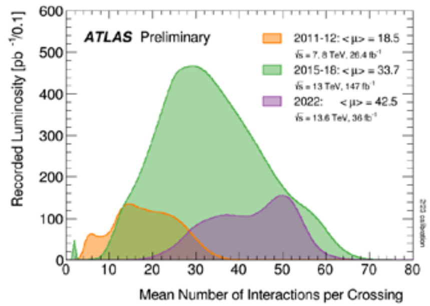
Run 3 Performance of New Hardware in ATLAS

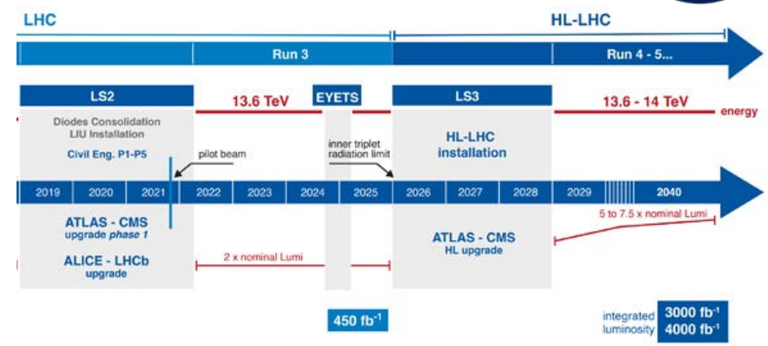
Liang Guan University of Michigan
On behalf of the ATLAS Collaboration

11th Large Hadron Collider Physics Conference, Belgrade, Serbia
23 May 2023

ATLAS new hardware in Run 3

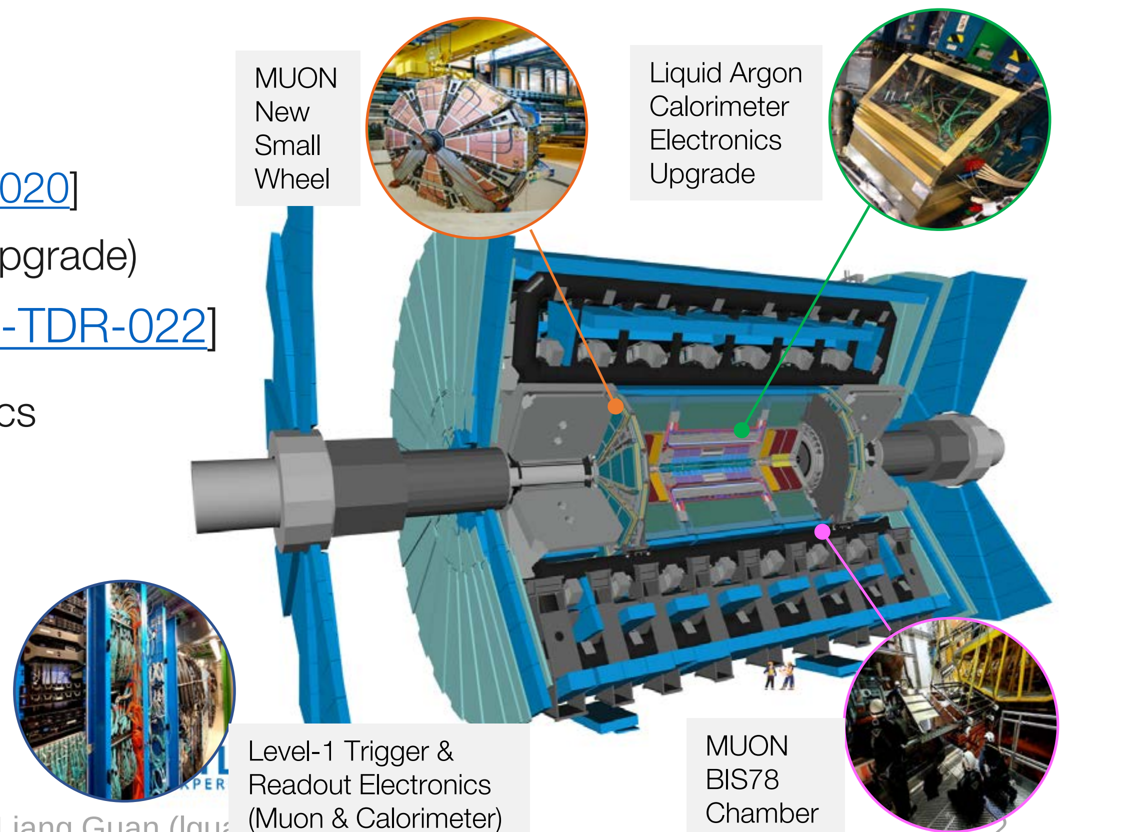
- ATLAS went through major hardware upgrade during LHC Long Shut 2 to improve trigger and maintain excellent detector performance in high pile-up (<μ> more than 60) environment after Run 2.





- Muon Spectrometer
  - New Small Wheel [ATLAS-TDR-020]
  - Barrel BIS78 (pilot for phase-II upgrade)
- Liquid Argon Calorimeter [ATLAS-TDR-022]
  - Front-end & Back-end Electronics
- TDAQ [ATLAS-TDR-023]
  - Level-1 Trigger (Muon & Calo)
  - New readout system (FELIX)

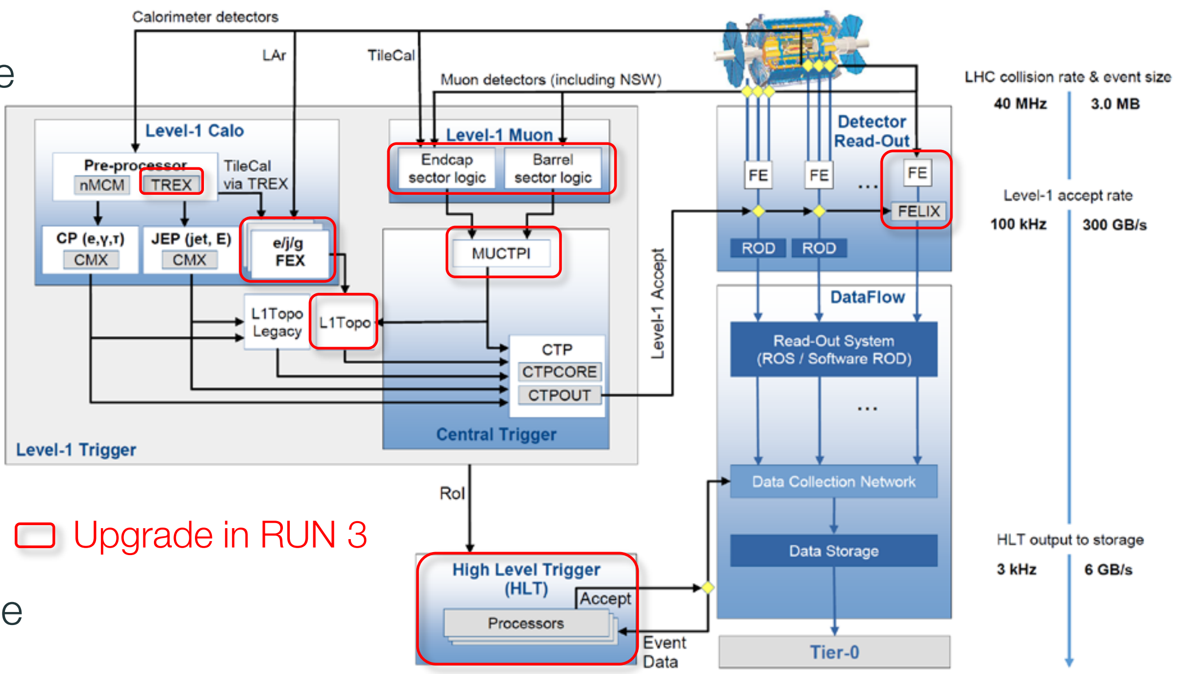
Disclaimer: this is not a full ATLAS detector status report. Focus on new hardware in Run 3.



ATLAS TDAQ upgrade in Run 3

- ATLAS select events based on a multi-level trigger system. Level-1 trigger utilizes custom hardware to accept event up to 100 kHz within a 2.5 μs latency.
- Overview of new TDAQ hardware
  - L1 Calorimeter Trigger
    - ✓ LAr electron/jet/global Feature EXtractors
    - ✓ TREX (Tile Rear Extension)
    - ✓ New L1Topogical trigger
  - L1 Muon Trigger
    - ✓ New Sector Logic
    - ✓ New MUCTPI
  - Readout
    - ✓ New Front-End Link eXchange system (FELIX) + software Readout Driver (swROD)
    - ✓ ROS refurbishment
  - HTL farm upgrade

ATLAS Trigger and DAQ scheme for Run 3

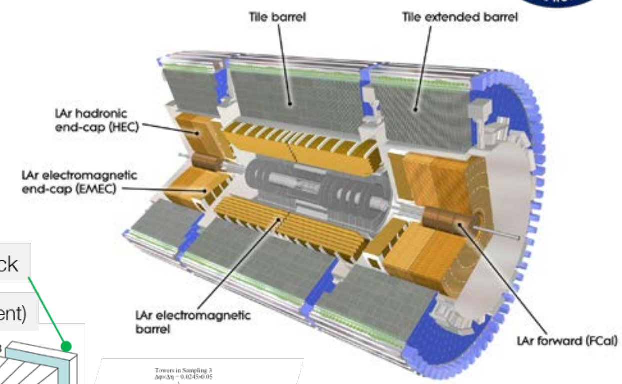


see poster from Ricardo Barrue: The ATLAS Trigger system

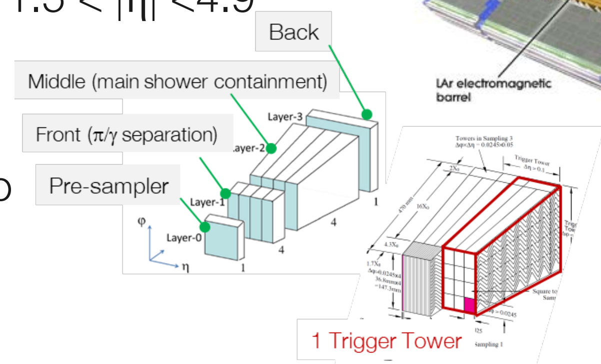
New trigger hardware status and performance to be presented in the following within the context of sub-detector system upgrade

Liquid Argon (LAr) Calorimeter

- Sampling Calorimeter
  - Pb/Cu/W absorber + LAr ionization detection layers
  - EM Calorimeter in Barrel (EMB) & Endcap (EMEC) $|\eta| <3.2$
  - Hadronic Endcap (HEC) and Forward (FCAL) $1.5 < |\eta| <4.9$
  - Typical 4-layers. In total ~180k channels to provide E_T measurements.
  - Grouped into ~5.4k Trigger Towers & input to ATLAS Level-1 trigger.

