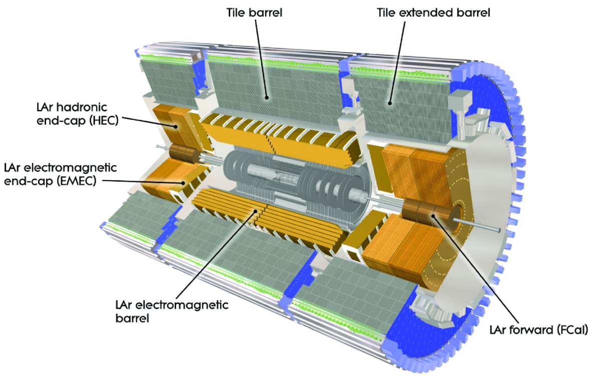
Performance and upgrade of the ATLAS Hadronic Tile Calorimeter

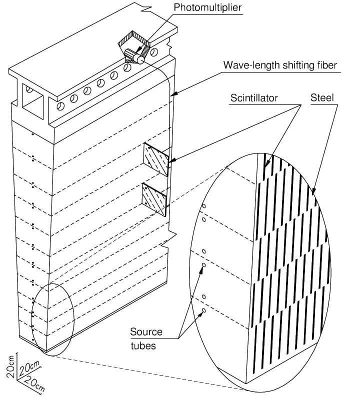
J. Faltova (Charles University)
on behalf of the ATLAS Collaboration

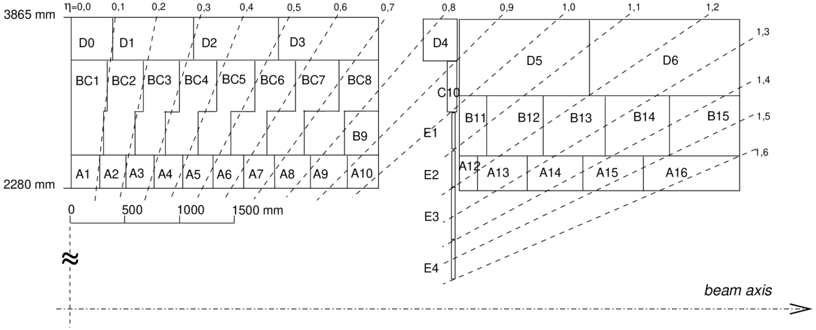
EPS-HEP 2025, 7-11 July 2025

ATLAS Tile Calorimeter

- Tile Calorimeter (**TileCal**) is a **central hadronic calorimeter** of ATLAS covering $|\eta|<1.7$
- **Sampling calorimeter** with steel absorber plates and scintillating tiles
- Long barrel and two endcaps divided into four read-out partitions, each composed of 64 modules
- Optical signal from scintillator collected on both sides by wavelength shifting fibers and transmitted to photomultipliers (PMTs)
- Total of **5182 cells** (three radial layers, cell sizes $\Delta\varphi$ x $\Delta\eta \approx$ 0.1 x 0.1-0.2)





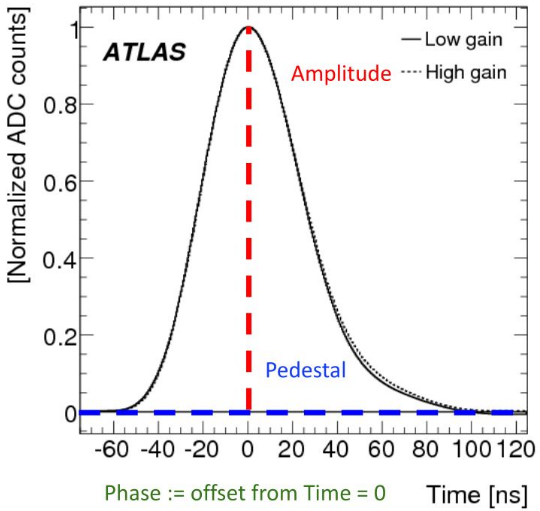


Signal reconstruction

Signal sampled every 25 ns, Optimal Filtering used for reconstruction of the signal amplitude (*A*) and phase (*t*)

