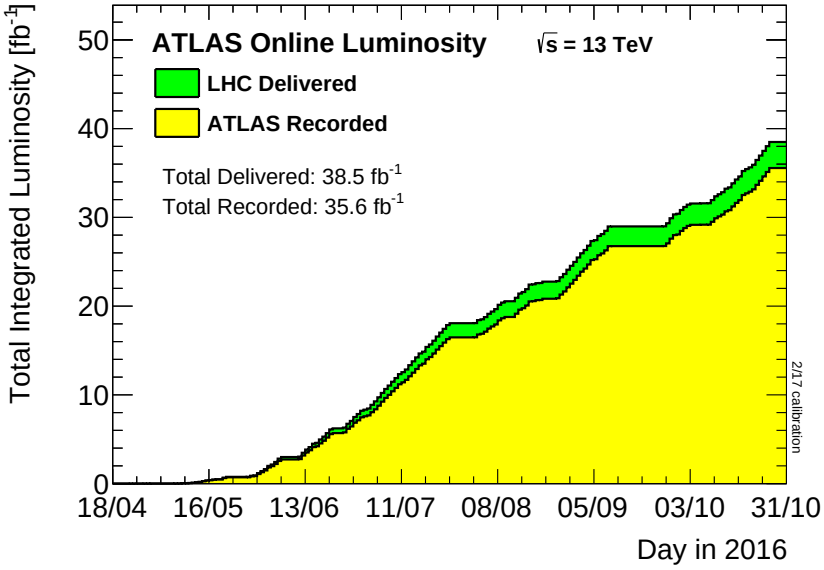
Operational Experience and Performance with the ATLAS Pixel detector with emphasis on radiation damage

P. Butti
On behalf of Atlas Collaboration

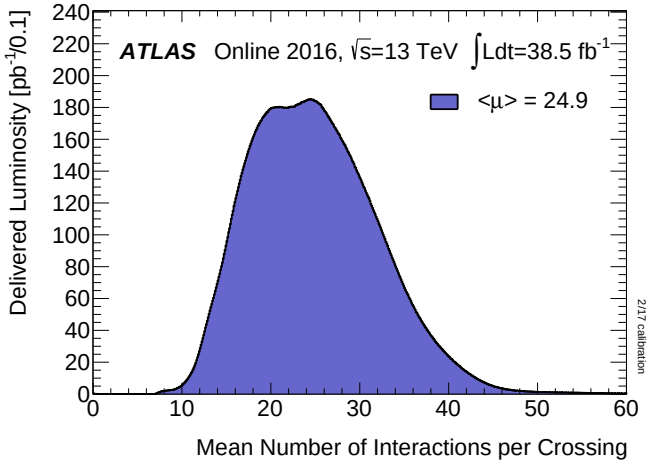
EPS Venice 2017
Detectors and data handling

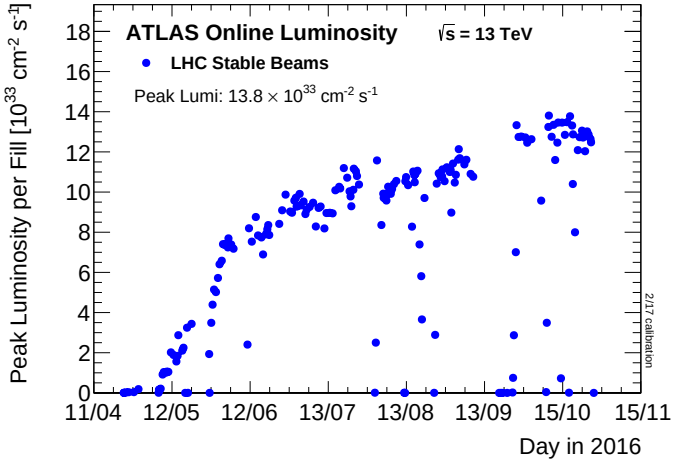
July 6, 2017

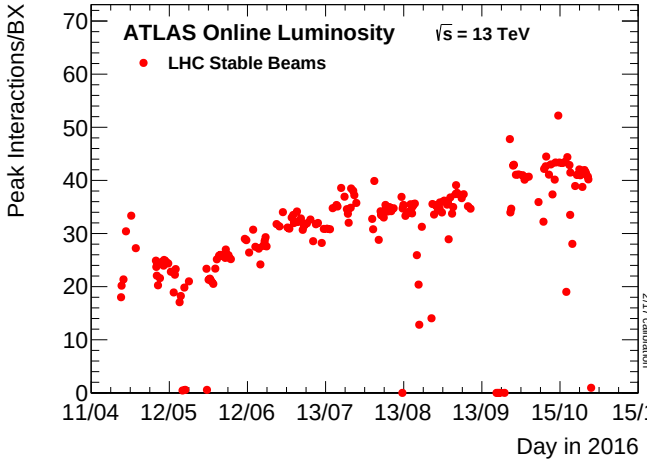
Summary of operation conditions in 2016



- Original design for ATLAS Inner Detector systems: $\mathcal{L} = 1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and $\langle\mu\rangle = 23$
- Limit passed already during 2016 $\rightarrow$ continuous upgrades during shutdown and through data taking
- Pixel Detector underwent a major ReadOut update
- The data collected during 2016 sums up to 38.6 fb^{-1} $\rightarrow$ study of the performance of the Pixel Detector and the effect of radiation







ATLAS Pixel Detector in Run-2 - Pixel

General Structure:

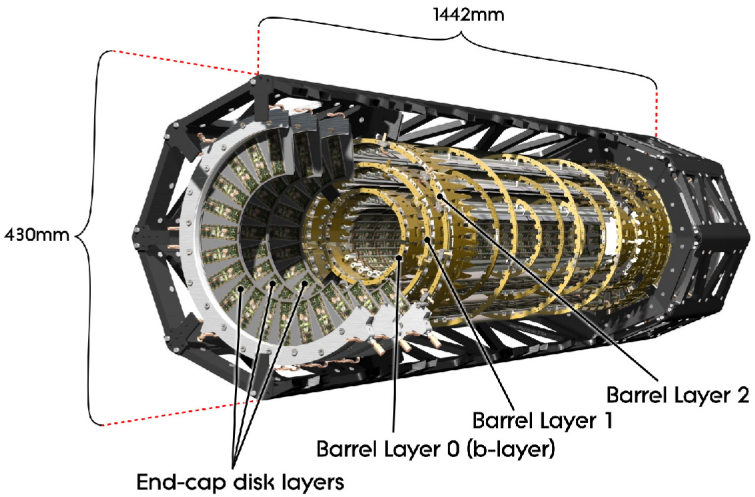
- 3 cylindrical layers (B-Layer, Layer 1, Layer 2) closed by two-endcaps (3 disks each)
- 80M channels 97.5% operational
- 1744 modules with 46080 Read-out channels each

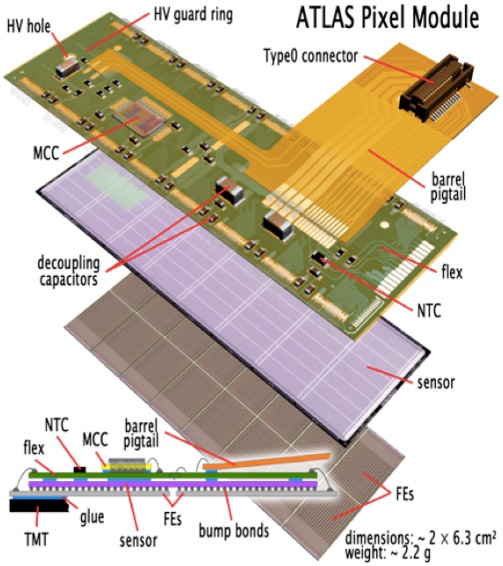
Front-end chip: FE-I3

- On standard 0.25 μm CMOS
- 2880 (18x160 matrix) channels
- Analog block: amplification and programmable threshold discriminator
- Digital block: pixel address, time stamp, digitised ToT (Time over threshold)

Sensor:

- n^+-on-n; 250 μm thick
- 328 columns (50 μm $r - \phi$ pitch)
- 144 rows (400 μm η pitch)





ATLAS Pixel Detector in Run-2 - Insertable B-Layer

General Structure:

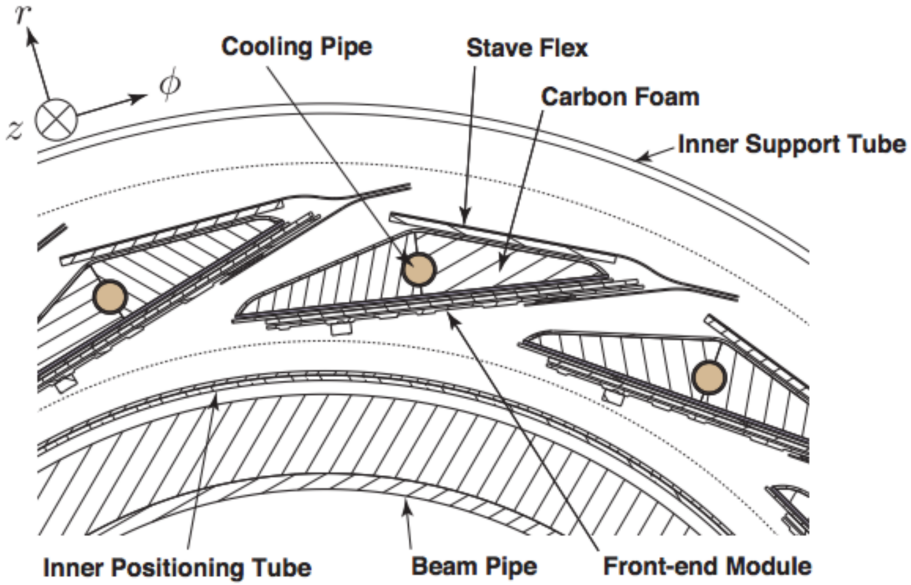
- 64 cm length ($\sim$ 7 m with services)
- 14 staves at $r = 3.27$ cm with ϕ overlap
- Two sensor technologies: 12 **Planar** (central region) and 8 **3D** (high-η) region
- Total 12M channels 99.3% operational

