The Global Feature Extractor: A New Component of the Level-1 Calorimeter Trigger Phase-I Upgrade for the ATLAS Experiment

Cecilia Tosciri
On behalf of the ATLAS TDAQ Collaboration

ICHEP 2022 BOLOGNA

ICHEP 2022
XLI
International Conference
on High Energy Physics
Bologna (Italy)

THE UNIVERSITY OF CHICAGO

ATLAS EXPERIMENT
"YOU ARE WELCOME HERE!"

Outline

- The ATLAS Trigger System
- The ATLAS Level-1 Calorimeter Trigger System for Run 3
- The Global Feature EXtractor (gFEX)
  - Introduction & Motivations
  - Architecture
  - Firmware
  - Algorithms
  - Installation & Commissioning
  - Simulation & Monitoring

ATLAS Trigger System

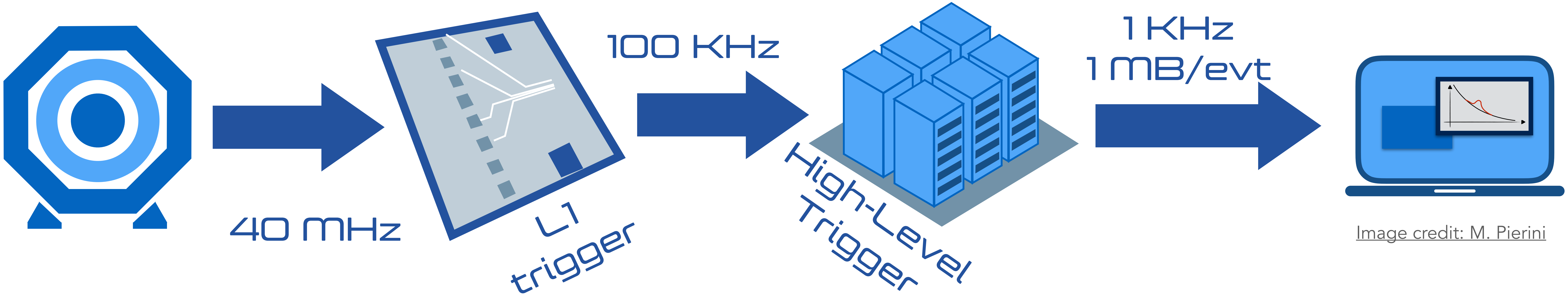
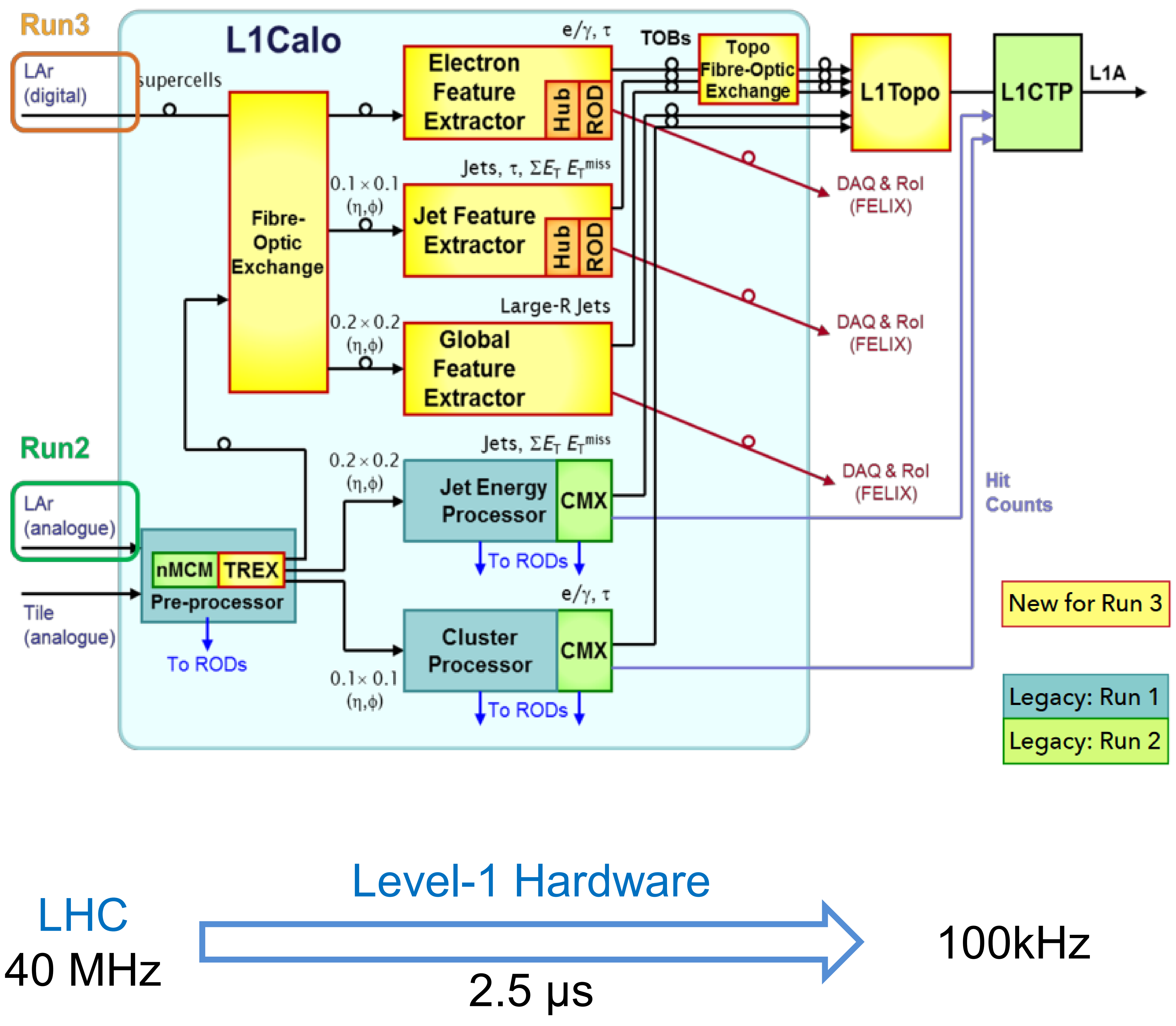


Image credit: M. Pierini

- The Large Hadron Collider has an average bunch crossing rate of **40 MHz**
- Two-level trigger system to reduce the rate of accepted events for physics analyses
- The hardware-based **Level-1** trigger (**L1**) uses input from the calorimeters and the muon spectrometer to identify interesting features and reduces the event rate to ~**100 kHz**
- The **High-Level Trigger** (**HLT**) reduces the event rate to ~**1 kHz**, by executing refined selection with offline-like algorithms within the interesting regions identified by L1 system

ATLAS Level-1 Calorimeter Trigger



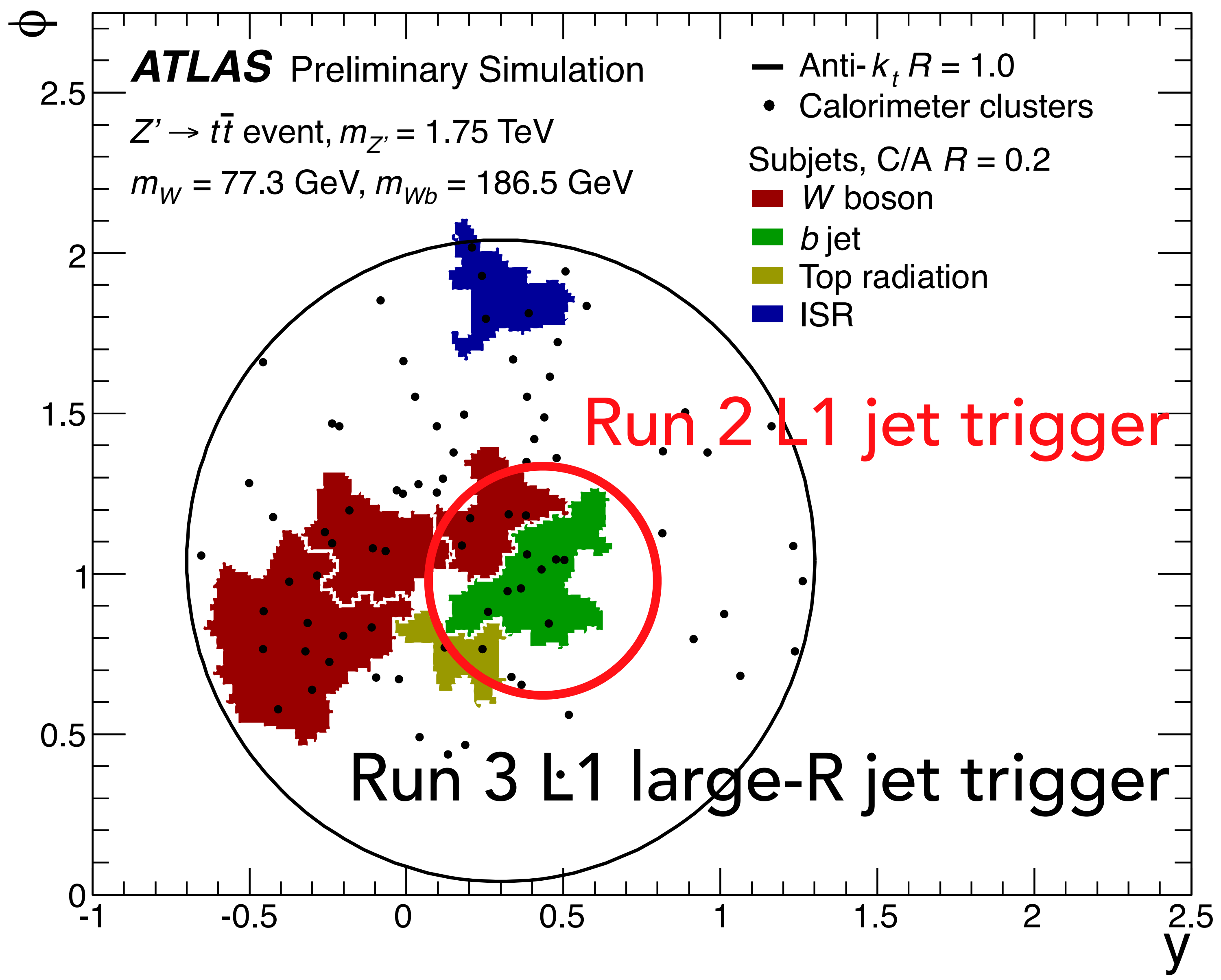
- Inputs from Liquid Argon (LAr) and Tile calorimeters
- ATLAS **Phase-I Upgrade** includes significant upgrades for Run 3 trigger system
- Increased granularity of the LAr calorimeter inputs (see talk *ATLAS LAr Calorimeter Commissioning for LHC Run-3*)
- New **F**eature **EX**tractor (**FEX**) modules use custom-made electronics to identify events containing calorimeter-based physics objects: **e/γ**, **τ**, **jets**, and **MET**
- More sophisticated algorithms thanks to advanced and modern electronics (high-power FPGAs)
- Better performance of trigger in high-luminosity and high pileup* environment in Run 3

