Technical challenges and performance of the new ATLAS LAr Calorimeter Trigger

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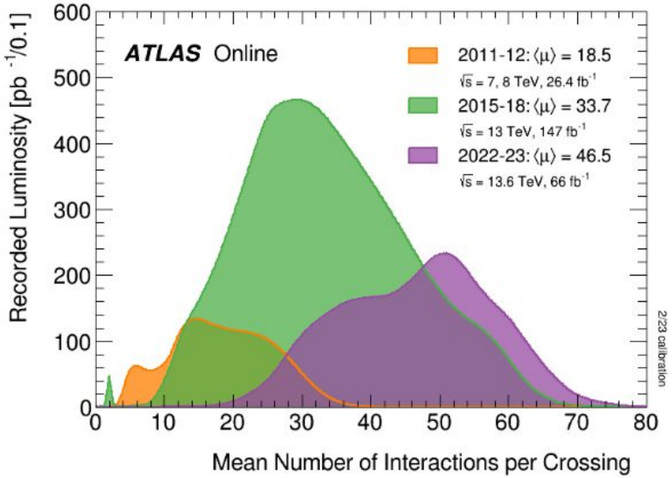
Digital trigger for Run3

- Higher instantaneous luminosity during Run 3
  - **LAr Analog Trigger** upgraded to **LAr Digital Trigger** to cope with higher pile-up (aim for <μ> above 60)
- **Analog trigger** operational until end of 2023
- **Digital trigger** fully operational from 2024 and expected to be used also during HL-LHC (after electronics upgrade during LS3)
- Maximum ATLAS L1 trigger rate in Run 3 must remain the same as for Run 2



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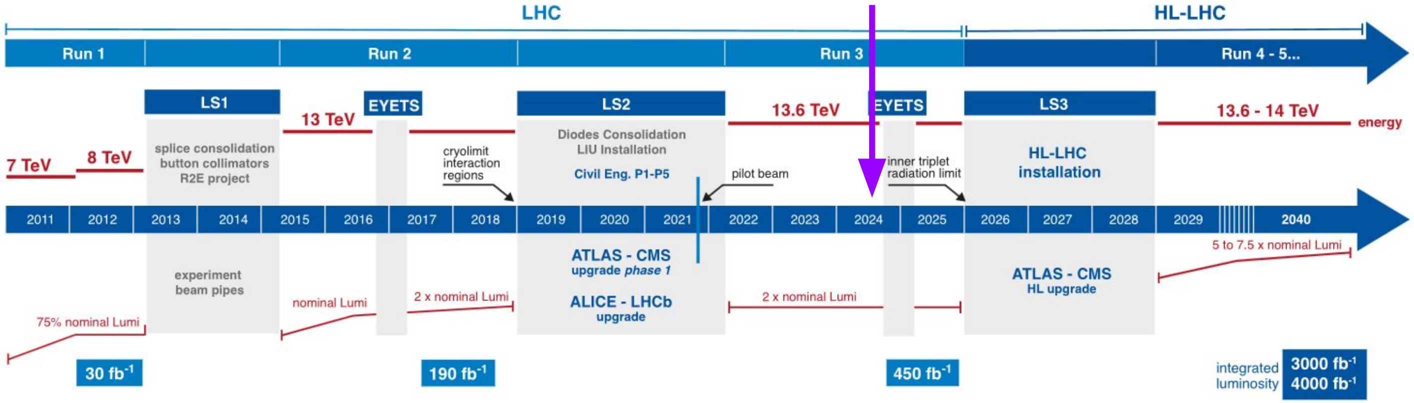
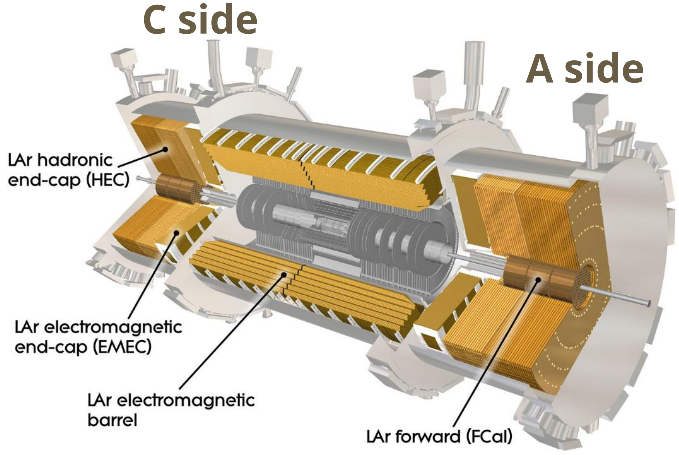


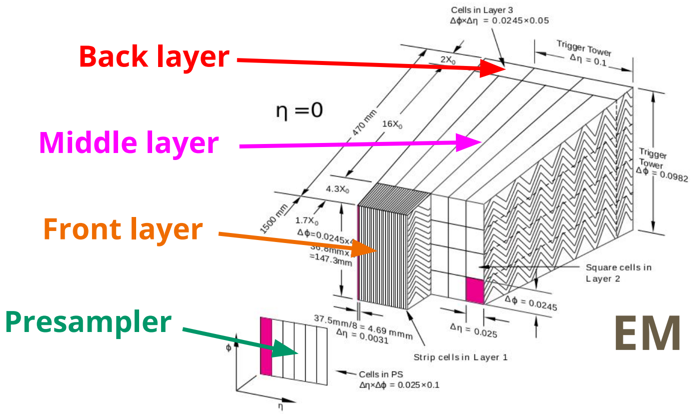
ATLAS Liquid Argon Calorimeter

- **Sampling calorimeter** segmented into **four parts** (EMB, EMEC, HEC, FCAL)
- **Active material:** Liquid Argon
- **Passive material:** Lead (EM), Copper (HEC), Copper + Tungsten (FCAL)

- Each partition consists of **3** (FCAL) **or 4 layers**:
  - **Presampler** (EM) - measure energy loss before the calorimeter
  - **Front** - distinguish π^0 and γ
  - **Middle** - deepest, absorbs most of the EM shower
  - **Back** - catch the tail of EM shower

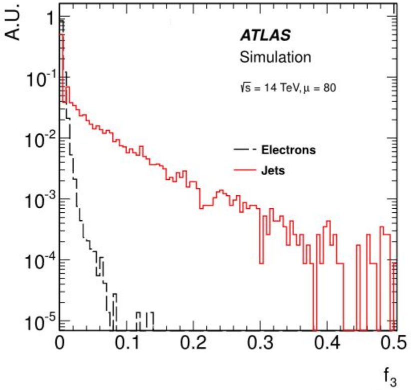
- 180k calorimeter cells, coverage **$|\eta|<4.9$**

