Performance and calibration of the ATLAS Tile Calorimeter

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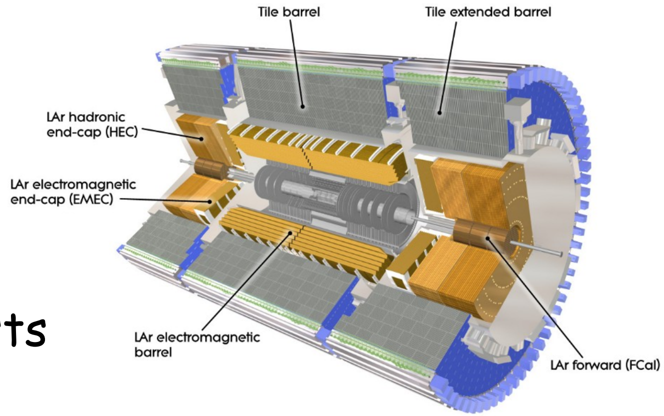
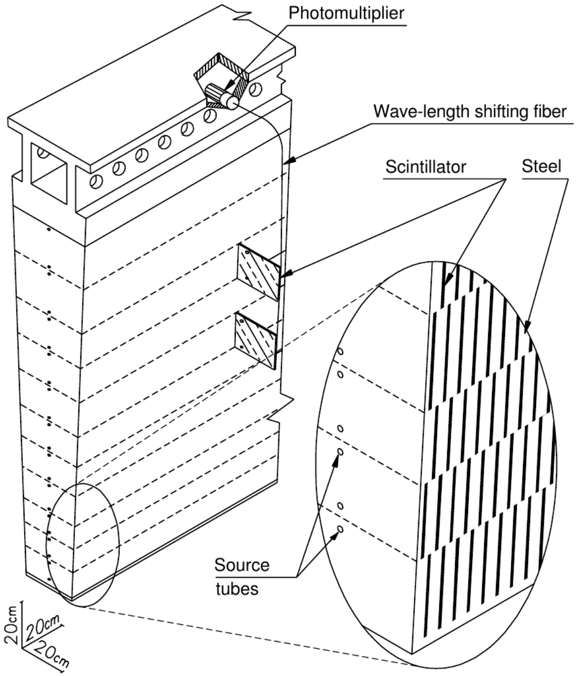
on behalf of the ATLAS Collaboration

Tile Calorimeter (1)

