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

Stergios Kazakos

(On behalf of the ATLAS Tile Calorimeter Upgrade Team)

Michigan State University

MICHIGAN STATE UNIVERSITY

ATLAS EXPERIMENT

BTTB12

12th Beam Telescopes & Test Beams Workshop
15 - 04 - 2024

ATLAS Tile calorimeter

★ The ATLAS **Tile calorimeter** (TileCal) is the hadronic calorimeter surrounding the electromagnetic calorimeter (ECal).

- Primary purpose to measure jet energy & assist in the E_T^{miss} reconstruction.

★ It is segmented into:

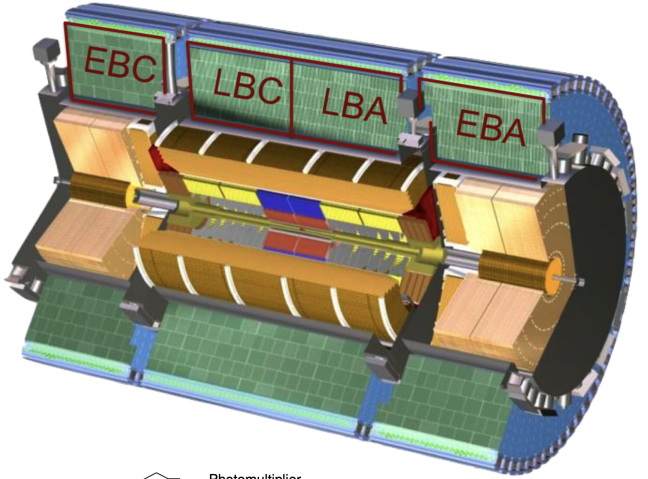
- **Long Barrel (LB)** region with coverage of **$|\eta| < 1.0$** containing **LBA** & **LBC** partitions.
- **Extended Barrel (EB)** region with coverage of **$0.8 < |\eta| < 1.7$** containing **EBA** & **EBC** partitions.

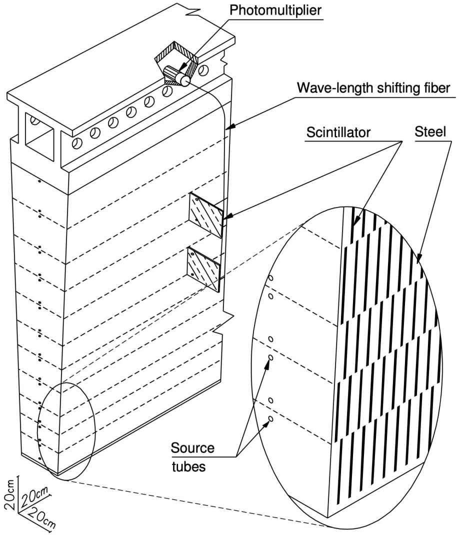
★ **64 modules** in each partition vertical to the beam pipe achieving a **2π** coverage.

- **48 photomultiplier tubes** (PMTs) in each module.
- Succession of 3 mm plastic scintillator plates + 14 mm steel absorber plates.

★ The light produced in the **scintillators** by the particles transerving the calorimeter is collected on both sides of the tile.

- Then transported to the **PMTs** with wavelength shifting (WLS) fibres.





TileCal in Phase-II upgrade

★ A number of major upgrades is planned for TileCal (Phase-II upgrade):

- **Redesign of electronics** (on- & off- detector) for improved radiation hardness, data acquisition & speed.
- Modules will be organised in **4 Mini Drawers** w/ independent High-Voltage (HV) system.
- **New power supply systems** to comply with the higher radiation requirements.
- **Replacement of PMTs** and **crack scintillators** damaged by radiation.

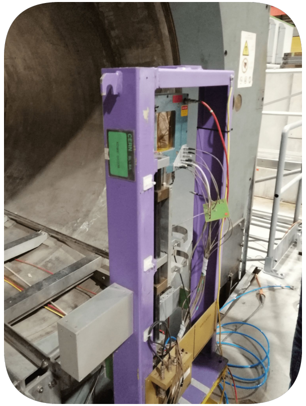
★ New TileCal electronics are expected to have:

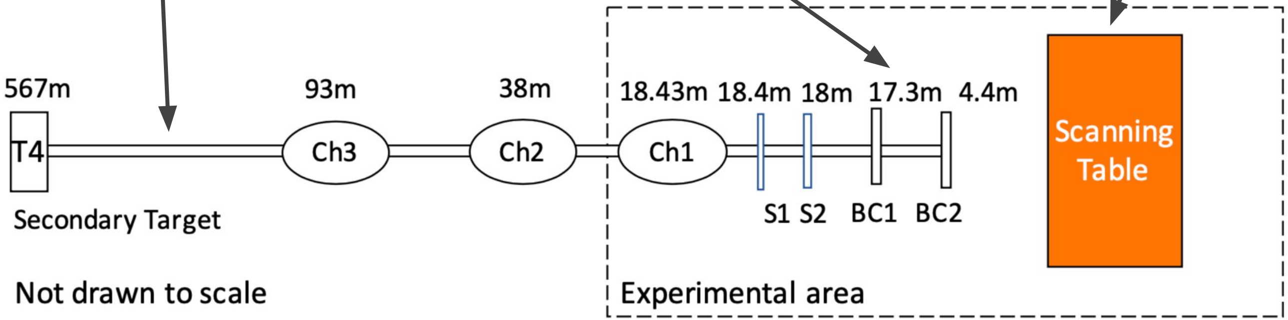
- **Lower latency**,
- **Higher frequency** (40 MHz),
- **Fully digital integration** with the ATLAS trigger system.

⇒ Digitised signal will be stored & redirected to Level-0 (L0) trigger with a 40 MHz rate (increased from 100 kHz).

Test-beam setup: H8 beam line

★ Located at the Super Proton Synchrotron (SPS) North Area - H8 beam facility at CERN.





★ Secondary beams with energies from 10 to 350 GeV:

- **Beryllium** as primary target.

★ Tertiary beams:

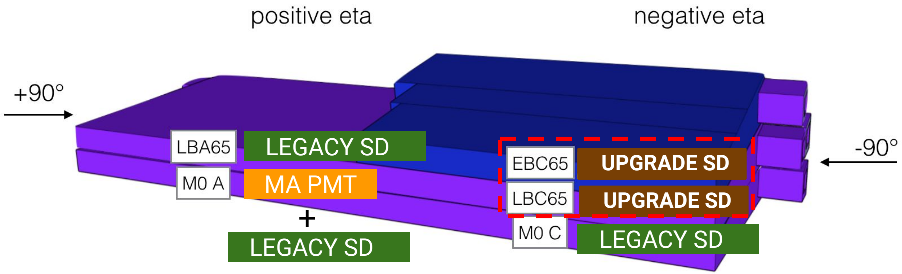
- **Polyethylene** + **lead** absorber as secondary target.

