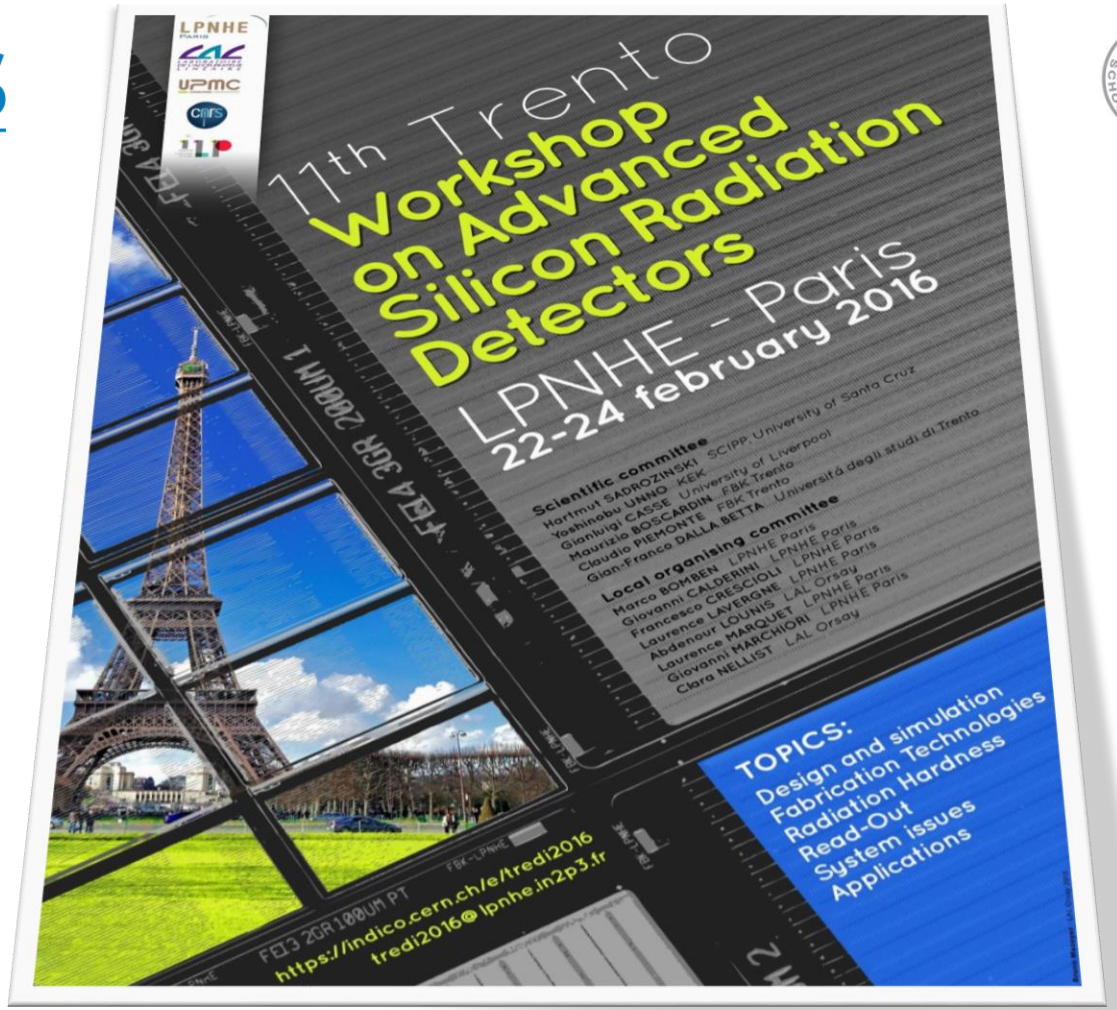
# The upgraded Pixel Detector of the ATLAS experiment for Run II




*D. Ferrère, Université de Genève*
on behalf of the ATLAS collaboration

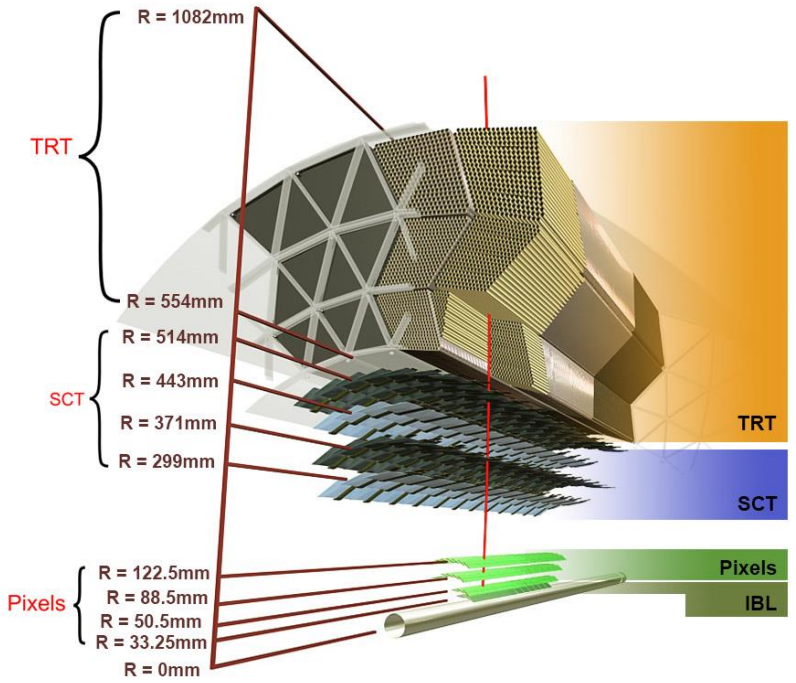
# ATLAS Inner Detector in Run II

**ATLAS Inner Detector** (ID) consists of 3 sub-systems:

- **Pixel** detector: silicon pixel modules
- **SCT** (Semiconductor Tracker): silicon micro-strip modules
- **TRT** (Transition Radiation Tracker): gaseous drift tube

**ID main or new features:**

- Embedded in a 2T solenoid field (axial)
- Reconstruction of charged particle tracks within $|\eta| < 2.5$
- An innermost Pixel layer has been added in 2014 during LS1 called IBL

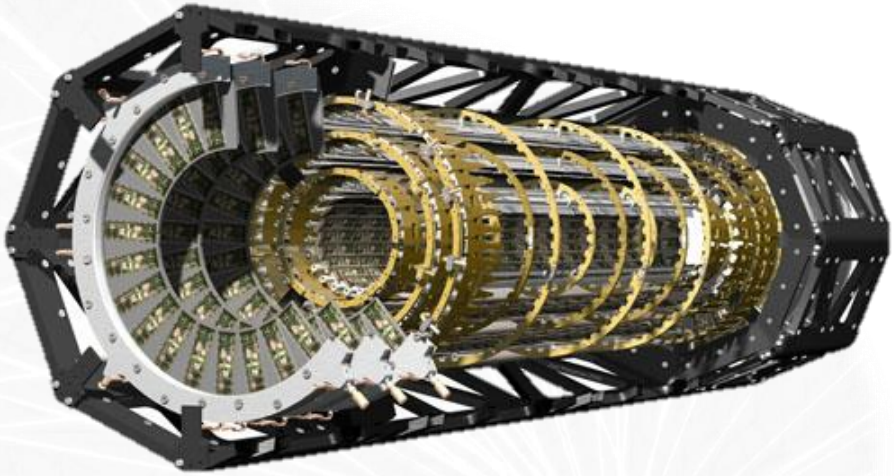



| Subdetector | Element size/Radius | Intrinsic resolution [µm] | Barrel layer radii [mm] |
|---|---|---|---|
| IBL | 50 µm x 250 µm | 8 X 40 | 33.3 |
| Pixel | 50 µm x 400 µm | 10 X 115 | 50.5, 88.5, 122.5 |
| SCT | 80 µm | 17 | 299, 371, 443, 514 |
| TRT | 4 mm | 130 | from 554 to 1082 |

# Pixel Detector as Built in Run 1

**Pixel detector as built and operated during Run 1**
**→ 3 space points in the innermost tracking volume**

- 3 barrel layers at ~5, 9 and 12 cm from IP
- 3 disks on each side $9 \leq r \leq 15$ cm
- Same module layout used everywhere
- Module size: 62.4 mm long X 21.4 mm wide
- Module read out by 16 FEI3 chips, each serving an array of 18 by 160 pixels
- An area of ~1.7 m2 for ~80M pixels



**Pixel detector was operating extremely well during Run 1**

**However some concerns remained:**

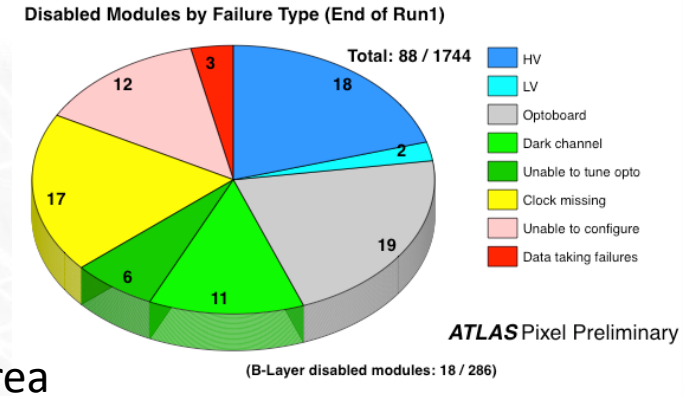
1. The number of defective modules growing after thermal cycling – up to 5% at the end of Run1
2. The potential degradation of opto-elements in a non-accessible location
3. B-layer occupancy limitation and long term radiation damage of the Si-sensors
4. The band width limitation of the other 2 barrel layers

During LS1 an ambitious but **successful program** was addressed to improve the Pixel detector robustness

# Pixel Improvements

**Beneficial visible impact** → Module defects

- 2008 (Run 1 start): 2.5%
- 2013 (Run 1 end): 5.0% (88 of 1744 modules)

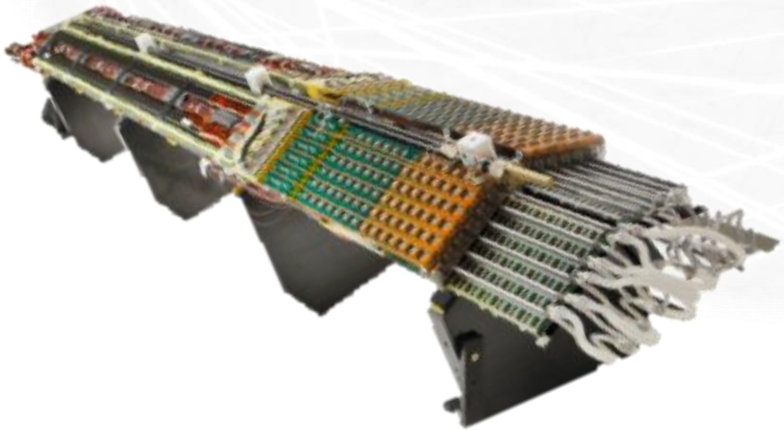



**Replacement of Service Panels** (nSQP) allowed:

- Repairing accessible module defects
- Moving opto-electronic conversion to an accessible area
- Adding optical fibers to increase the bandwidth
- Adding Diamond Beam Monitor (DBM) telescope

*While keeping the detector untouched*

**nSQP as built**



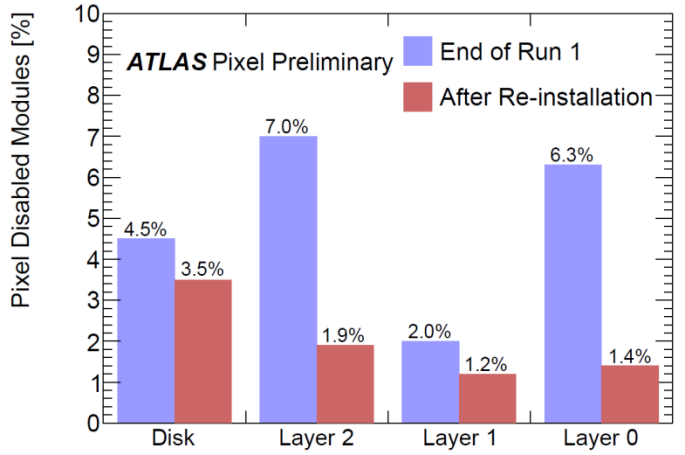
# Pixel Improvements – con't

**Pixel Refurbishment during LS1:**

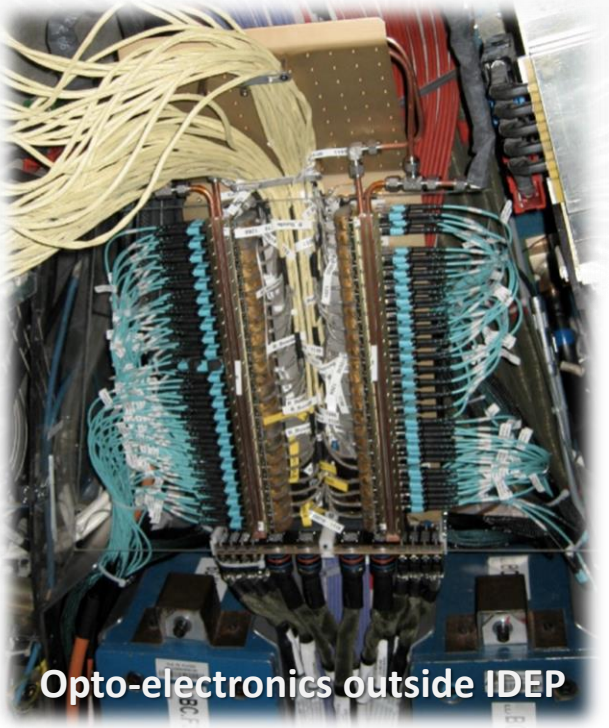
- April - Dec 2013: Pixel on surface
- 75% of defective modules repaired
- Jan - April 2014: Electrical and service reconnection

