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The ATLAS Tile Calorimeter performance and its upgrade towards the High-Luminosity LHC

Ryan Mckenzie, University of the Witwatersrand,
on behalf of the Tile Calorimeter System

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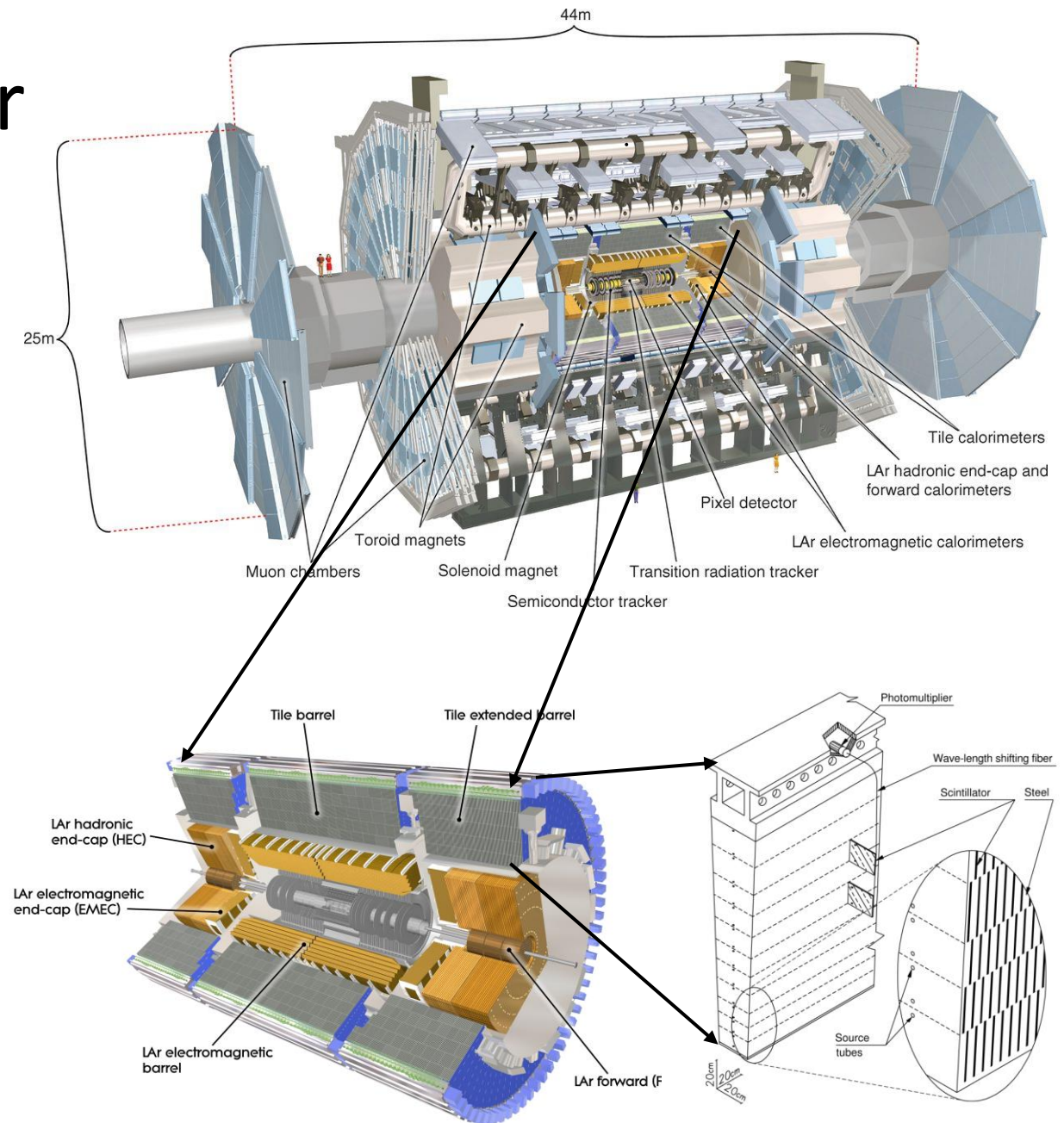
XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

This work is based on research supported in part by the National Research Foundation of South Africa (Grant number: 123017)



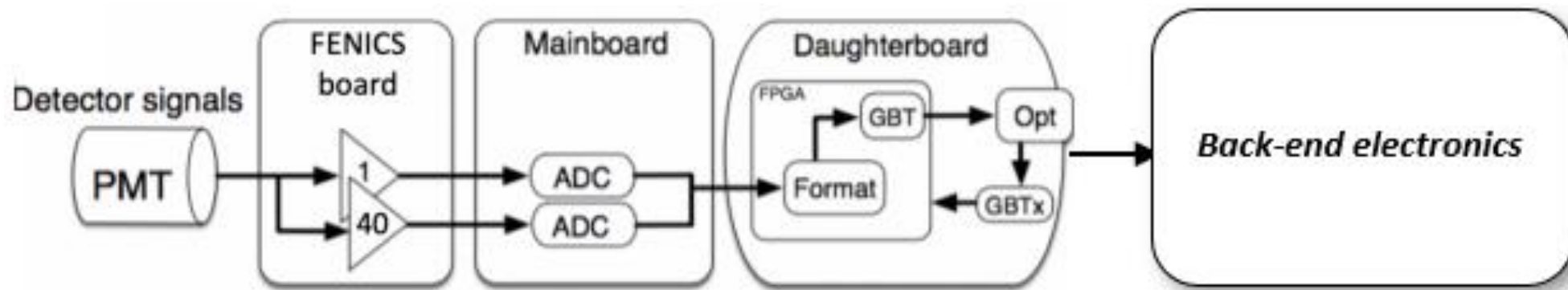
The ATLAS Tile Calorimeter

- **The Tile-Calorimeter (TileCal)** is a sampling calorimeter which forms the central region of the Hadronic calorimeter of ATLAS;
- **TileCal is responsible for the measurement** of jet- and missing-energy, jet substructure, and triggering (including muon information);
- **TileCAL is Modular** and consists of 256 wedge shaped modules arranged azimuthally around the beam axis. An individual module consists of alternating steel (absorber) tiles and plastic scintillating (Active media) tiles and a Super Drawer (SD) which houses the Front-End (FE) electronics.
- **Particles produce light when passing through the tiles.** This light is then transmitted to Photo-Multiplier Tubes (PMTs) located in SDs via wave-length shifting fibers.



