Exploiting the ATLAS triggering potential

Adriana Milic

February 13, 2025

Seminar at University of Warwick

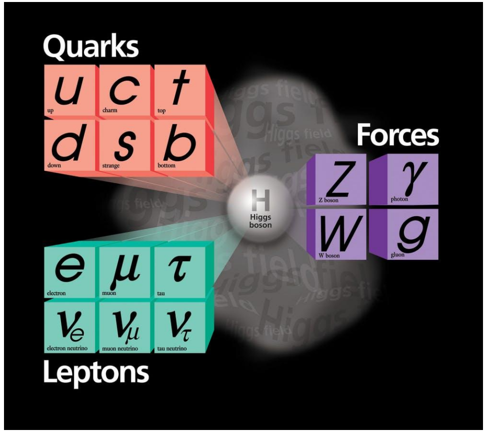
Overview

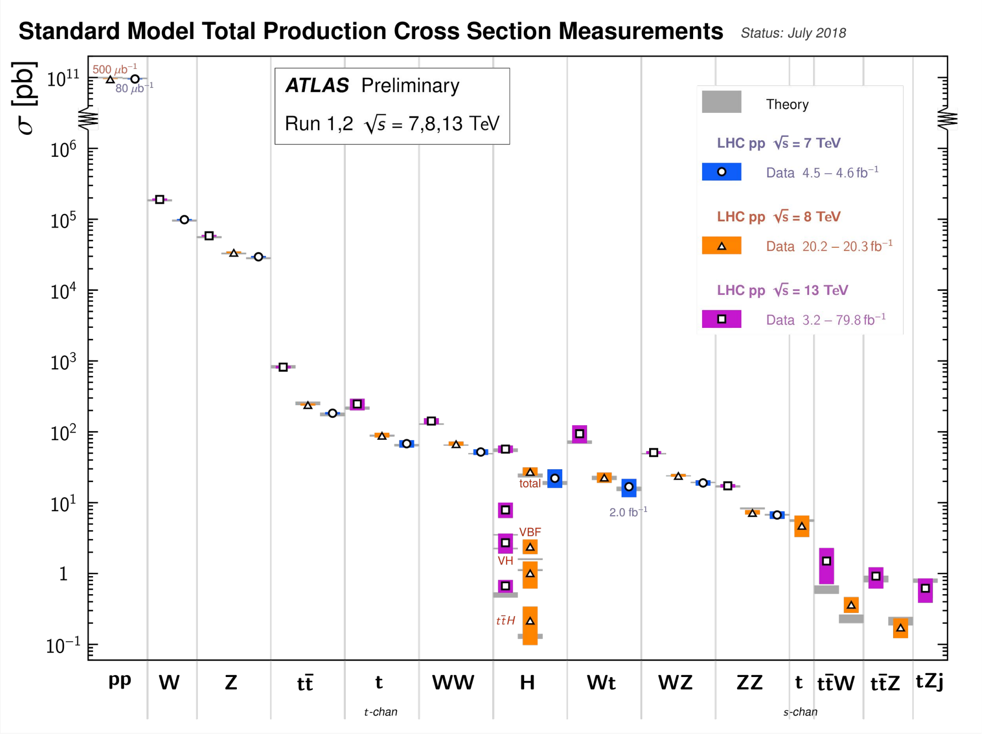
- The Standard Model and beyond
- LHC & ATLAS
- ATLAS Liquid Argon Calorimeter and Triggering system
- Possible improvements

The Standard Model

The Standard Model

- The **Standard Model (SM)** describes all **elementary particles** and their **interactions**.
- It has been tested at the LHC and various other experiments
- However, we cannot explain all known phenomena with the SM.





Shortcomings of the SM

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the W and Z bosons?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+ \tau^-$)?

Several questions remain unanswered by the SM

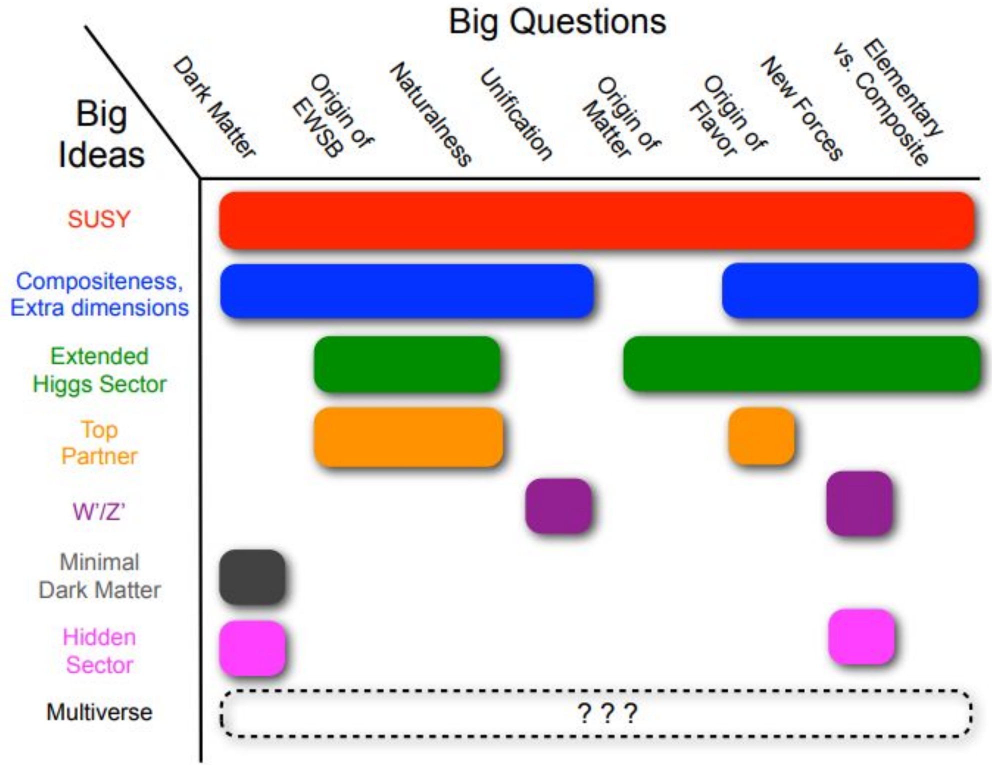
Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

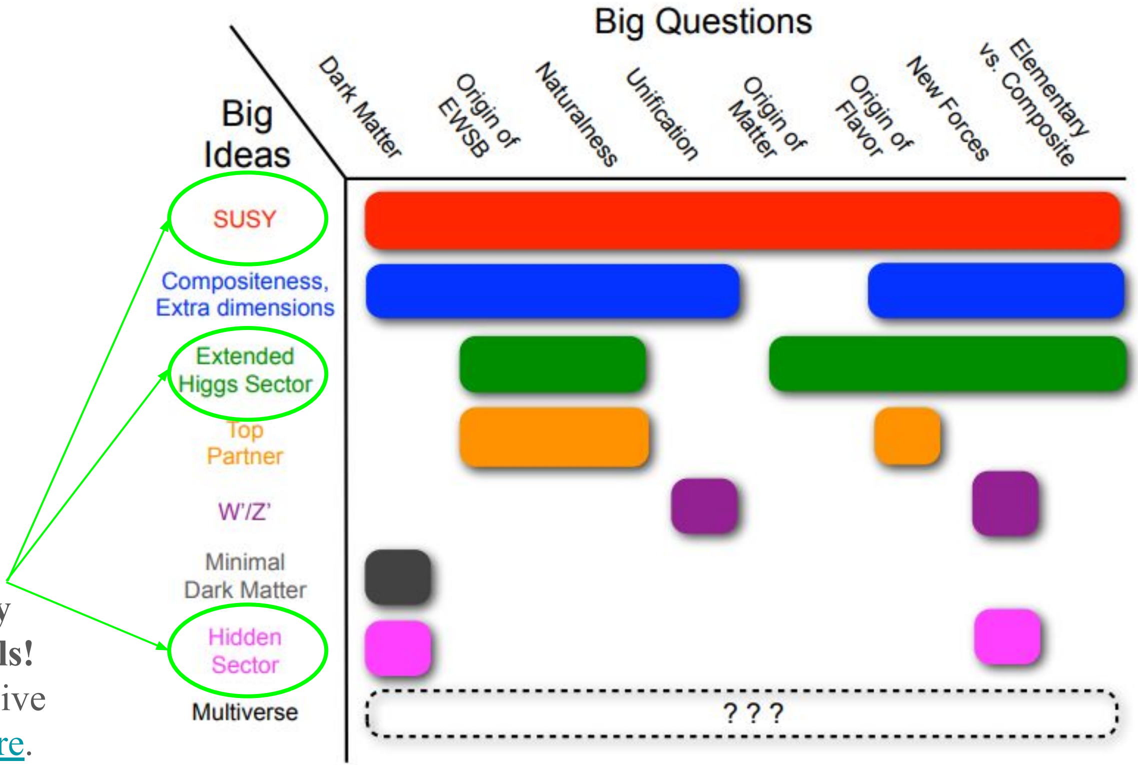
What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

Many questions, many possible solutions



Many questions, many possible solutions



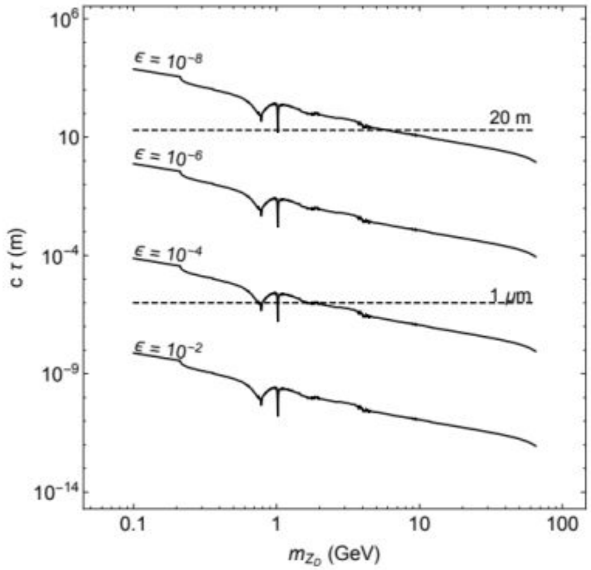
Long-lived particles predicted by many models! Comprehensive summary [here](#).

Dark photons

- **Hidden Abelian Higgs Model** introduce long-lived "**dark photons**" Z_D

- Z_D mixes kinetically with the SM hypercharge with strength ϵ
  - If **ϵ is small Z_D can be long-lived**
  - Particle proper lifetimes between micrometers and several meters.

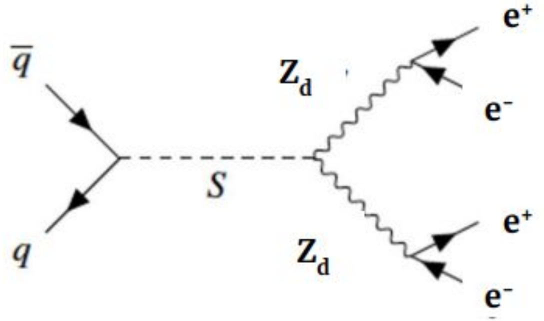
- **Sizable Z_D branching ratio to leptons** makes it possible to examine a broad range of dark photon masses.

