# ATLAS Tile Calorimeter Overview and Performance

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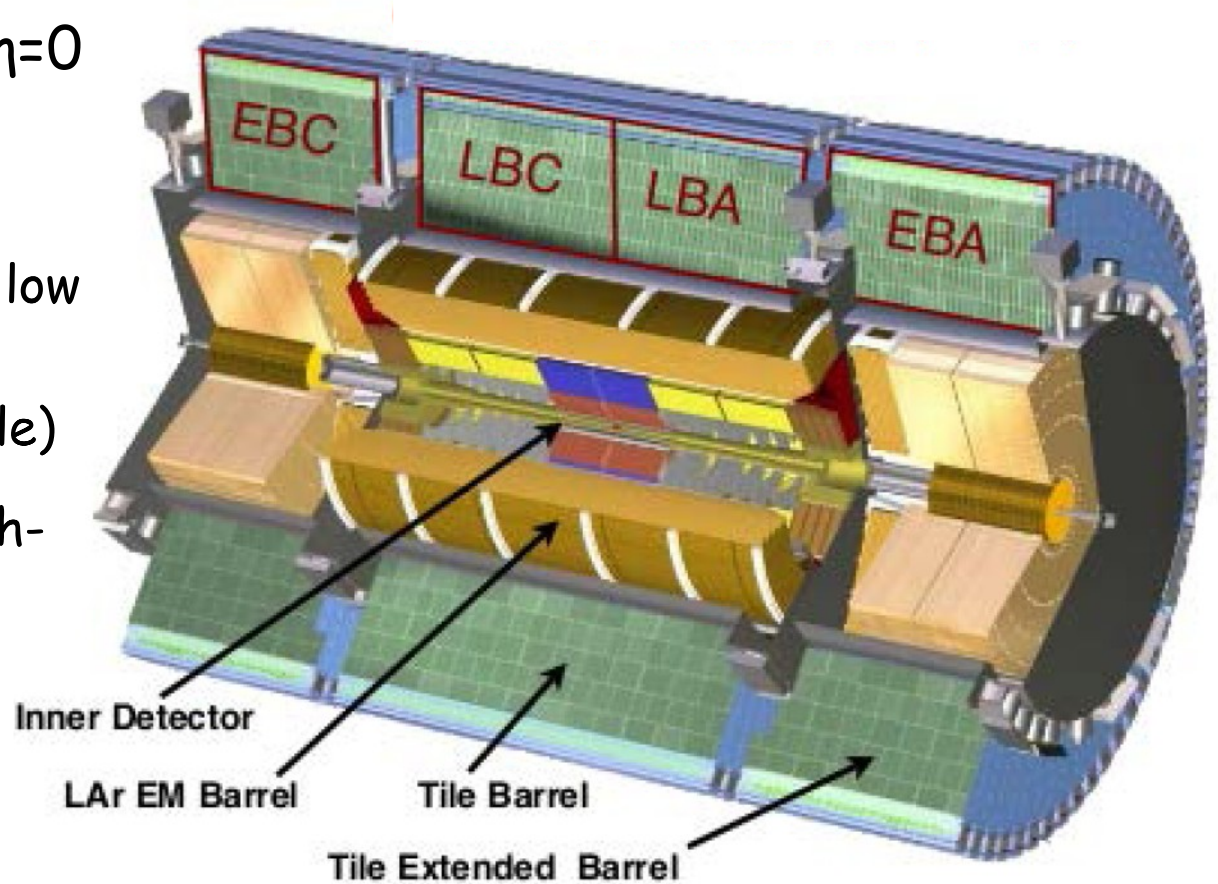
on behalf of the ATLAS Collaboration

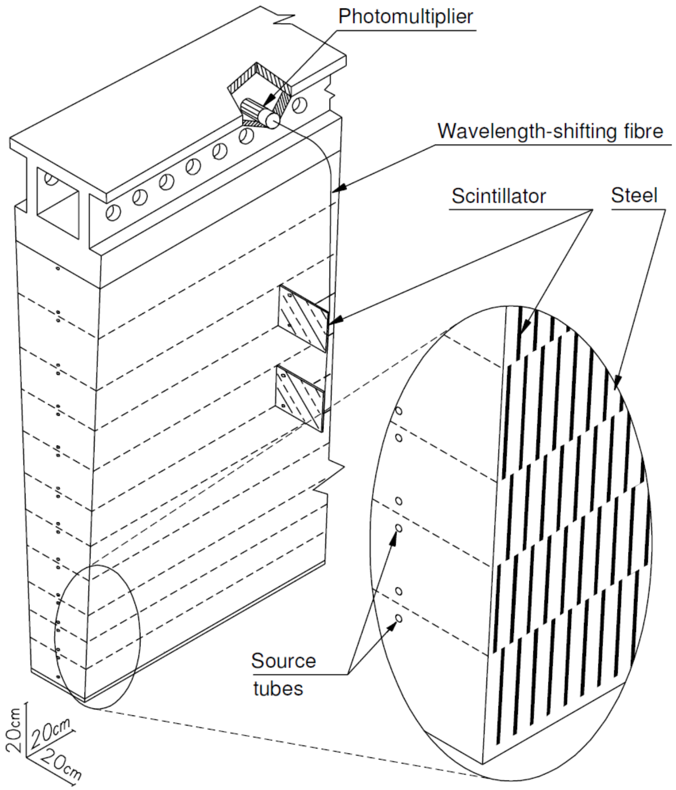
# Tile Calorimeter – Introduction (1)

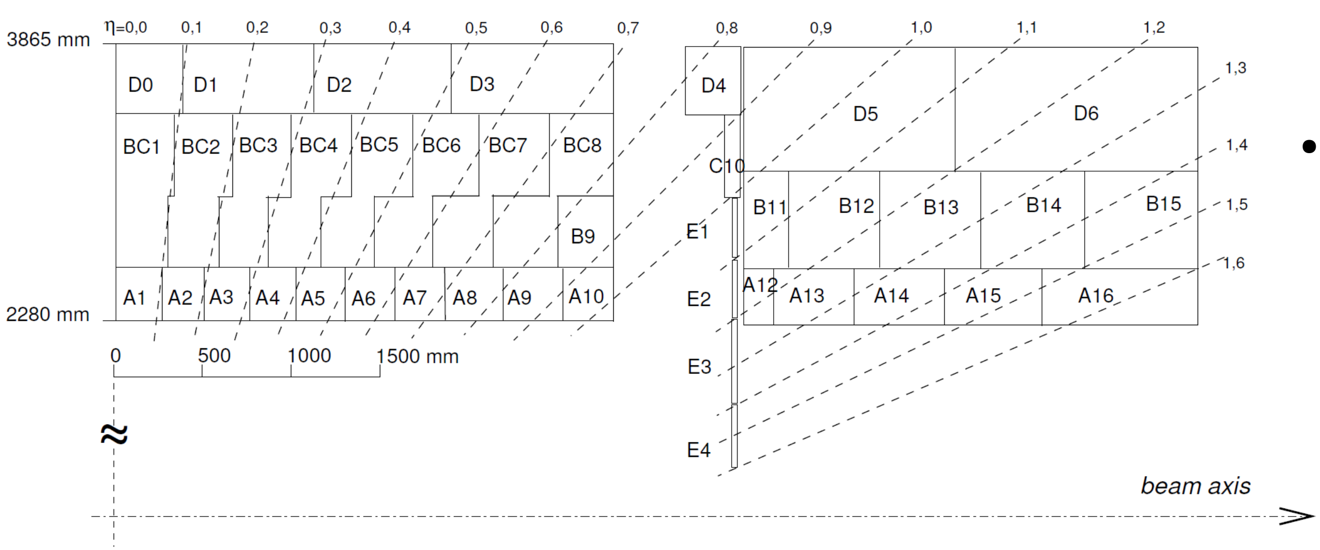
- Hadronic sampling calorimeter made of steel/plastic scintillator
- Three cylinders (1 long barrel, 2x extended barrel) jointly cover the central region $|\eta| < 1.7$
- Total length ~12 m, weight 2900 tons
- Total thickness of $7.4\lambda_{int}$ at $\eta=0$
- Design goals:
  - large dynamic range (detect low signal from muons up to high signals from jets at TeV scale)
  - energy linearity ~2% for high-pT jets up to few TeV
  - jet energy resolution
    $$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$



# Tile Calorimeter – Introduction (2)

- Structure & principles:
  - each cylinder consists of 64 module wedges
  - tiles inserted in the iron structure; 11 tile rows in each module
  - scint. light from tiles collected by WLS fibers and delivered to photomultipliers (PMTs)
  - cells defined by grouping the fibers onto 1 PMT



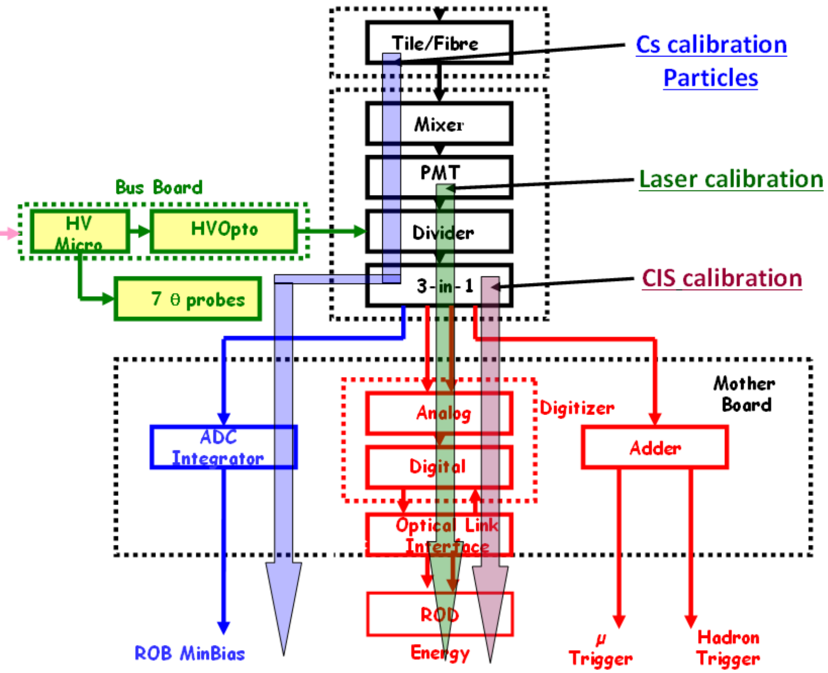

- Readout cell granularity:
  - three radial layers
  - $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ ($0.2 \times 0.1$ in outermost layer), each cell readout by 2 PMTs except of special cells

