The CMS Level-1 Trigger for LHC Run II

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Calorimetry for the High Energy Frontier

Lyon, France

2 - 6 October 2017

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

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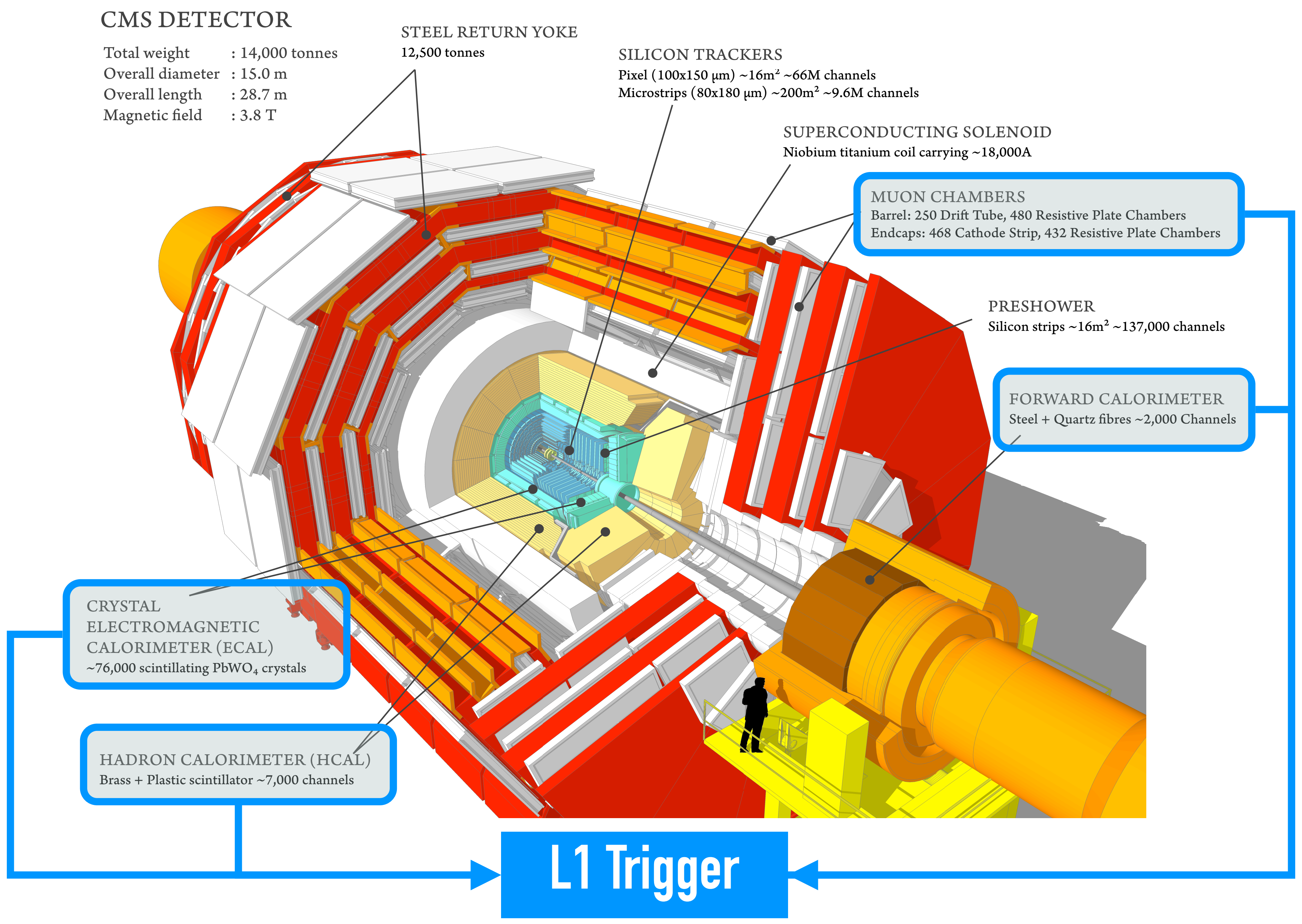
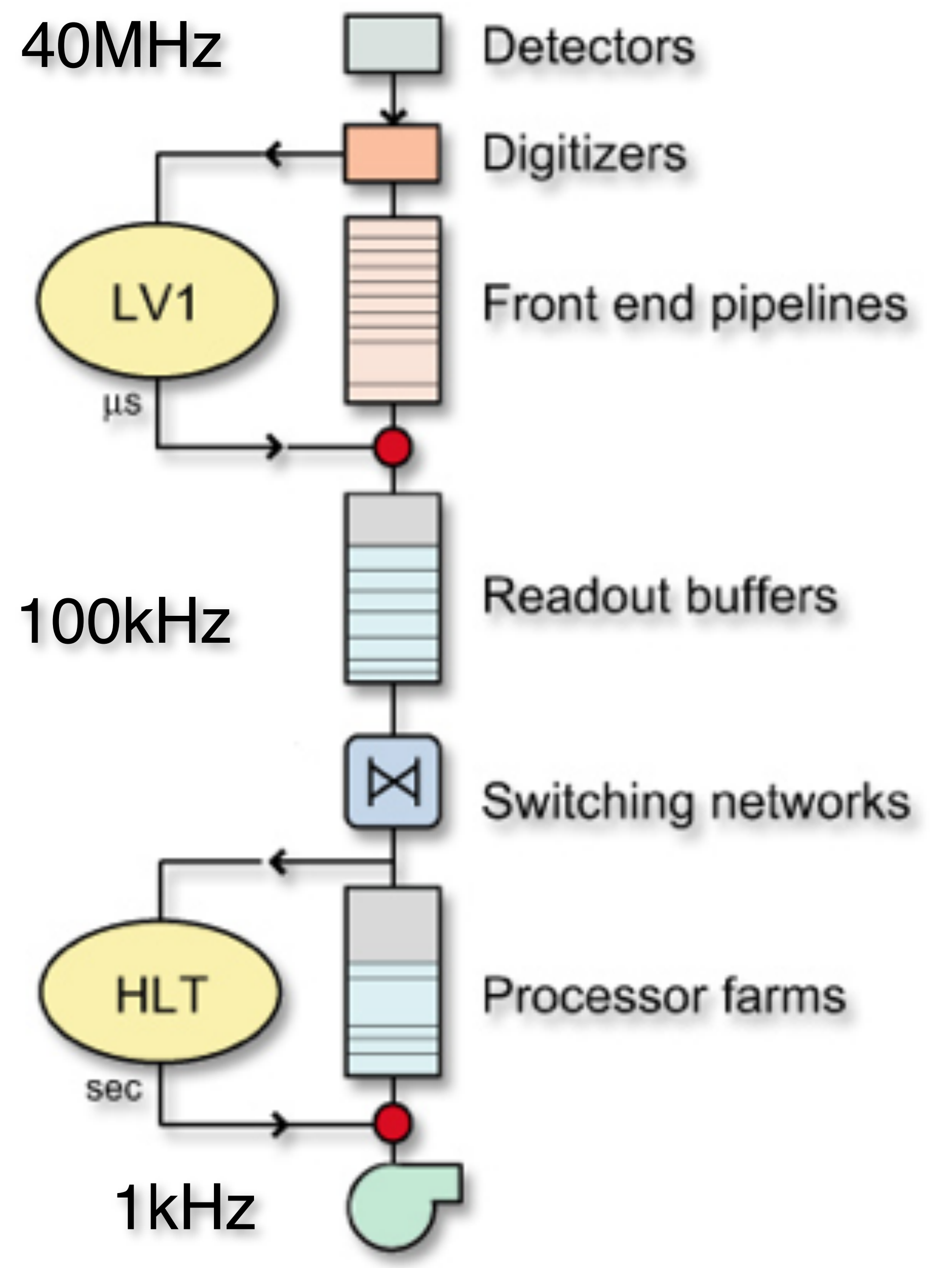
 CHEF2017: Calorimetry for the High Energy Frontier 2017, 2-6 October 2017, Lyon, France.

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

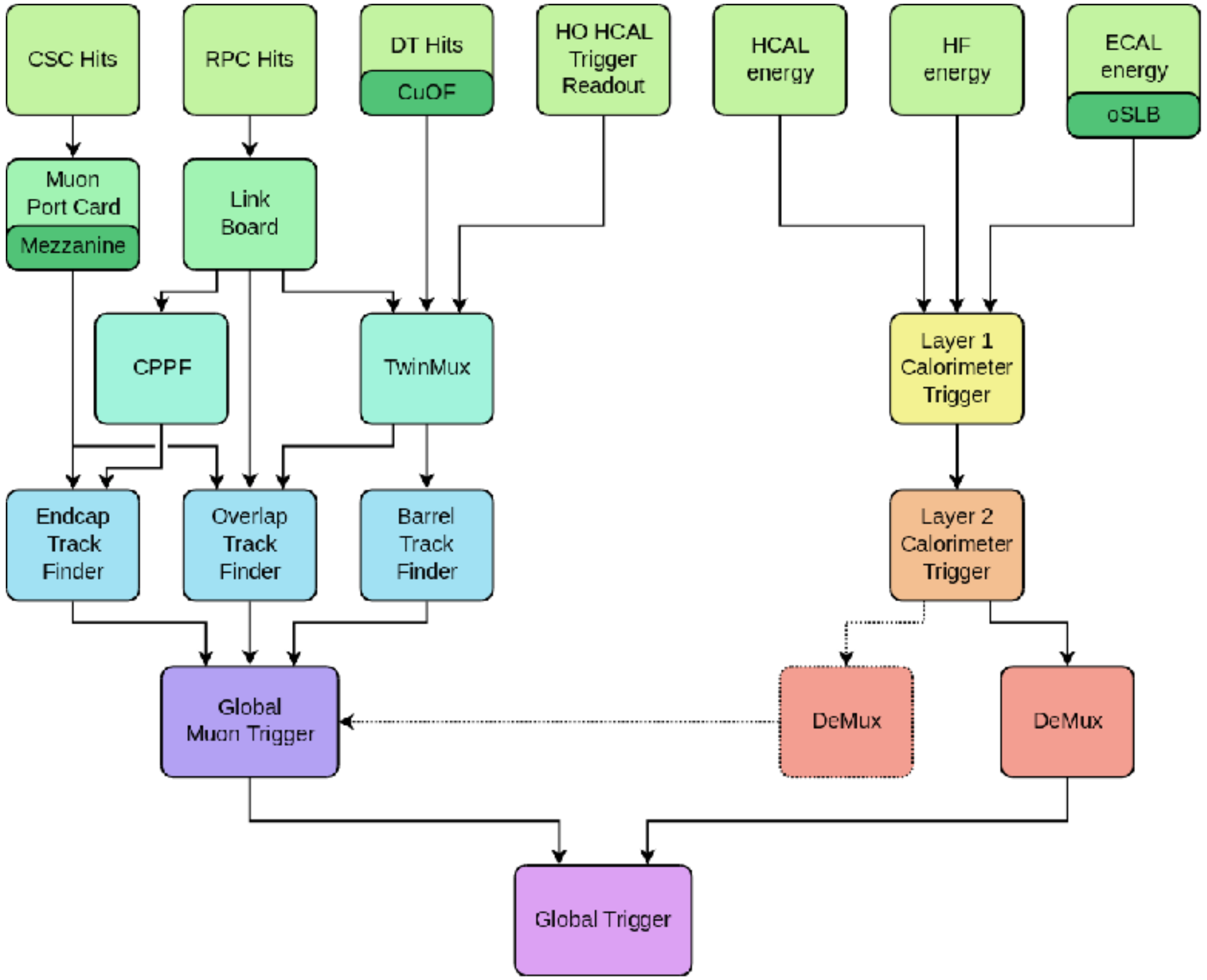




- L1 trigger upgraded in 2016
  - LHC Run II: increased luminosity and higher PU
  - Higher trigger rates but CMS detector electronics limited to L1 trigger rate of 100 kHz
  - Upgrade necessary to maintain sensitivity to electroweak scale physics and for TeV scale searches as in Run I

