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

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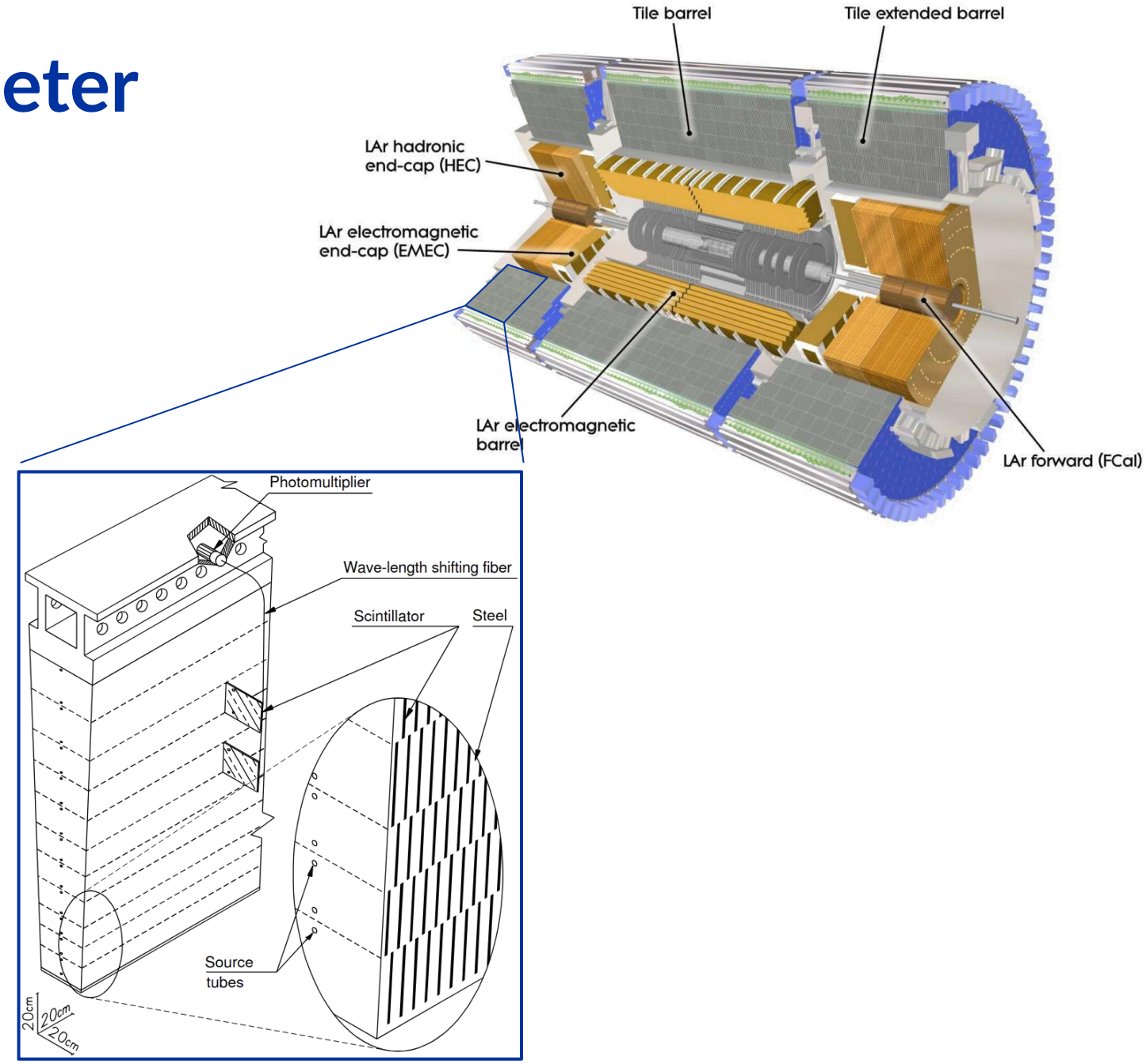
CERN

ATLAS EXPERIMENT

The ATLAS Tile Calorimeter

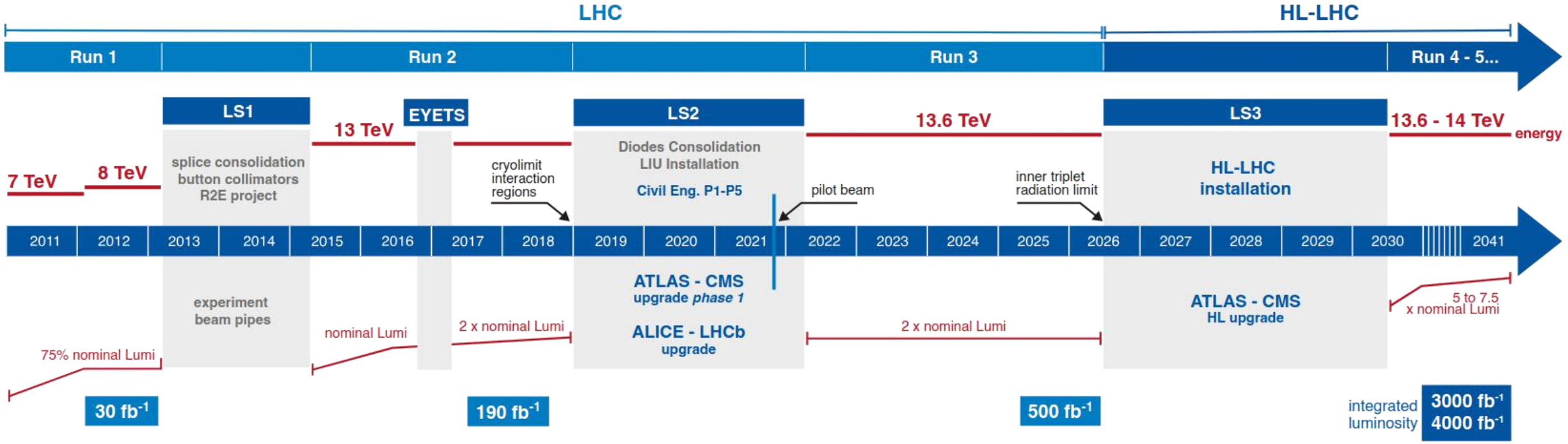
- Tile Calorimeter (TileCal): **central ATLAS hadron calorimeter**, crucial for measurements of high energy jets, $E_{\mathrm{T}}^{\mathrm{miss}}$ and τ-leptons.
- **Steel plates** and **plastic scintillator** tiles.
- Calorimeter divided into three cylindrical barrels: a central long barrel (LBA, LBC) covering $|\eta| < 1.0$ and two extended barrels (EBA, EBC) covering $0.8 < |\eta| < 1.72$. Each barrel consists of 64 modules ($\Delta\phi \cong 0.1$).
- Light read out with two wavelength-shifting fibers per tile. Grouping of fibers form ~5000 cells.
- Light from each cell sent to two photomultiplier tubes (~10,000 PMTs in total, Hamamatsu R7877).
- Dynamic range **10 MeV–2 TeV** per cell. Energy resolution for hadrons:

$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E/\mathrm{GeV}}} \oplus 3\%$$



