ATLAS Pixel Detector Operational Experience

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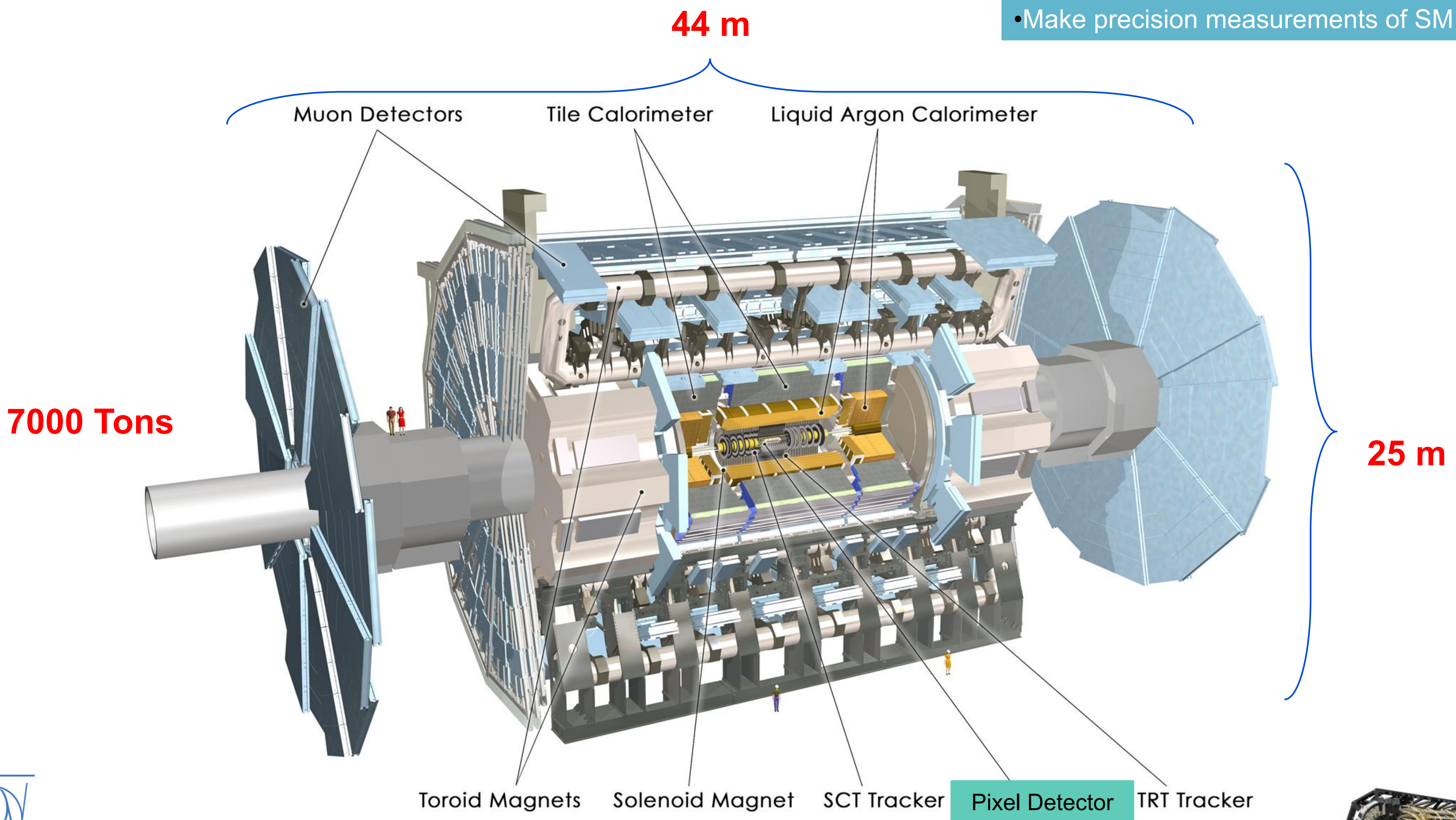
on behalf of the ATLAS Collaboration

Outline

- ATLAS
- The Pixel Detector
- Operational experience: Calibration, tuning and performance
    - Threshold and noise
    - Charge measurement, charge sharing and spatial resolution
    - Efficiency and noise occupancy
    - Lorentz angle and having fun
    - Timing
    - In-time threshold
- Operational issues
    - Monitoring detector quality and radiation damage
    - External issues
- Data taking conditions and efficiencies

The ATLAS Detector

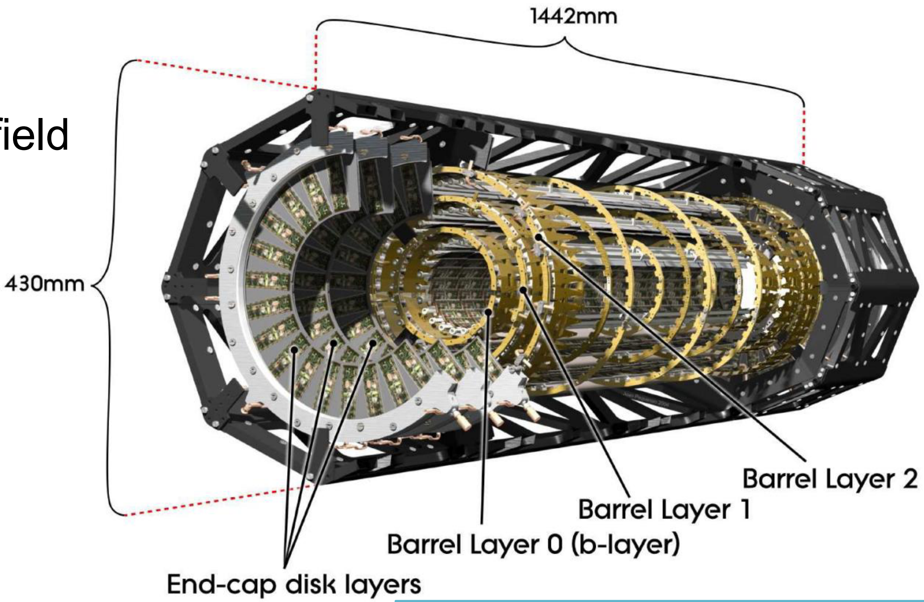
Multi-purpose detector designed to:
- Investigate the TeV scale
- Search for the Higgs boson
- Search beyond the Standard Model
  - Supersymmetry
  - Mini-black holes
  - Leptoquarks
  - Extradimensions
- Make precision measurements of SM



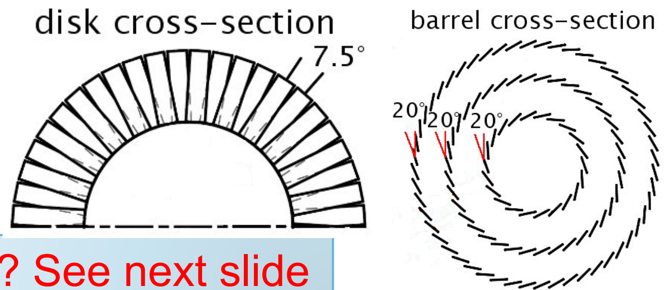
The ATLAS Pixel Detector

- Requirements:
  - Position resolution in rϕ-direction < 15 μm
  - 3 track points for |η| < 2.5
  - Time resolution < 25 ns
  - Hit detection efficiency > 97%

2 T field

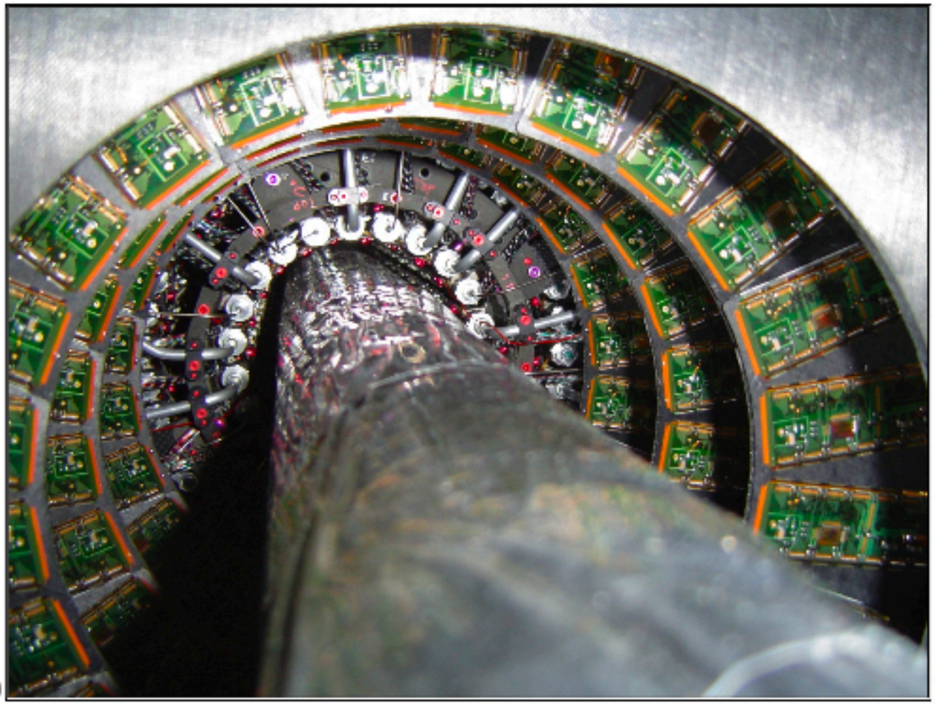


- Basic Properties:
  - 3 barrel layers: 1456 modules
  - 3 disks per end-cap: 288 modules
  - 80M readout channels
  - Innermost layer at 50.5 mm
    - Radiation tolerance 500 kGy / 10^{15} 1 MeV $n_{eq}cm^{-2}$
  - Evaporative C_3F_8 cooling integrated in local support structures
    - Set temperature -20 ^oC (2.02 bara press)
    - Average temperature on modules -13 ^oC, warmest module at -5 ^oC

