Description of the CMS Trigger Design and Performance

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University of Florida

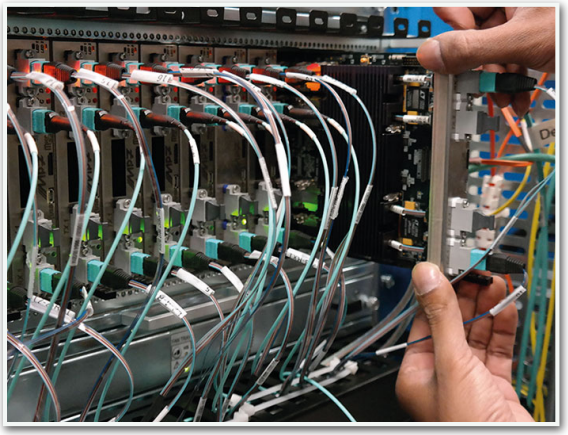
Triggering Discoveries 2018
Puebla Mexico

CMS Trigger Overview

CMS has a 2 tier trigger system

Level-1 Trigger

custom design electronics



High Level Trigger

commercial PCs

Outline

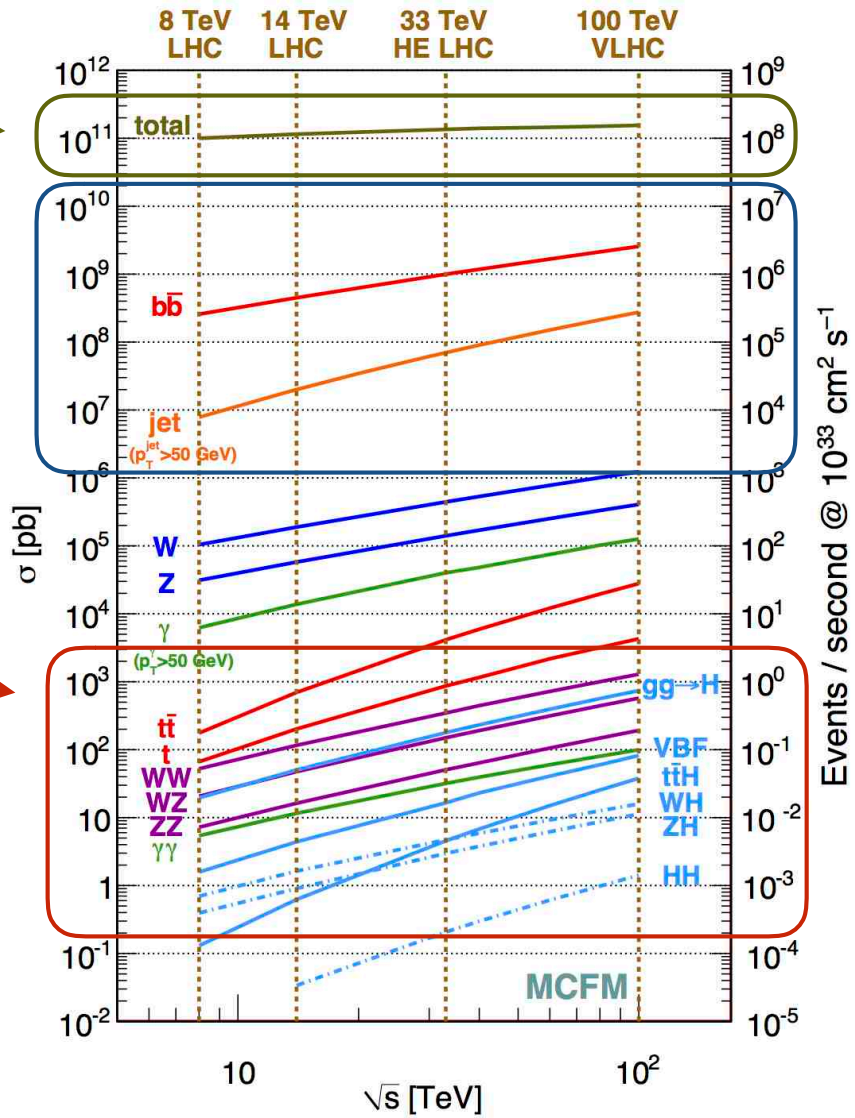
- Level-1 trigger
  - Design
  - Hardware and software
  - Algorithms and performance
- High Level Trigger

CMS Trigger Overview

LHC total cross section

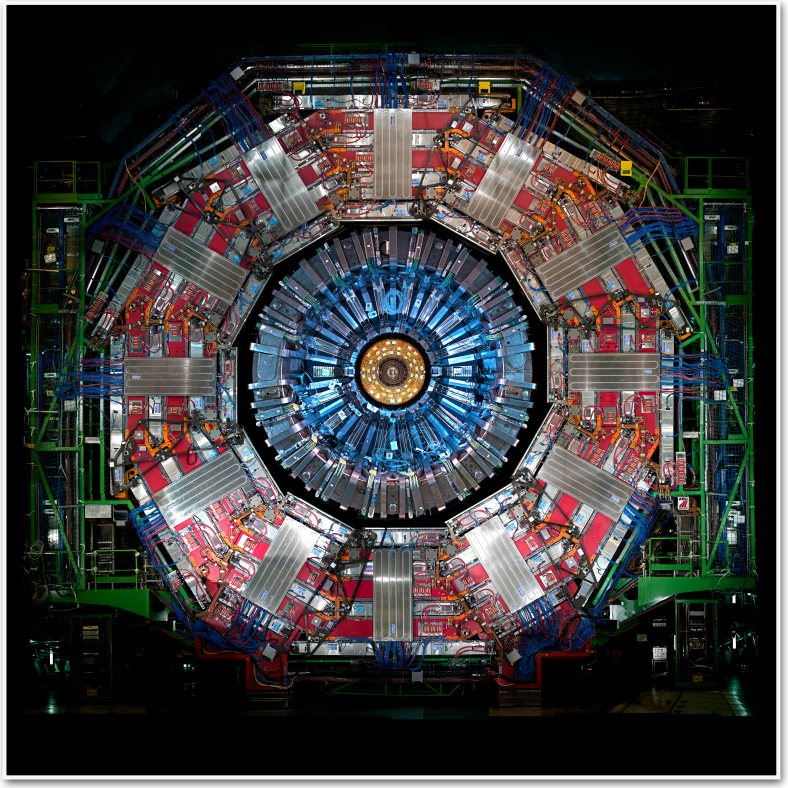
No need to store all events

- Most are low energy multi-jet events
- Interesting events are rare



CMS Trigger Overview

- CMS can take **pictures at a rate of 40 MHz**
  - **BUT** can record ~**1000 full events per second**
- Select possibly interesting events
- **Needs a fast and precise triggering system**



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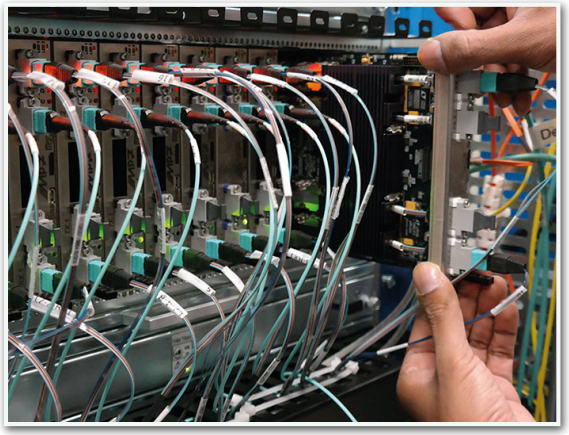


3.8 μs

High Level Trigger

commercial PCs

~300 ms

40 MHz → 100 KHz → 1 KHz

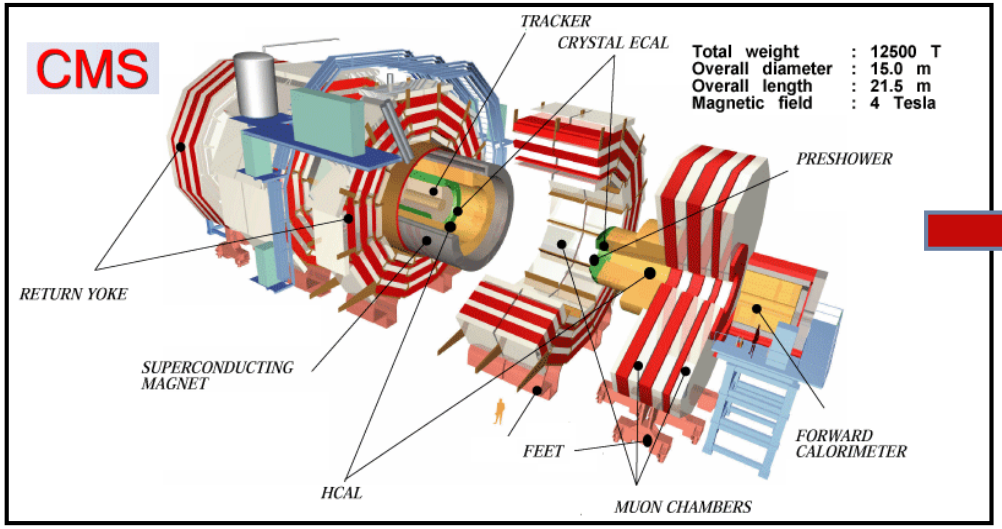
Outline

- **Level-1 trigger**
  - **Design**
  - Hardware and software
  - Algorithms and performance
- High Level Trigger

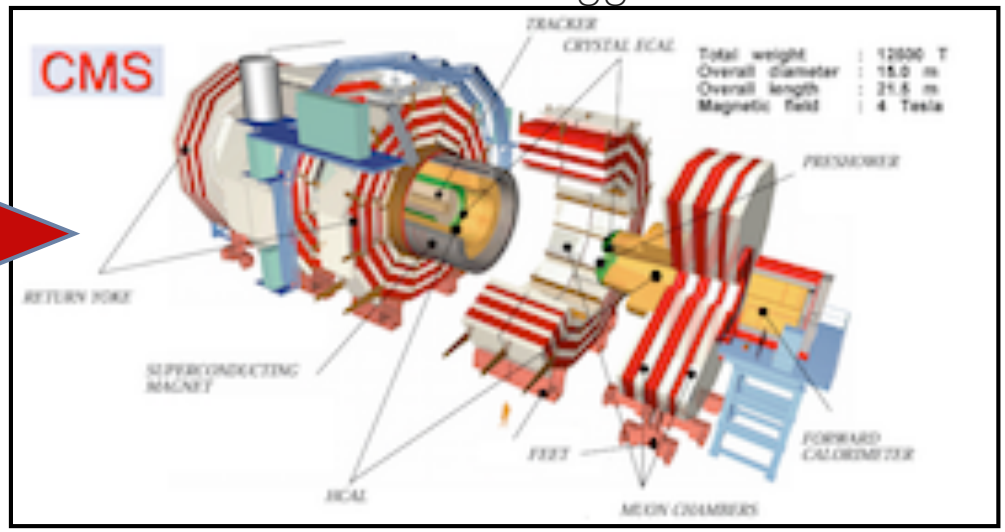
Compromise time with resolution

- CMS full event reconstruction ~ 40 seconds
- Reducing the amount of information speeds up reconstruction
- **Trigger primitives** are a coarse grain detector readout
  - number of channels is reduced
  - scales are compressed (η, phi, p_T, etc) in limited number of bits

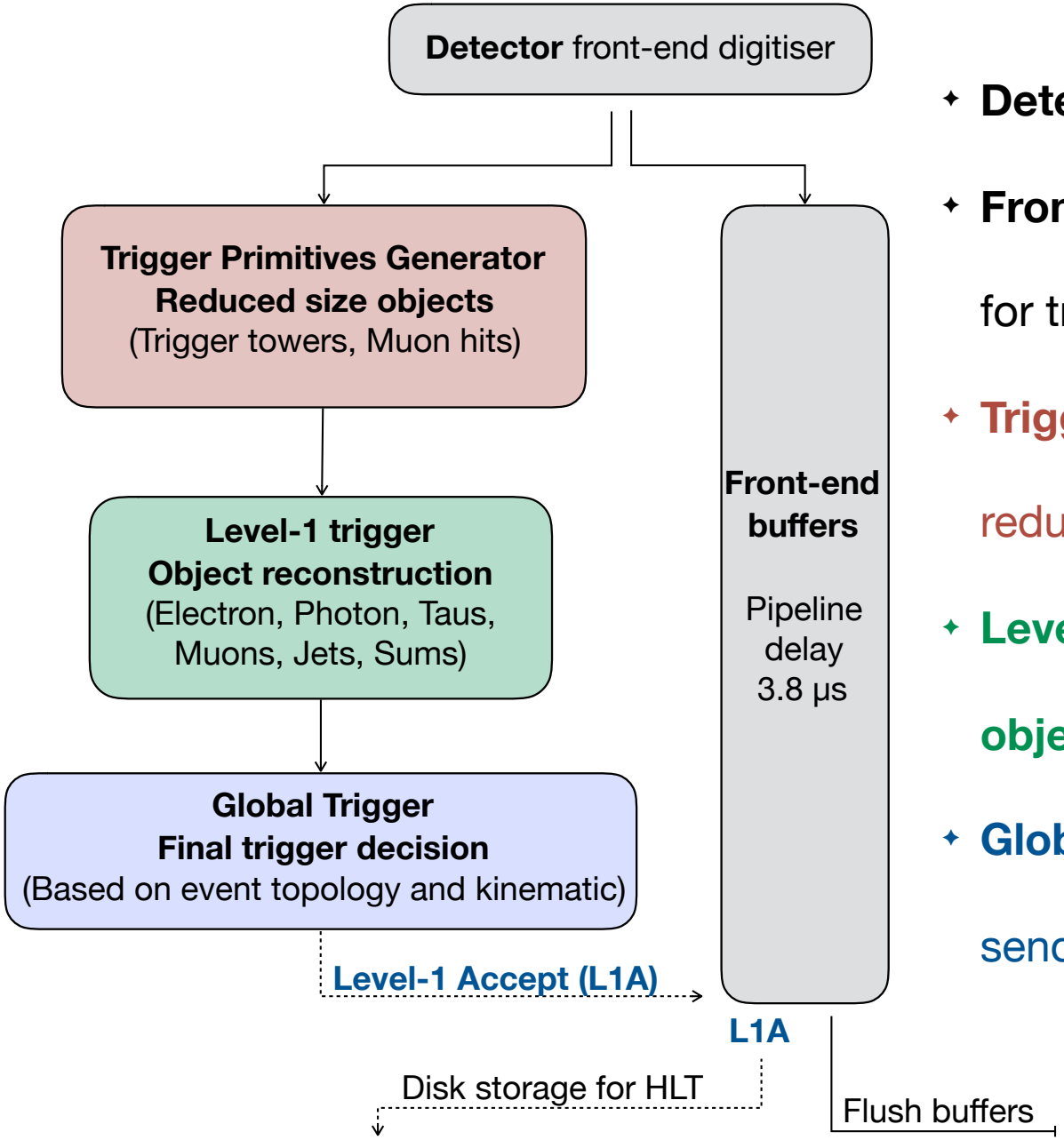
Full readout



Level-1 trigger



The CMS level-1 trigger path

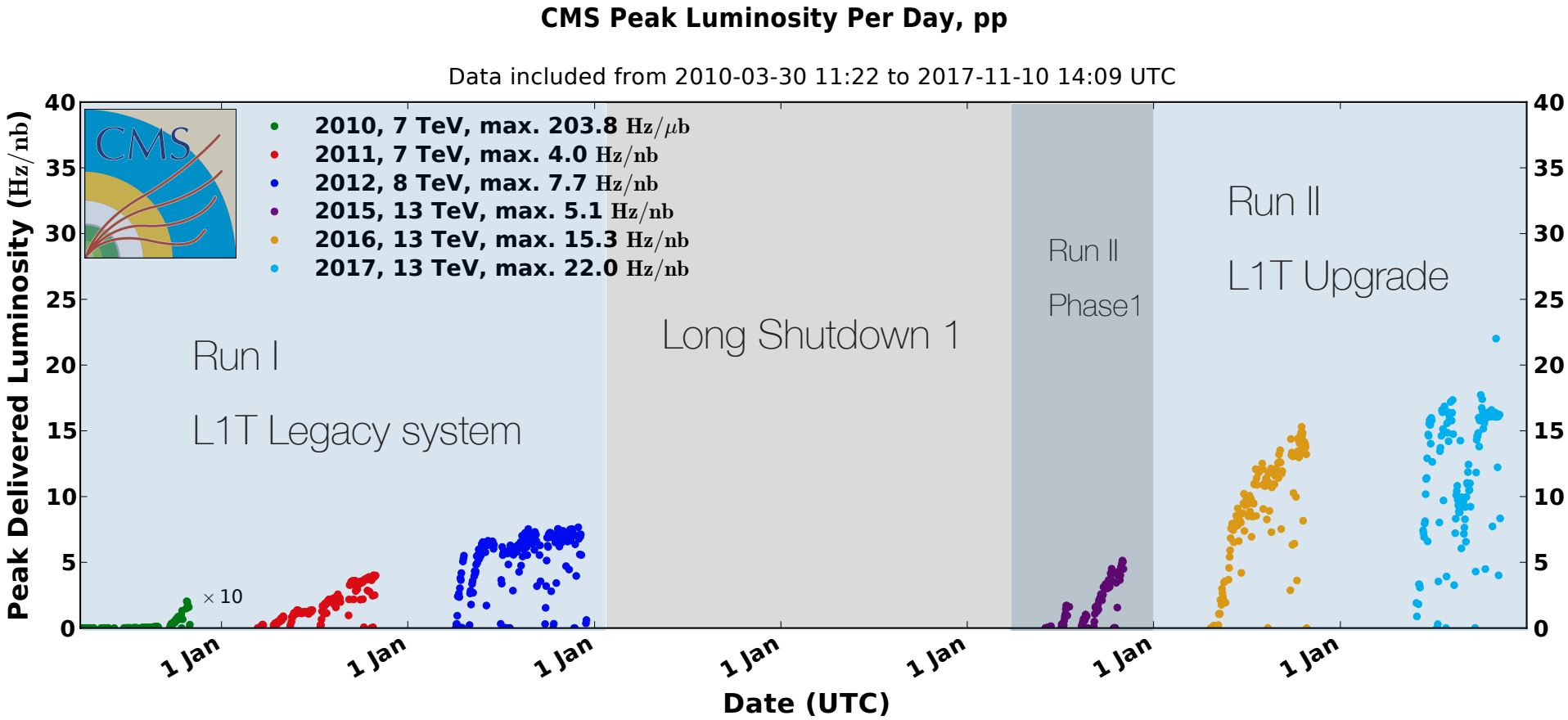


- **Detector** signals duplicated at front-end
- **Front-end buffers** store full event waiting for trigger decision
- **Trigger primitive generators** produce reduced size objects
- **Level-1 processors** reconstruct **physics objects** from trigger primitives
- **Global trigger** takes **final decision** and sends it to buffers for **disk storage or flush**

