Upgrade of the ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC

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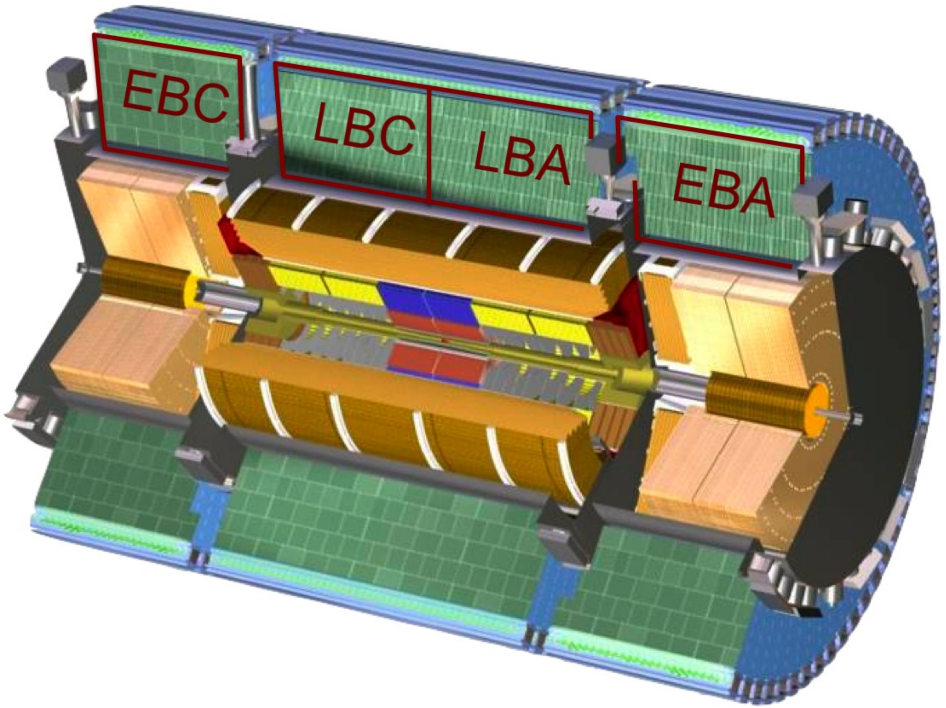
ATLAS Tile Calorimeter