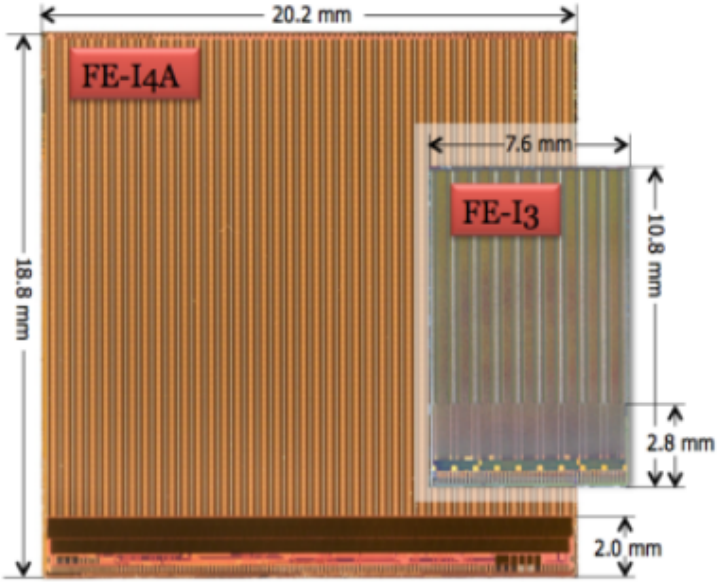
Front-end chip: FE-I4

- 0.13 μm CMOS IBM
- 26880 (80x336 matrix) channels
- Pulse height measured in ToT digitised in 4-bit
- Radiation hard (<250 Mrad)
- 90% active area

Sensors:

- Planar: 200 μm n^+-in-n; 2FE-I4/sensor
- 3D: 230 μm n^+-in-p; 1FE-I4/sensor
- 50 μm x 250 μm pixels



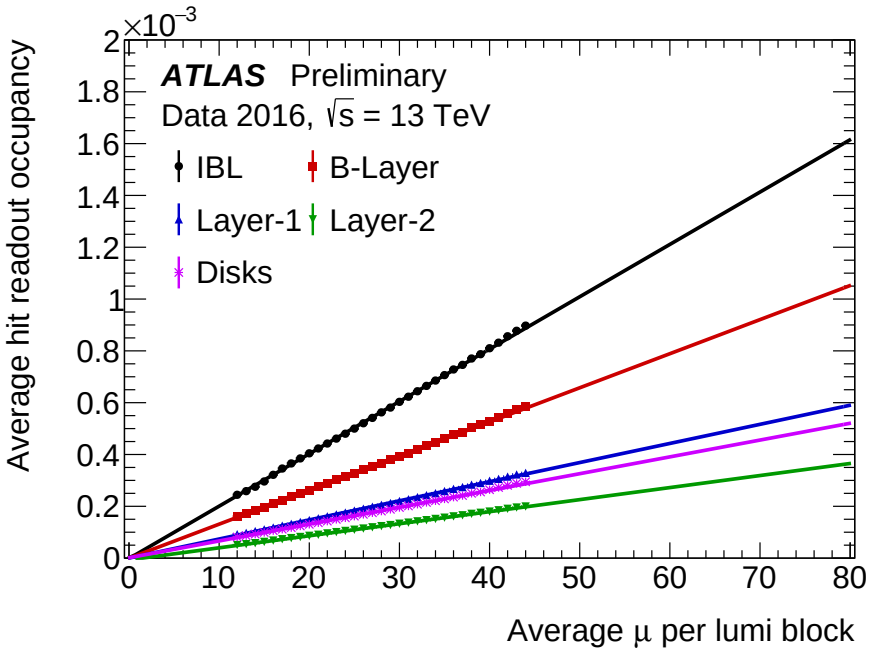


Upgrade of the readout system

Motivation

- LHC will increase peak luminosity to $3 \times 10^{34} cm^{-2} s^{-1}$
- During 2016 Run record of $1.4 \times 10^{34} cm^{-2} s^{-1}$
- Maintain a L1 trigger rate above 90kHz
- **Readout bandwidth will saturate**

- The Read-Out System for the Barrel Layer-1 and Layer-2 has been updated to the IBL-ReadOut
- **Dedicated poster by Nico Giangiacomi in the poster session**

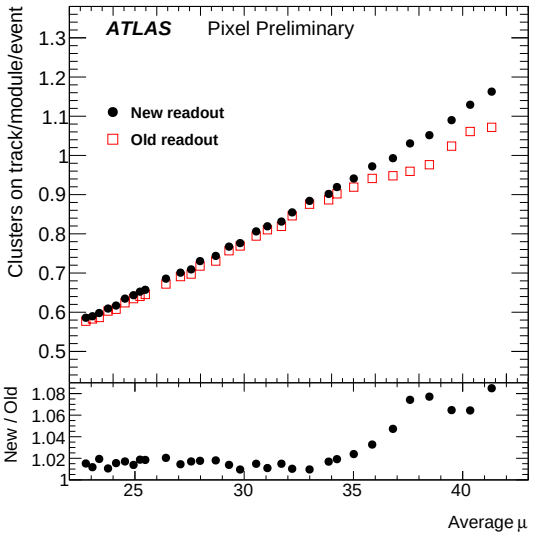


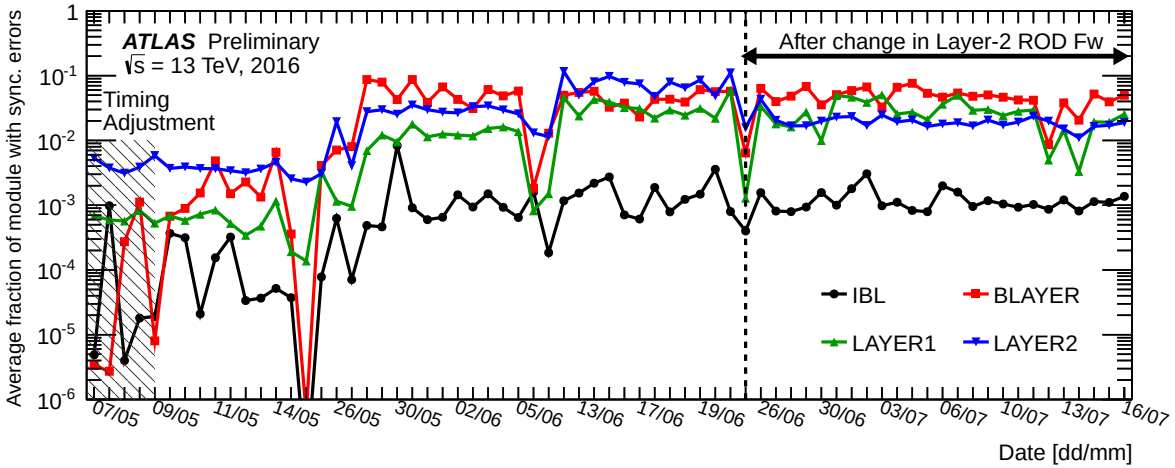
Module Link Occupancy at 100kHz L1					
	μ	B-Layer 160Mbps	Layer-1 160Mbps	Layer-2 80Mbps	Disks 80Mbps
Maximum in 2016	40	60%	81%* → 41%	119%* → 59%	75%
Maximum in Run 2	60	81%	103%* → 52%	159%* → 79%	96%
Maximum in Run 3	80	101%	125%* → 63%	188%* → 94%	115%

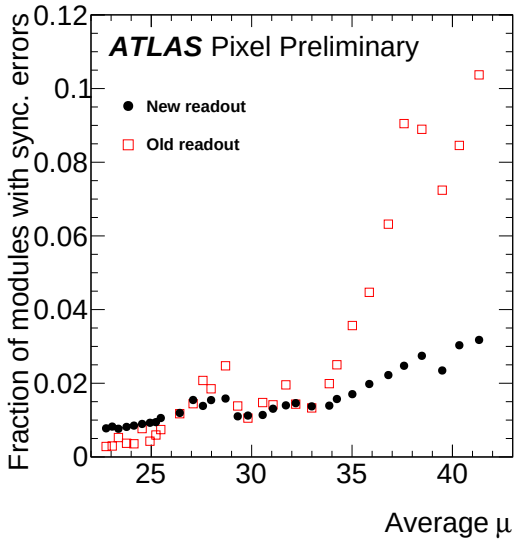
* Before upgrade

IBL readout on Pixel improvements

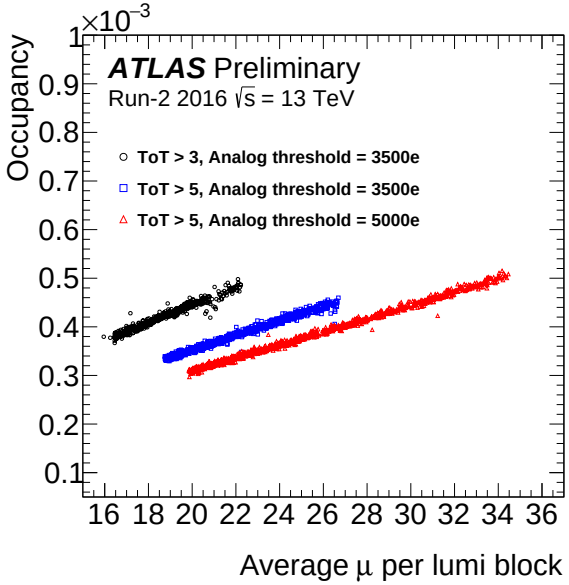
- Visible effects with **new HW and SW**
- Commissioning phase till June where desynchronisation errors stabilised by new ROD Firmware
- The Event Count Reset (ECR) is a signal propagated by ATLAS that acts on the ROD Firmware clearing ROD level desynchronisation errors → **only available in the IBL ROD, clear improvement at high pileup**
- **Major efforts currently ongoing to extend this functionality to the old readout** (B-Layer and Disks)