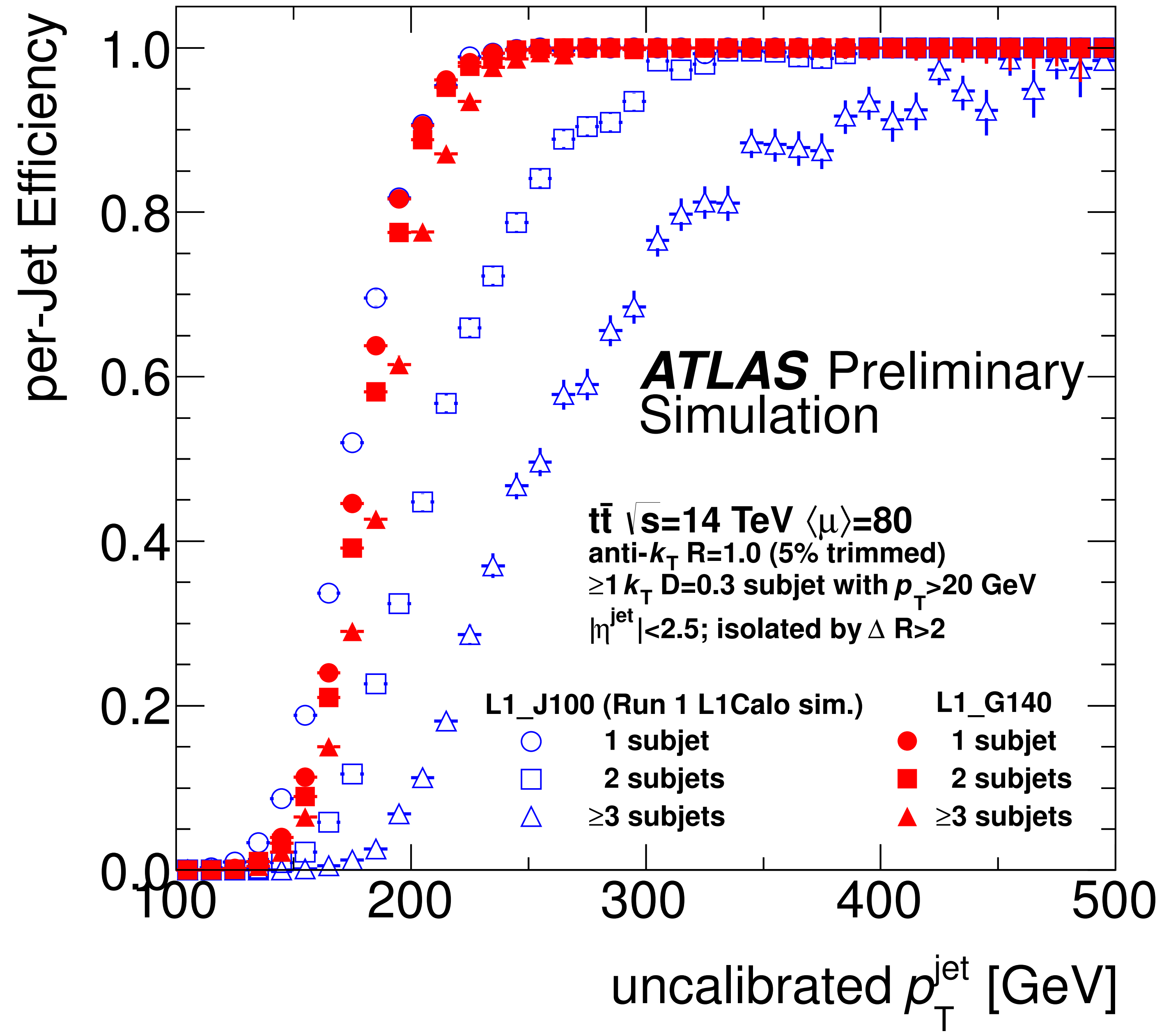
**Pileup: the average number of particle interactions per bunch-crossing*

gFEX (global Feature EXtractor)

- Full calorimeter available in a single ATCA module (Advanced Telecommunications Computing Architecture)
- Algorithms can scan the entire η-ϕ range
- Event-by-event local pileup suppression and calculation of global observables (MET, SumET)
- Optimized trigger capabilities and flexibility for selecting events containing large-radius jets, typical of Lorentz-boosted objects
- Identify patterns of energy associated with the hadronic decays of high momentum Higgs, W, & Z bosons, top quarks, and exotic particles in real-time at the 40 MHz LHC bunch crossing rate

ATLAS-CONF-2014-003



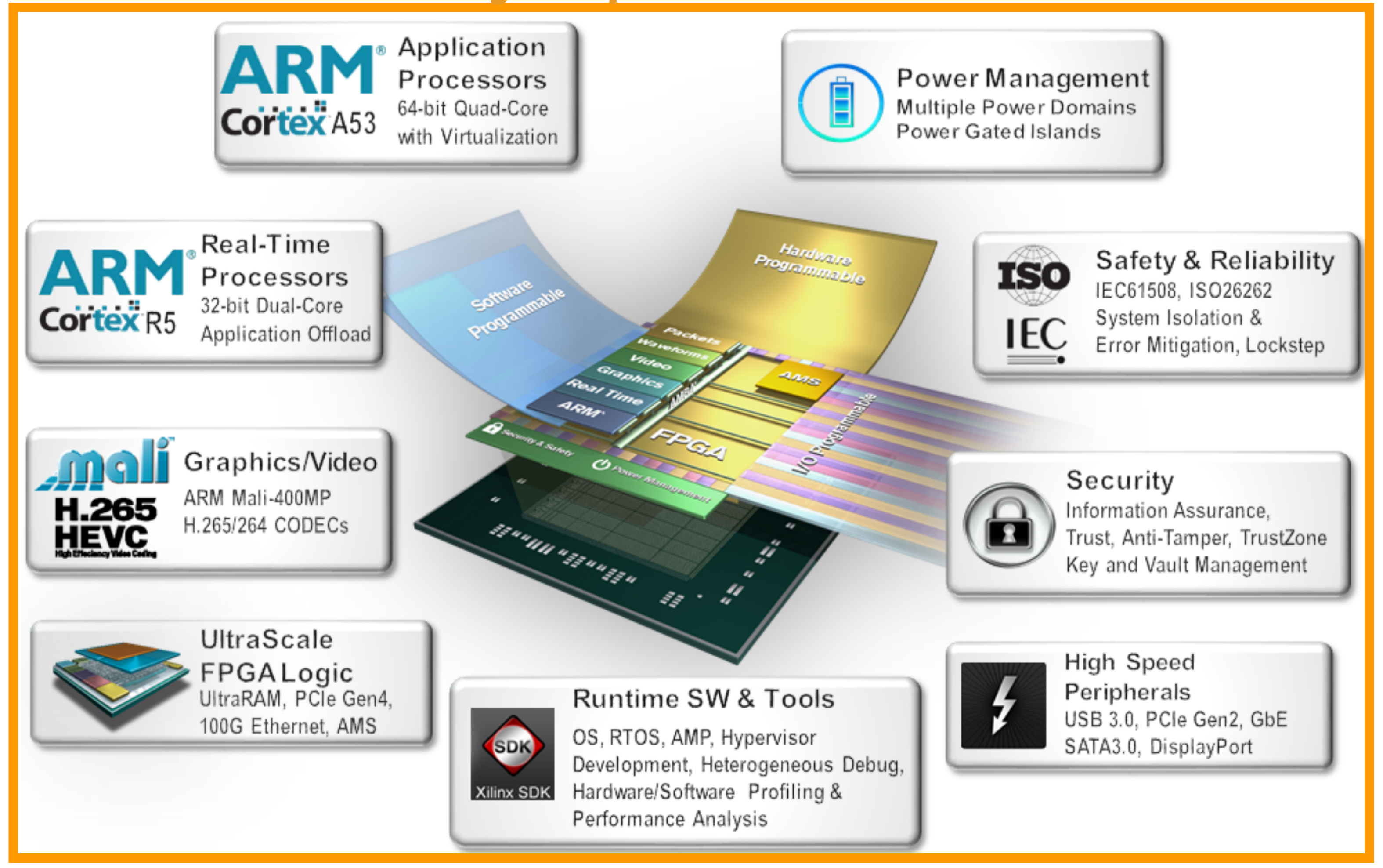


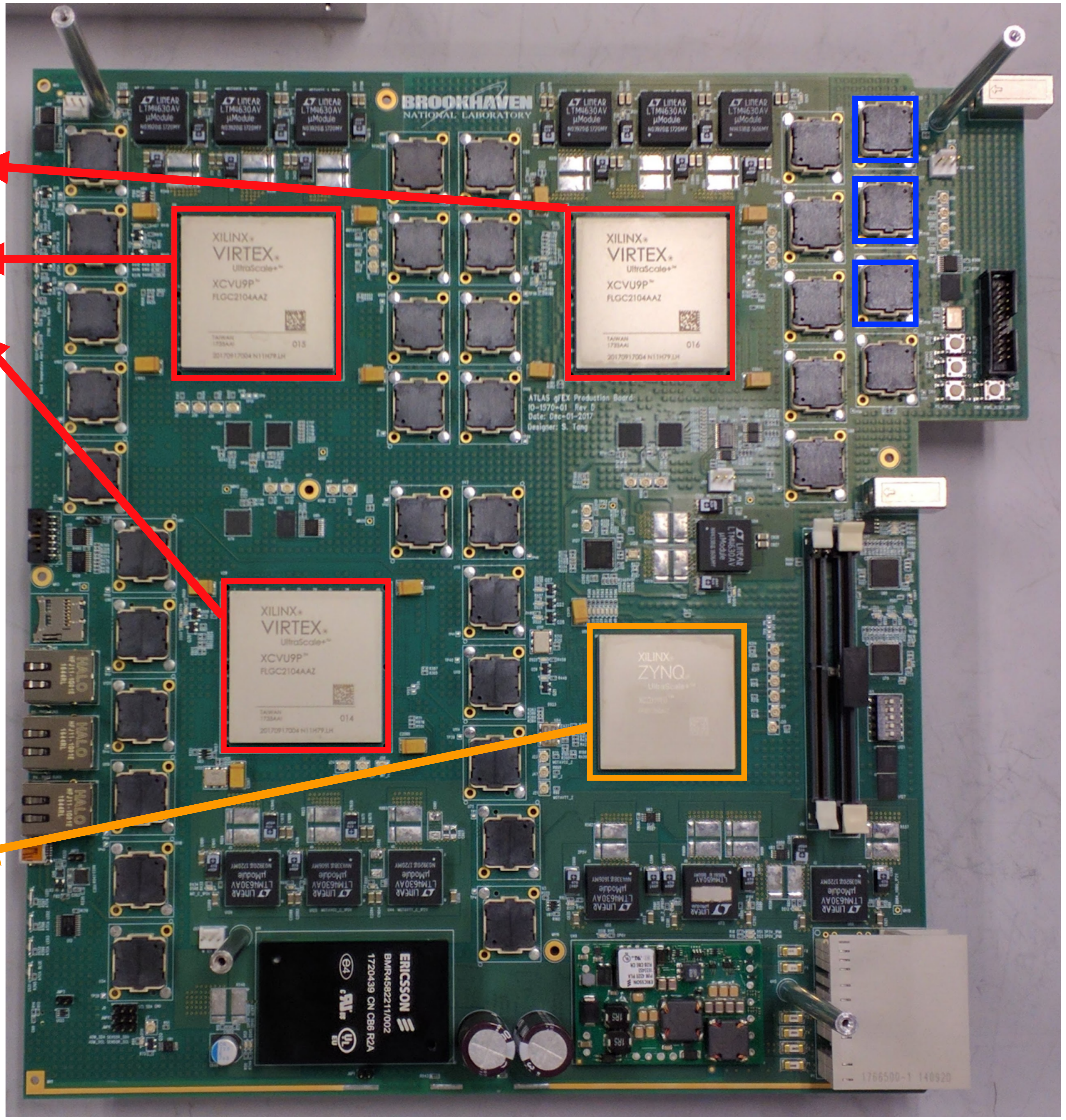
gFEX Electronics

- Three processor FPGAs (pFPGA) process data via low-latency links and on-board MiniPOD receivers
- Zynq provides configuration and monitoring for gFEX, combining an FPGA and a CPU into a Multi Processor System-on-Chip (MPSoC)
- The MPSoC configures the pFPGAs, implements a Linux operating system, and the on-board Detector Control System (DCS)

