Calibration and Performance of the ATLAS Tile Calorimeter During the LHC Run 2

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On behalf of the ATLAS Collaboration

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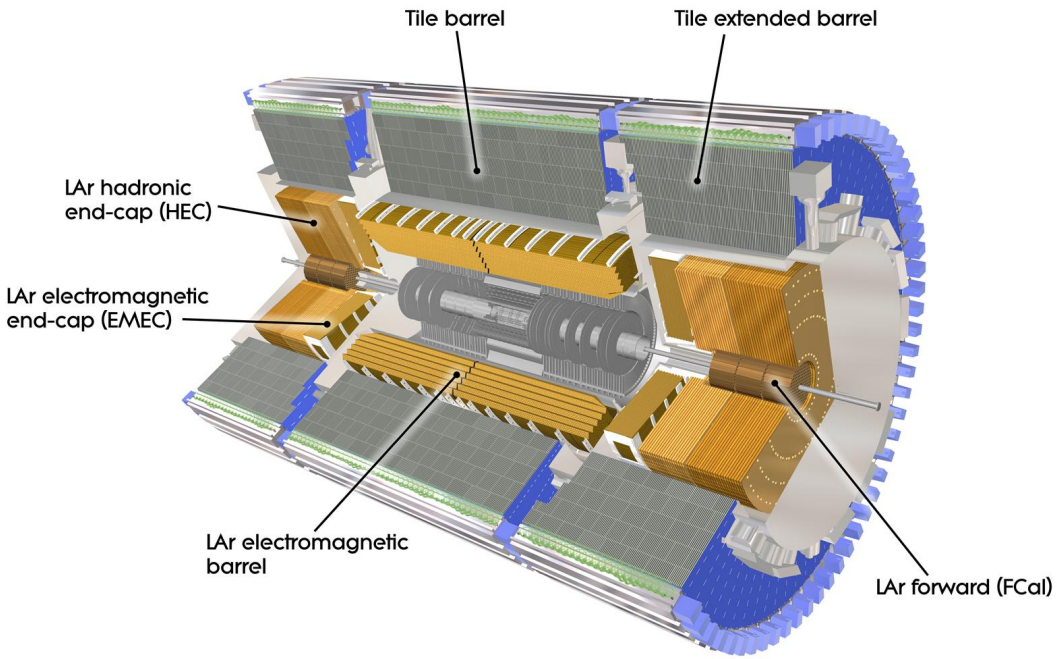
ATLAS Tile Calorimeter

- The ATLAS Tile calorimeter (TileCal) is the central section of the hadronic calorimeter.
- Sampling calorimeter using iron plates as absorber and scintillating tiles as active medium.
- 3 sections: Long Barrel (2 readout regions: LBA, LBC) and two Extended Barrels (EBA, EBC).
  - Long Barrel: $0 < |\eta| < 1.0$
  - Extended Barrel: $0.8 < |\eta| < 1.7$
- The readout is segmented into ~5000 cells (longitudinally and transversally), each read by two PMTs.



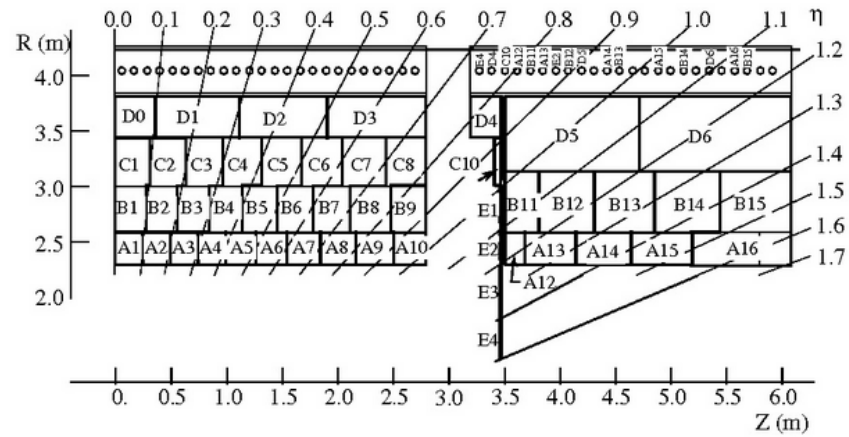
- TileCal provides important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy.
  - Single hadron energy resolution obtained in test beams for TileCal: $\sigma_E/E(\pi) = 45\%/\sqrt{E} \oplus 2.7\%$

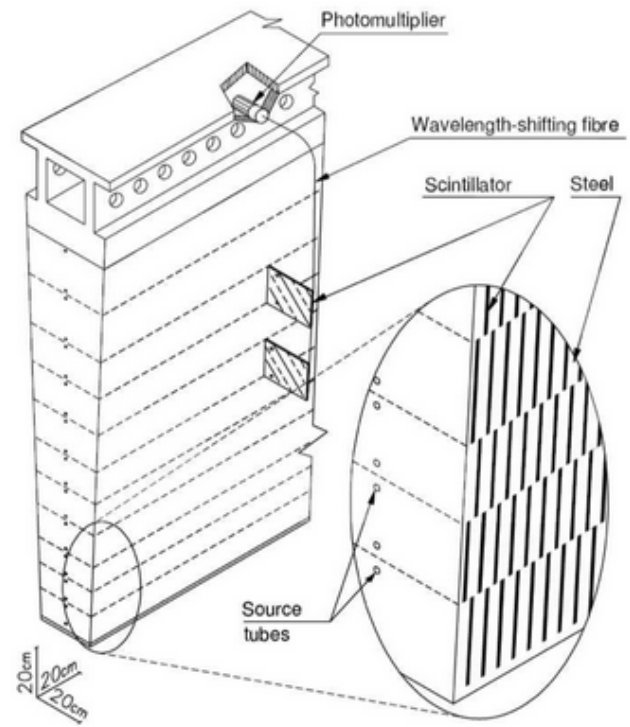
ATLAS Tile Calorimeter

- Each partition is divided into 64 symmetric ϕ slices (modules), with 45 instrumented channels in LB modules and 32 channels in EB modules.

- η and radial structure of TileCal cells
  - $\eta - \phi$ granularity: $\Delta\eta$ x $\Delta\phi = 0.1$ x 0.1
  - Radially: 3 longitudinal layers (total thickness of ~7.4 λ).
    - A-cells closest to beam axis, followed by BC- and D-cells.
    - E-cells installed in the gap/crack region ($1.0 < |\eta| < 1.6$). They are non-standard calorimeter cells made of single large scintillators whose aim is to measure the energy of particles lost in the inactive material located in the gap/crack region.

- Optical readout of signals in TileCal:
  - Light produced in scintillating tiles.
  - Readout via WLS fibres connected to both edges of the scintillating tiles.
  - Converted into electric currents by the PMTs.
    - Their signal is shaped and amplified with two gains (LG, HG). Dynamic range: ~10 MeV to ~800 GeV.





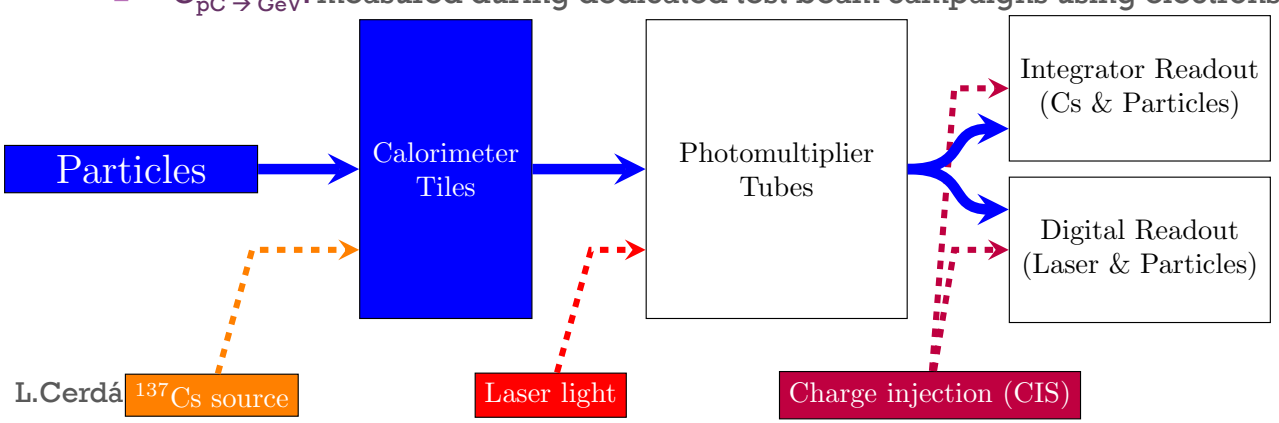
Calibration Systems

The reconstructed energy is derived from the raw response:

$$E(GeV) = A(ADC) \cdot C_{ADC \rightarrow pC} \cdot C_{Cesium} \cdot C_{Laser} \cdot C_{pC \rightarrow GeV}$$

- Systems used for calibration in TileCal
  - Charge Injection System (CIS):
    - Calibrates the response of ADCs (electronics): $C_{ADC \rightarrow pC}$
  - Cesium system:
    - Calibrates optical components and PMT gains, checks the integrator readout: C_{Cesium}
  - Laser System:
    - Calibrates the variations of PMTs gains: C_{Laser}
  - Minimum Bias System (MB):
    - Monitors beam conditions, TileCal optic components and PMT gains.
  - $C_{pC \rightarrow GeV}$: measured during dedicated test beam campaigns using electrons.

