Fundação
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This work was financially supported by 2024.00227.CERN

Operation and Performance of the ATLAS Tile Calorimeter in LHC Run 3

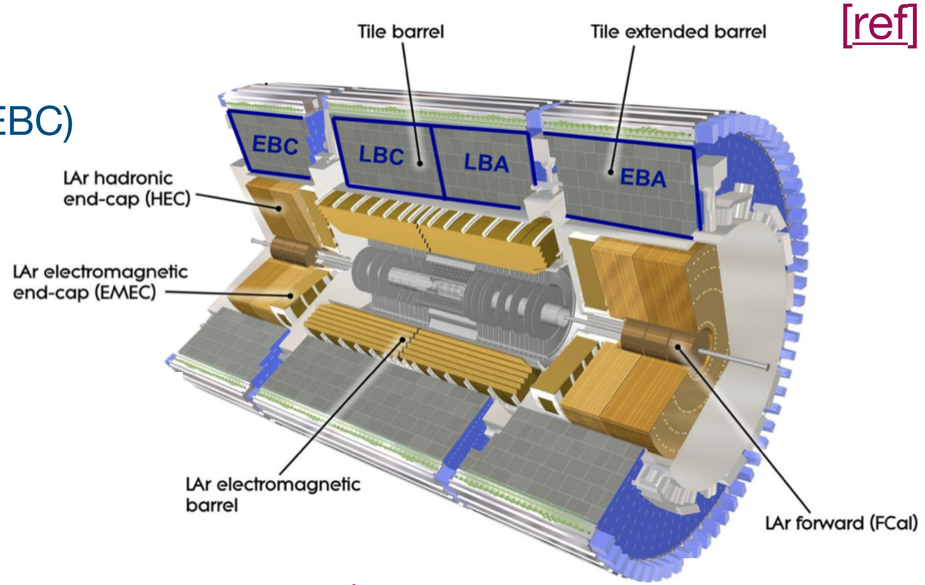
Helena Santos (LIP) on behalf of the ATLAS Collaboration

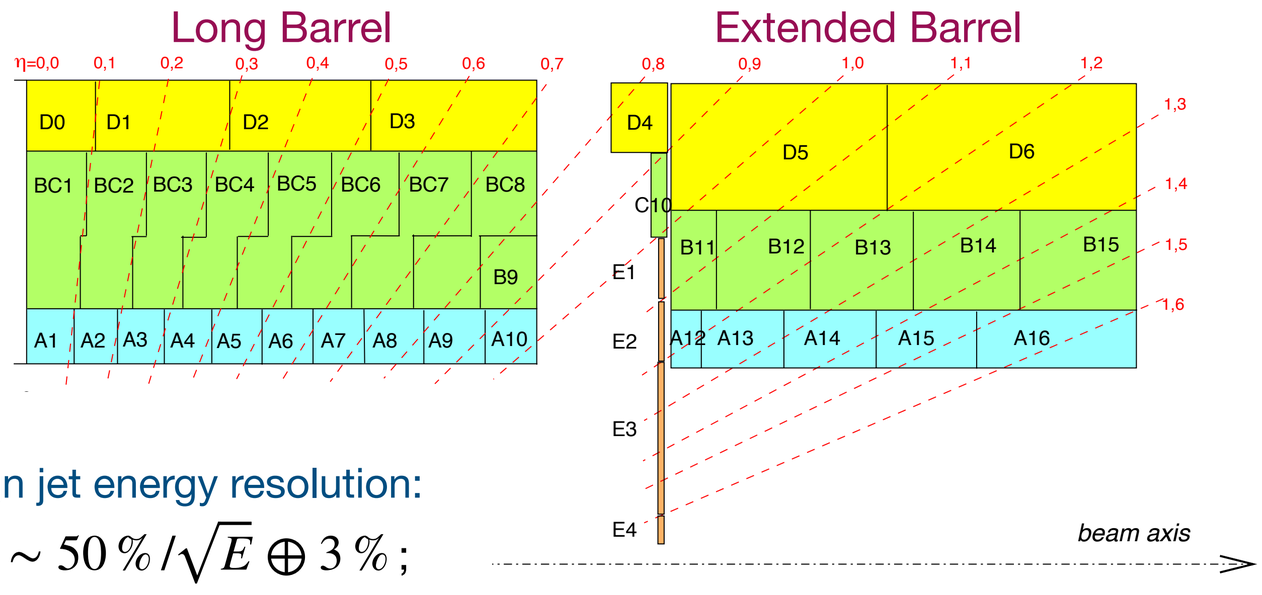


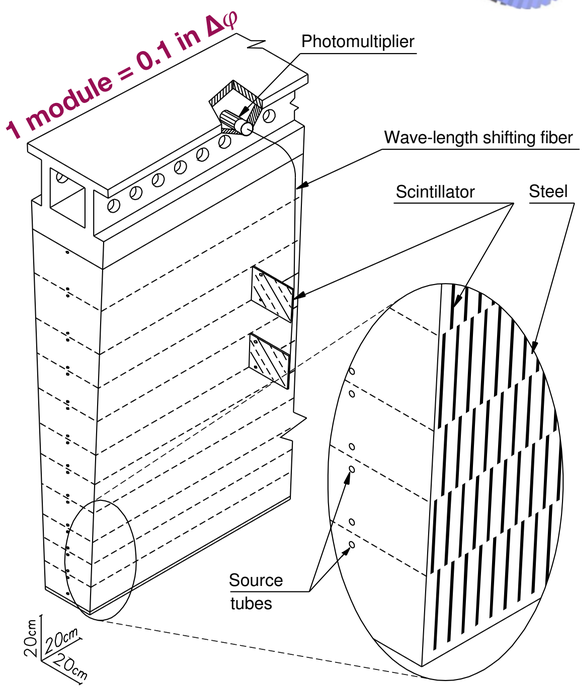
The Tile Calorimeter

- Central hadronic calorimeter of ATLAS, covering $|\eta|<1.7$;
  one Long Barrel divided into 2 partitions (LBA+LBC) and two Extended Barrels (EBA+EBC)
- Sampling calorimeter: plastic scintillating tiles interleaved with steel absorbers;
  Each tile is read out by two wavelength-shifting (WLS) fibres;
  fibres from all tiles in a cell are bundled and coupled to two PMTs.
  → ~5,000 cells → ~10,000 readout channels
- Each partition segmented in 64 modules in ϕ; cells are arranged in 3 radial layers with $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the A and B/BC layers and 0.2×0.1 in the D layer;
  special E-cells instrument the gap region between the Long and Extended Barrels.

[ref]







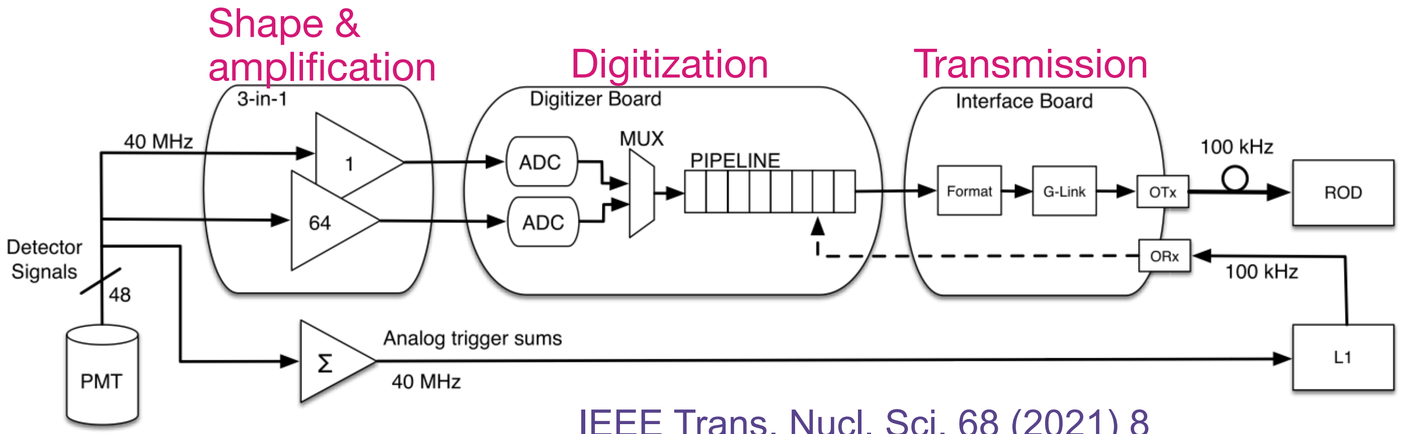
Design jet energy resolution:

$\sigma_E/E \sim 50\,\%/\sqrt{E} \oplus 3\,\%$;

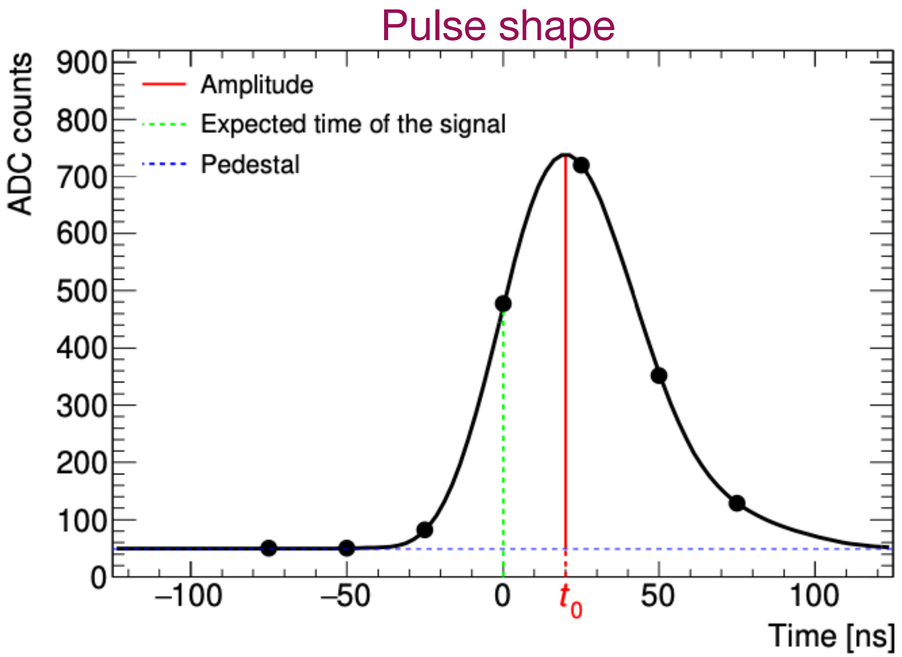
ATLAS jet energy resolution <10% for jet p_T >100 GeV

TileCal Signal Reconstruction

- PMT signals are shaped and amplified in two gain branches to cover a large dynamic range: high gain (HG, 0–12 GeV) and low gain (LG, 12–800 GeV), with HG/LG = 64:1. Switch to LG when HG saturates.
- Both gains are digitised at 40 MHz with 10-bit ADCs synchronised to the LHC clock and stored in pipelines.
- On a Level-1 trigger accept, 7 samples around the pulse peak are sent to the Read-Out Drivers (RODs).
- A parallel integrator path reads out PMT currents for calibration purposes.