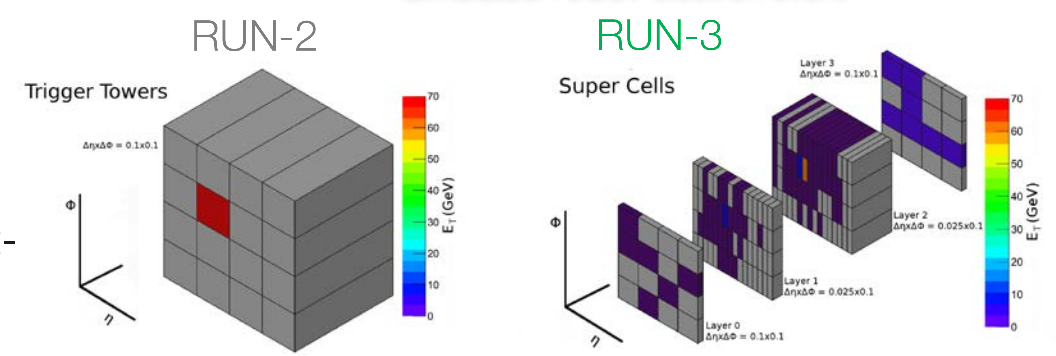


Cut view of the ATLAS Calorimeter



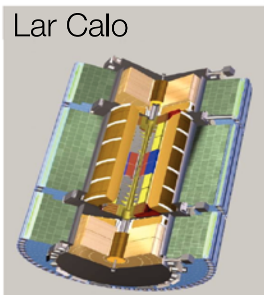
- LAr Phase-I upgrade during LHC LS2:
  - Essential improvement to the level-1 trigger at higher instantaneous luminosity and severe pile-up environment after Run-2. Increase the readout granularity in the LAr front and middle layers by factor ~10 -- From coarse trigger tower to ~34k trigger "supercells".
  - Allow to enable shower shape discrimination for improved single object (e,γ,τ,jets) identification.
  - on-detector digitization (increased readout channels) + advanced reconstruction algorithms and event-by-event pile-up subtraction on backend FPGA (digital trigger)

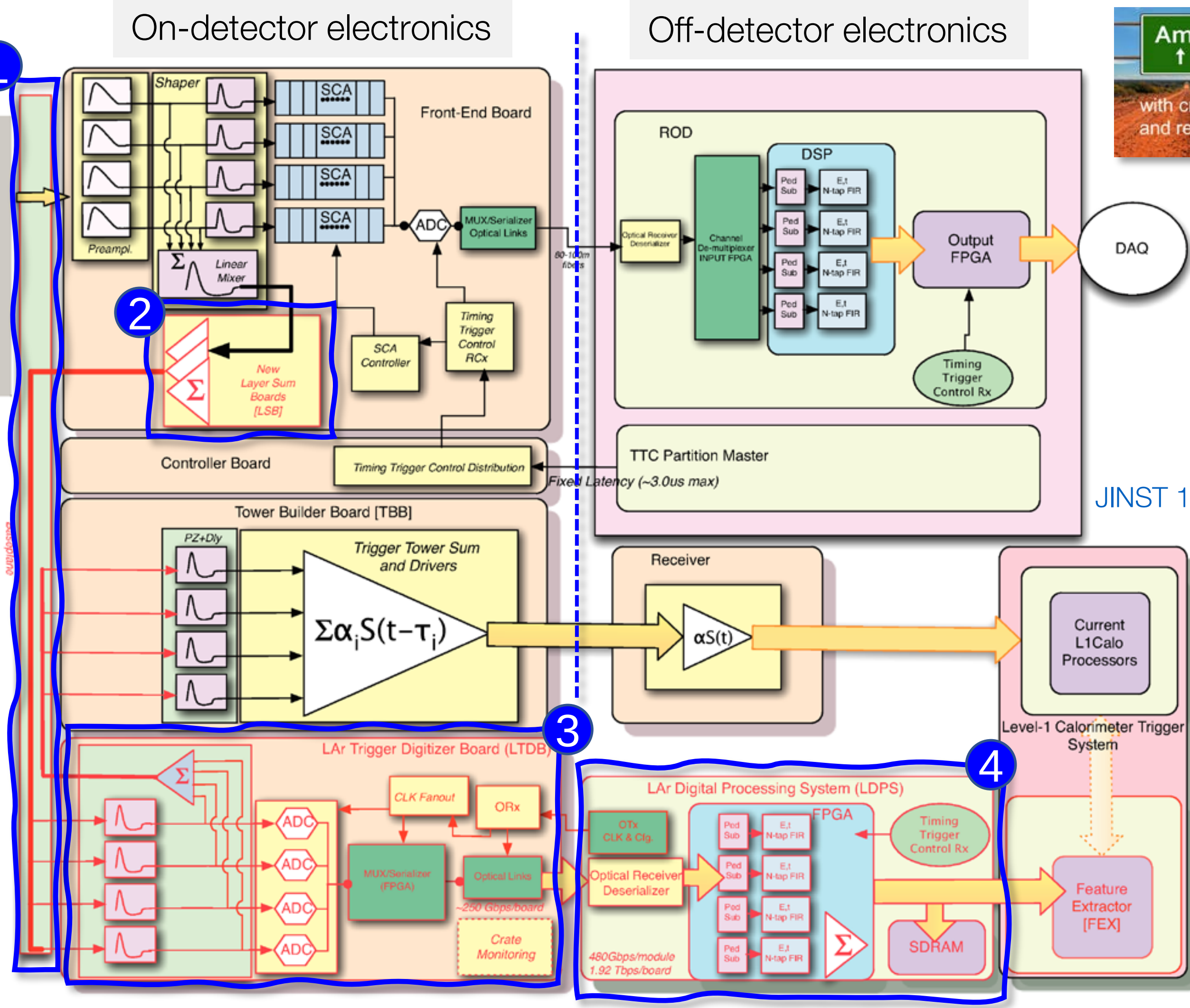
Simulated 70GeV electron event



LAr readout electronics upgrade

- Both legacy analog-based and phase-I digital trigger electronics run in early Run-3.



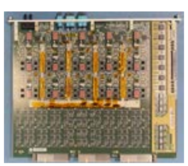


JINST 17 P05024

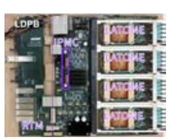
1. 114 New Baseplanes: handle increase signal traces

2. 2968 New Layer Sum Boards: summing signal from supercells

3. 124 LTDB: digitize supercell signals and shift data off detector for level-1 trigger



4. 116 LDPS: reconstruct E_T and time for input to L1Calo trigger



see poster from Mars Lyukova: ATLAS LAr Calorimeter Commissioning for LHC Run-3

LAr new digital electronics performance

- All digital trigger electronics installed, connected and commissioned during LS2. 99.7% supercells active and 98.5% in good condition (no noise and linearity issues).
- Accurate reconstruction of E_T and time from digitized signal pulses (sampled @ 40MHz) relies on dedicated supercell-dependent calibrations (baseline, linearity, optimal filtering coefficient etc.).

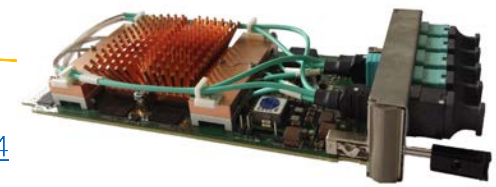
Optimal filtering coefficients — Pedestal — Baseline (pile-up dependent)

$$E_{Tj} = \sum_{i=0}^{N} a_i (S_j^i - P_j - BL_j^i)$$

$$E_{Tj} \cdot \tau_j = \sum_{i=0}^{N} b_i (S_j^i - P_j - BL_j^i)$$

Signal peak (ADC)

i: signal samples
j: supercell-id

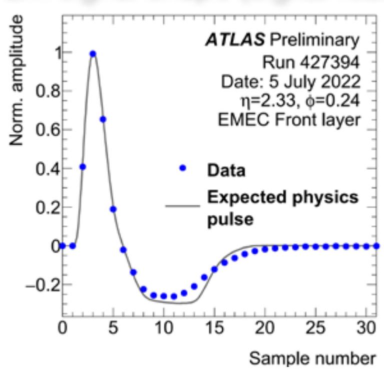


LAr Trigger prOcessing Mezzanine (LATOME)
JINST 17 P05024

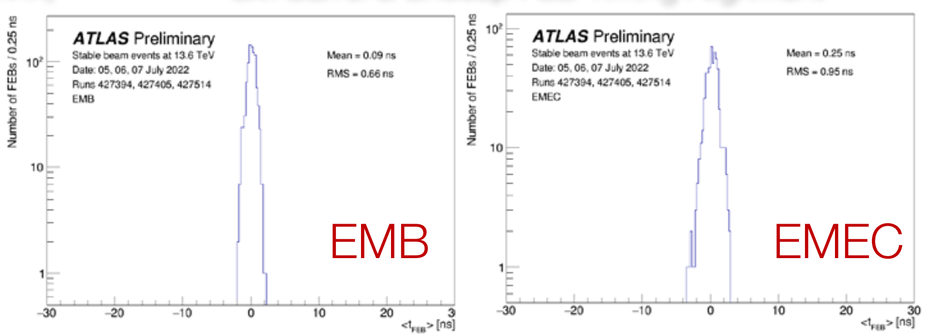
- Validation of Front-end Boards:
  - well-understood signal shape reconstruction.
  - good timing alignment (at BC & ns fine-time level)

LAr digital trigger in ATLAS TDAQ partition

EM signal shape (digital readout)



EM Barrel & Endcap FEB Timing Alignment

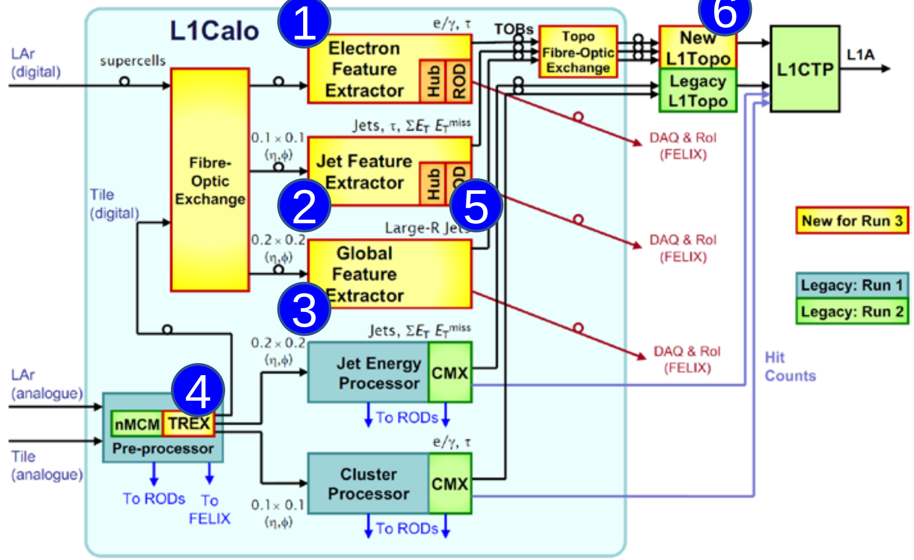


ATLASLArCaloPublicResults-2022

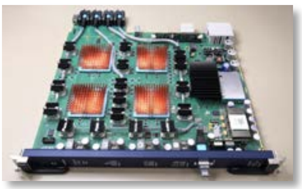
L1Calo new trigger electronics

- FPGA-based ATCA modules for Run 3 to process fine-granularity information from LAr digital trigger board and Tile Calorimeter. Fast and complex trigger algorithms. Optical link interconnections with high throughput.