→ **Status for Run 2 (2015)**

98% of modules stable and working




**Pixel insertion after nSQP refurbishment end of 2013**



# IBL – Insertable B-Layer

*Pixel detector originally designed to replace innermost Pixel layer called B-Layer*

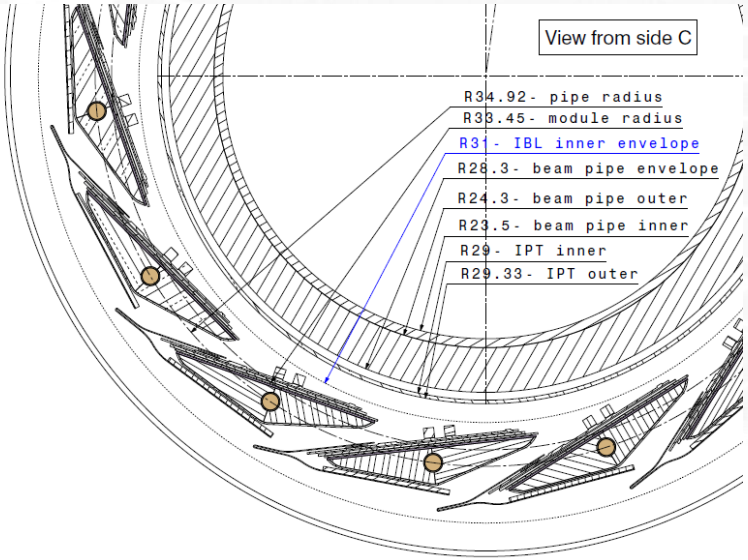
**Reduced LHC beam pipe radius** (OD of 24.3 mm) **offers new options:**

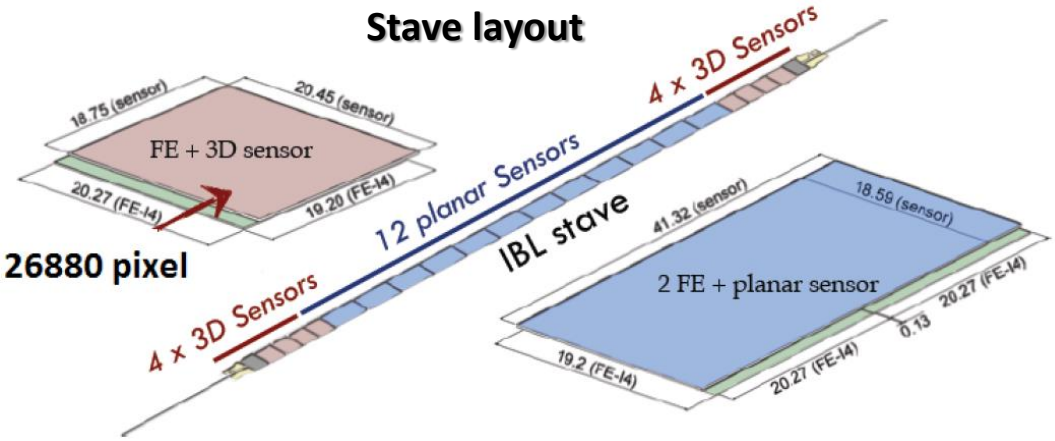
- Insert a 4th layer for "B"-jet tagging inside Pixel detector: IBL
- Improved tracking performance and robustness
- Improvements to sensors, front-ends, back-ends, module design, cooling

**IBL description:**

- **14 staves overlapping in phi**, surrounding beam pipe at ~3.3 cm from the beam axis
- **0.13 m²** of silicon surface and **12M** of readout channels
- **Instrumented stave** (32 FE chips) consists of **12 planar** and **8 3D** sensor modules **along 664mm**
- **IBL package** of 7 m long and **inside only an envelope of 10 mm radius** (clearance < 1mm)

**IBL cross section view**




*For 3D sensors → Ref. S. Grinstein's talk yesterday*

# Main IBL Features

## Sensor

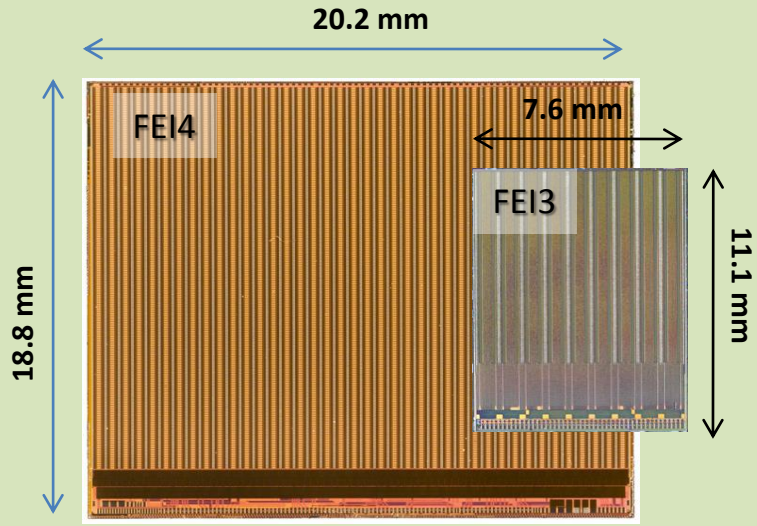
3D and planar technology are used in combination on the same stave

| Features | Planar | 3D |
|---|---|---|
| Thickness (nominal) [μm] | 200 | 230 |
| Depletion voltage [V] | ~50 | 10 - 25 |
| Working voltage after LHC fluence ($5x10^{15}$ 1MeV $n_{eq}/cm^2$) [V] | ~1000 | ~160 |
| Pixel [FE x Row x Column] | 2x336x80 | 1x336x80 |
| Active size WxL [$mm^2$] | 16.8 x 40.9 | 16.8 x 20.0 |
| Inactive edge along beam axis [μm] | 200 | 200 |

## FE readout

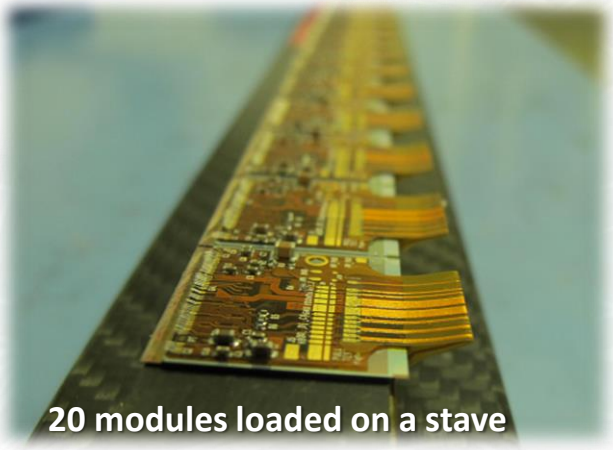
**FEI4 main features:**

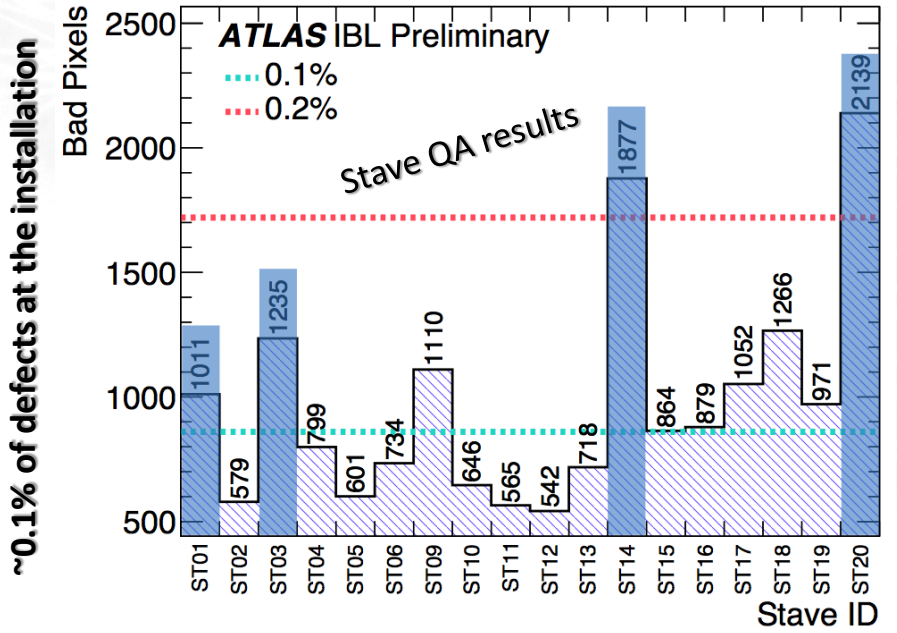
- IBM (130 nm)
- 70 Million transistors
- 26880 pixels (50 x 250 $\mu m^2$)
- Lower noise than FEI3 (~150e- with sensor)
- Lower threshold operation
- Higher rate capability
- Radiation hard to >250Mrad
- In use for pixel R&D and towards Upgrade phase2

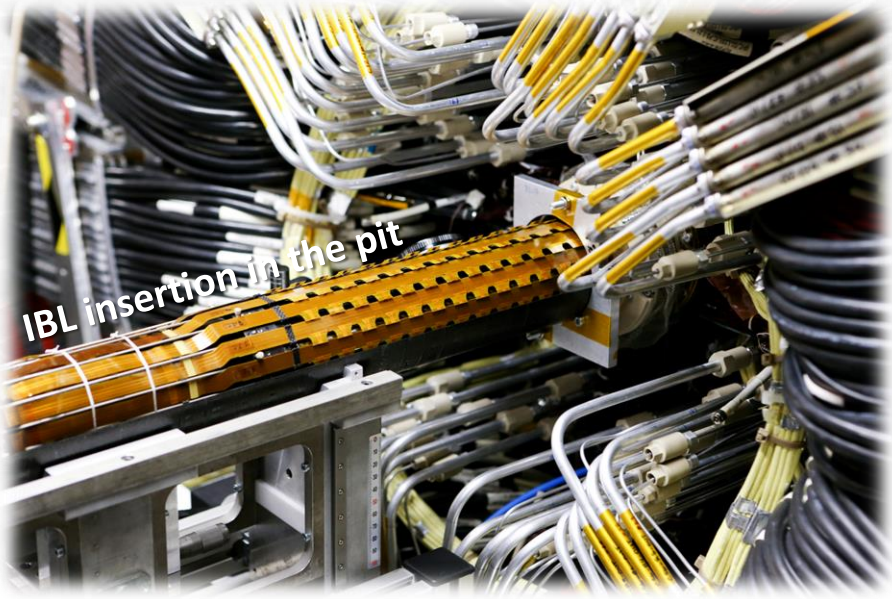


# IBL Project on Very Fast Track

R&D and prototyping: ~3 years
Production, integration, and installation: ~2 years



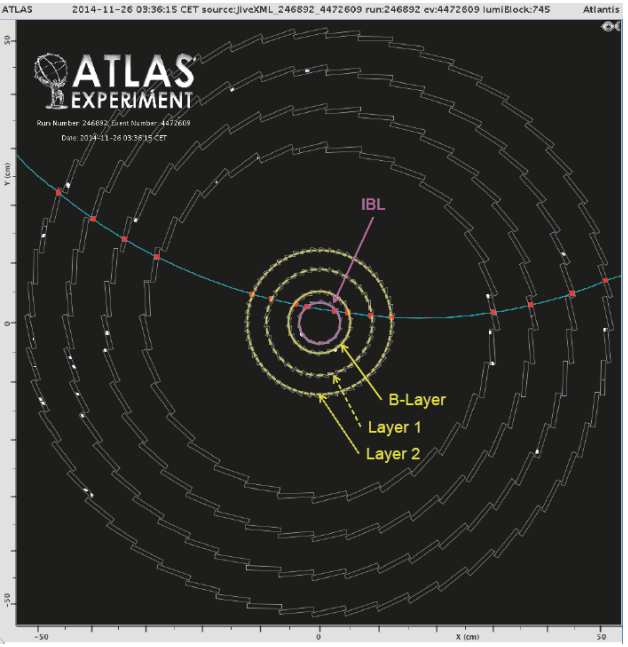


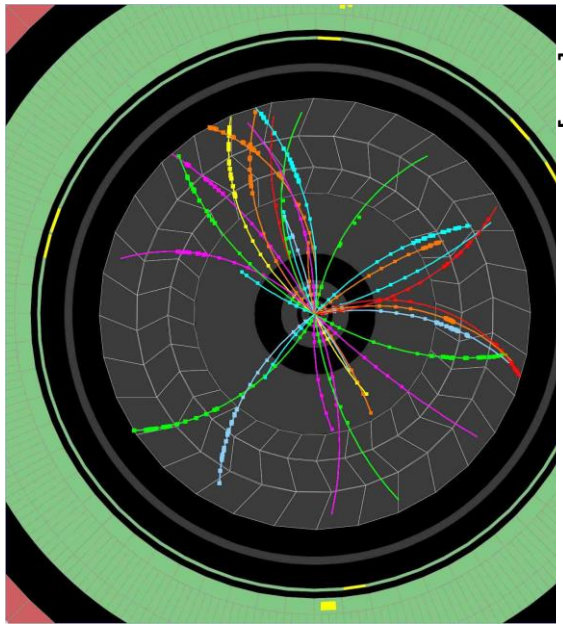
# IBL Commissioning in ATLAS

- Aug 2014 – March 2015: Integration into ATLAS DAQ, Cosmic data taking with 2T B- field
- October 2014: LHC beam pipe bake-out @ 230 °C & IBL < 0°C, stable $CO_2$ cooling
- May 2015: First low luminosity, "Quiet Beam" collisions to commission experiment