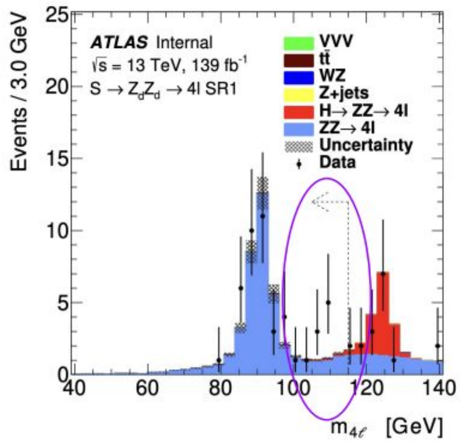


arXiv:1412.0018

Dark photons

- Z_D can be produced in direct production/decay of dark Higgs S
- Long-lived light dark photon searches with an S mediator are **so far uncovered.**
- Would provide a long-lived follow up to the prompt $S \rightarrow Z_D Z_D \rightarrow 4l$ analysis [arXiv:2410.16781]
  - 3.4 **σ** local excess at (110 GeV, 30 GeV)
- **Important to increase sensitivity at trigger level to catch these particles!**



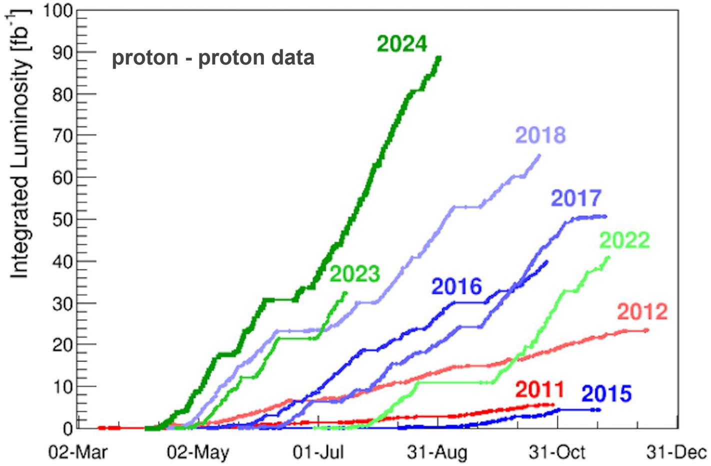


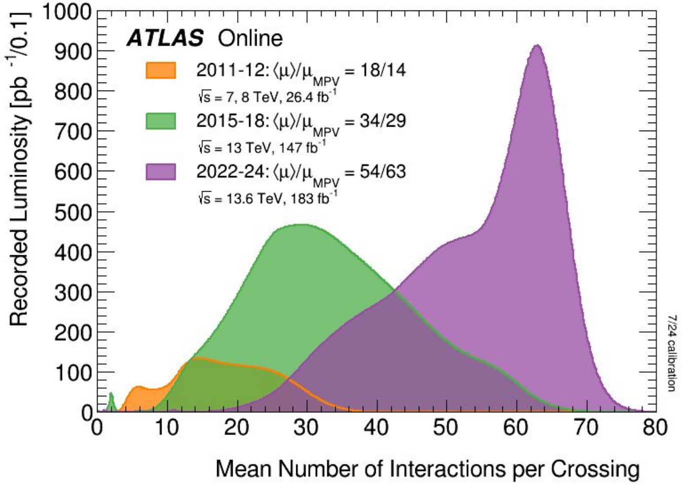
LHC & ATLAS

How to look for new particles: The LHC

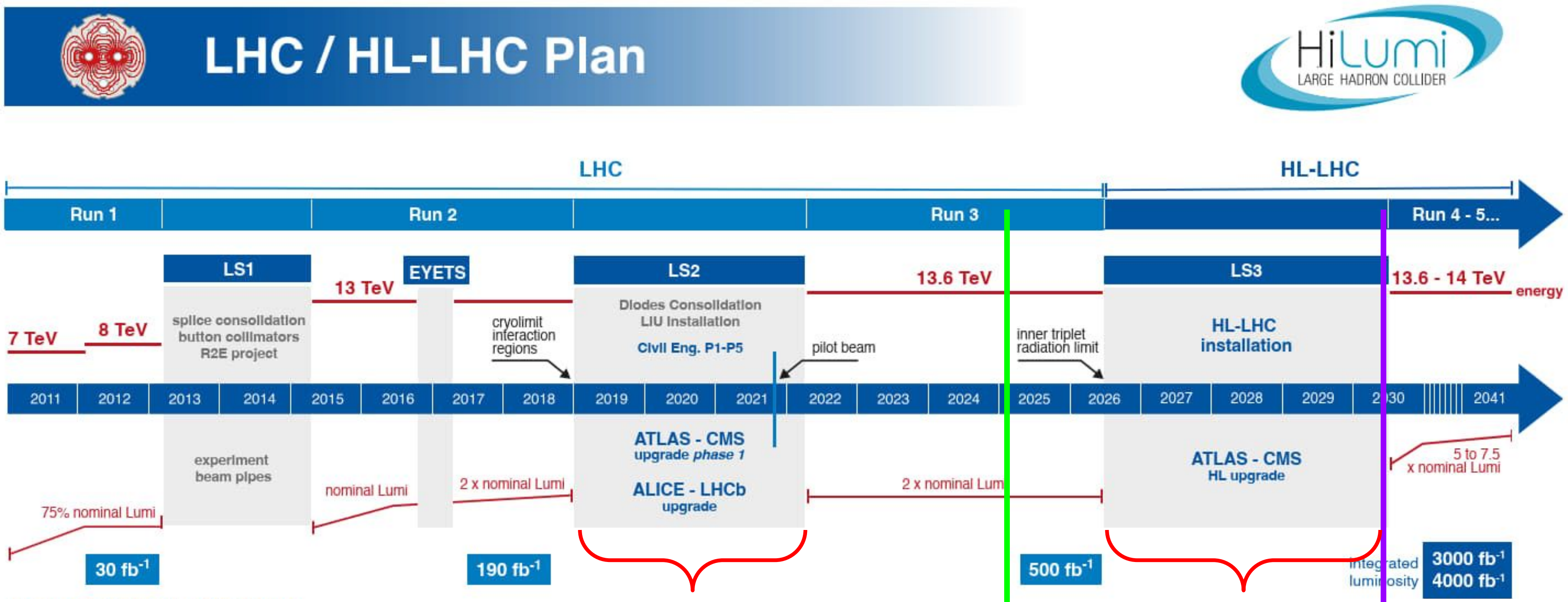
- The Large Hadron Collider (LHC) **collides protons and light/heavy ions** @ 40 MHz.
  - proton-proton integrated luminosity @$\sqrt{s}$ = 7-8 TeV, 13 TeV, 13.6 TeV ~ **355 fb^{-1}**
  - Pb-Pb integrated luminosity @$\sqrt{s}$ = 2.76 TeV, 5.0 TeV, 5.4 TeV ~**200 nb^{-1}**

- Data taking conditions increasingly harsher for detector and data acquisition systems.
  - Increasing pileup and radiation.





LHC Schedule



Phase-I Upgrade

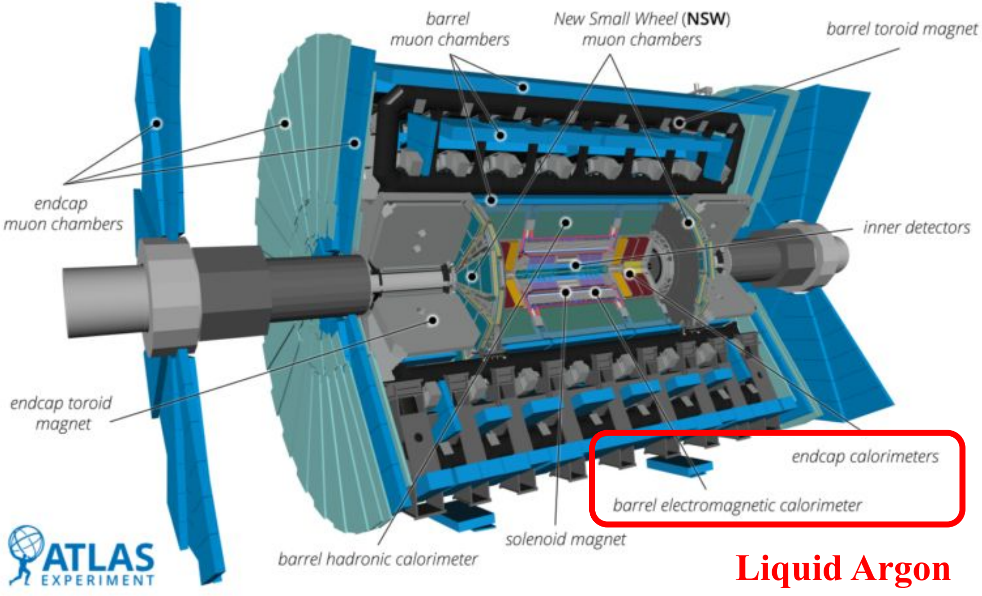
Phase-II Upgrade

We are here!
1.5 years until the
end of Run 3.

Run 4 (HL-LHC)
starting ~2030

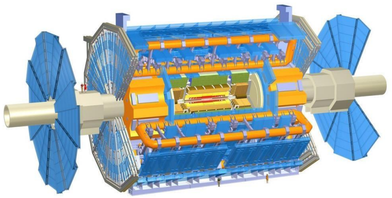
How to look for new particles: Experiments

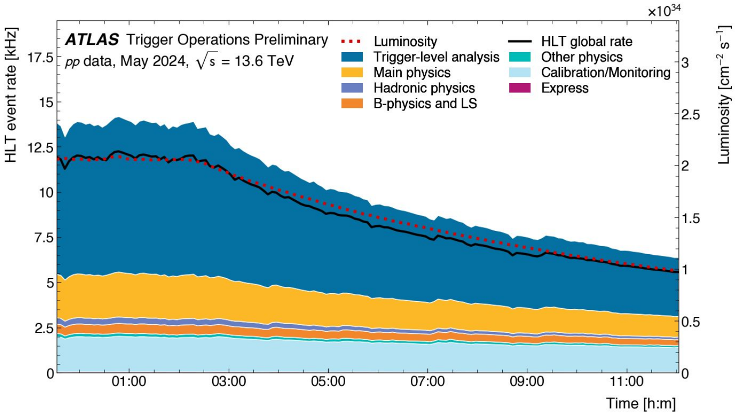
- ATLAS (and CMS) are **general-purpose detectors**, both consisting of several subsystems, designed to exploit the physics potential at the LHC.



Liquid Argon (LAr) calorimeter

ATLAS trigger system





Raw data from detector at 40 MHz

Level-1 Trigger (hardware):
Muon chambers and **calorimeter cells** with reduced granularity used
Regions of Interest (RoI) defined

100 kHz

Level-2 Trigger:
Seeded by Level-1 RoI
Full granularity of the detector used

2-3 kHz

Event to tape

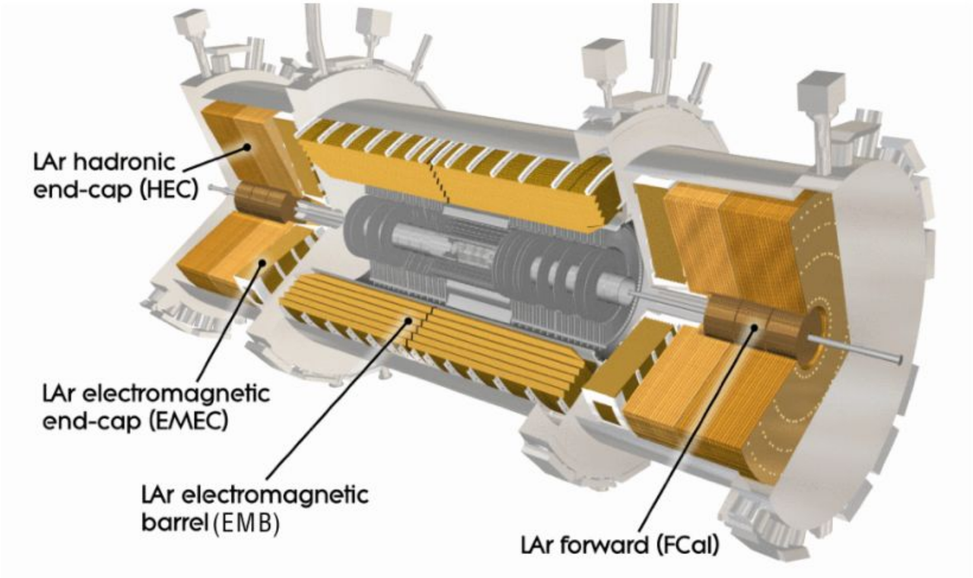
~2.5 μs ~10 ms ~1 s

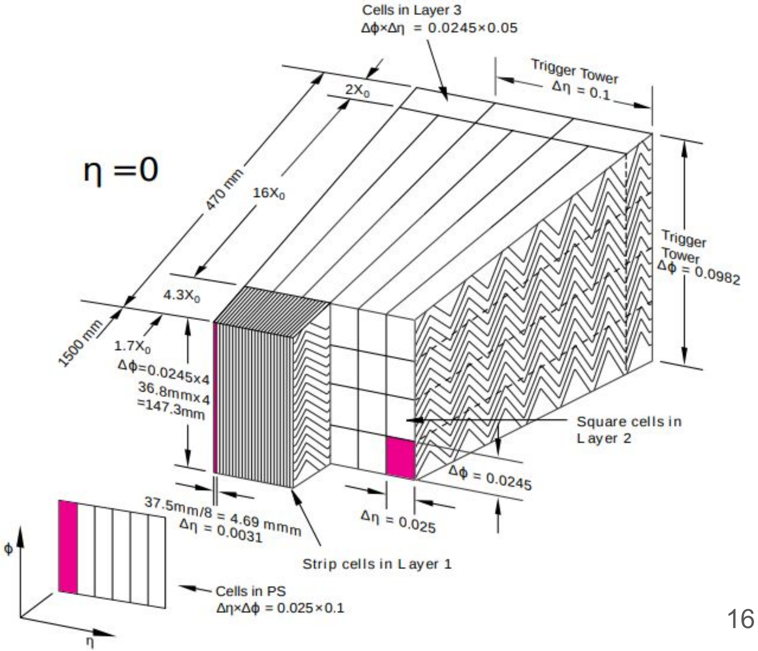
Execution time

LAr Calorimeter

ATLAS LAr Calorimeter

- Sampling calorimeter
- Longitudinally segmented (4 layers, presampler, front, middle, back) with different granularities
- Coverage $|\eta| < 4.9$