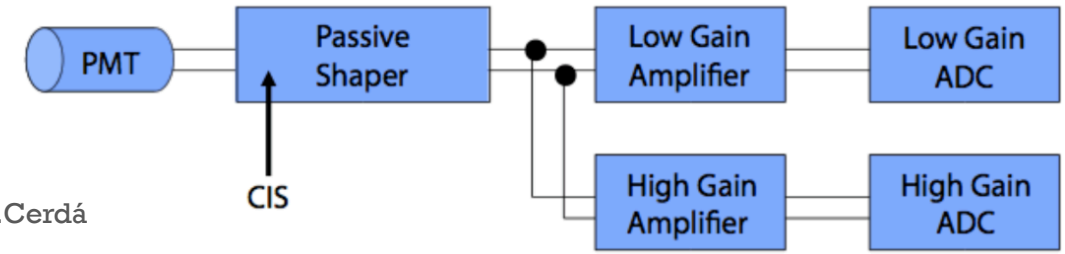
Cell response is not constant in time due to the PMT gain variation and scintillator degradation due to the exposure to beam.

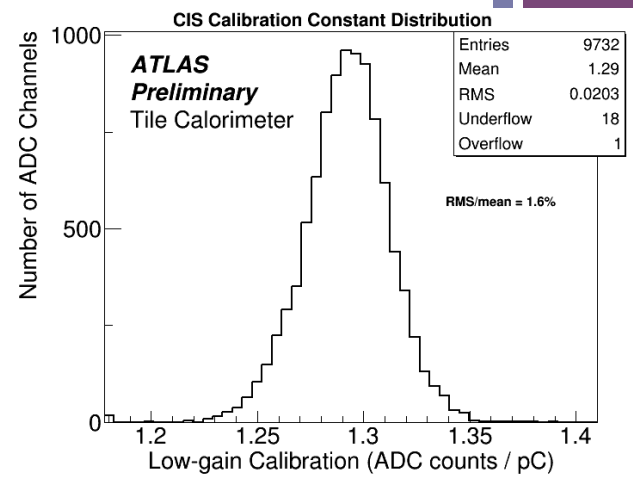


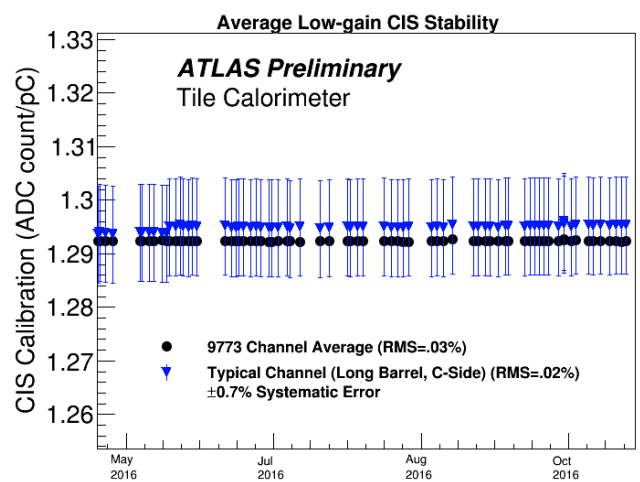
The inter-calibration of the cells of the three layers is performed primarily with Cesium, then using test beam (TB) muons incident at 90° and ^{90}Sr source measurements.

Charge Injection System (CIS)

- Calibrates the response of ADCs (electronics): digital gains and linearities.
- Extract the conversion factors from ADC counts to pC ($C_{ADC \rightarrow pC}$)
  - Spanning the full ADC range (0-800 pC; 1 pC~1 GeV).
  - Monitors both LG and HG for all channels.
- Allows to simulate a physics signal from the PMT.
- Calibrations taken from daily to weekly.
- CIS systematic uncertainty ~0.7%.
- The stability of the calibration factors is at the level of 0.03-0.04% (for both gains).
- Less than 1% of TileCal channels exhibit large fluctuations.

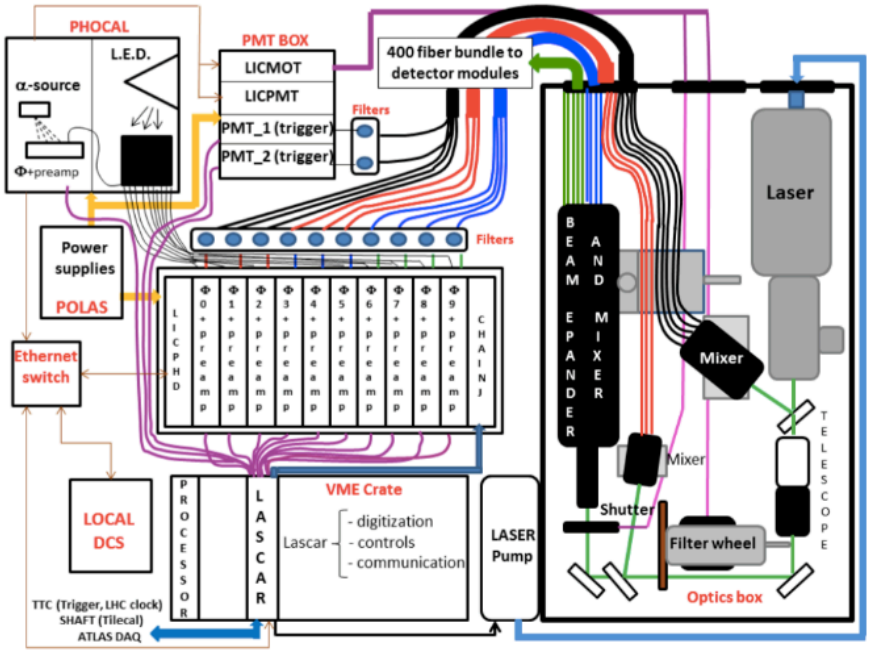


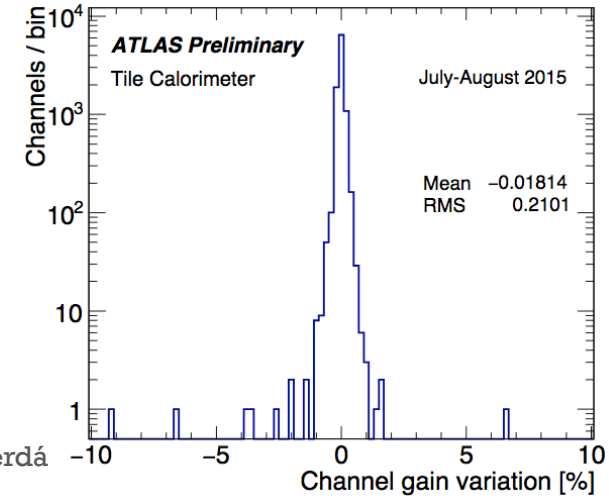




Laser System

- The gain stability of each PMT is measured using the Laser system.
  - PMT gain drifts affects the detector response and thus should be measured regularly.
- The system sends a controlled amount of light into each PMT (532 nm green light).
- Deviations of any channel response wrt nominal is translated into a calibration constant: C_{Laser}
- Laser pulses also sent during collision runs (empty bunches), used to calibrate the calorimeter timing.