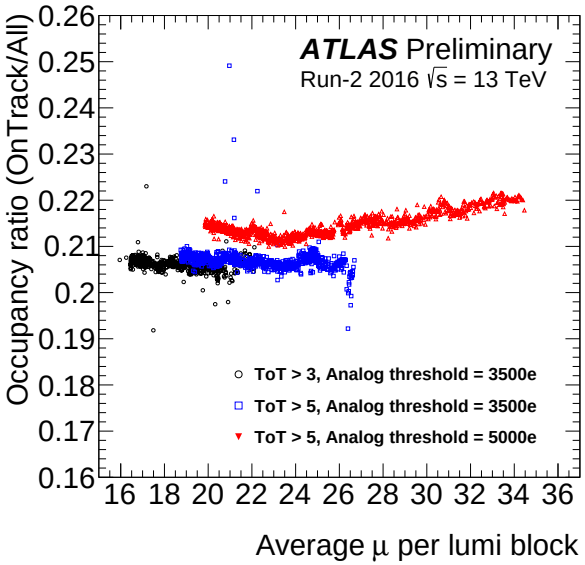


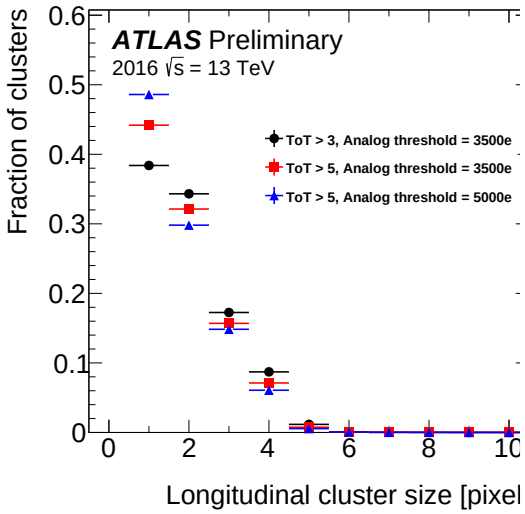


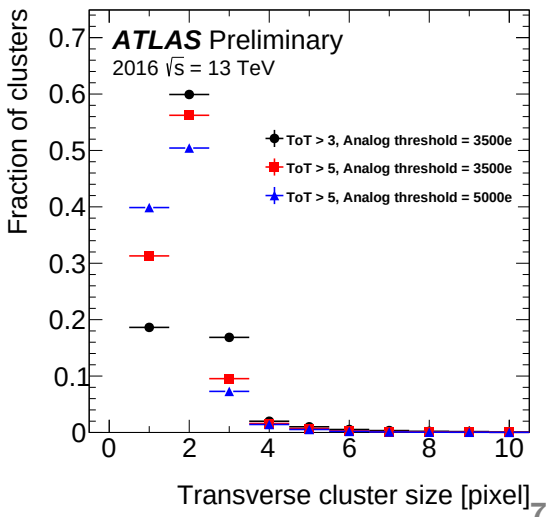
B-Layer changes during 2016 operation



- Most affected by luminosity rise: high level of desynchronisation and module timeout
- **Increased ToT cut and analog threshold to reduce occupancy** → minimal effect on physics
- Number of hits-on-tracks over all hits only slightly increases, while clear effect in cluster shapes.
- **Latency reduced from 255 to 150 bunch crossings**







General Operation Summary

- Pixel operated with 98.9% data taking efficiency during 2016 year.
- We successfully addressed the problems and challenges we encountered

ATLAS pp 25ns run: April-October 2016											
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1
98.9	99.9	99.7	99.3	98.9	99.8	99.8	99.9	99.9	99.1	97.2	98.3
Good for physics: 93-95% (33.3-33.9 fb^{-1})											

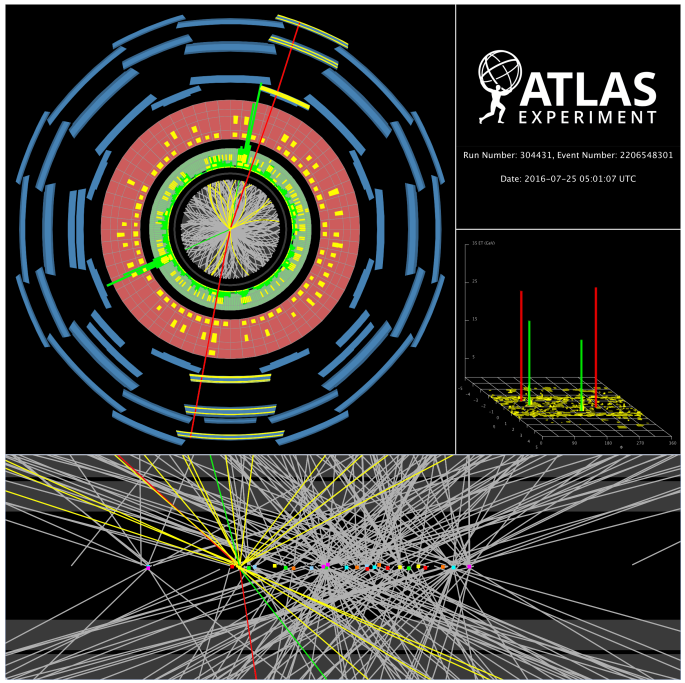
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

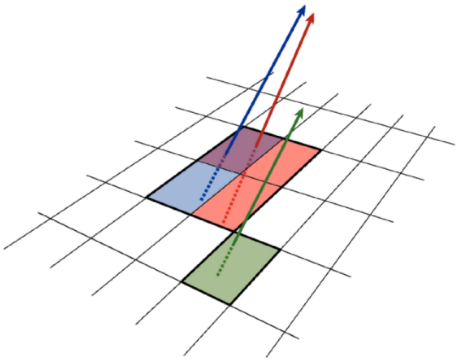
- Pixel still gave 1.1% of busy time that can and will be improved with future SW/FW developments

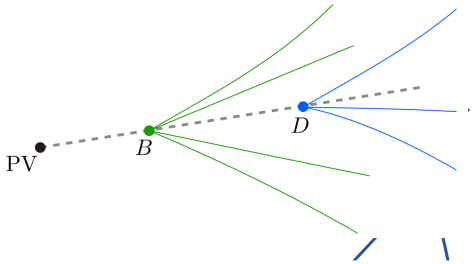
Importance of IBL and Pixel subsystems

Pixel and IBL subsystems are of fundamental importance for

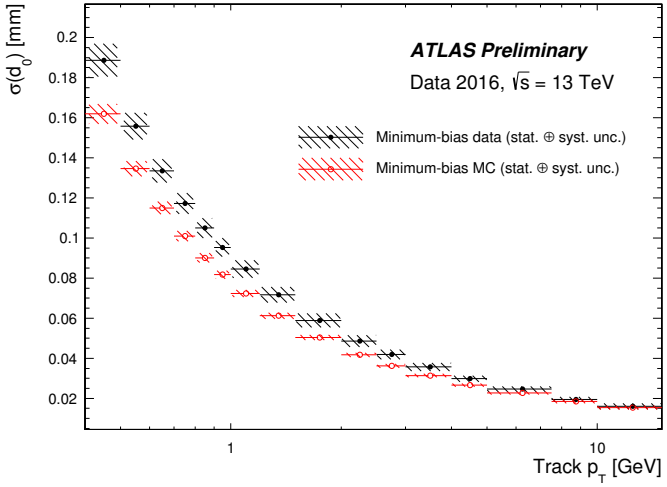
- Accurate reconstruction of charged particle trajectories (**tracks**)
- Precise determination of the position of primary and secondary **interaction vertices**
- Determination of **track impact parameters** d_0 and z_0
- **Flavour tagging**
- **Exotic tracking signatures** coming from displaced vertices, large dE/dx
- Resolution of tracks inside jet cores (**Tracking in dense environment** (TIDE))