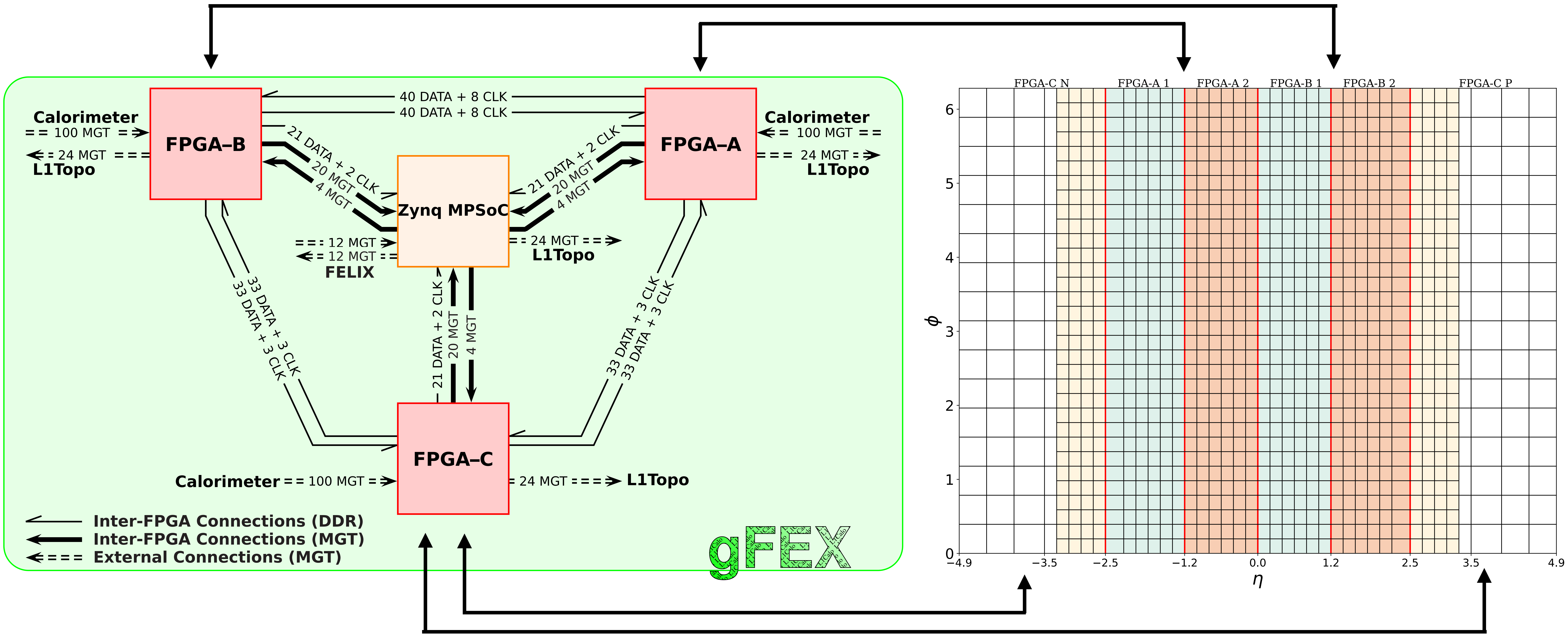
Vertex Ultrascale+

Zynq UltraScale+





gFEX Architecture



FPGA-A: -2.5 < η < 0
FPGA-B: 0 < η < 2.5
FPGA-C: 2.5 < |η| < 4.9

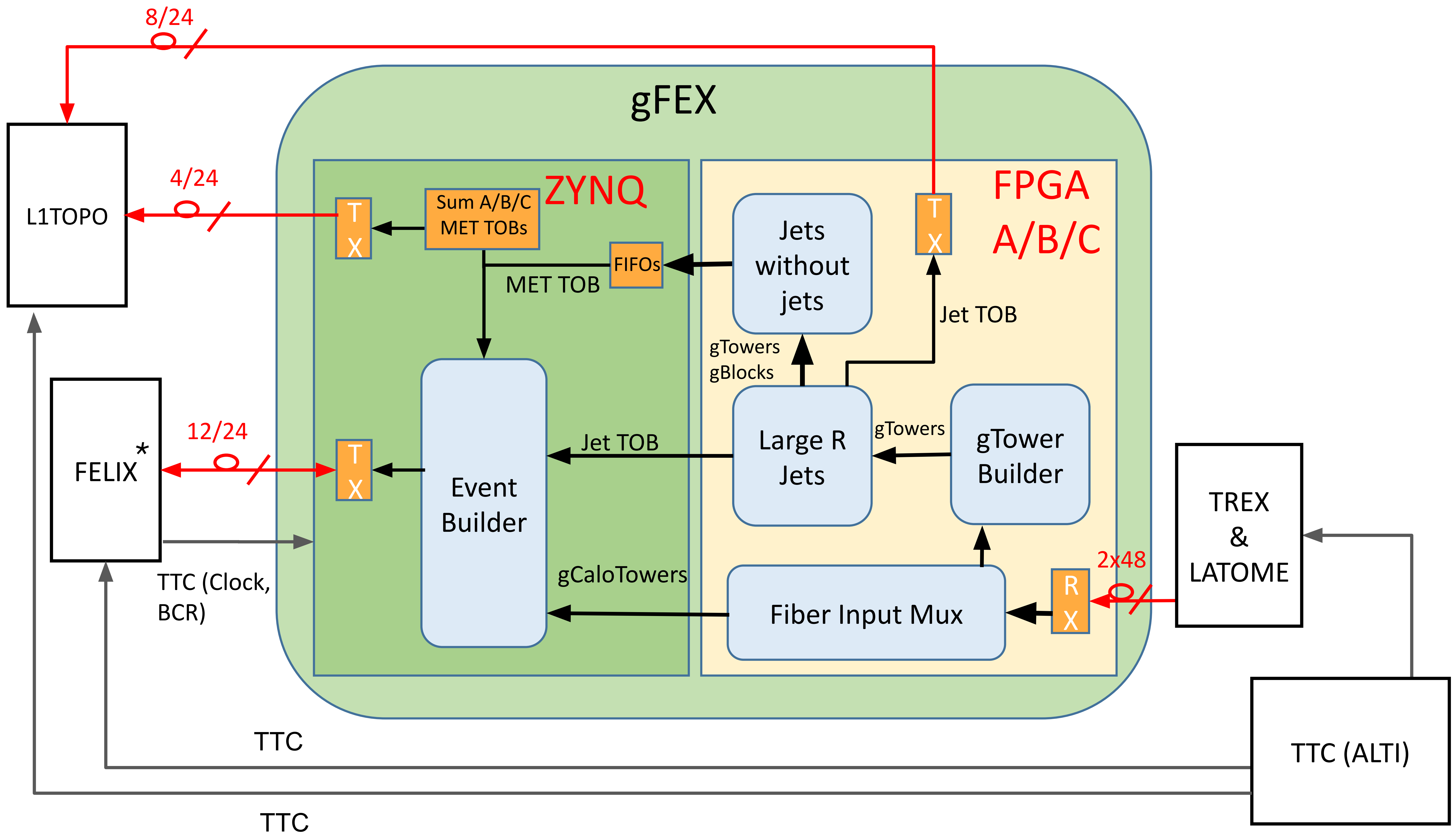
- Connectivity: 100 input fibers (from calorimeter) and 24 output fibers (to L1Topo) per pFPGA
- Each pFPGA executes feature identification algorithms covering different regions of η
- The pFPGAs communicate with each other via low-latency links
- MPSoC receives data from pFPGAs and computes global quantities

**FELIX: the new ATLAS readout system (see ICHEP talk)*

gFEX Firmware

gFEX team has deployed a complete set of firmware for algorithm processing, real-time path, infrastructure, and readout functionality that has been tested and used in various forms and contexts

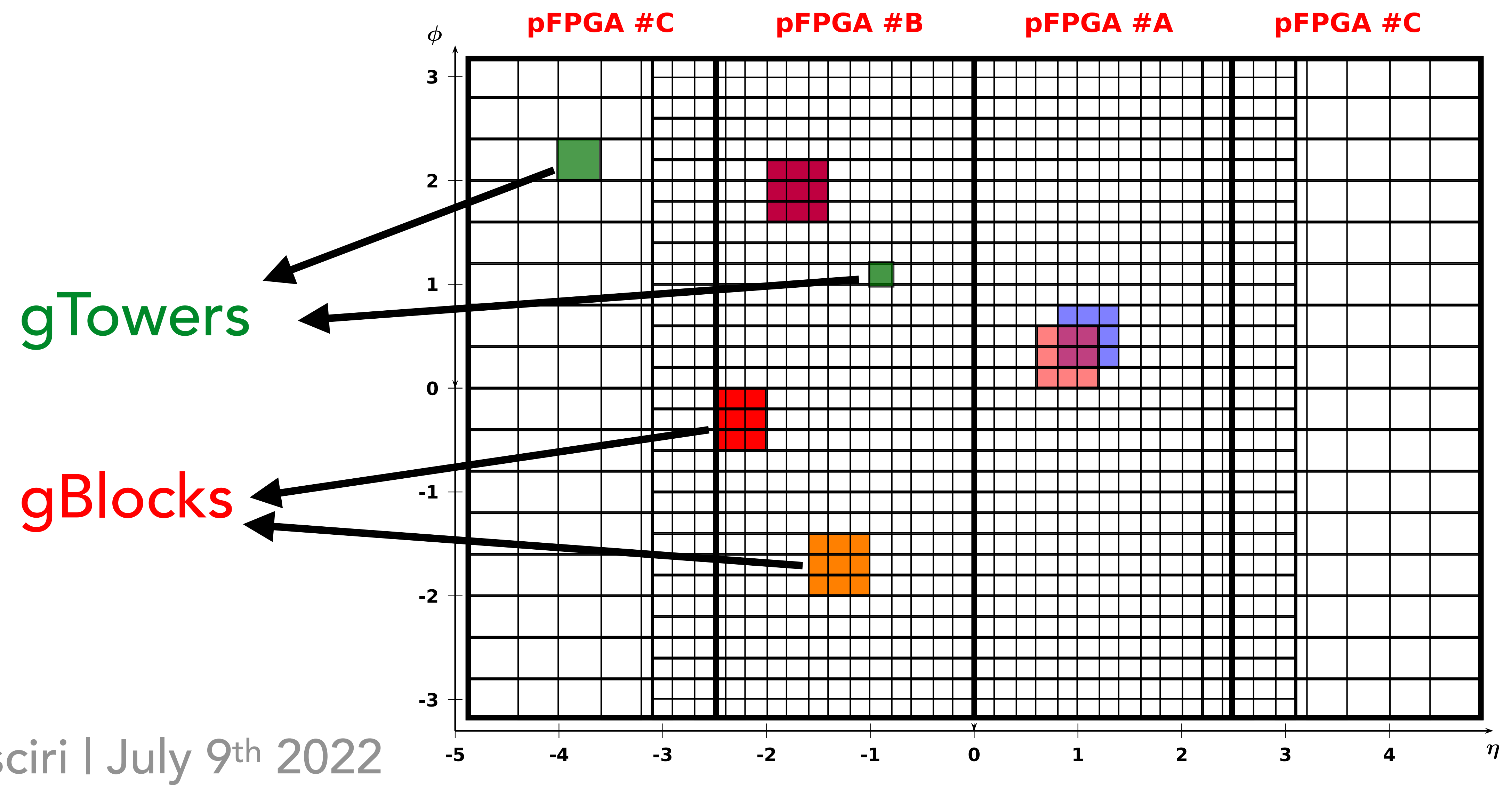
- Integrated firmware meets resource usage constraints without timing violations
- Robust and flexible Continuous Integration (CI) system has been developed
- Inter-FPGA communication timing optimization

