Study of the ATLAS Tile Calorimeter response to beams of particles using Phase II upgrade readout

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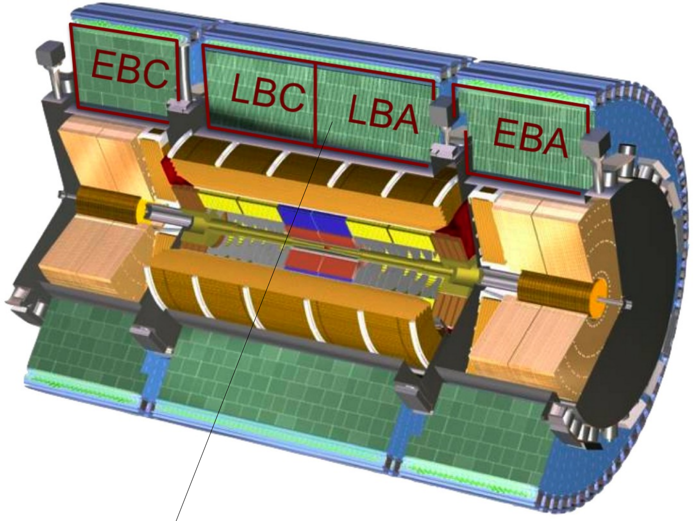
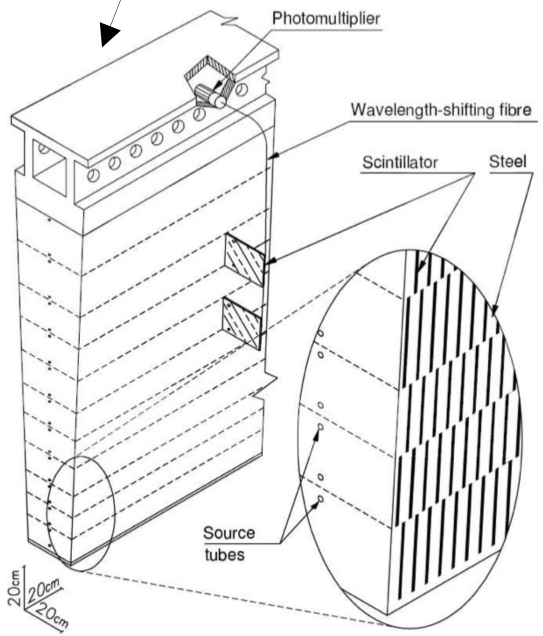
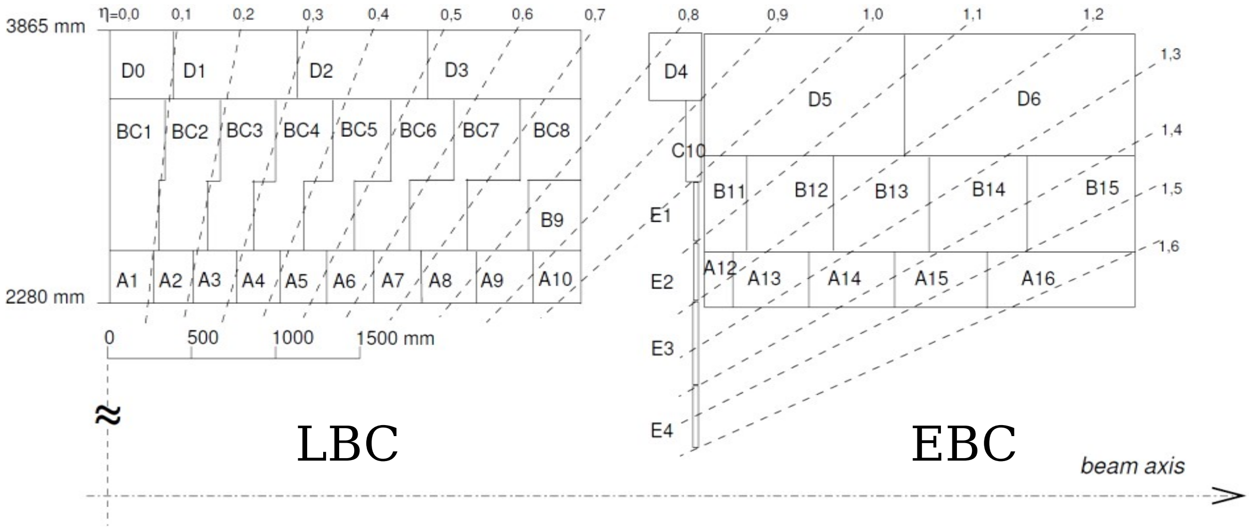