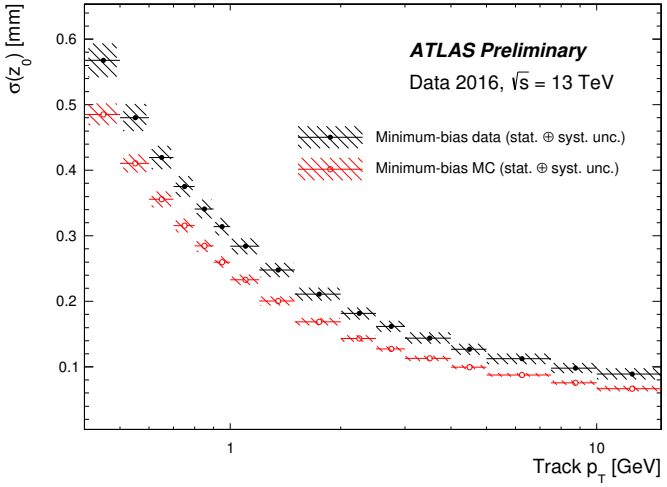


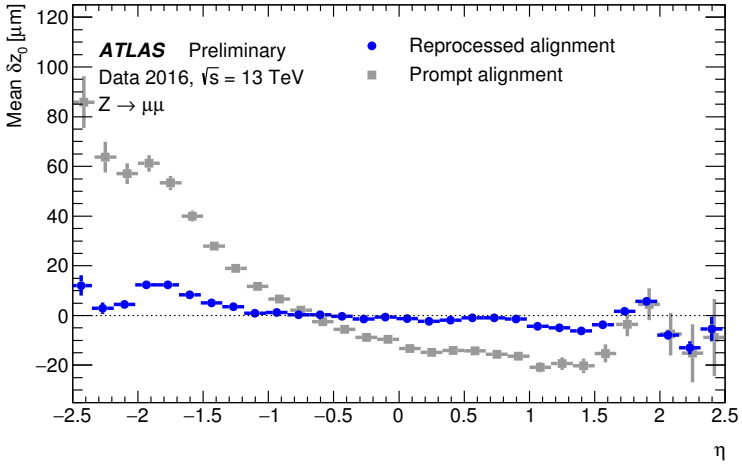


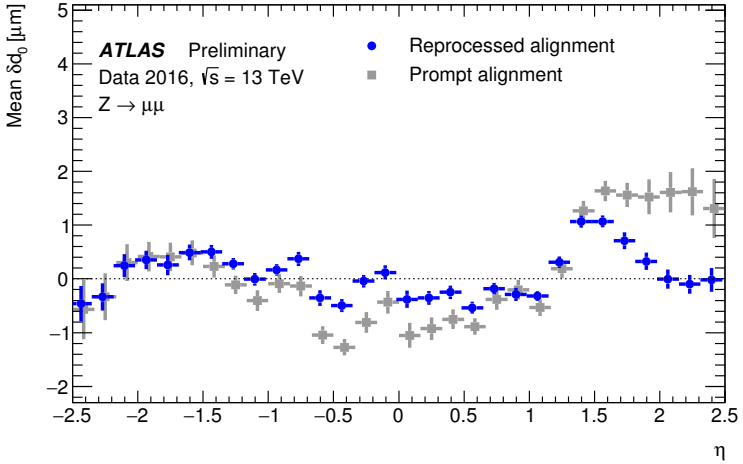


General Pixel-Tracking Performance in 2016









- d_0 and z_0 resolution from Minimum Bias events show a discrepancy at low momentum $\rightarrow$ corrected in analyses by a smearing factor
- d_0 and z_0 biases from $Z \rightarrow \mu\mu$ events show excellent alignment and weak mode corrections

Radiiation Damage Studies - Introduction

- Excellent Pixel and IBL performance during 2016
- However, radiation damage affects the sensor properties and degrades the detector response

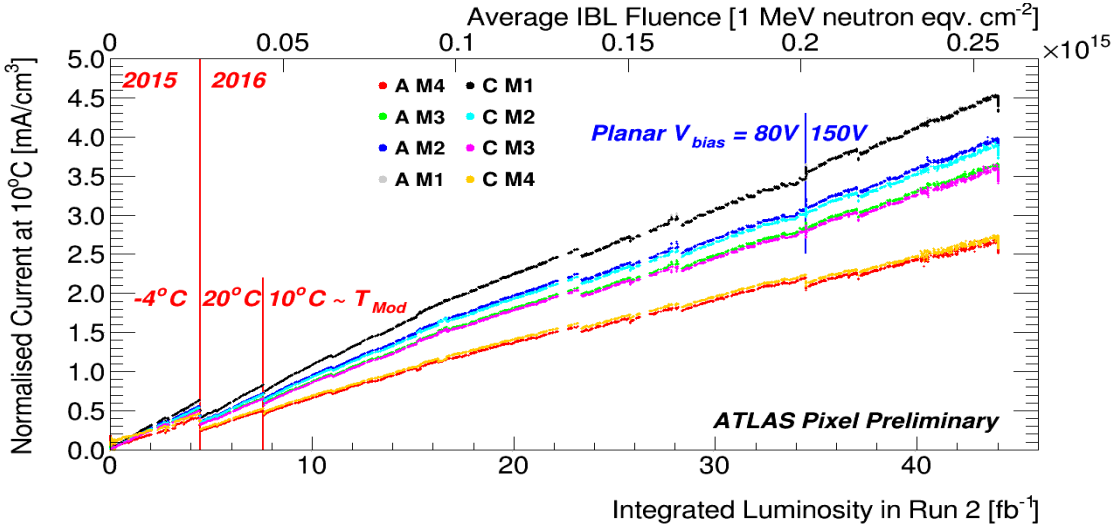
Two general types of radiation damage

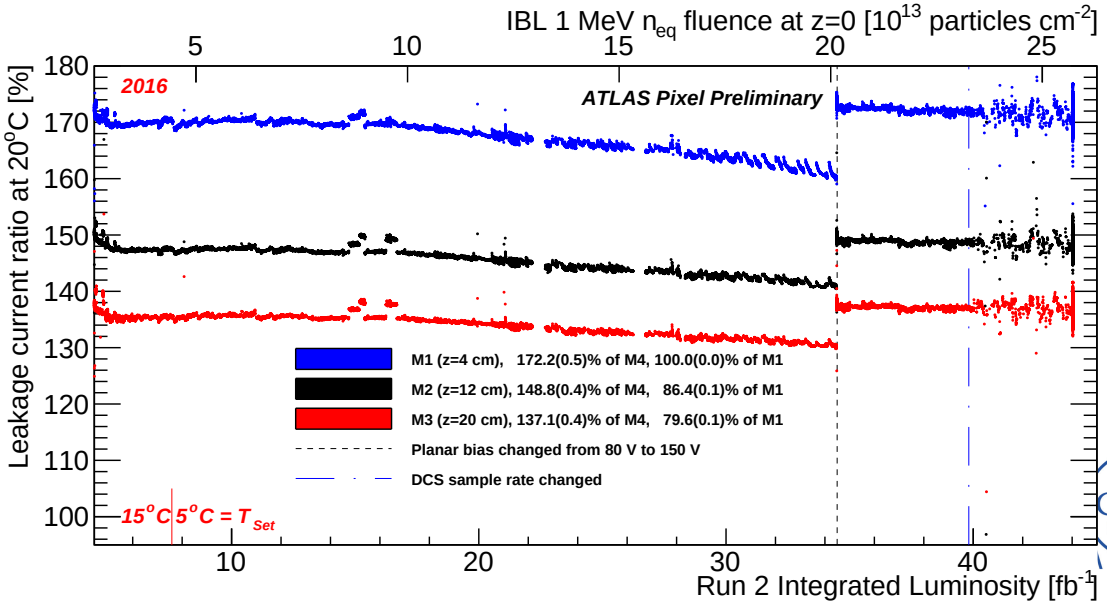
- **ionizing**: damages the SiO_2 and the SiO_2-Si inducing trapped charges
- **non-ionizing**: damages the sensor bulk effecting charge collection and electric field profile

- Increase of leakage current
- Reduced size of the depletion area
- Reduced fraction of collected charge
- Change in Lorentz Angle
- Reduction of hit-on-track efficiency
- Degradation of the dE/dX distribution
- ...

Radiation Damage Studies - Collected Charge

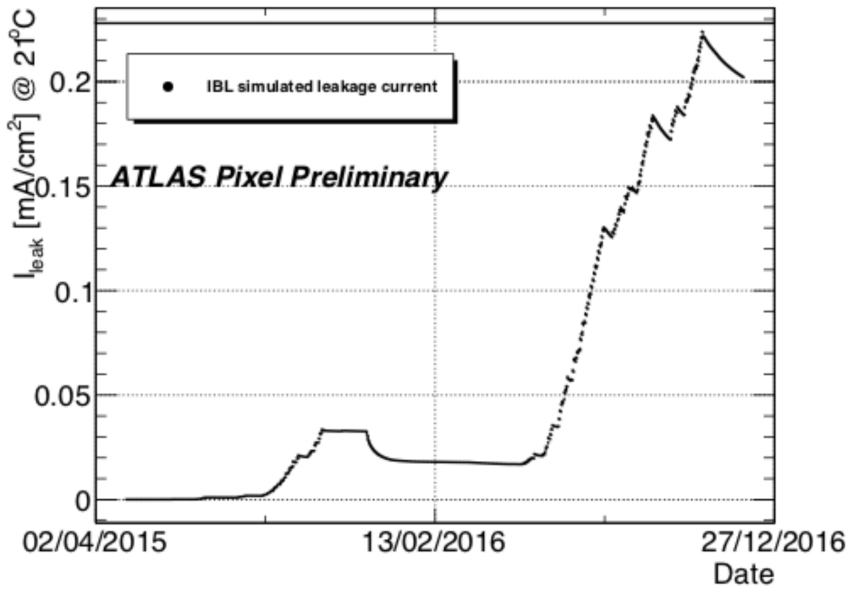
- **Leakage current proportional to integrated luminosity:** reduction of LV and increase of operating temperature to mitigate the effect in 2016
- The fluence and Total Ionising Dose (TID) in each period are obtained from delivered integrated luminosity and based on Fluka simulations
- Ratio of leakage current in planars and 3Ds constant when HV(planar)=150V → **restored full depletion area**

