Timeline ($^{1}/_{14}$)
Introduction…
Upgrade design...
Demonstrator…
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Optical chain…
Physics Response…
Conclusions…

A First Look at the Future of the ATLAS Tile Calorimeter: Phase-II Demonstrator Design and Performance in Run 3

LCWS2026 - Calorimetry and Particle ID, Nov 4th, 2026.

Eduardo Valdes Santurio on behalf of the ATLAS Collaboration

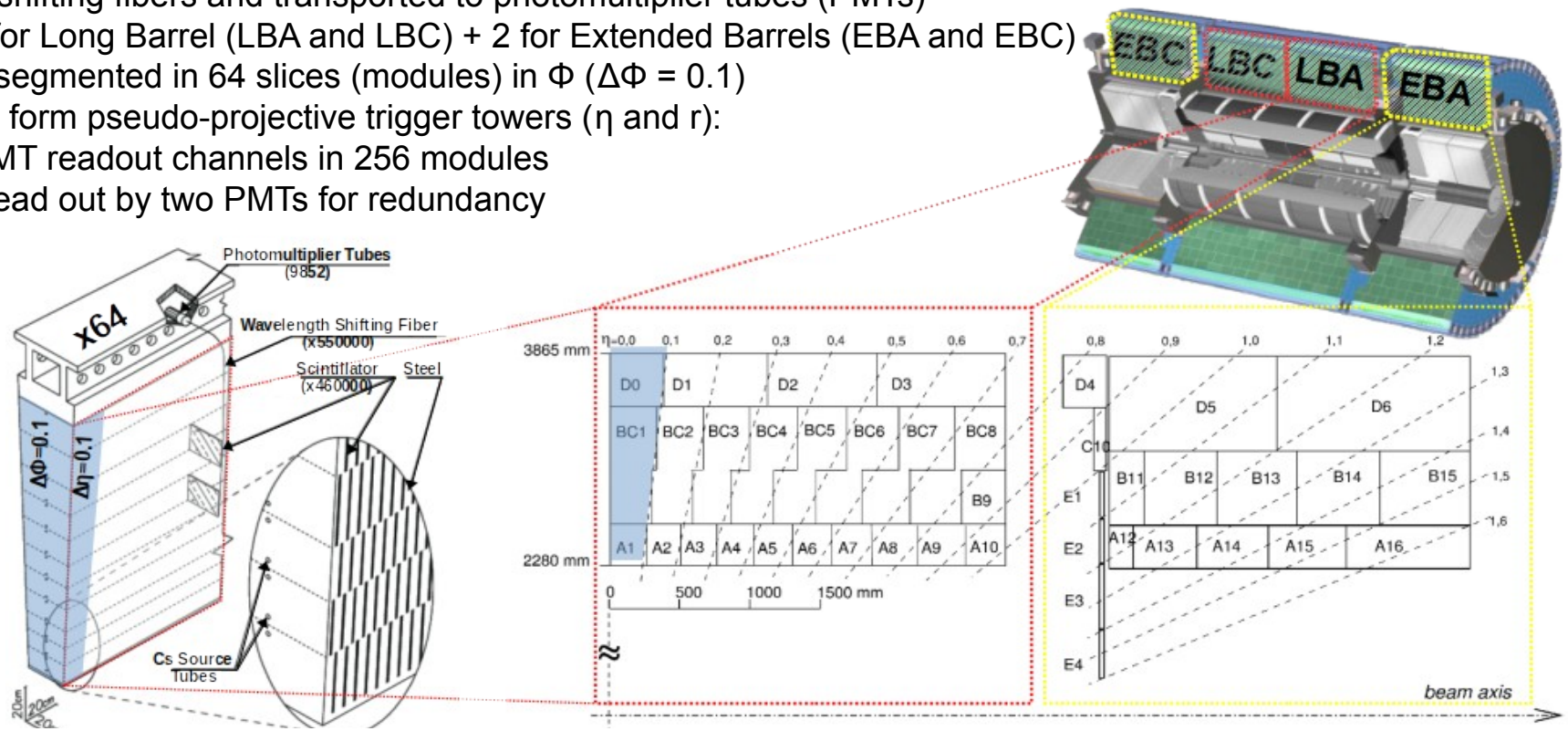
Phone: +46 721473470
EMail: eduardo.valdes@fysik.su.se, eduardo.valdes@cern.ch

Introduction - Overall architecture

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Conclusions…

- **ATLAS is a general-purpose LHC detector**, built in layers around the collision point
- The **ATLAS Tile Calorimeter** (TileCal) is the **central hadronic calorimeter of ATLAS**:
  - Measures jets, τ leptons, missing transverse energy and muon identification
  - Provides energy sums of pseudo-projective towers to the first level trigger (L1 trigger)

- TileCal is a steel-scintillator sampling calorimeter. Particles produce light in the plastic scintillators, which is collected by wavelength-shifting fibers and transported to photomultiplier tubes (PMTs)
  - 4 readout partitions: 2 for Long Barrel (LBA and LBC) + 2 for Extended Barrels (EBA and EBC)
  - Each readout partition segmented in 64 slices (modules) in Φ (ΔΦ = 0.1)
  - Each slice is layered to form pseudo-projective trigger towers (η and r):
  - 5182 cells and 9852 PMT readout channels in 256 modules
  - Each cells is typically read out by two PMTs for redundancy



See talk: 14:50 - 15:10 : Operation and Performance of the ATLAS Tile Calorimeter in LHC Run 3
https://agenda.linearcollider.org/event/11000/contributions/59670/

LBx: Long Barrel A|C
EBx: Extended Barrel A|C
PMT: Photomultiplier Tube
Φ: Azimuthal angle
η: Pseudorapidity (related to polar angle)
Cells distributed:
- Δη × ΔΦ = 0.1 × 0.1 in A, B, BC, C and E cells
- Δη × ΔΦ = 0.2 × 0.1 in D cells

Helena Santos Dr
Eduardo Valdes S... Dr

High Luminosity LHC conditions and Upgrade design

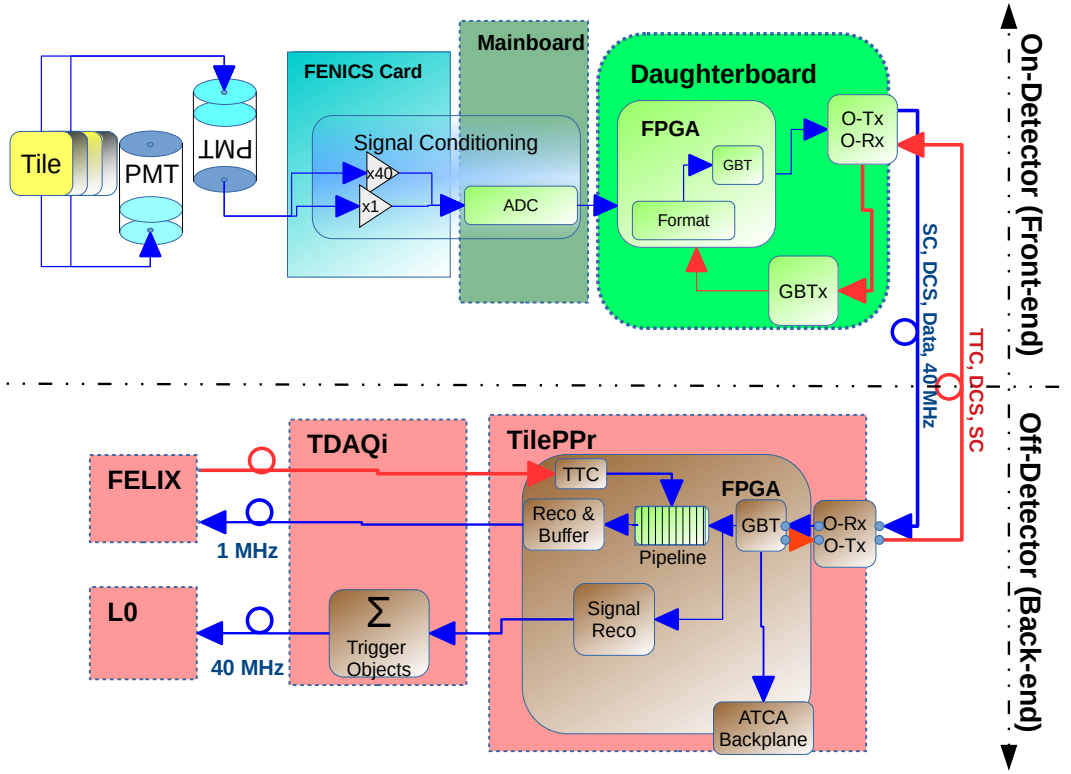
Timeline ($^{3}/_{14}$)
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- **HL-LHC conditions**:
  - Up to 7.5x nominal LHC instantaneous Luminosity to an integrated Luminosity of 4000 fb−1
  - Pile-up no less than ⟨μ⟩ ≈ 180 pp interactions per bunch cross and 10x to 20x times more radiation than LHC

- **Replace on- and off-detector electronics**, using COTS components (Commercial FPGAs, ADCs, POLs, etc)
- Increased readout rates, off-detector fully digital trigger, radiation tolerance, robustness and redundancy

- The Upgraded System:
  - On detector:
    - **PMTs** instrumented with new Active High Voltage Dividers (~10% of the PMTs in the most exposed cells will be replaced with the newer R11187 model)
    - **FENICs** cards and **Mainboards** shape and digitize two gains (HG/LG=40/1) of **PMT** signals shaped @40 MHz, in parallel runs the **integrator** data slow-signal circuit
    - **Daughterboards**: format data and send off-detector over high-speed fibers
  - Off detector:
    - **Tile PreProcessor** modules, **TDAQi** interfaces, **FELIX**: read the data into pipeline memories, reconstruct signals calculate cell energies, find trigger objects

- **This required a demonstrator module with upgrade hardware to gain experience in real ATLAS conditions!**
  - Challenge:
    - Interface with the legacy system!
    - R&D running in parallel



COTS: Commercial off the shelf
ADC: Analog to digital converter
POL: Point of load regulator
HG/LG: High Gain/Low Gain
FPGA: Field Programmable Gate Array
FENICS: Front-End ElectroNICS card
O-Tx/O-Rx: Transmitter/ Receiver Optic link
L0: Level-0 Trigger system
TTC: Trigger Timing and Control
GBTx: radiation tolerant chip with bi-directionl 4.8 Gbps communication via bidirectional optic links.
TilePPr: Tile Preprocessor
FELIX: Front End Link eXchange system.
TDAQi: Trigger and Data Acquisition Interface