Beam line elements:

- **3 Cherenkov counters** (Ch1, Ch2 & Ch3):
  ⇒ Separate **p/K/π/e** for low beam energies (< 50 GeV).
- **2 trigger scintillators** (S1 & S2):
  ⇒ Used in coincidence to trigger the data acquisition and provide the trigger timing.
- **2 wire chambers** (BC1 & BC2):
  ⇒ Transverse beam profile monitoring.

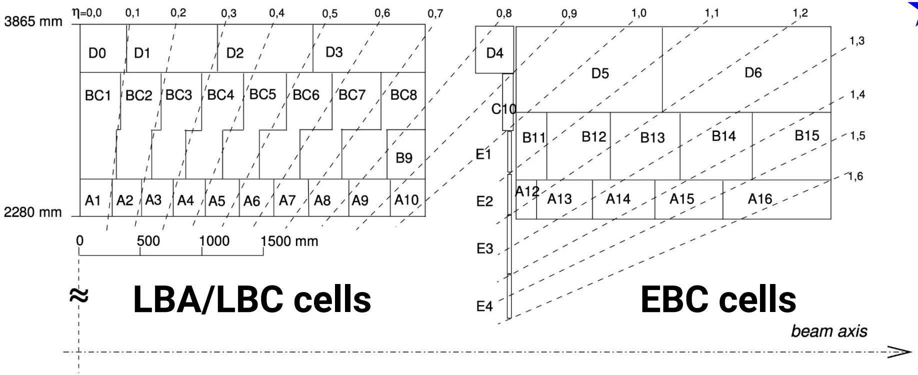
Test-beam setup: Module placement

★ Spare 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 **2021-2023**.



★ Modules from both sides of the detector (positive & negative η):

- **3 longitudinal layers** (A, BC or B and D) per module
- **23 cells** in LB modules, **14 cells** in EB modules (+4 special purpose cells E1-E4)
- Granularity (in Δη x Δφ):
  0.1 x 0.1 (A- & BC/B-layer) & **0.2 x 0.1** (D-layer)

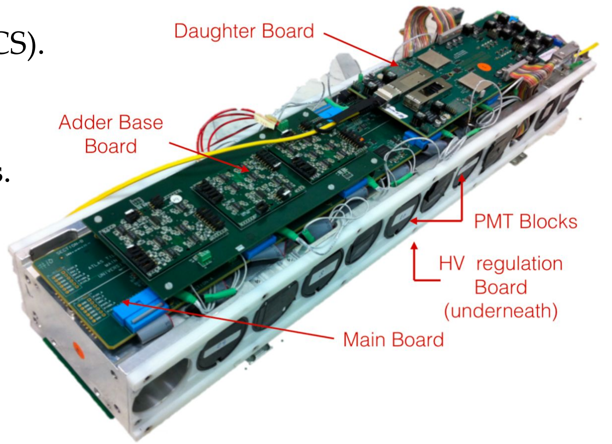


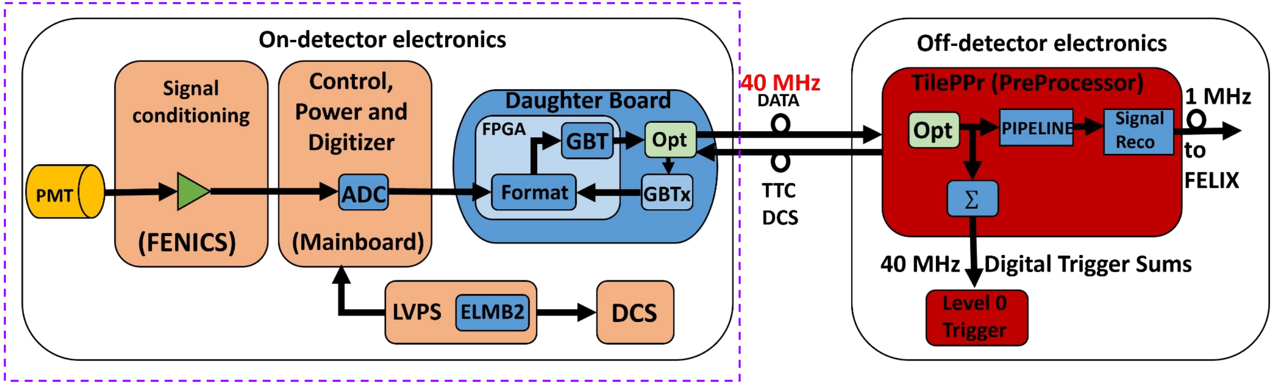
★ Modules exposed to **different particle types (e/μ/h)** and **energies**, at **different incident angles**.

- Upgrade SD inserted in the EBC & LBC modules from 2022 TBs onwards.
- EBC module placed on top of LBC module.
- Total energy is summed in the 3 modules (LBA, LBC & EBC).

Test-beam setup: On-detector electronics

- **4 Mini Drawers (MDs)** each with independent readout and power supplies.
- **12 PMTs & 12 Front-End Boards** (FEBs) in each MD reading 6 Tile cells (called FENICS).
  - The **FENICS** card performs signal shaping and amplification.
- **1 x MainBoard** (MB): digitises the input from the FEBs, operation of front-end boards.
- **1 x DaughterBoard** (DB): high speed link of data with the off-detector electronics.
- **1 x High Voltage** distribution board.
- **2 x Low Voltage Power Supply** bricks: one for each independent side.





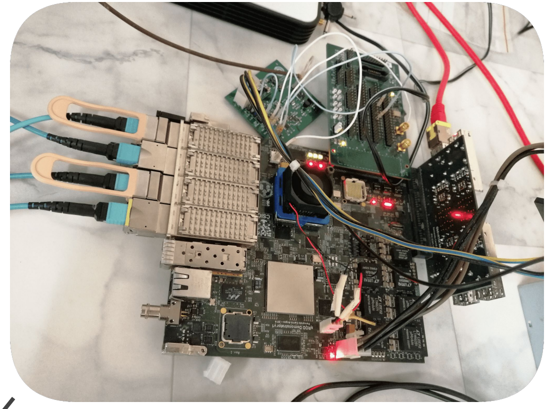
- Currently testing new DB (v6.4) and focusing on migration to Alma9 and TDAQ11.

