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

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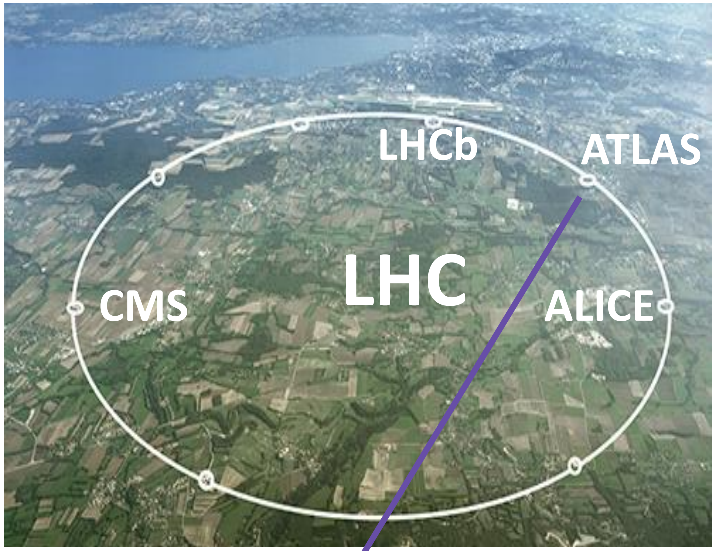
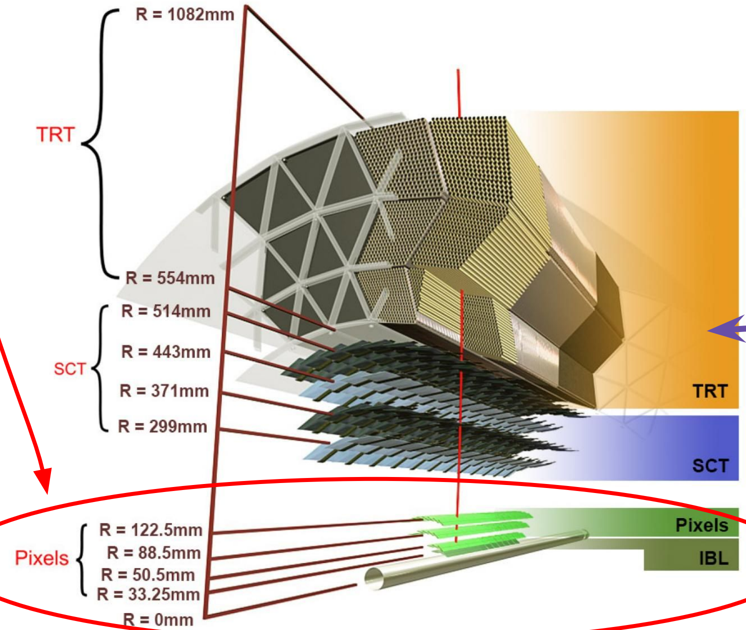
ATLAS Inner Detector

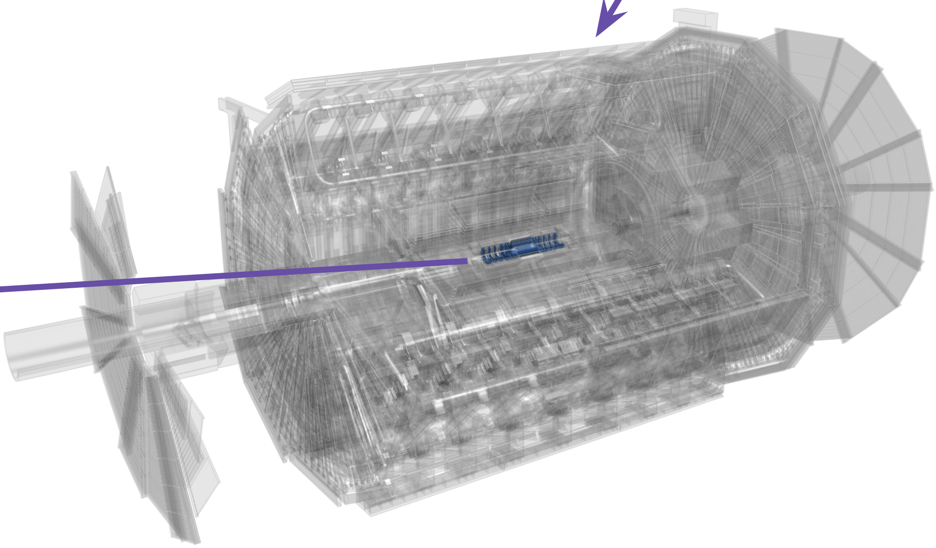
ATLAS is a general-purpose detector located at the LHC ring.



The **Inner Detector** has three different subsystems:

- **Pixel Detector**
  - Insertable B-layer (IBL)
  - Pixel
- **SemiConductor Tracker (SCT)**
- **Transition Radiation Tracker (TRT)**