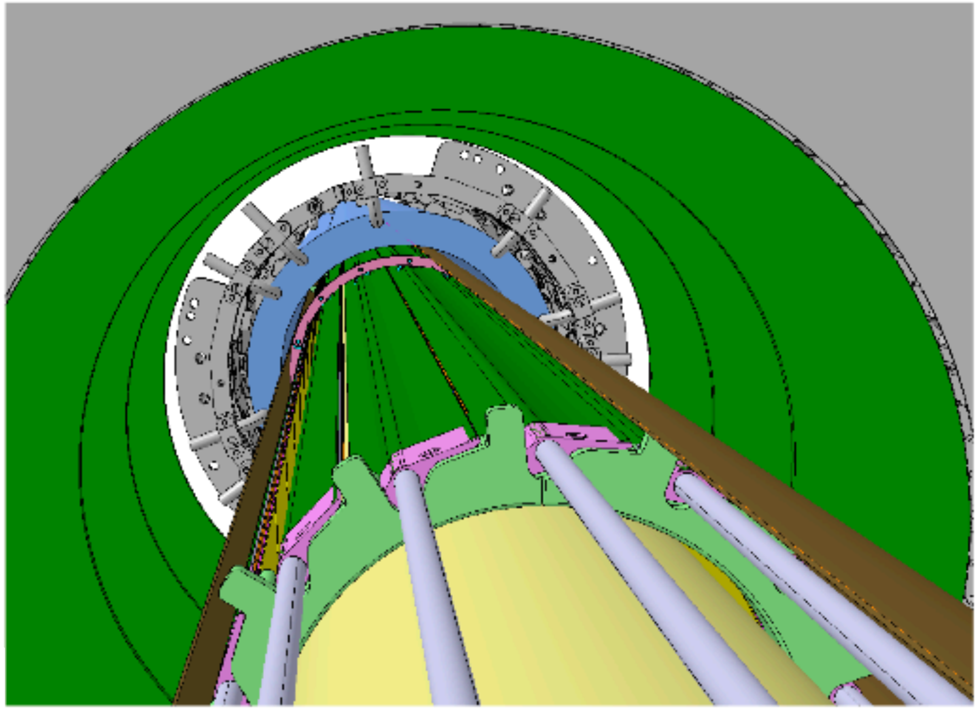


How close to the beam pipe? See next slide

Now: impressively close

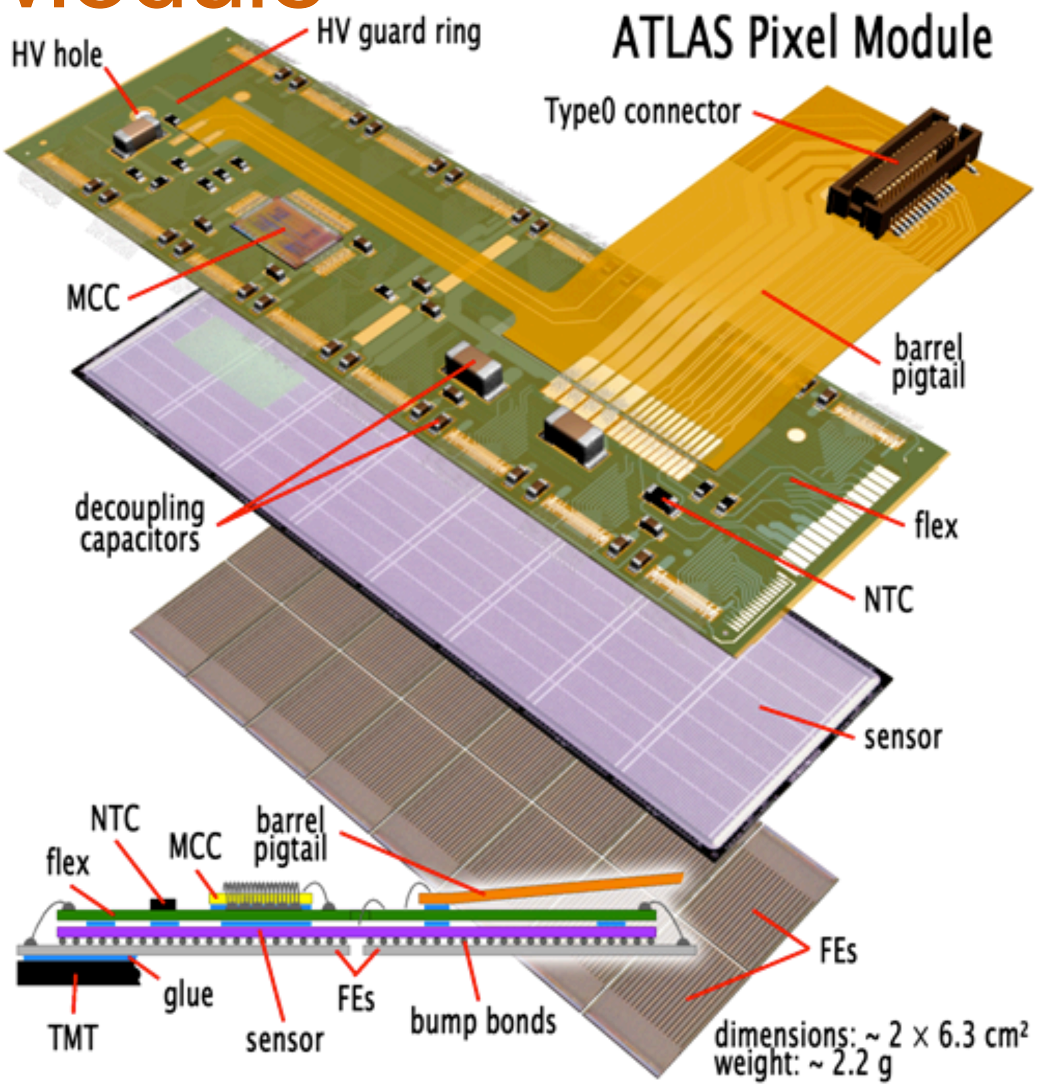


Why not closer? Yes, IBL
Pernegger's talk: don't miss it



The ATLAS Pixel Module

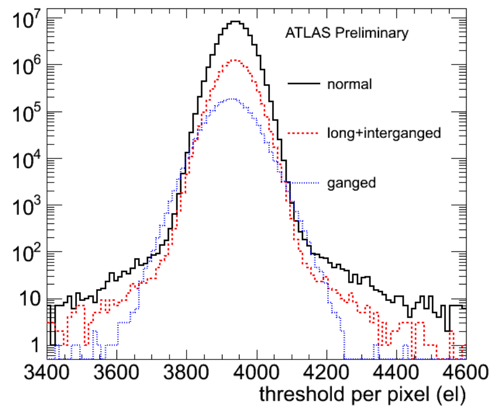
- Sensor
  - 250 µm thick n-on-n Si sensor
  - 47232 (328 x 144) Pixels (46080 read channels)
  - Typical pixel size 50 x 400 µm (50 x 600 µm pixels in gaps between FE chips)
  - Bias voltage 150 – 600 V
- Readout
  - 16 FE Chips with 2880 pixels each
  - Pulse height measured by means of Time-over-Threshold
  - Zero suppression in the FE chips, MCC chip builds module event
  - Data transfer 40-160 MHz depending on layer



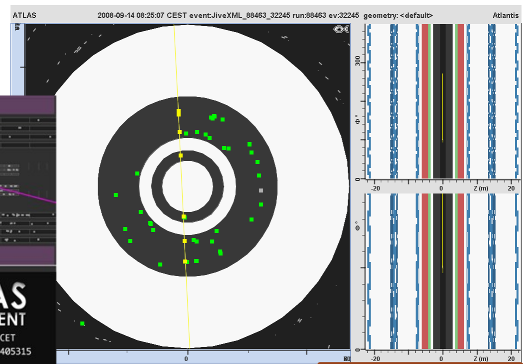
Timeline

- May 2007 – Installation in ATLAS
- Sept 2008 – First cosmic events
- Oct 2008 – LHC incident
- Nov 2009 – First beam 450 GeV
- Dec 2009 – 0.9 TeV and 2.36 TeV collisions
- March 2010 – 7 TeV Collisions
- End 2010 – Heavy Ions: great period!
- May 2011 – Luminosity 10^{33} cm^{-2} s^{-1}

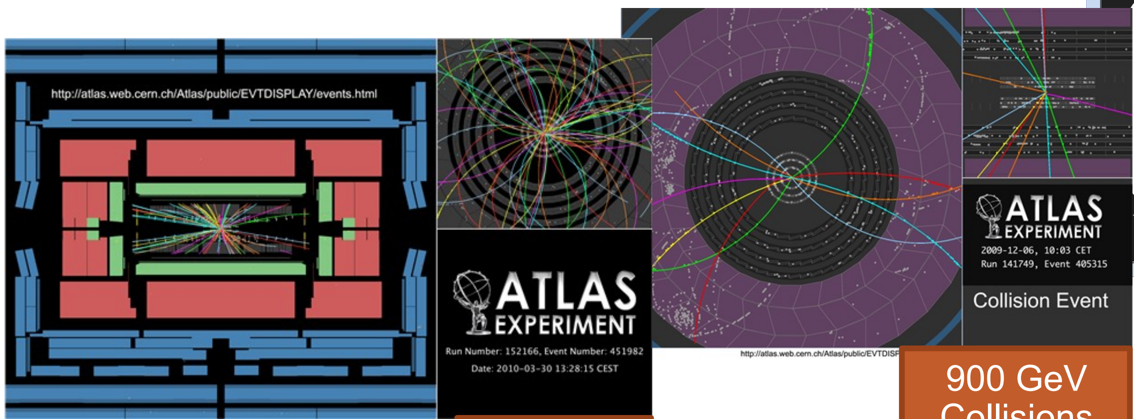
Installation



Calibration



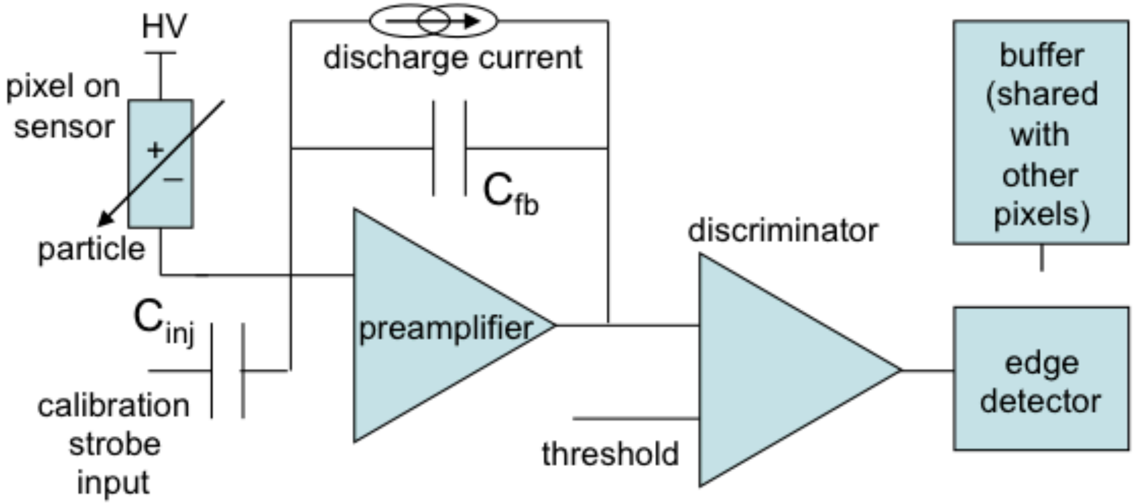
Cosmics



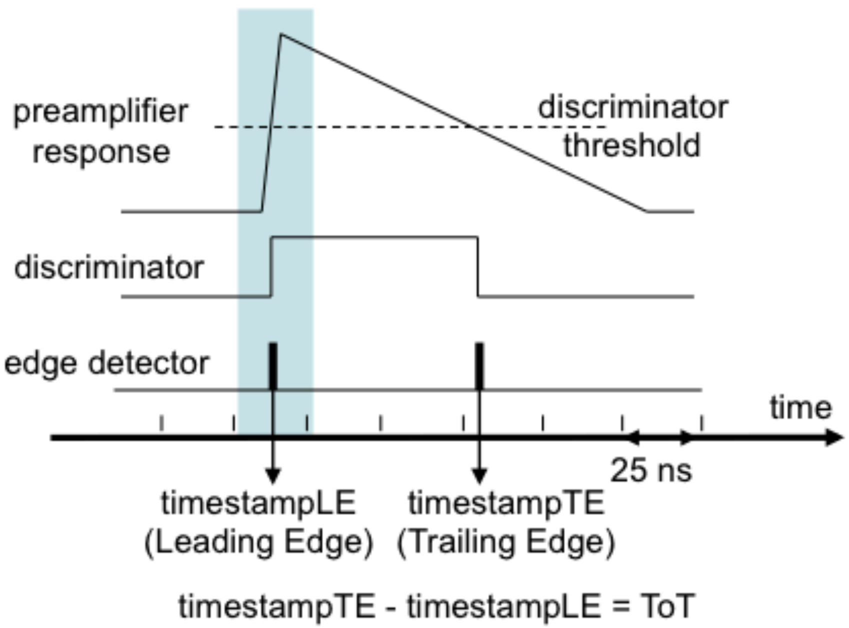
7 TeV Collisions

900 GeV Collisions

The Pixel calibration in few words



- for calibration test charge is injected through strobe input
- discharge current is adjustable and defines charge measurement precision and dynamic range
- timestamp is generated from module clock, which is sourced by LHC clock (40 MHz)



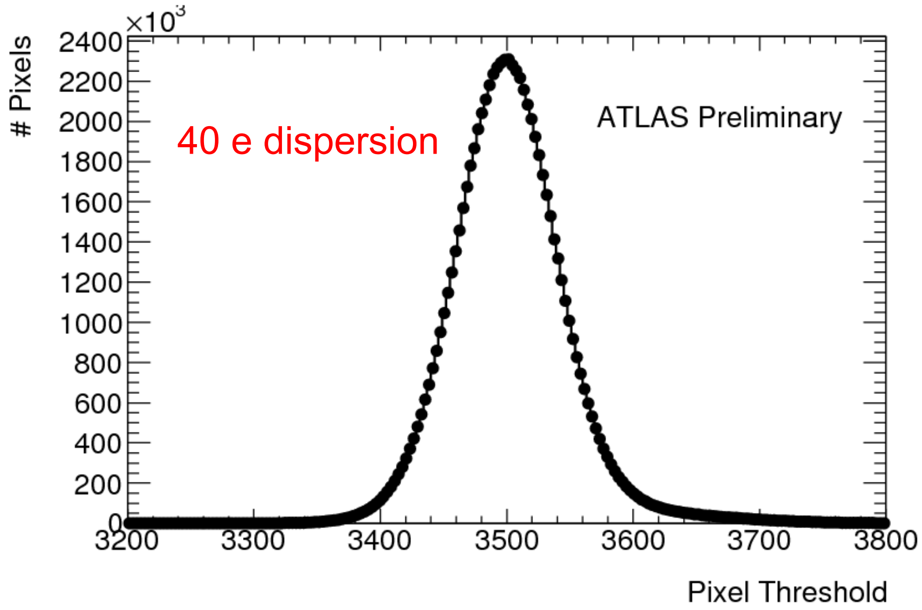
- length of discriminator pulse, measured as Time over Threshold (ToT), is proportional to deposited charge
- hit position, timestampLE, ToT stored in the buffer