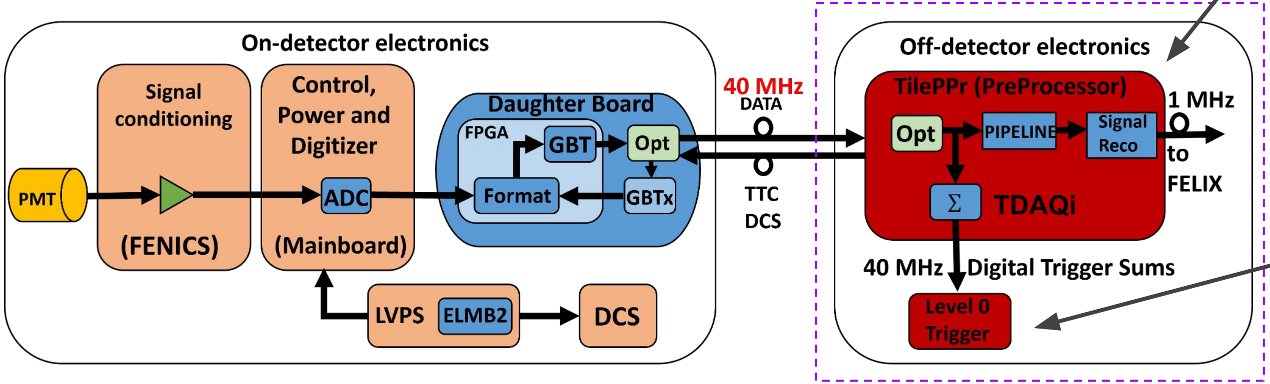
Test-beam setup: Off-detector electronics

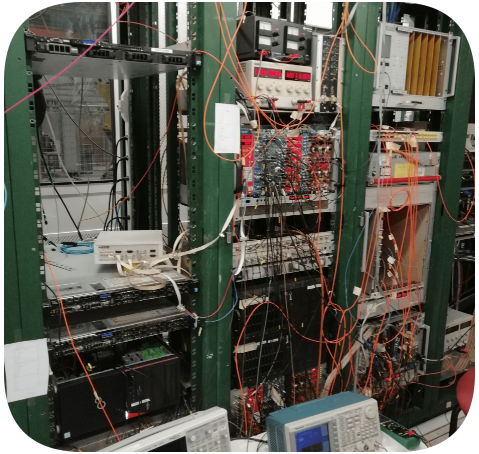
★ Tile PPr (Preprocessor):

- Located off-detector away from the scanning table.
- **Buffers data** from all MDs in pipelines.
- **Evaluates signal** at the full 40 MHz rate.
- **Distributes** the system **clock**, **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).







Test-beam strategy

★ Very rich test-beam program during the years **2015-2018** & **2021-2023**, plan in place for 2024 TB.

- Increased number of analysers, opportunity to cover various topics.

★ Close collaboration with **MC experts** to improve the modeling of particles interacting with the detector in **Geant4**.

★ Studying the response of different beam types with the new electronics (usually needed to isolate them first):

Hadron beams

⇒ The role of the hadron calorimetry is to measure the energy and the angle of isolated hadrons.

⇒ Identify **pions**, **kaons** and **protons** in hadronic showers & compare their measured energy to the predictions from **Geant4**.

- Taking care of particle overlap.

⇒ Study their **response** and **resolution** to validate and improve their modeling in the simulation.

Electron beams

⇒ Crucial to accurate model electrons that are often created inside the hadronic showers.

⇒ Useful to verify the **linearity** of the response vs energy (and in general the **uniformity** of the detector).

⇒ Validate if the **electromagnetic (EM)** scale is set correctly by measuring electron signal at known energies.

Muon beams

⇒ Well-understood interaction of muons with matter.

- **Ionisation** as the dominant energy-loss process.

⇒ Study of the **detector response** using high energy muons traversing the entire module for different incident angles.

⇒ Useful to check the **equalisation of the cell response** verifying the performance of new electronics.

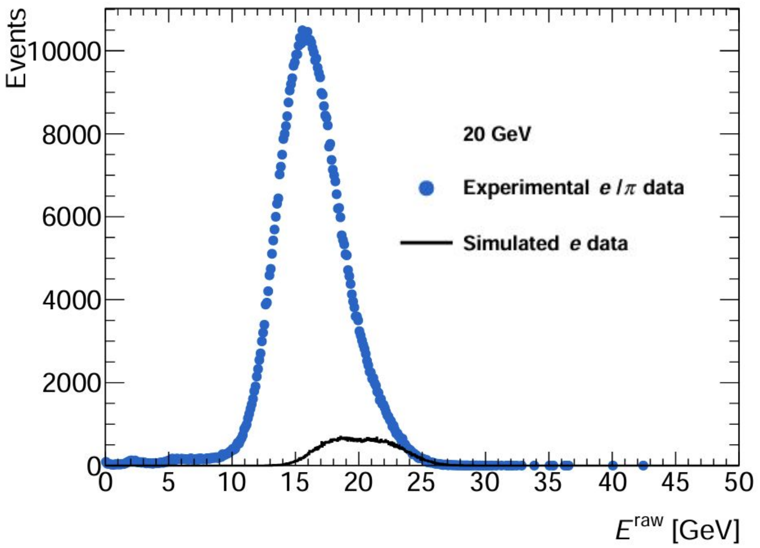
Particle identification in test-beam data

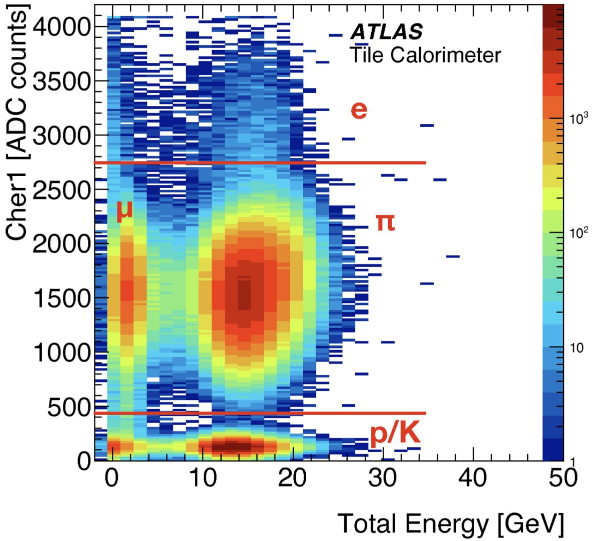
★ A common issue when trying to study a specific particle type could be its overlap with other particles:

- Common overlap for **e-π** & **π-p/K**.

★ One of the strategies is to use **Cherenkov** counters to separate them.

★ Cherenkovs work best for particles with E_{beam} **< 50 GeV** & need to be properly tuned.