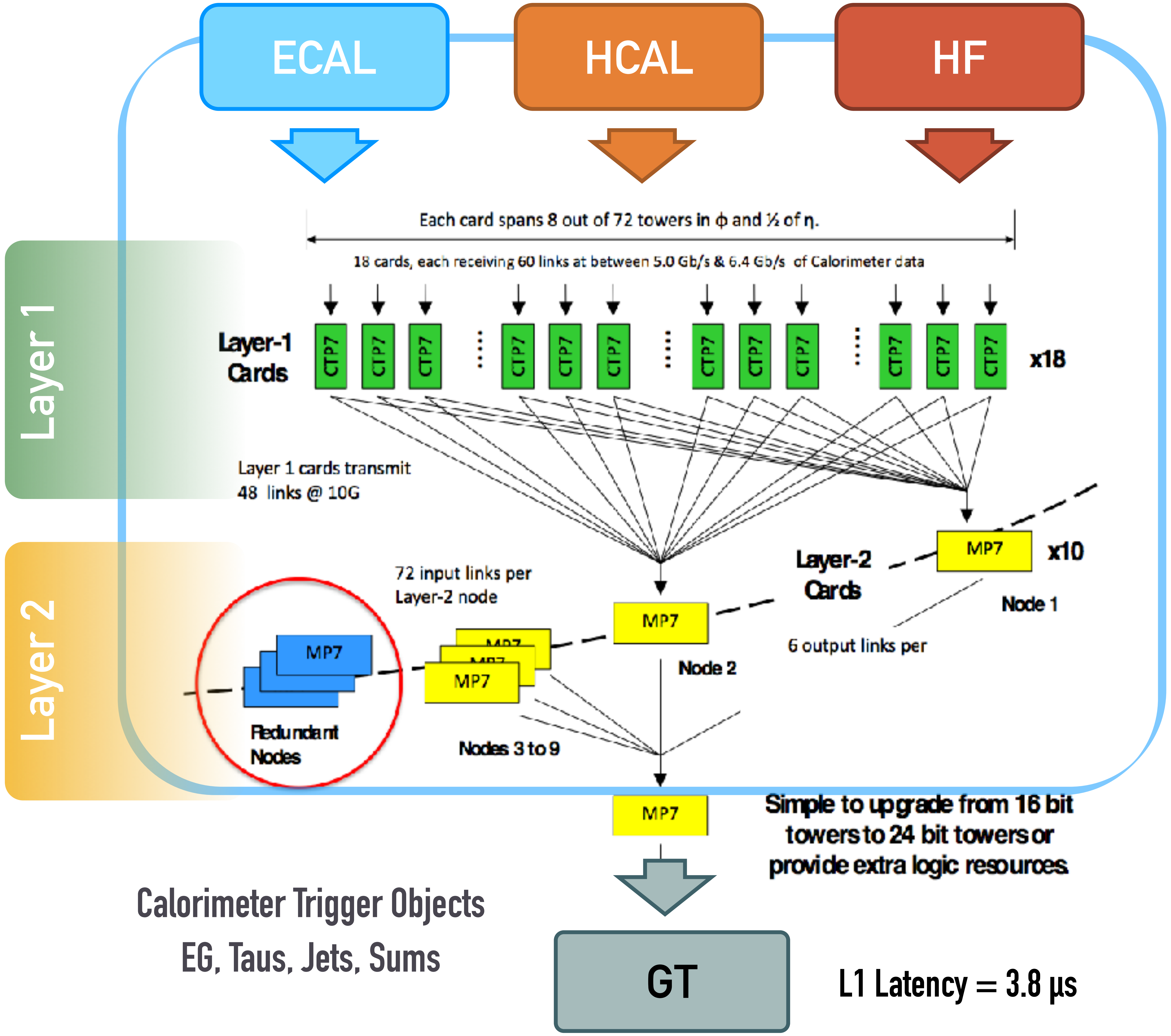
System overview

- 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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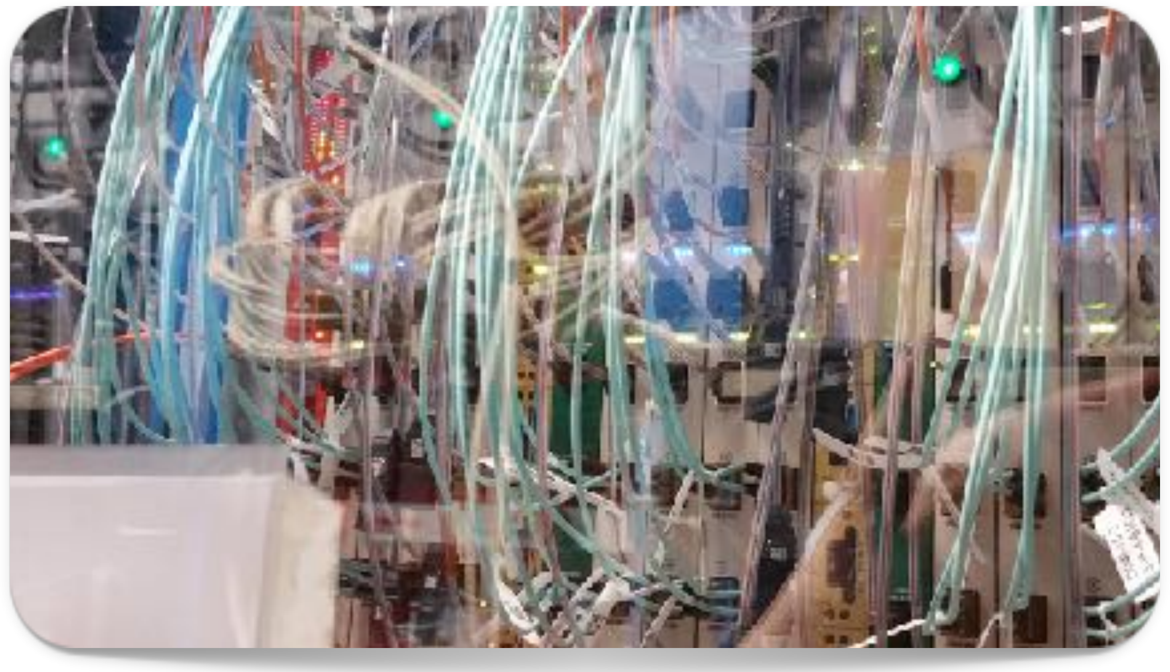
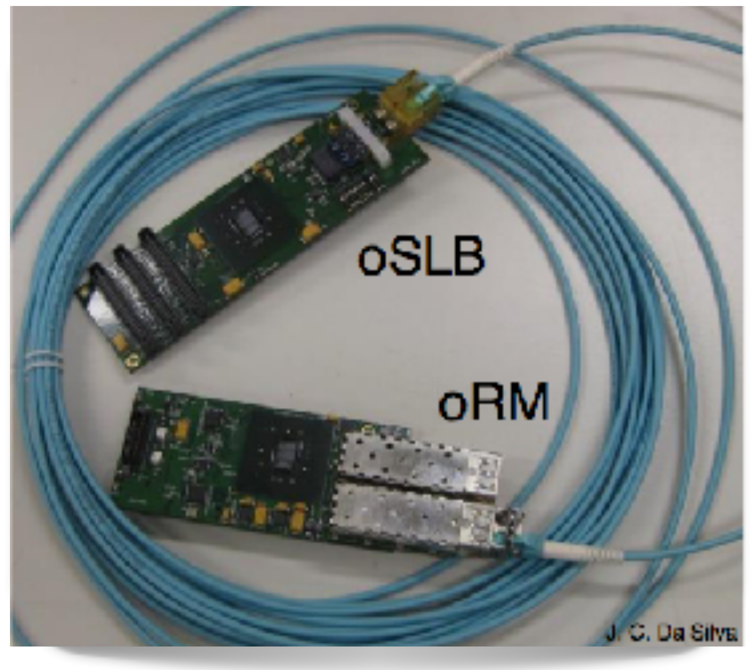
Optical input links

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



ECAL: 576 × 4.8 Gb/s links

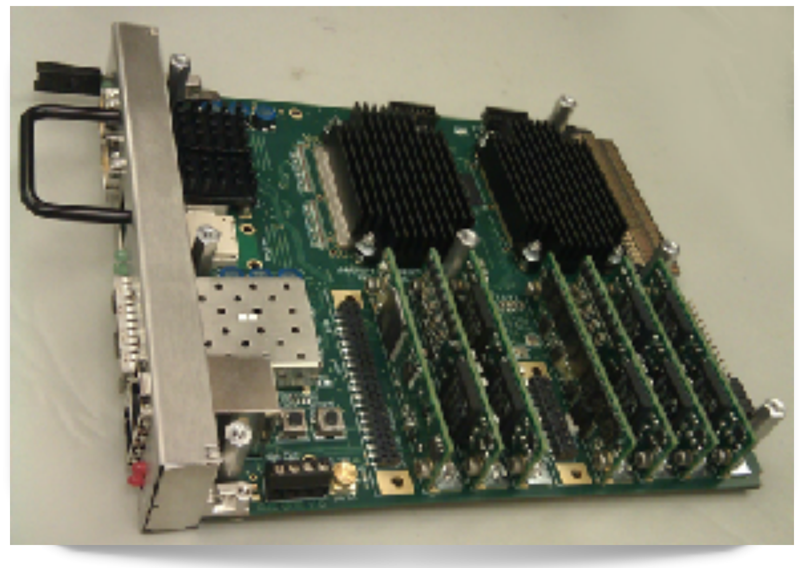


Optical Synchronisation Link Board

CERN VTTx to commercial SFP

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

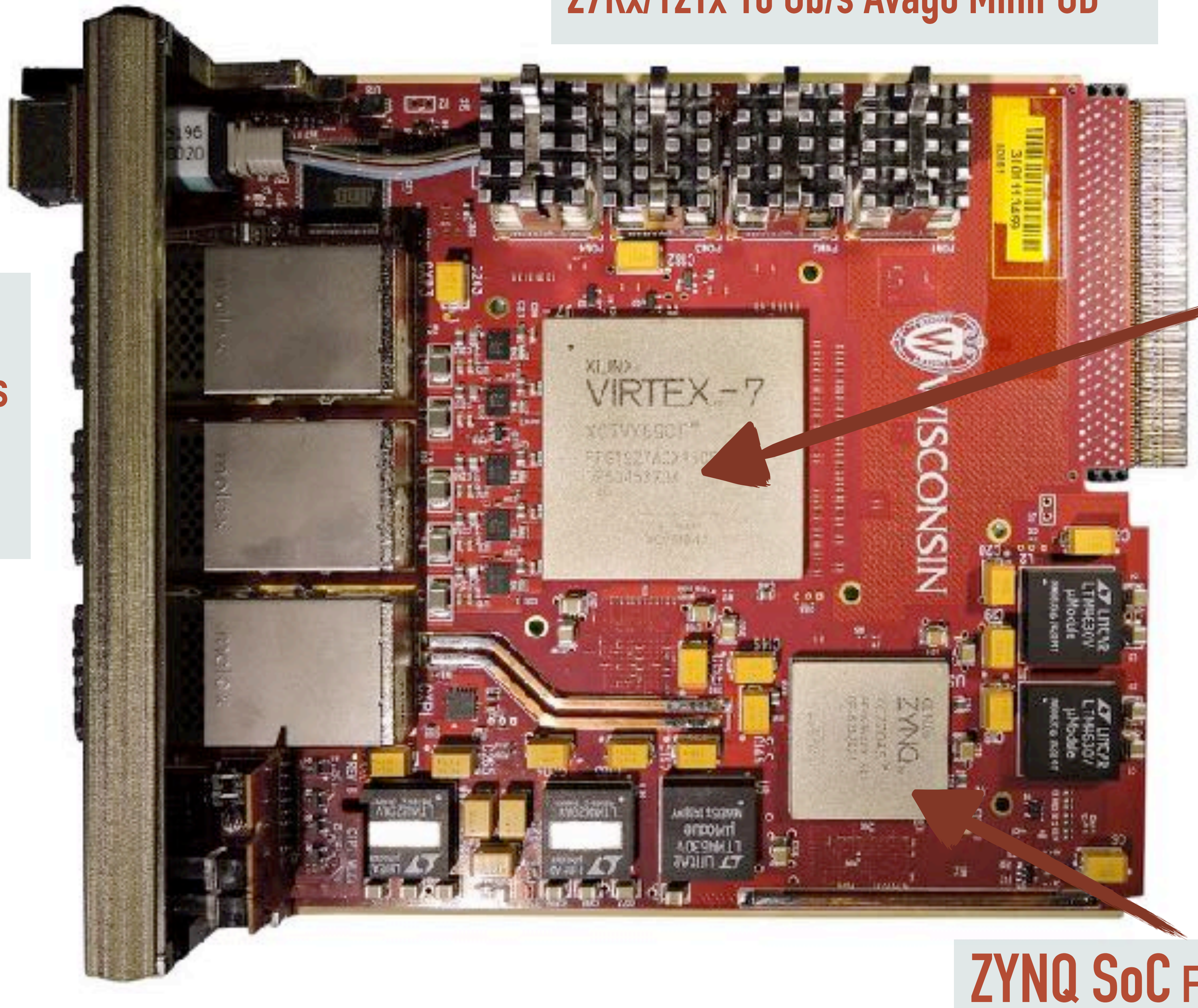
576+504+72 links in total (ECAL, HCAL, HF) = **1152 links**