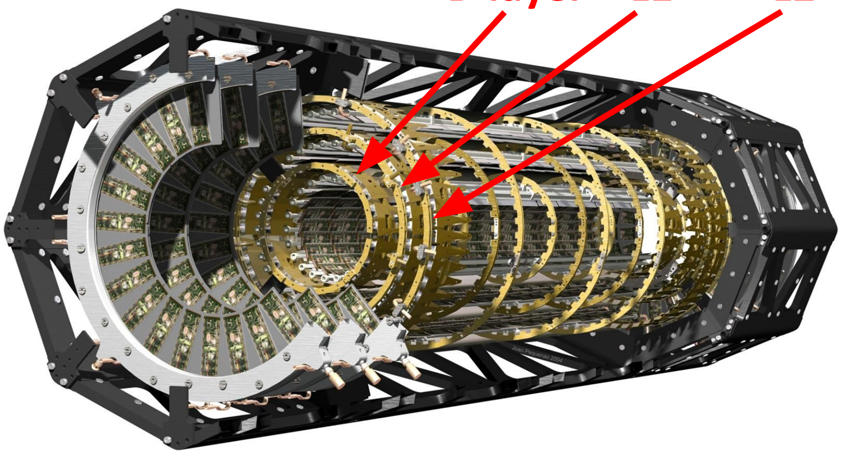


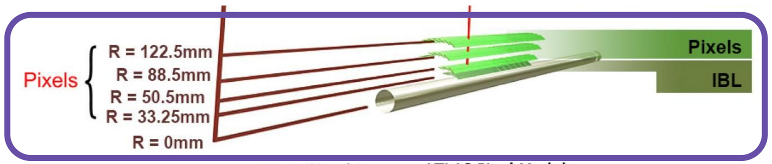


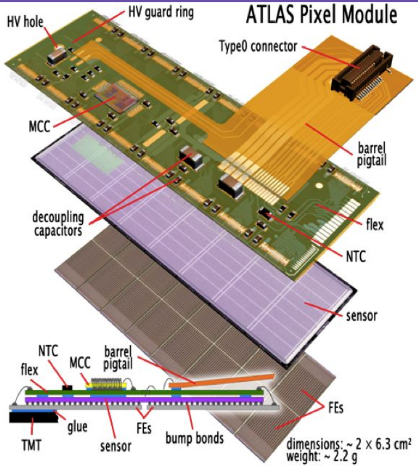
Pixel Detector

Three barrel layers (**B-layer**, **L1** and **L2** from inner to outer) and **2x3 endcap-disks since the start of Run 1**.

- Angular coverage **|η| < 2.5**
- **C_3F_8 evaporative cooling**
- 1744 modules
- 1.7 m^2 of silicon.
- Fluence specification 1 x 10^{15} n-eq cm^{-2}







(b)

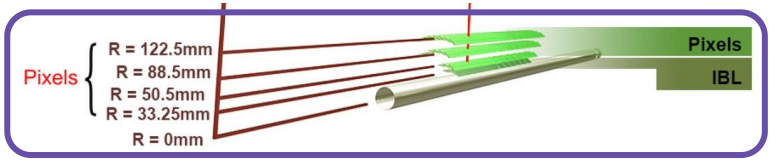
Each pixel module has the following properties:

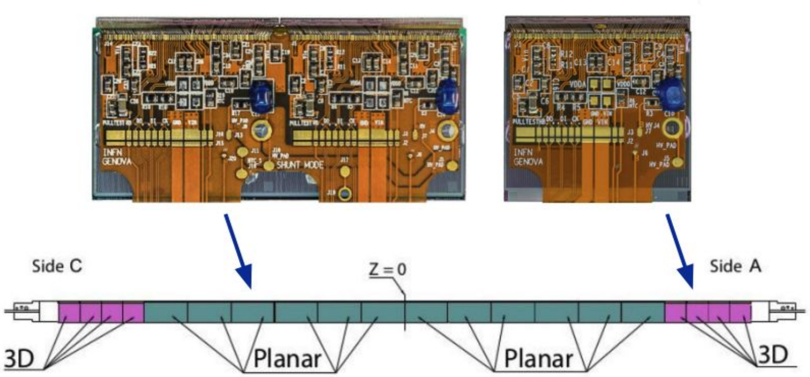
- **16 FE-I3 250 nm CMOS frontend chips**
- 60.8 x 16.4mm active area
- **250 µm thickness**
- **50 x 400 µm^2 pixel size**
- Total 46080 pixels

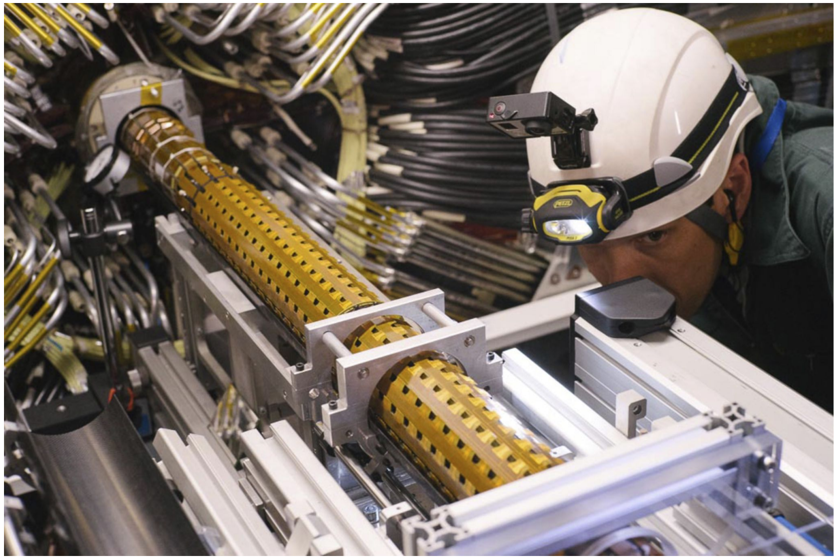
IBL Detector

The **Insertable B-Layer (IBL)** was inserted in 2014 during the first long LHC Shutdown (LS1), **adding a 4th barrel layer**

- Closest to the **interaction point, at 3.3 cm** away
- **CO_2 evaporative cooling**.
- **Better resolution** and b-tagging rejection
- Fluence specification 5 x 10^{15} n-eq cm^{-2}
- **Two different sensors Planar and 3D**







Each IBL modules has the following properties:

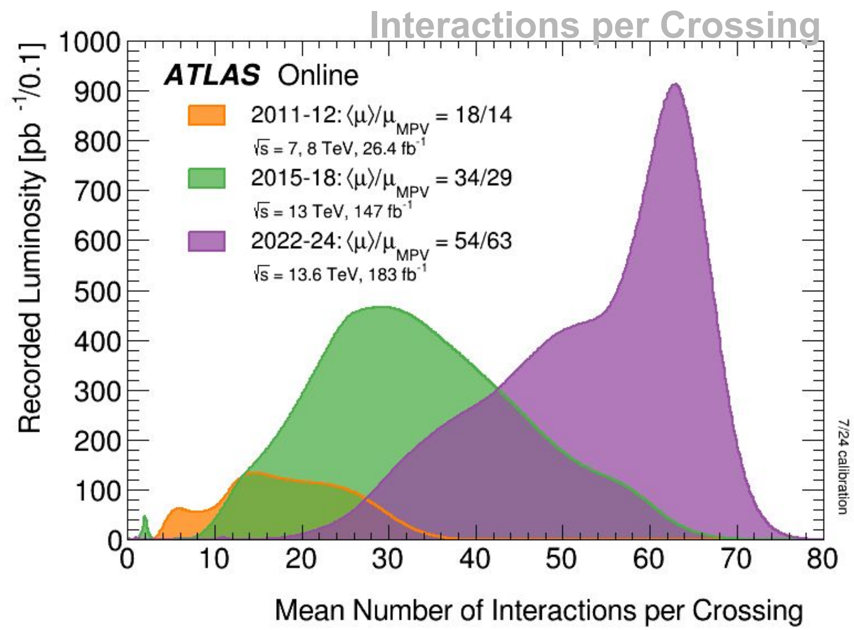
- 2(1) **FE-I4 130nm CMOS chip** on sensor Planar (3D)
- 41.3(20.5) x 18.6 mm active area in Planar (3D)
- **200(230) µm thickness Planar (3D)**
- **50 x 250 μm^2 pixel size**
- Total 26880 pixels

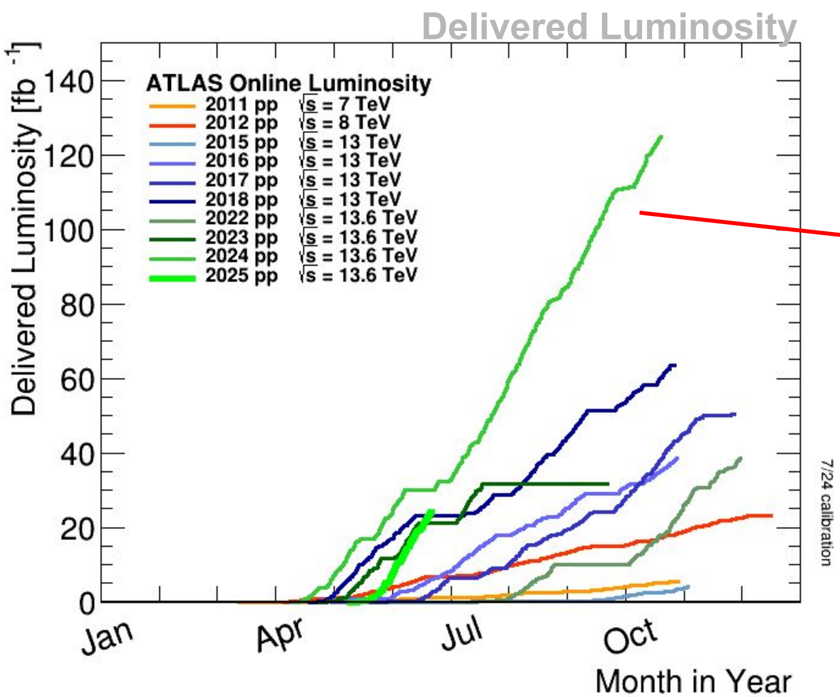
LHC status

After ATLAS Phase I upgrade items: (NSW, LAr Digital trigger, L1Calo Trigger..) enabled **ATLAS to cope with higher integrated and instantaneous luminosity while** keeping **dead time low**.

Increased LHC luminosity in Phase I leads to:

- **Substantially higher pile-up**
- **More radiation damage**





In 2024 LHC delivered almost as much luminosity as the full Run 2 period

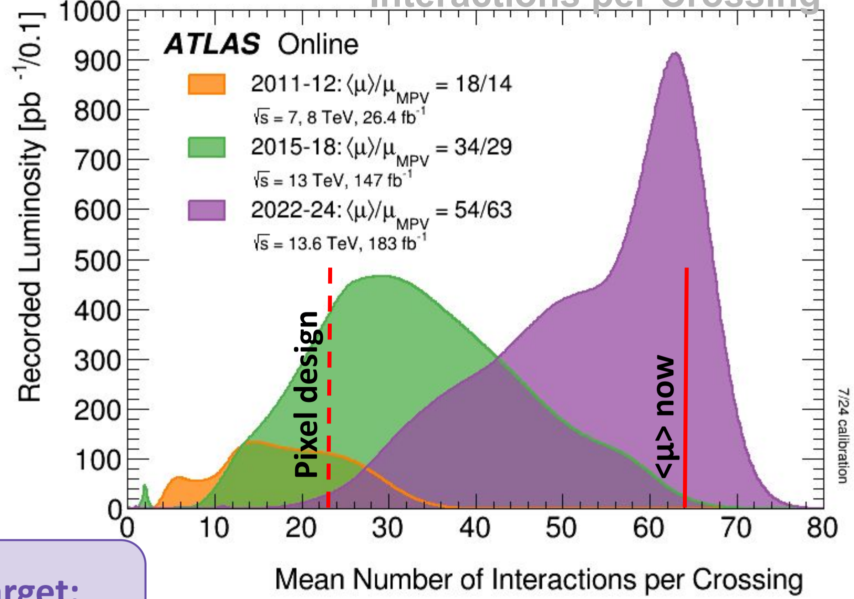
Challenging conditions for the Pixel Detector that need to be mitigated and handled accordingly!