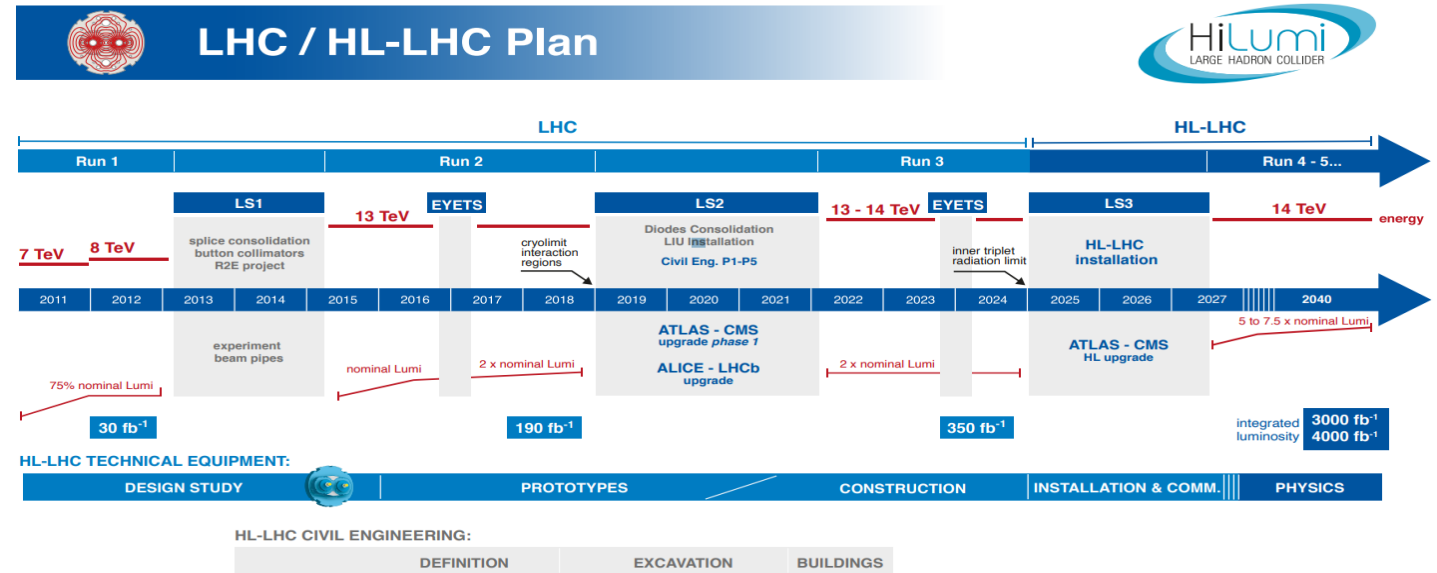
HL-LHC TileCal Front-End

- **PMTs** convert light to electric signals.
- **Front-End electronics(FENICS) boards** perform signal shaping and amplification;
- **Mainboards** receives analogue data and convert it to digital data which is then sent to the Daughterboard;
- **Daughterboards** are responsible for Data collection, formatting, transmission to the Back-End as well as clock and command distribution to the Front-End.
- **Low-Voltage Power Supply (LVPS)** provides power to the FE electronics while also monitoring critical values such as its operating temperature and output voltages;
- **High-Voltage (HV) Power Supply** supplies HV to the PMTs in the system, control the voltage for each tube and monitors the applied voltage.



TileCal and the HL-LHC

- The start of the operation of HL-LHC is planned for 2027 with a foreseen integrated luminosity of 4000 fb^{-1} ;
- TileCal must be upgraded to allow for continued high performance in the new HL-LHC environment.



A summary of the TileCal HL LHC upgrade:

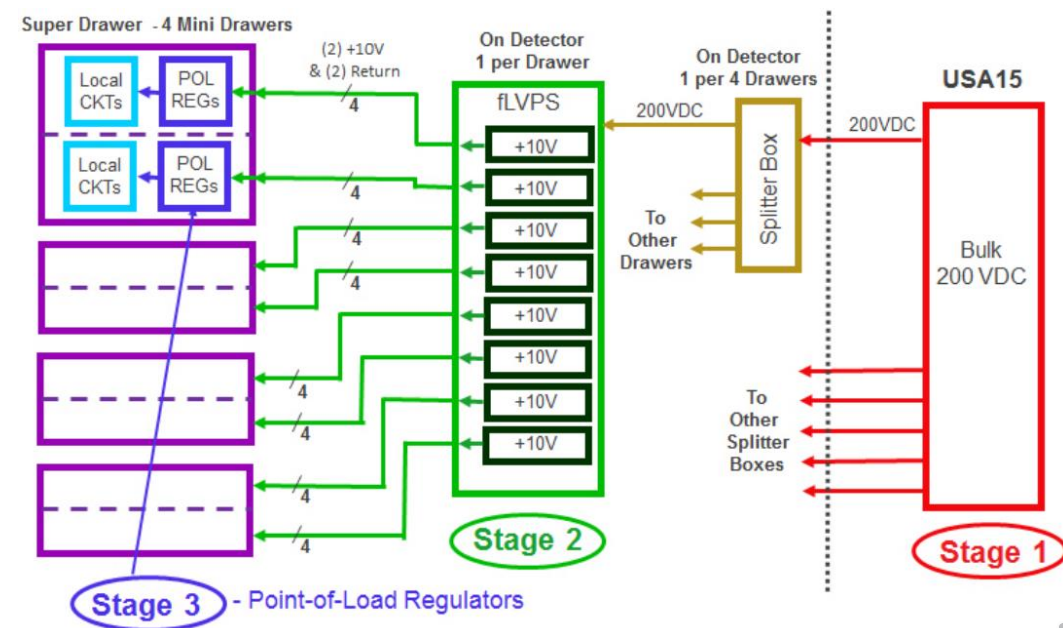
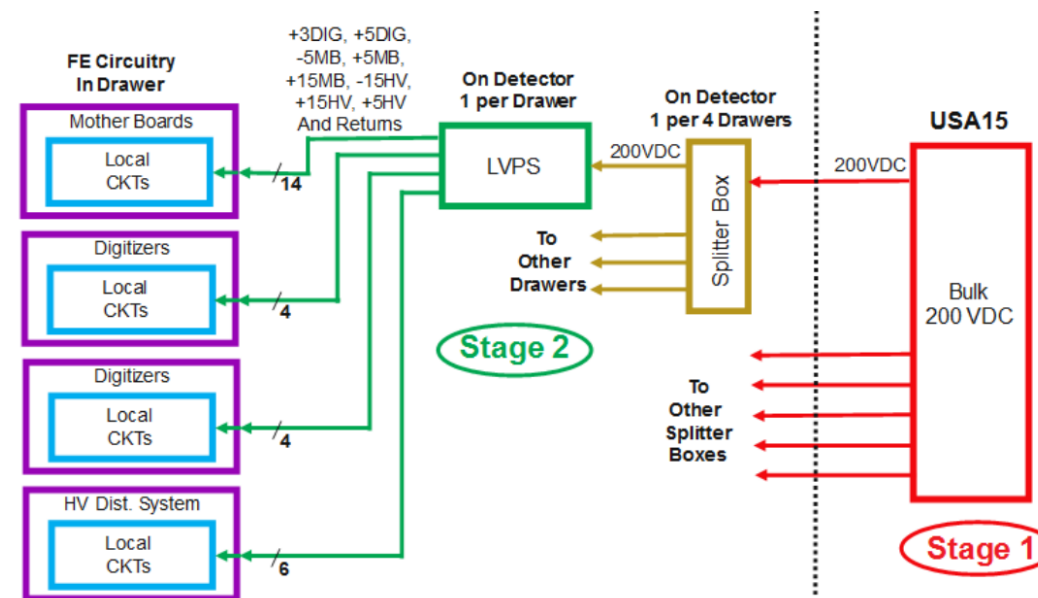
- Readout, Front and Back-end electronics are to be upgraded;
- Active dividers are replacing passive dividers to provide better linearity for the HL-LHC;
- 10% of PMTs to be Replaced in the most ex-posed regions;
- Mechanical alterations to the Super-Drawers structure;
- The High Voltage system is being upgraded to provide HV to PMTs with greater temperature and voltage stability, as well as remote/internal control;
- The Low-Voltage system is undergoing extensive upgrades;
- The Calibration systems are being upgraded with improvements to the stability and safety of the Cesium system as well as the Laser system receiving upgraded electronics and optical components

Legacy Low-Voltage System

- A **2-stage system** in which Bulk 200VDC power is converted to the voltages required by the FE electronics by different types of Brick(Transformer coupled buck converter);
- **Provides ON/OFF control** (Via Aux-boards) of the bricks in two groups which start successively.