- external trigger signal retrieves data with the same timestampLE from the buffer
- optionally hits with up to 16 consecutive timestamps can be retrieved

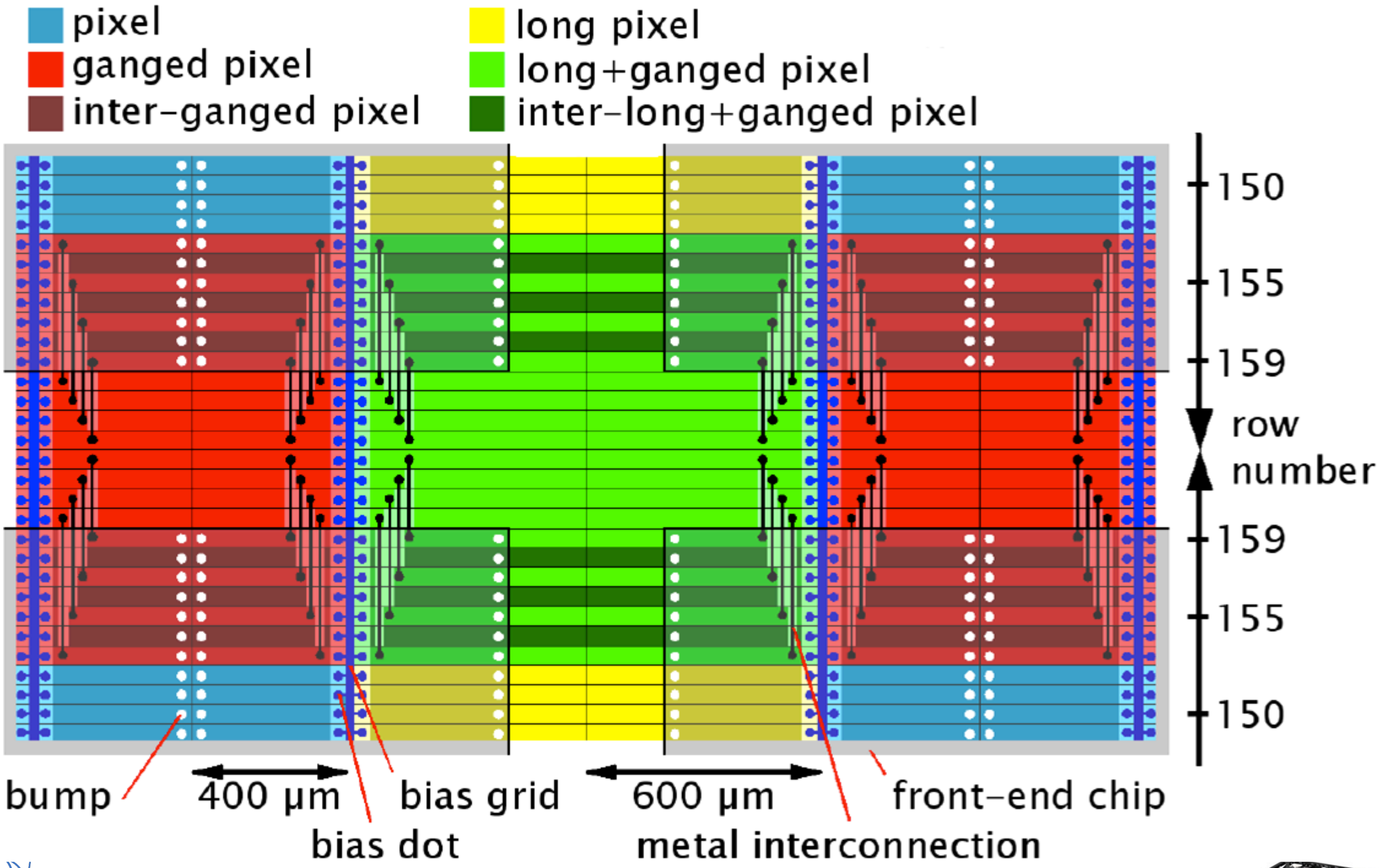
➔ multiple Bunch Crossing (BC) readout

Threshold settings

- Threshold setting: 3500 e (we will come back on that later)
- Fraction of masked pixel ~ 0.1%
- Future settings:
  - actual value very good for tracking (see later and don't miss Elsing's talk): improvements in our clustering show this value is what we need
  - First tests at 3000 e were promising for normal pixels, not satisfactory for higher capacitance ones (too many masked pixels)
    - Need of more time to exercise and tools to have "personalized settings"

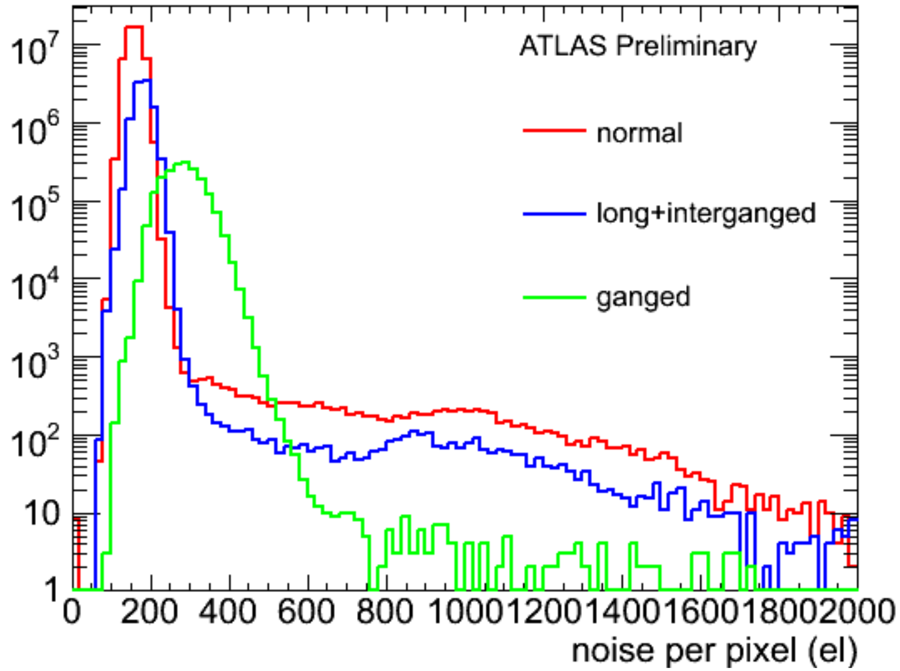


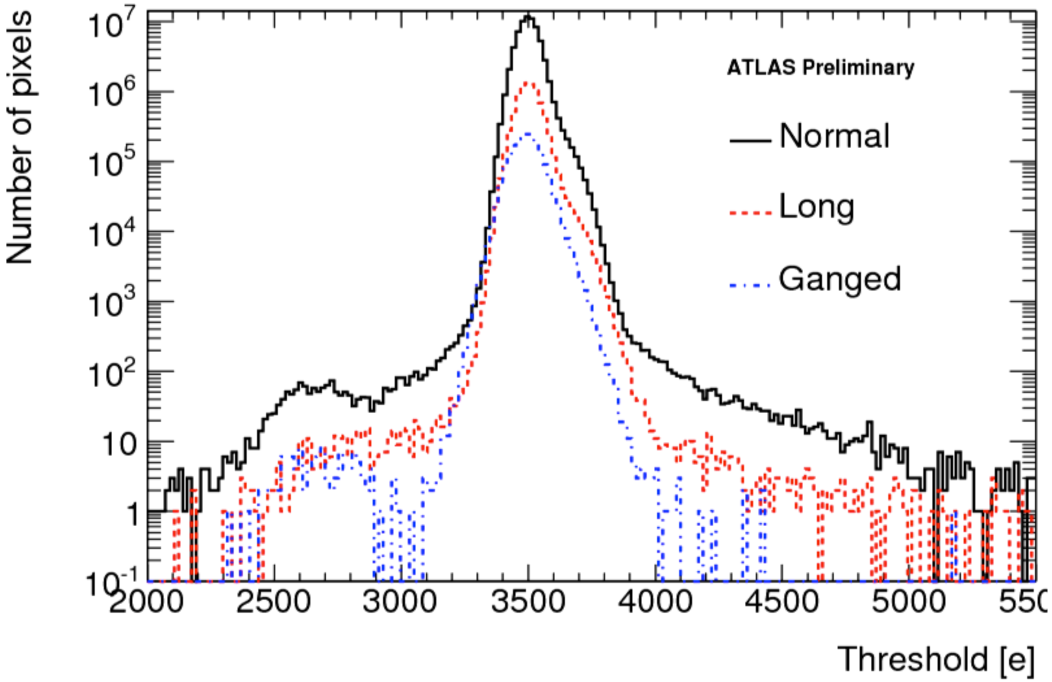
Inter-chip Region

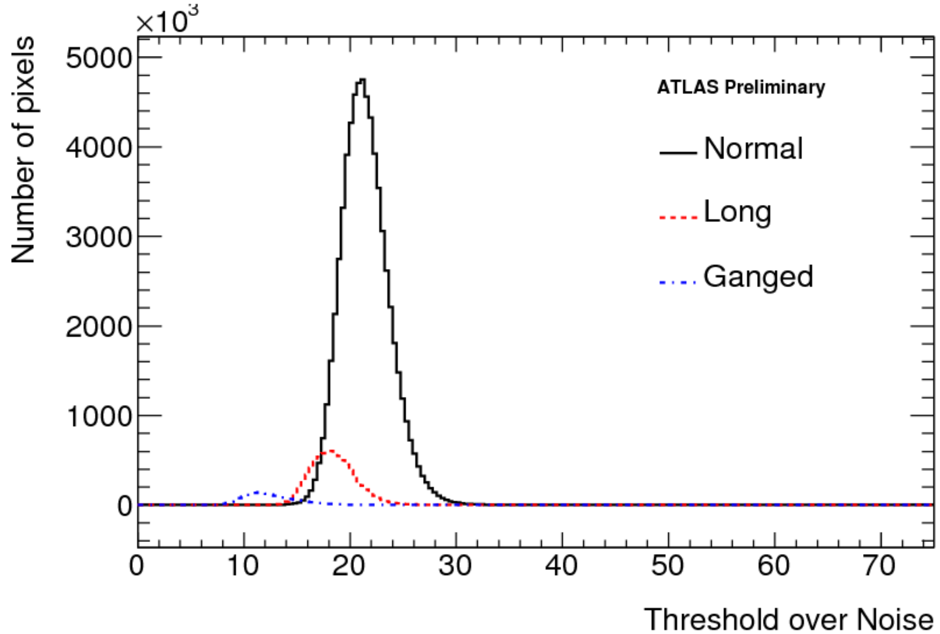


Threshold and noise aftermath

- Typical threshold dispersion after tuning: σ ~ 40 e
- Very few outliers in all pixel classes
  - To be checked whether this can be improved in the tuning algorithms
- Noise for normal pixels ~170 e, higher in ganged pixels (~300 e) due to higher load capacitance
  - Reflected in threshold over noise, but still >10 for "worst" pixel class, ~25 for normal pixels

