The global Feature Extractor: Hardware Triggers for Jets in Run 3 and Beyond

August, 18th, 2022
BOOST
Emily Smith

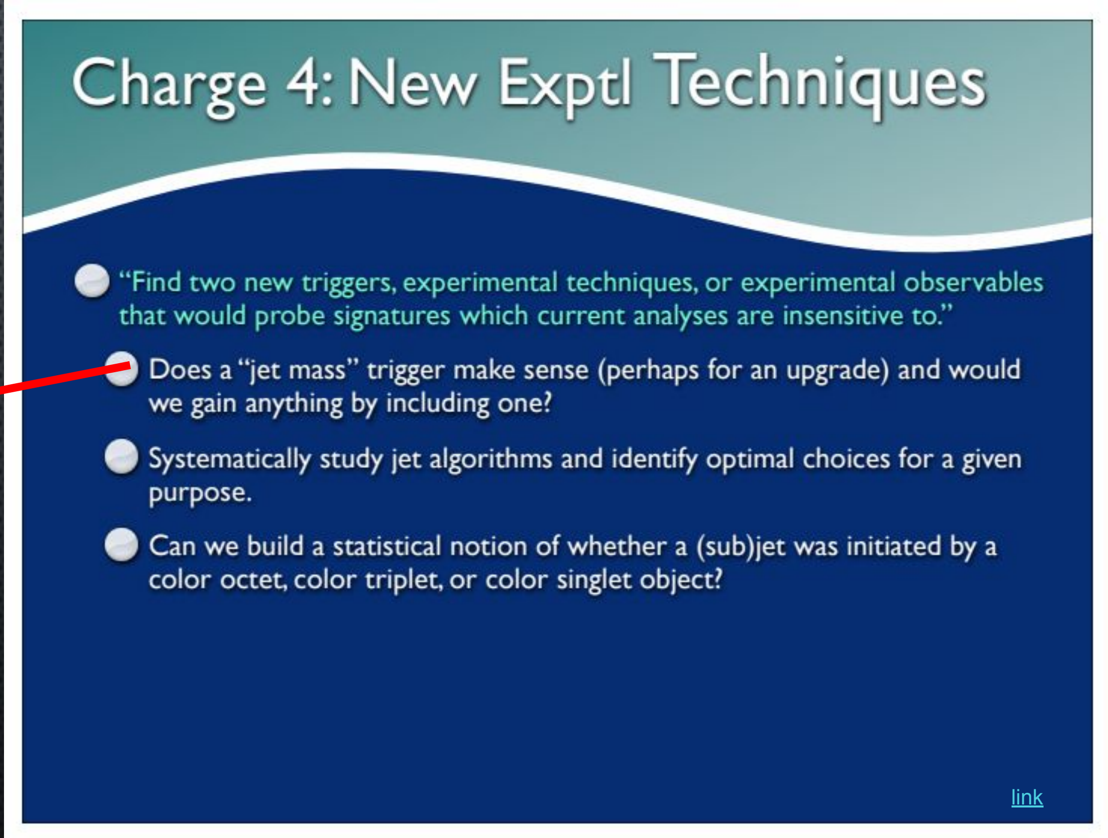
Triggering on Boosted Objects

“jet mass” trigger mentioned in 2009 BOOST

YES!

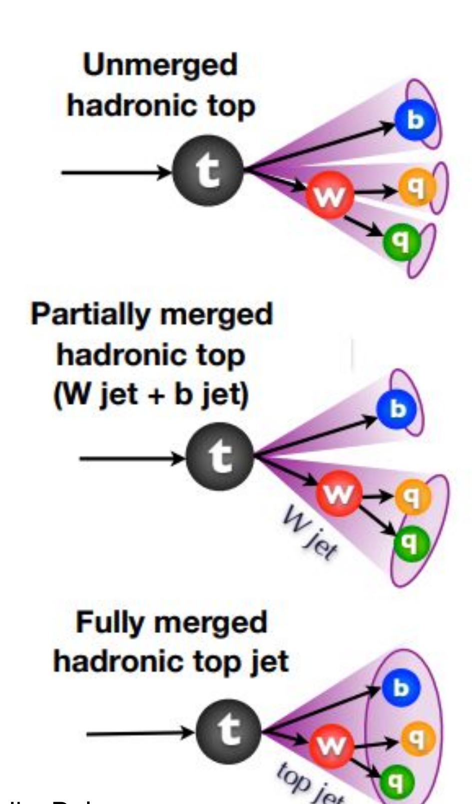
implemented in Run 2 at the software level

Can we target boosted objects in the hardware trigger?



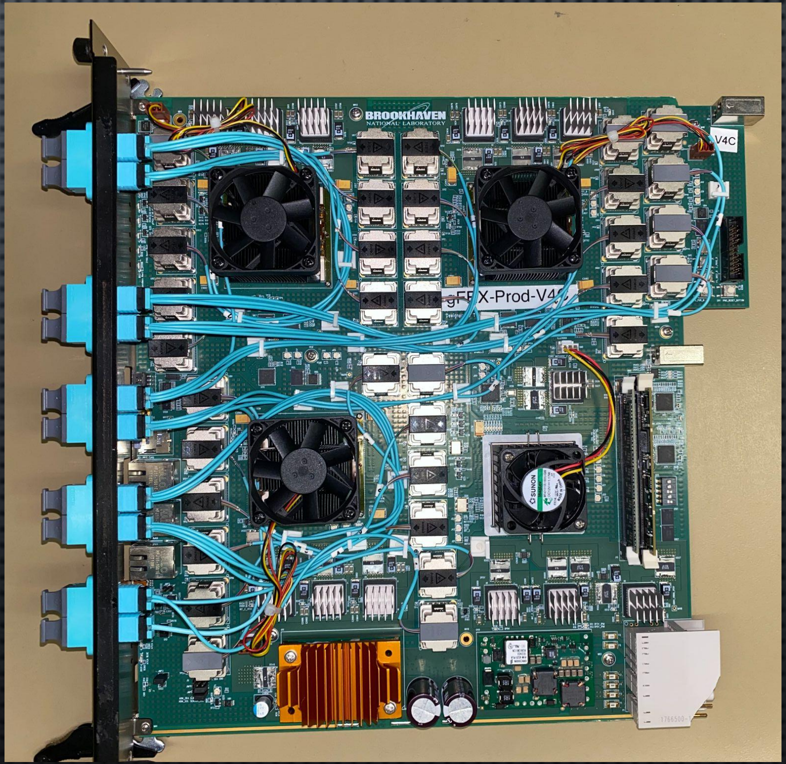
Hardware Triggering on Boosted Objects

- With boosted objects you get fewer, **larger jets**
- Vital to look at large pieces of the calorimeter for triggering
  - difficult to do within the latency allowance available
  - transferring data between boards/chips takes valuable time
- Can't just modify algorithms running on existing Hardware (though combinations on L1Topo possible)
- Requires a system specifically designed to solve this problem



