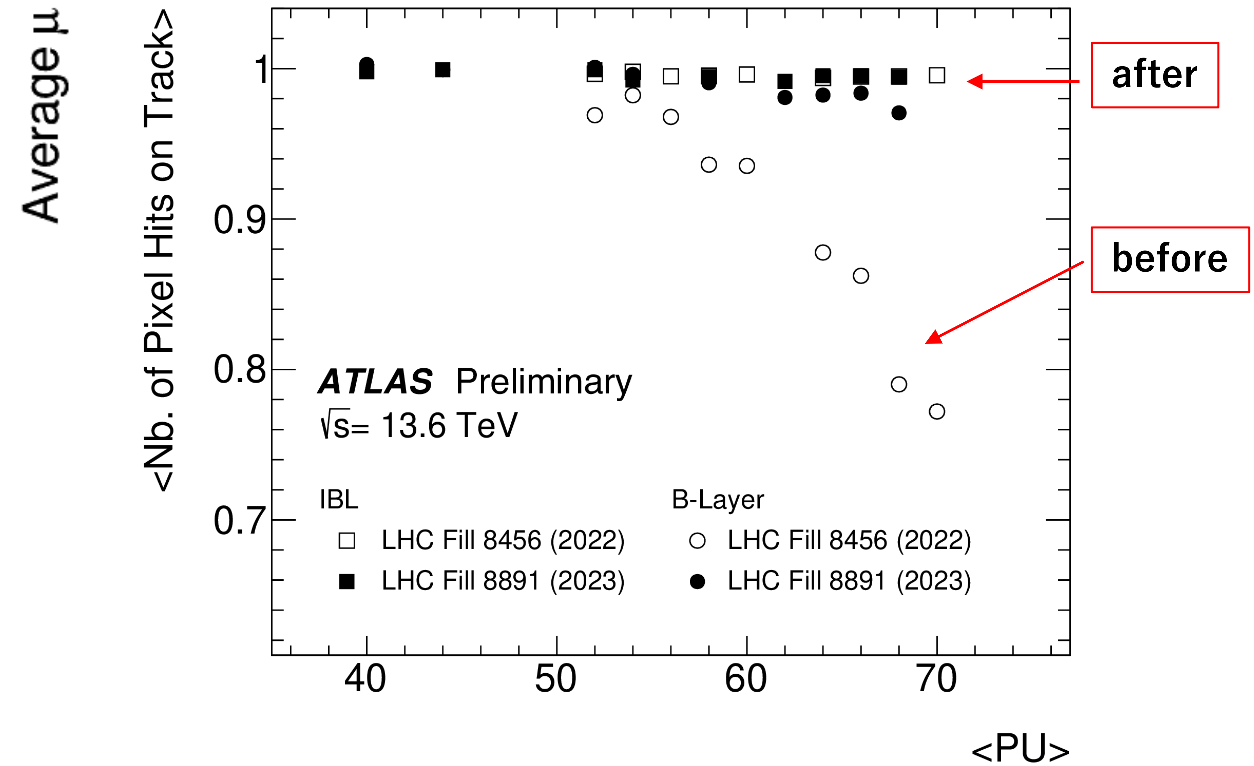
Pixel/IBL can **handle up to 16 triggers at a time**. Once a trigger has been missed, the module will be desynchronized until the next ATLAS event counter reset (ECR) every 5 sec.



Solution:

In case >16 triggers, the trigger command is not sent to the module in firmware. In this way, only these triggers are missed, but others are kept without waiting for ECR.