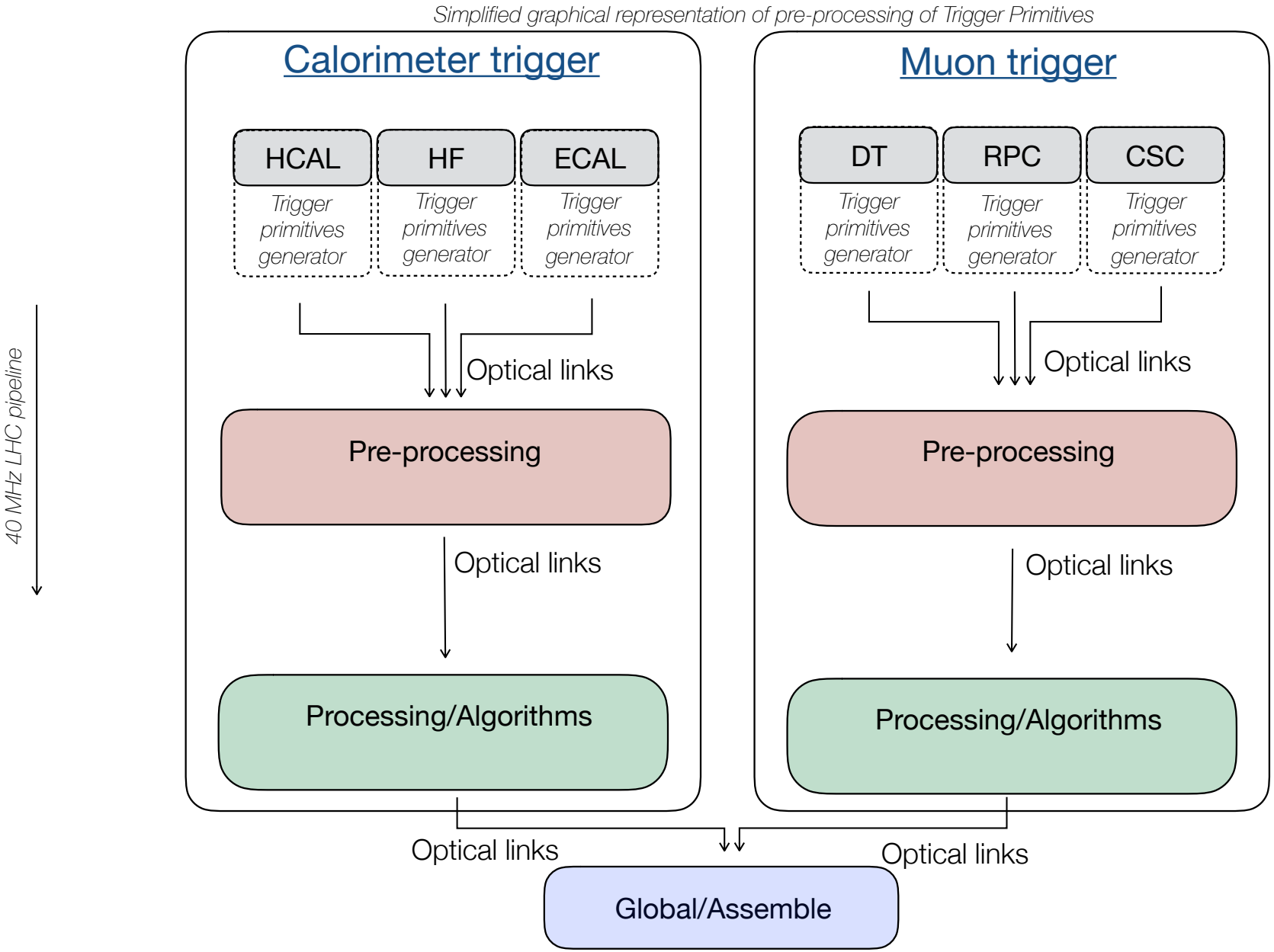
Level-1 trigger history

In 2016 L1T was upgraded.

We changed everything

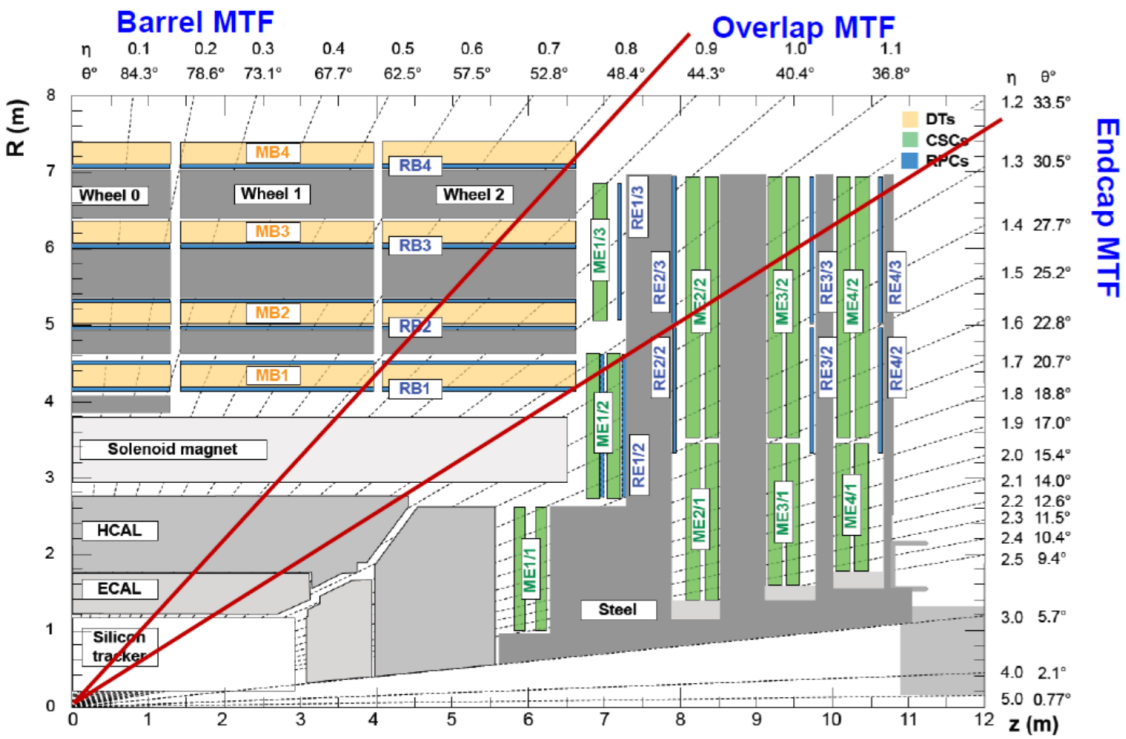


The CMS Level-1 trigger design



L1T Muons design

- Detector divided in **three η regions** (Barrel, Overlap, Endcap)
- Exploiting detector redundancy at trigger level



3 Regional Track Finders

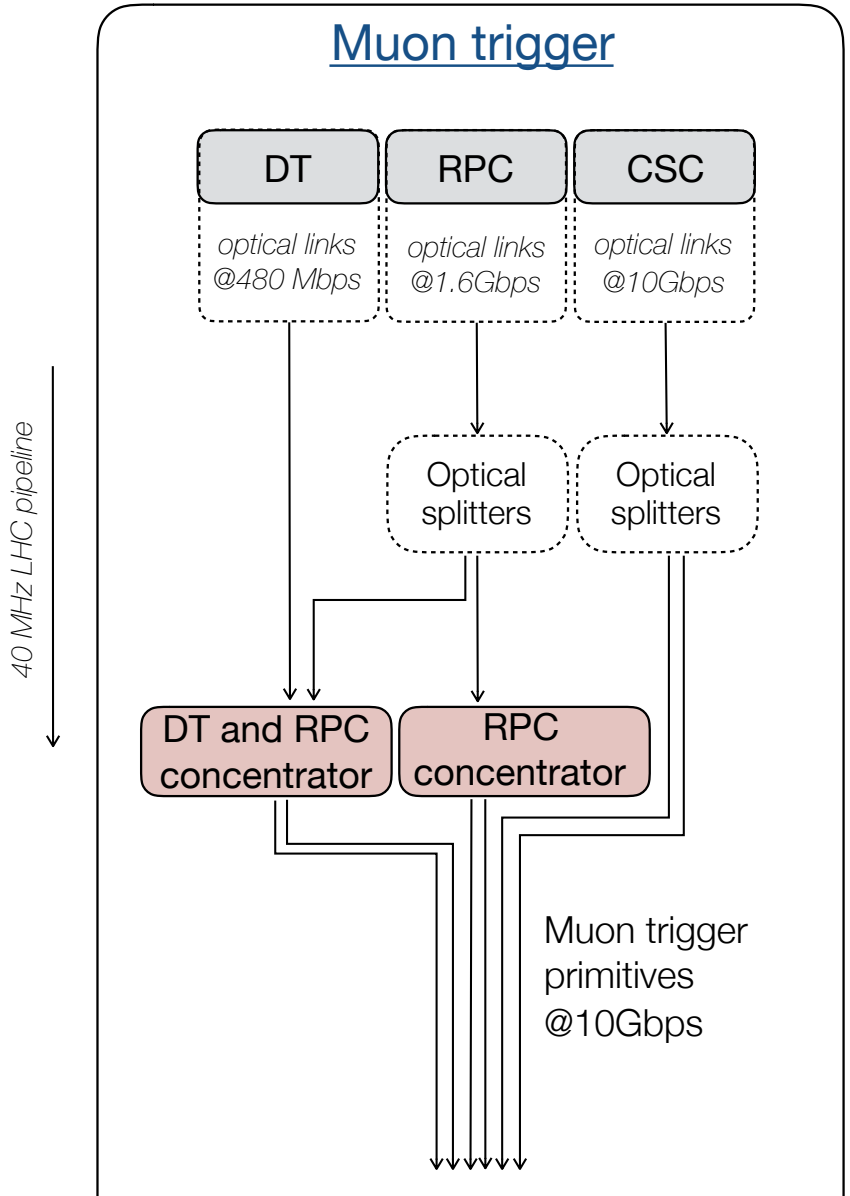
- **Barrel** (|η| < 0.8): **DT, RPC**
- **Overlap** (0.8<|η|<1.24): **DT**, **RPC**, **CSC**
- **Endcap** (1.24<|η|<2.4) **CSC**, **RPC**

Global Muon Trigger

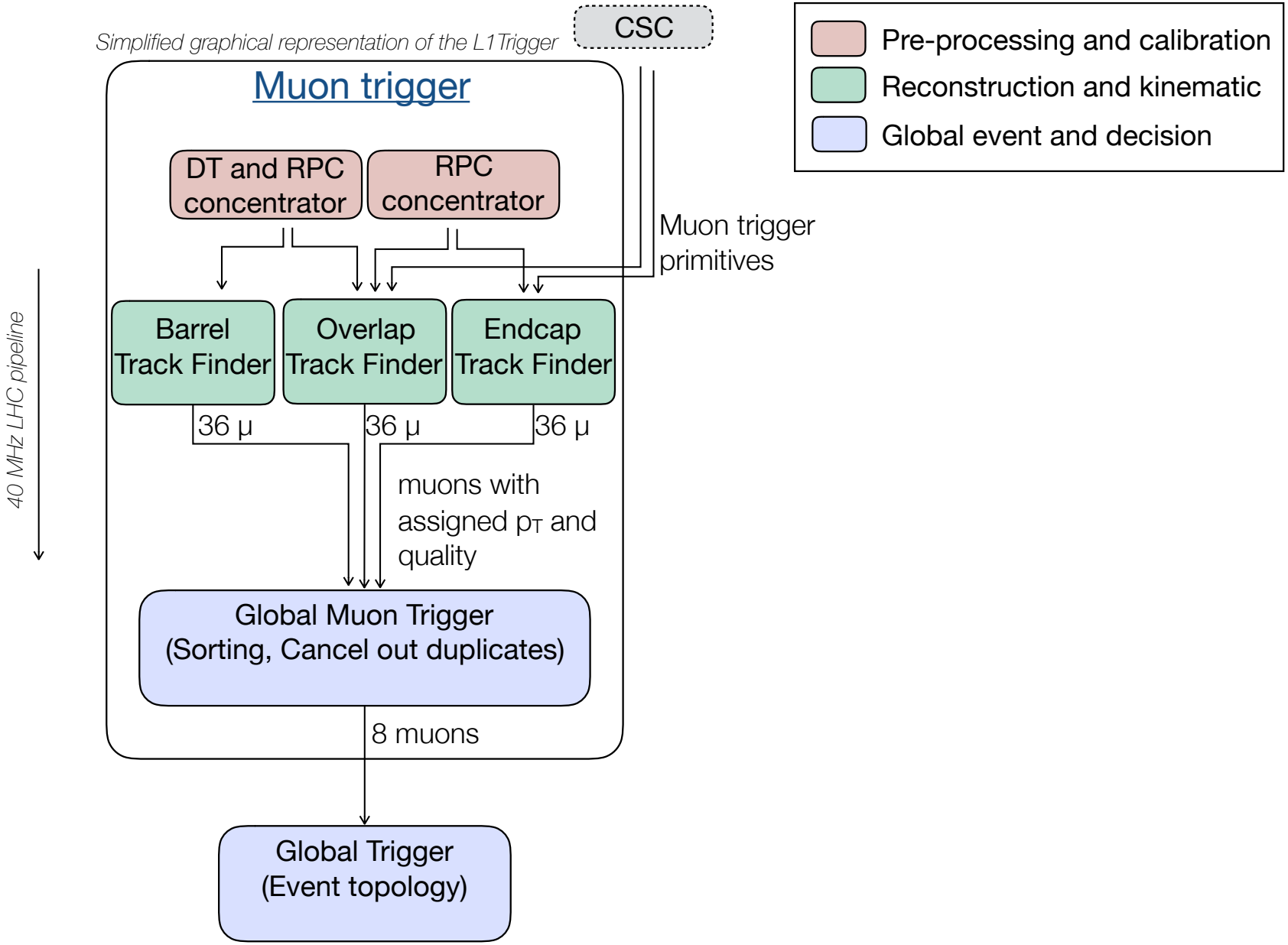
- Collect, sort, duplicate merging

L1T Muon design

Simplified graphical representation of pre-processing of Trigger Primitives

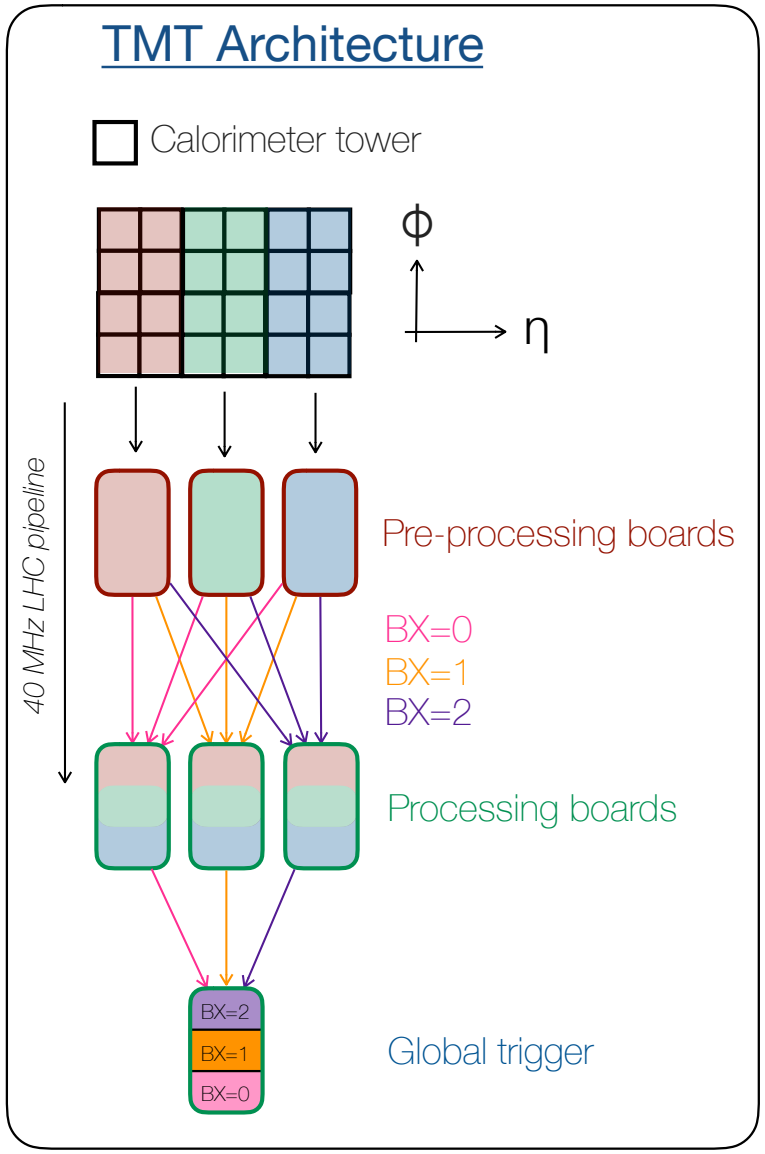


L1T Muon design



L1T Calo design - Time Multiplexing

An innovative architecture (Time Multiplexing) has been used for the calorimeter trigger



