The ATLAS Tile Calorimeter performance and its upgrade towards the High-Luminosity LHC

Ammara Ahmad
(On behalf of the ATLAS Collaboration)

Lomonosov Conference on Elementary Particle Physics
19-25 August 2021

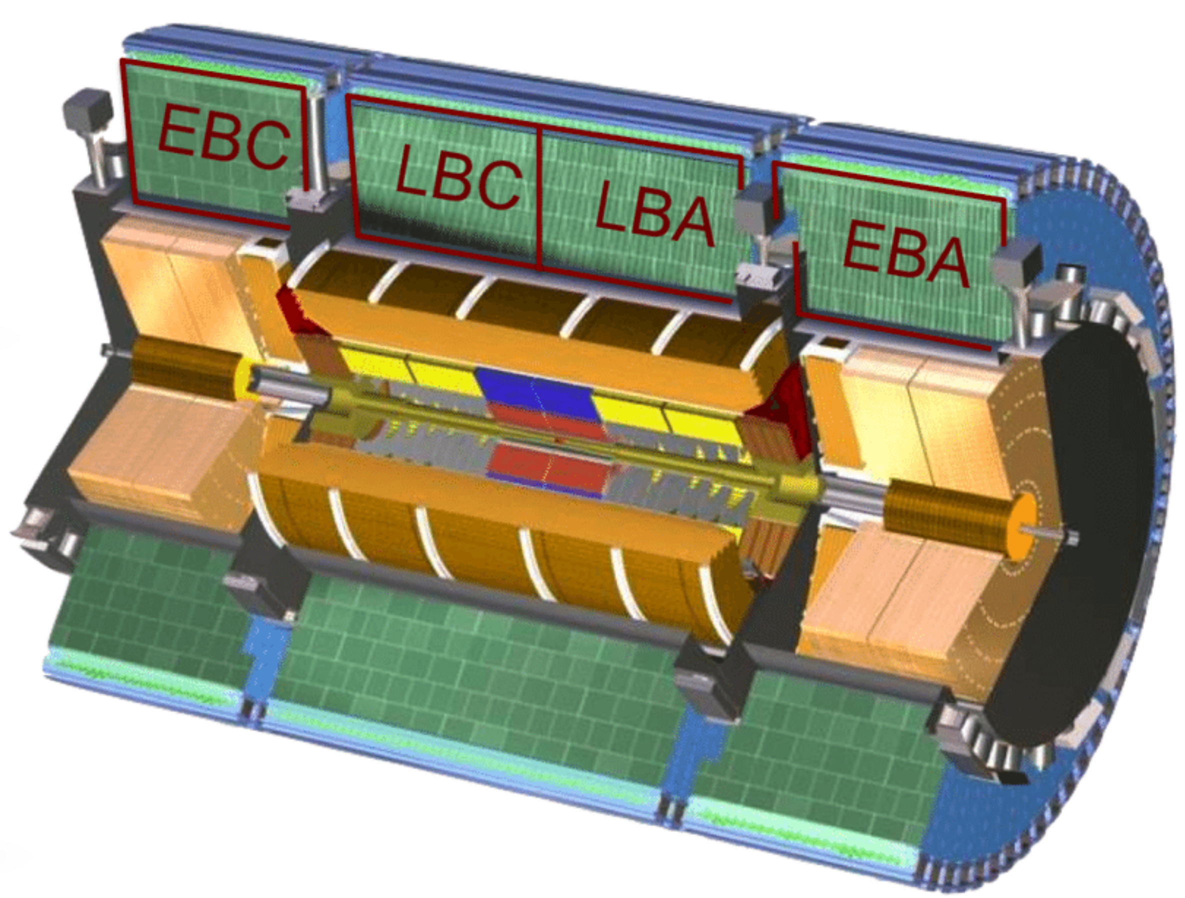
Institut de Física d'Altes Energies

The ATLAS Tile Calorimeter

- The Tile Calorimeter (TileCal) is the central hadronic calorimeter of the ATLAS experiment.
- Composed of layers of steel as absorber medium interleaved with layers of scintillators as active medium.
- The TileCal has four longitudinal sections (two central and two extended barrels), each containing 64 modules.

Dimensions
- Weight : 2900 T
- Length : 12 m
- Diameter: 8.5 m

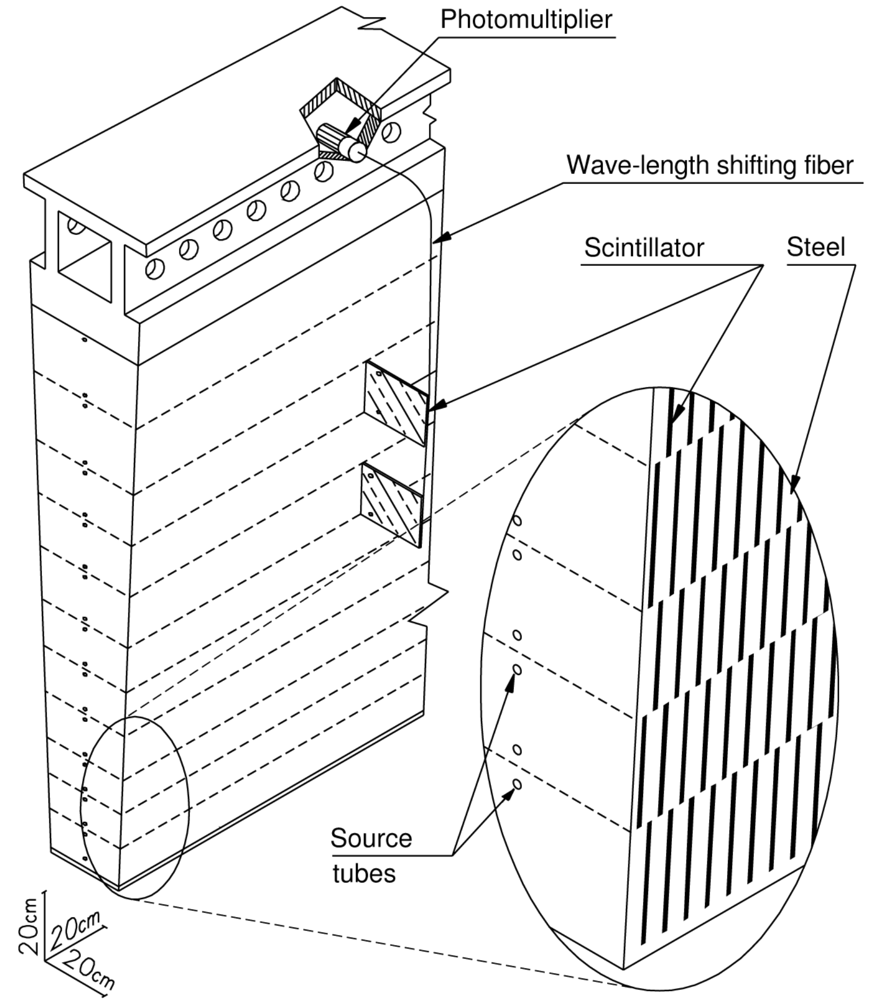
Basic Principle
- Measure light produced by the charged particles in plastic scintillators (tiles).

