

Muon Response in Projective Geometry Configurations of the ATLAS Tile Calorimeter

Miranda Williams, on behalf of the
ATLAS Tile Calorimeter System

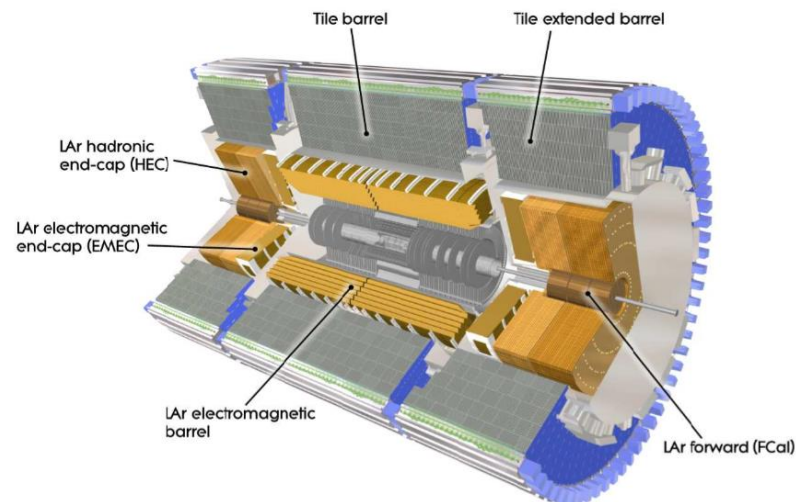
**13th Beam Telescopes and Test Beam
Workshop (BTTB13)**
19-23 May 2025, Valencia



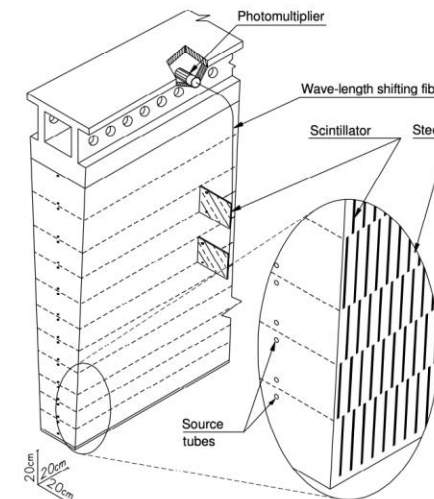
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The Tile Calorimeter

- The hadronic **Tile Calorimeter** (TileCal) is the central calorimeter of the **ATLAS detector** located at CERN.
- The main purpose of the Tile Calorimeter is to **reconstruct hadronic jets**, as well as to reconstruct the **missing transverse energy** and to **provide input to trigger and muon** identification.
- TileCal is segmented into four partitions— **two extended barrel (EB)**, **two long barrel (LB)** – made of alternating steel plates and plastic scintillator tiles.



- Each partition consists of **64 modules**, and each module is divided into **3 longitudinal layers** (A, BC, D).
- These layers are further subdivided into cells with **double readout**, resulting in approximately 10,000 signals.
- TileCal covers a pseudorapidity range of $|\eta| < 1.7$

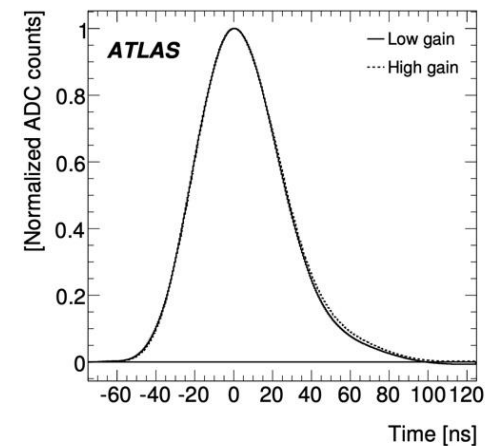


The Tile Calorimeter

- When a **charged particle** passes through TileCal, the light it produces in the **scintillators** is **collected by wavelength-shifting (WLS) fibers** and **delivered to the photomultiplier tubes (PMTs)**.
- The PMT signal is **amplified, shaped, and digitized** by fast ADCs.
- The ADC samples are then used by an **Optimal Filtering** algorithm to **reconstruct the signal amplitude, time, and pedestal**.

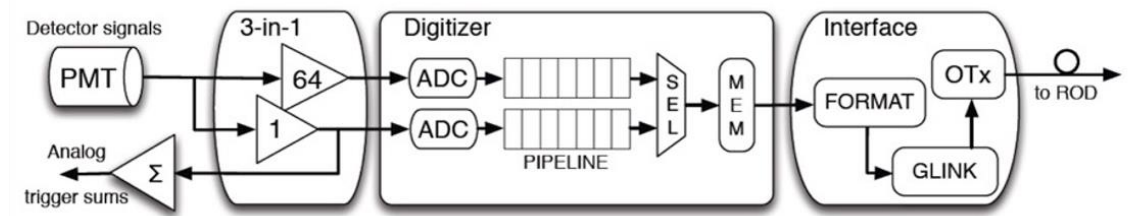
$$E_{GeV} = A(ADC) * C_{ADC \rightarrow pC} * C_{pC \rightarrow GeV} * C_{Cesium} * C_{Laser}$$

Variable in Energy Reconstruction	Purpose
$A(ADC)$	Raw ADC signal amplitude
$C_{ADC \rightarrow pC}$	Intercalibration of electronics
$C_{pC \rightarrow GeV}$	EM scale
C_{Cesium}	Intercalibration of optical chain
C_{Laser}	Intercalibration of PMT gain

