Studies of the response of the ATLAS Tile Calorimeter to beams of particles at the CERN test beams facility

Michaela Mlynarikova
On behalf of the ATLAS Tile Calorimeter Upgrade Team

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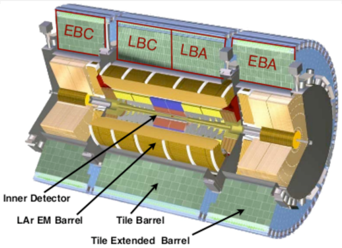
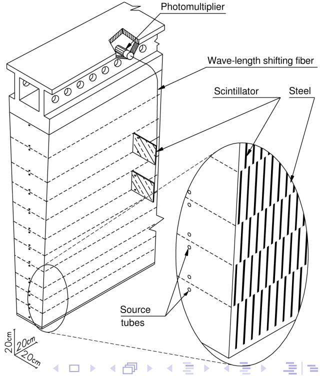
CHARLES UNIVERSITY
Faculty of mathematics
and physics

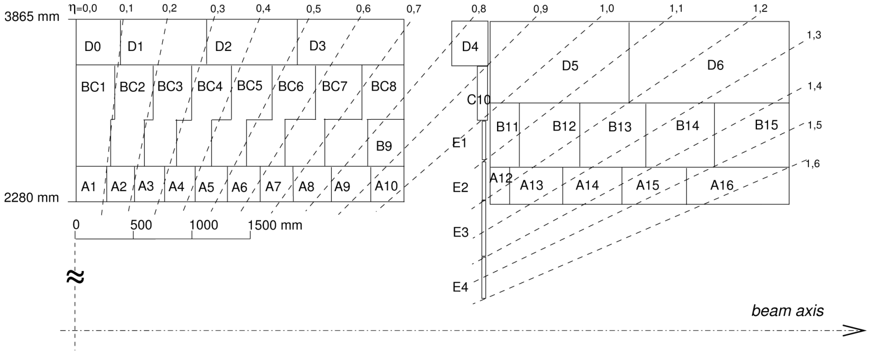
ATLAS Tile Calorimeter – Introduction

- Measures energies of hadrons, jets, τ-leptons and contributes to the E_T^{miss} reconstruction
- 4 partitions: EBC, LBC, LBA, EBA
  - LBC and LBA form Long barrel (LB) $\rightarrow$ coverage: $|\eta| < 1.0$
  - EBC and EBA form Extended barrel (EB) $\rightarrow$ coverage: $0.8 < |\eta| < 1.7$
- Each partition has 64 modules $\rightarrow$ to achieve full azimuthal coverage around the beam axis
  - One module hosts up to 48 photomultiplier tubes (PMTs)
- Sampling calorimeter built from plastic scintillator tiles and steel absorber plates
- A particle traversing the detector generates light in the scintillators, which is collected on both sides of the tile and further transported to the PMTs by wavelength shifting (WLS) fibres
- Around 10.000 readout channels





ATLAS Tile Calorimeter – Readout cells geometry



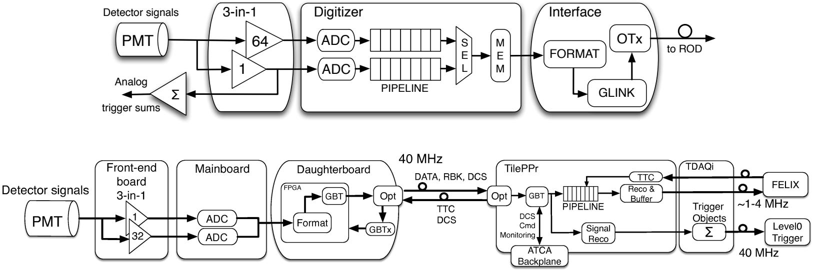
- The readout cell geometry is given by a group of WLS fibres from individual tiles coupled to PMTs
- Usually, a cell is read out by two PMTs, with each corresponding to a single channel
  - The cell energy is then reconstructed as the sum of energies measured by two channels
- The radial segmentation divides the module into three layers – A, BC (B in the EB), D
  - Layers comprise of cells with different dimensions
  - Dimensions of A and BC cells are $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
  - Dimensions of D cells are $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$

