THE UPGRADED PIXEL DETECTOR OF THE ATLAS EXPERIMENT FOR RUN-2 AT THE LHC

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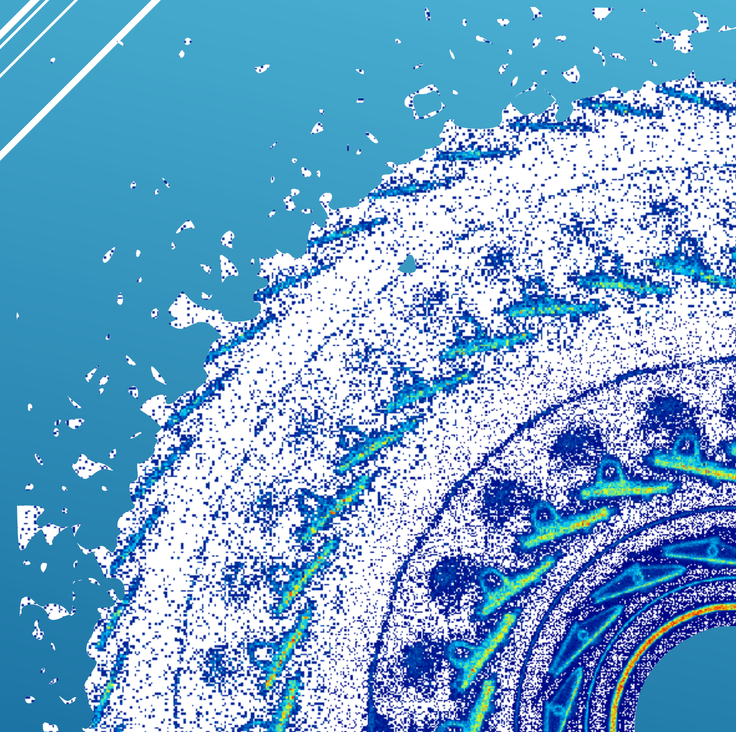
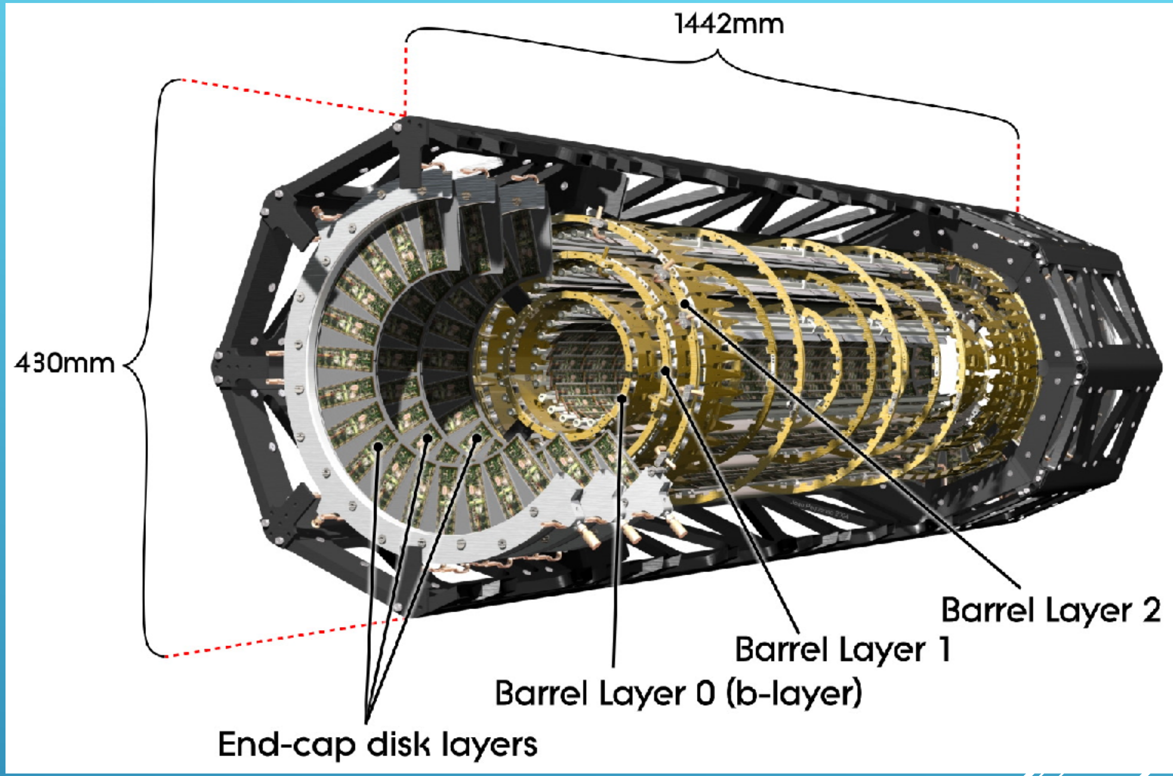
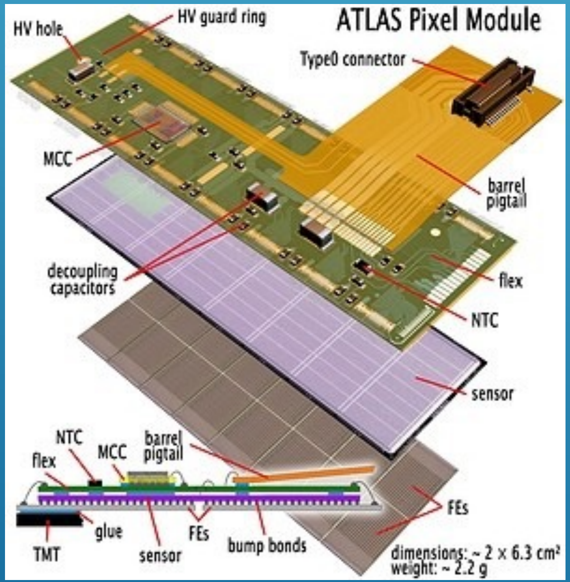
on behalf of the ATLAS Collaboration



- Innermost part of ATLAS Inner Detector
- 3 cylindrical layers, 5.05-12.25cm from beamline
- 3 disks per side, 49.5-65cm from IP
- 1744 identical hybrid modules
  - n-in-n planar sensors, 47232 $50\times400\mu m^2$ pixels
  - 16 FE-I3 chips/sensor, each reading 18×160 pixels
  - 40-160Mbps transmission lines to back-end

