Technical challenges and performance of the new ATLAS LAr Calorimeter Trigger

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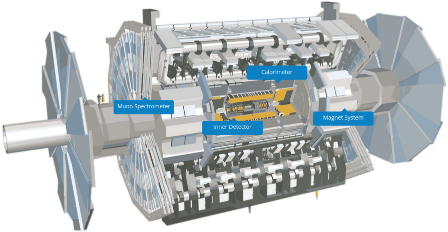
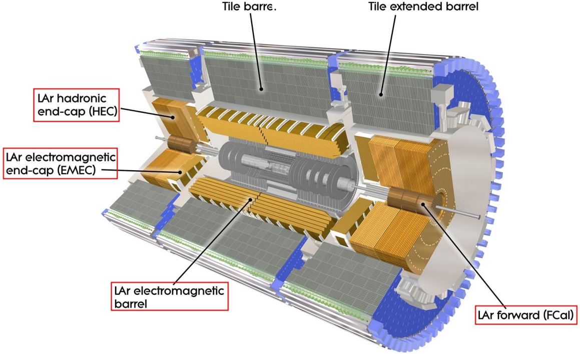
ATLAS calorimeters

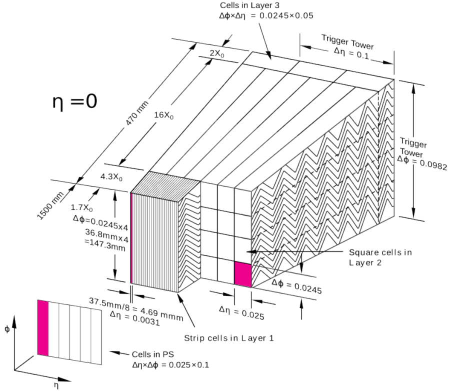
- Two calorimeter technologies: liquid argon and hadronic tile (plastic scintillator)
- LAr: sampling calorimeter with liquid argon as active material and lead (EM), copper (HEC+FCAL EM) or tungsten (FCAL HAD) as passive material

- 4 parts: EMB, EMEC, HEC, FCAL
- 3 layers each (+ pre-sampler for EMB and EMEC)
- $\approx$ 188k cells



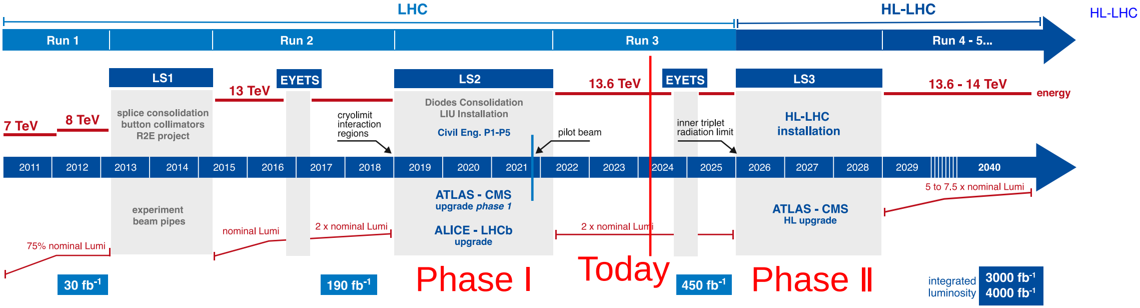


LAr cells: EM barrel

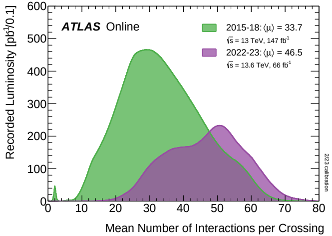


- 3 layers (+ a pre-sampler)
- $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$ in the second layer (EM shower max)
- Accordion geometry $\to$ no dead areas

ATLAS upgrades



- New LAr digital trigger electronics installed during LS2 as part of the ATLAS Phase-I upgrades to cope with the **higher pileup**
- The rest of the LAr readout electronics will be upgraded during LS3 (Phase-II upgrades)
  - LAr digital trigger electronics will remain