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

S_i : sample *i* readout



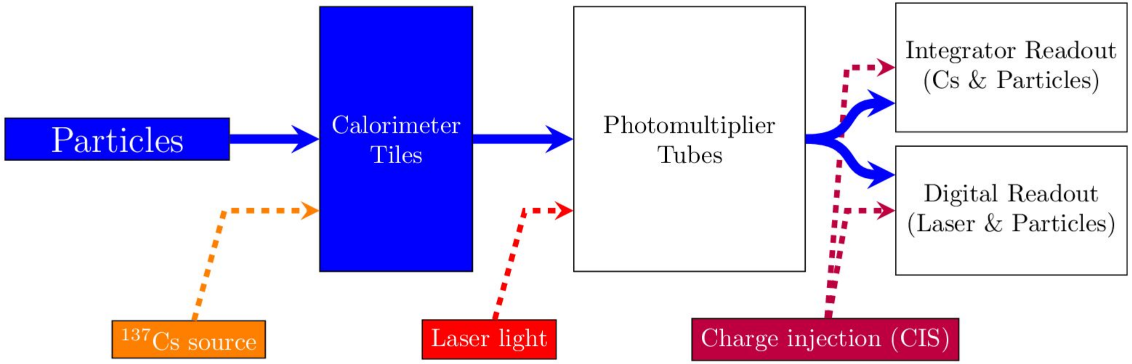
Signal amplitude (*A*) calibrated to the electromagnetic scale (E_{reco}) with dedicated calibration systems

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

Calibration and performance

Calibration systems

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



Charge injection (CIS): Monitoring and calibration of the front-end electronics, conversion factor from ADC to pC

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

Laser: Laser source located 100 m from the detector, monochromatic light delivered to all TileCal PMTs, Monitoring and equalization of the PMT response

JINST 18 (2023) 06, P06023

Cesium: Capsule with ^{137}Cs travels through the TileCal cells, read-out with an integrator chain (10 ms), monitoring of the whole optical chain

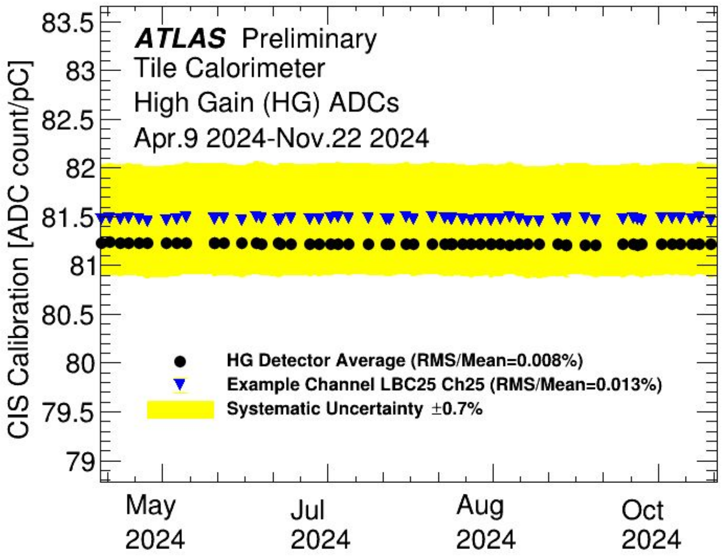
JINST 15 (2020) P03017

Minimum Bias currents: Read-out of the collision events with the integrator chain, calibration of cells not accessible with Cesium (cells in the gap region)

Calibration systems: Run 3 results (I)

