Performance and calibration of the ATLAS Tile Calorimeter

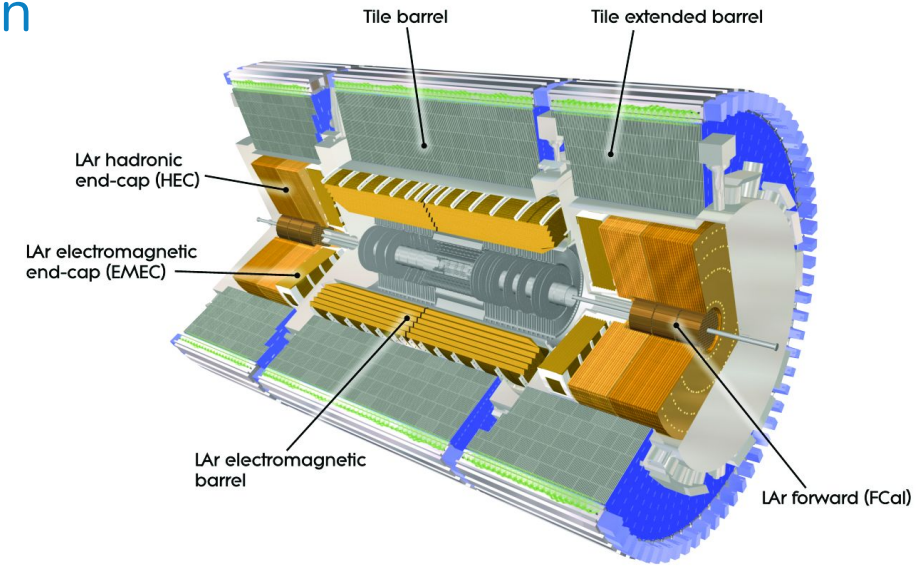
Martin Divíšek

on behalf of the ATLAS Collaboration

30.04.2025

Charles University, Prague

CorfuFA2025
Corfu, Greece



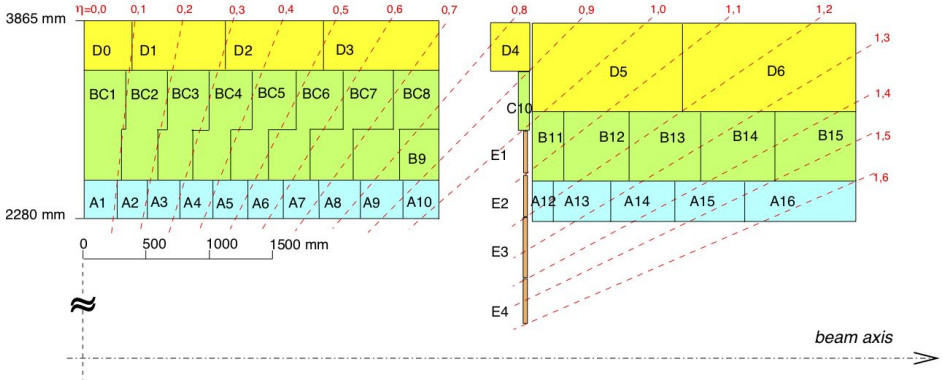
ATLAS EXPERIMENT

FACULTY OF MATHEMATICS AND PHYSICS
Charles University

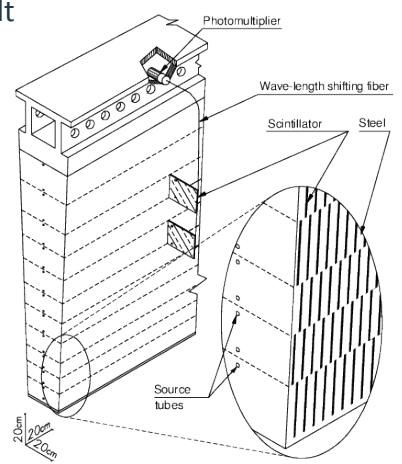
ATLAS Tile Calorimeter

HL-LHC: High Luminosity LHC
PMT: photomultiplier tube

- Sampling calorimeter consisting of passive (steel) and active (plastic scintillator) layers
- Responsible for measuring energy of hadronic particles and jets that pass through Liquid Argon calorimeter
- Consists of Long Barrel (read out as LBA/C) and two Extended Barrel (EBA/C) endcaps
- Each partition segmented along φ into 64 nearly identical modules
- Further segmentation into radial layers (A/BC/D in LB, A/B/D in EB)
- Each radial layer subdivided into cells, each cell read out by two PMTs by default