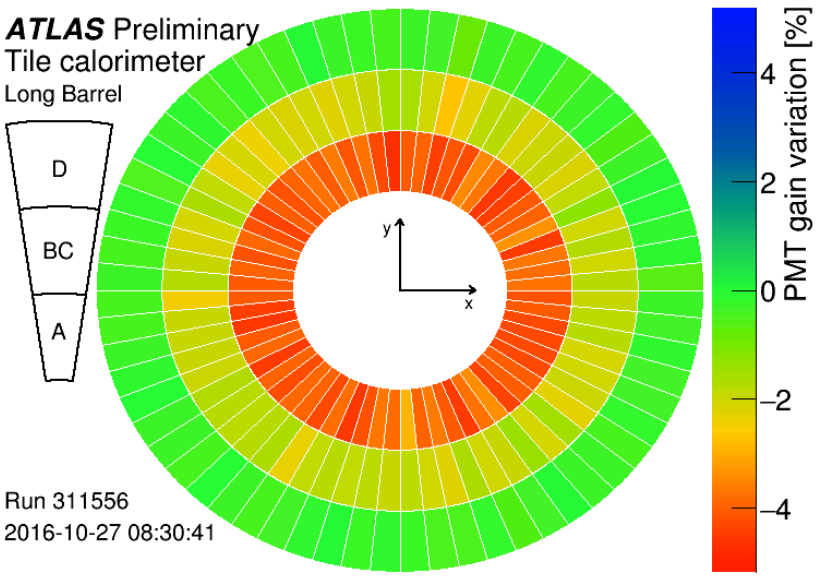


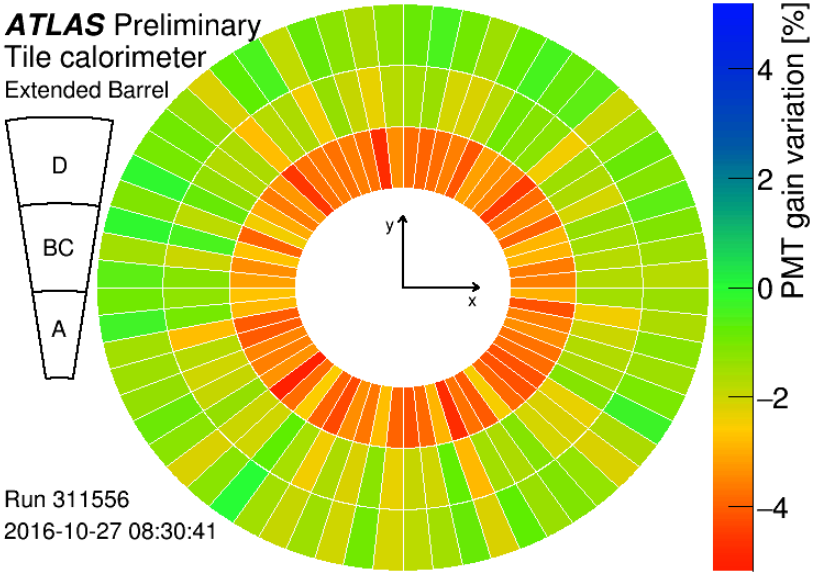


- During the LHC Long Shutdown between Run I and Run II a new Laser II system was developed to correct shortcomings in electronics and improve light monitoring from the original system.
  - Upgraded optics box and control electronics for Run II.
  - Improved laser light estimation (more photodiodes).
  - Improved precision on the gain variation measurement: better than 0.5%

Laser Calibration

Map of the PMT response variation during pp runs of 2016

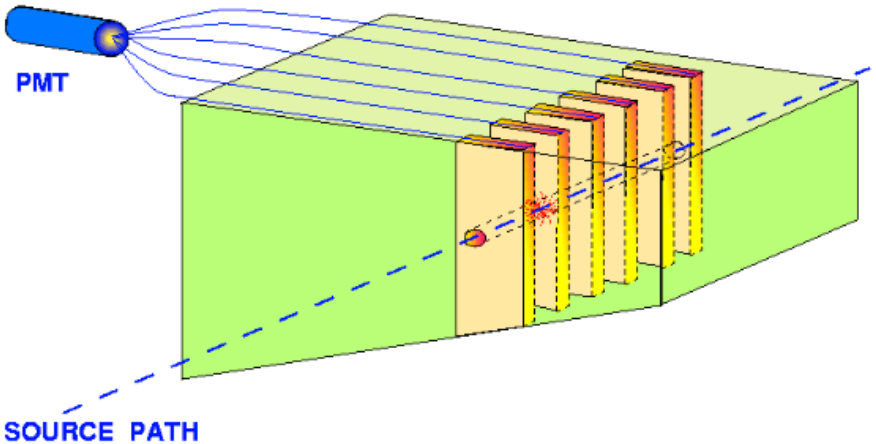


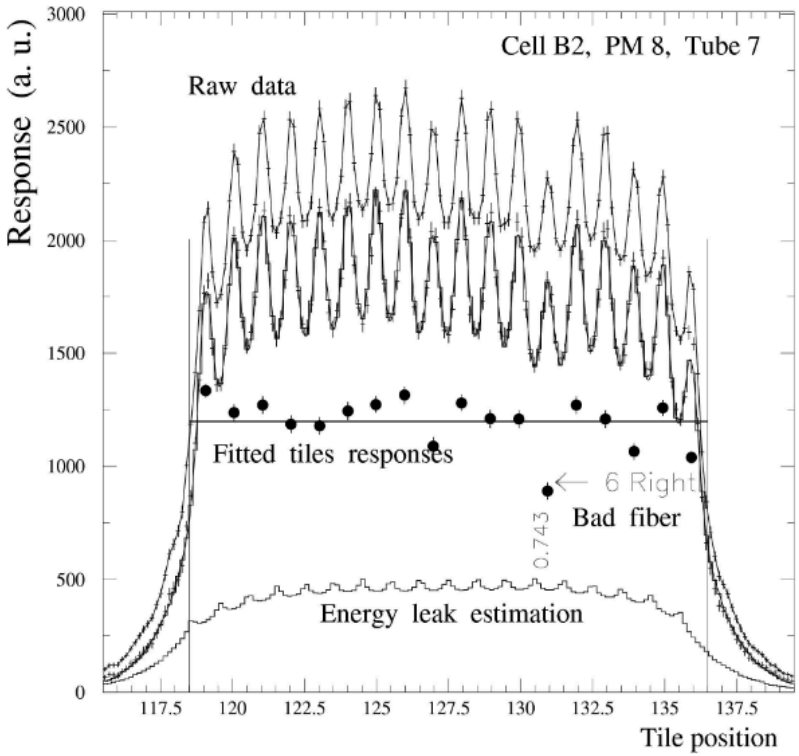


- Precision on gain variation measurement < 0.5%.
- Cross check problems (e.g. unstable HV or bad CIS).
- Updates to calibration constants are done as often as weekly, to track changes in PMT responses.

