The CMS Level-1 Trigger for LHC Run II

Alex Tapper for the CMS collaboration

Imperial College London

ICHEP2016CHICAGO

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

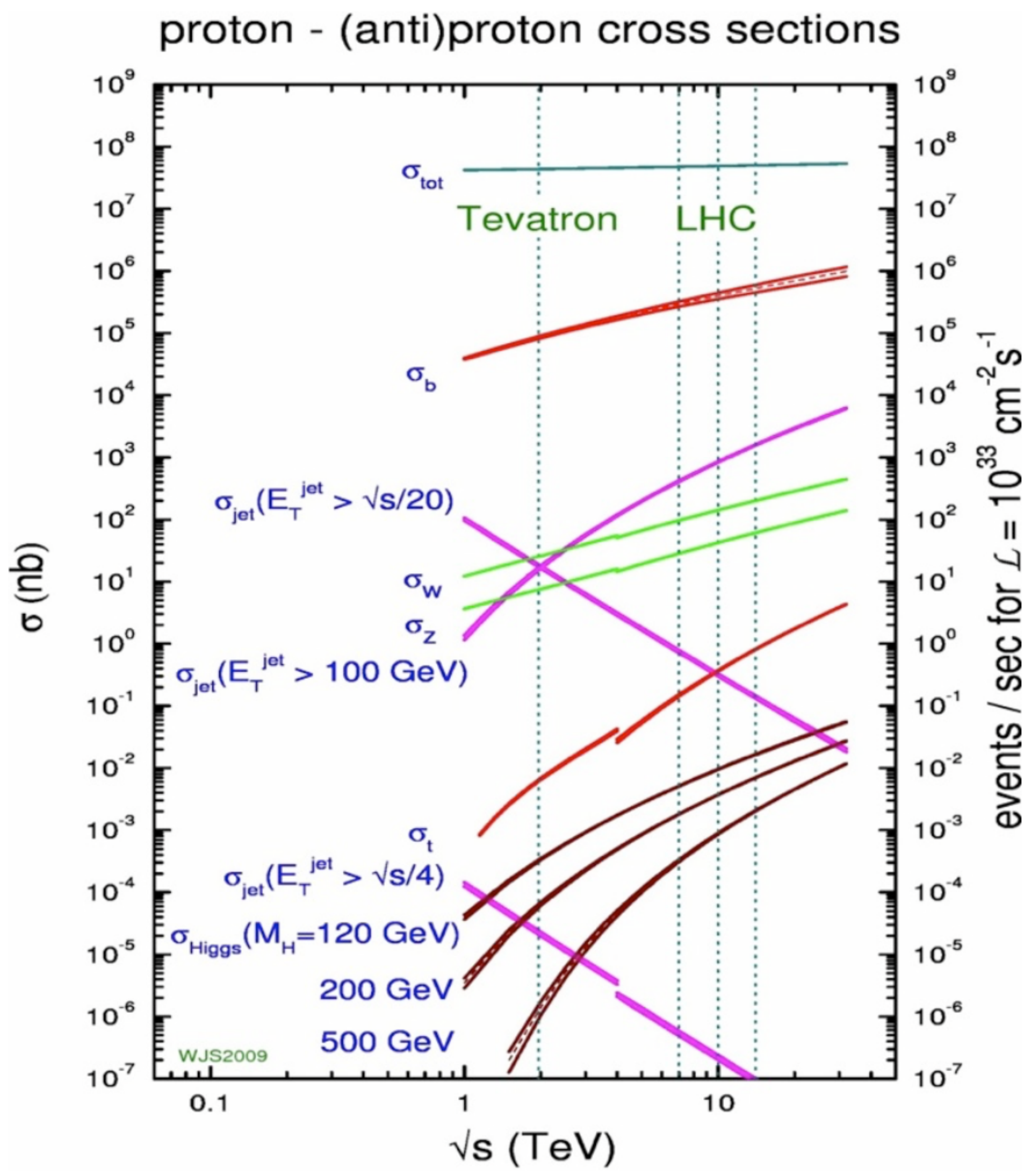
AUGUST 3 - 10, 2016

CHICAGO

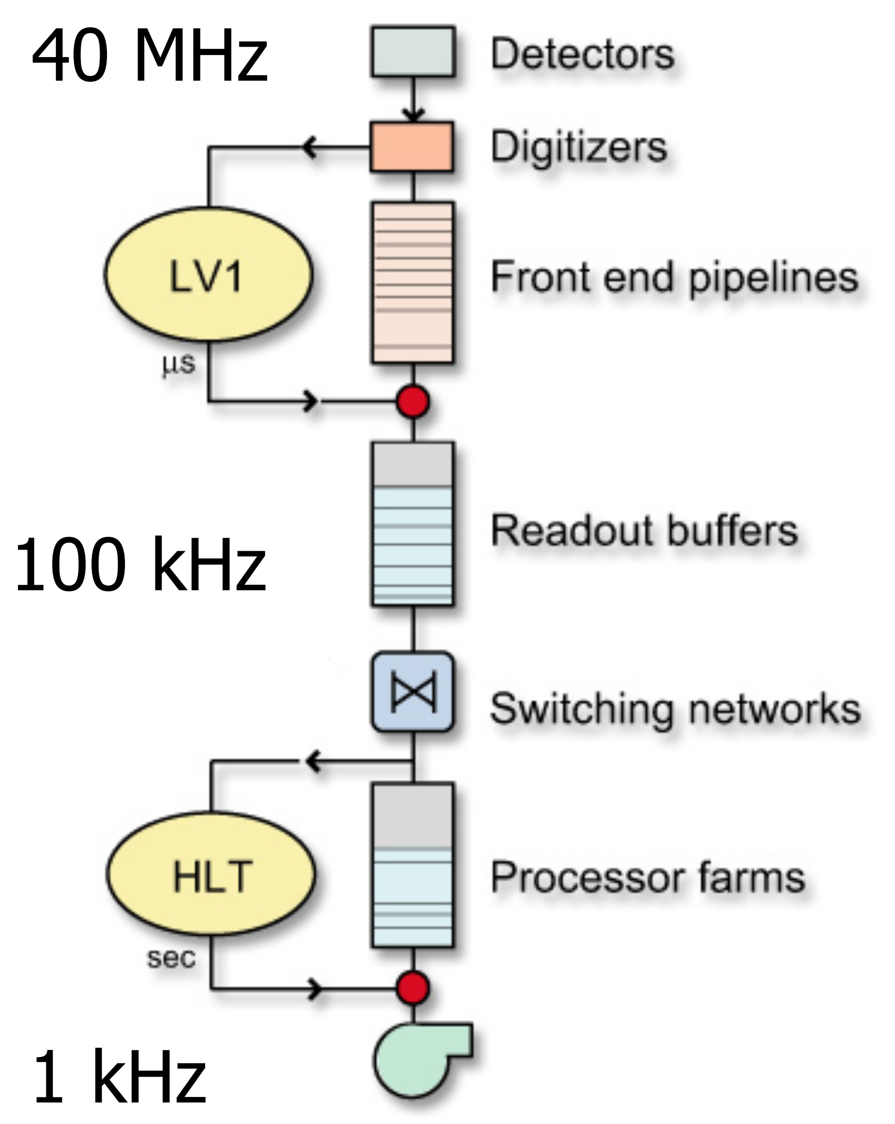
Overview

- Introduction and challenges
- System overview and commissioning
- Algorithms and performance results
  - Muon track finders
  - e/γ finder
  - τ finder
  - Jet finder and energy sums
- Summary and outlook

Introduction and challenges



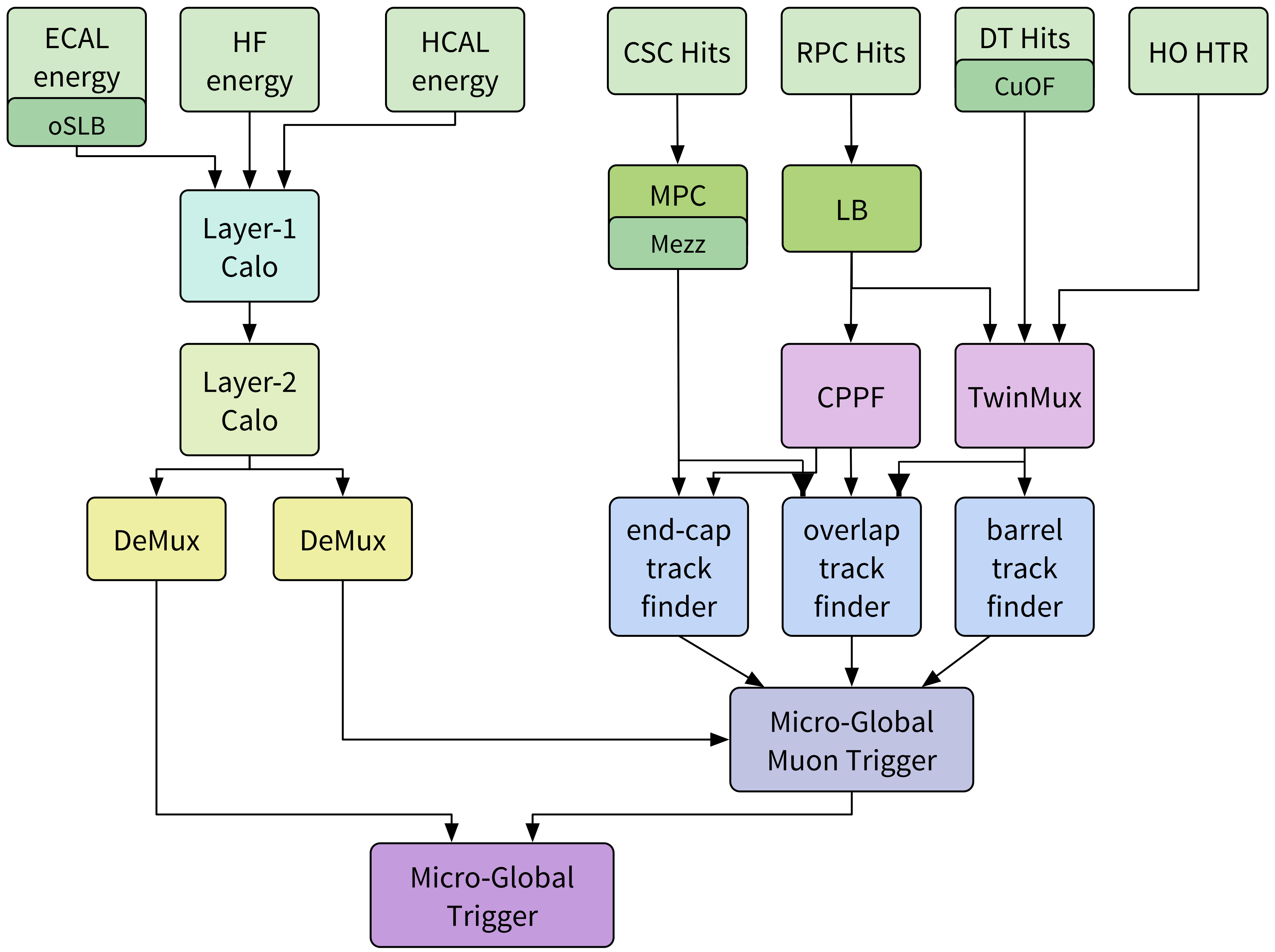
- *Interesting* processes many orders of magnitude low cross sections than total pp cross section
- Cannot store all events (TB/s)
- Select interesting events without dead time
- Implemented as a two level system in CMS →



- 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 concept

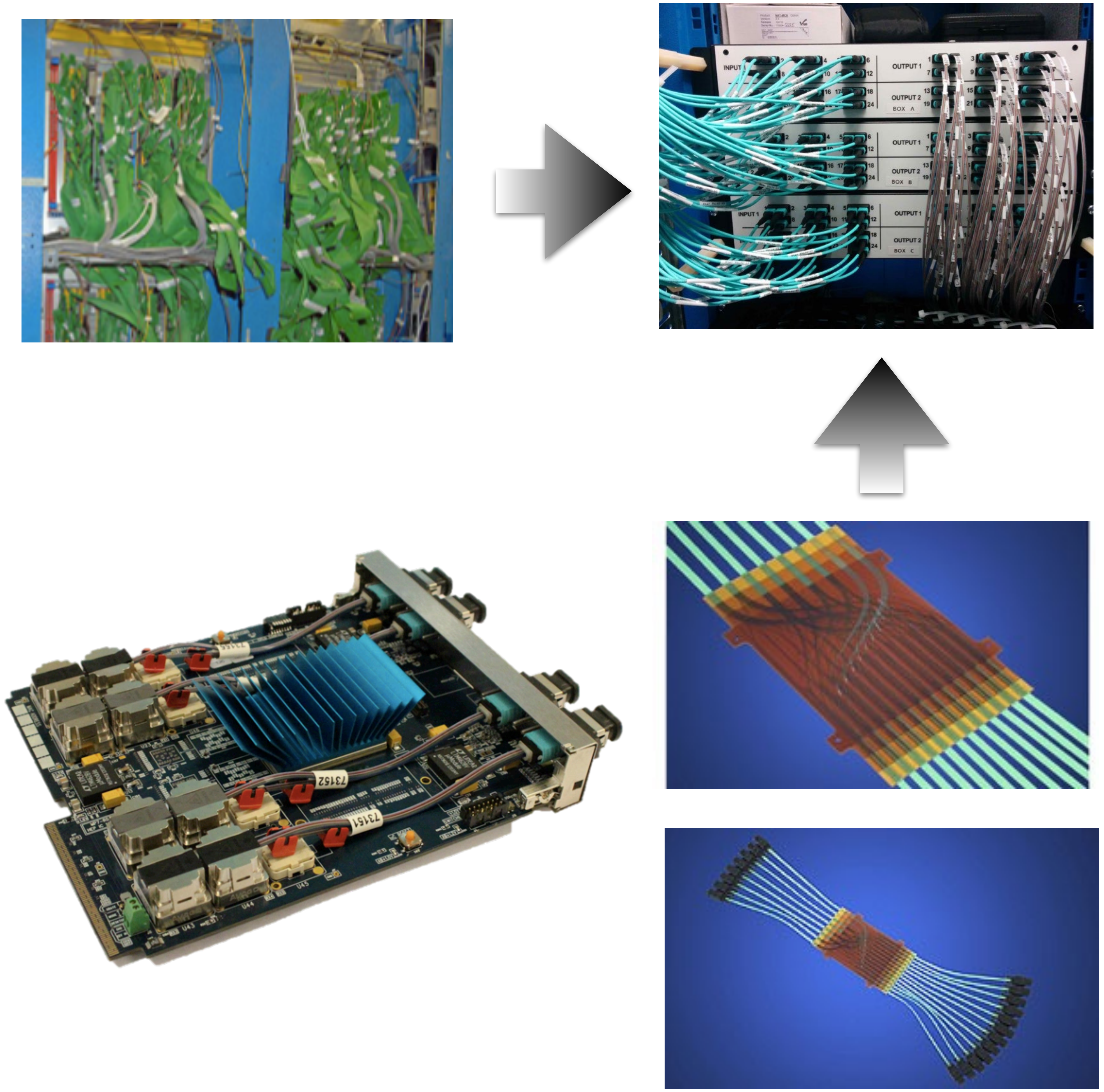
- Key conceptual changes
  - Muon system — use redundancy of three muon detector systems early to make a high resolution muon trigger
  - Calorimeter system — remove boundaries by streaming data from single event into one FPGA
  - Global trigger — expandable to many more possible conditions and more 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

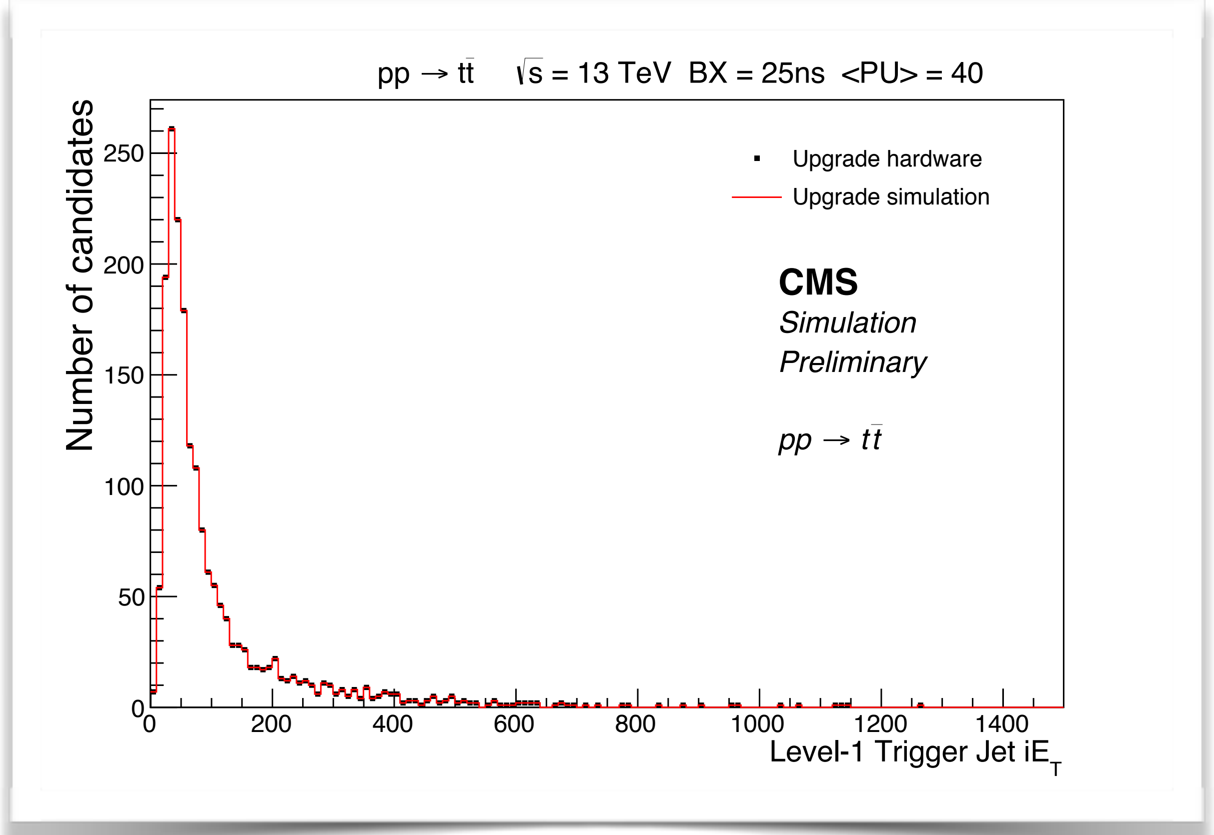
- Key technology changes
  - VME → µTCA (modern telecoms standard)
  - System wide use of latest FPGAs → Xilinx Virtex® 7
  - Parallel copper links → serial optical links
  - Link speeds 1 Gb/s → 10 Gb/s
  - Large optical patch panels → custom made commercial solution (Molex Flexplane™)
  - Online software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

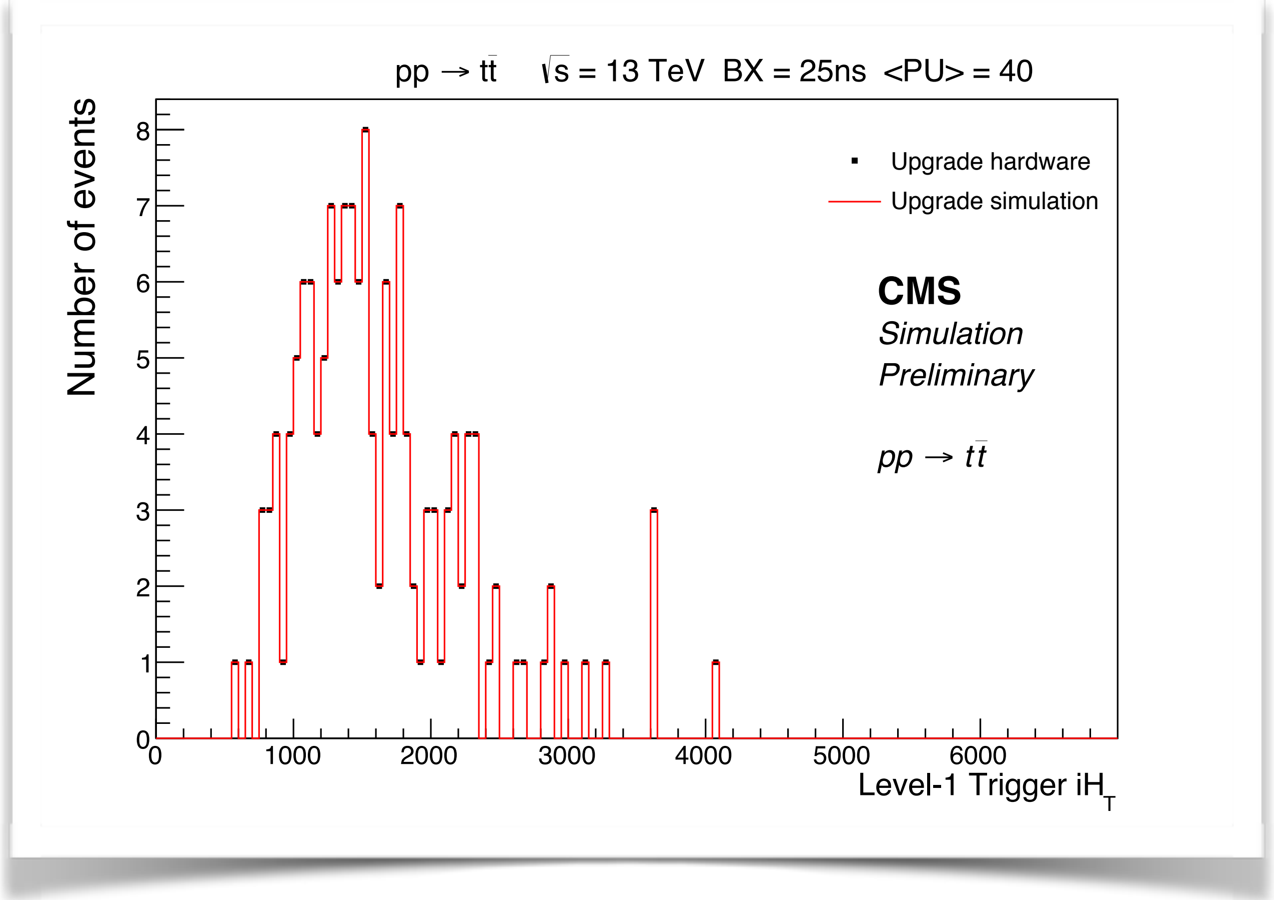


- Aim for flexible, maintainable system
  - Adapt to evolving CMS physics programme