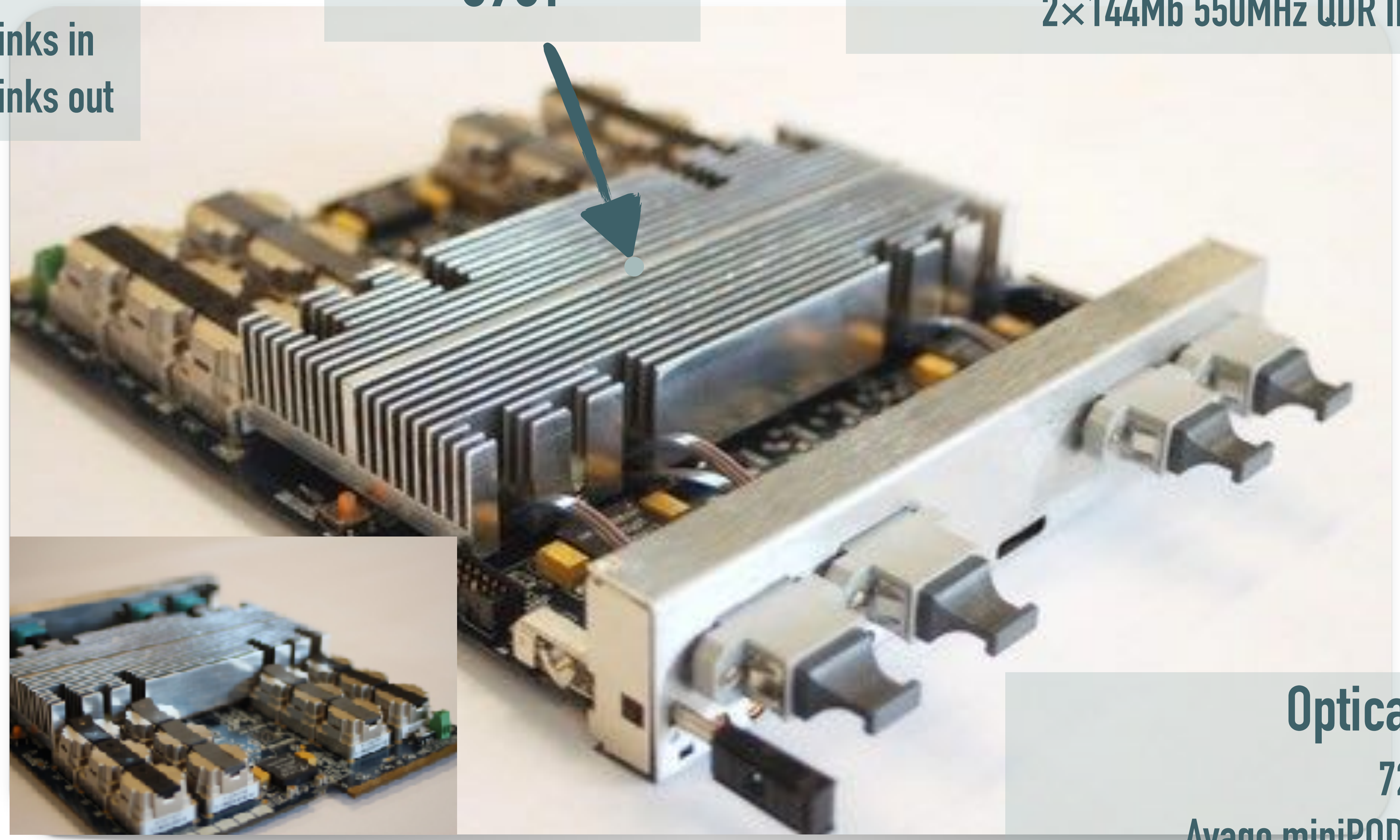
Processors

CTP7 Calorimeter Trigger Processor

Layer 1 - Pre-processing

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



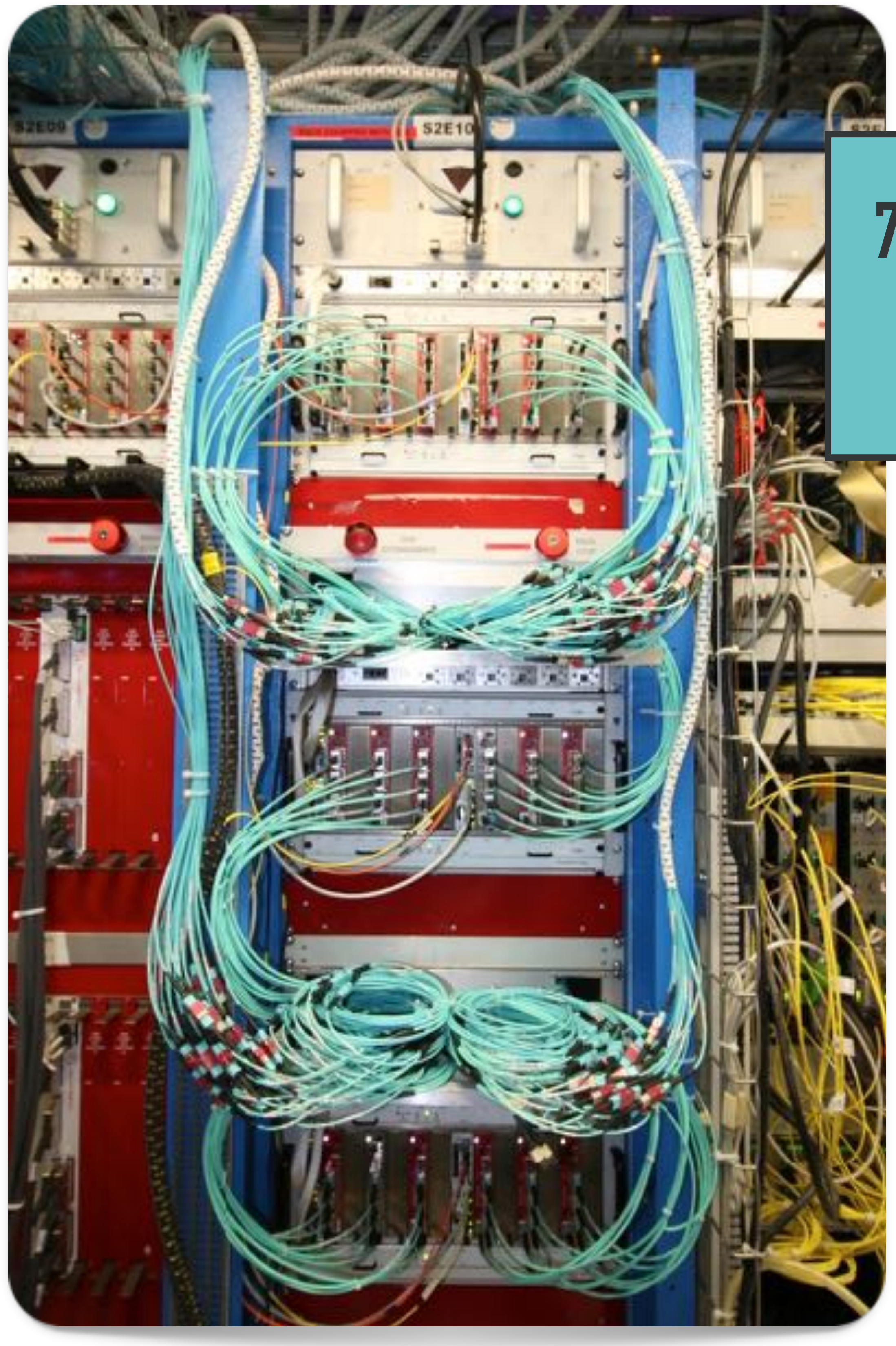


MP7 Master Processor

Layer 2 - Trigger Algorithms

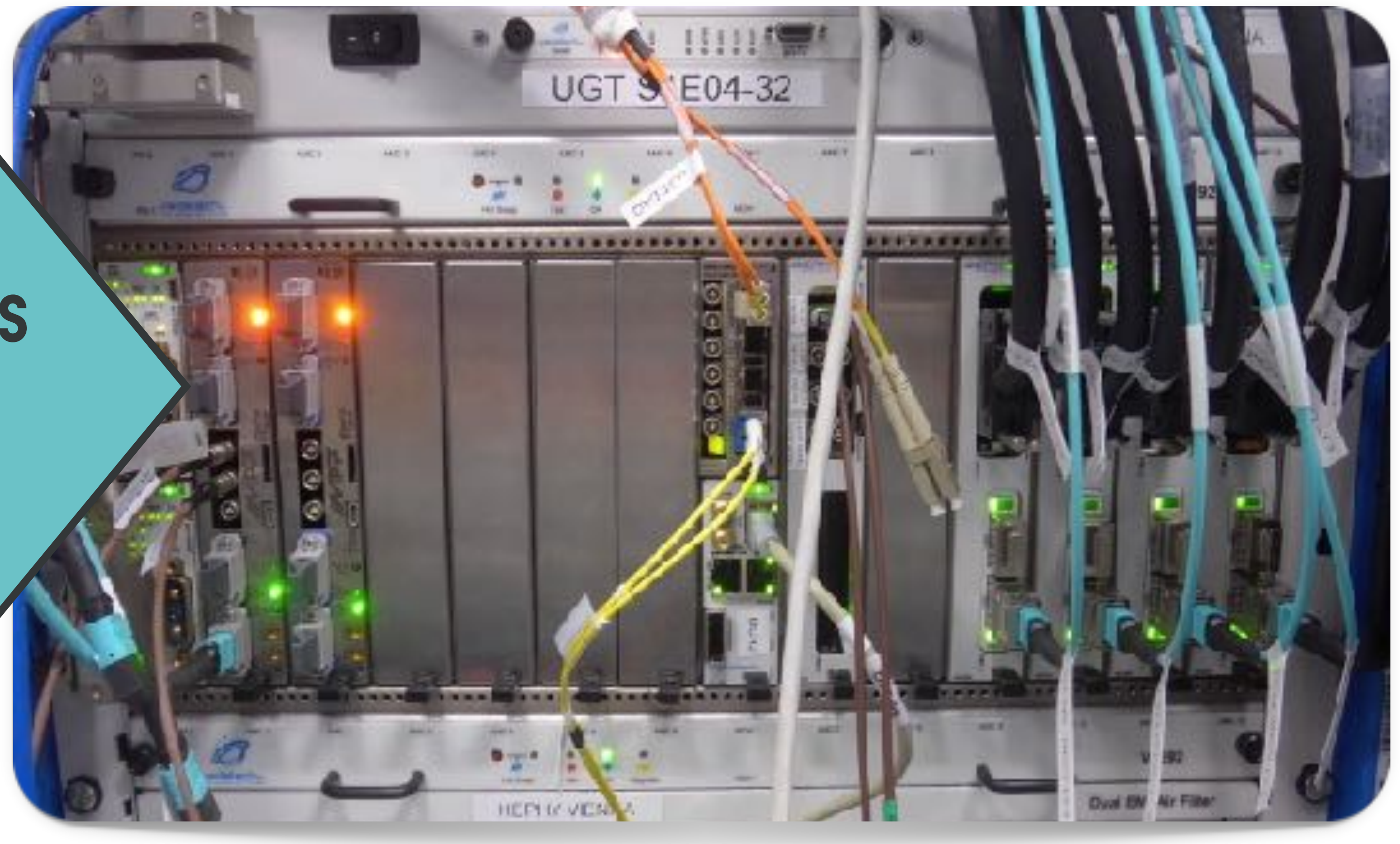
- Hosts most of the algorithms
- DAQ readout for monitoring

System Integration



720×10Gb/s links

8×10 Gb/s links

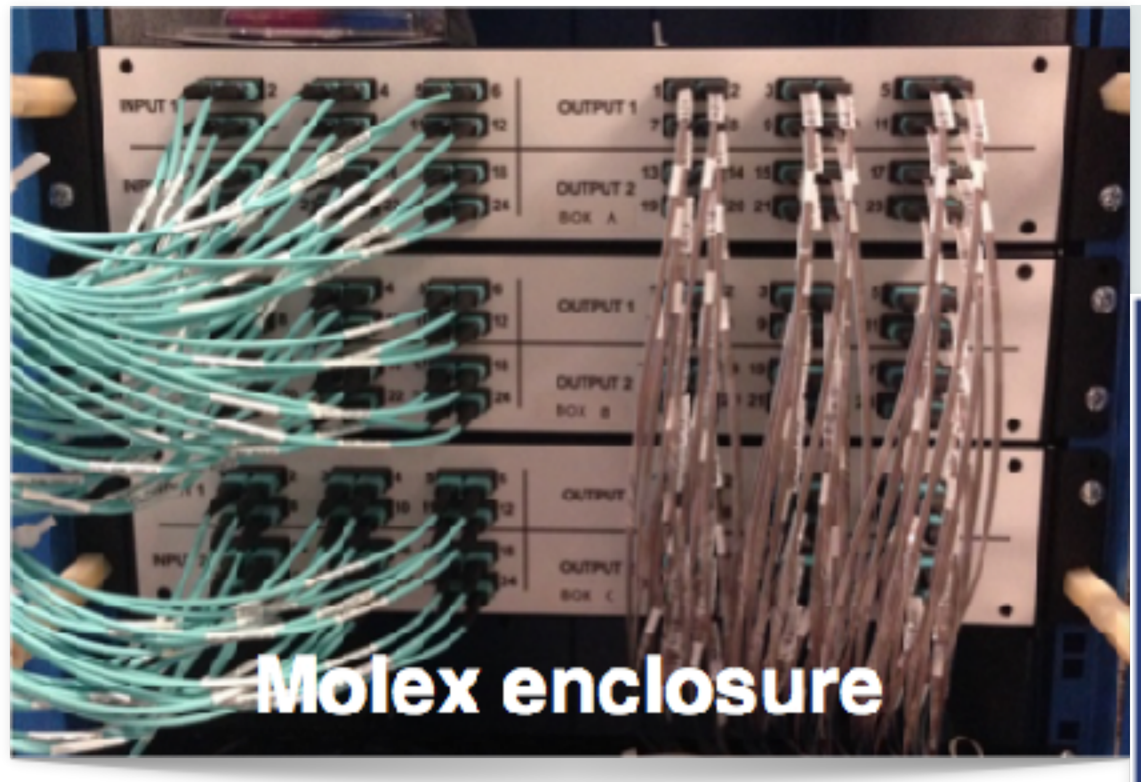


Layer 2
1 Vadatech VT894 Crate, 10 MP7 boards

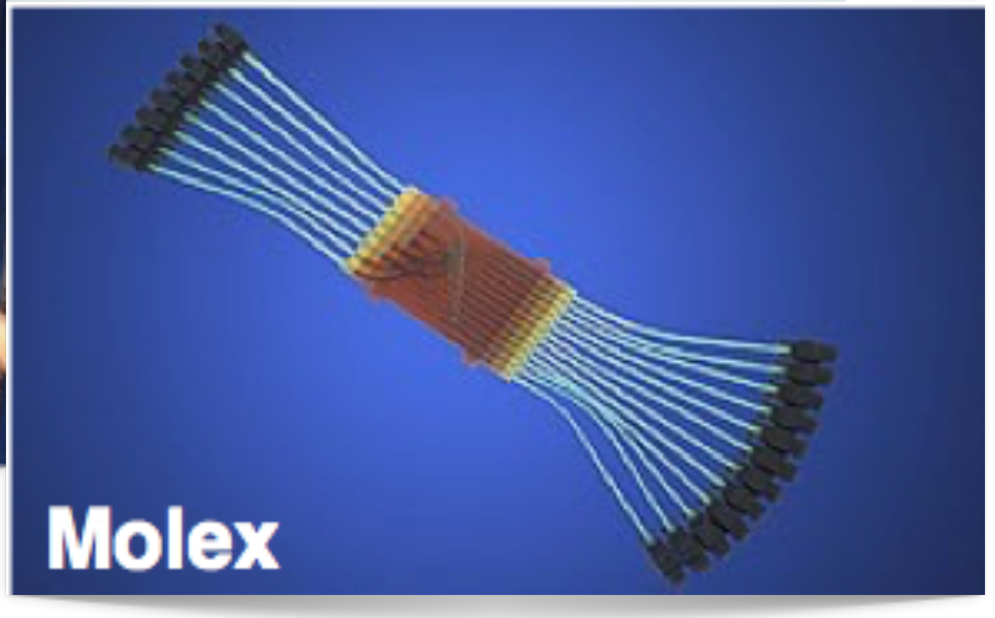
Global Trigger
receives 12 electron/photon + 12 Tau iso/non-iso candidates + 12 Jets and sums.