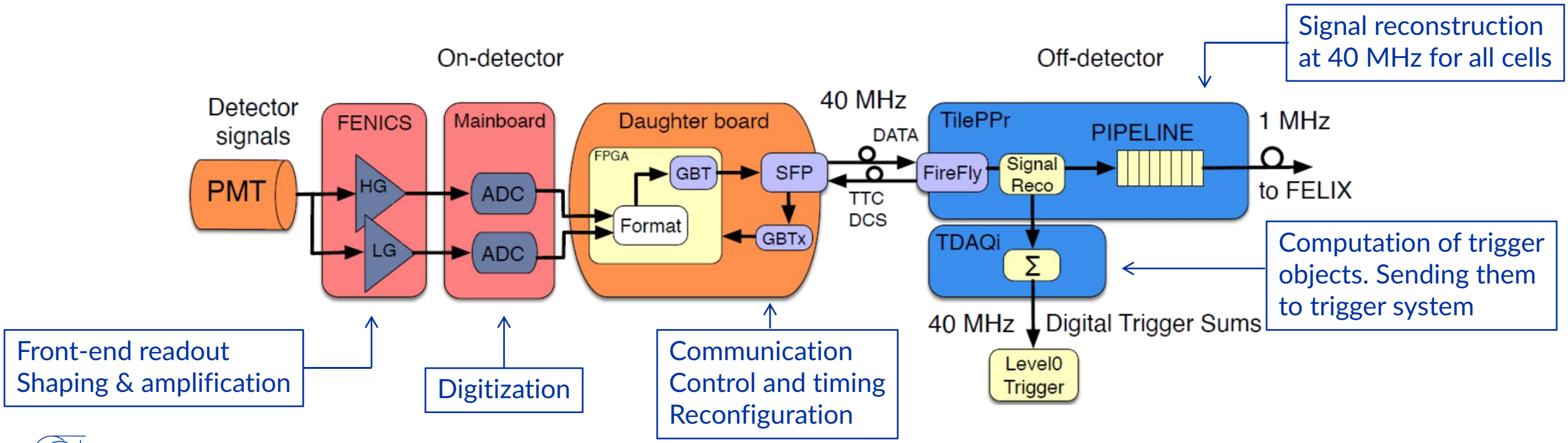
The HL-LHC upgrade

- The **High-Luminosity LHC (HL-LHC)** will start after Long Shutdown 3 (LS3) and aims to deliver up to 4000 fb^{-1} of integrated luminosity.
- **Instantaneous luminosity** will increase by a **factor of 5 to 7.5**, with up to **200 pp collisions** per bunch crossing.
- This presents significant challenges for detectors: **higher radiation** doses, **increased** data **rates**, stricter timing and trigger requirements.
- The ATLAS HL-LHC (Phase-II) Upgrade includes a complete **redesign** of several subsystems, including **TileCal electronics and power distribution systems**.



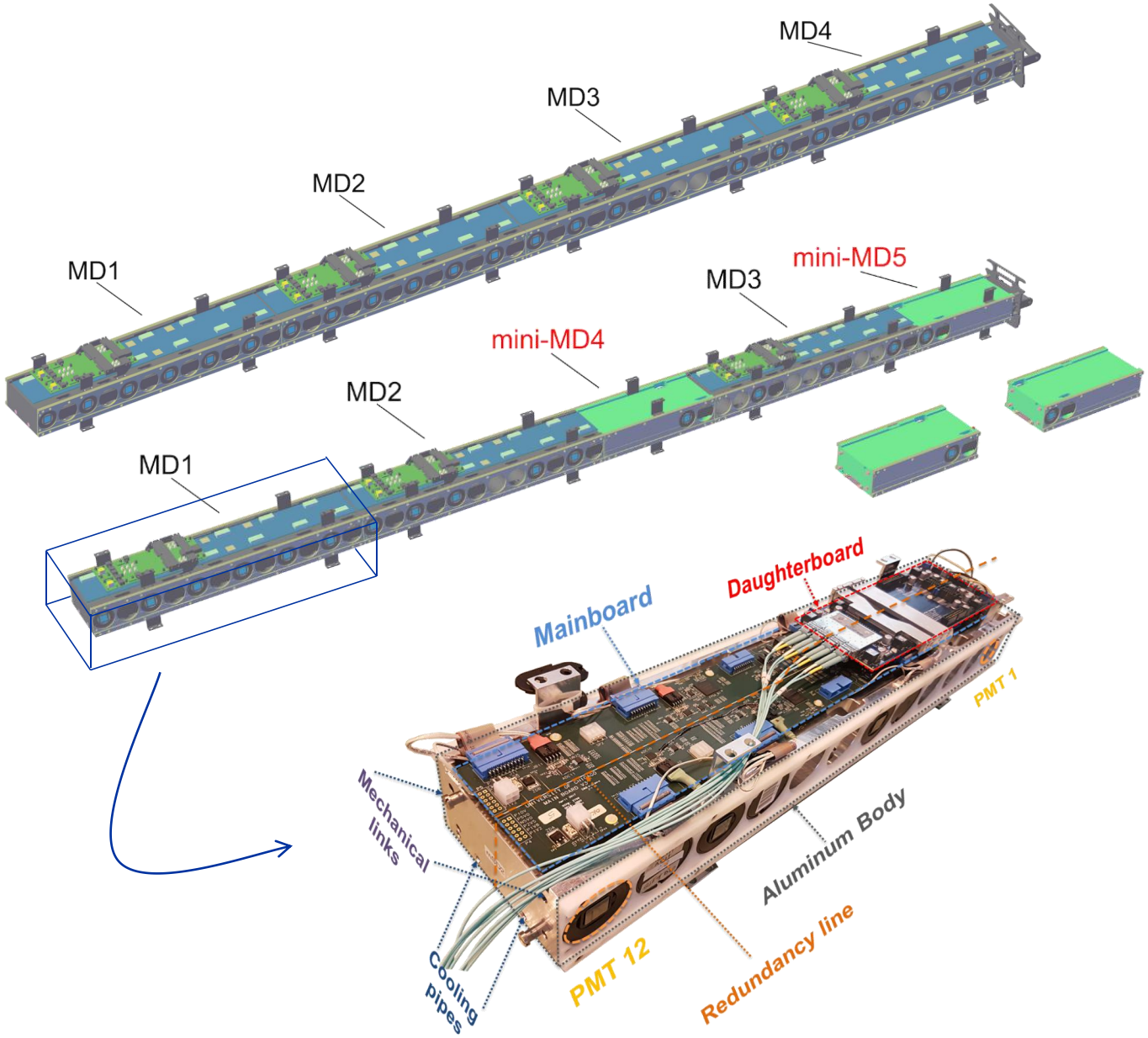
The ATLAS Tile Calorimeter upgrade for the HL-LHC

- **TileCal Phase-II upgrade:**
  - TileCal exposed to higher radiation. Existing readout **electronics** is **ageing** and **not designed** for such **radiation levels**.
  - Current **architecture incompatible** with **fully digital Trigger and Data Acquisition (TDAQ) system,** operating at 40 (1) MHz readout (accept) rate. In the new architecture, data need to be reconstructed @40 MHz, and will be sent to the trigger systems. New front-end must match timing and data flow requirements.
  - Most detector optics will be reused (scintillators, fibers, steel), but **~10% of PMTs** will be **replaced** due to degradation.
  - New radiation-tolerant electronics and **modular power distribution systems** required to sustain HL-LHC operation.



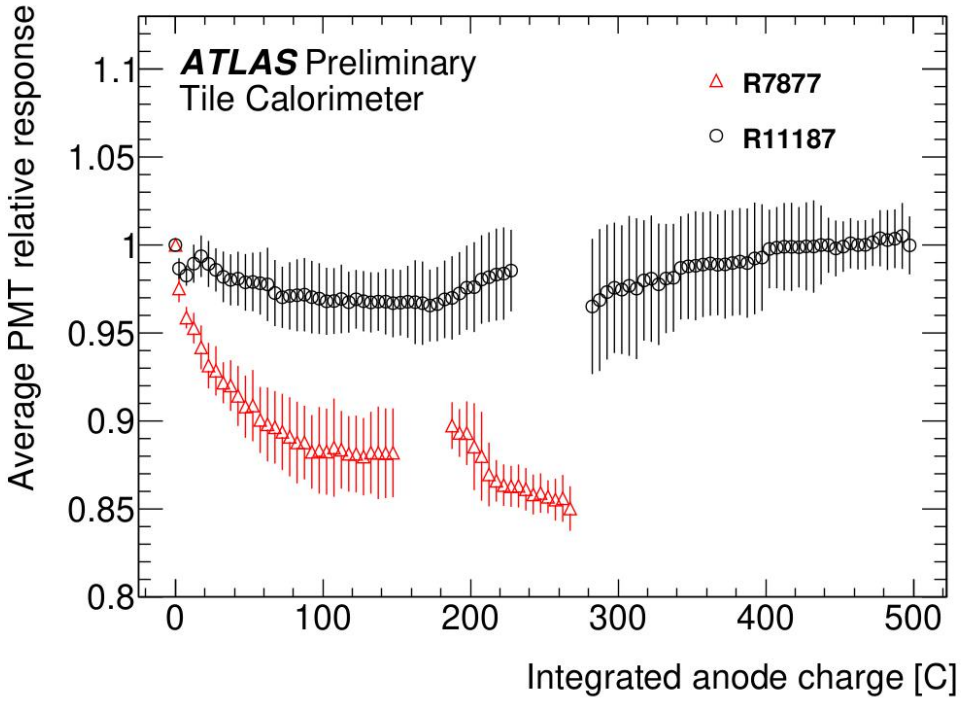
Mechanics

- Current TileCal superdrawers are ~2.8 m long, heavy and difficult to extract for maintenance.
- Upgrade introduces **Mini-Drawers** (MDs): shorter substructures (694 mm, ~22 kg equipped) to simplify handling and access.
- New mechanical layout:
  - Long Barrel modules: 4 MDs → 45 PMTs total.
  - Extended Barrel modules: 3 MDs + 2 mini-MDs (mechanical structure to hold PMTs in correct position) → 32 PMTs total.
- Each MD is divided into **two independent sections** for redundant cell readout (6 cells per MD, 12 PMTs).
- **Electronics and readout** are **fully independent** for each half of the MD.
- Dedicated tooling developed for MD insertion/extraction and routing of low voltage (LV) and high voltage (HV) cables, fiber optics, and cooling.
- Existing module mechanics outside of the drawers remains unchanged.