Jim Dolen

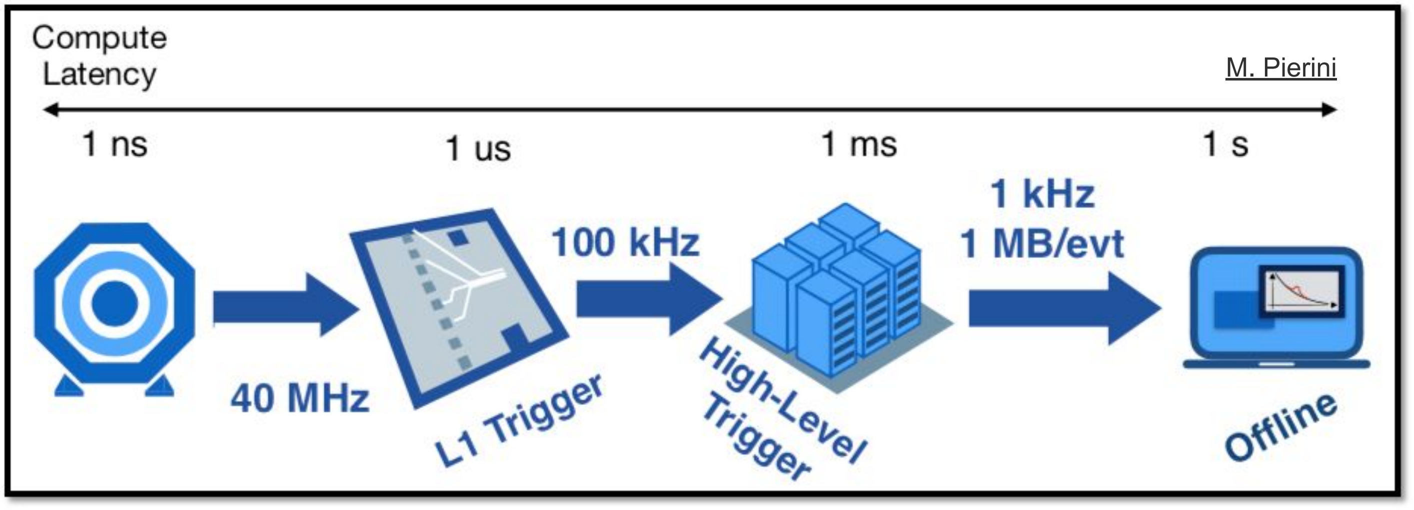
This system is the global Feature Extractor (gFEX)!



Outline

- ATLAS Trigger Introduction
- global Feature Extractor (gFEX)
  - Introduction & Design
  - Testing & Deployment
  - Trigger Efficiency
- global Feature Extractor additional capabilities
- Triggering for Run 4

ATLAS Hardware Calorimeter Trigger for LHC Run 3



ATLAS Hardware Calorimeter Trigger for LHC Run 3

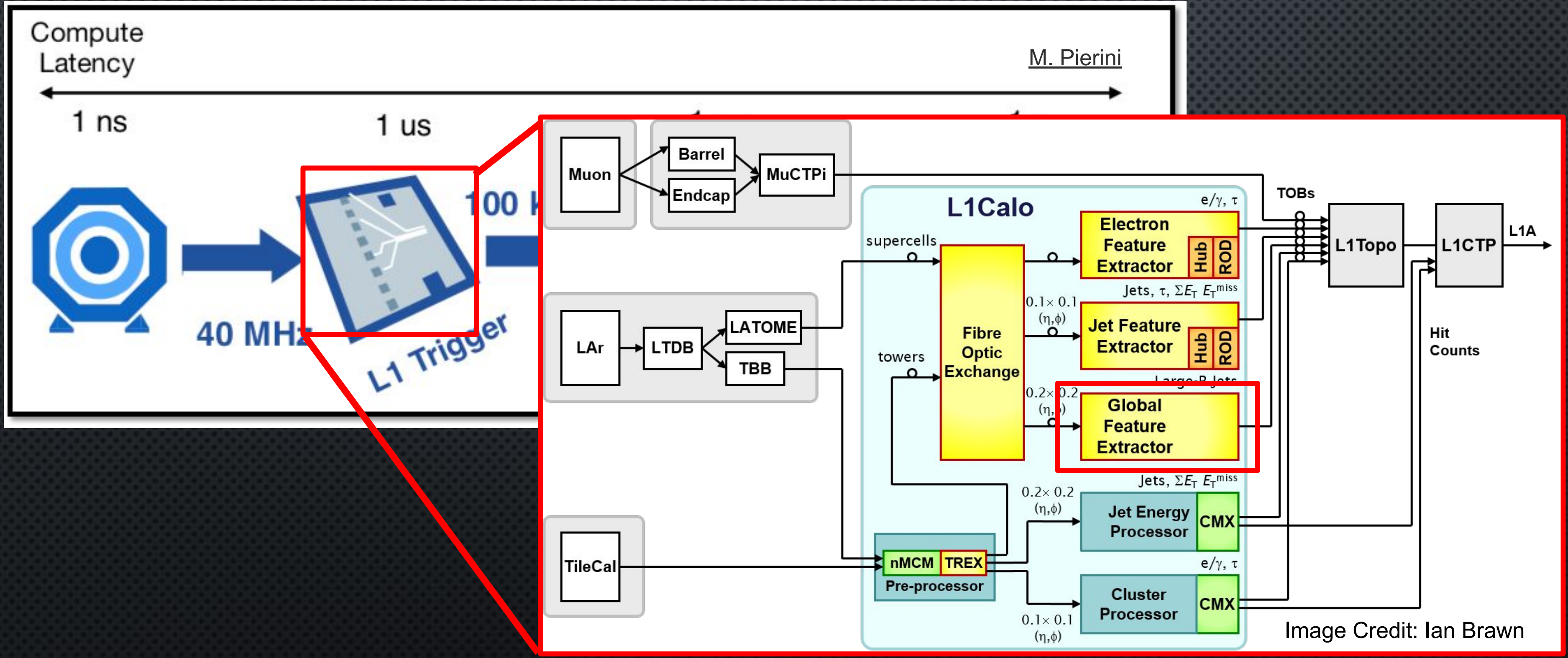
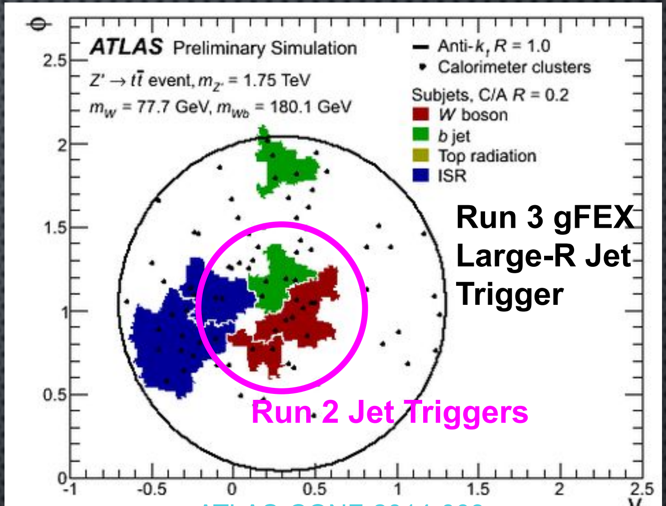