ATLAS Tile Calorimeter

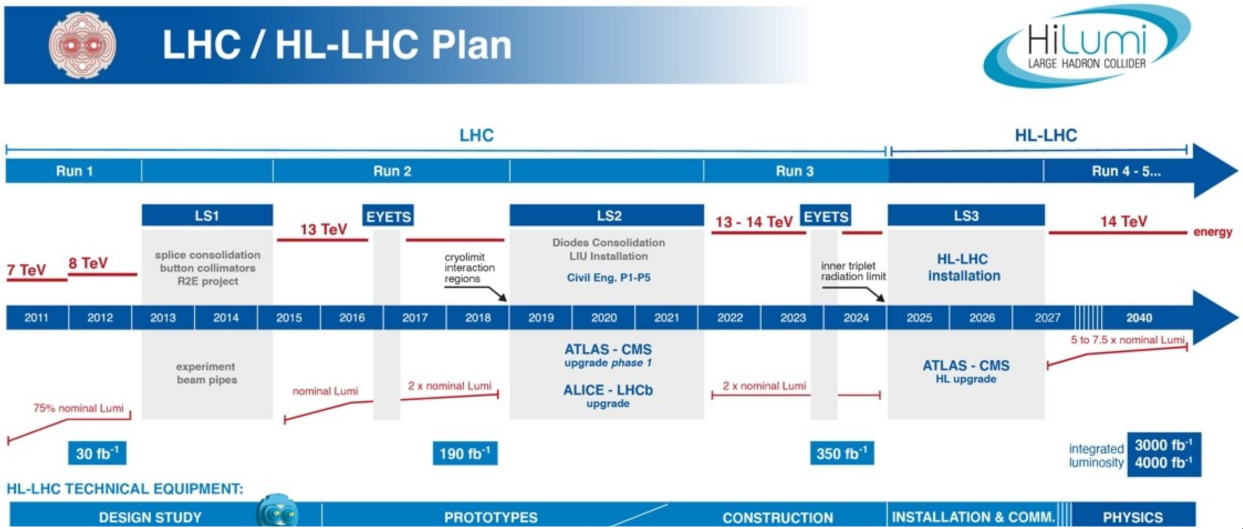
Principle of TileCalorimeter – hadronic calorimeter of the ATLAS detector

- The defining role of hadron calorimetry is to measure the energies of jets and event transverse energy.
- Measure light produced by charged particles in plastic scintillator.
- Scint. light from tiles collected by WLS fibers and delivered to PMTs.
- Tile readout is grouped into projective geometry cells. Each cell readout by 2 PMTs except special cells (layer E).
- Each barrel consists of 11 tile rows which form 3 longitudinal layers (A, BC and D).





TileCal in Phase-II upgrade – HL-LHC



TileCal major upgrades for the HL-LHC:

- Full electronics redesign, both on- and off- detector.
- New modular mechanics: 4 Mini Drawers.
- New low voltage and high voltage power supply systems due to higher radiation requirements.
- Replacement of most degraded PMTs (~10%) and crack scintillators.

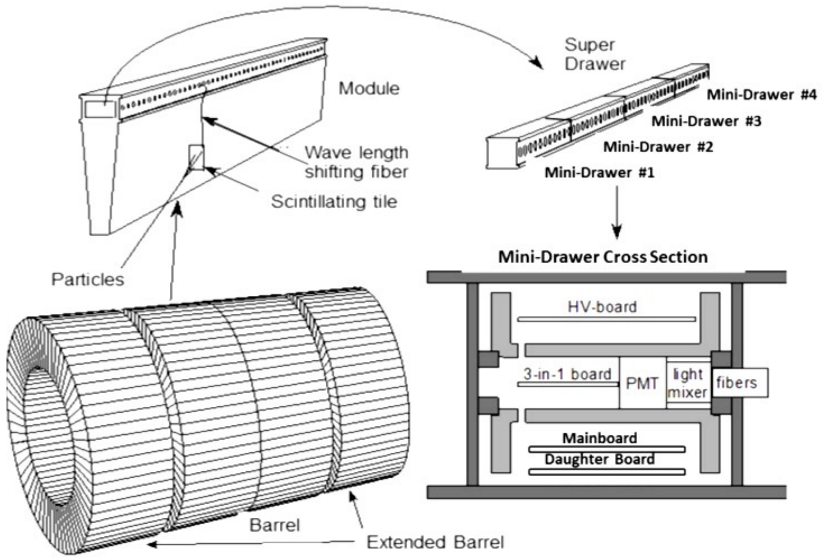
New TileCal electronics should withstand:

- Higher ambient radiation,
- The high luminosity environment (∼200 collisions per bunch crossing).

