ATLAS Tile calorimeter: Performance and upgrade for HL-LHC conditions

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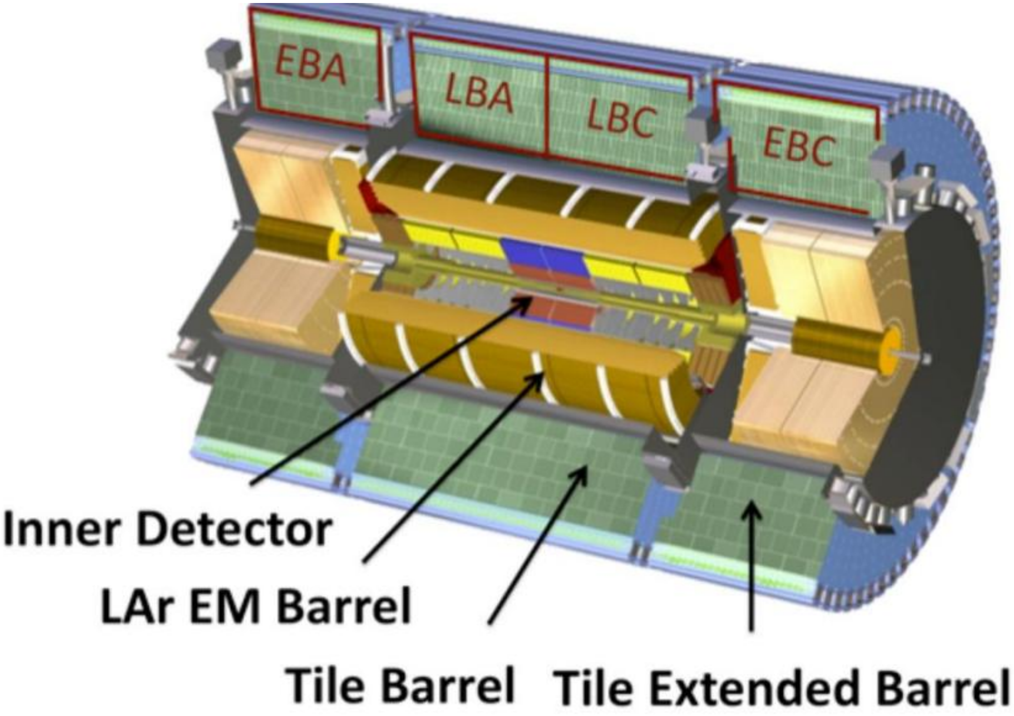
ATLAS Tile Calorimeter (TileCal)

- TileCal is the central hadronic calorimeter of the ATLAS experiment.

Dimensions
- Weight : 2900 T
- Length : 12 m
- External diameter: 8.5 m

- Sampling calorimeter consisting of passive (steel) and active (scintillating plastic) material
- Consists of a Long Barrel (LB) and two Extended Barrels (EBs)
- Readout is organized in four partitions
  - barrel is split in two partitions called LBA for η>0 and LBC for η<0
  - the extended barrel at η>0 (η<0) is called EBA (EBC)
- They are segmented along φ into 64 modules
- Aim for single hadron energy resolution:

$$\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$$



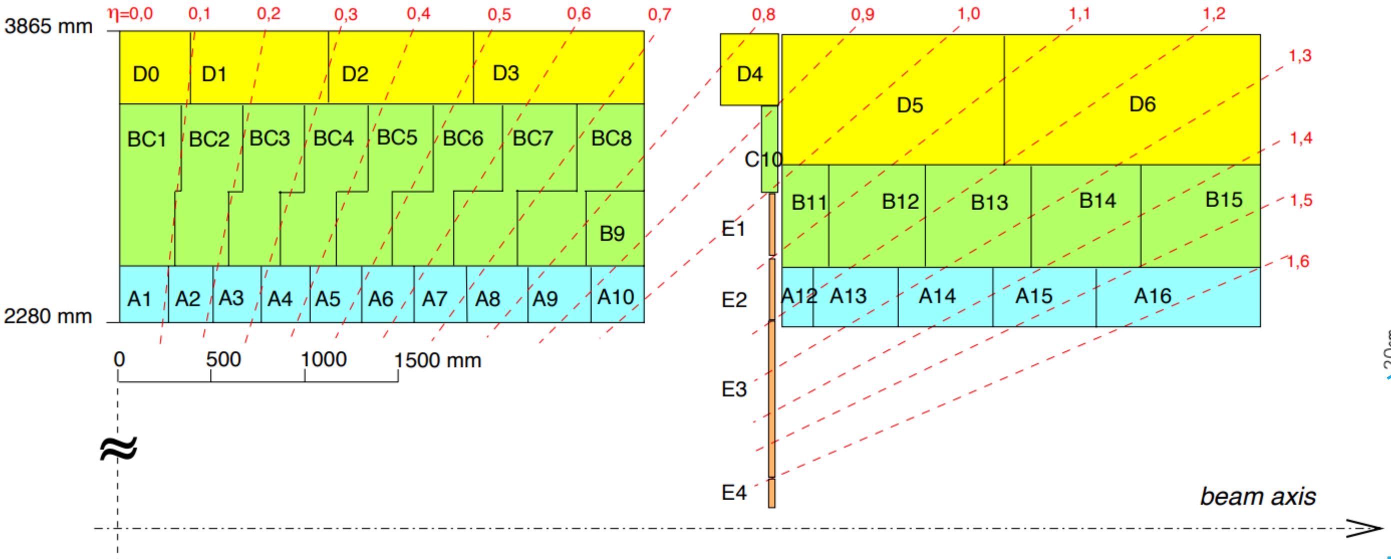
Basic Principle:
Measure light produced by the charged particles in the plastic scintillating tiles