Image Credit: Ian Brawn

global Feature Extractor (gFEX)

- Entire calorimeter inputs on one board for calculating global observables
- Calculation of global quantities like large-radius jets, MET, and pile-up suppression for triggers at 40 MHz
- Optimize trigger capabilities for selecting events with interesting substructure visible from a global perspective like Higgs, W & Z bosons, top quarks, and exotic particles



ATLAS-CONF-2014-003

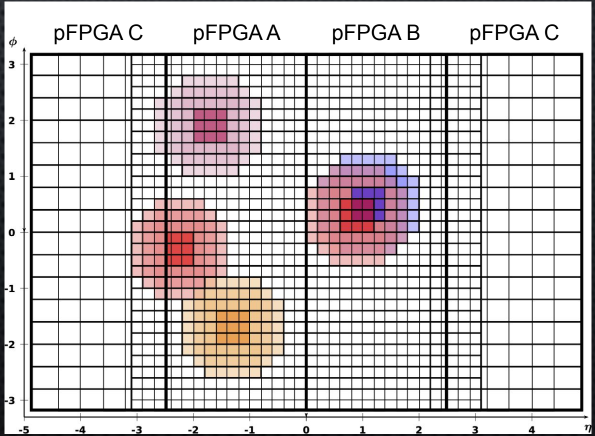
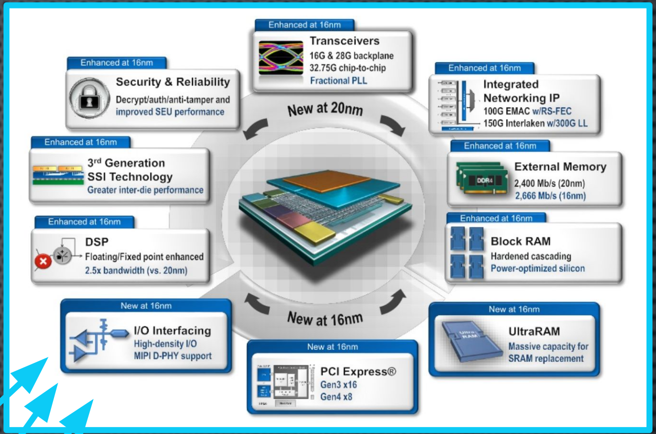


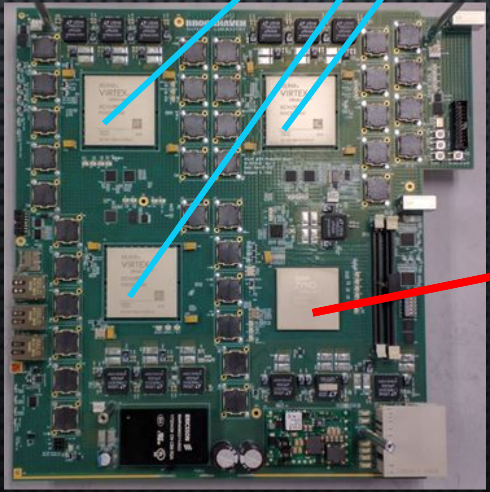
Image Credit: David Miller

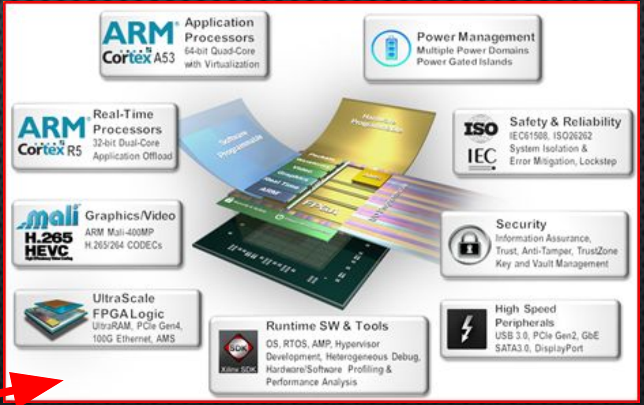
gFEX Hardware Design

Virtex
Ultrascale+
FPGAs



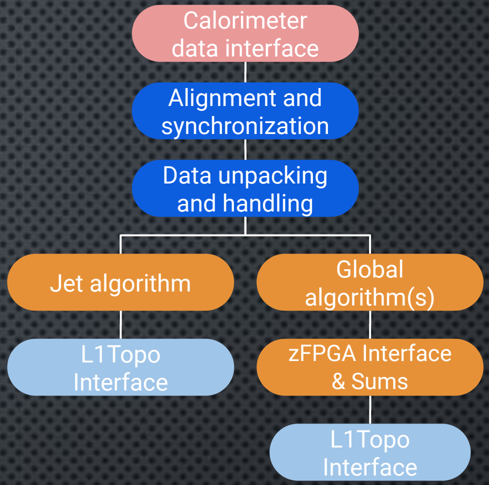
- 3 Ultrascale+ (VU9P) processor FPGAs for data processing via low latency gigabit transceivers
- Zynq Ultrascale+ Multi Processor System On Chip (SoC) (ZU19EG) for monitoring, control and data aggregation
- Custom linux operating system on SoC with substantial code for monitoring and configuration



