The CMS Level-1 Calorimeter Trigger Upgrade for the LHC Run II

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on behalf of the CMS collaboration

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Rutherford Appleton Laboratory

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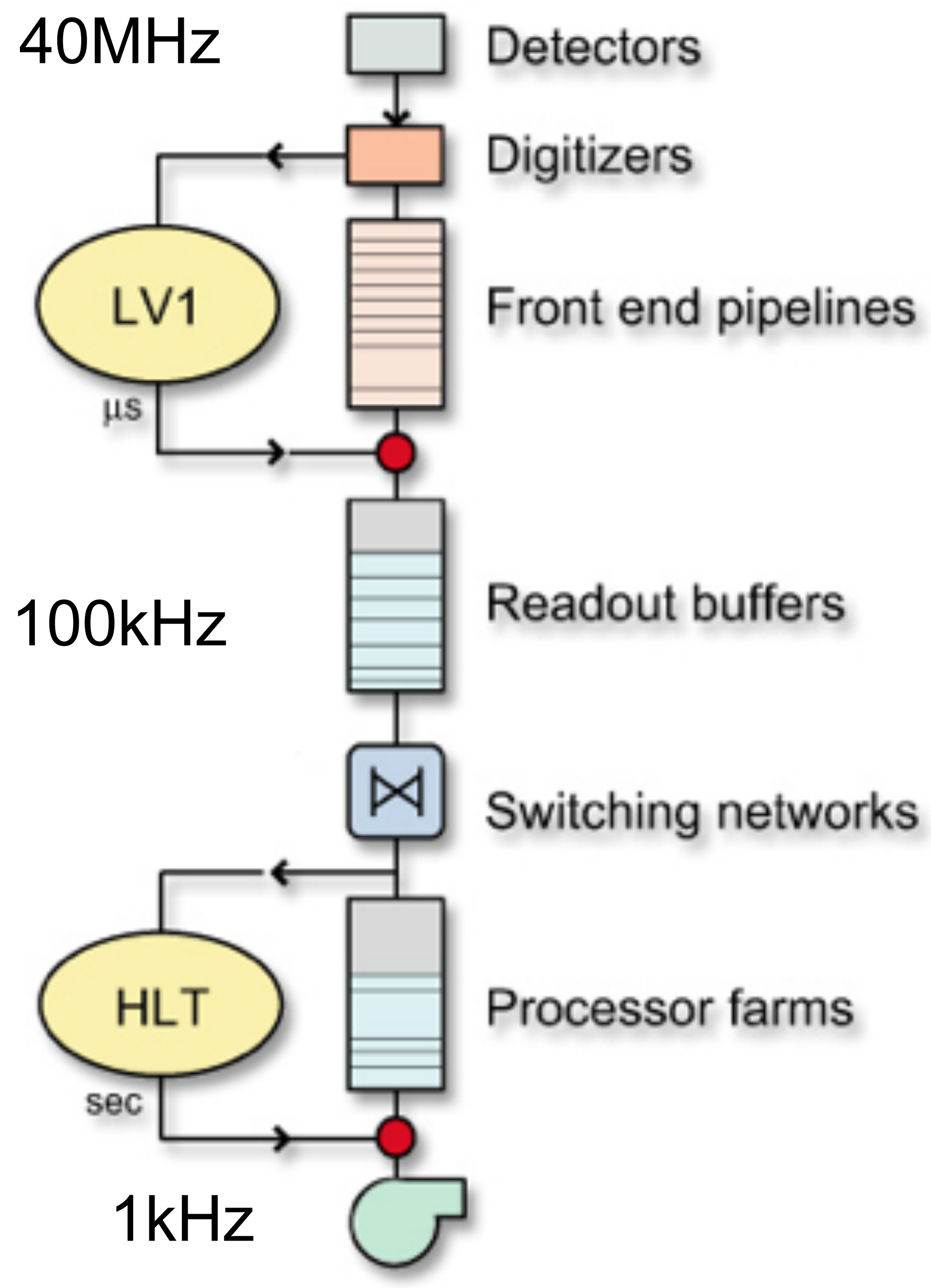
OUTLINE

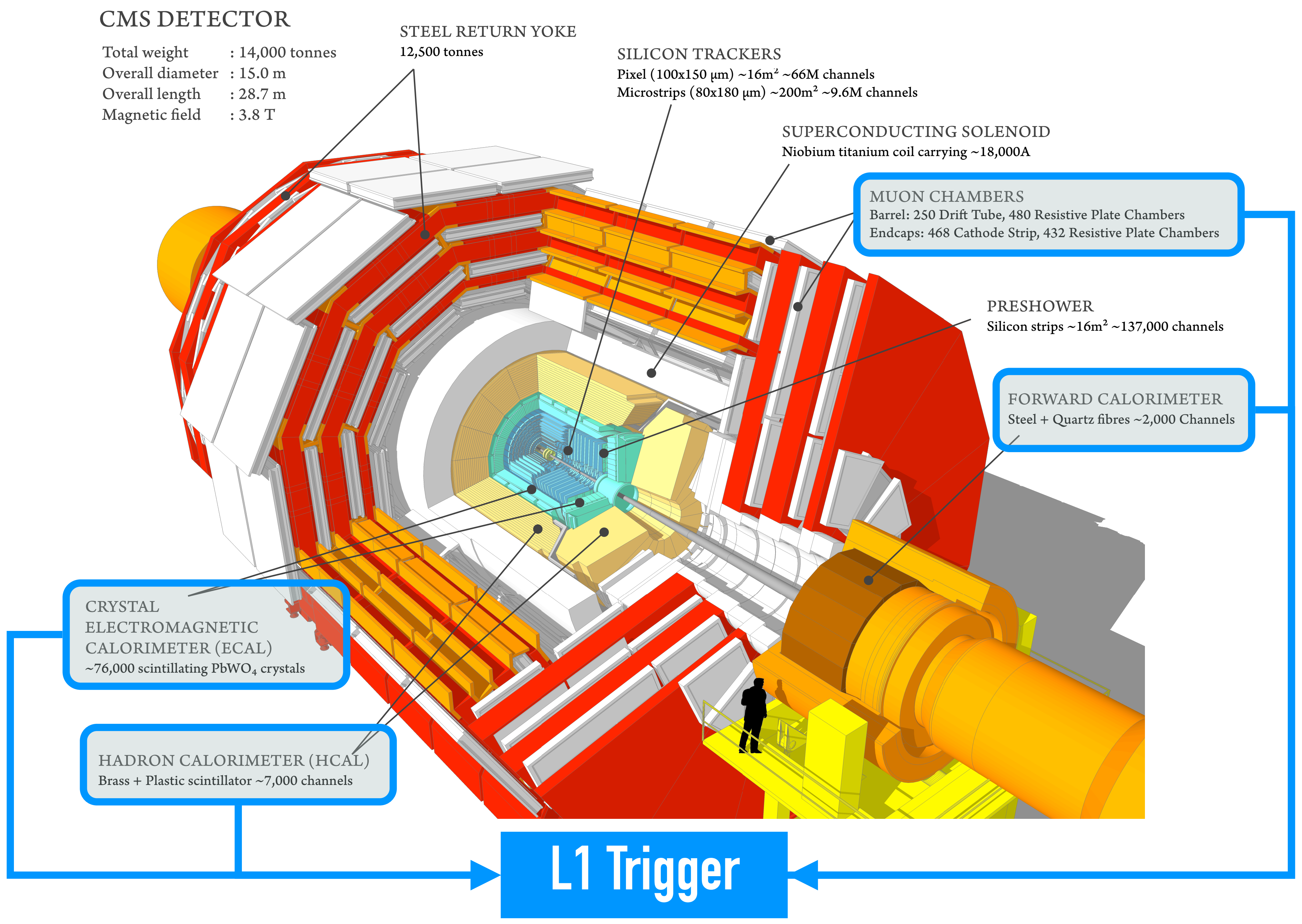
- **System overview**
- **Upgraded processors** and **high-speed** optical links.
- **Triggering algorithms** and their **implementation**
- **Commissioning** and **performance** with collision data
- **Summary** and **outlook**

THE LEVEL-1 TRIGGER



The **CMS trigger system** consists of two levels, **Level-1** and **High Level Trigger (HLT)**, designed to

- select events of *potential physics interest*
- achieve a **10^5** rate reduction with no dead time



L1 trigger upgraded in 2016

- **LHC Run 2:** Increased **luminosity, centre-of-mass energy,** and **higher PU**
- Higher trigger rates but **CMS detector electronics limited to a L1 trigger rate of 100 kHz**
- Upgrade necessary to maintain sensitivity for *electroweak scale physics* and for *TeV scale searches* as in Run I

Conceptual choices

Increase Signal/Bkg for single physics objects: optimise reconstruction, identification, energy calibration etc.

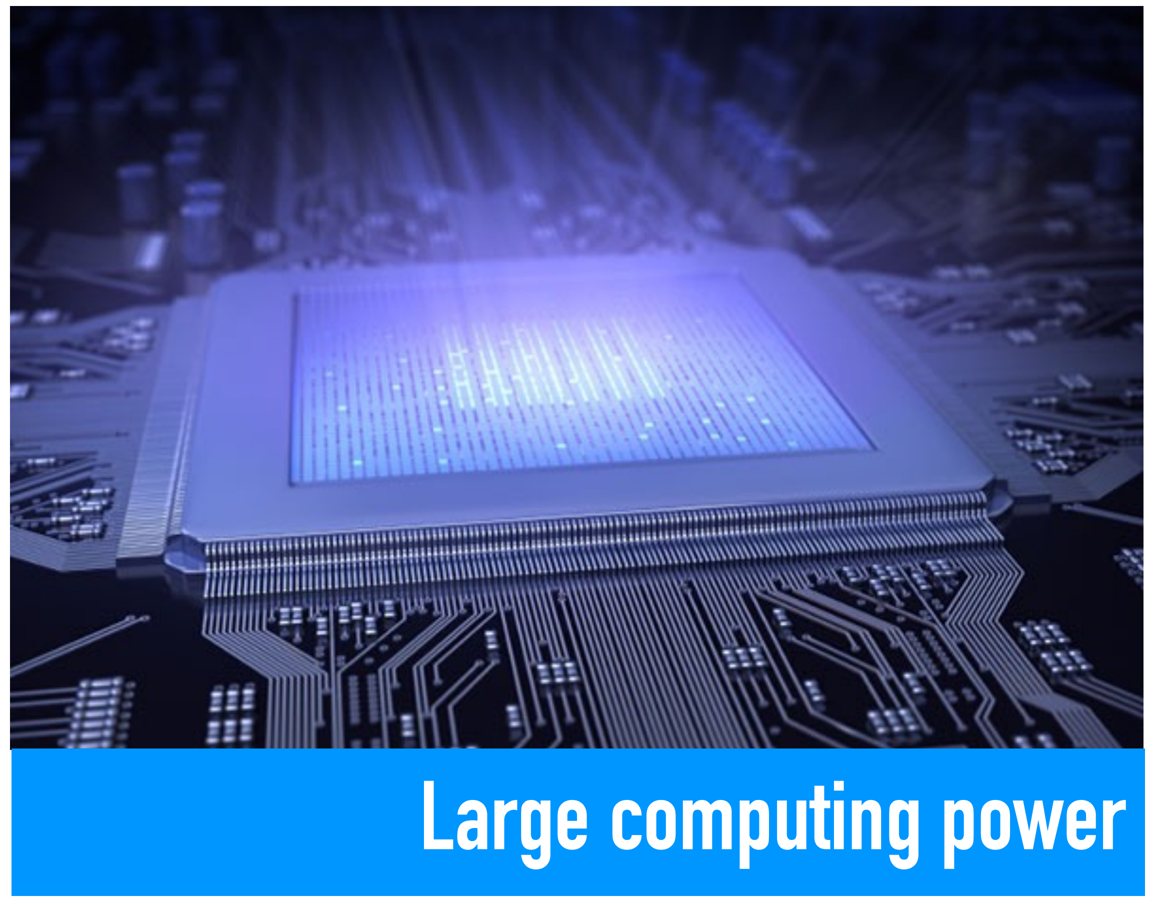
- Use **large FPGA** to increase the available computing power

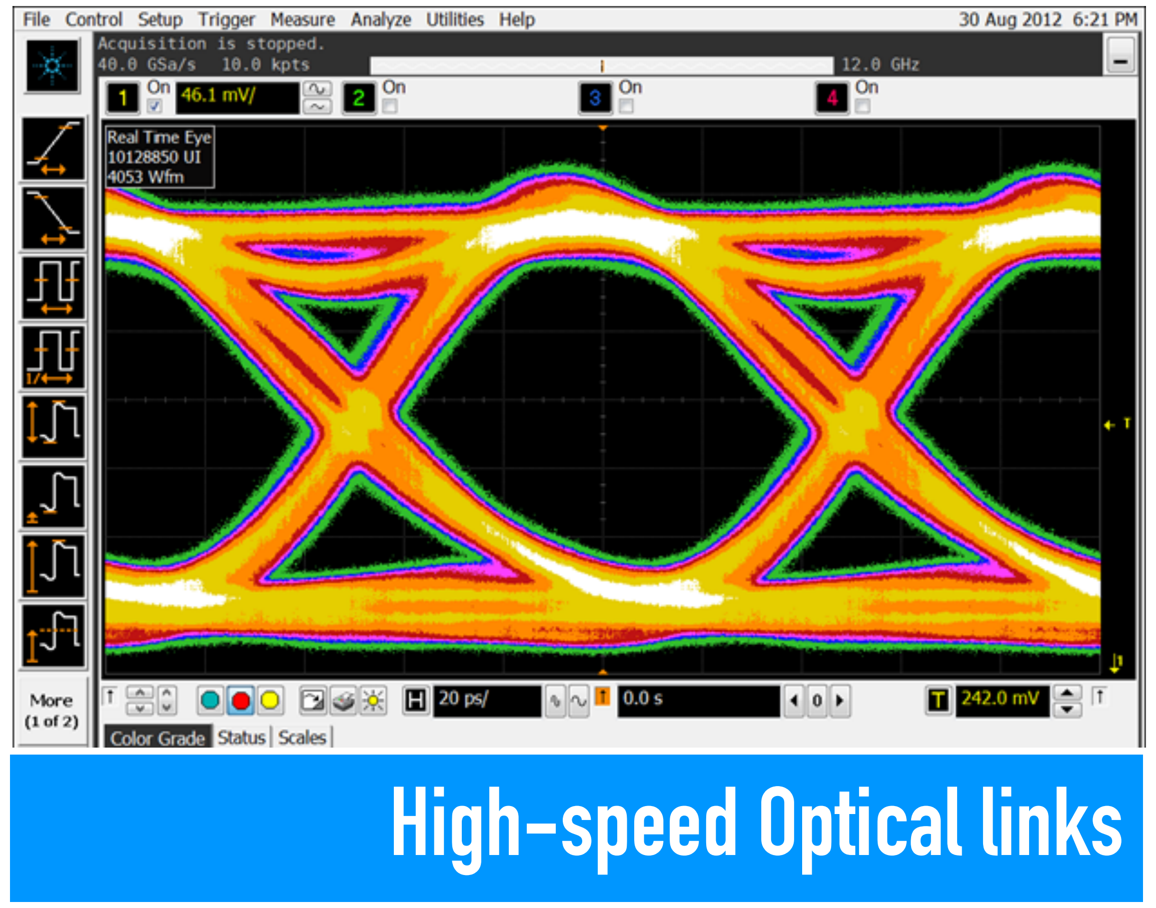
Evaluate global quantities : VBF trigger, MET, SumET and Pile-UP mitigation

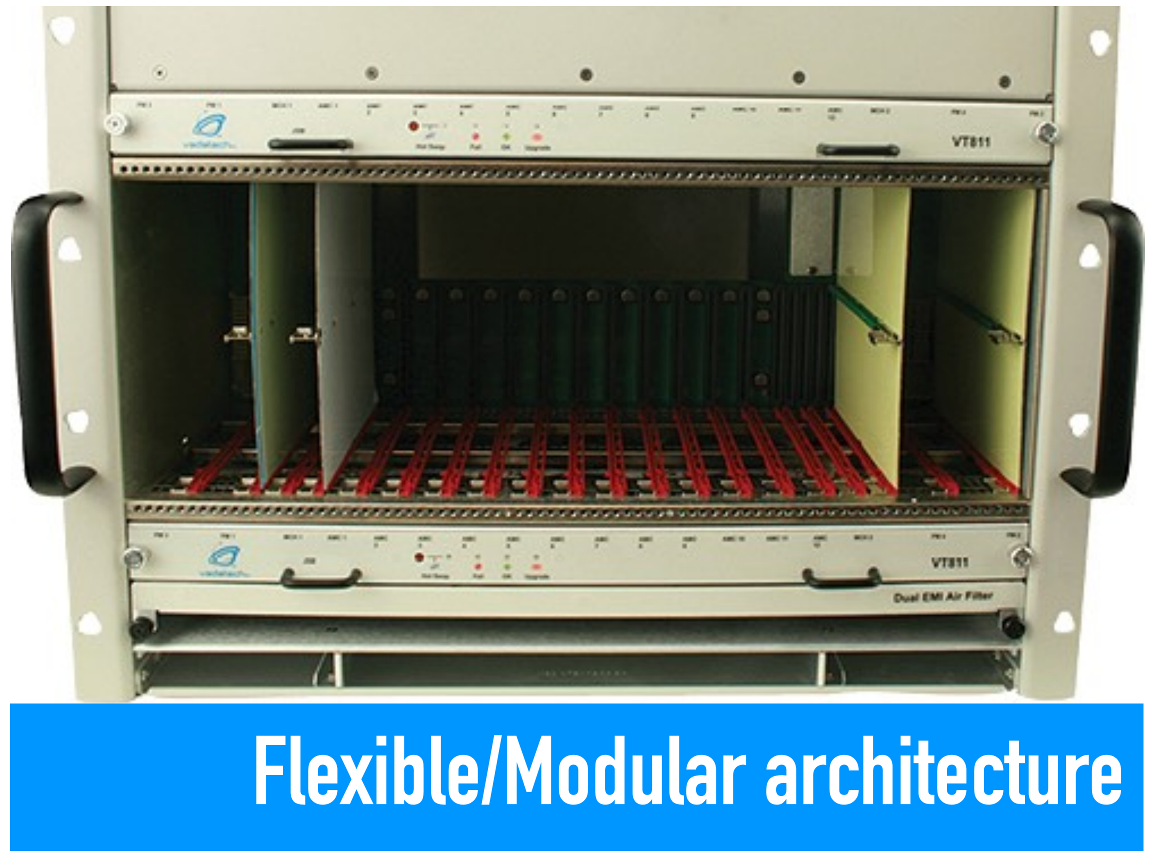
- **Remove boundaries** by streaming data from single event into **one FPGA via high speed optical links**

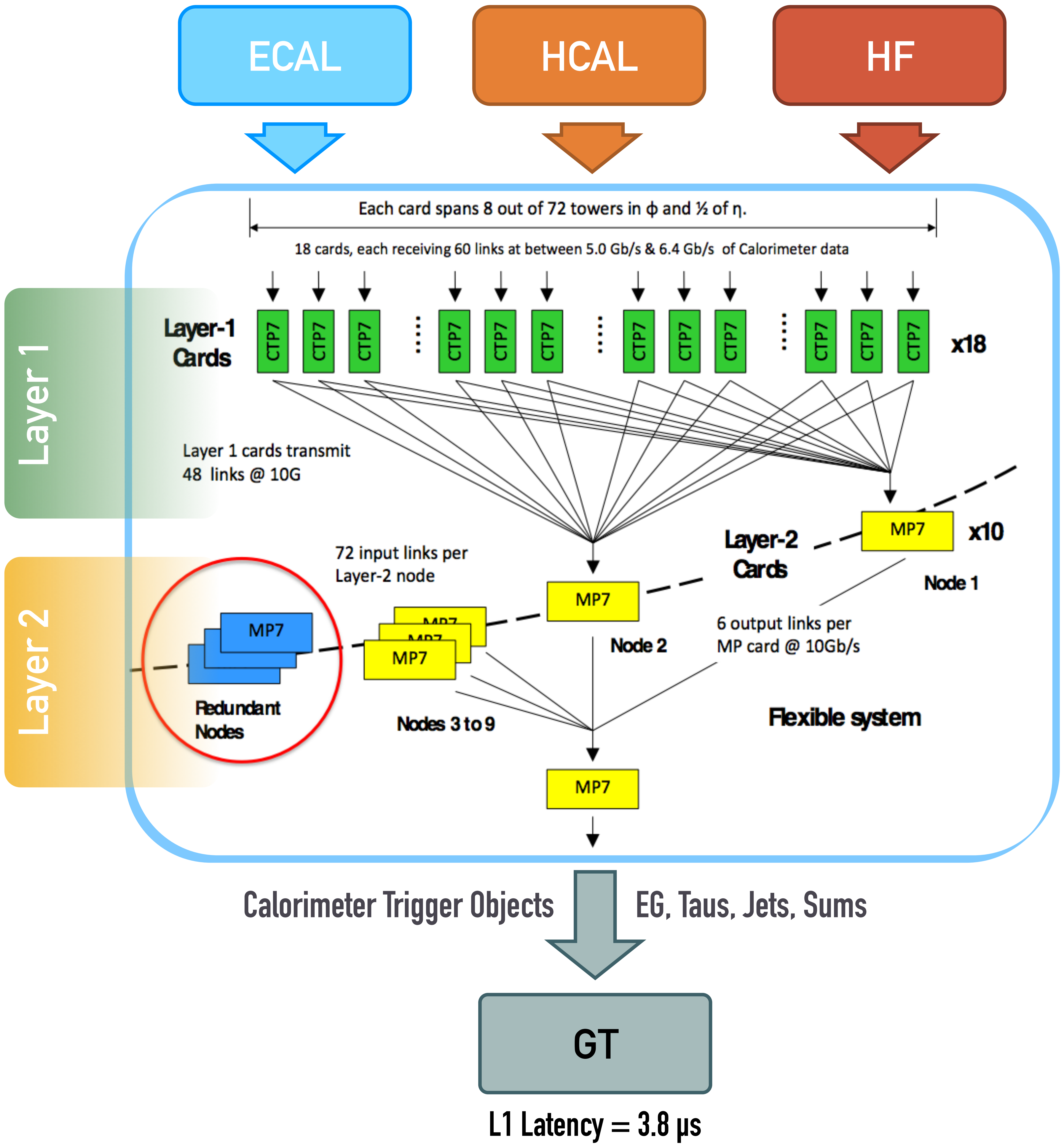
Increase selectivity: Global Trigger expandable to many more possible conditions and more sophisticated quantities

- **Flexible and modular architecture** based on modern standards









System Implementation

Organised in **two layers,** implementing a **time-multiplexed** architecture

Key technology changes

- **μTCA Standard** (modern telecoms)
- FPGAs: **Xilinx Virtex® 7 XC7V690T**
- High Speed serial optical links: **10 Gb/s**
- Large optical patch panels: **custom made commercial solution** (Molex Flexplane™)

Replaced everything!

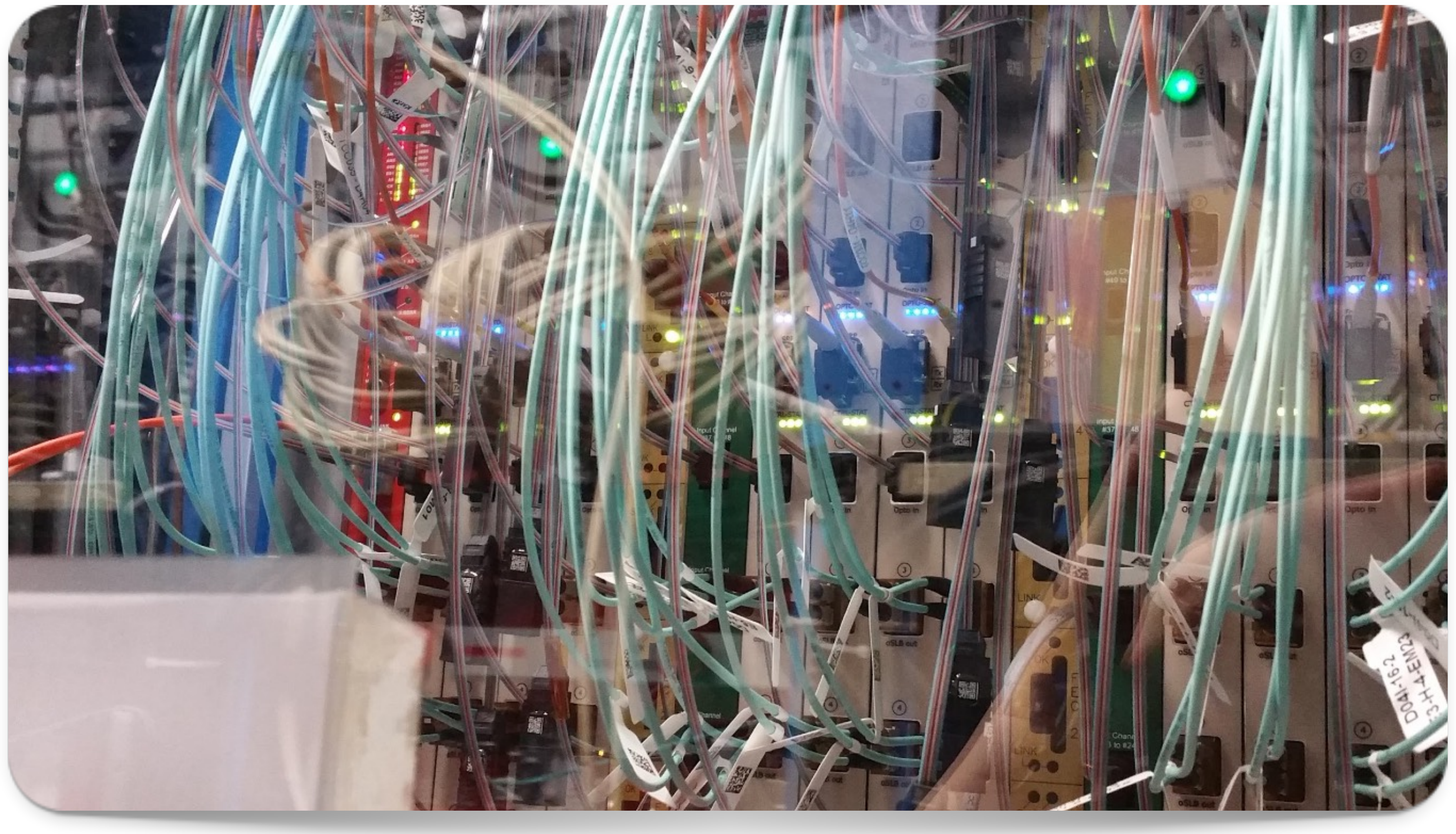
- All hardware, all software, databases

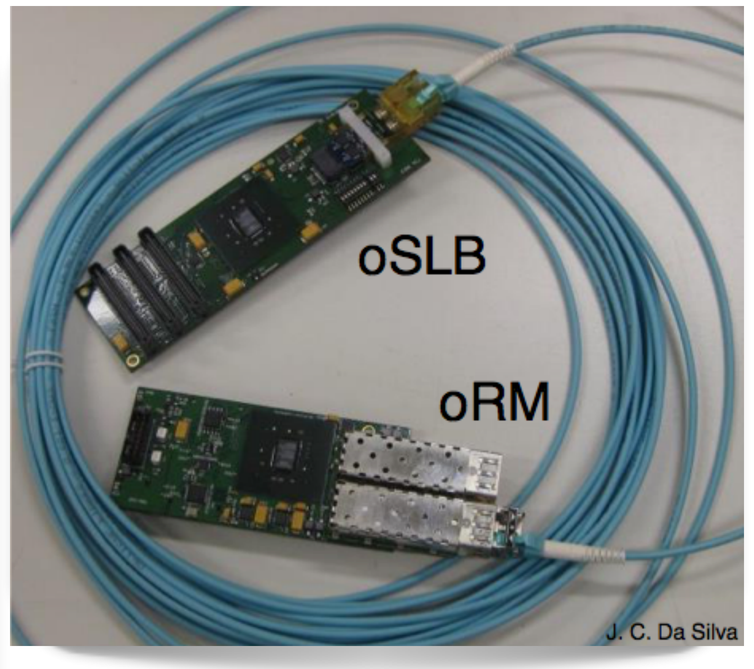
Hardware

CMS Level-1 Calorimeter Trigger

OPTICAL INPUT LINKS

- Replaced all parallel copper links by **serial optical links**
- Implementing patch panel modules **LC - MPO**





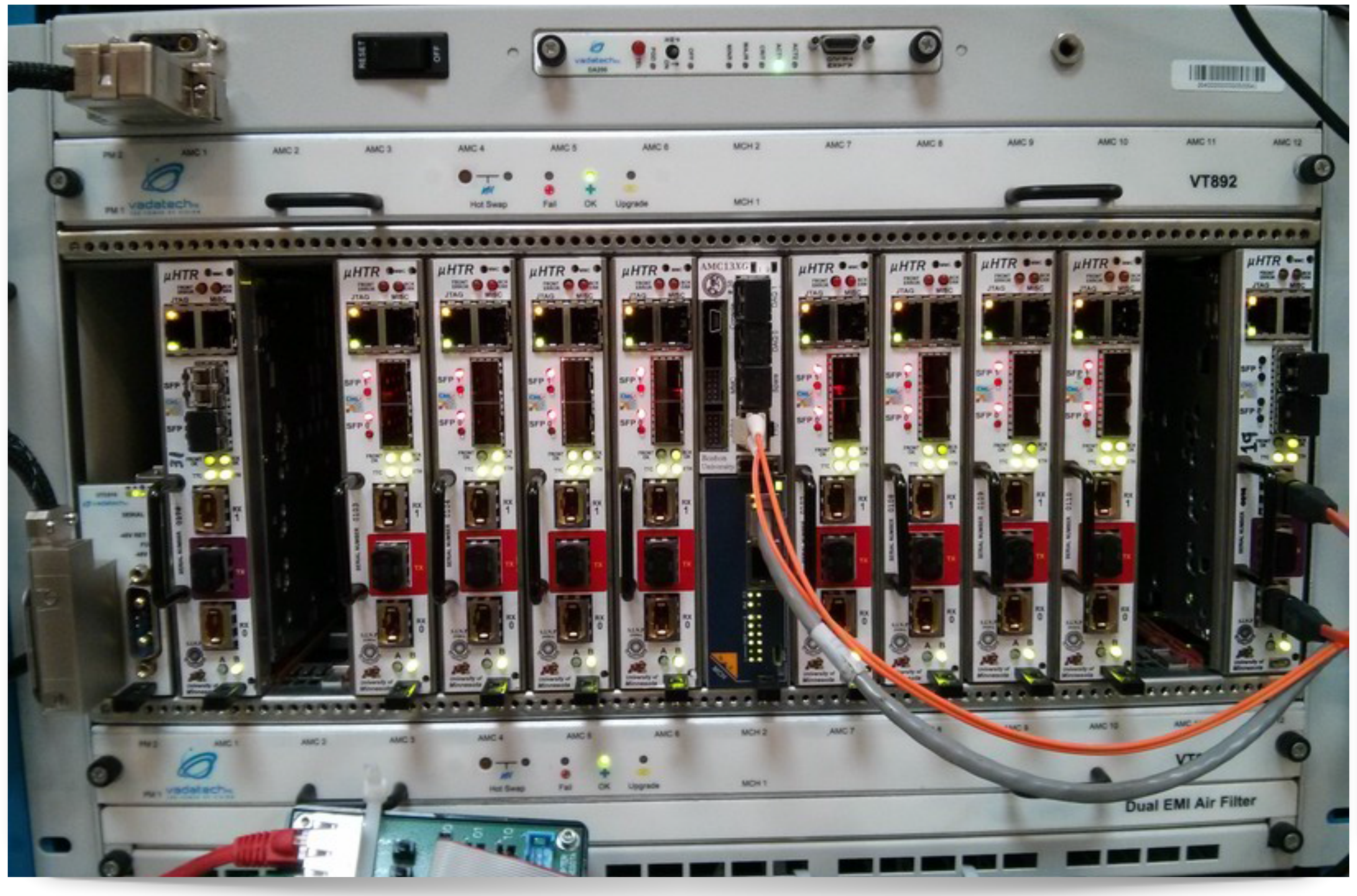
Optical Synchronisation Link Board

CERN VTTx to commercial SFP

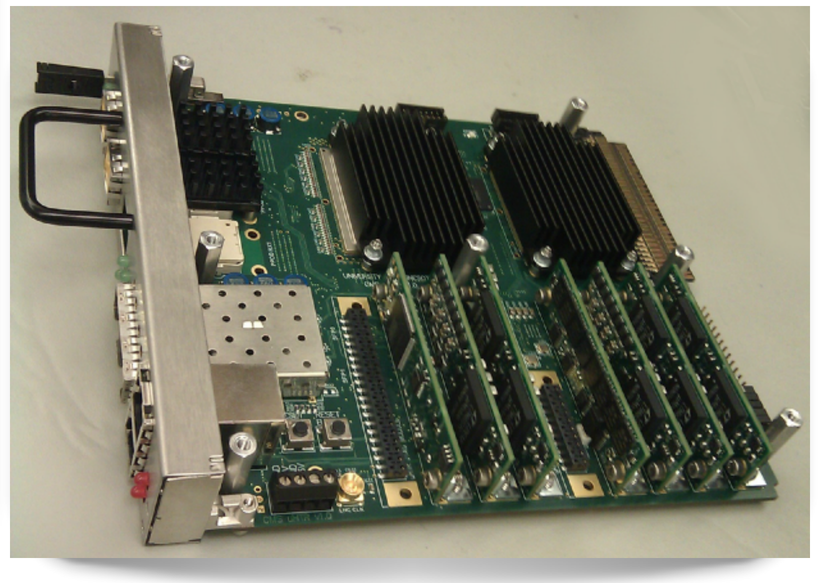
ECAL: 576 × 4.8 Gb/s links

HCAL: 504 × 6.4 Gb/s links

HF: 72 × 6.4 GB/s links



micro Hcal Trigger and Readout boards (μHTRs)



Layer 1 input links

576+504+72 links in total (ECAL, HCAL, HF) = **1152 links**

Processors

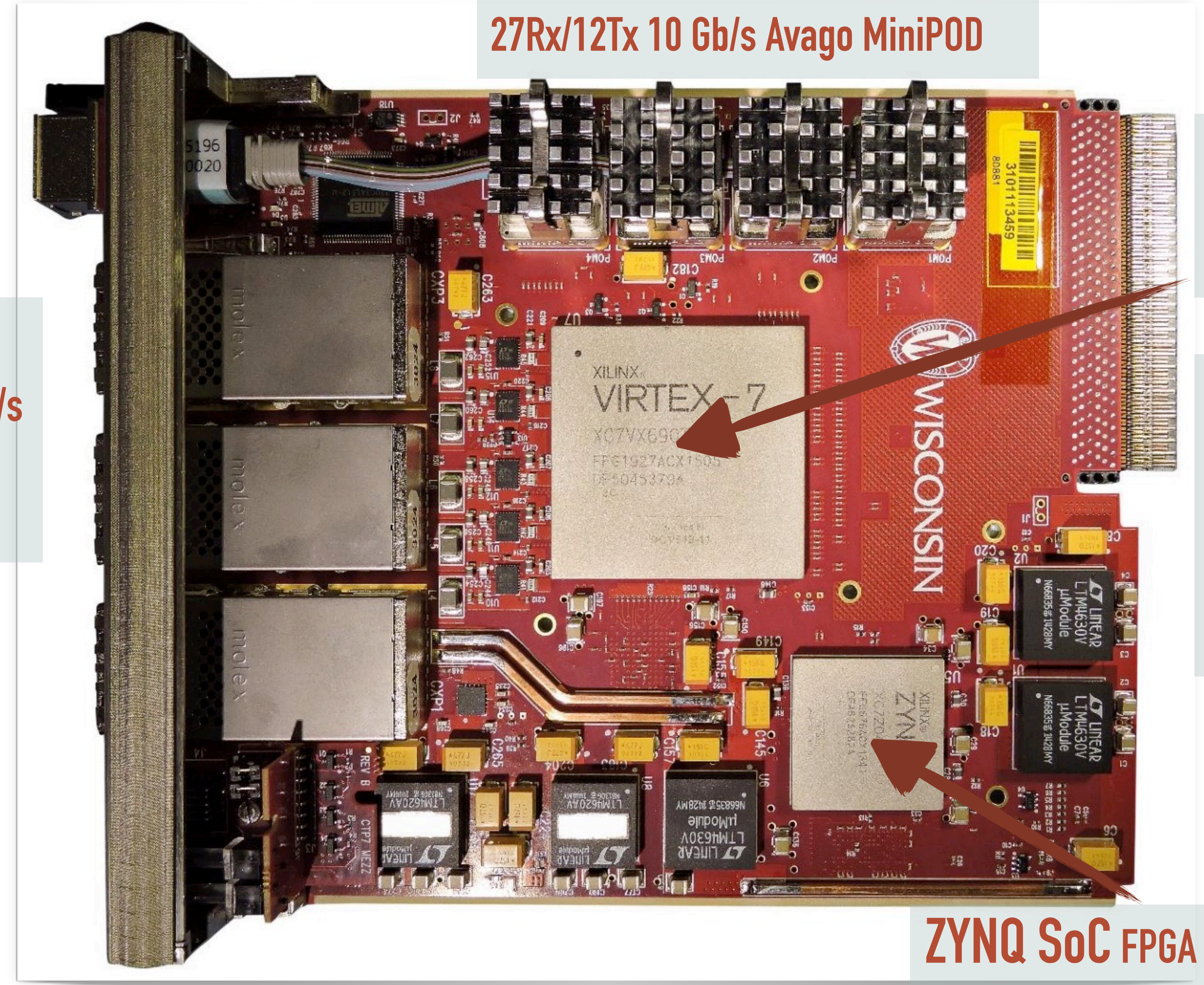
CTP7 Calorimeter Trigger Processor

Layer 1 - Pre-processing

- Aggregates & time-multiplexes calorimeter data
- DAQ readout for monitoring

Optical links
27Rx/12Tx 10 Gb/s Avago MiniPOD

Optical links
40Rx/36 Tx 10 Gb/s
Avago MicroPod
Pluggable CXP



Xilinx Virtex 7
690T

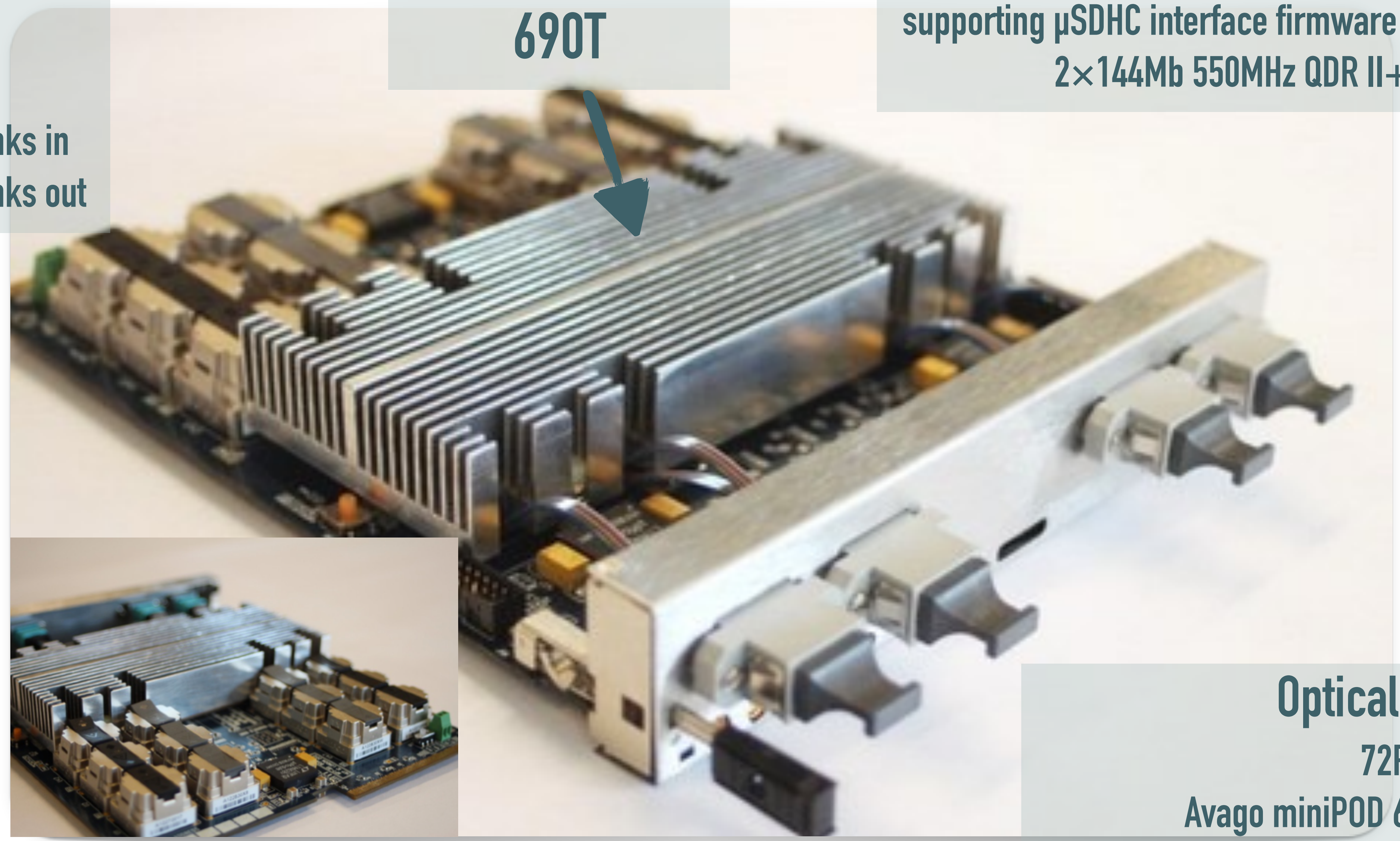
Backplane
8Rx/8Tx Rack fabric
4Rx/4Tx MCH1
DAQ Rx/Tx AMC13 in MCH2
GbE Tx/Rx MCH1 to AMC13

ZYNQ SoC FPGA Dual ARM Cortex-A9 CPU + Linux. Communication & support functions

Backplane
Ethernet, PCIe×4
TTC, DAQ, SATA/SAS
11×1.8Gbps LVDS links in
11×1.8Gbps LVDS links out

Xilinx Virtex 7
690T

Atmel 32-bit MMC
supporting μSDHC interface firmware upload
2×144Mb 550MHz QDR II+ SRAM



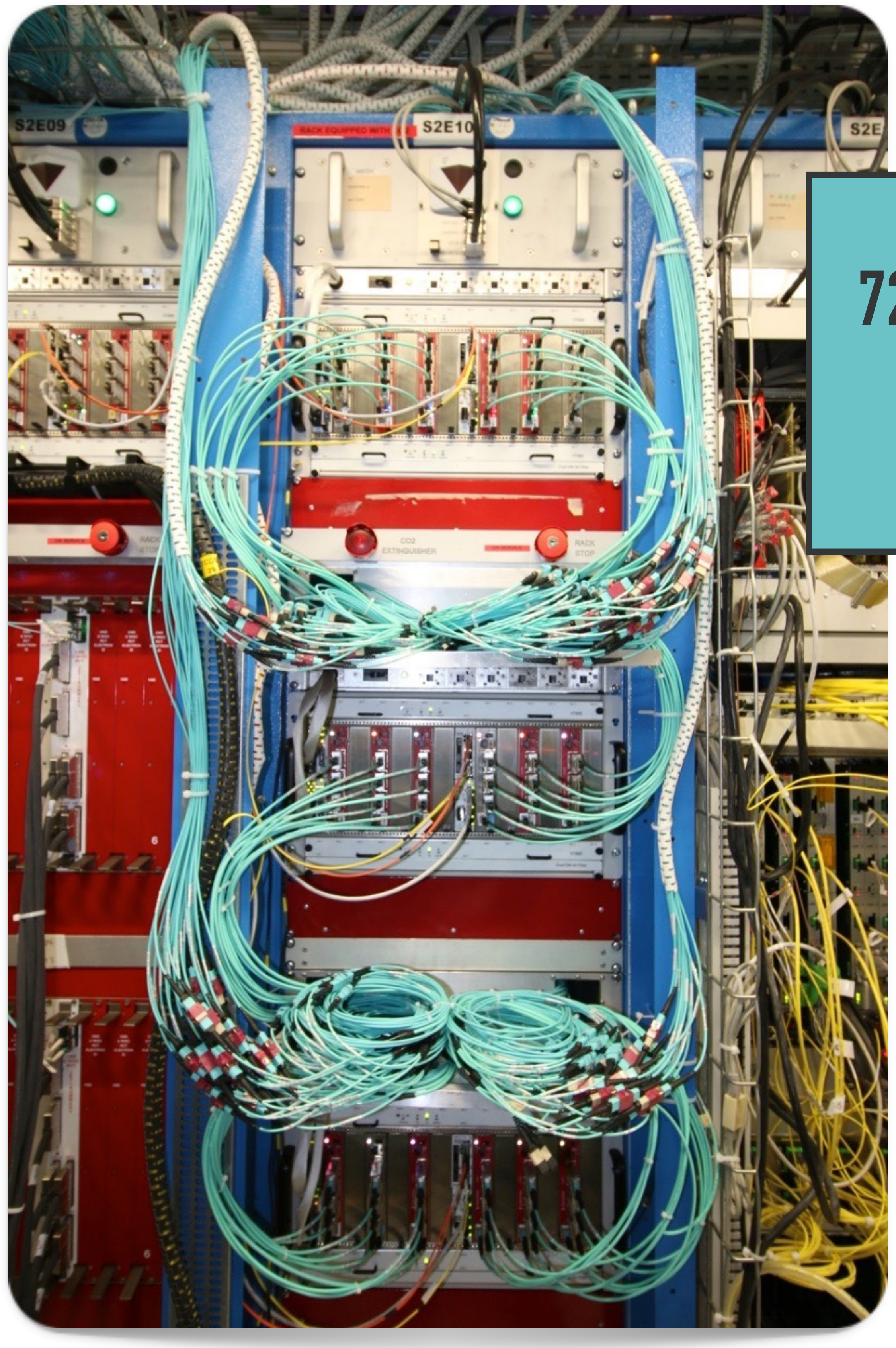
Optical links
72Rx/72Tx
Avago miniPOD 6Rx/6Tx
10.3 Gb/s each, 740 Gbps I/O

MP7 Master Processor

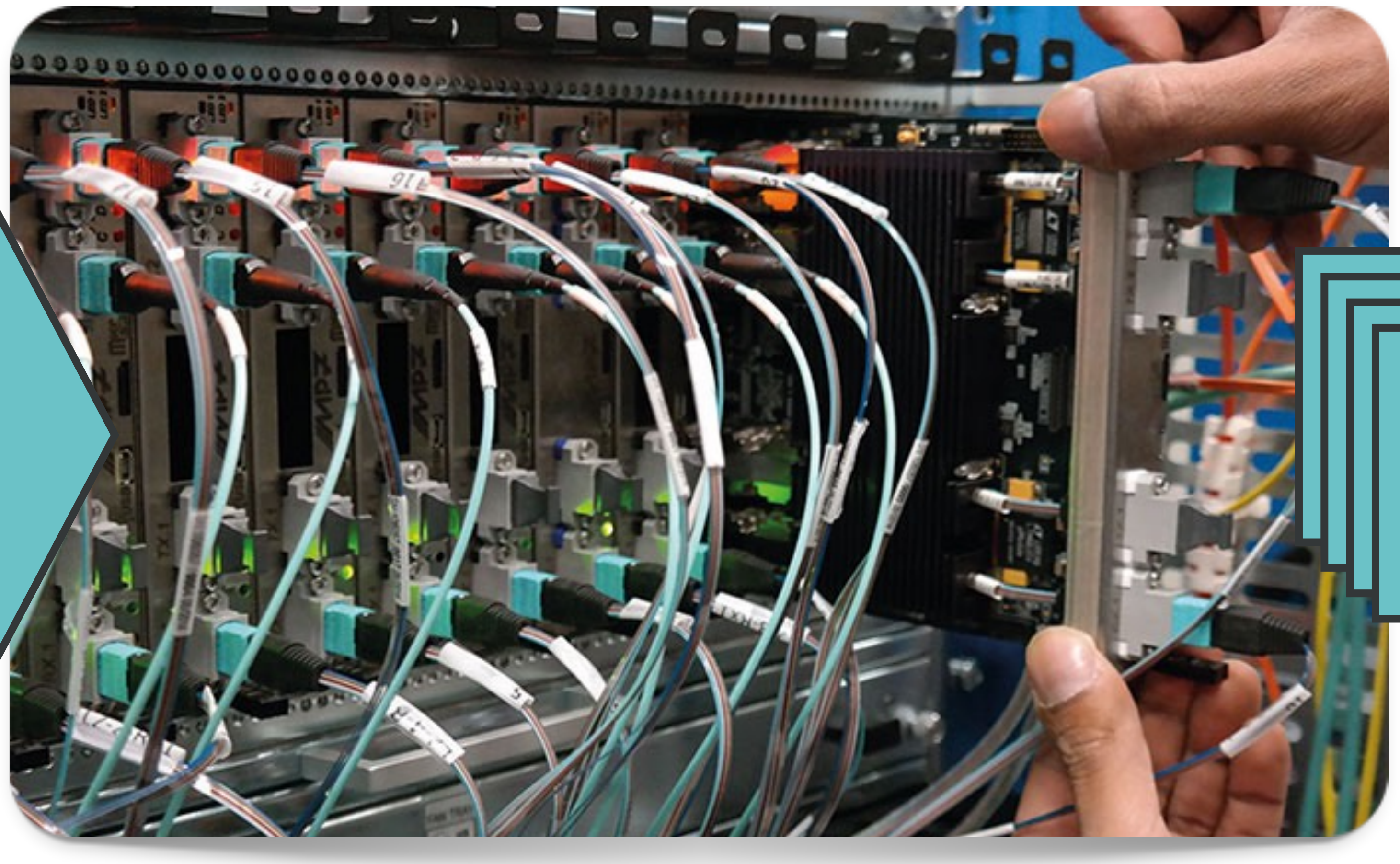
Layer 2 - Trigger Algorithms

- Hosts all the algorithms
- DAQ readout for monitoring

SYSTEM INTEGRATION

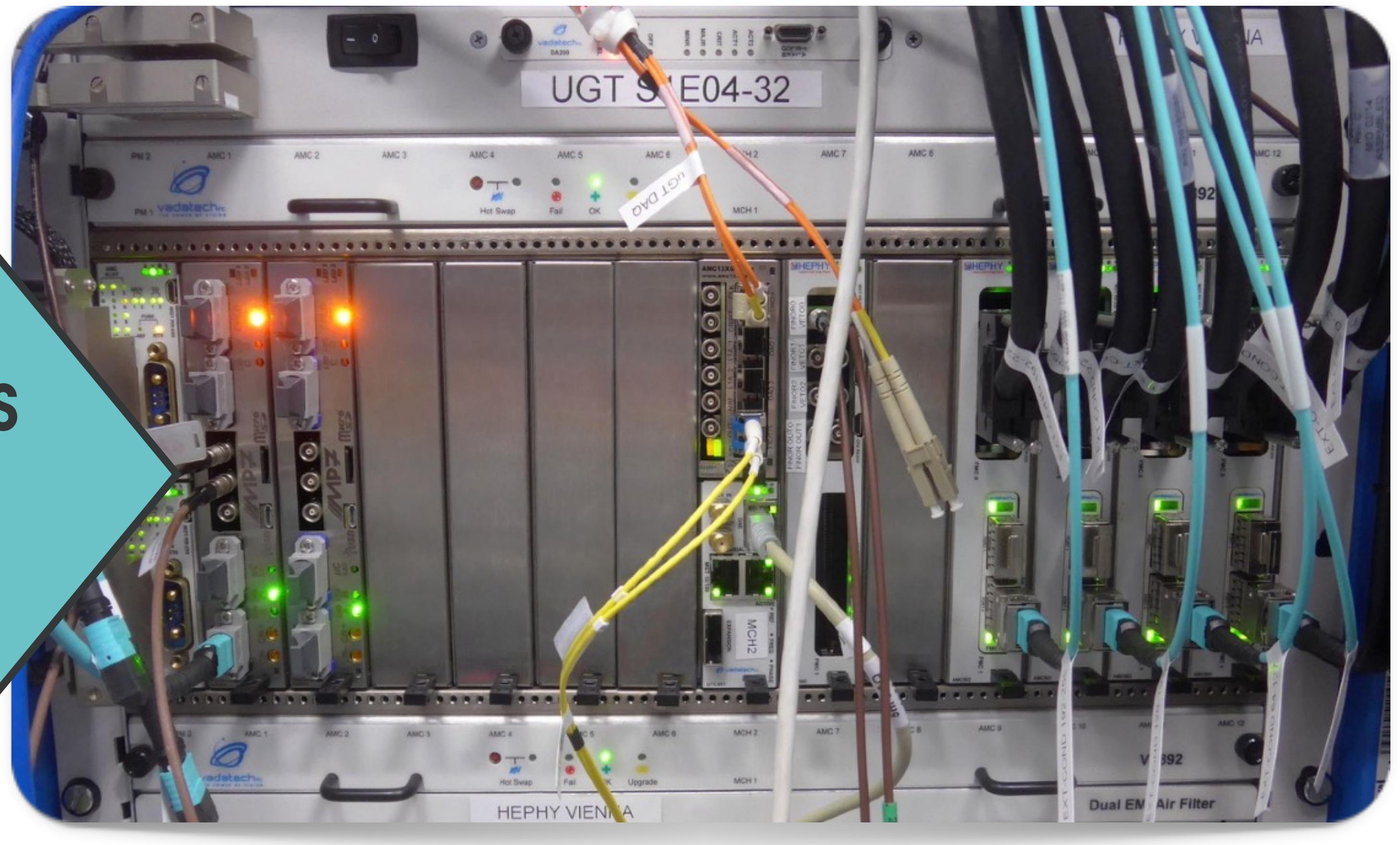


720×10Gb/s links



Layer 2
1 Vadatech VT894 Crate, 10 MP7 boards

8×10 Gb/s links

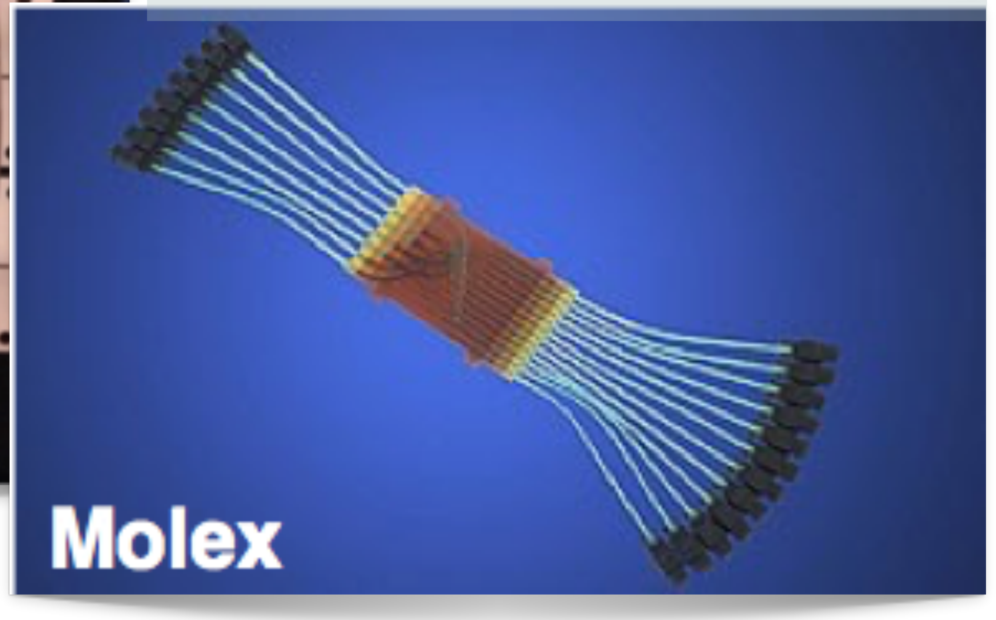


Global Trigger
receives 12 electron/photon + 12 Tau iso/non-iso candidates + 12 Jets and sums.

Layer 1
3 Vadatech VT894 Crate,18 CTP7 boards
6 bits ECAL+HCAL energy + veto & feature to Layer 2

Time multiplexing routed through 72 to 72 12-fiber MPO connectors

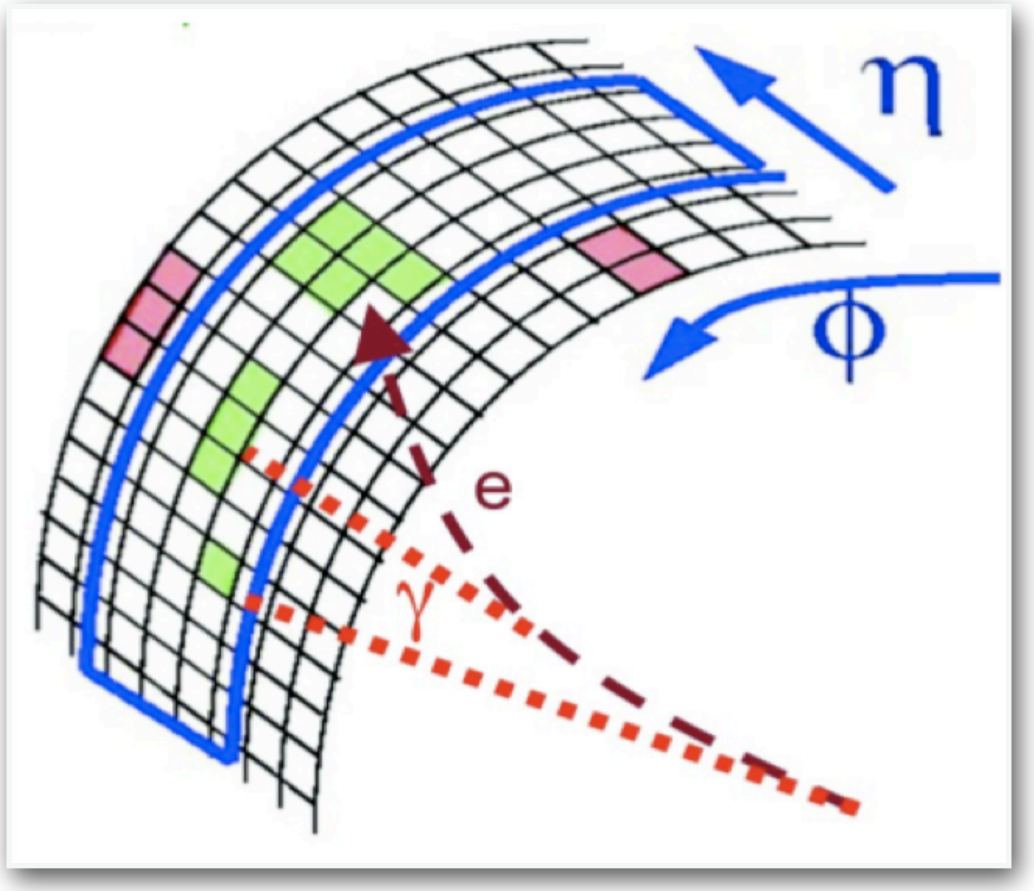
Molex Enclosure
Flexplane (commercial)



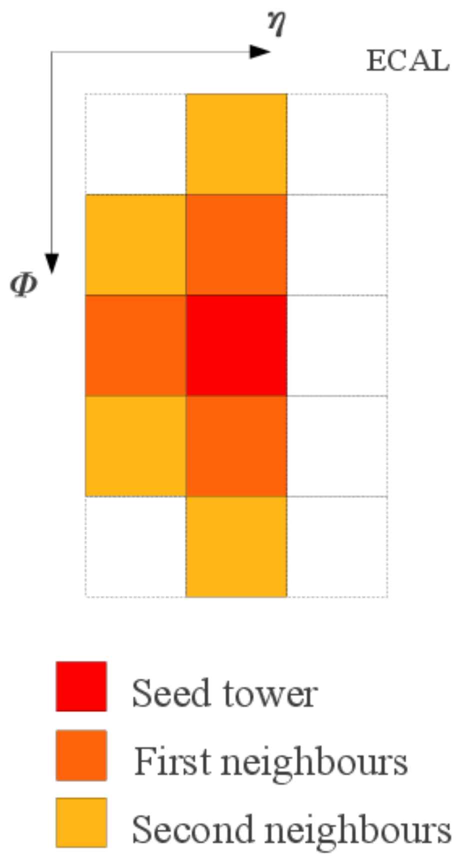
Algorithms & Firmware

CMS Level-1 Calorimeter Trigger

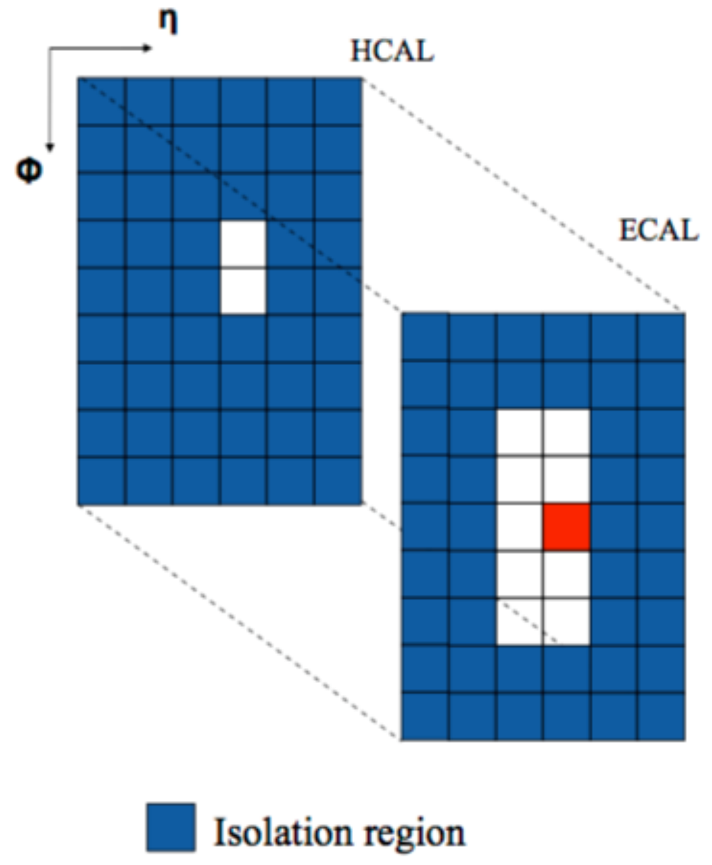
Electrons in CMS



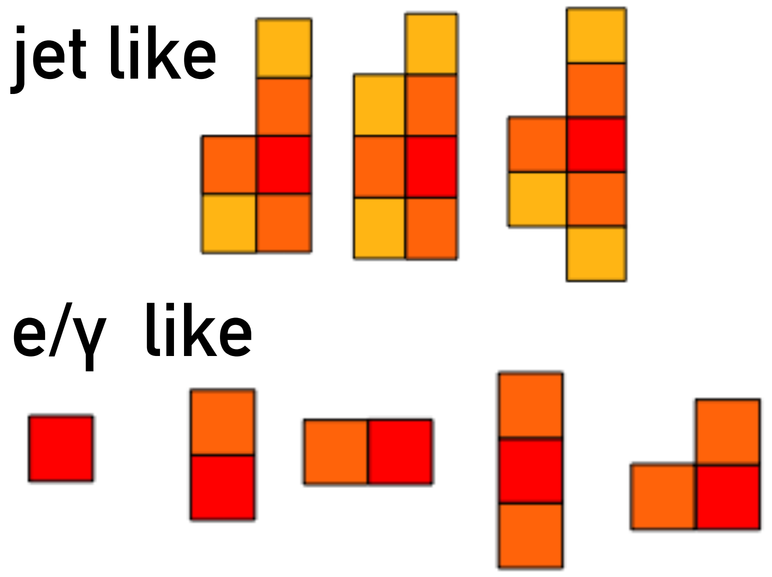
Cluster building



Isolation



Cluster shapes



Isolation
Create isolation annuli (removing footprint) for ECAL and HCAL around cluster Isolation energy requirement fn. of PU and η

E/G FINDER ALGORITHM

- Optimised clustering to recover energy loss due to tracker material.
- Cluster shape used remove pile-up induced candidates

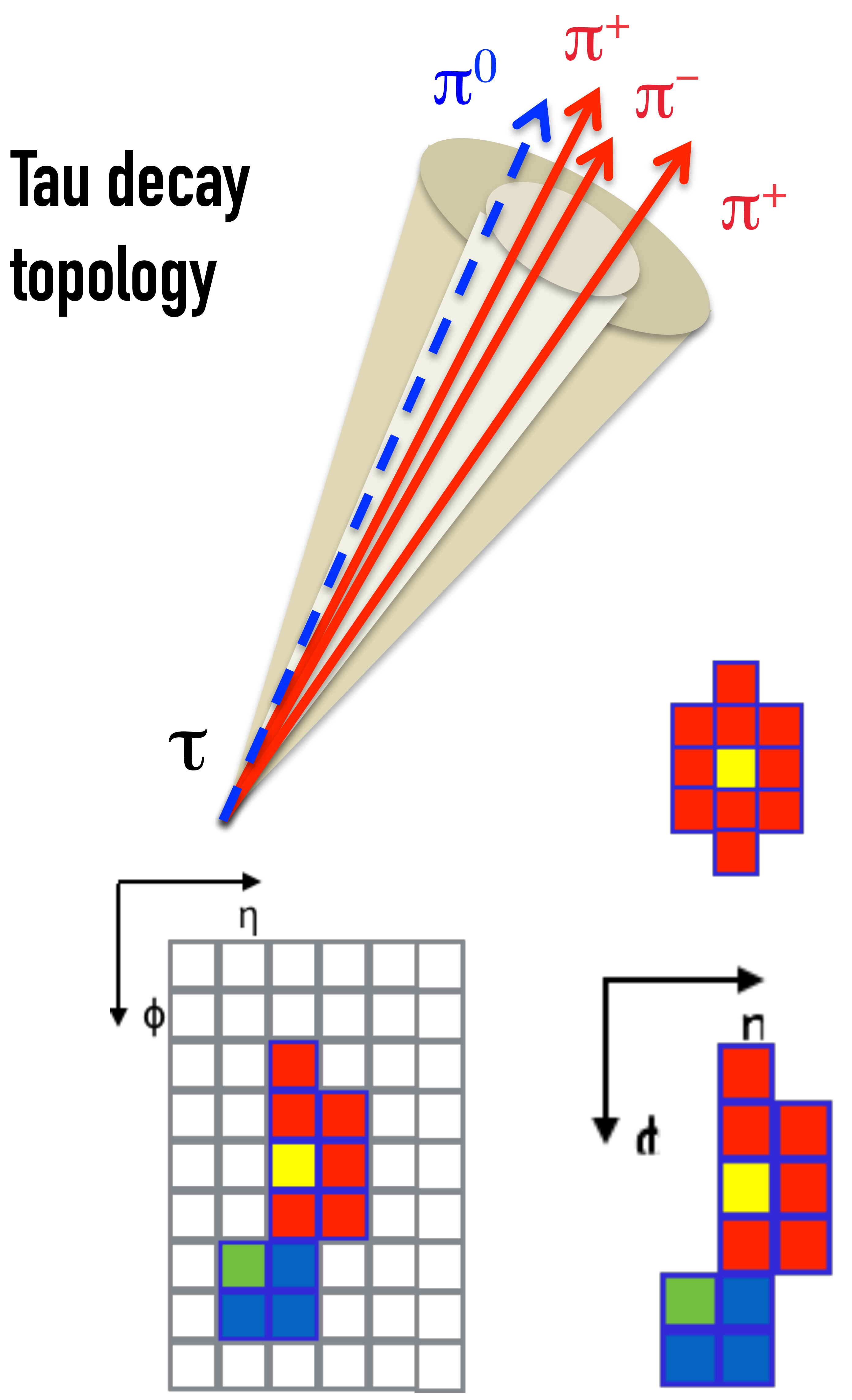
Dynamic clustering
Improved energy containment Showing electrons, photon conversions Minimise effect of pile-up Improved energy resolution

Cluster shape veto
Discriminate using cluster shape and EM energy fraction between e/γ and jets

Calibration
e/γ cluster energy calibrated as fn. of E_T, η and cluster shape

Energy weighted position
Potential use in correlating objects e.g. invariant mass

TAU FINDER ALGORITHM



- Based on **EG cluster merging**.
- Optimise reconstruction of **multiple-prong object** spread by magnetic field.

Clustering, shape and position

Very similar to e/γ — optimised for τ

Merging

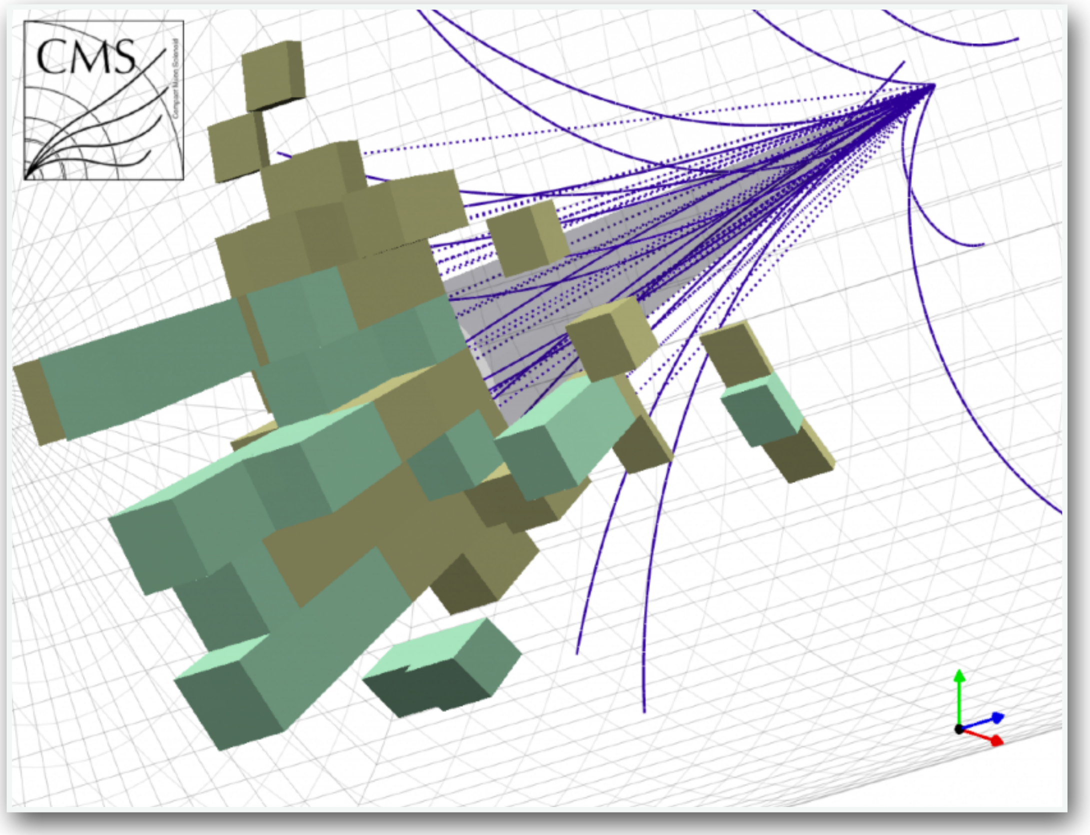
Merge neighbouring clusters (~15% of clusters)
Recover multi-prong τ decays

Calibration

τ cluster energy calibrated as fn. of E_T, η, merging and EM fraction

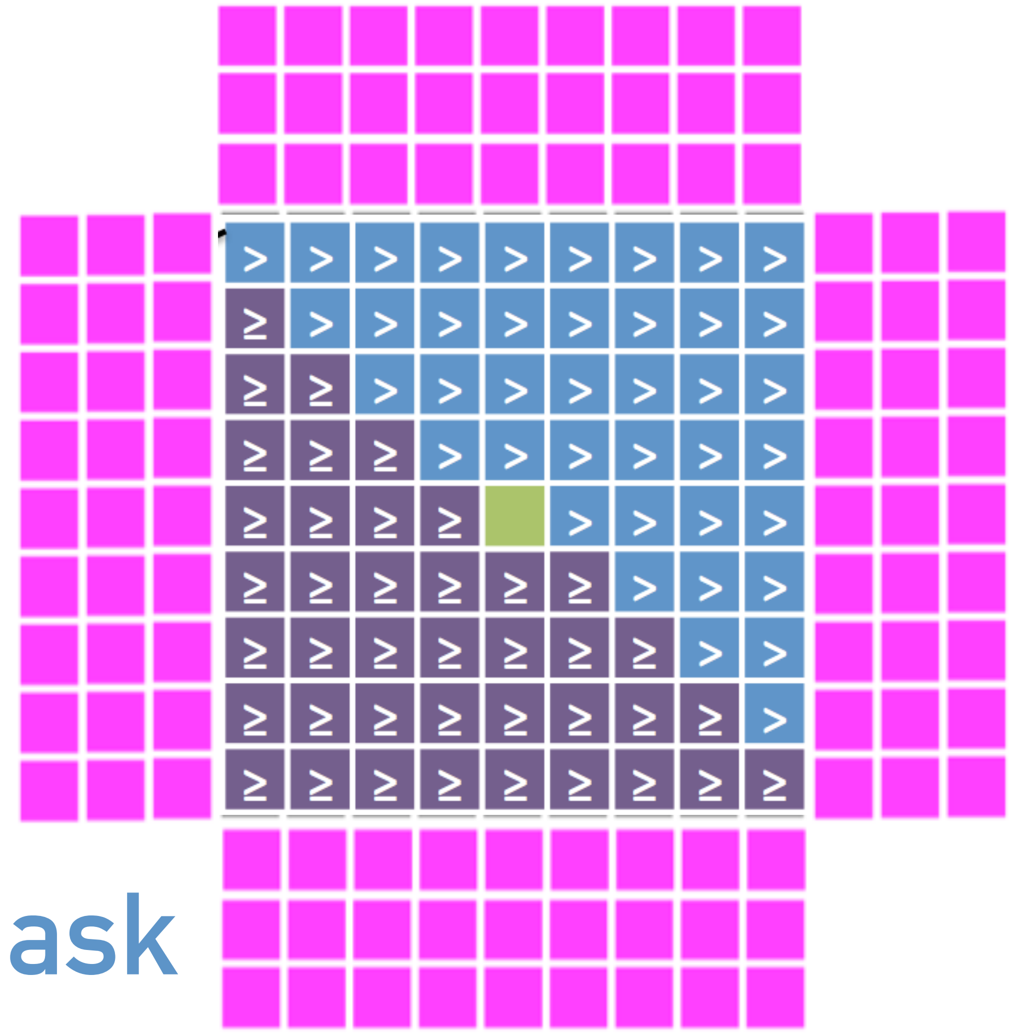
Isolation

Very similar to e/γ — optimised for τ including merging as input — two working points



PUS areas

Seed tower



Veto mask

9x9 sliding window around seed tower

JET FINDER ALGORITHM

- Optimised cone size to **match offline reconstruction algorithm**.
- Pile-Up subtraction technique **less sensitive to fluctuations**.

Input granularity

Access to higher granularity inputs than Run I

Sliding window jet algorithm

Search for **seed energy** above threshold
Apply **veto mask** to remove duplicates
Sum 9x9 trigger towers to approximate R=0.4 used offline

Pile-up subtraction

Consider **four areas** around jet window
Subtract sum of energy in lowest three from jet energy

Calibration

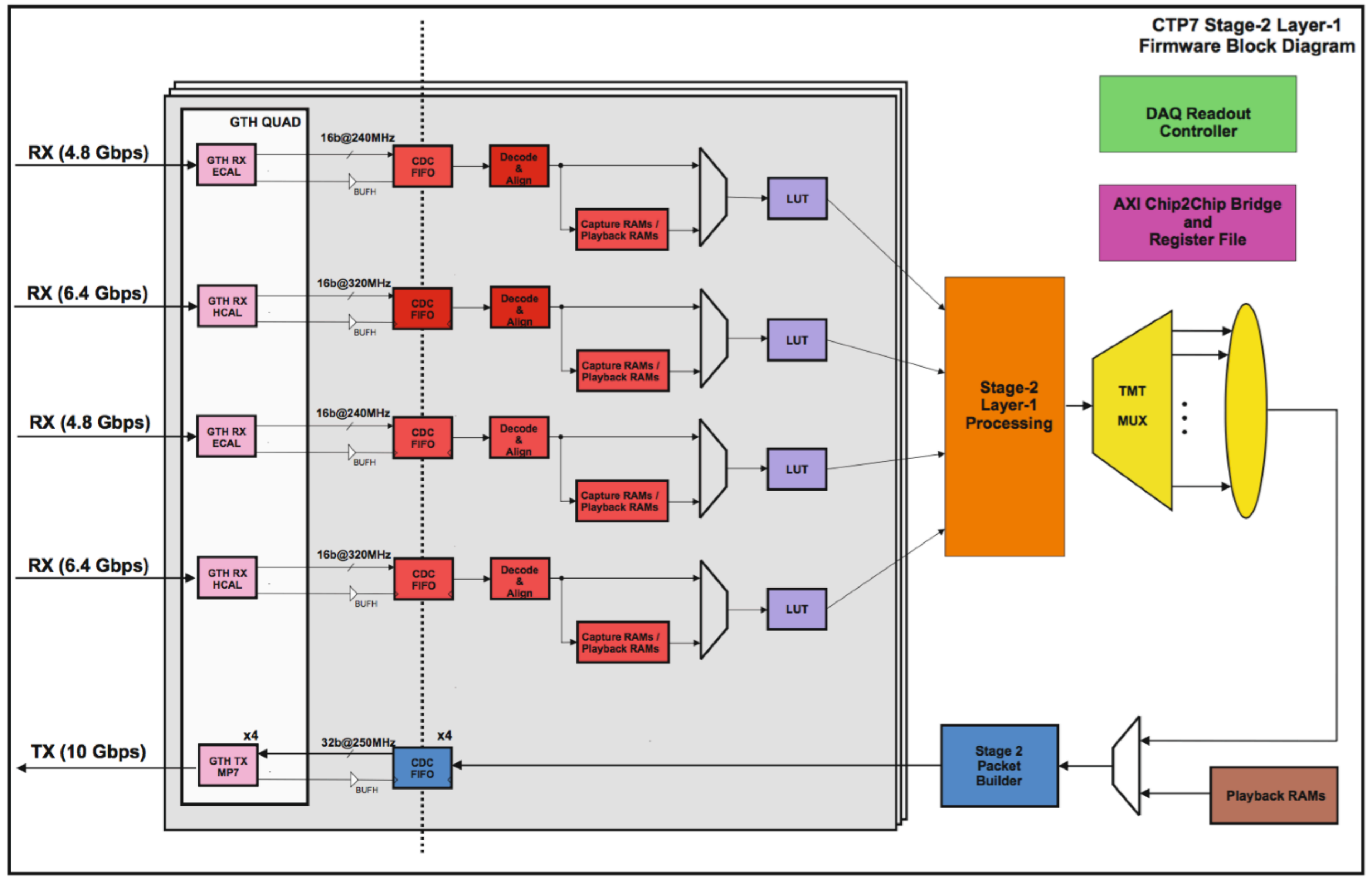
Correct jet energies as a function of jet E_T and η

ALGORITHMS – LAYER 1

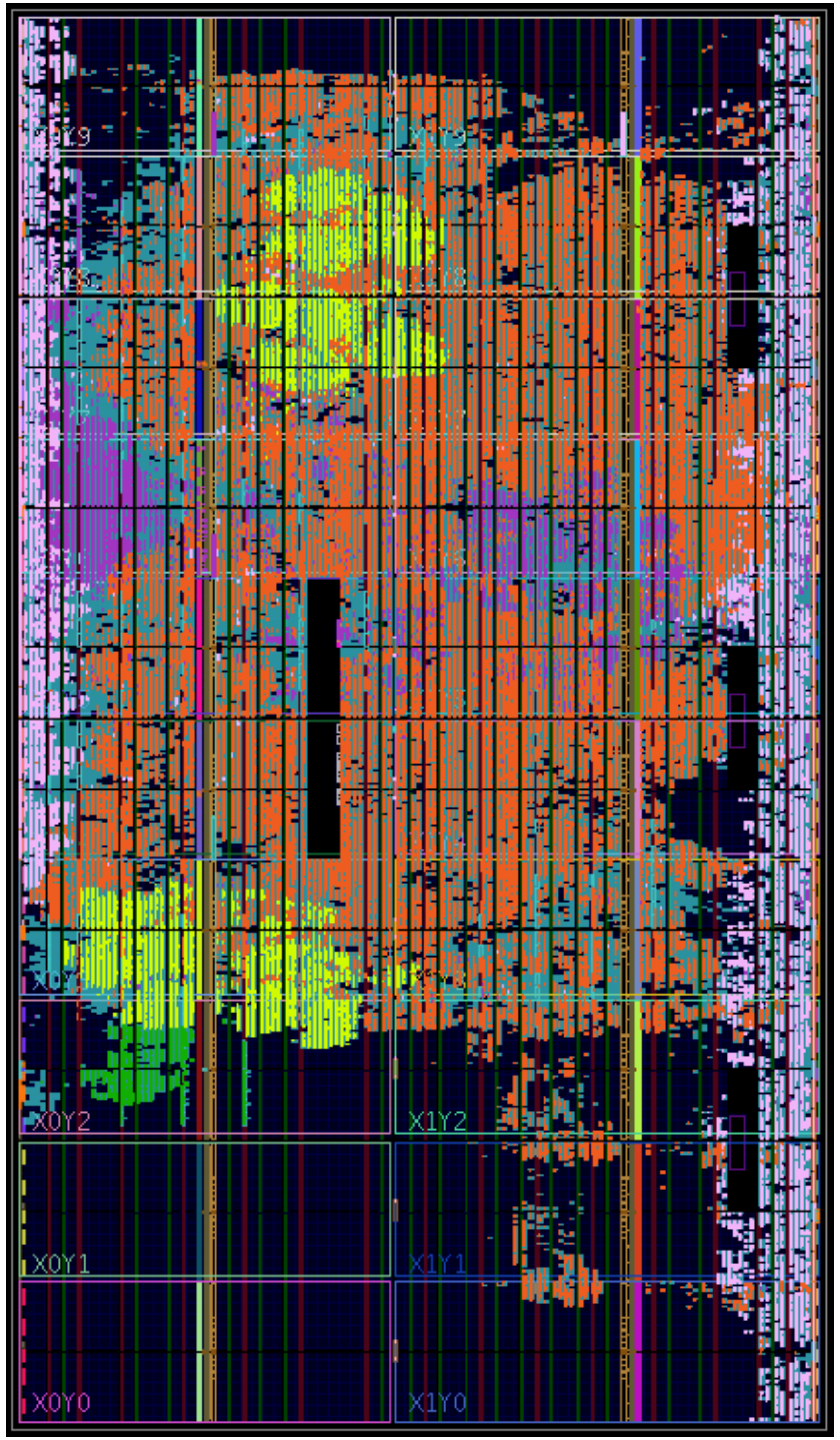
Tower Level operations

- **Calibration and Vetos** (H/E : ratio of the HCAL and ECAL energies, used in to discriminate electromagnetic and hadronic objects)
- **Mixed Link Speed MGT operations**
  4.8 and 6.4 Gb/s synchronous and 10 Gb/s asynchronous.

LAYER 1 Preprocessor

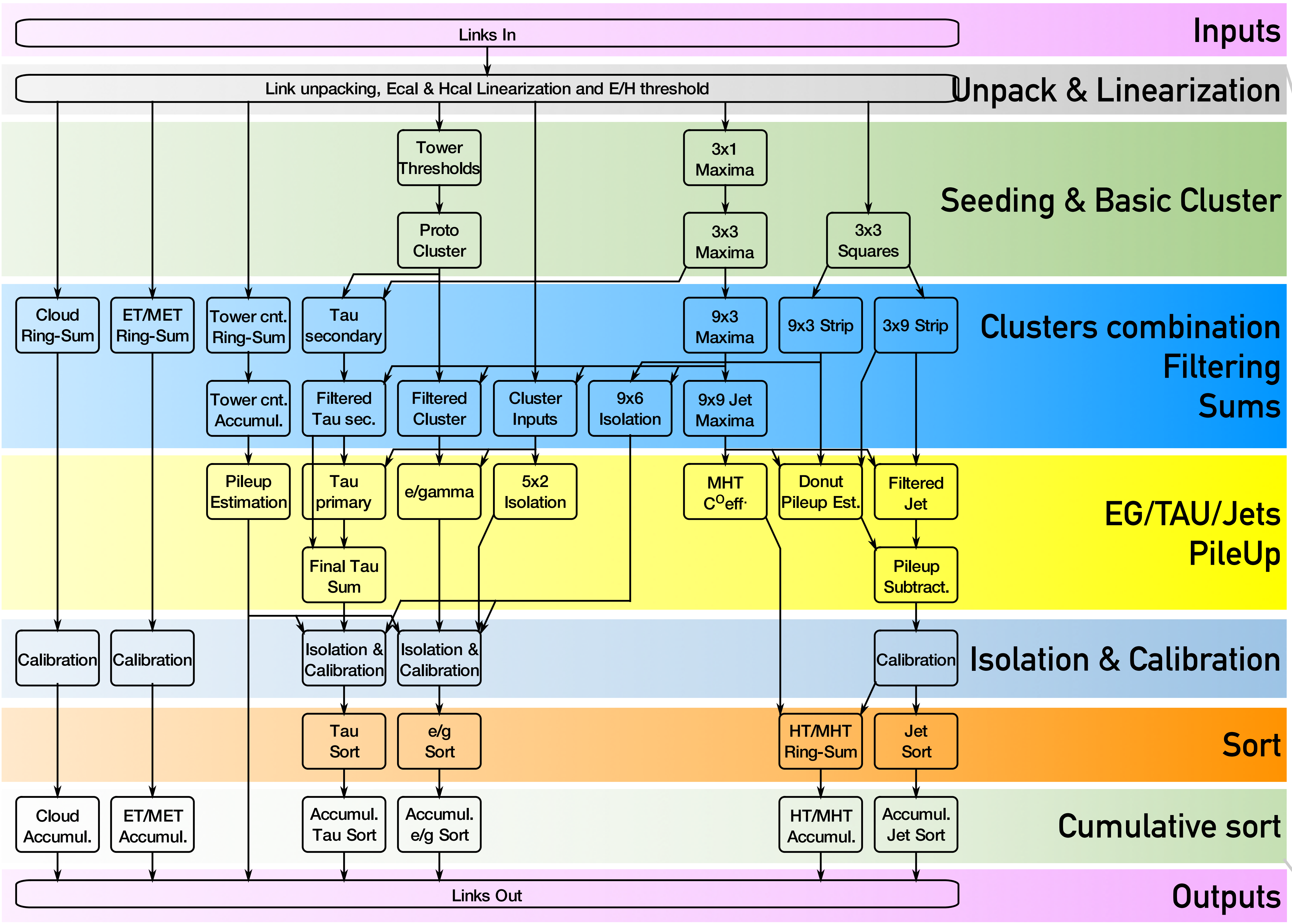


CTP7 floorplanning



Algorithms – Layer 2

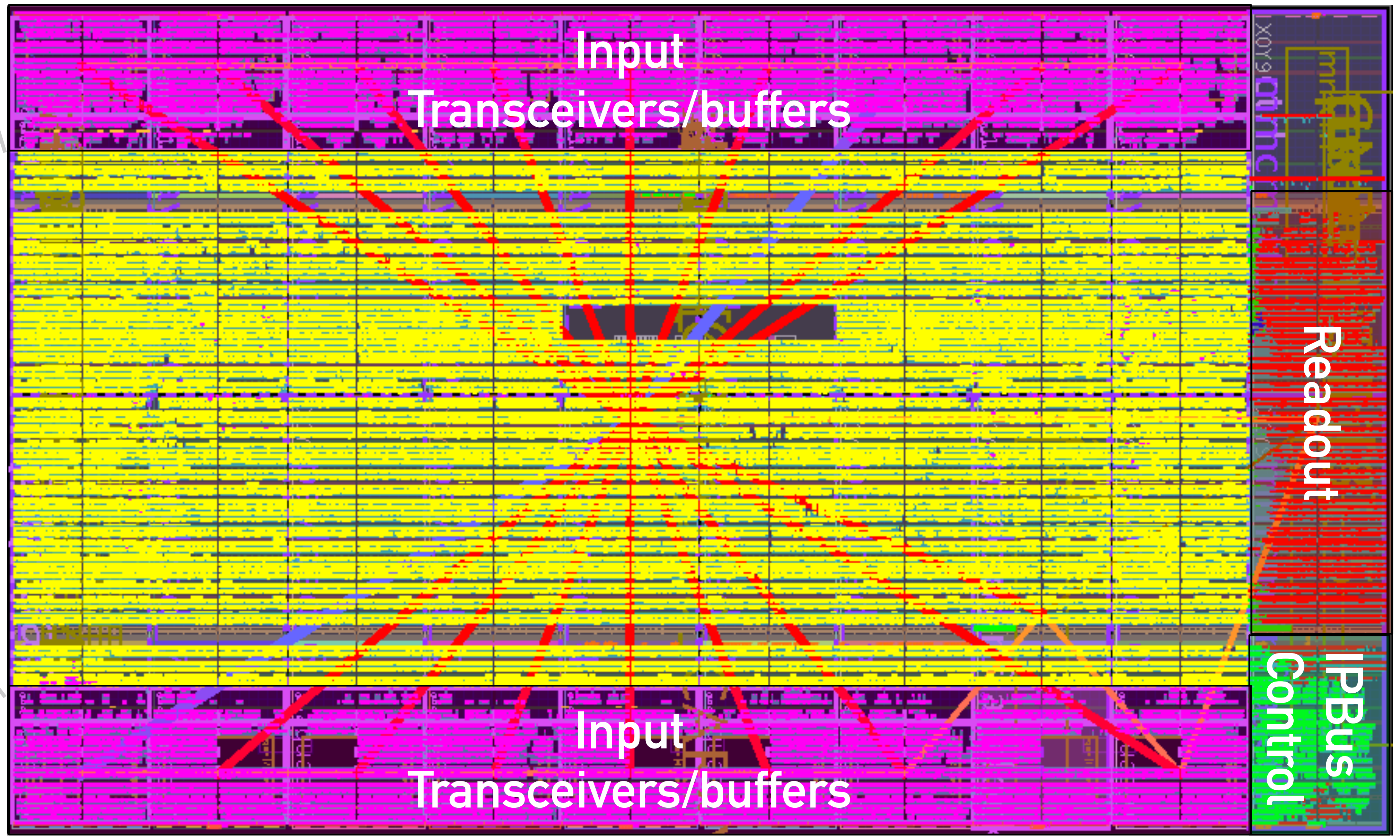
Layer-2 algorithms structure



- **240 MHz** algorithm clock
- **Compact, maintainable firmware**
  - rebuilt several times since the start of operations

Time-multiplexed processing

- **Calorimeter data** received in **geometric order** (increasing η) in **one FPGA**
- **Fully pipelined algorithms**: local processing, reduce signal fanout, eliminate register duplication and routing delays minimised.



Processor floor planning

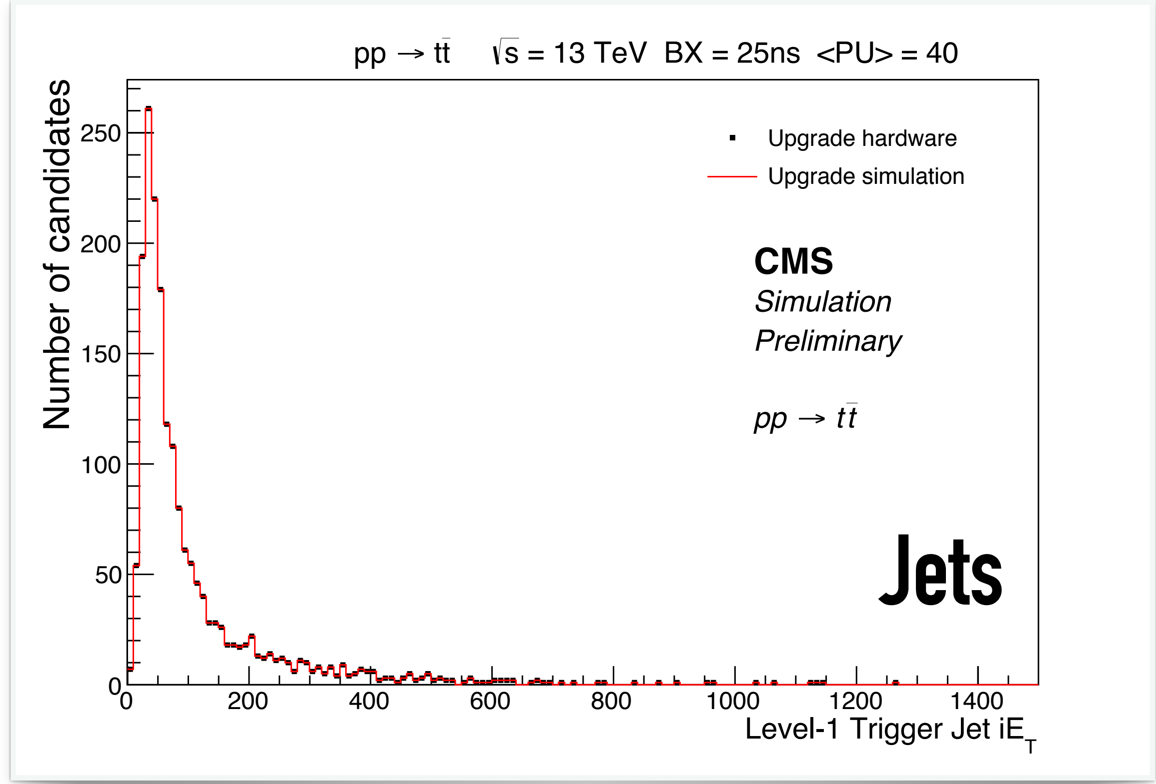
Commissioning & Performance

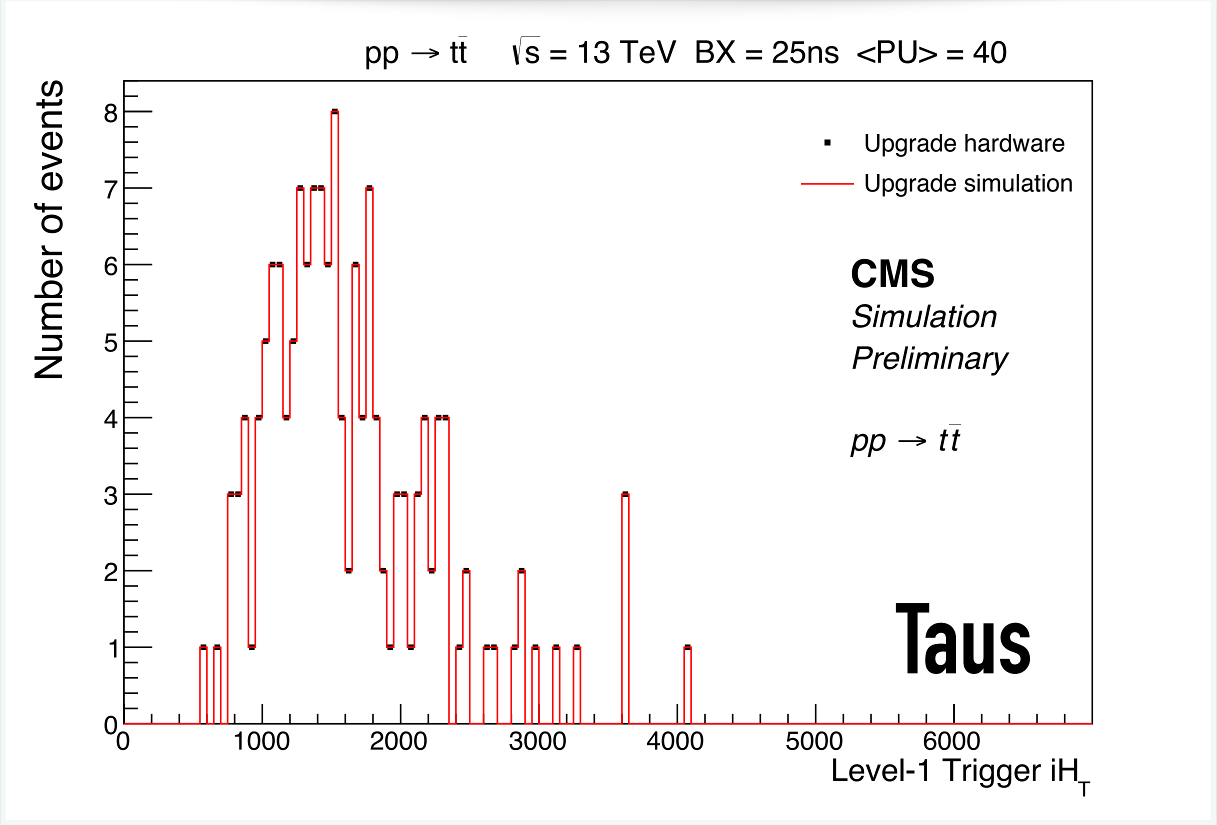
CMS Level-1 Calorimeter Trigger

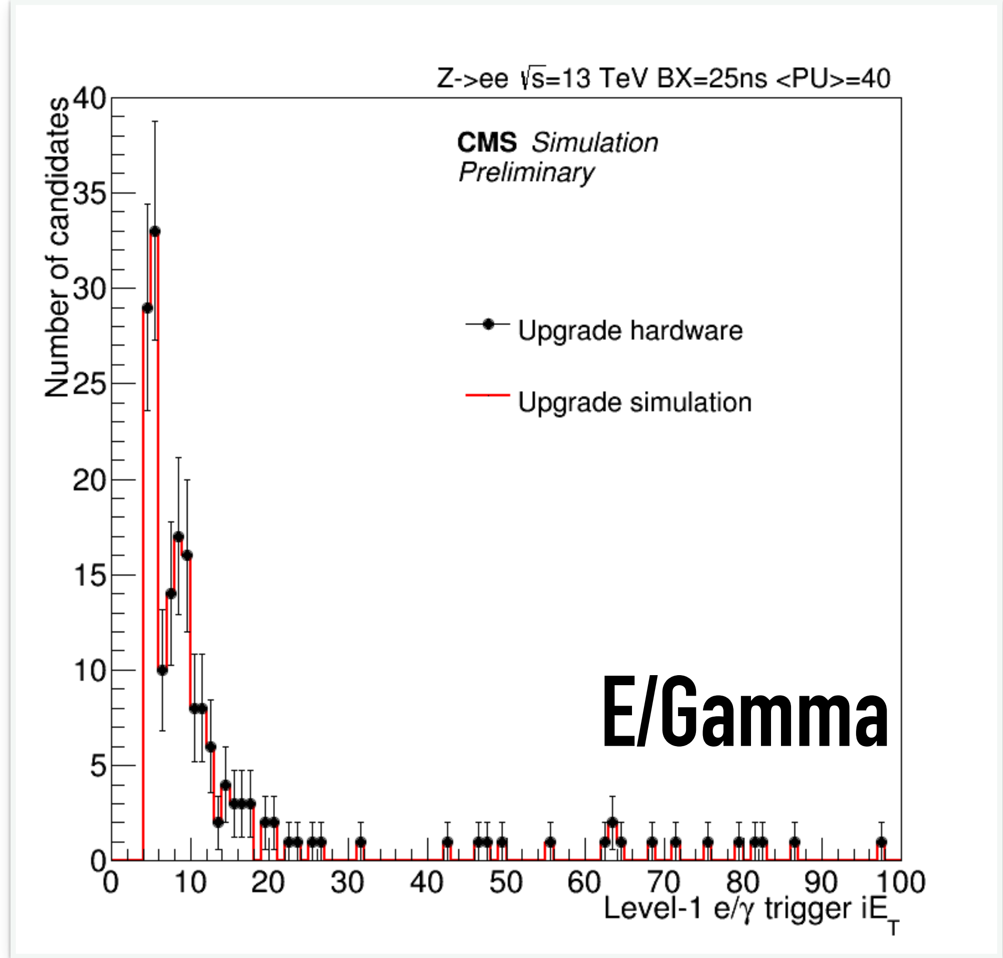
Commissioning

Parallel commissioning

- Calorimeter inputs **duplicated** (in FPGAs and optically)
- **Parasitic running** with CMS during data taking (not triggering!)







Examples of pattern tests with simulated events

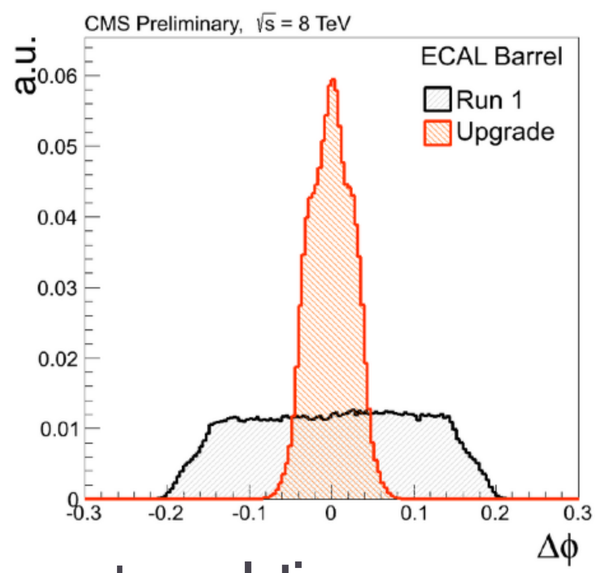
Steps to completion

- **2012-2014** - Interconnection tests
- **2015** - MC pattern test campaign
- **2015** - Data taken in CMS global running
  - Over **7 billion events in pp**
- **2016** - Cosmic runs and beam splashes
- **2016** - First collision
- **2016** - Started physics run

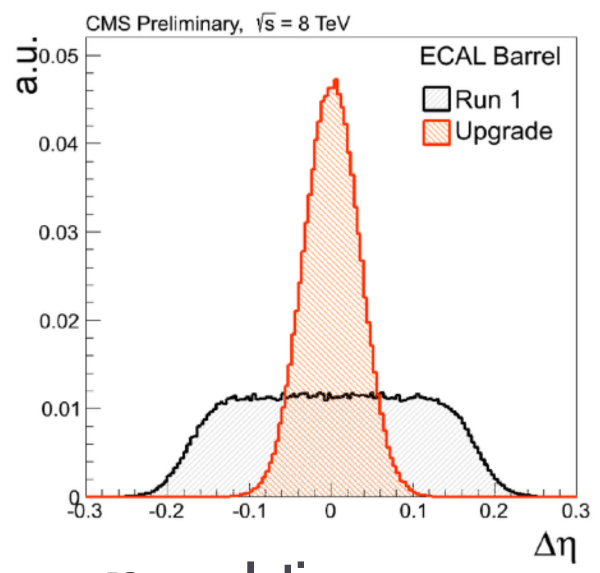
Performance results – E/Gamma and taus

L1 Electron Photon Finder

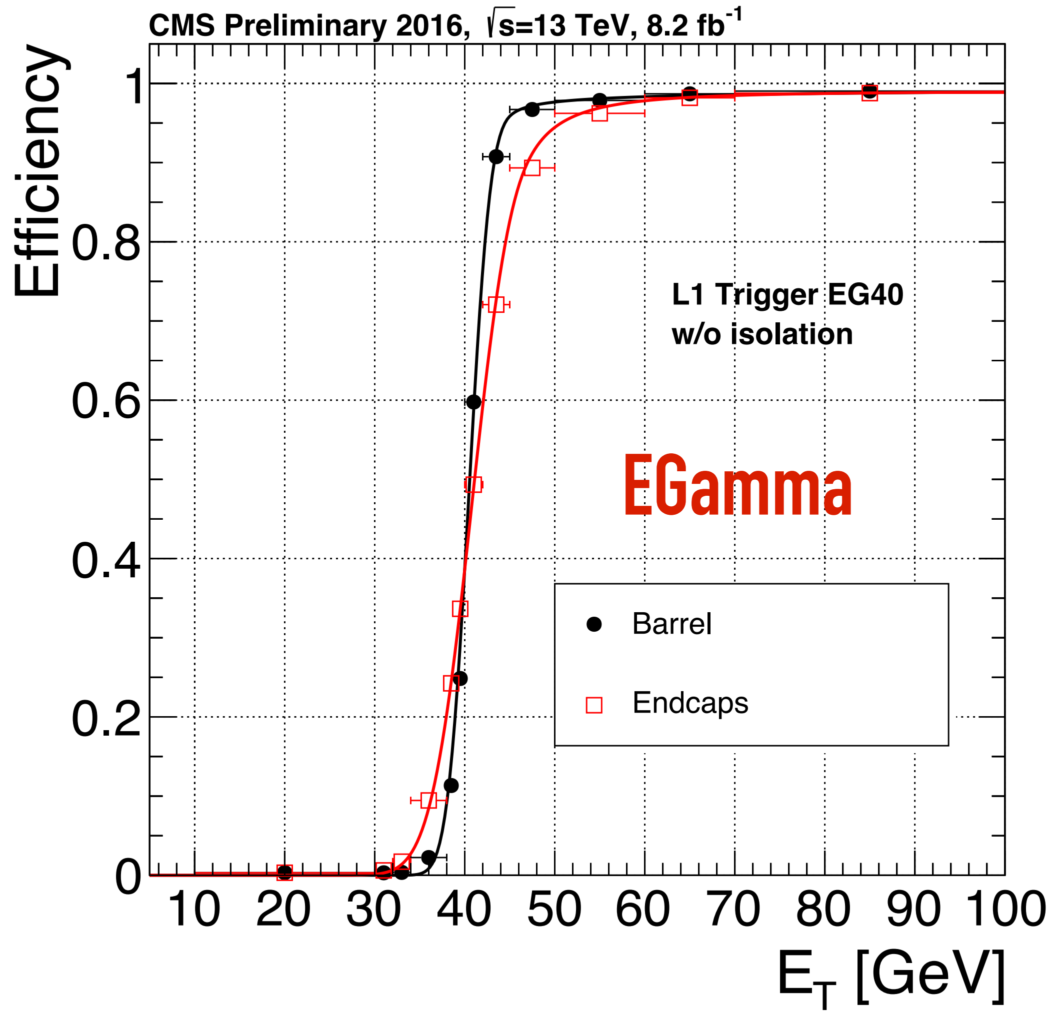
4× position resolution improvement

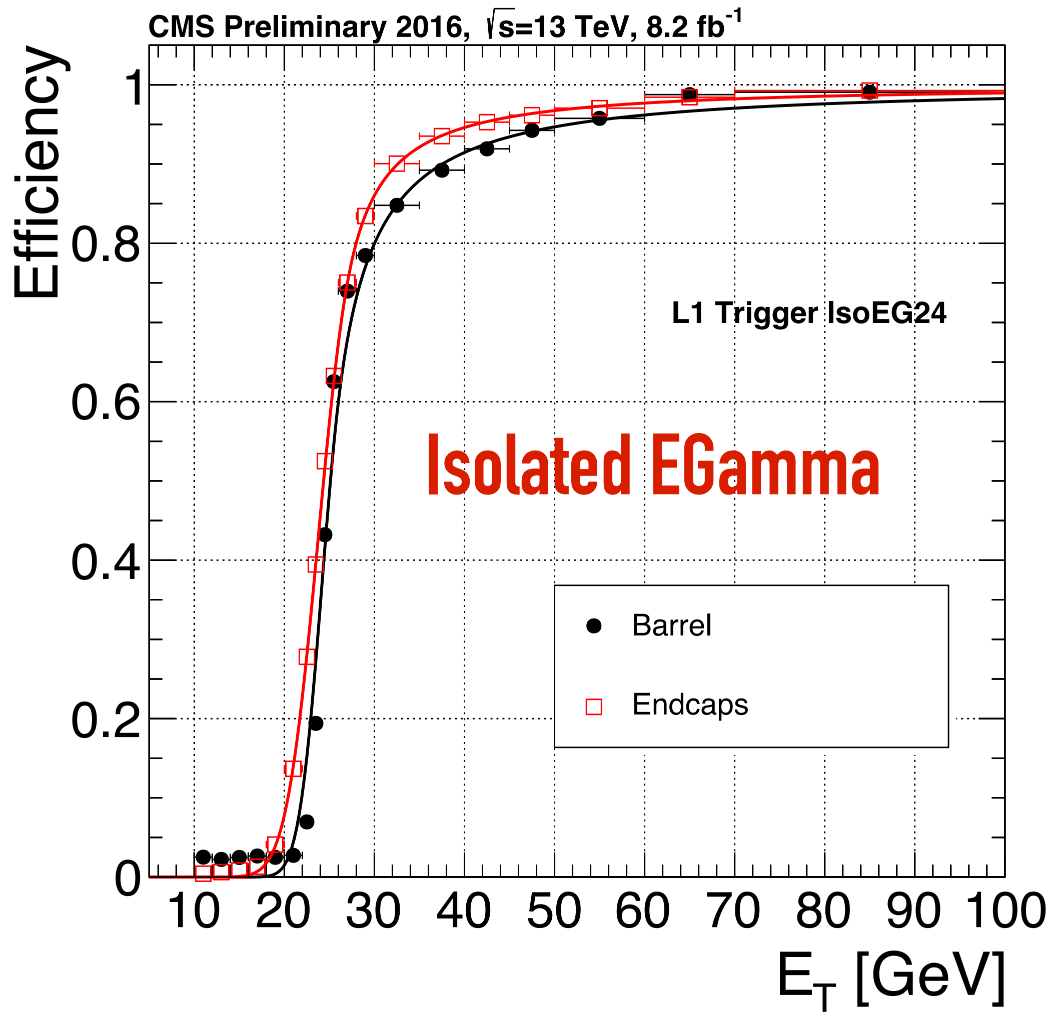


ϕ resolution



η resolution

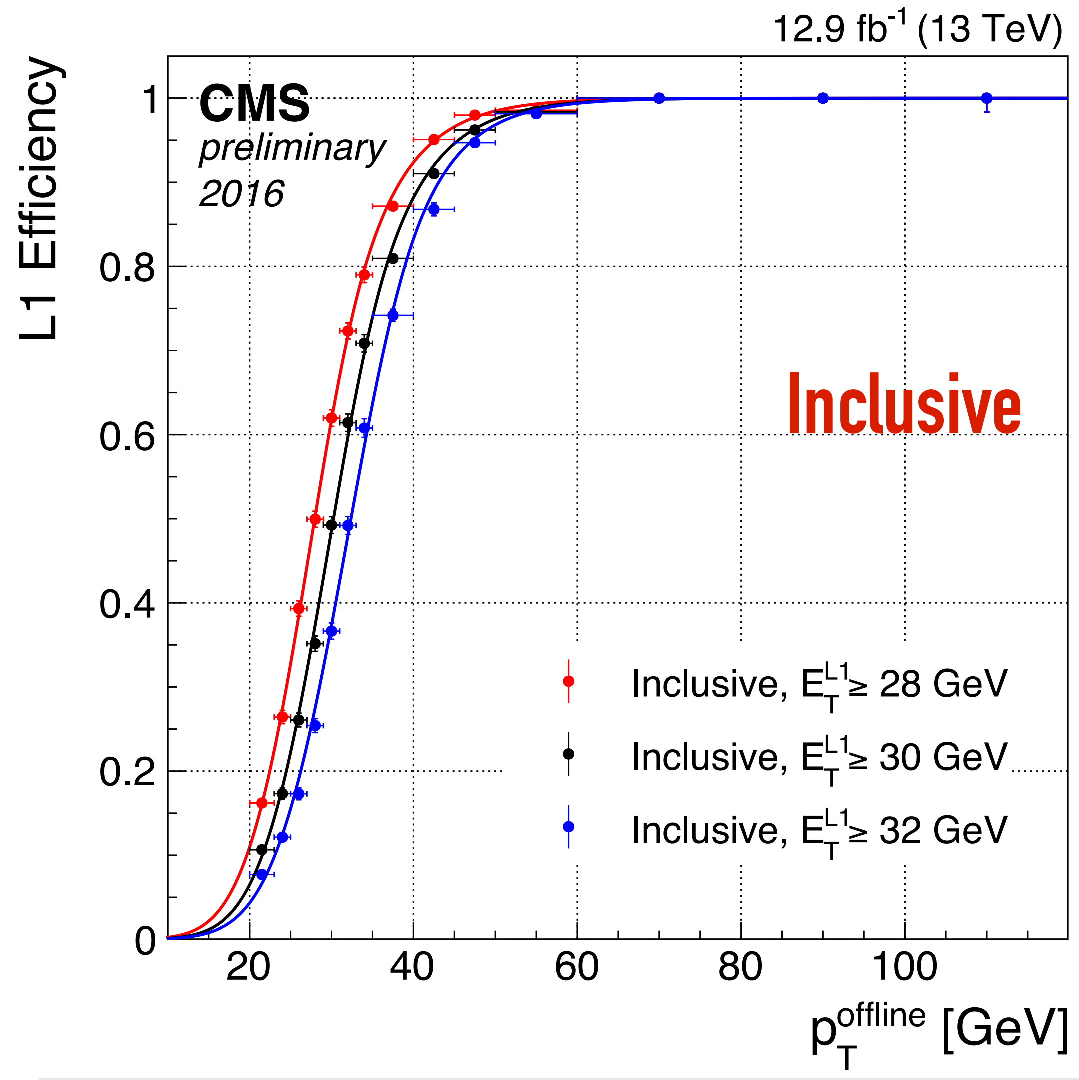


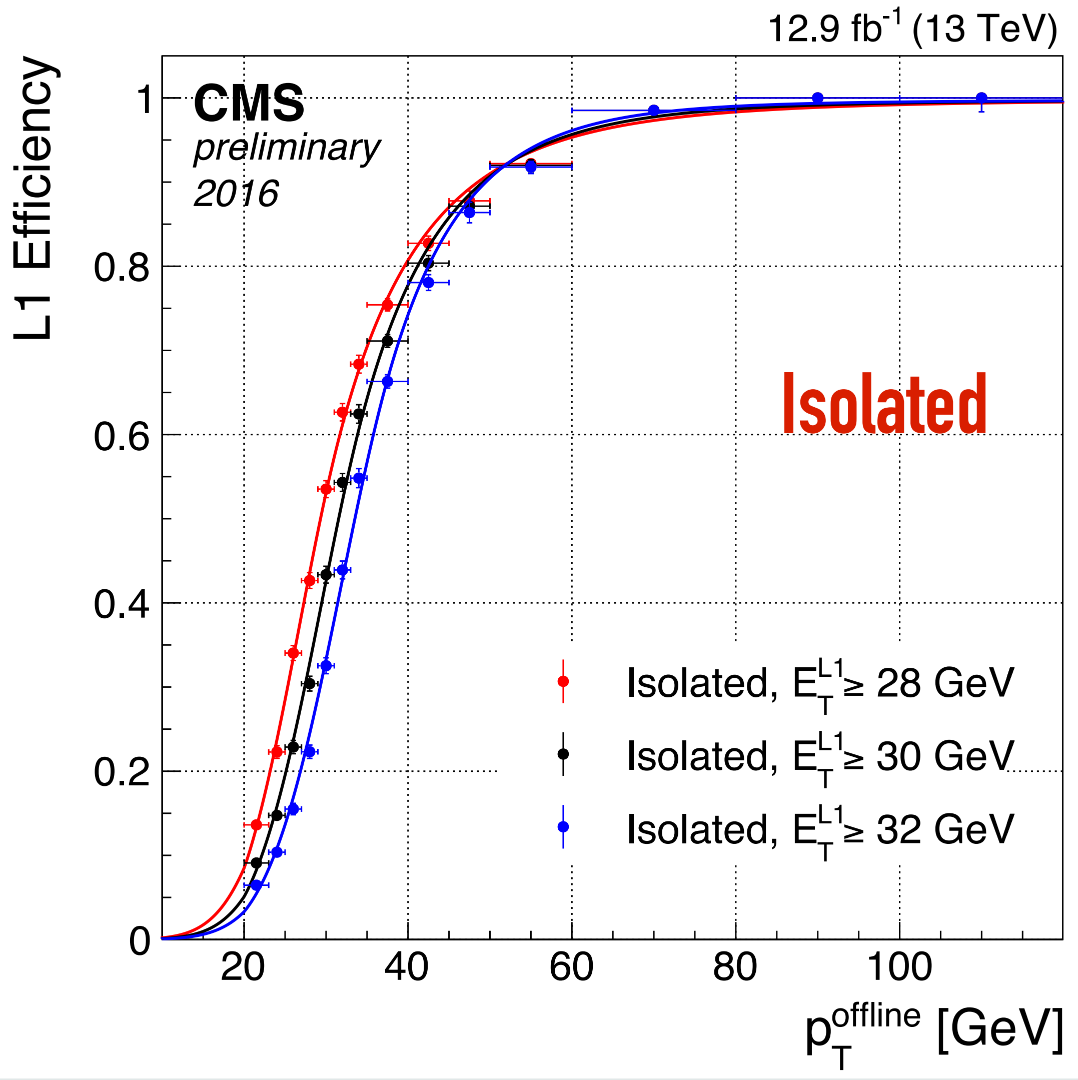


Efficiency for a single e/γ with **ET > 40 GeV** vs offline ET

Using tag&probe method on a Z⟶ee dataset

L1 Tau Lepton Finder



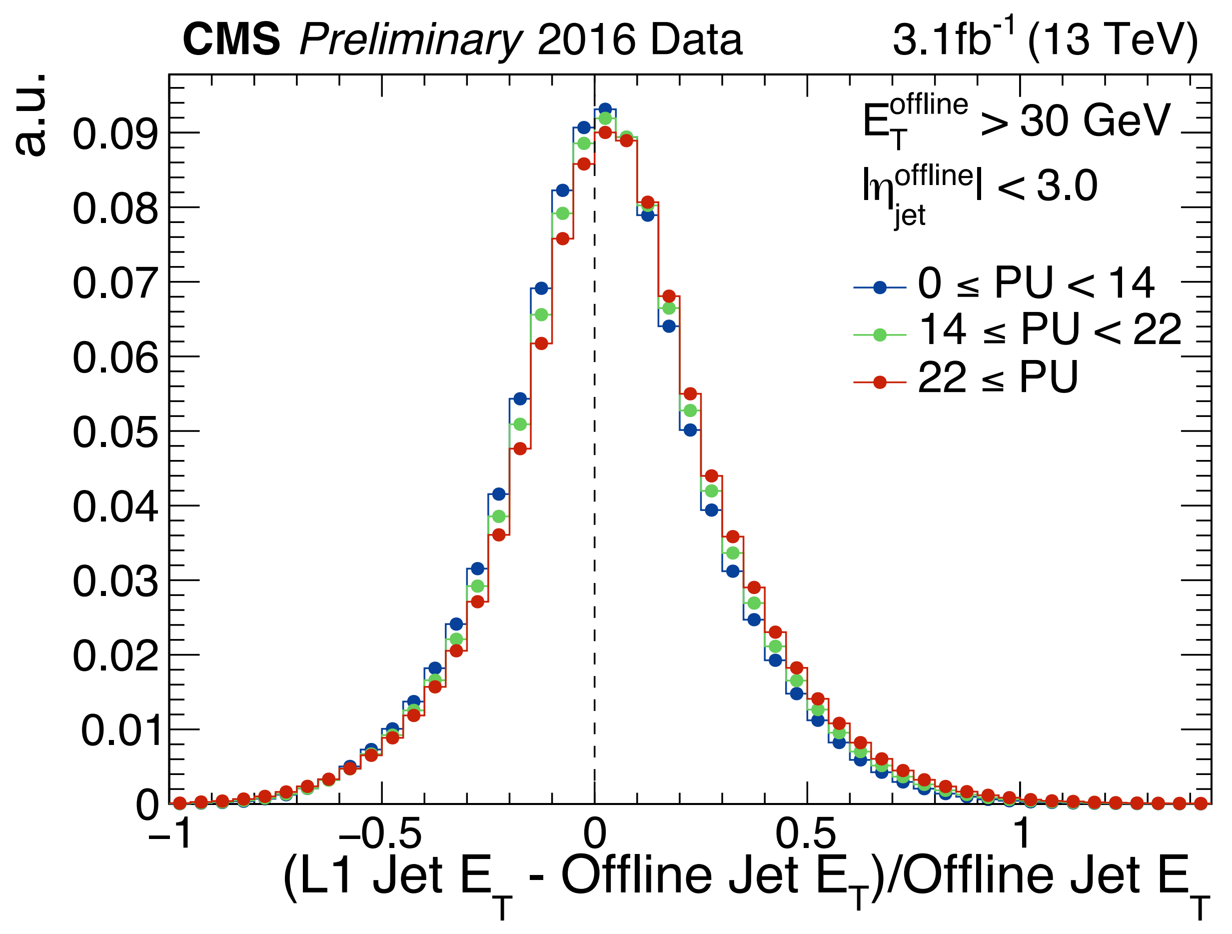


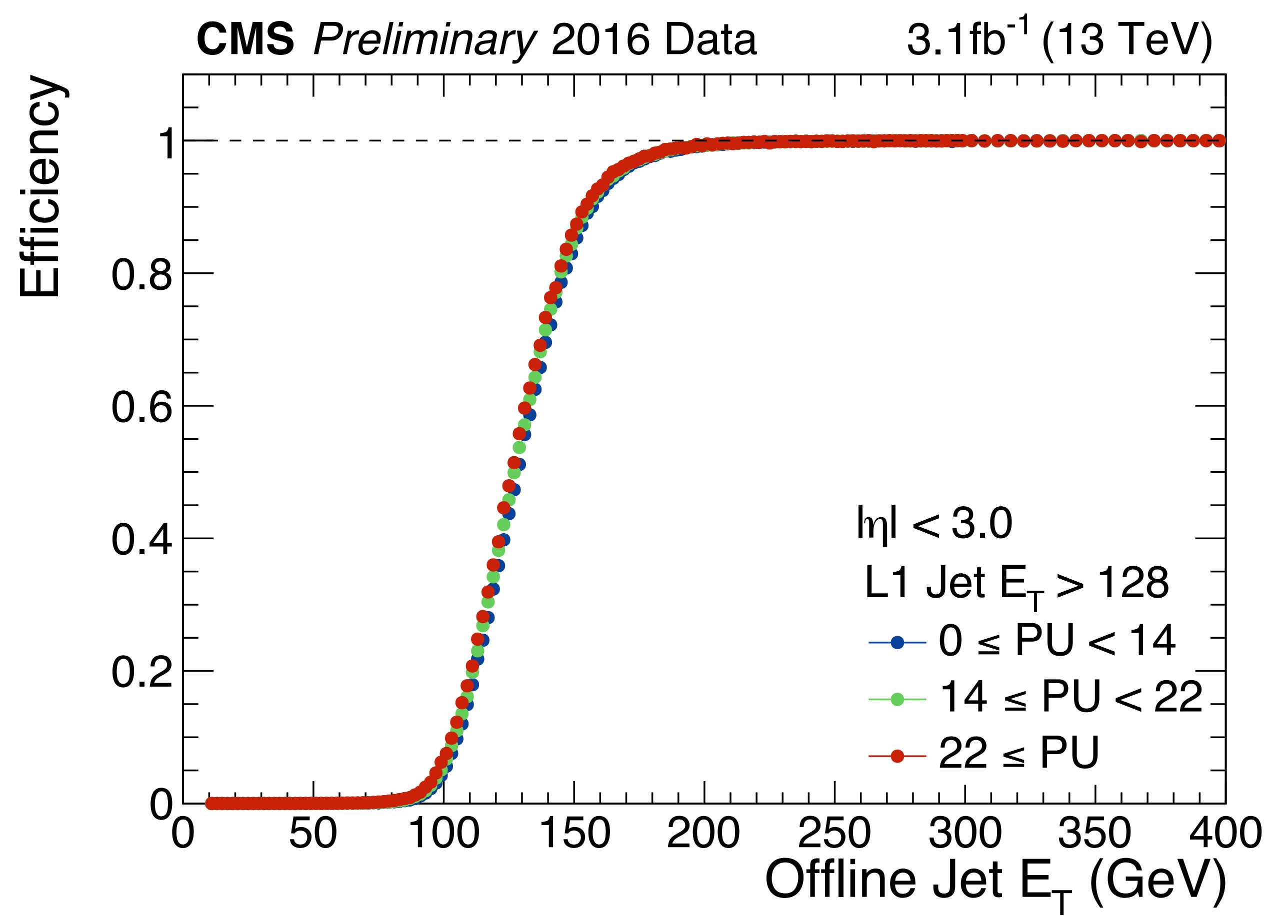
Trigger efficiency for a single τ with **ET > 28**, 30 and **32 GeV** vs offline τ pT

Using tag and probe method on a dataset of Z⟶μτ events

Performance results – Jet and sums

L1 Jet Finder



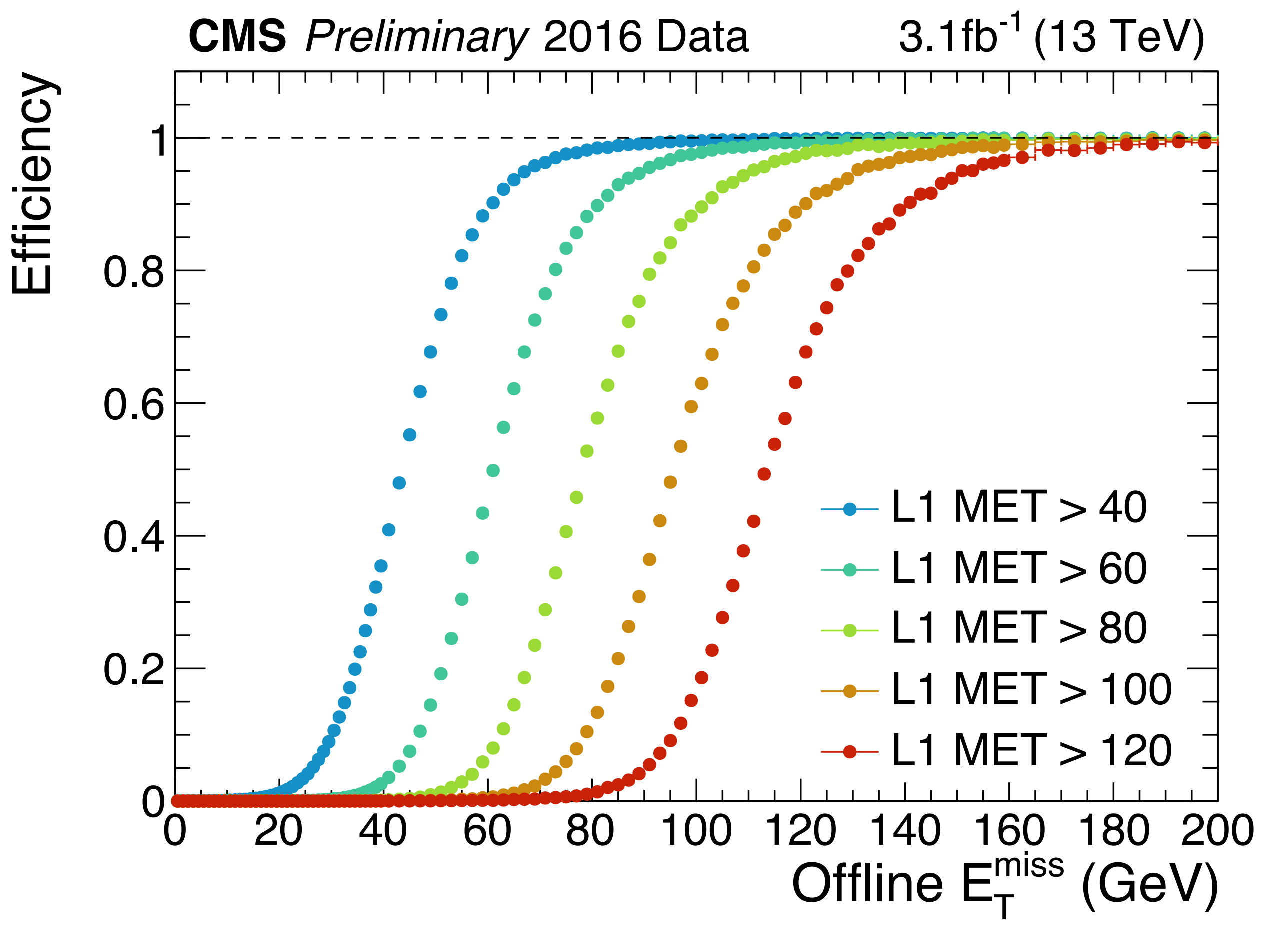


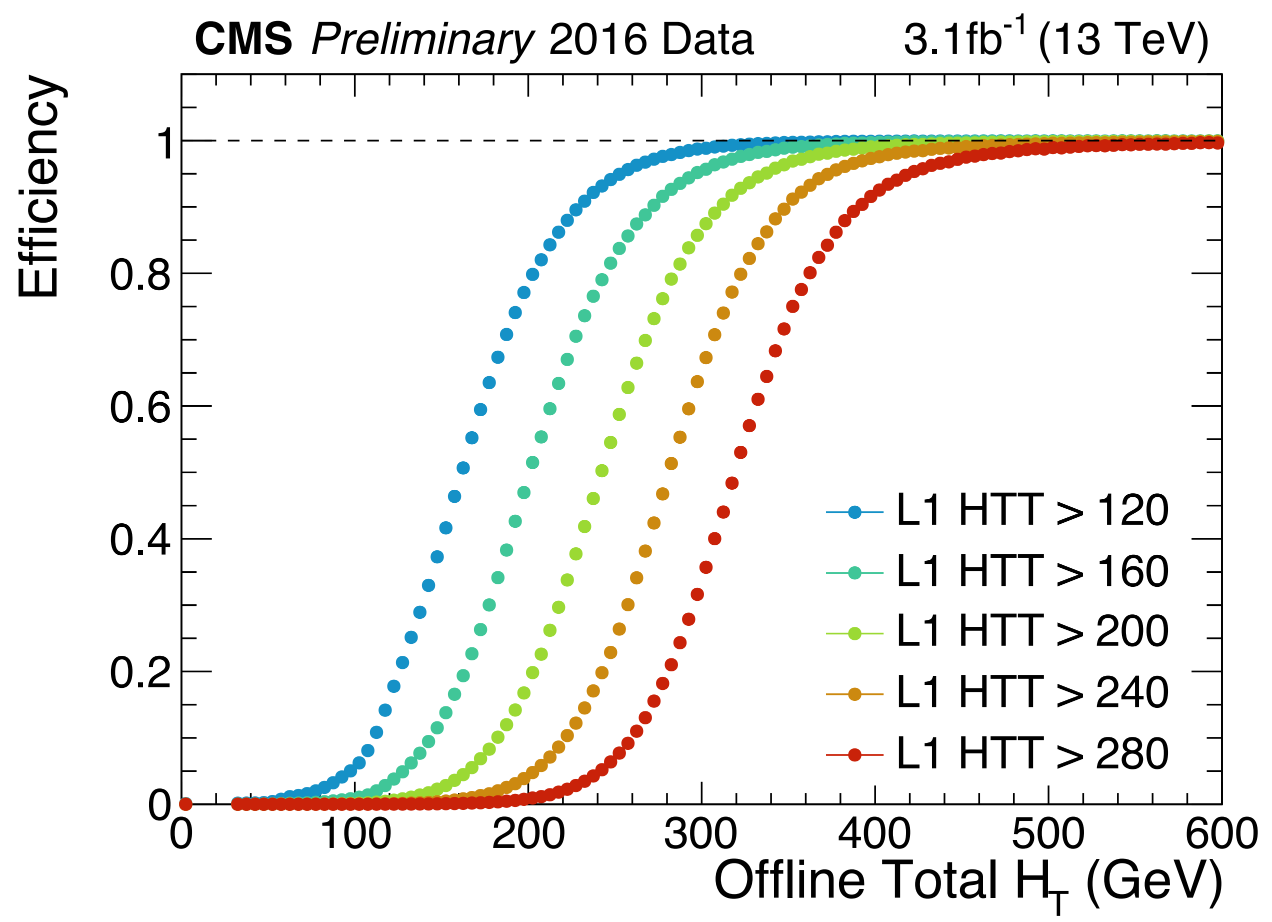
Match **Level-1 Trigger jets** to offline (anti-kt R = 0.4) jets using **$\Delta R < 0.25$ in single muon data**

Compare energies and calculate efficiencies as a function of offline jet quantities

Sharp efficiency turn-on with well calibrated ET scale
Insensitive to pile-up

Sum Triggers





Use jets to calculate **scalar sum $H_T = \Sigma E_{Tj}$ for $E_{Tj} > 30$ GeV and $|\eta| < 3$** using **single muon data**

ET^{miss} : Vector sum of trigger towers with **$|\eta| < 3$**

Summary

CMS Level-1 Calorimeter Trigger

Summary and Outlook

The newly installed CMS L1 calorimeter trigger has successfully completed the first year of operations

- In the LHC Run II challenging environment, at higher luminosity, centre-of-mass energy, increased pileup…
- With excellent performance on single physics objects and complex global quantities

Development, installation and commissioning completed under a very tight schedule

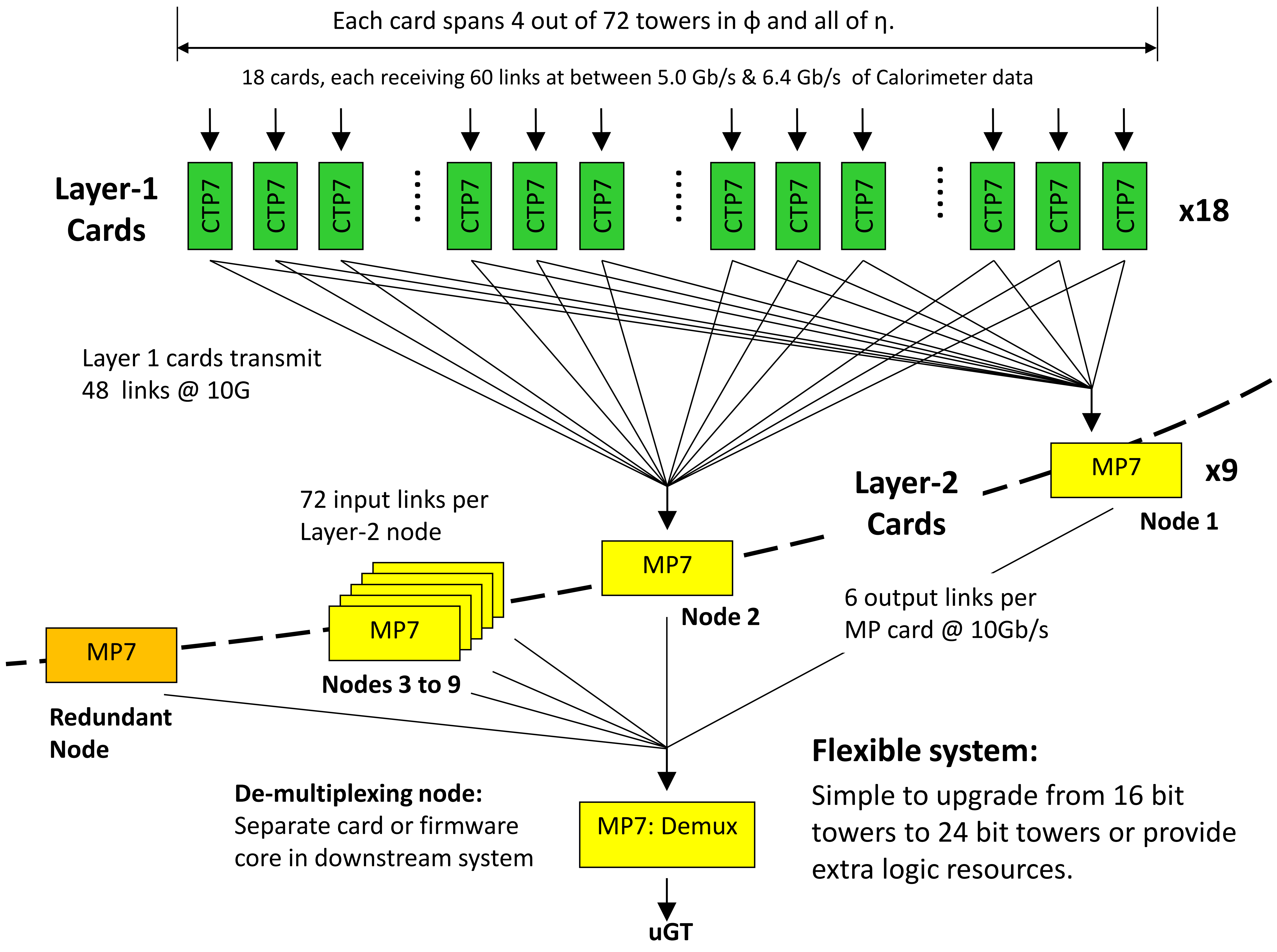
- State-of-the-art, FPGA based, very high bandwidth processors with sophisticated, programmable algorithms
- The system has successfully evolved with the changing LHC conditions.

Study the performance of this new trigger and learn from design and commissioning to begin designing Phase II trigger upgrade for HL-LHC

Spares

CMS Level-1 Calorimeter Trigger

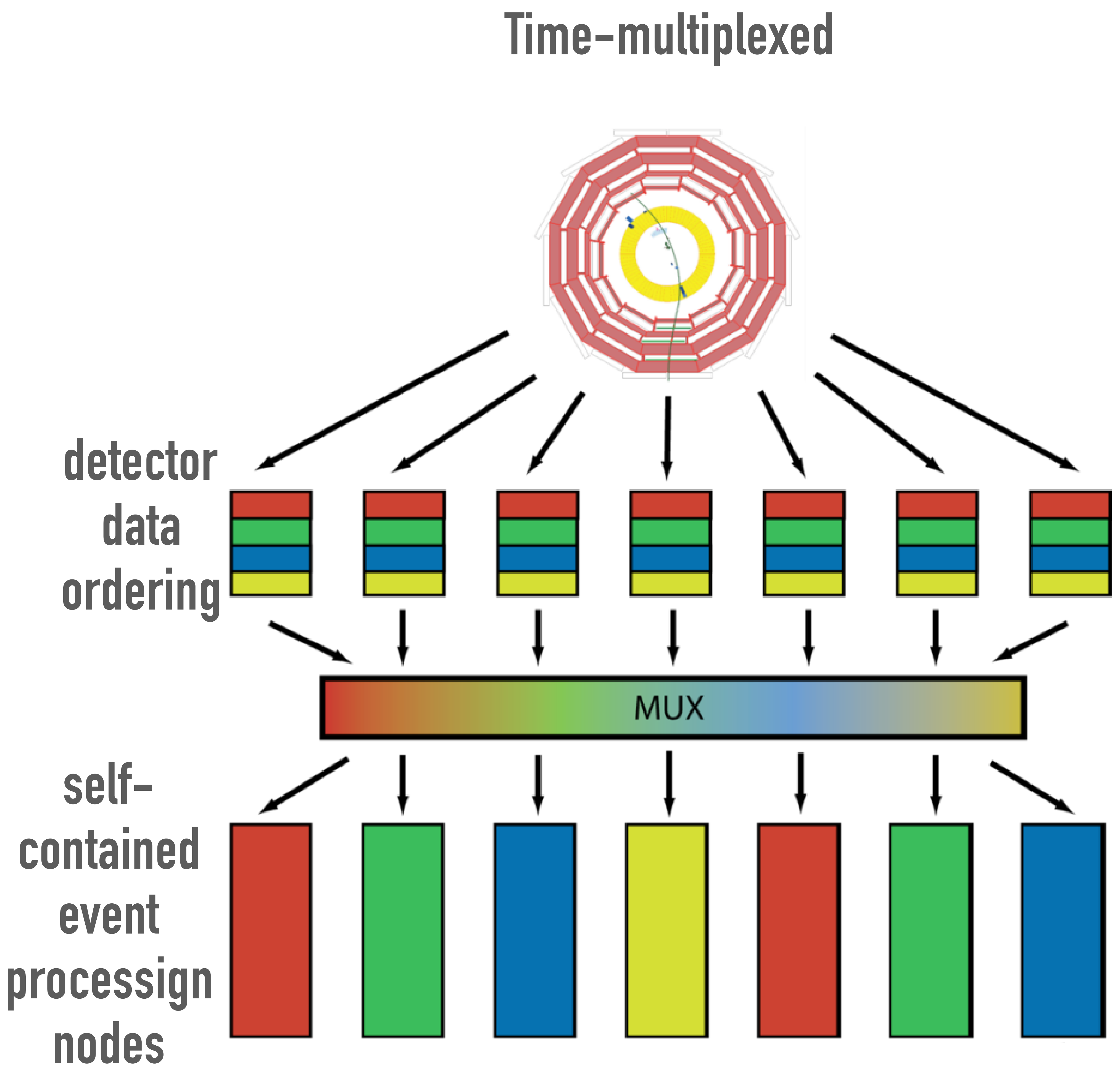
Time–Multiplexed Calorimeter Trigger

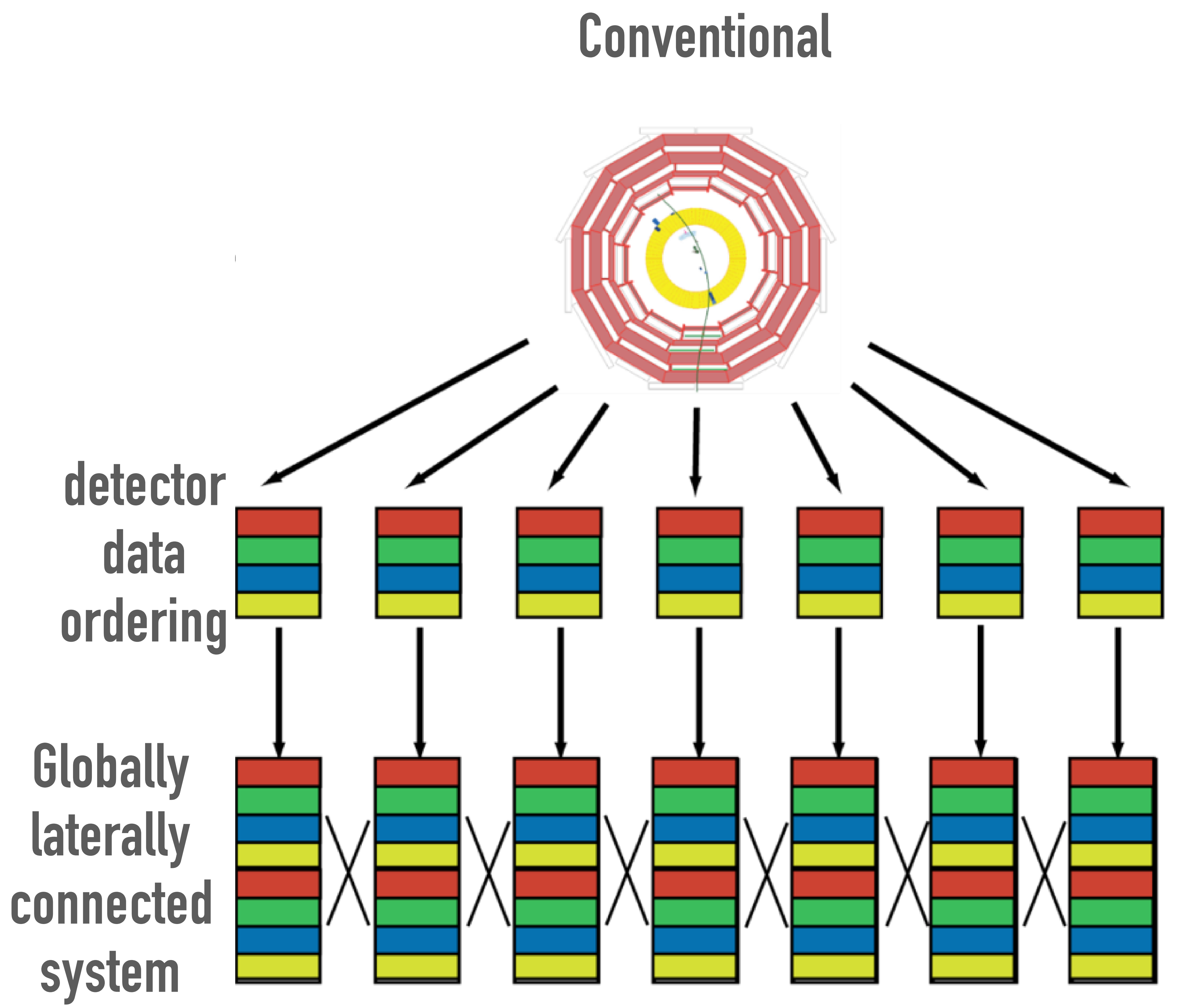


Flexible system:

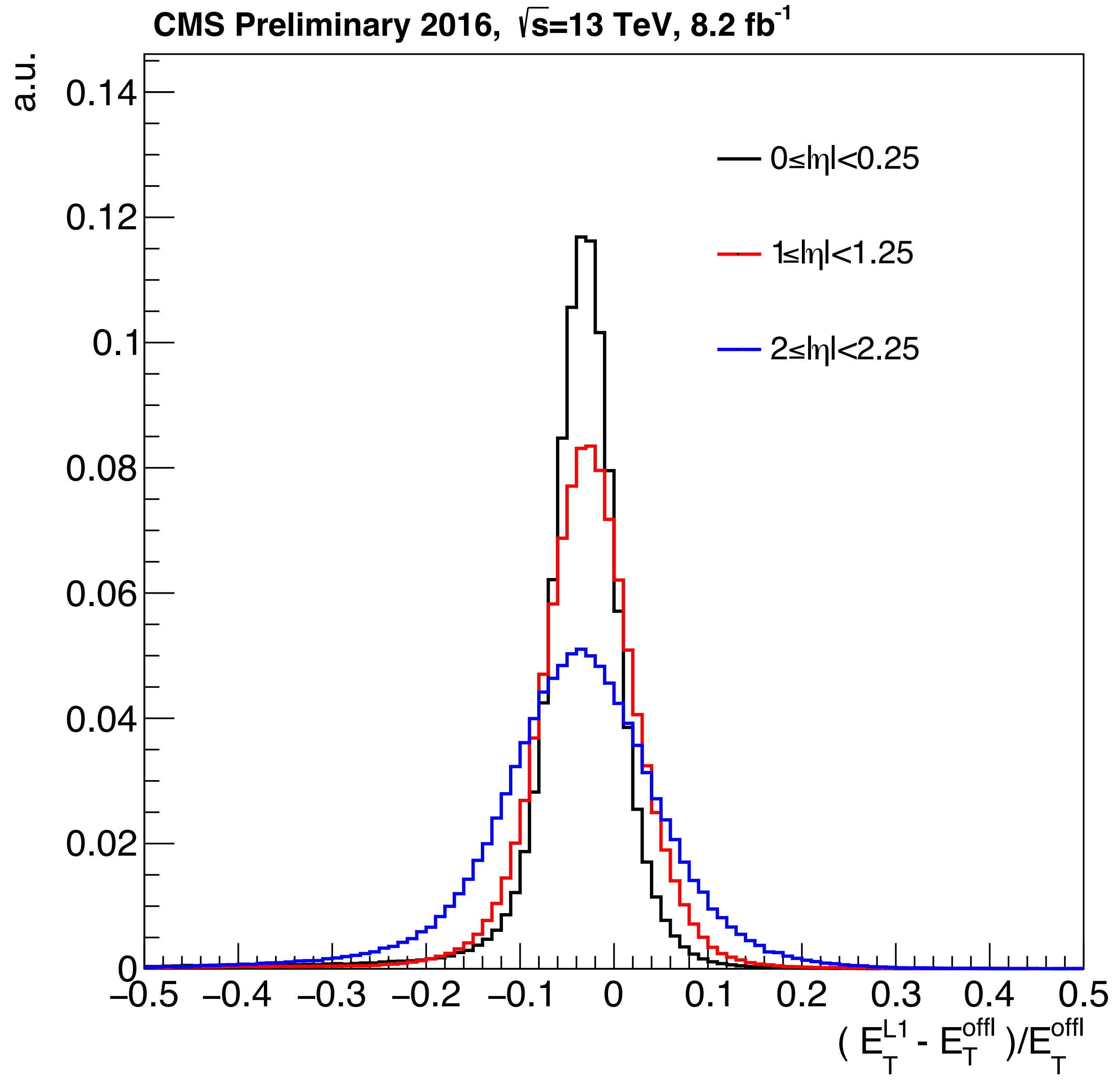
Simple to upgrade from 16 bit towers to 24 bit towers or provide extra logic resources.

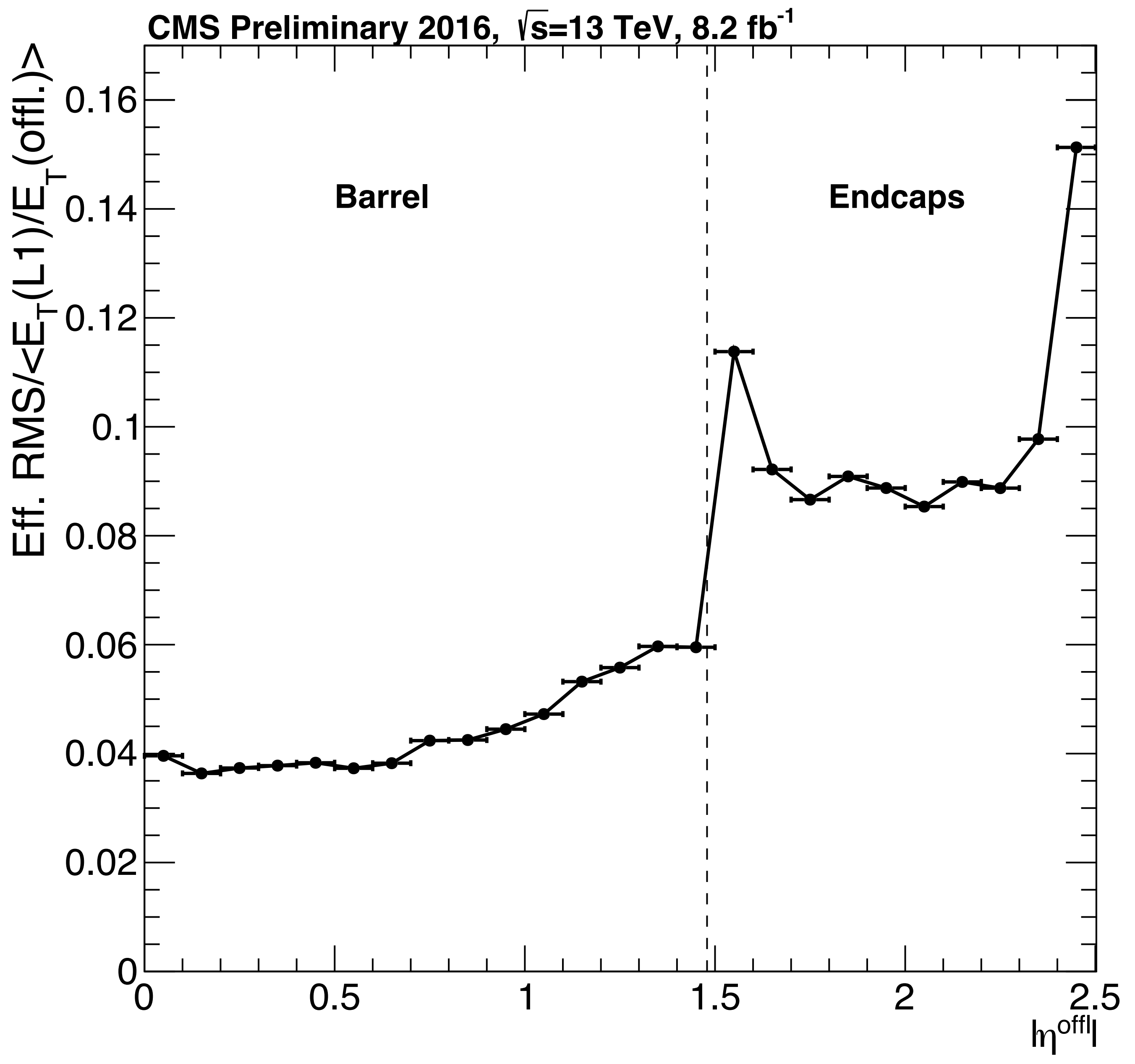
Time-multiplexing



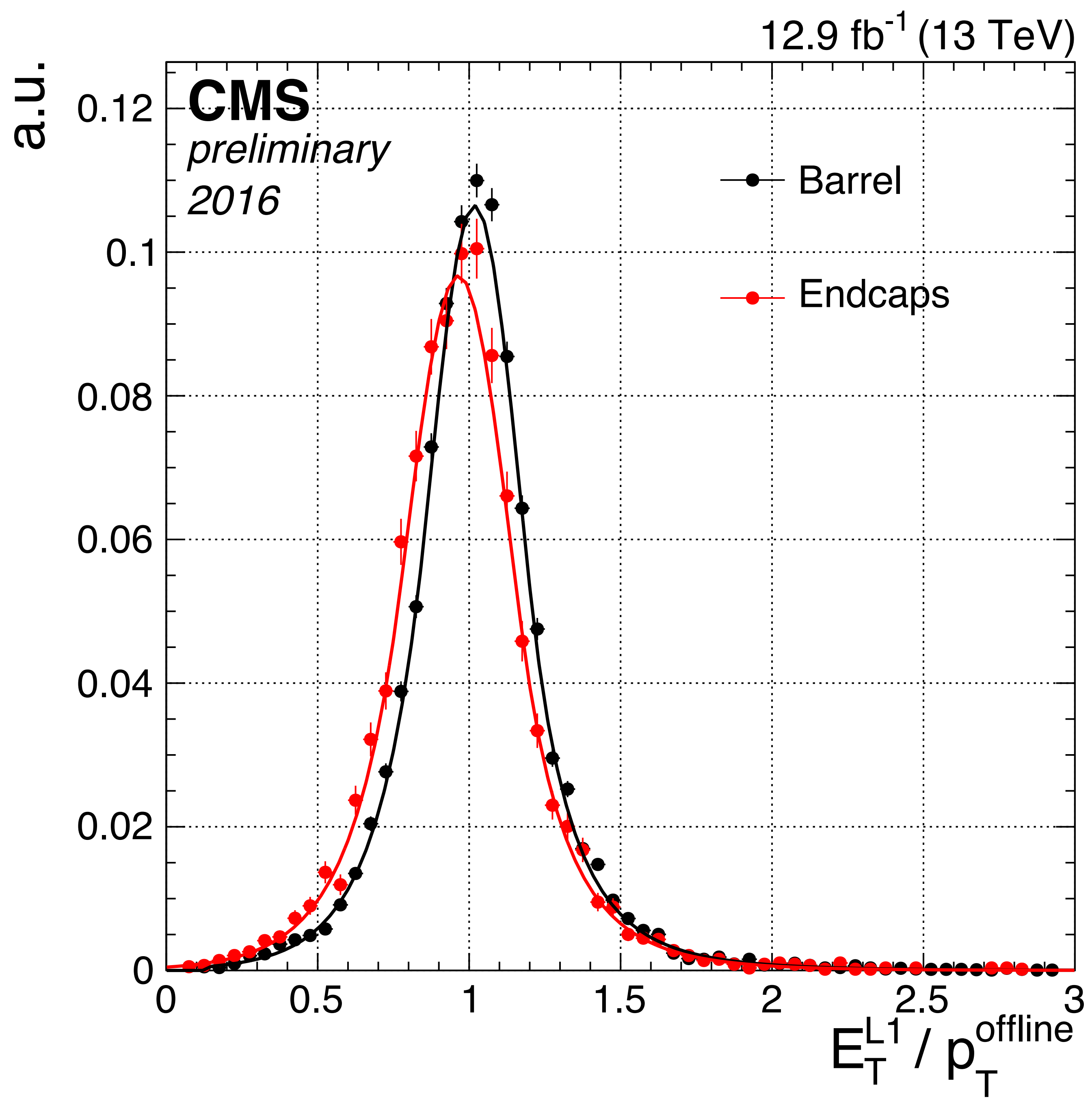


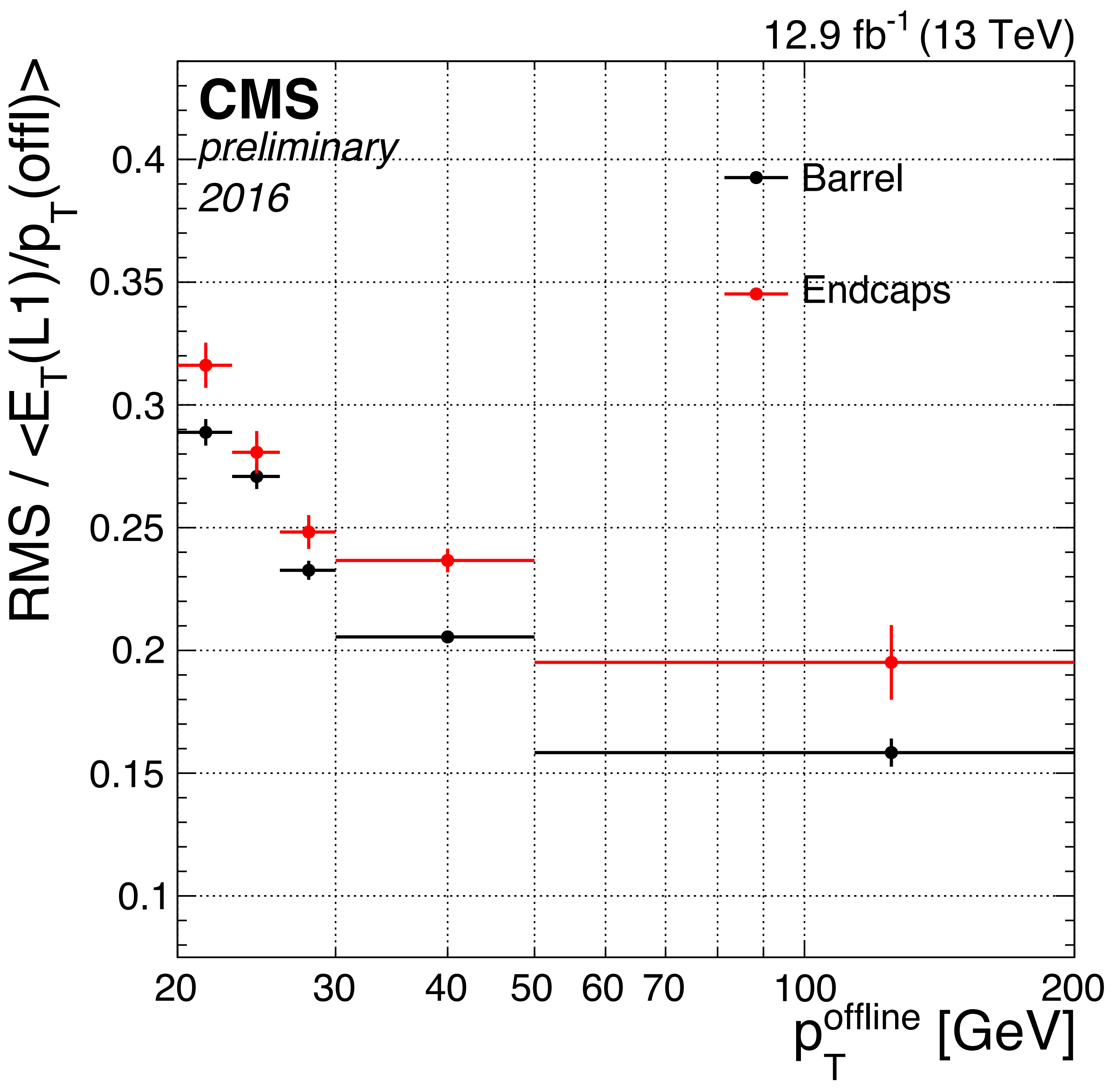
E/Γ RECONSTRUCTION PERFORMANCE

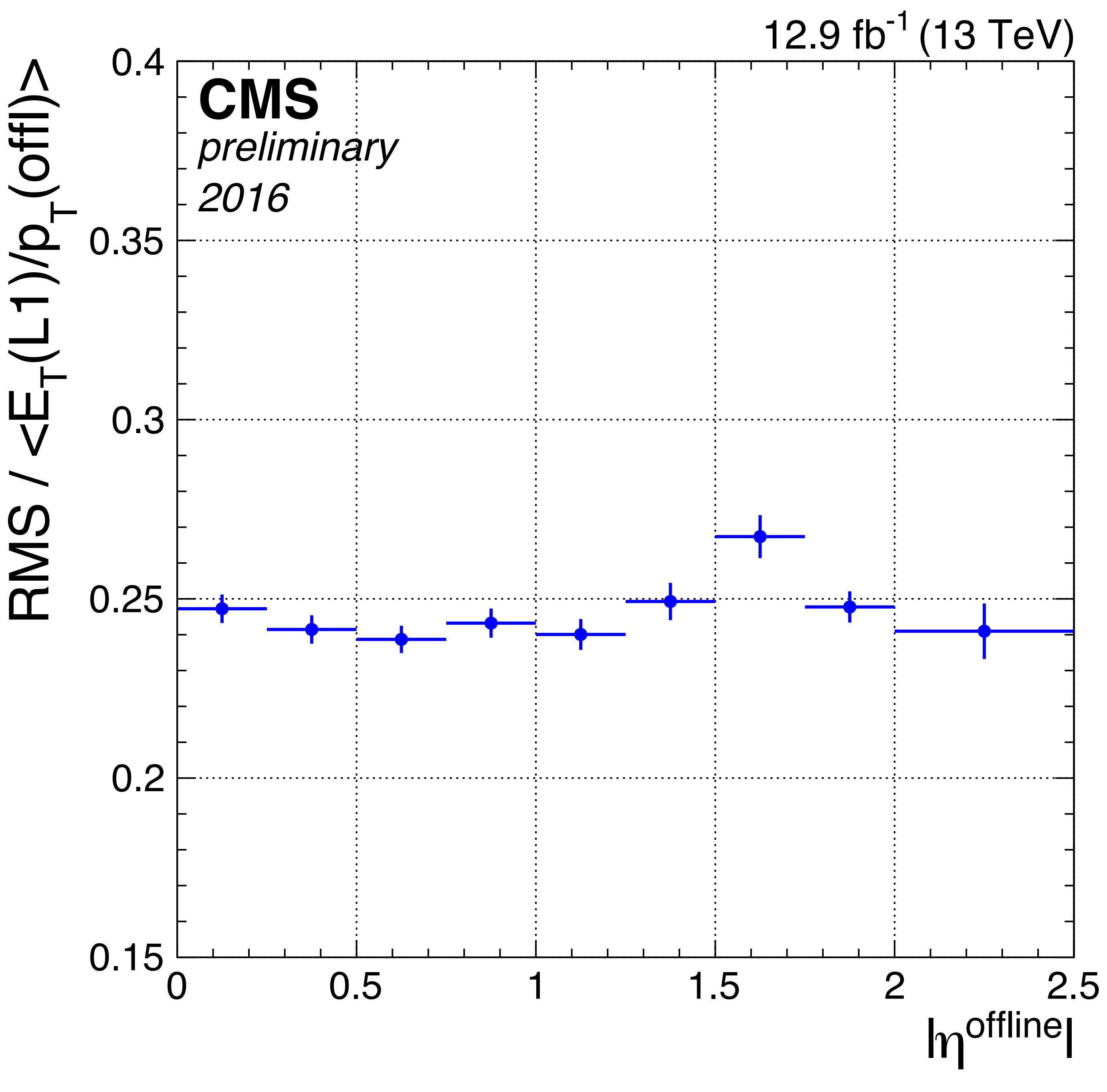




T RECONSTRUCTION PERFORMANCE

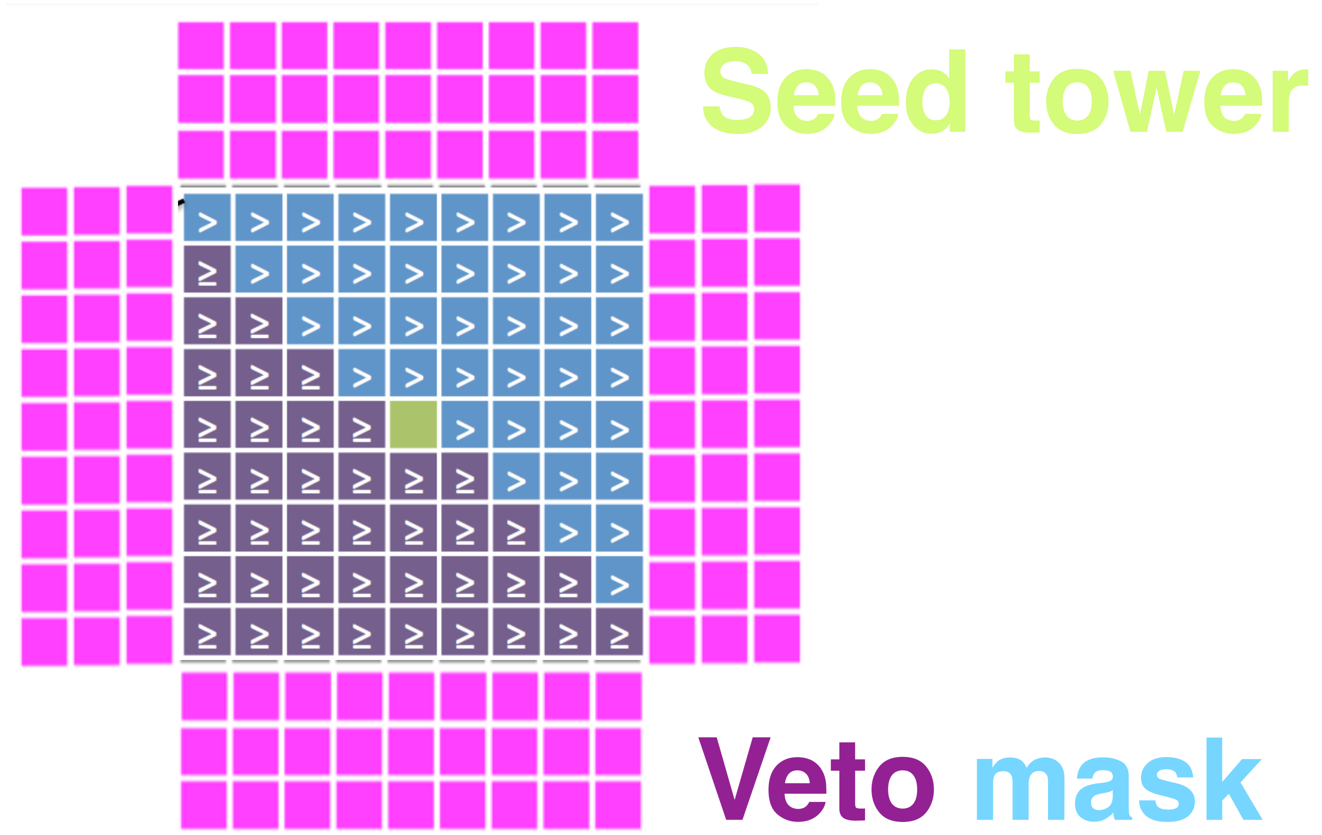


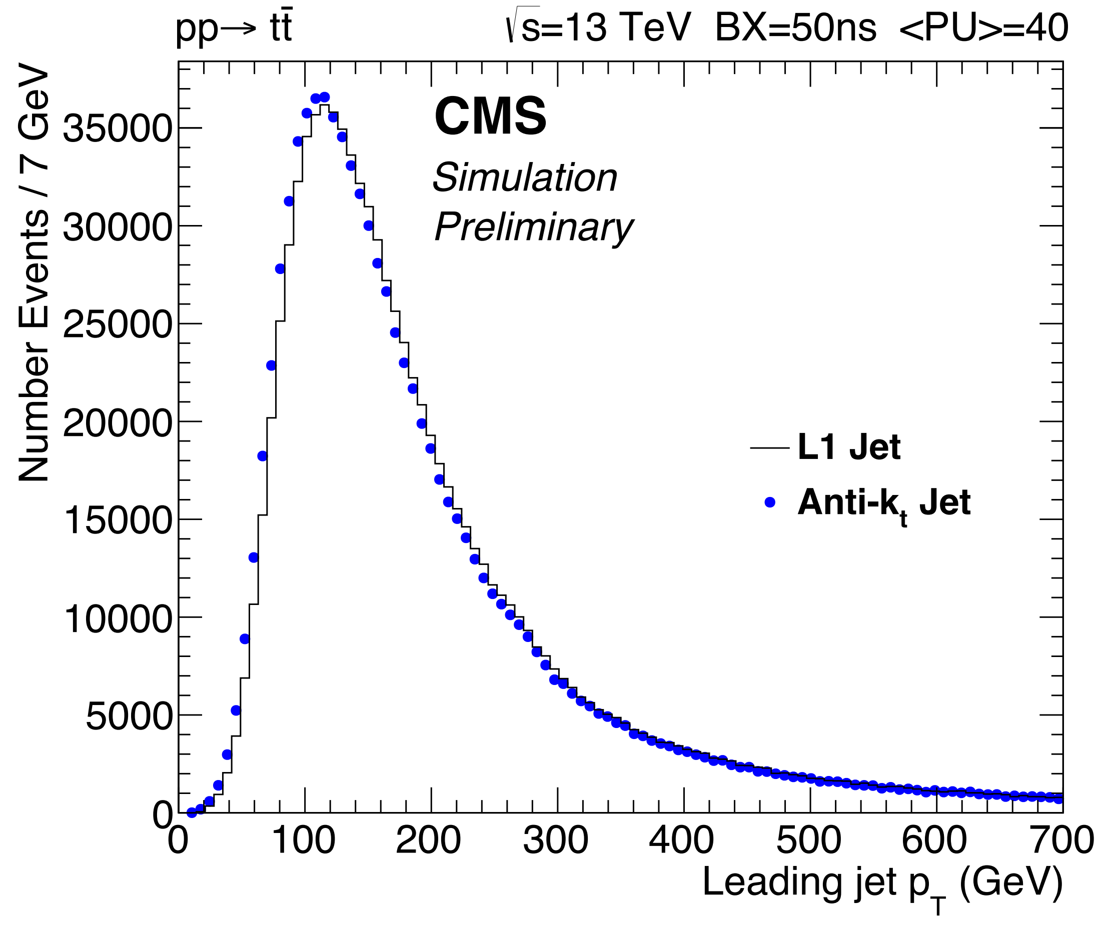


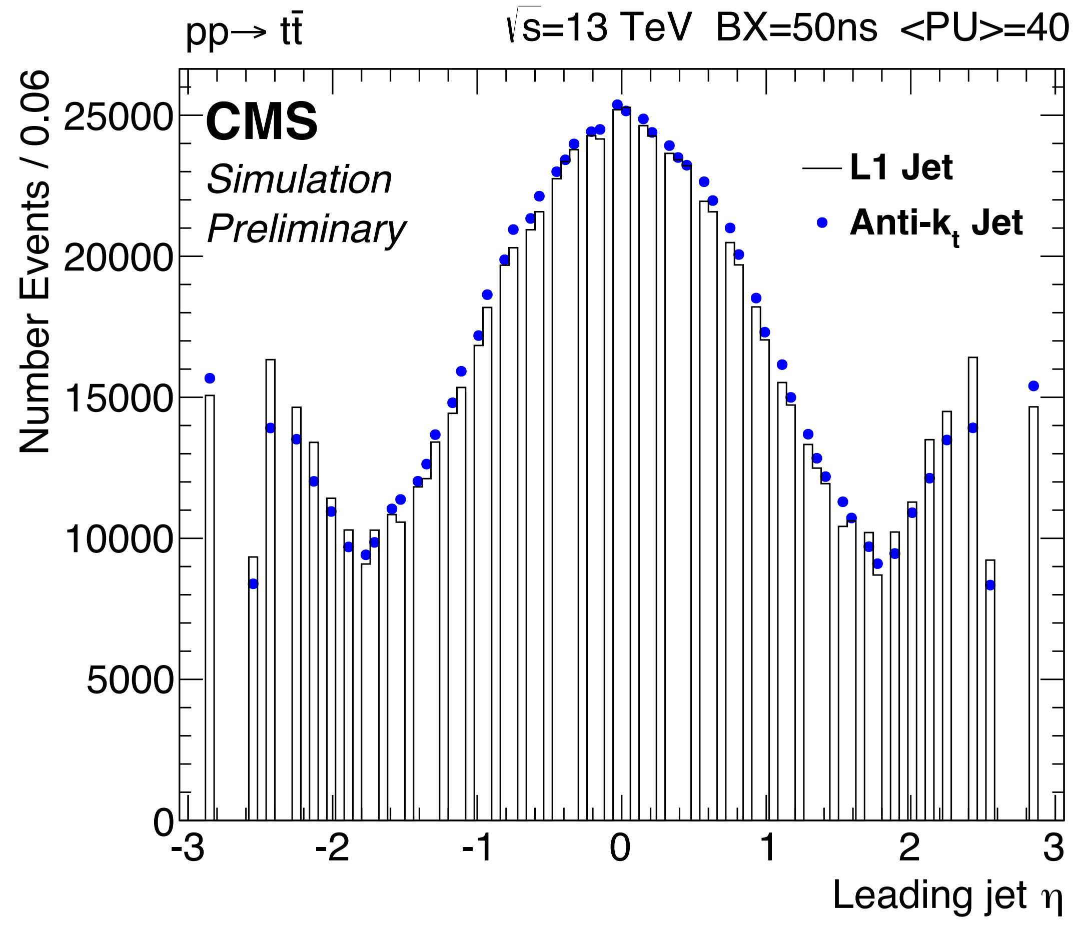


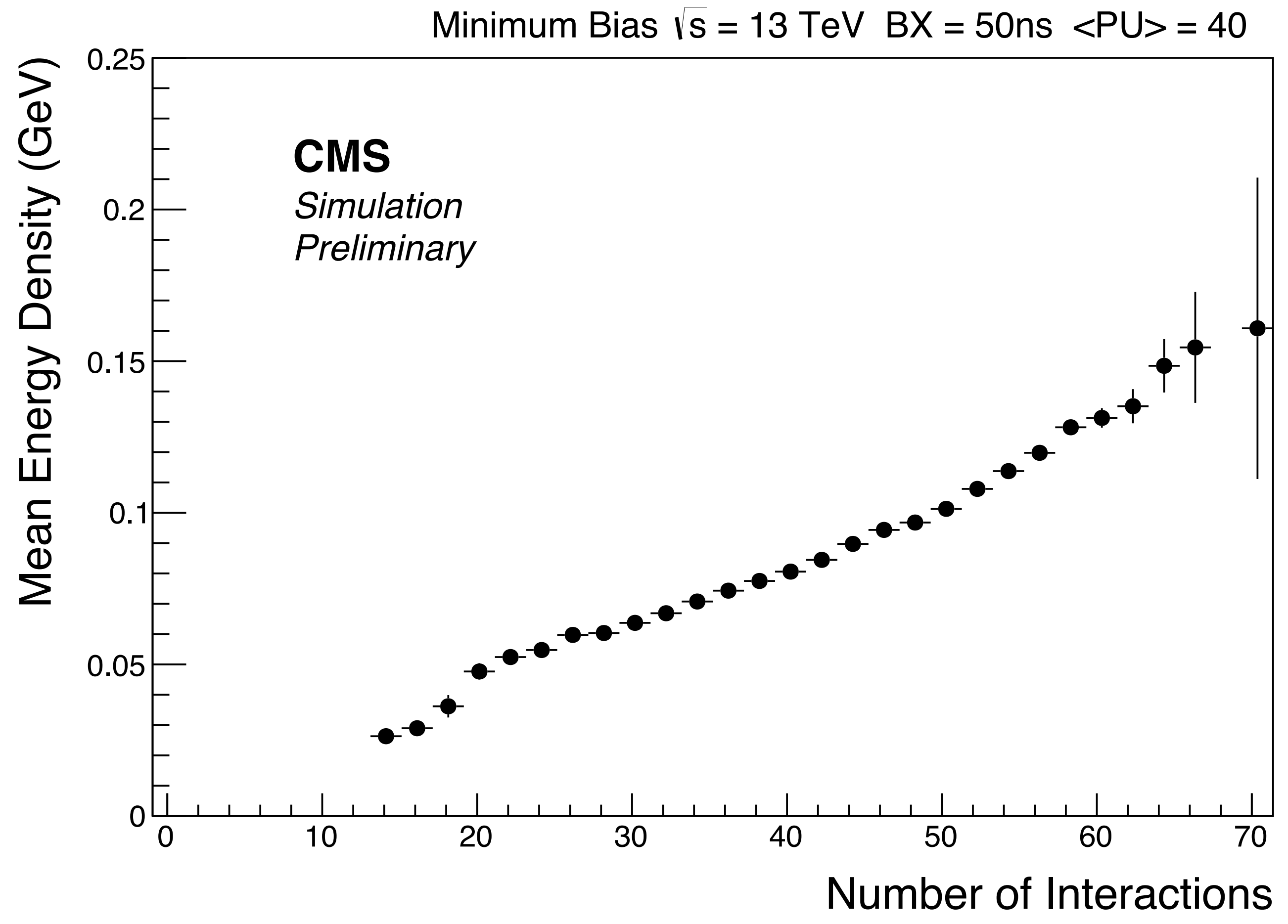
JET ALGORITHM PERFORMANCE

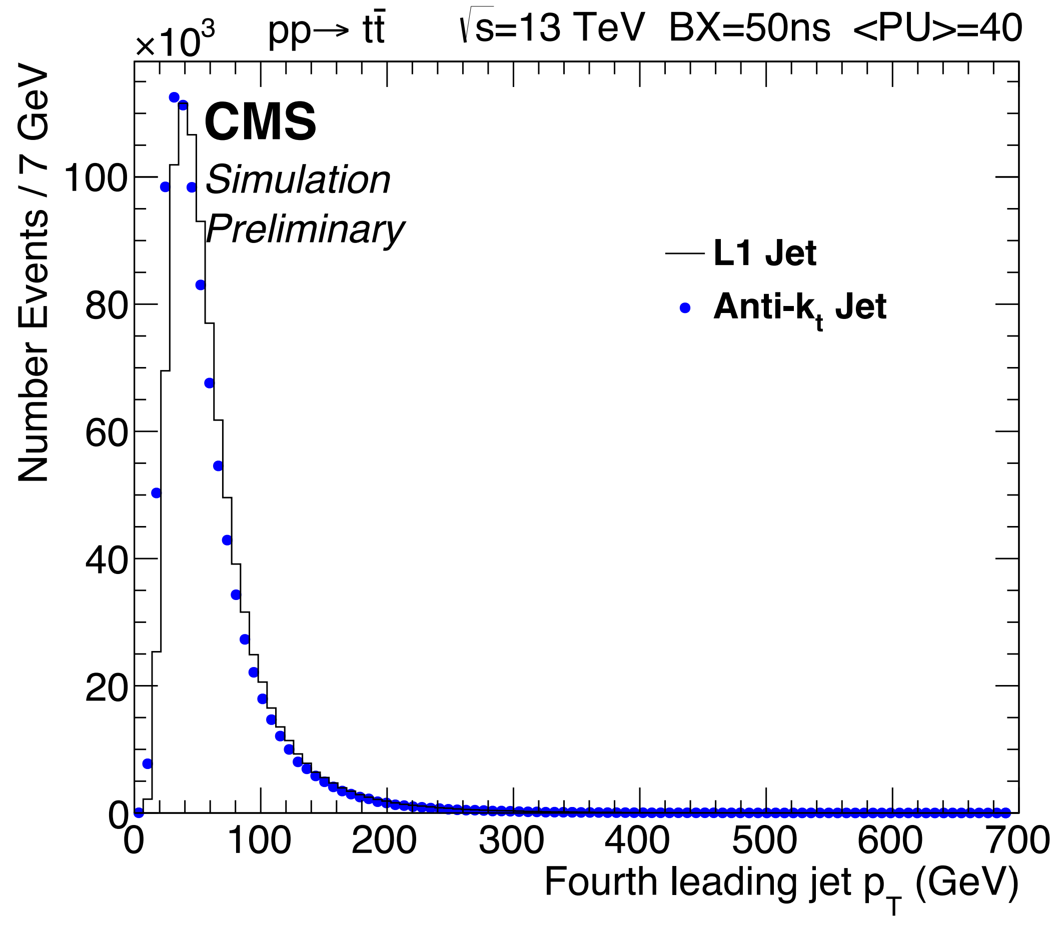
PUS areas

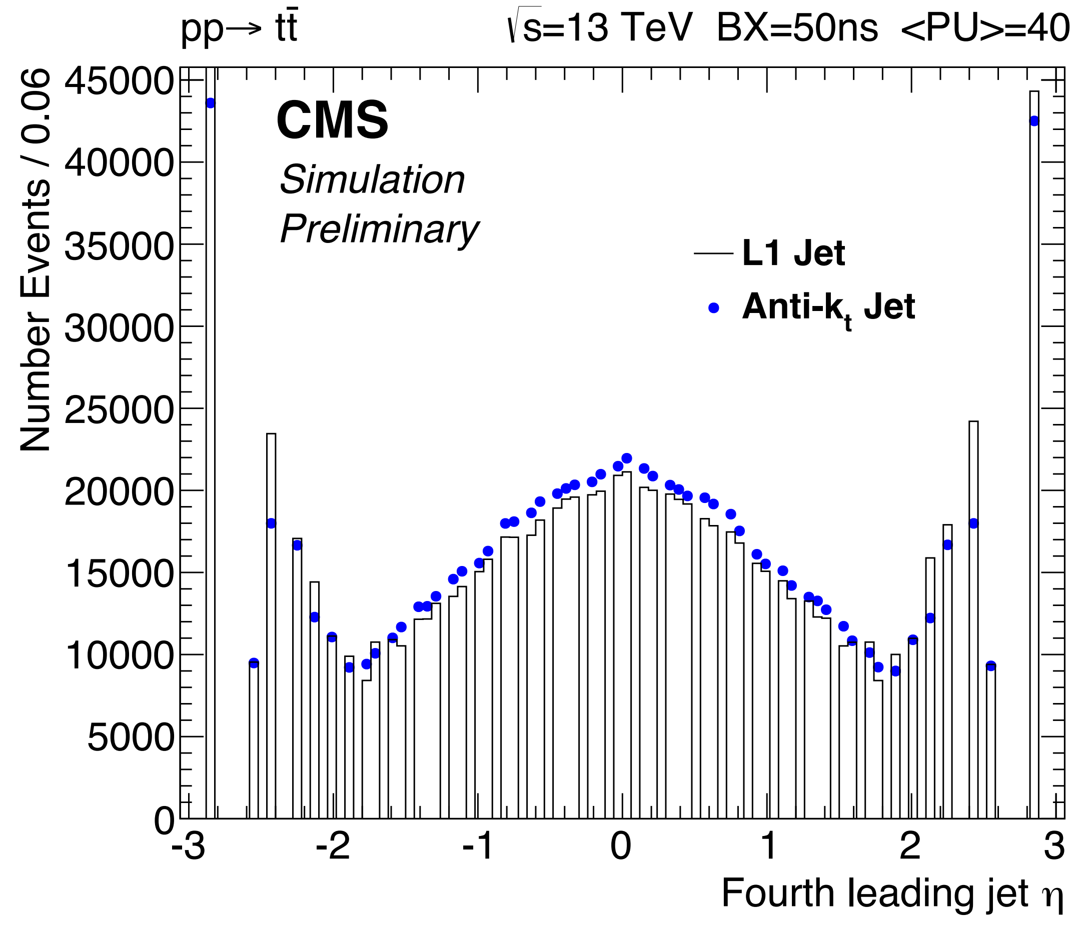




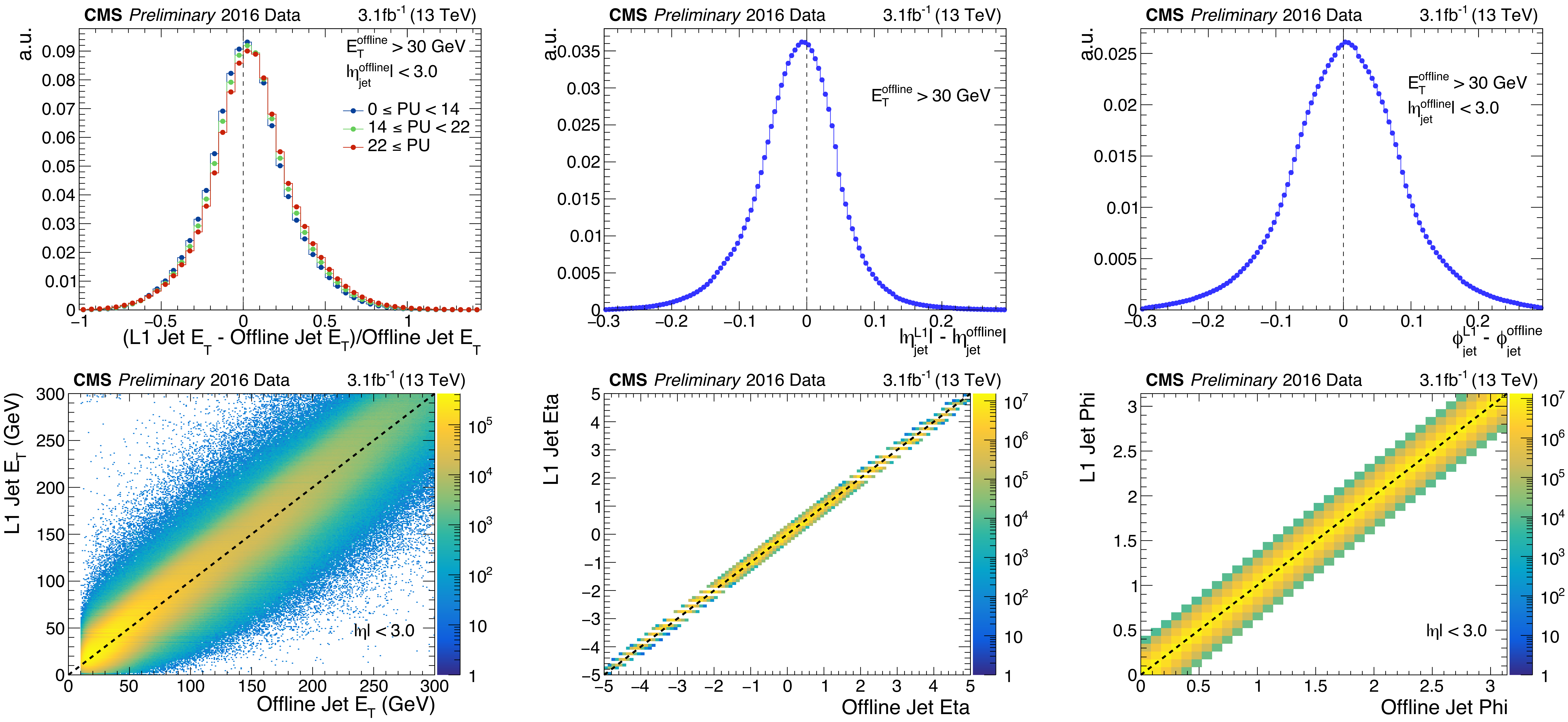








JET RECONSTRUCTION PERFORMANCE



MET RECONSTRUCTION PERFORMANCE