LV System Upgrade

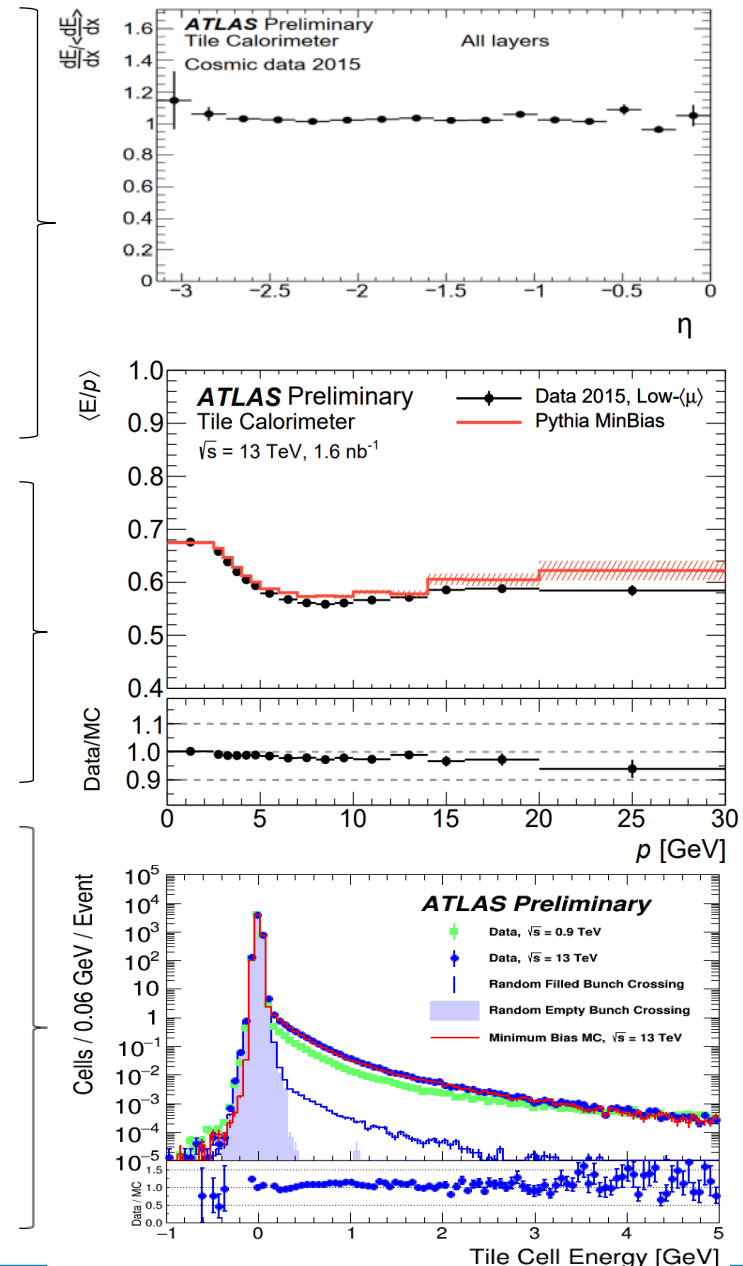
- **Conversion to a 3-stage system** which makes use of Point-of-load regulators (POLs). POLs function to step-down the 10VDC received from an LVPS Brick to the voltage required by local circuits. This allows for the use of a single type of brick with a standardized 10V output;
- **Tri-state functionality** is being introduced which allows for individual Bricks startup/shutdown. This functionality is so named due to the Aux-boards ability to send 3 different state signals to an LV Brick;
- An extensive **radiation campaign** is underway in order to validate LV system components operation within HL-LHC environment.



Performance during Run-II

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

- Cell response is evaluated as the energy deposited by the muon path length dE/dx ;
- Non-uniformity in eta (η) below 5%
- The ratio of the calorimeter energy at EM scale to the track momentum $\langle E/p \rangle$ of single hadrons is used to evaluate both uniformity and linearity during data taking;
- Good agreement between Data and MC sim
- Deposition of energy in TileCal cells for 0.9 and 13 TeV 2015 collision data, Minimum Bias MC, and randomly triggered events.



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileSingleParticleResponse>

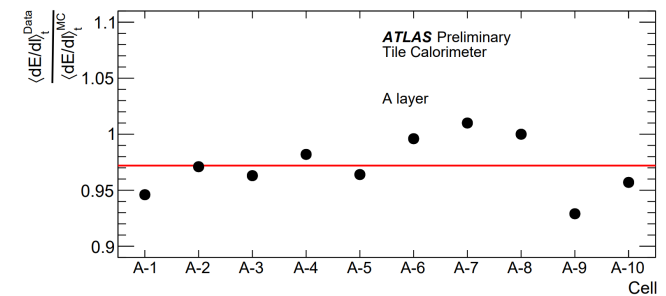
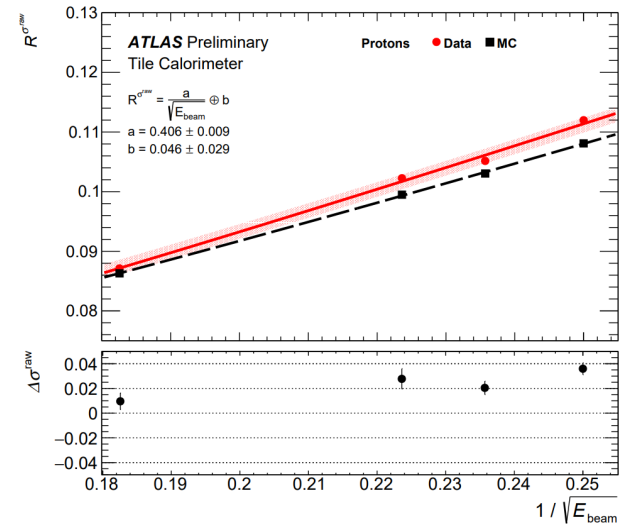
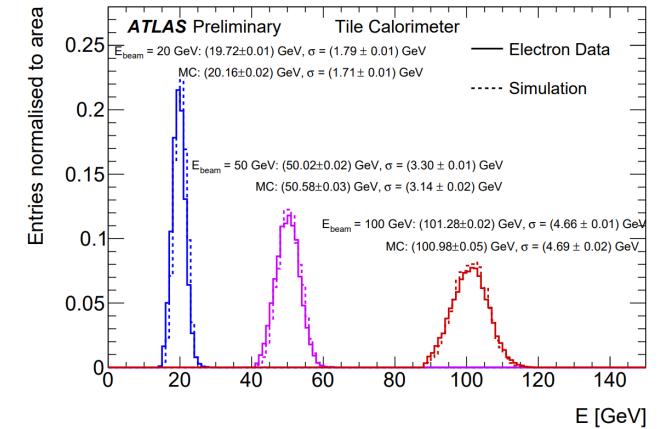
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileEnergyDeposit>



Test-Beam Performance

- Seven test beam campaigns were carried out between 2016 – 2018 with prototype FE electronics as well as prototype elements of the low/high voltage systems;
- The test beams show good performance of the new Front-End electronics;
- The fractional resolution in Data and MC for protons, kaons and Pions was obtained with a slight improvement in resolution being observed;
- The detector response has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl)
- The data shows a layer uniformity at 1%. An offset of max 4% is observed for Data/MC.

ATL-COM-TILECAL-2018-002



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileTestBeamResults>

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileTestBeamResults#Protons>

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileEnergyDeposition>

The ATLAS Tile Calorimeter

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- **Particles produce light** when passing through the tiles. This light is then transmitted to Photo-Multiplier Tubes (PMTs) located in SDs via wavelength shifting fibres.

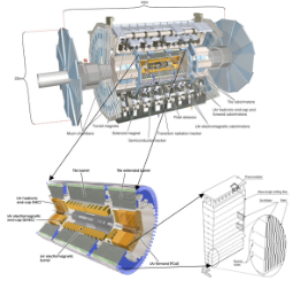


Fig. 1 Top - The ATLAS detector, Bottom left - The inner Barrel, Bottom right - A TileCal module.

Legacy Low-Voltage System

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LV System Upgrade

- Conversion to a **3-stage system** which makes use of Point-load regulators (POLs). POLs function to step-down the 10VDC received from an LVPS Brick to the voltage required by local circuits. This allows for the use of a single type of brick with a standardised 10V output;
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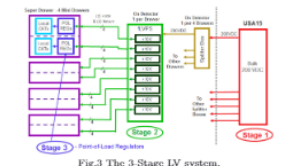


Fig.3 The 3-Stage LV system.

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Fig. 2 HL-LHC Tilecal Front-end electronics.

Performance during Run-II

- The ratio of the calorimeter energy at EM scale to the track momentum (E/p) of single hadrons is used to evaluate both uniformity and linearity during data taking;
- Good agreement between Data and MC sim.

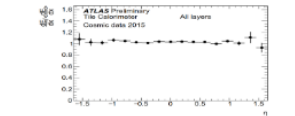


Fig. 4 Ratio of the truncated means of the distributions of the energy deposited in the layer cells by cosmic ray muons per unit of path length dE/dx .

- Isolated muons from cosmic rays are used to study the EM scale in-situ EM as well as the cells inter-calibration;
- Cell response is evaluated as the energy deposited by the muon path length dE/dx ;
- Non-uniformity in eta (η) below 5%;

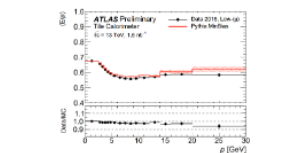


Fig. 5 Calorimeter response to single isolated charged hadrons.

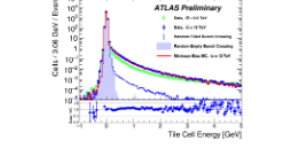


Fig. 6 Deposition of energy in TileCal cells for 0.9 and 13 TeV 2015 collision data, Minimum Bias MC, and randomly triggered events.