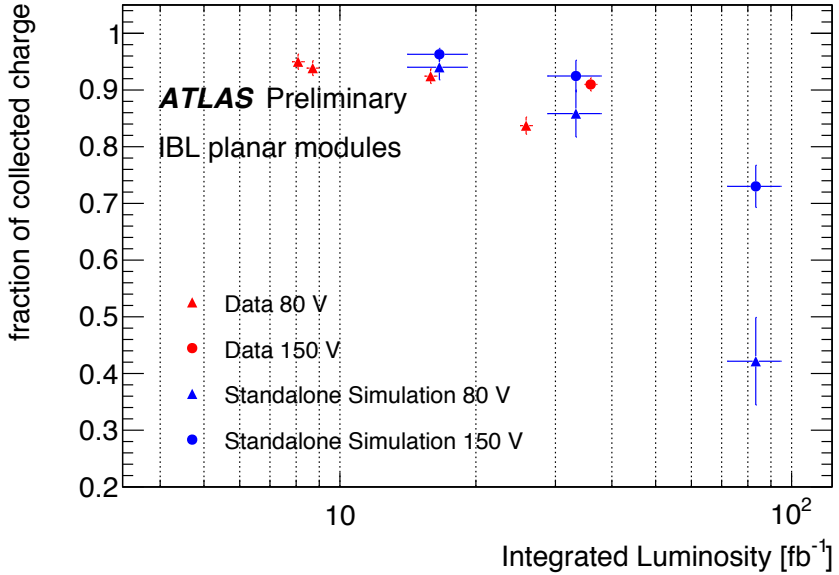




Radiation Damage Studies - Collected Charge

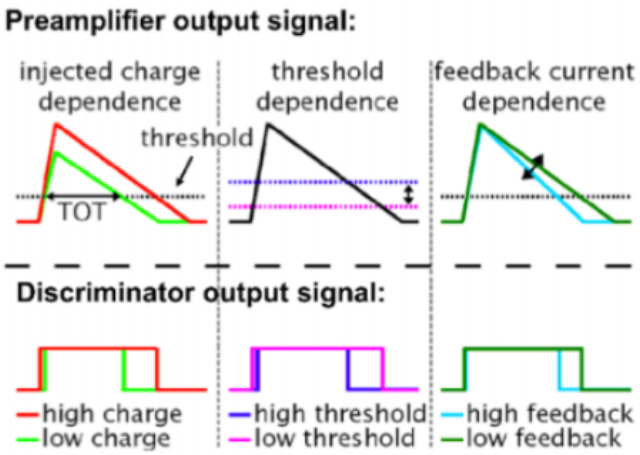
- Collected Charge fraction for Run 2 Data and Standalone Simulation based on Geant4
- Data is corrected to account for ToT drift (next slide). Simulation normalised to un-irradiated sensor
- FLUKA simulation crosschecked using leakage current measurement at the end of 2016 (horizontal bar in the first plot)
- Data in agreement with simulation within 1σ.
- Bias voltage increase to 150V increases charge collection in agreement with expectation and leakage current analysis
- Dedicated working group to study and model radiation effects has been formed and paper will be ready soon!

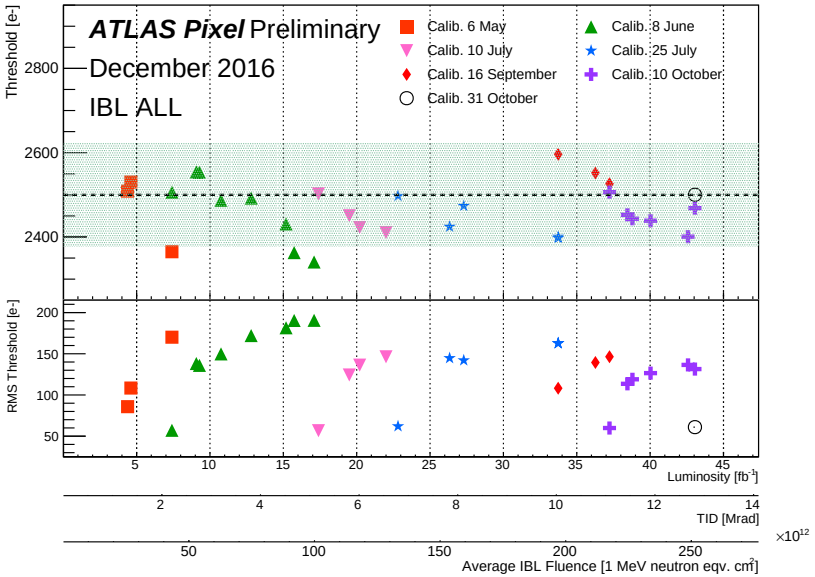


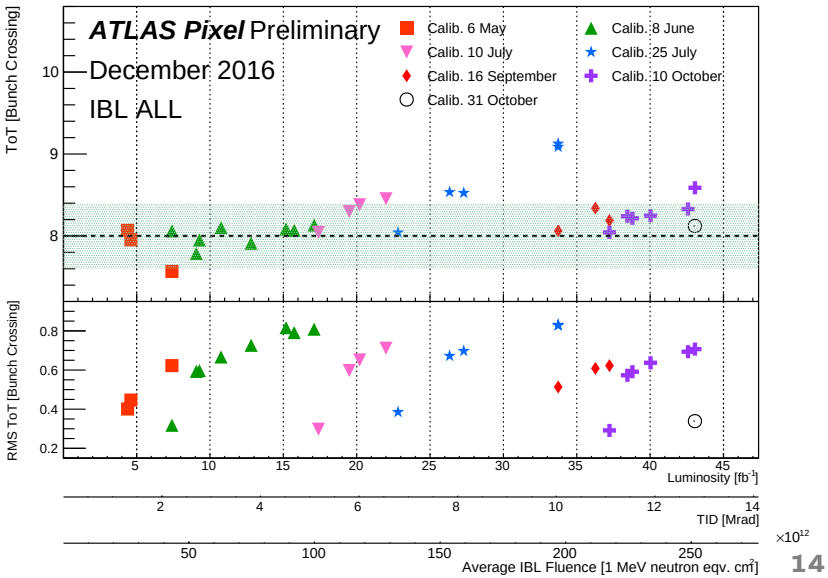


Radiation Damage Studies - Effects on IBL Calibration

- Pixel/IBL sensors calibration procedure includes determination of the value of ToT and analog threshold and eventual tuning to desired values
- **In IBL it observed a change in threshold and ToT tuning points of the FE-I4 due to radiation damage**
- Bi-weekly tuning of the detector → maintain good high data collection quality
- Data to check effect on FE-I3 will be collected this year

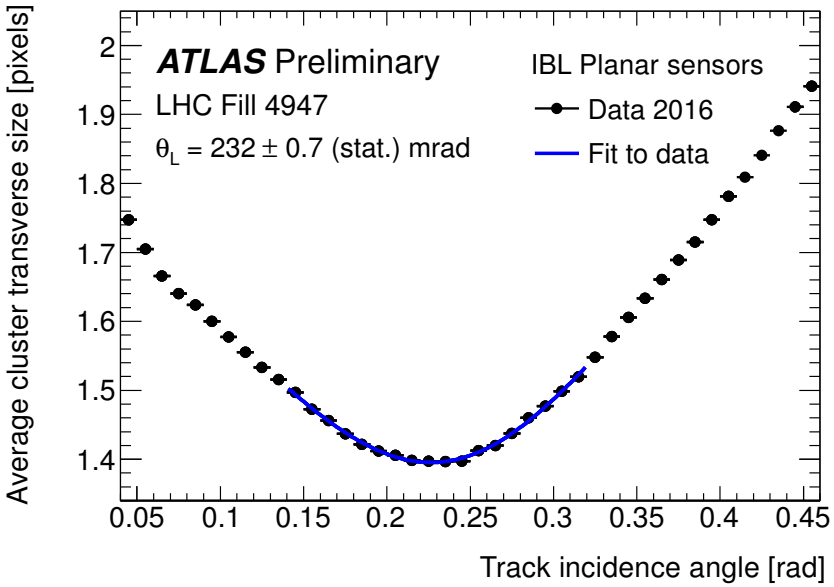


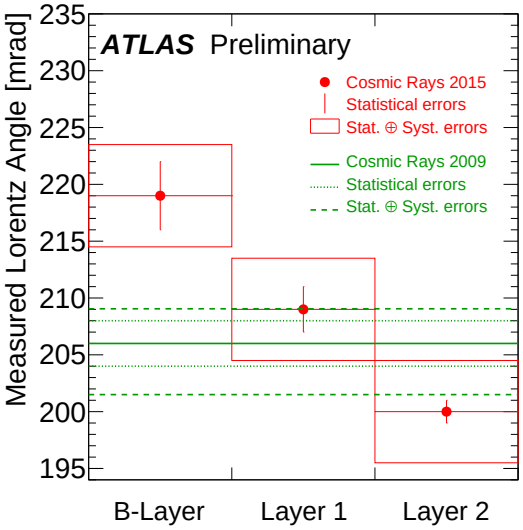


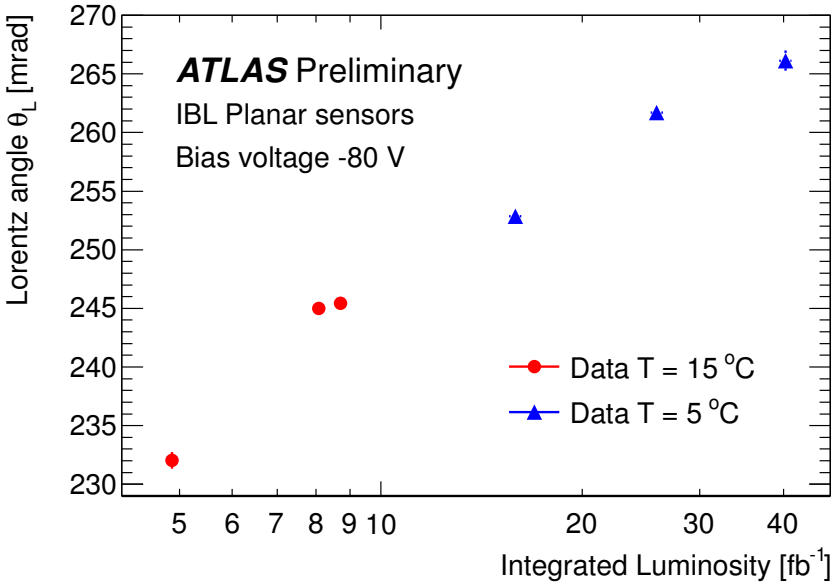


Radiation Damage Studies - Lorentz Angle

- In presence of $\vec{B}$, charge carriers drift at an angle θ_L (**Lorentz Angle**)
- Charged particles with incidence angle equal to θ_L generate clusters with minimum size
- B-Layer, Layer-1 and Layer-2 evolution from Cosmic ray at absorbed 6.3, 2.6 and 1.6×10^{13} n_{eq}/cm^2
- Use of 2016 collisions to measure IBL Lorentz Angle and its time-evolution