Cell segmentation of modules in the Long/Extended barrel (left/right) [1]

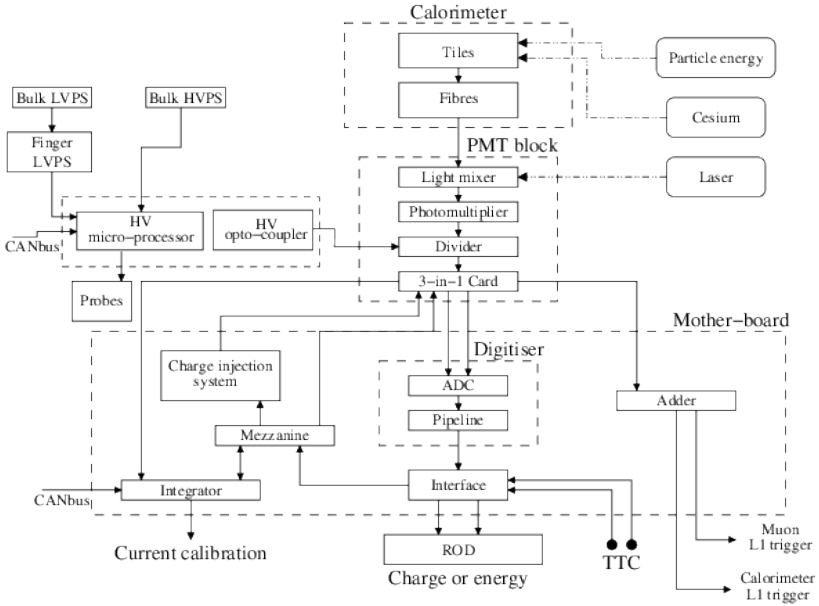


Tile arrangement inside one module [1]

From Signal to Data

ADC: analog-to-digital converter

- Incident particles create particle showers which create a light signal proportional to their energy in the scintillator tiles
- Light signal is collected by optical fibres and directed into PMTs, converted into electric charge
- Charge pulse is shaped to constant width, split into two gains (High/Low), and sent into a 10-bit ADC => effective 16-bit range, 20 MeV to 1.3 TeV
- In the ADC, the charge pulse is digitized into binary information and stored in pipeline memory
- If the event is approved by the trigger algorithm, it is sent to back-end for storage and offline reconstruction



A schematic of the TileCal Data Flow [1]

High gain (HG) is amplified by a factor of 64x and is read out by default unless the signal exceeds 1022 counts => Low gain (LG, no amplification) is read out instead

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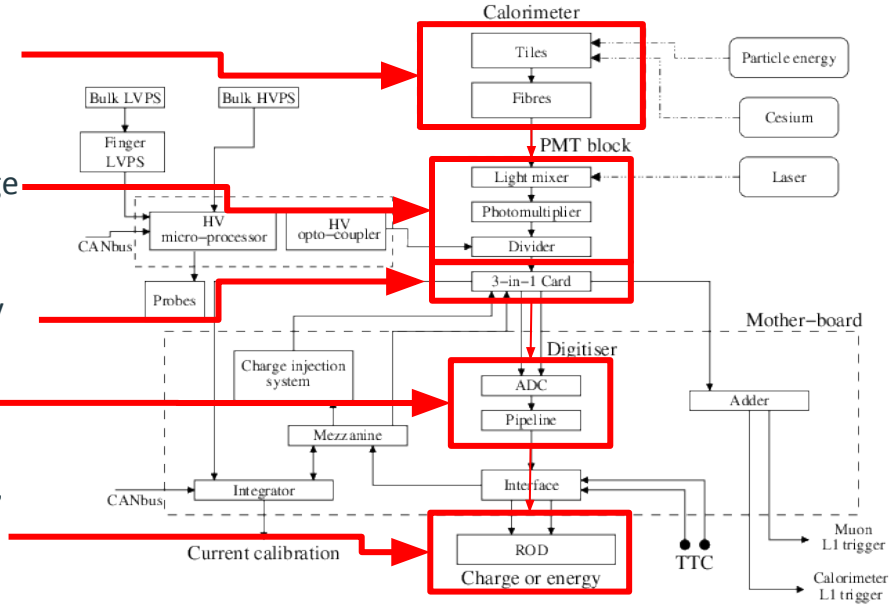