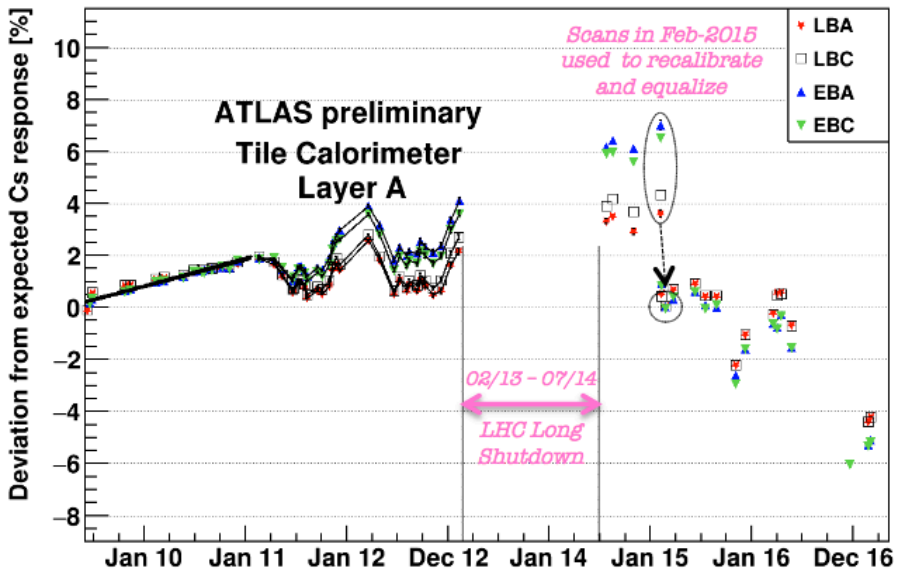
Cesium System

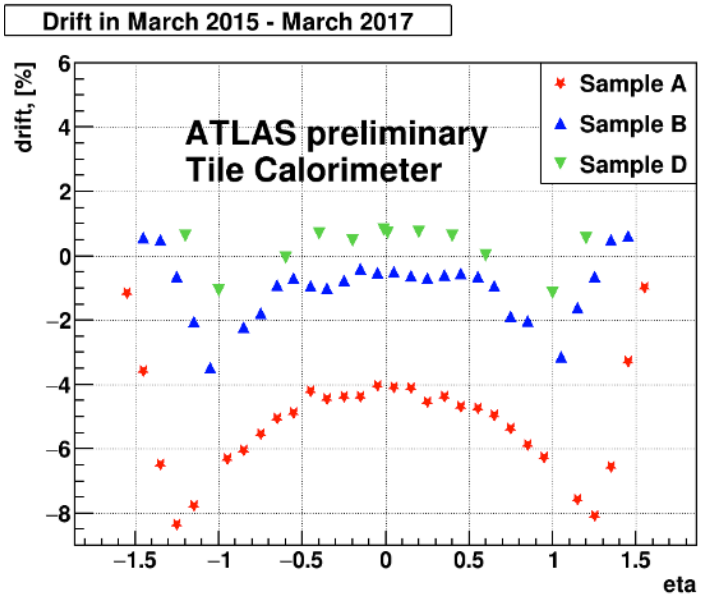
- The Cesium system is based on three moveable radioactive sources ($t_{1/2}$~30 years) using a hydraulic control through a system of steel tubes.
- The ^{137}Cs γ-sources move inside the calorimeter, emitting 0.662 MeV photons to illuminate the scintillators.
- It uses the integrator readout system during source movement.
- Calibration of the complete optical chain (scintillator tiles, fibers, PMTs) and monitoring of the detector response over time: C_{cesium}
- Between Run I and Run II: improvement of stability and safety of the operation (new water storage system, lower pressure, precise water level metering).





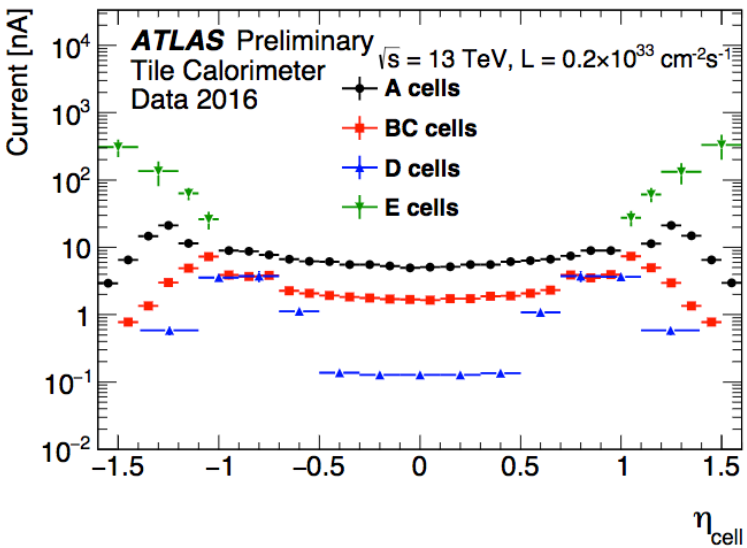
Cesium Calibration

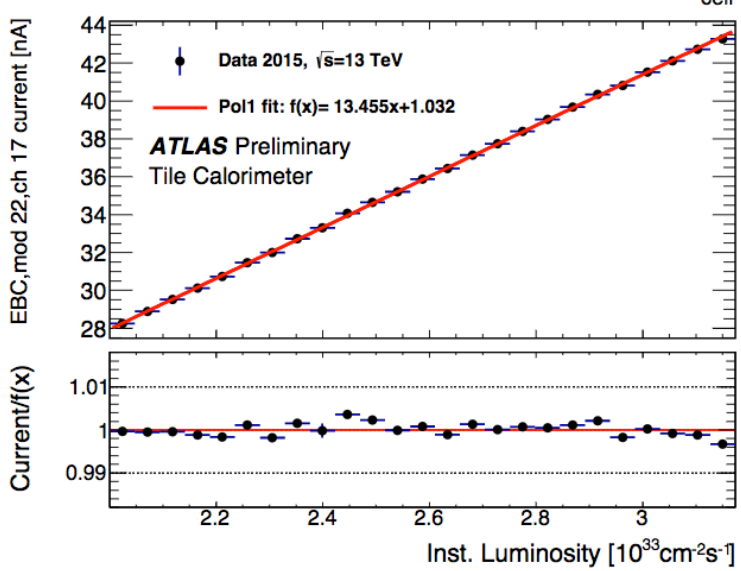




- Variation of TileCal channels response measured in Cesium calibration runs.
- Cell response is not constant in time due to the PMT gain variation and scintillator degradation due to the exposure to beam.
- Precision of a single channel response measurement in the order of 0.5%.
- Larger deviations in time observed for cells closer to the beam line.

Minimum Bias System

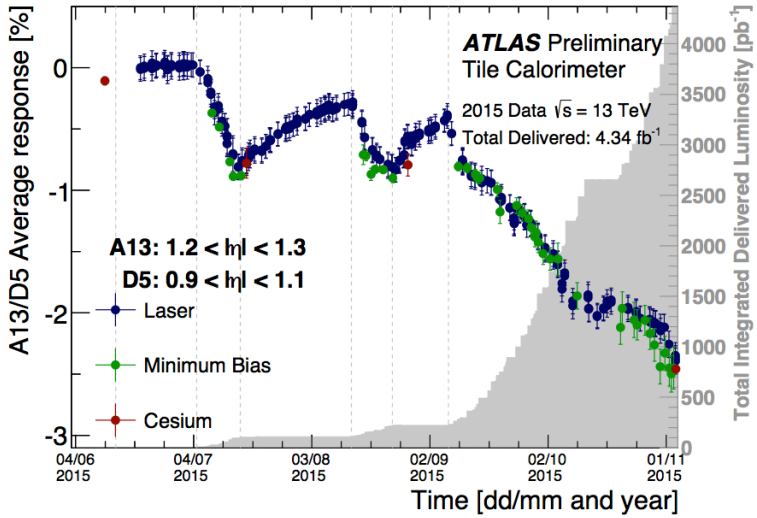




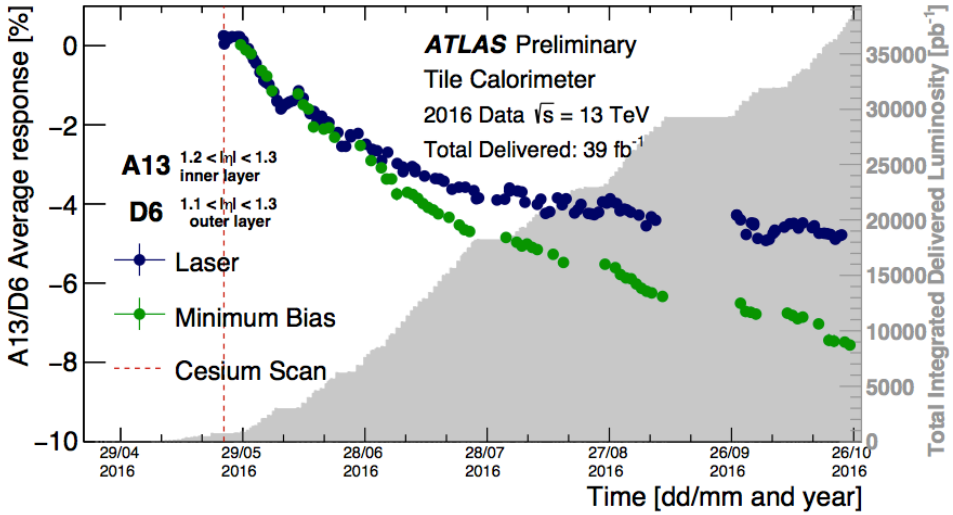
- High energy proton-proton collisions are dominated by soft parton interactions (MB events).
- The integrator readout measures integrated PMT signals over a large time (~10 ms).
- As the Cesium system, the MB system monitors the full optical chain. As of 2016 it was used to calibrate in between scans (part of C_{Cesium}).
- Measured currents are linearly dependent on the instantaneous luminosity.
- The system can then be used to monitor the instantaneous luminosity.
  - Or provide an independent measurement given an initial calibration (luminosity coefficient computed from a single run).

