The response of gap and crack scintillators of the Tile Calorimeter of the ATLAS detector to isolated muons from proton-proton collisions

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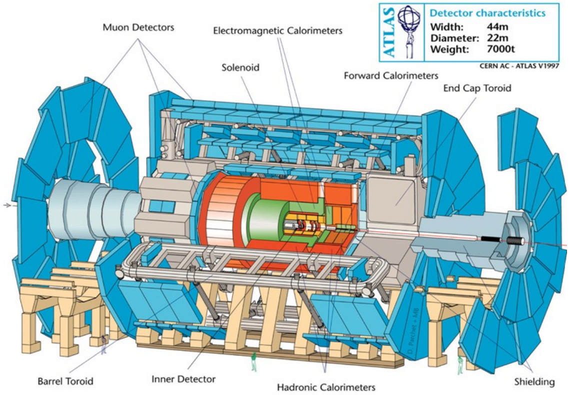
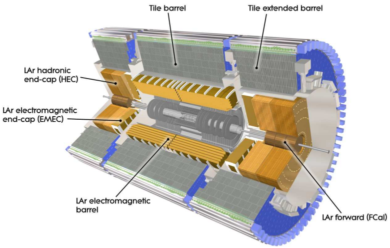
Overview

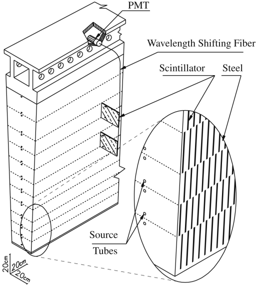
The ATLAS Detector at the LHC



- It is a general purpose detector.
- It is purpose-built for the precise measurement of known physics and for searching for physics Beyond the Standard Model.
- It is made of systems of tracking detectors and calorimeters.

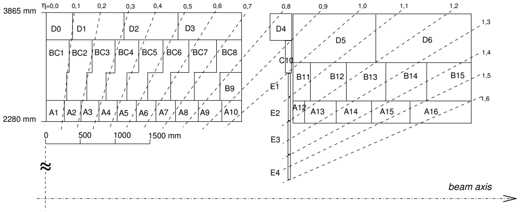
Layout of TileCal Cells.





- The Tile Calorimeter (TileCal) is made of a fixed central barrel and two moveable extended barrels.
- The TileCal is composed of 64 modules, made of alternating layers of iron as an absorbing medium and plastic scintillating tiles as the active medium

The ITC



- The Intermediate Tile Calorimeter (ITC) is a plug detector located gap region, in between the long and the extended barrels.
- It was designed to correct for energy lost in the passive material that fills the gap region.
- The gap/crack region is covered by the E1, E2, E3 and E4 scintillators.
- The gap scintillators are 12.7 mm wide and the crack scintillators are 6 mm wide

Response of gap and crack scintillators to isolated muons

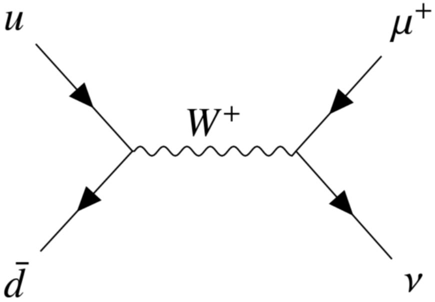
- Muons can traverse the whole calorimeter without loosing much of their initial energy.
  - Ideal particles to study the response of the TileCal cells.
- For muons with energies below 100 GeV, ionisation is the dominant energy loss mechanism.
- The ratio of the deposited muon energy and its path length in the cell ($\Delta E/\Delta x$) gives the response of the cell.

- This study uses muons originating from the $W \to \mu\nu_\mu$ events from proton-proton collisions observed the ATLAS detector.
  - The $W \to \mu\nu_\mu$ process was chosen for its large cross-section and a relatively clean experimental signature in the detector.
- The performance is evaluated in three data taking periods

Period	$\int \mathcal{L}dt$ [fb^{-1}]
2015 - 2016	36.2
2017	44.3
2018	58.5

- Three sets of Monte Carlo were generated to match pile-up conditions of the three data taking periods.
  - The W boson production was simulated with Sherpa event generator and PYTHIA8 was used for parton showering.