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-fibre MPO connectors



Molex Enclosure
Flexplane (commercial)



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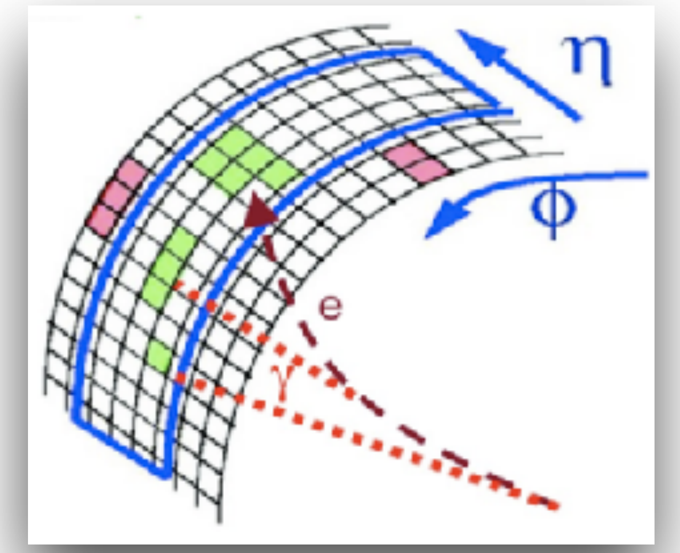
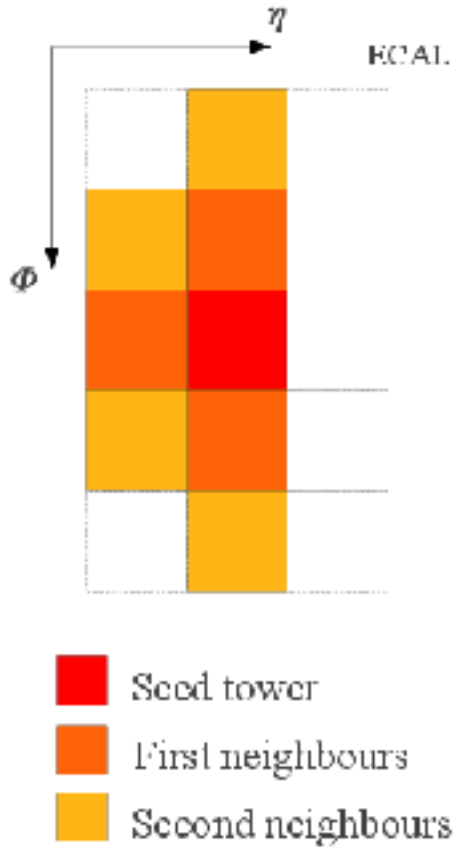
e/γ finder algorithm

Electrons in CMS

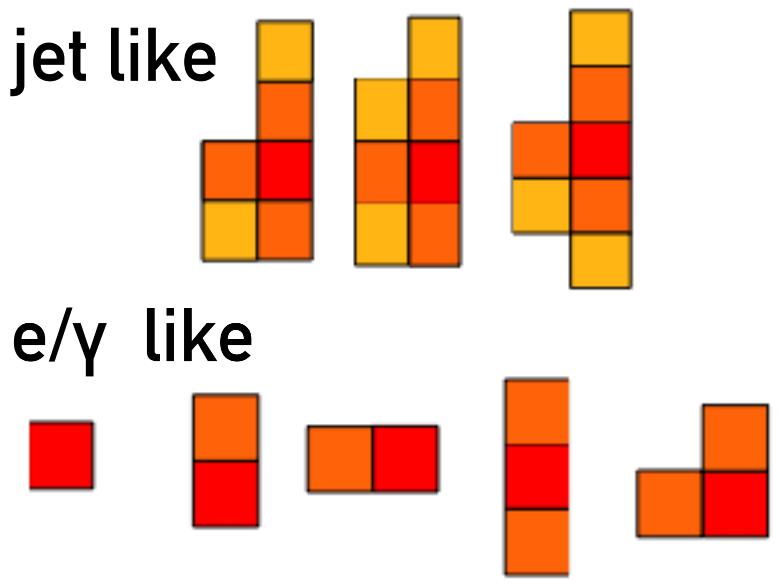


Cluster building

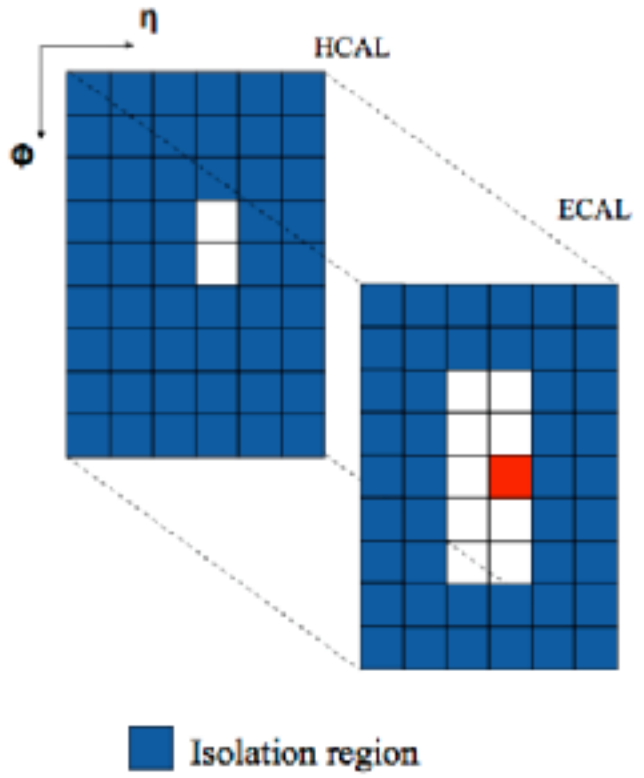


ηxφ
0.087x0.087

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

Isolation

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

Calibration

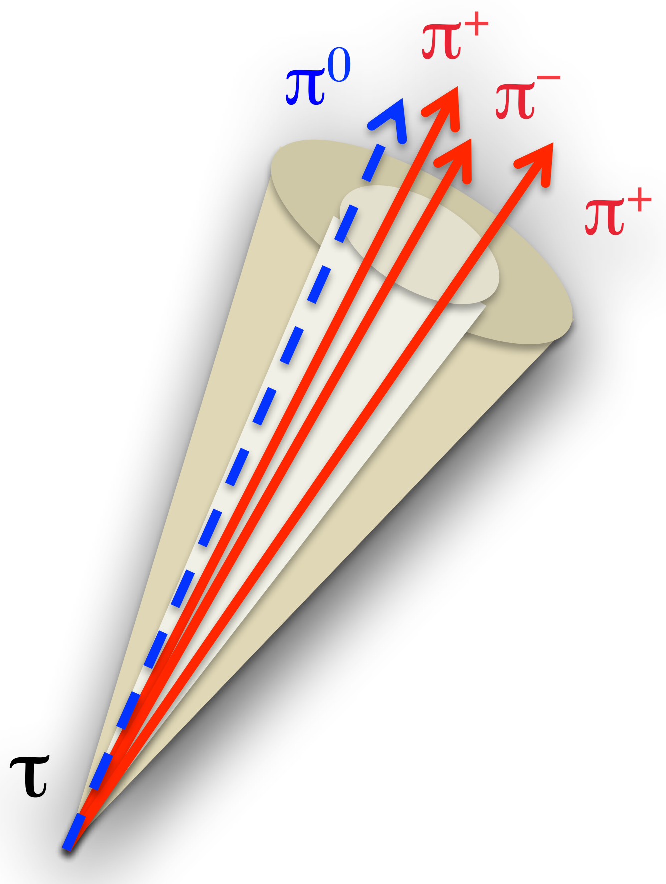
e/γ cluster energy calibrated as fn. of E_T, η and cluster shape

