Status Report of the ATLAS Tile Calorimeter

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for the ATLAS collaboration

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Outline

• The ATLAS Tile Calorimeter

• “Readiness” of TileCal for LHC collisions
  - Calibration system
    ‣ Charge injection, Laser, Cesium
  - Performance
    ‣ Electromagnetic scale measurement
      ‣ Muon in the Combined TestBeam
      ‣ Cosmic rays
    ‣ (Timing)
      ‣ Single beam

• 2009 Collision Data
  - Energy Scale
  - Missing $E_T$ by noise
    ‣ Double gaussian treatment
  - (Jet)

• Summary
TileCal group

- **Institute**
  - Academy of Sciences of the Czech Republic, Institute of Physics and Institute for Computer Science
  - Argonne National Laboratory
  - Bratislava University
  - Charles University in Prague, Faculty of Mathematics and Physics
  - Department of Physics, University of Wisconsin
  - European Laboratory for Particle Physics, CERN
    - T. Sumida, S. Shimizu
  - INFN Pisa and Universita di Pisa, Dipartimento di Fisica
  - Institut de Fisica d’Altes Energies, Universitat Autonoma de Barcelona
  - Institute of Physics, Azerbaijan Academy of Sciences
  - Institute of Physics, National Academy of Sciences
  - Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC
  - International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo
    - S. Yamamoto, Y. Kataoka
  - Joint Institute for Nuclear Research (JINR)
  - Laboratoire de Physique Corpusculaire (LPC), Clermont Universite, Universite Blaise Pascal, CNRS/IN2P3, Clermont-F
  - Laboratorio de Instrumentacao e Fisica Experimental de Particulas (LIP)
  - Michigan State University, Department of Physics and Astronomy
  - National Centre for Particle and High Energy Physics
  - National Institute of Physics and Nuclear Engineering (IFIN–HH), Institute of Atomic Physics
  - Northern Illinois University
  - State Research Center Institute for High Energy Physics (IHEP)
  - Stockholm University
  - The University of Texas at Arlington
  - Universidade Federal do Rio De Janeiro, COPPE/EE/IF
  - University of Athens
  - University of Chicago, Enrico Fermi Institute
  - Yerevan Physics Institute

- ~100 shifters
The ATLAS detector

The ATLAS detector is nominally forward-backward symmetric with respect to the interaction point. The magnet configuration comprises a thin superconducting solenoid surrounding the inner detector cavity and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. This fundamental choice has driven the design of the rest of the detector.

The ATLAS detector is immersed in a ~2 T solenoidal field. Pattern recognition, momentum and vertex measurements, and electron identification are achieved with a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detectors with the capability to generate and detect transition radiation in its outer part.

High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, cover the pseudorapidity range $|\eta| < 3$.

The hadronic calorimetry in the range $|\eta| < 0.47$ is provided by a scintillator-tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. In the end-caps ($|\eta| > 0.57$), LAr technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of end-cap electromagnetic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements and extend the pseudorapidity coverage to $|\eta| = 4.9$.

The calorimeter is surrounded by the muon spectrometer. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. Multiple-scattering effects are thereby minimised, and excellent muon momentum resolution is achieved with three layers of high precision tracking chambers.
The ATLAS Tile Calorimeter

- Hadronic “tile” calorimeter
  - Flat iron absorbers + scintillator tiles
  - $|\eta| < 1.7$
    - Long Barrel: $|\eta| < 1.0$
    - Extended Barrel: $0.8 < |\eta| < 1.7$

- $\sigma_E/E (\text{jet}) = \sim 50\%/\sqrt{E} \pm 3\%$
  - goal
    - Jet energy scale uncertainty: 1–2%
TileCal Module

