Performance and calibration of the ATLAS Tile Calorimeter

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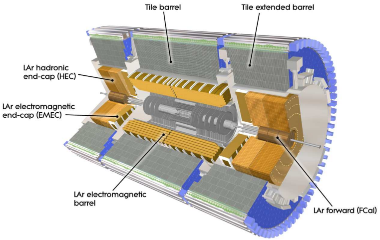
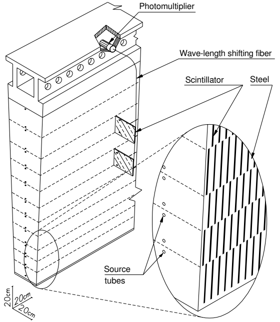
Kruger 2022 (4-9 Dec 2022)

Tile Calorimeter

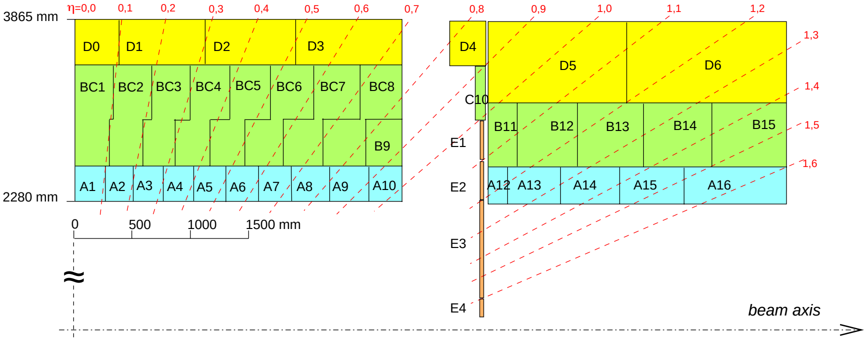
- Central hadronic calorimeter ($|\eta| < 1.7$) of ATLAS
- Measures energy and direction of jets, taus, $E_{\mathrm{T}}^{\mathrm{miss}}$, assists in muon identification and provides input to L1-trigger
- Mechanically divided into 3 parts – 1 central long barrel (LB) and 2 extended barrels (EBs)
  - 4 readout partitions – EBA, LBA, LBC, EBC
- Full azimuthal coverage around the beam axis is achieved with 64 modules (in each barrel), each module covering $\Delta\phi < 0.1$ radians
- Built from plastic scintillator tiles regularly spaced between steel absorber plates (perpendicular to the beam axis)
- The light generated in the scintillators is collected on both sides of the tile and further transported to the photomultiplier tubes by wavelength shifting (WLS) fibres



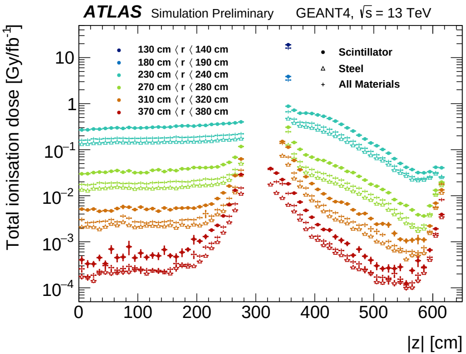


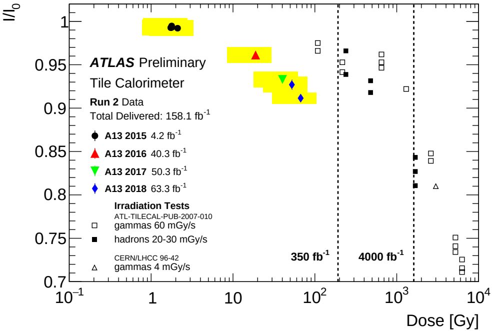
Tile Calorimeter layout in Run-3

- The read-out cell geometry is given by a group of WLS fibres from individual tiles coupled to PMTs $\rightarrow$ most cells readout with 2 PMTs, $\sim$ 5000 cells in total
- Cell geometry: 3 radial layers, $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.2 $\times$ 0.1 in the outermost layer)
- $\Delta\eta$ size of E3 and E4 scintillators has changed in Run-3 geometry:
  - E3: $1.2 < |\eta| < 1.4 \rightarrow 1.2 < |\eta| < 1.6$
  - E4: $1.4 < |\eta| < 1.6 \rightarrow 1.6 < |\eta| < 1.72$