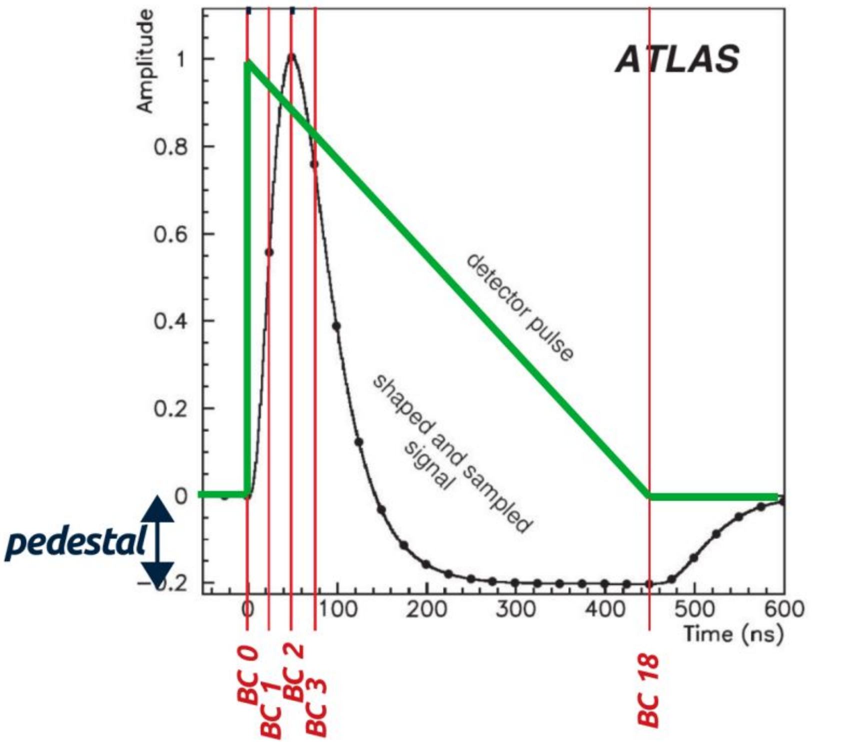




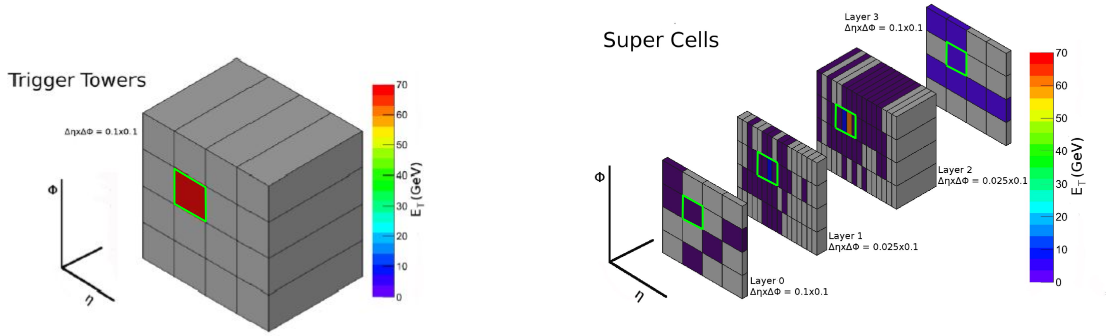
LAr Calorimeter Signals

Fine granularity readout
- 180k cells are the smallest readout units
- Energy and timing are computed by the back-end electronics with Optimal Filter Coefficients (OFCs)

Trigger
- Signals from close-by cells are summed to form Super Cells (SC)
  - Feed L1 Calorimeter Trigger (L1Calo)



LAr + L1Calo Trigger Phase-I Upgrade Overview



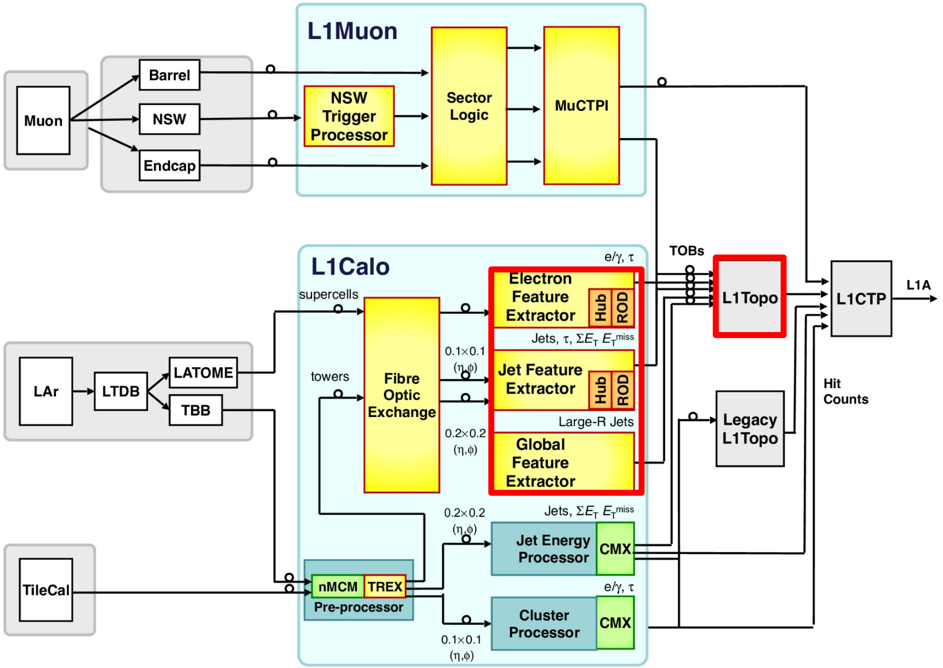
Simulation for a 70 GeV electron

- No longitudinal segmentation
- Fixed size in $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- 5.4k trigger towers from 180k cells

- Longitudinally segmented
- Increased granularity in front and middle to $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$
- 34k SCs from 180k cells

Use more information at trigger level to better reject background
Phase-I = Digital Trigger

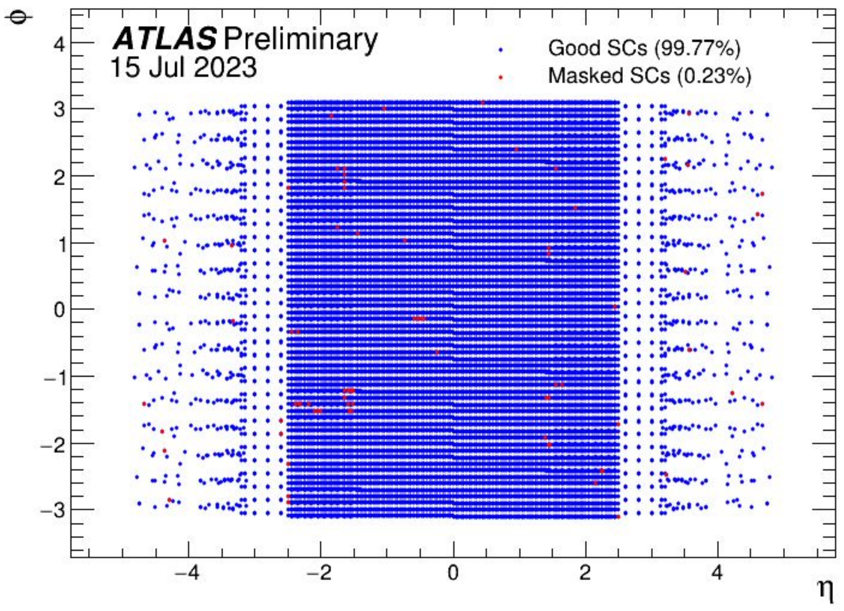
LAr + L1Calo Trigger Phase-I Upgrade Overview



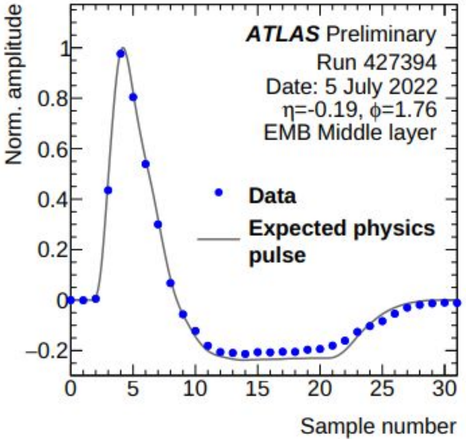
- Liquid Argon Digital Trigger provides higher granularity and resolution E_T to L1Calo
- L1Calo exploits fine granularity information from the LAr SCs using Feature EXtractor (FEX) processors: electromagnetic, jet and global (eFEX, jFEX and gFEX)

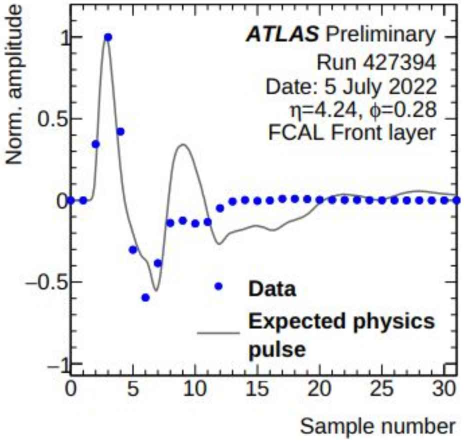
arXiv:2401.06630

Digital Trigger Performance



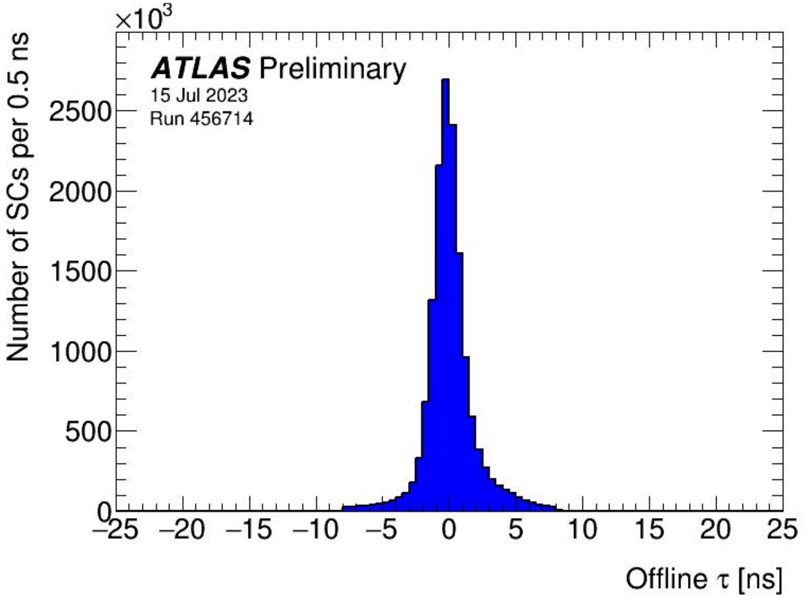
> 99.7% coverage during high luminosity pp runs in 2023

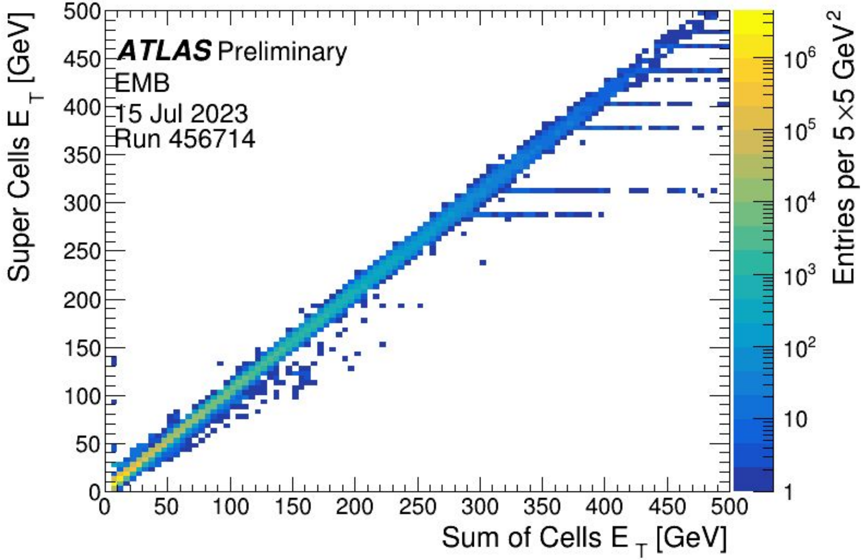




- Pulse shape is consistent with expected pulse from calibration. In FCAL, working on improving the SC pulse shape modelling
  - Obtain the shape from collision data with special runs with higher effective sampling frequency (< 25 ns)