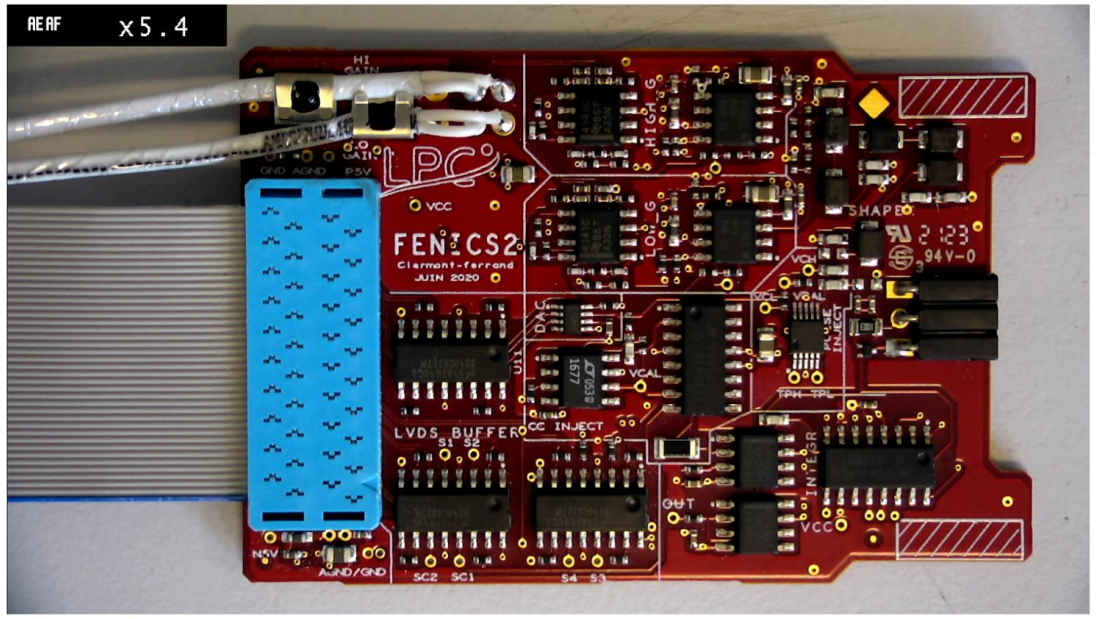
On-detector electronics: PMT and active divider

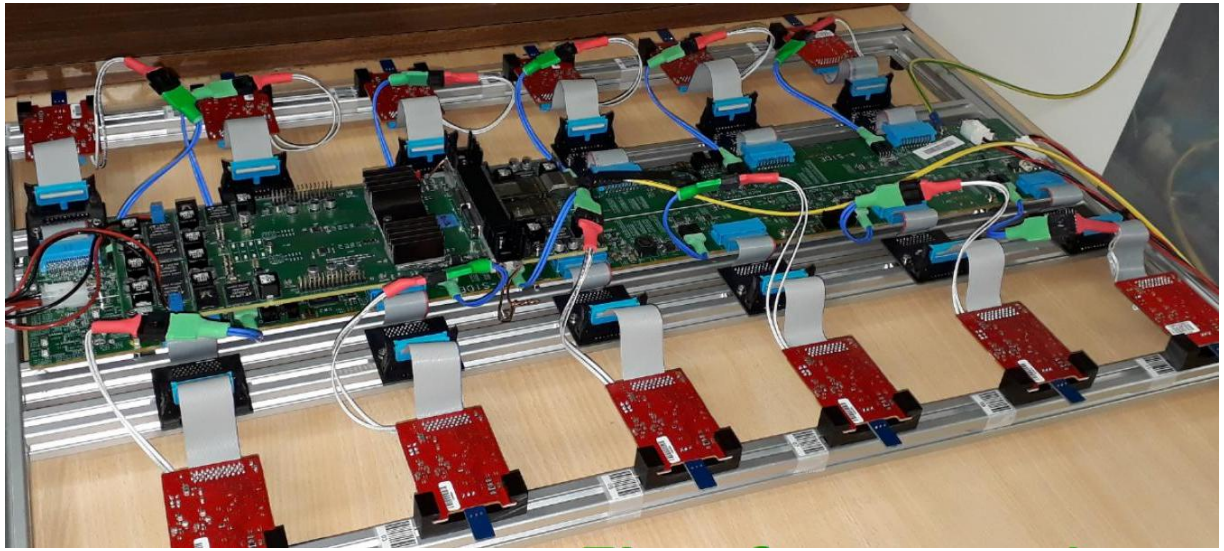
- About 10% of the PMTs (~1000 units) will be replaced due to aging (response loss > 25%) in most exposed regions (close to gap between barrel and extended barrel).
- New PMTs: **Hamamatsu R11187**, same geometry as old PMTs (Hamamatsu R7877), but with **improved stability** and higher **quantum efficiency**.
- All PMTs (new and reused) will be connected to active HV dividers, offering:
  - **Improved linearity** at high anode currents (up to 100 μA).
  - **Better** response **stability**.



On-detector electronics: FENICS card

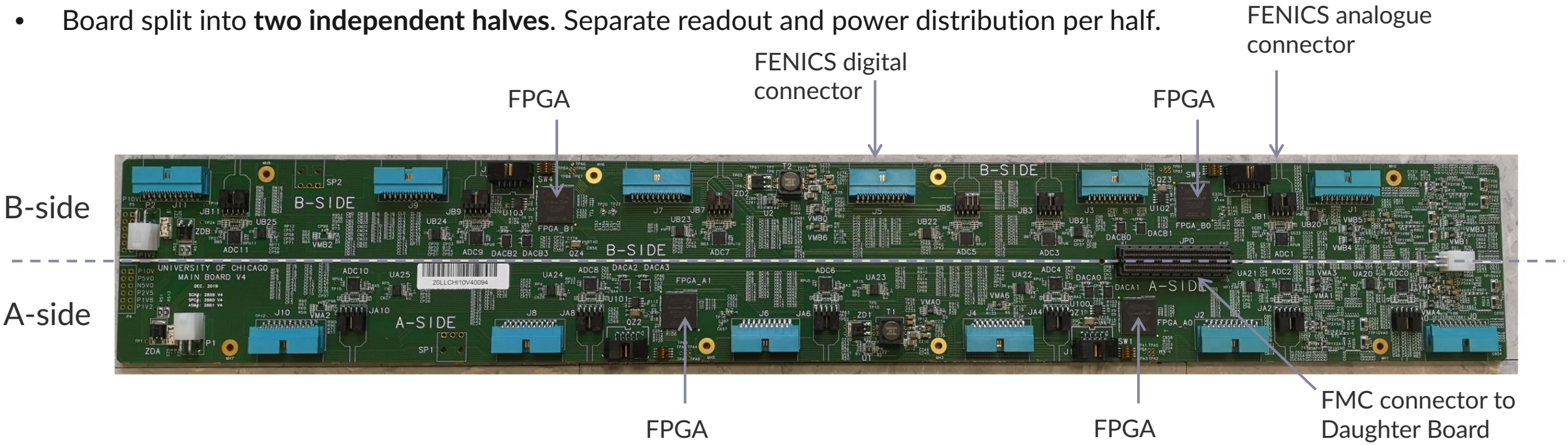
- New **front-end board** for HL-LHC: Front-End for the New Infrastructure with Calibration and Signal shaping (**FENICS**)
- Provides **pulse shaping** for PMT signals with **two gain amplifications**: Low Gain (×0.4) and High Gain (×16). Dynamic range: **0.2 pC to 1000 pC**.
- **Integrates slow signal readout** (~ms current integration). Used for cesium calibration and luminosity monitoring.
- Equipped with built-in **Charge Injection System** for **Analog-to-digital converter (ADC) calibration**. Analog signals are forwarded to the next board in the chain (Main Board)