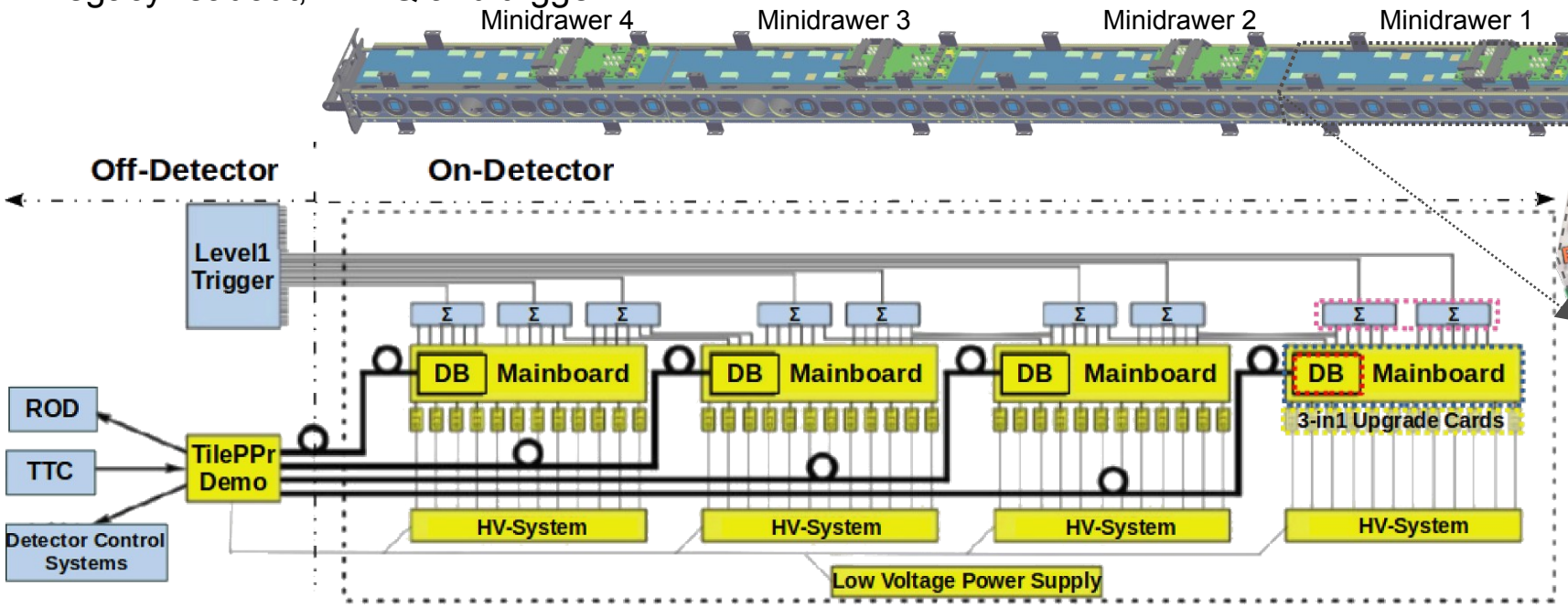
See talk: 15:10 - 15:30 : ATLAS Tile Calorimeter Upgrades for the High-Luminosity LHC Era
https://agenda.linearcollider.org/event/11000/contributions/59671/

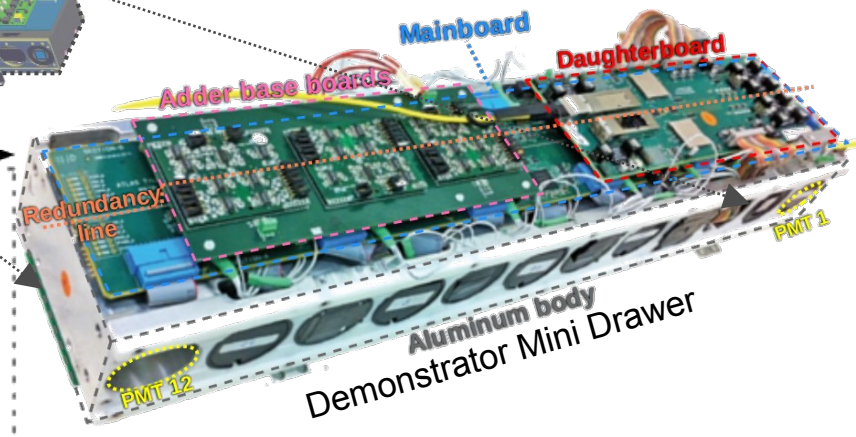
Demonstrator

Timeline ($^{4}/_{14}$)
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- Hybrid readout: new digital chain + legacy analogue trigger
- Off-detector: **1x TilePPr Demonstrator** reads the demonstrator module and manages compatibility with legacy Read-out driver (ROD) format, Trigger and Timing Control (TTC) and the Detector Control Systems (DCS)
- On-detector: A demonstrator module consisting on **4x Minidrawers,** each with **12x PMTs** (instrumented with "upgraded 3-in-1" front-end cards to assure compatibility with legacy adder boards), **1x Mainboard**, **1x Daughterboard** and **1x Legacy Adder board**

- **Demonstrator prototyped** and tested in testbeam campaigns. **Installed in the ATLAS detector as LBA14** (Long Barrel A, Slice 14) in 2019.
- The module was **operated seamlessly in Run 3 running besides the legacy system** with data compatible with the legacy readout, TDAQ and trigger





Hybrid readout concept (new digital chain legacy)

DB: Daughterboard
Σ: Adder cards
HV System: High voltage System

Upgrade design - Calibration systems

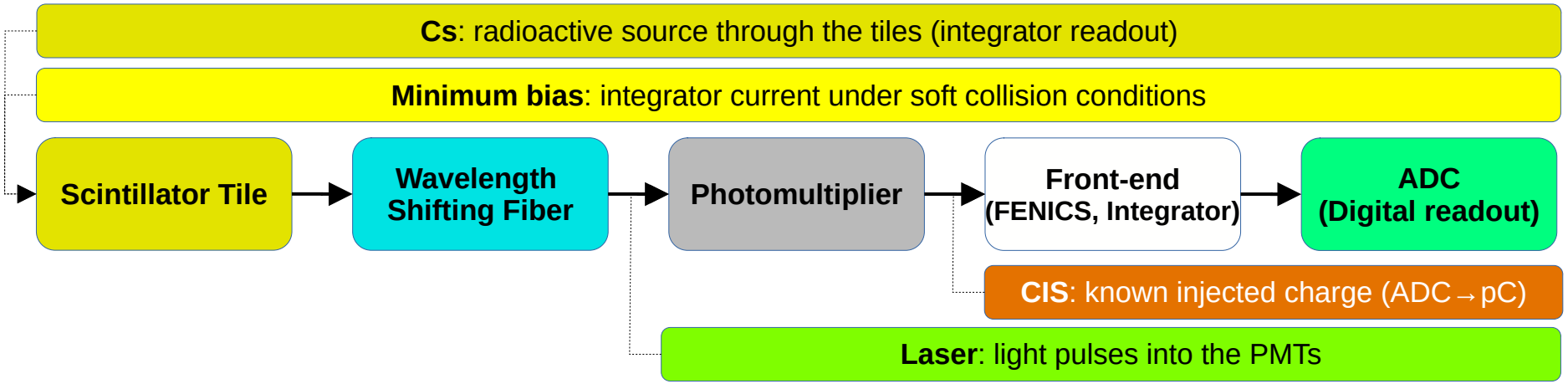
Timeline ($^{5}/_{14}$)
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- Electronics of the **calibration systems** also upgraded

- The four calibration systems:
  - **Charge Injection System (CIS)**: charge injected into the front end giving the ADC-counts-per-pC conversion
  - **Laser:** short pulses of light fired between collisions to track the PMT gain and channel timing
  - **Minimum bias (MB)**: collision currents in the PMTs, track response loss with luminosity
  - **Cesium (Cs)**: a radioactive source moved through the tiles. Calibrates tile, fiber and PMT

  - Together they separate **scintillator aging**, **PMT drift** and **electronics stability**
  - The calculated **calibration constants** of these systems are used in the **reconstruction of physics events**

$$E\ [\mathrm{GeV}] = \frac{A\ [\mathrm{ADC}]}{C_{\mathrm{ADC}\to\mathrm{pC}} \times C_{\mathrm{pC}\to\mathrm{GeV}} \times C_{\mathrm{Cs}} \times C_{\mathrm{MB}} \times C_{\mathrm{Las}}}$$



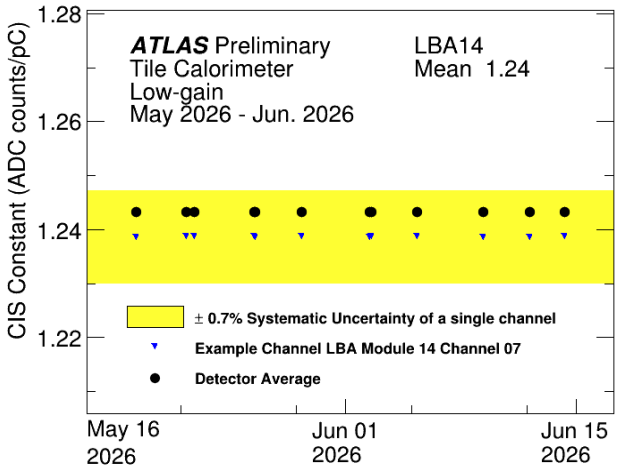
FENICS: Front-End ElectroNICS card
Integrator: a slow-signal processing circuit present in the FENICS card that continuously sums (integrates) the current coming from a photomultiplier tube (PMT) over a set time period

