Upgrade of the ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC

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On behalf of the ATLAS Tile Calorimeter System

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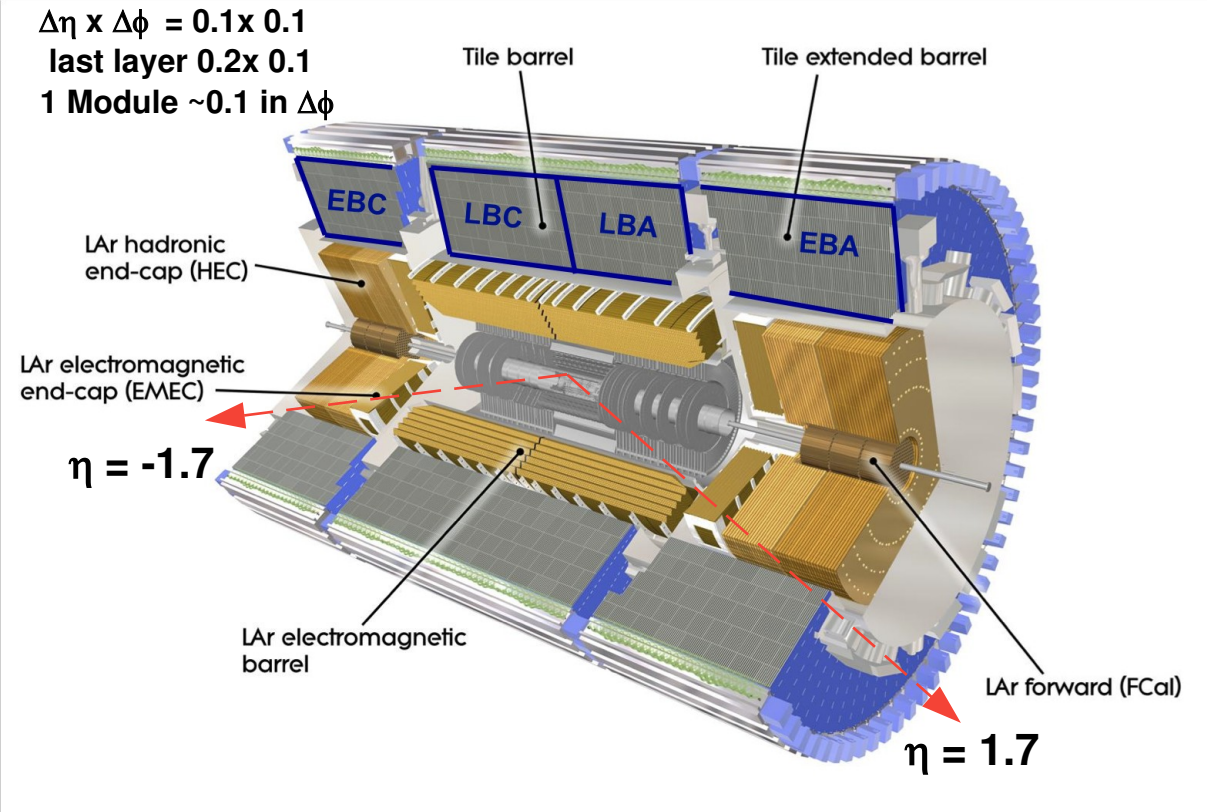
ATLAS Tile Calorimeter

- The **Tile Calorimeter** (TileCal) is the central hadron calorimeter of **ATLAS**.

- Two sides of Long Barrel (LBA, LBC) and Extended Barrels (EBA, EBC).
- Three barrels (LBA+LBC, EBA, EBC), 64 modules each.
- Coverage $|\eta| < 1.0$ (LB), $0.8 < |\eta| < 1.7$ (EB).
- It measures energy of jets, taus and missing transverse energy.
- Constructed from steel plates and plastic scintillators – **tiles**.
- Light read-out with two optical fibers per tile.
- Divided into ~5000 cells by grouping the fibers.
- Light is directed to two PMTs per cell, ~10,000 PMTs total.



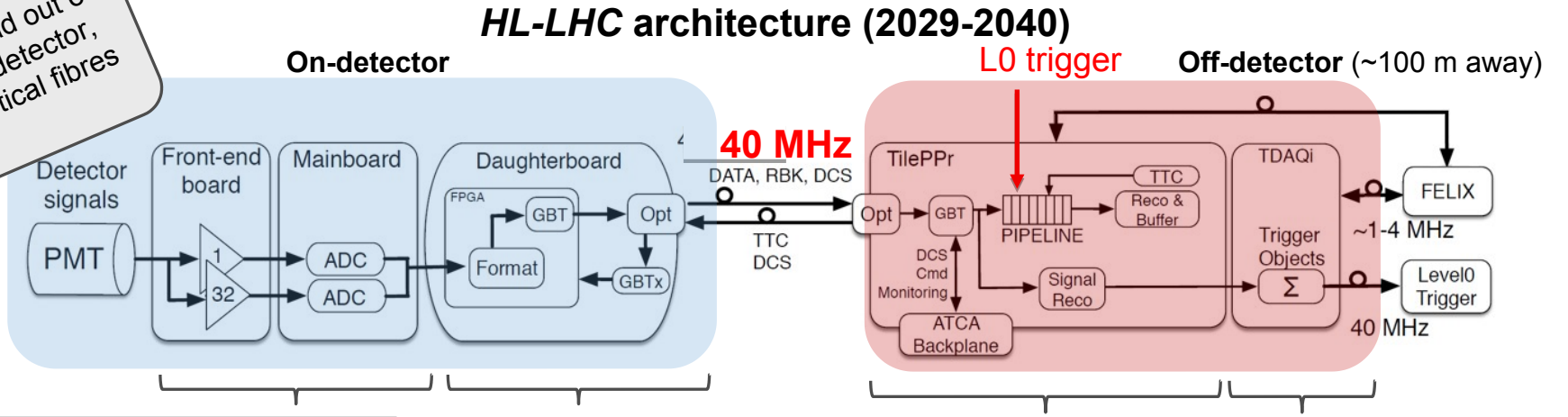
- Dynamic range from ~10 MeV to ~2 TeV per calorimeter cell
- Energy resolution for hadrons:

$$\frac{\sigma}{E} = \frac{50\,\%}{\sqrt{E\ [\mathrm{GeV}]}} \oplus 3\%$$

TileCal Upgrade for the HL-LHC

- High Luminosity LHC, starting around 2029, will achieve an instantaneous luminosity 5-7 larger than the LHC nominal value.
- This requires an upgrade of the ATLAS detector (Phase-II upgrade), which is in progress.
- Upgrade of the Tile Calorimeter:
  - Active dividers for all PMTs and replacement of the 10% most exposed PMTs.
  - Complete replacement of on-detector and off-detector electronics.
  - New digital ATLAS trigger system up to 40 (1) MHz read-out (accept) rate.
  - Increased detector read-out bandwidth – 40 Tbps for the entire TileCal.
  - Improved LV and HV system.