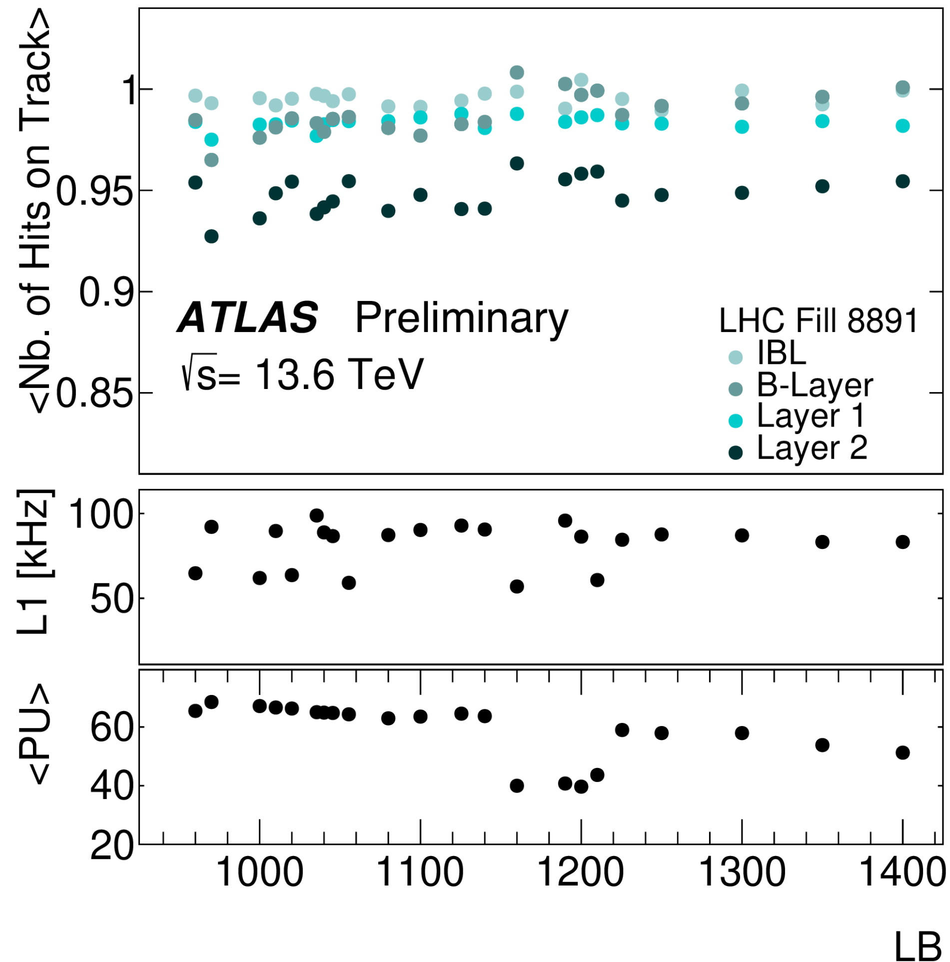


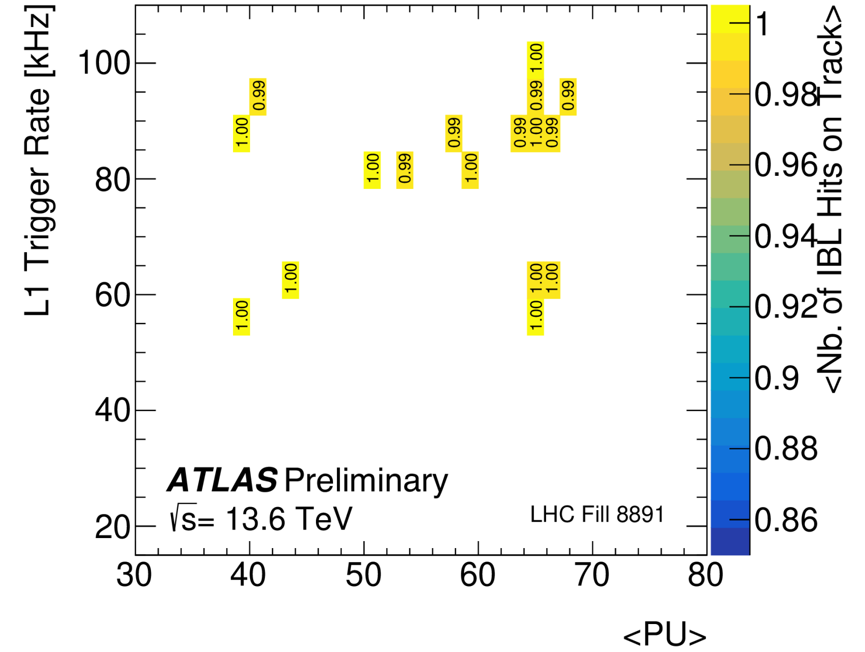


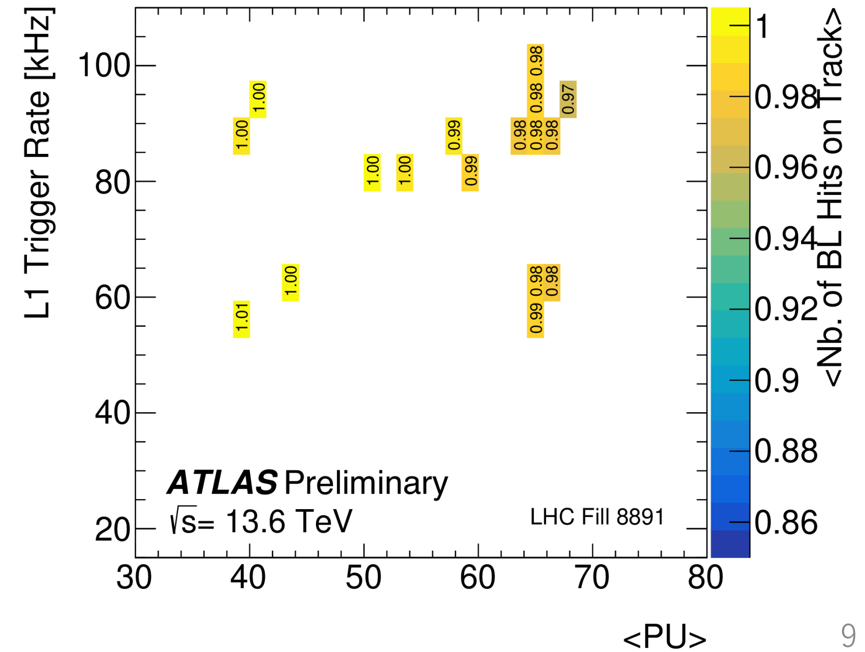
Operation highlight

Average number of pixel hits-on-track

Demonstrates the stability over the run / pileup.