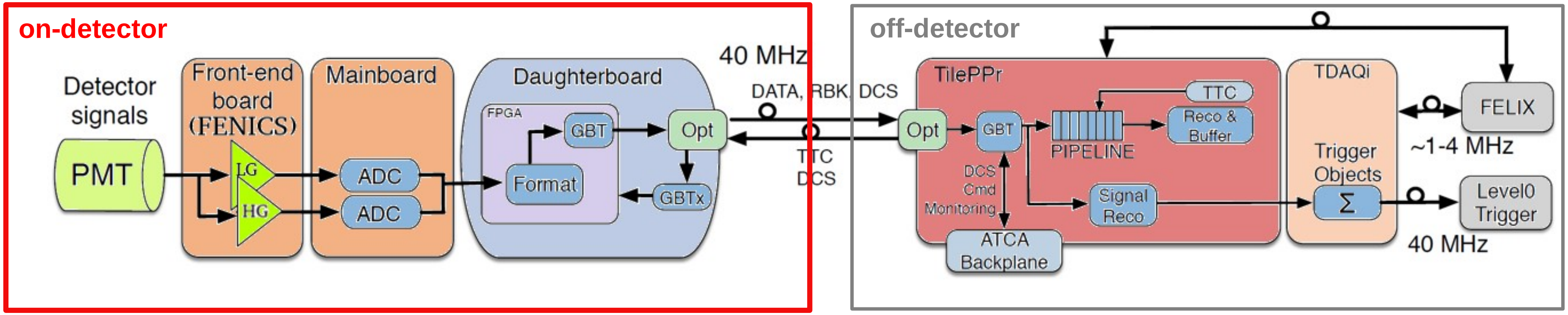
Will provide:

- Low-latency,
- High-frequency (40 MHz),
- Fully digital input for ATLAS trigger system.

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

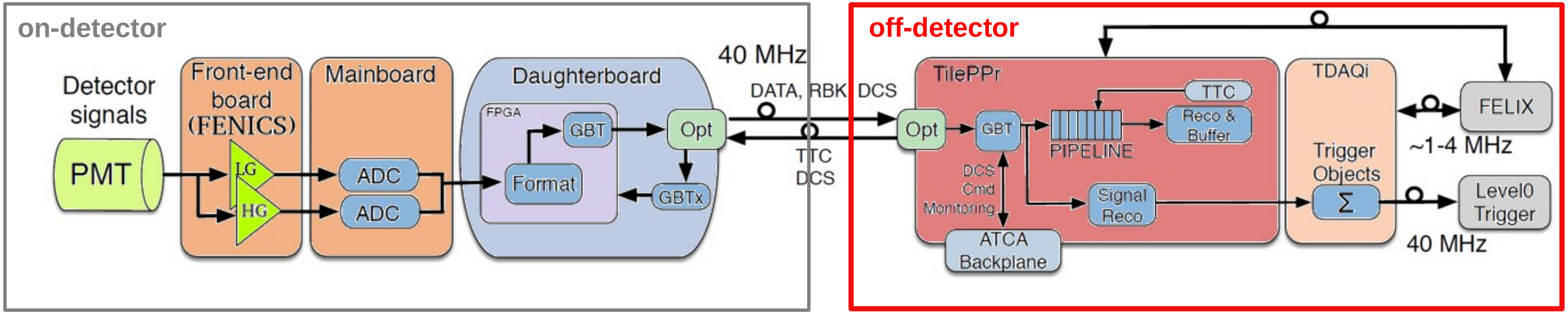


- A Super Drawer (SD) is divided into 4 Mini Drawers (MDs) each with independent readout and power supplies.
- A MD hosts 12 PMTs and 12 Front-End Boards (FEBs) named FENICS.
- The FENICS card performs signal shaping and amplification (2 gains, 1/40 ratio) resulting in a 17-bit dynamic range (0 – 1000 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.