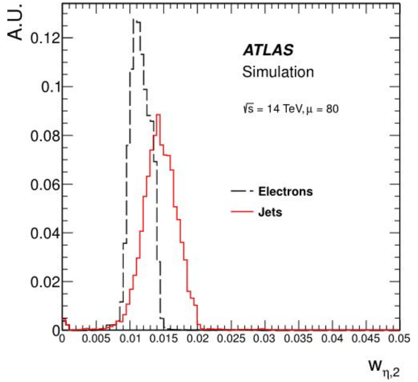


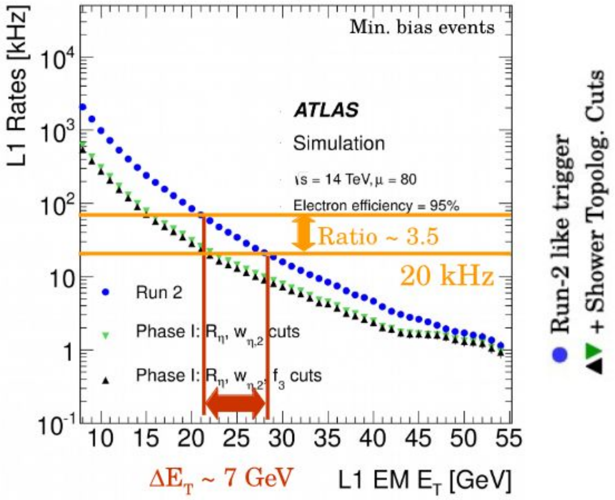


Motivation for a new trigger

- L1 trigger rates same as in Run 2
  - Maximum 100 kHz, **20 kHz allocated for EM trigger**
- Inclusive electron trigger:
  - **Analog trigger** - in Run 2 minimum E_T cut for electrons ~28 GeV
  - **Digital trigger** - in Run 3 L1 rate can be reduced for the same E_T cut, thanks to:
    - Improved selection with shower shape variables (R_η, $w_{\eta,2}$, f_3)
    - **10x finer granularity** for triggering (Trigger Towers → Super Cells)
  - Or possible to reduce E_T cut down to ~ 22 GeV while keeping the Run 2 rate

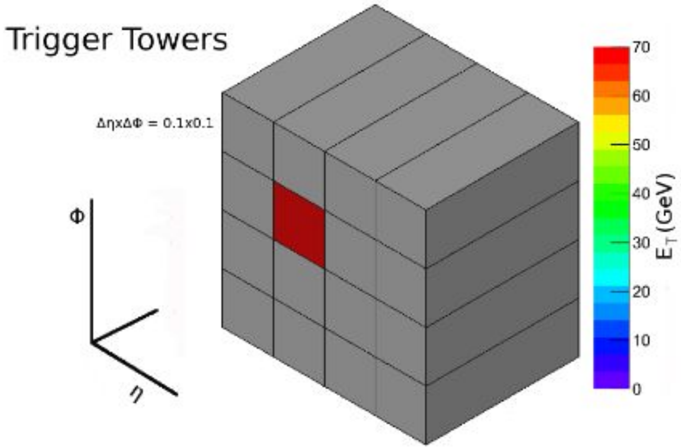




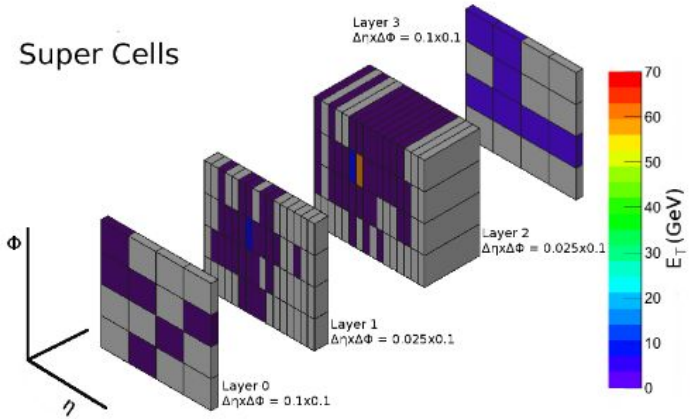


LAr Phase-I Upgrade

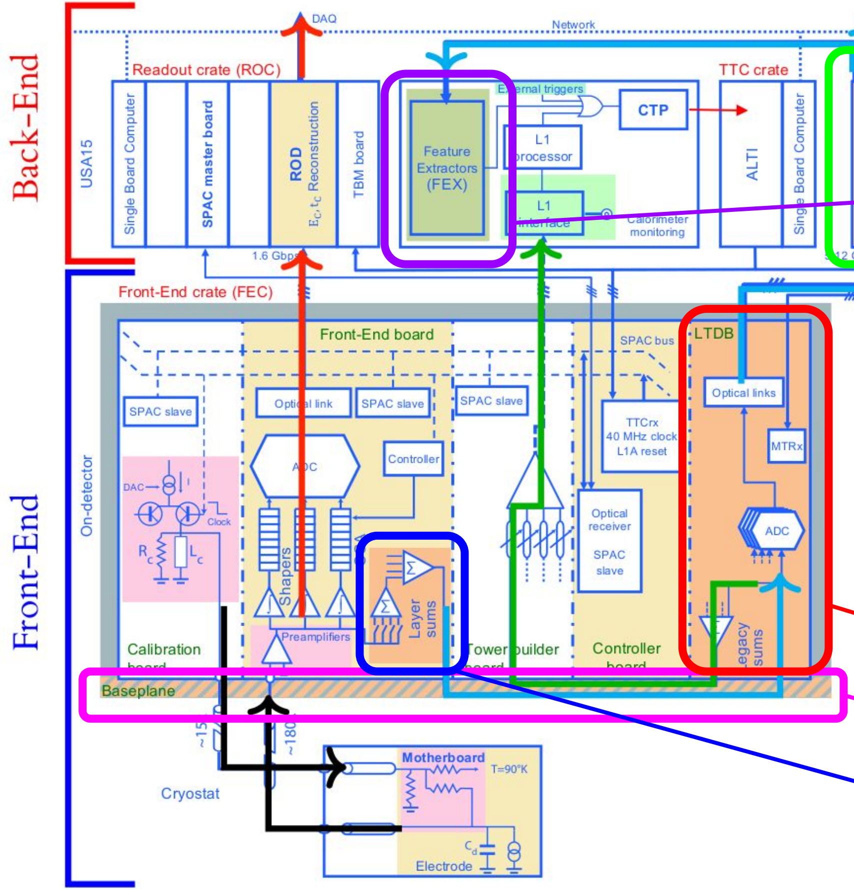
- **Analog trigger setup:**
  - 180k cells grouped into **5.4k Trigger Towers (TT)** ($\Delta\eta \times \Delta\phi$ = 0.1x0.1) - using **analog** signals
  - E_T in all 4 layers summed - shower shape information lost



- **Digital trigger setup:**
  - Calorimeter cells grouped into **34k Super Cells (SC)**
  - Added **segmentation to layers** + **increased resolution** ($\Delta\eta \times \Delta\phi$ = 0.025x0.1) **of front and middle layers**
    - ↪ Access to the longitudinal and lateral shower shapes
  - Signal **digitised** on-detector



LAr Digital Trigger electronics



→ Calibration

→ Main Readout (Samples buffered then digitized and transmitted at L1A rate 100 kHz)

→ Digital Trigger (SC) (digitized samples streamed at 40 MHz)

→ Legacy Trigger (TT) (analog sums digitized in the back-end)

