Operational experience with the ATLAS Pixel Detector

Hongtao Yang[1]

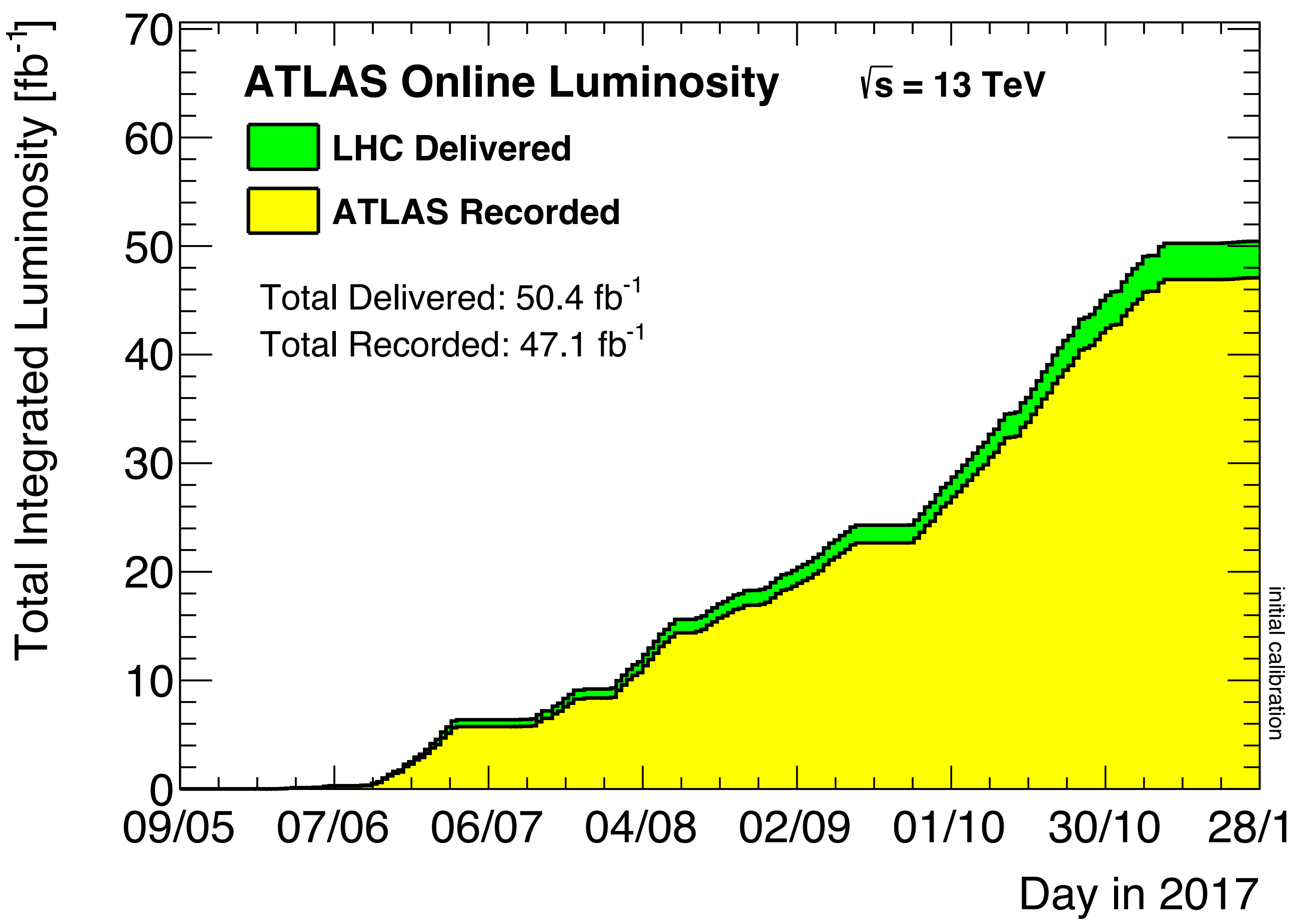
on behalf of the ATLAS collaboration

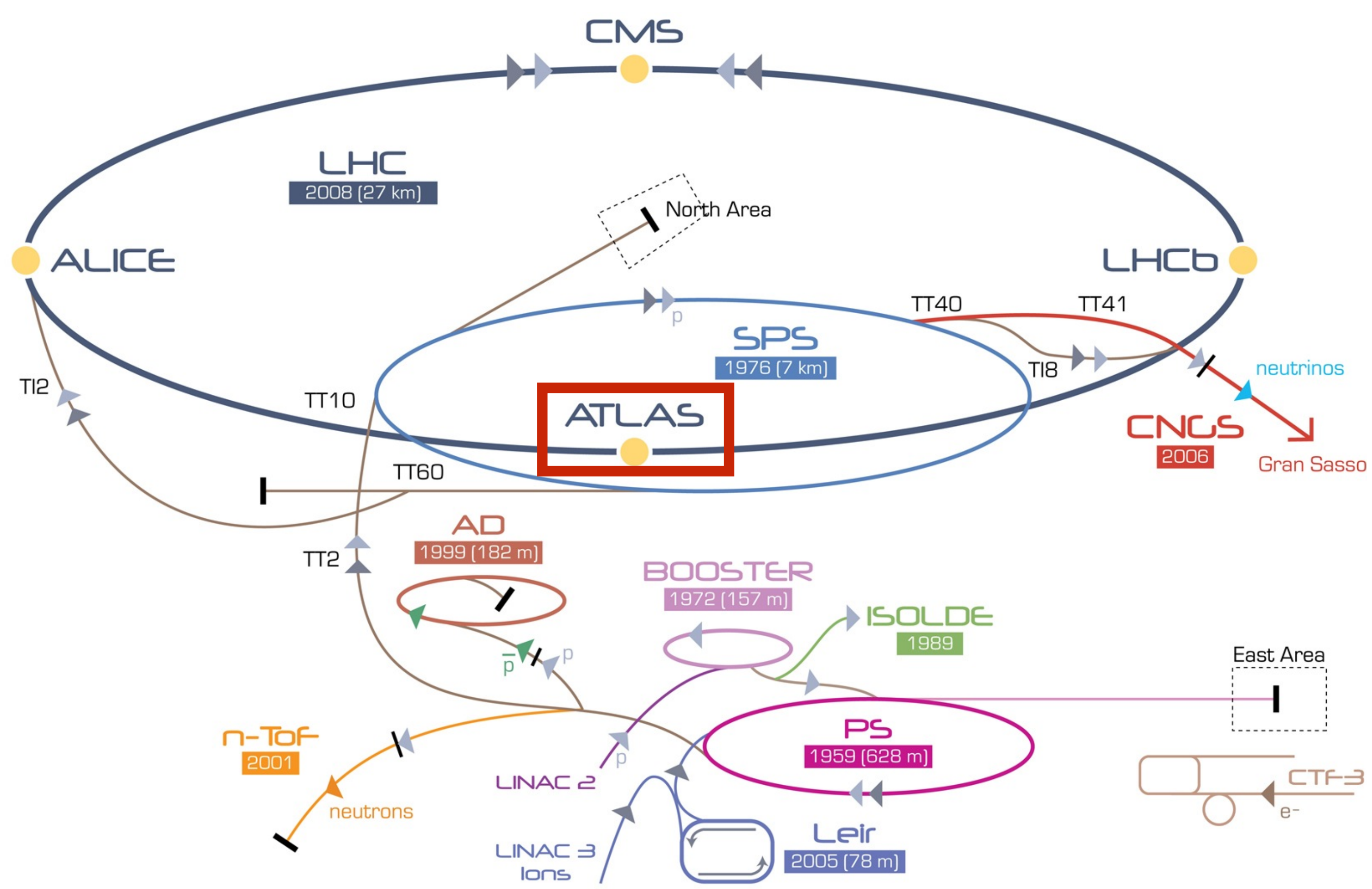
[1]Lawrence Berkeley National Lab

13th "Trento" workshop, Munich, Germany
Feb 19, 2018

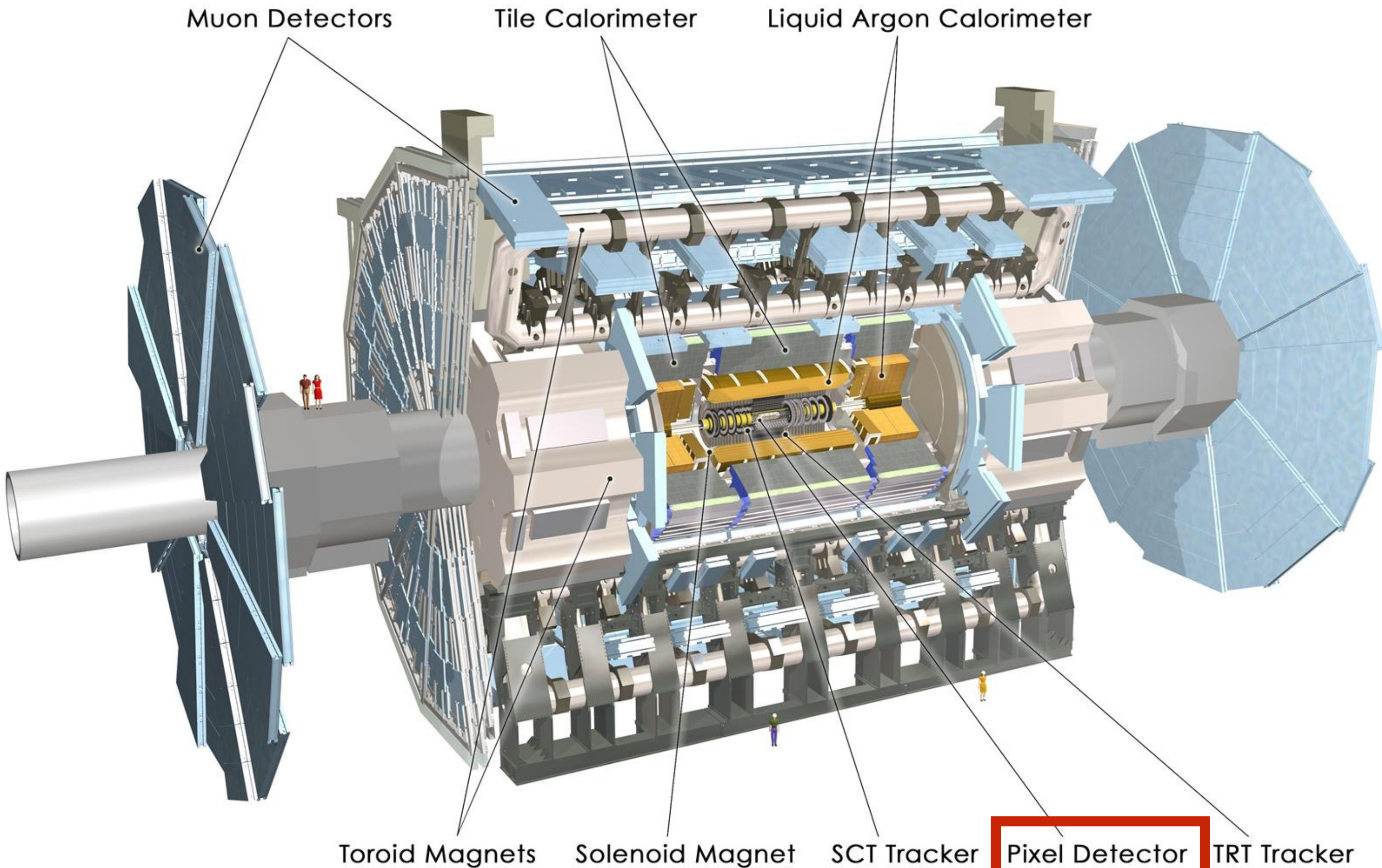
Introduction

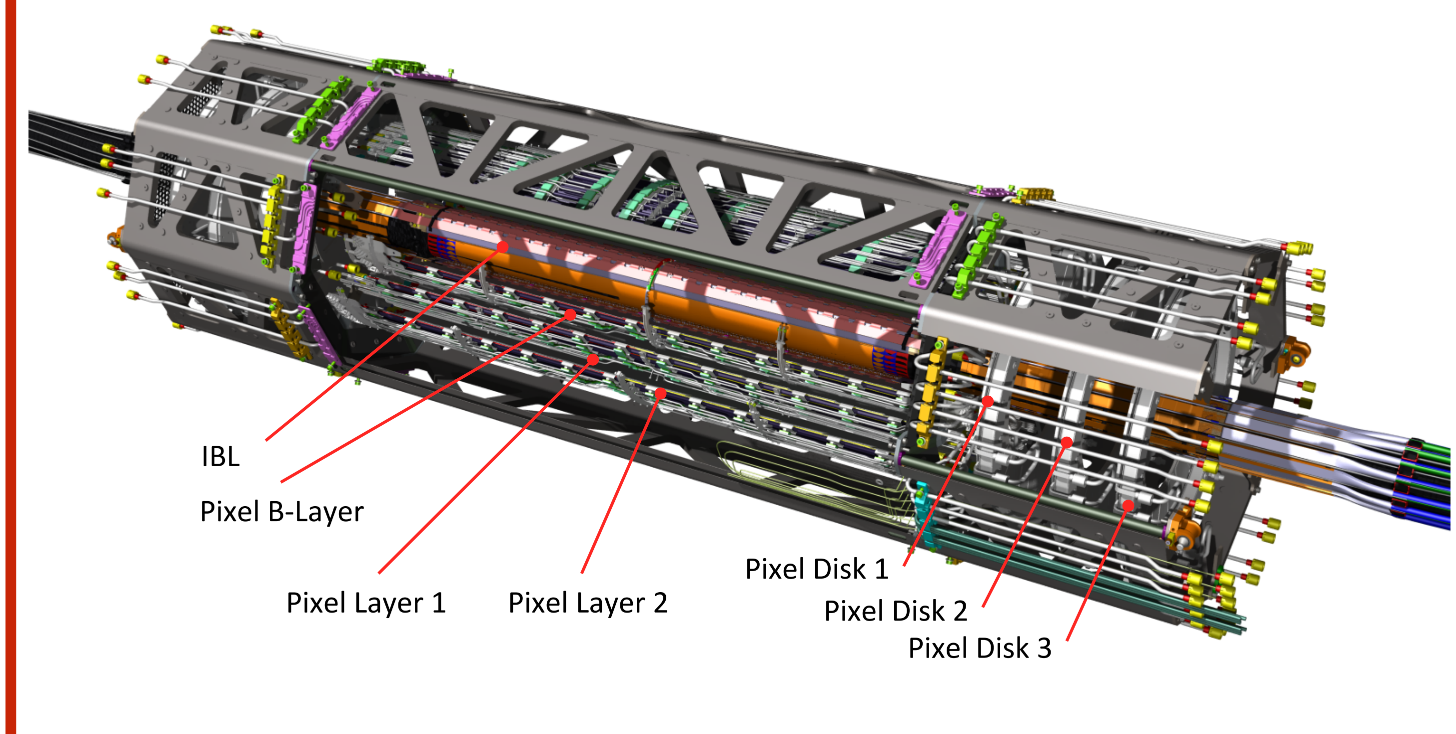
- Detector operation is fundamental to the success of an experiment
- Pixel Detector is at the center of ATLAS
  - Crucial for physics: reconstructs tracks and vertices
  - Faces great challenges: pileup, radiation
- **This talk will focus on ATLAS Run 2 proton-proton data-taking at √s=13 TeV in 2017**