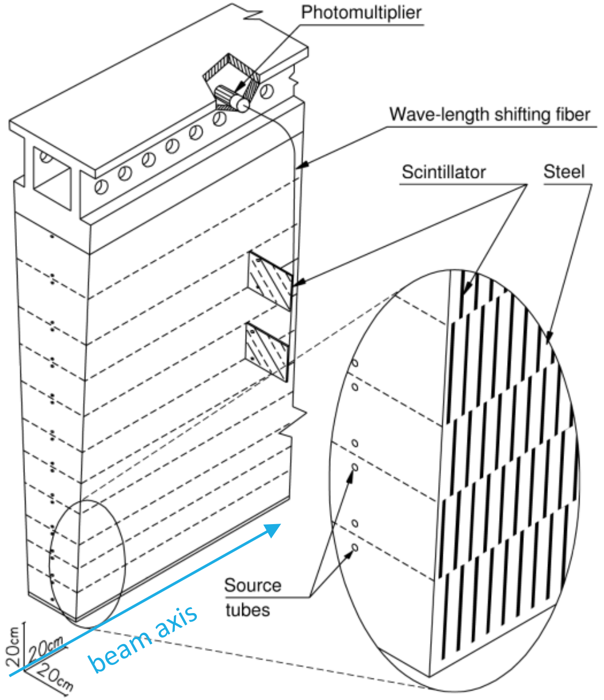
TileCal purpose:
Measurements of hadrons, jets, missing transverse energy as well as provide input signal to Level 1 calorimeter trigger

Tile Calorimeter Readout

- Every scintillating tile in 11 rows is readout by *wavelength shifting fibers*
- Fibers go along both sides of every module to outer radius and are grouped together to obtain *pseudo-projective geometry cells* in 3 layers
- Granularity $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ in first innermost two layers and 0.2×0.1 in outermost layer
  - number of scintillating tiles in one cell varies from 16 to 300
- TileCal has a total of 5182 cells:
  - each cell is readout by two Photomultiplier tubes (PMTs)
  - each module hosts up to 45 PMTs
  - total 9852 photomultipliers in 256 modules

Cells layout





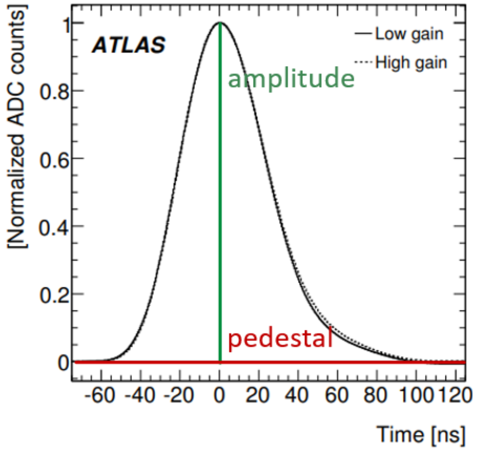
Mechanical assembly and optical readout of TileCal module

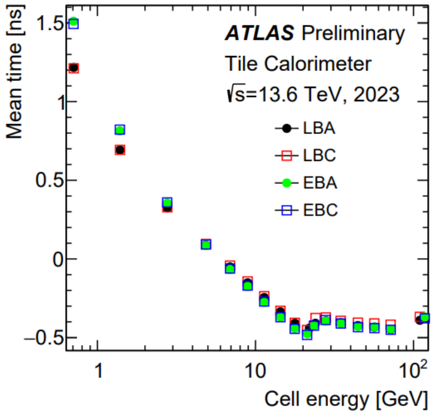
TileCal signal processing and calibration

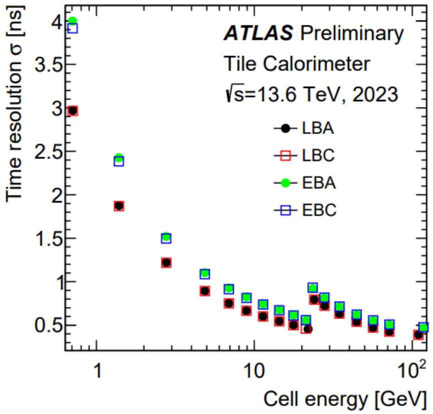
- Signal from PMT is passed to the on-detector electronics for shaping, amplification (2 gains 1/64 ratio) and digitization (10-bit ADC)
- Optimal Filter (OF) algorithm reconstructs Amplitude (A), Time (t) and Pedestal (P) of the signal from 7 consecutive 25 ns time samplings

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

- To allow optimal reconstruction, the time difference between the digitizing sampling clock and the peak of the PMT pulses must be minimized, measured and accounted for in the OF
- Timing is set using jets from proton-proton collisions and monitored during physics data







- Deposited energy is evaluated based on reconstructed amplitude in ADC counts and calibration coefficients provided by different calibration systems

