Performance of the ATLAS Tile Calorimeter

Calorimetry for High Energy Frontier (CHEF 2019)

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on behalf of the ATLAS Collaboration

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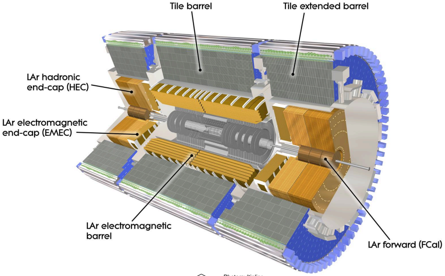
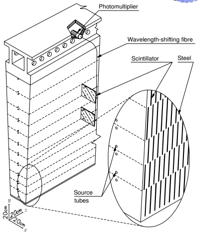
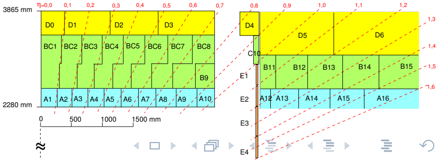
The Tile Calorimeter

- Central hadronic calorimeter ($|\eta| < 1.7$) in ATLAS detector
- Used to measure the 4-vectors of the jets and the missing transverse energy and in the ATLAS Level-1 trigger
- Sampling calorimeter: steel and scintillating plastic tiles
- Double photomultiplier readout using wave length shifting fibers
- 9892 PMTs





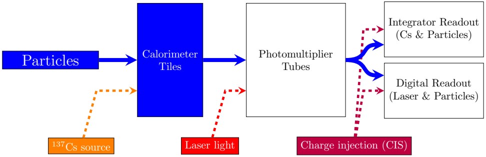


Calibration Systems

$$E\ [\mathrm{GeV}] = A\ [\mathrm{ADC}] \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{TileSize}} \cdot C_{\mathrm{Cs}} \cdot C_{\mathrm{Las}}$$

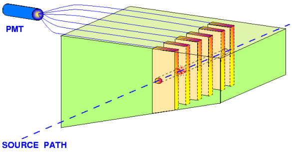
- Systems used for calibration in Tile calorimeter
  - Charge Injection System (CIS): Calibrates the response of ADCs: $C_{\mathrm{ADC}\to\mathrm{pC}}$
  - Cesium system: Calibrates optical components and PMT gains: C_{Cs}
  - Laser System: Calibrates variations due to electronics and PMTs: C_{Las}
  - Minimum Bias System (MB): Calibrates optical components and PMT gains
- $C_{\mathrm{pC}\to\mathrm{GeV}}$ EM scale constant measured during test beam campaigns
- C_{TileSize} correction addressing the different size of tiles in different layers

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



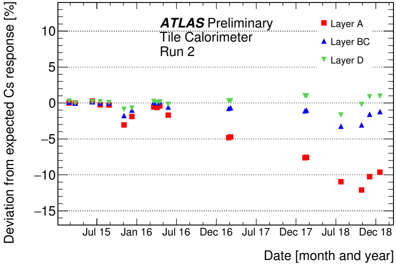
Cesium Calibration

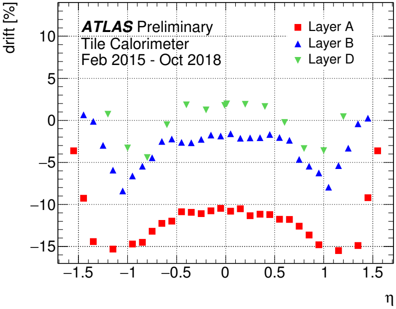
- A moveable radioactive source ^{137}Cs passes through the calorimeter body, 2-3 times per year in Run-2
- The source emits γ-rays with well known energy 662 keV
- It uses the independent integrator readout system ($\tau = 10$ ms) during source movement
- Calibration of the complete optical chain (scintillators, fibres, PMTs) and monitoring of the detector response over time: C_{Cs}
- Between Run I and Run II: Improvement of stability and safety of Cesium system and procedure (new water storage system, lower pressure, precise water level metering)

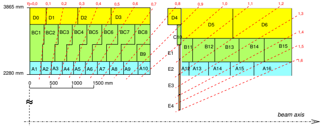


Cesium Calibration

- Precision of the system in a single typical cell is approximately 0.3%
- Deviation of the cell response in time is caused by the PMT gain variation and scintillator degradation due to the exposure to beam
- Maximal drift is observed for layer A, that is closest to the collision point
- It allows to adjust PMT gain (changing high voltage) to restore EM scale and calorimeter response uniformity