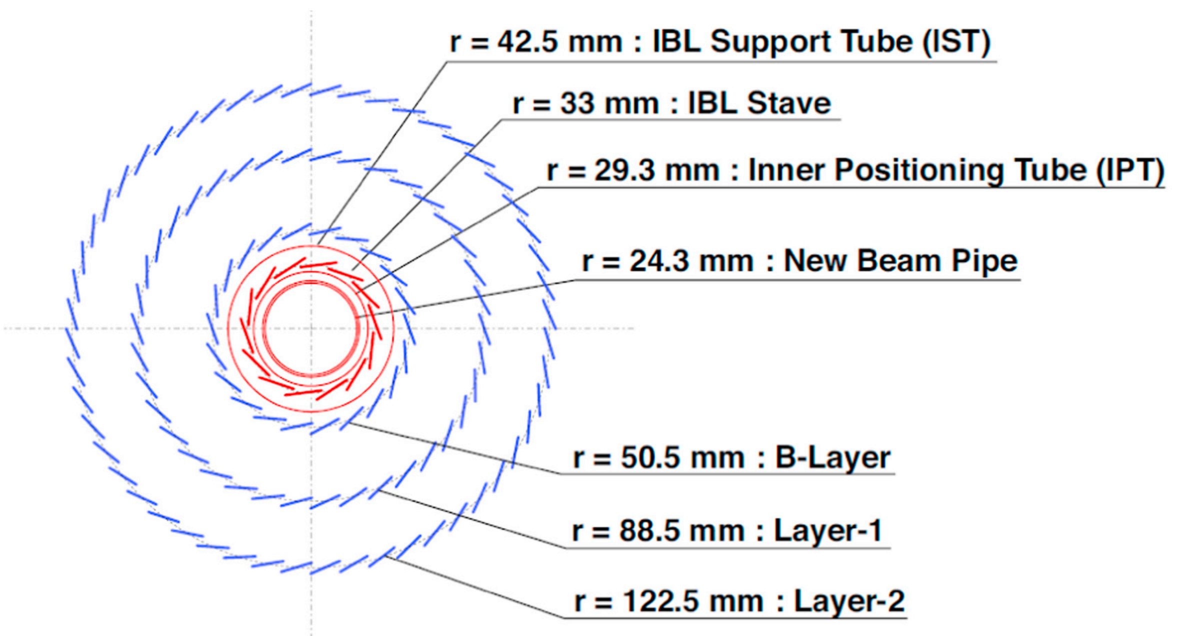


ATLAS Pixel subsystem

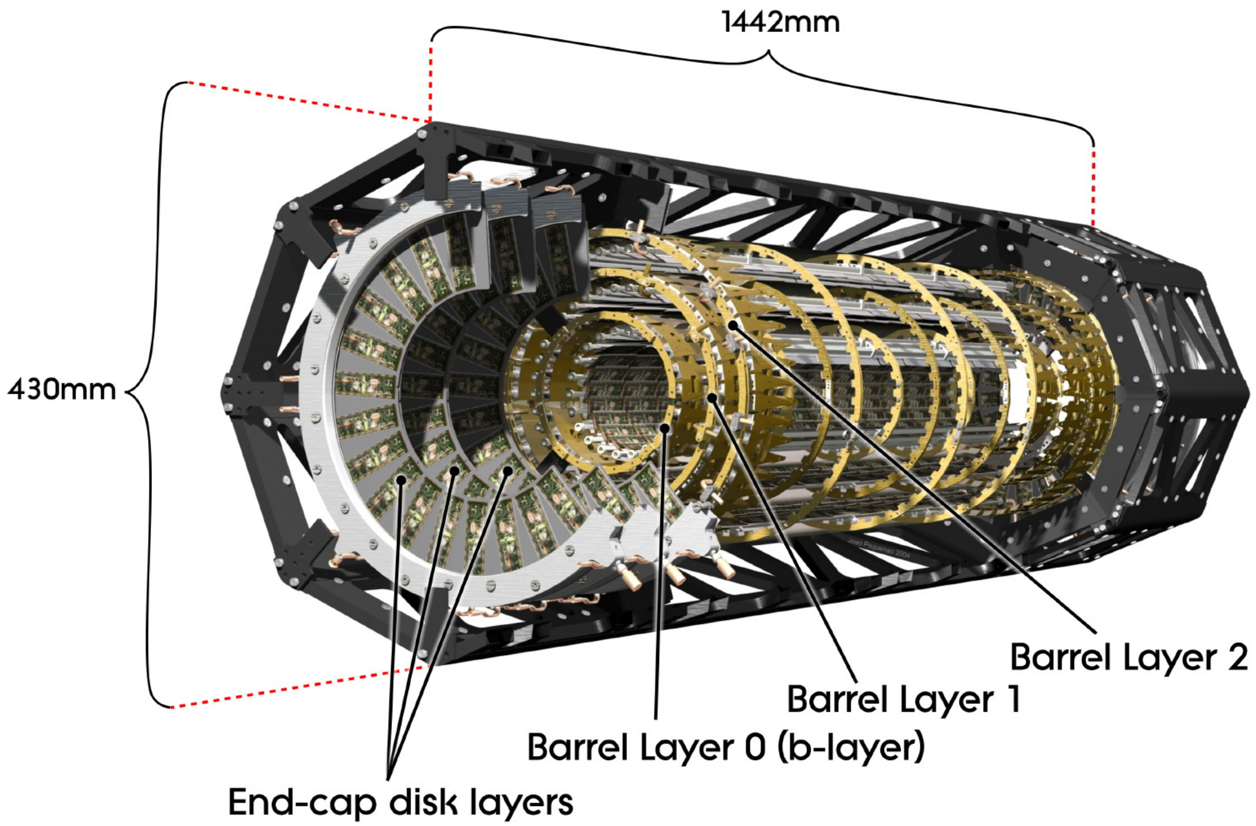


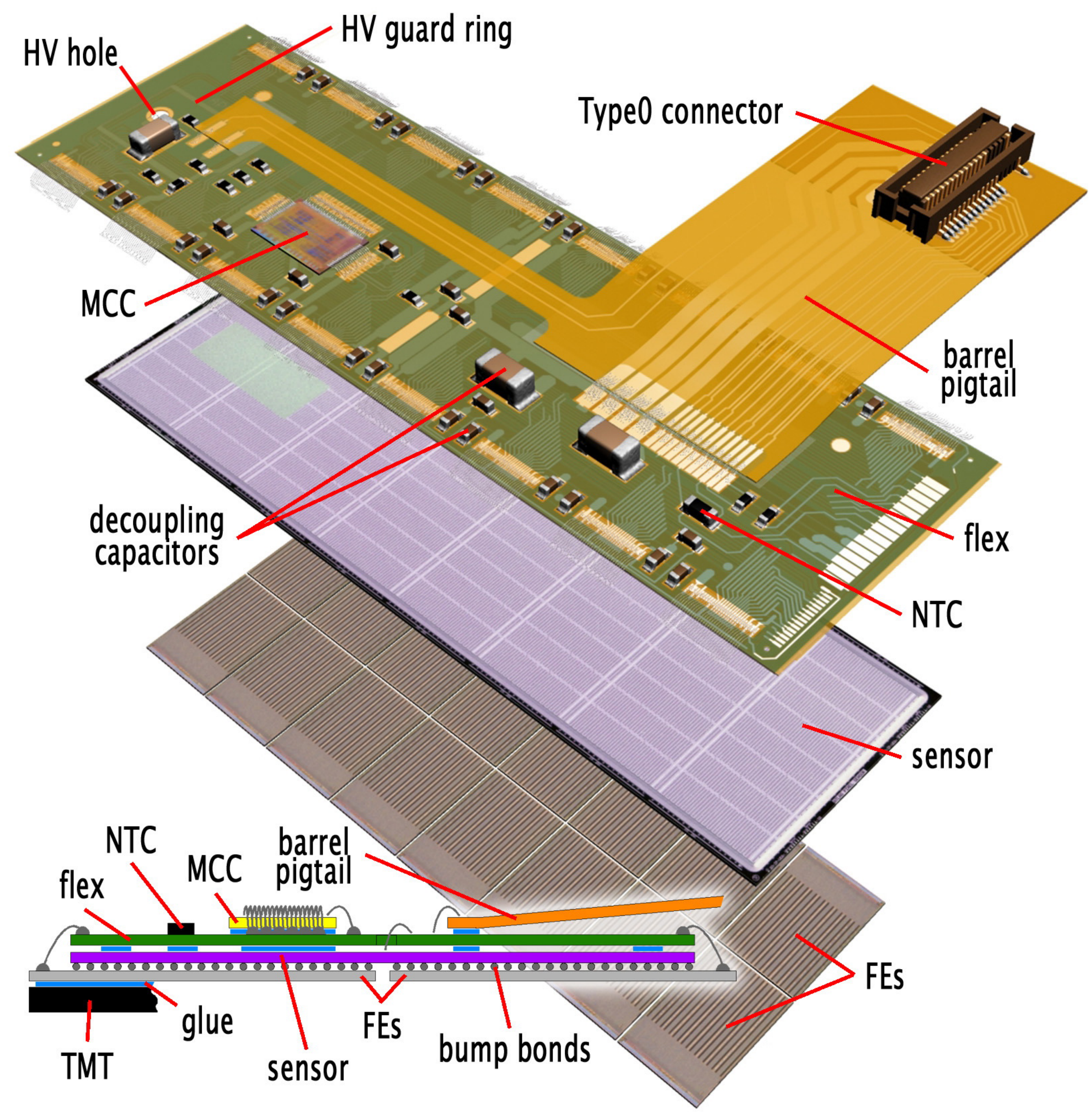


- Innermost part of the ATLAS detector surrounding beam pipe
- 4 barrel layers and 3 endcap disks on each side, providing coverage for |η| < 2.5
  - IBL was added for Run 2
- Providing excellent spatial resolution for tracking and vertex reconstruction
- Radiation hardness matching LHC requirements



Pixel detector in Run 1

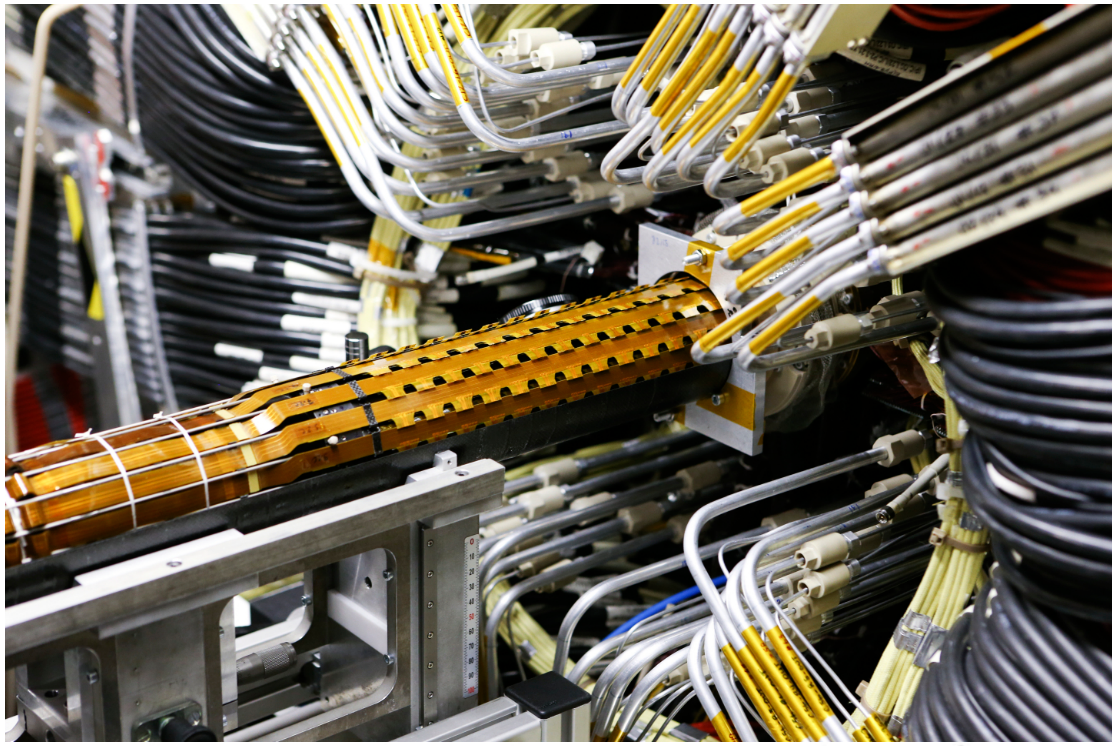


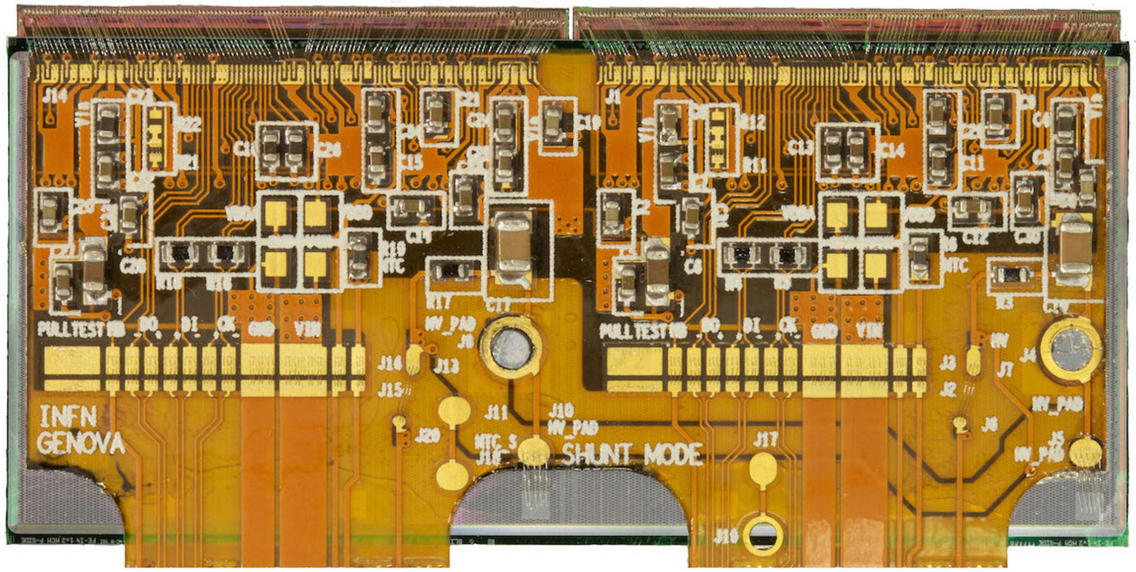


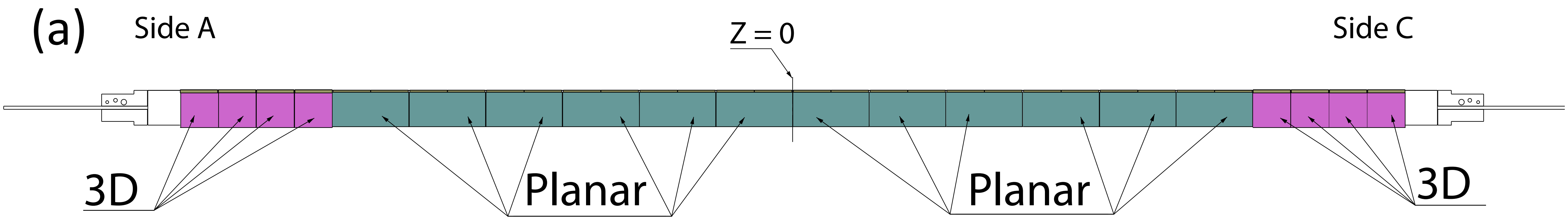
- Originally 3 barrel layers in Run 1
- In total 80M electronic channels
- Frond-end: FE-I3 based on 250 nm CMOS technology
  - 2880 (18×160) channels
  - Pixel size 50 × 400 µm²
- Sensor: n-on-n planar, 250 µm thick
- Module: 16 FE-I3 chips bump bounded to one sensor and connected to one MCC