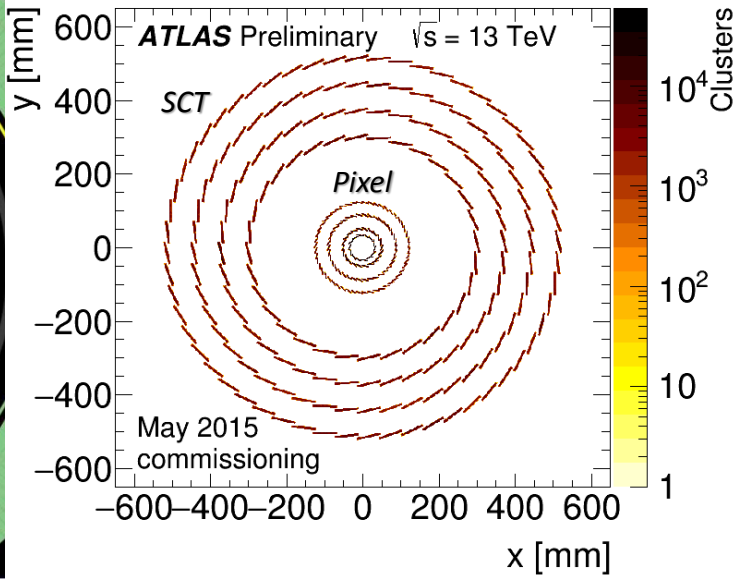
**Cosmic track reconstructed in 4 pixel layers**



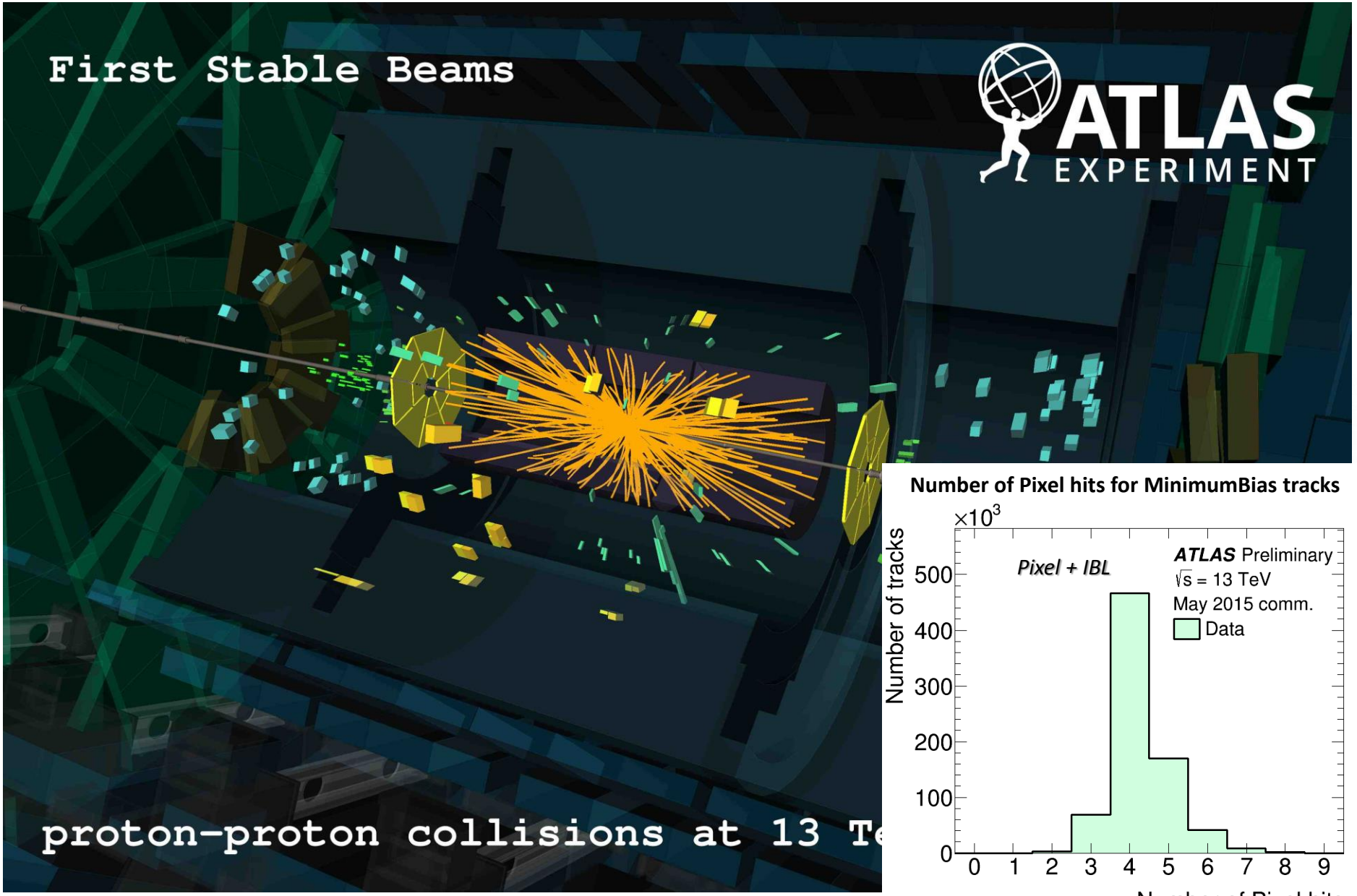

**900 GeV pp collisions during beam commissioning in May 2015**



**13 TeV pp collisions during beam commissioning in May 2015**



# pp collisions at 13 TeV in 2015



# pp Collisions at 13 TeV in 2015

- 1st stable beam with pp collisions at 13 TeV: June 3rd
- Smooth luminosity ramp up until August
- Most of the integrated luminosity delivered from mid of September to November
- Good for physics:
  - 2015 – Run 2: 3.3 $fb^{-1}$ $\sqrt{s}$ = 13TeV
  - 2012 – Run 1: 20.3 $fb^{-1}$ $\sqrt{s}$ = 8TeV
  - Expected integrated luminosity for this year 30 $fb^{-1}$
- Excluding 2 runs (0.2 $fb^{-1}$) when IBL was OFF, IBL + Pixel efficiency was ~98% → Comparable to Run 1

**ATLAS pp run: June-August 2015**

| Inner Tracker | | | Calorimeters | | Muon Spectrometer | | | | Magnets | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pixel | SCT | TRT | LAr | Tile | MDT | RPC | CSC | TGC | Solenoid | Toroid |
| 98.5 | 99.7 | 100 | 99.1 | 100 | 100 | 99.3 | 100 | 100 | 100 | 99.6 |

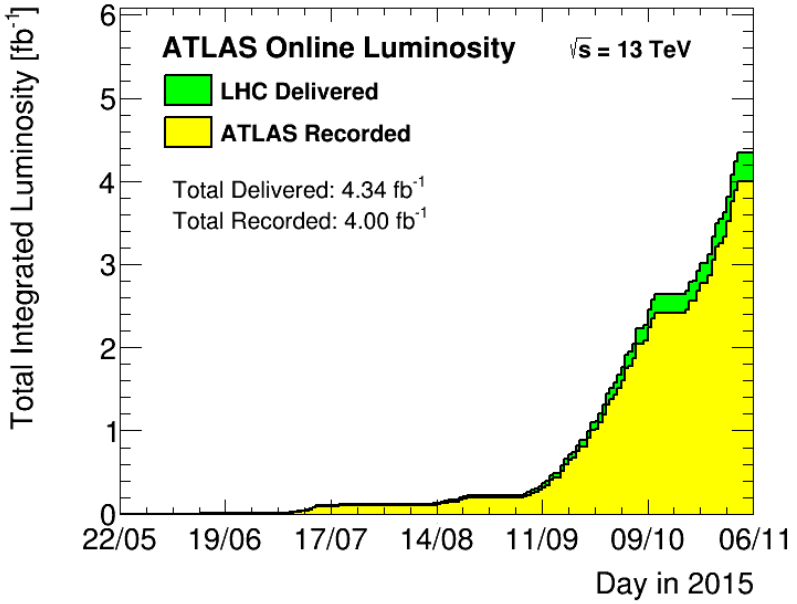
Luminosity weighted relative detector uptime (in percent) and good quality data delivery during the stable beams in pp collisions at 13 TeV between June-August 2015, corresponding to 173 $pb^{-1}$ recorded luminosity.

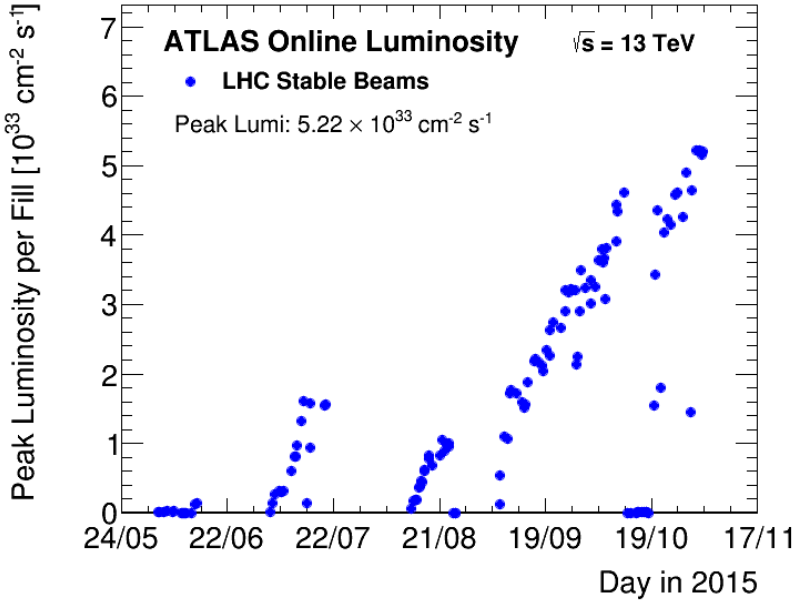
**ATLAS pp run: August-November 2015**

| Inner Tracker | | | Calorimeters | | Muon Spectrometer | | | | Magnets | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pixel | SCT | TRT | LAr | Tile | MDT | RPC | CSC | TGC | Solenoid | Toroid |
| 93.5 | 99.4 | 98.3 | 99.4 | 100 | 100 | 100 | 100 | 100 | 100 | 97.8 |

**All Good for physics: 87.4% (3.3 $fb^{-1}$)**

Luminosity weighted relative detector uptime and good data quality (DQ) efficiencies (in %) during stable beams in pp collisions with 25ns bunch spacing at √s=13 TeV between August-November 2015, corresponding to an integrated luminosity of 3.8 $fb^{-1}$. The lower DQ efficiency in the Pixel detector is due to the IBL being turned off for two runs, corresponding to 0.2 $fb^{-1}$. Analyses that don't rely on the IBL can use those runs and thus use 3.5 $fb^{-1}$ with a corresponding DQ efficiency of 93.4%.