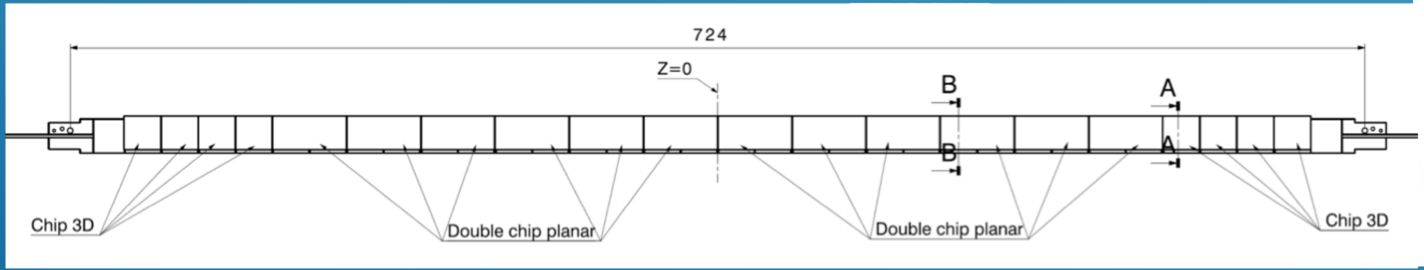


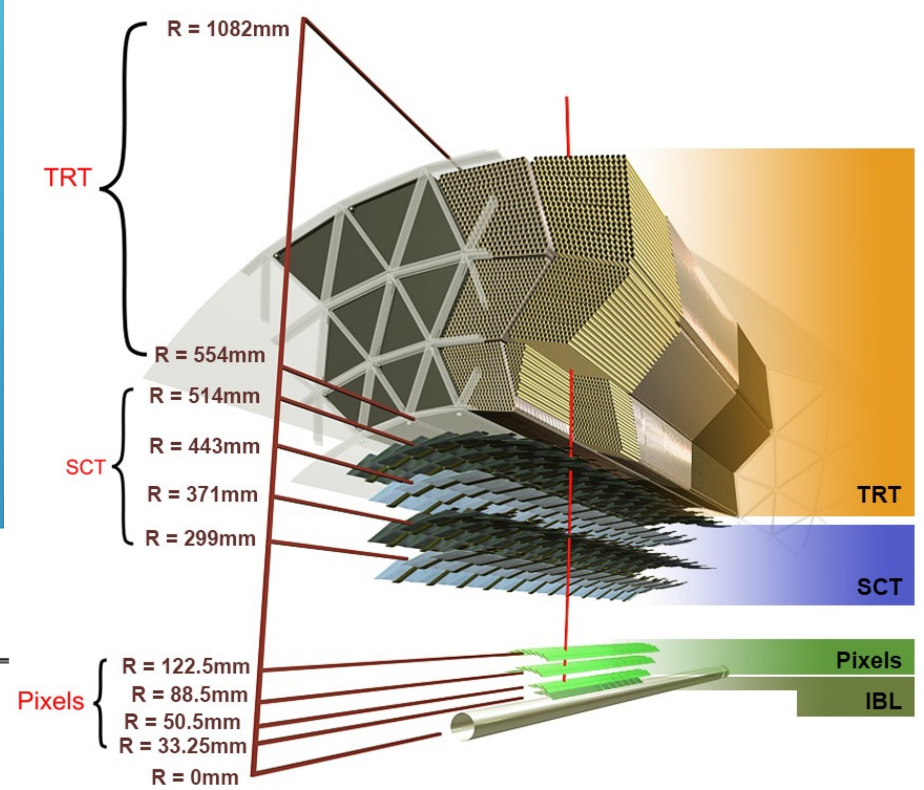


- Data taking with efficiency of 97.5% to 95% across Run-1
- 88 disabled modules at the end of the run
- Detector refurbishment (new services) at the end of Run-1
  - 55 recovered modules, doubled Layer-1 fibres (bandwidth to 160Mbps)

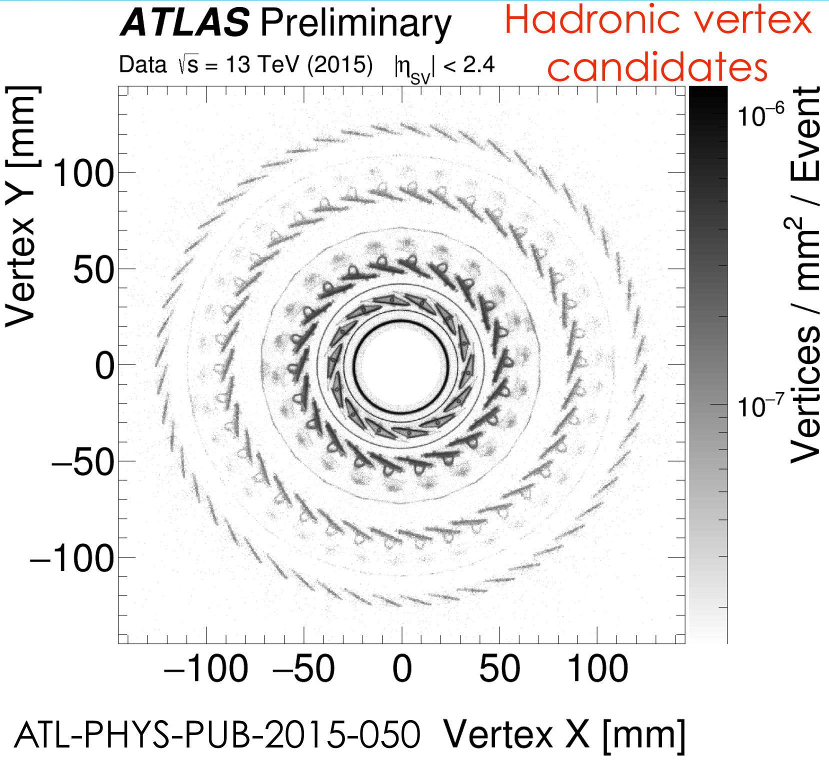
LAYOUT: RUN-1 PIXEL

- Motivated as B-Layer back-up against failures due to radiation and readout inefficiencies
- Directly clamped to new narrower beam-pipe at 3.325cm from beamline
- Additional material compensated by enhanced tracking performance
- Major technological challenge
  - insertion in pixel package (2mm mechanical clearance)
  - higher particle flux (i.e. occupancy, radiation) than B-Layer
- New FE-I4 readout chip, mixed sensor technology
  - 160Mbps transmission to back-end
  - fitting common sensor layout (80×336 50×250μm^2 pixel matrix)
  - 200μm-thick n-in-n double chip planar modules
  - 230μm-thick n-in-p 3D single chip modules

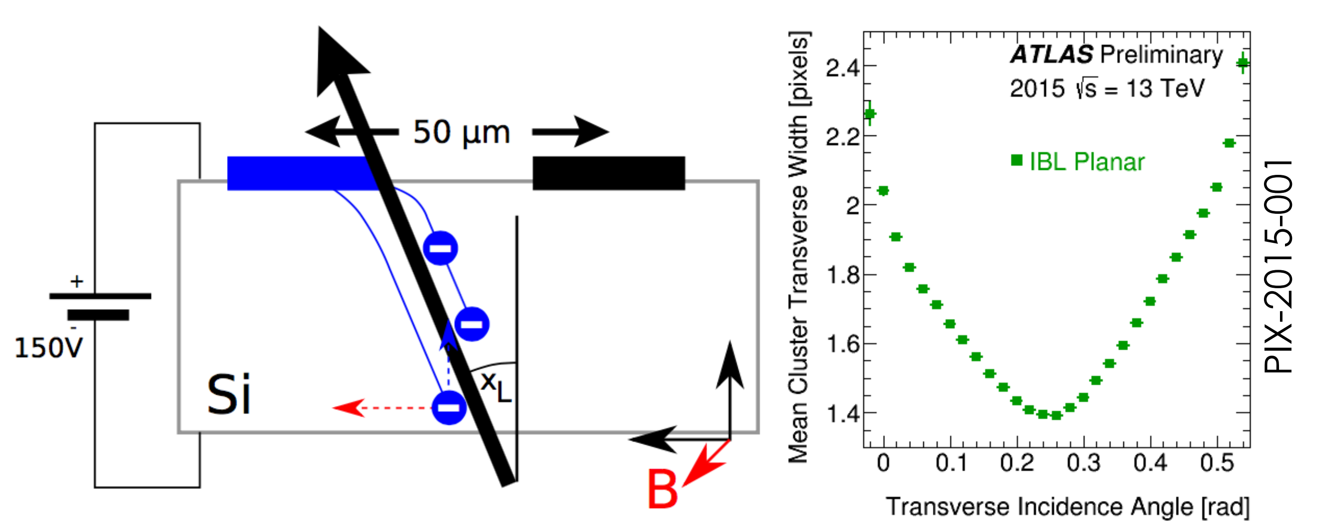




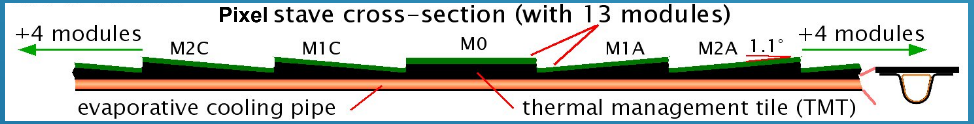
LAYOUT: INSERTABLE B-LAYER (IBL)



- Turbine layout for hermetic track coverage
  - Stave tilt angles chosen to compensate for Lorentz force
  - Minimise charge sharing between pixels