Insertable B-Layer (IBL)

- **New innermost layer** added during 2013-2014 LHC shutdown between beam pipe and b-layer
- 12M electronic channels in total
- FE-I4 chip: 130 nm CMOS
  - 26880 (80 × 336) channels
  - Pixels size 50 × 250 μm²
- Two sensor technologies tested
  - Central: planar n-in-n, 200 μm thick
  - Edge: 3D n-in-p, 230 μm thick

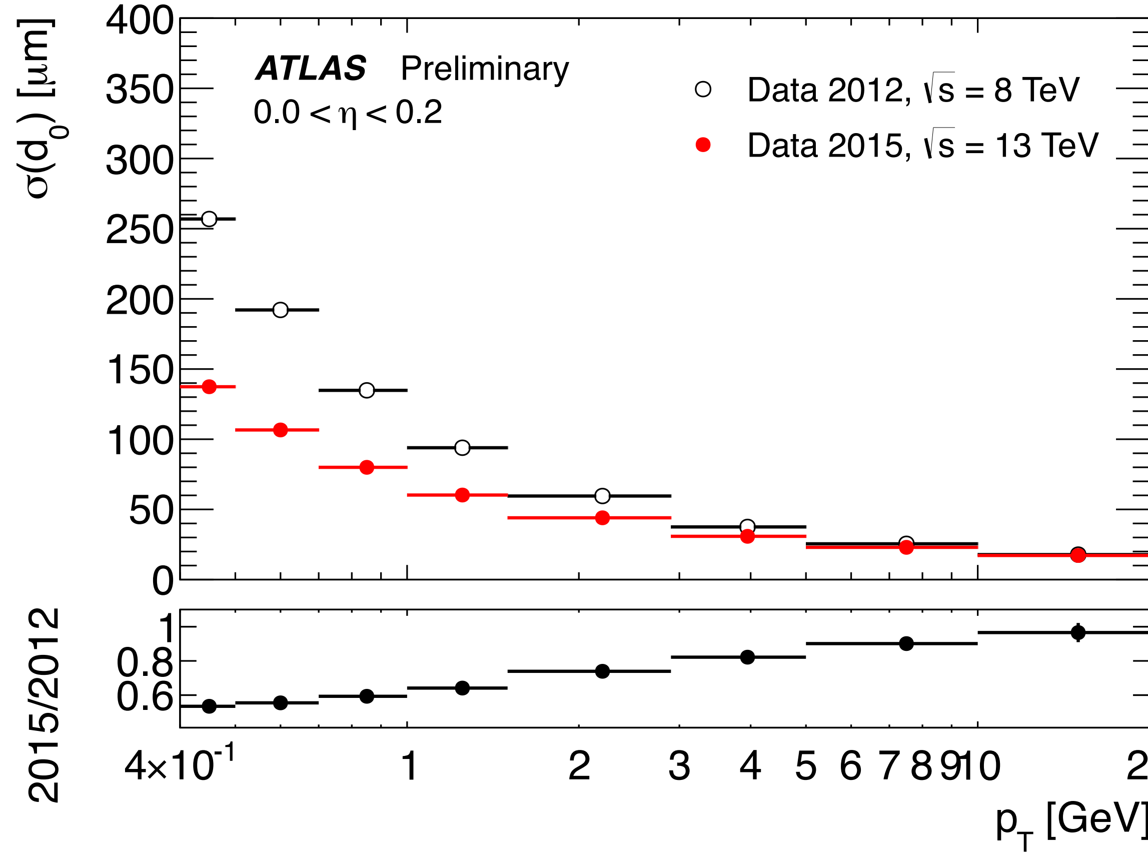


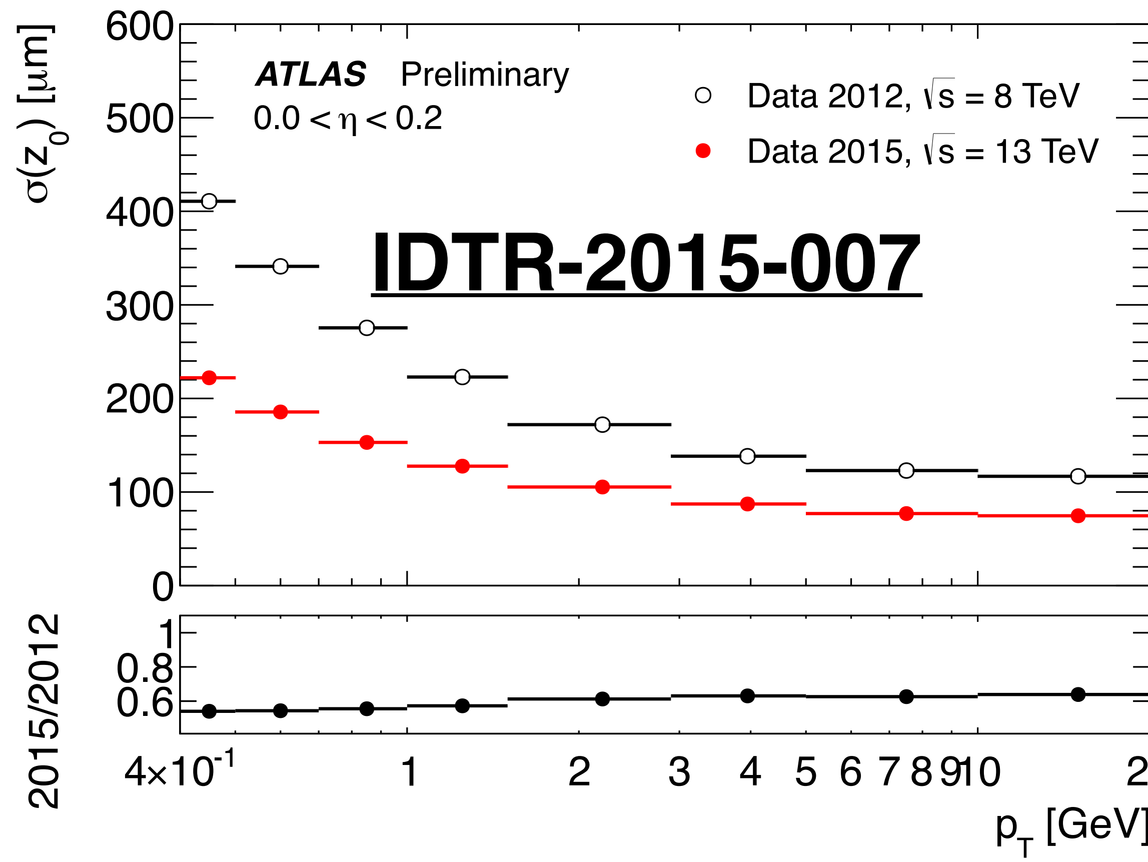


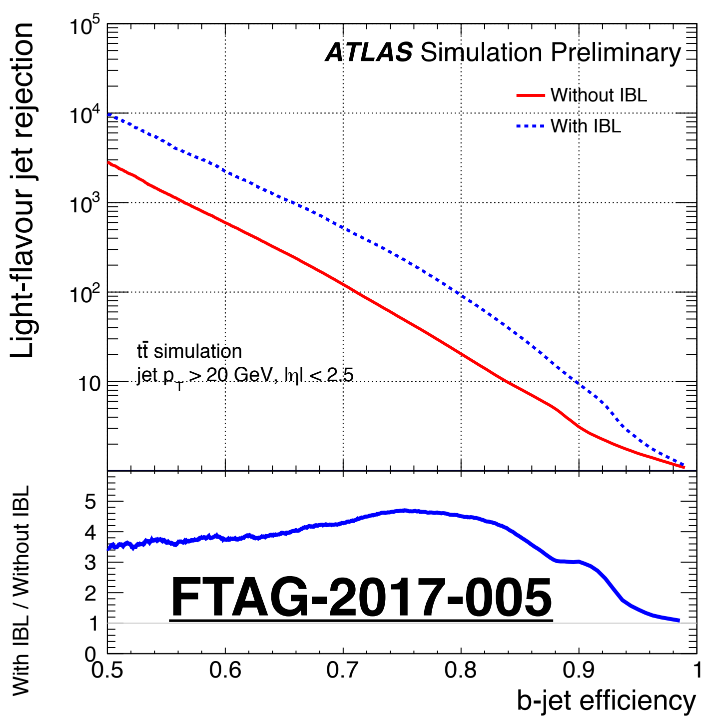


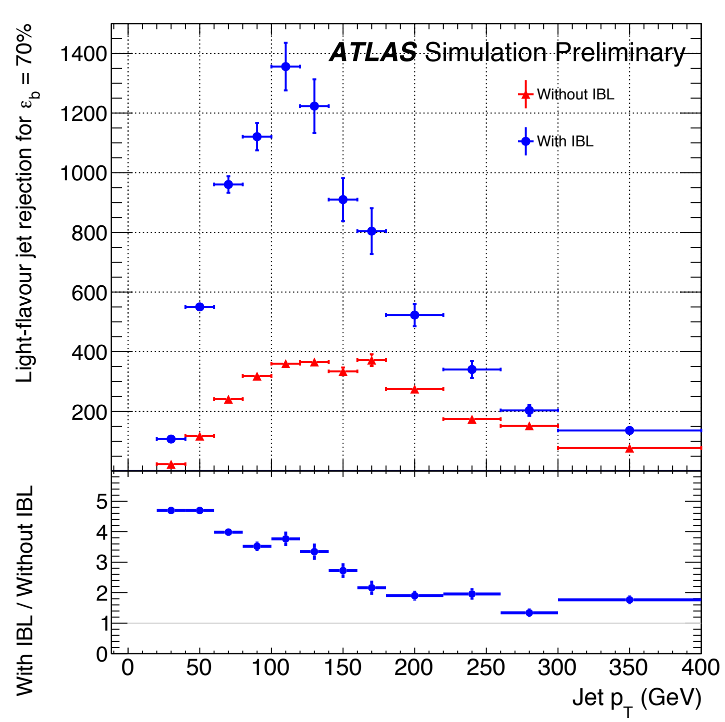
Improvement from IBL

- Impact parameter resolution is paramount for vertexing and b-tagging performance
- IBL significantly improves the resolution of impact parameters, in particular at low pT
- Also it ensures performance robustness when B-layer starts to deteriorate from radiation damage