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

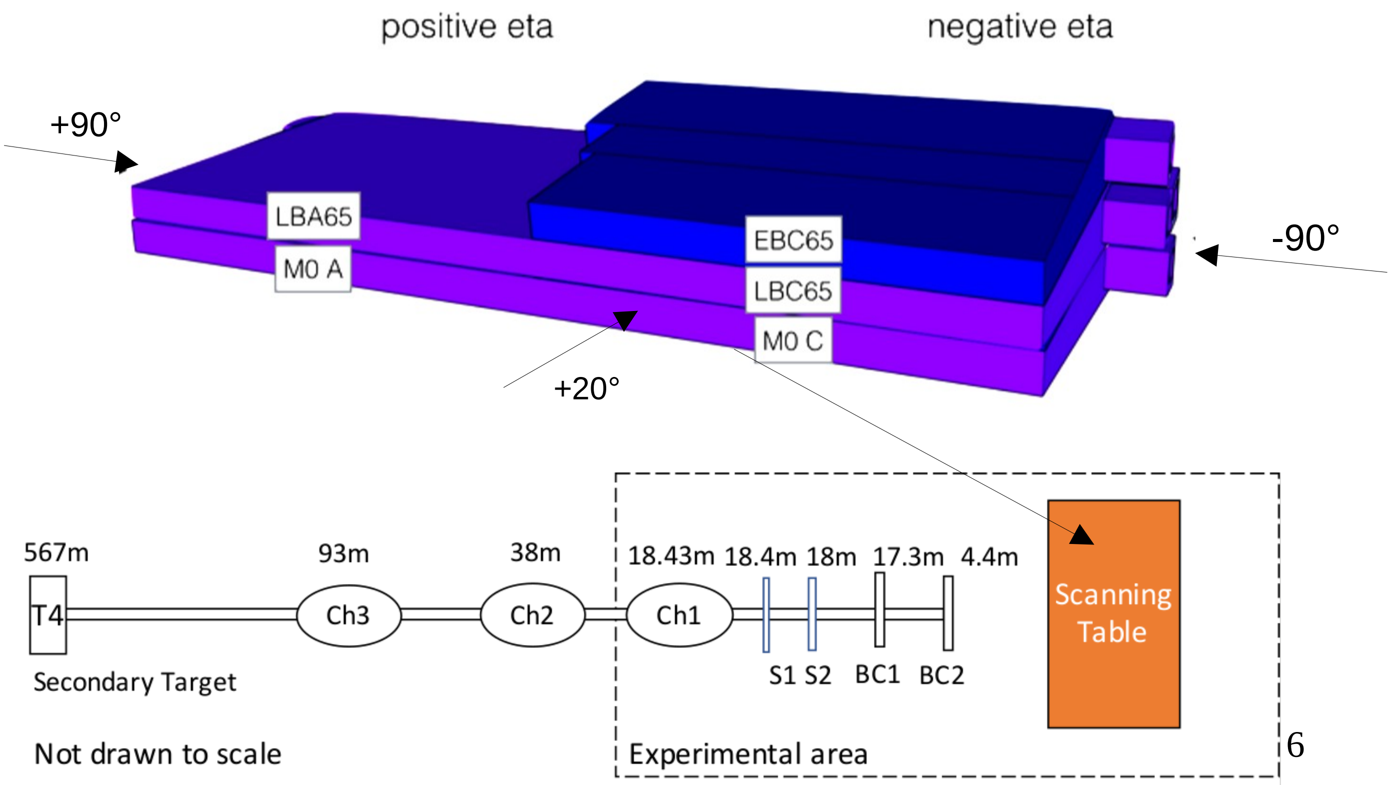
- A Tile PPr (Preprocessor):
  - Located off-detector in the counting rooms.
  - Buffers data from all MD in pipelines.
  - Evaluates signal at the full 40 MHz rate.
  - Distributes the system clock and detector control and configuration information.
  - Provides reconstructed energy per cell to the TDAQi 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**nk e**X**change).