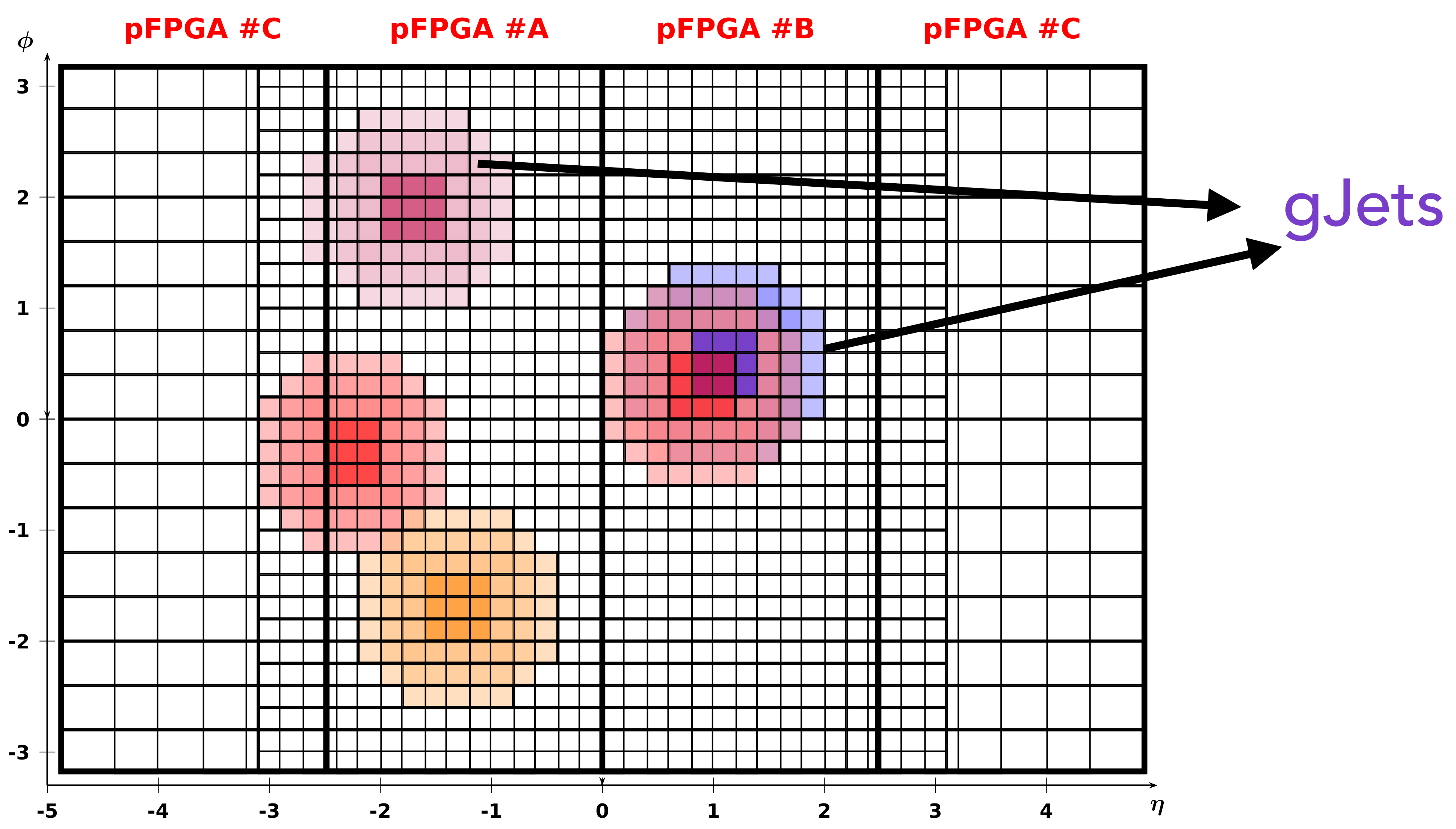


*FELIX: the new ATLAS readout system (see ICHEP talk)

Jet Finder Algorithm

- gTowers: the digital units of gFEX with typical size **$\Delta\eta x \Delta\phi$=0.2x0.2**, constructed in the **gTower Builder** with inputs from LAr ($\Delta\eta x \Delta\phi$= 0.025x0.1) and Tile calorimeter ($\Delta\eta x \Delta\phi$= 0.1x0.1)
- The **Jet Finder algorithm** is responsible to identify jet objects:
  - gBlocks: **3x3 gTowers**, corresponding to small-radius jets
  - gJets: **69 gTowers**, large-radius jets built with a seeded cone algorithm
  - Pile-up correction is performed by subtracting the energy density ρ from the gJet energy
- For each central pFPGA (A and B), the algorithm outputs the following Trigger Objects (TOBs) and sends them to the L1Topo system: energy density ρ, 4 gBlocks and 2 gJets with highest E_T





Jets without Jets Algorithm

- Original proposal for Jets without Jets JHEP04(2014)013
- Default algorithm for missing energy (MET) calculation
- Receives gTowers and gBlocks from jet algorithm
- Separates gTowers into two terms, based on gBlock threshold
- Hard term (MHT) includes gTowers with gBlock E_T >25 GeV,
- Soft term (MST) includes the remaining gTowers
- MET is a linear combination: $\text{MET}_{x,y} = a_{x,y}\,\text{MHT}_{x,y} + b_{x,y}\,\text{MST}_{x,y} + c_{x,y}$
- *a*, *b*, *c* parameters for each pFPGA (configurable in firmware)
- MET terms calculated in each pFPGA and summed up as:

  $$\text{MET} = \sqrt{\text{MET}_x^2 + \text{MET}_y^2}$$

- The algorithm outputs the scalar MET/SumE_T , MET/MHT/MST *x,y* components as Global TOBs

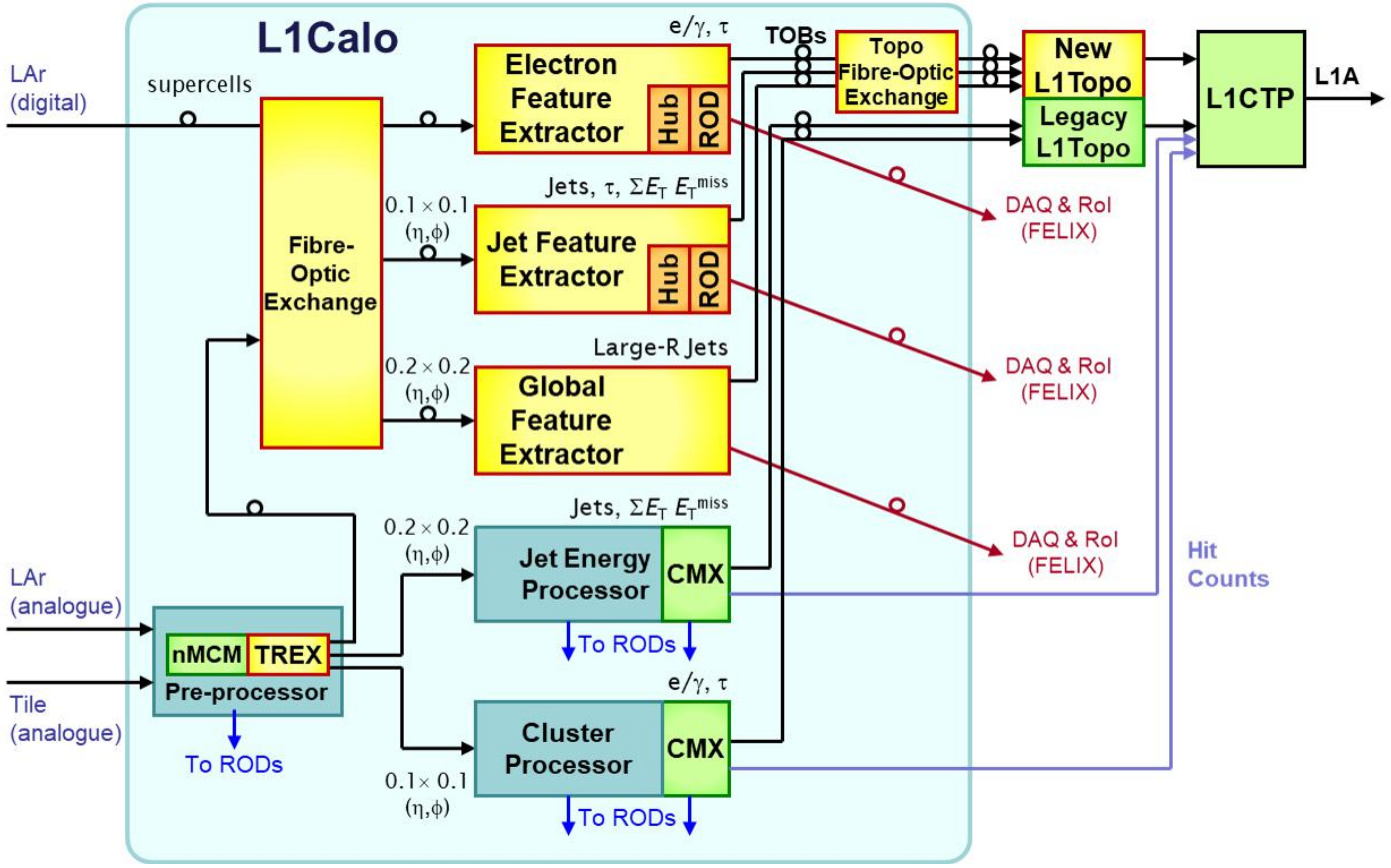
gFEX Installation and Commissioning

- 1 gFEX installed in ATLAS in the electronics room beside the LHC cavern (Point 1)
- 1 gFEX installed in the Surface Test Facilities (STF) at CERN
- 1 gFEX (spare) resides at BNL

- ∘ gFEX firmware tests are underway in the STF: testing input mapping, firmware algorithms and interfaces, latency, timing closure etc.
- ∘ Integration tests at Point 1: readout tests, input link mapping tests
- ∘ gFEX is well-integrated in the online Trigger Data Acquisition (TDAQ)
- ∘ Data recorded during commissioning runs for splashes and collisions at 900 GeV and 13.6 TeV, and first data of Run 3 recorded!