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Test-Beam Performance

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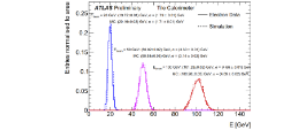


Fig.6 Distributions of the total energy deposited in the calorimeter obtained using electrons beams.

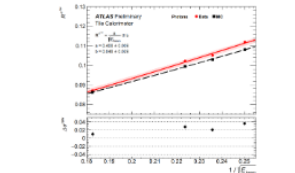


Fig. 7 Fractional resolution and predicted by Monte Carlo simulation obtained in the case of protons.

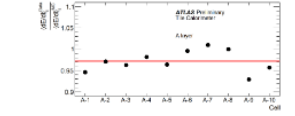


Fig. 8 Experimental and simulated muon data as a function of the cell number.

References:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

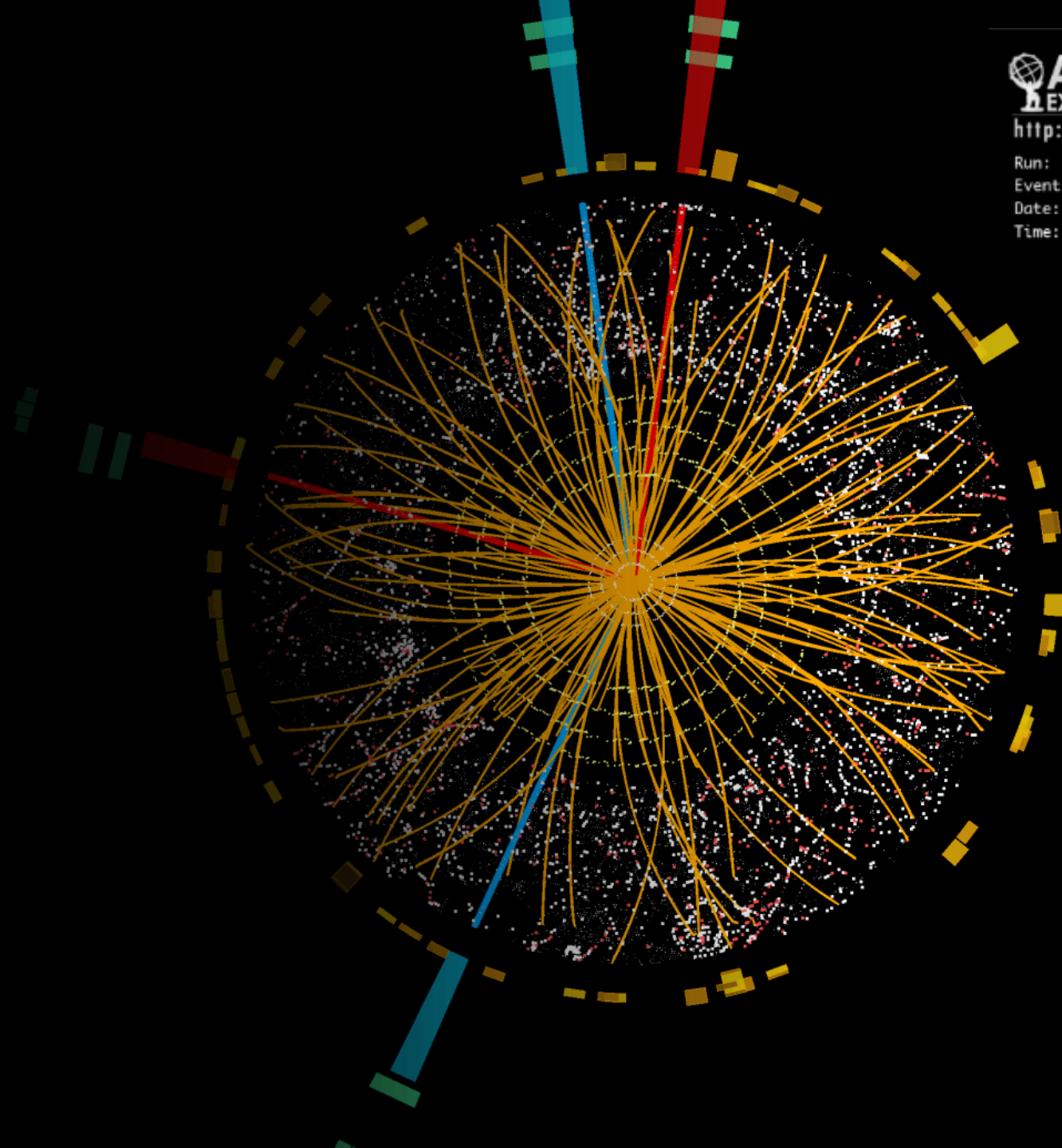
- /ApprovedPlotsTileTestBeamResults
- /ApprovedPlotsTile
- /ApprovedPlotsTileElectronics

Interactive session

- Additional slides will be provided to enable discussion of the topics introduced.
- Session 1: 13th of April (Tuesday) afternoon, from 14:15 to 15:45 (US EDT)
- Session 2: 15th of April (Thursday) morning from 6:45 to 7:45 (US EDT)



Back-up slides



Front-end electronics for TileCal at HL-LHC

FENICS

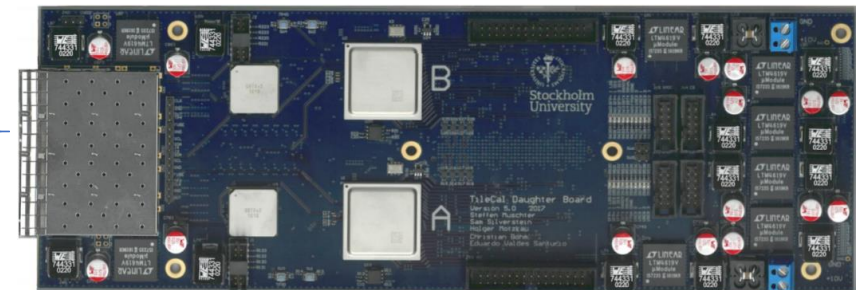
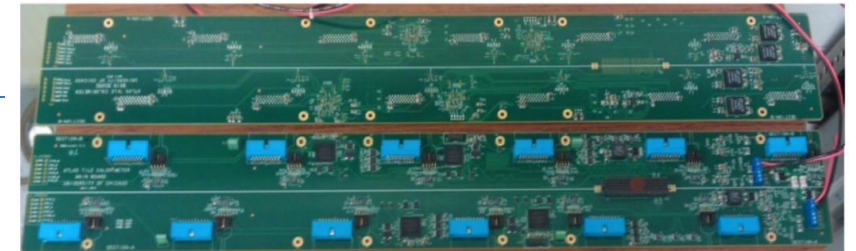
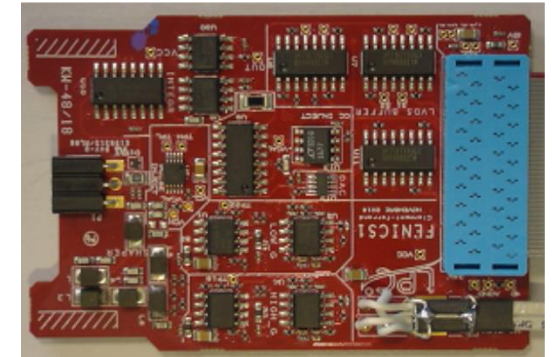
- Fast Readout: two gain amplification for physics;
- PMT Current Integrating Readout for 137Cs calibration & Luminosity measurements;
- Integrator Readout has 6 gains to cover 7-8 orders of magnitudes in luminosity;
- Improved precision and better noise performance than legacy;
- Charge injection system for precise calibration.

Mainboard

- Fast readout: 24 12-bit ADCs @40 Msps ;
- Integrator Readout: 12 16-bit SAR ADCs § Routes the digitized data to the Daughter Board ;
- Digital control of the front-end boards (configure for calibration or Physics).