- **Geometry**
  - **Length**
    - LB: 5.8m, EB: 2.6m
  - **Radius**
    - Inner: 2.28m, Outer: 4.25m
  - **Granularity**
    - 64 modules in each barrel
      - $\Delta \varphi \sim 0.1$ rad
    - 3 layers
      - A, BC, D: “Cells”
    - “Tower”
      - $\Delta \eta = 0.1$ for A and BC cells
      - 0.2 for D cells
      - ~5000 cells

- **Planarity**
  - $\Delta \eta \sim 0.1$ rad

- **Granularity**
  - ~5000 cells

**Numbers on rays are $\eta$ values**

- **Plug tile calorimeter**
- **Iron support girder**
- **Extended barrel tile calorimeter**
- **Gap scintillator**
- **Cryostat scintillator**
- **End-cap electromagnetic and hadronic LAr calorimeters**
Structure of the modules

- Material
  - periodic steel-scintillator
    - ratio
      - 4.7 : 1 (by volume)

- WLS Fibre readout

- 2 PMTs for each cell
  - 9856ch (98% operated)

- Tubes for Cs source
Calibration

• Schematic view of readout and calibration system

• “Calibration”
  - Energy deposition  \( \downarrow \) Cs source
  - Light yield  \( \downarrow \) Laser pulse
  - Charge  \( \downarrow \) Charge injection
  - (Readout)

\[
E_{\text{channel}} = A \cdot C_{ADC\rightarrow pC} \cdot C_{pC\rightarrow GeV} \cdot C_{Cs} \cdot C_{Laser}
\]

(A: pulse height)
Charge injection system

- variation among ch. - 1.5%
- long time stability - +/- 0.7%
Laser system

• Stability of PMTs
  - over 50 days
  - bad channel (red region)
    ‣ variation > 1%: 0.14% in low gain
      0.28% in high gain
Cesium calibration

- Cs scan works
  - signal integrated within each cell
- “Up-drift” seen
  - 1.0 % for LB
  - 0.5 % for EB
  - fixed and included in DB

![Graph showing Cs decay curve and maintenance period](image)

- Cs decay curve (2.3%/year)
- Maintenance period
- Response [a.u.]

![Graph showing PMT current as a function of source position](image)
Performance with muons

- **Data**
  - 20 GeV muons in TestBeam 2005
  - Cosmic 2008
    - 10–30 GeV muons measured with SCT

- **Analysis**
  - EM scale measurement: \( \frac{dE}{dx} \)
    - E: energy deposition in each cell
    - L: path length in each cell (>20 cm)

- **Result**
  - Consistent with MC within 4% of the systematic errors
Cell energy scale

- 900 GeV collision data
  - Good agreement with MC in high energy region
  - Noise description not enough
Double Gaussian Noise

- **Fitting with 5 parameters**
  - $C$, $\mu$, $\sigma_1$, $\sigma_2$, $R$
    - $R$: relative normalization
  - Double gaussian describes data very well
- **New MC**
  - Implementation of double gauss. noise
  - Missing $E_T$ in Tile

![Chart showing fitted data and MC simulation](chart.png)

![Histogram comparison of data and MC simulation](histogram.png)
Summary

• Readiness for the collision
  - Calibration systems
    ‣ PMT gain by Charge injection
    ‣ Light connection and timing by Laser
    ‣ EM scale by Cesium source
      ‣ Cs up-drift fixed
  - Performance
    ‣ Muon response in Cosmic and TestBeam data
      ‣ Agreement with MC within ~4%
  - Publication ready

• 2009 Collision data
  - Good energy scale
  - Noise issue understood
    ‣ Missing $E_T$ distribution reproduced by MC with double gaussian

✓ We are ready, waiting for 7 TeV data!!
Backup
TileCal structure

Master plate

Wavelength–shifting fibre (decoupled from tile)

Scintillator tile

Wavelength–shifting fibre (viewing tile)