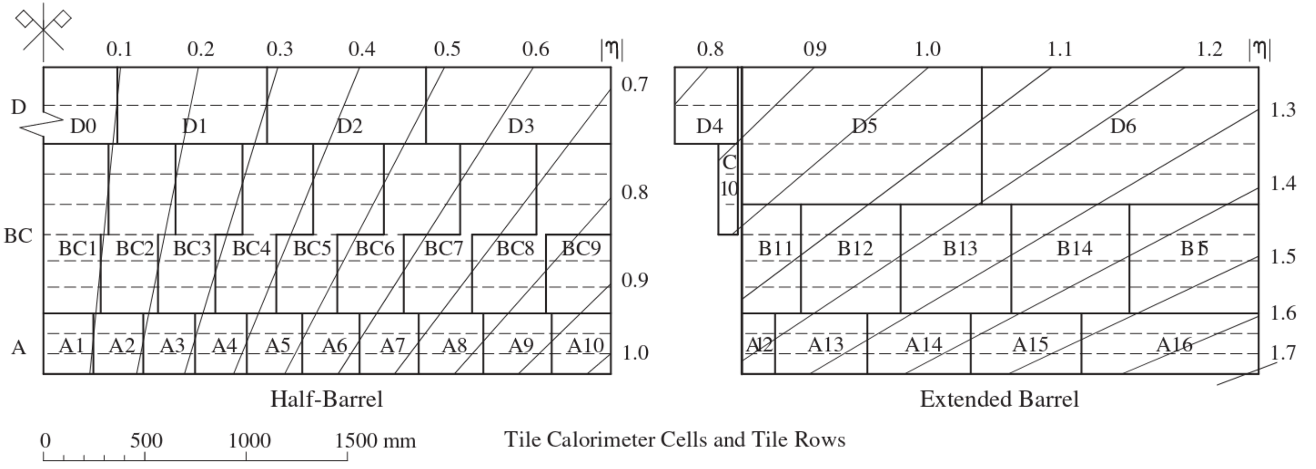


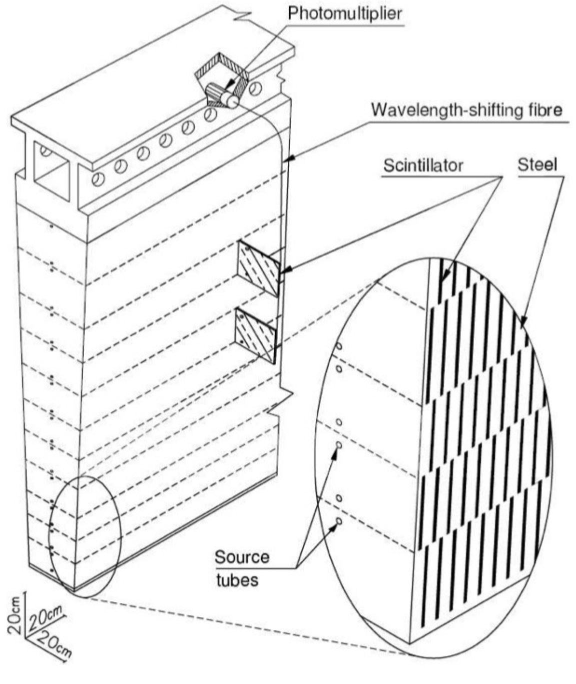
- The Tile Calorimeter (TileCal) is the central hadronic calorimeter within the ATLAS at the LHC situated at CERN, Geneva.
- It is a hadronic sampling calorimeter: iron/scintillator.
- The TileCal is composed of four barrel sections (two central and two extended barrels), each containing 64 azimuthal slices.
- **The role of a hadron calorimeter is to make a precise measurements of hadrons, jets**, missing transverse energy as well as provide input signal to Level 1 Calorimeter Trigger.

TileCal readout

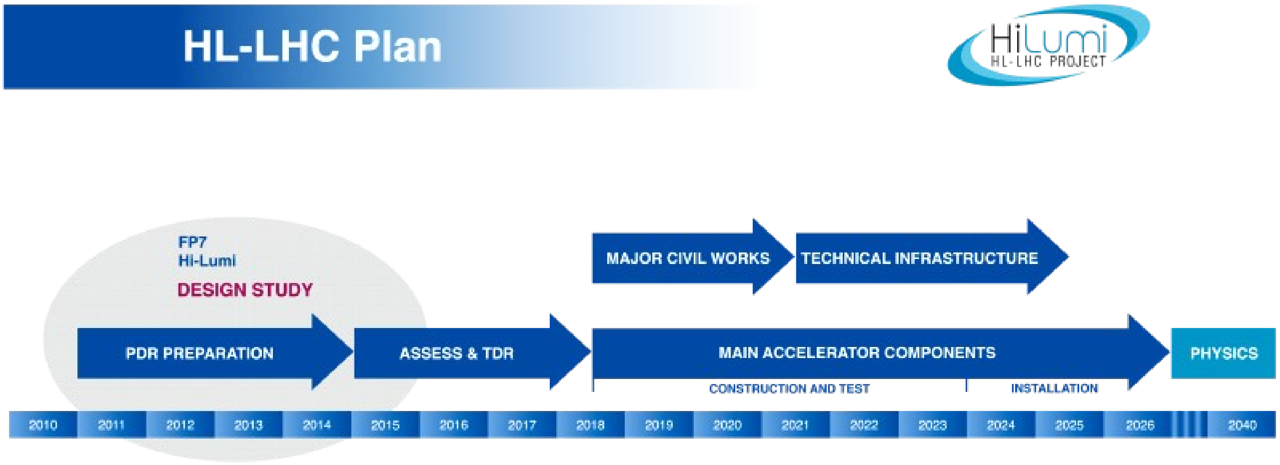
Principle of TileCal:

- The defining role of hadron calorimetry - measuring the energies of jets.
- Measure light produced by charged particles in the plastic scintillators.
- Scint. light from tiles collected by WLS fibers and delivered to PMTs.
- Tile read out is grouped into pseudo-projective geometry cells, each cell readout by 2 PMTs except for some special cells.
- Each barrel consist of 11 tile rows which form 3 longitudinal layers.





TileCal in Phase II upgrade – HL-LHC



High Luminosity upgrade of the LHC – HL-LHC in 2027 – **increase the instantaneous luminosity** by a factor of 5-10 (nominal LHC value - 10^{34} cm^{-2} s^{-1}).