Level-1 Calorimeter trigger scheme in Run 3

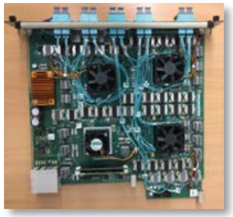


1. 24 electron Feature EXtractor (eFEX): e,γ,τ identification

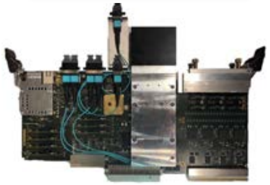


2. 6 jet Feature EXtractor (jFEX): for τ, large/small-R jets, $E_T^{missing}$

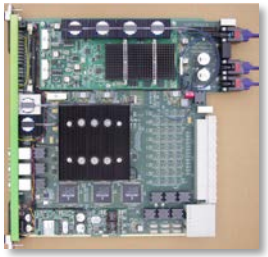
3. 1 global Feature EXtractor (gFEX): receives input from the entire calorimeter system for large-R jets, $E_T^{missing}$



4. 32 VME Tail Rear Extension Module (TREX): digitized TailCal signal to FEX (optical) & legacy system (electrical)



5. HUB+ROD: interface to send trigger readout to FELIX system. Resides in the same shelf as FEX modules for TTC distribution.

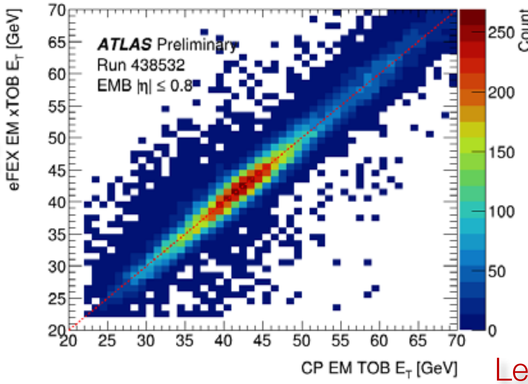


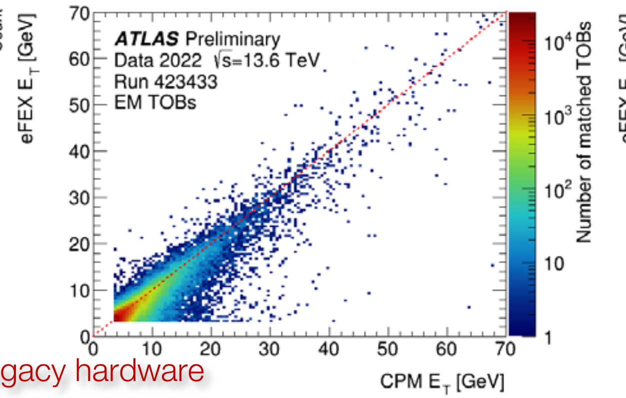
6. New L1 Topological trigger (L1Topo): multiplicity counting & multi-object based topological trigger.

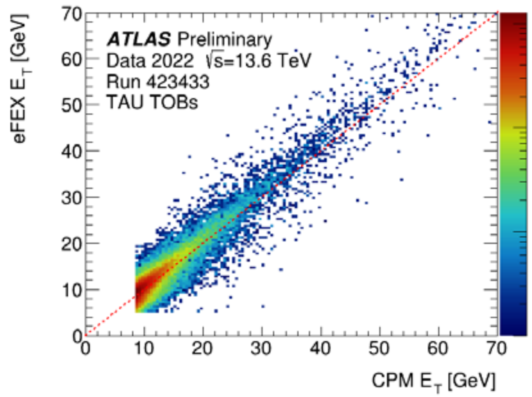
LAr Level-1 trigger performance

- Validation of new LAr trigger ongoing with √s=13.6 TeV collision data ongoing.
- Comparisons between legacy and the Phase-I system: good agreement on single electron trigger efficiency. good match on the reconstructed trigger objects (TOBs)

Phase-I new trigger hardware



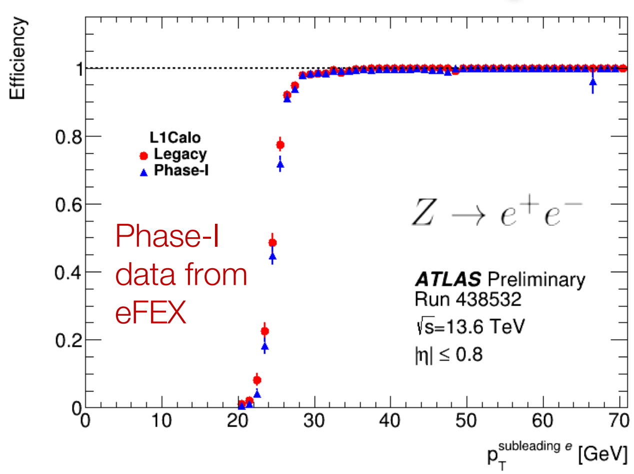


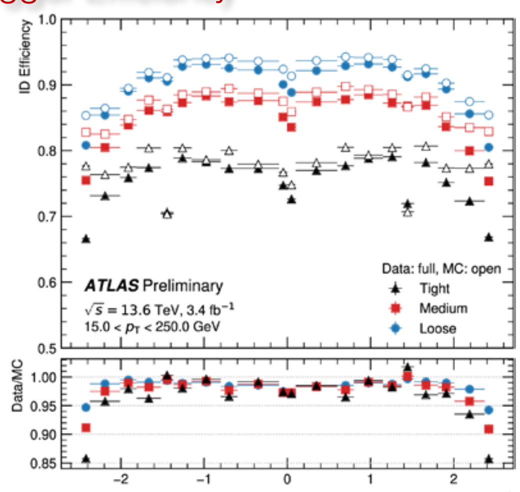


Legacy hardware

ATLAS-L1CaloTrigger-PublicResults

Single Electron Trigger Efficiency

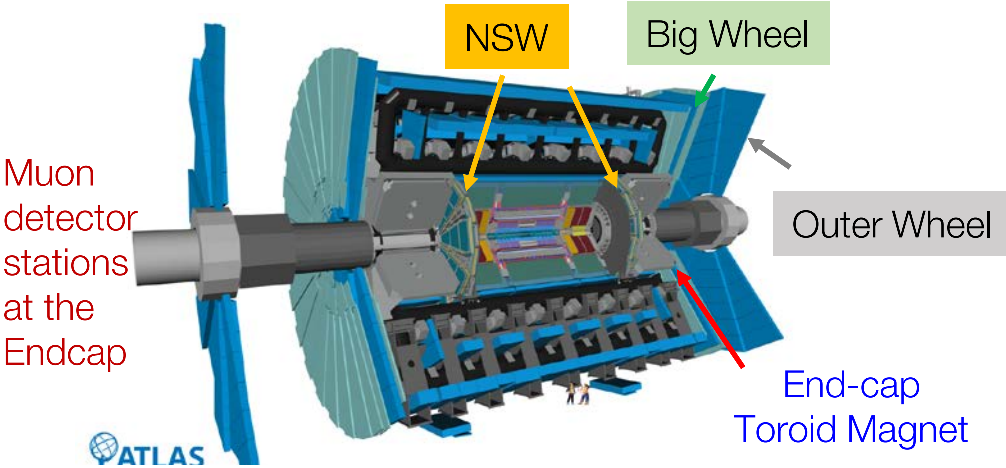




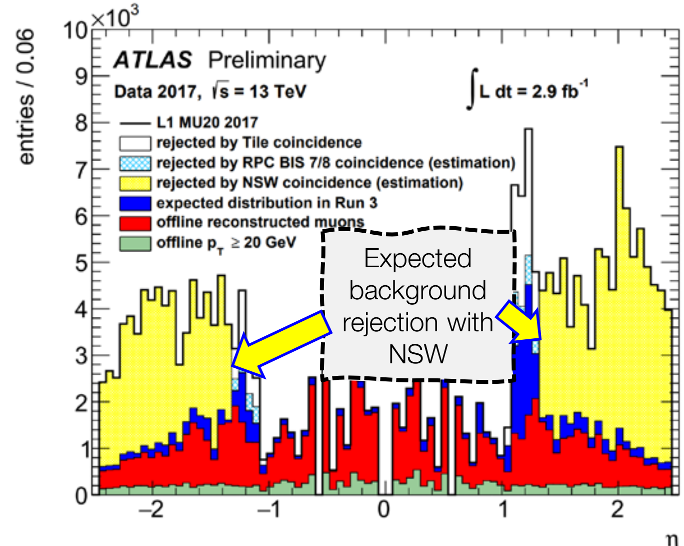
- Continuous improvement on monitoring, stability and firmware.
- To be used as main trigger in 2023

Muon New Small Wheel (NSW)

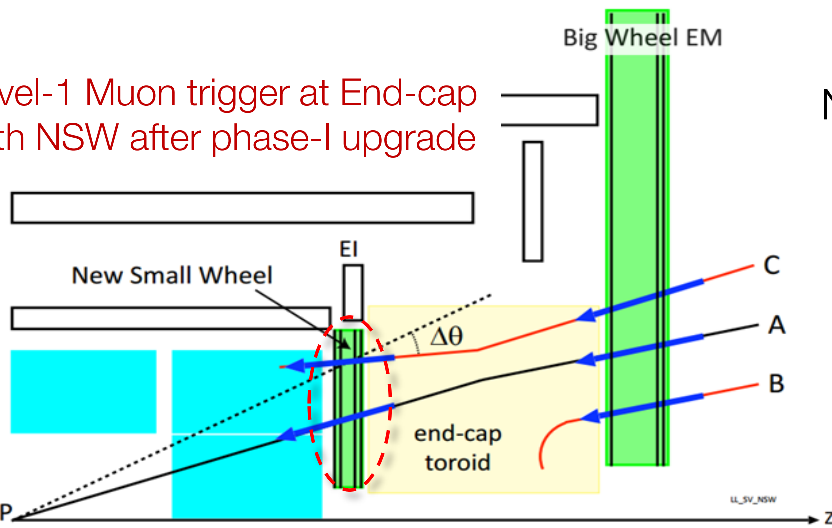
- Innermost Muon station in the forward region replaced with completely new detector to provide muon trigger and tracking with high background rates (up to 20 kHz/cm²) towards HL-LHC runs.



