GENOVA

BOOST 2024

16th International Workshop on Boosted Objects Phenomenology

ATLAS EXPERIMENT est. 2022 13.6 TeV LHC RUN 3

Triggering Jets in Run3 with the ATLAS Global Feature Extractor

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gFEX

- The Global Feature Extractor (gFEX) as part of the upgraded Level-1 Calorimeter Trigger System
- gFEX Architecture & Algorithms
- gTowers Calibration
- gFEX MET Trigger Performance
- gFEX Large-R jets Trigger Performance
- gFEX for triggering on emerging jets

The ATLAS Trigger System in Run3

Event size

LHC Collision rate
40 MHz

3.0 MB

~2.5 μs

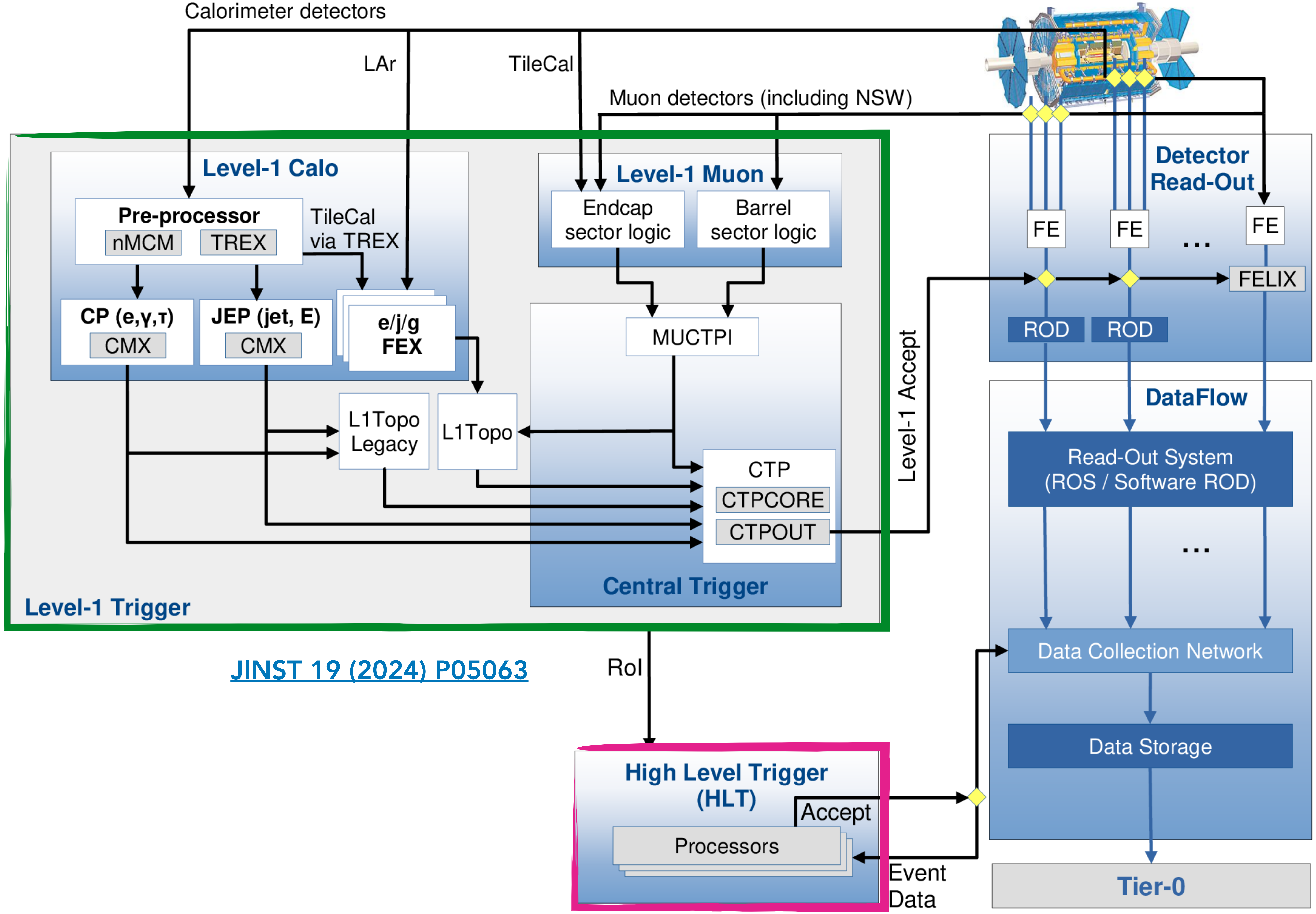
L1 acceptance rate
~100 kHz

300 GB/s

~500 ms

HLT output rate
~2 kHz

8 GB/s



JINST 19 (2024) P05063

ATLAS Level-1 Trigger

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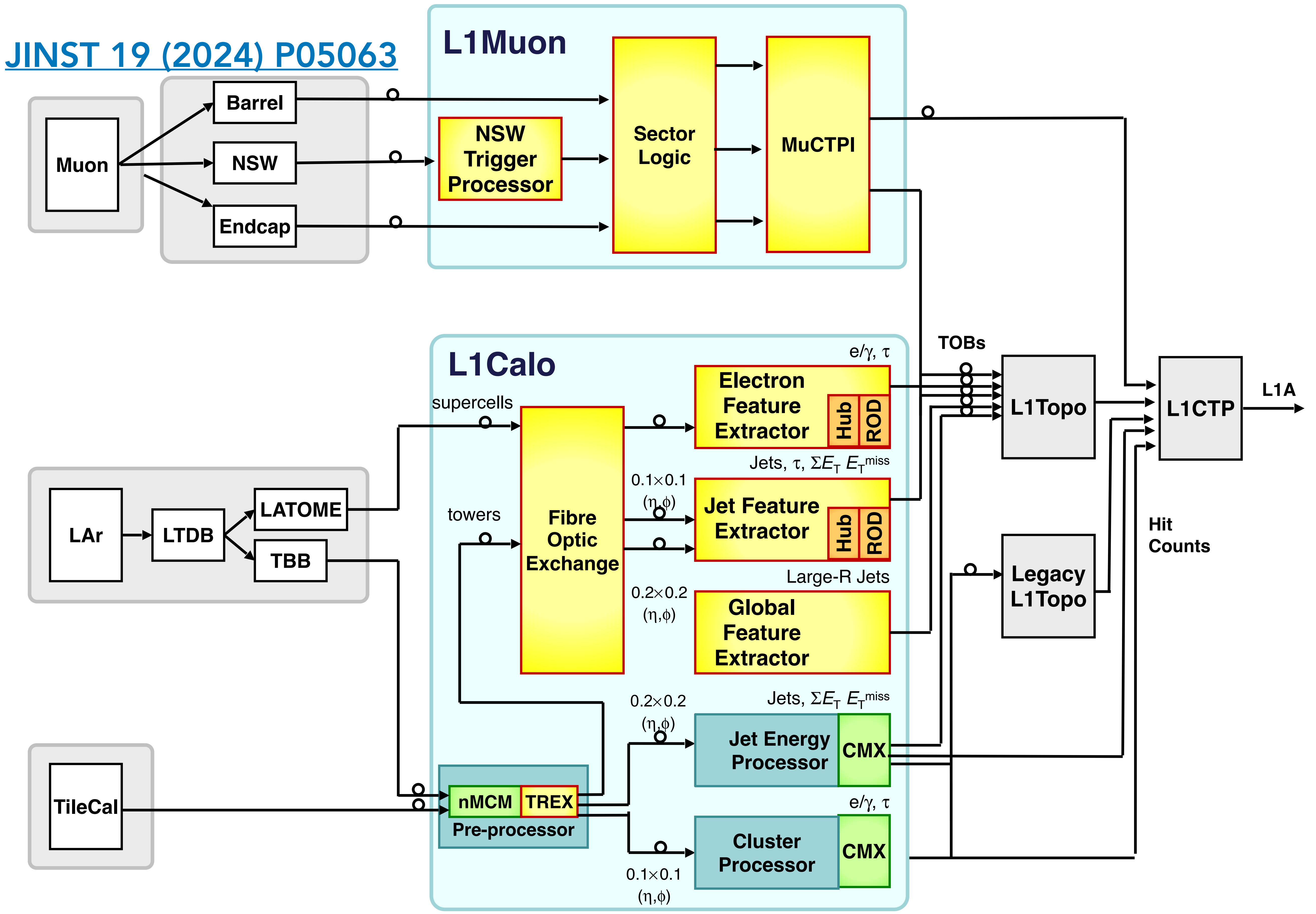

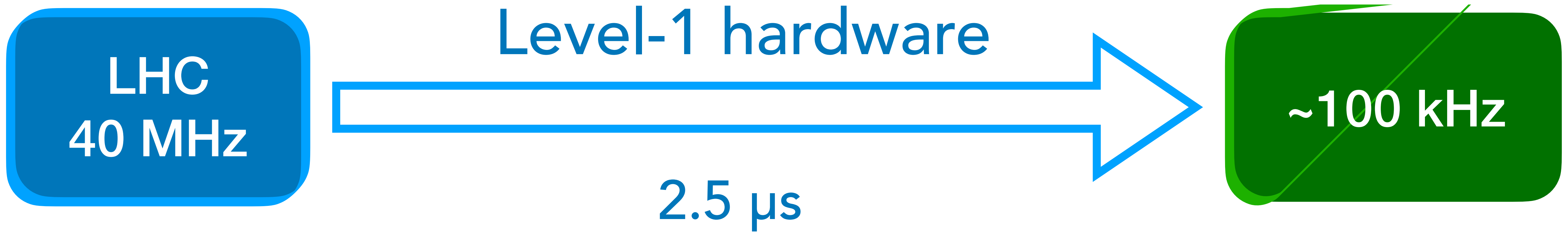

Phase-I Upgrade

Hardware and software upgrades to improve performance of trigger in high-luminosity and high pile-up environment in Run-3

ATLAS Level-1 Calorimeter Trigger

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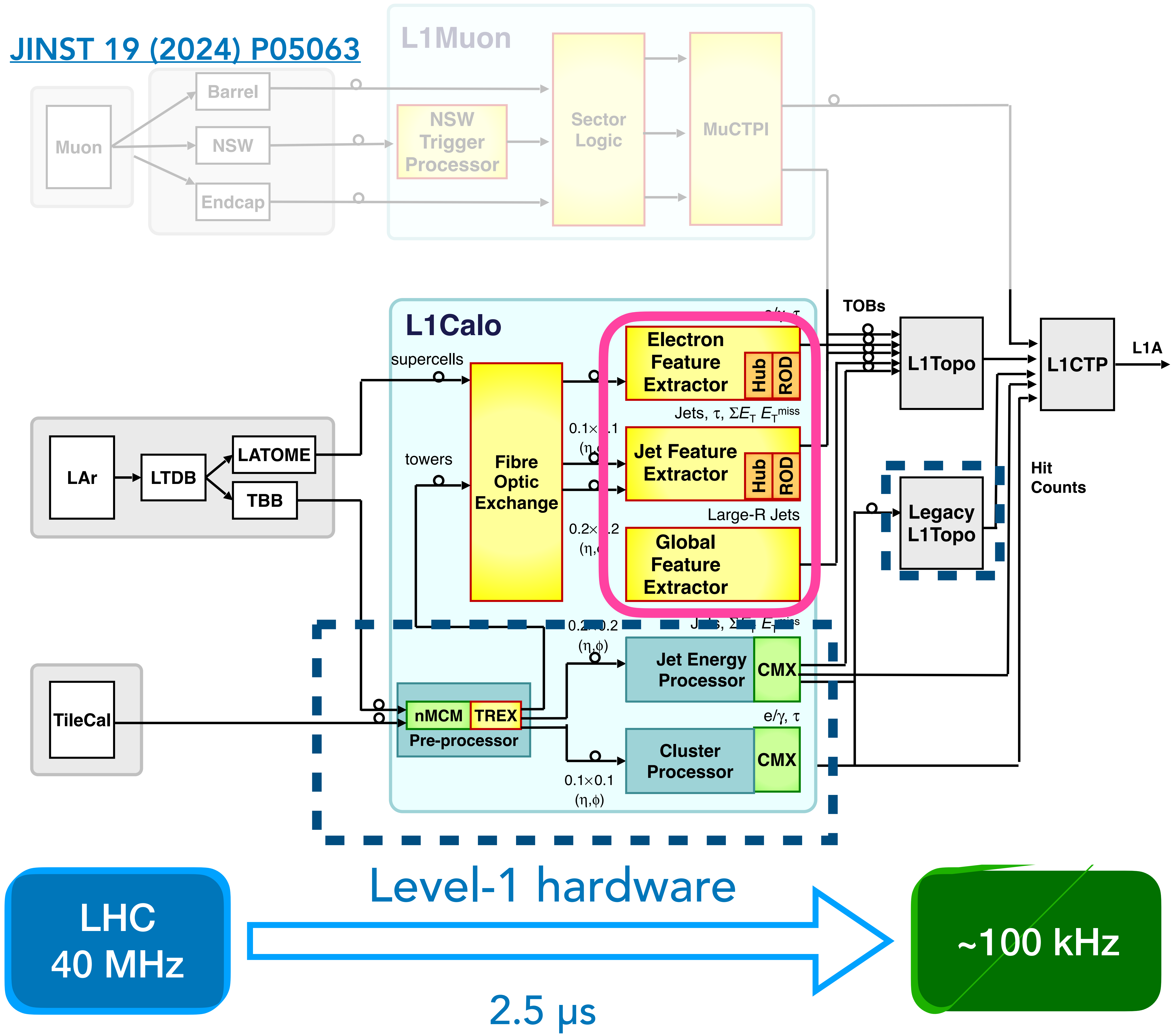

- ATLAS **Phase-I Upgrade** includes significant upgrades for the Run 3 Level-1 Calorimeter trigger system
- Inputs from Liquid Argon (LAr) and Tile calorimeters
- Increased granularity of the LAr calorimeter inputs
- New Feature EXtractor (FEX) modules to identify events containing calorimeter-based physics objects: e/γ, τ, jets, and MET
- Custom-made electronics (high-power **FPGAs**) to implement more sophisticated algorithms
- **Phase-I system** running in parallel to the **Legacy system** during the commissioning phase