TileCal major upgrades for the HL-LHC:

- Full electronics replacement, both on and off detector.
- New modular mechanics : 4 mini-drawers instead of one super Drawer.
- Data and power redundancy to improve system stability.
- New low voltage and high voltage power supplies systems due to higher radiation requirements.

Plans:

- Radiation tests with new electronics components.
- Replacement of most degraded PMTs (~10%) and crack scintillators.

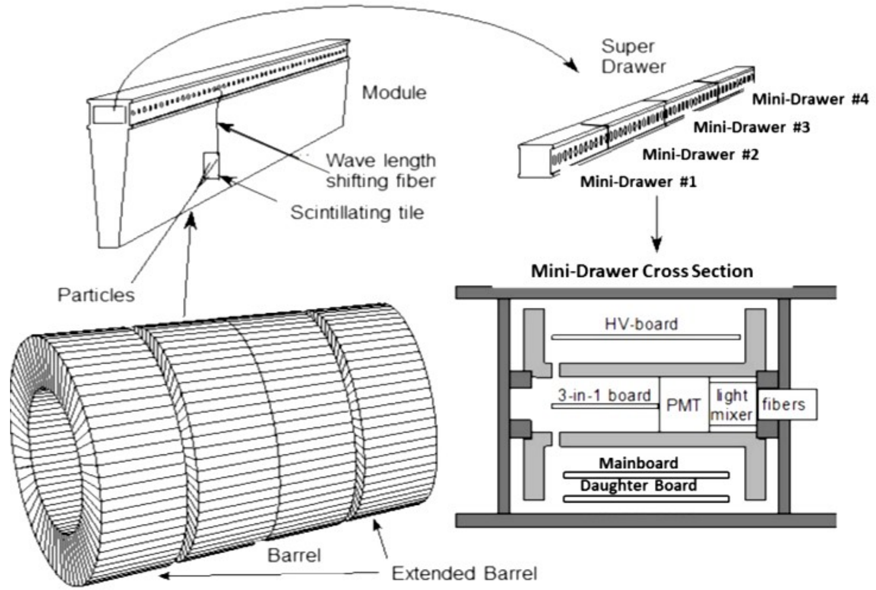
New TileCal electronics should withstand:

- higher ambient radiation,
- the high luminosity environment (~200 collisions per bunch crossing).

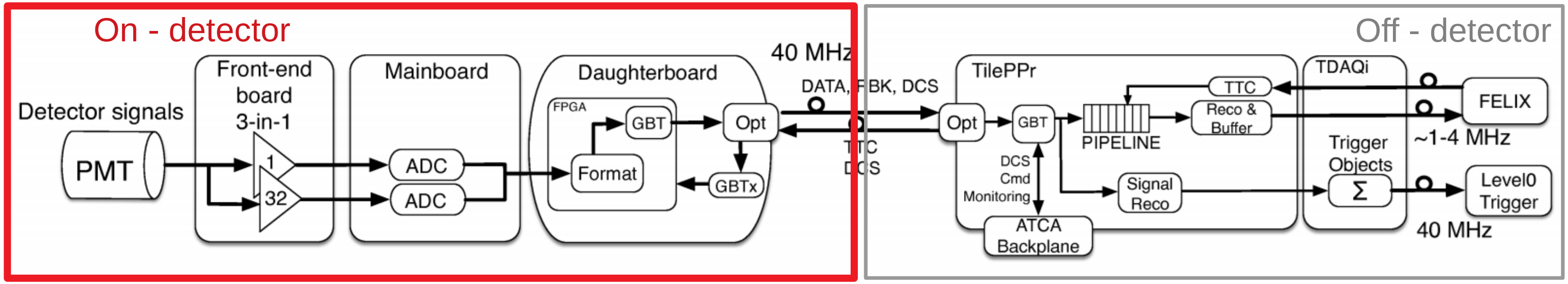
will provide:

- low-latency,
- high-frequency (40 MHz),
- fully digital input for ATLAS trigger system.

