Performance, Calibration and Optics Robustness of the ATLAS Tile Calorimeter

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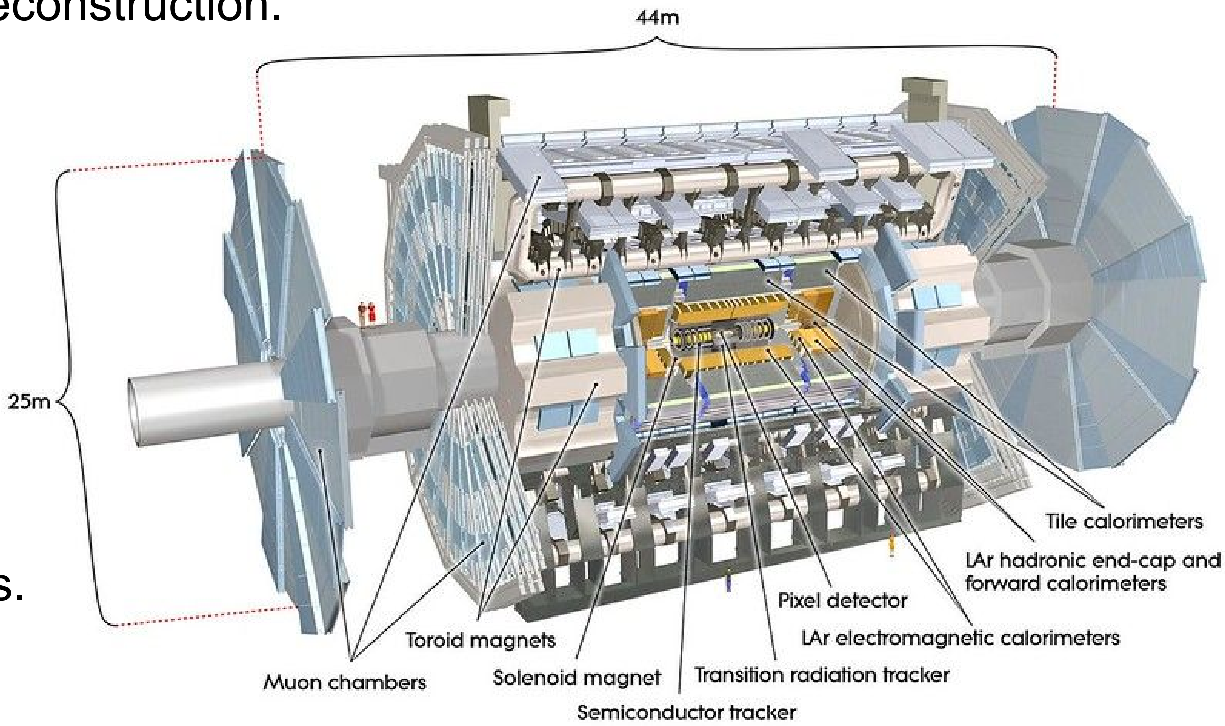
Outline

- TileCal – central hadronic calorimeter of the ATLAS experiment at LHC in CERN.
- TileCal read-out system and signal reconstruction.
- Calibration systems.
  - Cesium, laser, charge injection, minimum bias.
- Performance.
  - Isolated muons response.
  - Timing with jets.
- Ageing studies of optical components.
- Conclusions.

