Performance of the ATLAS Tile Calorimeter

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Introduction

ATLAS detector

Hadronic Tile Calorimeter

• ATLAS is the multipurpose detector at the LHC.
• Consists of internal tracker, electromagnetic and hadronic calorimeters, and external muon spectrometer.
• Allows a wide spectrum of high energy physics studies both within the Standard Model and Beyond.

• Tile Calorimeter is the hadronic sampling detector within ATLAS
• Located at the outer barrel of the ATLAS calorimetry system
• Intended for energy measurements of jets, single hadrons, tau-particles and missing transverse energy
Tile Calorimeter structure

Long barrel (LB) $|\eta| < 1.0$

- D layer
- BC layer
- A layer

Extended barrel (EB) $0.8 < |\eta| < 1.7$

- Crack / Gap

- Tile Calorimeter consists of one central Long Barrel cylinder and two Extended Barrels cylinders covering $|\eta| < 1.7$ and $0 < \varphi < 2\pi$
- Segmented into 64 modules in azimuth
- Has three radial layers ($7.4 \lambda_{int}$) and the longitudinal Gap/Crack layer between barrels
- The granularity is $\Delta \eta \times \Delta \varphi = 0.1 \times 0.1$ ($0.2 \times 0.1$ in the last radial layer)
- Consists of 5182 readout cells
- Designed energy resolution $\sigma/E = 50% / \sqrt{E} \oplus 3%$
Tile Calorimeter Read-Out

Tile Calorimeter is the sampling detector made of plastic scintillator and steel as absorber (scintillator only in crack/gap cells)

- Signal from each cell is routed by WLS to two PMTs (giving 9852 readout channels)
- Analog signal from each PMT is amplified by two gains (1:64), shaped and digitized by 3-in-1 card every 25 ns
- The digitised samples are stored in pipeline awaiting for L1 trigger accept
  - Analog signals contribute to L1 trigger
- The slower Integrator readout is routed before amplifiers and used for Cs (or MinBias) calibration
Signal reconstruction

- 7 sets of ADC counts (samples) spaced by 25 ns are used for signal reconstruction (150 ns window)
- Amplitude ($A$), time ($t_0$) and quality factors ($QF$) are obtained with Optimal Filter (OF) algorithm
- OF uses weighted sum of samples ($S_i$) in order to minimise noise
  \[ A = \sum a_iS_i, \quad t_0 = \frac{1}{A} \sum b_iS_i, \quad QF = \sum (S_i - (Ag_i + At_0g_i + Ped))^2 \]
- The time calibration is important for OF performance
- Time measurements and calibration is performed using “splash” events (single beam events hitting closed collimator)
- Tuned later with collisions, exploiting jet events

The slope matches the time the particles cross calorimeter across beam axis
Energy calibration

- The energy calibration allows to reconstruct the energy of jets in GeV.
- Performed using various calibration systems (with precision of 1% of the cell response)
  - The injection of known charge to digitiser (CIS) allows to calibrate electronics ($C_{ADC\rightarrow pC}$)
  - $C_{pC\rightarrow GeV}$ conversion factor has been defined at testbeam via the response to electron beams of known momentum (setting the absolute energy scale)
- Injected laser light with known intensity allows to equalise PMT response ($C_{Laser}$)
- Cs source moved through all the cells (except crack scintillators) allows to equalise scintillator response ($C_{CS}$)
- Scintillator response equalisation can be improved using Minimum Bias events

\[ E = A \cdot C_{CS} \cdot C_{Laser} \cdot C_{ADC\rightarrow pC} \cdot C_{pC\rightarrow GeV} \]
Energy calibration: Cs

\[ E = A \cdot C_{CS} \cdot C_{Laser} \cdot C_{ADC\rightarrow PC} \cdot C_{PC\rightarrow GeV} \]

Deviation from expected response in 2009-2015

The deviation from expected response rises due irradiation effects in scintillators, variations of PMT gain.

- Calibration of the initial part of the signal readout path (scintillator response) with movable radioactive $^{137}\text{Cs}$ $\gamma$-sources ($E_{\gamma} = 0.662 \text{ MeV}$)
- The signal is read out through a special “slow” integrator
- The correction applies to maintain global conversion factor and corrects for residual cell differences
- The calibration is usually performed ~1th per month (was not available in 2016 due to water leak)
Laser light pulses are sent directly to PMT to measure PMT gain variation and correct for non-linearities of the readout electronics. Laser is also used for time calibration and monitoring. Calibration is usually done 2 times per week (or even more often in case Cs is n/a).

\[ E = A \cdot C_{Cs} \cdot C_{Laser} \cdot C_{ADC\rightarrow pC} \cdot C_{pC\rightarrow GeV} \]

The difference between Laser and MinBias (or Cesium) response allows to estimate the effect of the scintillators irradiation.

Highest PMT gain variations are observed during 2016 pp collisions: 5% to 10% in cells closest to beam pipe.

- Laser light pulses are sent directly to PMT to measure PMT gain variation and correct for non-linearities of the readout electronics.
- Laser is also used for time calibration and monitoring.
Energy calibration: CIS

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

- Calibration of the front-end electronic gains with a charge injection system (CIS) located in 3-in-1 card (allows to test each channel)
- Fires both amplification gains
- Corrects for non-linearities of electronics associated to the PMTs
- Performed 2 times per week for monitoring

CIS calibration was very stable during 2016 data taking
The 2016 was the best year for the Tile Calorimeter from the beginning of LHC data taking.

• Good stability of electronics

Less than 1% cells were excluded from reconstruction at the end of 2016 pp collisions.

• One module is excluded due to the water leak in cooling system
• Another module had readout problems
**Noise performance**

**Electronics noise**

- Electronics noise is measured and monitored in special runs without collisions
- Defined as the width of Gaussian fit to the reconstructed cell energy distributions
- Stays at the level of 15-20 MeV for most of cells

**Pile-up noise**

- Energy distribution in Tile Calorimeter cells gets wider and larger in presence of pile-up
- Total noise (standard deviation of the energy distribution) is increasing as the function of average number of interactions per bunch crossing (driven by pile-up contribution)
- Cells closest to beam beam pipe are affected by higher noise
Performance with jets and hadrons

• The ratio of the calorimeter energy over the track momentum (E/p) of single hadrons is used to evaluate TileCal uniformity and linearity during data taking.

• The calorimeter calibration at the electromagnetic scale results in E/p<1, while jets are further calibrated in a more complicated way.

• Good linearity and uniformity is observed. The data/MC agreement is within 3%.

• The jet energy resolution is below 10% for jets with p_T > 100 GeV.

• The constant term is at the level of 3%, compatible with the expectations.
Performance with muons

- Muons from cosmic rays, beam halo and collisions (e.g. $W \rightarrow \mu\nu$ events) are exploited to study the electromagnetic energy scale in-situ
- Energy deposited by muons in scintillator proportional to its path length ($dE/dx$)

Cosmic muons

- 1% response non-uniformity with $\eta$ in Long Barrel
- 2-3% response non-uniformity with $\eta$ in Extended Barrel
- The response is uniform across $\phi$ within 2%

Collision muons ($W \rightarrow \mu\nu$)

- A good energy response uniformity is found with 8 TeV collisions data in all calorimeter layers
- The data/MC agreement is within 3%
Summary

• Tile Calorimeter has shown a great performance in 2016 year of data taking providing 98.9% of good data for physics analyses

• Solid multistep calibration and monitoring system allows to maintain uniform and stable cell energy response with precision better than 1%

• The results show that the Tile Calorimeter performance is within the design requirements and gives essential contribution to reconstructed physics objects and physics results