Pixel Run 3 performance

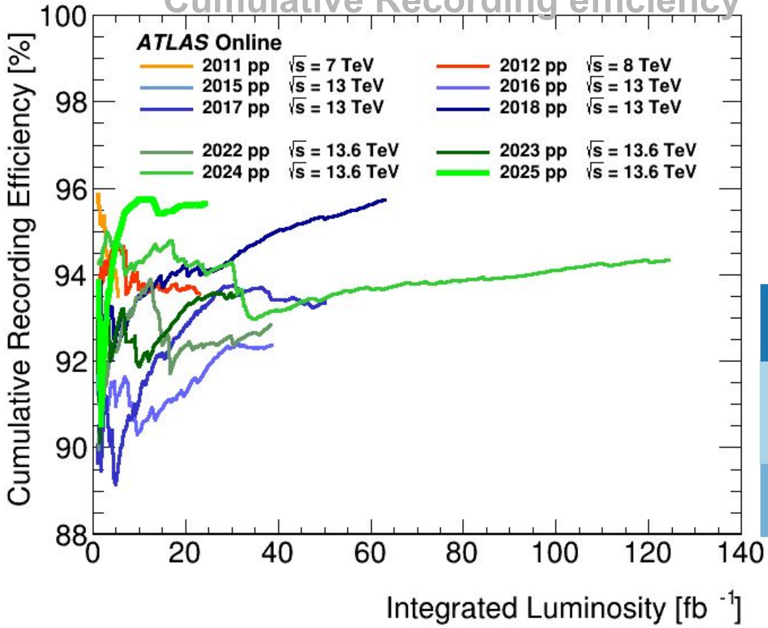
In 2024:

- **99.7% data quality efficiency**
- Average **deadtime below <0.1%**
- Extremely **stable running** with no major issues
- Average design pileup (<μ>) for FE-I3 is 23… **running now at <μ> around 64**

Interactions per Crossing



Cumulative Recording efficiency



Run 3 target: μ=65 @ 90kHz

Data Quality Plots

ATLAS pp Run-3: 2024

Trigger	Inner Tracker			Calorimeters		Muon Spectrometer					Magnets		Global	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	MM	sTGC	Solenoid	Toroid	Lumi. calib.	Other
99.7	99.7	99.8	99.9	99.8	99.3	100	99.8	99.8	100	100	98.3	96.6	99.6	99.9

Good for physics: 93.8% (110 fb^{-1})

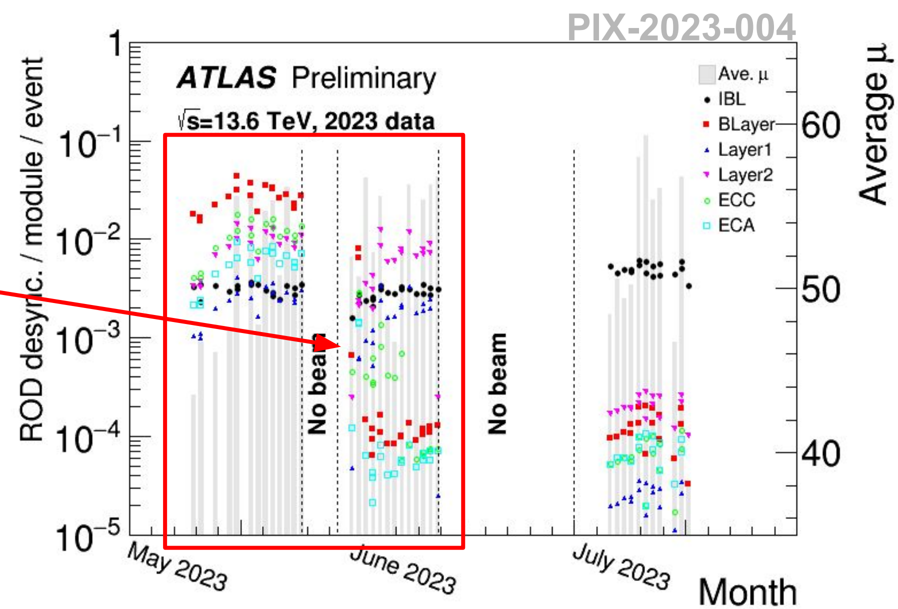
Handling Pile Up

Each Pixel module can only handle a limited number of triggers, if an **additional trigger** arrives, the **module can desynchronize** (the buffer overflows)

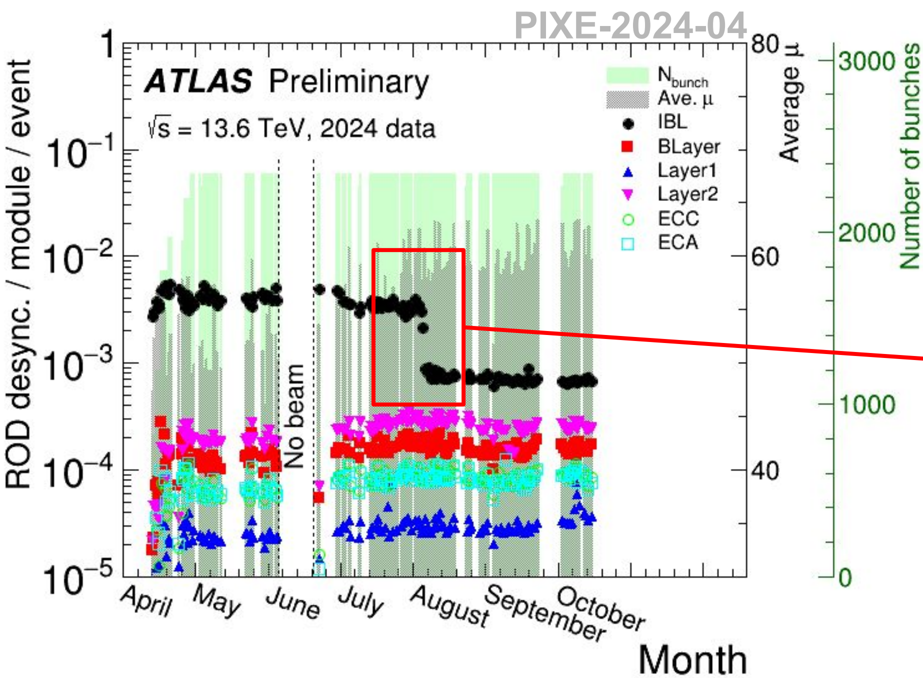
- **High desynchronization especially in the B-layer (5%)**

In 2023, **Smart L1 Forwarding Firmware was deployed** in the Read Out Driver (ROD) **keeps track of the triggers propagated** to each module

- No trigger propagation if more than the limit
- Only few events are lost (known limited inefficiency), but modules keep synchronized



Two/Three orders of magnitude reduction in desynchronisation.