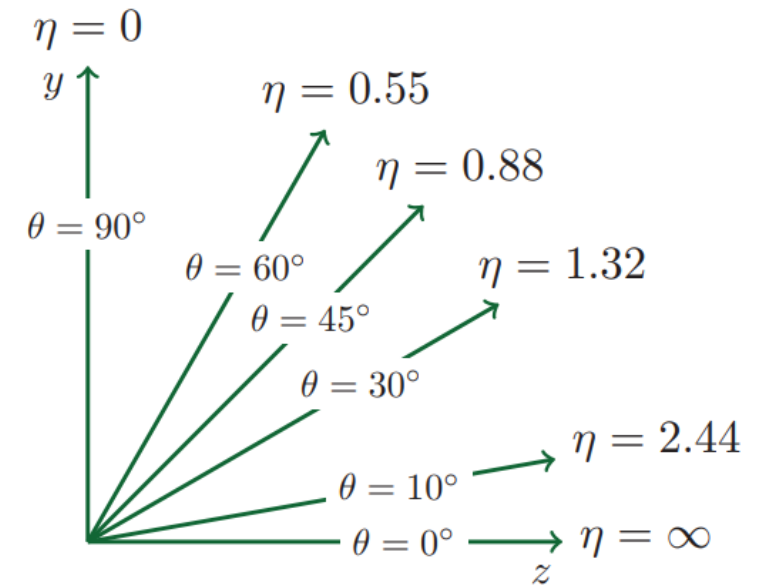
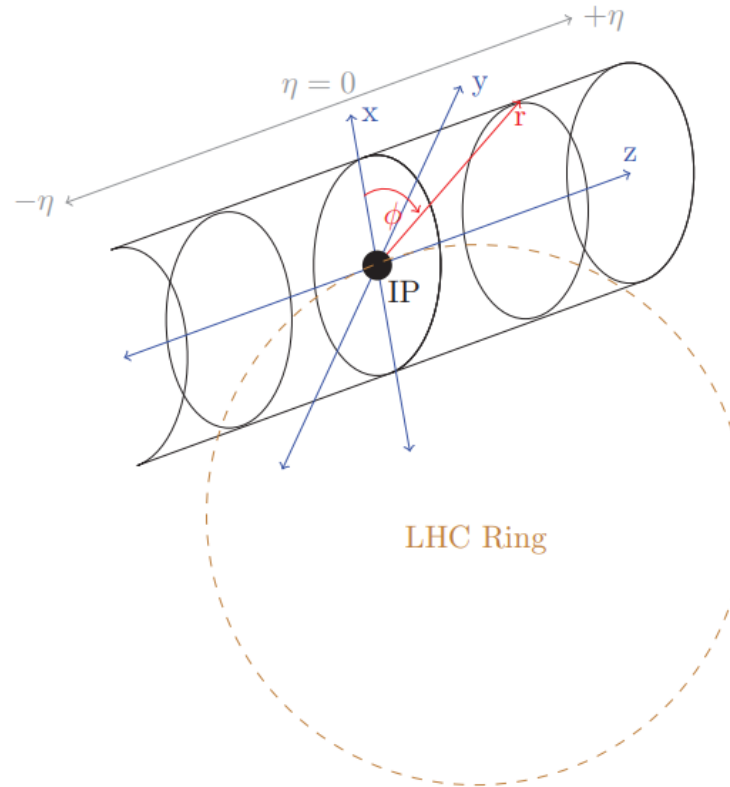
Daughterboard

- High Speed communication 4.8/9.6 Gbps;
- Send detector data to off-detector electronics;
- Receive, distribute LHC clocks, configurations and control ;
- 2 FPGAs Kintex Ultrascale (KU);
- Recent redesign due to single event latch-ups observed in previous FPGA (KU+)



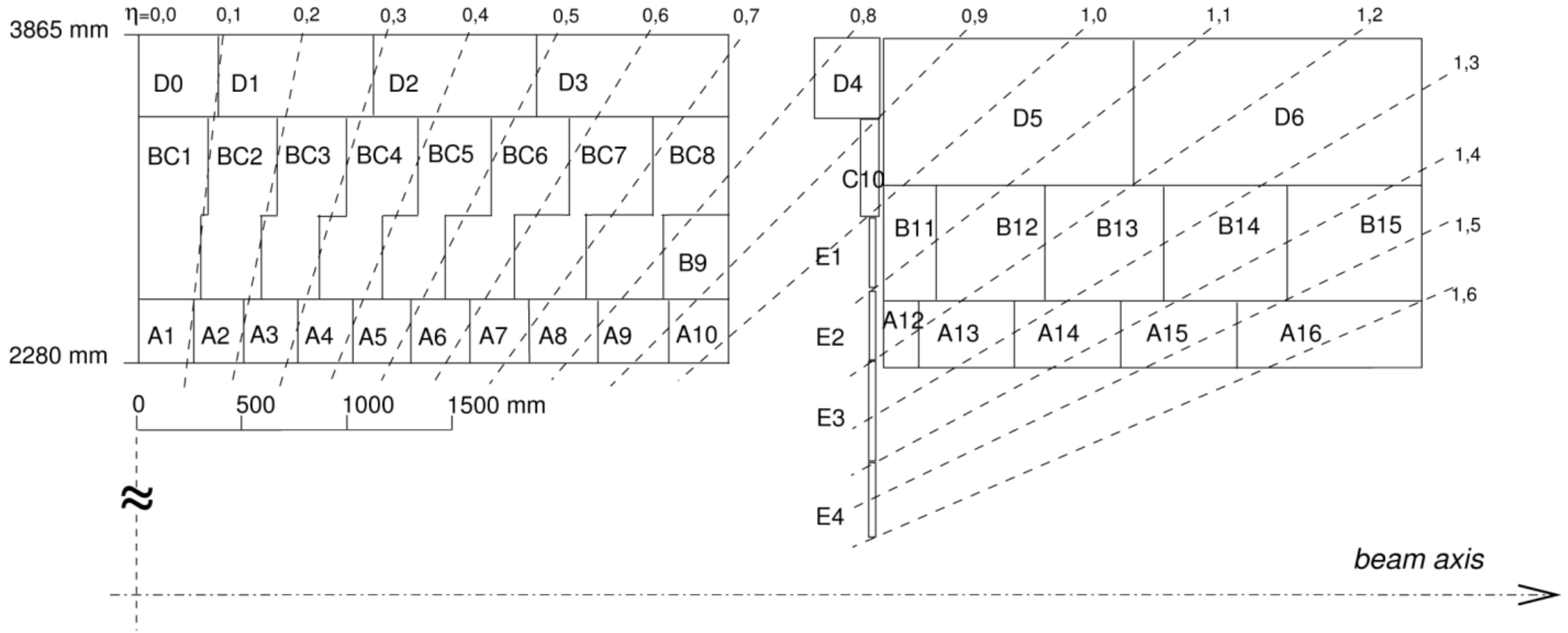
Coordinate system used in LHC experiments

- The Z axis is oriented along the beam pipe;
- The azimuthal angle (ϕ) is defined with respect to the x-y plane;
- The pseudorapidity (η) is defined to exploit the cylindrical geometry.