Plastic channel

Master plate

5.3.1.3 Optical components

Eleven sizes of scintillating tiles (one for each depth in radius), 1 mm thickness, and radial lengths ranging from –/ mm to 9/- mm and azimuthal lengths ranging from 088 mm to :88 mm form the active medium of the tile calorimeter. Ionising particles crossing the tiles induce the production of ultraviolet scintillation light in the base material (polystyrene) and this light is subsequently converted to visible light by wavelength-shifting fluors (the polystyrene is doped with 96,y PTP as the primary fluor and with 868::y POPOP as the secondary fluor). Over :;84888 scintillating tiles were produced for the tile calorimeter by injection molding of individual tiles (this eliminated the need for machining to form the trapezoidal shapes and drilling to cut the holes through which the calibration tubes must pass). The tolerance for all dimensions was held to ±8698 mm. Approximately 9y of the tile production was tested with a –8 Sr radioactive source and the results were used to characterise the light output of each small group of approximately twenty tiles in terms of maximum intensity and attenuation length. Two sources of raw polystyrene were used for tile fabrication; during assembly, the groups of tiles were sorted so that tiles with similar response were inserted in contiguous areas of the detector.

Irradiation tests of tile-fibre assemblies indicated that in the first longitudinal sampling, for an integrated dose corresponding to ten years of operation at the LHC design luminosity, a light loss of less than 98y is expected. Smaller losses will occur in the other samplings, where the radiation dose is less.
Integrator

- Charge integration for Cs system

![Graph showing integrator gain variation and electronic noise](image-url)
Muon signal

- Figure 8: Example of the muon signal and corresponding noise for projective cosmic muons entering the barrel modules at $6 < |\eta| < 6.2$.

- Top and bottom modules are treated separately.

- Left: the total energy summed up over selected cells.

- Right: the similar distribution of last radial compartments that can be eventually used to assist in muon identification.

- The signal comes from the cosmic muon data sample, the corresponding noise is obtained with the random trigger sample.

- The signal and noise distributions are well separated for both the total calorimeter response and the last radial layer signal.

- In order to estimate the signal-to-noise ratio, the energy distribution is fit to the convolution of a Landau function with a Gaussian.

- Considering the peak of that convolution fit (most probable value) as the signal and the RMS of the random trigger distribution as the noise, the signal-to-noise ratio is then $S/N = 0.6$ for the total response and $S/N = 7.5$ for the A, B, and C cells, respectively.

### 5.2 Methods for muon response studies

A brief overview of the analysis methods applied to investigated data samples is provided in this Section. First, we briefly describe the dedicated testbeam (TB) studies with low-energy muons (Section 5.2.1).

#### 5.2.1 Analysis of low energy testbeam muons

The TB setup, operating conditions, and results are summarized in Ref. [7]. Since most of the previous muon TB results were obtained with 7-6 GeV beams and this energy is too high for the comparison with cosmic ray data, a dedicated study was performed with low-energy muons selected from a pion beam at a nominal energy of 86 GeV. These muons originate from pion decay, the distribution of their momenta ranges from 7.74 GeV to 86 GeV, peaking at around 7.5 GeV.

Data was collected from ten runs with pion beams impinging on one LB module at different projective incidences, from $-6 \leq \eta \leq -6$.7:4.

In testbeam [7], where muon beams at a nominal energy of 7-6 GeV were used for this study, the $S/N$ ratios were higher. Taking into account the 86 GeV to 7-6 GeV response ratio, the testbeam $S/N$ ratios at 86 GeV for the tower and the D cells should amount to 0.8 and 7.5, respectively.
Alignment of the modules

