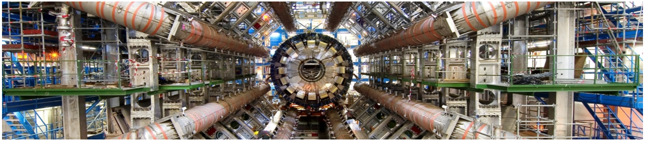

Performance of the ATLAS Tile Calorimeter

Siarhei Harkusha
on behalf of the ATLAS Collaboration

Institute of Physics of the NAS of Belarus, Minsk

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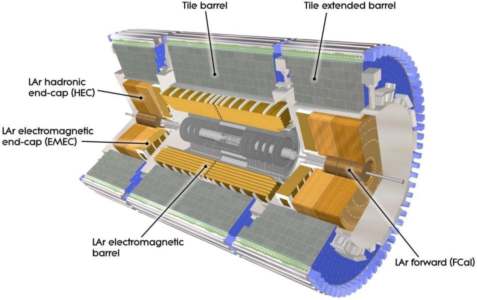
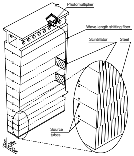
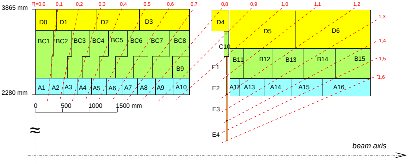
The ATLAS Tile Calorimeter

- Central hadronic calorimeter ($|\eta| < 1.7$) in the ATLAS detector
- Measures hadrons, jets, missing transverse energy, provides input to Level 1 Calorimeter trigger and assists in muon identification
- Sampling calorimeter: iron plates and plastic scintilating tiles (4.7:1)
- Double photomultiplier readout using wave length shifting fibers
- 9852 readout channels (PMTs)
- 5182 cells, granularity $\Delta\eta \times \Delta\phi$ in layers:
  - A,B(C) - 0.1×0.1
  - D - 0.2×0.1
- Jets (aim): $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$

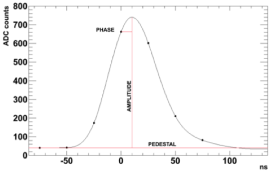






Signal Processing and Calibration

- Signal from PMT is shaped, amplified (2 gains, 1/64 ratio), and digitized each 25 ns
- Amplitude and time are reconstructed from 7 consecutive measurements (S_i):

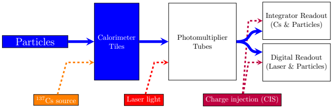


$$A = \sum_{i=0}^{7} a_i \cdot S_i, \ \tau = \frac{1}{A} \sum_{i=0}^{7} b_i \cdot S_i$$

- Energy is evaluated from amplitude using calibration coefficients (C_i):

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

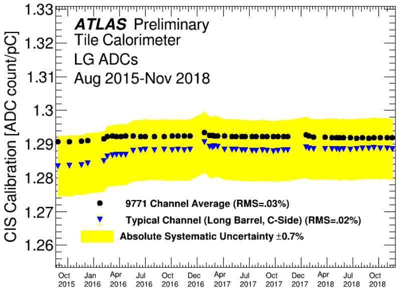
- $C_{ADC \to pC}$ is provided by Charge Injection System (monitors electronic chain stability and linearity)
- $C_{pC \to GeV}$ was measured in dedicated testbeam campaigns (2001-2003)

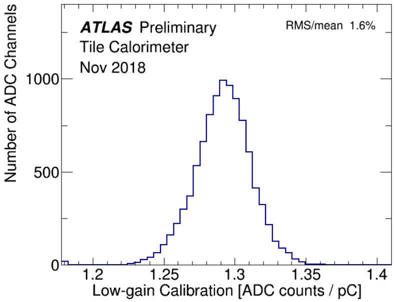


- C_{Cs} is provided by Cesium Calibration System (monitors all optics components: tiles, fibers, PMTs)
- C_{laser} is provided by Laser Calibration System (monitors PMTs stability)

Charge Injection Calibration

- Injects a signal of known charge and measures the electronic response
- Spanning full ADC range (0-800pC)
  - 2 gains for each channel
- Calibration performed ∼ weekly during dedicated calibration runs