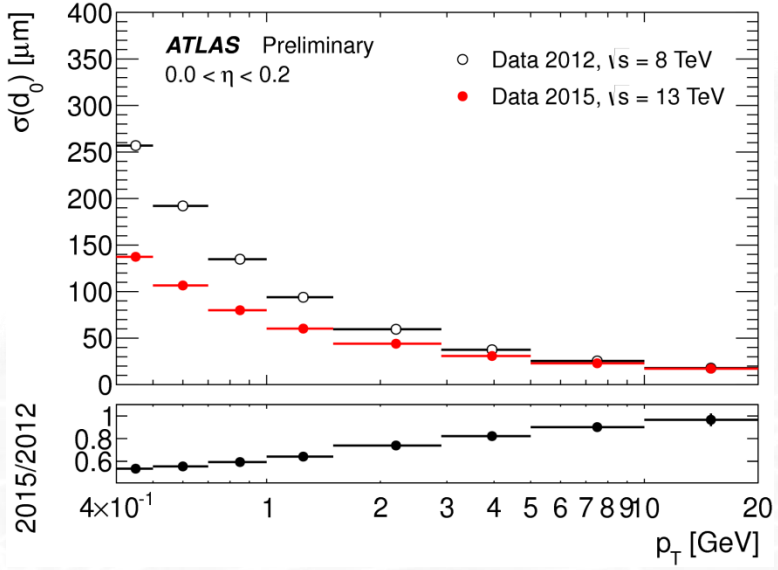


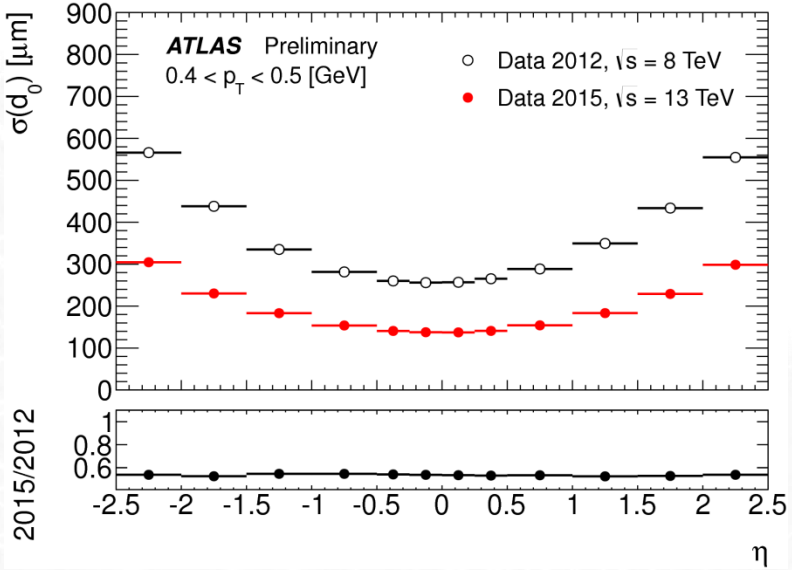



# IBL Improves Tracking Performance

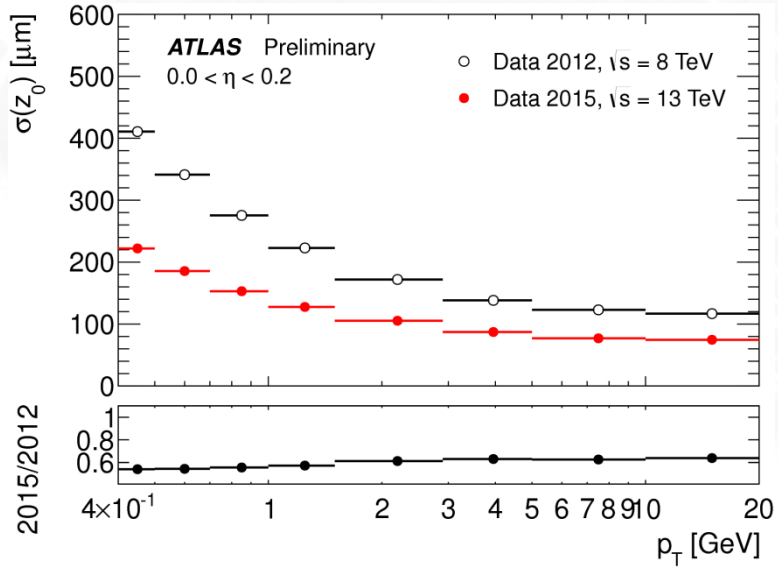
Comparison of Run 1 and Run 2 impact parameter resolution

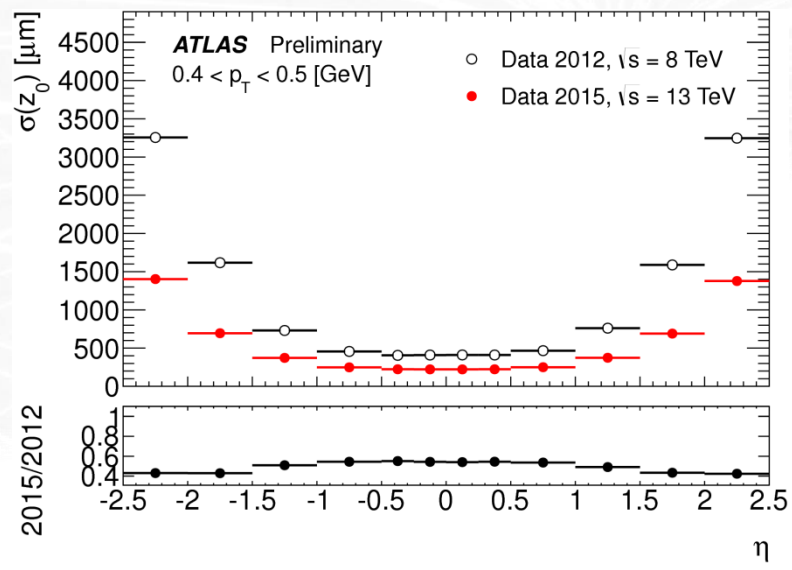
Transverse impact parameter



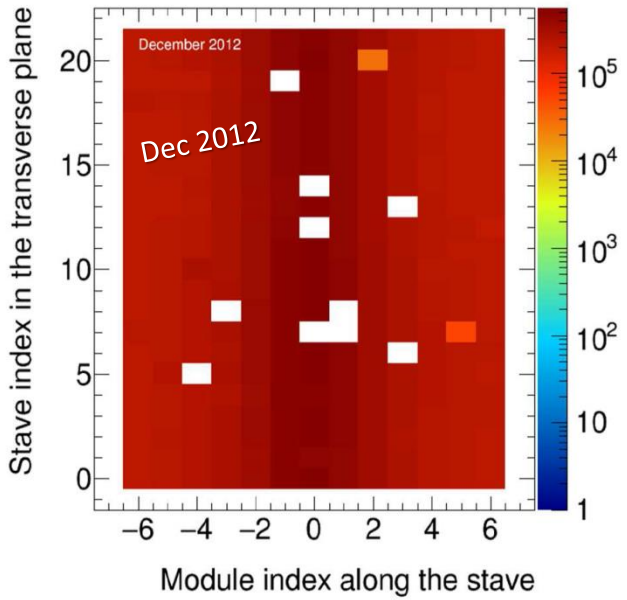

Longitudinal impact parameter

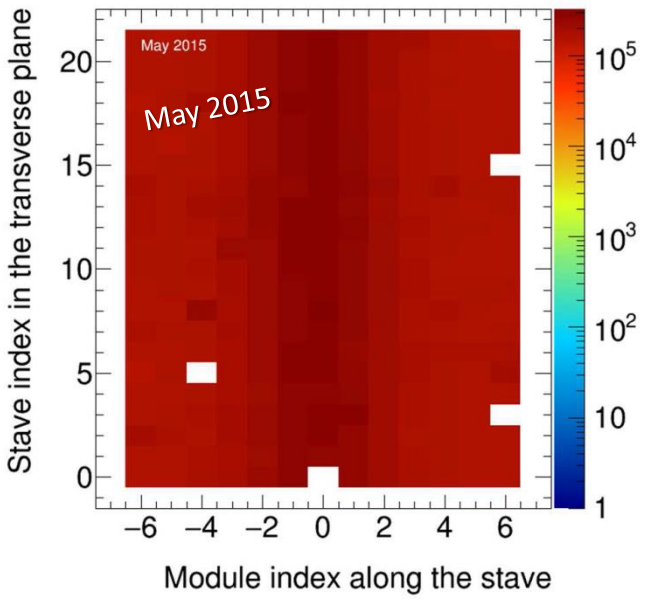


# Pixel Module Defects During Data Taking

*B-Layer cluster occupancy per module at the end of run I versus beginning of run II*

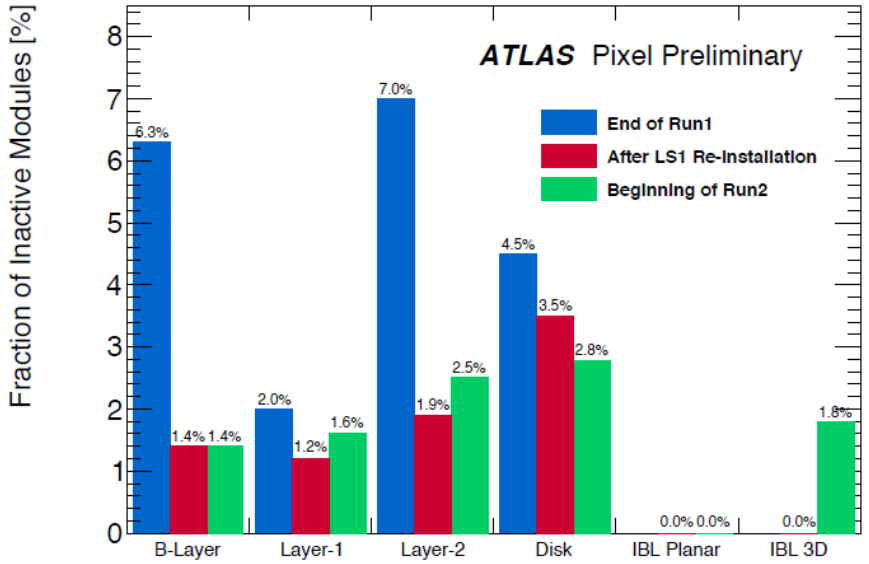



***Confirmation with data of Pixel module defect improvement made during LS1***

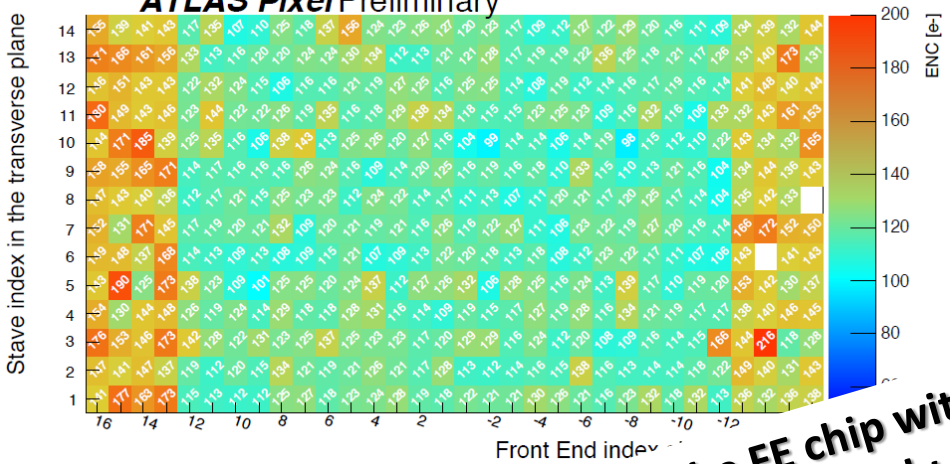
Fraction of inactive modules for each component of the ATLAS pixel detector at the end of Run I, after LS1 re-installation and at the beginning of Run II

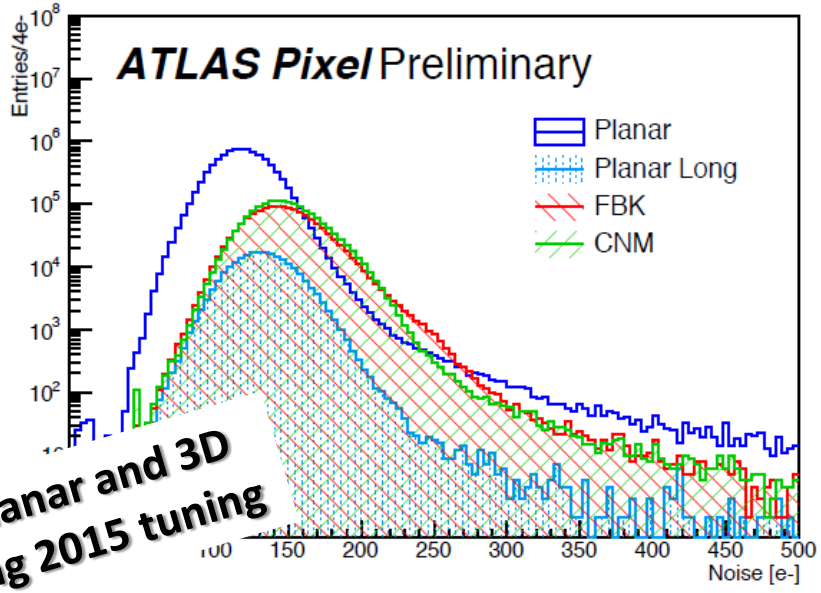
IBL: 99.5%
Pixel: 98.0%



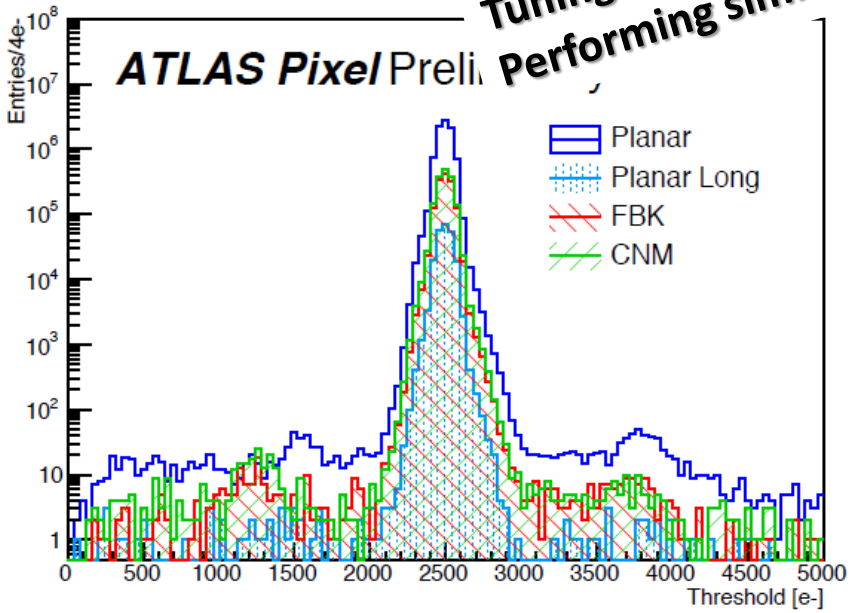
# IBL – Planar and 3D modules fully Operational