Scintillator and WLS fibres ageing



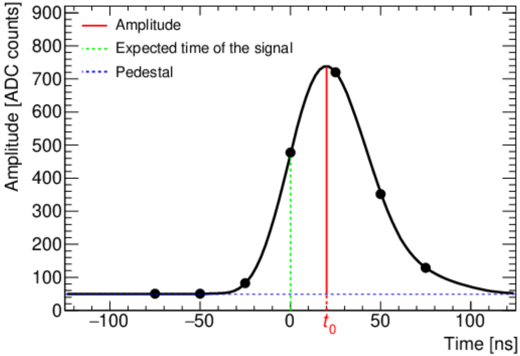


- The relative light yield of the cells decreases with exposure to radiation due to scintillator and fibres ageing
  - the largest doses, up to 20 Gy/fb^{-1}, occur in the region $|z| \sim 360$ cm, where the E cells are localised ($130 < r < 280$ cm), and in the A cells ($230 < r < 240$ cm)
  - at the end of Run 2, for the most irradiated standard cell, cell A13, $I/I_0 \sim 0.91$ after receiving the integrated dose ~ 60 Gy

Signal reconstruction

- Signal from each PMT is shaped such that all pulses have the same width
  - pulse amplitude is proportional to the deposited energy
- Shaped signal is amplified in two separate gains, the high-gain and the low-gain (64:1)
  - the high- and low-gain allow to measure the energies in the range 0 – 12 GeV and 0 – 800 GeV, respectively.
  - the two gains ensure a good signal-to-noise ratio for small and large signals

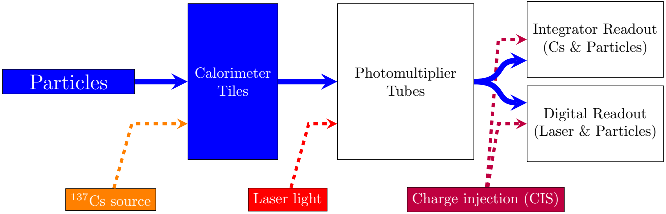
- Signals from each gain is sampled and digitised by 10-bit ADCs every 25 ns
- Data sent off-detector for further processing upon L1-trigger accept
- Amplitude A and time t_0 reconstructed with Optimal Filtering algorithm



Overview of the calibration systems

Three dedicated systems cover different parts of the readout chain

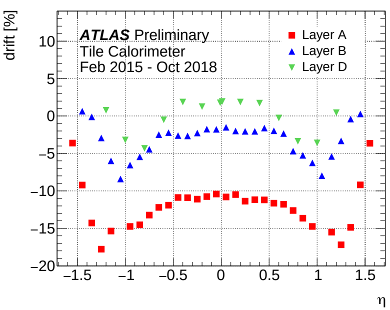
- Cs – optics, PMT $\rightarrow C_{\mathrm{Cs}}$
- Laser – PMT, fast readout electronics $\rightarrow C_{\mathrm{las}}$
- Charge Injection System (CIS) - fast readout electronics $\rightarrow C_{\mathrm{CIS}}$

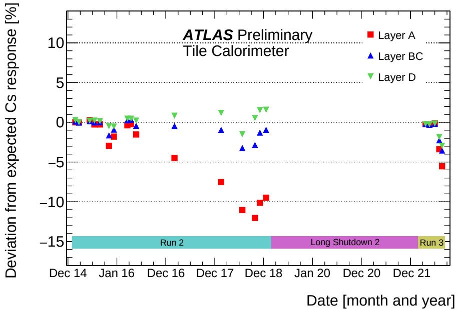


- Energy reconstructed at the EM scale: $E[\mathrm{GeV}] = \frac{A[\text{ADC counts}]}{C_{\mathrm{Cs}} \cdot C_{\mathrm{las}} \cdot C_{\mathrm{CIS}}[\text{ADC counts/pC}] \cdot C_{\mathrm{TB}}[\mathrm{pC/GeV}]}$
- where C_{TB} was determined at dedicated beam tests

Cesium system

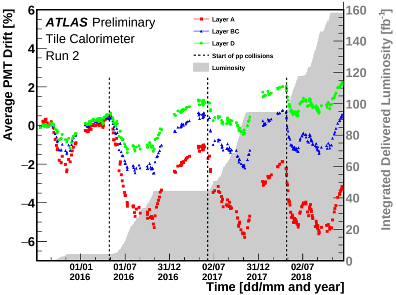
- Radioactive ^{137}Cs source hydraulically driven through all calorimeter tiles
  - calibrates the whole readout chain (optics, PMTs)
  - readout through integrator system (time = 10-20 ms)
  - allows for PMT response equalisation through PMT HV settings at high precision (∼0.3%)
  - Cs scans performed once per month
- Response deviations caused by optics degradation (due to radiation dose) and PMT gain variations
  - At the end of Run 2, the most irradiated cells in layer A had their response drifting downward by 18%, while central cells in outer layer D drifted up by 2%