Digital Trigger Performance

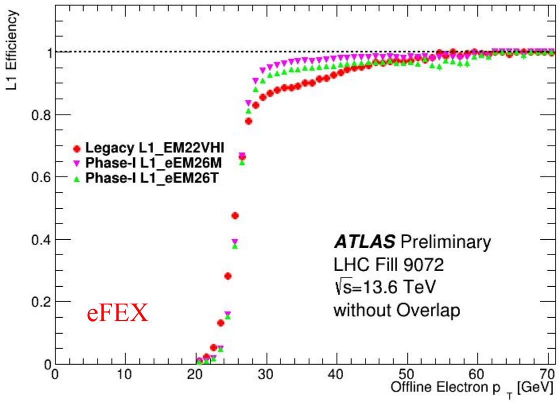


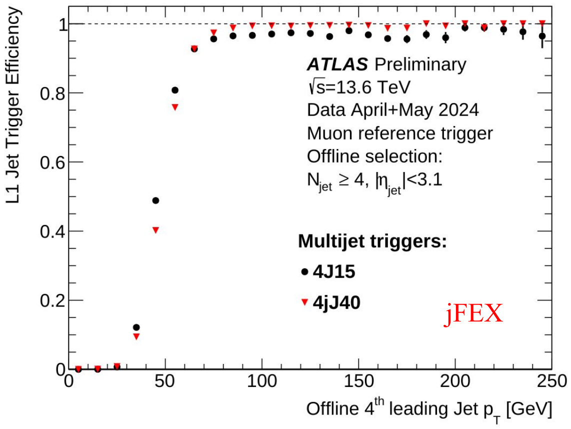


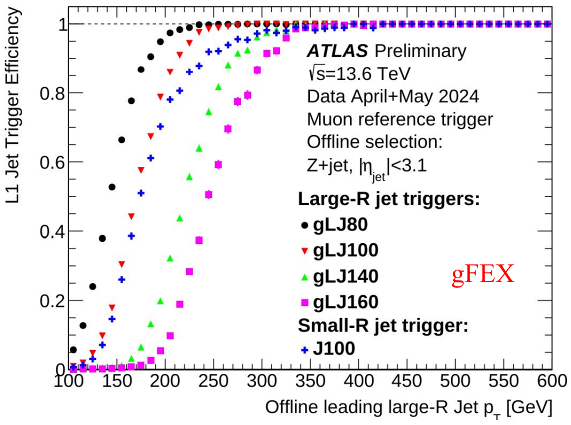
- Very narrow timing distribution for the SCs
- Used only for bunch cross identification → avoiding late or early triggers

- Excellent agreement between cells (main readout) and SC energy
  - Saturation at high energy expected and visible

Digital Trigger Performance

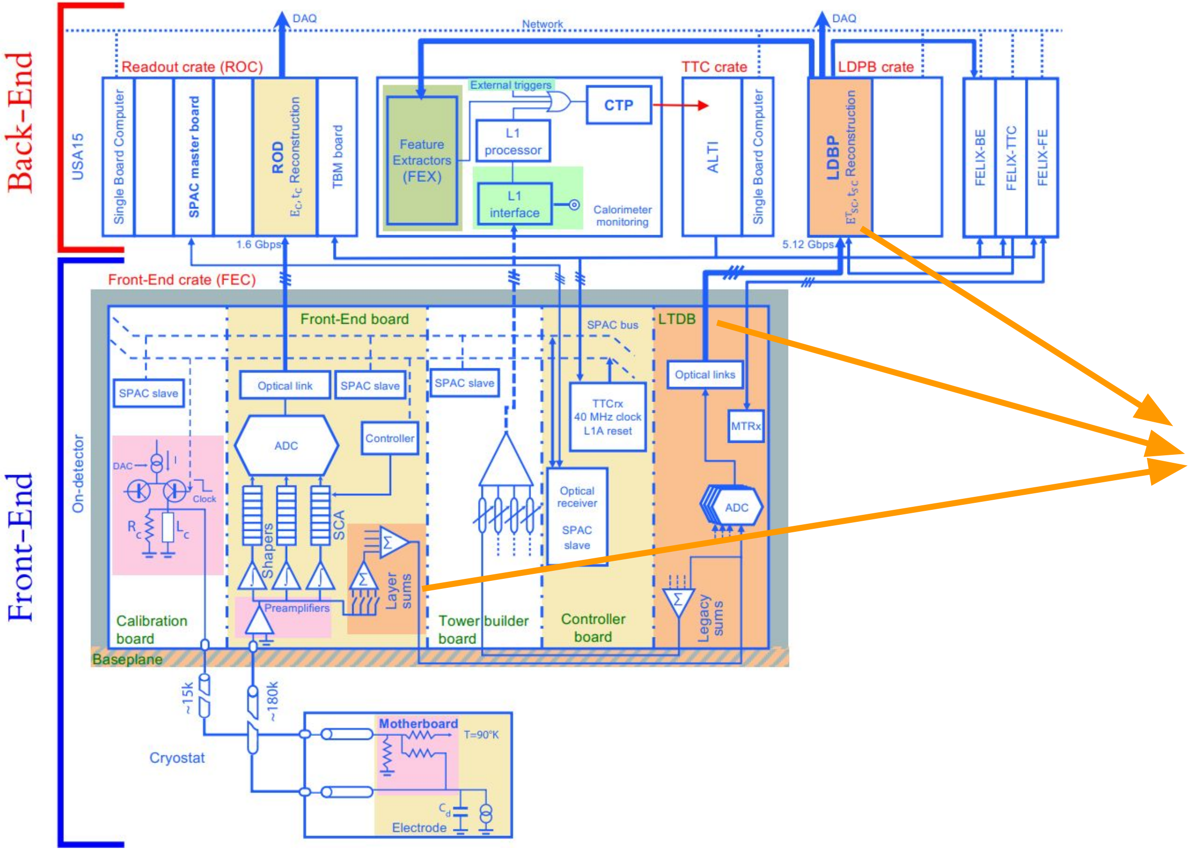






- Sharper turn-on curves with the same thresholds for electrons and jets
- L1 rate reduction around 10% for the same thresholds due to better discrimination against pileup

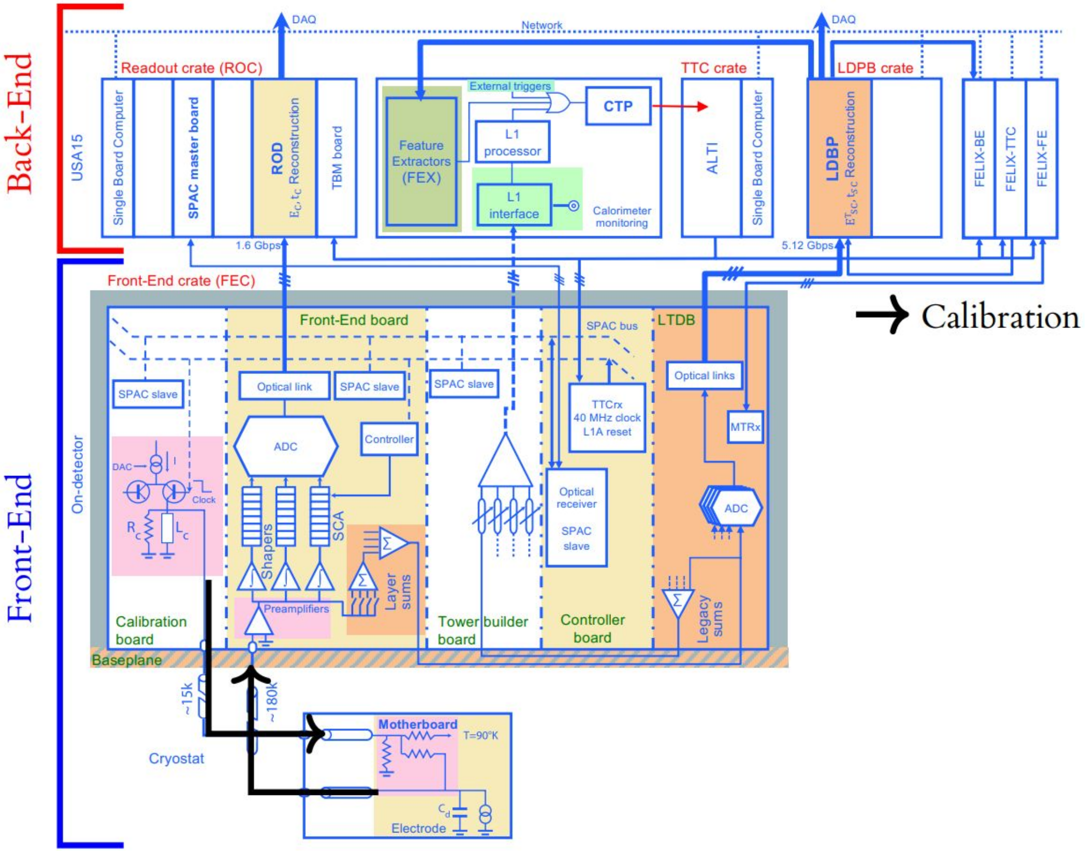
Digital Trigger Electronics Overview



New components

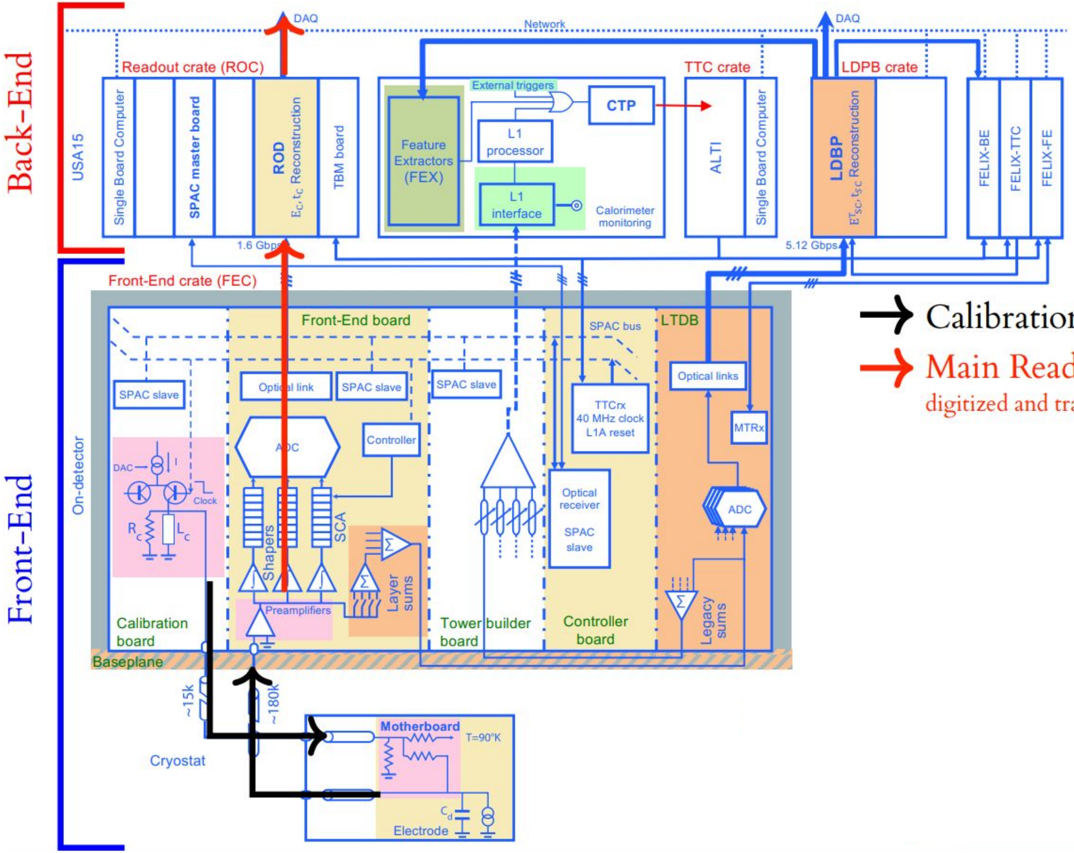
- **LDPB (LAr Digital Processing Blade)**
- **LTDB (LAr Trigger Digitizer Board)**
- **LSB (Layer Sum Board)**
- **Baseplane**

