The CMS Level-1 Trigger for LHC Run II

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Calorimetry for the
High Energy Frontier
Lyon, France
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Imperial College
London

CERN

Outline

- System overview
- Upgraded processors and high-speed optical links
- Trigger algorithms and implementation
- Commissioning and performance with collision data
- Summary and outlook

Focus on calorimeter trigger, muons in backup

 CHEF2017: Calorimetry for the High Energy Frontier 2017, 2-6 October 2017, Lyon, France.

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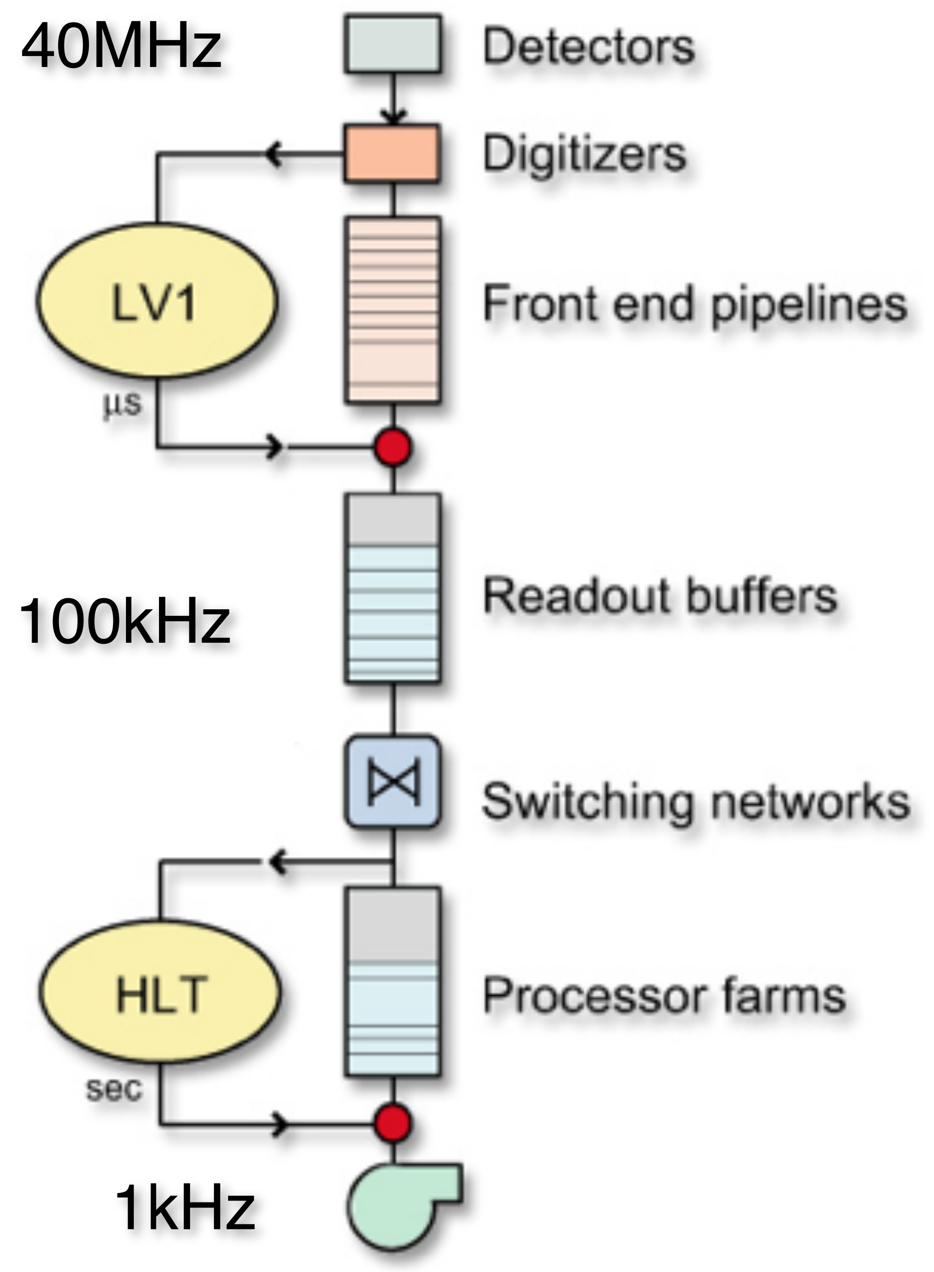
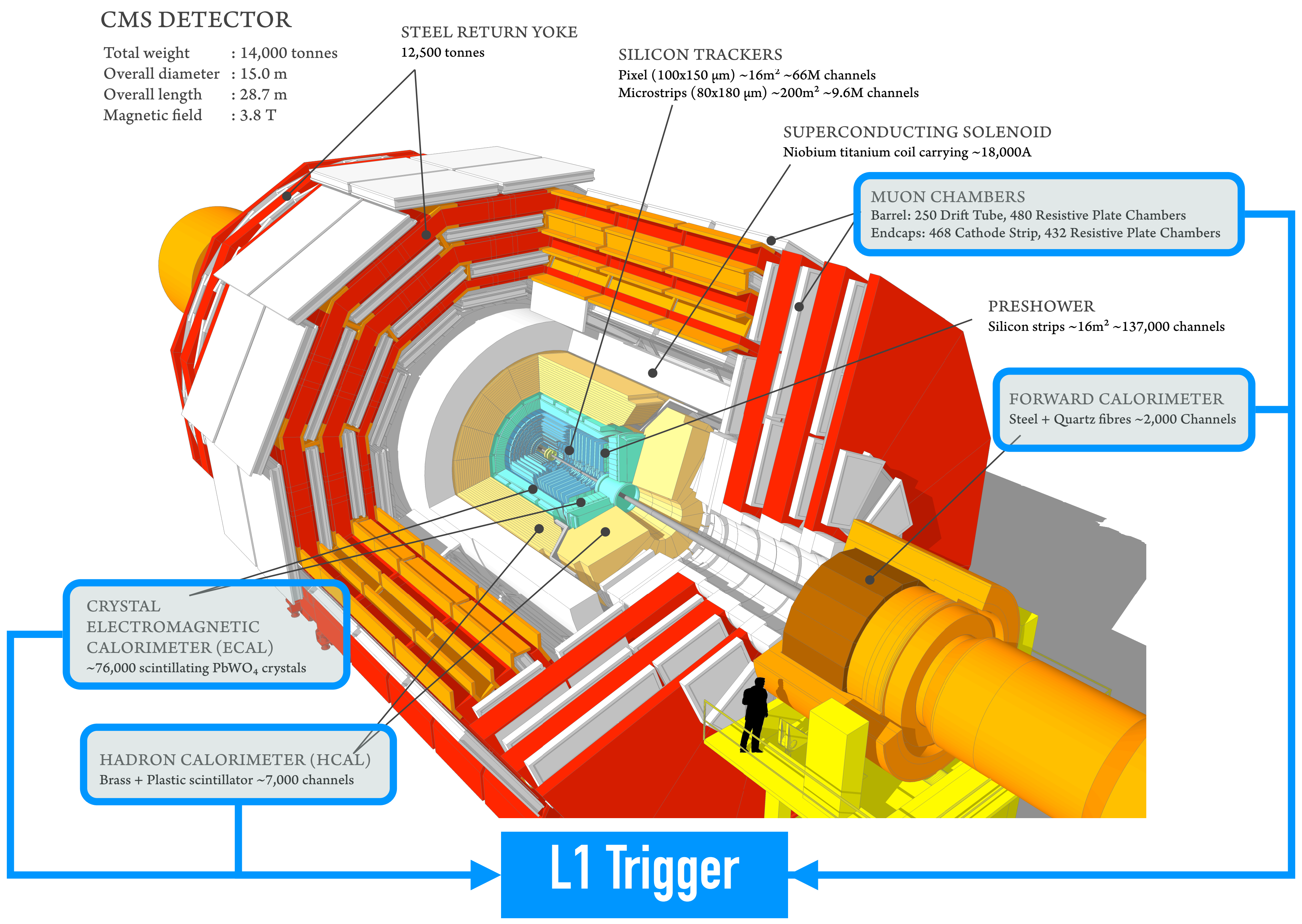
The CMS Level-1 trigger

- The CMS trigger system consists of two levels, **Level-1 (L1)** and **High Level Trigger (HLT)**, designed to
  - select events of *potential physics interest*
  - achieve a **10^5** rate reduction with no dead time

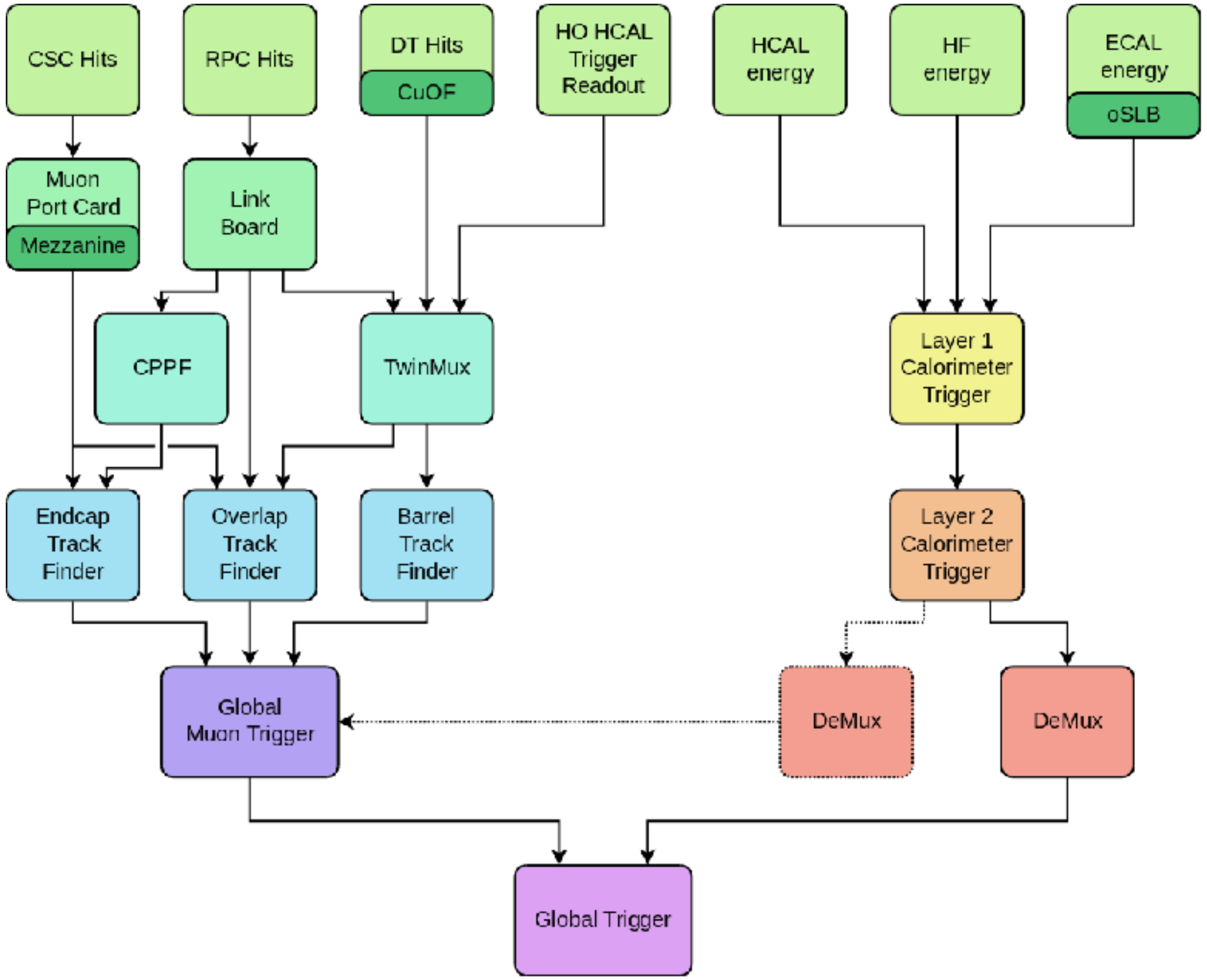




- L1 trigger upgraded in 2016
  - LHC Run II: increased luminosity and higher PU
  - Higher trigger rates but CMS detector electronics limited to L1 trigger rate of 100 kHz
  - Upgrade necessary to maintain sensitivity to electroweak scale physics and for TeV scale searches as in Run I

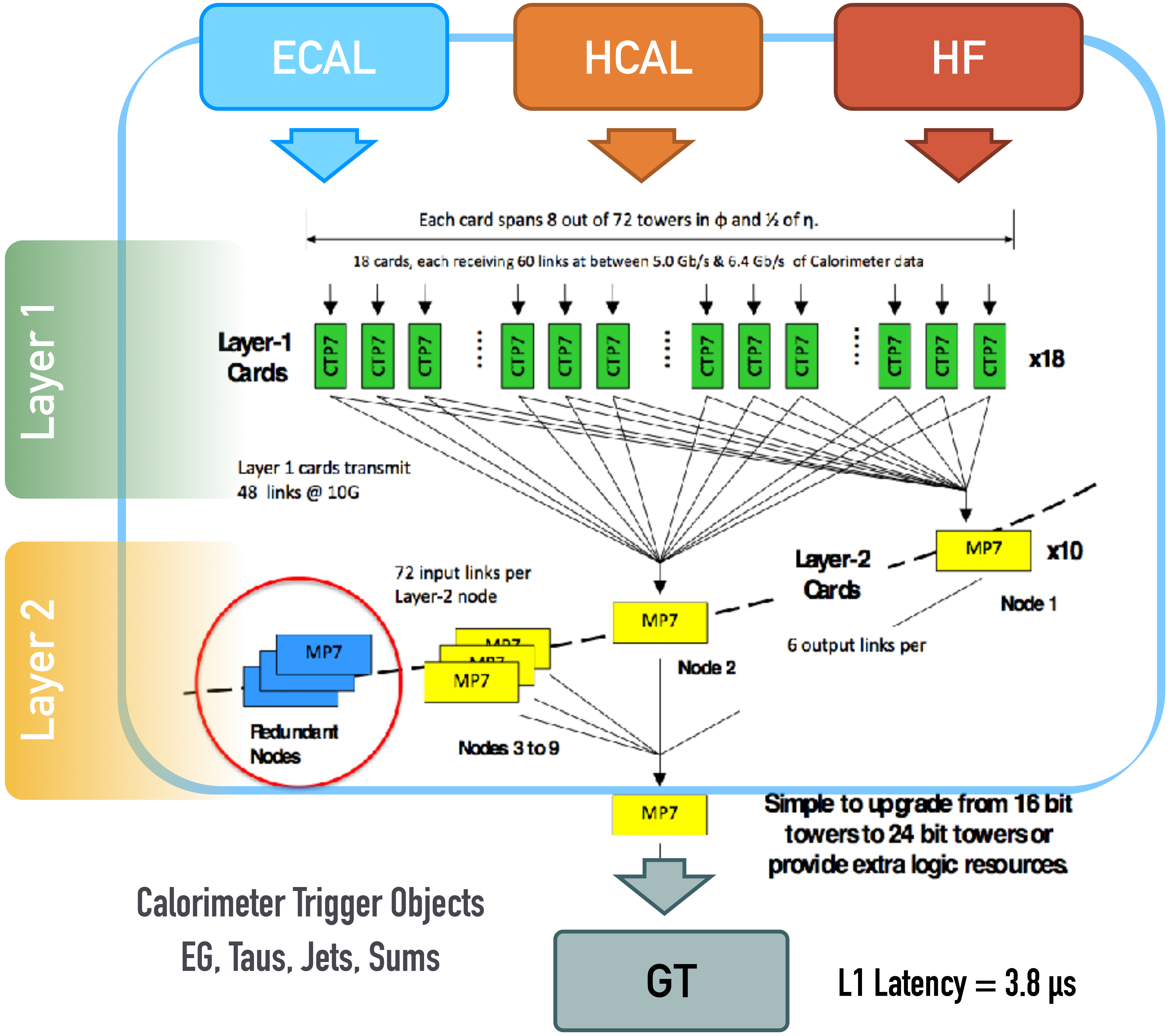
System overview

- Key concepts
  - Calorimeter system — remove boundaries by streaming data from single event into one FPGA
  - Muon system — use redundancy of three muon detector systems early to make a high resolution muon trigger
  - Global trigger — expandable to many more possible conditions and more sophisticated quantities, to give a richer menu á la Higher Level Trigger



- Replaced EVERYTHING!
  - All hardware, all software, databases… even the timing control system and DAQ interface…

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™)

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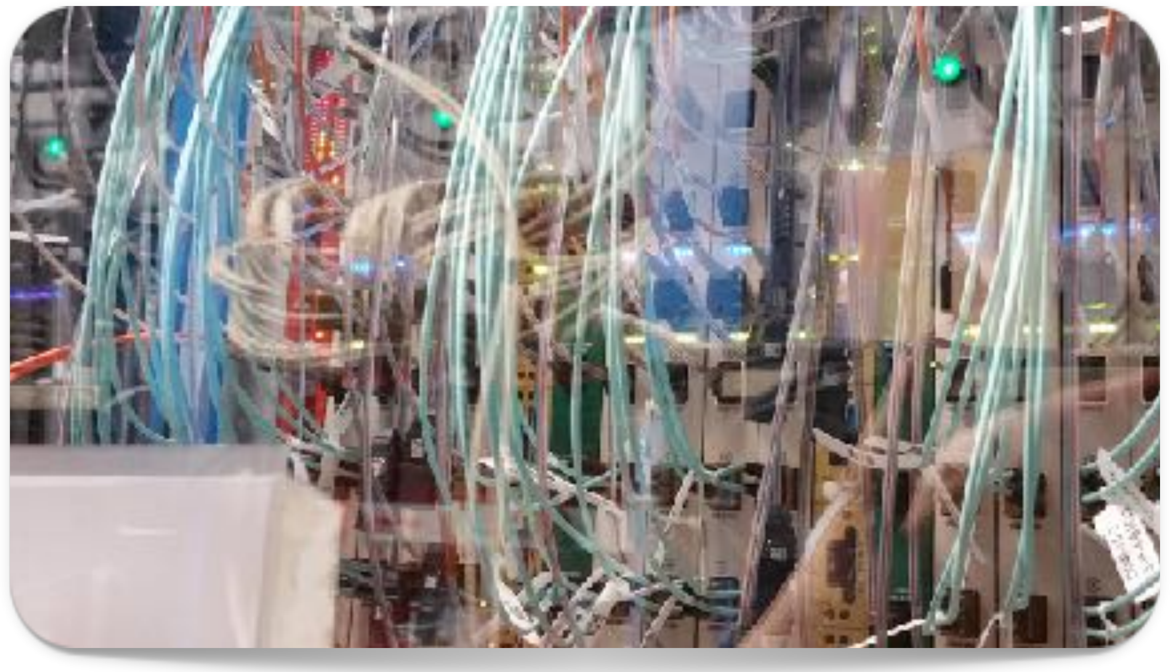
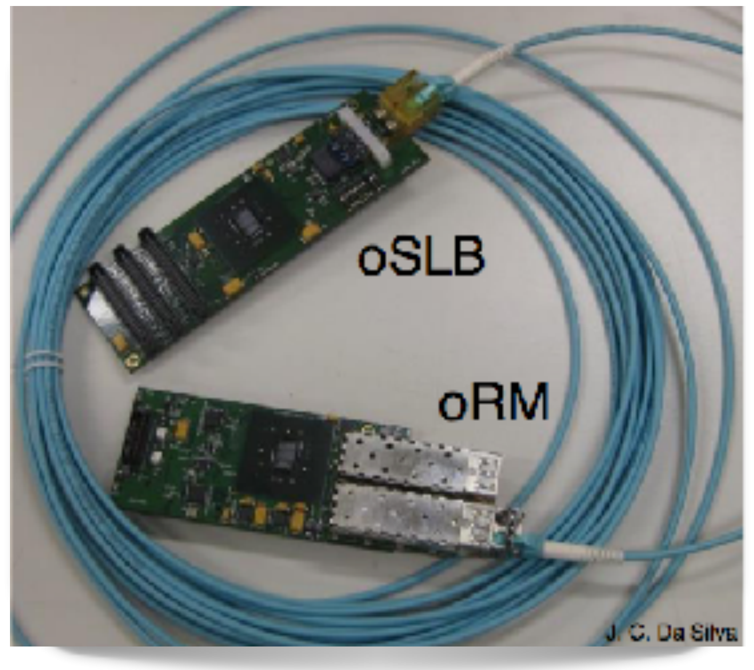
Optical input links

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



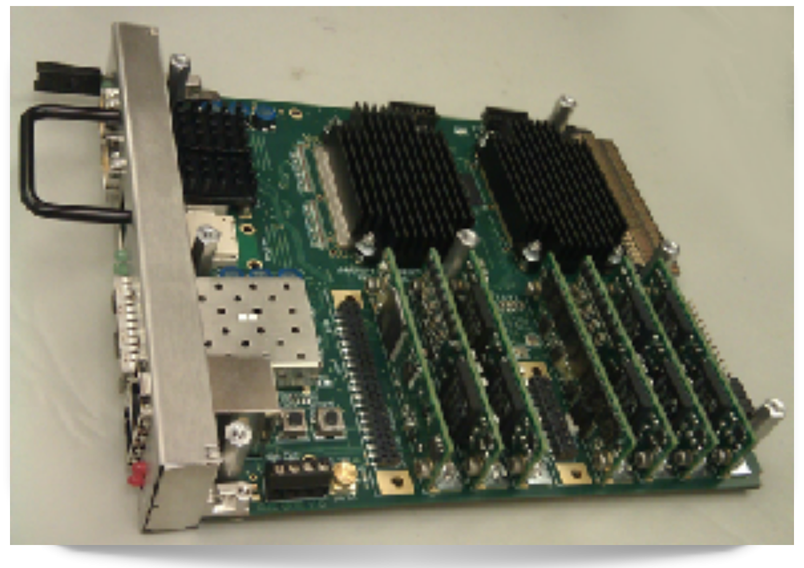
ECAL: 576 × 4.8 Gb/s links

HCAL: 504 × 6.4 Gb/s links
HF: 72 × 6.4 GB/s links



Optical Synchronisation Link Board
CERN VTTx to commercial SFP

micro Hcal Trigger and Readout boards (μHTRs)



Layer 1 input links

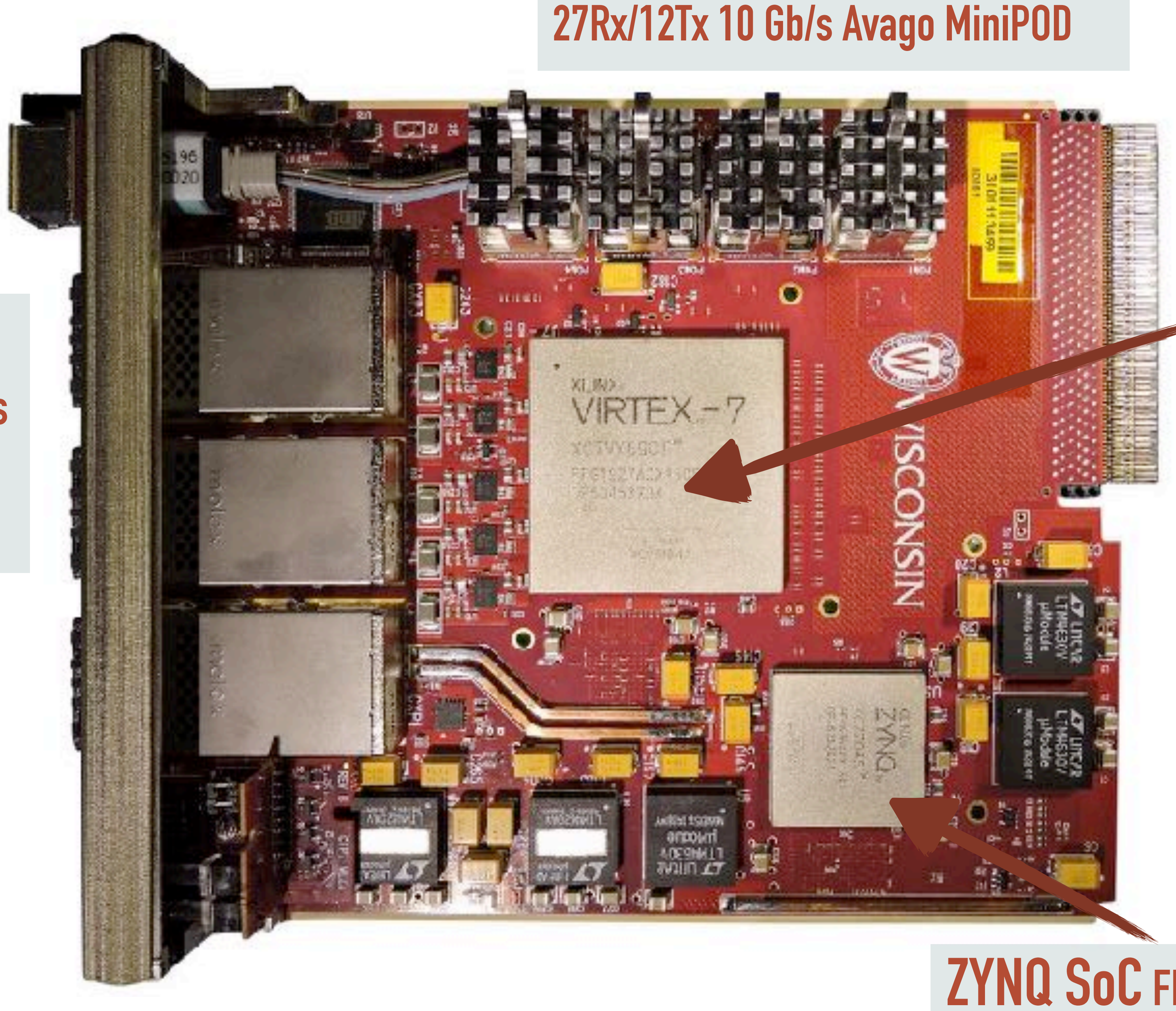
576+504+72 links in total (ECAL, HCAL, HF) = **1152 links**