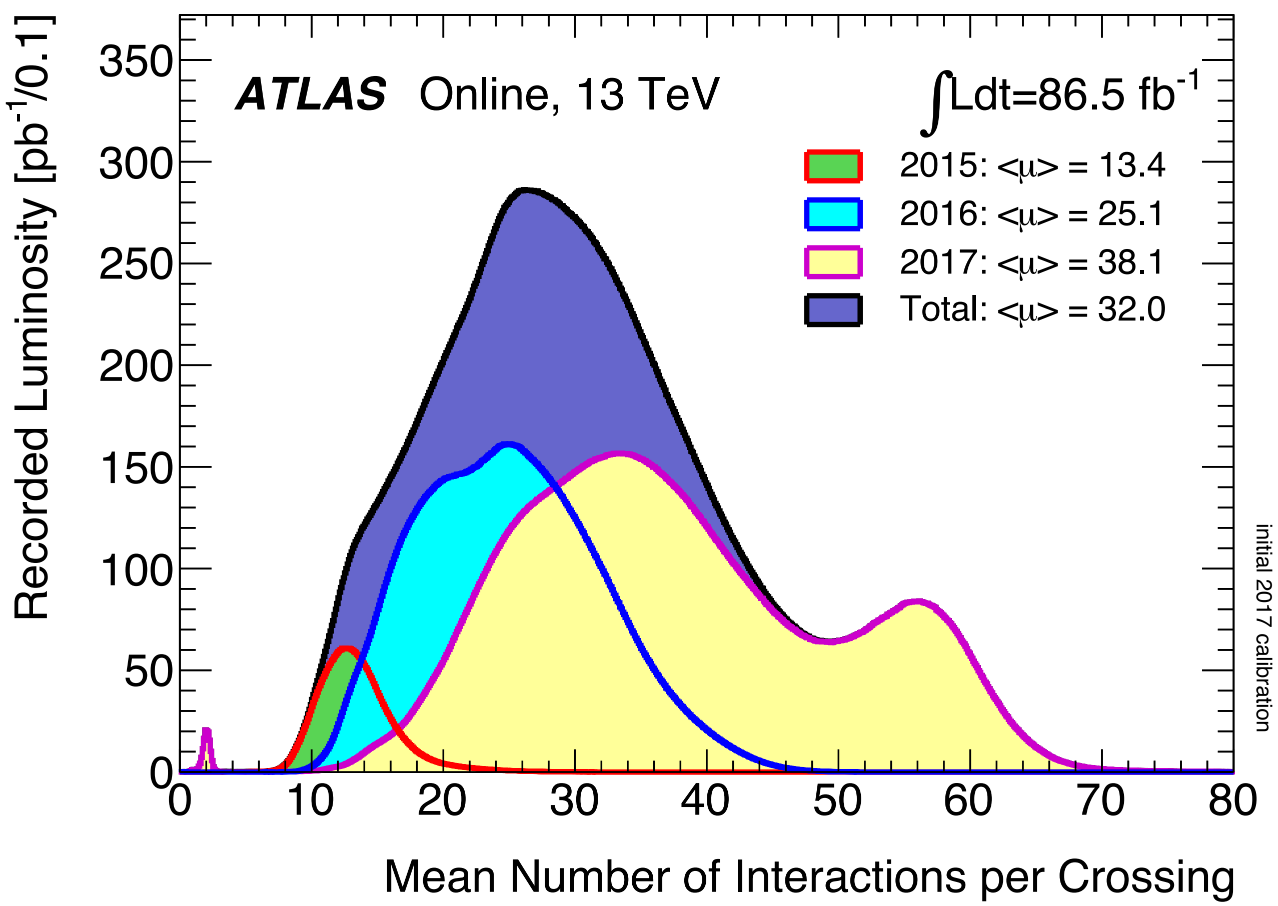


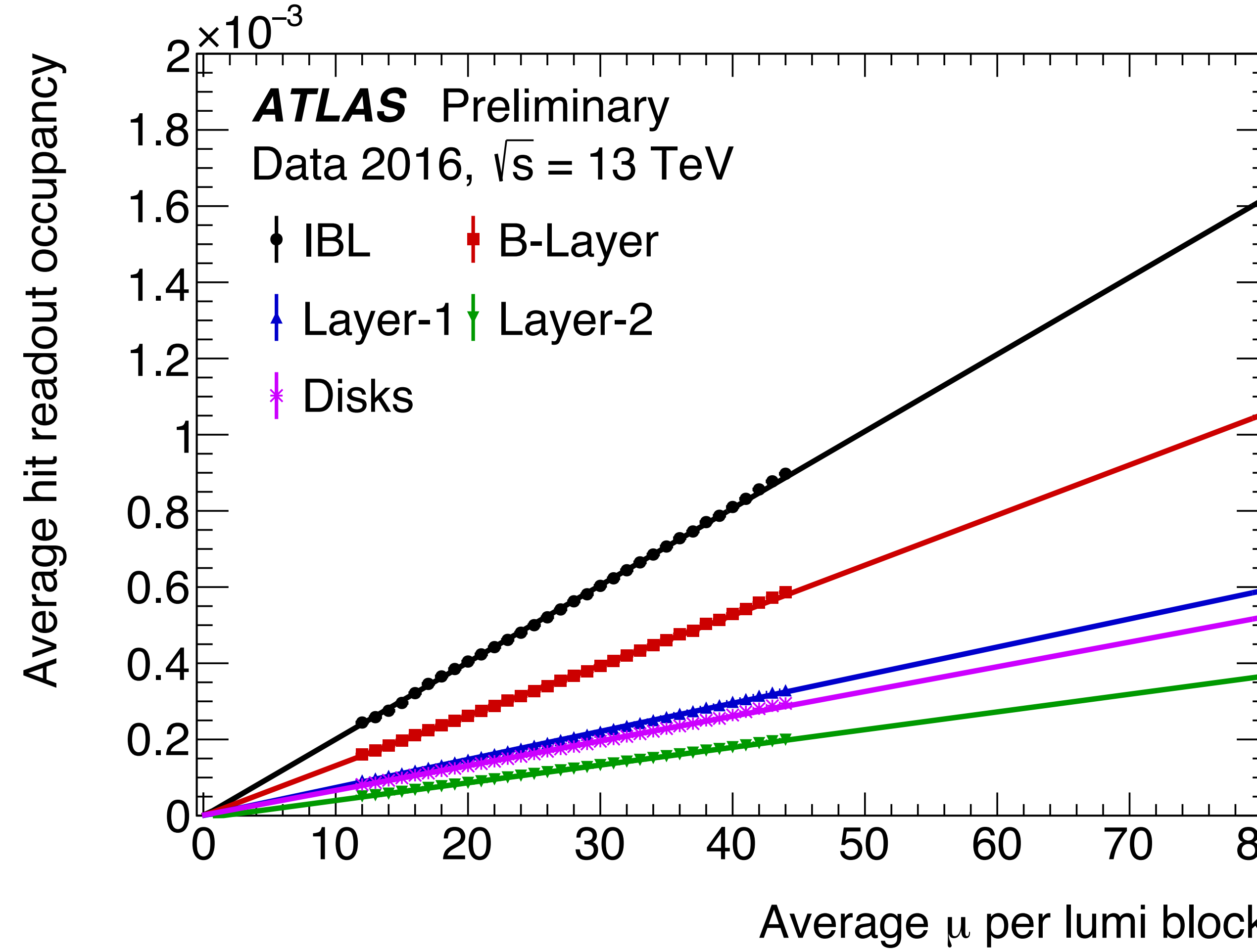






LHC is running beyond designed parameters





Proton-proton collisions	Design	2017 records	2017 ATLAS leveling
Beam energy [TeV]	7	6.5	6.5
Nominal luminosity [$10^{34}cm^{-2}s^{-1}$]	1	**2.06**	**1.53**
Bunches per beam	2808	2544	1866
Max. avg. events per bunch crossing	23	**78.6**	**58**

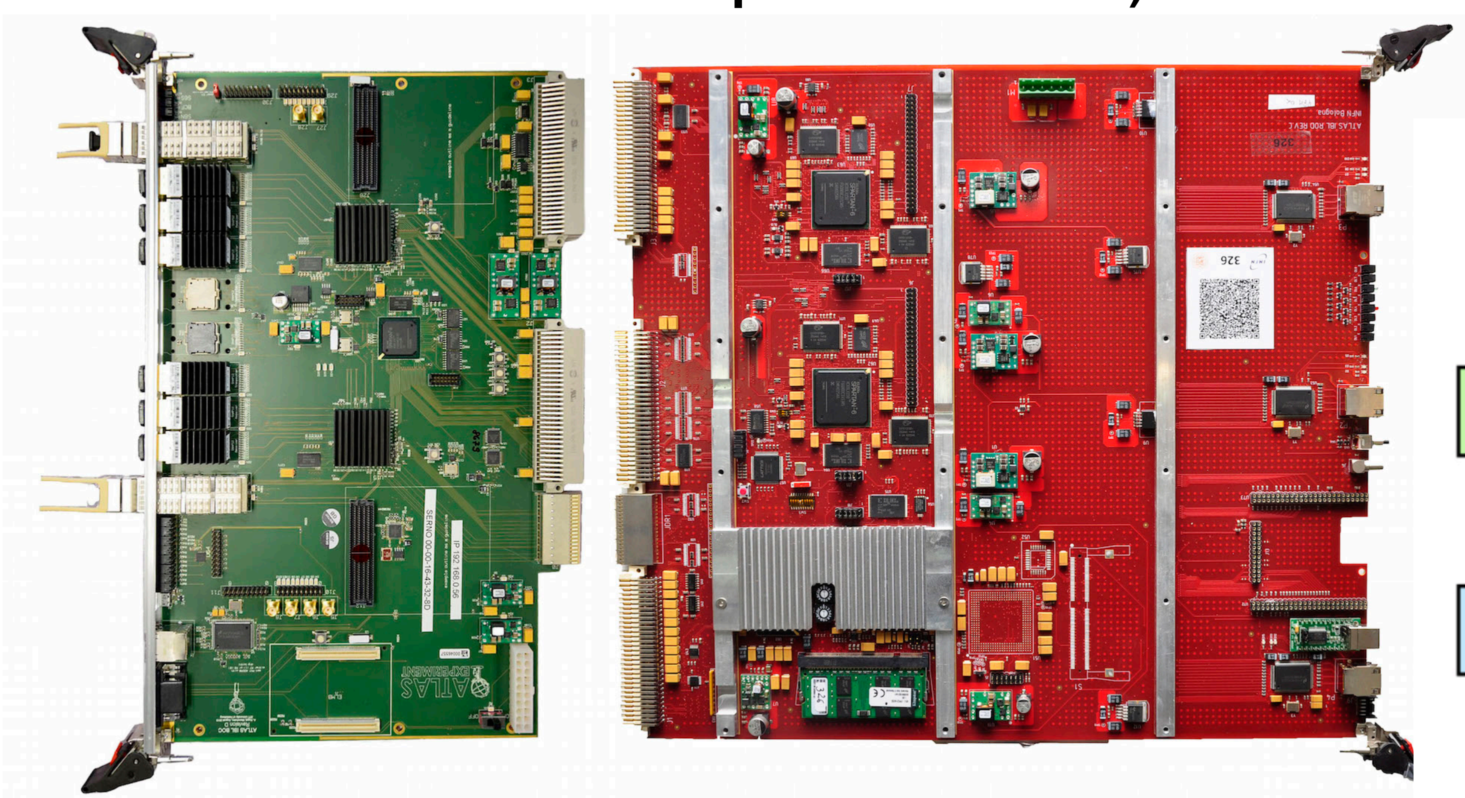
Backend readout upgrade

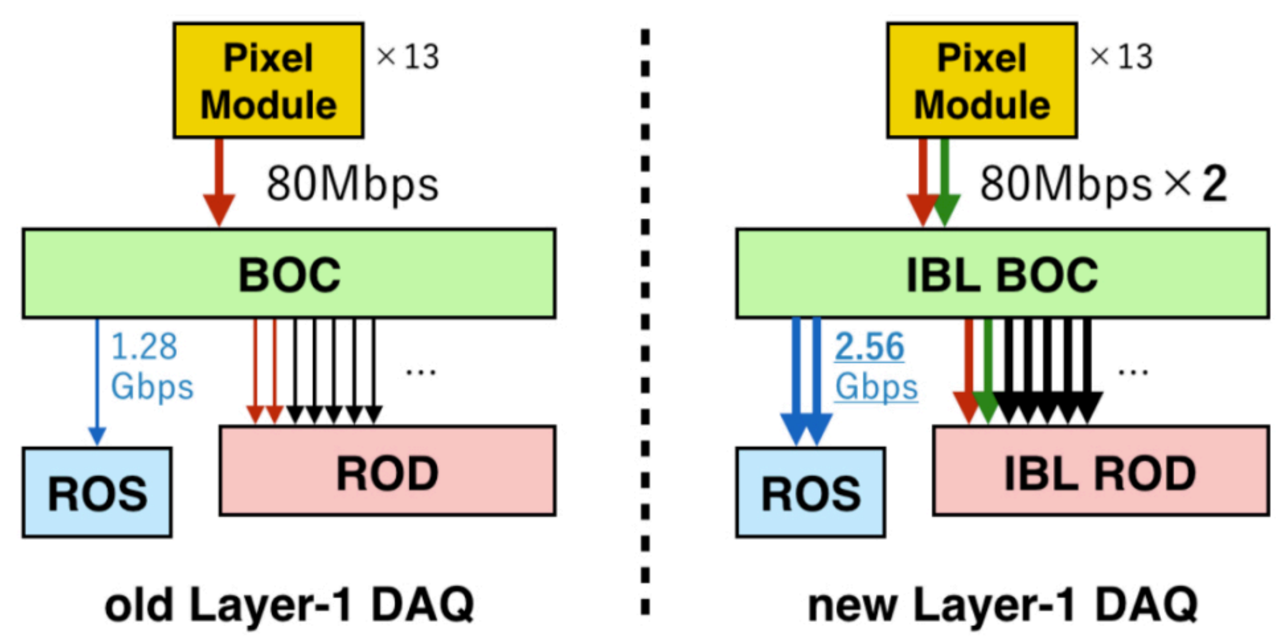
- New backend readout introduced with IBL in Run 2 to cope with bandwidth issue
  - Layer-2 (2015) and Layer-1 (2015 – 2016) upgraded
  - B-layer and Disks were upgraded this year (without bandwidth improvement)

Module link bandwidth usage at 100 kHz LV1 rate 25 ns at 13 TeV (prediction from early Run 2)

μ	B-layer 160 Mbps	Layer-1 160 Mbps	Layer-2 80 Mbps	Disks 80 Mbps
30	50%	33%	49%	62%
50	71%	92% ↓ 46%	139% ↓ 69%	86%
80	101%	125% ↓ 63%	188% ↓ 94%	115%

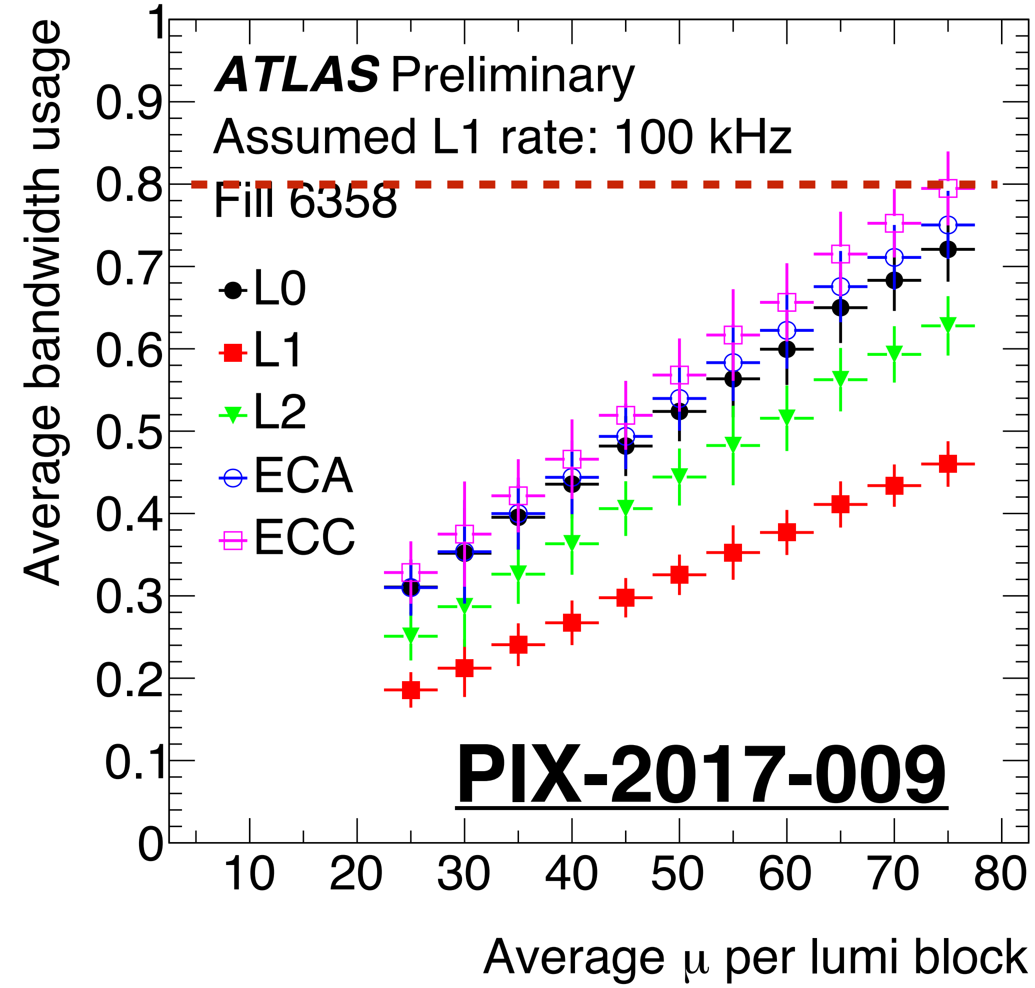
"↓" indicate the impact of backend readout upgrade

