ATLAS TILE CALORIMETER PHASE-II UPGRADE – CURRENT STATUS AND ITS DEMONSTRATOR MODULE

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ON BEHALF OF THE **ATLAS TILE CALORIMETER SYSTEM**

33RD INTERNATIONAL WORKSHOP ON DEEP INELASTIC SCATTERING AND ITS RELATED SUBJECTS
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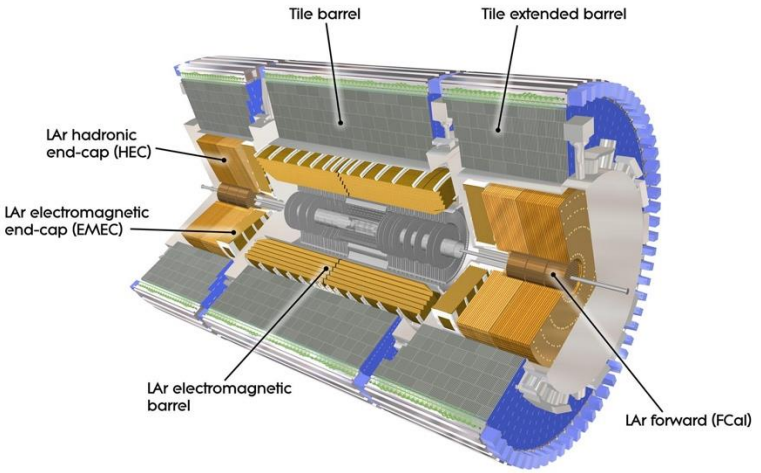
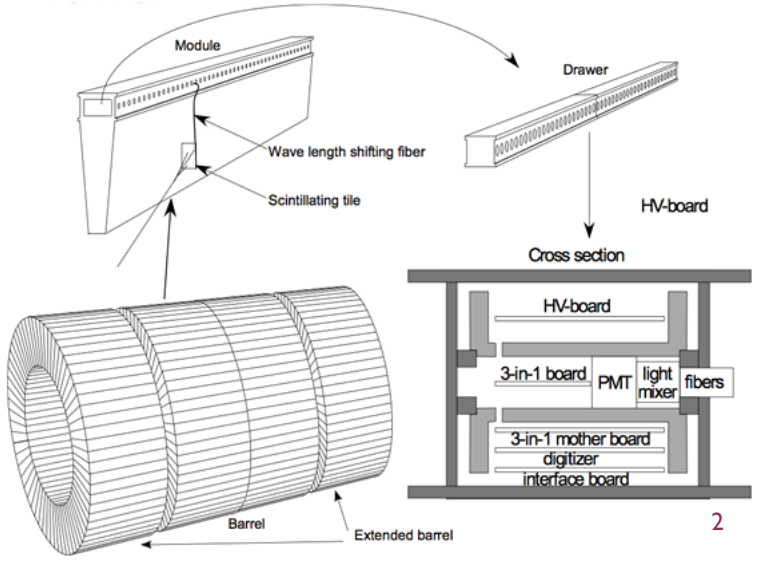
ATLAS TILE CALORIMETER

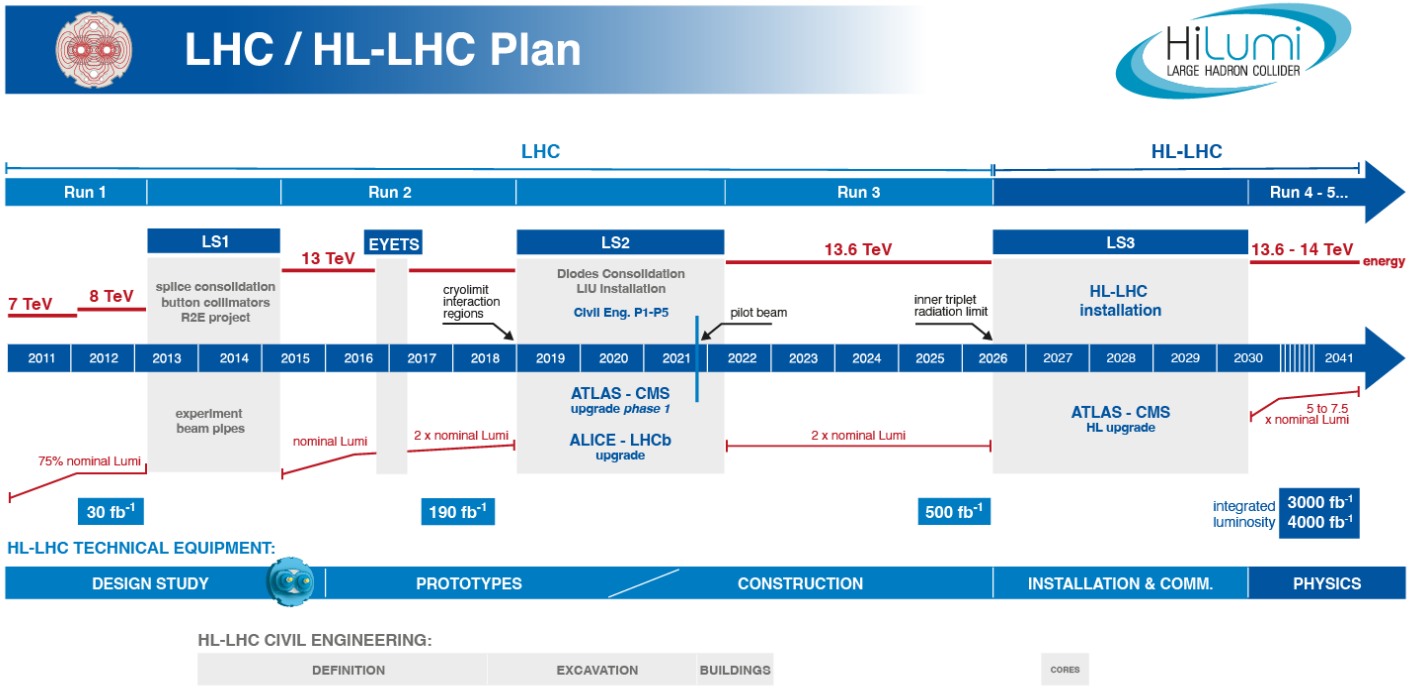
- Central Hadronic Calorimeter: Steel as absorber and scintillating tiles as the active medium
- TileCal is divided into four parts: two halves of the central barrel and two extended barrels, partitions refer to the readout structure, each partition consisting of 64 wedge shaped modules.
- As particles hit the layers of steel, they generate a shower of new particles. The plastic scintillators in turn produce photons, which are converted into an electric current whose intensity is proportional to the original particle's energy
- Responsible for the measurement of jets, missing transverse energy and the hadronic decay of tau leptons
- For a more detailed review of the ATLAS detector please refer to Martina's talk





TileCal legacy structure

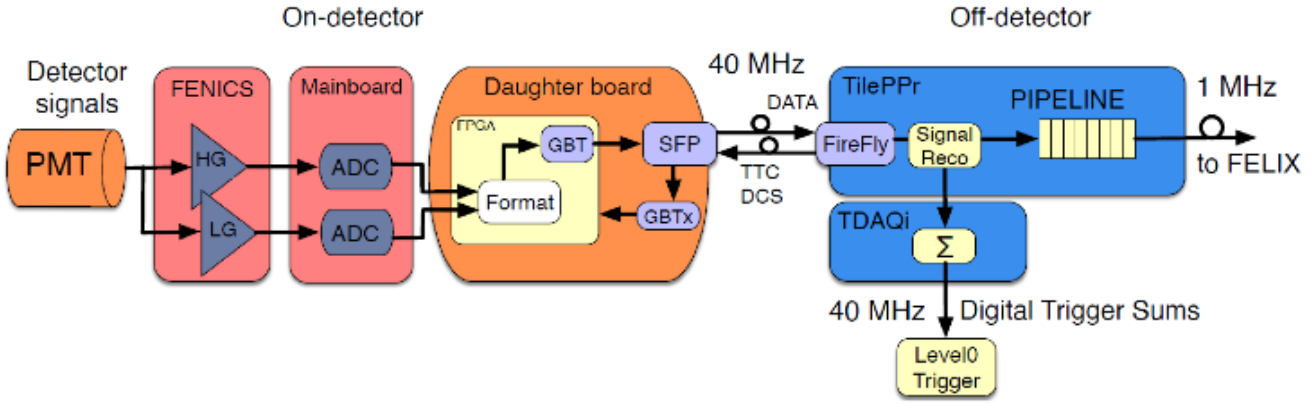
- Last few months of the Run 3 campaign- ending in June
- Starting with decommissioning and then transitioning to the High Luminosity Phase
- Increase in the Instantaneous Luminosity by a factor of 5-7.5
- Implications for Tile Calorimeter (TileCal)
  - Aging components (since late 90's)
  - Build a system which is reliable and operable >15 years from now
  - Degradation of Photo Multiplier Tubes (PMTs) due to large integrated anode current
  - HV and LV Power Supply (PS) must withstand the radiation
  - Change in ATLAS Data Acquisition (DAQ) to match the HL-LHC requirements
  - Upgrade electronics to be more radiation tolerant