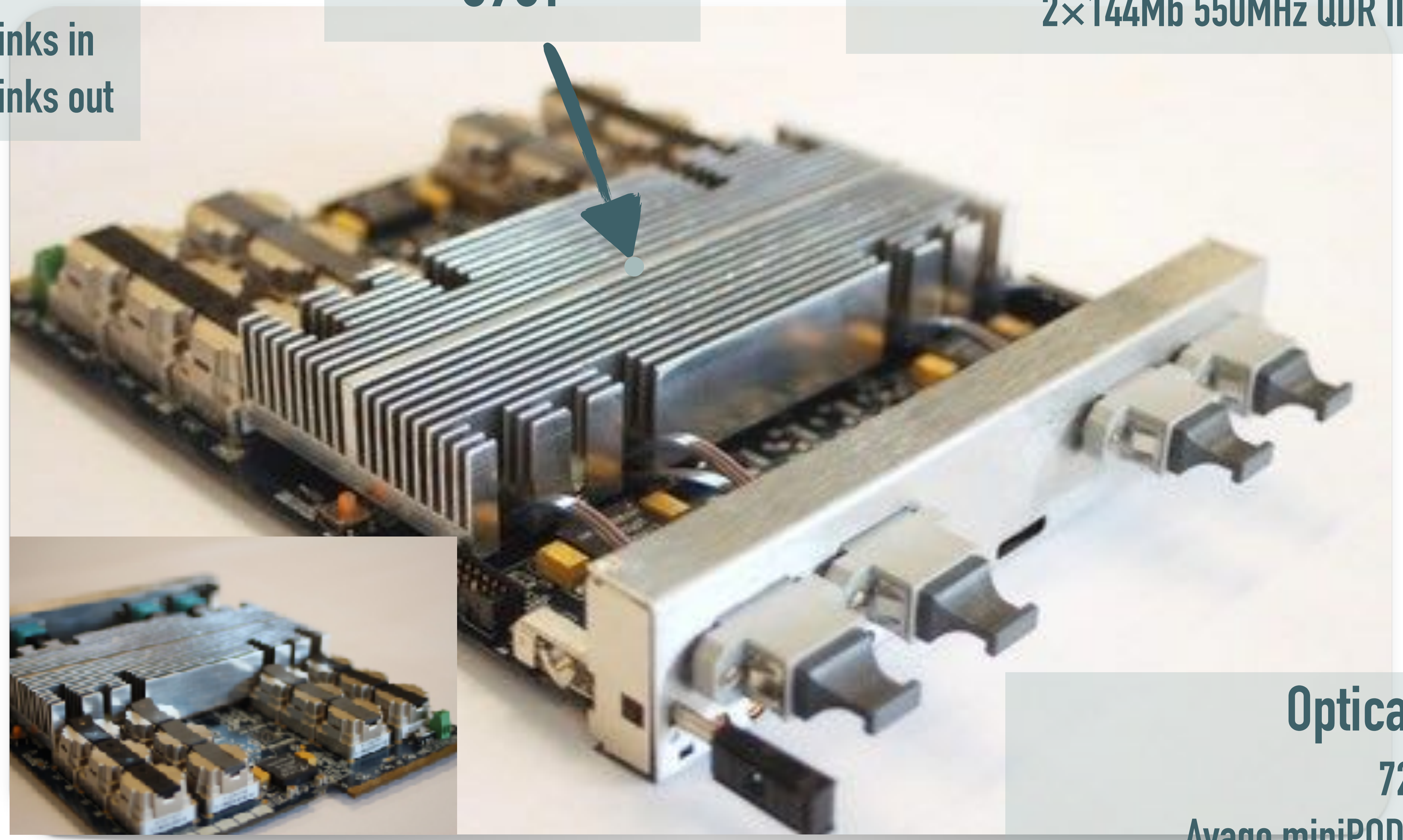
Processors

CTP7 Calorimeter Trigger Processor

Layer 1 - Pre-processing

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



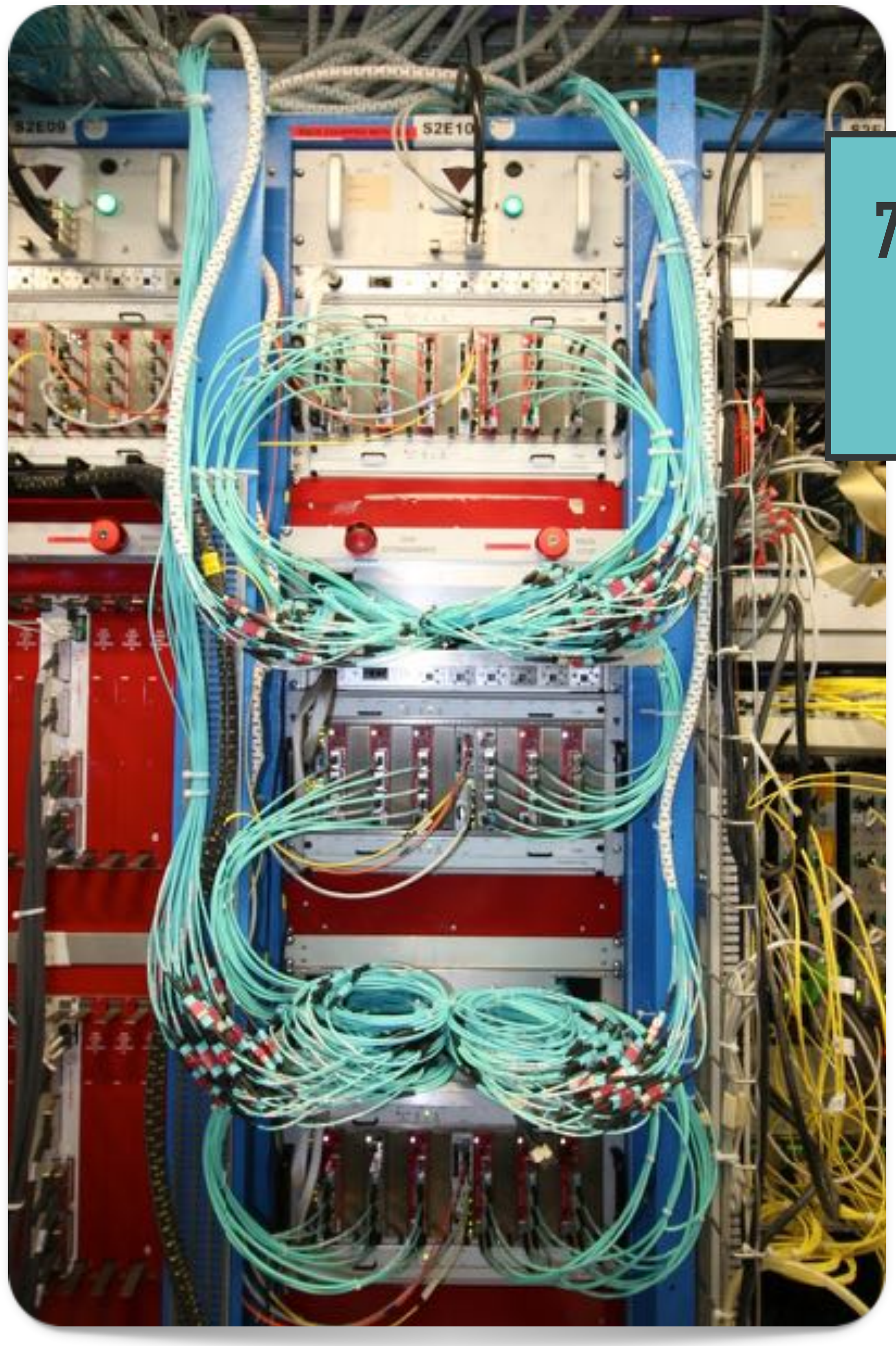


MP7 Master Processor

Layer 2 - Trigger Algorithms

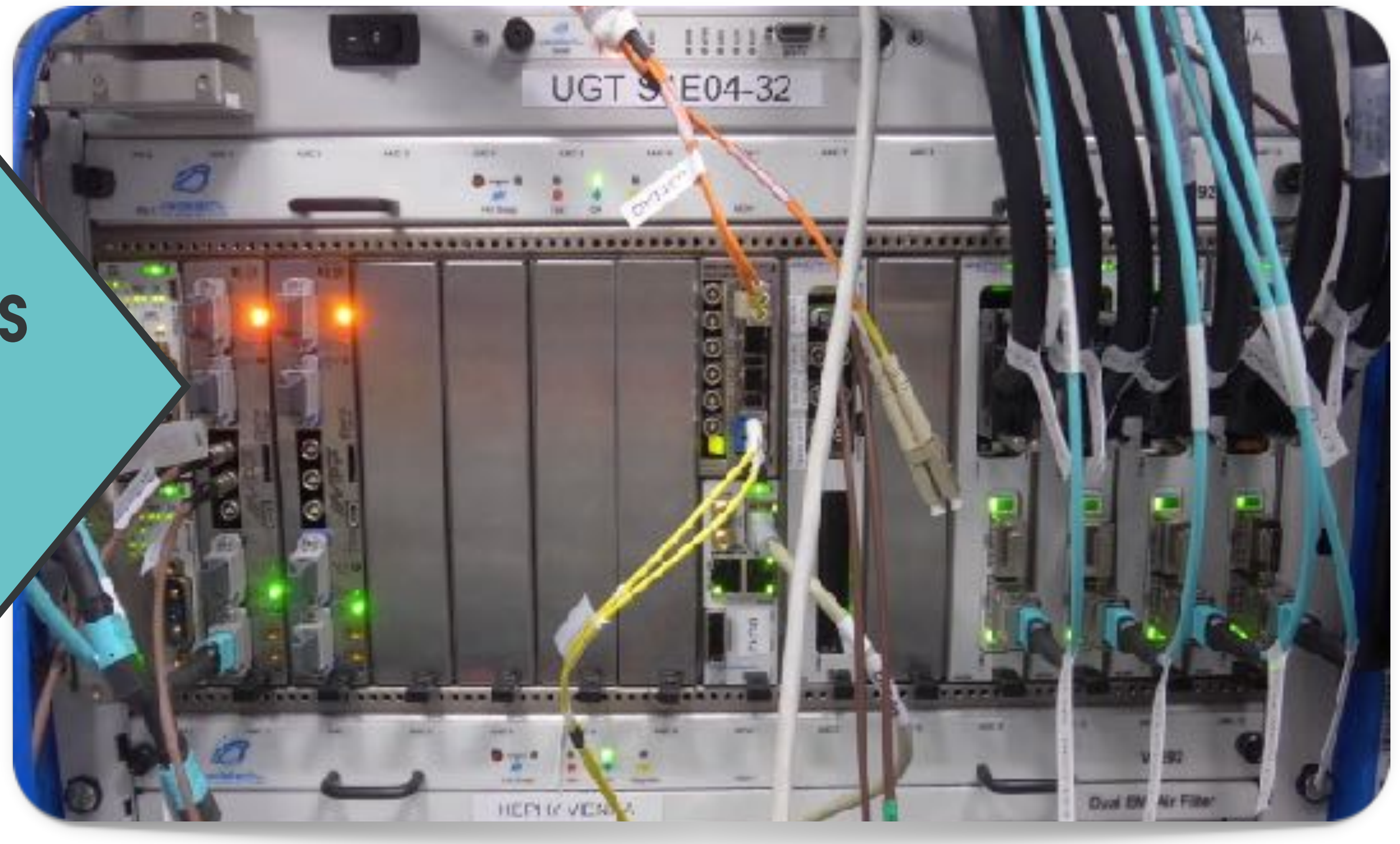
- Hosts most of the algorithms
- DAQ readout for monitoring

System Integration



720×10Gb/s links

8×10 Gb/s links

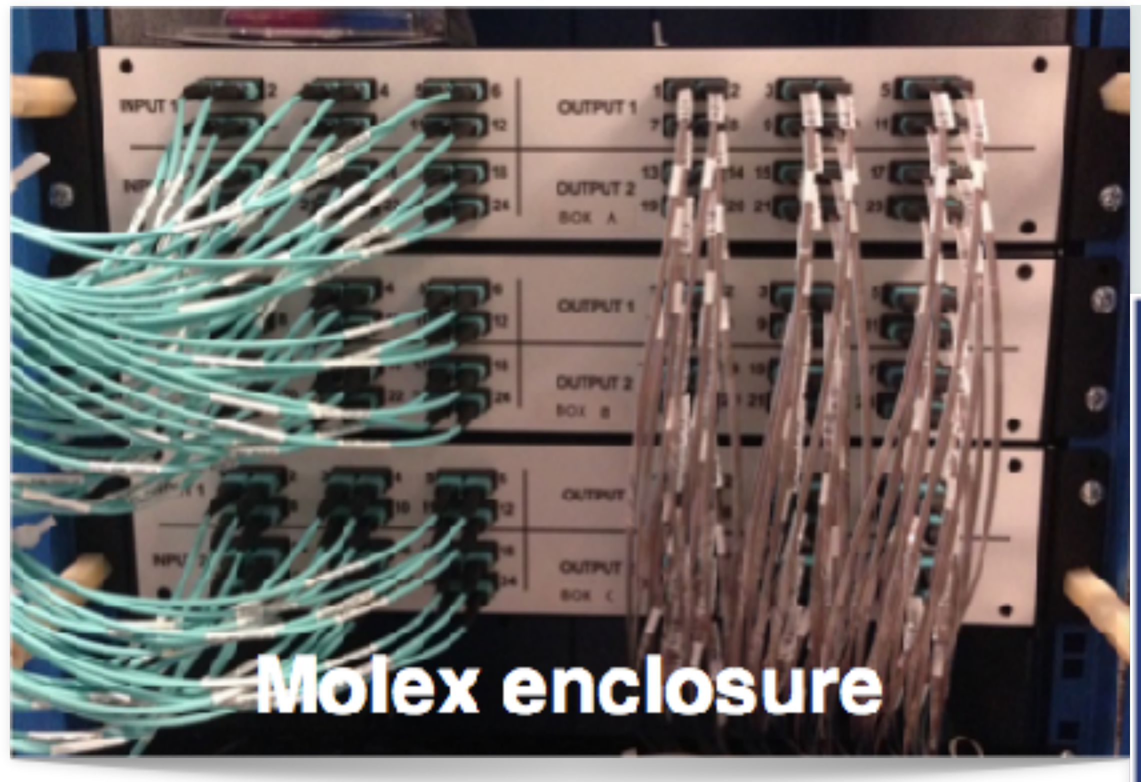


Layer 1
3 Vadatech VT894 Crate,18 CTP7 boards
6 bits ECAL+HCAL energy + veto & feature to Layer 2

Layer 2
1 Vadatech VT894 Crate, 10 MP7 boards

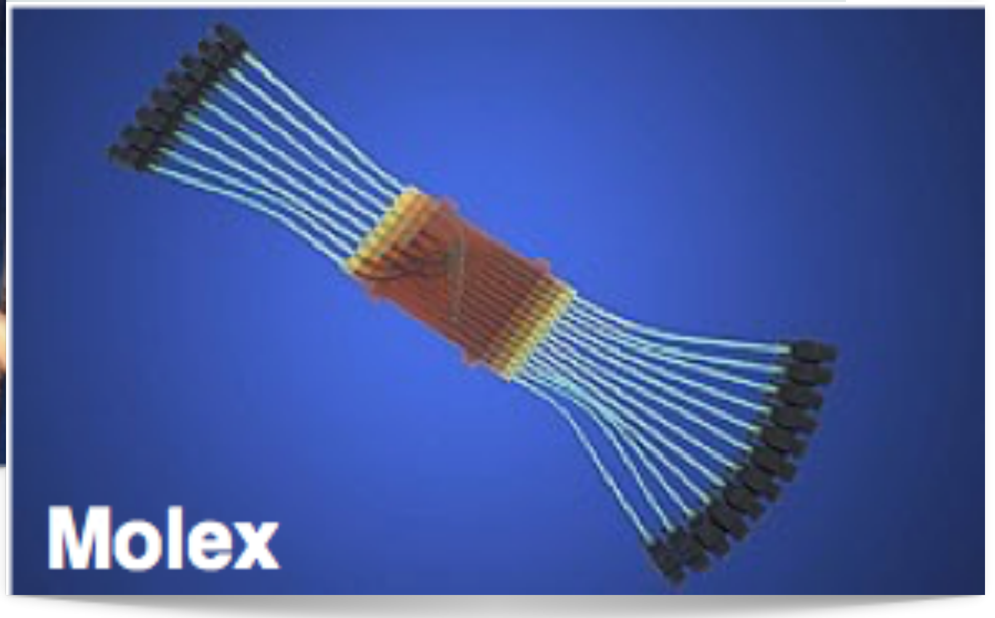
Global Trigger
receives 12 electron/photon + 12 Tau iso/non-iso candidates + 12 Jets and sums.

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



Molex Enclosure

Flexplane (commercial)



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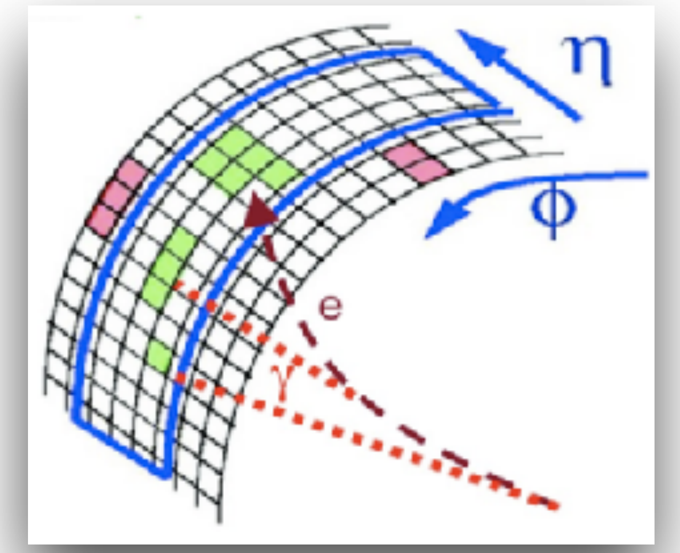
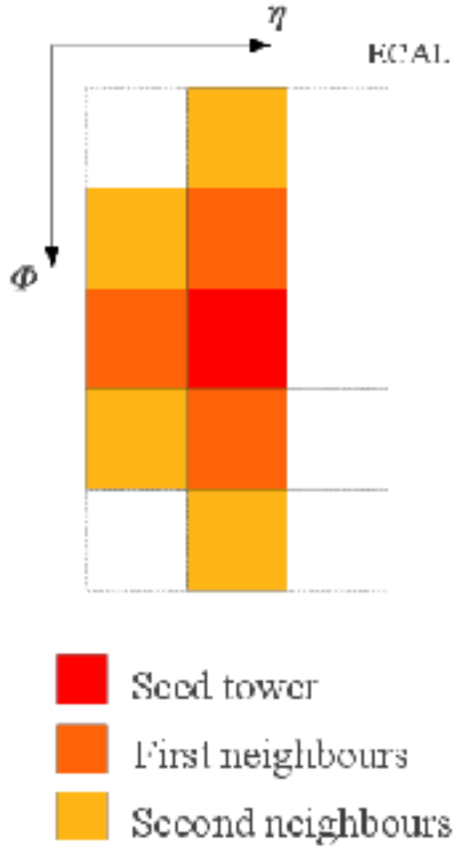
e/γ finder algorithm

Electrons in CMS

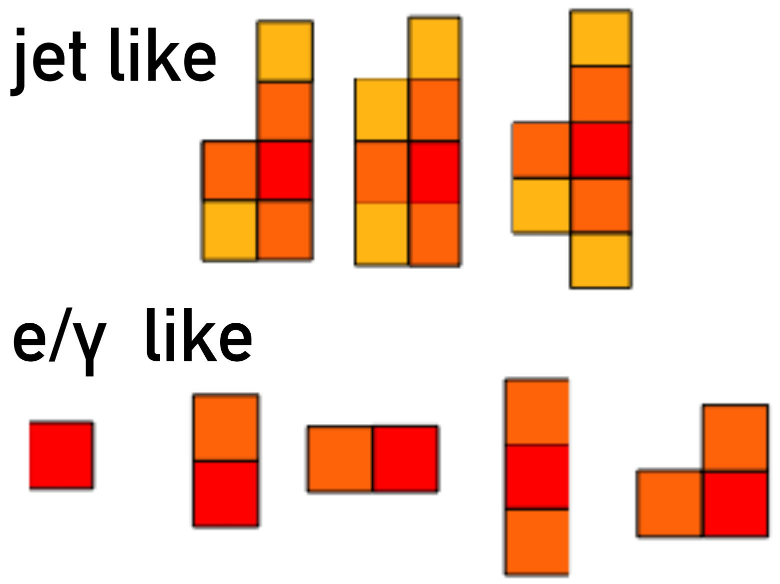


Cluster building

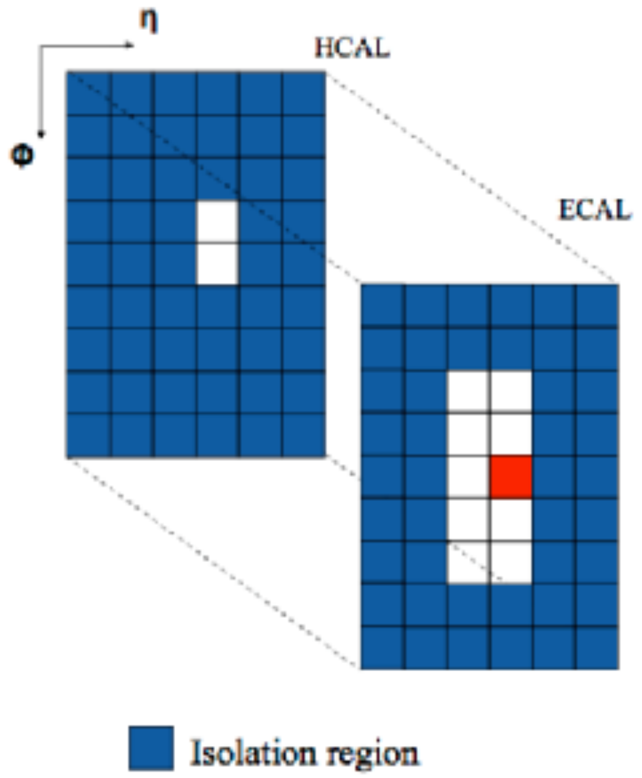


$\eta \times \phi$
0.087x0.087

Cluster shapes



Isolation



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

Dynamic clustering

Improved energy containment
Showering 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 — 99.5% efficiency for e/γ

Calibration

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

Energy weighted position

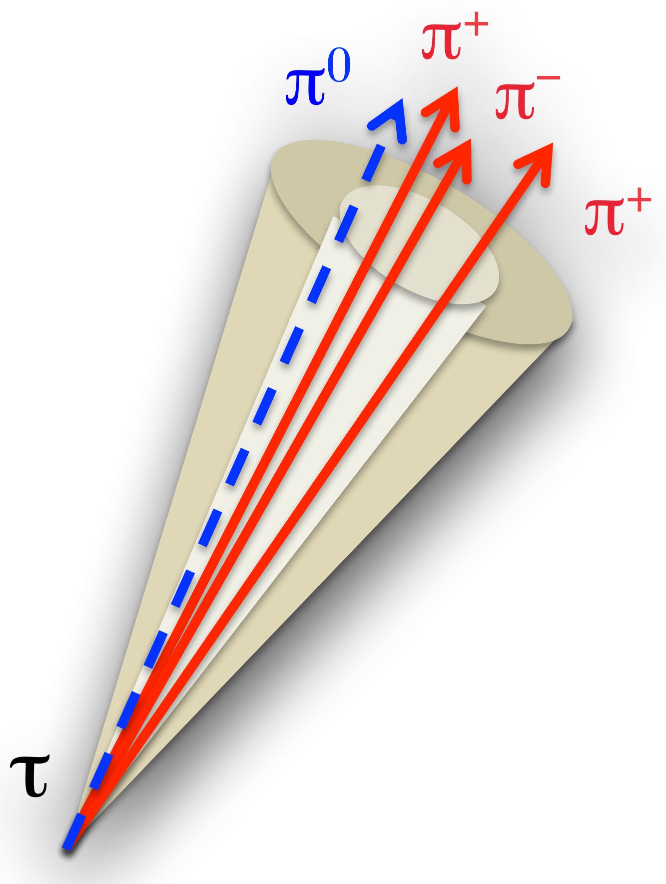
Potential use in correlating objects e.g. invariant mass

Isolation

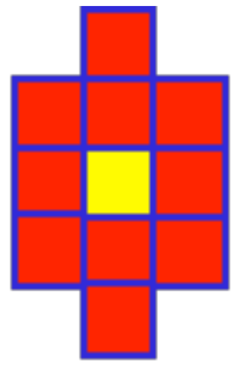
Create isolation annuli (removing footprint) for ECAL and HCAL around cluster
Isolation energy requirement fn. of PU and η
Two working points

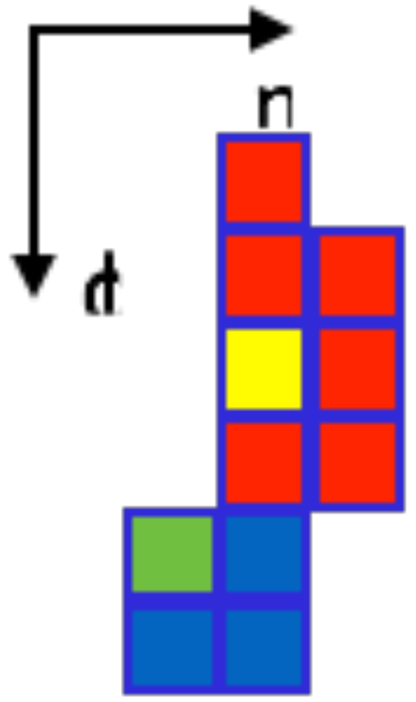
Tau finder algorithm

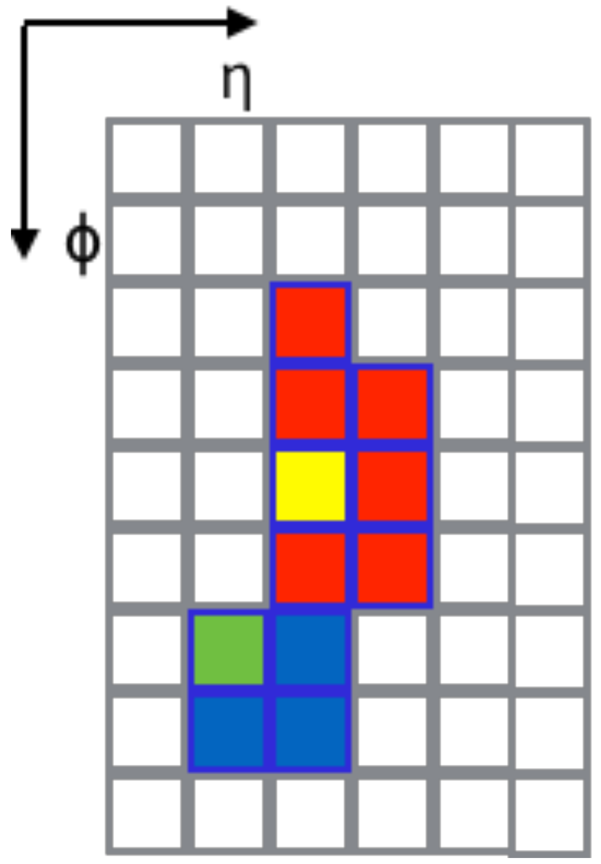
Tau decay topology



ηxϕ
0.087x0.087







- **Dedicated τ trigger**
- Based on e/γ clusters
- Optimise reconstruction of multiple-prong object spread

Clustering, shape and position

Very similar to e/γ — optimised for τ
Cluster shape veto — under study

Merging

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

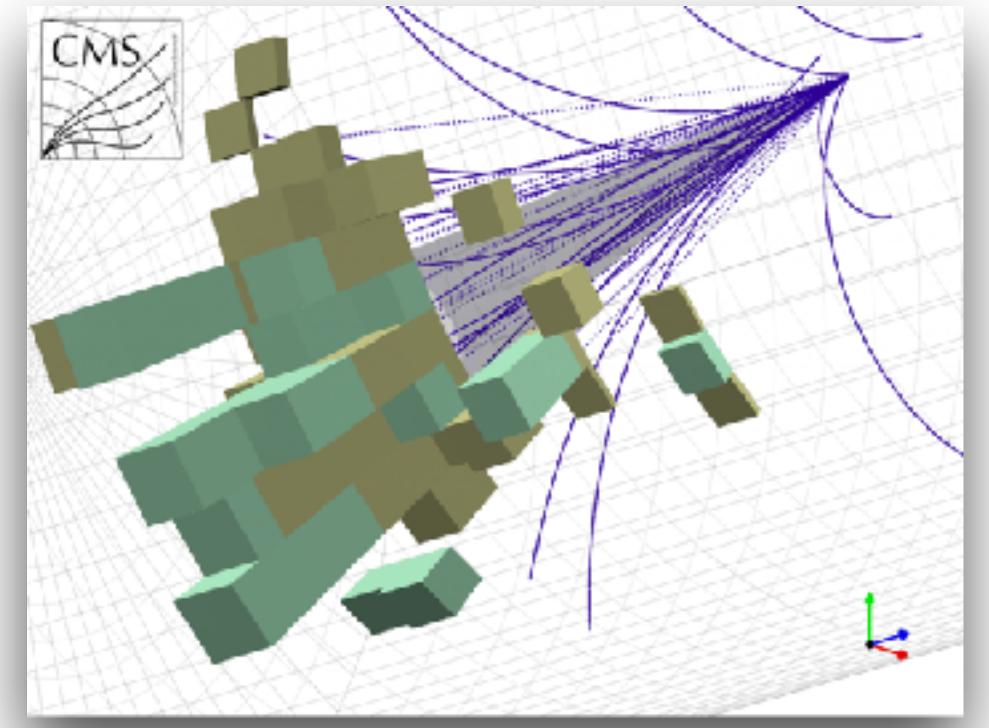
Calibration

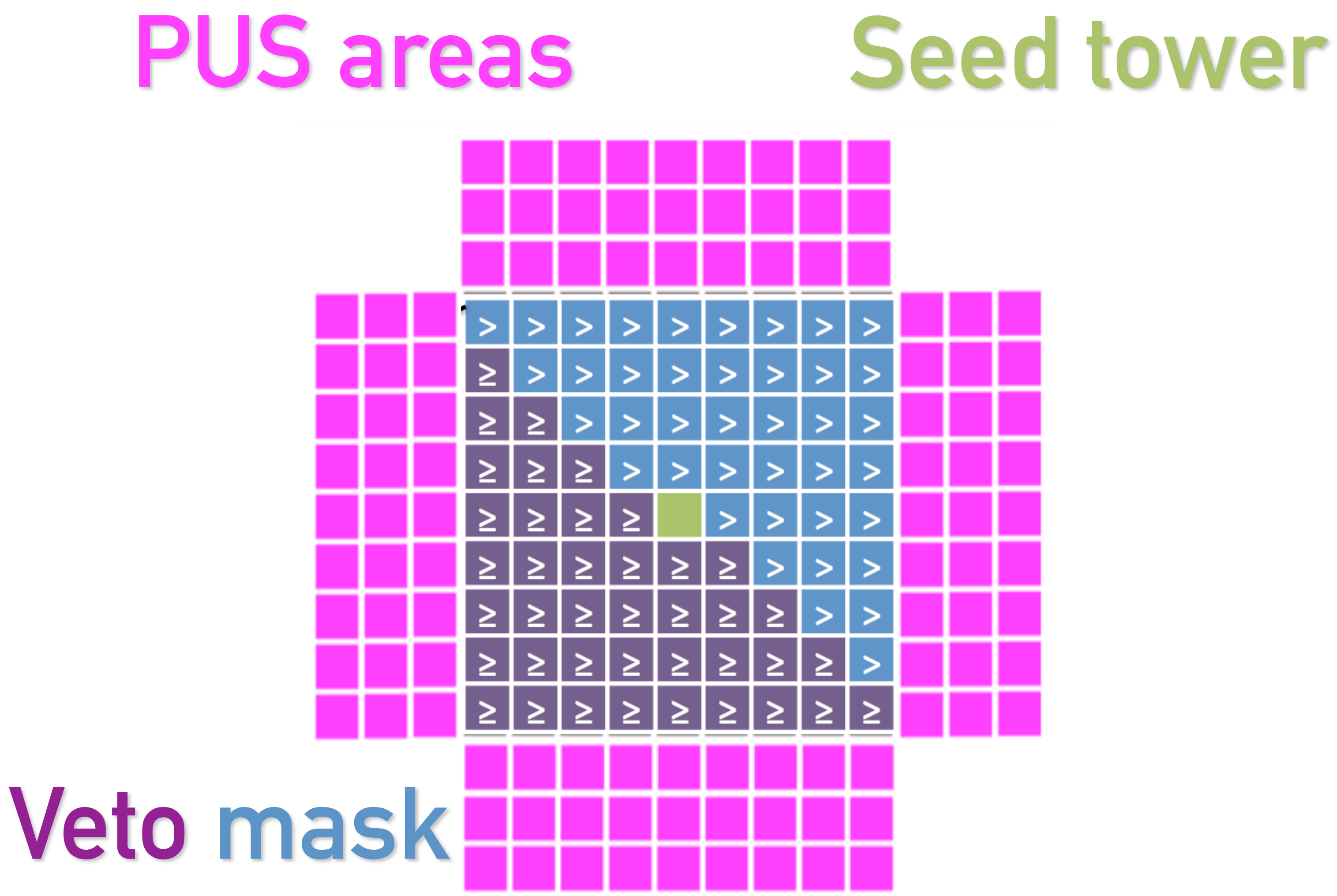
τ cluster energy calibrated as fn. of E_T, η, merging and EM fraction

Isolation

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

Jet finder algorithm





9x9 sliding window around seed tower

- 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

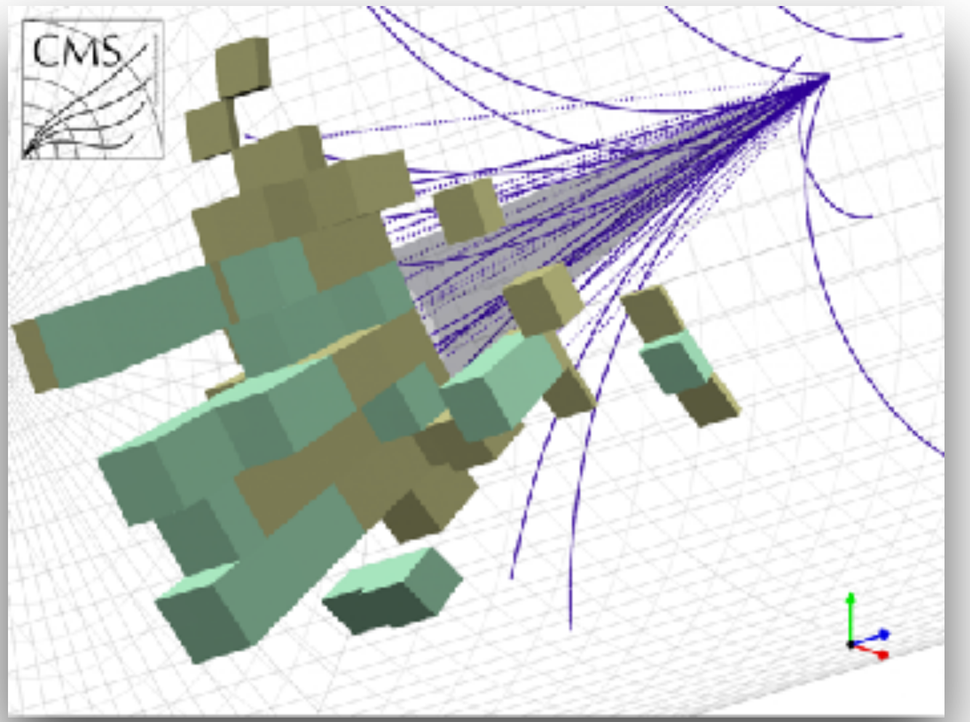
Pile-up subtraction

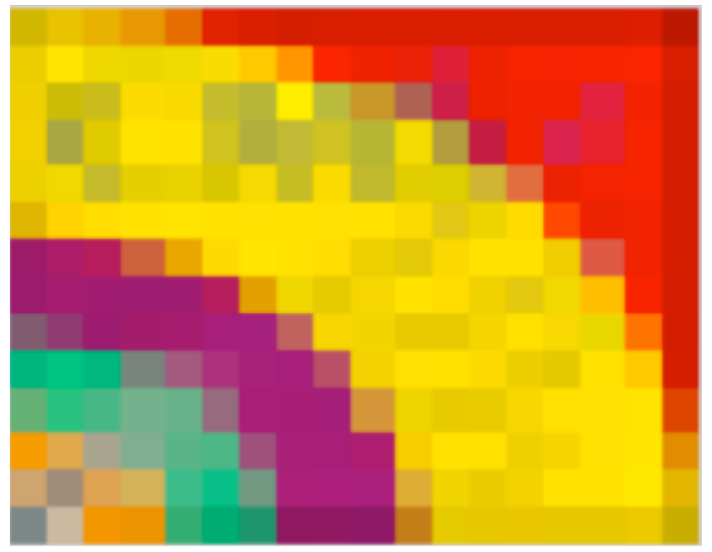
Consider four areas around jet window
Subtract sum of energy in lowest three from jet energy

Calibration

Correct jet energies as a function of jet E_T and η

Missing transverse energy et al.