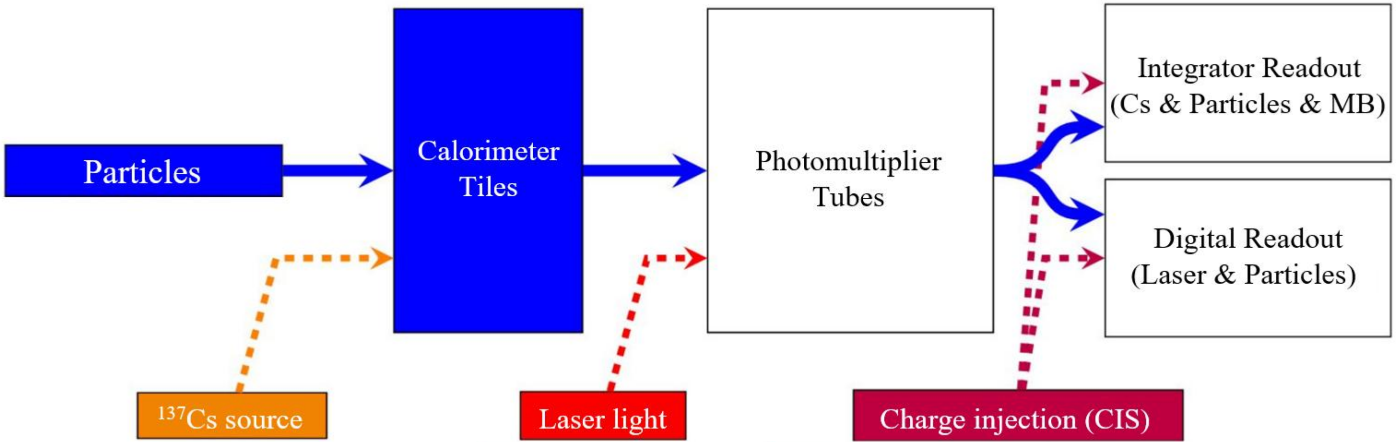
provided by calibration systems

$$E[GeV] = A[ADC] \times \boxed{C_{ADC\to pC} \times C_{Cs} \times C_{MB} \times C_{laser}} \times \boxed{C_{pC\to GeV}}$$

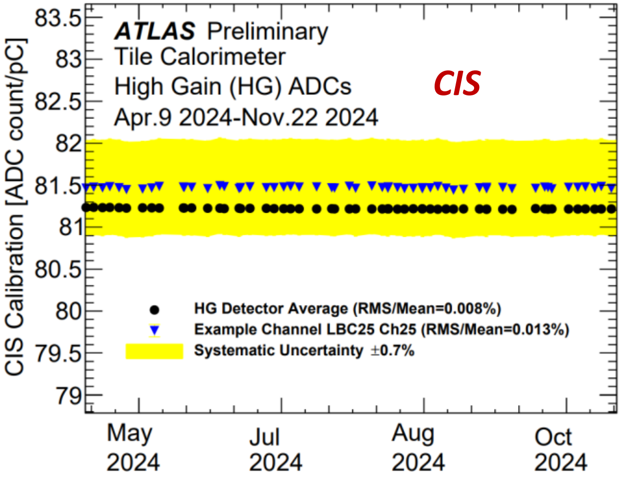
measured with electrons at test beams (EM scale)

TileCal calibration

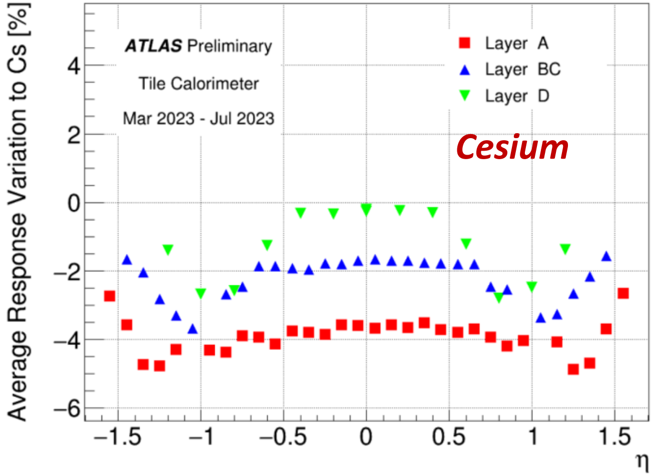
1. ***Charge Injection System (CIS) calibrates*** front-end ADCs by injecting pre-defined charge into readout chain
   - performed twice per week
   - monitors stability of electronic chain and measures the ADC/pC conversion factor
2. ***Cesium calibration*** is performed monthly using movable radioactive sources between physics runs
   - monitors all optic components stability
   - measures total drift in tiles/fibers/PMT, which allows to set correct EM scale
3. ***Laser calibration*** is performed by injecting monochromatic laser light into every PMT
   - done in daily calibration runs as well as in empty bunches during physics runs
   - allows to correct for PMT drift
   - it is used also for monitoring of synchronization between LHC clock and digitization time
4. ***Minimum Bias System (MB)*** measures the response of inelastic interactions with low energy transfer dominate LHC's collisions
   - measures PMT current during data taking and gives information about instantaneous luminosity
   - shares readout with the Cesium system and is used to calibrate E-cells, which can’t be calibrated with Cesium



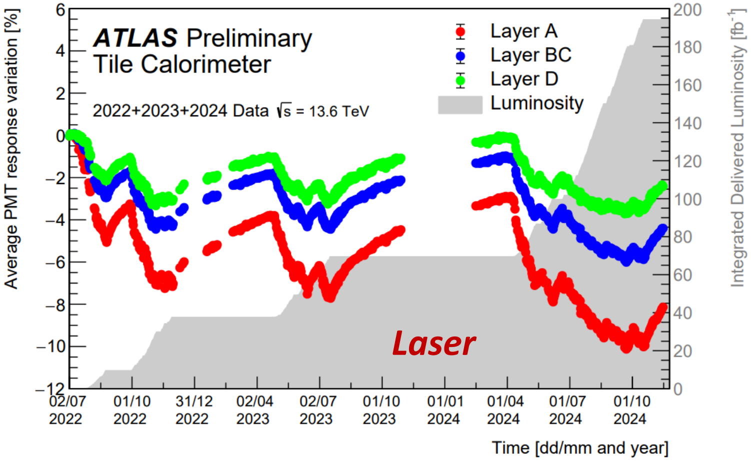
TileCal calibration



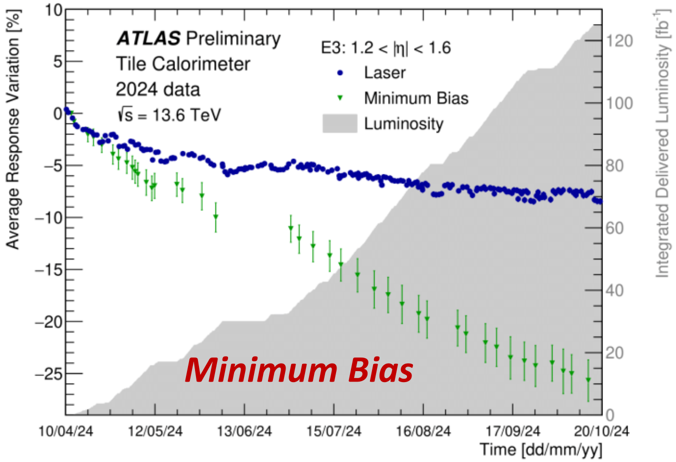
- ADC/pC conversion factor is very stable