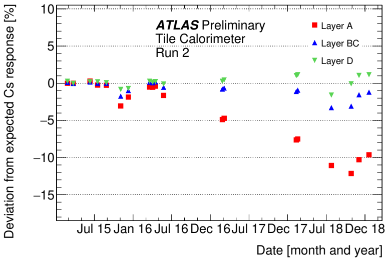


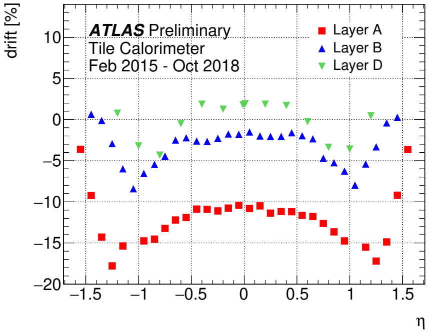


- Extracts the conversion factors from ADC counts to pC: $C_{ADC \to pC}$
- Precision ∼ 0.7%, stability ∼ 0.03%
- Also used to calibrate analog Level-1 Calorimeter trigger

Cesium Calibration

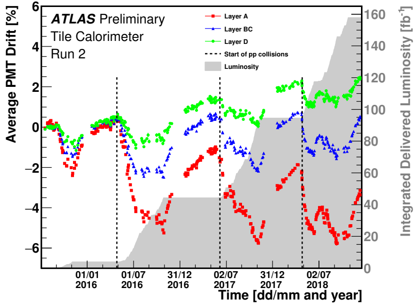
- A movable radioactive source 137Cs (γ-rays with energy 662 keV) passes through the calorimeter body, 2-3 times per year in Run 2
- Uses independent integrator readout ($\sim$ 10 ms) during source movement
- Deviation of the cell response in time is caused by PMT gain variation and scintilator degradation

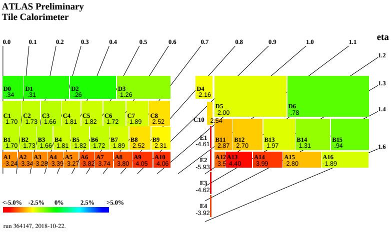




- Maximal drift is in layer A which is the closest to the collision point
- Precision in typical cell about 0.3%
- Allows to adjust PMT gain (changing high voltage) to restore calorimeter response uniformity

- A controlled amount of light is sent into each PMT (532 nm light)
- Performed $\sim$ weekly, during dedicated calibration runs and in empty bunches during collisions to monitor and calibrate timing
- Measures the drift seen in PMTs w.r.t the last Cesium scan
- Allows to detect the HV changes

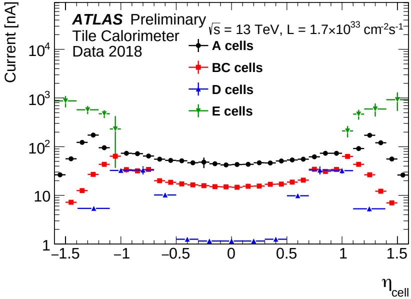


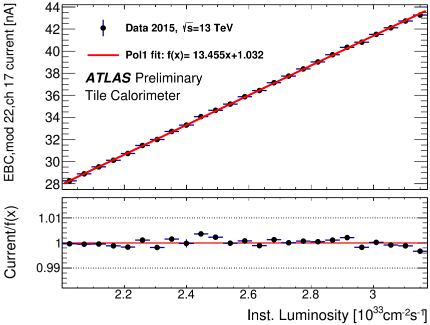


- The maximal drift is observed in A- and E-cells which are the cells with highest energy deposits
- Channel response deviation with respect to nominal gives C_{laser}
- Precision is better than 0.5%

Minimum Bias System

- Measures response to Minimum Bias events (soft inelastic parton interactions during pp collisions)
- Shares readout with Cesium system i.e. integrates PMT signals over $\sim$ 10 ms (during data taking)
- Monitors the full optical chain