14 (η) x 18 (ϕ)

56 (η) x 72 (ϕ)

ηxϕ
0.087x0.087

Inputs

Access to higher granularity inputs than Run I
Tower-level non-uniformity calibration

Energy sums algorithms

Scalar and vector sums of tower E_T (and also jets)
MET (MHT) — vector sum of towers (jets)
E_T (H_T) — scalar sum of towers (jets)
CORDIC algorithm used to convert x and y components to magnitude and angle

Pile-up mitigation

Tower zero-suppression fn. of PU and η as in lepton isolation

Calibration

Option to calibrate x and y components — under study

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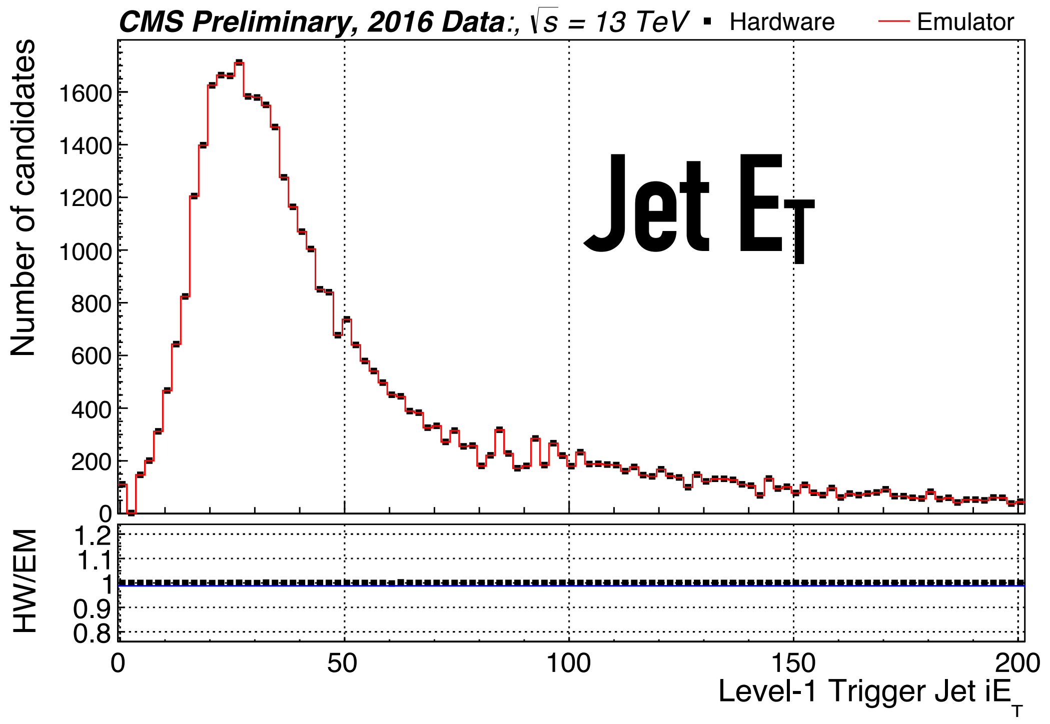
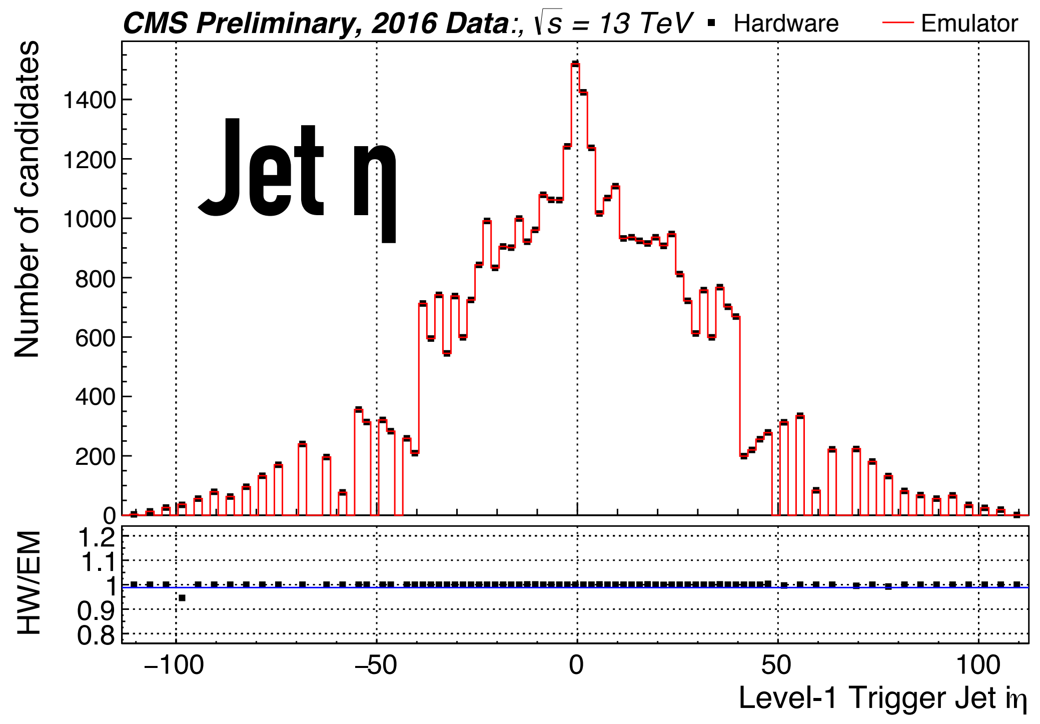
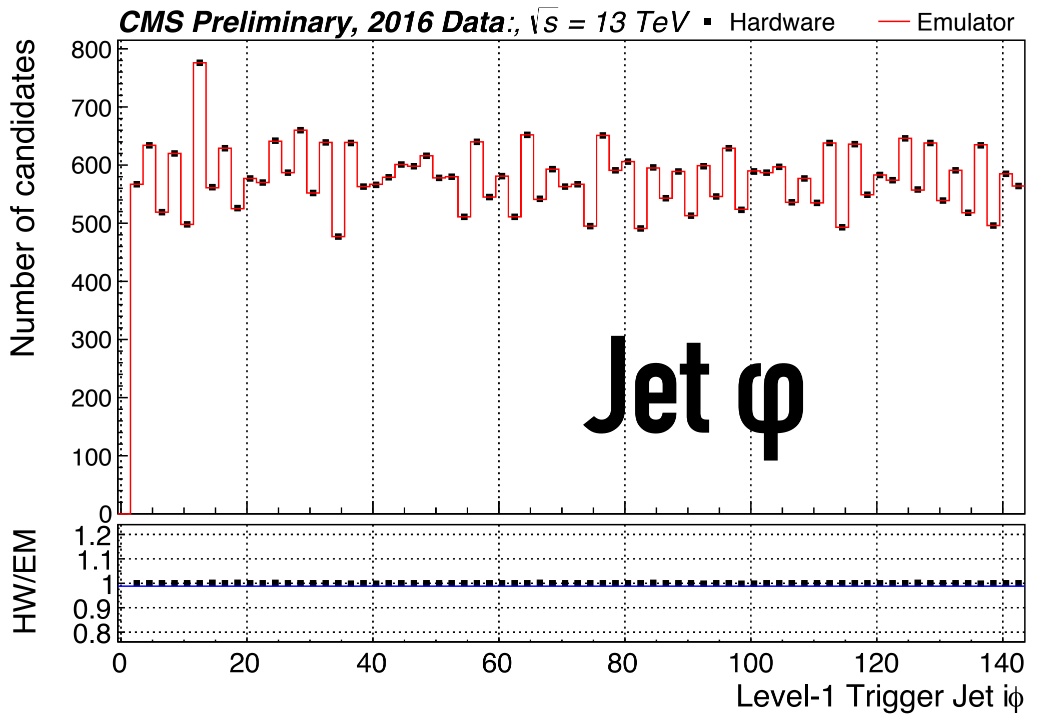
Commissioning

- Commissioned in parallel
  - Calorimeter inputs duplicated in FPGAs (ECAL) and optically (HCAL)
  - Run parasitically with CMS data taking (not triggering!)







Examples of tests with 2016 collision data

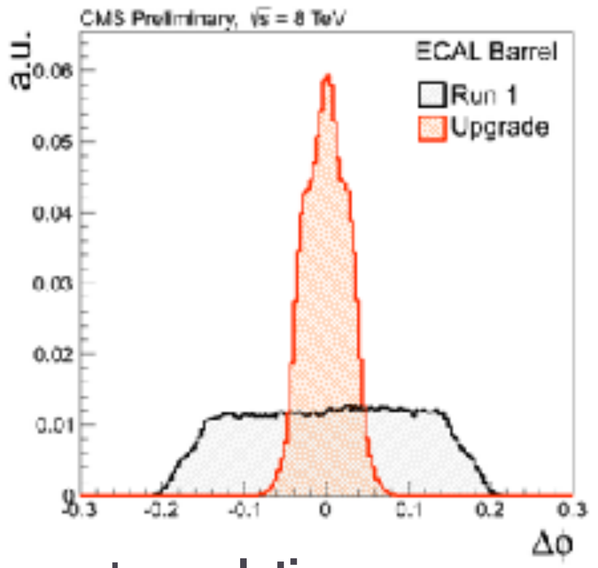
Data vs emulation

- 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 collisions ✓
  - 2016 Started physics run ✓
  - 2017 Optimised for high luminosity ✓

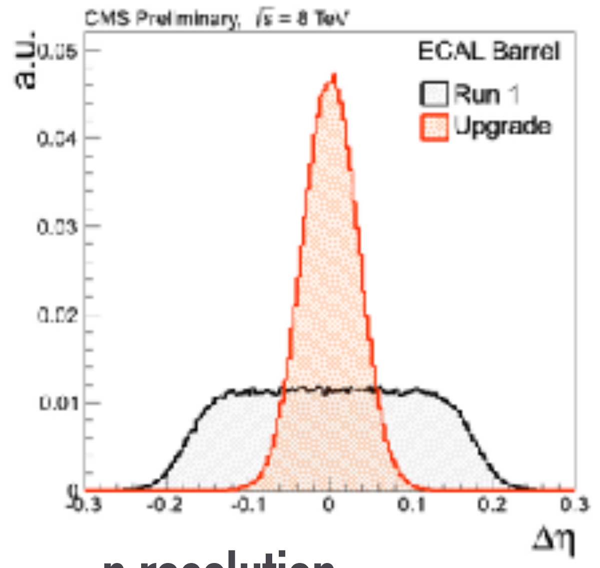
Performance results: e/γ and τ

L1 Electron Photon Finder

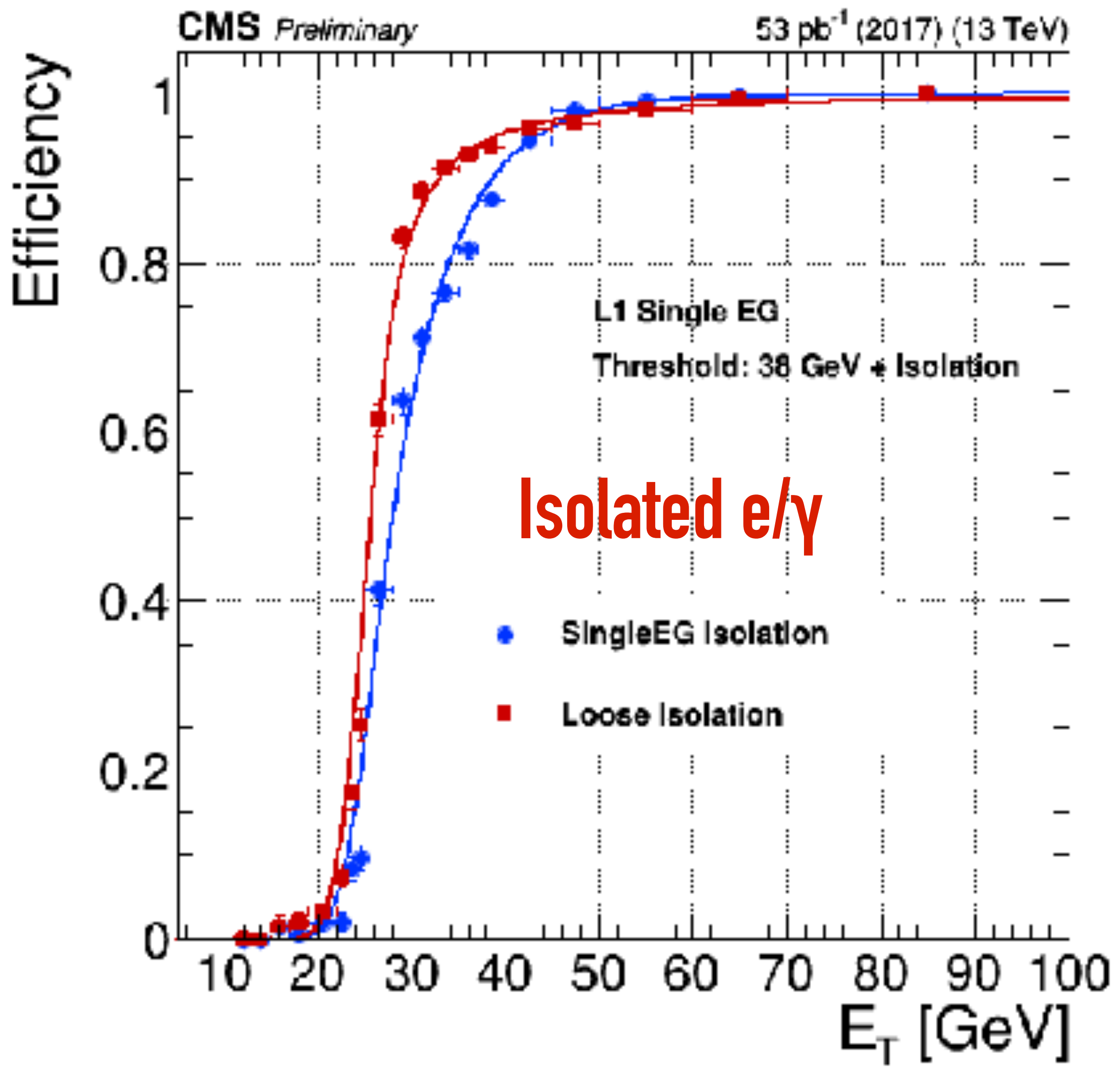
large position resolution improvement

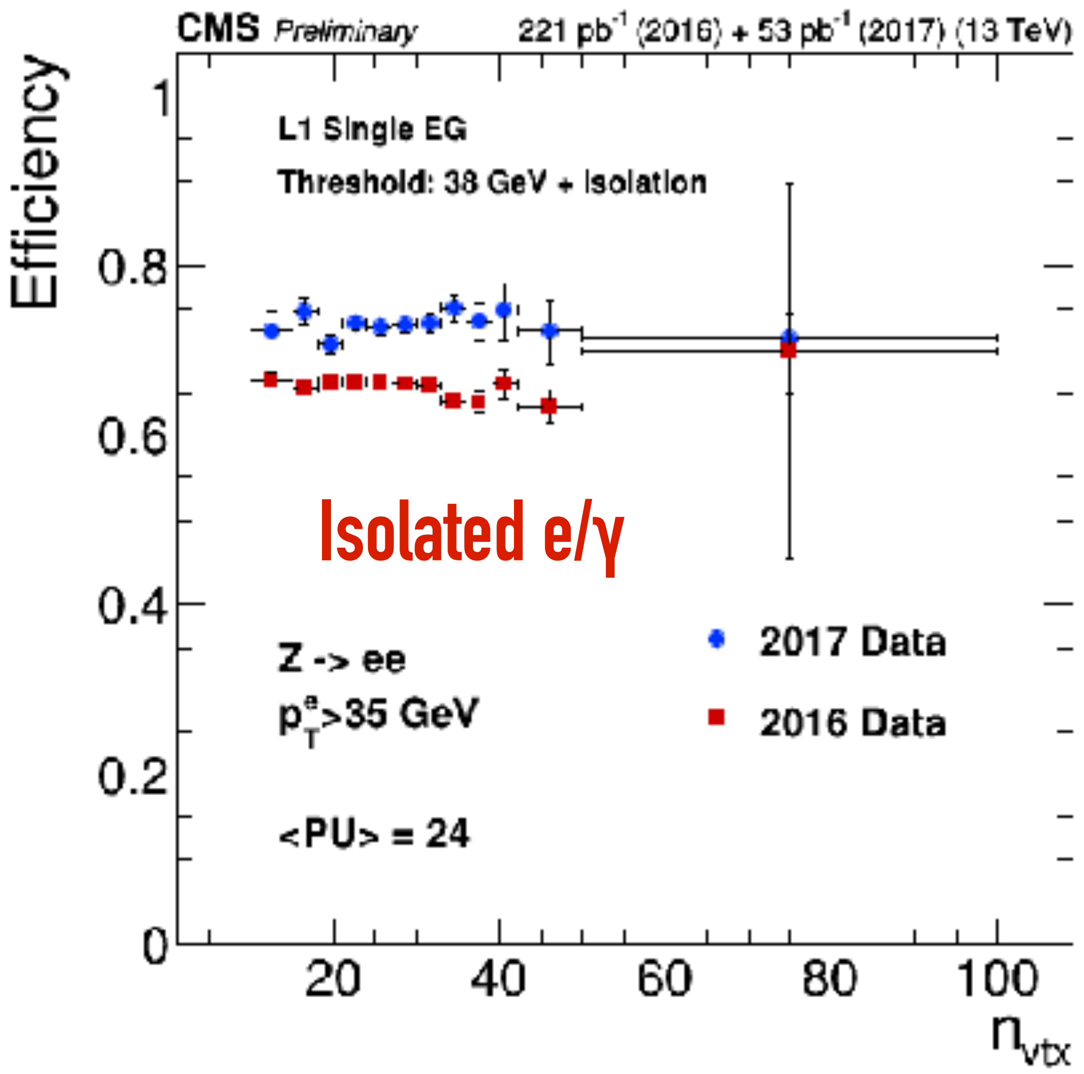


ϕ resolution



η resolution

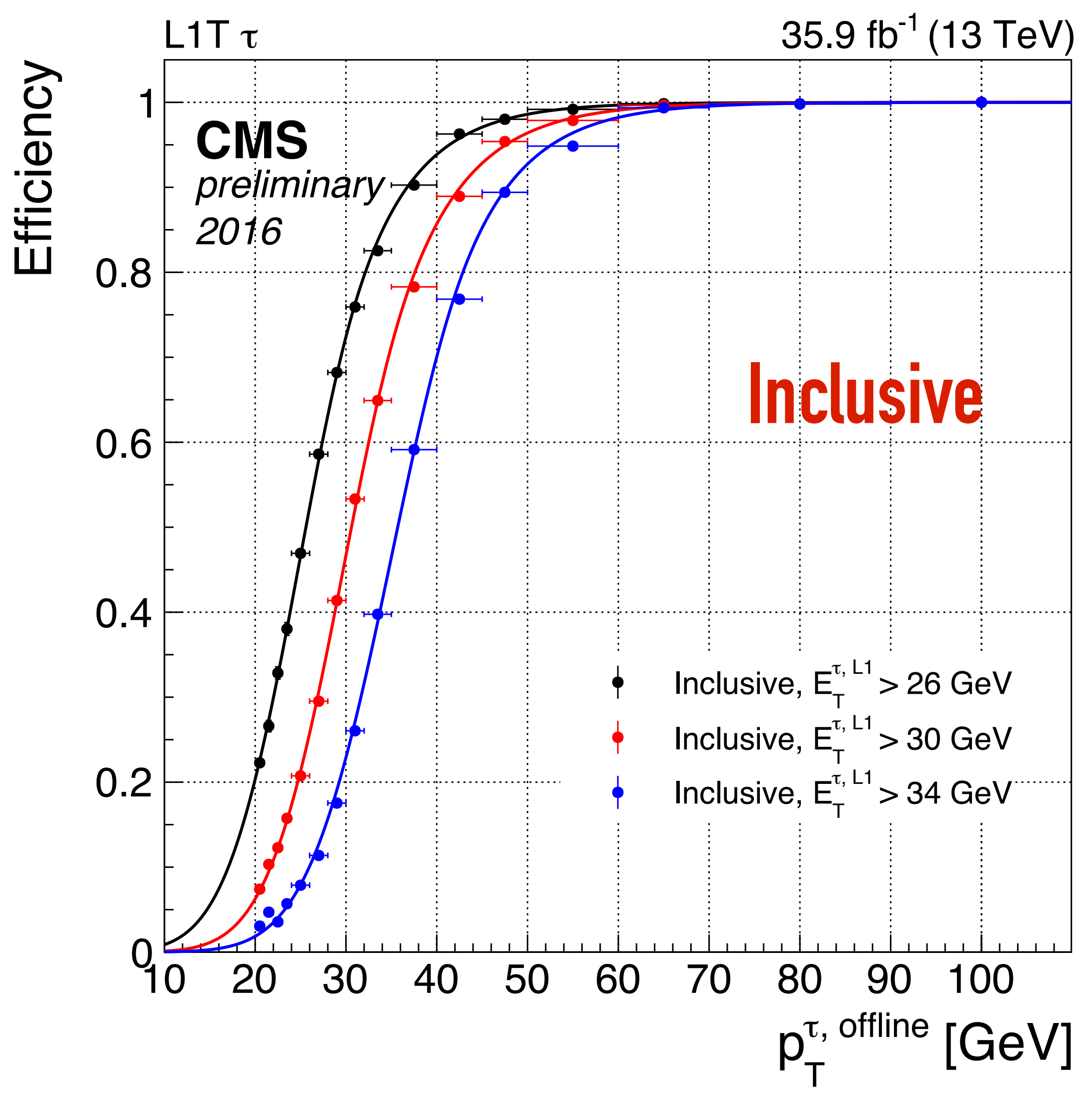


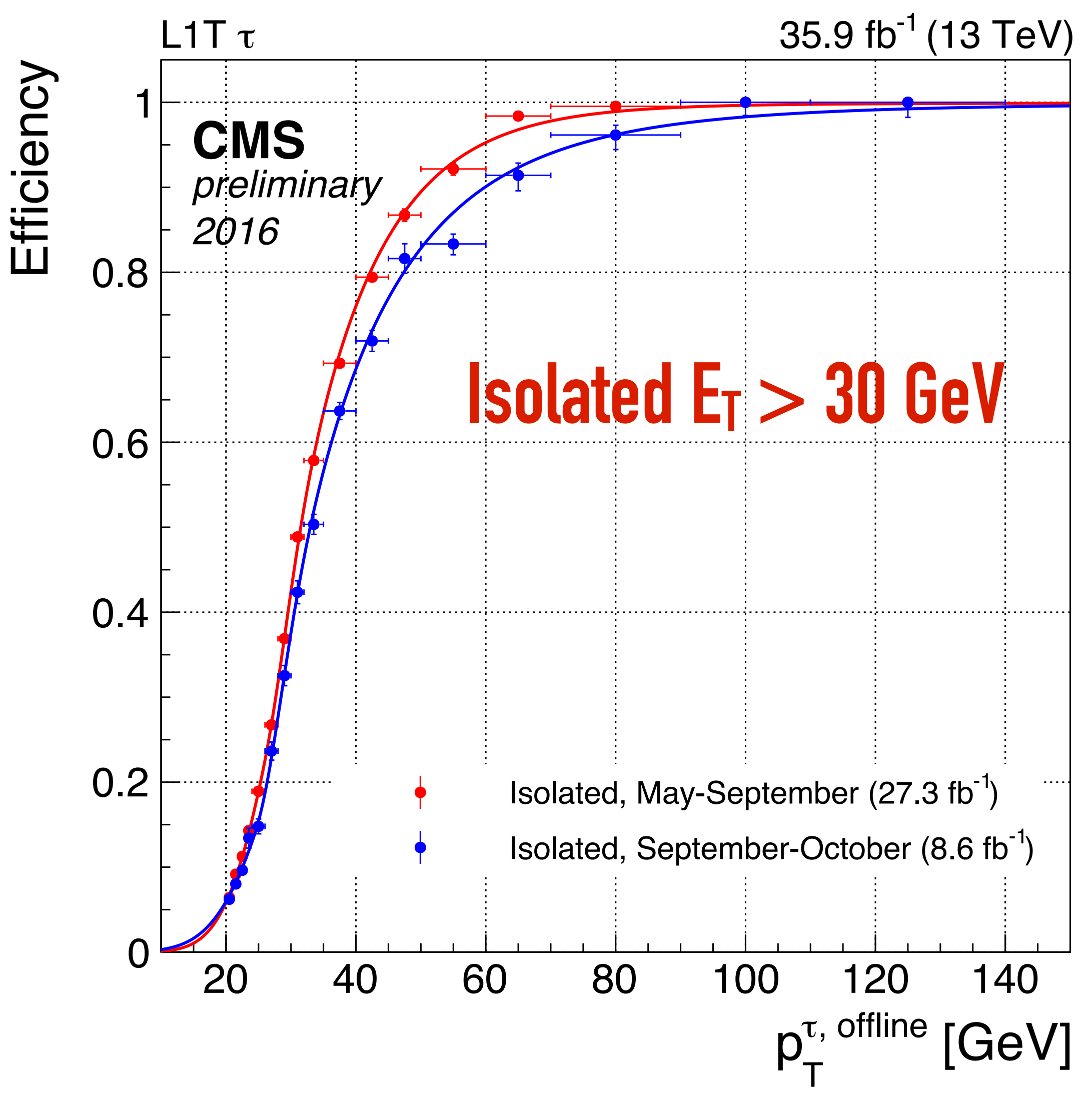


Efficiency for a single e/γ with $E_T > 38$ GeV vs offline E_T

Using tag&probe method on Z⟶ee dataset

L1 Tau Lepton Finder



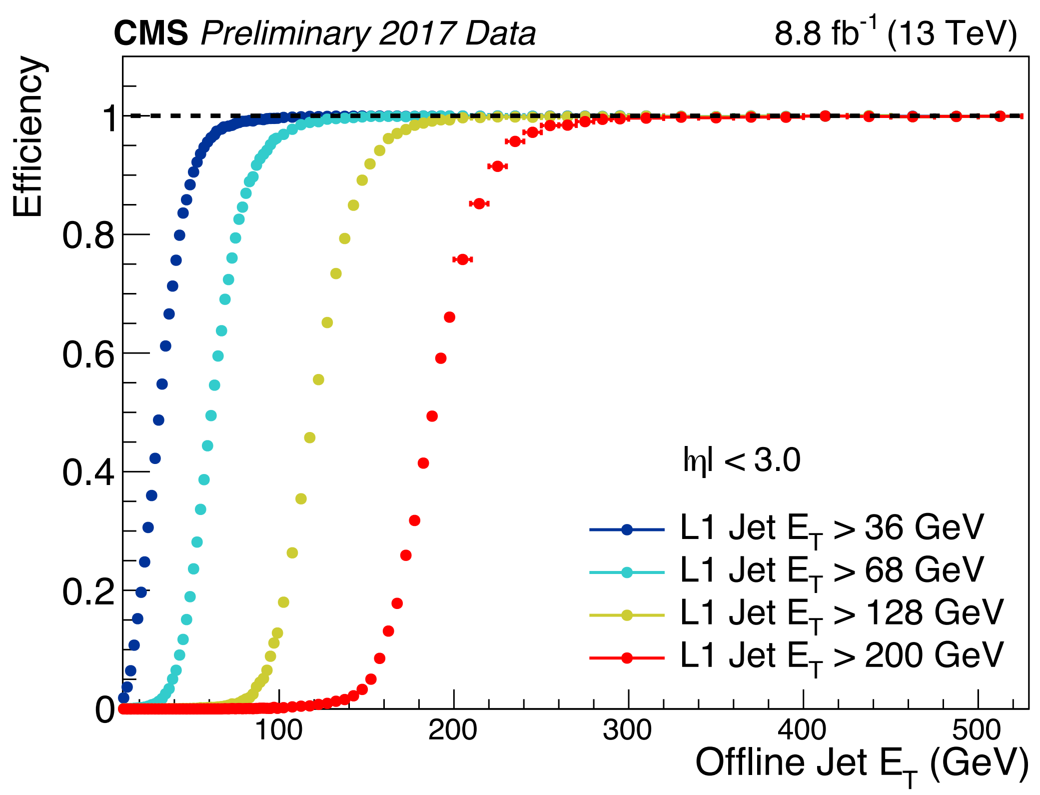


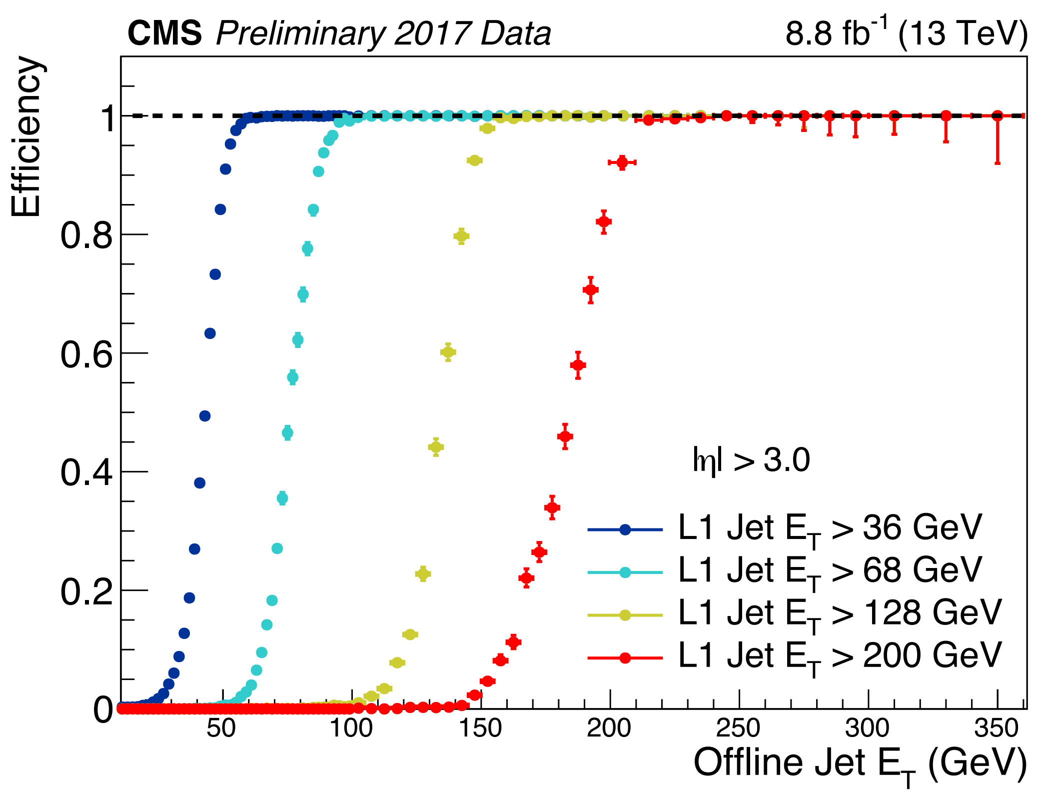
Trigger efficiency for a single τ with $E_T > 26$, 30 and 34 GeV vs offline τ p_T