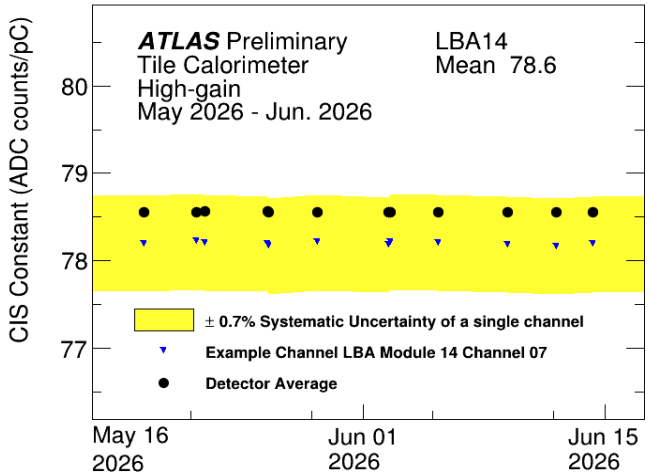
Charge Injection System

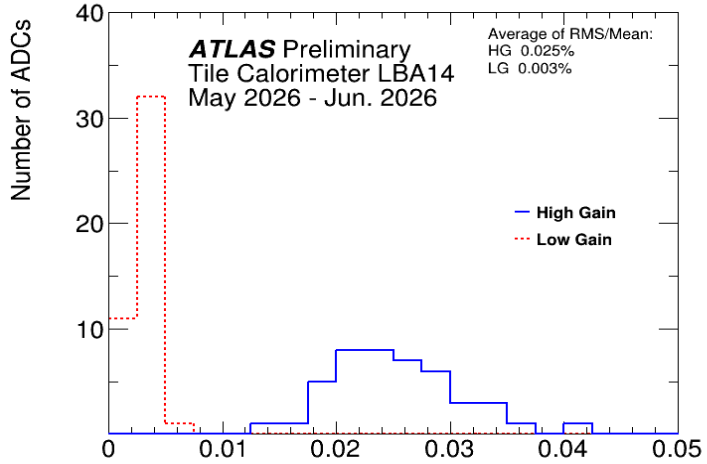
Timeline ($^{6}/_{14}$)
Introduction…
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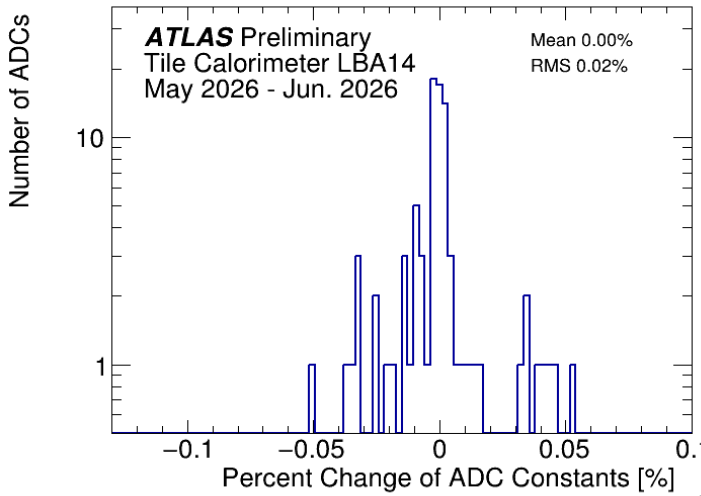
- **CIS calibration is stable** at the 10^{-4} level (0.01% for HG and 0.007% for LG run-to-run RMS/mean)
  - ±0.7% systematic from the capacitance of the injected-charge source
  - **Stable ADC-to-charge conversion** over time: fluctuations well inside the systematic band mean a stable electronics chain.

- The Demonstrator runs **showed better CIS DAC linearity response**
  (DAC non-linearity is 0.1% in the Demonstrator, against 0.4% in the legacy system)









CIS: Charge Injection System

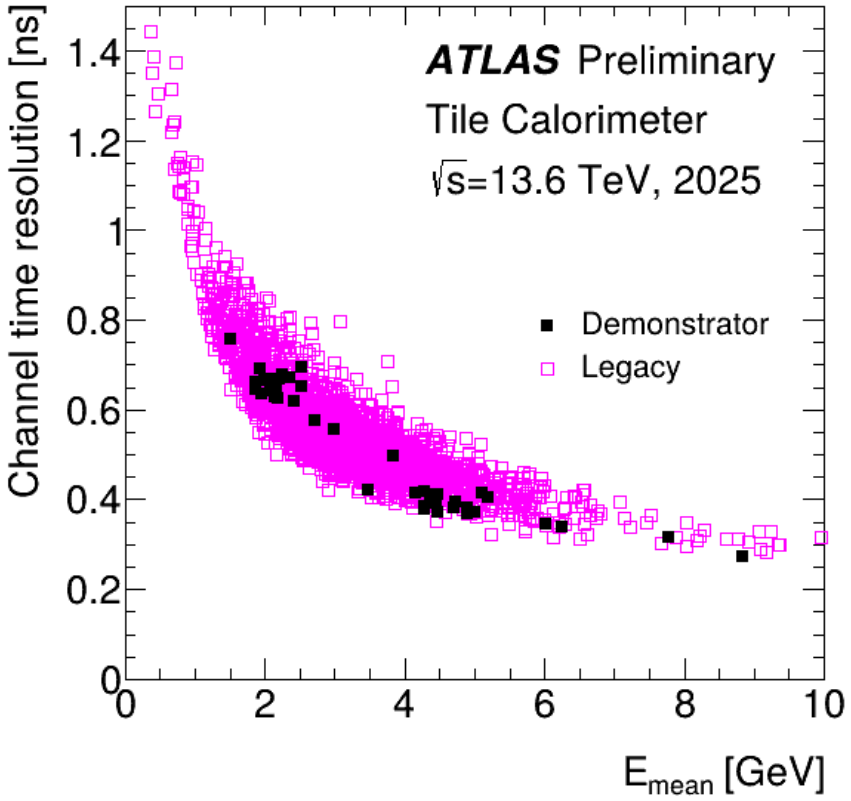
LG, HG: Low Gain, High Gain

For each validated CIS run, the CIS constant (ADC counts/pC) is averaged for both gains over all ADCs.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileCalibrationCIS

Timing calibrations with the laser calibration system

- **Timing resolution at least as good as legacy** → is important for **precise energy reconstruction**
  - Measured using laser events during LHC empty orbits (2025 collision run).
  - Each point represents one channel; channels with known issues are excluded.
  - Tests validate the **stability of the clock distribution** and **synchronization strategies** used in the upgraded module.



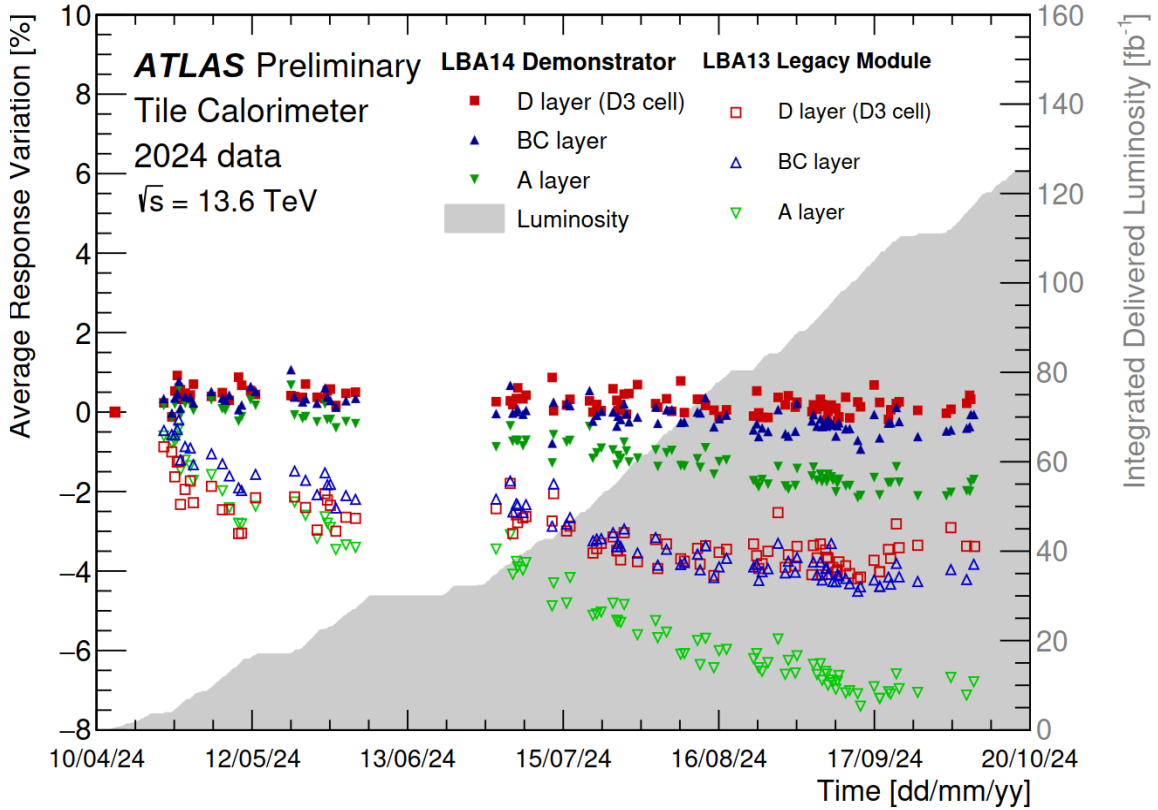
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TileCaloPublicResultsTiming

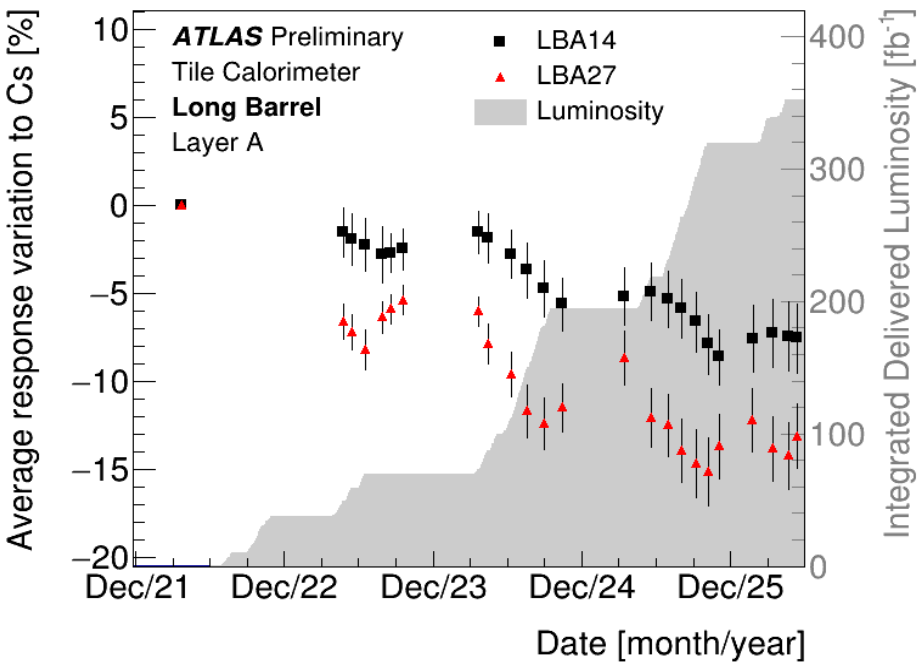
In the plot, each point represents one channel. Channels with known issues excluded.

Cesium and Minimum Bias calibration systems

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- Minimum-bias (MB) currents and Cesium (Cs) calibration showed **reduced response degradation**
  - MB: at the start of Run 3 → Demonstrator MB response was within 1.5% of legacy
  - After 124.7 fb^{-1}: **Layer A**: −1.7%(LBA14) vs −6.8%(LBA13) | **Layer BC**: −0.1%(LBA14) vs −4.2%(LBA13) | **Layer D**: practically unchanged → differences in response variation mainly attributed to the PMT type differences
  - Cs: Run 3: Demonstrator (LBA14) smaller down-drift than legacy (LBA27)





Minimum Bias: average over a well-behaved subset of cells of the minimum-bias integrator-current response, relative to the 2024-03-12
Cs: average cell response to the Cs source, relative to the 2022-03-24.