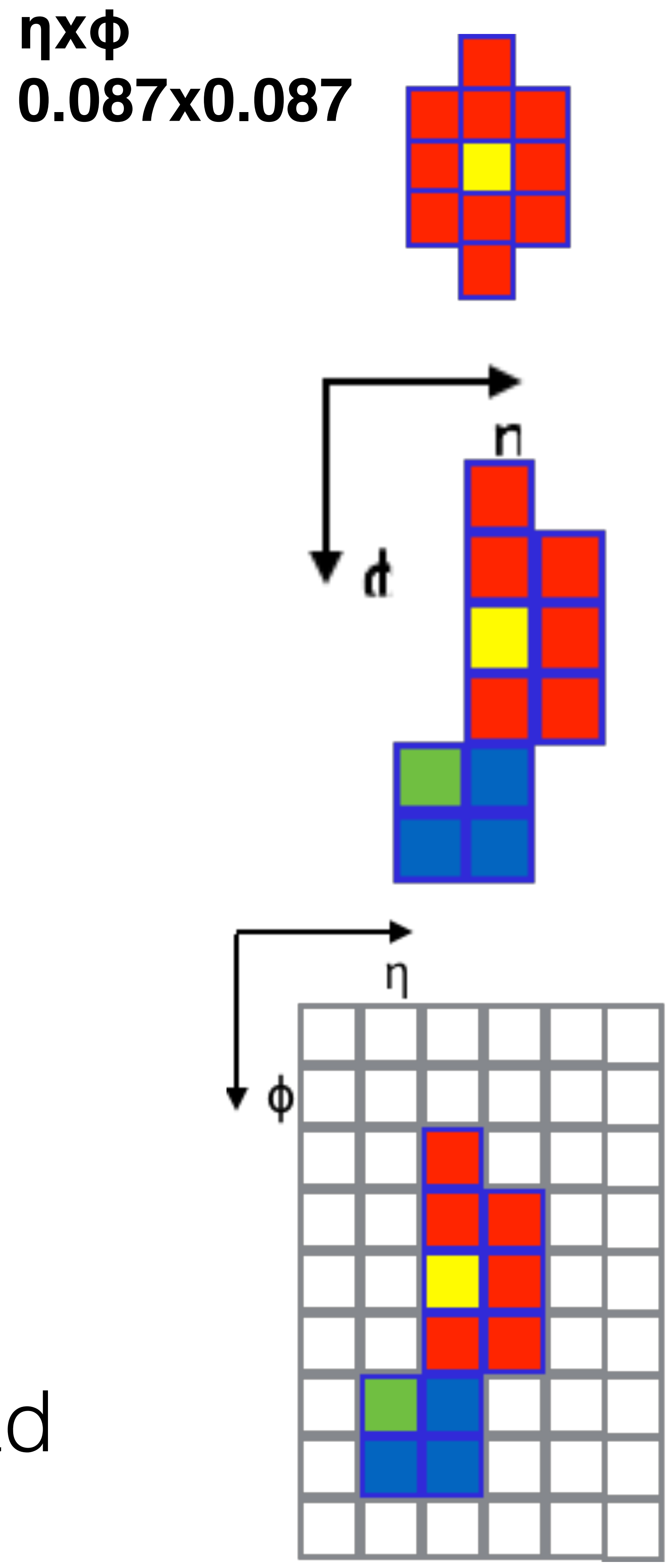
Energy weighted position

Potential use in correlating objects e.g. invariant mass

Tau finder algorithm

Tau decay topology





- **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

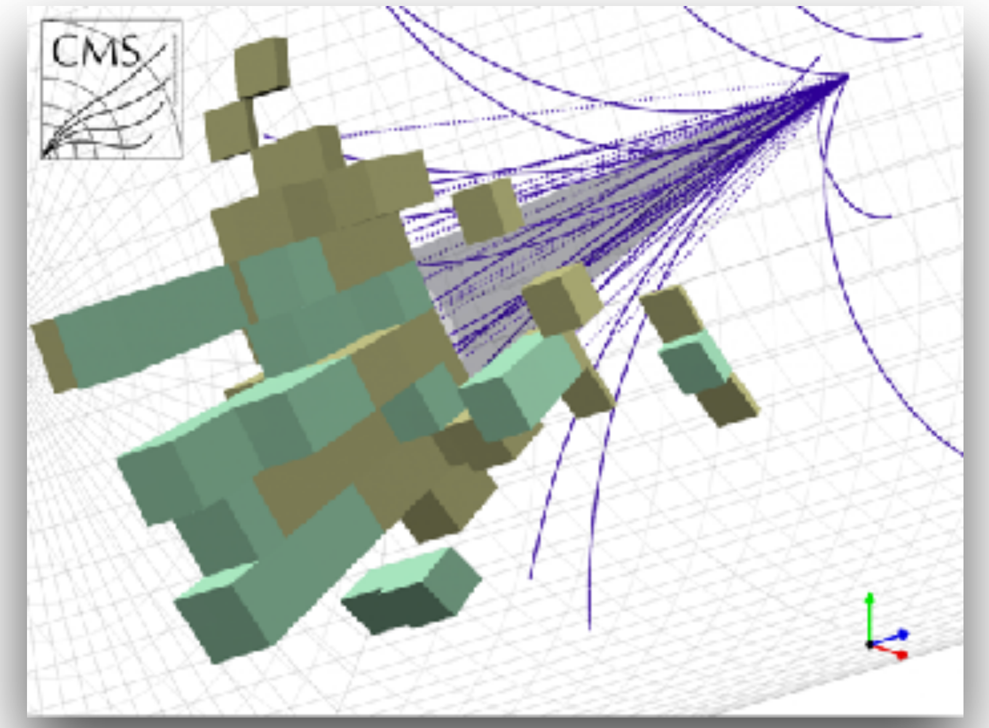
Calibration

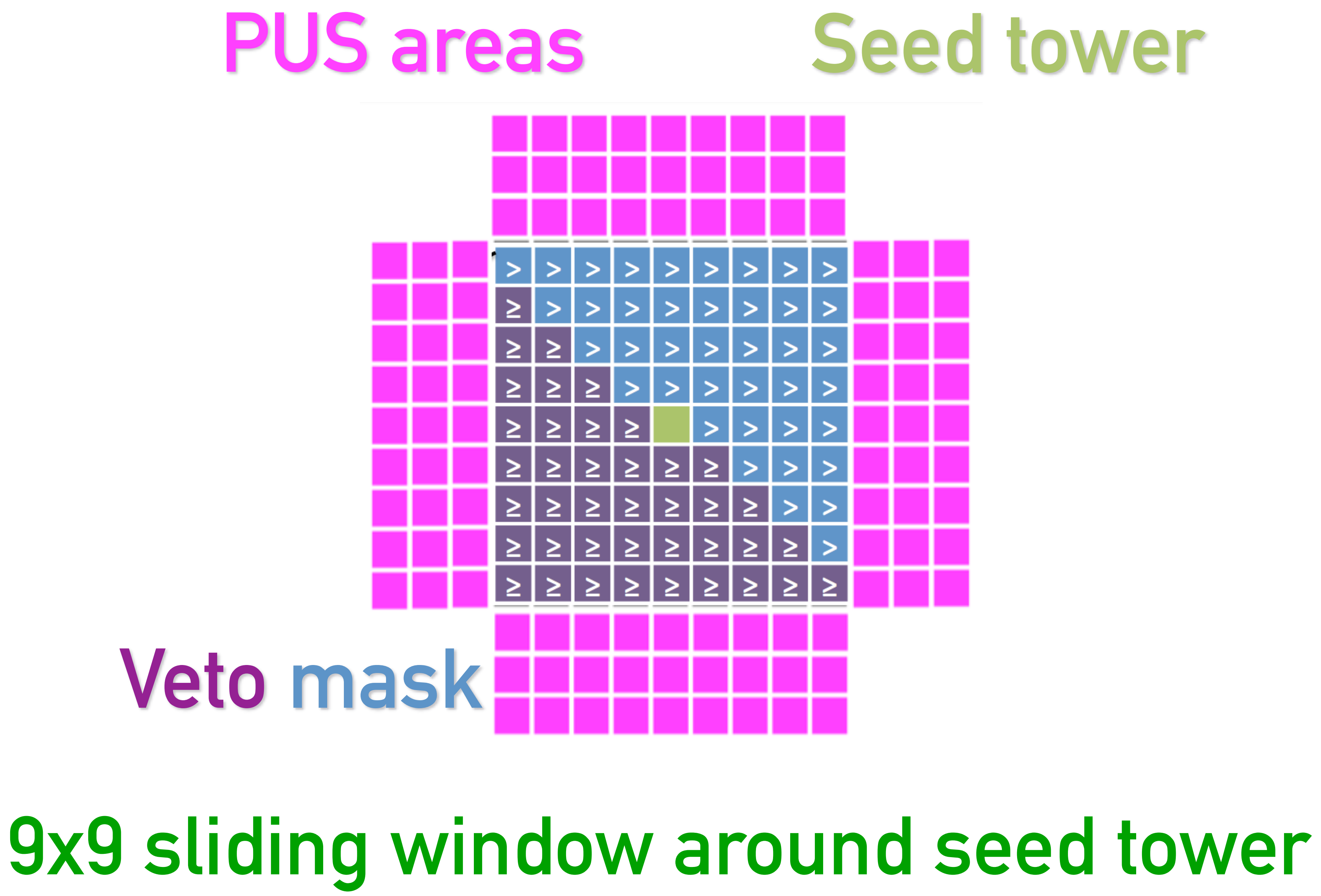
τ cluster energy calibrated as fn. of E_T, η, merging and EM fraction

Isolation

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

Jet finder algorithm





- 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

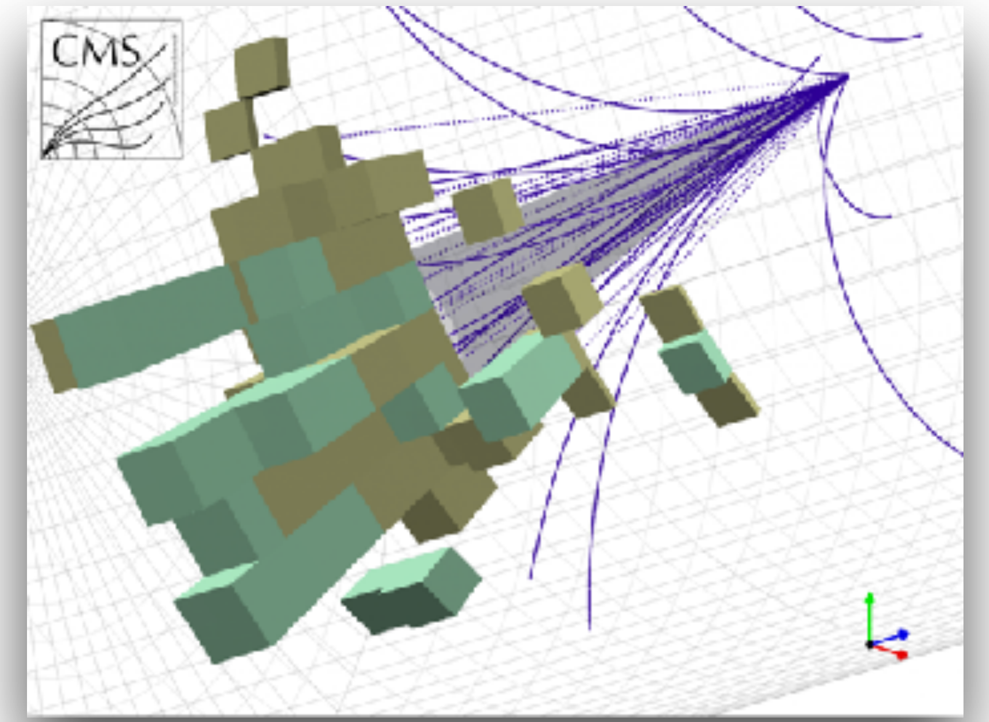
Pile-up subtraction

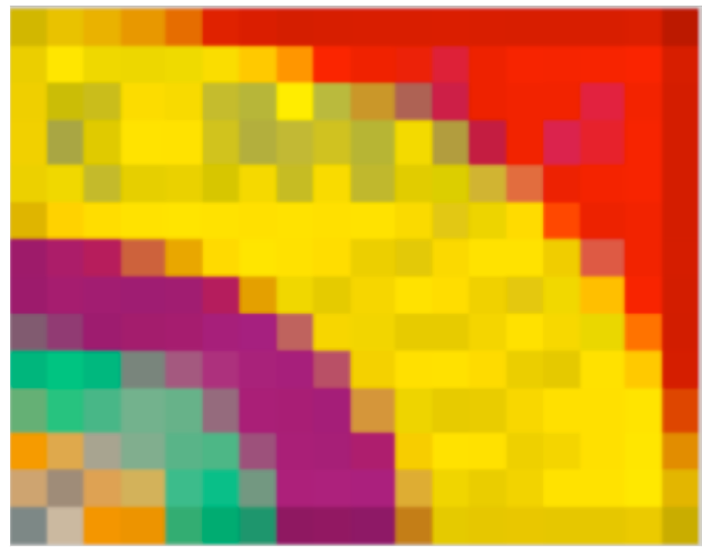
Consider four areas around jet window
Subtract sum of energy in lowest three from jet energy

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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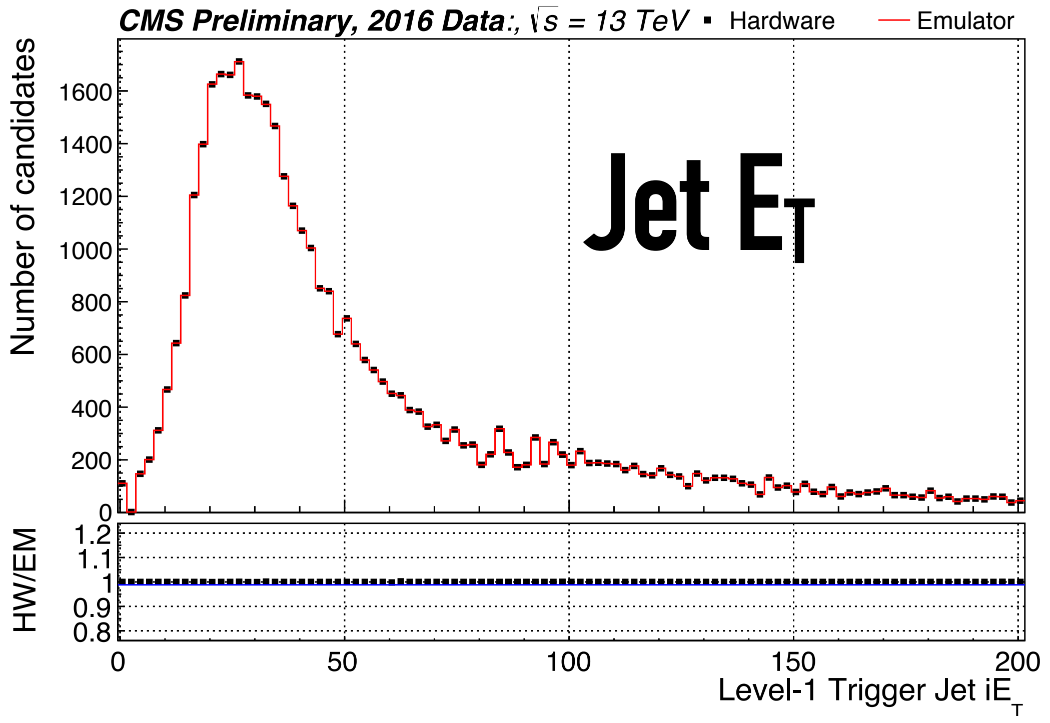
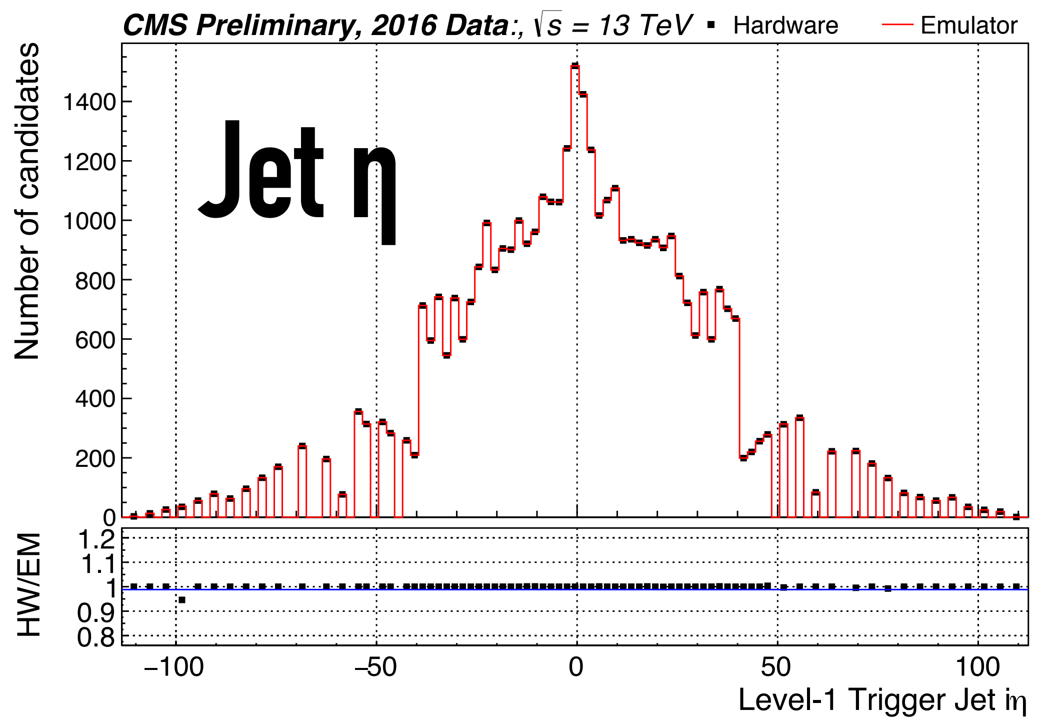
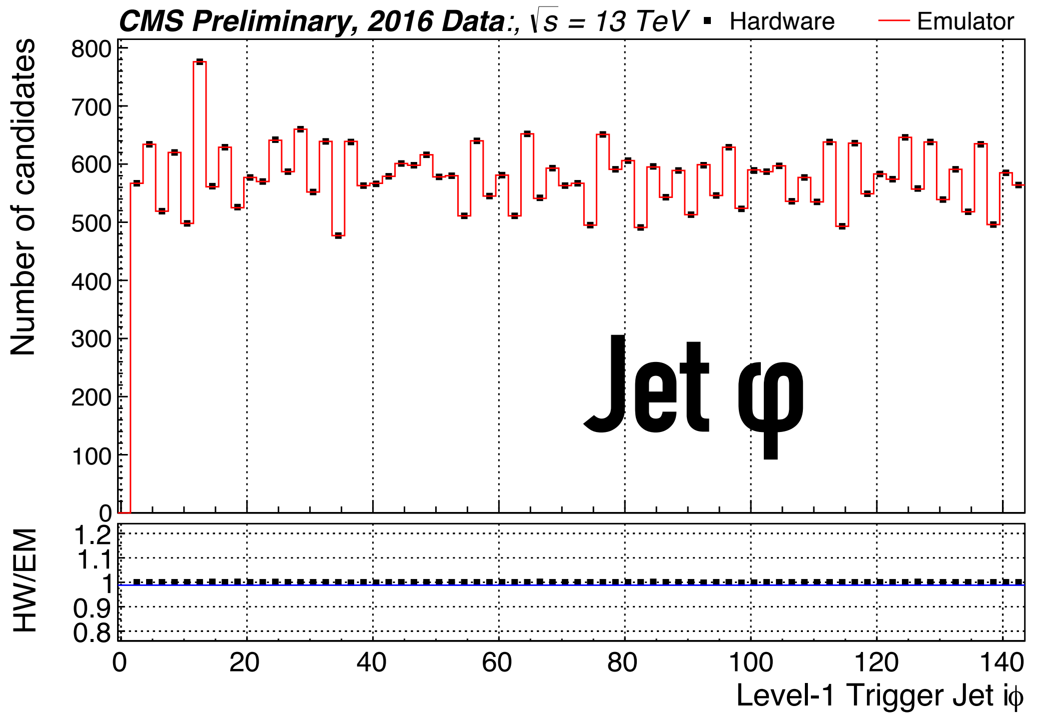
Commissioning