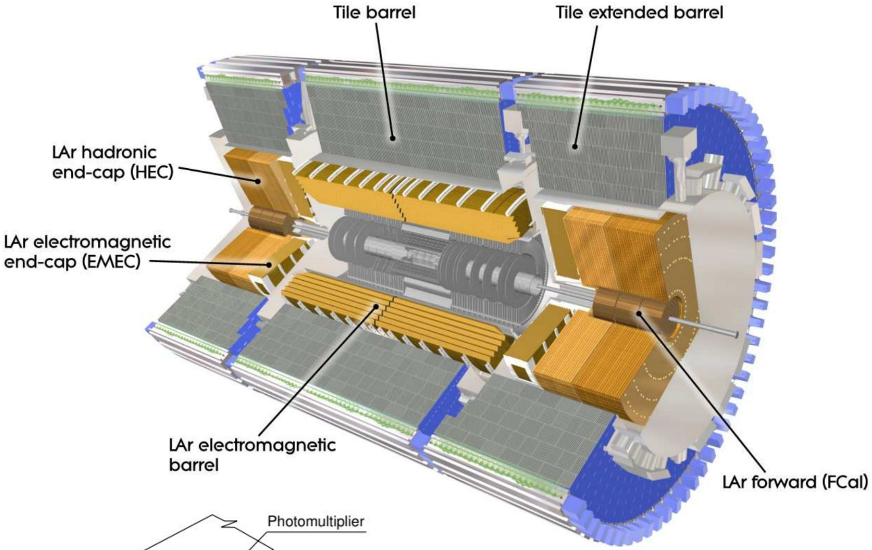


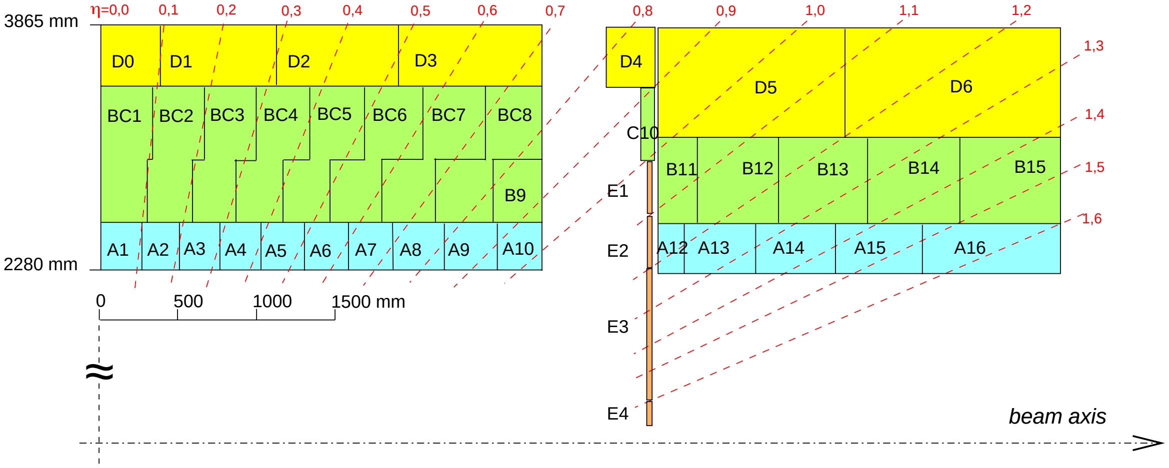
Experiment ATLAS

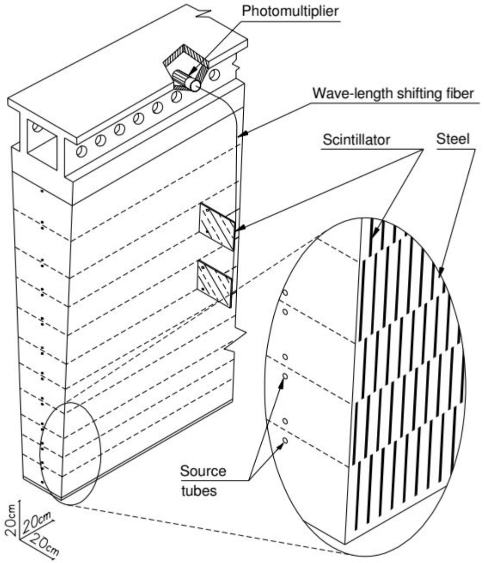
The ATLAS Tile Calorimeter

TileCal – Central hadron ATLAS calorimeter.

- Two sides of Long Barrel (LB) and two Extended Barrels (EB).
- Three cylinders, 64 wedge-shaped modules each.
- Coverage $|\eta| < 1.0$ (LB), $0.8 < |\eta| < 1.7$ (EB).
- Measures jet energy and missing transverse energy. $\frac{\sigma}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$
- Constructed from steel plates and plastic scintillators – **tiles**.
- Light readout with two optical fibres per tile.
- Divided into ~5000 cells by grouping the fibres.
- Two PMTs per cell (only single PMT in certain cases), ~10,000 PMTs total.
- Granularity: $\eta \times \varphi = 0.1 \times 0.1$ for the inner layers (A, BC), 0.2×0.1 for the outer layer (D).



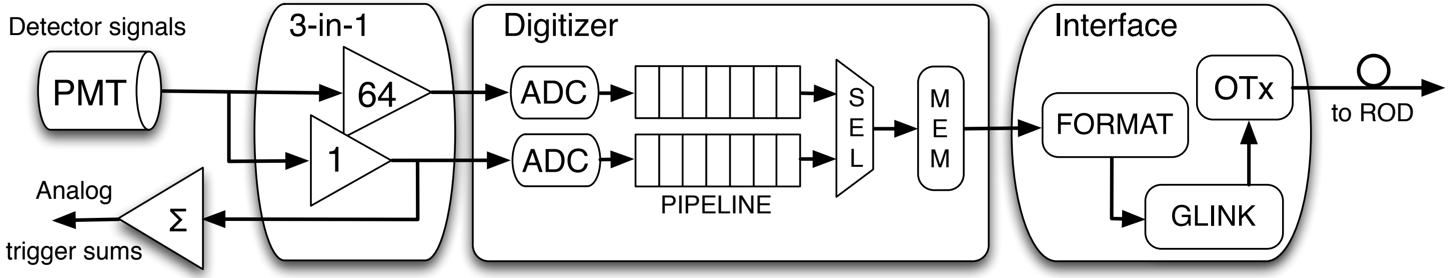




Ref: [1]

TileCal read-out system

- Incident **particle** creates particle **showers**.
- **Charged particles** create a **light signal** in the scintillating **tiles** proportional to their energy losses.
- The **light signal** is collected from the tiles by the wavelength shifting **fibres** and directed into **PMTs**.
- The **PMT** signal is **shaped** and **digitised** in the front-end readout boards.
- The shaped signal is transmitted in parallel via two paths:
  - **High Gain** (HG) and **Low Gain** (LG), with relative gain ratio of **64:1**.
- Signals of both paths **sampled** every **25 ns** using a 10-bit ADC. Samples stored in a pipeline memory.
  - Effective range: 16 bit, **20 MeV – 1.3 TeV**.
- If event approved by ATLAS trigger algorithms, **7** stored **samples** around the triggered event sent to back-end electronics (ROD) for **offline** reconstruction.
- In addition to the fast **digital read-out**, TileCal contains an **integrator** read-out for instantaneous luminosity measurement and cesium source calibration and an **analog trigger** output.

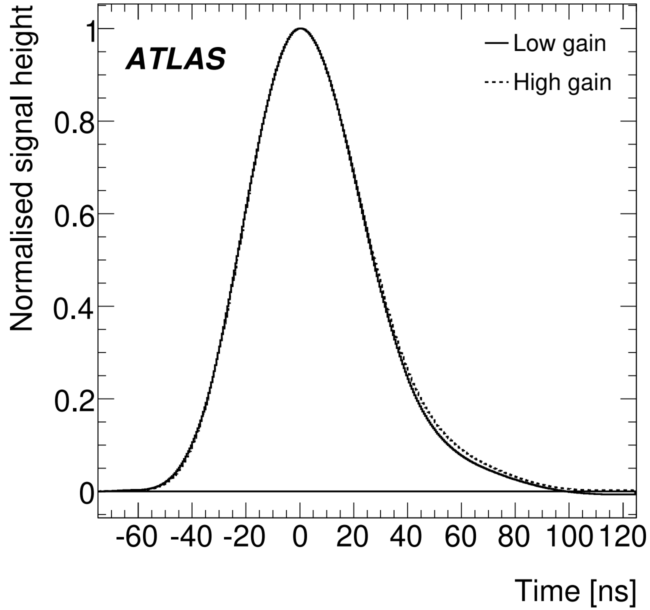


Tiles
Fibres
PMTs
Digital readout
Integrators

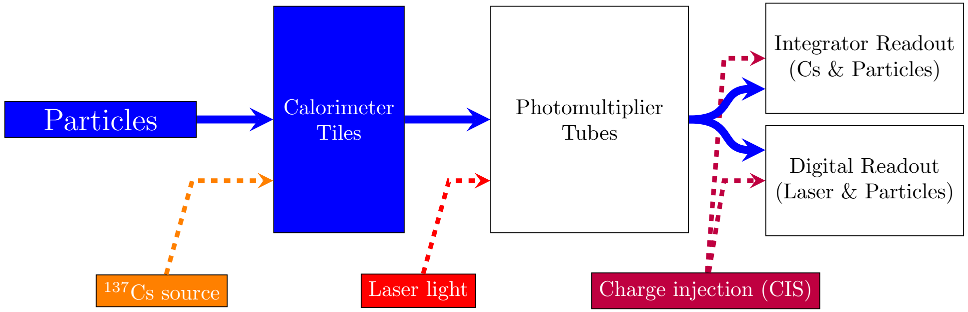
Ref: [1]

Signal reconstruction and calibration

- Signal amplitude reconstructed from **7 samples** (S_i) with the **optimal filtering** (OF) algorithm in units of ADC counts. Parameters: **amplitude** (A), **time** (t), **pedestal** (P).