Comparison of the different calibration systems results

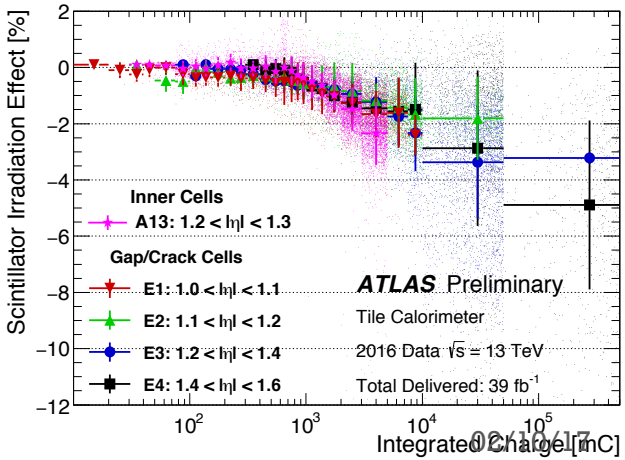
2015 data taking period



2016 data taking period

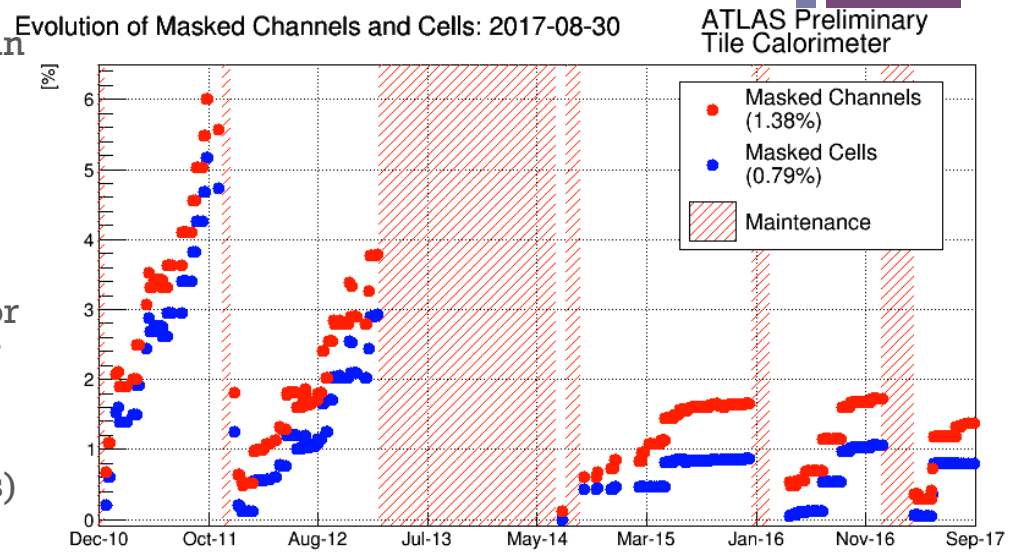


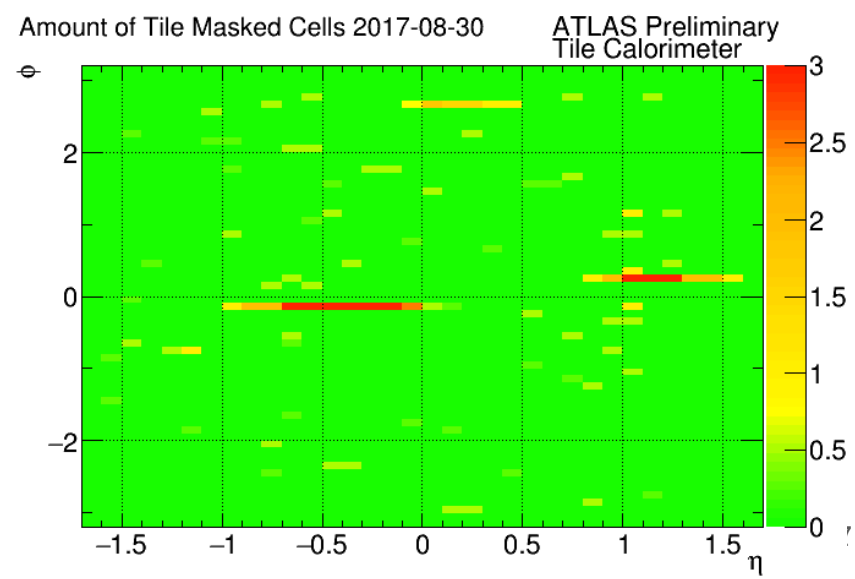
- Down-drifts observed during collision periods.
- Up-drifts during maintenance periods (recovery of PMTs).
- Differences between Laser and MB measurements in 2016 can be interpreted as a scintillator ageing due to irradiation
  - No ageing observed in 2015
- During 2016 this effect was clearly observed for some of the most irradiated cells in the A-layer and E-cells (larger instantaneous and integrated luminosity).



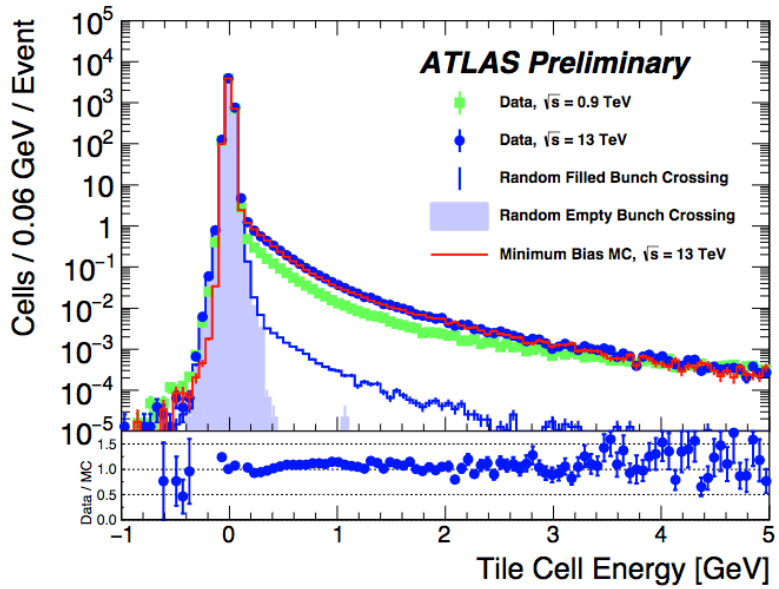
Detector Status & Data Quality

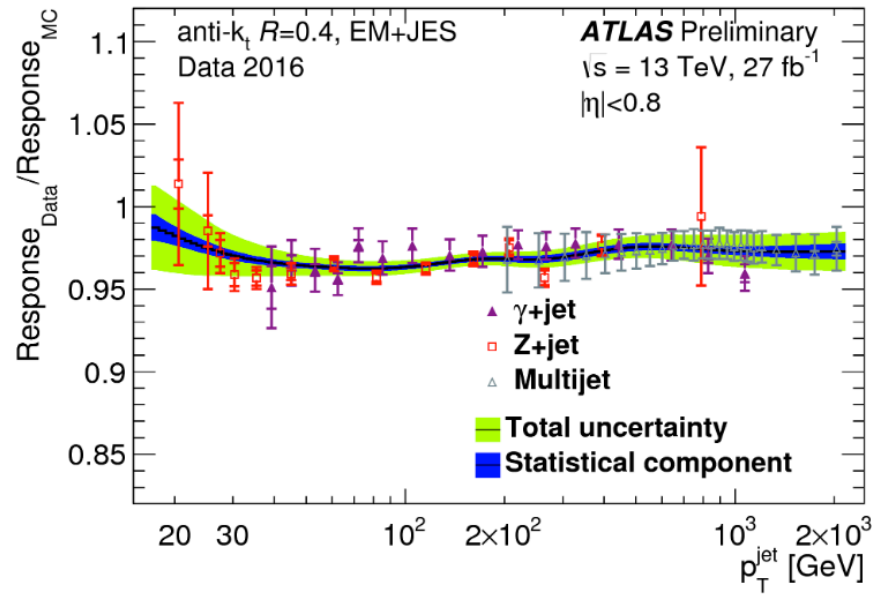
- Tile achieved 99.6% data quality efficiency in 2012, 100% in 2015 and 98.8% in 2016, with minor (< 1% of cells) losses by the end of October, 2016, and by September of 2017.
- TileCal monitoring includes identifying and masking problematic channels correcting for timing jumps, monitoring data corruption or other hardware issues.
- During maintenance periods (hatched areas) there is an intense campaign to fix all issues (from high to low priority), allowing for a good recovery of the system.
  - 48/256 (~19%) modules were opened in the last shutdown of 2016-2017
  - Typical errors:
    - Digital errors
    - HV off for ¼ of module's channels
    - Cooling air leaks
    - Integrator failures (FEB latch-up)
    - Cold soldering in power connector
    - Trigger tower low or no signal