Expected Level-1 muon trigger rate reduction w. NSW



Level-1 Muon trigger at End-cap with NSW after phase-I upgrade



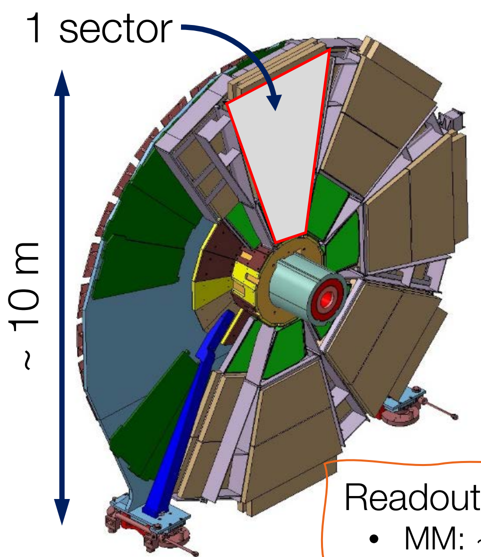
NSW- to meeting phase-I & phase-II upgrade goals:

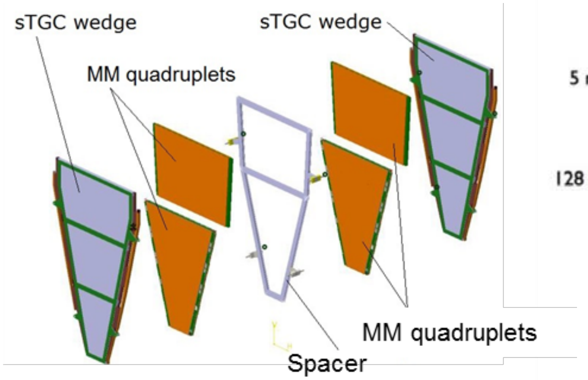
- Offline muon construction: 15% p_T resolution at ~1TeV/c. 97% segment reconstruction efficiency for muon p_T >10 GeV/c.
- Online (Level-1) triggering: segments measurements with up to 1 mrad pointing accuracy (Phase-II requirement)

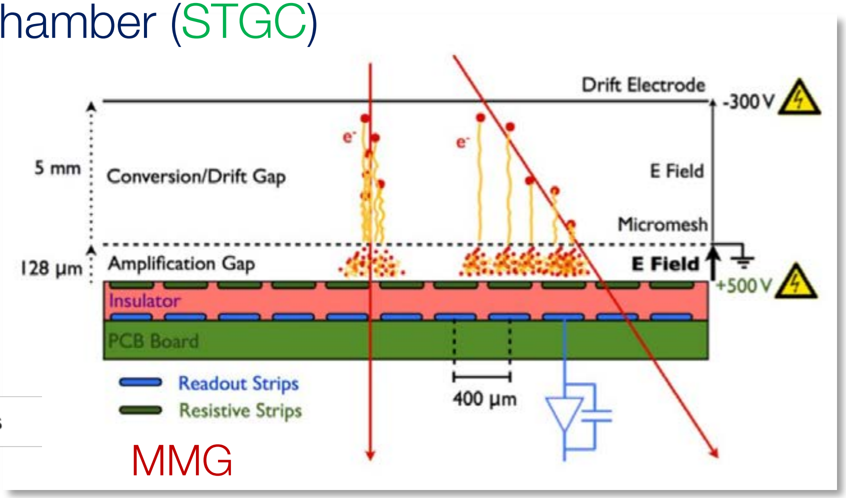
Muon NSW detector

- Two Novel Gaseous Detector Technologies Employed:
  - Resistive Micromesh Gaseous Structure, Micromegas (MMG)
  - Resistive cathode Small-strip Thin Gap Chamber (STGC)

First time construction of large area MMG

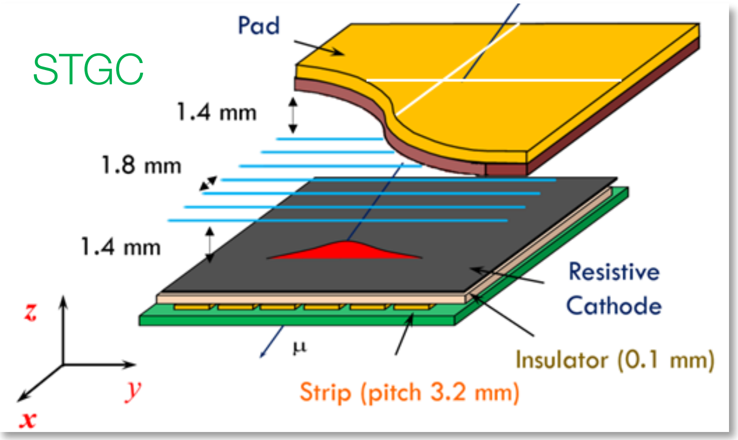






Readout channels (25x replaced system):
- MM: ~ 2.1M
- sTGC: ~ 280k (strip) + 46k (pads) + 28k (wires)

Detector area: ~2400m^2

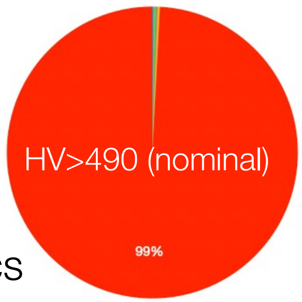


- Both detector technologies provide precision trigger ($1.3 < |\eta| < 2.4$) and tracking ($1.3 < |\eta| < 2.7$) for muons in the ATLAS forward region.

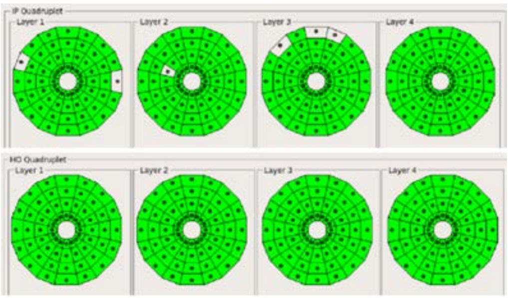
NSW detector and electronics status

- 99% MMG and 98% STGC HV channels could hold nominal HV with working gas components. MMG Ar:CO2:iC_4H_{10} (93:5:2); sTGC CO_2:n-pentane (55:45).

MMG HV general status



STGC HV Status side C

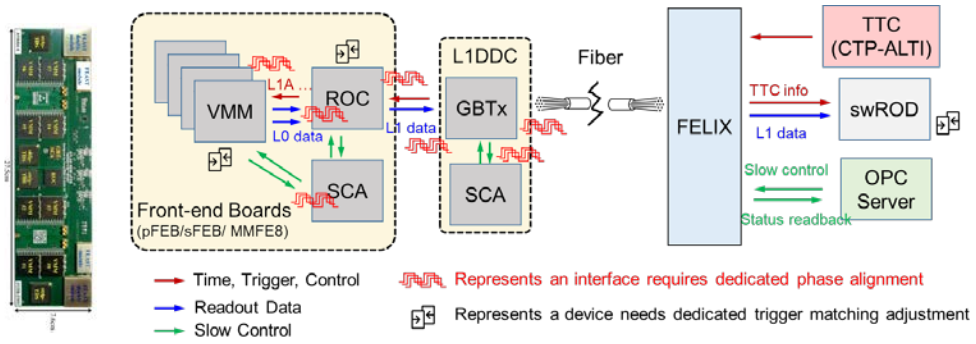


- Cooling and Low Voltage to Front-end electronics operational since start of Run 3.

Caveat: occasional purging of cooling loop needed. ~2% LV modules failed in 2022 and replaced during Year-End Technical Stops

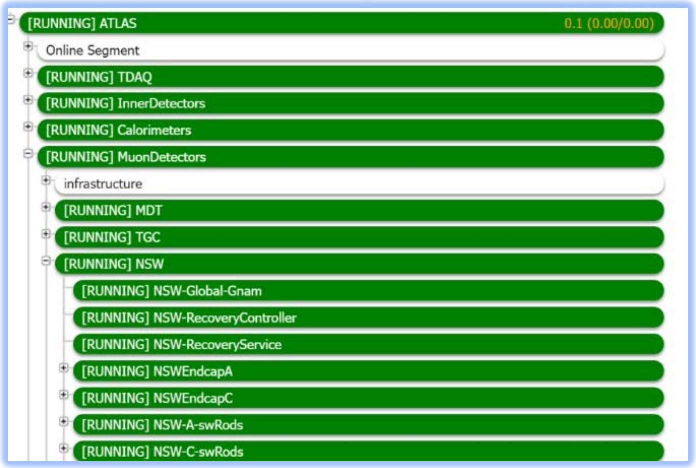
- NSW uses more than 50k radiation-tolerant Front-end ASICs with 70+ million configuration registers! Calibrations are sophisticated and vital.

NSW Front-end ASIC phase calibration scheme



- NSW employs new generation DAQ for ATLAS Run-3: FELIX + software Read Out Driver. Slow control via OPC servers.

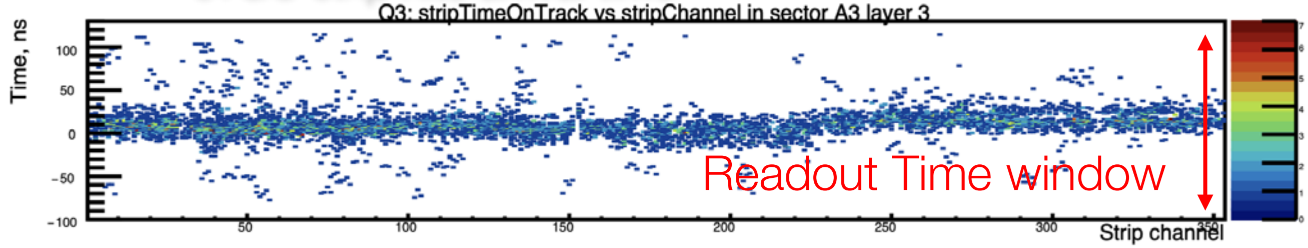
Both NSWs in ATLAS DAQ partition for data-taking



Muon NSW preliminary performance

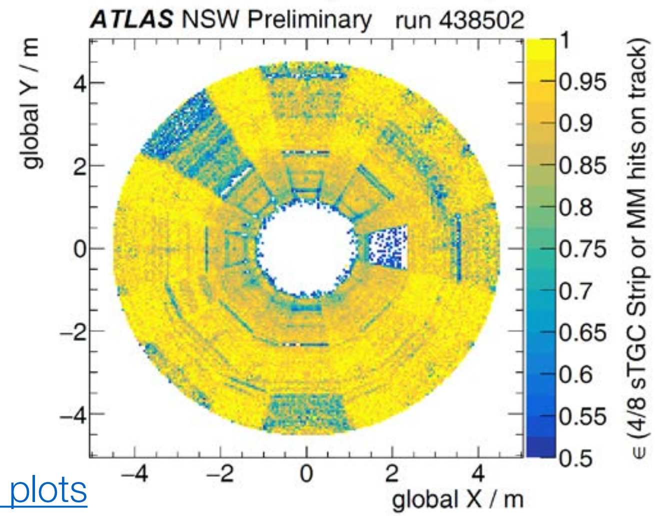
- All NSW (MMG and sTGC) detector readout channels are timed-in after the tunning with 2022 collision data.

sTGC strip hits arrival time



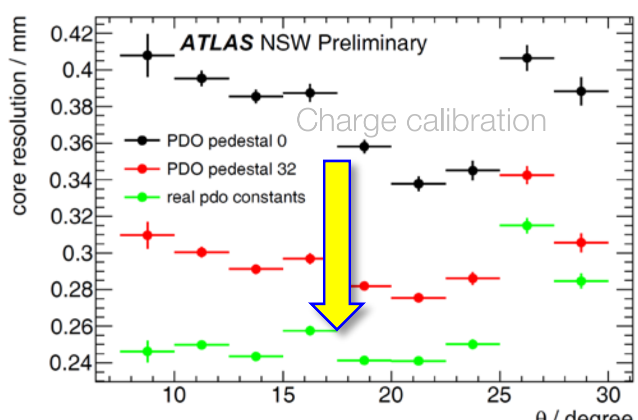
- Detector efficiency in (first!) 2022 runs: > 95% for functional regions. However, significantly affected by DAQ instability at high trigger rate, LV failures, and lost of optical link (known weak point with VTRx electronics)