- 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

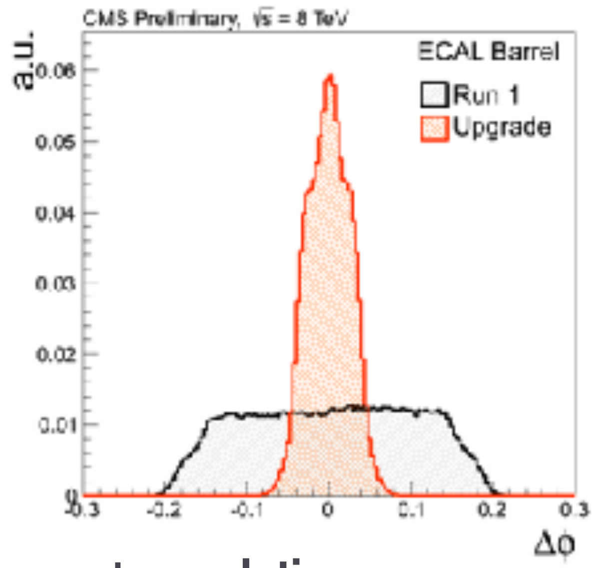
Data vs emulation

- 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 ✓

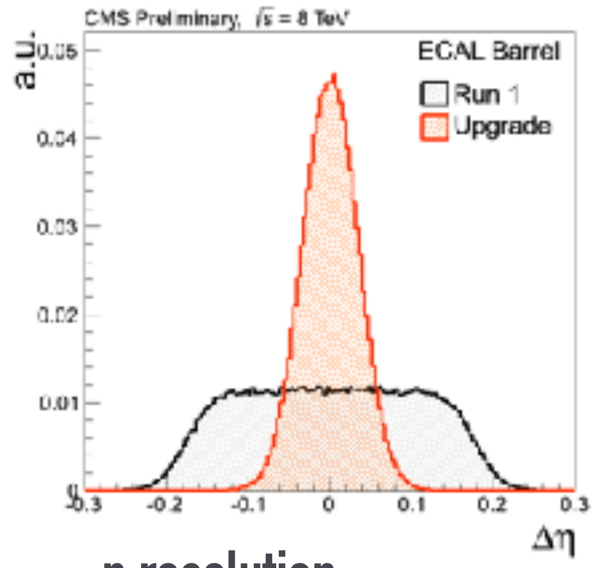
Performance results: e/γ and τ

L1 Electron Photon Finder

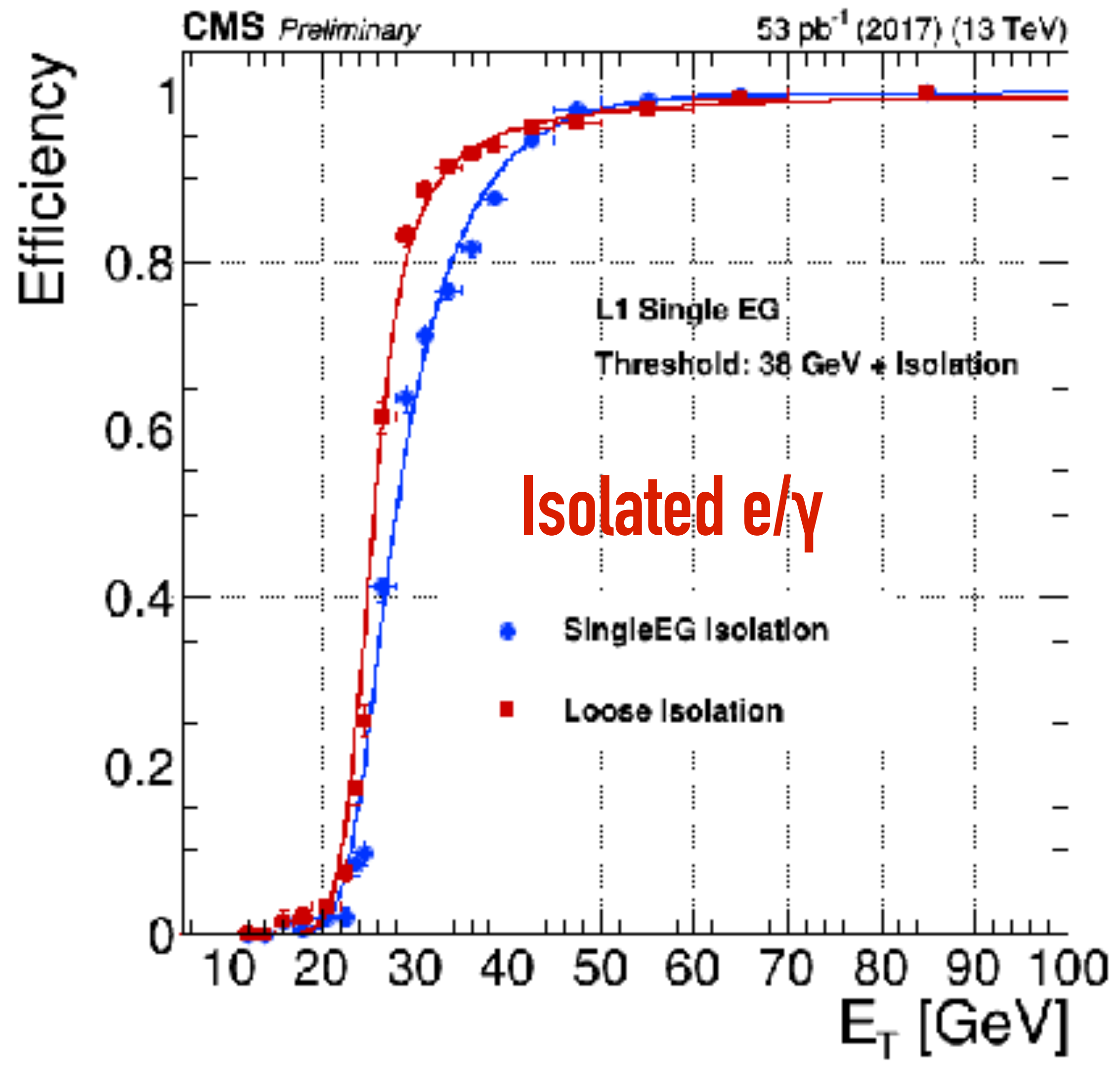
large position resolution improvement

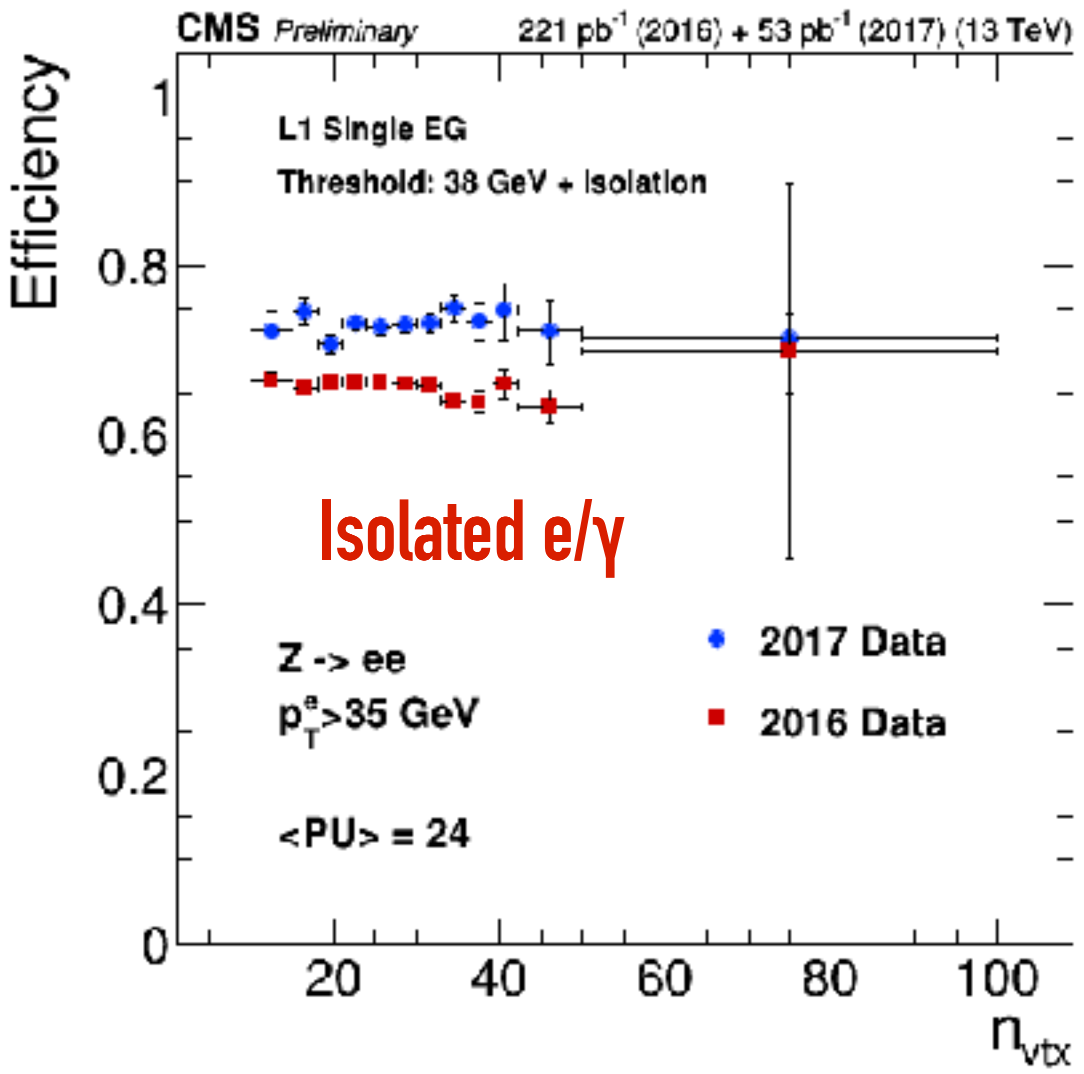