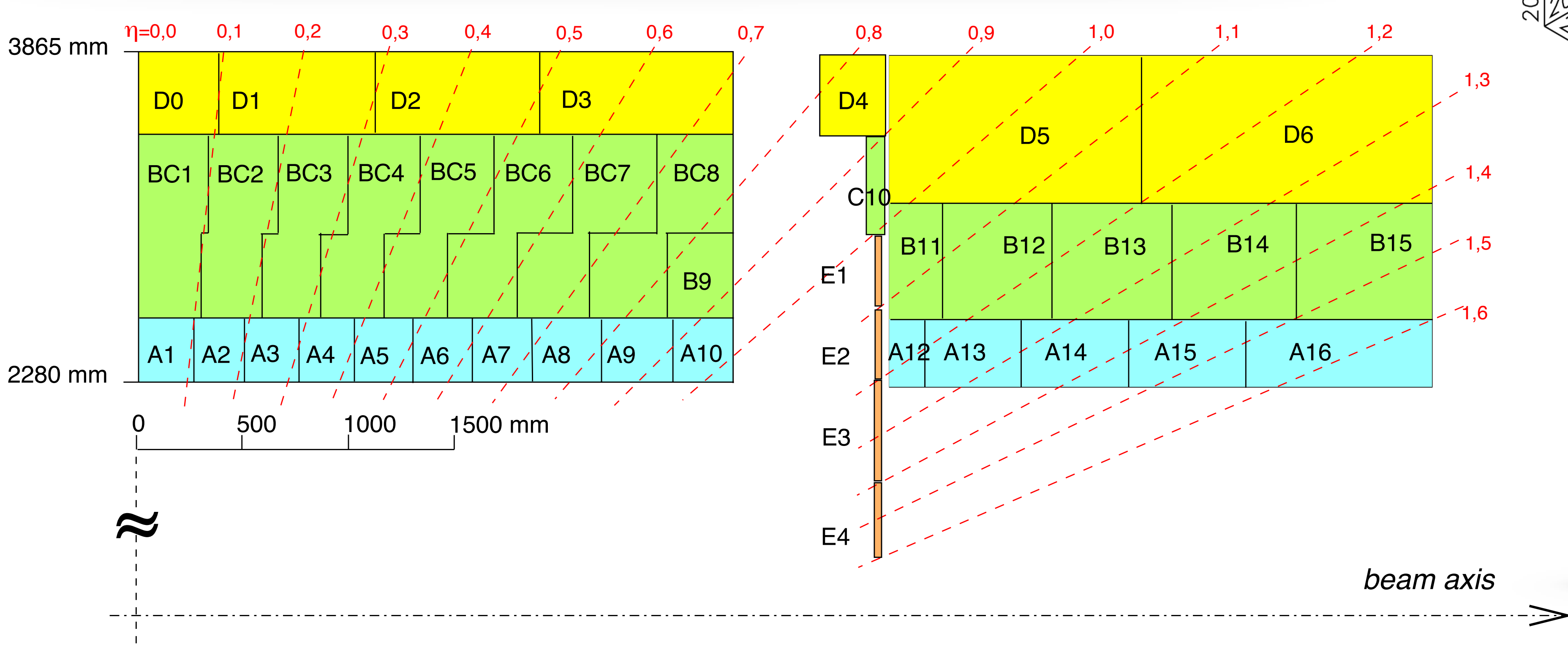


TileCal purpose
- Perform precise measurements of hadrons, jets, missing transverse energy as well as provide input signal to Level 1 calorimeter trigger.

Tile Calorimeter Readout

- Every scintillating tile is readout by 2 wavelength shifting fibres (WLS).
- Fibres go along both sides of every module and are grouped into pseudo-projective geometry cells in 3 layers.
- TileCal has a total of 5182 cells:
  - each cell is readout by wavelength shifting fibres (WLS) and two Photomultiplier tubes (PMTs)
  - Each module hosts up to 45 PMTs
  - Total 9852 Photomultipliers in 256 modules





- Readout is organised in 4 partitions
  - Barrel divided into 2 partitions LBA for $\eta > 0$ and LBC for $\eta < 0$
  - Extended barrels into 2 partitions EBA and EBC

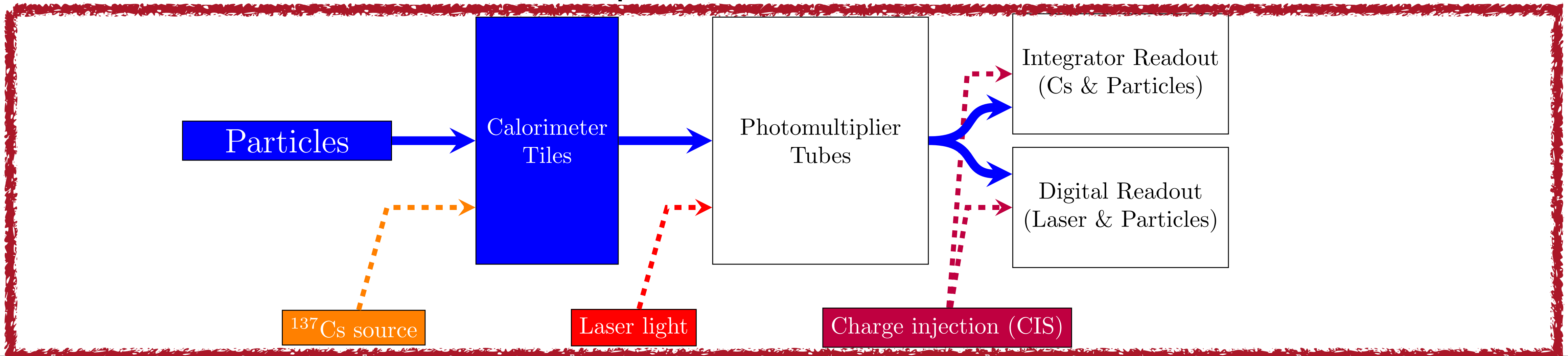
Calibration Systems

- Dedicated calibration system at each level of TileCal signal reconstruction to monitor the behaviour of different detector components.
- The reconstructed energy of each TileCal channel:

$$E[GeV] = A[ADC]\,.C_1\ .\,C_2\ .\,C_3\,.\,C_4$$

  - $A[ADC]$ the signal amplitude A is reconstructed in units of ADC counts using the Optimal Filter algorithm.
  - C_1 = photoelectrons per GeV (characteristic of scintillator and cell) obtained during test beam.
  - C_2 = picocoulomb per photoelectron (characteristic of the PMT).
  - C_3 = volts per picocoulomb (characteristic of the amplifier).
  - C_4 = ADC counts per volt.

- **Cesium System (C_{Cs})**: Calibrates the entire optic components and the PMTs by providing calibration constant (C_{Cs}) for C_2, C_3 and C_4.
- **Laser System**(C_{laser})**:** Calibrates and monitors the PMTs and front-end electronic components used for collision data in between cesium calibrations by providing calibration constant (C_{laser}) for C_2 and C_3
- **Charge Injection System (CIS)** ($C_{ADC\to pC}$): calibrates the front-end electronics i.e. C_3 and C_4.
- **Minimum Bias System (MB)**: uses the integrator readout of Physics events to calibrate the PMT and monitor the full detector response.