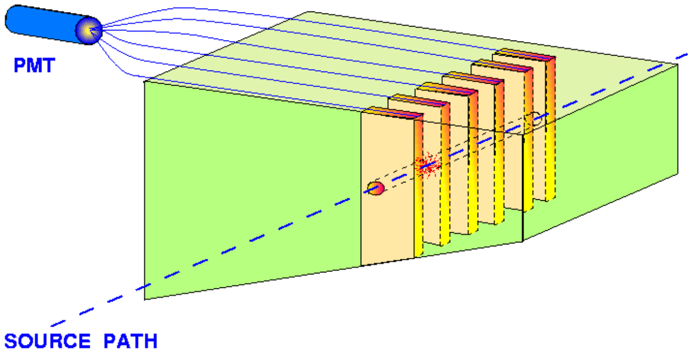
- $$A=\sum_{i=1}^{7} a_i S_i,\quad t=\frac{1}{A}\sum_{i=1}^{7} b_i S_i,\quad P=\sum_{i=1}^{7} c_i S_i$$
- a_i, b_i, c_i: coefficients optimised using test beam data to minimise electronic noise.
- $$E_{\mathrm{reco}}[\mathrm{GeV}]=\frac{A[\mathrm{ADC}]}{C_{\mathrm{ADC}\rightarrow\mathrm{pC}}\times C_{\mathrm{pC}\rightarrow\mathrm{GeV}}\times C_{\mathrm{MB}}\times C_{\mathrm{Cs}}\times C_{\mathrm{Las}}}$$
- $C_{\mathrm{ADC}\rightarrow\mathrm{pC}}$, $C_{\mathrm{pC}\rightarrow\mathrm{GeV}}$, C_{MB}, C_{Cs}, C_{Las} are **calibration** constants.
- Calibration systems:
  - Cesium System: optical components and PMTs
  - Laser system: electronics and PMTs.
  - Charge Injection System (CIS): ADCs.
  - Minimum Bias (MB) system: radiation damage or ageing compensation.



Ref: [1]

Cesium System

- Capsule containing radioactive ^{137}Cs source passes through hydraulic tubes in the detector cells.
- Signals readout by a dedicated integrator system.
- Responsible for measuring optical chain degradation.
- Changes in the response: degradation of the fibres, scintillating tiles, and PMTs.
  - Radial layer A (closest to the beam) most affected.
  - PMTs recovery in the periods without *pp* collisions.
- Precision ~0.3 %



Tiles
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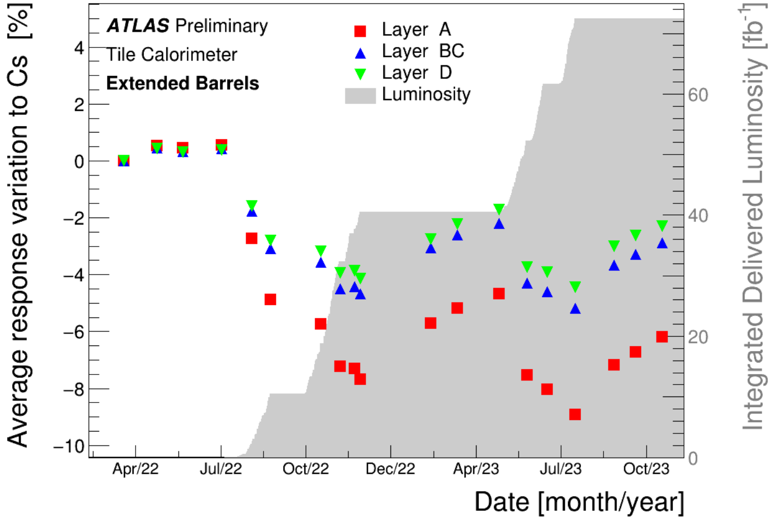
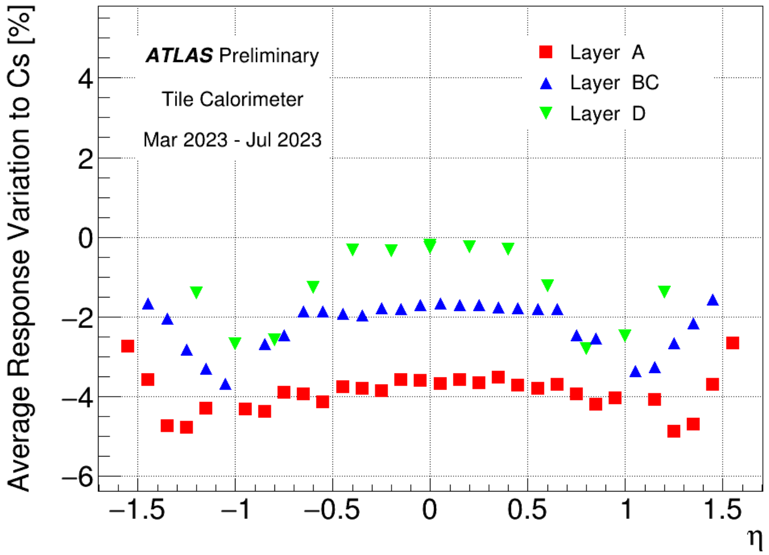
PMTs
~~Digital readout~~
Integrators





Ref: [2, 3]

Laser System

- Short 10 ns laser light pulses with 532 nm wavelength simultaneously distributed to all PMTs.
- Monitors PMT and fast readout electronics response and timing.
- Precision ~0.5 %.

