LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
*partículas e tecnologia*

ATLAS
EXPERIMENT

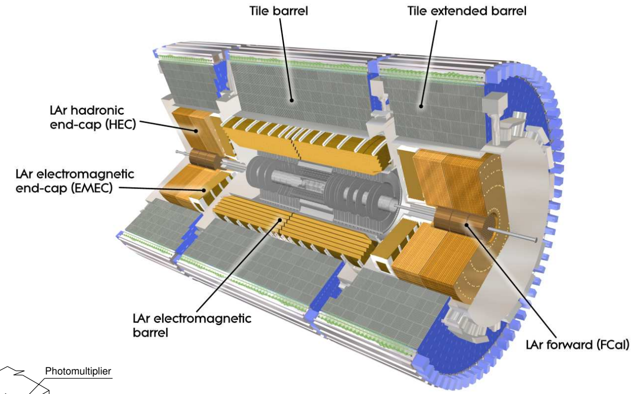
# *Operation and Performance of the* **ATLAS Tile Calorimeter**

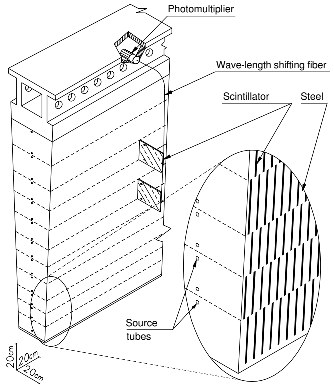
**Rute Pedro** on behalf of the ATLAS Collaboration

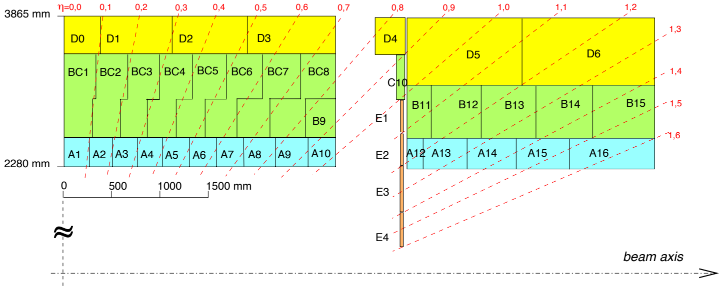
International Conference on Particle Physics and Astrophysics | 5-9 October 2020

# Overview of the Tile Calorimeter

- Central hadronic calorimeter of ATLAS, covering |η|<1.7
- Measures hadrons, jets, taus, missing transverse energy, assists in the muon reconstruction and provides input to the Level 1 Calorimeter trigger
- Designed for jet energy resolution $\frac{\Delta E}{E} \sim \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$
- Sampling calorimeter with steel plates (absorber) interleaved with plastic scintillator tiles (active medium) (4.7:1)
- Double photomultiplier (PMT) readout using wavelength shifting (WLS) optical fibres: 9852 readout channels
- 5182 cells, $(\eta, \phi)$ granularity: cells in the A, B(C) layer 0.1 X 0.1
  cells in the D layer 0.2 X 0.1

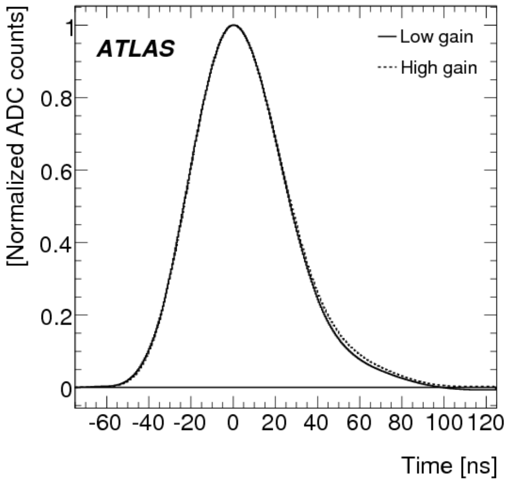


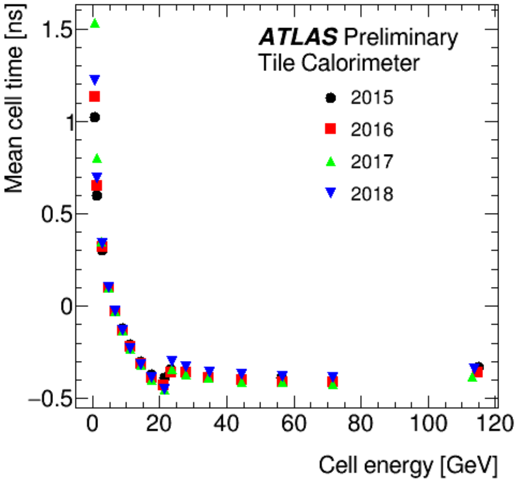



# Signal Reconstruction and Timing

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

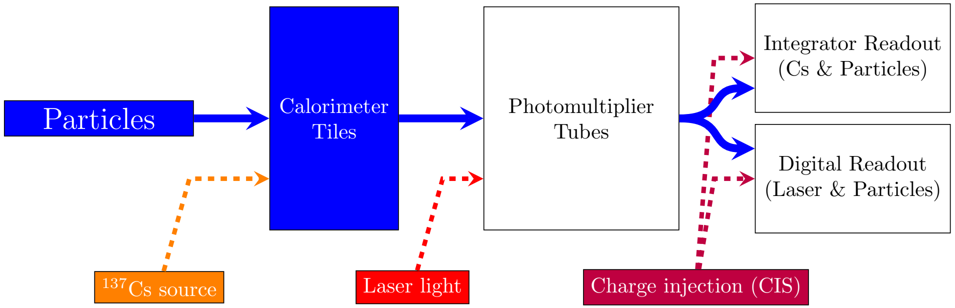



- **Time calibration** impacts the signal reconstruction
  - Adjusts the digitiser sampling clock to the peak of the signal produced by a particle traveling through the cell
  - Time offsets derived from time distribution in cells associated to jets, additional monitoring from laser signals
  - Time resolution better than 1 ns for $E_{cell} > 4$ GeV