Four readout partitions (two extended barrels, long barrel split into 2 parts)

# Signal processing (1)

- Light signal converted into electrical pulse in PMTs
- Digital readout path:
  - shaping → pulse shape → sampled every 25 ns → energy reconstruction in RODs
  - two gains (ratio 64:1) to cover the required dynamic range (HG: up to ~12 GeV, LG: ~12 - 800 GeV)
  - used for physics, laser and CIS
- Integrator readout path:
  - PMT signal integrated over long time (~10 ms)
  - used by Cs and minimum bias
- Trigger readout path:
  - two analog outputs provided to level-1 trigger:
    - tower sum (signal from cells of $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$), so-called hadron trigger
    - D-layer signal (single PMT, μ trigger)

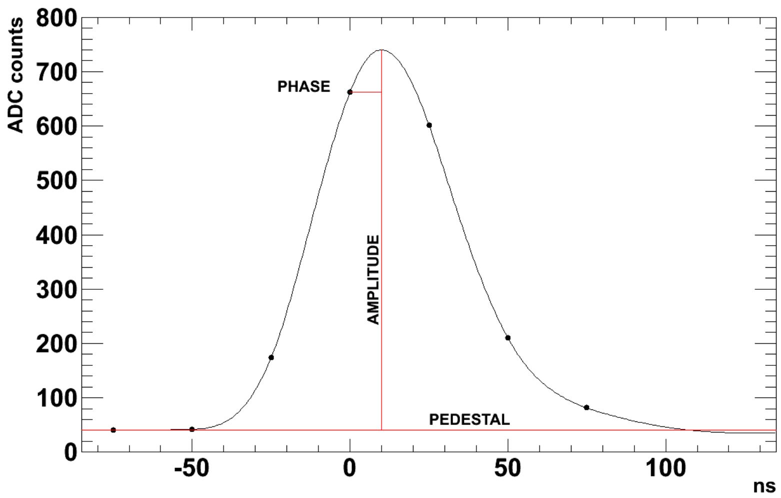
Calibration schema in Tile Calorimeter




- More details about calibration systems in next slides

# Signal processing (2)

- Energy is reconstructed by Optimal Filtering algorithm (digital readout) :
  - weights for individual samples are calculated using reference pulse shape, same for all physics-like signals
  - these weights account for noise autocorrelation matrix (pedestal runs)
  - calculates amplitude (A), phase (τ), quality factor (QF)



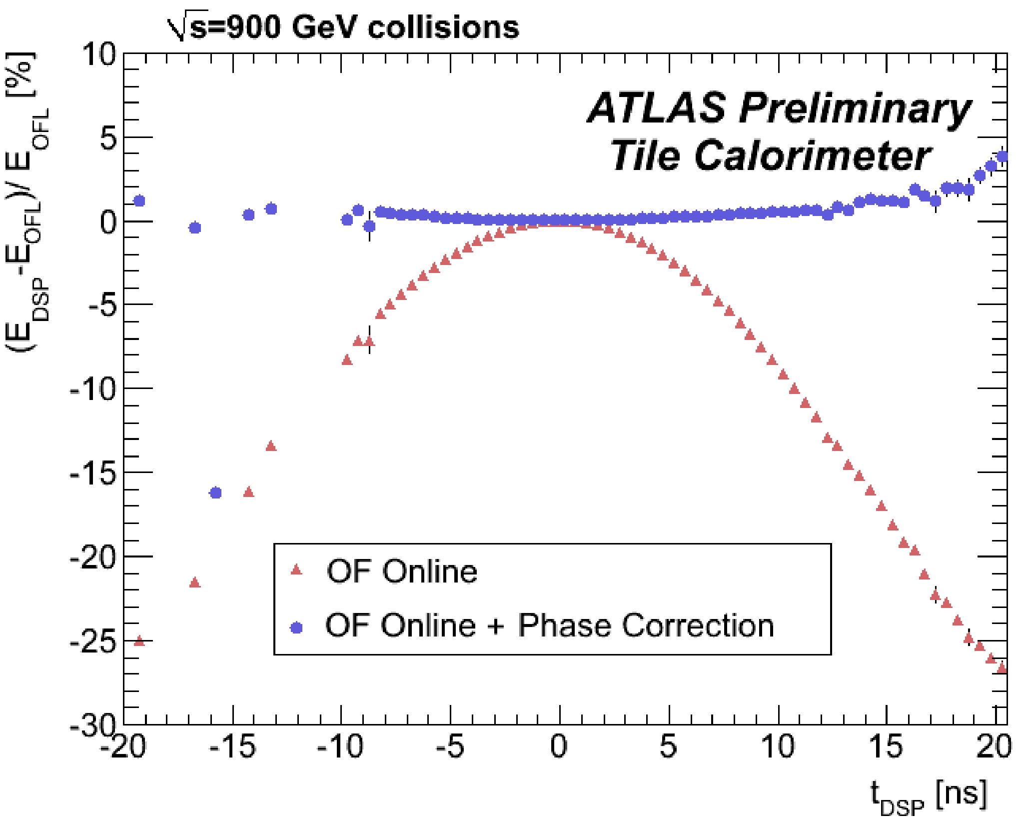

$$A = \Sigma a_i S_i \qquad \tau = \frac{1}{A} \Sigma b_i S_i$$

$$QF = \Sigma \left( S_i - (A g_i + A \tau g'_i + p) \right)^2$$

- Iterative OF used for cosmics data taking (iterate until phase stable)
- Collision data uses fixed phase OF algorithm (performed online in RODs)
  - pulses are synchronized with LHC bunch crossing, requires well timed-in detector

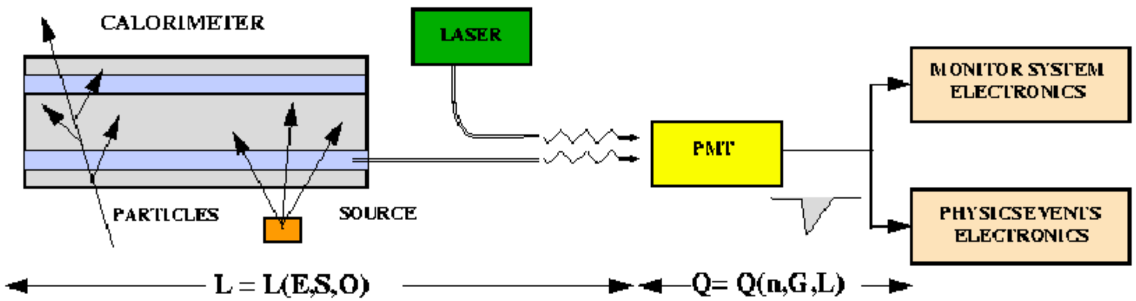
# Signal processing (3)

- Iterative vs. fixed phase OF algorithm:
  - if phase significantly differs from zero, energy might be underestimated
  - can be corrected offline by "parabolic" correction, residual error below 1% in the range +/-12.5 ns



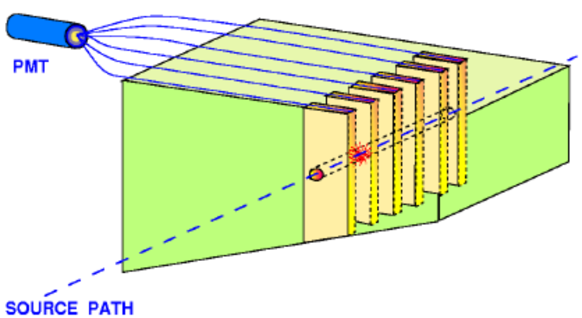

- Pile-up:
  - non-interative OF is more robust
  - best approach is to keep all raw data for offline treatment
    - bandwidth limitations, studies ongoing

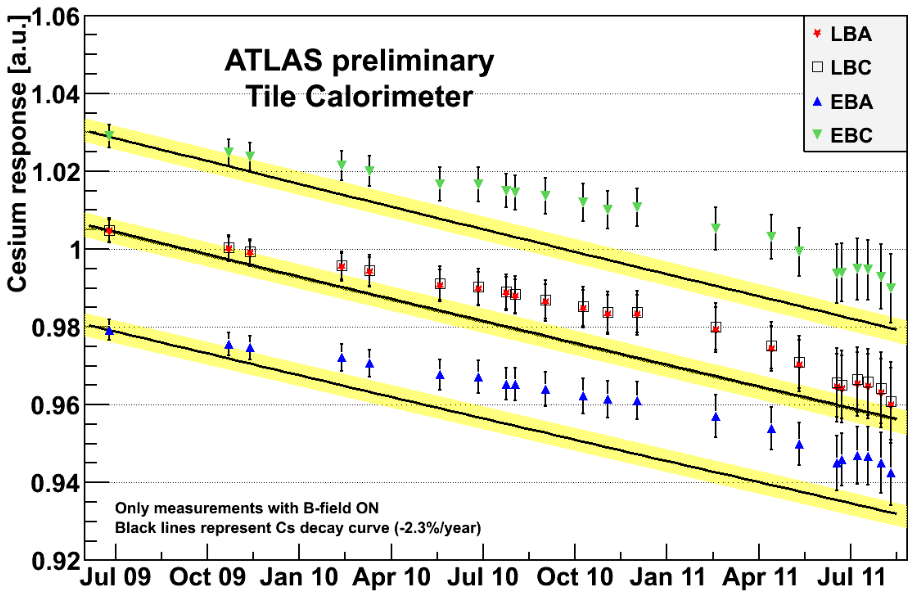
# Calibration systems (1)