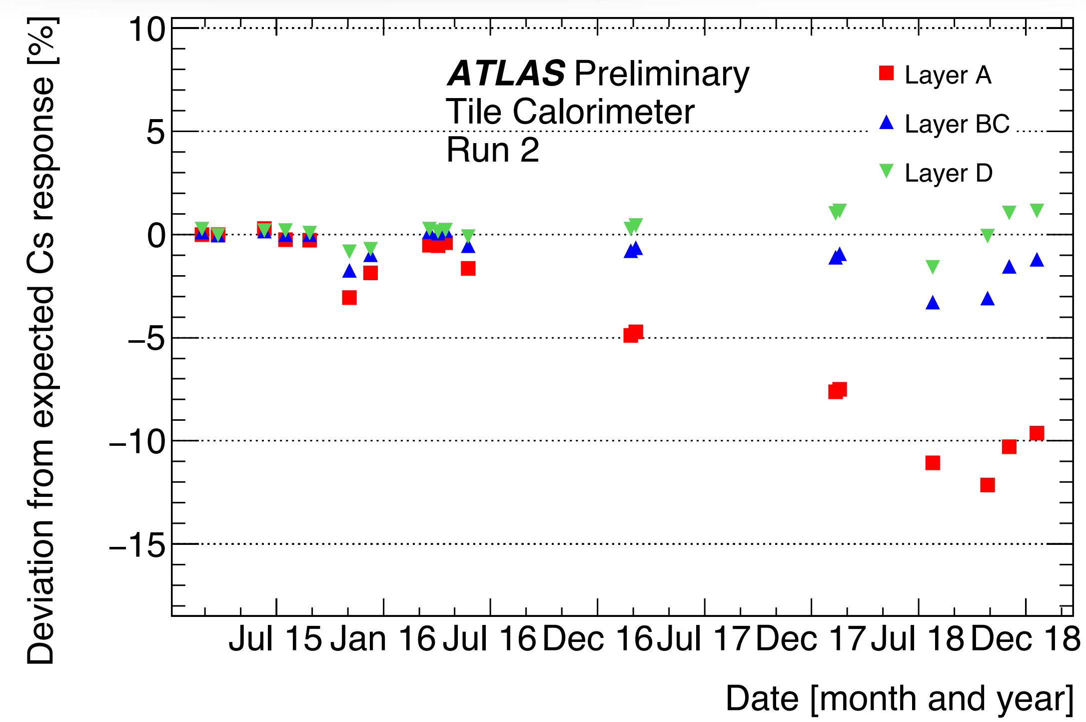


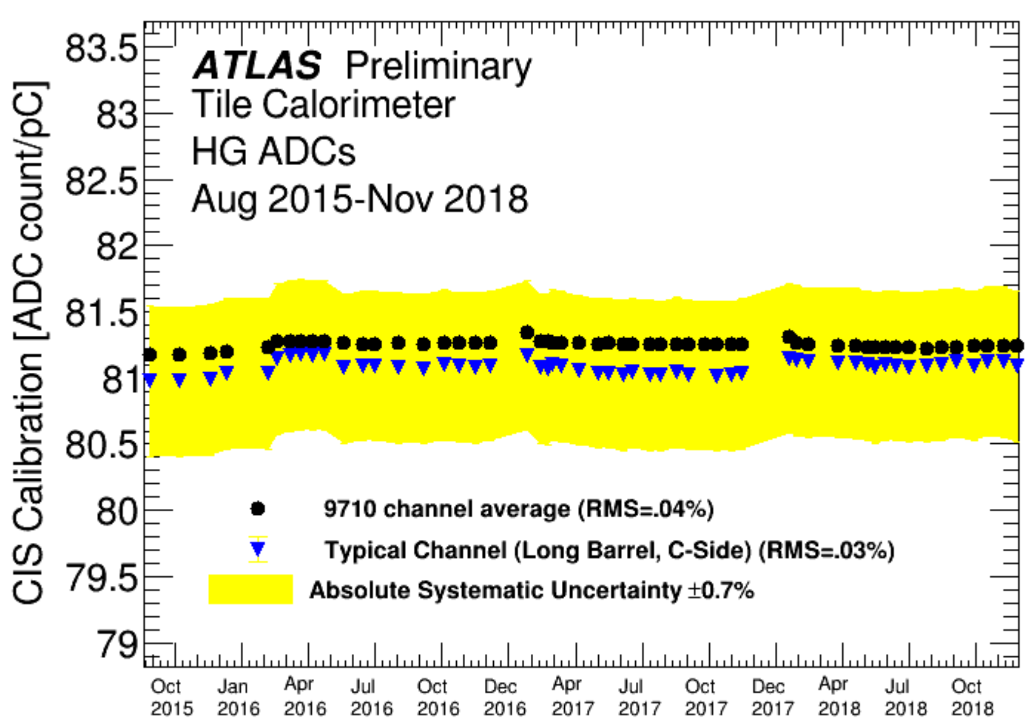
Cesium and Charge Injection System

Cesium System

- A moveable ${}^{137}Cs$ radioactive source passes through the calorimeter body few times a year:
  - the source emits $\gamma-$rays with well known energy of 662 keV.
  - calibrates the entire optical chain i.e., scintillators, fibres and PMTs
- The precision of the Cs calibration in one typical cell is ~0.3%
- Deviation in the response of cells is caused by the PMT gain variation and scintillator degradation

- By the end of Run 2 the most irradiated cells in A layer drifted down by 18% while central cells at outer D layer drifted up by 2%





Detector-wide CIS constants averages of all HG ADCs

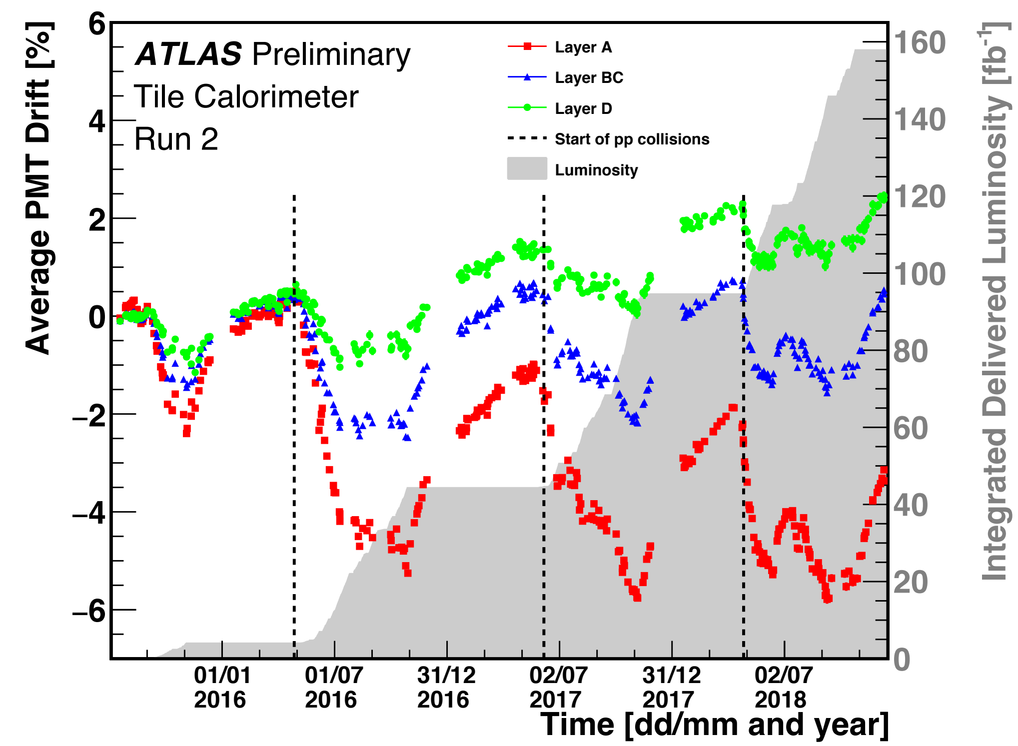
Charge injection System

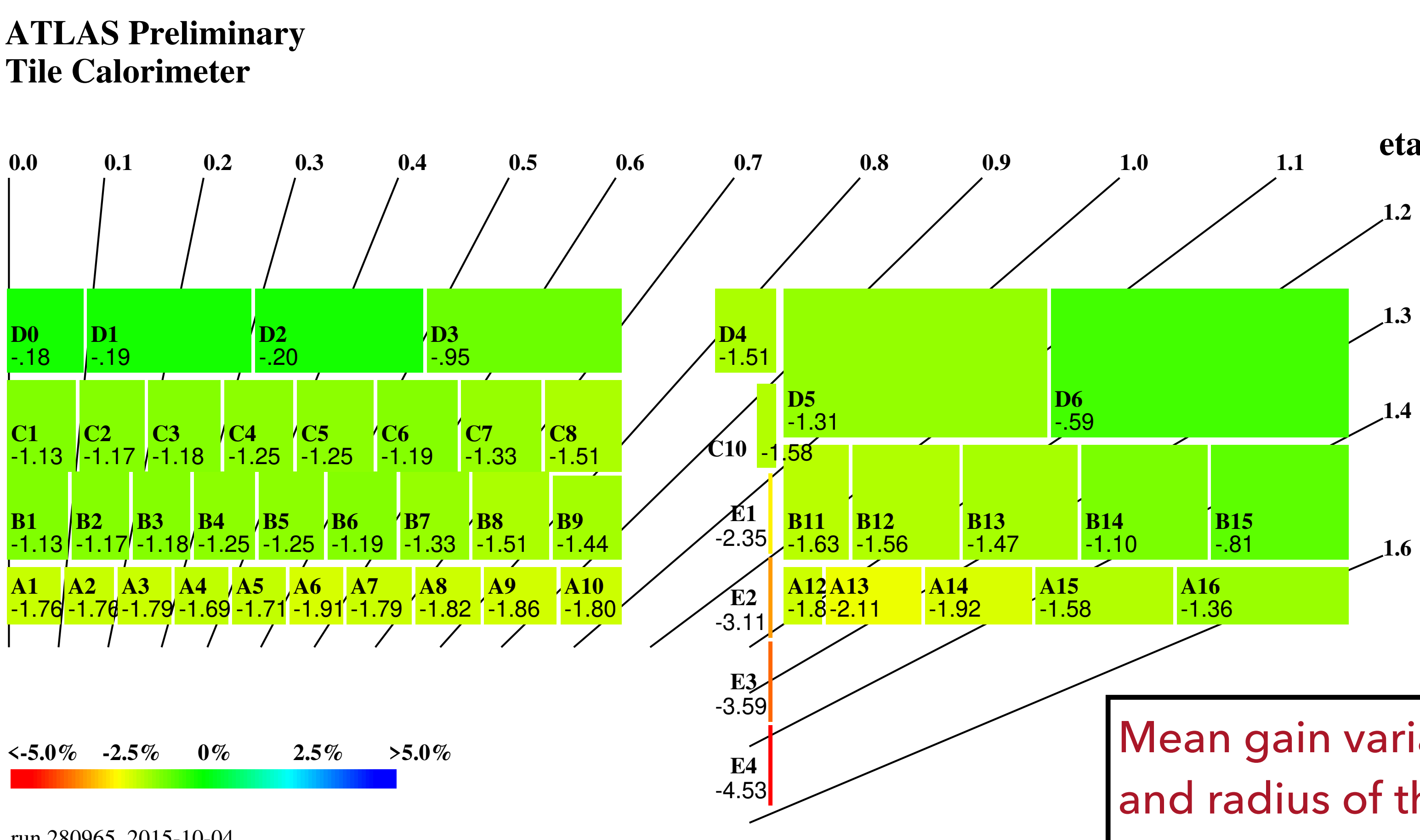
- Calibrates the response of ADCs (electronics), digital gains and linearities in dedicated runs taken twice per week.
- Simulates physics signals in the TileCal channels by injecting a known charge into the ADC and measuring the electronic response.
- Precision of 0.7%, stability over time of 0.03%