40 Tbps read out of the entire detector, ~6000 optical fibres



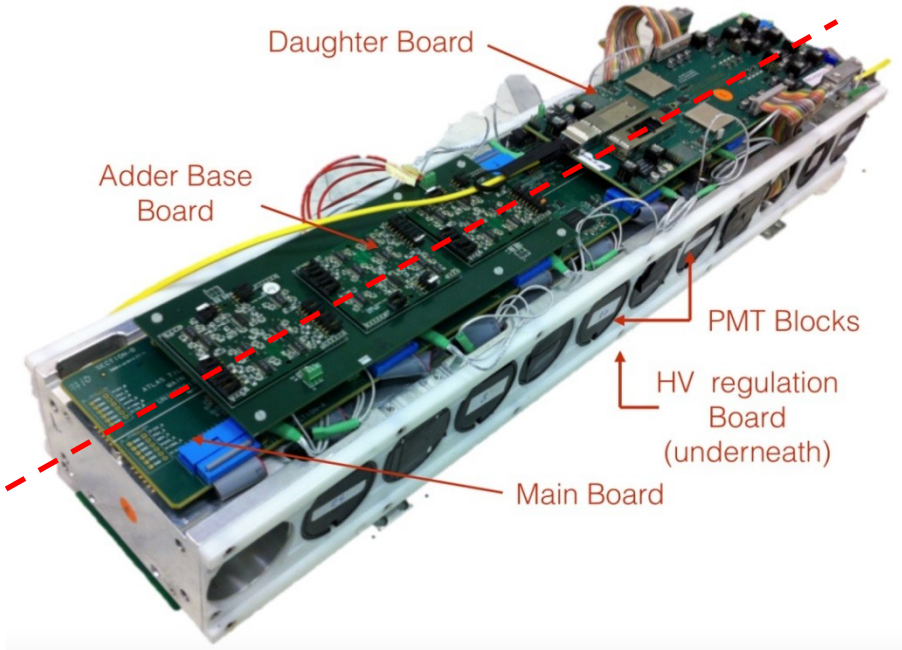
-Shaping
-Amplification (2 gains)
-Digitization
-Calibration for electronics

- Data acquisition
- Clock distribution
- Pipelines buffer
- Online energy & time reco

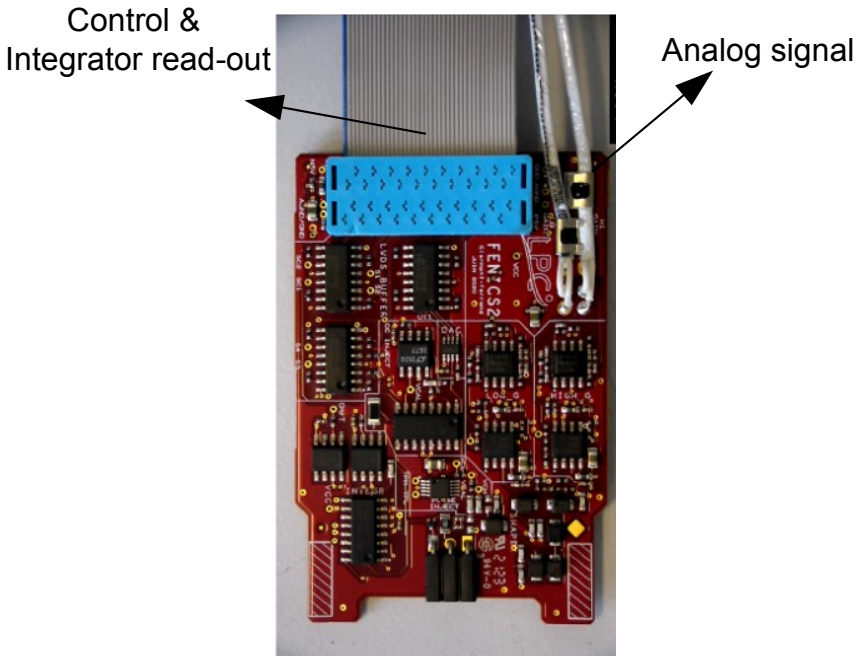
- Trigger objects computation
- Interface with ATLAS TDAQ subsystems

On-detector mechanics & electronics

- New mechanic substructures to facilitate accessibility during maintenance
- Different configuration for Long and Extended Barrel modules:
- **4 mini-drawers for Long Barrel modules** → 45 PMTs
- **3 mini-drawers + 2 micro-drawers for Extended Barrel modules** → 32 PMTs
- Each mini-drawer has 2 independent sections for redundant cell read-out



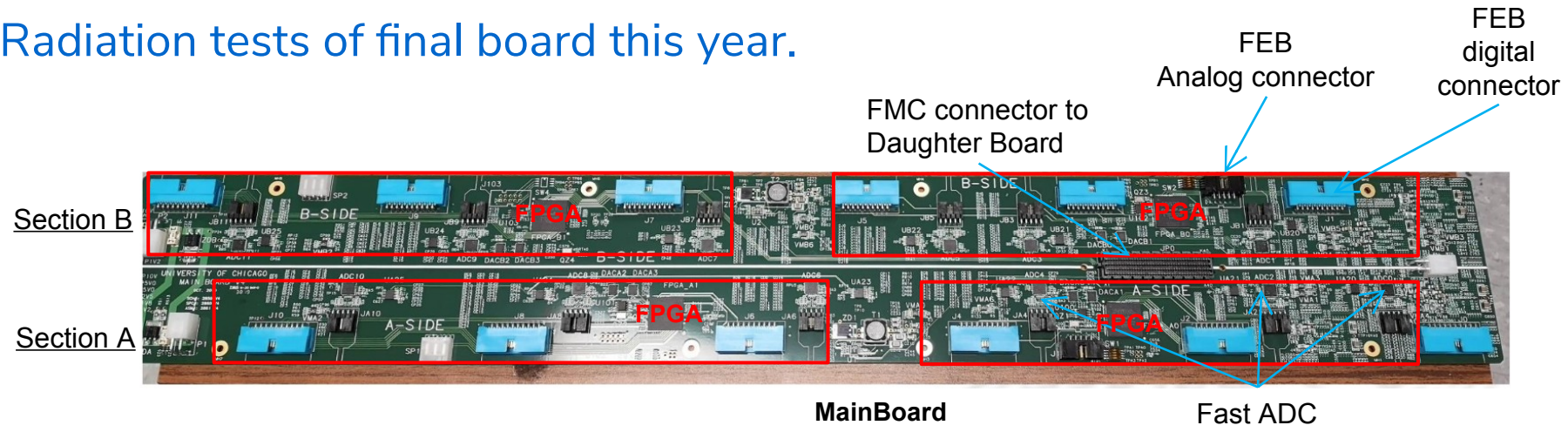
- Front-End Boards (FEB): **FENICS**
- Provides PMT pulse shaping with 2 gain amplifications
- Slow "Integrator" read-out for luminosity measurements and calibration with Cs source
- Built-in Charge Injection System for electronics calibration
- Final Radiation Hardness tests this year