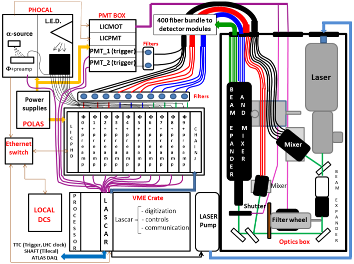


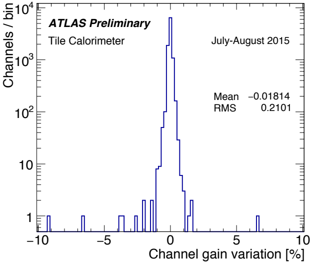




Laser Calibration

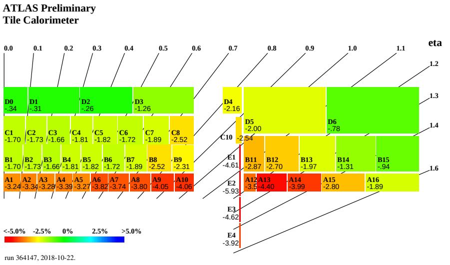
- PMT gain drift affects the detector response and calibration thus it is measured regularly
- A controlled amount of light with wavelength close to the one of physical signals (532 nm light) creating a pulse with similar shape and duration sent into each PMT
- The gain variation is measured between two Cesium scans: Laser measures the drift seen in PMTs w.r.t the last Cesium scan. Also, it allows to detect the HV changes
- Performed during dedicated calibration runs. Laser pulses also sent during collision runs (empty bunches), used to calibrate timing.

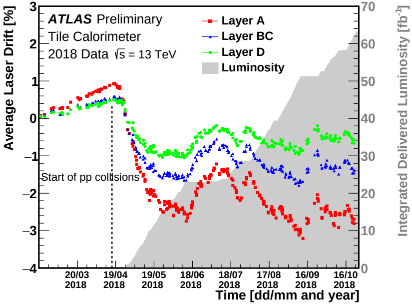




Laser Calibration

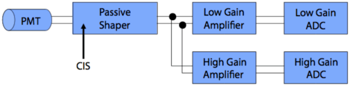
- Precision better than 0.5%
- Since 2016, updates of calibration constants are done weekly in order to track changes in PMT responses
- The maximal drift is observed in A- and E-cells which are the cells with highest energy deposits
- Deviations of any channel response with respect to nominal is translated into a calibration constant: C_{Las}
- Between Run I and Run II: upgraded electronics and optical components, better control of the emitted light

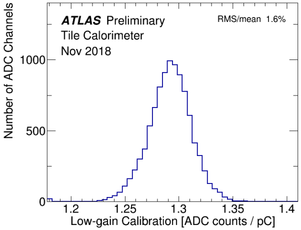


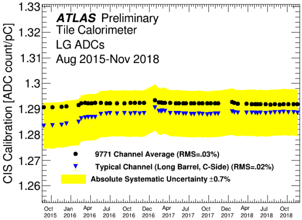


Charge Injection Calibration

- Calibrates the response of ADCs (electronics) digital gains and linearities
- Calibration performed weekly
- The system injects a signal of known charge and measures the electronic response
- Spanning the full ADC range (0-800 pC) and saturate both LG and HG for all channels
- Also used to calibrate analog L1 calo trigger
- Extract the conversion factors from ADC counts to pC: $C_{\mathrm{ADC}\to\mathrm{pC}}$
- Precision of 0.7%, stability over time of 0.03%