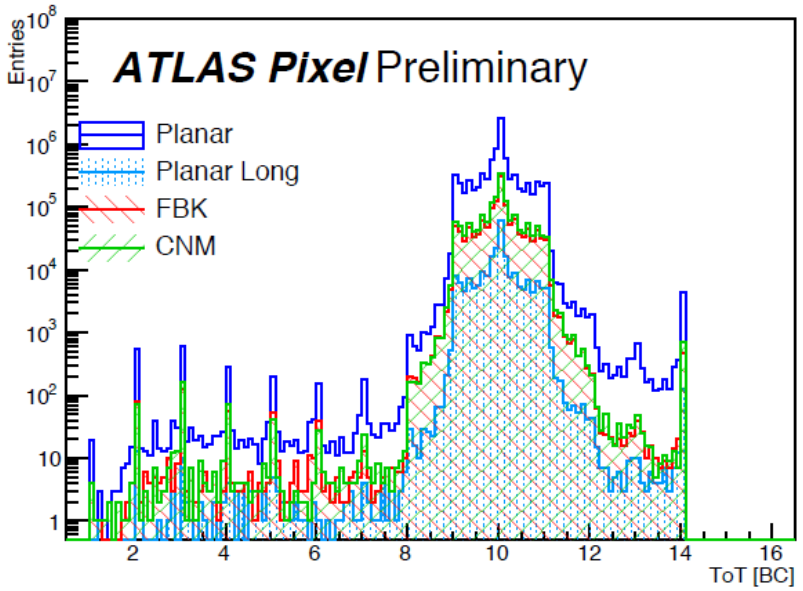
**Noise distribution after re-tuning – Run-2 in 2015**




**Tuning the FE chip with planar and 3D Performing similarly along 2015 tuning**

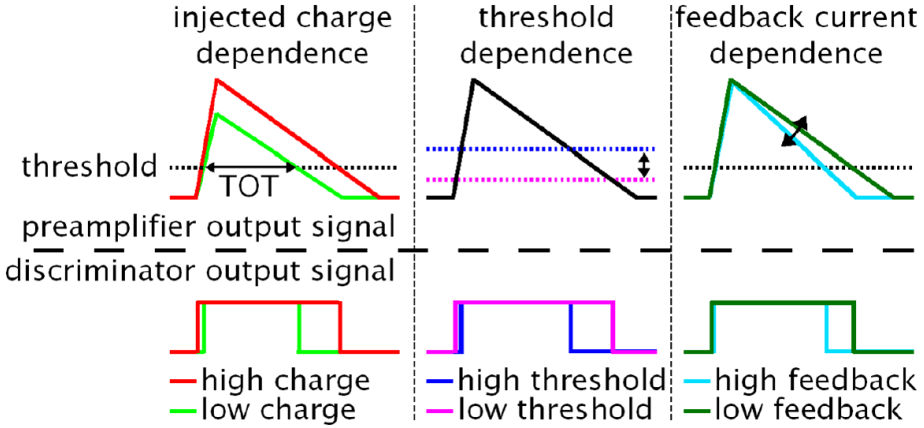


# Time over Threshold

**Time-over-Threshold** (ToT) provides measurement of **deposited charge** :

- Measured in unit of Bunch Crossing (BC) time (25ns) for every pixel hit
- Converted to charge via the calibration made at the FE injection circuit

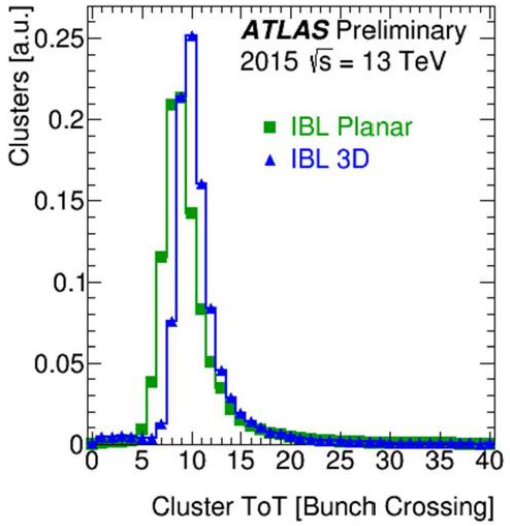



**The charge measurement is used for:**

- Tracking: Neural Network (NN) cluster seeding improvement of residuals
- Specific ionization dE/dx

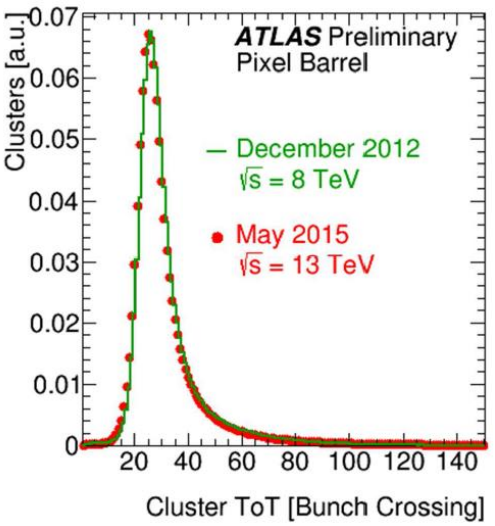
→ Some physics studies like SUSY and Exotics

**IBL cluster ToT**
Calibration for 1MIP at 10BC




Sensor thickness:
- Planar 200 µm
- 3D 230 µm

**Pixel barrel cluster ToT**
Calibration for 1MIP at 30BC

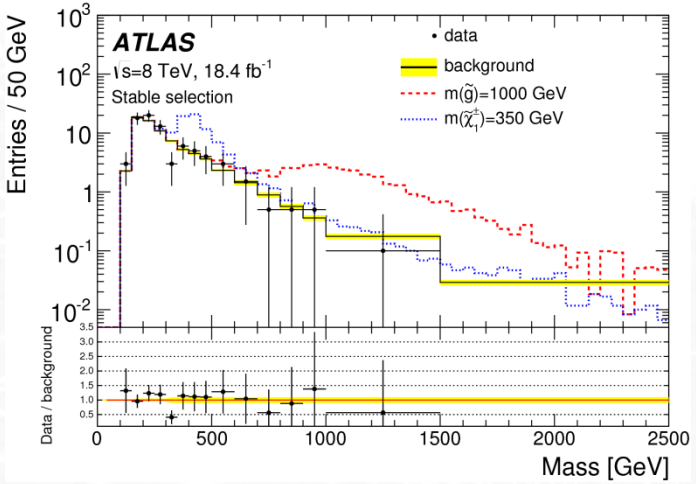


# Energy Loss and related studies

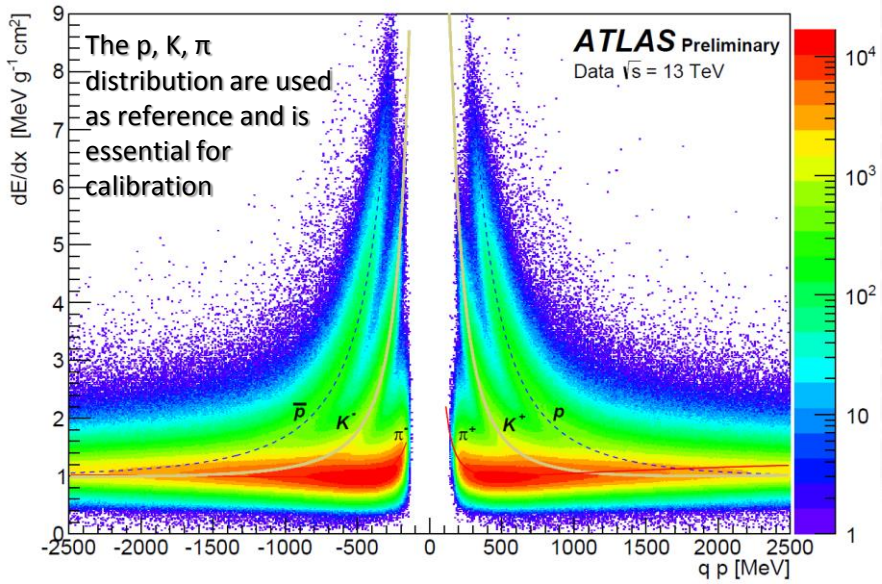
**The dE/dx study is essential for metastable heavy charged particles with large ionization energy loss**

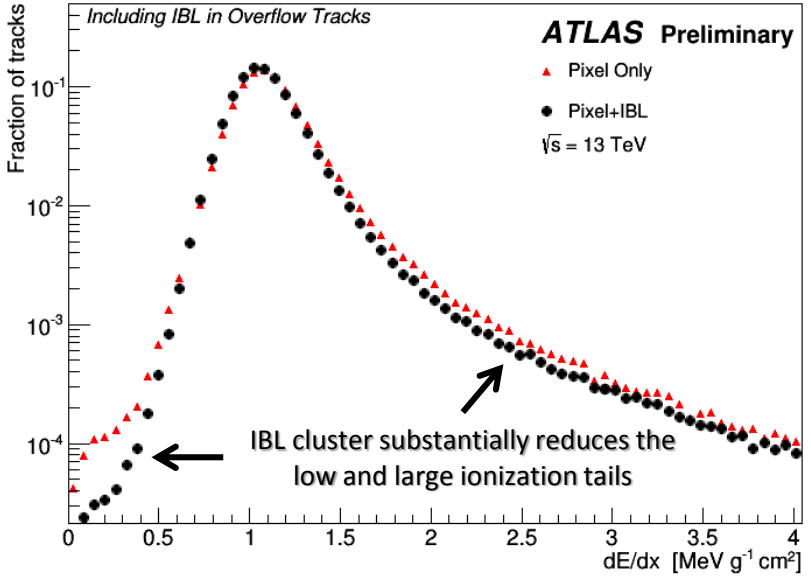
Search for metastable heavy charged particles with large ionization energy loss in pp collisions at 8 TeV during Run 1
Eur.Phys.J. C75 (2015) 407 (2015-09-03)

**→ New results using Run 2 2015 data will be published in few weeks**




Energy loss measured in the Pixel detector with improvement in Run 2 using IBL data