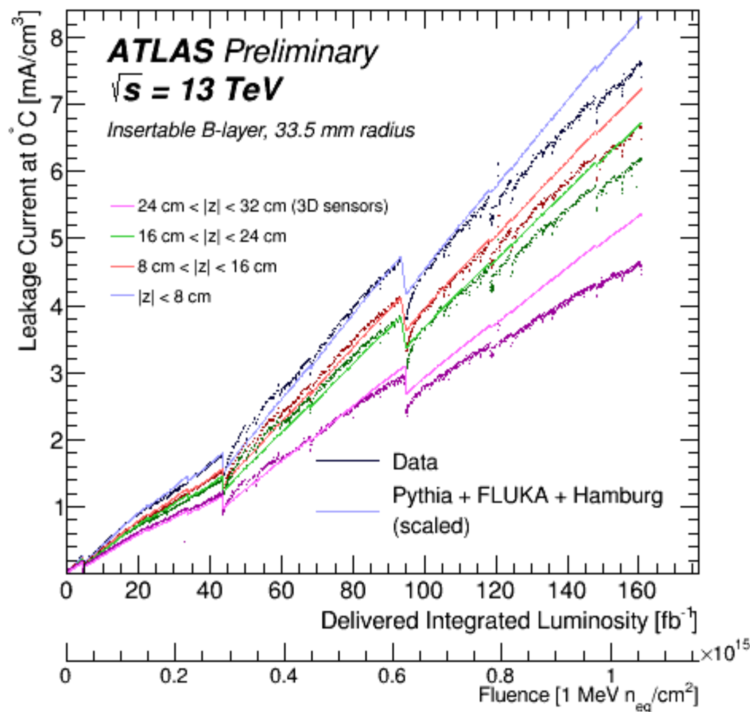


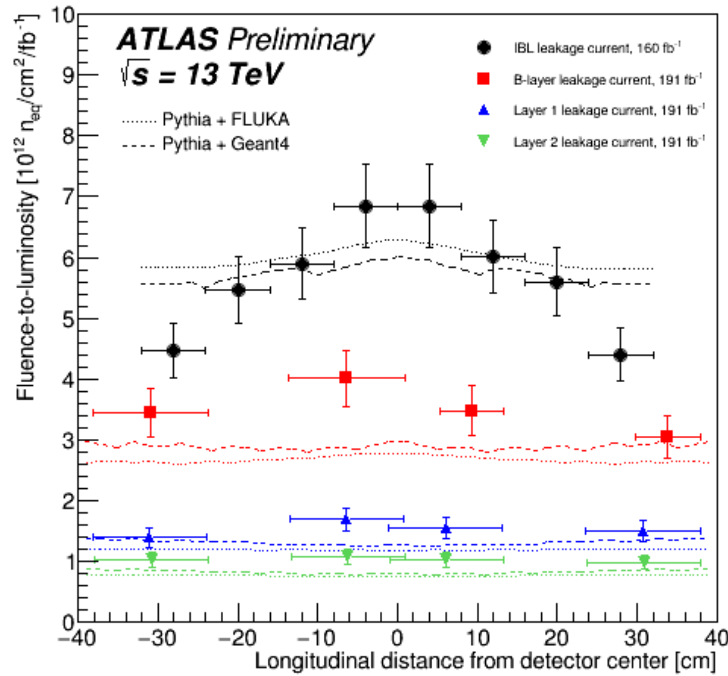
Leakage current and fluence

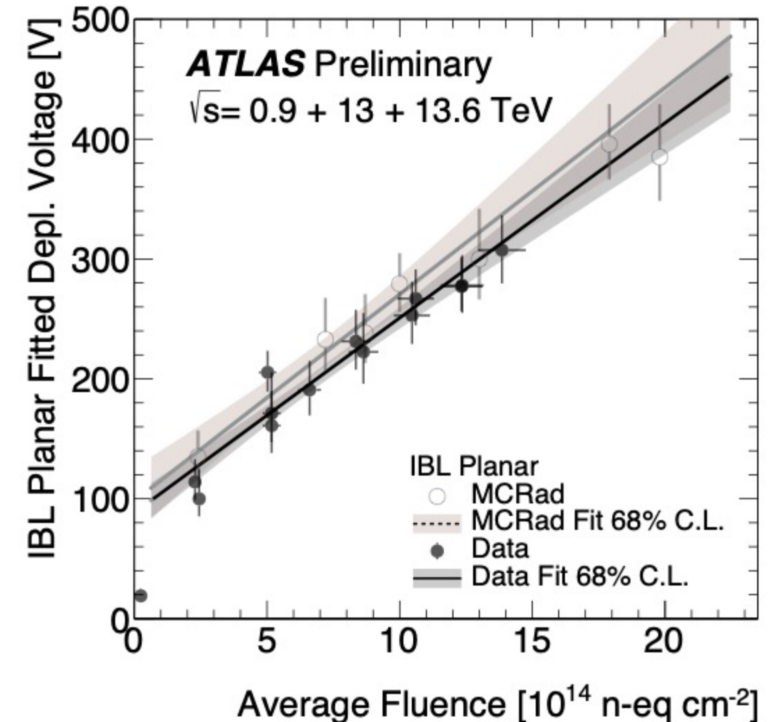
The leakage current evolution is compared with Hamburg model.

Large z-dependence in leakage current measurement, while not in MC (FLUKA/G4).

The z-dependence is also confirmed by the HV scan data.