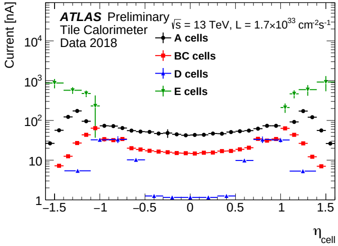


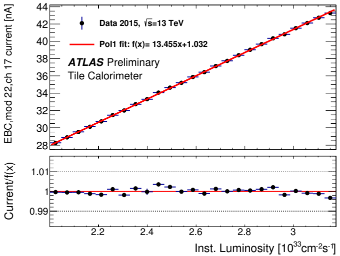




Minimum Bias System

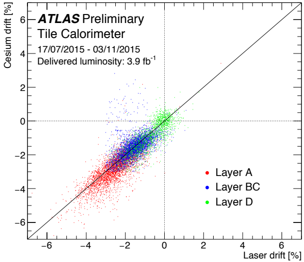
- High energy proton-proton collisions are dominated by soft parton interactions: Minimum Bias (MB) events
- The same integrator readout as in Cs system measures integrated PMT signals over a large time (∼10 ms)
- As the Cesium system, the Minimum Bias system monitors the full optical chain. Also calibrates E-cells and MBTS.
- Measured currents are linearly dependent on the instantaneous luminosity
- Monitors the instantaneous luminosity and provides an independent measurement given an initial calibration (luminosity coefficient)

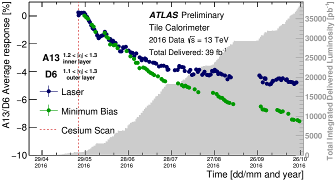


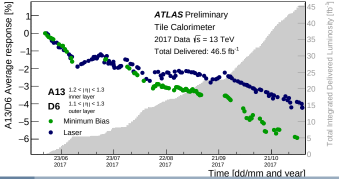


Combined Calibration

- Comparison of cell response variation between Cesium/MB and Laser measurements
  - Cesium and Minimum Bias access PMT gain drift and scintillator aging
  - Laser only monitor PMT gain drifts
- Down drifts observed during collisions. Up drifts during maintenance periods
- Differences between Cesium/MB and Laser measurements interpreted as a scintillator aging due to irradiation
- In 2015, a good agreement observed
- In 2016 - 2018 this effect was clearly observed for some of the most irradiated cells in the A- and E-cells

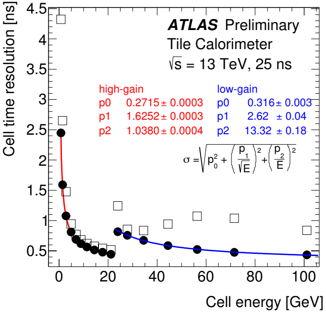


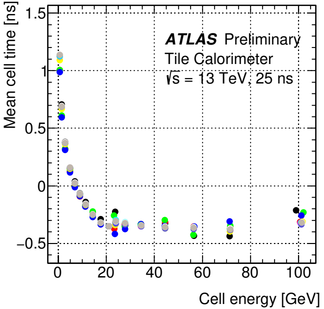




Time Calibration

- A precise time calibration is important for the cell energy reconstruction
- It adjusts a digitizer sampling clock to the peak of signal produced by the particle traveling from the interaction point at the speed of light through the cell. Large phases result in underestimated reconstructed amplitude.
- Can also be exploited in TOF measurements, e.g. in search for heavy R-hadrons
- Time calibration calculated using jets and monitored during physics data taking with laser
- Resolution is better than 1 ns for $E_{\mathrm{cell}} > 4$ GeV





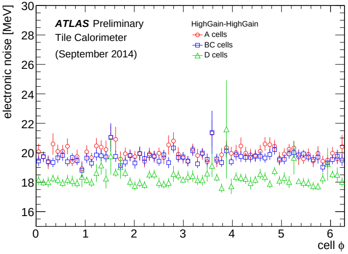
Noise

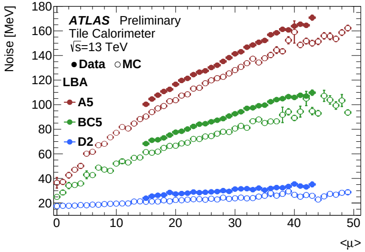
- The total noise per cell in the calorimeter comes from two sources:
  - Electronic noise - measured in dedicated runs with no signal in the detector
  - Pile-up contribution - originates from multiple interactions occurring at the same bunch crossing or from the events from previous/following bunch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

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

- Total noise is increasing with pile-up

- The largest noise values are in the regions with the highest exposure (A-cells, E-cells)