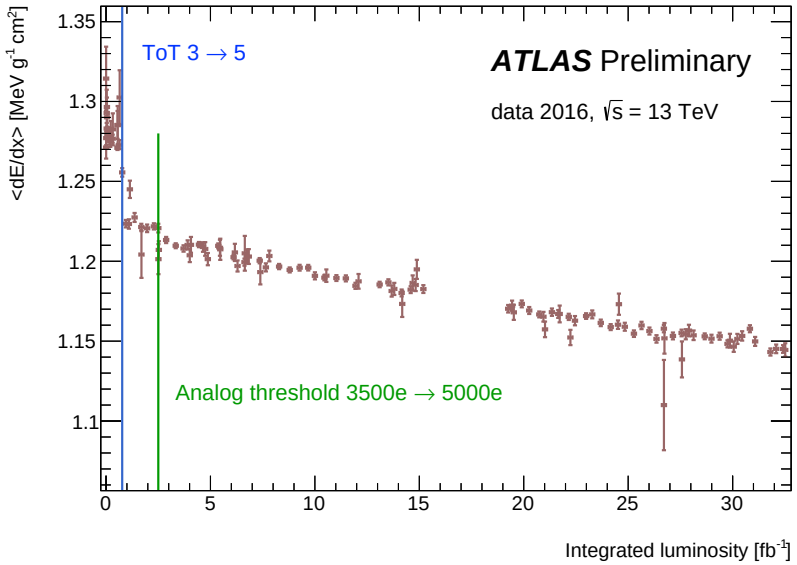




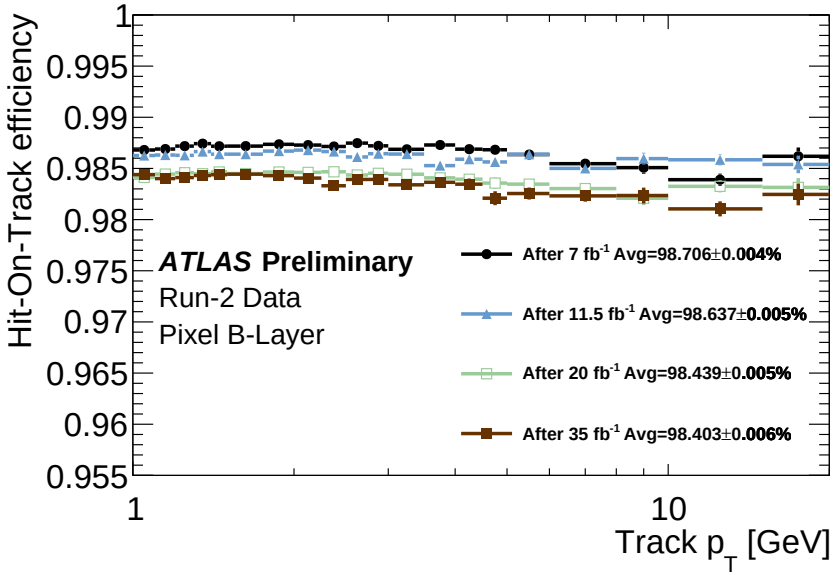


Radiation Damage Studies - Effects on B-Layer

- Observed time/dose dependence of the energy loss dE/dx in B-Layer during 2016 data taking
- Measure extracted from tracks inside the jet-cores (dense environments)
- Two main effects visible: **abrupt drop due to change in the digital threshold and steady decrease in throughout the year**



- Hit-on-track efficiency in B-Layer shows a mild decrease over 2016 data set → up to 0.3% drop
- Linked to radiation damage effect
- Measured with an inclusive track selection



Conclusions

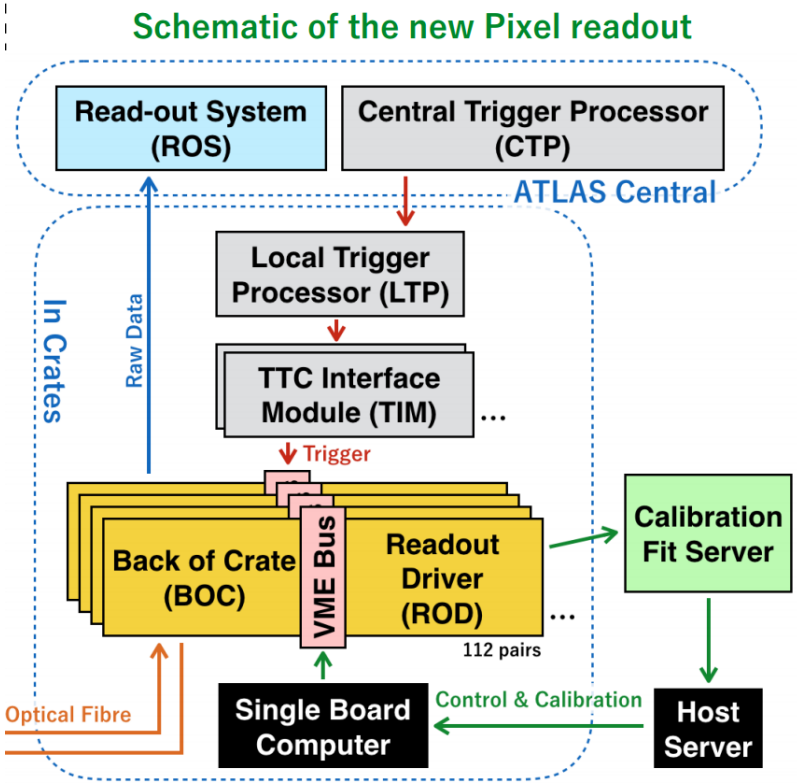
- Presented overview of the ATLAS Pixel/IBL Detector system.
- Summary of the improvements due to the upgrade of the Pixel Read-Out system to the IBL system
- Pixel/IBL sub detector operated with 98.9% efficiency over the 2016 data taking period
- Shown basic tracking/residuals performance during 2016
- Summarised the latest measurements of the radiation damage on the Pixel/IBL detector
- A working group has been formed and actively working on understanding and computing the radiation effects
- Paper in preparation and will be out soon - Stay Tuned!

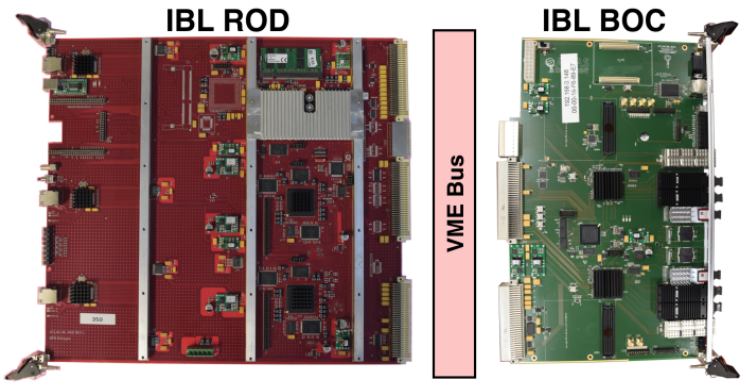
Backup

New IBL readout system

- New debug capabilities
- Available to spy data stream at the ROD/BOC by using logic analyzer
- Flush of FIFOs at Event Counter Reset (see later)
- Embedded processor (PowerPC) in ROD with GigaBit network communication
- New calibration stream:Data transmission via Ethernet to the Calibration Fit Server

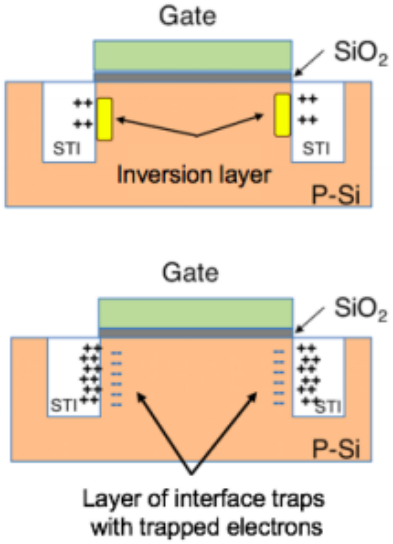
- **Layer 2:** Updated module link speed from 40 to 80 Mbps, S-Link speed increased to 2.56 Gbps, IBL Readout
- **Layer 1:** Same updates on a small fraction. During 2016 end of the year shutdown entire layer update: module link speed from 80 to 160 Mbps
- **B-Layer/Disks:** Will be updated at the end of 2017 data taking