1. The digital trigger system

From Trigger Towers to Super Cells

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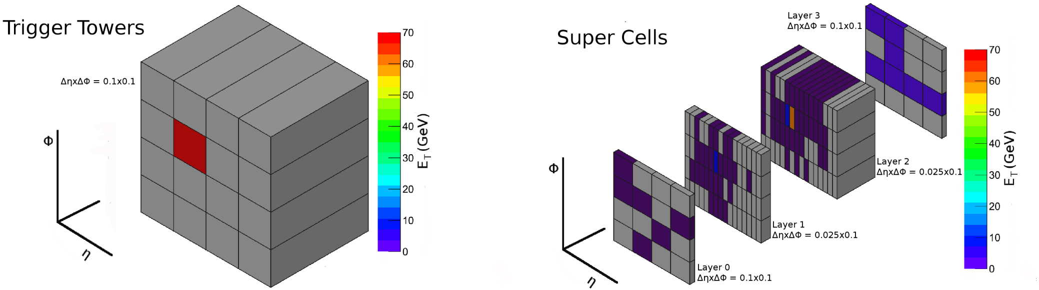
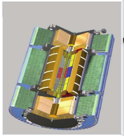


$\approx$ 10-fold increase in granularity (5k trigger towers $\rightarrow$ 34k Super Cells)

- Higher granularity (layers 1 and 2)
- Longitudinal shower information
- Better energy resolution
- Better efficiency for selecting signal (e / τ / γ / jets / E_T^{miss})
- Better background rejection $\rightarrow$ lower trigger rates

Current LAr readout electronics

- New electronics for digital trigger:
  - **Front-end** (on-detector): LAr Trigger Digitizer Boards, Layer Sum Boards, baseplane
  - **Back-end** (off-detector): LAr Digital Processing System
  - Optical fibers connecting front-end to back-end
- Analog trigger (legacy) electronics being decommissioned
- Level-1 Calorimeter System accordingly upgraded



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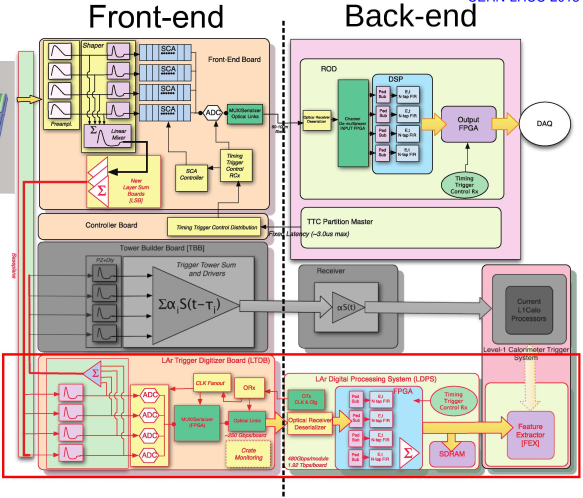

Digital Trigger

Front-end: new electronics

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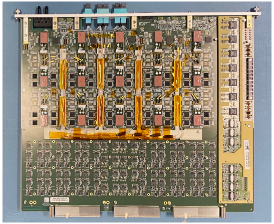
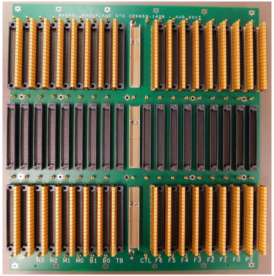
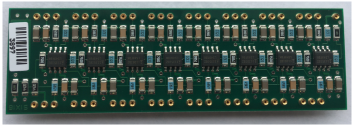
- LAr Trigger Digitizer Boards (124 LTDB):
  - Digitise Super Cell signals at 40 MHz (4-channel 12-bit ADCs, 80/board)
  - Send analog signals to Tower Builder Boards (legacy analog trigger)
  - Send data to the back-end (40 optical fibers @ 5.12 Gbps / board)
- Baseplane (114): holding and connecting together front-end electronics
- Layer Sum Boards (2328 LSB replaced): analog sums of LAr cell signals within one layer, grouped into Super Cells







Back-end: new electronics

- Intelligent Platform Management Controller (IPMC):
  - hardware management system for ATCA boards: manage the power, cooling, and interconnect needs of intelligent devices
- LAr Trigger prOcessing MEzzanine (116 LATOME):
  - Receive Super Cell data from 48 optical links
  - Process data on Intel Arria 10 FPGA
  - Transmit to the new L1 Calorimeter Trigger system (Feature EXtractors, FEX) with 48 optical links at 11.2 Gbps
- LAr Carrier (30 LArC):
  - ATCA boards hosting the LATOME processor daughtercards, transmitting data from and do the readout system, and distributing clocks and trigger signals synchronised with the LHC beam clock

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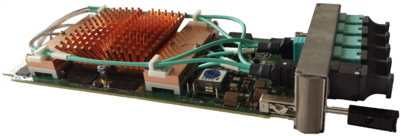

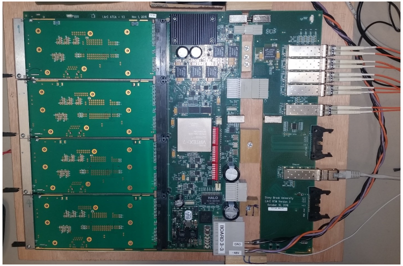

Energy and time reconstruction

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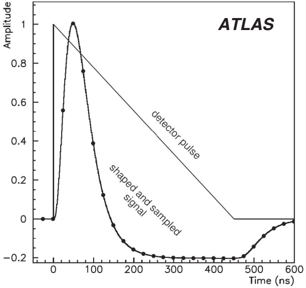


$$A = \sum_{j=1}^{N_{\text{samples}}} a_j (s_j - p)$$

$$t = \frac{1}{A} \sum_{j=1}^{N_{\text{samples}}} b_j (s_j - p)$$

$$E = F_{\mu A \to \text{MeV}} \times F_{\text{DAC} \to \mu A} \times \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \times \sum_{j=(0,1)}^{N_{\text{ramps}}} G_j A^j$$

Same energy and time reconstruction procedure for main readout and digital trigger:

- Pulse amplitude and time computed from $N_{\text{samples}} = 4$ digitised samples s_j using Optimal Filtering Coefficients (OFC) a_j and b_j and pedestal p from calibration
- Energy is deduced from the pulse amplitude using constants[1] determined from calibration runs, test beam data, and electronics parameters.

[1] G_j: gain; $\frac{M_{\text{phys}}}{M_{\text{cali}}}$: ionisation to calibration pulse response; $F_{\text{DAC} \to \mu A}$: calib DAC to injected current; $F_{\mu A \to \text{MeV}}$: ionisation current to energy

Status

Timeline for the new LAr digital trigger:

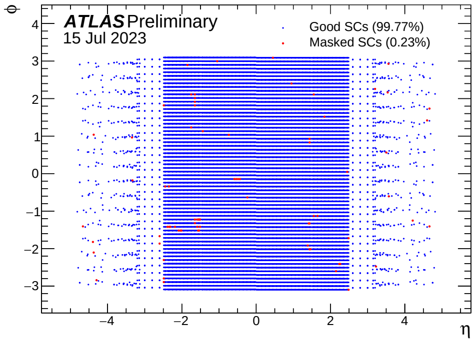
- New electronics installed during LS2, before the start of Run 3
  - Very stable operation and performance (see next slides)
  - A few weak optical transmitters / transceivers preventively replaced on 20 / 124 LTDBs during the last EYETS[2] (2023–2024) to ensure best coverage (only 3 / $\approx$ 4000 links dead before refurbishment)
- 2022: commissioning
- 2023: LAr DT used for electrons and photons (eFEX)
  - Legacy system still used for jets, τ, $E_{\mathrm{T}}^{\mathrm{miss}}$
- 2024: Phase-I Level-1 Calo system will be the default for physics
  - Legacy system decommissioned

[2] Extended year-end technical stop

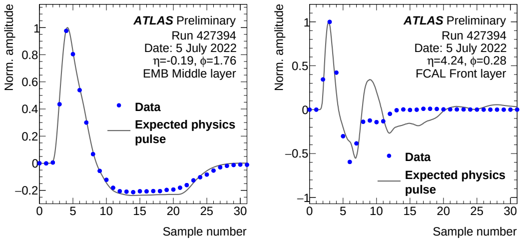
2. Performance

Performance in 2023

More plots



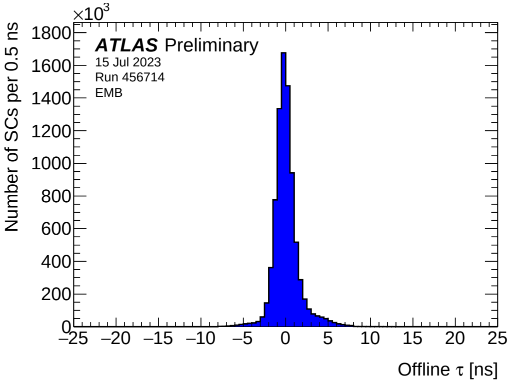
- $>$ 99.7% coverage during high luminosity pp runs in 2023