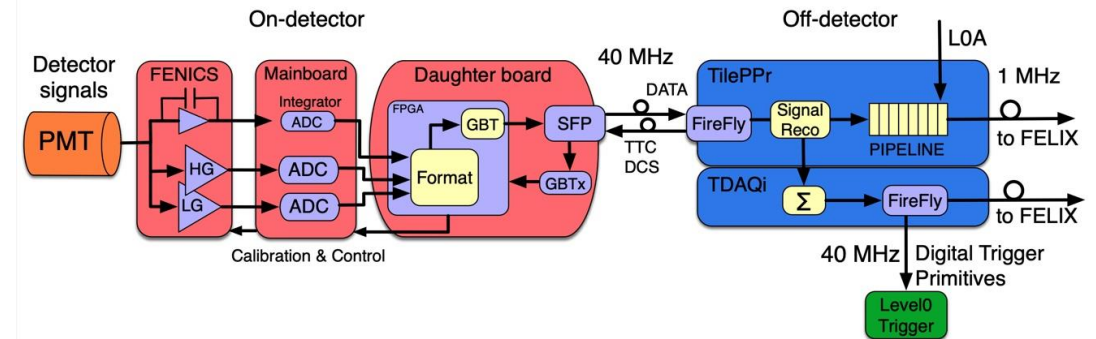


The Phase-II Upgrade

- The upgrade of the LHC to the High Luminosity-LHC (HL-LHC) is expected to have an **increase of instantaneous luminosity by a factor of up to 7.**
- For TileCal, the challenge is then the **replacement of the on- and off-detector components** to meet new radiation, trigger scheme, and readout performance requirements.



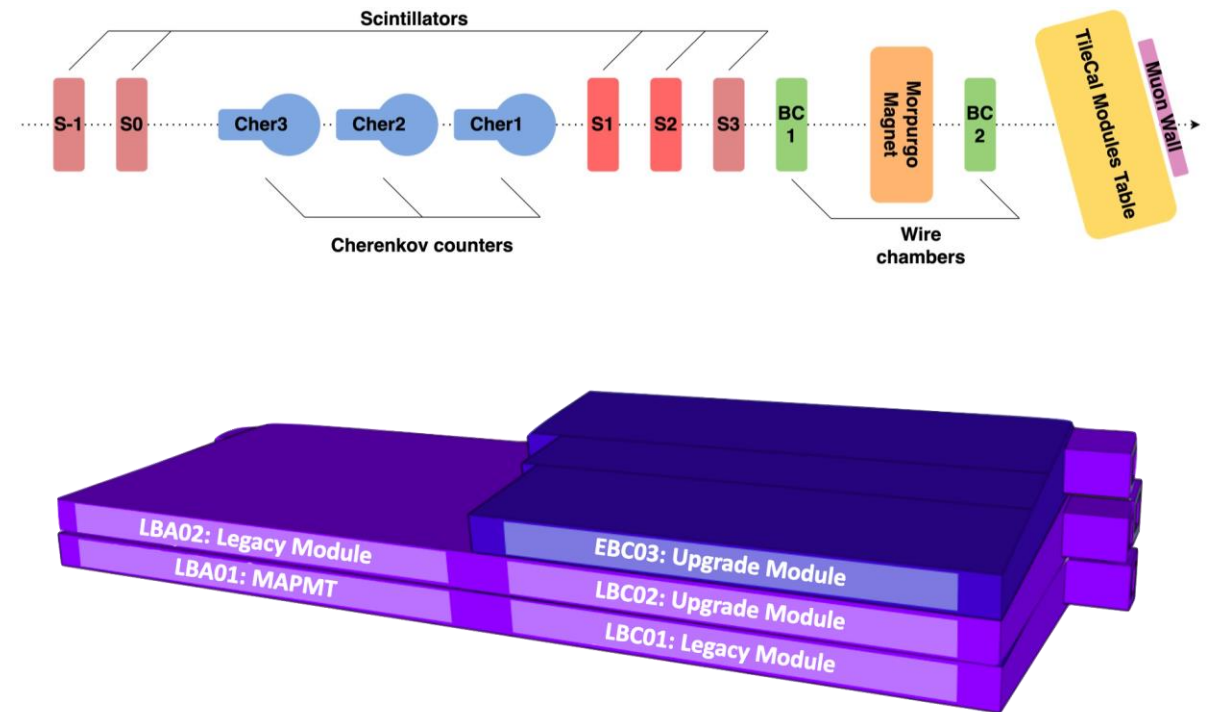
Legacy TileCal readout electronics system.



Phase-II Upgrade TileCal readout electronics system.