Digital Trigger Electronics Overview



→ Calibration

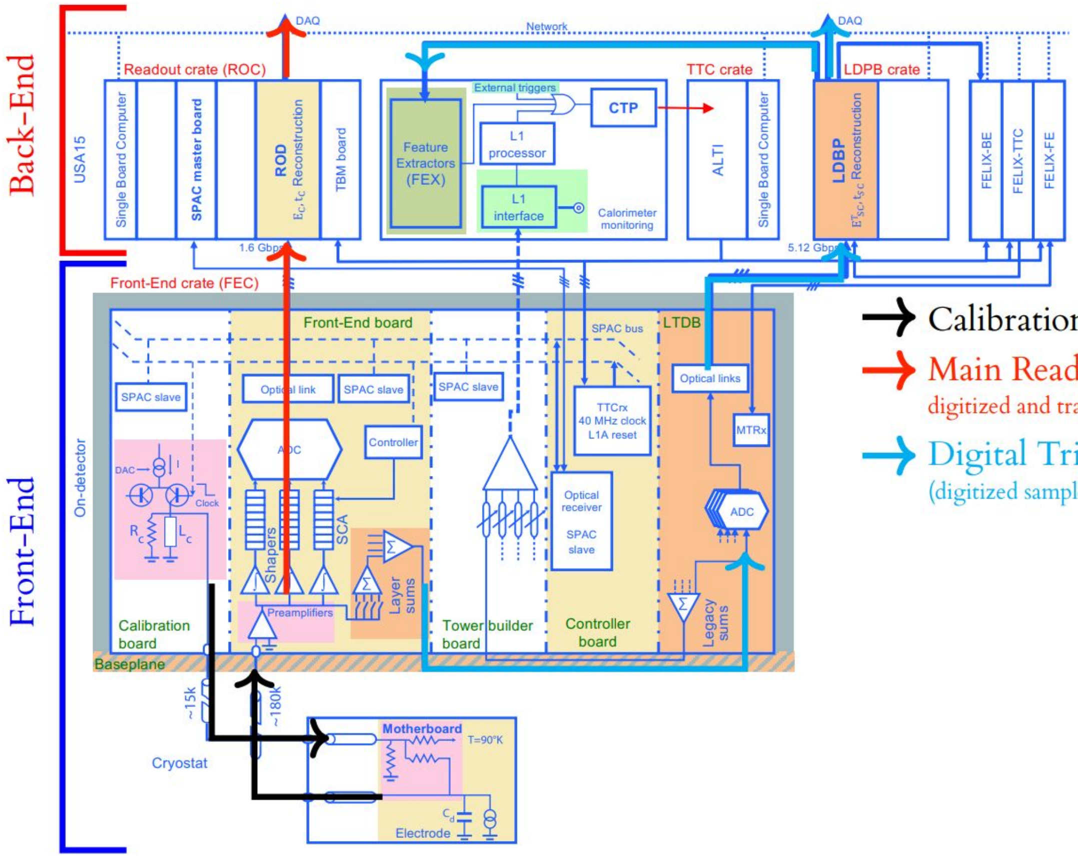
Digital Trigger Electronics Overview



→ Calibration

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

Digital Trigger Electronics Overview

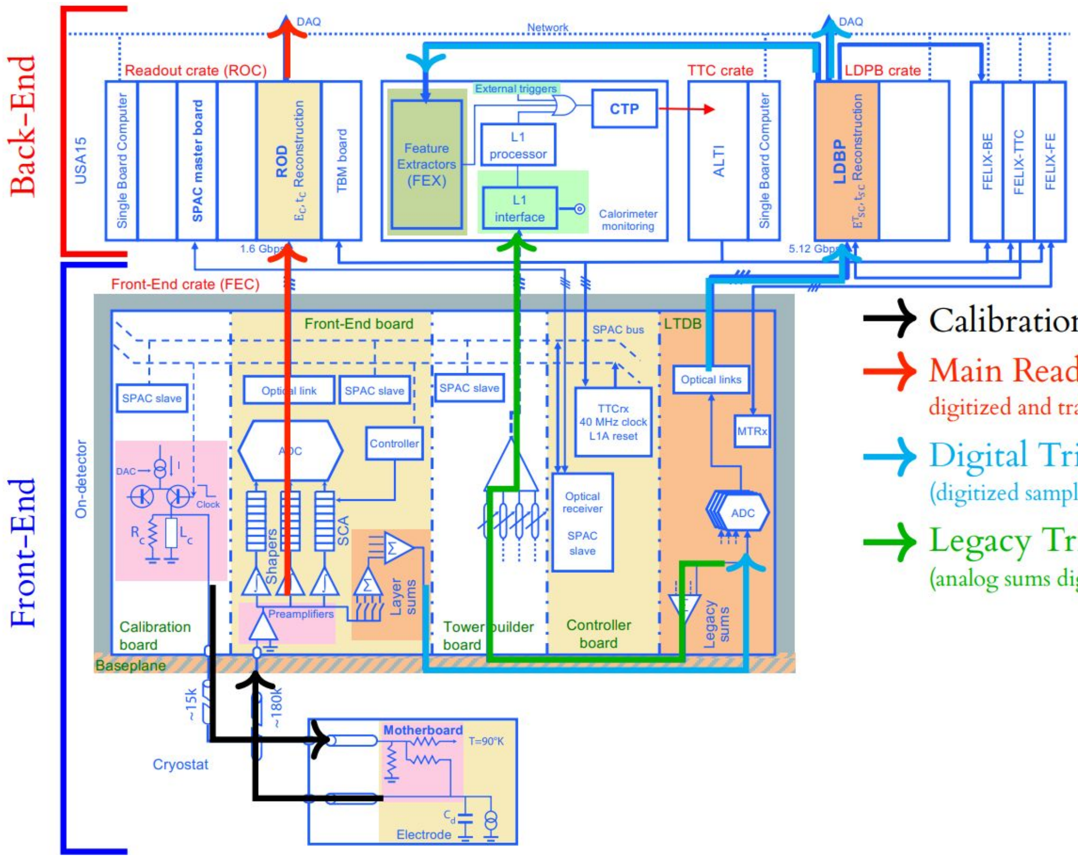


→ Calibration

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

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

Digital Trigger Electronics Overview



Calibration

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

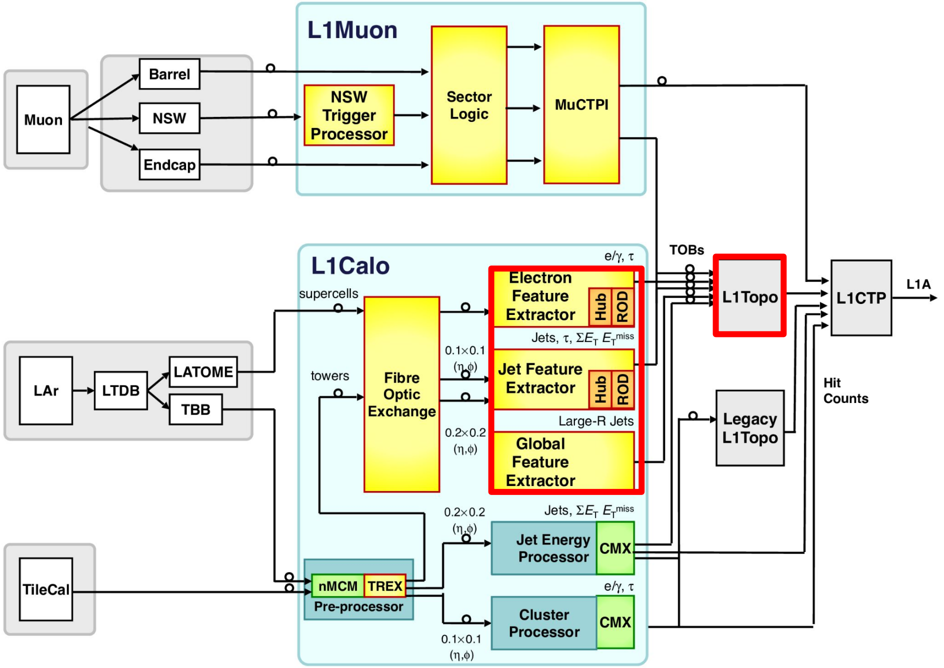
Digital Trigger (SC) (digitized samples streamed at 40 MHz)

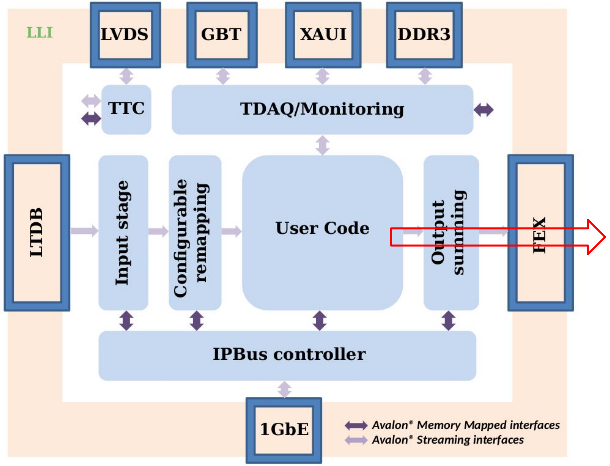
Legacy Trigger (TT) (analog sums digitized in the back-end)

(Decommissioned this year)

LAr backend firmware

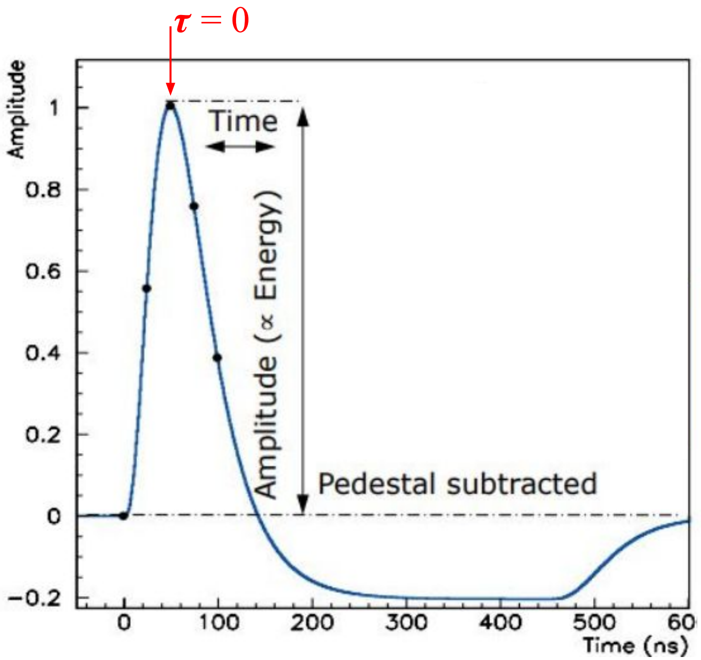
- From digitized pulses, LAr computes **transverse energy E_T** and **event time τ** at **fixed latency.**
- Sends **E_T at 40 MHz** to L1Calo trigger system after **τ selection.**
- VHDL based firmware, divided into several blocks.





Realtime path @ 40MHz

Optimal Filtering



- Optimal Filtering Coefficients (OFCs, A_i, B_i) are derived from the ideal pulse shape & noise autocorrelation matrix
- Applying OFCs gives
  - Amplitude ($\propto$ energy) of the pulse
  - Time shift between pulse & ideal pulse shape
- This means that **LAr decides on the timing for the trigger**! Fundamental change wrt. legacy system.

$$E_T = \sum_{i=0}^{3} A_i(S_i - p - b)$$

$$E_T\tau = \sum_{i=0}^{3} B_i(S_i - p - b)$$

A_i	Coefficients for energy reconstruction
S_i	Sampled signal
B_i	Coefficients for timing
p	Pedestal level
b	Baseline correction

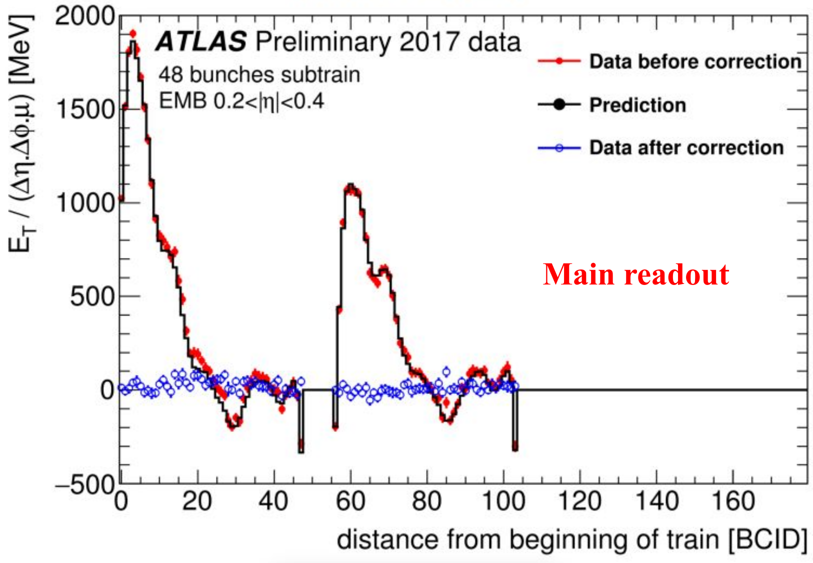
(Super) Cell Energy Computation

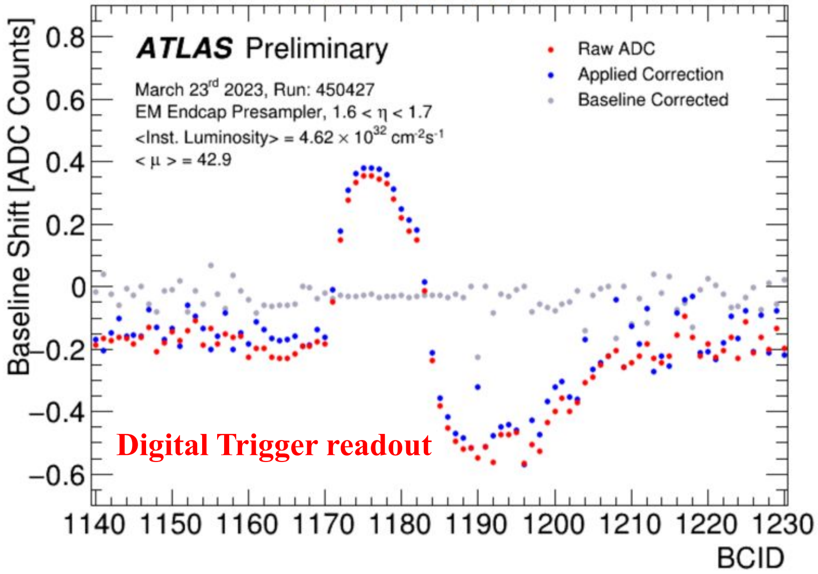
$$E_{\text{cell}} = F_{\text{DAC}\to\mu\text{A}} \cdot F_{\mu\text{A}\to\text{MEV}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N^{\text{samples}}} a_i\,(s_i - p)$$

$F_{\text{DAC}\to\mu\text{A}}$	=	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

Daily/weekly calibration runs and quantities measured during test beam needed to obtain input for energy computation

Baseline Correction





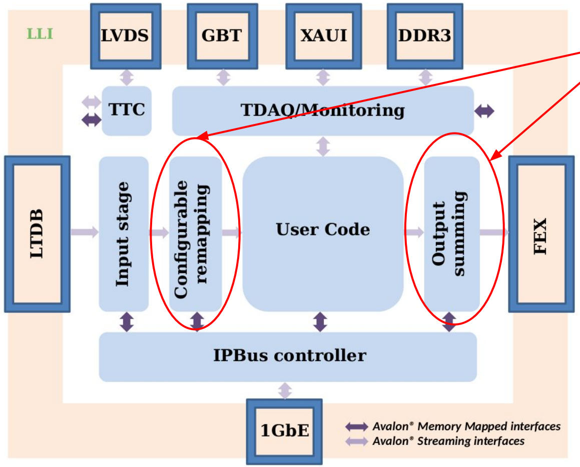
LAr pulse is significantly longer than distance between two bunch crossings

- ➔ Out-of-time (OOT) pileup raises the baseline ⇒ overall higher reconstructed energies
- ➔ Bipolar shaping partially compensates in-time with OOT pileup
  - ◆ With bunch trains, the cancellation is not perfect, in particular at the start/end of trains
- ➔ Correction applied both in main readout and digital trigger
  - ◆ Applied offline for main readout
  - ◆ Calculated and updated on-the-fly per SC and Bunch Crossing ID (BCID) for digital trigger

Possible improvements

LAr backend firmware

- Currently, LAr backend firmware being rewritten **using an HLS based approach.**
  - Two blocks restructured for reducing logic.
  - Idea is to have a pool of people being able to modify and adjust the firmware as needed.
  - For VHDL version: Most developers who worked on it left ATLAS or the field.
- Plan is to **put it into production in 2025**!
  - Will need quick and efficient commissioning.

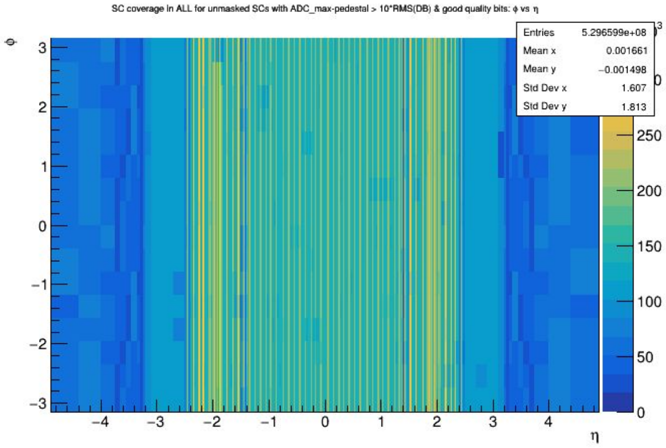


Two blocks being reworked in HLS based approach.

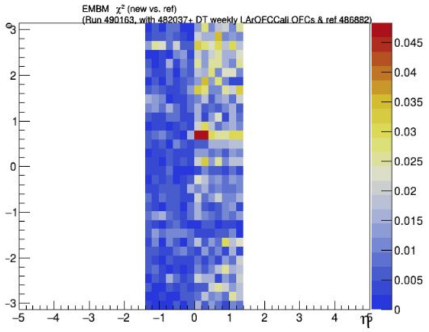
HLS based firmware

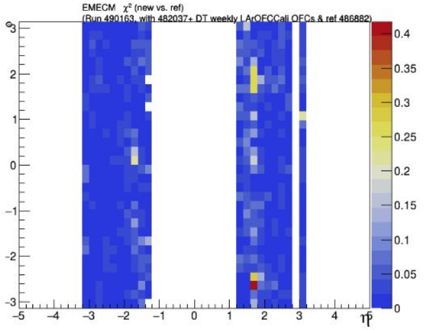
- Full firmware already implemented.
- Most paths tested in calibration and collision runs and working fine.

Super cell coverage plot from collision run

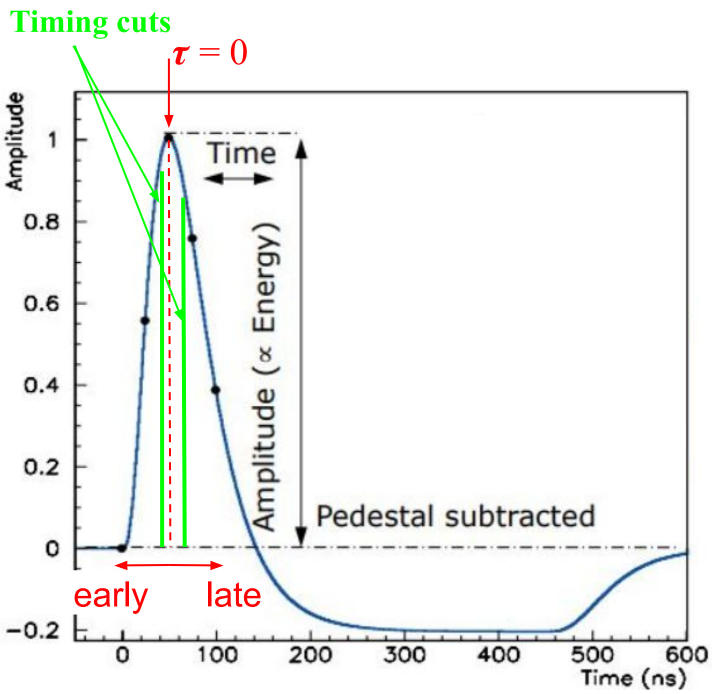


Super cell coverage plot from calibration run





Delayed signals →Late particles

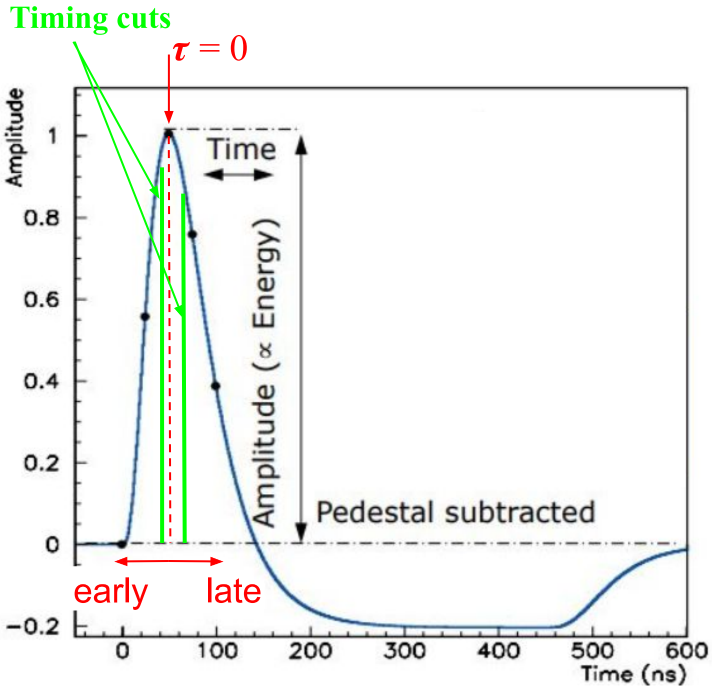


- Timing cuts applied to trigger on correct BC
- **Widen timing cuts**
  - **Let also signals that arrive late pass.**
  - Current cuts for pp running:

$$\begin{cases} -8\text{ ns} < \tau < 14\text{ ns}, & \text{if } E_T \geq 10\text{ GeV} \\ |\tau| < 8\text{ ns}, & \text{if } E_T < 10\text{ GeV} \end{cases}$$

- **Main challenges:**
  - Keep noise under control
  - Still trigger on correct BC

Delayed signals →Late particles



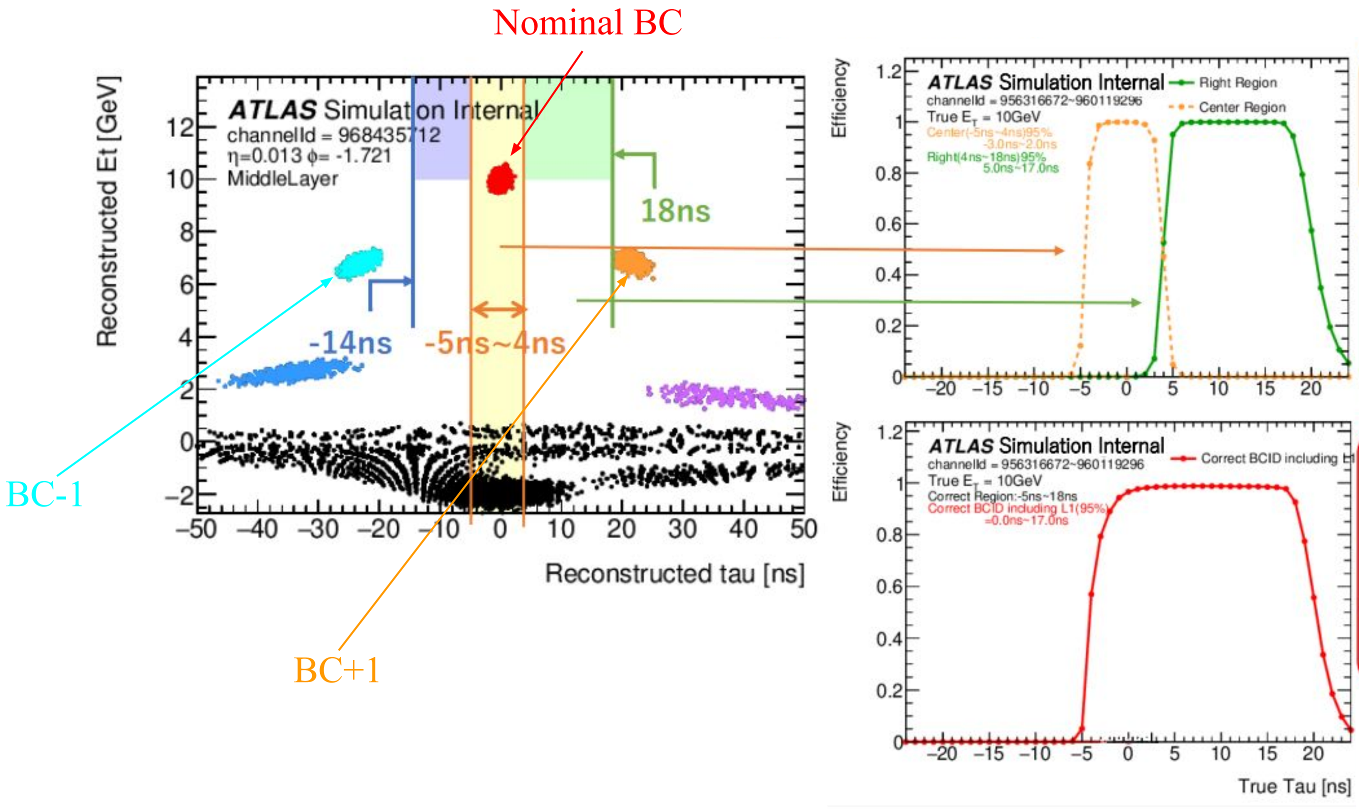
- Timing cuts applied to trigger on correct BC
- **Widen timing cuts**
  - **Let also signals that arrive late pass.**
  - Current cuts for pp running:

$$\begin{cases} -8\text{ ns} < \tau < 14\text{ ns}, & \text{if } E_T \geq 10\text{ GeV} \\ |\tau| < 8\text{ ns}, & \text{if } E_T < 10\text{ GeV} \end{cases}$$

Light late particles largely missed.