LAr Digital Processing Blade (LDPB)

Feature Extractors (FEX)

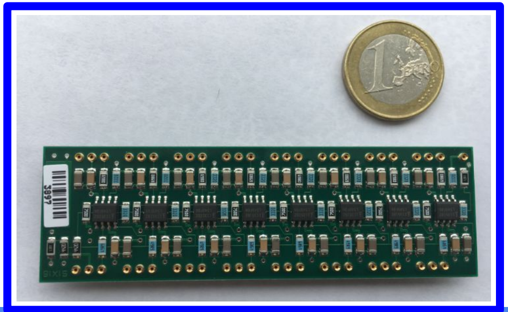
LAr Trigger Digitiser Board (LTDB)

Baseplane

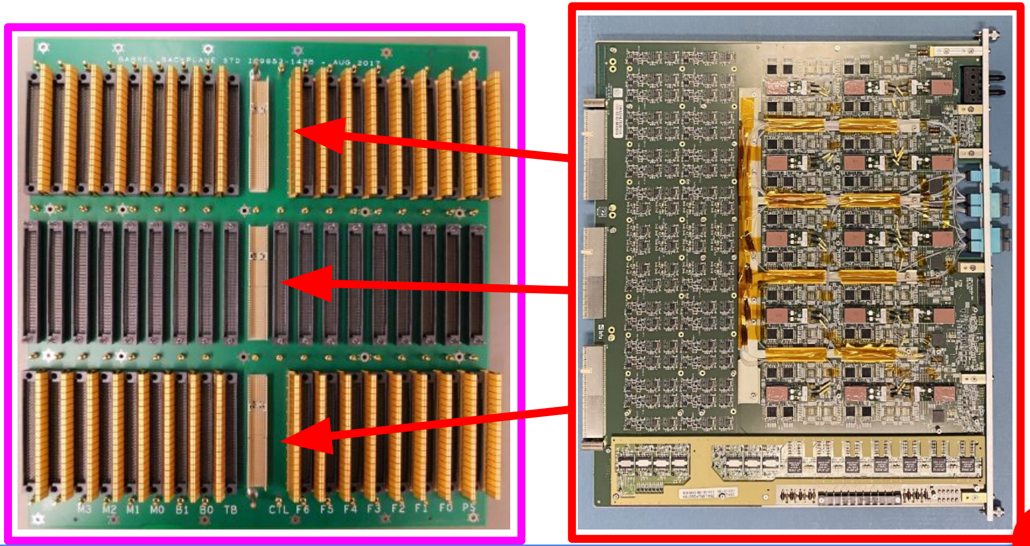
Layer Sum Boards (LSB)

Front-end electronics upgrade

- **Baseplanes:**
  - Used to provide **connection between various elements** in Front End Crate (FEC)
  - Allow **routing for both analog and digital trigger**
  - **114 new baseplanes** equipped with LTDB ports
- **Layer Sum Boards:**
  - **Plug-in card for** Front End Board (FEB) that **performs summing of the analog signals**
  - Provides **finer granularity** for front and middle layers, while **retaining the signals for legacy trigger**



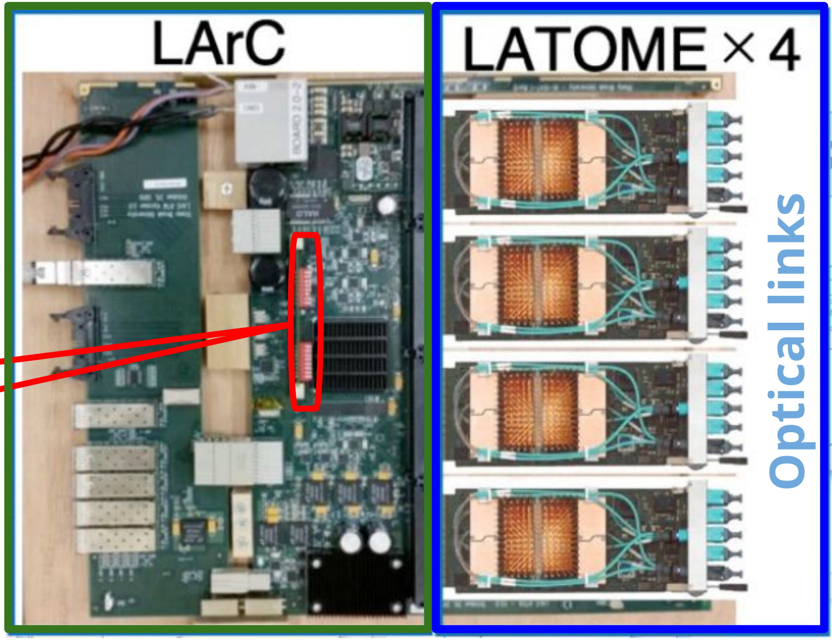
- **LAr Trigger Digitiser Boards:**
  - **124 new boards** used to **shape, sample and digitise SC signals** and send them to back-end electronics via optical links
  - **Custom-designed 12 bit ADCs** operable at 40 MHz
  - Send legacy layer sums to TT builder board



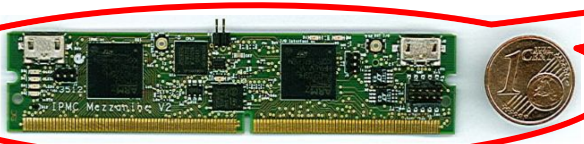
Back-end electronics upgrade

- **LAr Digital Processing Blades**
  - Each one of **30 new LDPBs** consists of:
    - **1 LAr Carrier (LArC)**
    - **4 LAr Trigger PrOcessing MEzzanine (LATOMEs)**
    - **1 Intelligent Platform Management Controller (IPMC)** for control and monitoring

LDPB



IPMC

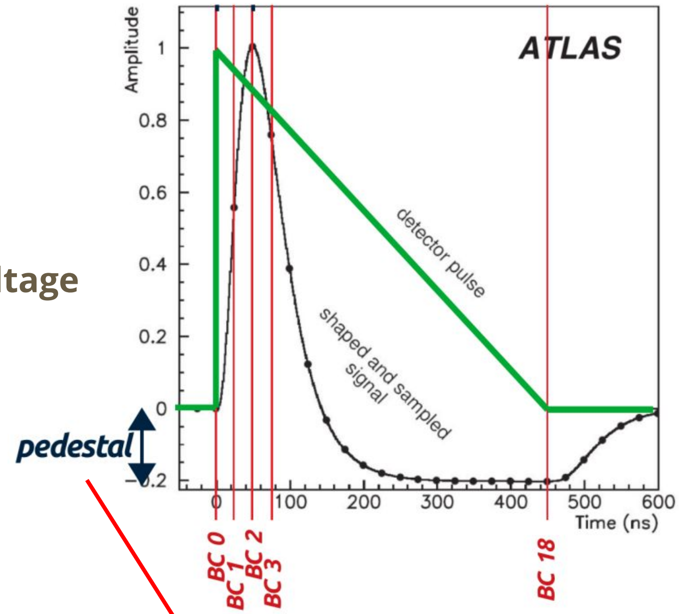


- **LATOMEs**
  - **Receive signal** from LTDBs at 40MHz (25 Tbps)
  - Reconstruct $\mathbf{E_T}$ of the SC and **identify bunch crossing**
  - **Transmits energies** to L1Calo FEX via 48 optical links (41 Tbps)
  - Use **Intel Arria 10 FPGAs** to process up to 320 SCs