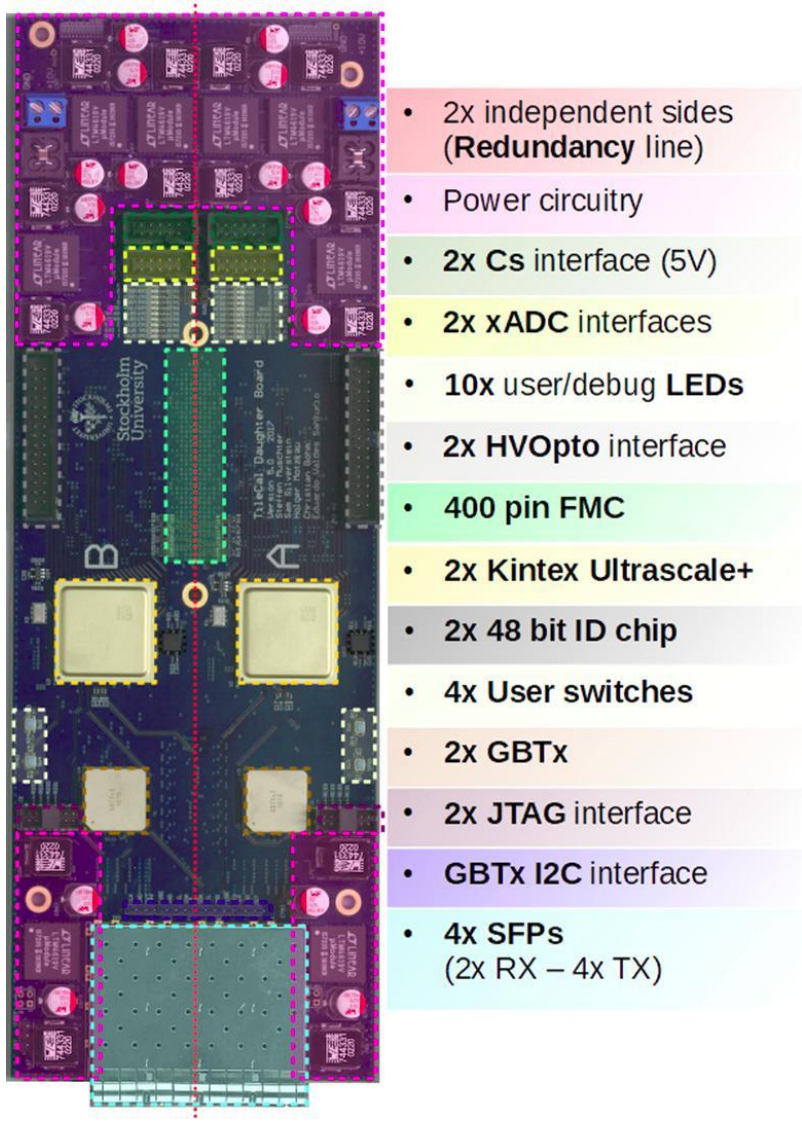
On-detector electronics: Main Board

- 69 cm long board. One board per MD.
- Function: **digitization of signals** from up to **12 FENICS**. Control and configuration of FENICS. Routing of digitized data to Daughter Board.
- ADCs:
  - 24 **12-bit dual ADCs @40 Msps** (fast readout).
  - 12 **16-bit ADCs @50ksps** (integrator readout).
- Board split into **two independent halves**. Separate readout and power distribution per half.



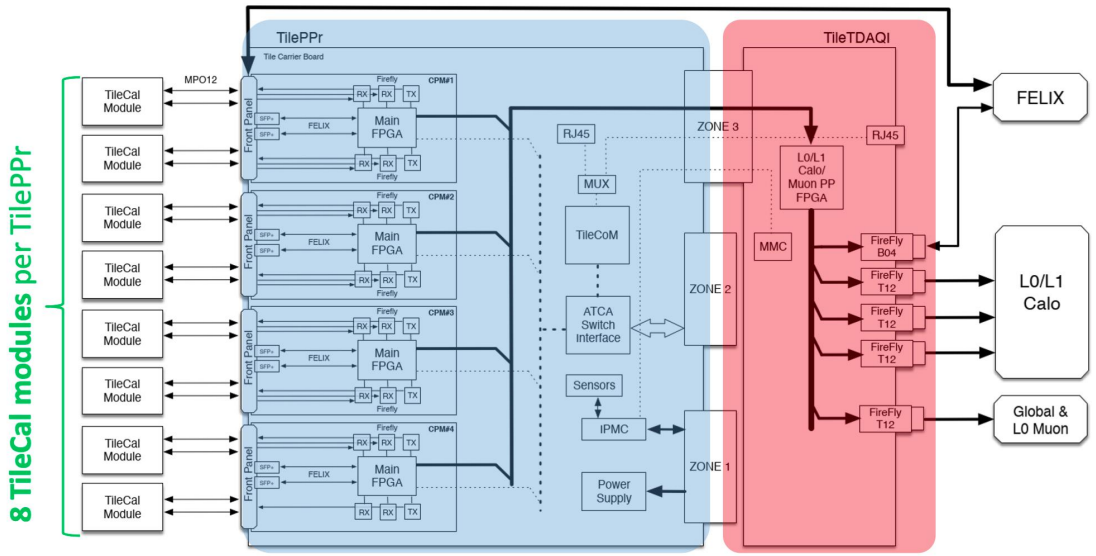
On-detector electronics: Daughter Board

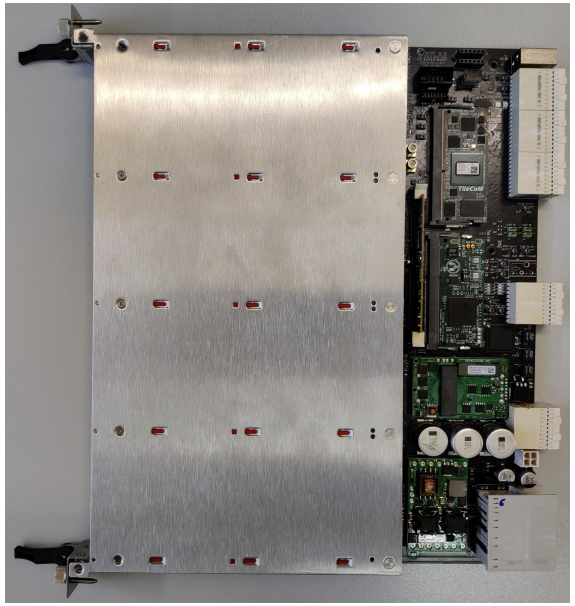
- High-speed **interface** between **Main Board** and **off-detector** electronics.
- Collects digitized PMT signals from the Main Board and transmits data optically.
  - **2 × Quad Small Form-factor Pluggable (QSFP)** high-speed optical modules. **4 uplinks** at **9.6 Gbps**. 2 **downlinks** at **4.8 Gbps**.
- **Clock** and **command recovery/distribution** via 2 GigaBit Transciever (GBTx) chips (LHC clock).
- Data processing and communication using 2 Kintex UltraScale+ FPGAs.
- Redundant design: Each half controls 6 PMTs → 12 PMTs per Daughter Board.
- Data link redundancy.