~~Tiles~~
~~Fibres~~
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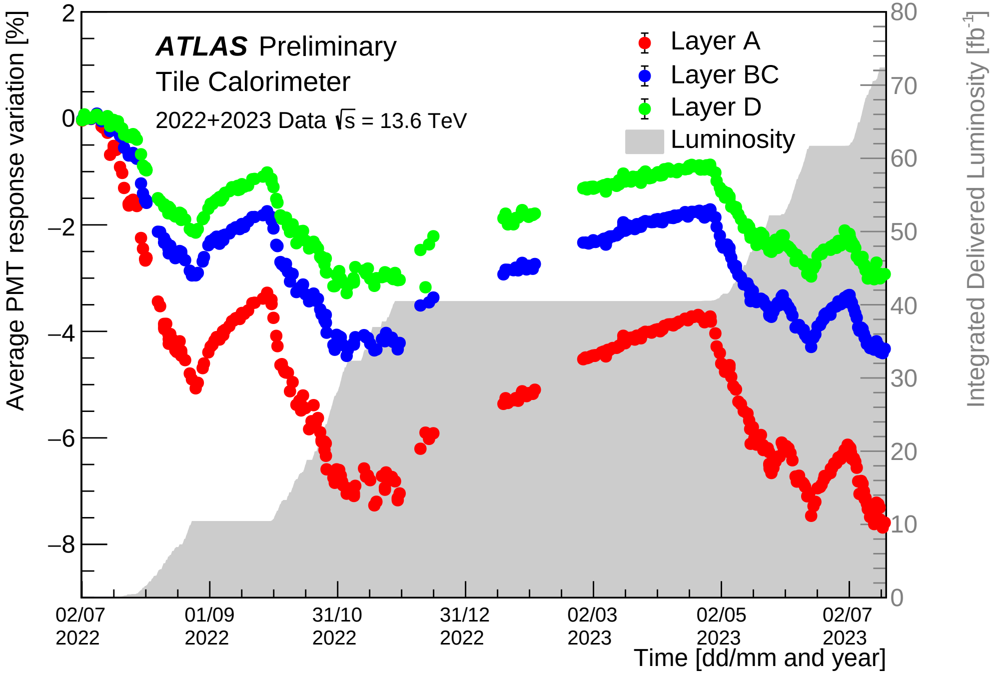
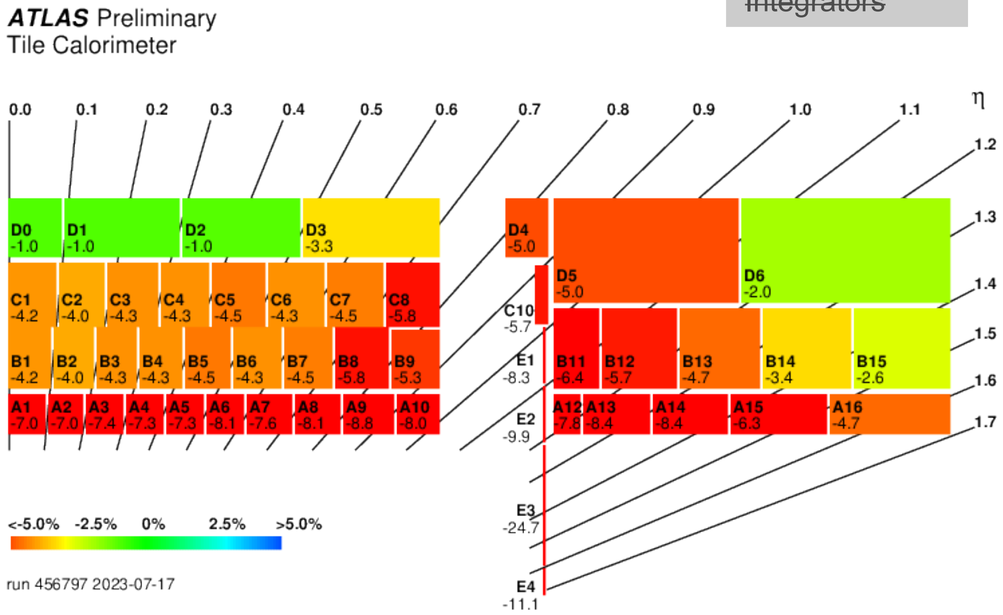




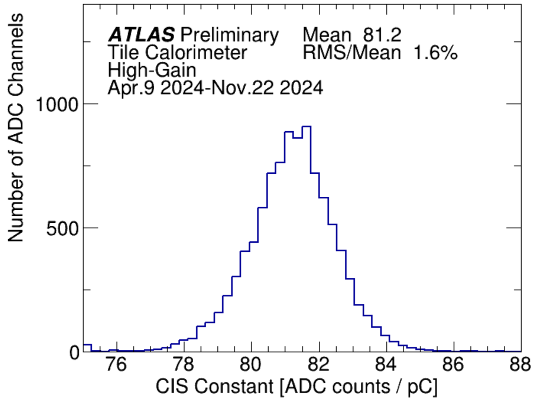
Average response variation between 2nd July 2022 and 17th July 2023.

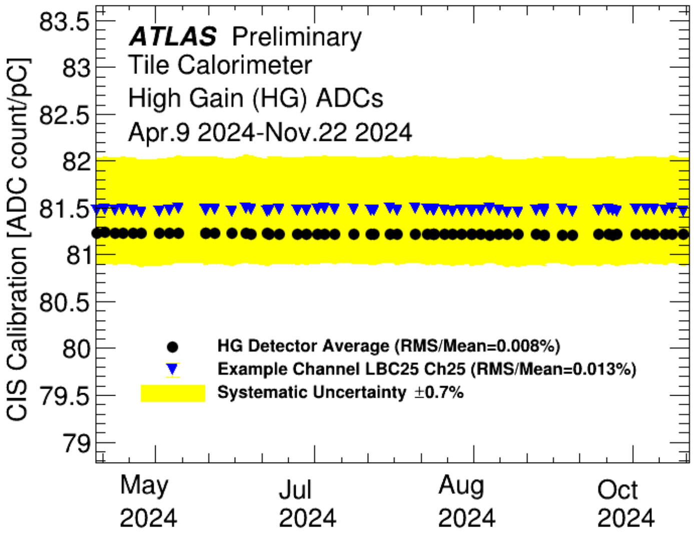
Ref: [3, 4]