NSW tracking efficiency



- Large improvement anticipated in 2023 due to significant improvement of DAQ stability, refurbishment of Front-end electronics during 2022 Year-End-Technical-Stop.

sTGC residual resolution

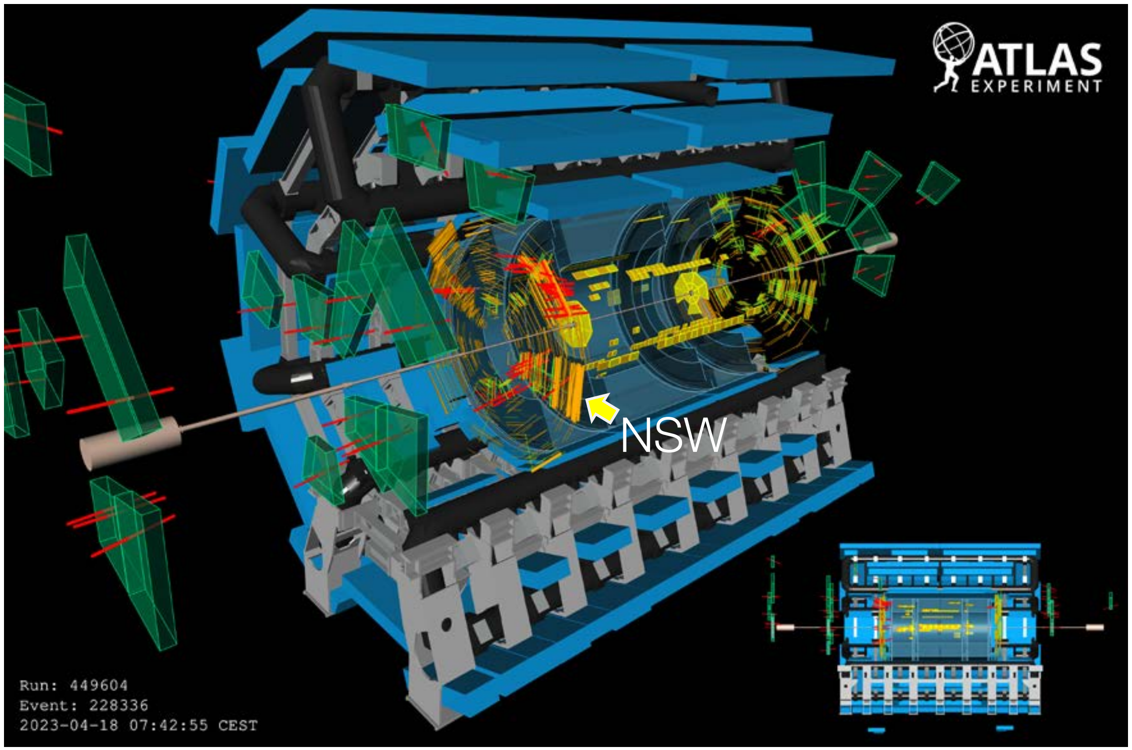


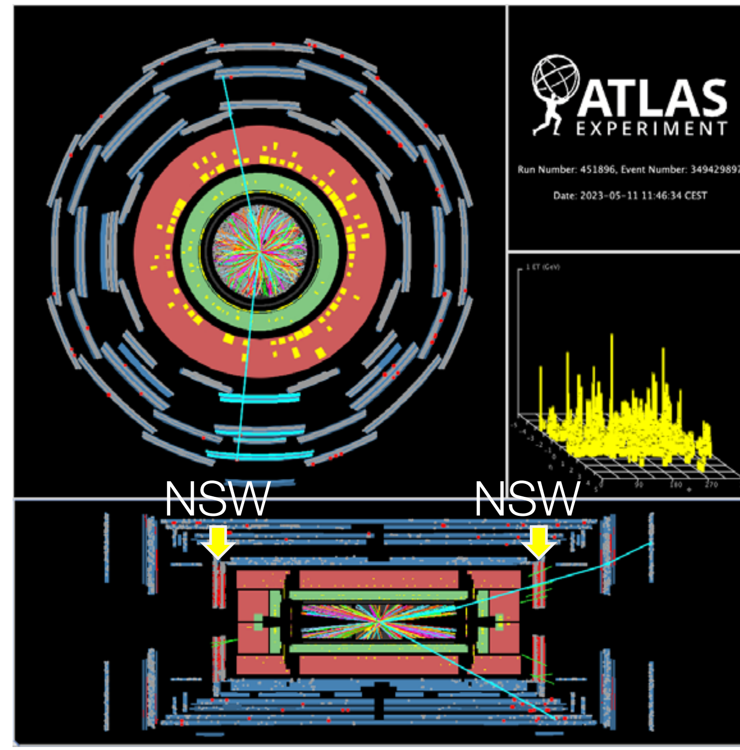
More NSW Performance plots

- Initial look at the sTGC residual resolution for muons (P_T>15GeV/c) from a 2022 run without any systematic alignment correction and dedicated cluster reconstruction. Further studies on going.

Muon NSW in the ATLAS event display

Segments reconstructed by NSW during special commissioning beam run with Horizontal muons (parallel to beam pipe) April 2023



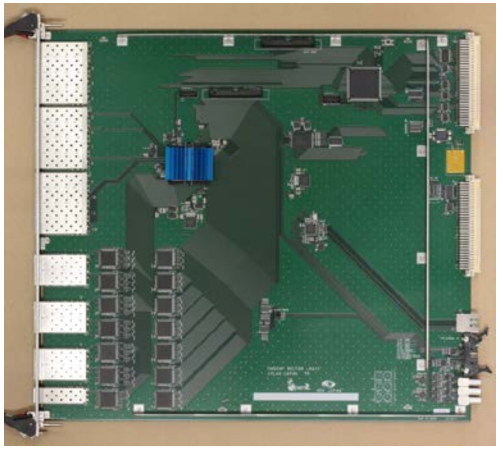


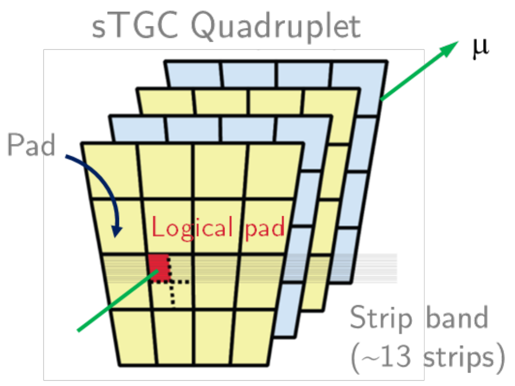
Display of di-muon event recorded with NSW segments at the first 2400 bunch run in May 2023

Muon Level-1 trigger at Endcaps

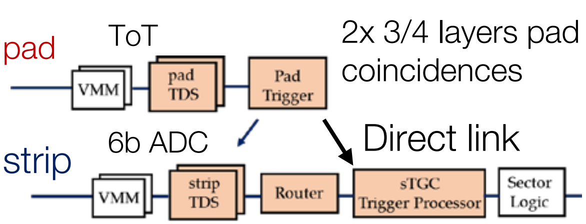
- New Endcap Sector Logic Board commissioned to accept trigger input from new muon hardware (NSW & BIS78) and Tile Calorimeter.
- Commissioning of NSW trigger chain to join the Muon Big wheel (BW) for Level-1 triggering ongoing with a step-wise integration and activation plan.
- NSW sTGC pad coincidences will be first commissioned with the aim to provide trigger this year to reduce single muon fake trigger rate (goal: 8 kHz reduction).
- All (32) pad trigger boards and NSW trigger processors operational. Active participation of special commissioning beam runs. Validation of trigger LUT, optimization of timing and coincidence parameters with BW ongoing.

New Muon Sector Logic Board



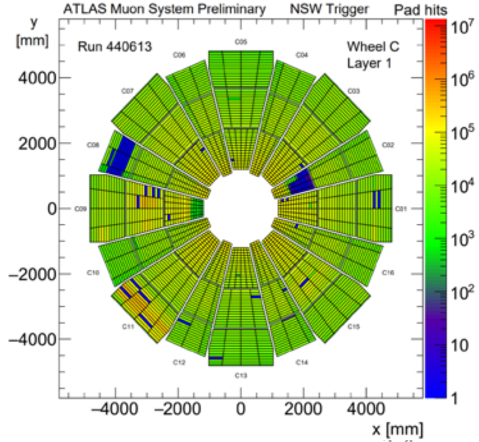


NSW sTGC Trigger Path



TDS: trigger data serialize ASIC for trigger data preparation, strip-pad match

1 layer pad occupancy

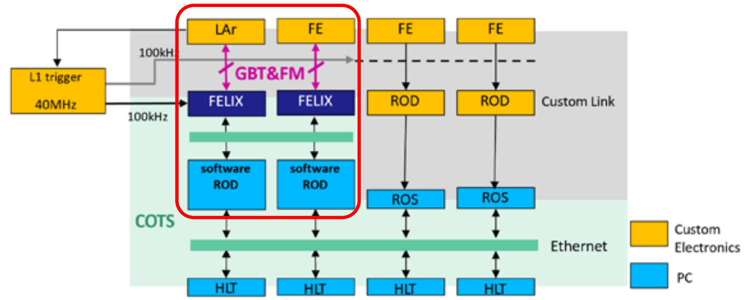


Status of new readout system

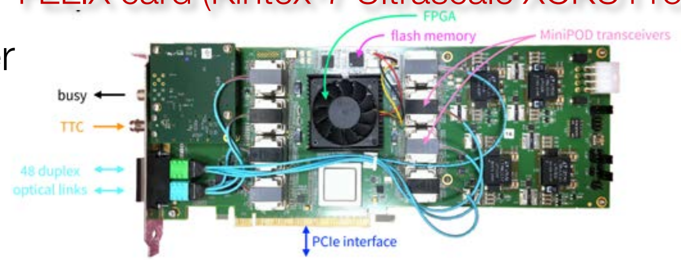
- ATLAS Run 3 takes data with a mixture of the legacy and new readout system.
- New Front-end Link eXchange (FELIX) system: custom FPGA-based PCIe card running on commodity computers. Acts as a router between the Front-end and the readout data processing hardware & software.
- Software Readout-Driver (swROD): builds and buffers Level-1 event fragments before hand the data over to the High-Level Trigger (HLT) system.
- New readout system used by all phase-I hardware trigger data monitoring or event readout.

- Performance and status
  - LAr digital trigger: stable w. 0.2% busy fraction
  - L1Calo: a few known issues (dropping packets at beginning of high rate run etc.) addressed w. workaround
  - NSW: most demanding due to large number (20k+) of links and complexity in front-end electronics architecture. Significant improvement at the beginning of 2023 to allow readout at 100 kHz trigger rate.