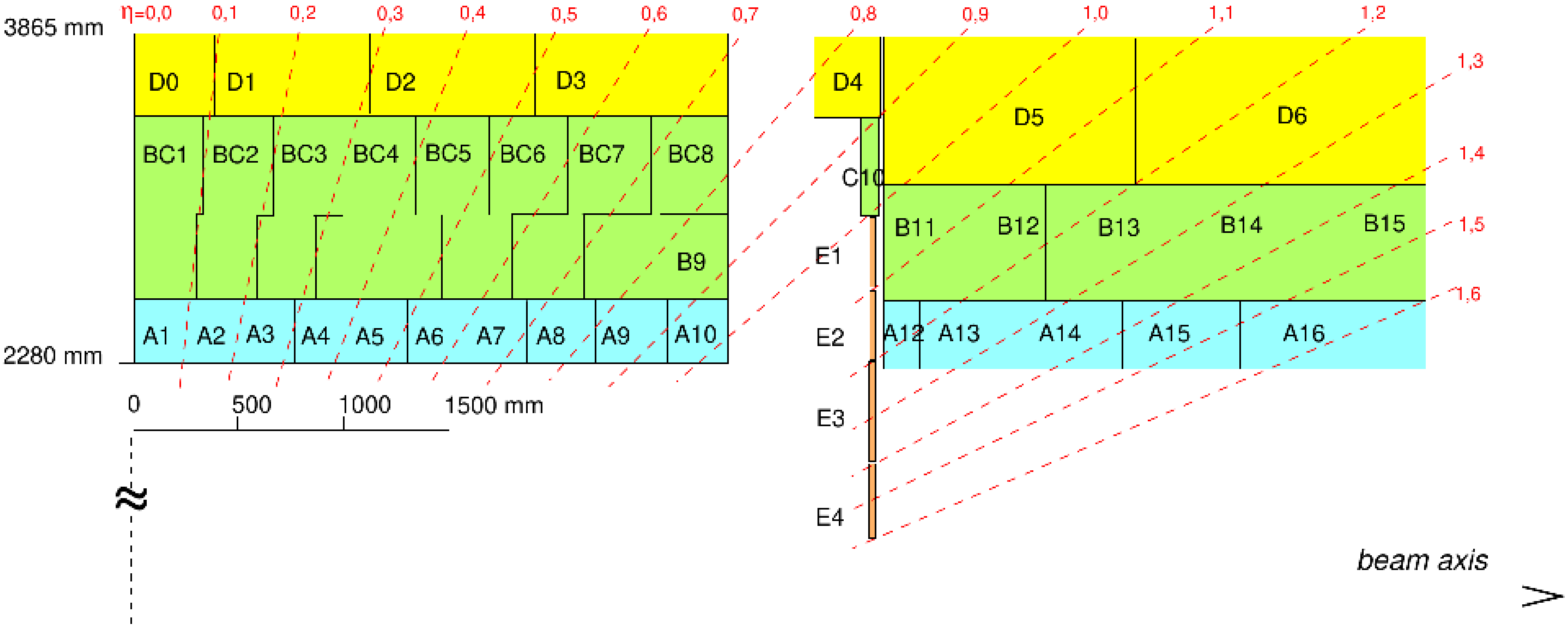
- Hadronic sampling calorimeter (steel/scintillator) in ATLAS covering $|\eta| < 1.7$
- Measures energy & direction of jets, taus, missing E_T, assists in muon identification and provides input to L1-trigger
- Central Long Barrel and two Extended Barrels
- Signal collection & processing
  - charged particles produce scintillating light absorbed in WLS fibres, re-emitted and transmitted to PMTs
  - PMT signal shaped, amplified (two gains, 64:1) and digitized @ 40 MHz frequency with 10-bit ADCs
  - data sent off-detector for further processing upon L1-trigger accept
  - amplitude A and time t_0 reconstructed with Optimal Filtering algorithm
  - most cells readout with 2 PMTs (one on each side), ~5000 cells in total





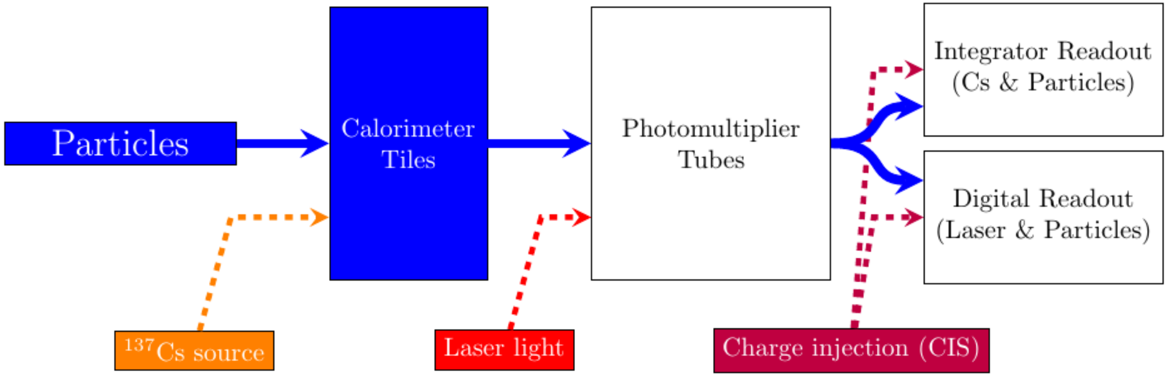
Tile Calorimeter (2)

- Pseudo-projective cell geometry
  - 3 radial layers, $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (0.2 x 0.1 in the outermost layer)



Overview of the calibration systems

- Three dedicated systems cover different parts of the readout chain
  - Cs – optics, PMT → C_{Cs}
  - Laser – PMT, fast readout electronics → C_{las}
  - Charge Injection System (CIS) – fast readout electronics → C_{CIS}