HL-LHC UPGRADE OVERVIEW

- HL-LHC conditions will present a significant challenge to the detectors
- High radiation environment as the number of collisions per bunch crossing increases from 65 to up to 170
- TileCal upgrades needed for HL-LHC readiness:
  - New on/off-detector readout electronics, with 40 MHz continuous data readout required for compatibility with full digital trigger and DAQ architecture
  - Upgraded high/low voltage power systems redesigned for new electronics and increased radiation tolerance
  - Upgrade of calibration systems new control electronics (cesium & laser), optics, and improved Cesium system hydraulics
  - New super drawer mechanics smaller mini-drawers with enhanced mechanical and cooling support

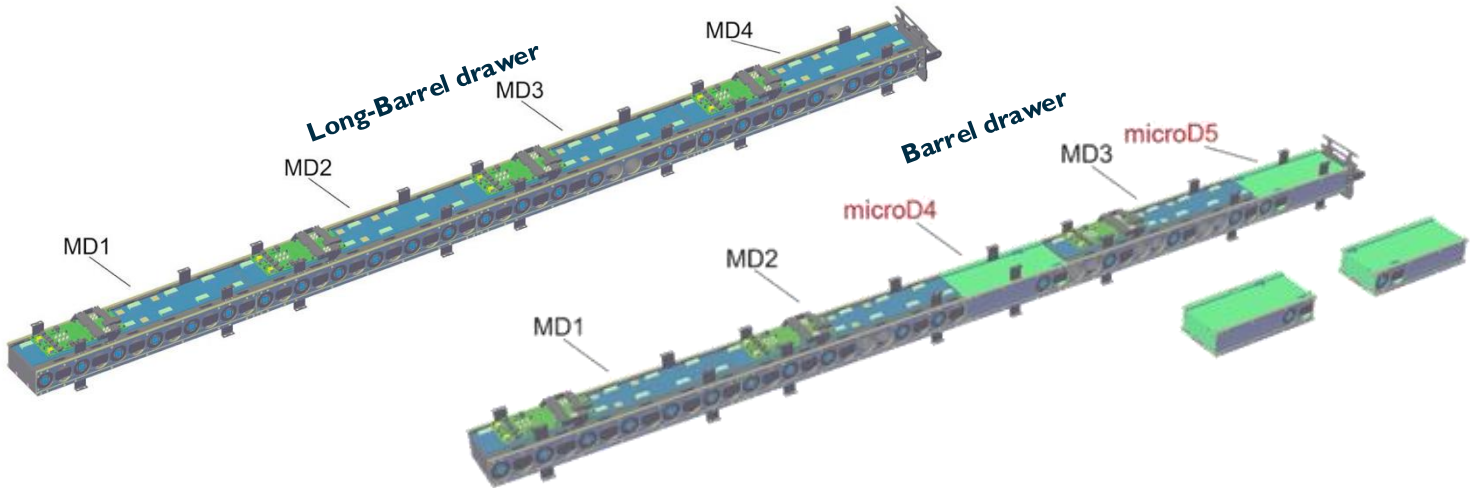
UPGRADED READOUT FOR THE HL-LHC

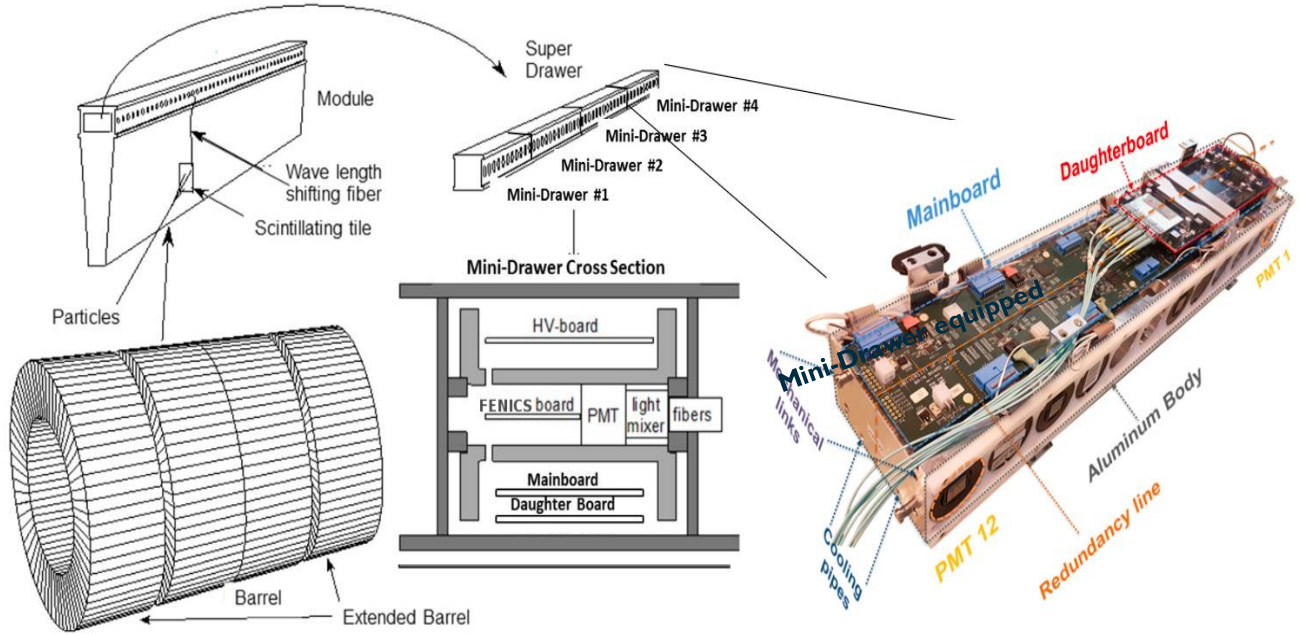


- On-detector electronics will transmit full digital data at the LHC frequency → 40 MHz read out the entire detector and 6,000 optical fibres
- Provides reconstructed energy for every bunch crossing to the Level 0 system
- Buffer pipelines are moved to off-detector and real-time data processing is introduced
- Front-End Link eXchange (FELIX) is the upgraded interface between the front-end electronics and the ATLAS Trigger and Data Acquisition (TDAQ) system of the detector
- Redundancy in data links and power distribution for improved system reliability

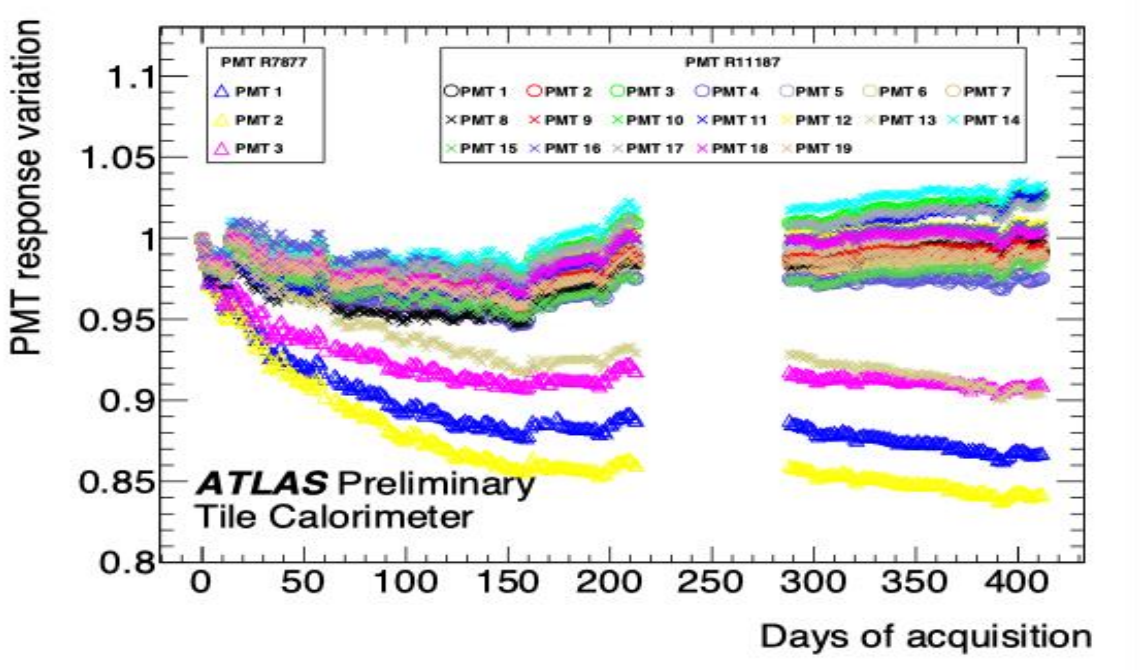
MECHANICS

- Current PMTs and on-detector electronics are housed in a single superdrawer, about 3.0 m in length, making it difficult to extract for accessing electronics
- The new design features minidrawers (MD) with:
  - LB consisting of 4 MDs
  - EB consisting of 3 MDs with two micro-drawers
- Each minidrawer has 12×PMTs, 12×FENICS, 1×Mainboard, 1×Daughterboard, 1×High Voltage distribution board, 1× Low Voltage Power Supply (LVPS)
- The MDs are multipurpose; providing robust mechanical and cooling links
- Make it easier for installing and servicing electronics