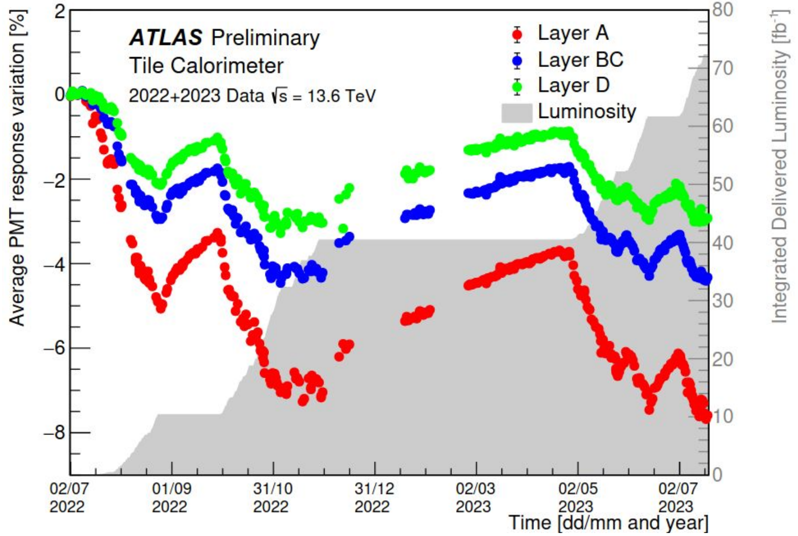
CIS

- Very stable response in time
- Precision of 0.7%



Laser

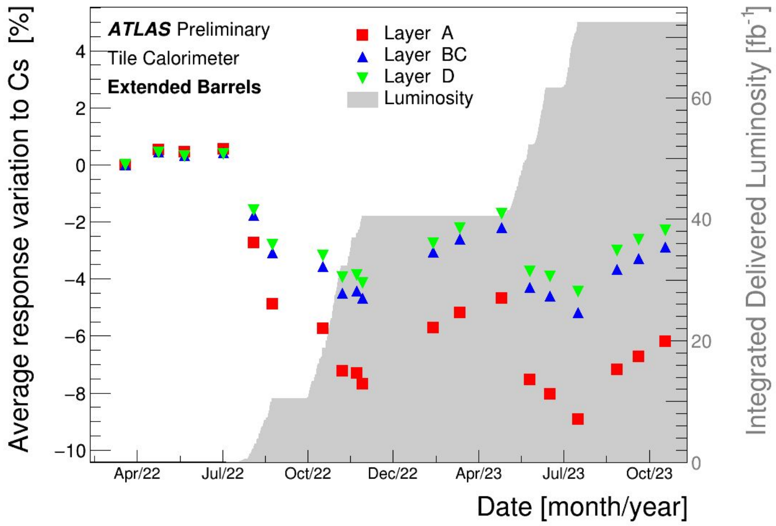
- PMT gain degradation during LHC *pp* collisions
- Precision of 0.5%



Calibration systems: Run 3 results (II)

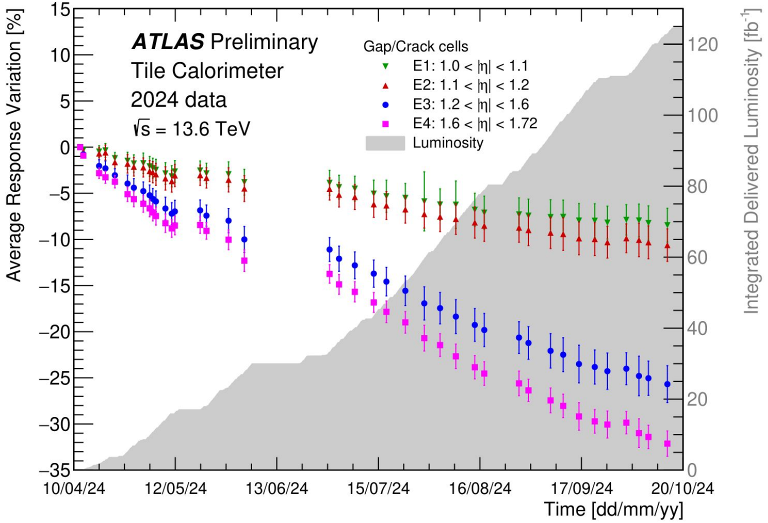
Cesium

- Response decreases during LHC *pp* collisions
- Precision of 0.3%



Minimum Bias

- Large decrease of response for cells in the gap/crack region



Performance studies

Calibration of the detector and uniformity of the response tested with **isolated muons originating from W →μν decays**

- Truncated mean of deposited energy in the cell (*ΔE*) per path length (*Δx*) as an estimator

Response to **isolated charged hadrons** studied using ratio of energy deposited in TileCal (*E*) and momentum measured in the inner detector (*p*) [Eur. Phys. J. C 84 (2024) 1313]

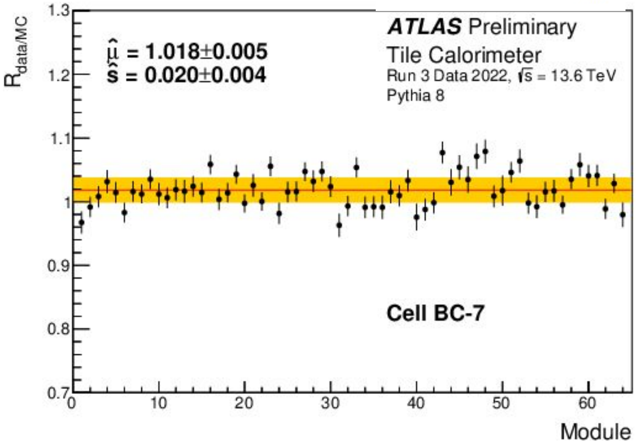
- Analysis using *pp* Run 2 data with low pile-up published, Run 3 analysis is ongoing