FENICS card

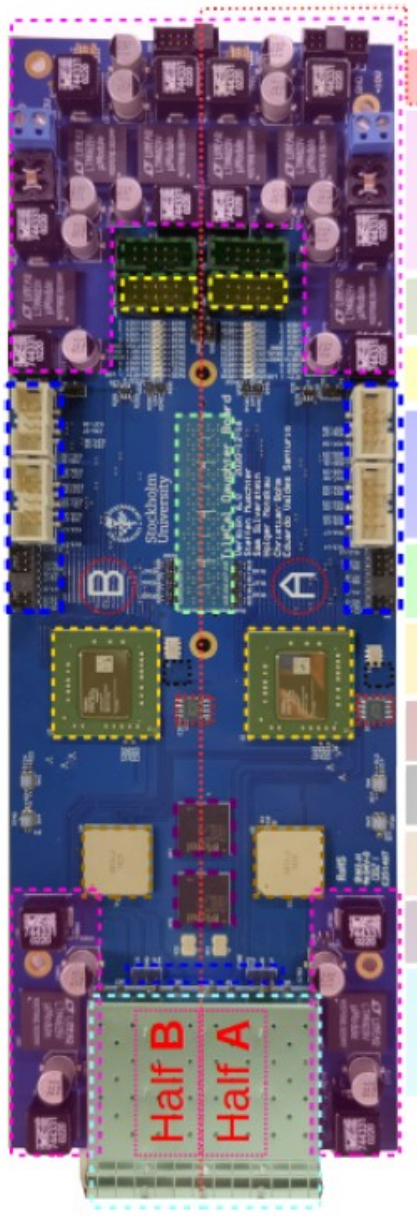
On-detector electronics (2)

- **MainBoard**:
- 69 cm long board, FPGAs used only for configuration
- Digitizes signals coming from 12 FENICS
- 12-bit dual ADCs @ 40 MSps for 2 gain signals
- 16-bit ADCs @ 50kSps for integrator read-out
- Provides digital control and configuration of FENICS + high-speed path to the DaughterBoard
- Divided in two halves for redundancy → independent read-out and power distribution
- Radiation tests of final board this year.



On-detector electronics (3)

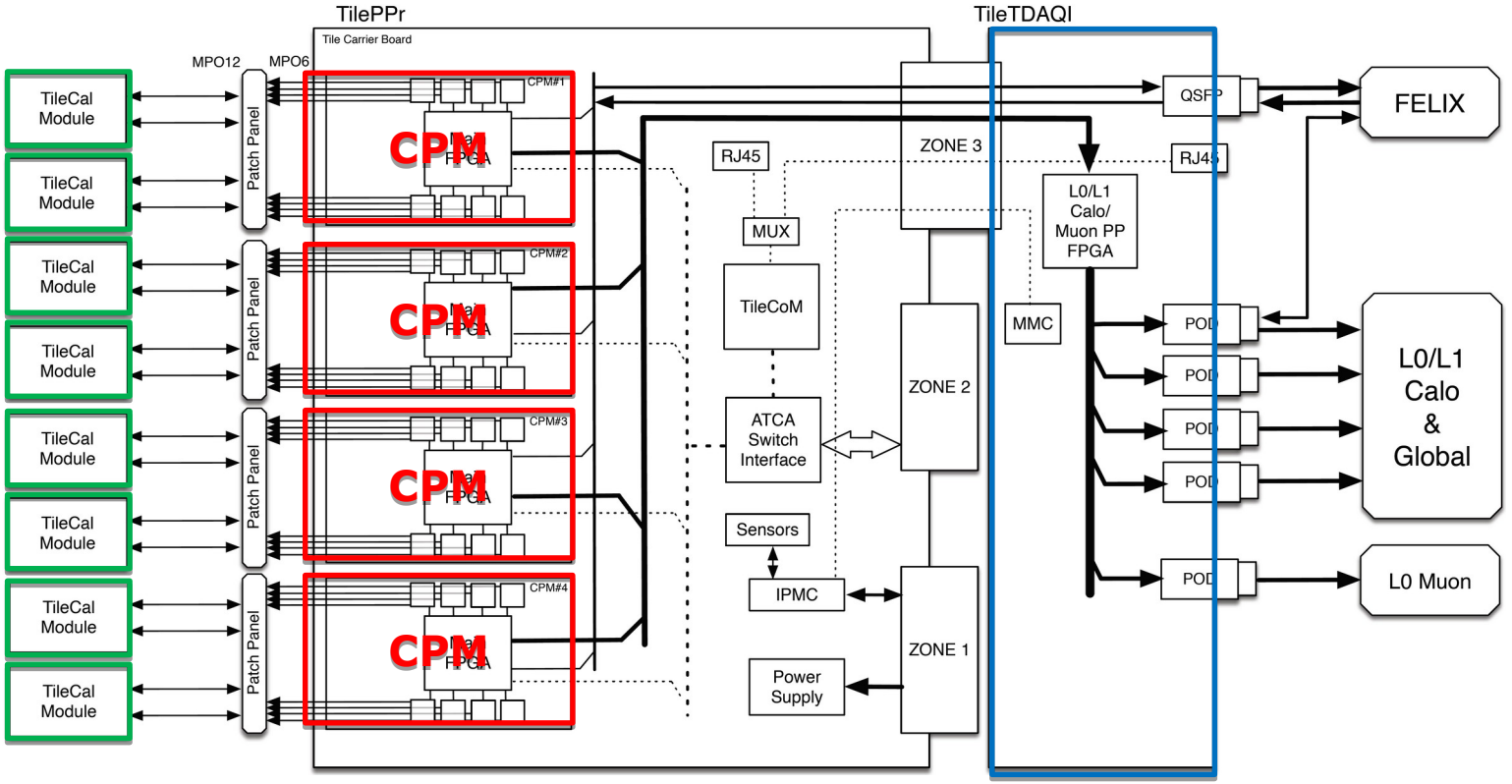
- High-speed interface with the off-detector electronics: **Daughterboard**
- Collects PMT digitized data from Mainboards
- Data transmission to off-detector electronics
- Clock and command distribution to FENICS
- Implements data link redundancy
- DaughterBoard specs:
  - 2 × GBTx chips for LHC clock recovery and distribution
  - 2 Kintex Ultrascale FPGAs for communication and data processing (SEL tolerance)
  - Each side serving 6 PMTs (12 in total)
  - 2 × QSFP high-speed optical modules



DaughterBoard

- **Redundancy** Line
- **Power circuitry**
  - Chained Power-up and Fast triggered power-cycle sequence
  - Current monitoring
- **Cesium** interfaces (5V)
- **xADC** interface
- **GBTx I2C/configuration**
- **ProASIC JTAG**
- **Kintex Ultrascale JTAG**
- **400 pin FMC** connector to MB
- **Kintex Ultrascale** FPGAs
- **128-Mbit** PROM chips
- **48-bit ID** chips
- CERN radiation tolerant **GBTxs**
- **ProASIC** FPGAs
- **4x SFPs+**
  - **2x Downlink RX** @4.8Gbps
  - **4x Uplink TX** @9.6 Gbps

Off-detector electronics



The backend electronics is formed by Tile PreProcessor (PPr) and TDAQi RTM systems.