- Degradation depends on the layer (larger for closest to the beam A-layer)



- PMT response decreases during data-taking periods, during technical stops partial recovery is observed



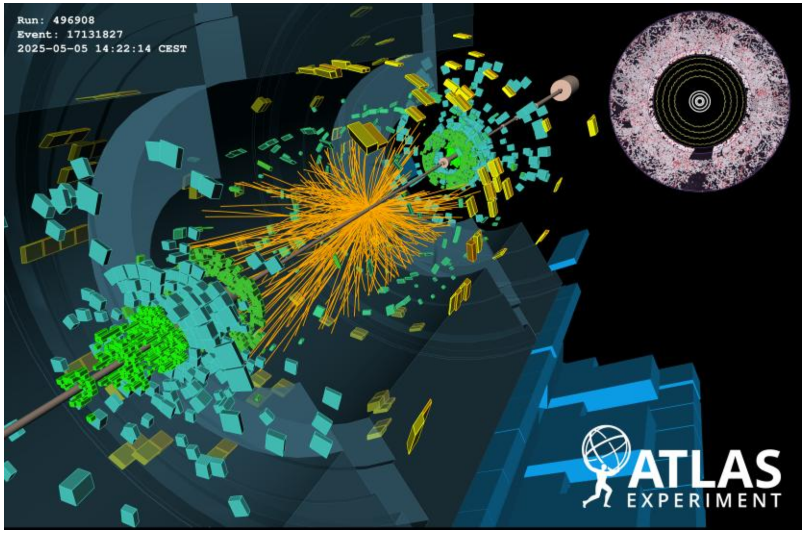
- Differences with laser are interpreted as a scintillator and wavelength shifting fibers aging due to irradiation

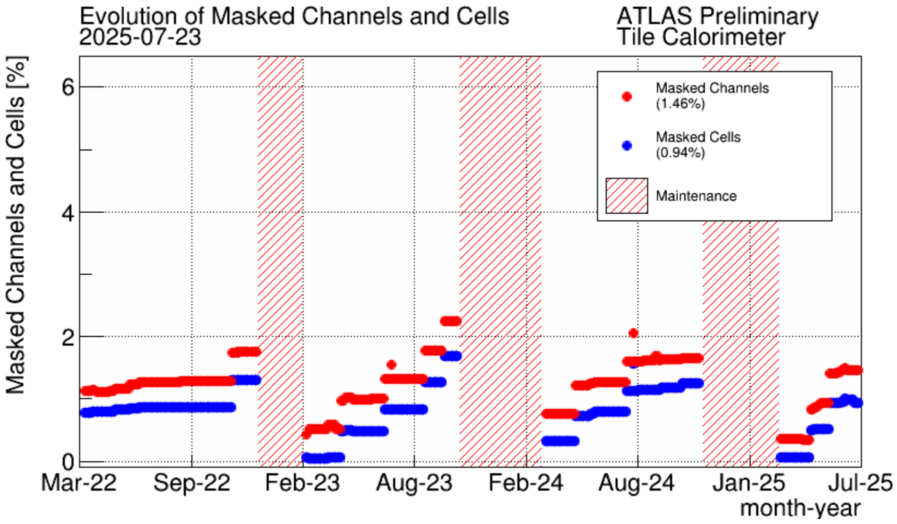
TileCal operation and Data quality

- ○ Dedicated infrastructure controls and monitors detector operations and parameters
- ○ Daily acquisition and data quality monitoring activities are performed
- ○ Long technical stops of the LHC after each data-taking year used to fix hardware issues
- ○ Number of bad channels is kept below ~2%, impact further reduced due to cell readout redundancy
- ○ Run 3 TileCal Data quality efficiency is **better than 99.3%** in proton-proton collisions

Data Quality efficiencies in pp collisions, %

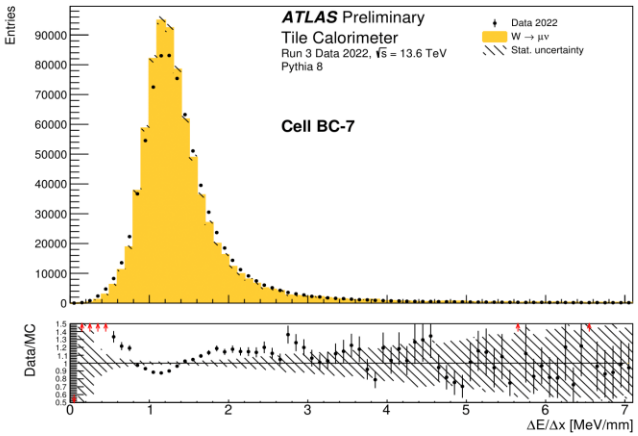
	2022	2023	2024
TileCal	99.7	99.6	99.3
ATLAS	93.1	94.6-96.5	93.8