MECHANICS - PMT BLOCKS

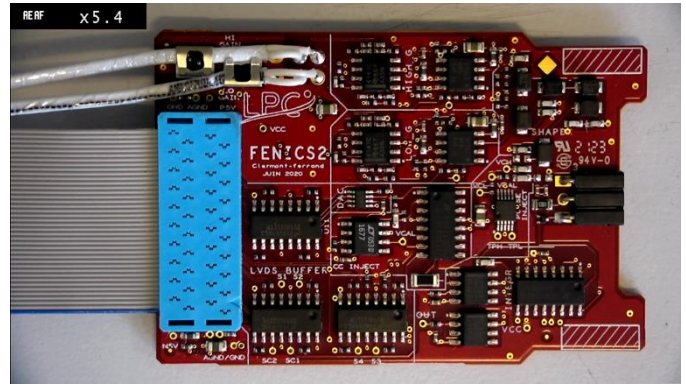


- Time evolution of the PMT response for different PMT models - data taken between 12/18/2020 and 4/17/2022
- Statistical uncertainty is negligible, systematics uncertainty on individual measurement - determined by monitors - is less than 2%.
- Missing data points correspond to a period (Fall 2021), with many interruptions of data taking due to several upgrades and maintenance of the DAQ system, while still integrating charge.

- Radiation damage and ageing electronics degrade the light yield and uniformity across the detector
- 10% of the most degraded PMTs will be replaced by an improved version – HAMAMATSU R11187
- Passive high voltage dividers will be replaced with active dividers, more stable at high currents for HL-LHC
- Most of the electronics have already been produced and delivered to CERN

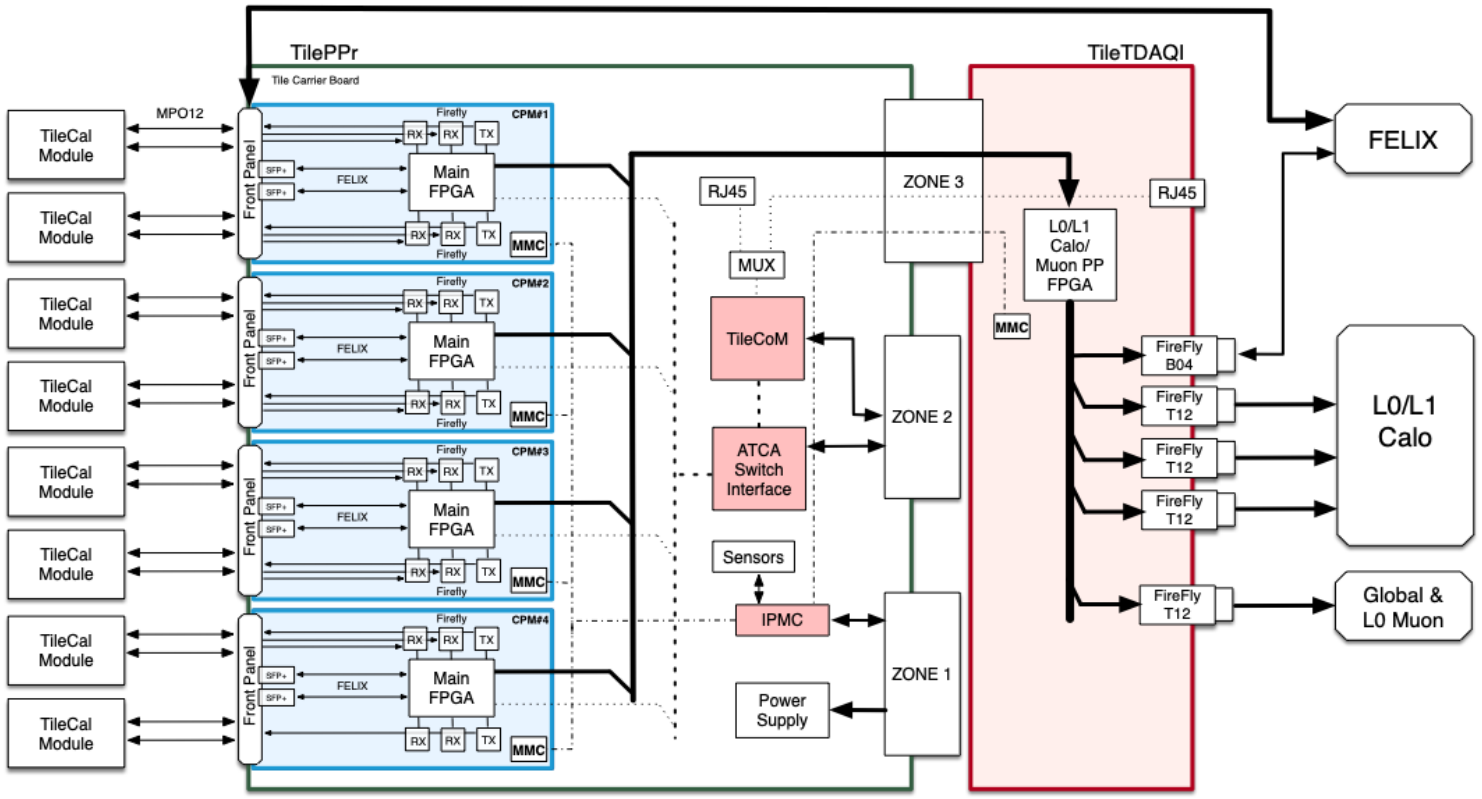
ON-DETECTOR ELECTRONICS

- **FENICS Card**
  - Shapes and amplifies signals from the PMTs and sends the outputs to the Main Board
  - Bi-gain amplification with 1:40 ratio, with current from 0.2 pC to 1000 pC dynamic range
  - Enables high precision integration for Cs calibration system and luminosity monitoring
  - Includes an Internal Charge Injection System (CIS)
- **Mainboard**
  - Digitizes analog signals from 12 FENICS cards at 40 MHz and transmit the data to the Daughterboard
  - Uses FPGAs to provide digital control and configuration of FENICS
  - Independently distributes low power voltage to the Daughterboard and FENICS
- **Daughterboard**
  - High-speed interface with the off-detector electronics using optical links
  - Detector data transmitted to PreProcessors using 4 uplinks at 9.6 Gbps using Kintek Ultrascale FPGA
  - 2 * GBTx chips for LHC clock distribution and command reception with 2 downlinks at 4.8 Gbps
  - Distributes LHC synchronised clocks, configuration settings and slow-control commands