The TileCal Test Beam Setup

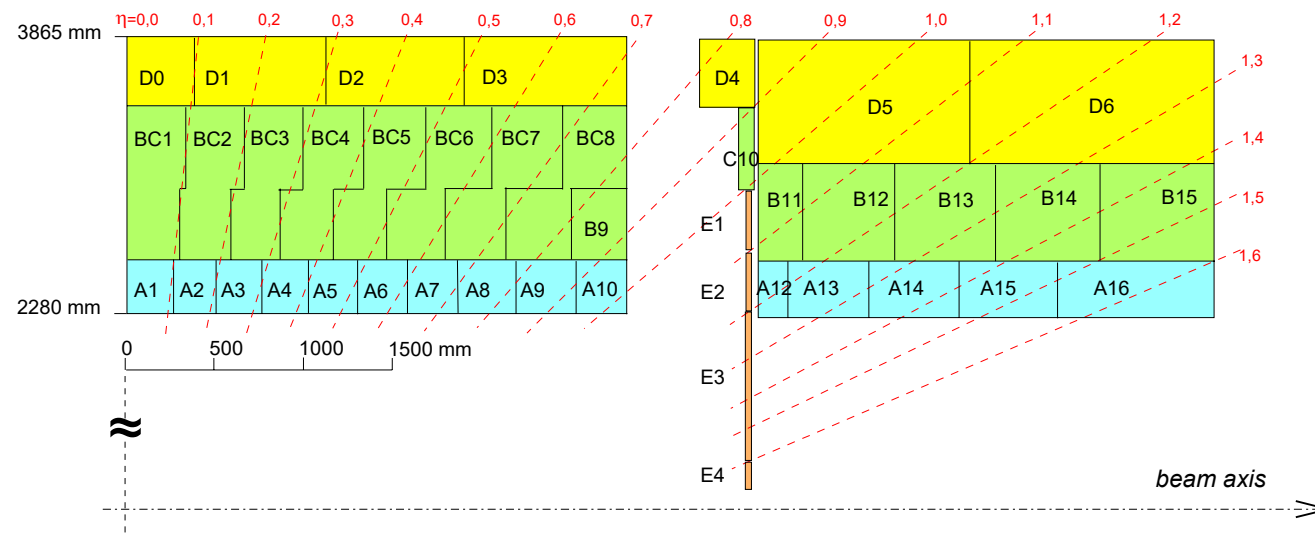
- The TileCal test beam serves to **validate the upgraded electronics system** and study calibration of new electronics.
- The “Upgrade” module, **LBC02**, is equipped with the **upgraded electronics** but two possible data streams: one to the Legacy **Read-Out Driver (ROD)** system, one to the Upgrade **Front-End Link eXchange (FELIX)** readout system system.
- The “Legacy” module, **LBA02**, is equipped with the **Legacy electronics (ROD)**.
- For more details on the hardware of the test beam, see Antonio Cervelló’s talk: [TileCal TB HW](#)



Top: TileCal test beam beamline schematic. Bottom: Scanning Table schematic.

Methodology: General Information

- The response of the **Upgrade module** to **160 GeV/c muon beams** impinging at **projective angles** with **various PMT gains** (HV settings) is measured and **compared to Geant4 Monte-Carlo** simulations. **Comparisons with the Legacy module** are also performed.
- Studies are focused on trigger towers $\eta = -0.15$ to -0.95 in the **Upgrade module**, while the **Legacy module** studies focus on trigger towers $\eta = 0.15$ to 0.45 .



Methodology: Selections

- Several selections are made to 1) **exclude hadron contamination** of the beam, 2) **filter out any rare high-energy processes of muons** that may be occurring, and 3) **filter out any electronic noise** that may be present:
 - *Beam Chamber 2*: Event selection between -20 and 20 mm in X and Y.
 - *Total energy*: Event selection below 50 GeV throughout the entire scanning table.
 - *Cell noise*: Event selection above 30 MeV per individual cell.

- In addition, **path lengths** across a cell are **calculated per cell, per η** , by using the equation of **pseudorapidity**:

$$\theta = 2 \arctan(e^{-\eta})$$

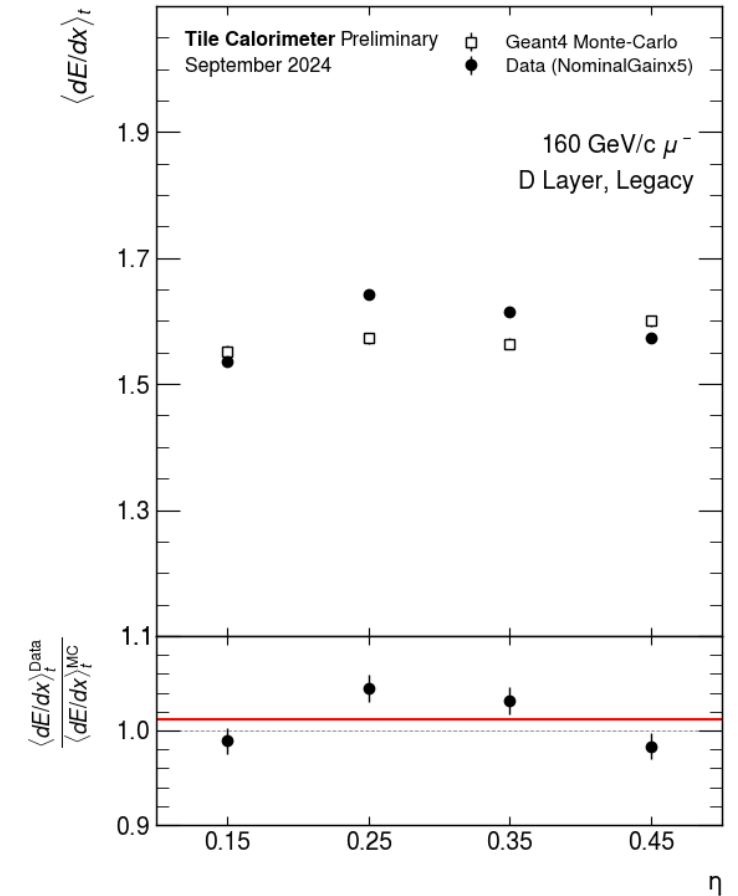
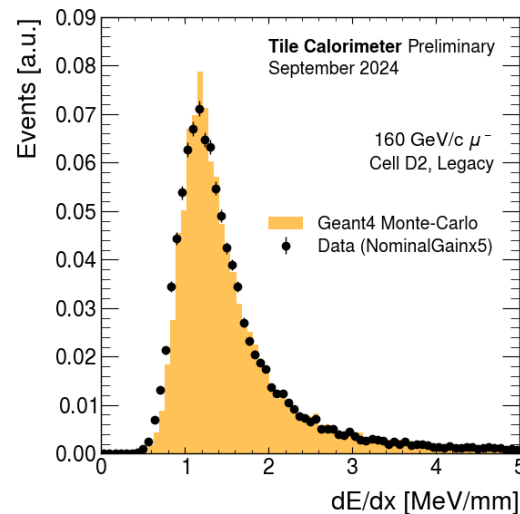
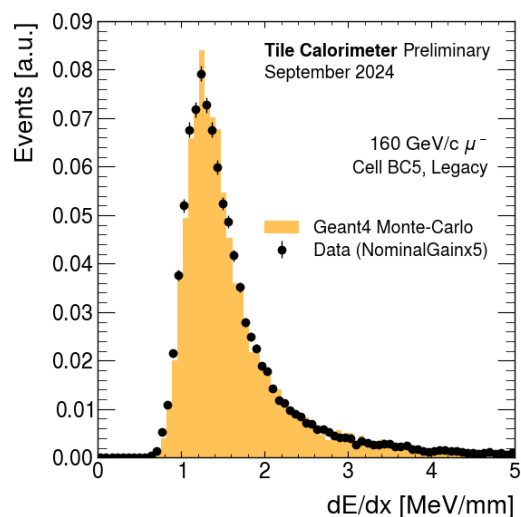
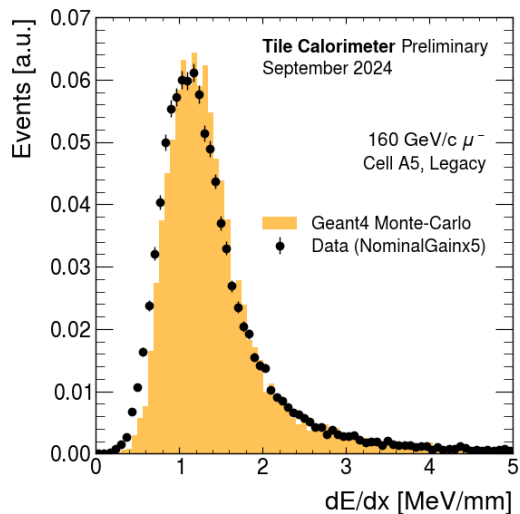
- Responses per cell are characterized by **dE/dx histograms** and a **97.5% truncated mean**, where further comparisons are then made.

Methodology: Systematic Errors

- **Systematic errors** of this study come from the **selections and truncation choices** themselves.
- To calculate the **total error**, the selection and truncation **parameters were varied** and **added in quadrature** to the **statistical error** of the **experimental-simulated data agreement per cell**:
 - Beam chamber 2: ± 5 mm in X and Y \rightarrow applied to experimental values only.
 - Total energy: ± 20 GeV
 - Cell noise: ± 15 MeV
 - Truncation: $\pm 1\%$
- In addition, a **1.3% relative uncertainty** of the **Monte-Carlo values** was included from the variation of simulation parameters.