- **LArCs**
  - Responsible for readout + providing trigger, timing and control signals for LATOMEs
  - Use **Xilinx Virtex 7 FPGAs**

LAr Calorimeter Signal

- Signal formation is based on the **ionization of the liquid Argon** triggered by the passing particle
- **Ionization current** is produced in the LAr gap **by applying high voltage** (250 - 2500 V)
- Initial **triangular signal is amplified, shaped and digitized** in the front-end
- **Energy and timing is computed in the back-end**:
  - In **Main Readout** for individual cells
  - In **Trigger**, cells are summed to form TTs or SCs
- Energy is estimated from pulse amplitude, calibration constants and optimal filtering coefficients



Physical to calibration pulse response

ADC to DAC (Ramps)

Pulse Samples

$$E_{\text{cell}} = F_{\text{DAC}\to\mu\text{A}} \cdot F_{\mu\text{A}\to\text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i \, (s_i - p)$$

Energy

Sampling fraction

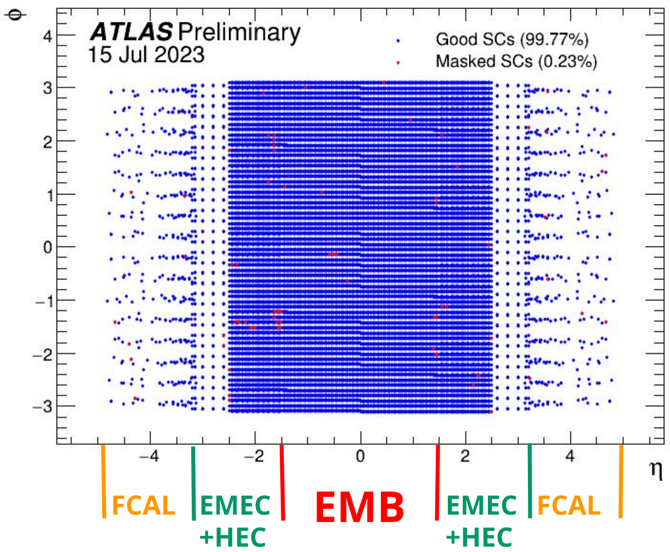
Calibration board

Optimal Filtering Coefficients

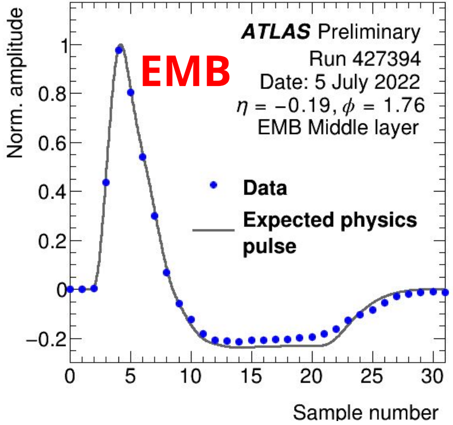
Pedestals

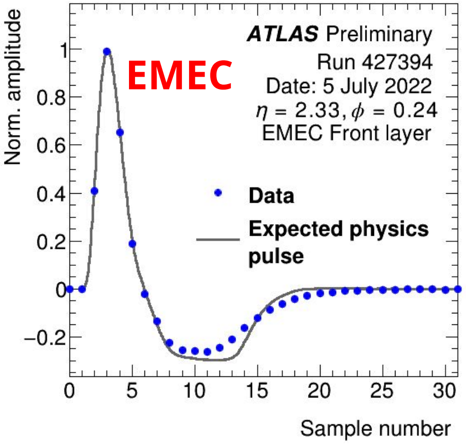
Coverage and pulse shape

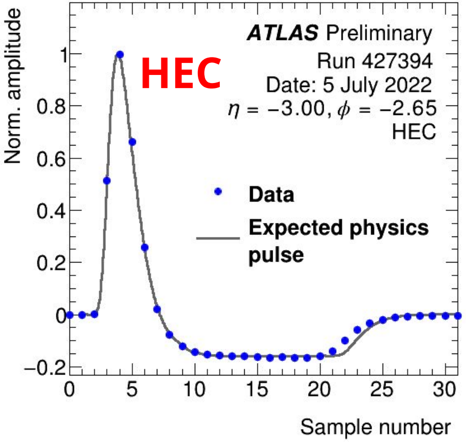
- Very **good overall coverage (> 99.7%)** - only few problematic SCs

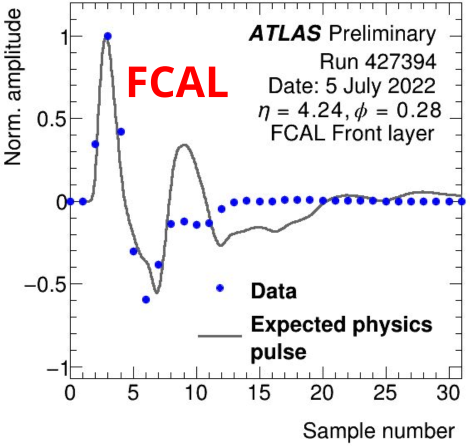


- **SC pulse shape from data consistent with pulse shape predicted from calibration**
- FCAL pulse shape different from the other parts due to different electronics layout
  - Electronics calibration not applicable for FCAL