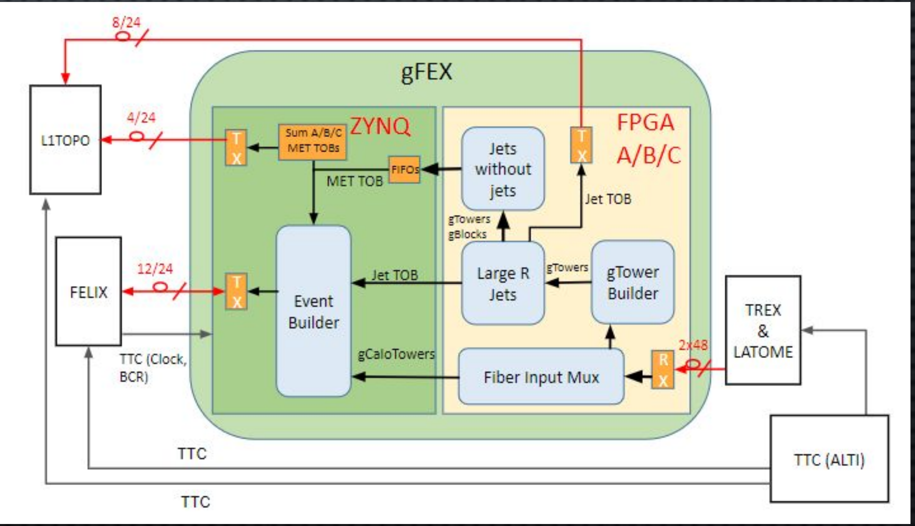


Zynq Ultrascale+ MPSoC
(ARM + zFPGA)

gFEX Firmware Development and Testing



- gTower Builder: adds EM and Had calorimeter towers
- Large-R Jets algorithm: JetFinder
  - seeded cone algorithm, implemented and undergoing validation
- MET algorithm: Jets without jets (JwoJ) [J. Thaler 1310.7584]
  - fully implemented in firmware, extensively validated
  - additional algorithms also possible and in development
- Input / readout firmware baseline implemented in 2019, tested and expanded in the CERN test lab since then

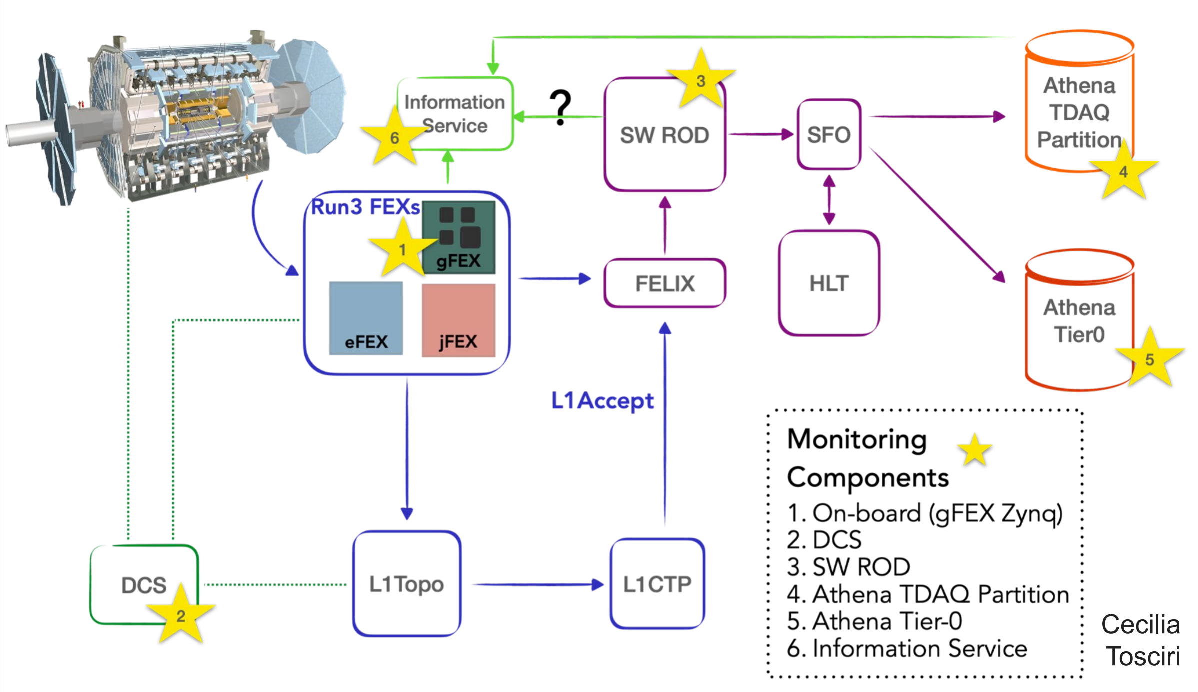


gFEX & L1Calo Latency

- Fixed latency system, only **2.2 μs for all of Level-1**! [ATLAS-TDR-023] (compared to 4.4 μs for the Level-0 trigger in Run 4 [ATLAS-TDR-029])
- Latency affected by:
  - input/output cable lengths
  - transceiver uncertainty
  - alignment of input/output signals
  - firmware
- Firmware optimization necessary to minimize latency of data processing, algorithm execution, and trigger object output