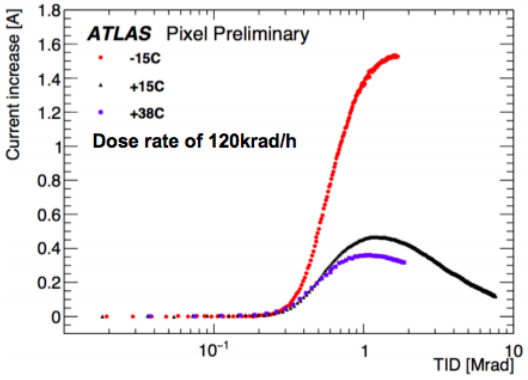


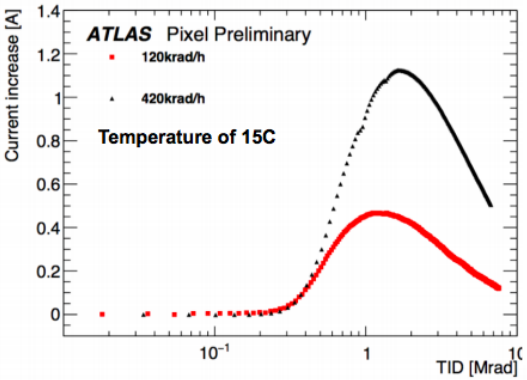


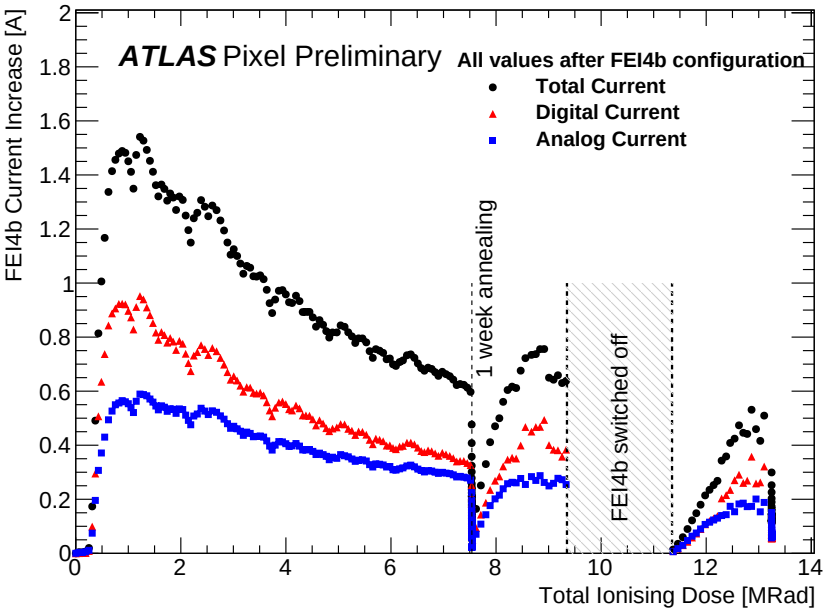
Radiation Damage Studies - Leakage Current and Alignment

- **Trapped positive charge**: in the bulk of the Shallow-Trench-Isolation (STI) oxide gives origin to the source-drain leakage current → function of TID with peak at $\sim 2-3$ Mrad.
- **Interface traps**: filled with electrons in the NMOS structures → compensates the trapped holes → decrease of leakage current
- **Dose and temperature dependence** and annealing of trapped positive charges at low temperature during sensors OFF.

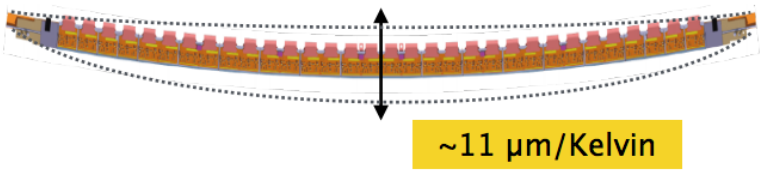




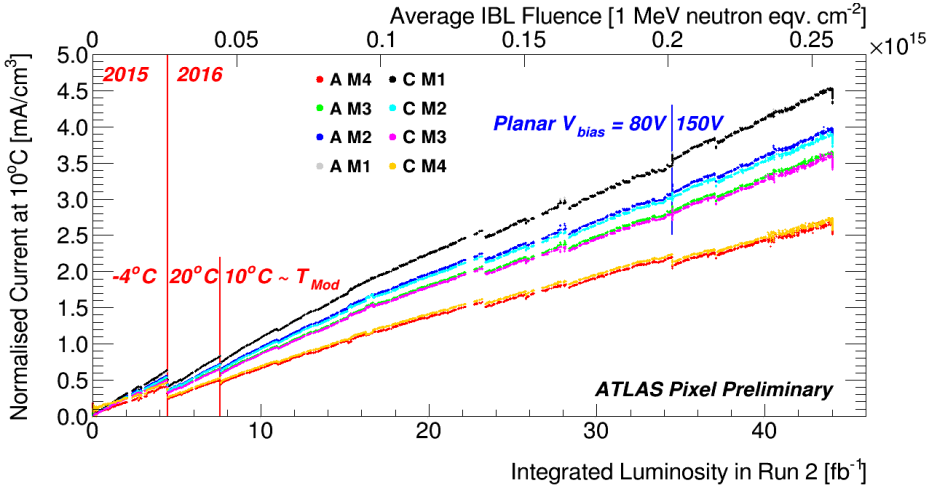


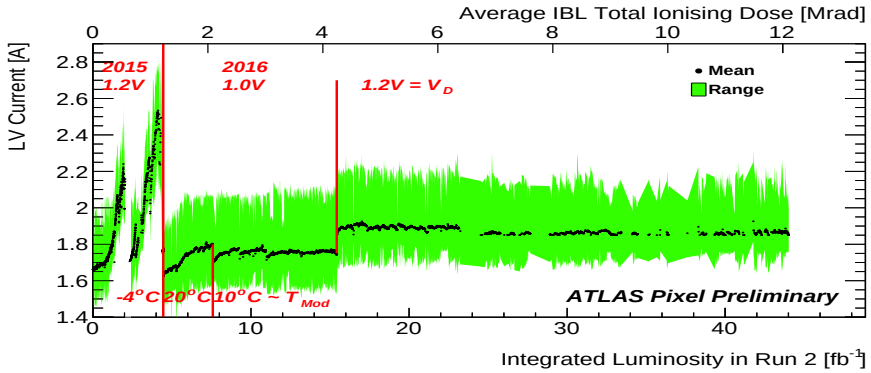


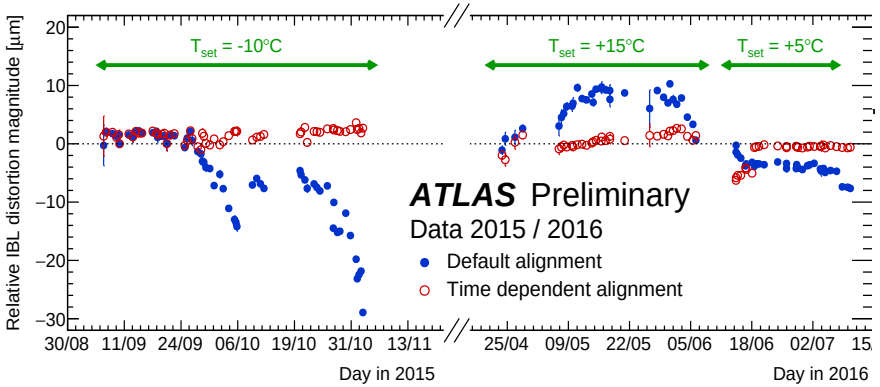
Radiation Damage Studies - Leakage Current and Alignment

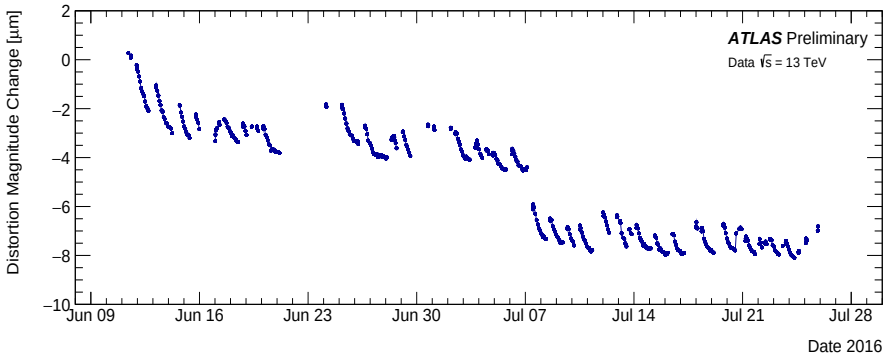


- IBL stave is sensitive to local power consumption change → bowing due to thermal expansions coefficients mismatch and over constraining
- Rapid change of IBL stave bowing distortion → addressed offline by dynamic track-based-alignment techniques