ϕ resolution



η resolution

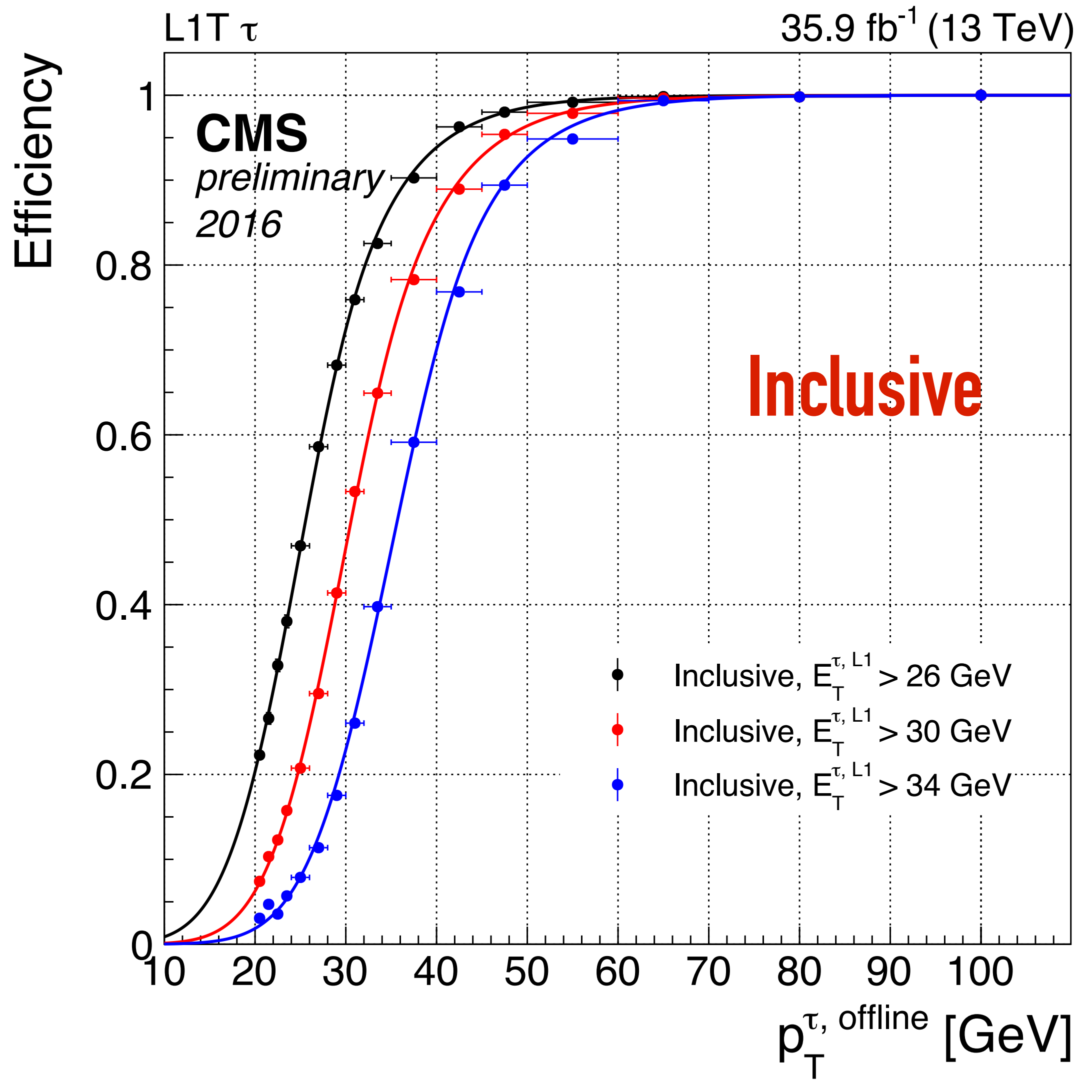


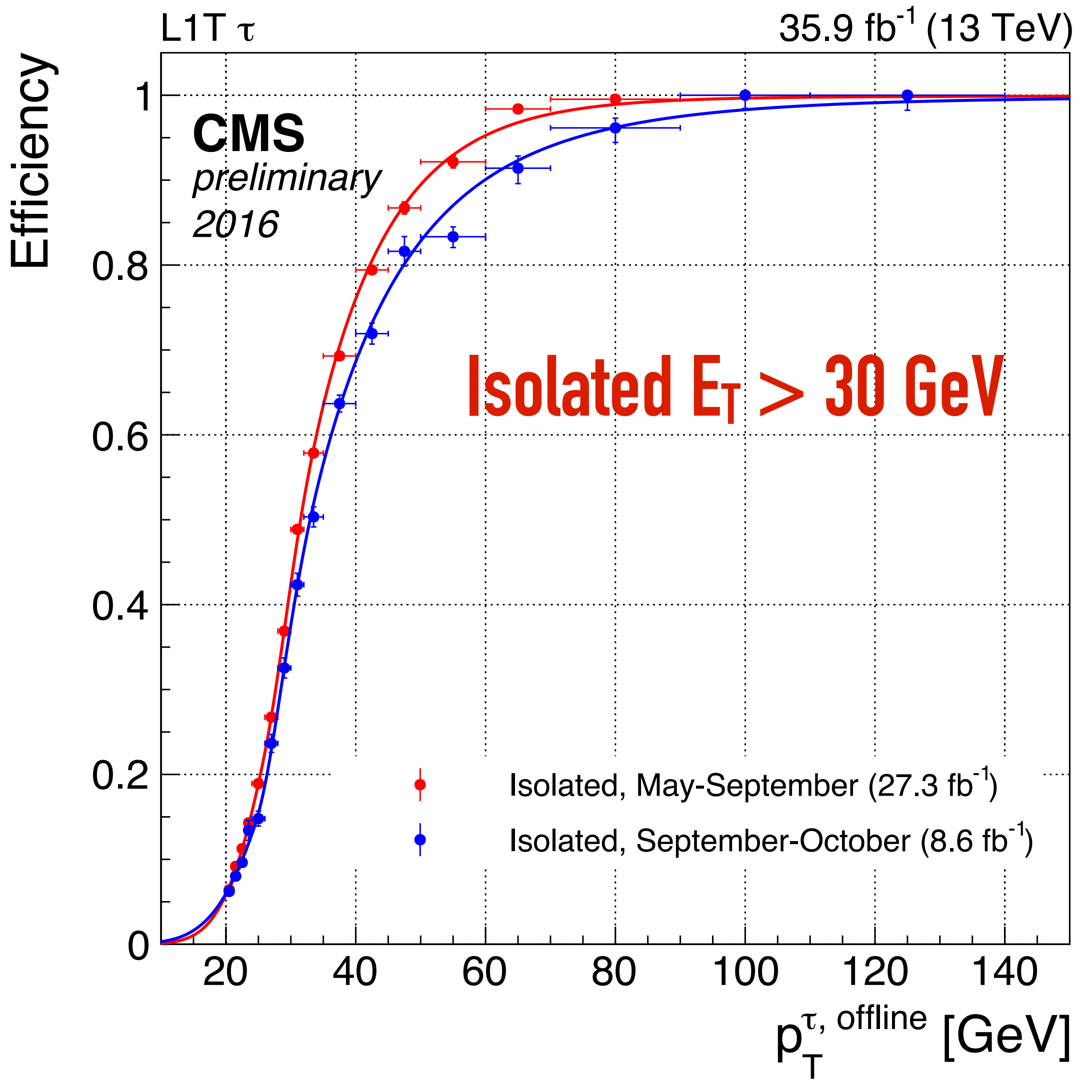


Efficiency for a single e/γ with $E_T > 38$ GeV vs offline E_T

Using tag&probe method on Z⟶ee dataset

L1 Tau Lepton Finder



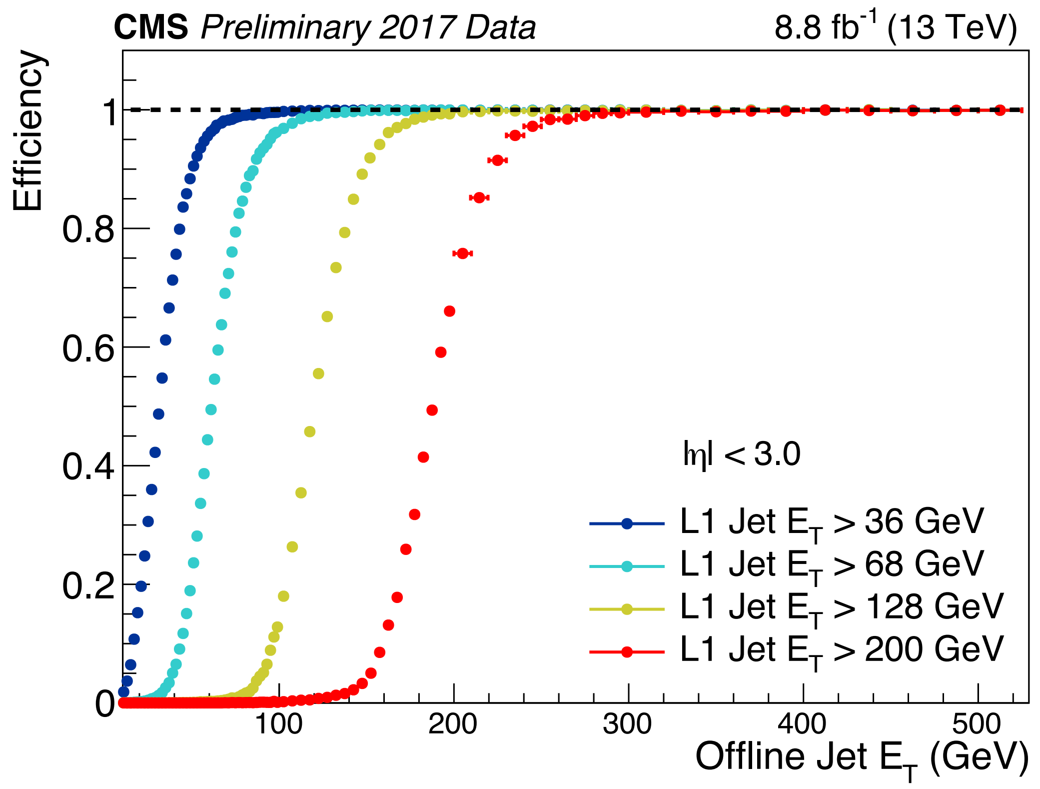


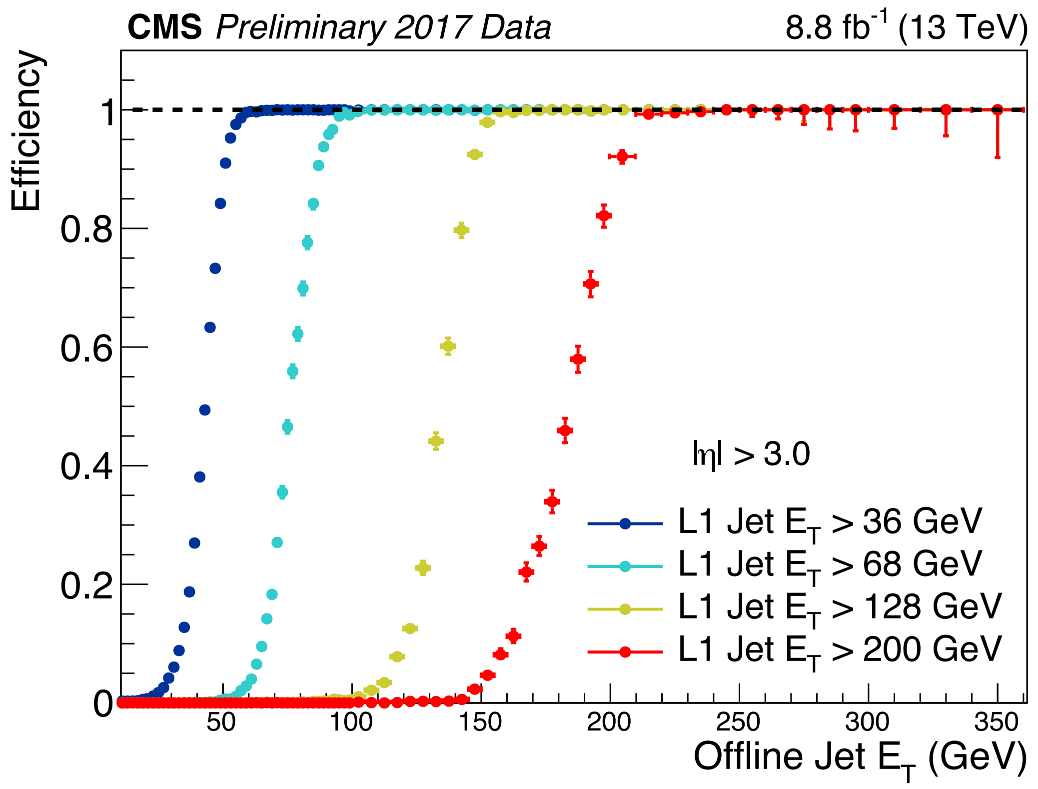
Trigger efficiency for a single τ with $E_T > 26$, 30 and 34 GeV vs offline τ p_T