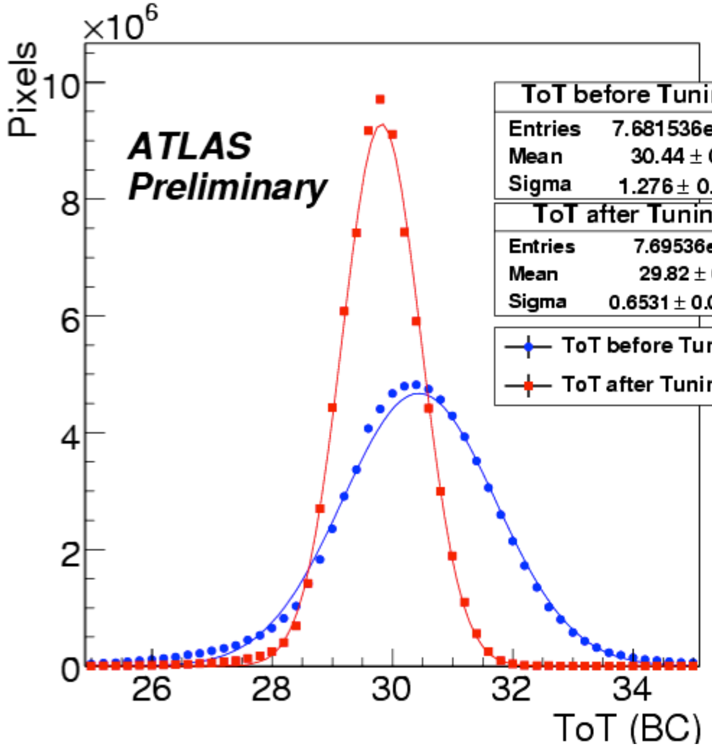


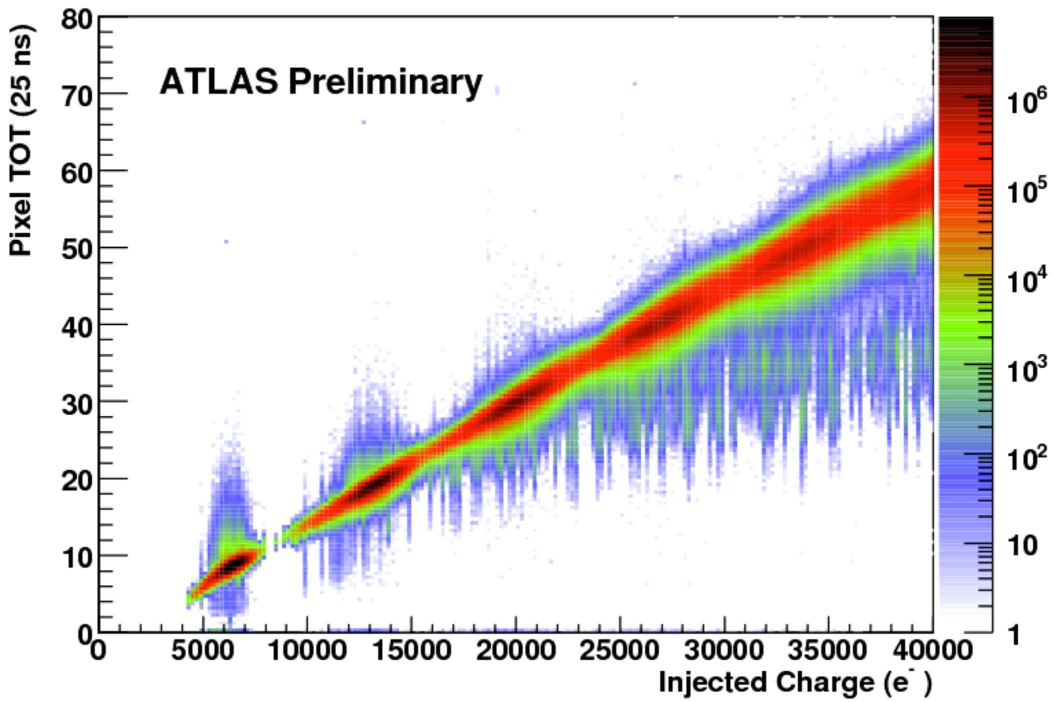




ToT Tuning and Calibration

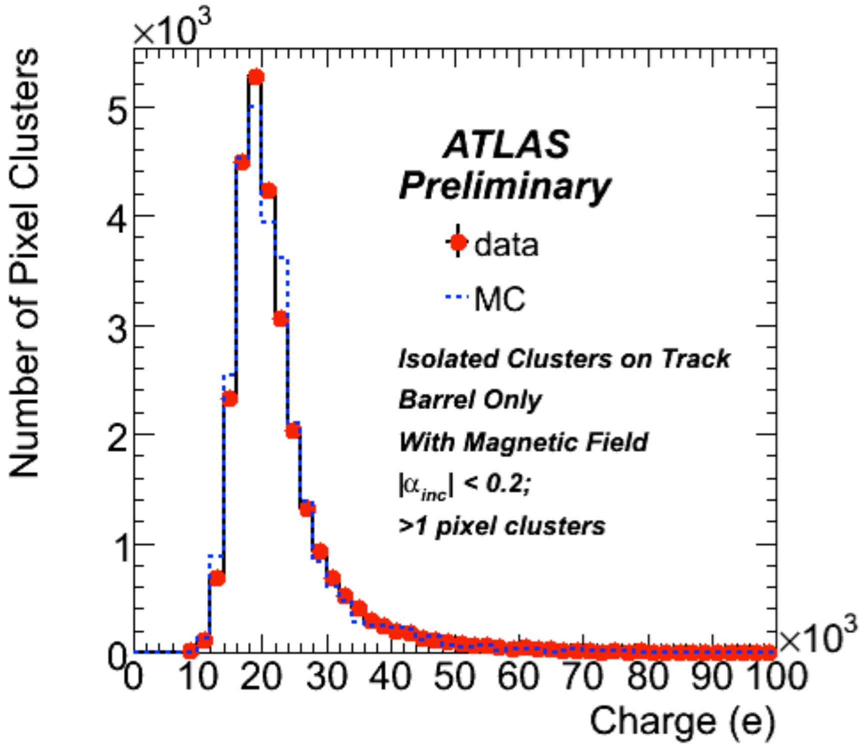
- Time-over-threshold tuned pixel by pixel to 30 BC @ 20ke
- Calibration by means of test charge injections to reconstruct amount of deposited charge offline

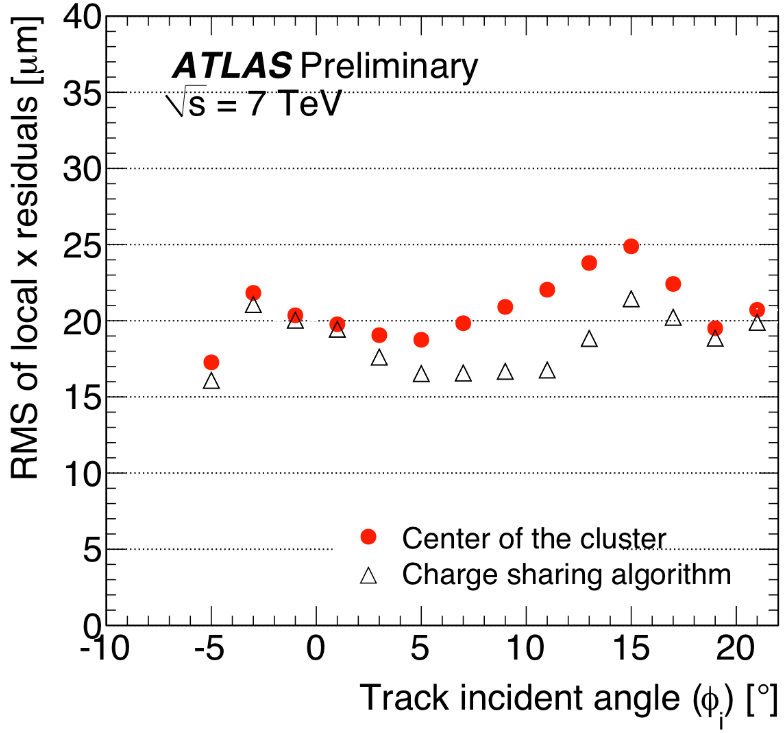




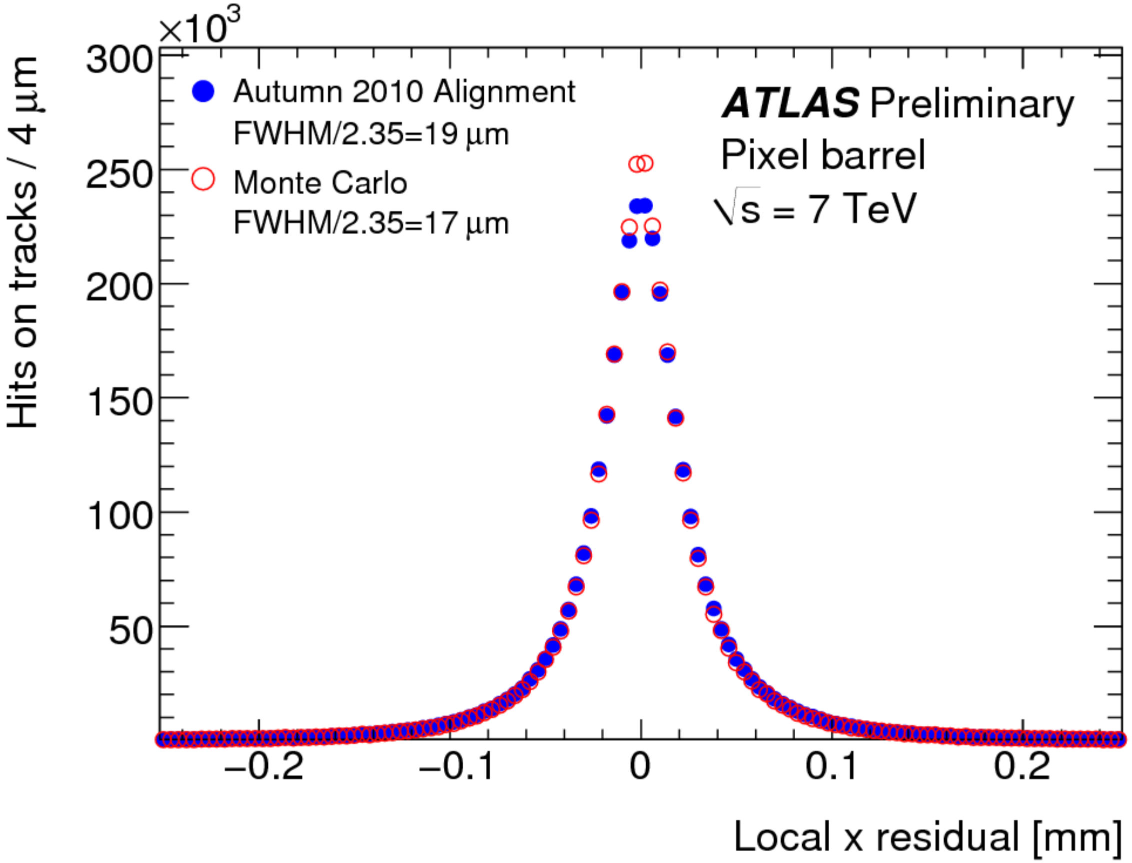
ToT for resolution enhancement

- Charge measurement with ToT in cosmic ray data taking
  - "Landau" peak at 18300 e (Simulation 19000 e): Confirms ToT Calibration
- Impact on resolution in collision data is remarkable