# Energy Reconstruction and Calibration

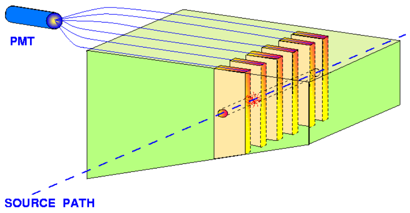
- $E[GeV] = A[ADC] \times f_{ADC \to pC} \times f_{pC \to GeV} \times f_{Cs} \times f_{Laser}$
  - $f_{pC \to GeV}$ is the EM energy scale constant measured during test beam (2001-2003)



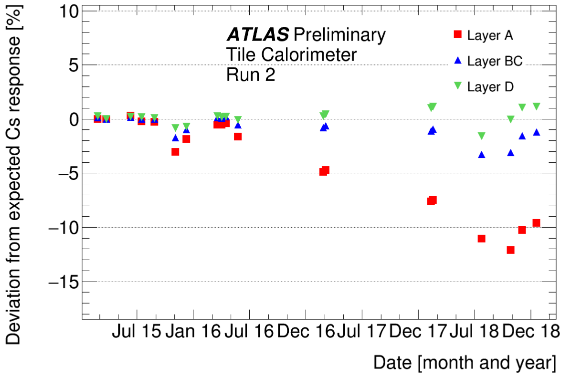

Dedicated system to probe and monitor each step of the readout chain

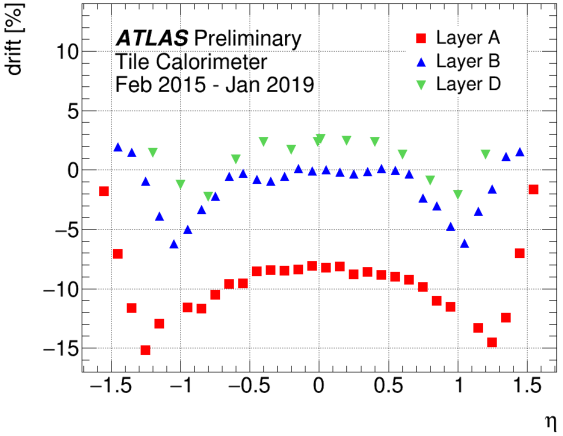
- Cesium source calibrates optical components and PMTs responses: $f_{Cs}$
- Laser light calibrates the response of PMTs and readout electronics: $f_{Laser}$
- Charge Injection System (CIS) calibrates the response of ADCs: $f_{ADC \to pC}$
- Integrator readout of Physics events to monitor the full detector response

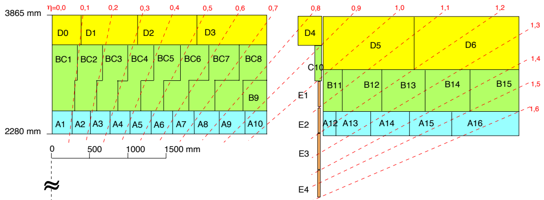
# Calibration with the Cesium system




- Moveable $^{137}Cs$ $\gamma-$source (662 keV) scans the calorimeter cells, 2-3 times/ year in Run 2
- Signal measured by the integrator readout (10 ms)
- Cell response drifts due to scintillator degradation with exposure to radiation and PMT response loss with accumulated anode current
- Precision of the system for a typical cell is around 0.3%
- Maximal down-drifts for the innermost A layer, closest to the collision point