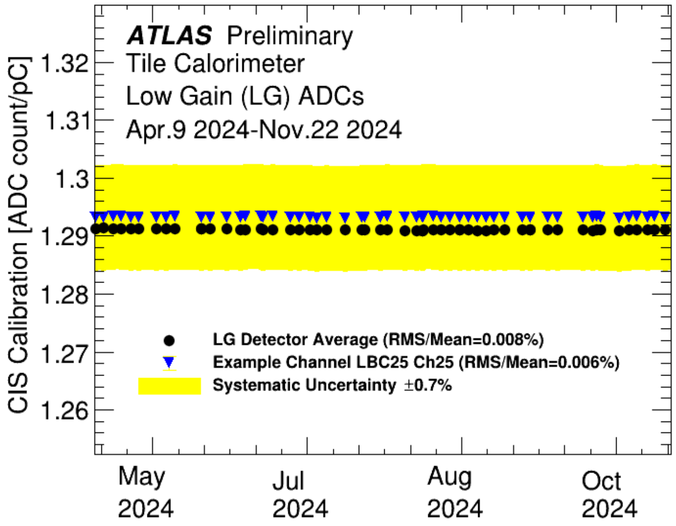
Charge Injection System

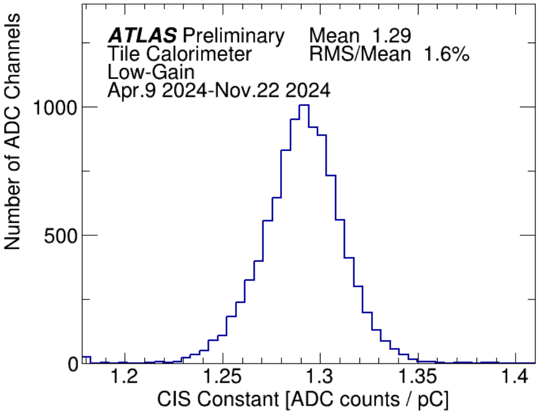
- Injects a defined charge signal to the readout electronics covering the full dynamic range.
- Linear fit provides ADC/pC conversion coefficient.
- Calibration of all front-end electronics, spotting data integrity and timing problems.
- Precision ~0.7 %. Very stable over time.

~~Tiles~~
~~Fibres~~
~~PMTs~~
Digital readout
~~Integrators~~









Ref: [3]

Minimum Bias System

- Minimum bias events produce PMT currents proportional to the LHC luminosity.
- Signal readout by the same integrator system as the Cesium calibration.
- Allows degradation studies of cells in the gap region (E cells, inaccessible to the Cesium system).
- 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 fibres.
- Precision ~1.2 %.

Tiles
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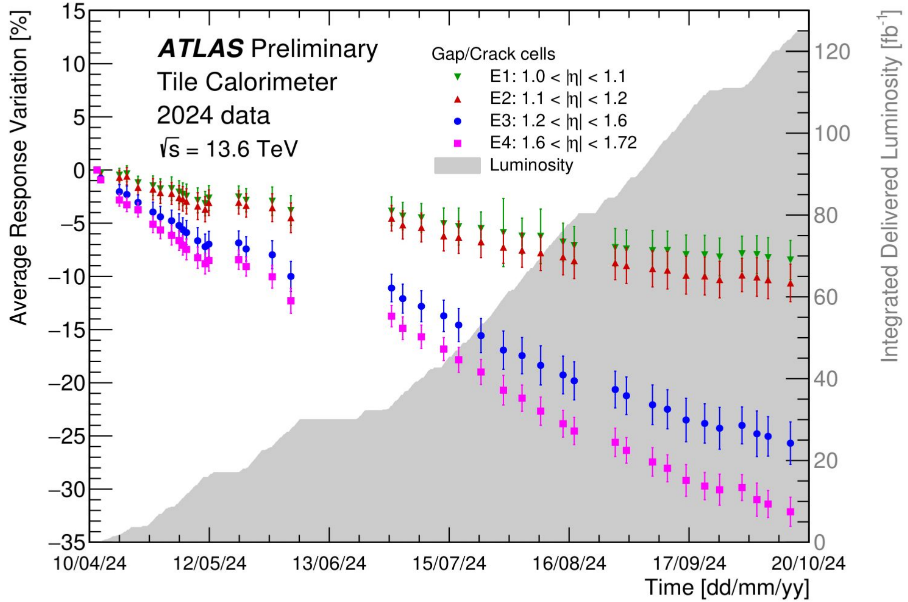
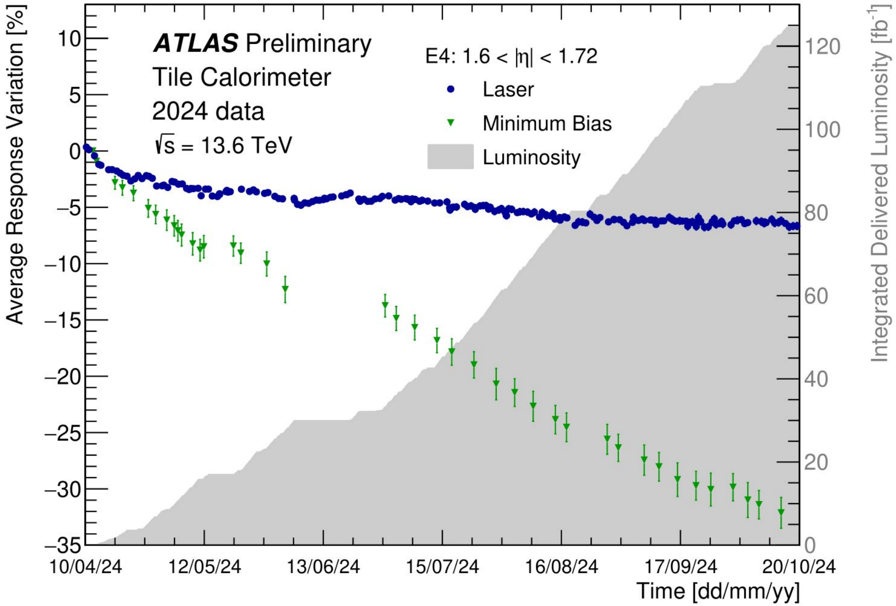




Ref: [5]