ATLAS RUN-3 Data Acquisition System



FELIX card (Kintex-7 Ultrascale XCKU115)



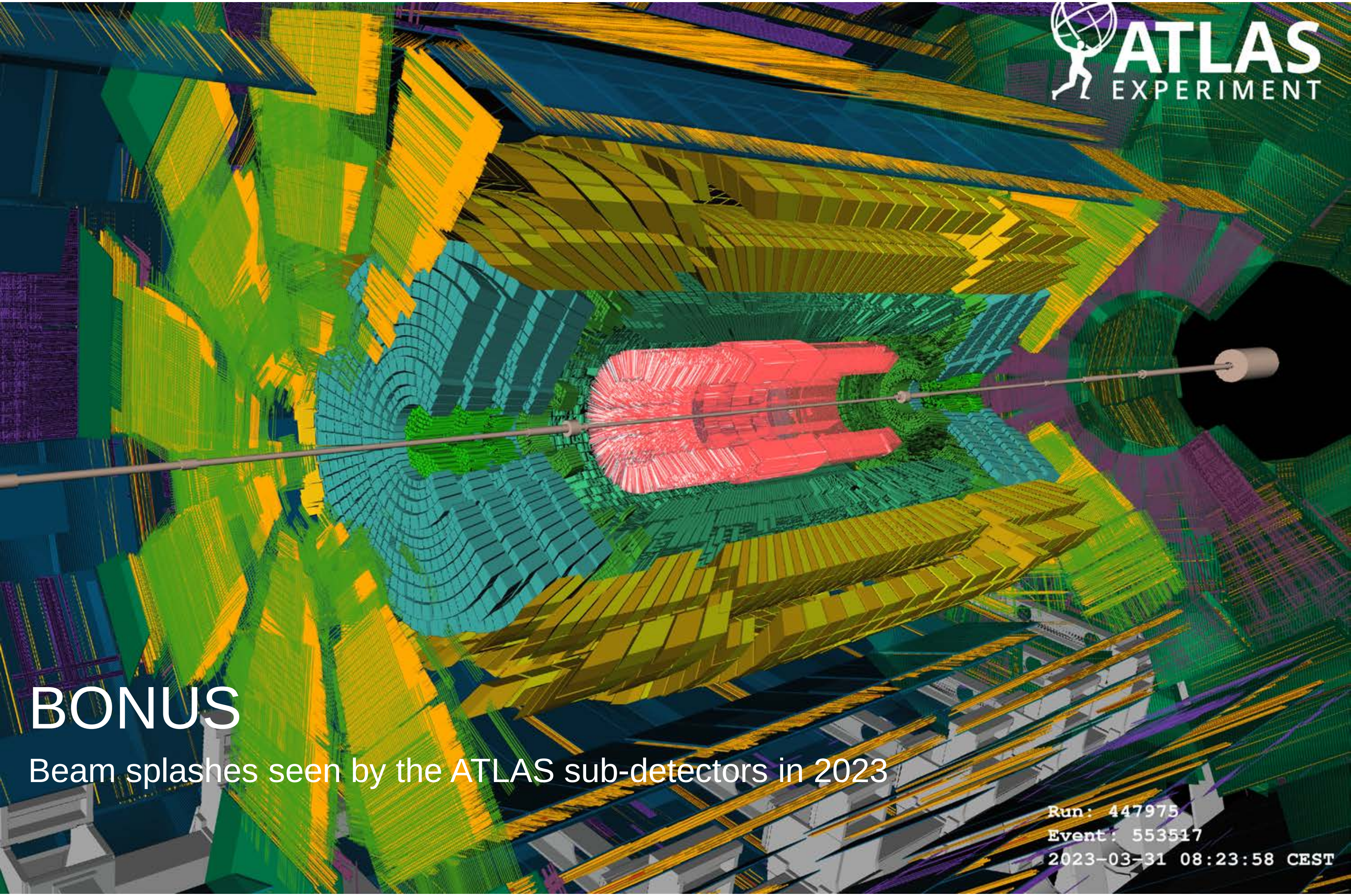
LAr digital trigger readout with swROD

Conclusions

- ATLAS detector made major upgrade to enhance its trigger capability and maintain its excellent performance at higher pile-up environments after Run-2:
  - Phase-I upgrade to innermost muon station at Endcaps (New Small Wheel): high-rate precision muon detectors for both muon trigger and tracking in decades.
  - Phase-I upgrade to LAr electronics with higher readout granularity
  - Phase-I upgrade to L1 Muon and Calo trigger, readout system
- All phase-I new hardware are going through intensive commissioning phase and participate in the Run 3 data-taking. LAr/L1Calo well advanced. NSW improvement to DAQ and performance ongoing. NSW trigger to be activated step-wise with attempt to include sTGC pad trigger this year.
- The successful upgrade is essential to maximize the physics potential of the ATLAS towards Run 3 and beyond.

and

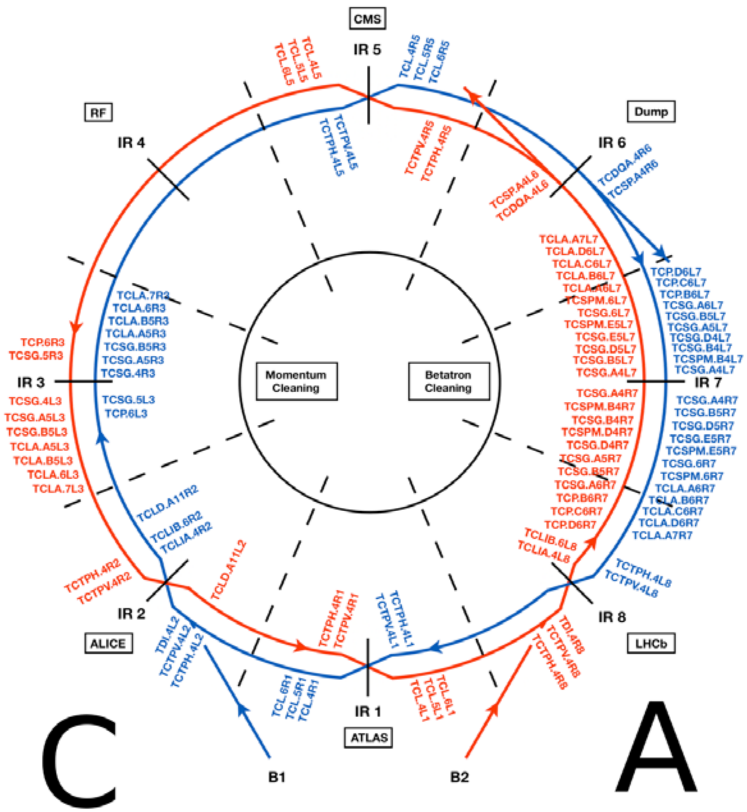
ahead



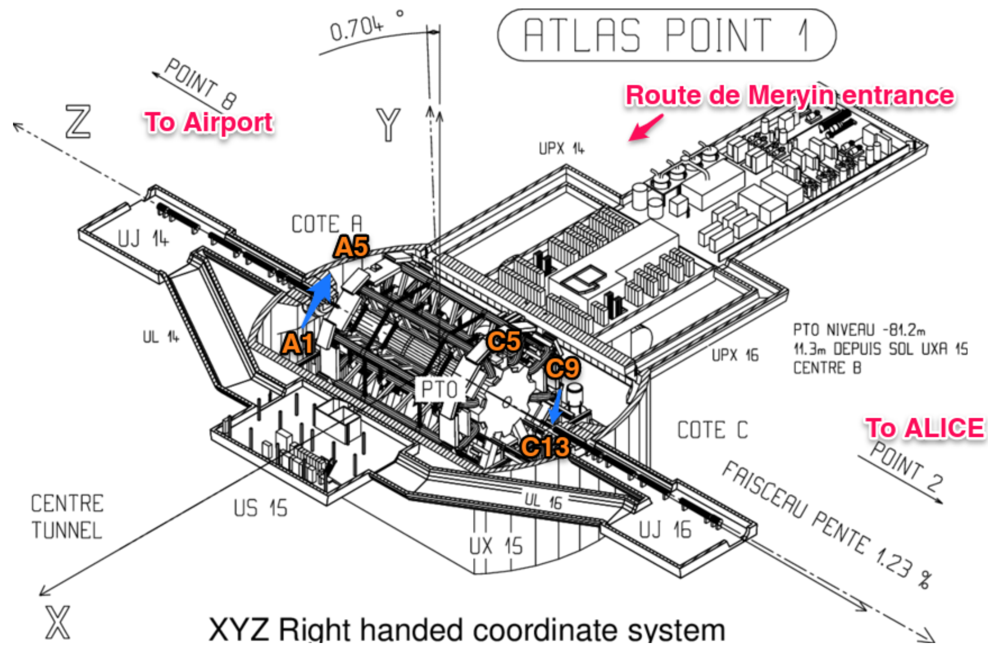
BONUS

Beam splashes seen by the ATLAS sub-detectors in 2023

Backup



LHC Beam



ATLAS Coordinate System

Backup: LAr Phase-I upgrade motivation

The Super Cell trigger readout of the LAr Calorimeter upgrade enables the use of shower-shape variables for a more effective identification of electrons, photons and tau lepton, and sharpening the EM, jet, and missing-E_T turn-on curves.

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:

$$R_\eta = \frac{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.175\times0.2}} \qquad (1)$$

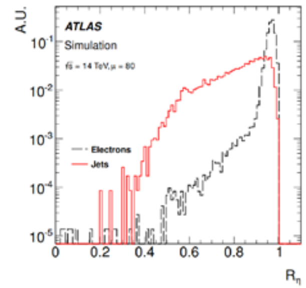
f_3 The ratio of the transverse energy measured in the back EM layer (3) in an area of size $\Delta\eta\times\Delta\phi = 0.2\times0.2$ to that deposited in all three layers for an EM cluster; the energies in the front (1) and middle (2) EM layers are reconstructed in the area $\Delta\eta\times\Delta\phi = 0.075\times0.2$:

$$f_3 = \frac{E^{(3)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.2\times0.2}}{E^{(1)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times0.2}+E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times0.2}+E^{(3)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.2\times0.2}}. \qquad (2)$$

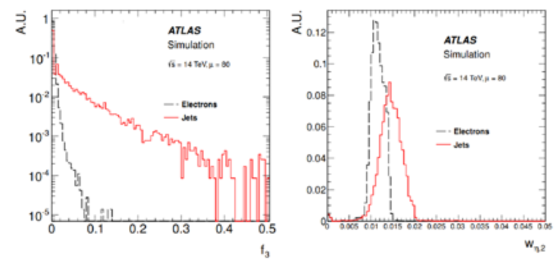
$w_{\eta,2}$ The spread of the shower in the middle EM layer (2) in a 3×2 Super Cell region, defined as:

$$w_{\eta,2} = \sqrt{\frac{\Sigma\left(E^{(2)}_{\mathrm{T}}\times\eta^2\right)_{\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times0.2}} - \left(\frac{\Sigma\left(E^{(2)}_{\mathrm{T}}\times\eta\right)_{\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{\mathrm{T},\Delta\eta\times\Delta\phi=0.075\times0.2}}\right)^2}, \qquad (3)$$

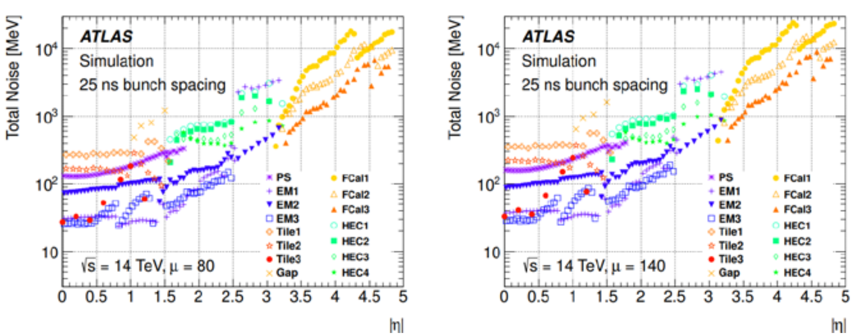
where the sums run over the Super Cells.