Laser System

- Laser light pulses (532 nm) sent to each PMT in dedicated runs taken twice per week.
- Pulses also sent during collisions (in empty bunches) to calibrate timing and to study PMT non-linearity.
- PMT response variation evaluated w.r.t last Cesium scan.
- Precision of the measurement is better than 0.5%.

Evolution of the mean relative response as a function of time





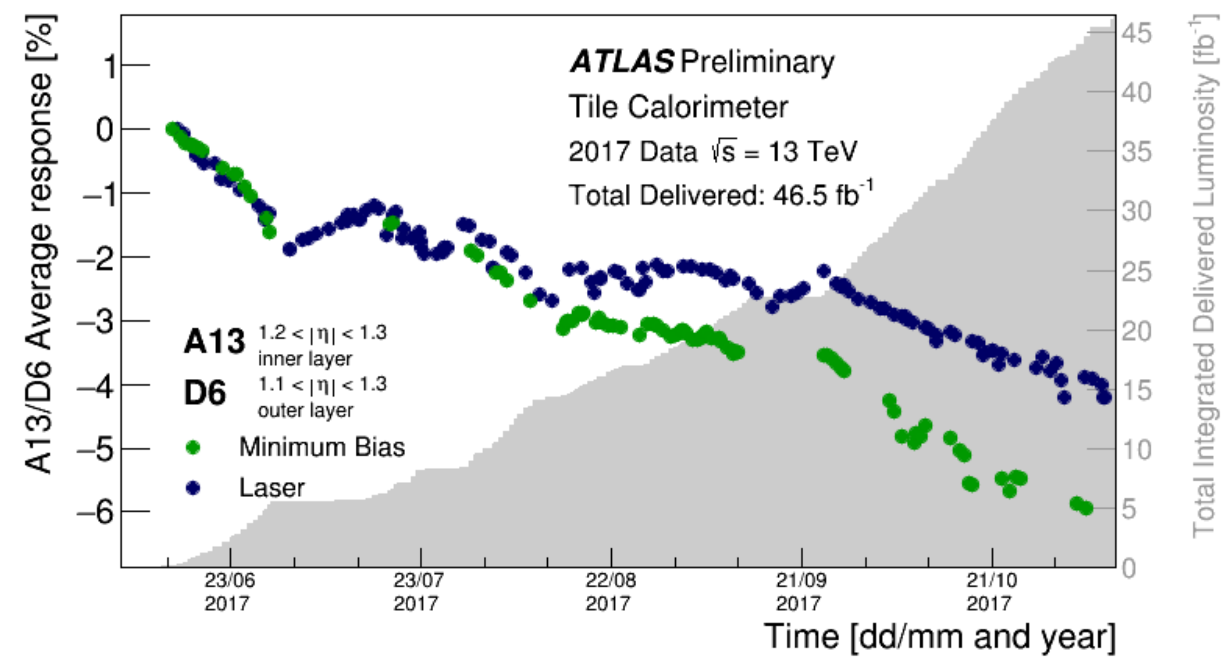
✦ Larger drifts observed in PMTs of A-cells and E-cells which are the cells with highest energy deposits (ie, due to depletion of photocathode, activation of iron)

Mean gain variation as a function eta and radius of the TileCal PMTs covering entire 2018 pp collision period

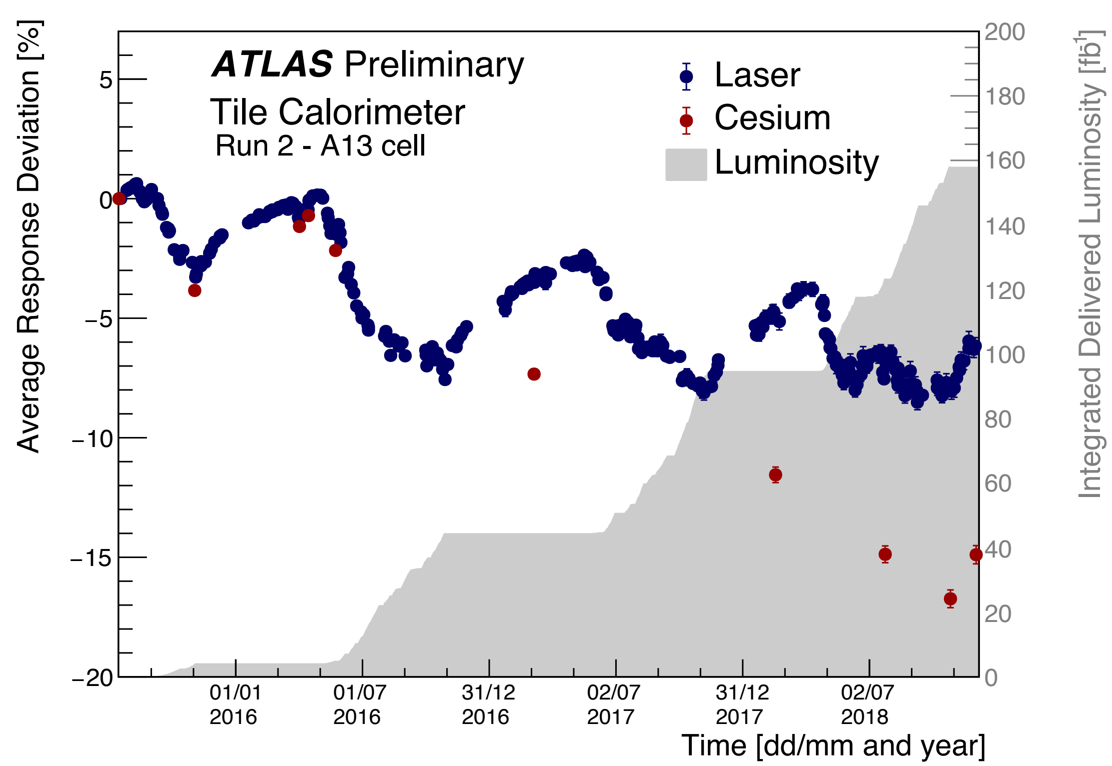
Minimum Bias Systems and Combined Calibrations

Minimum Bias System

- Measures the response of Minimum bias events (soft parton interactions during high energy pp collisions).
- Measures integrated PMT signals over a large time (~10 ms) by using the same the integrator readout system as for the Cs system.
- Monitors the full optical chain.
- Monitors the instantaneous luminosity and provides an independent measurement given an initial calibration (luminosity coefficient).