ATLAS Level-1 Calorimeter Trigger

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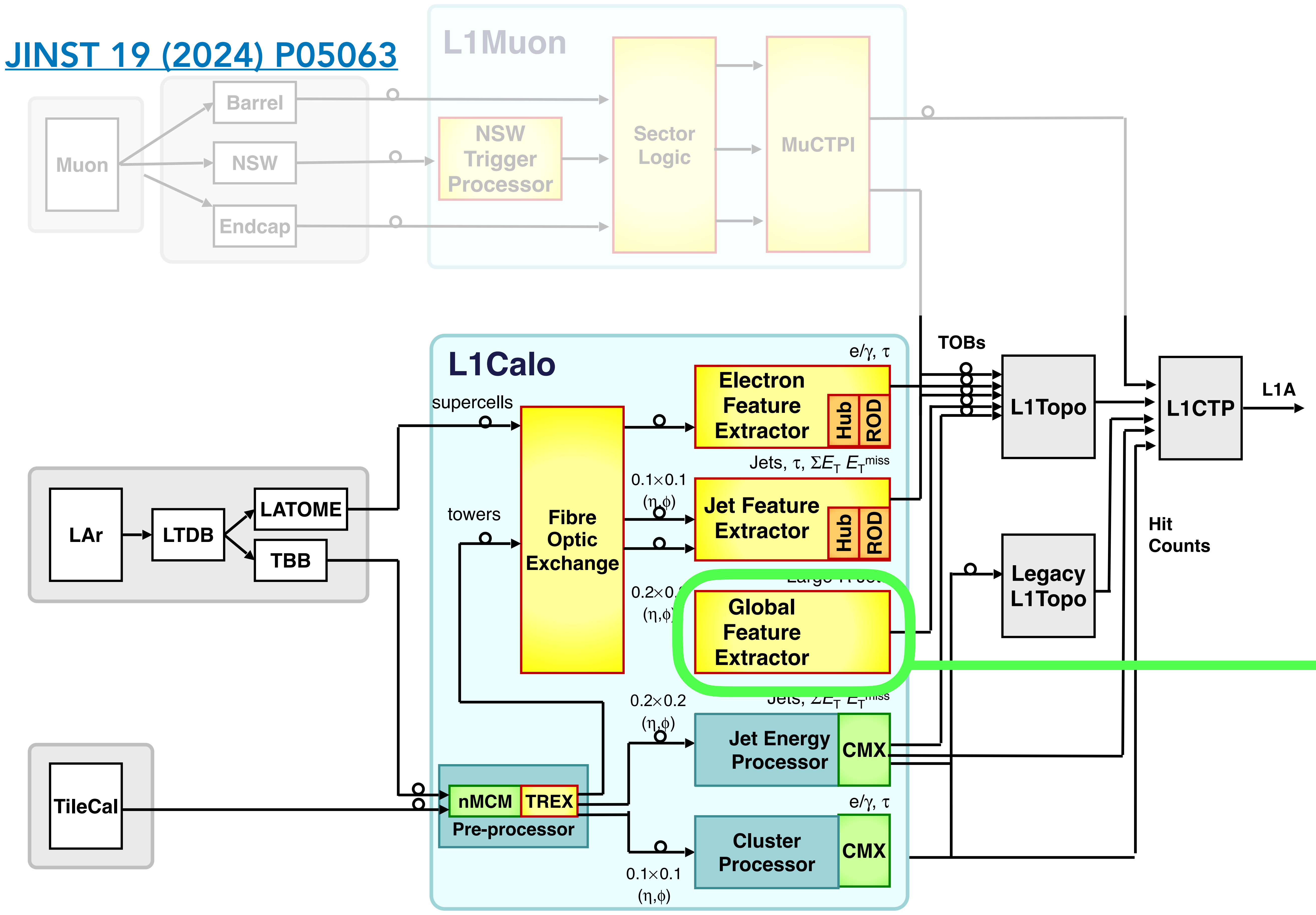

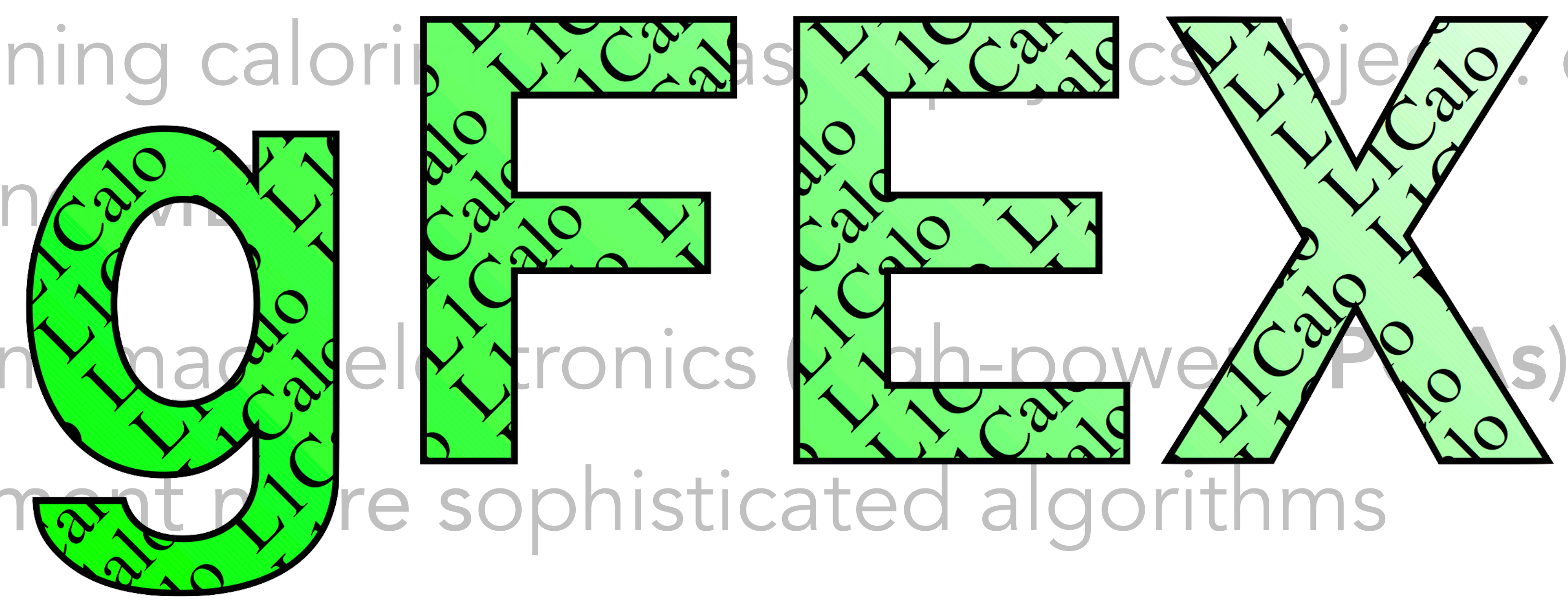

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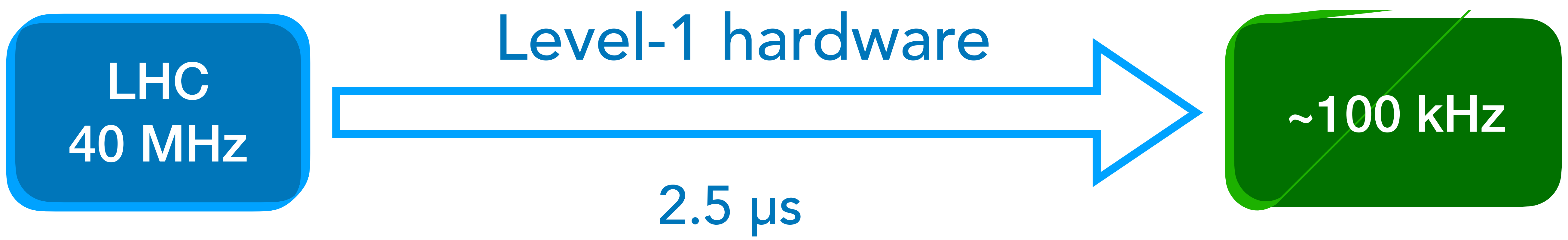
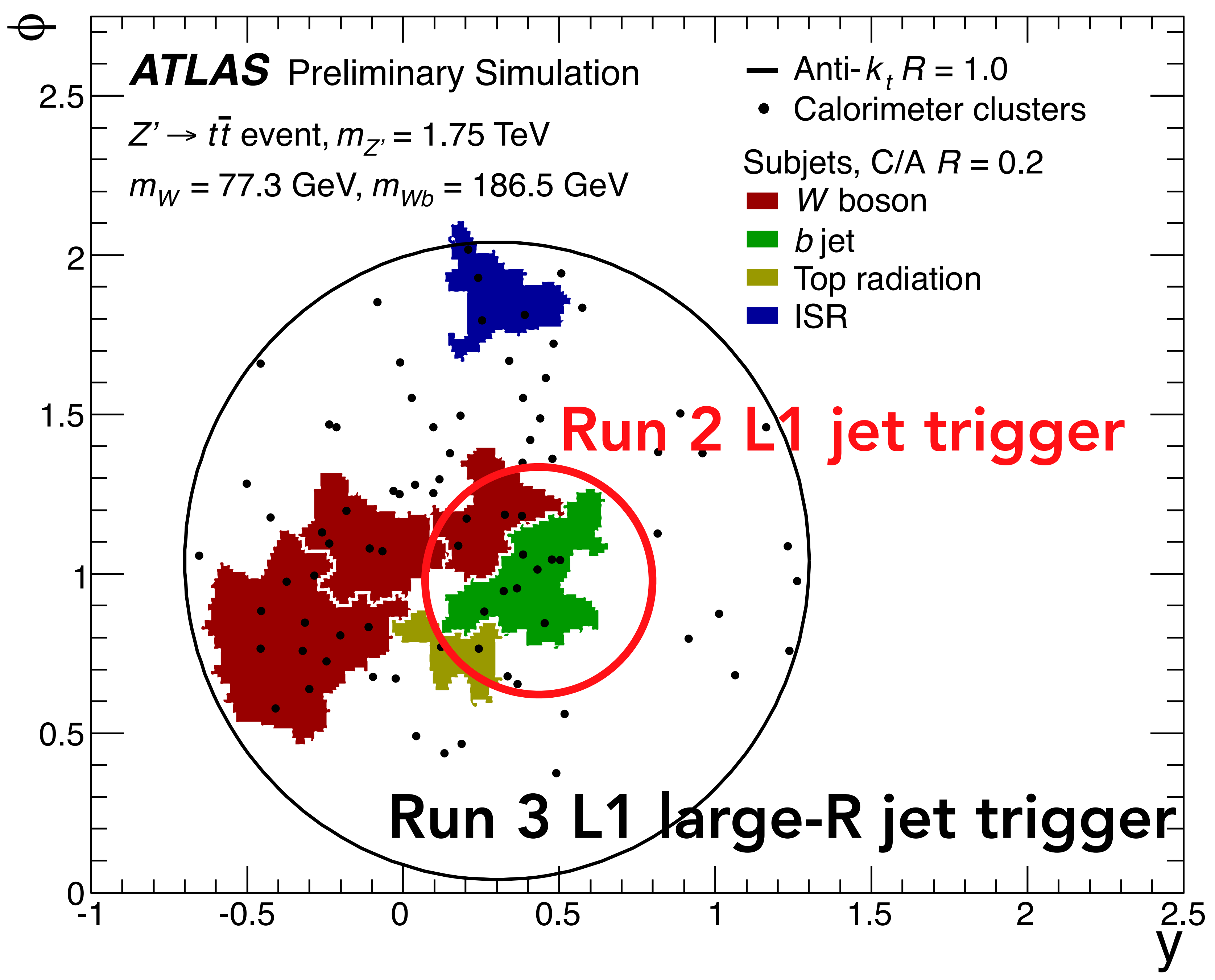


gFEX global Feature EXtractor

- Designed to provide **large-radius jet triggers**, estimation of **local pile-up**, **MET**, and other global observables for triggers at low rates and maximal acceptance
- Full calorimeter available in a single module: the algorithms can scan the entire η-ϕ range
- 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

