# Radiation Damage Effects in ATLAS Pixel Detector

# Monte Carlo Simulations: Status and Perspectives


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- Due to active electrical defects in the Si bulk, performance of trackers degrades over time
- Higher sensor leakage current leads to increased noise, heat generation and power consumption
- The space charge distribution is distorted, and that leads to low electric field regions in the sensor. This means that higher operating voltages are needed for the detector
- The trapping of the charge carriers results in signal reduction, which impacts the spatial resolution and the hit efficiency of the detector

Signal reduction is the most noticeable radiation damage effect on performance of the ATLAS Pixel detector

Need to have simulated events that model the evolution of radiation damage with the accumulation of fluence.

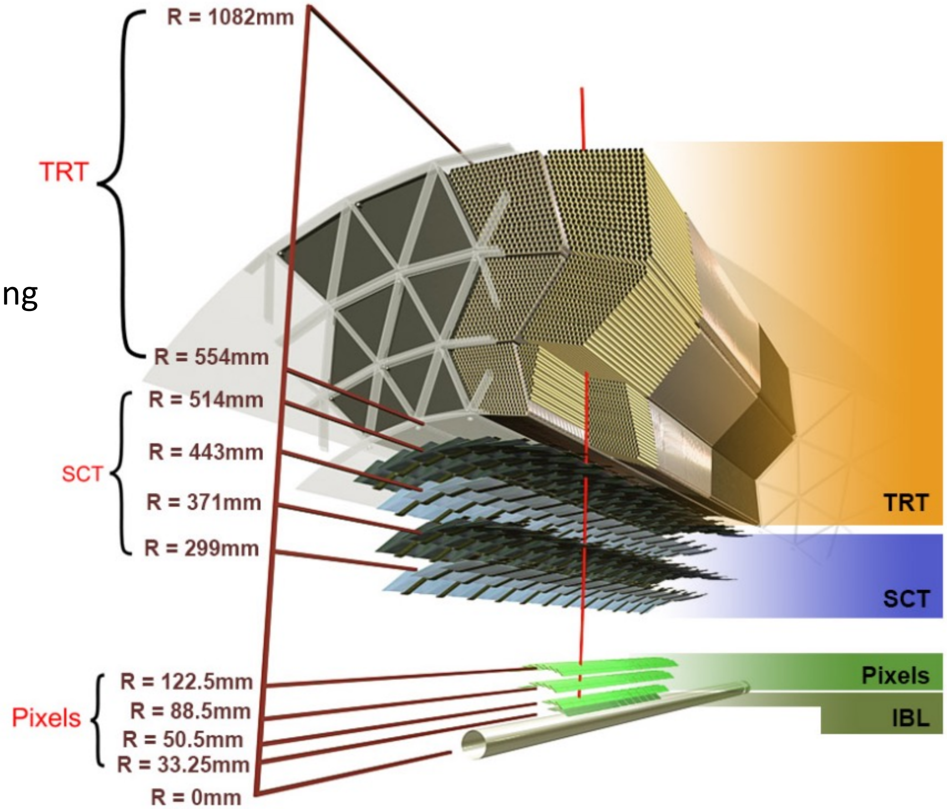
ATLAS has developed a digitization model incorporating effects of radiation damage upon the pixel sensors.

Four barrel layers + six disks

- IBL – $200\ \mu m$ thick, $50 \times 250\ \mu m^2$ pitch, in data-taking since Run 2
- Outer layers (B-Layer, Layer-1, Layer-2) - $250\ \mu m$, $50 \times 400\ \mu m^2$ pitch

Technology

- Planar sensors (all layers) - $n^+$-$in$-$n$ sensors
- 3D sensors (IBL, high $\eta$) – $n^+$-$in$-$p$ sensors




[Relevant Talk at TIPP 2023 - Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider at CERN by Vinicious Franco Lima on Sept 5th at 11:00 am]

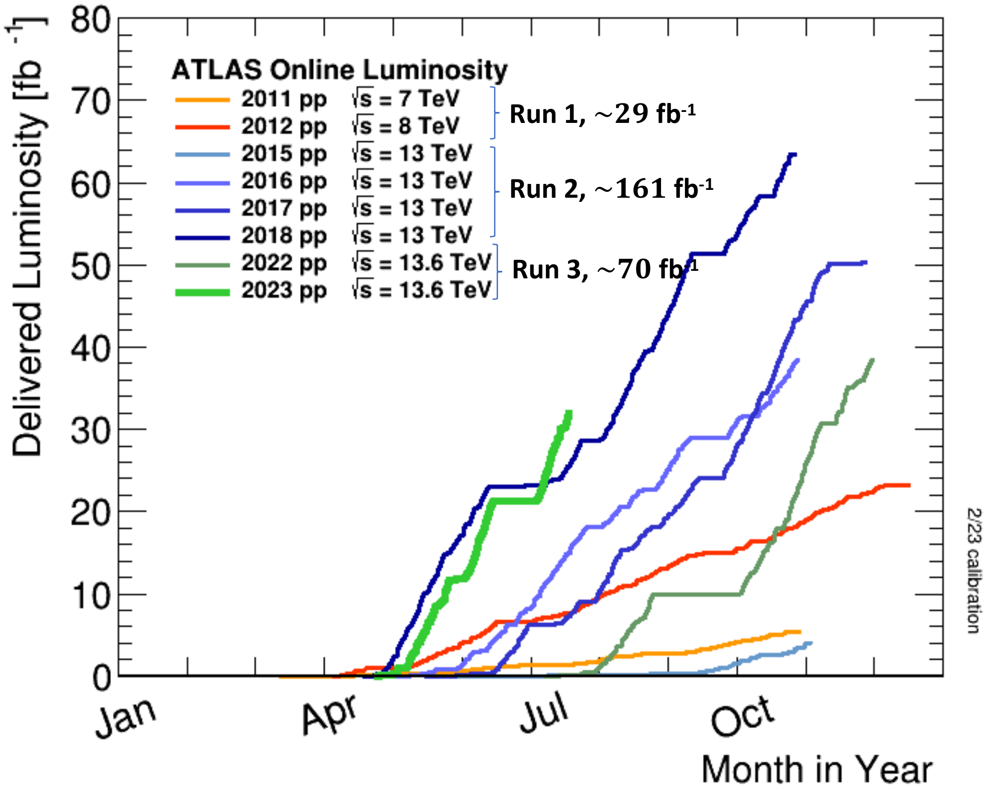
# Luminosity Integrated So Far[1]