Response variation of A13-cell to Minimum Bias and Laser w.r.t D6 cell during 2017 data taking



Combined Calibrations

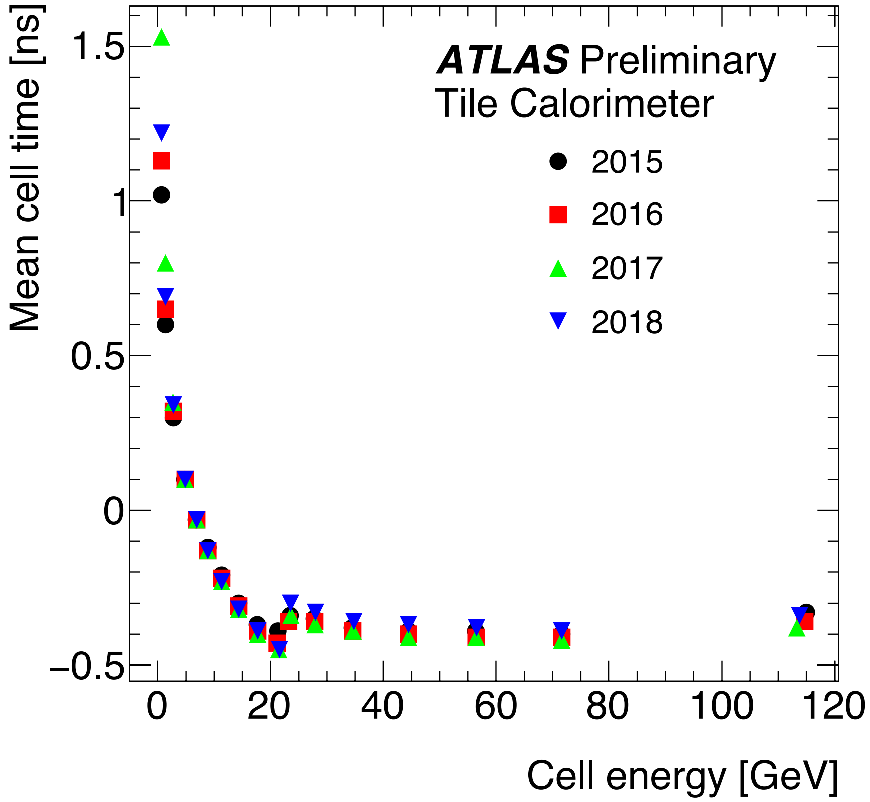
- Comparison between the cell response to Cesium/Minimum Bias events and Laser measurements
- Allows to isolate the relative response of scintillators and fibres.
- Differences between Cesium/MB and laser measurements are interpreted as a scintillator aging due to irradiation.

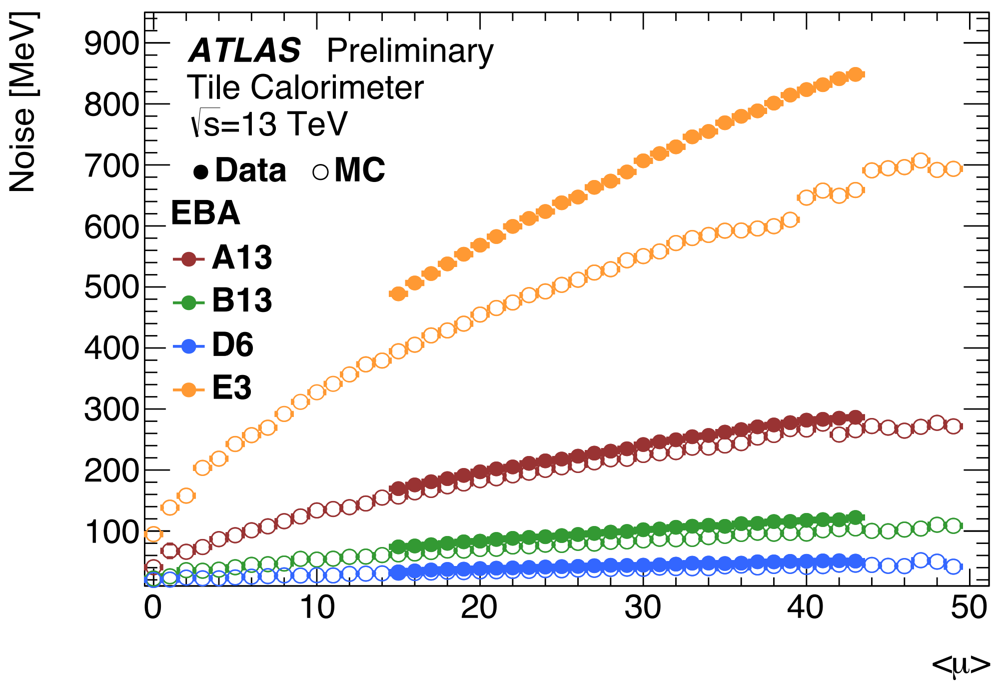
Time calibration and noise

Time Calibration

- Time calibration is calculated using jets from pp collisions and monitored during physics data.
- A precise time calibration is crucial for reconstruction of cell energy.
- Adjusts a digitiser sampling clock to the peak of signal produced by the particle traveling from the interaction point.
- For $E_{cell} > 4$ GeV, resolution is better than 1 ns.

The mean cell time in jet events as a function of cell energy





TileCal noise dependence with the average number of Interactions per bunch crossing

Noise

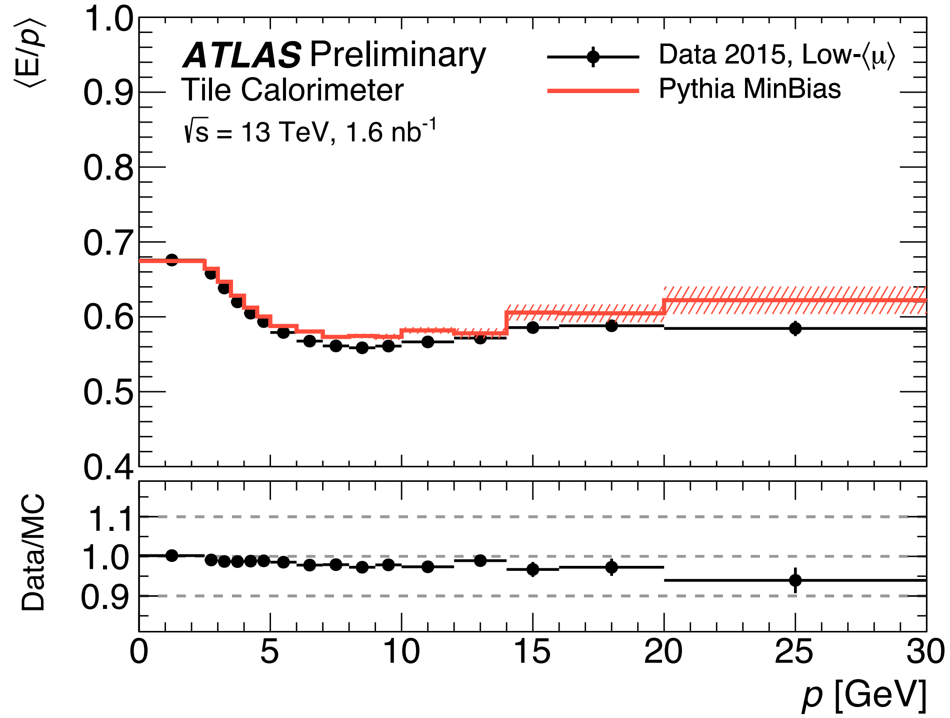
- Total noise per cell includes:
  - Pile-up contribution: multiple interactions during same/previous/following bunch crossing events.
  - Electronic noise: below 20 MeV. Measured regularly during dedicated calibration runs with no signal in detector.
- Regions with highest exposure (A-cells, E-cells) has largest noise