IBL not really affected by ROD desynchronization (FE-I4 chip optimized for higher data rate)

- **Improvements in the firmware** that deals with FE misbehaviour!

Single Event Effects (SEEs)

Paper: SEU in ATLAS IBL

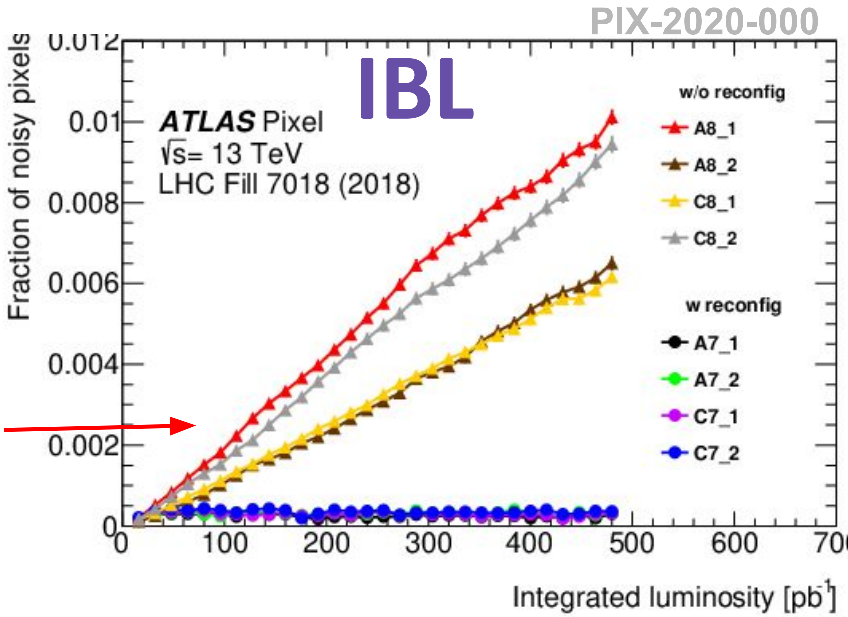
Single Event Upsets (SEUs) can alter data and compromise the functioning of the frontend chip.

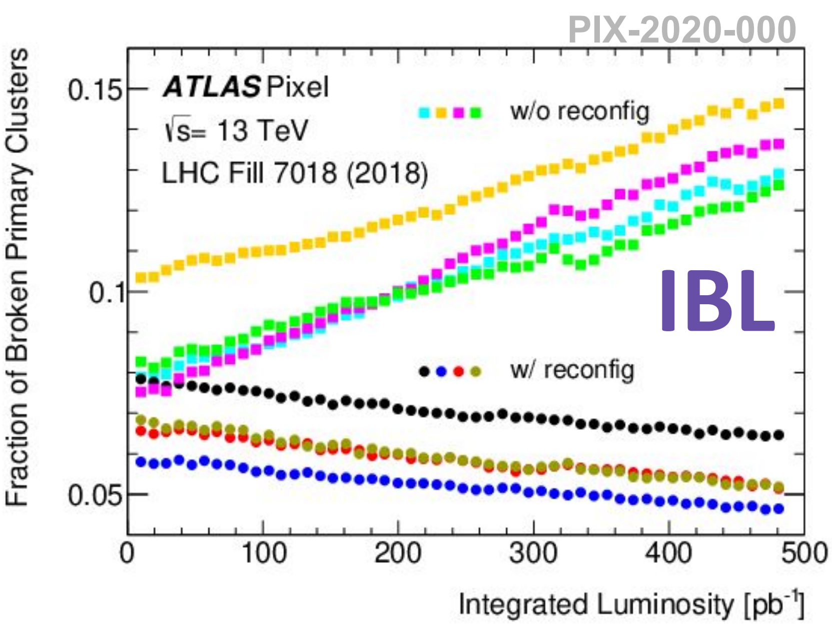
- Global register hit: module misbehaving
- Pixel register: noisy or silent pixels

IBL re-configures global registers every 5s, in each ATLAS Event Counter Reset (ECR)

Since 2023, **IBL pixel registers** are re-configured every 11mins

- LHC pp data fills last for about 12h





Pixel global reconfiguration for one FE per module every ECR, each FE is **reconfigured every 80s**

Advantages:

- This has led to **substantially lower noise** in IBL
- **No additional deadtime** since it happens in the ATLAS ECR gap, a 2ms busy period that is generated in ATLAS every 5s

Probing the limits

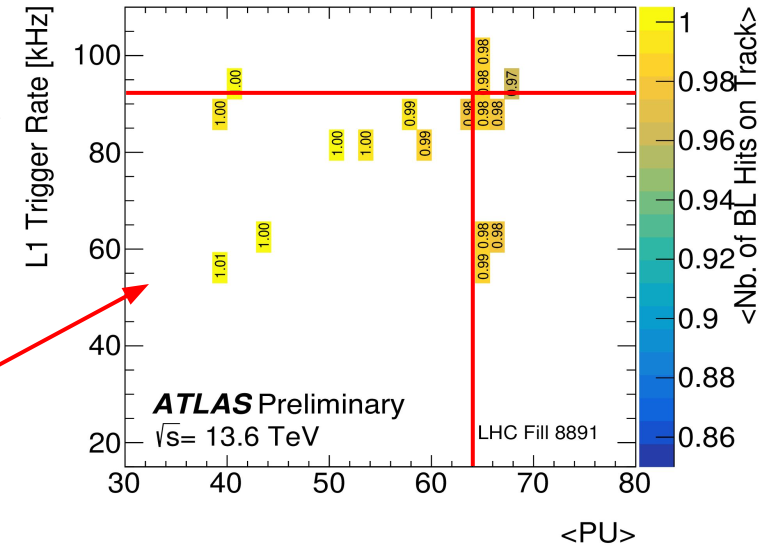
PIX-2023-003

End of 2022 the LHC found that they can increase the limits previously assumed, being able to increase instantaneous luminosity in 2023

- **B-layer efficiency was good up to 55**, but dropping fast above that.