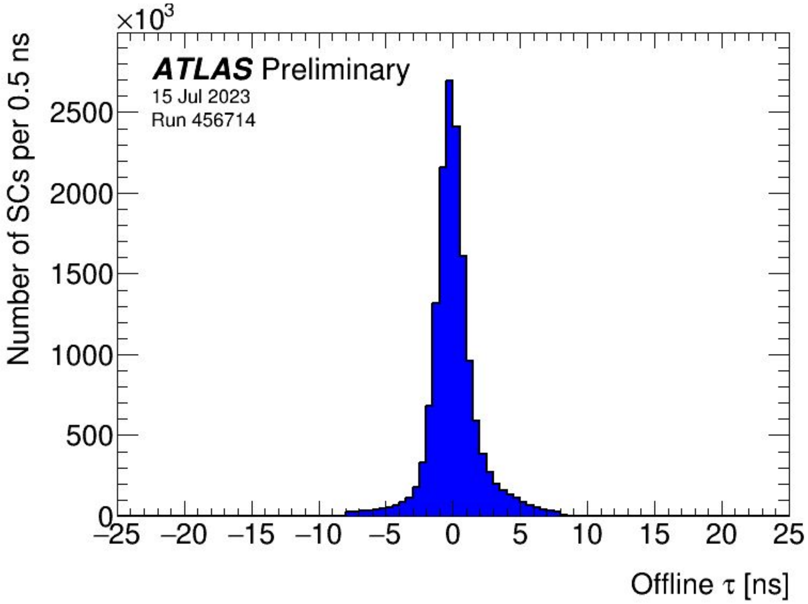


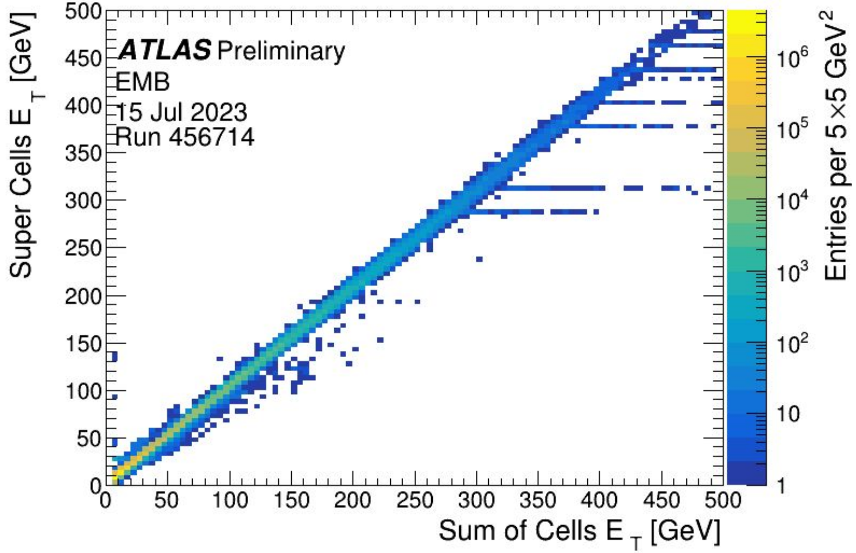




Timing and energy calculation

- **Good timing alignment and uniformity** for all LAr layers and partitions
- **Offline τ well below 25 ns** (time between two bunches) →eliminating late and early triggers

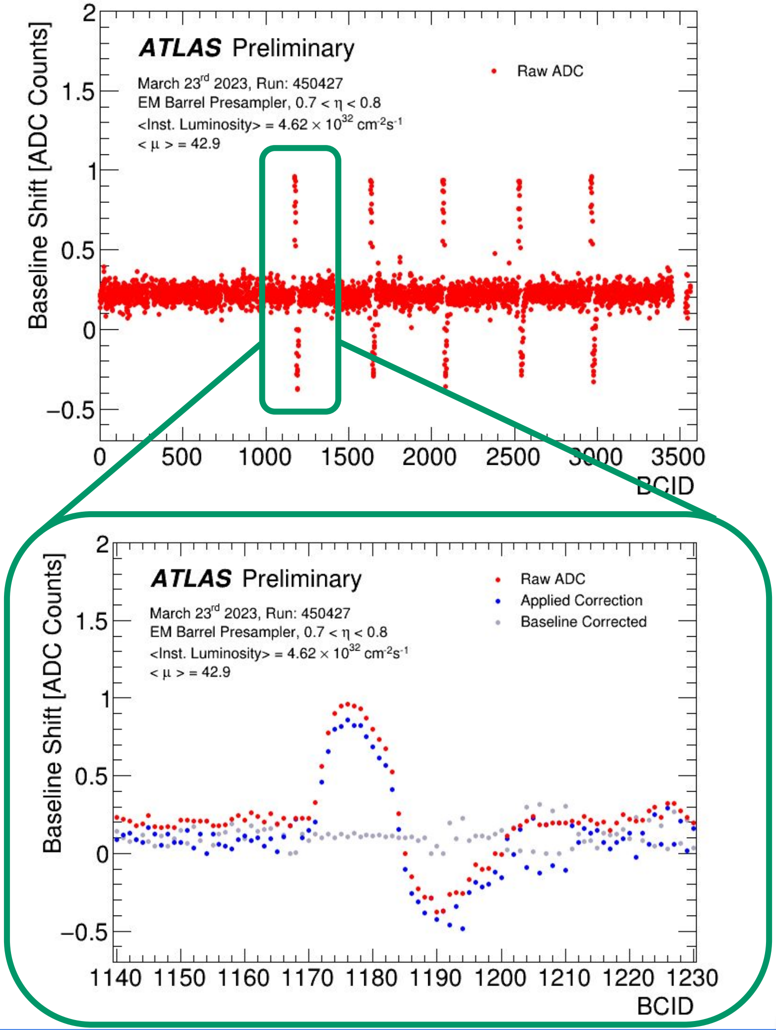




- **SC E_T** calculated on LATOMEs compared to the **sums of corresponding cells in the main readout**
  - Overall **very good agreement**
  - Dedicated **saturation criteria applied to some η regions** → visible saturation lines for some high E_T SCs

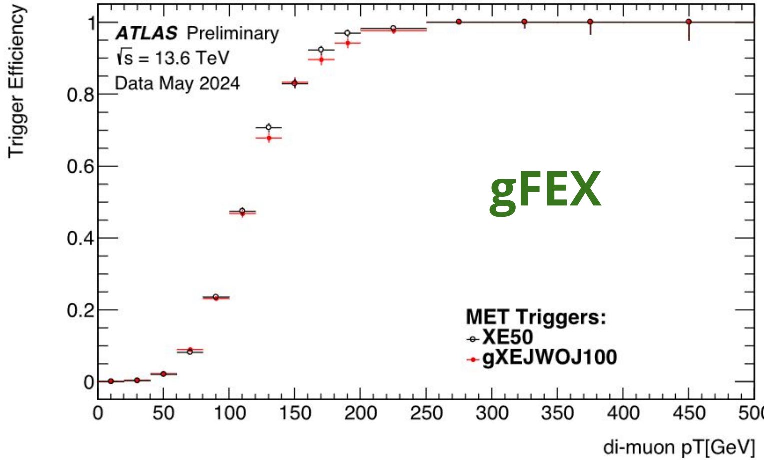
Baseline correction

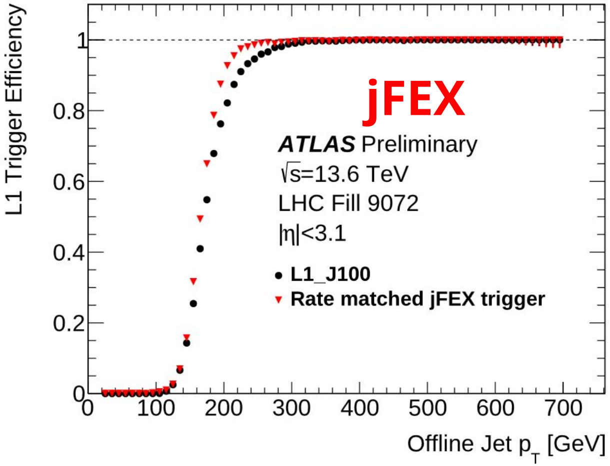
- Since **LAr pulses are long** (up to 700 ns), **out-of-time pile-up can shift the baseline** (level when zero energy deposited in the calorimeter)
- Shifts **most significant at the beginning of the bunch trains** - bipolar pulses are averaged to 0 after ~ 500 ns
- Algorithm implemented to correct for the baseline shift
  - Correction calculated **both on LATOMEs (online) and in the Main readout (offline)**
  - Applied **per SC** and bunch crossing identifier (**BCID**)
  - Recalculated and **updated every ~ 11 s**