Electronics layout for the HL-LHC TileCal
On – detector electronics

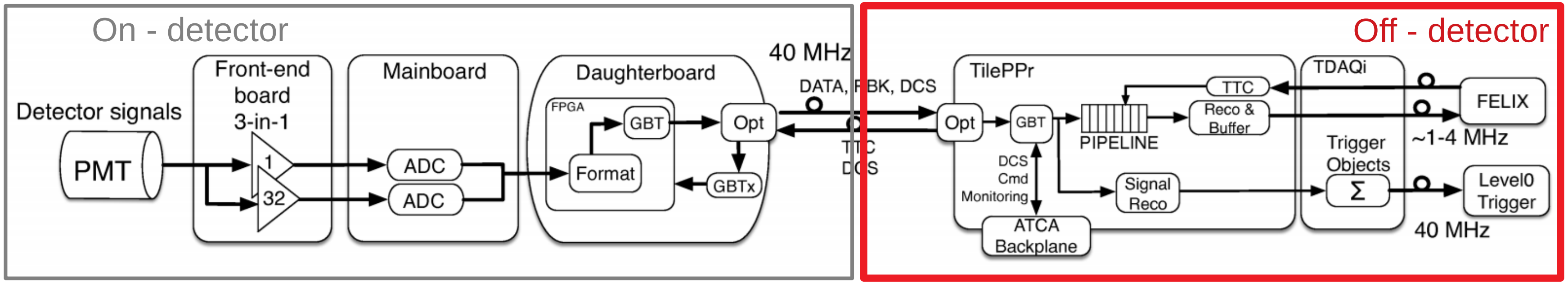


- A Super Drawer (SD) is divided into 4 Minidrawers (MDs) each with independent readout and power supplies.
- A MD hosts 12 PMTs and 12 Front-End Boards (FEBs) named FENICS **F**ront-**E**nd electro**NICS**.
- The FENICS card performs signal shaping and amplification (2 gains, 1/32 ratio) resulting in a 17-bit dynamic range (0-800 pC).
- A Mainboard (MB) digitizes the input from 12 FEBs with 2x12-bit ADCs at 40 Msps.
- A Daughterboard (DB) transfers redundant bi-gain high-speed (4 x 9.6 Gbps) output data from 12 channels every 25 ns to the back-end, distributes the LHC system clock, liaise the on- and off-detector electronics.



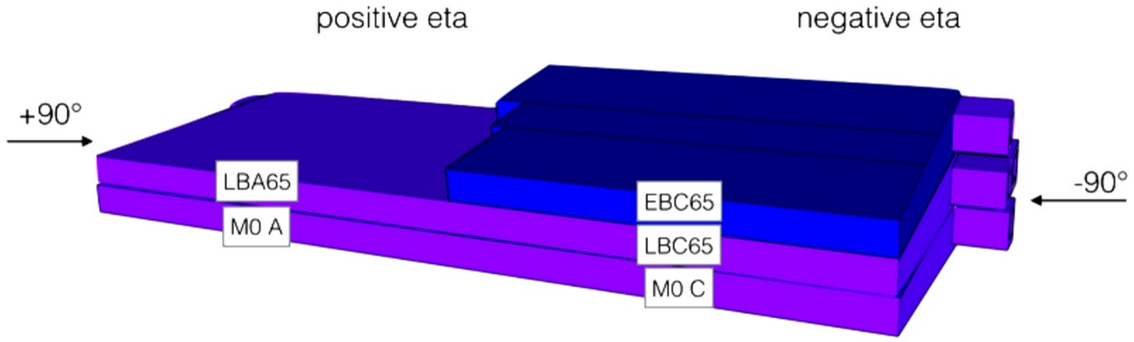
Electronics layout for the HL-LHC TileCal Off – detector electronics

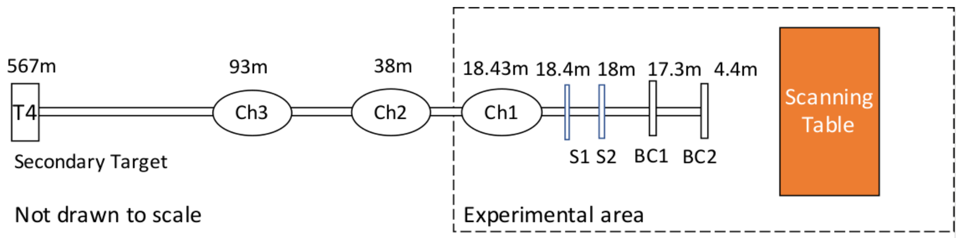
- A Tile PPr (Preprocessor):
  - located off-detector;
  - buffers data from all MD in pipelines;
  - evaluates signal at the full 40 MHz rate;
  - distributes the system clock and detector control and configuration information.
  - has to provide preprocessed trigger information for every bunch crossing.
- TDAQi calculates trigger objects and interfaces with trigger and ATLAS TDAQ by sending accepted data via the FELIX (**F**ront **E**nd **LI**nke**X**change).