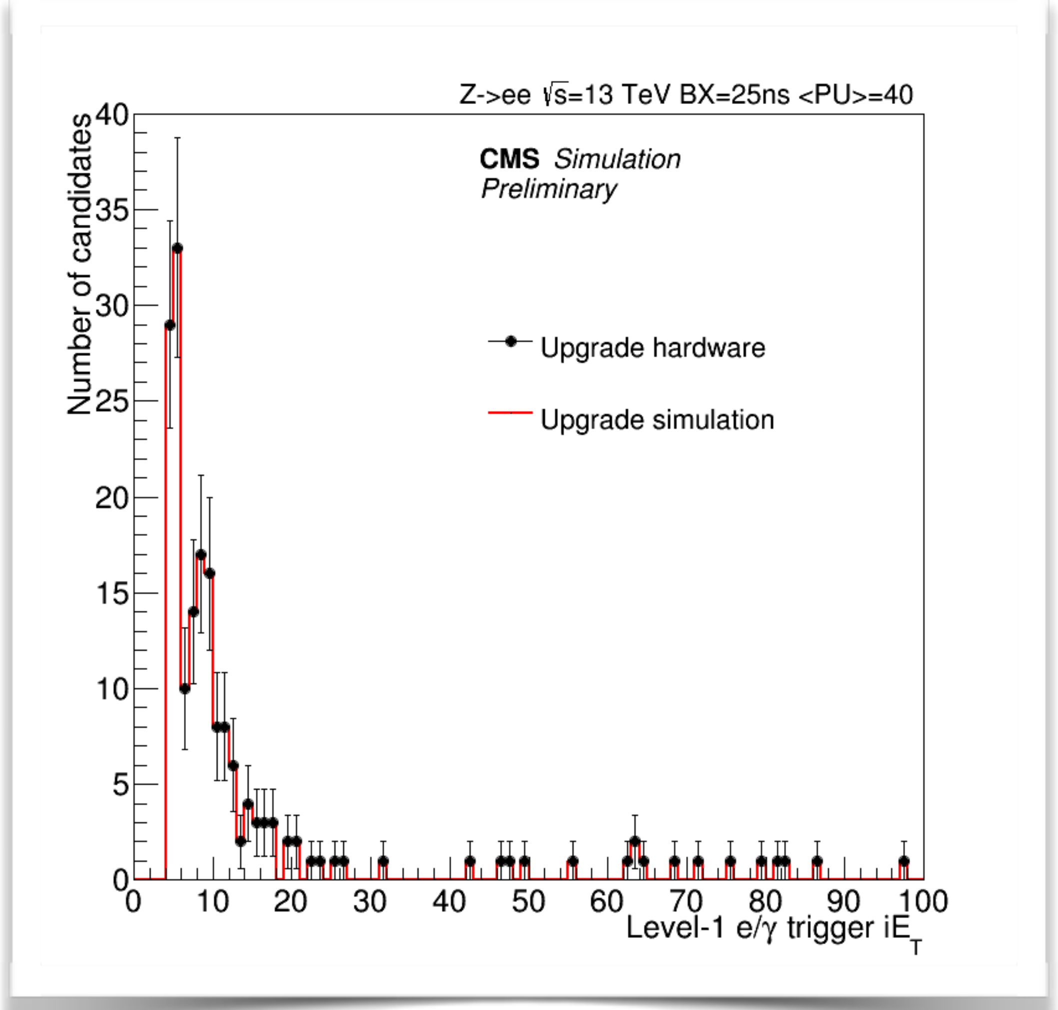
Commissioning overview

- Commissioned in parallel
  - Calorimeter inputs duplicated (in FPGAs and optically)
  - Muon inputs duplicated (endcap) and slice commissioned (barrel)
  - Run parasitically with CMS data taking (not triggering!)
- Steps to completion
  - Interconnection tests 2012-2014 ✓
  - MC pattern test campaign in 2015 ✓
  - Data taken in CMS global running in 2015 ✓
    - Over 7 billion events in pp
  - Cosmic runs and beam splashes in 2016 ✓
  - First collisions in 2016… ✓
  - Started physics run in 2016 ✓



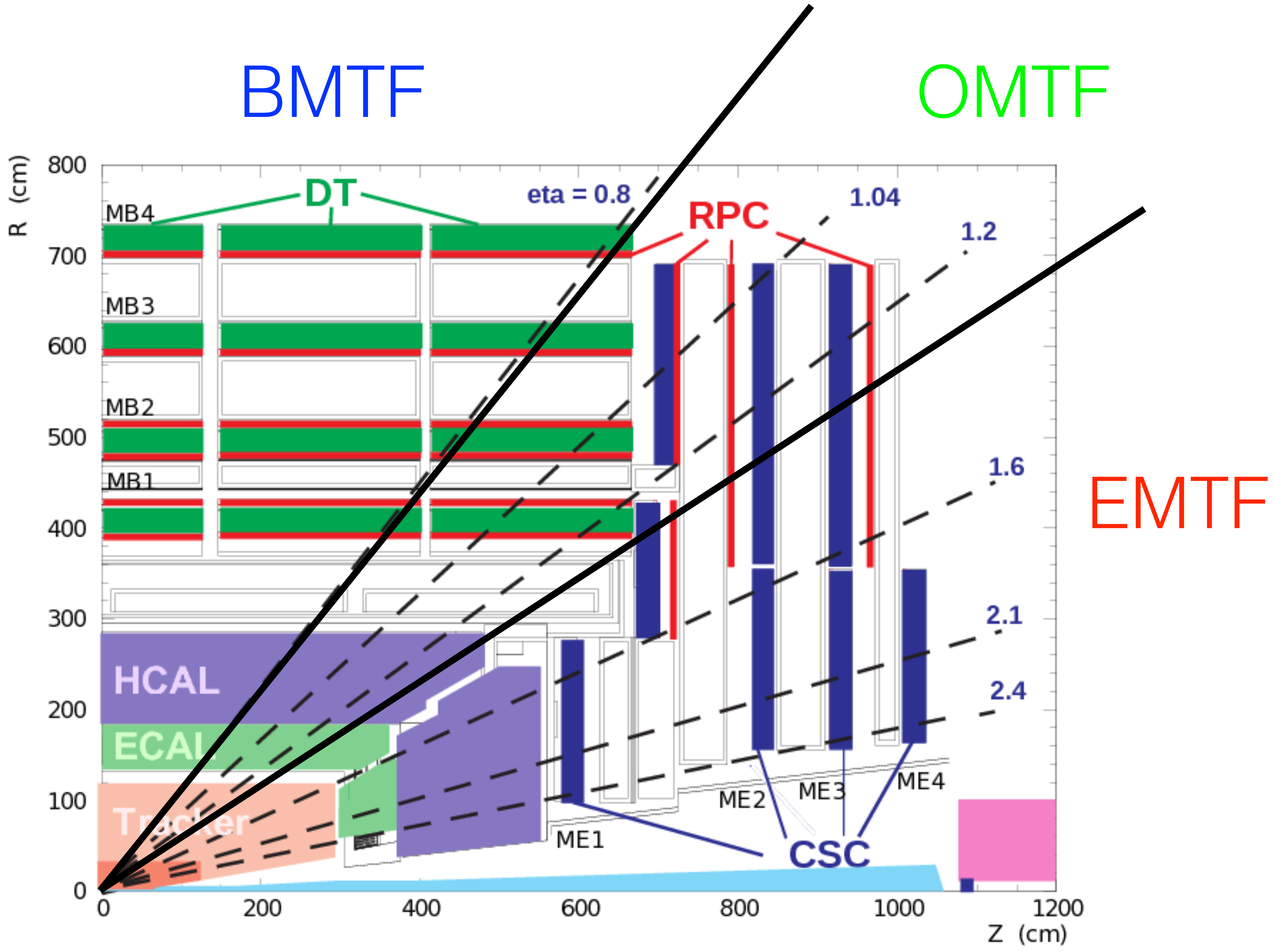


Examples of pattern tests with simulated events



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

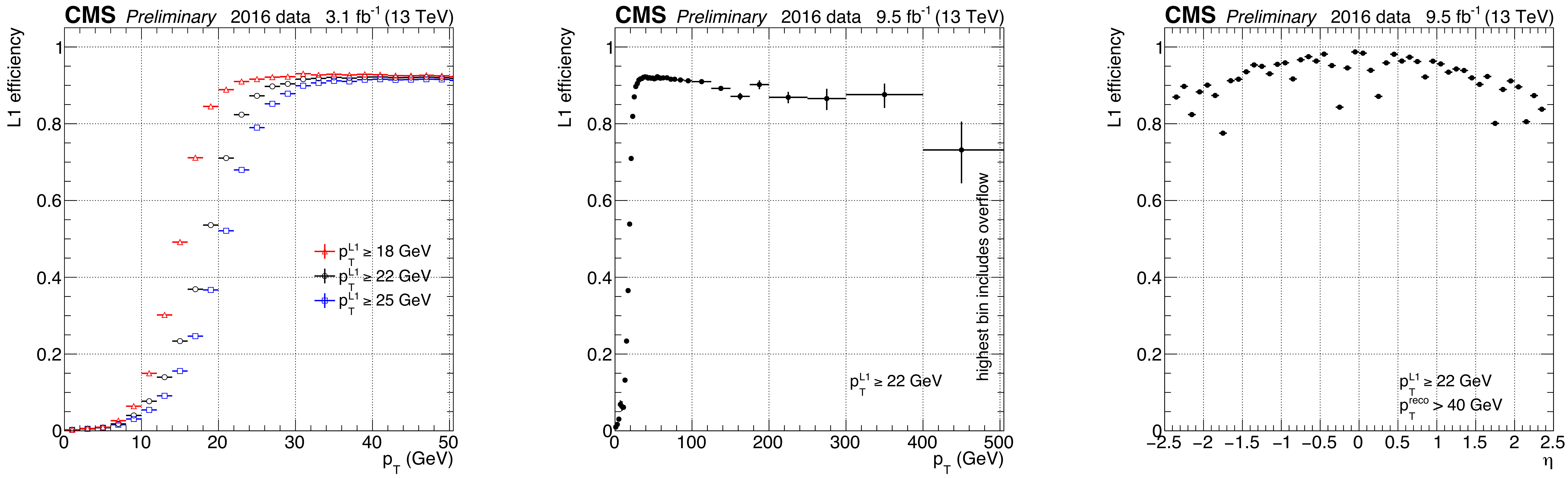


BMTF $|\eta| < 0.83$

OMTF $0.83 < |\eta| < 1.24$

EMTF $|\eta| > 1.24$

Muon trigger performance results



- Trigger efficiency for a single muon with p_T > 18, 22 and 25 GeV vs offline muon p_T and η
- Using tag and probe method on a dataset of $Z \longrightarrow \mu\mu$ events
- See more in poster "*Upgrade of the CMS muon trigger system in the barrel region*" D. Rabady

e/γ finder algorithm

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

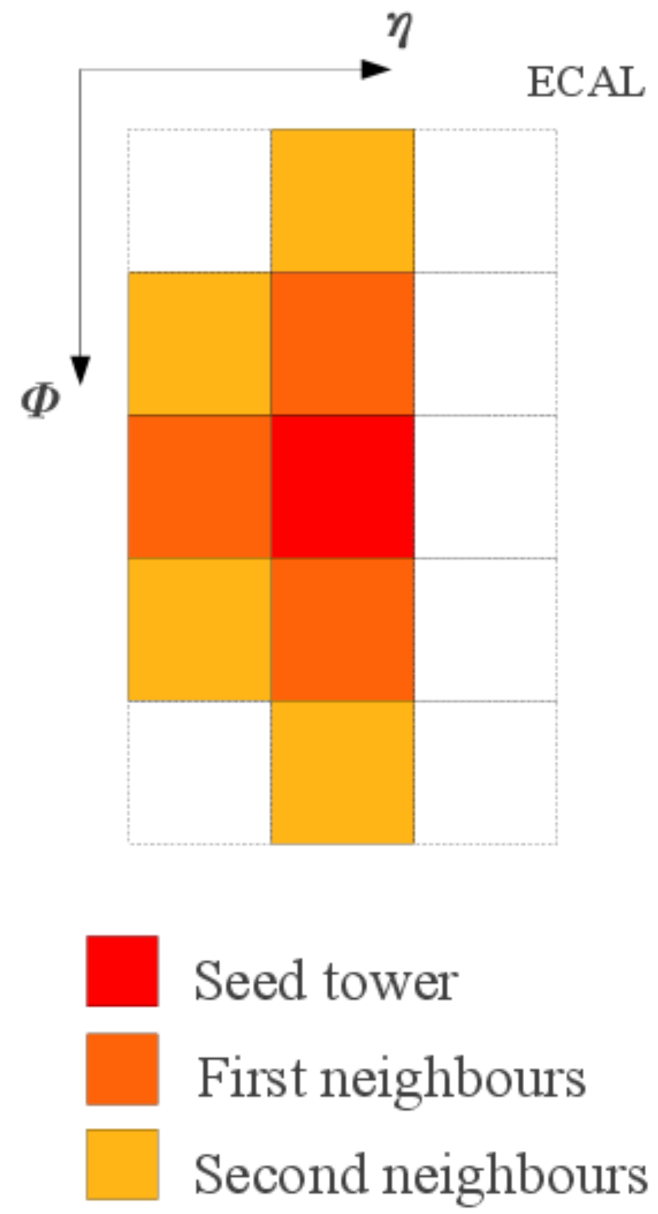
Calibration

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

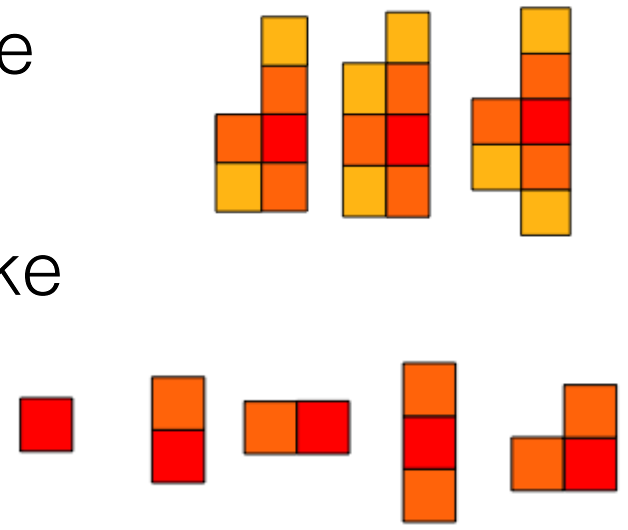
Cluster building

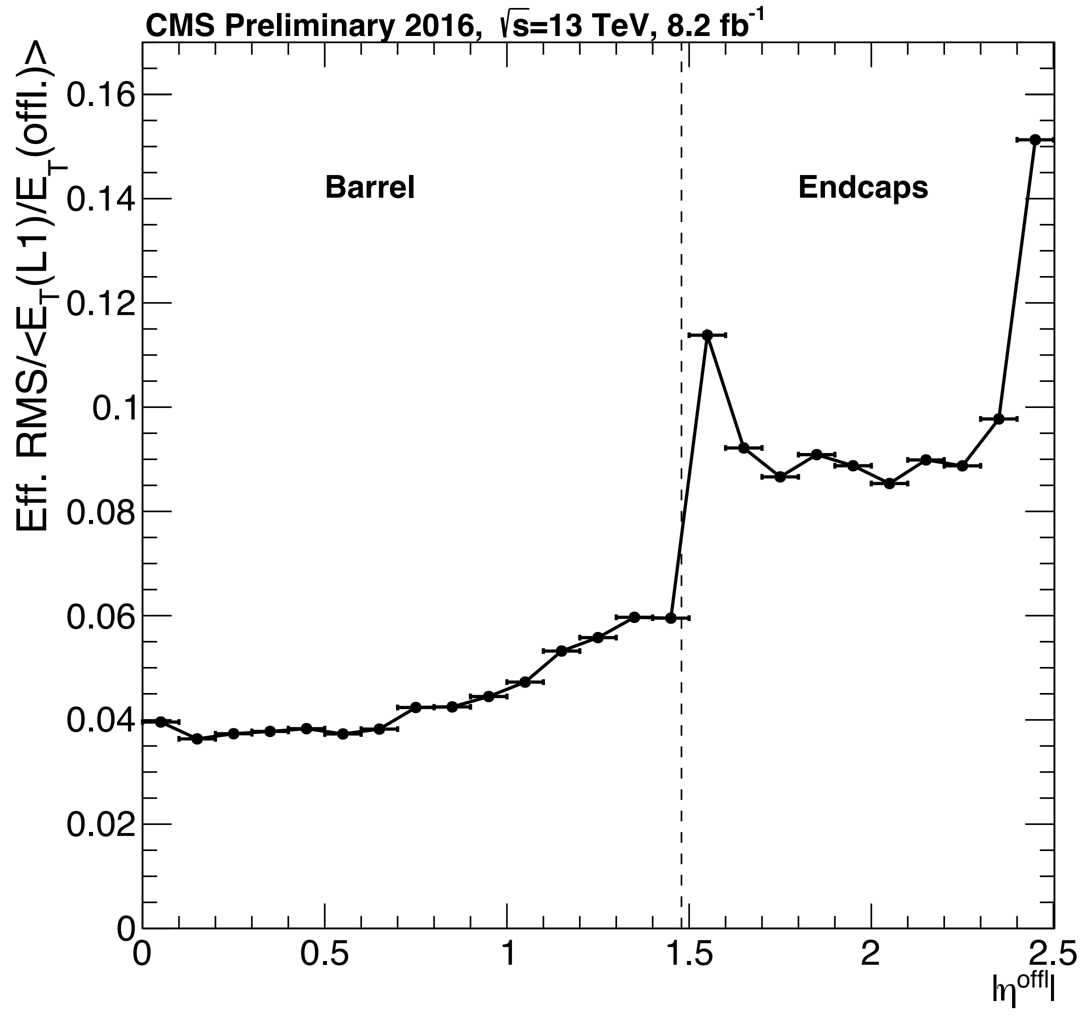


Cluster shapes

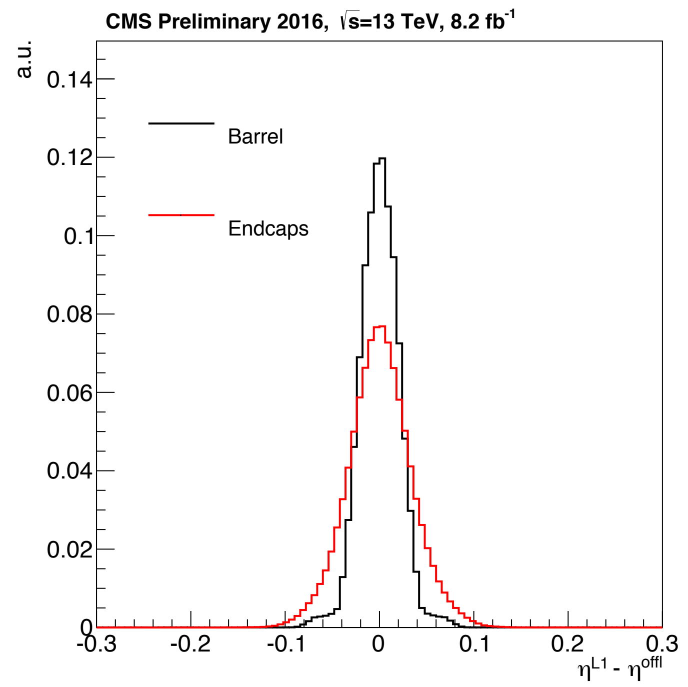
jet like

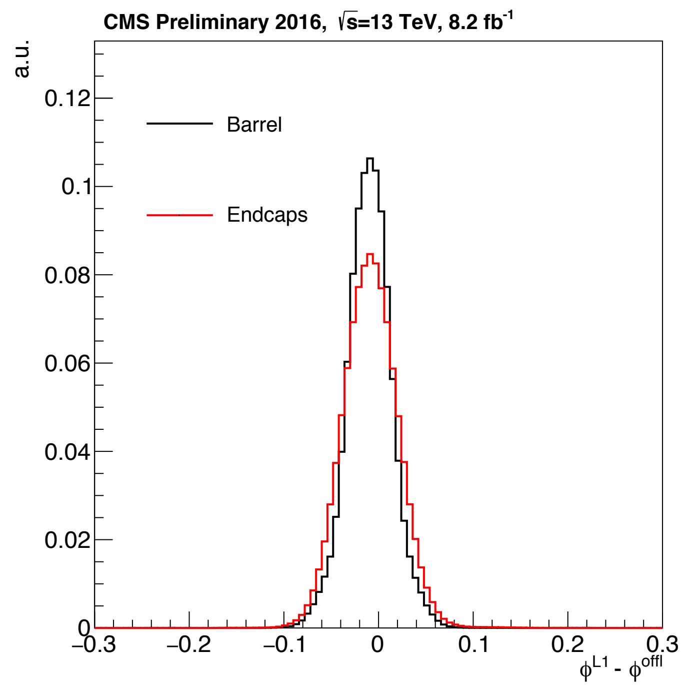
e/γ like





Energy comparison to offline

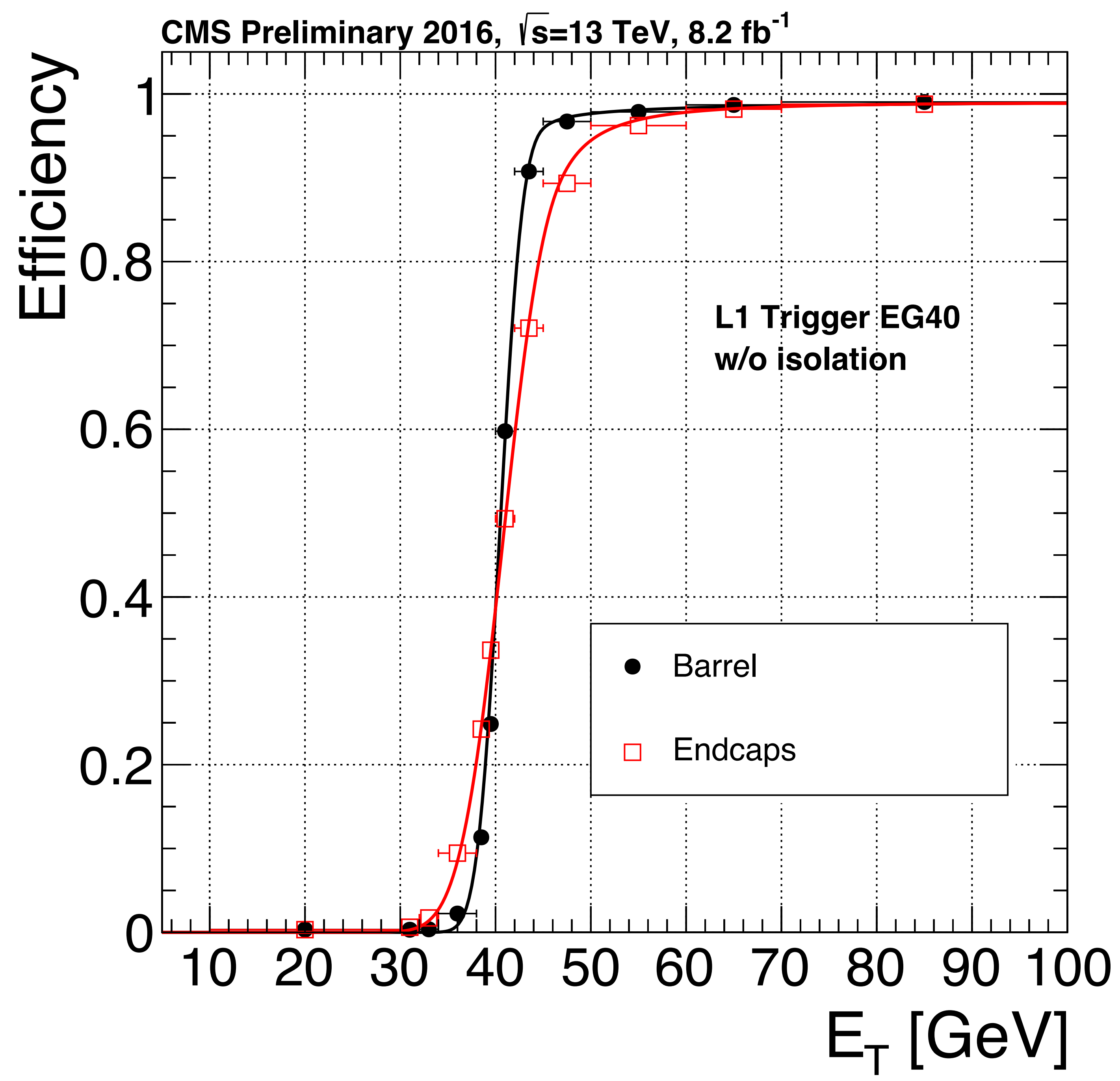




Position comparisons to offline

e/γ trigger performance results

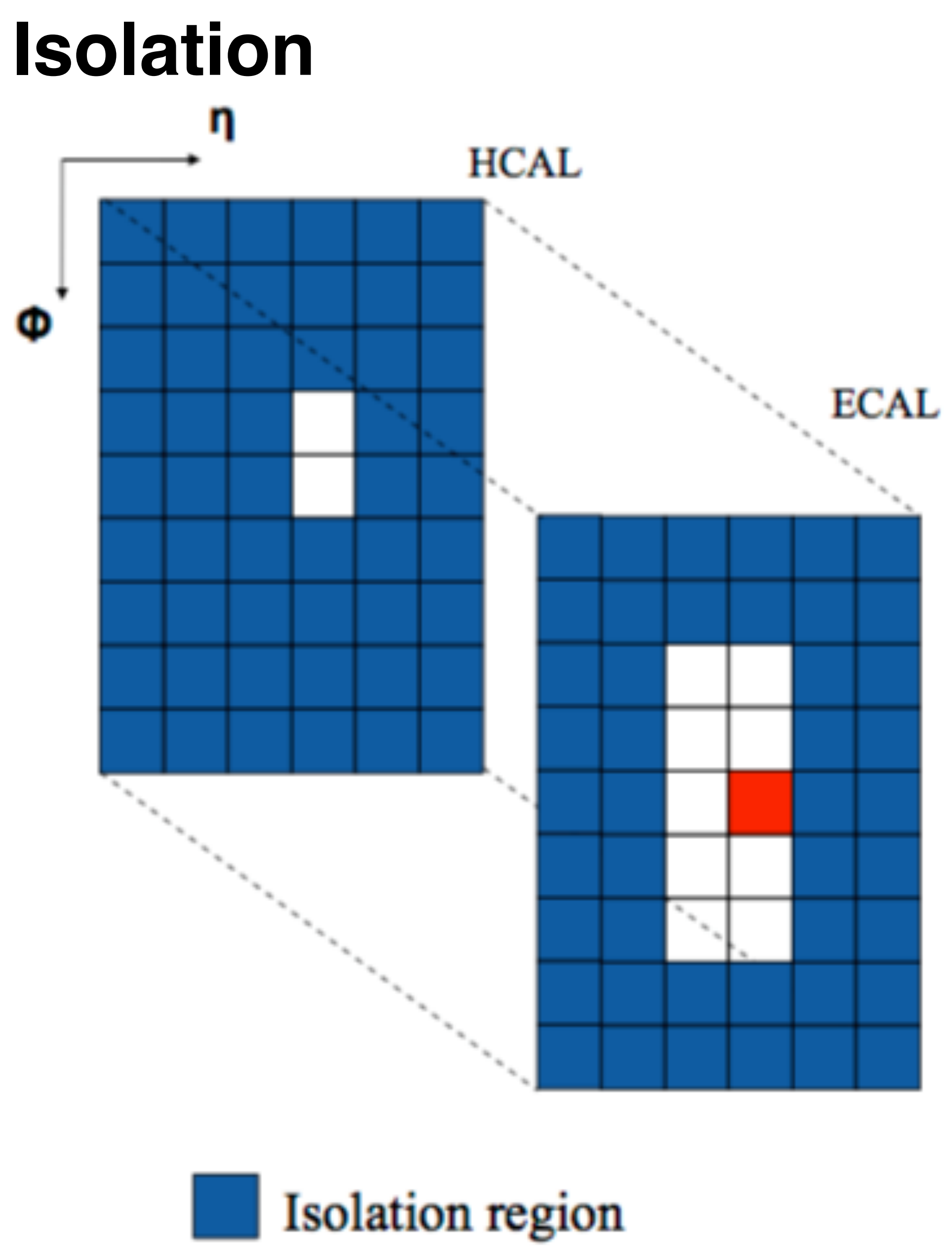
- Trigger efficiency for a single e/γ with E_T > 40 GeV vs offline E_T
- Using tag and probe method on a dataset of Z⟶ee events

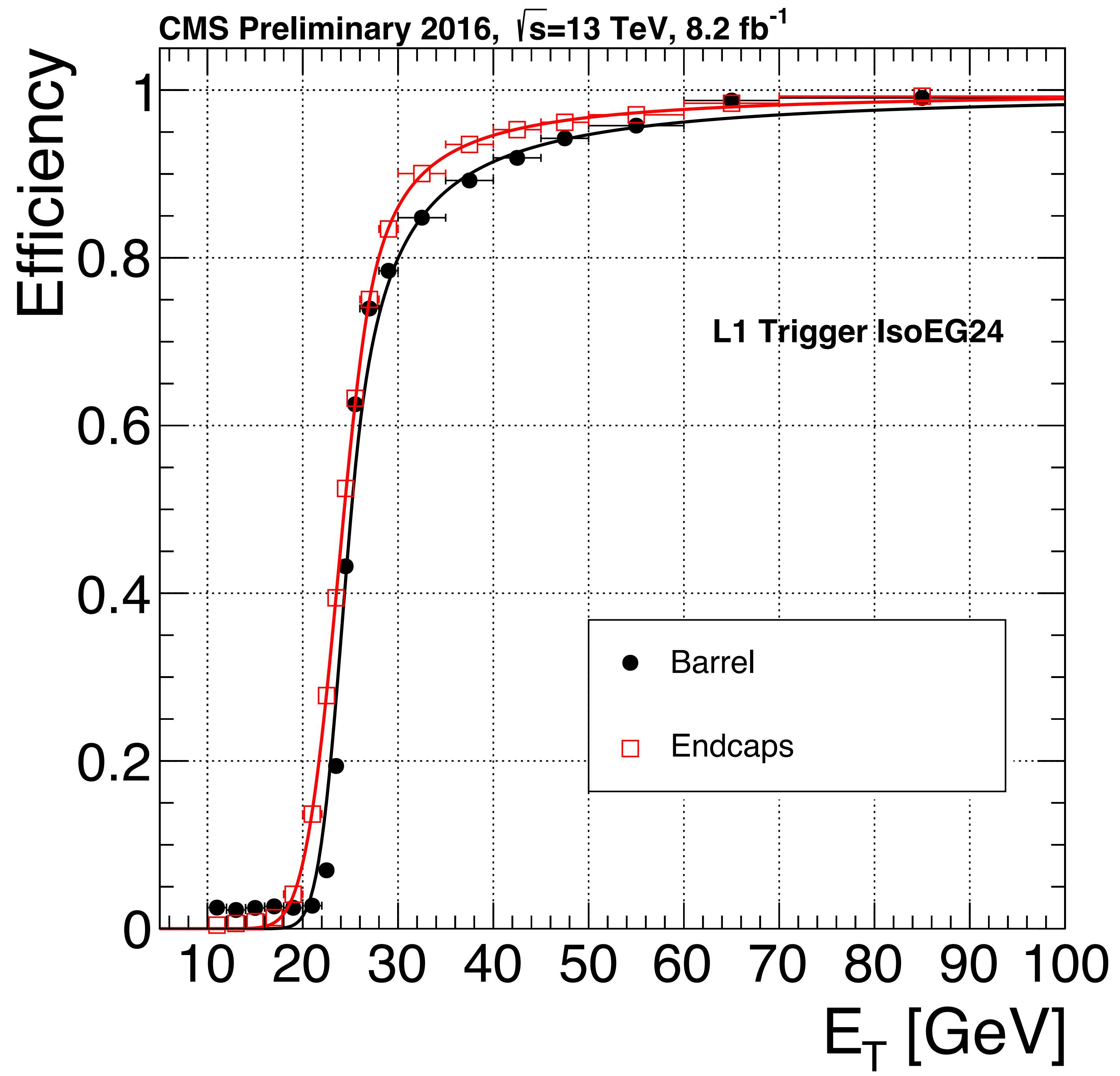


Isolation

Create isolation annuli (removing footprint) for ECAL and HCAL around cluster

Isolation energy requirement fn. of PU and η

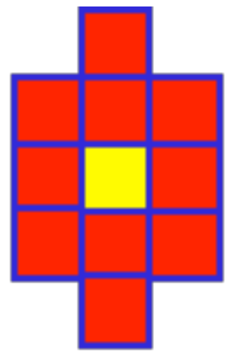




τ finder algorithm

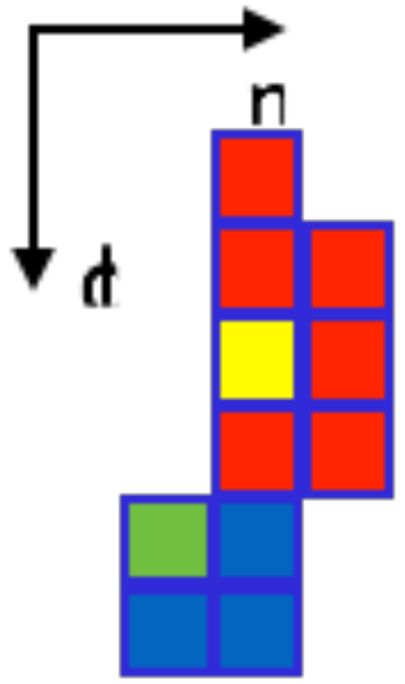
Clustering, shape and position

Very similar to e/γ — optimised for τ



Merging

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

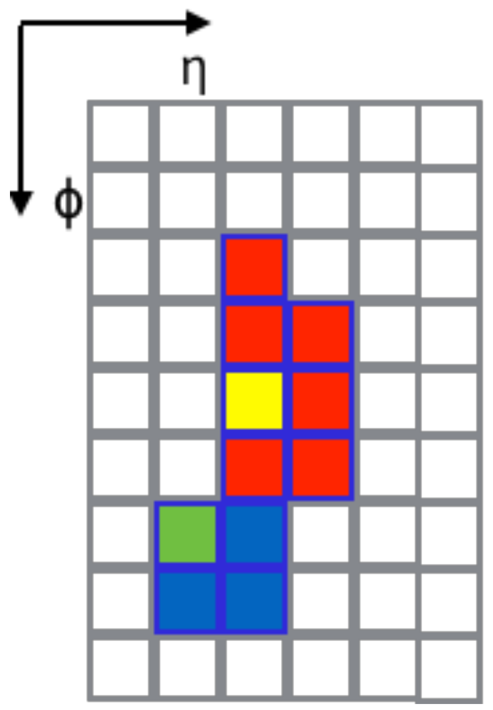


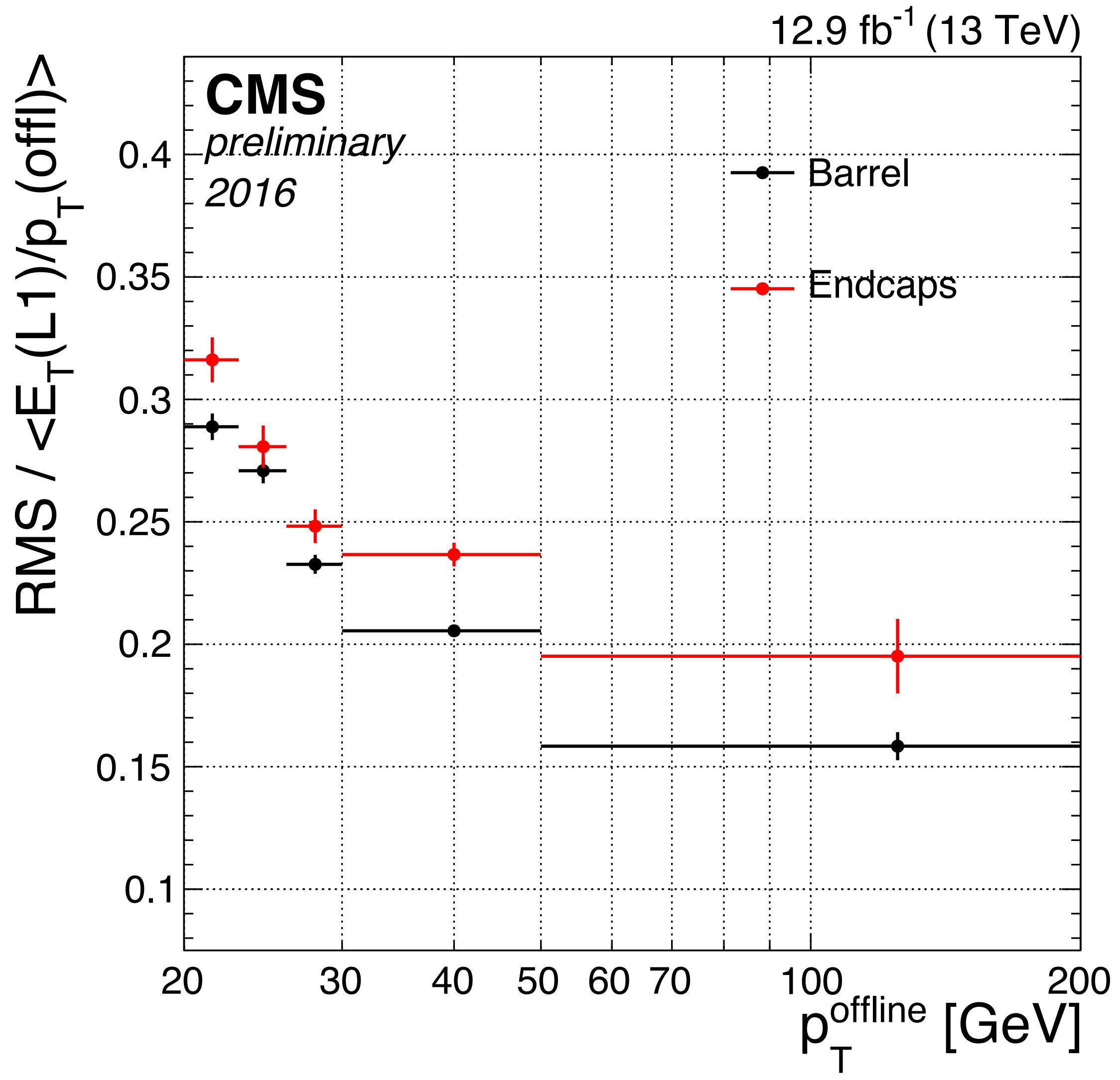
Calibration

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

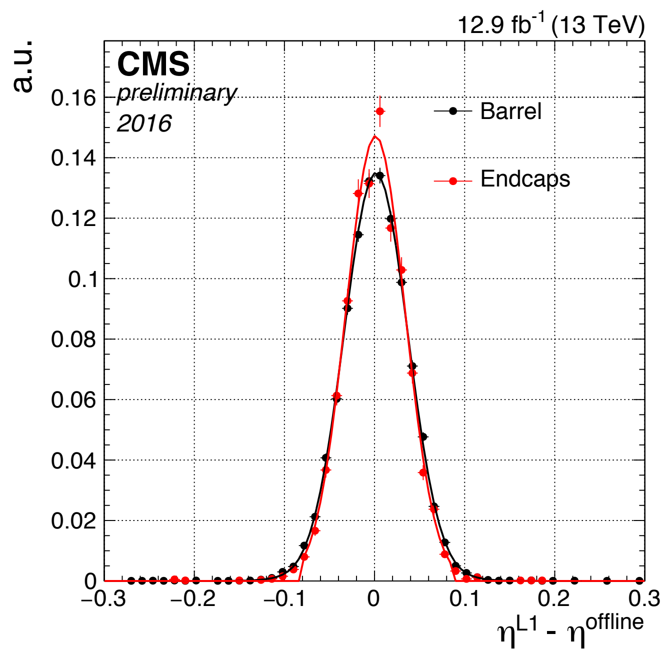
Isolation

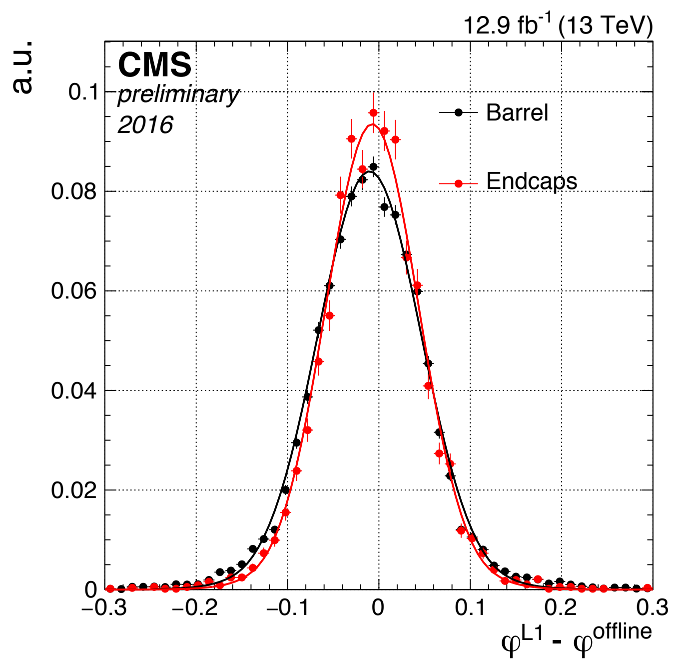
Very similar to e/γ — optimised for τ including merging as input — two working points





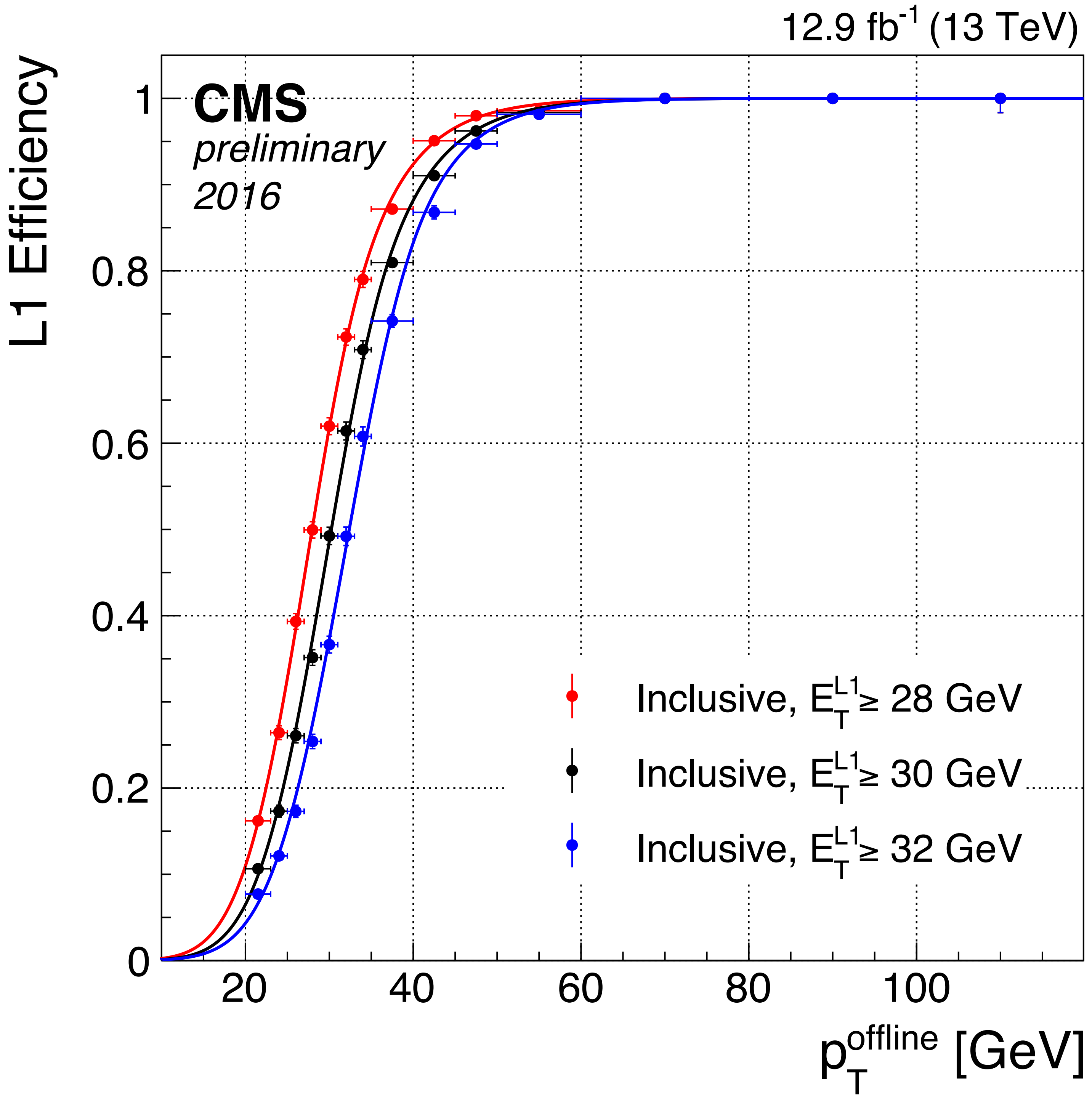
Energy comparison to offline

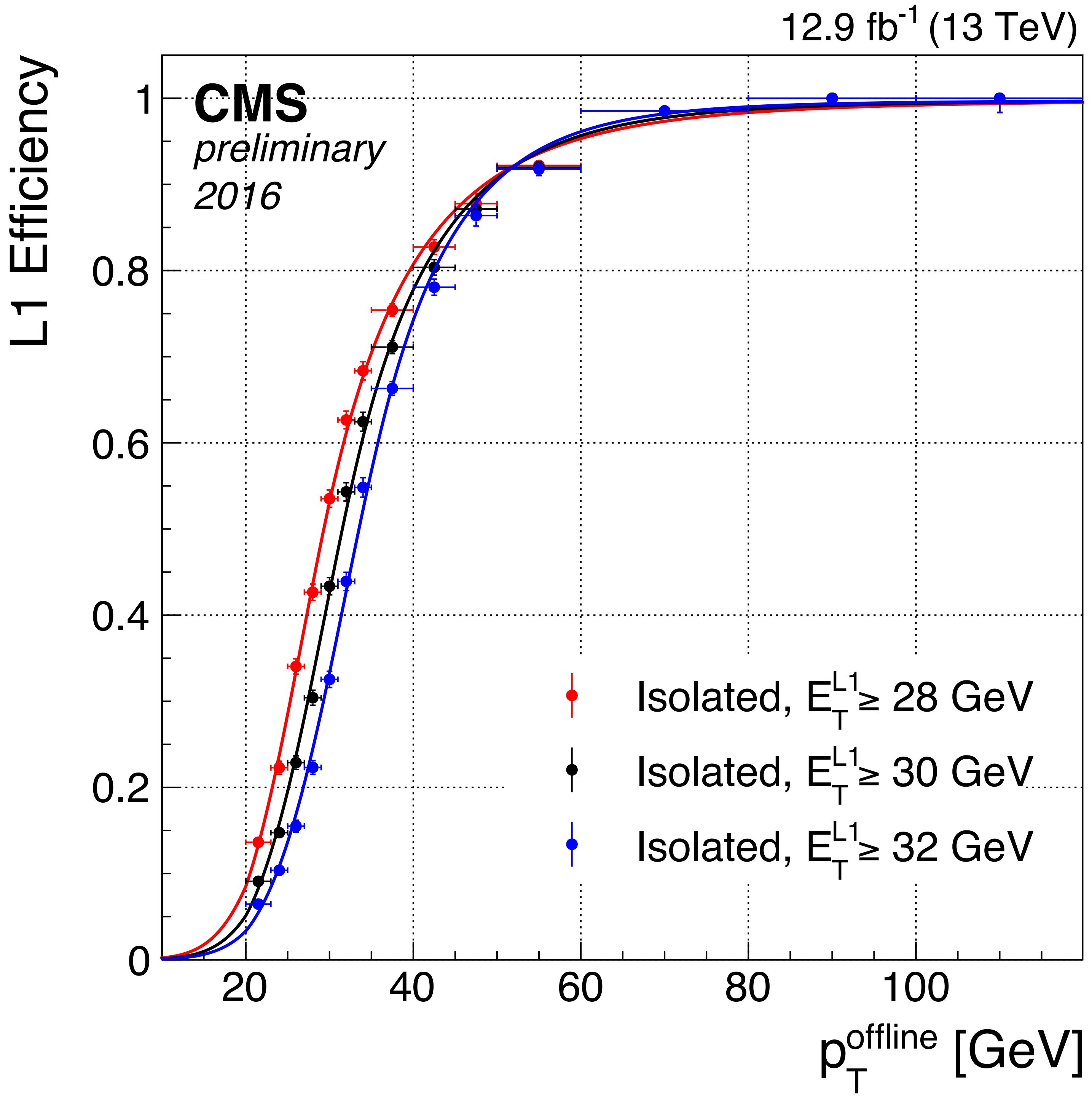




Position comparisons to offline

τ trigger performance results



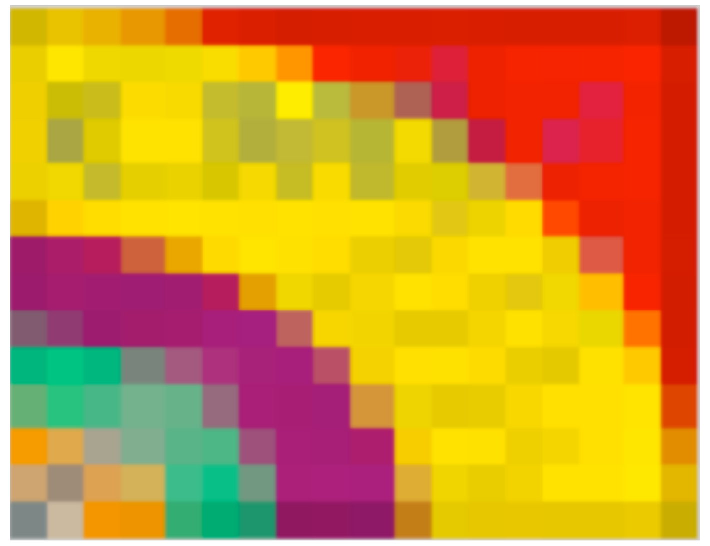


- Trigger efficiency for a single τ with E_T > 28, 30 and 32 GeV vs offline τ p_T
- Using tag and probe method on a dataset of Z⟶μτ events

Jet finder algorithm

Input granularity

Access to higher granularity inputs than Run I



14 (η) x 18 (ϕ)

56 (η) x 72 (ϕ)

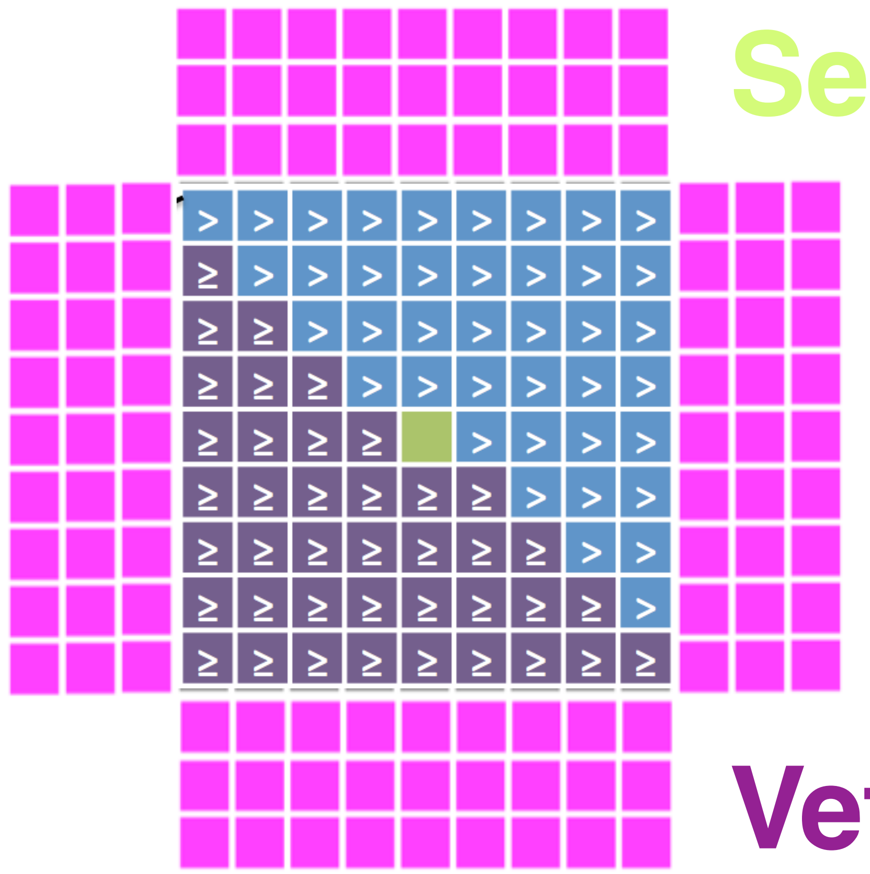
Sliding window jet algorithm

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

PUS areas



Seed tower

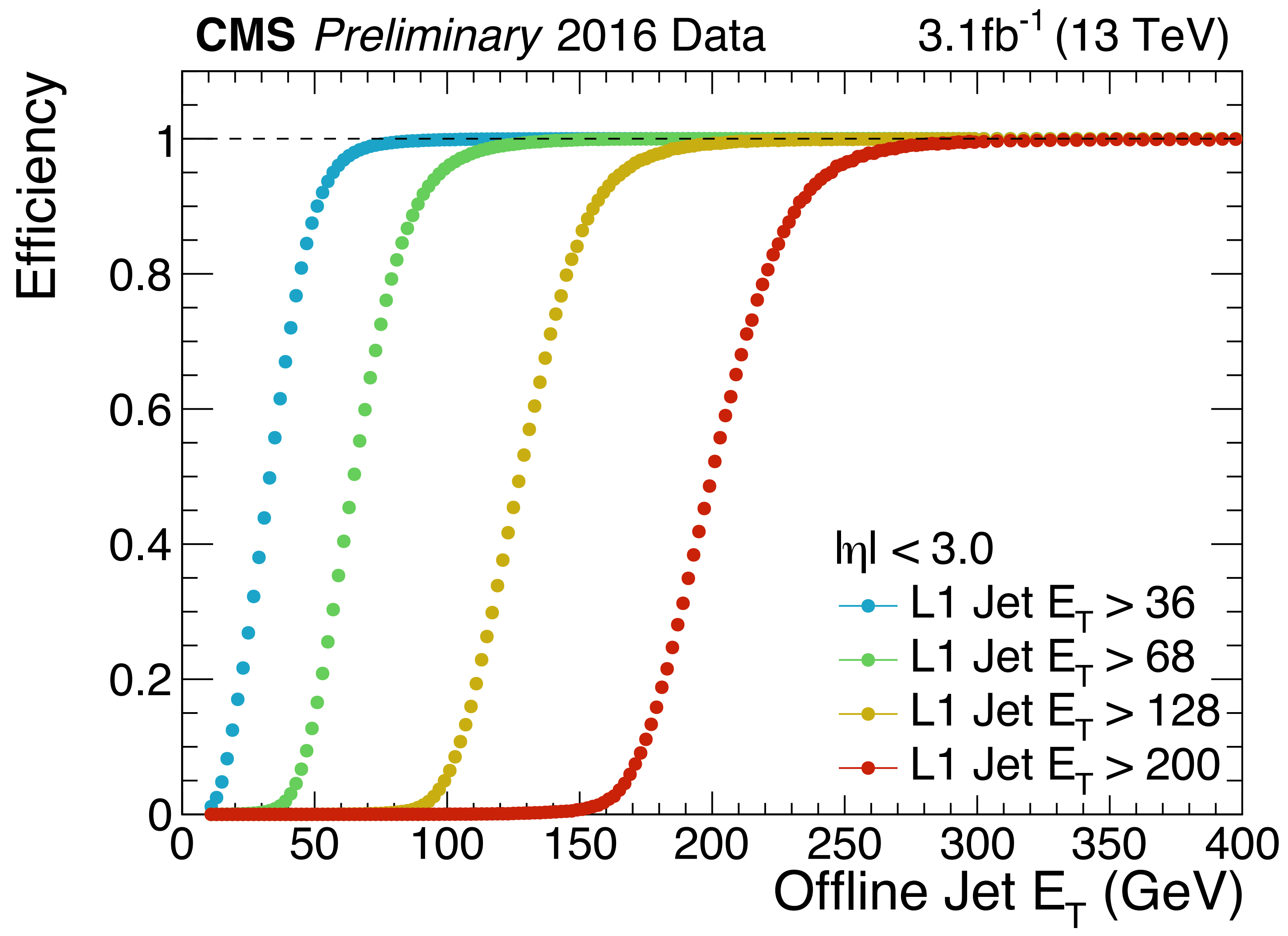
Veto mask

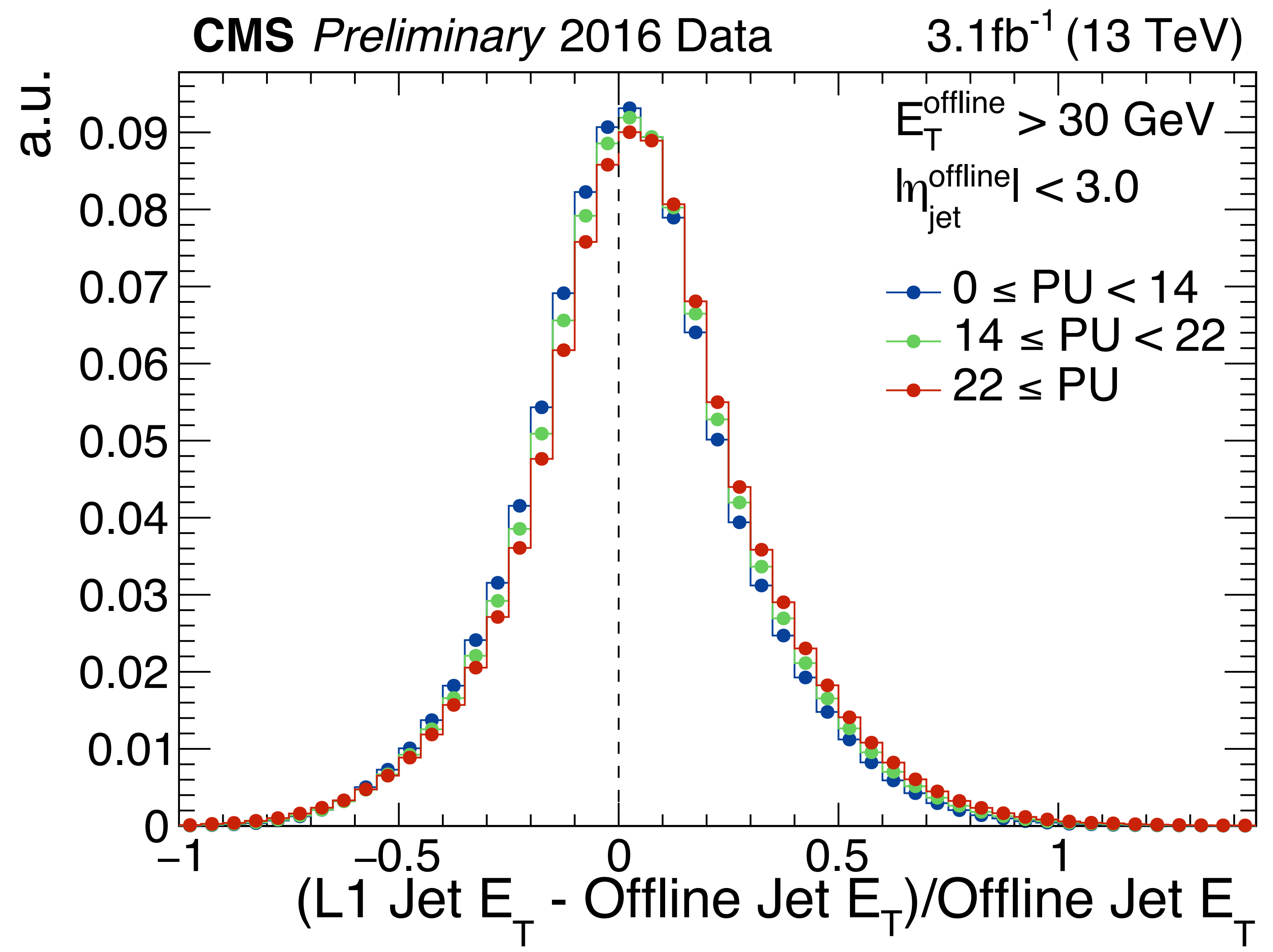
Calibration

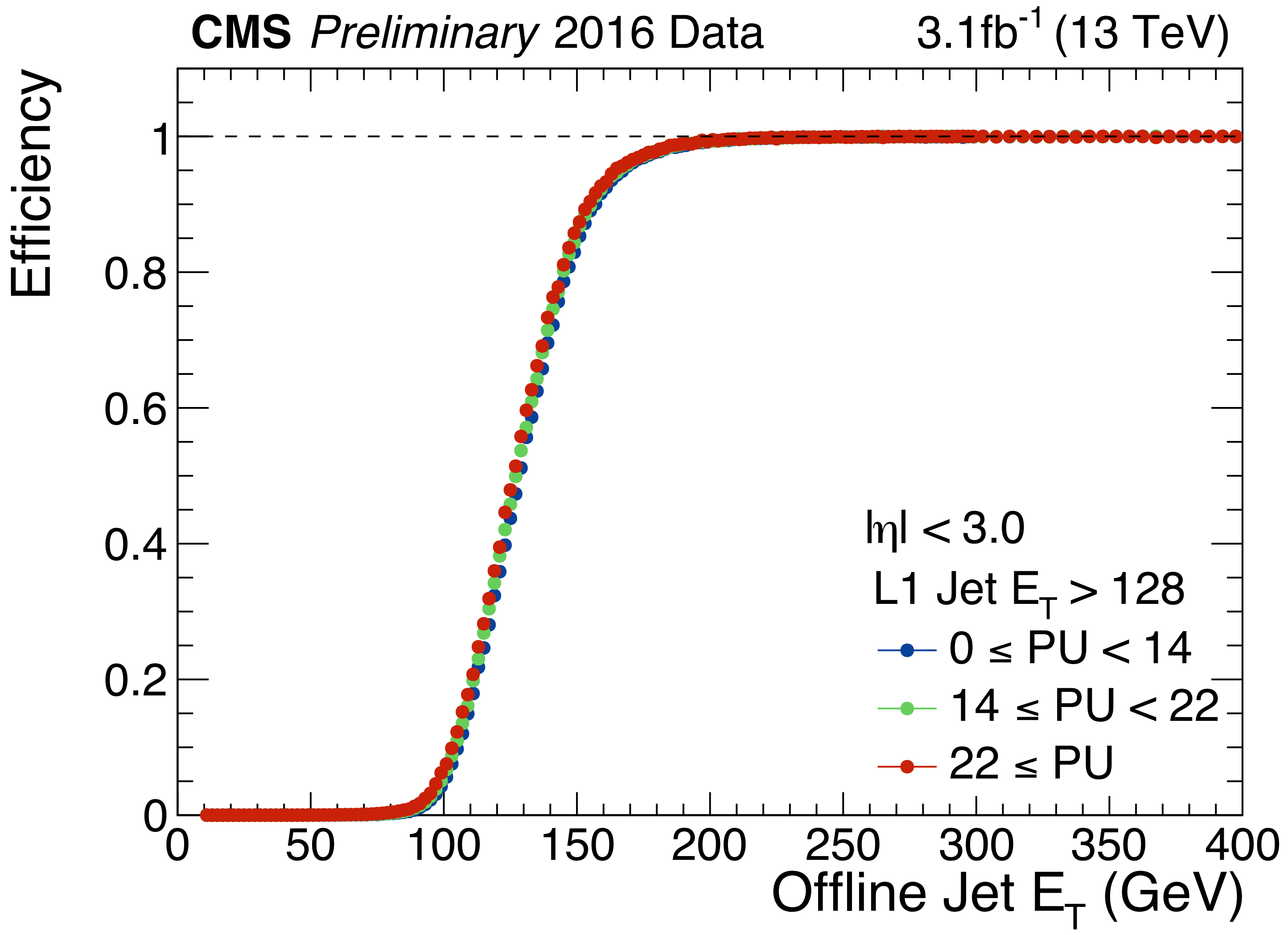
Correct jet energies as a function of jet E_T and η

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



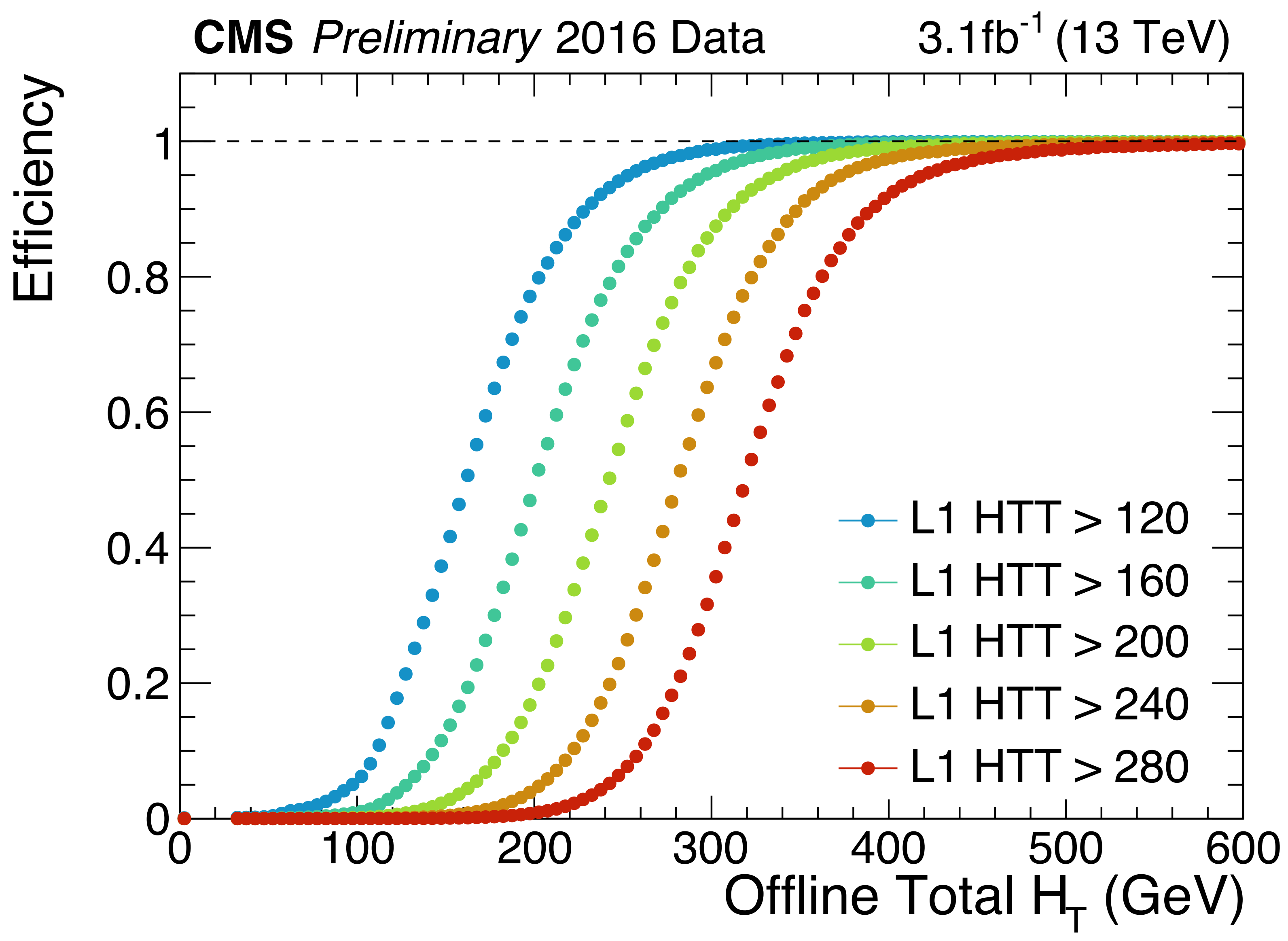


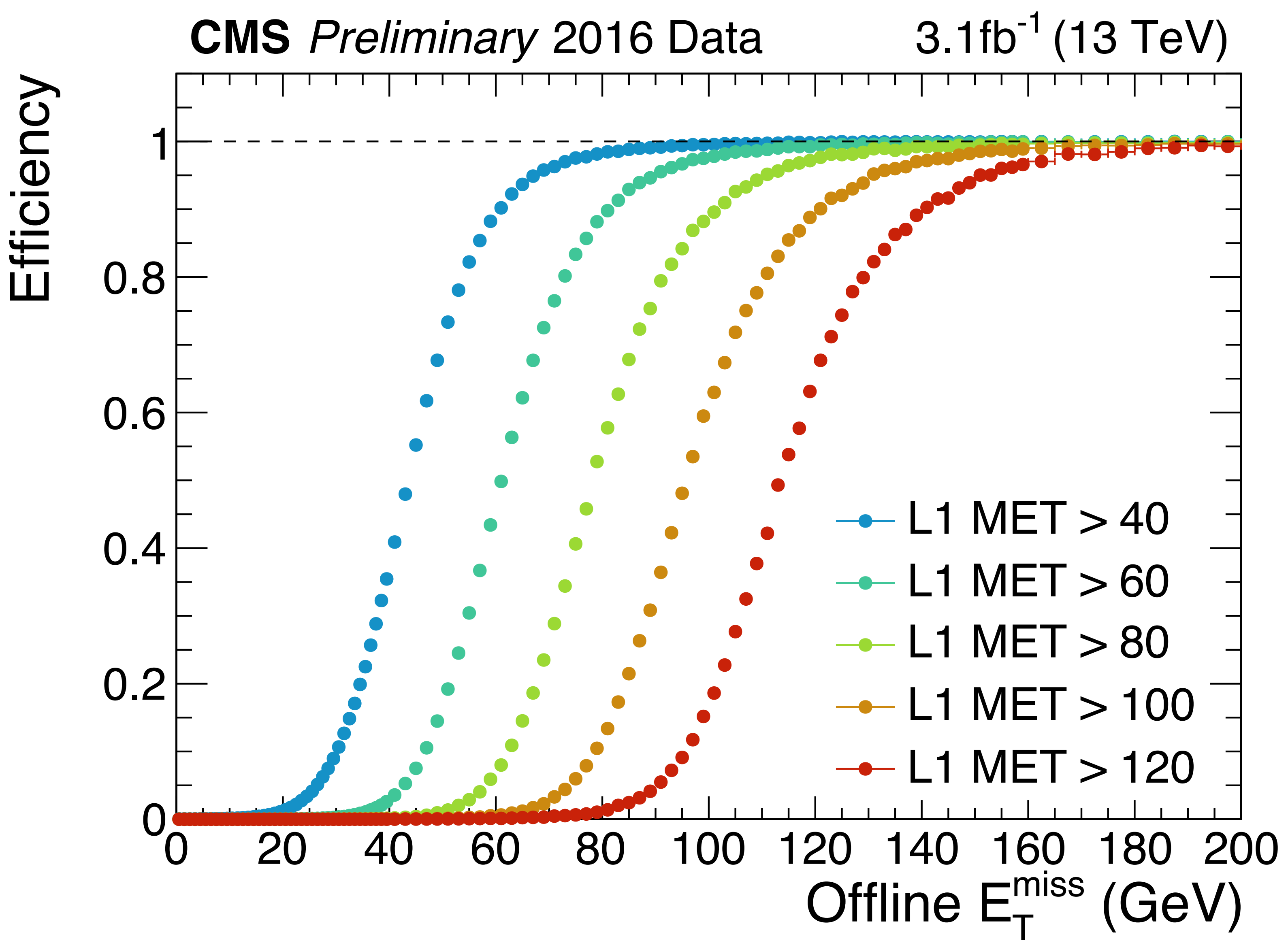


- Sharp efficiency turn-on with well calibrated E_T scale
- Insensitive to pile-up

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}





- Favourites with SUSY and exotics searches

Summary and outlook

- Run II at LHC is a very challenging environment to search for new physics and measure the properties of the Higgs boson
  - Increase in instantaneous luminosity, centre-of-mass energy, increase in pileup…
  - Requires improved performance online and offline
- Newly installed Level-1 trigger at CMS tackles these challenges
  - State-of-the-art, FPGA based, very high bandwidth processors with sophisticated, programmable algorithms
  - First performance results look good — flexible to evolve with CMS physics programme
- Study the performance of this new trigger and learn from design and commissioning to begin designing Phase II trigger upgrade for HL-LHC

References

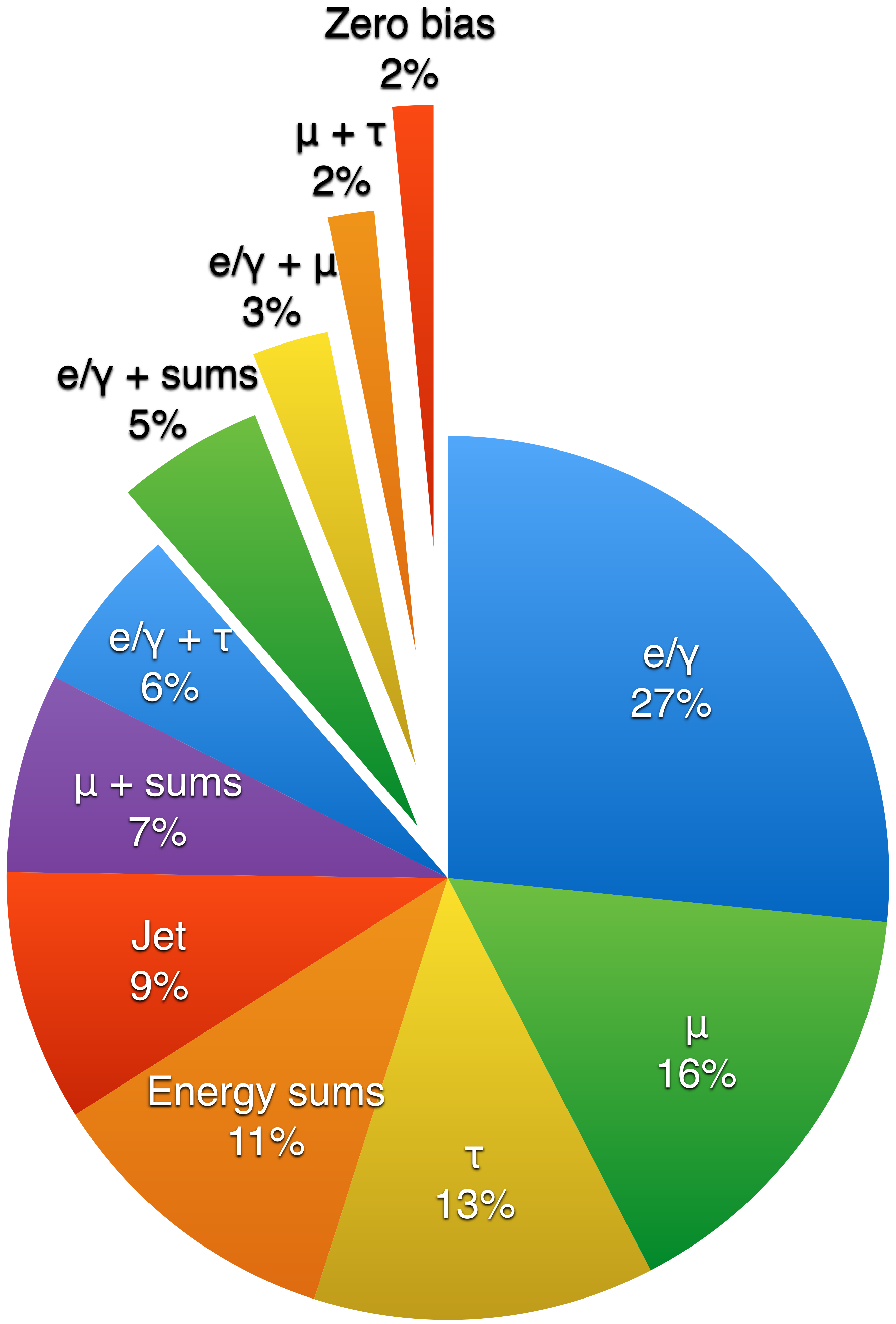
- CMS Level-1 Trigger TDR: https://cds.cern.ch/record/706847
- Run I performance paper: The CMS Trigger System, to be submitted to JINST
- Phase 1 upgrade TDR: https://cds.cern.ch/record/1556311
- Performance notes for ICHEP 2016
  - μ: https://cds.cern.ch/record/2202986
  - e/γ, τ, jets and sums: https://cds.cern.ch/record/2202966
- Earlier notes
  - Commissioning etc.: http://cds.cern.ch/record/2063468
- Area-based pile-up subtraction:
  - https://arxiv.org/abs/0707.1378
  - http://arxiv.org/abs/1010.1759

Backup

Future prospects

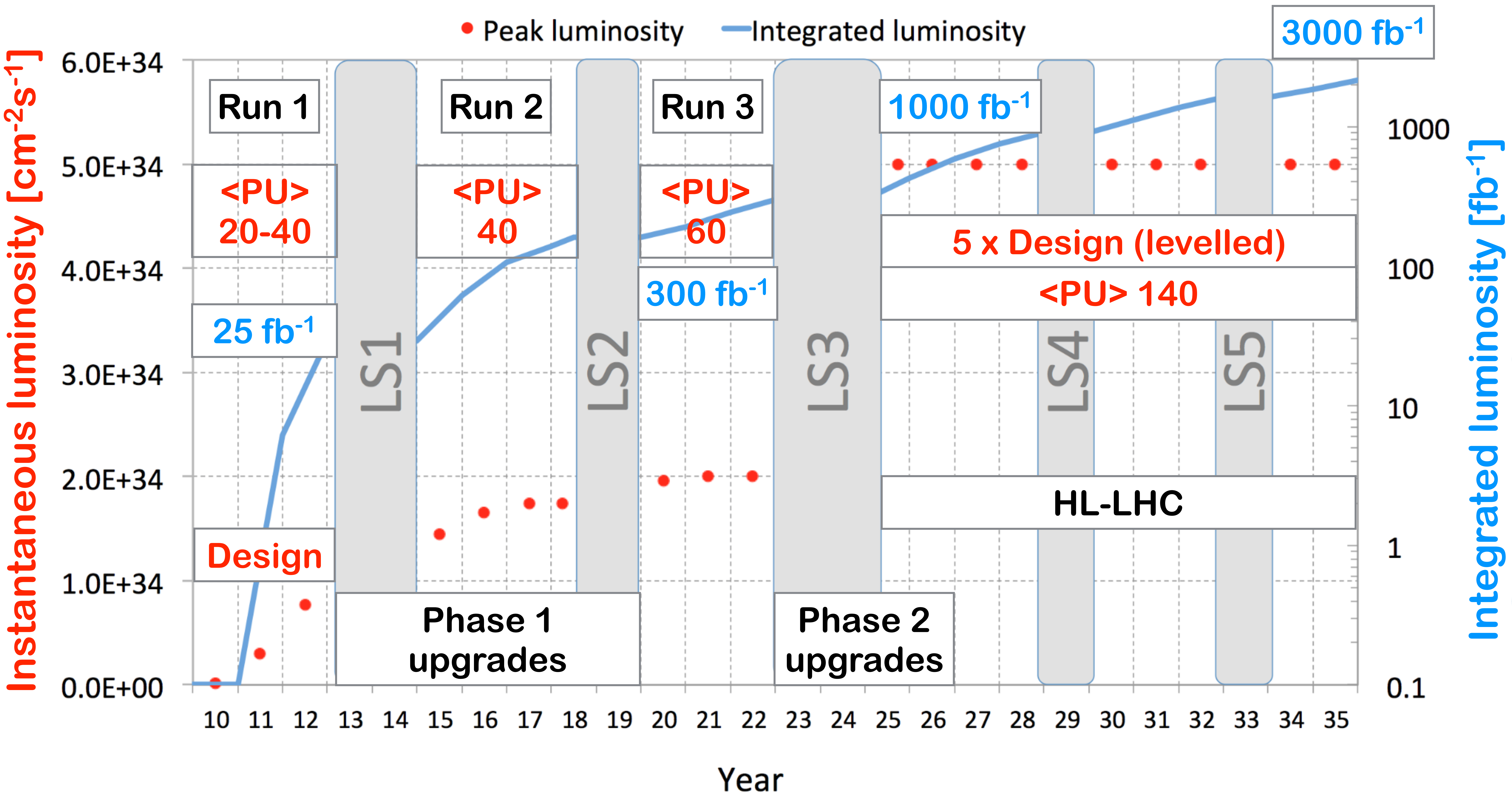
- Potential areas for improvement
  - Topological triggers e.g. M_{jj}, $\Delta\phi_{j,MET}$… being proposed now
  - Use of RPC data in barrel μ track finding now, forward μ coming…
  - Upgrade to HCAL provides depth and timing information, incorporate into trigger to mitigate in and out-of-time pileup
  - Use of cluster shape as veto/catagorisation/calibration in τ and jets (already in e/γ)
  - …

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

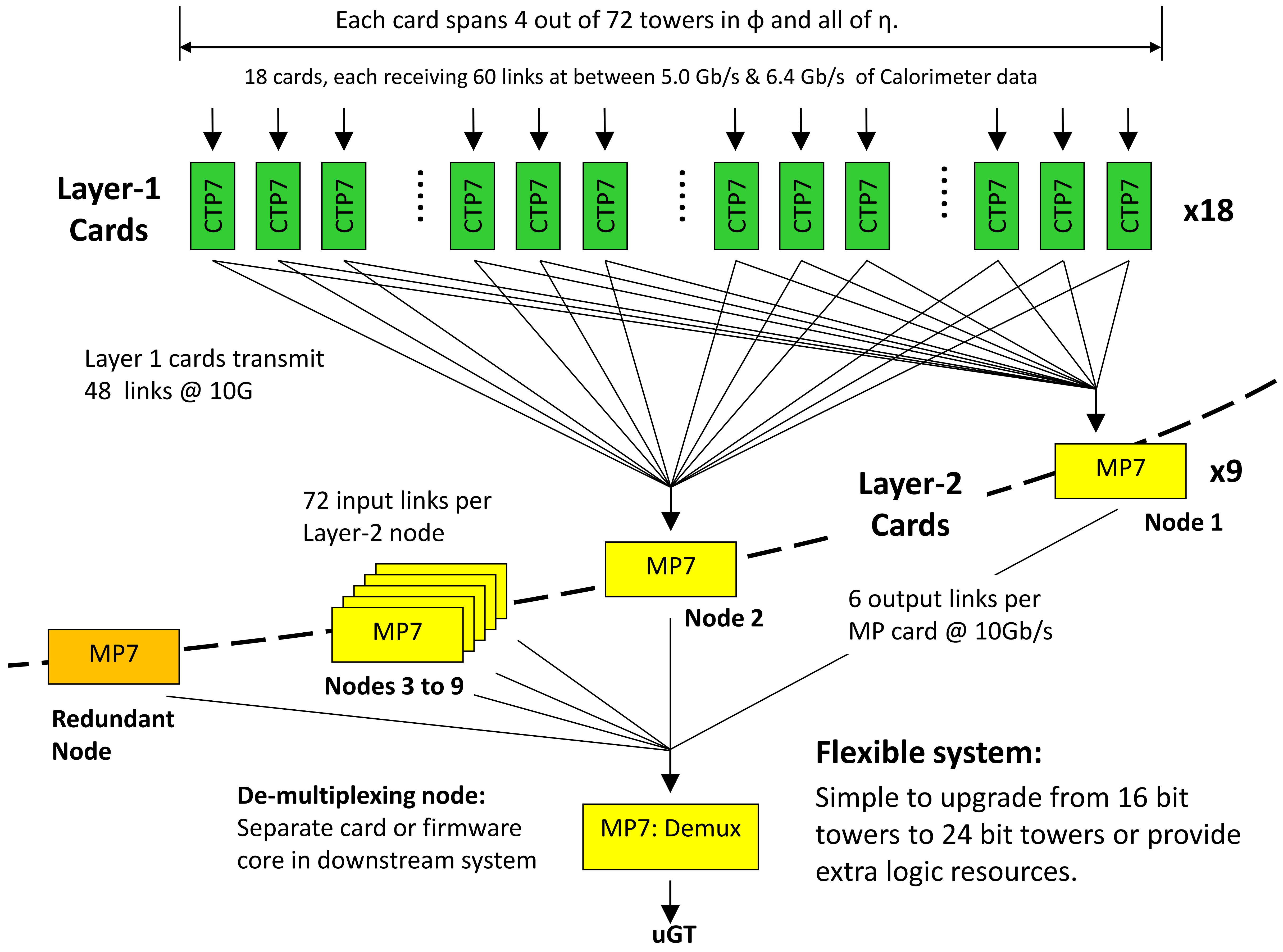


- Bandwidth allocated per trigger object type
- **Note that fractions are inclusive → no attempt to correct for overlaps between different types of trigger**

LHC: Future plans

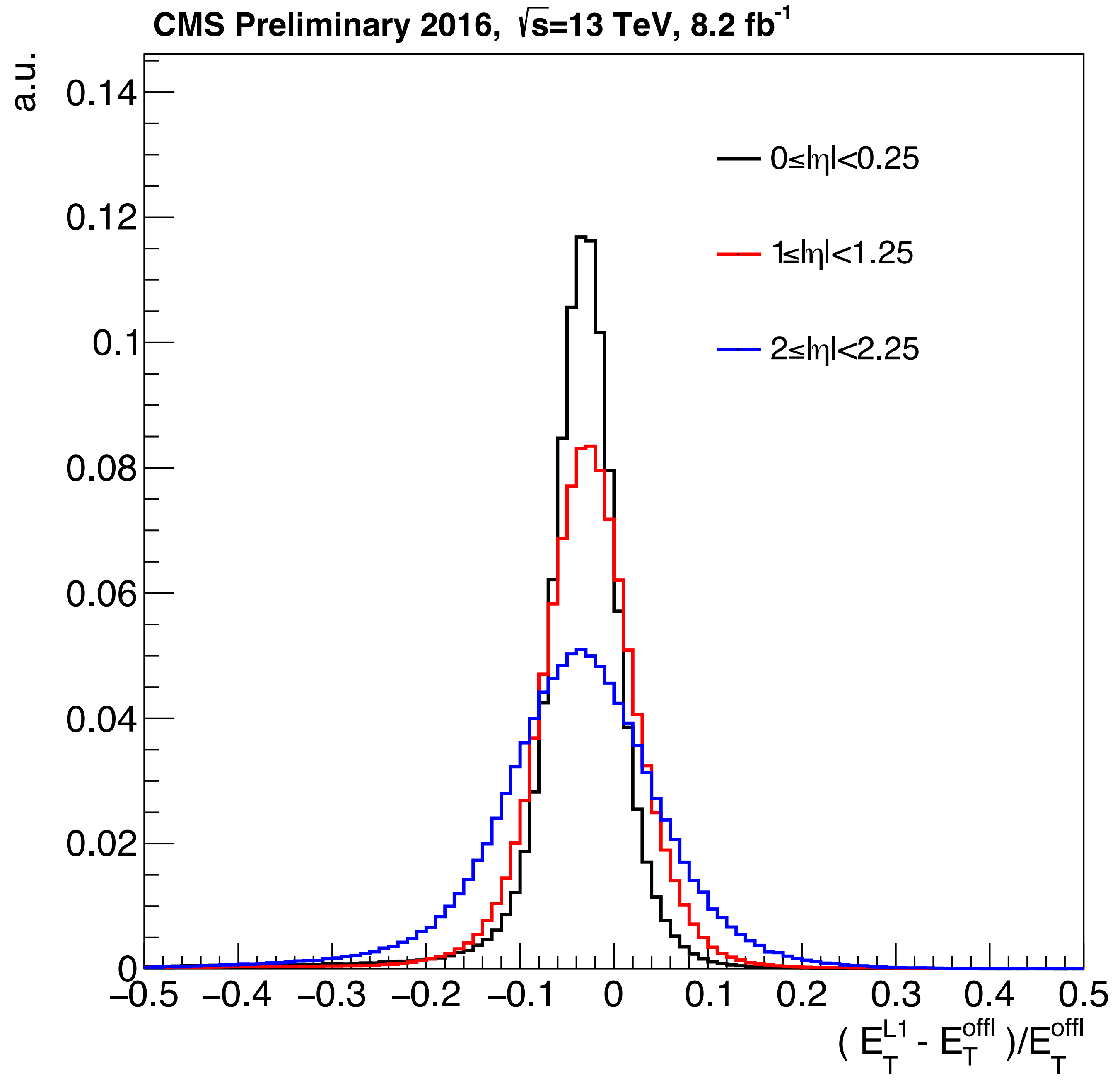


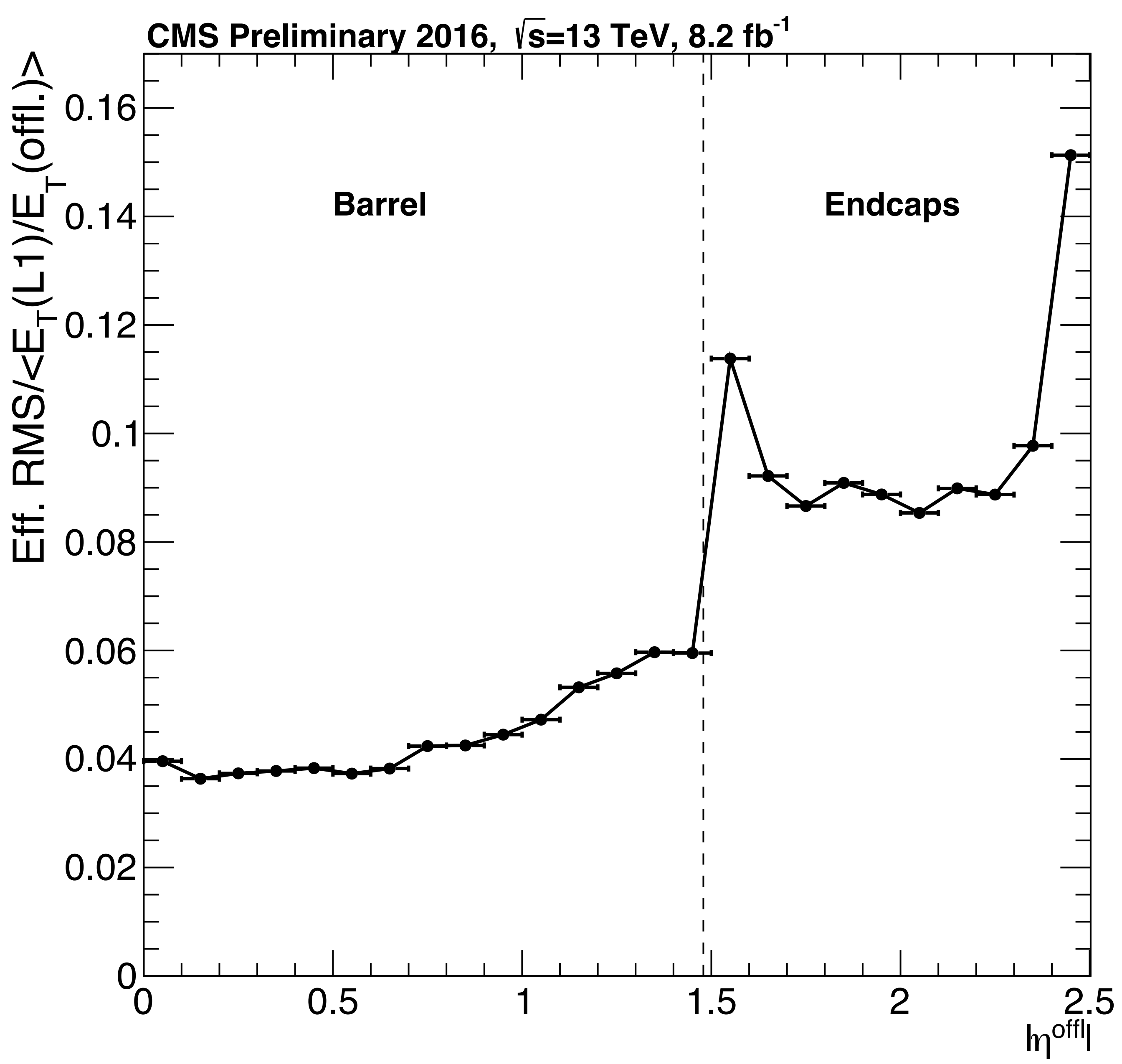
Time-multiplexed calorimeter trigger



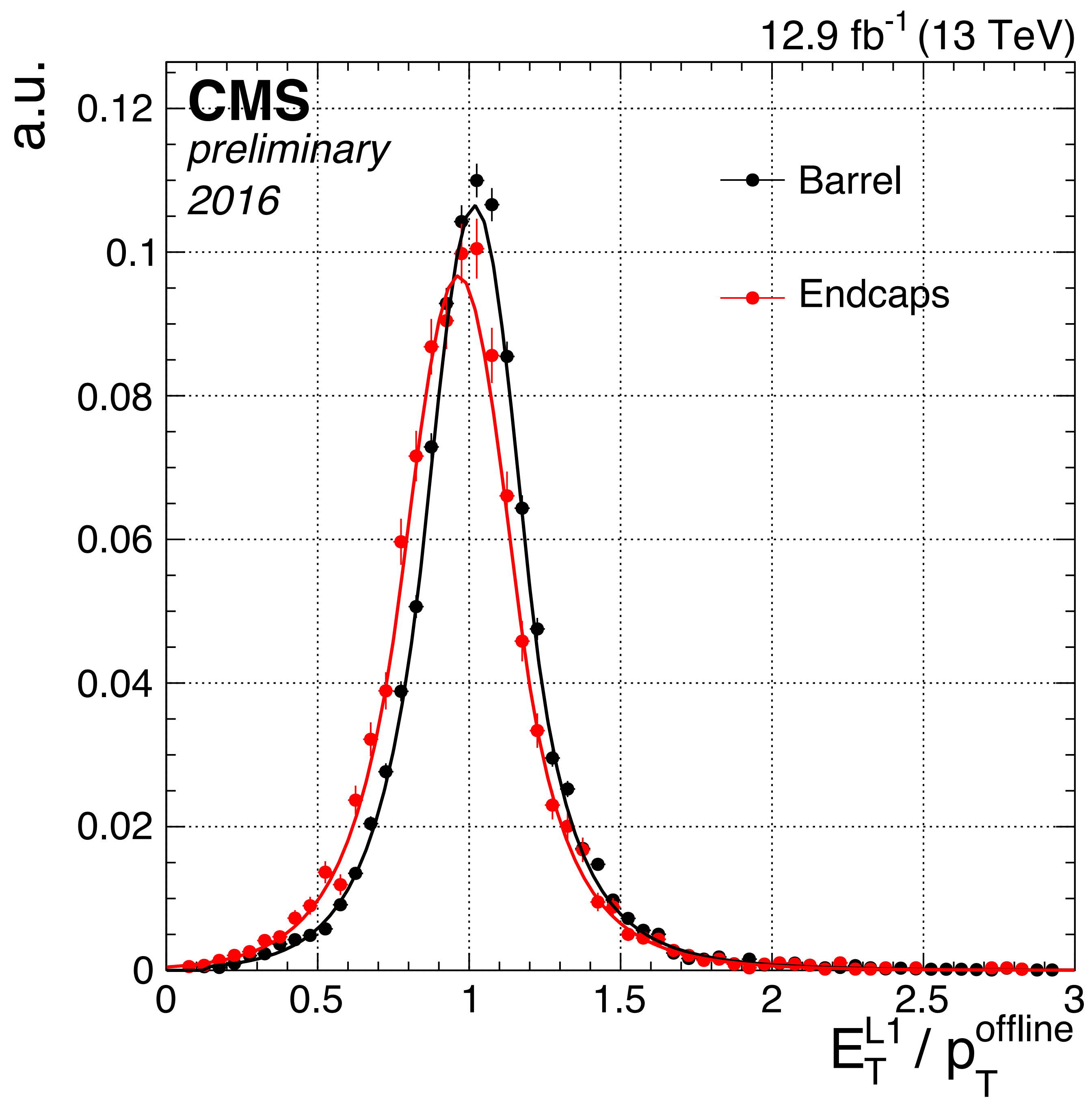
Flexible system:
Simple to upgrade from 16 bit towers to 24 bit towers or provide extra logic resources.

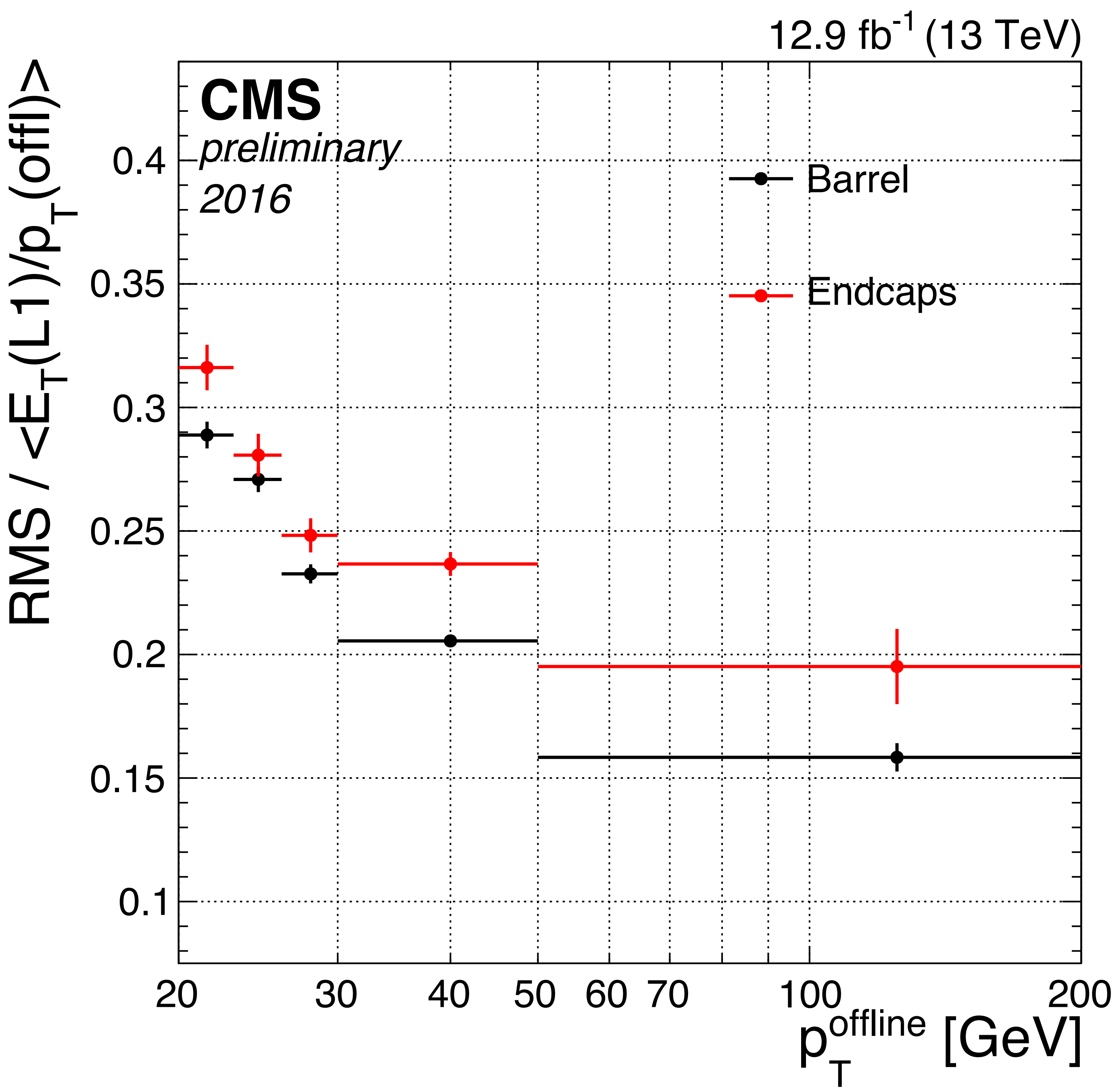
e/γ reconstruction performance

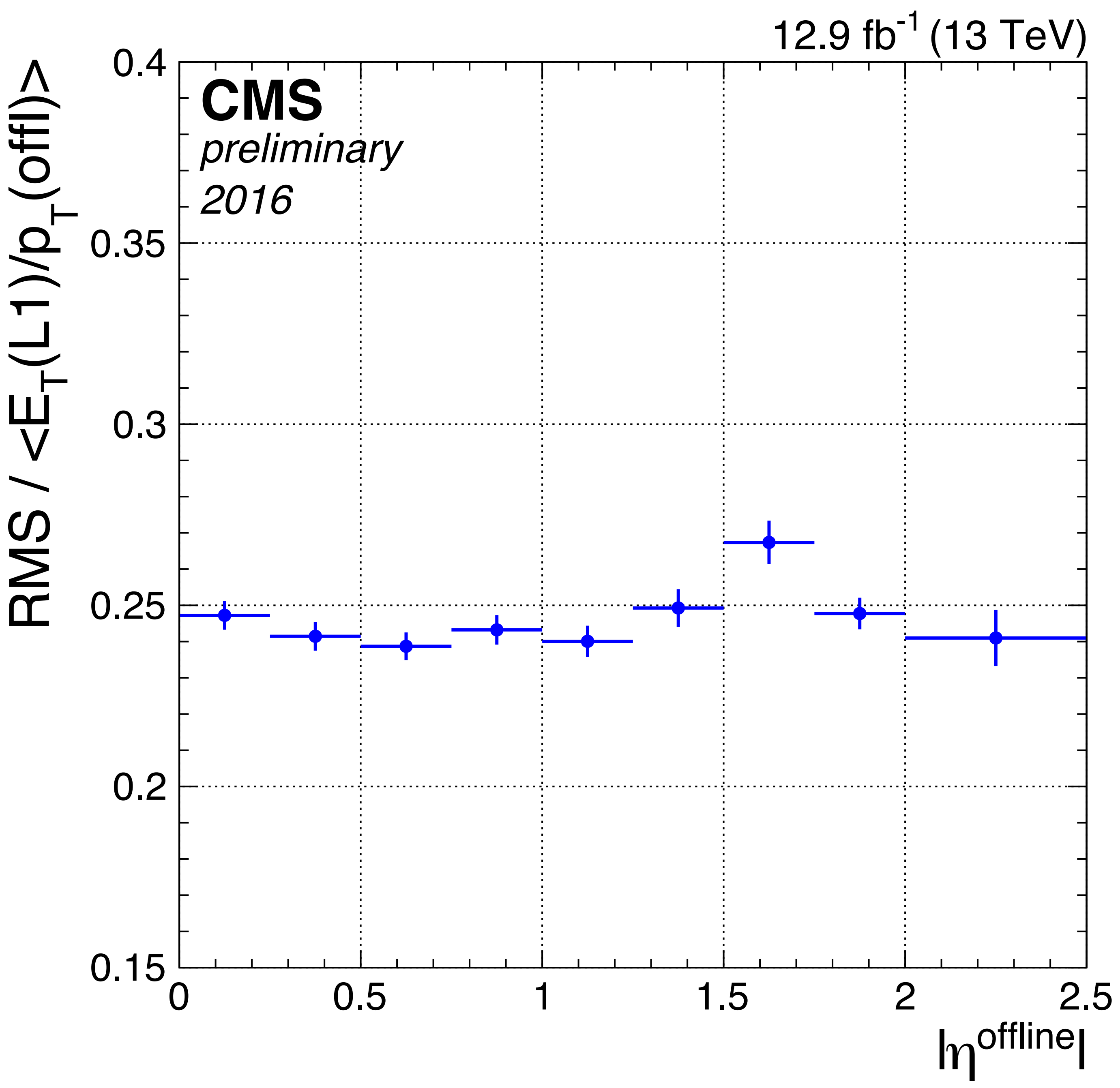




τ reconstruction performance

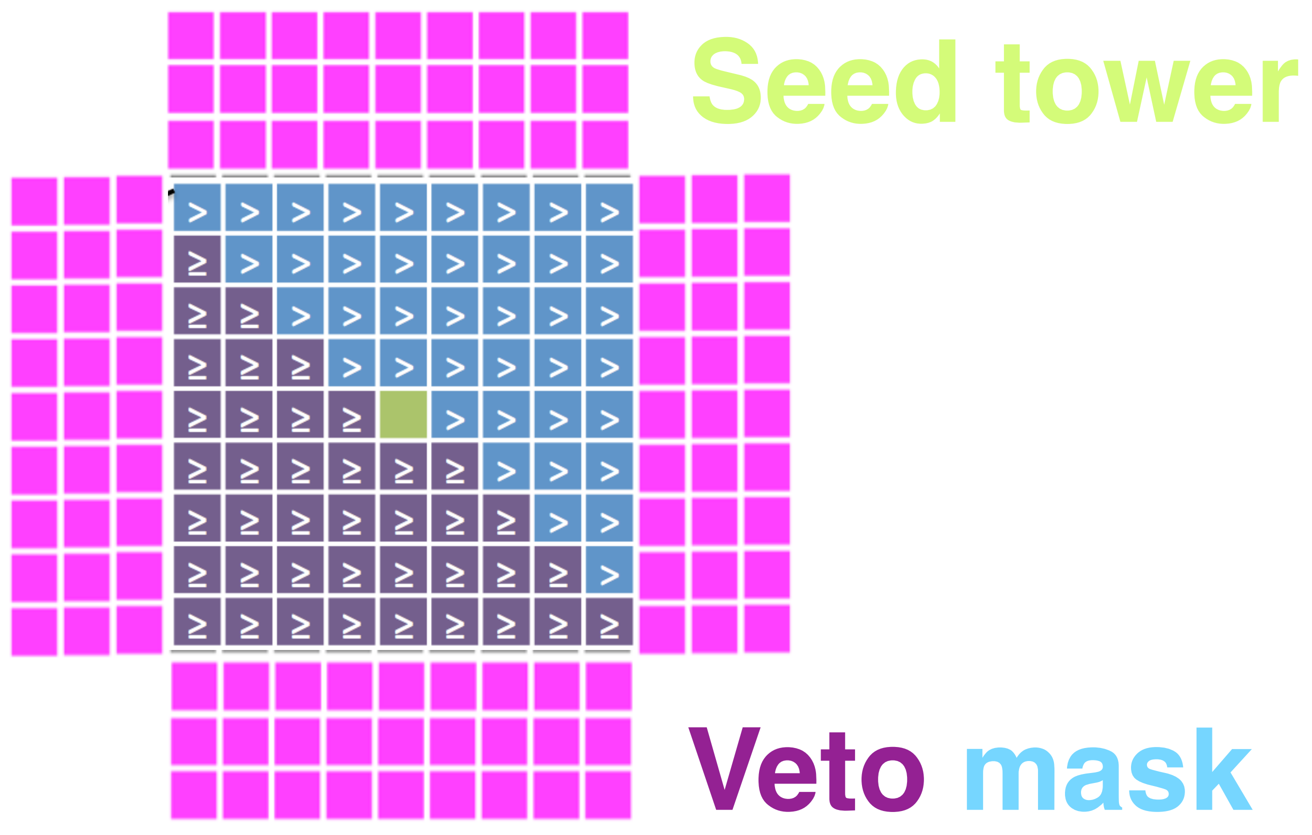


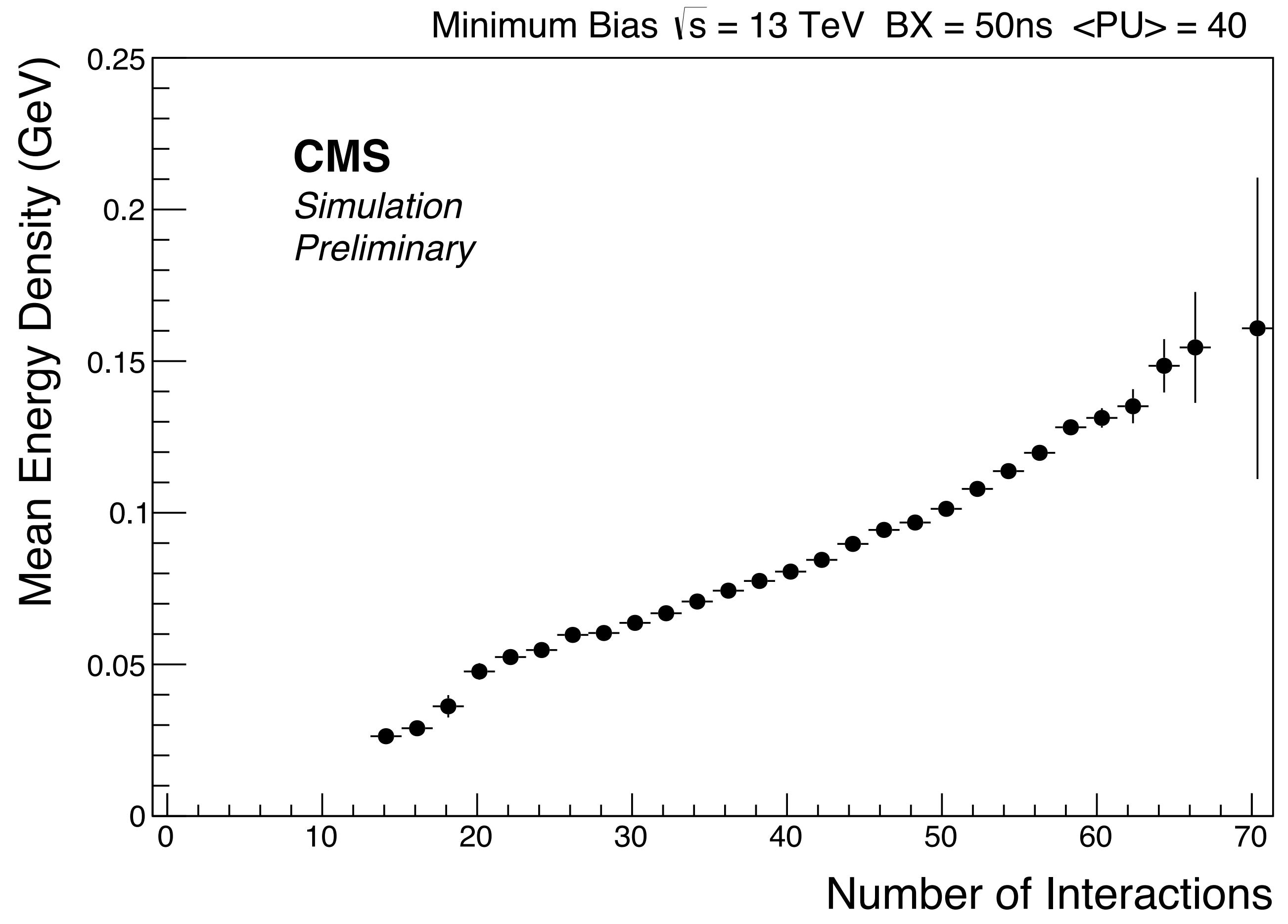


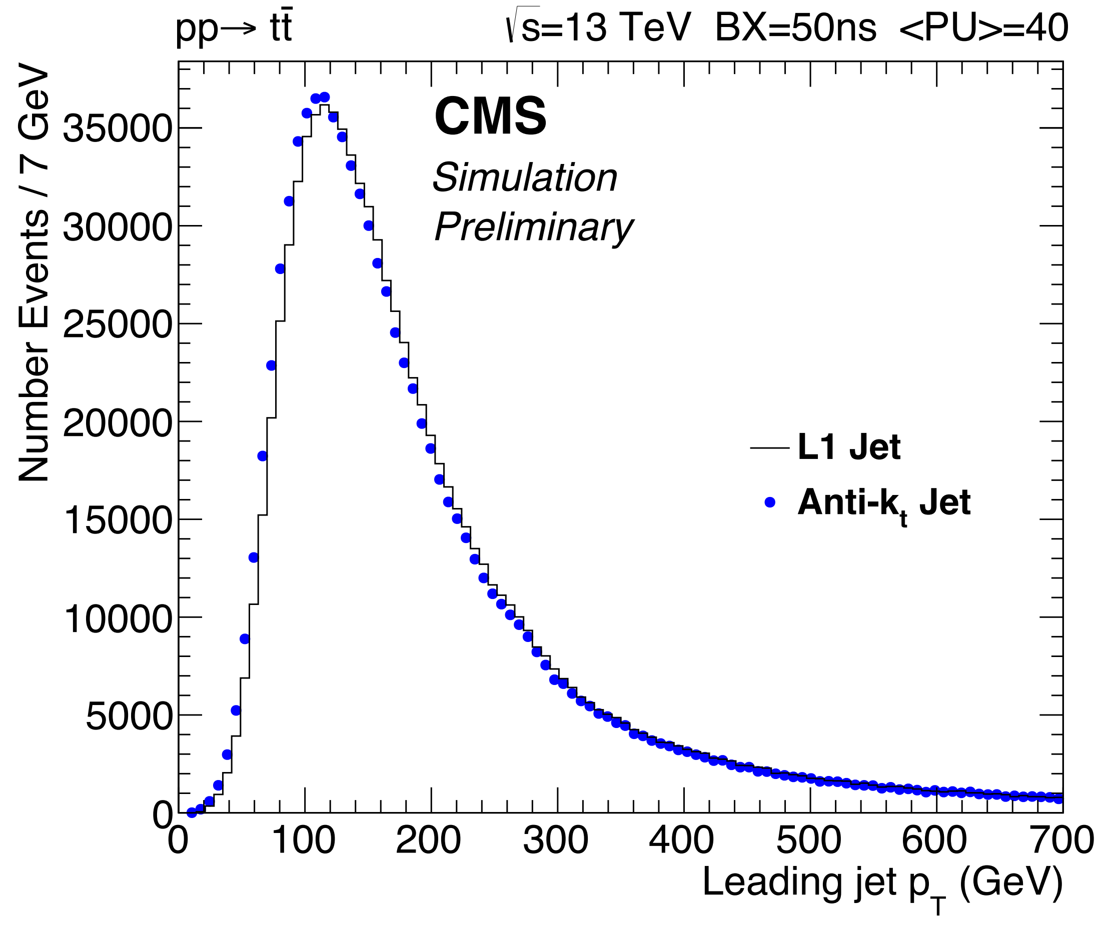


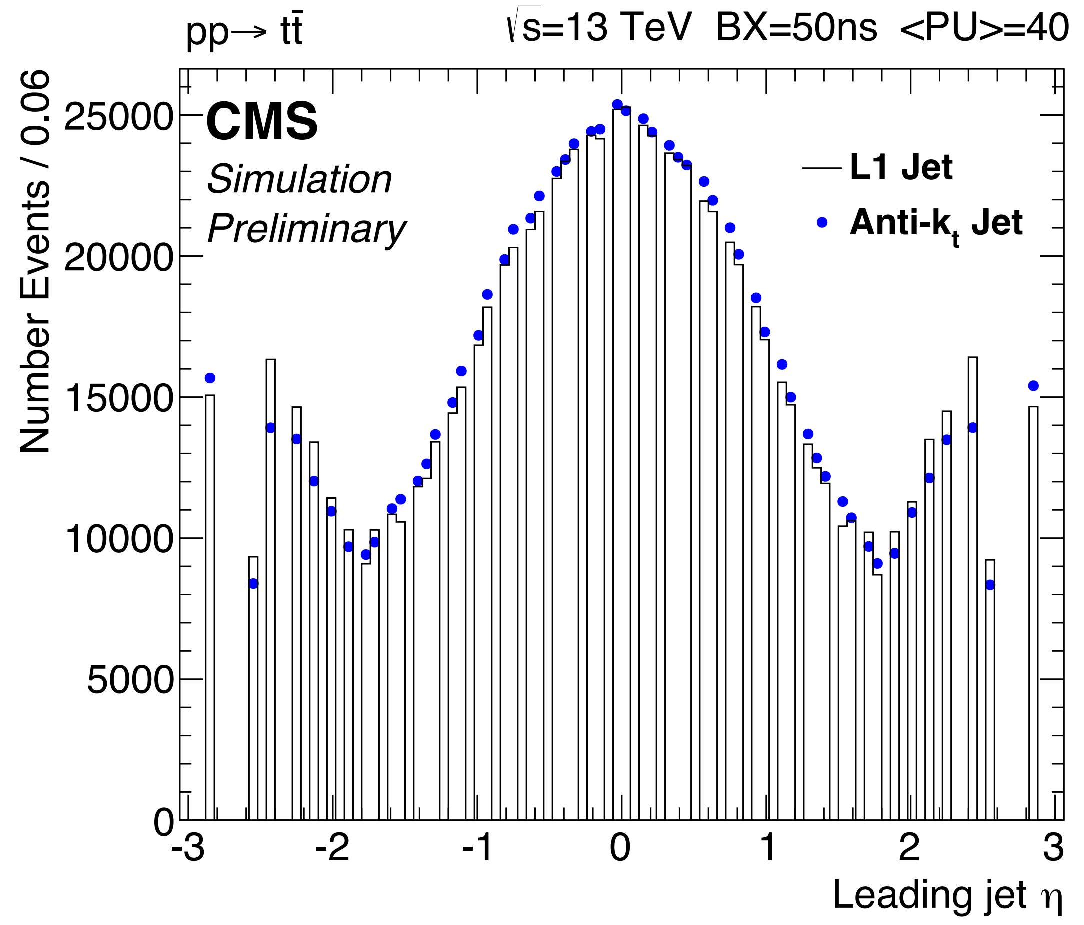
Jet algorithm performance

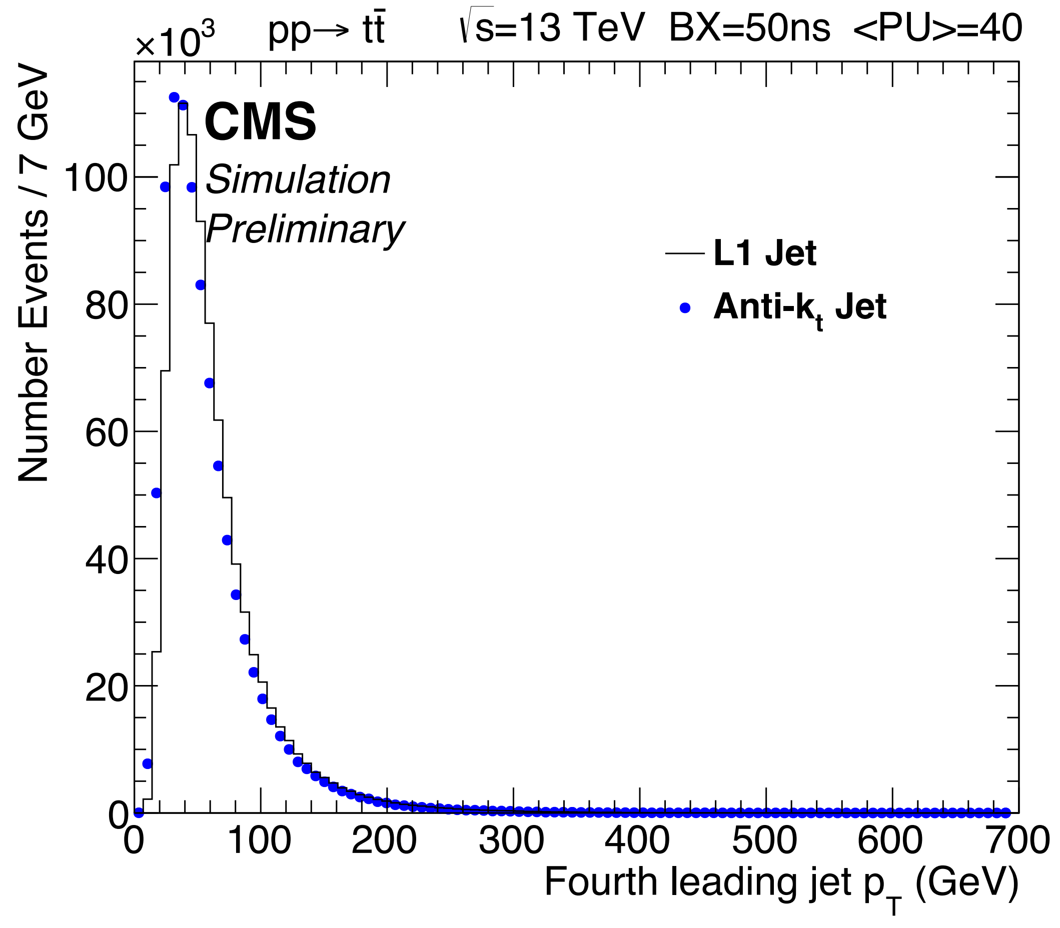
PUS areas

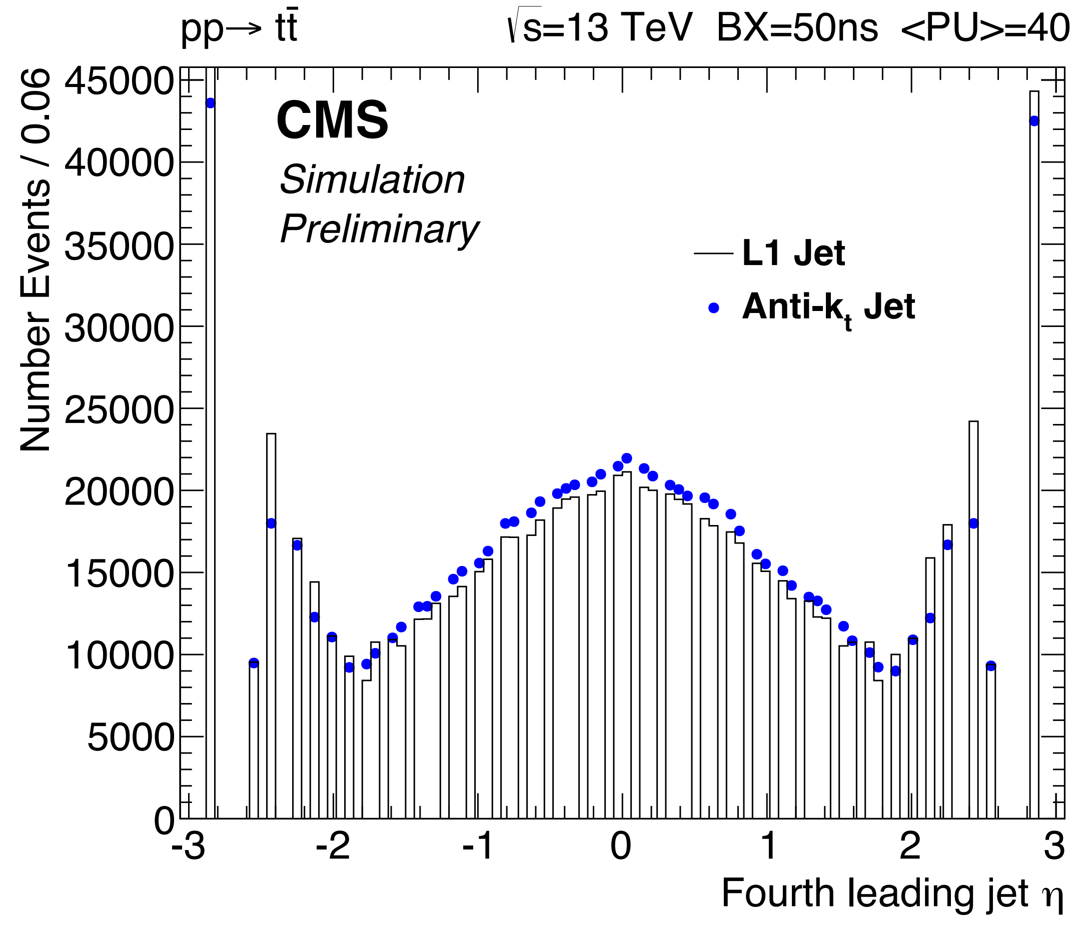




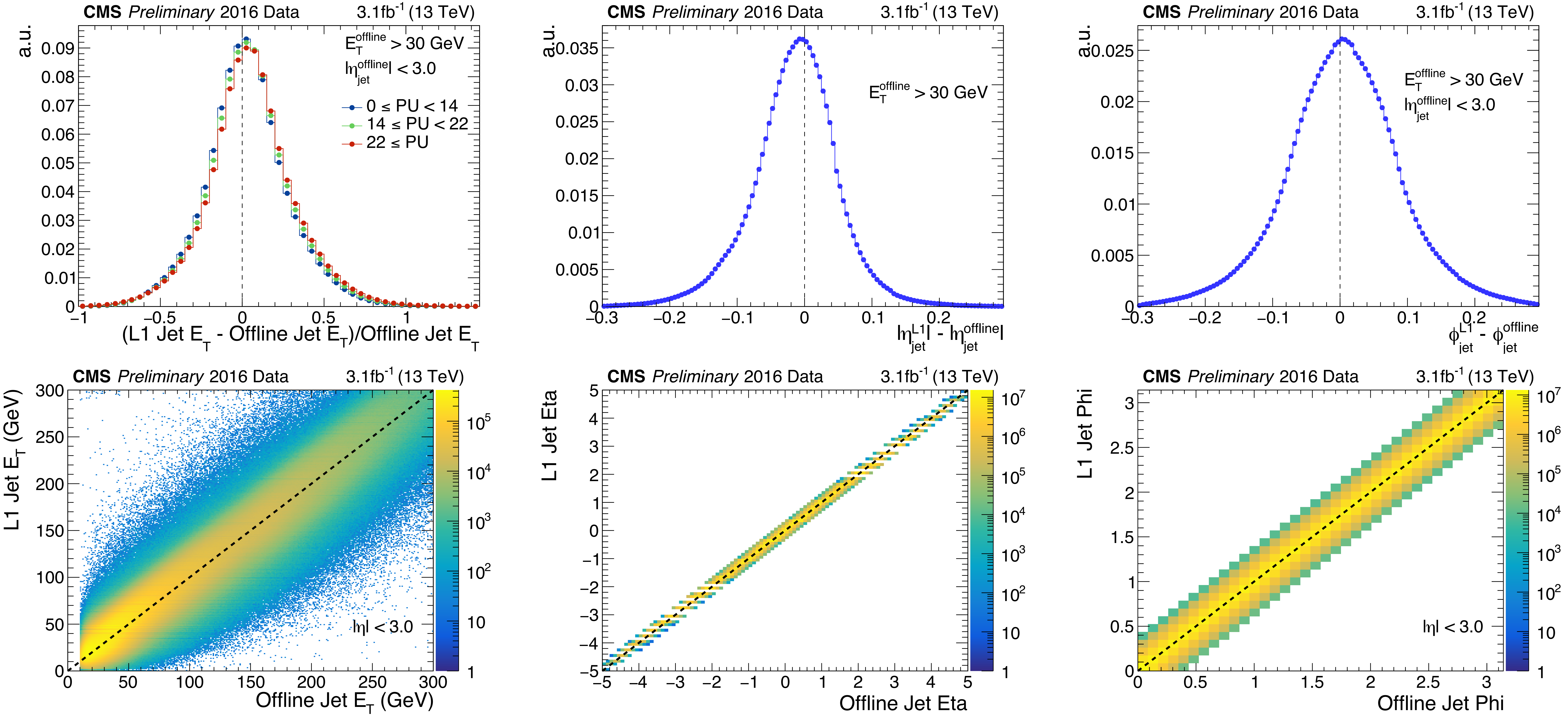




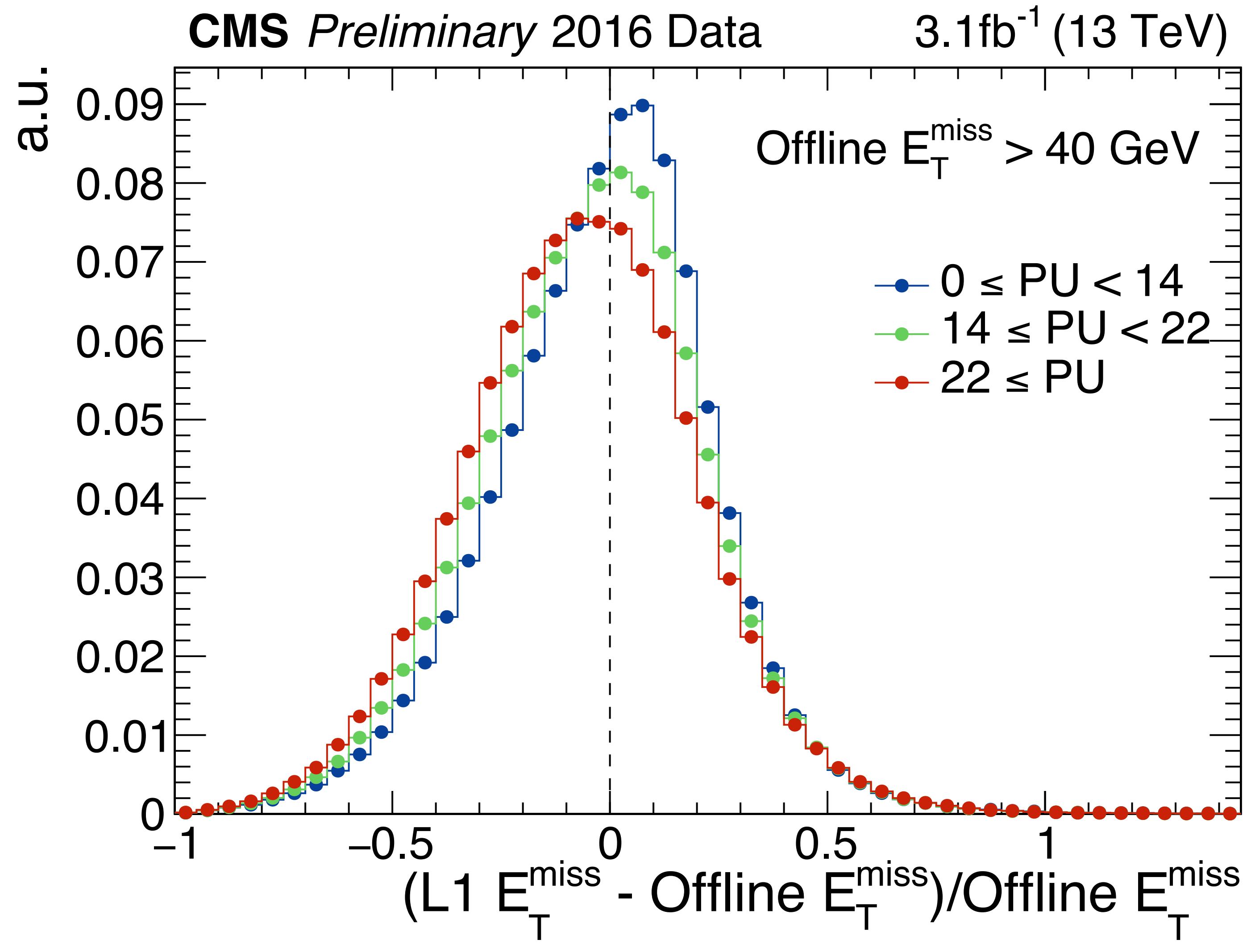


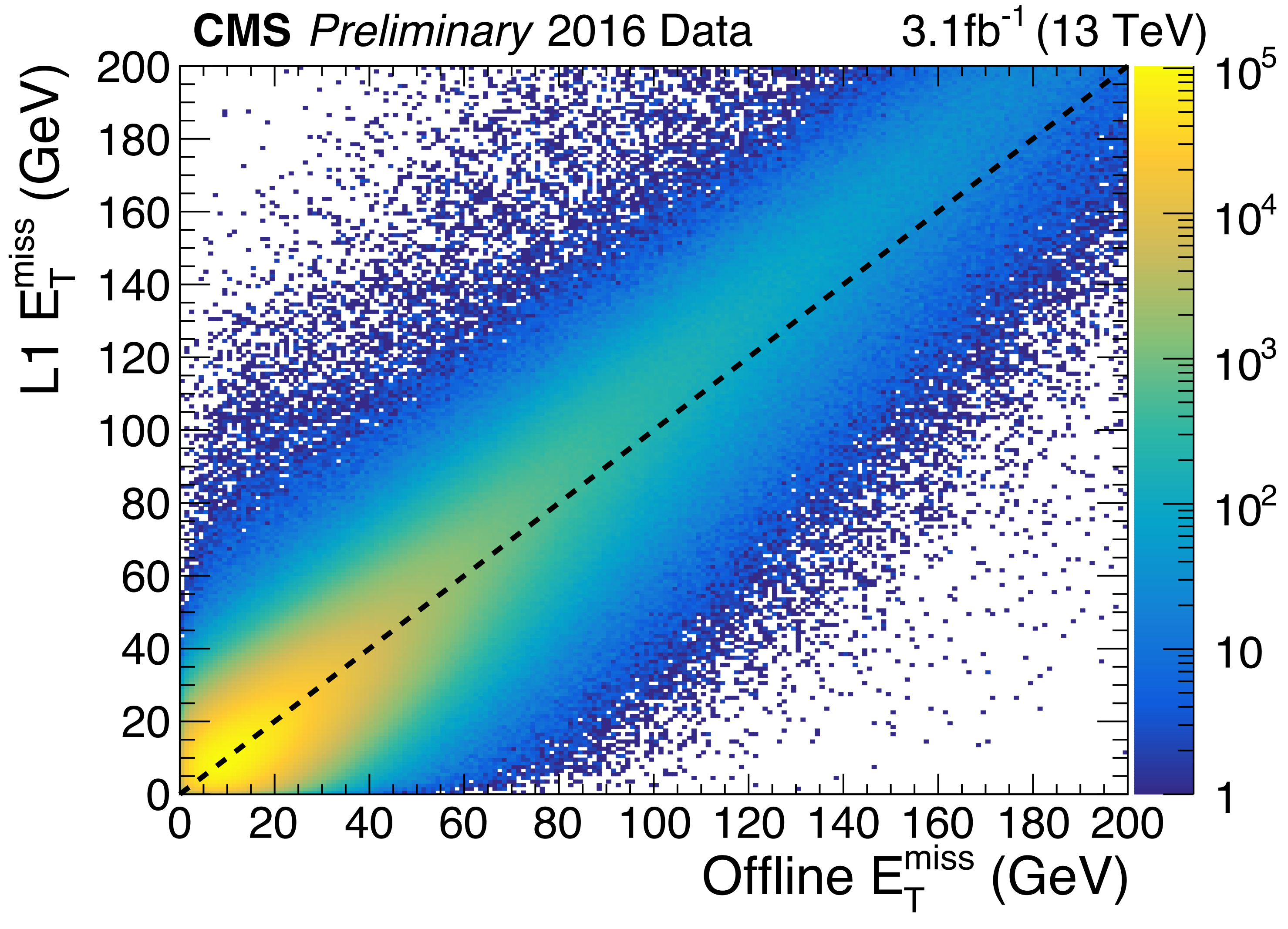


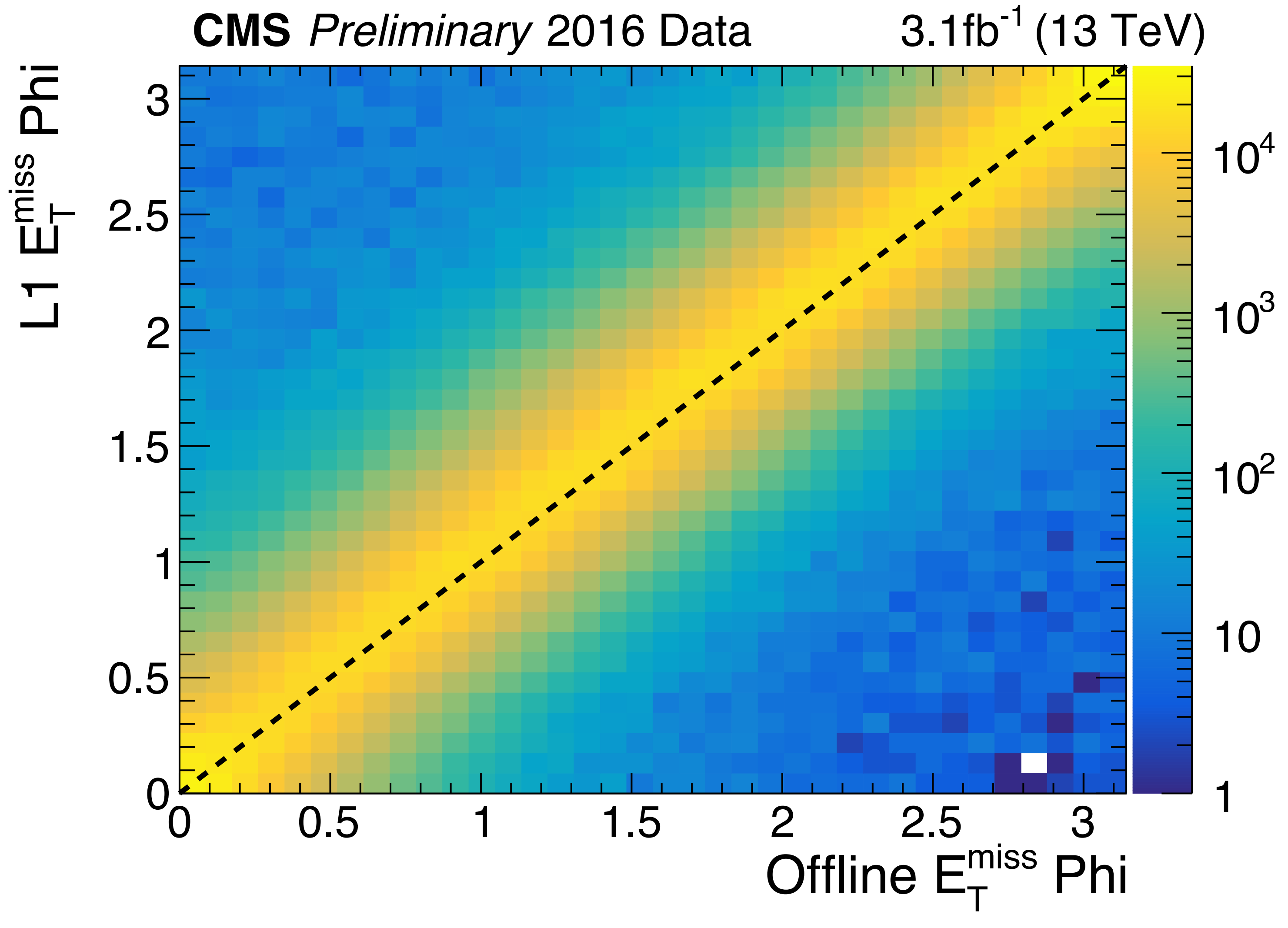
Jet reconstruction performance



MET reconstruction performance

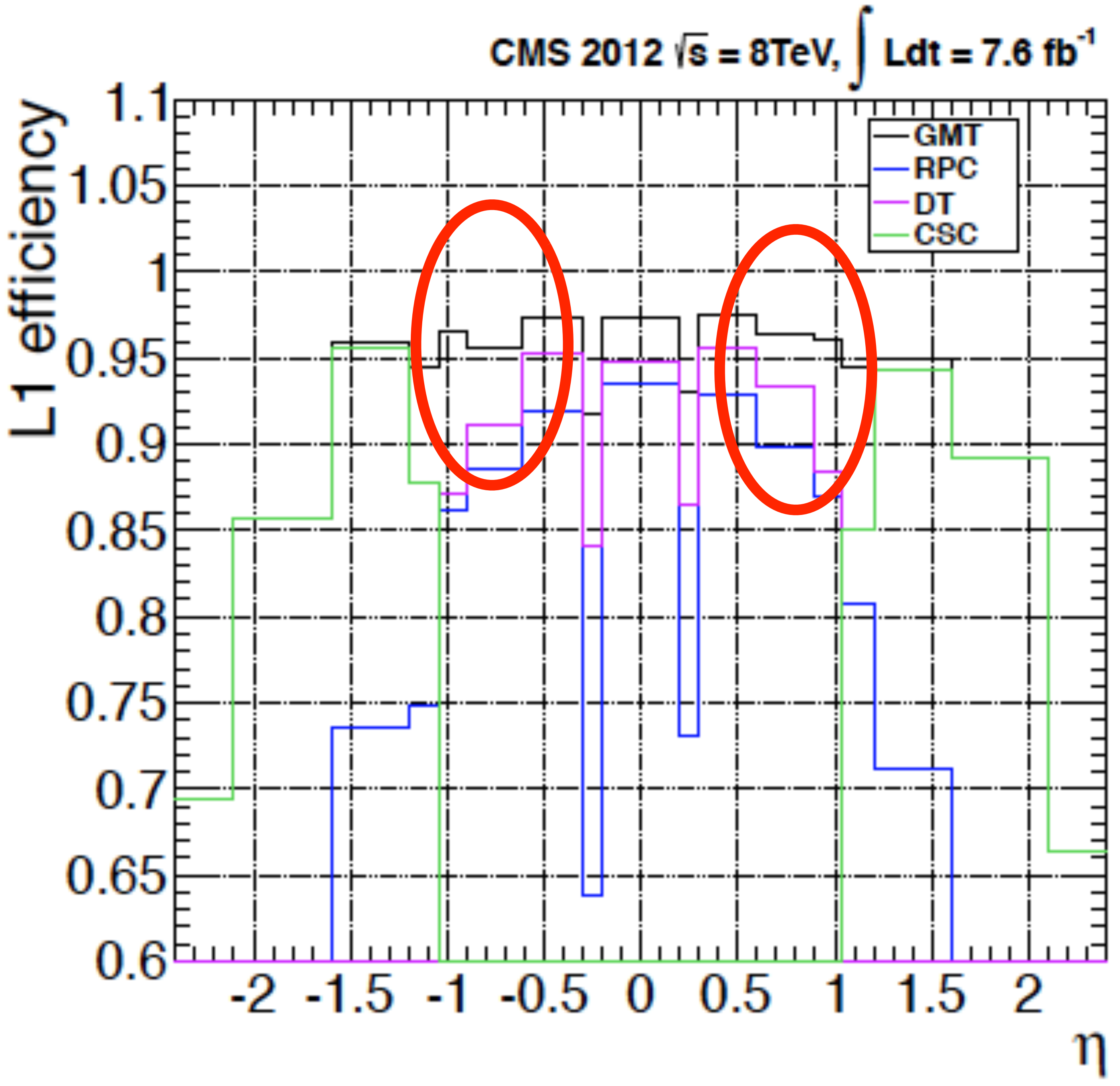


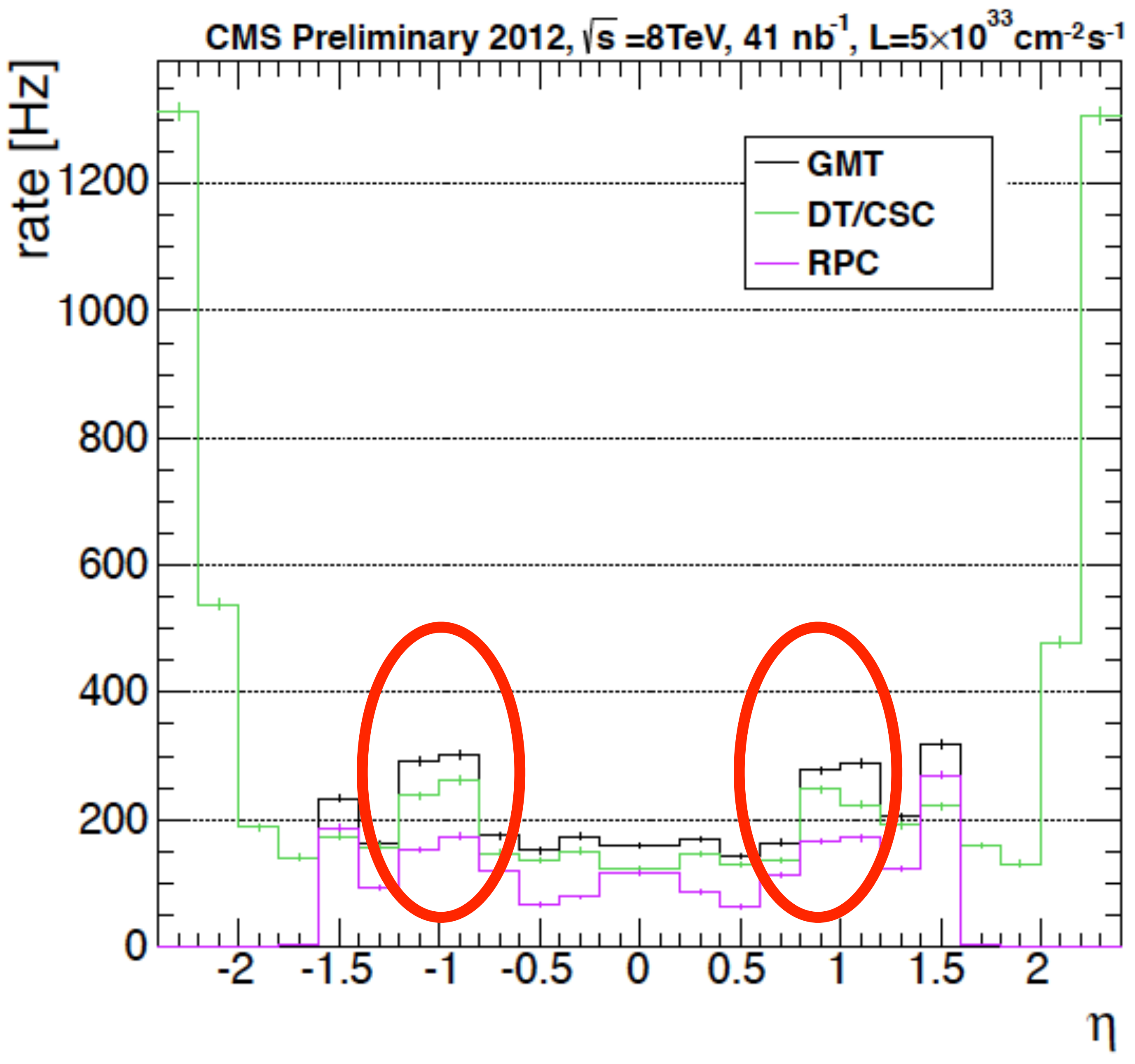




Legacy performance in overlap region

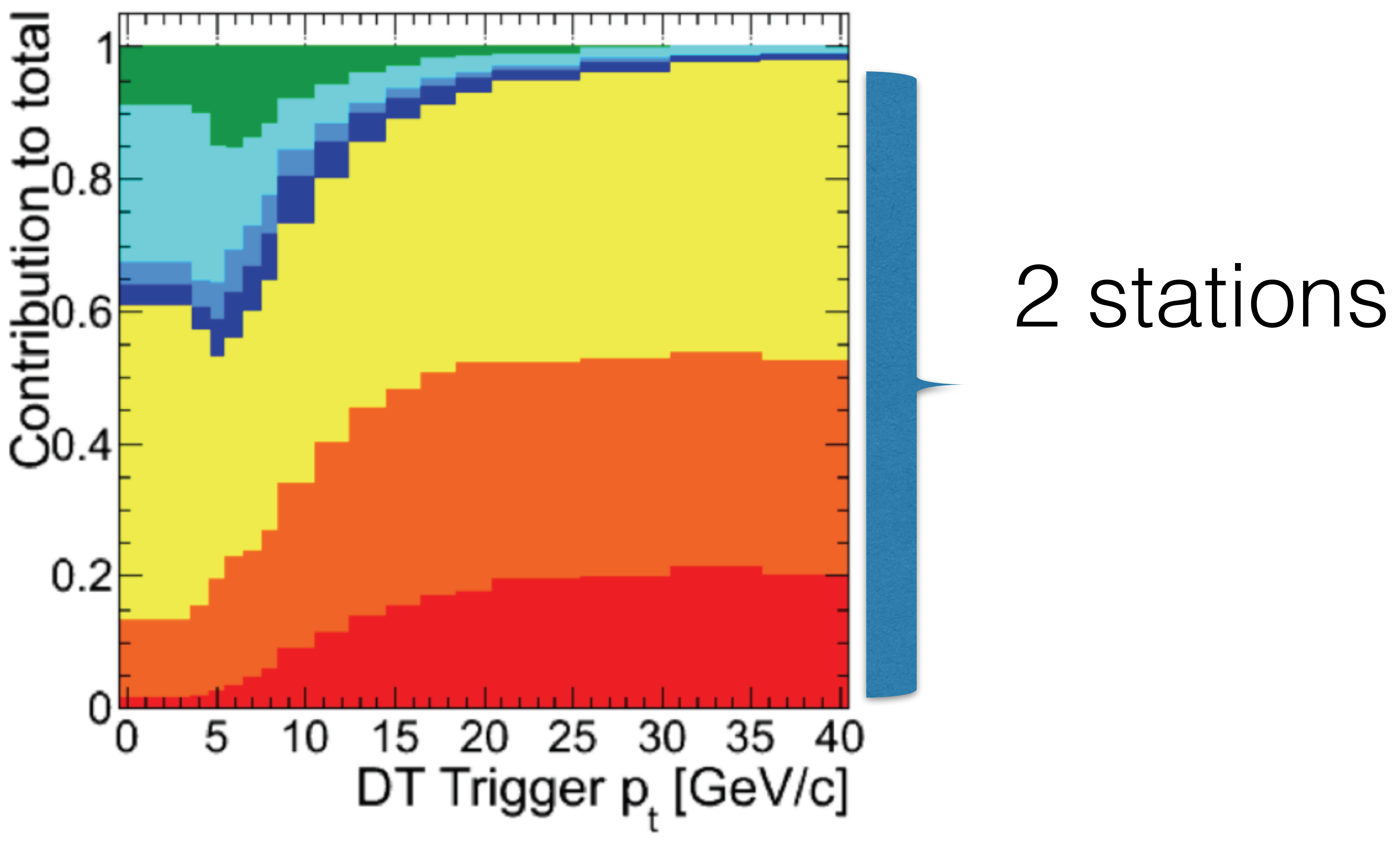
- Trigger efficiency for individual muon triggers was lower in overlap region
  - Only improved when combined by GMT
- Rate was higher in the overlap region (twice barrel rate per unit rapidity)





p_T>16 GeV

Combined μ Track-Finding



- For DT barrel trigger, 90% of the rate for p_T>15 GeV comes from tracks with only two station hits
- For CSC endcap trigger, majority of rate also comes from tracks with only two station hits. But 2/3 of such 2 station tracks have an RPC hit in another station
- p_T assignment algorithms, and resolution, are better with more track hits