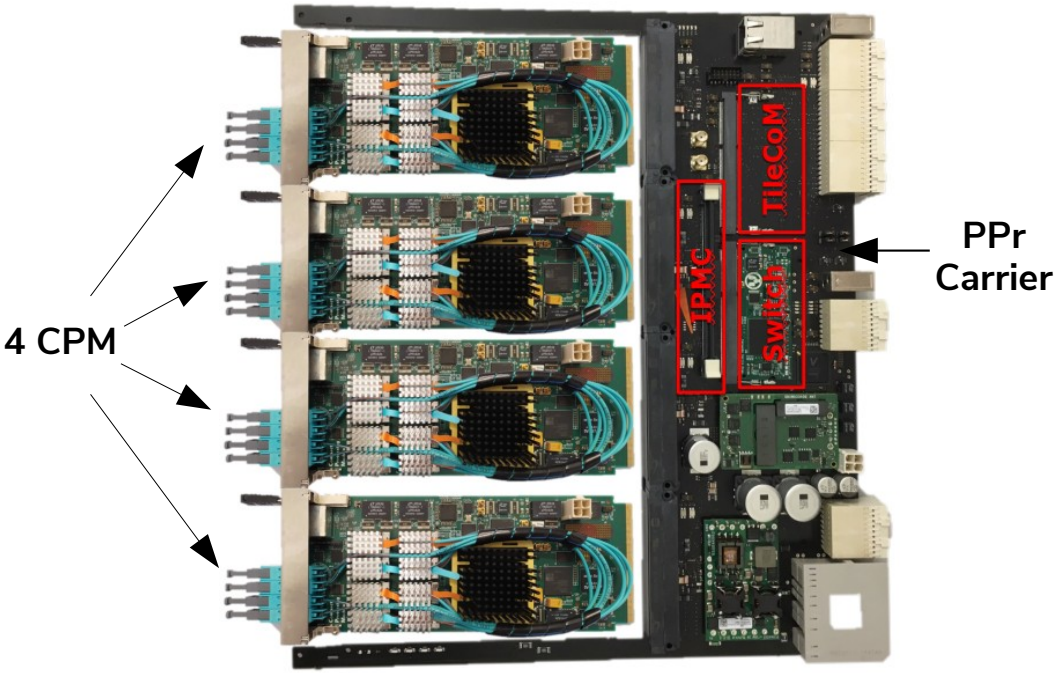
- Real time Data processing, handling and and reconstruction from on-detector electronics
- Provides clocks and configuration for the TileCal modules
- Interface with the ATLAS trigger and read-out systems (FELIX)

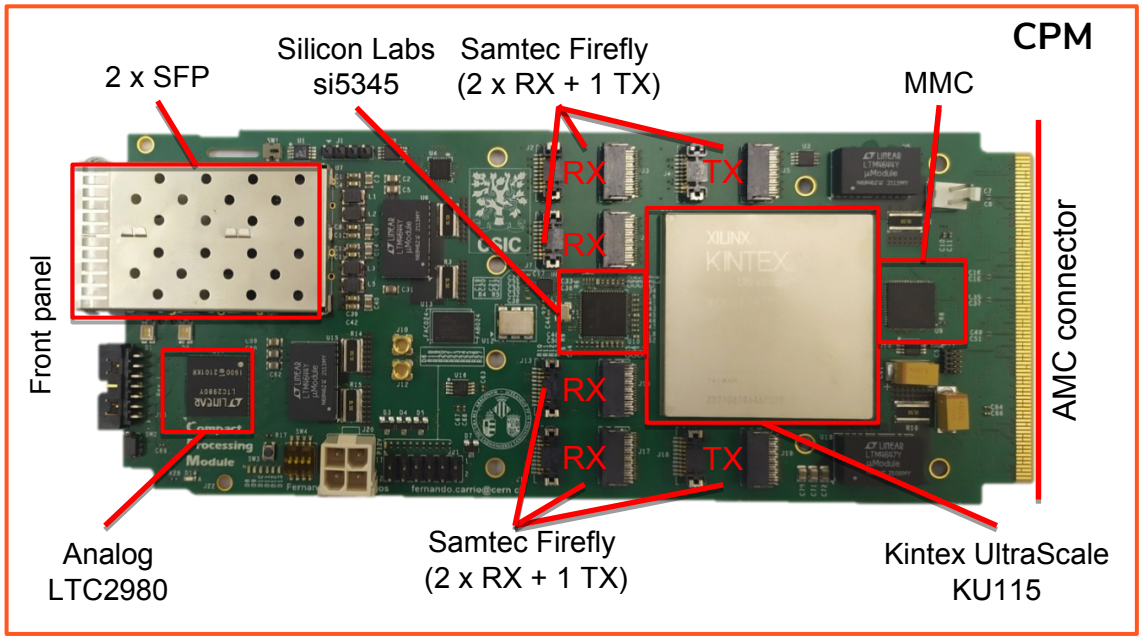
Each **PPr** formed by 1 ATCA carrier + **4 Compact Processing Modules (CPM) → 32 PPr in total**

- Each CPM receives data from 2 modules (8 minidrawer) → **128 CPMs in total**

32 TileTDAQ-i in total: Interfaces with L0Calo, Global, L0Muon and FELIX system

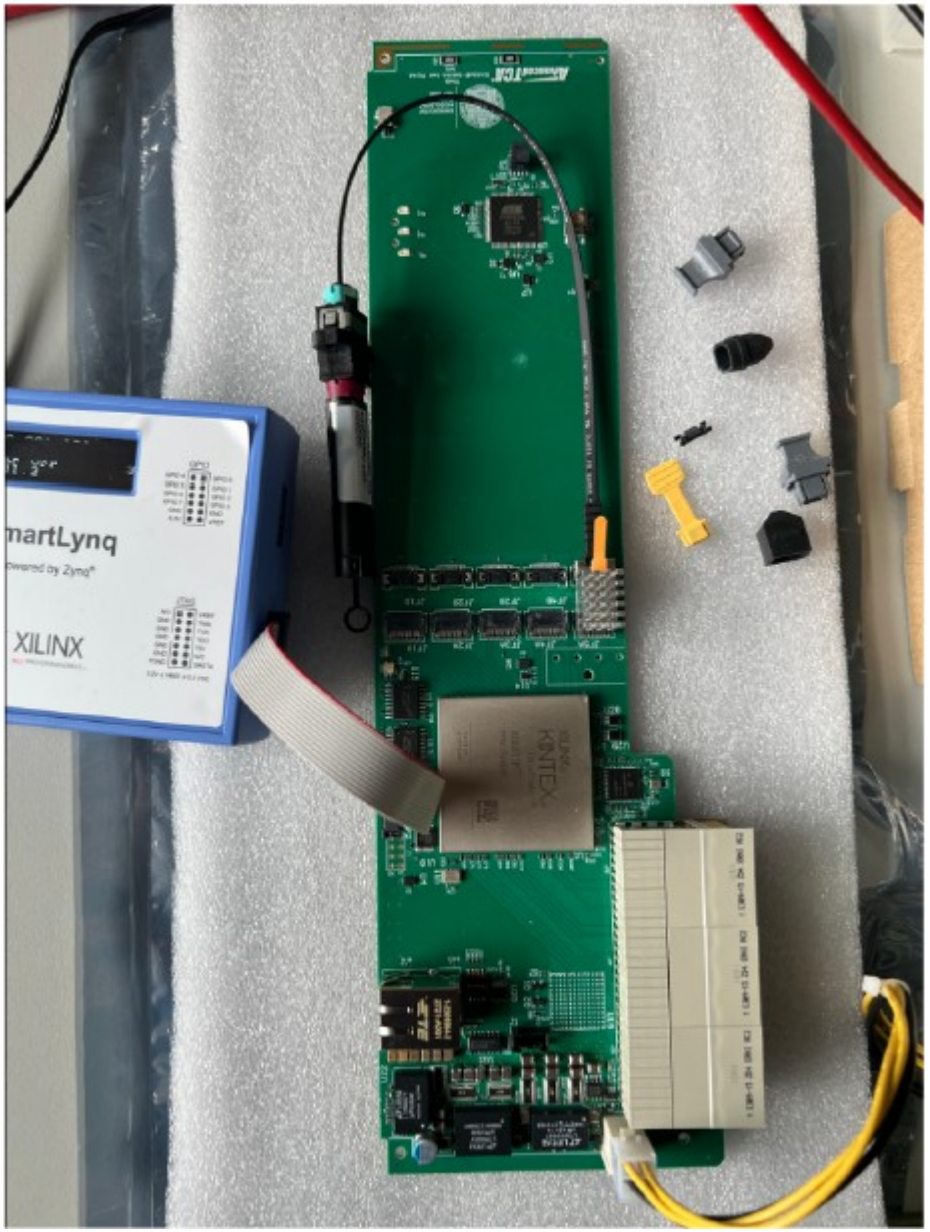
Off-detector electronics (2)