Particle identification in test-beam data

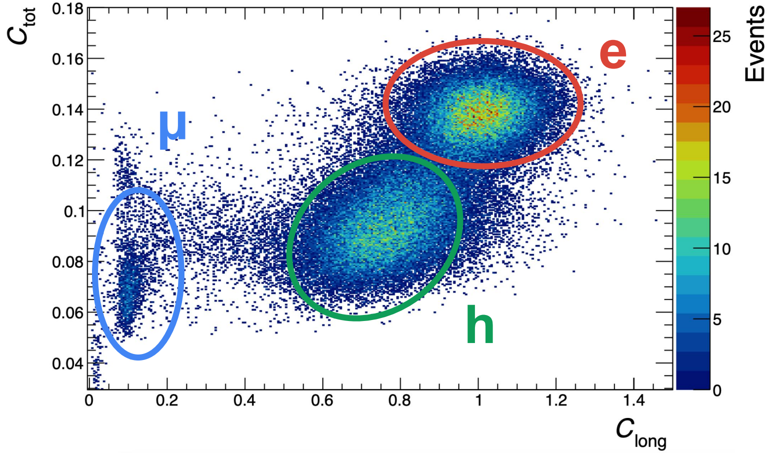
★ Another technique for particle separation is through topological analysis in the C-space (using $C_{\mathbf{tot}}$ & $C_{\mathbf{long}}$ variables) (sometimes used together with Cherenkovs).
- Mostly useful for **e-π** separation.
- Performs better with either elliptical or diagonal cuts.

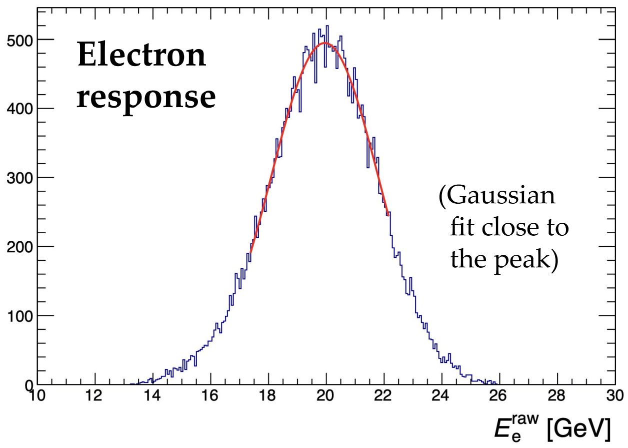
★ $C_{\mathbf{long}}$: sum of energy deposited in the targeted cell + its neighbouring ones.
- Index i running over the A- and BC/B-layers (excluding D-cells).
- Index j running over the 3 cells of each layer.

$$C_{long} = \sum_{i=1}^{2} \sum_{j=1}^{3} \frac{E_{ij}}{E_{beam}}$$

$$C_{tot} = \frac{1}{\sum_c E_c^{\alpha}} \sqrt{\sum_c \frac{\left(E_c^{\alpha} - \sum_c E_c^{\alpha} / N_{cell}\right)^2}{N_{cell}}}$$

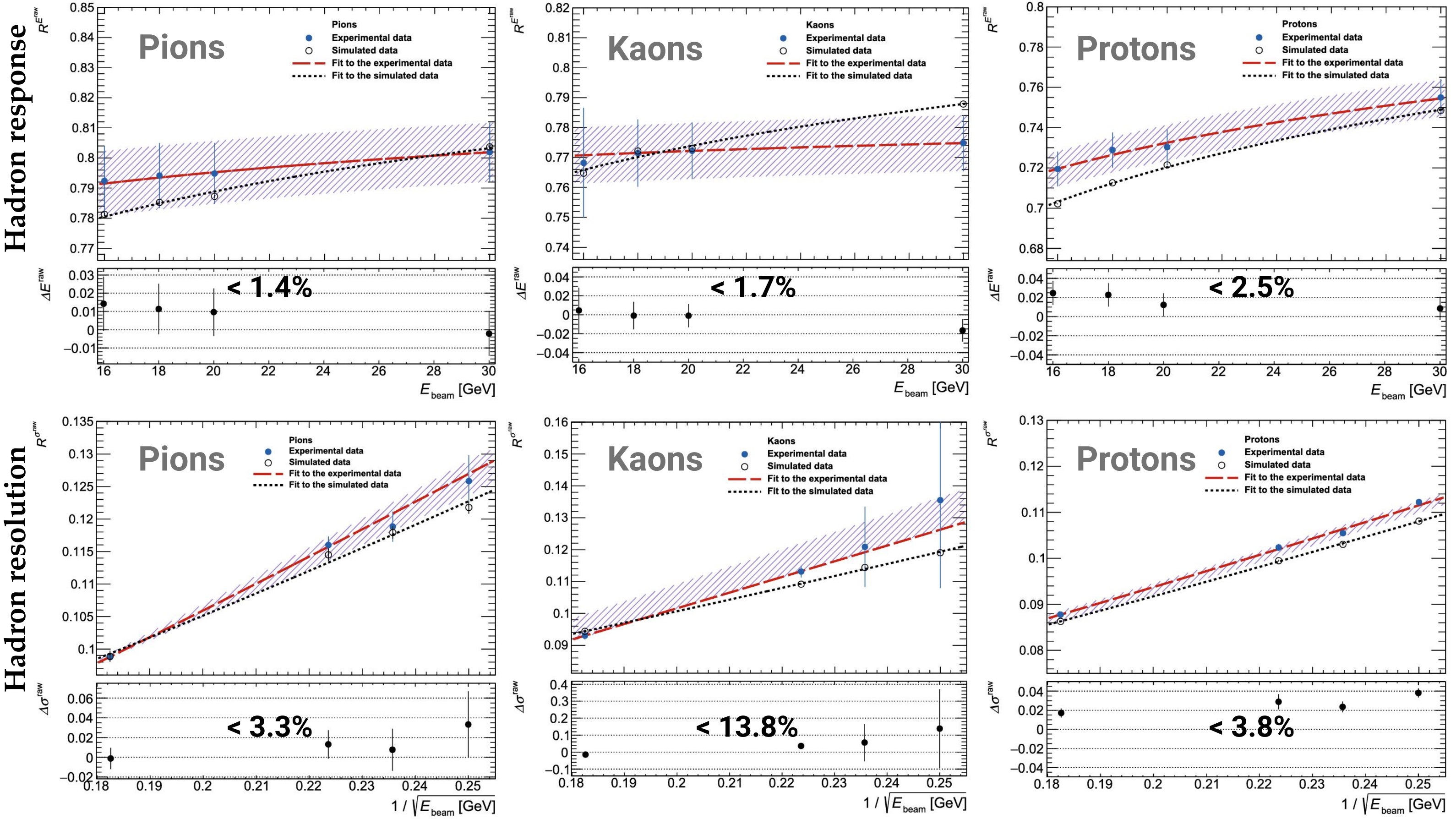
* definitions might change slightly according to the particle type





★ $C_{\mathbf{tot}}$: energy spread deposited in the calorimeter cells.
- $E_{\mathbf{c}}$ is the energy in cell c.
- $N_{\mathbf{cell}}$ **= 24** stands for the total number of cells considered (all layers).
- Exponent $\boldsymbol{\alpha}$ **= 0.6** optimised for better **e-h** separation.