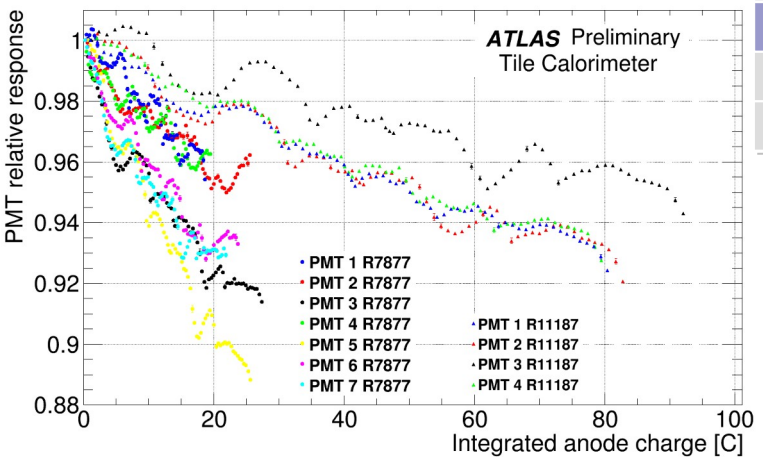
Note: Downward trend represents loss of response of tile, fibre and PMT with accumulated luminosity; the LBA14 vs legacy difference is mainly attributed to the PMT type

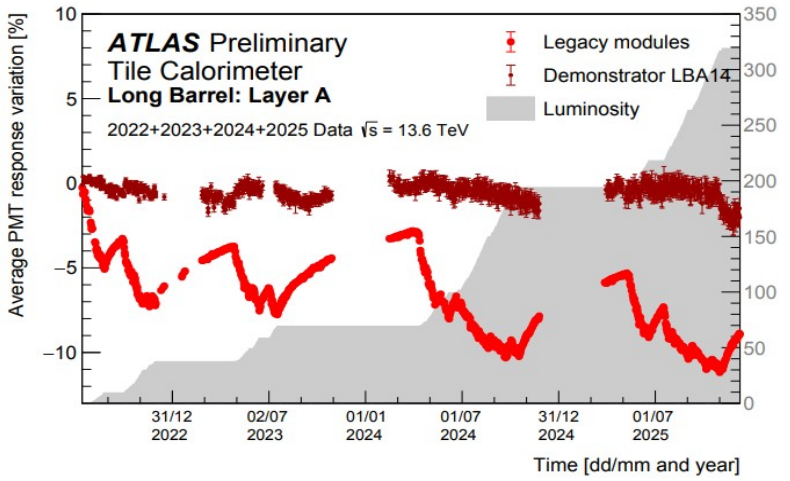
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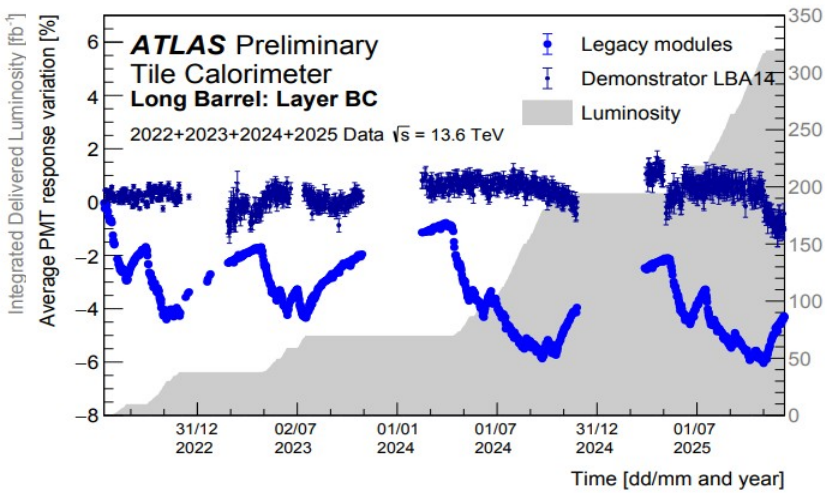
Optical chain stability

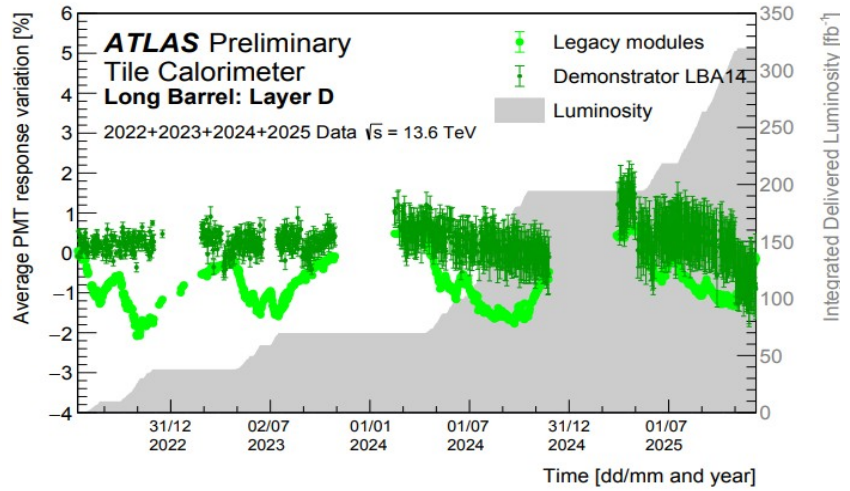
- PMT model R11187 and PMT model R7877 were preliminarily studied .
- The **R11187** has **smaller down drift** and has **a smaller spread**, with systematics below 2%
  → chosen for HL-LHC to replace the PMTs in the most exposed cells (10%)
  → installed with the Demonstrator

- **PMT response: stable in the Demonstrator**, **luminosity-correlated drifts in legacy**
  - Legacy:
    - PMT model: R7877 → Drifts up to ~10% (A), ~6% (BC), ~2% (D)
    - (follow luminosity and recover in heavy-ion runs/stops)
  - Demonstrator:
    - PMT model: R11187 equipped with Active Divider
    - Drifts within ±2% (A), <2% (BC), <1% (D)
    - Stays practically flat









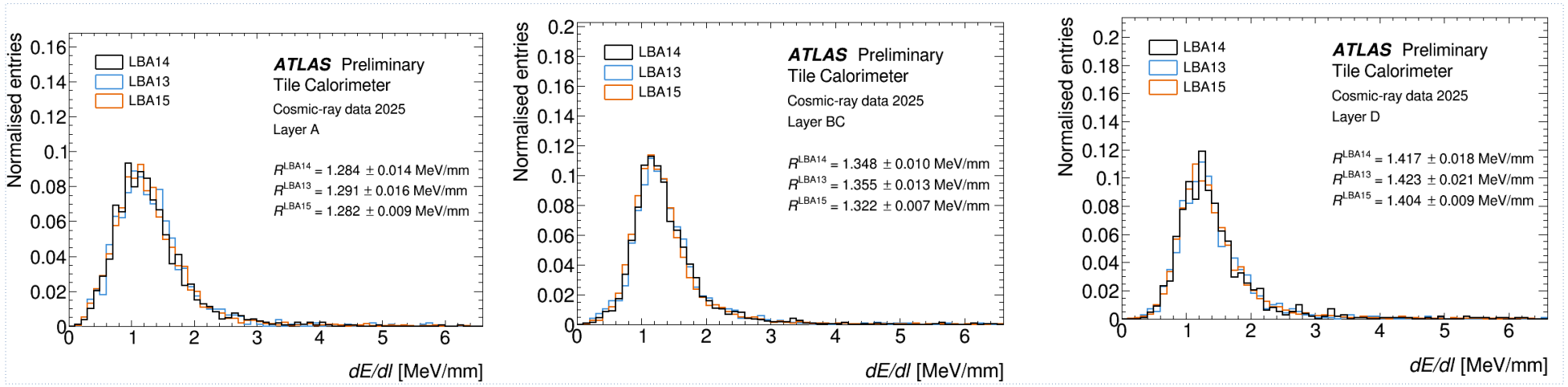
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileCalibrationCombined
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileUpgrades

Physics response to muons from cosmic rays or produced by collisions

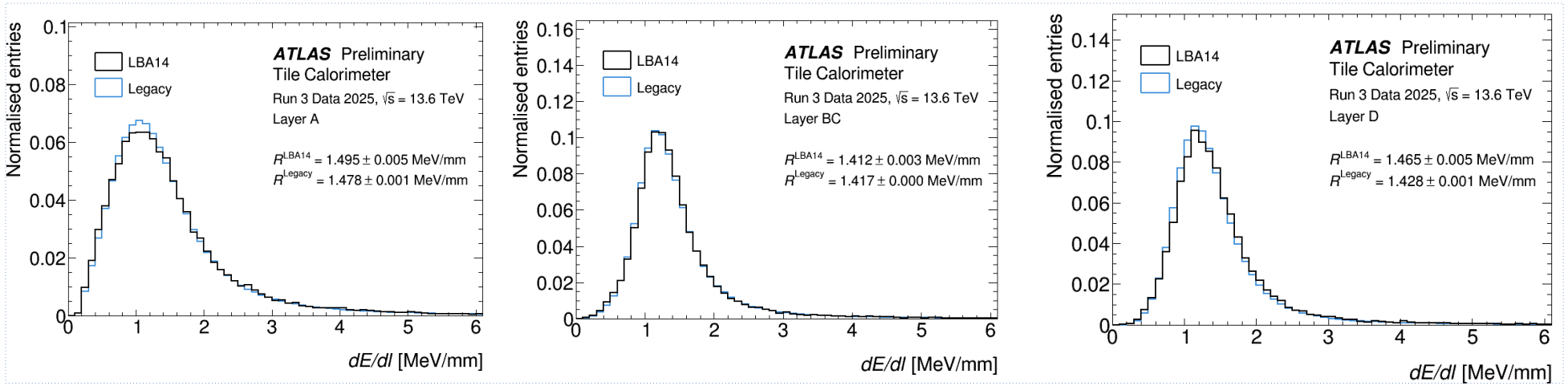
Timeline ($^{10}/_{14}$)
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- **Muon response agrees with legacy modules at the 1-3% level**
  (Comparison of the distributions of the energy deposited per unit path length (dE/dl) for demonstrator and adjacent modules)

Cosmic muons 2025



Collision muons



Cosmic muons: 0–30 GeV, $|\theta| > 0.13$ rad, $|\Delta\varphi| < 0.04$ rad, path length > 200 mm, and deposited energy > 60 MeV; basic track quality criteria applied.

Collision muons: W → μν muons (20–80 GeV, $p_t > 28$ GeV); cells with dE > 60 MeV, path dl > 100 mm, and $|\Delta\varphi| < 0.04$.

R (response) → truncated mean of dE/dl, with the upper 1% removed.