- Detector is divided in geometrical regions
- Each region sends data to a single board
- Each pre-processing board sends data to all processing board for a given bunch crossing (BX)
  - via a path panel
- Each processing board is processing a full event
- Each processing board is send event information to global trigger
  - time ordering is guarantee by demultiplexing board

L1T Calo design

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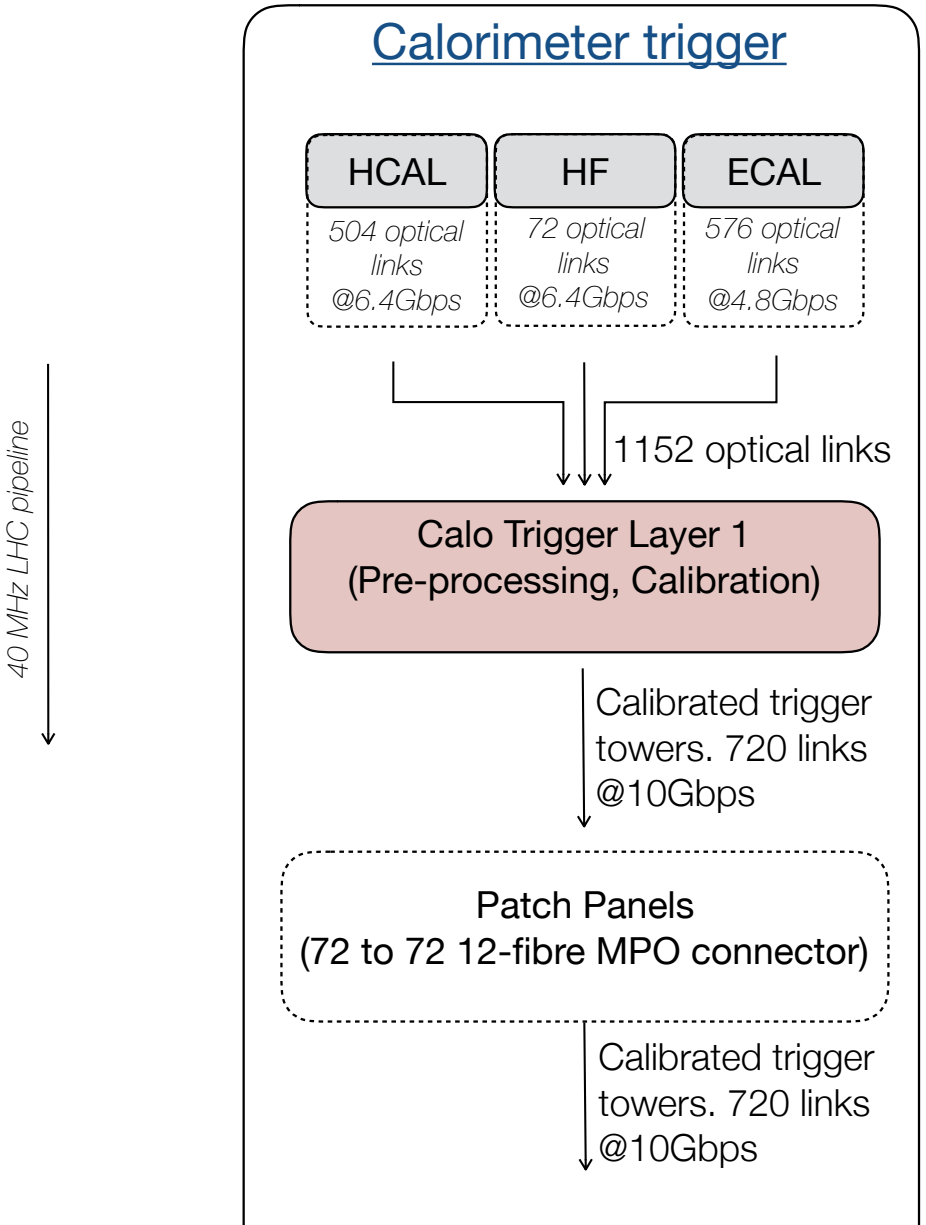
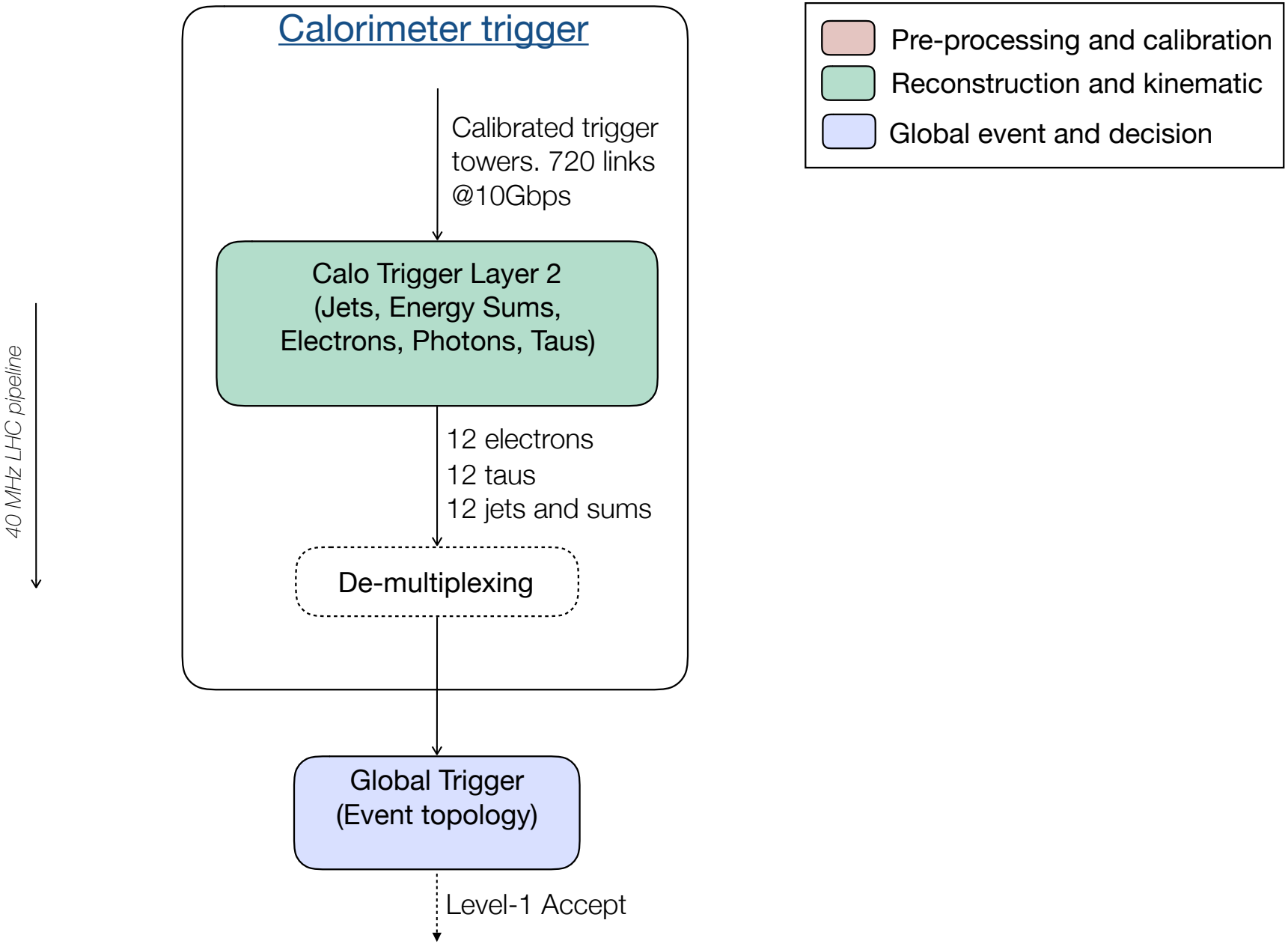
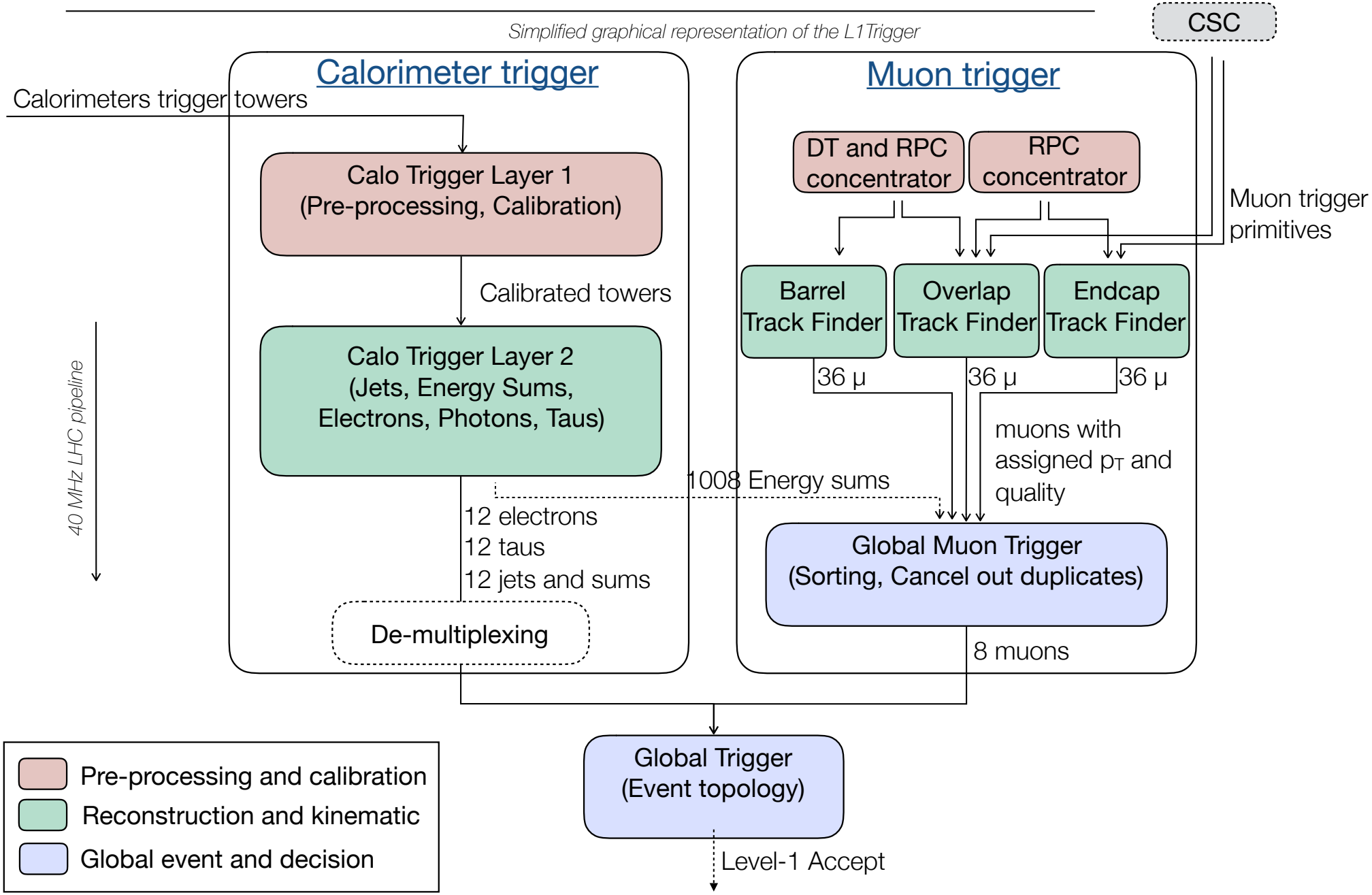


L1T Calo design

Simplified graphical representation of the L1Trigger



The CMS Level-1 trigger design



Outline

- **Level-1 trigger**
  - Design
  - **Hardware and software**
  - Algorithms and performance
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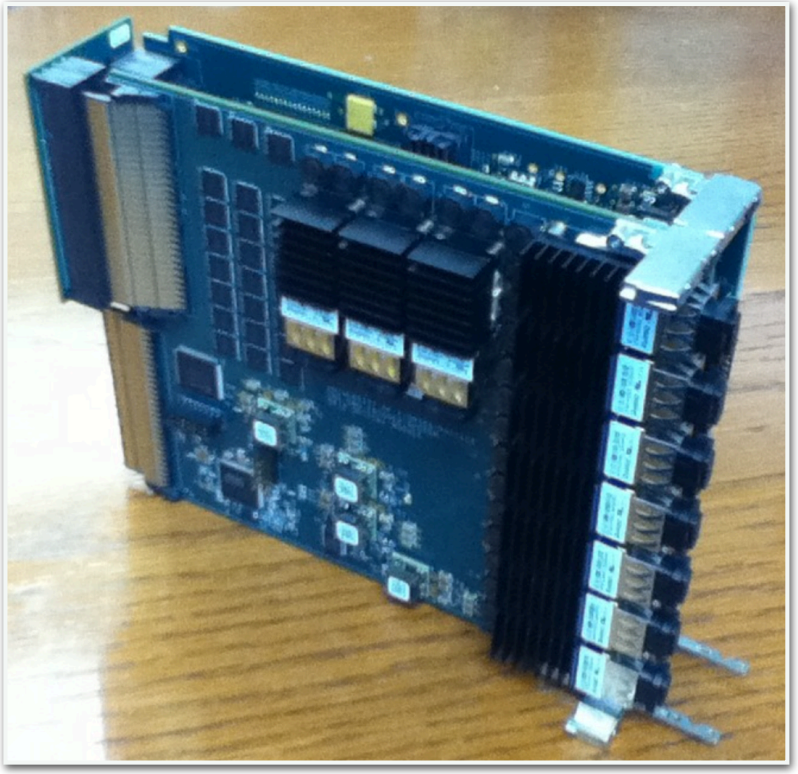
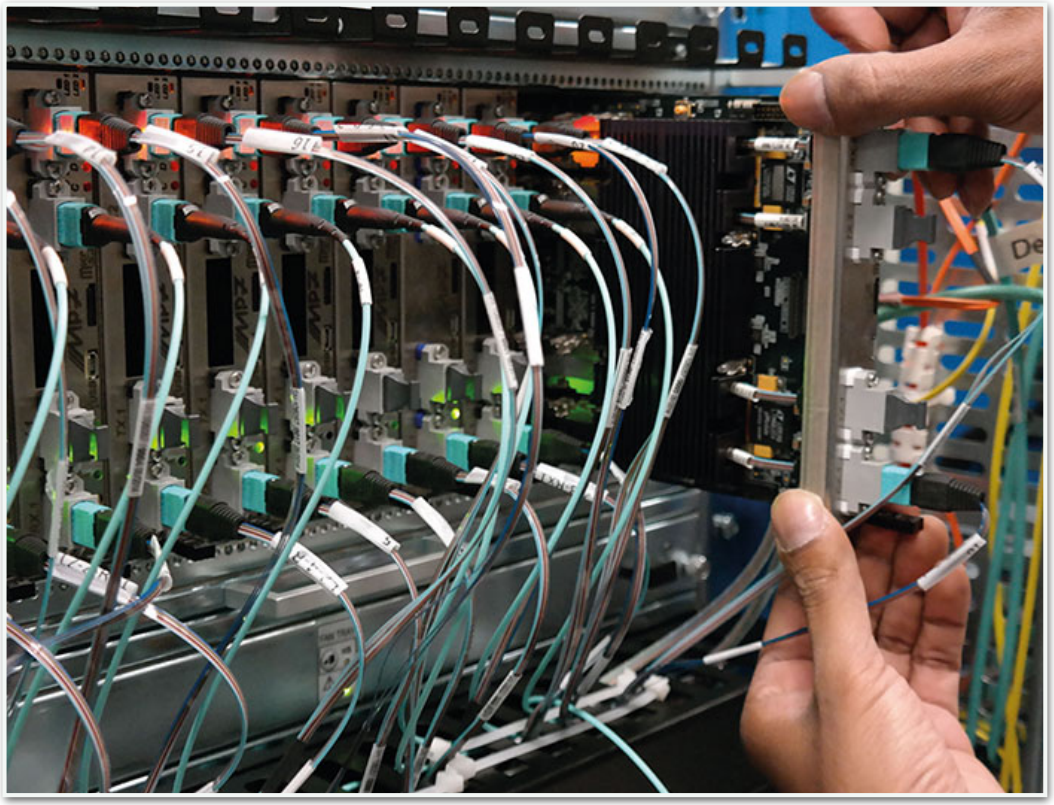
Level-1 Trigger hardware