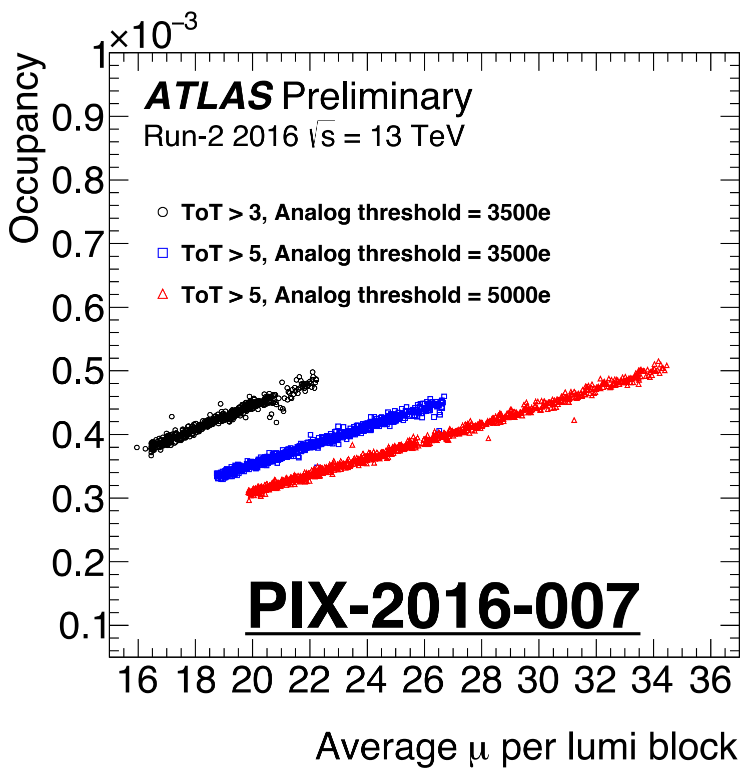


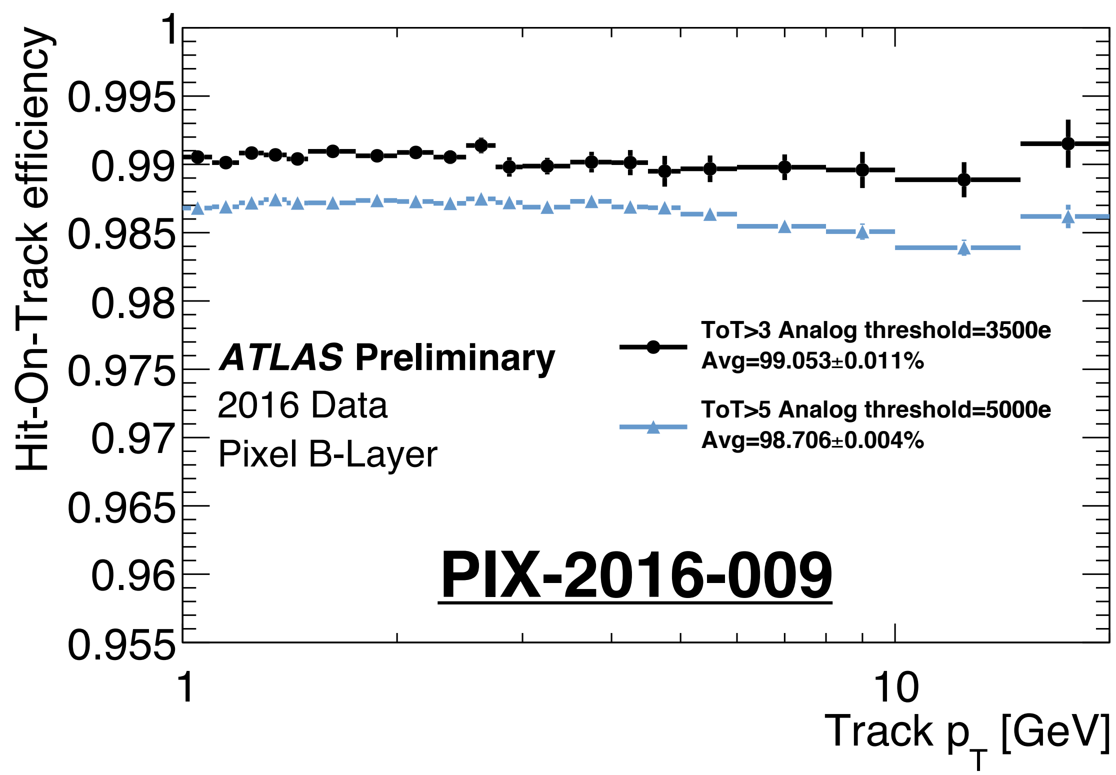


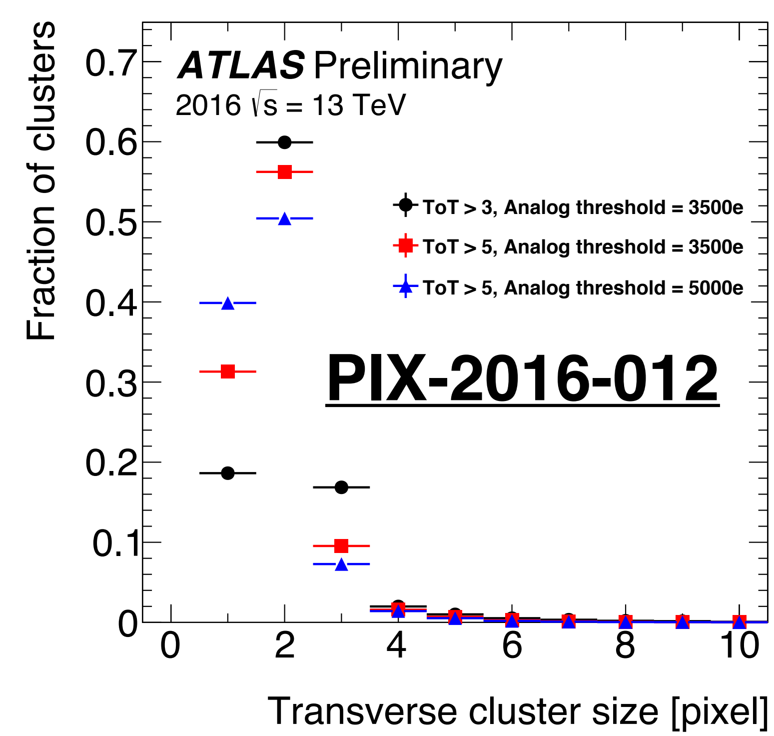
Threshold adjustments

- As LHC is outperforming, need to reduce data volume from B-layer and Disks by increasing thresholds
  - Time-over-threshold: increase from 3 to 5 bunch crossings for b-layer
  - Threshold: b-layer up to 5000e (2016) and disks up to 4500e (2017) from 3500e
- Small impacts from the adjustment
- **Combined with readout upgrade, pileup is now under control!**



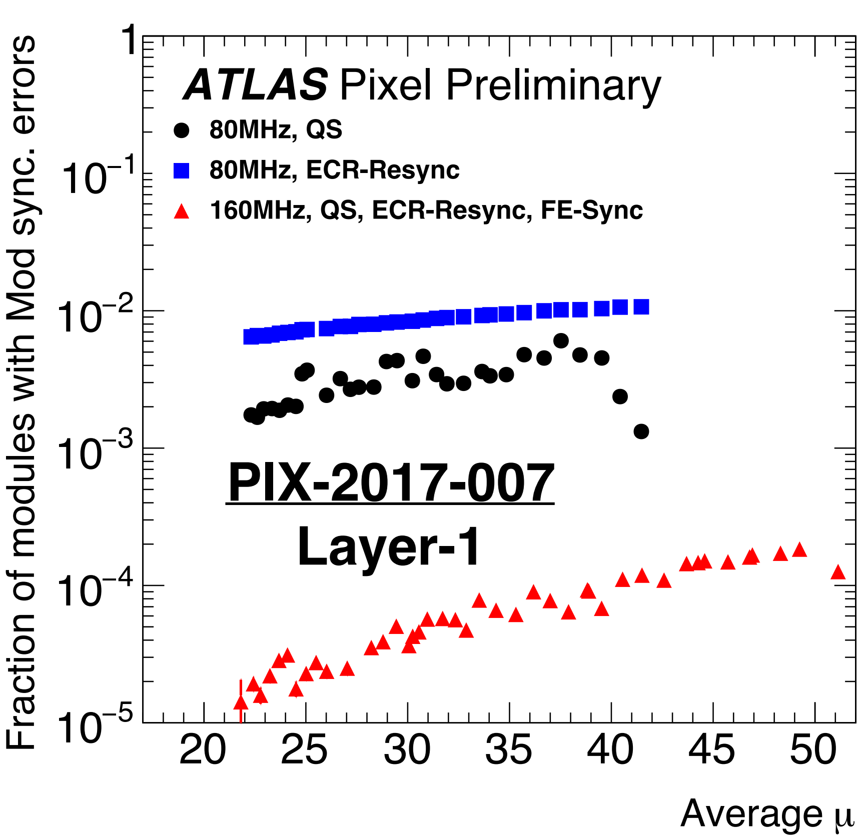


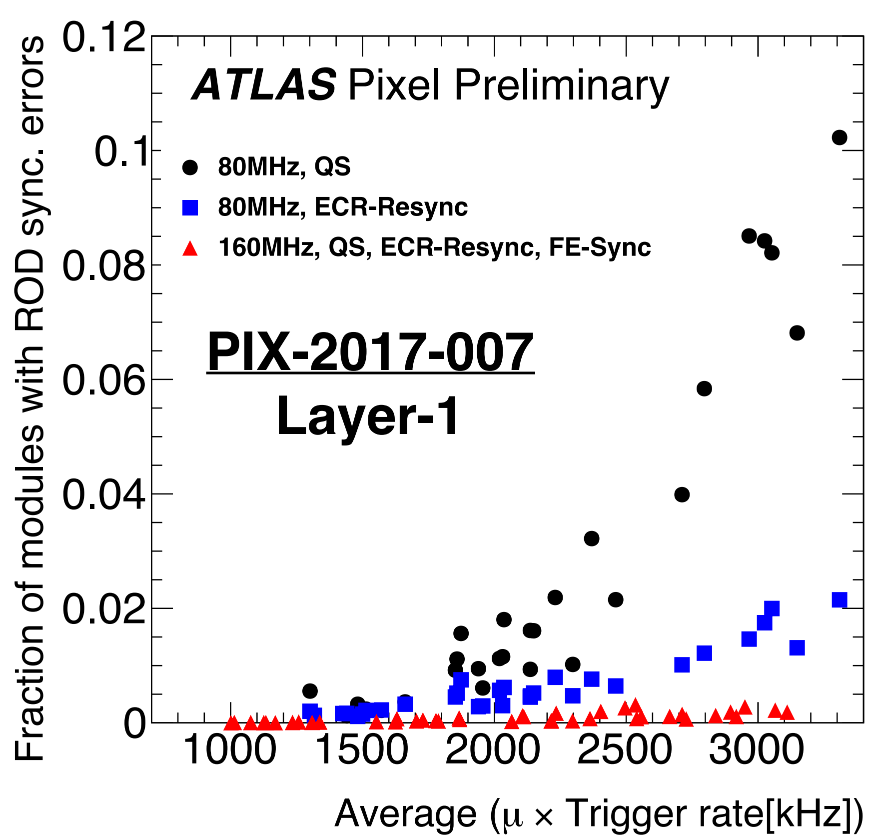


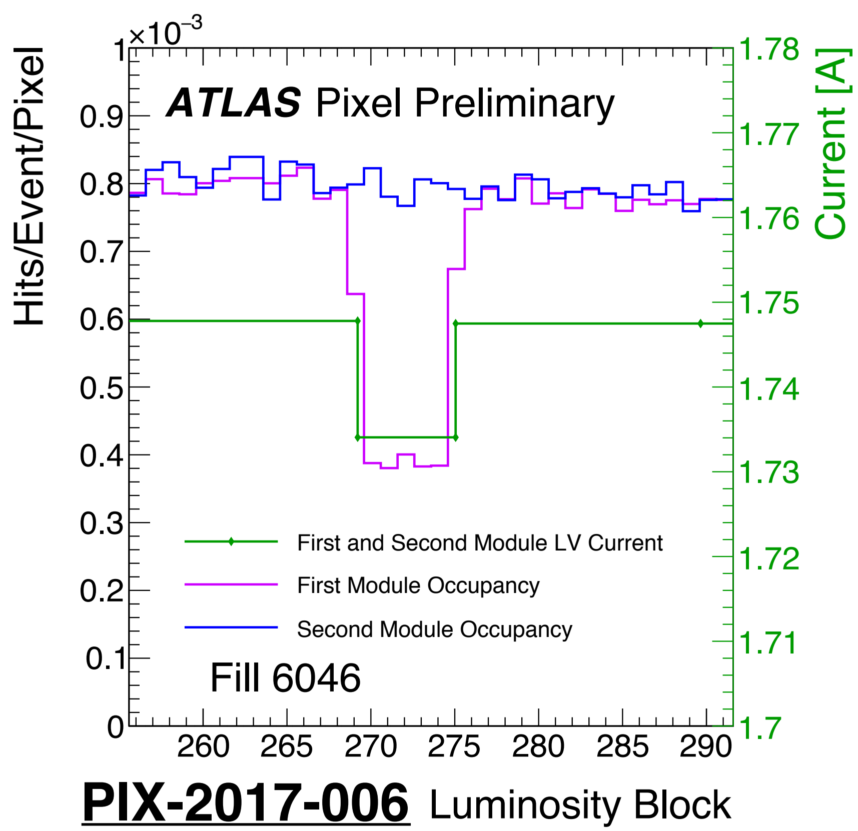


Maximizing performance

- During data-taking many issues can occur, in particular under high intensity condition
  - Mis-matched event fragments (sync. error) on module or ROD
  - Single event upset where module configuration bits flipped
  - Detector becomes busy / timeout
- Auto recovery actions essential for high efficiency data-taking!







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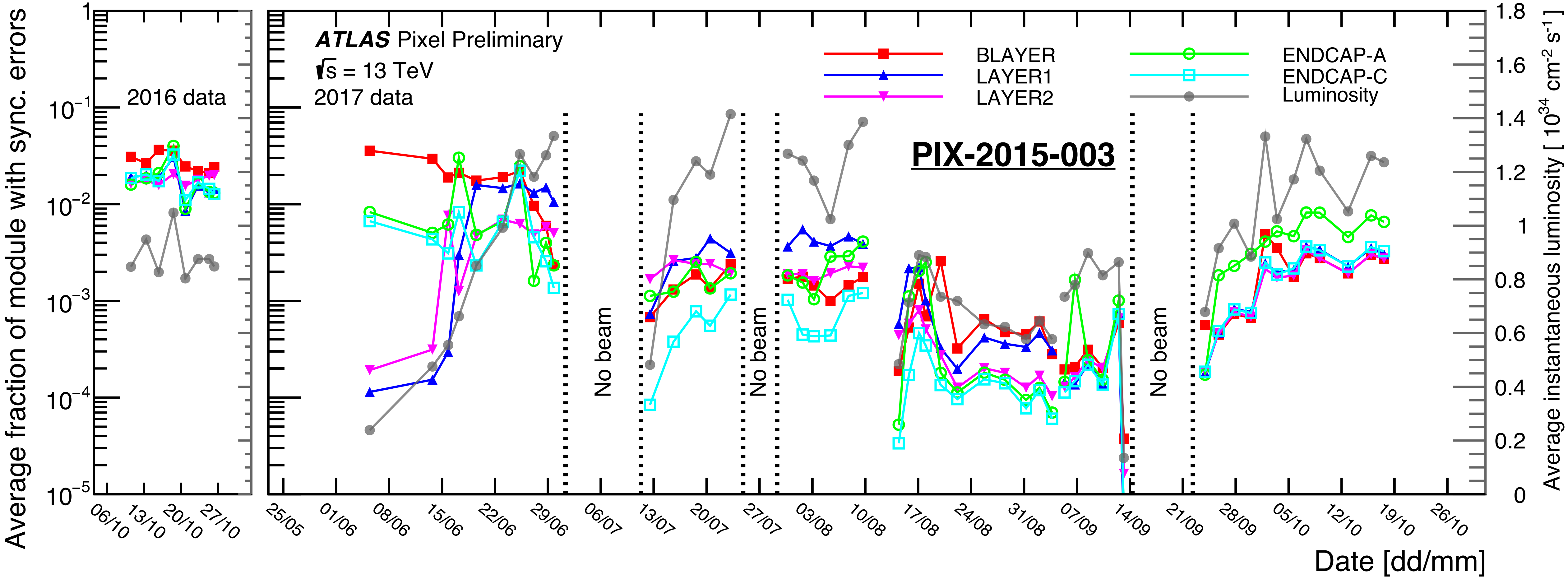
IBL