TileCal Phase II Upgrade

Complete replacement of on-detector and off-detector readout electronics for the High Luminosity LHC

- To be compatible with full digital TDAQ (analogue system will be replaced) and all information from the TileCal cells will be sent to the trigger system at 40 MHz
- Radiation and time ageing (will be 20x higher than legacy)
- Redundancy in data links and power distribution → Improvement in the system reliability

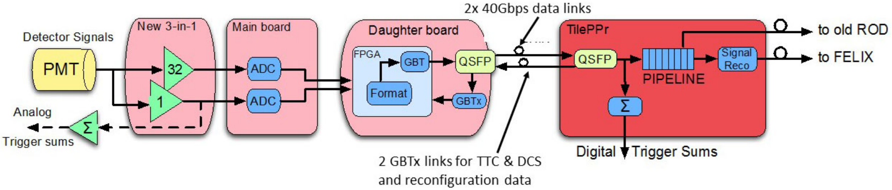
Top: current system (legacy). Bottom: upgraded system



- Shaping is done in the front-end board located in the PMT base, digitisation on the Mainboard, high-speed communications on the Daughterboard. The off-detector PPr processes and streams data to the DAQ system and trigger processors through the TDAQi module.

Demonstrator project and plans

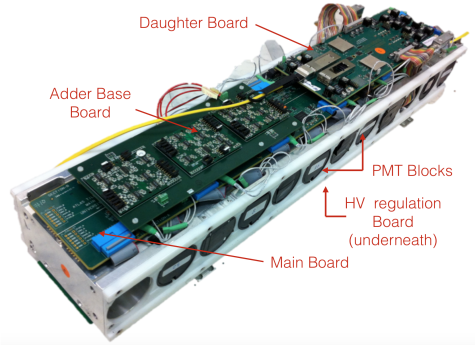
- Evaluation of the new readout schema and trigger system interfaces
- Showed a good performance and calibration during several test beam campaigns (TB)
- **A Demonstrator module was inserted into the ATLAS Detector in July 2019**
  - Fully integrated in the current system
  - Stable performance, low noise, good signals from calibration runs
  - Will operate in ATLAS during the Long Shutdown 2 and possibly Run 3
- Readout architecture for HL-LHC keeping backward compatibility with the legacy system
  - New 3-in-1 cards (FENICS): Provide analogue trigger signals to the current ATLAS trigger system
  - Physics and calibration data readout through the legacy Read Out Drivers (RODs) and the Front End Link Exchange (FELIX)



Demonstrator module

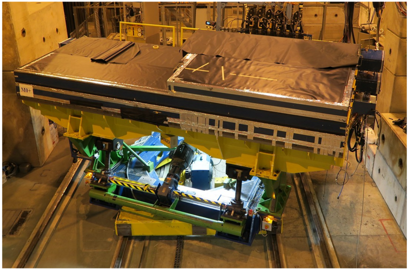
One module is composed of 4 mini-drawers (48 PMTs)
Each mini-drawer has 2 independent read out sections **for redundant cell readout**