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- Optimal filtering reconstructs the pulse amplitude A, time t_0, and pedestal p from the 7 samples.

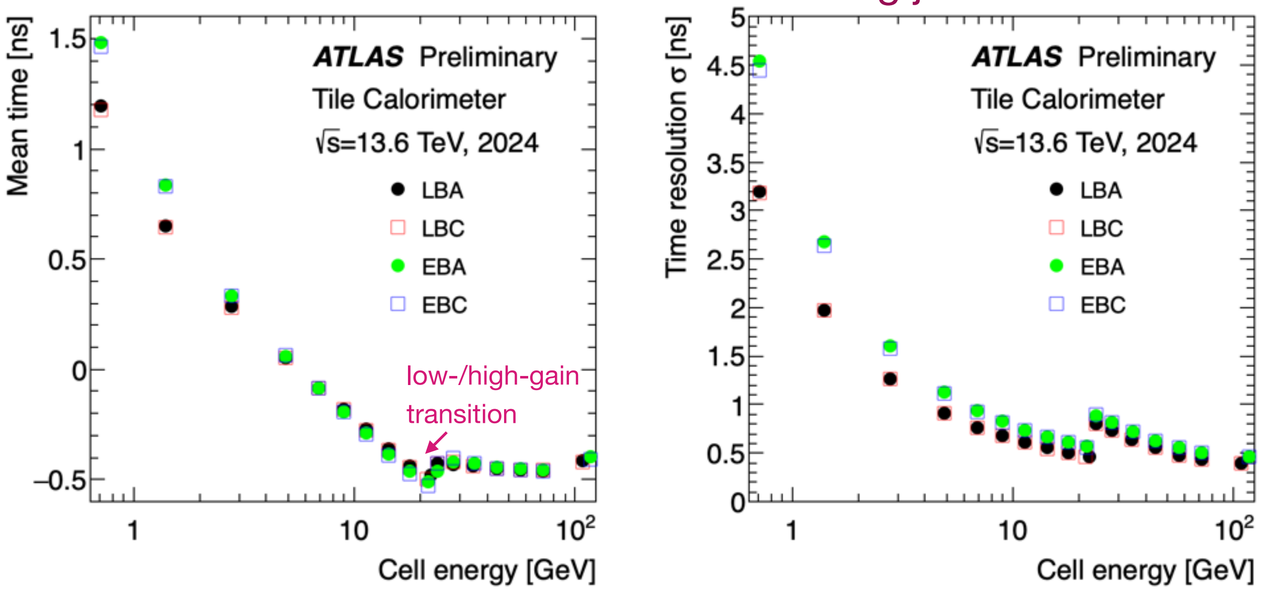
$$A = \sum_{i=1}^{7} a_i S_i, \qquad t_0 = \frac{1}{A} \sum_{i=1}^{7} b_i S_i, \qquad p = \sum_{i=1}^{7} c_i S_i,$$

Timing Calibration and Resolution

Time calibration is essential for the Optimal Filtering reconstruction and TOF measurements

- Timing offsets are calibrated so that particles from the interaction point give $t_{cell} \simeq 0$.
- Timing calibration is derived from cells associated with jets and monitored with the laser system (sl.12)
- Cell time resolution improves with energy, **reaching < 1 ns for E_{cell} > 4 GeV.**
- Resolution is worse in the Extended Barrel.

Time mean and resolution using jets [ref]

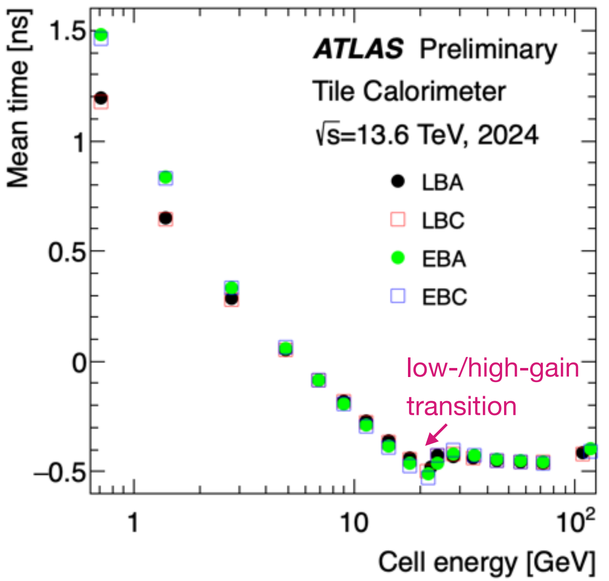


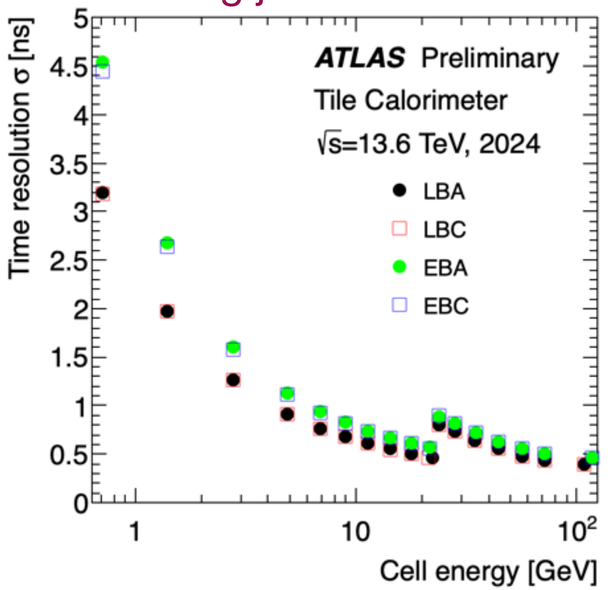
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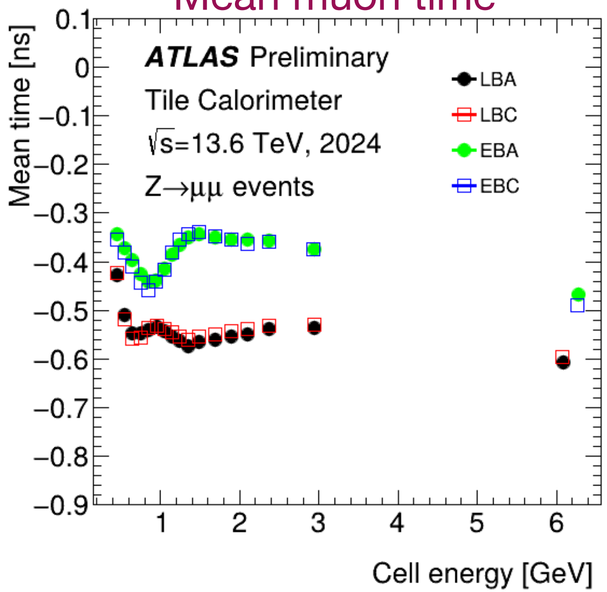
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- Cell time resolution improves with energy, **reaching < 1 ns for E_{cell} > 4 GeV.**
- Resolution is worse in the Extended Barrel.
- Muons from Z-boson decays provide an independent validation: **mean cell time is nearly independent on cell energy and remain within 1 ns.**

Time mean and resolution using jets [ref]





Mean muon time

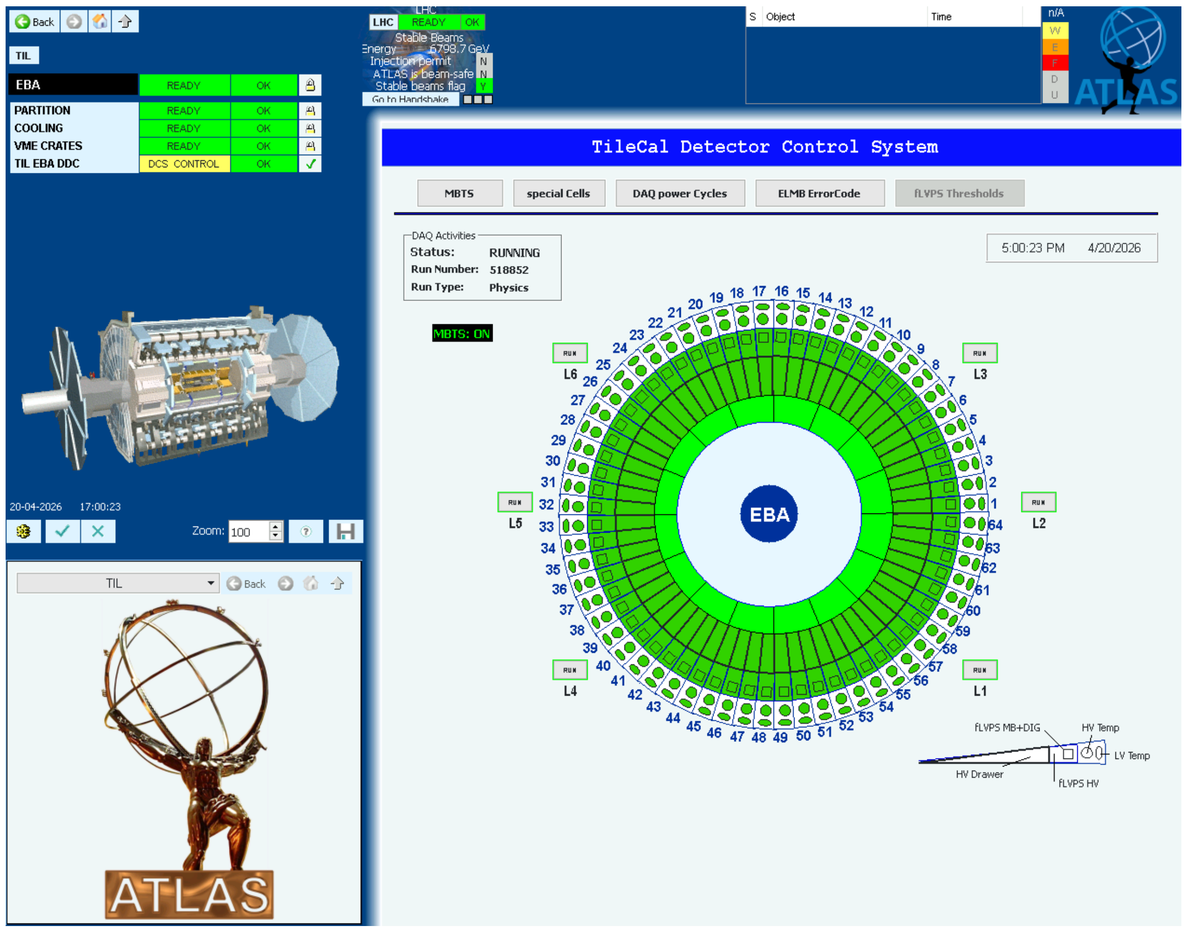


Operation

TileCal Operation and Data Quality

- Detector parameters controlled and monitored through the Detector Control System (DCS).
- Data taking shifters, run coordination, maintenance and data quality teams ensure reliable operation.

