Studies of the isolated hadron response with the projective eta configuration of the ATLAS Tile Calorimeter

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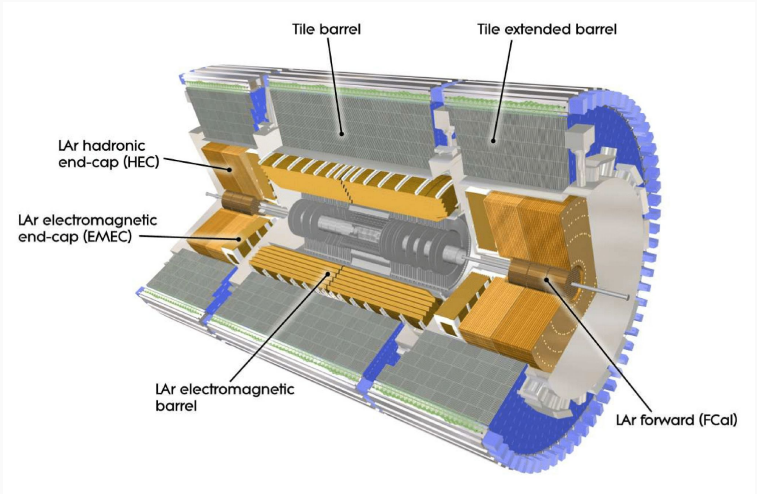
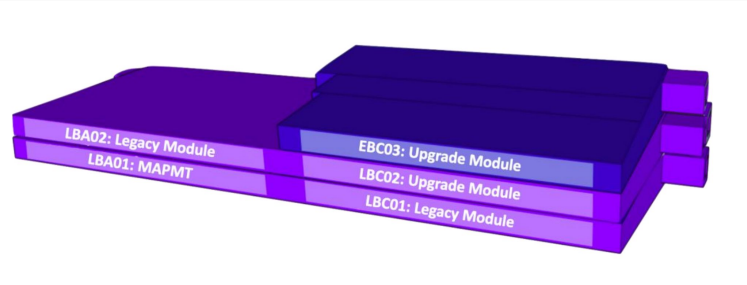
The ATLAS Tile Calorimeter

- The ATLAS Tile Calorimeter (TileCal) is the central hadronic calorimeter in ATLAS.
- Provides key inputs to jets and missing transverse momentum reconstruction.
- One barrel + two extended barrels; surrounds the LAr electromagnetic (EM) barrel and endcap calorimeters.



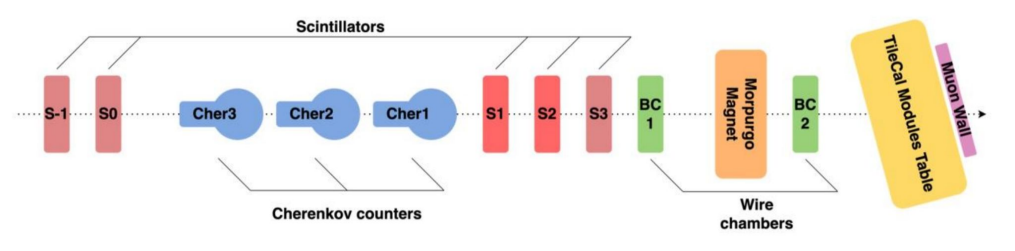
Motivation

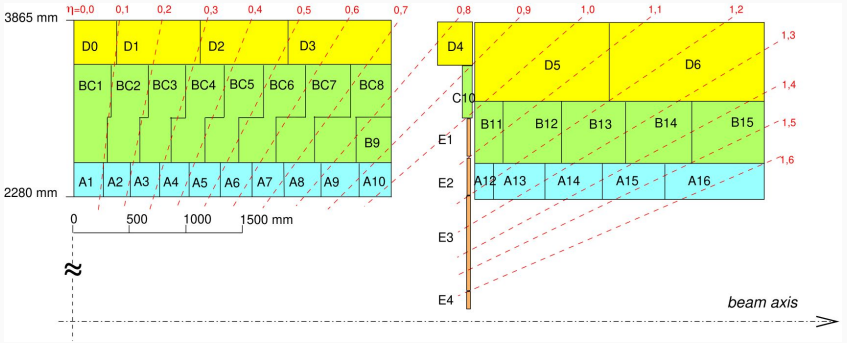
- The upgrade of the LHC to the High Luminosity-LHC (HL-LHC) is expected to increase instantaneous luminosity by a factor of up to 7.
- TileCal upgrade electronics must withstand higher radiation doses and meet new trigger/readout requirements.
- A stack of three modules TileCal equipped with upgraded front-end electronics for the HL-LHC has been exposed to beams at the SPS at CERN.
- Test-beam data provide controlled conditions (energy, particle ID, incidence angle).



Test Beam Campaign at CERN SPS

- Module scans performed using a movable table to vary η impact points.
- Modules were tested with various particle types (electrons, muons, hadrons) at different energies (10-180 GeV) and incident angles.
- Studies of Isolated-hadron response, energy-deposition patterns, and energy resolution were performed and compared with MC simulations.





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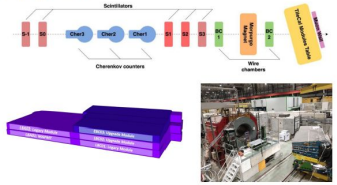
ATLAS EXPERIMENT

Motivation

▶ The upgrade of the LHC to the High Luminosity-LHC (HL-LHC) is expected to increase the instantaneous luminosity up to a factor of 7 [1].
▶ The ATLAS Tile Calorimeter (TileCal) upgrade electronics must withstand higher radiation doses and meet the increased data rate and precision.
▶ Test-beam data provide controlled conditions (energy, particle ID, incidence angle) to characterize response, resolution, and shower development.