Event display of a shower from simulated top quark decay



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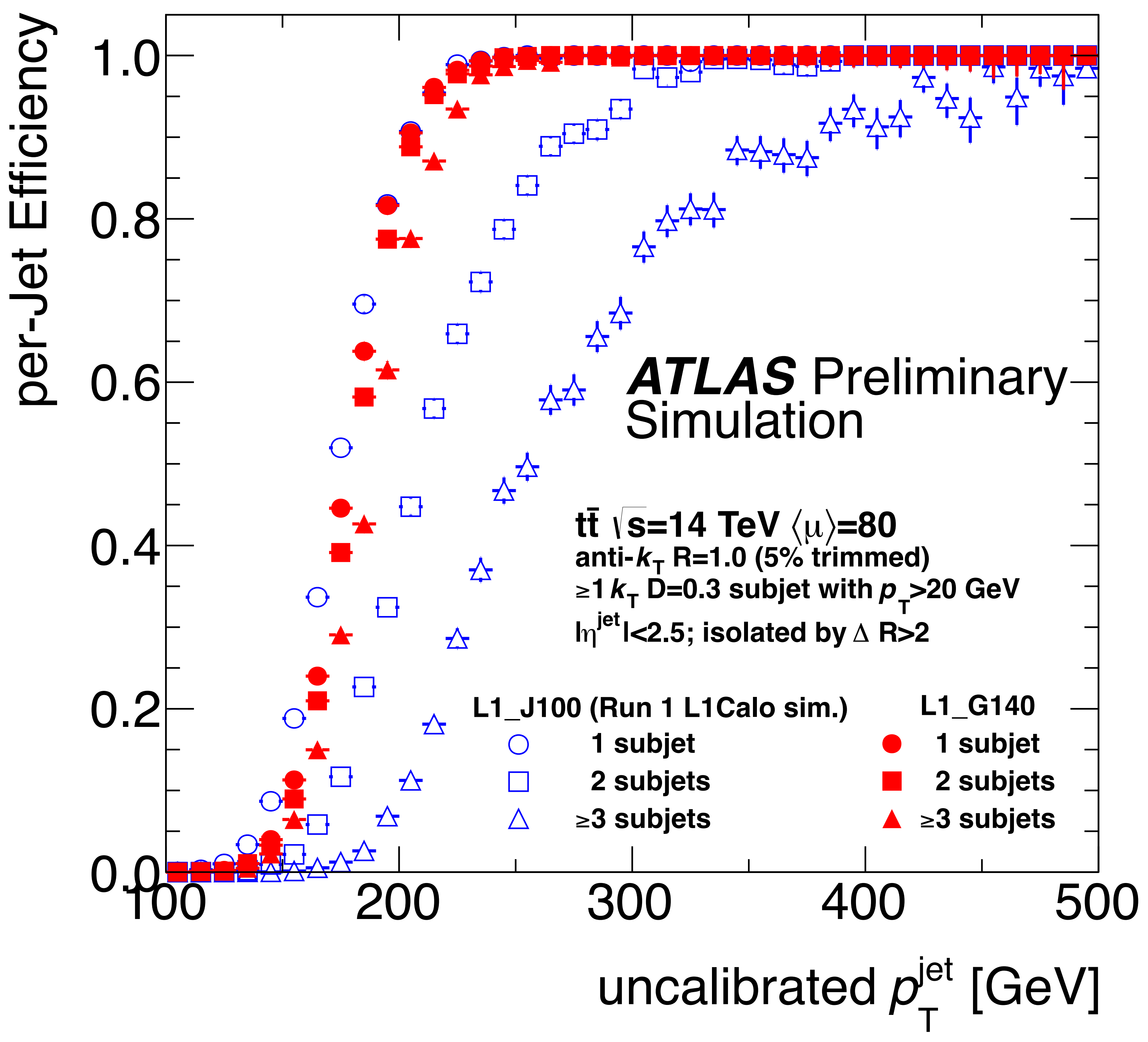
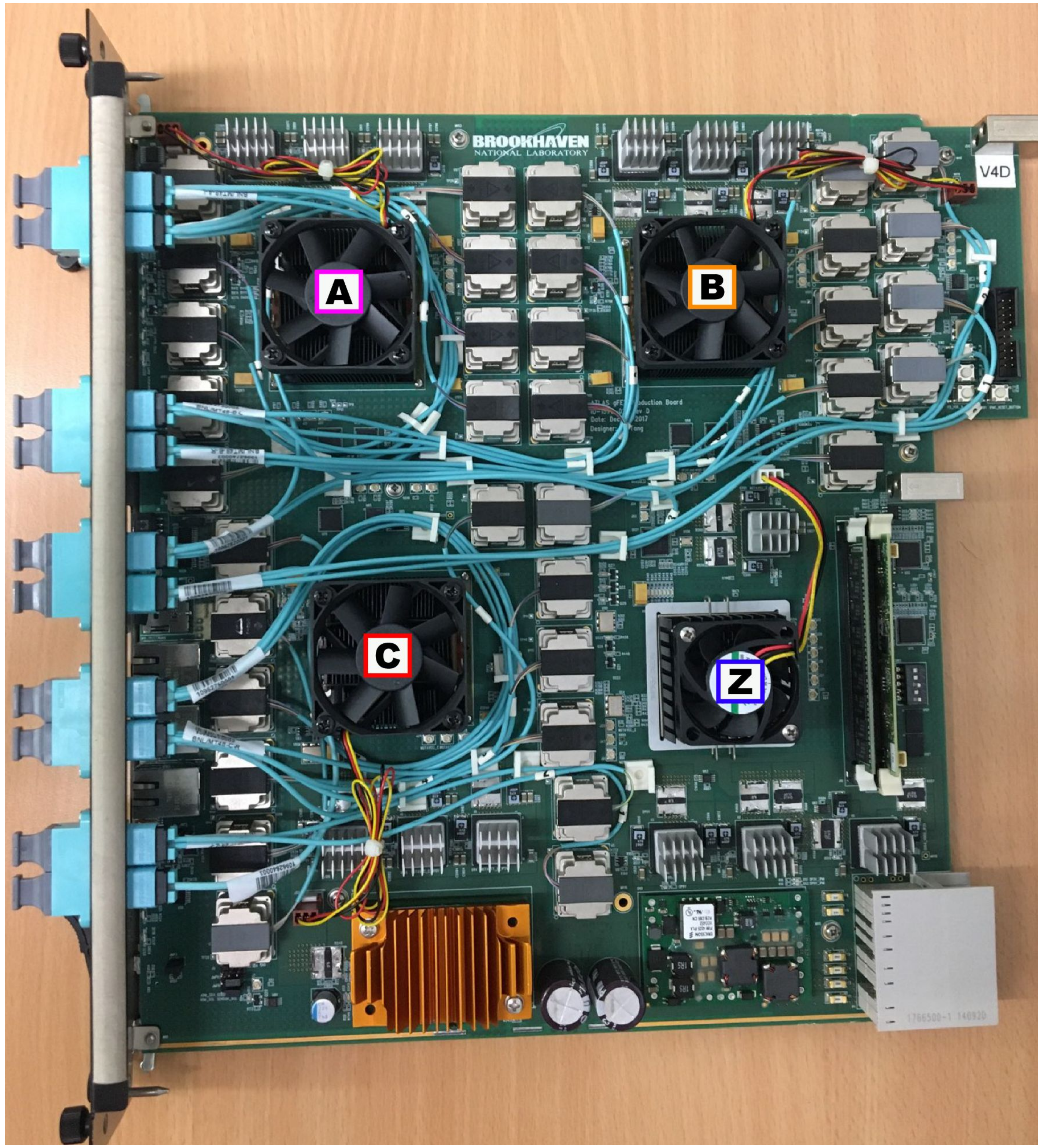


Expected performance of gFEX large-R jet trigger vs Run-1 L1Calo small-jet trigger

gFEX Components

- Three Vertex Ultrascale+ processor FPGAs (pFPGAs A, B, C) process calorimeter data via low-latency links
- Each pFPGA executes feature identification algorithms covering different regions of η:
  - FPGA-A: $-2.5 < \eta < 0$
  - FPGA-B: $0 < \eta < 2.5$
  - FPGA-C: $2.5 < |\eta| < 4.9$
- Zynq (Z) is a Multi Processor System-on-Chip (Zynq SoC) which combines an FPGA and a CPU
- Zynq provides configuration and monitoring for gFEX, implements a Linux operating system, and the on-board Detector Control System (DCS)



gFEX Architecture

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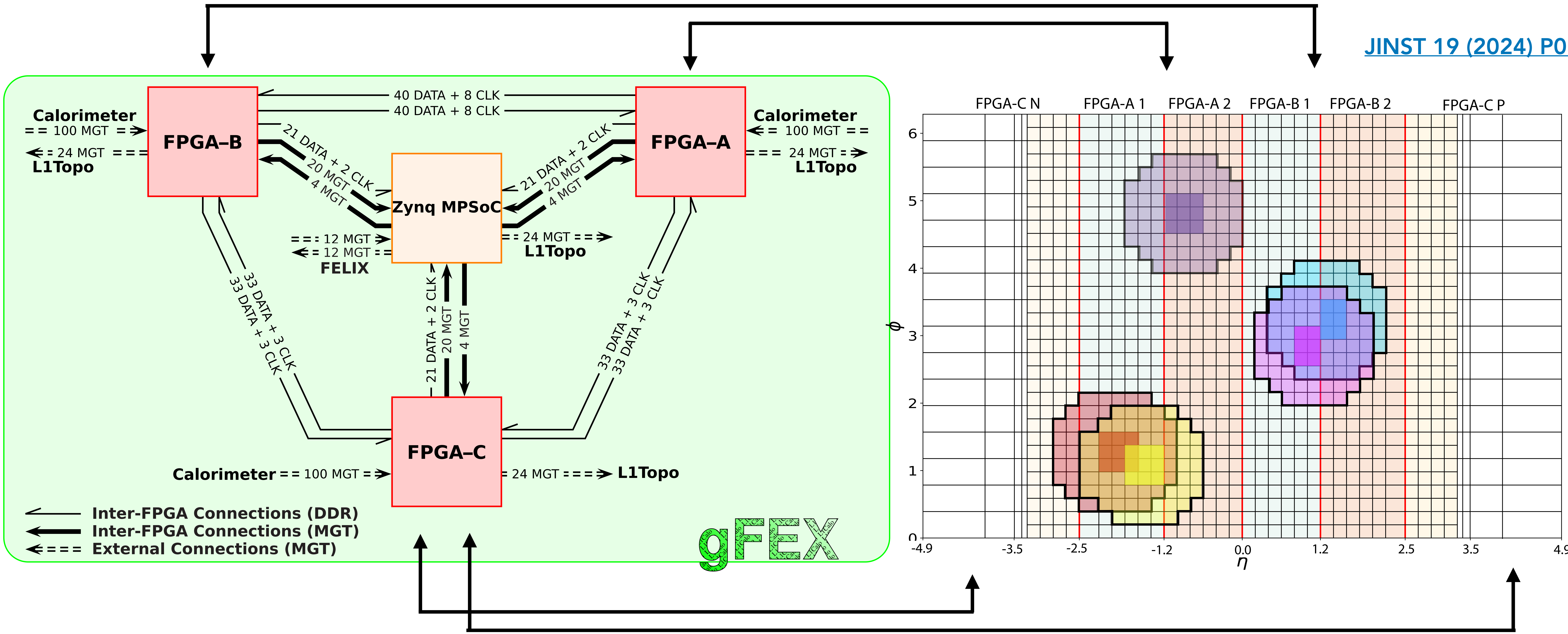
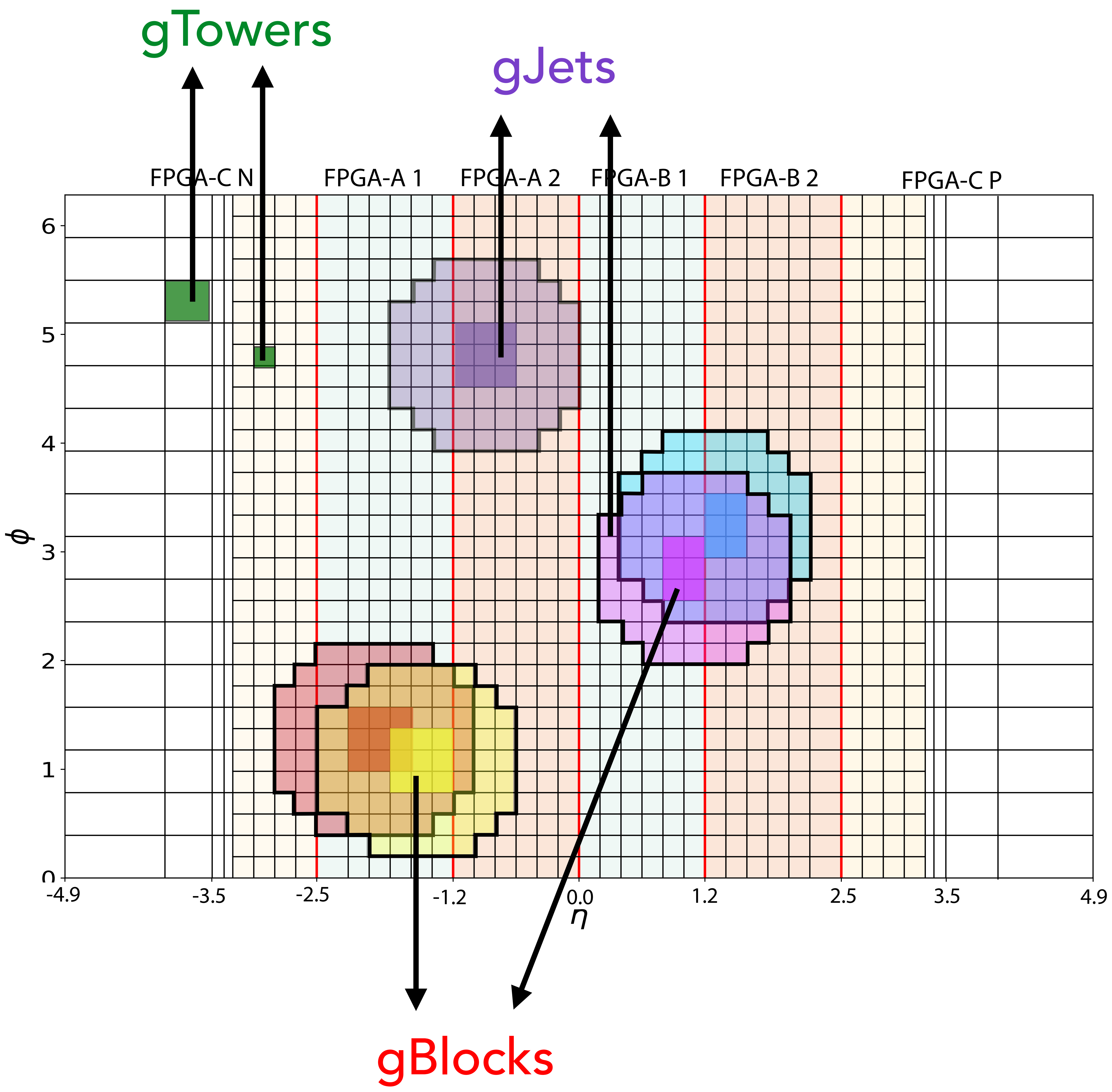