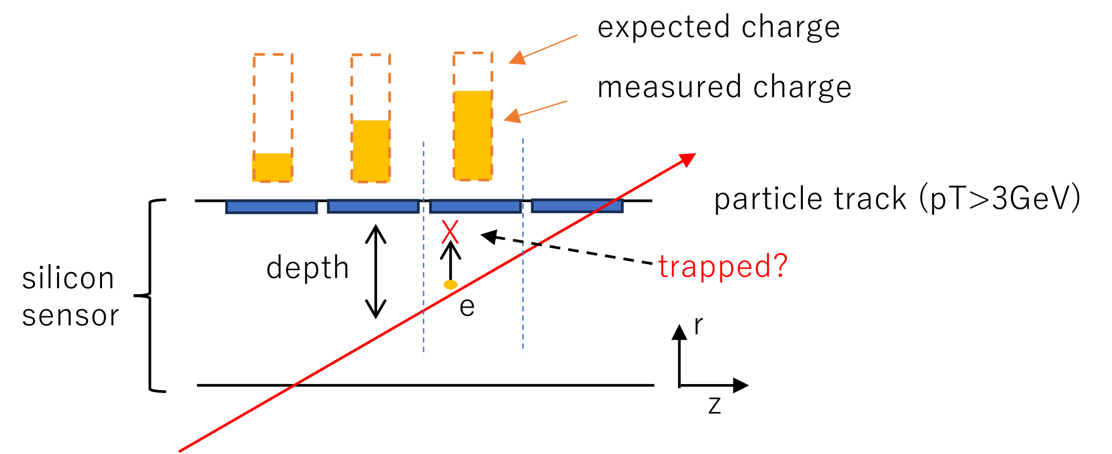


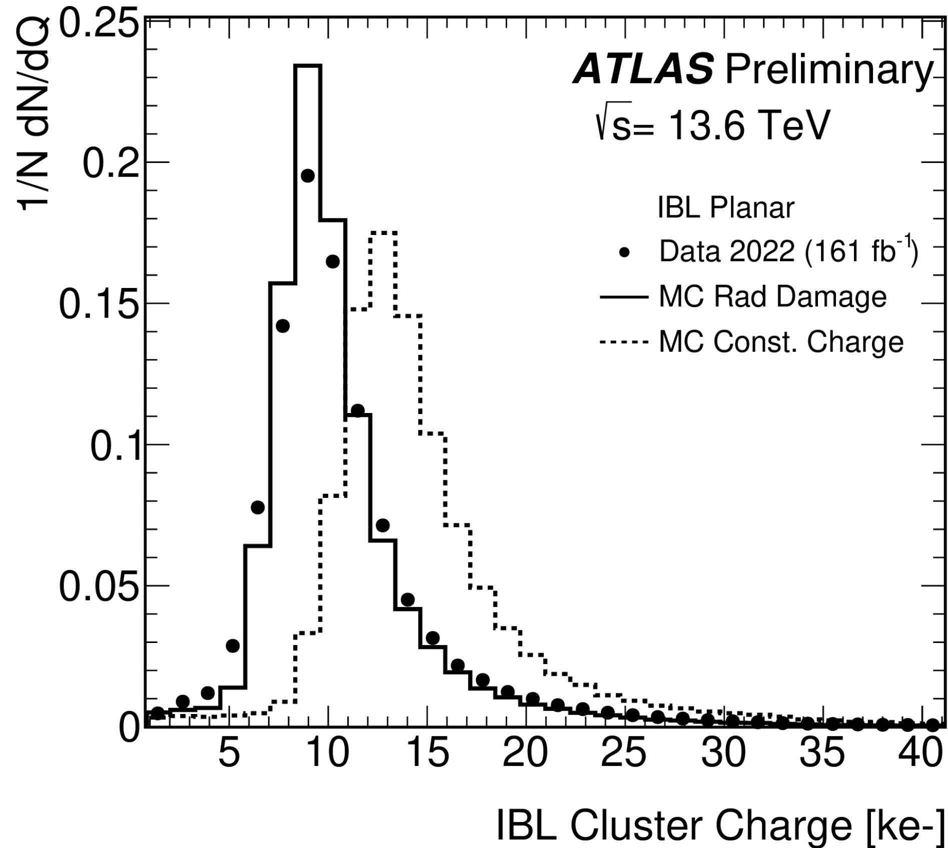


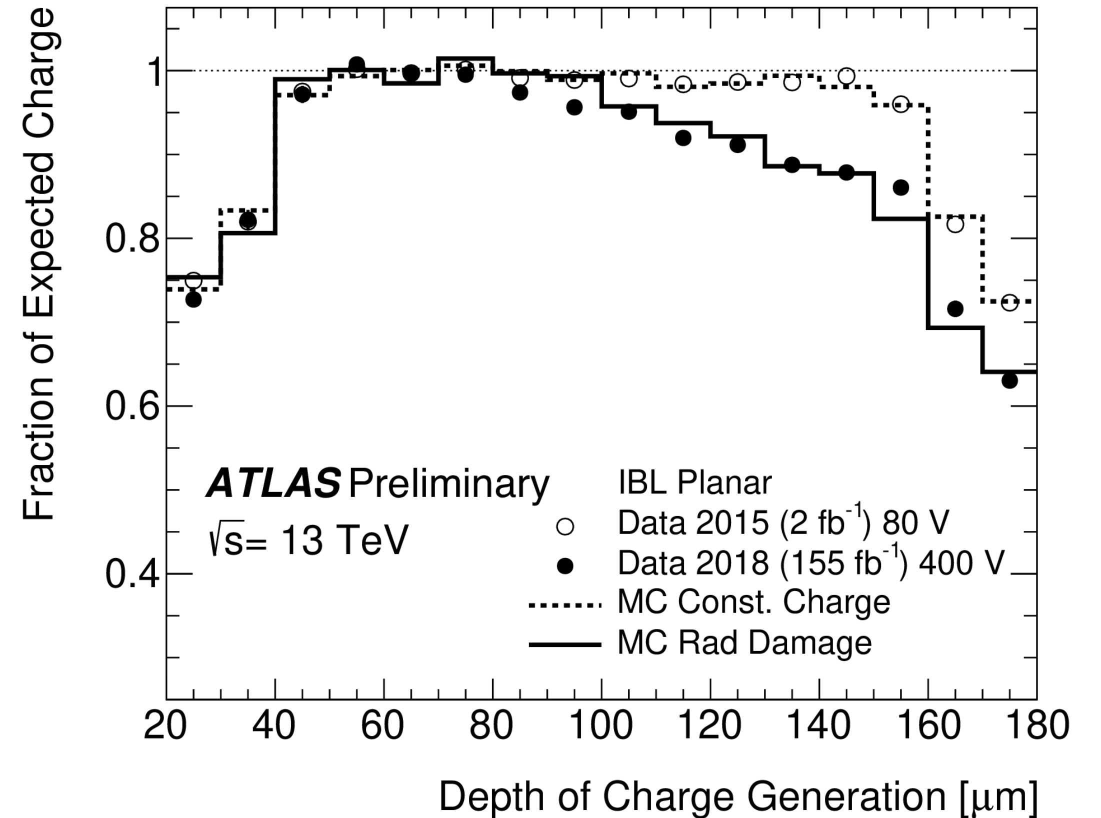


Pixel performance

New simulation agrees with data.