TileCal Test Beams

TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the legacy system were exposed to different particles and energies in 7 test beam campaigns at SPS during 2015-2018.



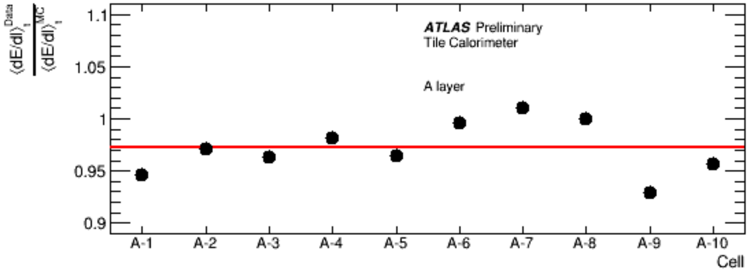


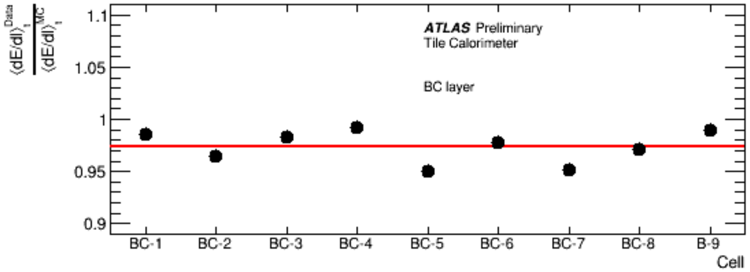
- A half-module (LBC65) has been equipped with the so-called Hybrid **Demonstrator**.
- The Demonstrator consist of upgrade 4 MiniDrawers adapted to “masquerade” as a legacy super drawer in ATLAS but with front-ends that can deliver analog trigger sums for backward compatibility.
- The extended barrel (EBC65) was equipped with new electronics in 2018 (latest generation of front-end cards).

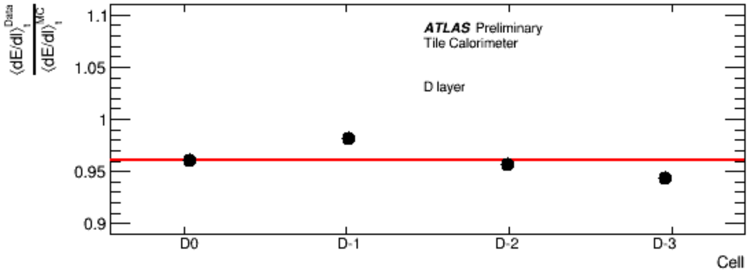
Test Beam results using:

- Muons
  - The high energy muons traverse the entire TileCal modules from any angle of incidence, thereby allowing a study of the module response in great detail throughout the entire volume.
  - The interaction of muons with matter is well understood. The dominant energy loss process is ionization and the energy loss is essentially proportional to the muon track path length.
  - Muon data allows us to:
    - **verify the new electronics performance.**
    - **review and improve the detector calibration procedure.**
- Electrons
- Hadrons

Muon energy response on unit of length





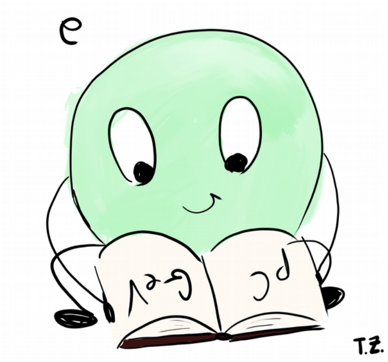


- The response of the detector has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl) using 165GeV muons at an incident angle of -90°.
- The ratio of experimental and simulated dE/dl values was defined for each calorimeter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

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

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

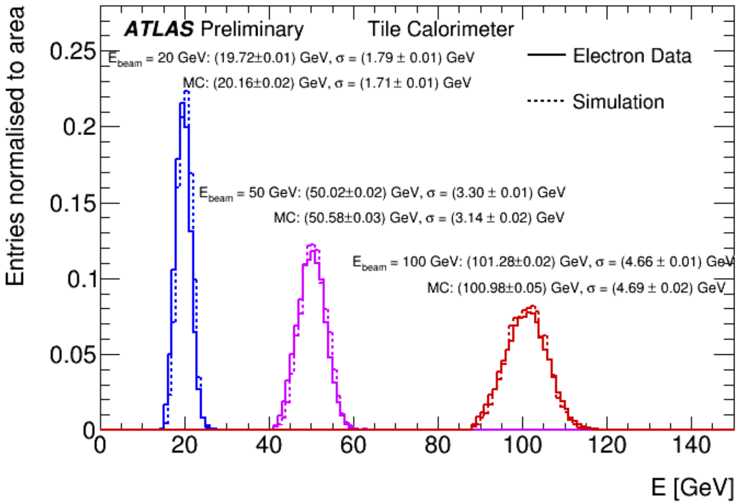
Test Beam results using:

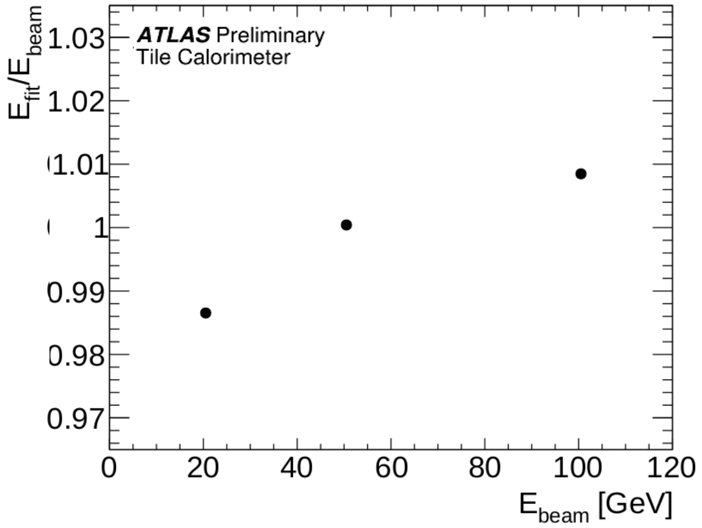


- Muons
- Electrons
  - electron beams provide the perfect tool to:
    - Determine the electromagnetic scale— by measuring signals of beam particles at known energies and calculating the average charge-to-energy conversion factor, in pC/GeV.
    - Verify the linearity of the response vs. energy and to test the detector uniformity and its energy resolution.
- Hadrons

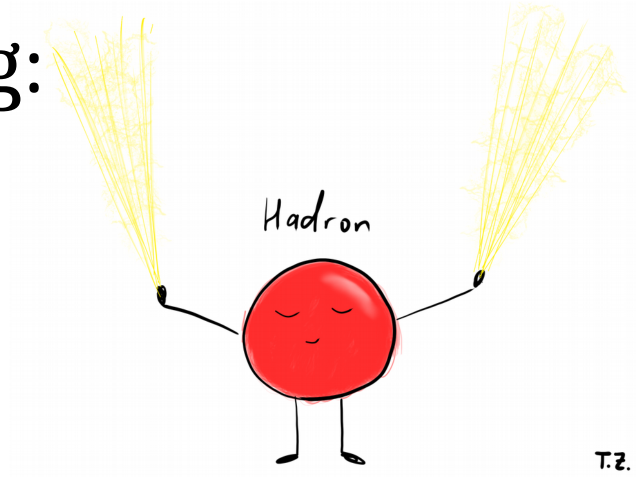
Data MC comparison and Response linearity

- The distributions obtained using experimental and simulated data in the case of beams incident in the A-4 cell at 20° are shown below.
- For a given beam energy the experimental and the simulated shapes are very similar proving the purity of the selected experimental electron samples.
- The linearity of the calorimeter response to electrons was checked in the range of 20-100 GeV.
- Further investigation is ongoing.





Test Beam results using:



- Muons
- Electrons
- **Hadrons**
    - The role of the hadron calorimetry is to measure the energy and the angle of isolated hadrons and jets.
    - To achieve good performance, the study of the sub-detector response to isolated hadrons is important.
    - The characterization of the response of the ATLAS calorimeter to hadrons is important to probe and validate and to improve the modeling of the jets energy characterization of the ATLAS simulation using the GEANT4 toolkit.