Hadron analysis: Response & resolution



- Response:

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

- Resolution:

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

- Comparison vs MC:

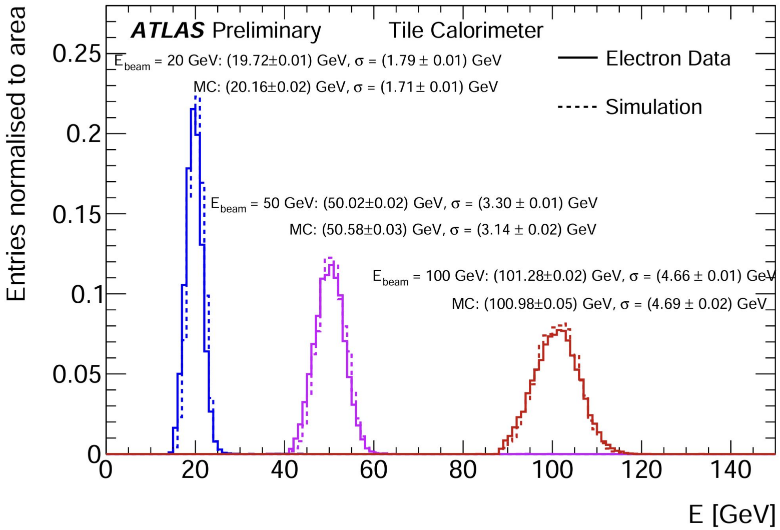
$$\Delta \langle E^{raw} \rangle = \frac{\langle E^{raw} \rangle}{\langle E^{raw}_{MC} \rangle} - 1$$

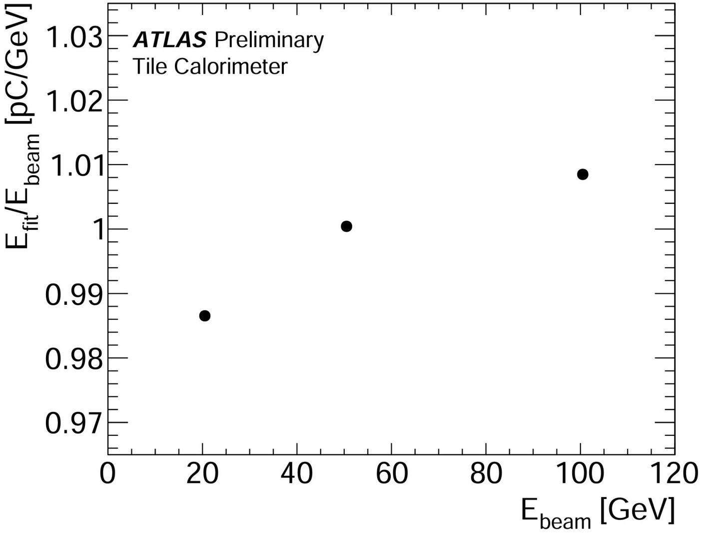
$$\Delta \sigma^{raw} = \frac{\sigma^{raw}}{\sigma^{raw}_{MC}} - 1$$

EPJC (2021)81:549

Electron analysis: Linearity & EM scale validation

- **Electron response** validated with MC for several energies (20, 50, 100 GeV), good agreement with simulation.
- **Setting** of the **electromagnetic (EM) scale** is validated if the response is close to the beam energy (nominal value is 1.05).
- Validated the **linearity of the response** vs E_{beam}.
- Current results are shown for **A-4** cell with an incident beam of **20º**.
  - Results available for more energies (with **10, 80 & 150 GeV** in **2021-2023** runs).
  - Achieving very **high electron purity** from 2023 onwards.





Muon analysis: Detector response uniformity

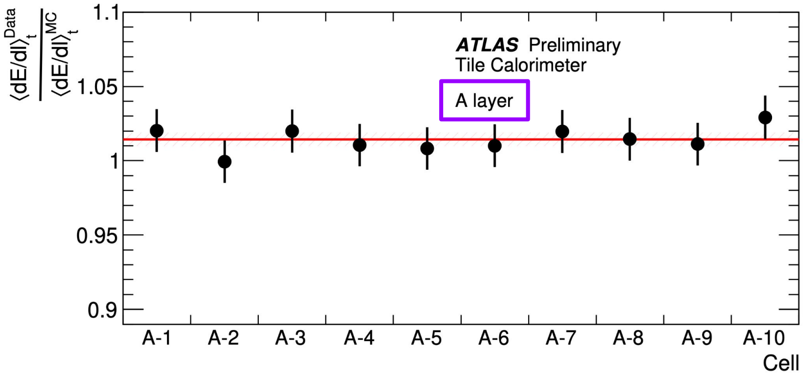
- Showing results of muon runs with energy **160 GeV** at an incident angle of **-90º** transversing the modules.

  ⇒ Interested in the energy loss per unit distance (dE/dl) for each cell.

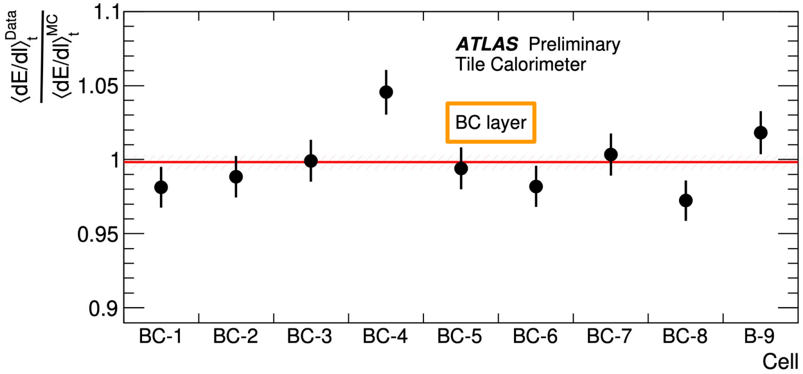
- Comparing the dE/dl values between experimental and simulated data using the ratio:

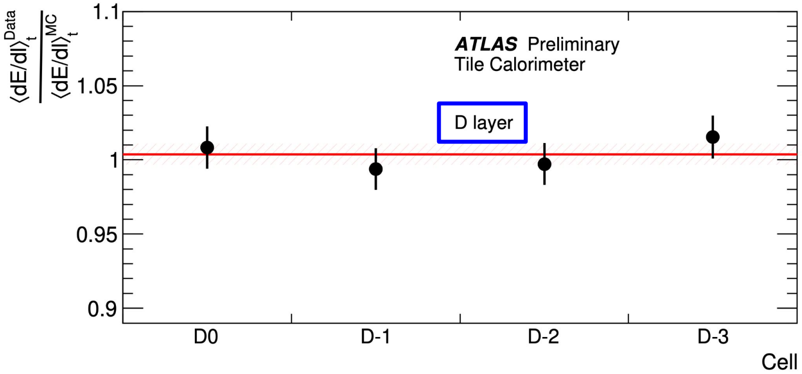
$$R = \frac{\langle dE/dl \rangle_t^{Data}}{\langle dE/dl \rangle_t^{MC}}$$

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



- Fitting to a 0th-order polynomial to get the mean values of dE/dl for each layer (red lines).