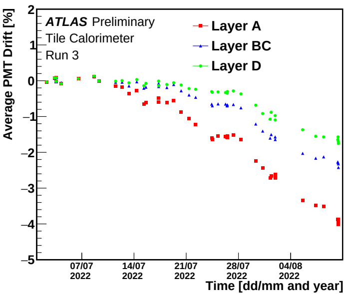




Laser system

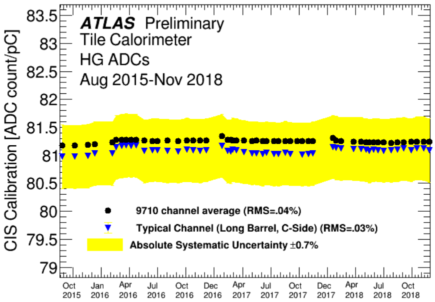
- Controlled short laser pulses sent simultaneously to all PMTs, used to monitor PMT gain and measure possible PMT non-linearity
  - PMT response determined w.r.t. last Cesium scan
  - **standalone laser runs** $\rightarrow$ performed daily, constants updated $\sim$weekly
  - **laser-in-gap events** $\rightarrow$ collected during collision runs in LHC empty bunches, used also to monitor timing
  - precision of the system at the level of 0.5%
- At the end of Run 2, largest drifts up to 6% observed for PMTs reading the innermost cells (layer A)
  - down-drift during collisions, recovery during beam-off periods

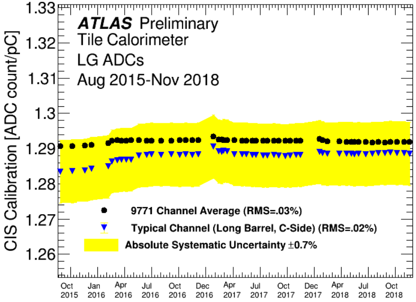




Charge Injection System

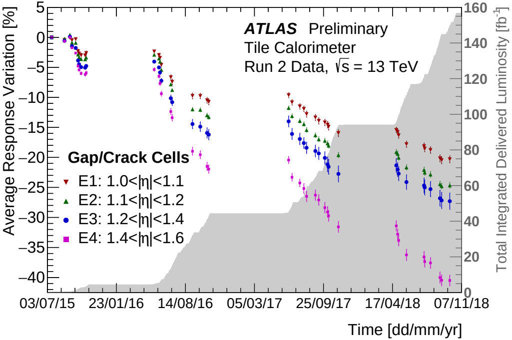
- CIS injects well-defined charge into fast readout electronics, spanning the whole dynamic range in both gains
  - determines the amplitude [ADC counts] to charge [pC] conversion and electronics non-linearities, also used to calibrate analog L1 trigger
  - CIS calibration runs taken twice per week, constants updated once per month
  - precision 0.7%, very good stability in time





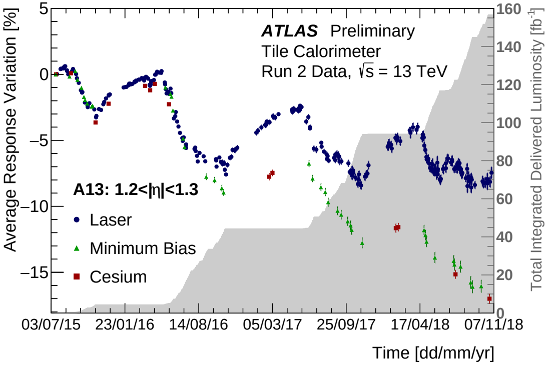
Minimum Bias systems

- Minimum Bias system measures response to soft inelastic interactions
  - shares readout path with Cs, integrates signal over $\sim$ 10-20 ms
  - also calibrates special cells (E-cells and Minimum Bias Trigger Scintillators) where Cs is not available
  - provides an independent measurement of the ATLAS instantaneous luminosity
  - at the end of Run 2, the maximum response loss in E4 (E3) cells is $\sim$ 40% ($\sim$ 27%)
    - E3 and E4 scintillators were replaced by new ones after Run 2