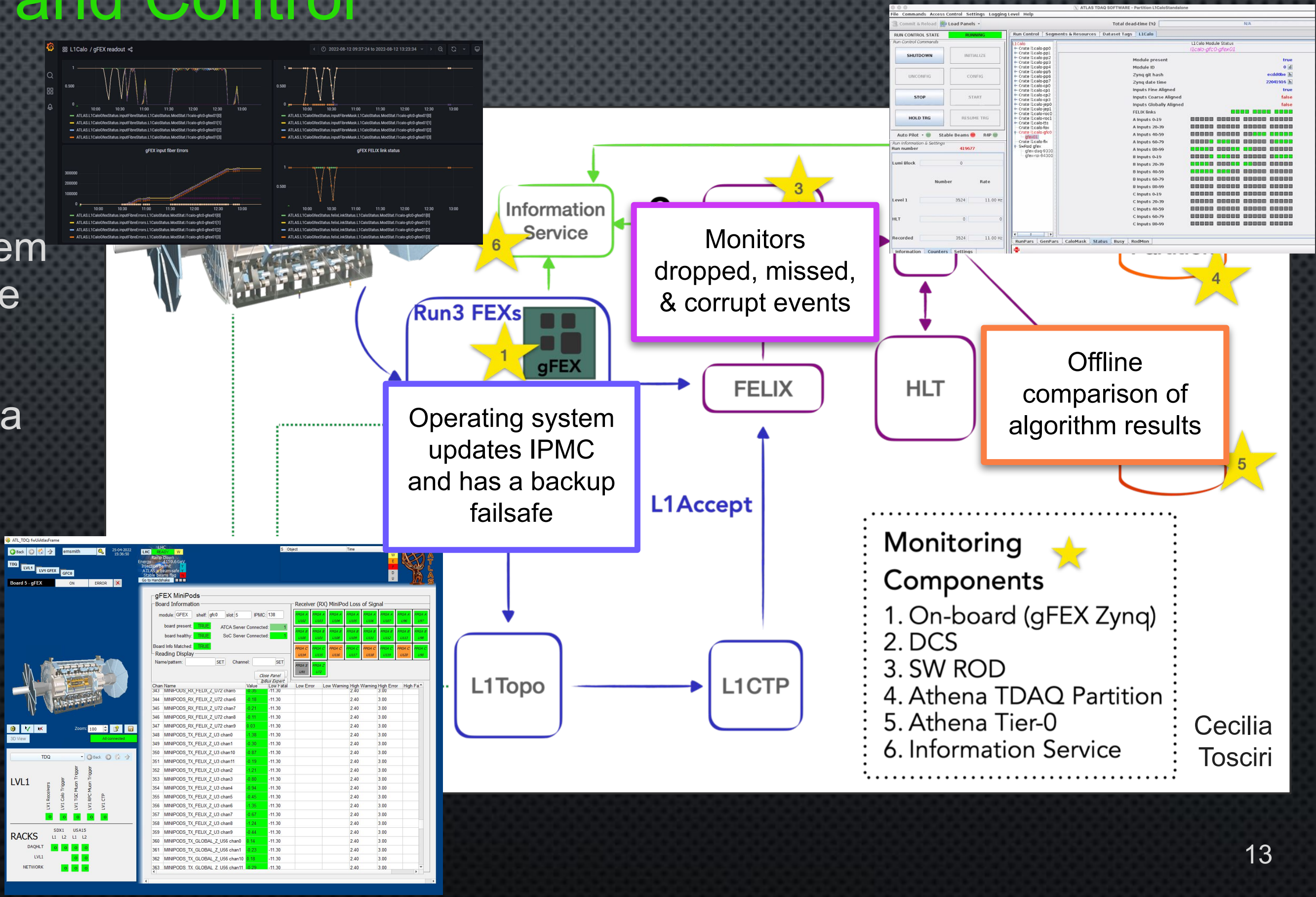
gFEX Monitoring and Control

1. Hardware monitoring via shelf
2. Detector Control System monitoring of hardware sensors
3. Readout monitoring via Software Rod system
4. TDAQ iGUI control & monitoring with IPBus packets
5. Offline monitoring
6. Informations Service



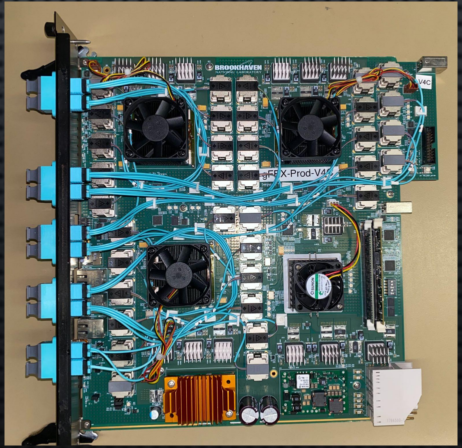
gFEX Monitoring and Control

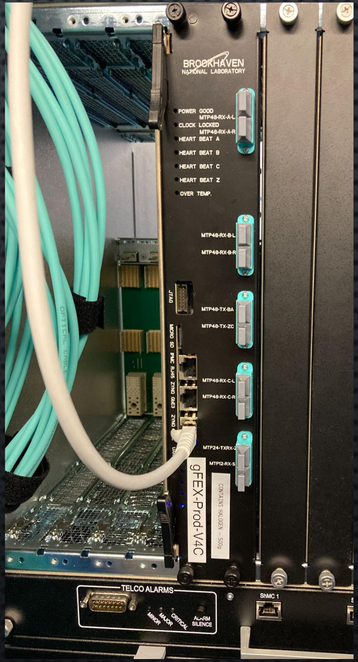
1. Hardware monitoring via shelf
2. Detector Control System monitoring of hardware sensors
3. Readout monitoring via Software Rod system
4. TDAQ iGUI control & monitoring with IPBus packets
5. Offline monitoring
6. Informations Service



gFEX Integration and Commissioning

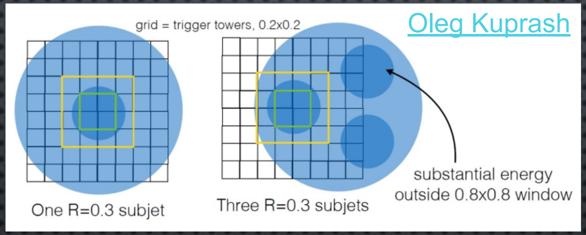
- Substantial work for many years, especially over the last two years from the entire team!
- Testing of all firmware elements and input/output protocols
- Full integration in ATLAS
  - validation of input and output mapping
  - online software written and working
  - on-board drivers and software
  - low level monitoring
  - physics data monitoring
  - lots of testing with ATLAS!





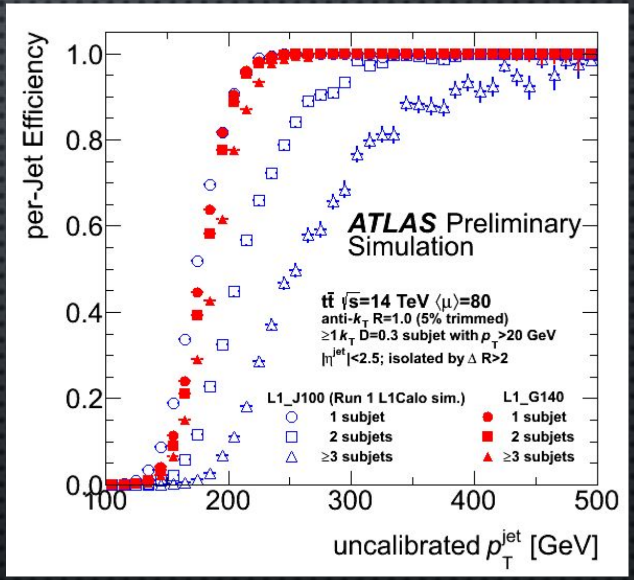
gFEX Large Radius Jet Efficiency

- ATLAS Run 2 trigger object: $E_T > 100$ GeV in a 0.8 Δη x 0.8 Δφ (L1_J100, R ~ 0.4)
  - good for small-R jets
  - misses energy from subjets in large-R jets