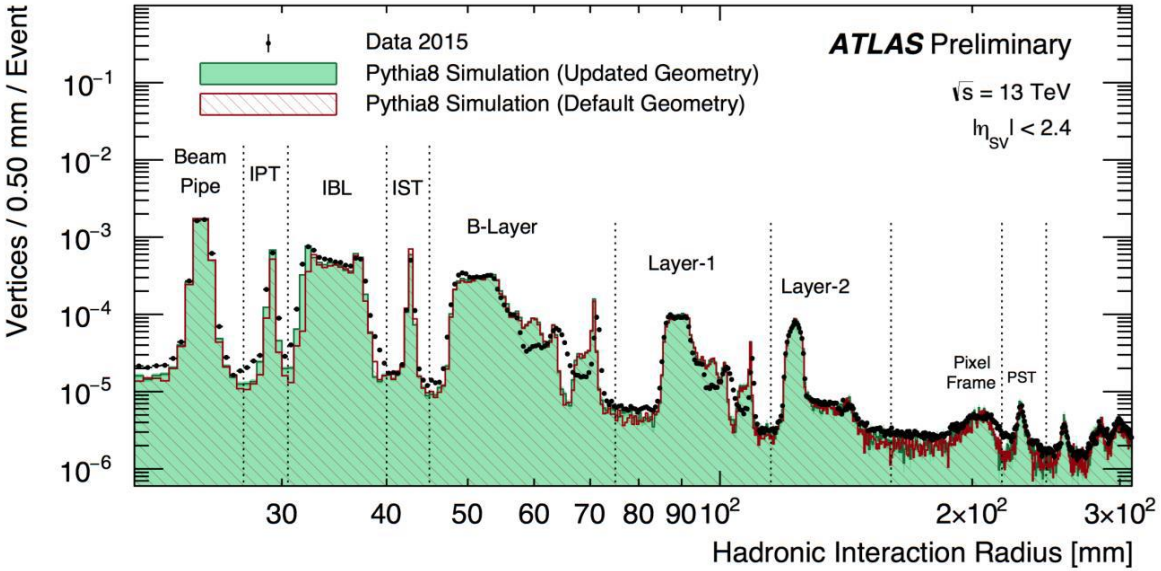


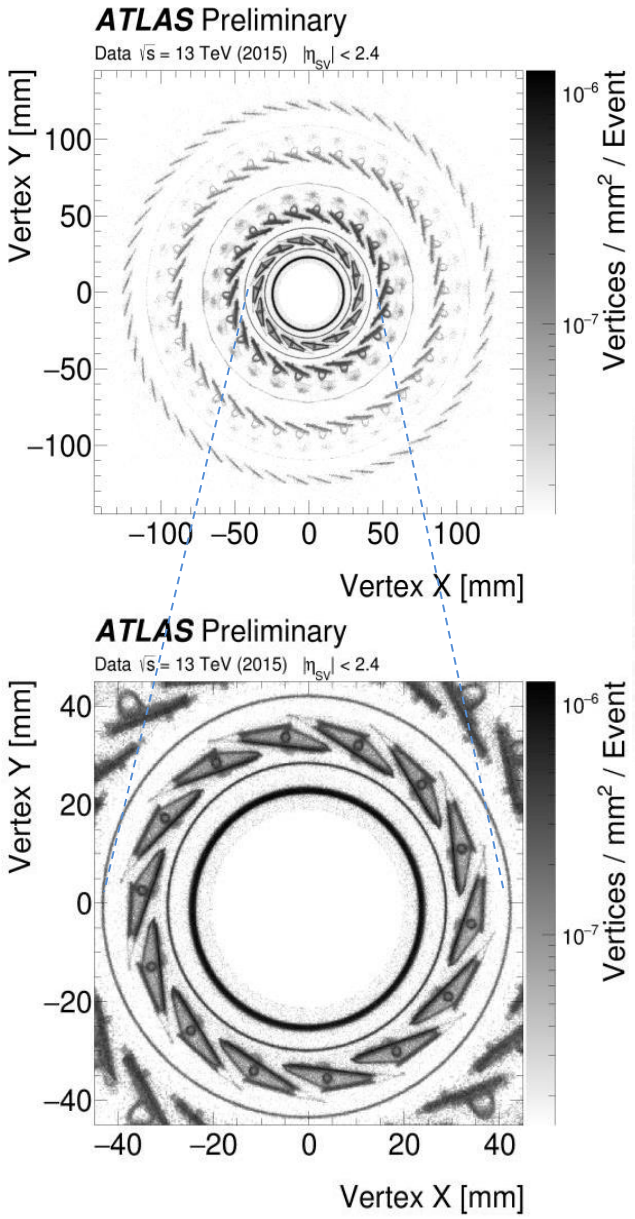



# Material Study in the Pixel Detector

- Detailed mapping of material in Pixel detector using
  - Hadronic interactions
  - Photon conversions
- Iterative geometry description and MC to data comparison to reach a good agreement with 2015 data
- SCT extension efficiency allows to probe the forward Pixel services (nSQP)

→ **Results published** ATL-PHYS-PUB-2015-050



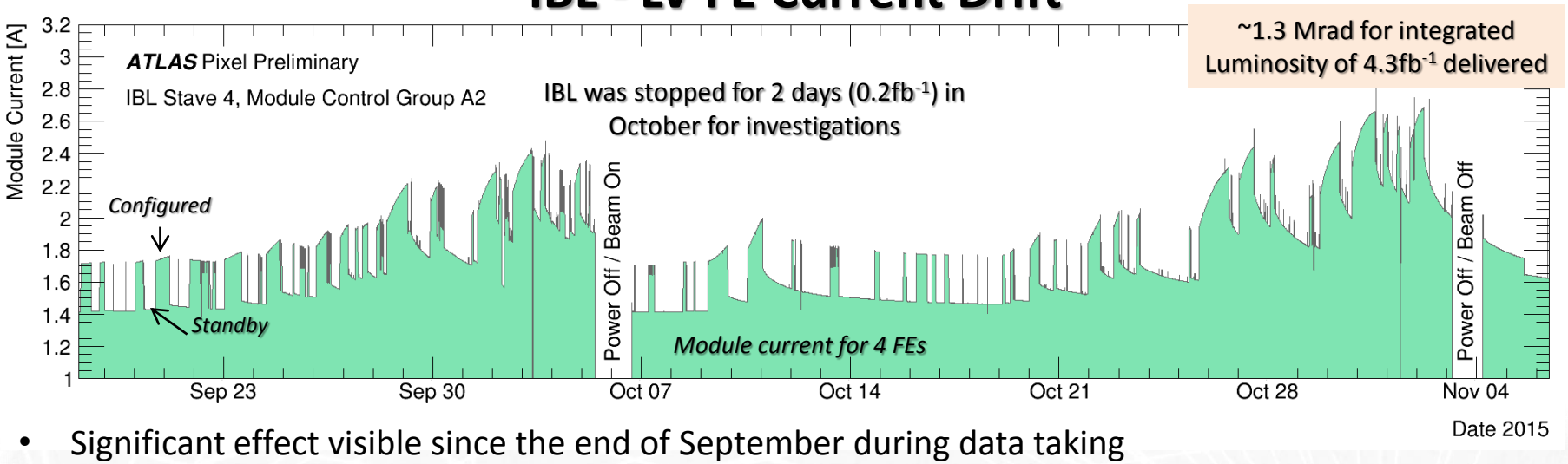
# IBL Challenges

**IBL is a new detector built relatively quickly and with a short R&D time**
**An excellent test bed for next generation silicon tracker for HL-LHC**

**Challenges met during production, integration, commissioning and operation:**

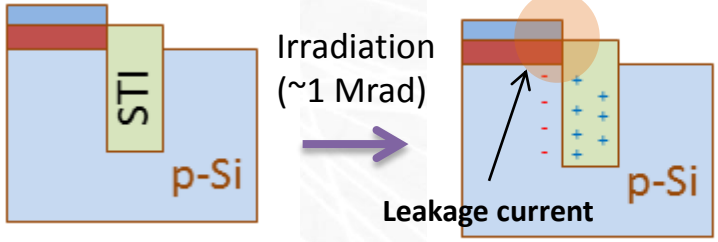
- **Bump bonding issue:** intolerable amount of open and short pixels discovered at an early stage of the production
  - consequences: delay and cost
- **Wire bond corrosion:** Met in the middle of the stave loading production
  - consequences: delay and extra work load
- **Type 1 service** Cu-clad Al wire crimping issue → led to use Cu-wire
  - Consequence: More material in the forward region
- **Wire bond oscillation** → led to implement protection mechanism into the readout chain
  - Consequence: dead time when machine is not fully filled leading to possible trigger limitation
- **IBL distortion:** discovered during cosmic run commissioning period
  - Consequence: tracking is affected →Mitigated by alignment correction
- **FE LV current drift:** Discovered in September 2015 during data taking
  - Consequences: Module trip (or disabled) and rather "chaotic" temperature increase + frequent FE retuning → distortion + risk on detector integrity

# IBL - LV FE Current Drift

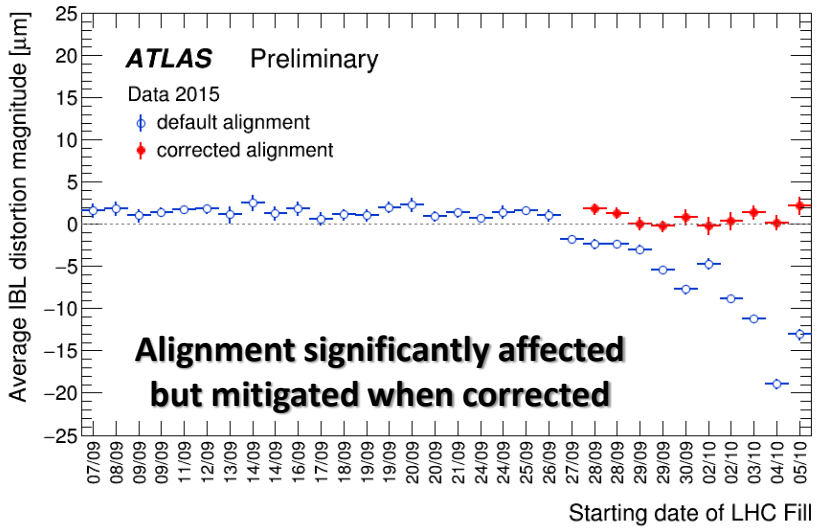



- Significant effect visible since the end of September during data taking
- Understood to be a FE N-MOS transistors leakage due to defects built-up at the Silicon Oxide (STI) interface and cumulated by ionizing dose → Known features but not tagged during construction
- It is an effect that is related to dose rate (traps built-up at the STI) and temperature (annealing)
- Lab investigations are ongoing → operational recommendations are expected

**N-MOS transistor cross section**




*IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 52, NO. 6, DECEMBER 2005*




**Consequences:**
- Temperature increase → Distortion
- LV current rising → Electrical failure risks
- Drift of FE tuning (TOT, Threshold) → often to be retuned

# Conclusions

- Significant **Pixel upgrades** took place during **LHC 1st long shutdown**:
  - **Pixel nSQP**: led to improve a number of defective modules
  - **IBL**: new innermost layer as close as 3.3 cm from the IP

- Pixel was re-installed in the pit end of 2013 while IBL installation took place in May 2014

- **IBL is a nice jewel for ATLAS** and towards ITK for HL-LHC leading to **improved tracking performances.**

- **LHC Run 2 with 13 TeV pp collisions started at the beginning of June 2015** with **successful** data taking for ATLAS Pixel and IBL → also opening a new era for physics searches

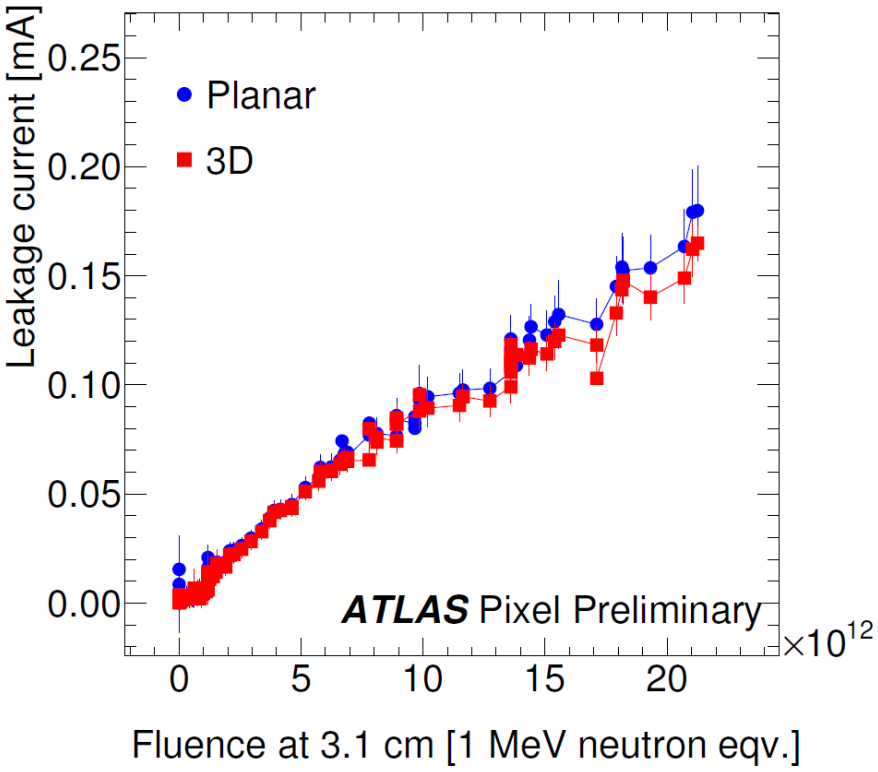
- IBL met various issues affecting the operation and alignment but there was always a solution to mitigate the effect thanks to a lot of dedication inside our community

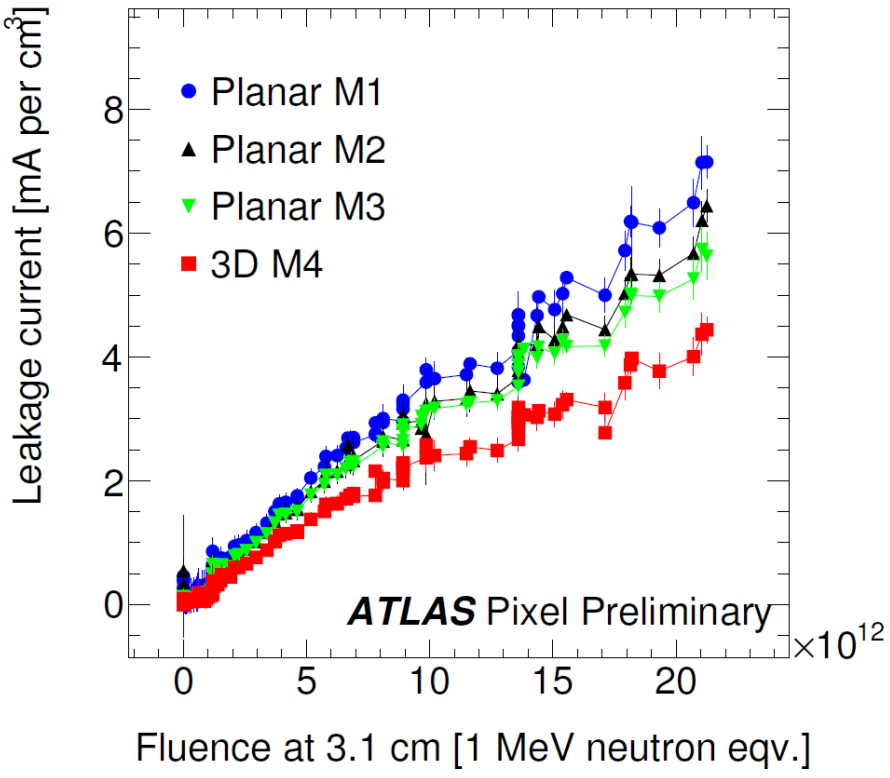
- ATLAS and Pixel is now getting prepared and upgraded during this Winter Shutdown to take data in **2016 with significantly more integrated and instantaneous luminosity** than last year

