Performance of the ATLAS hadronic Calorimeter at LHC

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Outline

• The detector
• Calibration
• Operations in 2012
• Detector response studies
• Conclusions
The calorimeter TileCal is a sampling plastic scintillator/steel detector, located in the region $|\eta| < 1.7$.

- It is divided into three cylinders: one Barrel and two Extended Barrels, EBA and EBC. The Barrel consists of two readout parts: LBA ($\eta > 0$) and LBC ($\eta < 0$).
- The gap regions are equipped by 4 sets of scintillators.
- Inner radius: 2.28 m
- Outer radius: 4.25 m
- Total length: 12 m
- Weight: 2900 tons

Aim for Jet energy resolution (TileCAI + Lar): $\sigma(E[GeV])/E[GeV] \approx 50%/\sqrt{E} \oplus 3\%$
The TileCal Modules

- Each cylinder is composed of 64 azimuthal modules each spanning $\Delta \phi = 2\pi/64 \approx 0.1$.
- The steel plates and scintillating tiles are perpendicular to the beam.
- Two sides of the scintillating tiles are read out by wave-length shifting (WLS) fibers into two separate PMT’s.
- By the grouping of WLS fibers to specific PMT’s the modules are segmented in $z$ and radial depth.
- The 3 radial layers span $1.5, 4.1$ and $1.8 \lambda_{int}$ in the barrel and $1.5, 2.6$ and $3.3 \lambda_{int}$ in the extended barrels.
- The resulting typical cell dimensions are $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ ($0.2 \times 0.1$ in the last layer).
- This segmentation defines a quasi-projective tower structure.

### Table

<table>
<thead>
<tr>
<th>Channels</th>
<th>Cells</th>
<th>Towers</th>
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<tbody>
<tr>
<td>9836</td>
<td>5182</td>
<td>2010</td>
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The Monitoring Systems

• Cs source (precision: 0.3%)
  o PMT voltage adjustments to inter calibrate cells and keep gain to the level established with electron beams at standalone beam tests.
  o Calibrate scintillating tiles optics, PMTs and integrator readout

• Laser (precision: <1%)
  o Measuring stability of PMT response and electronics, linearity and relative timing of digitizer boards.

• Charge Injection (stability: 0.7%)
  o Gives correspondence ADC counts->pC and electronics linearity.

• Minimum Bias current monitoring system
  o It integrates energy to monitor the cell response evolution and luminosity
A project 20 years old ...

P. Jenni – Expression of interest – EAGLE collaboration
General Meeting on LHC Physics and Detectors
Evian-les-Bains, France, 5 - 8 Mar 1992

Scintillator tile hadron calorimeter conceptual design

- Novel concept for a simple and economic hadronic scintillator calorimeter with Fe absorber and possibly integrated magnetic field return
- Vertical scintillator plates (w.r.t. barrel axis) read out with straight wave length shifting fibers at two edges (light collection experimentally checked)
- Granularity $\Delta\eta\Delta\phi \approx 0.1 \times 0.1$ with 4 longitudinal samples, 15000 channels total
- $\eta$-projectivity by grouping WLS readout fibers of the longitudinal samples to form approximatively pointing towers

Expected jet resolution (MC simulation assuming a 25 $X_0$ Pb - LAr EM calorimeter in front)

$$\sigma(E)/E = 41\%/E + 2\%$$
A bit of history

1993-1995 R&D

1996-2002 Mechanics and optics construction

1999-2002 Instrumentation

1999-2004: Electronics construction

2000-2004: Calibration at TB’s

2004-2006: Installation

2005-2009 Commissioning using cosmic muons and calibration triggers in the experimental hall

Since 2009 Continuous operation in p-p collisions with yearly maintenance in Christmas shutdown

2013-2015 Long shutdown
Beam Tests results

- Achievements
  - Validation of design performance
  - Cell response uniformity
  - Comparison with (Tuning) Geant 4 MC
  - EM scale using electrons

- The measurements show good performance and Data/MC agreement
TileCal Standalone: Pion response Linearity

- The pion non linear energy dependence is due to containment and calorimeter non-compensation
- $e/h=1.33$ using Groom's parameterization of the non-EM component of hadronic showers

$|\eta|=0.35$
TileCal Standalone: Pion response Resolution

η=0.35 \rightarrow \text{depth}=7.9 \lambda

- 5.7\% constant term affected by longitudinal containment

\[
\sigma(E) = \frac{(52.9\pm0.9)\%}{\sqrt{E_{\text{beam}}}} \oplus (5.7\pm0.2)\%
\]

- 350 GeV
- 180 GeV
- 100 GeV
- 50 GeV
- 20 GeV
- 10 GeV

MC-Geant4.8.3 QGSP+Bertini

Data
Energy reconstructed for each channel

\[ E = A_{ADC} \times C_{CIS} \times C_{Las} \times C_{Cs} \times EM \times C_{\mu} \]

- \( A_{ADC} \): Amplitude in ADC
- \( C_{CIS} \): ADC\( \rightarrow \text{pC} \) conversion factor from CS
- \( C_{Las} \): Relative variation from Laser system
- \( C_{Cs} \): Relative variation from Cs system
- \( EM \): \text{pC} \rightarrow \text{GeV} conversion factor from \( e \) at TB
- \( C_{\mu} \): Factor due to the different sizes of the cells from \( \mu \) at TB

The jet energy is corrected for containment, non-compensation, ...