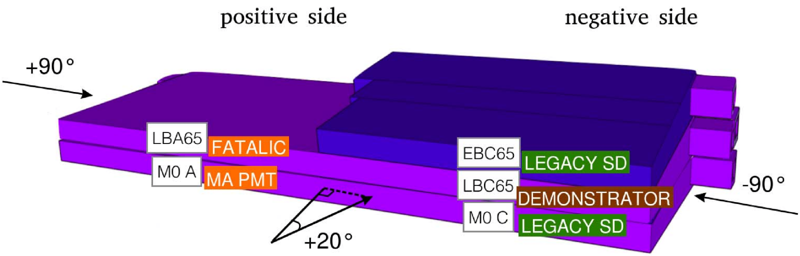
- 12 PMTs + 12 front-end boards reading out 6 TileCal cells
- 1 x MainBoard: provides low voltage and controls to the 3-in-1 cards, digitises their signals, and routes the data to the link DaughterBoard
- 1 x DaughterBoard: handles all high-speed communication with the back-end electronics preprocessor (PPr)
- 1 x High Voltage regulation board
- 1 x Adder base board + 3 adder cards: trigger analogue signals
- 1 x Low Voltage Power Supply (LVPS): low voltage power distribution



Test beam setup

- Located at the Super Proton Synchrotron (SPS) North Area – H8 beam facility
- Three detector modules equipped with legacy and upgraded electronics
  - **LBC65** with the Upgraded 3-in-1 cards → DEMONSTRATOR module
  - **LBA65** equipped with FATALIC (alternative to the 3-in-1 front-end option)
  - **MO C** and **EBC65** – Legacy SD
  - **M0 A** equipped with Multi-Anode (MA) PMTs





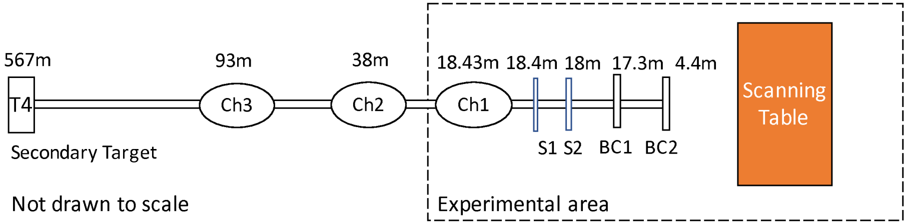
Beam Line

Beams produced by extracting 400 GeV protons from the SPS

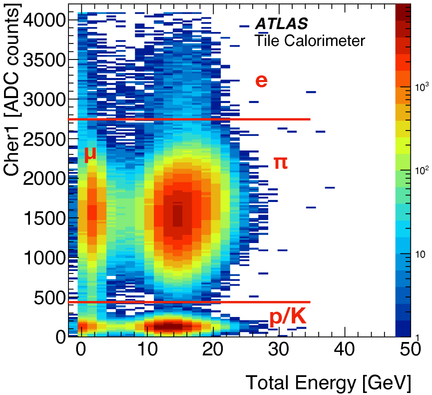
- Primary target (beryllium) $\rightarrow$ secondary beams with energies from 10 to 350 GeV
- Secondary target (polyethylene + lead absorber) $\rightarrow$ tertiary beams

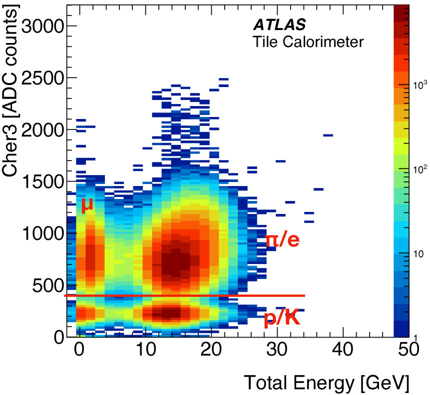
Beam line elements:

- **3 Cherenkov counters – Ch1, Ch2 and Ch3**
  - Separate $p/K/\pi/e$ for beam energy < 50 GeV
- **2 trigger scintillators – S1 and S2**
  - Used in coincidence to trigger the data acquisition and provide the trigger timing
- **2 wire chambers – BC1 and BC2**
  - Monitor the transverse beam profile