- Response uniformity within 1% with a maximum offset of 1.4% for Data/MC.

Summary

★ Studies related to the **ATLAS TileCal Phase-II upgrade** are currently ongoing:

- R&D phase is finished, initial tests demonstrate good performance.
- All on- and off-detector electronics will be replaced.
- New electronics are being tested to cope with the large pileup and higher radiation of HL-LHC.

★ **Test beams** are conducted on a regular basis at the H8 line (SPS, CERN):

- Five modules are tested.
- Rich plan completed for 2015-2018 & 2021-2023, TBs also planned for 2024.
- Aim to study the response of new electronics for different particle beams (first tests with Upgrade SDs).

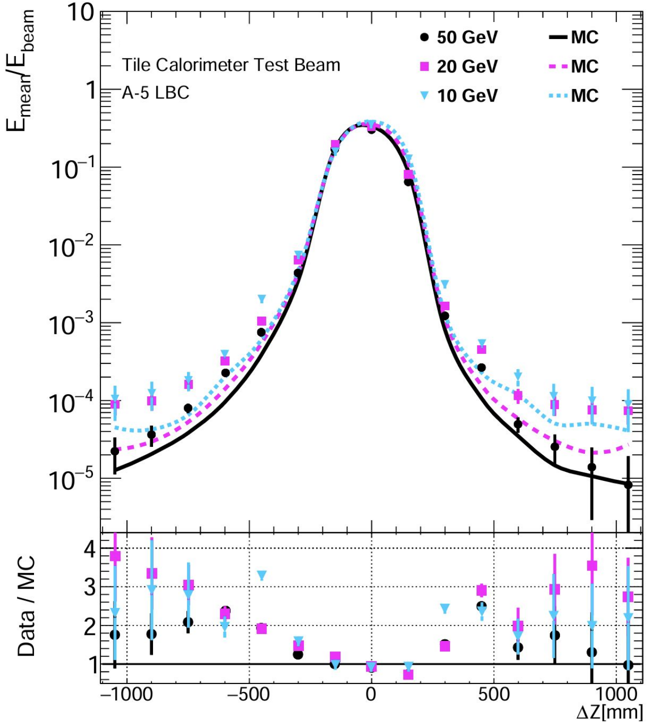
★ Results with **hadrons**, **electrons** and **muons** discussed:

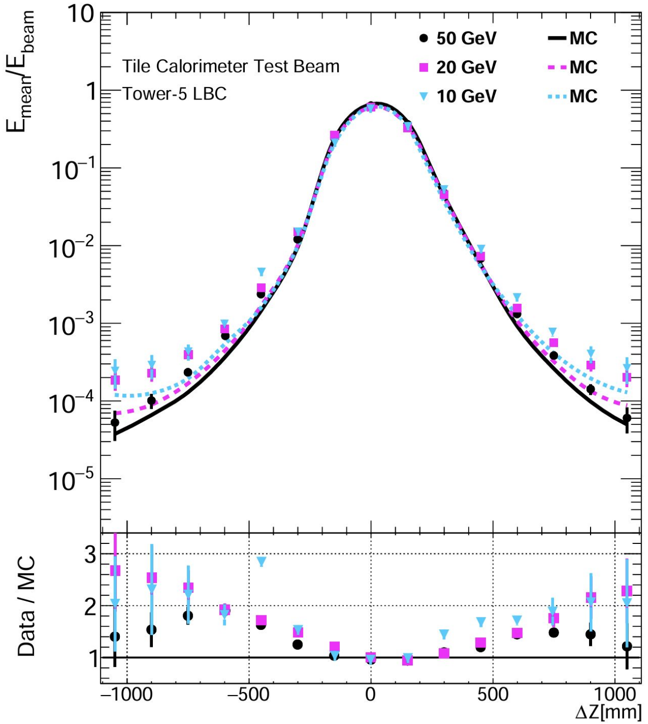
- Results with Legacy SD look as expected & in line with previous measurements.
- Studies with the Upgrade SD are ongoing.

Backup

Hadron analysis: Hadronic shower transverse shape

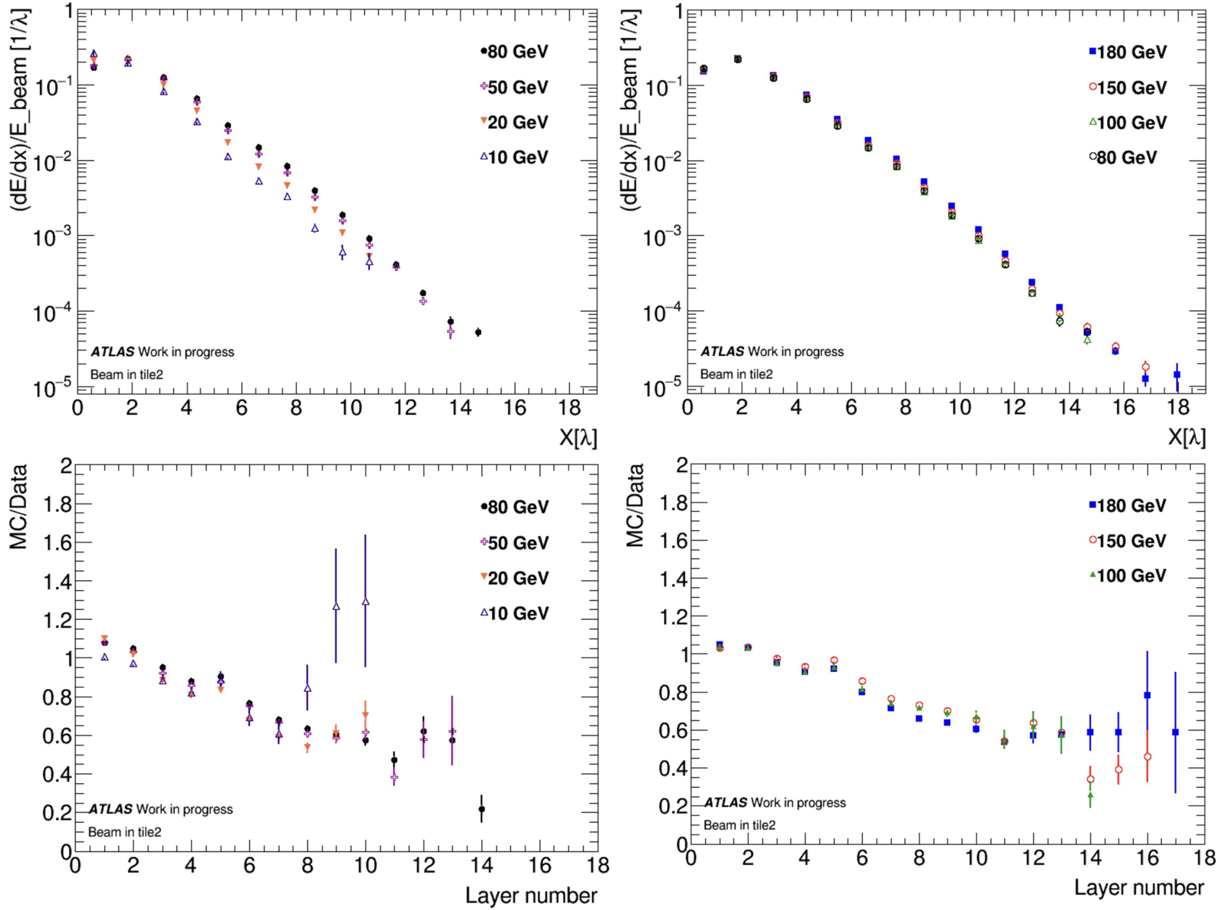
- ★ Studied energy dependence scanning over ΔZ (-1050 to 1050 mm) in Tower-5 and A-5 / BC-5 cells.
- ★ Comparison of the shower profile in data vs MC (Geant4).
- ★ Results with Sep 2023 data with the beam hitting at 20º.
- ★ Larger data/MC disagreement for large values of |ΔZ| probably due to electronics noise being non-negligible there.