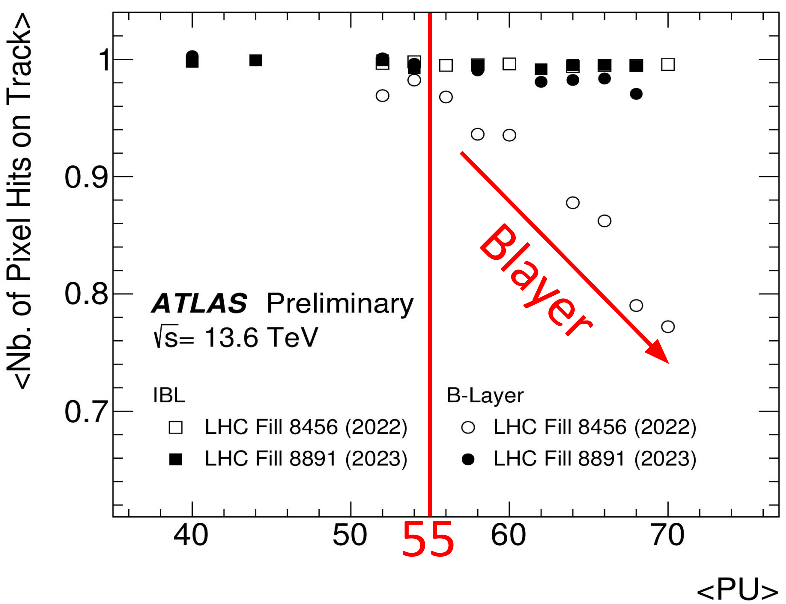
Thanks to increasing thresholds and the Smart L1 forwarding firmware deployment **all Pixel layers were able to cope with the ATLAS target conditions** and go beyond 55, allowing **the detector to run in extreme conditions.**

- **Pixel operated well at a <μ> 65 and 90 kHz trigger rate**

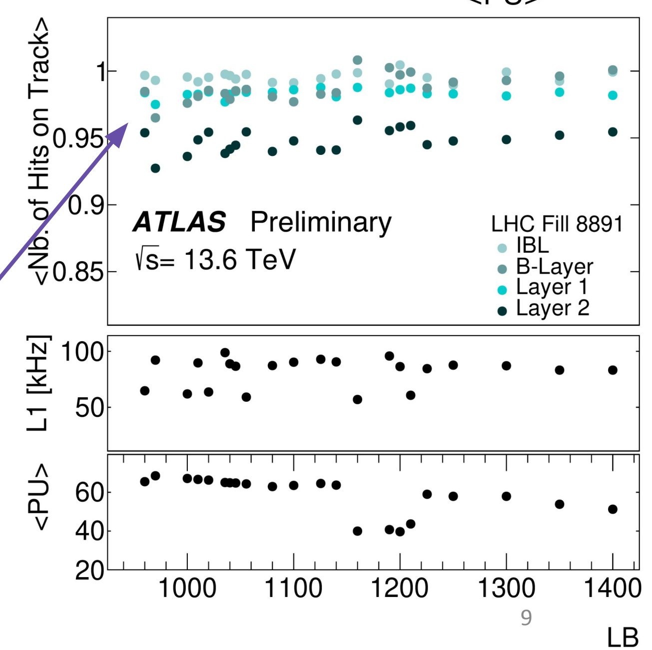


Special fill requested to prove out limits scanning over rate and μ, **reaching <μ> of 68.5 in 2023**

- Both **IBL and Blayer kept up tracking performance**!



Keep hit-on-track performance!



Radiation damage

PIX-2023-007

The **increased accumulated luminosity** also implies **increased radiation damage**

- Less concern about outer pixel layers (L1, L2, endcaps)

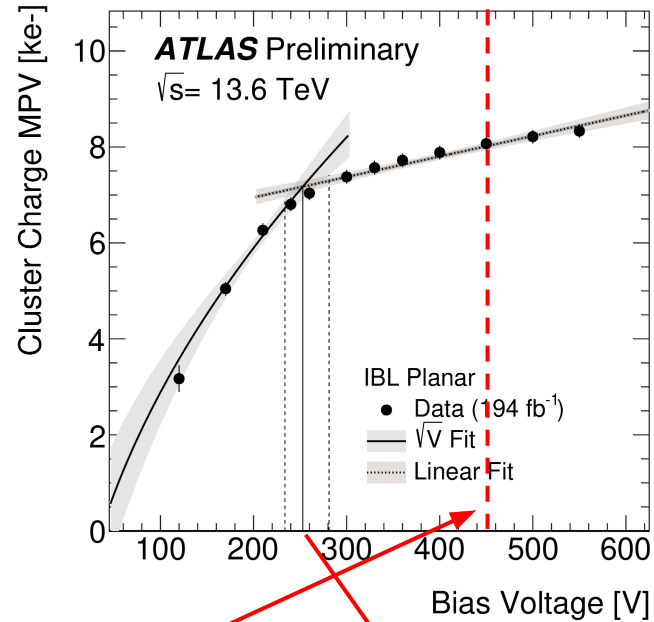
Lower charge collection efficiency can impact in the physics performance, hence in order to **keep high hit-on-track efficiency,** we have to mitigated with:

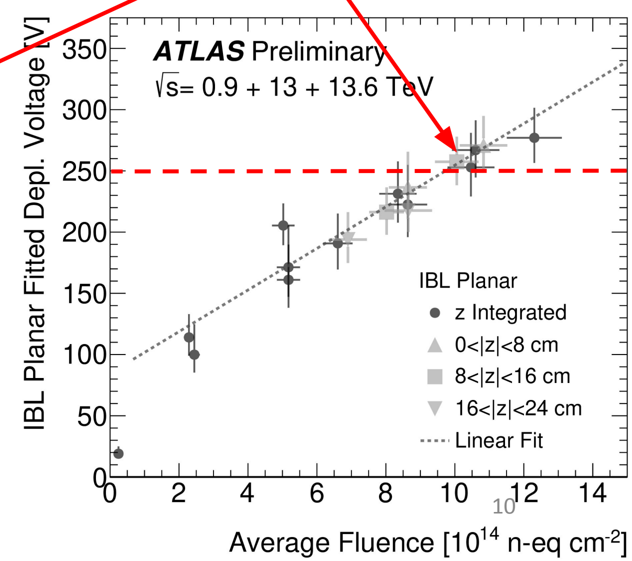
- **Increase of HV** to operate at full-depletion voltage
- **Tuning thresholds**