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

Performance results: Jet and energy sums

L1 Jet Finder



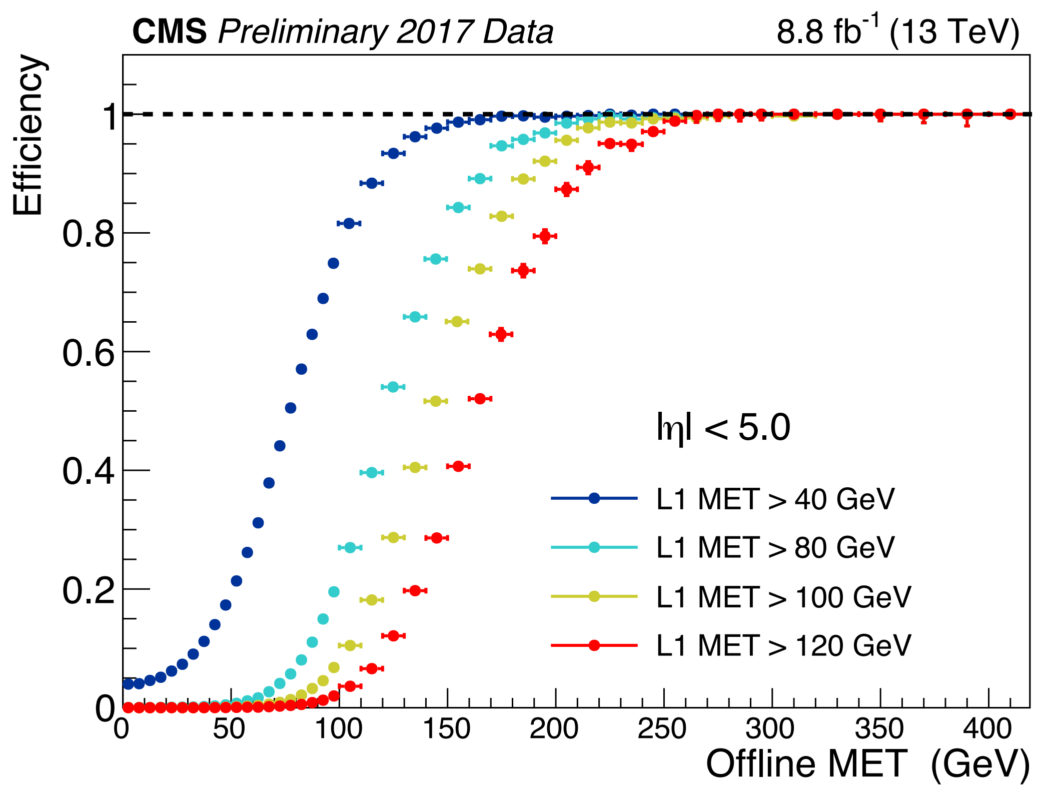


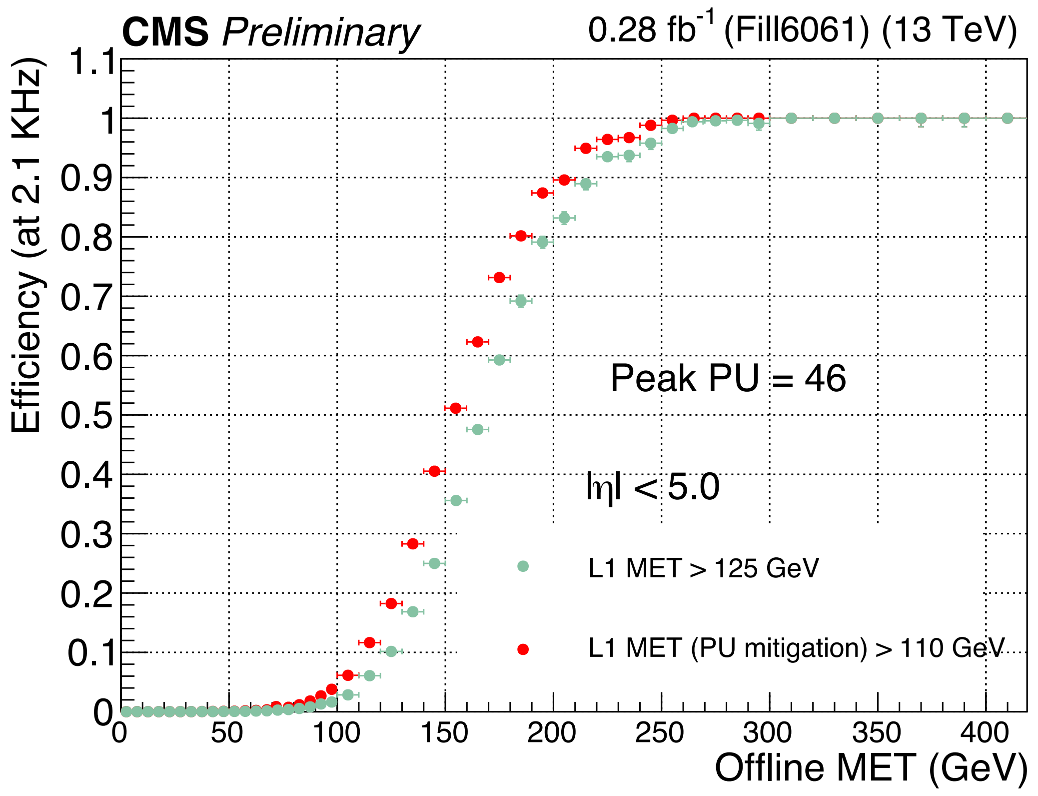
Match **Level-1 Trigger jets** to offline (anti-kt R = 0.4) jets using **$\Delta R < 0.25$ in single muon data**

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

Sharp efficiency turn-on with well calibrated E_T scale

Missing Energy Triggers





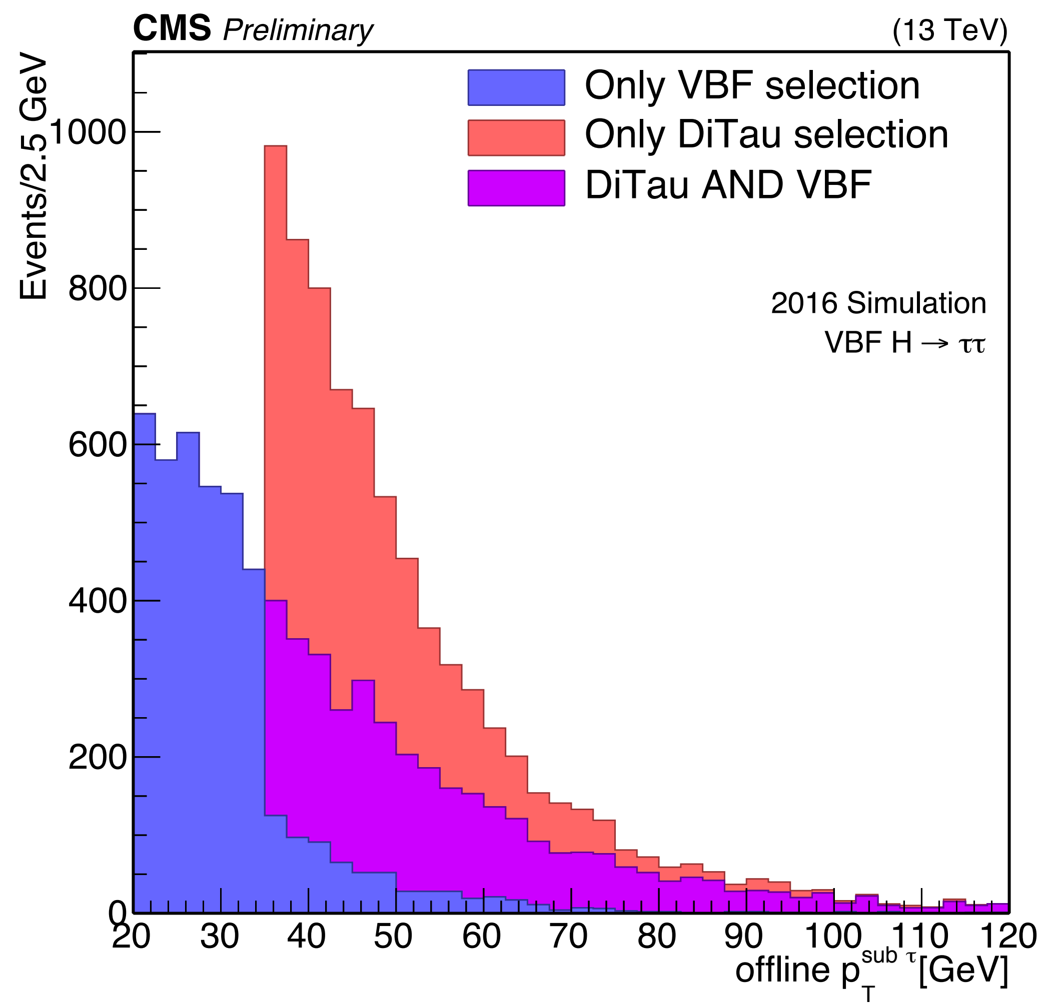
E_T^{miss} : Vector sum of trigger towers with PU dependent zero-suppression

Efficiency as a function of offline Missing E_T

PU mitigation gives lower rate (factor 2) at fixed efficiency, allowing lower thresholds

High level example: invariant mass

- Higher resolution objects - both E_T and position - feed into..
- **Global trigger** allows large range of operations:
  - Simple thresholds, P_T and η for example, as in Run I
  - Combinations of objects, like correlations between positions and energies, even handling overlapping objects



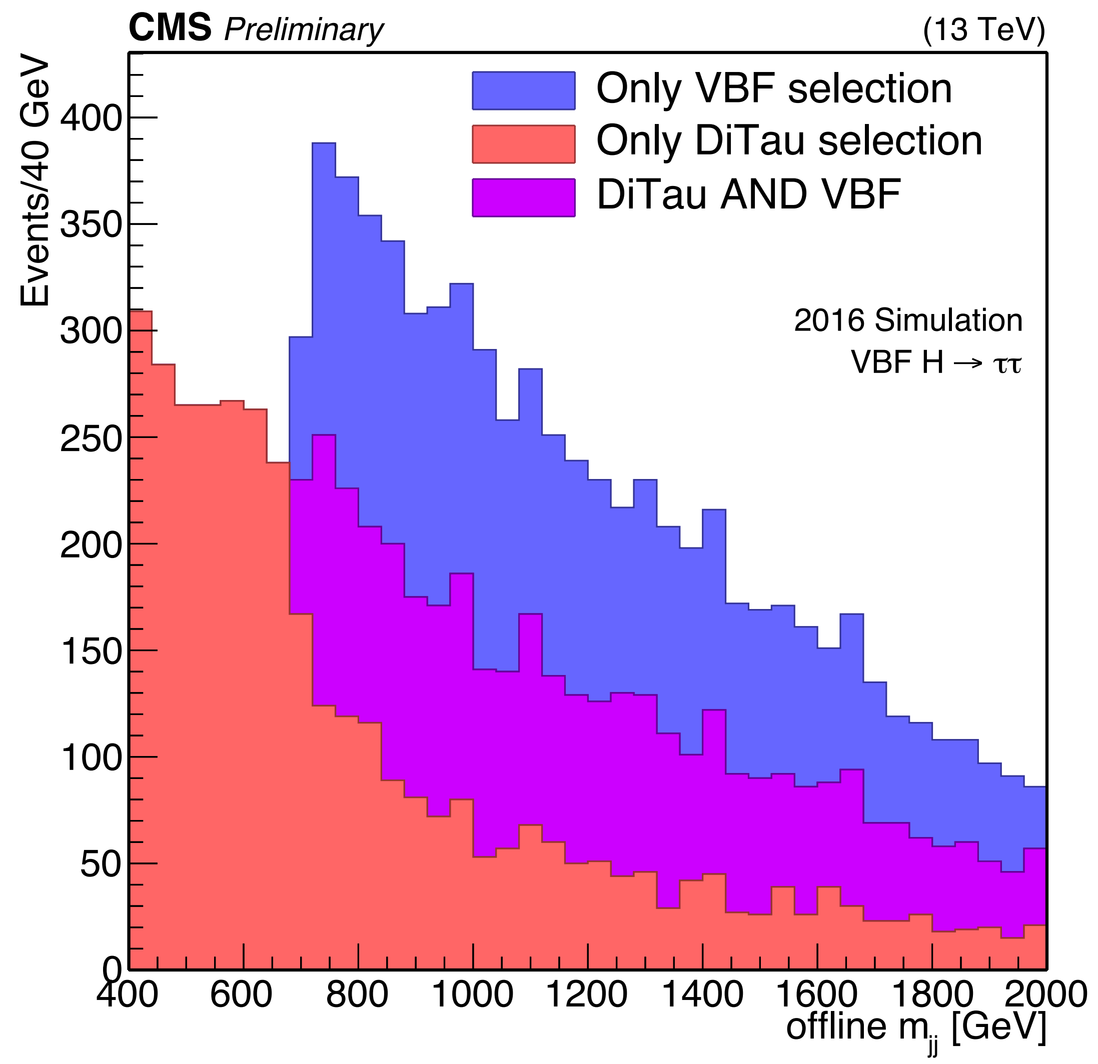
Di-jet selection with jet E_T > 35 GeV & m_{jj} > 620 GeV

Single jet E_T > 110 GeV

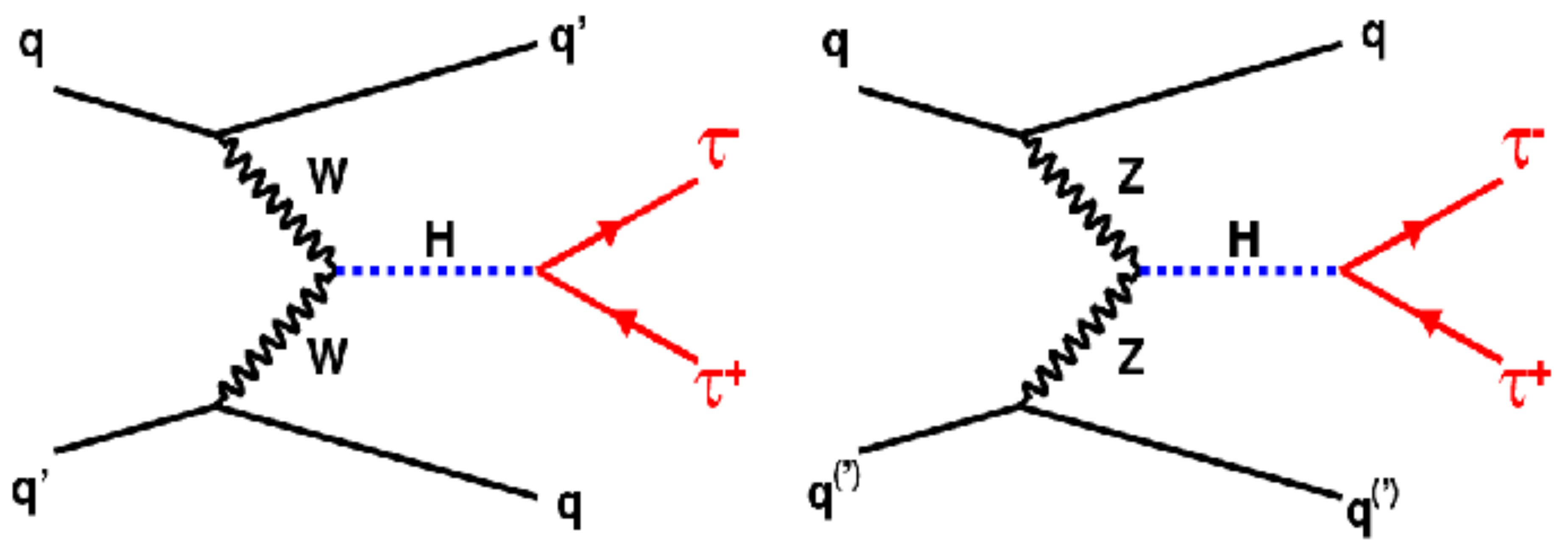
Di-τ selection with |η| < 2.1 & P_T > 32 GeV

Use of invariant mass allowed the jet threshold to be kept low

Combination of leptonic and hadronic selections adds ~**60% efficiency** for the Higgs signal



- Example VBF Higgs to di-tau decays:



  - **Two low E_T jets, separated by large η gap**
  - **Central high p_T τ-lepton pair from Higgs decay**

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Summary and outlook

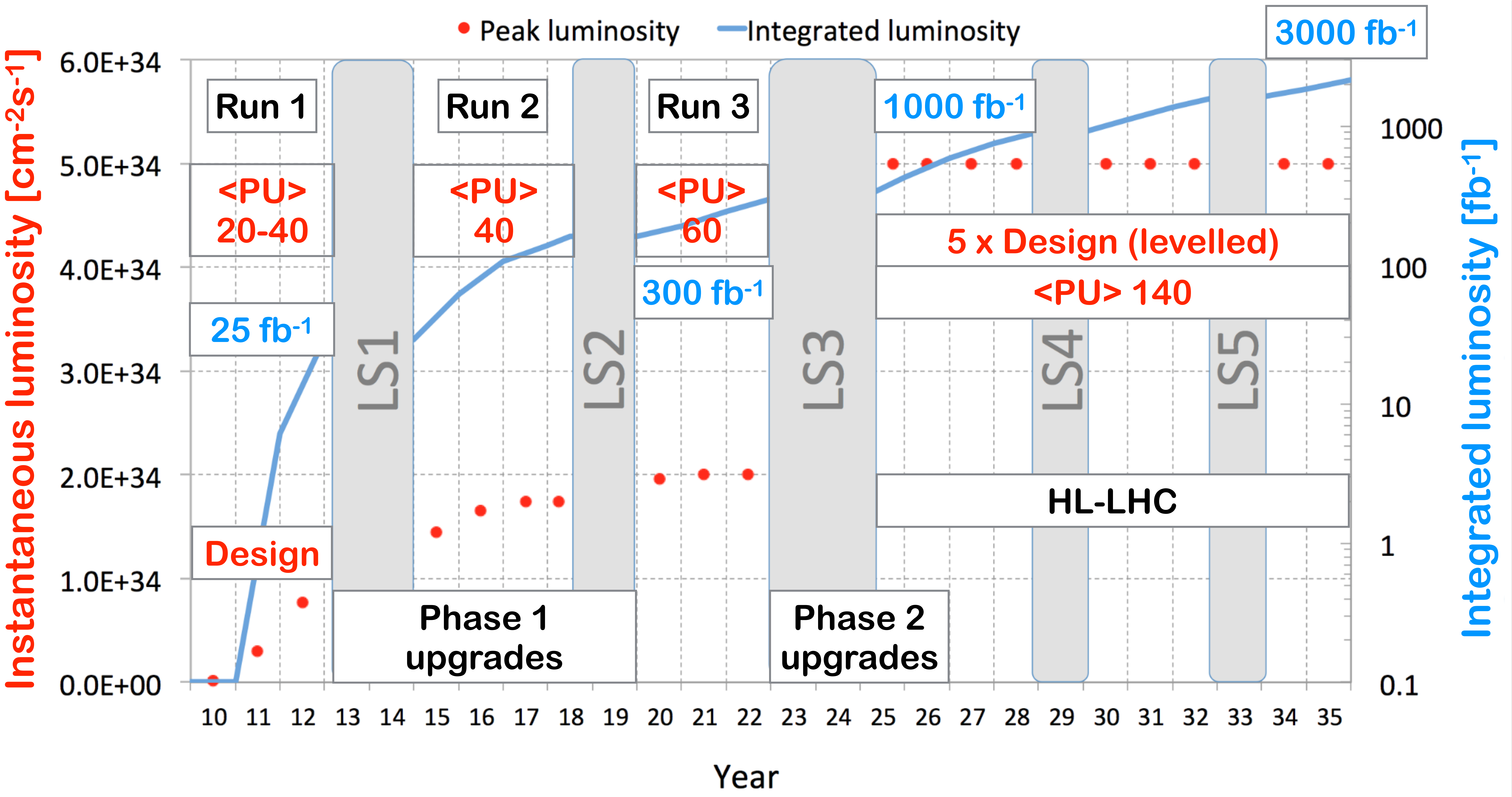
- The CMS L1 trigger has successfully completed first years of operation in Run II
  - LHC Run II challenging environment, higher luminosity, centre-of-mass energy, increased PU
  - Excellent performance on single physics objects and sophisticated global quantities
- Development, installation and commissioning completed on a very tight schedule with parallel running
  - State-of-the-art, FPGA based, very high bandwidth processors with sophisticated, programmable algorithms
  - The system has successfully evolved with the changing LHC conditions.
- Exploit detector upgrades in shutdown in 2019-20
  - Improved HCAL information: longitudinal energy profile, improved timing information…
- Study the performance of this new trigger and learn from design and commissioning to begin designing Phase II trigger upgrade for HL-LHC

References

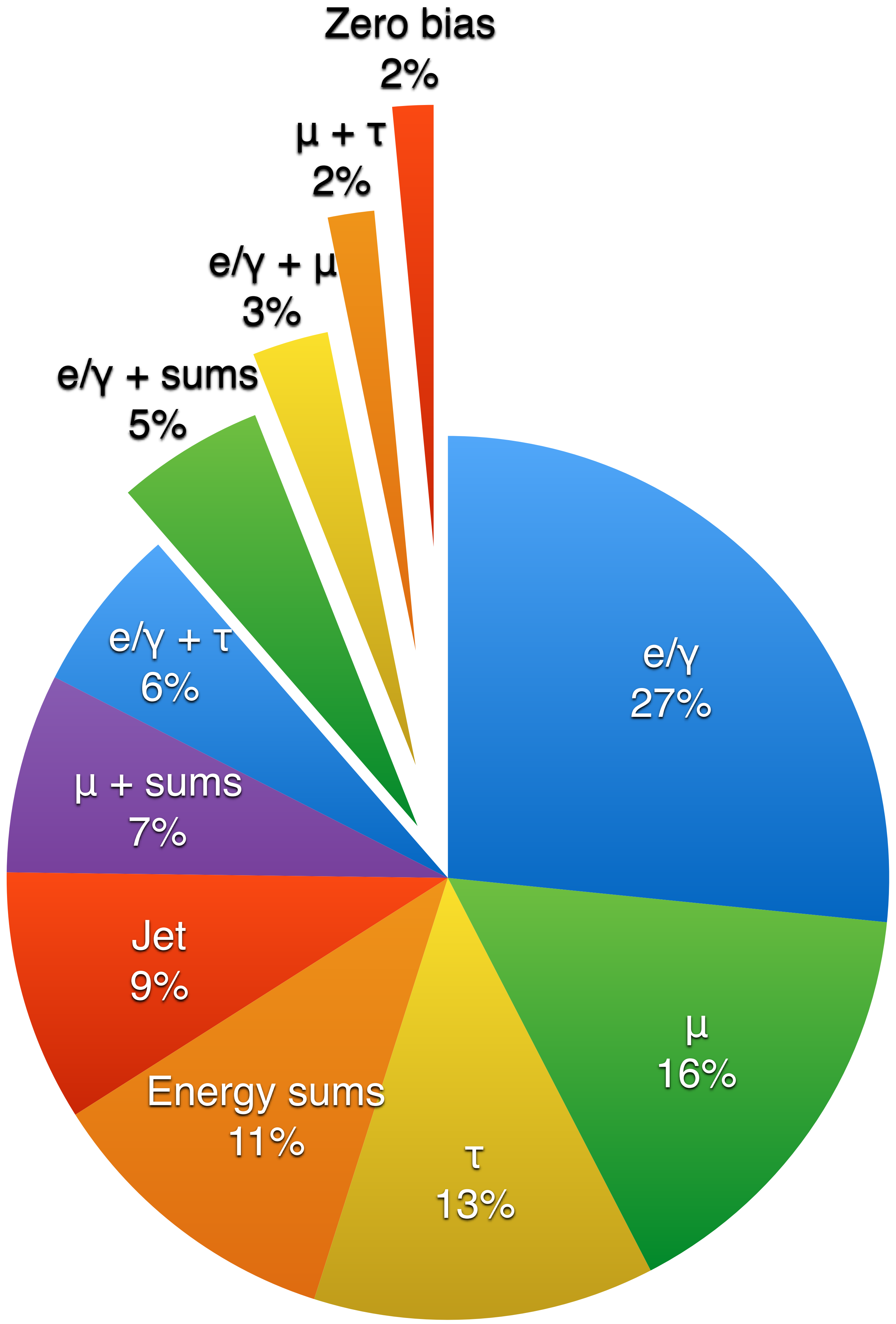
- CMS Level-1 Trigger TDR: https://cds.cern.ch/record/706847
- Run I performance paper: CMS Collab., The CMS trigger system, JINST 12 (2017) P01020.
- Phase 1 upgrade TDR: https://cds.cern.ch/record/1556311
- Performance notes for EPS 2017 and other conferences
  - e/γ: https://cds.cern.ch/record/2273270
  - τ and VBF with inv. mass: https://cds.cern.ch/record/2273268
  - Jets and sums: https://cds.cern.ch/record/2286149
  - μ: https://cds.cern.ch/record/2286327

Backup

LHC: Future plans



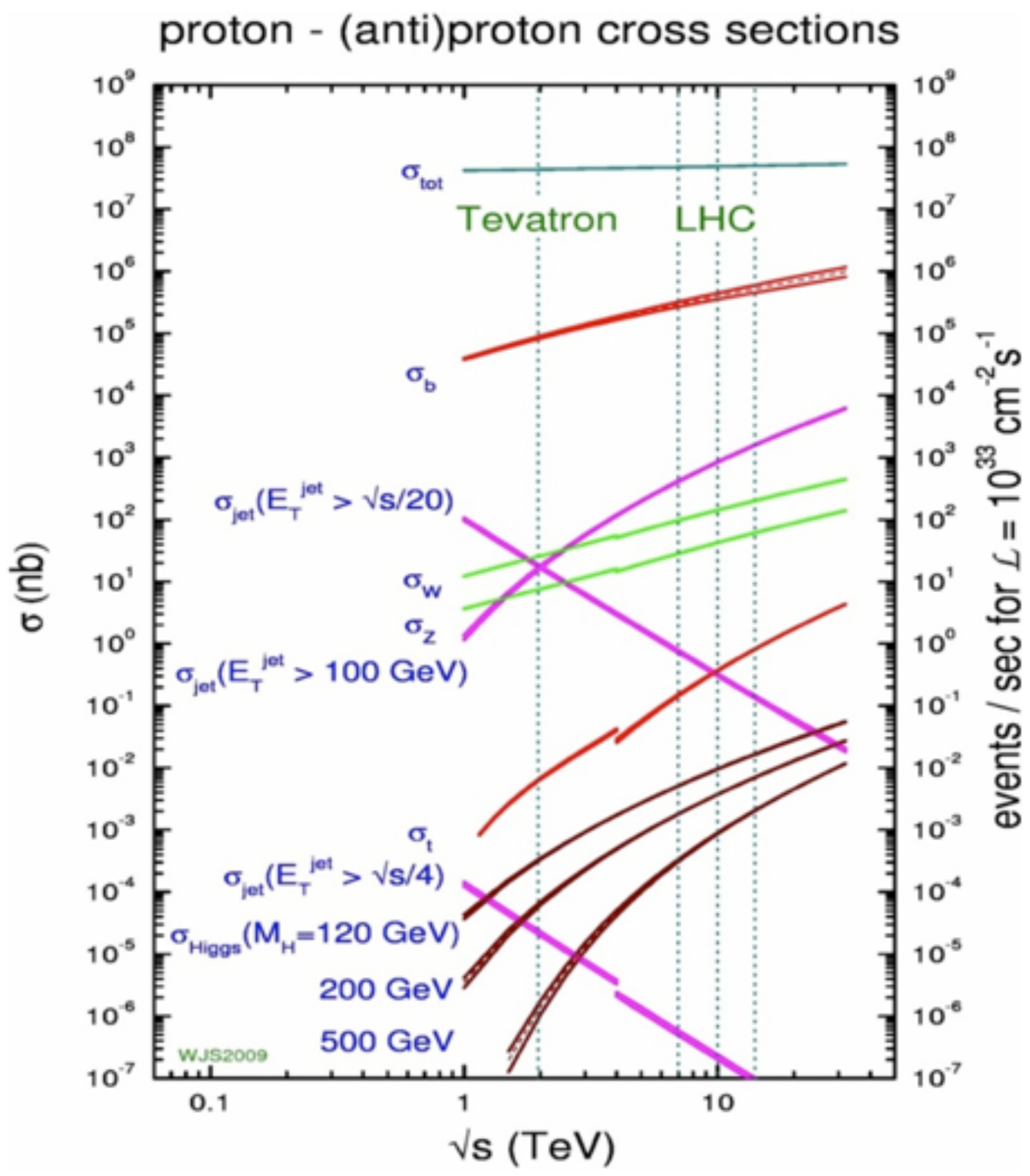
L1 menu for 10^{34} cm^{-2} s^{-1}



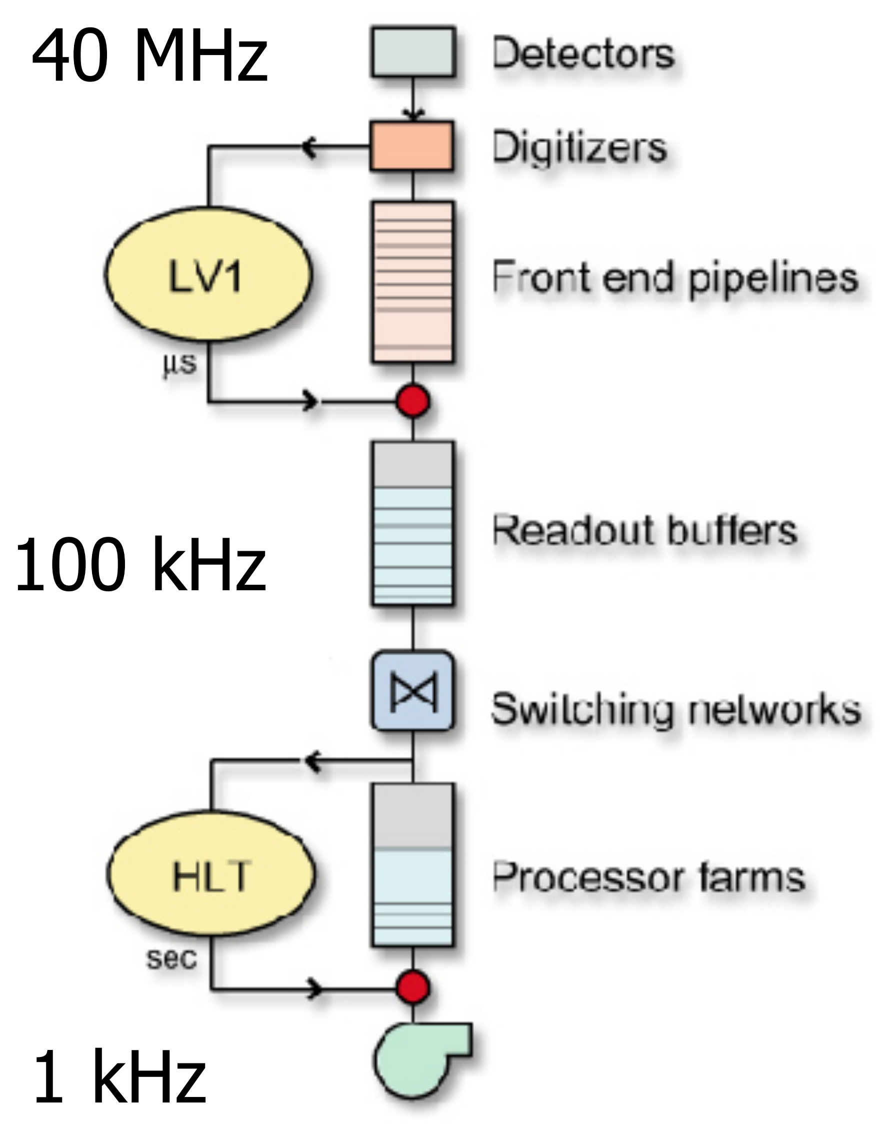
- Bandwidth allocated per trigger object type
- **Note that fractions are inclusive → no attempt to correct for overlaps between different types of trigger**