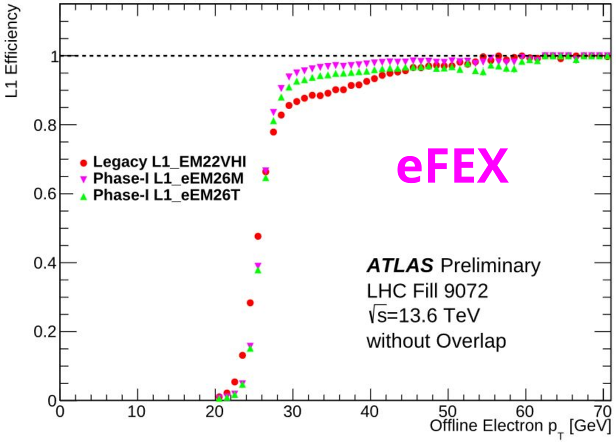


Efficiency of the new trigger

- **ATLAS L1Calo trigger system** now benefits from the increased resolution of the new digital trigger
- Decisions are made by **Feature EXtractors (FEX)** of 3 types:
  - **eFEX (electromagnetic)** → e, γ and τ
  - **jFEX (jets)** → jets, τ and E_T^{miss}
  - **gFEX (global)** → large jets, $\sum E_T$ and E_T^{miss}





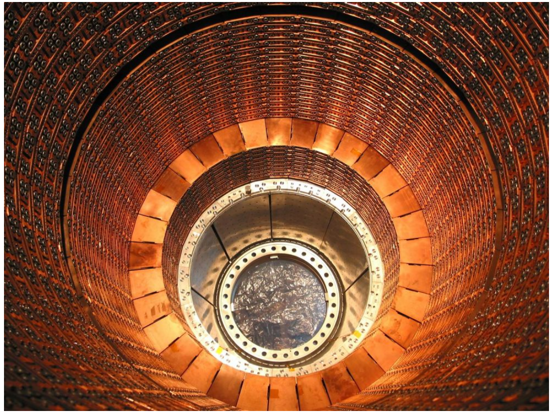


- With the new trigger:
  - **~10% decrease in the L1Calo rate for eFEX**
  - Comparable rate for jFEX
  - **Sharper turn-on curves** with new trigger → higher efficiency at the threshold

ATLAS EXPERIMENT

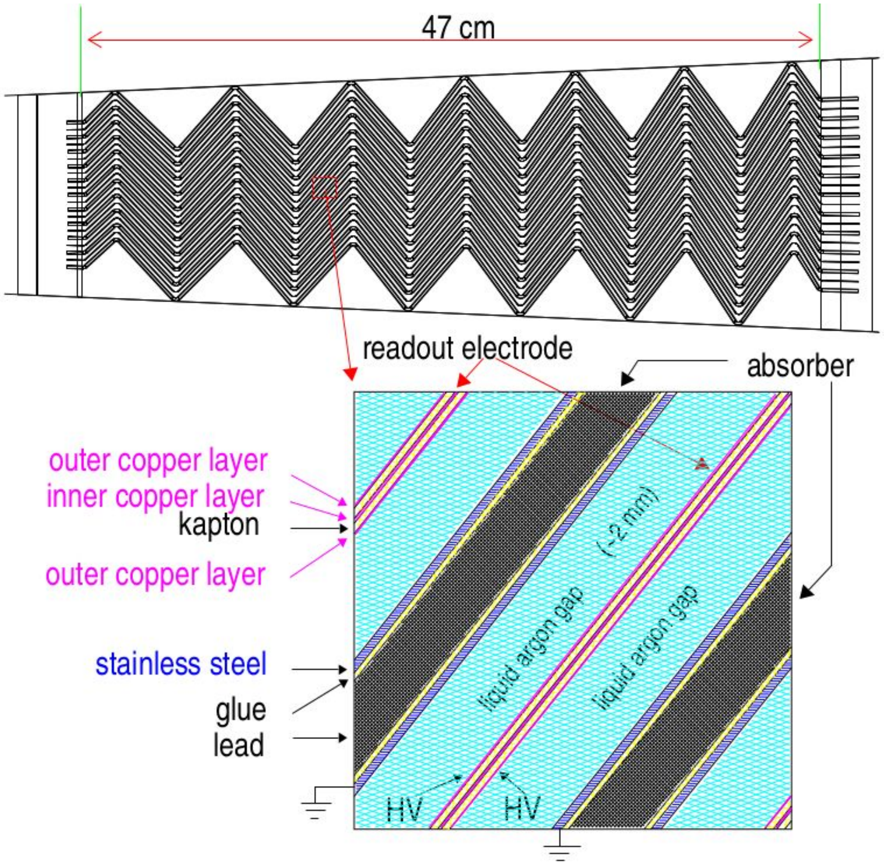
Conclusions

- **High pile-up conditions in Run 3 motivated upgrade of the LAr Analog Trigger**
- **LAr Digital Trigger** equipped with new electronics **and fully functional**:
    - **10 x finer granularity than legacy trigger** (Trigger Towers replaced with Super Cells)
    - **L1 Calo rate decreased** by around 5 kHZ while preserving (or even increasing) the efficiency
- **LAr Analog Trigger has been already decommissioned** for **eFEX** and **jFEX** at the start of 2024
- **Overall very good performance of the Digital Trigger**
    - Expected to be operational also during HL-LHC



Backup

Principle of operation



- Incoming particle interacts with absorber and produces shower
- Shower particles ionize LAr in the gap (~2 mm) - secondary particles drift to the readout electrodes (t_{drift} ~ 450 ns)
- Current is amplified, shaped and digitized

Accordion geometry in EM barrel and endcap, **pad** geometry in HEC and **rod** in FCAL

Shower shape variables for DT

R_η Given a 3×2 group of Super Cells in $\eta \times \phi$ centered on the highest-energy Super Cell in the middle layer (2), R_η is defined as the transverse energy measured in the 3×2 group divided by the transverse energy measured in a 7×2 group:

$$R_\eta = \frac{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times 0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.175\times 0.2}} \tag{1}$$

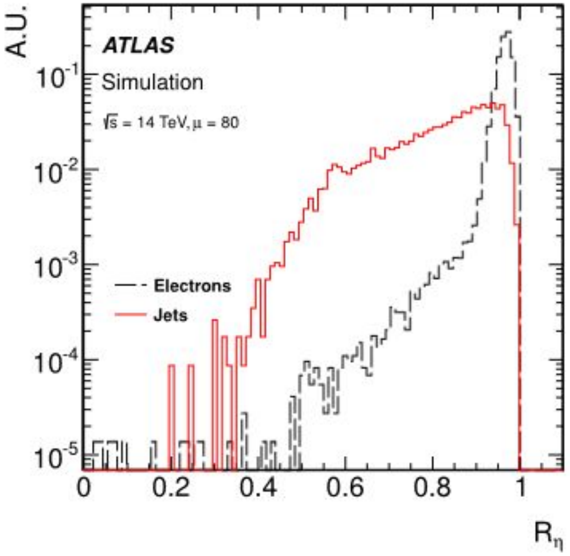
f_3 The ratio of the transverse energy measured in the back EM layer (3) in an area of size $\Delta\eta\times\Delta\phi = 0.2\times 0.2$ to that deposited in all three layers for an EM cluster; the energies in the front (1) and middle (2) EM layers are reconstructed in the area $\Delta\eta\times\Delta\phi = 0.075\times 0.2$:

$$f_3 = \frac{E^{(3)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.2\times 0.2}}{E^{(1)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times 0.2} + E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times 0.2} + E^{(3)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.2\times 0.2}}. \tag{2}$$