TileCal Detector Control System

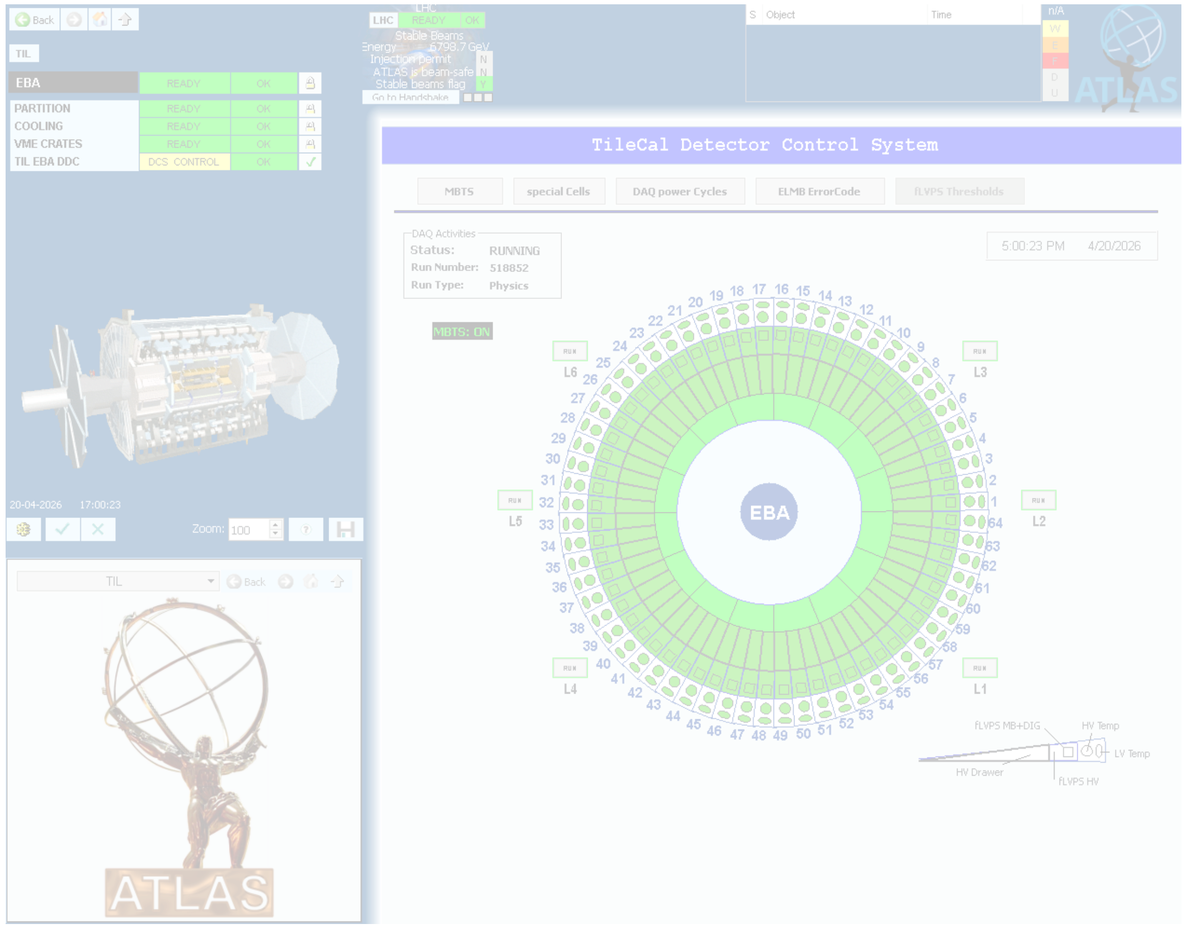


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TileCal Operation and Data Quality

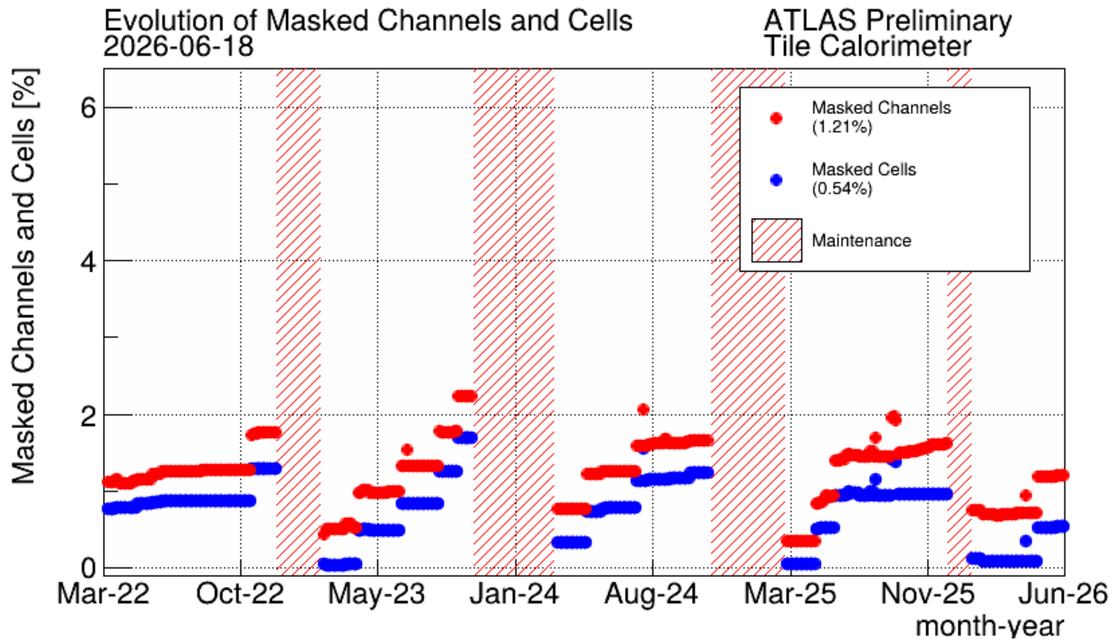
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TileCal Detector Control System



Eur. Phys. J. C 84 (2024) 1313

[ref]



- Continuous monitoring identifies problematic channels, miscalibrations, data corruption and hardware issues.
- Redundant cell readout limits the impact of masked channels.
- Maintenance campaigns (dashed bands) recover most affected channels.
- **TileCal data quality efficiency remained close to 100% throughout Run 3:**

2022	2023	2024	2025	2026
99.7	99.6	99.3	99.9	100

[ref]

Calibration

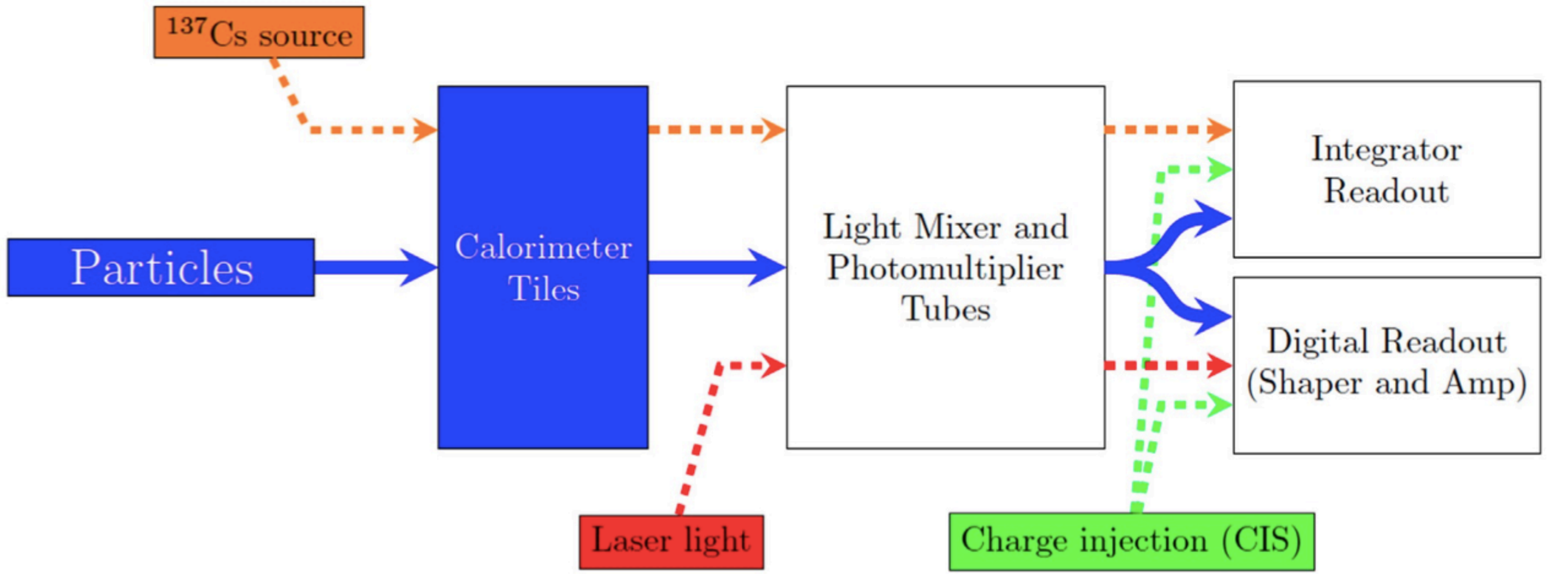
Energy Reconstruction

[ref]