Hadron analysis: Hadronic shower longitudinal shape

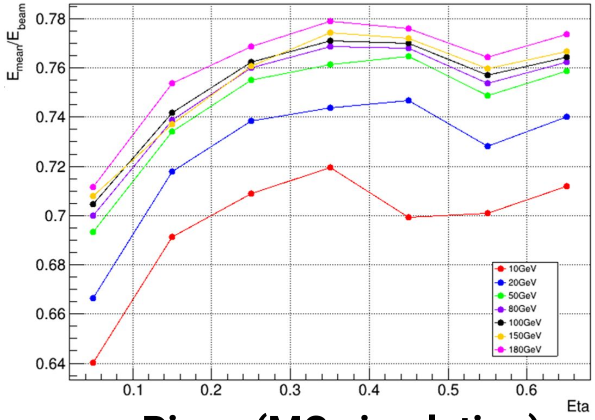
- Studied hadron energy loss vs distance travelled for different E_{beam}.
- Results with Sep 2023 data with the beam hitting at -90º.
  - Beam hitting first LBC A-layer cells and then propagating to LBA. (LBC: cells 1-10, LBA: cells 11-17)
- Comparison of the shower profile in data vs MC (Geant4).
- Simulated data (MC) need to have similar proportion of **protons/pions/kaons** as in experimental data:
  - Cherenkov counters crucial for this task.



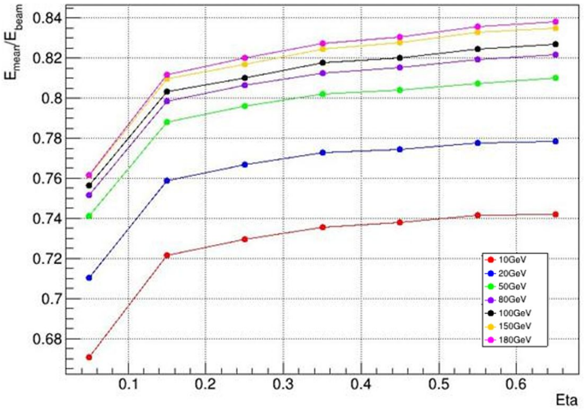
Hadron analysis: Hadronic response in data & MC

- Simulation of different types of hadrons (**kaons/pions/protons**) for a broad range of E_{beam} (from 10 GeV to 180 GeV).
- Currently trying to understand the dip in the response for experimental hadron data at higher eta values.

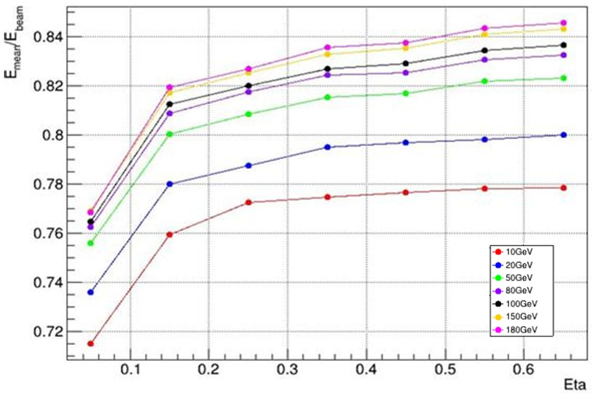
Hadrons (TB data)



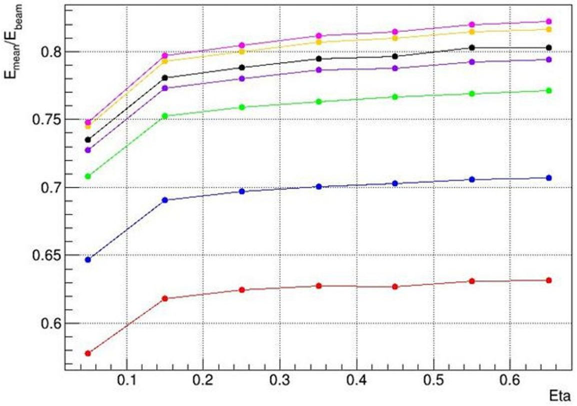
Kaons (MC simulation)



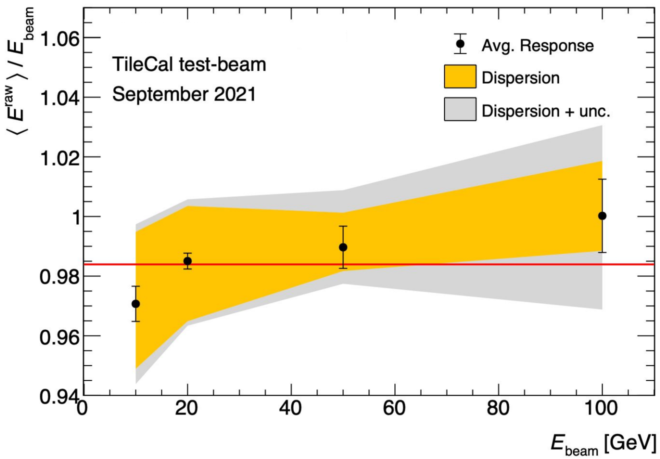
Pions (MC simulation)