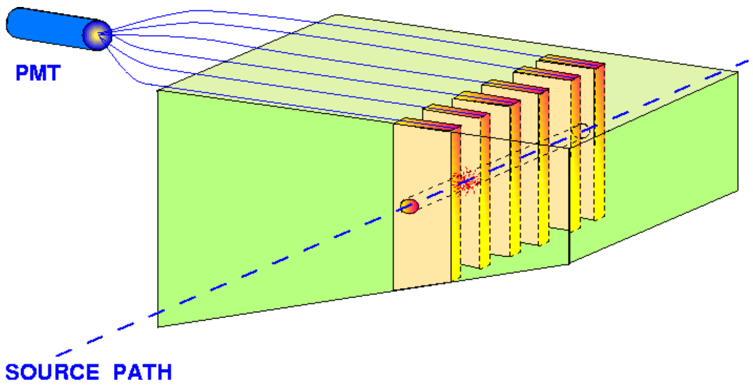
- Energy reconstructed at the EM scale

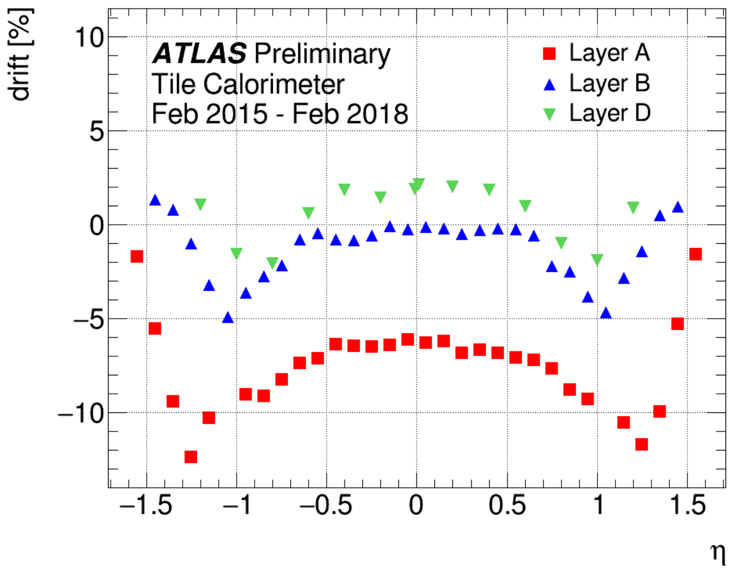
$$E[\mathrm{GeV}] = \frac{A[\mathrm{ADC\ counts}]}{C_{Cs} \cdot C_{las} \cdot C_{CIS}[\mathrm{ADC\ counts/pC}] \cdot C_{TB}[\mathrm{pC/GeV}]}$$

  - C_{TB} determined at dedicated beam tests

Cesium system

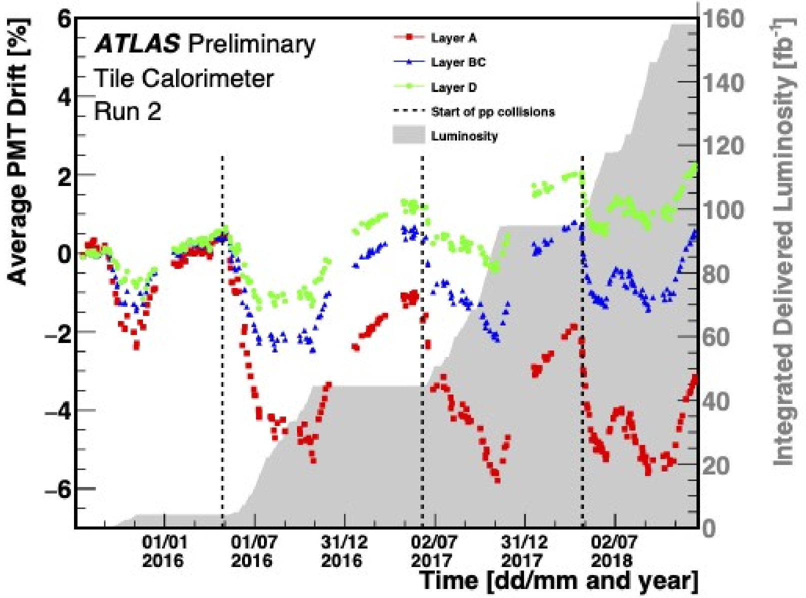
- Radioactive ^{137}Cs source hydraulically driven through all calorimeter tiles
  - calibrates the whole readout chain (optics, PMTs)
  - readout through integrator system (τ = 10-20 ms)
  - allows for PMT response equalisation through PMT HV settings at high precision (~0.3%)
- Deviations of the response caused by optics degradation (due to radiation dose) and PMT gain variations
  - largest drift during Run-2 period observed in the innermost radial layer, closest to the interaction point