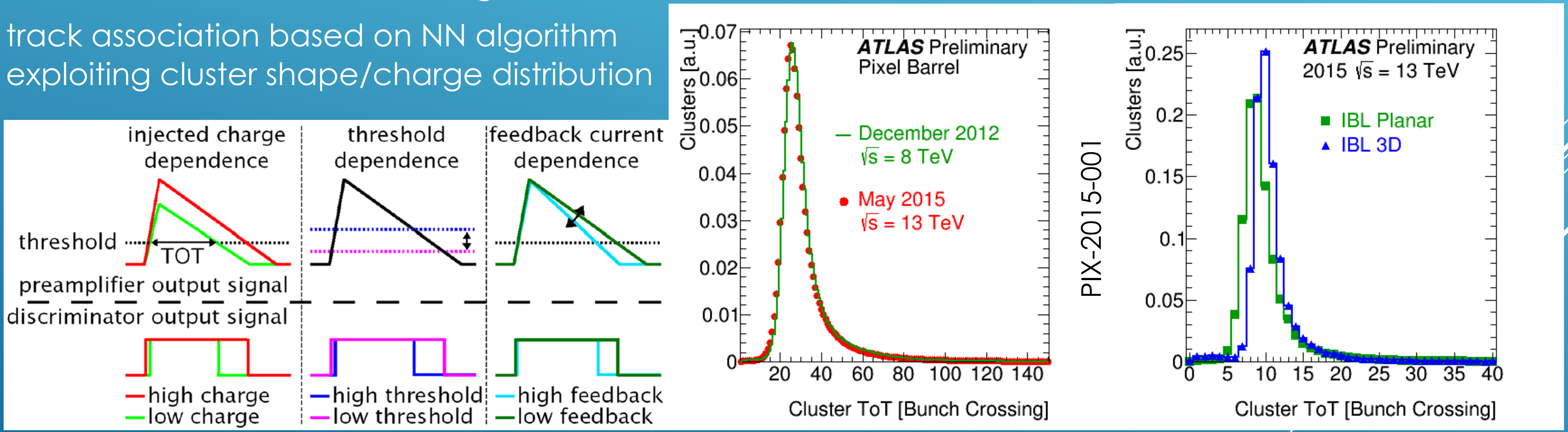


- Module shingling in pixel detector not achievable in IBL due to very limited clearance
  - Longitudinal hermeticity addressed by slim edge sensor design



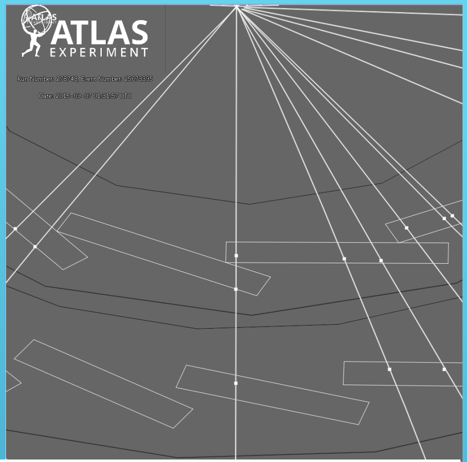
LAYOUT ZOOM: PIXEL VS IBL

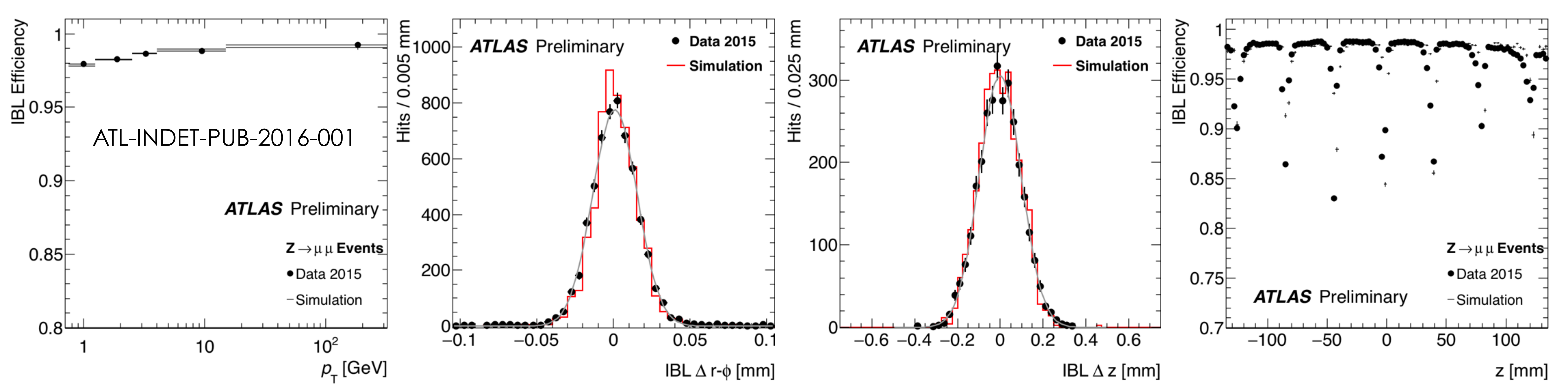
- FE-I3 and FE-I4 are digital readout chips
- Signals from collected charge is digitised after amplification
  - detector FE returns Time-over-Threshold (ToT): duration of signal above analog threshold in units of 25ns
  - rising edge at threshold assigns timestamp to hit
  - further possibility of controlling occupancy by acting on digital threshold (i.e. rejecting hits with small ToT)
  - requires charge-ToT calibration for operating detector and for comparison with MC
- ToT information is used in tracking
  - track association based on NN algorithm exploiting cluster shape/charge distribution



DIGITAL READOUT: TOT

- Based on $Z \rightarrow \mu\mu$ data collected in 2015 compared with MC
- Hit reconstruction + track association efficiency greater than 98%
- Transverse and longitudinal hit spatial resolutions of 10.0 and 66.5μm respectively
  - from sample of tracks traversing overlapping modules and having hits in both of them
  - single hit resolution from corrected hit position difference, $\Delta r\text{-}\phi$ and Δz: $\sigma_{point} = \sigma_{\Delta}/\sqrt{2}$
- Efficiency along z probing slim edge design, consistent with expectations

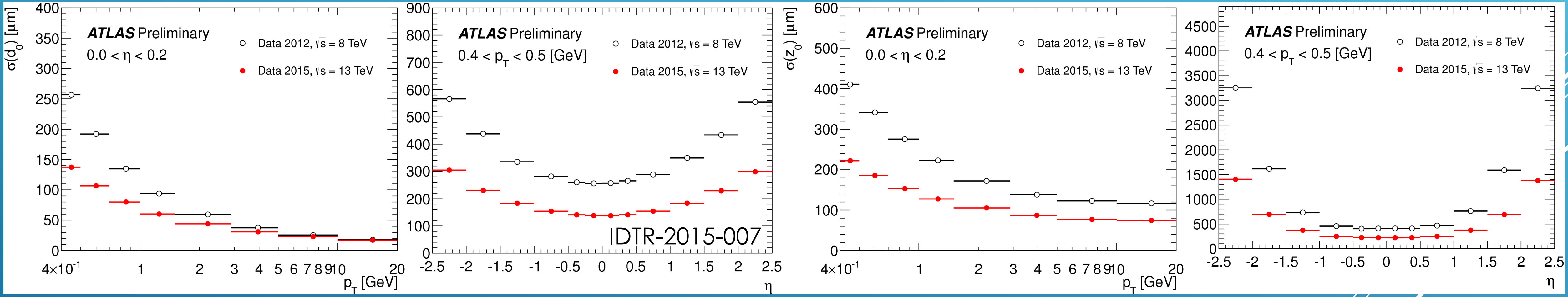




IBL EFFICIENCY AND SPATIAL RESOLUTION

- 4-layer 92Mpixel tracker at work!
- 2015 Run-2 vs Run-1 data comparison
  - enhanced tracking performance over all acceptance
  - overall improvement on impact parameter resolution by approximately a factor 2, in line with simulations
    - loose track selection
    - transverse and longitudinal impact parameter unfolded to remove contribution from vertex resolution
  - beneficial effects of reduced material (Be beam pipe), distance from IP and longitudinal pitch