Spatial Resolution

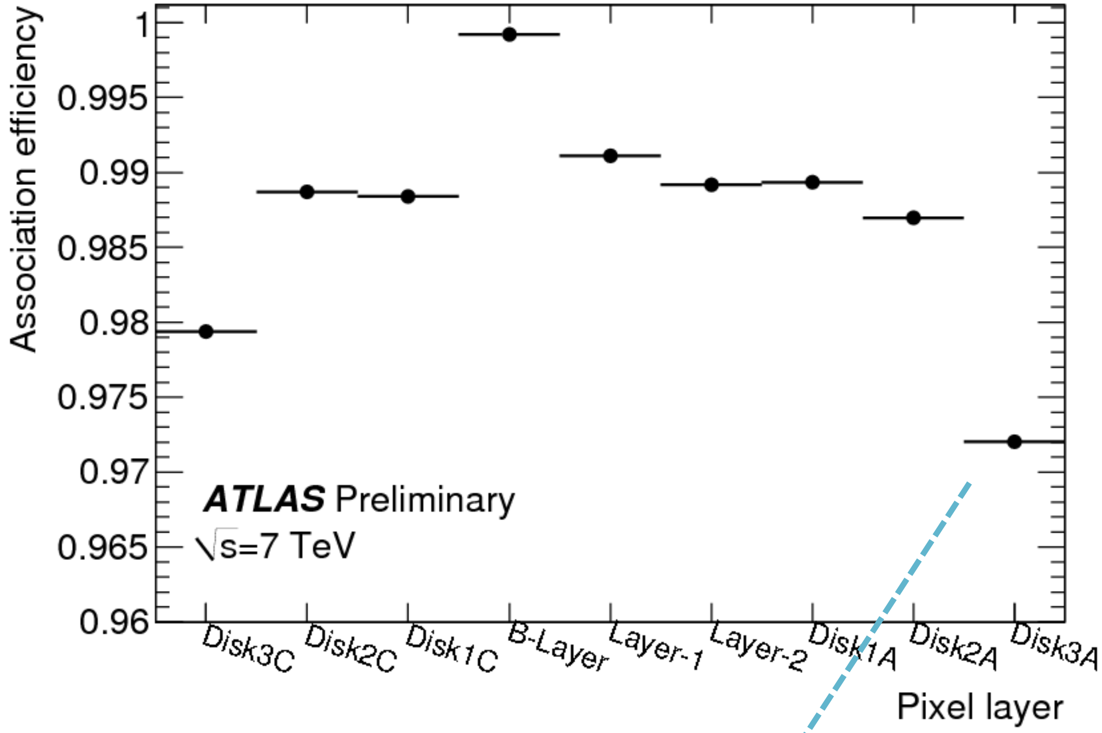


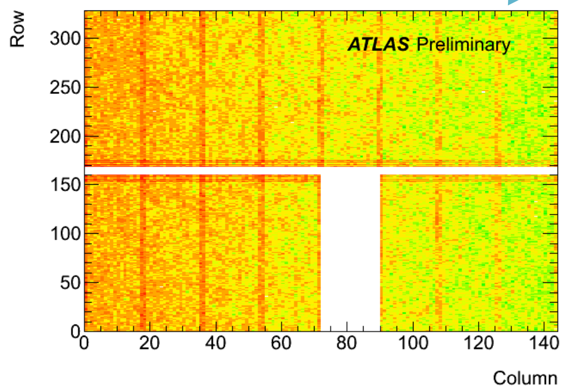
rϕ direction

- Residual distribution with newest alignment
- Width close to MC width for a perfectly aligned detector
- Resolution on beam direction coordinate of 115 μm

Hit-to-Track Association Efficiency

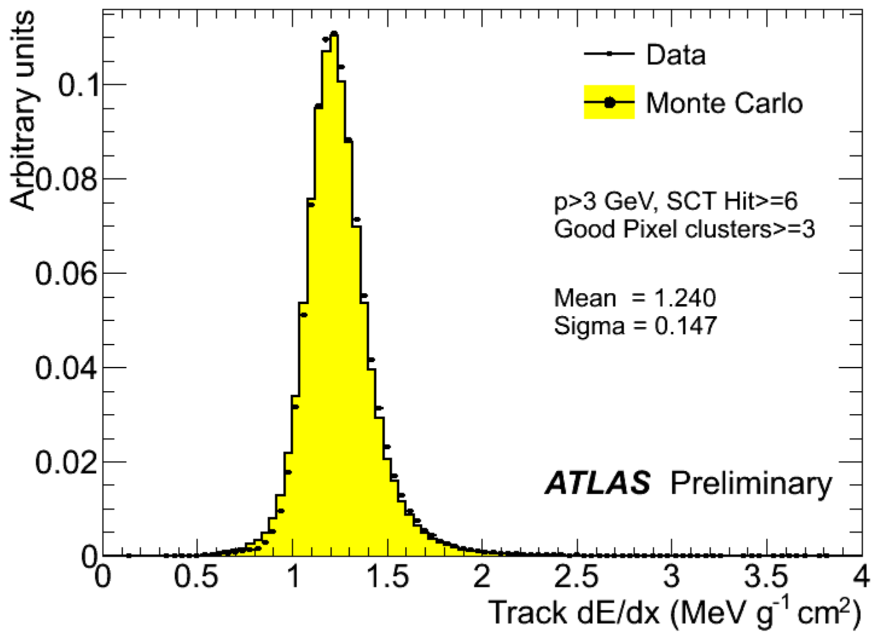
- Hit-to-track association efficiency for the different parts of the detector
- Disabled modules have been excluded, dead regions not
- (Full efficiency of the B-layer due to track selection)
- Efficiency ~99% for nearly all parts
  - Slightly lower efficiency in the outermost discs due to individual modules

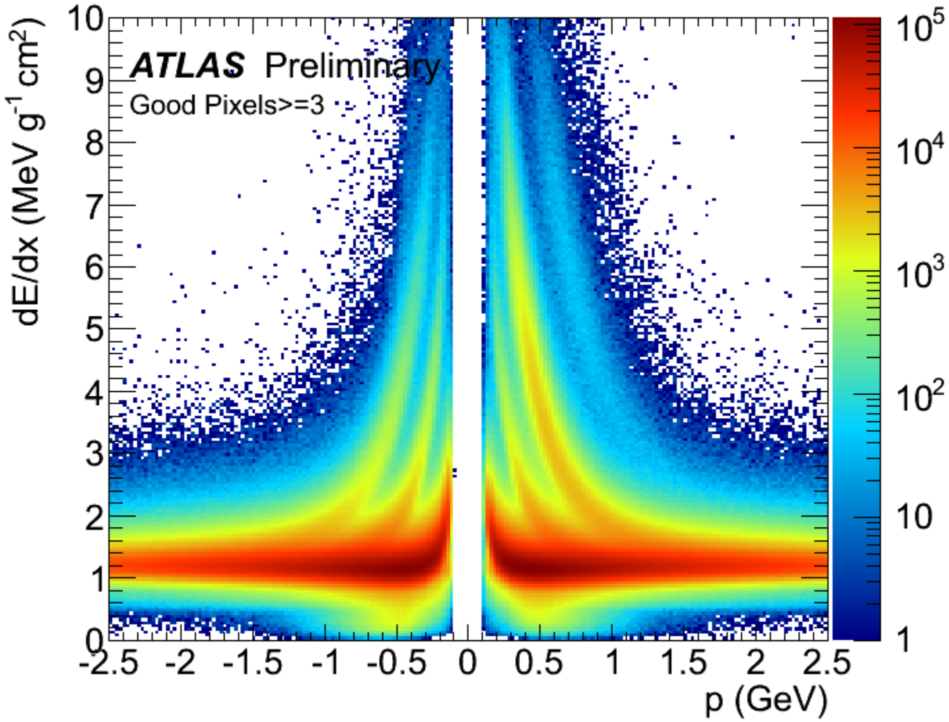




ToT to measure dE/dx

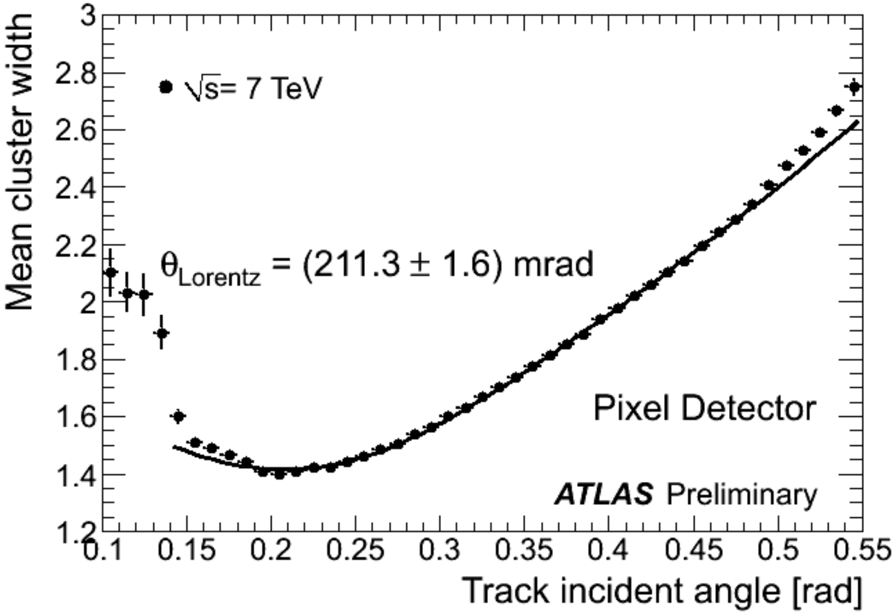
- Track dE/dx determined from ToT (truncated mean of all clusters)
  - Proper selection at the cluster level to ensure total charge is collected
- Track dE/dx resolution: 12%

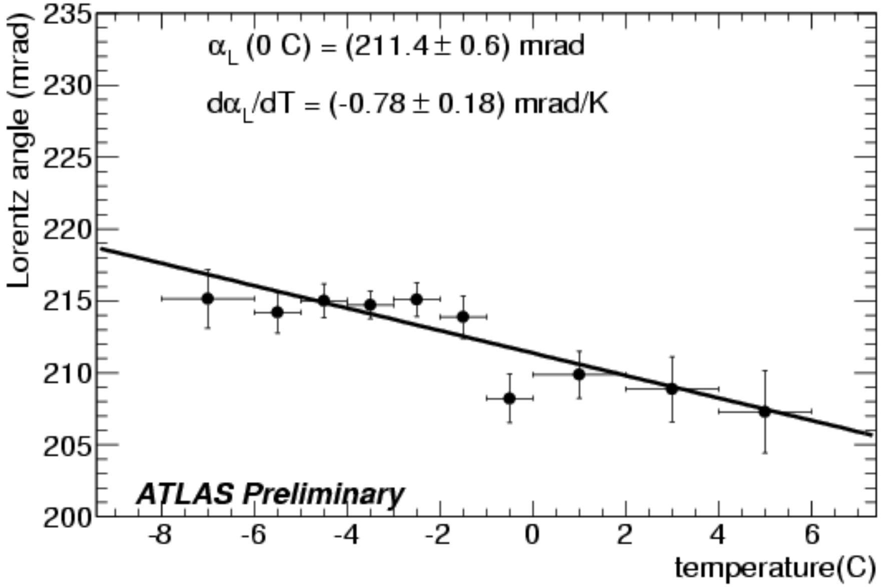




Lorentz Angle Measurement

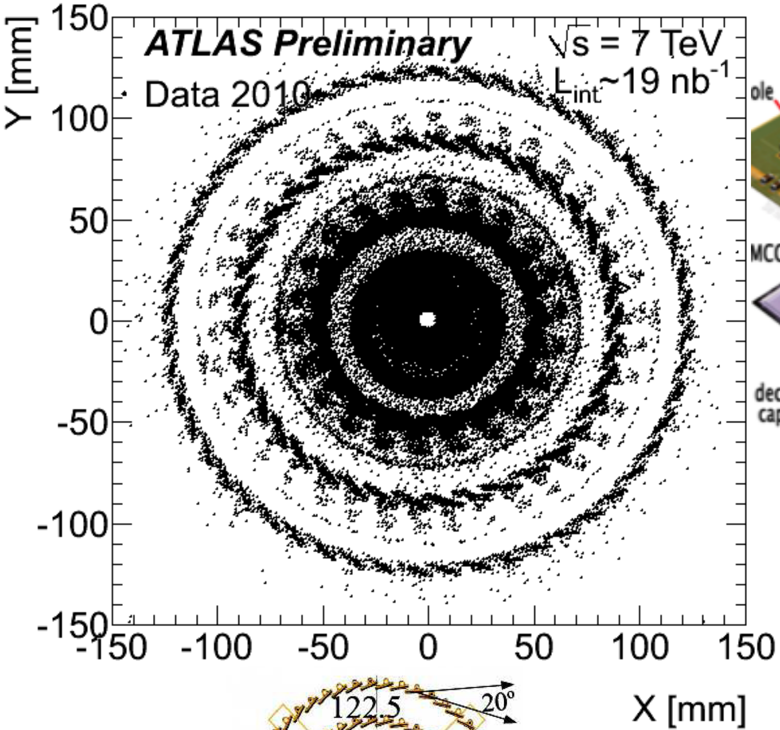
- Cluster size vs. track angle with and without magnetic field → Measurement of the Lorentz angle
- Measured value of ~ 211 mrad, close to expected value (225 mrad)
- Theoretically-expected dependence on mobility can be nicely seen when looking at modules of different temperature
  - Measured: (-0.78 ± 0.18) mrad/K, expected: -0.74 mrad/K

