Calibration and performance of the ATLAS Tile Calorimeter during the Run 2 of the LHC

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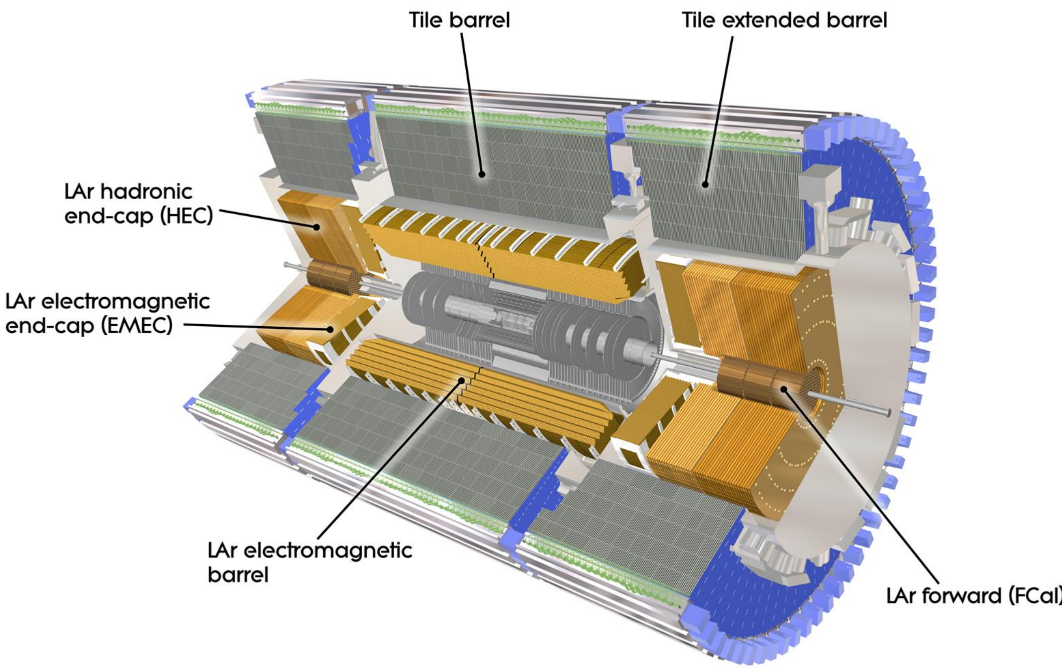
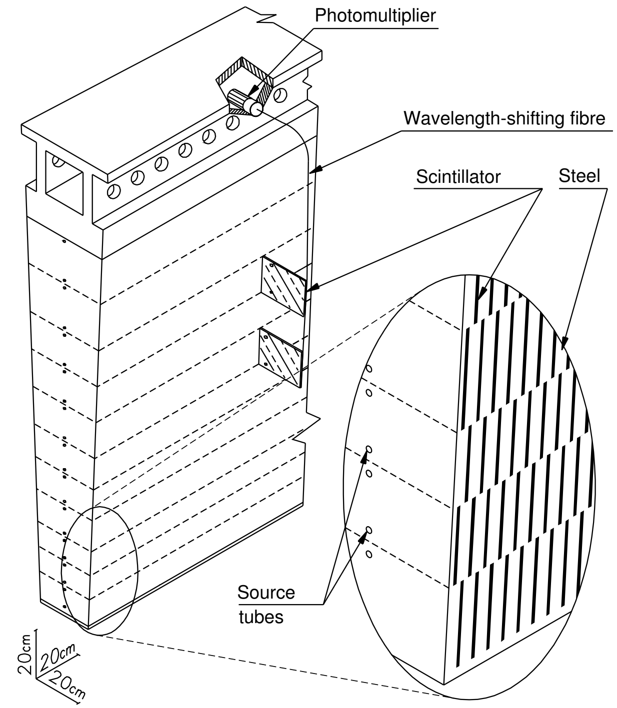
Oleg Solovyanov (IHEP, Protvino)
on behalf of the ATLAS Collaboration

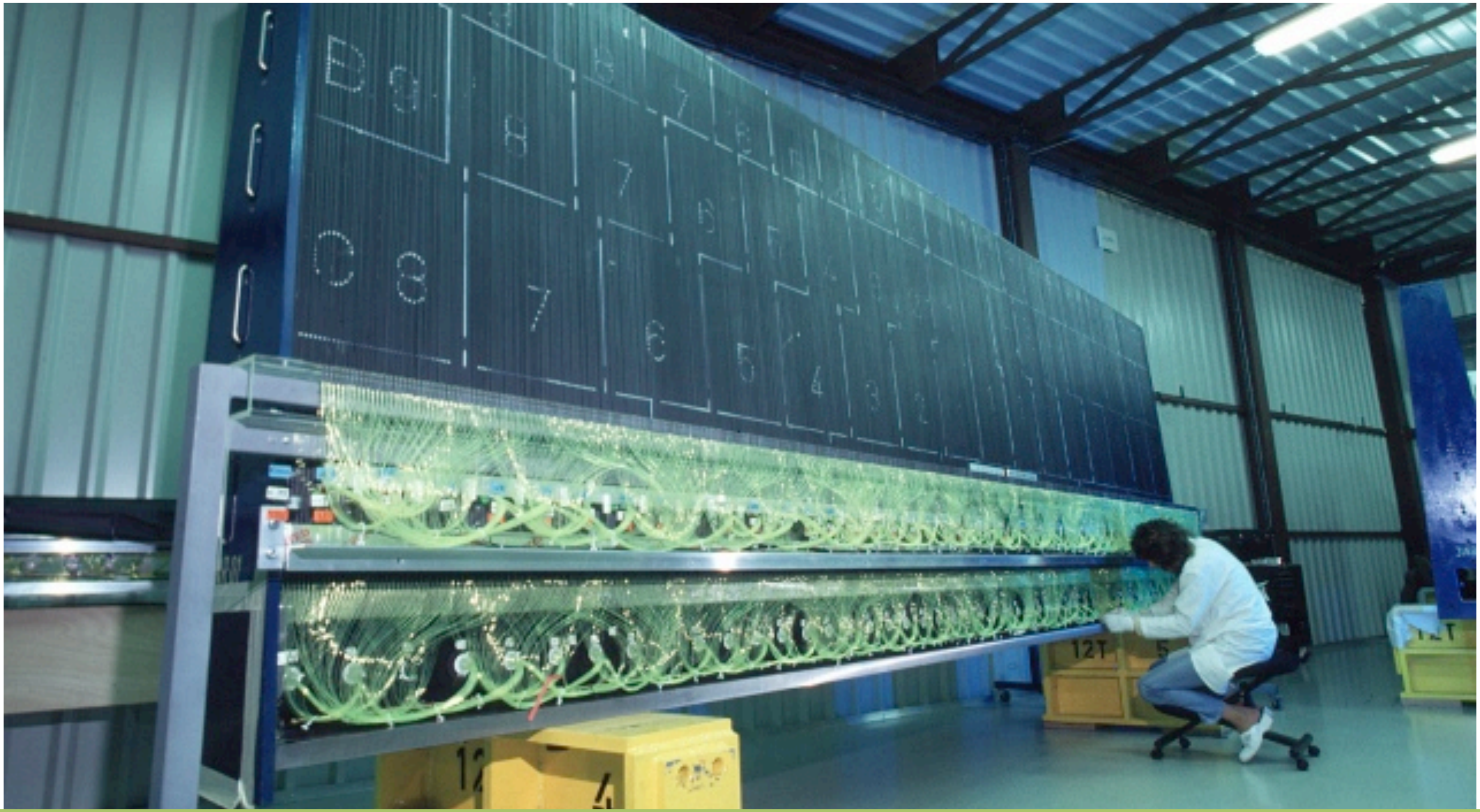
ATLAS Tile Calorimeter





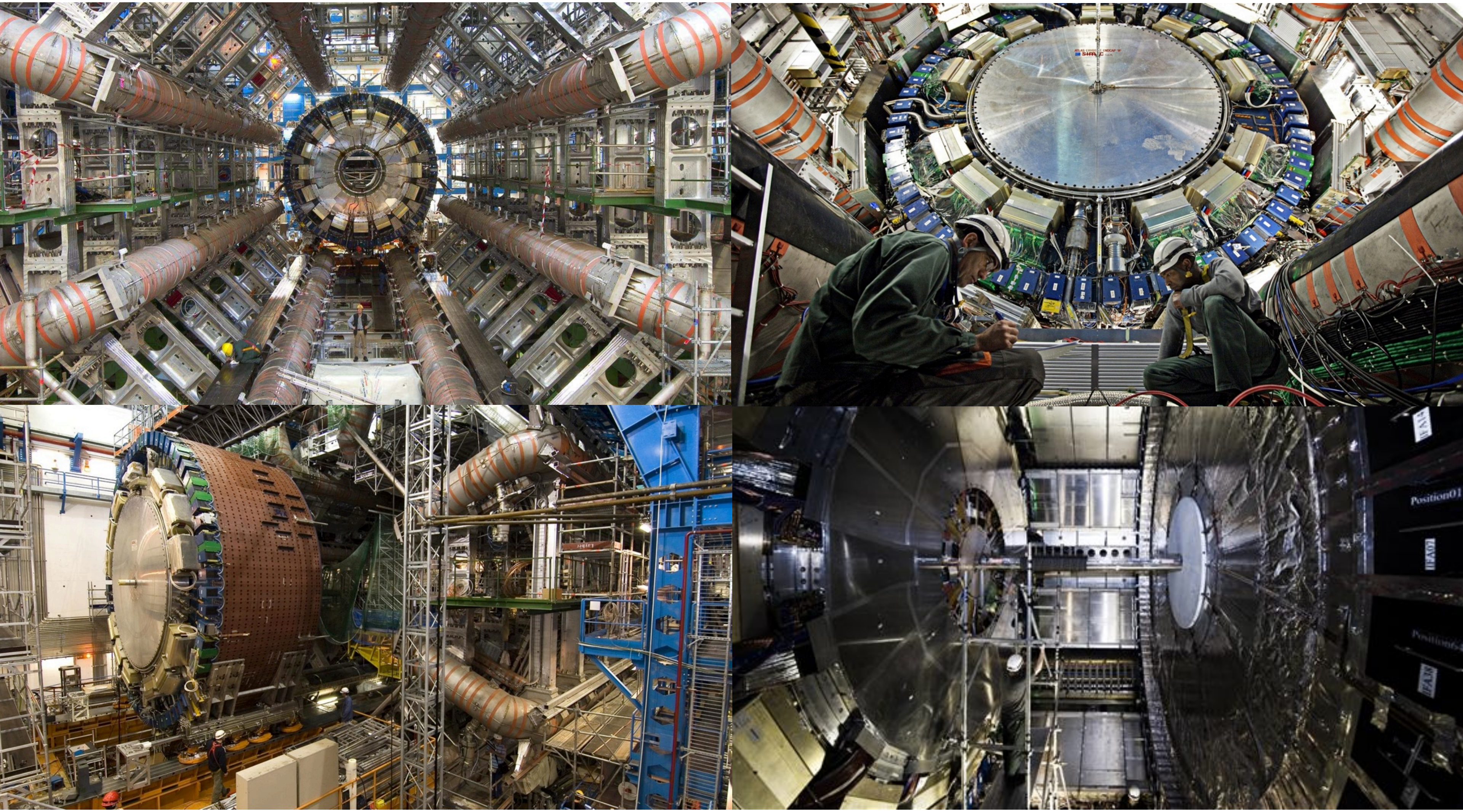
- Hadron non-compensating sampling calorimeter with steel as radiator and scintillating tiles as active medium. 3 mm thick scintillating tiles (PSM or BASF polystyrene + dopants) oriented perpendicular to beam axis, wrapped in Tyvek paper
- Readout via green WLS fibres (Kuraray Y11) connected to both short edges of scintillating tiles
- 10k Hamamatsu R7877 PMTs, located in a module's girder, collect light from the fibre bundles
- 3 cylinders: one Long Barrel (with two readout regions LBA,LBC) and two Extended Barrels (EBA,EBC), 64 modules in a cylinder, 12 m overall length with 4.25 m outer radius

Tile Calorimeter module

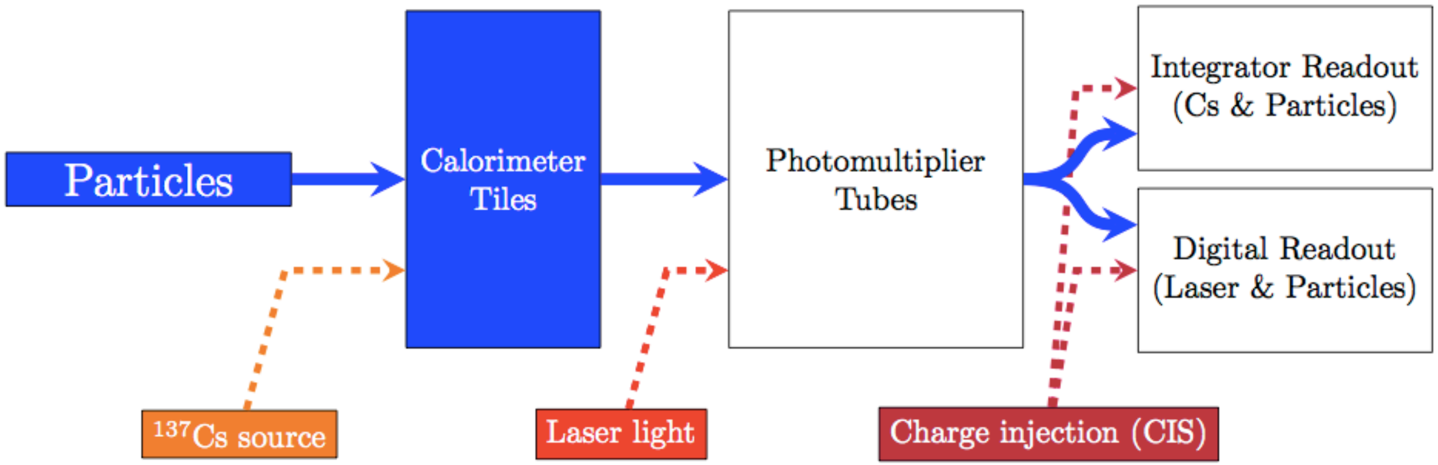


- Long barrel $|\eta|<1.0$, extended barrel $0.8 <|\eta|< 1.7$, three longitudinal layers (A,BC,D), total thickness of about 7.4λ
- WLS fibre routing defines 5200 calorimeter cells: 0.1x0.1 $\Delta\eta \mathrm{x} \Delta\phi$ cell granularity (0.2x0.1 for D layer cells)
- Hermetic coverage, pseudo-projective towers for first level trigger
- Dynamic range of PMTs: 10 MeV to 750 GeV
- Design resolution for jets $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$, linear within 2% for up to 4 TeV jets

Calorimeter in the cavern



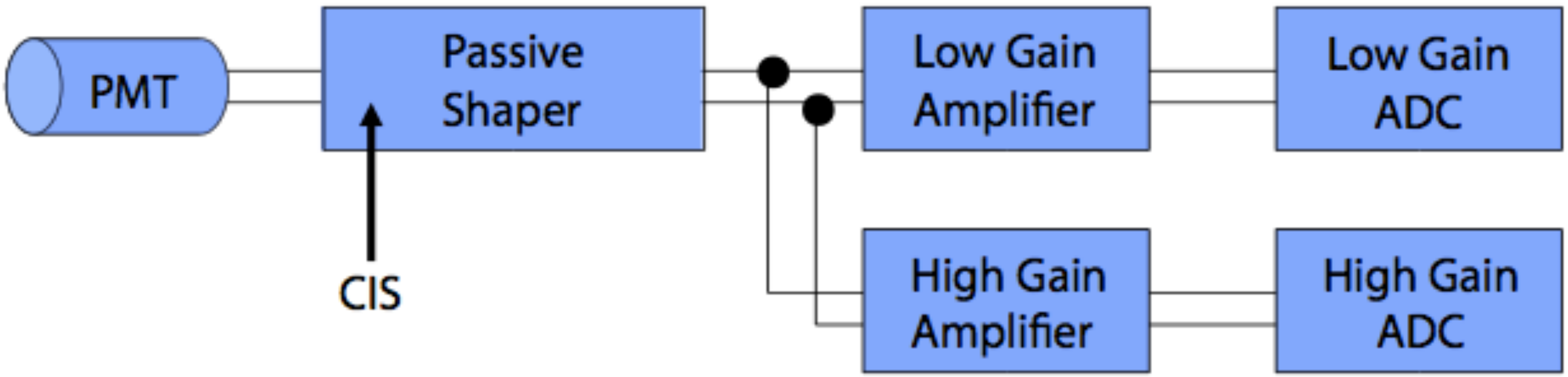
Calibration systems



$$E[\mathrm{MeV}] = A[\mathrm{ADC}] \times C_{CIS}\left[\frac{\mathrm{pC}}{\mathrm{ADC}}\right] \times C_{TB}\left[\frac{\mathrm{MeV}}{\mathrm{pC}}\right] \times C_{LASER} \times C_{Cs}$$

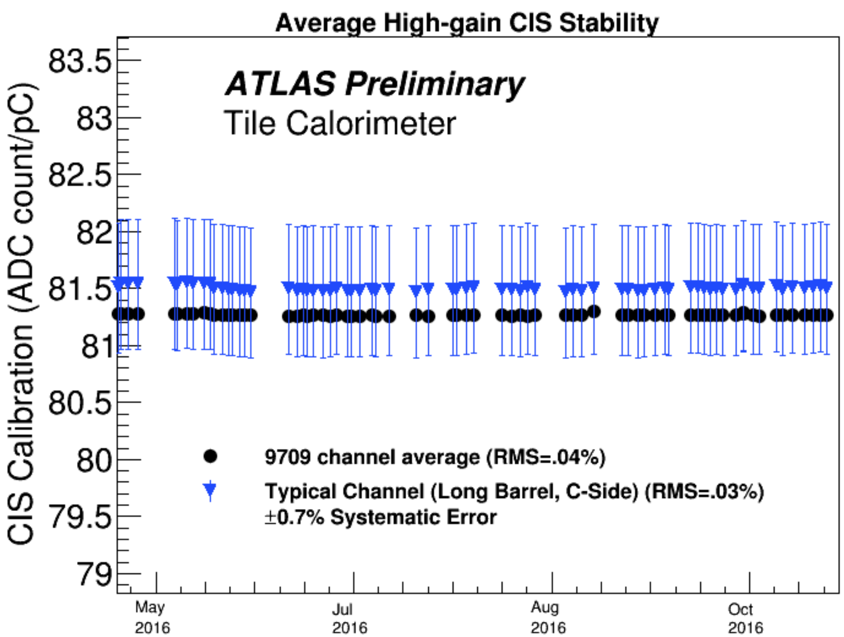
- To provide correct energy and time for data reconstruction, an elaborate chain of calibration systems is used:
  - Charge injection system (CIS) to calibrate the response of the ADC
  - Laser calibration system to measure the performance of the PMTs
  - Cesium radioactive source system (Cs) to calibrate the full optical path from scintillating tiles and WLS fibres down to integrated current of the PMT
  - Minimum bias monitoring system (MBM) to monitor the response of the calorimeter online via integrated currents of PMTs
- About 11% of 192 Tile calorimeter modules were calibrated at the test beams and the EM scale (1.05 pC/GeV) was transferred to the final detector with the help of calibration systems

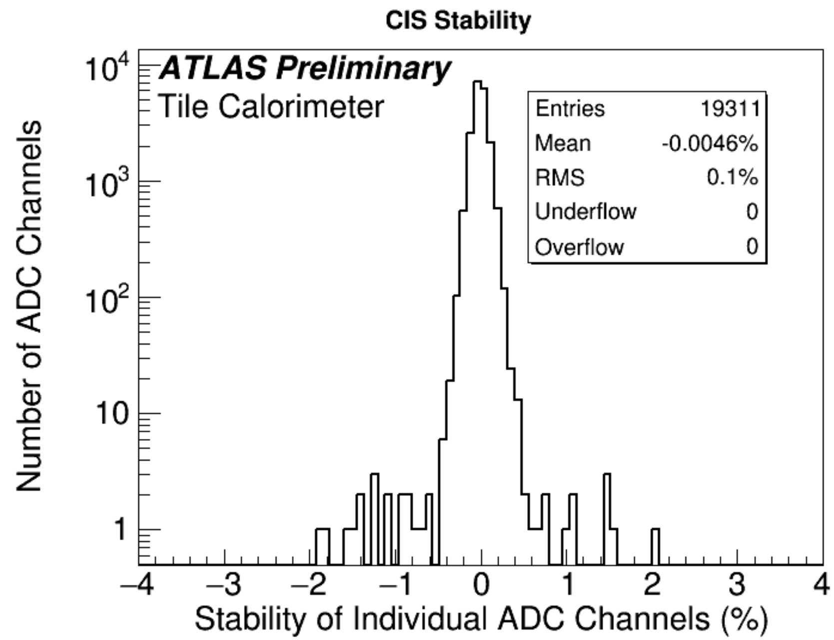
Charge injection system (CIS)



- Charges of known values, spanning the full range of ADC (0-800 pC) are injected by a 5.2 pF (±2%) or more precise 100 pF capacitor (±1%)
- The passive pulse shaper produces a pulse with a Gaussian shape (≈50ns), then the pulse is split and sent through 2 different amplifiers separated by a gain of 64
- The injection timing with respect to the ADC clock can be varied
- This allows to simulate a physics pulse from PMT and to calibrate both high and low gain ADCs (although the CIS pulse is shorter and has a leakage part)
- Also used to calibrate analog L1 calorimeter trigger

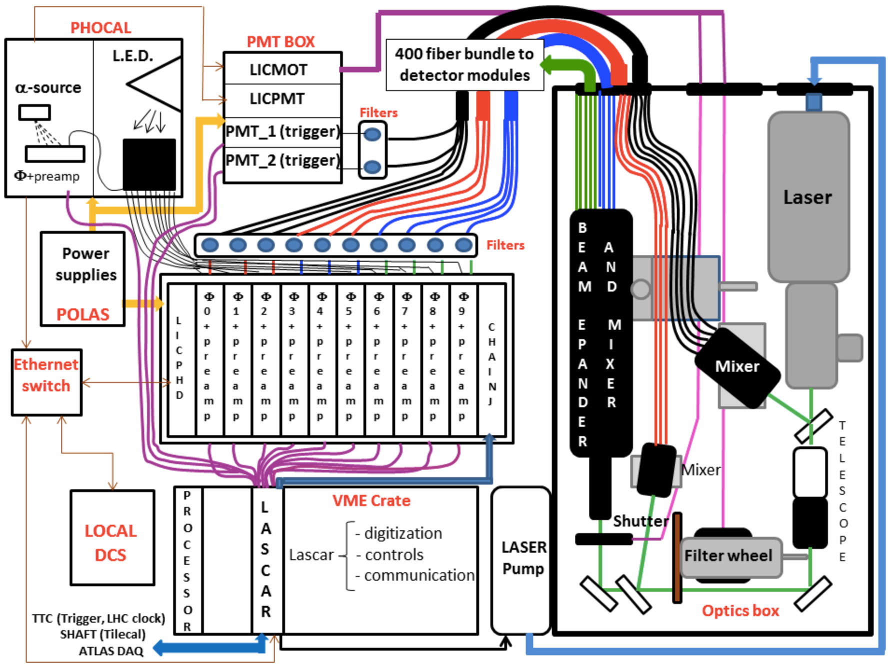
Charge injection calibration

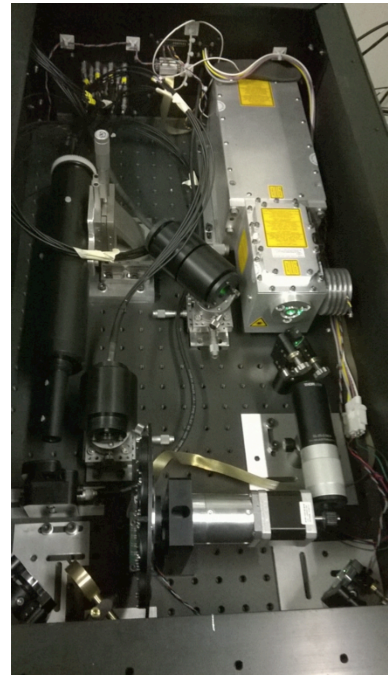


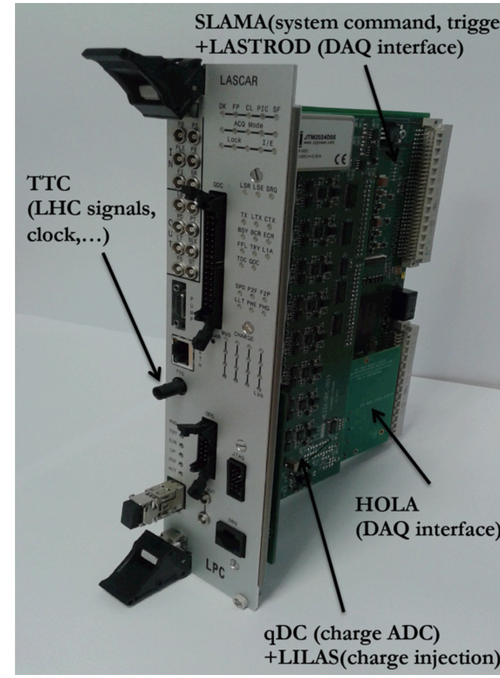


- The charge of varying amplitude is injected and the slope of the response vs. injected charge gives the CIS constant for that ADC
- Calibration is usually performed twice a week (few minutes)
- Typical uncertainty is 0.7%
- Stable within 0.04% overall in 2016

Laser system

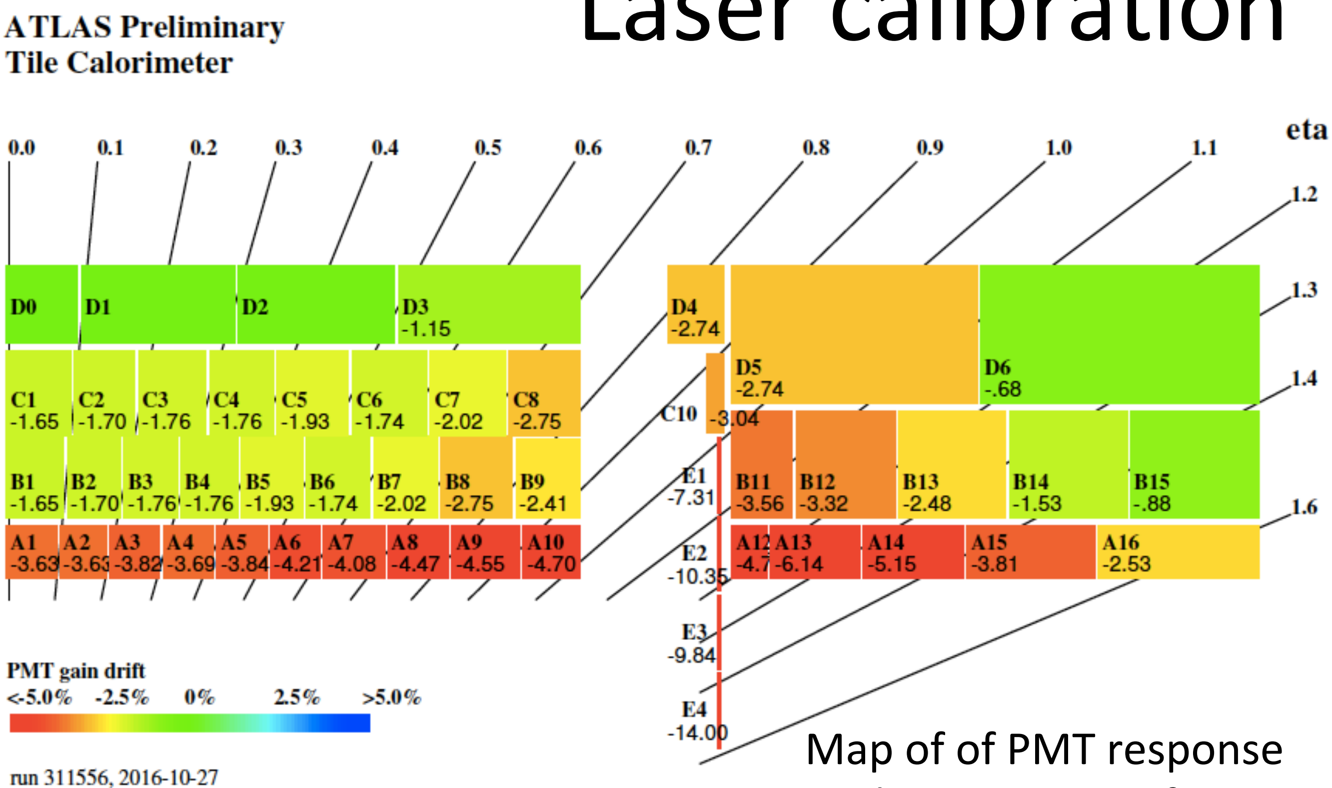




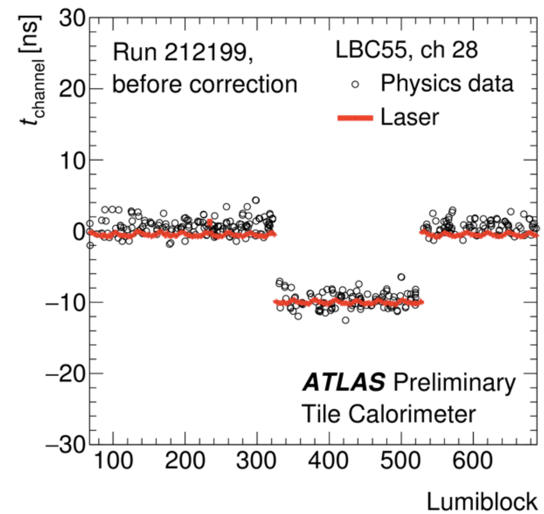


- PMT gain drift affects the detector response and calibration
- Laser system delivers 532 nm green light via 400x 100m long clear fibres to all PMTs
- Upgraded optics box and control electronics for Run 2
- Better laser light monitoring with more diodes, rack vibration isolation
- Precision on the gain variation measurement is better than 0.5%
- New integrated 6U VME control card

Laser calibration



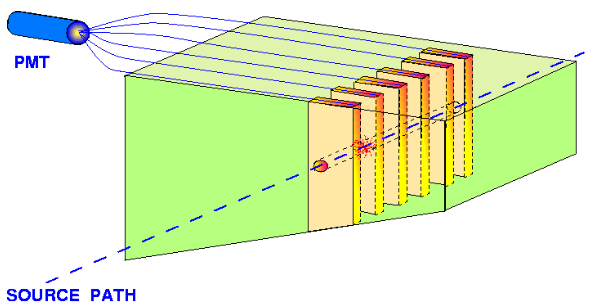
Map of of PMT response variation during pp run of 2016

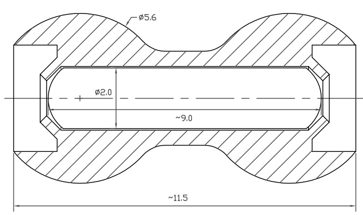


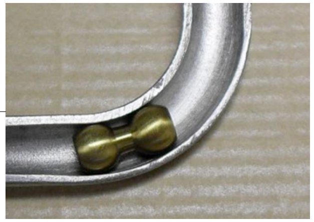
“Timing jump”

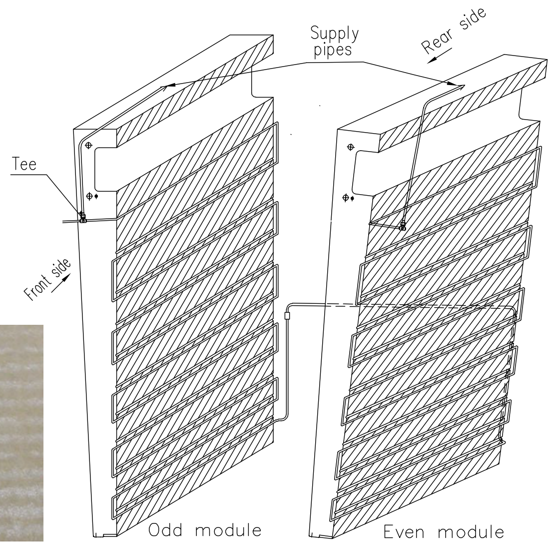
- Laser is used to monitor the gain and stability of the PMTs
- To cross-check problematic channels (unstable HV or bad CIS)
- To set-up and cross-check timing, provide correction for “timing jumps”
- Two calibration runs per week, special long sequence of runs (1 hour)

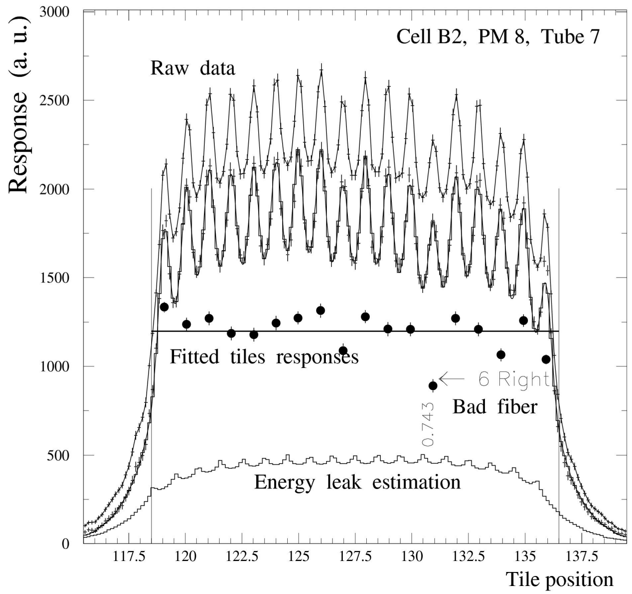
Cs system





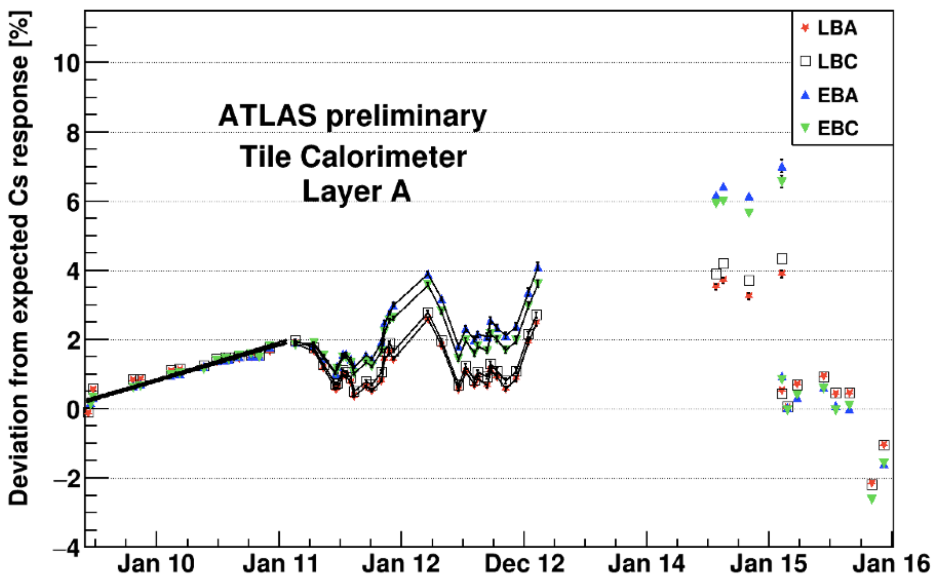


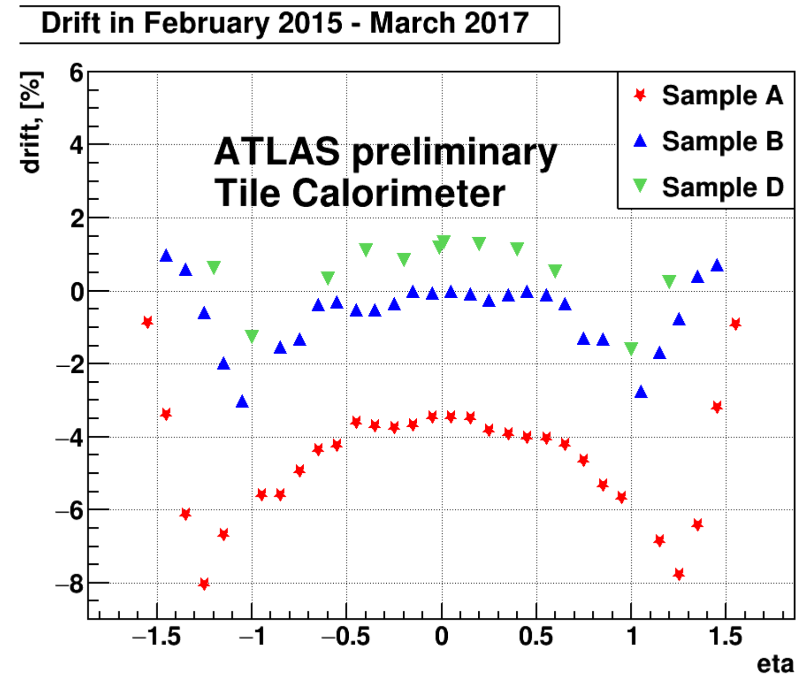




- Powerful (10 mCi) and stable ($t_{1/2}$ of 30 years) ^{137}Cs gamma-source (0.662 MeV) in dumb-bell shaped capsule
- Movable by flow of water inside calibration tubes through all of the 463000 of calorimeter scintillating tiles, with the speed of 30 cm/s
- PMT integrated currents readout during the source movement
- Allows to have calibration of complete optical chain and monitoring of the calorimeter response over time

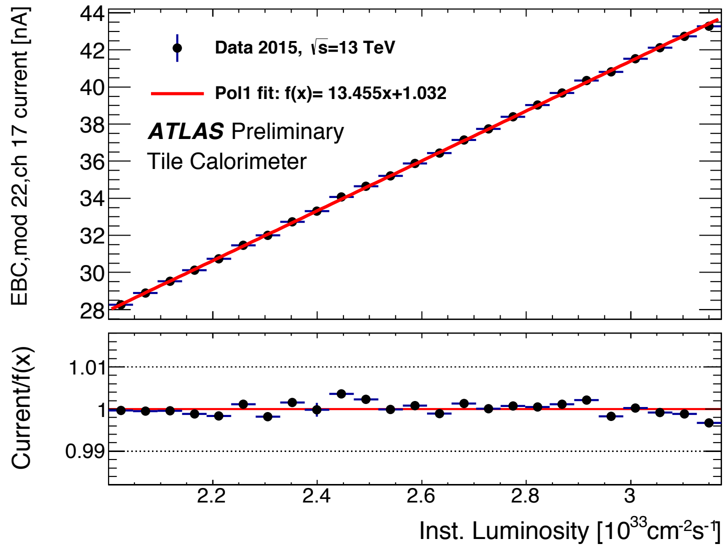
Cs calibration

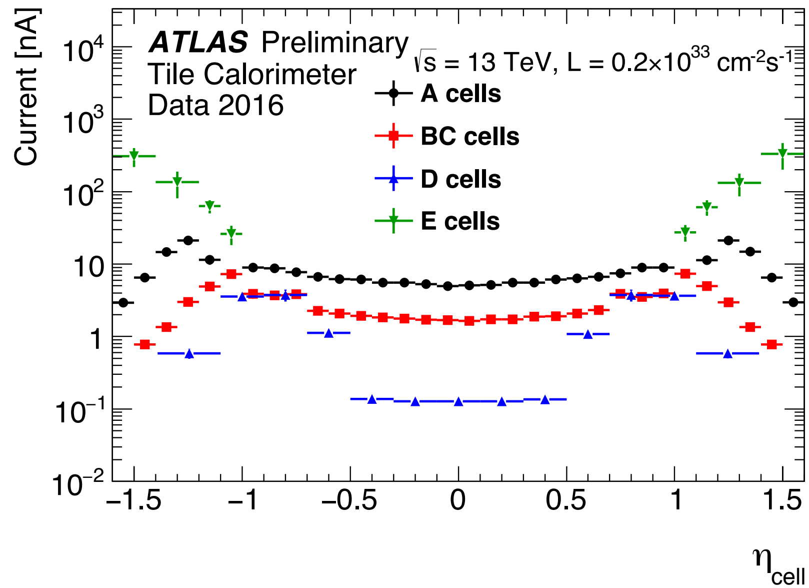




- Transfers EM scale from test beam measurements to all modules
- Provides pC->MeV calibration constants
- Allows to adjust PMT gain (changing high voltage) to restore calorimeter response uniformity
- Precision of the measurement is better that 0.3%
- Full calibration scans at the beginning and end of the year, monthly scans in between
- Scans are taken in parallel in 3 detector cylinders, 8 hours per scan

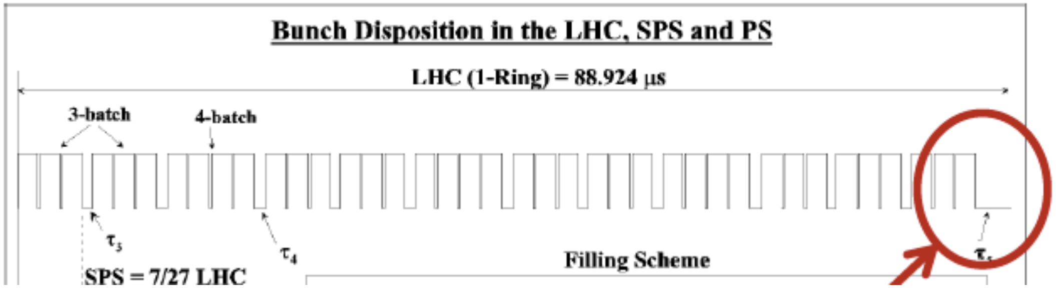
Integrated currents monitoring

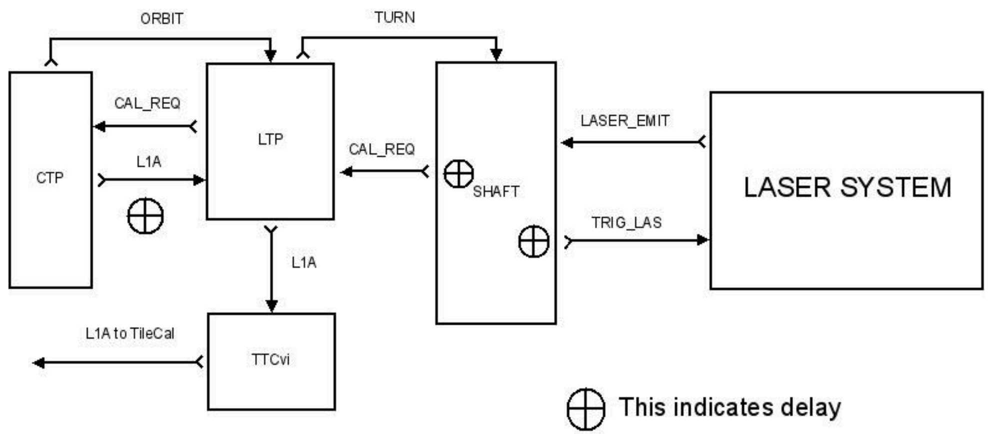


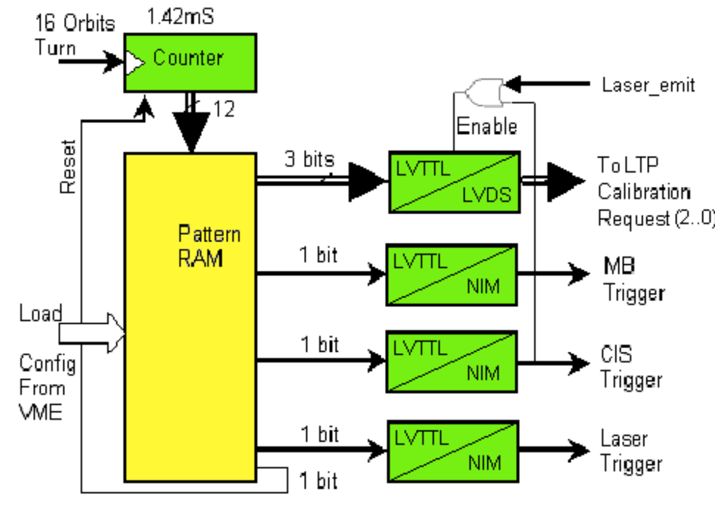


- Integrated currents (~10 ms) from PMTs are measured and stored by minimum bias monitoring system via separate slow data path (CANbus)
- Provides additional luminosity measurements and cross-check of other luminometers
- Tracks overall calorimeter response behaviour between Cs source scans

Calibration in empty bunches



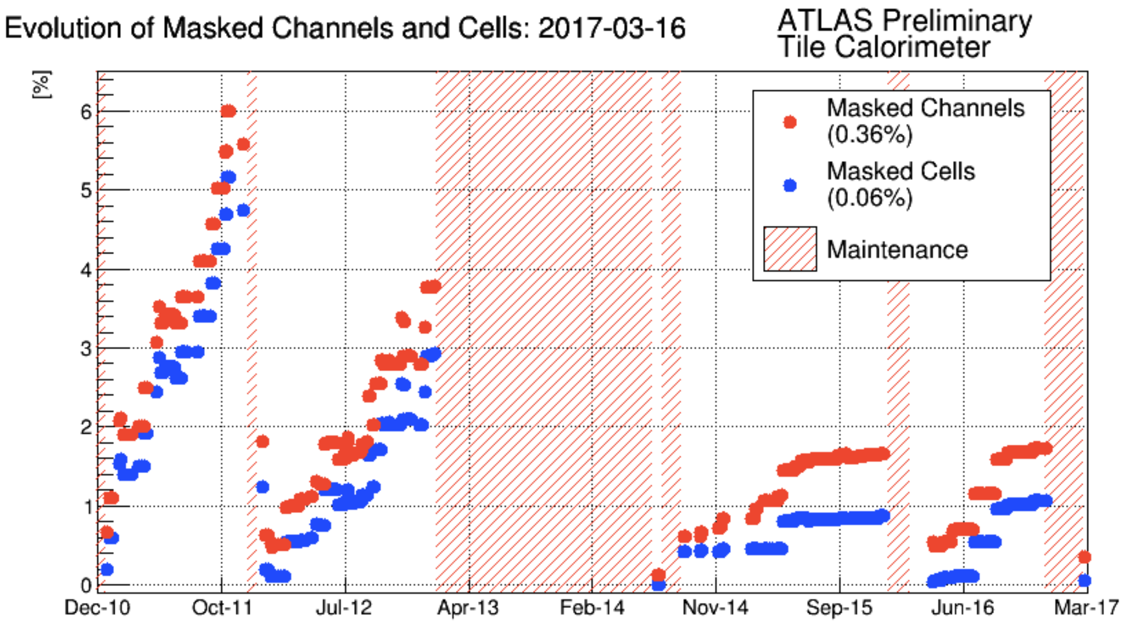


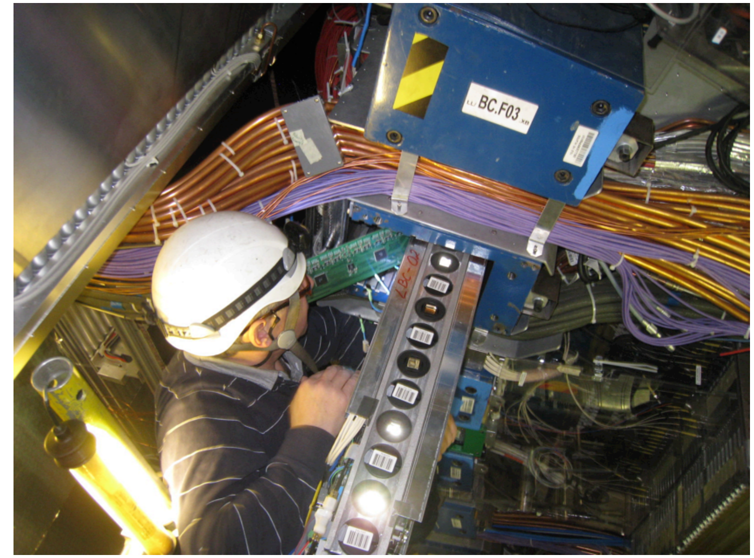


SHAFT board

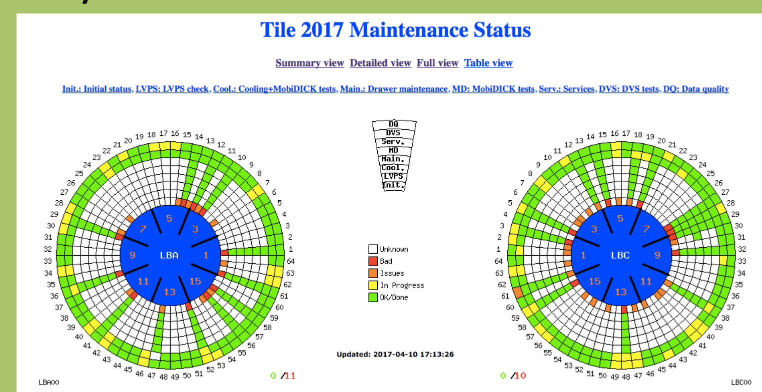
- LHC beam abort gap (~3 us) used for calibration “in parallel” with collisions
- Laser and minimum bias (currents) monitoring
- SHAFT 6U VME board with pattern memory to control, time in and arbitrate calibration pulses and calibration trigger requests
- Laser pulses at the rate of 3 Hz during physics runs

Detector status

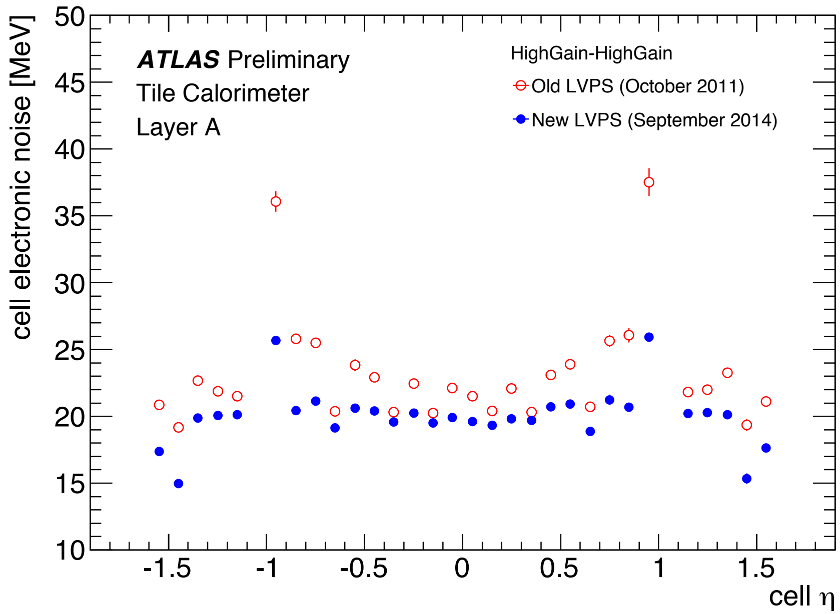


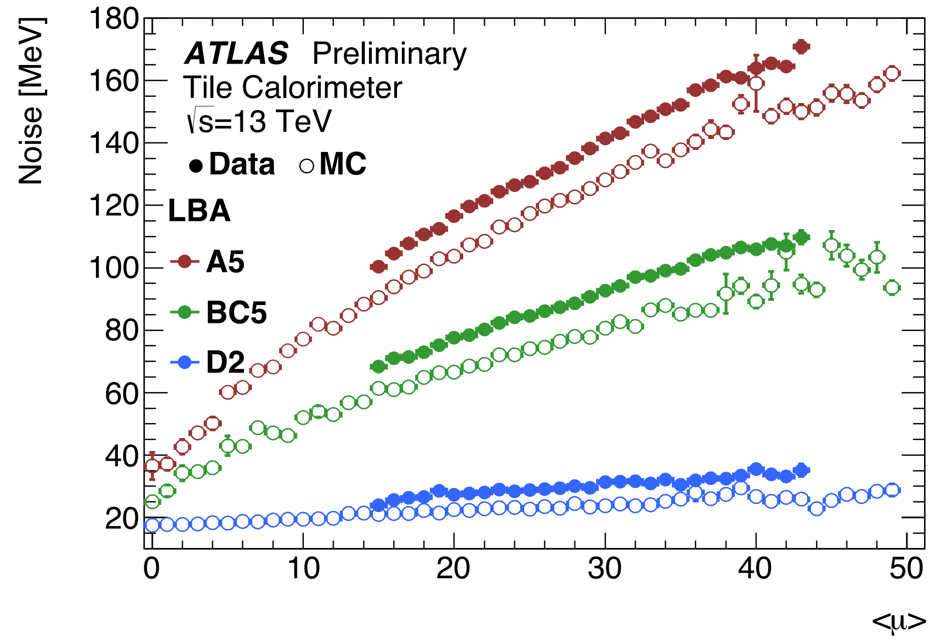


- 48/256 (~19%) modules were opened in the last shutdown of 2016-2017
- Fixed all high priority problems and many low priority ones
- Typical problems:
  - Digital errors
  - HV off for ¼ of module’s channels
  - Cooling air leaks
  - Integrator failures (FEB latch-up)
  - Cold soldering in power connector
  - Trigger tower low or no signal



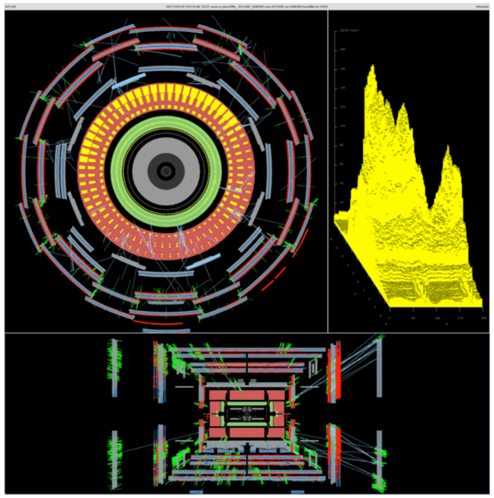
Noise

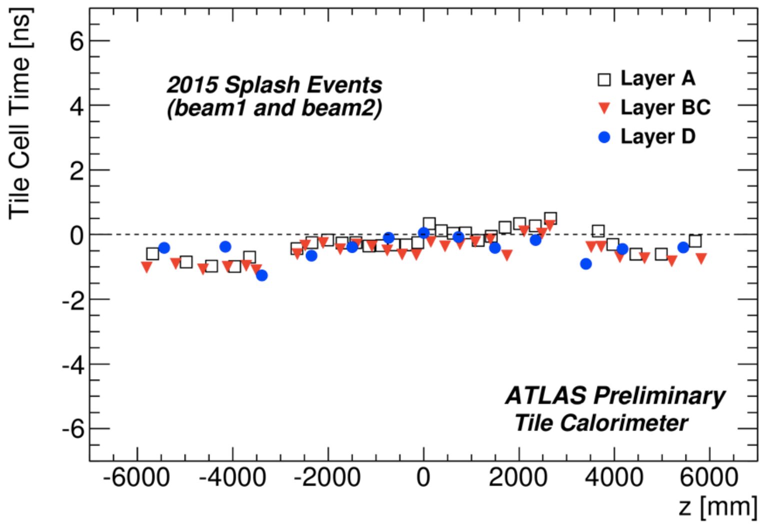


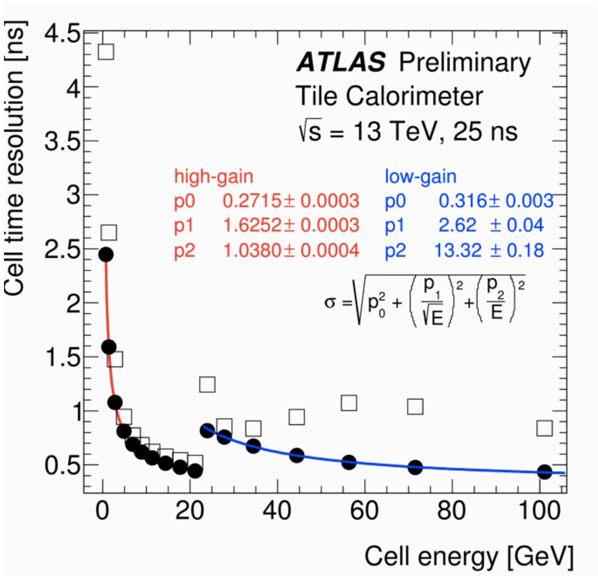


- Electronics noise stays at the level below 20 MeV for most of the cells. Pedestal and noise are measured regularly with calibration runs
- New power supplies (fLVPS), installed in long shutdown (2014), have better performance and more Gaussian noise
- Total noise is increasing with pile-up, especially for the inner layer

Time calibration

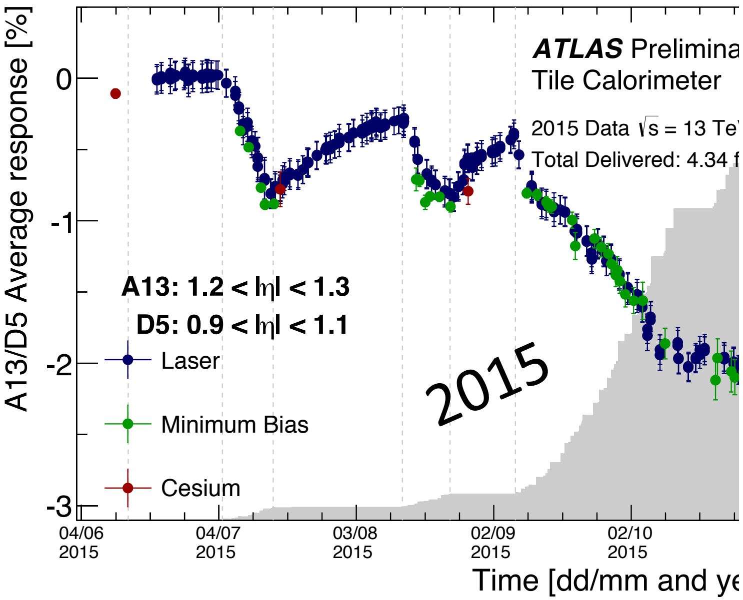


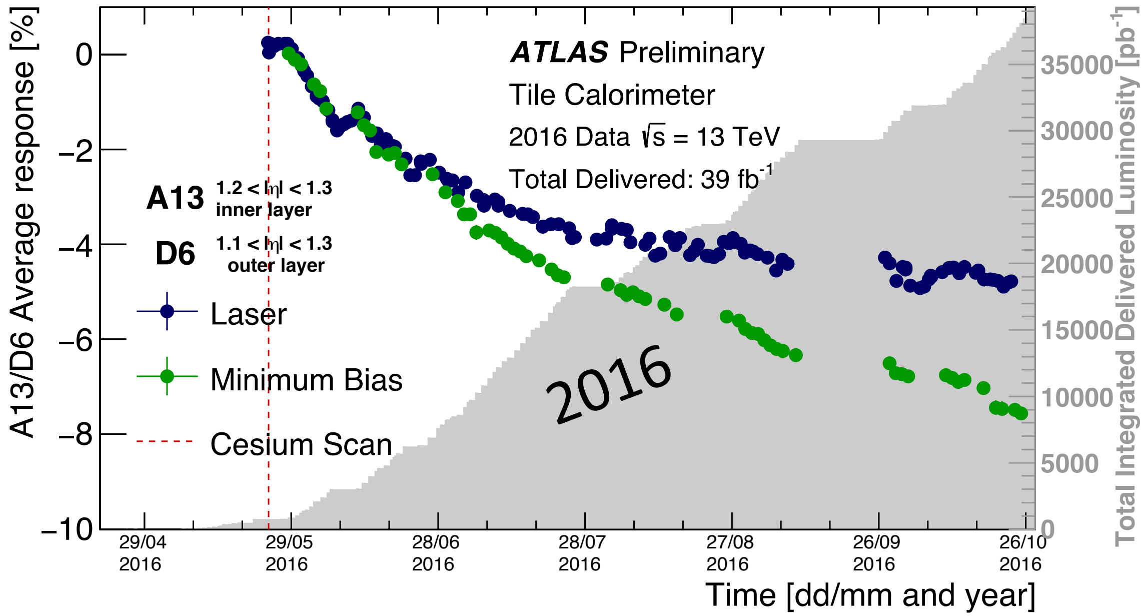




- Initially set with splashes (high-energetic muons from beam-collimator hits at the start of data taking period, few events)
- Tuned later with muons and jets
- Resolution is better than 1 ns for E_{cell} > 4 GeV
- Monitored during physics data taking with laser, eventual corrections

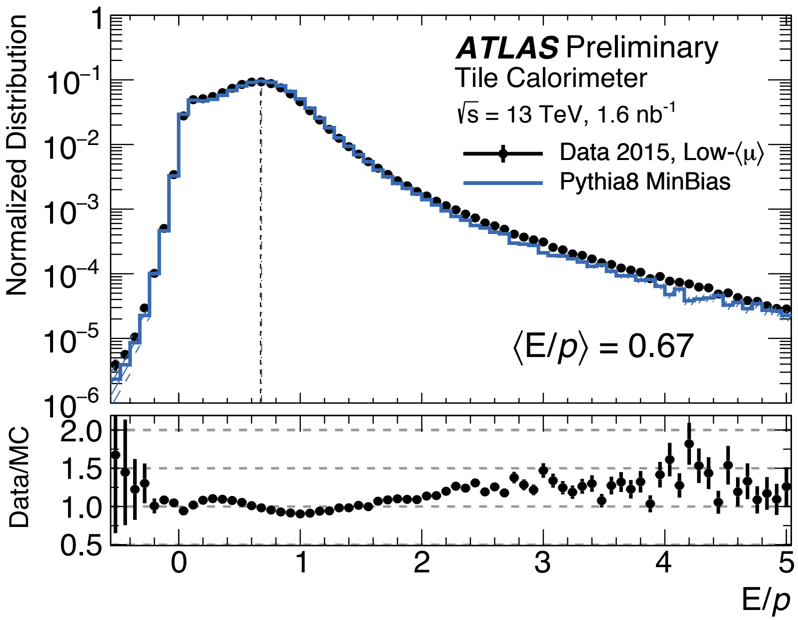
Detector response variation

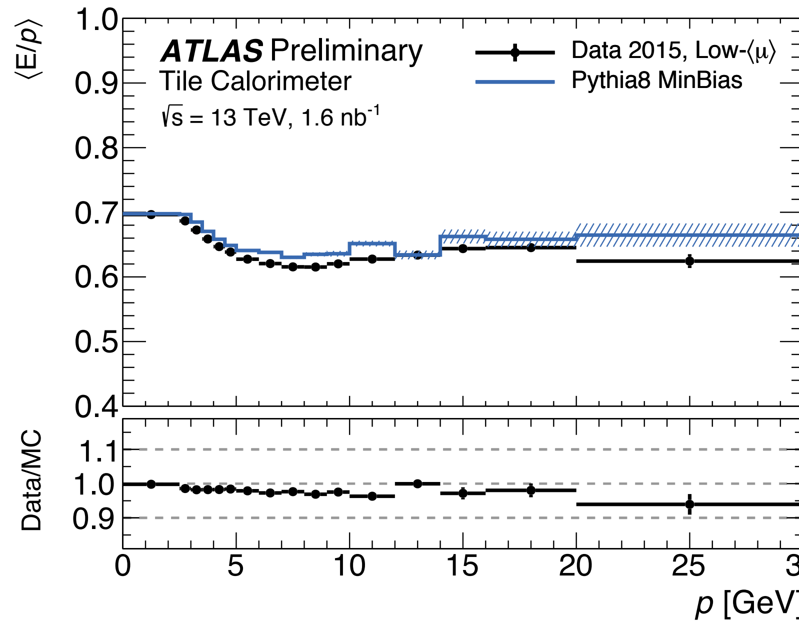




- Cell response is not constant in time due to the PMT gain variation and scintillator degradation, and the recovery of them
- Tracked with calibration systems
- Laser vs. Cs and minimum bias allows to derive irradiation effect
- Effect is more pronounced at higher integrated luminosity
- PMT gain can be recovered by raising the high voltage, while scintillator degradation is compensated by calibration constants

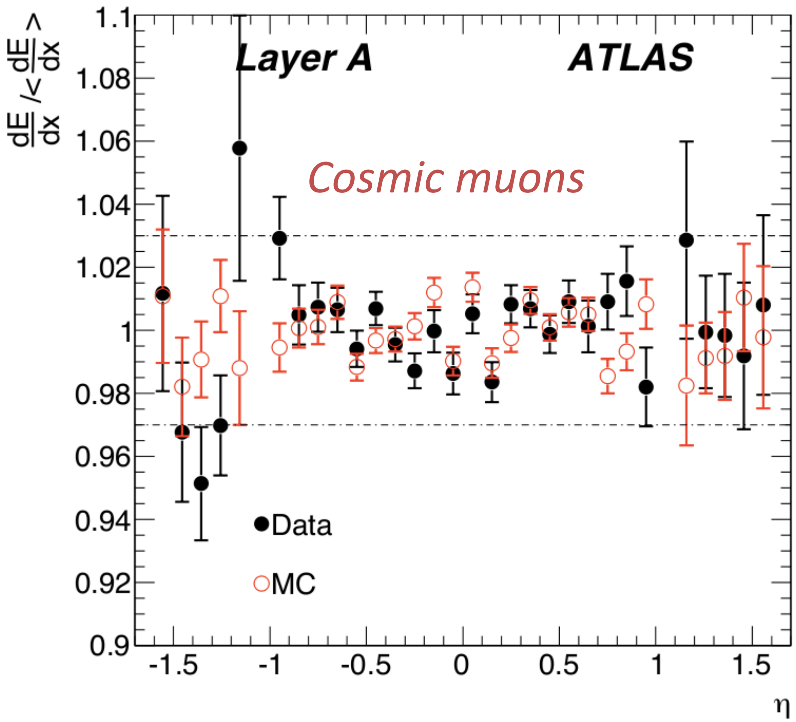
Single particle response

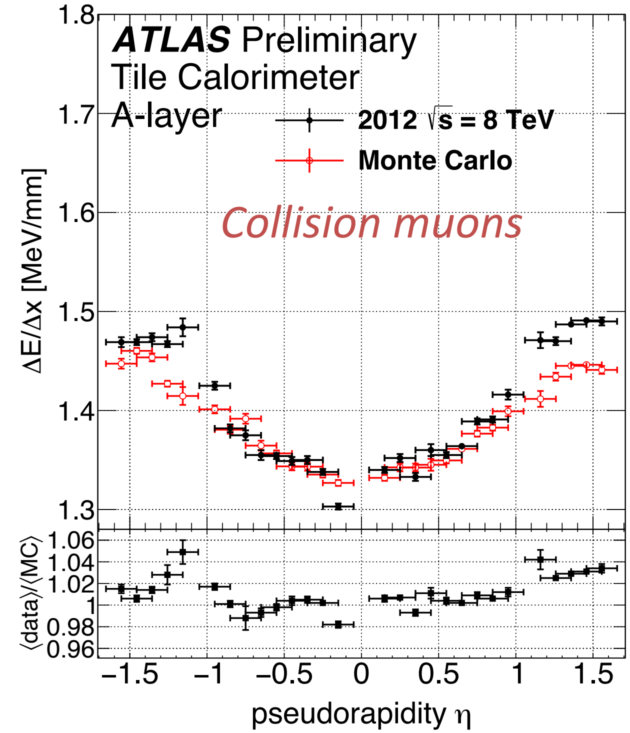




- An important Tile Calorimeter characteristic is the ratio of energy to track momentum (E/p) for isolated, charged hadrons in minimum bias events, is used to evaluate calorimeter uniformity and linearity during data taking
- Data and simulation do agree, showing linearity and uniformity in detector response
- dE/dx of minimum ionizing muons (near noise threshold) show data/MC within 3%

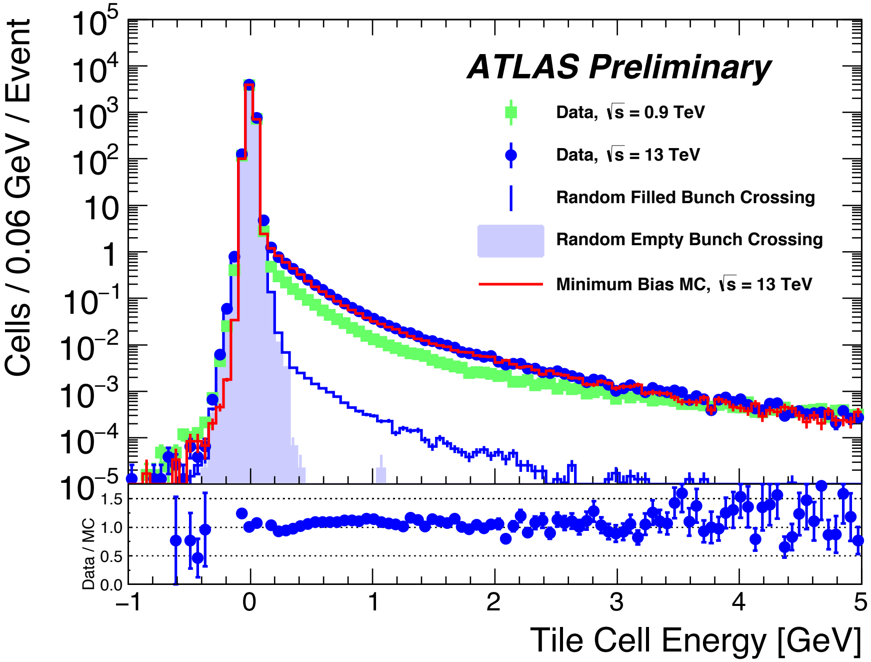
Muons

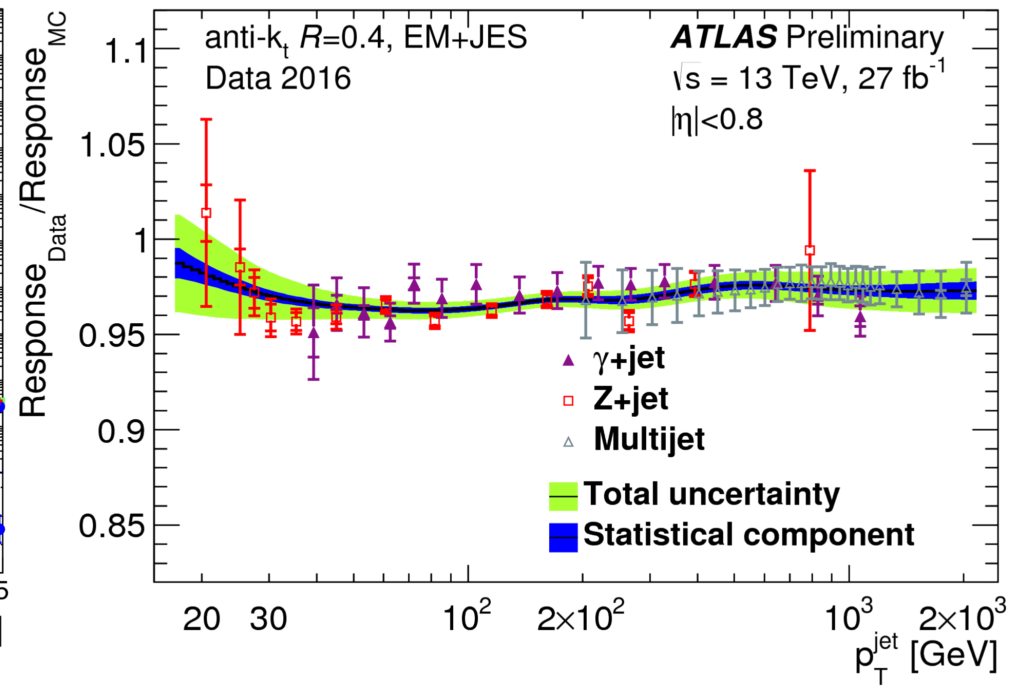




- Muons from cosmic rays, beam halo and collisions are used to study in-situ the electromagnetic energy scale
- 1% response non-uniformity in η in Long Barrel with cosmic muons
- A good energy response uniformity in all calorimeter layers
- The data/MC agreement is within 3%

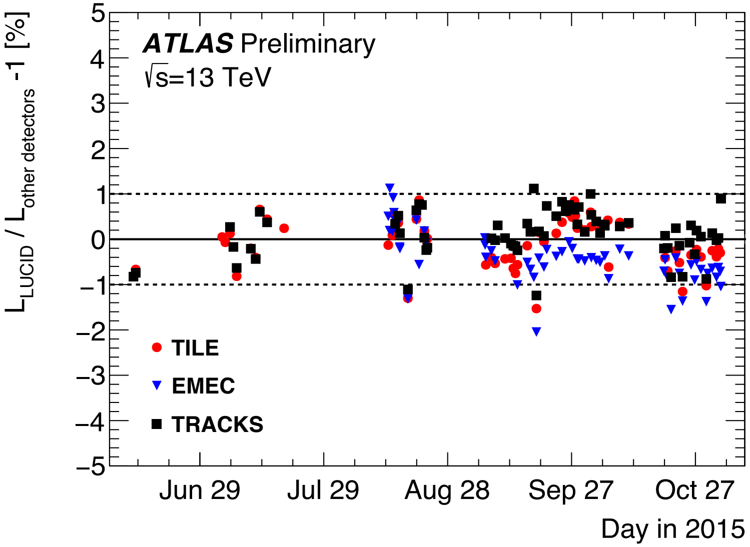
Jet performance

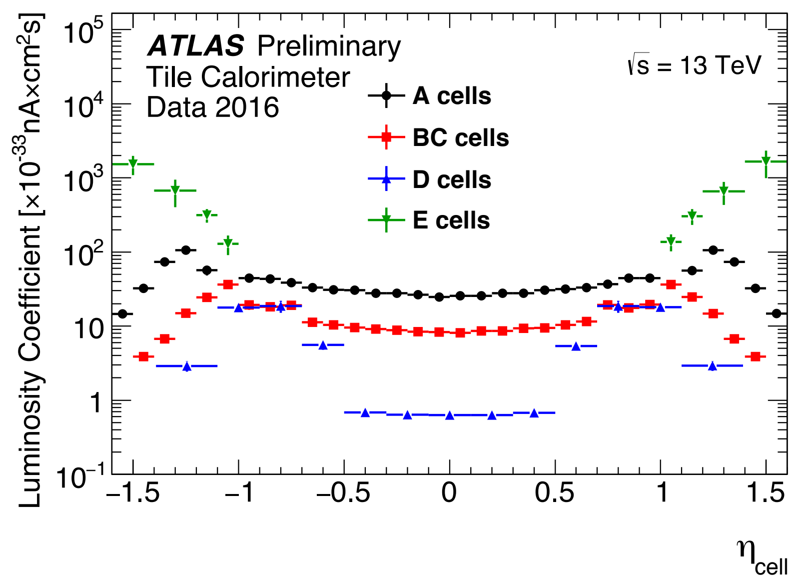




- Good agreement in Tile cell energy distribution
- Consistent overall jet energy scale
- Jet energy resolution is below 10% at p_T>100 GeV
- Constant term is within expected 3%

Luminosity measurements



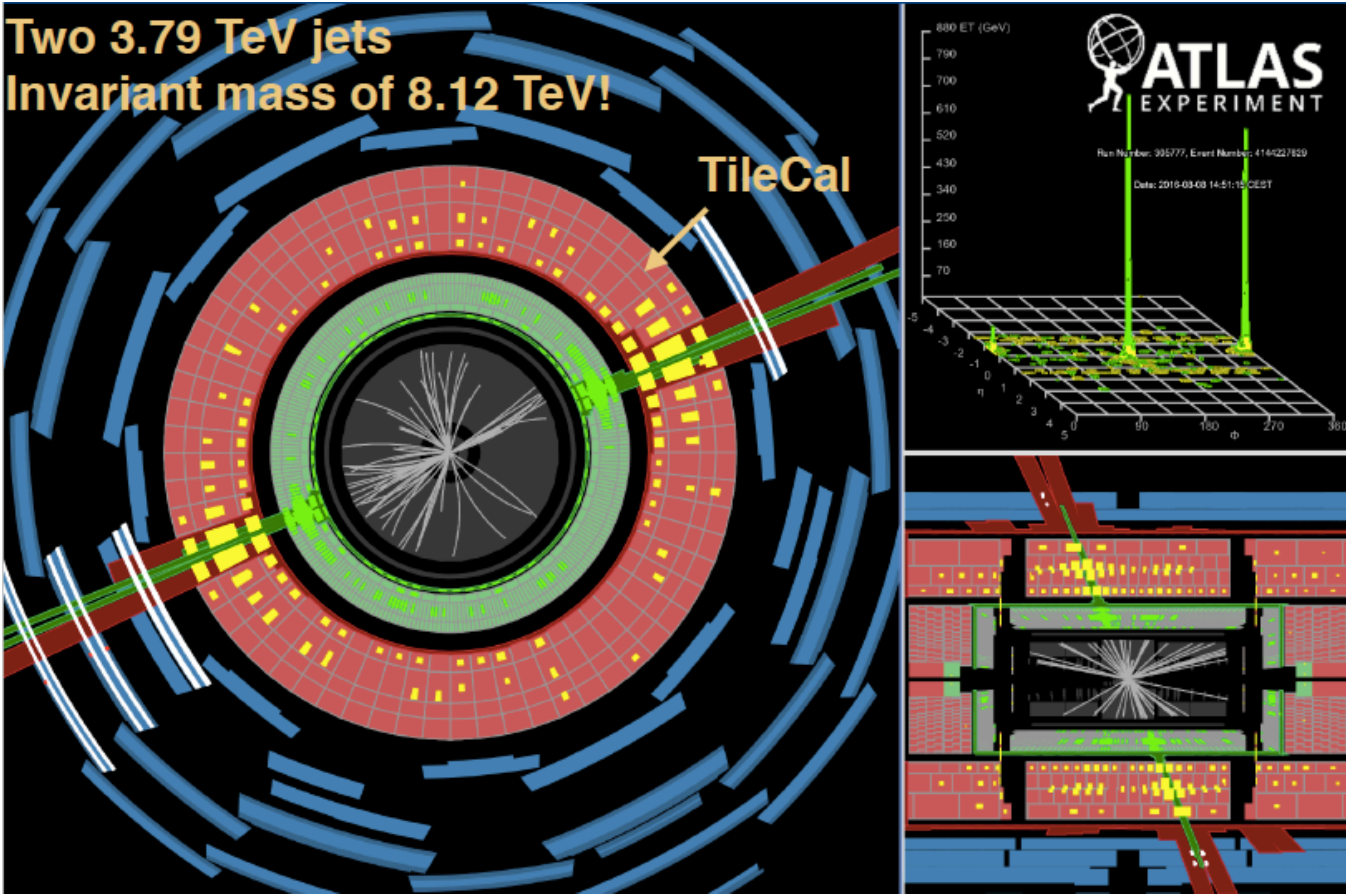


- Tile Calorimeter contributes to the ATLAS luminosity measurement
  - Calibration transfer from low to high luminosity conditions
  - Long term luminosity monitoring
- Dedicated readout of the anode currents in every channel
  - Fully decoupled from trigger
  - Intrinsically independent from pileup
- Allows to cross-check other luminometers

Summary

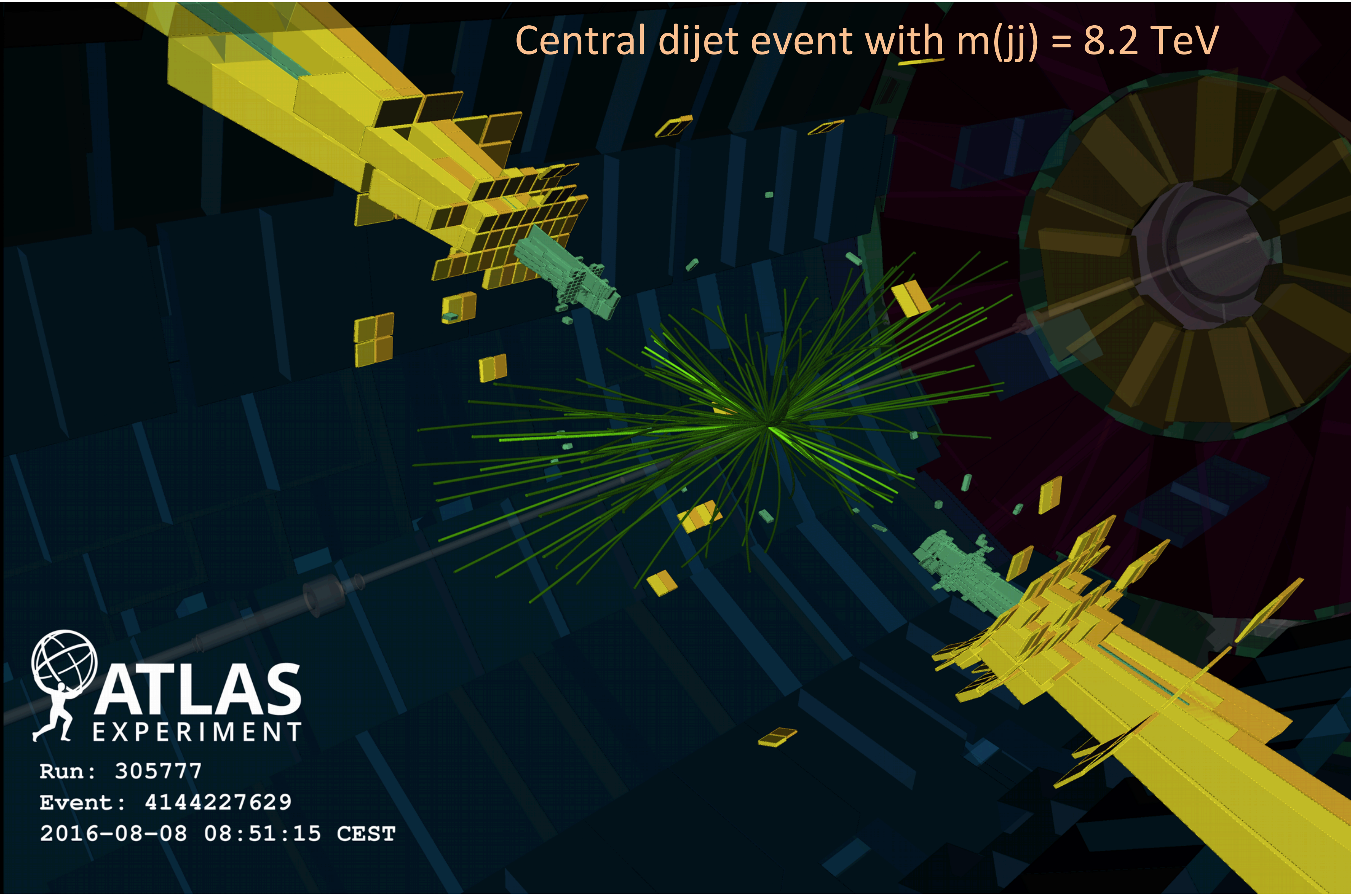
- Tile Hadron Calorimeter is a key detector to measure jet and missing E_T energy in ATLAS experiment at LHC
- To calibrate and monitor the calorimeter response a set of calibration systems is used
- Calibration systems allowed to achieve great performance of Tile Calorimeter in LHC Run 2 with better than 1% precision
- Getting ready for HL-LHC upgrade

Calorimeters (4) Fukun TANG



Two 3.79 TeV jets
Invariant mass of 8.12 TeV!
TileCal
ATLAS
EXPERIMENT

Central dijet event with m(jj) = 8.2 TeV



Thank you for your attention!