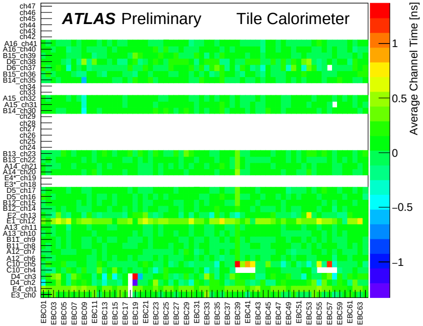
Combined calibration

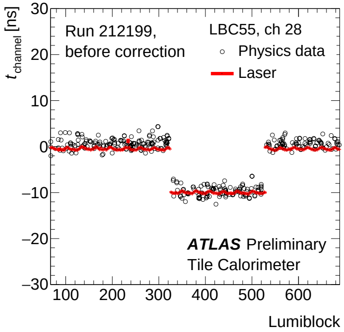
- Combination of individual systems allows to disentangle between various effects
  - Cs and Minimum Bias results are in good agreement
  - difference between laser and Cs (Minimum Bias) is due to scintillators and WLS fibre degradation
  - at the end of Run 2, the maximum response loss in A13 is $\sim 16\%$, where $\sim 8\%$ can be associated with loss of the PMT gain and approximately $\sim 8\%$ with the scintillators degradation



Time calibration and monitoring

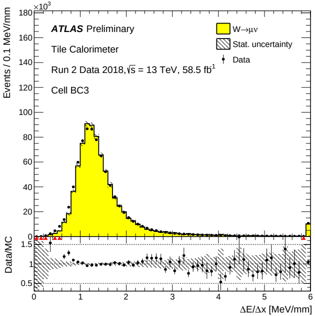
- Measured time t_0 is the phase of signal pulse w.r.t. readout window centre
- Goal: particles from IP travelling at speed of light give t_0 at 0, important for time-of-flight measurements and Optimal Filtering energy reconstruction
- Calibration performed with splash events and initial *pp* collisions
- Timing is monitored with laser-in-gap and *pp* collision data, afterwards corrections are applied

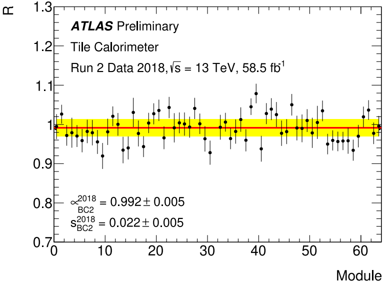




Isolated muons

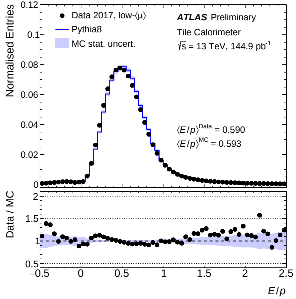
- Check of the EM scale and uniformity with isolated muons from W decay
  - momentum range 20-80 GeV (ionization dominates, ΔE scales with path length Δx)
  - evaluate truncated mean $\Delta E/\Delta x$ (remove 1% of events with highest values) in every cell
  - look at $R = (\Delta E/\Delta x)_{\text{data}}/(\Delta E/\Delta x)_{\text{MC}}$ to avoid residual non-linearity of the truncated mean
- Results
  - cell uniformity $\sim 2\%$ 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

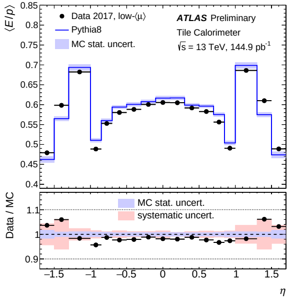




Single isolated hadrons

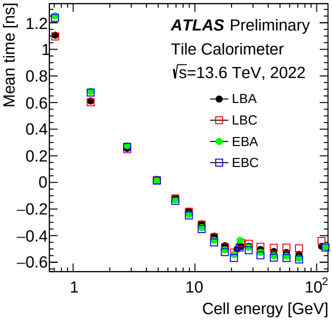
- The ratio of the energy deposited in the TileCal (E) divided by the momentum measured in the Inner Detector (p)
  - calorimeter clusters ($\Delta R = 0.2$) associated to tracks
  - muons and neutral particles removed from analysis
- Compare E/p for data and MC
  - non-compensated calorimeter $\rightarrow$ E/p < 1
  - good agreement data/MC for low pile-up ($\langle\mu\rangle \approx 2$)
  - systematic uncertainties considered:
    - residual contribution from neutral particles ($\sim$1%)
    - upstream dead material for $|\eta| > 0.7$ (few %)