- Consists of few tens of custom designed **uTCA boards using Virtex7 FPGA**
  - design of algorithms is **flexible** and **modular**
  - boards are connected via **optical fibre** links

Endcap Muon Track Finder (1 of 12 boards)



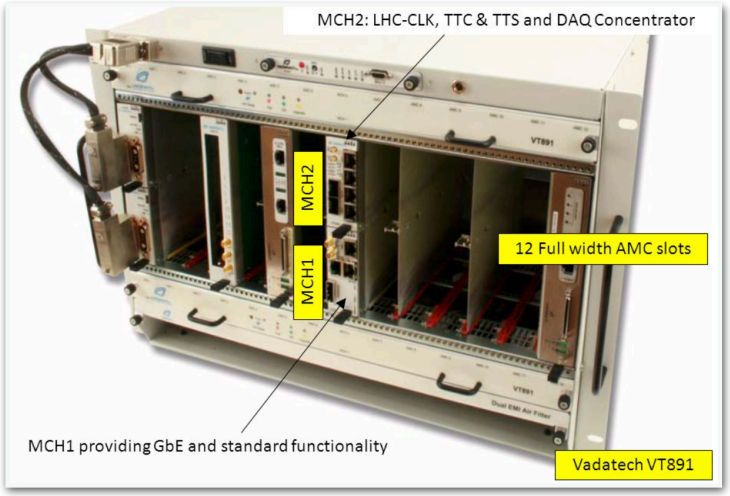
Calorimeter trigger boards in a crate

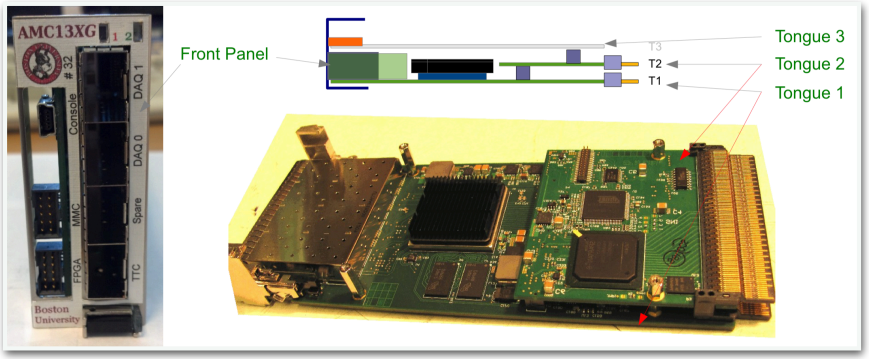


Level-1 Trigger crate and service board

Hardware used to monitor and control processor cards

- **uTCA Vadatech crate** (commercial)
  - uTCA standard define a backplane that allows
    - 12 slots for Advanced Mezzanine Cards (AMC)
    - 2 slots for MicroTCA Control Hub (MCH)
- **AMC13** (13th Advanced Mezzanine Card)
  - Distribute to all AMC the LHC clock, timing, throttling, and control signals
  - Collect DAQ data from all AMC of a crate for transmission to central DAQ

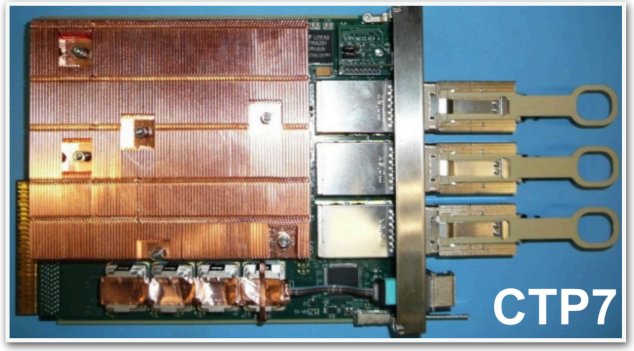


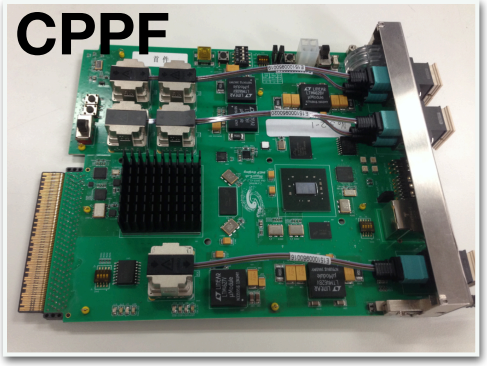


Level-1 Trigger pre-processor boards

Pre-processor boards **arrange and fan-out detector links**

- **CTP7** (Calorimeter Trigger Processor)
  - calibrates ECAL, HCAL and HF TPs (67Rx)
  - transfer to MP7s via 48 Tx Links @ 10 Gb/s
- **CPPF**
  - concentrate @10Gbs RPC links to OMTF and EMTF
- **TwinMux**
  - concentrate @10Gbs DT and RPC links to BMTF

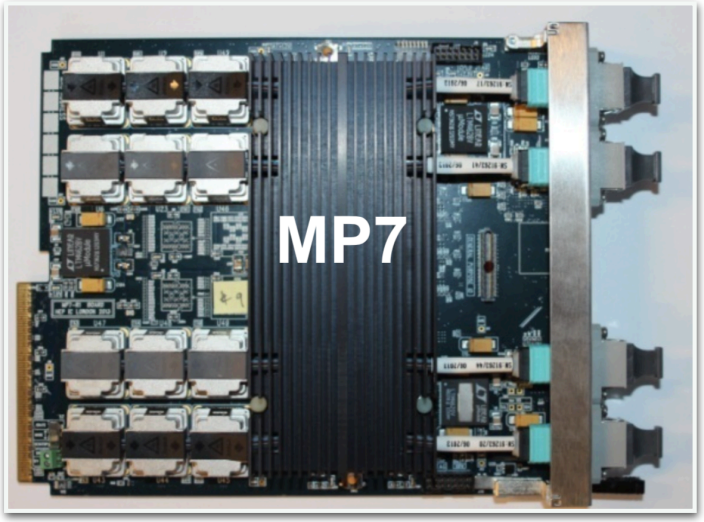




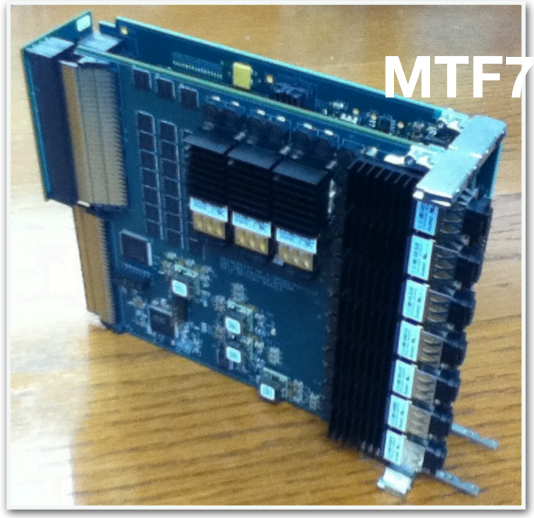
Level-1 Trigger processor boards

Processor boards host **algorithms for physics object ID and p_T assignment**

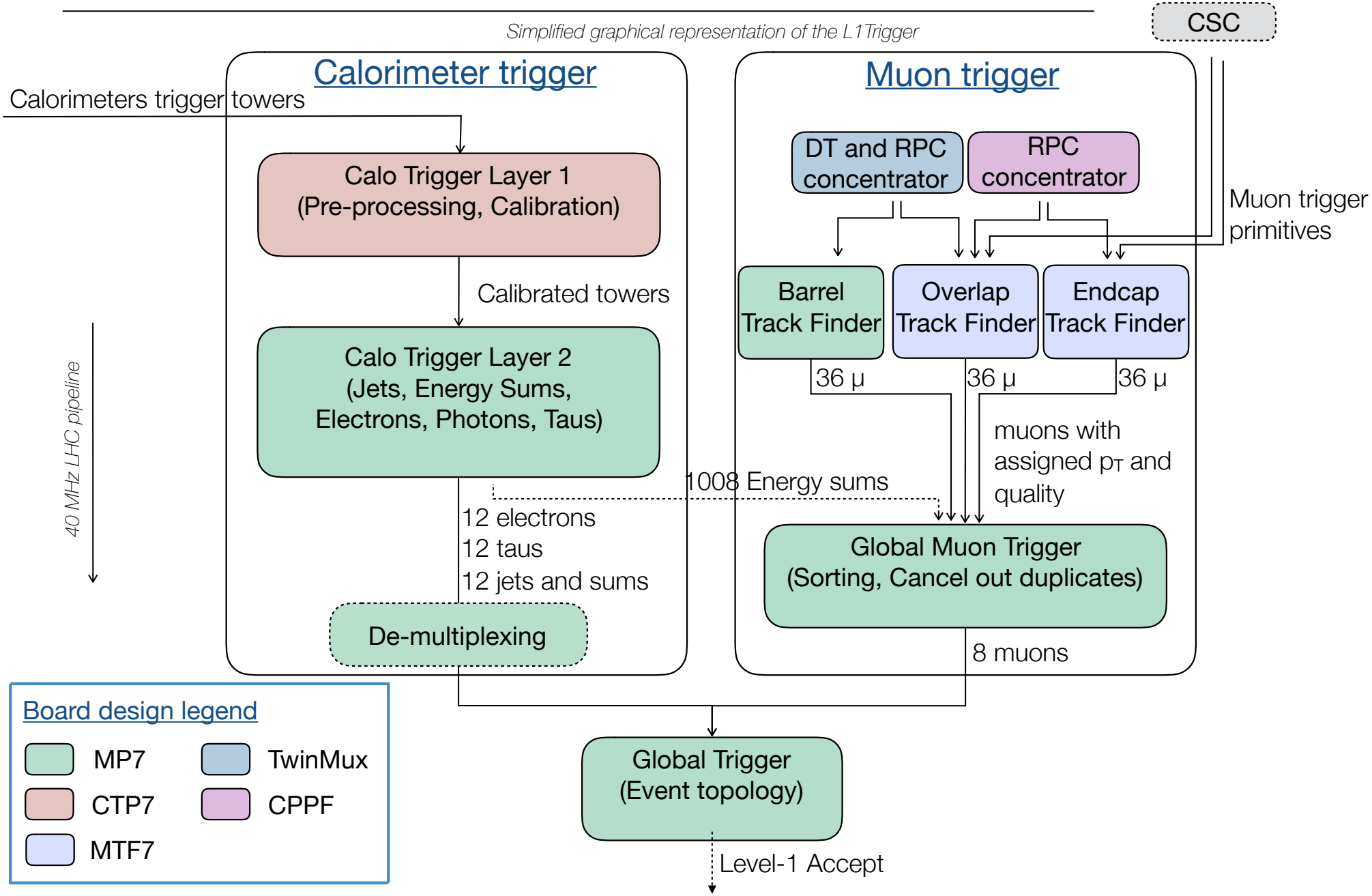
- **MP7** (Master Processor)
  - 72 I/O optical links @ 10 Gb/s
  - Time multiplexing processing



- **MTF7** (Modular track finder)
  - 84 Rx, 28 Tx @ 10 Gbps
  - Dual card with large capacity RAM (~1GB)



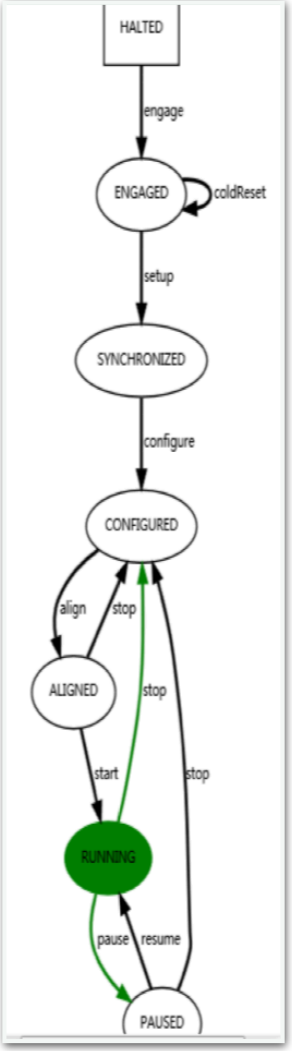
The CMS Level-1 trigger design



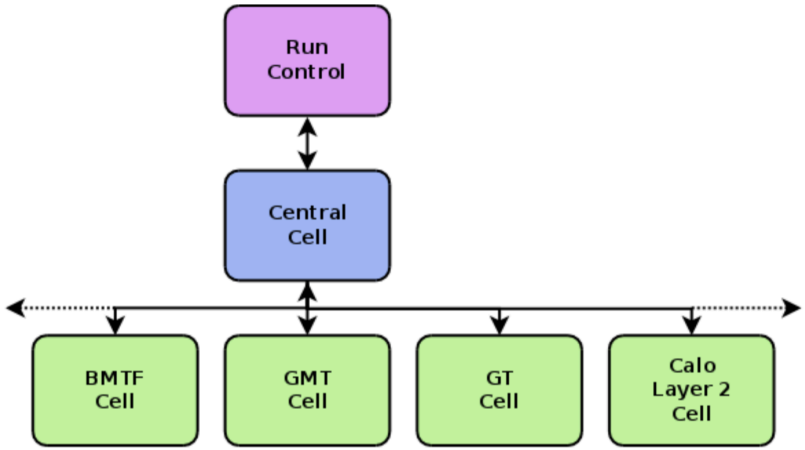
Control software (SWATCH)

Control software provides quick and reliable communication with boards

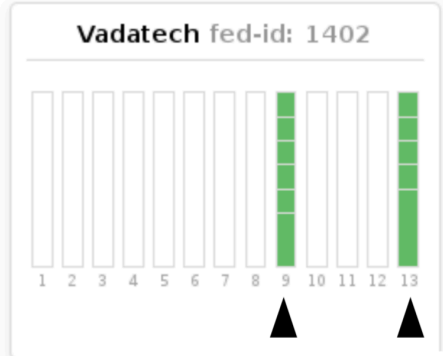
example of state machine for CPPF



- Configure trigger boards in a few seconds
- Centralised control and state machine for all boards via central cell
- Links and data flow between boards monitored during run-time
- Crucial monitorables (TP rate, clock, etc) monitored during run-time



example of SWATCH monitoring the boards in a crate



MP7 status AMC13 status

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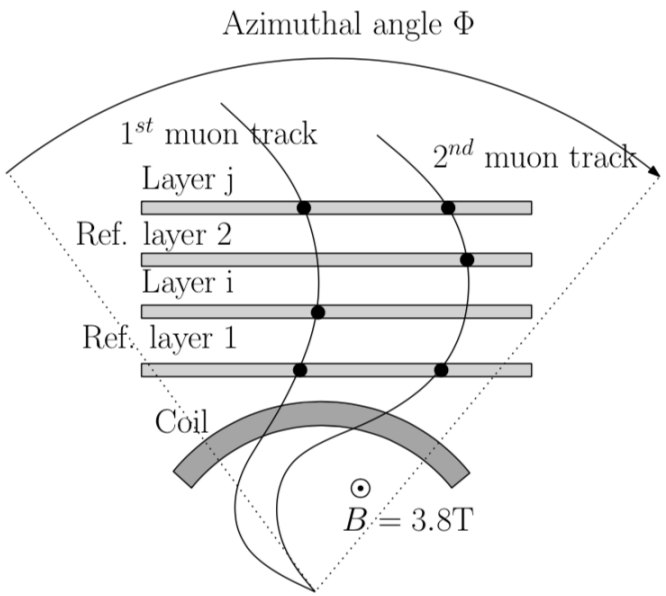
L1T Muons algorithms



- **Track finder** algorithms
  - **Road search extrapolation** track finding in **barrel**
  - **Pattern based** track finding in **endcap** and **overlap**
- Transverse **momentum assignment**
  - Based on **Δϕ between two stations** or bending in ϕ in one station in **barrel**
  - **Pattern based** assignment from Monte Carlo simulation in **overlap**
  - Based on **MVA techniques** (BDT regression) in **endcap**

L1T Muons - MVA-based pT assignment

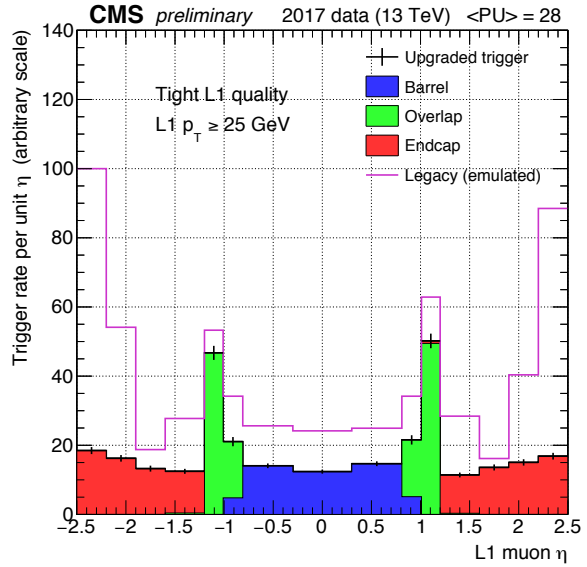
pT assignment based on **Boosted Decision Tree regression**