Oleg Kuprash

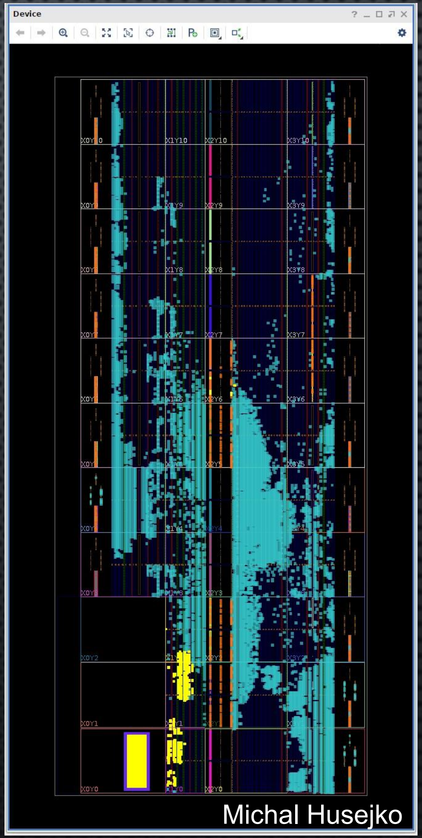
- gFEX Large-R jets (R~0.9) are more efficient for jets with substructure
  - 1.8 Δη x 1.8 Δφ size gJets, composed of 69 0.2 Δη x 0.2 Δφ gTowers
  - configurable energy cut in firmware, can be set as low as rate allows



ATLAS Public Jet Trigger Results

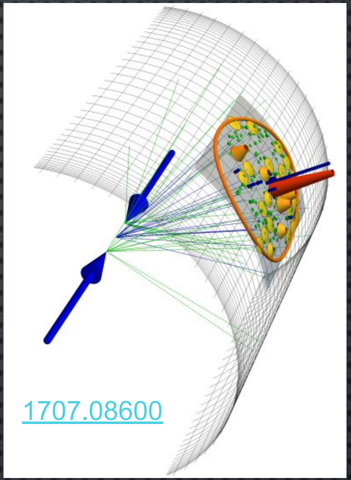
Zynq SoC Capabilities

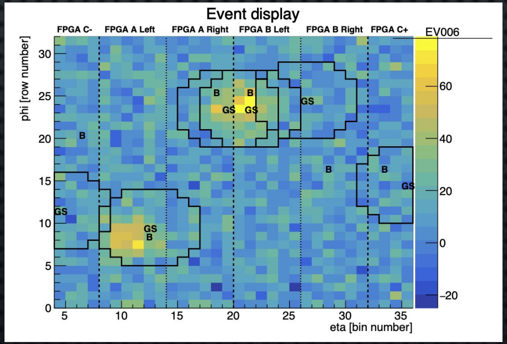
- zFPGA and processing system (PS) very underutilized, only about 10% used
- Zynq PS (operating system) also not overly taxed
- The Zynq SoC is on the real-time data path, make possible additional analysis of **real-time events** at low rate
- Possibilities include additional testing for Phase II, in depth monitoring, ML algorithms on the zFPGA



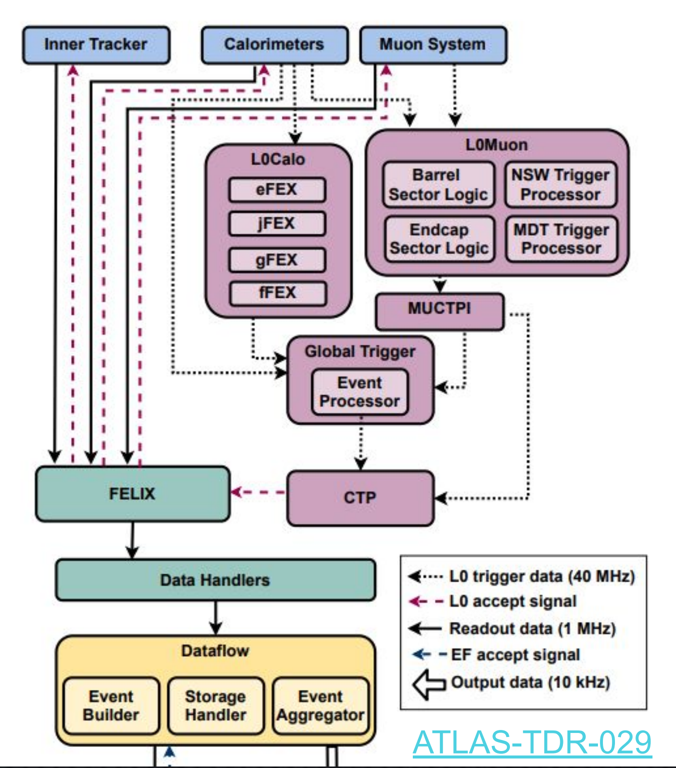
Machine Learning Algorithms on SoC

- Detector data is particularly well suited for representation as images of calorimeter energy deposition
- Convolutional neural network run on “images” and classify as signal or background
- Can use tools like hls4ml to translate machine learning algorithms into high level synthesis for running on FPGAs [2207.00559]
- Basic algorithm takes up 20% of zFPGA, additional room to expand and optimize the algorithm





Hardware Triggers for Run 4



ATLAS-TDR-029

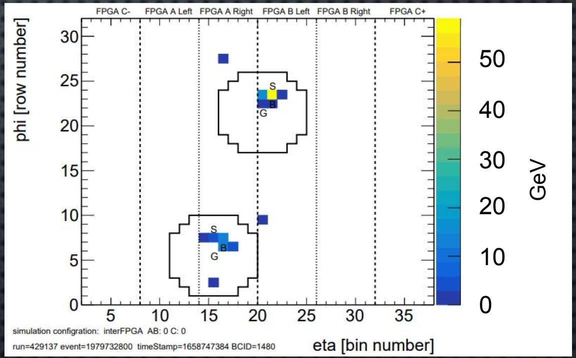
- gFEX will still operate in Run 4 as part of the L0Calo trigger!
- Global Event Processor (GEP) replaces L1Topological trigger in the current system
- GEP testing multiple features using spare production gFEX boards
  - plans to use a SoC similar to the Zynq+
  - gFEX pioneering many of the techniques for monitoring and control with an SoC

Conclusions

Triggering on large radius jets can be very important for locating boosted objects in physics events!