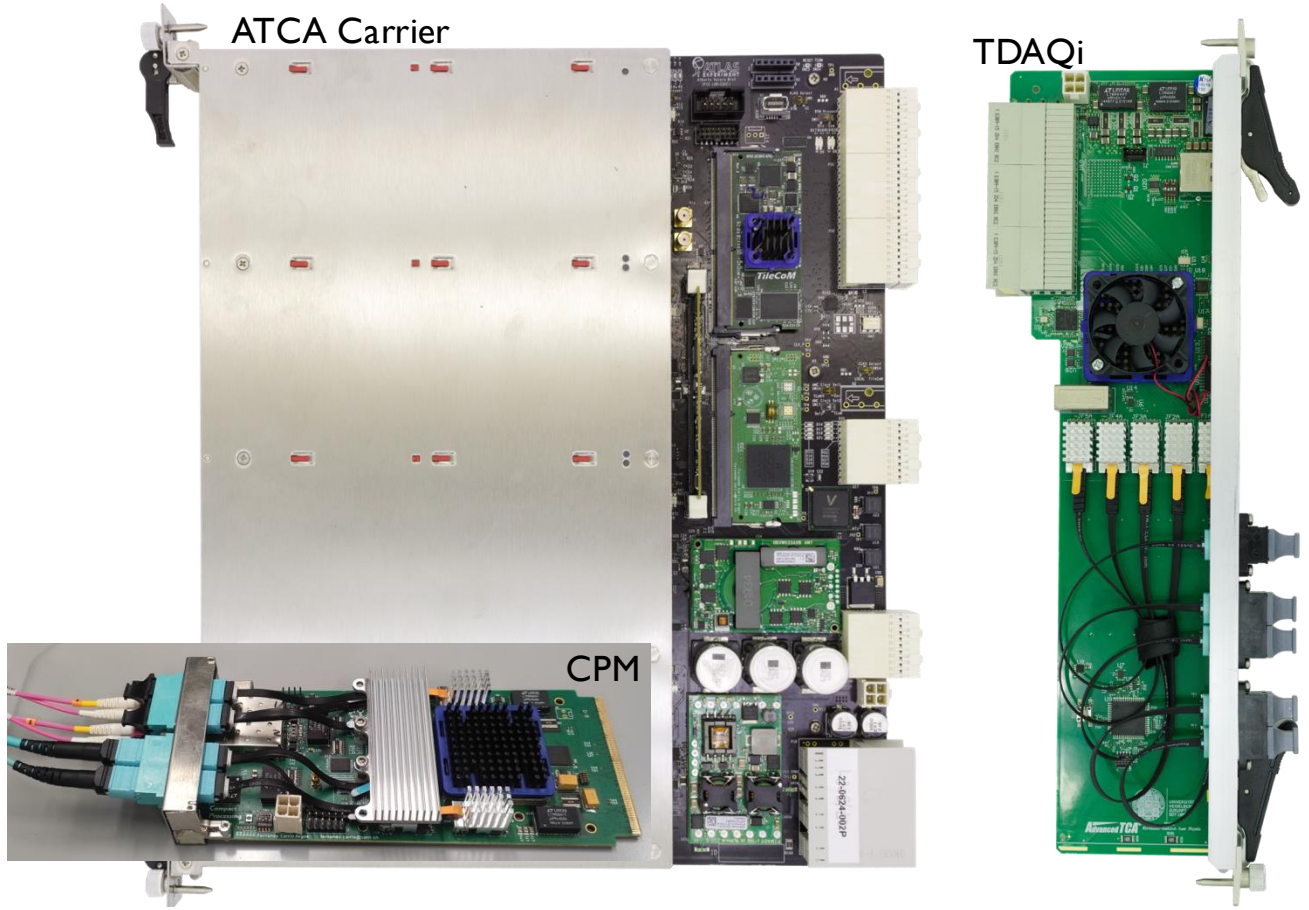
OFF-DETECTOR ELECTRONICS

- Tile Preprocessor (PPr) and the TDAQi are the main components to process full digital data
- PPr consists of: Modular off-detector unit with 1 Advanced Telecommunications Computing Architecture (ATCA) carrier, 4 Compact Processing Modules (CPMs), 1 Tile Controller Module (TileCoM) and 1 Gigabit Ethernet (GbE) switch
  - CPM- acts as the processor, responsible for receiving digitized data from the on-detector electronics and reconstructing cell energy and time at a 40 MHz rate
  - Installed in ATCA crates
- PPr boards process data sent by the daughter board
- ATCA provides power and cooling as well as high speed connections
- TileCoM is responsible for distributing the clock, trigger and timing signals as well as the configuration for the TileCal modules
- GbE connects the CPMs, TileCoM and the DAQ

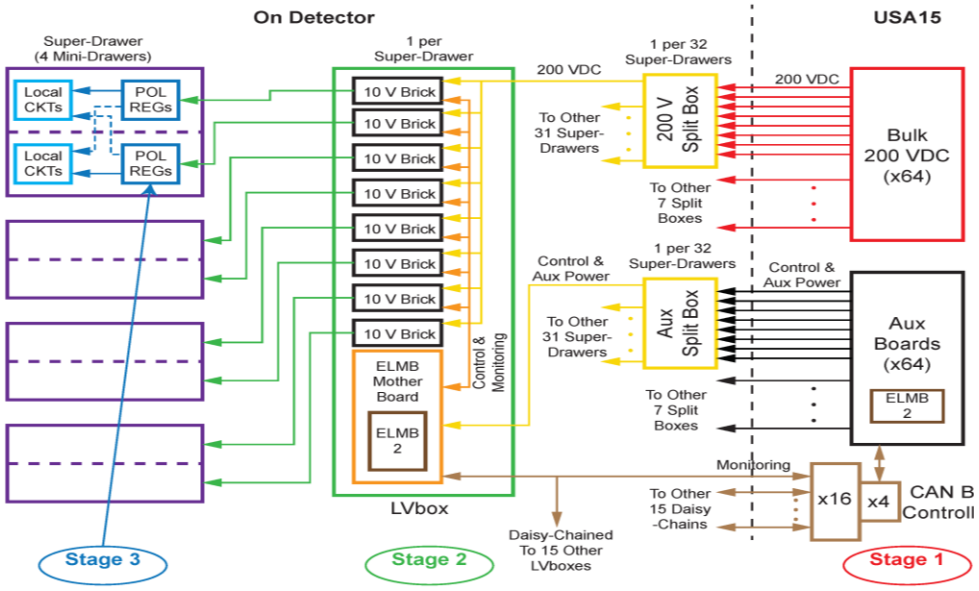


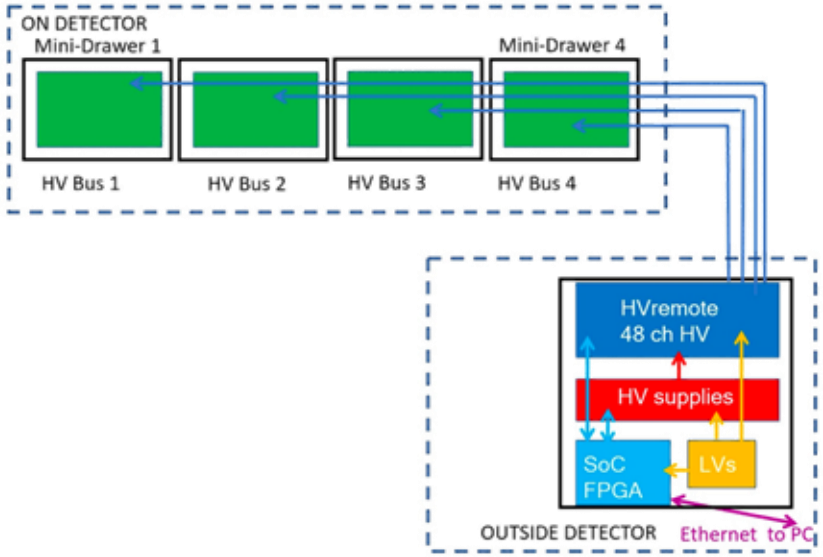
TDAQI

- Interface between TileCal and Phase-II Trigger system
- Manages configuration, clock distribution, and builds trigger primitives per bunch crossing
- FELIX-based off-detector readout and control path
- Sends L1-accepted data to FELIX; interfaces with L0Calo, L0Muon, and Global Trigger
- Uses Xilinx Kintex UltraScale+ (XCKU15P) FPGA with 1 FireFly B04 (FELIX), 4 FireFly T12 (trigger), and 1 SFP (debug)
- Ensures stable power and thermal performance at 9.6 Gbps



LOW AND HIGH VOLTAGE POWER SUPPLY





Low voltage (LV) system

- The on-detector electronics require radiation hard LV power supply
- Three stages of the LV power supply
  - Bulk 200V AC - DC (off-detector)
  - 10V DC-DC converters
  - 10V DC powers the Point of load regulators
- Two LV bricks are connected to each Mainboard
- A total of 8 bricks per LVPS
- Strong constraints for radiation tolerance, noise, power efficiency and reliability

High voltage (HV) system

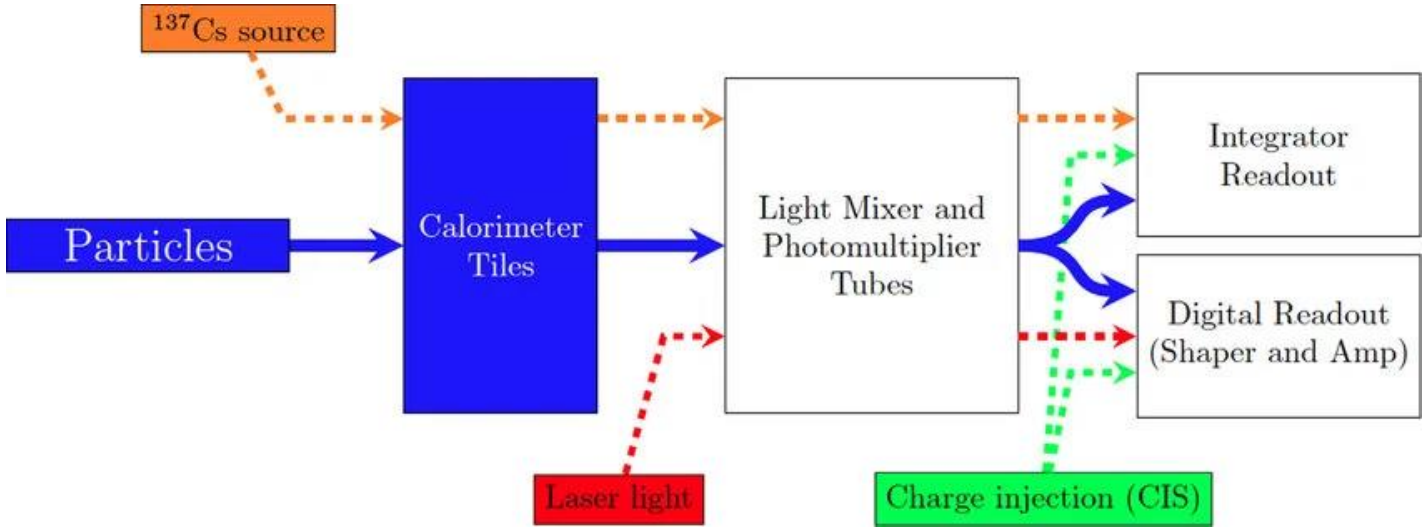
- New HV power supplies and regulator will be installed outside the cavern, away from the high radiation areas
- 256 HV Remote Boards provide regulated HV to 9,852 PMTs
- Controlled via System-on-Chip (SoC) through Detector Control System (DCS) interface, which is used to set voltages and monitor the currents
- HV remote boards will set the high voltage to individual PMTs