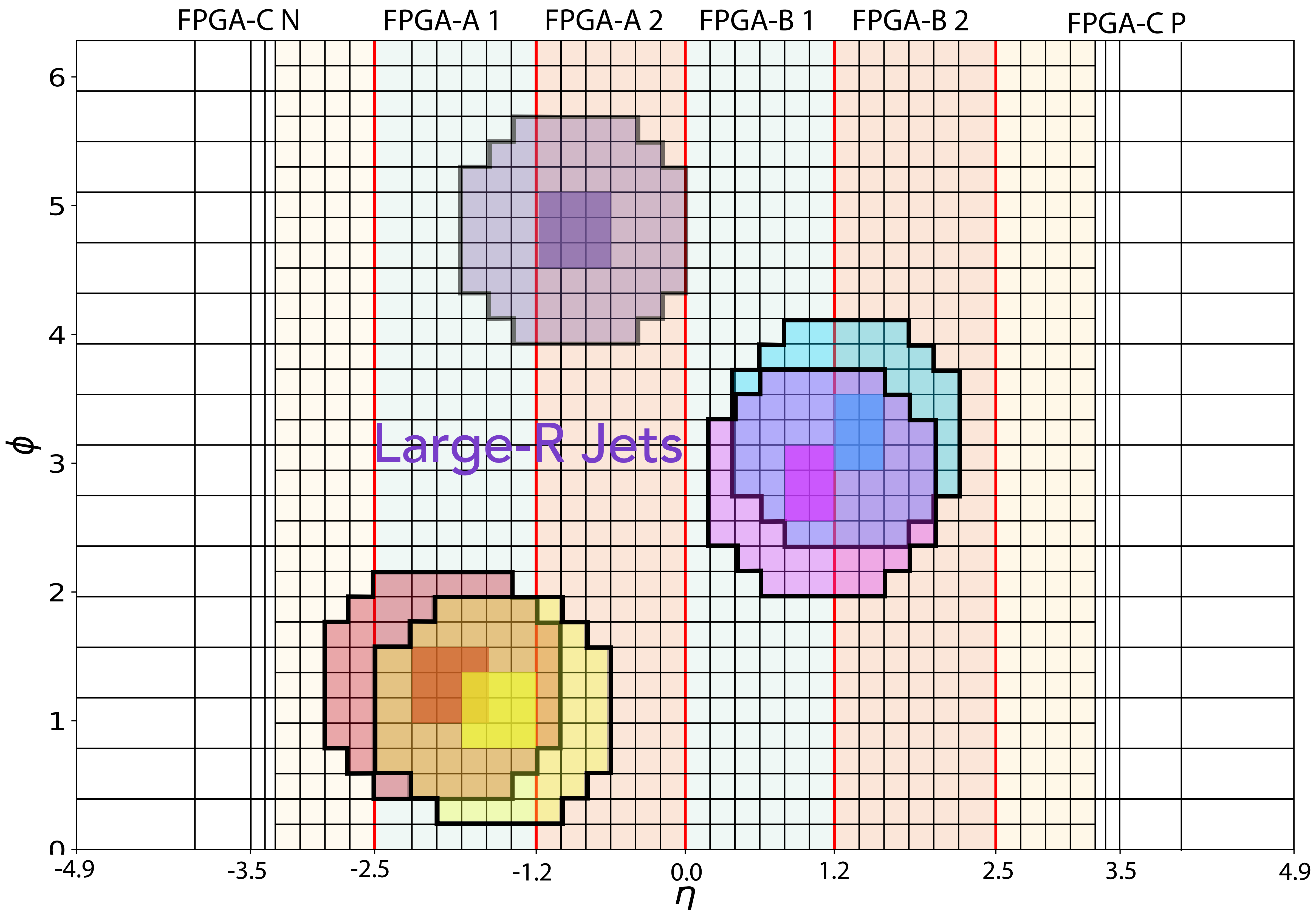
- pFPGAs: receive input fibers from calorimeter and send output jet trigger objects to Zynq and L1Topo
- Zynq SoC receives data from pFPGAs and computes global quantities that are sent to L1Topo (MET)
- The pFPGAs communicate with each other via low-latency links (inter-FPGA communication)

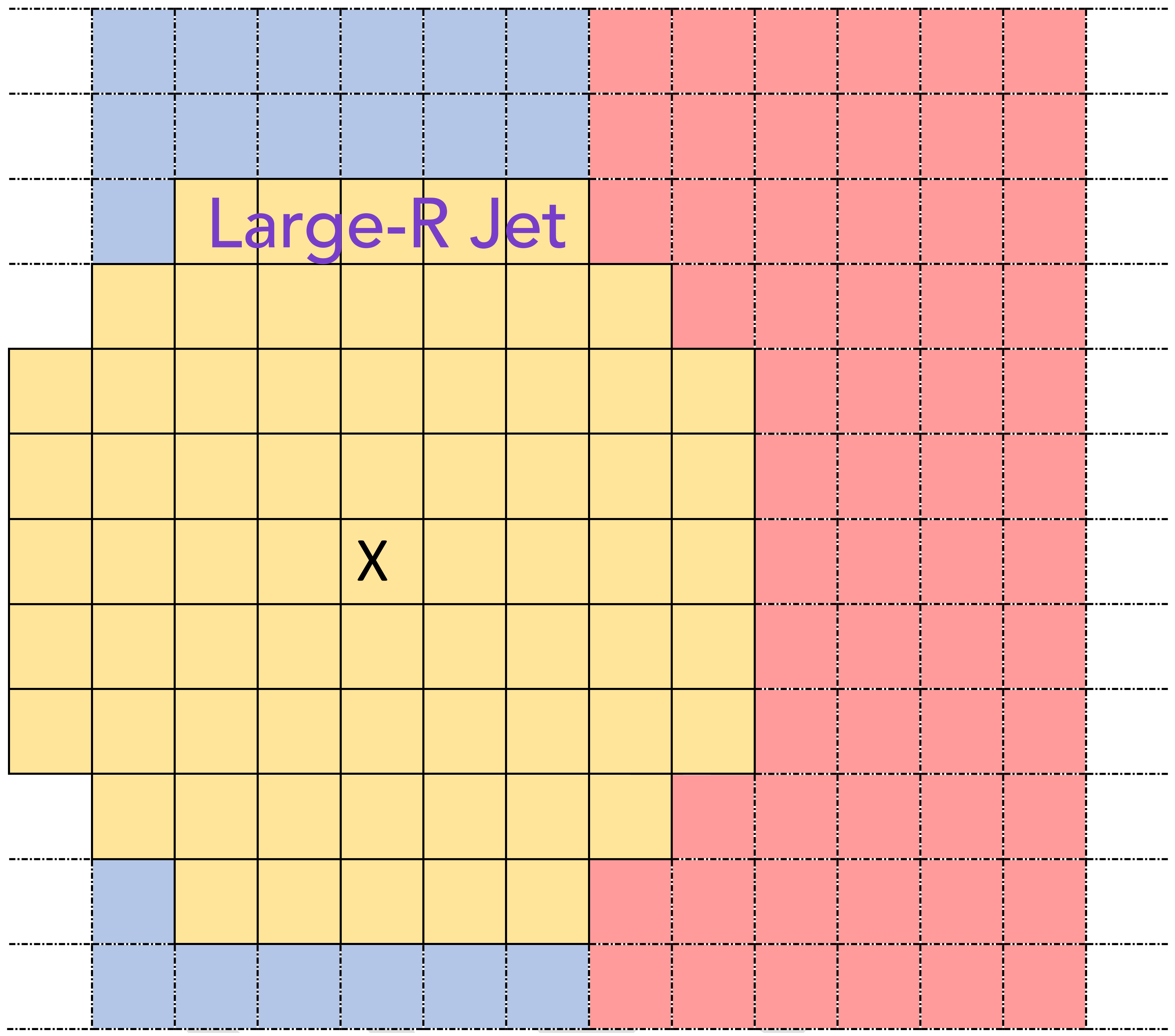
Jet Finder Algorithm

- gTowers: the digital units of gFEX with typical size **$\Delta\eta \times \Delta\phi$=0.2x0.2** (but larger in forward region), constructed in the **gTower Builder** with inputs from LAr ($\Delta\eta \times \Delta\phi$= 0.025x0.1) and Tile calorimeter ($\Delta\eta \times \Delta\phi$= 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 (requiring gBlock seed above threshold)
  - Pile-up correction is performed by subtracting the energy density ρ from the gJet energy (per tower)
- For each pFPGA, the algorithm outputs the following Trigger Objects (TOBs): energy density ρ, 4 gBlocks and 2 gJets with highest E_T (**only central objects are sent to the L1Topo system**)



Large Jets with gFEX





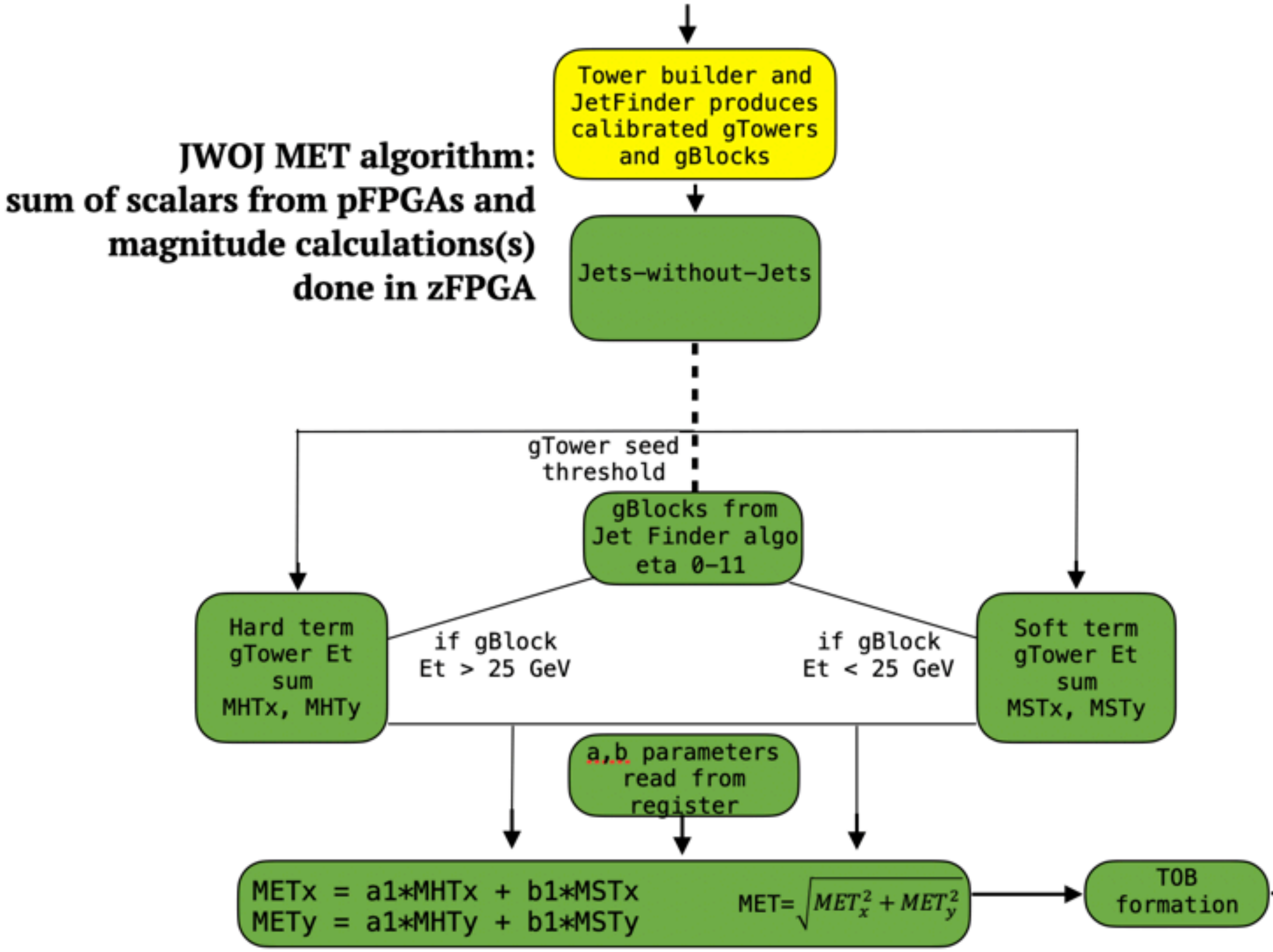
- The jet finder algorithm determines the sum of energies in the 69 towers forming a large-R jet
- All possible large-R jet locations are evaluated on every bunch crossing
- Algorithm selects most energetic jet with a central gBlock (3x3 region) above 20 GeV threshold
- No requirement that the central gBlock is a local maximum (no requirements on sub-structure)
- No plans to use large R jets with centers having leta|>2.5

Jets without Jets Algorithm

- Default algorithm for missing transverse energy (MET) calculation
- <u>Original proposal for Jets without Jets JHEP04(2014)013</u>
- Receives gTowers and gBlocks (small-R jets) 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: $\text{MET}_{x,y} = a_{x,y}\,\text{MHT}_{x,y} + b_{x,y}\,\text{MST}_{x,y}$
- *a, b* 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