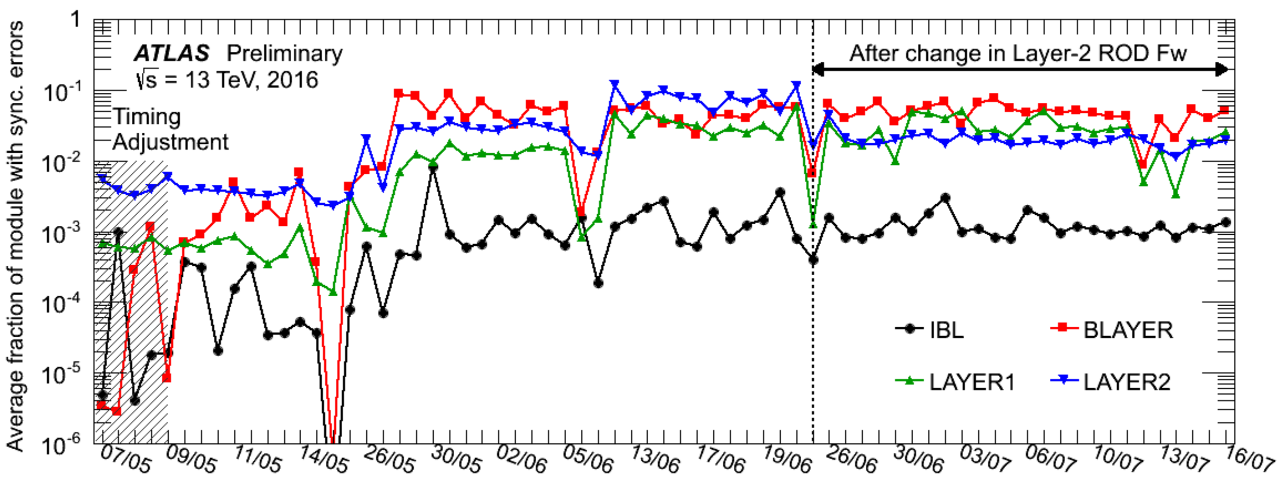
see S. Pagan Griso's talk on Aug 6
New developments in track reconstruction for the ATLAS experiment for Run-2 of the LHC



- This translates in a +10% on *b*-tagging efficiency for similar background rejection

PIXEL+IBL PERFORMANCE

- Good overall data-taking efficiency
  - Pixel/IBL can sustain high rates (85kHz) with low dead-time (less than 2-3%)
  - there have been several improvements during last year targeting mainly IBL and Layer-2
  - B-Layer is under the lens now
- Tracking efficiency affected by synchronisation errors
  - very sensitive to beam conditions (instantaneous luminosity, number of interactions per BC)
- Ongoing work on automatic recovery procedures expected to improve the situation



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ATLAS pp 25ns run: April-July 2016

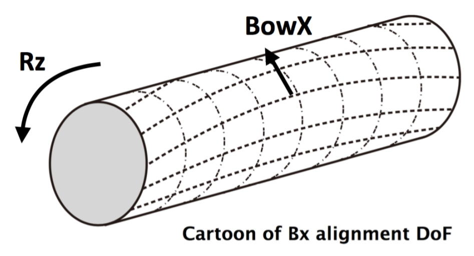
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
98.9	99.9	100	99.8	100	99.6	99.8	99.8	99.8	99.7	93.5

Good for physics: 91-98% (10.1-10.7 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between 28th April and 10th July 2016, corresponding to an integrated luminosity of 11.0 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

DETECTOR OPERATIONS

- IBL distortion discovered during 2015 cosmic runs, correlated to temperature changes (10μm/K)
- Induced by CTE mismatch between stave carbon structure and Cu/Al flex, reproduced by FEA
  - protect detector wrt rapid thermal cycles in order to prevent mechanical failures
- Corrected by Inner Detector alignment procedure
  - necessary if temperature varies by more than 0.2K during run
  - after September, in-run alignment procedure recovers tracking performance



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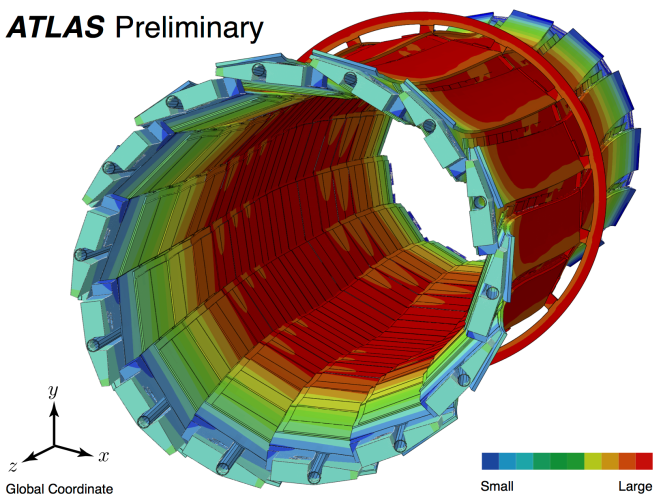
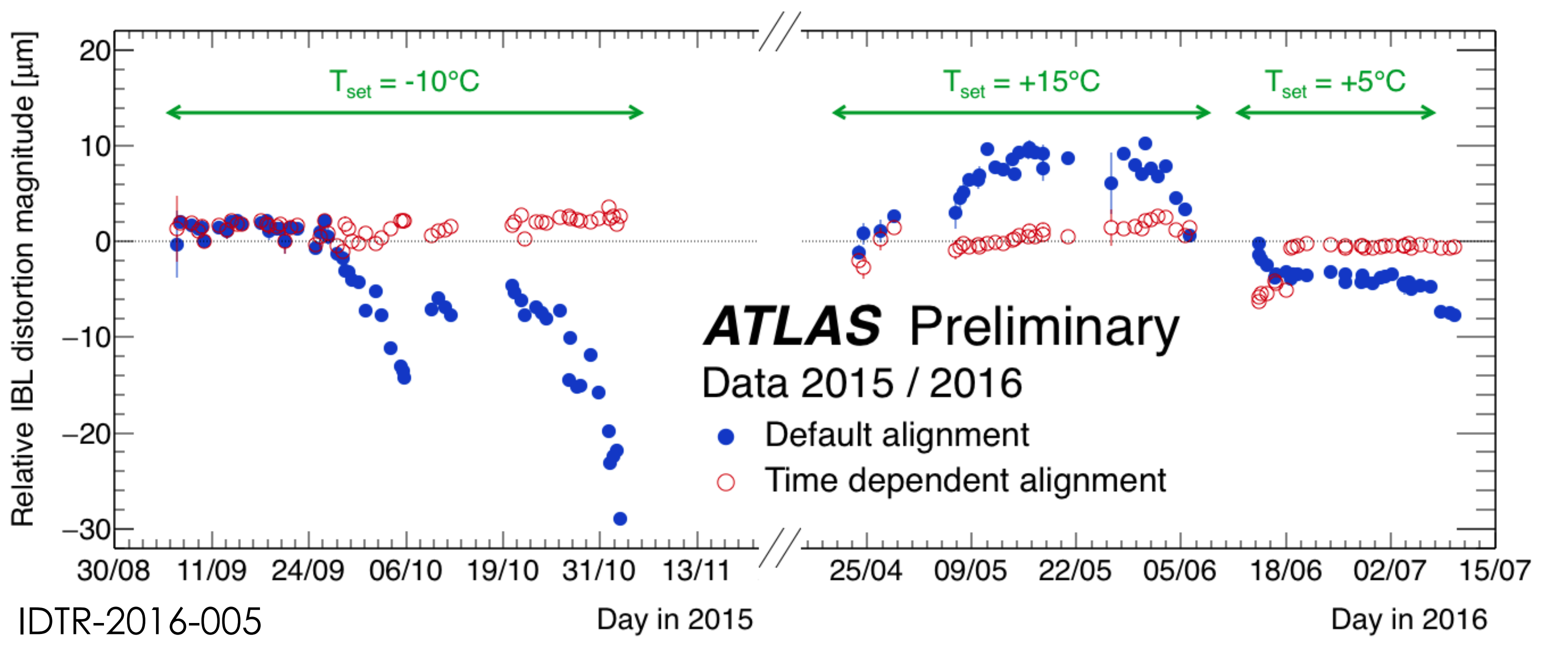
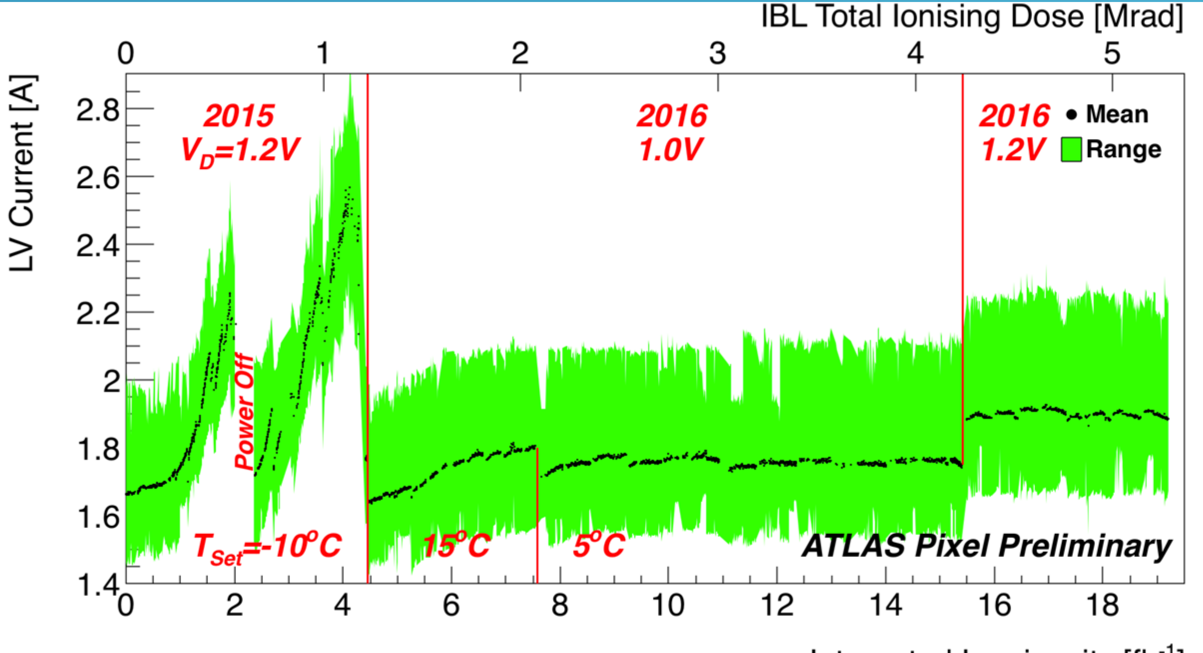