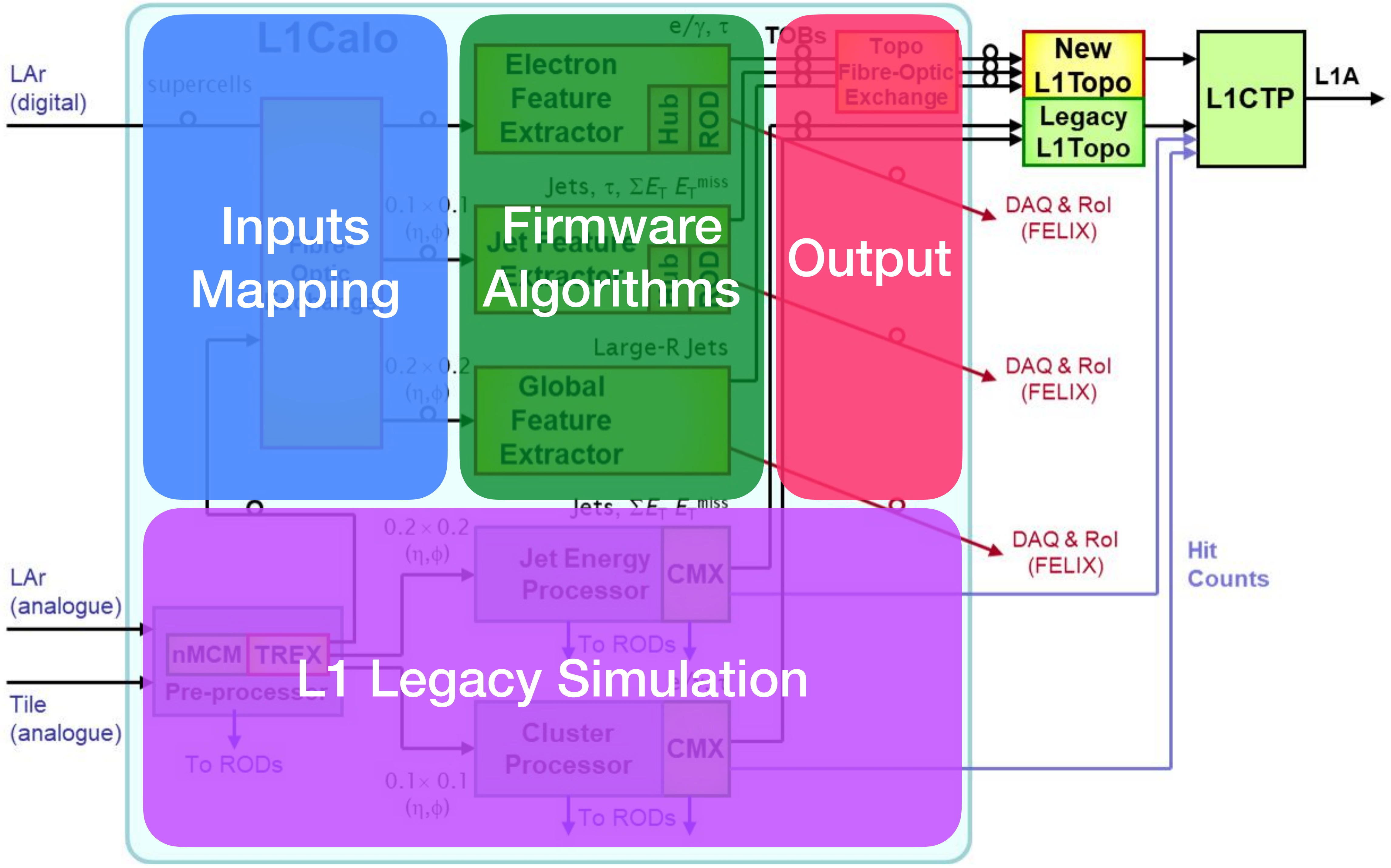
gFEX Simulation

- **Offline simulation:** bitwise accurate simulation of the new L1Calo trigger system, including gFEX, and related algorithms, used for **commissioning**, **monitoring**, **validation**, as well as **simulation** and **reconstruction**
- **Online simulation:** used for **configuring**, **controlling**, **testing**, and **monitoring** the hardware
- **C-simulation:** standalone bitwise simulation of the gFEX firmware, used for testing firmware implementation



gFEX Simulation

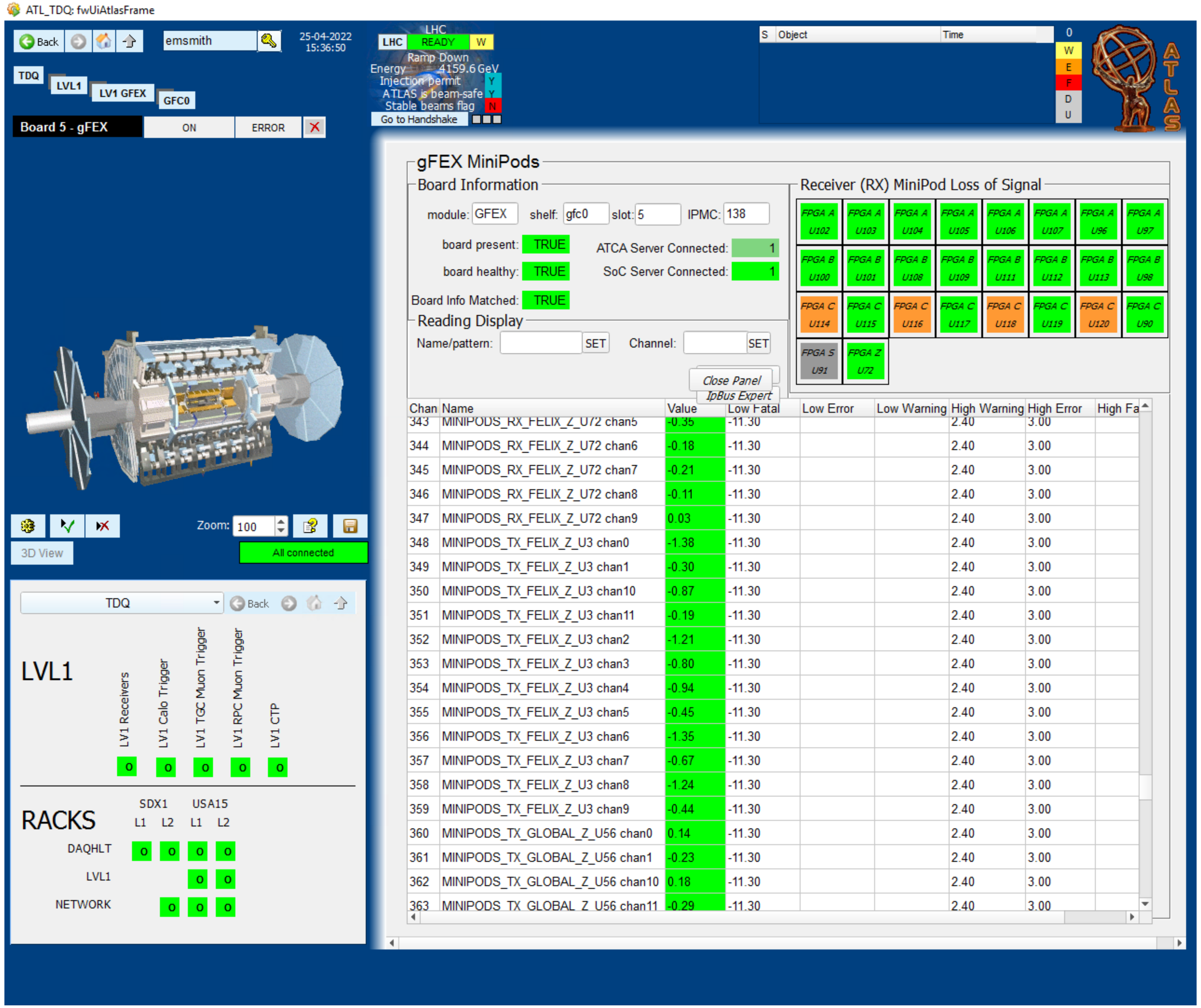
- **Offline simulation**: bitwise accurate simulation of the new L1Calo trigger system, including gFEX, and related algorithms, used for **commissioning**, **monitoring**, **validation**, as well as **simulation** and **reconstruction**
- **Online simulation**: used for **configuring**, **controlling**, **testing**, and **monitoring** the hardware
- **C-simulation**: standalone bitwise simulation of the gFEX firmware, used for testing firmware implementation



gFEX DCS and Athena Monitoring

- The MPSoC contains the control and status registers related to the operation of the gFEX, that can be read for monitoring purposes
- Data are transmitted to the gFEX **Detector Control System (DCS)**