Backup: system

Challenges



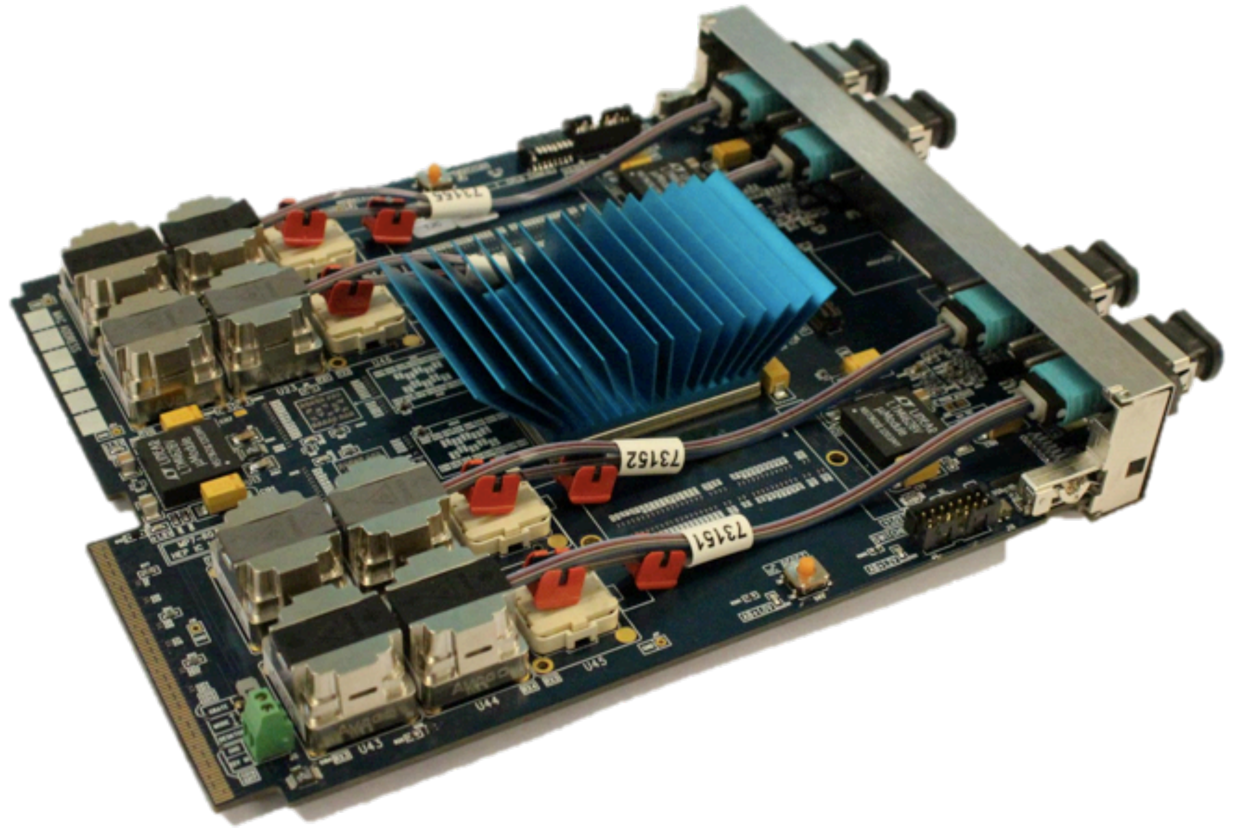
- *Interesting* processes many orders of magnitude low cross sections than total pp cross section
- Cannot store all events (TB/s)
- Select interesting events without dead time
- Implemented as a two level system in CMS →

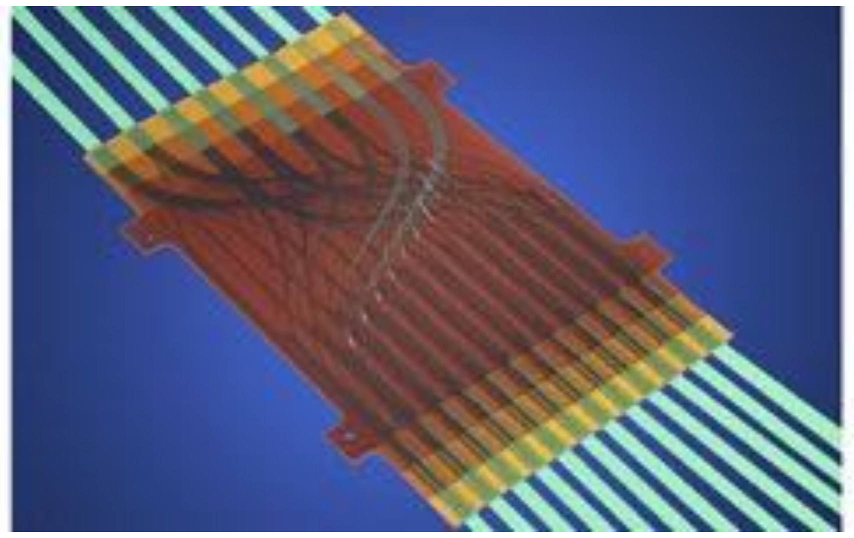


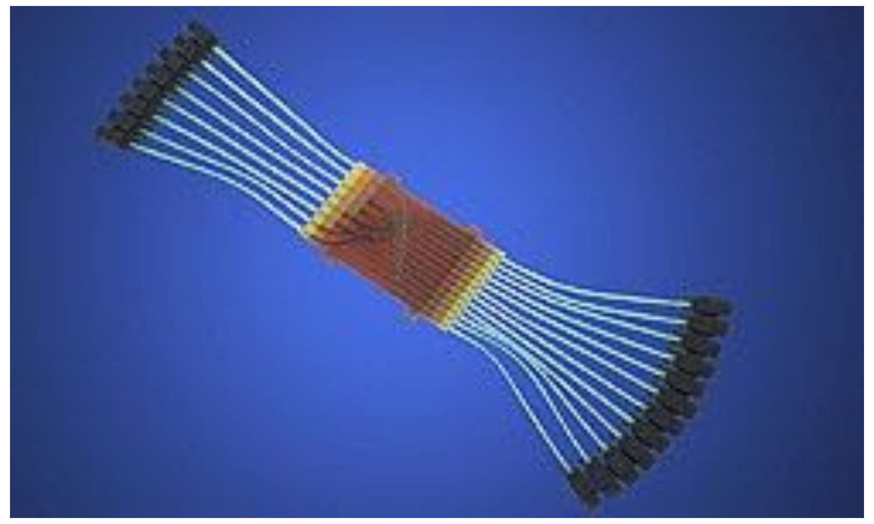
- Trigger rates are driven up in Run II by the increase in luminosity, the centre-of-mass energy, and by the higher PU (especially hadronic objects)
- CMS detector electronics are limited to a L1 trigger rate of 100 kHz
- Maintain sensitivity for electroweak scale physics and for TeV scale searches as in Run I

System implementation

- Key technology changes
  - VME → µTCA (modern telecoms standard)
  - System wide use of latest FPGAs → Xilinx Virtex® 7
  - Parallel copper links → serial optical links
  - Link speeds 1 Gb/s → 10 Gb/s
  - Large optical patch panels → custom made commercial solution (Molex Flexplane™)
  - Online software rewritten → more common code, modern libraries, more easily maintained

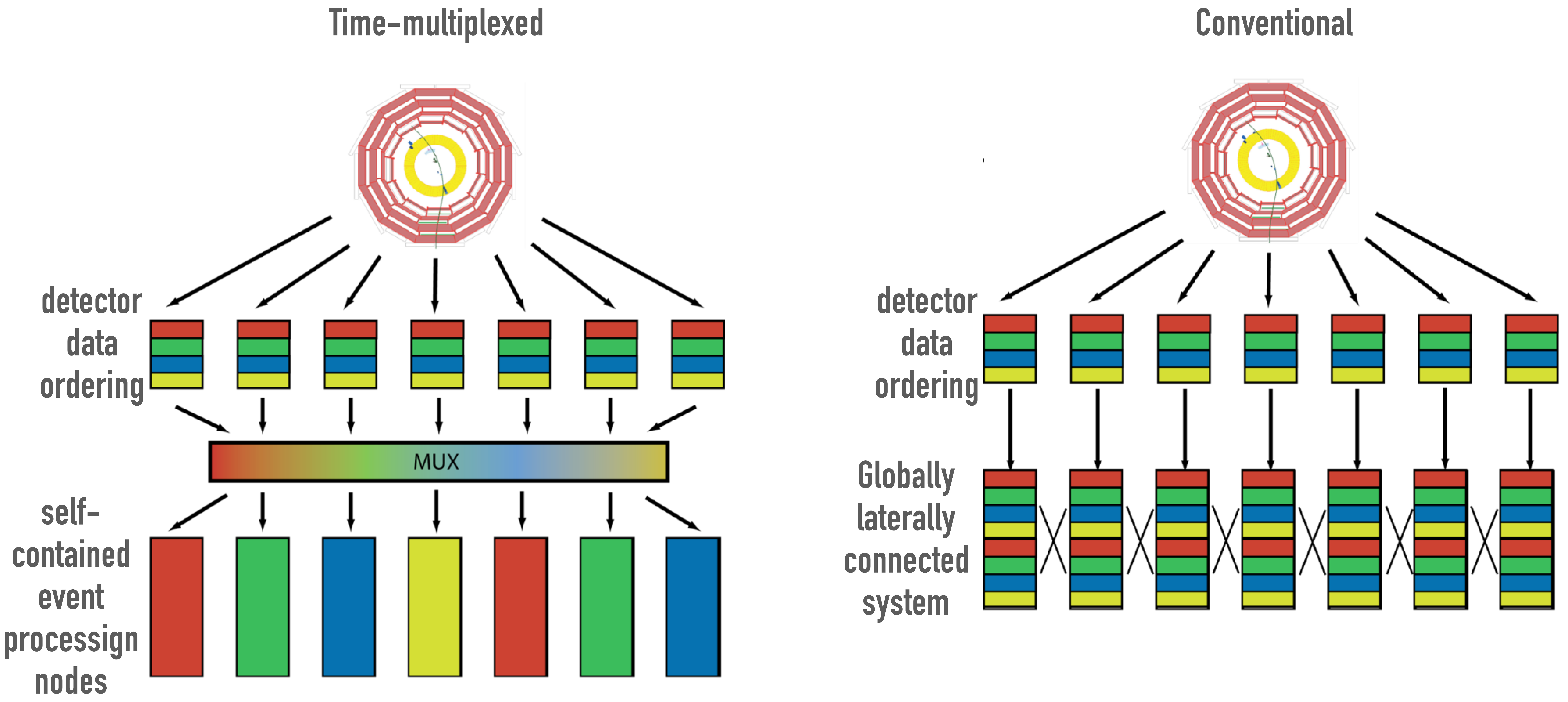




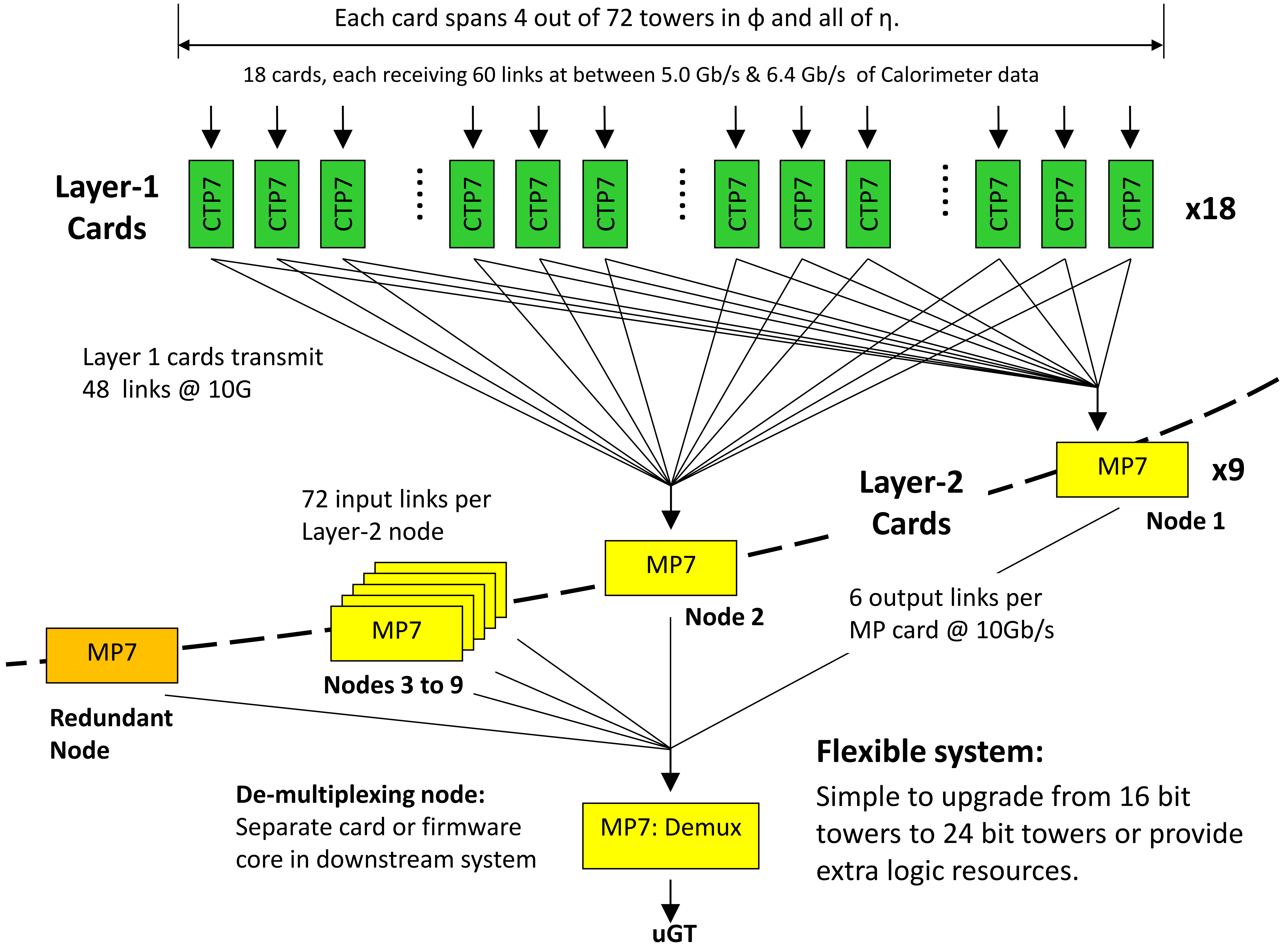


- Aim for flexible, maintainable system
  - Adapt to evolving CMS physics programme

Time-multiplexing



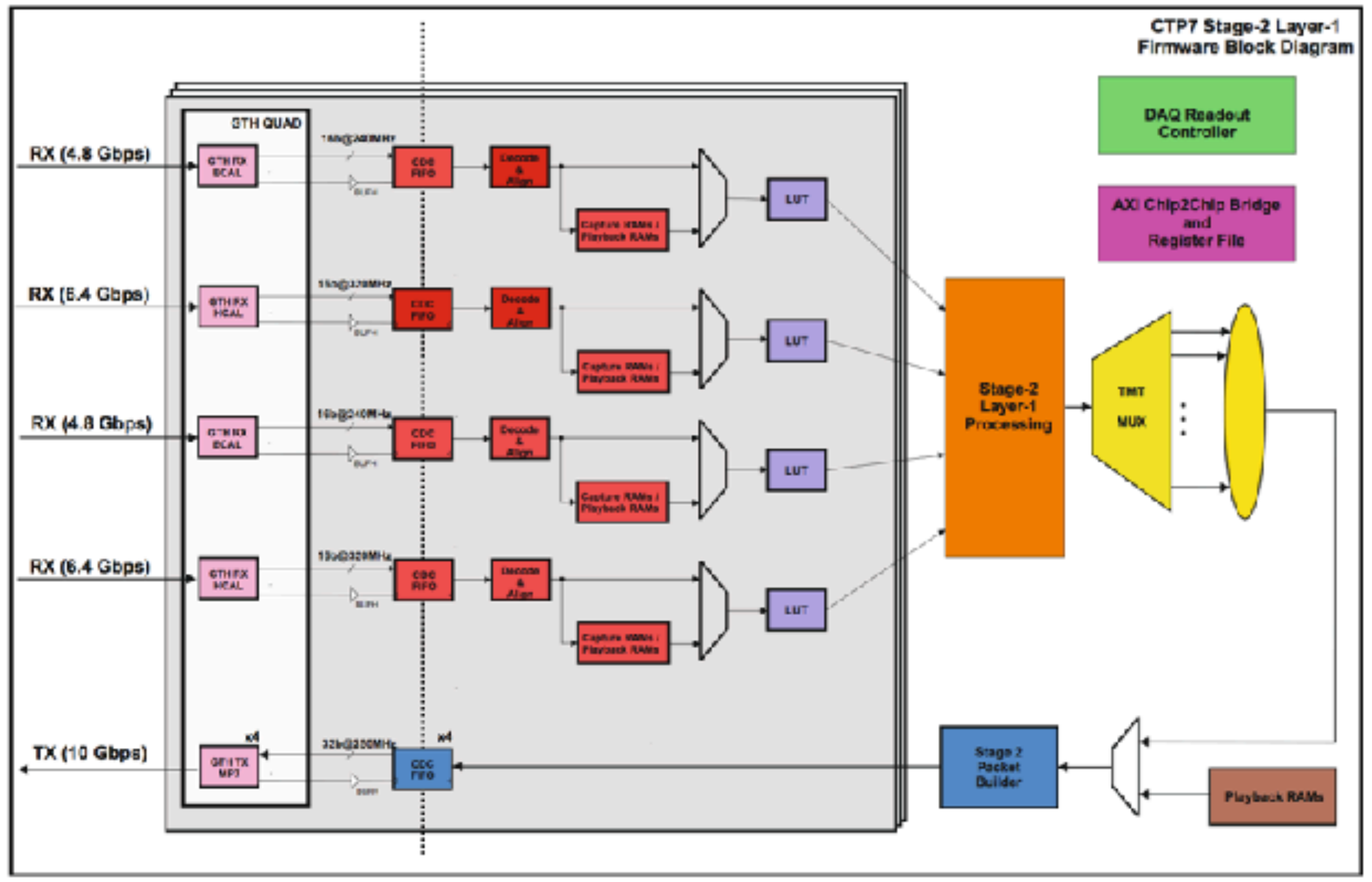
Time-multiplexed calorimeter trigger



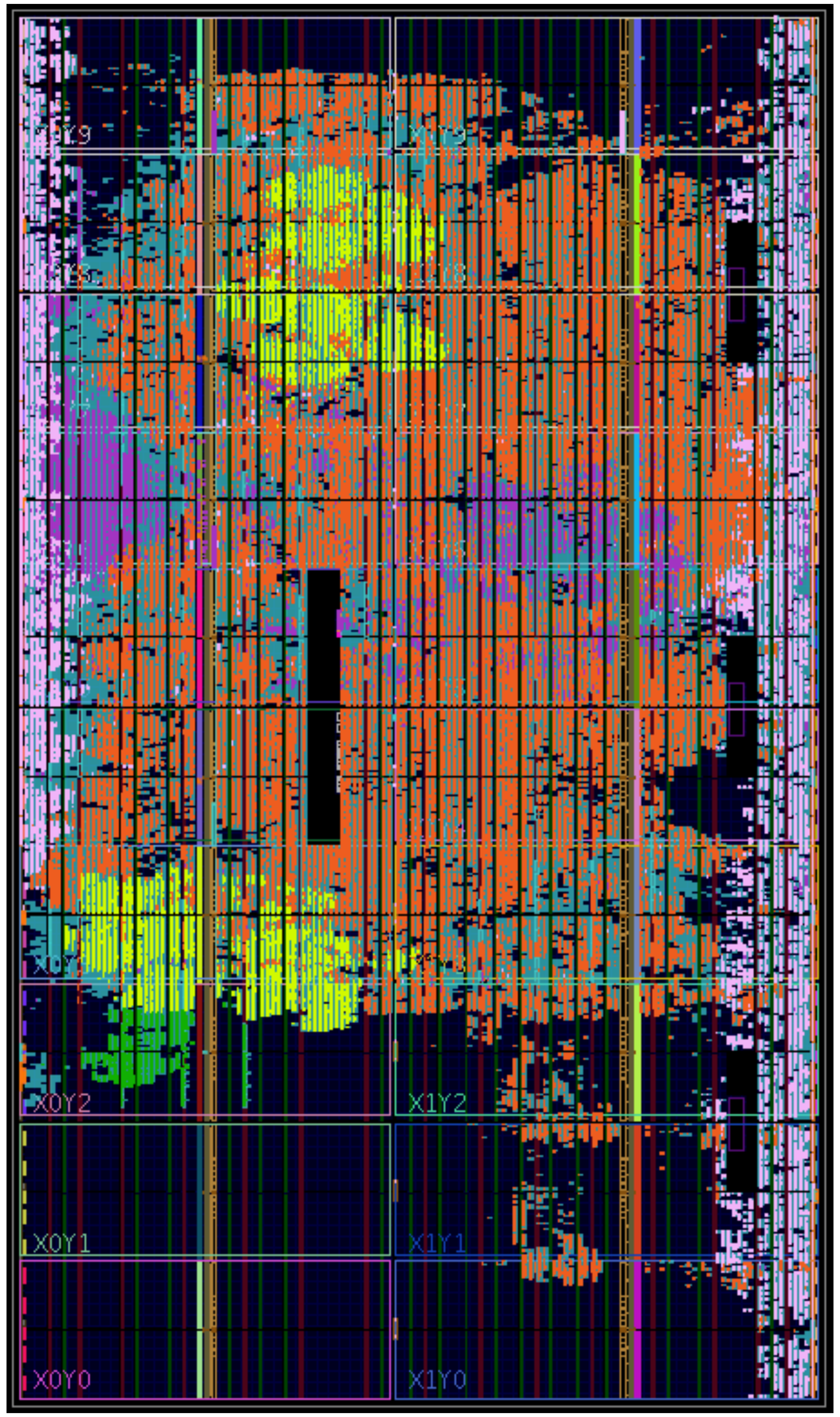
Algorithms - Layer 1

- **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

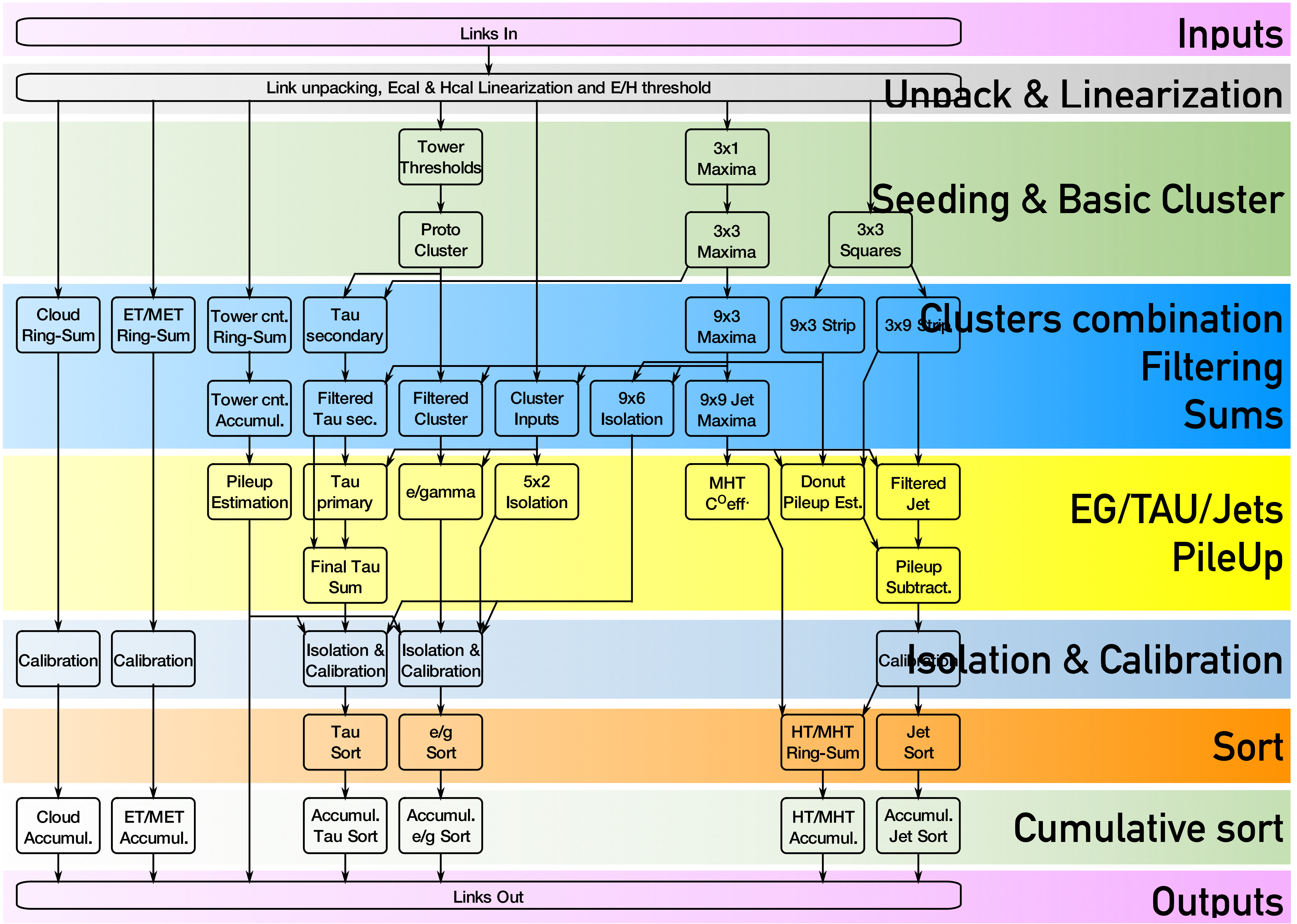


CTP7 floorplanning



Algorithms - Layer 2

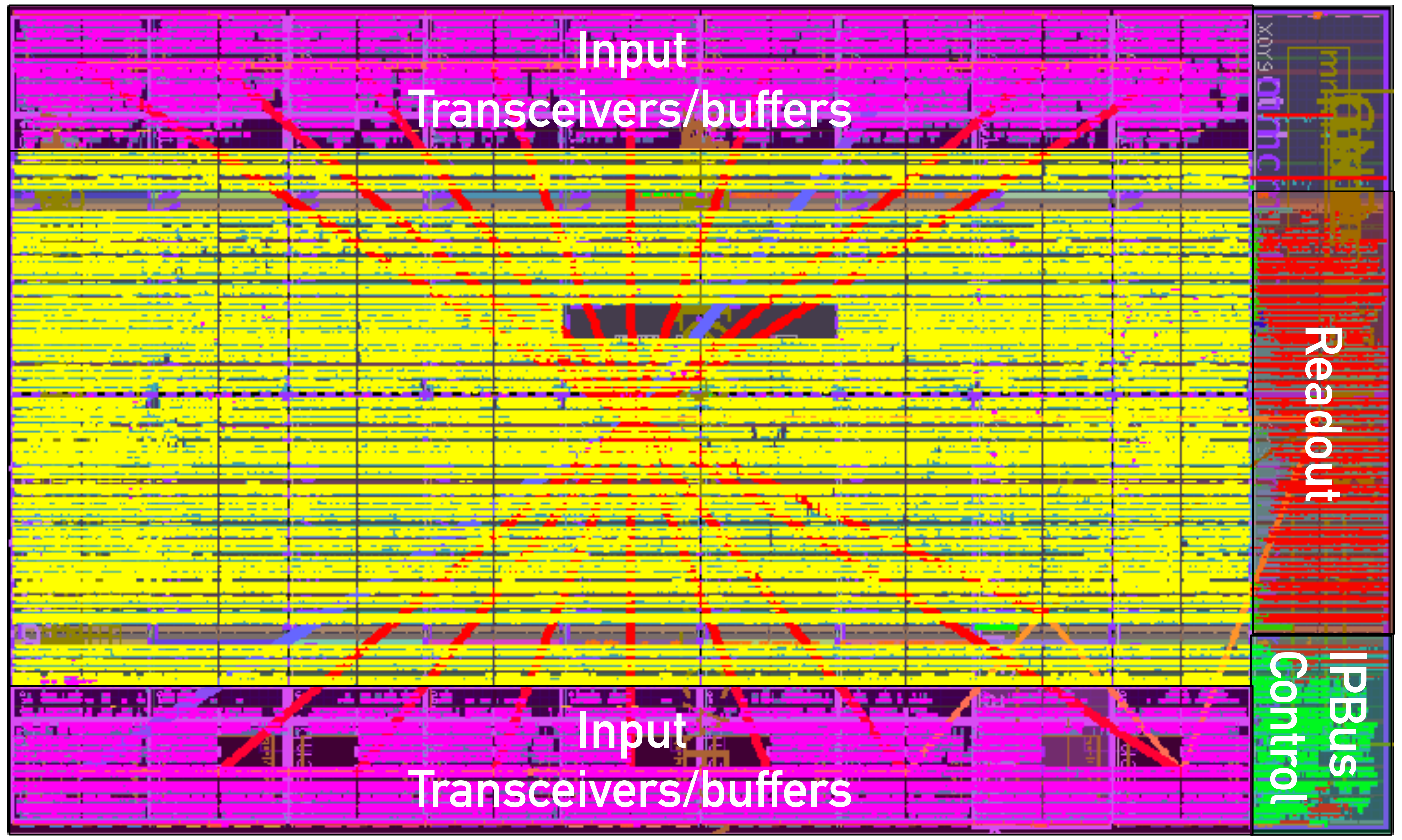
Layer-2 algorithms structure



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

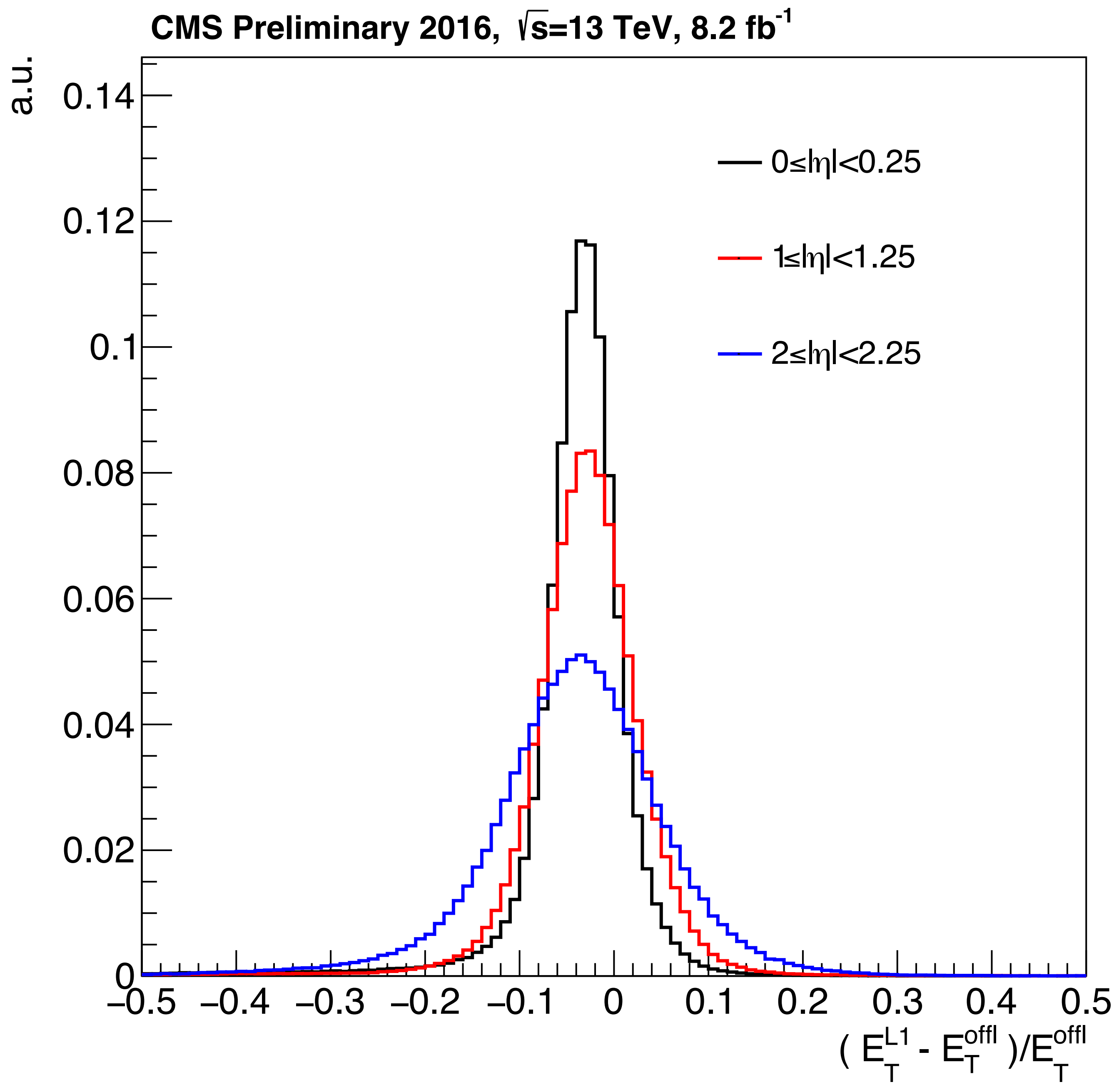
- **Time-multiplexed processing**
  - **Calorimeter data** received in **geometric order** (increasing η) in **one FPGA**
  - **Fully pipelined algorithms**: local processing, reduce signal fanout, eliminate register duplication and routing delays minimised.