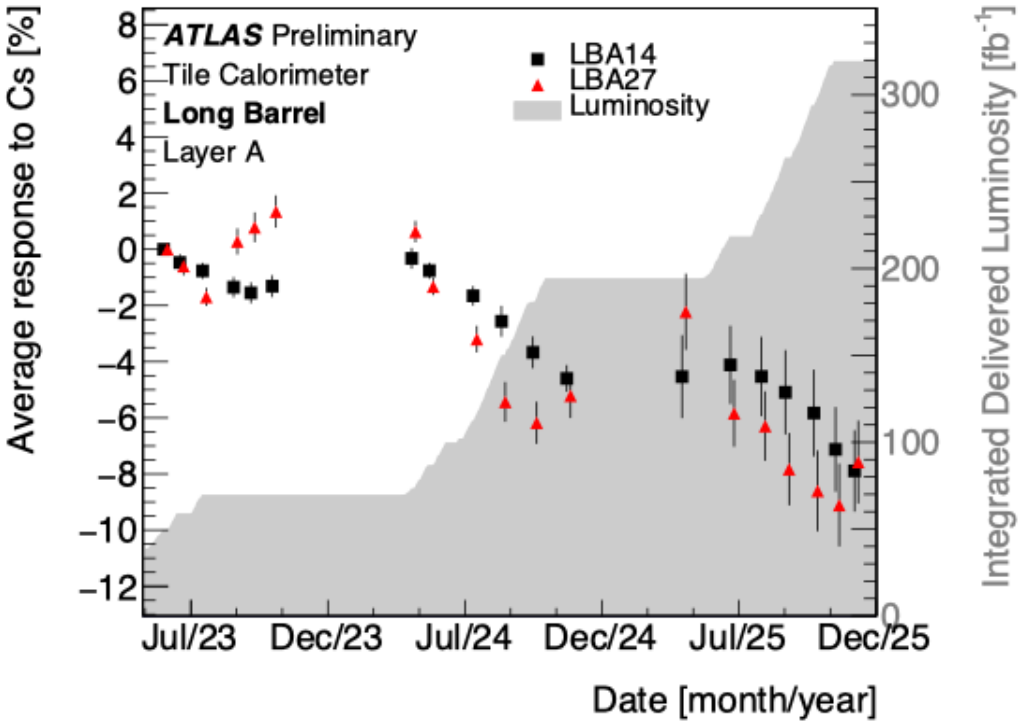
LVPS -- powers the chips, FPGAs while the bulk power goes to the off-detetcor electronics
HVPS – esures stable gain, uniform detetcor response, distributed centrally but controlled individually per PMT

CALIBRATION SYSTEMS

- Different parts of the read out are monitored using series of calibrations
- Laser System : Calibrates PMT response, fast and frequently
  - Short laser pulses simultaneously sent to all PMTs
  - New TDAQ interface and control electronics board
  - New optical line with new integrating sphere for mixing LASER light and light from new LED matrix to simulate pile-up
- Cesium System: Calibrates scintillator response
  - Radioactive $^{137}_{55}Cs$ source hydraulically driven through tiles
  - New control boards (3U and 6U) will be used to manage the Cs system and transfer data to DCS
  - Hydraulics: Existing circuits retained with changes made to improve safety
- Charge Injection system: Injects an electrical charge to the frontend electronics, measures the ADC response linearity and gain of the electronics

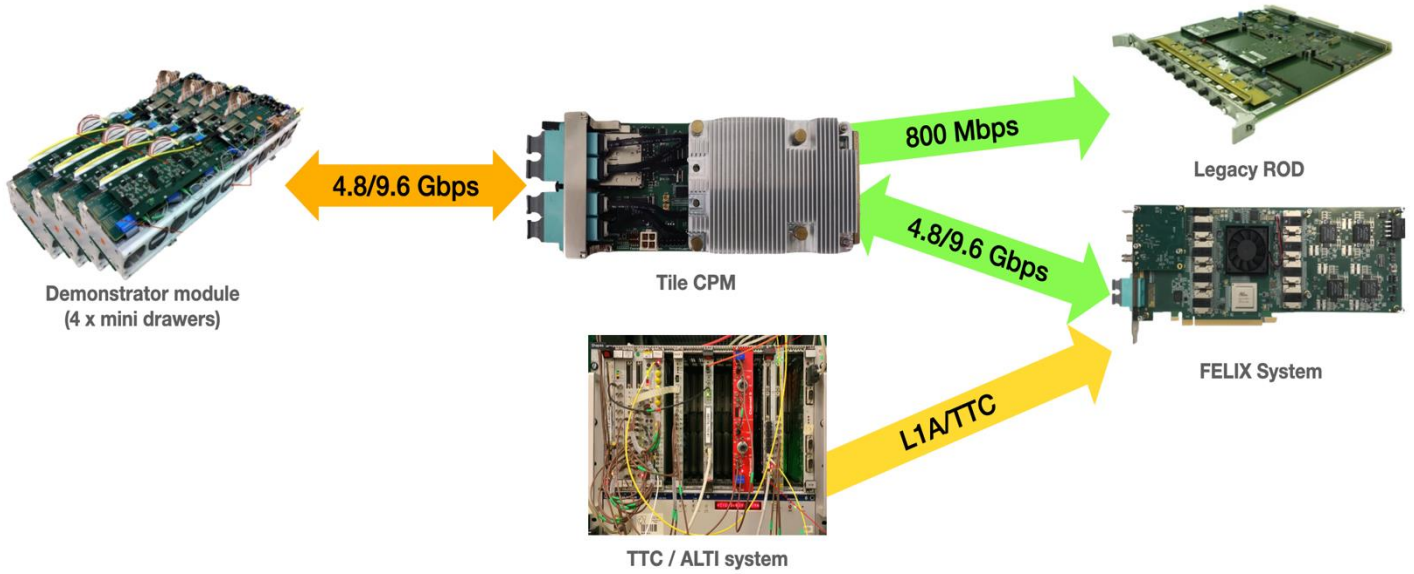
CIS – corrects the electronics gain
Laser – Corrects the PMT gain drift
Cs – Sets the absolute energy scale