Off-detector electronics: Tile PreProcessor

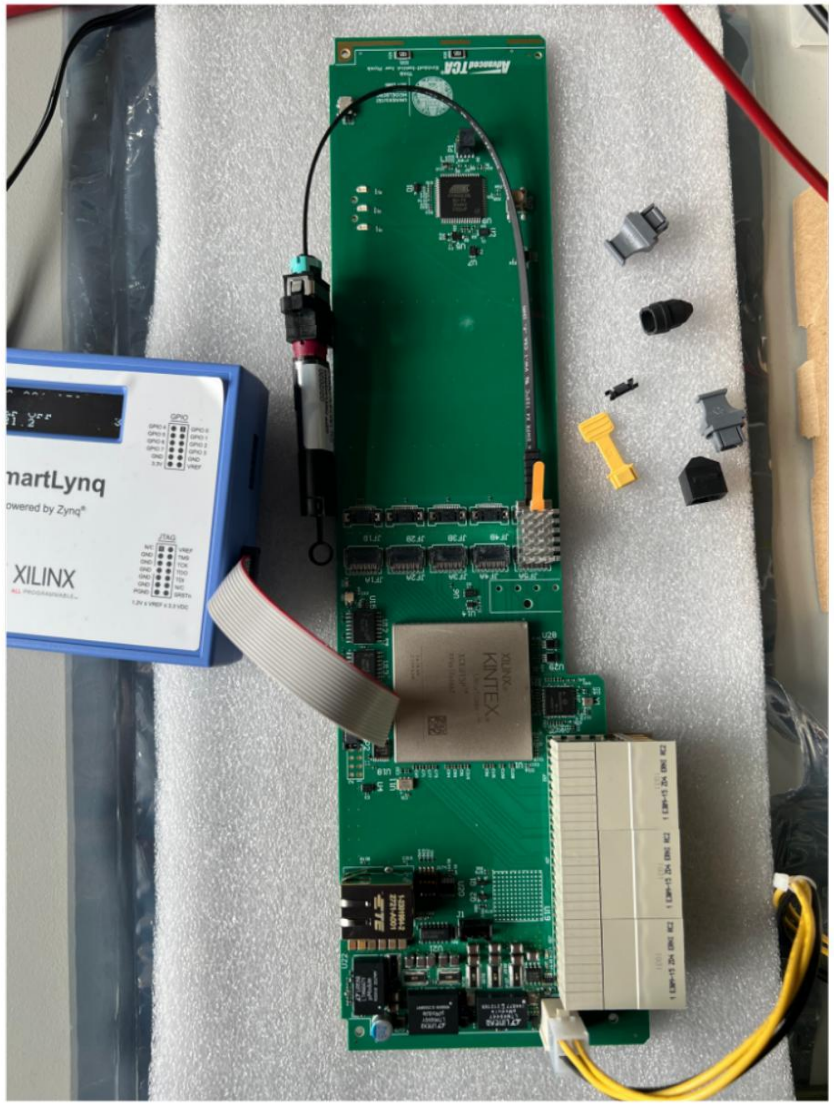
- **Tile PreProcessor** (PPr) → core of off-detector electronics.
  - Formed by 1 Advanced Telecommunications Computing Architecture (ATCA) carrier + 4 Compact Processing Modules (CPM).
  - CPM → Advanced Mezzanine Card (AMC) with 2 Small Form-factor Pluggables (SFPs) and Kintex UltraScale (KU115). Each CPM process data from 2 modules (one from long barrel and one from extended barrel, 7 MDs).
- Functions:
  - **Real time** data **processing** and signal **reconstruction** @40 MHz. **Storage** of up to **10 µs** of data samples in pipelines.
  - **Clock distribution** towards on-detector electronics. Remote **configuration** of the **front-end** electronics FPGAs.
  - **Interface** with **ATLAS trigger** and **readout system (Front-End Link eXchange, FELIX)**.





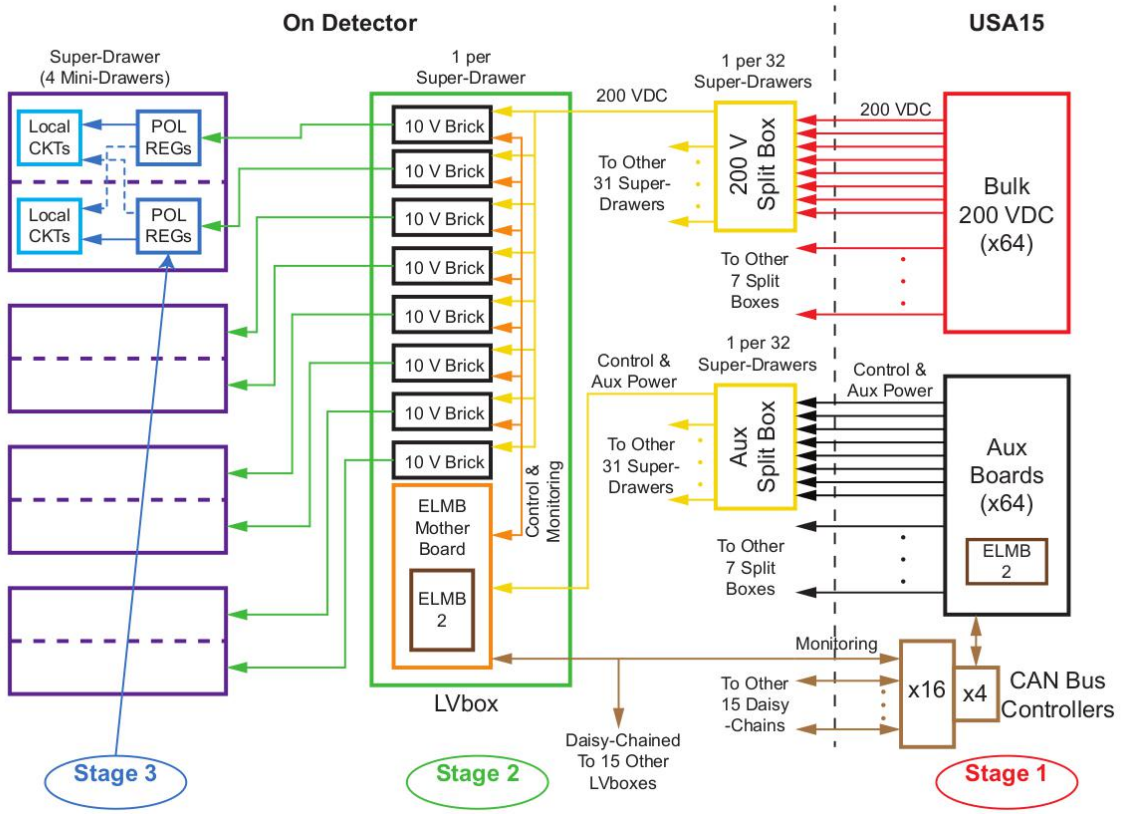
Off-detector electronics: TDAQi

- **TDAQi** Rear Transition Module (RTM):
  - Mounted on the rear side of the ATCA Carrier, **connected directly** to the **CPMs.**
- Performs synchronous reception of cell energies from CPMs.
- Computes **trigger objects** (e.g. trigger towers or groups of cells with varying granularity).
- Handles copying and **synchronous distribution of trigger objects** to L0Calo, L0Muon, and Global trigger systems.
- Sends **monitoring data to FELIX** for further analysis and diagnostics.
- 32 TDAQi RTMs required to cover the full TileCal interface with all L0 trigger subsystems.