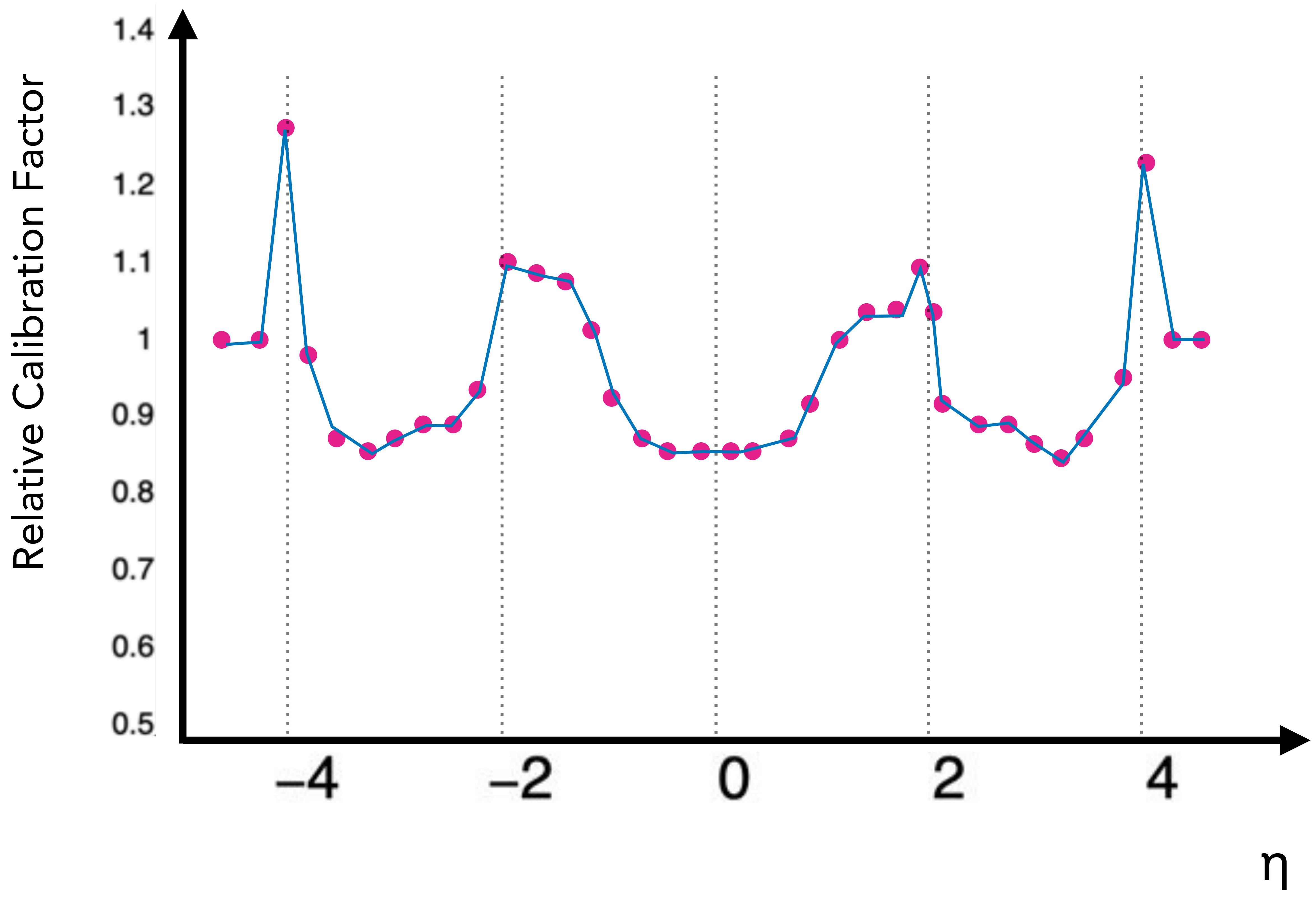


gTower Calibration

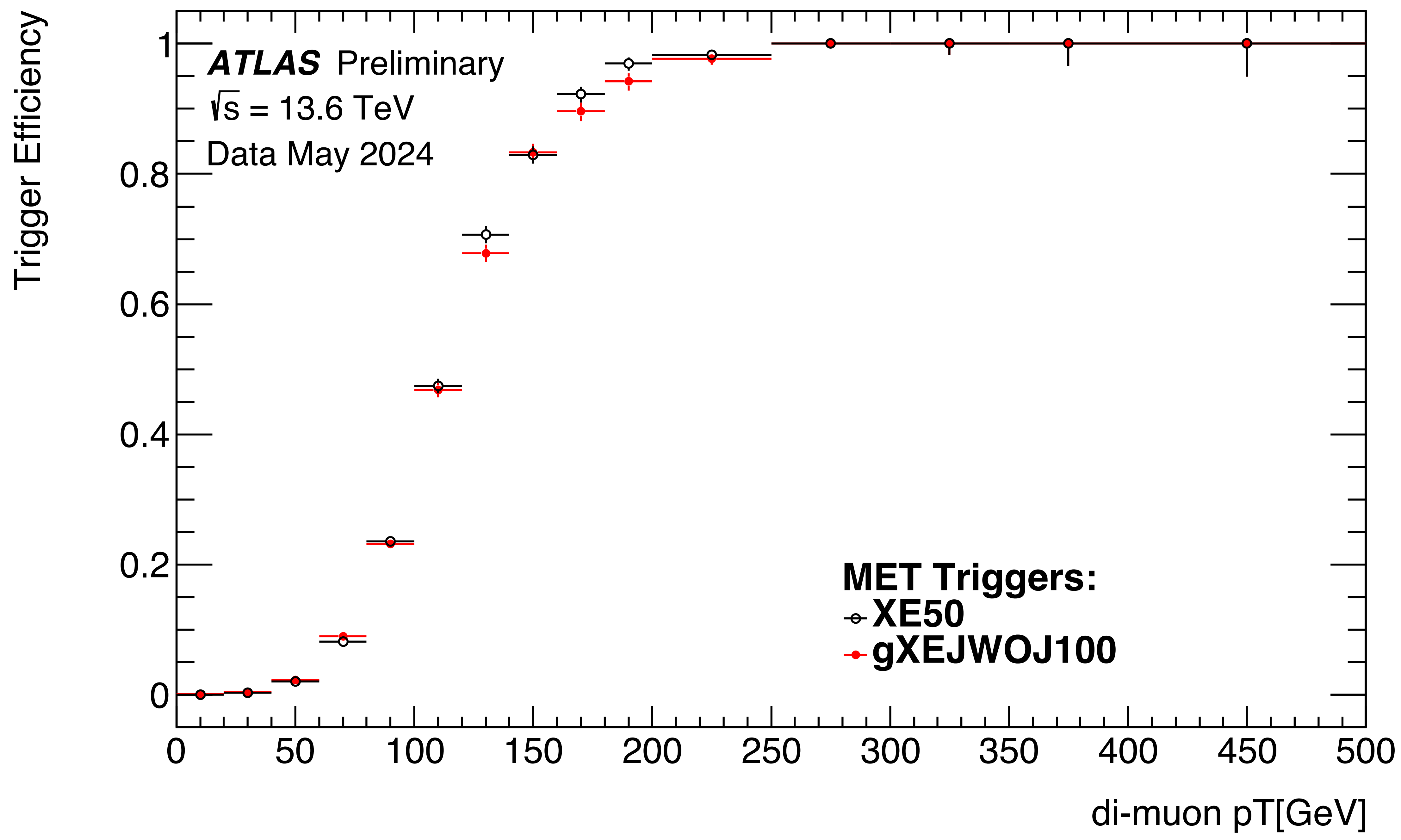
- gFEX implements calibration at the tower-level (important for MET evaluation)
- Eta-dependent calibration
- Using a $Z(\rightarrow \mu\mu) + jet$ selection
- For energy balance in the (Z, jet) system, require $Z_{pT} > 50$ GeV, $\Delta\Phi(Z, jet) > 1$
- In each eta bin for each FPGA:
    - Calculate the sum of energy in the gTowers within $\Delta R = 0.4$ around the offline jet with highest p_T

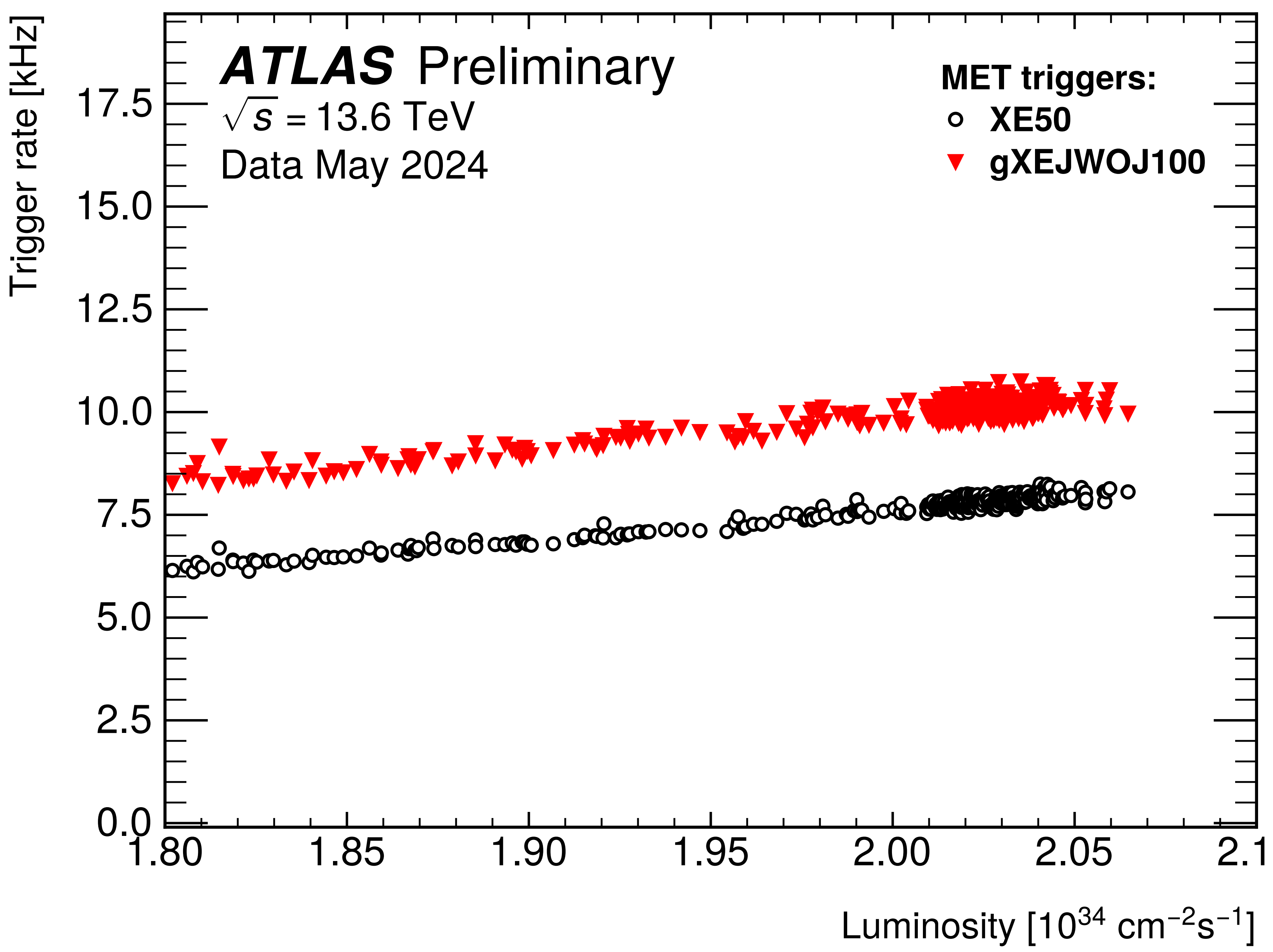
$$CF = \frac{\sum_{\Delta R=0.4} gTowerE_T}{Offline\ jet\ E_T}$$

- The calibration factor is extracted as the mean of the distribution in each eta bin
- The tower calibration has been recently deployed in firmware