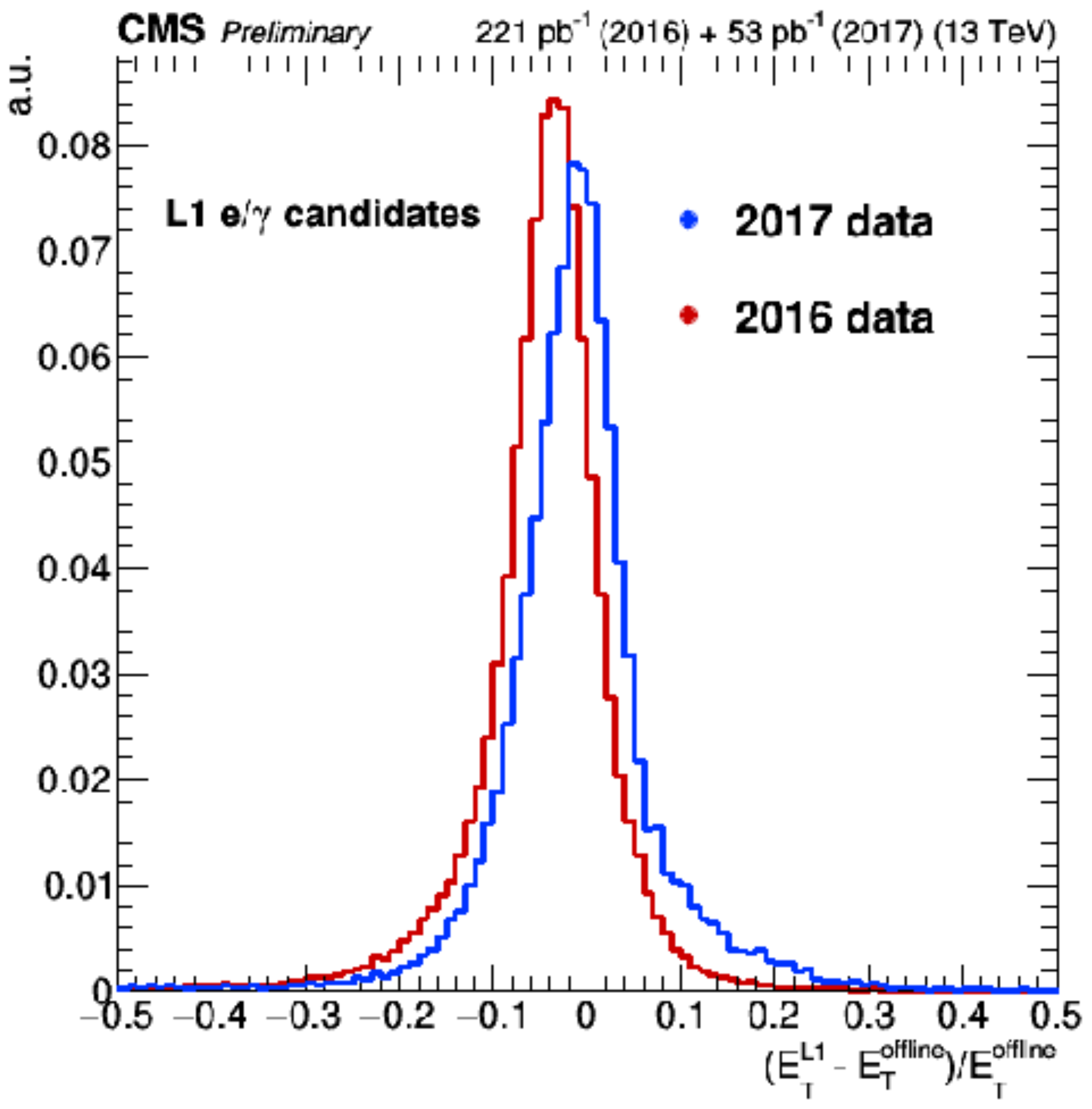
Processor floor planning

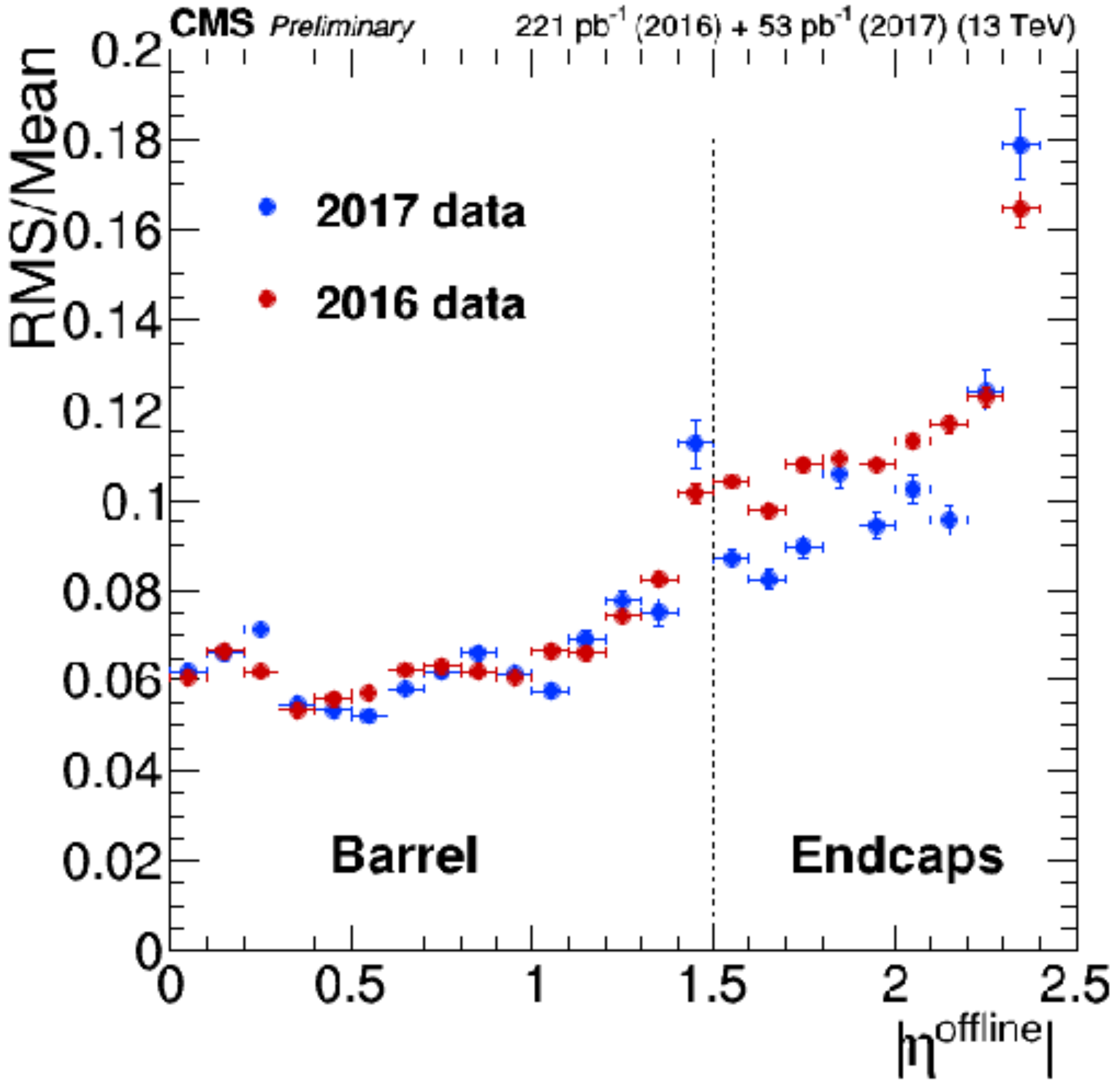


Backup: resolutions etc.

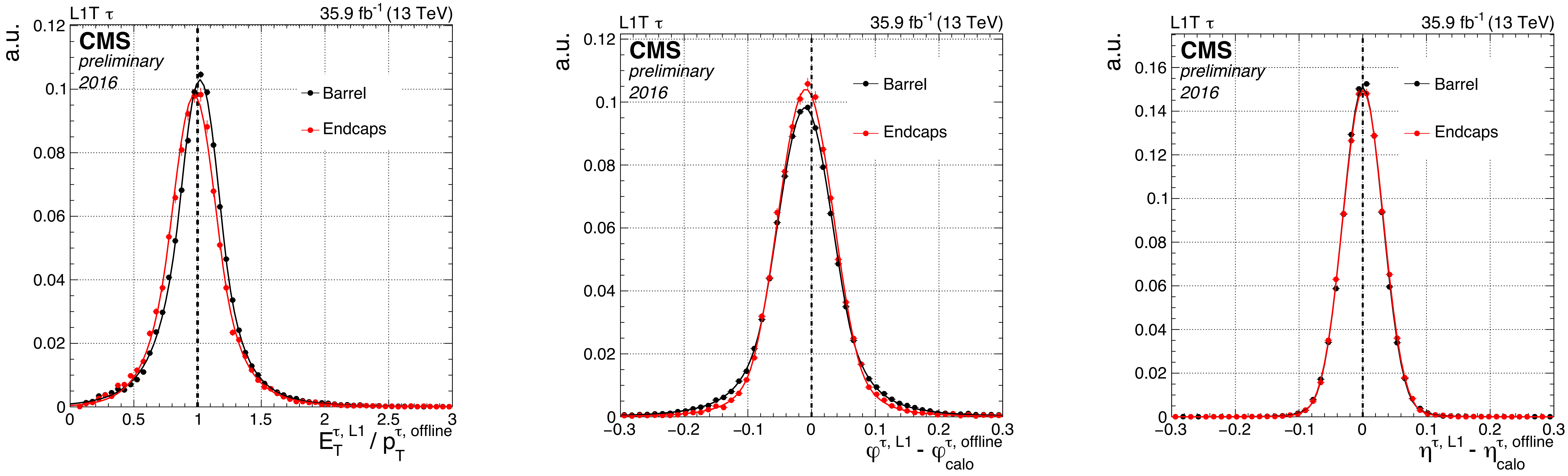
e/γ reconstruction performance



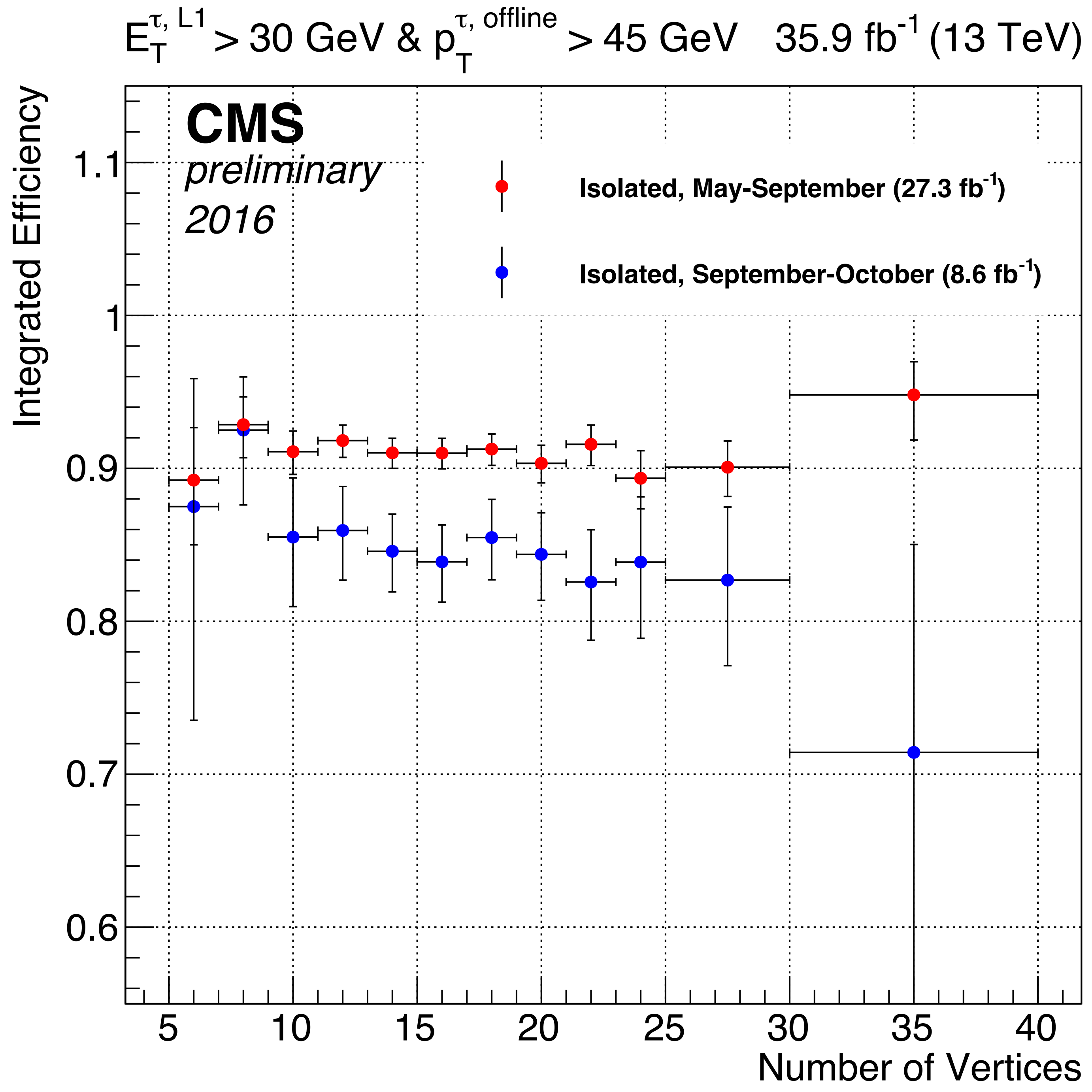


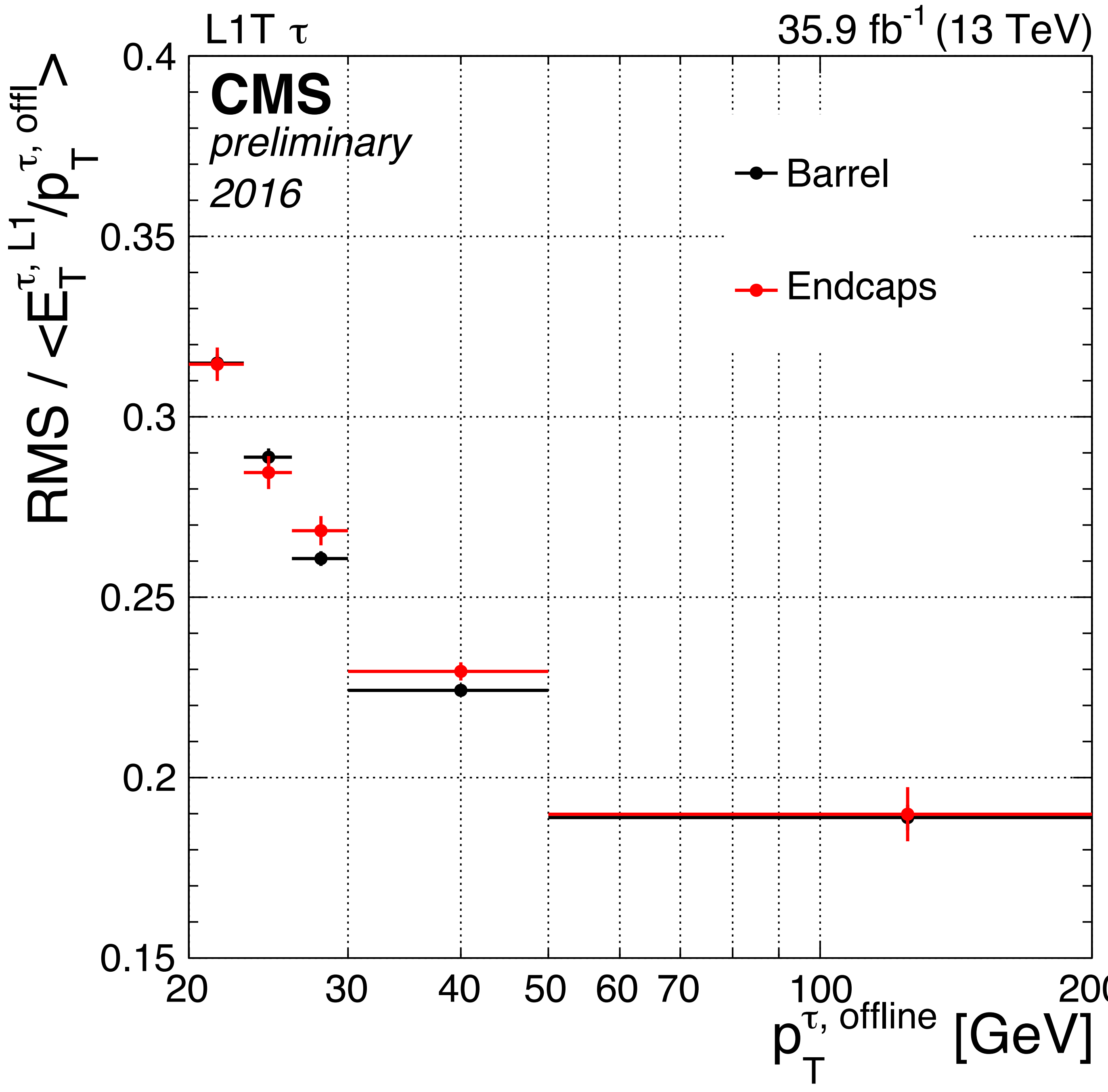


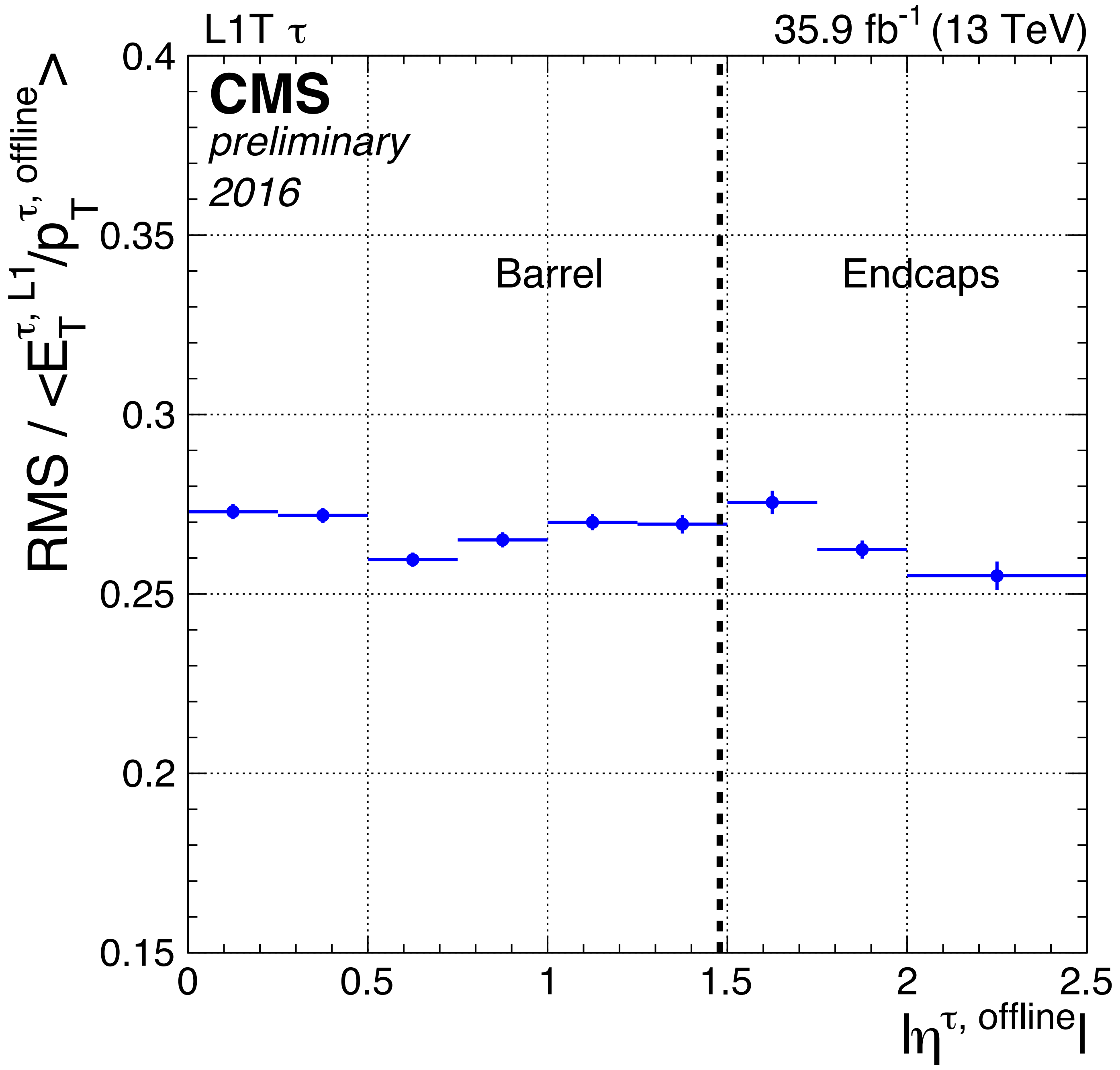
τ reconstruction performance



τ reconstruction performance

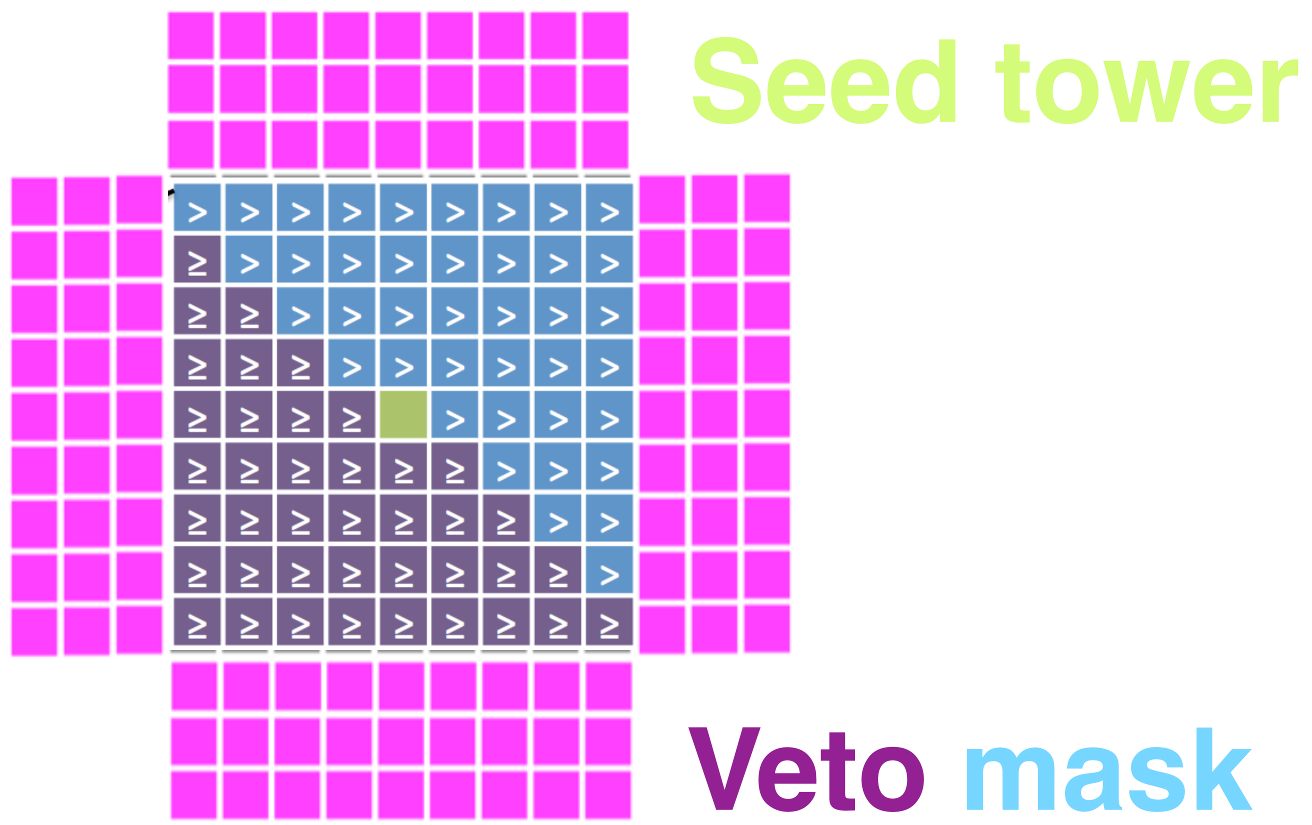


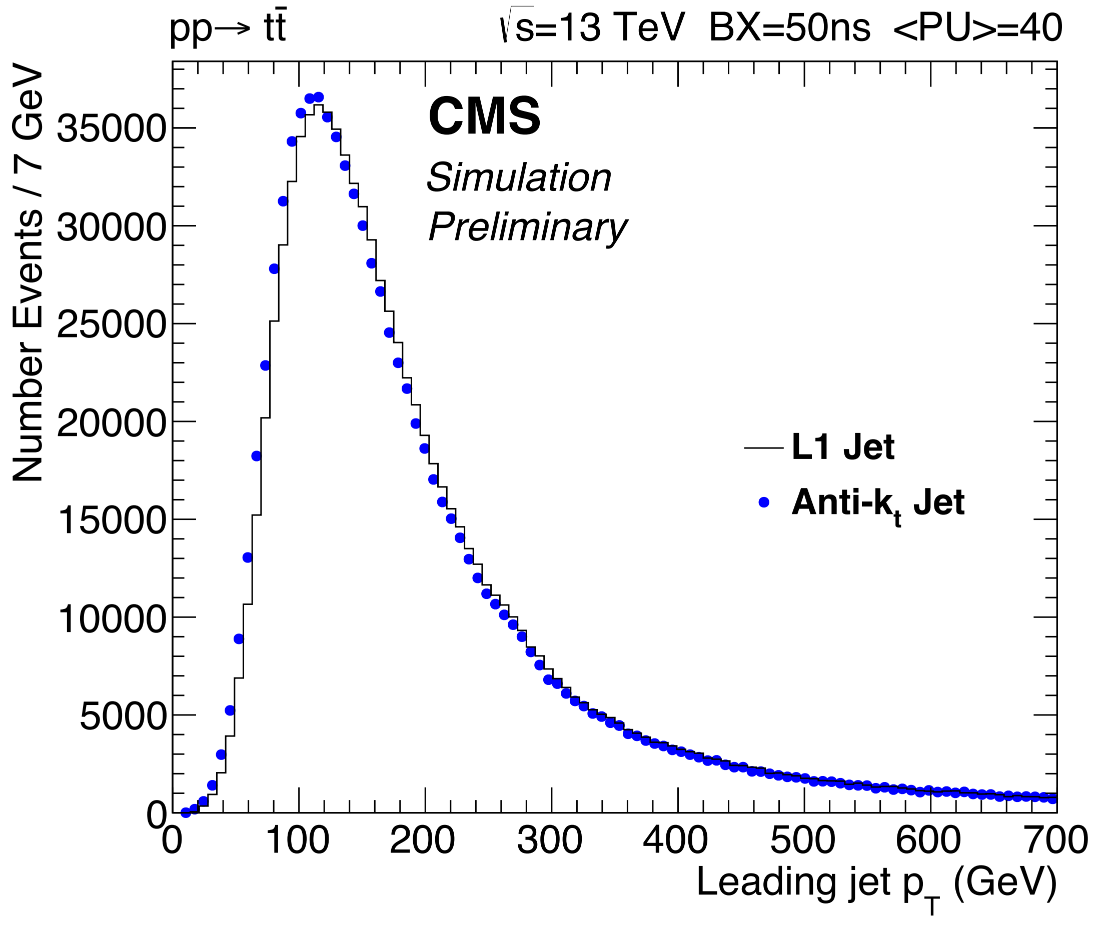


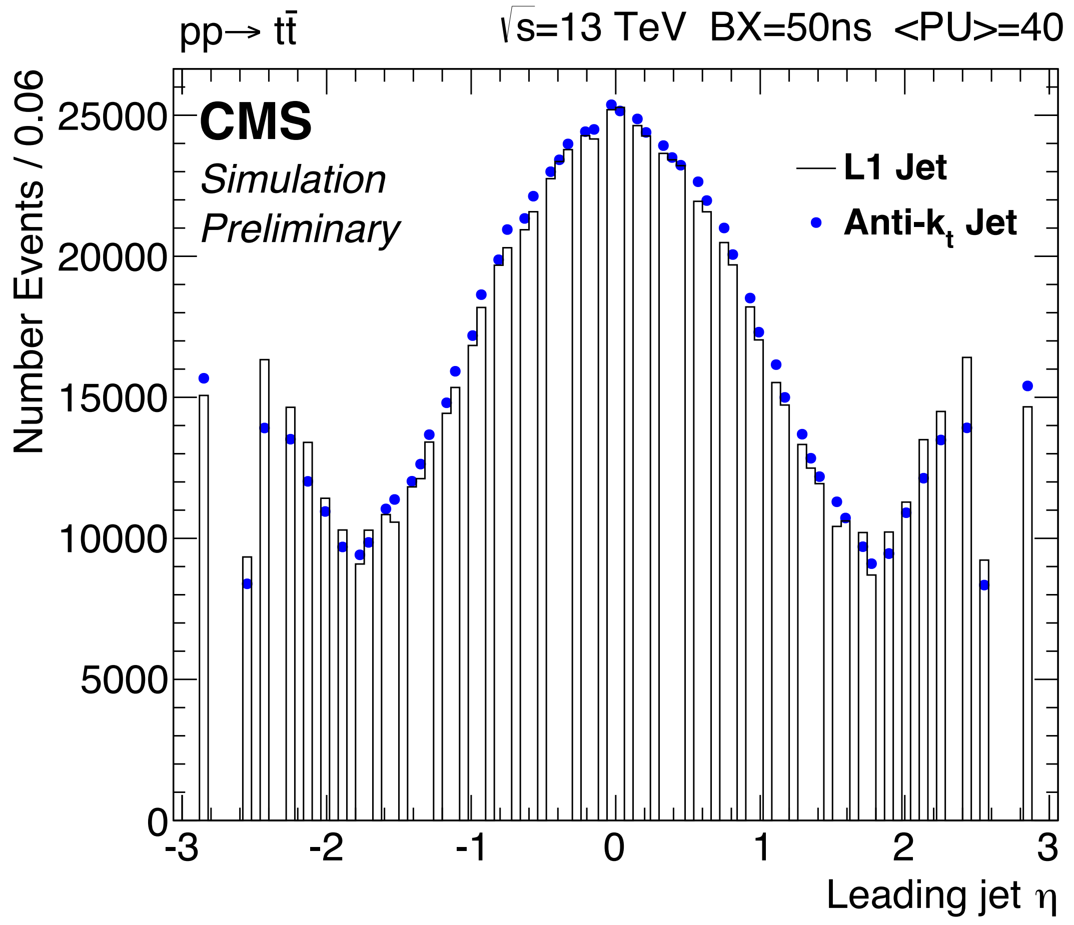


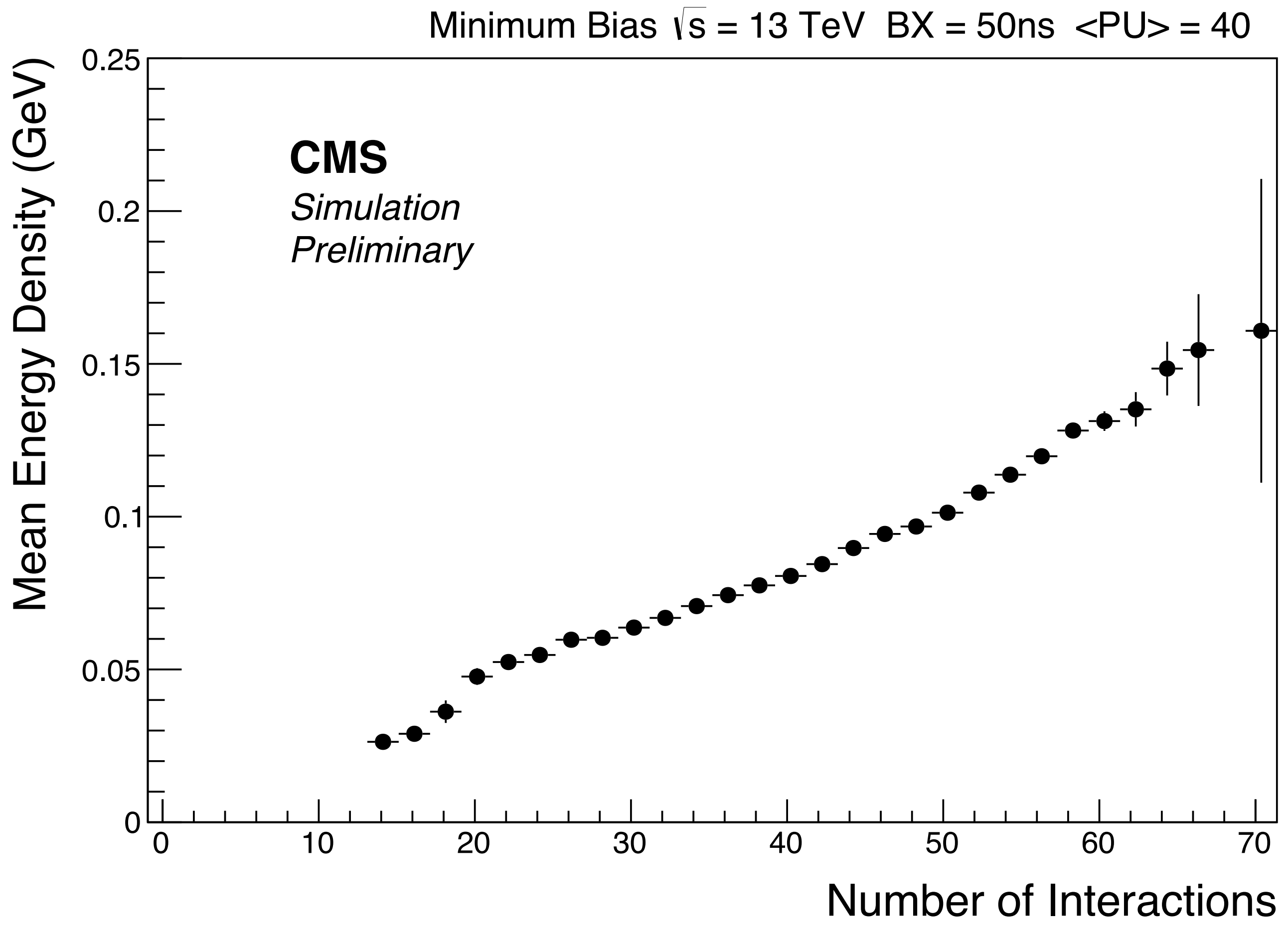
Jet algorithm performance

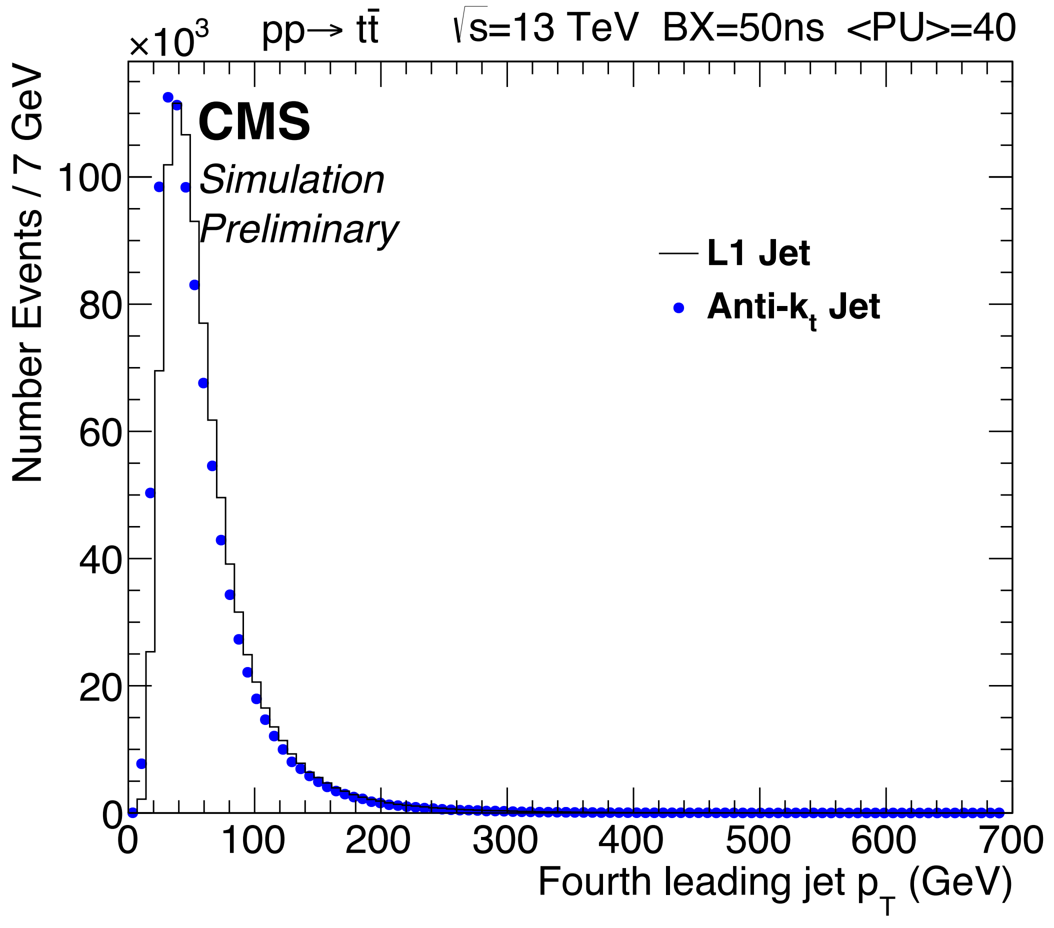
PUS areas

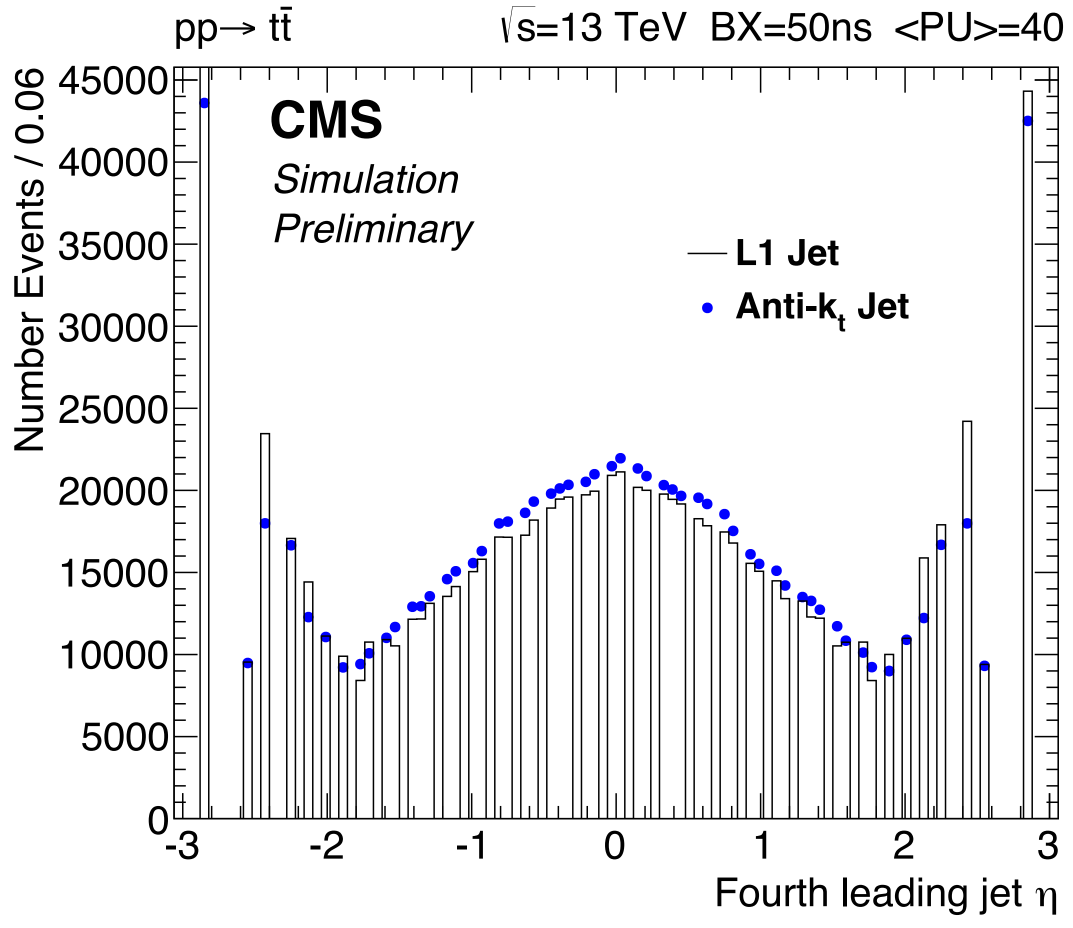




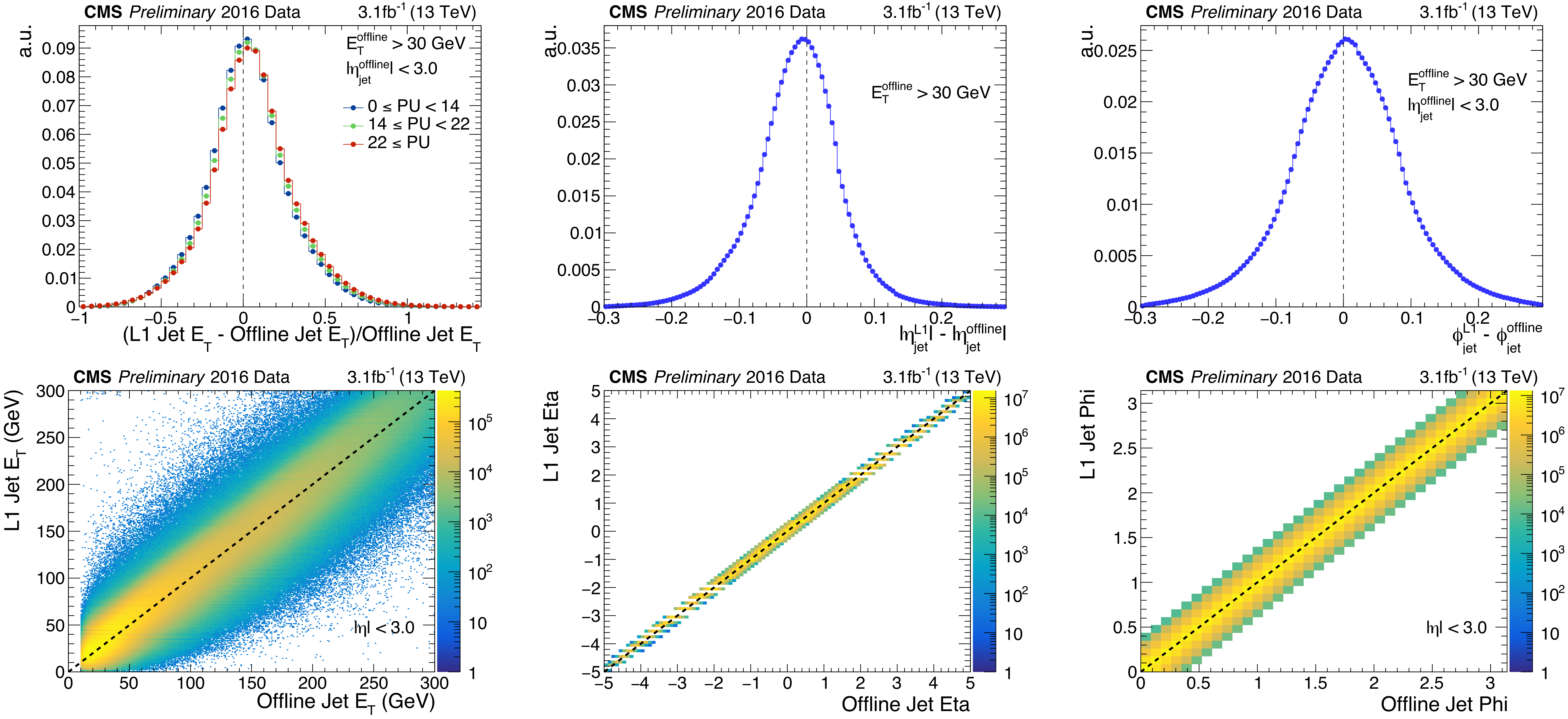






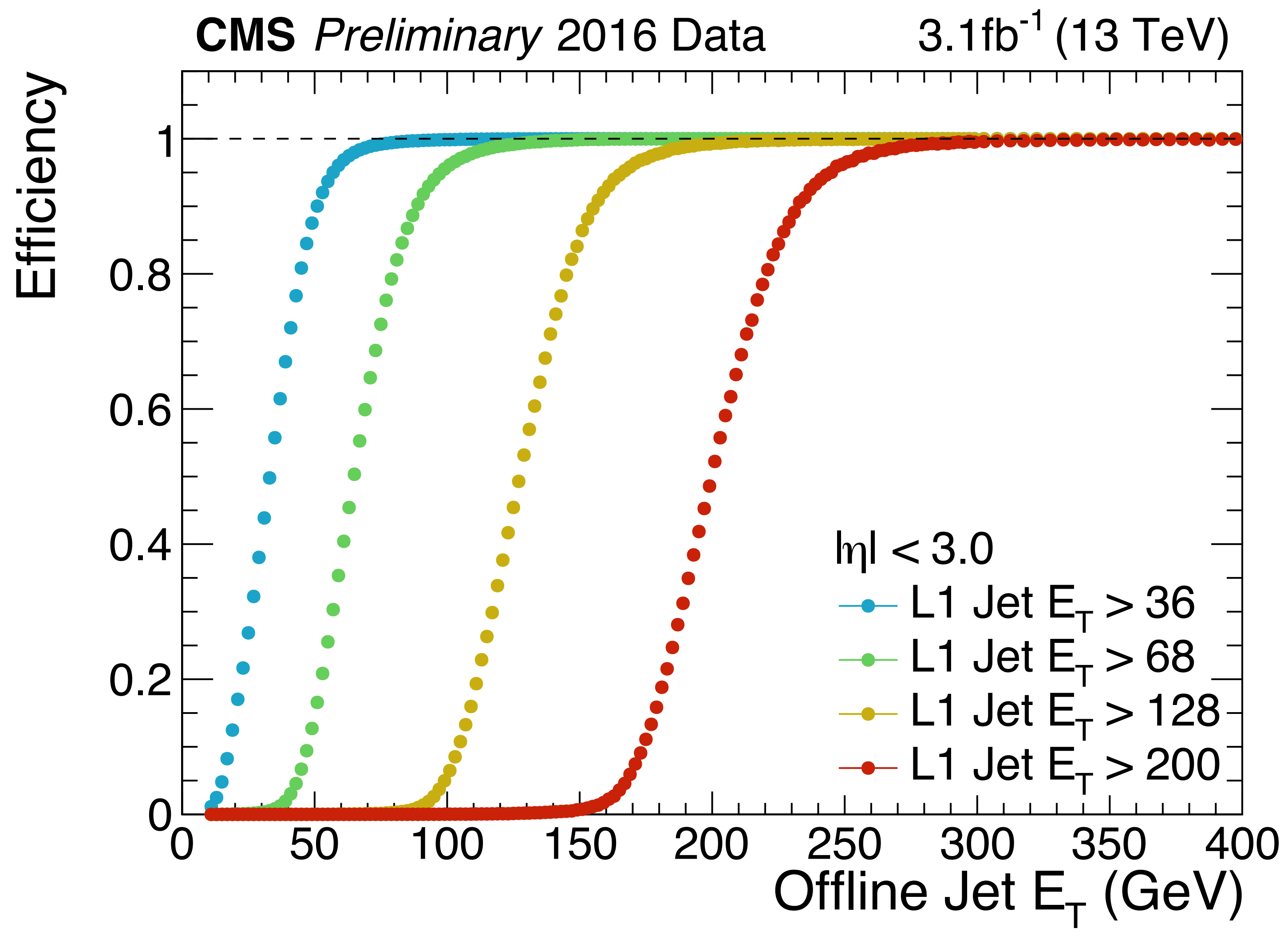


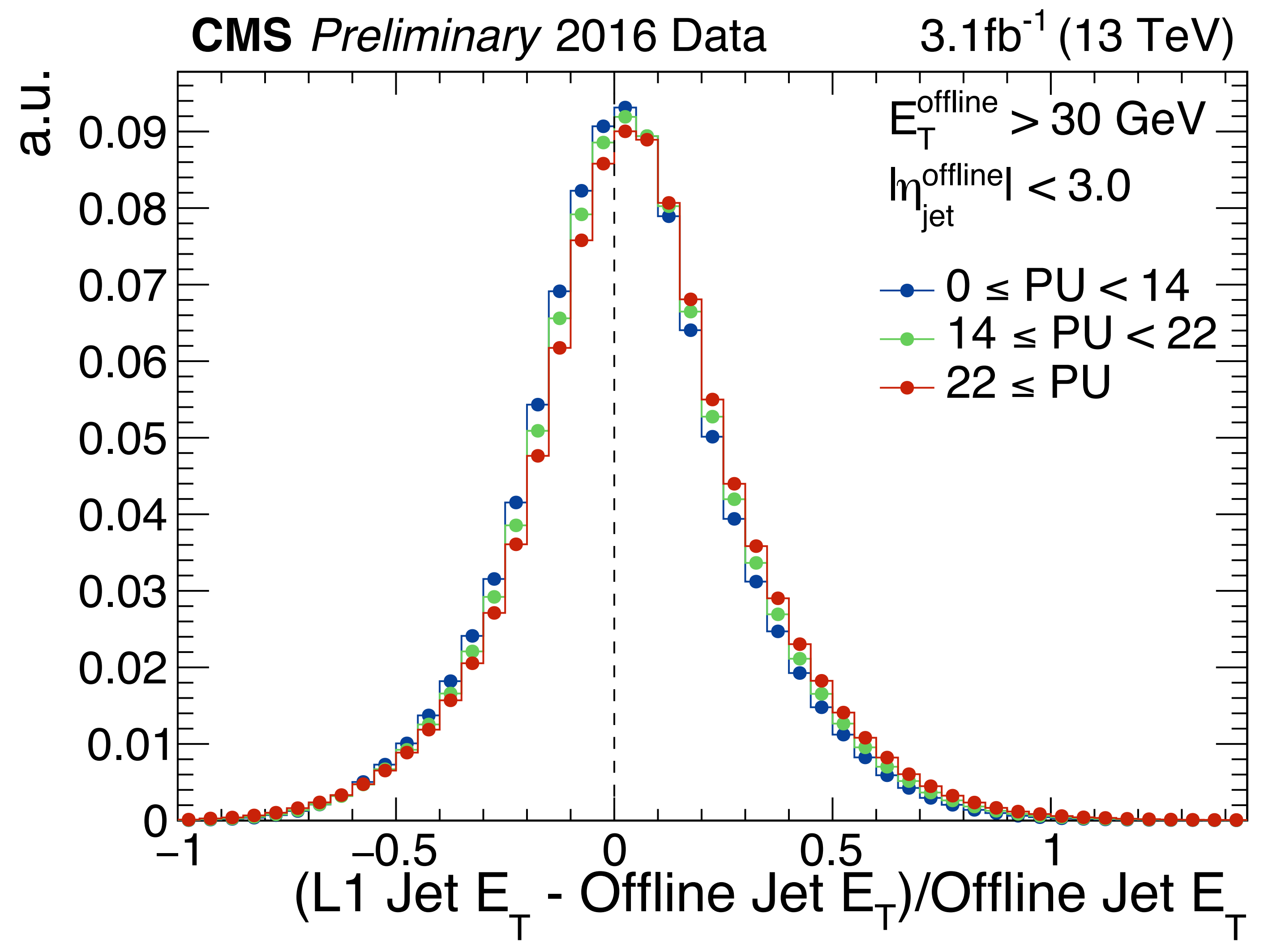
Jet reconstruction performance

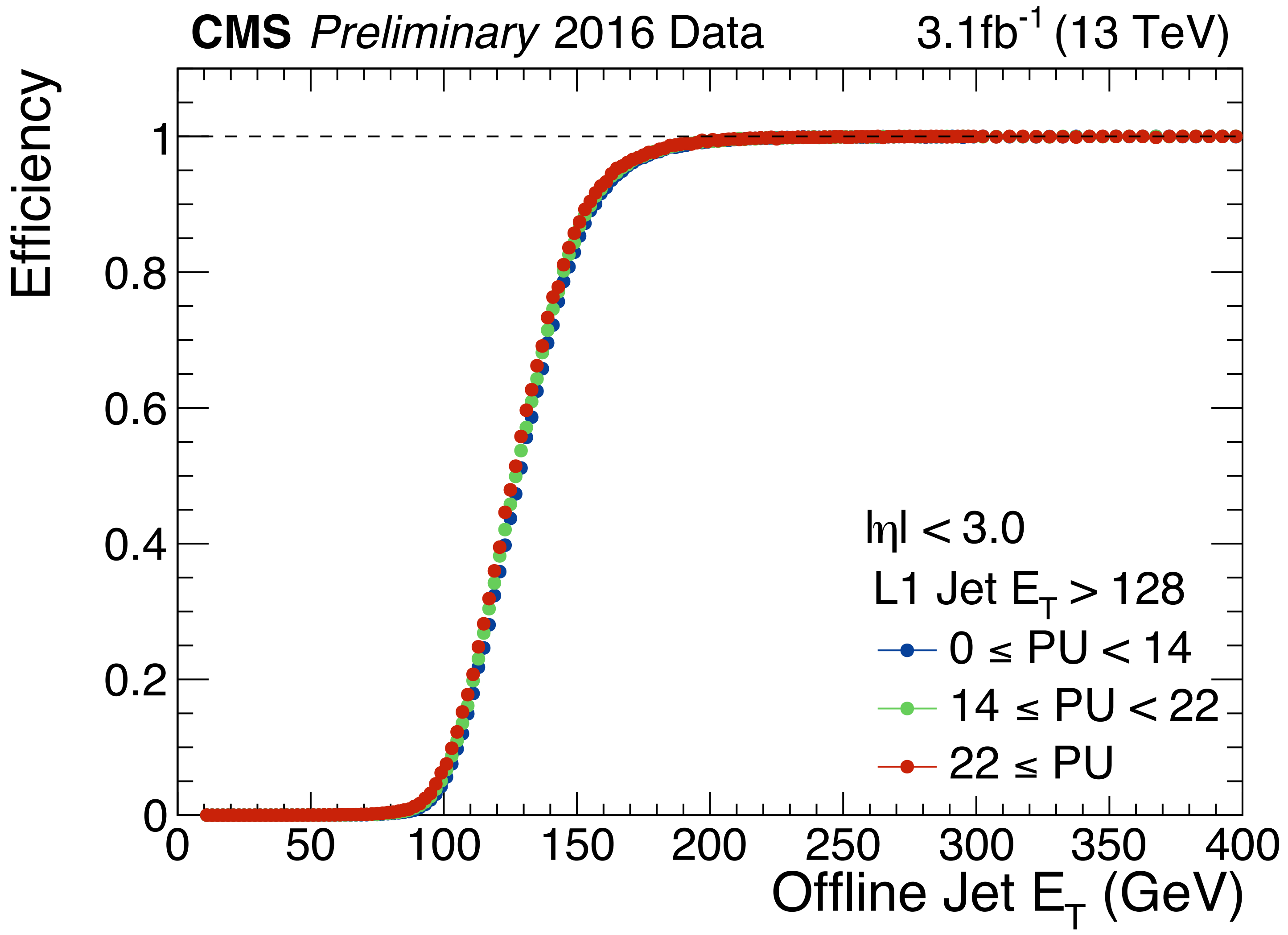


Jet trigger performance results

- Match Level-1 Trigger jets to offline (anti-k_t 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