Cell time resolution derived using cells associated to jets from *pp* collisions

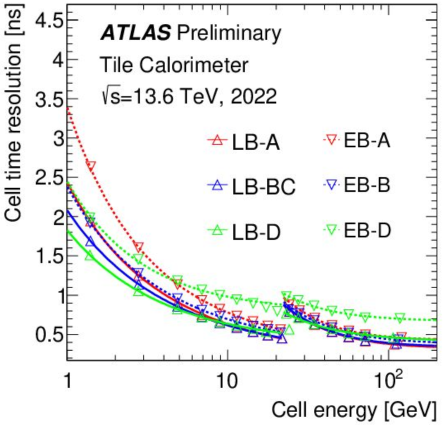
- Precision better than 1 ns for energy deposits larger than 4 GeV in most of the cells

Muons

$$R = \frac{(\Delta E/\Delta x)_{\mathrm{data}}}{(\Delta E/\Delta x)_{\mathrm{MC}}}$$



Cell timing



Ageing of the detector

Degradation of the optical components

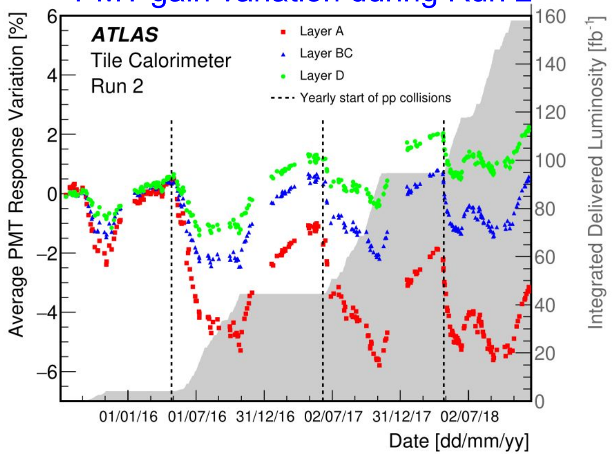
- **PMT gain** decreases with increasing light exposure
- **Scintillators and wavelength shifting fibers (WLS) ageing** degradation with accumulated dose evaluated by comparing changes in response measured with Cesium and laser
  - Results obtained during Run 2 extrapolated to the end of Run 3 and end of HL-LHC operation

$$I/I_0 = \frac{\Delta R_{\mathrm{Cs}}}{\Delta R_{\mathrm{Las}}}$$

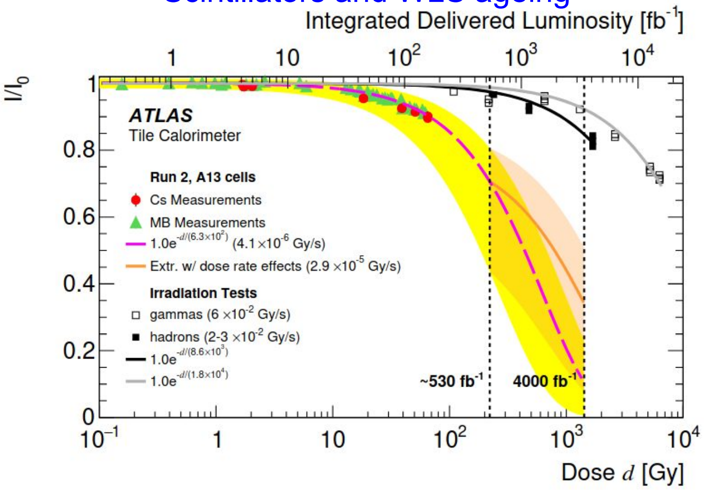
NEW: 2025 JINST 20 P06006

- *Note*: Loss of gain is compensated by **adjusting the HV of the PMTs**, individually