- **Main challenges:**
  - Keep noise under control
  - Still trigger on correct BC

Delayed particle detection efficiency



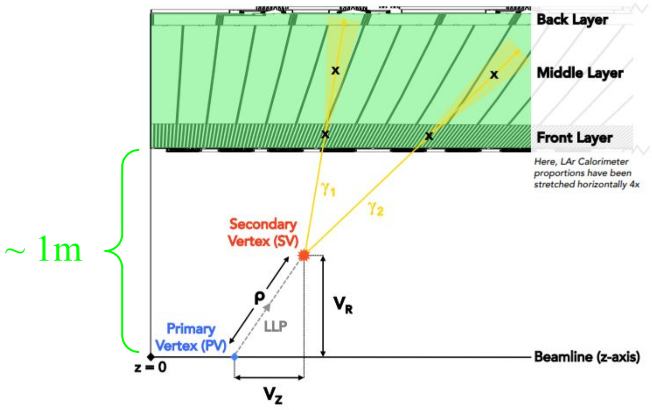
True τ -3~2ns
→ Nominal particle

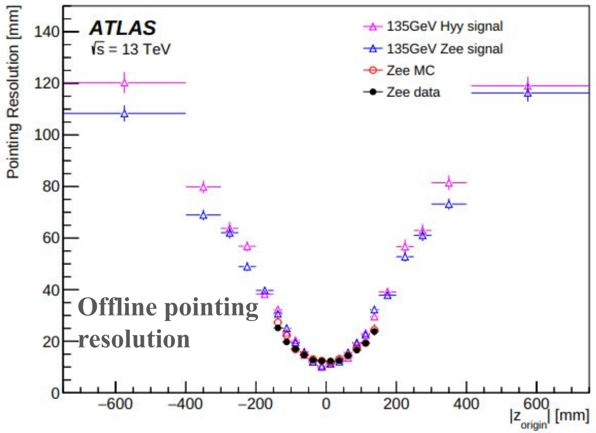
True τ 5~17ns
→ Slow Particle

True τ 0ns~17ns
→ More than 95% Correctly identify BC

Pointing information

- **Exploiting pointing information from LAr online** would be ideal.
- Pointing algorithms ("calo-vertexing") currently **only run offline** and use full calorimeter granularity. Have a spatial resolution of about 3-4 cm, and timing resolution < 1 ns.
- Resolution with trigger readout would be 3-4 times worse. Still well worth exploring as it **would allow to capture events that are currently lost at the trigger level**.



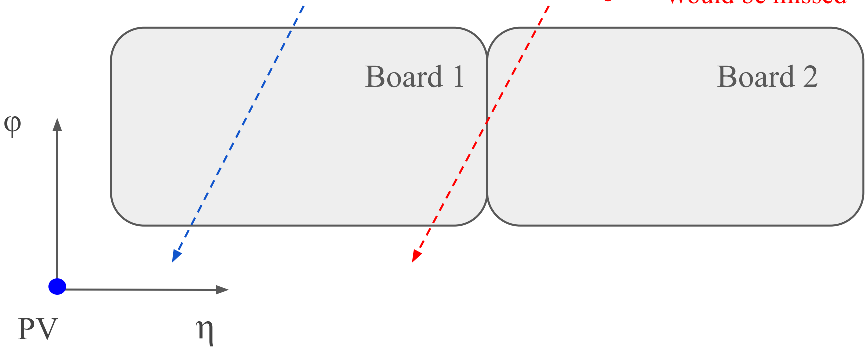


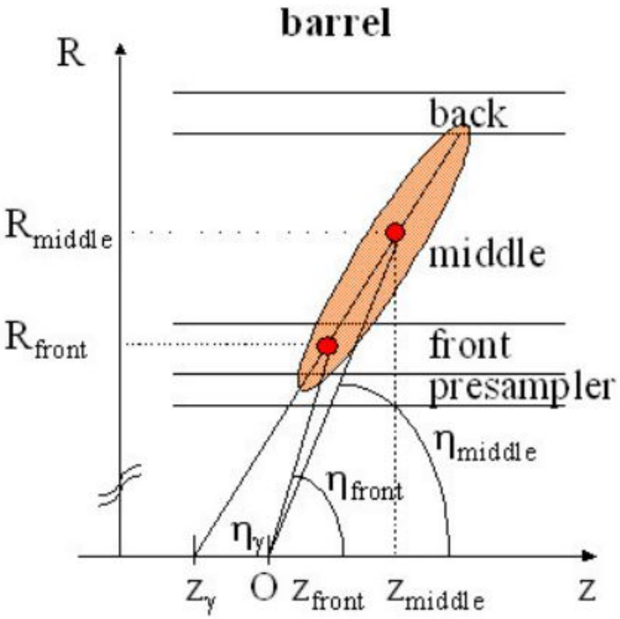
Pointing information

- **Super cell pointing** could be calculated already on LAr backend firmware or on eFEX.
- Special **trigger bit to force triggering** could be set in case particle track not pointing back to primary vertex.
- **Limitations**
  - FPGA resources
  - One LDPB board does not have full coverage and hence all information. Would lose some efficiency.

Particle 1
- Position info on one board
- Can be detected

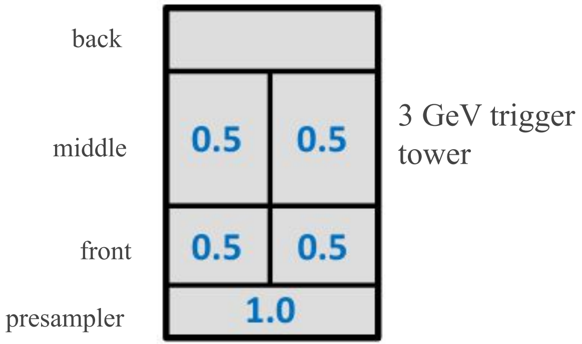
Particle 2
- Position info spread across boards
- Would be missed



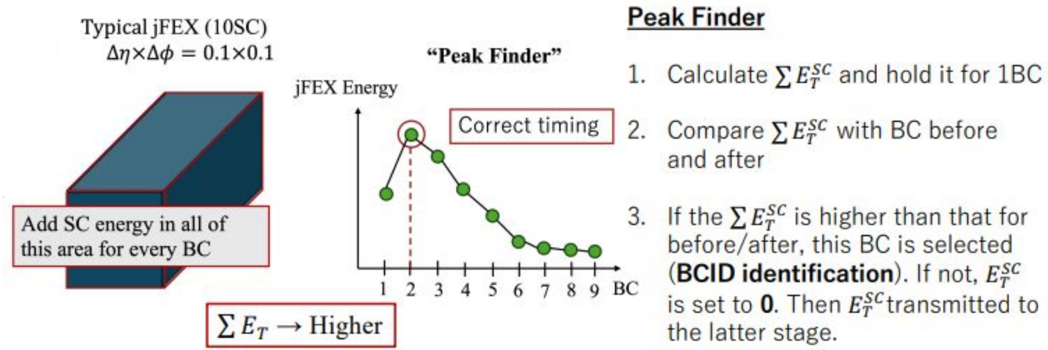


Small signals →Light particles

- Very challenging to trigger on **low pT** (thresholds around super cell noise levels)
  - New trigger by construction not as suited as legacy trigger.
  - Many energies have high probability to **not pass timing cut.**
  - Improvement especially important also for **heavy ion runs (Ultra peripheral collisions!)**



- **New idea: Peak finder firmware**
  - Summing several super cells without applying timing cut.
  - Deploy peak finder algorithm instead of OFCs on sums.
  - Needs significant firmware changes.
  - We believe we would still be within the latency budget.



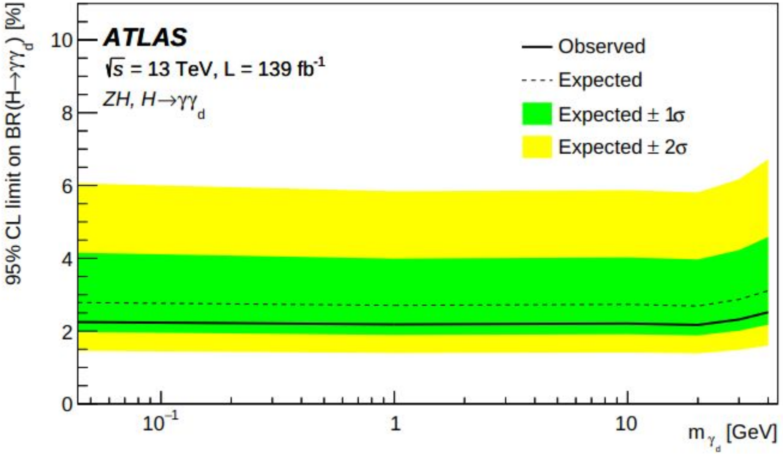
Final thoughts

- **Phase-I is here to stay for HL-LHC.**
    - We are still learning and haven't exploited its full potential yet.
    - Phase-I will then be the legacy system. Good to have a solid baseline.
- **We should push for possible improvements of Phase-I now.**
    - Last chance to commission with beam for next 4-5 years.
    - In Phase-II there will be many other priorities.
- **We need to keep people involved in operations and ATLAS at large.**
    - Continuous developments are one way of doing that.
    - Losing expertise is one of main problems in operations.

Backup

Search for dark photons in ATLAS

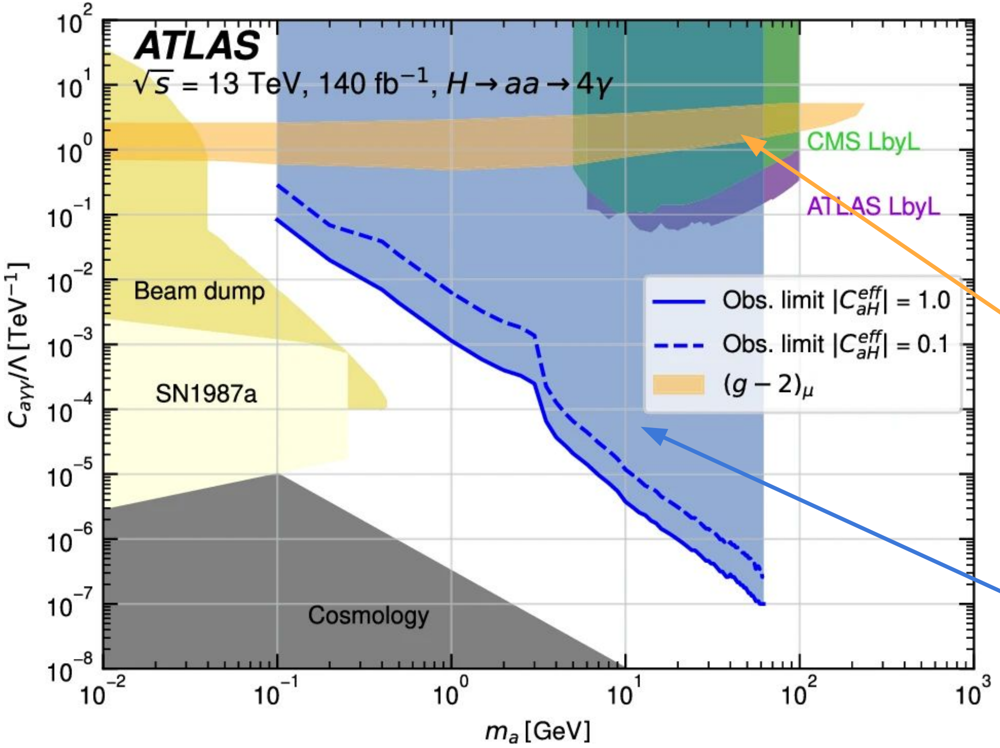
- No excess over the Standard Model observed.
- Observed limits:
  - Massless γ_d: $BR(H\rightarrow\gamma\gamma_d) < 2.28\%$
  - Massive γ_d: $BR(H\rightarrow\gamma\gamma_d)$ within [2.19,2.52]%
- Long-lived part missing!



ATL-COM-PHYS-2022-691

$H \to aa \to \gamma\gamma\gamma\gamma$

Full Run 2 analysis



- Limit on branching ratio converted to limit on photon coupling. Assuming new physics scale $\Lambda = 1$.