- PPr: 1 Carrier and 4 CPMs.
- Off-detector read-out based on FPGAs and high-speed connectors.
- CPM: AMC board hosting 2 SFPs, and Kintex Ultrascale
- Each CPM operates 2 TileCal module → up to 8 modules per PPr
- Processing, data handling from on-detector electronics and signal reconstruction.
- Real time reconstruction of up to 380 PMT signals at 40 MHz per PPr.
- Distribution of the LHC clock towards the on-detector electronics.
- Interface with the ATLAS read-out system.
- Communication with the Timing, Trigger and Control system for the LHC.

Off-detector electronics (3)



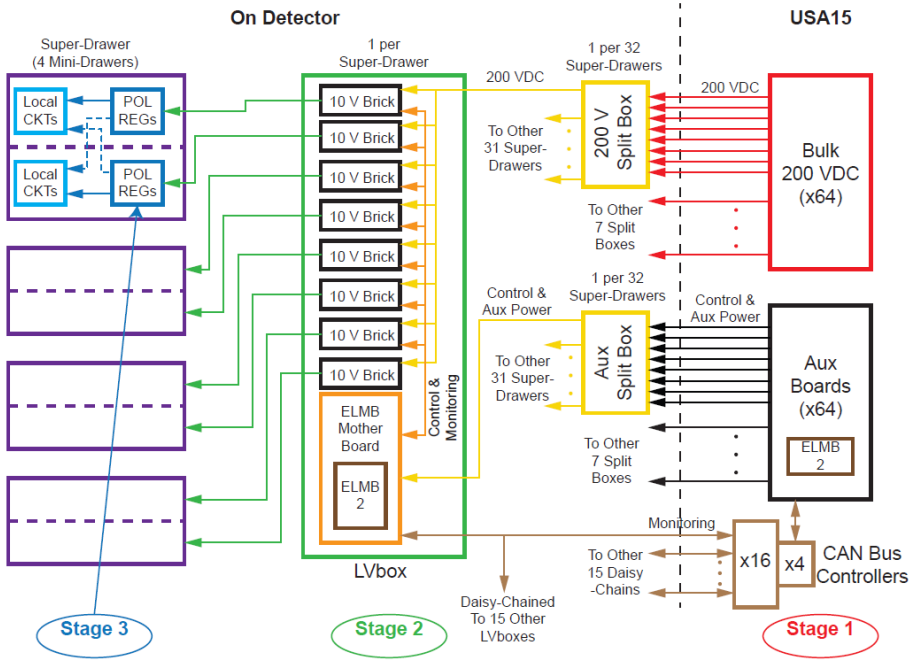
TDAQi

- The TDAQi connected to the rear side of the Carrier.
- Synchronous reception of cells energy from the CPMs
- Calculation of trigger objects (trigger towers or group of cells of different ϕ/η size)
- Copies of the trigger objects
- Building and synchronous transmission of trigger objects to the different electron/photon, jet, muon trigger sub-systems
- Sending monitoring data to the Felix

Low/High Voltage Power Supplies

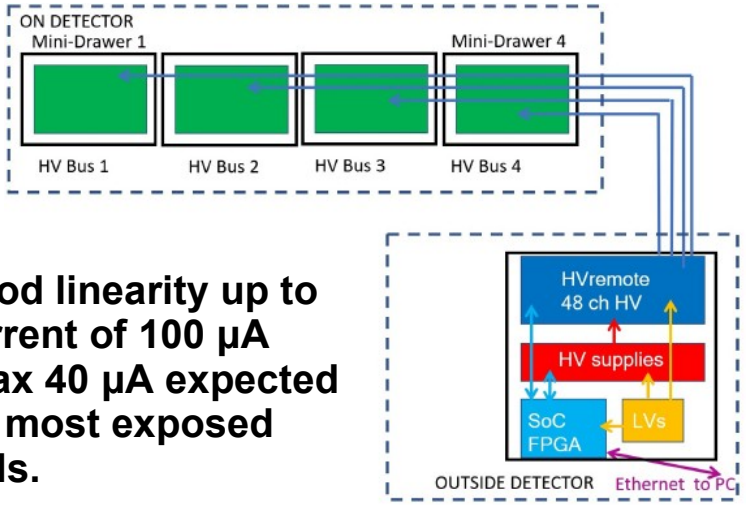
Low Voltage power supplies formed by a three stage power system provides

- Better reliability, lower noise
- Improved radiation tolerance
- Lower number of connections (single DC level (+10V) and regulators for the voltages needed by the local circuits)
- Redundant power distribution (two individual bricks per mini-drawer and redundancy control with diode on the mainboard)



High Voltage bulk power supplies and regulators installed in the ATLAS service cavern (USA15)

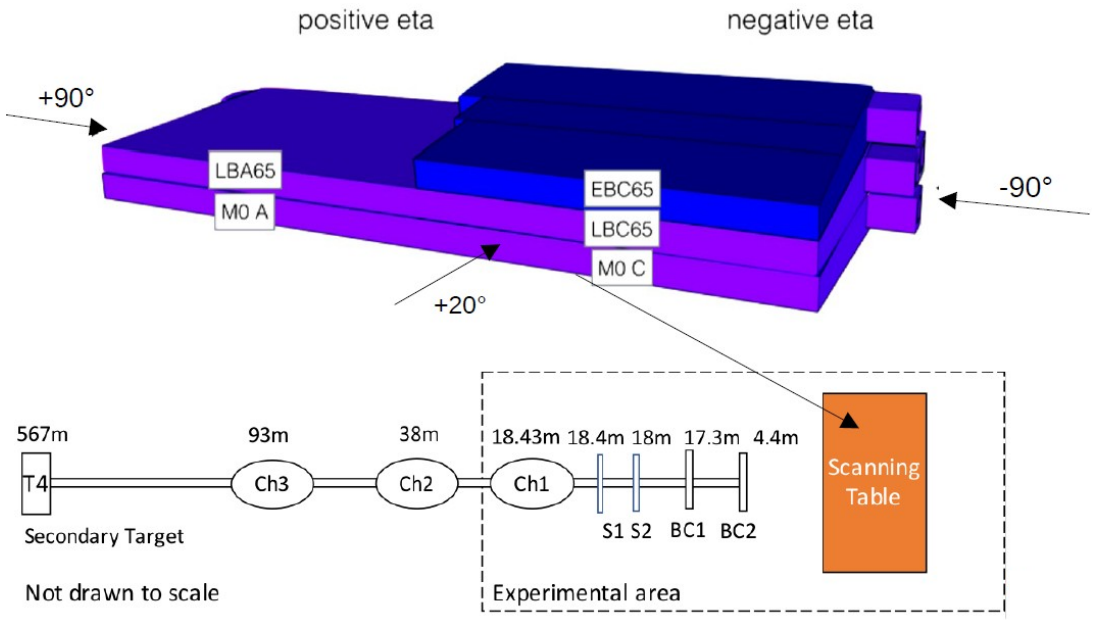
- 100 m long High-Voltage wires for each individual PMT.
- High-voltage bus board brings high-voltage to individual PMTs
- Easy maintenance, no radiation hardness issues
- Prototypes were produced and validated during the test-beam data-taking at CERN SPS.



