Gap/crack scintillators calibration in Run 3

K.Mosala (University of the Witwatersrand)

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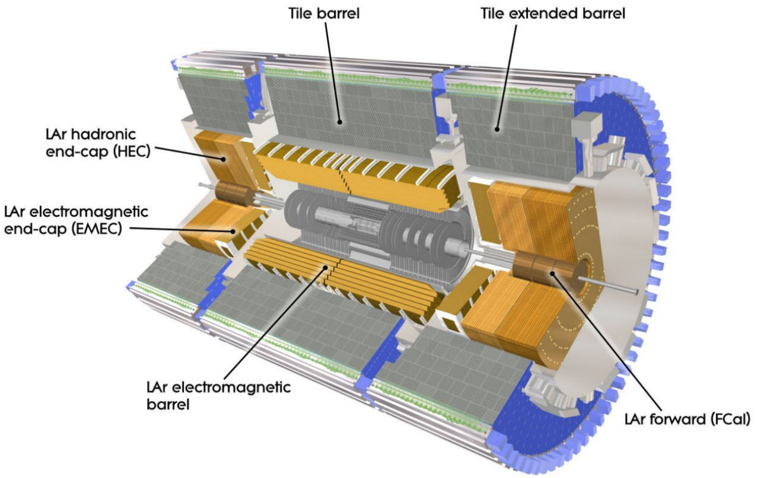
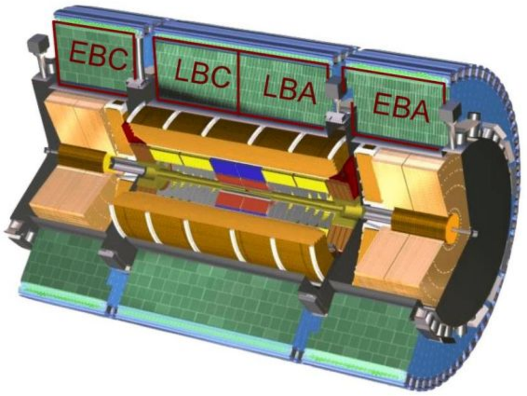
Introduction

- The ATLAS Tile Calorimeter (TileCal) is a hadronic sampling calorimeter that is used to measure the energy of hadrons and jets.
  - **Also, tau-lepton decay reconstruction, missing transverse energy reconstruction, muon identification and the Level-1 trigger.**
- TileCal sits in the outer hadronic calorimetry region of ATLAS, radially outside the LAr electromagnetic calorimeter, covering $|\eta| < 1.7$ across a central barrel and two extended barrels.





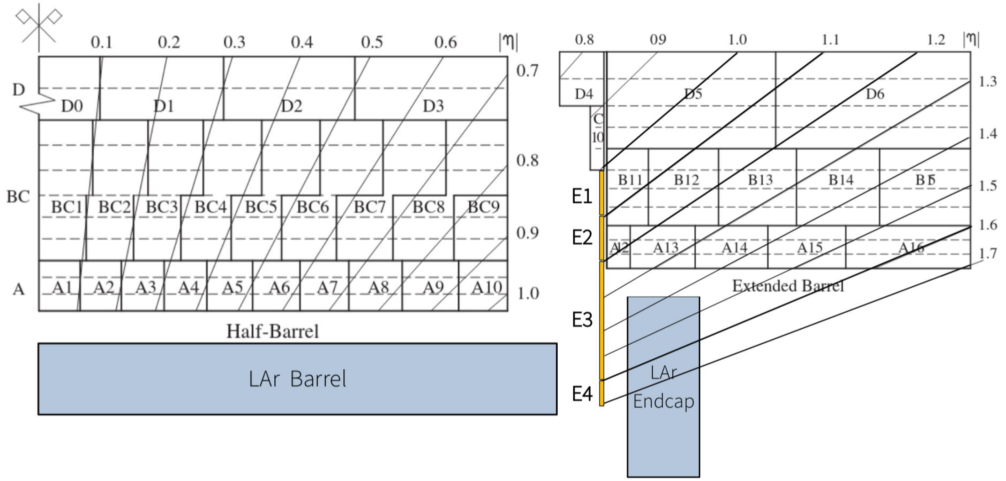
- Between the barrel and extended barrel there is a structural gap – the crack region ($1.0 < |\eta| < 1.72$) – where particles can lose energy to inactive material.
- Gap/crack scintillator cells (E1 - E4) sits in this transition region to recover some of that lost energy.
  - **All cells feed jet reconstruction; E3/E4 feed e/γ reconstruction ($1.4 < |\eta| < 1.72$)**

Motivation

- These gap/crack cells (E1-E4) are among the least well-understood regions of TileCal - geometrically complex, harder to model in simulation than main calorimeter body.

- Since all E-cells feeds jet reconstruction and E3/E4 feed e/γ reconstruction, mis-modelling/mis-calibration here propagates directly into jet energy scale and e/γ energy scale uncertainties – often leading systematics in precision ATLAS measurements.

- Run 3 conditions differ from Run 2, higher pileup, updated MC campaigns, revised detector conditions – previously derived calibration constants cannot be assumed to still hold.



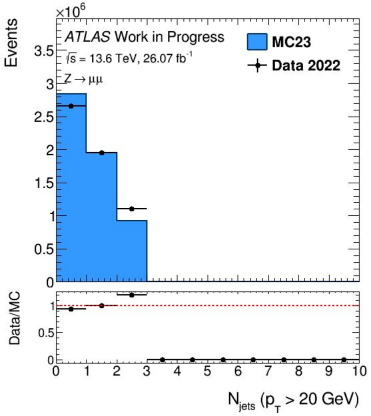
Data, MC Sample And Event Selection

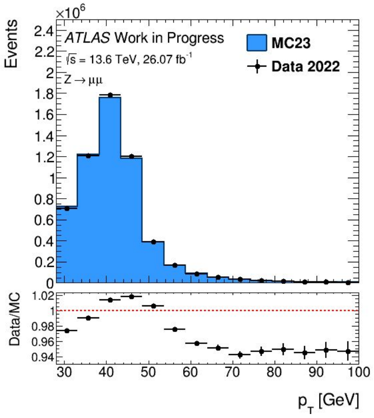
- **Data:**
  - **Data 2022 Physics_main** pp **collisions at** $\sqrt{s} = 13.6\ \mathrm{TeV}$

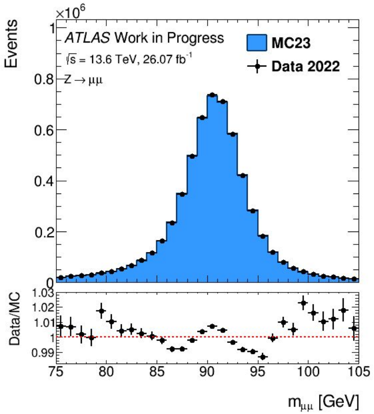
- **MC Samples:**
  - $Z \to \mu\mu$ **Events are used as main MC.**

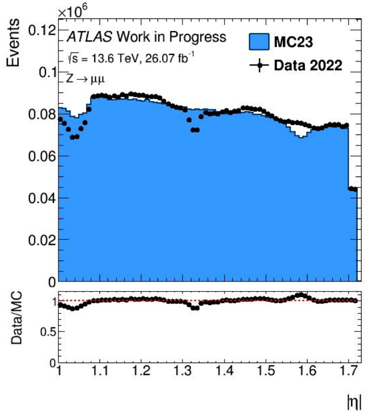
- **Event level Selection:**
  - **Trigger: HLT_mu24_invarmedium_L1MU14FCH)**
  - **Exactly 2 isolated muons**
  - **Leading muon** $\mathrm{p}_T > 28\ \mathrm{GeV}$
  - **Opposite-sign muon pair**
  - **Invariant Mass:** $75 \leq m_{\mu\mu} \leq 105\ \mathrm{GeV}$
  - **Pileup:** $20 \leq \langle \mu \rangle < 55$
  - **Jet Multiplicity:** $\mathrm{N}_{jets}(\mathrm{p}_T > 20\ \mathrm{GeV}) < 3$

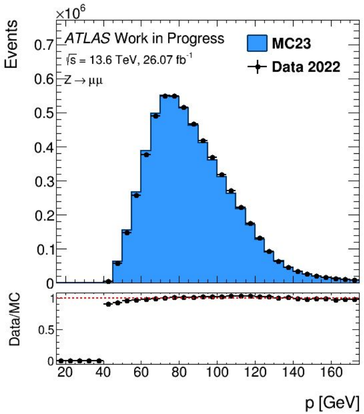
Data, MC Sample And Event Selection

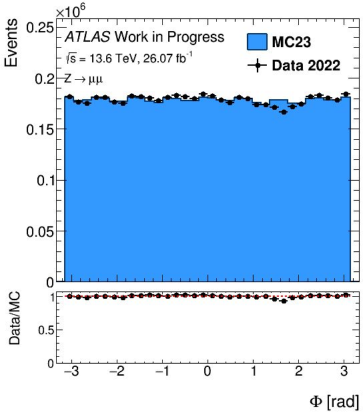




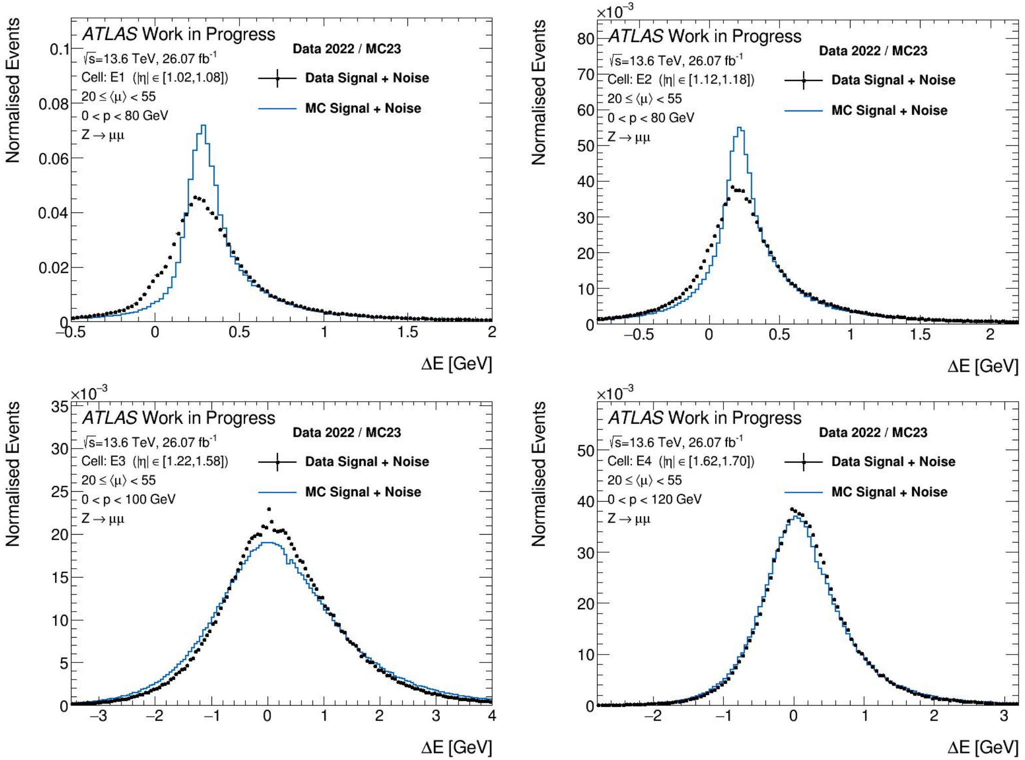








Results - Signal & Noise Separation



- For each event, cell energy is recorded in two angular distance from the muon track:
  - **Signal** $(\mathrm{d}\Phi < 0.045)$: cells the muon crossed – carries real energy deposit.
  - **Noise** $(0.15 < \mathrm{d}\Phi < 0.35)$: Nearby cells not crossed by the muon measures not only electrical but pileup noise as well.
- The distribution is dominated by the noise contribution near $\Delta\mathrm{E} \approx 0$:
  - **E1/E2** where noise-window statistics outweighs the muon energy deposit.
  - **E3/E4** noise contamination much larger.

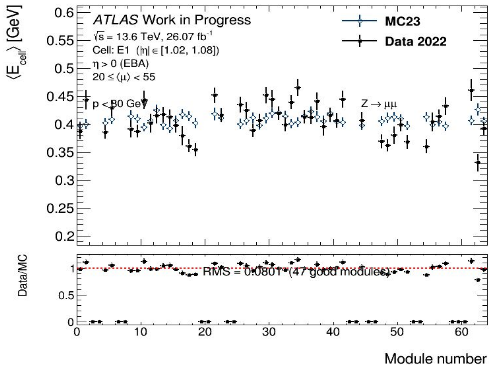
Uniformity Studies - The Method

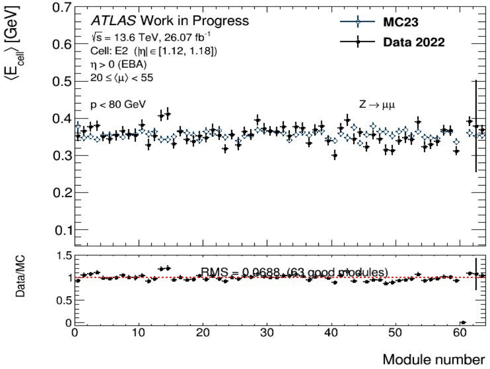
- The global energy scale for each E-cell type is defined as the average response across all modules, excluding outliers.
- **Step 1**: Merged E1 modules: certain E1 module pairs share a single PMT readout and are expected to have systematically lower response than standalone modules; these modules are excluded from both Data and MC before any further study:
  - **EBA E1**: 3,4 / 7,8 / 20,21 / 24,25 / 43,44 / 46,47 / 53,54 / 59,60
  - **EBC E1**: 3,4 / 7,8 / 18,19 / 24,25 / 43,44 / 46,47 / 53,54 / 59,60
- **Step 2**: Outlier detection: with merged-E1 modules already zeroed out, remaining non-zero module responses are tested via a modified Z-score:
  - Median and median absolute deviation (MAD) computed over nonzero modules.
  - Modified Z-score = 0.6745 x (response - median) / MAD
  - Modules with |Z| > 3.5 flagged and excluded.

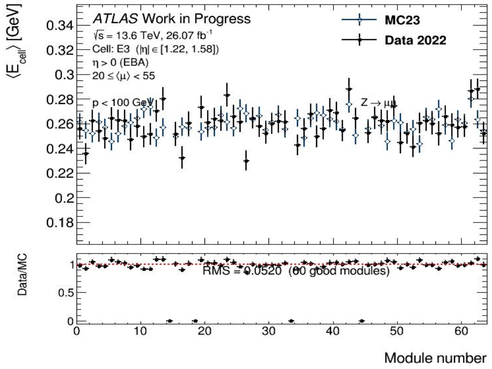
Cell	**Side**	**Reason**	**Count**	**Module numbers (1-based)**
$E1$ $\lvert\eta\rvert \in [1.02, 1.08]$				
$E1$	EBA	Merged (both data & MC)	16	3, 4, 7, 8, 20, 21, 24, 25, 43, 44, 46, 47, 53, 54, 59, 60
$E1$	EBC	Merged (both data & MC)	16	3, 4, 7, 8, 18, 19, 24, 25, 43, 44, 46, 47, 53, 54, 59, 60
$E1$	EBA	Outlier (data $\cup$ MC)	1	61
$E1$	EBC	Outlier (data $\cup$ MC)	2	2, 58
$E2$ $\lvert\eta\rvert \in [1.12, 1.18]$				
$E2$	EBA	Outlier (data $\cup$ MC)	1	61
$E2$	EBC	Outlier (data $\cup$ MC)	2	2, 10
$E3$ $\lvert\eta\rvert \in [1.22, 1.58]$				
$E3$	EBA	Outlier (data $\cup$ MC)	4	15, 19, 34, 45
$E3$	EBC	Outlier (data $\cup$ MC)	7	2, 17, 18, 39, 52, 57, 58
$E4$ $\lvert\eta\rvert \in [1.62, 1.70]$				
$E4$	EBA	Outlier (data $\cup$ MC)	1	15
$E4$	EBC	Outlier (data $\cup$ MC)	2	18, 37

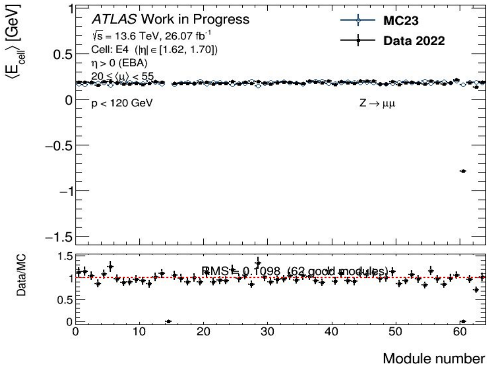
- Surviving “Good” modules define the reference set used for the per-cell RMS and Data/MC ratio shown in the next slide.

Results - Uniformity Studies: EBA



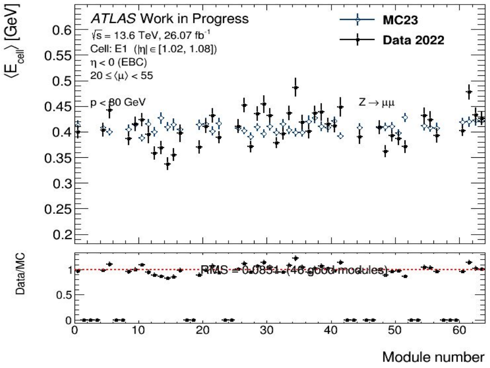


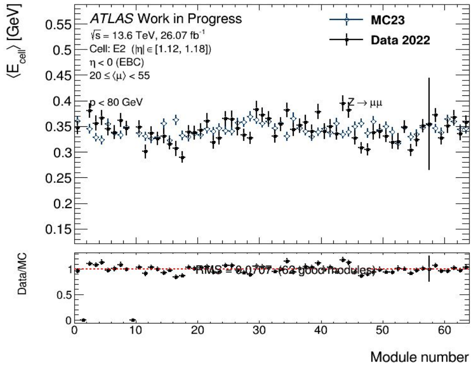


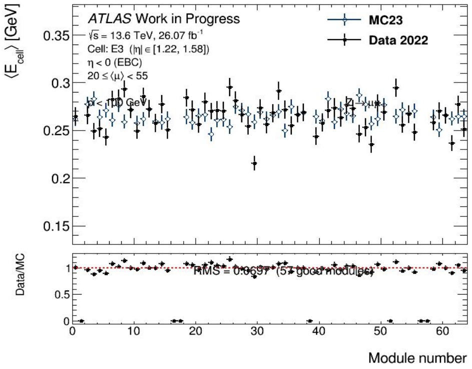


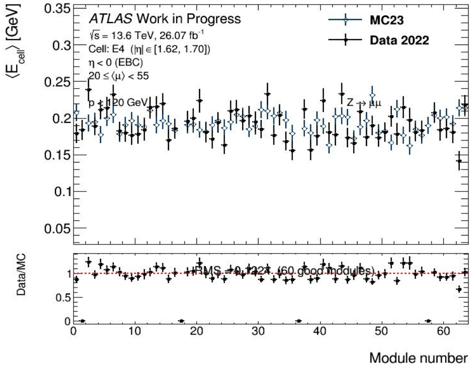
- ❑ $\langle E_{\text{cell}} \rangle$ Is measured per module (1-64) around the barrel, checking azimuthal uniformity –
- ❑ E1 shows the largest module-to-module scatter (RMS = 0.080, 47/64 good modules) – consistent with known dead /problematic modules near the 15-19 region.
- ❑ E2/E3 show the tightest Data/MC agreement (RMS = 0.069 and 0.052 respectively) – minimal scatter, most modules well behaved.
- ❑ E4 has one severely anomalous module (~ module 60) correctly excluded via outlier detection; remaining modules show good agreement (RMS = 0.110).

Results - Uniformity Studies: EBC









- E1 shows the largest scatter (RMS = 0.083,46/64 good modules) – consistent with the same dead/problematic module region seen on the EBA side.
- E2/E3 remain the most stable cells (RMS = 0.071 and 0.070 respectively) – though E3's RMS is noticeably higher on EBC than EBA.
- E4 shows the highest RMS of all four cells on this side (RMS = 0.122, 60/64 good modules) – slightly worse than EBA side.

Uniformity Studies – Truncated Mean

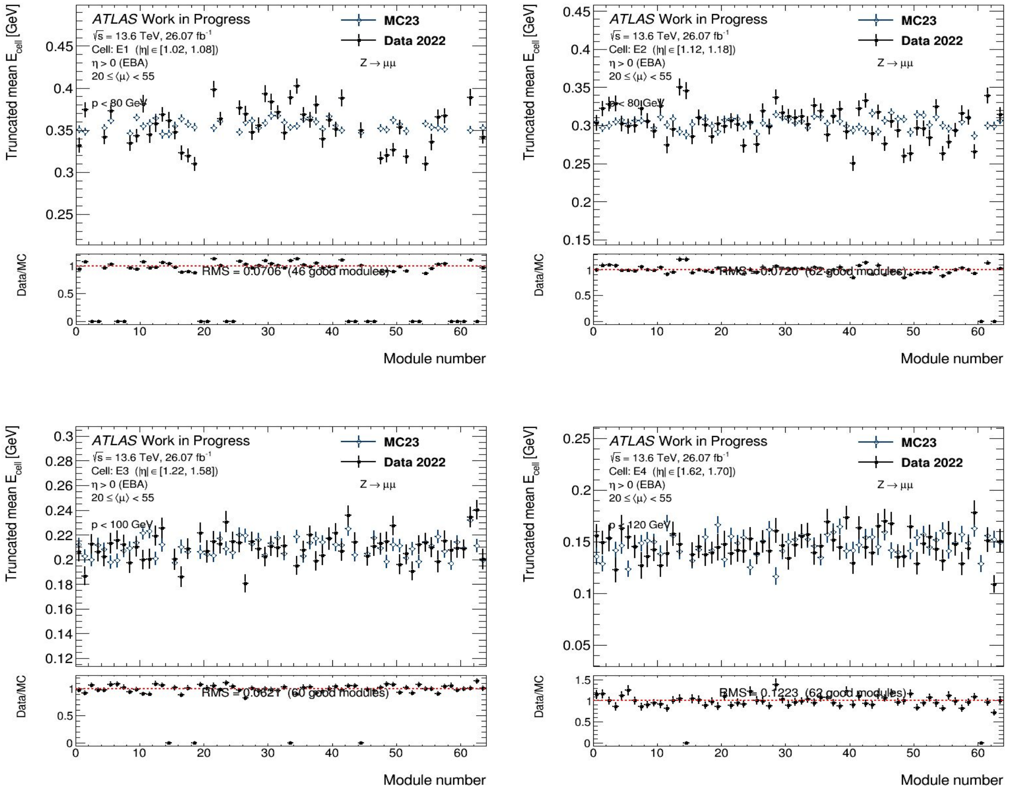
- Module-level response points show large statistical uncertainties, inflating the RMS score of the Data/MC ratio.
- Likely cause, rare high-energy muons losses (delta rays) populate the upper tail of the per-module $\Delta\mathrm{E}$ distribution, introducing large fluctuations in the mean.
- **Fix**: Replace the plain mean (Tprofile) with a truncated mean - the upper 1% of the $\Delta\mathrm{E}$ values per module is removed before averaging.
- The computed mean as (sum of retained 99%)/N, where N is the full sample size – this suppresses the outlier contribution rather than fully renormalizing after removing it.
- Applied identically to Data (unweighted) and MC (weighted-preserving), using the same 99% truncation criterion on $\Delta\mathrm{E}$ ordering in both.

$$\langle E_{\mathrm{cell}} \rangle_{\mathrm{trunc}} = \frac{1}{N} \sum_{i=1}^{\lfloor 0.99N \rfloor} \Delta E_i$$

$$\langle E_{\mathrm{cell}} \rangle_{\mathrm{trunc}}^{\mathrm{MC}} = \frac{\sum_{i=1}^{\lfloor 0.99N \rfloor} w_i \, \Delta E_i}{\sum_{i=1}^{N} w_i}$$

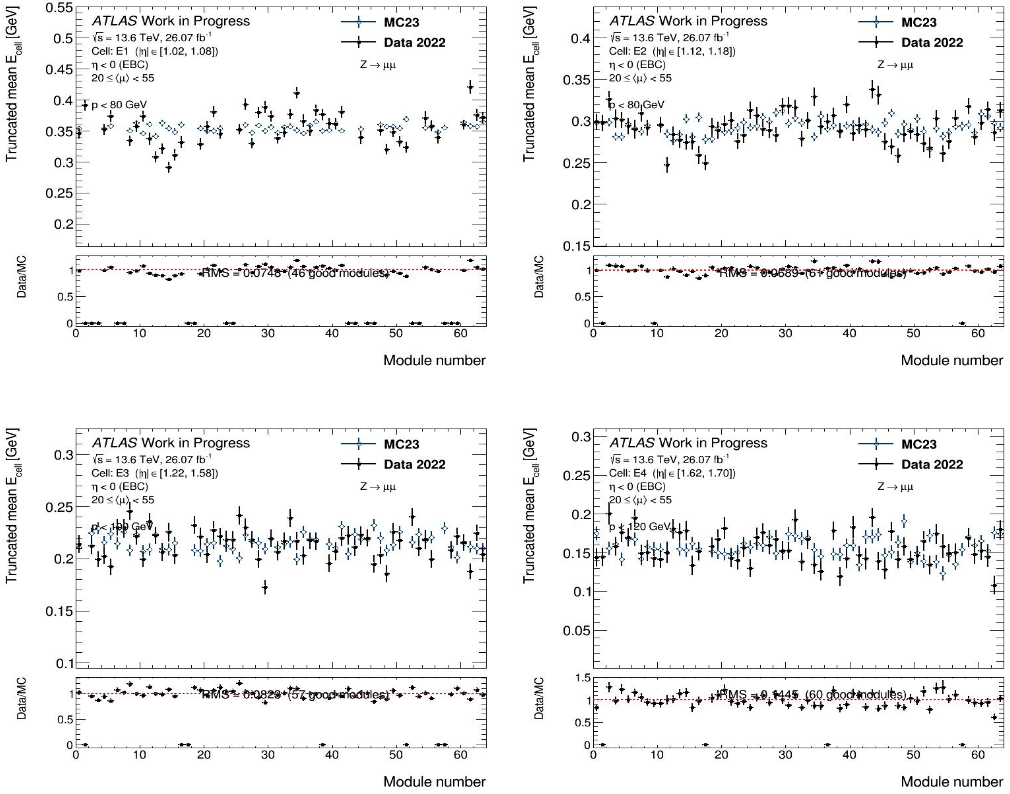
$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{\lfloor 0.99N \rfloor} \left(\Delta E_i - \langle E_{\mathrm{cell}} \rangle_{\mathrm{trunc}} \right)^2, \qquad \mathrm{err} = \frac{\sigma}{\sqrt{N}}$$

Uniformity Studies – Truncated Mean: EBA



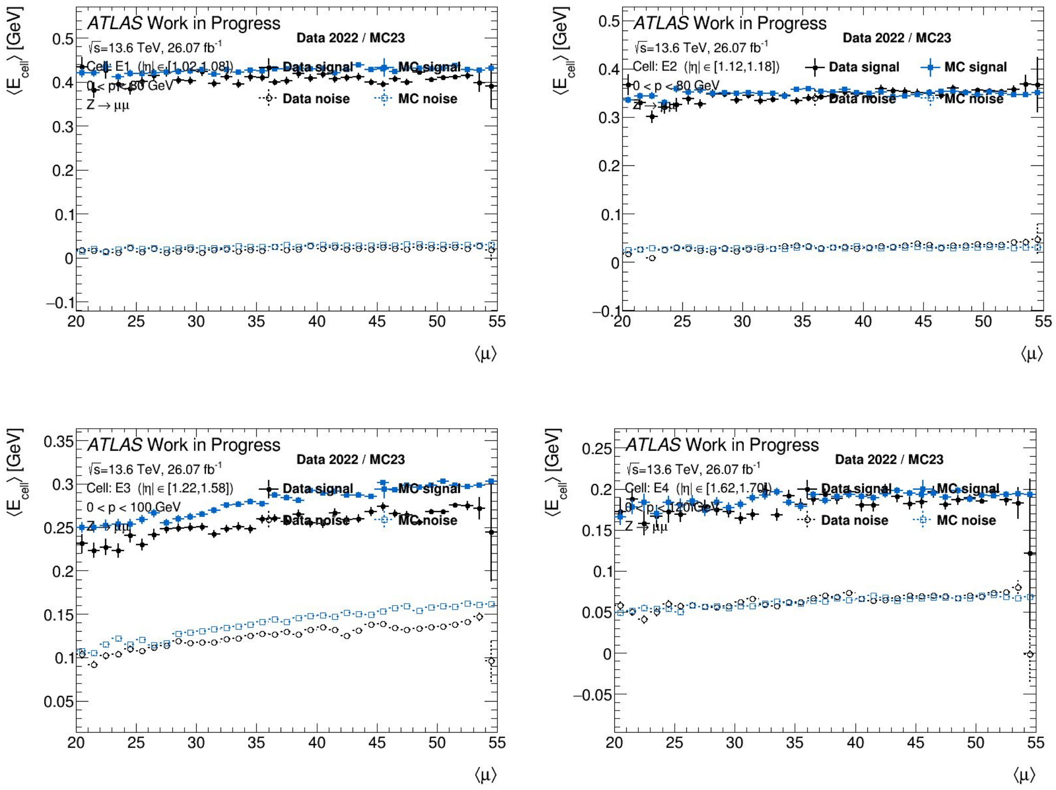
- Truncated mean (99% retained) applied per module, replacing the plain TProfile mean used previously.
- **E1** shows the expected improvement: RMS reduced from **0.080** to **0.071** – truncation is the most effective where the delta-ray tail is the largest.
- **E2**/**E3**/**E4** show a small RMS increase rather than a decrease, suggesting that truncation's benefit is cell-dependent, most relevant near the crack edge (**E1**) and less so further from it.

Uniformity Studies – Truncated Mean: EBC



- Same truncated mean (99% retained) applied per module, replacing the plain TProfile mean.
- **E1**/**E2** shows improvement: RMS reduced from 0.085 to 0.075 (**E1**) and 0.071 to 0.069 (**E2**) – truncation helps most where the delta-ray is the largest, which extends slightly further into **E2** on this side than on EBA.
- **E3**/**E4** shows a larger RMS increase than on EBA (**E3**: 0.070 to 0.083; **E4**: 0.122 to 0.145) – truncation appears to remove some genuine high-energy signal rather than just outlier noise in these cells.

Pileup dependence



- $\langle E_{\rm cell}\rangle$ (Signal + noise) measure vs $\langle \mu \rangle$ across the full 20 - 55 range, for both Data and MC23 (pileup-reweighted)
- Response depends on $\langle \mu \rangle$ meaning that the measurement is affected by the pileup noise.
- The pileup effect is larger for E3 and E4.
- In order to assess the data/MC agreement for the muon response we must extract genuine muon signal out of signal+noise.

Noise - Subtraction Methods

- Signal+noise (crossed-cell) response mixes real muon energy deposit with pileup-dependent noise.
- Noise level differs between Data and MC – a raw Data/MC comparison of crossed cells is contaminated by this mismatch.
- MC pileup reweighted to Data in all three methods before fitting/averaging.

Method 1

$$E_{\text{sig+noise}}(\mu) = a + b\,\mu \quad \text{(pol1 fit, Data and MC separately)}$$

$$\text{Data/MC} = \frac{a_{\text{Data}}}{a_{\text{MC}}} \quad \text{(noise removed implicitly via extrapolation to } \mu = 0\text{)}$$

Method 2

$$E_{\text{sig}}(\mu_i) = E_{\text{sig+noise}}(\mu_i) - E_{\text{noise}}(\mu_i)$$

$$E_{\text{sig}}(\mu) = a + b\,\mu \quad \Rightarrow \quad \text{Data/MC} = \frac{a_{\text{Data}}}{a_{\text{MC}}}$$

Method 3

$$\langle E_{\text{sig+noise}} \rangle = \frac{1}{N_{\text{bins}}} \sum_{i=1}^{N_{\text{bins}}} \langle E_{\text{cell}} \rangle_i$$

$$E_{\text{sig}} = \langle E_{\text{sig+noise}} \rangle - \langle E_{\text{noise}} \rangle \quad \Rightarrow \quad \text{Data/MC} = \frac{E_{\text{sig, Data}}}{E_{\text{sig, MC}}}$$

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Fitting the crossed-cell response as a function of pileup

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$$E_{\text{sig}}(\mu) = a + b\,\mu \quad \Rightarrow \quad \text{Data/MC} = \frac{a_{\text{Data}}}{a_{\text{MC}}}$$

Method 3

For each pileup bin, explicitly minus the noise-window measurement

$$\langle E_{\text{sig+noise}} \rangle = \frac{1}{N_{\text{bins}}} \sum_{i=1}^{N_{\text{bins}}} \langle E_{\text{cell}} \rangle_i$$

$$E_{\text{sig}} = \langle E_{\text{sig+noise}} \rangle - \langle E_{\text{noise}} \rangle \quad \Rightarrow \quad \text{Data/MC} = \frac{E_{\text{sig, Data}}}{E_{\text{sig, MC}}}$$

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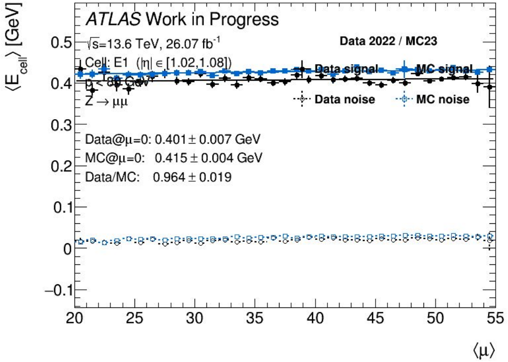
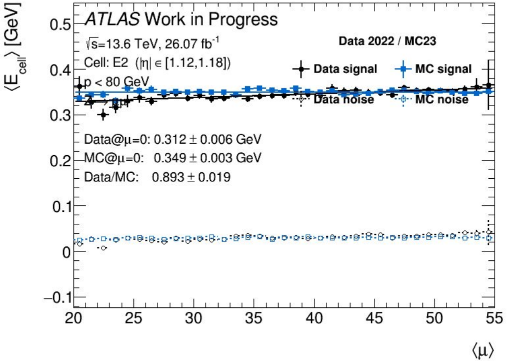
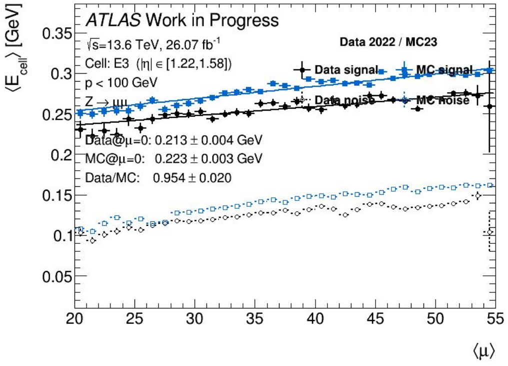
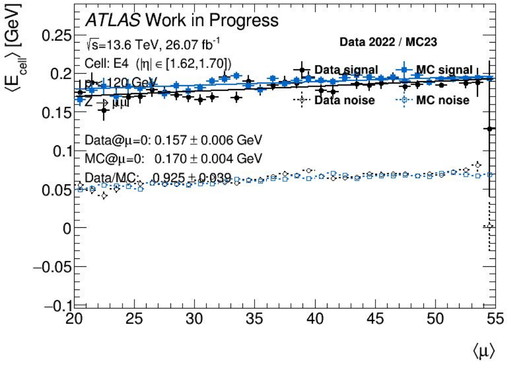
Rather than fitting a line, average noise across the full pileup range, minus from average signal-plus-noise

Noise - Subtraction Method 1



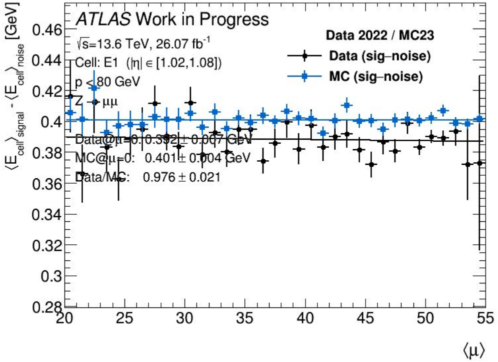


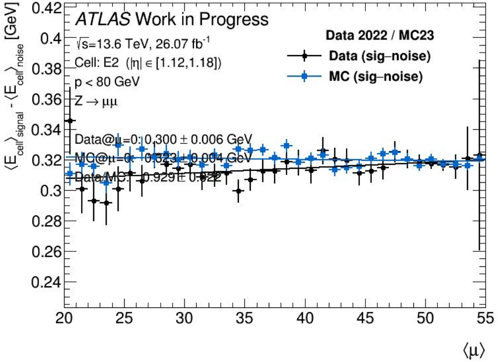


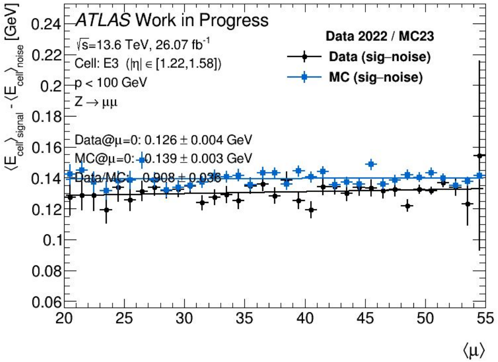


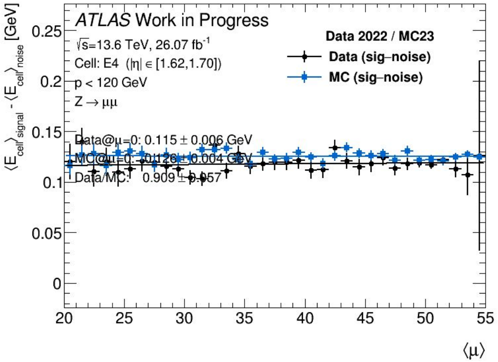
	E1	E2	E3	E4
Data @ μ=0	0.401 ± 0.007	0.312 ± 0.006	0.213 ± 0.004	0.157 ± 0.006
MC@ μ=0	0.415 ± 0.004	0.349 ± 0.003	0.223 ± 0.003	0.170 ± 0.004
Data/MC	0.964 ± 0.019	0.893 ± 0.019	0.954 ± 0.020	0.925 ± 0.039

Noise - Subtraction Method 2



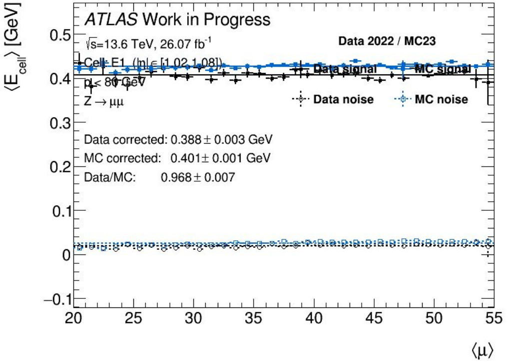


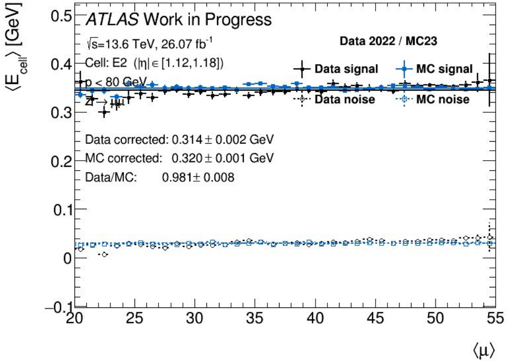


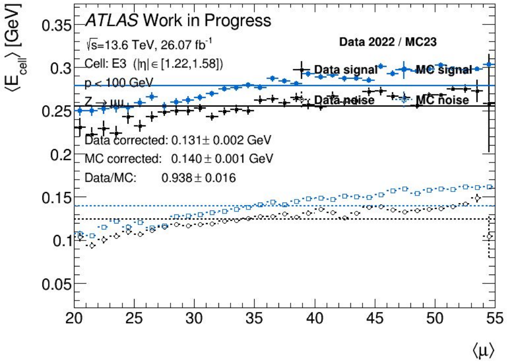


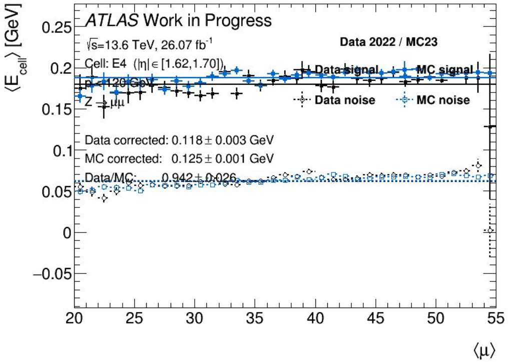
	E1	E2	E3	E4
Data @ μ=0	0.392 ± 0.007	0.300 ± 0.006	0.126 ± 0.004	0.115 ± 0.006
MC@ μ=0	0.401 ± 0.004	0.323 ± 0.004	0.139 ± 0.003	0.126 ± 0.004
Data/MC	0.976 ± 0.021	0.929 ± 0.022	0.908 ± 0.036	0.909 ± 0.057

Noise - Subtraction Method 3









	E1	E2	E3	E4
Data @ μ=0	0.388 ± 0.003	0.314 ± 0.002	0.131 ± 0.002	0.118 ± 0.003
MC@ μ=0	0.401 ± 0.001	0.320 ± 0.001	0.140 ± 0.001	0.125 ± 0.001
Data/MC	0.968 ± 0.007	0.981 ± 0.008	0.938 ± 0.016	0.942 ± 0.026

Noise - Subtraction Method: Summary

	E1: M1/M2/M3	E2: M1/M2/M3	E3: M1/M2/M3	E4: M1/M2/M3
Data @ μ=0	M1: 0.401 ± 0.007 / M2: 0.392 ± 0.007 / M3: 0.388 ± 0.003	M1: 0.312 ± 0.006 / M2: 0.300 ± 0.006 / M3: 0.314 ± 0.002	M1: 0.213 ± 0.004 / M2: 0.126 ± 0.004 / M3: 0.131 ± 0.002	M1: 0.157 ± 0.006 / M2: 0.115 ± 0.006 / M3: 0.118 ± 0.003
MC@ μ=0	M1: 0.415 ± 0.004 / M2: 0.401 ± 0.004 / M3: 0.401 ± 0.001	M1: 0.349 ± 0.003 / M2: 0.323 ± 0.004 / M3: 0.320 ± 0.001	M1: 0.223 ± 0.003 / M2: 0.139 ± 0.003 / M3: 0.140 ± 0.001	M1: 0.170 ± 0.004 / M2: 0.126 ± 0.004 / M3: 0.125 ± 0.001
Data/MC	M1: 0.964 ± 0.019 / M2: 0.976 ± 0.021 / M3: 0.968 ± 0.007	M1: 0.893 ± 0.019 / M2: 0.929 ± 0.022 / M3: 0.981 ± 0.008	M1: 0.954 ± 0.020 / M2: 0.908 ± 0.036 / M3: 0.938 ± 0.016	M1: 0.925 ± 0.039 / M2: 0.909 ± 0.057 / M3: 0.942 ± 0.026

Conclusions

- Measured Data/MC response ratios for TileCal gap/crack scintillator cells (**E1**-**E4**) using $Z \rightarrow \mu\mu$ collision muons, and the data from 2022 at $\sqrt{s} = 13.6$ TeV.
- Developed and validated three independent noise-subtraction methods to isolate the true crossed-cell (Signal) response from pileup-dependent noise contamination.
- The different data/MC ratios obtained with different methods indicates that we have a systematic uncertainty on the determination of Data/MC ratio of true signal.
- E1/E2 show the best agreement with MC (closest to unity); E3/E4 show consistent ~5-6% deficit across all three methods, pointing to a genuine cell-specific mismodeling rather than a noise-subtraction artifact.
- Module-level uniformity studies (truncated mean) confirm response stability across azimuth, with known dead/problematic modules identified and excluded.
- Results are stable across the full pileup range $(20 \leq \langle\mu\rangle < 55)$, validating the pileup reweighting procedure for Run 3 conditions.