- Tilecal includes 4 calibration systems: Cesium, laser, CIS, integrators

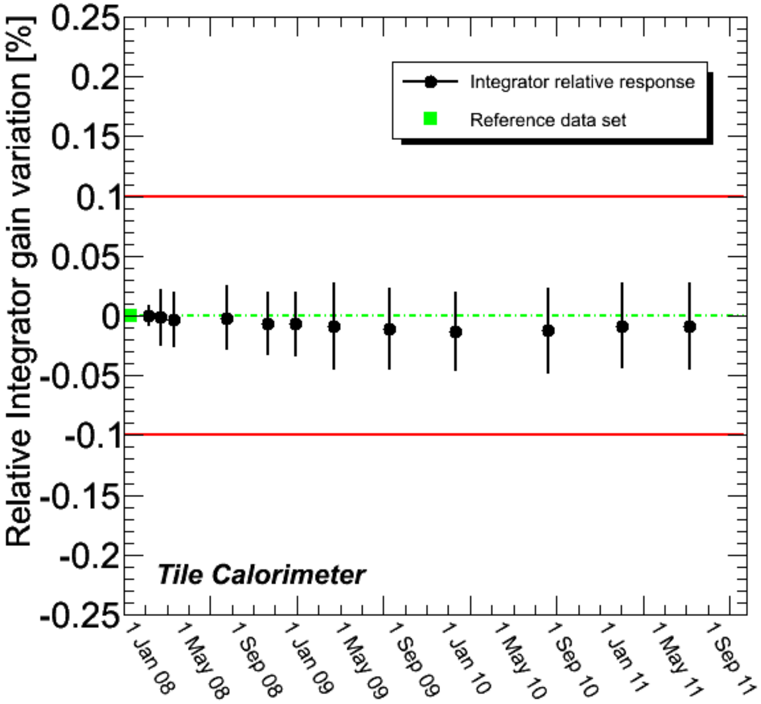
- Cesium:
  - Cs source traverses all tiles, monitors stability of all optics components
  - equalization of the cell responses
  - primary tool to transfer the scale from testbeam to ATLAS cavern
  - small difference with respect to expected decay curve due to up-drift of the PMT gain in the initial phase of light exposure



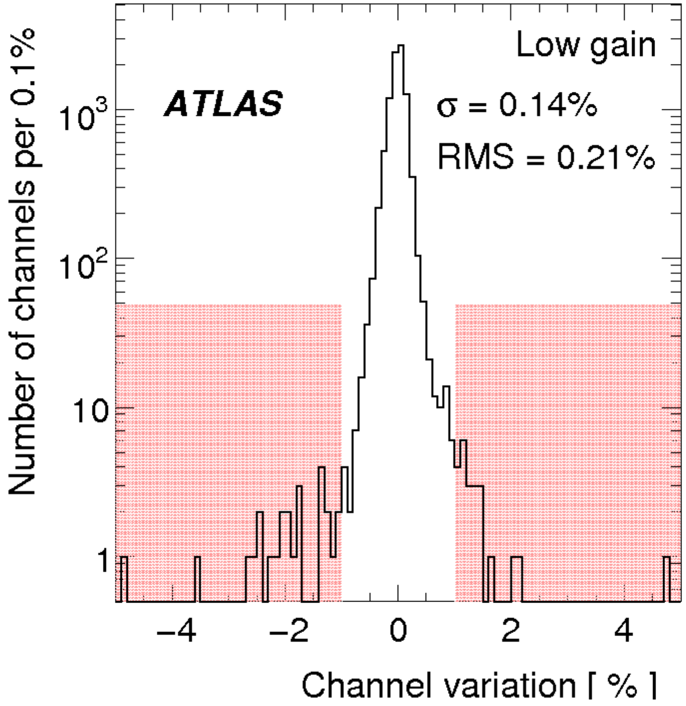
# Calibration systems (2)

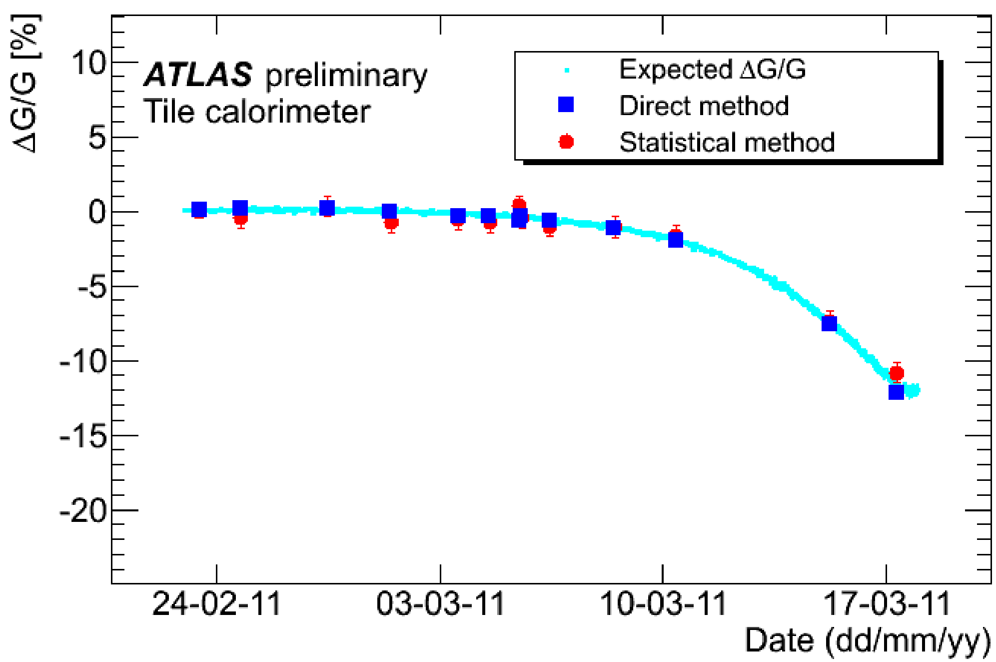
- Integrators:
  - provide readout for Cs calibration and minimum bias monitoring
  - calibration constants are very stable (RMS ~0.05% for individual channel)



# Calibration systems (3)

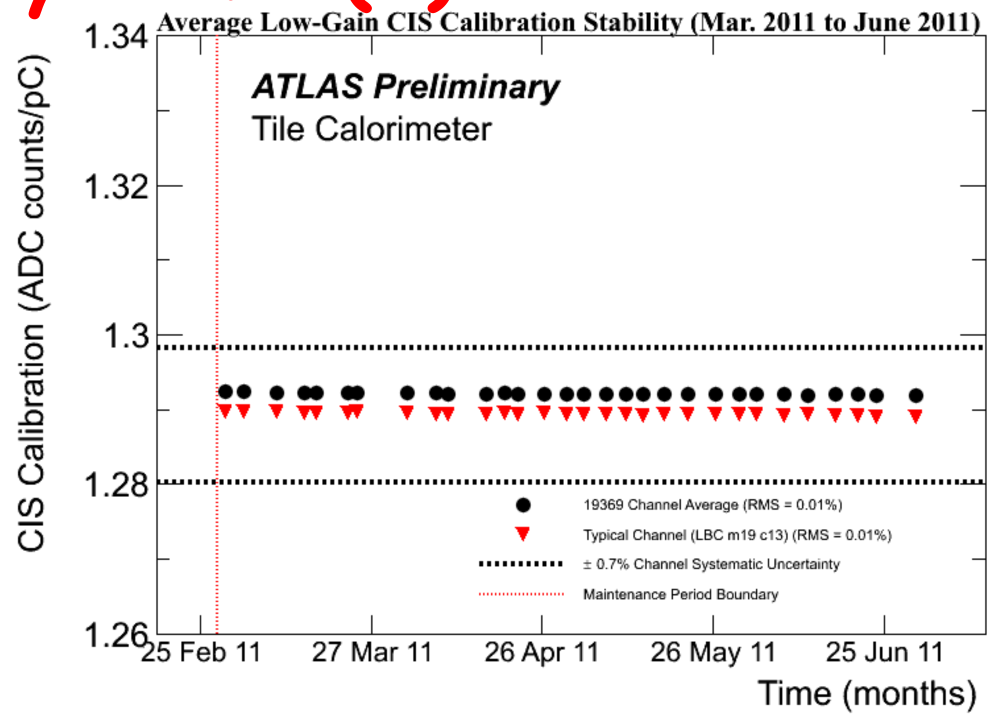
- Laser sends light pulses to all PMTs simultaneously via dedicated fibers
  - monitors the gain of individual PMTs, precision below 1%
  - laser events (frequency 1 Hz) during (part of) empty orbits to monitor short-term gain (and timing) changes
  - special calibration laser runs to monitor PMT linearity
- Two different methods to measure the gain mutually agree
  - gain variations
  - important for PMTs suffering from HV drifts (few such PMTs exist)