Cherenkov counters and particle identification





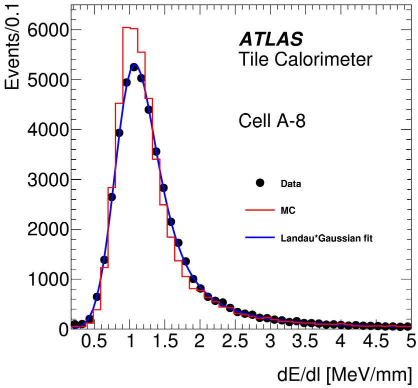
→ Scatter plot of the Ch1/Ch3 signals (left/right) vs. the energy measured in the calorimeter in the case of 18 GeV particle beams

Test beam results with:

- **Muons**
  - The high-energy muons available at the H8 beam-line traverse the entire TileCal modules for any angle of incidence, so we are able to **study of the module response** in great detail through their entire volume
  - The dominant energy loss process is the **ionisation** and the **energy lost is** essentially **proportional to the muon track path length**
  - Muons deposit approximately 300-600 MeV in TileCal cells
  - Muon data allows us to **verify the new electronics performance by checking the equalisation of the cell response**
- **Electrons**

Muons: Strategy

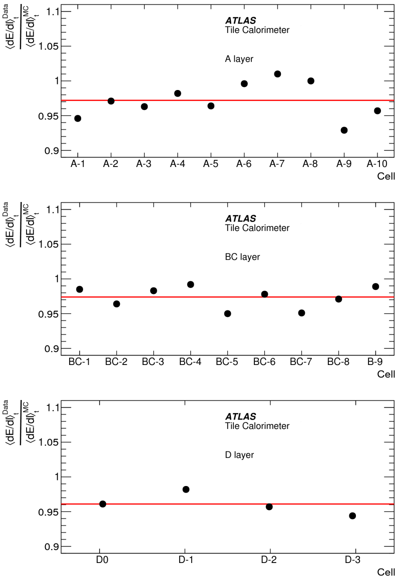
- The muon response has been studied determining the ratio between the energy deposited in a calorimeter cell (dE) and the track path-length in the cell (dl)
- The energy is obtained as the sum of the reconstructed energy in the each PMT of a cell
- To define the muon response we used a truncated mean, $\langle dE/dl \rangle_t$
  $\rightarrow$ preferred as it is less affected by rare high energy loss processes wrt the full mean
- The blue curve is a fit of Landau function, convoluted with a Gaussian, to the data



Cuts used to purify the muon beam:

- BeamChamber cuts: selecting correct region for response
- Cut on the total energy $E_{tot} <\sim 16$ GeV: to reject other particles in the beam
- At least one PMT with high signal ($E >\sim 0.06$ GeV): to reject false trigger muons

Muons: dE/dl vs. cell



- Furthermore, we measured the uniformity of the cells response in one layer
- The ratio of the experimental and simulated truncated means was defined for each calorimeter cell:

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

- The red horizontal lines - the mean values of dE/dl for each layer
- The data show a layer uniformity at 1% and a maximum offset of 4%

Test beam results with:

- Muons

- **Electrons**

  - Used to determine the **electromagnetic scale**
    - We measure signals of beam particles at known energies and calculate the average **charge-to-energy conversion factor** in pC/GeV

  - Used to verify the **linearity of the response vs. energy**

Electrons: Identification (I)

Particle beams at H8 beam facility are a mixture of electrons, hadrons and muons

- To **reject muons** we require the total measured energy to be $E_{tot} > 5$ GeV
- To **separate electrons/hadrons** we used two shower profile criteria, namely C_{long} and C_{tot}, which exploit the difference of electromagnetic and hadronic showers profiles in the calorimeter