Good linearity up to current of 100 µA (max 40 µA expected for most exposed cells.

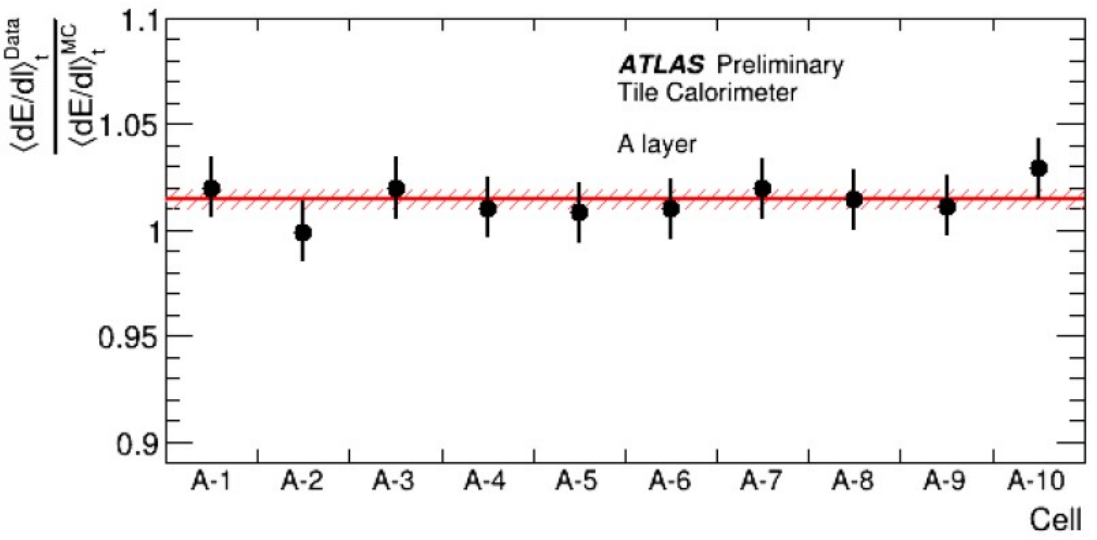
Testbeam

- 8 **Testbeams** at CERN SPS between 2015-2018 and 2021-2022 to validate the hardware with beam data and perform physics studies.
- 3 modules from the calorimeter (two Long-Barrel and one Extended-Barrel)
- The read-out uses different upgraded front-end electronics proposed for the ATLAS Phase-II upgrade.
- A half-module equipped with a prototype of the new Phase-II upgrade electronics.
- Exposed to electron, muon and hadron beams at various energy ranges.
- Hadron beams of 16-290 GeV energy.

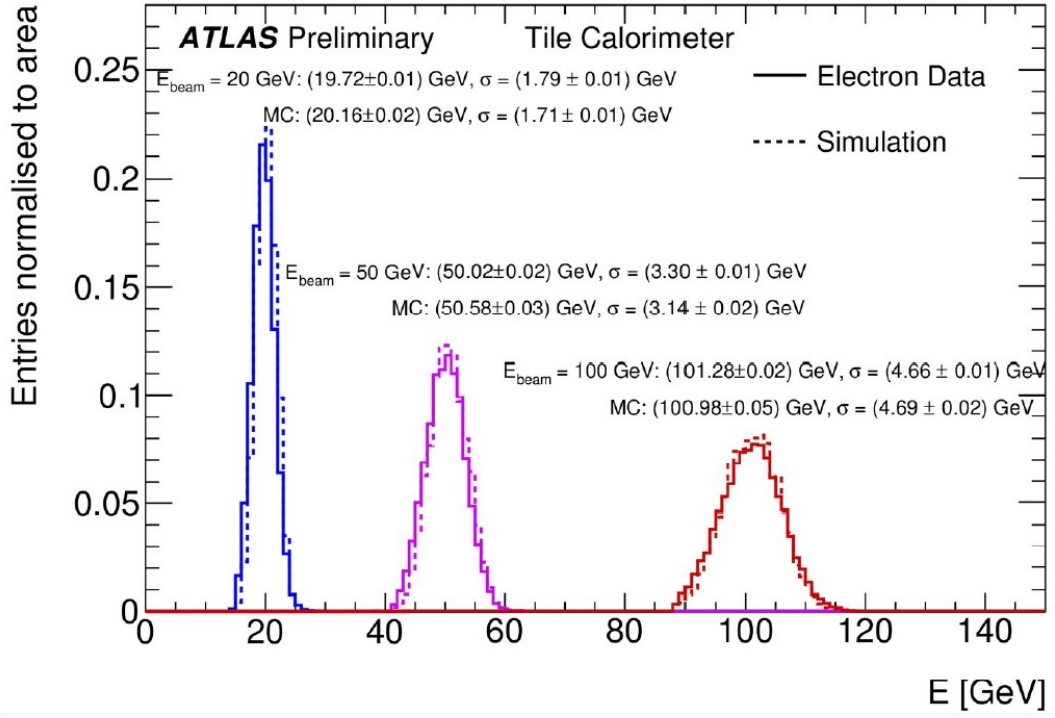


Testbeam Results

- **Muons** of 160 GeV traverse the entire TileCal modules with an angle of 90°.
- Energy loss is ~proportional to the muon track path length in the calorimeter → Checking the equalization of the cell response.
- Layer uniformity within 1%.
- Max offset of 1.4% for Data/Simulation.