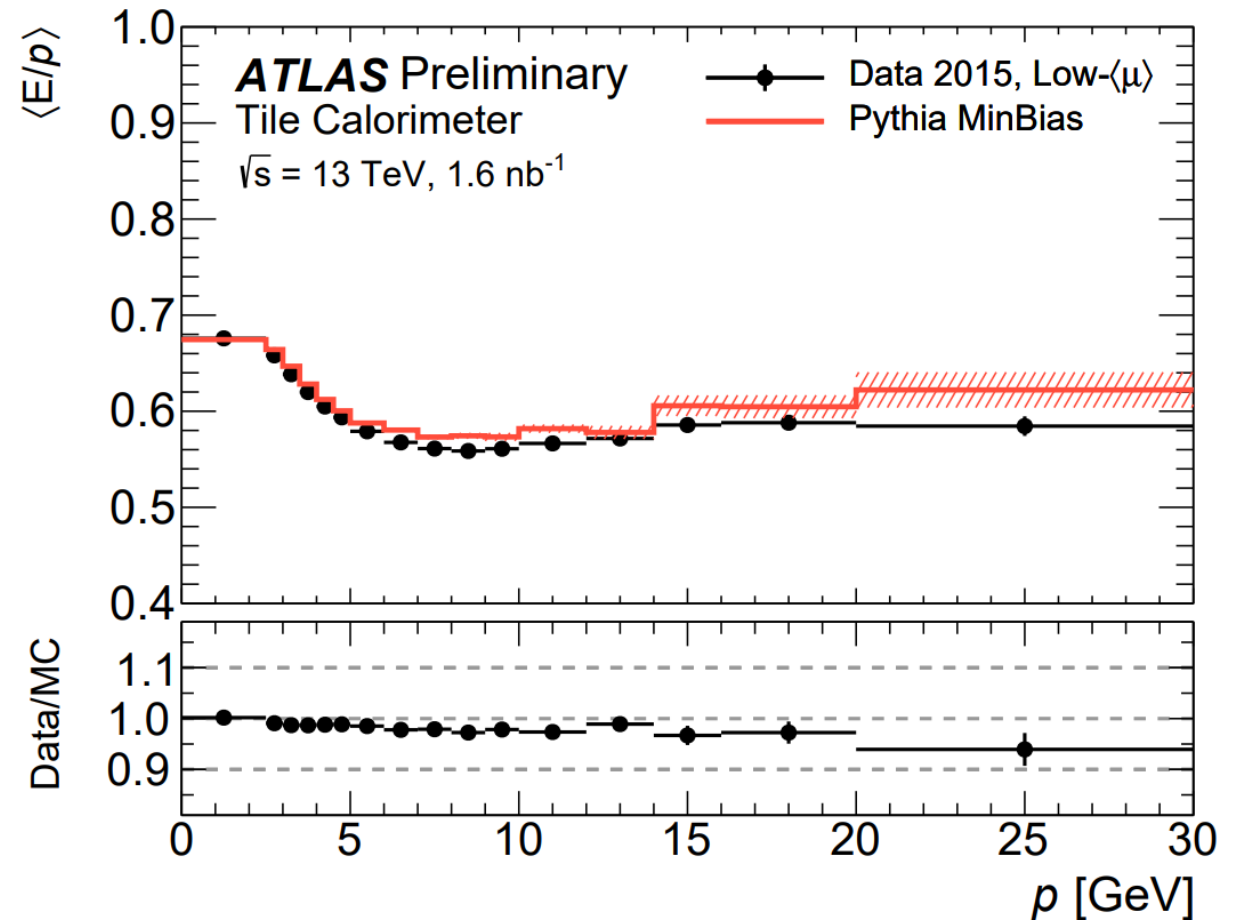
Experimental Particle Physics, Understanding the measurements and searches at the Large Hadron Collider, Deepak Kar, School of Physics, University of Witwatersrand, Johannesburg, South Africa, ISBN 978-0-7503-2112-9, Pg. 2-10.

Map of Tile cells, showing tower structure



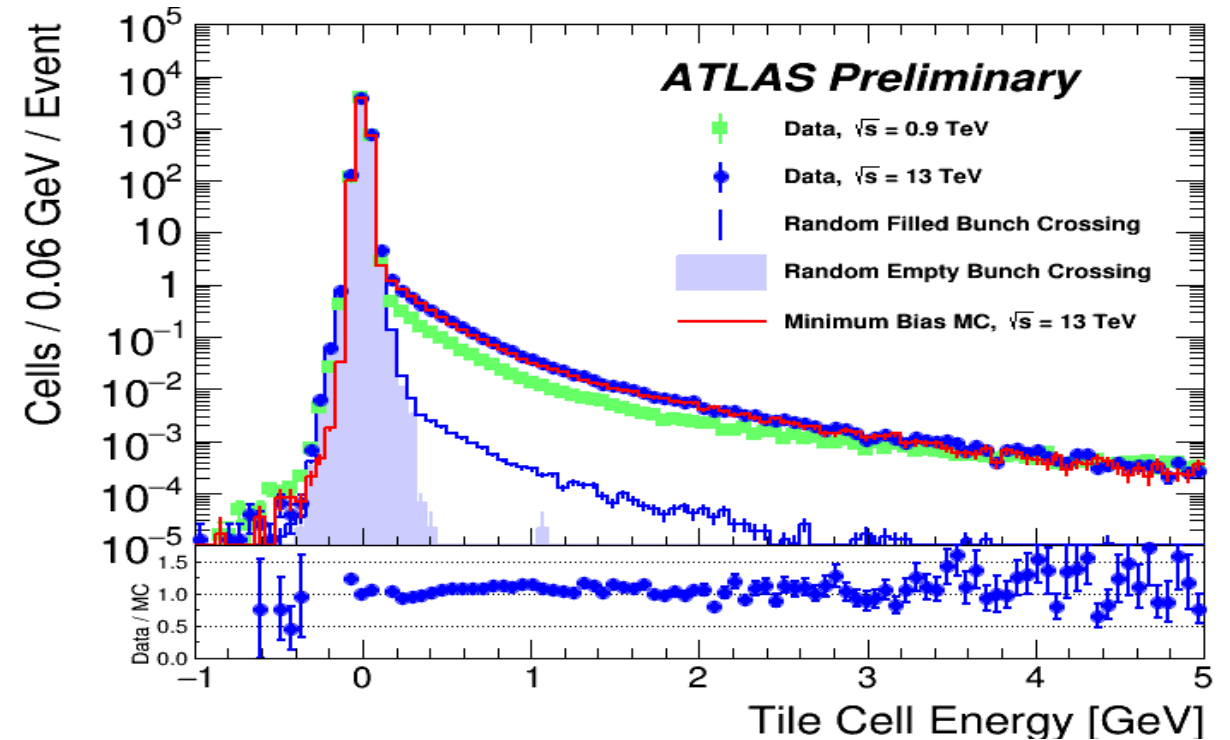
Calorimeter response to single isolated charged hadrons

- Characterized by the mean of the energy over momentum (E/p) as a function of momentum, integrated over the pseudo-rapidity and ϕ coverage of the calorimeter, as measured by the ATLAS Tile Calorimeter using 1.6 fb^{-1} of proton-proton collision data at 13 [TeV](#) collected in 2015.
- The fraction of events with additional simultaneous proton-proton collisions (pile-up) was negligible. The data is compared to simulated events generated using PYTHIA 8.186, with the A2 tune, and the MSTW2008 LO parton distribution function set.
- The energy is reconstructed from topological clusters matched to a track in a cone of $\Delta R < 0.2$. Tracks are required to pass minimum quality criteria and $p > 2$ [GeV](#). To reduce contamination from neutral hadrons and muons, the energy deposited in the electromagnetic calorimeter is required to be less than 1 [GeV](#), and the fraction of energy deposited in the Tile Calorimeter at least 70%.
- Black dots represent data and the blue line represents simulation. Statistical uncertainties are shown for data and simulation. The lower plot shows the ratio of data to simulation.



Tile Calorimeter Cell Energy Deposition Plot

- Distributions of the energy deposited in the TileCal cells from collision data at $\sqrt{s}=13$ and 0.9 TeV superimposed with Pythia minimum bias Monte Carlo and randomly triggered events from filled and empty bunch crossings.
- A Level 1 minimum bias trigger scintillator (MBTS) trigger is required for the 13 TeV data.
- To ensure exactly one interaction has occurred per bunch crossing, only events having a single reconstructed primary vertex are selected.
- Each distribution is normalized to unit area.



Test-Beam setup

- The beams were produced by extracting 400 GeV protons from the Super Proton Synchrotron (SPS) machine.
- The primary target made of beryllium, had a length of 300 mm. The produced secondary beams can have energies from 10 to 350 GeV.
- A secondary target of 1000 mm of polyethylene (T4) plus an absorber of lead can be placed in the beam to produce tertiary beams;
- Bending magnets were used to determine the beam momentum and charge;
- The transverse beam profile is monitored by four wire chambers (BC-1 to BC2). Two scintillators (S1/S2), with an active surface of $5 \times 5 \text{ cm}^2$, were used in coincidence to trigger the data acquisition (Physics trigger) and to provide the trigger timing. These two detectors were used to reject beam particles interacting upstream of the detectors. The Cherenkov counters (Ch1, Ch2 and Ch3) allowed the beam particle identification.

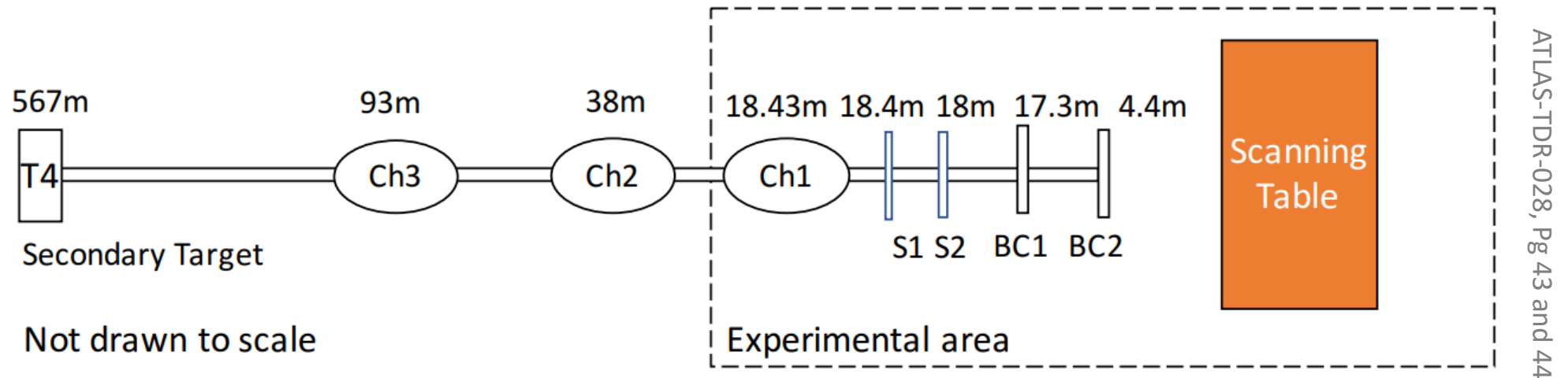


Fig. Schematic layout of the H8 beam line. The distances of the components of the beam line from the Scanning Table are reported.

Test-Beam setup

- The calorimeter setup in the H8 beam of the CERN SPS North Area consists of two long-barrels and one extended-barrel.
- The super-drawer of the long barrel LBC 65 is equipped with the 3-in-1 front-end upgrade option.
- The other option, FATALIC, alternative to the 3-in-1 and based on ASICs (An Application Specific Integrated Circuit), has been mounted in the super-drawer LBA 65.
- The super-drawers M0 C and EBC 65 were equipped with the Legacy SD system.
- Multi-Anode (MA) Photo-Multipliers (PMs) were installed in the M0 A super-drawer.
- Modules were stacked on a scanning table capable of placing modules at any desired position and angle with respect to the incoming particles.
- Data was collected with beams incident at the center of the front face of each A-cell at $\theta = 20^\circ$ from the normal and incident on the ends of the modules, into the center of each tile-row (referred to as 90° incidence).

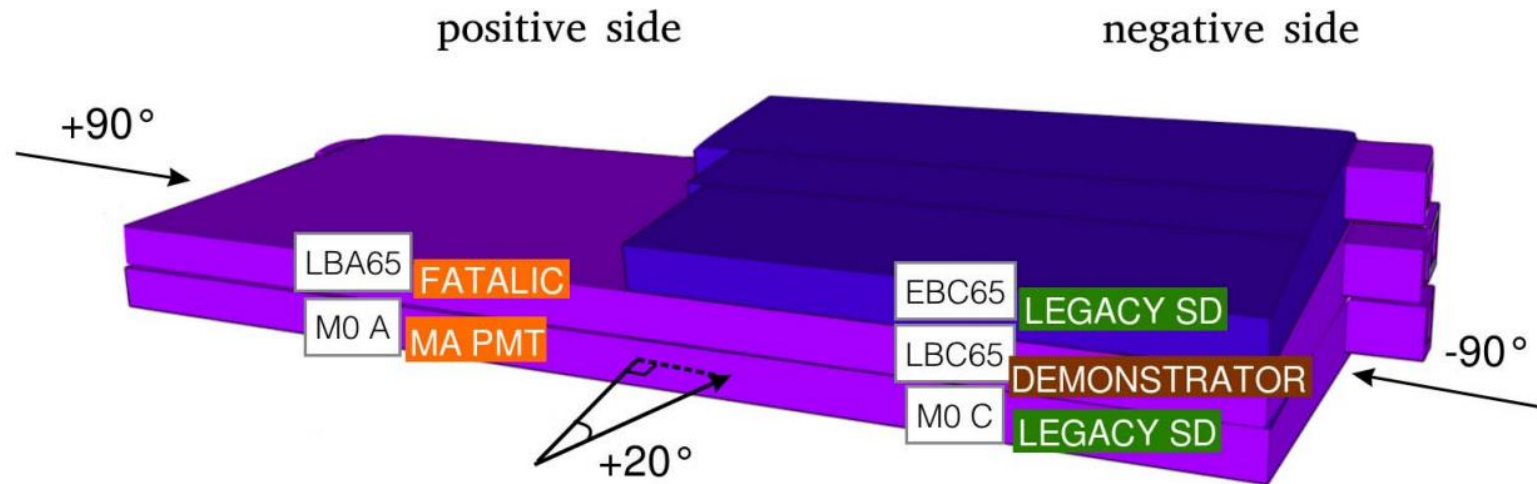


Fig. Schematic front view of the Tile modules as stacked on the scanning table at the H8 beam.

ATLAS-TDR-028, Pg 43 and 44

Test-Beam selection criteria

With all particle beams, two sets of selection criteria were usually applied:

- For all particle types, single-particle events were selected, using beam detectors upstream of the Tile. Signals in the upstream scintillator counters were required to arise from single minimum ionizing particles. This cut, especially useful for electrons, removed particles that initiated a shower upstream of the calorimeter, as well as two-particle events.
Events where the beam chambers indicated tracks far from the beam axis and/or not parallel to it were rejected because they might have scattered upstream and therefore be off-energy;
- The second set of selection criteria was specific to the type of particles being studied. Particles with different energies were identified mainly by the calorimeter response, however, the three beam-line Cherenkov counters further assisted in particle identification,

Electron data MC comparison

- The distributions obtained using experimental and simulated data in the case of beams incident in the A-4 cell at 20° are shown.
- For a given beam energy the experimental and the simulated shapes are very similar proving the purity of the selected experimental electron samples.

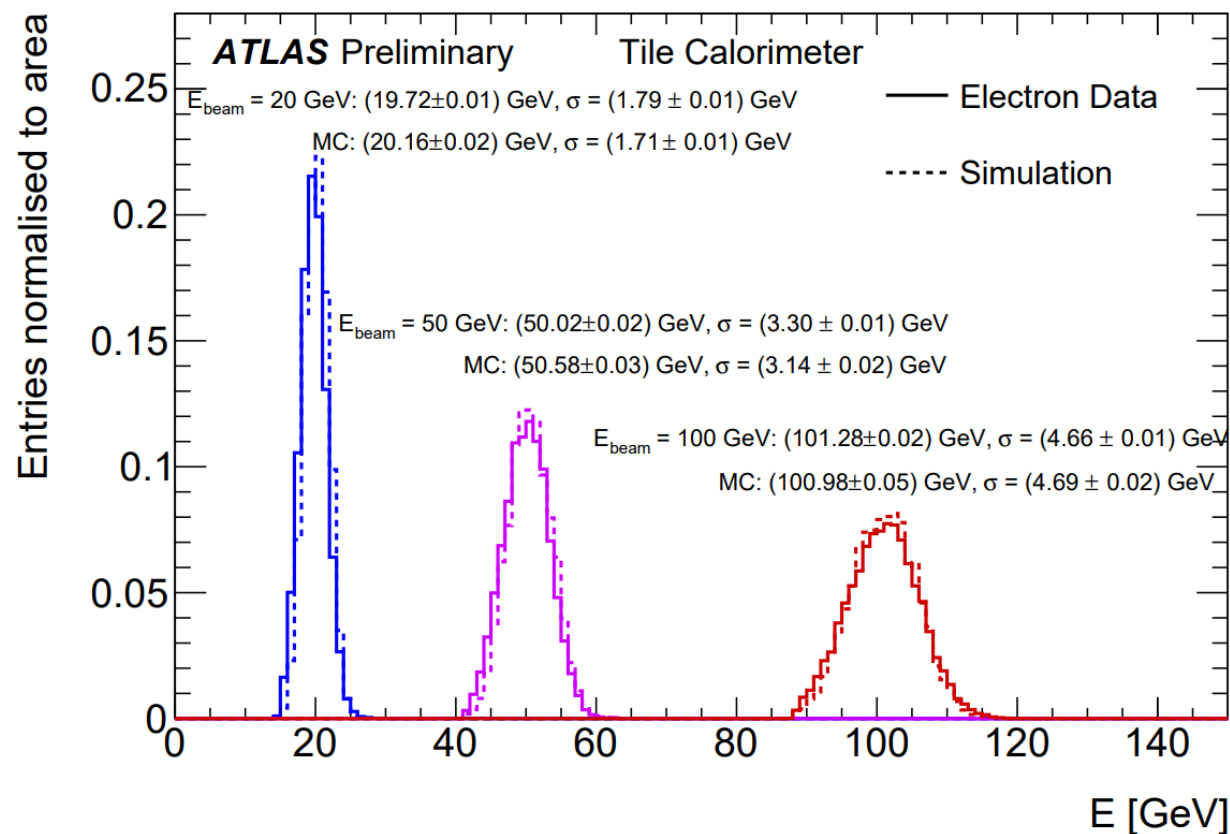


Fig. Distributions of the total energy deposited in the calorimeter obtained using electrons beams of 20, 50 and 100 GeV incident in the cell A4 of the middle layer of the stack.