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From Signal to Data II

The digitized signal reconstruction is provided by the Optimal Filtering (OF) algorithm which calculates amplitude (A), phase (t) and pedestal (P):

$$A = \sum_{i=1}^{7} a_i S_i, \quad t = \frac{1}{A} \sum_{i=1}^{7} b_i S_i, \quad P = \sum_{i=1}^{7} c_i S_i,$$

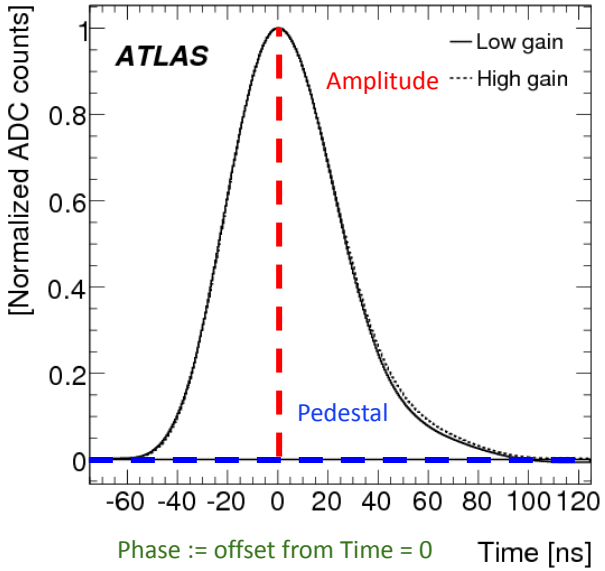
S_i: sample *i* readout a_i, b_i, c_i: coefficients derived from testbeam results

The reconstructed energy is then determined:

$$E_{\text{reco}} = \frac{A\,[\text{ADC}]}{C_{\text{ADC}\to\text{pC}} \cdot C_{\text{pC}\to\text{GeV}} \cdot C_{\text{MB}} \cdot C_{\text{Cs}} \cdot C_{\text{Las}}}$$

from calibrations

from testbeam

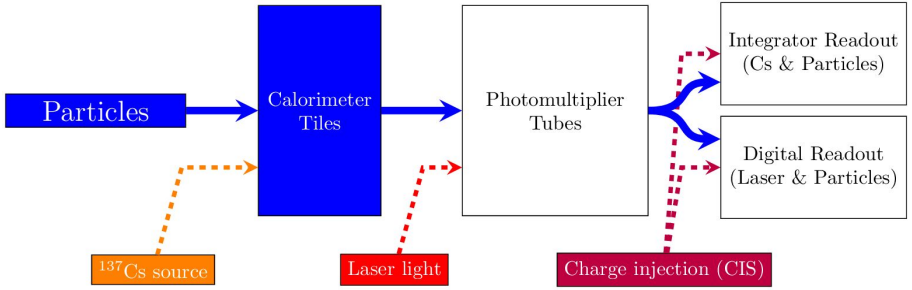


Physics signal pulse shapes used as reference for the OF weights calculation [1]

TileCal Calibration

TileCal is equipped with several systems designed to calibrate parts of the signal propagation chain:

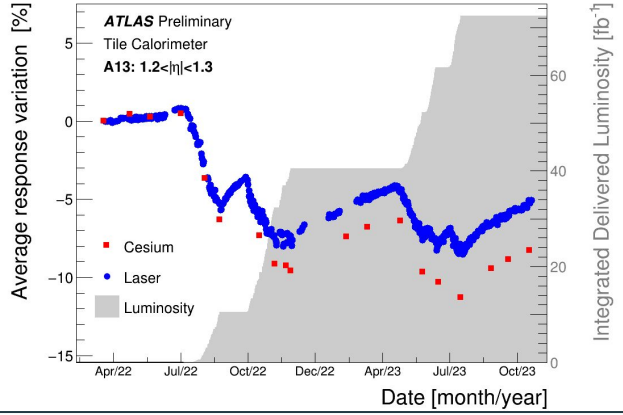
- Cesium: a radioactive source passing through the detector, used to calibrate the optics chain and the PMTs
- Laser: controlled pulses of light injected directly into the PMTs, used to calibrate variations in PMT response and electronics
- Charge Injection System (CIS): known charge injected directly into the electronics, used to calibrate ADC response
- Minimum Bias (MB) collisions: based on integrator readout of inelastic proton-proton collisions, used for monitoring of response and instantaneous luminosity