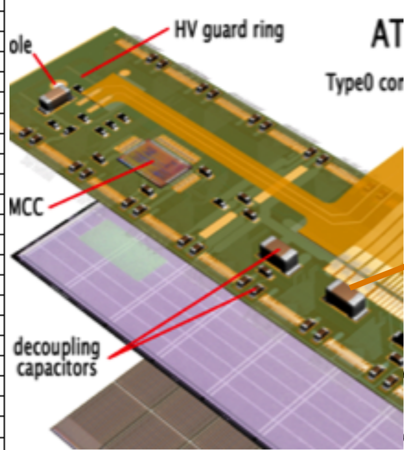


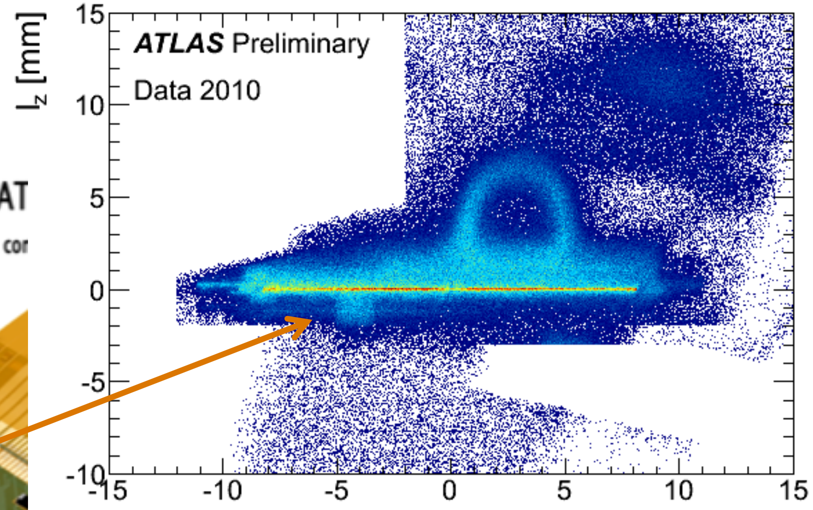


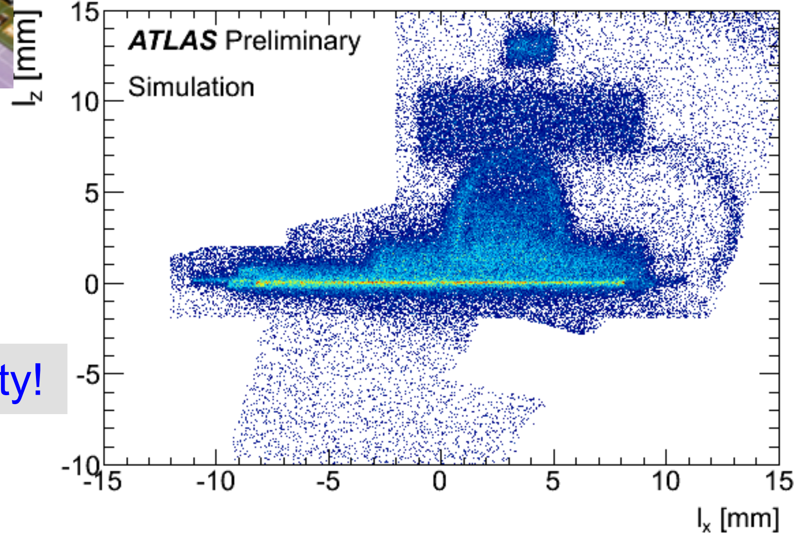
Having fun with tracks

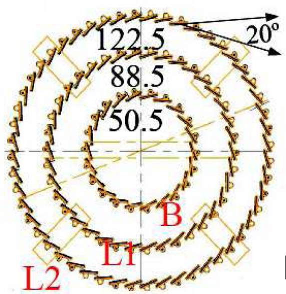
- Secondary vertices map for hadronic interactions
  - Imaging of the detector









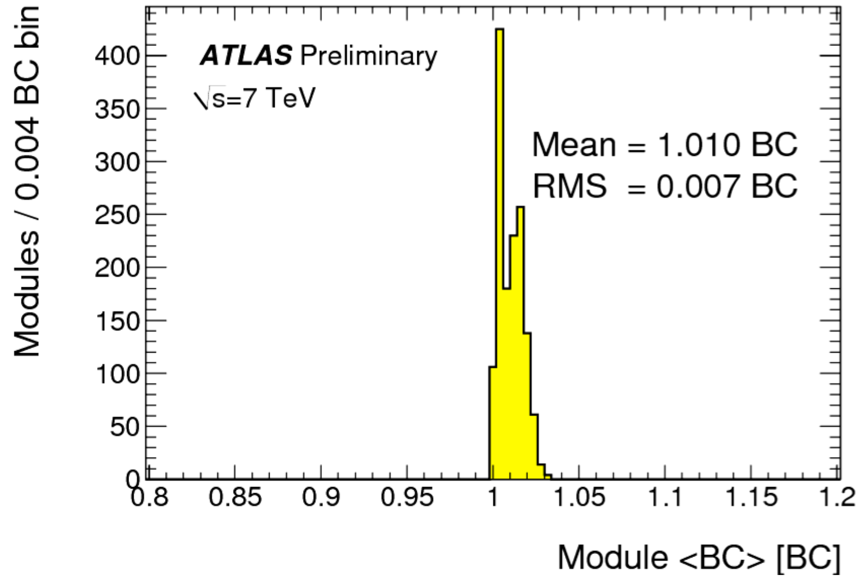


Detector drawing

How data describes the reality!

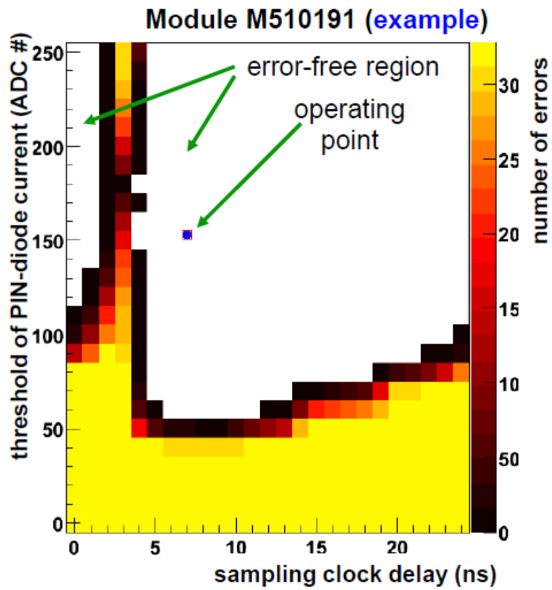
Timing: Homogeneity and Stability

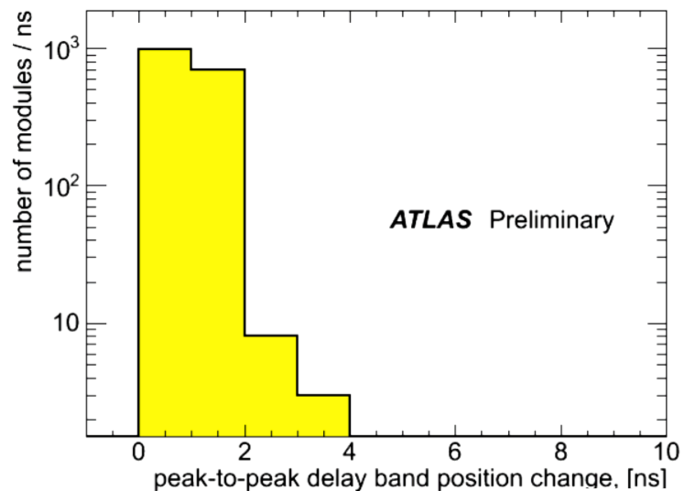
- Several steps for adjustment of timing:
  - Trigger delays: from cosmic ray data
  - Cable lengths: values measured during installation
  - Final adjustment: timing scans with collisions
- After all adjustments: module-to-module dispersion: 0.007 BC (corresponds to 0.17 ns)
  - Measured from average detection time for large charges



Stability can be measured from stability of delay edge in Rx-scan

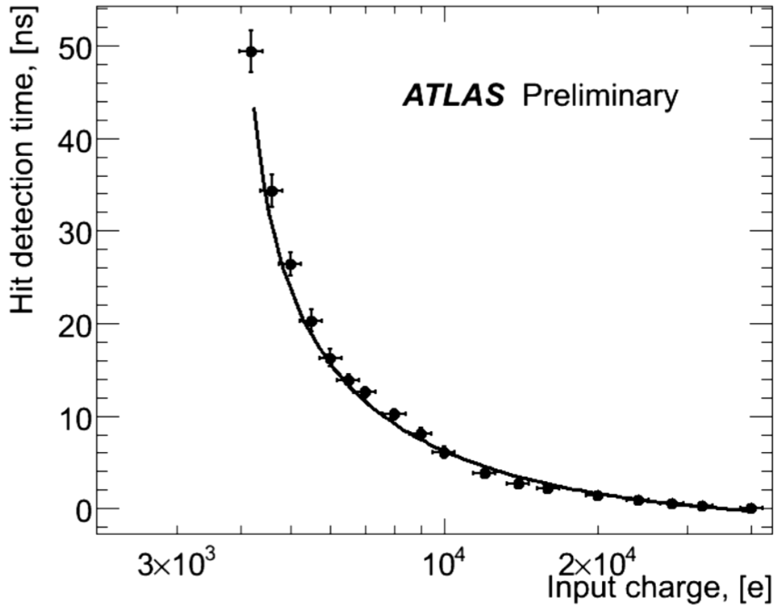
For most modules maximum delay band position changes ≤ 2 ns