Jet Performance

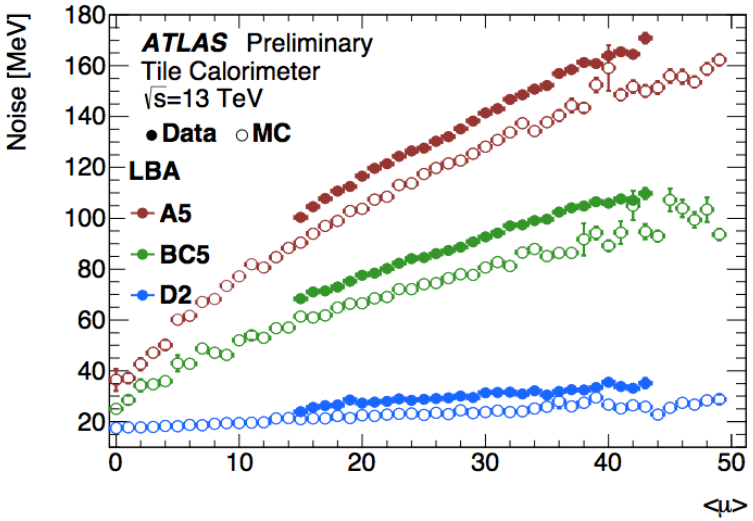




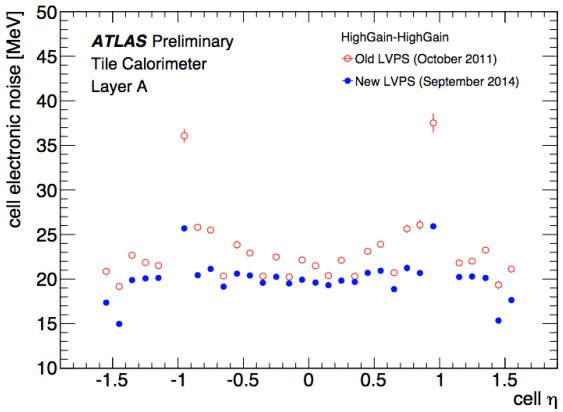
- A good description of the cell energy distribution and of the noise in the calorimeter is crucial for the building of topoclusters which are used e.g. for jet and missing transverse momentum reconstruction.
- Good agreement in Tile cell energy distribution.
  - To ensure exactly one interaction has occurred per bunch crossing, only events having a single reconstructed primary vertex are selected
- Consistent overall jet energy scale
- Jet energy resolution is below 10% at p_T >100 GeV
- Constant term is within expected 3%

Noise

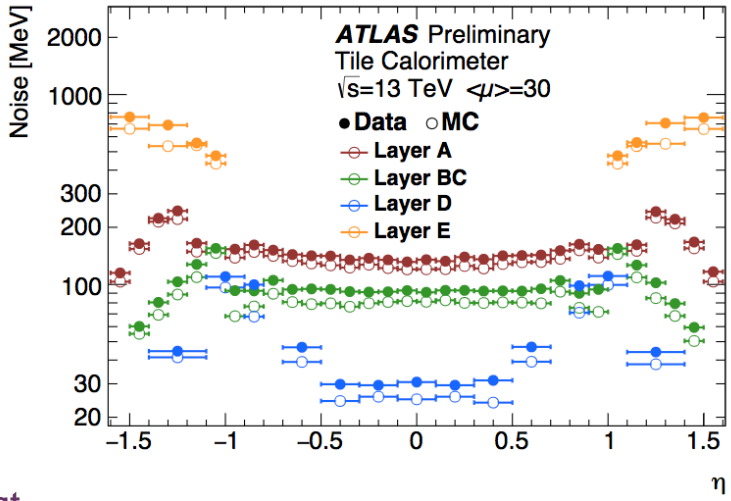
- The total noise per cell in the calorimeter comes from two sources:
  - Electronic noise – measured in dedicated runs with no signal in the detector.
  - Pile-up contribution – originates from multiple interactions occurring at the same bunch crossing or from the minimum bias events from previous/following bunch crossings



- Electronics noise stays at the level below 20 MeV for most of the cells. Pedestal and noise are measured regularly with calibration runs.

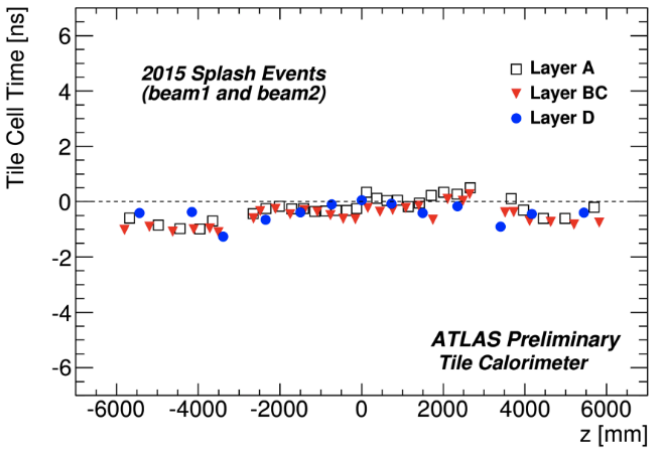


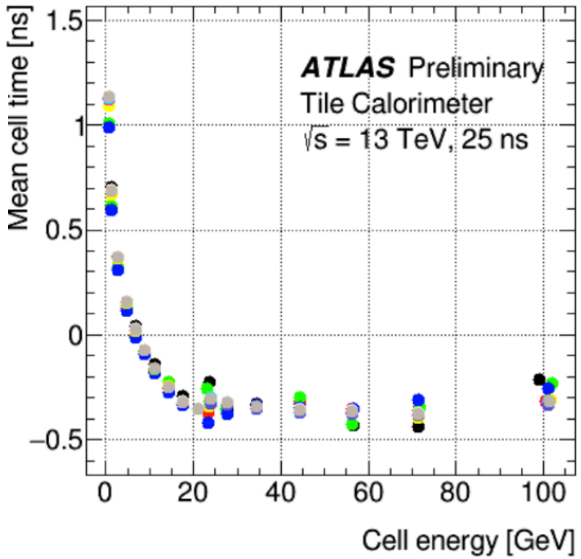
- New power supplies (fLVPS), installed in the long shutdown (2014), have better performance and more Gaussian noise

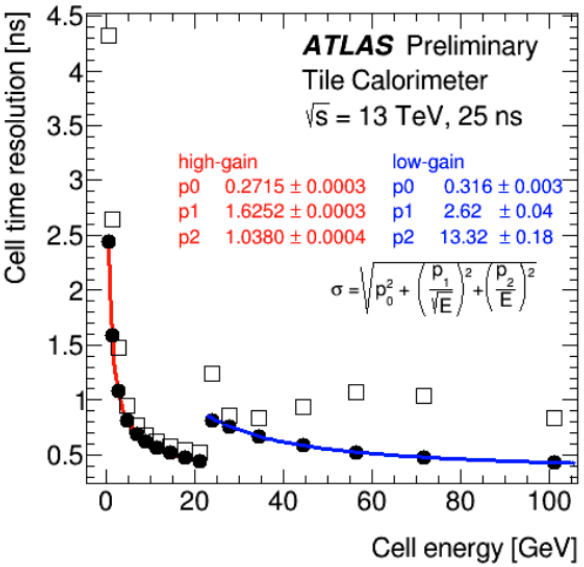


- Total noise is increasing with pile-up, especially for the inner A-layer
- The largest noise values are in the regions with the highest exposure (E-cells, A-cells).