The global Feature Extractor is providing exciting trigger capabilities for large radius jets in Run 3…

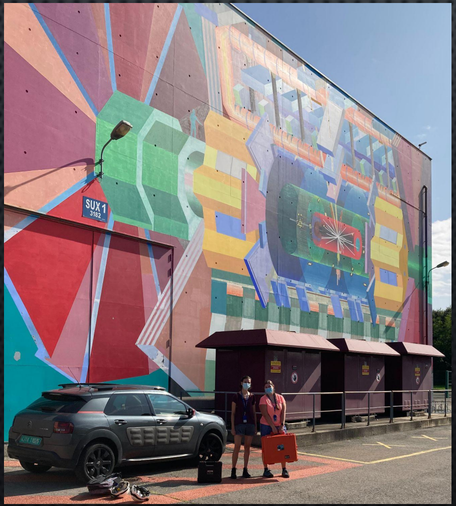
… while also helping us plan and implement the future jet triggers for Run 4!



gFEX Run 3 Event!

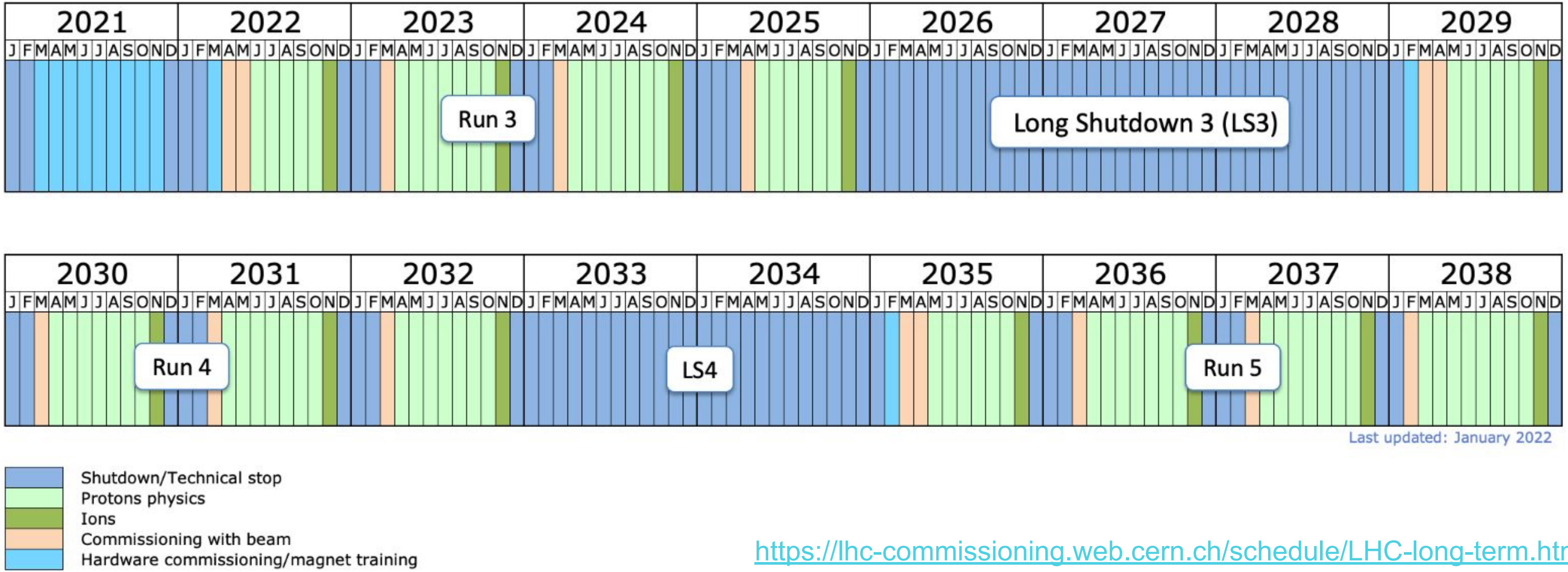
Thank You!

And many thanks to my fellow gFEX Colleagues!



Backup

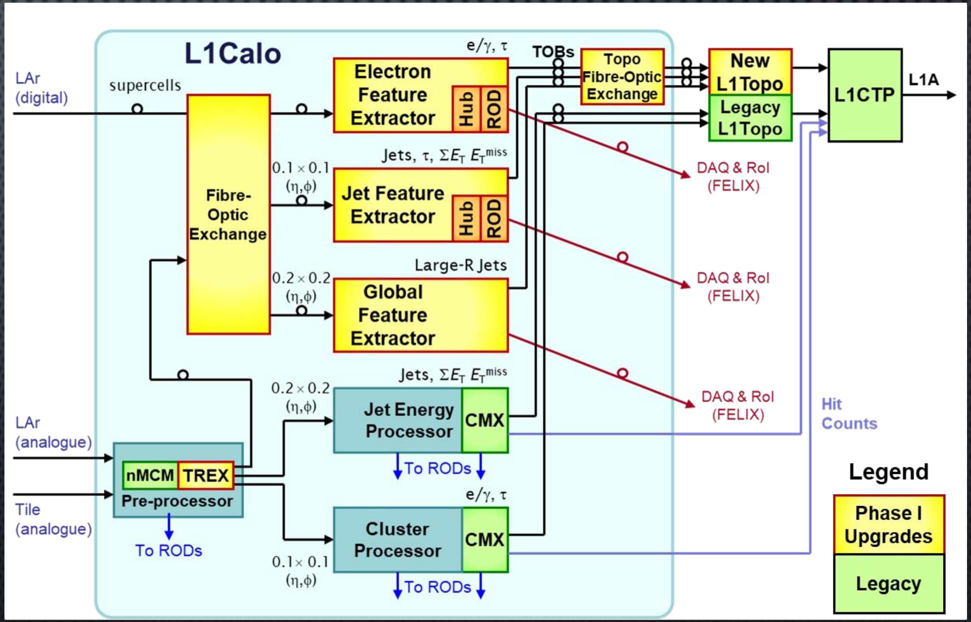
LHC Commissioning Schedule



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

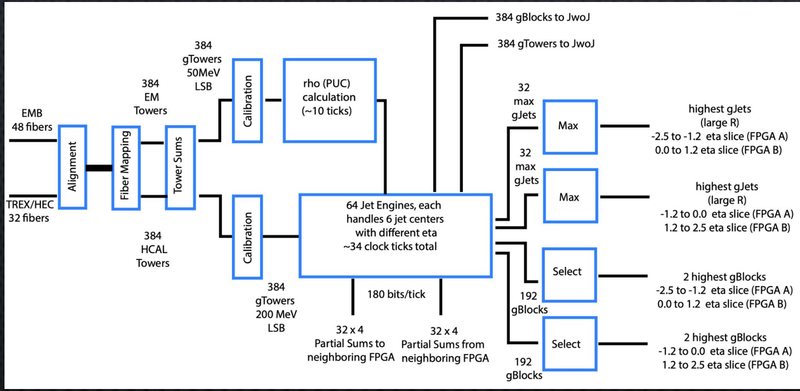
ATLAS Level-1 Calorimeter Trigger

- Hardware based triggers with hadronic and electromagnetic calorimeter inputs
- Trigger Objects (TOBs) produced include: photons, taus, electrons, jets, & missing energy
- TOBs sent to the Level-1 topological trigger for additional processing
- L1CTP receives outputs from L1Topo and makes the final Level-1 Accept (L1A) decision