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

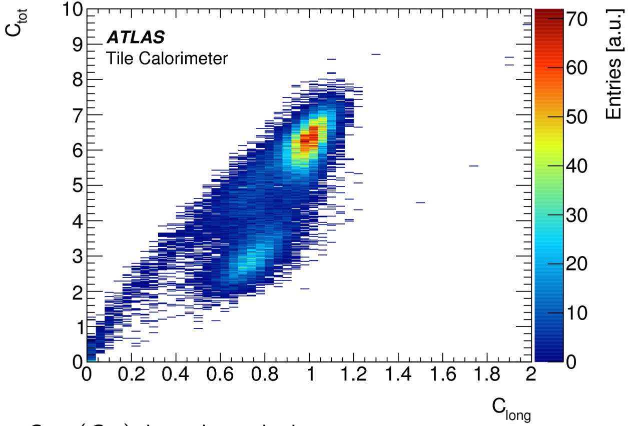
- C_{long} represents the fraction of energy deposited in the first two longitudinal layers
  - j runs over 3 adjacent cells of the layer i centred around the beam
  - E_{ij} is the energy measured in a cell

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

- C_{tot} measures the spread of the energy deposited in the calorimeter cells
  - E_c is the energy cell c
  - $N_{cell} = 9$ stands for the total number of cells considered
  - exponent $\alpha = 0.6$ was tuned using a MC simulation to achieve max e/had separation

Electrons: Identification (II)

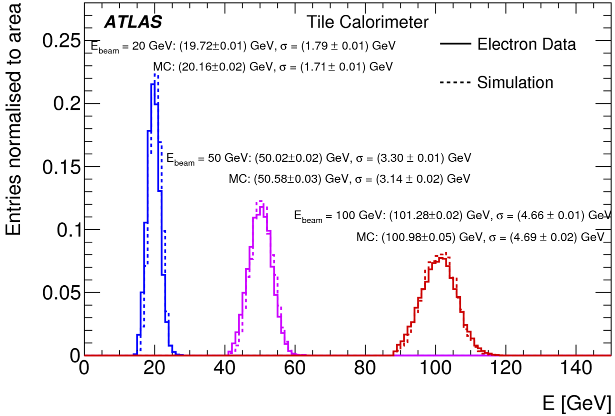
- Variables C_{long} and C_{tot} are used for electron/hadron separation
  - Example in the plot **50 GeV beam** hitting on the A4 cell
  - The region on the right/top corresponds to electrons, the other to hadrons



- The cut on C_{long} (C_{tot}) depends on the beam energy
  - ranges from 0.75 (2.1) at 20 GeV to 0.88 (6.5) at 100 GeV

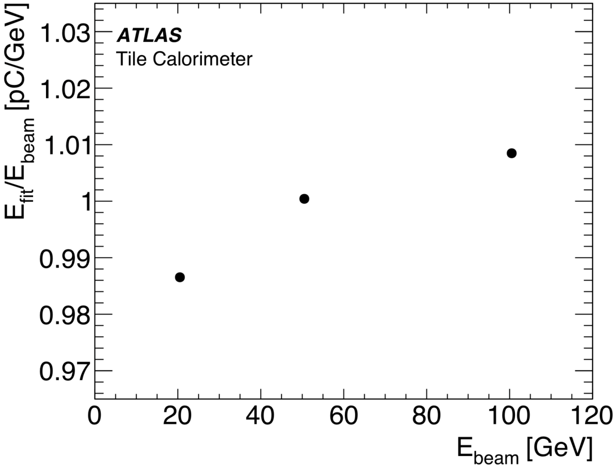
Electrons: Data vs. MC comparison

- Distributions of the total energy deposited in the calorimeter in case of electrons beams of 20, 50 and 100 GeV incident in the cell A4 are shown
- For a given beam energy the experimental and the simulated shapes are in good agreement proving the purity of the selected experimental electron samples.