At the electromagnetic scale the energy deposited by particles is reconstructed using:

$$E\ [\mathrm{GeV}] = \frac{A\ [\mathrm{ADC}]}{C_{\mathrm{ADC}\to\mathrm{pC}} \times C_{\mathrm{pC}\to\mathrm{GeV}} \times C_{\mathrm{Cs}} \times C_{\mathrm{MB}} \times C_{\mathrm{Las}}}$$

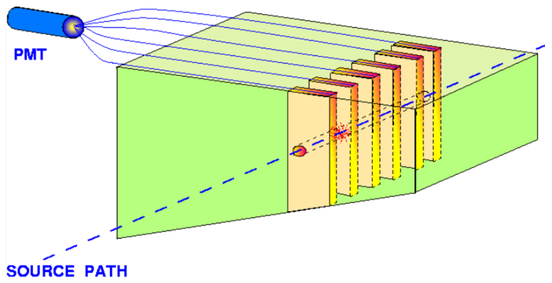
- The charge-to-energy conversion was set by the electron calibration constant, $C_{\mathrm{pC}\to\mathrm{GeV}}$, determined in TestBeam.
- **Cesium-137 response** measured in TestBeam calibrated modules **defined the reference**;
  after installation and before each LHC Run, **PMT High Voltage equalisation** was used to reproduce this response in all cells.



^{137}Cs, Minimum Bias, Laser and Charge Injection systems correct drifts in the calorimeter sub-components.

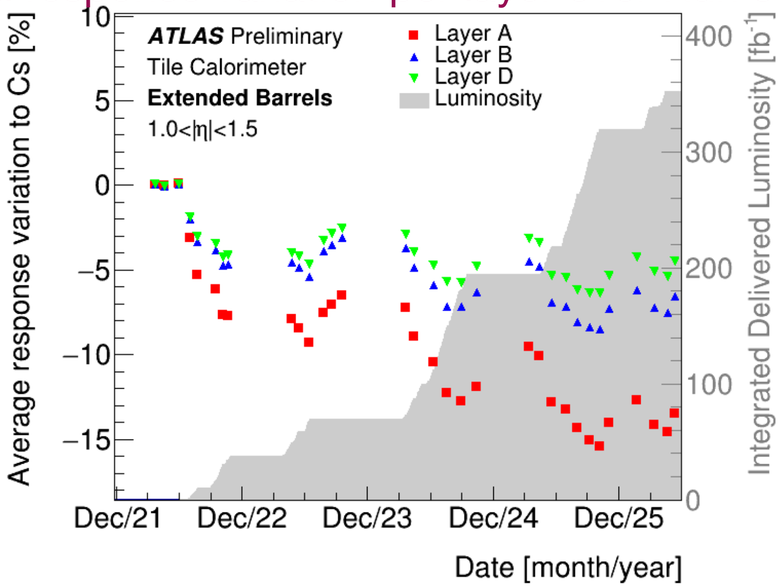
Calibration with the Cesium system

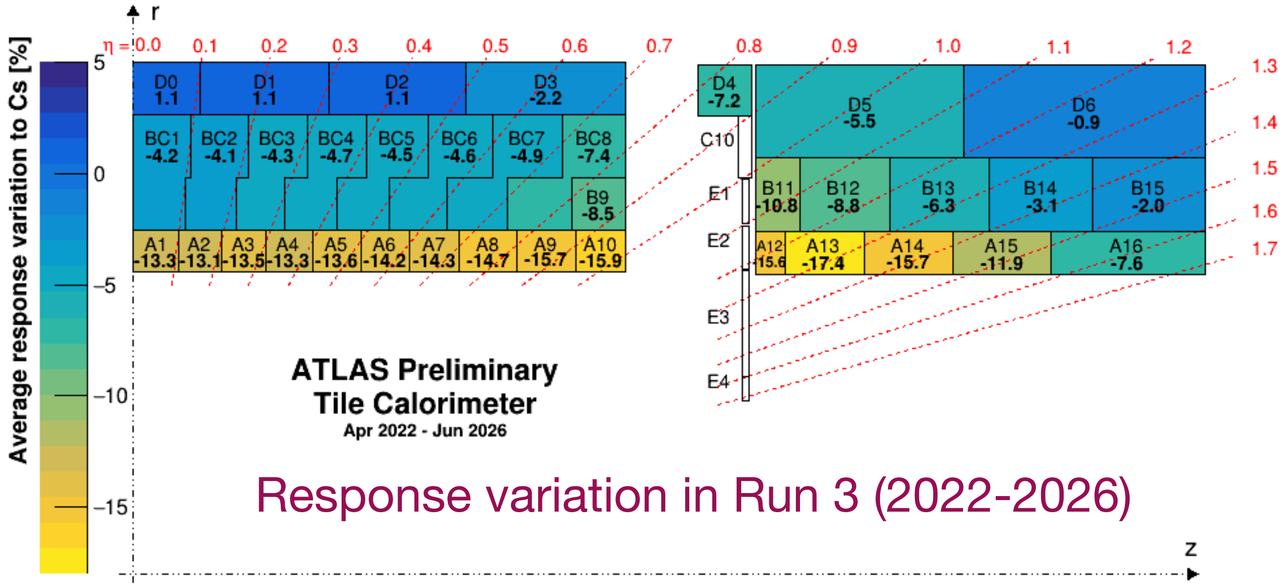
[ref]



- A ^{137}Cs source (E_γ = 662 keV) is driven through the calorimeter tiles, calibrating optics + PMTs using the integrator readout system.
- Scans performed monthly.

Cell response variation per layer over Run 3





Response variation in Run 3 (2022-2026)

Response degradation due to:

- **PMT gain instability**
- **Optical ageing**

- Strongly dependent on the radial distance from IP and on η, up to -17%.
- Deviation from nominal defines a calibration constant: C_{Cs}.

Recovery during technical stops and Heavy Ion collisions

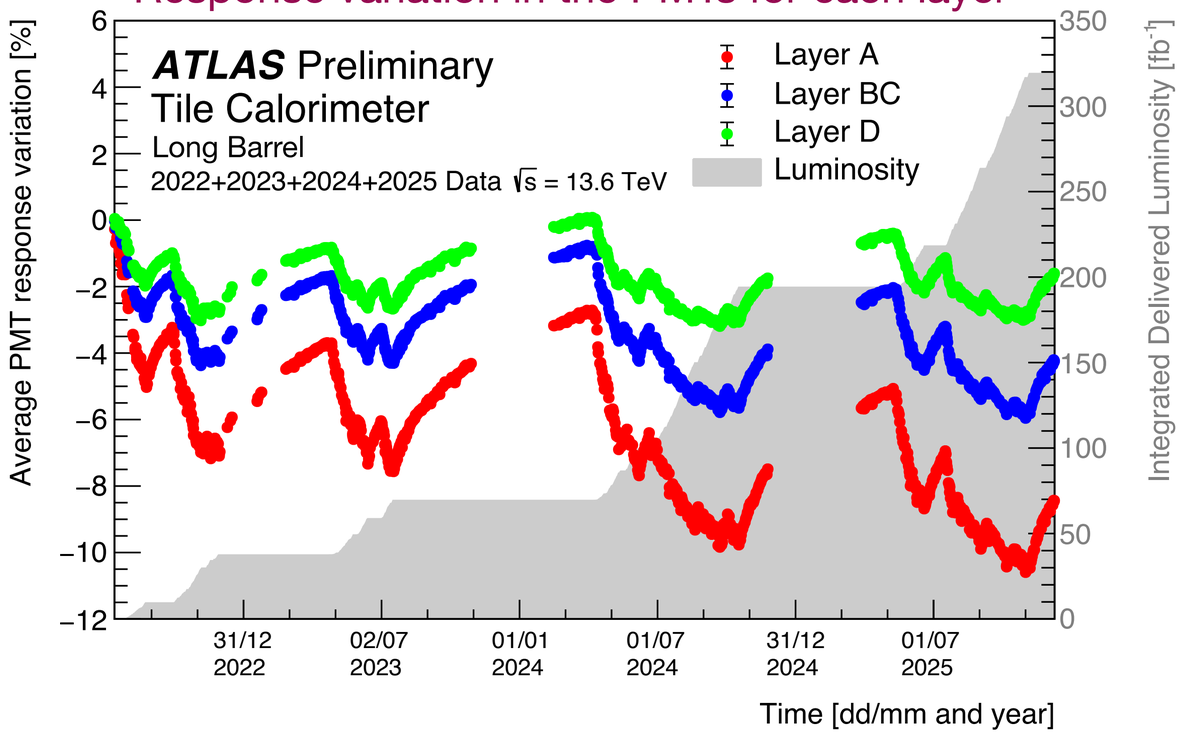
Luminosity is superimposed to show the correlation between increasing luminosity and response degradation.

Calibration with the Laser system

[ref]

- Laser pulses (λ=532 nm) sent to all PMTs in dedicated daily calibration runs.
- Pulses are also sent during empty bunches for timing calibration and to monitor stability during physics runs.