Using MC simulation
Cell Response Variation

- Down drift due to high instantaneous luminosity
- Up drift due to recovery during technical stops

Drift dominated by PMT gain effects

Corrections applied to the PMT response
Setting of the electromagnetic scale (EM) for the cells of layer A

- 11% of all Tilecal modules brought to beam test in H8/SPS/CERN
- Using electrons with $E=20-180\text{GeV}$; $\theta=20^\circ$ incident beam in innermost radial layer cells (A)
- EM scale (Response/$E_{\text{beam}}$): mean=$1.05\text{pC}/\text{GeV}$; RMS=2.4% (dominated by optics fluctuations)

- The scale is transferred to ATLAS using the Cs measurements $\rightarrow$ HV is set in a way that PMT response to Cs in ATLAS is equal to the one when the EM scale was measured at TB taking into account the Cs lifetime

- A similar procedure is used to determine the scale of the EM calorimeter energy measurements $\rightarrow E_{\text{jet}} = E_{\text{TileCal}} + E_{\text{Lar}}$
- One can compare the $E_{\text{jet}}$ obtained in experimental and simulated events
The correction factor $C_\mu$

- Due to the different dimensions of the cells, a precision analysis of the response to $90^\circ \mu$ vs radial layers was carried out in order to extend the measurement of the EM constant obtained with $e$ in layer A to all the cells of the TileCal modules.

The corrections factors range between $C_\mu = 1.009 \pm 0.005$ for the cells B of the EB and $C_\mu = 1.088 \pm 0.005$ for the cells D of the LB.
2012 Operations

- LVPS for Run I quite sensitive to radiations ⇒ many trips

- Automatic procedures to recover module within about one minute

- New design tested in 2012 ⇒ one trip only (38 LVPS) ⇒ All LVPS being replaced during current shutdown

The Energy of the dead cells is recovered Using the information of the neighbor ones

- 4 modules dead at the end of 2012

Dead modules introduced in the simulation
Detector response studies in the experimental hall

- **Performance with cosmic rays muons**
  - Check detector response uniformity and stability
  - Check the transportation of the EM scale from the test beam to ATLAS

- **Performance with isolated pions**
  - Check detector response uniformity and stability
  - Comparison with Geant 4 MC

- **Performance with inclusive p-p events**
  - Check detector response uniformity and stability
  - Comparison with Geant 4 MC
  - Monitor Pile-up level
Performance with single muons

- Muon signal in TileCal is well separated from electronics noise
- Cosmic muons can be used to cross-check cell energy inter-calibration and overall EM scale
- Data and MC dE/dx comparisons as a function of $\eta$ and $\phi$ show good cell inter-calibration within one layer (within 2-4%)
Layer Uniformity

- The ratio between the actual value of the EM energy scale in ATLAS and the value set at the beam tests is consistent with 1 within ±2%
- Difference between barrel layer D and all other layers is observed

Distributions of the pseudo measurements ratios of the experimental and simulated truncated means. The pseudo measurements were obtained changing the criteria applied to select and to reconstruct events
Comparison of cosmic muon signals over 3 years shows that signal in 3 barrel and 3 extended barrel layers is stable over time.

Results prove that the Cs calibration applied during this 3-years period is correct.

On the base of these results the contribution of TileCal measurements to the systematics on the jet energy reconstruction in ATLAS is about $3\% \times 0.25$ (average fraction of the jet energy deposited in TileCal) = 0.75%
E/p from hadrons in collisions (2010)

- Isolated particles showering in TileCal are selected
  - Particles are “MIPs” in the Electromagnetic Calorimeter
- Momentum ($p$) is measured with tracking inner detector
- Overall, simulation agrees with observation to within 3%, however this agreement degrades to 5% (2010 data right) and 10% (2011 data left) in the transition between the long barrel and extended barrel ($0.8 < |\eta| < 1.1$).
Noise in Minimum Bias events

- Includes noise due to pile-up and electronic noise

Good agreement between measured and simulated noise
Conclusions

- TileCal is performing well during the first years of LHC data taking. It fulfills the design goal.
- TileCal provided 99.1% of good data for physics in 2012.
- EM scale has been successfully transferred from beam tests and validated with cosmic rays muons (Maximum difference between radial layers is 4%).
- The calibration systems are commissioned and are working well. Precision of individual system is below 1%. Calibration constants applied to data make response stable in time.
- MC simulation agrees well with data (noise description, response to muons, single hadrons and Minimum Bias events).