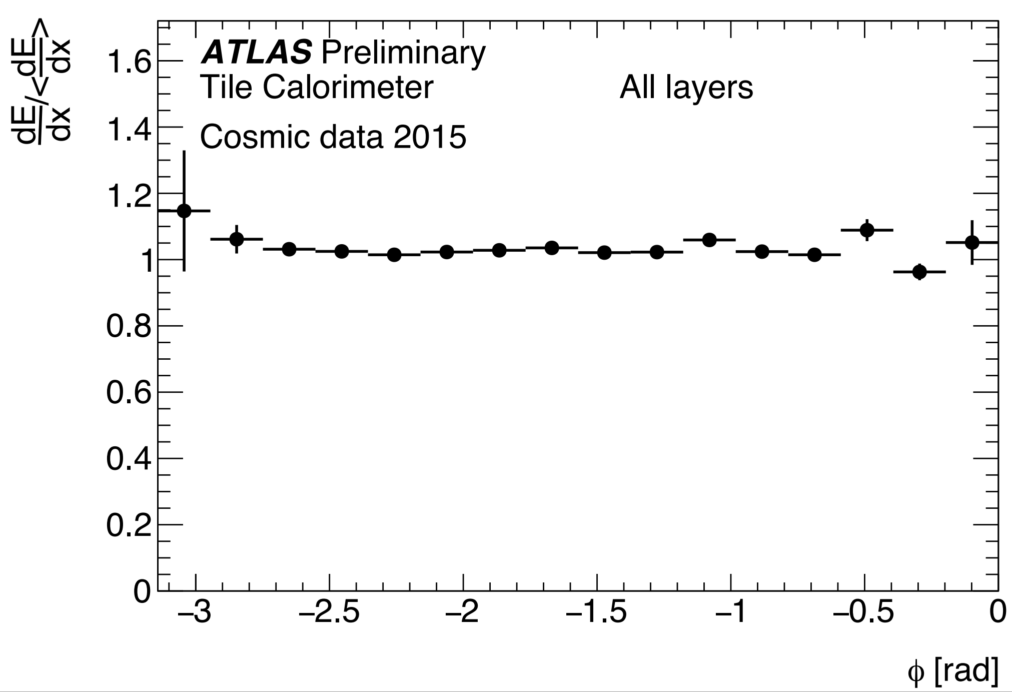
Performance Studies

Single Particle Response

- The TileCal energy response can be probed using single hadrons and jets.
- The ratio $< E/p >$ of single hadrons is used to evaluate uniformity and linearity during data taking.
    - E - calorimeter energy at EM scale
    - p - track momentum measured by ATLAS inner detector system.
- $< E/p > \; < 1$: since TileCal is non-compensating calorimeter
- Jets further calibrated to Jet energy scale.

Calorimeter response to single isolated charged hadrons, characterised by $< E/p >$ as a function of p





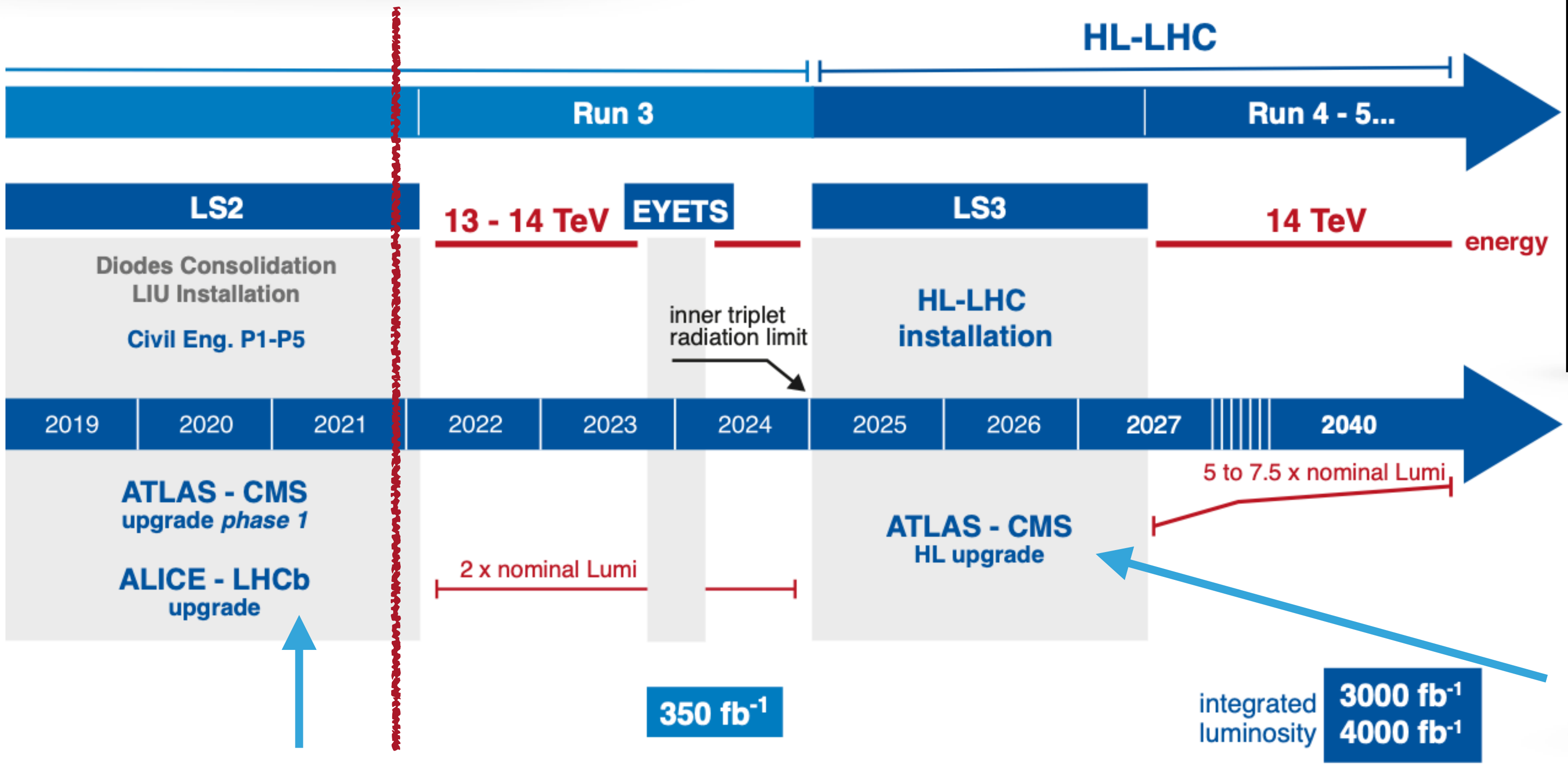
Cosmic- ray Muons

- Isolated muons from cosmic rays are used to study inter calibration of Tile cells and verifies the measured energy at EM scale.
- ~5% non-uniformity in the η and <1% in ϕ response to cosmic muons.

Ratios of the truncated means of the distributions of the energy deposited in the layer cells by cosmic-ray muons per unit of path length dE/dx, obtained using 2015 data as a function of the azimuthal angle ϕ

High-Luminosity LHC upgrade & TileCal

LHC Schedule



- **High Luminosity upgrade of the LHC in 2027**
  - increase the instantaneous luminosity by a factor up to 7.5 provide 4000 fb^{-1} dataset.
  - up to 200 collisions per crossing