Energy response ratios vs beam energy

The energy response ratio:

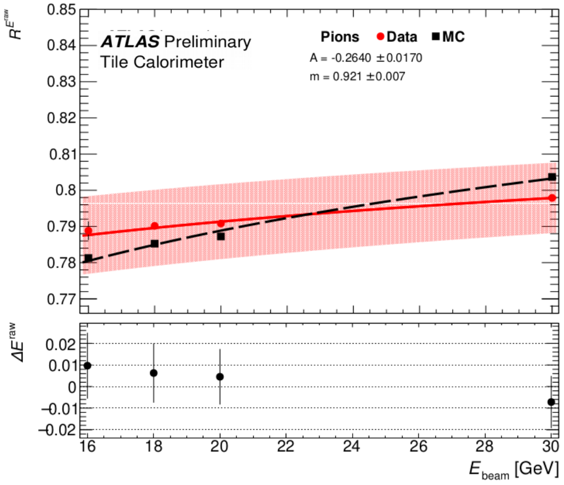
$$R^{\langle E^{\mathrm{raw}}\rangle} = \frac{\langle E^{raw}\rangle}{E_{\mathrm{beam}}}$$

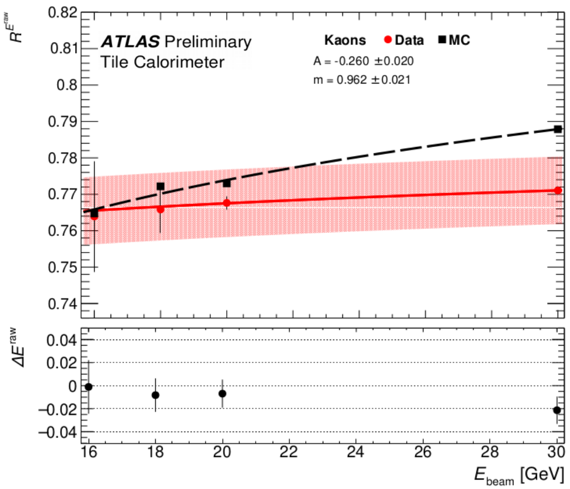
A quantitative comparison between experimental and simulated results is described as:

$$\Delta\langle E^{\mathrm{raw}}\rangle = \frac{\langle E^{\mathrm{raw}}\rangle}{\langle E^{\mathrm{raw}}_{\mathrm{MC}}\rangle} - 1$$

The ranges of variation of $\Delta\langle E^{\mathrm{raw}}\rangle$ are:

- Pions – 2%
- Kaons – 1%
- Protons – 2%





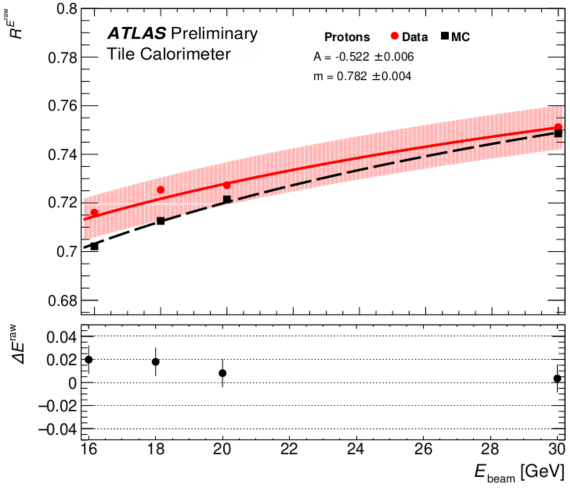
The hadron **energy response ratio can be parametrized as**[3] a function of the beam energy according to:

$$R^{\langle E^{\mathrm{raw}}\rangle} = (1 - F_{\mathrm{h}}) + F_{\mathrm{h}} \times \left(\frac{e}{h}\right)^{-1} , \qquad F_{\mathrm{h}} = \left(\frac{E_{\mathrm{beam}}}{E_0}\right)^{m-1}$$

F_{h} - the non-electromagnetic energy component of showers induced by incident hadrons of energy E_{beam},
E_0 - the energy at which multiple pion production becomes significant,
m - the relation between the average multiplicity of secondary particles and the fraction of π^0s,
e/*h* - the ratio of the EM and hadronic components of showers.