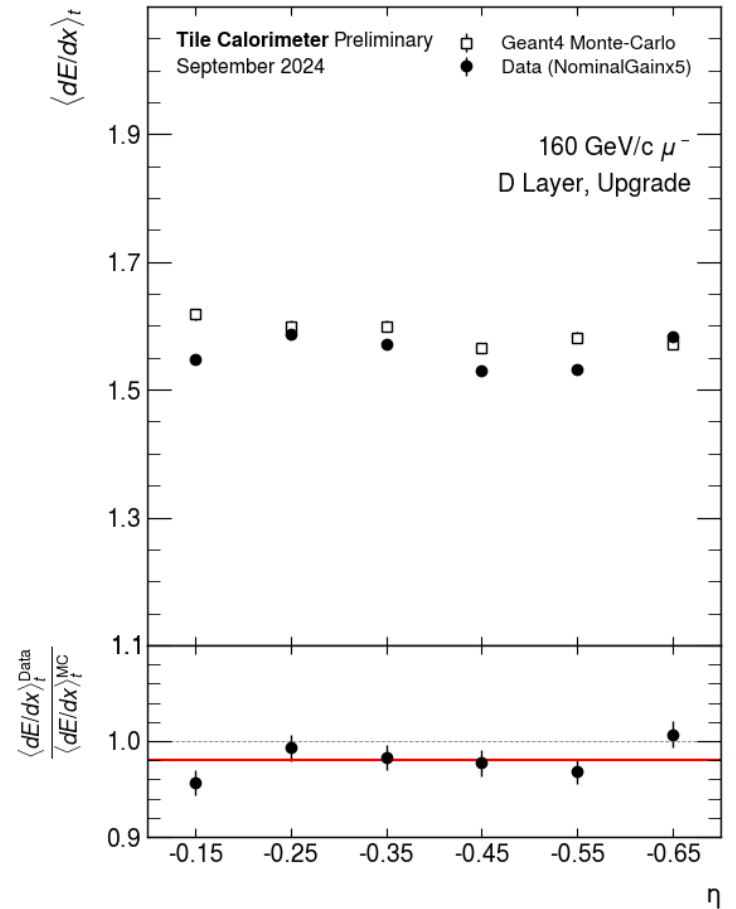
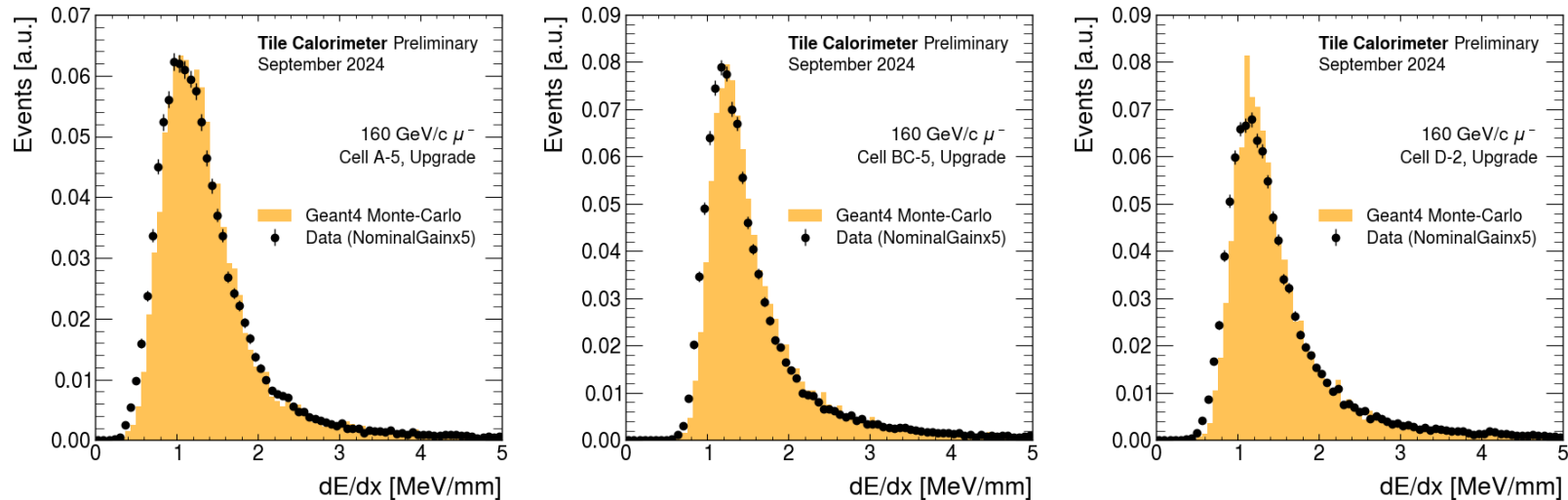
Muon Responses: Legacy

- Longer path length of a cell \rightarrow better resolution \rightarrow **smaller distribution width.**
- **Photostatistic effects** also plays a role in the **width of distributions** per layer.
- **Monte-Carlo agreement** per cell within **5%.**



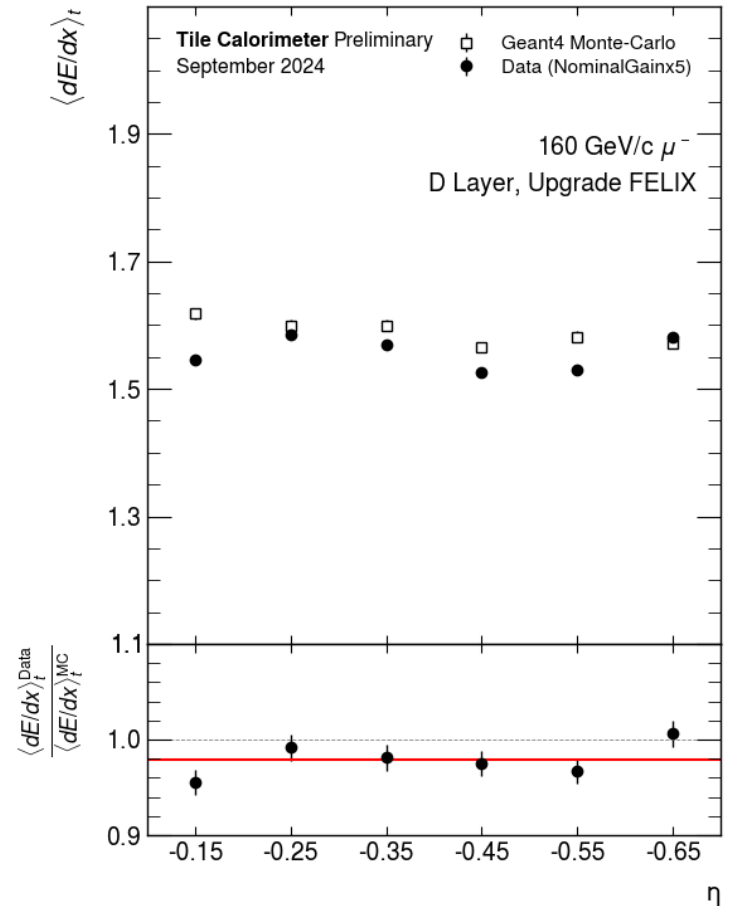
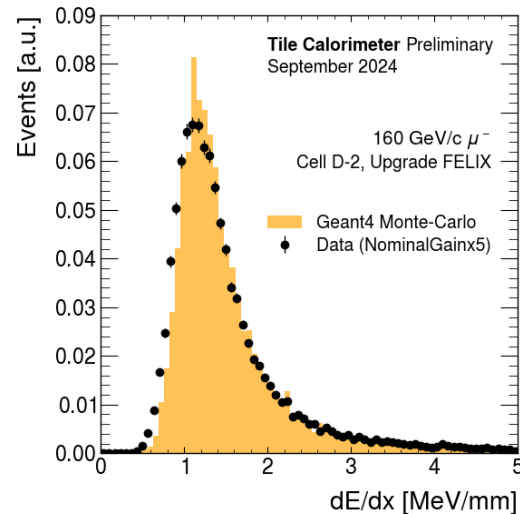
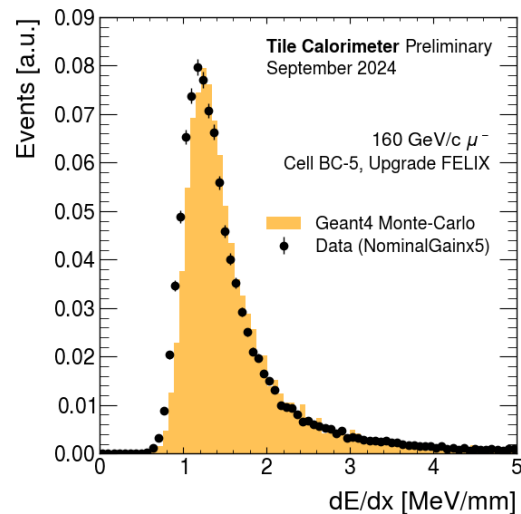
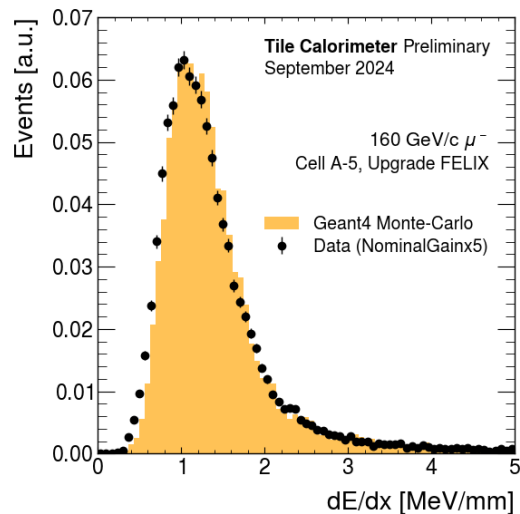
Muon Responses: Upgrade