Electrons: Response linearity

- The linearity of the calorimeter response to electrons was checked using electron beams with energies of 20, 50 and 100 GeV incident in the cell A4



Summary

- High Luminosity upgrade of the LHC plans to increase the instantaneous luminosity by a factor of 5-10
  - Electronics will have to withstand a much higher radiation dose as well as an increased demand for data throughput
  - Upgraded electronics will be installed during the LS 3 (2025 – mid-2027)
- Seven test beam campaigns during 2015 and 2018
  - Three TileCal modules equipped with the updated front-end electronics were exposed to the SPS beams at CERN
  - All prototypes extensively tested and showed a good performance
- Physics results obtained from the TB data confirm good performance of the new electronics
  - These results are in agreement with those obtained using the old electronics
- Demonstrator module was inserted in the ATLAS (end of July 2019)
  - Fully integrated in the current system
  - Showing good performance
  - Will operate during LS2 and possibly Run 3

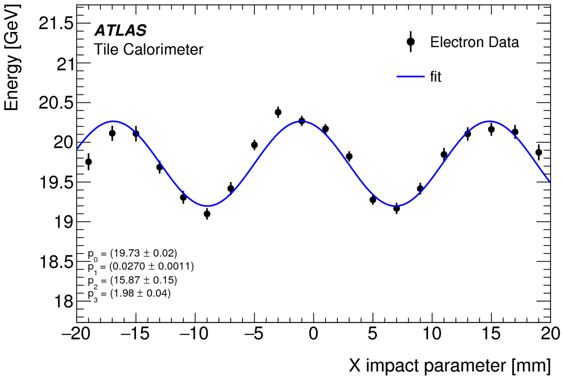
BONUS SLIDES

Electrons: Sampling fraction variation

- Due to the compactness of electromagnetic showers, the electron response varies with the periodicity of the sampling fraction and thus depends on the coordinate of the impact point along the x-axis of the front face of the calorimeter

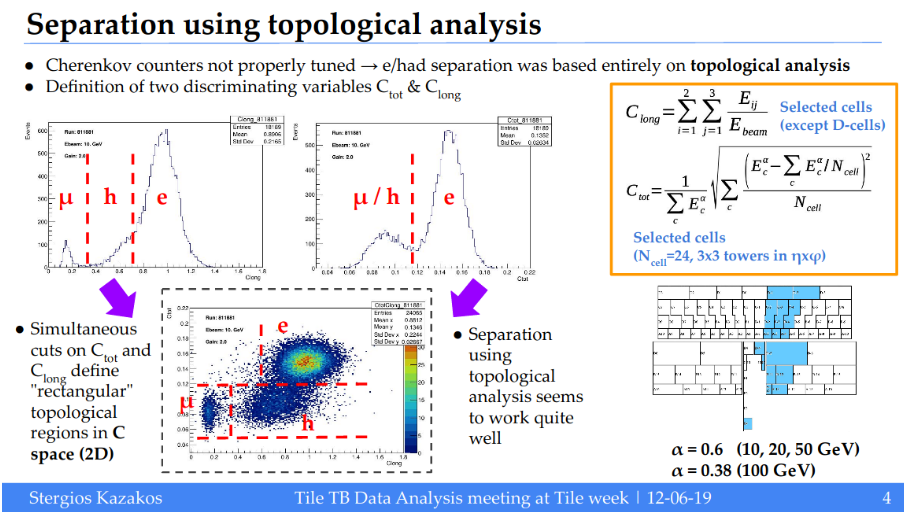
- The variation is described by a periodic function

$$E_{\text{raw}}(X) = p_0 \left[1 + p_1 \sin\left(\frac{2\pi X}{p_2} + p_3\right)\right]$$



- p_0 – mean energy (E_{fit})
- p_1 – relative amplitude of the oscillation
- p_2 – period thickness as seen by the beam
- p_3 – phase