Response variation in the PMTs for each layer



- **Down-drift during *pp* collisions; Recovery during shutdowns and Heavy Ion collisions.**
- **Maximal drift in A-cells (highest energy deposits).**

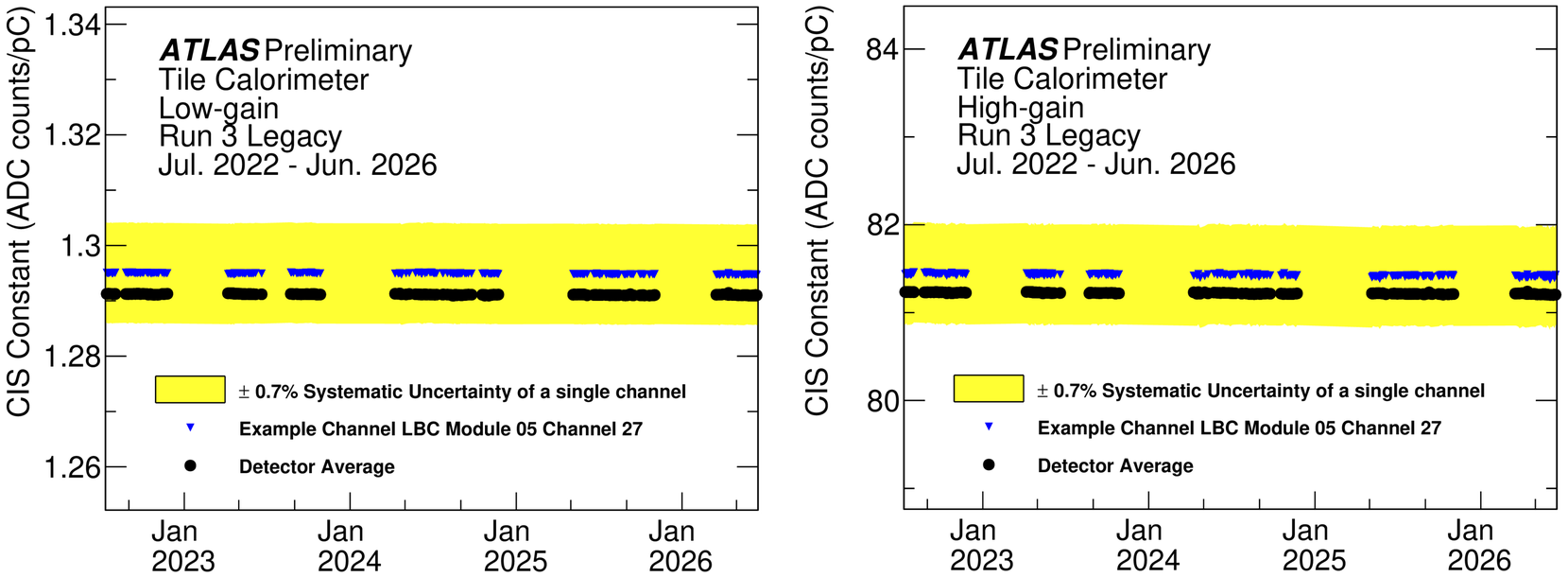
- Channel response deviations from nominal converted into a calibration constant: C_{Las}.
- Constants updated weekly if changes exceed 0.5%.

Calibration with the Charge Injection system

[ref]

- Injects controlled charges (0–800 pC) into the front-end electronics to calibrate the ADCs response, covering the full dynamic range in both gains and extracting the $C_{ADC \to pC}$ conversion constants.
- Calibration runs taken twice a week and constants are updated monthly.

CIS calibration constant averages of all the low- and high-gain ADCs over Run 3



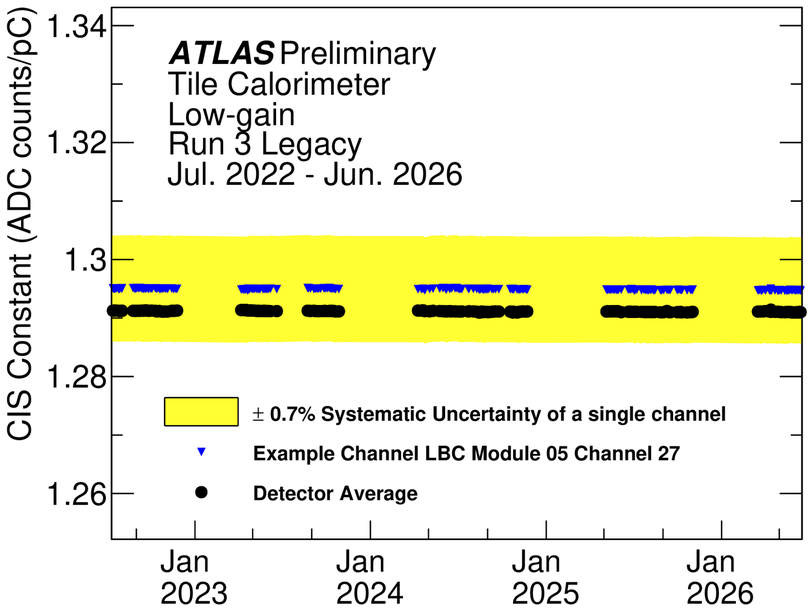
- **Remarkable stability of the CIS constants**
- Systematic uncertainty of 0.7%

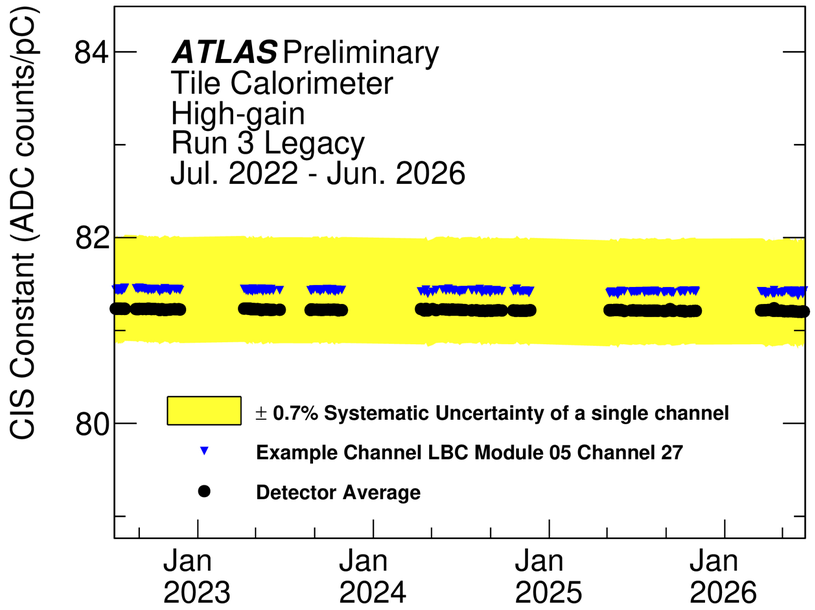
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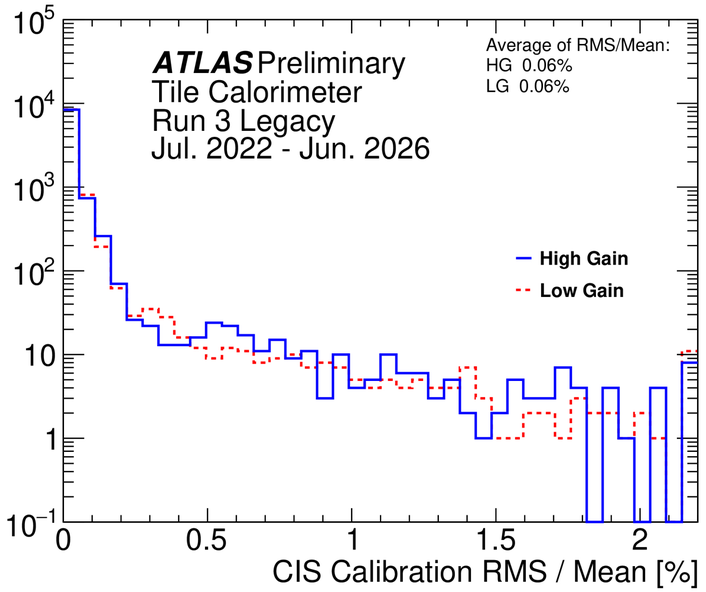
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CIS calibration constant averages of all the low- and high-gain ADCs over Run 3





RMS to the mean of the CIS constants



- **Remarkable stability of the CIS constants**
- Systematic uncertainty of 0.7%

Average of the RMS/mean values over channels is 0.06% for both gains

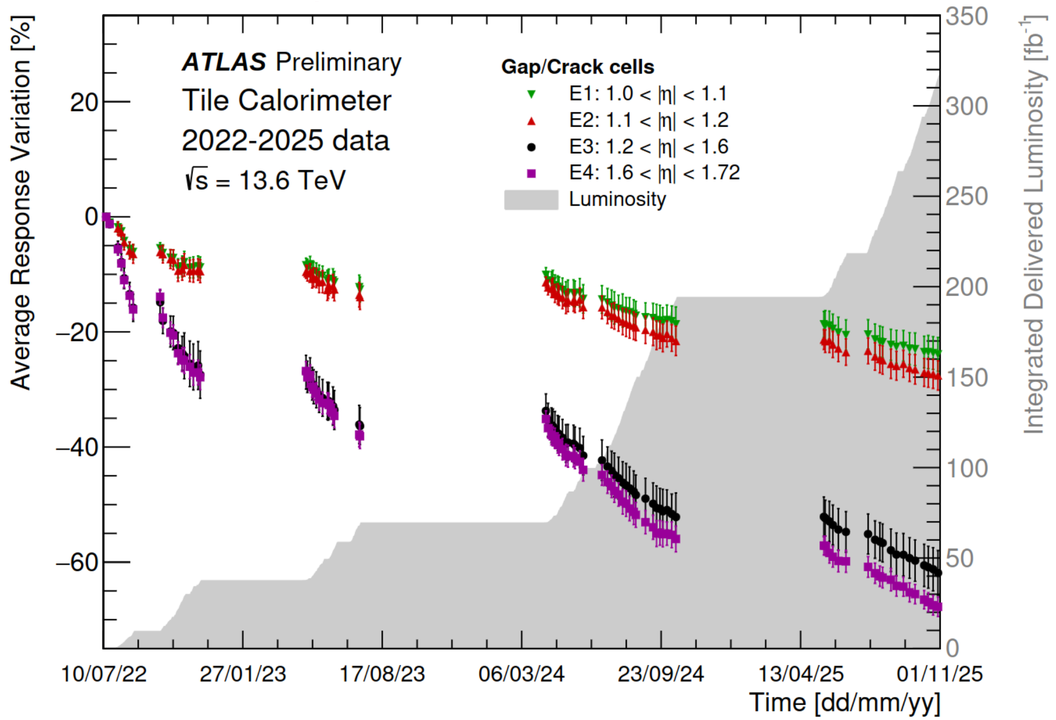
→ **consistent CIS calibration performance across channels**

Calibration using Minimum Bias collisions

[ref]

- The integrator readout system measures the response to particles produced in soft inelastic interactions (minimum bias).
- Like the Cesium system, it monitors the full optical chain, sharing the readout path.
- It is crucial for calibrating the special E-cells, not scanned by the Cs system.