Automatic recovery actions

- A periodic central ATLAS Event Counter Reset Signal (**ECR**) is sent every **5s**, surrounded by **2ms** window without triggers. Most corrective actions built around ECR:

1. FE-sync (firmware): resetting at ECR internal trigger FIFO and clearing all memory of events in FE-I3 chip
2. Reconfiguration of IBL FE-I4 global registers at ECR (firmware/software)
3. Flushing backend FIFO at ECR
4. QuickStatus (SW): monitoring readout status, and taking corrective actions when busy / timeout error occurs

Synchronization errors in 2017



- Synchronization error rate decreased in all layers until Sept. mainly due to automatic recovery actions
- After Oct., luminosity increased again, resulting in increased synchronization errors (mainly from sync. errors on the ROD, see backup for details)

Summary of 2017 data taking

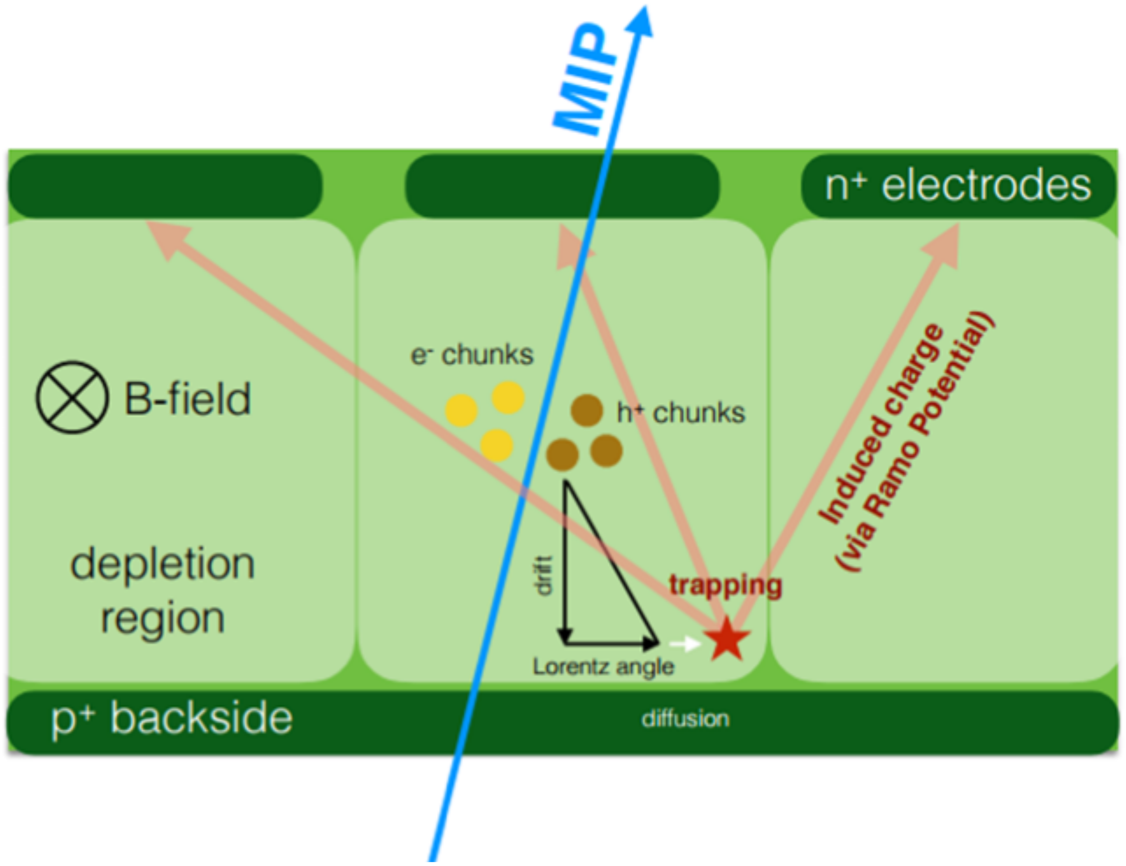
ATLAS pp 25ns run: June 5-November 10 2017										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2
Good for physics: 93.6% (43.8 fb^{-1})										

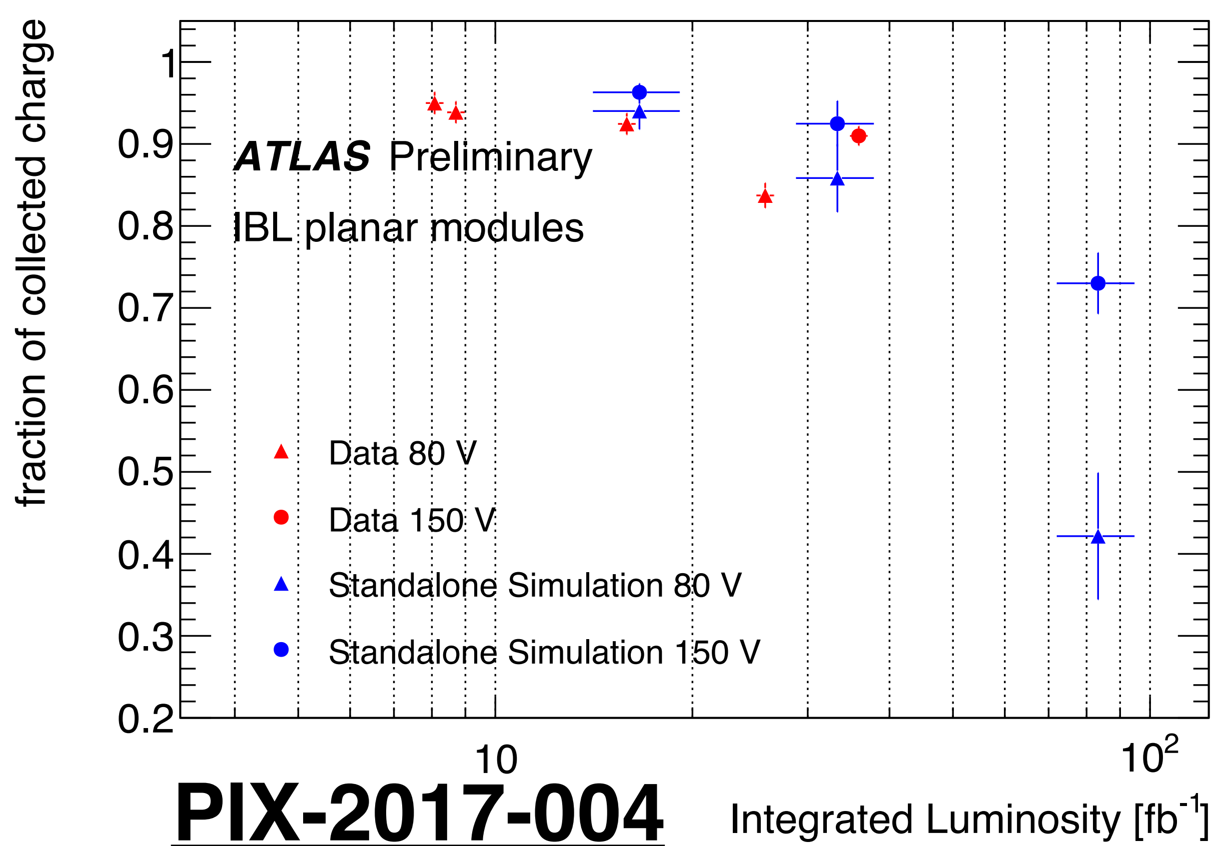
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.

- Pixel has ~100% data quality efficiency
- Dead-time in 2017 was reduced tremendously thanks to the firmware and software recovery actions
- **Successful year of data-taking for pixel** under challenges imposed by the outperforming machine

Radiation damage

- Most important effect in the sensor bulk, caused by non-ionizing interactions
  - Increasing depletion voltage caused by change in effective doping concentration
  - Decreasing signal collecting efficiency and dE/dx caused by charge trapping
  - Change in cluster size and Lorentz angle caused by deformed electrical field
  - Increasing leakage current
  - Annealing makes situation more complicated
- More details in Lorenzo Rossini's talk on Wednesday





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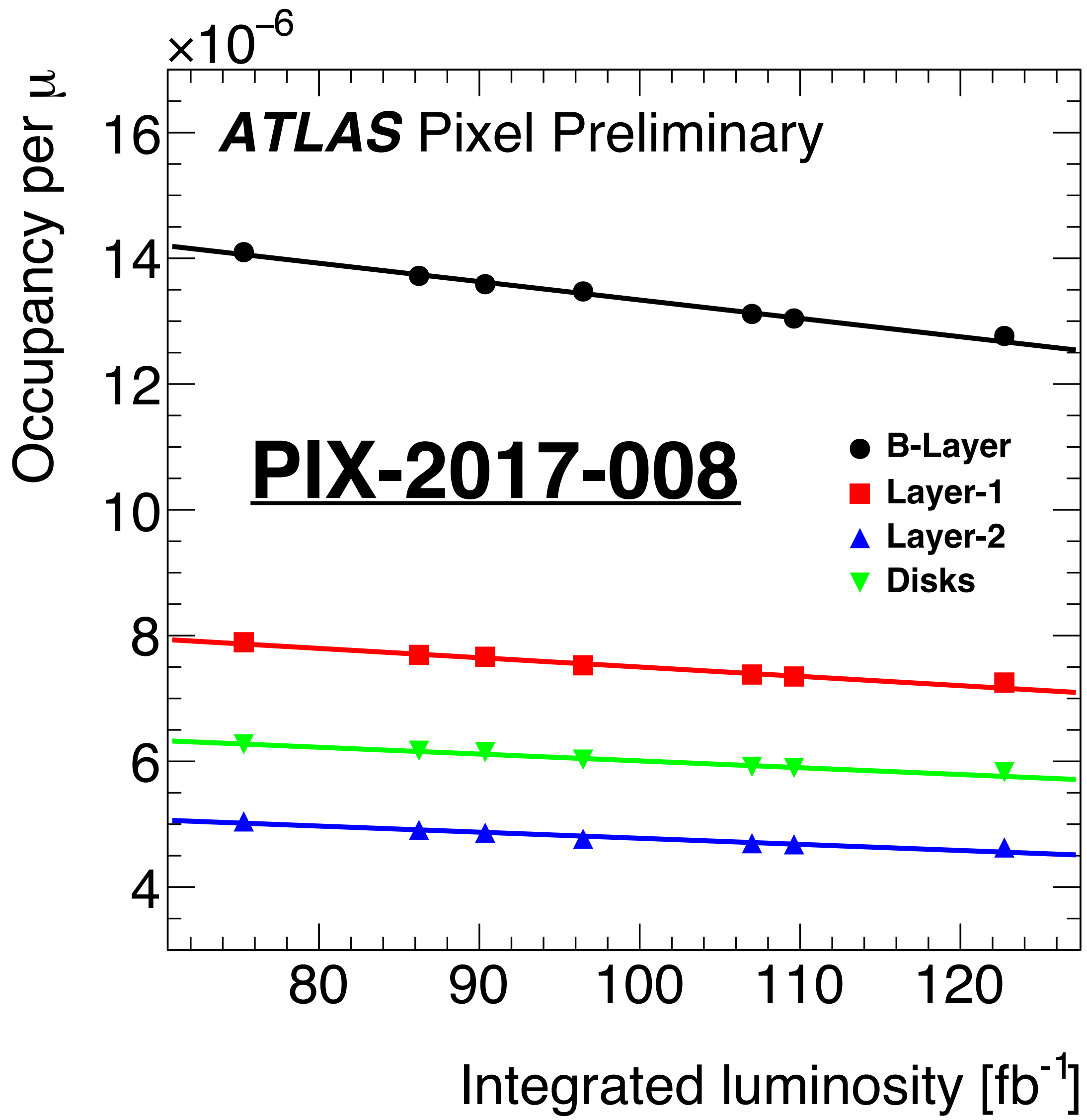
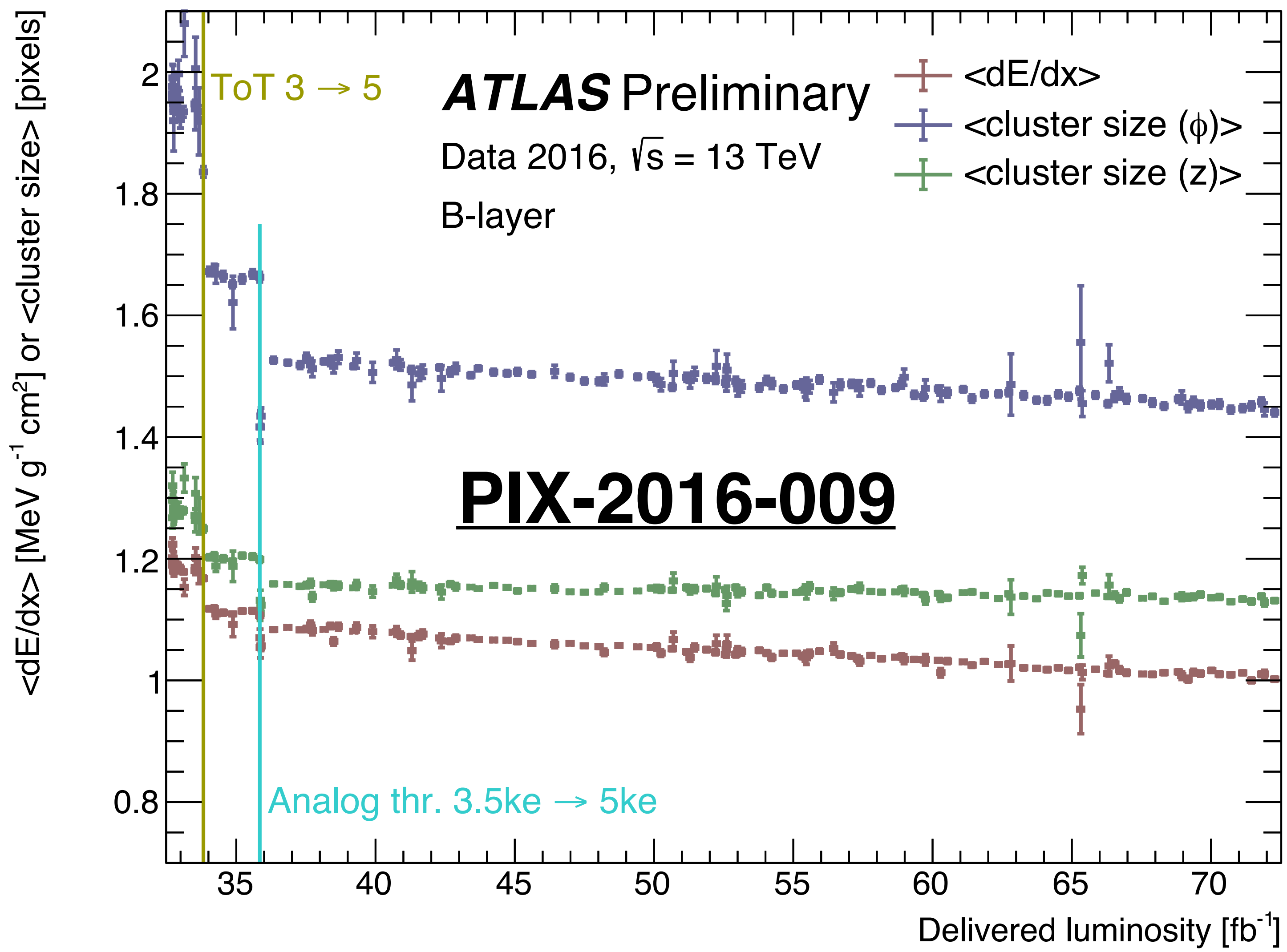
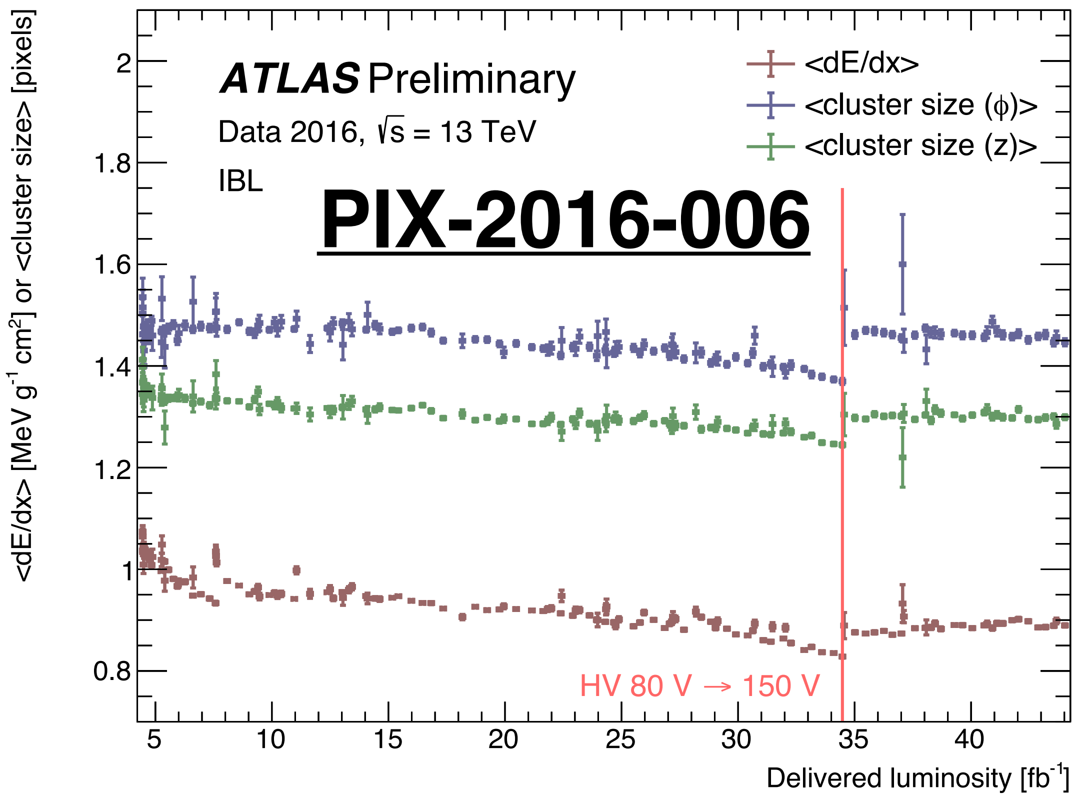
Radiation impact on Pixel