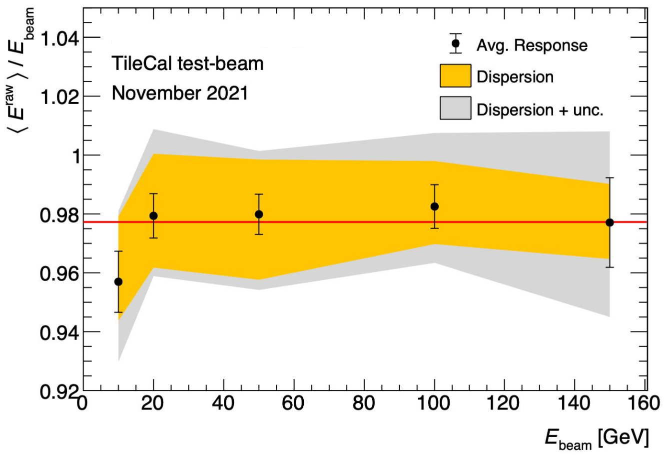


Protons (MC simulation)



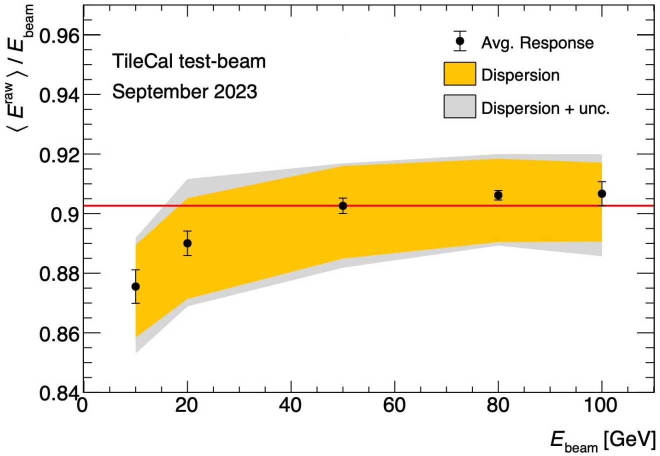
Electron analysis: Results from 2021 & 2023 (response linearity)





- ★ **Averaging** the **response** from all cell runs **at the same energy** (A-2 to A-9 for Nov 2021 / Sep 2023 and A-4 to A-9 for Sep 2021).
- ★ Validated the **linearity** of the **electron response** vs beam energy.

  ⇒ 10 GeV runs are traditionally a bit lower.



- ★ **Red line**: average response of all cells and beam energies.

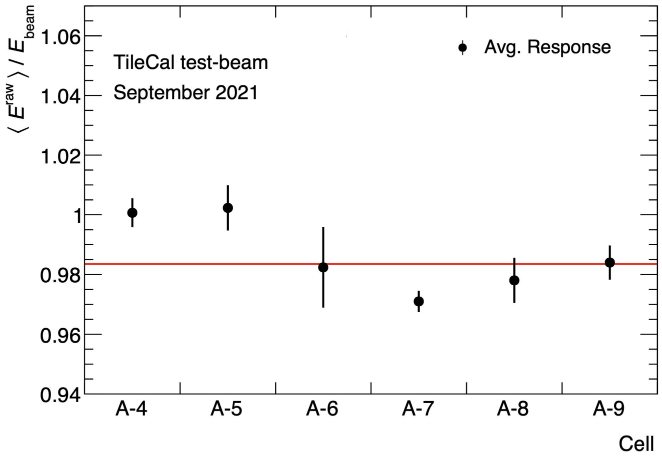
  Orange band: Dispersion of response for different cells.

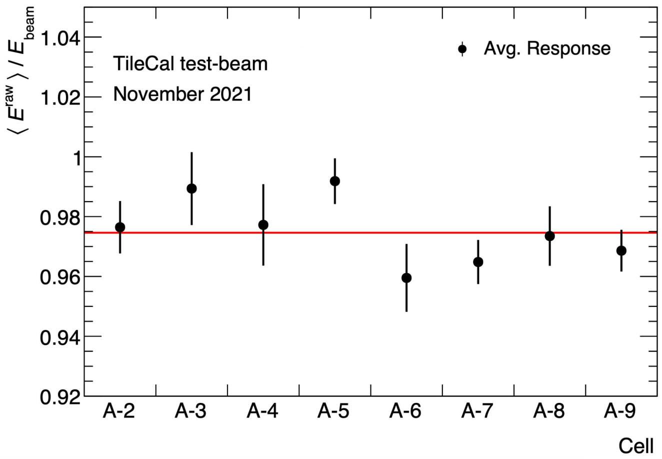
  Grey band: Dispersion of response for different cells including the uncertainty.
- ★ **Part of the total uncertainty** in the response comes **from electron purity** & **shower profile**.

  ⇒ Much better electron purity & electron separation in 2023:

  - Total uncertainty is significantly decreased.
- ★ ~10% offset in the response in 2023 (w/ Upgrade SD), under investigation.

Electron analysis: Results from 2021 & 2023 (response uniformity)

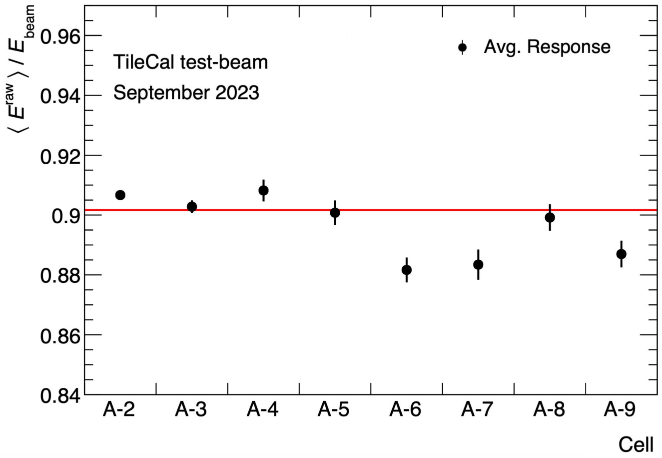




★ **Averaging** the **response** from **all energies**:

- 10, 20, 50, 100 GeV (Sep 2021)
- 10, 20, 50, 100, 150 GeV (Nov 2021)
- 10, 20, 50, 80, 100 GeV (Sep 2023)

with the **beam incident to the same cell**.



★ Validated the **uniformity of the response** with the beam incident to all LB cells.

⇒ Response of A-6 & A-7 cell runs is usually a bit lower than the rest (still within the energy dispersion error).

★ **Red line**: average response of all cells and beam energies.

★ A-2 & A-3 cell runs not analysed in Sep 2021 since there was a temporary connection issue with the PMTs in these channels.

Muon analysis: Results from 2022

- ★ Results from LBC module with the Upgrade SD installed.
- ★ Great response uniformity (investigating tension w/ BC-6 cell).
- ★ Offset of about ~5% similar to what seen in other particle types.
  - Similar offset seen in 2023 muon data.

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

Layer	Mean	St.Err.on Mean
A	0.954	0.004
BC	0.947	0.005
D	0.954	0.007