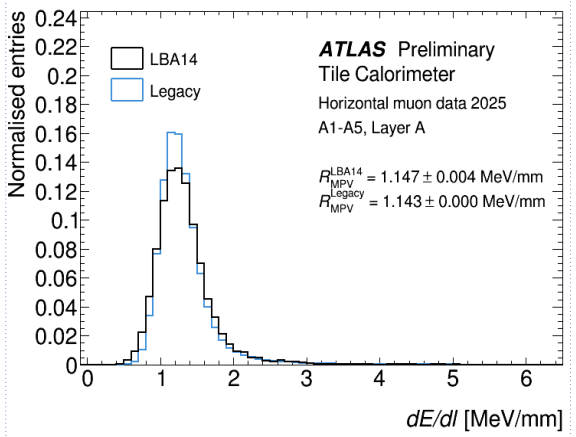
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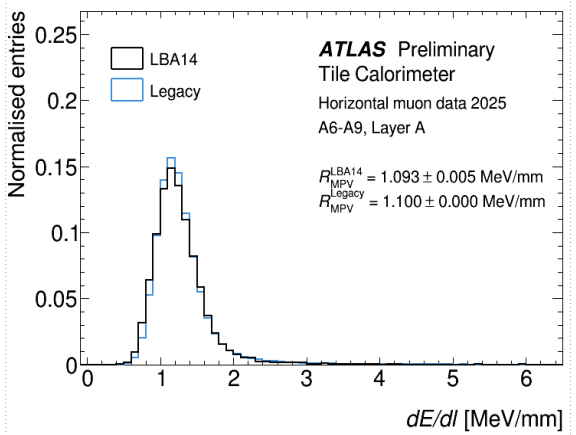
Physics response to horizontal muons

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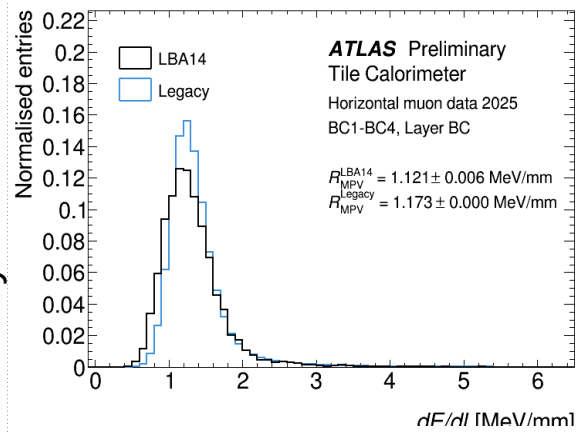
- Horizontal muon studies via beam scraping runs showed **comparable muon energy scale for the new electronics**:
  - Single-beam scraping runs used, beam configured to scrape collimators 140 m from the interaction point, to produce nearly horizontal muons. Trajectories come from linear fits to cell positions.
  - Minimum ionizing particle response layer by layer in agreement within a few percent range

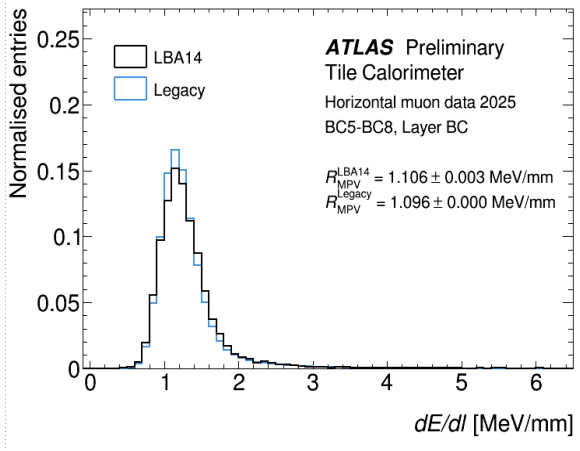
Horizontal Muons Layer A



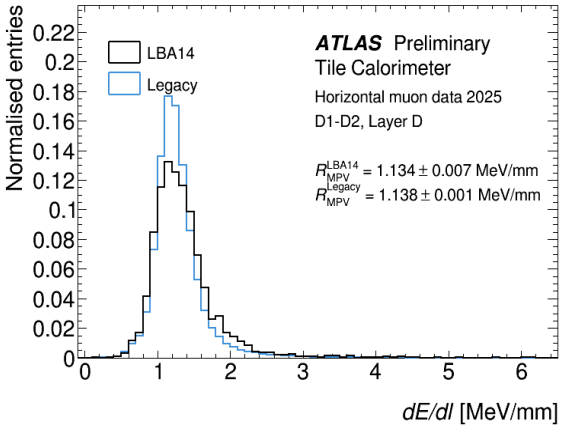


Horizontal Muons Layer BC





Horizontal Muons Layer D

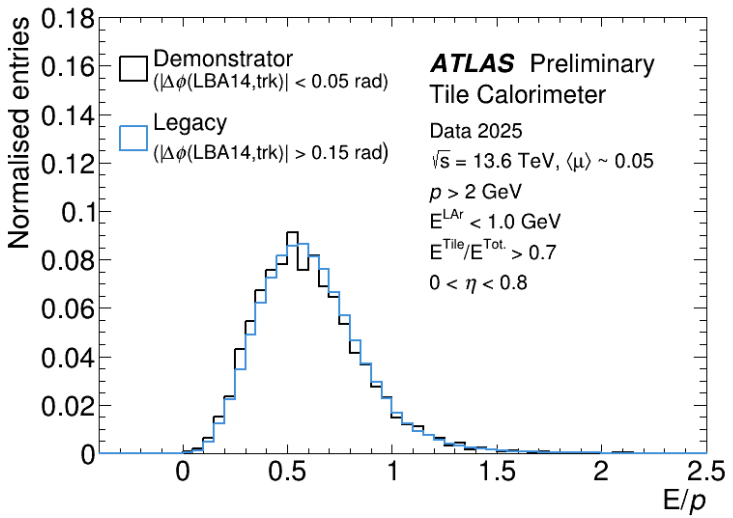


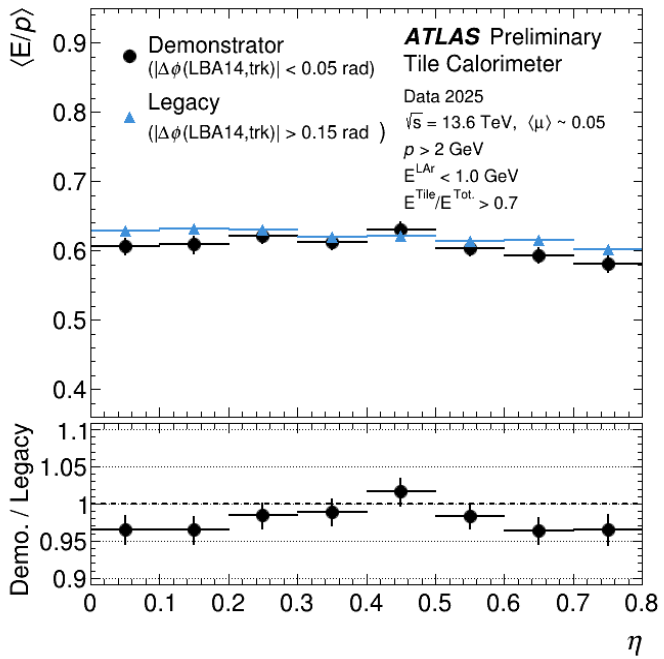
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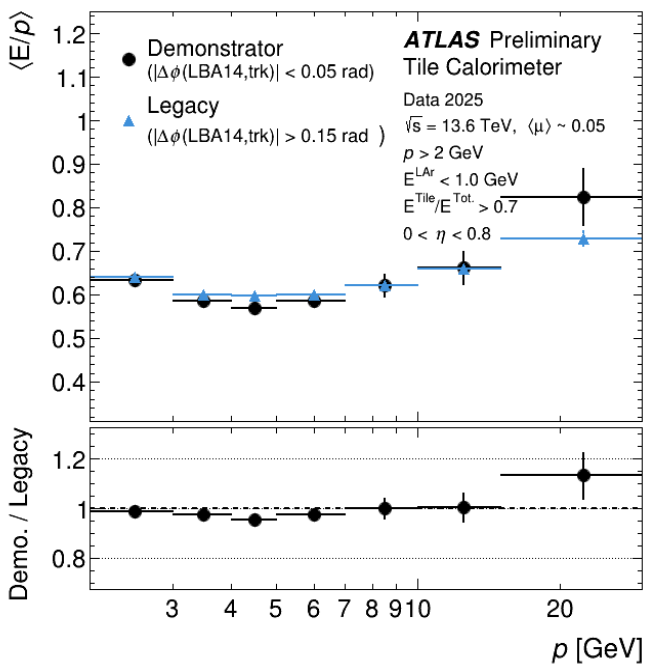
Physics response to hadrons

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- The ratio of E/p measured for isolated charged hadrons is used to characterize the calorimeter response to hadrons, where E is the energy deposited by an isolated charged particle in the calorimeter and p is the momentum of its inner detector track.
- **Equivalent response across η and p for Legacy and Demonstrator** (ratio Demo/Legacy → 0.96 to 1.02)
- **An end-to-end hadron response covers calorimeter and reconstruction**.



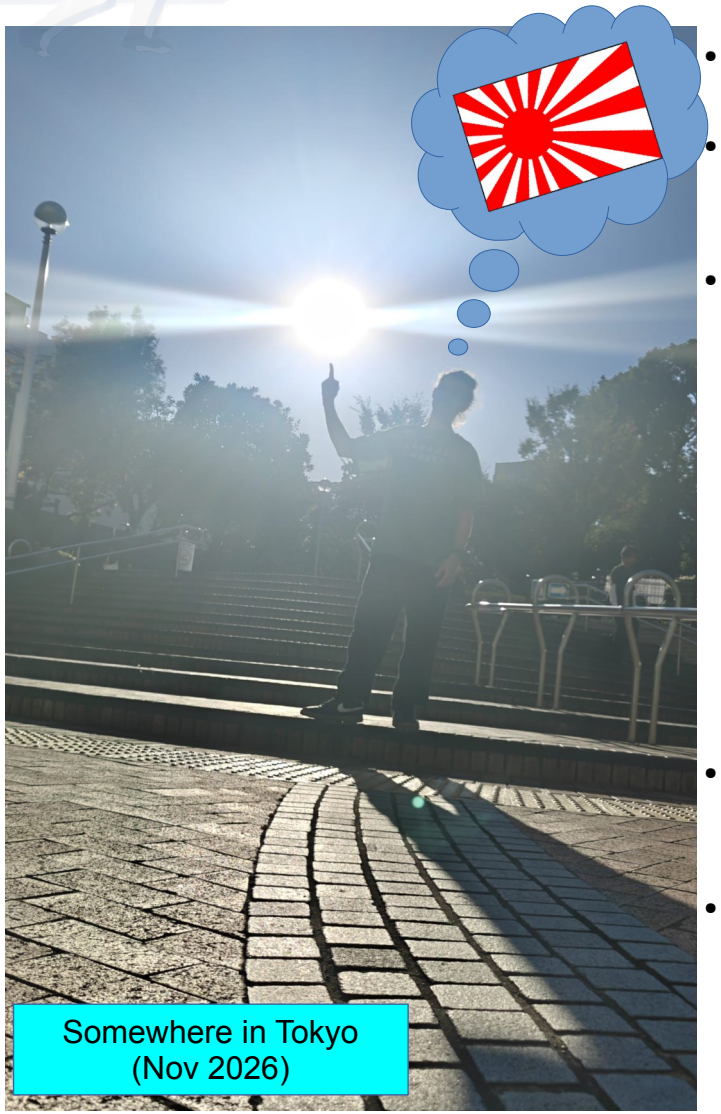




⟨μ⟩: average number of simultaneous proton–proton interactions per bunch crossing
Calorimeter energy over track momentum plot cuts:
- isolated tracks: p>2 GeV
- no other track within ΔR<0.4
- energy from clusters matched within ΔR < 0.2
- LAr energy below 1 GeV
- more than 70% of the energy deposited in TileCal
- Demonstrator → tracks within |Δφ|<0.05 of LBA14, - Legacy → tracks within |Δφ|>0.15 (neighboring modules).