IBL collected ~230 $fb^{-1}$

All other layers: ~260 $fb^{-1}$

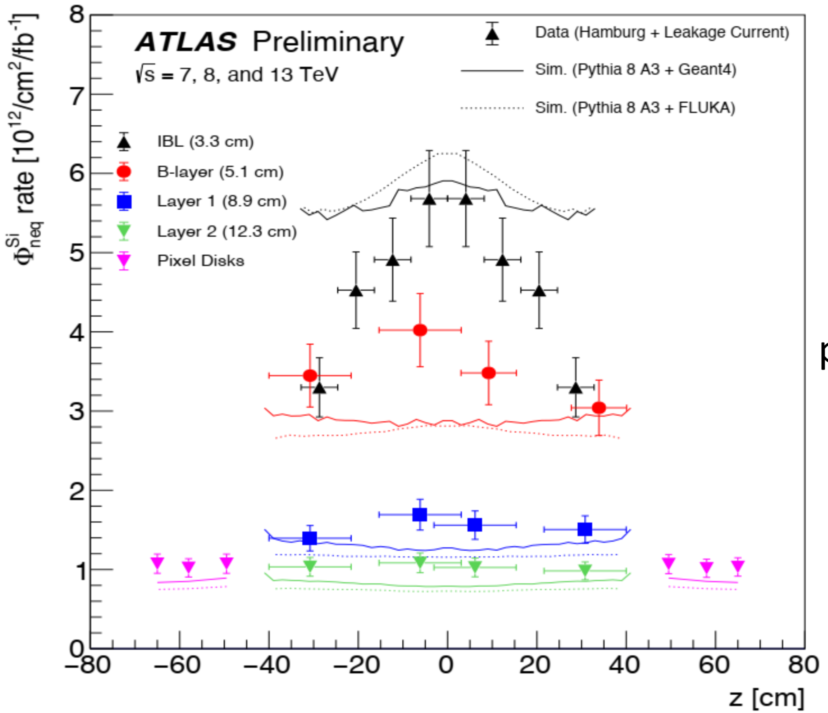
ATLAS aims to collect another 165 $fb^{-1}$ till the end of 2025[2]

A total of 425 $fb^{-1}$ in Runs 1-3




1. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3
2. https://lhc-commissioning.web.cern.ch/performance/Run-3-targets.htm

## Fluence Profiles[1] of the Pixel Detector




Unexpected non-uniform fluence profile for IBL

### IBL

(designed[2] for $5\times10^{15}$ 1 MeV $n_{eq}/cm^2$)

| Time | Int. Lumi (fb$^{-1}$) | Fluence ($n_{eq}/cm^2$) |
|---|---|---|
| End of Run 2 | 161 | $\sim 0.9\times10^{15}$ |
| Till now | 230 | $\sim 1.2\times10^{15}$ |
| End of Run 3 (projected) | 395 | $\sim 2.1\times10^{15}$ |

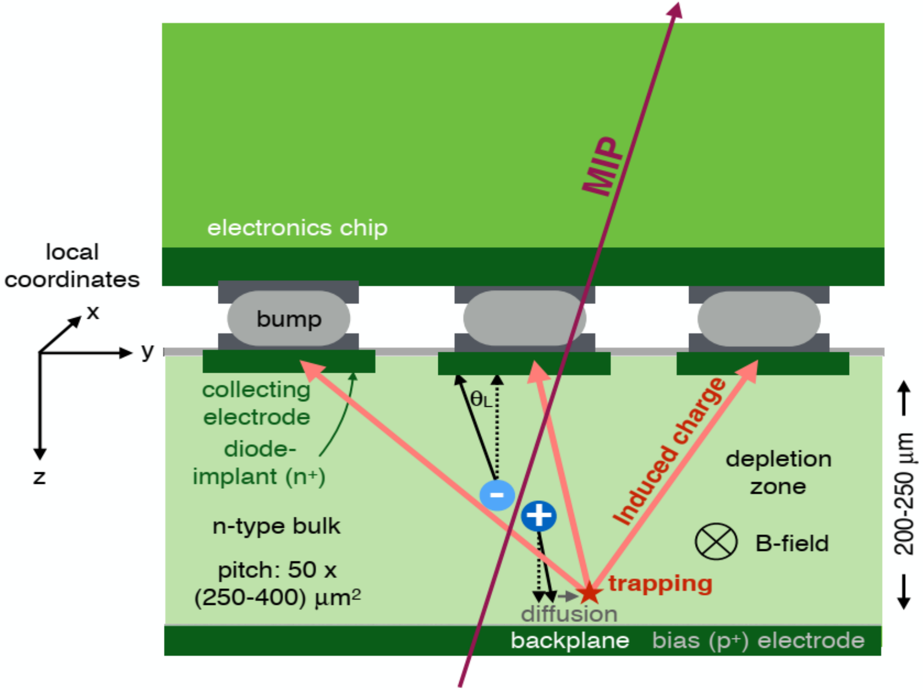
### B-Layer

(designed[3] for $1\times10^{15}$ 1 MeV $n_{eq}/cm^2$)

| Time | Int. Lumi (fb$^{-1}$) | Fluence ($n_{eq}/cm^2$) |
|---|---|---|
| End of Run 2 | 190 | $\sim 0.7\times10^{15}$ |
| Till now | 260 | $\sim 1.0\times10^{15}$ |
| End of Run 3 (projected) | 425 | $\sim 1.5\times10^{15}$ |


1. ATLAS Collaboration, Measurement of Radiation Damage through Leakage Current Monitoring of the ATLAS Pixel Detector, CERN-EP-2021-055 (2021)
2. B. Abbott et al, Production and integration of the ATLAS Insertable B-Layer, JINST 13 T05008 (2018)
3. G Aad et al, ATLAS pixel detector electronics and sensors, JINST 3 P07007 (2018)

As a charged particle traverses the sensor, charge carriers drift to electrodes under the electric field




Their path will be deflected by the solenoidal magnetic field (Lorentz angle) and diffusion

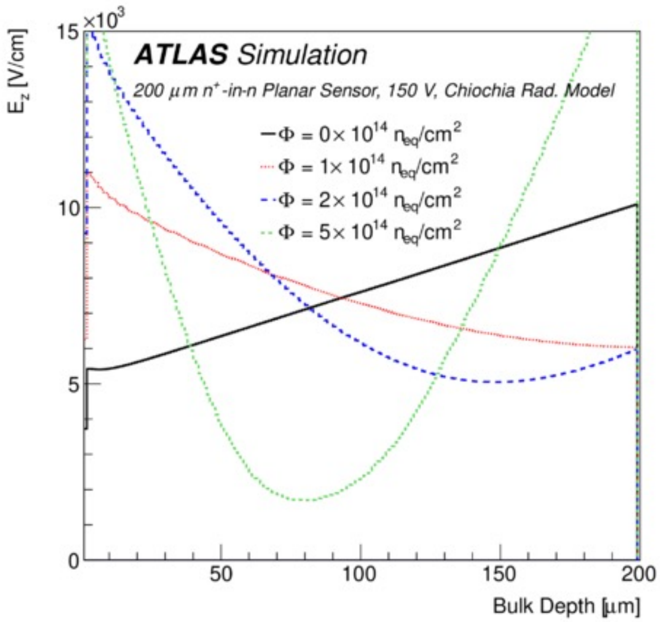
Radiation damage can alter the space-charge density which in turn affects electric field

Charge carriers get trapped due to distorted electric field and hence induce/screen a fraction of their charge onto the electrodes (Ramo potential)

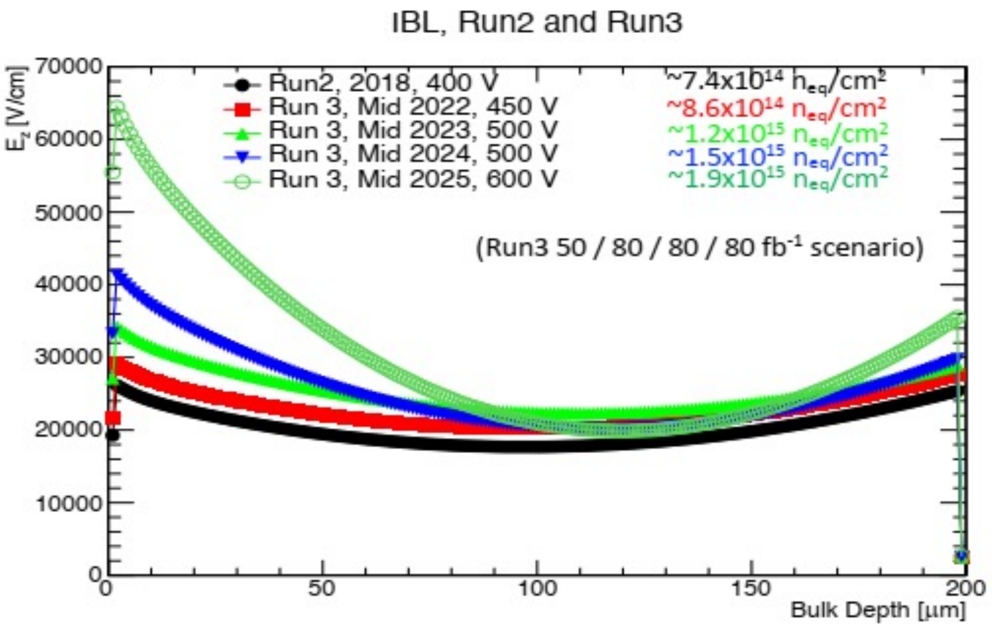
**Total induced charges are then digitized and clustered**

Digitization is done using the ATLAS software framework, Athena, interfaced with Geant4. It happens after simulated charge deposition but before induced charge reconstruction

As a result of the radiation damage, electric field in the Si is no longer linear with the bulk width, due to non-constant space charge density. Electric field profiles[1,2] for IBL from TCAD simulations for various fluences



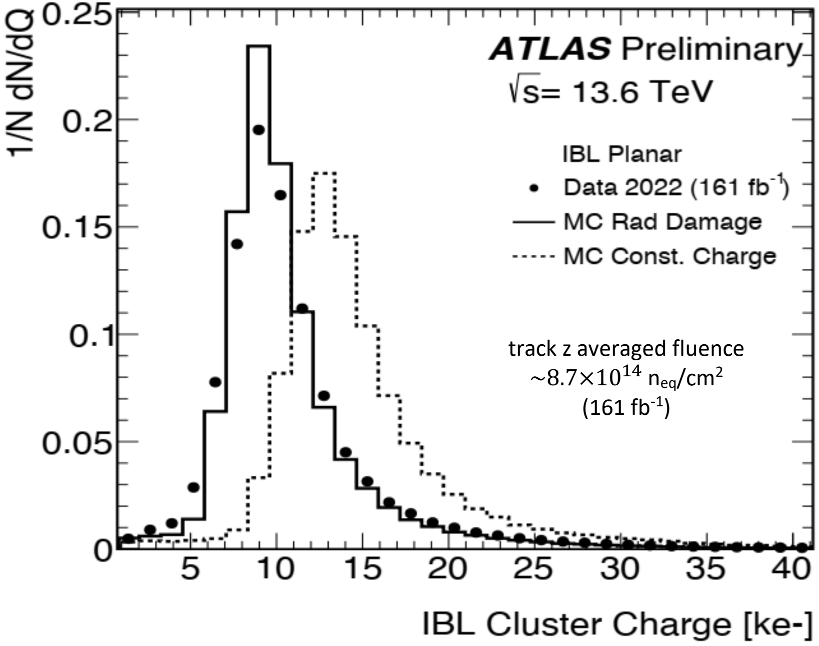

Minimum is broad for sensors that are not fully depleted

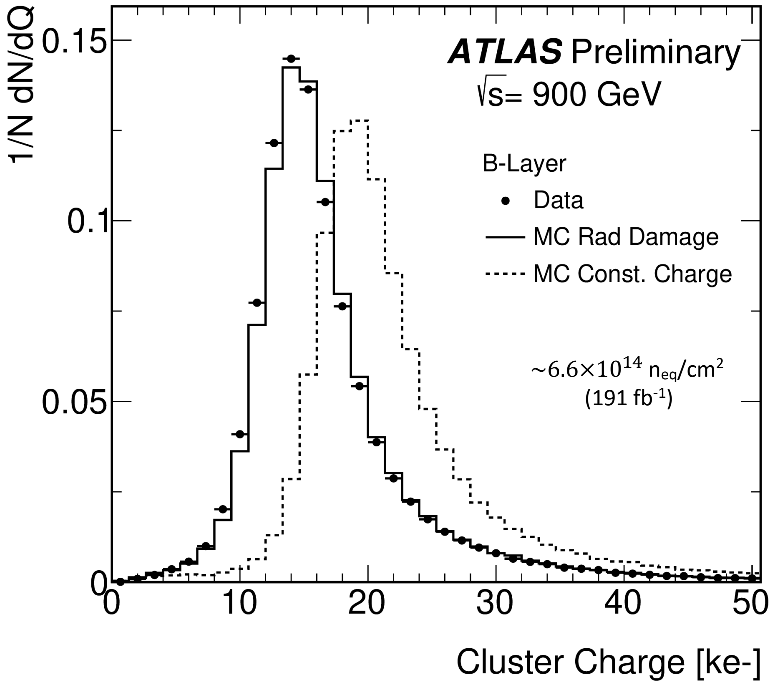




1. ATLAS Collaboration, Modelling radiation damage to pixel sensors in the ATLAS detector, JINST 14 P06012 (2019)
2. M. Bomben, Including radiation damage effects in ATLAS MonteCarlo simulations: status and perspectives, ATL-INDET-SLIDE-2023-360 (2023)

Collected charge distribution[1] by the pixel sensors shows the pixel response and radiation damage. Simulation using MC with radiation damage effects and data (Run 2) is compared to the simulation using MC with constant charge (no radiation damage effects)

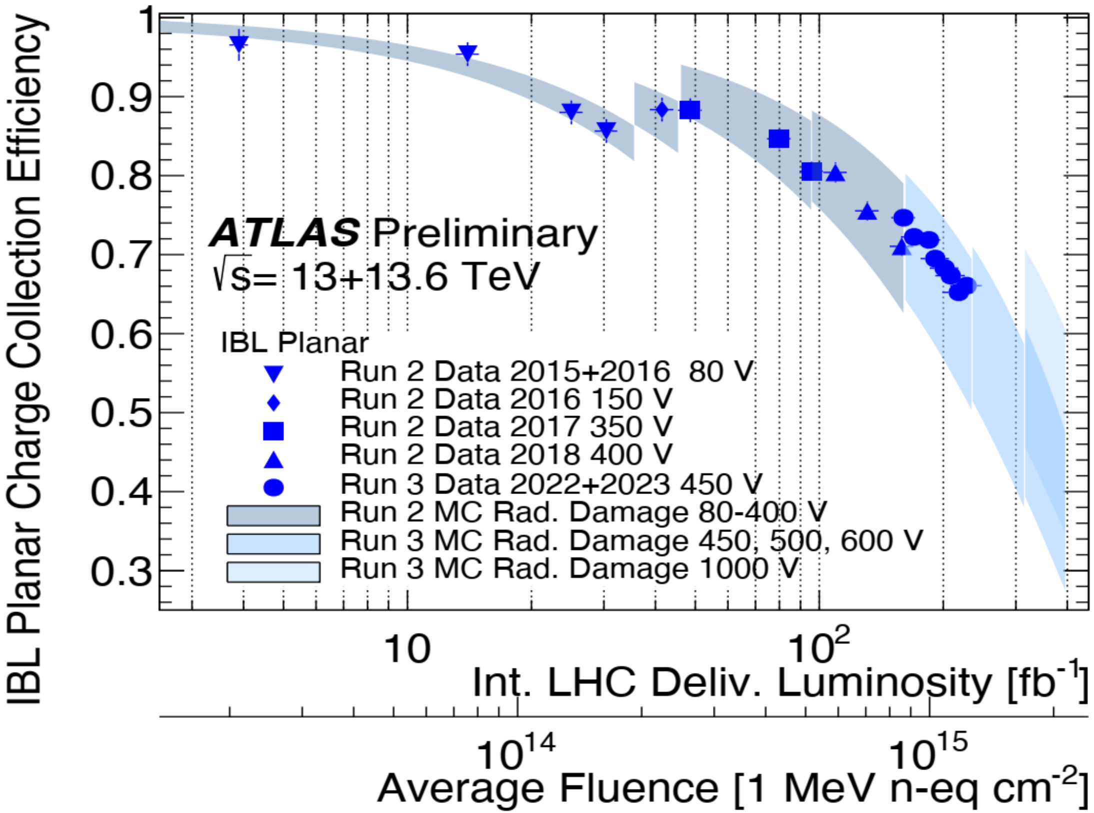



**Agreement between the data and MC at 1% level when it comes to the most probable value (MPV)!**

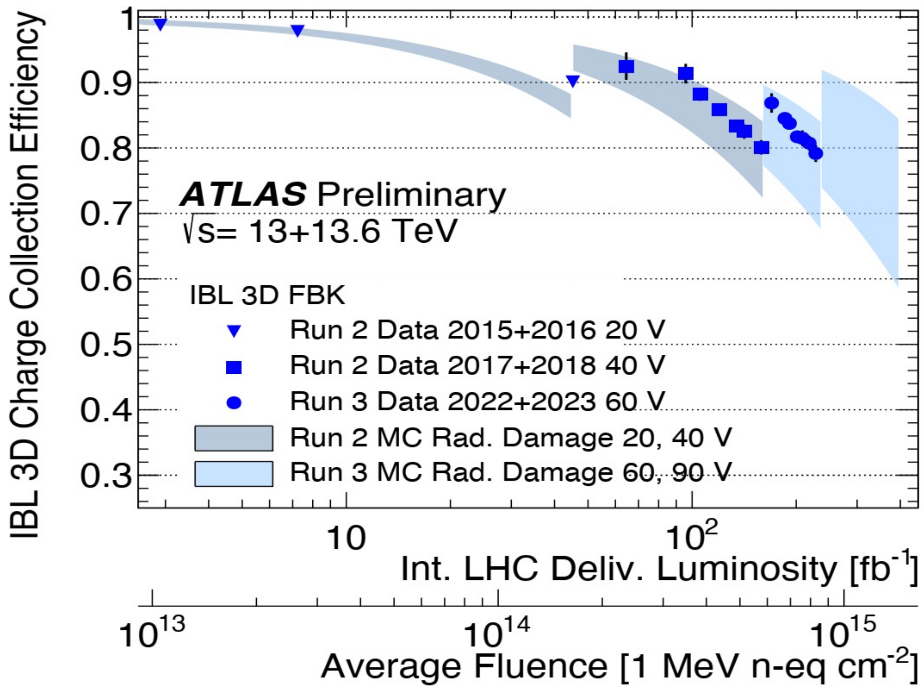
Differences are due to uncertainties in model parameters and fluence-to-luminosity conversion factors

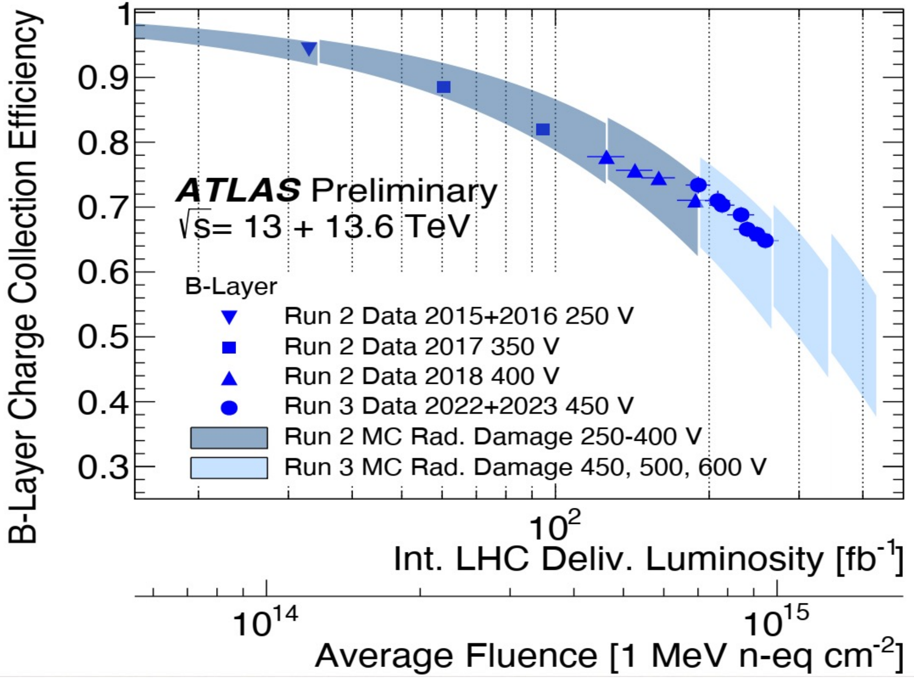
1. ATLAS Collaboration, Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at √s=900 GeV, ATL-PHYS-PUB-2022-033 (2022)




- Charge collection efficiency[1] (CCE) obtained by computing the MPV of the cluster charge normalized to that measured at the beginning of 2015 for IBL planar sensors
- Excellent agreement between data and radiation damage MC over almost two orders of magnitudes of fluence
- CCE reduced by more than 25% at the end of Run 2 and more than 35% till now
- Predictions indicate enough CCE till the end of Run 3

1. ATLAS Collaboration, Charge Collection Efficiency for the ATLAS Planar and 3D Pixel Sensors in Collision Data and Radiation Damage Simulation, ATL-INDET-INT-2023-001 (2023)




Excellent agreement between the data and radiation damage MC!

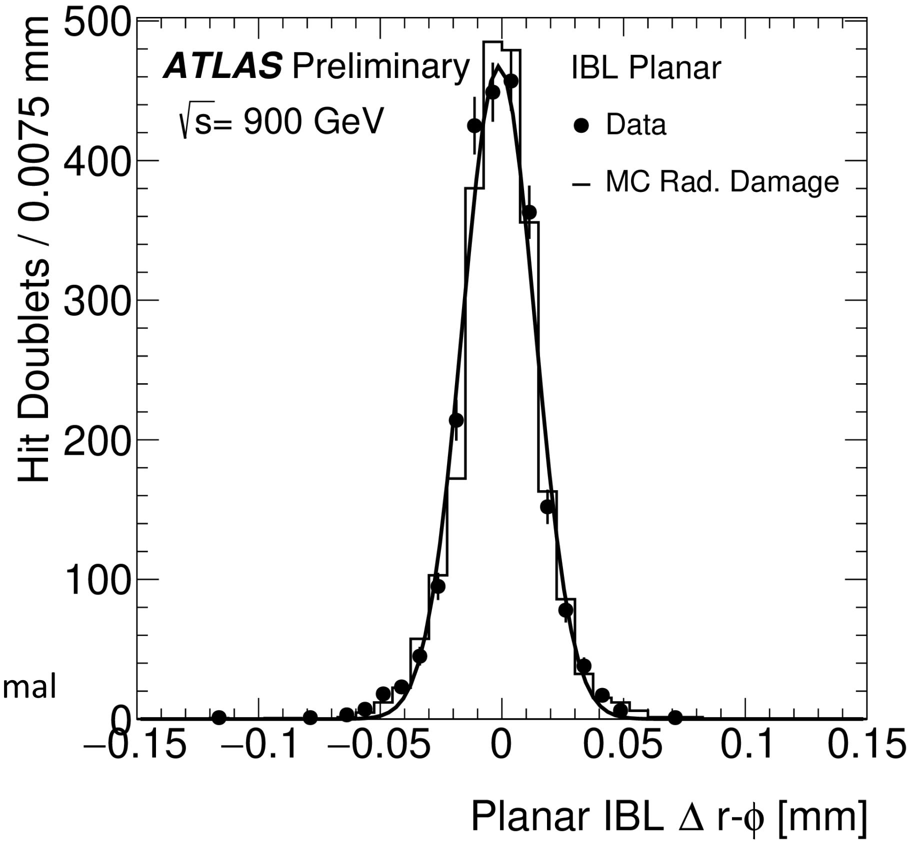
CCE reduced by more than 20% for IBL 3D sensors and more than 25% for B-Layer

1. ATLAS Collaboration, Charge Collection Efficiency for the ATLAS Planar and 3D Pixel Sensors in Collision Data and Radiation Damage Simulation, ATL-INDET-INT-2023-001 (2023)

One of the most crucial performance figures for pixel sensors in tracking applications

Essential to associate hits to a track candidate and perform the track fit

- Uses the IBL overlap[1] method to compute the difference between two IBL hits along $\phi$
- Resolution can then be extracted from the corrected difference in the coordinates of these hits
- Difference[2] between corrected positions in the IBL clusters

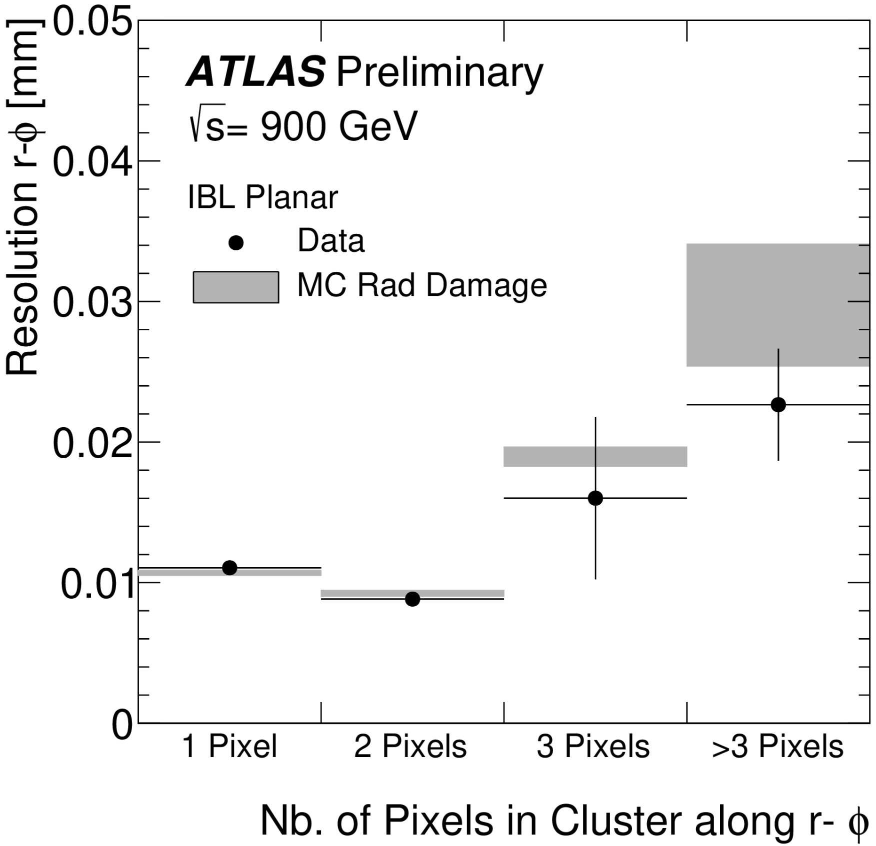



Impacts on pixel resolution by radiation damage effects are minimal since the determination of hit positions depends on relative quantities such as fraction of cluster charge shared between neighboring pixels

1. ATLAS Collaboration, IBL Efficiency and Single Point Resolution in Collision Events, ATL-INDET-PUB-2016-001 (2016)
2. ATLAS Collaboration, Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at √s=900 GeV, ATL-PHYS-PUB-2022-033 (2022)

The dependence[1] of the measured spatial resolution on the number of pixels in the cluster for $r - \phi$

- Clusters that use 2 pixels benefit from charge interpolation, leading to better resolution
- 2+ pixel clusters lead to degraded resolution mostly due to $\delta$-rays displacing the center of gravity of the charge released by the primary particle
- The spatial resolution of the detector was degraded by 25% due to radiation damage effects by the end of Run 2. This was improved by using a Mixture Density Network (MDN) instead of a Neural Network to estimate the cluster positions in Run 3 and by training the network on radiation damage MCs




1. ATLAS Collaboration, Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at √s=900 GeV, ATL-PHYS-PUB-2022-033 (2022)

- Anticipated to collect 3000 $fb^{-1}$ of data at $\sqrt{s} = 14$ TeV – at least 7 times more than entire Run 1+2+3* data
- The innermost layer of the ATLAS Inner Tracker (ITk) will receive 2000 $fb^{-1}$ which is equivalent to a fluence of $1\times10^{16}\ n_{eq}/cm^2$ - at least 10 times more than the fluence the IBL would receive by the end of Run 3
- Significantly higher event, track and hit rates
- Modified Digitizer which is the default for Run 3 agrees well with the data
  - But for each group of carriers, the induced signal per pixel is evaluated – too slow for HL-LHC

Relevant Talk at TIPP 2023 –

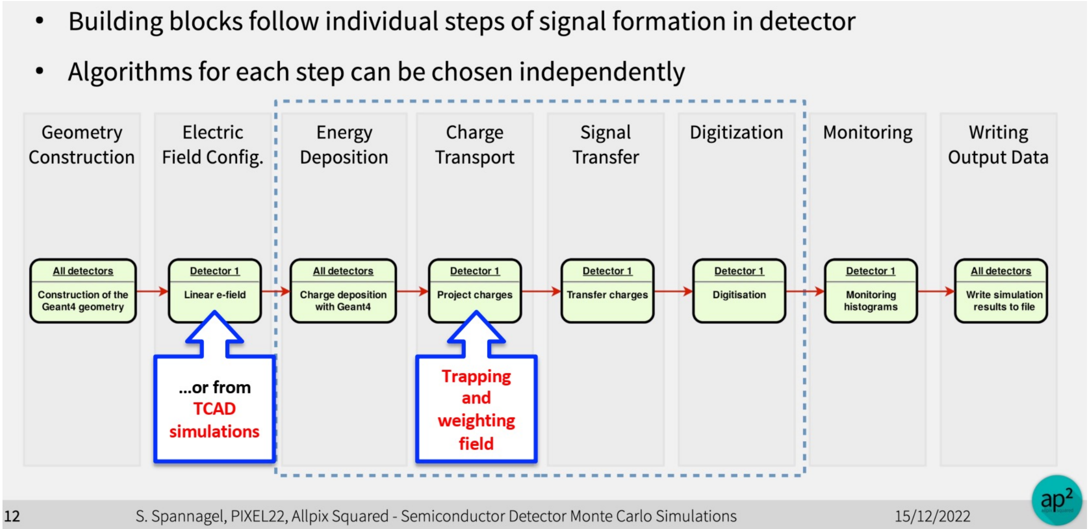
1. The ATLAS HL-LHC Upgrade Program by Claudia Gemme on Sept 6th at 11:00 am
2. ATLAS ITk Pixel Detector Overview by Koji Nakamura on Sept 6th at 12:00 pm
3. Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment by Stefano Terzo on Sept 7th at 12:40 pm

* If a total of 235 $fb^{-1}$ is collected in Run 3.

- Plan - For each simulated charge in the bulk, the fraction of the charge that gets induced on the electrodes, its corrected position (Lorentz angle, average free path in depth direction) will be estimated using Look Up Tables (LUTs)

- Inspired by CMS template method[1]

- The LUTs will be calculated with Allpix2[2] together with TCAD




1. M. Swartz, et al, A new technique for the reconstruction, validation, and simulation of hits in the CMS Pixel Detector, CMS-NOTE-2007-033 (2007)
2. https://allpix-squared.docs.cern.ch/

# Conclusion

- A more advanced digitizer model is the default in ATLAS since the beginning of Run 3
- The new model simulates the signals by incorporating the radiation damage effects on the electric field profiles, the charge trapping, and the charge mobility in the detector
- Simulations of the radiation damage provide guidelines for optimizing the operational parameters and the reconstruction algorithms
- Excellent agreement between the data and the MC samples
- Good performance till the end of Run 3
- Faster algorithm is needed for the HL-LHC
- Allpix2 + TCAD will provide templates to correct simulations

# BACK-UP

Higher Luminosity → Increased Particle Radiation → Damaged sensors

Searching for New Physics using rare processes requires large amounts of data. For this, luminosity is increased as much as possible

More collisions means increased particle radiation which is reported in neutron equivalent fluence (number of 1 MeV neutrons applied to a sensor of surface area of $1 cm^2$ that cause damage equivalent to that of all particles that went through the sensor)

Irradiation causes nonstop damage to the silicon, producing artificial donor- and acceptor-like sites in the lattice

## Types of Radiation Damage

Bulk damage:

- Dislocations in the crystal lattice that introduce states in the forbidden gap.
- Grows over time, hence needs to be monitored regularly

Surface Damage:

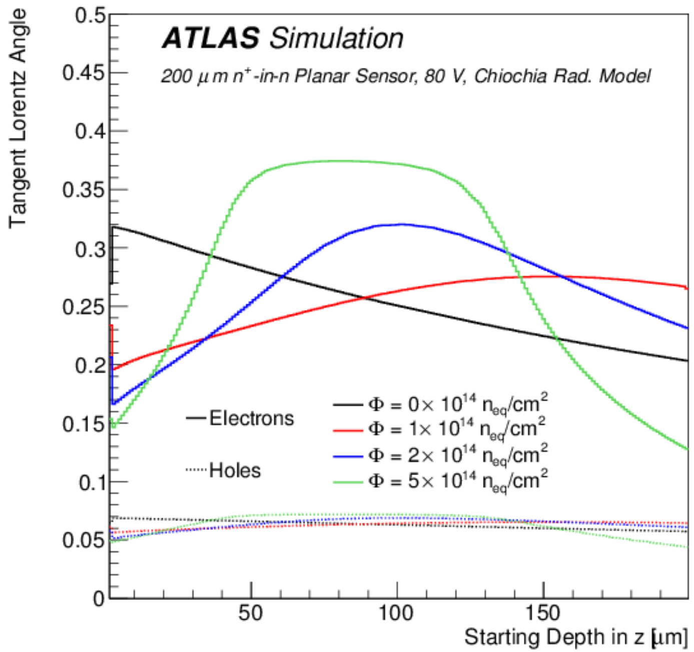
- Bound charges at the interfaces of silicon
- Significant effect on the electronics, but less problematic than the bulk damage, for the sensors
- Saturates[1] after initial radiation of about 100 kRad

Tracking detectors are placed closest to the interaction point, so they undergo the worst radiation damage. → ATLAS Pixel detector had received an unprecedented amount of radiation by the end of Run 2

- Monitor radiation damage in Run 3.
- Project to future years, to support development of HL-LHC detectors

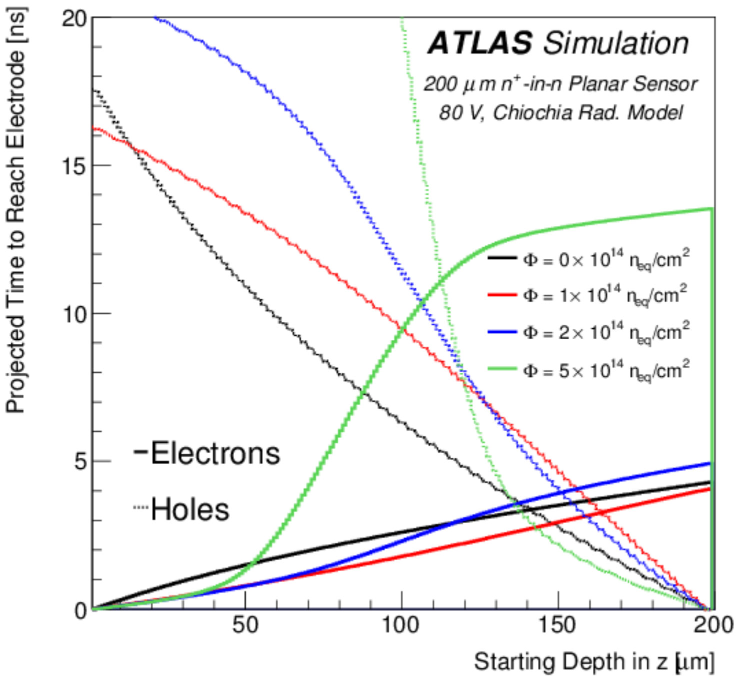
1. J. Wuestenfeld, Characterisation of Ionisation-Induced Surface Effects for the Optimisation of Silicon Detectors for Particle Physics Applications, UniDo-PH-E-2004-01-06 (2004)

The depth dependence[1] of the Lorentz angle for electrons and holes




As the mobility increases with decreasing electric field strength, the Lorentz angle is largest near the center of the irradiated sensors

Projected time to reach collecting electrodes in the absence of trapping

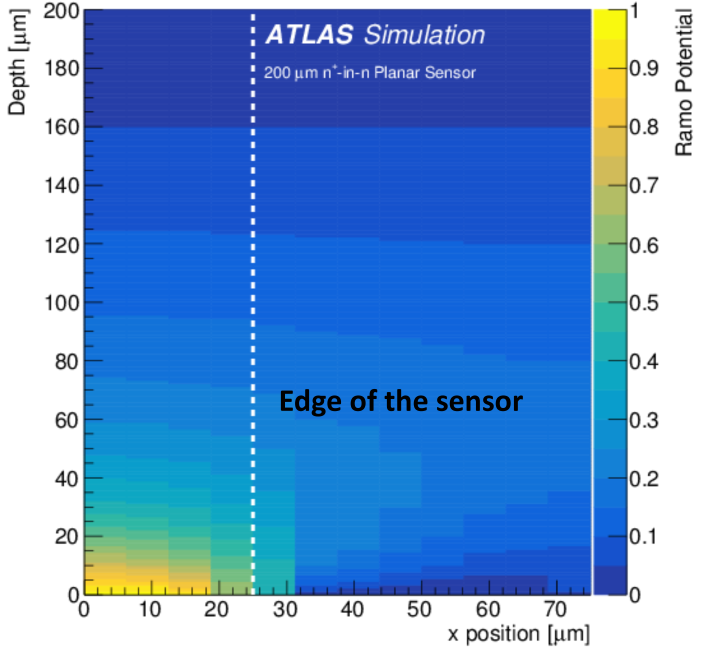



It takes holes much longer on average to arrive at the electrode. Worsens as fluence accumulates

1. [ATLAS Collaboration, Modelling radiation damage to pixel sensors in the ATLAS detector, JINST 14 P06012 (2019)]

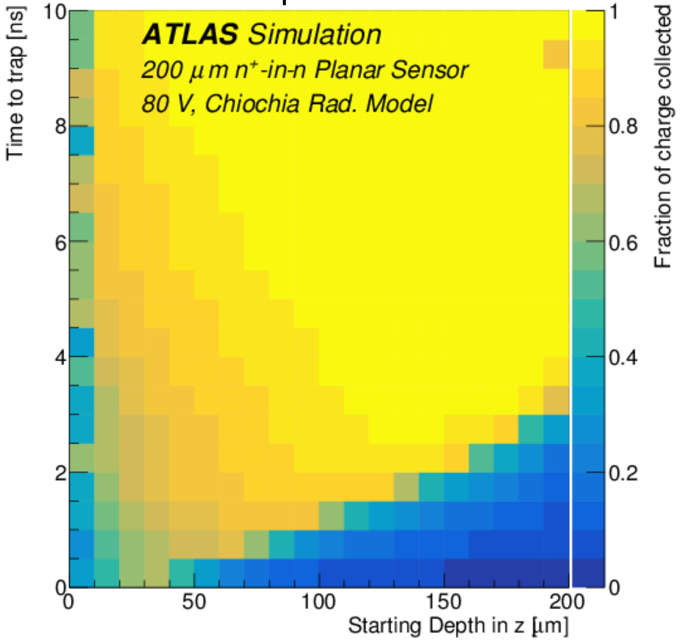
# Further Inputs to the Digitizer Model - Ramo Potential