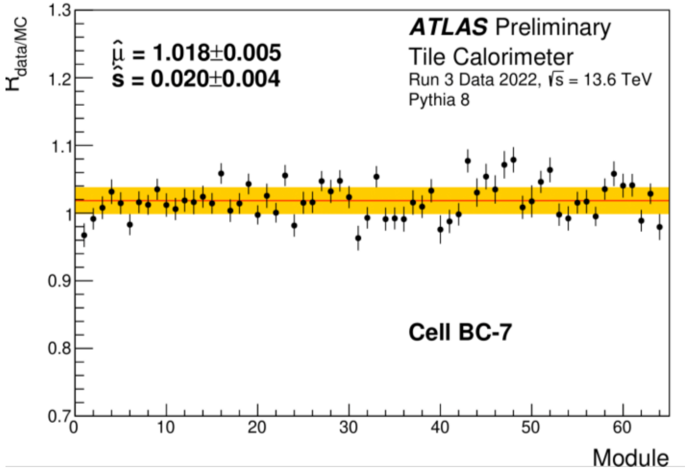




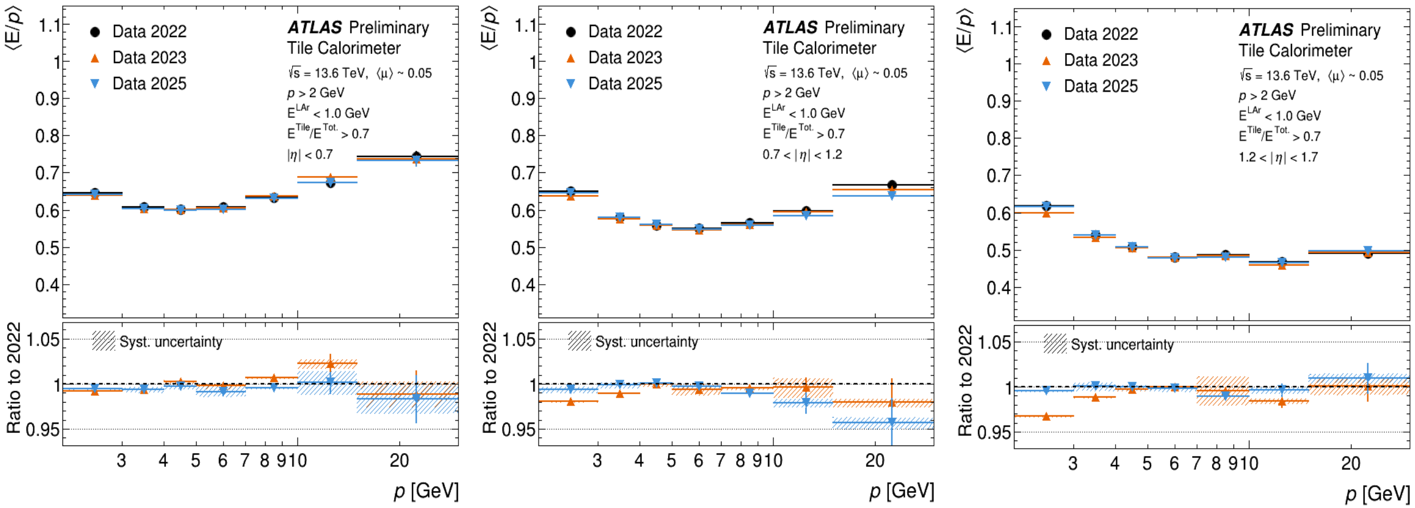
TileCal Performance: Single particle response

- ○ The response of muons from decaying W bosons verifies the stability, the uniformity and the scale of the cell energy measurements
    - ○ cell nonuniformity response: about 2%





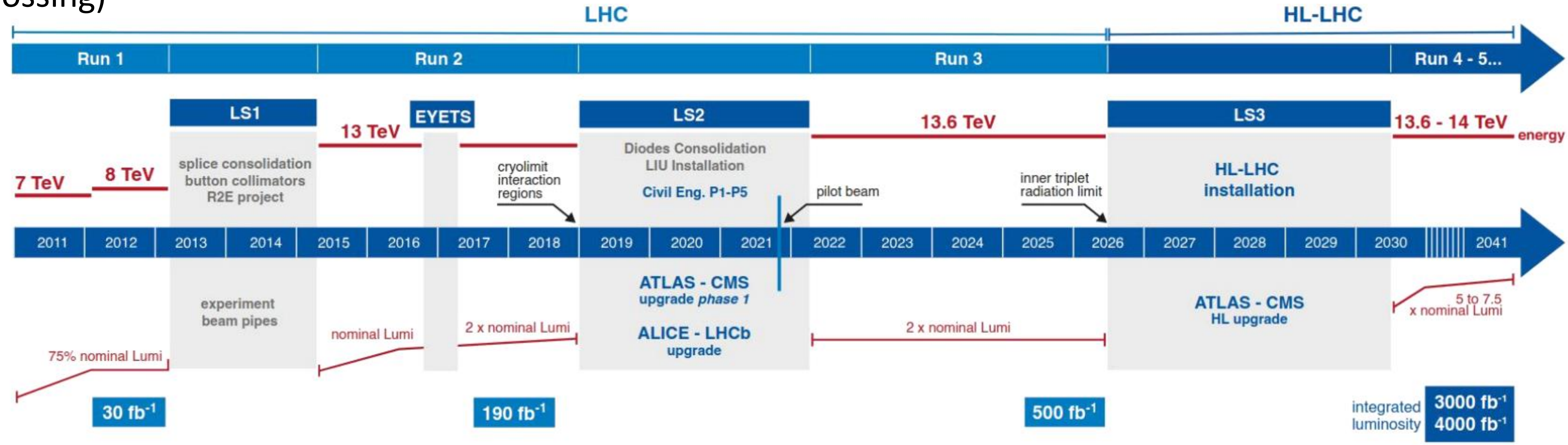
- ○ Isolated hadrons are used to compare the response to isolated hadrons at EM scale obtained using experimental and simulated data and check the stability
    - ○ detector response stability is observed (less than 3% difference between the years is observed)



E - calorimeter energy at EM scale; p - track momentum measured by ATLAS inner detector system

