RADIATION DAMAGE EFFECTS IN ATLAS PIXELS AND THEIR SIMULATIONS: STATUS, RESULTS AND AND PERSPECTIVES.

NEW

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Abstract

Signal reduction is the most important radiation damage effect on performance of silicon tracking detectors. Adjusting sensor bias voltage and detection threshold can help in mitigating the effects, but it is important to have simulated data that reproduce the evolution of performance with the accumulation of luminosity, hence fluence. The two innermost pixel layers of ATLAS (Insertable B-Layer and B-Layer), consisting in both planar and 3D sensors, have already integrated fluences in excess of 1×10^{15} n_{eq}/cm^2 and show significant charge collection loss and cluster modification. ATLAS collaboration developed and implemented an algorithm that reproduces signal loss, cluster modification and changes in Lorentz angle due to radiation damage. This algorithm is now the default for Run3 simulated events. In this talk the algorithm will be presented and results compared to Run3 collision data, with emphasis on cluster properties.

ATLAS IBL & Pixel Detector

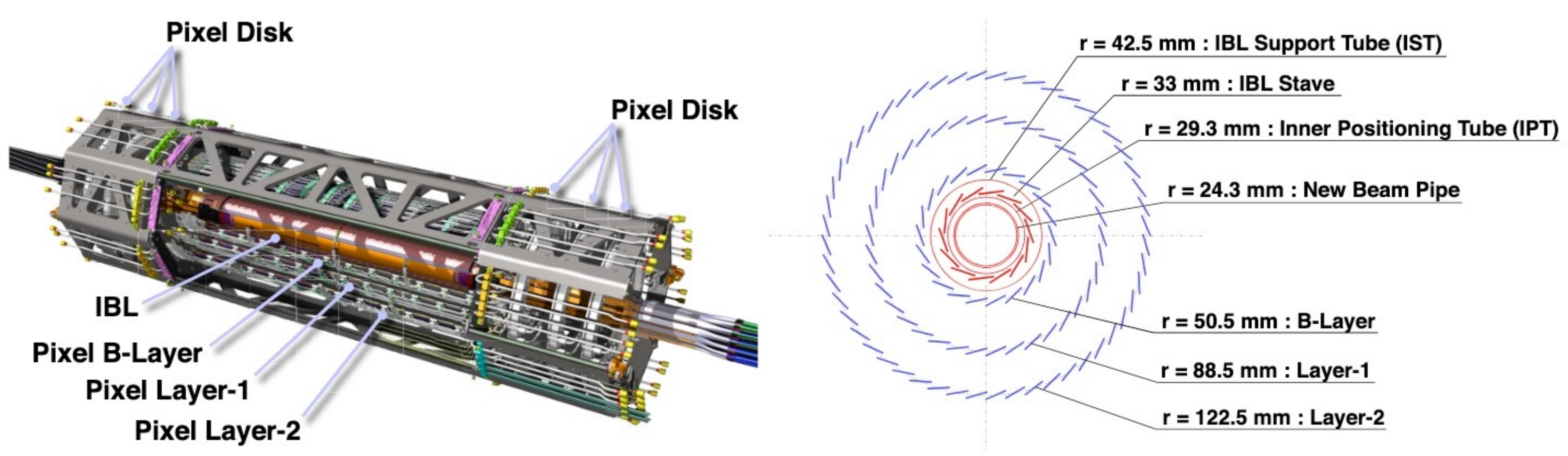

Figure 1 ATLAS IBL and Pixel detector

At the core of the ATLAS experiment [1] there are Silicon hybrid pixel modules made by mating sensors realised on high resistivity material to custom readout chips.

ATLAS features 4 pixel layers in the barrel (covering down to η = 2.5) plus 3 disks on each side.

Innermost pixel layer, called Insertable B-Layer (IBL) [2], was added for the Run2. It is composed of 200 μm thick planar n-on-n sensors with a pitch of 50 μm x 250 μm. Beyond the tracking acceptance there are hybrid pixel modules featuring novel 3D n-on-p sensors [3], same pitch as planar, with 2 junction columns per pixel cell.
For both planar and 3D sensors the readout chip is the FE-I4 [4]

Other pixel layers [5] have been in operation since the LHC Run1 and are made with 250 μm thick planar n-on-n sensors with a pitch of 50 μm x 400 μm coupled to the FE-I3 readout chip.