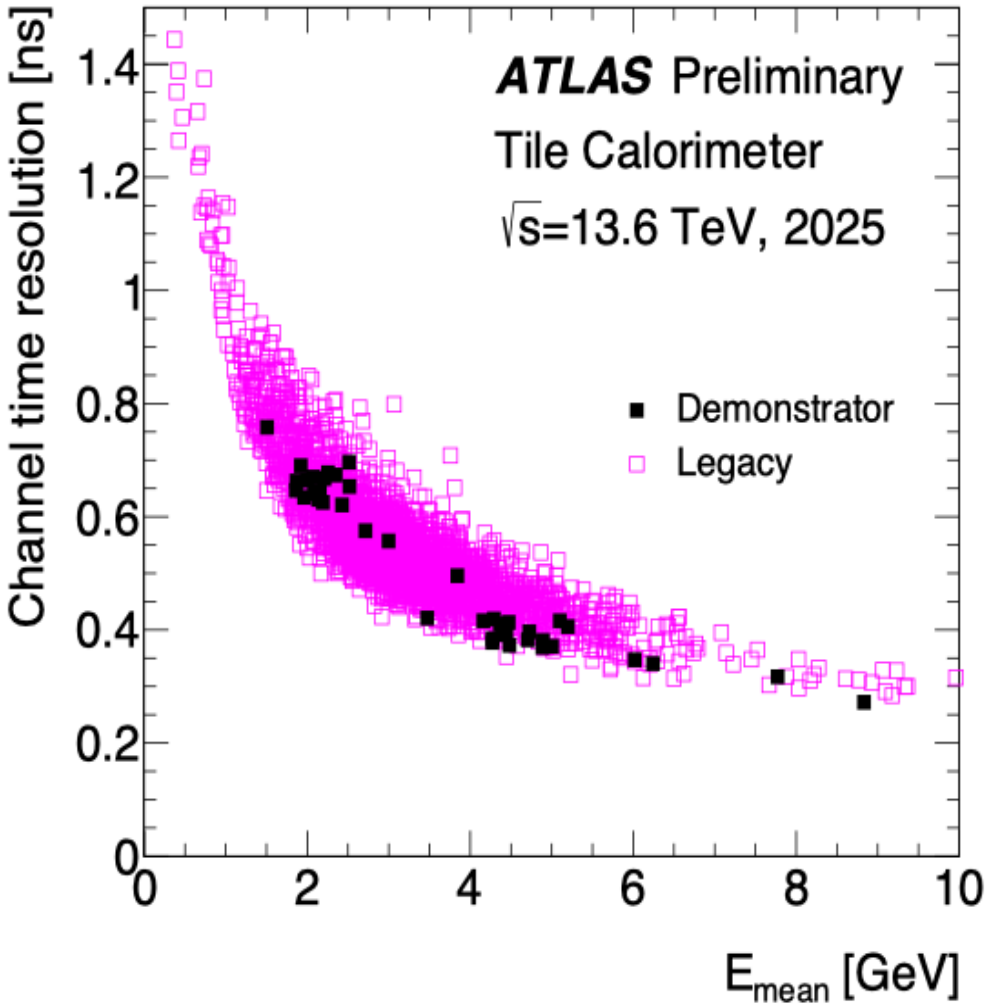


DEMONSTRATOR MODULE

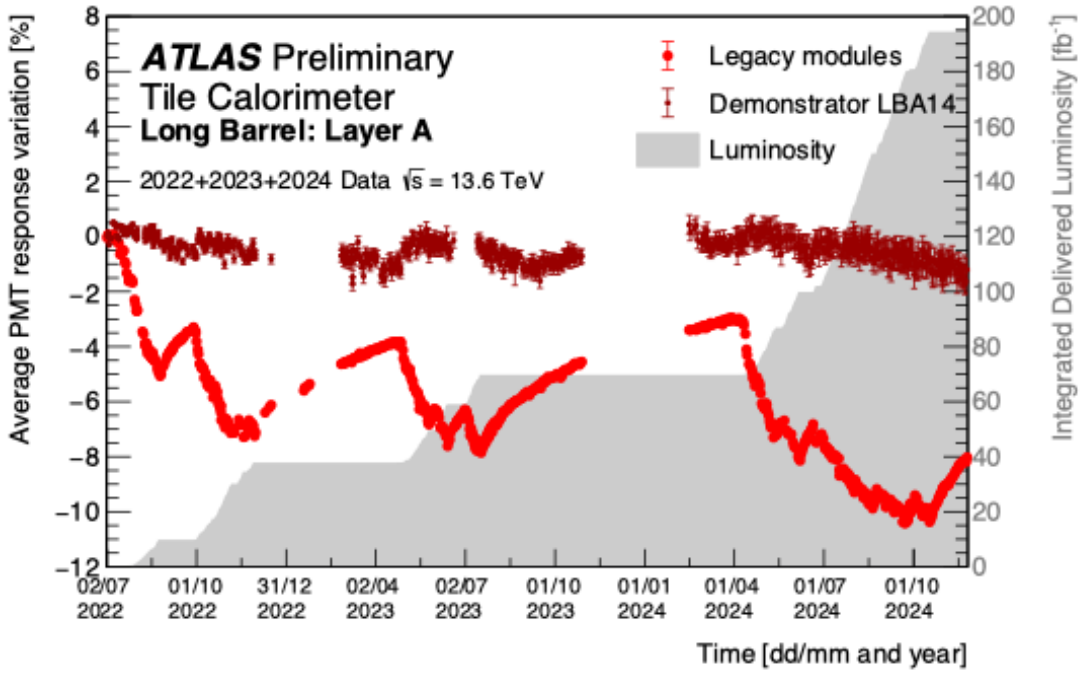
- Demonstrator module installed in ATLAS during Long Shutdown 2 (LS2) and also being operated in Run-3 data taking, designed to test the new electronics
- Equipped with the upgrade electronics and operating with backward compatibility with the current TDAQ system
  - Digital readout but analog trigger signals
  - Completely integrated within the DCS and Trigger-DAQ software
- Data taking through PPr Demonstrator :
  - Recovers clock and commands and propagates to the upgraded electronics
  - Transmits L1-triggered data to legacy system



DEMONSTRATOR PERFORMANCE



- The time resolution obtained with laser events shot into all channels and modules of the LBA partition in 2025 where each point represents one channel.
- Demonstrator module (LBA14) shows significantly improved PMT response stability over time as compared to legacy modules, with the statistical errors corresponding to the uncertainty in the mean.
  The Laser calibrations were not taken during the period from December 2022 to January 2023, corresponding to the missing data points in the plot below (right)



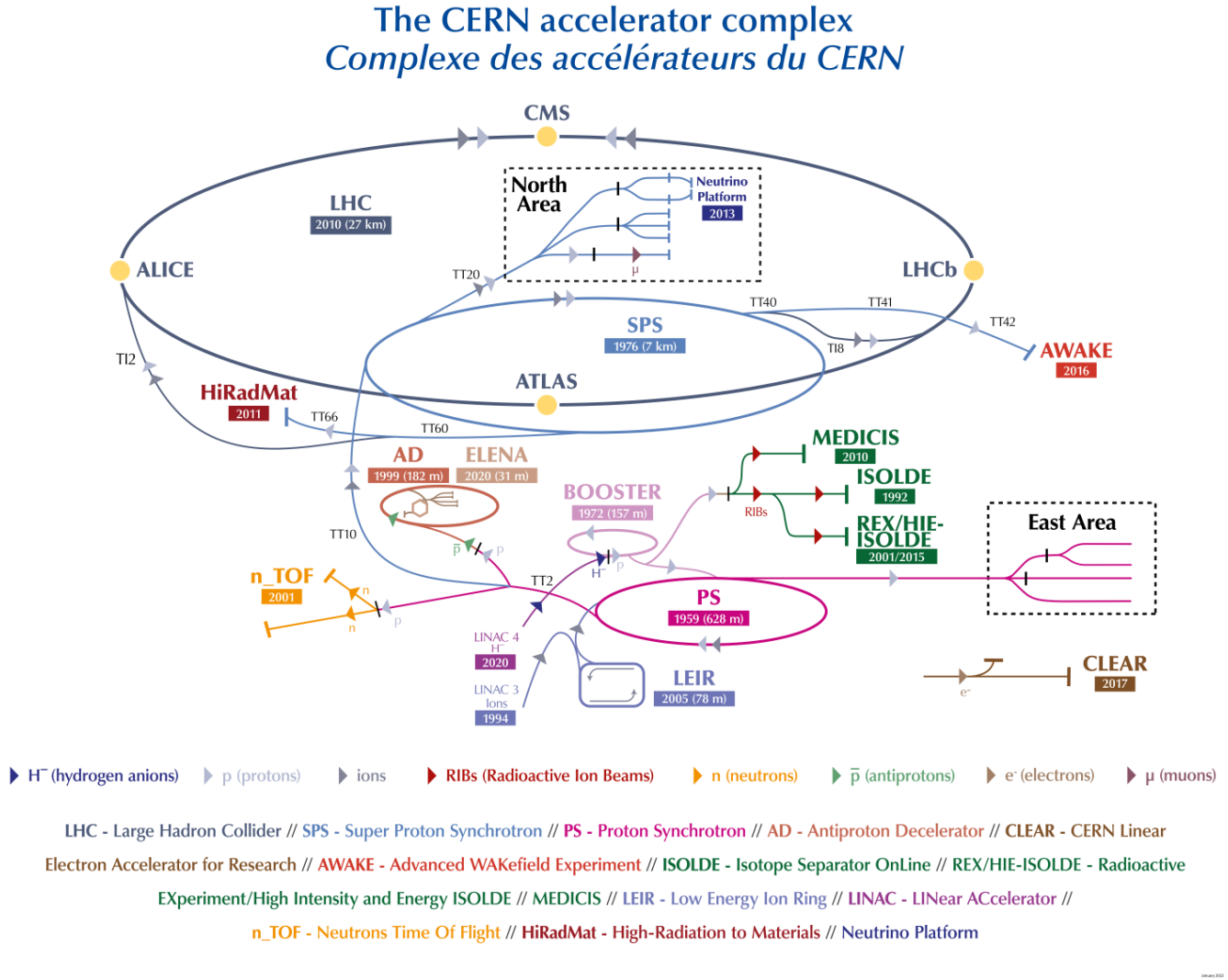
CONCLUSIONS

- HL-LHC will reach up to 7.5× the nominal LHC luminosity enabling new discoveries
- Conditions will significantly increase radiation levels and pile-up
- TileCal will undergo a major upgrade during Long Shutdown 3 to ensure performance and reliability under these conditions
- New mechanical structure with improved usability and integration
- On-detector electronics redesigned for enhanced radiation tolerance, while off-detector electronics upgraded to be able to process data at 40 MHz rate and handle pile-up.
- 10% of the most irradiated PMTs will be replaced for higher efficiency and stability
- Upgrade is progressing well, with mechanical and on-detector components completed or in production, and off-detector systems reaching production
- Demonstrator module fully integrated with ATLAS with stable performance