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileSingleParticleResponse

Conclusions/Outlook/Questions



- **HL-LHC requires new TileCal electronics**: every bunch crossing digitized at 40 MHz and streamed off-detector, with redundancy and radiation-tolerant links
- The **Demonstrator runs this chain in ATLAS alongside the legacy systems**, with the TilePreprocessor providing a compatible layer with the legacy TDAQ and trigger systems

- Run 3 demonstrated and exercised all capabilities needed for physics at HL-LHC
  - **Minimum bias and Cs: less layer loses** (layer A -1.7% for LBA14 vs -6.8% for Legacy at 124.7 fb^{-1})
  - **Laser: PMT response stable in the Demonstrator and drifting in legacy**; **timing resolution at least as good as legacy**
  - **CIS: stable and consistent** between 2024 and 2026 (0.01% HG, 0.007% LG)

  - **Good muon response** (muon energies within 1-3% of legacy)
  - **Good hadron response** (E /p for Isolated hadrons equivalent across η and p. Demo/Legacy 0.96-1.02)

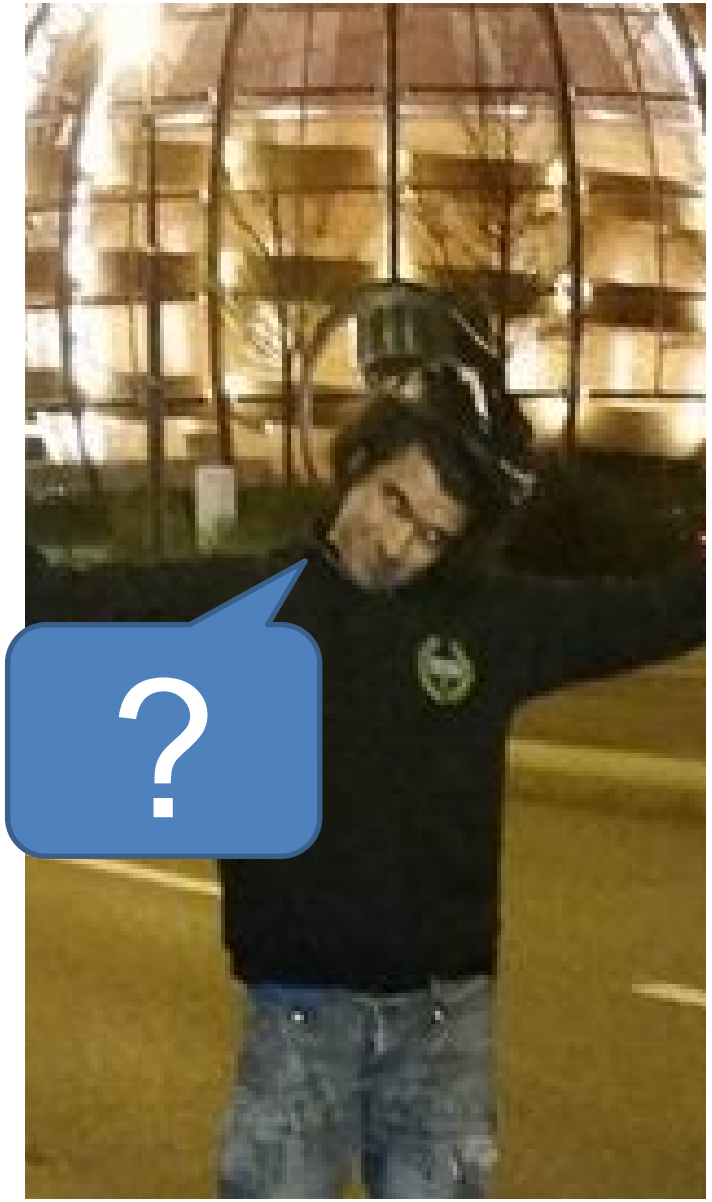
- First **demonstrator upgrade-module results are very encouraging**, towards operation at 1 MHz and $\langle\mu\rangle \approx 180$ with final firmware and latency

- The demonstrator studies provided valuable insights into the performance of the upgrade electronics under real ATLAS operating conditions, representing a significant milestone in the preparation of the ATLAS upgrade for Run 4

Gracias!

Eduardo Valdes S... Dr

Conclusions and Questions



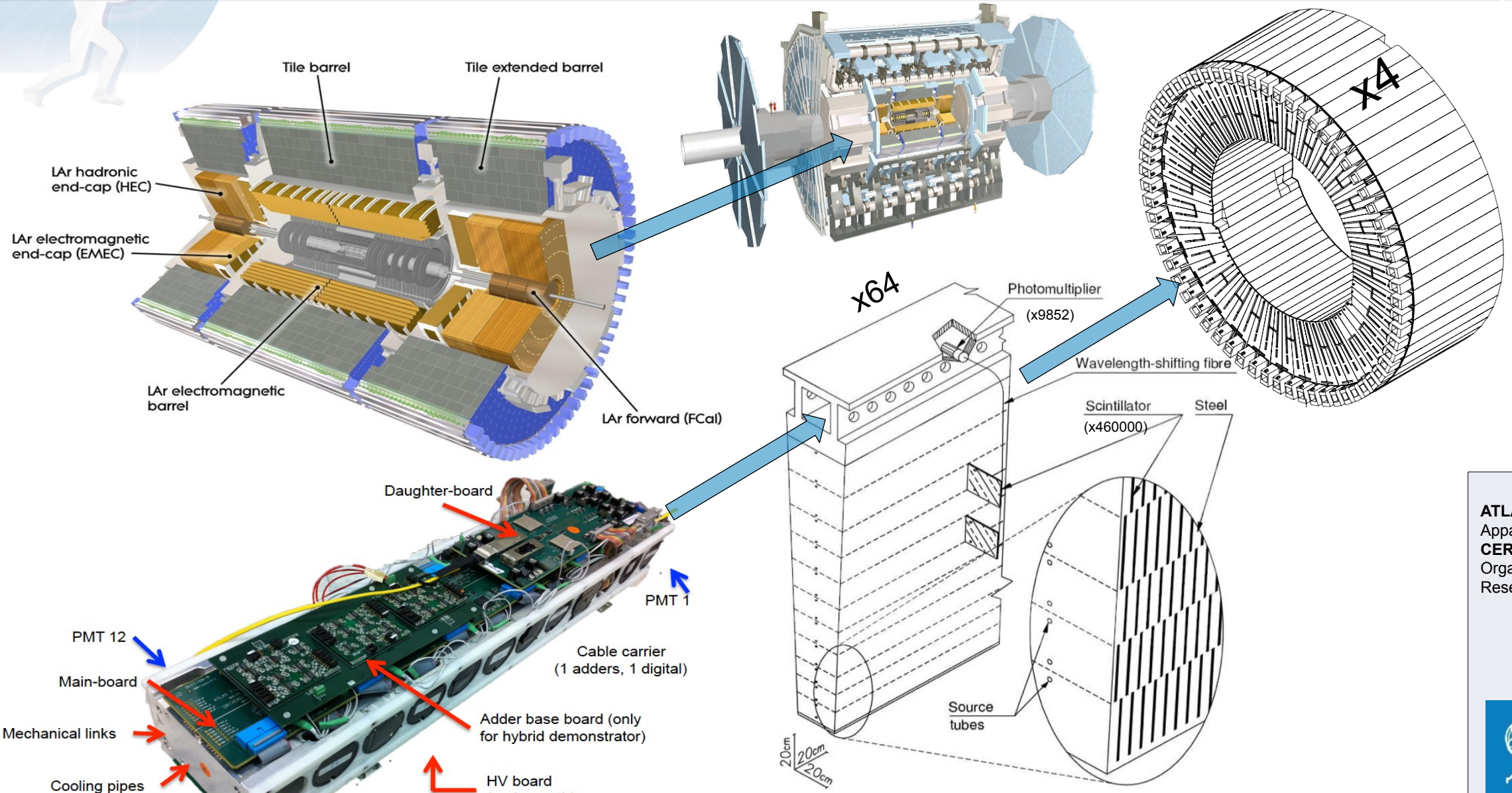
BACKUP Slides...

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Gracias!

Eduardo Valdes S... Dr

Introduction



ATLAS: A ToroidaL ApparatuS.
CERN: European Organization for Nuclear Research.