We do **HV scans to determine the HV settings for each year**

High Voltage in 2024 at 70 V for 3D and 450 V for IBL planar

- **Well below power supply limits** of 1000 V for IBL planar and 500 V for 3D





Radiation damage expectations

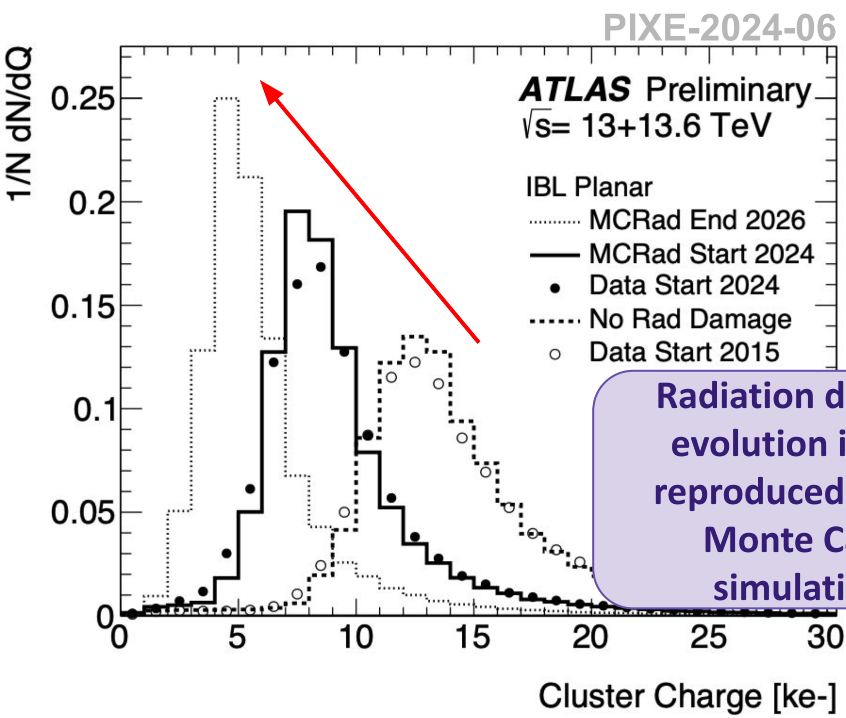
Cluster charge (corrected for Si path) **very well reproduced by Radiation Damage MC**

- **After LS2, a new radiation damage digitiser MC** was included in ATLAS Run 3 MC generator

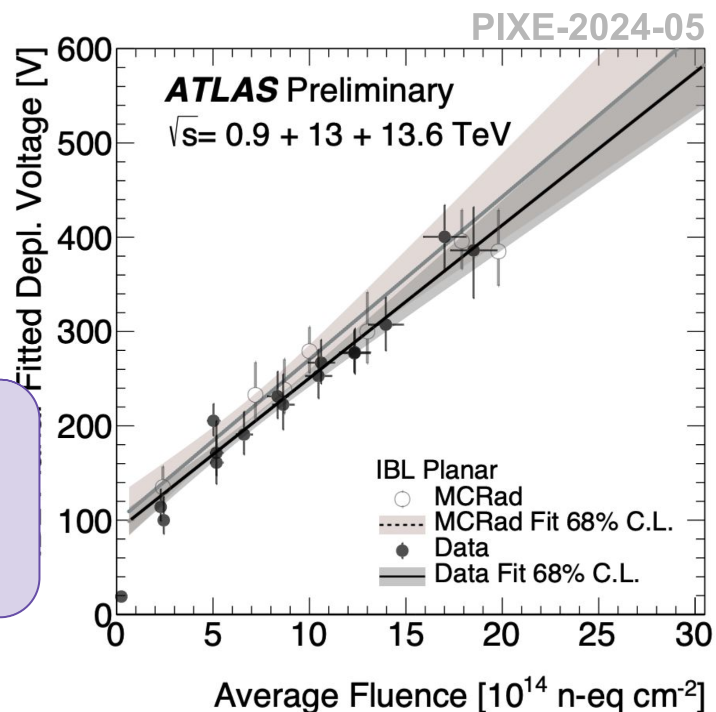
Exploiting the predictive power to check the cluster charge/shape at the end of Run 3!

Extraction of **depletion voltage from HV scan** during LHC fills

- **Good agreement between data and MC**
- Biggest uncertainties from fluence and electron trapping rate



Radiation damage evolution is well reproduced by the Monte Carlo simulation.



Radiation damage expectations

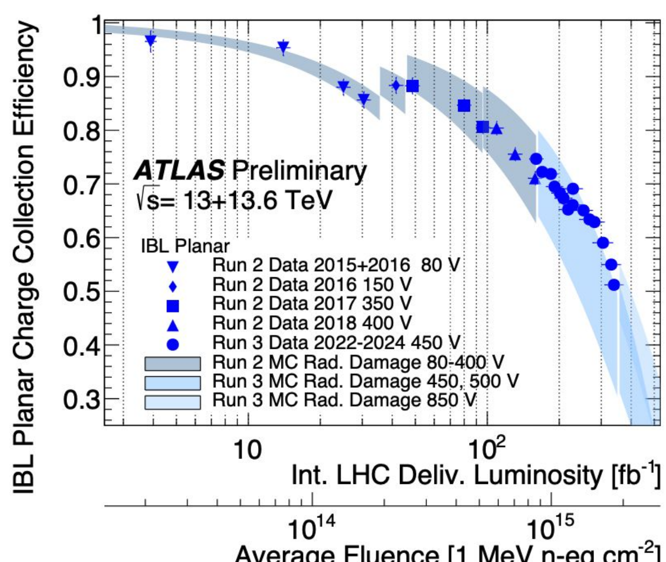
MC models are used to understand and **predict radiation damage effects**.

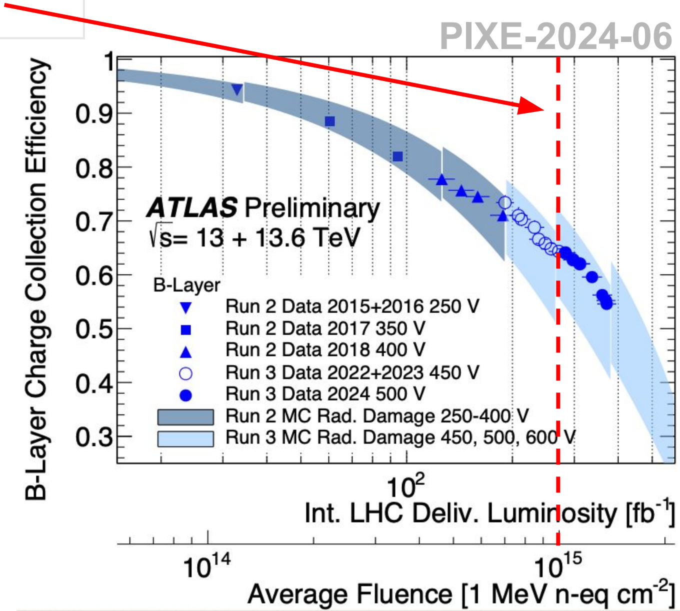
- Providing a **good description of the data at various fluences**

At the end of Run 3 **more than 500 fb^{-1} will be delivered,** the fluences in the innermost layers are:

	Now [n-eq cm^{-2}]	Specification [n-eq cm^{-2}]
IBL	1.8×10^{15}	5×10^{15}
Blayer	1.4×10^{15}	1×10^{15}

IBL well below the specification





Radiation damage expectations

IBL well below the specification (was built for that purpose since it is the closest to the interaccion point)
Blayer entering an unknown region, surpassing already the specification

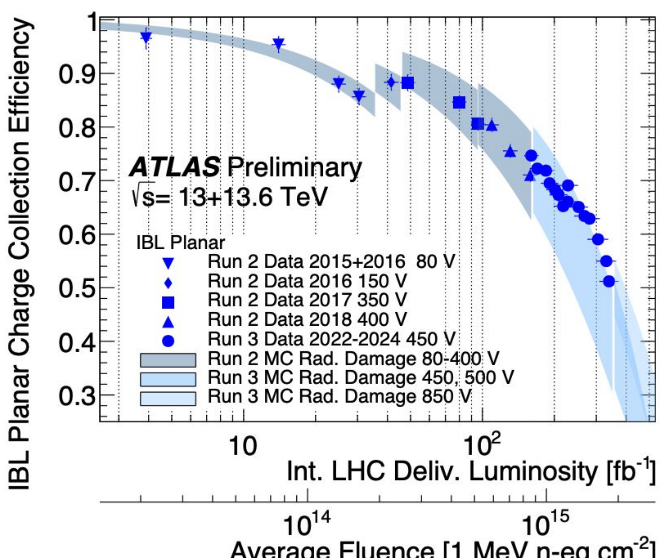
- **Charge collection efficiency ~30% at end of Run 3** for both IBL and Blayer
- Trying to **keep hit-on-track efficiencies > 95%**
- Outer pixel layers will not reach the specification limit

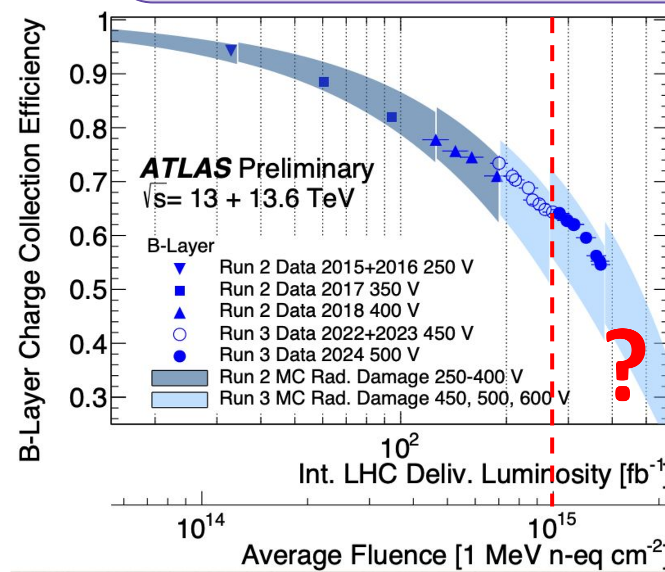
Hits-on-track:

	2024	2026
IBL	0.99	0.96
Blayer	0.97	0.95

	Now [n-eq cm^{-2}]	Specification [n-eq cm^{-2}]	End of Run 3 [n-eq cm^{-2}]
IBL	1.8×10^{15}	5×10^{15}	$\sim 3 \times 10^{15}$
Blayer	1.4×10^{15}	1×10^{15}	$\sim 2 \times 10^{15}$

Good agreement between MC and Data!
With a powerful predicting power
Good detector performance until end of 2026





Conclusions

Pixel Detector is operating under very challenging conditions

- **<μ> at around 64** (pixel part design to handle <μ> of 23)
- trigger rate **90 kHz**
- fluence **greater than the specification 10^{15} n-eq cm^{-2} in the B-layer**

There is still a continuous **tremendous effort to keep the detector running at these conditions**

Hardware failures are under control and **cooling very stable**, though aging infrastructure does contribute to occasional module or plugin issues.

Firmware and software improvements to counteract SEUs and desynchronization have been successfully deployed.

There was a highly evolved **effort to simulate all aspects of radiation damage**

- **New radiation damage digitiser developed** and included in ATLAS Run 3 MC
- **MC predicts very well the data**

Depletion voltage and leakage current are well under control

We expect 30% charge collection efficiency at the end Run 3

- We remain the **high hit-on-track efficiency** ($\gtrsim$ 95%) by tuning detector parameters

Very important experience for HL-LHC tracker upgrades, giving insight about future detector operation

Back up