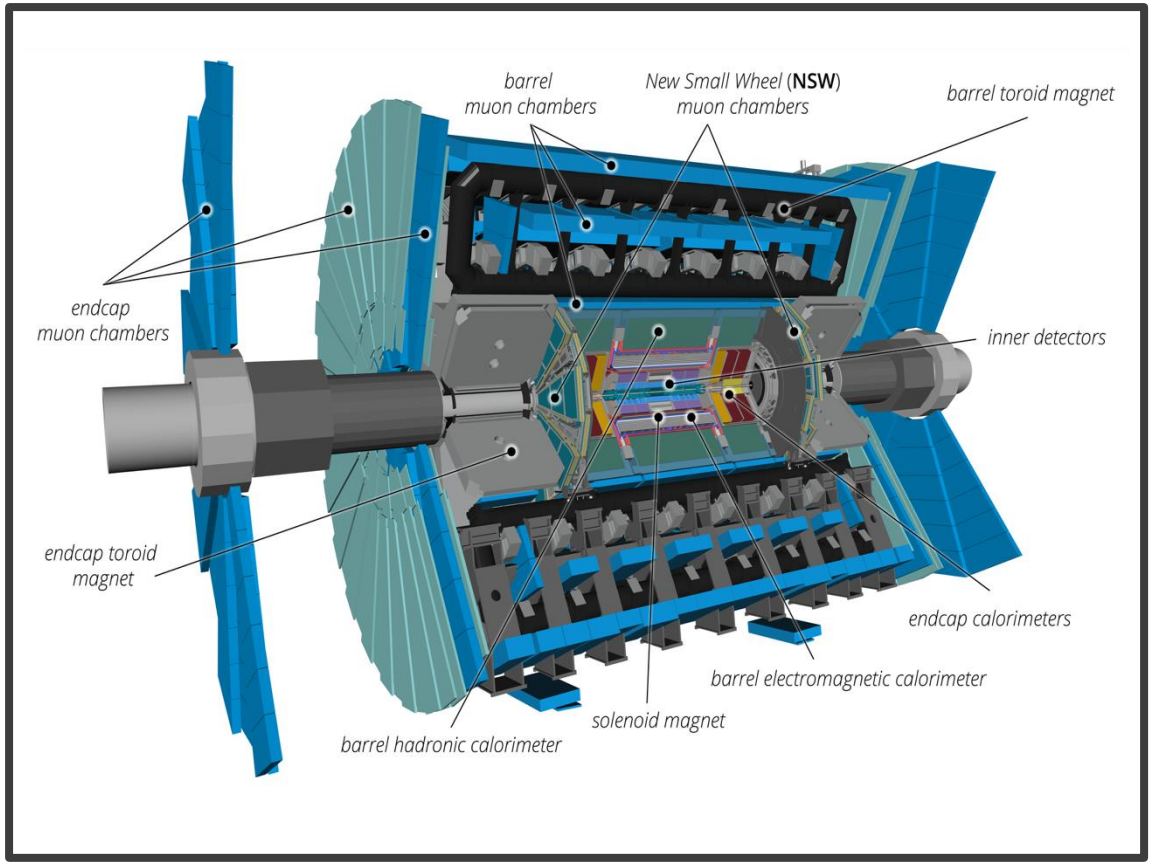
BACKUP

THE LARGE HADRON COLLIDER

- Located on the border between France and Switzerland
- Beginning with the Synchrocyclotron in 1957, evolving from early proton synchrotrons to the 27 km Large Hadron Collider (LHC), operational since 2008
- A chain of accelerators boosts proton bunches before injection into the LHC
- Proton-proton collisions 13.6 TeV
- Instantaneous luminosity up to $2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
- Four main interaction points: ALICE, ATLAS, CMS, LHCb

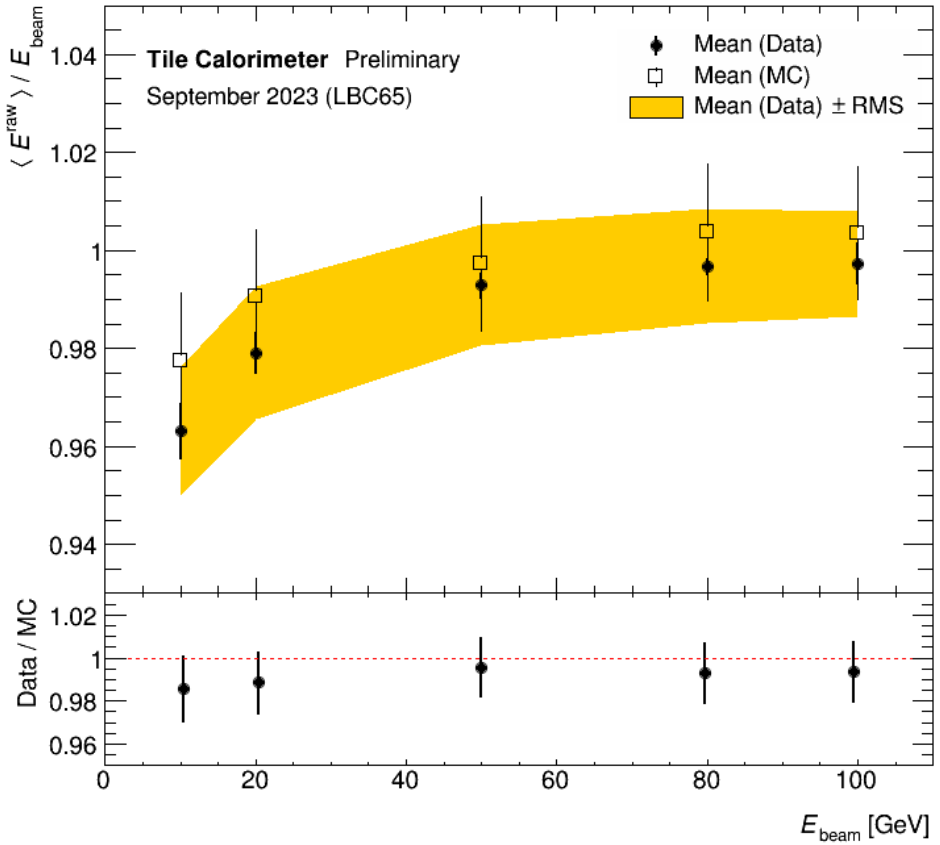


THE ATLAS DETECTOR

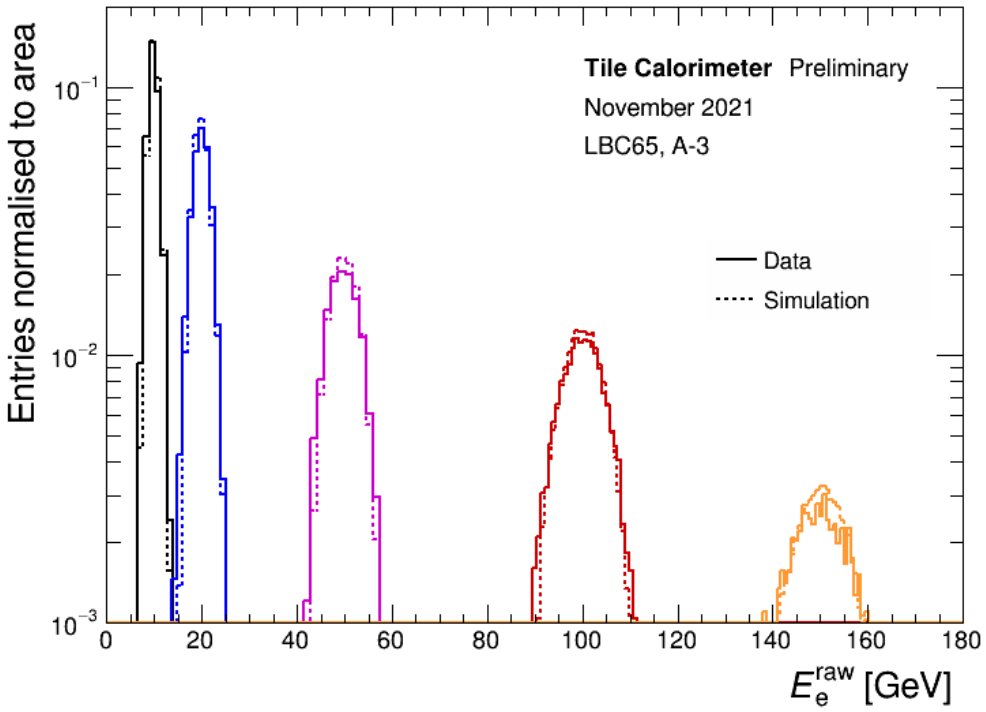


- Largest general purpose detector in the LHC complex- detects and measures the properties of very high energy particle collisions
- Comprised of various subsystems for tracking, detecting and measuring properties of various particles
- **Tracking Detectors:**
  - Inner Detector — measures direction, momentum, and charge of charged particles
  - Muon Spectrometer — identifies and measures muons
- **Calorimeters:**
  - Electromagnetic Calorimeter- Liquid Argon Calorimeter: Measures the properties of EM particles
  - Hadronic Calorimeter - Tile calorimeter : Measures the properties of hadronically decaying particles