Introduction…

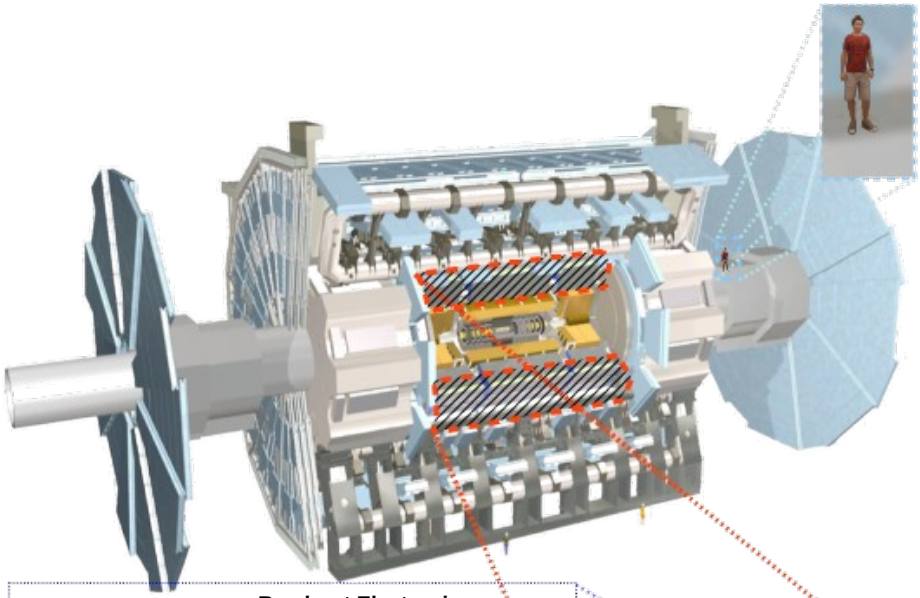
Timeline ($^{16}/_{14}$)
Introduction…
Upgrade design...
Demonstrator…
Calibration...
Optical chain…
Physics Response…
Conclusions…

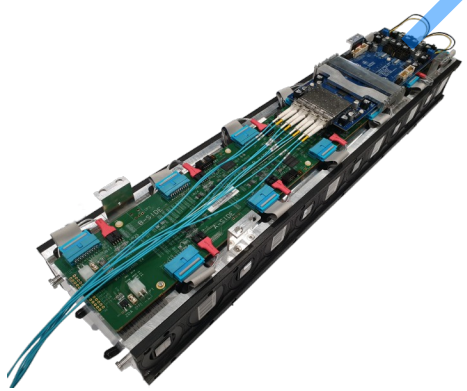
- ATLAS
  - General-purpose LHC detector, built in layers around the collision point
    - Inner detector in a solenoid field measures momentum and direction of charged tracks
    - Calorimeters:
      - Liquid-argon (LAr) for electromagnetic showers
      - Hadronic Tile Calorimeter in the barrel, LAr in the end-caps
    - Muon spectrometer

- TileCal:
  - jets, τ leptons, missing transverse energy and muon identification in the crack region
  - Provides energy sums to the first level trigger (L1 trigger)

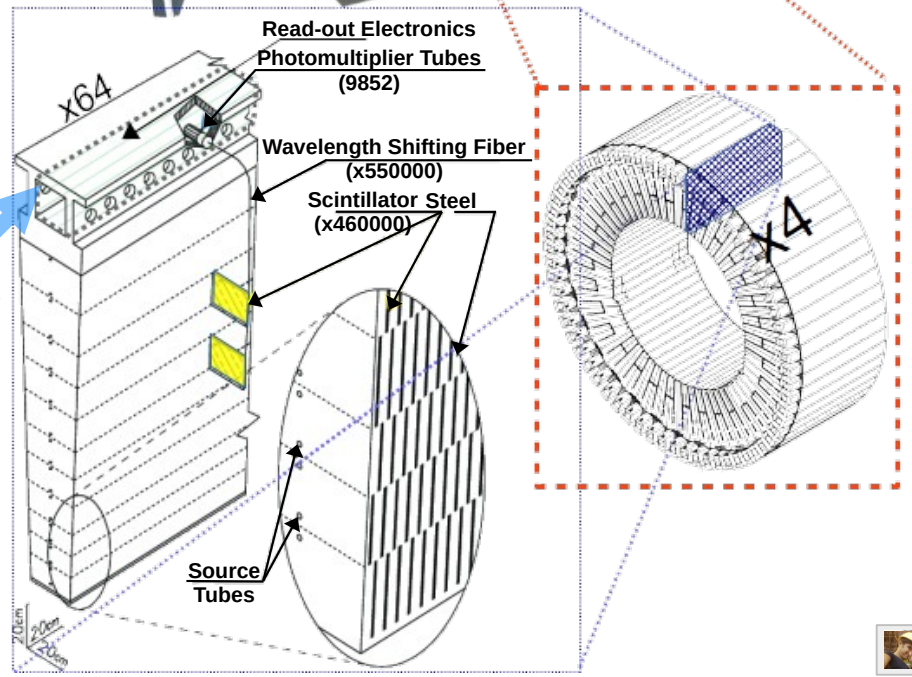
  - Central hadronic calorimeter
    - divided I four barrels covering, $|\eta| < 1.7$;
    - each barrel divided in 64 slices

    → steel absorber + plastic scintillator tiles
    → Wavelength Shifting Fibers + PMTs
    → pulse shaping + digitization + readout





Upgrade Minidrawer

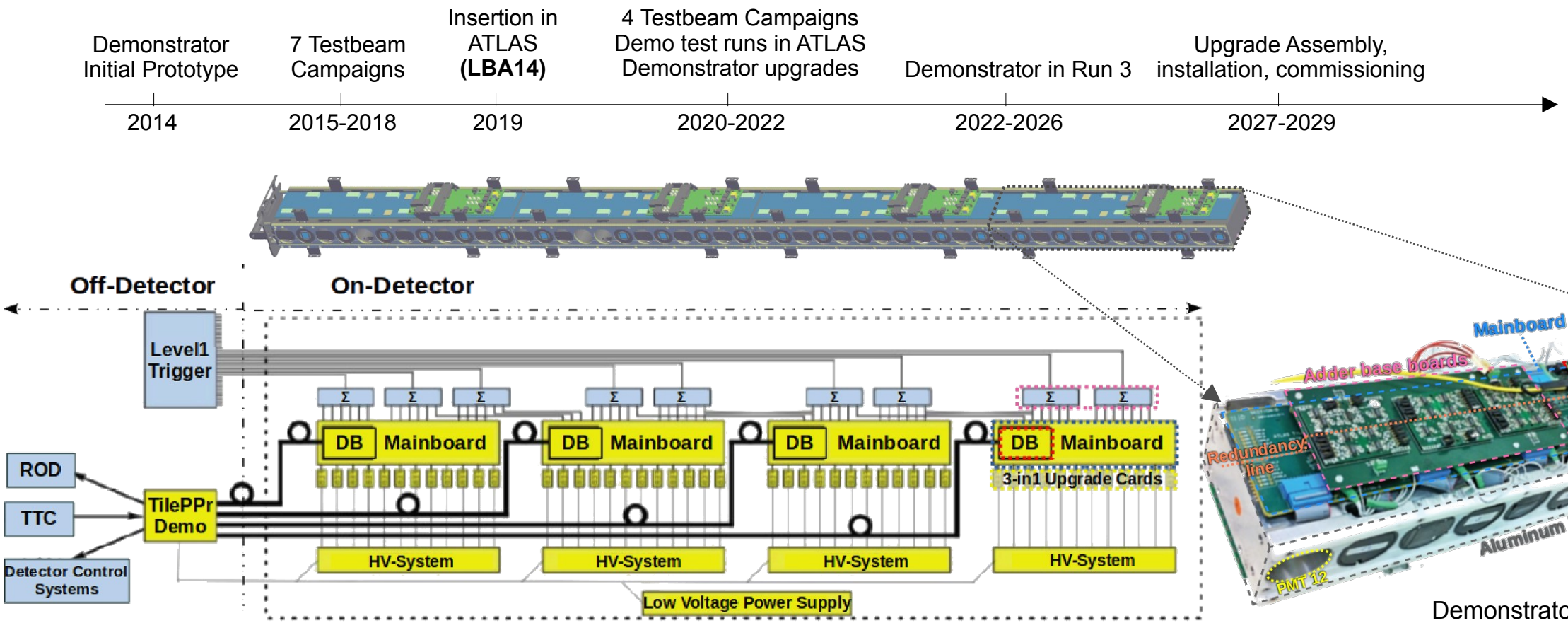


Demonstrator…

Timeline ($^{17}/_{14}$)
Introduction…
Upgrade design...
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- Hybrid readout: new digital chain + legacy analogue trigger
- Off-detector:TilePPr layers compatibility with legacy Read-out driver (ROD) format and Trigger and Timing Control (TTC)
- On-detector: 4x minidrawers each equipped with 12 PMTs, 1 Mainboard, 1 Daughterboard and 1 legacy Adder board

- Demonstrator prototyped and tested in testbeam campaigns finally installed in 2019 as LBA14 (Long Barrel A Slice 14)



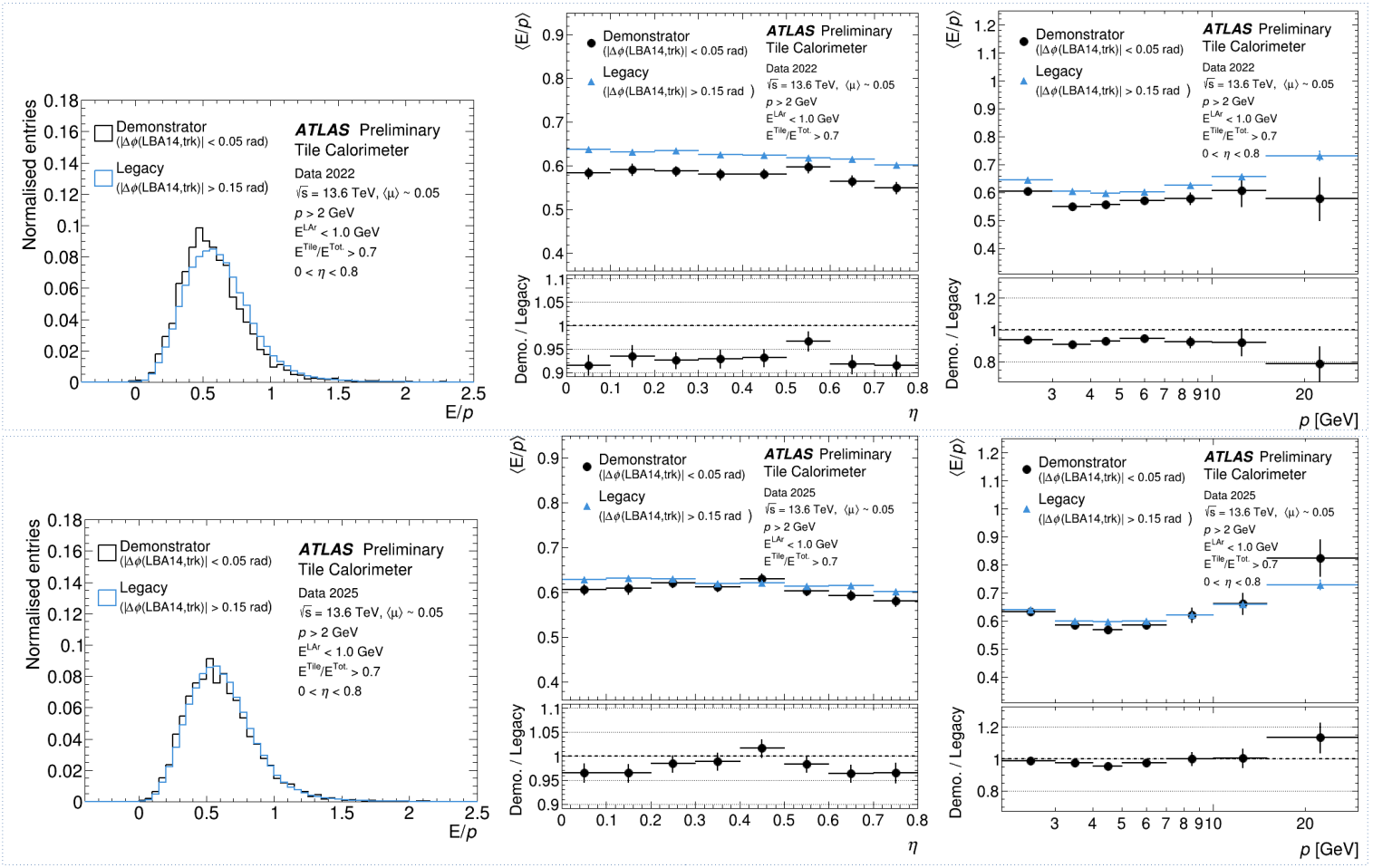
Hybrid readout concept (new digital chain legacy)

Demonstrator Mini Drawer

Physics response to hadrons

Timeline ($^{18}/_{14}$)
Introduction…
Upgrade design...
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- The ratio of E/p measured for isolated charged hadrons is used to characterize the calorimeter response to hadrons, where E is the energy deposited by an isolated charged particle in the calorimeter and p is the momentum of its inner detector track.
- Equivalent response across η and p for Legacy and Demonstrator (ratio Demo/Legacy → 0.96 to 1.02)
- An end-to-end hadron response covers calorimeter and reconstruction.