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

Performance results: Jet and energy sums

L1 Jet Finder



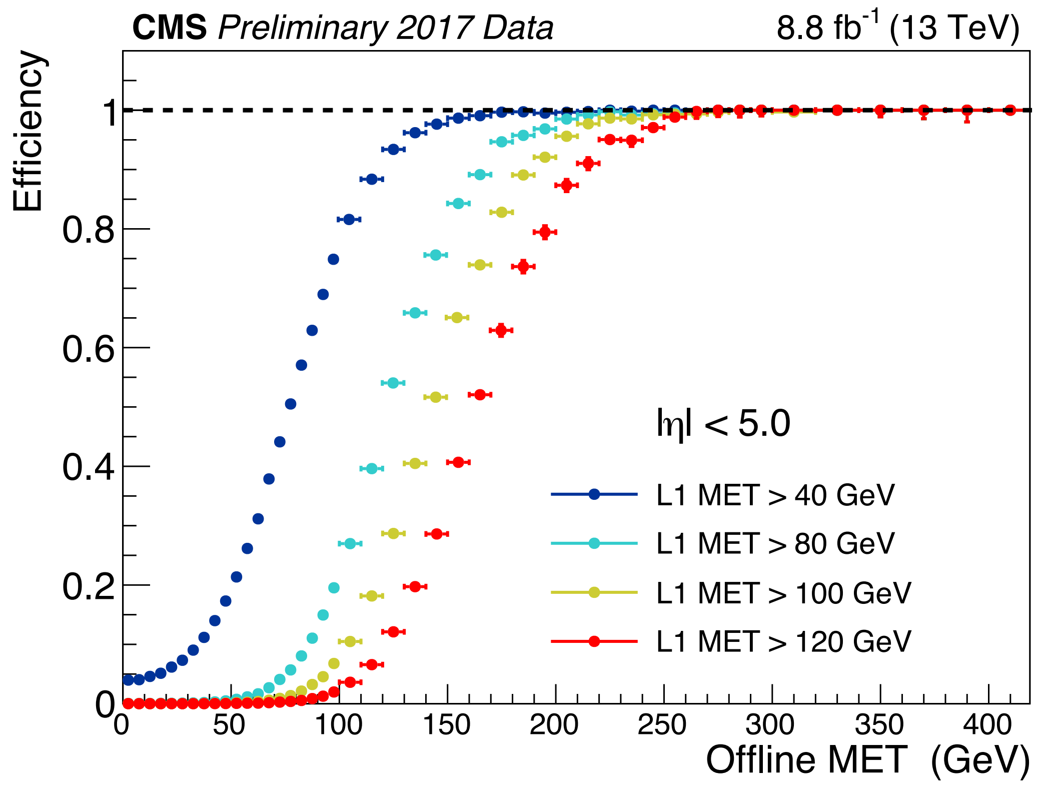


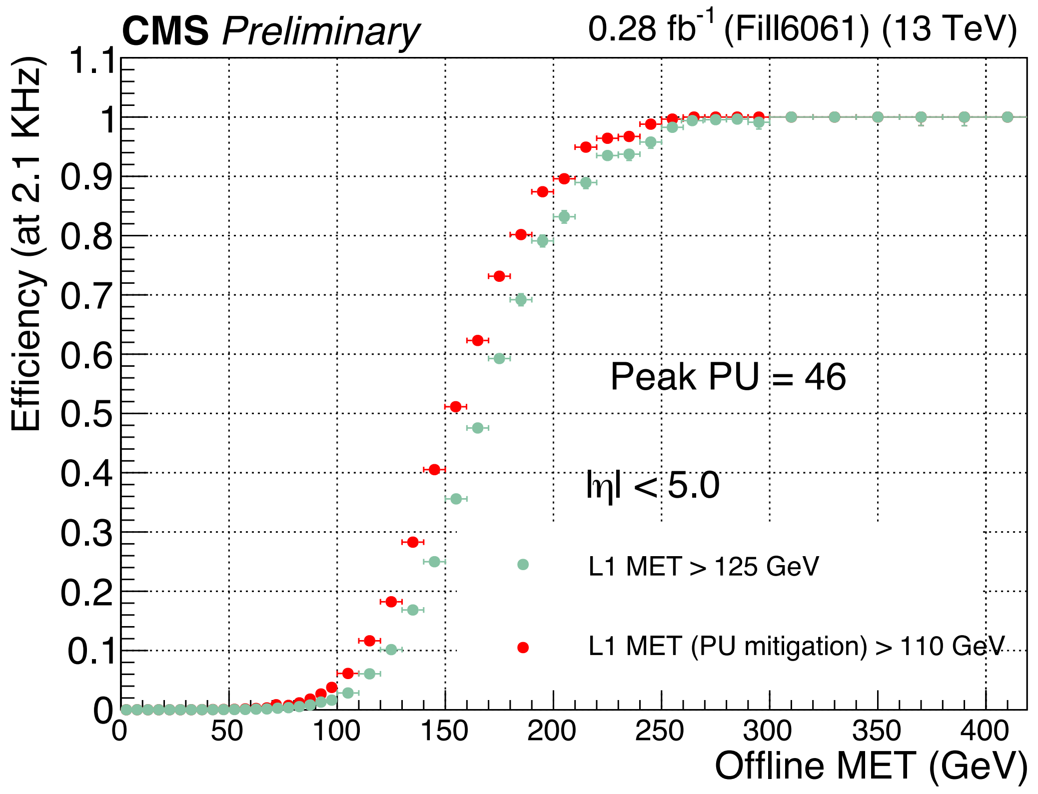
Match **Level-1 Trigger jets** to offline (anti-kt R = 0.4) jets using **ΔR < 0.25 in single muon data**

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





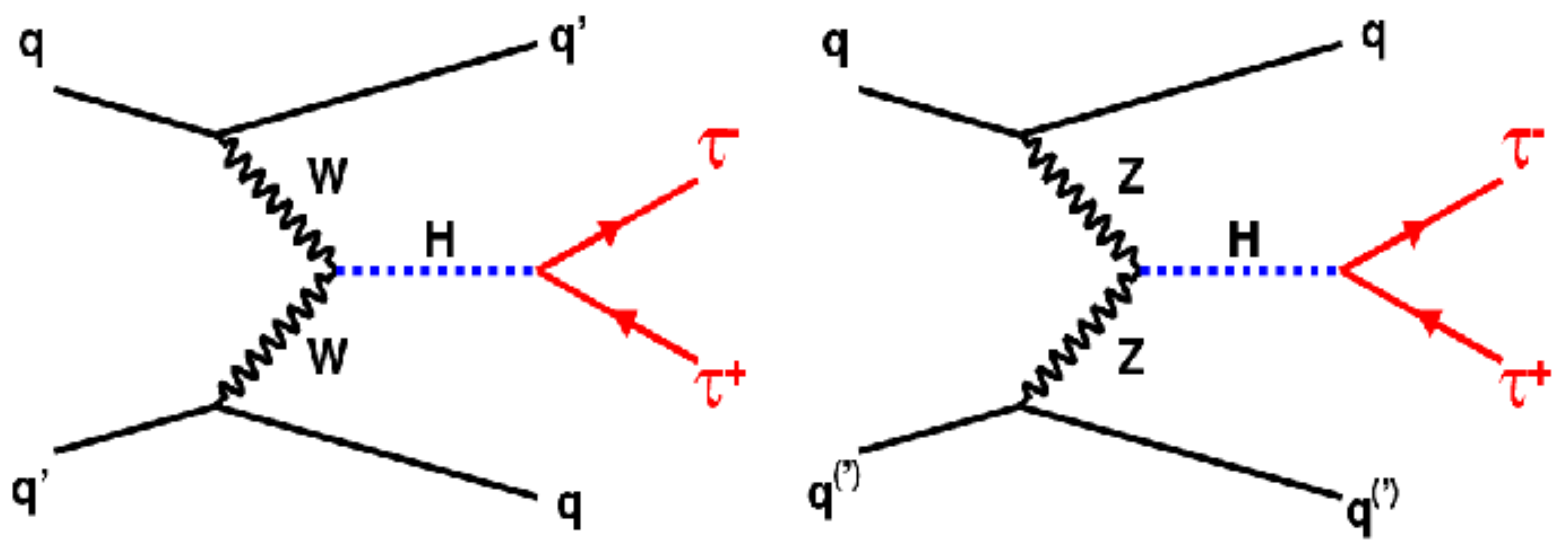
E_T^{miss} : Vector sum of trigger towers with PU dependent zero-suppression

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
- 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**

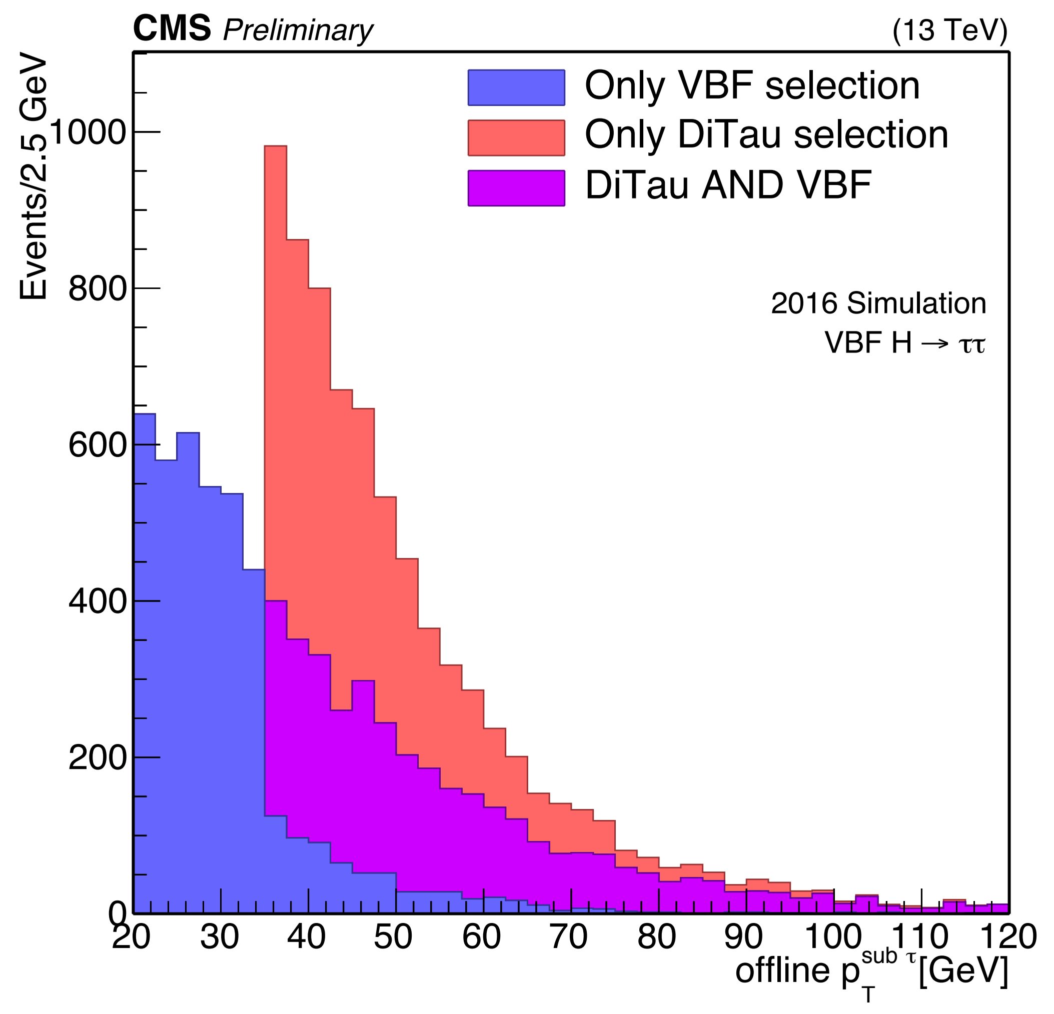
Di-jet selection with jet $E_T > 35$ GeV & $m_{jj} > 620$ GeV

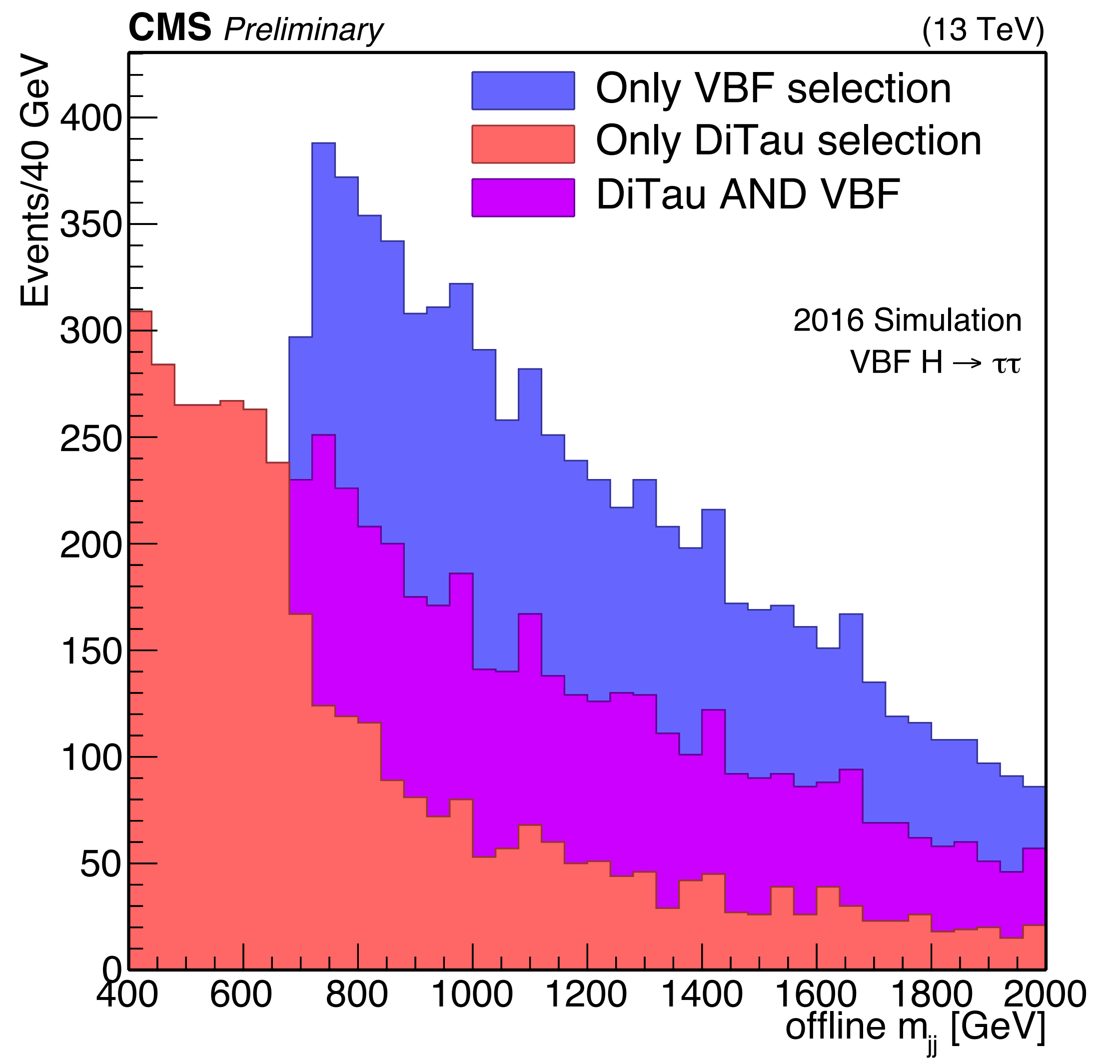
Single jet $E_T > 110$ GeV

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





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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