Time Calibration

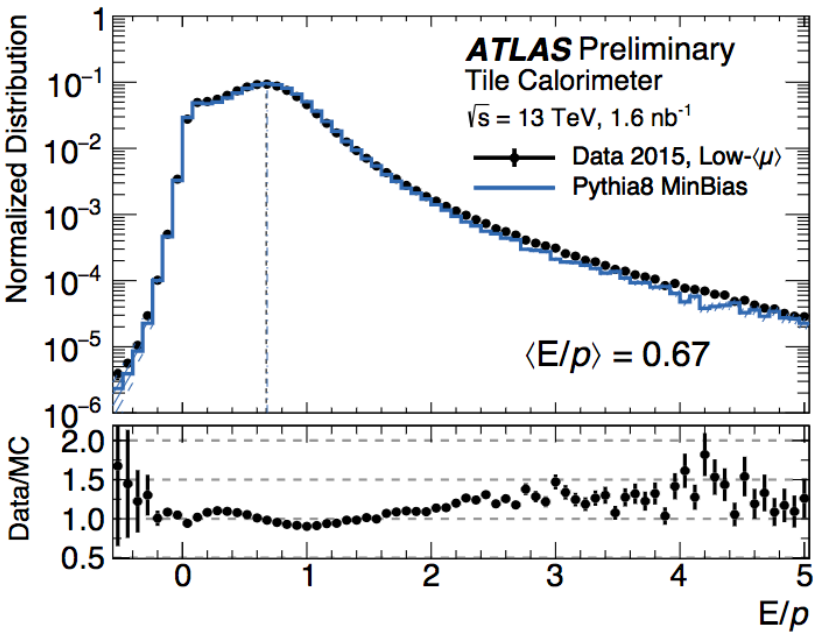


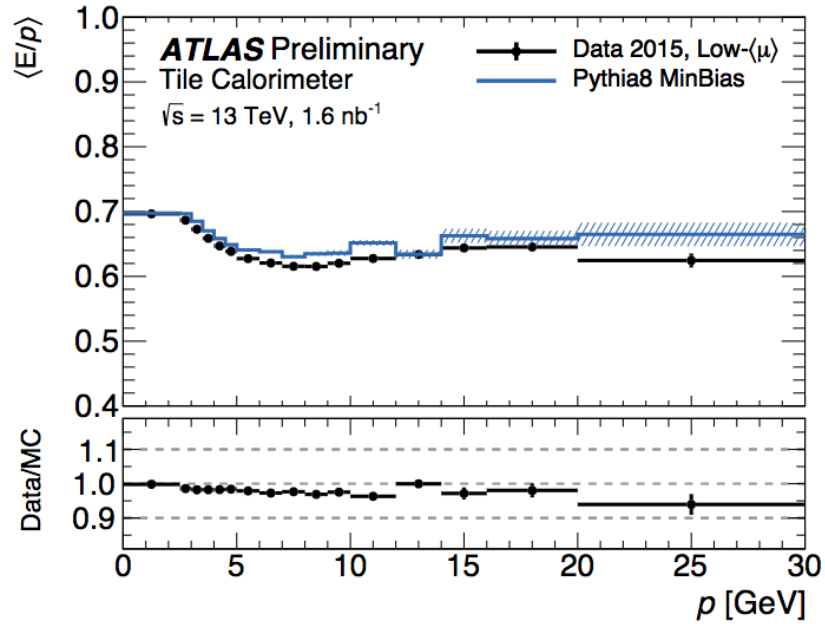




- A precise time calibration is important for the cell energy reconstruction.
  - The time calibration is used to set the phase in each channel so that a particle travelling from the ATLAS interaction point at the speed of light produces the signal with measured time equal to zero.
- Initially set with splashes (high-energetic muons from beam-collimator hits at the start of data taking period, few events).
- Tuned later with muons and jets.
  - Cells associated to jets are used for the timing studies in physics data to minimize the effect of the pile-up contamination in the sample.
  - The mean cell time decreases with deposited energy due to neutrons/slow hadronic components of the hadronic shower.
  - Resolution is better than 1 ns for $E_{cell} > 4$ GeV.
- Monitored during physics data taking with laser, eventual corrections.

Single Particle Response

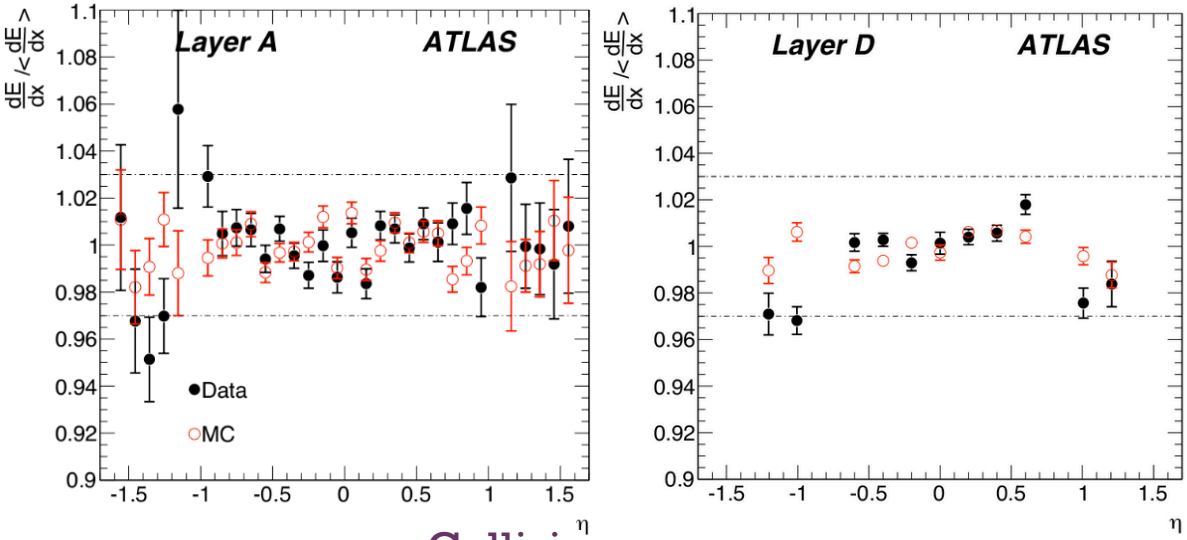




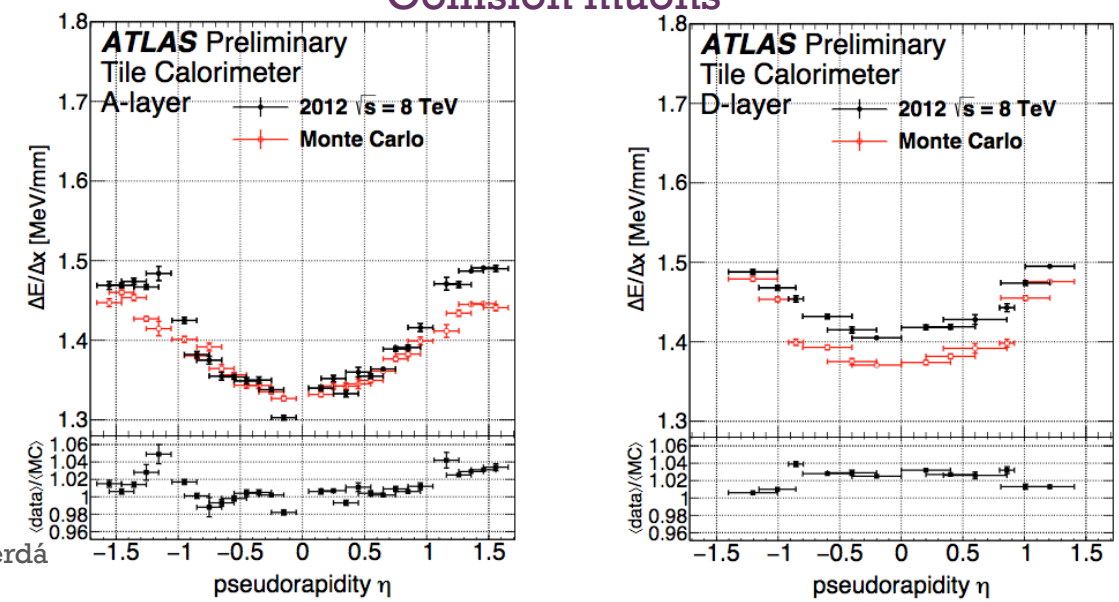
- An important Tile Calorimeter determination is the mean of energy to track momentum ratio (<E/p>) for isolated charged hadrons in minimum bias events.
  - Used to evaluate calorimeter uniformity and linearity during data taking
- Expect <E/p> <1 due to the sampling non-compensating calorimeter
- Data and simulation agree, showing linearity and uniformity in detector response
- dE/dx of minimum ionizing muons (near noise threshold) show data/MC agreement within 3%