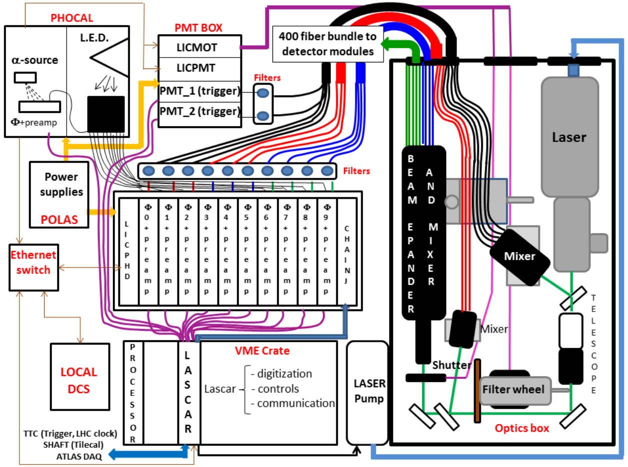


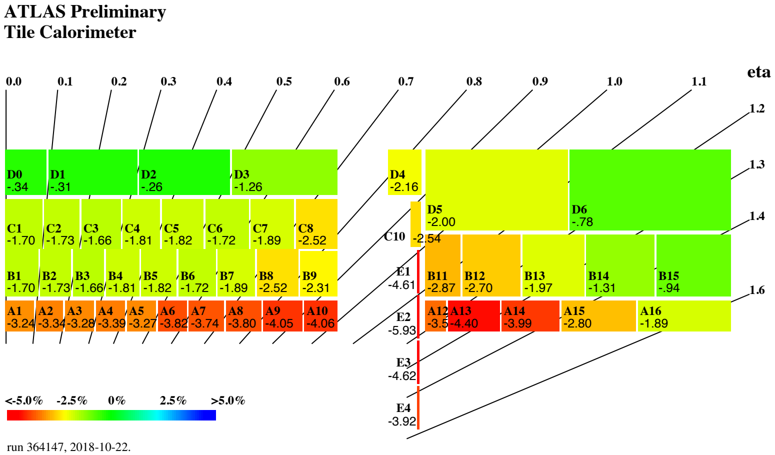



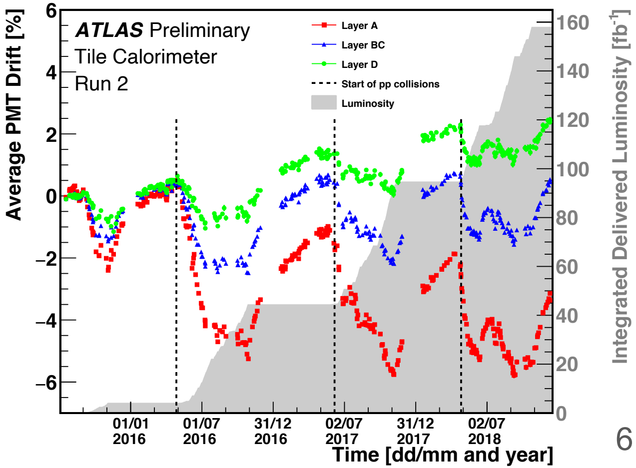



# Calibration with the Laser system

- Laser light pulses (532 nm) sent to each PMT in dedicated runs taken weekly
- Pulses also sent during collisions (in empty bunches) to calibrate timing
- PMT response variation evaluated w.r.t. last Cs scan, with calibration factors updated weekly (precision around 0.5%)
- Larger drifts in PMTs reading the A layer and E cells, with highest energy deposits

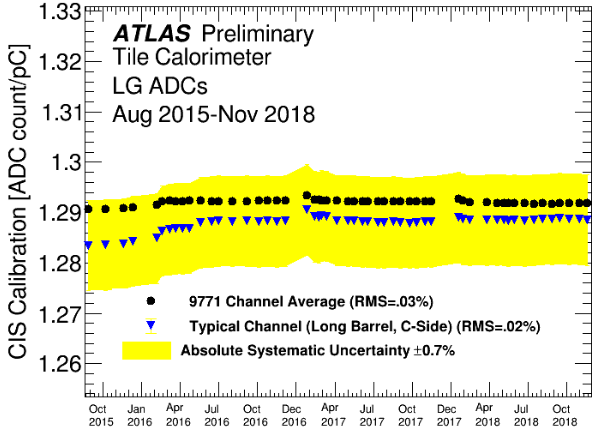


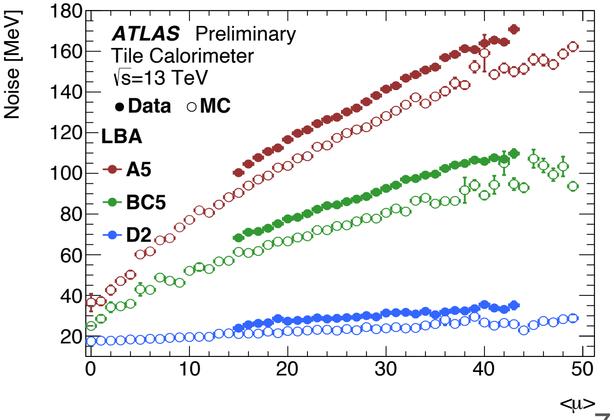
# Charge Injection system and Noise measurement

- **Injection of known charge** (0 to 800 pC), shaped to match PMT signal calibrates the response of analog amplifiers and ADCs, and evaluates their linearity
  - Dedicated runs taken daily to extract the pC to ADC conversion factor
  - Monthly updates of the conversion factors
  - Also used in the calibration of the analog Level 1 Calorimeter trigger
  - Precision of 0.7% and stability over time is ~0.03%



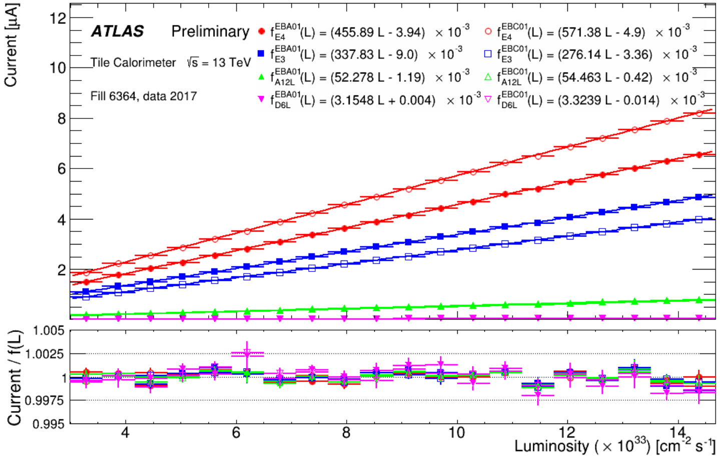

- **Total noise** per cell in the calorimeter comes from:
  - Electronics: measured in dedicated runs without signal in the detector
  - Pile-up: energy deposits from multiple collisions in the same event or from previous/next bunch crossing (dominant during LHC collisions)