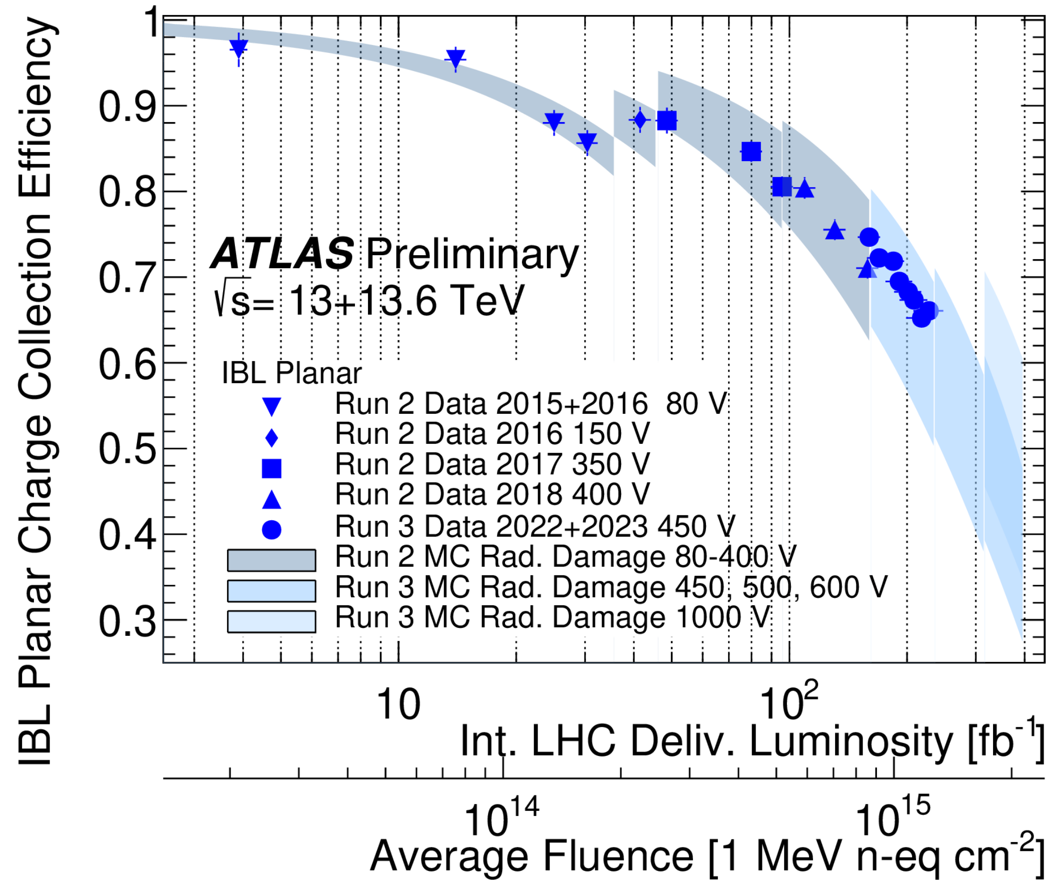


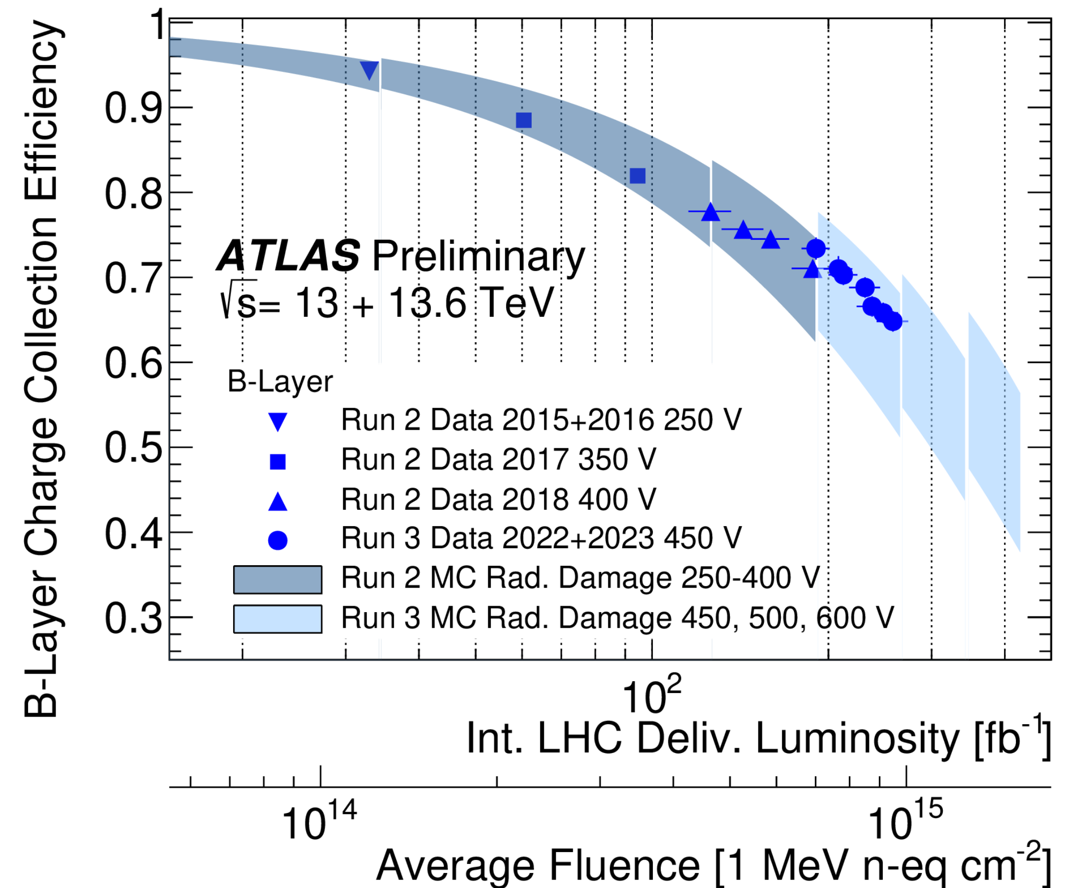




Radiation damage effect

In the end of RUN3 (~400fb^{-1}), the charge collection efficiency is kept by ~50%.





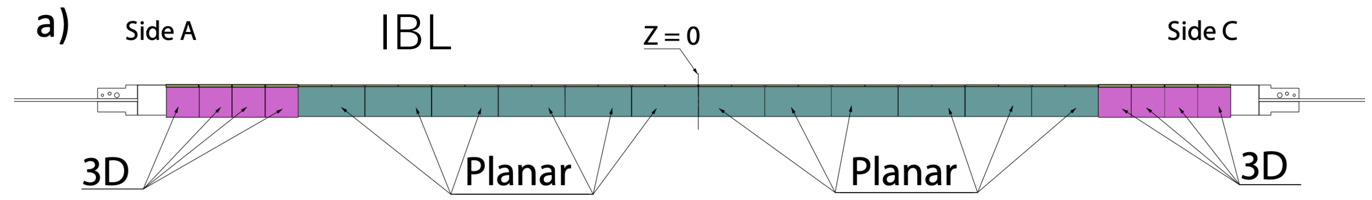
3D pixel sensor

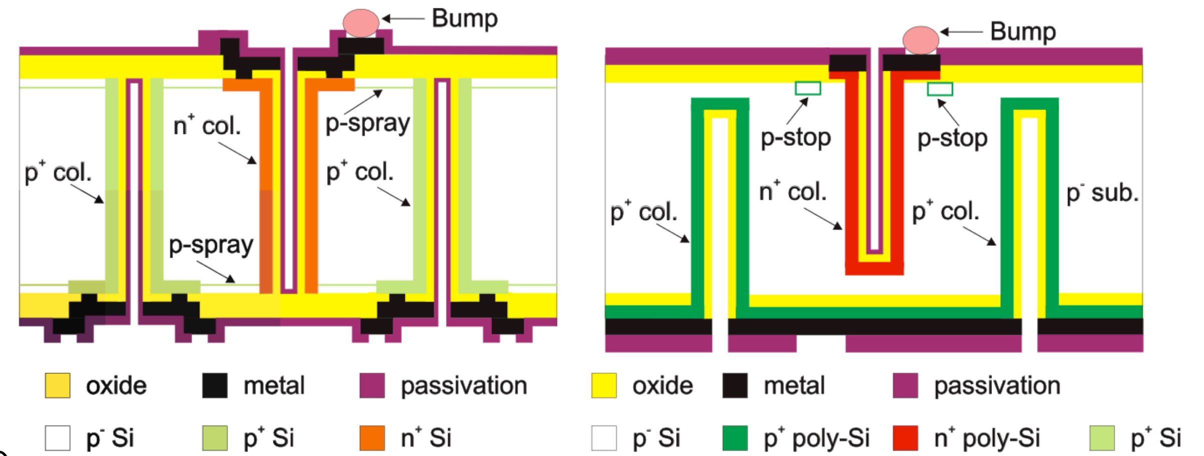
The 3D sensor technology is first time used in HEP experiments.

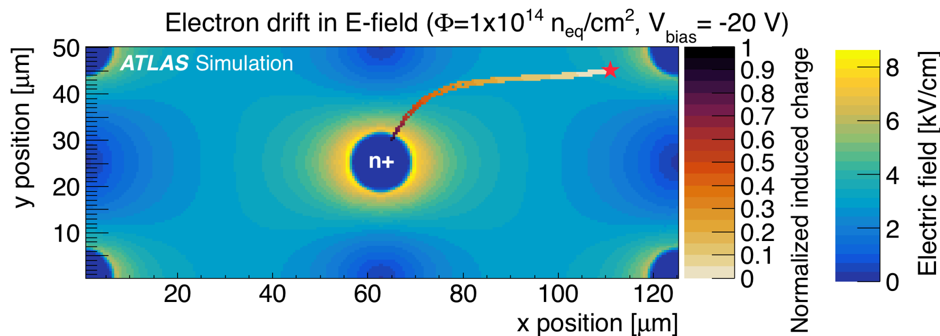
- Located in the outer end in inner-most-layer
- Two fabrications are adopted: FBK and CNM.

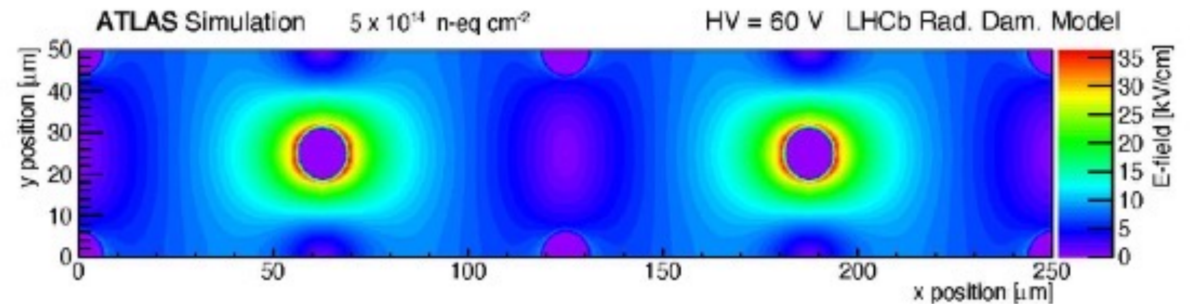
Simulation:

- E-field is generated by TCAD for given fluence.
- Profiling the electron-hole drift as look-up-table.