The TileCal HL-LHC upgrade

- ○ The High-Luminosity LHC will start after Long Shutdown 3 (2026 - 2030)
- ○ HL-LHC aims to deliver up to 4000 fb^{-1} of integrated luminosity
- ○ Instantaneous luminosity will increase by a factor of 5 to 7.5 (up to 200 proton-proton collisions per bunch crossing)



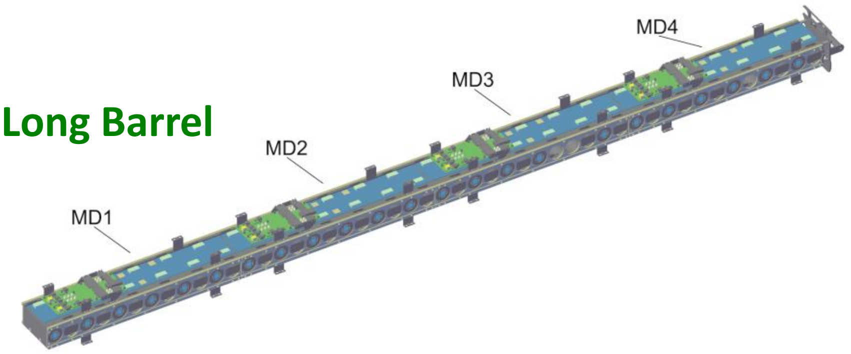
- ⇒ Significant challenges for detectors: higher radiation doses, increased data rates, stricter timing and trigger requirements
- ⇒ Full electronics replacement, both the on- and off-detector
- ⇒ 10% of the PMTs replacement associated to the most exposed cells
- ⇒ Data readout redundancy to improve system stability
- ⇒ New low voltage and high voltage power supplies systems due to higher radiation requirements
- ⇒ Three-stage low voltage power system for improved noise performance, reliability, and radiation tolerance
- ⇒ Improved radiation tolerance, simplified maintenance and easier access for high voltage power system
- ⇒ Upgrade of the calibration systems

Readout architecture of HL-LHC TileCal

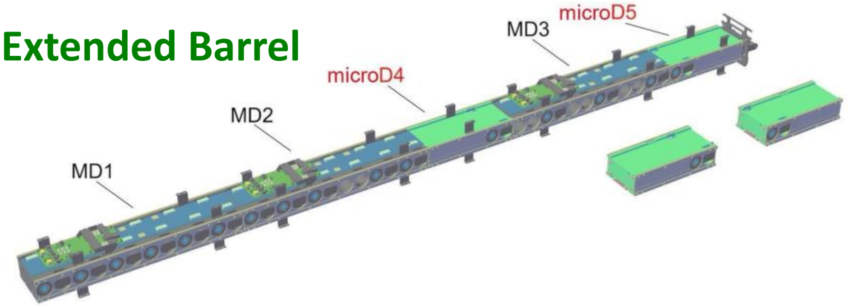
- New modular mechanics : 4 mini-drawers for LB or 3 mini-drawers + 2 micro-drawers for EB
- The on- and off-detector electronics replacement allows the signal reconstruction at 40 MHz for all cells
- HL-LHC face higher radiation levels. Existing readout electronics is ageing and not designed for such radiation levels
- Current architecture incompatible with fully digital Trigger and Data Acquisition (TDAQ) system, operating at 40 MHz readout rate
- In the new architecture, data need to be reconstructed at 40 MHz, and will be sent to the trigger systems. New front-end must match timing and data flow requirements

New modular mechanics

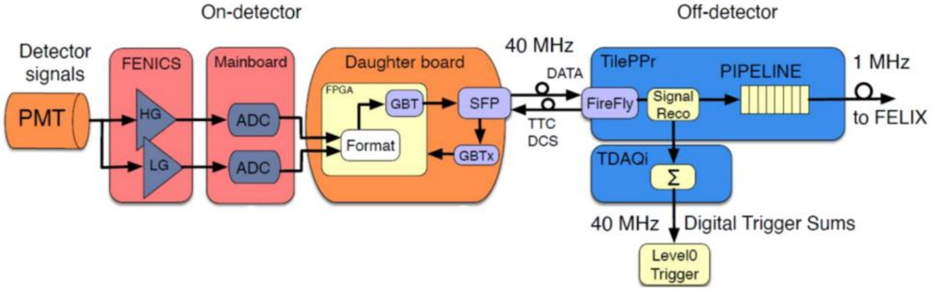
Long Barrel



Extended Barrel



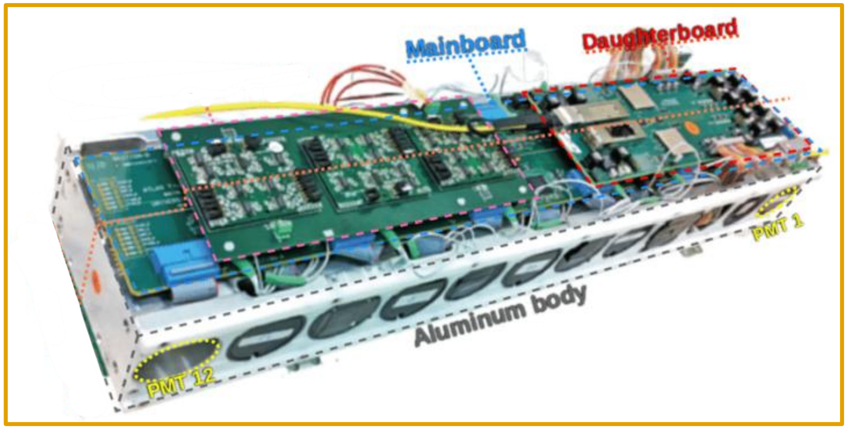
New readout



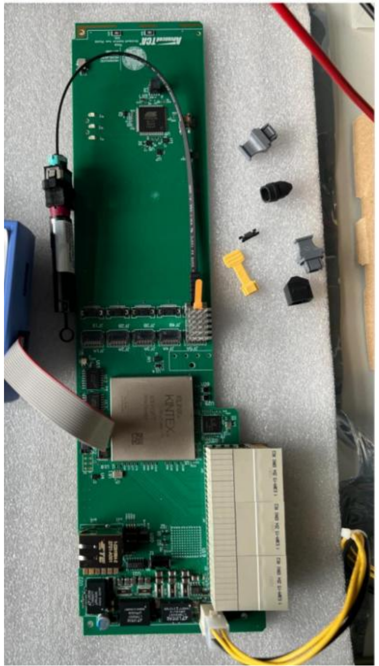
Electronics layout of the HL-LHC TileCal