PERFORMANCE STUDY IN THE TEST BEAM CAMPAIGN - ELECTRONS

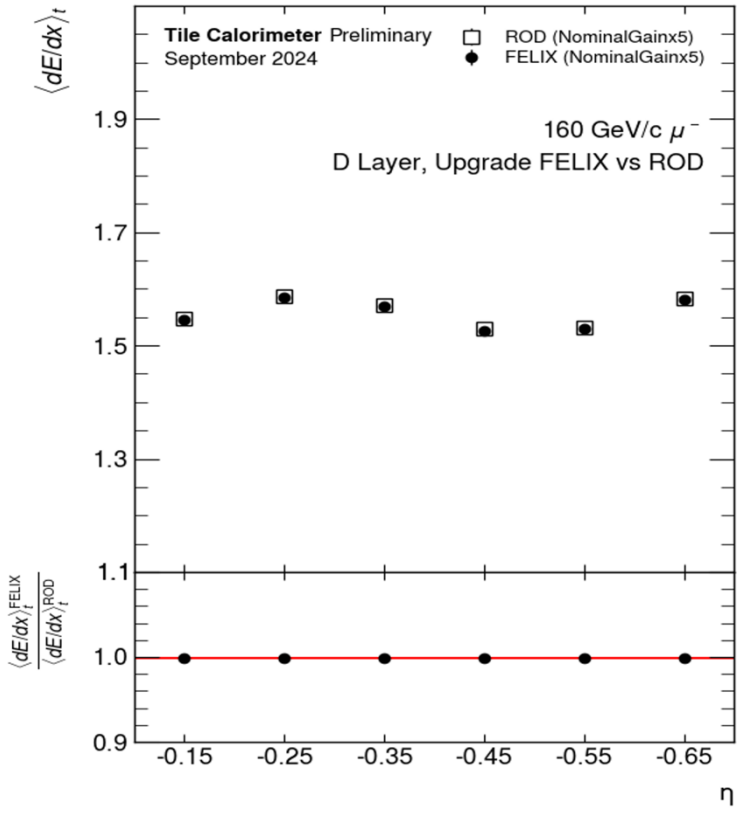


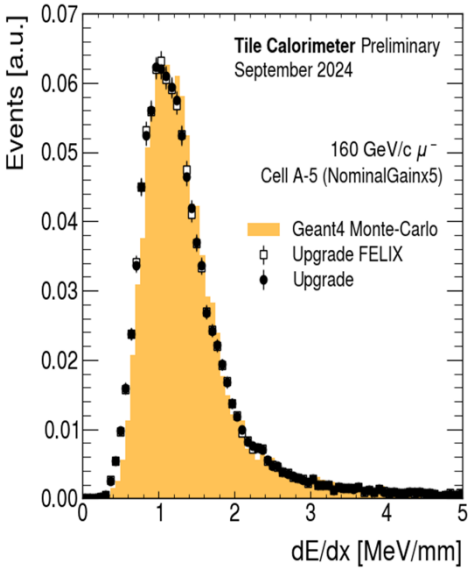
- Electrons with energies 10, 20, 50, 100 and 150 GeV show:
  - Electron energy: data-simulation disagreement < 1% (mean energy)
  - Total measured energy agree well with energy of the e- beam with non linearity smaller than 1%

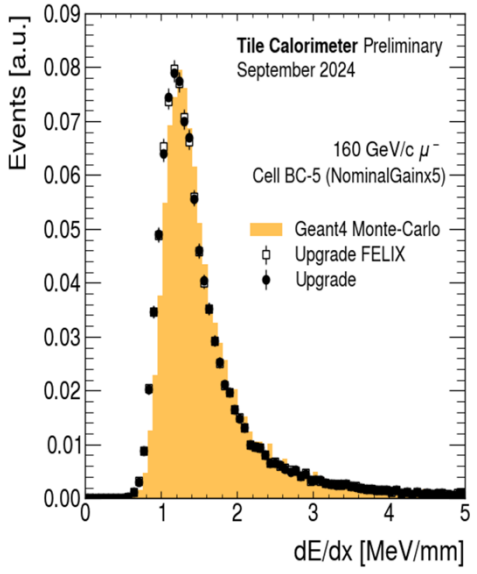


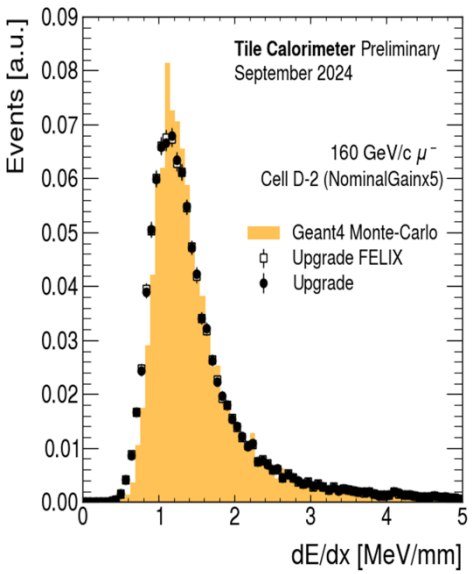
PERFORMANCE STUDY DURING TEST BEAM CAMPAIGN – MUONS

- Test beam campaigns at CERN are conducted to validate the performance of upgraded TileCal modules in more realistic conditions
- Beams of various particles and energies at SPS at CERN
- The setup includes two instrumented modules fully integrated with ATLAS TDAQ and FELIX systems, with Cherenkov counters used for particle identification together with modules equipped with the legacy system
- "Upgrade" refers to the LBC65 framework using Upgrade electronics and the Read-Out Driver (ROD) readout system
- "Upgrade FELIX" refers to the LBC65 framework using Upgrade electronics and the FELIX readout system.

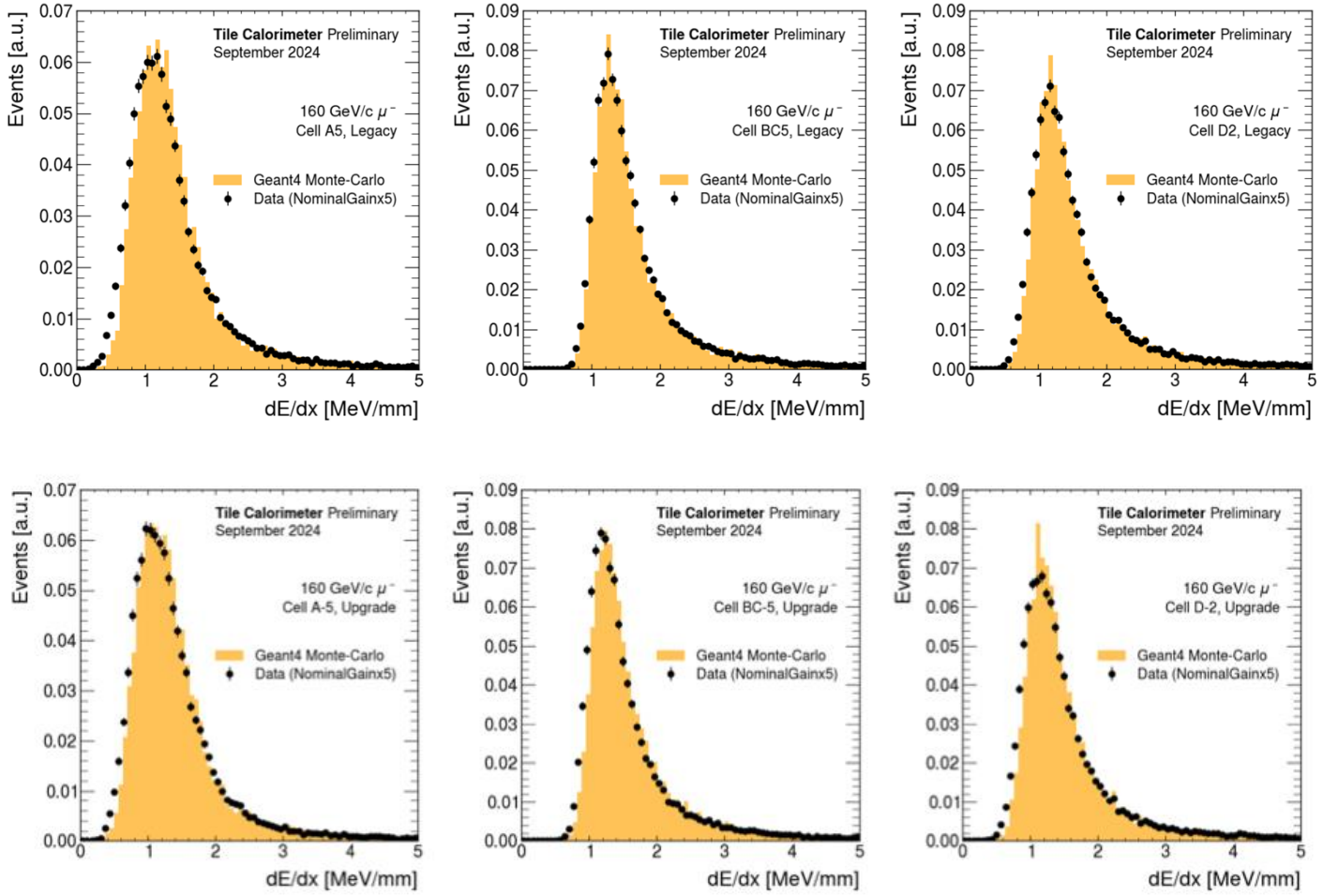








PERFORMANCE STUDY IN THE TEST BEAM CAMPAIGN - MUONS



- Comparison of dE/dx using 16 GeV muons for the Legacy and upgrade modules
- The study with muons verifies the working of the new electronics
- Shows uniformity better than 1% with minimal statistical errors