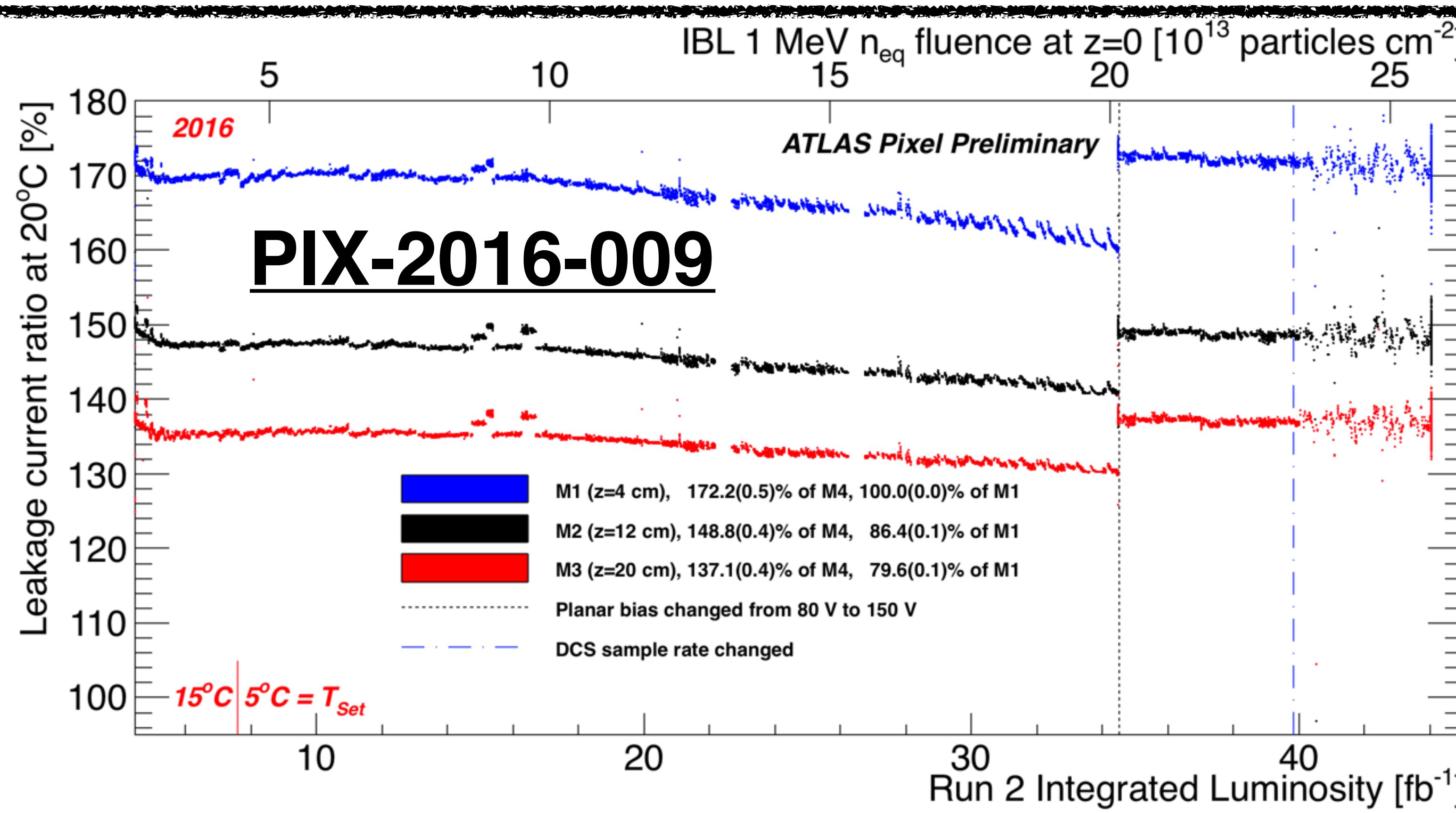




- Starting to see impact on original pixel layers, in particular B-layer
- Need to adjust operation parameters in order to maintain performance

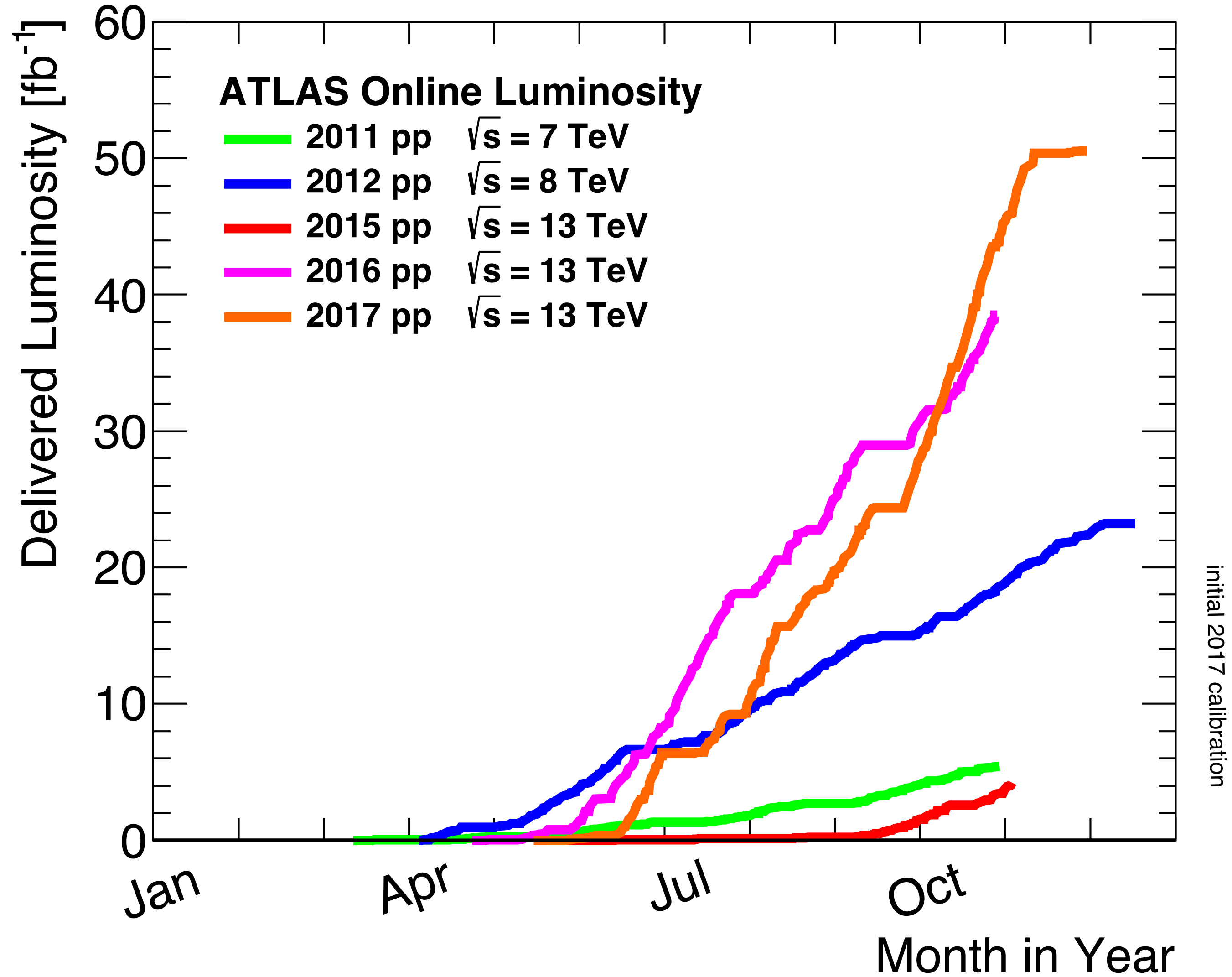
Radiation impact on IBL





- Fluence rate at IBL per fb^{-1}: $5.9\text{-}6.6\times10^{12}$ [1 MeV n_{eq}/cm^2]
  - Rest of Pixel barrel only experiences 50% of the IBL fluence rate
- Total ionizing dose per fb^{-1}: 0.3-0.35 Mrad
- Can compare leakage current between 3D and planar for detecting sensor depletion
- Detector closely monitored, and bi-weekly tuned to control radiation effect on the FE chip