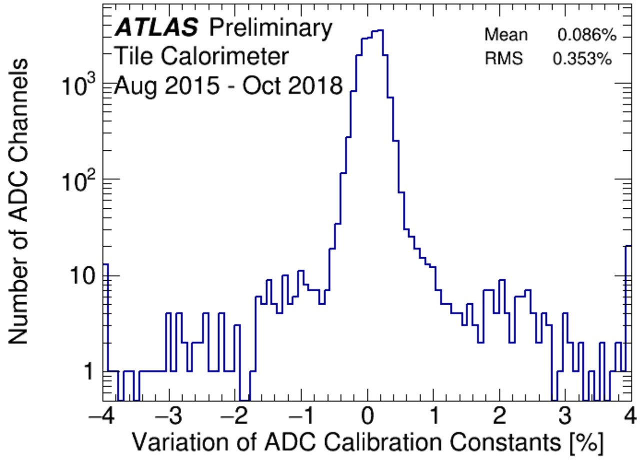
Laser system

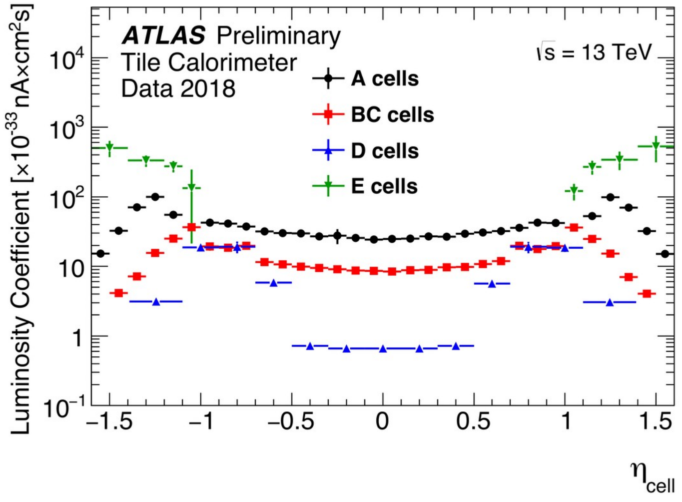
- Controlled short laser pulses sent simultaneously to all PMTs, used to monitor PMT gain and to measure possible PMT non-linearity
  - PMT response determined w.r.t. last Cesium scan
  - standalone laser runs (performed daily, constants updated ~weekly) as well as laser-in-gap events (collected during collision runs in LHC empty bunches, used also for time calibration monitoring)
  - precision of the system at the level of 0.5%
- Largest drifts observed for PMTs reading the innermost cells
  - down-drift during collisions
  - recovery during beam-off periods