Radiation damage measurements

Fast hadrons produced in LHC collisions can displace Si atoms from lattice sites; the combination of an interstitial Si atom and its vacancy is called a Frenkel pair and it is the basic point defect. Frenkel pair can combine with other impurities to form other point defects; group of point defects give rise to cluster of defects.

Point defects and cluster of defects are responsible for macroscopic radiation damage effects like the increase of leakage current, the change of operational voltage and the loss of signal amplitude. These effects are measurable in ATLAS IBL and Pixel detector.

The leakage current is monitored [6] as a function of the accumulated luminosity in ATLAS IBL and pixel detector . The latter is then transformed into radiation damage fluence ϕ expressed in 1 MeV neutron equivalent fluence.

Measurements are compared to simulations [6] to which scale factors based on data are applied (Fig. 2). Using Run2 data an unexpected effect appeared: the level of radiation damage fluence is larger for IBL at η~0 than at larger η values (Fig. 3).

The depletion voltage is estimated by recording the charge in clusters as a function of the bias voltage; the crossing of a $\sqrt{V}$ line with a linear function provides a proxy for the depletion voltage (Fig. 4) [7].

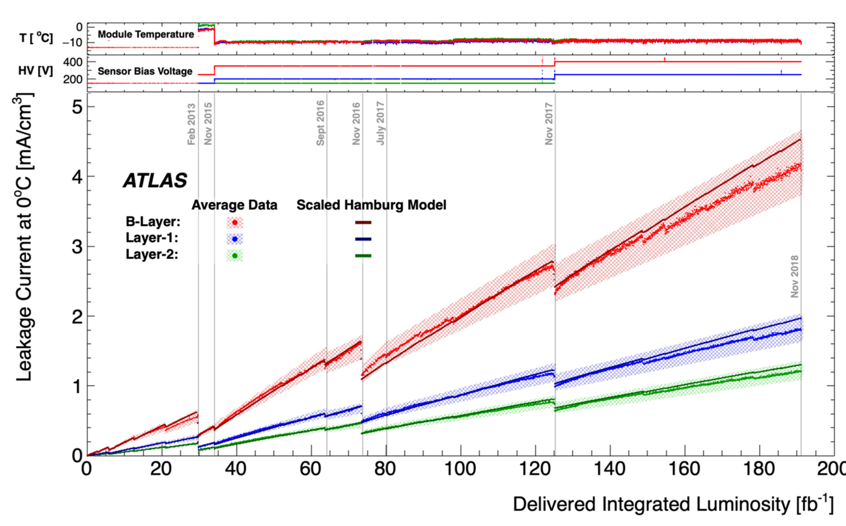

Figure 2. Average measured leakage current of pixel modules vs luminosity. The scaled prediction from the Hamburg Model is also shown. The bands include uncertainties on the measurement. (from [6])