- **Mini-drawer** hosts 12 PMTs, 12 Front-End Boards named FENICS, 1 MainBoard and 1 Daughterboard
- **FENICS card** performs signal shaping and amplification (2 gains, Low Gain (×0.4) and High Gain (×16). Dynamic range: 0.2 pC to 1000 pC)
- **MainBoard** digitizes signals from up to 12 FENICS two-gain outputs at 40 MHz with 12bit ADCs
- **Daughterboard** transfers bi-gain output from 6-12 PMTs every 25 ns to the back-end via 4 x 9.6 Gbps links, distributes LHC clock settings, liaise the on- and off-detector electronics
- **Tile Preprocessor (Tile PPr):** real time data processing and signal reconstruction at the full 40 MHz rate; storage of up to 10 μs of data samples in pipelines; distributes the sampling clock and detector control information
- **Trigger and Data Acquisition interface (TDAQi)** compute trigger objects, send them to trigger system, sends accepted data to the **Front End LInkeXchange**

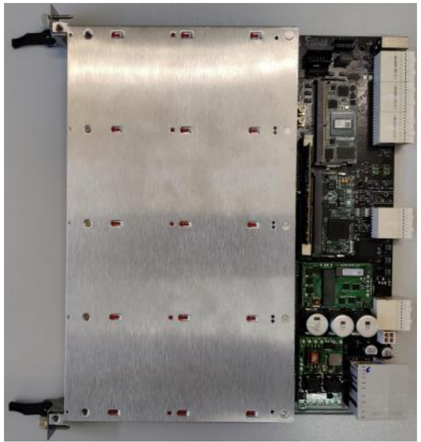
Mini-drawer



TDAQi



Tile PPr



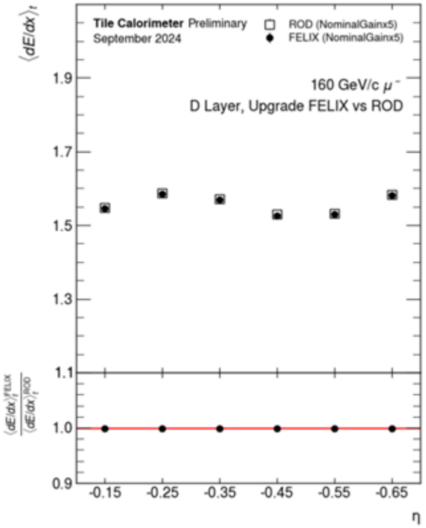
TileCal test beam

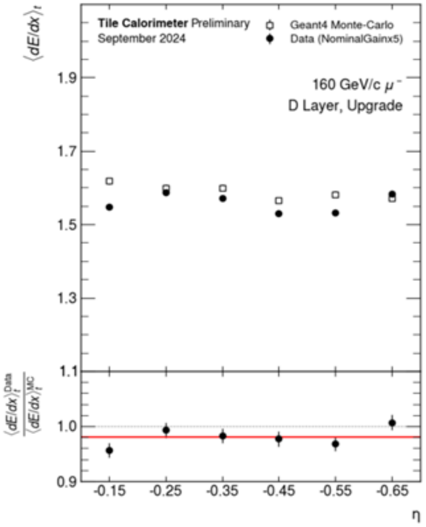
- ○ TileCal test beam aims at validating upgraded electronics and readout system with beam data as well as performing other physics studies
- ○ Last campaign has successfully finished in July 2025
- ○ Three layers stack with ***2 barrel modules and an extended barrel module***
- ○ Modules are partially equipped with prototypes of ***Phase-II electronics***
- ○ The set-up was exposed ***to electron, muon, and hadron beams over a wide energy range*** from H8 beam line of the CERN SPS North Area
- ○ ***Different module orientations*** used to study performance across configurations

Test Beam selected results

Muons

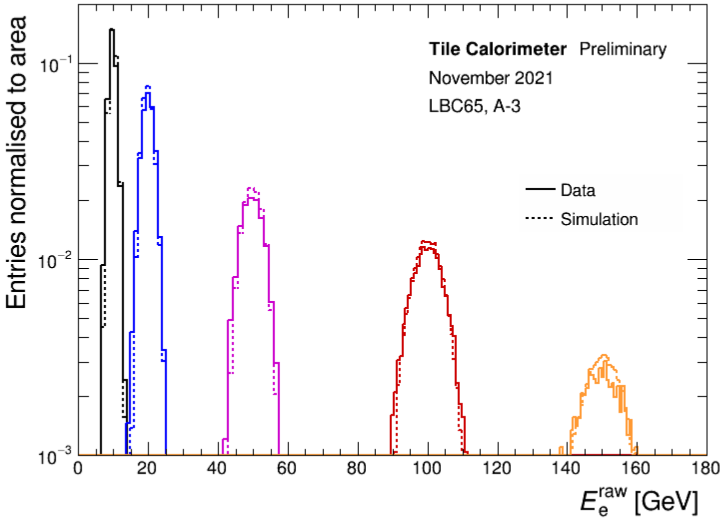
- Studies of projective muons with energy 160 GeV show:
  - Good agreement between legacy ReadOut Driver (ROD) and Upgrade Front End LInkeXchange (FELIX) readout systems
  - Average offset of 2% between Data and Monte-Carlo simulation based on GEANT4