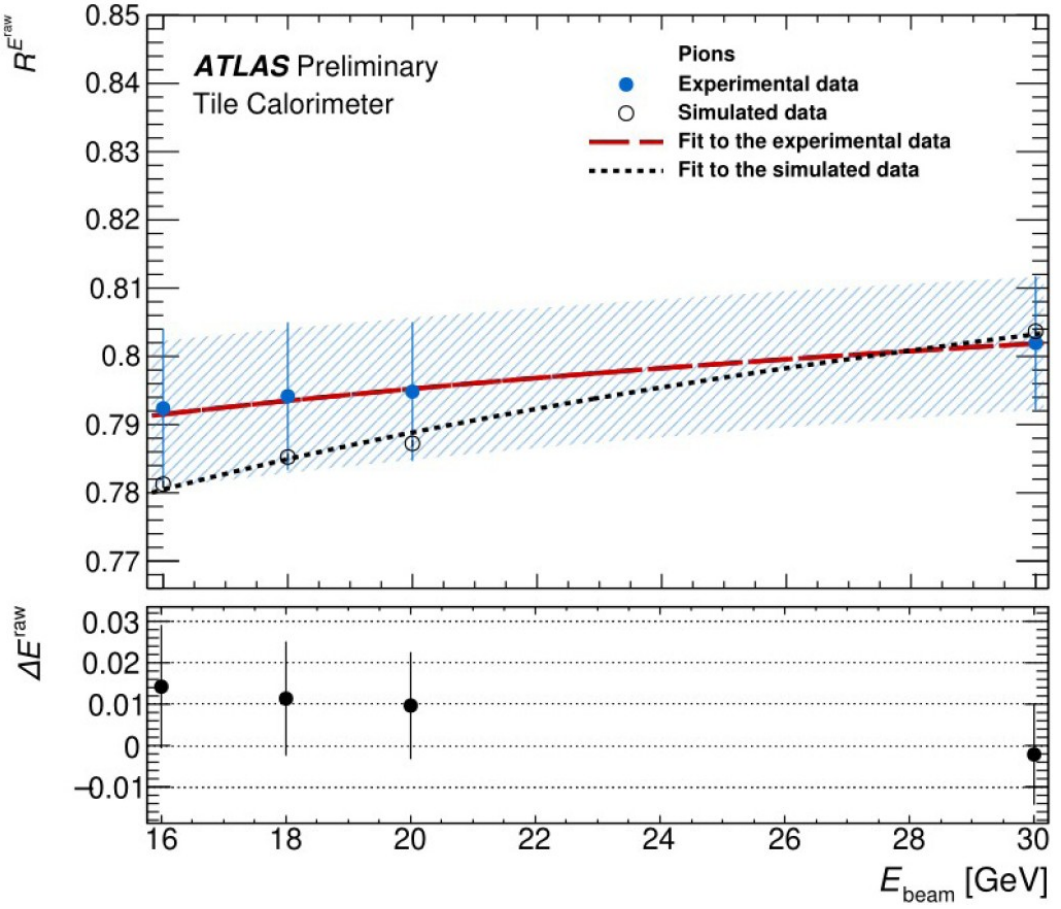
- **Electrons** to determine the EM scale by calculating the average charge-to-energy conversion factor, (pC/GeV) using electrons of different energies.
- Verify the linearity of the response vs. energy and to test the uniformity and energy resolution.



Testbeam Results (2)

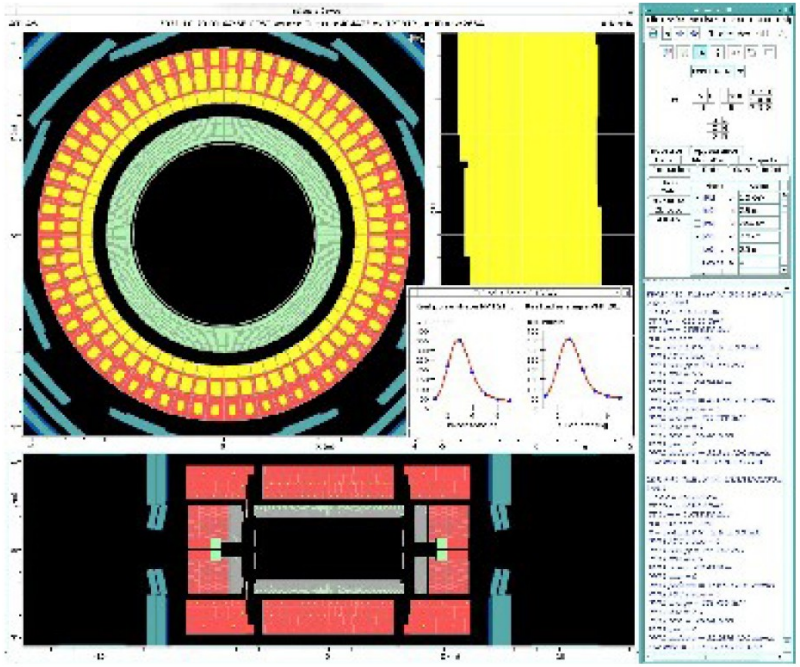
- Response to isolated hadrons important to validate and improve the modeling for jet and tau measurements.
- Energy characterization based on ATLAS simulation using the GEANT4 toolkit.
- Beam composition is hard to control and not known a priori.
- The ranges of data/MC variations:
  - Pions – 1.4%
  - Kaons – 1.7%
  - Protons – 2.5%
- Kaon content is small in the beam - dominated by statistical errors
- Protons have high statistics - low systematic and statistical uncertainties
- More results in EPJC 81 (2021) 549

$$R^{\langle E^{\mathrm{raw}}\rangle} = \frac{\langle E^{raw}\rangle}{E_{\mathrm{beam}}} \qquad \Delta\langle E^{\mathrm{raw}}\rangle = \frac{\langle E^{\mathrm{raw}}\rangle}{\langle E^{\mathrm{raw}}_{\mathrm{MC}}\rangle} - 1$$

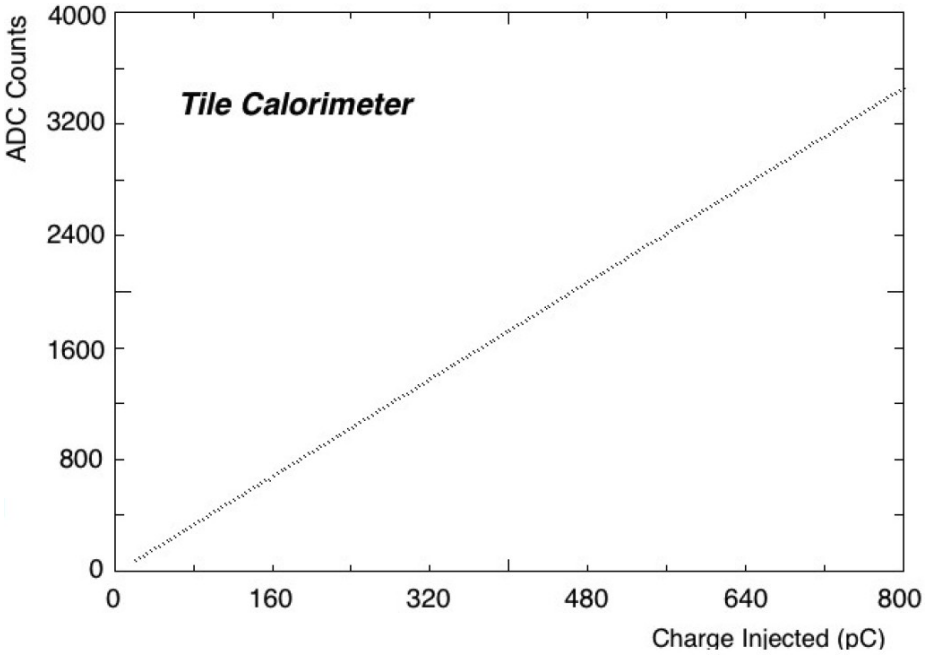


Demonstrator in ATLAS

- Demonstrator Project.
- TileCal Module in ATLAS (LBA14) equipped with upgraded electronics to operate a backward-compatible dual read-out: Legacy and Phase II.
- Inserted in ATLAS in July 2019.
- Demonstrator will be kept in ATLAS during Run 3.
- Stable performance, low noise and good CIS and laser signals.
- Commissioned trigger towers output system to ATLAS level 1 trigger.
- Recorded cosmic data and LHC splash events