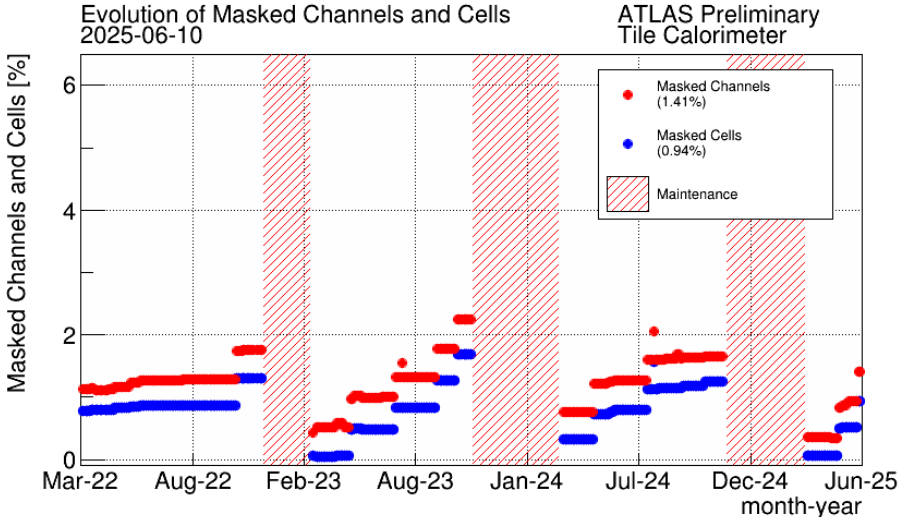
TileCal – performance

- The performance is assessed with isolated muons, hadrons and jets as well as with the calibration systems.
  - Each calibration system proves different parts of detector.
  - The calibration systems precision: ~1%.

pp collisions	2022	2023	2024
TileCal DQ efficiency [%]	99.67	99.6	99.3
ATLAS DQ efficiency [%]	93.1	94.6 – 96.5	93.8

Run 3 DQ efficiency for *pp* collisions of TileCal and ATLAS. [6]

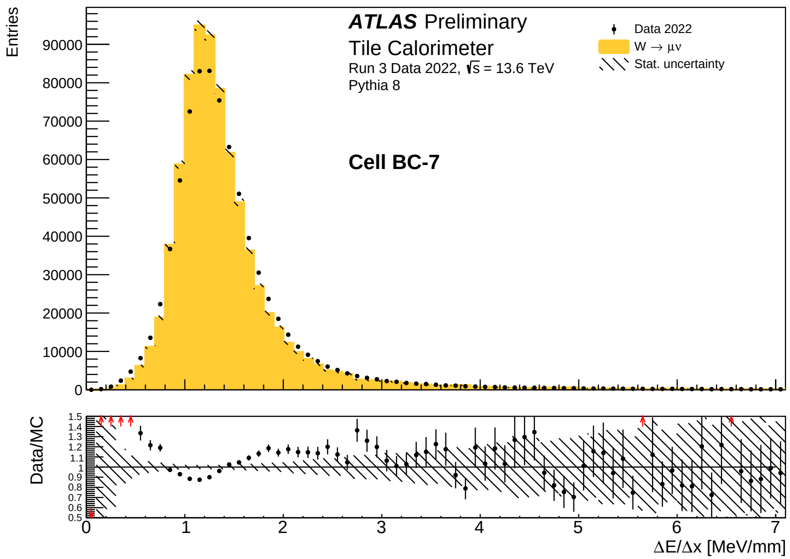
- Run 3 (since 2022) performance:
  - Data Quality (DQ) efficiency:
    - Over 99% for *pp* collisions.
    - 100% for ion collisions.
  - Less than 2% of non-operation cells at end of each year of data taking periods.
    - Radiation damage, ageing.
    - Repaired during winter shut-down periods.

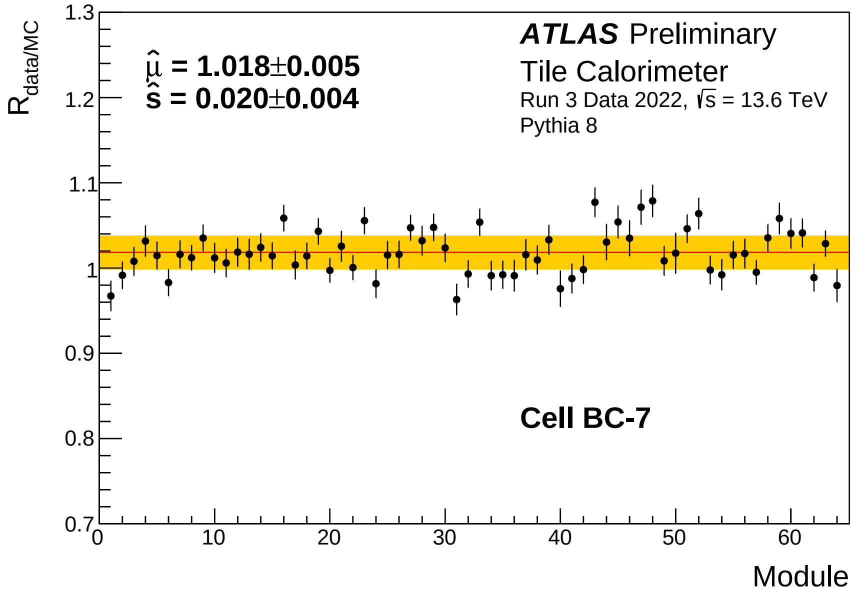


Ref: [3]

Performance – isolated muons

- Measuring the electromagnetic scale and detector uniformity using muons from decaying W bosons.
- Energy loss per unit path close to the minimum ionising level.
  - muon is an ideal particle to scan the entire TileCal volume.
- Good uniform response across φ (one module $\Delta\varphi = 2\pi / 64 \cong 0.1$).
- 1% of incident muons with highest $\Delta E/\Delta x$ omitted from calculation of ratio R: $R = \frac{\langle \Delta E/\Delta x \rangle_{\text{Data}}}{\langle \Delta E/\Delta x \rangle_{\text{MC}}}$