LS3 : Phase-2 upgrade

LS2 : Phase-1 upgrade

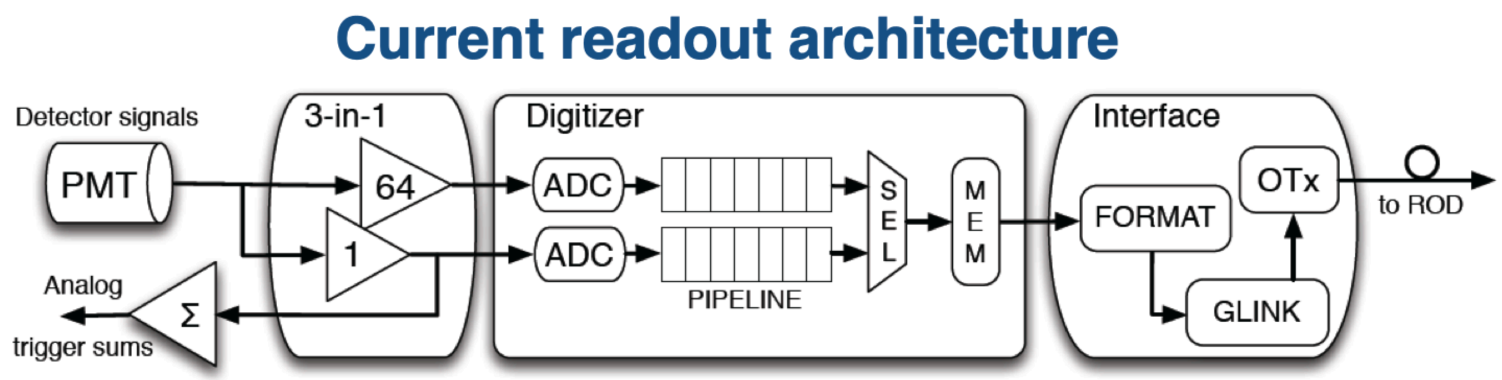
TileCal during Phase-1 upgrade

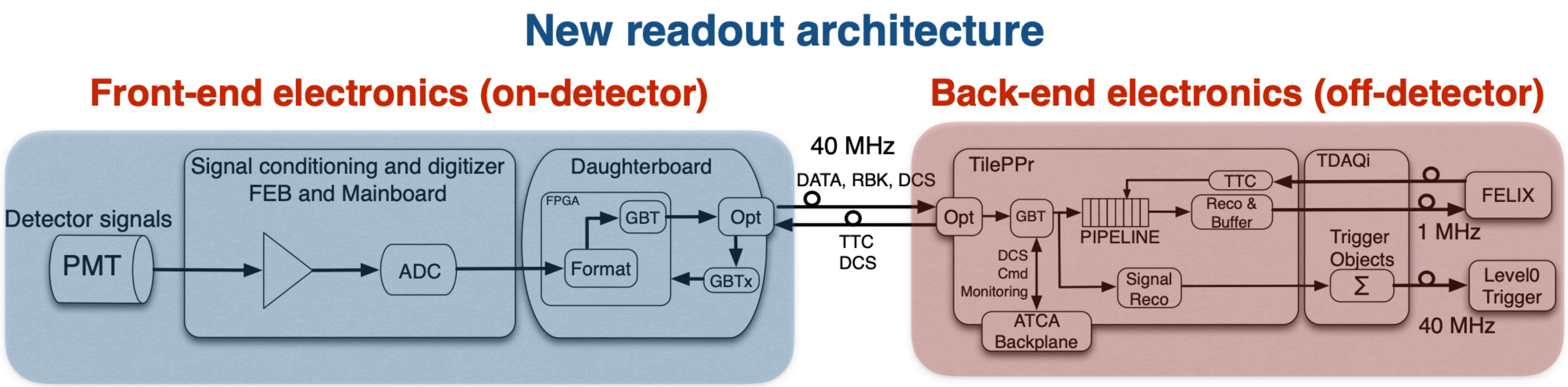
- Crack scintillators (E3/E4) and trigger scintillators are replaced
- Maintenance of the detector electronics done

TileCal plans for Phase-2 upgrade

- Full electronics replacement, both on and off detector.
- New modular mechanics : 4 mini-drawers instead of one super drawer.
- 10% of the PMTs replacement associated to the most exposed cells.
- New low voltage and high voltage power supplies systems due to higher radiation requirements.
- Data and power redundancy to improve system stability

The new Readout architecture of HL-LHC TileCal





OFF-detector and On-detector electronics replacement

- Higher trigger rate (1-4 MHz),
- extended data pipelines (35s, moved off detector)
- Higher radiation levels, improved reliability and robustness of electronics
- Increased bandwidth: 4096 up-links and 2048 down-links

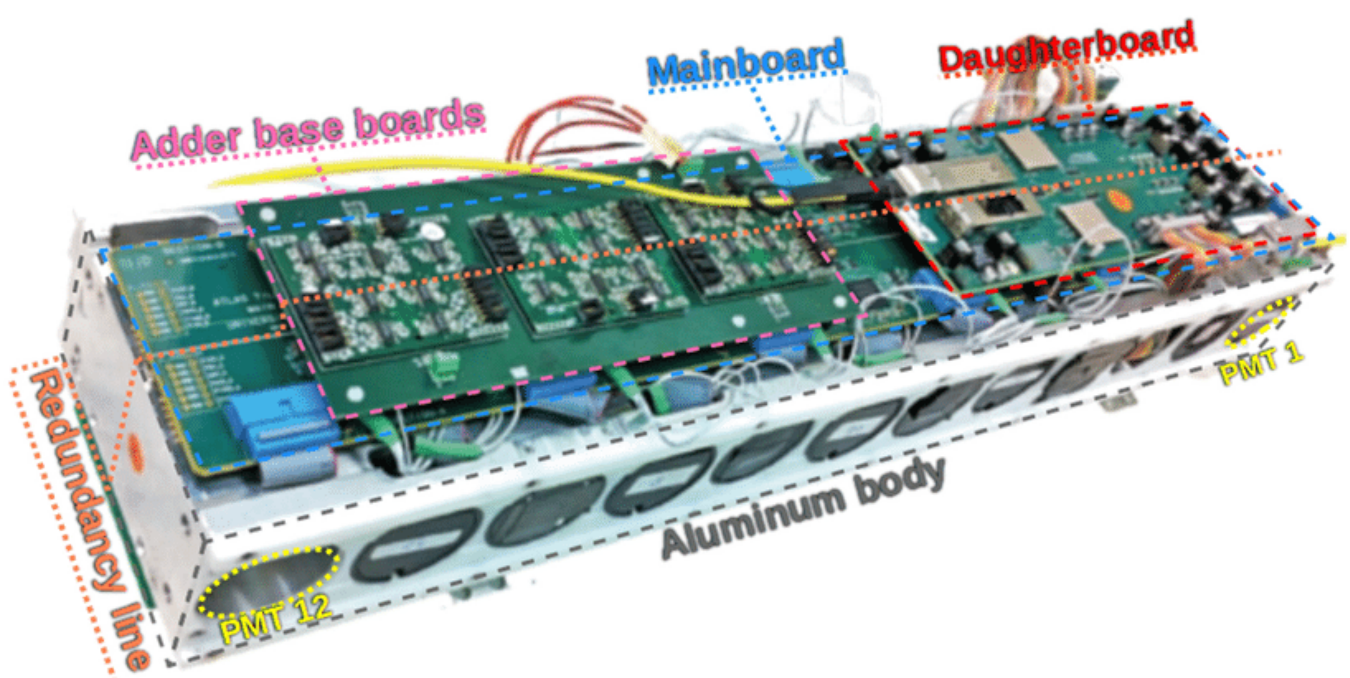
Shaping done in the front-end board located in the PMT block, digitisation on the Mainboard, high speed communications on the Daughterboard.

Electronics layout of the HL-LHC TileCal

TileCal Phase-2 upgrade electronics should withstand:
- High luminosity environment (~200 collisions per bunch crossing)
- Higher ambient radiation

TileCal Phase-2 upgrade electronics should provide:
- Low latency
- High frequency (40 MHz)
- Fully digital input for ATLAS trigger system

Mini-drawer



Mini-Drawer (MD) hosts upto 12 channels by means of:

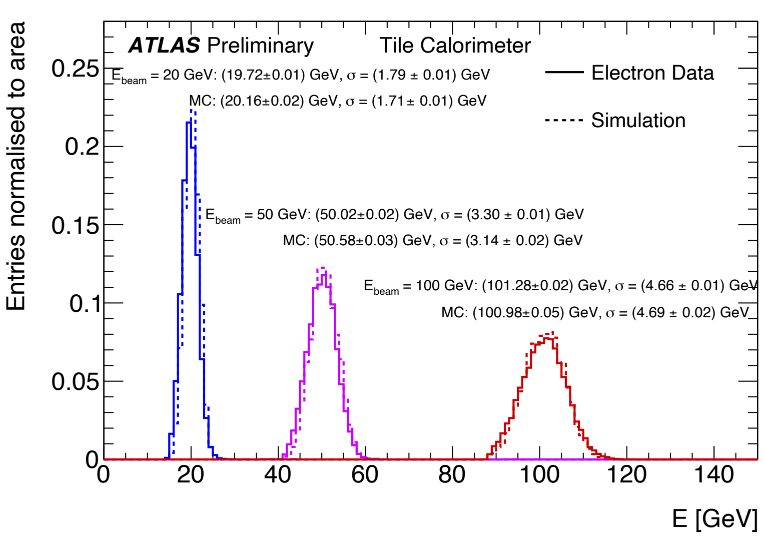
- 12 PhotoMultipliers (PMTs) to turn light pulses to electric signals
- 12 Front-End Boards (FEBs) named FENICS (Front-End ElectroNICS) to shape and condition the PMT signals.
- a MainBoard (MB) to continuously sample and digitise two gains of the PMT signals. MB also provides controls and power for the FENICS.
- a DaughterBoard to distribute LHC synchronized timing, configuration and control to the front-end and continuous read-out of the digital data from all the MB channels to the Off-detector systems.

Test Beam measurements

- TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the legacy system were exposed to different particles and energies in seven test-beam campaigns at SPS during 2015-2018.
  - Next campaigns in September 2021!

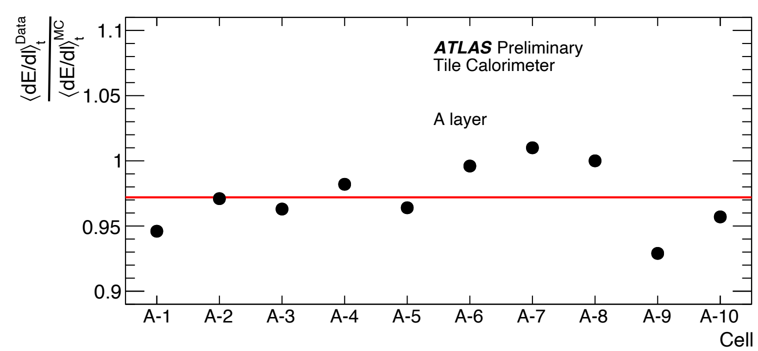
- Overall good performance has been demonstrated
  - Agreement between legacy and new electronics in terms of energy calibration.
  - Improvement in signal to noise ratio by a factor of ~2.
  - Response of each hadron type compatible with previous measurements.

Data to MonteCarlo response with electrons



Determine the EM scale of the calorimeter in pC/GeV and verify linearity.

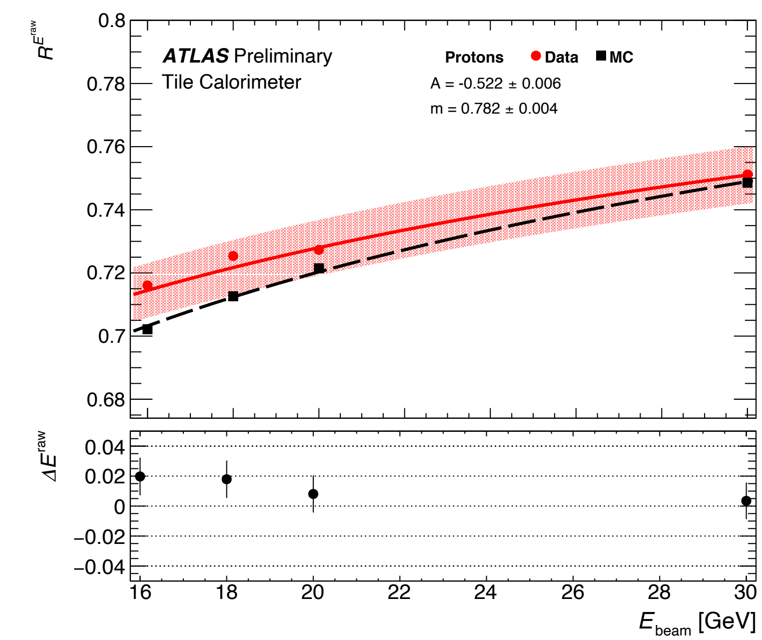
Data to MonteCarlo response with muons



Verifies the new electronics performance.

Review and improve the detector calibration procedure.

Data to MonteCarlo response with hadrons



To validate and improve the modelling of the jets energy characterisation of the ATLAS simulation.

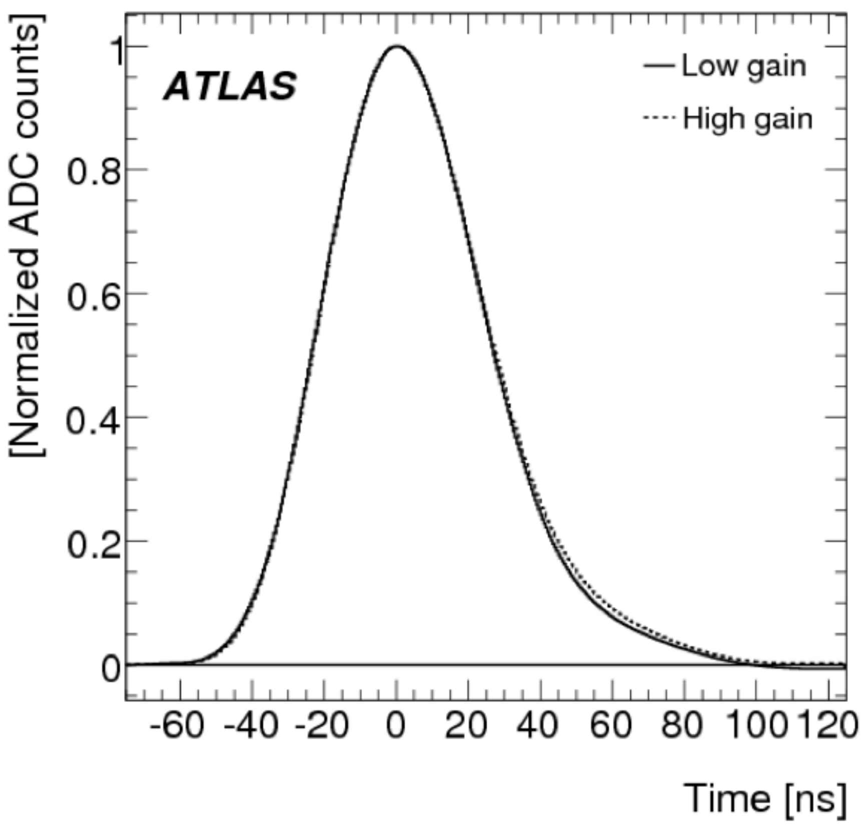
Summary and Conclusions

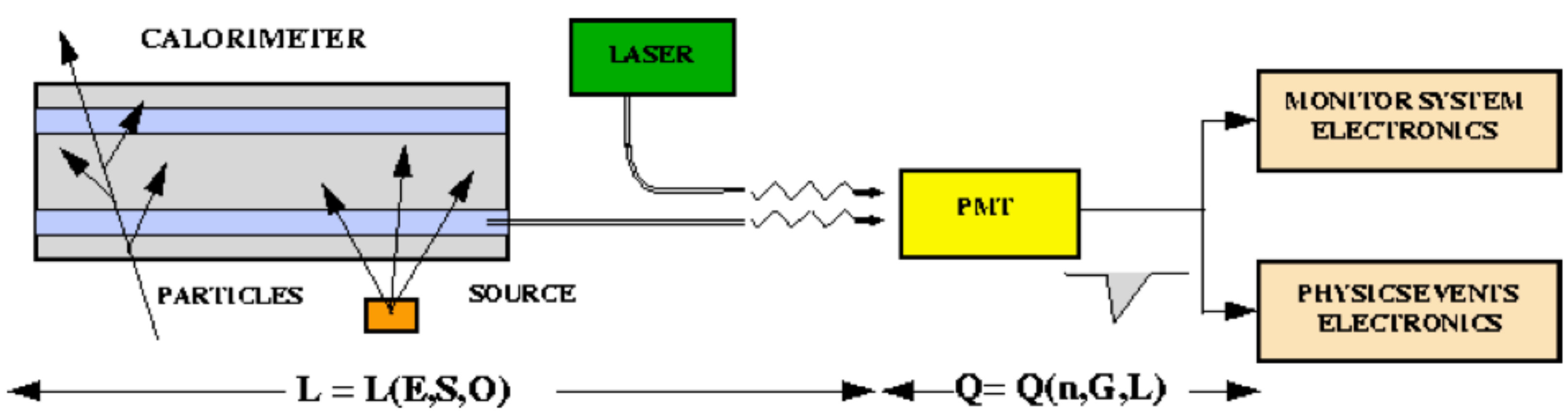
- Tile Calorimeter is an important part of ATLAS detector at LHC; contributes to the measurement of the 4-vectors of jets and missing energy.
- Each step of the signal production, from scintillation light to digital signal amplitude is monitored and calibrated using dedicated calibration systems.
- The stability of the absolute energy scale at the cell level was maintained to be better than 1% during Run2 data taking.
- During ongoing shutdown replacement of crack scintillators and maintenance of TileCal electronics have been performed.
- All TileCal on- and off- detector electronics will be replaced in 2024-2026 during the ATLAS Phase II upgrade for the HL-LHC era
    - R&D is done, initial tests demonstrate good performance.
    - Readout resolution and sensitivity are improved slightly.
    - Many components of the mechanics and front-end electronics have entered pre-production or production.

Backup

Signal Readout and Reconstruction

- PMT signals are shaped and amplified in two gains (low/high ratio 1:64) for high/low signals.
- Amplified signal is digitised every 25 ns by a 10-bit ADC.
- Signal amplitude A and time τ determined from a 7 signal samples.
  - $$A = \sum_{i}^{7} a_i S_i$$
  - $$\tau = \frac{1}{A} \sum_{i}^{7} b_i S_i$$
- Energy is reconstructed from signal amplitudes using calibration factors.





Calibration system