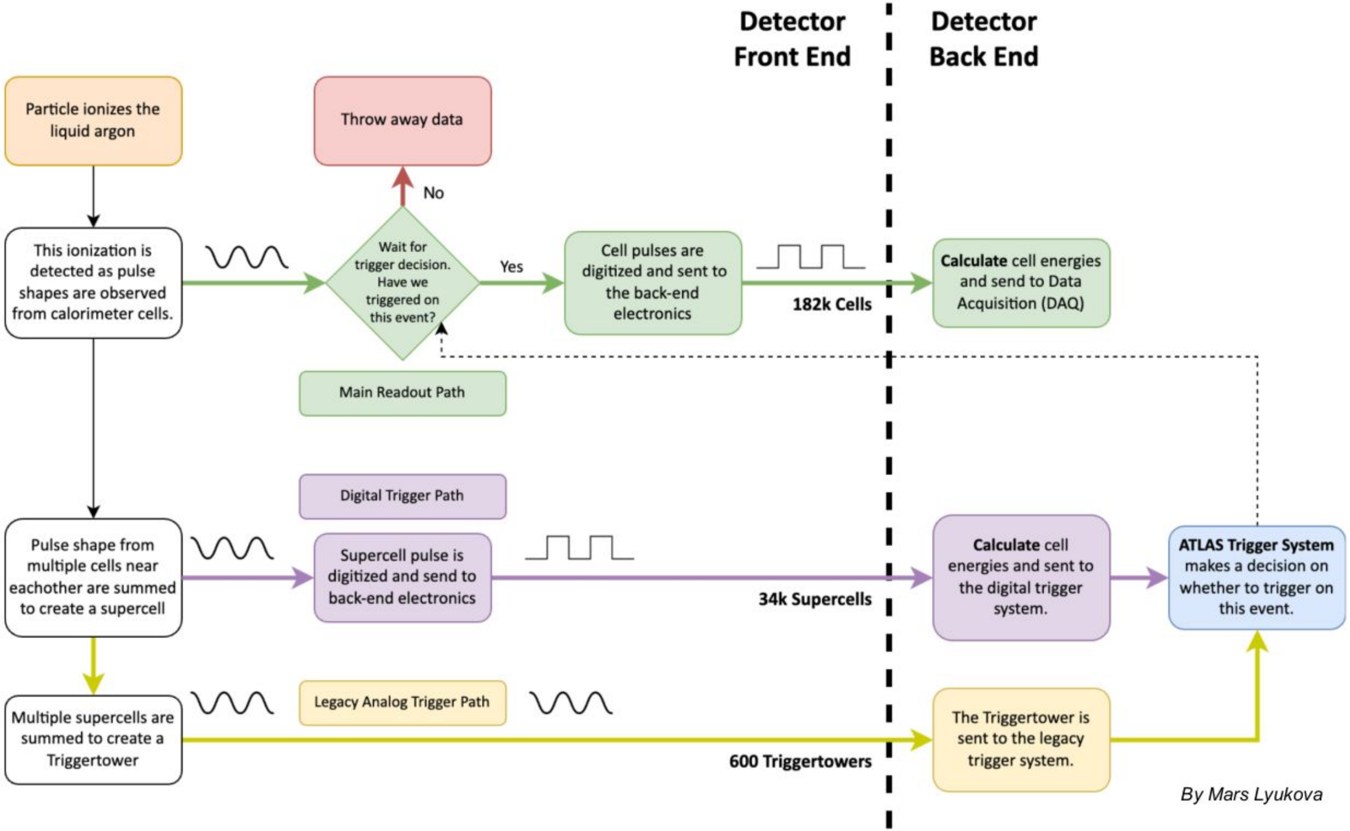
$w_{\eta,2}$ The spread of the shower in the middle EM layer (2) in a 3×2 Super Cell region, defined as:

$$w_{\eta,2} = \sqrt{\frac{\Sigma\left(E^{(2)}_{\mathrm{T}}\times\eta^2\right)_{\Delta\eta\times\Delta\phi=0.075\times 0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times 0.2}} - \left(\frac{\Sigma\left(E^{(2)}_{\mathrm{T}}\times\eta\right)_{\Delta\eta\times\Delta\phi=0.075\times 0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times 0.2}}\right)^2}, \tag{3}$$

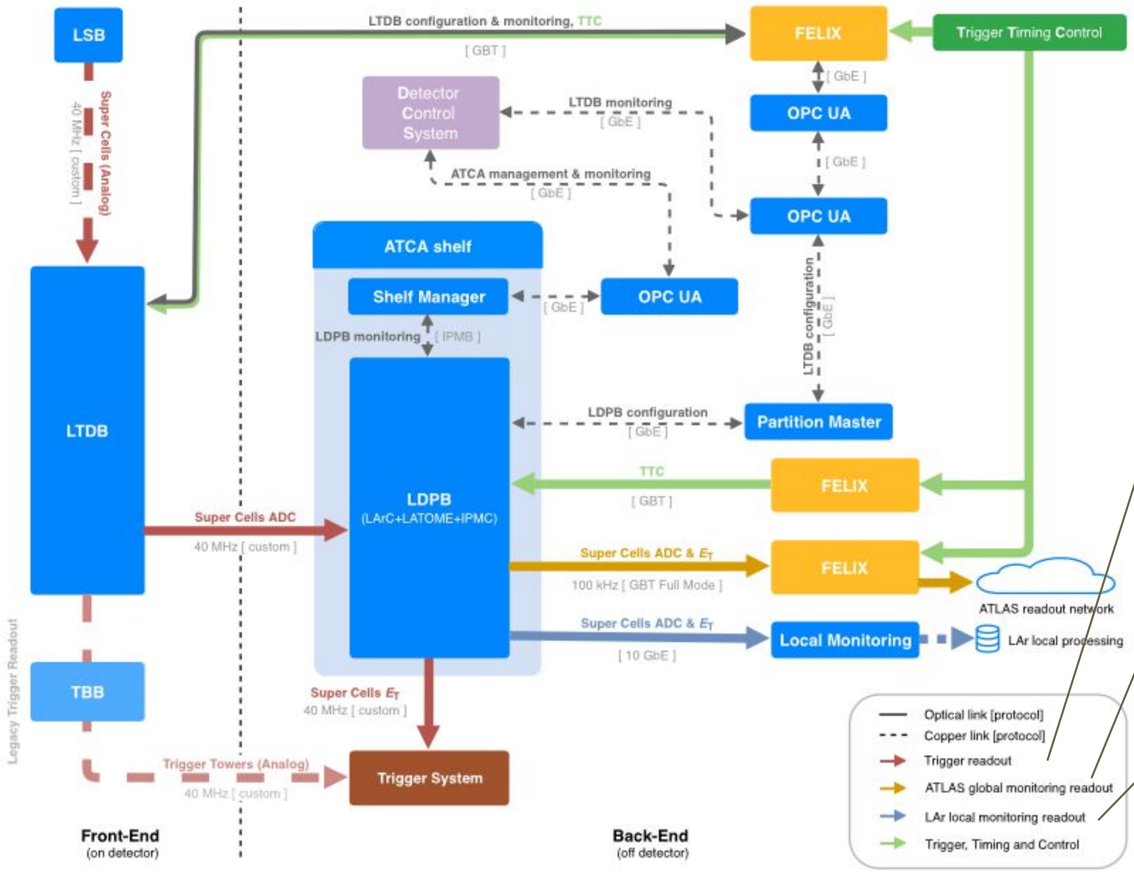
where the sums run over the Super Cells.