Electrons

- Studies of electrons with energies 10, 20, 50, 100 and 150 GeV show:
  - Less than 1% disagreement with simulation for electron total measured energy (verifying mean energy)
  - Total measured energy agree well with energy of electron beam (non linearity smaller than 1%)

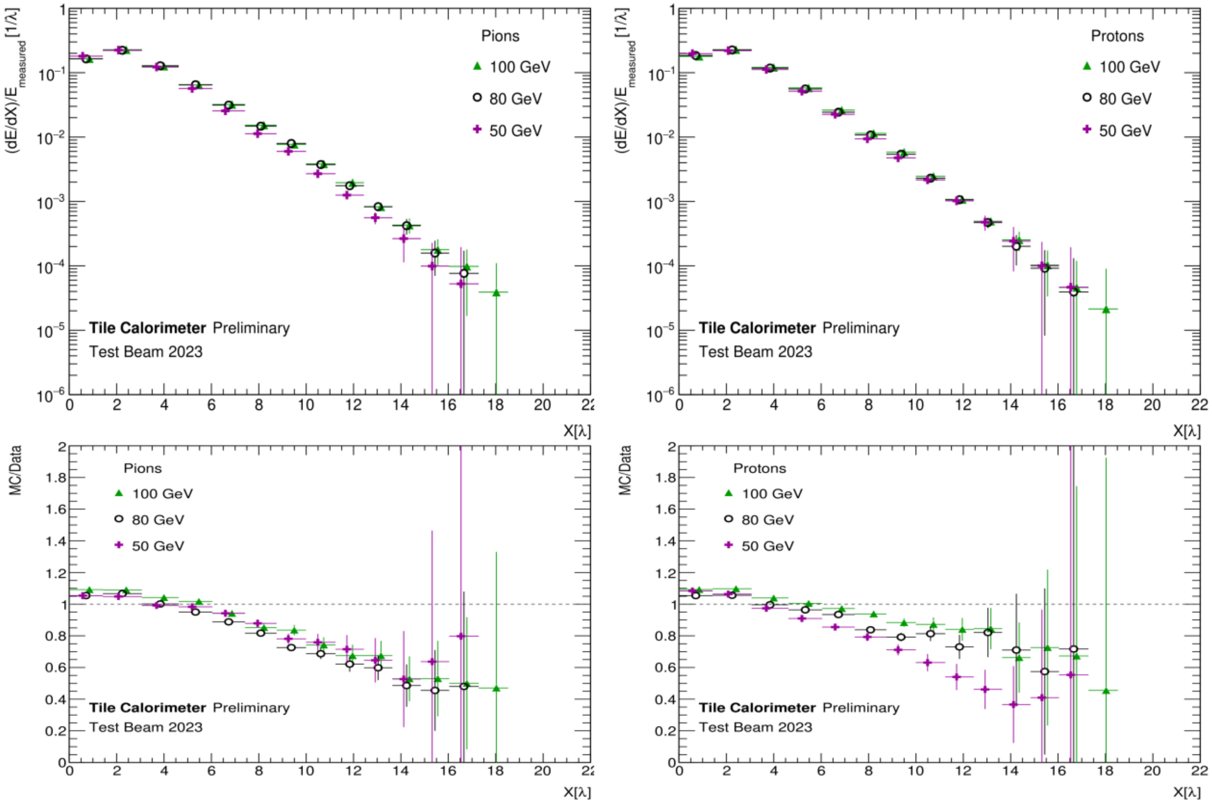


Test Beam results: hadronic shower profile

- *The test beam setup, when used in the 90˚ configuration, provides containment for approximately 20 interaction lengths and offers unique opportunities for longitudinal developmental studies*
- Protons and pions in hadronic beam were selected using Cherenkov counters
- λ corresponds to effective nuclear interaction length counted for pions in sampling calorimeter with 14 mm thick iron and 3 mm thick scintillator. λ equals to 20.55 cm
- Total uncertainty includes statistical and systematic effects. Systematic uncertainties dominate over statistical

Observations:

1. Longitudinal shower development differs in data and Monte-Carlo simulation based on GEANT4
2. Difference found between proton and pion modeling: Data/Monte-Carlo ratio behavior is similar for pions at different energies, but for protons high energy showers are modeled better than low energy showers



New results, never presented before

Conclusions

- TileCal is performing very well during RUN-3 (2022-2026)
  - Calorimeter routinely calibrated
  - Response to single particles and jets agrees with Monte-Carlo simulation based on GEANT4

- TileCal will undergo an upgrade for HL-LHC
  - HL-LHC aim: collecting up to 4000 fb^{-1} of integrated luminosity by the end of HL-LHC data-taking
  - Main challenges: higher radiation levels, increased readout rates, challenging pile-up conditions.
    - All on- and off-detector electronics will be replaced with radiation-hard and fully digital electronics, and fully digital electronics, respectively
    - Around 10% of PMTs will be replaced with newer, more stable models
    - New mechanical structure and modular services, easier to handle and maintain

- Test beam campaigns are performed regularly to validate the system, calorimeter performance and carry out other analyses of calorimeter physics (e.g. shower shape studies, measurement of photonuclear interactions of muons in iron)

Back-Up

Reference links to public plots

[1] Readiness of the ATLAS Tile Calorimeter for LHC collisions

[2] Charge Injection System (CIS) Calibration Plots

[3] Run 3 Cesium public plots

[4] Run 3 Laser public plots

[5] Single Particle Response public plots

[6] Run 3 Timing calibration

[7] TileCal TestBeam public plots

[8] TDR for the Phase-II Upgrade of the ATLAS TileCal

TestBeam results: hadronic response

- Analysis performed at TileCal TestBeam in 20˚ configuration, beam enters LB module
- Separation of particles of different types is possible thanks to upstream Cherenkov counters
- MC simulations agree well with experimental data