gFEX Jet Finder Algorithm

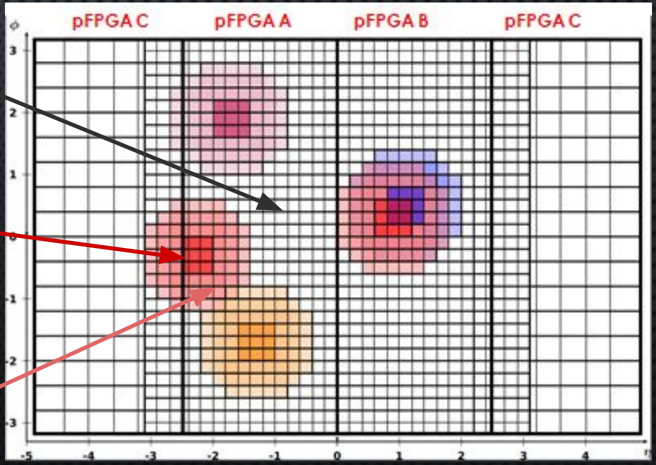
- **gTowers** constructed using inputs from LAr and Tile calorimeters
- gBlocks constructed for every gTower using 8 surrounding gTowers
- gJets calculated for every gBlock using a seeded cone algorithm
- Pileup correction performed by subtracting energy density ρ from the gJet energy
- Output TOBS: ρ, 2 gJets, 4 gBlocks with highest E_T from pFPGA A & B



gTower
(η x φ = 0.2 x 0.2)

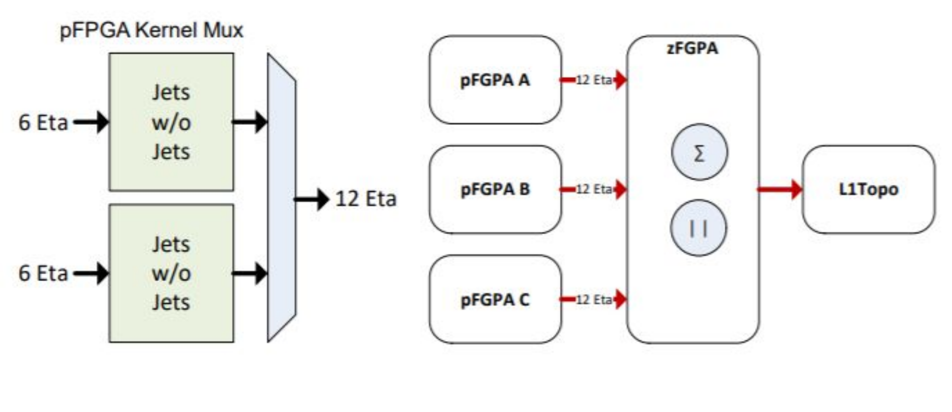
gBlock
3x3 gTowers
(η x φ = 0.6 x 0.6)

gJet
~9x9 gTowers
69 gTowers total
(η x φ = 1.8 x 1.8)



gFEX Jets without Jets Algorithm

- JwoJ is the default algorithm for calculating E_T^{miss} (MET)
- inputs to the algorithms are **gTowers** and gBlocks from the tower builder component of the Jet algorithm
- Hard Term (MHT) uses gTower with ET > 25 GeV
- Soft Term (MST) uses all other gTowers
- MET is a linear combination of the two: $MET_{x,y} = a_{x,y}\, MHT + b_{x,y}\, MST + c_{x,y}$
- a, b, c parameters configurable
- X & Y components summed and sent to zFPGA, to be summed
- Output TOBs: Scalar MET/SumE_T, MET/MHT/MST x,y components

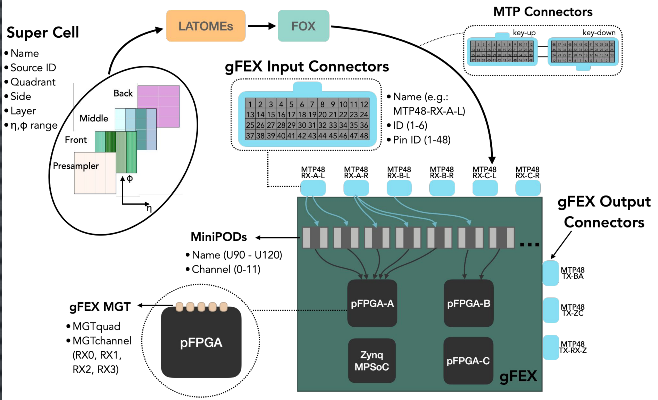


Additional MET Algorithms

- Noise Cut - Run 2 style
  - Evaluate noise σ according to RMS of E_T distribution for each gTower
  - Apply cut to gTower $E_T > 4\sigma$
  - Compute MET using x and y components
    - $MET_x = \Sigma E_T \times \cos\phi'$
    - $MET_y = \Sigma E_T \times \sin\phi'$
- Existing in gFEX firmware, not fully tested or validated yet

- Rho+RMS
  - Use pileup subtracted towers with 3σ noise cut when calculating MET
  - σ estimated with dynamic computation
  - Apply cut to gTower $E_T > 3\sigma$
  - Comput MET:
    - $MET_x = \Sigma E_T \times \cos\phi'$
    - $MET_y = \Sigma E_T \times \sin\phi'$
- Development of firmware algorithm ongoing

gFEX USA15 Installation



- gFEX production board installed in August 2021, Input mapping validated in early 2022
- Exchanged with a spare board in April 2022 due to small repairs needed on a monitoring component of the hardware
- Participated in pilot beam in October 2021, and splashes in early 2022
- Included and running alongside L1Calo legacy system in physics data taking run since July 5th!