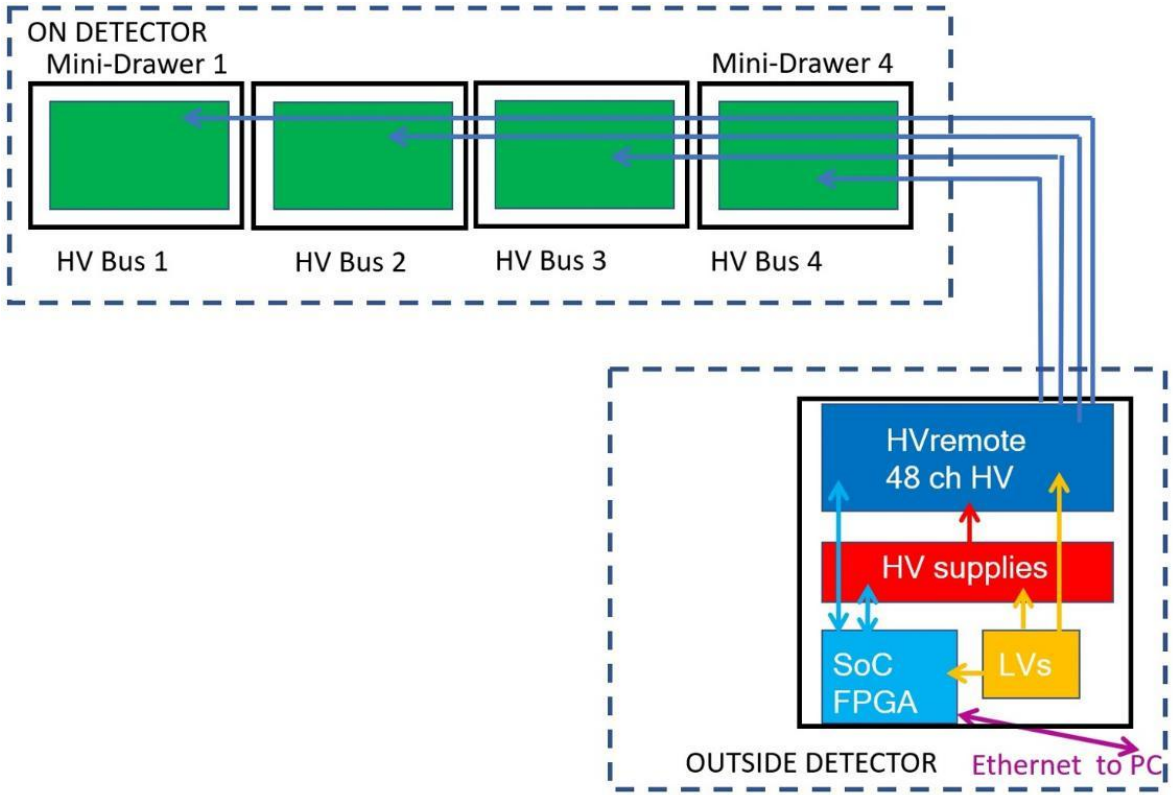
Low voltage power distribution

- **Three-stage power system** developed for improved noise performance, reliability, and radiation tolerance.
- **Input**: **200 V DC** supplied to the Low Voltage Power Supply (LVPS) bricks.
- Conversion:
  - **LVPS bricks** transform **200 V DC → 10 V DC**.
  - **Point-of-Load** regulators derive the voltages required by **on-detector electronics**.
- Redundant power scheme:
  - **Each MD** is powered by **two independent bricks**.
  - Redundancy control via diode circuits on the Main Board.
- System is remotely **monitored** via the Detector Control System, using the Embedded Local Monitoring Board (ELMB) through a CANbus interface.
- LVPS bricks and control electronics are located in the LV box in the finger of each module.



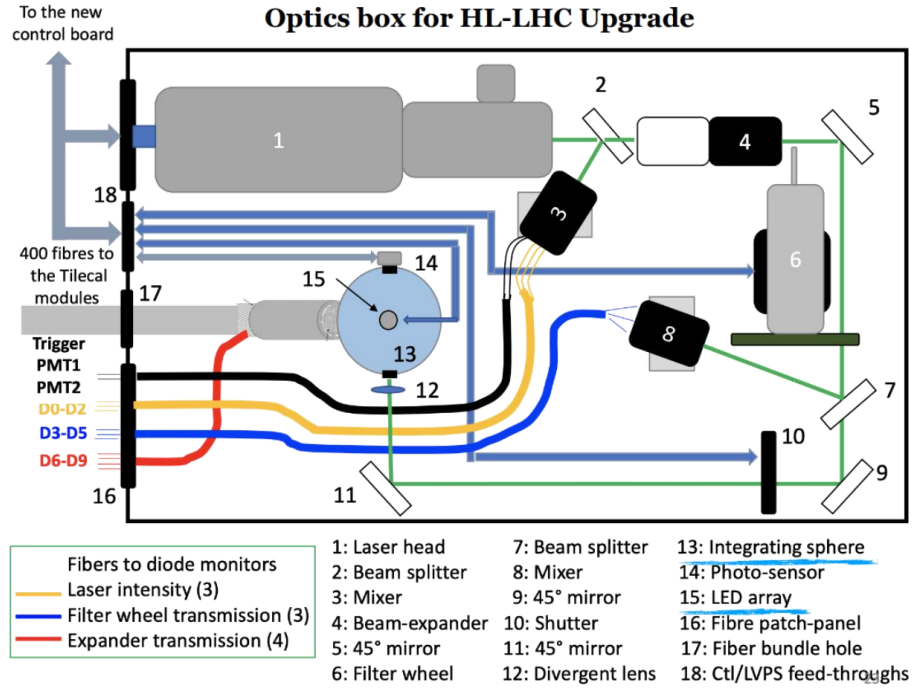
High voltage power distribution

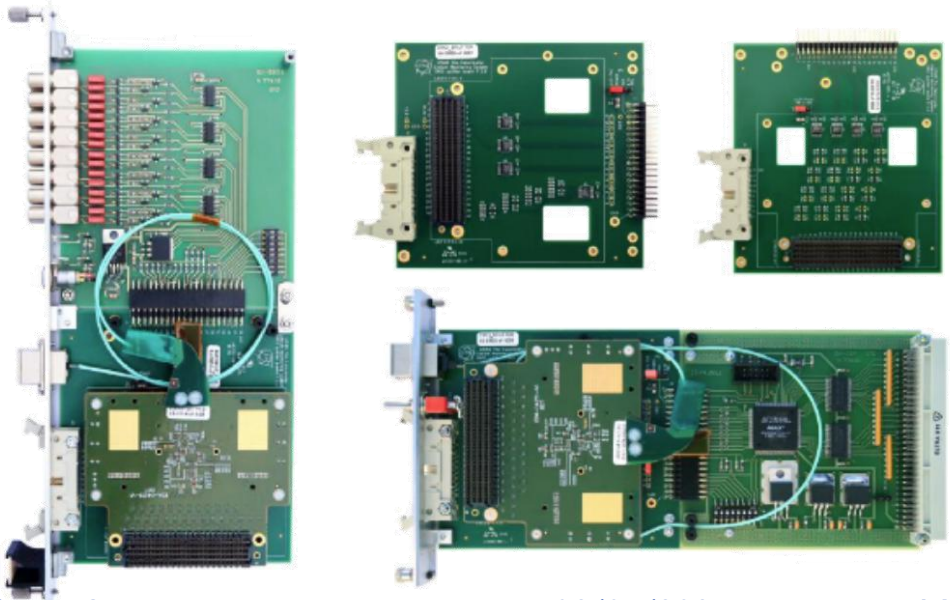
- New HV architecture: supplies and regulators **installed in ATLAS service cavern**, ~100 m away from the detector.
- **One HV channel per PMT**, with **good linearity** up to 100 μA (maximum 40 μA expected for exposed cells).
- **On-detector passive** bus boards **distribute HV** to each PMT in the MDs.
- **Remote regulation** for individual channels in boards **outside** of **high radiation area**.
- HV delivered via dedicated cables to each PMT (~100 m per channel).
- The new system guarantees:
  - **No radiation tolerance issues for regulation circuit**.
  - Simplified maintenance and easier access.



Calibration systems

- **Charge Injection** System (pC/ADC conversion).
  - New FENICS card equiped with two capacitors (200 pF, 5.1 pF) for fast readout calibration.
- **Laser Calibration** System (monitor PMT variations)
  - **New TDAQ interface** and control electronics under test.
  - Replacement of the pulsed laser and addition of a **continuous LED array to mimic pile-up** conditions (simultaneous signals from multiple interactions per bunch crossing).
  - Optical line redesigned with an **integrating sphere** to combine pulsed and continuous light.
- **Cesium** Calibration System (maintain global energy scale, monitor all the optical components).
  - Full **replacement of on- and off-detector electronics**. New electronics based on CERN EMCI-EMP architecture.