Response variation for E-cells



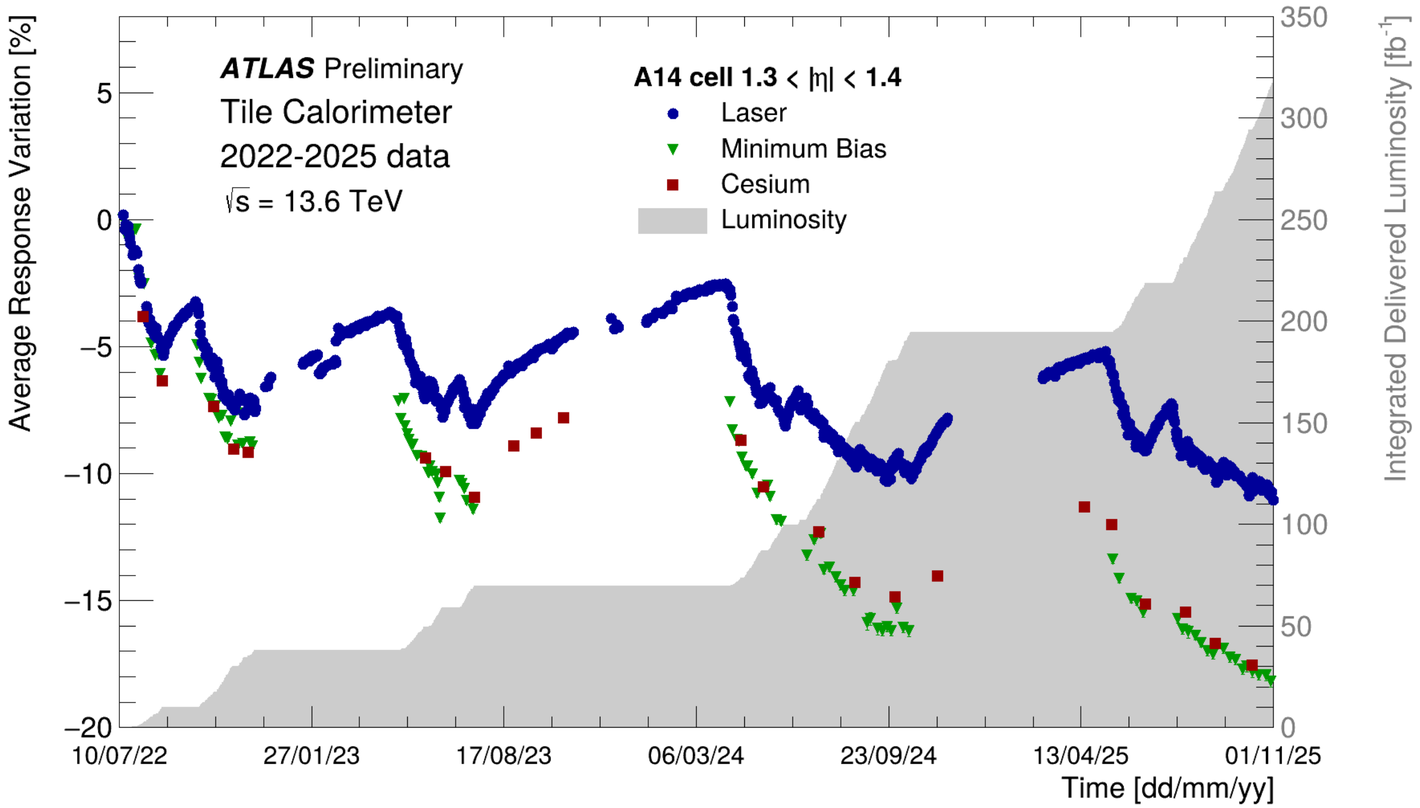
Large losses observed for E-Cells, in particular, the most irradiated ones, E3 and E4.

Deviation from reference defines a calibration constant: C_{MB}

Disentangling PMT Gain and Optical Ageing

[ref]

Combination of individual systems allows the various drifting effects to be disentangled.



- Cs and Minimum Bias results are consistent, showing a ~18% response decrease by the end of 2025 in A14 (one of the most irradiated standard cells) relative to the beginning of Run 3.
- **Discrepancy between Laser and Cs/MB interpreted as arising from scintillator and WLS fibre degradation**
  → Cell A14 shows ~6% optical degradation by the end of 2025.

Radiation Hardness

[ref]

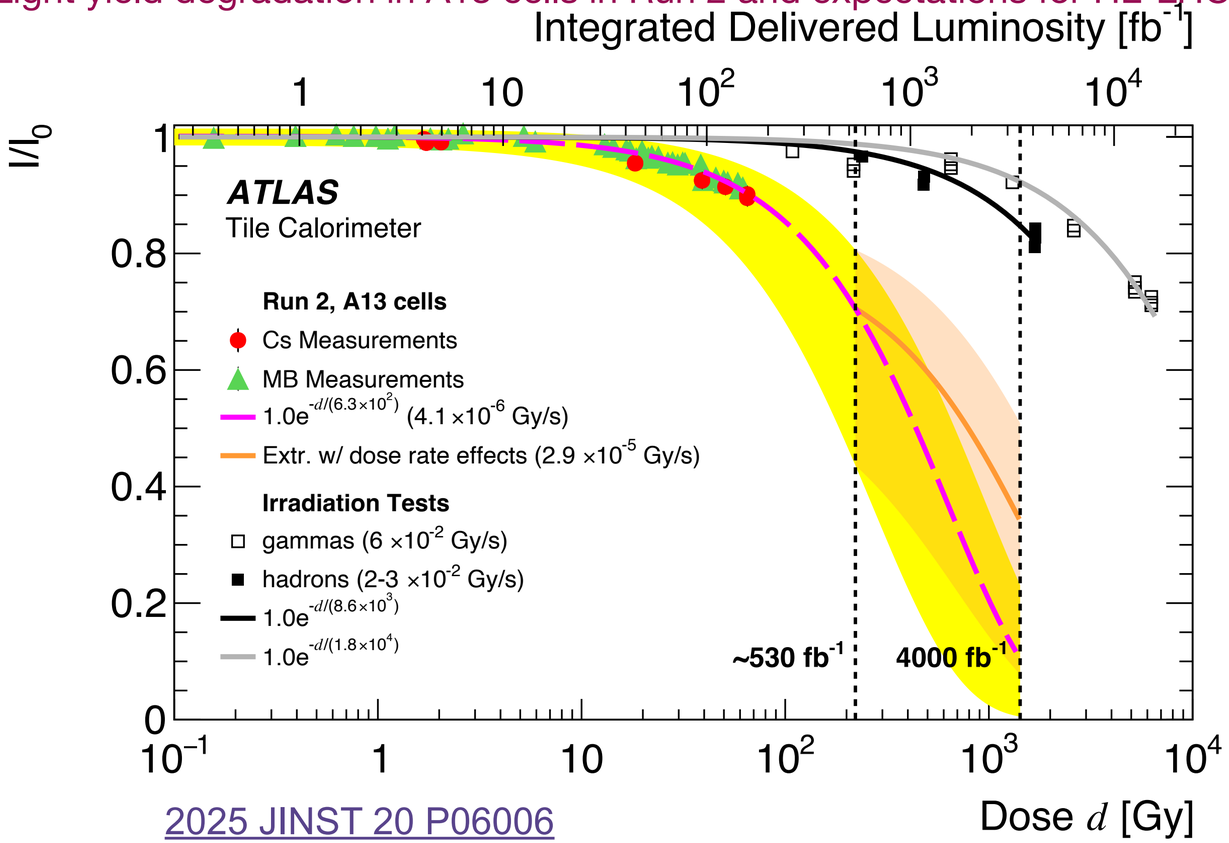
Radiation damage reduces the light yield of the scintillators and the transmission efficiency of the WLS fibres.

The light output relative to the start of Run 2 is

$$I/I_0 = \frac{R_{\mathrm{Cs(MB)}}}{R_{\mathrm{Las}}}$$

$R_{\mathrm{Cs(MB)}}$ and R_{Las} are the cell relative response to the ^{137}Cs source (MB currents) and laser pulses, respectively.

Light yield degradation in A13 cells in Run 2 and expectations for HL-LHC



2025 JINST 20 P06006

- Optical reduction follows $I/I_0 = p_0 \exp(-d/p_1)$
- For A13 cell:
  - **Up to ~55% degradation** projected by the end of Run 3, including uncertainties.
  - **~66% degradation** projected by the end of HL-LHC (4000 fb^{-1}), with large uncertainties.

Performance

Single Particle Response - Muons

[ref]

High momentum muons (p < 80 GeV) from W → μν decays traverse TileCal as minimum-ionising particles, providing a clean probe of the calorimeter response.

- Used to test the azimuthal response uniformity and **validate the electromagnetic energy scale.**

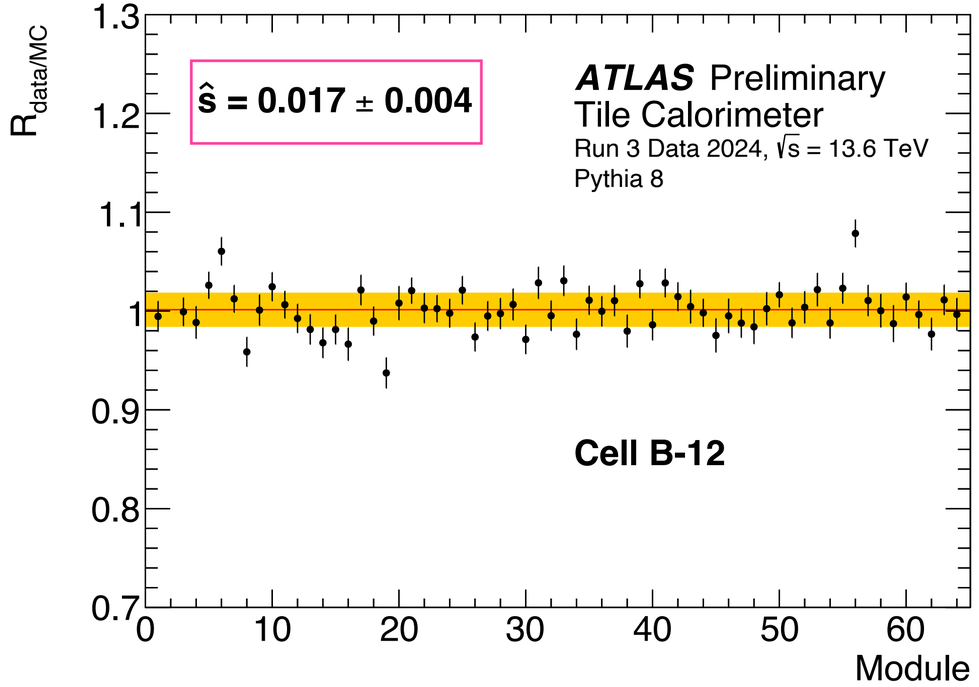
Response quantified by the ratio of the truncated mean dE/dx in data and MC:

$$R = \frac{\langle \mathrm{d}E/\mathrm{d}x \rangle^{\mathrm{data}}}{\langle \mathrm{d}E/\mathrm{d}x \rangle^{\mathrm{MC}}}$$