Function can be rewritten as:

$$R^{\langle E^{\mathrm{raw}}\rangle} = 1 + \frac{1}{(E_0)^{m-1}}\left[\left(\frac{e}{h}\right)^{-1} - 1\right](E_{\mathrm{beam}})^{m-1} , \qquad A = \frac{1}{(E_0)^{m-1}}\left[\left(\frac{e}{h}\right)^{-1} - 1\right]$$



Fractional resolutions vs $1/\sqrt{E}_{\text{beam}}$

The fractional resolution:

$$R^{\sigma^{\text{raw}}} = \frac{\sigma^{\text{raw}}}{E_{\text{beam}}}$$

A quantitative comparison between experimental and simulated results is described as:

$$\Delta\sigma^{\text{raw}} = \frac{\sigma^{\text{raw}}}{\sigma^{\text{raw}}_{\text{MC}}} - 1$$

The ranges of variation of $\Delta\sigma^{\text{raw}}$ are:

- Pions – 4%
- Kaons – 10%
- Protons – 3%

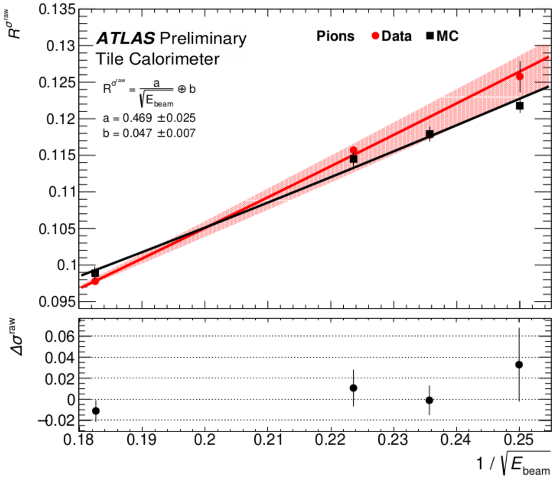
The **resolution can be parametrized according to**:

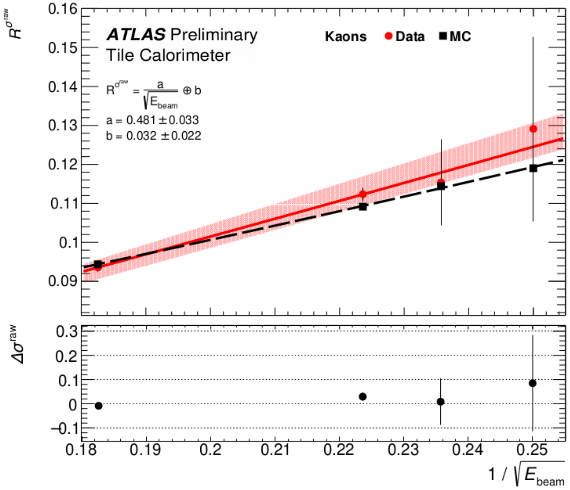
$$R^{\sigma^{\text{raw}}} = \frac{a}{\sqrt{E_{\text{beam}}}} \oplus b$$

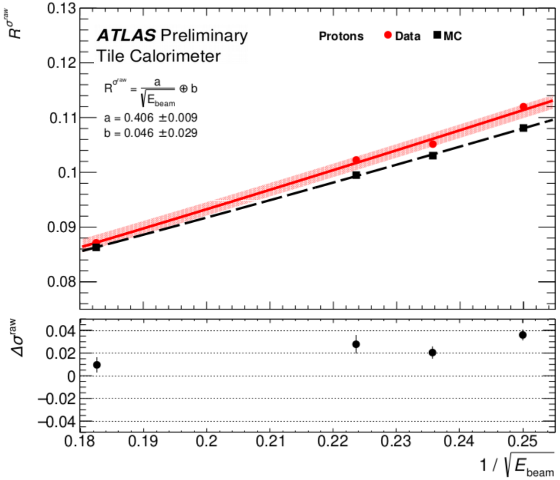
a - the stochastic term,

b - the cell response non-uniformity,

The symbol $\oplus$ indicates the sum in quadrature.







Summary

- The Phase II Upgrade of the LHC (HL-LHC) plans to increase instantaneous luminosity by a factor of 5-10. Electronics will need to withstand a much higher radiation dose as well as a increased demand for data throughput.
- A stack of three modules of the hadronic calorimeter of the ATLAS experiment (TileCal) equipped with the updated front-end electronics has been exposed to the beams of the SPS at CERN.
  - The results obtained using muons, electrons and hadrons are in agreement with the calibration settings obtained using the old electronics and with the expectations obtained using simulated data. They are consistent with previous measurements.
- All TileCal on- and off-detector electronics will be replaced in 2025-2027 during Phase II upgrade for the HL-LHC:
  - R&D is done, initial tests demonstrate good performance.
  - One Demonstrator super drawer with new electronics was inserted in the ATLAS detector and its performance is being evaluated.

Thank you!