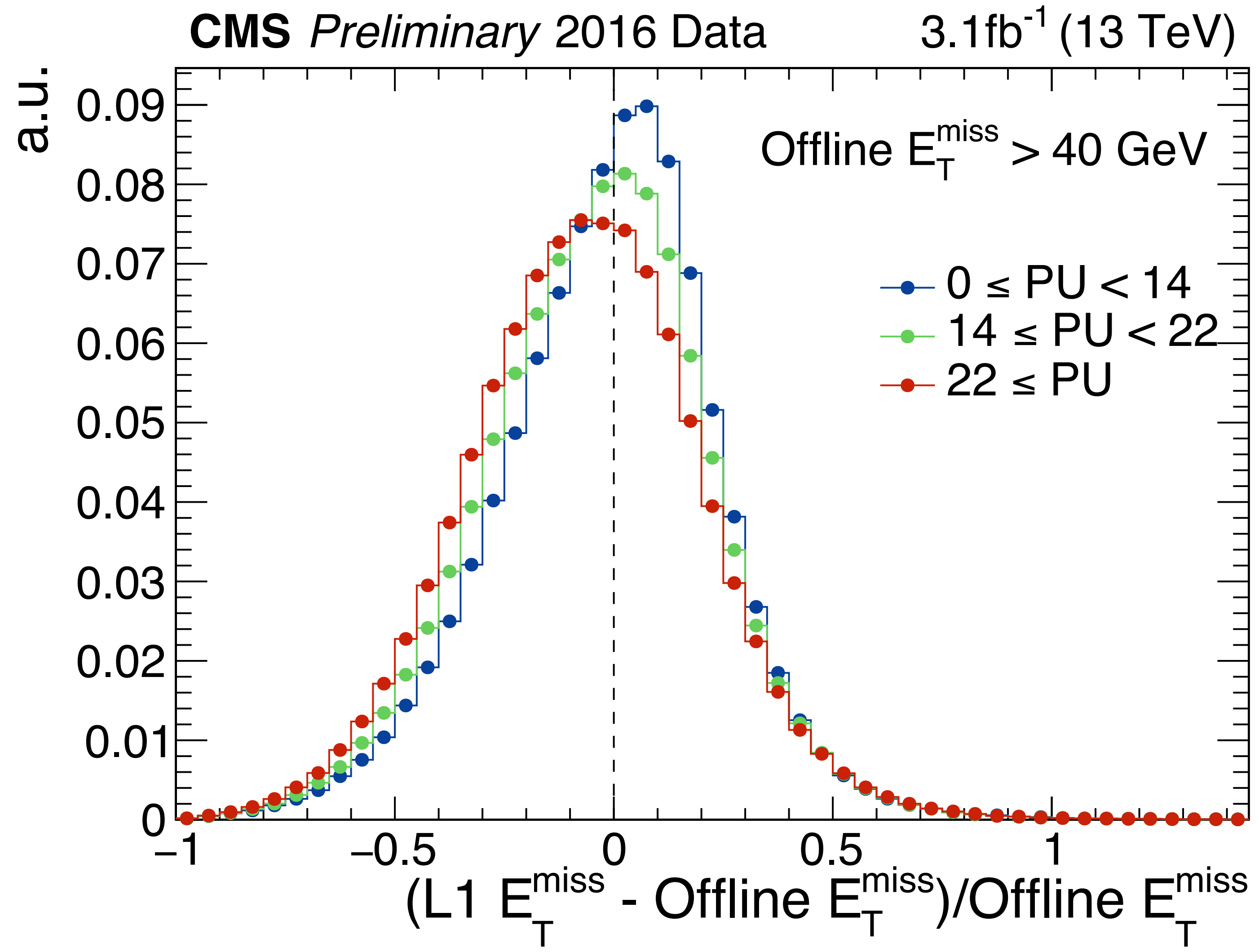


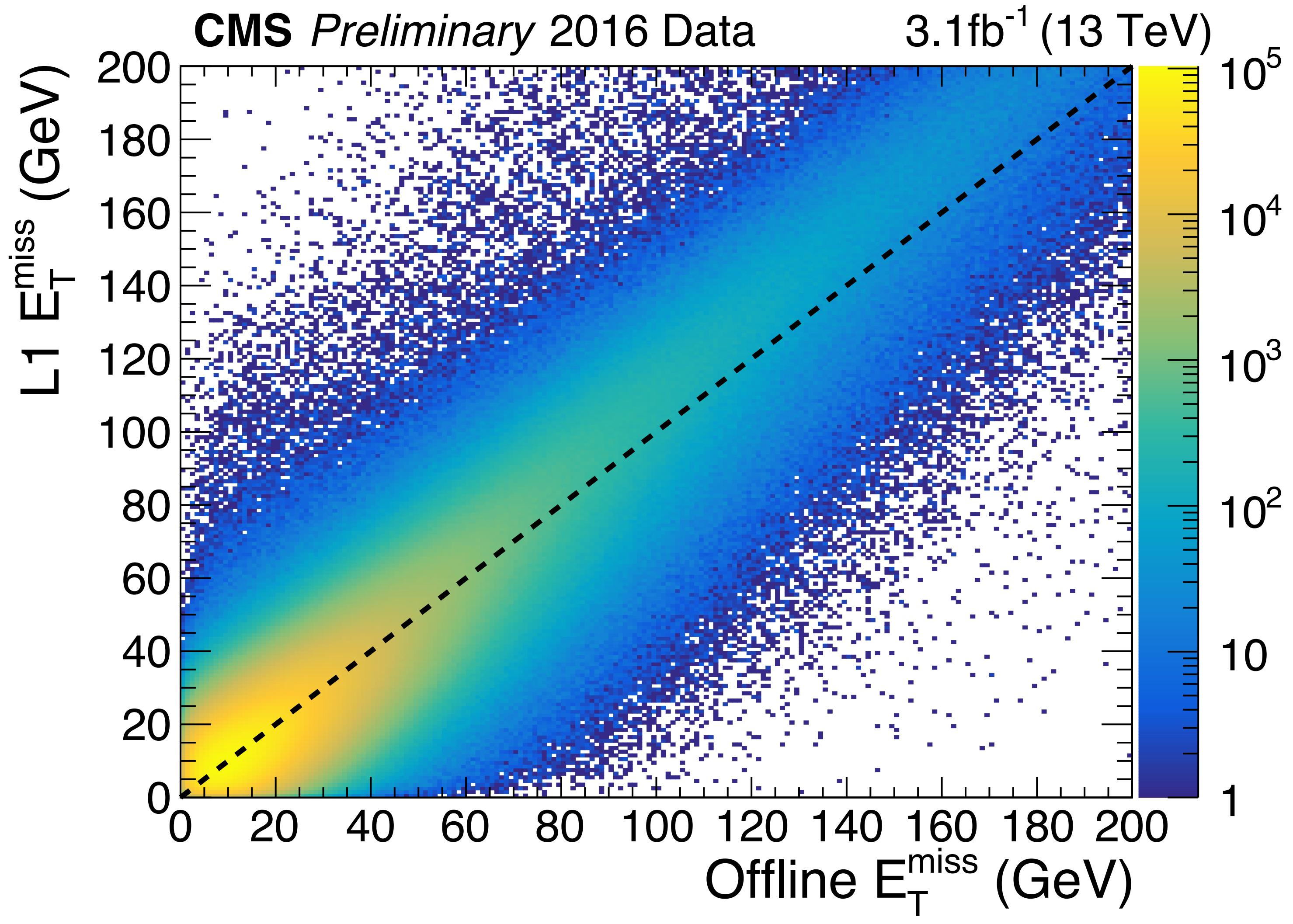


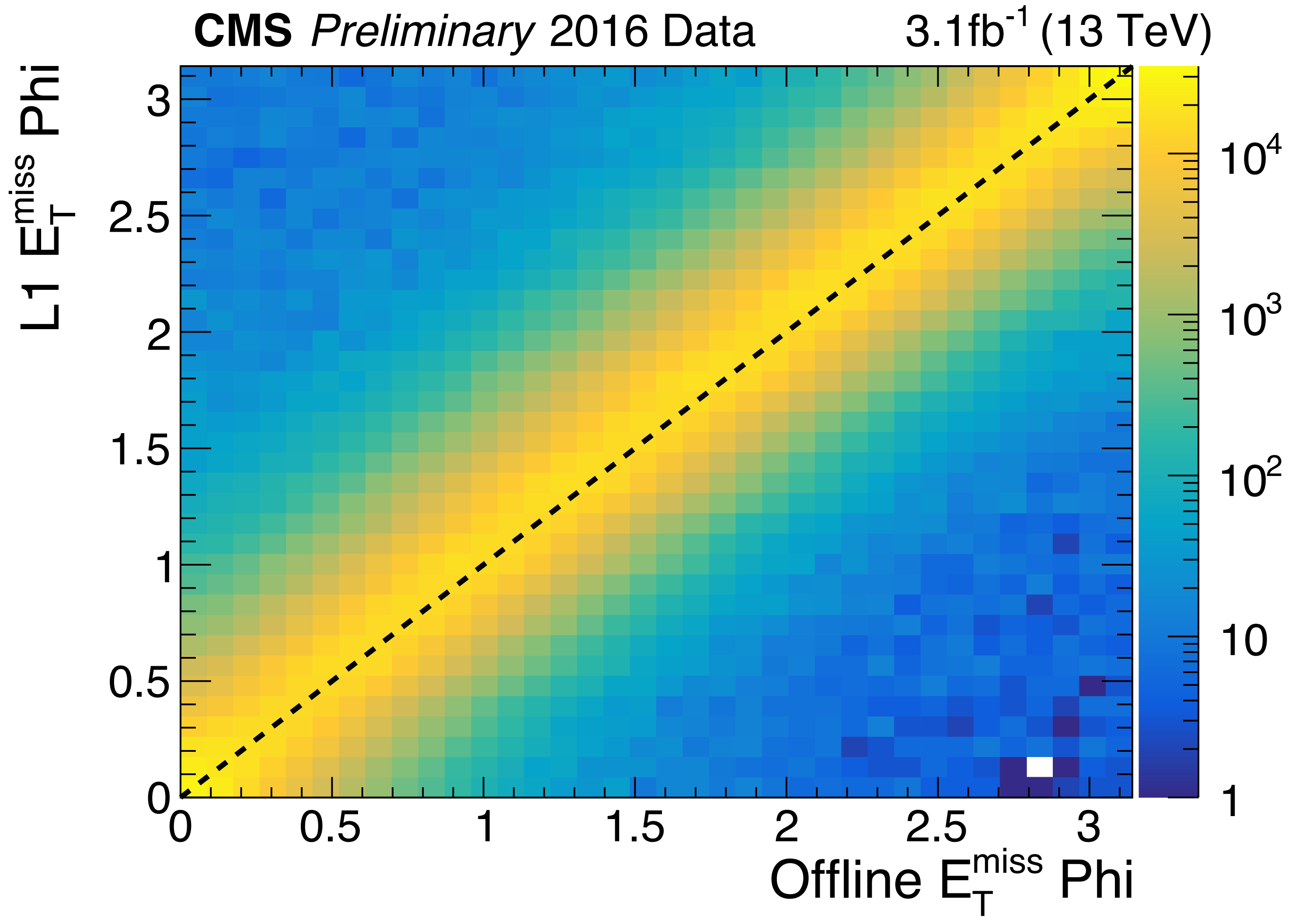


- Sharp efficiency turn-on with well calibrated E_T scale
- Insensitive to pile-up

MET reconstruction performance

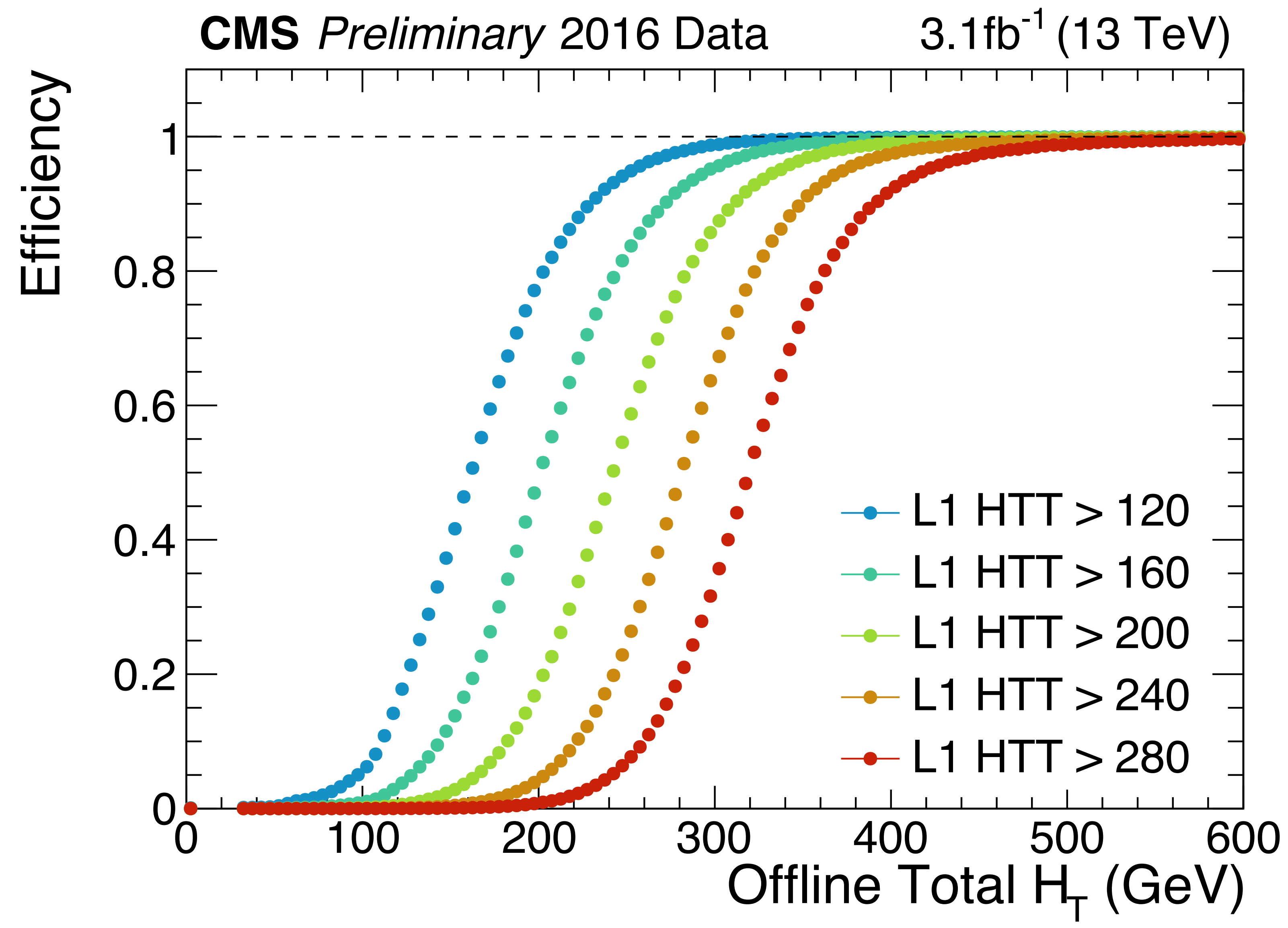


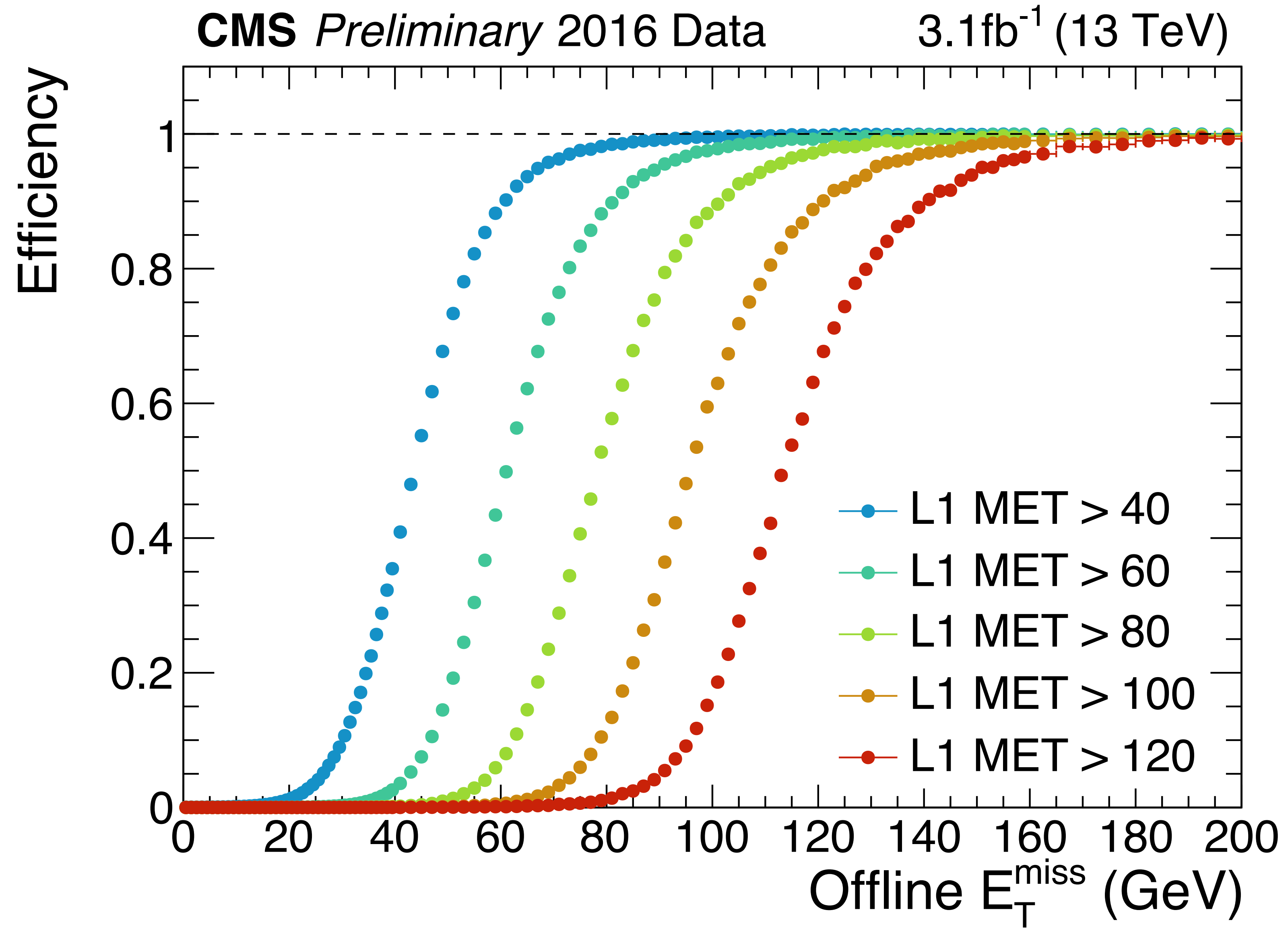




Energy sum trigger performance results

- Use jets to calculate scalar sum $H_T = \Sigma E_{Tj}$ for $E_{Tj} > 30$ GeV and $|\eta| < 3$ using single muon data
- Vector sum of trigger towers with $|\eta| < 3$ to form E_T^{miss}

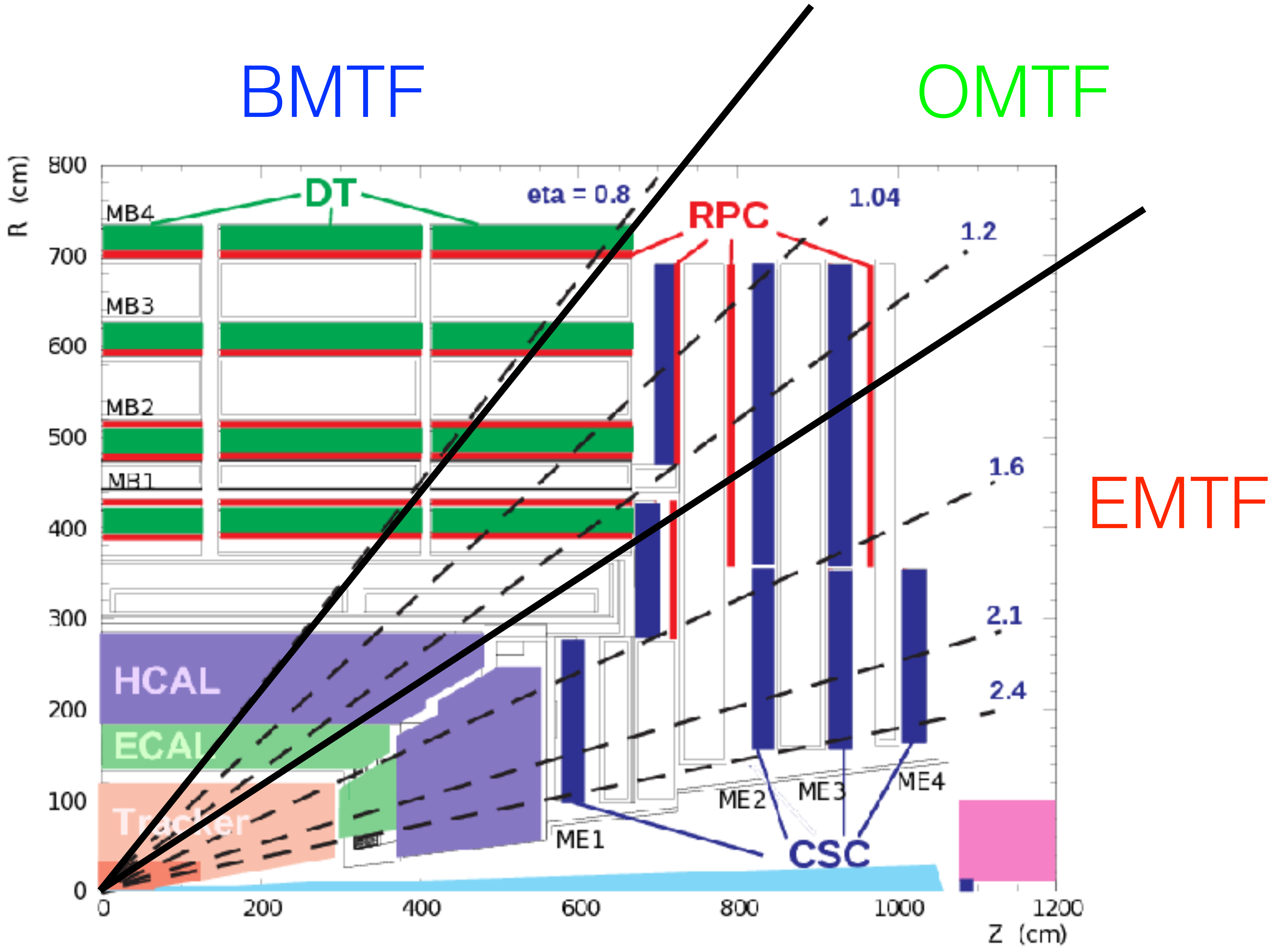




Backup: muon trigger

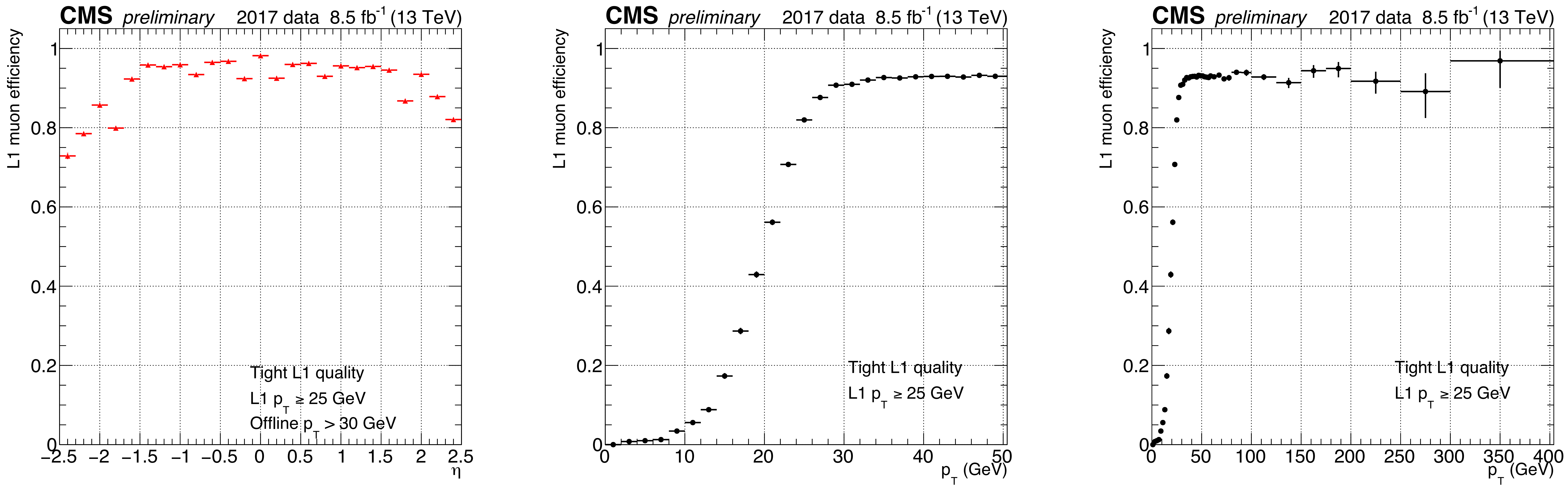
Muon track finder algorithms

- Muon track finding
  - Segment into Barrel, Overlap, and Endcap regional processors
    - Complementary detector strengths e.g. RPC timing
    - Improve robustness in the case of dead channels/ chambers and cracks
  - Pattern based track finding in endcap and overlap (with separate MVA LUT p_T assignment in endcap)
  - Road search extrapolation track finding in barrel
  - Global muon trigger takes muon tracks from regional finders, sorts by p_T and quality and cancels duplicates
  - Input from calorimeter trigger to apply isolation to muon candidates



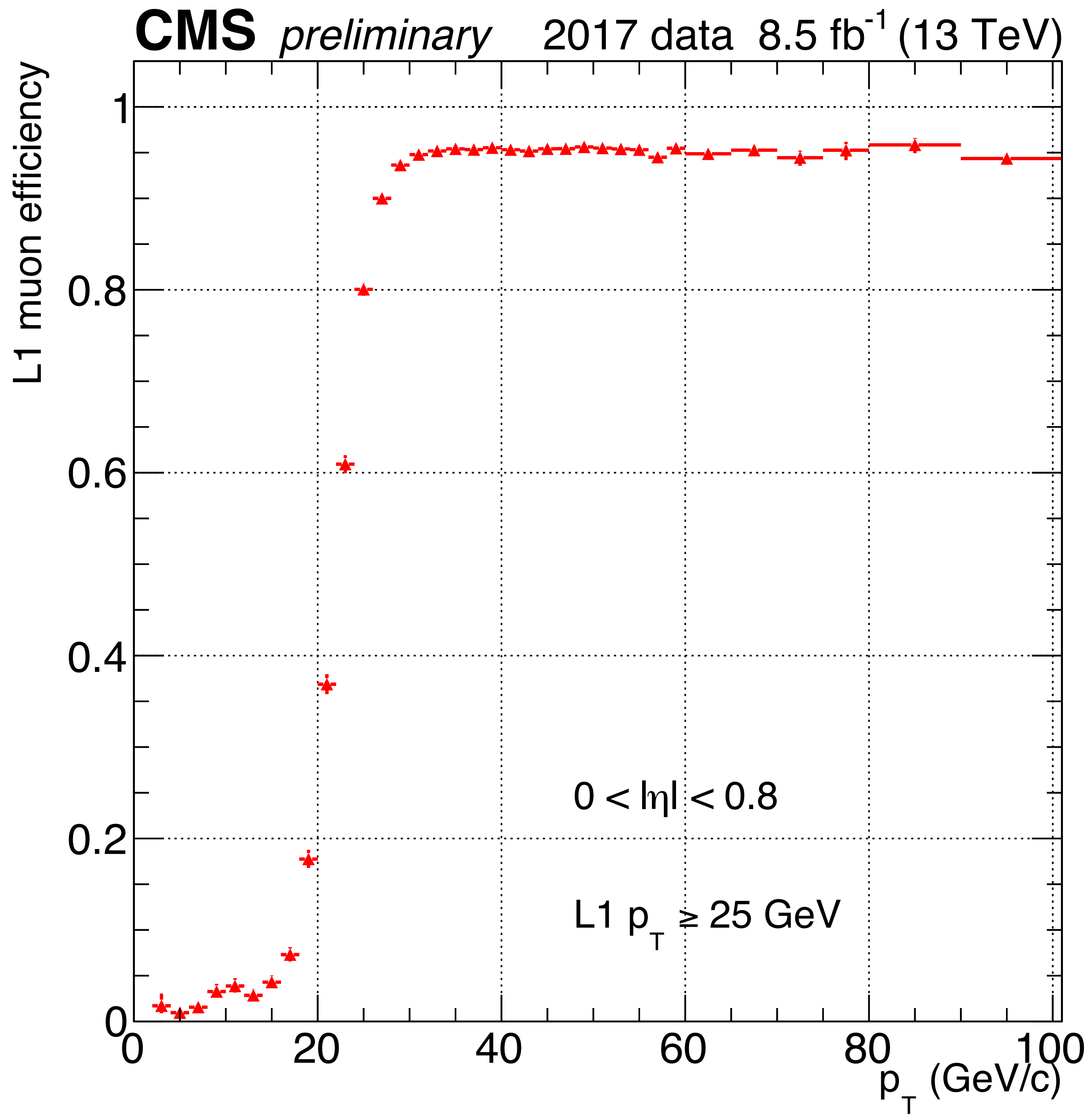
BMTF $|\eta| < 0.83$
OMTF $0.83 < |\eta| < 1.24$
EMTF $|\eta| > 1.24$

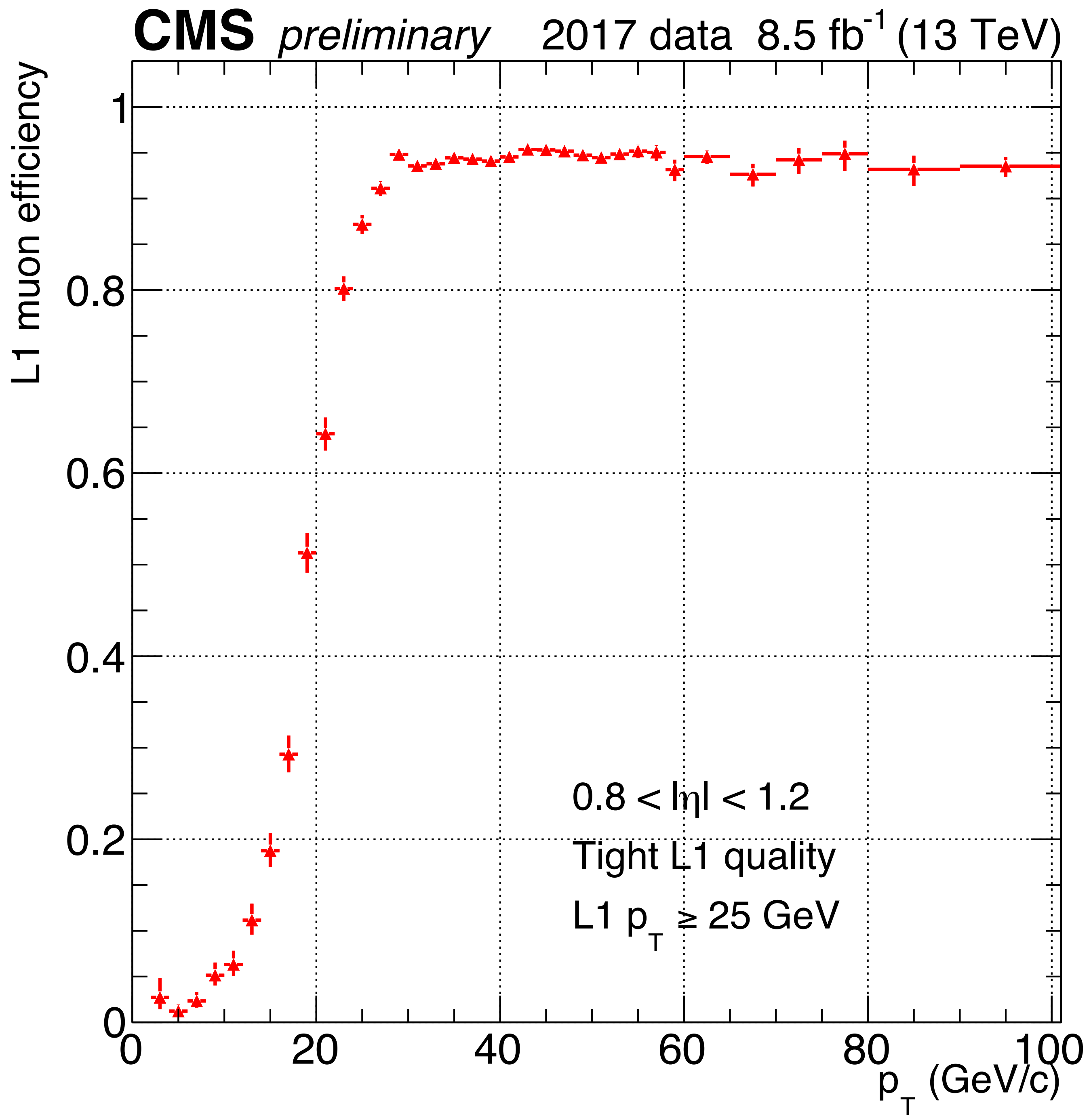
Muon trigger performance results

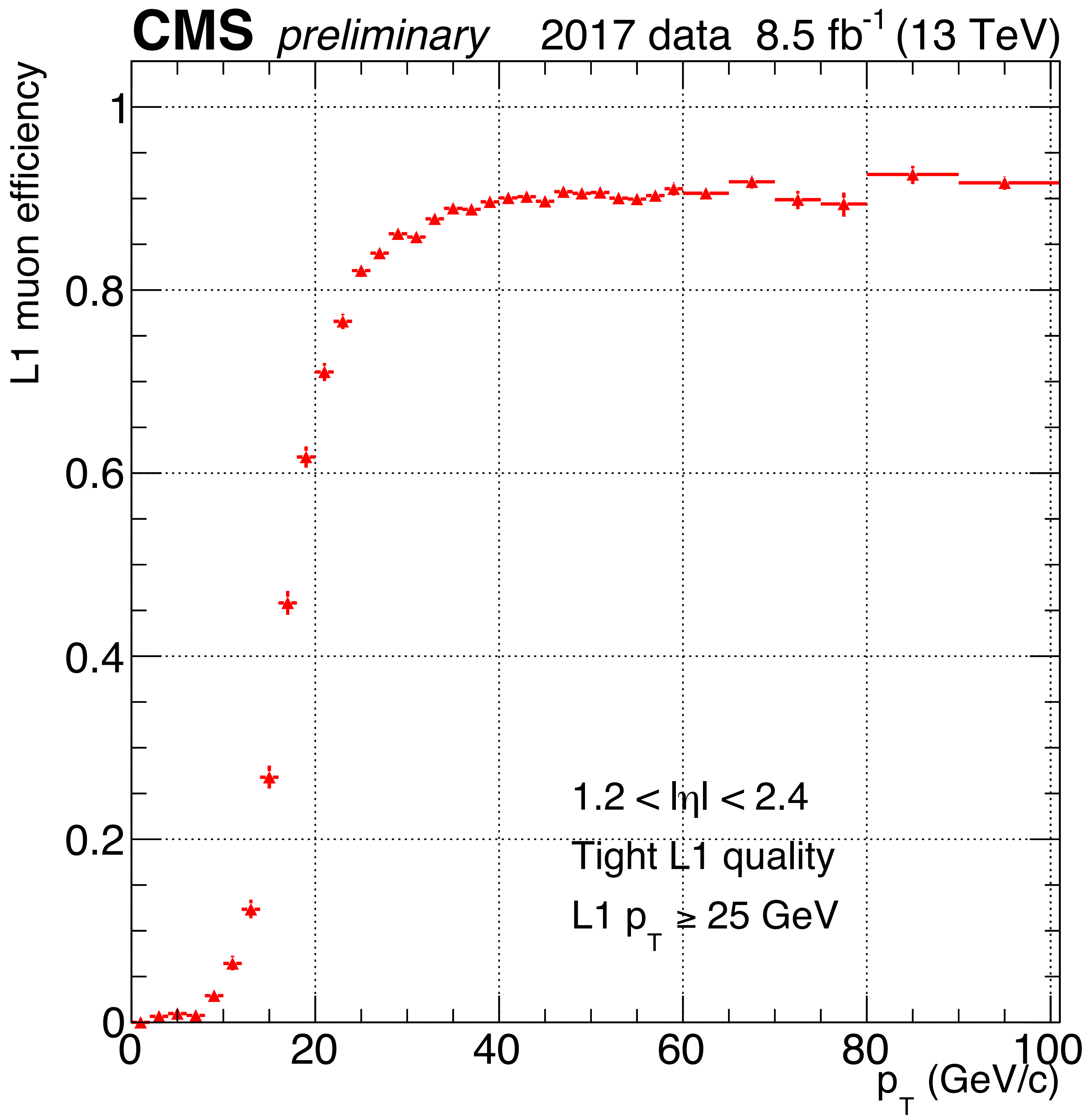


- Trigger efficiency for a single muon with $p_T > 25$ GeV vs offline muon p_T and η
- Using tag and probe method on a dataset of $Z \longrightarrow \mu\mu$ events

Muon trigger performance results







- Trigger efficiency for a single muon with p_T > 125 GeV vs offline muon p_T
- Using tag and probe method on a dataset of $Z \longrightarrow \mu\mu$ events