Calibration and performance of the ATLAS Tile Calorimeter

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on behalf of the ATLAS collaboration

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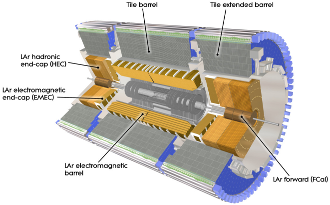
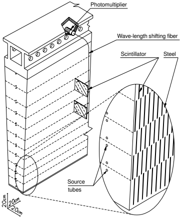
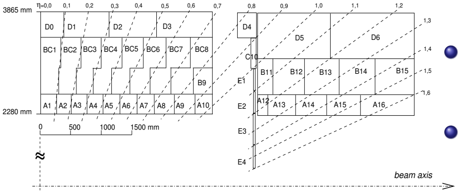
TileCal. Introduction

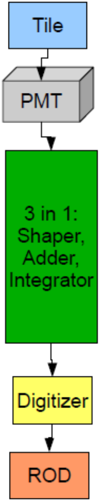






- TileCal – a central ($|\eta| < 1.7$) section of the hadronic calorimeter at the ATLAS experiment
- Measurement of energy deposited by hadrons
  - reconstruction of jet 4-vectors, hadronically decaying τ-leptons, and missing transverse energy (MET)
- Sampling calorimeter: interlaying plastic scintillator tiles (as active medium) and steel plates (as absorber)
- Symmetry in z-direction, 4 partitions, 3 radial layers, full azimuthal coverage
- 9856 read-out channels, 5182 cells

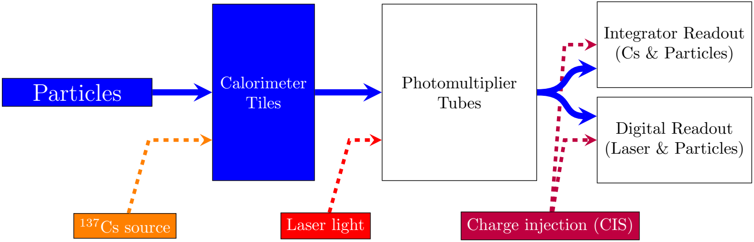
TileCal. Read-out. Signal reconstruction



- Particles passing through tiles produce light which is collected by fibers and transmitted to **photomultipliers** (PMT)
- Read-out is redundant (2 channel per cell)
- PMTs convert light into electric charge
- The signal is shaped in two gains (high:low gain amplification – 64:1) providing simultaneous measurement of high and low signal
- 10-bit digitizers sample and digitize the signal at 40 MHz
- Reconstructed energy from raw measured response: $E_{\mathrm{channel}}[GeV] = A[ADC] \cdot C_{ADC\to pC} \cdot C_{pC\to GeV} \cdot C_{Cs} \cdot C_{\mathrm{laser}}$
- Electromagnetic (EM) scale $C_{pC\to GeV}$ is measured during dedicated test beam campaigns
- Response is calibrated and contantly monitored at each step of signal path

TileCal. Calibration systems (1)

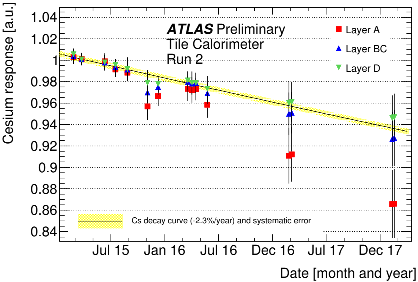
- Cesium system calibrates scintillators, PMT gains, fibers – C_{Cs}
- Laser system tests PMT response and provides additional checks of high voltage (HV) and time stability – C_{laser}
- **C**harge **I**njection **S**ystem (CIS) calibrates response of electronics to known charge in 2 read-out channels – $C_{ADC \rightarrow pC}$
- Integrator (Minimum Bias) system monitors optical path and PMT gain
  - provides measurement of instantaneous luminosity measuring signal from soft (MB) interactions