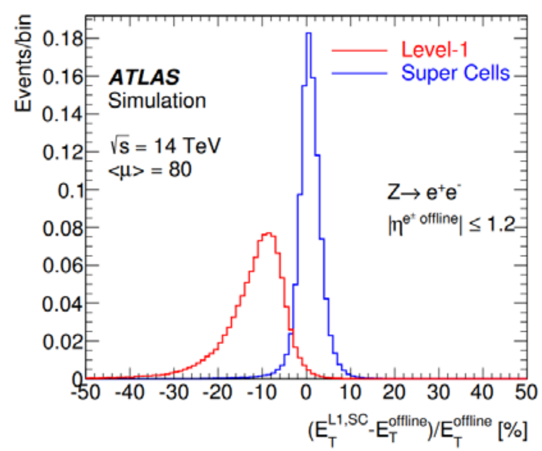


(a)



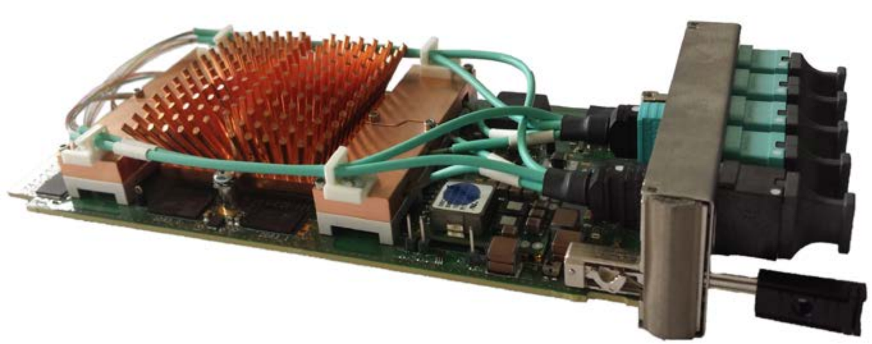
Simulated Pile-up cell noise (mu=80,140)

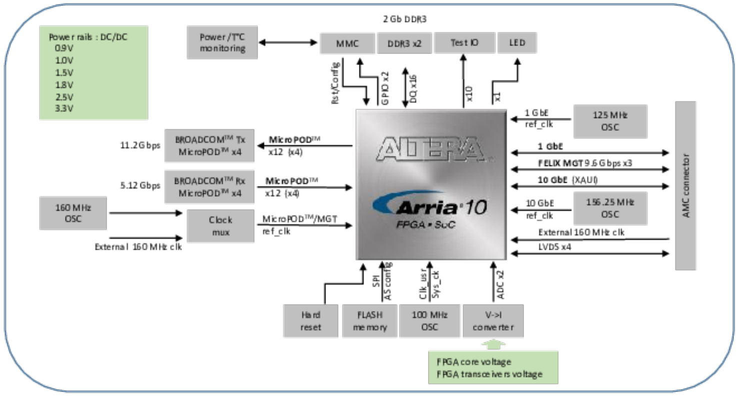


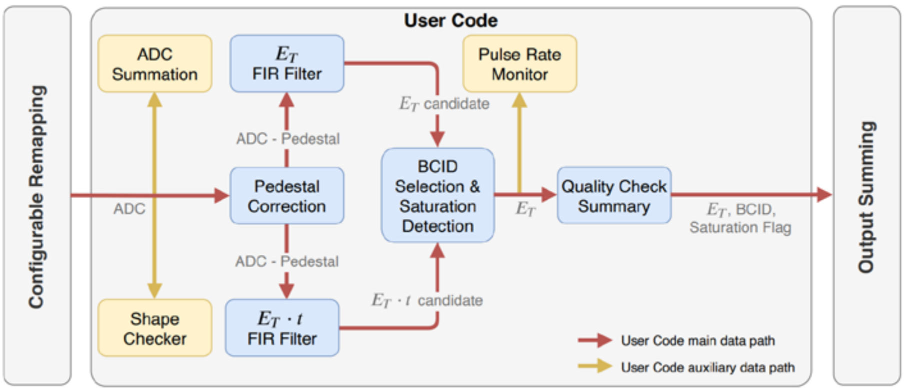


From LAr Phase-I upgrade TDR [ATLAS-TDR-022]

Backup: LAr E_T and time reconstruction



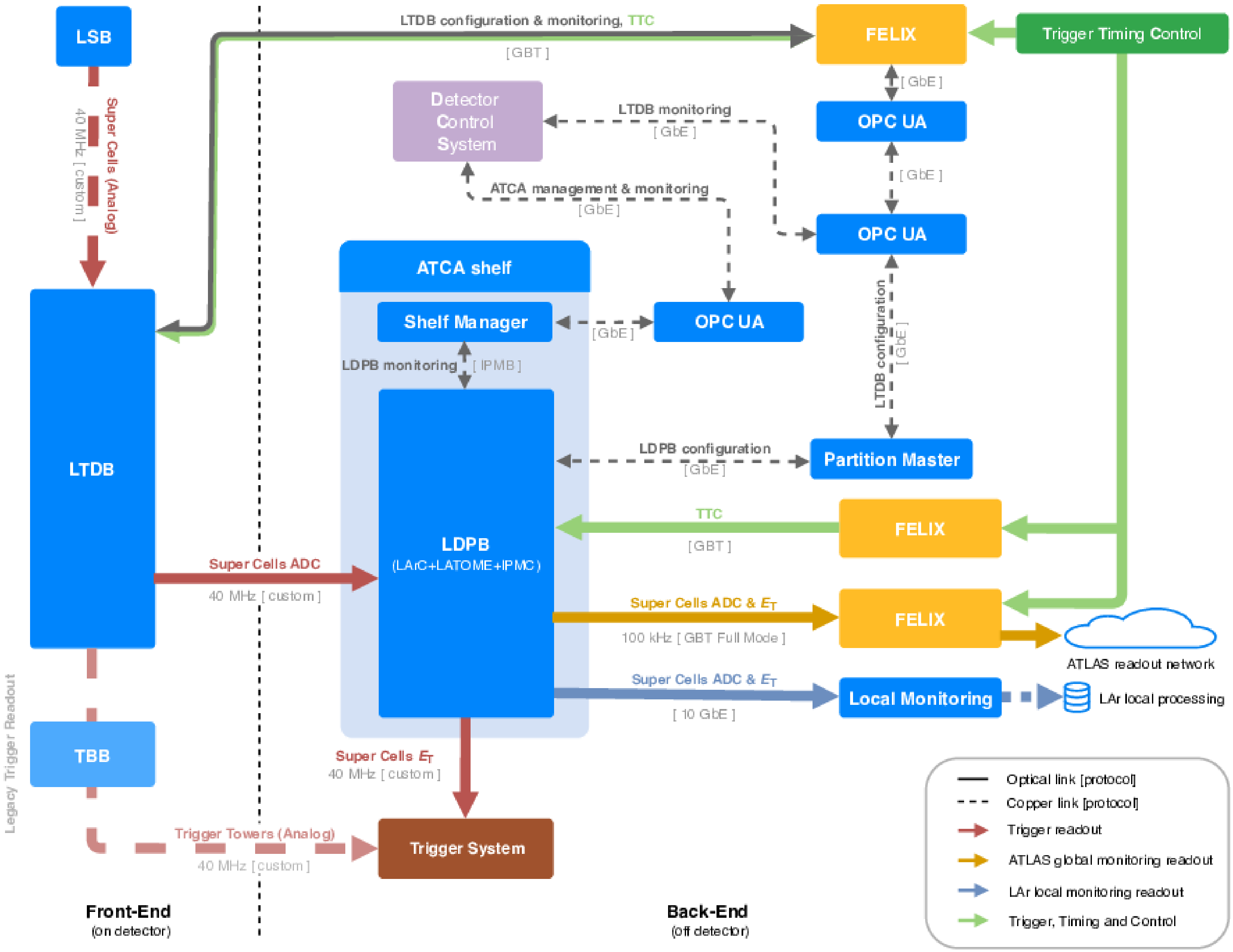




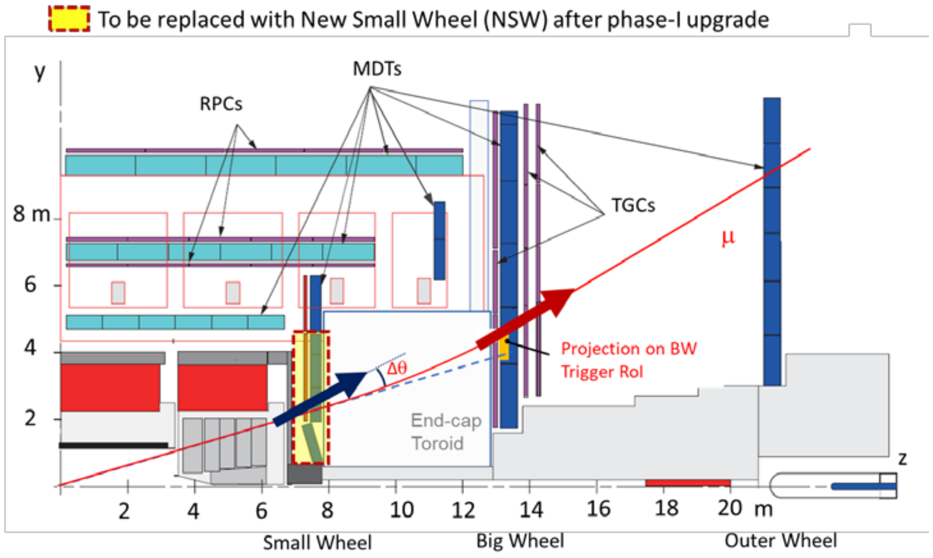
Category	Block	Description
Main-Path	BAS	Cancel out baseline shift
	FIR, SAT	Calculate transverse energy with optimal filtering
	SEL	Extract timing of energy deposition
	COM	Treatment for saturation pulses
Sub-Path	SUM	Calculate the sum of ADC data for 1 LHC cycle
	ADC, PEAK	Detect a pulse peak by using ADC shape and energy