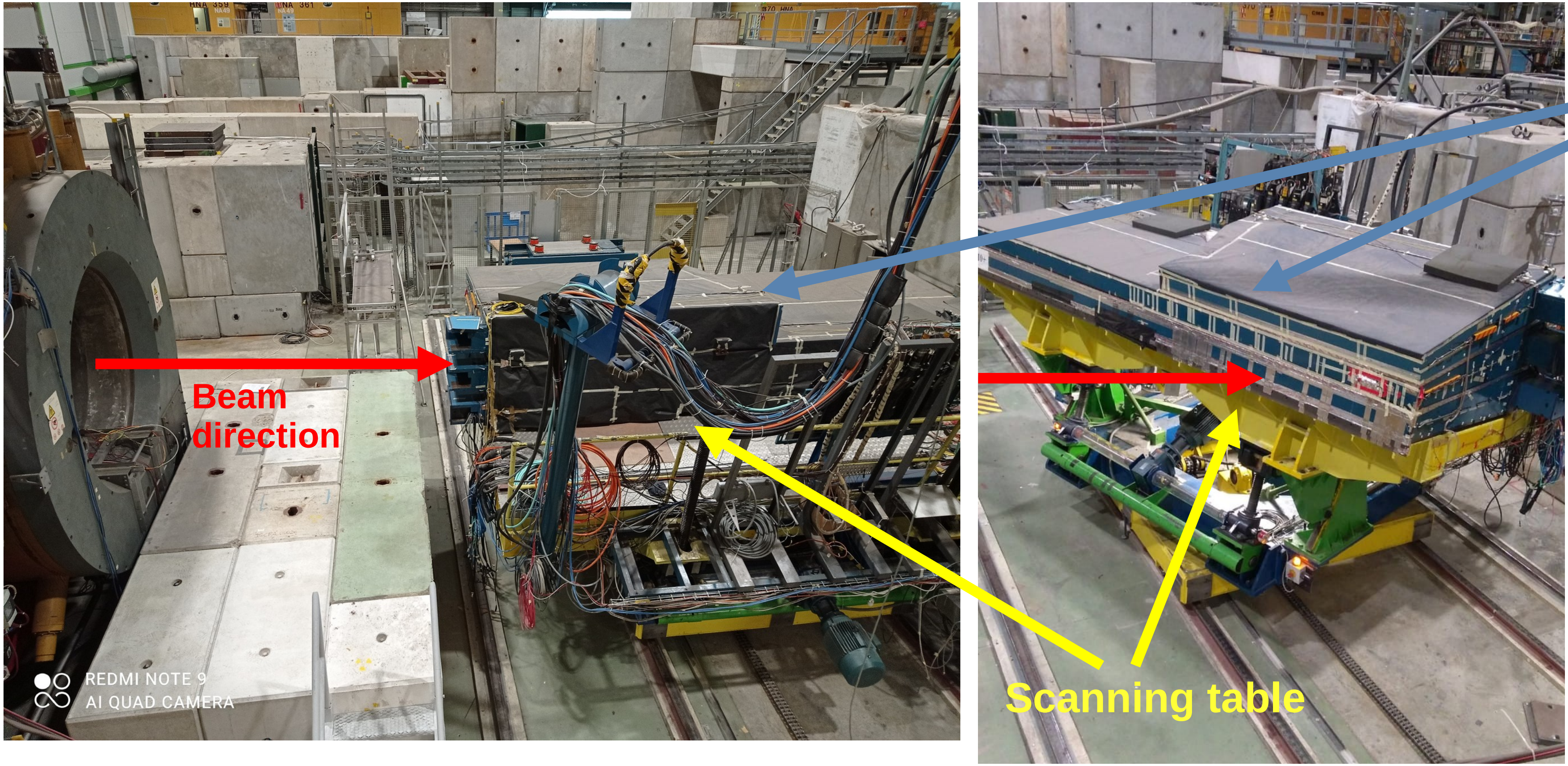
TileCal Test Beams: testing upgrade electronics

TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the legacy system were tested in several test beam campaigns at SPS during 2015-2018 and 2021-2022.

- The Super Drawers were equipped with different upgraded front-end electronics systems proposed for the ATLAS Phase-II upgrade.
- A half-module (LBC65) - the so-called hybrid Demonstrator was equipped with a prototype of the new Phase-II upgrade electronics.
- Modules were exposed to different particles and energies, at different incidence of angle.



Test beam area: H8 beam line



Test Beam results

- **Muon beams**
  - 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 by checking the equalization of the cell response.**
- Electron beams
- Hadron beams

Detector response uniformity

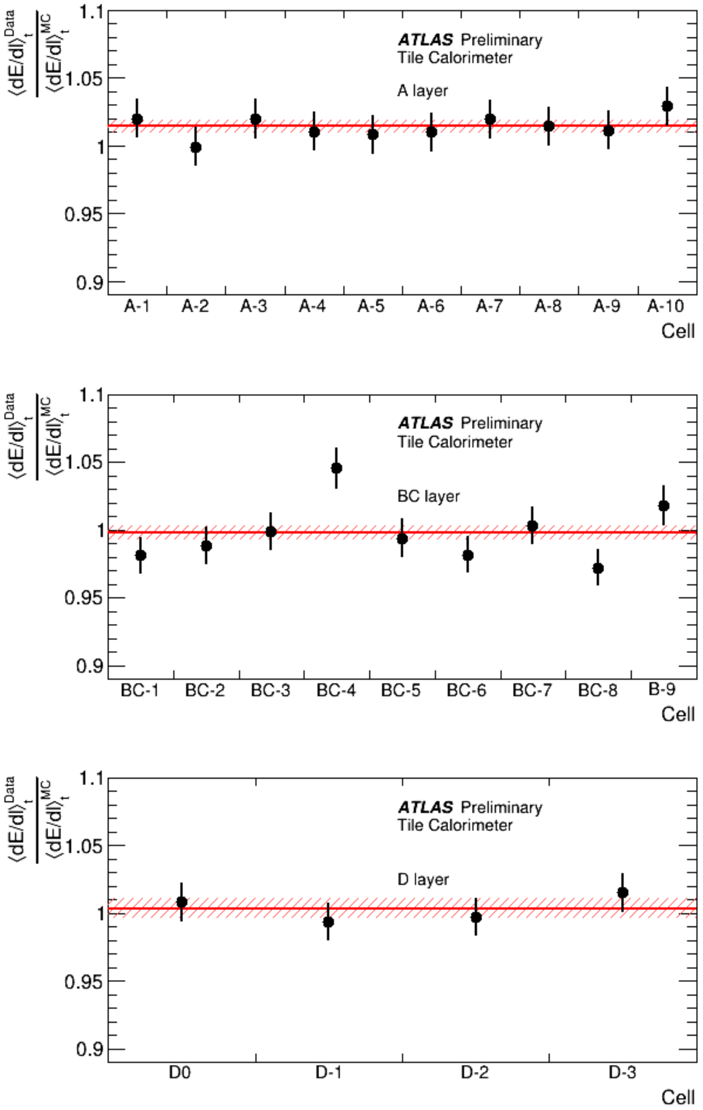
- The response of the detector in each layer and in each cell has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl) using 160GeV muons at an incident angle of -90°.
- The ratio of experimental and simulated dE/dl values was defined for each calorimeter cell:

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

- The red horizontal lines on the plot represent the mean values of dE/dl for each layer:

Layer	Mean	Uncertainty
A	1.014	0.005
BC	0.998	0.005
D	1.004	0.007

- The data show a layer uniformity within 1%.
- An offset of max 1.4% is observed for Data/MC.

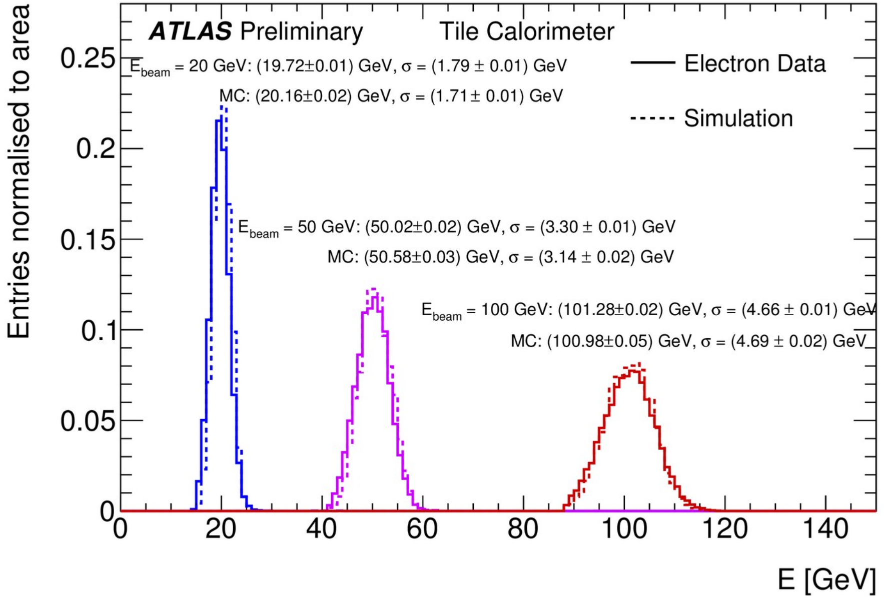


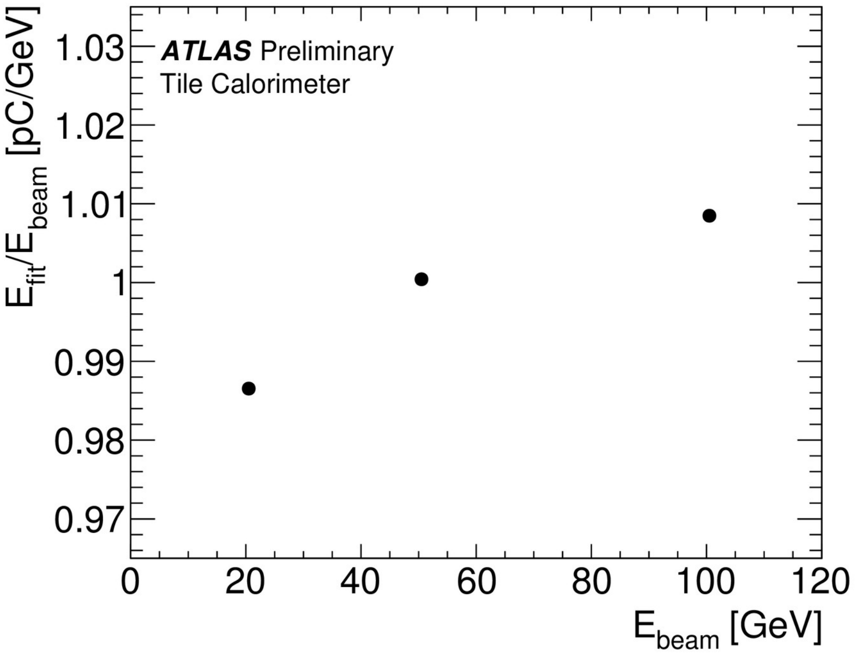
Test Beam results

- Muon beams
- **Electron beams**
  - Since electron's response is well modeled, electron beams provide 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 using electrons at an incident angle of 20°.
    - Verify the linearity of the response vs. energy and to test the detector uniformity and its energy resolution.
- Hadron beams

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.



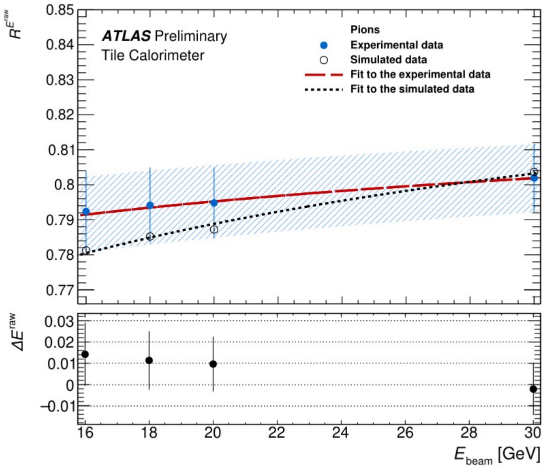


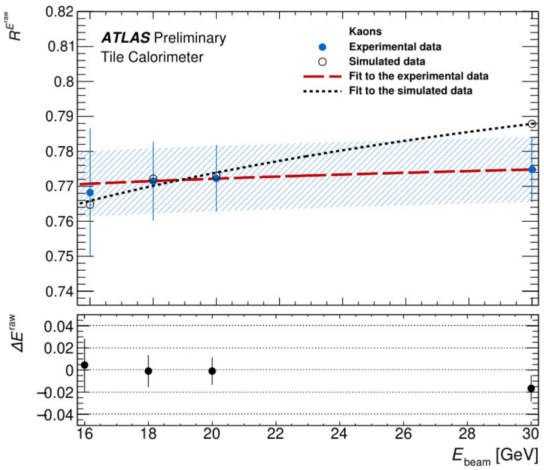
The linearity of the calorimeter response to electrons was checked in the range of 20-100 GeV. Further investigation is ongoing.