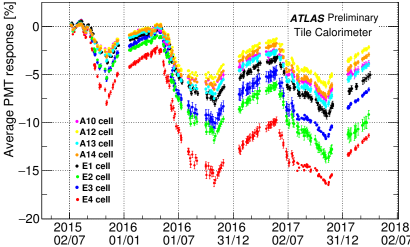


- Calibration systems partially overlap: cross-check and reliable data-taking

TileCal. Calibration systems (2)

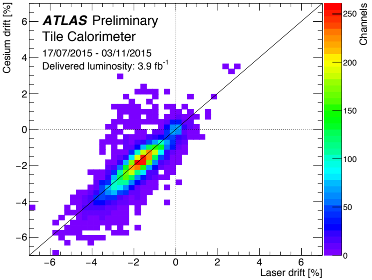
- Moveable ^{137}Cs radioactive γ-source (662 MeV) illuminates tiles
  - System calibrates optic components and monitors the detector response (identify PMT drift, scintillator ageing)
  - C_{Cs} system is used to equalize the detector response to the level of EM scale ($C_{pC \to GeV}$) measured during test beams (by changing high voltage)
- Laser system tracks PMT gain drifts
  - Controlled amount of light (532 nm) sent to each PMT via ~400 fibers to measure PMT response and detect gain variation
- For Run 2, improvement of safety and stability, electronics and optics
- Precision of: channel response to Cs is $< 0.3\%$, laser calibration – $< 0.5\%$

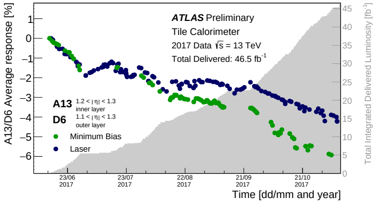




TileCal. Combined energy calibration

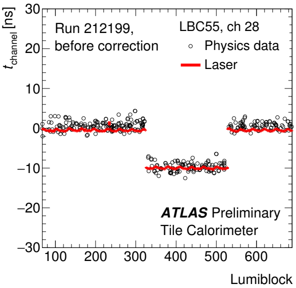
- Comparison of PMT gain variations seen by Cs and Laser gives information about scintillator ageing effect or/and bias in the laser measurement
  - Cs and Laser measurements agree
  - Larger drifts for Layer A (closer to the collision point)
- Scintillator ageing due to irradiation is seen by comparing variation of MB and Laser response
  - The difference in the response to MB events and Laser pulses $\Delta_{\mathrm{MB-Laser}}$ is interpreted as scintillator light yield loss (due to irradiation)
  - Average response measured by MB system matches to Cs system results

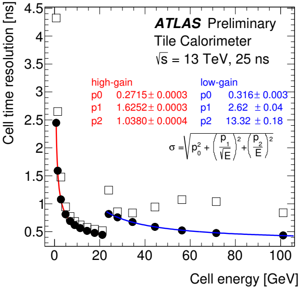




TileCal. Time calibration

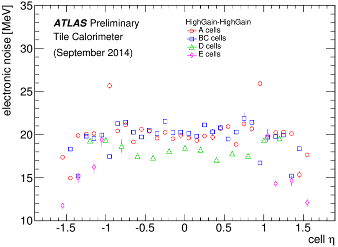
- The aim is to adjust digitizer sampling clock to the peak of signal produced by the particle traveling through the cell
  - Crucial for precise energy reconstruction
  - Useful for TOF studies
- In Run 2, calibration is performed with time distributions in the cells comprised by jets
- Timing stability is monitored using laser-in-gap events (± 3 ns)
- Resolution is below 1 ns for $E_{cell} > 20$ GeV
  - Slightly better for smaller cells
- In Run 2, time calibration is stable (no more than a dozen of changes) due to new low voltage power supplies (LVPS) and improved digitizer settings (from 2017)