Object Reconstruction and Event Selection



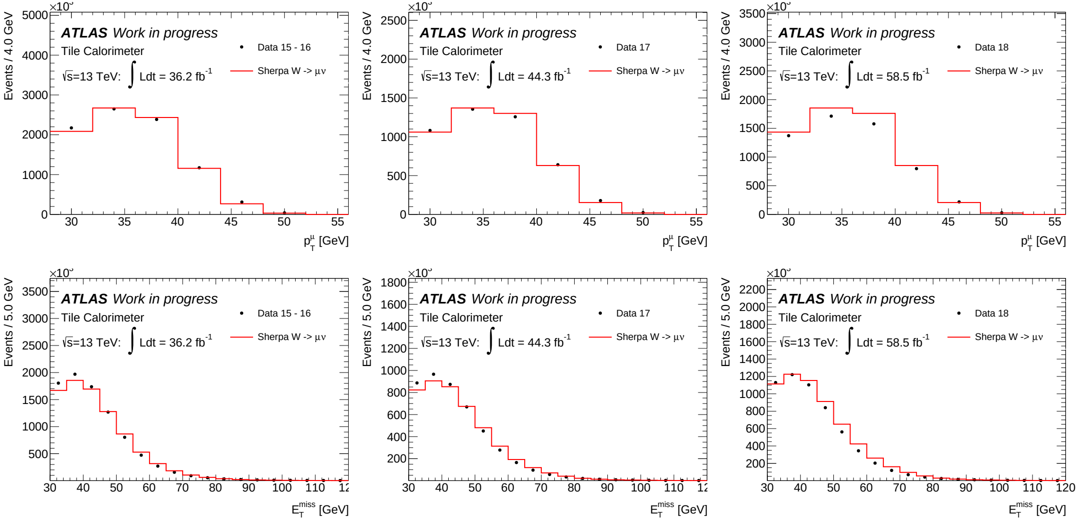
- A W^+ boson is created by interaction of up and antidown quarks.
- The interaction creates a single muon a neutrino
- The muon is reconstructed from the hits in the ID and MS
- The mysterious neutrino is reconstructed as the missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$

- The $W \rightarrow \tau\nu_\tau$ and $Z/\gamma* \rightarrow \mu^+\mu^-$ processes are the dominating electroweak processes
  - The $\tau \rightarrow \mu\nu_\mu$ process has a displaced τ vertex and low muon p_{T}

	Variable	Run 2 Requirement
1	Number of Muons	$\mathrm{N}_{\mathrm{muons}} = 1$
2	Transverse invariant mass	$40 < M_T < 140$ GeV
3	Missing transverse energy	$30 < E_T^{\mathrm{miss}} < 120$ GeV
4	Track isolation	$\sum p_T\|_{\Delta R=0.4} < 1$ GeV
5	Calorimeter isolation	$E_{\mathrm{LAr}}\|_{\Delta R=0.4} < 1.5$ GeV
6	Momentum of the muon	$p^\mu <= 80$ GeV
7	Transverse momentum of the muon	$p_T^\mu > 28$ GeV

- Quantum Chromodynamics multi-jet background processes contribute significantly to the total background.

Data - MC Comparisons



- The mismatch is primarily due to the background from multi-jet production.

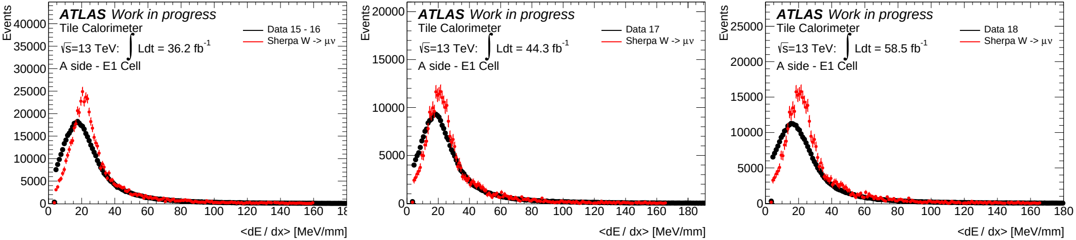
Cell Level Requirements

	Variable	Run 2 Requirement
1	Muon path length	E1, E2: $dx > 11$ mm; E3, E4: $dx > 5$ mm
2	Cell energy	$\Delta E > 60$ MeV
3	Track impact point	$\lvert\Delta\phi(\mu, \mathrm{cell})\rvert < 0.046$

Cell Response

- The cells' response is to be determine by computing the double ratio:

$$R \equiv \frac{< dE/dx >^{\mathrm{Data}}_{F=1\%}}{< dE/dx >^{\mathrm{MC}}_{F=1\%}}, \tag{1}$$



- The events are truncated minimise the effect of rare energy loss processes, such as bremsstrahlung or energetic δ rays.
- The double ratio R is used to estimate the calorimeter response.