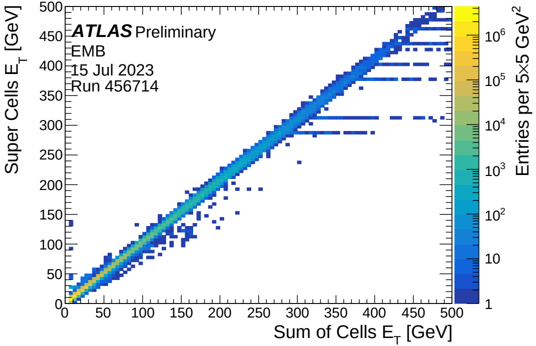


- Good agreement in EMB between Super Cell pulse shape and expected physics pulse (deduced from a calibration pulse)
- More complicated pulse shape in FCAL: ongoing work to improve the Super Cell pulse shape modelling (implications on OFC $\rightarrow$ energy and time resolution)

Performance in 2023

More plots

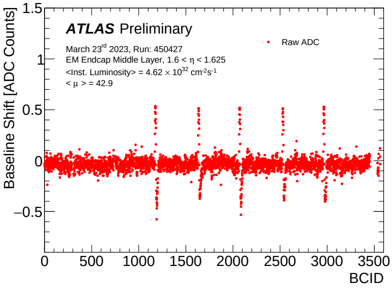


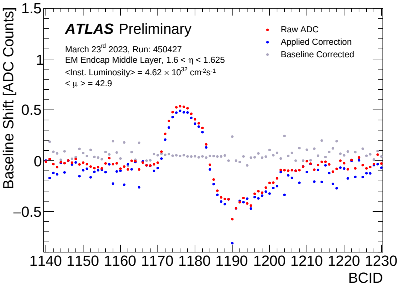


- Narrow timing distribution (here for $0 < E_T < 10\,\text{GeV}$)
- Efficient assignement to correct bunch crossing: avoid early or late triggers
- Excellent agreement between cell (precision readout) and Super Cell (trigger) energies
- Horizontal lines: saturation at high energies (no impact on trigger performance)

Baseline correction

More plots

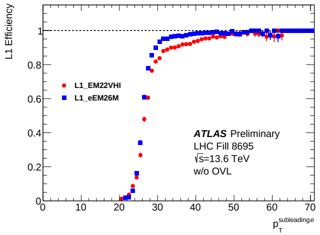


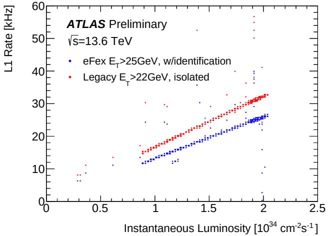


- In a high-pileup environment, overlapping LAr pulses effectively create a baseline shift
- Potential energy measurement bias
- Solution: baseline correction implemented in LATOME firmware
- Validated in 2023 high-pileup collision data

L1Calo performance

2401.06630, more plots





- Legacy vs Phase-I (eFEX) single electron trigger:
  - Sharper efficiency turn-on curve
  - $\approx$ 10% reduction in L1 rate

- Crucial improvements in maintaining physics performance (similar trigger thresholds) at higher instantaneous luminosity than Run 2

L1Calo performance

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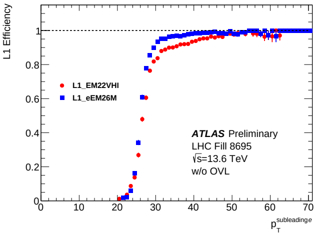

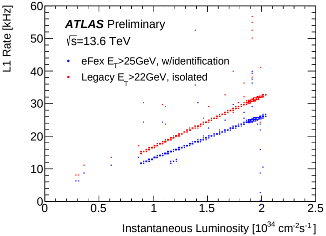

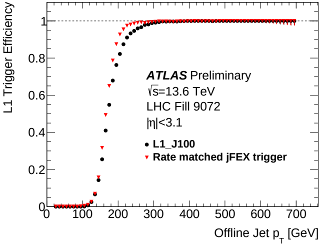

- Legacy vs Phase-I (eFEX) single electron trigger:
  - Sharper efficiency turn-on curve
  - $\approx$ 10% reduction in L1 rate
- Legacy vs Phase-I single jet trigger:
  - Sharper efficiency turn-on curve for the same L1 rate
- Crucial improvements in maintaining physics performance (similar trigger thresholds) at higher instantaneous luminosity than Run 2

Summary

- Successful upgrade of the ATLAS liquid argon calorimeter trigger electronics
  - Higher granularity, higher resolution digital trigger
- Excellent performance validated in data
- Phase-I system used for e/γ in 2023 and all calorimeter signatures in 2024
- It will still be used during the HL-LHC phase (Phase-II): see Elena's talk