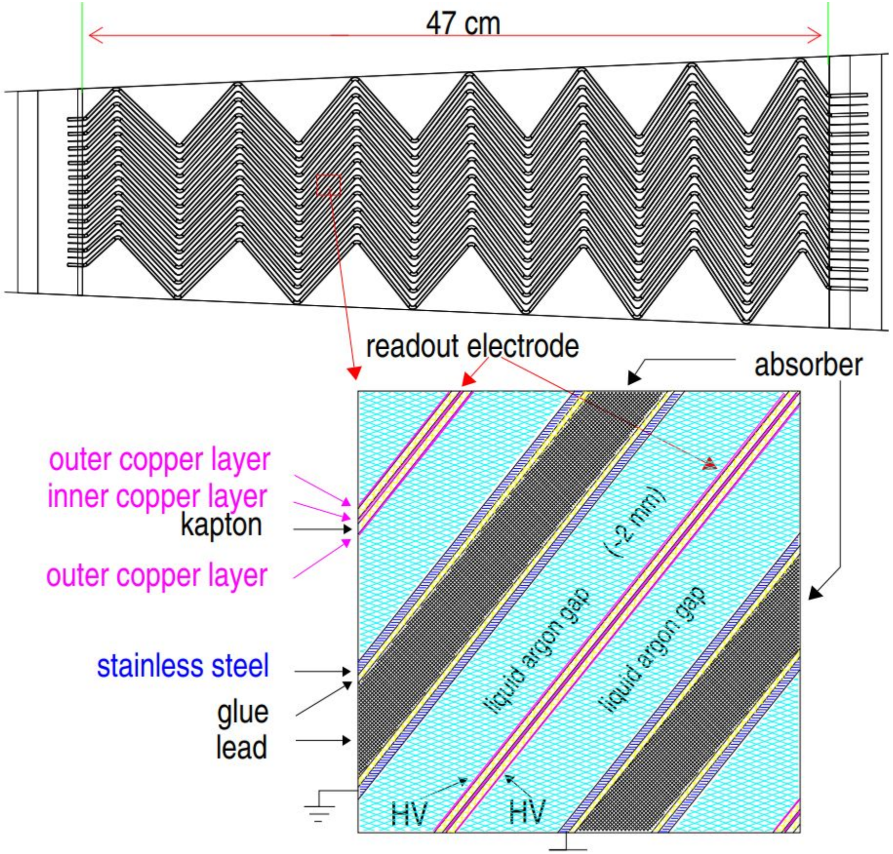
- Allowed parameter space for ALP-based models that could explain the $(g-2)\mu$ discrepancy in the $H \to aa \to 4\gamma$ decay mode significantly reduced

Orange shaded area indicates the region favoured by an ALP explanation for the $(g-2)\mu$ discrepancy

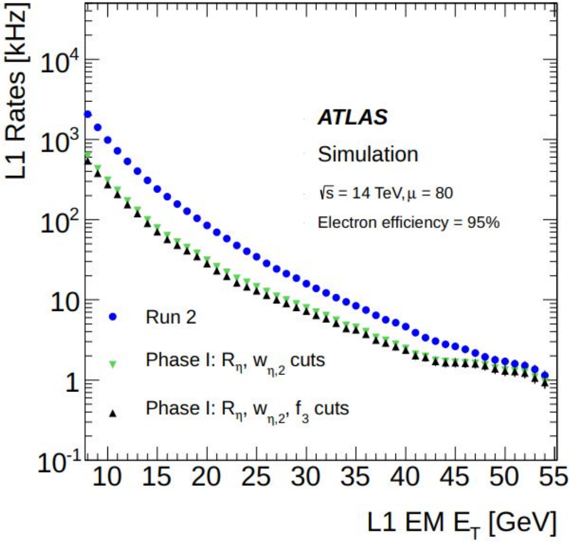
Region excluded by this analysis

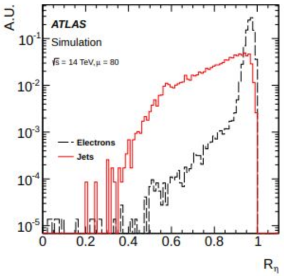
Physics signals from LAr cells

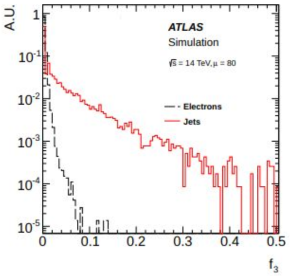
- 2.1 mm gap with ∼2 kV applied
- Particles interact with the absorber creating secondary particles ⇒ shower
- Secondary particles ionize LAr ⇒ collected by electrodes, drift time ∼450 ns,
- Current is read out, amplified and shaped (CR-RC^2)
- Signal then sampled and stored in analog memory on the Front End waiting for L1 trigger decision



LAr + L1Calo Trigger Phase-I Upgrade Motivation



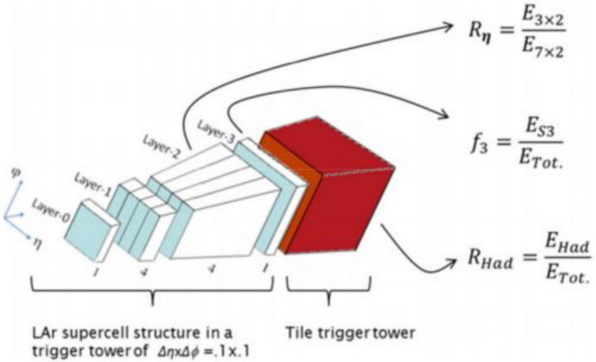




Use shower information as done in offline analysis to improve background rejection

Example 95% efficiency on electrons from Z → ee events with Run 3 conditions

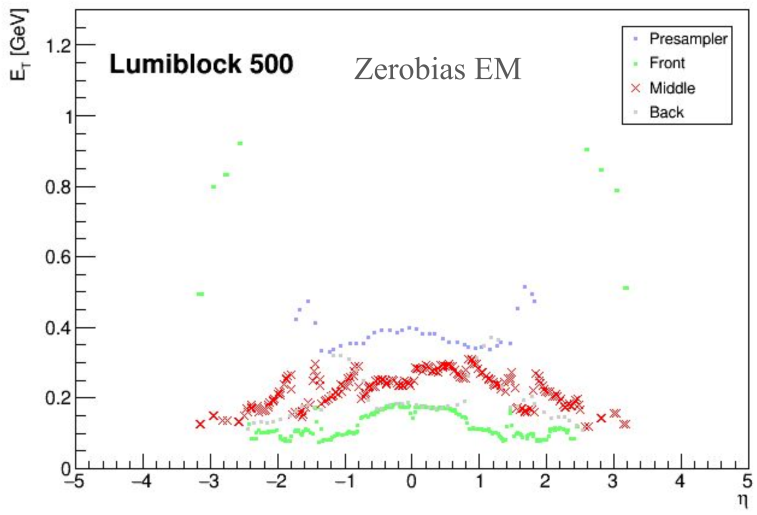
- Assuming Run 2 trigger algorithms: to have L1 rate 20 kHz need E_T = 28.5 GeV threshold
- Using shower shapes from SCs, lower to E_T = 21 GeV threshold

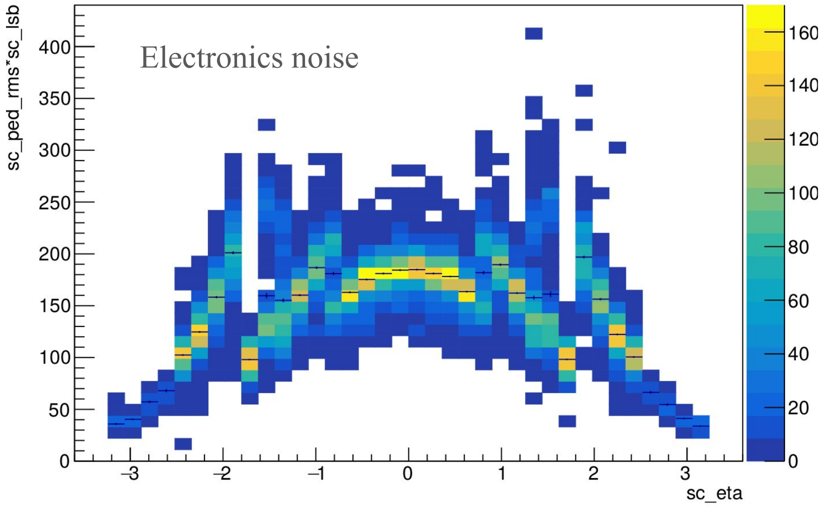


Moreover, improved L1 EM resolution ⇒ substantially sharpen the trigger turn-on curves ⇒ reduction offline E_T threshold and increase acceptance

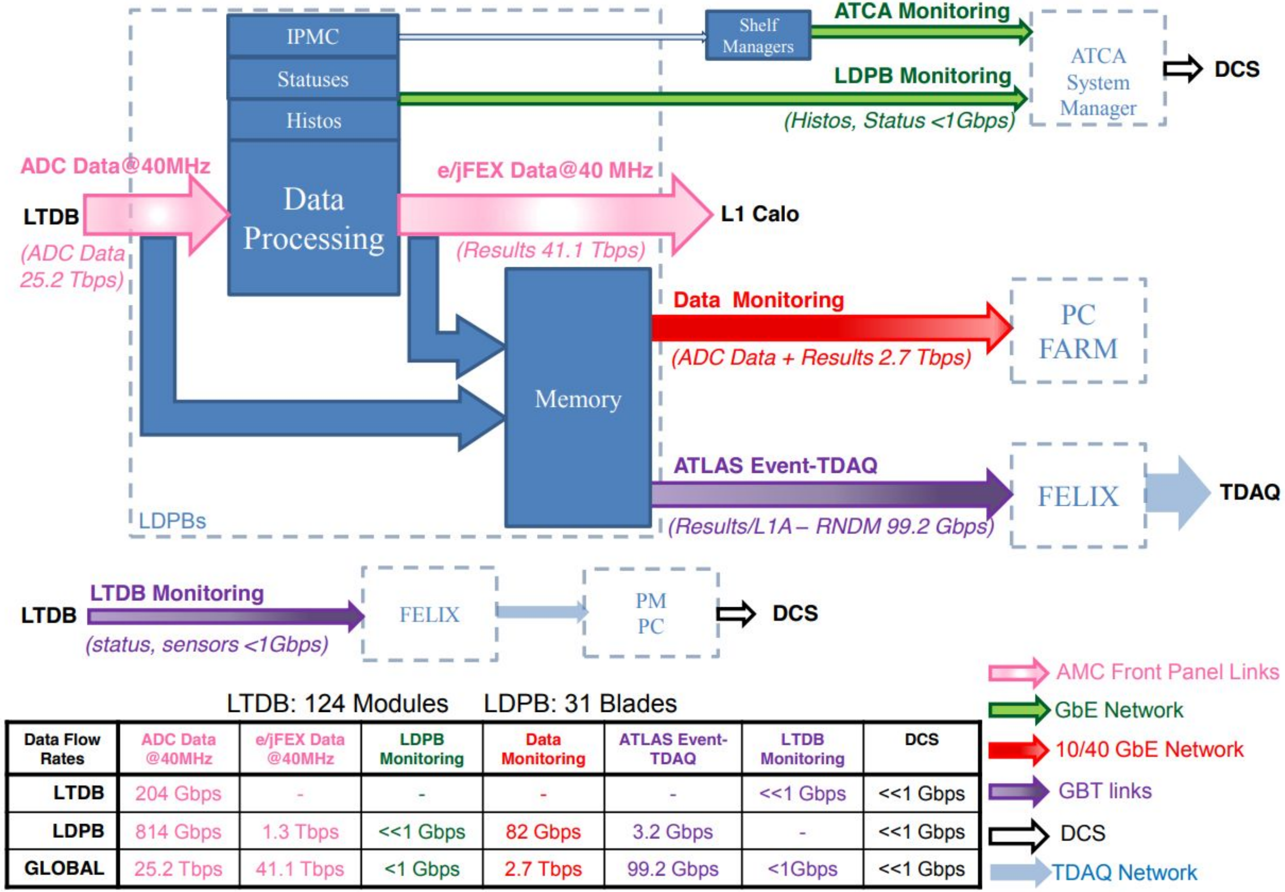
Super cell noise levels

- **Super cells' LSBs** in some regions/layers are quite high.





Data Flow



LTDB: 124 Modules LDPB: 31 Blades

Data Flow Rates	ADC Data @40MHz	e/jFEX Data @40MHz	LDPB Monitoring	Data Monitoring	ATLAS Event-TDAQ	LTDB Monitoring	DCS
LTDB	204 Gbps	-	-	-	-	<<1 Gbps	<<1 Gbps
LDPB	814 Gbps	1.3 Tbps	<<1 Gbps	82 Gbps	3.2 Gbps	-	<<1 Gbps
GLOBAL	25.2 Tbps	41.1 Tbps	<1 Gbps	2.7 Tbps	99.2 Gbps	<1Gbps	<<1 Gbps

Additional ideas for improvement

- **Low pileup OFCs (2-4 instead of 0 pileup?)**
    - Compute pileup noise autocorrelation and add it to pedestal autocorrelation

- **Use 5 instead of 4 samples for energy/time calculation**
    - Might be able to better filter out low energy pulses

- All these studies are being done on data from the 2024 heavy ion run.