OPERATIONAL ISSUES: IBL DISTORTION

- Steep rise in IBL LV currents observed in 2015 since the beginning of September
  - potentially catastrophic due to temperature increase and risk of electrical failure
- Correlated to 130nm n-MOS FE transistor leakage current
  - hole trapping in bulk oxide dominating the beginning of irradiation, fast annealing
  - interface trap generation dominating at high TID (rebound effect), annealing at high temperatures



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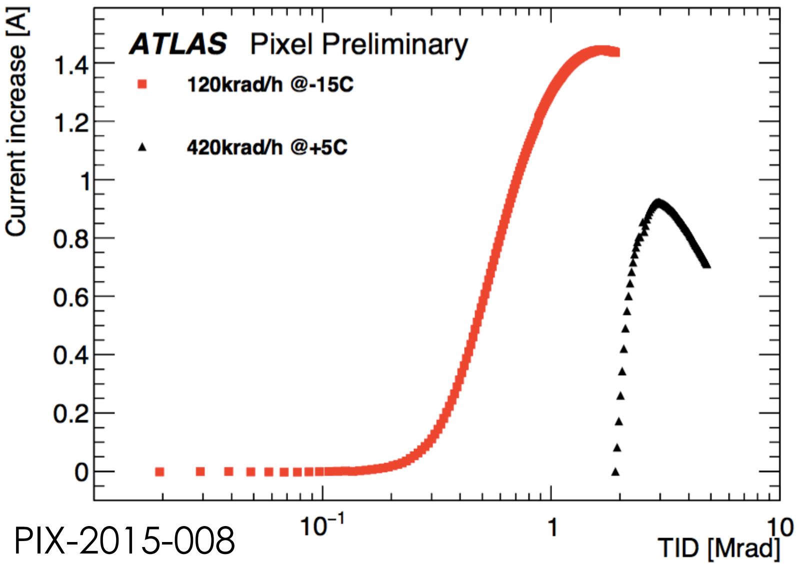
- Ad-hoc irradiation campaign on FE samples
- Effect controlled by operating temperature



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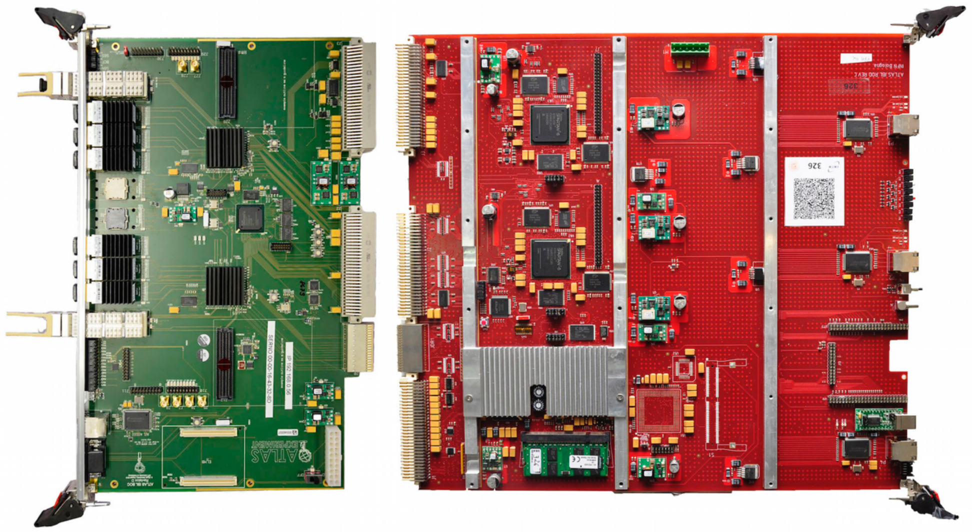
OPERATIONAL ISSUES: IBL LV CURRENTS