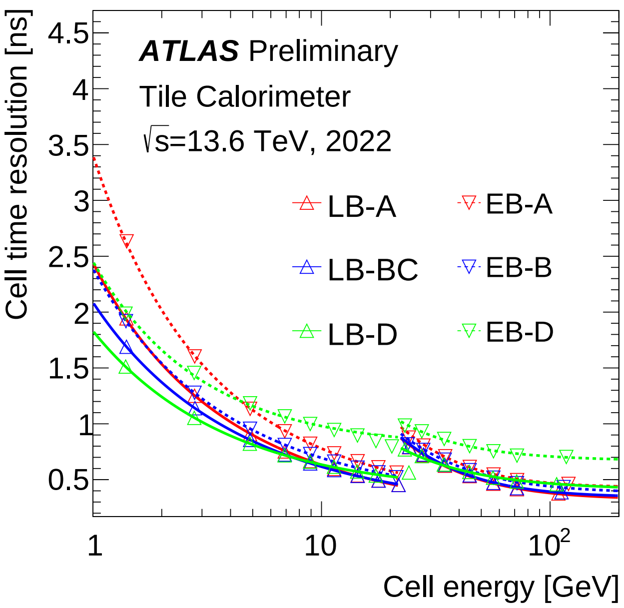


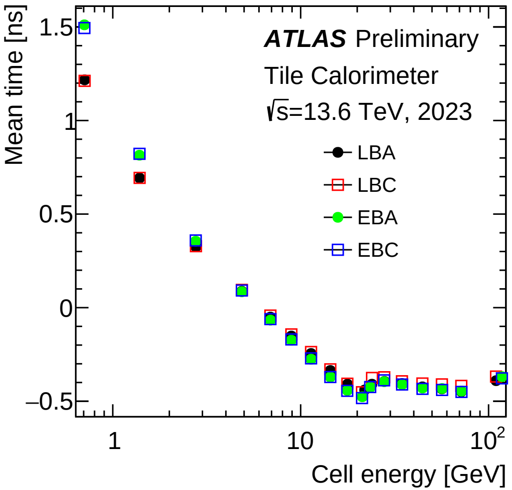


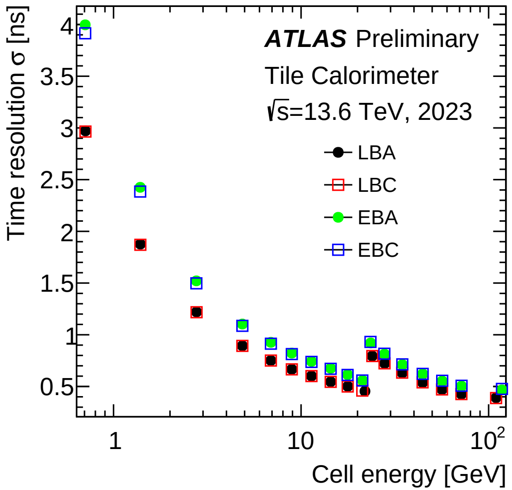
Ref: [5]

Performance – time

- TileCal time resolution in cells grouped by radial detector layers.
  - Important when searching for long-lived exotics.
- Cell time resolution: σ of a Gaussian fit of a timing distribution in a given energy slice.
  - Transition between high and low gain at ~22 GeV.
  - Worse resolution for the extended barrel due to larger cell size and for outermost D-layer.
  - Resolution better than 1 ns for cell energy > 4 GeV.



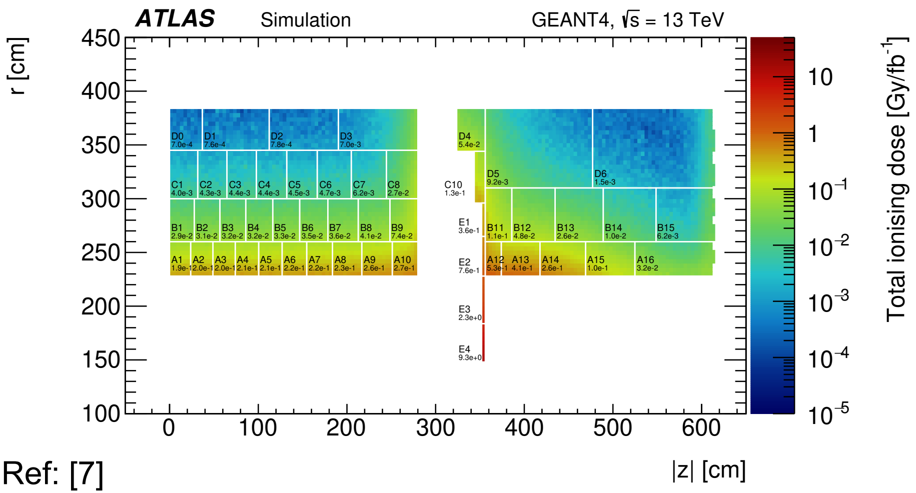




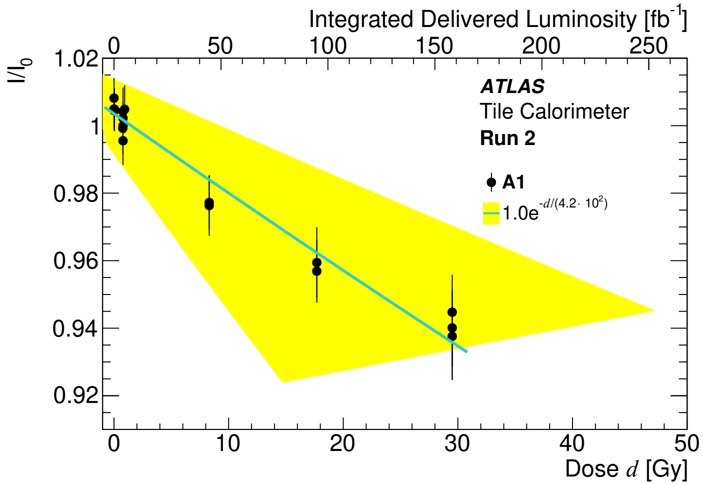
Ref: [5]

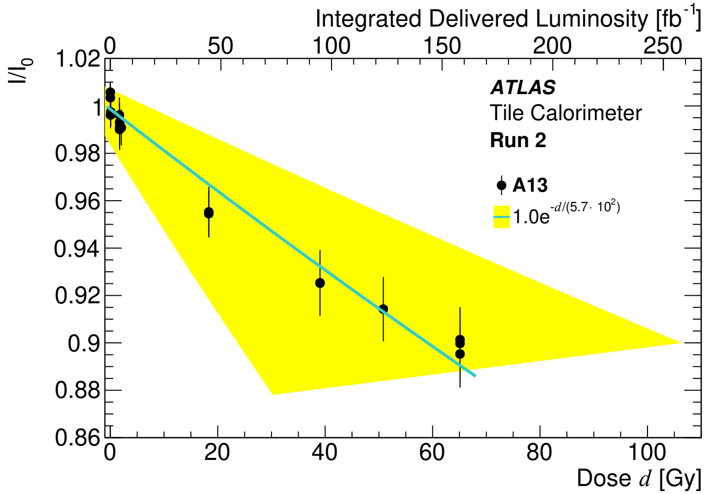
Performance – ageing

- Variation of response of the TileCal components.
  - PMT gain, monitored with the laser system, is known to decrease with increasing light exposure.
  - Scintillators and optical fibres degrade with irradiation.
  - Degradation of scintillators and fibres – differences between laser and cesium/MB data.
- Important for HL-LHC.
  - Scintillators and fibres located inside the calorimeter volume cannot be replaced.