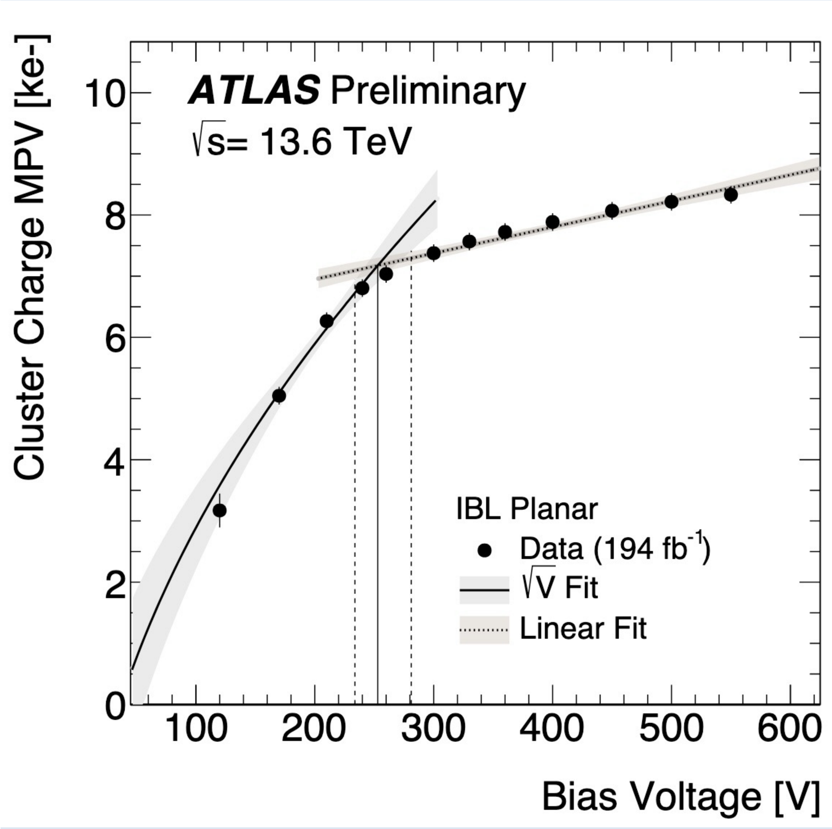

Figure 4. Most probable value of cluster charge distribution as a function of the bias voltage. Data are from IBL planar sensors after having integrated a fluence of about 1.1×10^{15} n_{eq}/cm^2. (from [7])

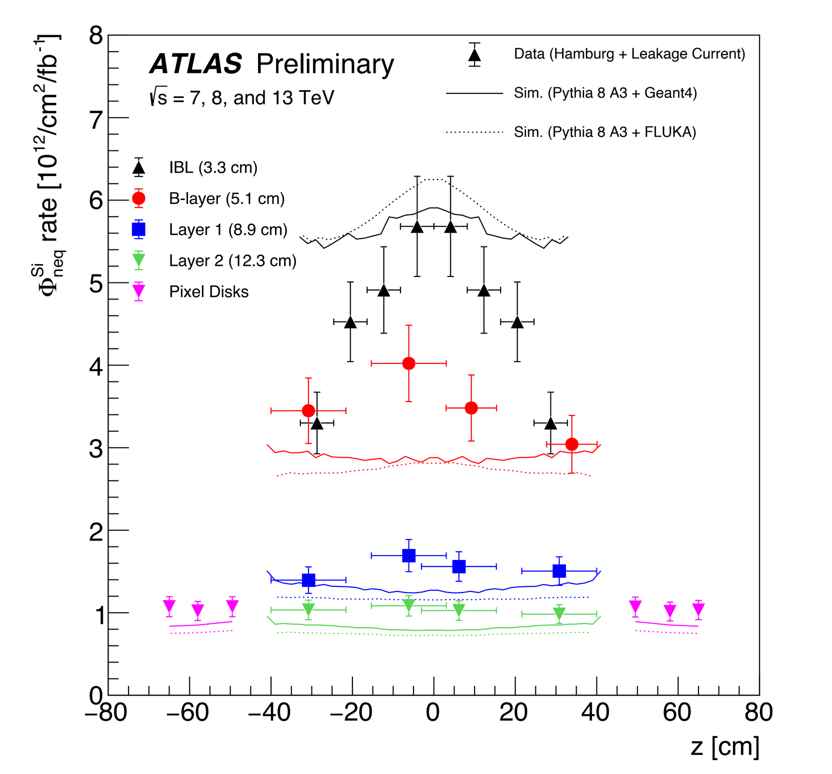

Figure 3. Leakage current rate per unit of integrated luminosity for ATLAS IBL and Pixel detector modules as a function of their position along the beam axis. Predictions from FLUKA and Geant4 simulations are also shown. (from [6])

See also these talks:

"Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider at CERN", Marcello Bindi, 20 nov. 2024, 11:10
"A lightweight algorithm to model radiation damage effects in Monte Carlo events for High-Luminosity LHC experiments", Marco Bomben, 20 nov. 2024, 11:30

Radiation damage simulation

Since the beginning of LHC Run3 radiation damage effects to pixels sensors are included in ATLAS Monte Carlo events [8] thanks to the radiation damage digitizer.

Charge carriers are grouped together and made drift to respective electrodes using electric field profiles taken from precise TCAD simulations (Fig. 5).
Time to reach the electrode is calculated and compared to a randomly generated trapping time to determine if the carriers will make it to the electrode.

Induced signal is calculated using TCAD simulated Ramo potential.

Simulated samples are compared to data at fixed fluence and bias voltage (Fig. 6). Most probable value between data and simulation agree at percent level.

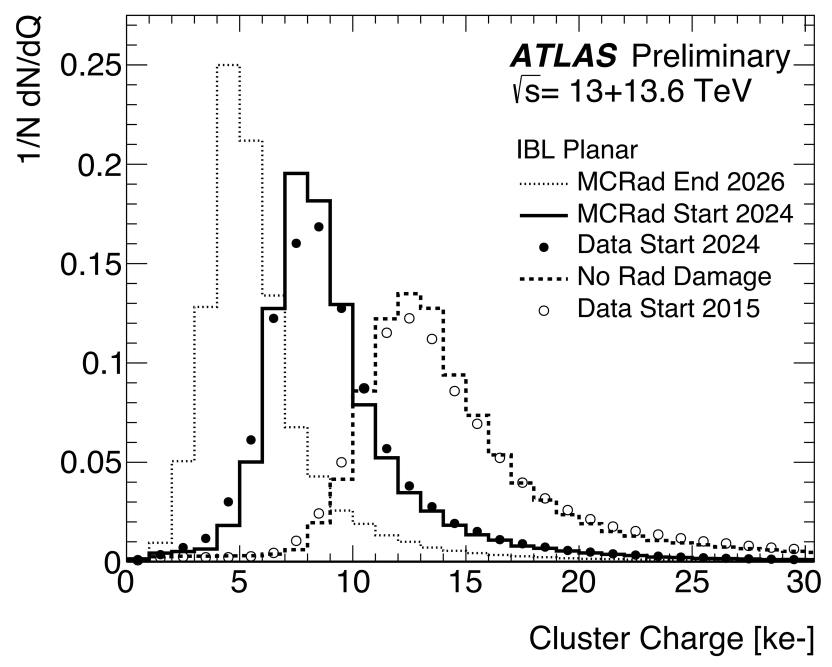

Figure 6. Cluster charge distribution in IBL planar modules. MC events at different fluences are shown too, including predictions for the end of LHC Run3.

Depletion voltage extracted from data is compared to simulated MC events and again the level of agreement is excellent (Fig. 8). Extrapolation of depletion voltage from simulated events is used to prepare data taking conditions for future runs.

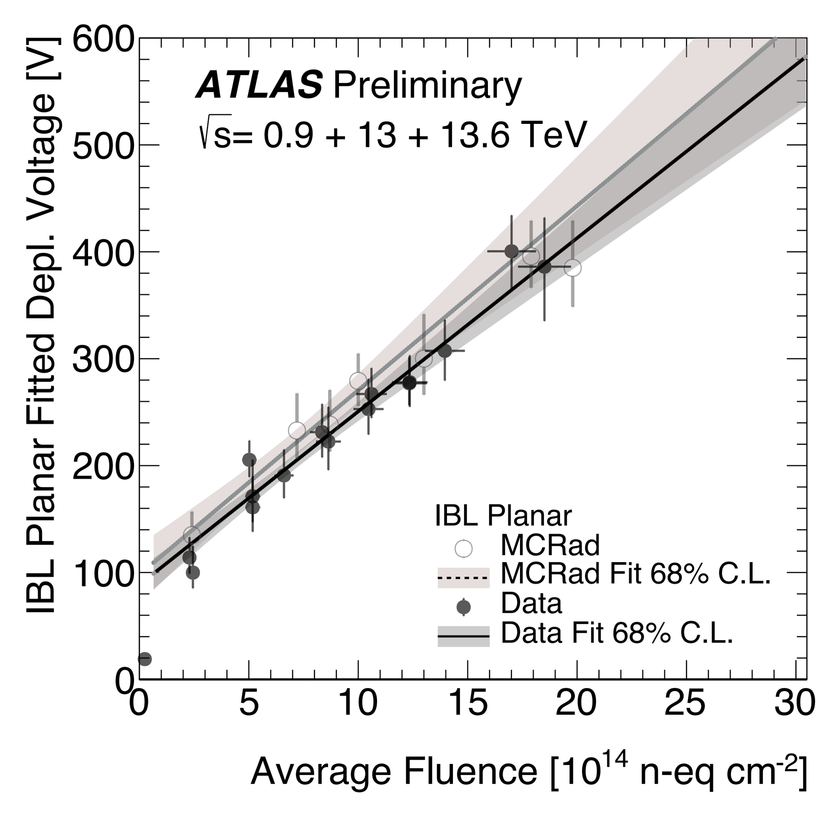

Figure 8. Depletion voltage in IBL planar sensors as a function of integrated fluence. Predictions from radiation damage MC are shown too.

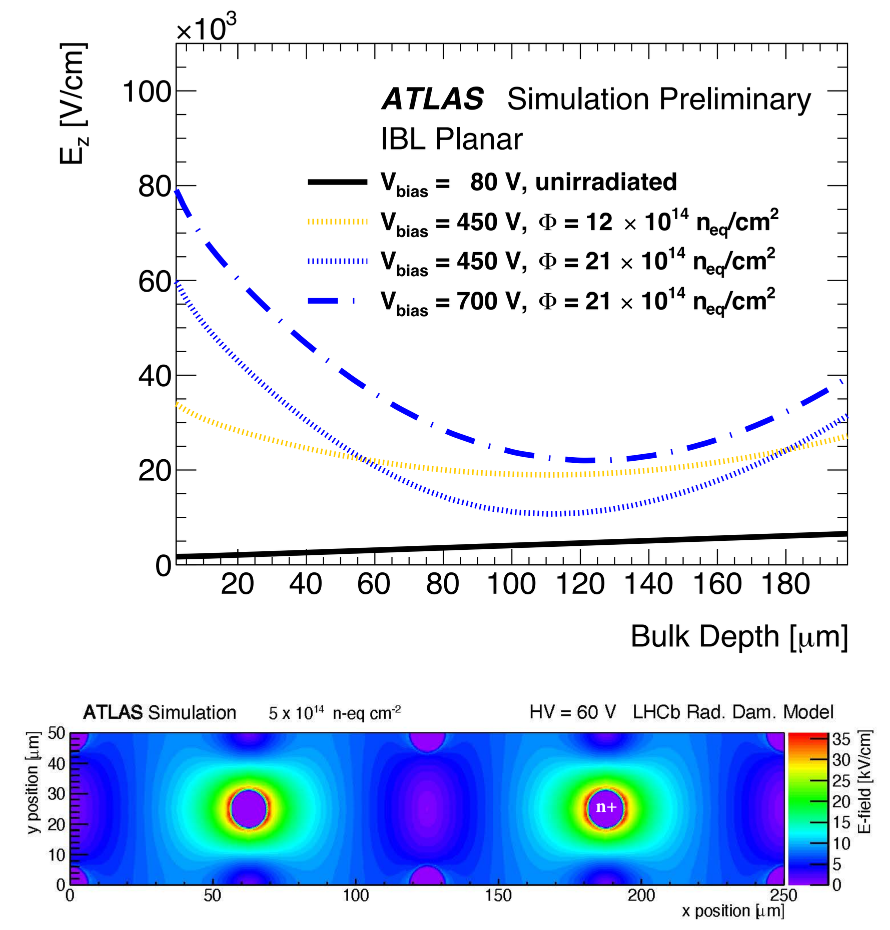

Figure 5. TCAD simulated electric field profiles for IBL sensors. (top) Planar (from [9]) (bottom) 3D. (from [3])

Charge collection efficiency (CCE) is defined as the ratio of measured most probable value of cluster charge distribution to the value before irradiation. The agreement between simulations and data is again remarkable on over two orders of magnitude of fluence (Fig. 7).

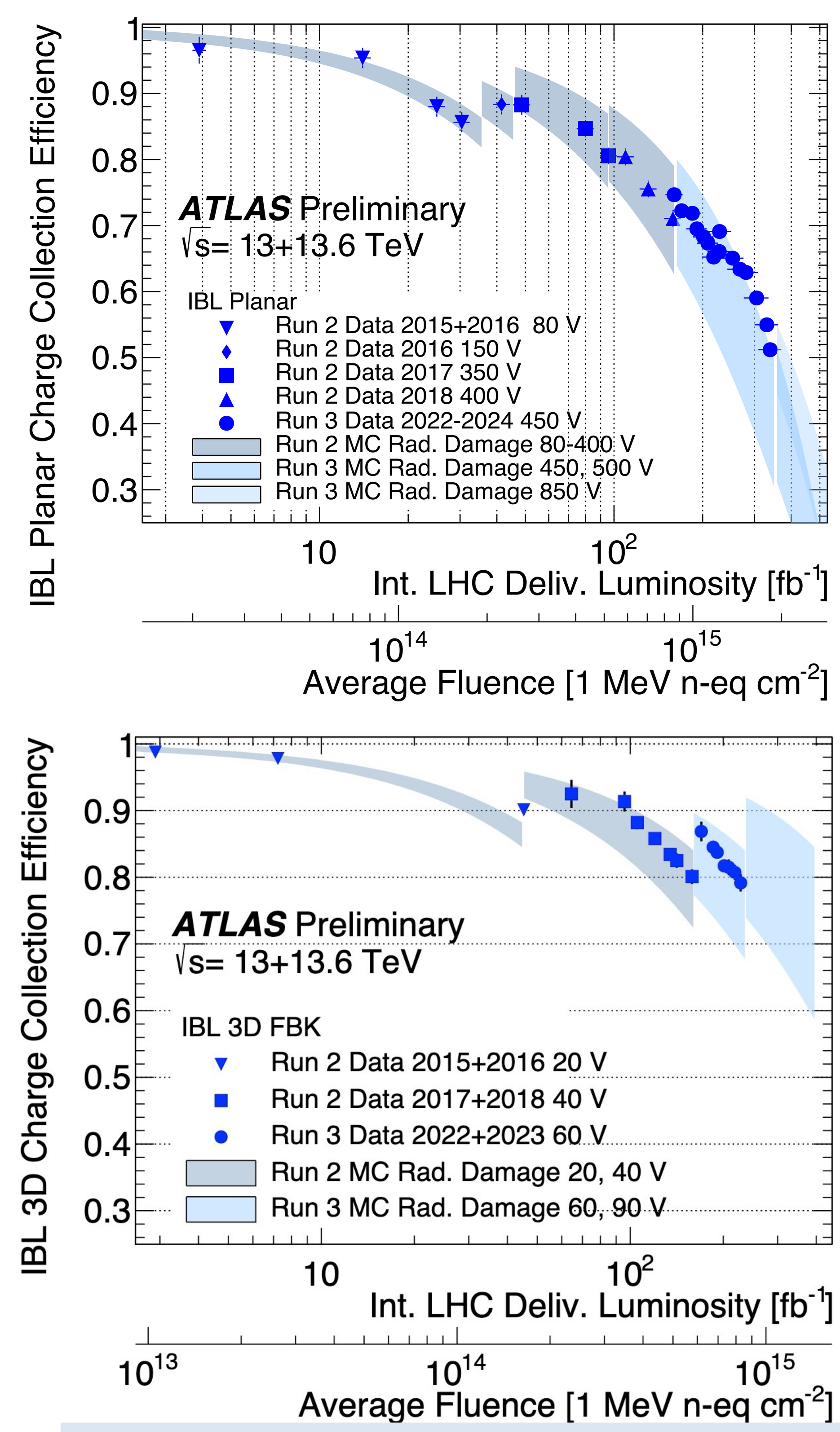

Figure 7. CCE vs luminosity (and fluence) in IBL (top) planar and (bottom) 3D sensors [3]. Predictions form MC radiation damage are presented too.

Conclusions

Radiation damage effects are sizeable in ATLAS IBL and pixels sensors. Simulate MC events that include radiation damage effects to pixels are capable to reproduce the evolution of sensors conditions and performance with integrated radiation damage fluence to a percent level over two order of magnitudes of luminosity.
Simulated events that include radiation damage effects to pixels are used to predict future data taking conditions and to train reconstruction algorithms.
For the High-Luminosity phase of the Large Hadron Collider a faster algorithm is under development [10].

References

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[3] G. Aad et al 2024 JINST 19 P10008
[4] M. Garcia-Sciveres et al., NIM A 636 (2011) 155-159
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[7] ATL-INDET-INT-2023-009, https://cds.cern.ch/record/2875608
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[10] Sensors 2024, 24(12), 3976

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