- 20 GeV electron beam incident in the cell A4



→ slide from Stergios Kazakos' talk at Tile Calorimeter week

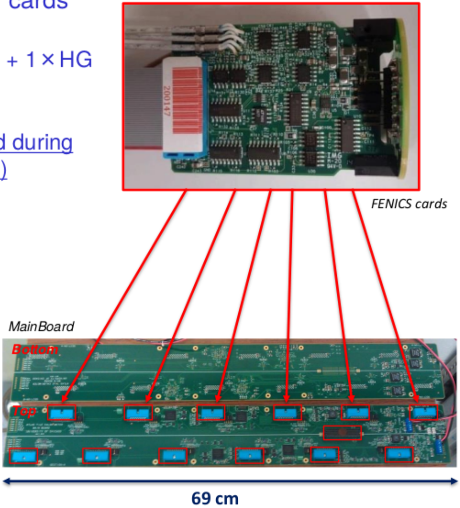
Front-End Boards and MainBoard

Front-end boards: Upgraded 3in1 cards

- **PMT pulse shaping**
- Shaper with bi-gain output : 2 × LG + 1 × HG
- Improved noise and linearity
- Improved calibration circuitry
- Final version: FENICS cards tested during the last testbeam (November 2018)

MainBoard

- **Digitize analog signals coming from 12 FEBs**
- Routes the digitized data from the ADCs to the DaughterBoards
- Digital control of the FEBs
- HG and LG, 12-bit samples @40 Msps
- TID, NIEL, SEE tests performed



→ slide from Fernando Carrio Argos' talk at 7th Beam Telescopes and Test Beams Workshop

DaughterBoard

High-speed link with the back-end electronics

- Data collection and transmission
- Clock and command distribution
- Data link redundancy

Daughterboard version 4

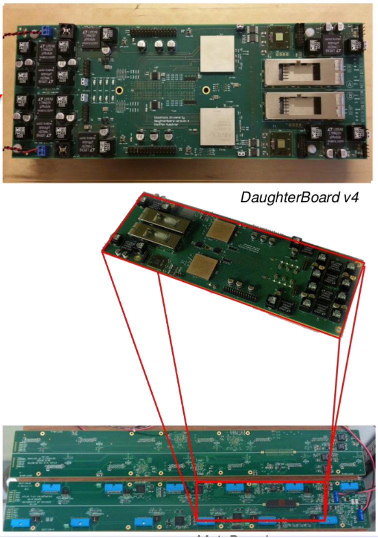
- 2 × Xilinx Kintex 7 FPGAs
- 2 × QSFP modules (~40 Gbps each)
- 2 × GigaBit Transceiver (GBT) chips

New version 5 being qualified

TID tests with ~ 9 MeV electron beam

SEE and SEL tests done with 58 MeV and 226 MeV proton beam

- Soft error rate is low → Triple redundancy
- No destructive effects observed



→ slide from Fernando Carrio Argos' talk at 7th Beam Telescopes and Test Beams Workshop

TilePreprocessor Demonstrator

First element of the back-end electronics

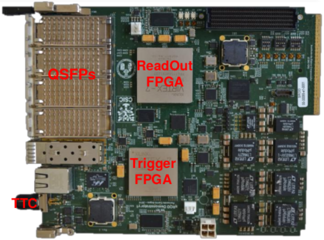
- Data processing and handling from detector
- Clock distribution towards the modules
- Detector Control System data distribution
- Interfaces up to 4 mini-drawers (one module) through the DaughterBoards → **160 Gbps!**

Fully functional prototype

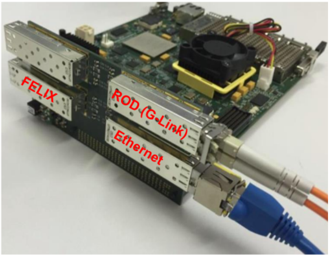
- Xilinx Virtex 7, Kintex 7, 4 QSFPs
- Double mid-size AMC (μTCA / ATCA carrier)
- 1/8th of the full-size PreProcessor for HL-LHC

Used during the testbeam campaigns to validate the new readout electronics

- Keeps backward compatibility with the legacy system: TTC system, RODs
- **Triggered events are transmitted to FELIX system**



PPr Demonstrator



PPr Demonstrator + backplane

→ slide from Fernando Carrio Argos' talk at 7th Beam Telescopes and Test Beams Workshop