PMT gain variation during Run 2



Scintillators and WLS ageing



Upgrade for HL-LHC

TileCal upgrade for HL-LHC

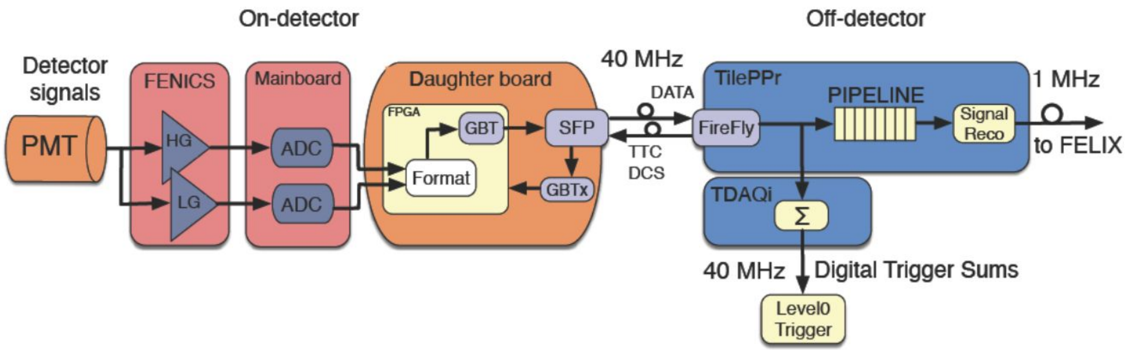
High-Luminosity LHC (HL-LHC) will run with instantaneous luminosity 5-7 times larger compared to LHC

- Challenges: High radiation doses, increased data rates, changes in trigger architecture

Main upgrades in TileCal

- Complete replacement of on and off-detector electronics
- 40 MHz read-out, digitization and signal reconstruction
- Improved reliability and maintainability

ATLAS-TDR-028



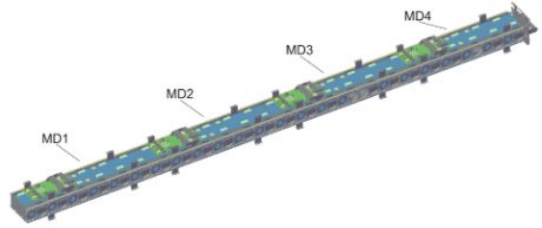
Mechanics & PMTs

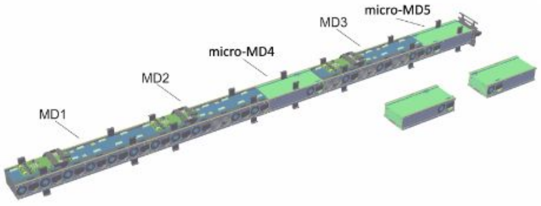
Drawers

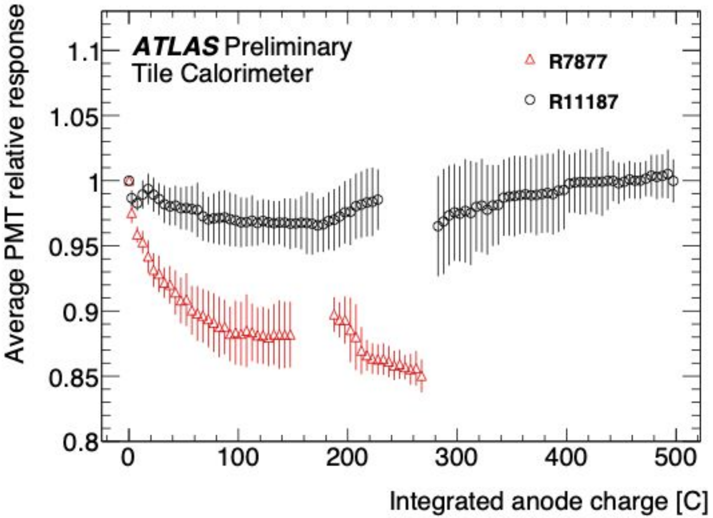
- PMTs and on-detector electronics located on so-called “drawers”
- New design with 4 mini-drawers (MD) per module in the long barrel, 3 MDs with 2 micro-drawers in the extended barrel for easier maintenance
- Failure of any component will result in a loss of no more than 6 PMTs

PMTs and active dividers

- Replacement of most exposed PMTs
- New high voltage active dividers in all PMTs to enhance stability at high anode currents







On-detector electronics

FENICS

- Shaping of the PMT pulse, bi-gain amplification (1:40), charge injection, current integration
- FENICS ADCs with 12 bits (10 bits used in Legacy)

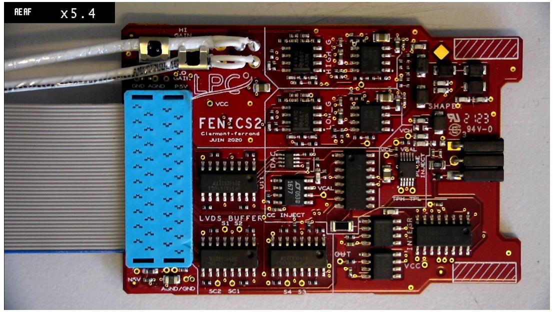
Mainboard

- Digitization of FENICS outputs, control for FENICS
- Connection to DaughterBoard

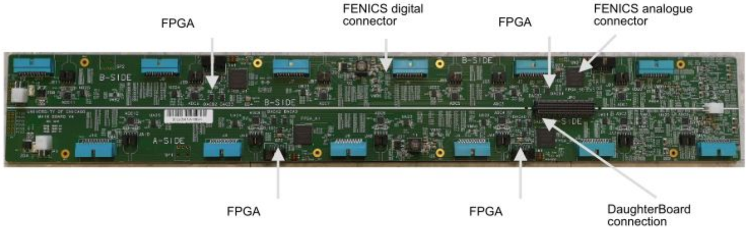
DaughterBoard

- Send digitised data to the off-detector electronics via optical links
- GBT protocol at 9.6 Gb/s, using SFP+
- Kintex Ultrascale FPGA

FENICS



Mainboard



DaughterBoard

Off-detector electronics

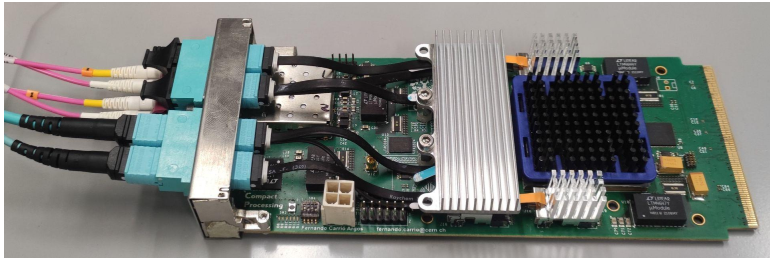
Compact Processing Module (CPM)

- Transforms the raw data into deposited energy for up to 90 channels at 40 MHz on a Kintex UltraScale (KU115)
- Processes data from 2 modules, connection of modules to Front-end

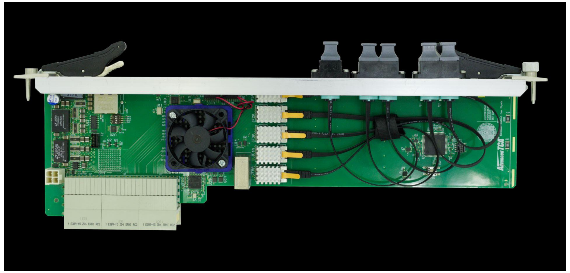
Trigger DAQ interface (DAQi)

- Receives the cell energies from 4 CPMs synchronously
- Produces primitives for ATLAS Level 0 triggers
- Sends the calorimeter data to the FELIX system

Compact Processing Module (CPM)



Trigger DAQ interface (DAQi)



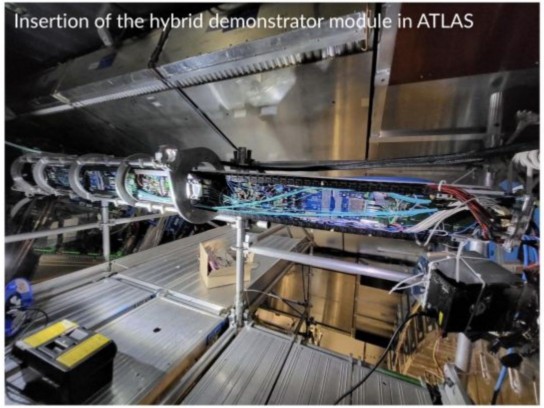
Testing the upgraded electronics

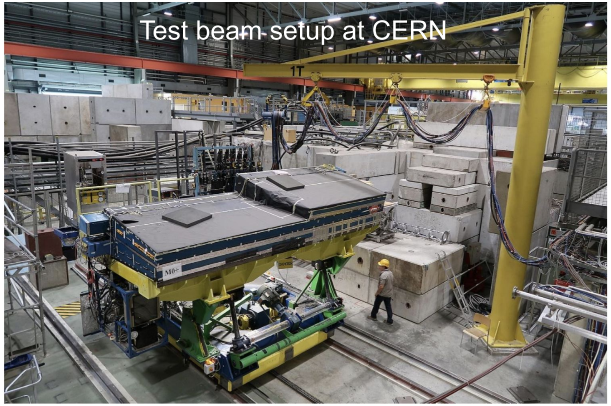
Prototype with upgraded electronics (demonstrator) inserted in TileCal long barrel in 2019

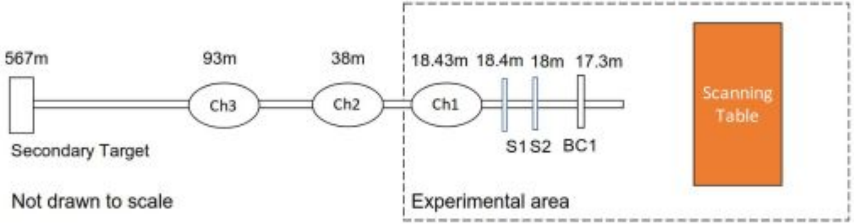
- Hybrid mode: Read-out using new digital path, but analog trigger signals provided to the legacy system
- Module fully integrated and collecting data during Run 3

Regular beam tests at CERN North Area since 2015

- Some of the modules with upgraded electronics, others with legacy
- Beams of electrons, muons and hadrons at various energies and under different directions







Selected results from the beam tests

Electrons

- Normalised average response as a function of beam energies (10 to 100 GeV)
- Electron beam incident at θ = 20° (electromagnetic scale definition)

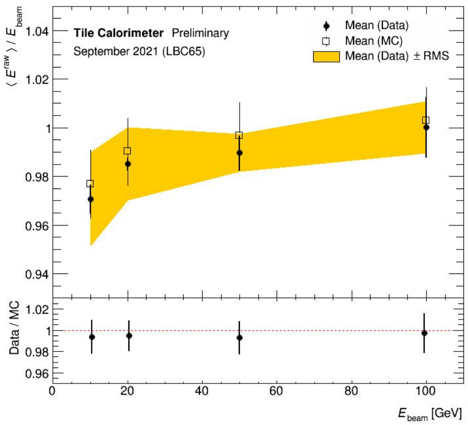
Muons

- Truncated mean of deposited energy per path length as a function of pseudorapidity in individual calorimeter layers

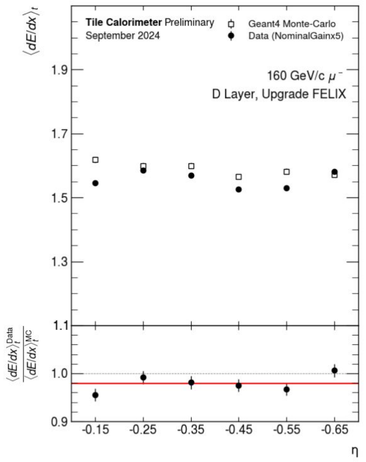
Hadrons

- Longitudinal shower profiles for pions and protons
- Geant4 (version 10.6.3) with FTFP_BERT_ATL physics list

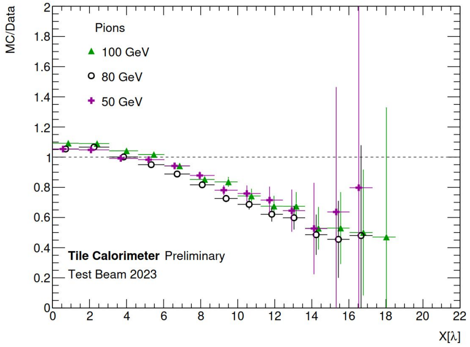
Electrons



Muons



Pions



Conclusions

TileCal operates well during LHC Run 3

- Excellent performance of the detector system, less than 1% of cells not usable for physics
- Detector response is regularly calibrated
- Performance studies with Run 3 data ongoing

Upgrades of the TileCal for HL-LHC processing well in time

- Demonstrator prototype operating successfully during LHC Run 3
- Beam tests confirmed good performance of the upgraded electronics, good agreement between data and Monte Carlo