- In the Upgrade module, **three gains** (NominalGains) were studied by adjusting the **PMT HV** per cell.
- **PMT gain generally doesn't have a large effect** on distributions unless looking at η values on the outside of the table.
- **Monte-Carlo agreement per cell within 5%.**



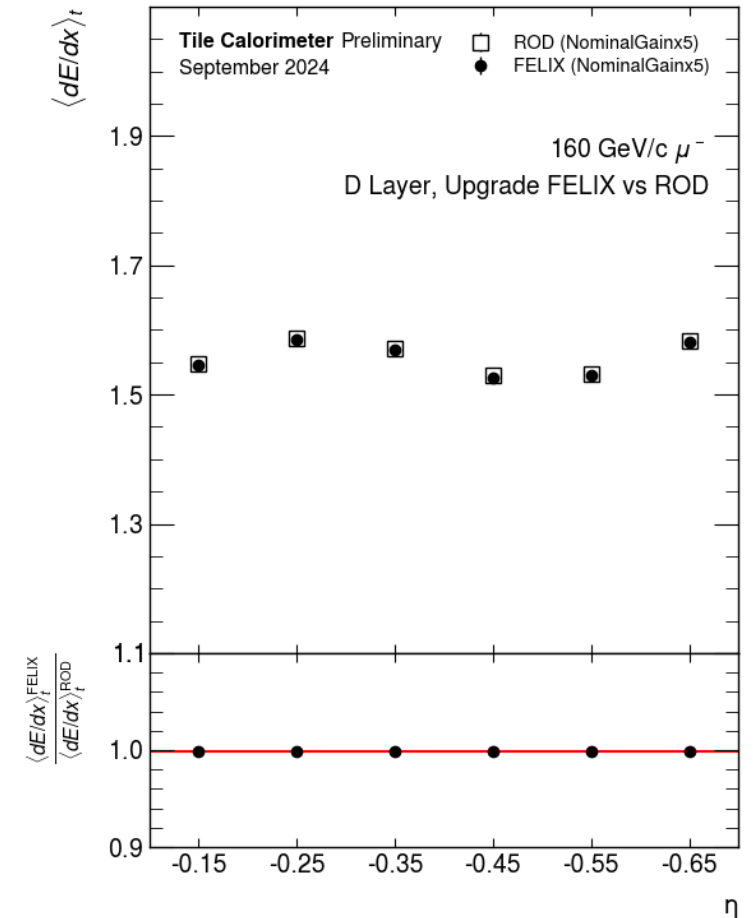
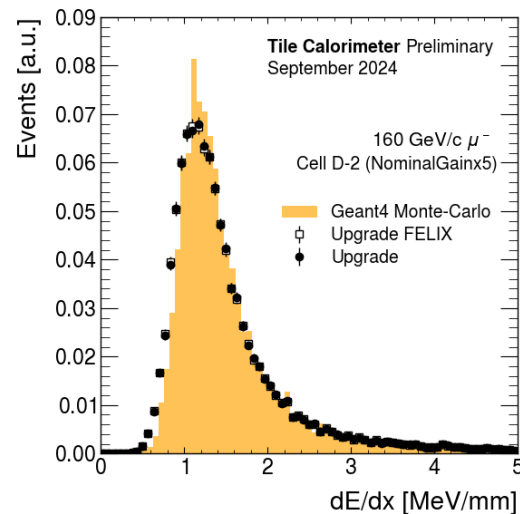
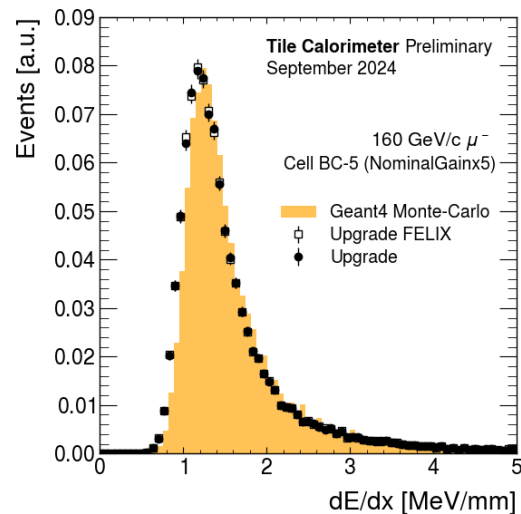
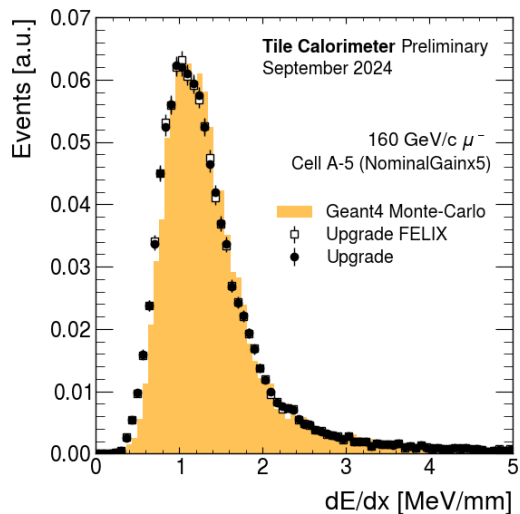
Muon Responses: Upgrade FELIX