Tile Calorimeter beam setup

▶ CERN SPS North Area facility: secondary beams 10–360 GeV; tertiary hadron beams formed with Cu/Al targets.
▶ The TileCal test beam serves to validate the upgraded electronics system and study calibration of new electronics.
▶ Modules LBA01, LBC01 and LBA02 are equipped with legacy electronics, modules LBC02 and EBC03 are equipped with HL-LHC upgraded electronics.
▶ Module scans performed using a movable table to vary η impact points.
▶ Modules were tested with various particle types (electrons, muons, hadrons) at different energies and incident angles.



Energy response and energy resolution

Definitions:

$$\text{Response } R \equiv \langle E_{\text{rec}}/E_{\text{beam}}\rangle,$$

$$\text{Resolution } \sigma(E_{\text{rec}}) = \text{RMS}\,(E_{\text{rec}}/E_{\text{beam}}).$$

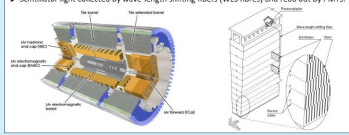
Resolution model:

$$\frac{\sigma(E_{\text{rec}})}{E_{\text{rec}}} = \frac{a}{\sqrt{E_{\text{beam}}}} \oplus b$$

where a is the stochastic term and b is the constant term (electronic noise neglected).
▶ TileCal is calibrated to the electromagnetic (EM) scale;
▶ The energy dependence of the resolution is quantified via fits and is consistent with previous TileCal test-beam studies [2].

ATLAS Tile Calorimeter

▶ TileCal is the central hadronic calorimeter in ATLAS.
▶ Provides key inputs to jets and missing transverse momentum reconstruction.
▶ One barrel + two extended barrels; surrounds the LAr electromagnetic (EM) barrel and endcap calorimeters.
▶ Three longitudinal layers (A, BC, D), segmented into projective cells with double readout by 2 photomultipliers (PMTs).
▶ Scintillator light collected by wave-length shifting fibers (WLS fibres) and read out by PMTs.

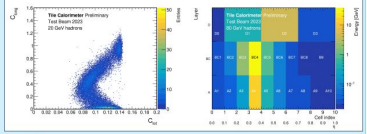


Test beam hadron data

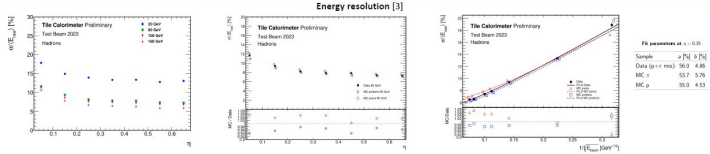
▶ Hadron beams are a mixture of pions and protons with population fraction that depends on the momentum.
▶ Data selections: events with a single particle are retained; electron and muon contamination are rejected.
▶ Monte-Carlo (MC) simulations: Geant4 v10.6.3, physics list FTFP_BERT; only energy cuts applied to MC where stated.
▶ Shower-shape variables are used for electron/hadron separation [2]: C_{long} quantifies early longitudinal energy fraction; C_{lat} measures the lateral energy spread across the considered cells. E_i^{raw} stands for the energy measured in a cell.

$$C_{\text{long}} = \frac{\sum_{i=1}^{3}\sum_{j=1}^{3}(E_i^{\text{raw}})_{ij}}{E_{\text{beam}}}$$

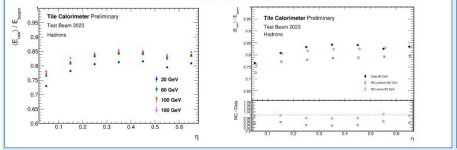
$$C_{\text{lat}} = \frac{1}{\sum_{i=1}^{N_{\text{cell}}}(E_i^{\text{raw}})_i} \times \sqrt{\frac{1}{N_{\text{cell}}}\sum_{i=1}^{N_{\text{cell}}}\left((E_i^{\text{raw}})_i - \frac{1}{N_{\text{cell}}}\sum_{i=1}^{N_{\text{cell}}}(E_i^{\text{raw}})_i\right)^2}$$



Energy resolution [3]



Energy response [3]



Summary and Next Steps

▶ A stack of three modules TileCal equipped with upgraded front-end electronics for the HL-LHC has been exposed to beams at the SPS at CERN.
▶ Preliminary studies of isolated-hadron response, energy-deposition patterns, and energy resolution were shown for projective incidence angles.
▶ Geant4 proton/pion pure beams simulations are used to guide MC/Data comparisons.
▶ Next steps:
  ▶ Study the beam composition estimates for a precise MC/Data comparison.
  ▶ Quantify systematics (energy scale, shower containment, calibration) to finalize results.

Reference: [1] ATLAS Collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter*, CERN, Geneva, CERN-LHCC-2017-019; ATLAS-TDR-028 (2017).
[2] P. Adragna *et al.*, "Testbeam studies of production modules of the ATLAS Tile Calorimeter," *Nucl. Instrum. Meth.* A 606 (2009) 362–394, doi:10.1016/j.nima.2009.04.009
[3] ATLAS Collaboration, *Public Tile Calorimeter Plots for Test Beam*, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileCalTestBeamResults#Hadrons (2026)

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