TOWARDS THE FUTURE

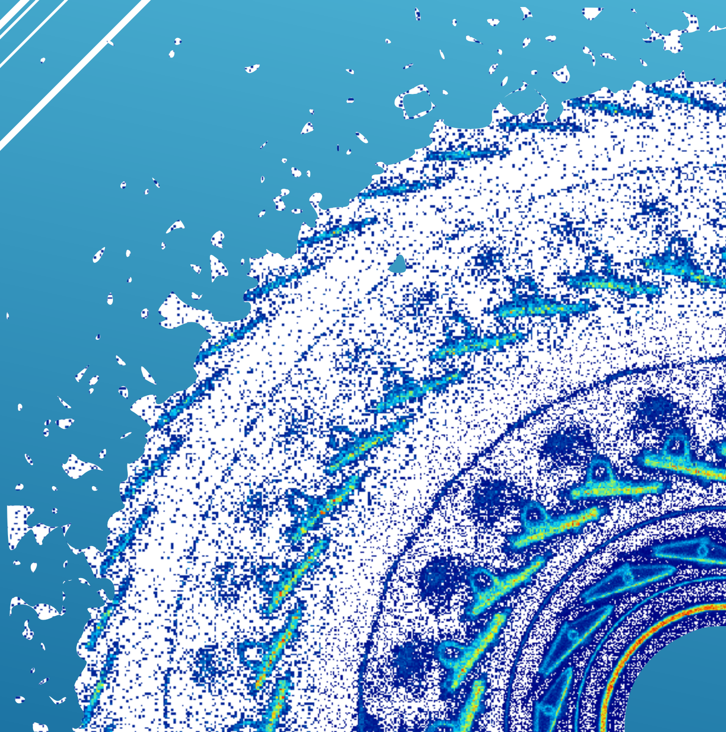
- Bandwidth limitations in back-end transmission observed already at the end of Run-1
- Layer-1 and Layer-2 back-end electronics subject of upgrade in 2015-2016
  - relying on recent hardware used for IBL and capable of up to 160Mbps transmission speed
- Installation completed for Layer-2
  - exploits up to 80Mbps bandwidth due to available fibres
  - successfully recommissioned in 2016
- Upgrade will continue with Layer-1
  - new services deployed during IBL installation included double fibres for Layer-1 (160Mbps achievable)
- Might want to extend the same treatment to the rest of the detector (B-Layer and disks)
  - opportunity of running more recent and robust hardware to the 2020+
    - we are expected to collect 10× more data till the end of Run-3
  - uniform readout system easier to maintain
  - benefit from more powerful diagnostic tools in order to prevent issues in data-taking

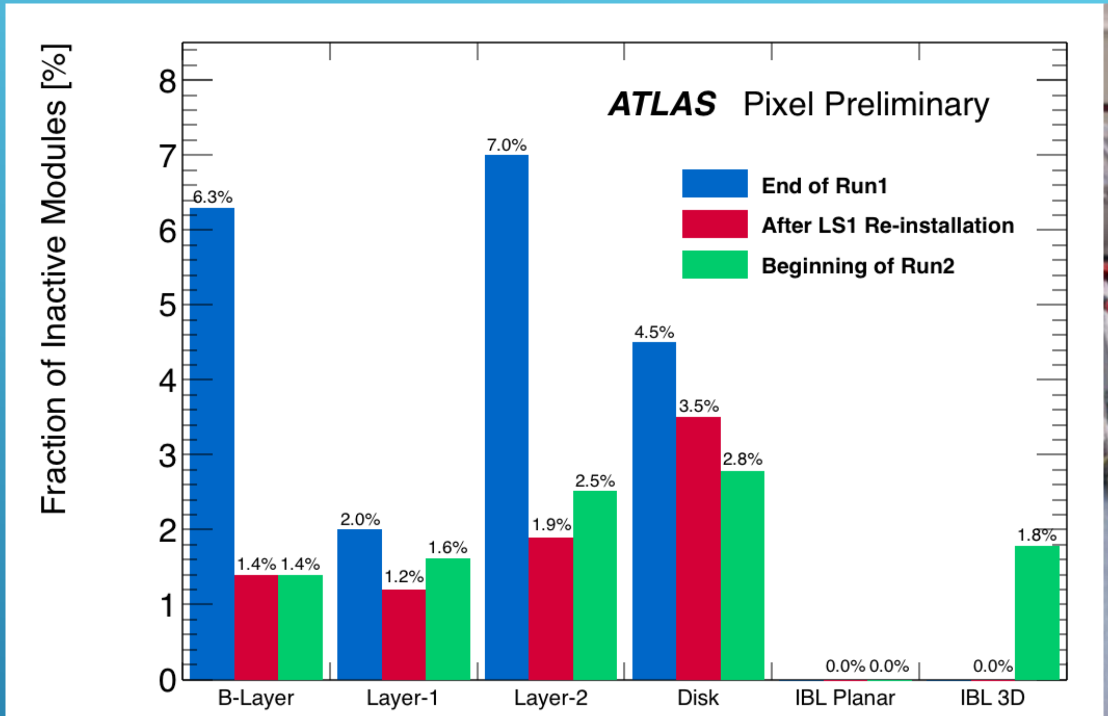


CONCLUSIONS

- Successful operation of ATLAS 4-layer pixel detector to (almost) design conditions in 2016
  - 13TeV, peak luminosity exceeding 1.1E34cm^{-2}s^{-1} and average μ consistently above 40 at beginning of fill
  - data taking efficiency steadily above 95% with trigger rates in the 80kHz's and dead time of 2-3%
- So far IBL has complemented B-Layer, boosting the tracking performance observed in Run-1
  - precision tracking and vertexing are at the basis of any discovery (or precision measurement)
- However, detector operation is becoming increasingly challenging with LHC performance
  - there is a long way to go before the next major upgrade in the years 2020+
  - it will be important to preserve and tune the detector in order to operate it at its optimal performance
  - we are getting ready to operate the detector beyond its design specs (thanks to an outperforming LHC)
    - this requires enhancing our diagnostic capabilities in order to promptly mitigate problematic situations
- There are lessons to be learnt for the future, when detectors will face harsher conditions
  - so far we faced (and solved) some serious issues thanks to the dedication of a great team
- We must all remember that good physics necessarily requires good detector operations
  - and that operation experience is necessary to build future detectors