- Similarly, the same process was repeated but instead using the FELIX readout system.
- **PMT gain does have a slightly larger effect on the FELIX readout, but it is still negligibly small.**
- **Monte-Carlo agreement per cell within 5%.**



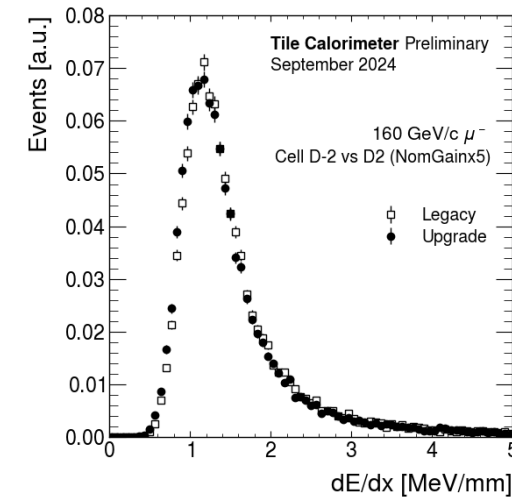
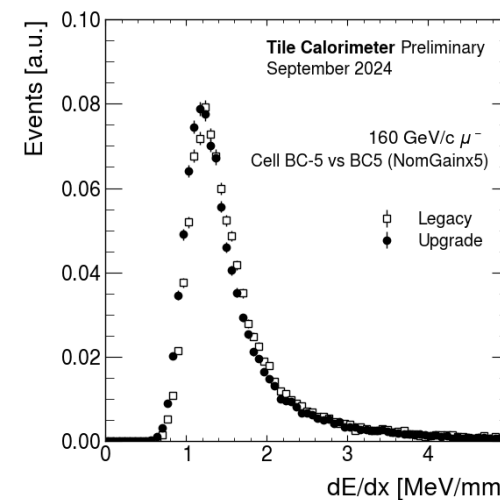
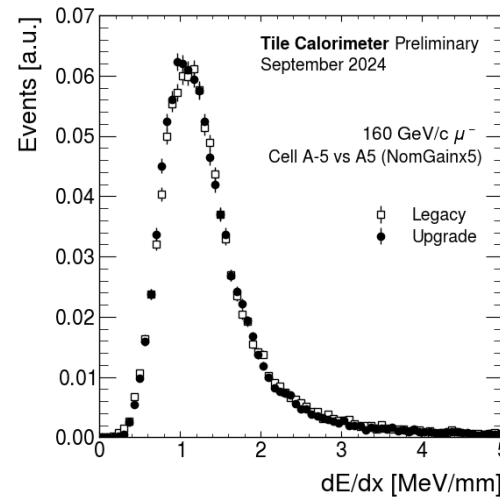
Muon Responses: Upgrade ROD vs FELIX

- Between the Upgrade ROD and FELIX systems, **most cells give the same if not nearly identical response, quantitatively.**
- **Differences in precision** between 10-bit (ROD) and 12-bit (FELIX) readout systems have **little effect** on the resulting **distributions or mean responses.**