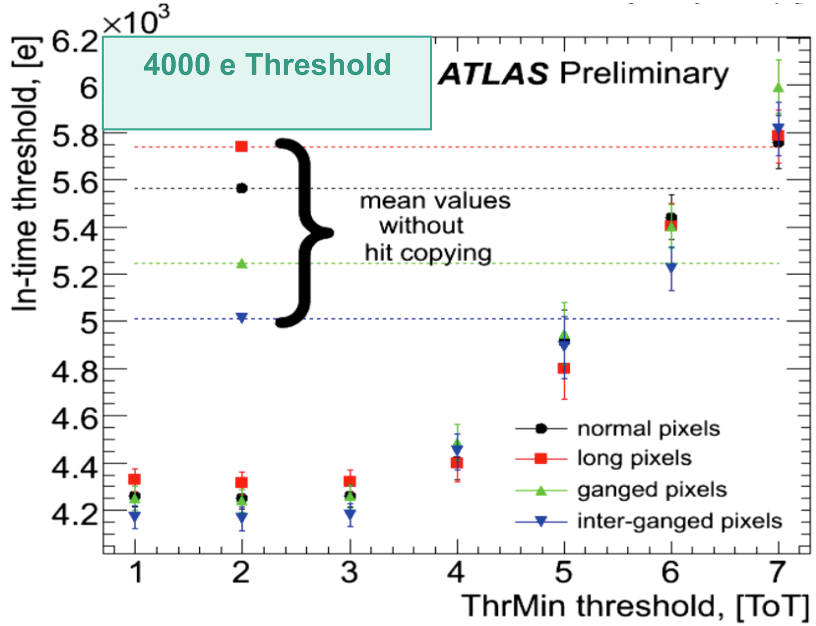




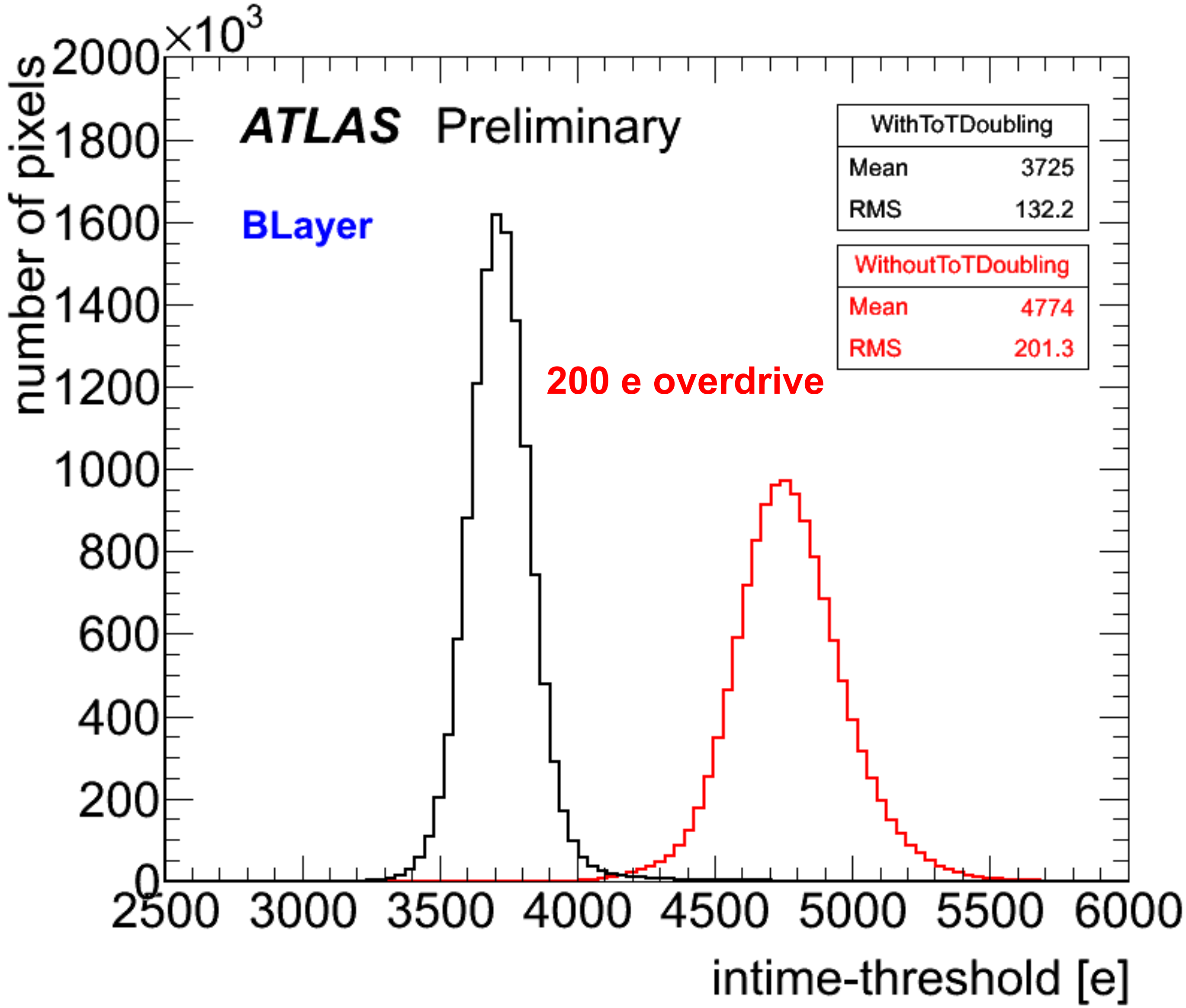
Time-walk and In-time Threshold

- Hits with lower charge suffer time-walk
- This leads to an "In-time threshold" higher than the discriminator threshold for a hit detection "in time"
  - Higher load capacitance has been compensated for in ganged and inter-ganged pixels
- At 3500 e threshold:
  - 4800 e for normal pixels, BUT…
- Time-walk can be compensated for by on-chip hit doubling (using ToT information)
  - Using the hit doubling the in-time threshold is 3700 e
  - Overdrive of only 200 e
  - Data volume increases (Measured test-beam: 10%)



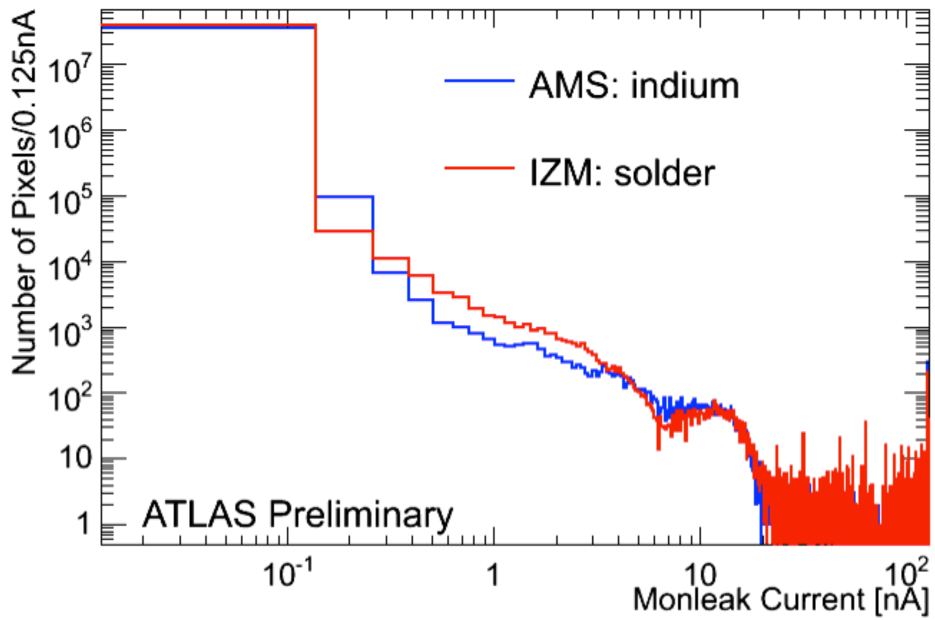


In-time threshold



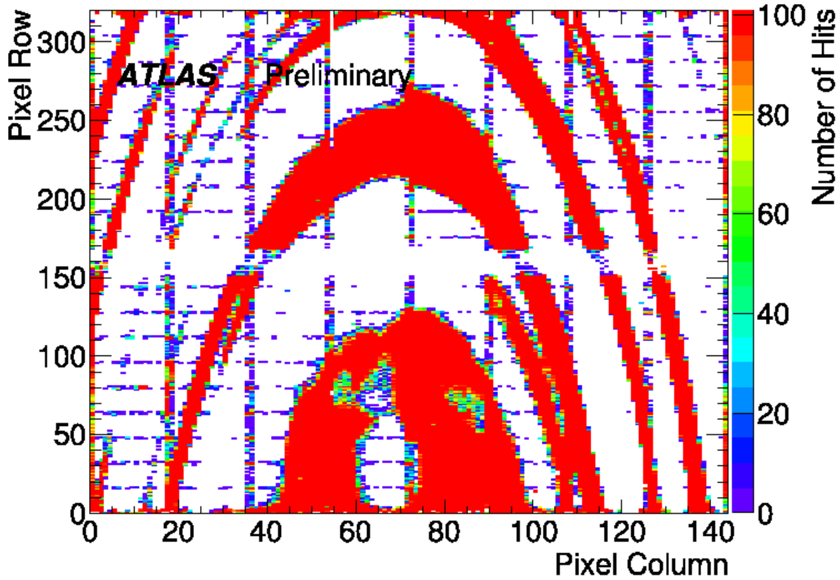
Single-Pixel Leakage Current

- FE-Chip has the possibility to measure leakage current pixel by pixel ("Monleak")
- Currently majority of pixels at 0
  - Measurement range and resolution optimised for after irradiation: LSB ~0.125 nA
- Single-pixel leakage current will be monitored with time
- In addition: we have equipping our DCS hardware with the possibility to measure the single-module leakage current with 10 nA precision
  - First channels already equipped, rest following during MD/TS phases

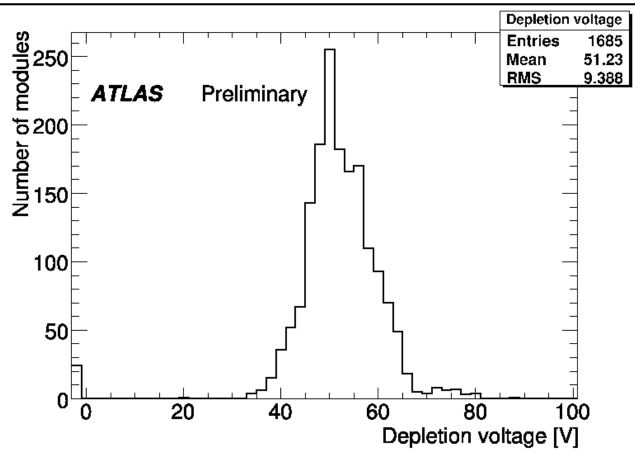


Depletion Voltage

- Goal: measure voltage needed for full depletion V_{FD} during *calibration* time
- Idea: use cross-talk, i.e. inject charge into one pixel, read out neighbours
- Before type inversion:
  - When not fully depleted: (high-ohmic) short between pixels
  - When fully depleted: pixels are isolated from each other
  - Choose injected charge such that cross-talk hits are seen only for $V_{bias} < V_{pinch\text{-}off}$ ($\approx V_{FD}$)



Example: single module close to depletion voltage
White: (already depleted) pixels with no crosstalk hits
Measurement shows structure of sensor production



Measured depletion voltage for all modules: the detector is operated at 150 V

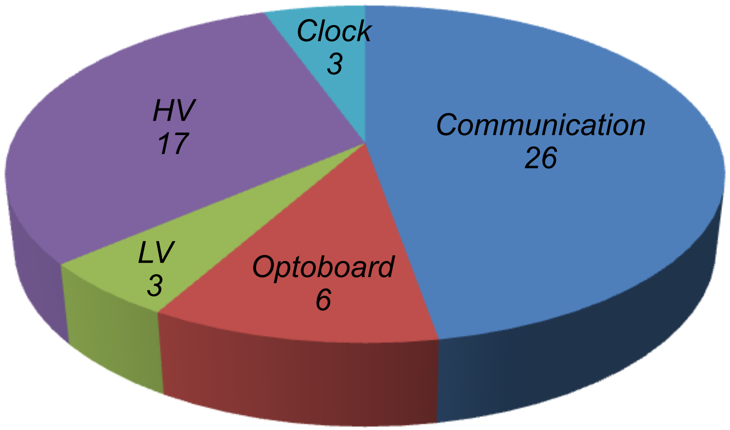
Radiation damage effects

- We are still slightly below the sensitivity of the single pixel leakage current measurement
- We start to see the increase of leakage current at the module level
  - HV power supply sensitivity: 80 nA (6 or 7 modules on 1 HV ch)
  - Specialized current monitoring boards with sensitivity of 10 nA
- Scanning the HV we do see the expected decrease of the depletion voltage
- The depletion depth is still equal to sensor thickness
- We have prepared a refined simulation including E field effects, Fano potential, trapping, depletion depth etc.
- Soon we will publish few notes in support of a public one

Pixel Detector Status

- 96.8% of the detector active in data taking
  - 55 Modules disabled (3.2%)
    (6 modules due to a single opto-board failure)
  - 47 FE chips disabled (0.16%)
  - In particular failures are linked to thermal cycles
    → an attempt has been made to reduce the problem by smaller temperature variations with first modest results, more refinements will be tried
  - The percentage of disabled modules grew from 2.1% to 3.2% in 3 years of operations: IBL help us!

Disabled modules by failure type:

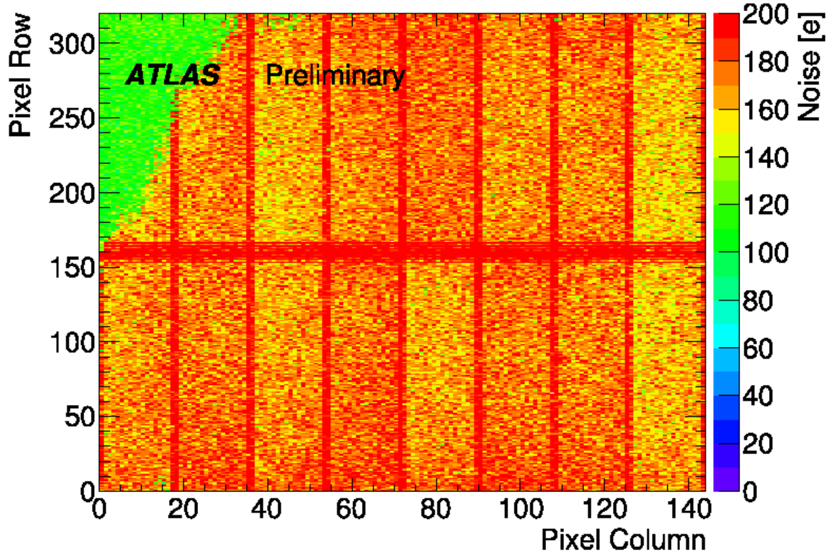


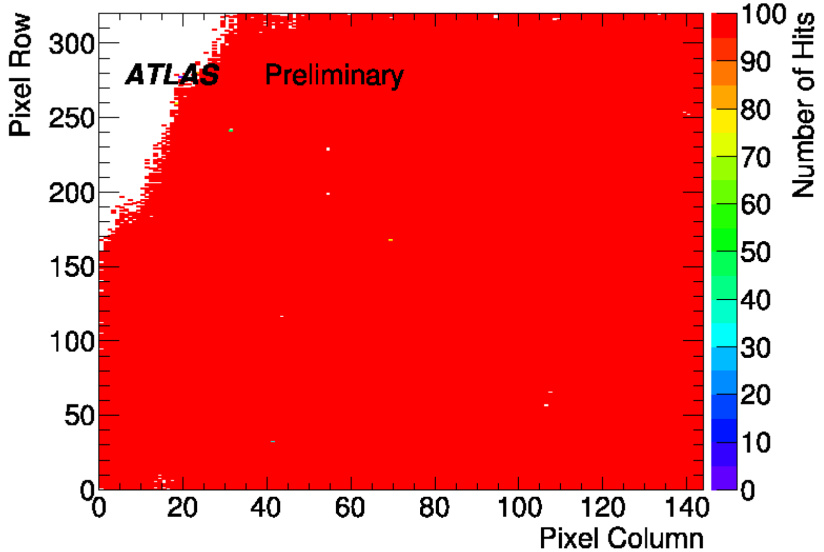
Inactive fraction per layer:

B-layer	3.1 %
Layer 1	1.4 %
Layer 2	4.6 %
Endcap A	2.8 %
Endcap C	2.8 %

Bump Connectivity

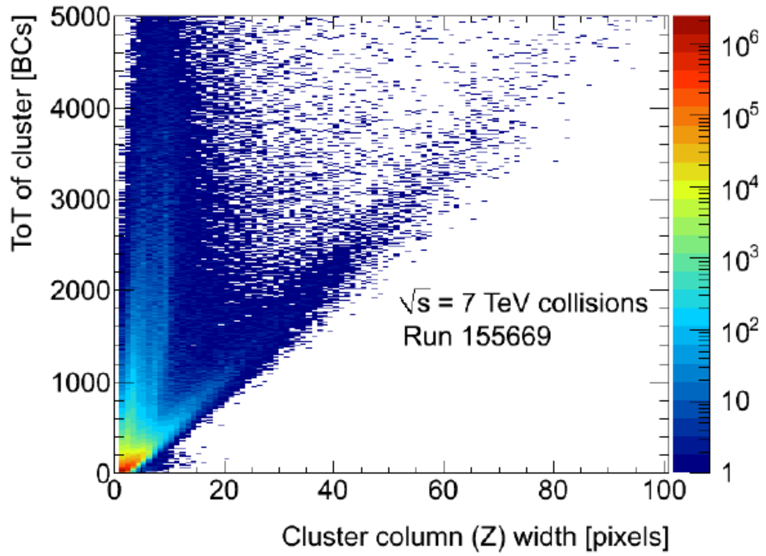
- Test of bump connectivity: combination of several calibration measurements
- Disconnected bumps:
  - Low noise
  - No cross-talk to neighbor
- Merged candidates
  - Digitally working, analogue dead pixels
- Example: particularly bad module: noise (top) and cross-talk hits (bottom)
  - Overall fraction: 0.1%
- Comparison with beam data ongoing

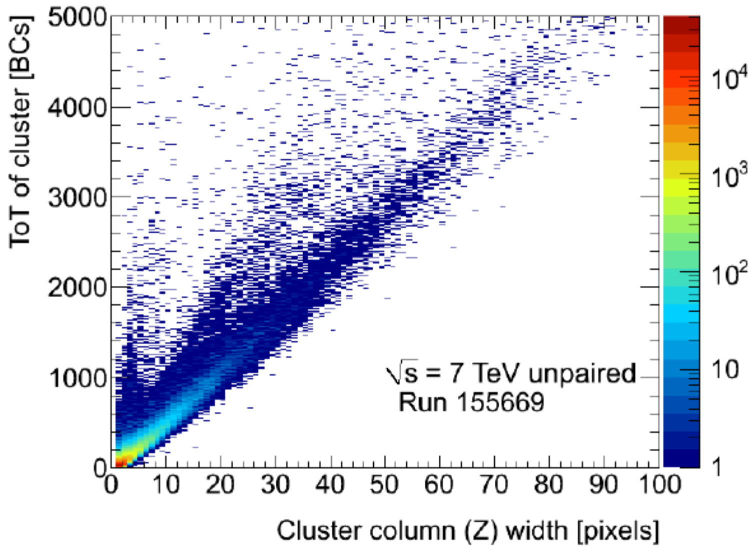




Background effects

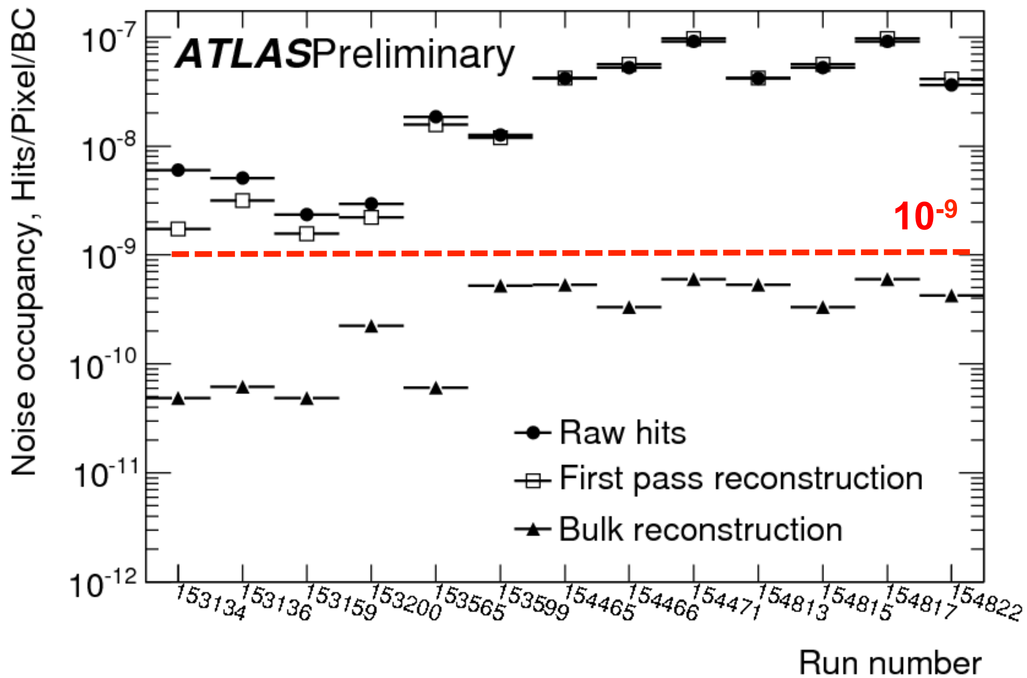
- Last year we suffered from background, unexpectedly high because of vacuum issues in the warm regions around IP1
- We studied carefully the variation with β* and with vacuum conditions: useful cuts for eliminating background offline
- We managed with a new firmware of the off-detector electronics to solve the problems, so far
- We do not have buffer problems to date and we are still using half speed for emptying the FE buffers
- See Barbero's talk for future





Noise Masks and Module Occupancy

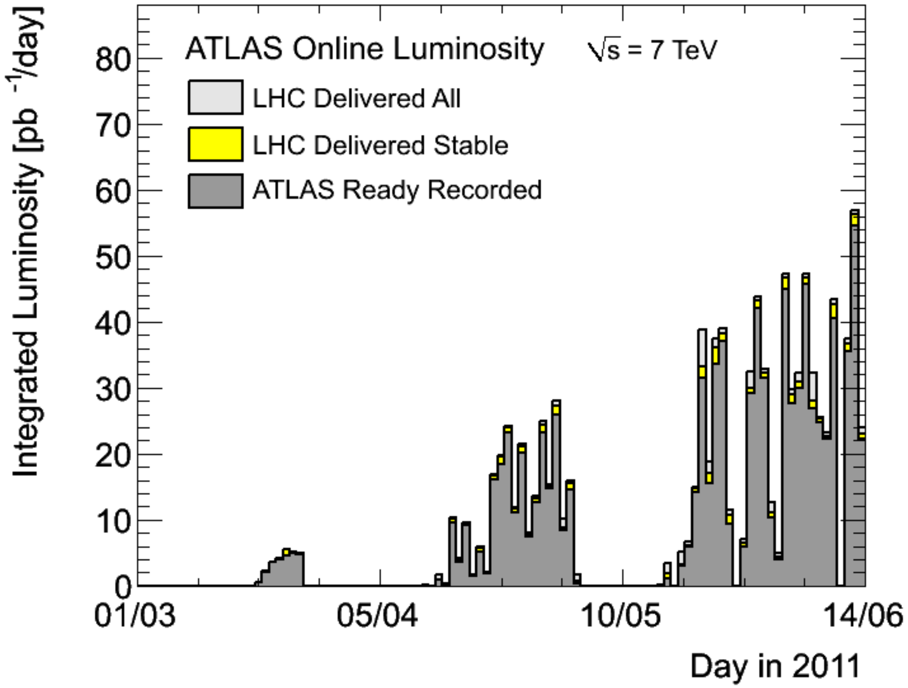
- Pixels with hit rate higher than 10^{-5} (now 10^{-8}) in dedicated noise runs are masked online (0.1% @ 3500 e)
- A few additional noisy pixels (1-2 x 10^{-5}) are masked offline on run-by-run basis
- After offline masking noise rate <10^{-9} it corresponds to less than 0.1 noise hits per event in 80 million channels (without offline mask: ~1 hit/event in the full detector)

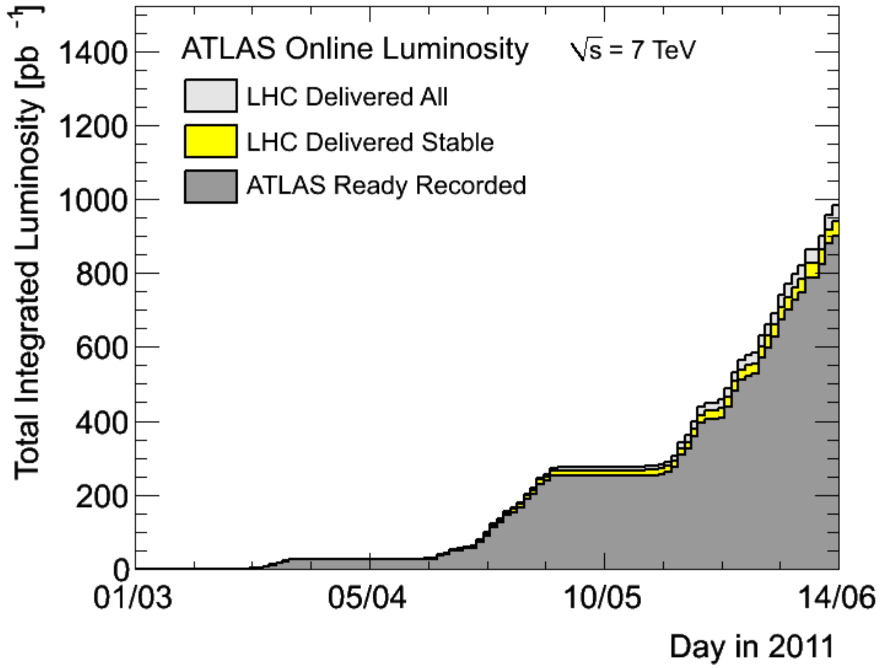


Typical module occupancies (readout speed):
At luminosities ~10^{33} cm^{-2} s^{-1}

B-layer (160 MHz)	1.5 x 10^{-4}	hits/pixel/bc
Layer 1 (80 MHz)	0.7 x 10^{-4}	
Disks (80 MHz)	0.55 x 10^{-4}	
Layer 2 (40 MHz)	0.45 x 10^{-4}	

Data taking efficiency





Pixel data taking efficiency
99.5%
Mainly dominated by switch-on time being now reduced

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.4	100	87.5	92.4	94.5	100	100	99.0	99.9	99.8	96.8	95.1

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and May 3rd (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

Conclusions

- We spent time calibrating the detector and it pays off
  - Threshold Dispersion ~ 40 e, average noise ~ 170 e
  - Charge measurement resolution < 1000 e
  - Online noise occupancy $O(10^{-8})$
- We are enjoying taking data
  - Offline performance is impressive
- What makes me unhappy
  - The increase in number of non-operational modules and the cooling cycles
  - The off-detector transmitters (didn't mention, see next talk)
- What makes me happy
  - 3700 e average in-time threshold
  - A wonderful data taking efficiency > 99%
- Ready for the future
  - Radiation damage signs are there, a lot of activity for future
    - No boring years to come and waiting for IBL to restore performance