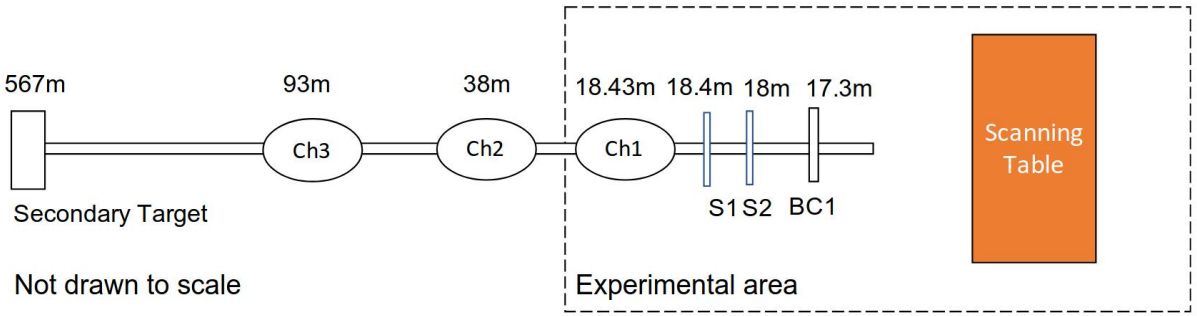


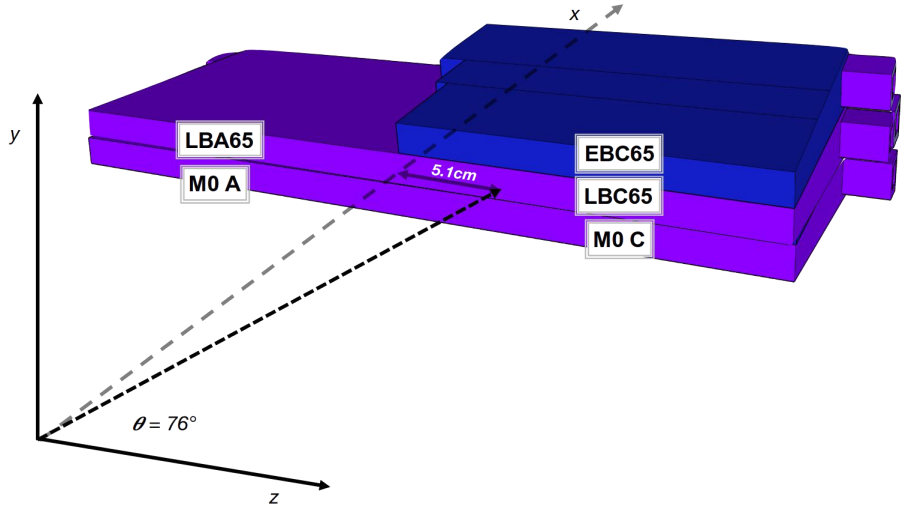


Test-beam campaigns

- Purpose: **validate upgraded electronics** with real beam data and **carry out physics studies**.
- **Three modules tested**: two Long Barrels and one Extended Barrel.
- Modules partially **equipped** with **prototypes of Phase-II** electronics.
- Exposed to **electron**, **muon**, and **hadron** beams over a wide energy range.
- **Different module orientations** used to study performance across configurations.
- Cherenkov detectors were used for particle identification in the beamline.

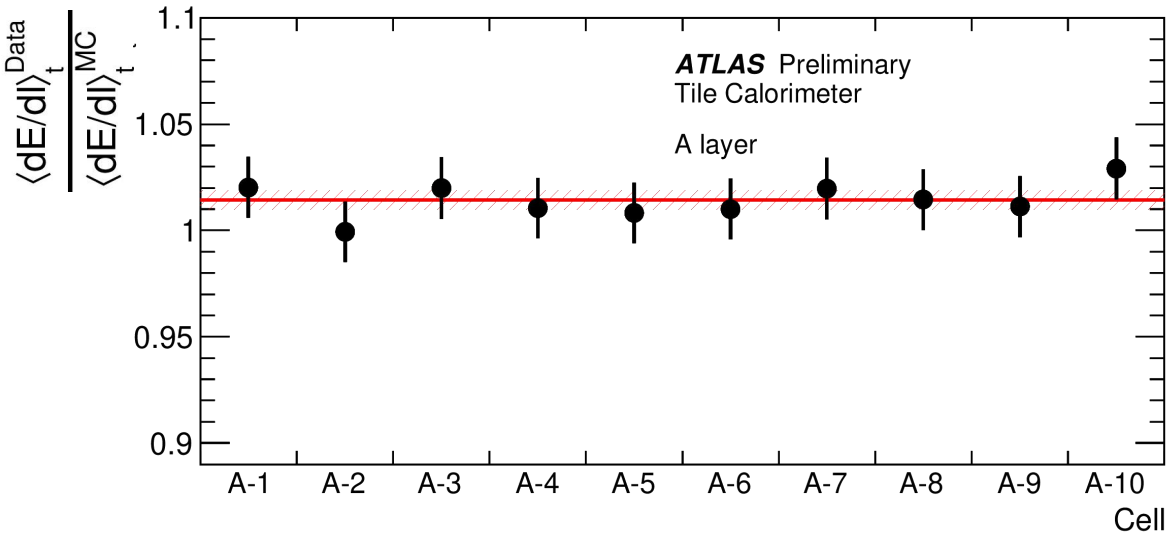
TileCal modules on the scanning table at the test beam area at CERN