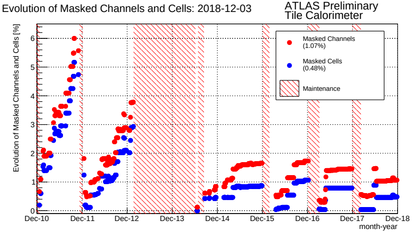


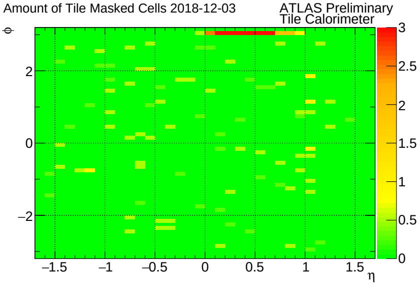


Detector Status and Data Quality

- TileCal monitoring includes identifying and masking problematic channels correcting for miscalibrations, monitoring data corruption or other hardware issues
- During maintenance periods there is a campaign to fix all issues, allowing for a good recovery of the system
- Redundancy of cell readout system reduces the impact of masked channels
- Tile had 99.7% DQ efficiency in Run-2
  - 2015: 100%, 2016: 99.3%, 2017: 99.4%, 2018: 100%

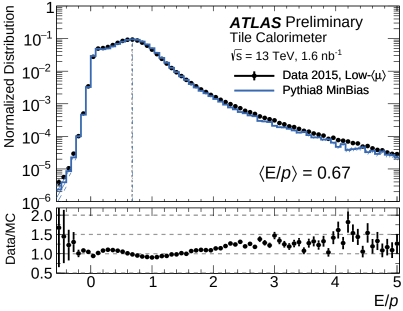
TileCal status at the end of Run-2

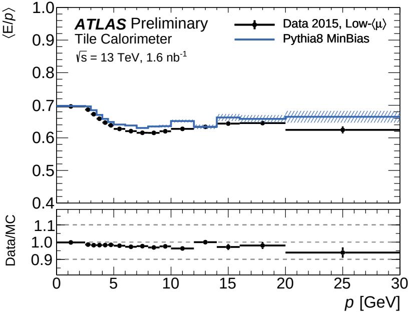




Single Particle Response

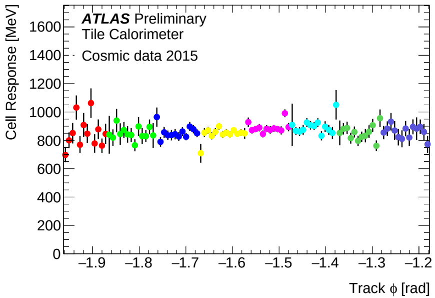
- The ratio of the calorimeter energy at EM scale to the track momentum $\langle E/p \rangle$ of single hadrons is used to evaluate uniformity and linearity during data taking
- Measured in Minimum Bias events
- Expect $\langle E/p \rangle < 1$ due to the sampling non-compensating calorimeter
- Data and Monte Carlo simulation (Pythia8) agree within 5%
- Jets are further calibrated to jet energy scale

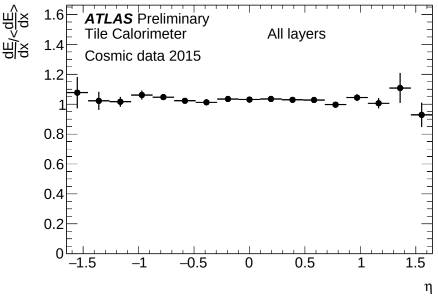




Muons

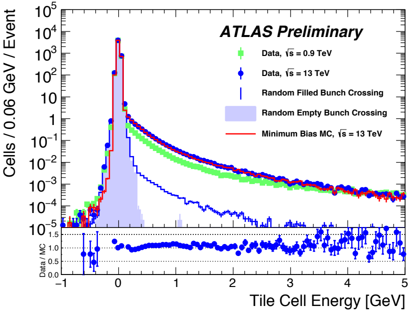
- Muons from cosmic rays are used to study in situ the electromagnetic energy scale and intercalibration of Tile cells
- A good energy response uniformity between calorimeter cells
- $< 5\%$ response non-uniformity in η with cosmic muons

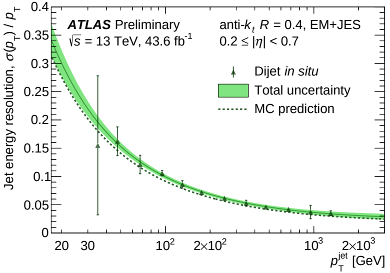




Jet Performance

- 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 for jet and missing transverse energy reconstruction
- Good agreement in Tile cell energy distribution
- Aim for jet energy resolution: $\frac{\sigma_E}{E} = \frac{0.5}{\sqrt{E}} \oplus 0.03$
- Jet energy resolution is better than 10% at $p_{\mathrm{T}} > 100$ GeV
- Constant term is within expected 3%