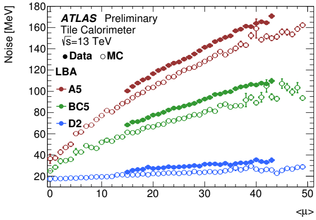




TileCal. Noise measurement

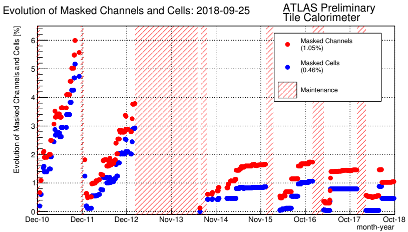
- Noise in the TileCal cells comes from:
  - Electronics
  - Pile-up: multiple interaction occurring at the same bunch crossing ($< \mu >$)
- Electronic noise is estimated as RMS of pedestal
  - $\sim$20 MeV for most of the cells
  - Better description (Gaussian-like shape) in Run 2 with new LVPS
- Pile-up noise is defined by learning dependence of the TileCal cell noise (RMS of energy distribution) on $< \mu >$
  - Zero-bias data runs considered
  - It depends on exposure to beam: the highest for E- and A-cells
- Noise description is used in jet and MET reconstruction

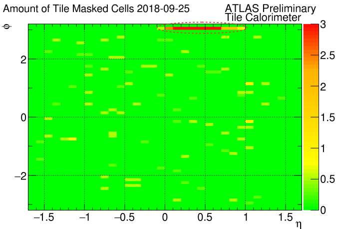




TileCal. Data Quality

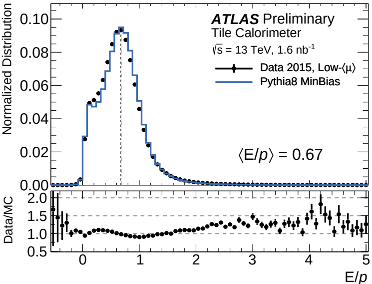
- Calibration parameters, cell response and time stability are continuously monitored, and necessary fine corrections are seasonably applied
- Problematic channels are identified and masked
- During long shutdowns, maintenance campaign aims to fix hardware failures
  - 30/256 modules were opened during 2017/2018 shutdown
- Data Quality (DQ) efficiency: 100% (2015), 98.8% (2016), 99.4% (2017), and 100% (in 2018 up to now)
- Currently, 0.46% of cells and 1.05% of channels are masked
- Majority of masked cells belong to a single module
  - LBA32 which is off due to cooling problem

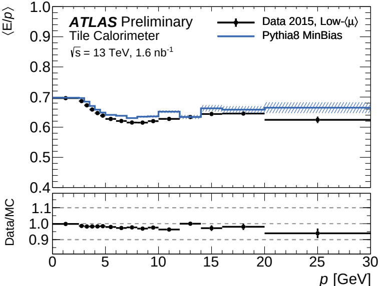




TileCal. Performance with isolated hadrons

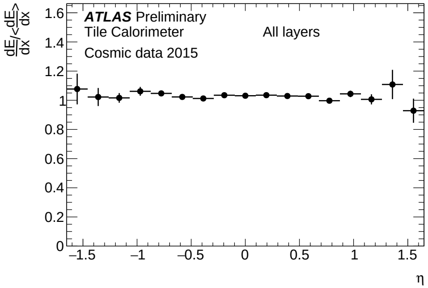
- Response to single isolated charged hadrons is described by the ratio of energy at EM scale to track momentum using low-$< \mu >$ (MB) events
- $< E/p >$ is used for evaluation of calorimeter uniformity and linearity
- The average response is 0.67 (below the unity due to non-compensating nature of the calorimeter)
- Zero-bias data and MB MC samples are in agreement within 5%

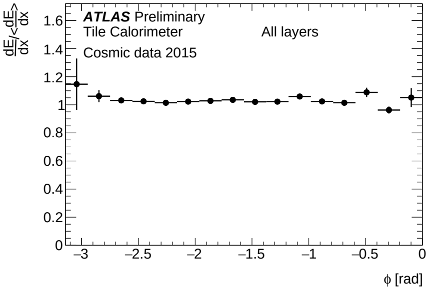




TileCal. Performance with isolated muons

- Inter-calibration of the TileCal cells as well as derivation of EM scale with *in situ* methods are performed with muons using cosmic data
- Cell response is estimated as the energy deposited by the muon per the length of track path (dE/dx)
- Good energy response uniformity over ϕ
- Non-uniformity in η below 5%