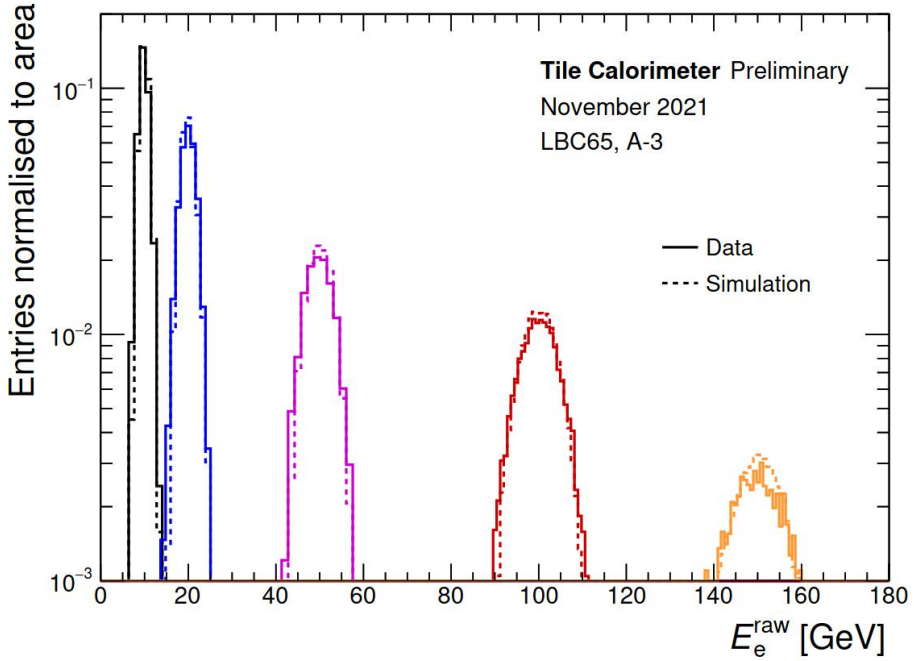




Test-beam campaigns - Selected results

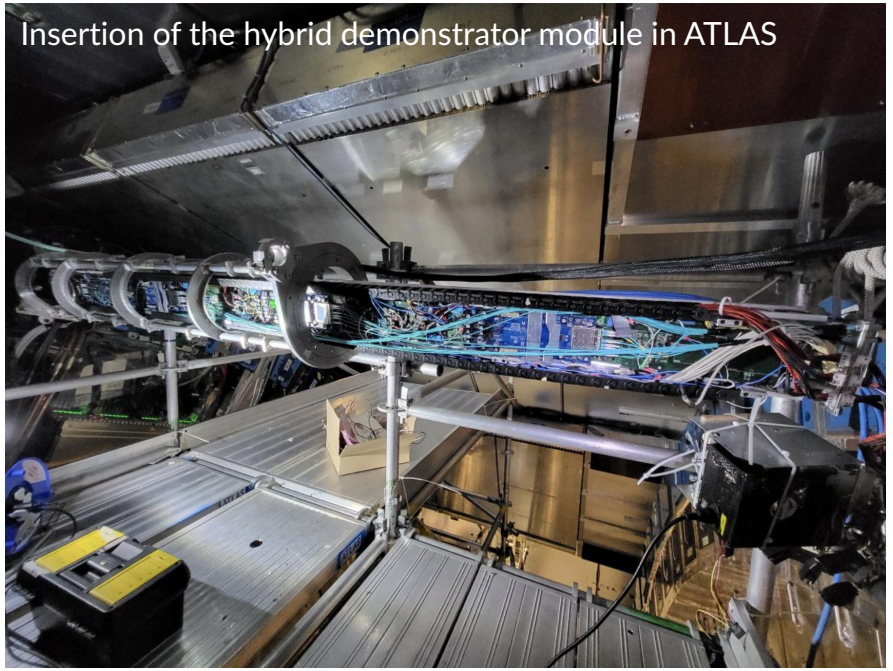
- **160 GeV muons** used to probe layer uniformity across cells.
  - Energy loss proportional to muon track length. Validates cell equalization.
  - **Response uniformity** better than **1%**, with maximum data over Monte Carlo (MC) offset of 1.4%.
- **Electrons** used to determine the EM scale via charge-to-energy (pC/GeV) calibration.
  - Data collected with 10, 20, 50, 100 and 150 GeV beams.
  - Very **good agreement with simulation**, verifying **linearity** and energy resolution.

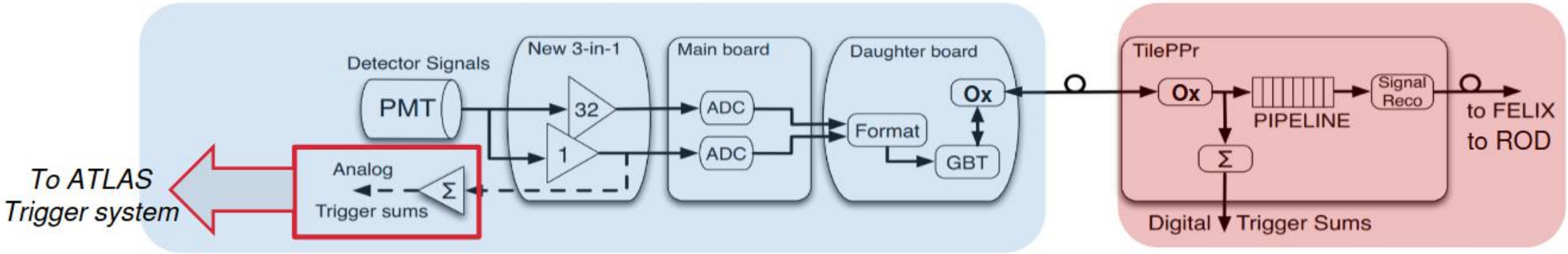




Phase-II demonstrator in ATLAS

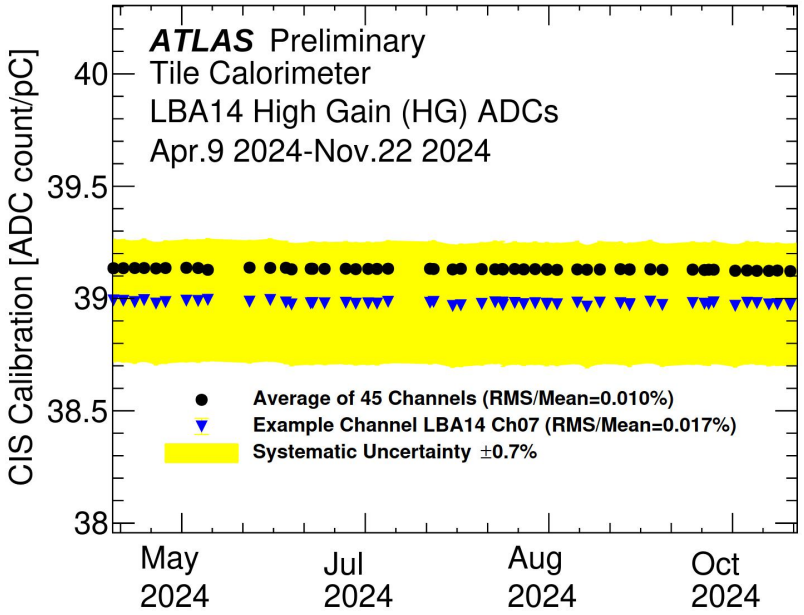
- In Summer 2019, a TileCal long barrel module (LBA14) was installed with prototype Phase-II electronics.
- The **demonstrator** operates in a **hybrid mode**: data read out using **new digital path** while **analog trigger** signals are still provided to the legacy system.
- The module is **fully integrated** with the **ATLAS** system and has been successfully collecting physics data during Run 3.
- Extremely useful exercise to learn how to operate new electronics and identify problems timely.

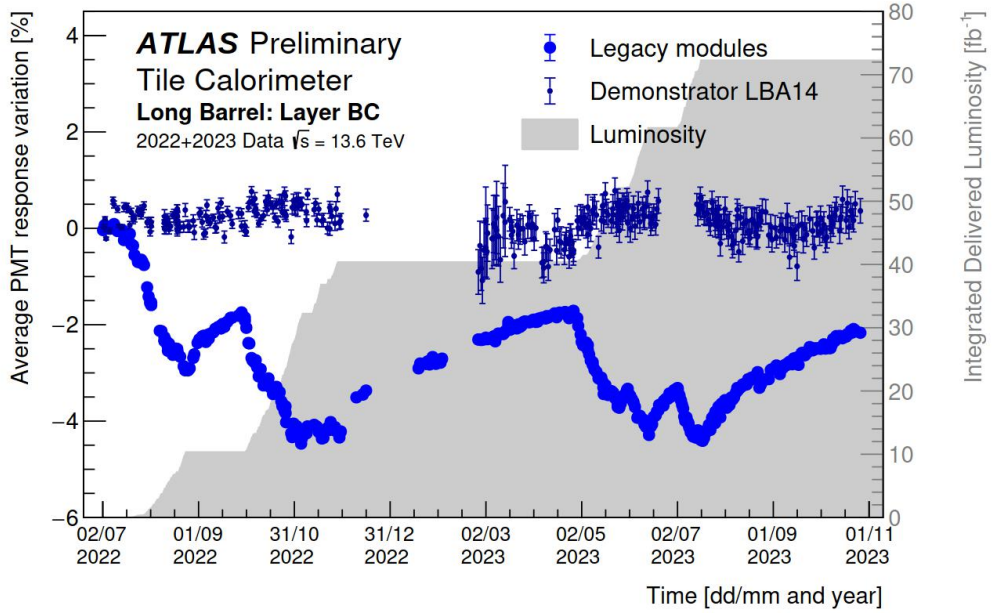

Insertion of the hybrid demonstrator module in ATLAS



Phase-II demonstrator in ATLAS

- Phase-II demonstrator performance in calibration systems:
  - Charge Injection System Calibration Stability.
    - Shows the average calibration constants of all High Gain (HG) ADCs in Demonstrator (2024). Excellent stability over time, with RMS ~0.01% across 45 channels.
  - Laser Calibration Response.
    - Legacy modules (R7877 PMTs) show clear down-drifts during high-luminosity proton-proton collision periods. **Demonstrator** module (R11187 PMTs) exhibits **remarkable stability**, with minimal drift.





Summary

- The goal of collecting up to 4000 fb^{-1} of integrated luminosity by the end of HL-LHC data-taking offers excellent opportunities to test the Standard Model with high precision and to probe physics beyond it.
- However, this opportunity comes with several challenges:
  - **Higher radiation** levels.
  - **Increased** readout **rates**.
  - Challenging **pile-up** conditions.
- To address these challenges, TileCal will undergo an upgrade after Run 3:
  - All on- and off-detector **electronics** will be **replaced**. Radiation-hard, fully digital electronics compatible with 1 MHz trigger rate.
  - Around **10% of PMTs** will be **replaced** with newer, more stable models.
  - **New mechanical structure** and **modular services**, easier to handle and maintain. New **robust power distribution** systems.
- **Extensive test-beam** campaigns validate the system and enhance understanding of calorimeter performance.
- **Prototype electronics** are already **integrated** in the **ATLAS** detector via the TileCal Demonstrator.