Simulated ionisation dose deposited [GEANT4] in the scintillator tiles for integrated luminosity of 1~fb^{-1}.



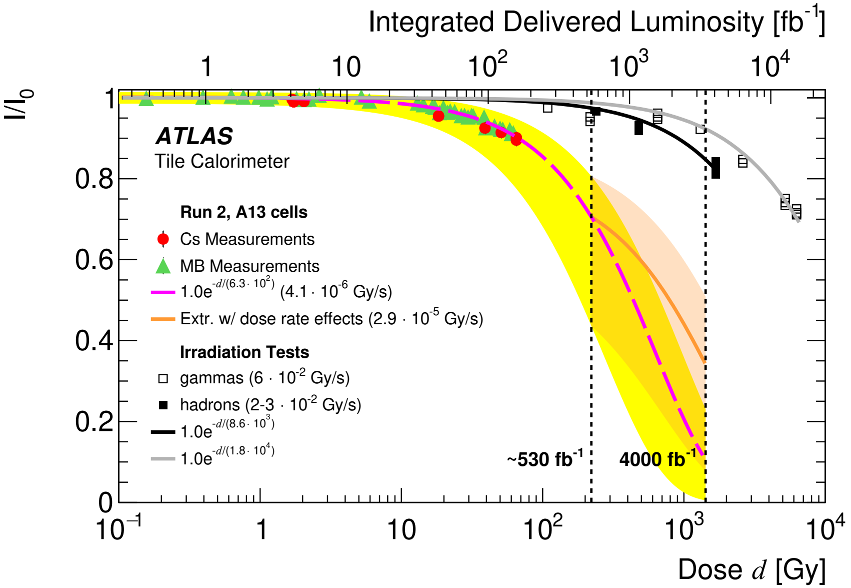


Average relative light yield of cells A1 and A13 as a function of simulated dose and integrated luminosity.

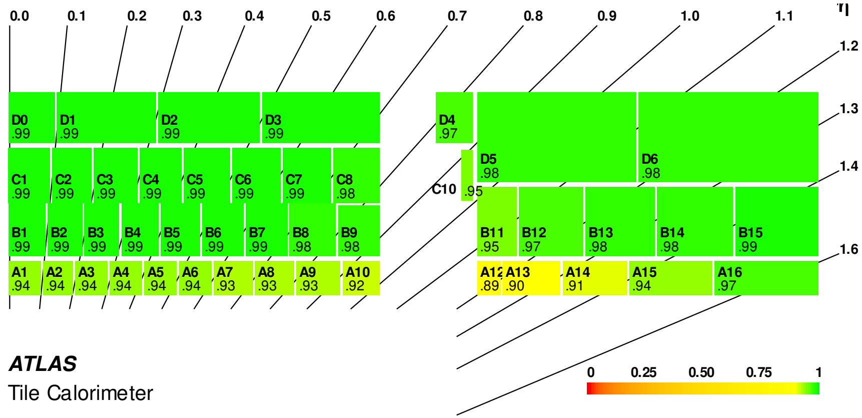
Ref: [7]

Performance – ageing

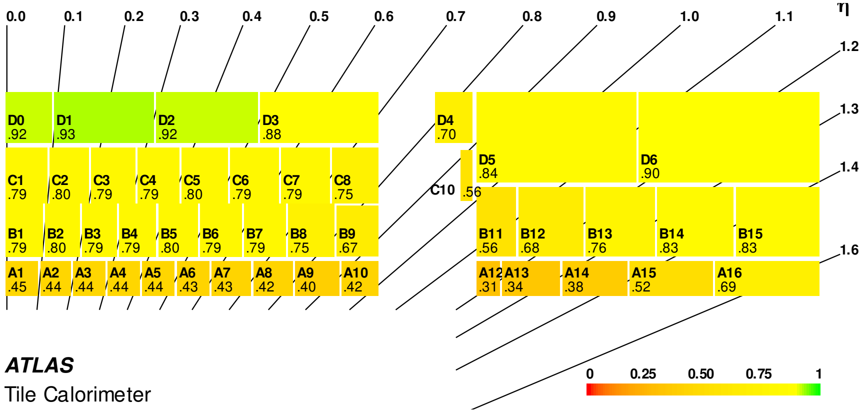
- Degradation of components as a function of dose.
  - On detector: tiles, E1 – E4 scintillators.
  - Irradiation tests.
- Extrapolation to HL-LHC expectations.



Average relative light yield as a function of simulated dose and integrated luminosity.



Measured light-yield at end of Run-2.



Expected light-yield at end of the HL-LHC.

Ref: [7]

Conclusions

- The ATLAS Tile Calorimeter is operating well in LHC Run 3 data taking period.
- Good performance ensured and monitored by several calibration systems.
- Calibration and monitoring procedures being validated with dedicated performance studies with isolated muons, hadrons, and jets.
- Updates on the Tile performance studies using Run 3 data presented.
  - EM response validated using isolated muons - good uniformity across azimuthal modules
  - Time performance studies performed using jets in collision data.
    - Resolution better than 1 ns for cell energy > 4 GeV.
- Ageing studies of optical components.
- Detector components are ageing mainly for irradiation:
  - Response degrades with irradiation.
  - Calibration systems allow track variations of response and compensate them.
  - Still get good quality data from the TileCal.
  - Predicted response at the end of the HL-LHC.

References

[1] ATLAS Collaboration, Operation and performance of the ATLAS tile calorimeter in LHC Run 2, 2. Eur. Phys. J. C 84, 1313 (2024), 10.1140/epjc/s10052-024-13151-4, https://arxiv.org/abs/2401.16034

[2] G. Blanchot et al, The Cesium source calibration and monitoring system of the ATLAS Tile Calorimeter: design, construction and results, 2020 JINST 15 P03017, 10.1088/1748-0221/15/03/P03017, https://arxiv.org/abs/2002.12800

[3] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTile

[4] M.N. Agaras et al, Laser calibration of the ATLAS Tile Calorimeter during LHC Run 2, 2023 JINST 18 P06023, 10.1088/1748-0221/18/06/P06023, https://arxiv.org/abs/2303.00121

[5] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TileCaloPublicResults

[6] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/DataQualityResults

[7] J. Abdallah at all, Study of the Radiation Hardness of the ATLAS Tile Calorimeter Optical Instrumentation with Run 2 data, 2025 JINST 20 P06006, 10.1088/1748-0221/20/06/P06006, https://arxiv.org/abs/2412.15944