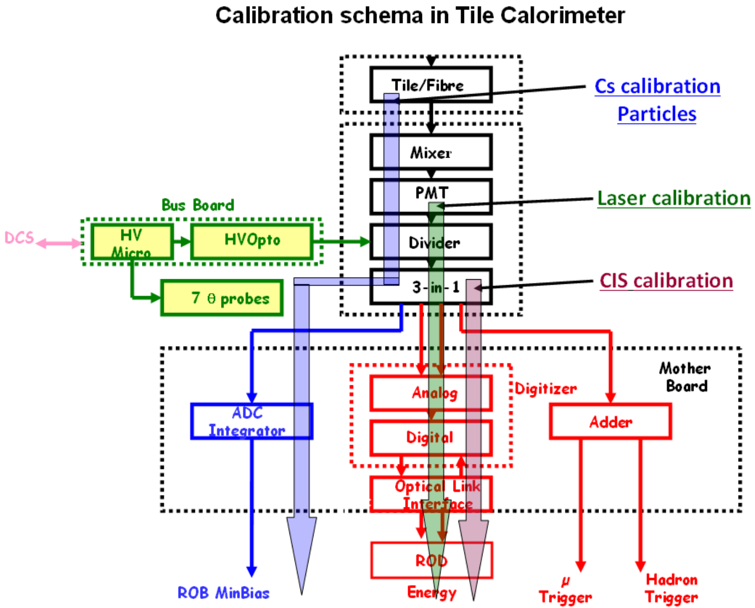


Summary

- Tile Calorimeter provides decisive information for reconstruction of jets and missing transverse energy in the ATLAS experiment
- Stability of cell energy scale stays below 1%
- Uniform, linear, and stable response is ensured by
  - 4 calibration systems of the TileCal (Cesium, Laser, Charge Injection and Integrator (Minumum Bias))
  - Monitoring of time and noise stability
  - Control of cell response uniformity and inter-calibration with cosmic muons and isolated charged hadrons
- Experience gained during Run 1 was used for improvement of the TileCal calibration systems for Run 2
- A number of inefficient cells is kept below 0.5%
  - Read-out system redundancy (2 channels per a typical cell)
  - Careful monitoring of the calorimeter response
  - Effective maintenance
- Quality of data collected by the TileCal is checked ceaselessly, resulted in $>$ 99% efficiency averaged throughout Run 2

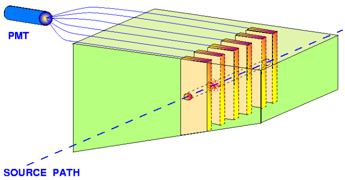
back-up

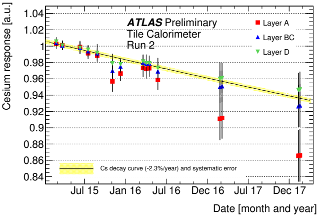
TileCal Calibration Systems



TileCal. Cesium system

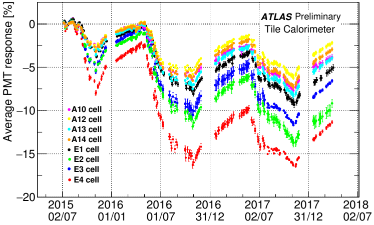
- Moveable ^{137}Cs radioactive γ-source (662 MeV, $t_{1/2} \sim 30$ y.) illuminates tiles
- System calibrates optic components (scintillators, PMTs, fibers)
- Cs calibration system monitors the detector response in time defined by
  - E.g. PMT drift, scintillator ageing
- C_{Cs} is used to equalize the response for all channels and setup EM scale
  - Large deviations can be addressed by adjusting PMT gain (with HV change)
  - PMT response is adjusted to the level when $C_{pC \to GeV}$ was measured during test beams (with HV change)
- Improvement of safety and stability before Run 2
- Precision of channel response is $< 0.3\%$