ϕ-uniformity of the cell response

- For a cell c in a module m a Gaussian likelihood function is defined as:

$$\mathcal{L}_c = \prod_{m=1}^{64} \frac{1}{\sqrt{2\pi}\sqrt{\sigma_{c,m}^2 + s_c^2}} \exp\left[-\frac{1}{2}\frac{(R_{c,m} - \mu_c)^2}{\sigma_{c,m}^2 + s_c^2} \right], \quad (2)$$

  where $R_{c,m}$ and $\sigma_{c,m}$ are the observed R and its statistical uncertainty for a given cell in module m.
- The statistical uncertainty of $\sigma_{c,m}$ is given by the standard error of the mean of the dE/dx distribution.
- $-\log \mathcal{L}$ is minimised find $R_{c,m}$ and σ_c which are the $< R >$ and the systematic uncertainty attributed to the non-uniformity across the modules.

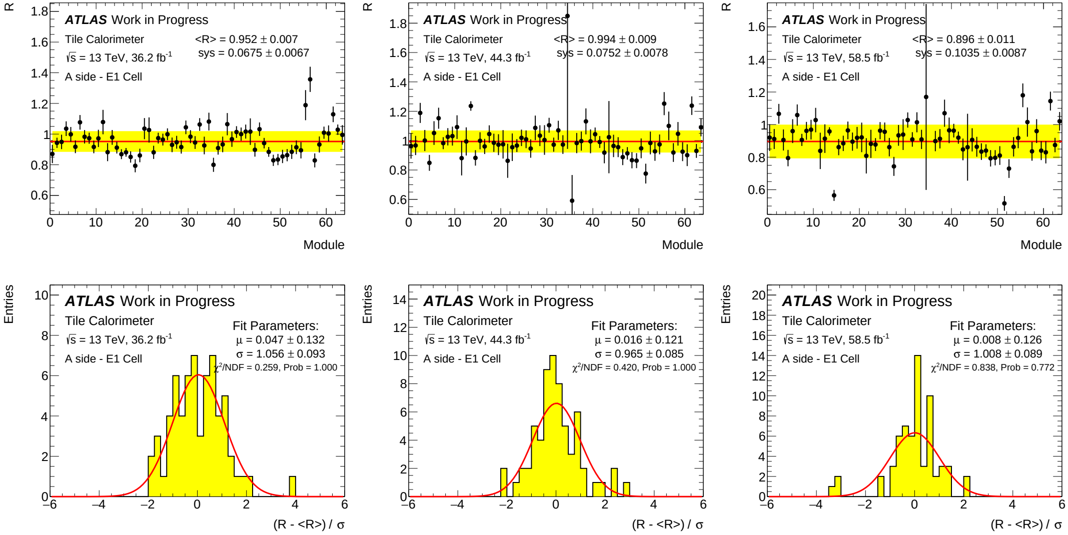
How to identify bad modules (On going)

- For module m in cell c we have,

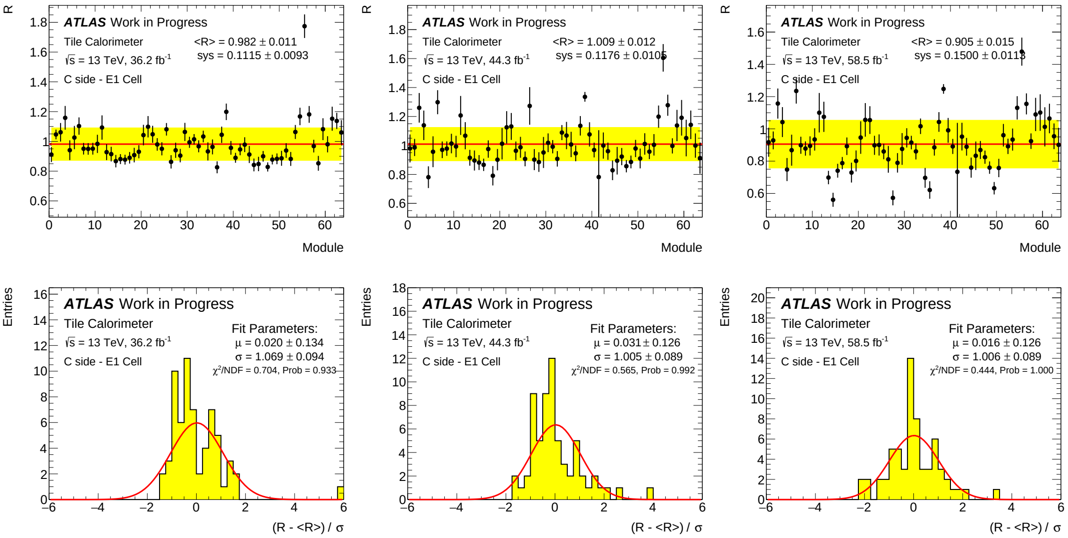
$$\Delta_{m,c} = \frac{R_{c,m} - < R >}{\sqrt{\sigma_{c,m}^2 + s_c^2}} \tag{3}$$