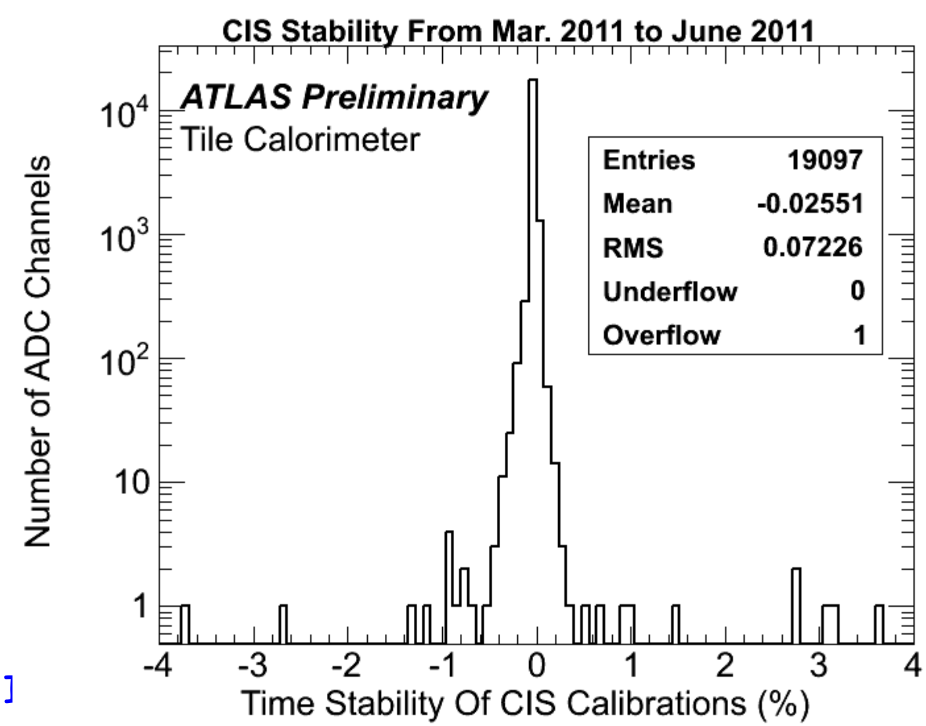


# Calibration systems (4)

- Charge Injection System (CIS)
  - injects well-defined charge into readout electronics
  - precisely calibrates both readout gains, ensures linearity over the whole range
    - corrects for small non-linearity in LG
  - calibration constants are very stable over long time period

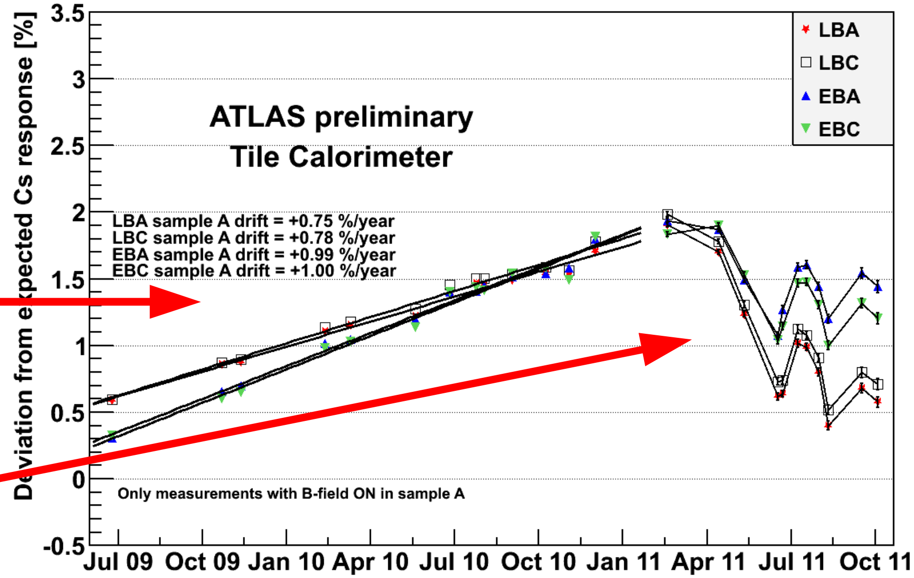


# Calibration Systems (5)

- Cs response evolution with time:
  - in 2010, we observed a PMT gain up-drift in all channels
    - higher Cs response than expected, including Cs decay line
  - in 2011, more complicated stucture of the PMT gain changes is observed
  - more details in next page

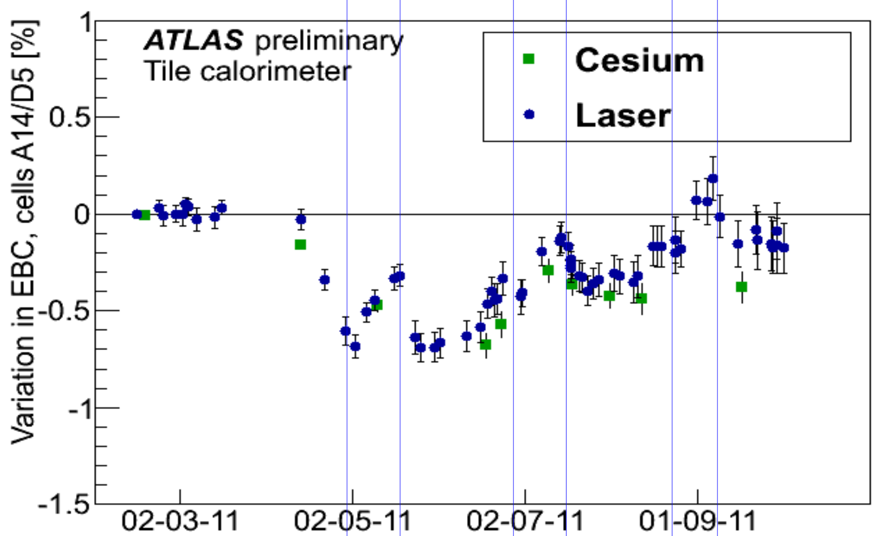
- Response of the cells in the TileCal 1st radial sampling (closest to interaction point)

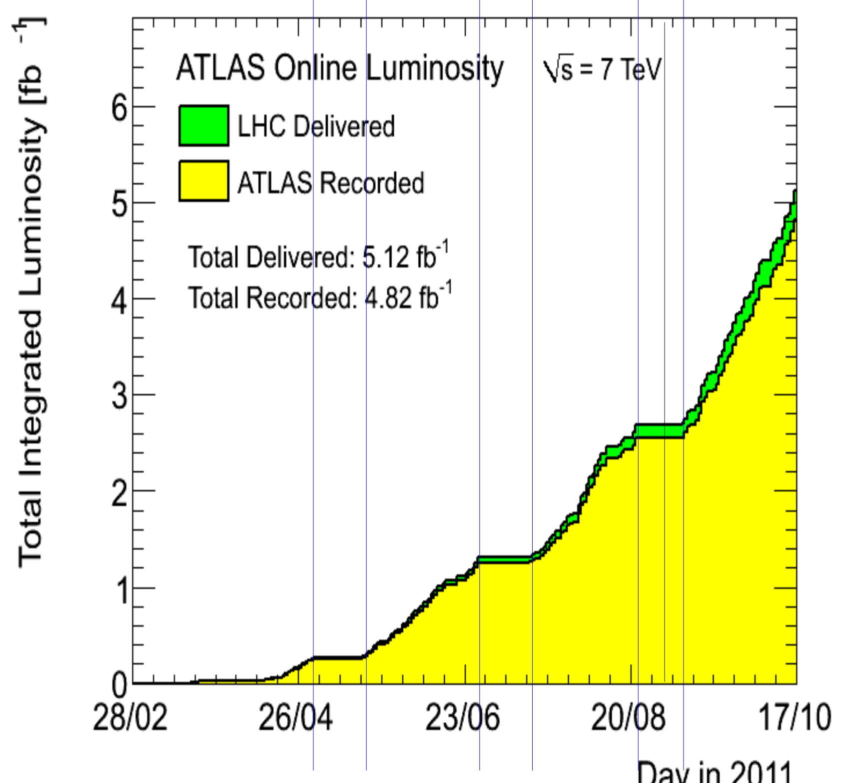



We monitor the gain changes and apply appropriate corrections to Cs calibration constants in order to keep the calorimeter response stable within 0.5%

# Calibration systems (6)

- Closer look at Cs response evolution in 2011:
  - PMT gain changes are related to the beam activity (luminosity)
    - mostly down-drifts during beam-on periods
    - gain (partly) recovers during beam-off periods
- Changes seen with Cs very well reproduced also with laser
  - we are confident that the PMT gain changes are real, it is not an artefact of any calibration system



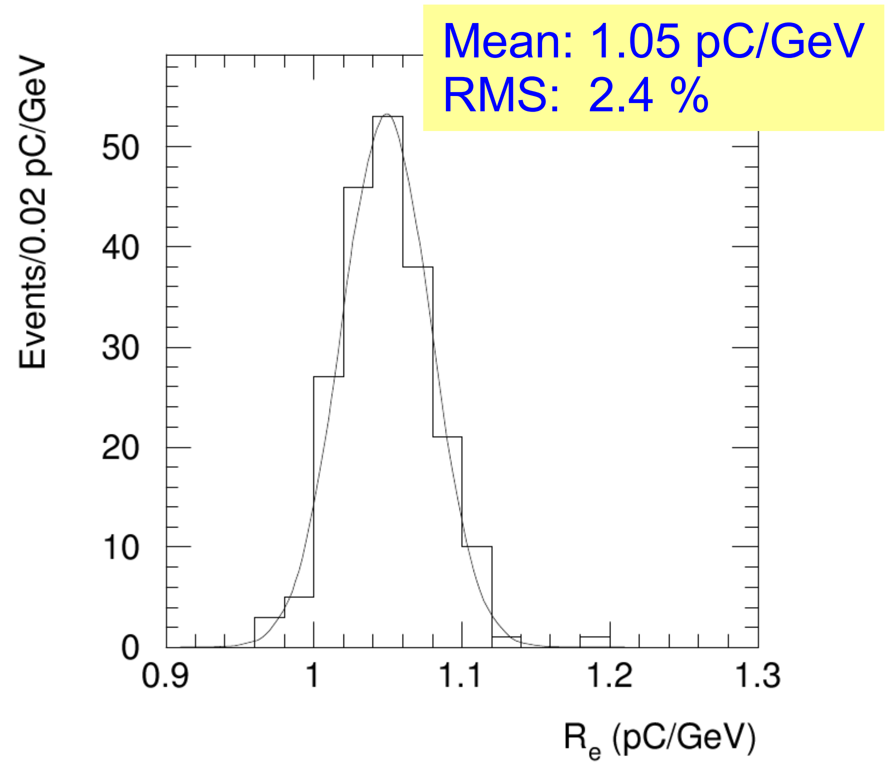



# Energy calibration

- Conversion of the amplitude in ADC counts to the final energy deposit:

$$\text{Energy [GeV]} = A \text{ [ADC]} \times C_{CIS} \text{ [pC/ADC]} \times C_{laser} \times C_{Cs} \times C_{TB} \text{ [GeV/pC]}$$

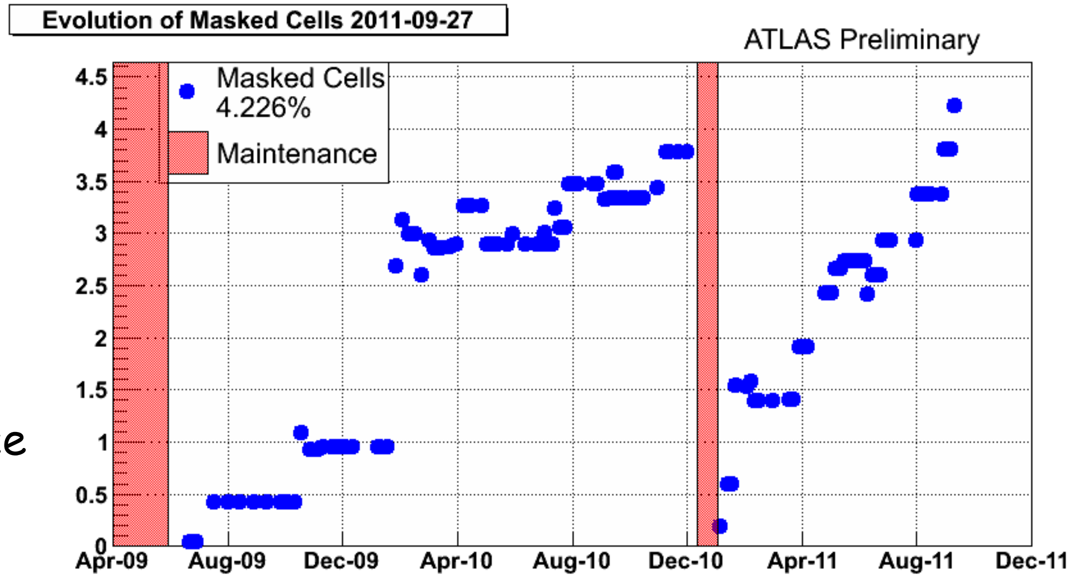
- $C_{Cs}$, $C_{laser}$ and $C_{CIS}$ are provided by individual calibration systems
- $C_{TB}$ conversion factor was measured in standalone testbeams in 2001-2003 at the SPS
  - 11% of Tilecal modules calibrated in beams
  - EM scale set up in first radial layer with electrons (E=20 – 180 GeV) impinging the Tilecal modules at 20° incident angle
  - Cesium and muons at 90° used to transfer the scale to other radial layers




NIM A 606 (2009), 362-394

# Detector status & problems

- Currently 4.3% of non-working (masked) cells for physics
  - 3.8% are off (9 modules off)
    - 5 modules due to power supplies, 4 due to other problems. To be recovered during winter maintenance
  - energy from masked cells is recovered using interpolation between working neighbouring cells




- Frequent trips of Low Voltage Power Supplies
  - scale with luminosity, approximate rate is 0.8 trips/$pb^{-1}$
  - automatic recovery procedure in operation, but still one of the major issues

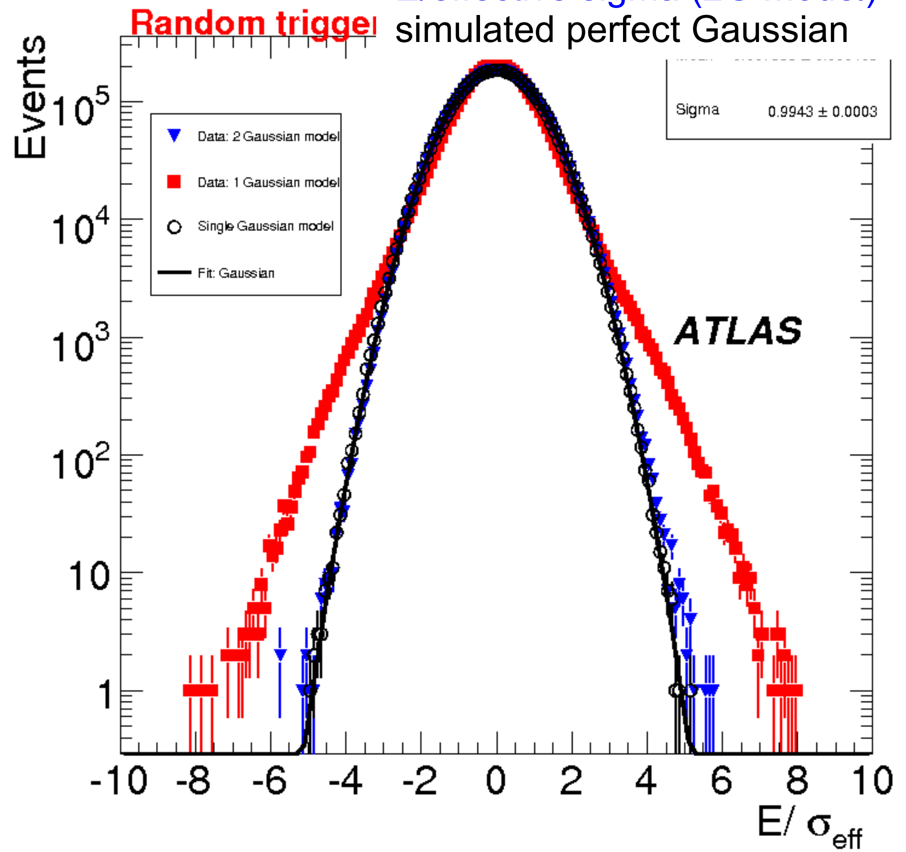
More details in Giorgi Arabidze's talk

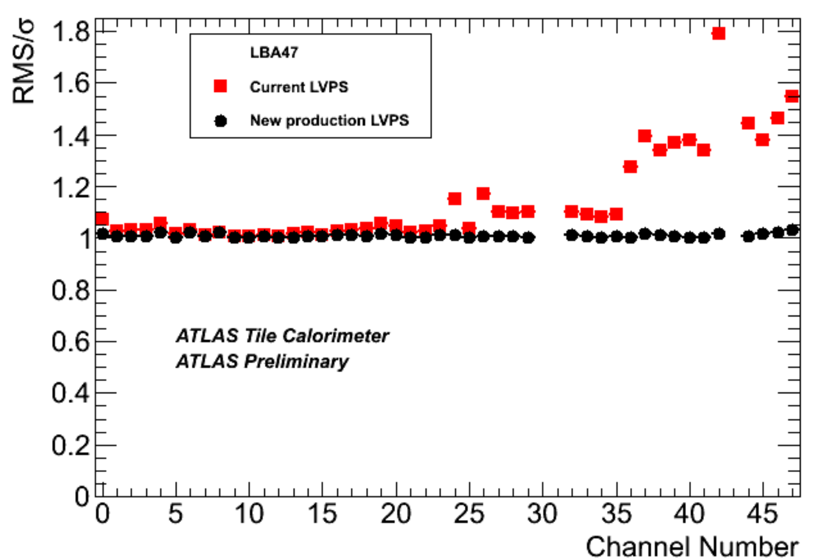
# Performance in situ

# Electronic noise (1)

- Noise is measured in special pedestal calibration runs and in zero-biased (or random) trigger events
- Noise is not Gaussian, double Gaussian (2G) distribution is used as the probability function
  - applied to discriminate signal/noise, important e.g. for clustering algorithms
- Deviation from non-gaussian behaviour increases in channels towards higher |η|:
  - due to presence of the power supply next to the patch-panel
  - feature is greatly suppressed with new power supplies (see Irene Vichou's talk)

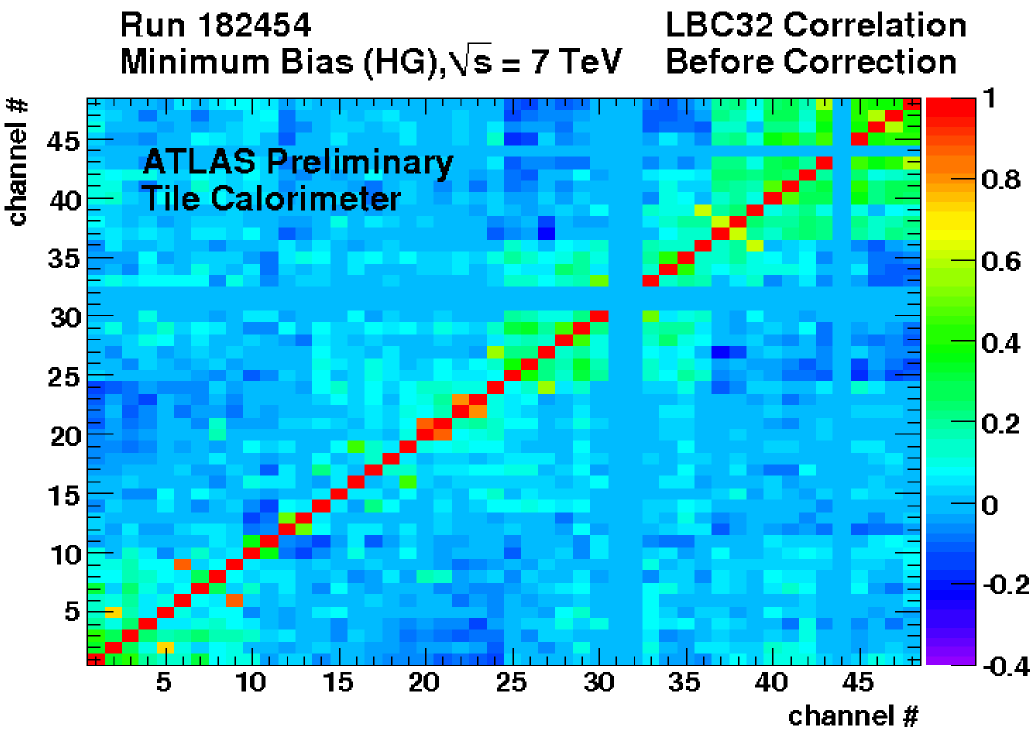
E/single Gaussian sigma
E/effective sigma (2G model)
simulated perfect Gaussian

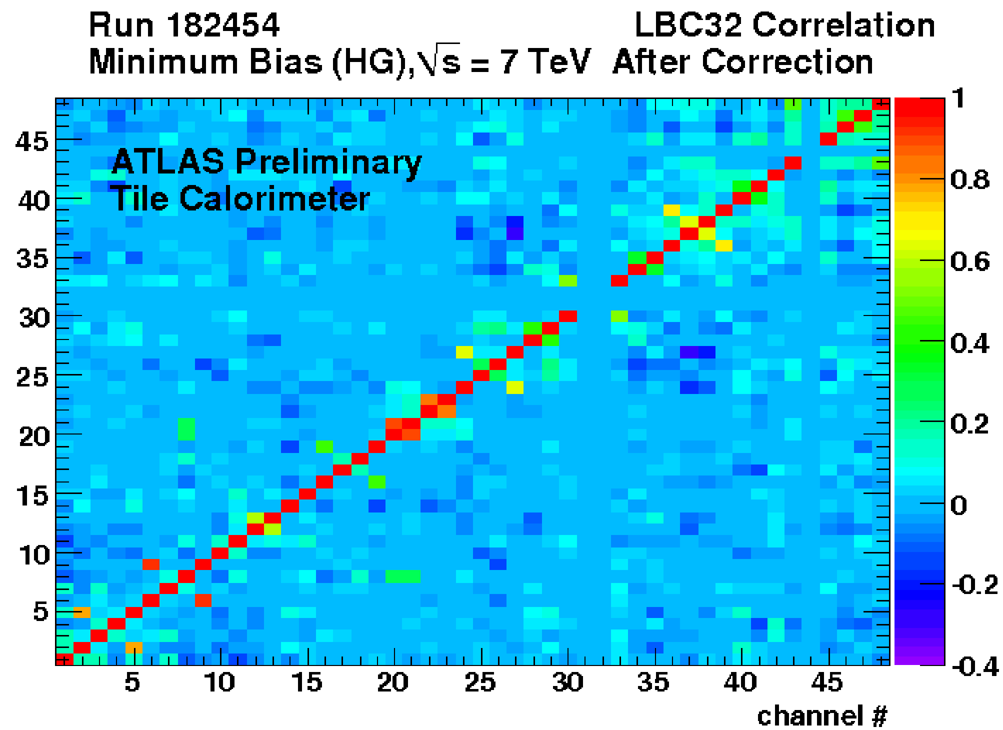


# Electronic noise (2)

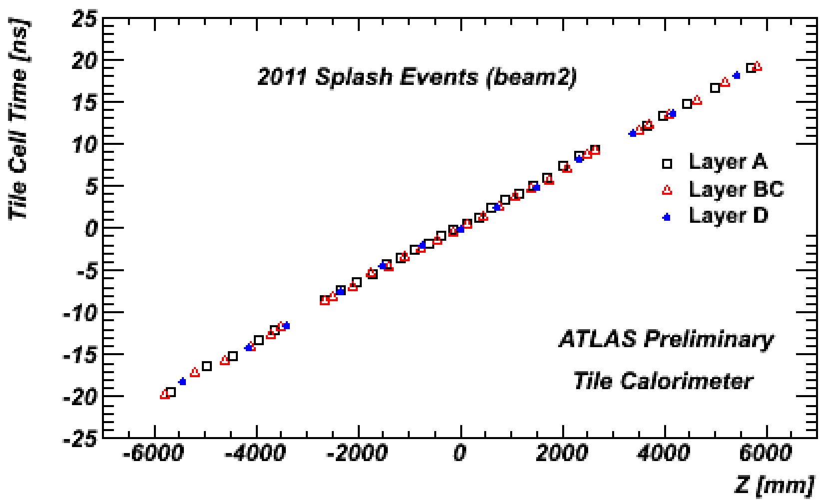
- Coherent noise:
  - channels at the same motherboard show typically ~4% noise correlation
  - subtracting the common-mode noise between such channels reduces the correlation to ~1.3%



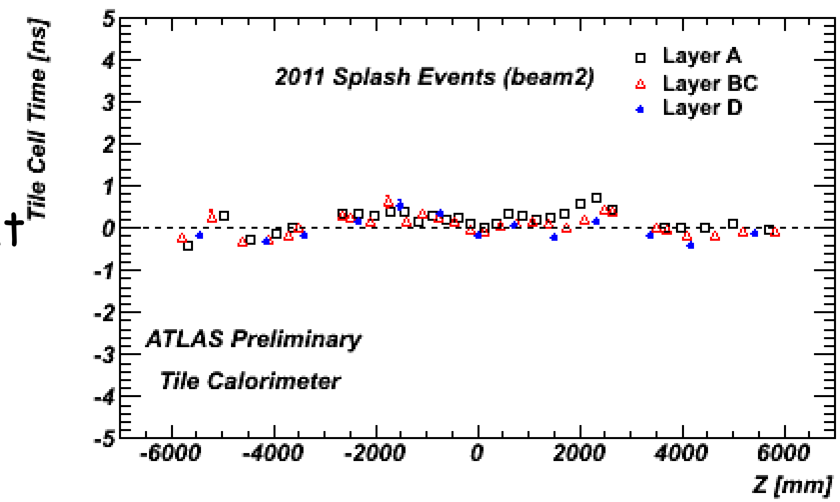



# Timing (1)

- Detector timing is important for energy reconstruction as well as for time-of-flight measurement
  - e.g. search for heavy stable particles, jet cleaning
- Timing constants measured with beam splash events
  - beam hitting closed collimator ~140 m in front of the detector
  - high energy deposits in calorimeters by particles ~parallel to the beam axis (example in next slide)

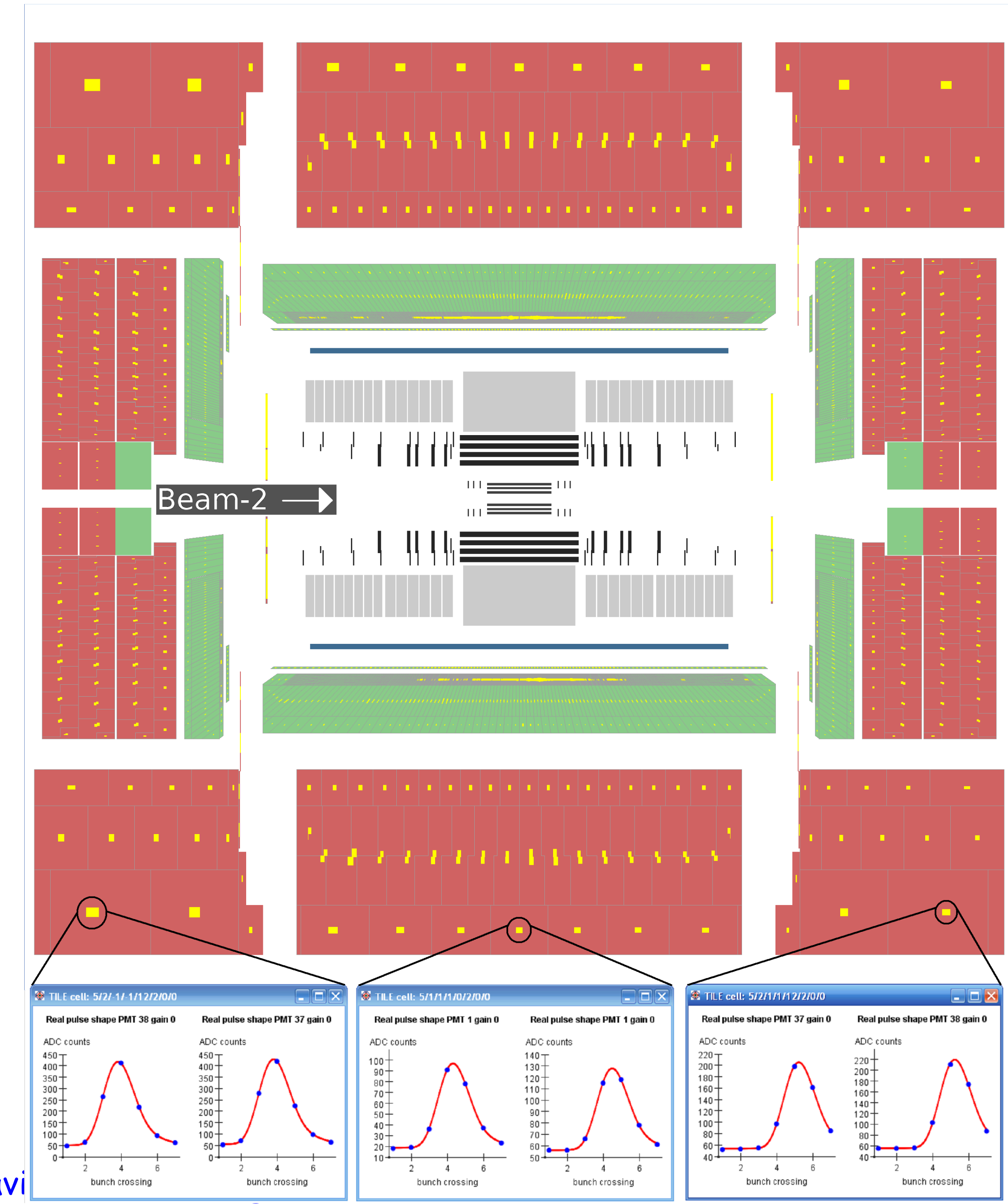



time-of-flight correction



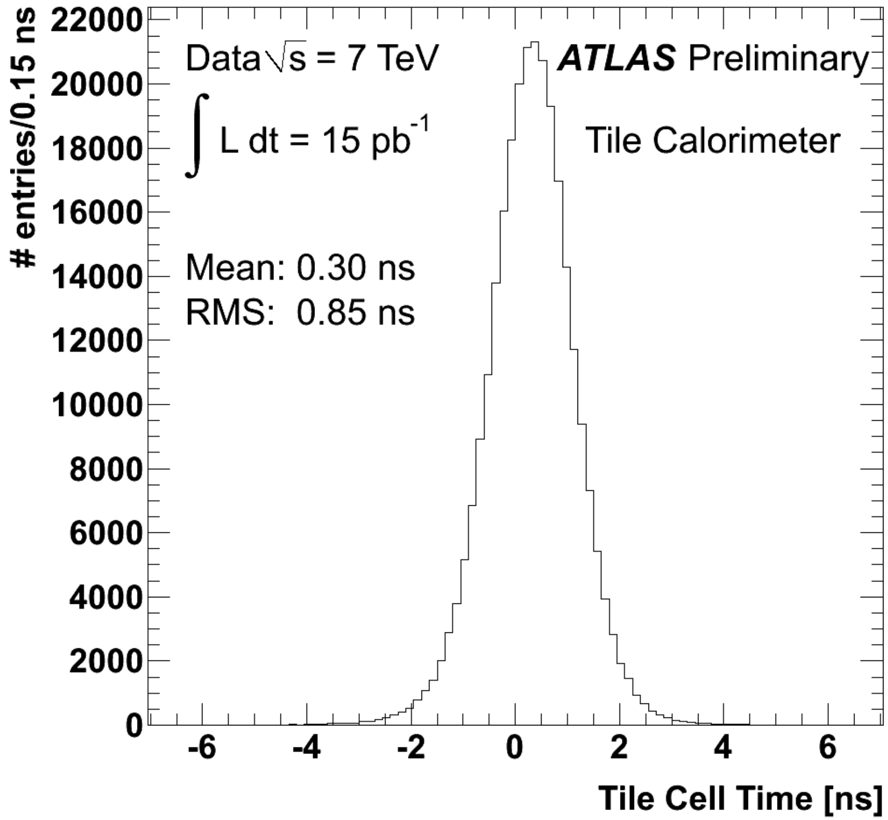
# Timing (2)

- ATLAS event viewer of one splash event (2009 data)
  - high energy deposits in calorimeters
  - nice pulse shapes observed in Tilecal



# Timing (3)

- After timing constants were determined with beam splashes, they were later validated and eventually adjusted with collision jet data
  - example of the timing performance with 2010 jet data: cell time distribution (LG) for cells belonging to topoclusters of reconstructed jets with pT>20 GeV

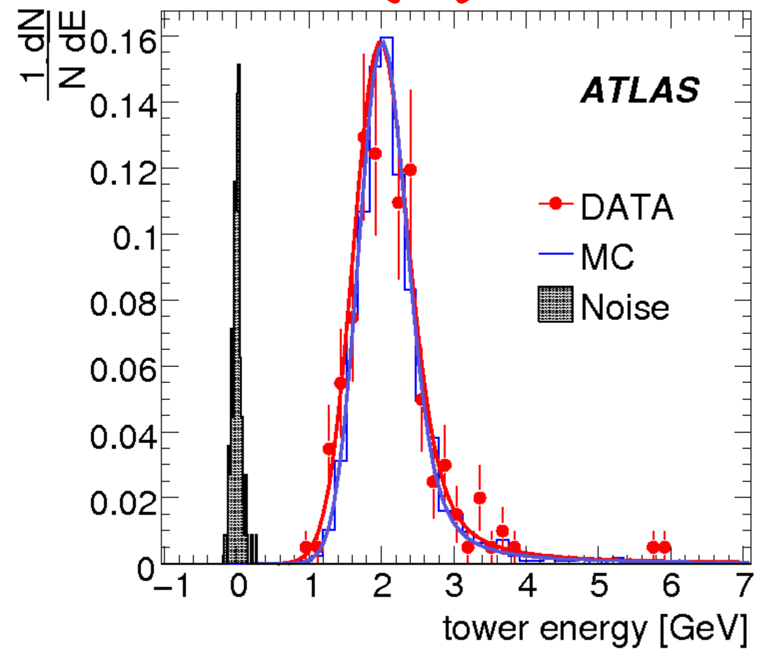



Time synchronization between cells is well below 1 ns

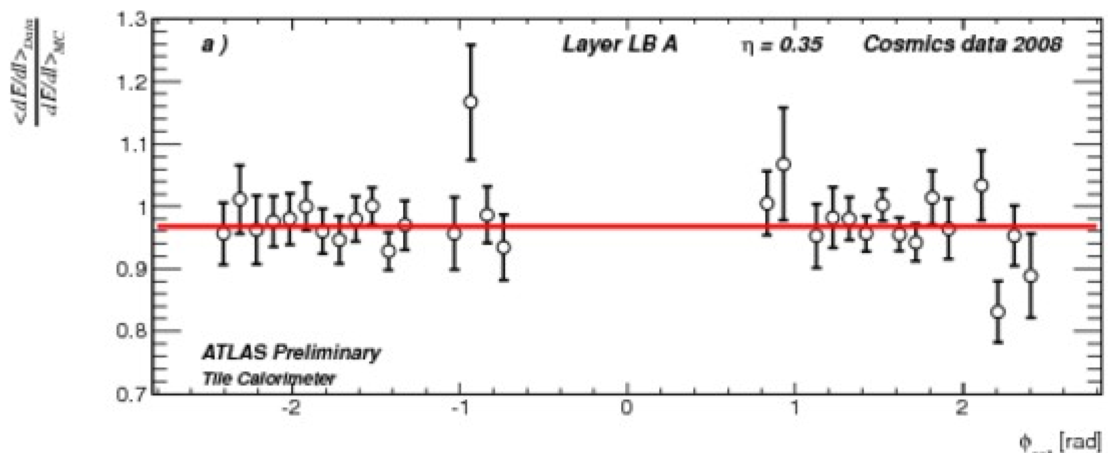
- Timing performance also being studied with collision muons and beam scraping events
  - time resolution, mean time as a function of deposited energy

# Response to isolated muons (1)

- Calorimeter response to muons studied extensively with cosmic and collision muons.
  - muon signal is very well separated from the noise
  - truncated mean (cutting off 1% of events at high-energy tail) used in analyses
- Results with cosmic muons show good uniformity in η and φ
  - comparing $(dE/dl)_{data}/(dE/dl)_{MC}$ to avoid (most of) the systematics associated with truncated mean scaling
- Overall cell uniformity within radial layers shows upper limit ±2% (ATL-TILECAL-PUB-2011-001)




Example of the total muon response passing through the calorimeter at |η|=0.35




Uniformity of the cell responses in the 1st radial sampling, as a function of azimuth φ, no/little statistics for horizontal muons

# Response to isolated muons (2)

- EM scale validation with cosmic muons in 2008 – 2010:
  - compare $(dE/dl)_{data}/(dE/dl)_{MC}$ in each radial layer to check the EM scale
  - difference between LB-D layer and all other layers observed
  - results very stable in time, the EM scale in the pit found to range between -3% and +1% wrt testbeam
- The EM scale in ATLAS is compatible with the value set at testbeam with an uncertainty of 4%

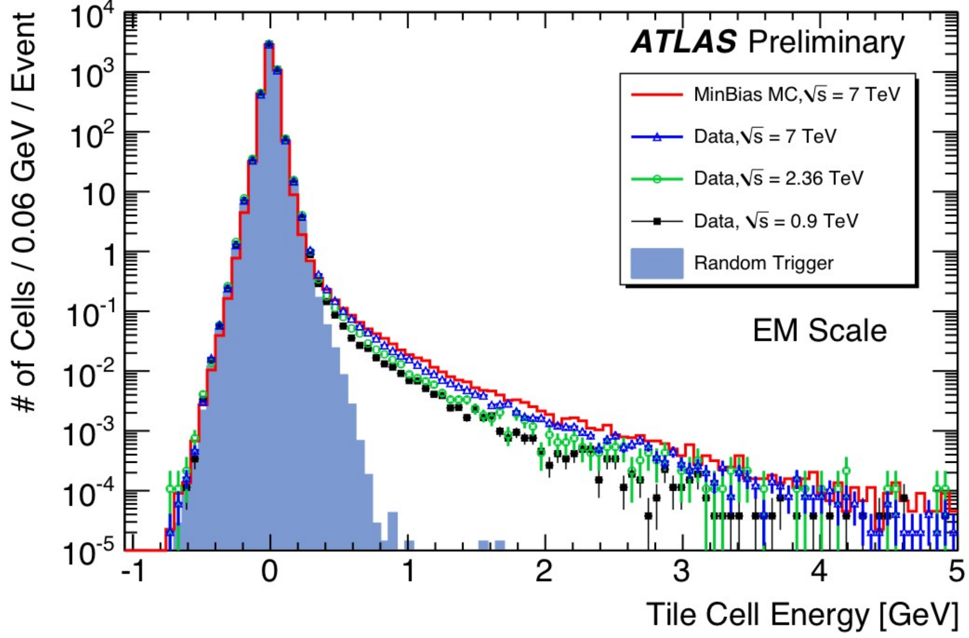
| Layer | 2008 data | 2009 data | 2010 data |
|---|---|---|---|
| LB-A | 0.966±0.012 | 0.972±0.015 | 0.971±0.011 |
| LB-BC | 0.976±0.015 | 0.981±0.019 | 0.981±0.015 |
| LB-D | 1.005±0.014 | 1.013±0.014 | 1.010±0.013 |
| EB-A | 0.964±0.043 | 0.965±0.032 | 0.996±0.037 |
| EB-B | 0.977±0.018 | 0.966±0.016 | 0.988±0.014 |
| EB-D | 0.986±0.012 | 0.975±0.012 | 0.982±0.014 |