R. Oishi 2020 JINST 15 C05013

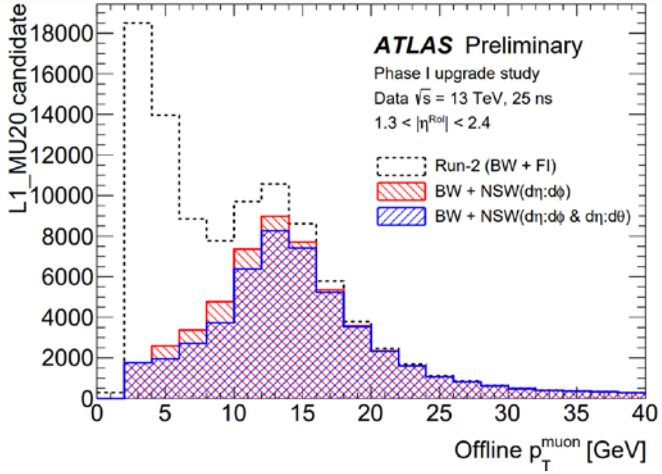
Backup: LAr digital trigger scheme



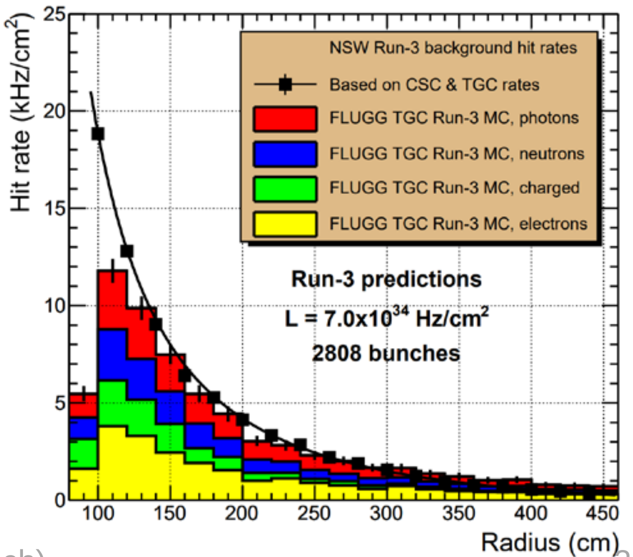
Backup: NSW trigger and rates



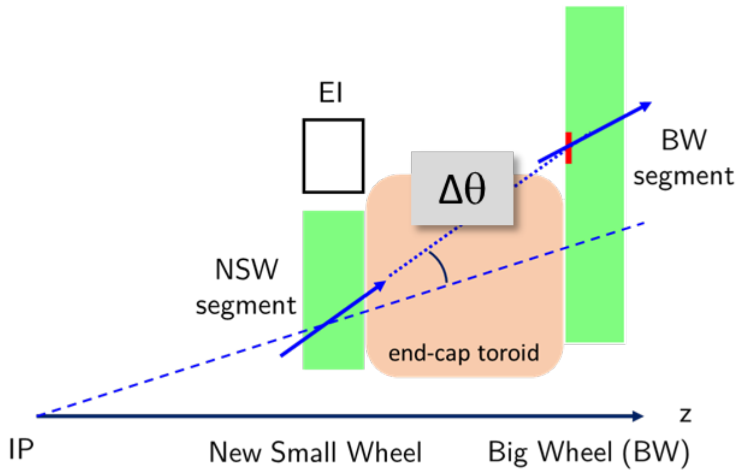
Expected low p_T fake rejection with NSW

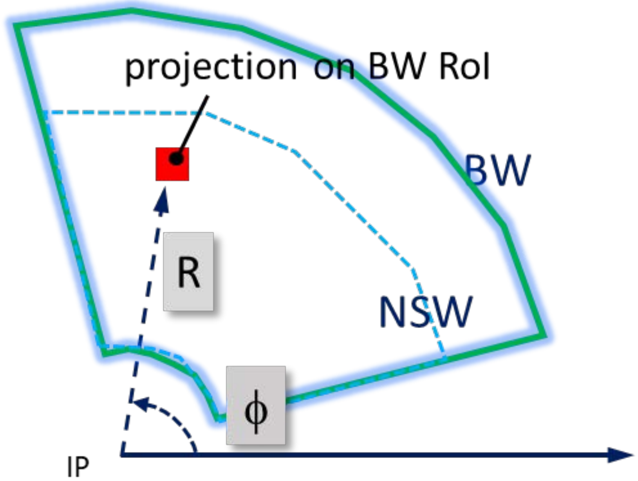


Simulated NSW rate at HL-LHC runs



Backup: NSW trigger primitives





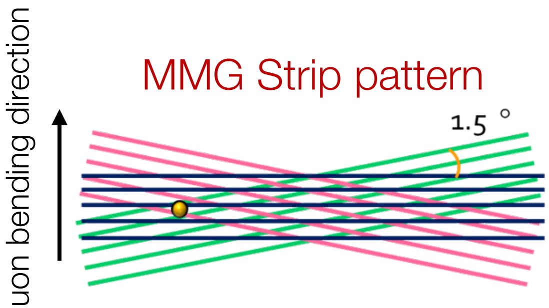
Segment pointing — Projection on BW RoI

Data format for 1 segment

Field	sTGC hit	MM hit	Δθ (mrad)	ϕ index	R index	Spare
#. of bits	2	2	5	6	8	1
		Resolution:	1 mrad	20 mrad	0.005 (η)	

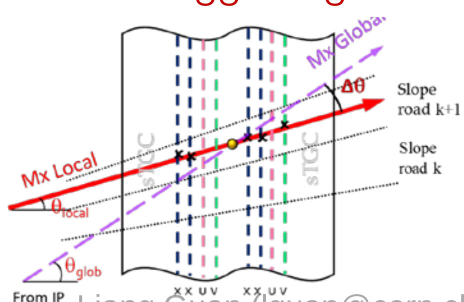
- MMG Trigger Concept: reconstruct slopes pointing to IP based on addresses of earliest threshold-crossing strips among multiple layers.

MMG Strip pattern

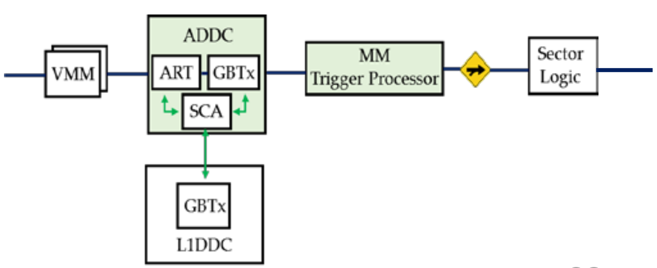


x: horizontal strip (2 plans per quad.)
u,v: stereo strip (1 each per quad.)

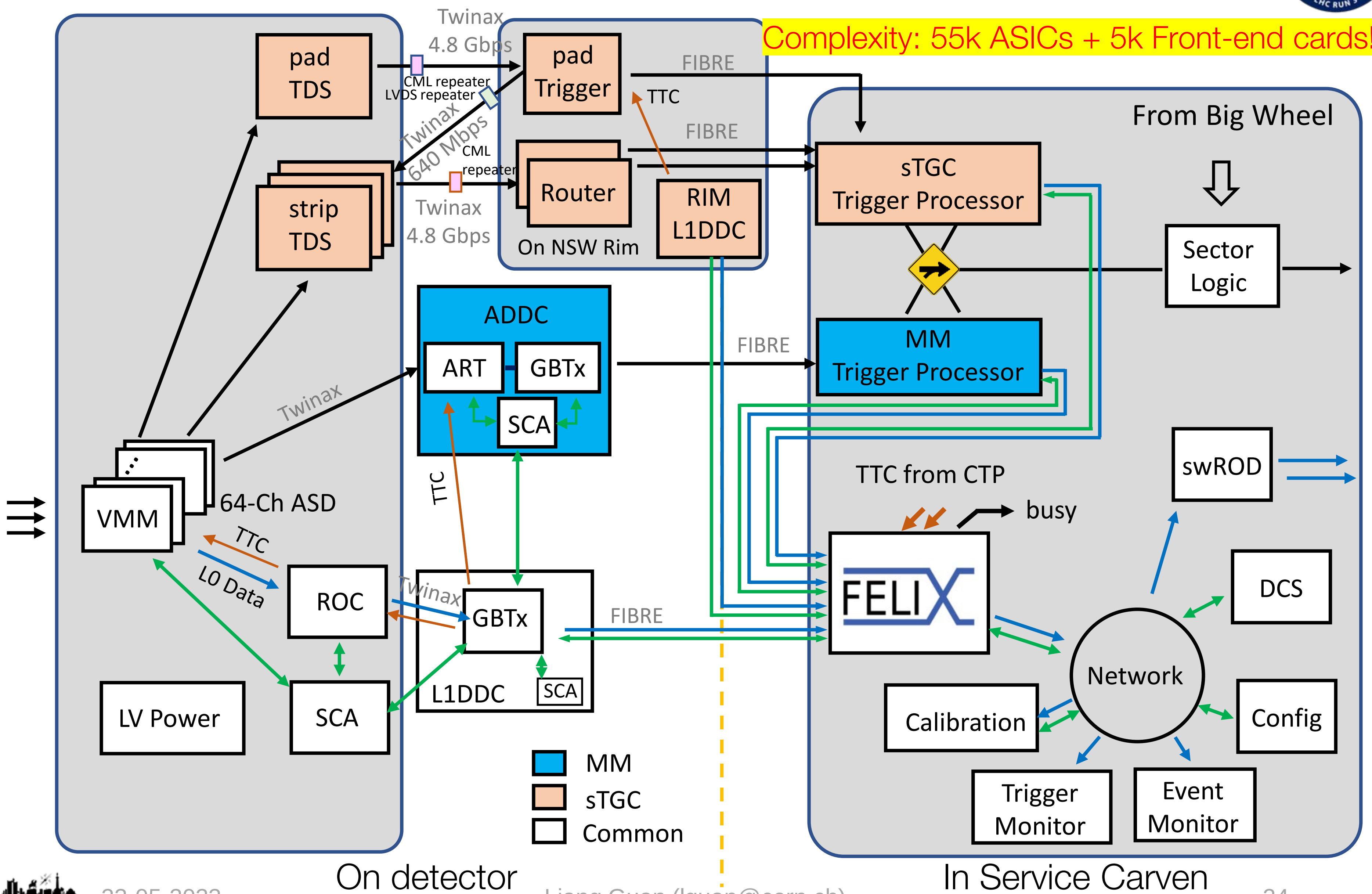
MMG Trigger Algorithm



MMG Trigger Path

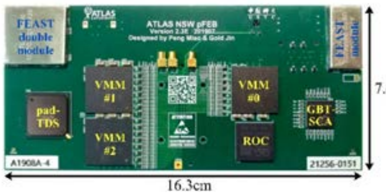


Introduction: NSW Electronics

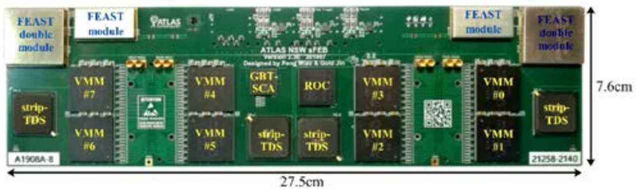


Backup: NSW Front-end Electronics

pFEB



sFEB



Pad Trigger Board

Rim L1DDC

8x Router