- It is expected that the pull will be Gaussian distributed with a mean of zero and a unit width.
- Cells observed to have a pull 3σ away from the mean will be listed as problematic and special attention will be paid to them.

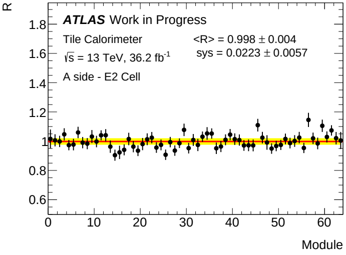
ϕ vs dE/dx in the E1 Cells on the A - side

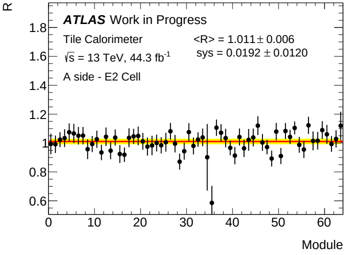


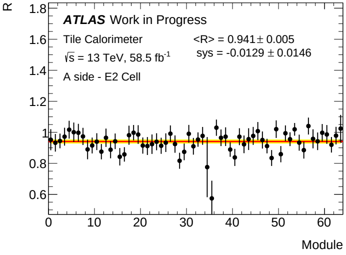
ϕ vs dE/dx in the E1 Cells on the C - side