Fractional resolutions vs $1/\sqrt{E_{beam}}$

The fractional resolution is defined as : $R^{\sigma^{RAW}} = \frac{\sigma^{RAW}}{E_{beam}}$

A quantitative comparison between experimental and simulated results is described as $\Delta\sigma^{RAW} = \frac{\sigma^{RAW}}{\sigma_{MC}^{RAW}} - 1$

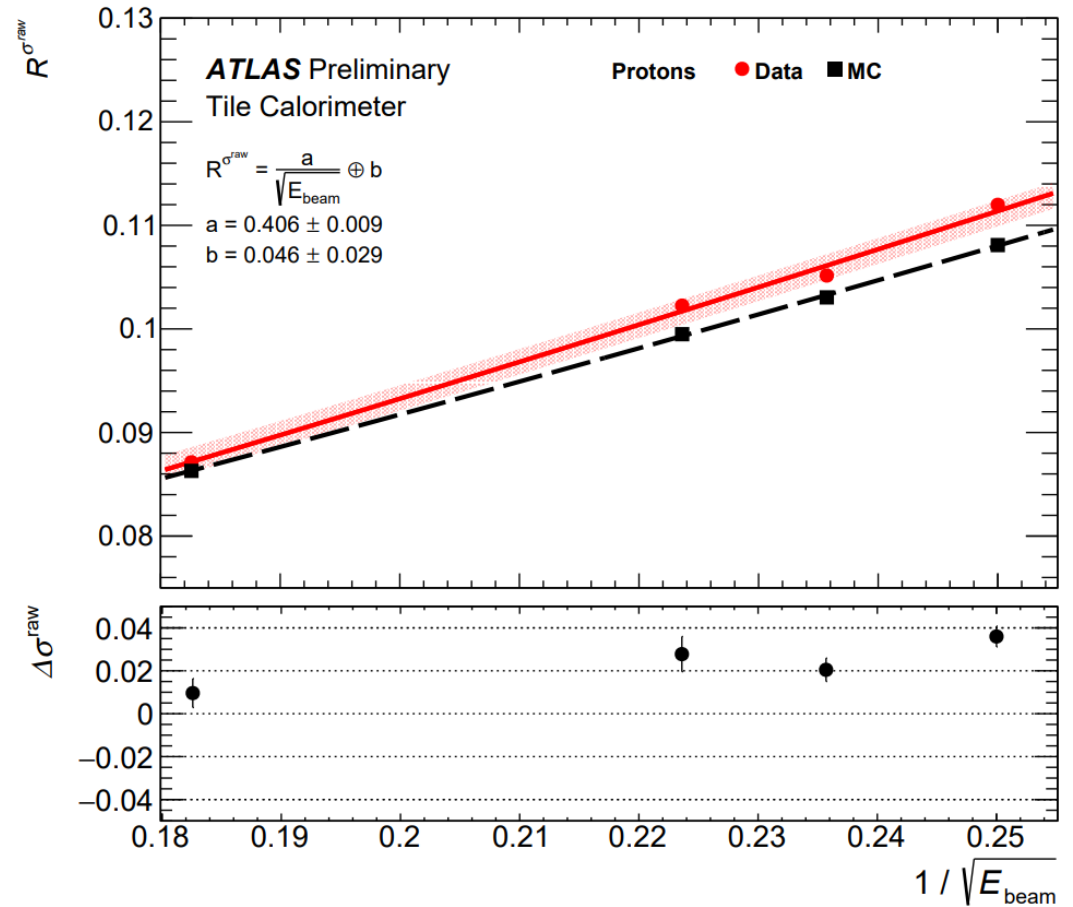
The range of $\Delta\sigma^{RAW}$ is:

- Protons - 3 %

The resolution can be parameterized according to

$$R^{\sigma^{RAW}} = \frac{a}{\sqrt{E_{beam}}} \oplus b$$

- a - the stochastic term,
- b - the cell response non-uniformity,
- The symbol \oplus indicates the sum in quadrature.



Results with muons: dE/dl VS cell

- The response of the detector has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl) using 165GeV muons at an incident angle of -90°;
- The ratio (R) of experimental and simulated dE/dl values was defined for each calorimeter cell –

$$R = \frac{\langle dE/dl \rangle_t^{\text{Data}}}{\langle dE/dl \rangle_t^{\text{MC}}}$$

- The red horizontal lines - the mean values of dE/dl for each layer.
- The data show a layer uniformity at 1%. An offset of max 4% is observed for Data/MC.

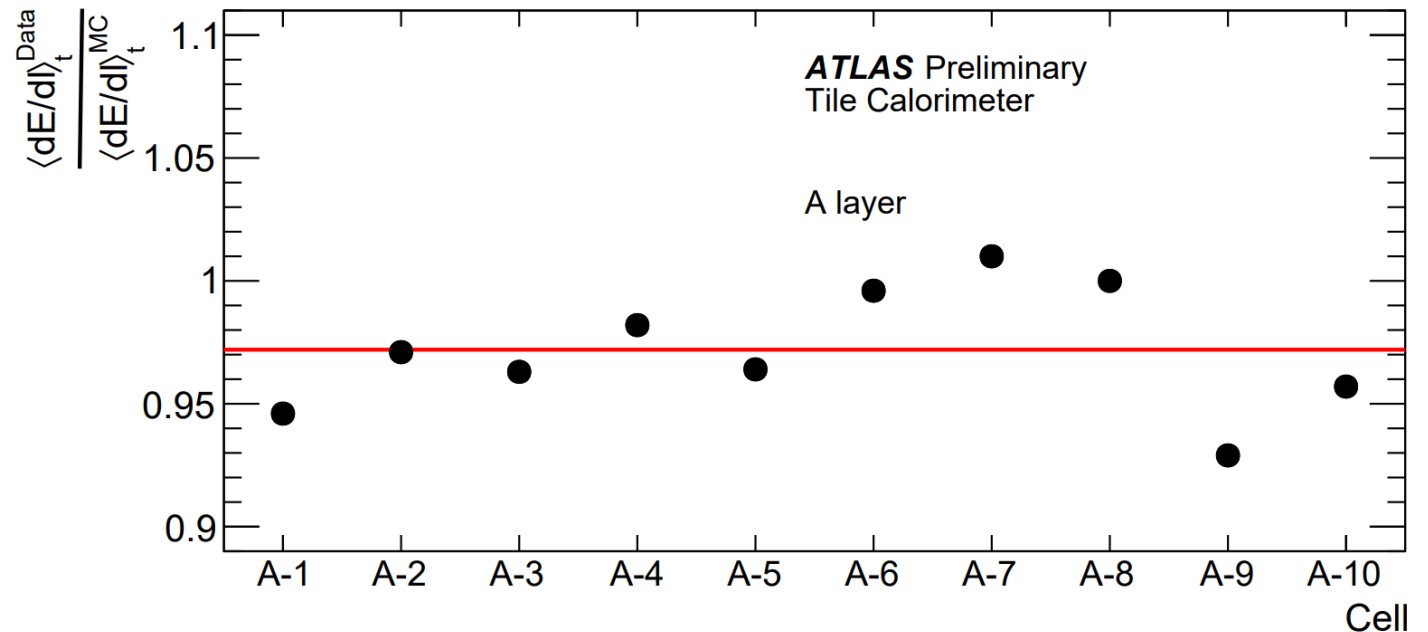


Fig. Ratios of the truncated means of the distributions of the energy deposited in the layer cells per unit of path length obtained using 900 experimental and simulated muon data as a function of the cell number. The horizontal lines correspond to the mean values of the determinations.