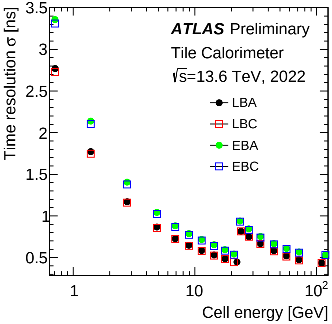


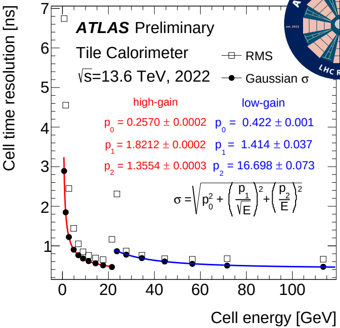


Timing performance

- Measured with jets using associated cells
- Mean cell time slightly depends on the deposited energy due to neutrons/slow hadronic component of the shower
- Time resolution affected by pile-up at small energies, improved calibration procedure at higher energies since 2016 (time resolution improved by $\sim$ 10%)

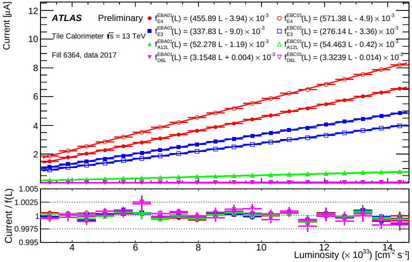






Luminosity measurements

- TileCal and the Inner Detector play an important role due to their luminosity measurements being independent of pileup
- TileCal is used to measure and study the dominant systematic uncertainty associated with the ATLAS luminosity measurement



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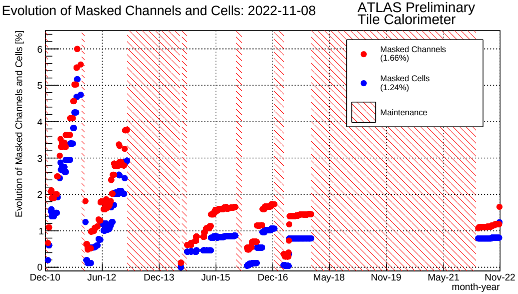
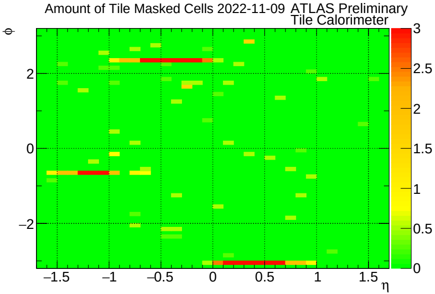
- The dependence of the PMT anode current on track-counting luminosity for a few TileCal channels
  - The intercept at zero luminosity has nonzero values due to a small non-linear contribution to the anode current from the PMT HV divider.

TileCal status in 2022

- Started Run 3 with 0.79% of cells masked (1.1% of channels)
  - Two modules failed during the closing of the detector
    - In 2018, had two modules off due to an unrelated issue, overall impact on data is manageable
  - One module in emergency mode
    - Not possible to tune high voltage for individual PMTs, still good for physics data taking
- Recently we lost one more module $\rightarrow$ 1.24% of cells masked (1.66% of channels)
- Plan to repair malfunctioning modules during the year end technical stop





Conclusion

- All Tile Calorimeter calibration systems have precision below 1%, combined energy calibration guarantees very good response stability
- At the end of Run 2, the maximum response loss in the cell A13 is $\sim 16\%$, where $\sim 8\%$ can be associated with loss of the PMT gain and approximately $\sim 8\%$ with the scintillators degradation (after receiving the integrated dose ~ 60 Gy)
- Good timing stability observed in Run 2 due to extensive monitoring and the same approach is applied during Run 3
- Tile Calorimeter performance assessed with muons, single hadrons and jets using Run 2 and Run 3 data
  - isolated muons have been used to study and validate the electromagnetic scale
  - hadronic response has been probed with isolated hadrons
  - time resolution measured and understood using jets
- In parallel working on upgrade for HL-LHC, see dedicated talk by Henric Wilkens

BONUS SLIDES

TileCal luminosity measurements

- Ratios of the instantaneous luminosity measured by TileCal E-cell scintillators to that from track-counting
- Shown are different periods with various number of bunches/luminosity scale which affect the agreement between TileCal and track-counting measurements
- Effects from activation decay can be seen in the negative slope for the low mu part of fill 6847 while signs of activation build up is visible in the positive slopes at the beginning of the three middle plots
- Ratios using TileCal E-cells averaged over 5 min intervals and with the integrated ratio normalised to unity, in the range indicated by the green box