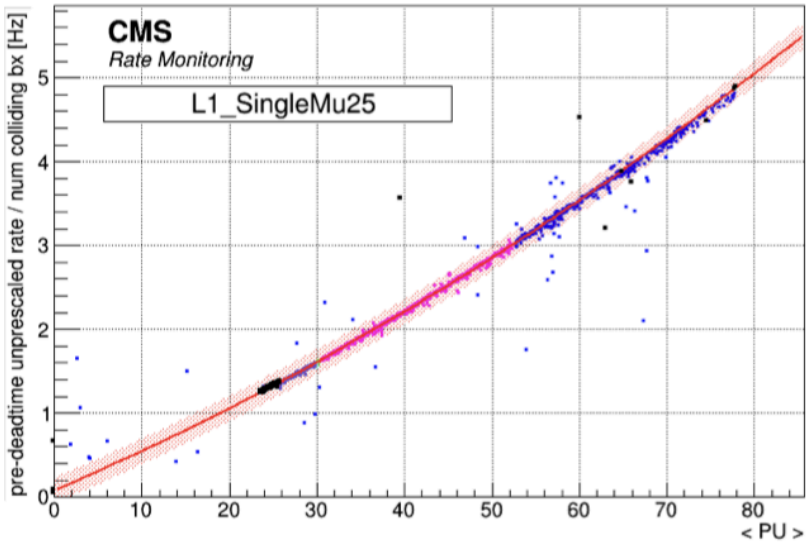
- Training on Monte Carlo simulation of Single Muon events
- BDT parameters optimised based on both trigger rate and efficiency as figure of merit
- **Can not evaluate BDT on FPGA (time consuming)**
  - **input variables compressed word of 30 bits** with optimised scale
  - **output pT compressed in a 9 bit word**
- **Record of the BDT response in a 1.2GB LUT for fast access**

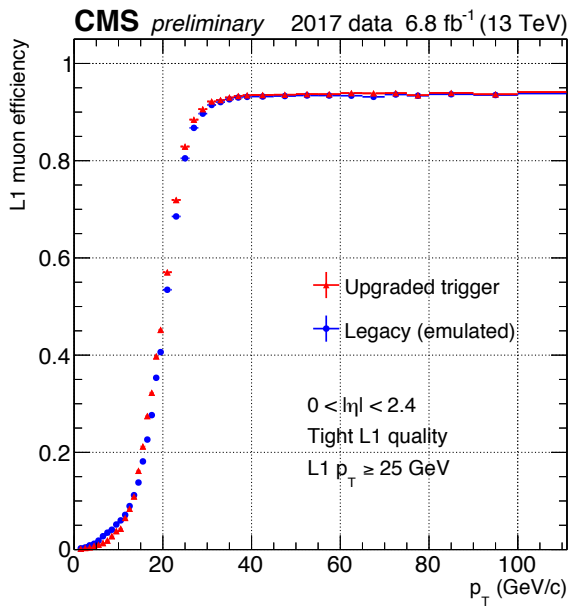
L1T Muons performance

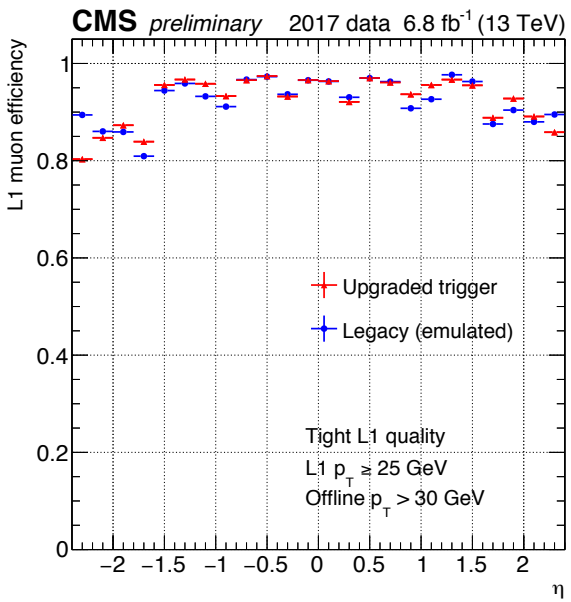
from Z⟶μμ tag and probe

- Large improvement compared to Run1
  - **lower rate by a factor of 2 for p_T > 25GeV**
  - **similar efficiency**
- Algorithm **rate linear with pileup**



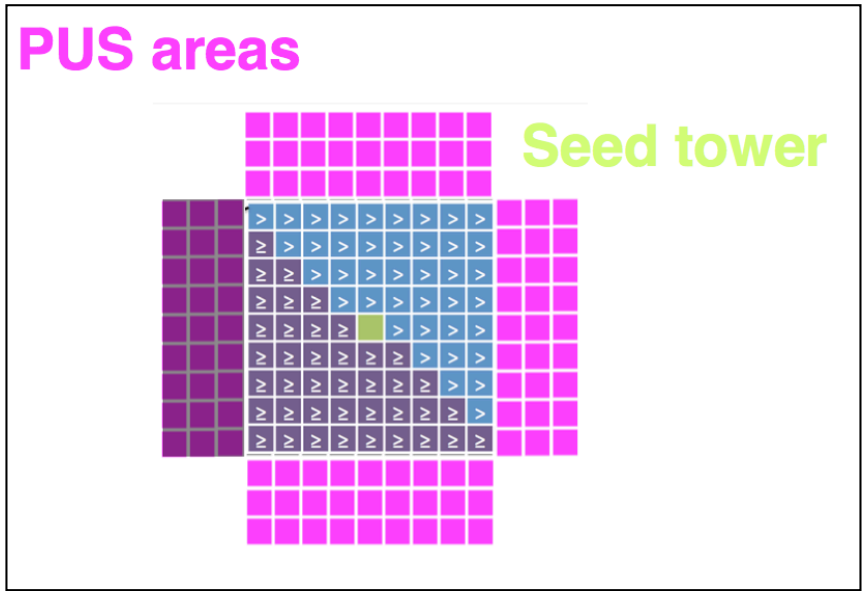




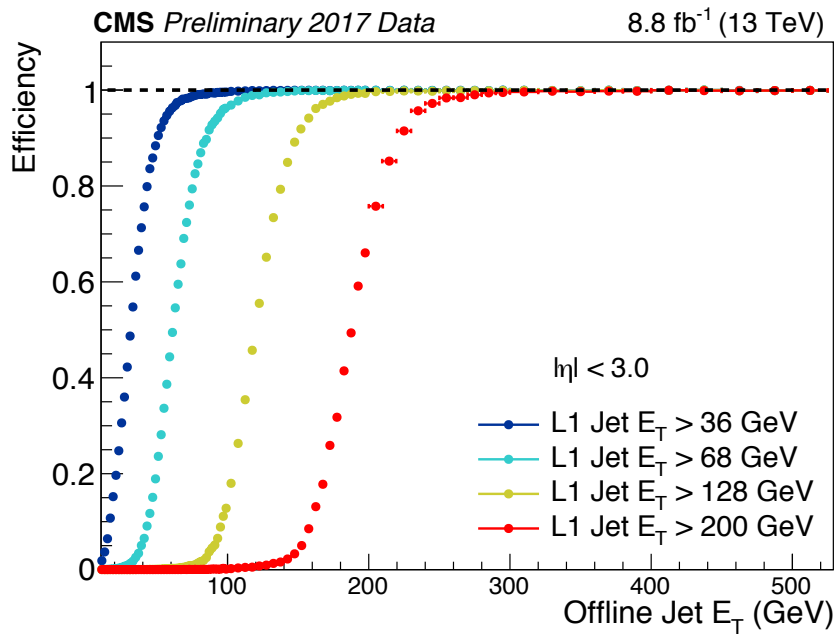


L1T Jets Algorithms and Performance

- Sum 9x9 trigger towers (~R=0.4 jets)
  - comparable with offline jets size
- L1T jets are **pileup subtracted** (PUS)
- Jet energy is calibrated for better energy resolution

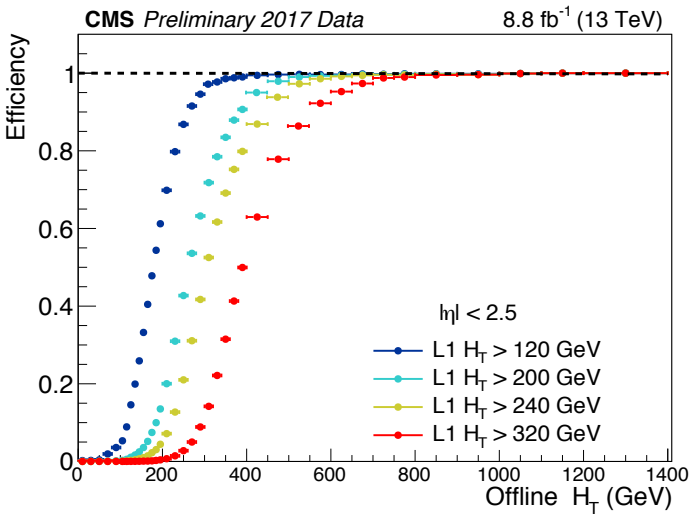


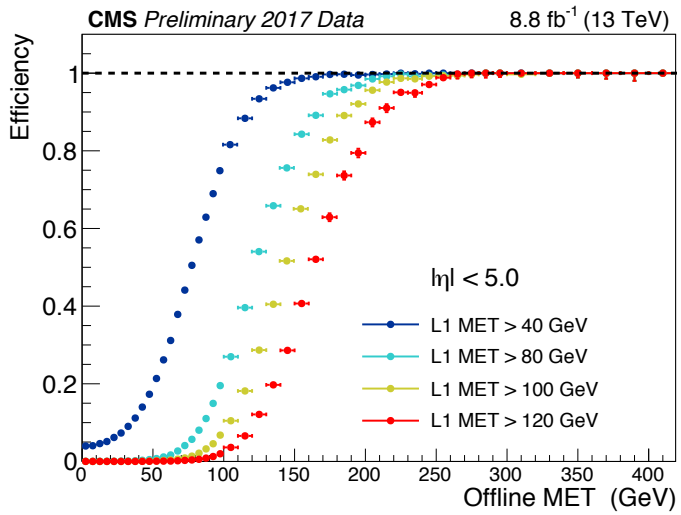
- Efficiency measured on Single Mu dataset
  - matching ak4 offline jets within dR < 0.15
- **Efficiency turn-on curve PU independent**

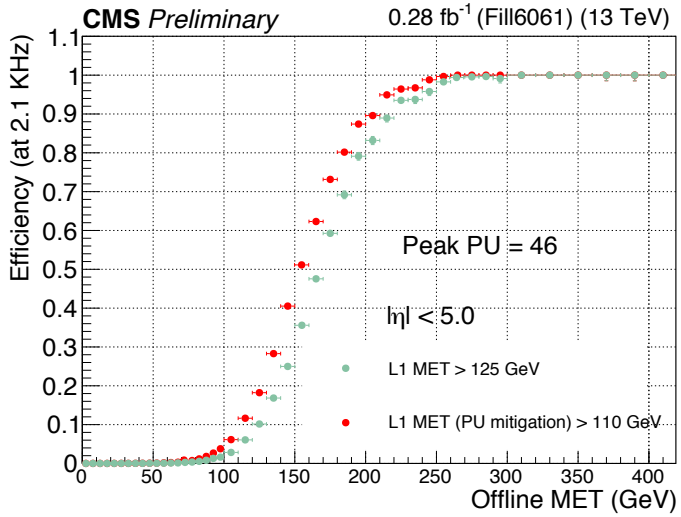


L1T Energy Sums Algorithms and Performance

- Use jets to calculate scalar sum $H_T = \Sigma E_{Tj}$ for $E_{Tj} > 30$ GeV and $|\eta| < 2.5$
- E_T^{miss} defined as vector sum of calibrated trigger towers with $|\eta| < 3$ (5)
- Efficiency measured from SingleMu triggered events (unbiased)
- **PU mitigation in E_T^{miss} gives lower rate (factor 2) at fixed efficiency**
  - allows lower thresholds
  - event-by-event trigger tower energy correction function of η and estimated PU

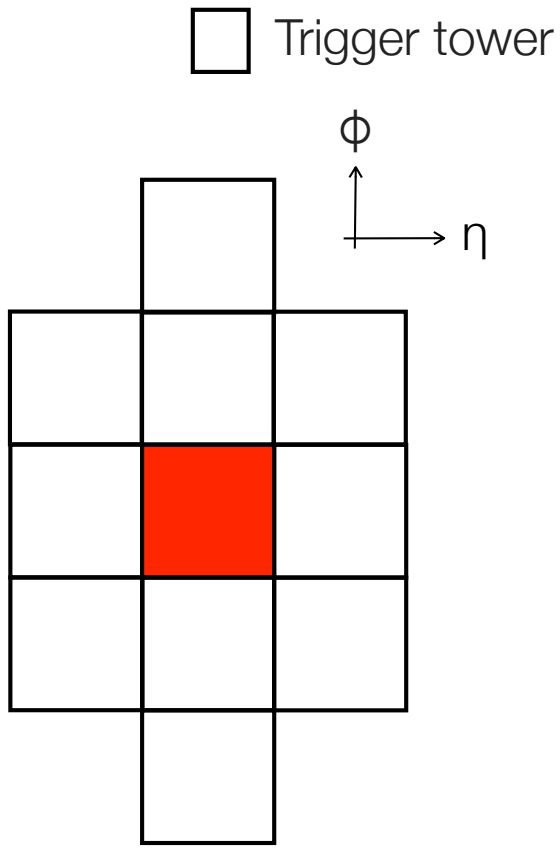






L1T e/γ clustering

- Electrons and photons are not distinguishable at L1T
- Reconstruction based on calo trigger towers
- EG reconstructed using **dynamic clustering**
  - **trigger tower over threshold gives seed for clustering**
  - clustering include neighbour towers over threshold
  - shape can be irregular
    - better energy containment
    - better pile-up resistance
    - discrimination against jet by jet-shape veto



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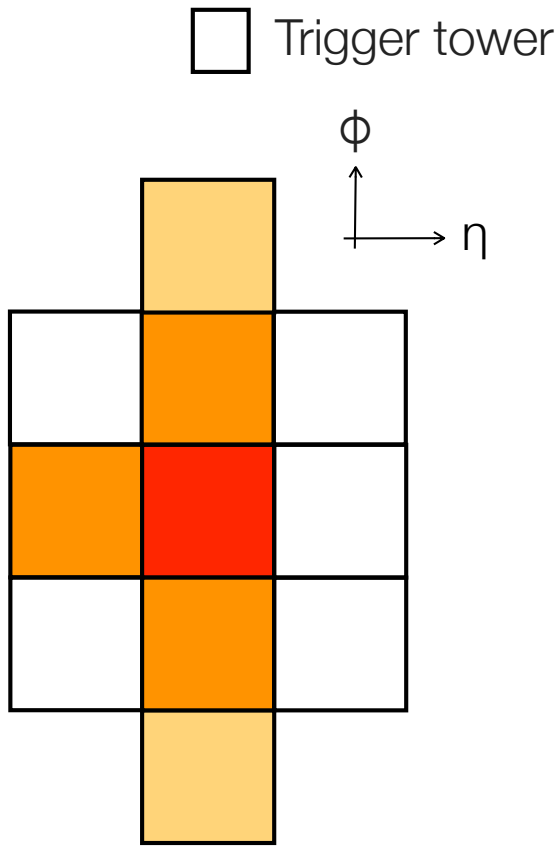

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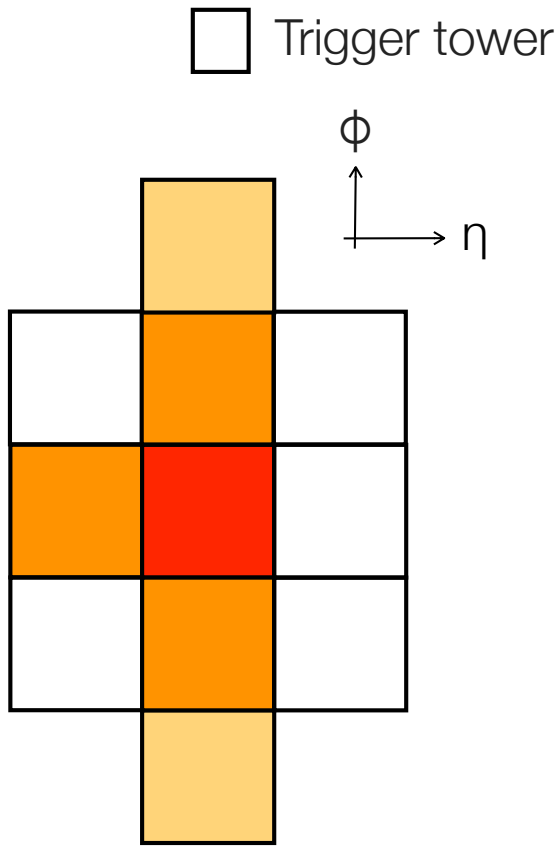
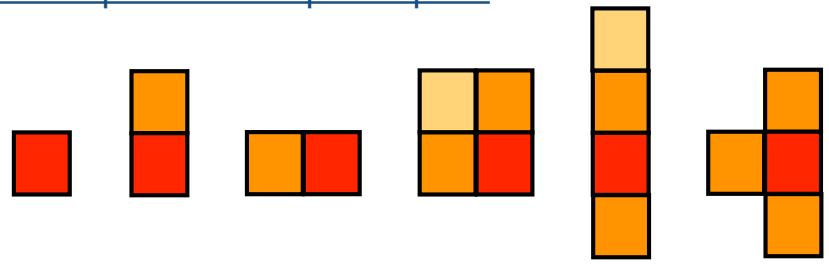