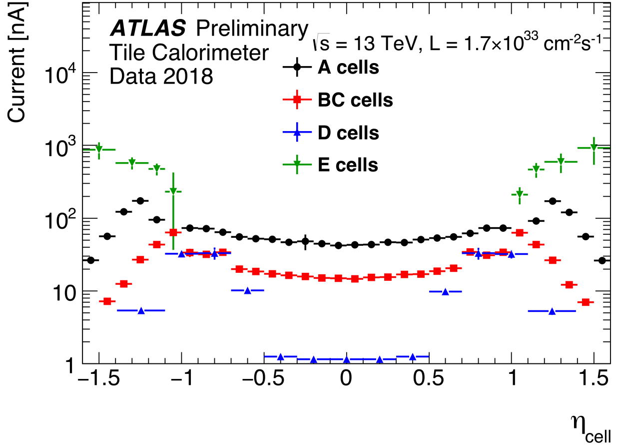
- Electronics noise ~20 MeV for all cells, measured regularly in dedicated runs

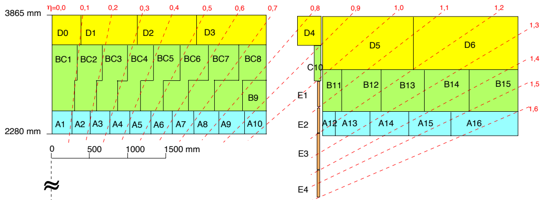


# Integrator readout of Minimum Bias events

- Soft inelastic interactions (minimum bias events) are the most frequent in high energy proton collisions
- The total energy deposit in the calorimeter over a large time is proportional to the instantaneous luminosity
- Integrator readout of the PMT signals (10 ms) provides an independent measurement of the instantaneous luminosity (given an initial calibration)
- The system also monitors the full detector chain and allows finer grained calibration of more drifting cells in between Cs runs (specially relevant for E-cells not scanned with the Cs-source)



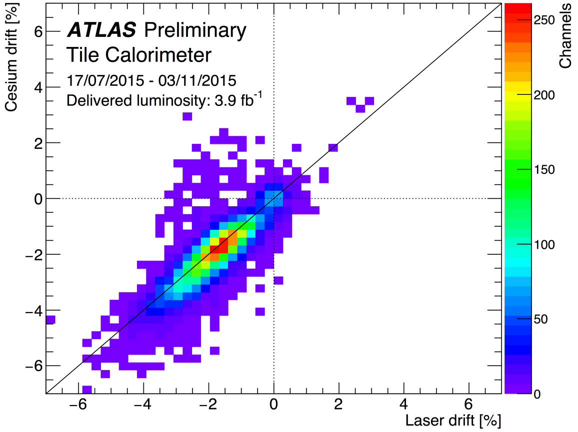
# Combined Calibration and Performance

- Comparison between the cell response to Cs or Minimum Bias (MB) $\Delta Cs(MB)$ events and Laser pulses $\Delta Las$

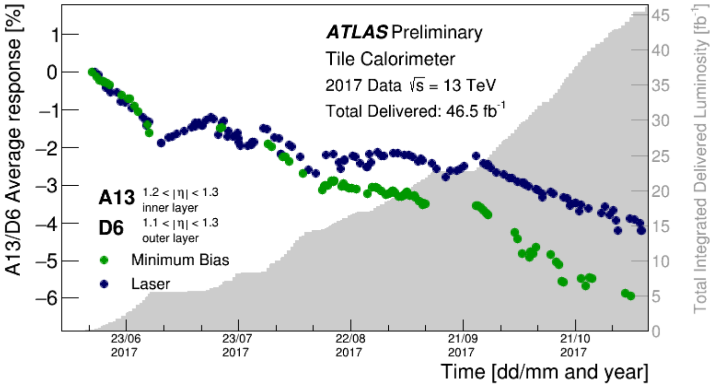
- Allows to isolate the relative response of the scintillators and fibres:
  $I/I_0 = 1 + (\Delta Cs(MB) - \Delta Las) \times 100\,\%$

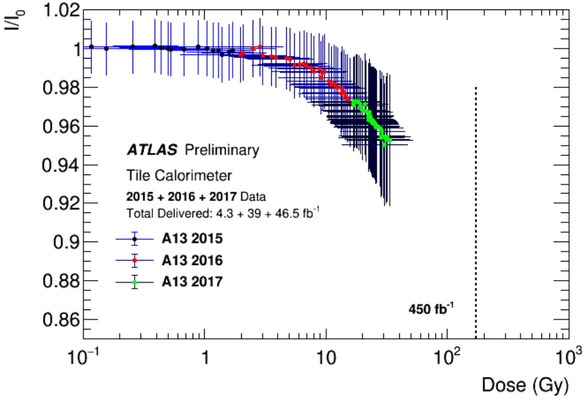
- In 2015 no diference in the response

- In 2016-2018 we observe scintillator+fibres degradation for the cells more exposed to irradiation