For each cell type, R is evaluated in the 64 azimuthal modules:

- data/MC $dE/dx \simeq 1$ validates the EM energy scale in situ.
- the fitted spread $\hat{s}$ quantifies the response non-uniformity.

data/MC dE/dx across azimuthal modules



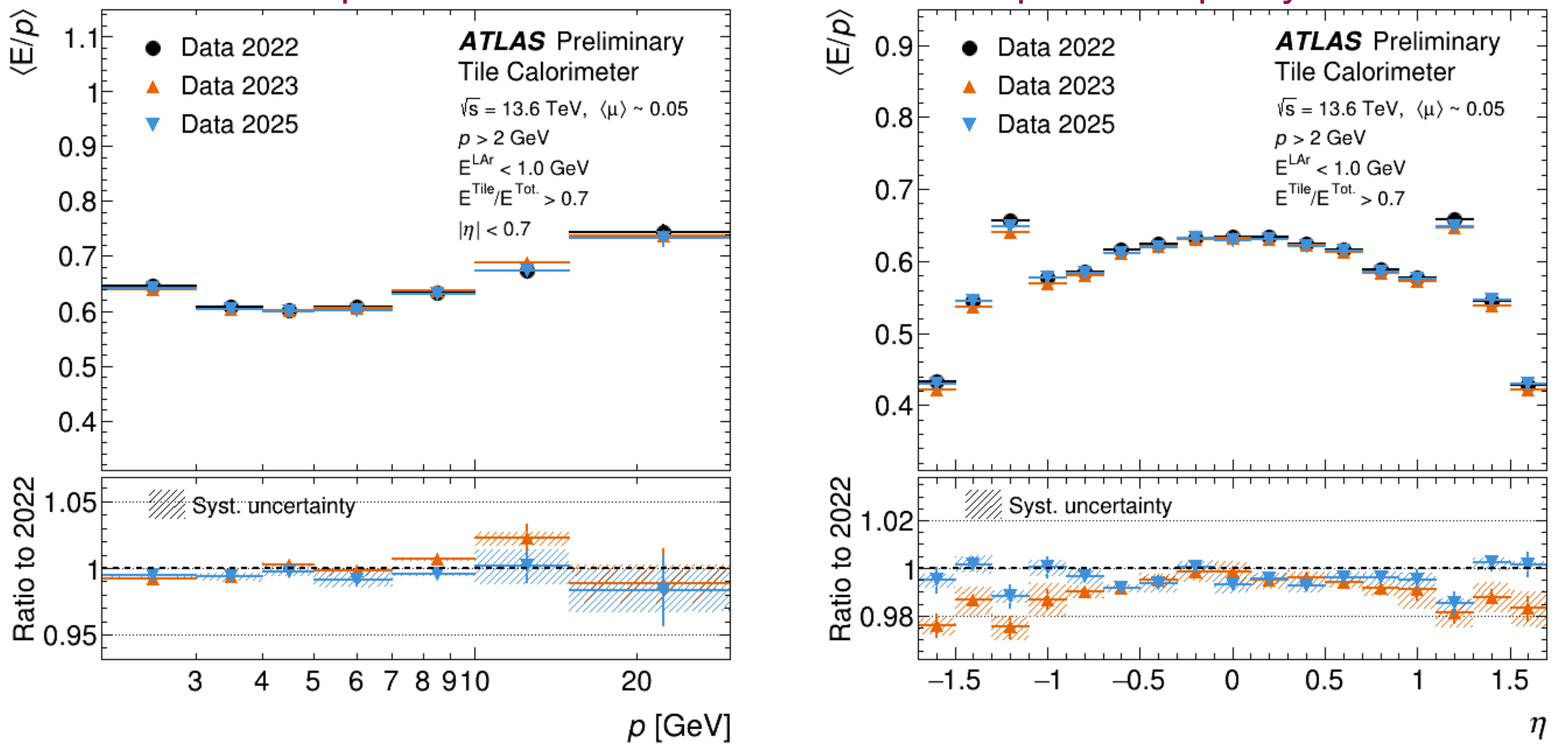
For B-12 cell, the azimuthal non-uniformity is 1.7 ± 0.4 %, consistent with the average over TileCal cells.

Tests of the Energy Scale Stability with Hadrons

[ref]

- Isolated charged hadrons in low-pileup data: *p* from the Tracker, *E* from calorimeter clusters associated with the track.
- Little energy in the Liquid Argon Calorimeter and most of the cluster energy in TileCal.

⟨E/p⟩ as a function of momentum and pseudorapidity



- ⟨E/p⟩ < 1 at EM scale reflects the non-compensating nature of TileCal.
- **Run 3 response stable at the percent level across the measured phase space.**

Summary

- TileCal operated very reliably throughout Run 3, with data-quality efficiency close to 100% and high detector coverage.
- Complementary calibration systems monitor the full signal chain, correcting electronics, PMT and optical response variations.
- Excellent Run 3 performance: EM scale validated in situ, with percent-level muon response uniformity; stable hadron *E/p;* less than 1 ns timing resolution above 4 GeV.
- Radiation-induced optical ageing is observed and monitored, providing input to projections towards HL-LHC operation.



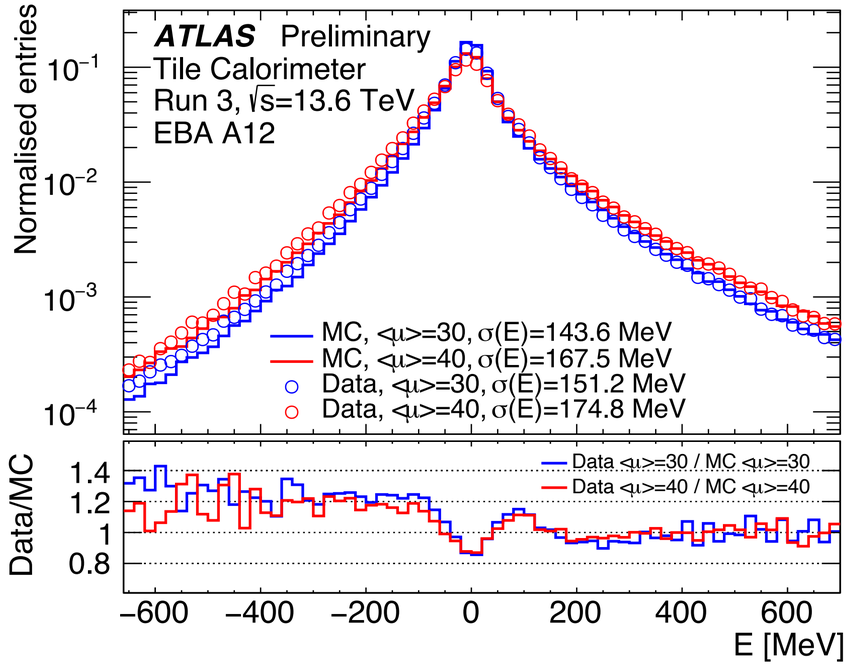
The ATLAS-TileCal community celebrating the end of Run 3 at P1, CERN
https://atlas-tilecal.web.cern.ch/

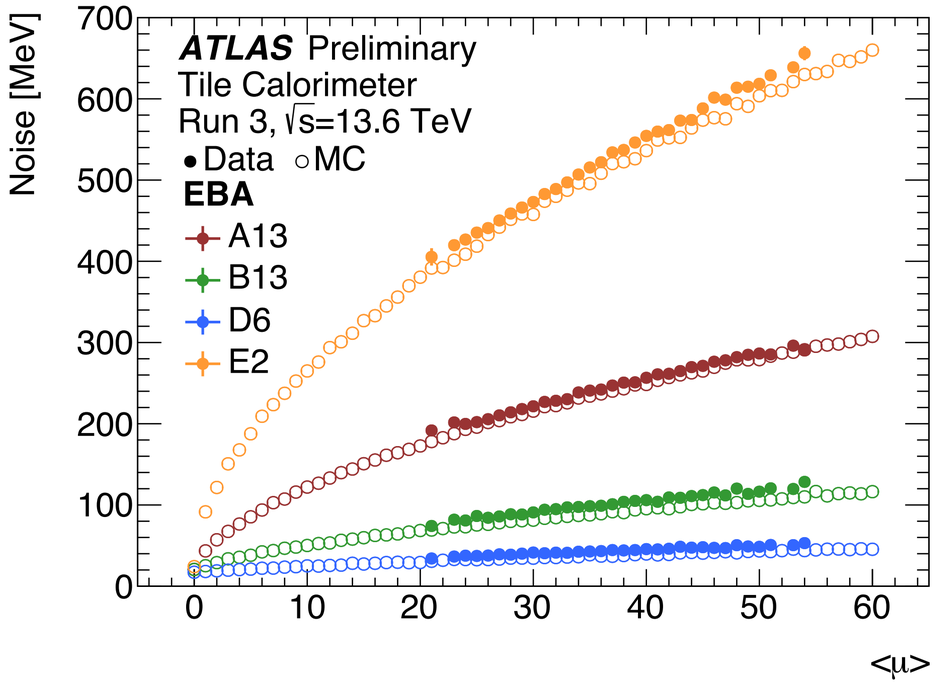
Backup

Noise Measurement

[ref]

- Measurement of TileCal noise is crucial for topoclustering reconstruction.
- Two sources contribute: electronic noise, determined from pedestal data and unaffected by μ, and pile-up noise arising from both in-time and out-of-time interactions.
- Pile-up noise constants determined for each cell type using zero-bias data:
  RMS of the cell-energy distribution measured as a function of μ, with the electronic noise fixed.