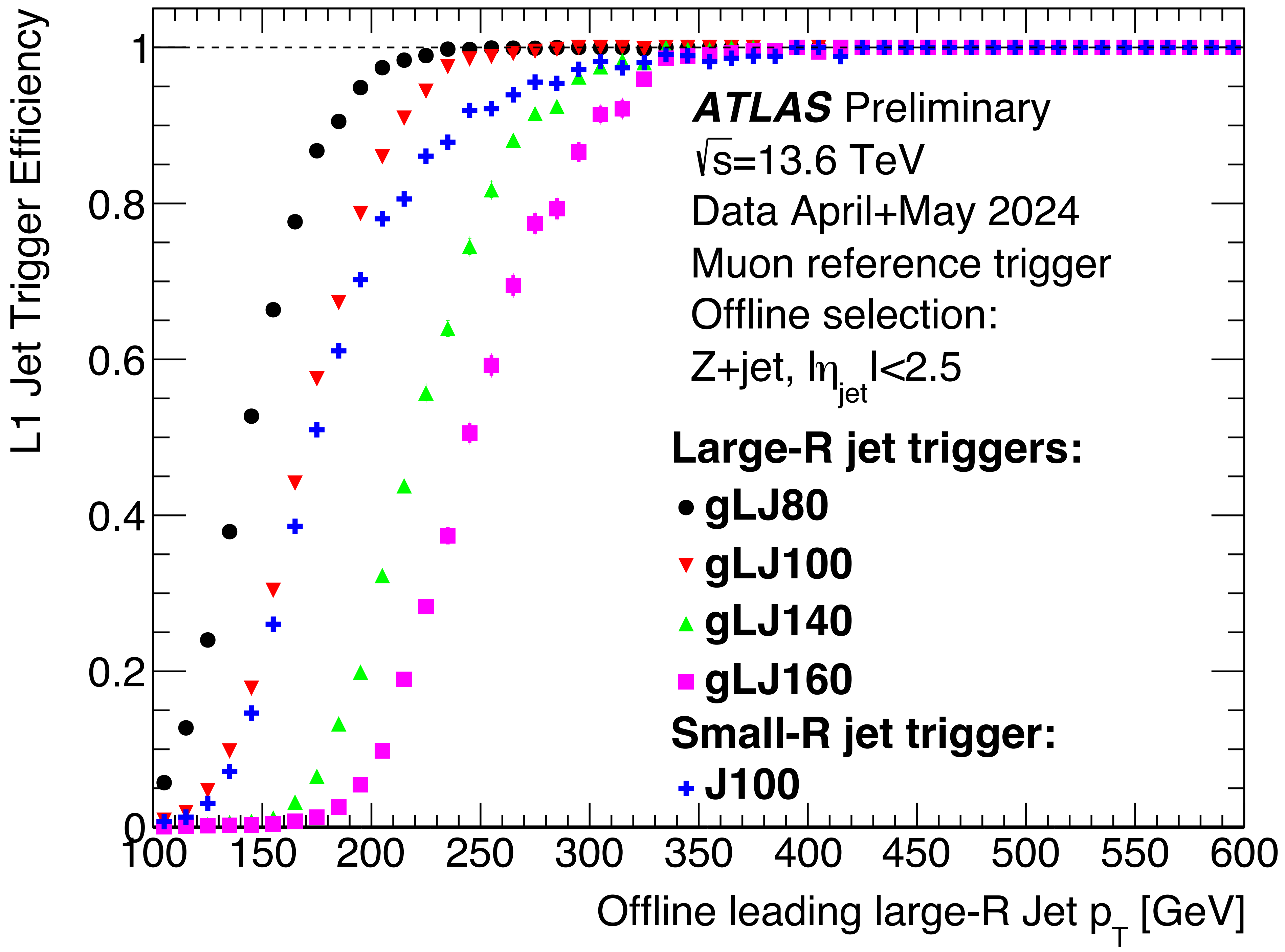
JwoJ MET Trigger Performance in 2024

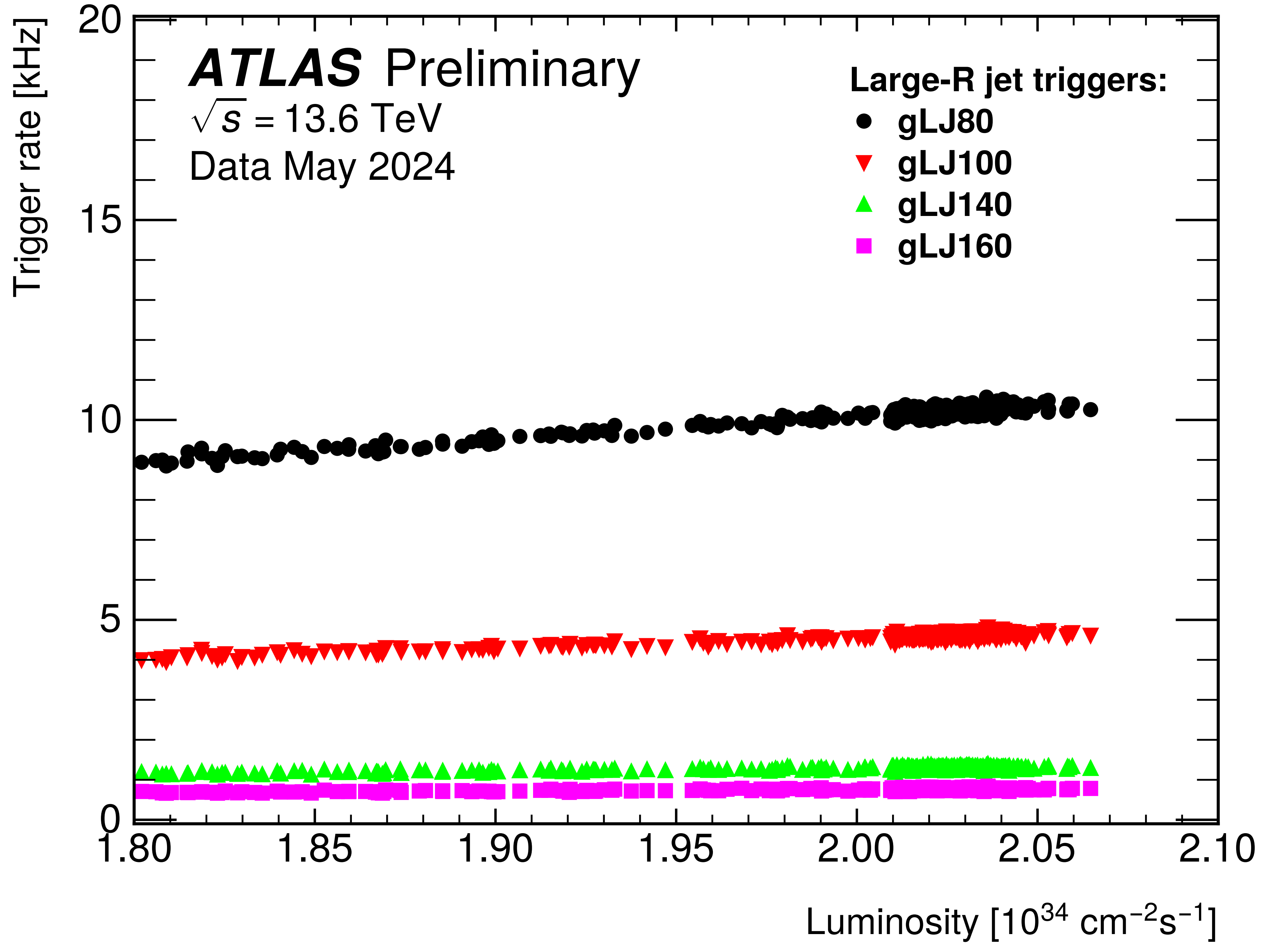




- Trigger efficiency extracted from a Z+jet data sample using a completely independent muon trigger
- L1Calo uncalibrated missing transverse energy (MET) efficiency for the gFEX JwoJ algorithm, and missing ET efficiency from the L1calo legacy system as a function of the di-muon system pT
- Corresponding trigger rates are shown as a function of instantaneous luminosity
- The efficiency curves and rates are determined using data recorded in ATLAS in May 2024
- Significant rate reduction expected with the gTower calibration

Large-R Jet Trigger Performance in 2024

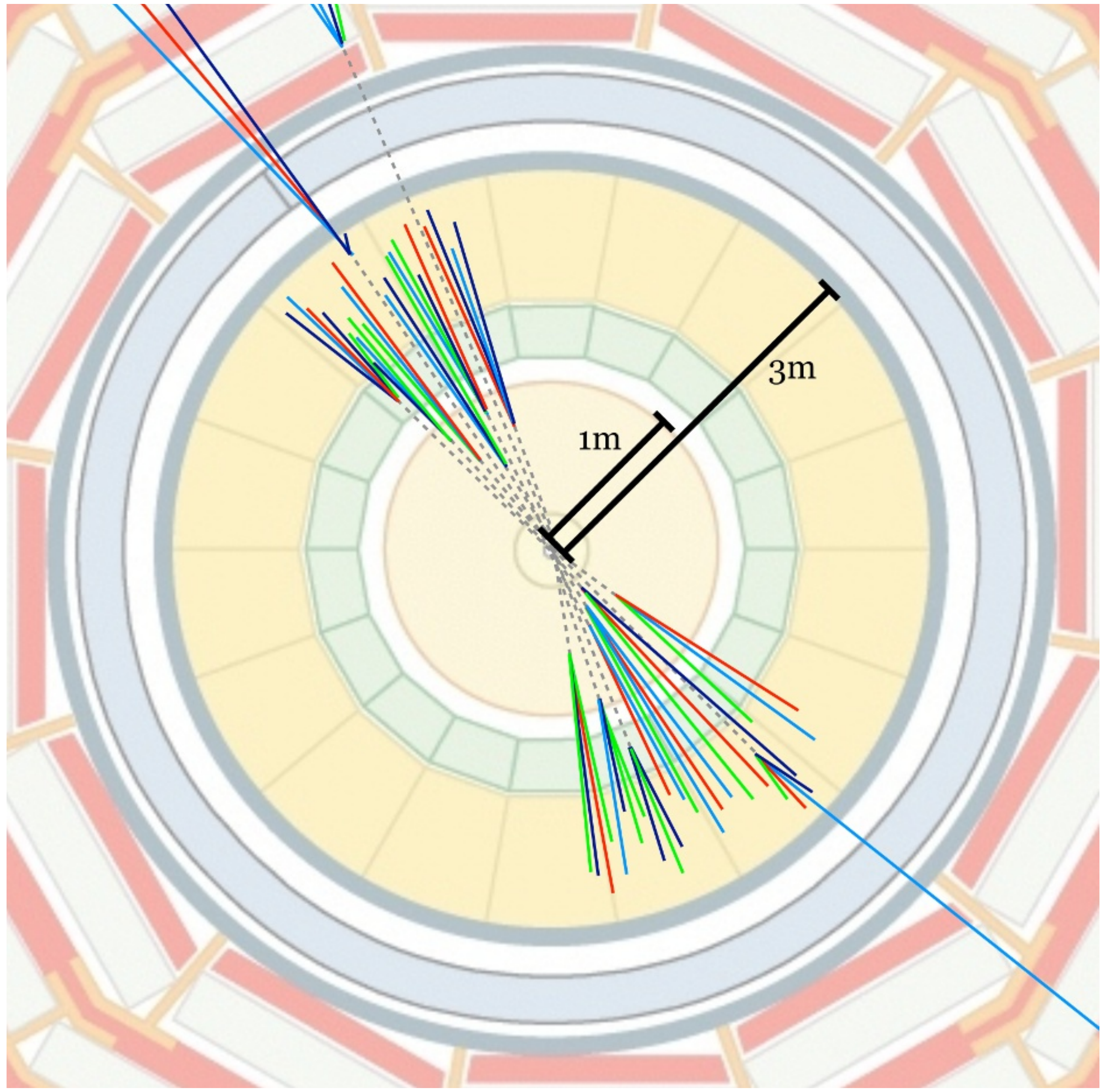




- Single large-R jet trigger efficiencies for the Phase-I system compared to the Legacy system trigger L1_J100 for offline jet pseudorapidities of |η| < 2.5 as a function of the offline large-R jet p_T
- gLJ100 is running at a rate of 4.4kHz and J100 is running at a rate of 4.2kHz at a luminosity of about 2×10^{34}cm^{-2}s^{-1}
- LR jet triggers used by most of the analyses in Run2 are based on L1 Legacy J100, now outperformed by gLJ100
- Evaluated before gtower calibration and trigger threshold update, using data recorded in ATLAS in April-May 2024

Emerging Jets Trigger with gFEX

- Many new physics scenarios with the dark sector have final states with long-lived particles (for example, Z′ decaying to dark mesons) that might be heavy, resulting in LR-jets
- These scenarios can produce a large fraction of events with a **displaced vertex** and **tracks with large impact parameter *d_0*** (non-prompt tracks),
- **Run3 ATLAS new trigger** based on the fraction of momentum associated with prompt tracks in the jet relative to the total jet momentum $promptTrackFrac = \frac{1}{p_T\ jet} \sum_{i \in trackjs} p_{T_i}(|d_0| < 2.5\ \sigma_{d_{0,i}}(p_{T_i}))$
- Previously seeded by L1 Legacy and jFEX small-R jet
- gFEX will provide a reliable L1 trigger for the PTF trigger in 2024
- Emerging jets triggered with L1 large-R jets is new for Run 3



Pair production of dark quarks forming two emerging jets (JHEP)

Emerging Jets Trigger with gFEX

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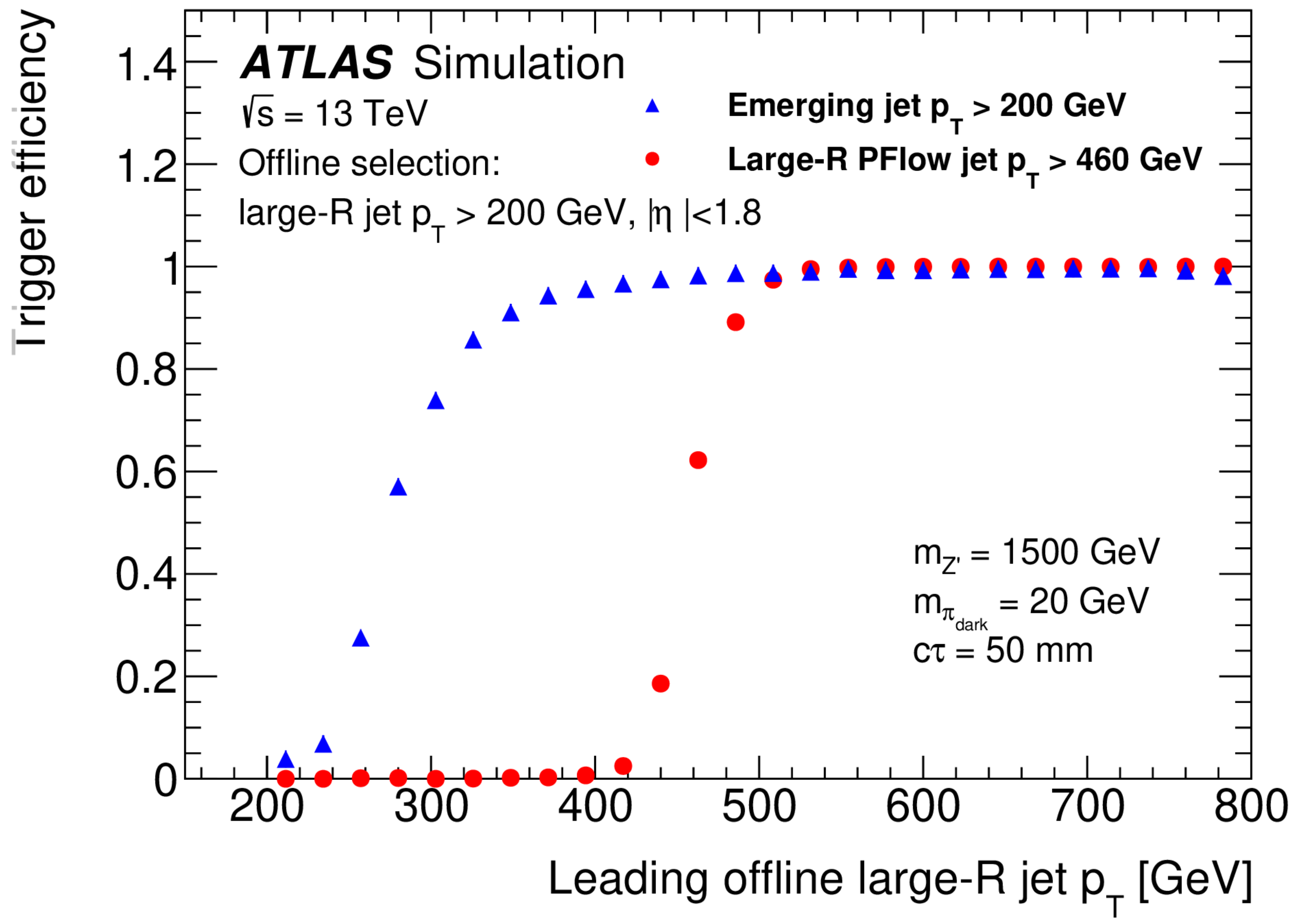