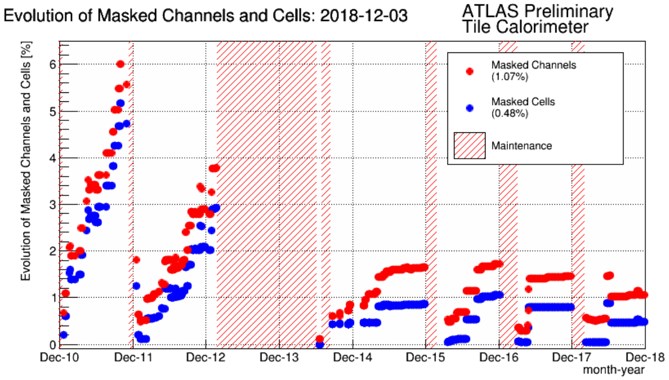

More about this topic in the poster session by B. Pinheiro



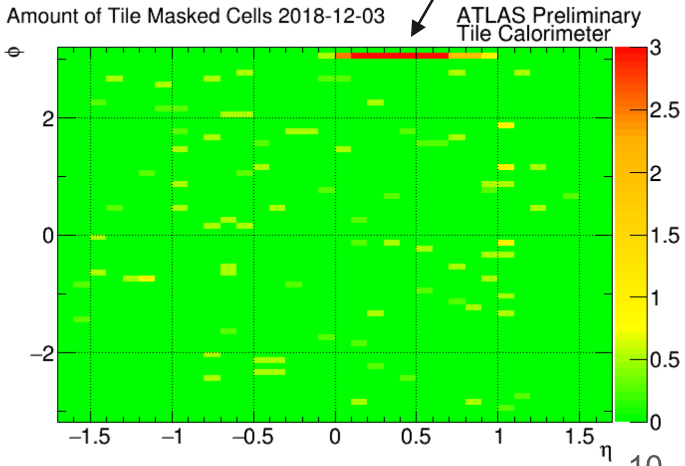



# Detector Operation and Data Quality

- Control and monitoring of the TileCal operation and parameters through Detector Control System (a SCADA infrastructure)
- Run coordination, maintenance and data quality teams ensure the smooth operation of the detector
- Continuum monitoring to identify and mask problematic channels, correct mis-calibrations, detect data corruption and hardware issues
- Redundancy in the cell readout  reduces the impact of masked channels
- Maintenance campaigns fix all issues to fully recover the system
- TileCal had 99.7% DQ efficiency in Run 2

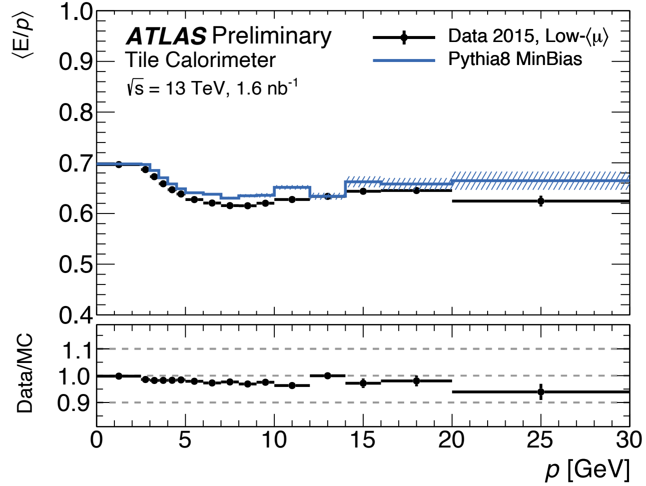



Masked module, also modelled in data simulation

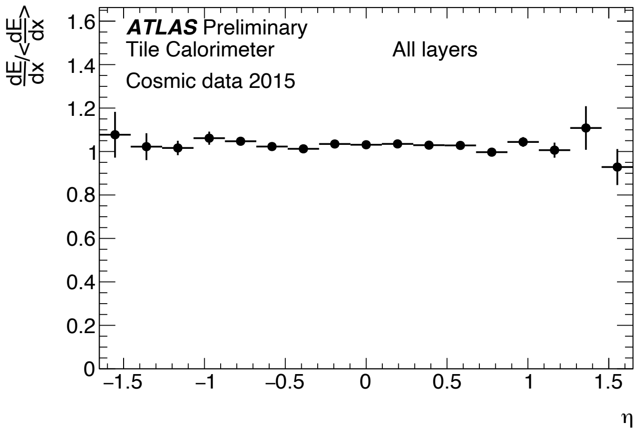


# Performance: Response to isolated particles

- The ratio of the calorimeter energy response to isolated **charged hadrons** (EM scale) to the track momenta $< E/p >$ is measured to evaluate uniformity and linearity during data taking
  - Expected $< E/p > < 1$ due to the non-compensating nature of TileCal (sampling calorimeter: $e/h = 1.36$)
  - Jets are further calibrated to the jet energy scale
  - Data/MC agreement within 5%




- Isolated **muons from cosmic rays** are used to study in situ the EM scale and the cells inter-calibration
  - Cell response is evaluated as the energy deposited by the muon path length $dE/dx$
  - < 5% non-uniformity in the $\eta$ response to cosmic muons and <1% in $\phi$



# Performance: Response to jets

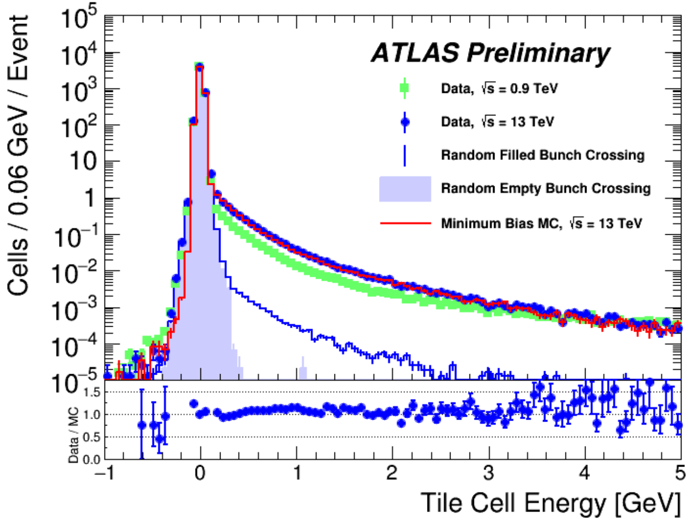
- Good description of the cell energy and noise distributions are crucial for building topoclusters and to reconstruct the missing transverse energy