Examples of e/γ shapes

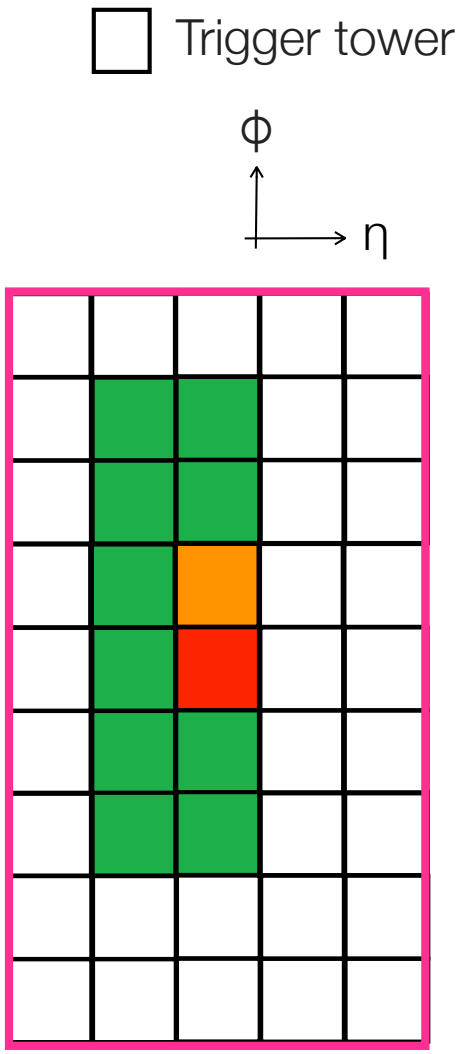


L1T e/γ isolation

- Most physics analyses use **isolated e/γ** objects offline
- Isolation of clusters can be calculated at L1T level
- Subtracts **ECAL** and **HCAL** footprint from **(9x5) trigger tower area**
  - isolation cut function of PU estimator and eta
  - tuned for constant efficiency as a function of PU and η

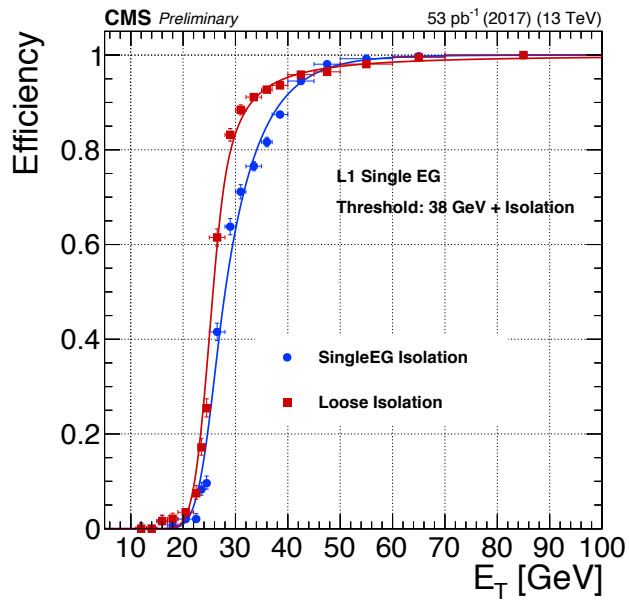
$\sum E_T$ (9x5 TT - e/g footprint) < cut(PU,η)

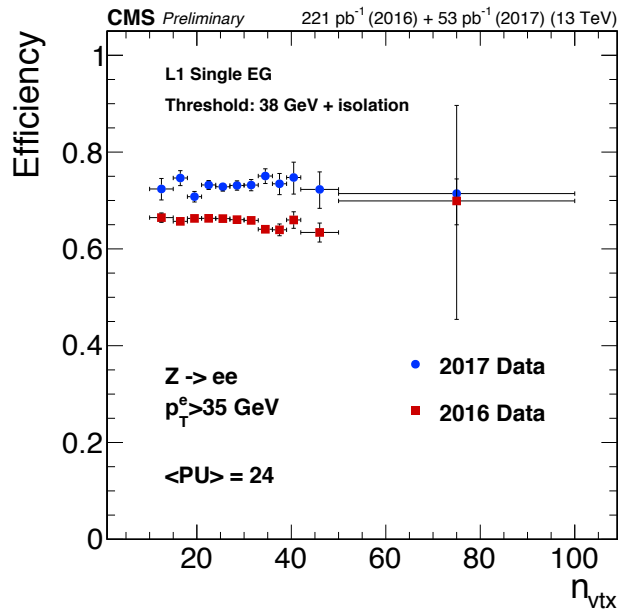
- **Two isolation requirements** for single object and multi objects



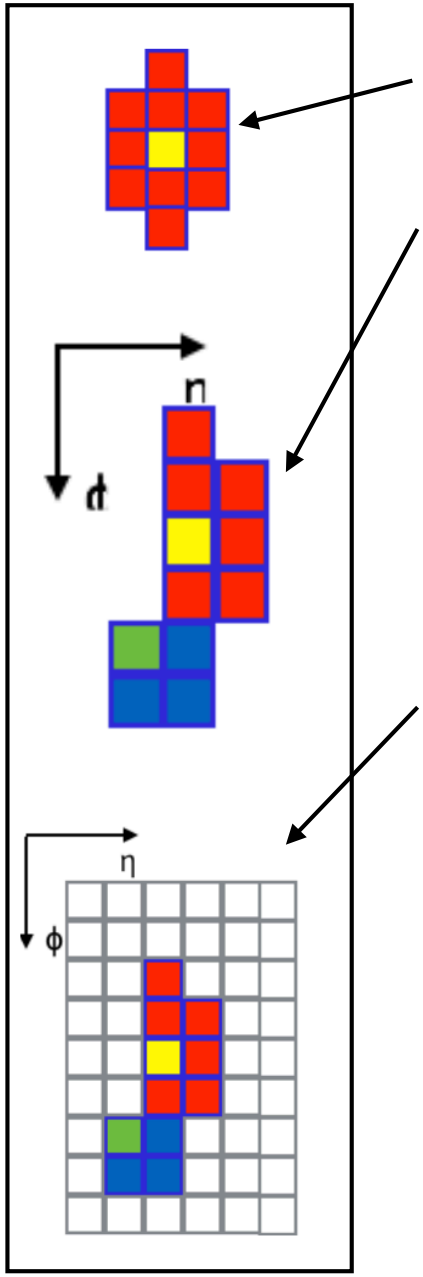
L1T e/γ Performance

- Single object rate linear with pileup
- Energy resolutions improves with lowering eta
- **L1T EG 38 GeV physics threshold for 2017**
  - **fully efficient offline at 50GeV**
- **Efficiency independent on pile-up**
  - improved compare to 2016





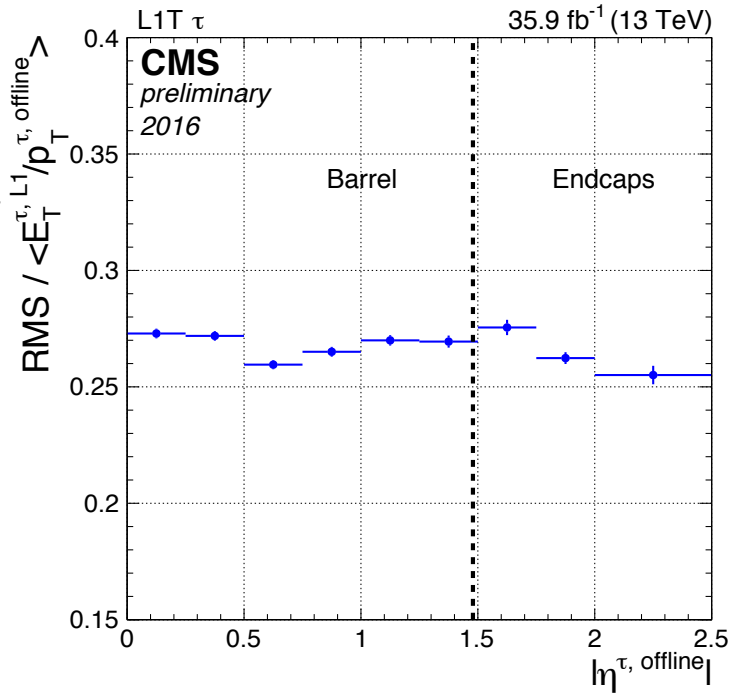
L1T τ Algorithm



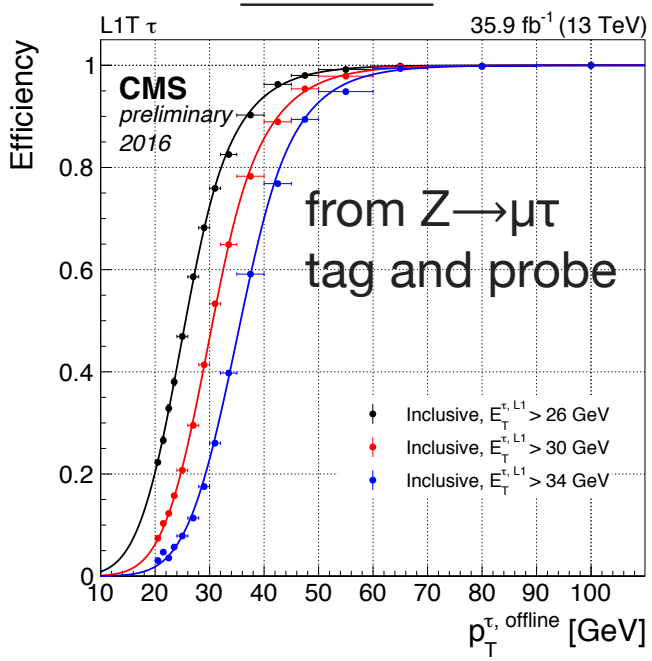
- **Clustering** is dynamic same as EG
- **Merge** neighbouring clusters (~15% of clusters)
  - recover multi-prong τ decays
- τ cluster energy **calibration** using MVA techniques (BDT regression)
- **Isolation** very similar to e/γ
- Jet shape-veto very similar to e/γ

L1T τ Performance

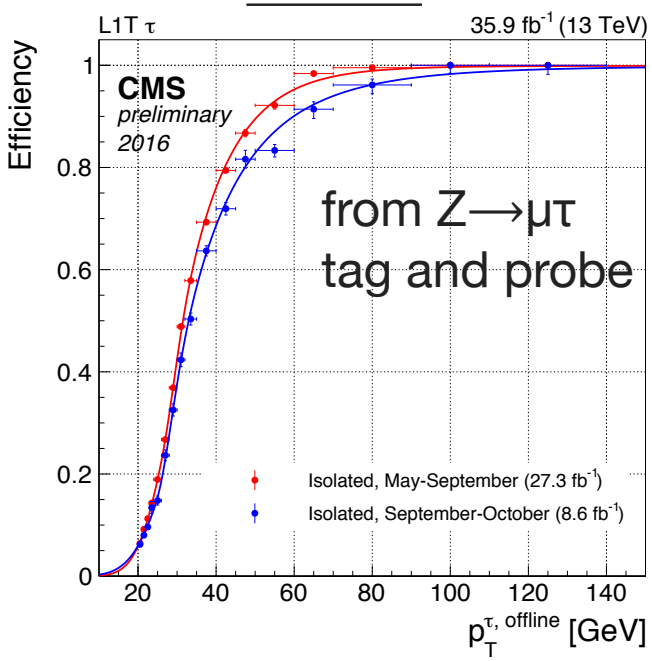
- **Calibration improves energy resolution**
  - **independent on η**
- Isolation allows lower threshold
  - Isolation working point retuned to adapt to LHC running condition



Inclusive



Isolated



Luminosity May-September
$L=1.34\times10^{34}\ cm^{-2}s^{-1}$

Luminosity September-October
$L=1.53\times10^{34} cm^{-2}s^{-1}$

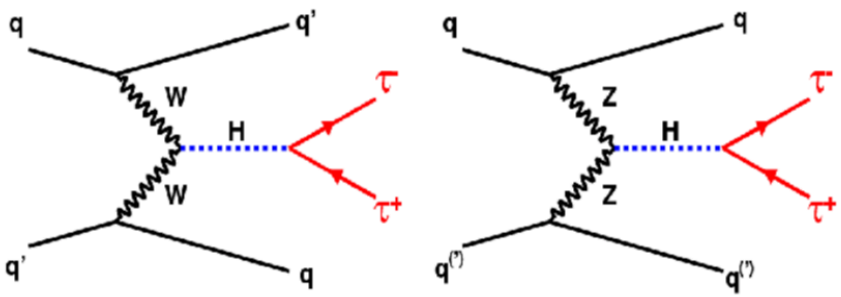
The L1T menu

The Global Trigger allows to define a **large number of topology and phase space** using the L1T algorithms

- **during Run-2 used ~ 440 triggers**
- can use complex operations such as **invariant mass (VBF), transverse mass**, di-object pt, etc
- L1T Menu bandwidth
  - **~45%** rate dedicated to **single or double objects**
  - **~55% special topologies**, calibration, monitor, etc
- Allocation of bandwidth is a complex and iterative task
  - 5 versions L1T menu only in 2017 following LHC

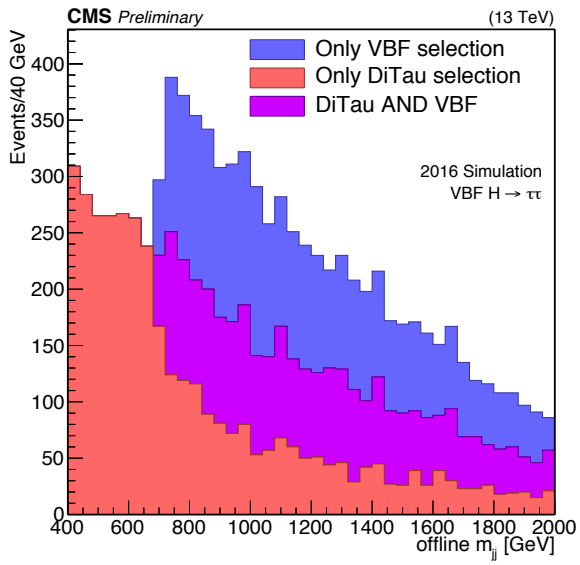
Physics object correlation: invariant mass

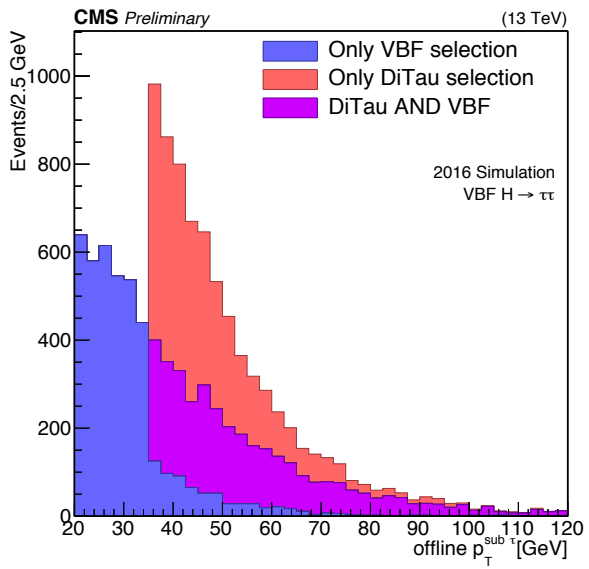
- Example VBF Higgs to di-tau decays:



  - Two low ET jets, separated by large η gap
  - Central high pT τ-lepton pair from Higgs decay
- Use of invariant mass allowed lower jet threshold
- Combination of leptonic and hadronic selections adds

  ~60% efficiency for the Higgs signal





Outline

- **Level-1 trigger**
  - Design
  - Hardware and software
  - Algorithms and performance
- **High Level Trigger**