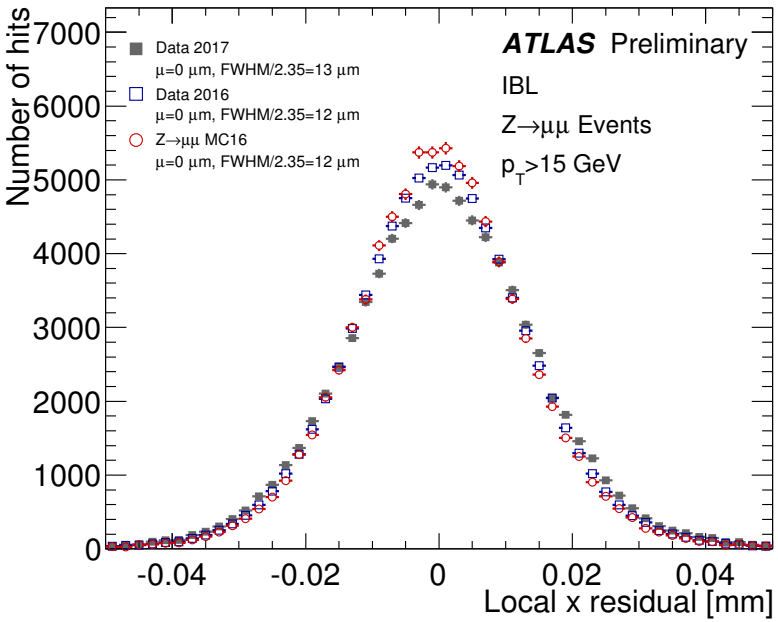


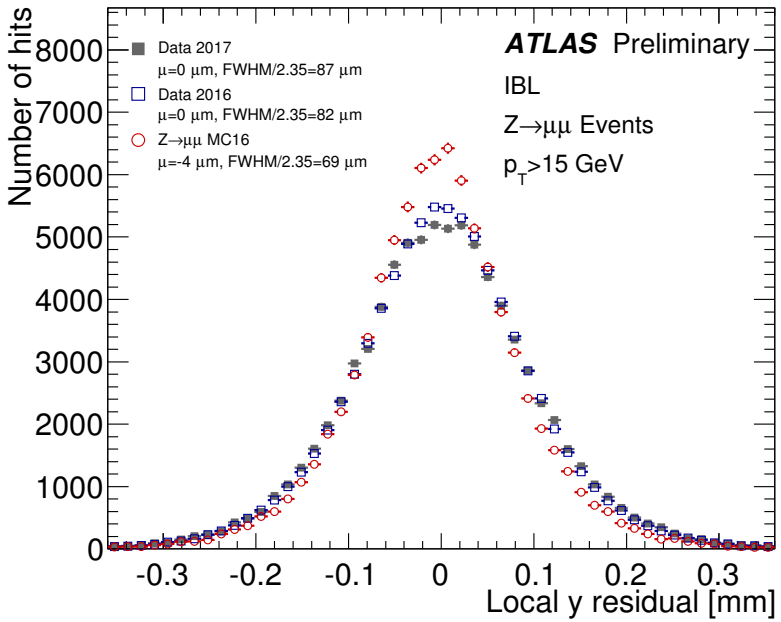






General Pixel-Tracking Performance in 2016





- Residuals obtained from $p_T \geq 15$GeV muon tracks from Z decays
- First 2017 data shows good aligment
- Improved agreement with MC Simulation after the introduction of the Bichsel Model
- Detector general

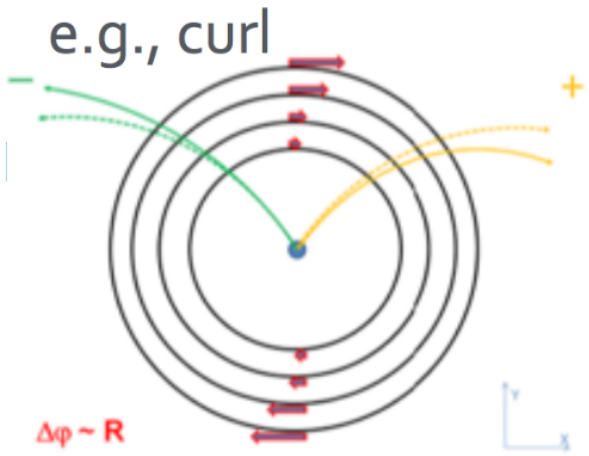
Weak Modes

- ID Alignment is NOT only IBL Alignment

- One of the challenges is the *weak-mode* reduction
- Track based alignment is insensitive to deformations that leave invariant the χ^2
- Use of external constraints such as standard candles (Z, J/ψ or K_S) or calorimeter information (E/p)

2015: Use of $Z \to \mu\mu$ events

- The two μ's must come from the same vertex: δ_{d_0} / δ_{z_0} constraints
- Imposing the Z mass corrects for p_T biases: δ_s
- Biases parametrised as a function of η and ϕ



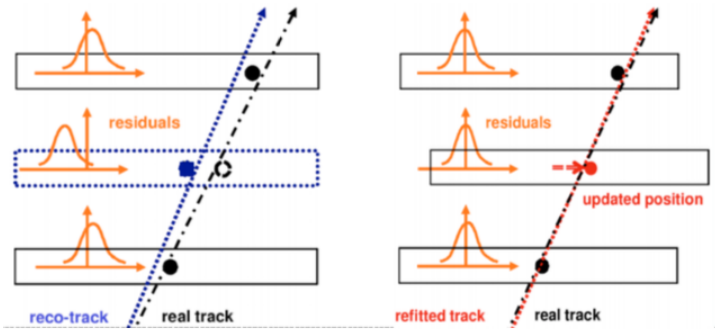
$$q/p \to q/p(1 + qp_T\delta_{\text{sagitta}})$$

$$\Delta(m^2) = \frac{m^2_{\text{rec}} - m^2_Z}{m^2_Z} \approx q_1 p_{T,1}\delta_{\text{sagitta},1} + q_2 p_{T,2}\delta_{\text{sagitta},2}$$

Align

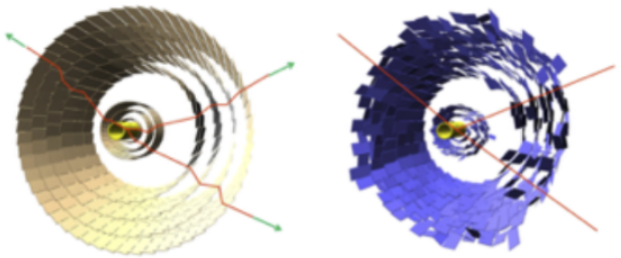
Aim:

- Correct the assumed ATLAS geometry to determine the actual relative positions of all active elements.



- **Track based technique** based on χ^2 minimisation
- $\chi^2 = \sum_{hits} \left(\frac{m_i - h_i(\vec{\alpha})}{\sigma_i} \right)^2$
  m_i measurements, h_i extrapolated hits, σ_i intrinsic resolution, $\vec{\alpha}$ align parameters

- Solve for small corrections iteratively



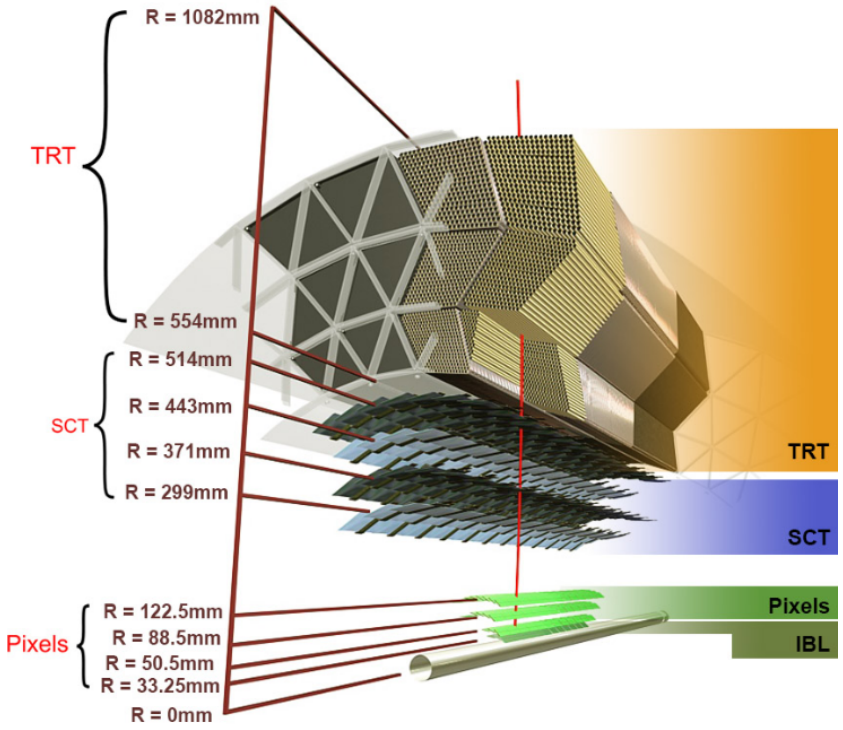
- Alignment is an iterative procedure, that adds corrections to a defined initial condition
- A basic tool to check the performance of the aligned solution is the *unbiased* track-to-hit residual.

Align

- Sub detectors are composed of silicon (pixel modules or microstrips) and gaseous drift tubes sub detectors

- Pixel System
- The Insertable B-Layer (IBL) (**NEW**)
- Silicon Tracker (SCT)
- Transition Radiation Tracker (TRT)

- Embedded in a 2T axial B Field
- Reconstruction of charged particles within $|\eta| < 2.5$



Subdetector	Element size	Intrinsic resolution [μm]	Radius barrel layers [mm]
IBL	50 μm×250 μm	8×40	33.45
Pixel	50 μm×400 μm	10×115	50.5, 88.5, 122.5
SCT	80 μm	17	299, 371, 443, 514
TRT	4 mm	130	from 554 to 1082

23

Align

- Innermost layer in the Pixel system between the B-Layer and the Beam Pipe
- Composed of 14 staves:
  - Inner Titanium cooling pipe
  - Readout service bus (stave flex)
  - Stave fixation mechanism:
    - A side can sling in z
    - C side blocked in z by a screw