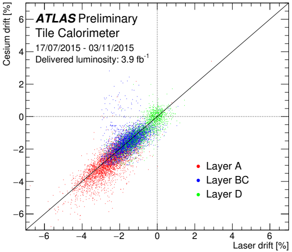




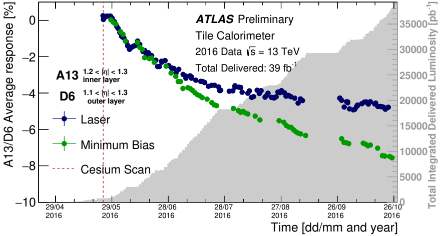
- Also calibrates E-cells and MBTS (Minimum Bias Trigger Scintillators)
- Measured currents dependent on the instantaneous luminosity (L) linearly
- Provides an additional way to measure and monitor L in ATLAS

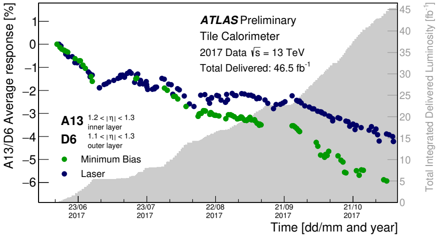
Combined Calibration

- Cell response variation comparison between Laser and Minimum Bias measurements
  - Cesium and Minimum Bias systems see PMT gain drift and scintillator ageing while Laser system only monitors PMT gain drift
- Down (Up) drifts are observed during collisions (maintenance) periods



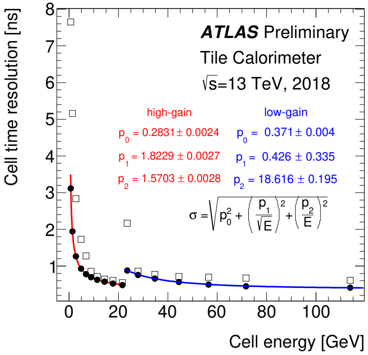
- Difference between Laser and Minimum Bias measurements can be interpreted as scintillator ageing due to irradiation (clearly seen after 2015)

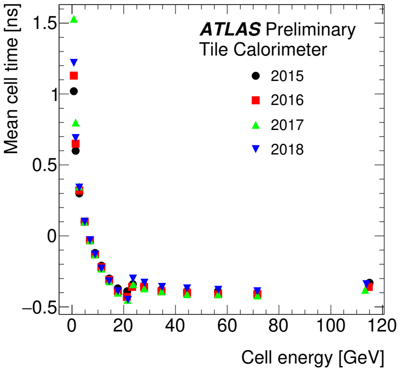




Time Calibration

- Precise time calibration is important for cell energy reconstruction
- Set the phase so that a particle traveling from the interaction point at the speed of light gives the signal with measured time equal to zero

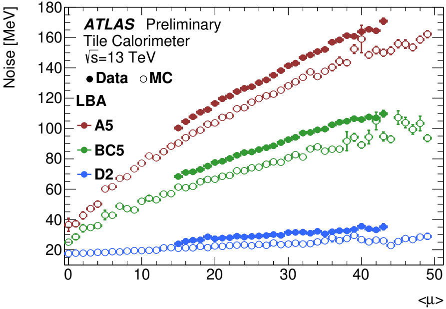


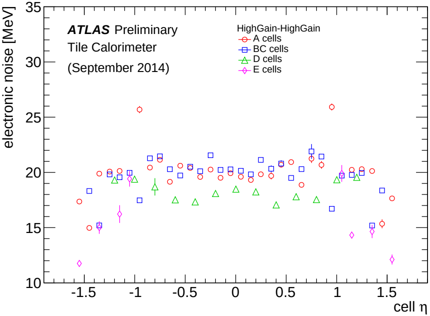


- Time calibration is calculated using jets and monitored with laser
- Resolution < 1 ns for $E_{\text{cell}} > 4$ GeV
- Can be used in TOF measurements e.g.: search for heavy *R*-hadrons

Noise

- Total noise per cell in calorimeter comes from two sources:
  - Electronic noise - measured regularly in dedicated runs without signal in detector
  - Pile-up noise - originates from multiple interactions in the same or neighboring events