The High Level Trigger

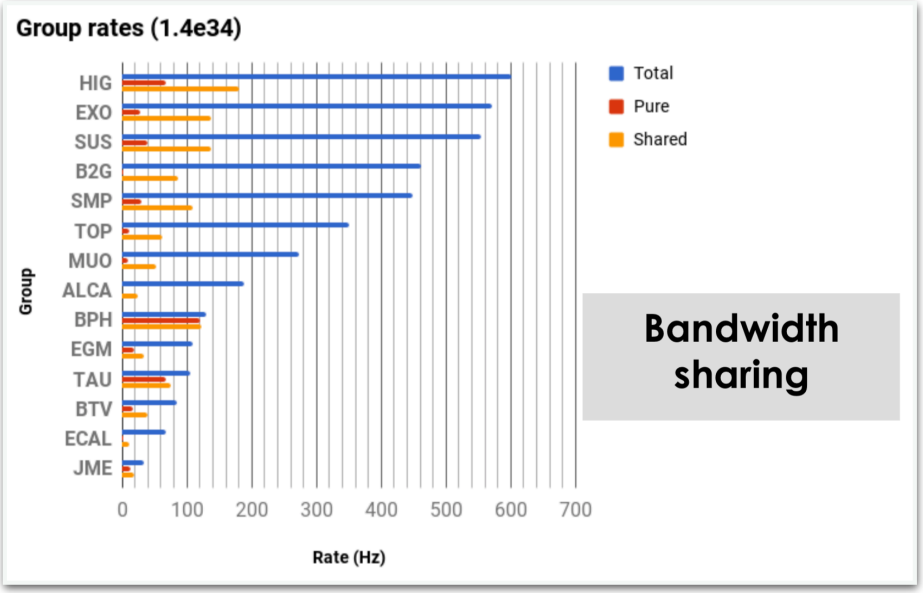
- Entirely in **software**
  - HLT frameworks and algorithms implemented in python and C++
  - composed by a **sequence of reconstruction and filtering** modules
    - when an event is rejected by a filter the sequential modules are not run
- Running on a farm of **~26000 cores**
- Working on full events
- **Average output ~1 KHz**
  - stored on disk for full reconstruction and analysis

The High Level Trigger tracking

- **Tracking** is used to performed a **simplified particle flow** algorithms
  - the pT relative resolution of a simulated jet with pT ~30GeV is of 28% for the online calorimetric jets and of 18% for online PF jets
- **Tracking** and PF reconstruction are also used **for b-jet identification**
- **New pixel detector reduced fake rate** by more than a factor ten and increased efficiency

The Trigger Menu

- Defining a menu is a complex and iterative process



- **Total rate** per group: sum of the triggers rate used by group
  - Largest consumer HIG, EXO, SUSY
- **Proportional rate** per group: rate from single-group trigger (takes into account co-ownership)
- **Pure rate** per group = rate from single-group trigger
  - Largest consumer: B-PHYSICS collects events from unshared phase space

Summary

- Main challenges for a design of a trigger systems
  - limited time to take a decision
  - large amount of signals from detectors to process
  - performance dependency on pileup
- Design and tools in CMS Level-1 trigger
  - custom design electronics with programmable FPGA
  - event size reduction and trigger primitives
  - time multiplexing for efficient high bandwidth data handling
  - pileup subtraction and MVA algorithms
  - complex objects correlations at global trigger level

Conclusions and outlook

- Trigger systems are crucial and delicate detectors
- Need to follow the steep rise of LHC instantaneous luminosity
  - CMS will upgrade (Phase-II) in 2023
    - Dedicated talk by V. Rekovic

References

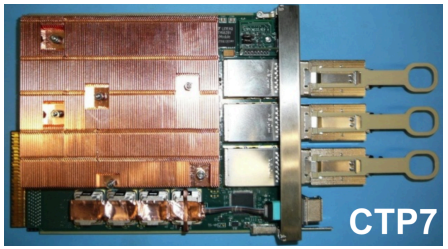
- CMS Level-1 Trigger TDR: https://cds.cern.ch/record/706847
- Run I performance paper:
  - CMS Collab., The CMS trigger system, JINST 12 (2017) P01020.
- Phase 1 upgrade TDR: https://cds.cern.ch/record/1556311
- Performance notes
  - e/γ: https://cds.cern.ch/record/2273270
  - τ and VBF with inv. mass: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

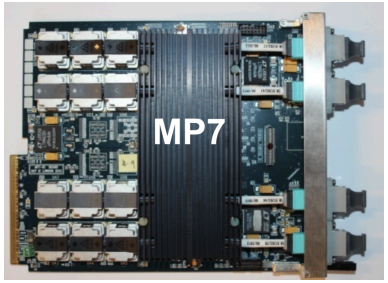
Thank you for your attention

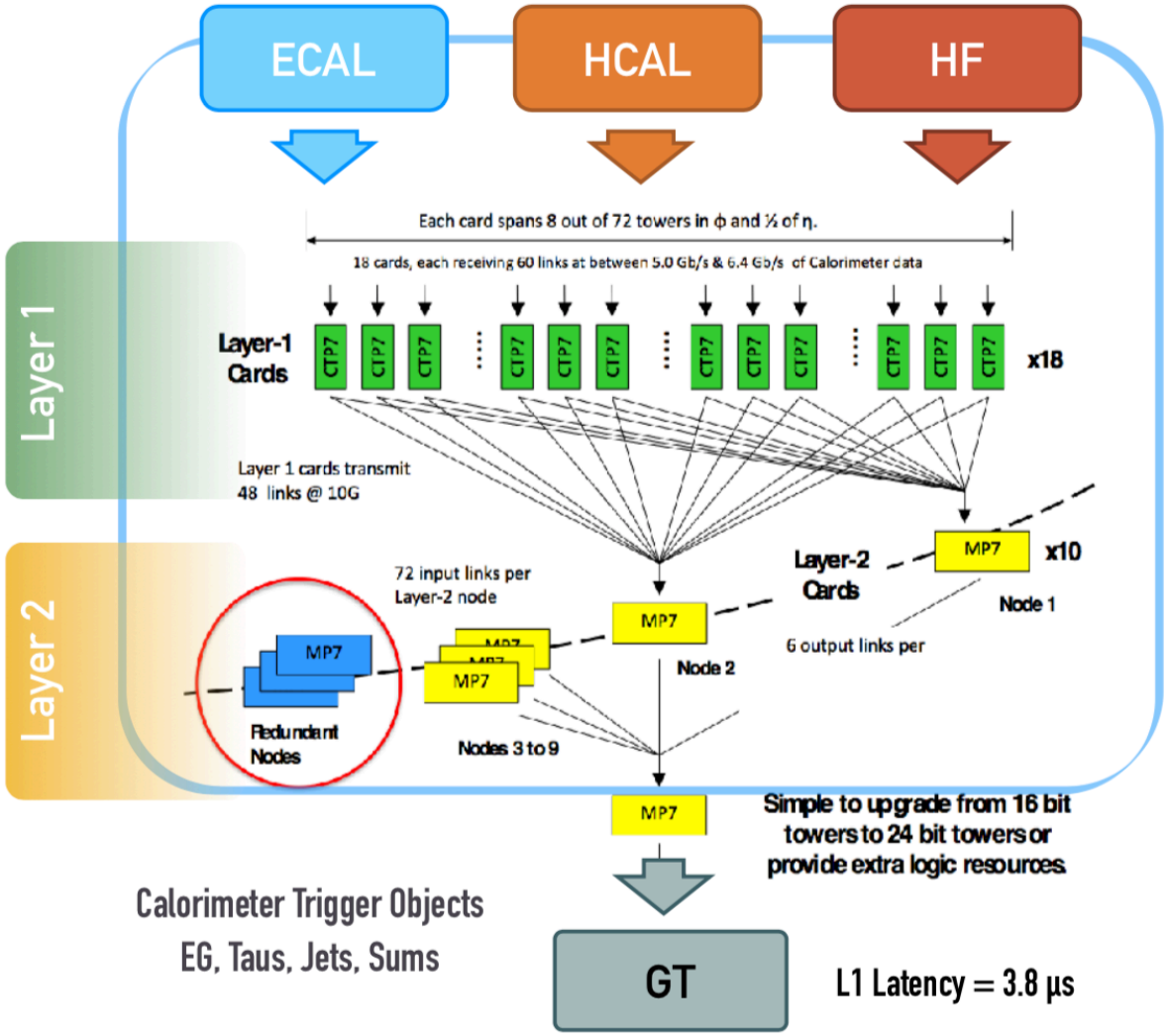
backup

L1T calorimeter design

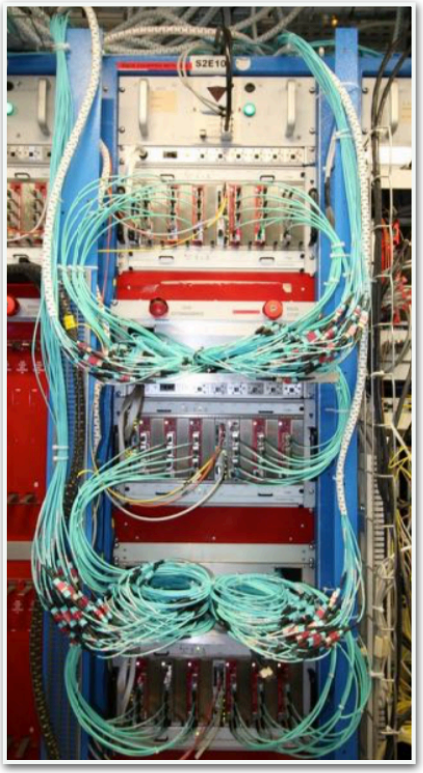
- Organised in **two layers** implementing **time-multiplexed** architecture



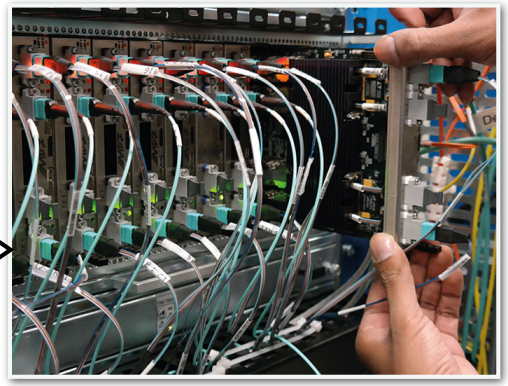




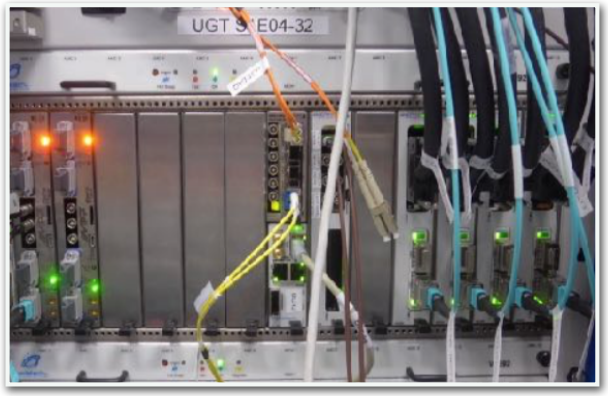
L1T calorimeter design



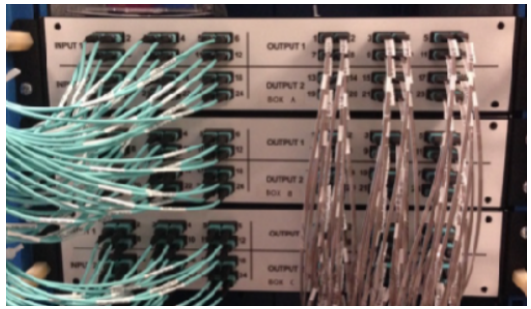
Layer-1



Layer-2



Global Trigger

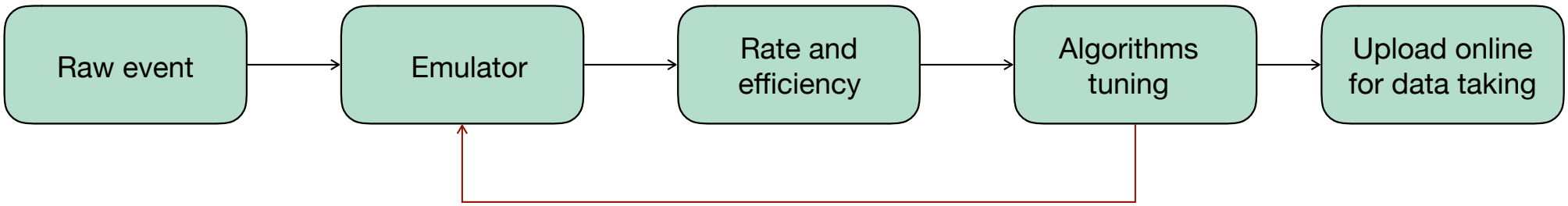


Time multiplexing routed trough 72 to 72 12-fiber MPO connector

Emulators

Emulators are the software equivalent version of the firmware algorithm

- **Provide validation of algorithms (rate, efficiency) before loading them online**
- Provide the trigger simulation for the Monte Carlo event generation
- Provide an excellent online monitoring tool of possible firmware problems



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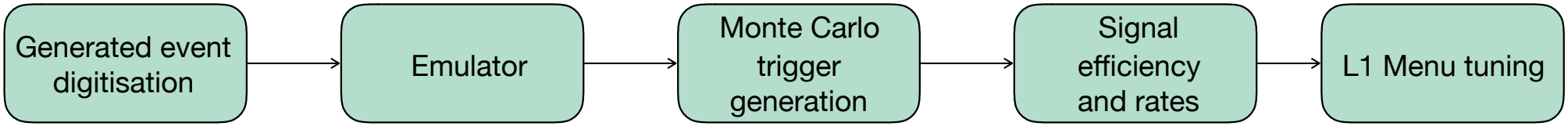

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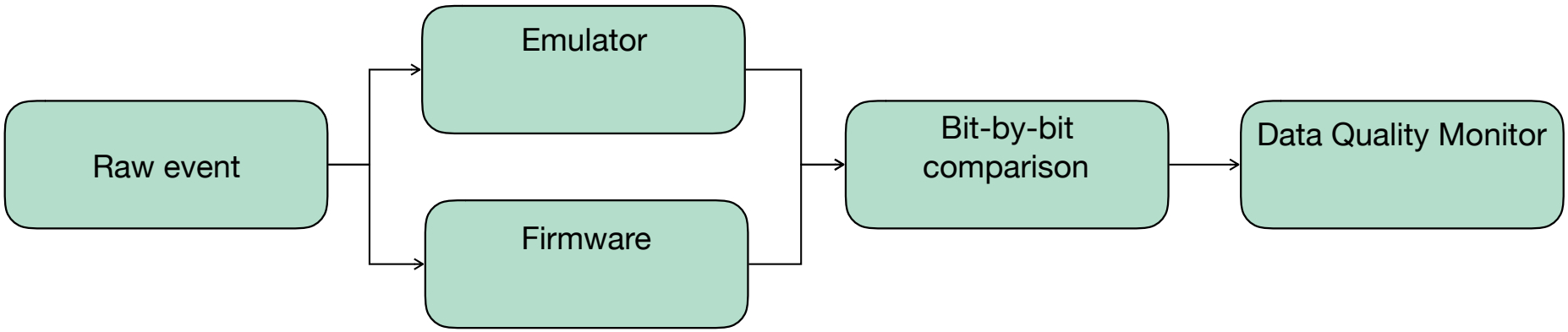
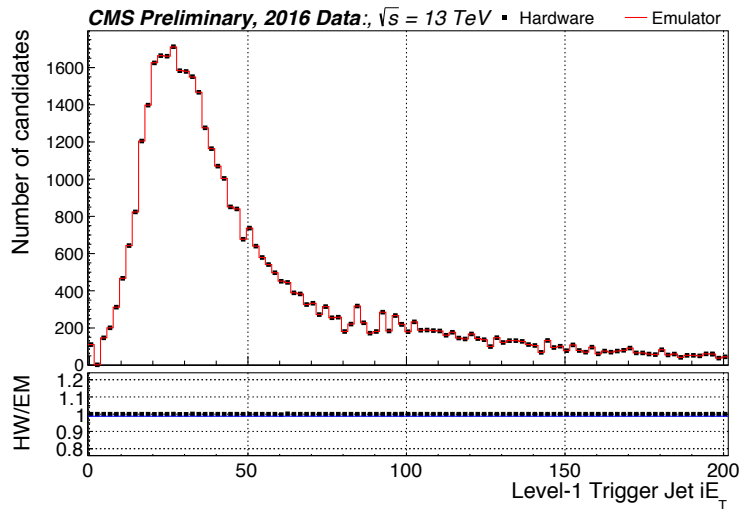


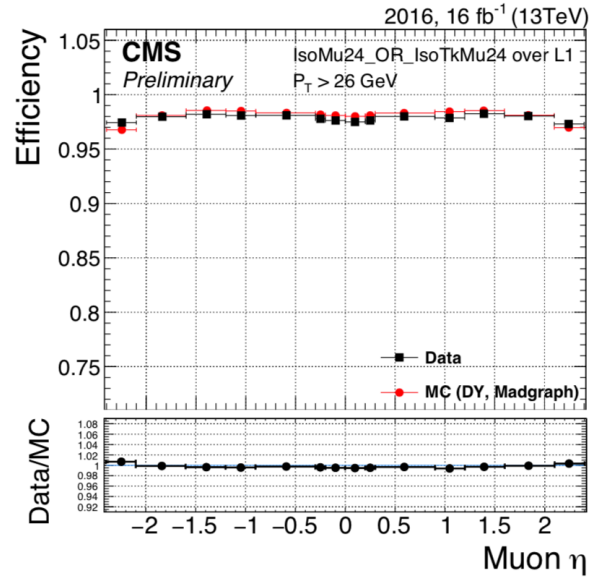
Data Quality Monitoring

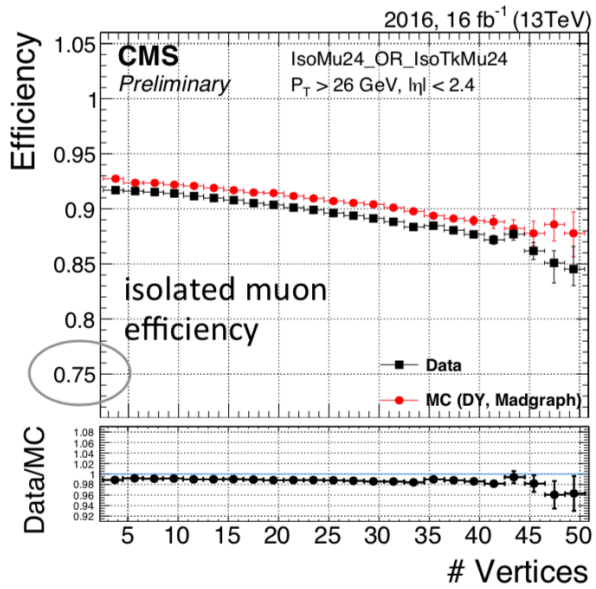
- Each processor implements a DAQ readout for data monitoring
- Online DQM software
  - displaying critical information to shifters via a GUI using subset of events
  - **comparison with emulators** provides diagnostics for hardware problem
- Offline DQM software
  - Performance measurement compared to offline
  - Detailed information in case of problems