Muon Responses: Legacy ROD vs Upgrade ROD

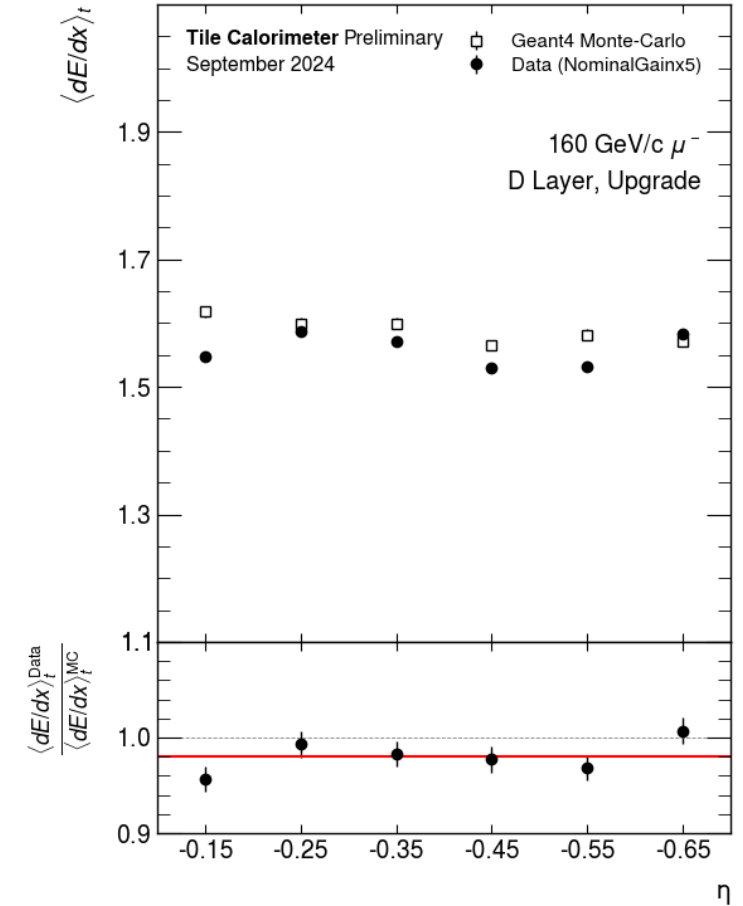
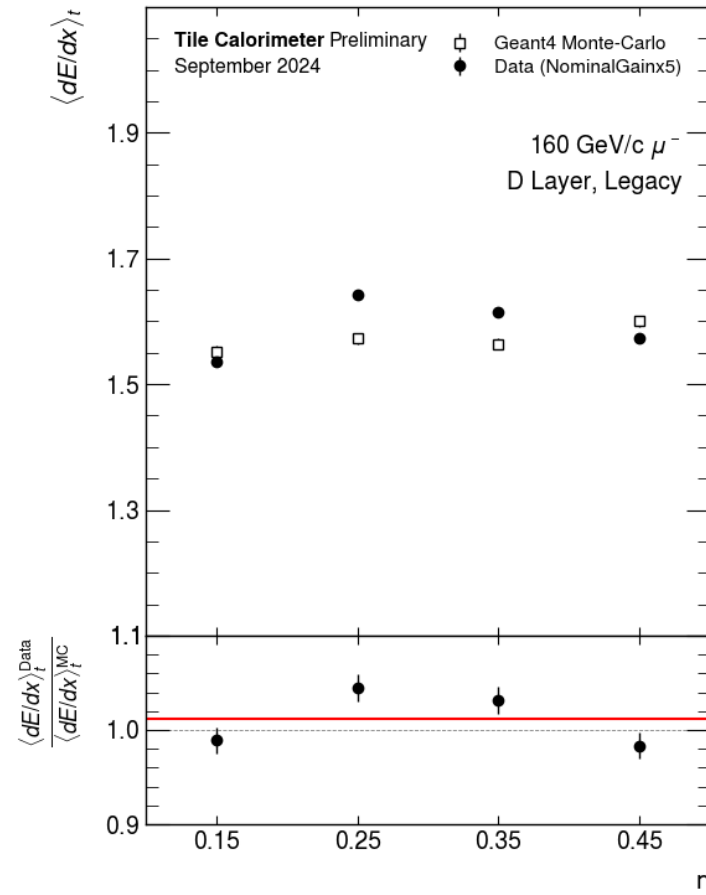
- Distributions of dE/dx for **Legacy** tend to have **slight variations in shape or location** (narrower, shifted right) for some cells compared to those of the Upgrade.
- However, **distributions from either electronic system are similar to one another overall.**



dE/dx response comparisons of the $\eta = \pm 0.45$ trigger tower cells A-5 (left), BC-5 (middle), and D-2 (right) for the Upgrade and Legacy readout systems, NominalGainx5.

Muon Responses in D-Layer: Legacy ROD vs Upgrade ROD

- **Per cell, agreement with Monte-Carlo is relatively the same:**
 - Legacy: 2-5%
 - Upgrade: 1-5%
- However, **overall average agreement is slightly different – Legacy electronics agree with Monte-Carlo more on average.**
- **A few possibilities** as to the explanation for this (miscalibration, photostatistic effects...).



Summary

- Performance studies were done on the Tile Calorimeter Test Beam to **validate the performance of Upgrade electronics in comparison to Geant4 Monte-Carlo and Legacy electronics** on-detector.
- In each standalone readout system of the **D-layer at NominalGainx5** (shown for demonstrative purposes), **results tend to be consistent throughout the layer** with good agreement in Monte-Carlo.
- **PMT gain changes do not have a significant effect on response distributions** for most cells in either Upgrade readout system.
- When comparing the Upgrade ROD and FELIX systems to Monte-Carlo, **results largely remain the same → loss of precision off-detector has little effect on response.**
- When comparing Upgrade and Legacy ROD systems to Monte-Carlo, the **differences are more pronounced**– this could be due to miscalibration of the D-layer, photostatistic effects not being well reproduced in Monte-Carlo, or beam conditions.

Thank you for your attention!