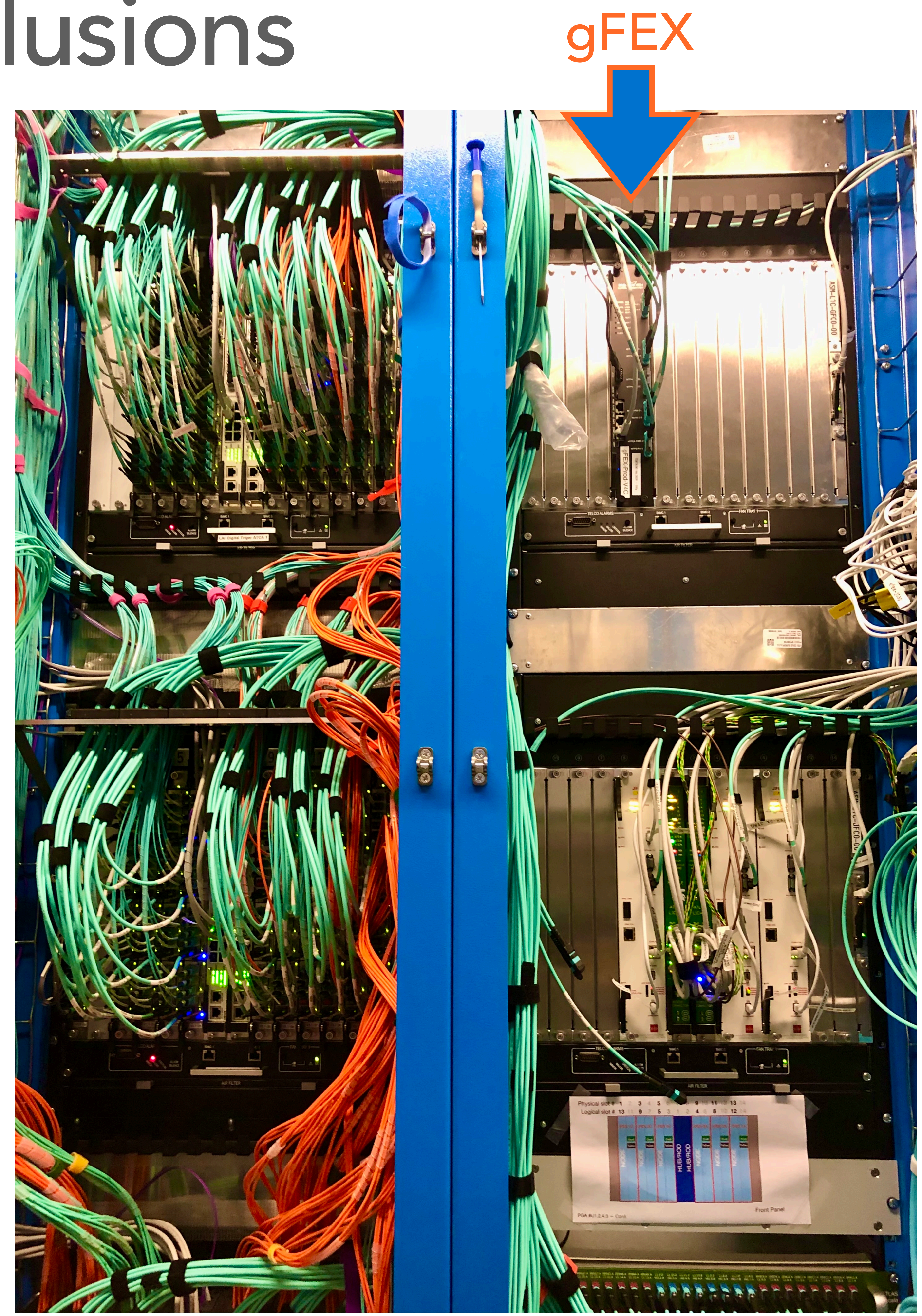
- **Athena monitoring**: run by the ATLAS partition for selection of events to test if the hardware is working properly
- The Athena monitoring is used to fill histograms of e.g. occupancy rate and also to compare with the digital simulation



<u>Athena</u>: the ATLAS offline software

Summary & Conclusions

- gFEX is part of the Run 3 Phase-1 upgrade of the ATLAS Trigger System
- gFEX is installed, and great progress towards integration into Level-1 Calorimeter trigger and ATLAS has been made
- Converging on a stable and robust firmware
- Inputs mapping is fully validated
- Connectivity, readout, and timing tests are underway
- gFEX DCS monitoring is up and running
- Simulations are in place and used for testing and monitoring the system
- The acceptance for large-radius jets will be greatly enhanced by the inclusion of the gFEX in the L1Calo system
- gFEX will significantly contribute to a robust and efficient trigger system for physics in Run 3

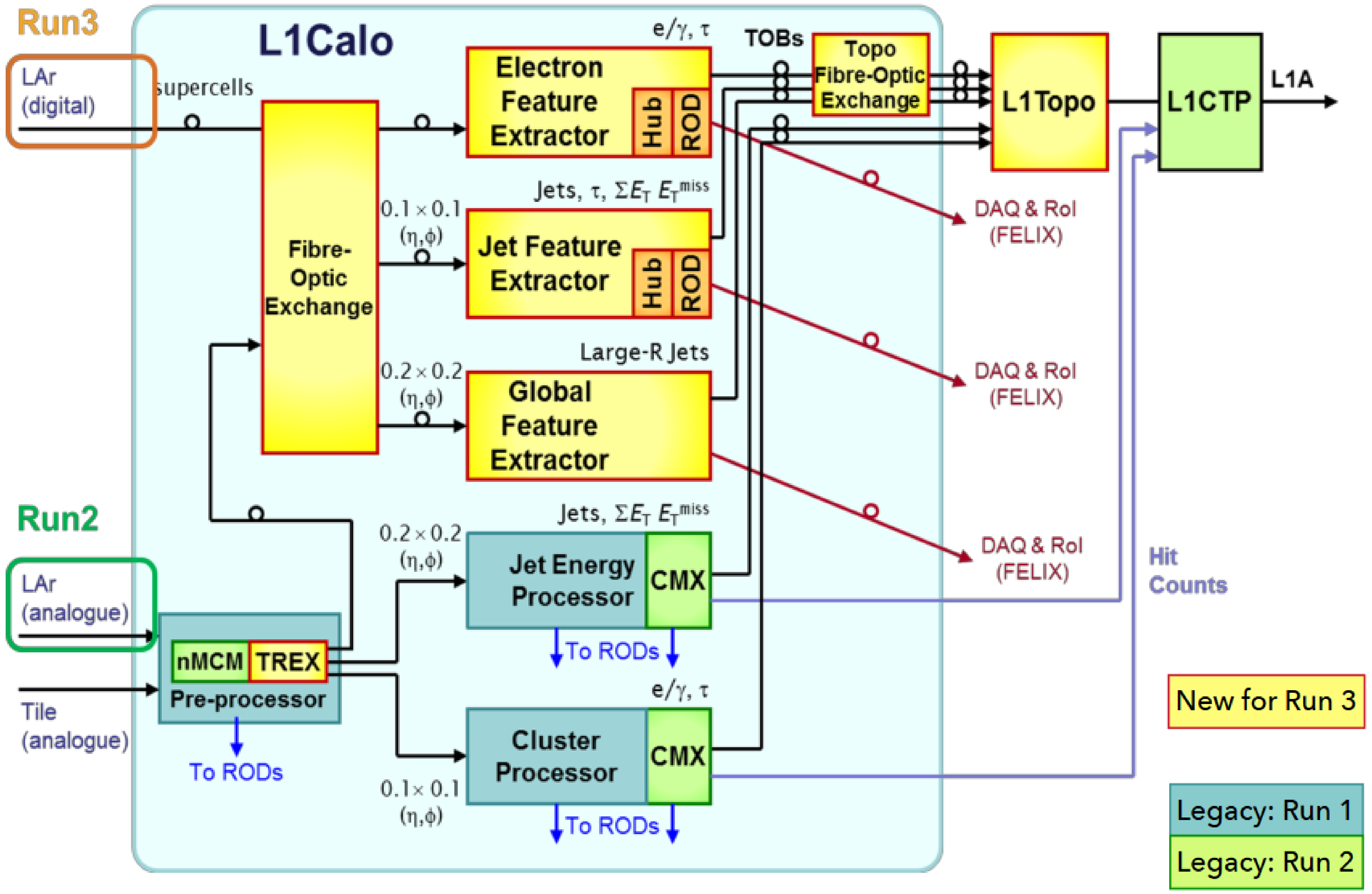


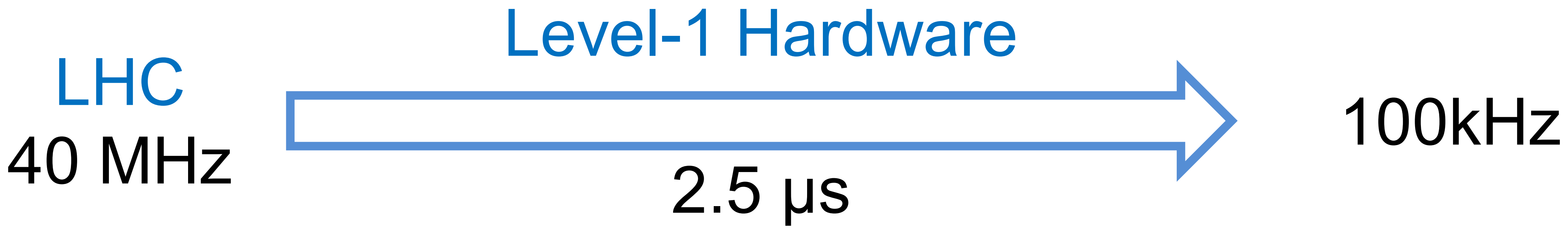
Thank you!