The High Level Trigger muons

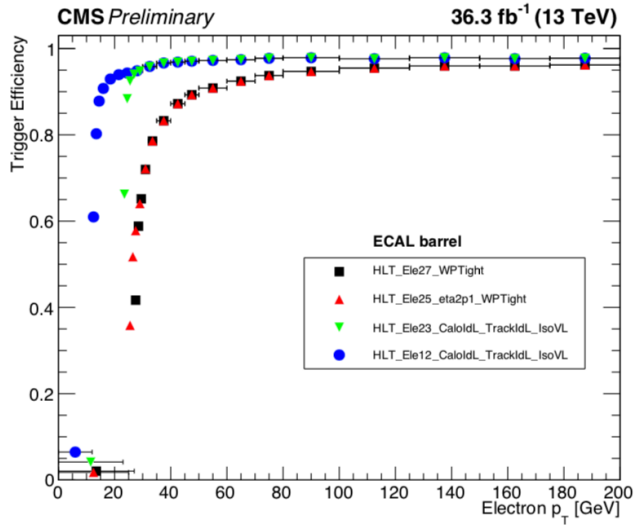
- Muons are reconstructed using muon detector and tracking
- **Momentum resolution improved** compare to Level-1 thanks to the **tracking** information
- The HLT **efficiency** for reconstructing muons is **>99%**
- In 2016, the lowest un-prescaled muon trigger was pT > 24GeV
- **Isolation reduces rate** of more than a factor two
  - paying a small inefficiency of 2 – 3%

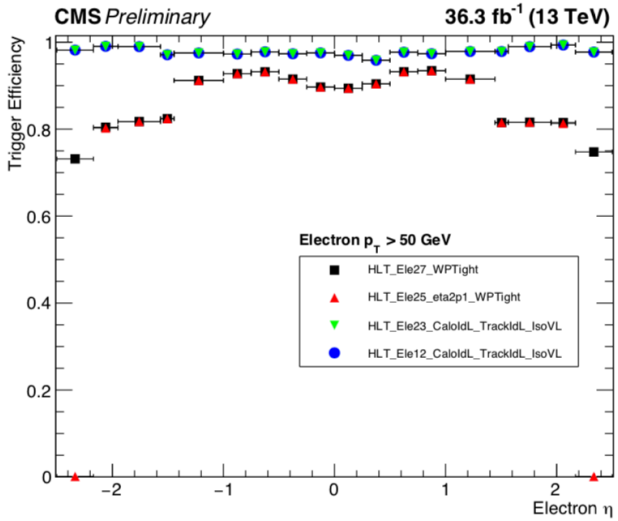




The High Level Trigger electrons

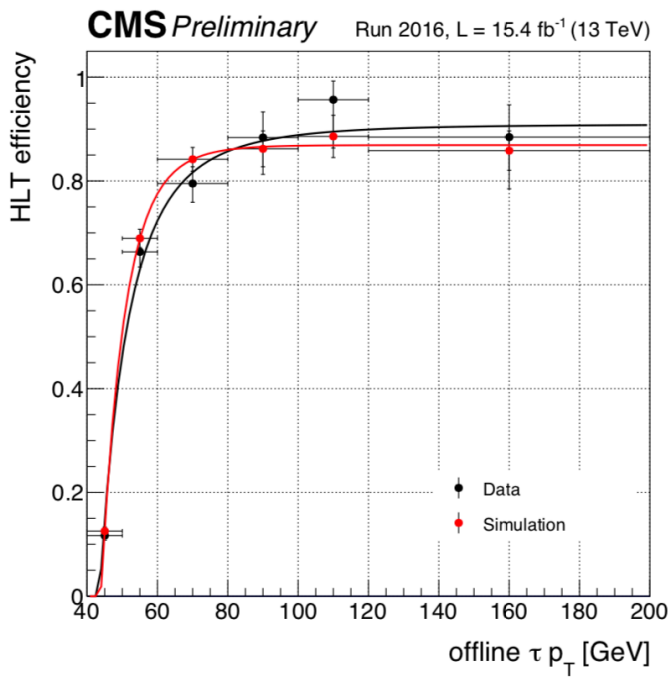
- Track combined with calorimeter information
- Electrons tracks are reconstructed using a **dedicated algorithms** (Gaussiam Sum Filter) that take into account a strong breastrahlung energy loss
- **Isolation** and **identification** requirements are applied to **reduce the rate** allowing lower thresholds
- **Efficiency is > 90% in the barrel and >80% in the endcap**
- **Efficiency independent from PU**





The High Level Trigger taus

- Hadronically decaying taus are reconstructed using tracking information
- Look for τ in either one or three charged particles decay and up to two π0 → γγ, reconstructed as a ϕ-long strip in the electromagnetic calorimeter



LHC and CMS

LHC is an **hadron collider** (proton-proton)

Centre of mass energy

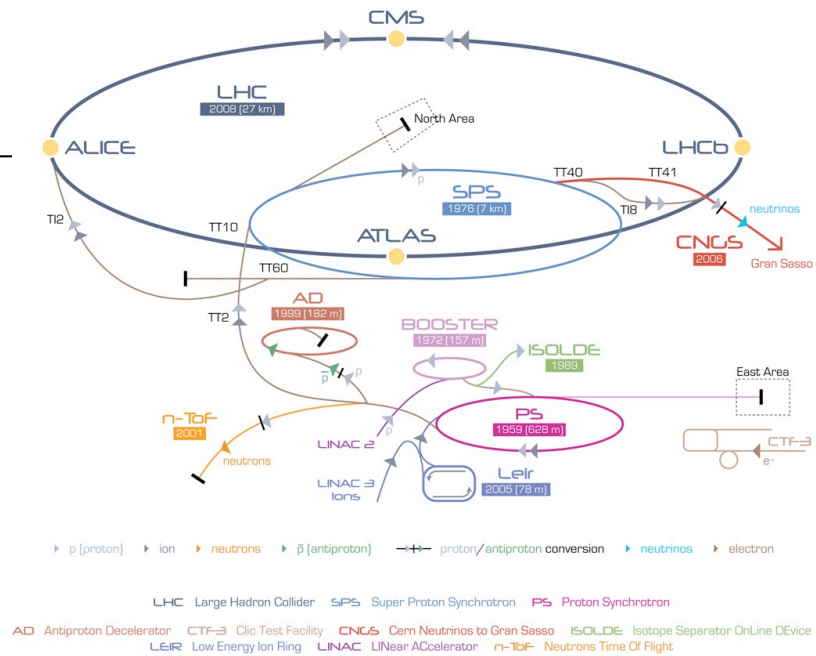
- $\sqrt{s}$ = 7, 8, 13 TeV

Maximum bunch crossing rate

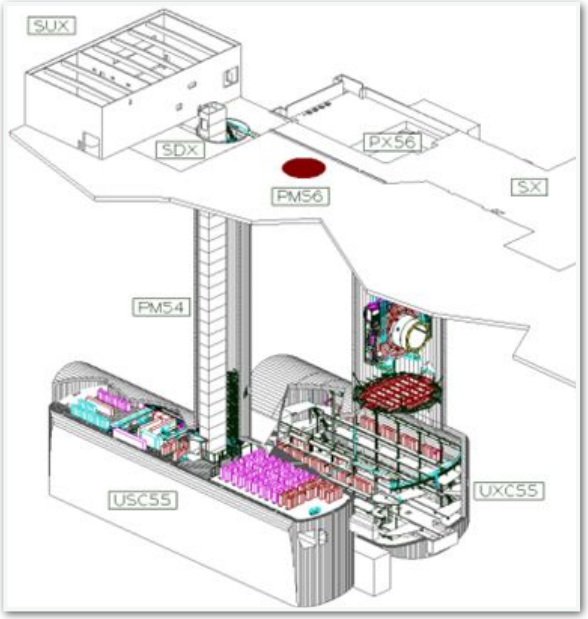
- 40 MHz (25 ns bunch crossing spacing)

Four main experiments

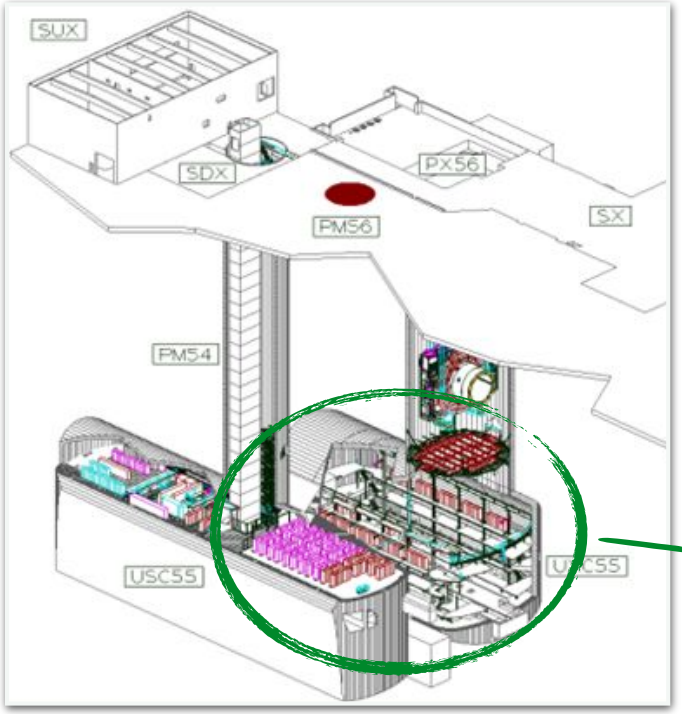
- **CMS** and **ATLAS** multipurpose
- **LHCb** investigates B-physics
- **ALICE** designed for heavy ion collisions

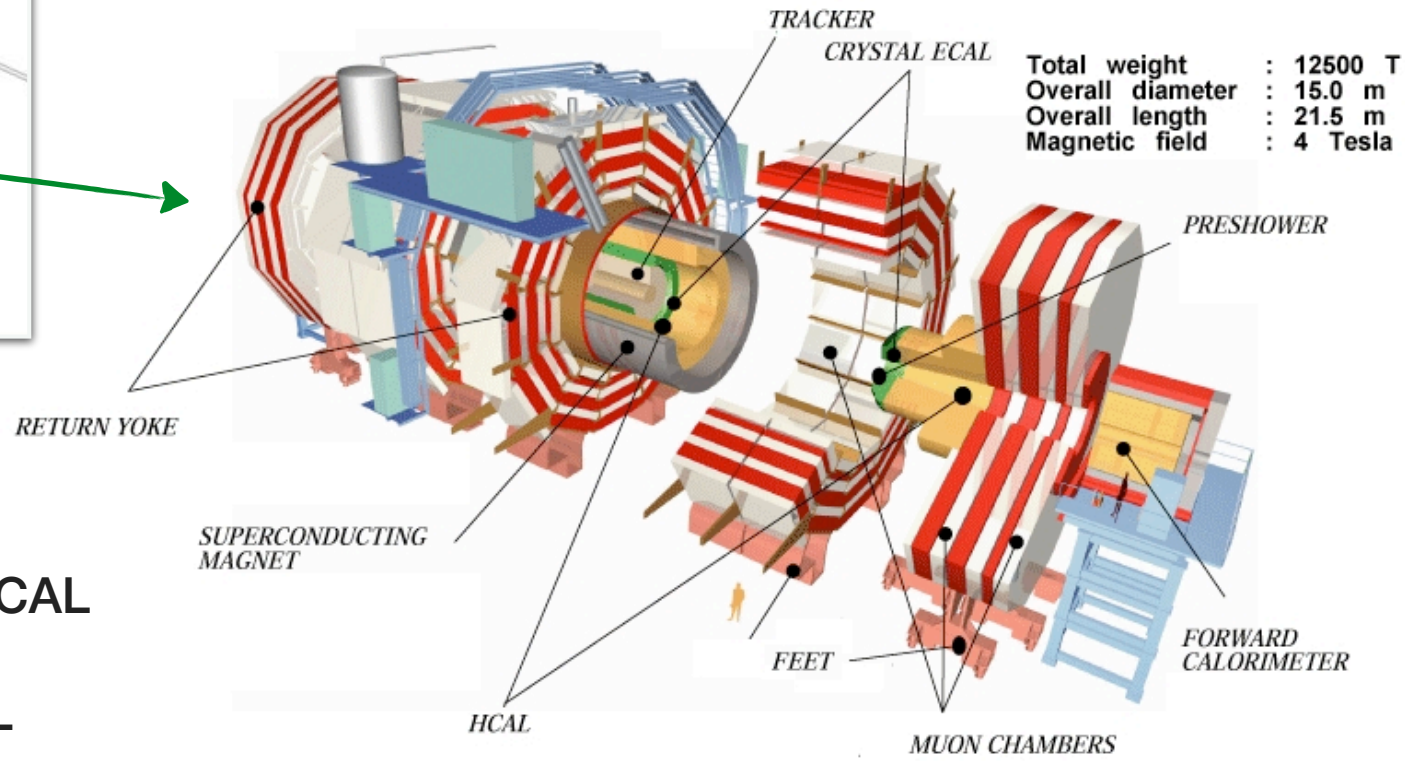


CMS facilities



CMS inside the cavern





Silicon tracker

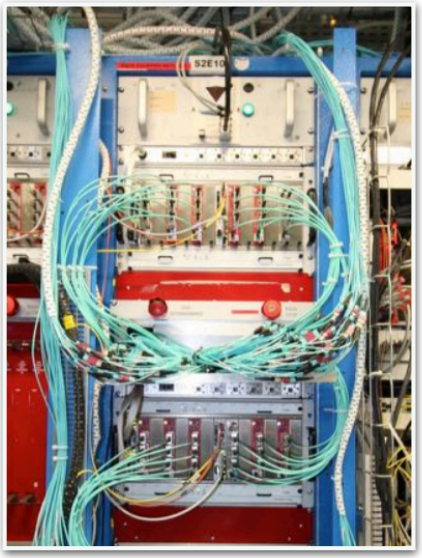
80000 $PbW0_4$ crystal ECAL

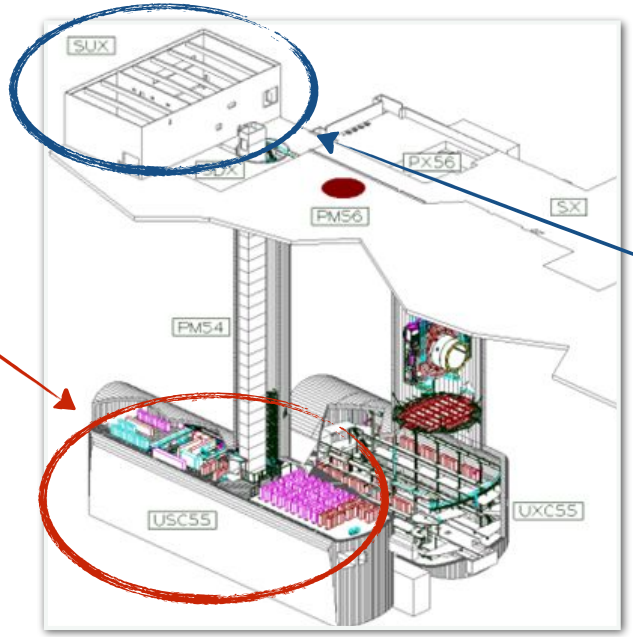
Scintillator/brass HCAL

Redundant muon system (1400 chambers)

CMS outside the cavern

The **Level-1 Trigger** located in the service cavern





The **High Level Trigger** located in the computing room at surface

- No need to be installed close to interaction point
- No radiation damage
- Easier access

L1 Trigger components

Layer1

- calibrates ECAL and HCAL
- combines ECAL and HCAL energy
- defines H/E

Muon Track Finders

- builds tracks from muon segments
- assigns pT to each track
- assigns quality to each muon

Layer2

- clusters and defines objects (Jets, EG, Taus, Sums)
- defines and calibrates isolation
- defines and calibrates pileup subtraction

Global Muon trigger

- ranks track finders muons
- selects best muons to send to uGT
- looks for duplicate and arbitrates them
- define isolation using trigger towers from layer2

Global trigger

- collects all objects form layer2 and uGMT
- collect BPTX signal
- builds cross triggers
- TAKE L1 ACCEPT DECISION

Graphical outline