*Many thanks for your attention*

# IBL sensor leakage current

**Leakage current evolution aduring 2015 data taking and with a maximum integrated luminosity of 4.2 fb-1**

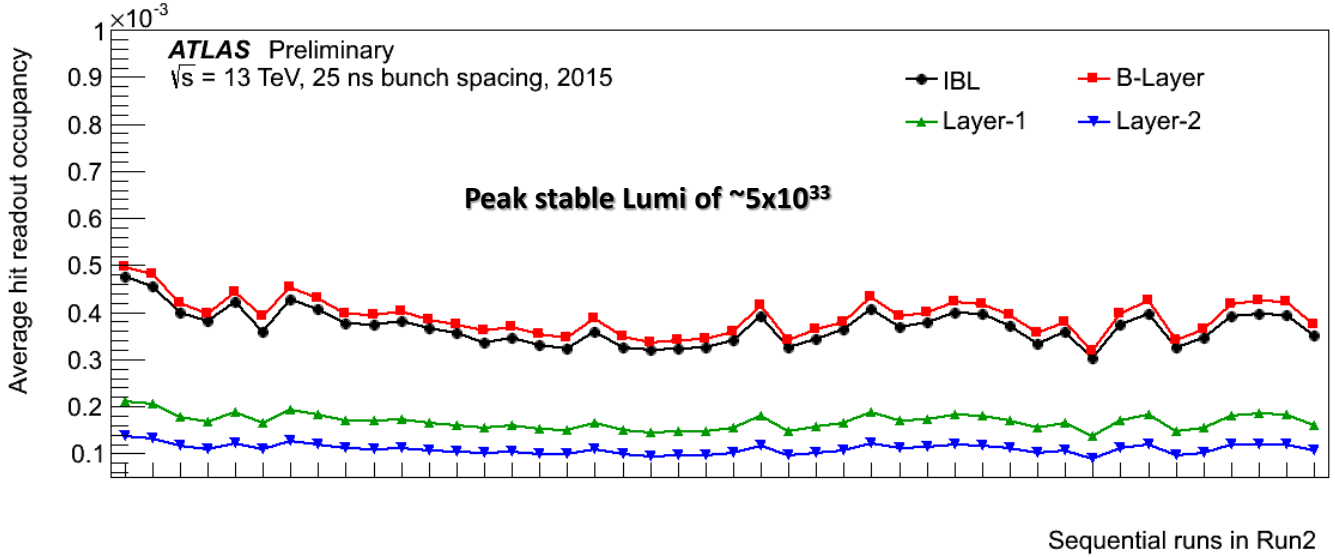



M1, M2, M3 and M4 are the module group Id from the center toward the stave extremities

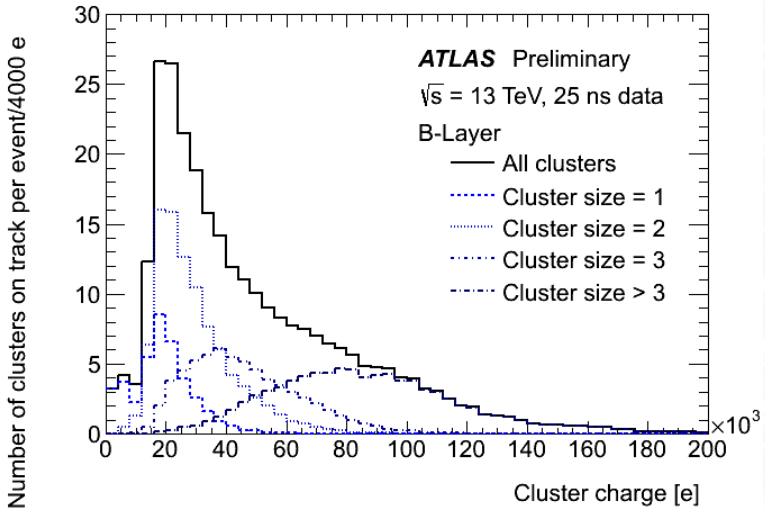
Conversion from Fluka simulation for IBL at 3.3cm is $6 \times 10^{13}$ 1MeV $n_{eq}$ for 10 $fb^{-1}$

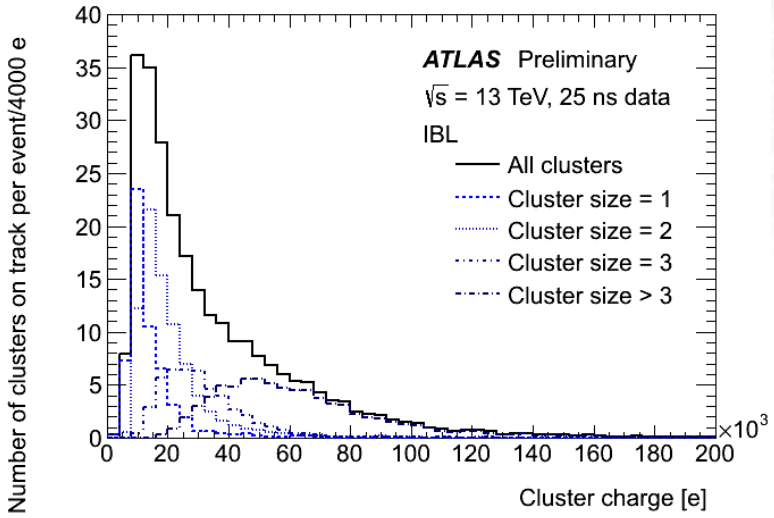
# Detector occupancy and charge




B-Layer: ~19 hit/ readout link

IBL: ~11 hit/ readout link




Peak is expected at 20ke and 16ke for Pixel and IBL respectively
which is related to the sensor thickness difference (250 vs 200 µm)

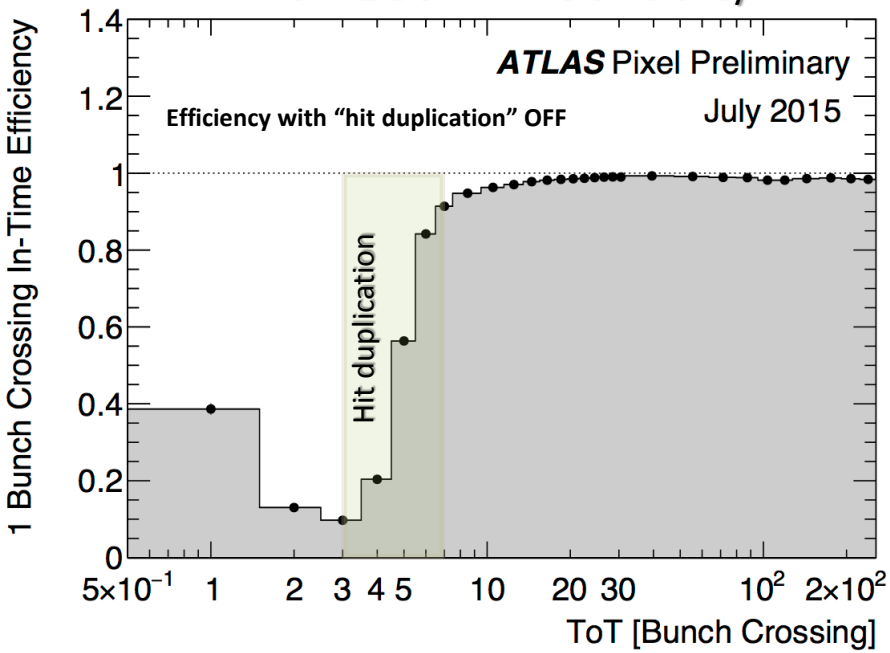
# Pixel and IBL Timing adjustment

The FEI3 (Pixel) and FEI4 (IBL) frontends have slightly different features with respect to the ToT information:

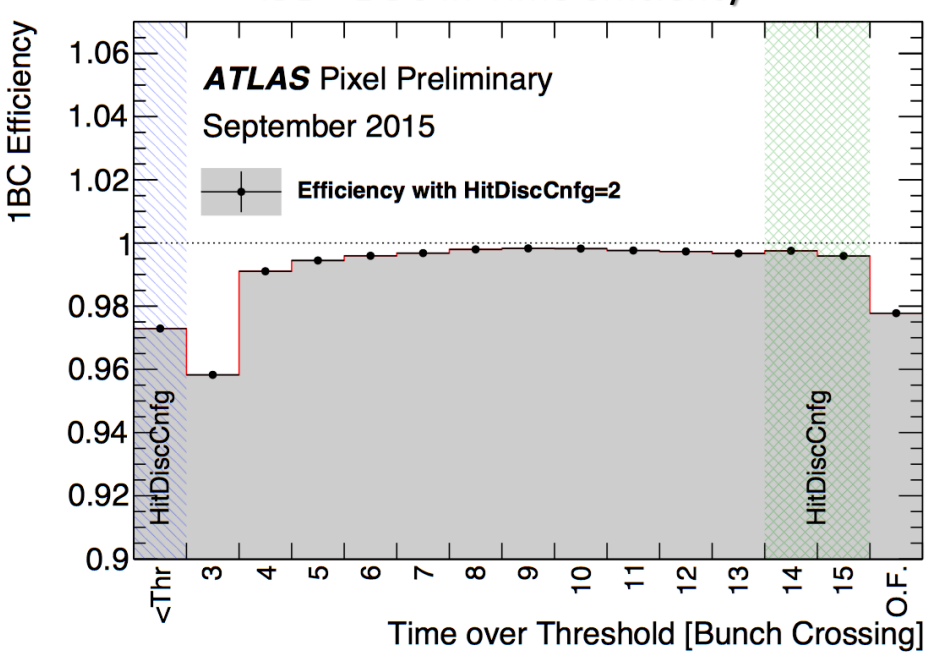
- 4 bit for IBL and 8 bit for respectively Pixel
- Hit copy mechanism is different but mainly allows to recover low ToT hits that have a time walk in the next BC

- ToT reading must be adjusted with the proper time walk for the In-Time efficiency
- Test scans are done with many consecutive BCs to optimally adjust each of the readout links and maximizing Pixel and IBL performance.