Additional Material

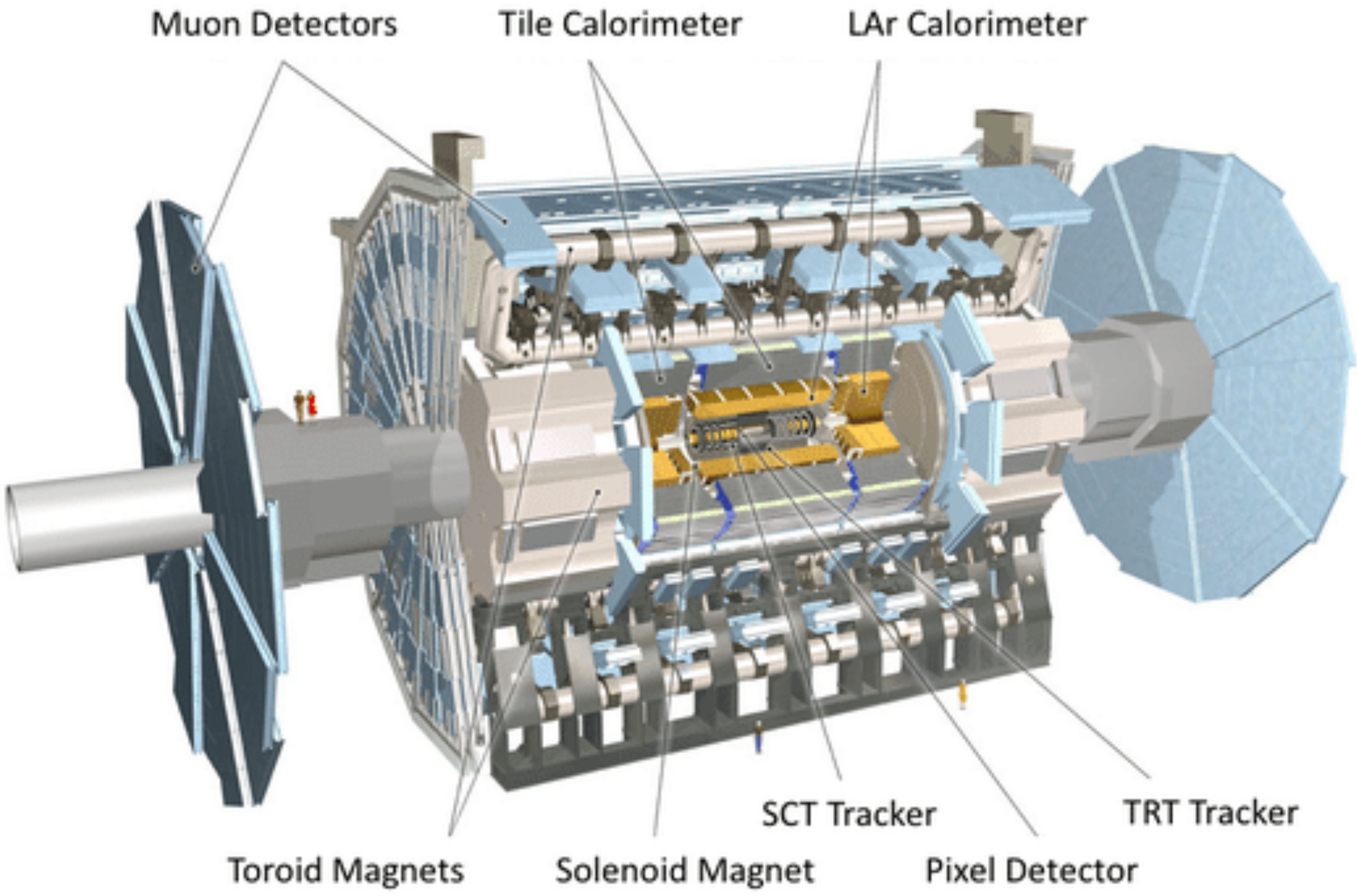
ATLAS Level-1 Calorimeter Trigger

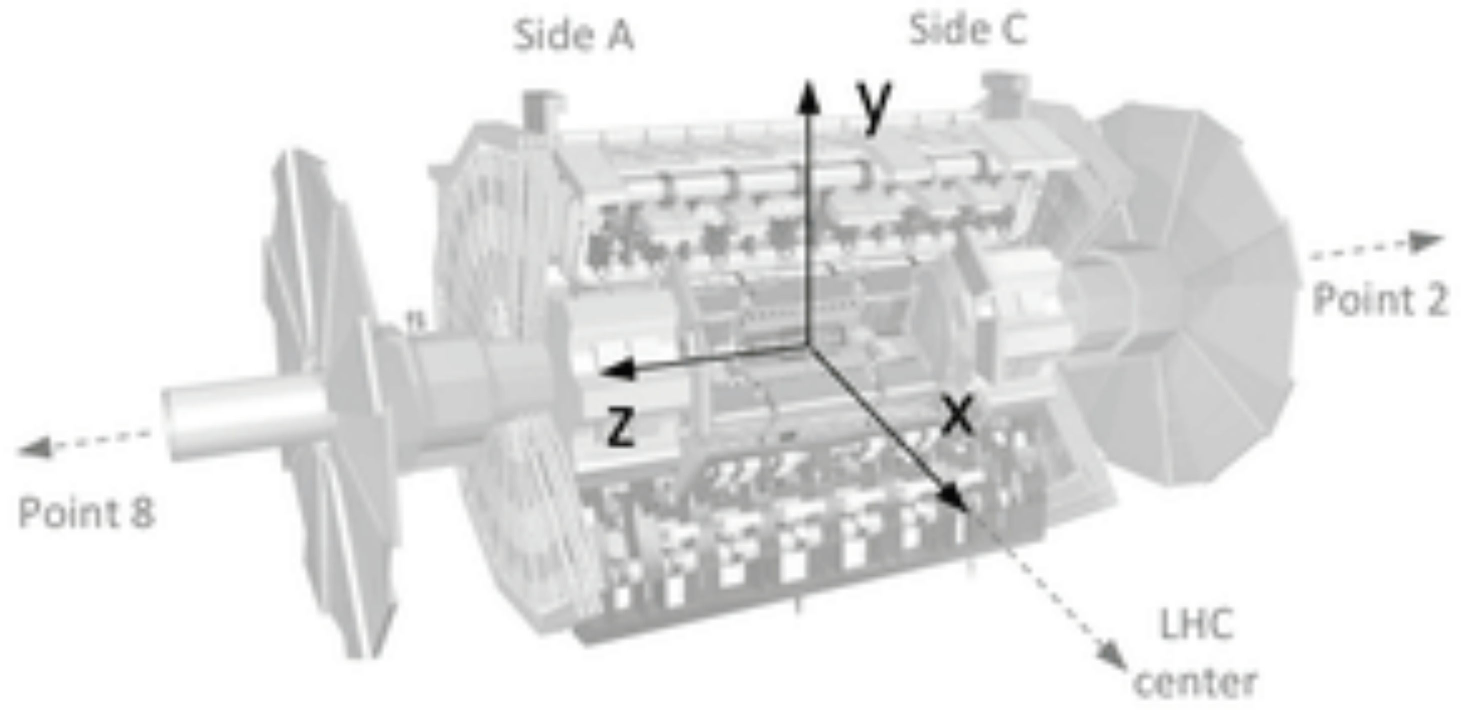
- Hardware-based system: identifies events containing calorimeter-based physics objects, including electrons, photons, tau leptons, jets, and missing energy
- Trigger Objects (TOBs) identified and sent to L1 Topological trigger (L1Topo) for additional selection
- Objects multiplicities sent to L1 Central Trigger (L1CTP) for final L1Accept decision