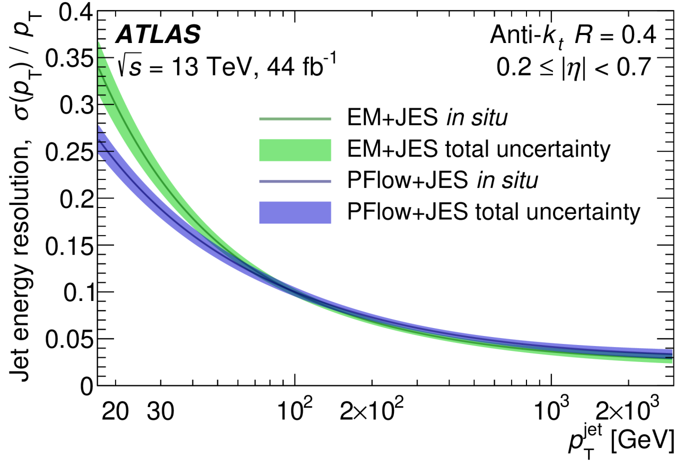
- Good data/MC agreement in the tile cell energy distribution

- Jet energy resolution better 10% for $p_T^{jet} > 100$ GeV

- TileCal designed for $\frac{\Delta E}{E} \sim \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$

- Constant term within the expected 3%



# Summary and Conclusions

- The Tile Calorimeter is an important part of the ATLAS detectors: contributes to the measurement of the 4-momenta of jets and the missing energy
- Each step of the signal production, from scintillation light to digital signal amplitude is monitored and calibrated using dedicated calibration systems
- Inter-calibration and uniformity are assessed with isolated charged hadrons and high-momentum cosmic muons
- The stability of the absolute cell energy scale was maintained to be better than 1% during Run 2 data taking
- Maintenance and Data Quality activities kept the overall Data Quality efficiency ~ 99.7 % in Run 2
- Much more activities related to the Phase II Upgrade in C. Clement's talk

# ACKNOWLEDGEMENTS

Fundação para a Ciência e a Tecnologia

Lisb@20^20

COMPETE 2020 PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

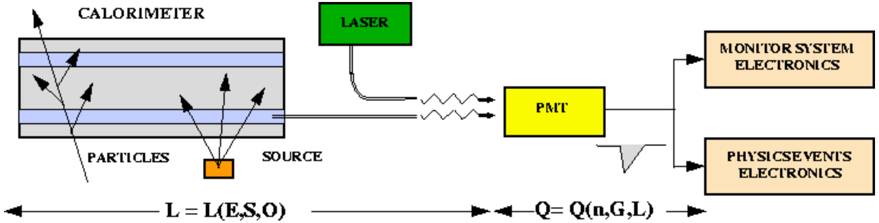
PORTUGAL 2020

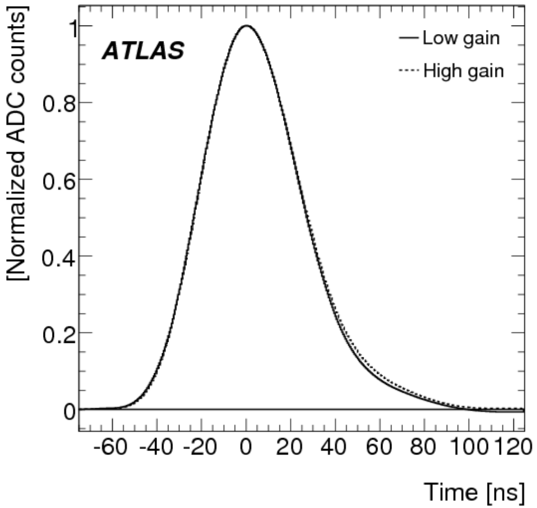
UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional

CERN/FIS-PAR/0002/2019

# BACKUP

# Signal Readout and Reconstruction




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

$$E[GeV] = A[ADC] \times f_{ADC\rightarrow pC} \times f_{pC\rightarrow GeV} \times f_{Cs} \times f_{Laser}$$

- $f_{pC\rightarrow GeV}$ is the EM energy scale constant measured during test beam (2001-2003)

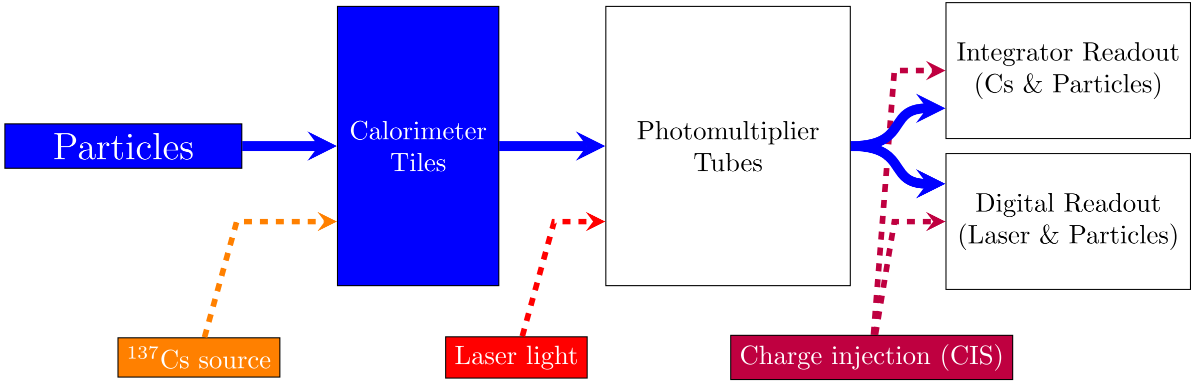
# TileCal Calibration Systems

$$E[GeV] = A[ADC] \times f_{ADC\to pC} \times f_{pC\to GeV} \times f_{Cs} \times f_{Laser}$$

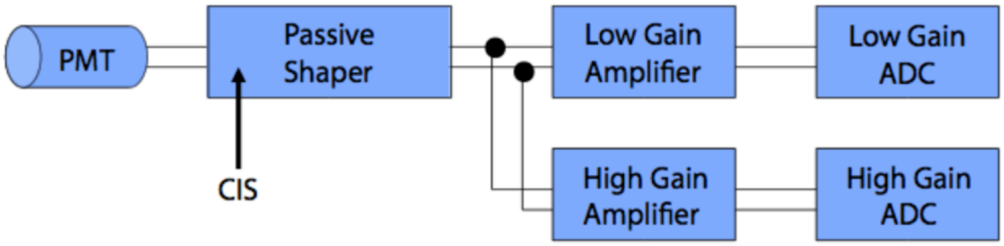
- A calibration system dedicated to monitor each step of the readout chain

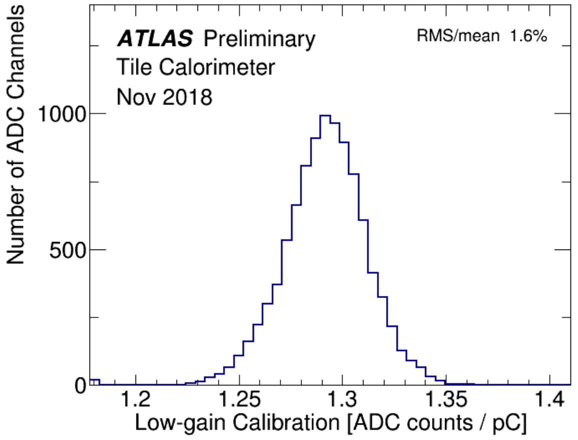
- Cesium source calibrates optical components and PMTs responses: $f_{Cs}$
- Laser light system calibrates the response of PMTs and readout electronics: $f_{Laser}$
- Charge Injection System (CIS) calibrates the response of ADCs: $f_{ADC\to pC}$
- Integrator readout of Physics events to monitor the full detector response

- Cell response fluctuates due to PMT and scintillators performance variation, correlated to LHC operation

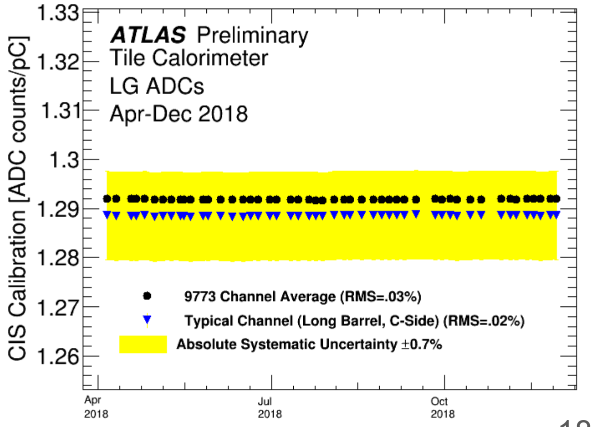


# Charge Injection system



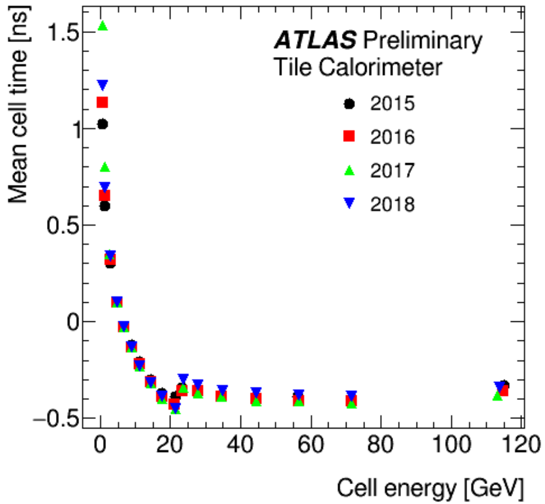



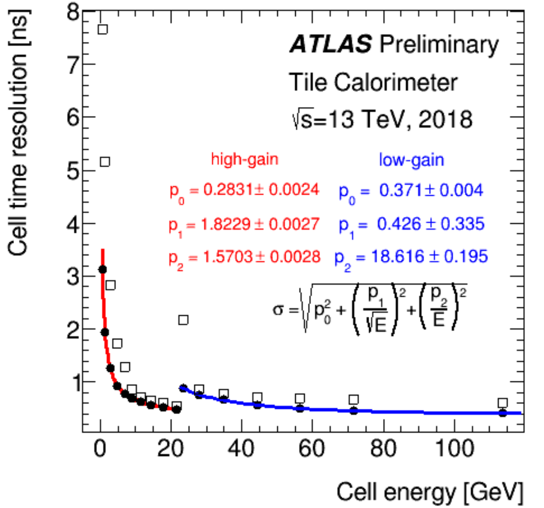

- Calibrates the response of analog amplifiers and ADCs, and evaluates their linearity
- Injection of known charge signal (0 to 800 pC), shaped to match PMT signal
- Dedicated runs taken weekly to extract the pC to ADC conversion factor
- Also used in the calibration of the analog Level 1 Calorimeter trigger
- Precision of 0.7% and stability over time is ~0.03%



# Time Calibration

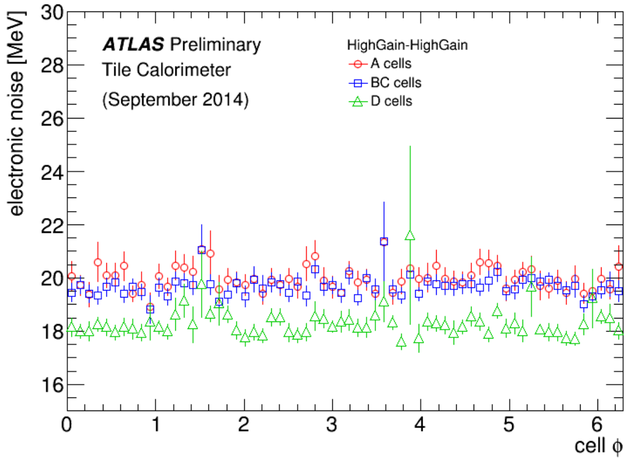
- Time calibration impacts the cell energy reconstruction
- Adjusts the digitiser sampling clock to the peak of the signal produced by a particle traveling through the cell
- Bad time calibration can underestimate reconstructed signal amplitude
- Time calibrations derived from time distribution in cells associated to jets, additional monitoring from laser signals
- Average cell time ~0.4 ns for $E_{cell} >$ 20 GeV
- Resolution better than 1 ns for $E_{cell} >$ 4 GeV
- Timing can also be explored to perform TOF measurements useful in searches for long-lived particles (e.g. R-hadrons)

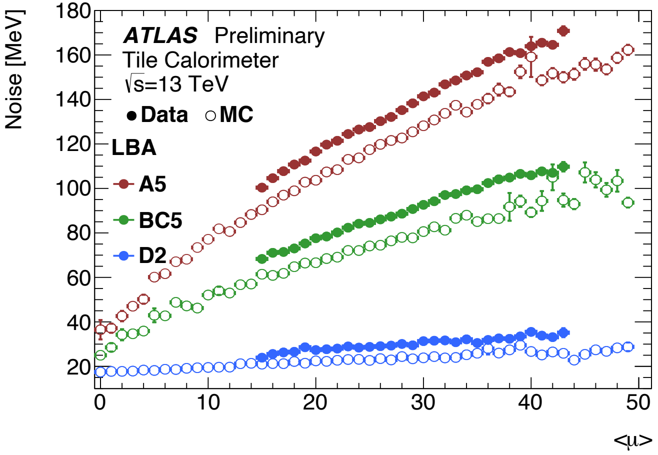


# Noise measurement

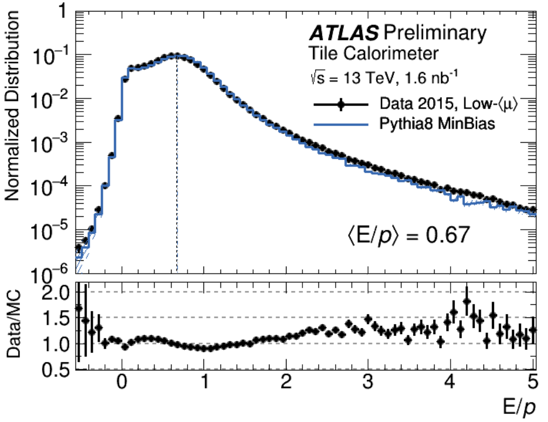
- Total noise per cell in the calorimeter comes from:
  - Electronics: measured in dedicated runs without signal in the detector
  - Pile-up: energy deposits from multiple collisions in the same event or from previous/next bunch crossing
- Electronics noise ~20 MeV for all cells, measured regularly in dedicated runs
- Pile-up noise dependent of the average number of interactions per bunch crossing
- Innermost cells in the A layer with larger energy deposits are more affected by pile-up noise

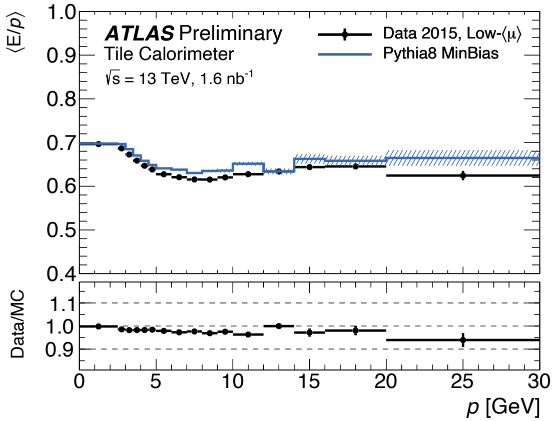


# Performance: Response to isolated hadrons

- The ratio of the calorimeter energy response to isolated charged hadrons (EM scale) to the track momenta $< E/p >$ is used to evaluate uniformity and linearity during data taking
- Measured in Minimum Bias events
- Expected $< E/p > < 1$ due to the non-compensating nature of the TileCal (sampling calorimeter: $e/h = 1.36$)
- Data/MC agreement within 5%
- Jets are further calibrated to the jet energy scale



# Performance: Response to cosmic muons

- Isolated muons from cosmic rays are used to study in situ the EM scale and the cells inter-calibration

- Cell response is evaluated as the energy deposited by the muon path length $dE/dx$

- Good energy response uniformity over $\phi$

- < 5% non-uniformity in the $\eta$ response to cosmic muons