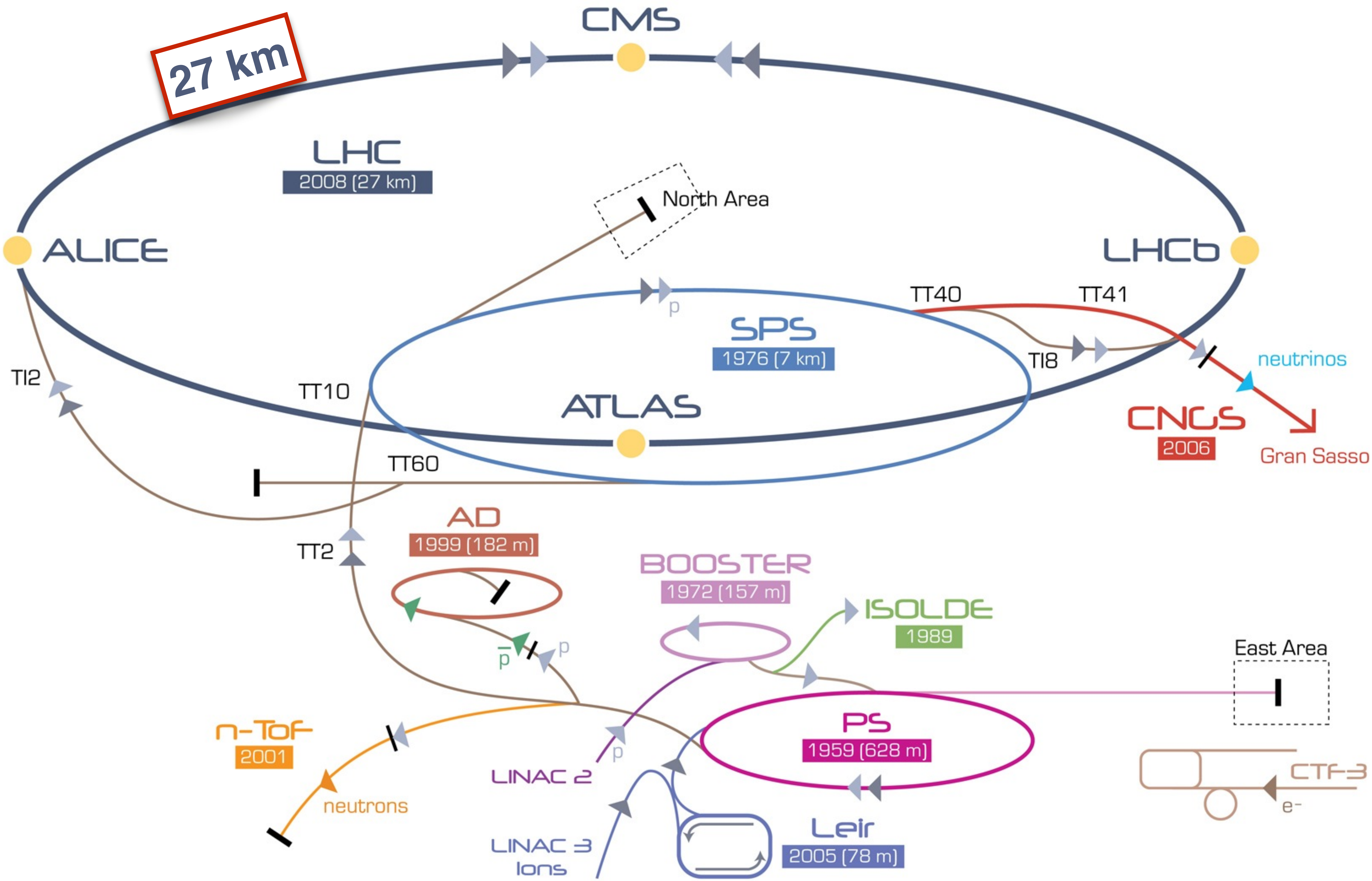
Conclusion



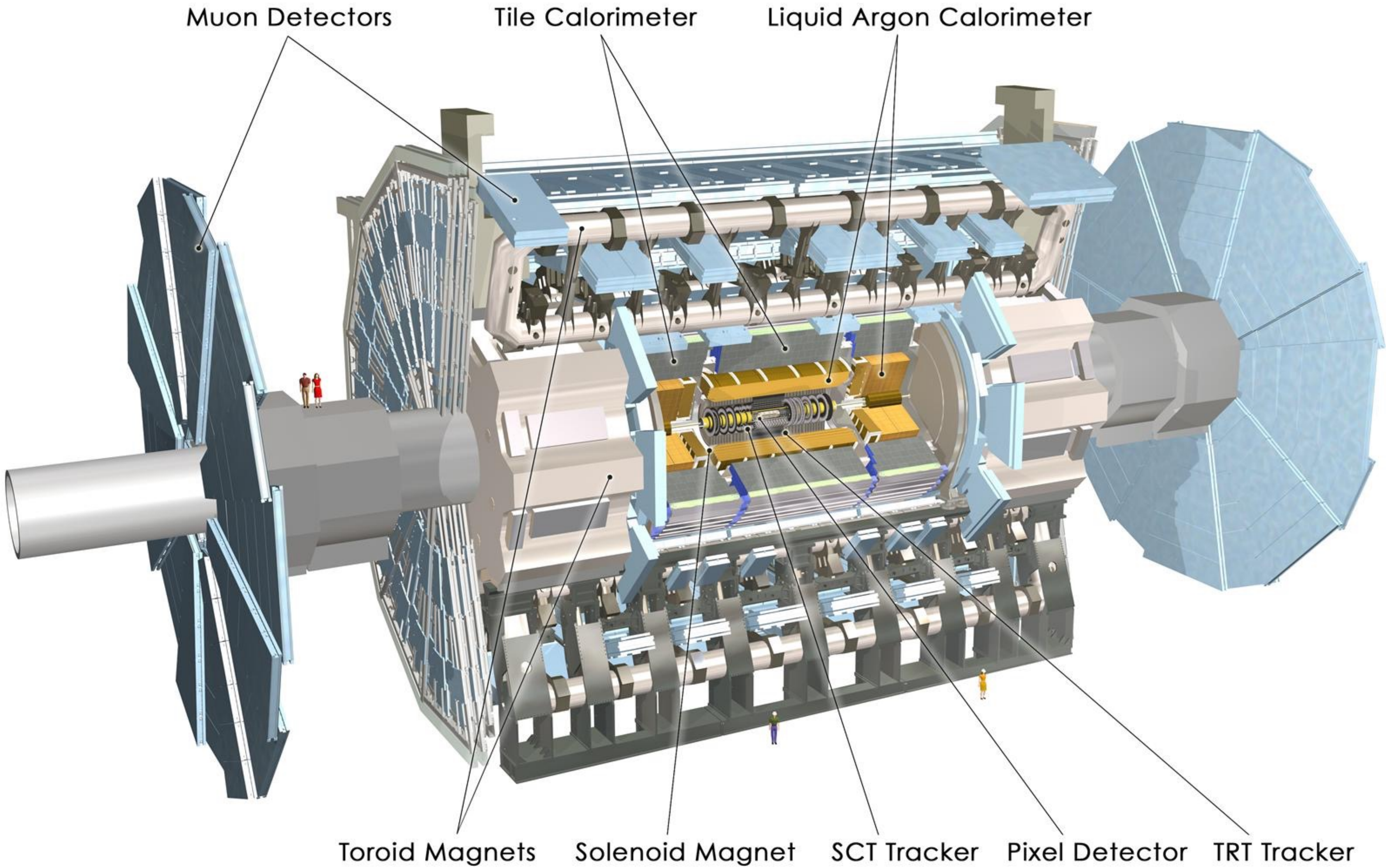
- 2017 was a very challenging year for ATLAS Pixel Detector operation
- Readout upgrade and threshold adjustments managed to cope with high pileup
- Firmware and software corrective features significantly reduce inefficiency and dead time
- Radiation damage will be next challenge. Closely monitoring the detector status and mitigate the effects
- ATLAS Pixel Detector is ready for continued successful operation in 2018 and onward

Backup

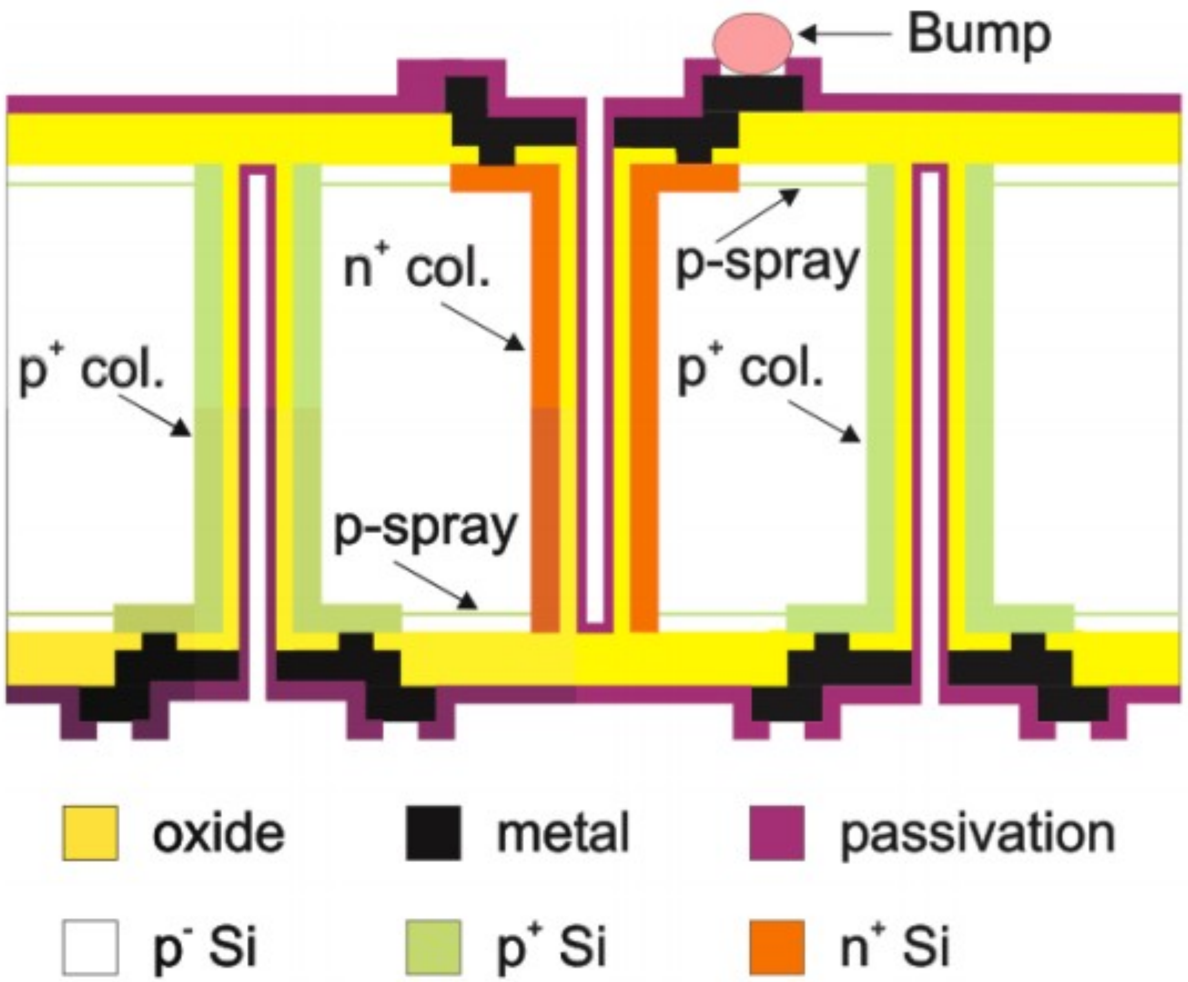
Large Hadron Collider at CERN

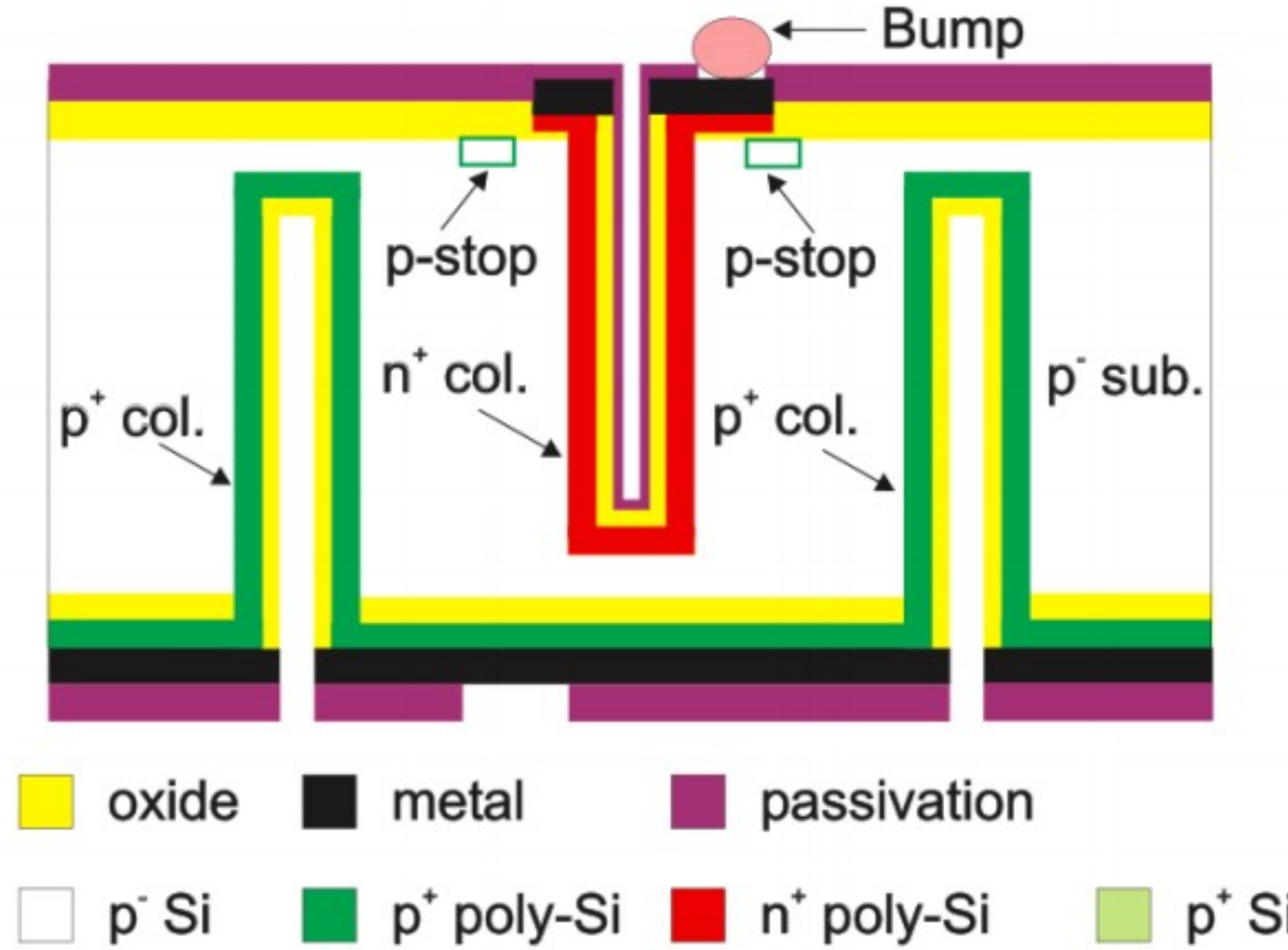


ATLAS Detector

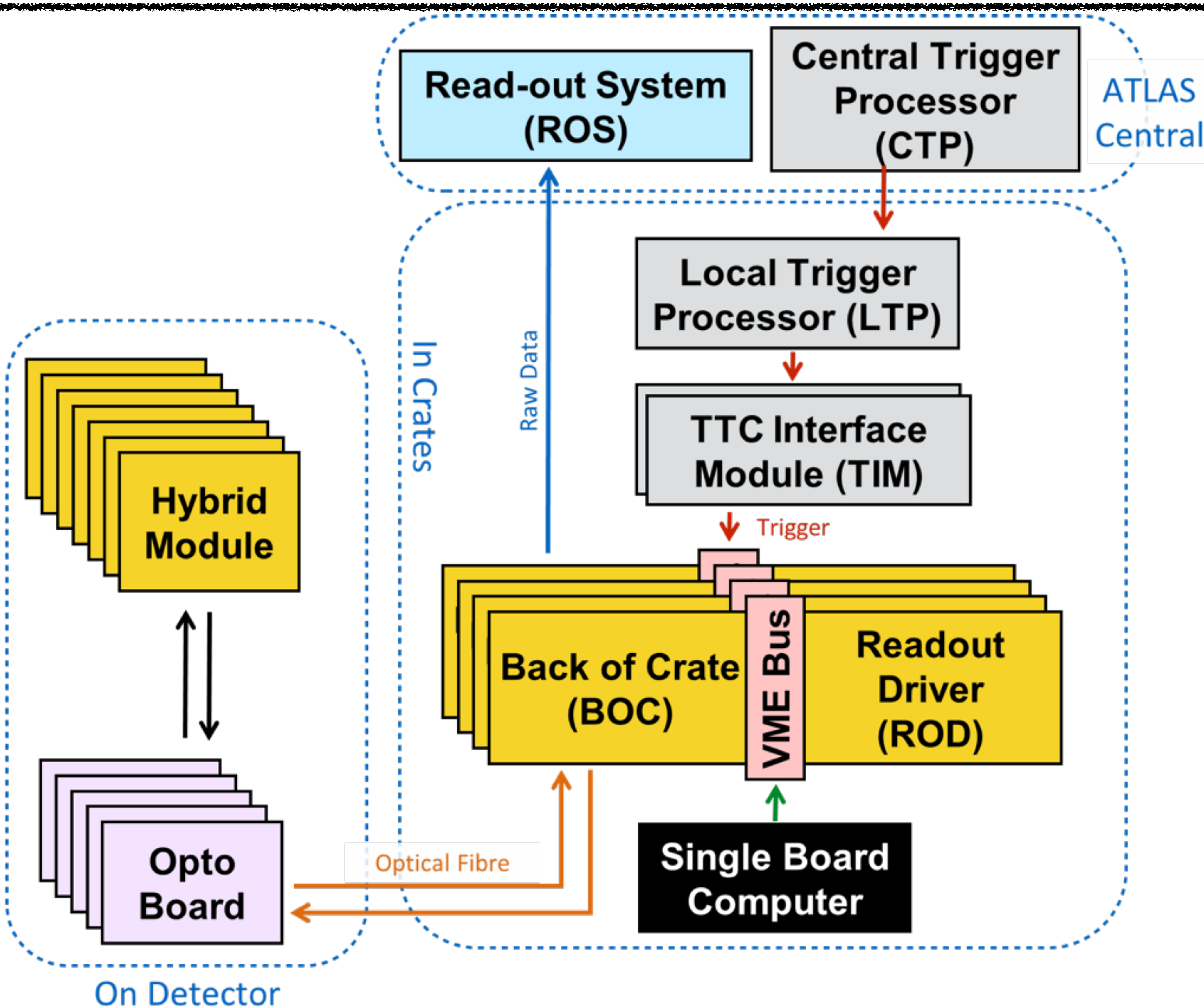


Schema of 3D sensors





Pixel detector readout system



Synchronization errors on ROD (up) and module (down)