BACK-UP MATERIAL





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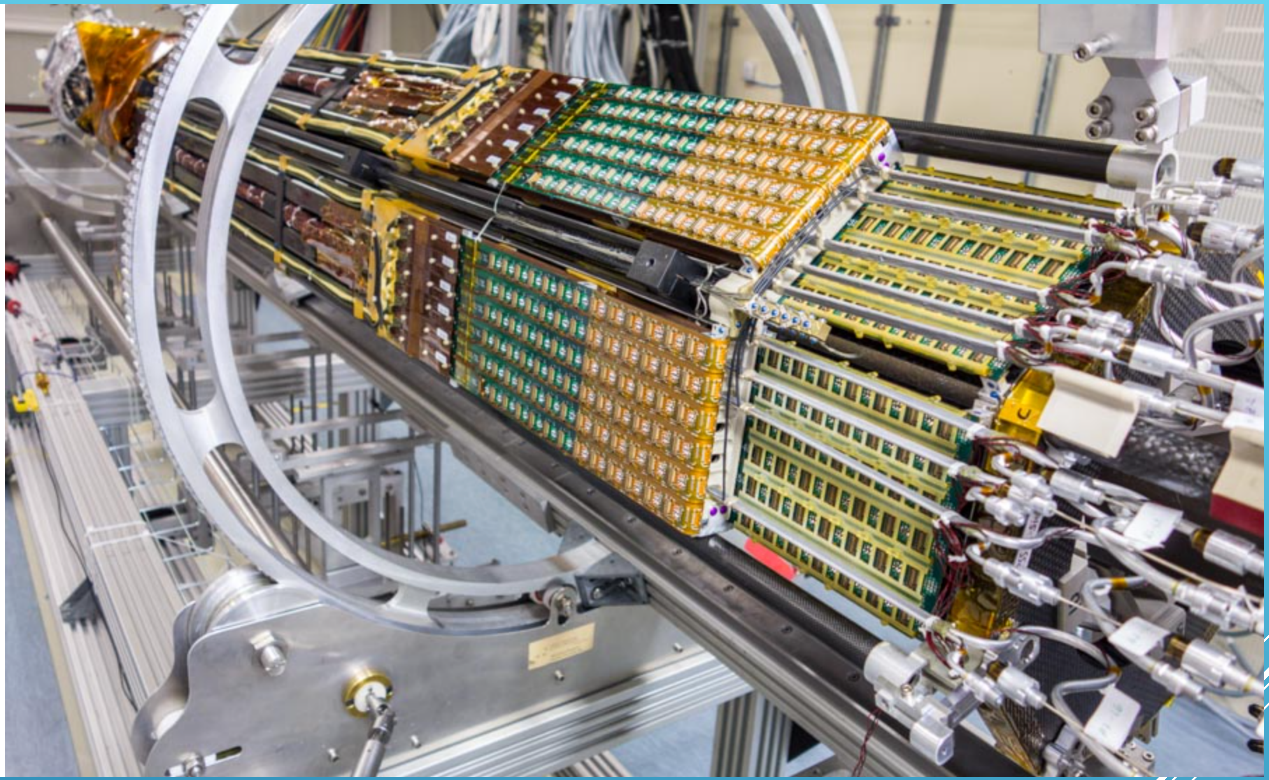
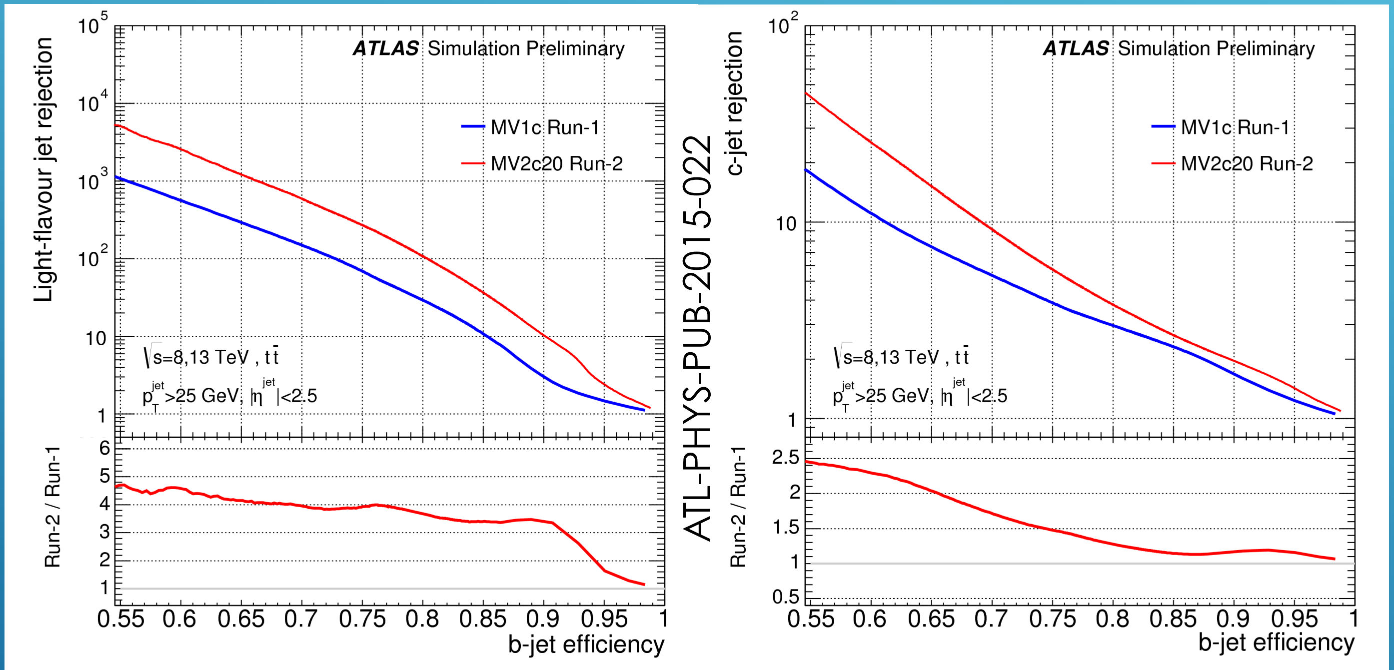


- New Service Quarter Panels installed during LS1
- Electrical-optical conversion moved outside ID volume ➔ improved accessibility
- Accessible connections and services of faulty modules repaired
- Added fibres ➔ doubled readout speed capabilities for Layer-1 (2×80Mbps)

BACK-UP: NSQP AND PIXEL REFURBISHMENT

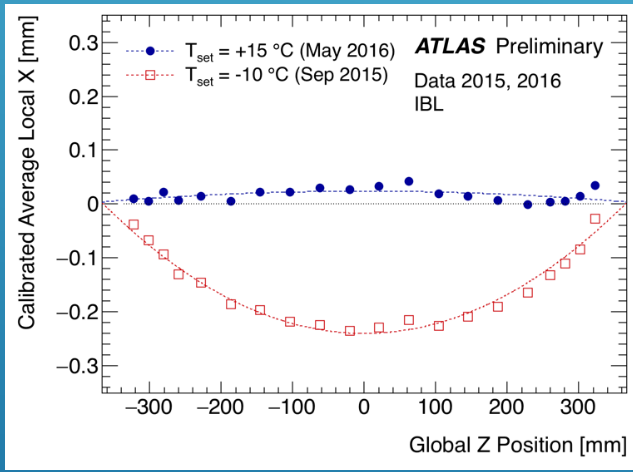
- Tracking improvements immediately translate on b-tagging performance
- Run-2 vs Run-1 detector and reconstruction simulation comparison
  - better light and c-jet rejection over the whole acceptance and p_T spectrum allow +10% b-tag efficiency
    - in most analyses, this means moving from 70% to 77% efficiency for similar background rejection
  - IBL plays a role in low-p_T rejection, while high-p_T performance due to algorithm improvements

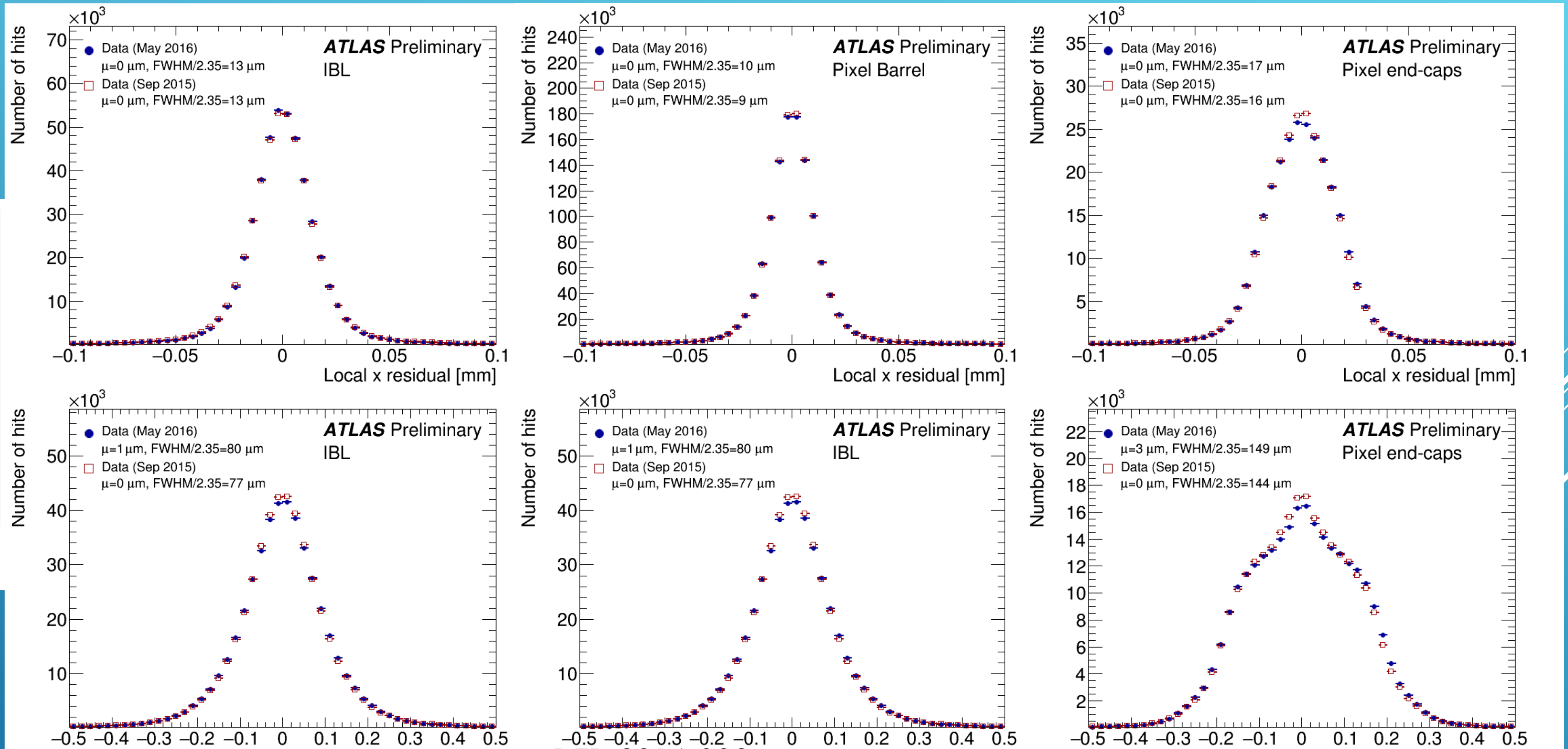


BACK-UP: B-TAGGING PERFORMANCE

BACK-UP: 2016 VS 2015 RESIDUALS

- Comparison based on two fills
- Very different operating temperature, very similar performance