LAr readout path



Electronics in the readout system



TTC synchronized with LHC reference clock, determination of the collision time of an event via its BCID

Digital Trigger - full line,
Analog Trigger - dashed line

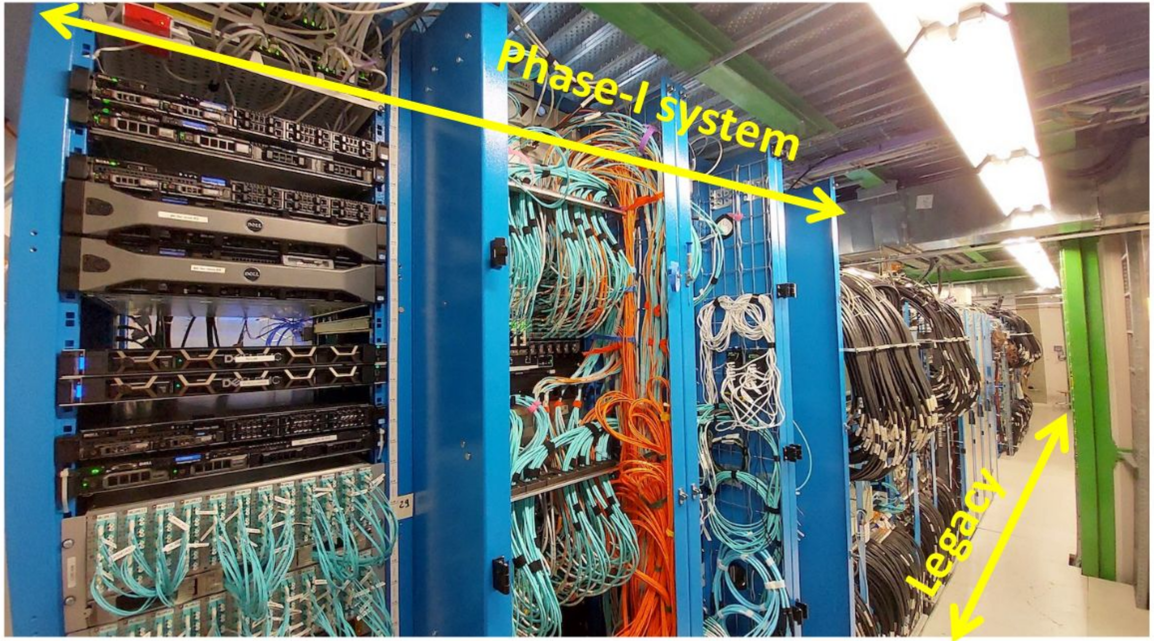
Purpose is to **verify that the E_T sent to the trigger system is correct**, by reading the SCs ADC data and the E_T values for all events selected by the L1A (recomputation of the calculation performed on the LATOMEs)

LAr specific local monitoring not connected to the ATLAS main readout - can operate independently, at L1A rate but also at any other rate

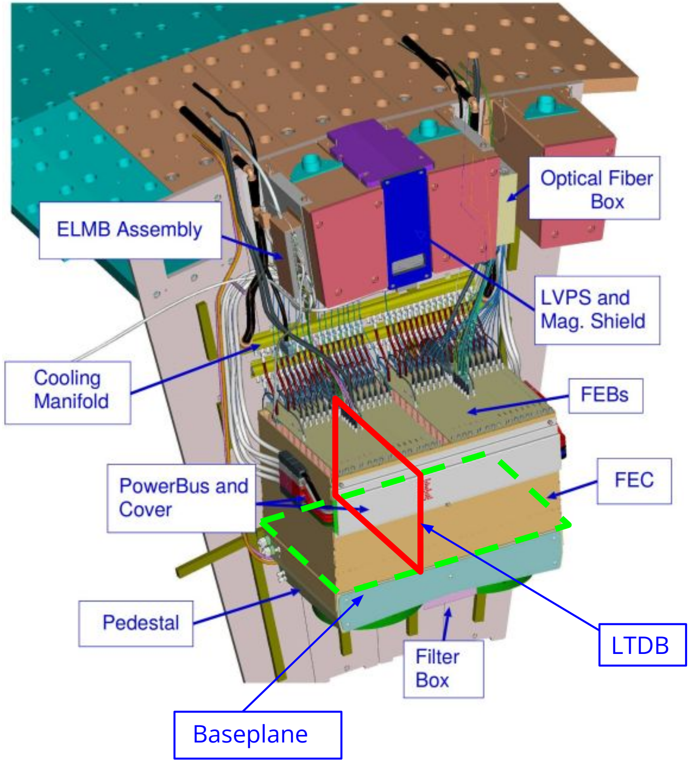
FELIX = Front-End LInk eXchange

Visual comparison of AT vs DT

Back-end (off-detector)



Front-end (on-detector)



Digital Trigger system benefits significantly from the signal digitization on detector

Details about energy computation

$$E_{\text{cell}} = F_{\text{DAC}\to\mu\text{A}} \cdot F_{\mu\text{A}\to\text{MEV}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i \left(s_i - p\right)$$

$F_{\text{DAC}\to\mu\text{A}}$	=	sampling fraction, converts calibration board DAC counts to current
$F_{\mu\text{A}\to\text{MEV}}$	=	factor which converts ionisation current in the calorimeter to total deposited E, from test-beam studies
$\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}$	=	ratio of maxima of physical and calibration pulses with the same input current
G_1	=	cell gain - ADC to DAC from calibration pulse
a_i	=	Optimal Filtering Coefficients (OFCs), derived from predicted pulse shape & noise autocorrelation
s_i	=	samples of the shaped signal digitised in a given electronic gain, measured in ADC counts
p	=	read-out electronic pedestal, measured for each gain

Three types of electronic calibration runs, **pedestals**, **ramps** and **delays** provide many of the inputs required for cell energy computation (as well as timing & quality factor).