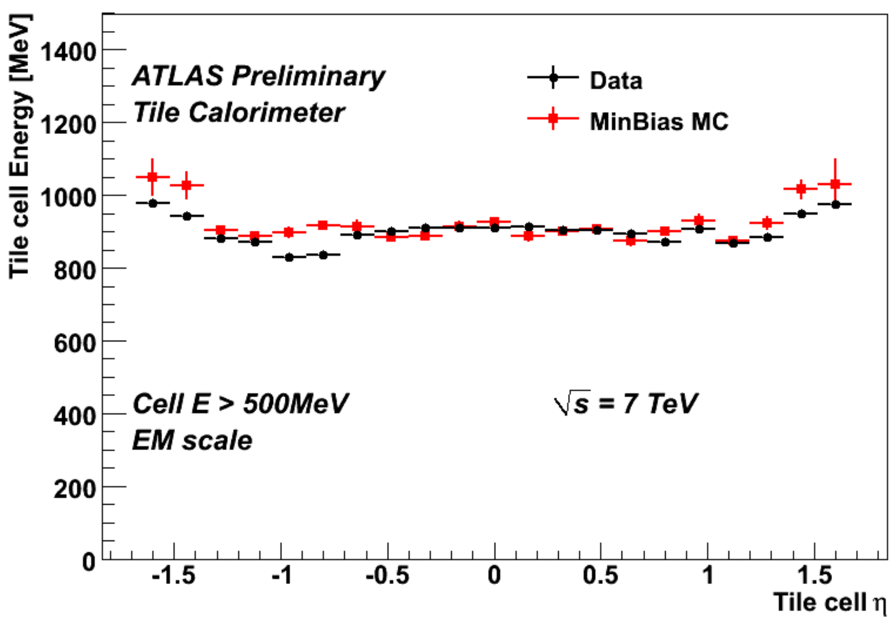
- Preliminary results with collision muons indicate similar differences between layers
- Analysis of 2010 scraping events (beam hitting edge of the collimator, getting horizontal muons in the calorimeter) did not reveal such differences between layers

The tile response map not implemented yet in the MC, possible impact on the MC results. Work ongoing...

# Minimum bias events (1)

- Very good match of the cell energy spectra observed between data at various √s and minimum bias Pythia MC.
    - match in negative part of the noise peak demonstrates correct implementation of the noise description (2G) in our MC
- Mean cell energies are almost uniform across pseudorapidity
    - small difference between barrel and extended barrel due to pile-up
    - difference data vs MC due to slightly different pile-up used in the non-diffractive Pythia MC

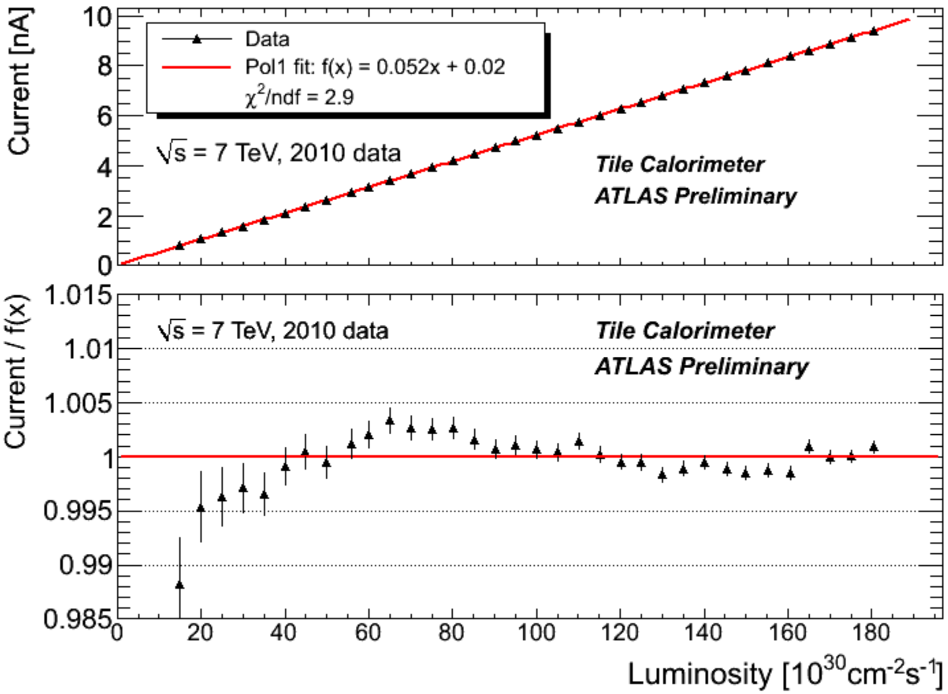



- Very good uniformity in mean cell energies across azimuth observed as well.

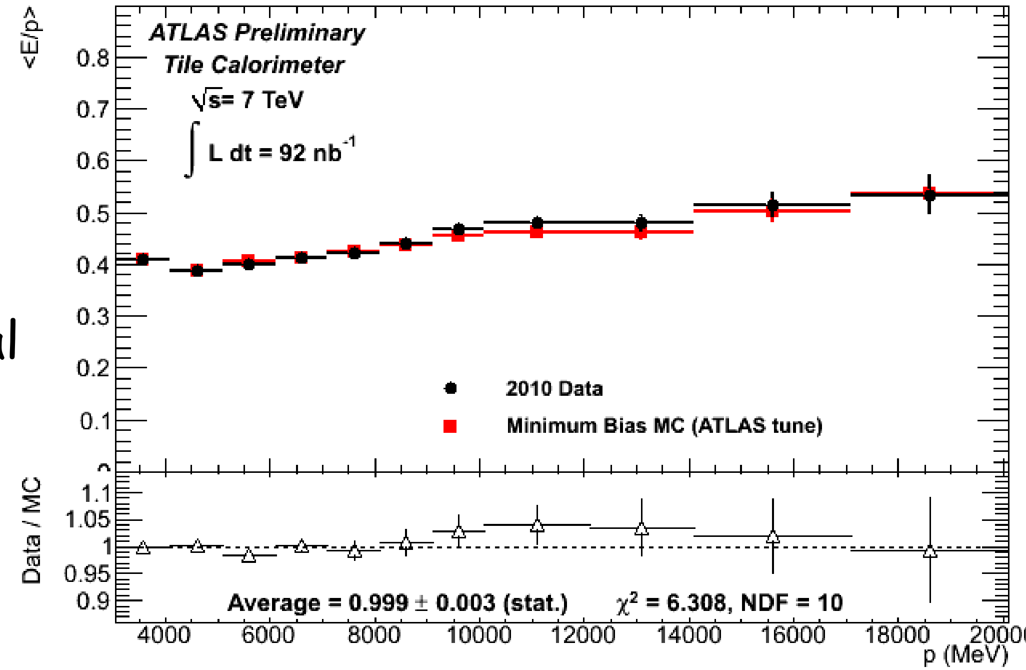
# Minimum bias events (2)

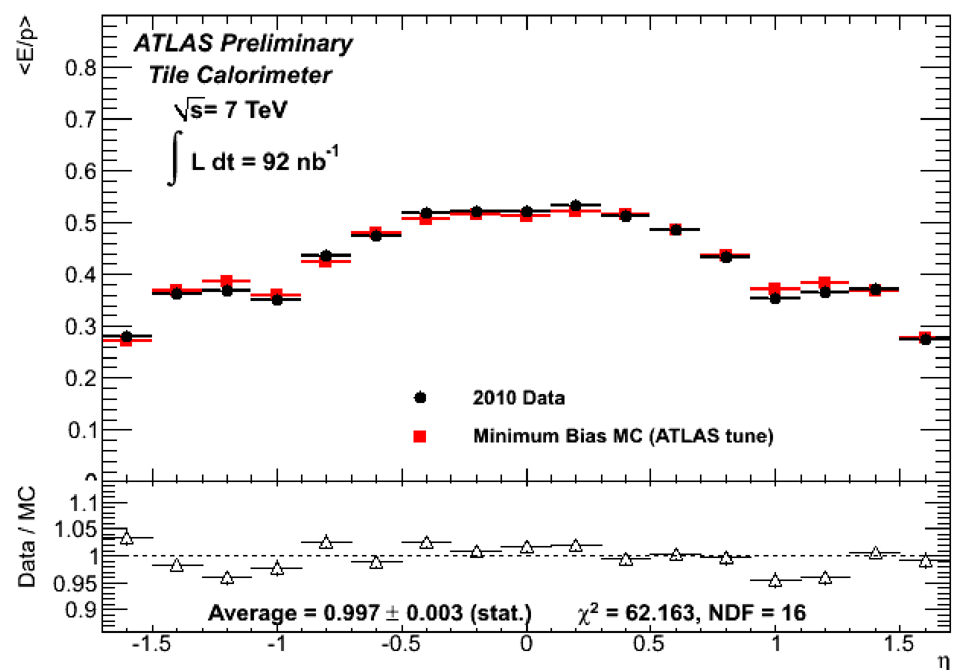
- Integrators allow for precise luminosity measurement with minimum bias events
- System also very useful for online spotting problematic cells/modules (e.g. module off)



# E/p with isolated hadrons

- Response from isolated hadrons can be directly compared to the testbeam results
  - hadrons showering "only" in Tilecal selected by imposing a MIP-like response in EM calorimeters
  - momentum measured in tracking detector
  - one of the first tests of the EM scale, but not that precise (cannot resolve the problem seen in cosmic data)
- Very good match data vs MC obtained since shower models are tuned on TB data



# Conclusions

- Tilecal is performing very well during the first years of LHC data taking.
- Currently 4.2% of cells cannot be used for physics, recovery expected during the forthcoming detector maintenance.
- The calibration systems are commissioned and working well. Calibration constants applied to data make response stable in time. Precision of the individual calibration system is below 1%.
- EM scale has been successfully transferred from testbeam and validated with cosmic muons, maximum difference between radial layers is 4%.
- MC simulation agrees well with data (noise description, response to single hadrons).
- Many other performance studies ongoing.