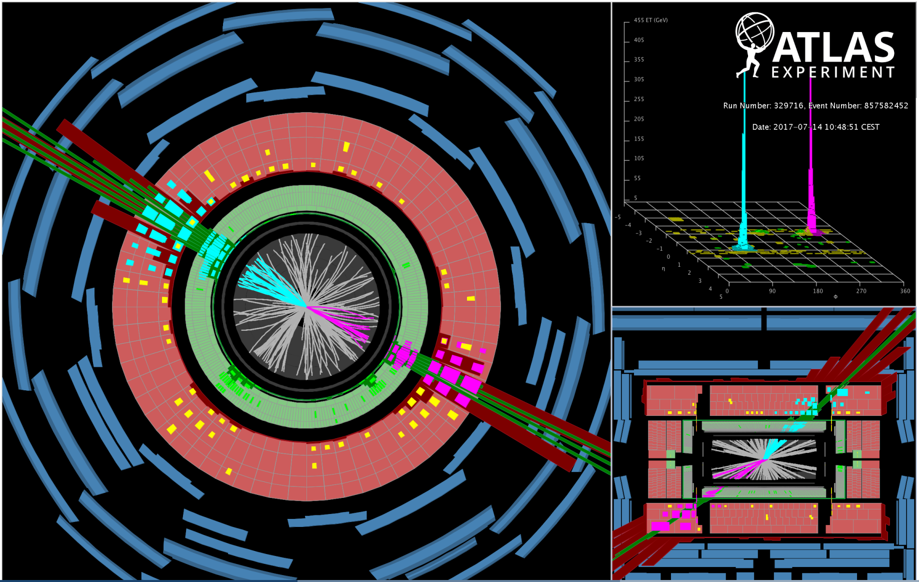


Conclusions

- Tile Calorimeter is an important part of ATLAS detector at LHC
- It is a key detector to measure the 4-vectors of the jets and missing energy
- A set of calibration systems is used to calibrate and monitor the calorimeter response
- Intercalibration and uniformity are monitored with isolated charged hadrons and cosmic muons
- The stability of the absolute energy scale at the cell level was maintained to be better than 1% during Run 2 data taking
- In Run-3: New crack scintillators (E3-4), covering a larger $|\eta| < 1.72$ range, will result in a significant improvement in the energy resolution for electrons, photons and jets in this region

The Di-jet Event Produced in 2017

Two jest with $p_{\mathrm{T}} = 2.9$ TeV and $m_{jj} = 9.3$ TeV



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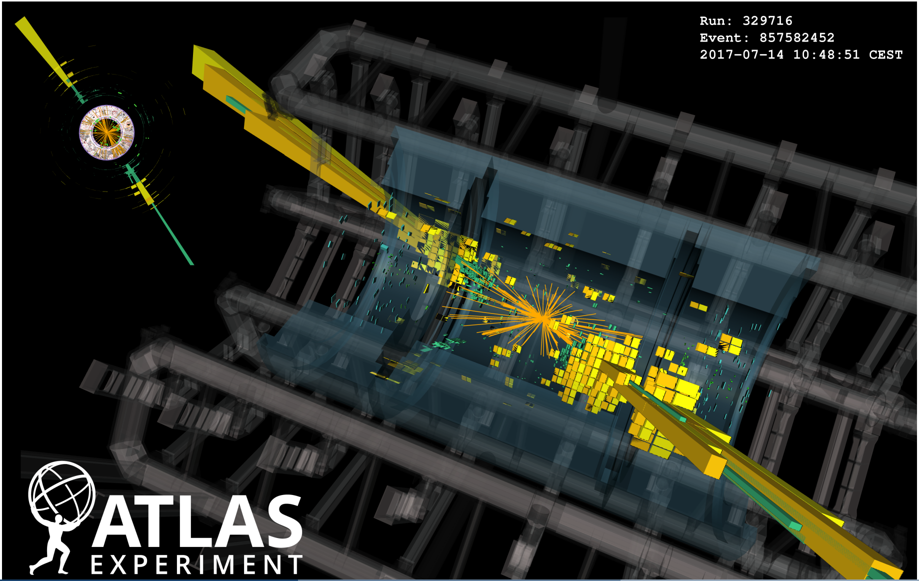

Back-up

Calibration System