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileSingleParticleResponse

⟨μ⟩: average number of simultaneous proton–proton interactions per bunch crossing
Calorimeter energy over track momentum plot cuts:
- isolated tracks: p>2 GeV
- no other track within ΔR<0.4
- energy from clusters matched within ΔR < 0.2
- LAr energy below 1 GeV
- more than 70% of the energy deposited in TileCal
- Demonstrator → tracks within |Δφ|<0.05 of LBA14, - Legacy → tracks within |Δφ|>0.15 (neighboring modules).

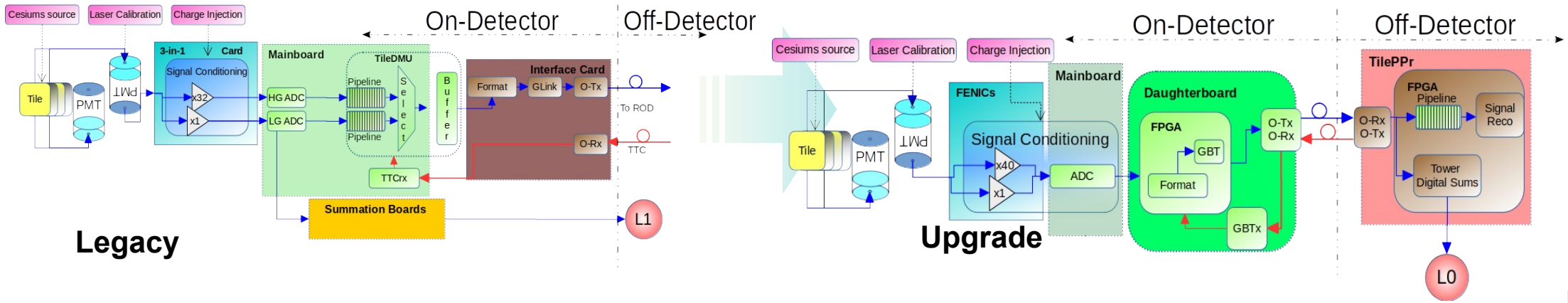
Upgrade design… High Luminosity Design Constraints...

Timeline ($^{19}/_{14}$)
Introduction…
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- HL-LHC conditions:
  - Up to 7.5× nominal instantaneous Luminosity to an integrated Luminosity of 4000 fb^{-1}
  - Pile-up no less than $\langle\mu\rangle \approx 180$ pp interactions per bunch cross
  - 10x to 20x times more radiation than LHC

  - Replace on- and off-detector electronics, using COTS components (Commercial FPGAs, ADCs, POLs, etc)
  - Increased readout rates, off-detector fully digital trigger, radiation tolerance, robustness and redundancy

- From **Legacy** LHC system → **Upgrade** HL-LHC system:
  - On-detector pipeline, 1-gain (x1 or x64) triggered event readout → Off-detector pipeline, dual-gain (x1 and x40) 40 MHz readout
  - Readout of 7x 10-bit ADC samples per PMT → Readout of 16x 12-bit ADC samples per PMT
  - Trigger via analogue tower sums (100kHz L1 Trigger) → Fully digital trigger (1 MHz L0 Trigger)
  - Passive High Voltage Dividers in the PMT → Active Hight Voltage Dividers
  - PMTs in the most exposed cells will be replaced with the newer R11187 model (~10% of the PMTs)



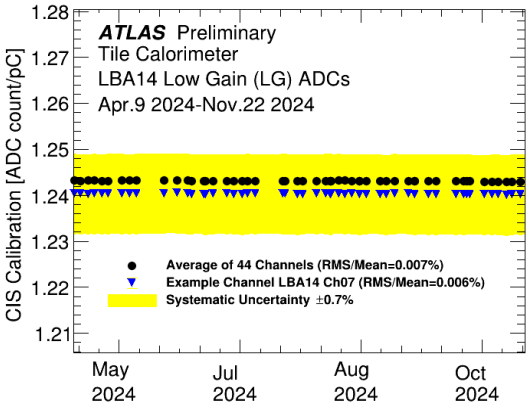
Lx Trigger: Level 0|1 trigger
FPGAs: Field Programmable Gate Arrays
POL: Point of Load regulator
COTS: Commercial off the shelf
ADC: Analogue to Digital
DAC: Digital to Analogue
PMT: Photomultiplier Tube

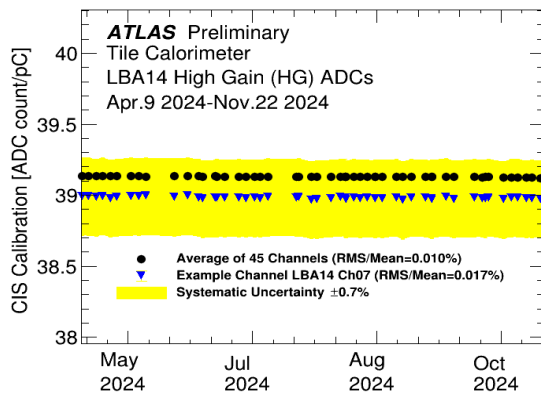
Charge Injection System

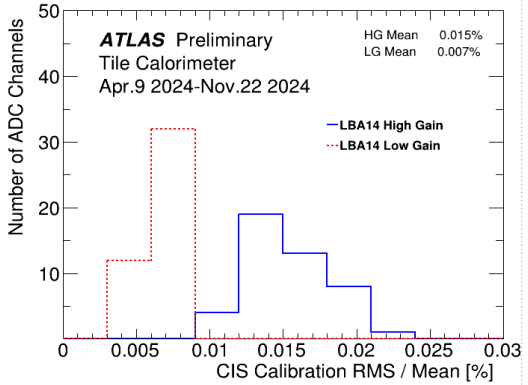
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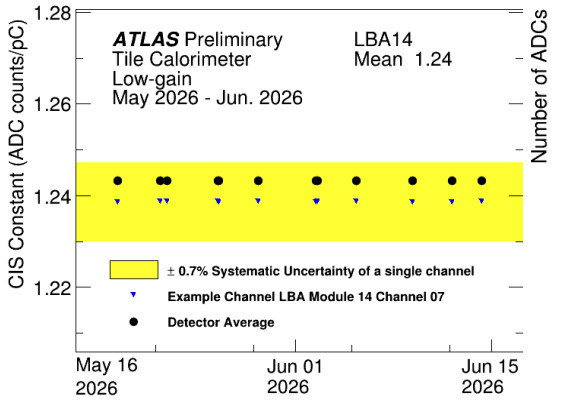
- CIS calibration is stable at the 10^{-4} level (0.01% for HG and 0.007% for LG run-to-run RMS/mean)
  - ±0.7% systematic from the capacitance of the injected-charge source
  - Stability of the ADC-to-charge conversion in time: fluctuations well inside the systematic band mean a stable electronics chain.

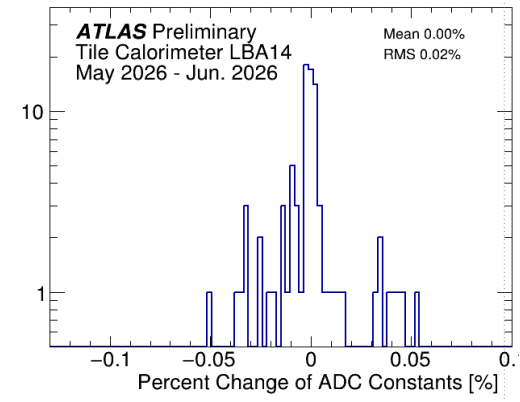
- HG range extended 12.5 → 25 pC with 12-bit ADC (following a correction during 2025 to a HG gain truncation effect found during horizontal muon measurements → lower HG amplification (64x legacy and 32x Demonstrator), plus 10-bit to 12-bit truncation)
- The Demonstrator's DAC non-linearity is 0.1%, against 0.4% in the legacy system

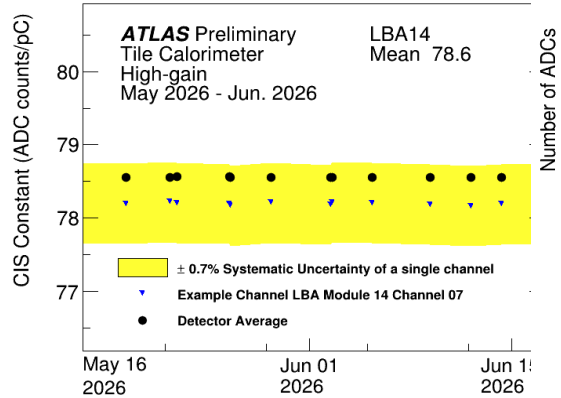


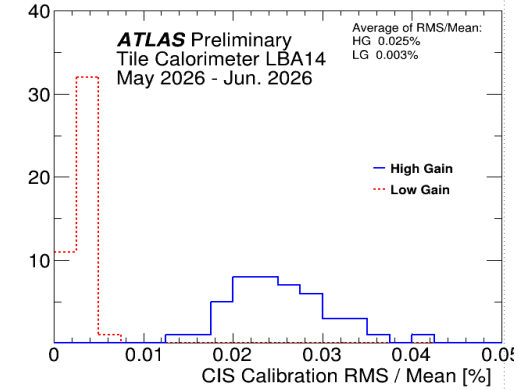












CIS: Charge Injection System

LG, HG: Low Gain, High Gain

For each validated CIS run, the CIS constant (ADC counts/pC) is averaged for both gains over all ADCs.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileCalibrationCIS