

Operation of the ATLAS Liquid Argon Calorimeter during LHC Run 3 and Status of the Readout Electronics Upgrade for the High-Luminosity LHC

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On Behalf of the ATLAS and ALLEGRO Collaborations

INSTR 2026, Hefei, China

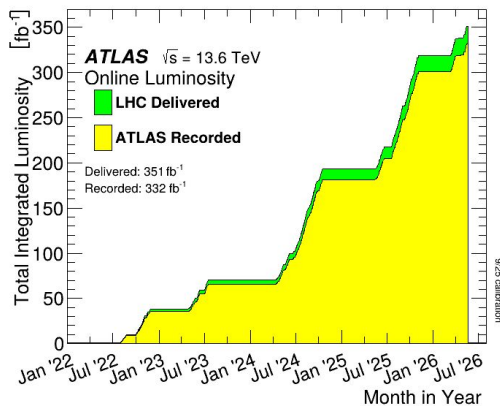


Outline

Three topics: from running the LAr calorimeter today to building the calorimeters of the future

1 LAr Run 3 operation

Run 3: 2022 – 2026



- LAr operation
- Readout system and the new Phase-I digital trigger (DT)
- Data quality

2 Upgrade for HL-LHC

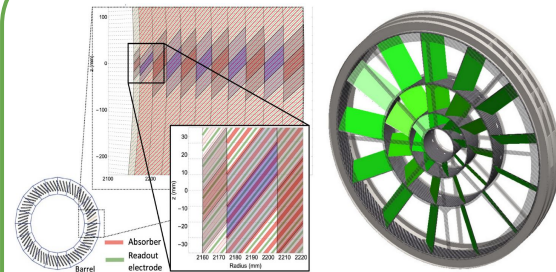
LS3 installation → HL-LHC



- Why a new readout: **1 MHz** trigger, **pileup up to 200**
- New front-end ASICs and boards, new FPGA-based back-end boards

3 ALLEGRO for FCC-ee

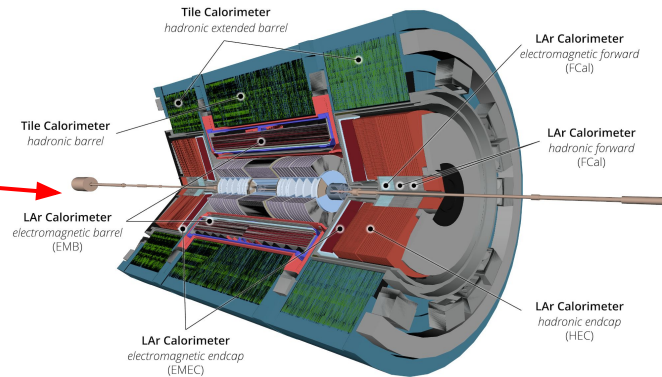
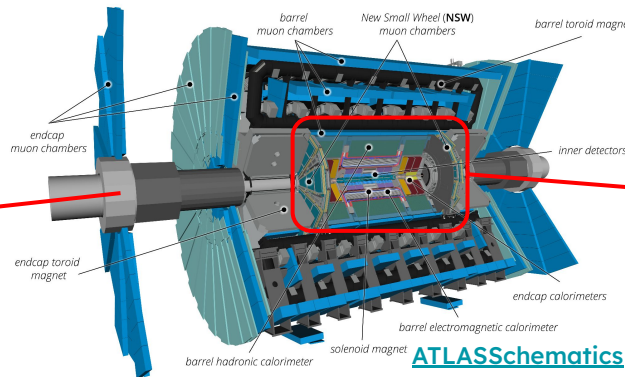
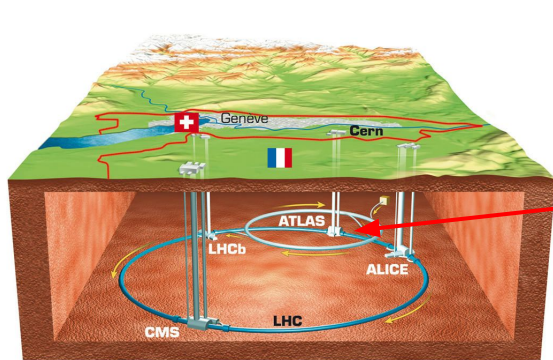
Future e⁺e⁻ collider



- Noble-liquid ECAL concept with straight electrodes
- Simulated performance and γ/π^0 separation
- R&D: mechanics, readout electrodes, cold electronics

LAr LHC Run 3 operation

The ATLAS Liquid-Argon Calorimeter



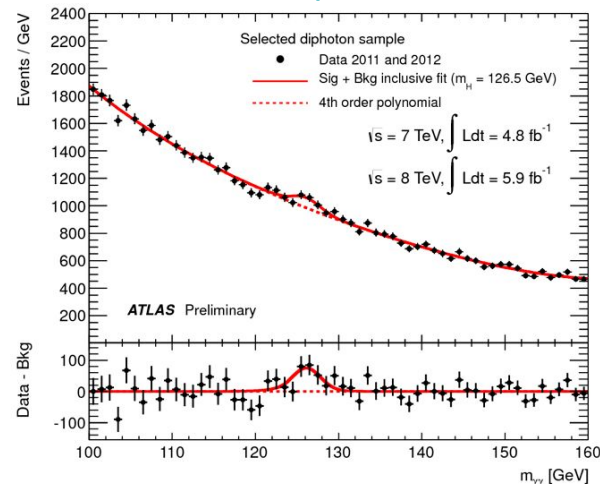
- Alternating layers of **passive absorber** and **liquid-argon ionisation gaps**. Absorber chosen per region:

Section	Absorber	η range
EM barrel (EMB)	Pb	$ \eta < 1.475$
EM end-cap (EMEC)	Pb	$1.375 < \eta < 3.2$
Hadronic end-cap (HEC)	Cu	$1.5 < \eta < 3.2$
Forward (FCal)	Cu / W	$3.1 < \eta < 4.9$

- Electromagnetic energy resolution for e/γ : **stochastic term** $\approx 10\%/\sqrt{E}$, **constant term** $\approx 0.7\%$. $\rightarrow$ **excellent resolution** $\rightarrow$ **Higgs boson discovery in 2012!**
- LAr also contributes to jets and missing transverse energy measurements.

Covering $|\eta| < 4.9$, LAr provides most ATLAS calorimetry outside the Tile barrel.

[Phys. Lett. B 716 \(2012\) 1](#)



LAr Basics: from Ionisation to Energy

Segmentation

About 182k readout cells, up to four layers in depth. The zig-zag (accordion) electrodes in the EM part ensure uniform, crack-free coverage in ϕ

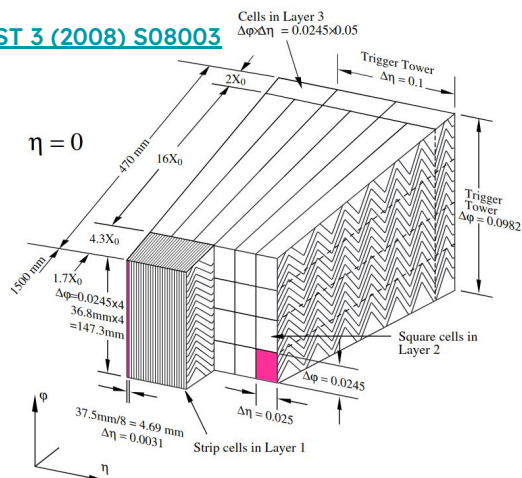
Ionisation signal

Showers ionise the argon: electrons drift across ~ 2 mm gaps under 250–2000 V, giving a current that falls linearly to zero in ~ 450 ns

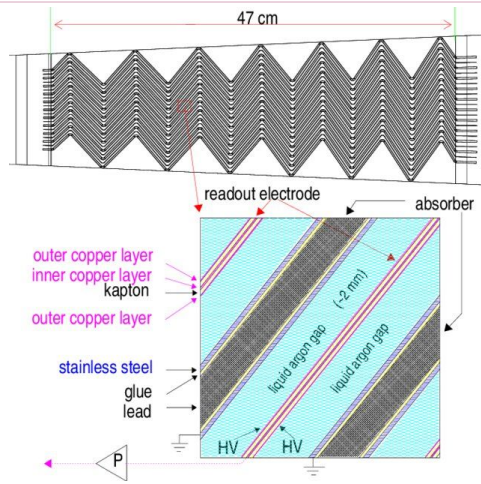
Readout chain

Bipolar shaping samples the pulse every 25 ns, while Optimal Filtering determines the amplitude ($\propto E$) and timing (t_0).

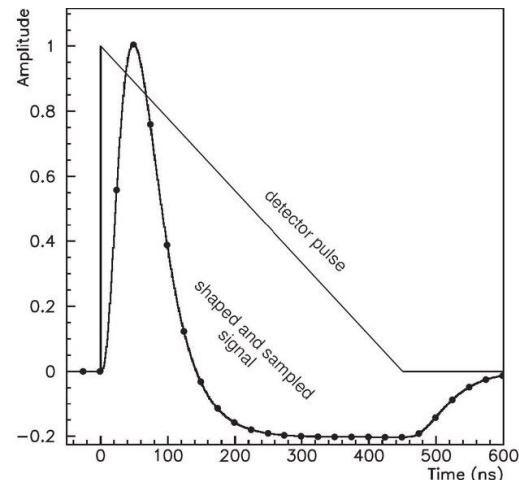
[JINST 3 \(2008\) S08003](#)



Layer structure of a barrel EM module



Absorbers, electrodes and argon gaps



Raw triangular pulse vs. shaped, sampled signal

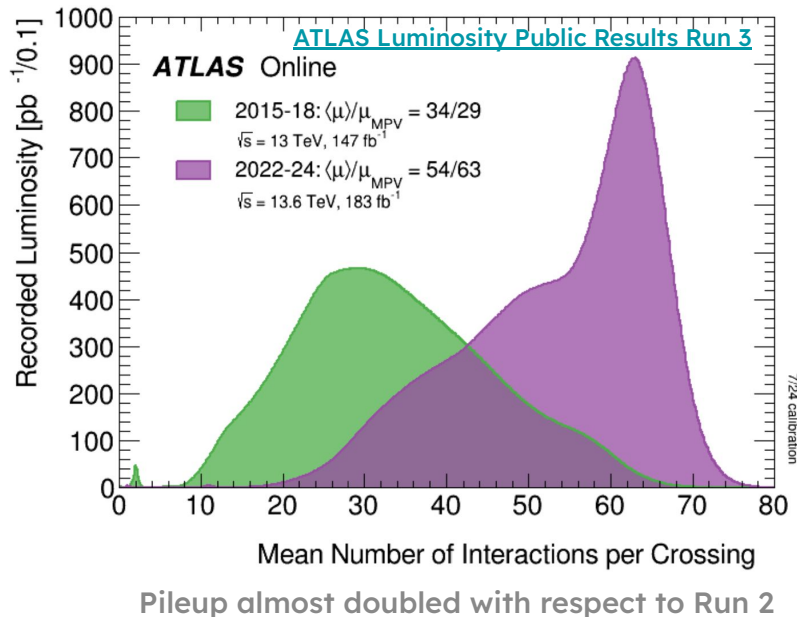
In Run 3 the same signals feed two paths: precision cell readout at 100 kHz and the 40 MHz super-cell digital trigger

LHC Run 3: Operating Conditions



	Run 2 (2015–18)	Run 3 (2022–26)
$\sqrt{s}$	13 TeV	13.6 TeV
Peak luminosity	$2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	$2.6 \times 10^{34} (+25\%)$
$\langle \mu \rangle / \mu_{\text{MPV}}$	34 / 29	56 / 63 ($\approx \times 2$)
Recorded pp	148 fb^{-1}	327 fb^{-1}

- **High-luminosity pp** as main physics programme + low- μ pp, Pb-Pb, O-O, Ne-Ne runs.
- Phase-I LAr Digital Trigger installed in LS2 (2019 - 2021), commissioned and in physics production. **SINCE 2024**
- **Run 3 ended 30 June 2026** → LS3 and HL-LHC installation.



Run 3: 327 fb^{-1} recorded at 13.6 TeV, more than twice the Run 2 pp dataset

LAr Readout System

Front End

Back End

Main Readout

FEB

1524,
on-detector

Amplifies and shapes the cell signals, stores samples in an analogue pipeline, digitises them for each L1 accept (100 kHz)

ROD

off-detector

Computes cell energy and time (Optimal Filtering) and sends them to DAQ

Legacy Trigger

TBB

Sums analogue signals into 0.1×0.1 trigger towers for the old L1Calo

REPLACED BY DT IN 2024

Phase-I digital trigger

Layer Sum Board

LSB

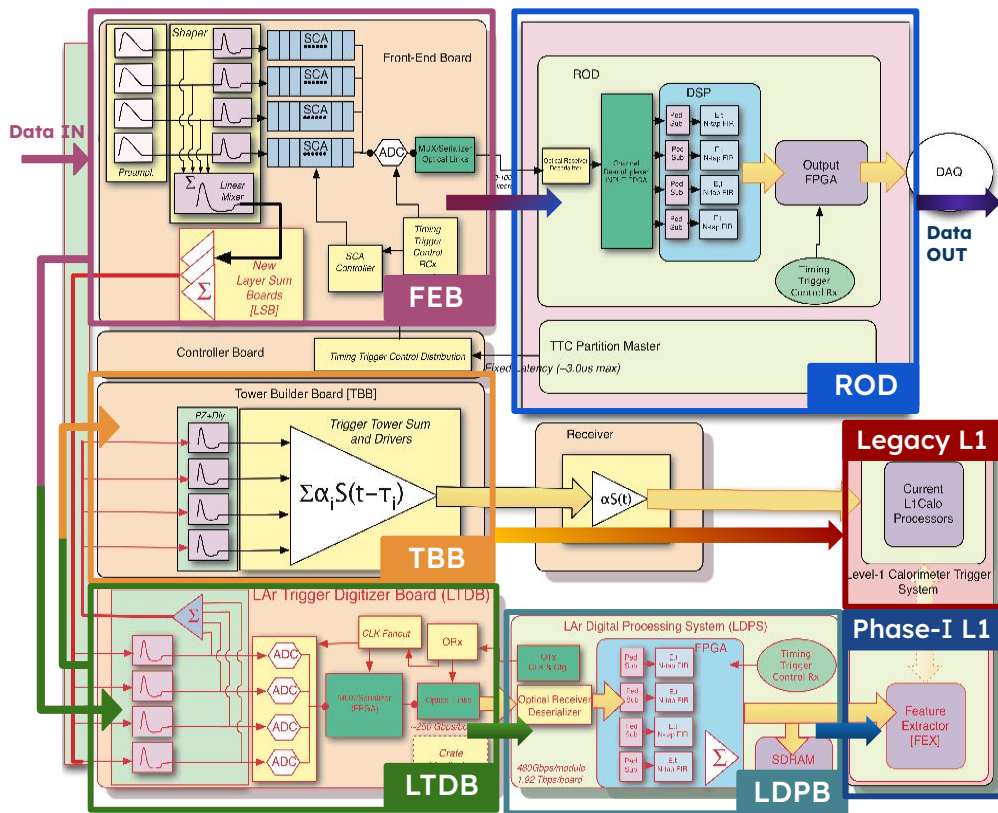
New boards on the FEBs: form the finer analogue super-cell sums

LTDB

Digitise super cells at **40 MHz** and send them over optical fibres

LDPB

Each with 4 FPGA-based mezzanine boards (LATOME): compute super-cell E_T and time every 25 ns



CERN-LHCC-2013-017

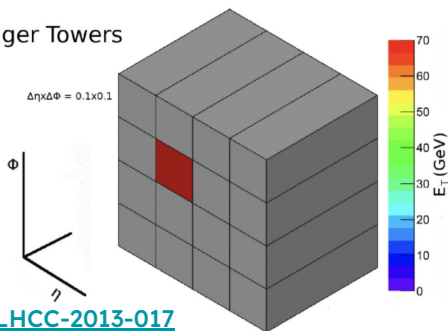
Digital Trigger: Commissioning & Performance

Period	L1 seeding	
2022–2023	Legacy trigger; FEX items in menu but disabled → commissioning in parallel	
early 2024	eFEX fully enabled	READY
mid 2024	jFEX and gFEX enabled	READY
2025	Commissioning effort significantly reduced	STABLE

FEX = feature extractor

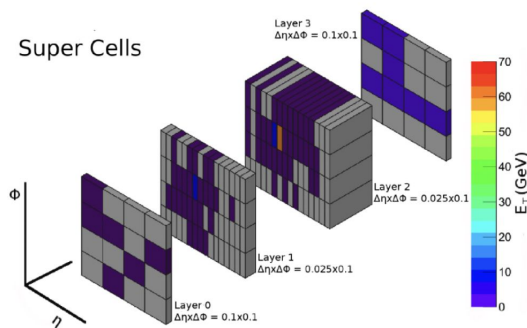
- **Super cells:** up to 4× finer granularity + depth information: shower shapes at L1
- SC energy agrees with ΣE_{cell} from the main readout
- SC timing well aligned, within a few ns
- **≈ 99.6% good super cells** during data taking

Trigger Towers



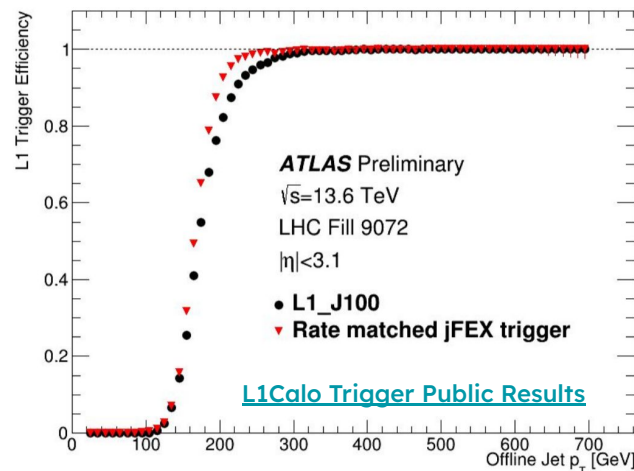
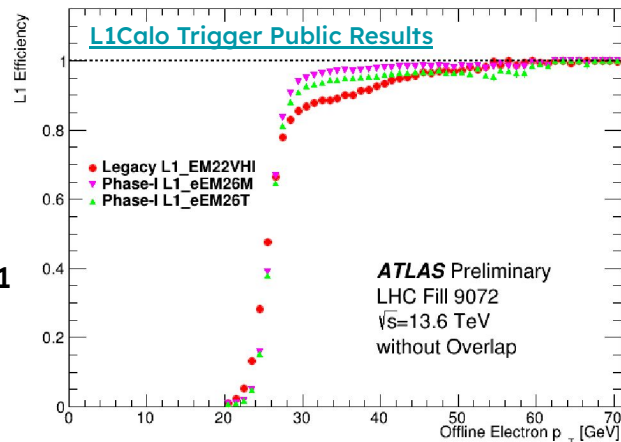
[CERN-LHCC-2013-017](#)

Super Cells



TT (~5.2k, 0.1×0.1, no depth) → super cells (~34k, up to 0.025×0.1, 4 layers)

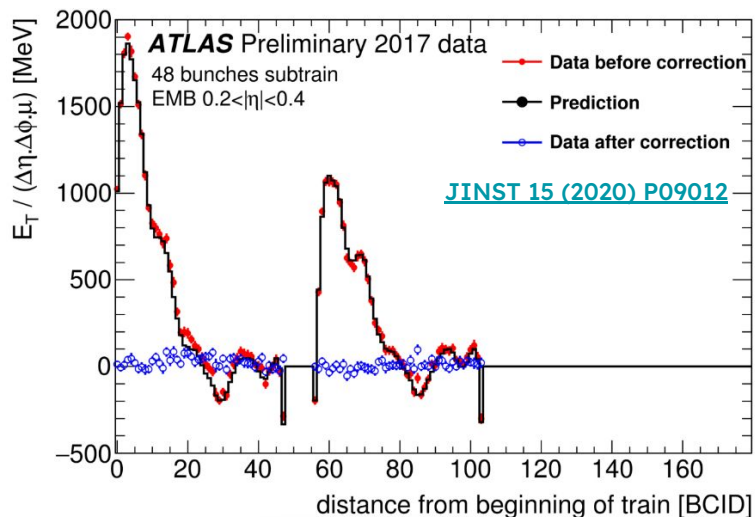
Sharper turn-ons: full efficiency at lower thresholds within the same L1 rate budget



Pileup Mitigation: Baseline Correction

- LAr pulse (~600 ns) spans many bunch crossings → out-of-time pileup shifts the baseline
- Pileup cancels on average only inside long bunch trains → residual shift at train start/end

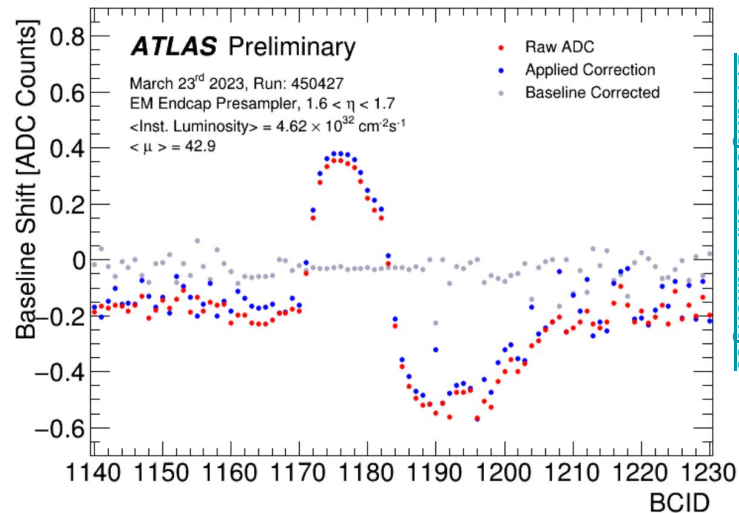
Main readout: correction applied offline



Example from Run 3

Essential for DT energy scale. An FCal baseline-correction bug degraded MET until fixed in LATOME FW (2024)

Digital trigger: computed on-the-fly per super cell and BCID in LATOME



D. Mungo, Tech. challenges

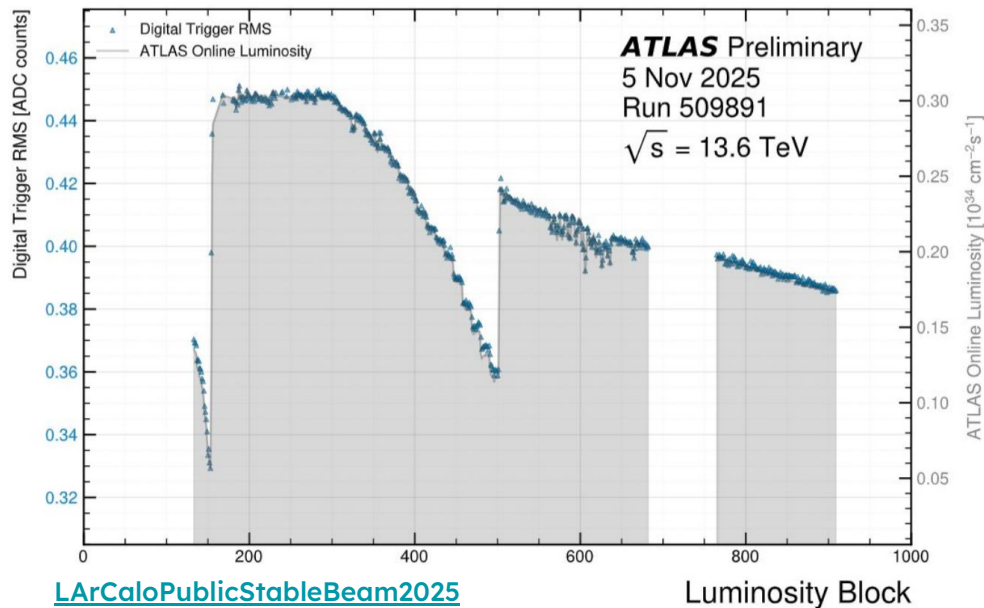
Example from Run 3

Pileup ≈ 0 : switching it off avoids rate spikes every 32 BCs, but noise increases, not yet understood

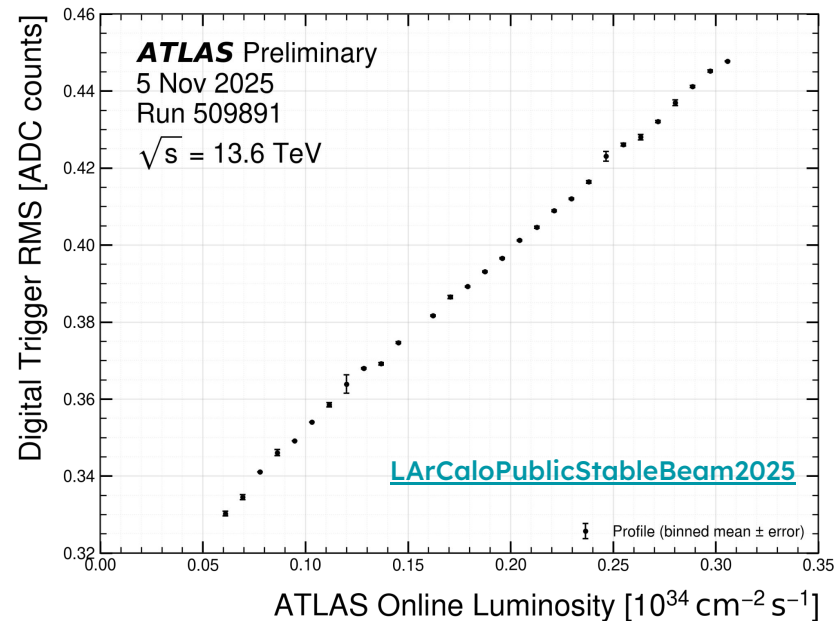
Even more important at HL-LHC pileup: baseline correction is part of the LASP firmware

Luminosity Measurement with DT

- Pileup particles create a continuous low-level ionisation, proportional to the instantaneous luminosity
- The RMS of the digital trigger ADC counts is compared with dedicated ATLAS luminometers (e.g. LUCID)



DT RMS follows the luminosity profile along the fill



Linear dependence on online luminosity

A new, independent handle on luminosity from the 40 MHz super-cell data stream

Data-Taking Efficiency in Run 3

- Luminosity chain: **delivered** → **recorded** → **good for physics**
- Recording efficiency 92–96%, DQ efficiency 93–96%
- LAr DQ efficiency per year (mainly reflects the main readout. DT issues appear as L1 inefficiency)

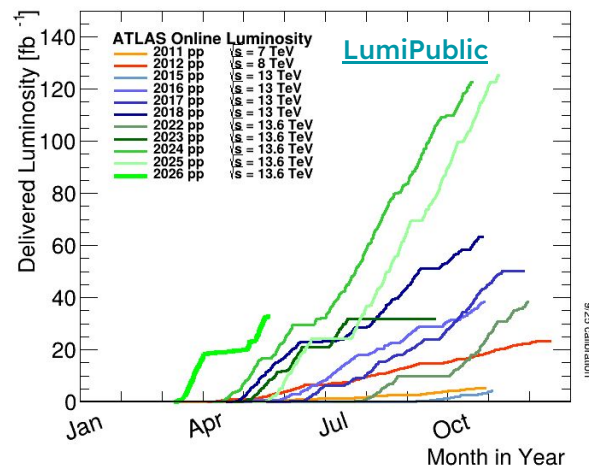
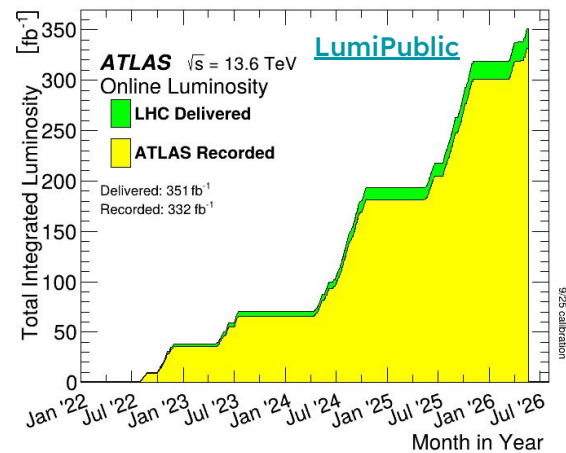
Year	L_{rec} [fb^{-1}]	LAr DQ eff.	ATLAS good for physics
2022	34	98.98%	93.1% (31 fb^{-1})
2023	28.8	99.5%	94.6–96.5% (27.2 – 27.8 fb^{-1})
2024	116	99.8%	93.5% (108 fb^{-1})
2025	119	99.2%	96.7% (115 fb^{-1})
2026	29.2	99.7%	96.5% (28.1 fb^{-1})
Run 3	327	99.64%	

Average LAr efficiency 99.64% despite ageing front-end electronics

Trigger	Inner Tracker			Calorimeters		Muon Spectrometer		
L1	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC
99.29	99.81	99.49	99.88	99.64	99.69	99.84	99.41	99.84

[DQresults](#)

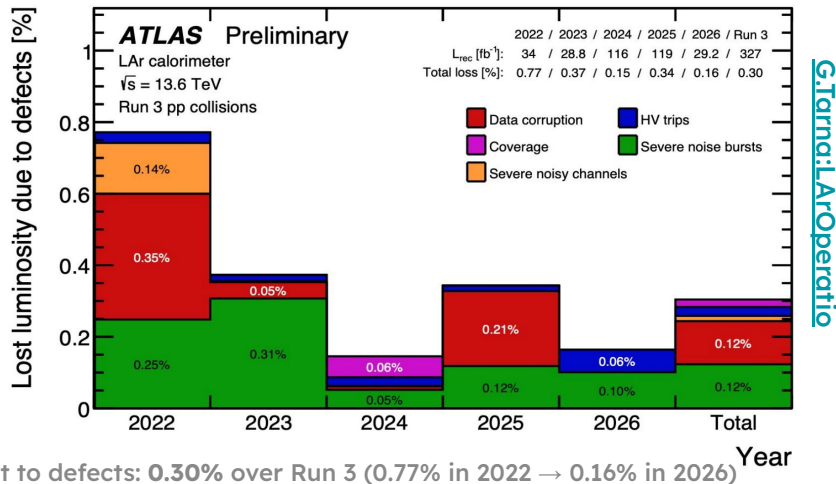
LAr delivers high data quality efficiency



LAr Data Quality: Sources of Losses

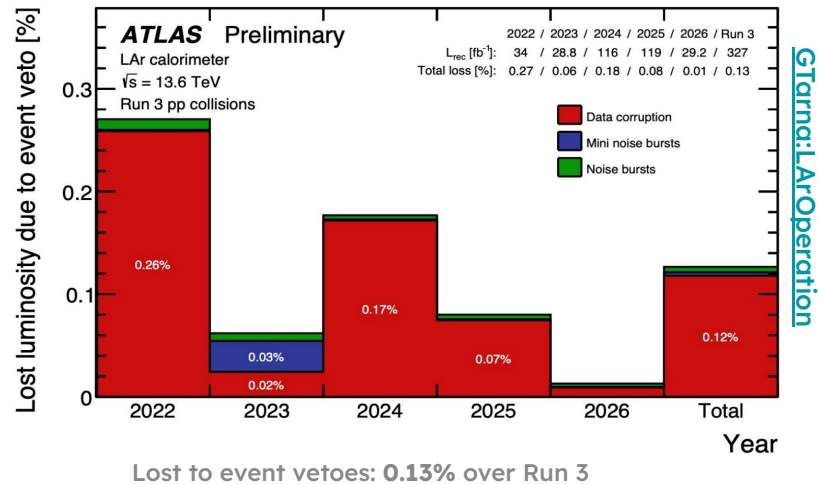
Defect

Problem lasts long → the **whole luminosity block (~1 min)** is thrown away



Event veto

Problem is short → only the **affected ms-s window** is removed, the rest is kept

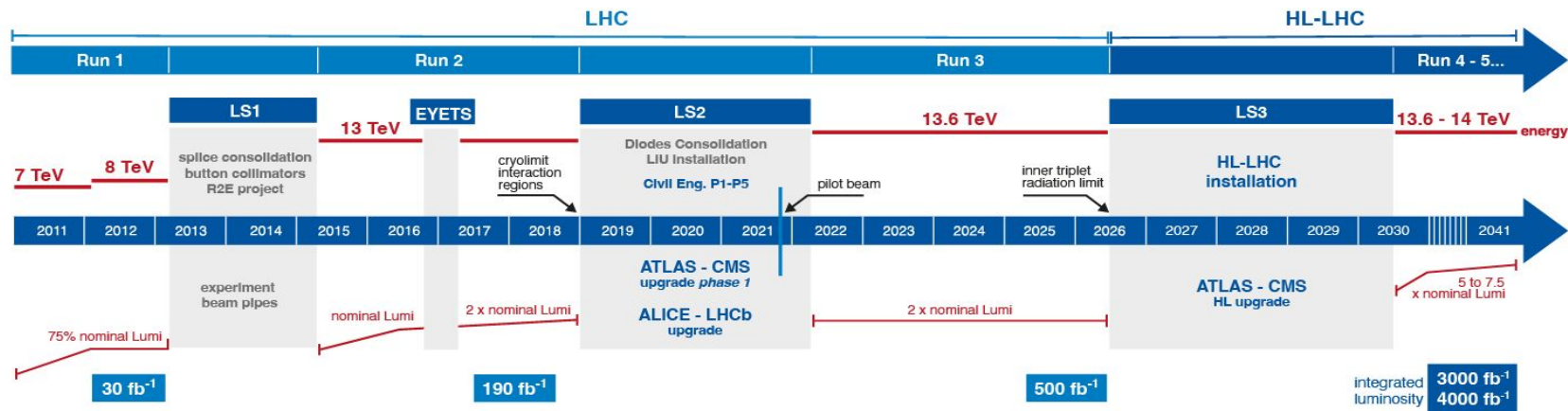


Source	What happens	Notes
Data corruption	Readout electronics deliver corrupted data — the largest loss	Short cases → event veto, long ones → defect
Noise bursts	Short (μs –ms) noise seen in many channels at once; origin unknown	
HV trips	A high-voltage line switches off and must ramp up again	Grow with luminosity → may increase in Run 4 & 5
Noisy channels	Single cells give fake energy → masked	

Total LAr inefficiency < 1% in every year of Run 3

Upgrade for HL-LHC

HL-LHC and the LAr Phase-II Upgrade



- **HL-LHC after LS3 (from mid-2026):**
 - 5-7x instantaneous luminosity
 - pileup of 140-200 collisions per bunch crossing
 - up to 3000-4000 fb⁻¹ integrated luminosity
- **New ATLAS trigger:** L1 accept rate 100 kHz → 1 MHz, with longer latency
- Current LAr readout electronics **were not built for these rates, latency and radiation doses**

Replaced

Full main readout chain: calibration, front-end and back-end electronics, timing & control

Kept

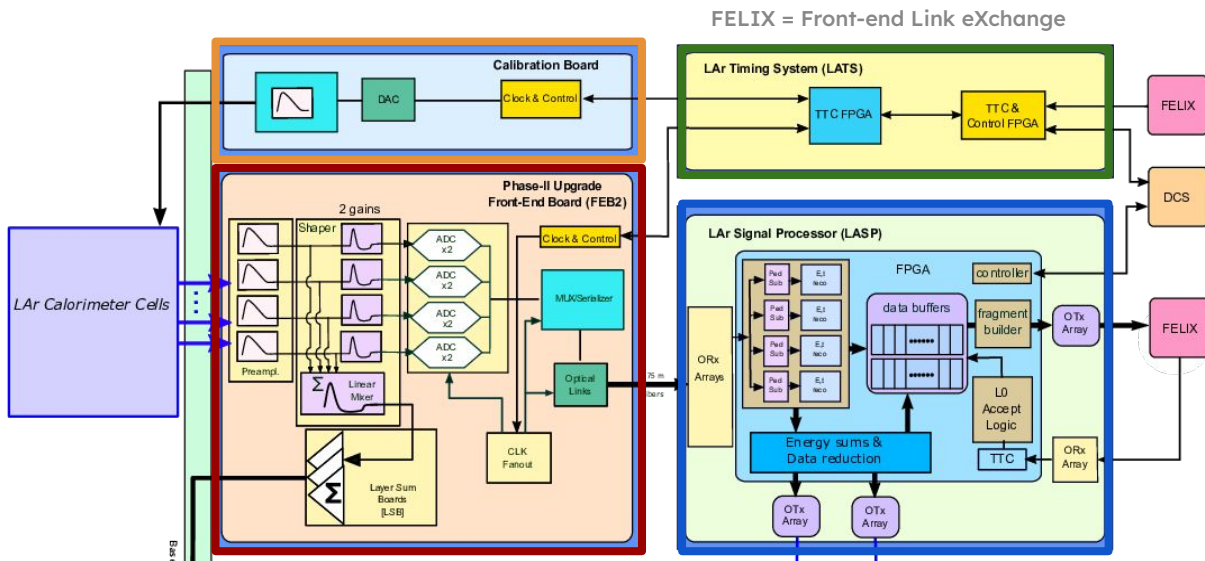
The calorimeter itself and the Phase-I digital trigger (refurbished)

Bigger scale than Phase-I

Remove and install front- and back-end electronics, move to the new TTC system

LS3 schedule: dismantling started July 2026, removal of all front-end boards from mid-February 2027

LAr Phase-II Readout Architecture



[CERN-LHCC-2017-020](#)

On-detector

Calibration board

Injects a precisely known pulse into the cells to calibrate the whole chain

FEB2

Amplifies, shapes and digitises every cell at 40 MHz (2 gains), sends all data to the back-end. Analogue sums still go to the DT

Off-detector

LASP

278 boards

FPGA processors: compute energy and time of every cell, send them to the trigger (40 MHz) and to readout (1 MHz)

LAr Signal Processor

LATS

Timing system: distributes clock & trigger signals, configures and monitors the front-end

LAr Timing System

Key change: no more analogue pipeline, all cells digitised at 40 MHz and processed in FPGAs

On-Detector ASICs: Preamp/Shaper & ADC

ALFE
preamp +
shaper

Amplifies and shapes the cell signal in **two gains**. **50k chips**,
testing complete, available for production (> 90%) **DONE**

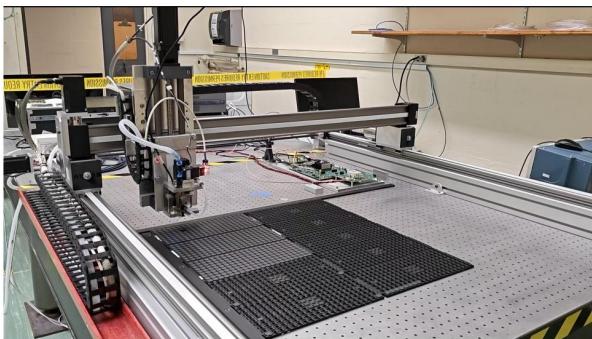
HPS
for the HEC

Same role for the hadronic end-cap, which already has
preamps in the cryostat. > 80% pass **DONE** Hadronic Pre-Shaper

COLUTA
ADC

Digitises both gains of every channel at 40 MHz. 77k
produced, ~80% pass **In testing**

ALFE and COLUTA are tested chip by chip on **robotic test stands** (HPS manually).
Yield = fraction of tested chips passing all selections. All above requirements.

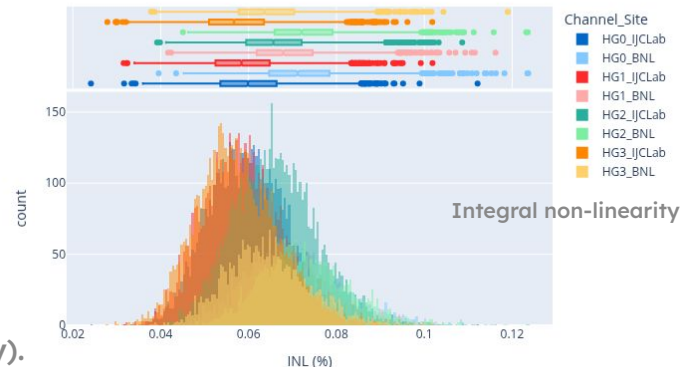


ALFE robotic test stand

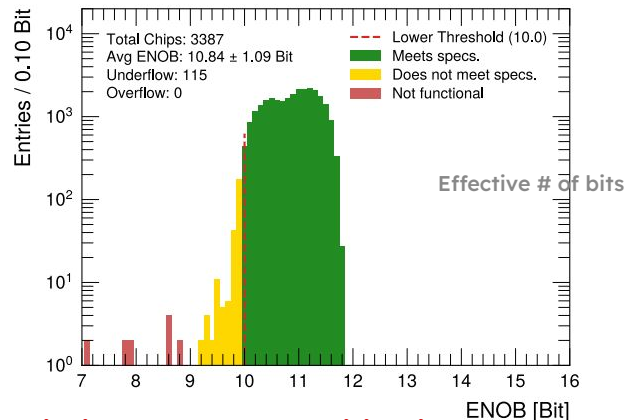


COLUTA robotic test stand

Measured INL with High Gain
Should be below 0.2%



Measured ENOB from 8 MHz sine wave



All custom ASICs nearly done or in final production testing phase and pass radiation tests and specifications

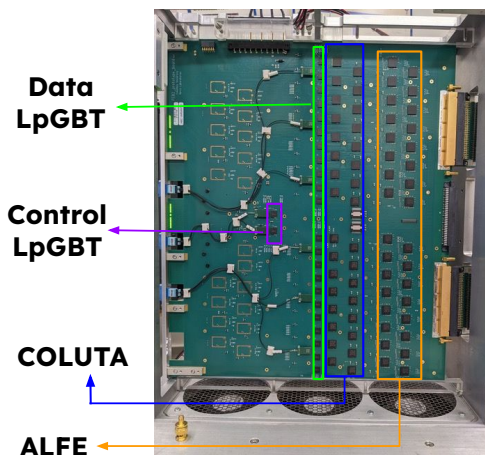
Front-End Boards (FEB2) & Calibration Board

FEB2 PROTOTYPE

LpGBT = Low power GigaBit Transceiver

- ALFE/HPS + COLUTA + LpGBT. LSB mezzanine for DT analogue sums
- 128 channels, ~120 W; tested in crate with detector load & cooling
- Pedestal noise consistent with ALFE: $O(10)$ ADC (HG)
- Coherent noise < 5% of total: 3.3% (1 board), 1.6% (6 boards)

FEB2 board



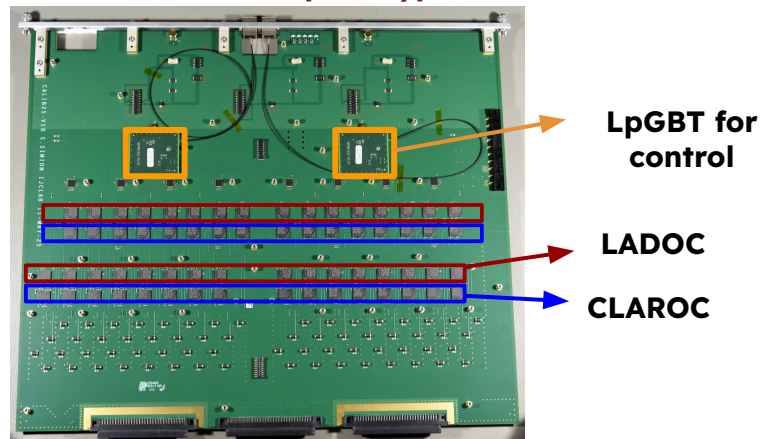
Coherent noise (2 board matrix)
1.6% per channel for all 6 boards

Board ID	231500	390322	391703	391701	391702	394169
231500	4.6	3.0	3.2	3.0	2.9	2.9
390322	3.0	4.0	2.8	2.7	2.7	2.6
391703	3.2	2.8	3.7	2.5	2.7	2.5
391701	3.0	2.7	2.5	3.6	2.5	2.5
391702	2.9	2.7	2.7	2.5	3.7	2.5
394169	2.9	2.6	2.5	2.5	2.5	3.5
Board ID	231500	390322	391703	391701	391702	394169

Calibration board FINAL PROTO END 2026

- Injects pulses of precisely controlled amplitude
CLAROC = Calibration of LAr Output Chip
- CLAROC (HF switch, XFAB 180 nm HV SOI): **testing done**, all chips for production available
- LADOC (16-bit DAC, TSMC 130 nm): **dies received**, packaging starts soon, **tested and ready by end of 2026**
LADOC = Link and DAC of CLAROC
- Final prototype expected before end of 2026. Pre-production in mid-2027

Calibration board prototype



Front-end prototypes meet noise and linearity specifications. Production to start in 2026/2027

Off-Detector: LATS & LASP

LATS

timing
system

Distributes TTC, configures & monitors FEB2 and calibration boards. **30 LATOURNETT boards**, 12+1 Cyclone V FPGAs (1 central: TTC/DAQ/DCS, 12 matrix: front-end links)
Prototype passed FDR, now in production. Firmware used in integration tests. **IN PRODUCTION**

LASP

signal
processor

Energy & time for trigger (40 MHz) and readout (1 MHz)
ATCA, 2x Agilex 7 + Max10, 20-layer PCB, 5000 components
278 boards: O(300 Tb/s) from 1524 FEB2, 35k fibres @ 10 Gb/s in, 4k @ 25 Gb/s out **PROTOTYPE**

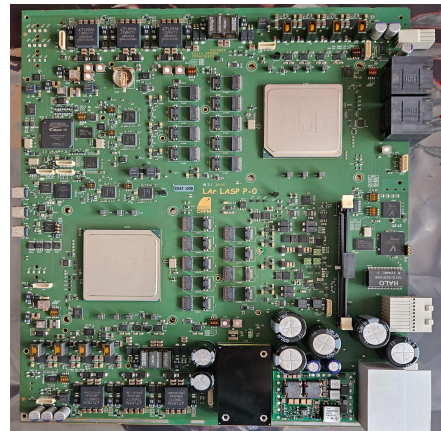
sRTM

Zynq UltraScale: TTC and DAQ interface, DCS (OPC-UA)
12 prototypes operational **READY for production**

Firmware

Up to 25 Gb/s links, 480 MHz clocks. Demonstrator FW used with FEB2 **In progress**

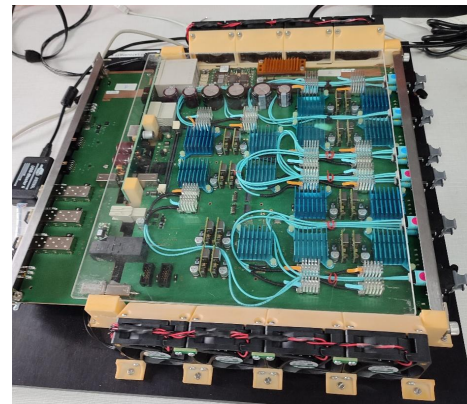
LASP board



sRTM



sRTM = smart Rate Transition Module



LATOURNETT board + RTM

All back-end systems have working prototypes. Demonstrator firmware in use for integration

AI-Powered Energy Reconstruction in LASP

Optimal Filtering today

Fixed weighted sum of a few samples (4 in Run 3). Assumes an isolated pulse $\rightarrow$ degrades with pileup

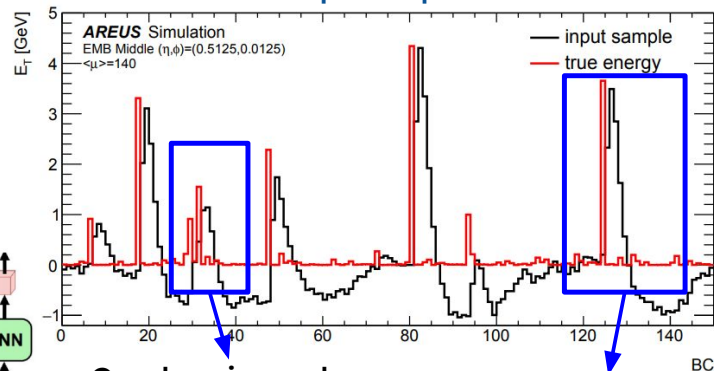
Neural networks

Use ~ 20 – 30 past samples + a few after. Outperform OF over the full energy range (high gain). Demonstrator firmware tested

- At $\langle \mu \rangle = 140$ pulses from consecutive collisions overlap and distort the shape
- Neural networks also look at the samples before the deposit $\rightarrow$ learn and subtract the pileup
- Small networks designed to fit the FPGA resources and fixed latency
- Can also provide the time and an uncertainty on each prediction

[JINST 18 \(2023\) P05017](#)

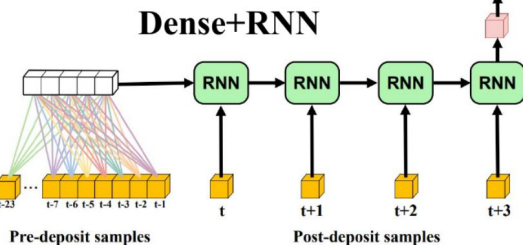
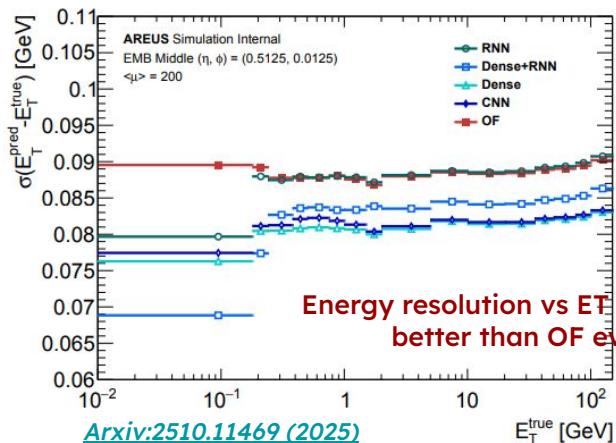
Sample Sequence



Overlapping pulses
Distorted pulse shape

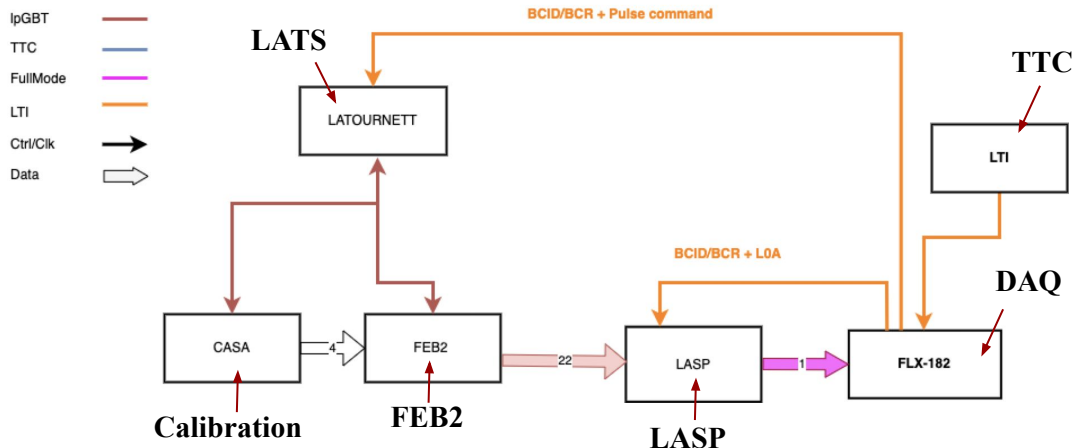
Relatively
isolated pulse

- Largest gain at low energy, where pileup dominates:
 $\sigma \approx 0.07$ – 0.08 GeV vs 0.09 GeV for OF



Machine learning on FPGAs recovers the energy resolution at HL-LHC pileup

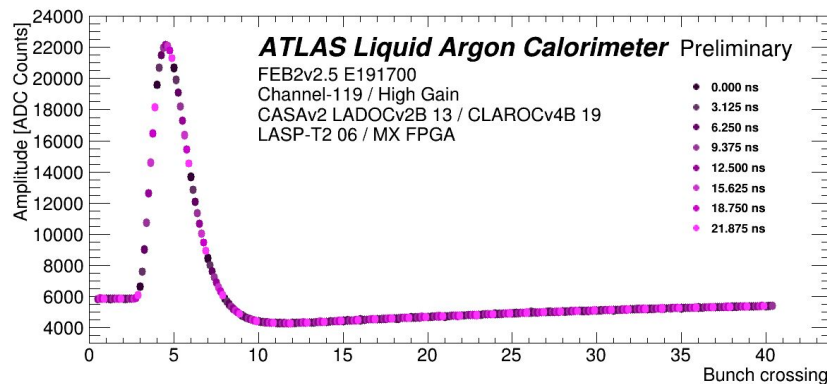
System Integration & LS3 Roadmap



When	Milestone
30 Jun 2026	End of Run 3, detector powered off
Jul-Sep 2026	Dismantling in USA15: TTC, RODs, L1Calo receivers, DT back-end, HV
2026 / 2027	Start of board production
mid-Feb 2027	Removal of all LAr front-end boards
LS3	Installation & commissioning; EMF test lab with full readout chain

- Integration of a LAr phase-II mini-readout system with prototype or demonstrator boards
 - All major subsystems covered
- Validates the integration of different hardware boards
- Development of the firmware and software infrastructure
- Integration with **TTC**, **TDAQ**, and **DCS**
- Continuous update of the hardware, firmware, and software

Pulse recorded by the Phase-II mini-setup



Mini-setup close to the final system: the key tool for firmware and software development

Summary: Run 3 Operation & Phase-II Upgrade

Run 3 operation

COMPLETED

Stable and reliable operation **2022–2026 at 13.6 TeV** with $\sim 2\times$ Run 2 pileup, **327 fb⁻¹ recorded**

99.64% average LAr DQ efficiency. Losses < 1% per year

Phase-I digital trigger in production since 2024: sharper turn-ons, pileup rejection, even luminosity monitoring

Phase-II upgrade

On track

All custom **ASICs** nearly done or in final production / **testing phase**, meeting specifications and radiation requirements

Prototypes available for all boards (FEB2, calibration, LATS, LASP/sRTM). Production 2026/2027

NN-based energy reconstruction demonstrated in LASP firmware

Full-chain mini-setup running. Integration with TDAQ, DCS and Global ongoing

LAr calorimeter well on track for installation during LS3 and operation at the HL-LHC

**ALLEGRO calorimeter
for FCC-ee**

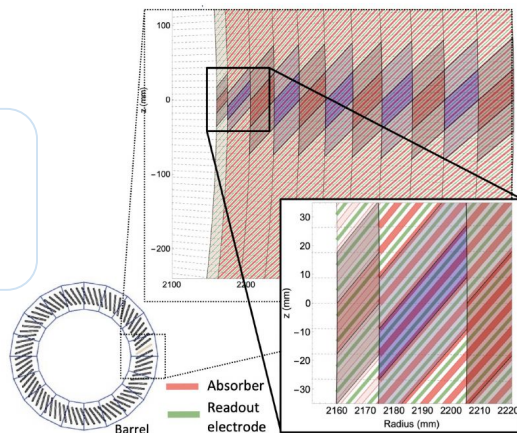
From FCC-ee physics to the ALLEGRO ECAL

- FCC-ee will run at several energies: Z pole, WW threshold, ZH (Higgs factory), $t\bar{t}$ threshold.

Goal

Measurements with uncertainties **below 0.1%** → the ECAL must have good energy resolution, a **linear** and **uniform** response, and a calibration that stays **stable for years**

- Particle flow and π^0/γ separation → fine segmentation in depth and angle.
- Noble liquids** (D0, ATLAS, NA62): **uniform**, **linear**, **stable**, **radiation-hard**.



[J. Pekkanen, NIM A 1069 \(2024\) 169921](#)

Inclined straight electrodes in the barrel (left), "turbine" end-cap (right)

Barrel parameter	Baseline	Alternative
Medium / absorber	LAr / Pb (2 mm)	LKr / W (1 mm)
Gap (2 per electrode)	[1.2, 2.4] mm	[1.7, 2.9] mm
Depth	22 X_0	25 X_0
Electrodes / layers	1536 straight PCBs at 50.2°, 11 layers, 40 cm	
Granularity	$\Delta\phi \approx 8$ mrad, $\Delta\theta \approx 10$ (2.5 strips) mrad, ~ 2.2 M cells in total	

End-cap

Absorber/PCB blades repeated in ϕ , 3 nested wheels to keep sampling uniform

Cryostat

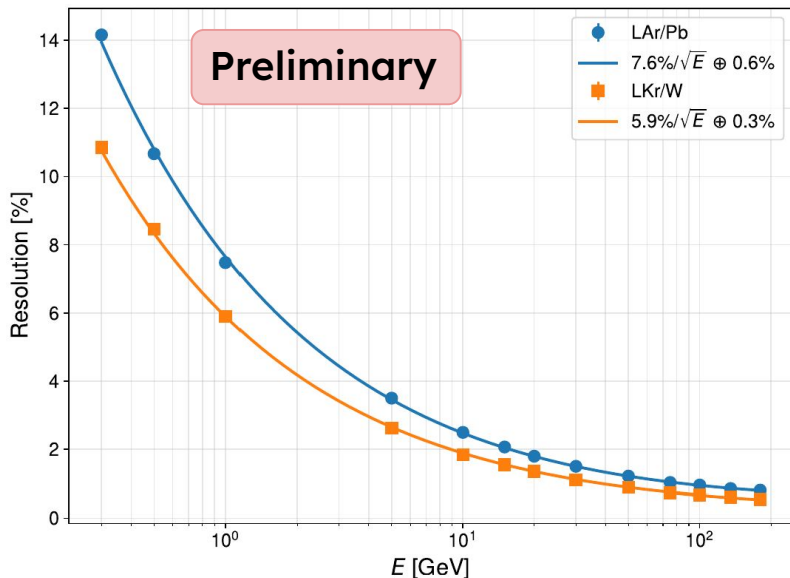
Carbon fibre reinforced polymer (CFRP) option: only $\sim 0.15 X_0$ in front of the active volume

R&D status

Full Simulation **READY** · absorber & electrode prototypes **TESTED** · FE ASIC prototypes **TESTED**
 beam-test module **In preparation**

Simulation & Expected Performance

- Full Geant4 simulation in **Key4hep**. Geometry in DD4hep (k4geo), flexible choice of materials and granularity.
- Digitisation with calibration, noise, cross-talk. Sliding-window or topological clustering + BDT correction for upstream material.

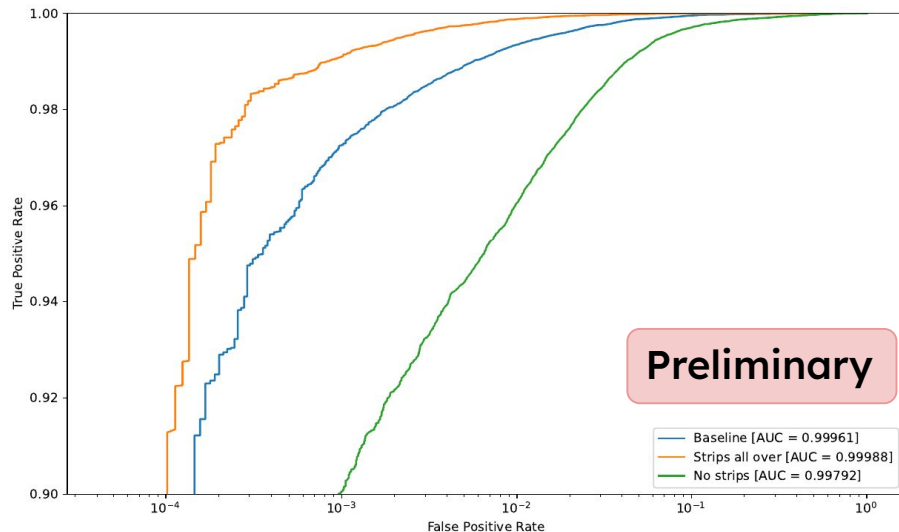


LAr/Pb: $7.6\%/\sqrt{E} \oplus 0.6\%$

LKr/W: $5.9\%/\sqrt{E} \oplus 0.3\%$

γ/π^0
separation

Transformer for γ/π^0 separation using cell energies and positions only.
99.85% π^0 efficiency at 1% fake rate (π^0 from τ in ZH events)



One finely segmented layer is enough for π^0/γ separation. Making all layers fine barely helps

Absorbers & Mechanical Structure

Absorbers

1.8 mm Pb core + **0.1 mm steel** skins (0.05 mm showed defects after cryo cycling), bonded with FR4 prepreg

Gaps

Variable-thickness **Nomex honeycomb** spacers (1.2 → 2.4 mm), preferred over 88 PEEK pins per gap

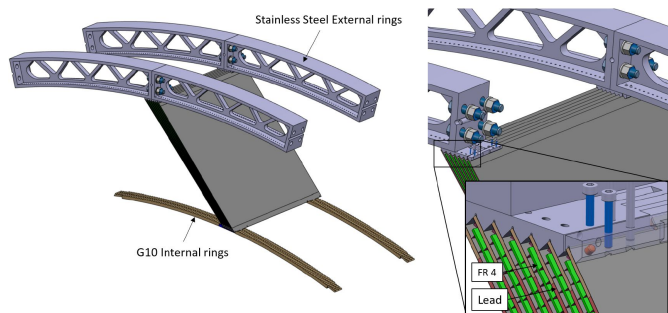
Structure

G10 inner rings and steel H-beam outer rings every 500 mm, 24 × 15° sectors. Barrel weight ~150 t

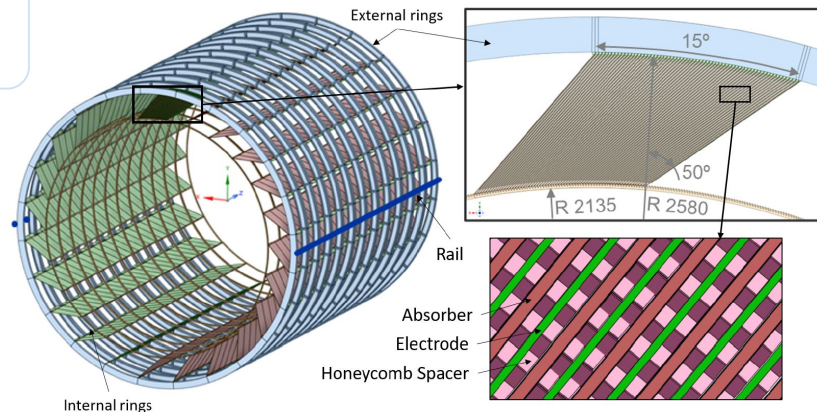
Electrodes

Fixed at a single radial point so they can slide during thermal contraction

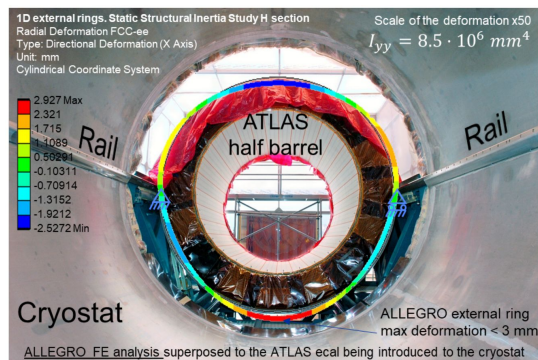
Two 15° ring sectors with absorbers



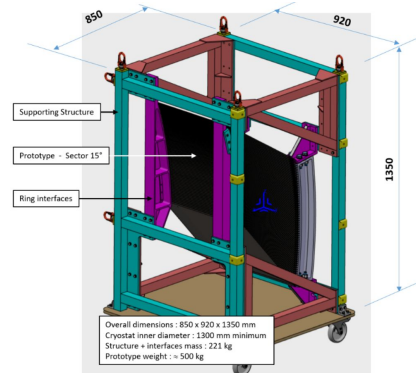
Barrel structure (1 absorber in 64 shown)



FEM: ring deformation < 3 mm

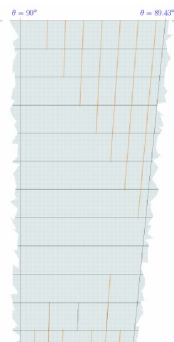


Test-beam frame

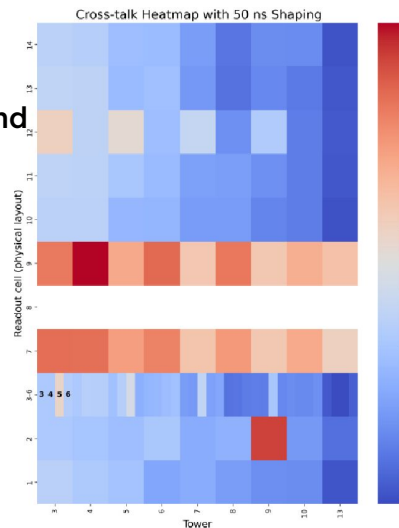
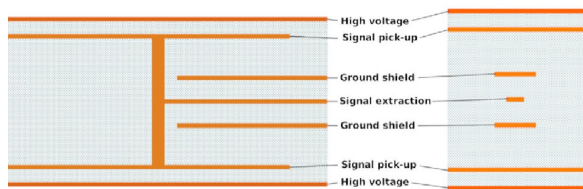


Readout Electrodes: Multilayer PCBs

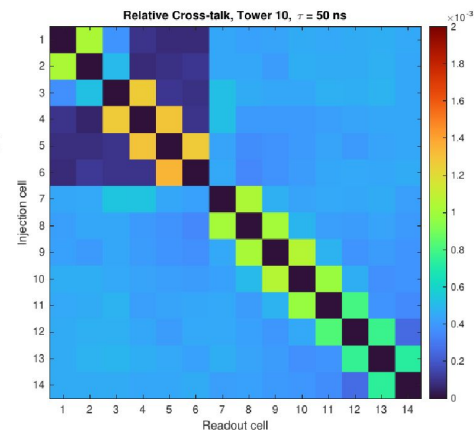
- Signal traces run inside the electrode, under the pads, to the inner/outer edges → no dead regions.
- Shielded **strip-lines** ($\sim 50\ \Omega$) separate pick-up, routing, ground and HV layers. $\sim 1.3\ \text{mm}$ board.
- Several full-length prototypes with different routing and shield layouts measured.



Embedded routing (left) and electrode stack-up (right)



Cross-talk with 50 ns shaping (one misplaced shield in tower 9 visible)



Max. 0.5% (strips, 20 ns) down to 0.02–0.03% (cells, 200 ns) $\approx$ **10× lower than ATLAS** (up to 7% for strips at 13 ns)

Prototype (towers 4 / 10 / 13)

Measured

Peak-to-peak cross-talk, $\tau = 50\ \text{ns}$

0.13–0.15%

Non-adjacent cells, $\tau = 50\ \text{ns}$

$\leq 0.08\%$

Full / strip cell capacitance

148–176 / 91–98 pF

- Measured cell capacitances agree with a simple model: strip-line + coupling to shields of upstream cells.

Embedded shielded routing works at full scale: sub-percent cross-talk, capacitance fit for low noise

Cold Front-End Electronics & Outlook

- **Baseline: electronics inside the cryostat** - no cable between electrode and preamp (lower series noise, $e_n \propto \sqrt{T}$), only digital & power lines cross the cryostat. Summing boards merge the 2 electrodes of a cell and distribute HV.

CALOROC1C

In progress

Adapted from the CMS HGCROC chip: 36 channels, measures both **charge and time**, works from room to cryogenic temperature

CHARMS250

In progress

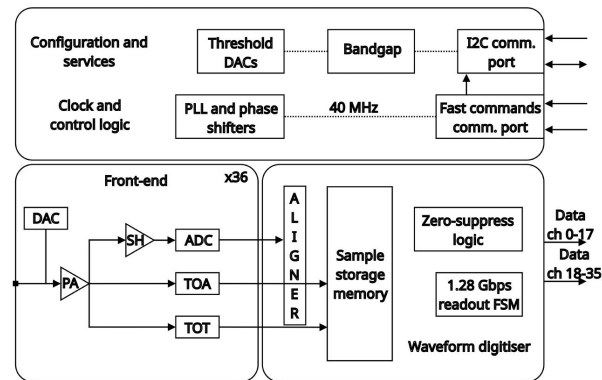
Derived from the DUNE LAr chip: optimised for **very low noise** in the cold, noise more than halved at LAr temperature

CFEB

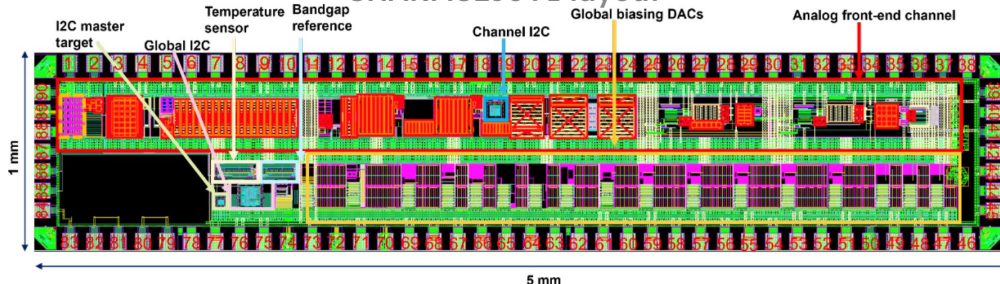
In progress

Cold front-end board: **digitises and compresses** 224 channels inside the cryostat and sends the data out on a few fast links

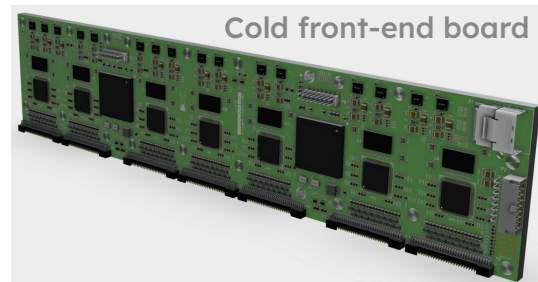
CALOROC1C architecture



CHARMS250V1 layout



Cold front-end board



Next steps: full-depth barrel prototype and beam tests • more advanced reconstruction • design optimisation from simulation + test-beam results

ALLEGRO: Summary

Concept & performance

Noble-liquid ECAL with **straight inclined electrodes**:
 ϕ -uniform, crack-free, ~2.2M cells for particle flow

Full Key4hep simulation: **7.6%/√E ± 0.6% (LAr/Pb)**,
5.9%/√E ± 0.3% (LKr/W) for barrel photons

Transformer-based γ/π^0 separation reaches 99.85% π^0
efficiency at 1% fake rate

Hardware R&D

Absorbers validated at cryogenic temperature. Support
structure designed with FEM (< 3 mm deformation)

Multilayer PCB electrodes: **sub-percent cross-talk**, ~10×
below ATLAS, capacitance fit for low noise

Cold electronics baseline: CALOROC1C and CHARMS250
prototypes promising, cold FE board designed

Next steps: full-depth barrel prototype → beam tests → design optimisation with simulation and test-beam data

Noble-liquid calorimetry is a strong candidate for a precision ECAL at FCC-ee

Thank you!

Backup