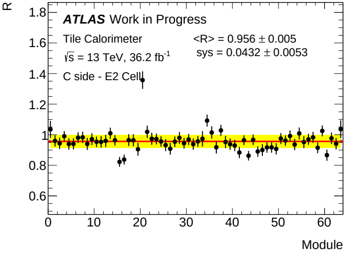


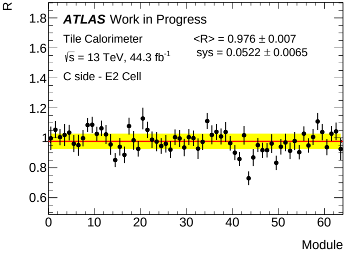
ϕ vs dE/dx in the E2 Cells

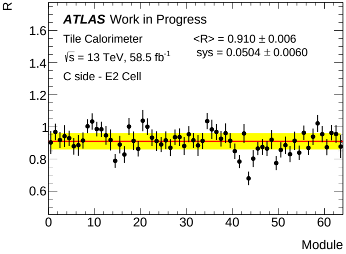




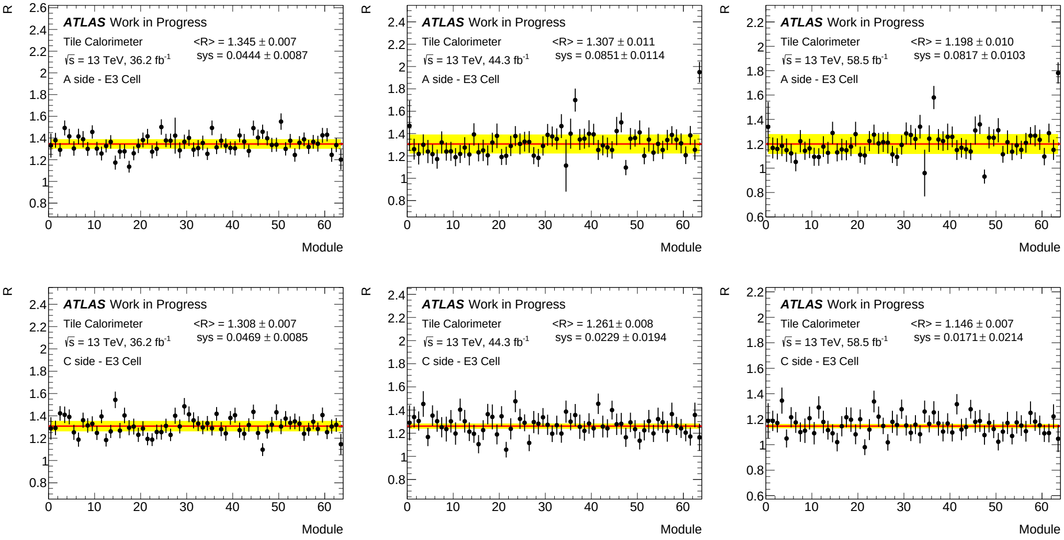




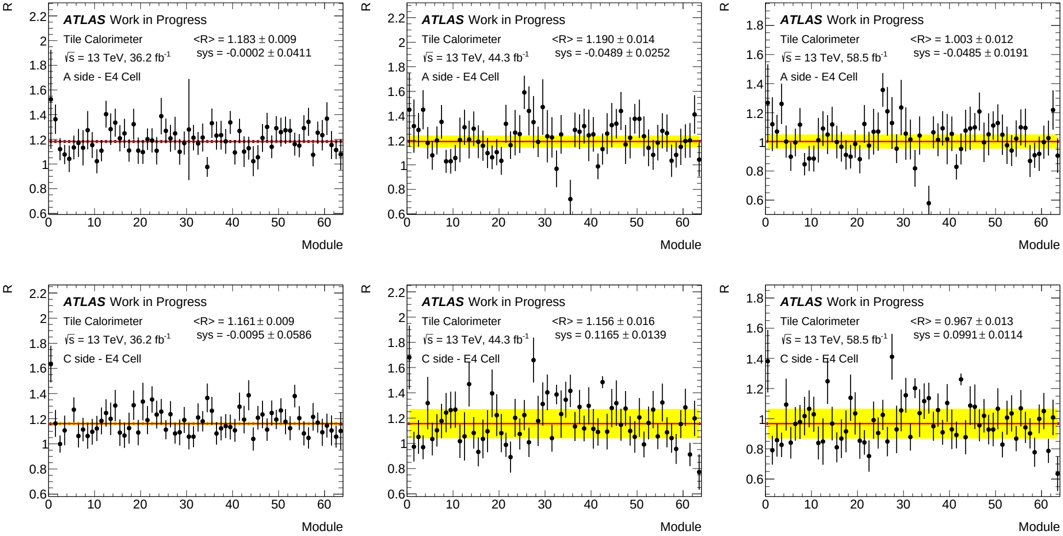




ϕ vs dE/dx in the E3 Cells



ϕ vs dE/dx in the E4 Cells



Summary of the results

	2015-16		2017		2018	
	<R>	syst	<R>	syst	<R>	syst
E1	0.952 ± 0.007	0.0675 ± 0.0067	0.994 ± 0.009	0.0752 ± 0.0078	0.896 ± 0.011	0.1035 ± 0.0087
E2	0.998 ± 0.004	0.0223 ± 0.0057	1.011 ± 0.006	0.0192 ± 0.0120	0.941 ± 0.005	0.0129 ± 0.0146
E3	1.345 ± 0.007	0.0444 ± 0.0087	1.307 ± 0.011	0.0851 ± 0.0114	1.198 ± 0.010	0.0817 ± 0.0103
E4	1.183 ± 0.009	0.0002 ± 0.0411	1.190 ± 0.014	-0.0489 ± 0.0252	1.003 ± 0.012	0.0485 ± 0.0191

	2015-16		2017		2018	
	<R>	syst	<R>	syst	<R>	syst
E1	0.982 ± 0.011	0.1115 ± 0.0093	1.009 ± 0.012	0.1176 ± 0.0105	0.905 ± 0.015	0.1500 ± 0.0113
E2	0.956 ± 0.005	0.0432 ± 0.0053	0.976 ± 0.007	0.0522 ± 0.0065	0.910 ± 0.006	0.0504 ± 0.0060
E3	1.308 ± 0.007	0.0469 ± 0.0085	1.261 ± 0.008	0.0229 ± 0.0194	1.146 ± 0.007	0.0171 ± 0.0214
E4	1.161 ± 0.009	0.0095 ± 0.0586	1.156 ± 0.016	0.1165 ± 0.0139	0.967 ± 0.013	0.0991 ± 0.0114

Summary and further steps

- Problematic modules 34 and 35 on the A-side are currently being looked at.
- E3 Cells show the most deviation from unity.
  - The E3 is positioned just in front of the A13 cells. Both receiving high dose of radiation (See Michaela Mlynarikova's talk)
- Modules that we masked at different periods during Run 2 will be excluded from the study

Thank You