Muons

Cosmic muons



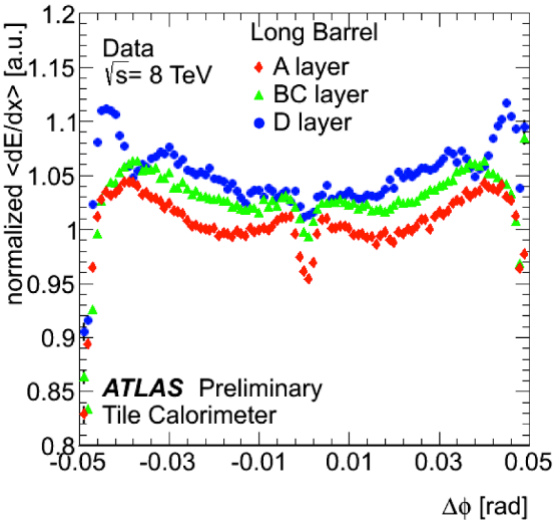
Collision muons

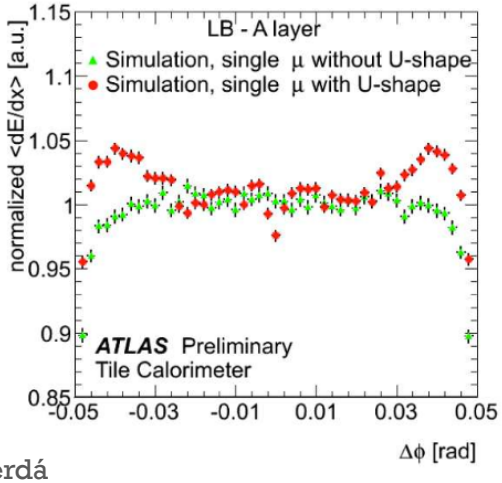


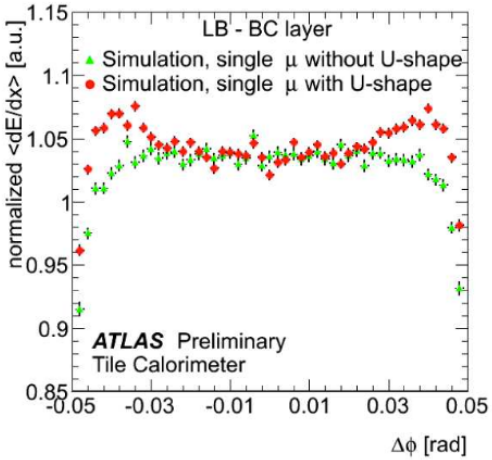
- Muons from cosmic rays, beam halo and collisions are used to check the cells inter-calibration and the electromagnetic energy scale
- 1% / 3% response non-uniformity in η in Long / Extended Barrel with cosmic muons
- A good energy response uniformity in all calorimeter layers
- The data/MC agreement is within 3-4%

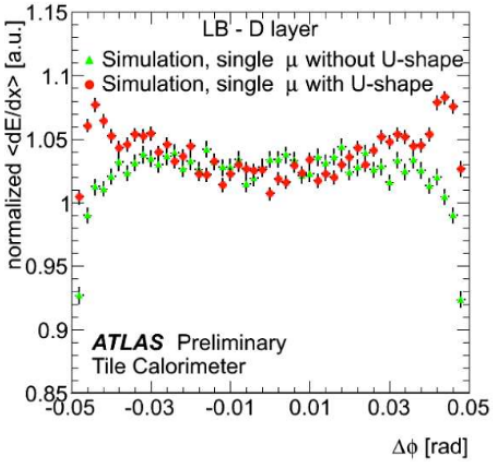
U-shape

- The response of the PMTs is not flat in the azimuthal angle difference between the energy deposition point and the center of the cell ($\Delta\phi$)
  - It shows a non-negligible dependence referred to as U-shape
- The dependence of the response on $\Delta\phi$ was measured using $W \rightarrow \mu\ \nu$ events in the 2012 collisions data
  - A steep dip at the center of the cell ($\Delta\phi = 0$) corresponds to the position of the apertures in the scintillating tiles
- The light propagation in the Monte Carlo simulations has been improved by introducing the U-shape

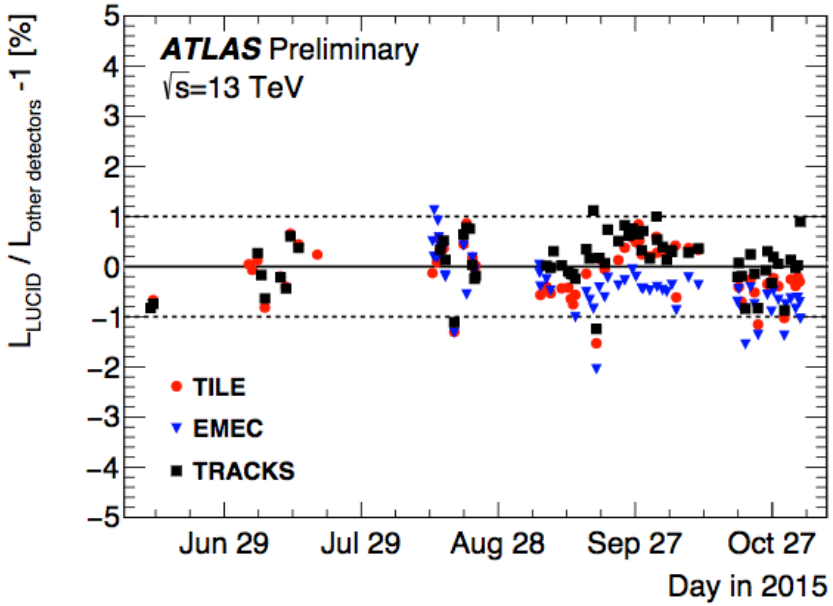


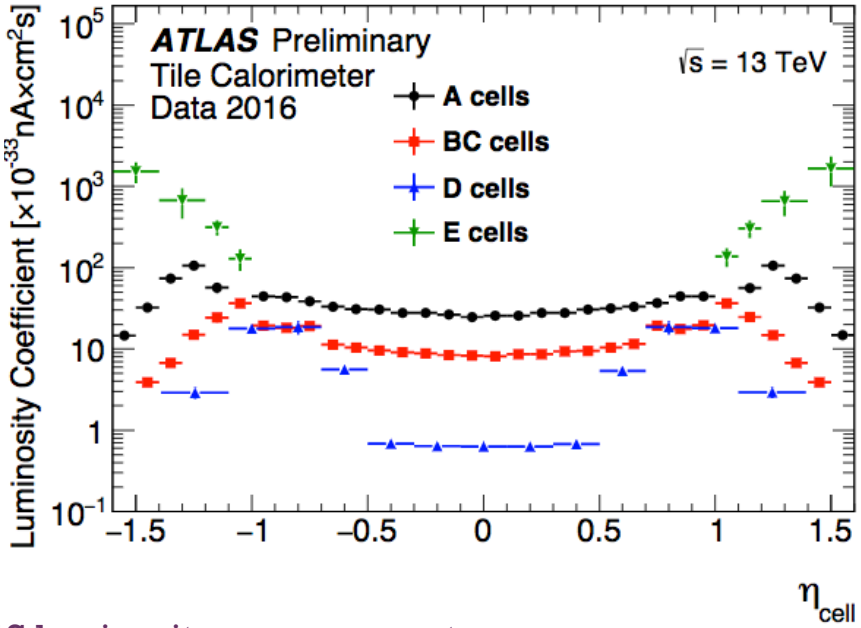






Luminosity Measurements





- Tile Calorimeter contributes to the ATLAS luminosity measurement
  - Calibration transfer from low to high luminosity conditions
  - Long term luminosity monitoring
- Dedicated readout of the anode currents in every channel
  - Fully decoupled from trigger
  - Intrinsically independent from pile-up
- Allows to cross-check other luminometers

Summary

- TileCal provides important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy.
- Multiple systems are used to calibrate and monitor the response of the TileCal cells.
- These calibration systems allowed to achieve great performance of the calorimeter during the LHC Run I and Run II.
  - Stability of absolute energy scale better than 1%.
- Getting ready for HL-LHC upgrade
  - Talk in tomorrow's Prototypes, upgrades and concepts session by Sergi Rodriguez

Thank you!

Back-up

Calibration Systems

- Calibration schema in Tile Calorimeter