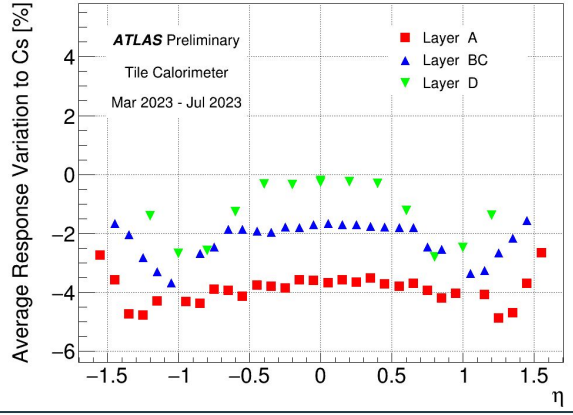
Flow diagram of the readout signal path of the different TileCal calibration systems [1]

Calibration - Cesium

- A capsule containing the source passes through hydraulic tubes in the detector cells
- Dedicated integrator circuit responsible for signal readout
- Responsible for measuring optical chain degradation
  - Degradation of light yield caused by radiation damage to tiles, charge depletion in PMTs
  - Radial layer A (closest to the beam) most affected
  - Precision ~0.3%
- Cesium scan taken monthly during an 8-hour gap between physics runs



Average response variation of A13 cells to Cs source and Laser [2]

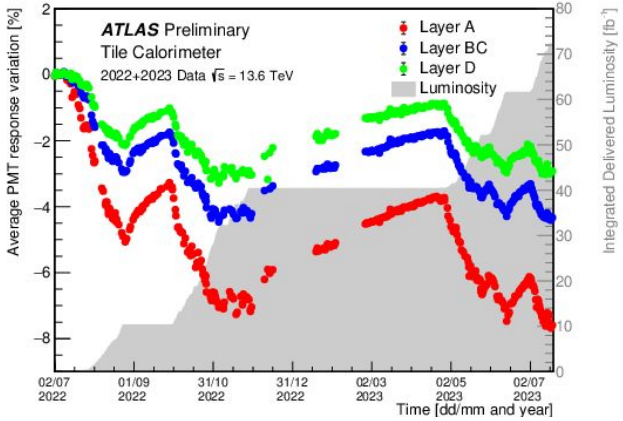


Layer-averaged response variation of TileCal cells to Cs source [2]

Calibration - Laser

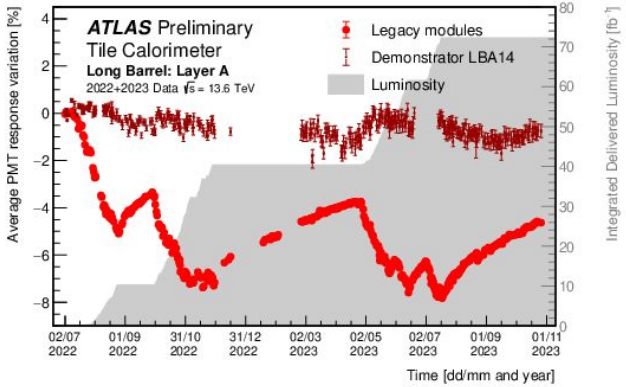
For more on TileCal upgrades in HL-LHC check out Antonio's Talk on Saturday!

- Off-detector laser source delivers monochromatic light signal to all PMTs in the detector
- Monitors PMT response as well as fast readout electronics
  - Laser runs intended for PMT response calibration taken daily, variation is corrected w.r.t. latest Cesium calibration results
  - While taking data, laser calibration intermittently active in abort gaps between bunch train collisions, allows for calibration of electronics and timing



Layer-averaged PMT response variation Laser [3]

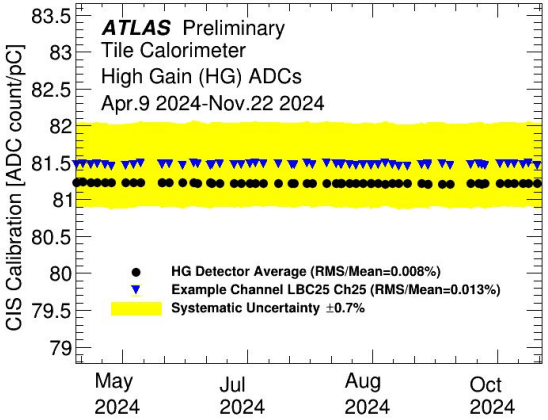
LBA14 - test module for HL-LHC

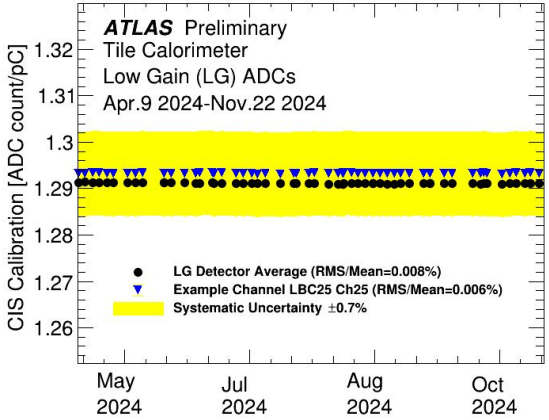


Layer A PMT response variation in legacy and LBA14 [3]

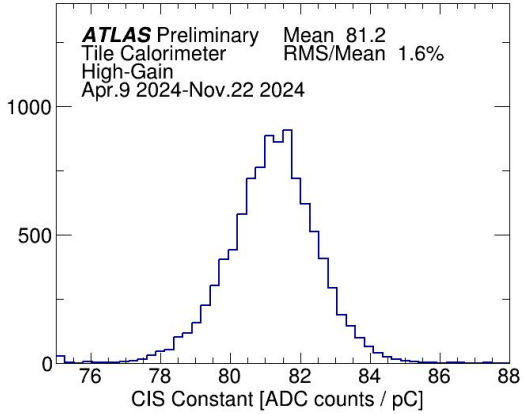
Calibration - CIS

- Calibrates front-end ADCs by discharging a capacitor on the 3-in-1 card (between PMT and digitizer) and measuring the number of counts for wide range of charge values
- Linear fit provides ADC/pC conversion coefficient
- Useful for calibration of all front-end electronics, spotting data integrity and timing problems
- Charge Injection calibration runs are taken twice per week





$C_{ADC \rightarrow pC}$ averages over time in High (left) and Low (right) gain [4]

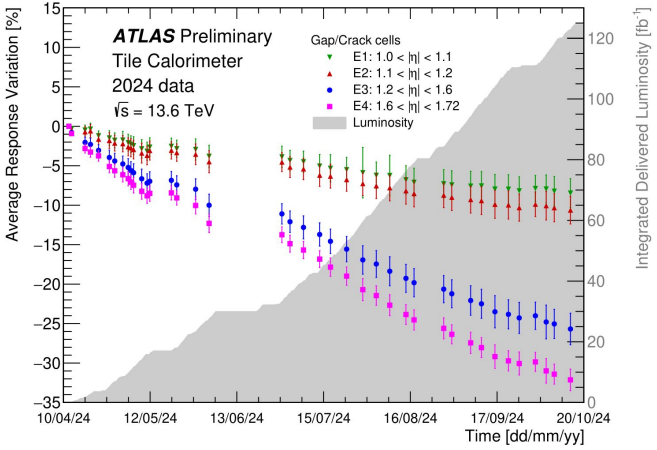


Distribution of $C_{ADC \rightarrow pC}$ in High Gain[4]

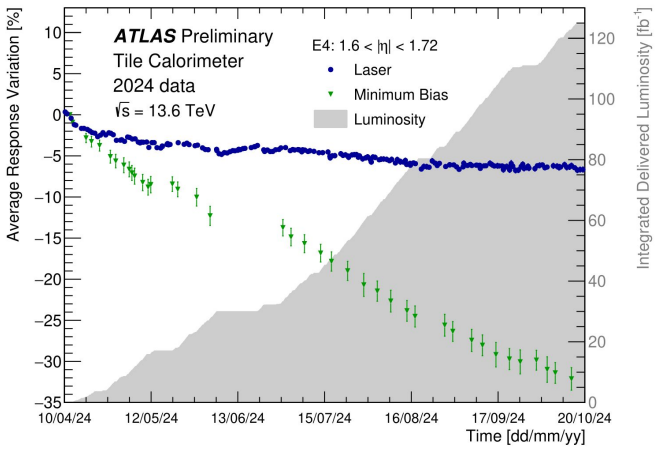
Calibration - Minimum Bias

E cells: special cells covering the gap between Long and Extended Barrels (E1,E2), or sitting on the LAr endcap (E3,E4)

- Special E cells located between the Long Barrel and the Endcaps cannot be calibrated using Cesium due to missing hydraulic tube system => MB Currents are used instead
- Response variation of Minimum Bias in E cells is derived with respect to the D5 cell
- Difference of the calorimeter response to the Laser versus the Minimum Bias or Cesium systems corresponds to damage and ageing of the scintillators and wavelength shifting fibers



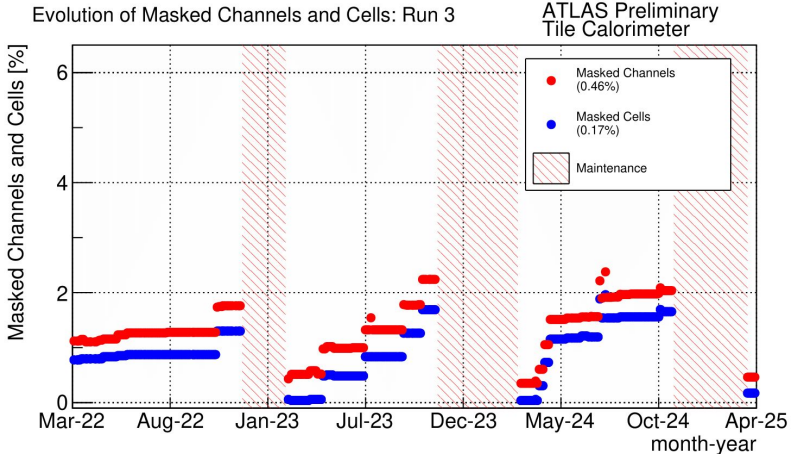
MB average response variation in the gap/crack region of EB over time [5]



Average response variation of MB in cell E4 vs Laser [5]

TileCal Performance

- Typically assessed with isolated muons, hadrons, or jets
- Individual calibration systems operate with a precision of roughly ~1%
- Subject of multiple ongoing studies
- Run 3 data-taking period (since 2022):
  - In p-p collisions, TileCal Data Quality efficiency at and above 99.3%
  - In heavy ion collisions (lead-lead), TileCal Data Quality efficiency at 100% so far
  - Less than 2% of all cells deemed non-operational at the end of each data-taking year
- Biggest enemies: radiation damage, ageing



Percentage of masked detector cells over time in Run 3 [6]

	2022	2023	2024
TileCal DQ Efficiency [%]	99.67	99.6	99.3
ATLAS DQ Efficiency [%]	93.1	94.6-96.5	93.8

Data Quality efficiencies for p-p collisions @ $\sqrt{s}$=13.6 TeV in Run 3 [7]