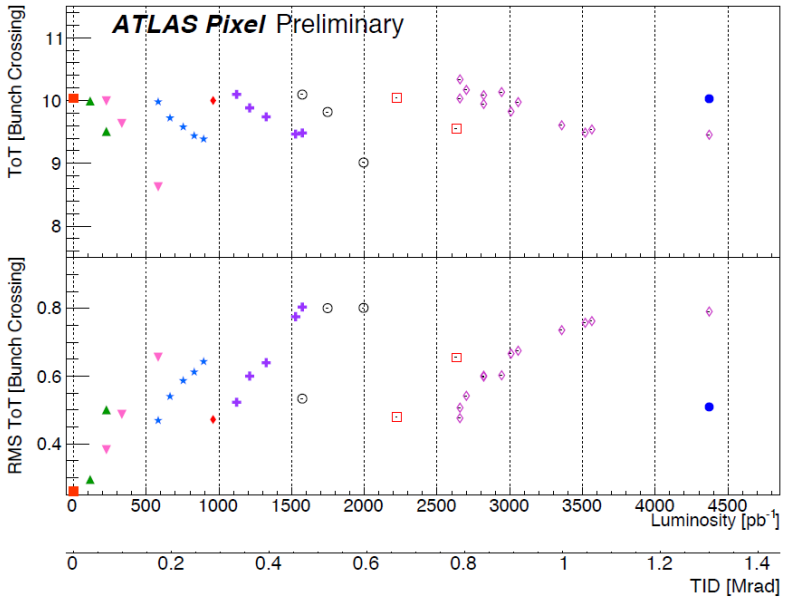
Pixel – 1 BC In-Time efficiency

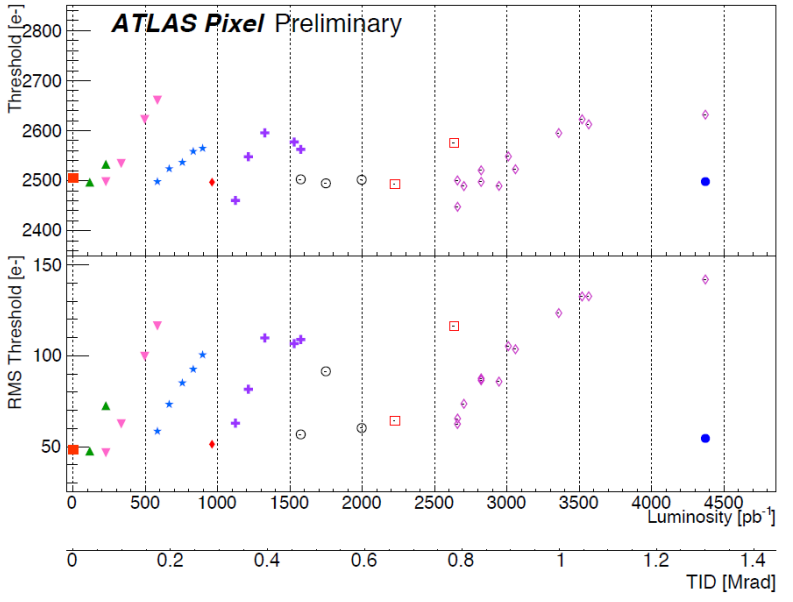



IBL – 1 BC In-Time efficiency

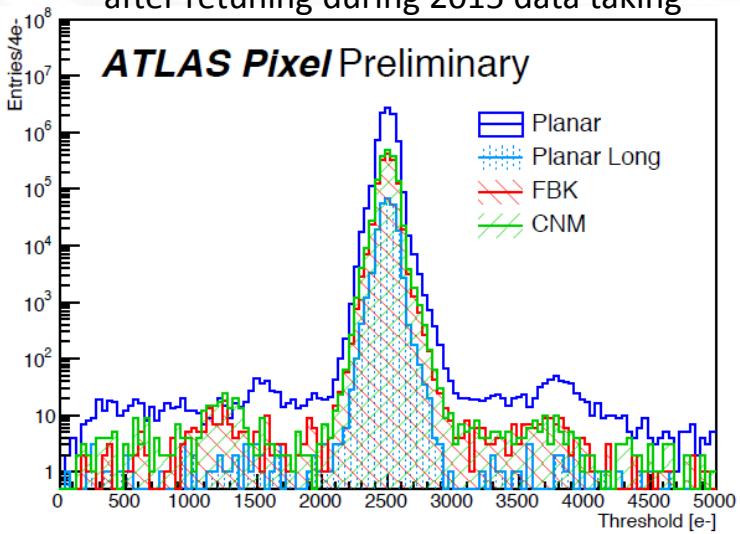


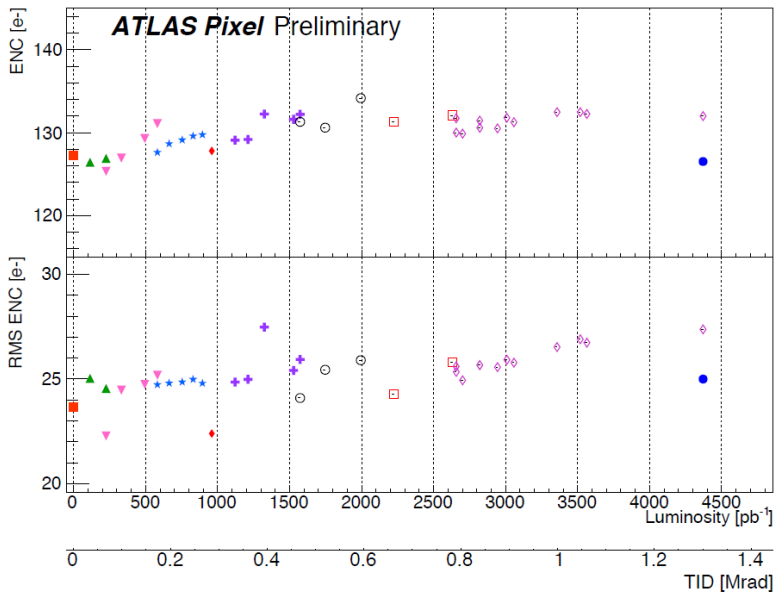
# TID effects on FEI4 calibration parameters




Average threshold distribution of IBL after retuning during 2015 data taking

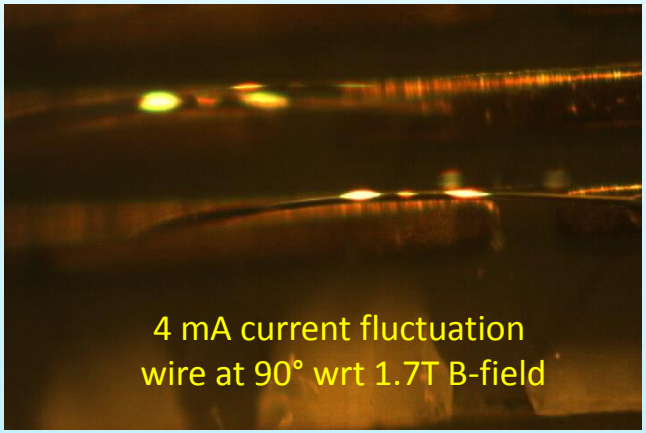


# Wire Bond Oscillation

- **IBL wire bonds susceptible** to some resonance frequencies during data taking
- **Protection Scheme** implemented into the readout chain firmware

## Lab measurements

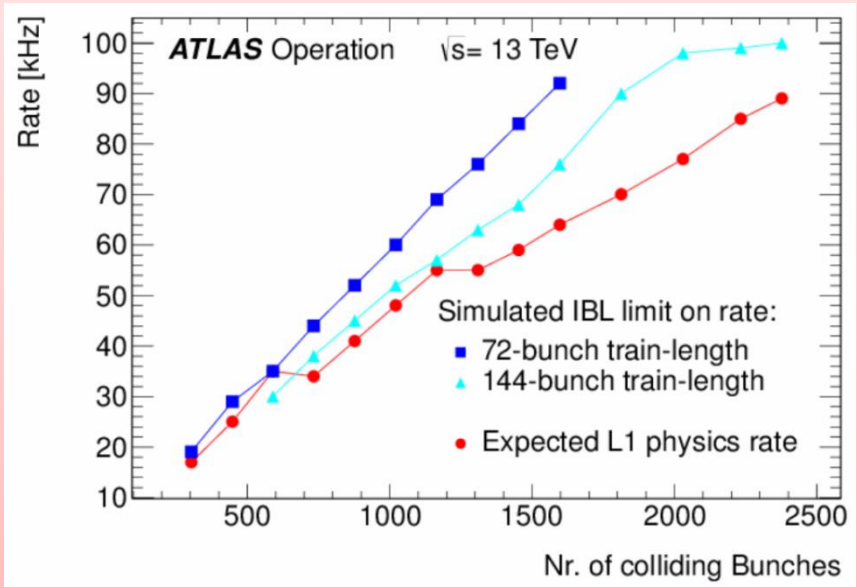



Lab measurements could show that even with IBL orientation wires could break when at the resonance frequency or in one of the harmonic or sub-harmonic modes.

→ *Also confirmed with ANSYS FEA*

**Digital supply line is susceptible to current fluctuation when receiving triggers**

## Trigger rate for physics and IBL limitation




- **IBL protected** against wire bond oscillations by limiting the number of triggers in resonance region.
- Protection is called **FFTV** (Fixed Frequency Trigger Veto).

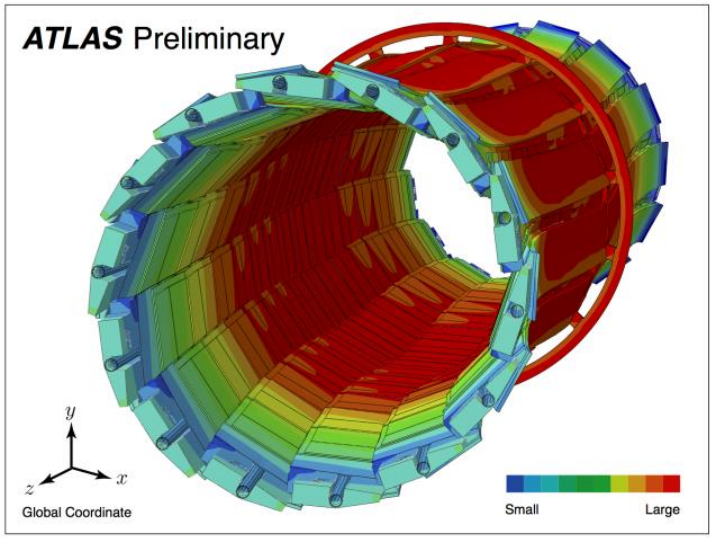
**Level of protection was:**

- Dependent of the LHC filling scheme and bunch pattern
- **Essential** during some trigger mishandling
- **Never a limitation** for data taking (even if close)

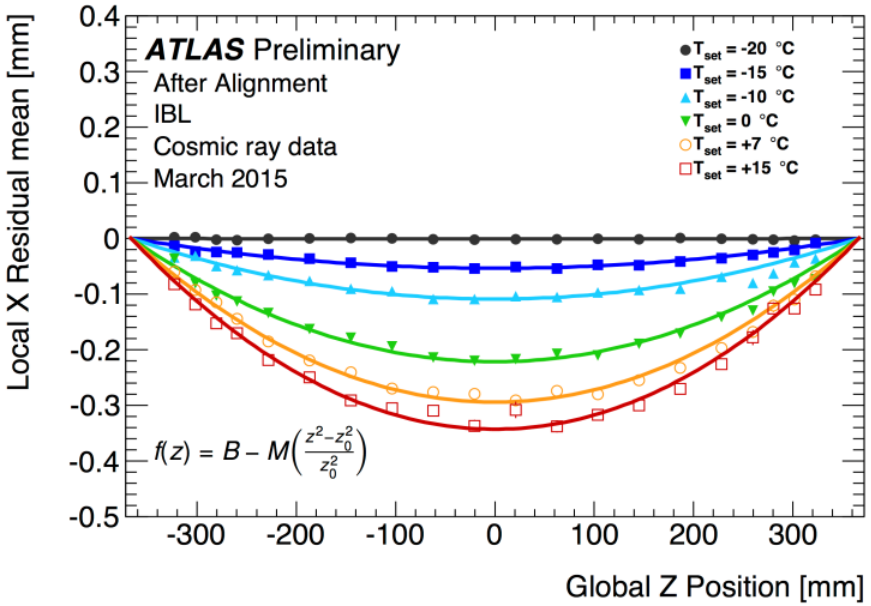
# IBL Mechanical Distortion

## IBL distortion summary:

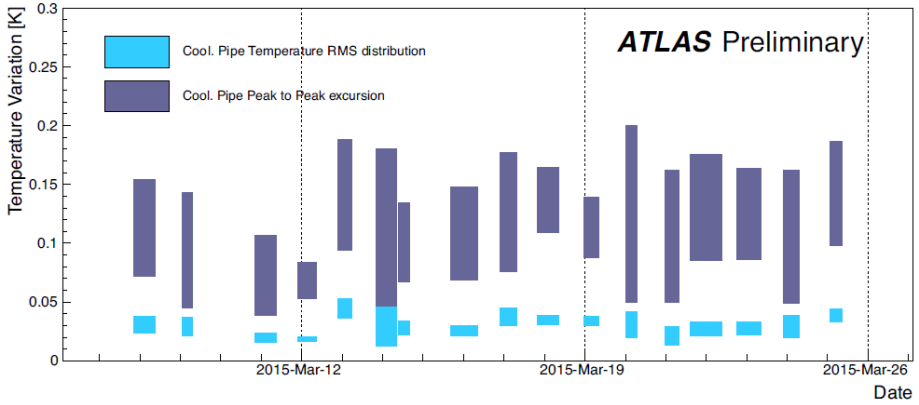
- Issue discovered early in 2015 during cosmic runs
- **Temperature dependency** exhibited - O(10 μm/K)
- Origin: **CTE mismatch** between the service bus and stave that twists the stave and a rotation free central ring
- Confirmed by the mechanical engineers with 3D simulations and lab measurements
- Direct **impact on the tracking** performance
- **Alignment correction was sufficient to mitigate** the effects
- Temperature and cooling stability ok until September




Distortion versus cooling temperature




Early studies of the IBL cooling and stave stability was satisfactory and rms not exceeding 0.2K which is also compliant for the required alignment stability



# Lessons for Future

**IBL is a new detector built relatively quickly and with a short R&D time**
**An excellent test bed for next generation silicon tracker for HL-LHC**

- **Major issues discovered late** in the production, during commissioning, and during data taking but **no show stoppers**
- **Successfully IBL running during 2015 – A big plus for tracking performance.**

**Very shortly the lessons learned:**

- A new detector even if built by experienced people needs time for R&D, reviews with senior experts, extensive qualifications in all domains
- Wire bond oscillation: potting, thick wires, no wire (TSV + laser bond)
- Mechanical distortion: Stiff structure, low susceptibly to temperature (low CTE)
- FE NMOS transistor leakage current:
  - Qualification to radiation should not be done only for intermediate to high doses but also low dose and for realistic dose rates
  - Enclosed transistors significantly reduces the effect

"Those who cannot remember the past are condemned to repeat it." – George Santayana