- pointing with the SCT tracks
dE/dx with Muons

- Cosmic and TestBeam

<table>
<thead>
<tr>
<th>Radial layer</th>
<th>A</th>
<th>BC</th>
<th>D</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic, LB</td>
<td>Data</td>
<td>1.27 ± 0.03</td>
<td>1.31 ± 0.05</td>
<td>1.35 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>1.32 ± 0.04</td>
<td>1.35 ± 0.05</td>
<td>1.34 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>Data/MC</td>
<td>0.97 ± 0.01</td>
<td>0.97 ± 0.03</td>
<td>1.01 ± 0.01</td>
</tr>
<tr>
<td>Cosmic, EB</td>
<td>Data</td>
<td>1.30 ± 0.06</td>
<td>1.29 ± 0.05</td>
<td>1.34 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>1.31 ± 0.03</td>
<td>1.32 ± 0.05</td>
<td>1.34 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>Data/MC</td>
<td>0.99 ± 0.04</td>
<td>0.98 ± 0.02</td>
<td>1.00 ± 0.02</td>
</tr>
<tr>
<td>Testbeam, LB</td>
<td>Data</td>
<td>1.25 ± 0.03</td>
<td>1.39 ± 0.04</td>
<td>1.39 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>1.30 ± 0.02</td>
<td>1.37 ± 0.03</td>
<td>1.36 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>Data/MC</td>
<td>0.96 ± 0.02</td>
<td>1.02 ± 0.04</td>
<td>1.02 ± 0.02</td>
</tr>
<tr>
<td>Double ratio</td>
<td>(Data/MC)_{\text{Cosmics, LB}}/\text{MC}</td>
<td>1.01 ± 0.02</td>
<td>0.95 ± 0.05</td>
<td>0.98 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>(Data/MC)_{\text{TB, LB}}/\text{MC}</td>
<td>1.01 ± 0.02</td>
<td>0.95 ± 0.05</td>
<td>0.98 ± 0.03</td>
</tr>
</tbody>
</table>
Systematic errors for cosmic

<table>
<thead>
<tr>
<th>Systematic Errors (MeV/mm for Data and MC)</th>
<th>Long Barrel</th>
<th>Extended Barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error source</td>
<td>A</td>
<td>BC</td>
</tr>
<tr>
<td>Path</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.018</td>
<td>0.036</td>
</tr>
<tr>
<td>MC</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.008</td>
<td>0.030</td>
</tr>
<tr>
<td>Momentum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.024</td>
<td>0.033</td>
</tr>
<tr>
<td>MC</td>
<td>0.032</td>
<td>0.043</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>MC</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Truncation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td>MC</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Top/Bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>MC</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.034</td>
<td>0.052</td>
</tr>
<tr>
<td>MC</td>
<td>0.038</td>
<td>0.046</td>
</tr>
<tr>
<td>Data/MC ratio</td>
<td>0.013</td>
<td>0.032</td>
</tr>
</tbody>
</table>
Timing in the “splash” events

- Resolution, Rejection for Single beam

ATLAS Preliminary

Number of Cells

Mean = -0.54 ns
\( \sigma = 1.02 \text{ ns} \)

- TOF correction
Cluster moment

Cluster $\lambda_{\text{center}}$ (mm)

Cluster $\langle r^2 \rangle$ (mm$^2$)

MC
MC (2-G noise)
Data

Cluster EM fraction

Cluster $\langle r^2 \rangle$ (mm$^2$)
Calorimeter Jets

**ATLAS Preliminary**

- **anti-k** jets R=0.6

Data 2009 $\sqrt{s}=900$ GeV

MC non-diffractive minimum bias

- **Number of jets / 1 GeV**

- **Number of jets / 0.4**

- **Number of jets / (\alpha/16 rad)**

- **Number of events / (\alpha/25 rad)**

- **Number of events / (|\Delta \phi|/25 rad)**
Track Jets

- Data 2009 \( \sqrt{s} = 900 \text{ GeV} \)
- MC non-diffractive minimum bias
- anti-\(k_t\) track jets \(R=0.6\)

**ATLAS Preliminary**

**Track Jet \( p_T \) [GeV]**

**Track Jet \( \eta \)**

**Events / (\pi/30 \text{ rad})**

**\( |\Delta\phi| \) [rad]**
Jet Energy Scale

- quark structure

![Graph showing jet energy scale with different models and uncertainties.](image_url)