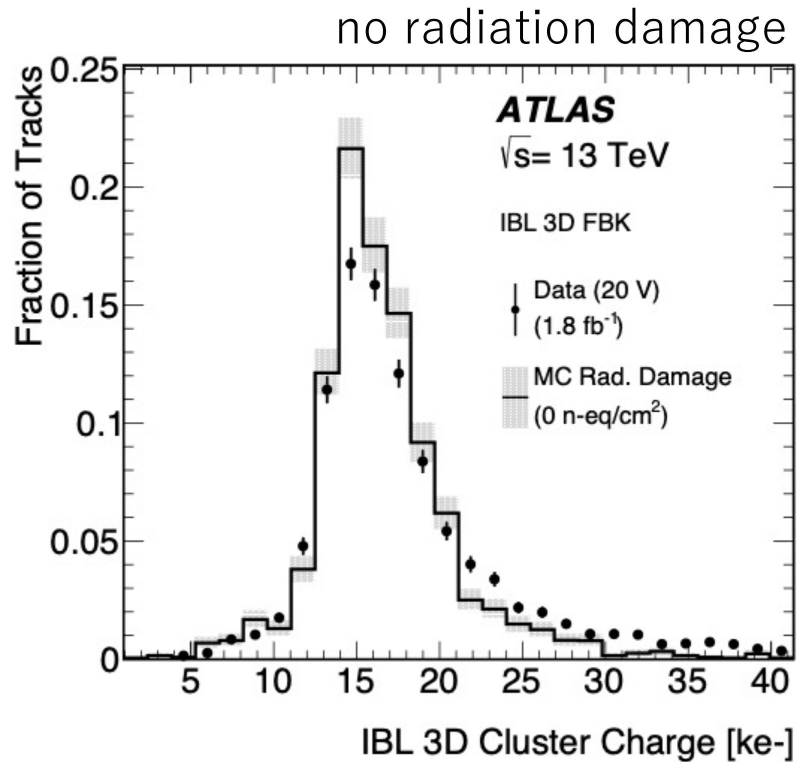


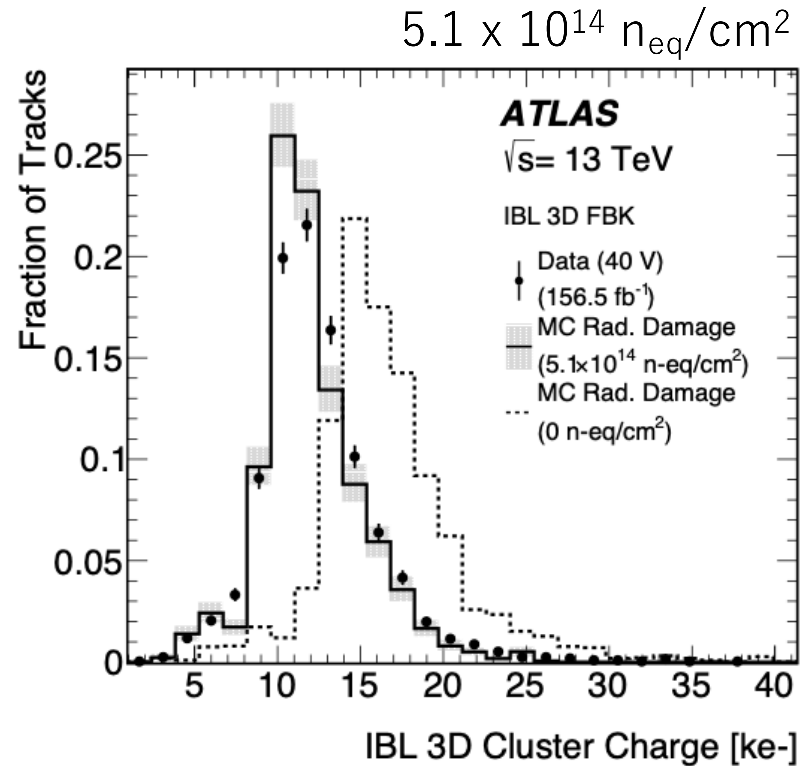


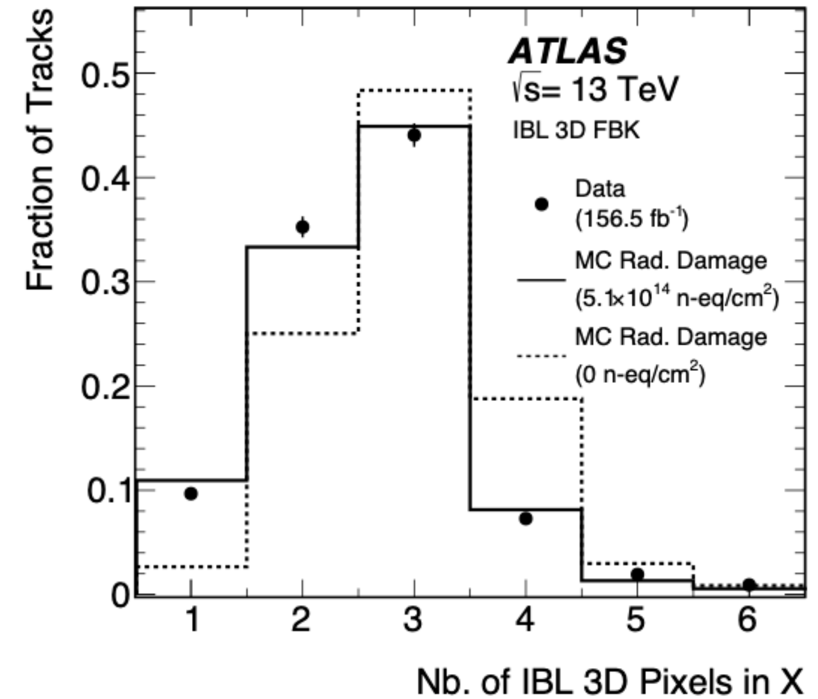
3D pixel performance

no radiation damage

$5.1 \times 10^{14}\ n_{eq}/cm^2$





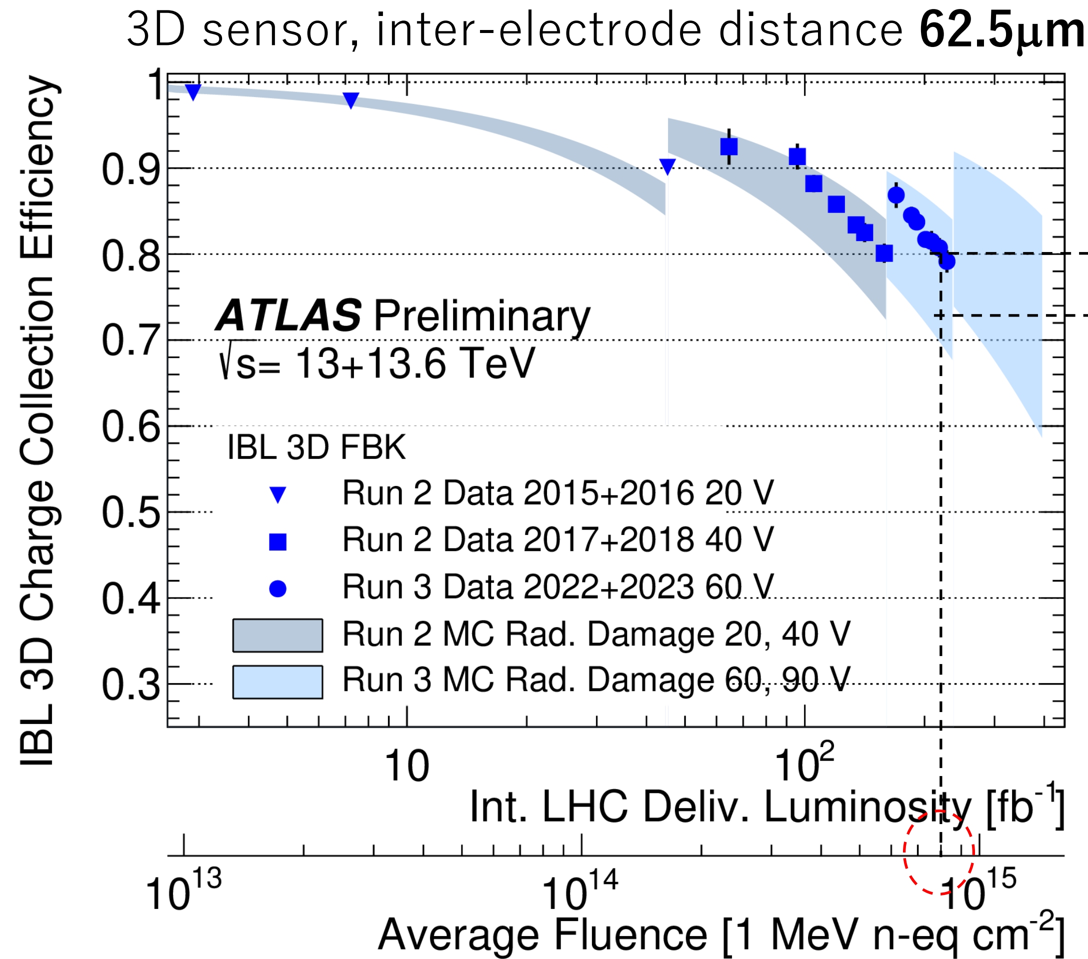


3D sensor radiation damage effect