Efficiency of the new emerging jet trigger compared to a single large-radius jet trigger for a Z' decaying into two dark pions with a proper decay length (cτ) of 50 mm. Emerging jet trigger is efficient down to much lower jet pT than the single large-R jet trigger. JINST 19 (2024) P06029

Summary and Conclusions

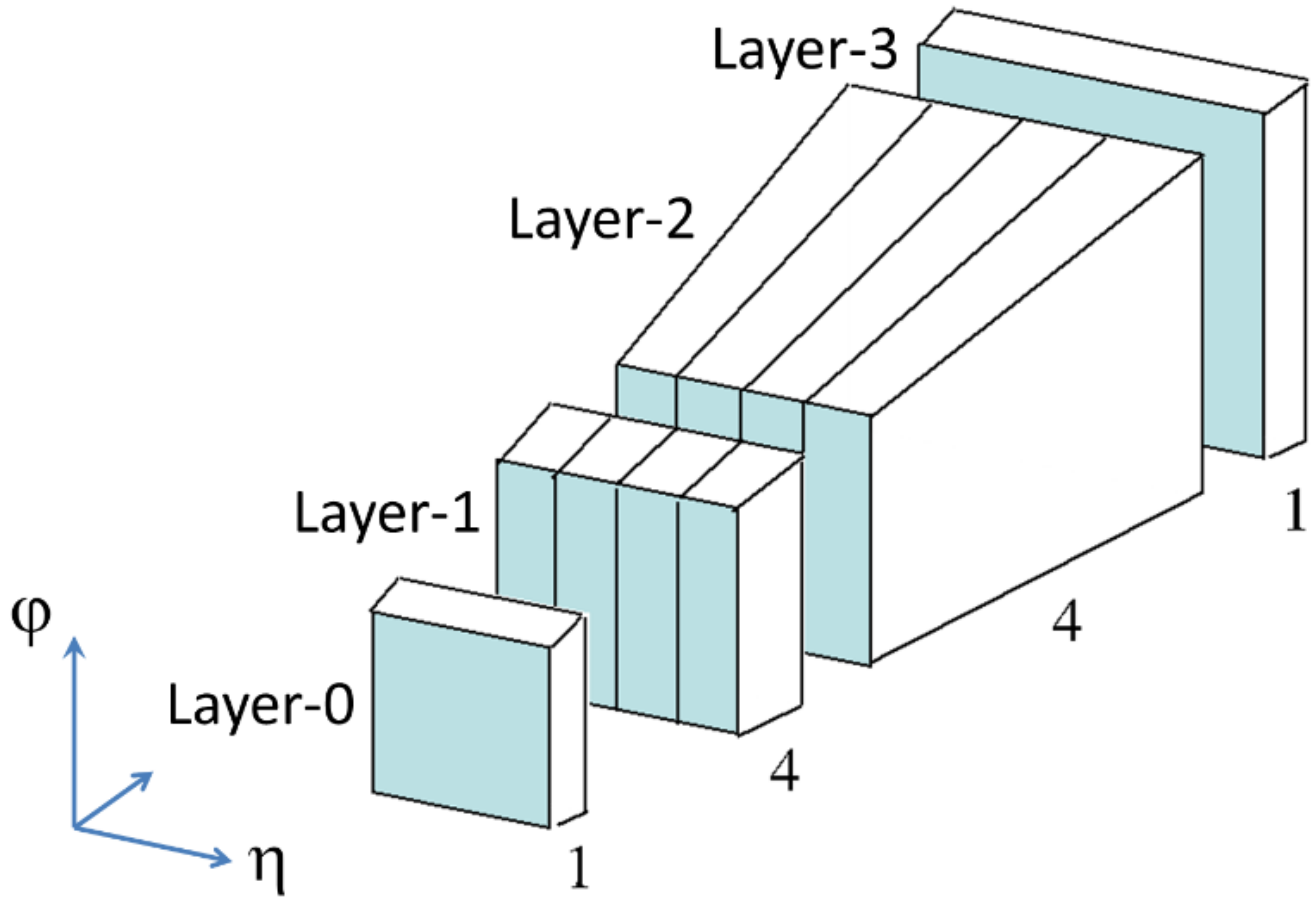
- gFEX is operating as part of the Level-1 Calorimeter Trigger System in ATLAS
- Designed to provide large-radius jet triggers, estimation of local pile-up, MET, and other global observables for triggers at low rates and maximal acceptance-> **very inclusive trigger**
- Good performance of the gFEX MET and large-R jet trigger items, with **no requirements on sub-jets**
- Large-R jet trigger outperforms the L1Topo Simple Cone algorithm (default large-R jet at L1) in rate
- gTowers calibration recently deployed in firmware-> unique capability of **tower-level calibration**
- Significant rate reduction expected with tower calibrations
- Opportunities for physics cases, e.g. emerging jets trigger seeded by gFEX large-R jets
- Analyses with boosted jets, e.g. bosons (di-Higgs, SH) or top quark decays, Dark Matter and SUSY searches can benefit from the large-R jets gFEX trigger
- MET and invisible particles, e.g. H->invisible can benefit from a MET gFEX trigger

Thank you!

Additional Material

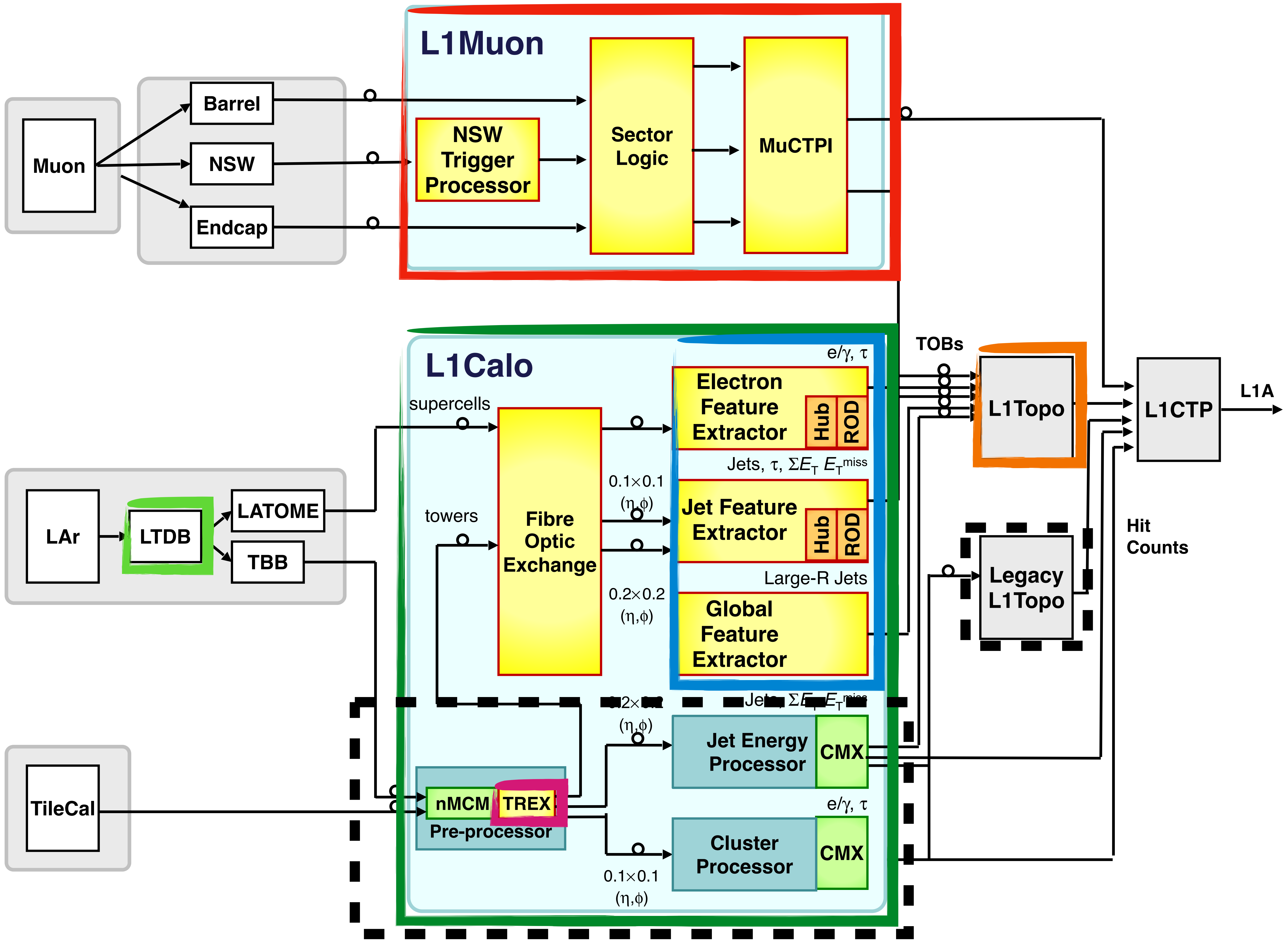
LAr Calorimeter Upgrade

Super Cells



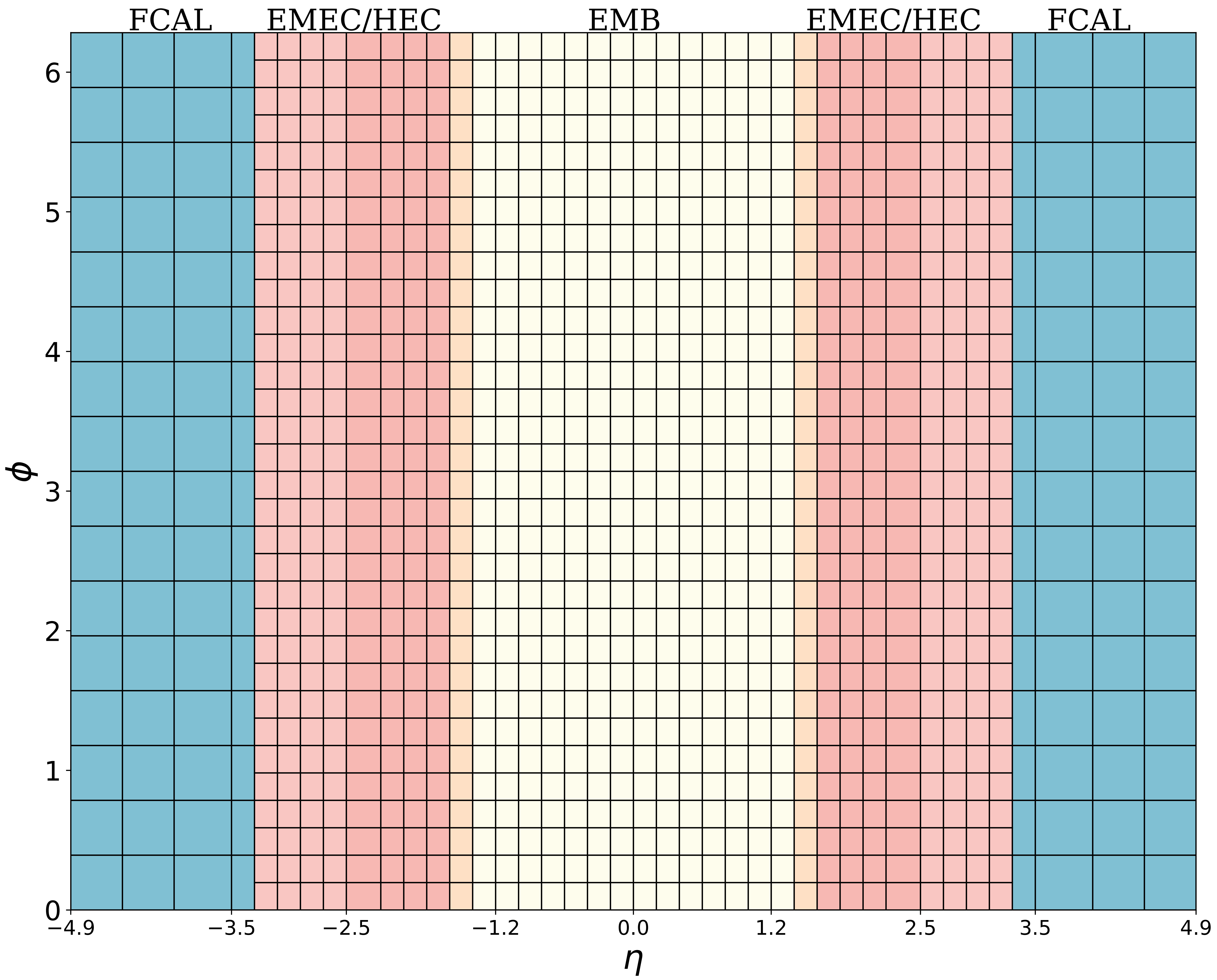
- In Run1 and Run2, input from LAr calorimeter consisted of **trigger towers** spanning $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- **Finer granularity** data provided by the LAr Digital Processing System in Run3, both in η-ϕ and longitudinally
- New **readout element** called **SuperCell (SC)**
- Each Legacy tower is divided into 10 SCs, each providing an E_T value
- Improved resolution for Level-1 Calorimeter trigger, especially for e/γ, and τ triggers

Level-1 Trigger System



- **L1 Muon**: new EndCap Sector Logic for NSW, and new Muon-to-CTP interface (MUCTPI)
- New calorimeter electronics for the digitization and calibration of LAr data (**LAr Trigger Digitizer Board**)
- Tile Rear EXtension (**TREX**) provides digitized input from Tile calorimeter
- New Feature EXtractor (**FEX**) modules for **L1Calo** to identify events containing calorimeter-based physics objects
- Level-1 Topological Processor (**L1Topo**) for multiplicities and topological selections (uses inputs from FEXs)
- **Legacy system** working in parallel to Phase-1 in 2023, now being decommissioned

gTowers


FCAL
EMEC/HEC
EMB
EMEC/HEC
FCAL
ϕ
6
5
4
3
2
1
0
−4.9
−3.5
−2.5
−1.2
0.0
1.2
2.5
3.5
4.9
η

Input to gTowers

gCaloTower sum of inputs from LAr or TREX, with size 0.2x0.2, built for gFEX

gTower sum of gCaloTowers from LAr and Tile, the input to gFEX, with typical size 0.2x0.2