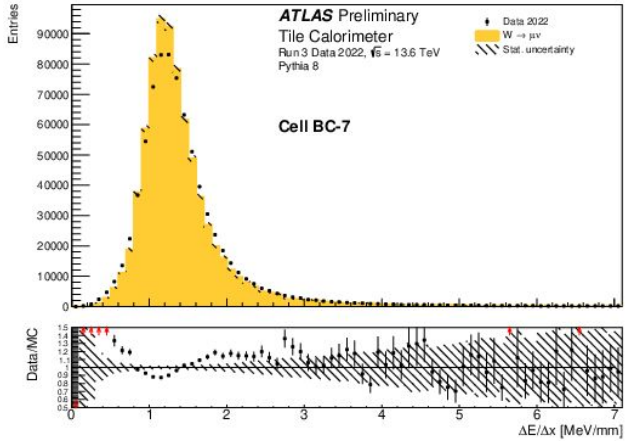
Performance - Single Muons

ΔE/Δx: particle energy loss over unit length in the detector

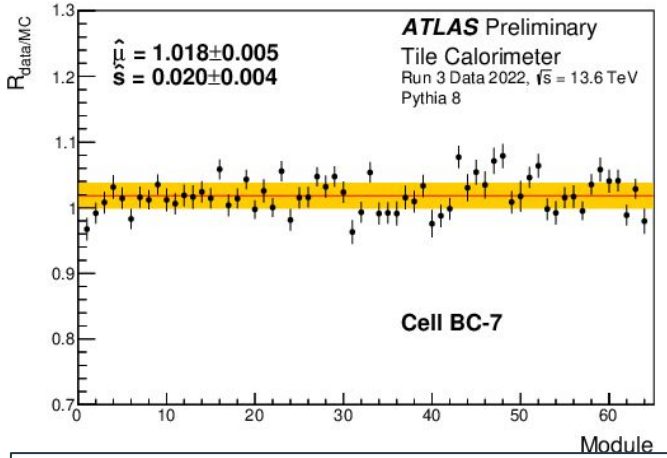
$$R \equiv \frac{\langle \Delta E/\Delta x \rangle_{Data}}{\langle \Delta E/\Delta x \rangle_{MC}}$$

Example performance study: Analysis of single muons response

- Measures the electromagnetic scale and uniformity using muons from decaying W bosons
- TileCal modules show uniform response across φ (module 1 corresponds to φ=0, one module ~ π/32)
- 1% of incident muons with highest ΔE/Δx omitted from calculation of ratio R



Muon ΔE/Δx spectrum in the same cell; N.B. tail [8]



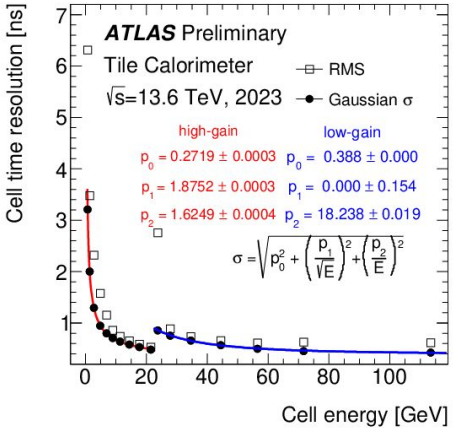
Uniformity of muon response across TileCal modules [8]

Performance - Time

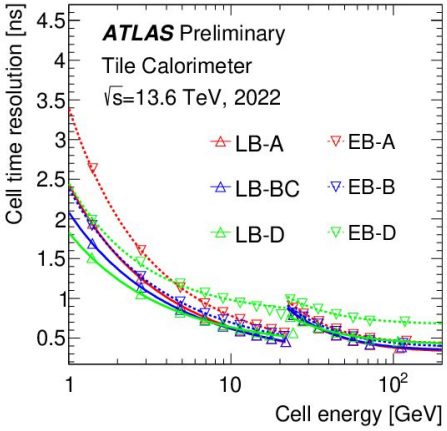
Example performance study:
TileCal time resolution in cells grouped by radial detector layers

- Important when searching for long-lived exotics
- Time resolution := gaussian sigma of reconstructed event times distribution
- Depends on energy deposited in the cell
- Difference in time resolution for different radial layers in LB/EB driven by cell size, distance from IP, pile-up
- Study of single-cell resolution an ongoing effort using new dataset

IP: Interaction point
Pile-up: average number of collisions produced per bunch crossing



Combined time resolution [9]

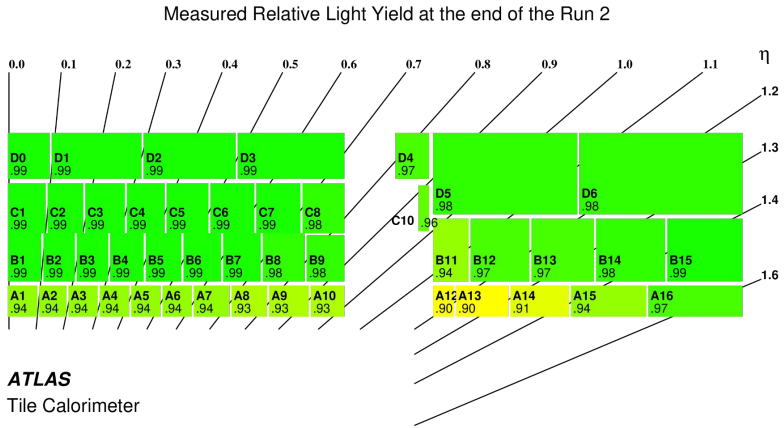


Time resolution in layers [9]