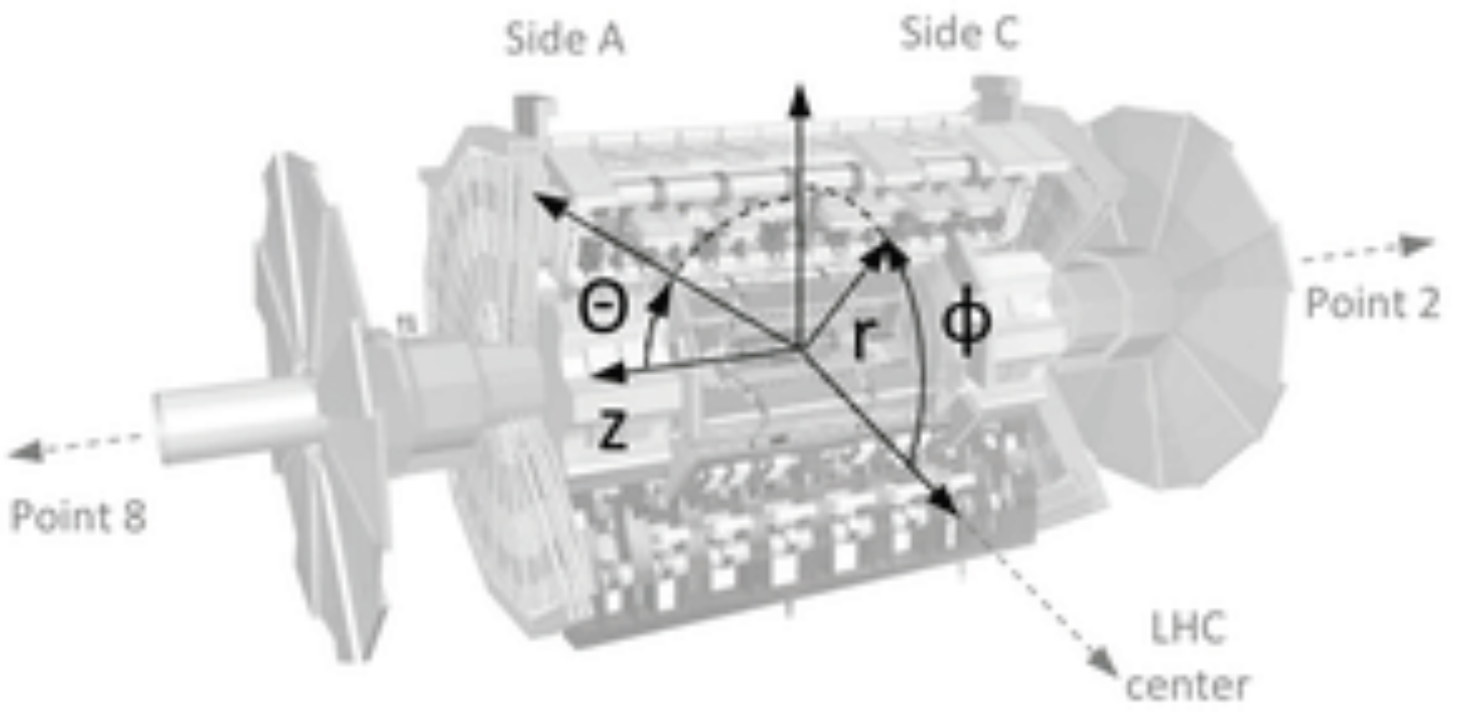


The ATLAS Coordinate System

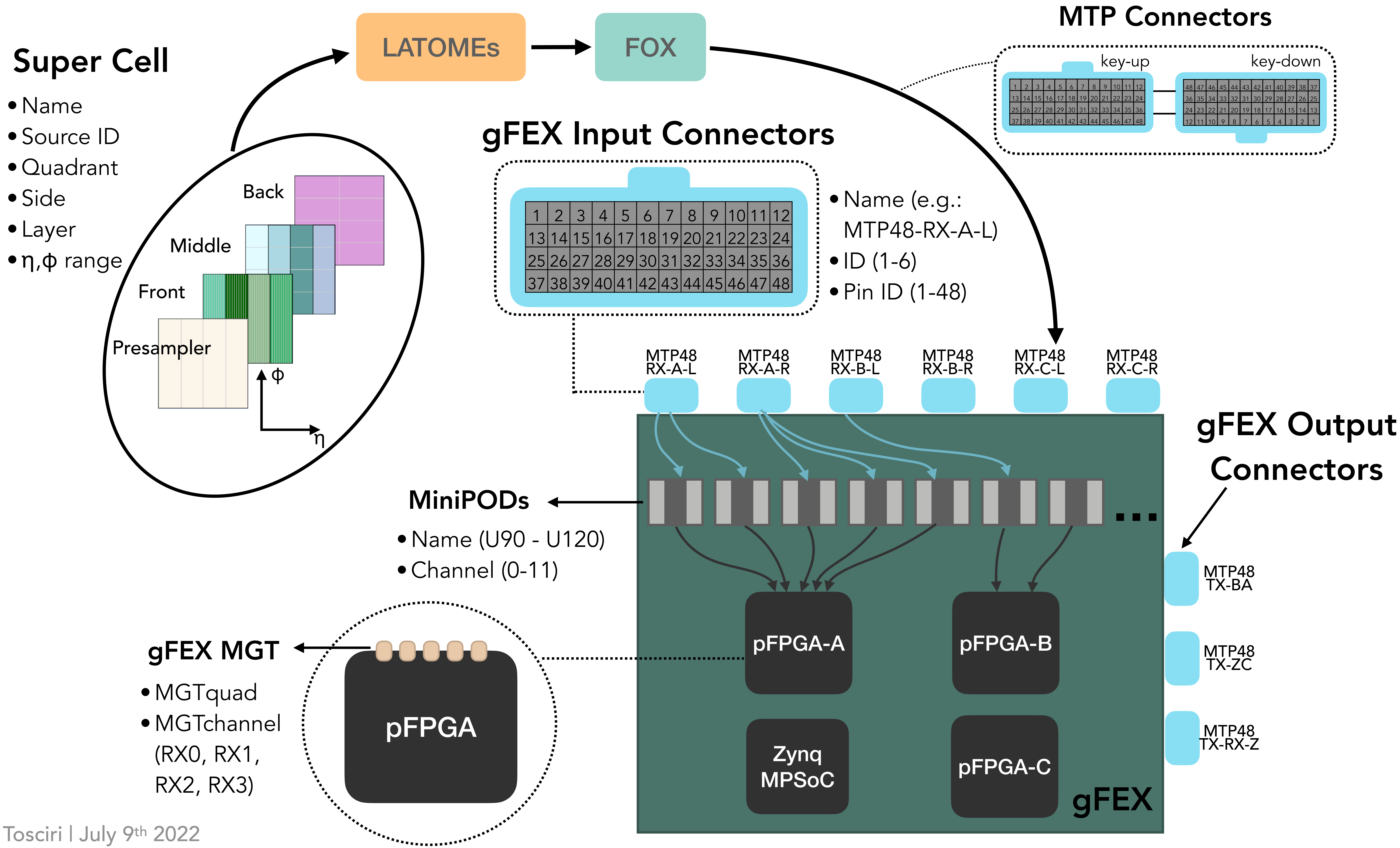




x-y-z right-handed Cartesian coordinate system



r-ϕ-z cylindrical coordinates and **Θ** - visualization


Super Cell
• Name
• Source ID
• Quadrant
• Side
• Layer
• η,ϕ range
Back
Middle
Front
Presampler
ϕ
η
LATOMEs
FOX
MTP Connectors
key-up
key-down
gFEX Input Connectors
1 2 3 4 5 6 7 8 9 10 11 12
13 14 15 16 17 18 19 20 21 22 23 24
25 26 27 28 29 30 31 32 33 34 35 36
37 38 39 40 41 42 43 44 45 46 47 48
• Name (e.g.: MTP48-RX-A-L)
• ID (1-6)
• Pin ID (1-48)
MTP48 RX-A-L
MTP48 RX-A-R
MTP48 RX-B-L
MTP48 RX-B-R
MTP48 RX-C-L
MTP48 RX-C-R
gFEX Output Connectors
MTP48 TX-BA
MTP48 TX-ZC
MTP48 TX-RX-Z
MiniPODs
• Name (U90 - U120)
• Channel (0-11)
...
pFPGA-A
pFPGA-B
Zynq MPSoC
pFPGA-C
gFEX
gFEX MGT
• MGTquad
• MGTchannel (RX0, RX1, RX2, RX3)
pFPGA

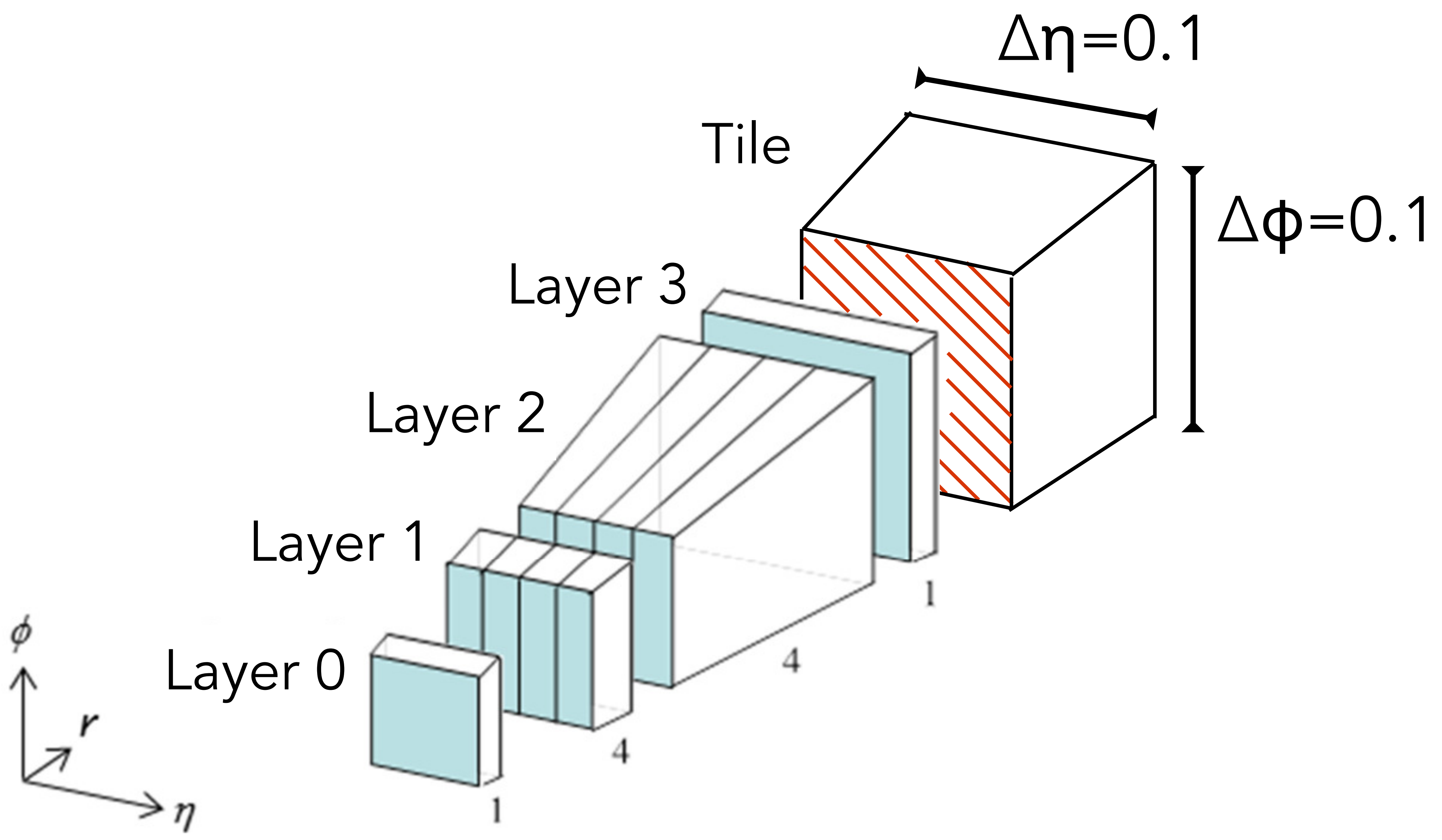
gTowers

Each FEX receives data from LATOME (SuperCells from LAr calorimeter) and TREX (input from Tile calorimeter)

Super Cells (SC) retrieved from CaloCellContainer

Variable granularity, up to $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$, depending on the sub-detectors origin

Tile Towers (TT) retrieved from TriggerTowerContainer, cover the pseudo-rapidity range $|\eta| < 1.6$ and the full azimuthal range (ϕ), more regular binning



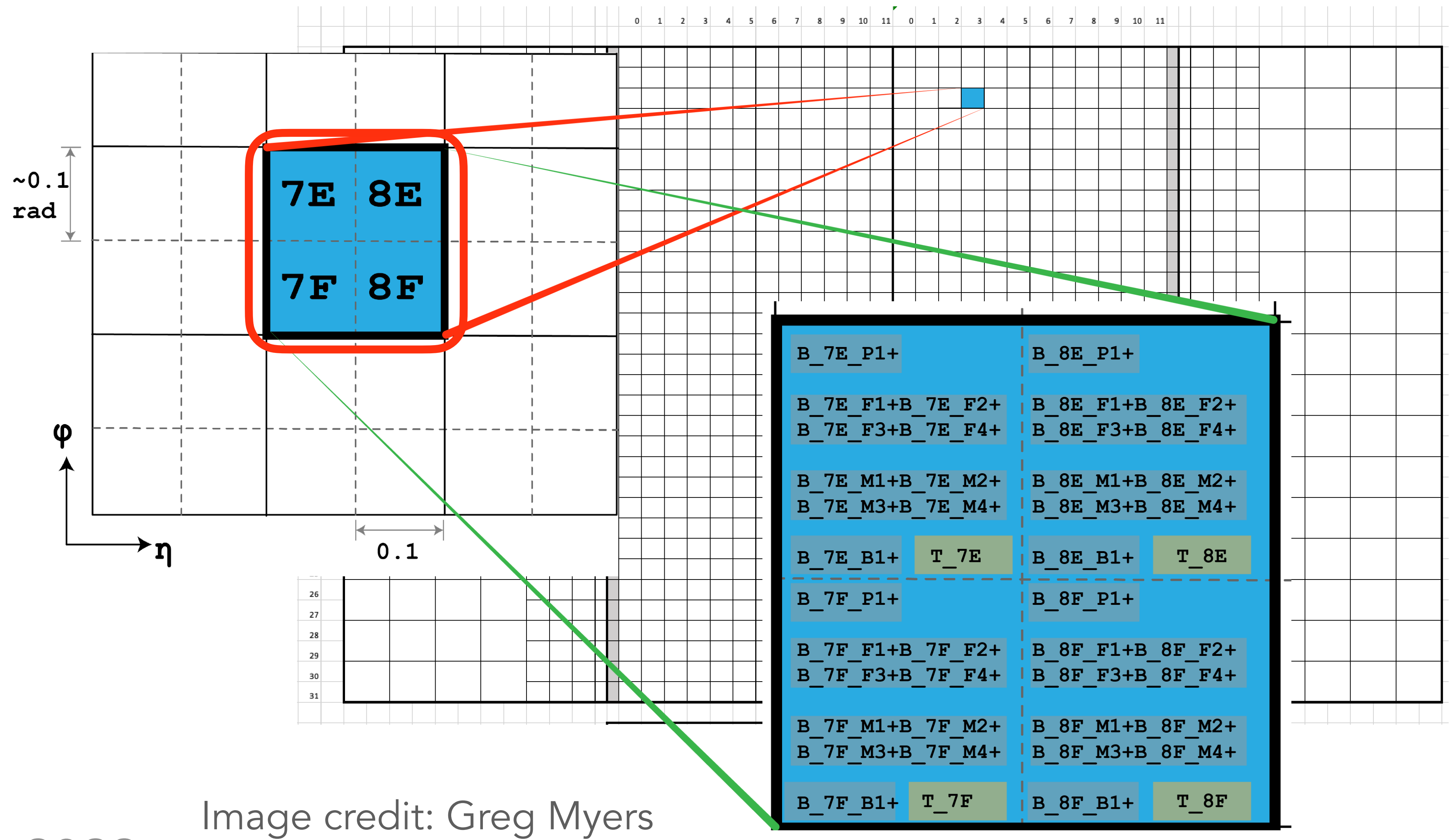


Image credit: Greg Myers

- A gTower is a combination of SC and TT
- gTowers (typical size 0.2x0.2 in $\Delta\eta \times \Delta\phi$ in barrel, 0.4x0.4 in forward)

gFEX MET Alternative Algorithms

Noise cut (Run-2 Style)

- Existing in the FW but not merged into main development branch
- Evaluate noise σ according to the RMS of the E_T distribution for each gTower
- Apply cut $E_{T,gTower} > 4\sigma$
- Compute MET by evaluating the *x*,*y* components, using non-zero towers:

$$\text{MET}_x = \sum_t E_T^t \times \cos\phi^t, \text{MET}_y = \sum_t E_T^t \times \sin\phi^t$$

Rho+RMS

- Ongoing development
- Pileup subtraction using

$$\rho = \frac{\sum_{i \in gTowers} E_{T,i}}{\sum_{i \in gTowers} n_i} \quad (E_{T,i} < 10 \text{ GeV})$$

- σ estimated with the RMS of gTower energy (dynamic computation)
- 3σ noise cut applied to each gTower
- Compute MET:

$$\text{MET}_x = \sum_t E_T^t \times \cos\phi^t, \text{MET}_y = \sum_t E_T^t \times \sin\phi^t$$