Charge Injection and Minimum Bias systems

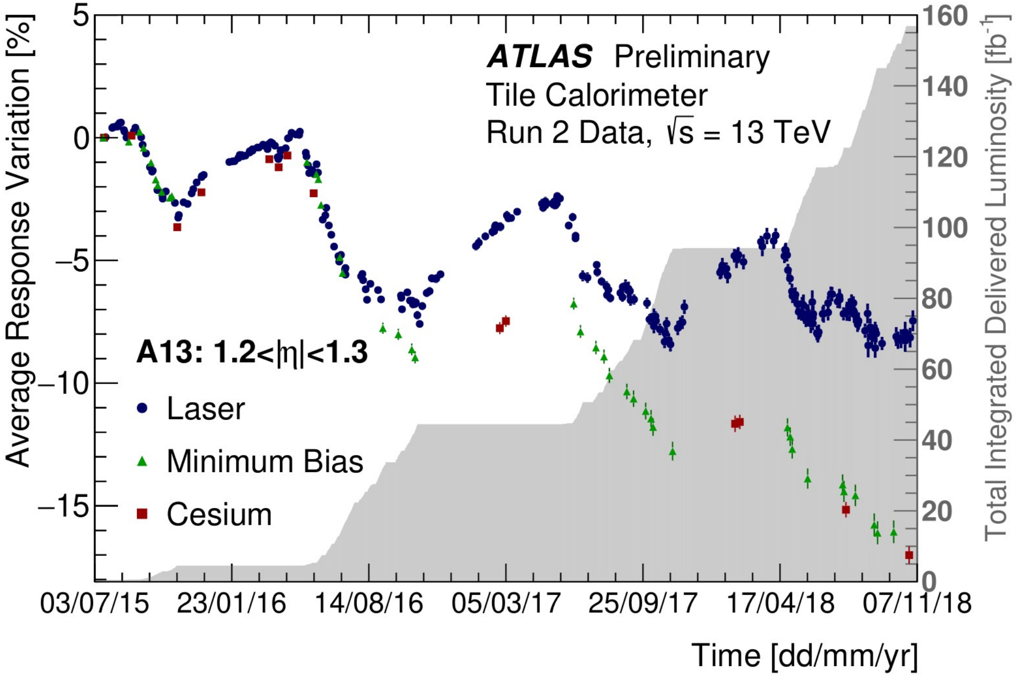
- CIS injects well-defined charge into fast readout electronics, spanning the whole dynamic range in both gains
  - determines the amplitude [ADC counts] to charge [pC] conversion and electronics non-linearities, also used to calibrate analog L1 trigger
  - precision ~0.7%, very good stability in time
- Minimum bias system measures response to soft inelastic interactions
  - shares readout path with Cs, integrates signal over ~ 10-20 ms
  - also calibrates special cells (E-cells and Minimum Bias Trigger Scintillators) where Cs is not available
  - signal proportional to instantaneous luminosity → used in luminosity measurements





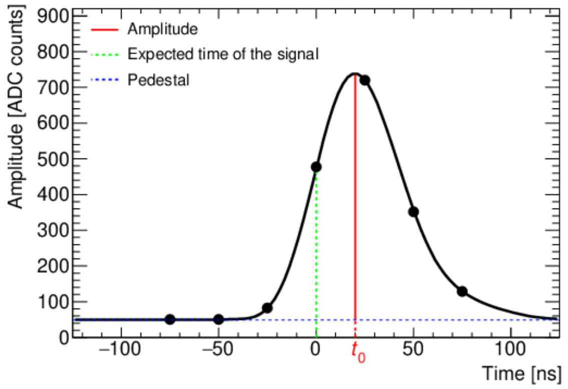
Combined calibration

- Combination of individual systems allows to disentangle between various effects
  - Cs and minimum bias results are in good agreement
  - difference between laser and Cs (minimum bias) is due to tile and WLS fibre degradation
  - ~10% optics degradation seen in cell A13 during Run 2 (most irradiated standard cell)



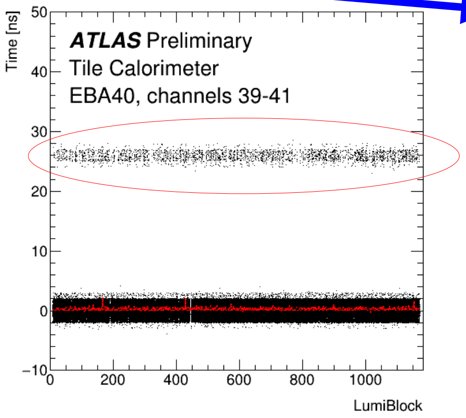
Time calibration & monitoring

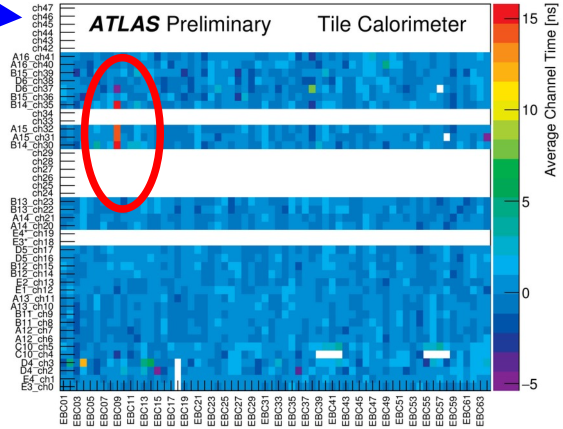
- Measured time t_0 is the phase of signal pulse w.r.t. readout window centre



- Goal: particles from IP travelling at speed of light give t_0~0, important for time-of-flight measurements and Optimal Filtering energy reconstruction
- Calibration performed with splash events and initial pp collisions
- Timing is monitored with laser-in-gap and pp collision data. Examples of problems during Run 2:
  - intermittent events with +25 ns offset
  - sudden changes in time calibration

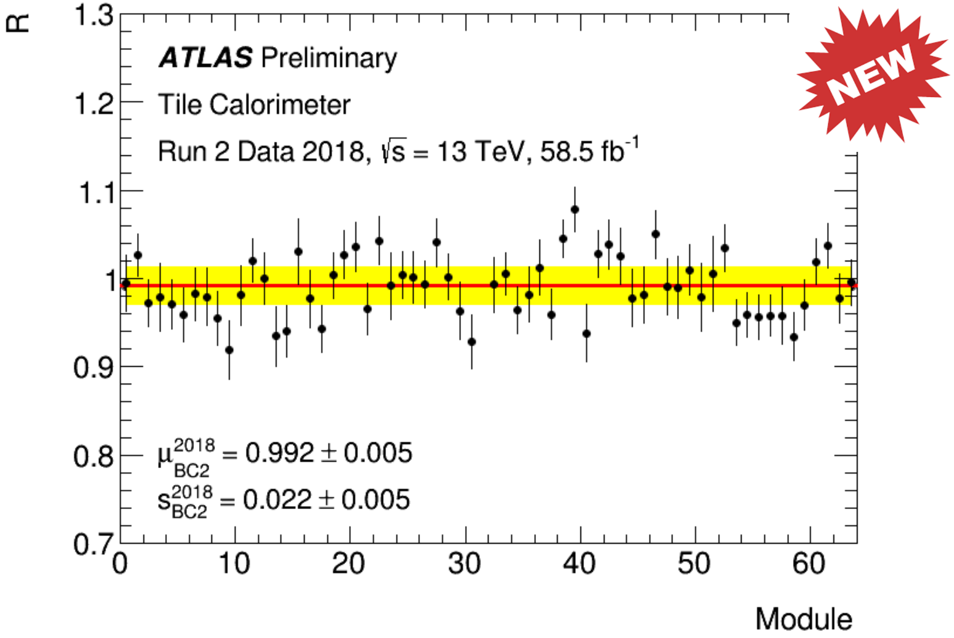
  These problems are corrected in (re)processed data





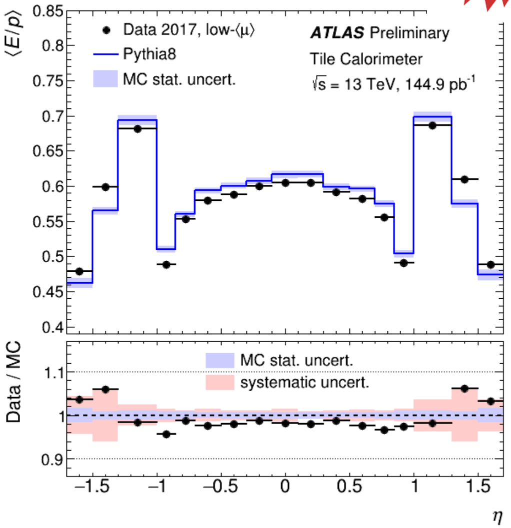
Isolated muons

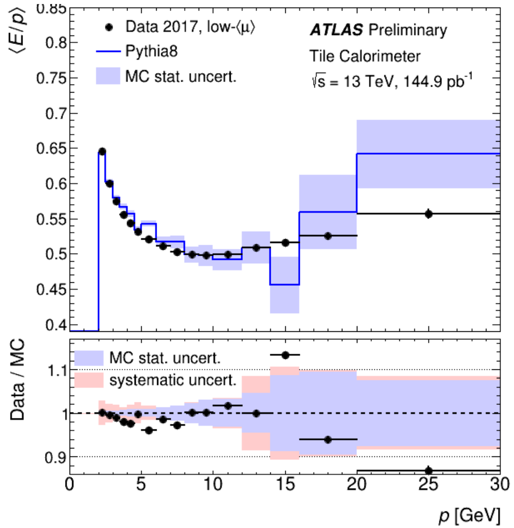
- Check of the EM scale and uniformity with isolated muons from W decay
  - momentum range 20-80 GeV (ionization dominates, ΔE scales with path length Δx)
  - evaluate truncated mean $\Delta E/\Delta x$ (remove 1% of events with highest values) in every cell
  - look at $R = (\Delta E/\Delta x)_{data}/(\Delta E/\Delta x)_{MC}$ to avoid residual non-linearity of the truncated mean
- Results
  - cell uniformity 2.4% across azimuth, consistent between different cell types
  - all layers consistent with R=1 within 2%
  - comparison of 2015+2016 vs 2017 vs 2018 shows very good stability in time, at the level of few percents



Single isolated hadrons

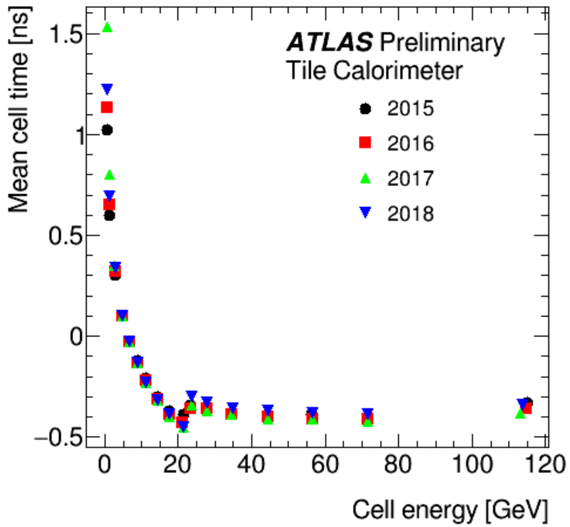
- Isolated tracks with EM calorimeter MIP-like signal
  - calorimeter clusters (ΔR=0.2) associated to tracks, cluster energy measured in TileCal, track momentum in Inner Detector
  - muons and neutral particles removed with further calorimeter cuts
- Compare **E/p** for data and MC
  - non-compesated calorimeter → E/p < 1
  - good agreement data/MC for low pile-up (<μ> ≈ 2)
  - for higher pile-up (<μ> ≈ 15) differences ~3% due to pile-up mismodelling
  - systematic uncertainties:
    - residual contribution from neutral particles (~1%)
    - upstream dead material for |η| > 0.7 (few %)

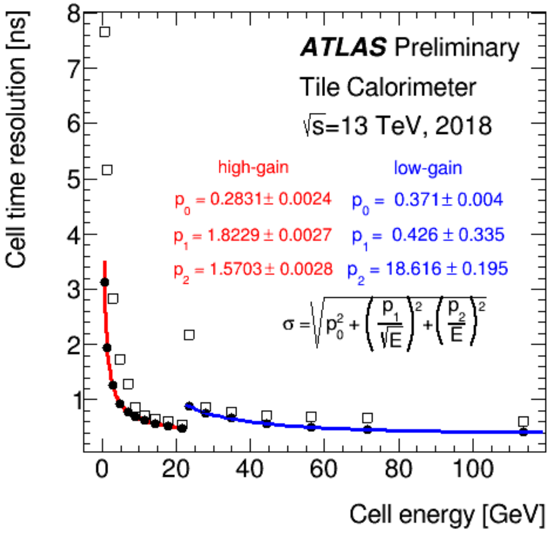


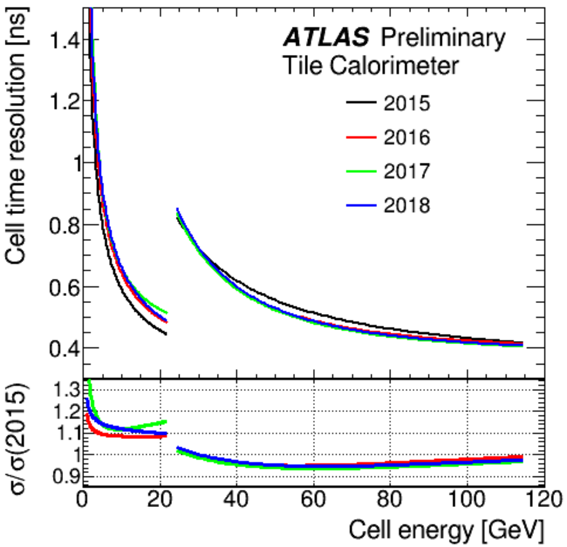


Timing performance

- Measured with jets using associated cells
- Mean cell time is very stable across Run 2 period
  - slightly depends on the deposited energy due to neutrons/slow hadronic component of the shower
- Time resolution
  - affected by pile-up at small energies, best in 2015 (lowest pile-up)
  - benefits from improved calibration procedure at higher energies since 2016

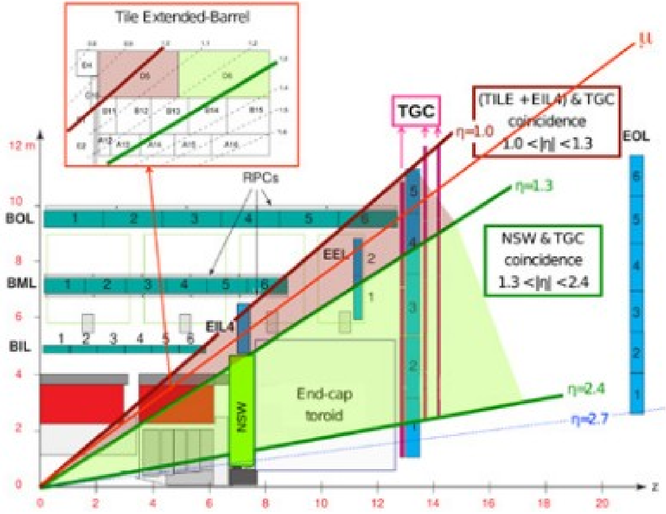


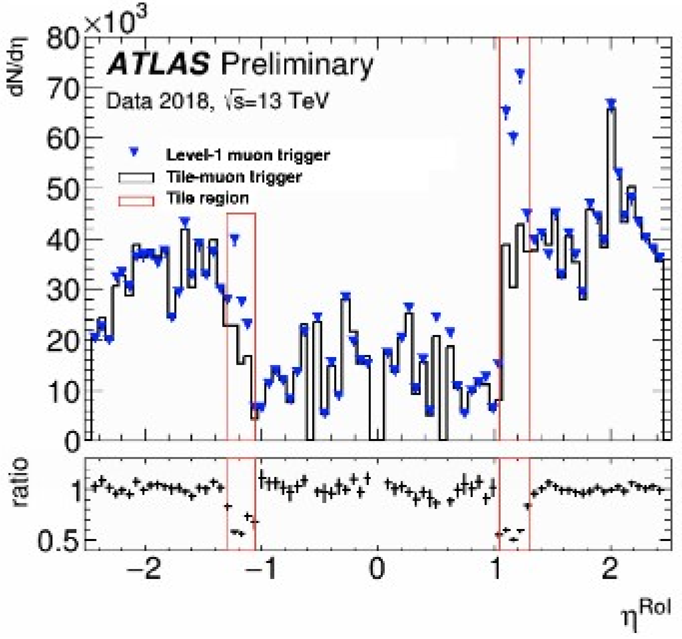




Tile-Muon trigger

- Special Tile-Muon trigger improves the background rejection in L1 trigger (new in Run 2)
  - coincidence of the 3rd (outermost) TileCal layer and TGC in the region $1.0 < |\eta| < 1.3$
- Total rate is reduced by 6%, but significantly in the corresponding region
- Inefficiency of 2.5% measured with $Z \to \mu\mu$, compatible with thin gaps between Tile modules





Conclusions

- All Tile Calorimeter calibration systems have precision below 1%, combined energy calibration guarantees very good response stability
- Good stability of timing due to extensive monitoring
- Tile Calorimeter performance assessed with muons, single hadrons and jets
  - verified EM scale settings and the response uniformity
  - time resolution measured and understood
  - new Tile-muon trigger improved the first level trigger
- In parallel working on upgrade for HL-LHC, see the dedicated talk on Thursday morning

BACKUP