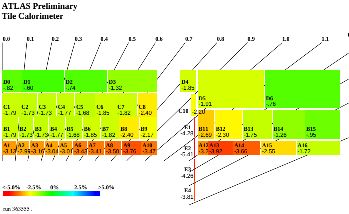




TileCal. Laser calibration

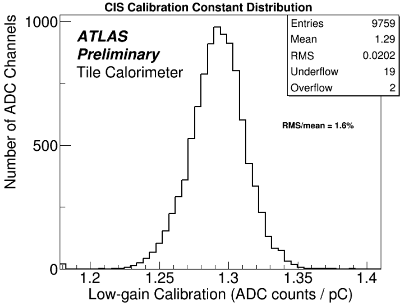
- Laser system track PMT gain drifts and monitors electronics components. It is used for time studies
- Light (532 nm) sent to each PMT via ∼400 fibers to identofy PMT response and gain variation
- Down-drifts of the PMT response coincide with p-p collision periods
- Response is recovered during heavy-ion collisions and technical stops
- Mean gain variation is below 2.5% for a standard TileCal cell, maximal drift (up to 5.5%) in E-cells with large energy deposits
- Precision is better than 0.5%
- For Run 2, improved electronics and optical components

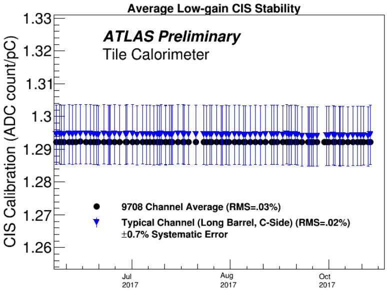




TileCal. CIS calibration

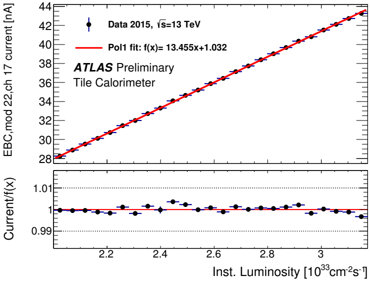
- CIS calibrates read-out channels in 2 gains (HG and LG) based on their response to changes of known value
  - CIS is also used for correction of non-linearities in response and calibration of analoug L1 trigger
- Voltage source injects into capacitor (100 pF) charge (0-800 pC) which is discharged into FE electronics
- ADC=$C_{ADC\to pC} \times Q$, $C_{ADC\to pC}$ ~1.3 (LG), ~82 (HG) ADC-c./pC
- Precision is ~0.7%, the average fluctuation over all channels is 0.03%

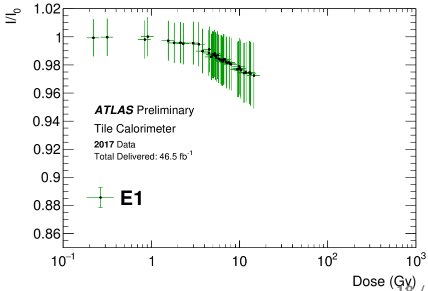




TileCal. Minimum Bias (Integrator) system

- Miminum Bias (MB) system identifies response to MB events (soft inelastic parton interactions during p-p collisions)
  - integrator read-out measures signal over $\sim$10 μs $\sim$10 mln MB events
  - MB system monitors full optical route (pC/GeV) and luminosity
    - ★ instantaneous luminosity measurement: $< I >$ depends on $\mathcal{L}$
  - it also calibrates E-cells and MBTS
- comparison of laser drifts with response measured by MB currents reveals scintillator ageing due irradiation: light yield depends on dose





TileCal. Performance in p-p colisions

- Agreement between noise description in zero-bias data (events triggered by MBTS) and MB MC simulation
- Energy scale correction is defined by jet response ratio in data and MC simulation
  - consistent between all measurement methods: Z+jet, γ+jet, multi-jet
- Jet are calibrated with the EM and **j**et **e**nergy **s**cale (JES)
- Jet energy resolution is $\sim$ 1%, constant term is 3% (expected)