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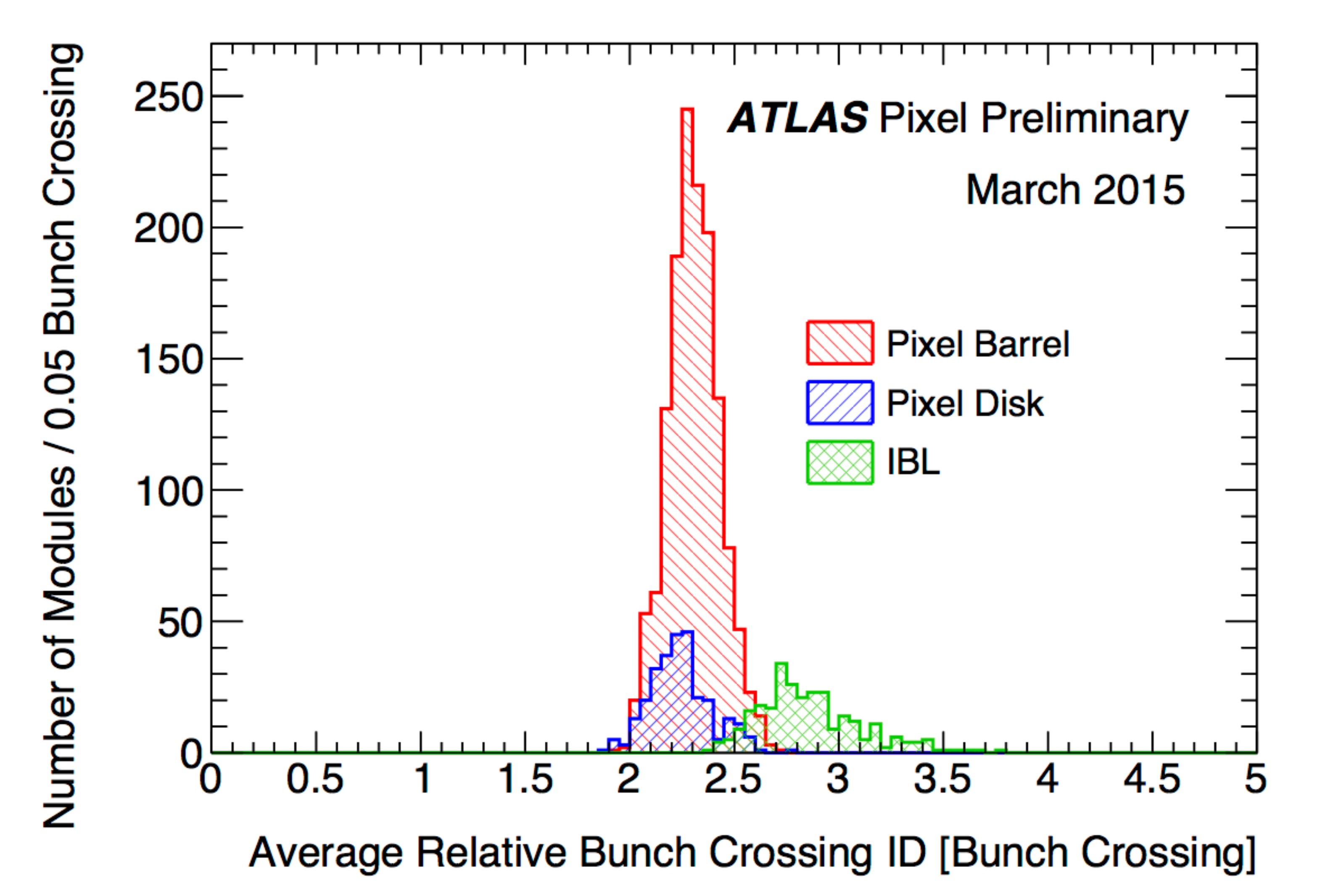
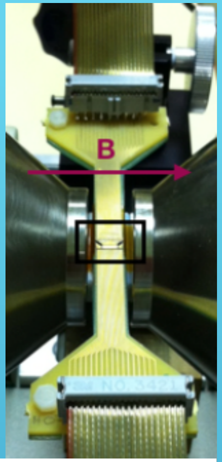
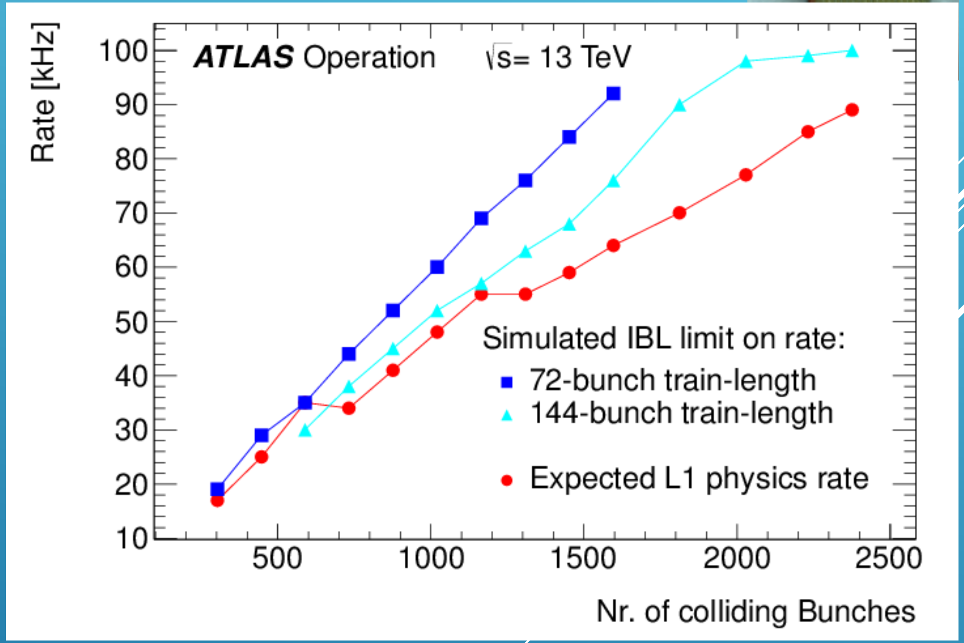


BACK-UP: TIMING

- Before the start of Run-2, campaign to evaluate effects of magnetic field on wire bonds
  - ad-hoc PCB used for extensive testing
  - AC current mimicking trigger signal with varying frequency and direction wrt magnetic field
  - lab measurements proved that induced oscillations can damage or break wires or their bonds
  - observations confirmed by FEA simulations
  - triggering at wire resonant frequencies (with harmonics and sub-harmonics) must be avoided



- Protective countermeasure: Fixed Frequency Trigger Veto implemented in DAQ chain/calibration
  - sustainable trigger rate depends on LHC filling scheme and bunch pattern
  - never a limitation in data taking, in particular with filled machine (definitely the case in 2016)
  - impact of protection decreases with number of bunches in the LHC, not a concern any longer
  - still an effective protection in pathological situations



BACK-UP: IBL WIRE BONDS PROTECTION