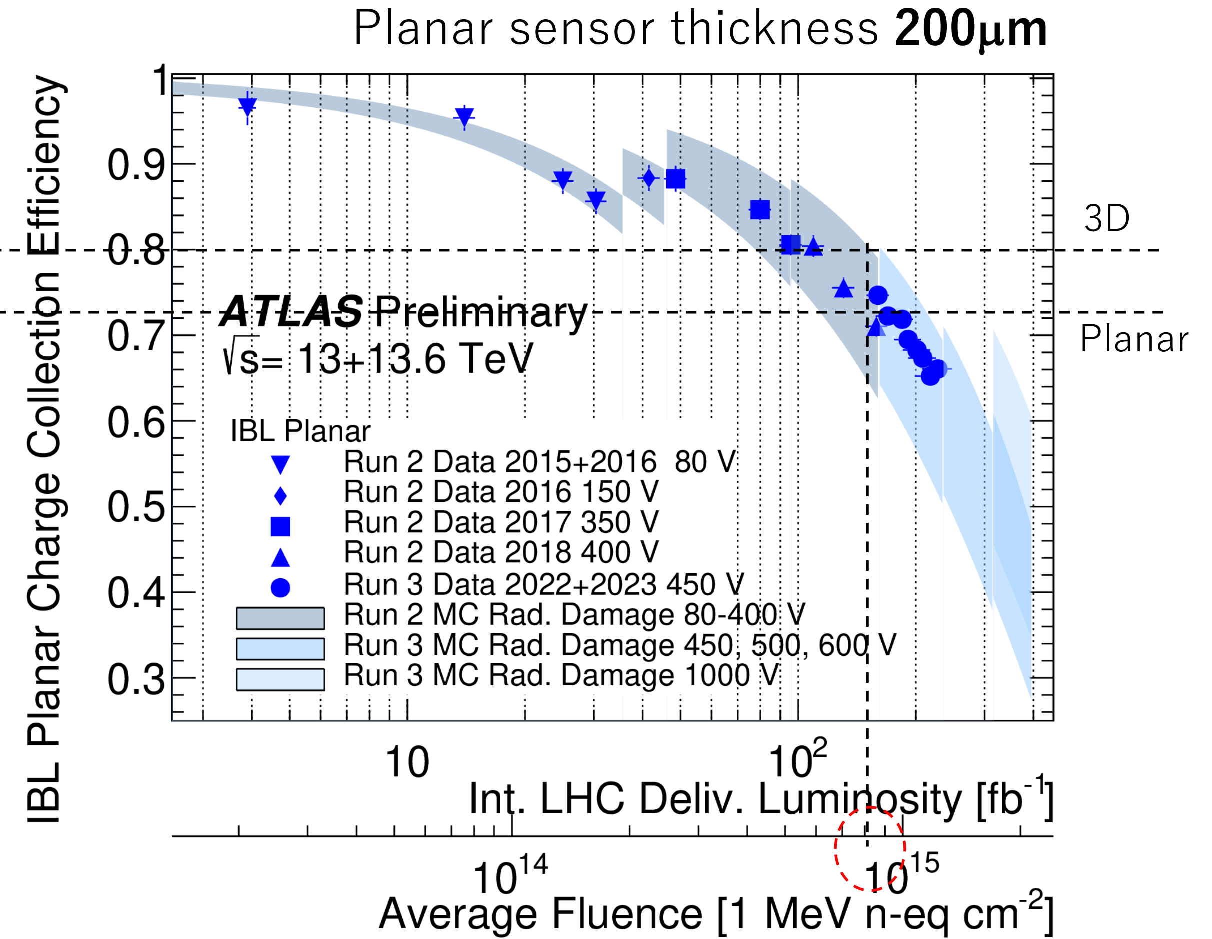
Submitted to JINST
https://arxiv.org/abs/2407.05716

The 3D sensor is more radiation hard than planar sensor.

3D sensor, inter-electrode distance **62.5μm**



Planar sensor thickness **200μm**



Summary

So far, the pixel operation is very stable in RUN3.