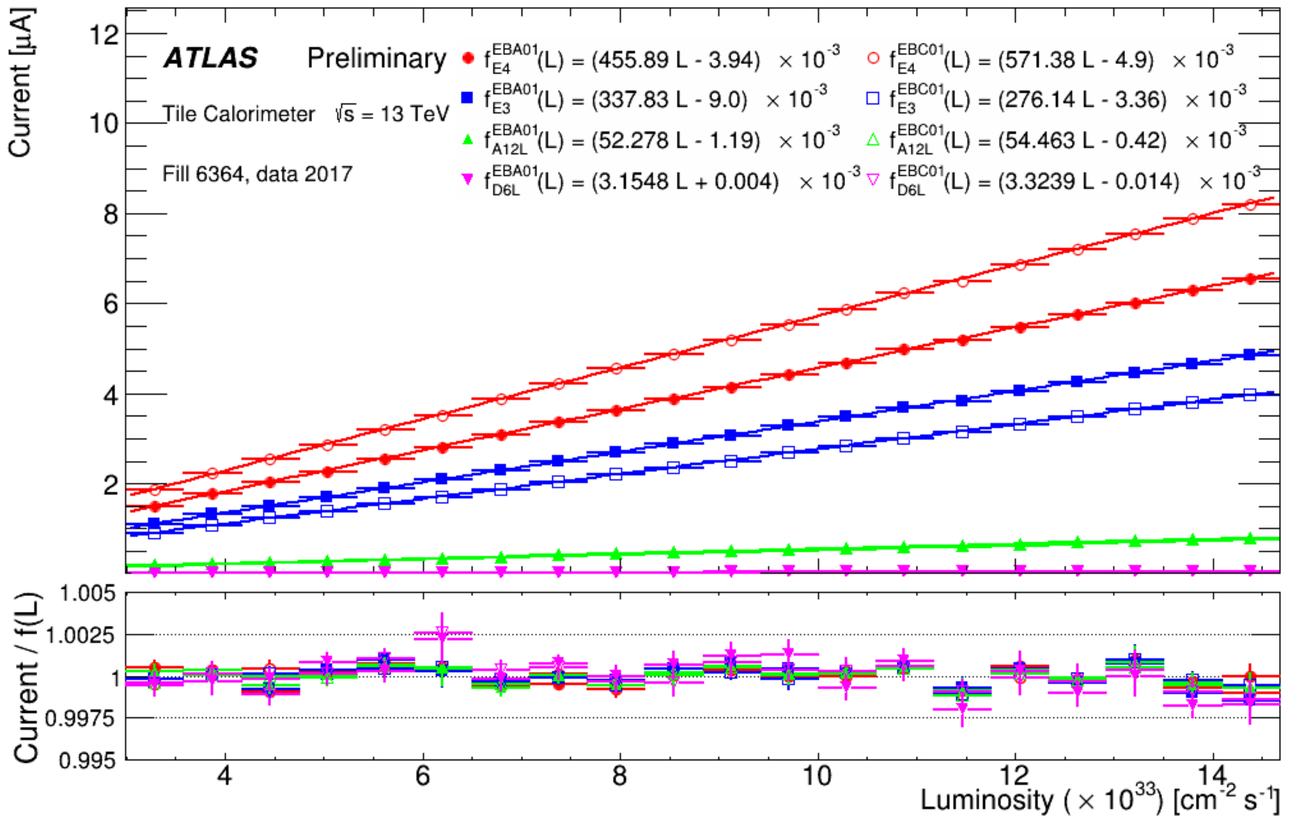
$$\sigma_{\text{tot}} = \sqrt{\sigma^2_{\text{elec}} + \frac{\sigma^2_{\text{pile-up}}}{k}\langle\mu\rangle}$$

Contribution to Luminosity Measurements

[ref]

- The integrator readout system measures the response to particles produced in soft inelastic interactions (minimum bias).

PMT anode current as a function of luminosity



- The integrator readout integrates PMT signals over 10—20 ms.
- Different cells, depending on their position, receive different amounts of signal.
- Currents proportional to the luminosity → TileCal contributes to luminosity measurements.

Radiation Hardness

[ref]

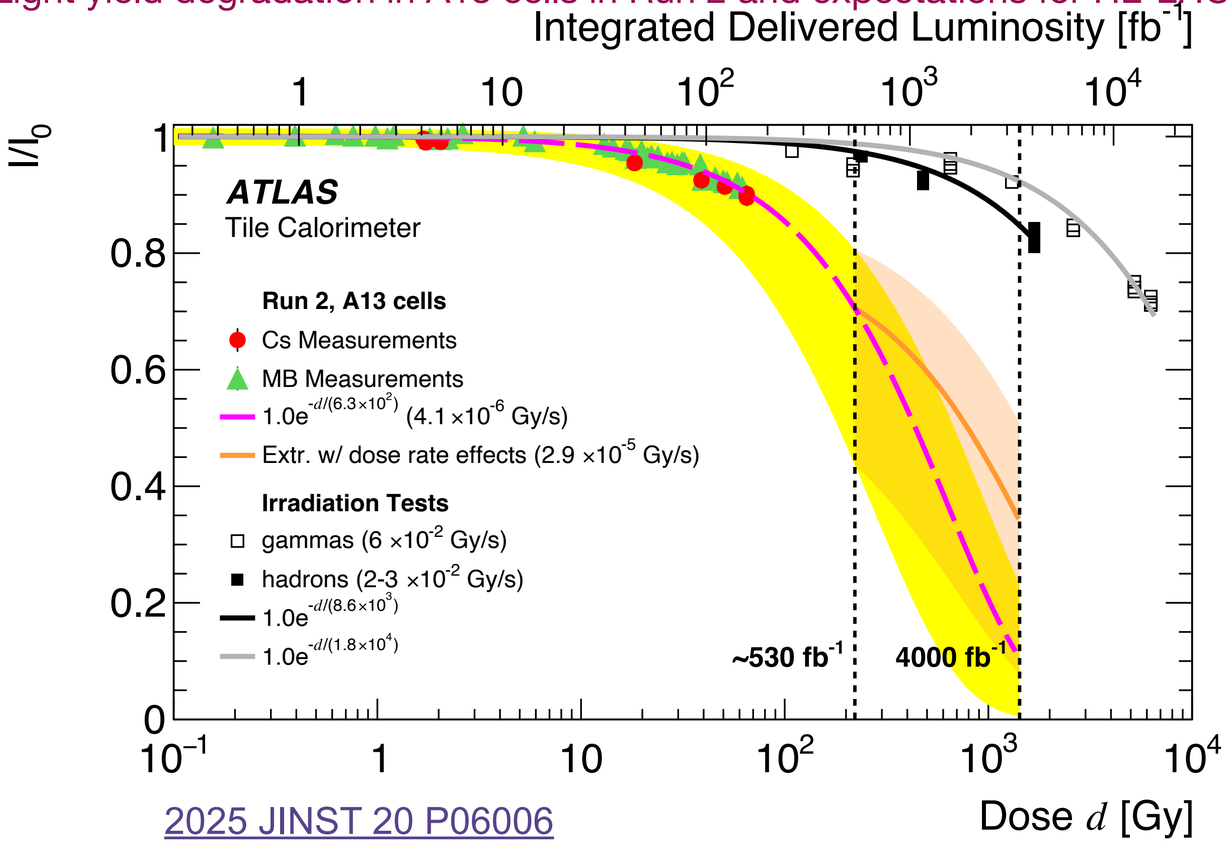
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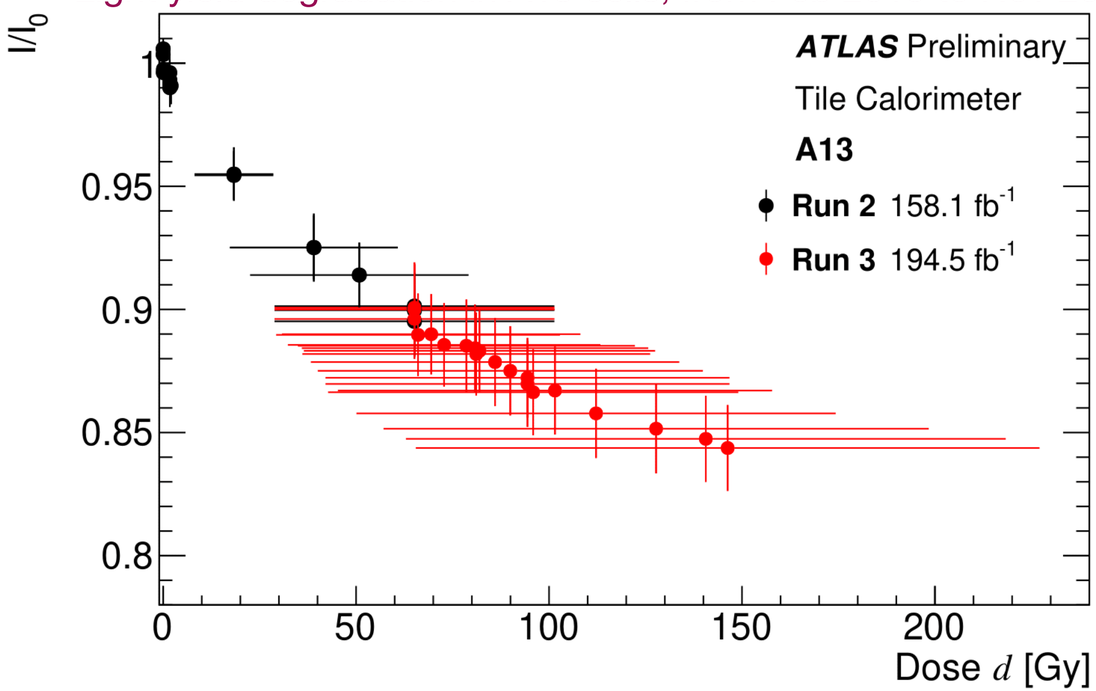
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Light yield degradation in A13 cells in Run 2 and expectations for HL-LHC



2025 JINST 20 P06006

Light yield degradation in A13 cells, from Feb 2015 to Nov 2024



Run 3 data extend the dose range and are being used to test **these projections.**

More on Radiation Hardness

[ref]

Light yield degradation in Run 2 + 2022-2024 Run 3 data