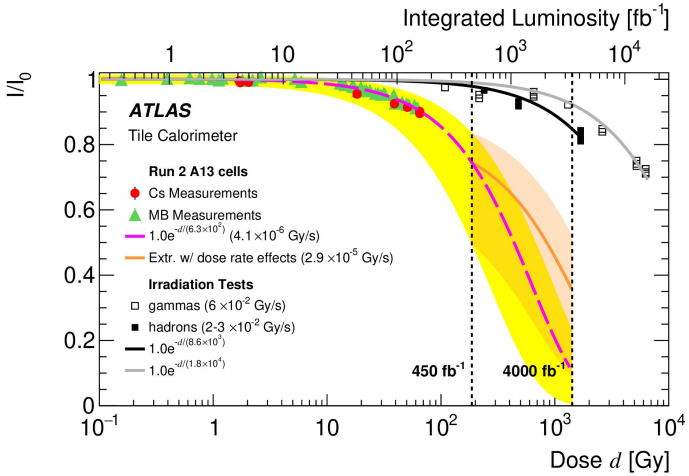
Performance - Ageing

For more on Ageing check out Adrian's Talk from Tuesday!

- PMT gain, monitored with the laser system, is known to decrease with increasing light exposure
- Scintillators and optical fibres degrade over time (can be differentiated from PMT degradation using laser)
- Important for HL-LHC
- Paper (link) accepted in JINST



Relative PMT yield at the end of Run 2 [10]



Avg. relative light yield as a function of simulated dose and integrated luminosity [10]

Conclusions and References

- TileCal continues to operate well as Run 3 draws to a close
- Calorimeter routinely calibrated
- Multiple performance studies are ongoing
- Public results from recent years on the way
- Long Shutdown 3 and HL-LHC looming ahead

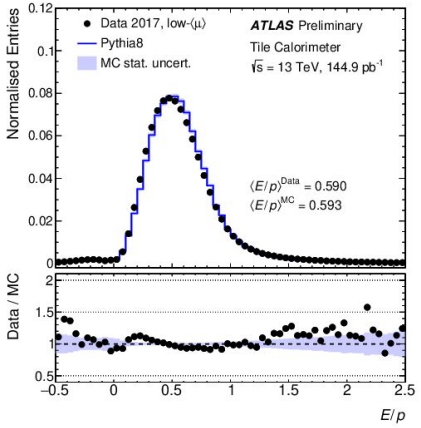
[1] Readiness Paper (Eur. Phys. J. C 70 (2010) 1193-1236)
[2] Run 3 Cesium public plots
[3] Run 3 Laser public plots, 2022+2023
[4] Charge Injection System (CIS) Calibration Plots
[5] Combined Tile Calorimeter Calibration Plots
[6] Detector Status public plots
[7] Data Quality Efficiency public plots
[8] Single Particle Response public plots
[9] Run 3 Timing calibration and performance public plots
[10] Study of the Radiation Hardness of the ATLAS Tile Calorimeter Optical Instrumentation with Run 2 data

Backup

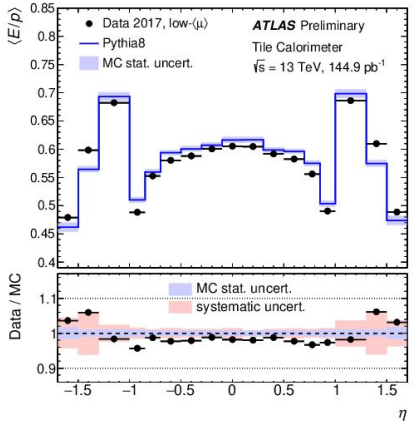
Performance - Single Hadrons

Example performance study from Run-2:
Analysis of single hadrons response

- E/p ratio determined by comparing energy deposited in TileCal to momentum measured by Inner Detector
- E/p < 1 due to non-compensating nature of the calorimeter
- Distribution in η associated with geometrical effects
- Good agreement between measurement and simulated data
- Analysis using Run 3 data underway



E/p in collision data [8]



<E/p> as function of η [8]