A slice of the three-dimensional Ramo Potential[1] as computed with TCAD at y = 0




Ramo potential has sizeable contributions in the neighboring pixels

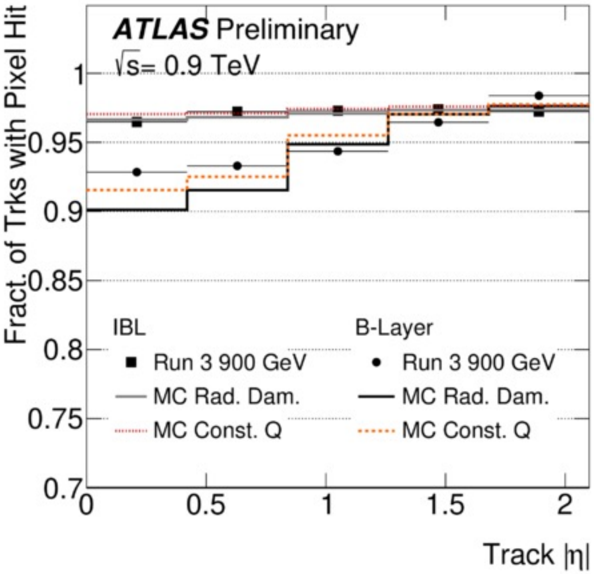
The average fraction[1] of charge collected as a function of the starting location and the time to be trapped for the same pixel

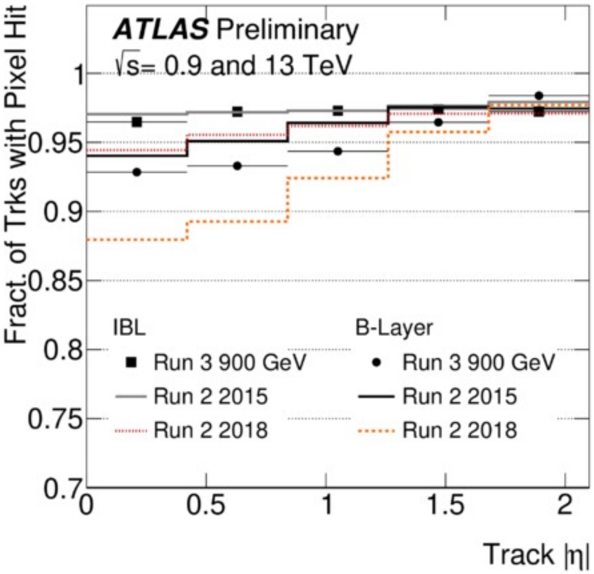



The induced charge includes the contribution from electrons and holes, while the electron time to trap is used for the vertical axis

1. [ATLAS Collaboration, Modelling radiation damage to pixel sensors in the ATLAS detector, JINST 14 P06012 (2019)]()

The fraction of particle tracks[1] reconstructed with associated pixel detector hits in a given layer gives an indication of the detector efficiency for tracking purposes



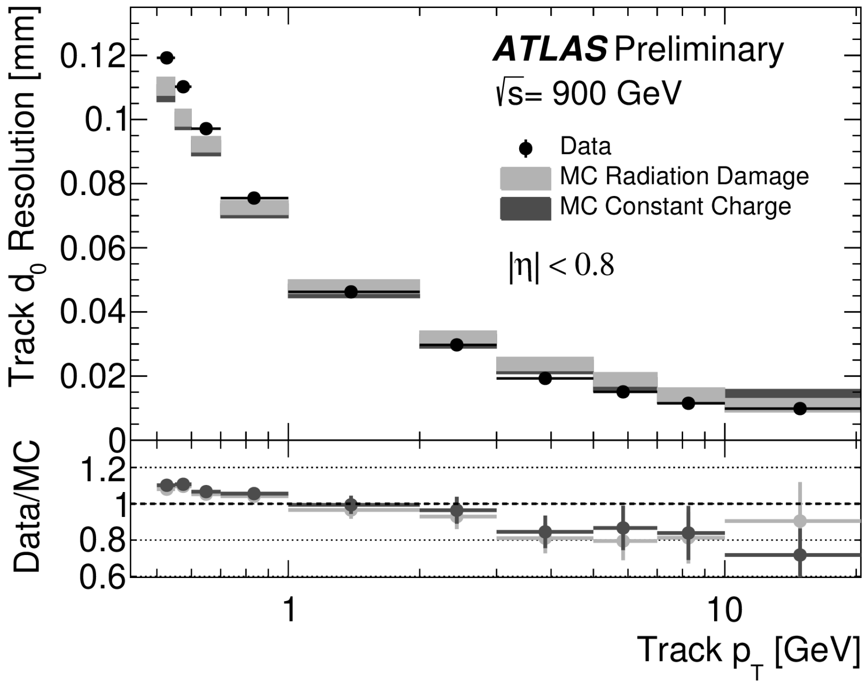




- Good agreement between the data and MC
- Higher efficiency registered at the start of Run 3 compared to that at the end of Run 2 for both the IBL and B-Layer is due to optimization of pixel operating conditions (increased bias voltage, reduction of ToT thresholds, reduction of inactive modules, etc. )

Radiation damage effects on the efficiency for associating pixel hits to tracks are manageable for the fluences integrated so far

1. ATLAS Collaboration, Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at √s=900 GeV, ATL-PHYS-PUB-2022-033 (2022)

- Resolution of the impact parameter projection in the plane transverse to the beam axis
- Crucial for flavor tagging/vertexing
- Depends on the Inner Detector (ID) hit resolution and scales as $^1/_{p_\mathrm{T}}$ due to multiple scattering effects
- Results are close to that obtained with 13 TeV collision data at the start of Run 2
- Agreement between data and MC is good considering the limited span of $p_\mathrm{T}$ distribution of tracks in 900 GeV collisions




The tracking performance of the ATLAS Pixel Detector is not much affected by radiation damage for the fluence integrated so far. This is shown by the similarity of the results using radiation damage and the constant charge MC samples

1. ATLAS Collaboration, Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at √s=900 GeV, ATL-PHYS-PUB-2022-033 (2022)