Test Beam results

- Muon beams
- Electron beams
- **Hadron beams**
  - 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 of the detector





The energy response ratio:

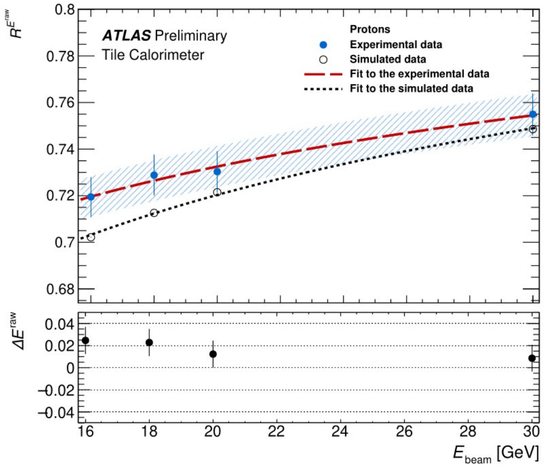
$$R^{\langle E^{\mathrm{raw}}\rangle} = \frac{\langle E^{raw}\rangle}{E_{\mathrm{beam}}}$$

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 – 1.4%
- Kaons – 1.7%
- Protons – 2.5%



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

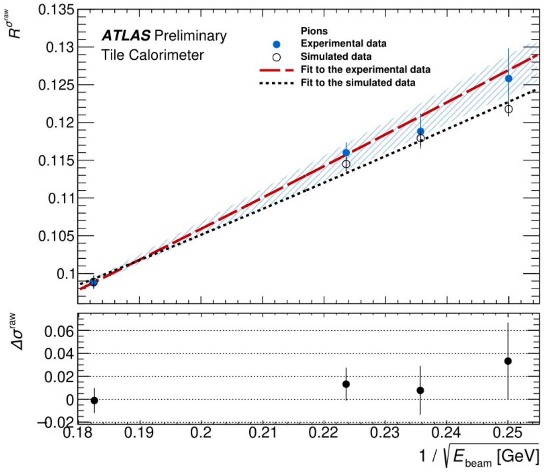
$$R^{\langle E^{\mathrm{raw}}\rangle} = (1 - F_{\mathrm{h}}) + F_{\mathrm{h}} \times (\frac{e}{h})^{-1} \quad , \qquad F_{\mathrm{h}} = (\frac{E_{\mathrm{beam}}}{E_0})^{m-1}$$

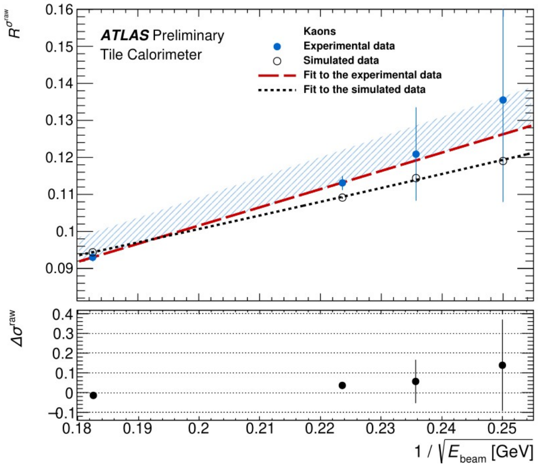
F_h - the non-electromagnetic energy component of showers induced by incident hadrons of energy E_{beam},
E_0 - the energy at which multiple pion production becomes significant,
m - the relation between the average multiplicity of secondary particles and the fraction of π^0s,
e/h - the ratio of the EM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

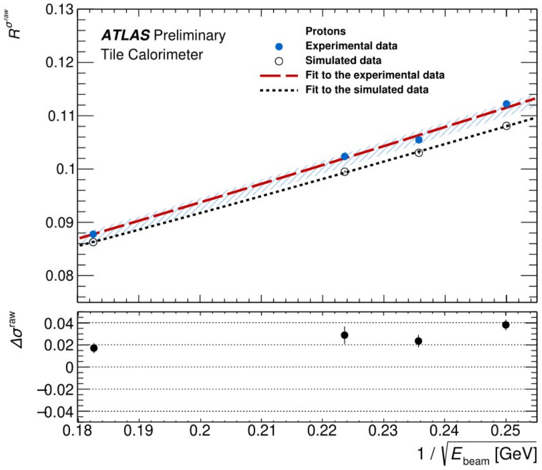
Function can be rewritten as:

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

Resolution of the detector







The fractional resolution:

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

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

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

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

- Pions – 3.3%
- Kaons – 13.8%
- Protons – 3.8%

The resolution can be parametrized according to:

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

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

Summary

- The ATLAS 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 an 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.
  - Further goals: do standard calorimeter measurements at the future test beams with the final Phase-II read-out electronics.
- All TileCal on- and off-detector electronics will be replaced in 2026-2028 during ATLAS Phase-II upgrade for the HL-LHC:
  - R&D is done, initial tests demonstrate good performance.
  - Demonstrator was inserted in the ATLAS detector and shows good performance - it is planned to operate for Run3.

Thank you!