LHC Splash event in 2022



Charge Injection Scan

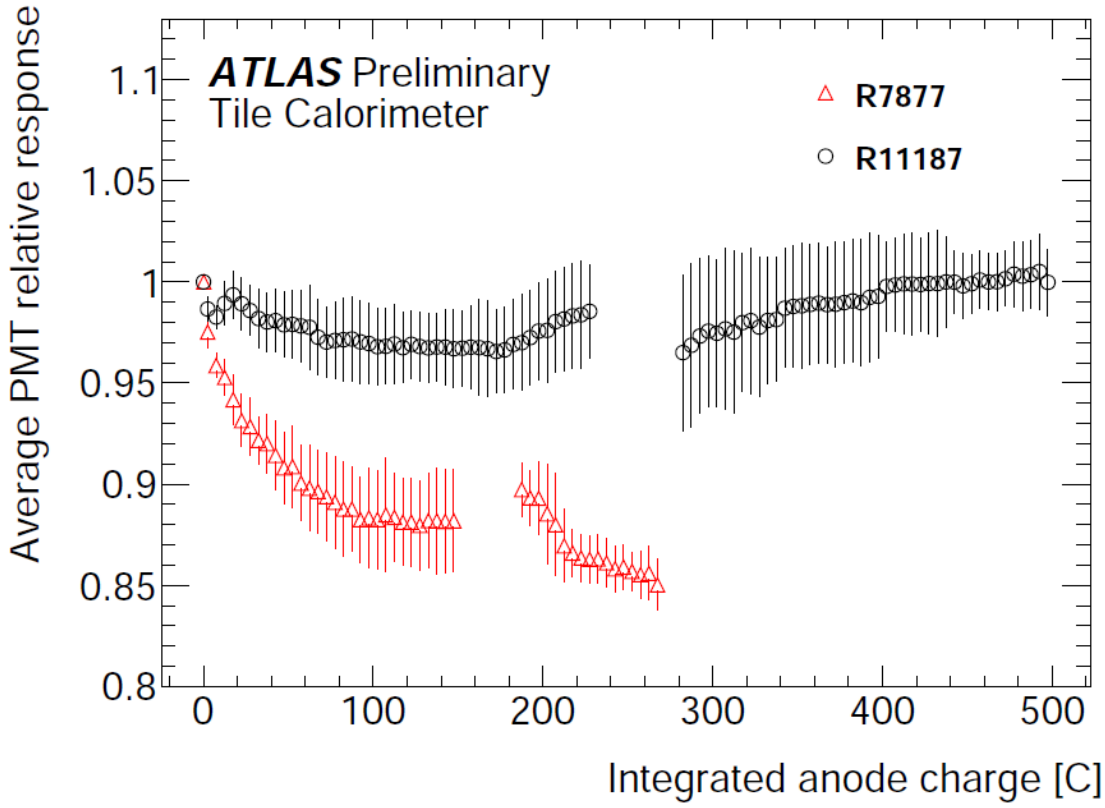
Summary

- The High-Luminosity LHC era will bring new challenges:
  - higher luminosity and read-out rates
  - higher pile-up,
  - higher radiations.
- 10% of the PMTs and all TileCal on- and off-detector electronics will be replaced in 2026-2028 during ATLAS Phase-II upgrade.
- Upgrade of the Tile Calorimeter system is required and well on track:
  - New mechanical structure and electronics, more reliable and radiation-hard.
  - New digital read-out and trigger system for higher rate.
- Regular test-beam campaigns allow to validate and integrate different components of the upgraded detector and provide interesting physics results.
- The Tile demonstrator is fully operational:
  - Full integration of the Tile demonstrator in the current ATLAS DAQ and DCS systems, ready for Run 3 data.

Bonus Slides

Photo-multipliers

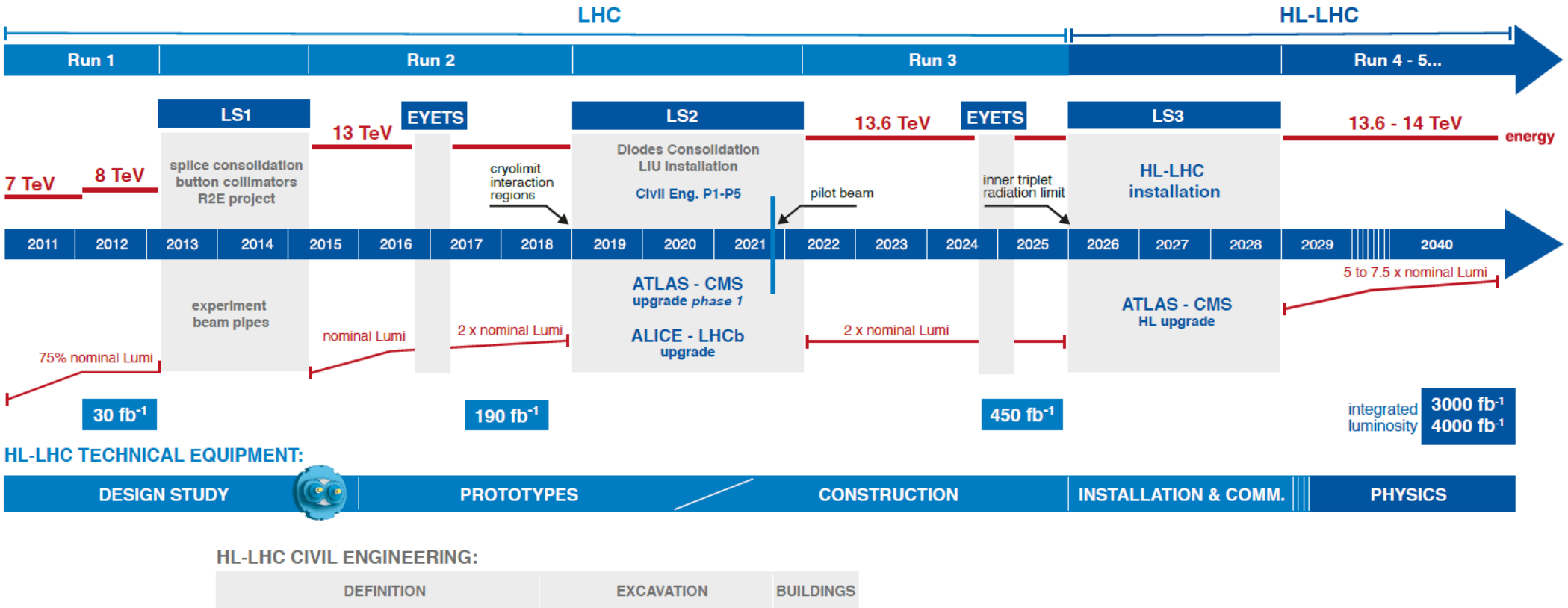
- Photo-multipliers (PMT):
- 1024 PMTs of 9582 in Tilecal to be replaced due to ageing effects (response loss > 25%)
- Characterization of new Hamamatsu PMTs model R11187 completed (same
- geometry as legacy model R7877, better response stability)
- Three identical test-benches for PMT qualification are set-up.



HL-LHC maximum expected anode charge 600 C

HL-LHC Schedule

LHC / HL-LHC Plan



HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY	PROTOTYPES	CONSTRUCTION	INSTALLATION & COMM.	PHYSICS

HL-LHC CIVIL ENGINEERING:

DEFINITION	EXCAVATION	BUILDINGS

Test Beam results