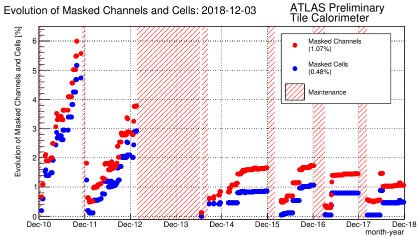


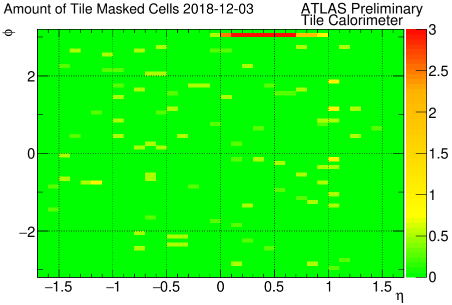


- Electronic noise is below 20 MeV for most of the calorimeter cells
- Total noise is increasing with pile-up
- The largest noise in the region with highest exposure (A- and E -cells)

Detector Status and Data Quality

- Monitoring includes identifying [and masking] problematic channels, data corruption, other hardware issues, correcting miscalibration, timing
- The identified issues are fixed during maintenance campaigns and that allows good recovery of the system





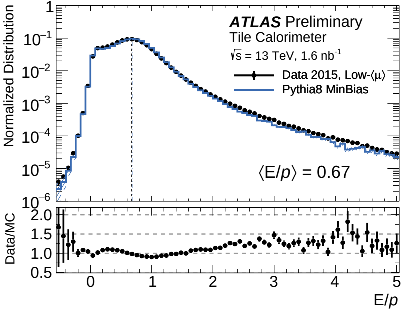
- Data Quality efficiency is $\sim$ 99.7 % during Run 2 (2015 - 2018)

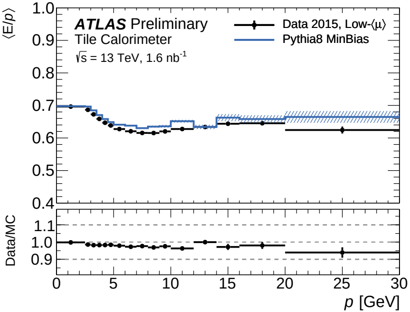
Year	Efficiency [%]
2015	100
2016	99.3
2017	99.4
2018	100

- Red line corresponds to switched off module due to cooling problem

Single Particle Response

- The ratio of the calorimeter energy at electromagnetic (EM) scale to the track momentum $\langle E/p \rangle$ for isolated charged hadrons is used to evaluate uniformity and linearity during data taking period
- Measured in Minimum Bias events

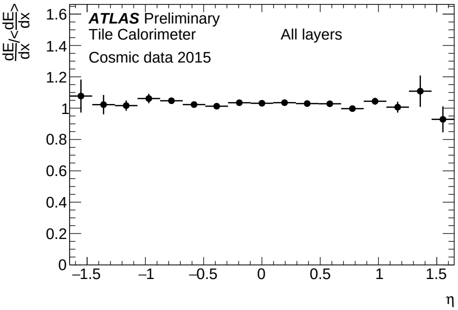


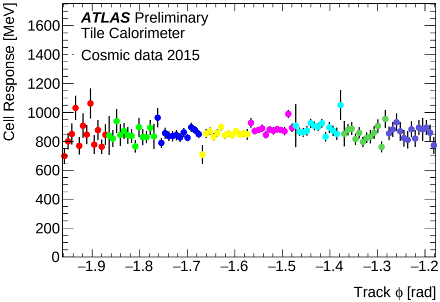


- Expected $\langle E/p \rangle$ below unity due to the non-compensating nature of the sampling calorimeter (e/h = 1.36)
- Data and Monte Carlo simulation (Pythia8) do agree well (within 5%)

Muons

- Muons from cosmic rays are used to study in situ the EM scale and the calorimeter cells intercalibration
- Cell response is estimated as the energy deposited by the muon per the length of the track path: dE/dx





- Good energy response uniformity between the calorimeter cells in ϕ
- Response non-uniformity in $\eta < 5\%$ with cosmic muons

Conclusions

- The Tile Calorimeter is an important part of the ATLAS detector at the LHC
- It is a key detector to measure hadrons, jets, and missing transverse energy
- Each stage of the signal production from scintillation light to the signal reconstruction is monitored and calibrated using a set of calibration systems
- Intercalibration and uniformity are monitored with isolated charged hadrons and high-momentum 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
- The overall Data Quality efficiency $\sim$ 99.7 % in Run 2