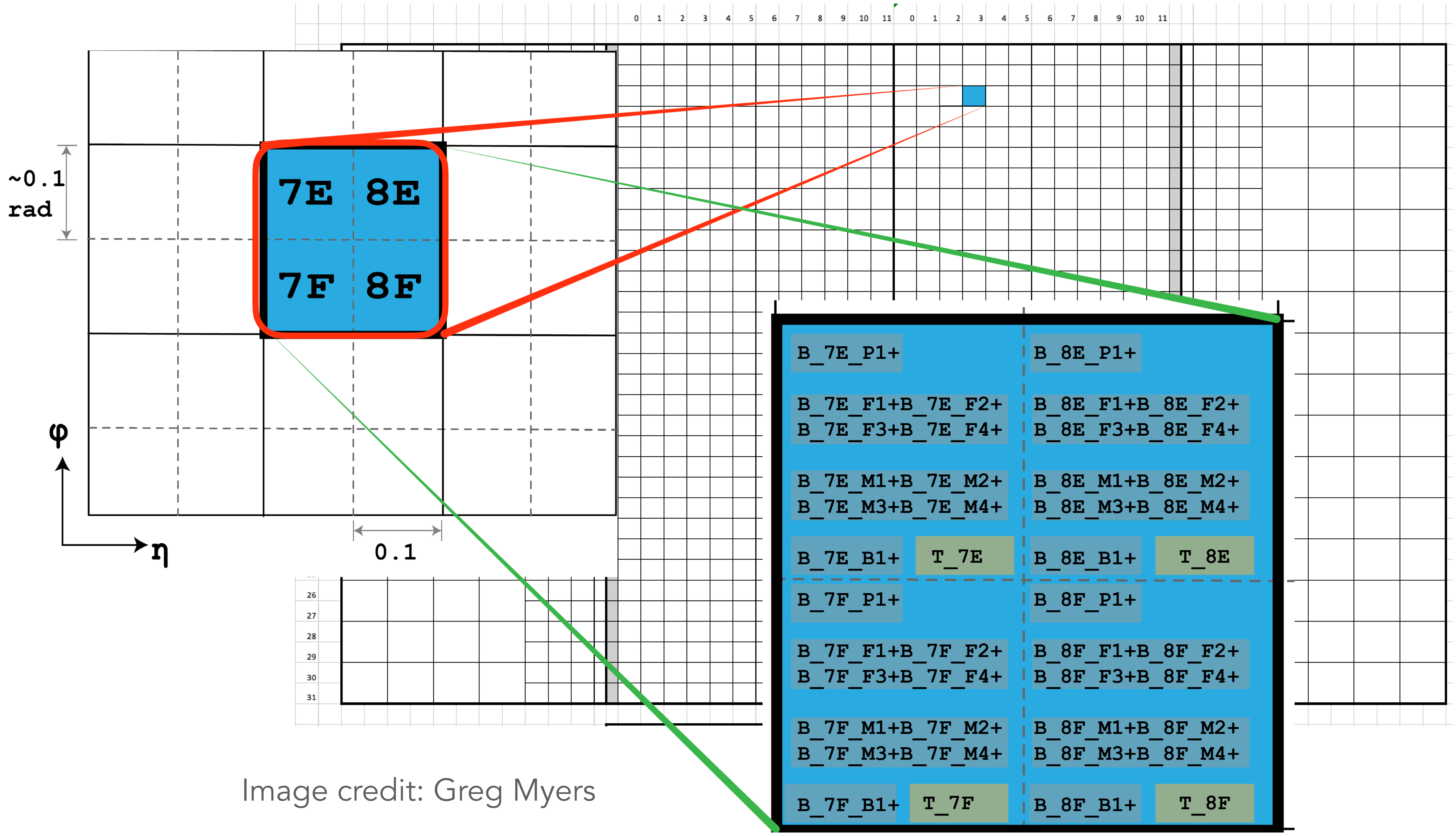


Image credit: Greg Myers

- Fibers have either 8 or 16 gCaloTowers in them
- 48 fibers with 8 energies (EMB, EMEC)
- 16 LAr EMEC-HEC fibers each with 16 energies (overlap)
- 16 Tile fibers with 16 energies (up to Ieta| ~ 1.6)
- 896 unique slots for gCaloTower energies input to one pFPGA
- Some of them from LAr EMEC-HEC are not used

gFEX Alternative MET Algorithms

Noise cut (NCMET)

Implements a noise-cut, similar to the Run-2 style of MET in HLT

- 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 (RhoMET)

- 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:

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

Trigger Naming Convention

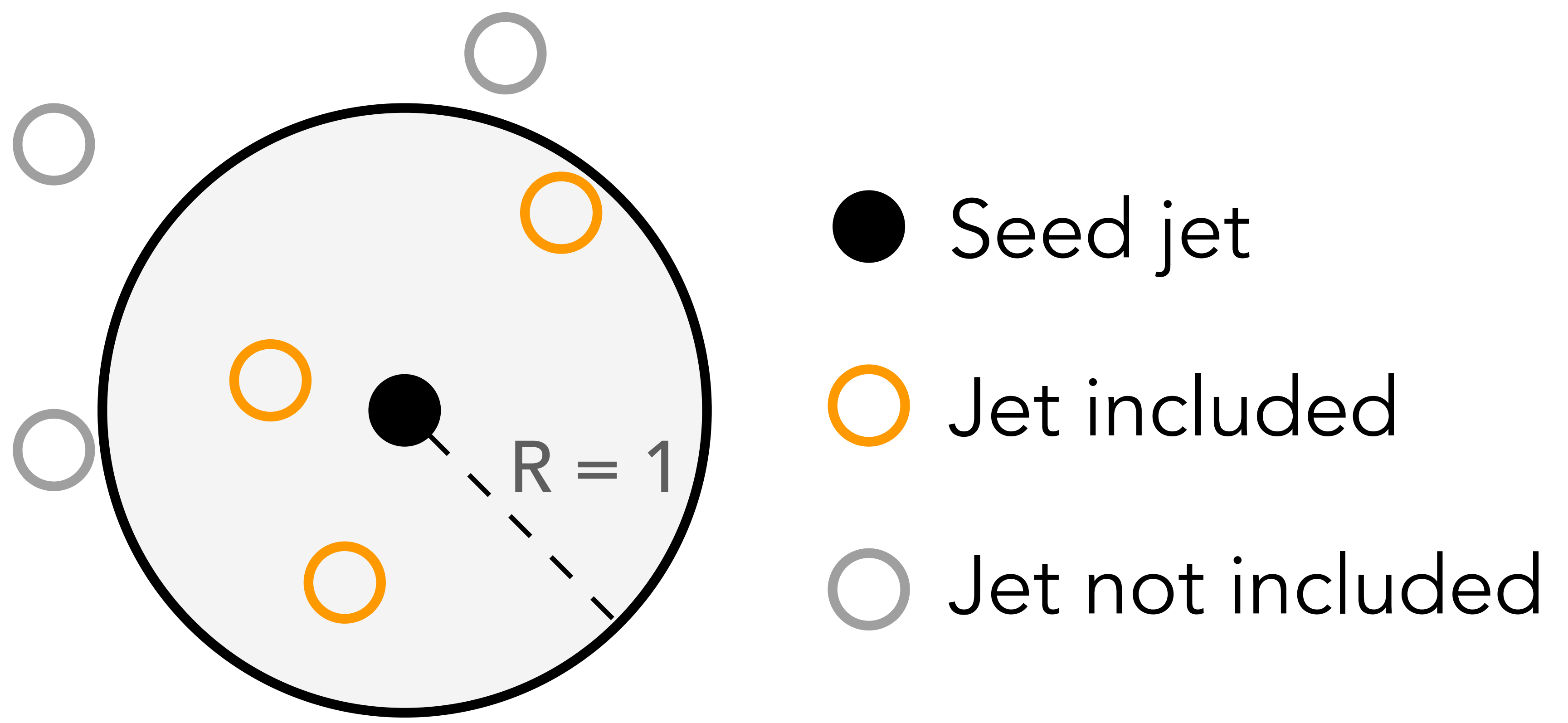
- The naming convention for L1 has to accommodate the running in parallel of multiple systems (jFEX, gFEX, etc…)
- gFEX small-R jets are indicated with **gJ**
- Large-R jets are computed only by gFEX and are denoted with **gJL**
- XE (missing transverse energy) items can be computed in different systems and with different algorithms, the current gFEX default is **gXEJWOJ** (MET obtained with the jets without jets algorithm)
- Energy values used in the names of the Run-3 L1 items reflect the mid-point of the turn-on curve (in Run-2 was the HW energy cut)
- E_T thresholds associated with the gLJ trigger items have been recently updated to account for this new convention (bottom table)
- Note that the gLJ efficiency plot (next slides) does not include the thresholds update, which only produces a shift of the curves

gXEJWOJ Trigger Item	Threshold [GeV]
gXEJWOJ60	30
gXEJWOJ70	35
gXEJWOJ90	40
gXEJWOJ100	50
gXEJWOJ100	55
gXEJWOJ120	60
gXEJWOJ500	300

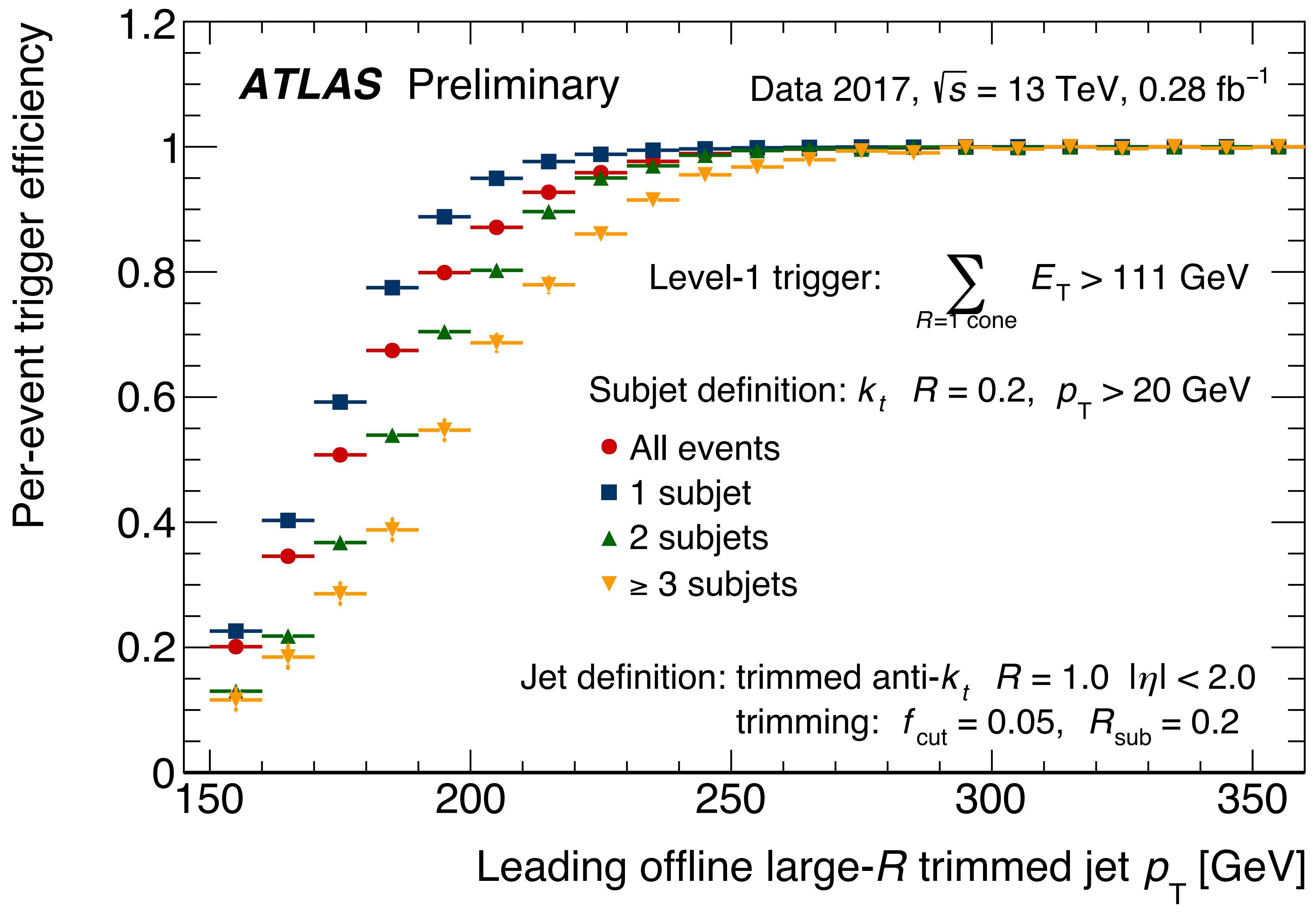
gLJ Trigger Item	Old Threshold [GeV]	New Threshold [GeV]
gLJ80	80	50
gLJ100	100	70
gLJ140	140	110
gLJ160	160	130

L1Topo Simple Cone Algorithm

- The **L1Topo Simple Cone algorithm** is the default L1 large-*R* jet algorithm used to seed all HLT triggers targeting boosted hadronically decaying massive particles
- It sums the transverse momenta E_T of all jet TOBs above a threshold within a cone of $R = 1$ around a seed jet
- The obtained sum, representing the energy of the large-*R* jet, is required to be larger than a certain threshold
- The resulting trigger item is currently called **SC111_CjJ40** (LR jet threshold = 111 GeV; SR jet threshold = 40)



Visual representation of the L1Topo Simple Cone



L1Topo simple cone algorithm trigger efficiency for events with jets of various numbers of subjets (link)