Reported in this presentation:

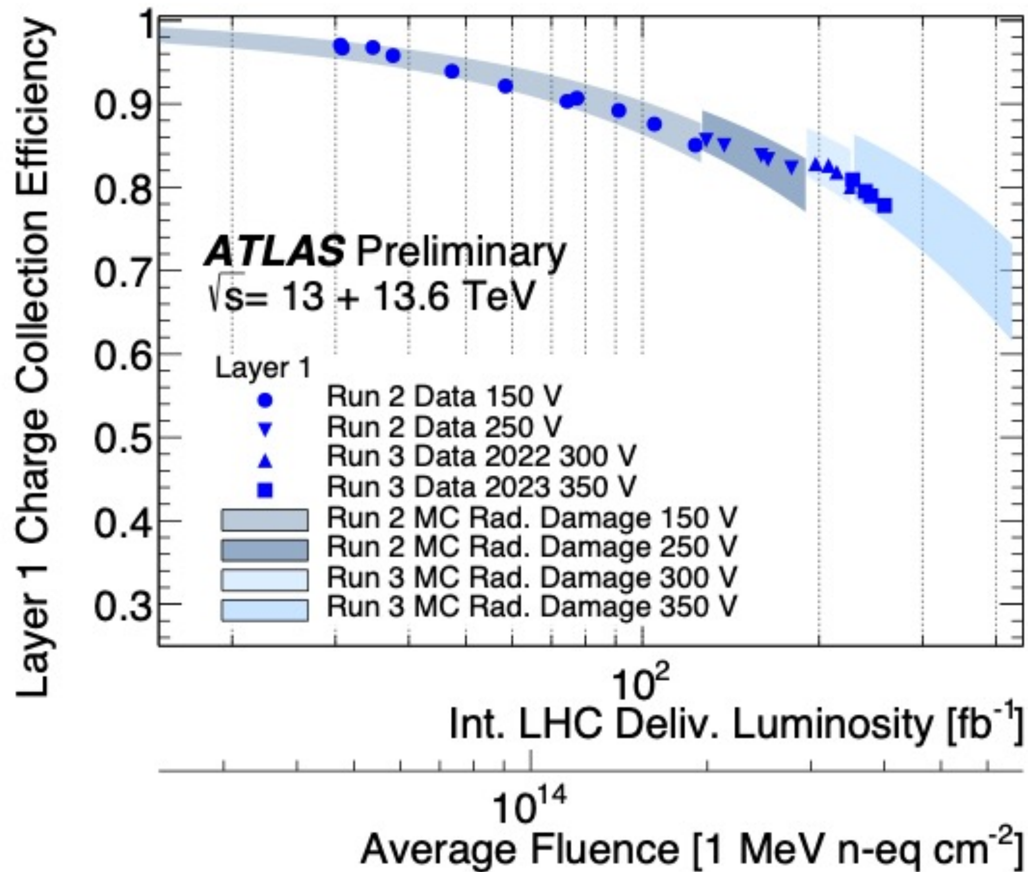
- Optoboard replacement
- Reduction of synchronization errors in outer pixel layers
- Deployment of the radiation damage simulation
- Leakage current measurements
- First results of 3D sensor performance

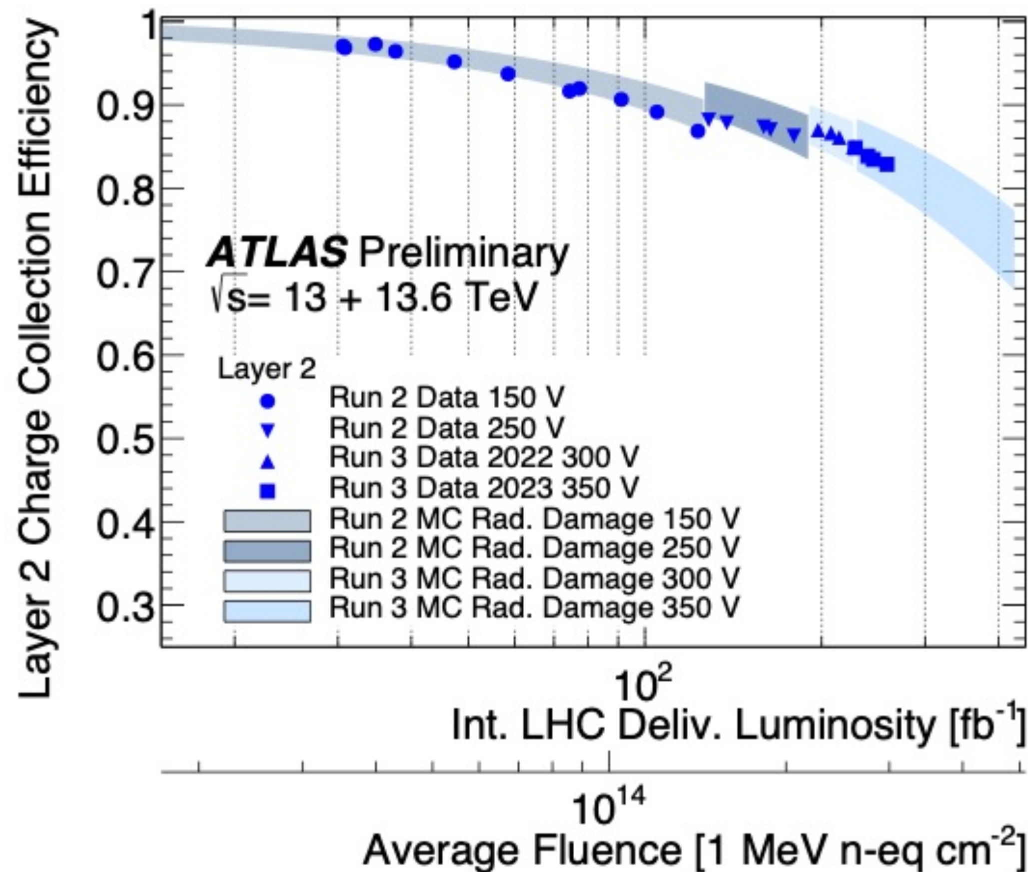
Yet important developments (not reported):

- Reduction of the hole by finer masking at FE-level
- Deployment of several firmware reset machinery to avoid SEU
- Handling bytestream errors in the tracking
- Light weight of DB contents
- etc…

The Run-3 experiment will be successful.

Backup


ATLAS Preliminary
$\sqrt{s}$= 13 + 13.6 TeV
Layer 1
Run 2 Data 150 V
Run 2 Data 250 V
Run 3 Data 2022 300 V
Run 3 Data 2023 350 V
Run 2 MC Rad. Damage 150 V
Run 2 MC Rad. Damage 250 V
Run 3 MC Rad. Damage 300 V
Run 3 MC Rad. Damage 350 V
Layer 1 Charge Collection Efficiency
Int. LHC Deliv. Luminosity [fb^{-1}]
Average Fluence [1 MeV n-eq cm^{-2}]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