DESIGN OF THE CMS UPGRADED CALORIMETER TRIGGER FROM PHASE I TO PHASE II OF THE LHC

CALOR 2018

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THE CHALLENGES OF CALORIMETER TRIGGERS

Increasing complexity of the calorimeter trigger architectures

With the intense LHC running conditions in terms of instantaneous luminosity and average pile-up events per crossing, the calorimeters structures and readout have grown in complexity. As a result the trigger architecture became increasingly complex to provide sophisticated selection algorithms to ensure the highest acceptance for Physics already at hardware level.

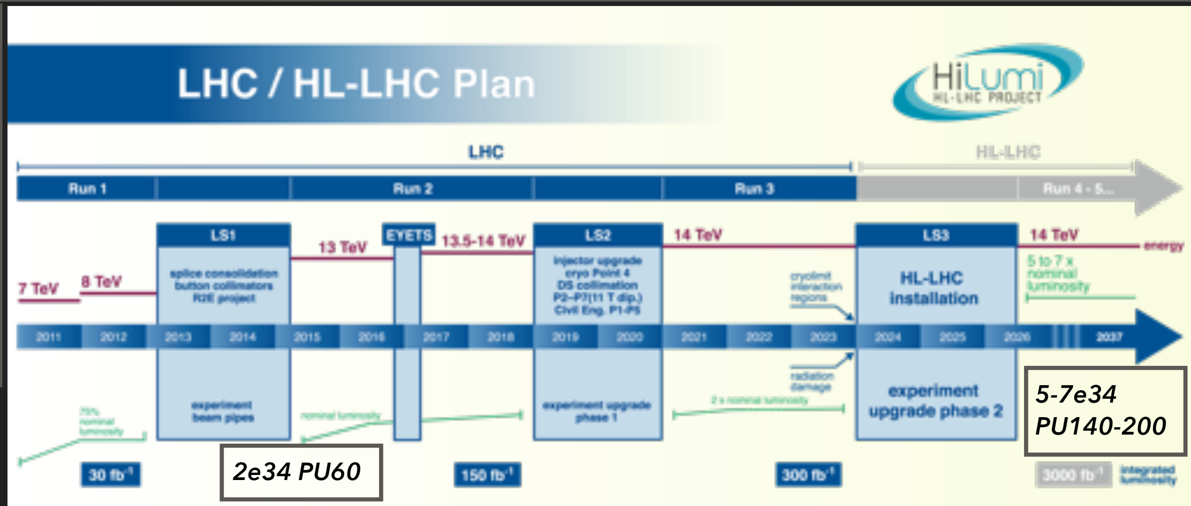
- Increasing the number of channels i.e. the granularity to achieve optimum reconstruction, particle identification, isolation and energy calibration

  –> Need large computing resources (FPGAs)
- Evaluate global quantities (VBF, MET, embedded Pile-up mitigation techniques etc..)

  –> Need high speed optical links to provide a global detector view
- Increase selectivity: provide global triggering expandable to many more possible conditions and more sophisticated quantities to give a rich physics menu.

  –> Need flexible and modular architecture based on uTCA/ATCA

This presentation will cover the technical challenges faced when designing, commissioning and operating the Phase I upgraded calorimeter trigger and the approach for Phase II



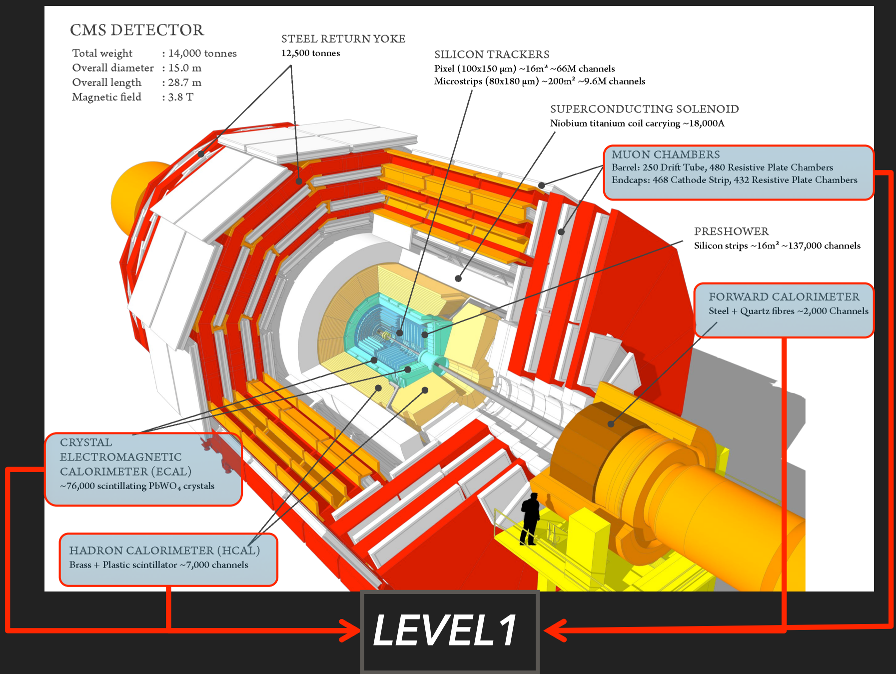
OUTLINE

- Level-1 trigger: introduction and role within the CMS data acquisition system. Description of its upgraded architecture and the technical challenges of its implementation
- Phase I Calorimeter trigger algorithms: Design of sophisticated algorithms and their performance.
- Introducing the new trigger challenges for the Phase II calorimeter trigger: Triggering with enhanced granularity, what implications on the architecture (scalability of the Run II system)
- Phase II Calorimeter trigger algorithms: The introduction of the higher level object reconstruction, identification and isolation.

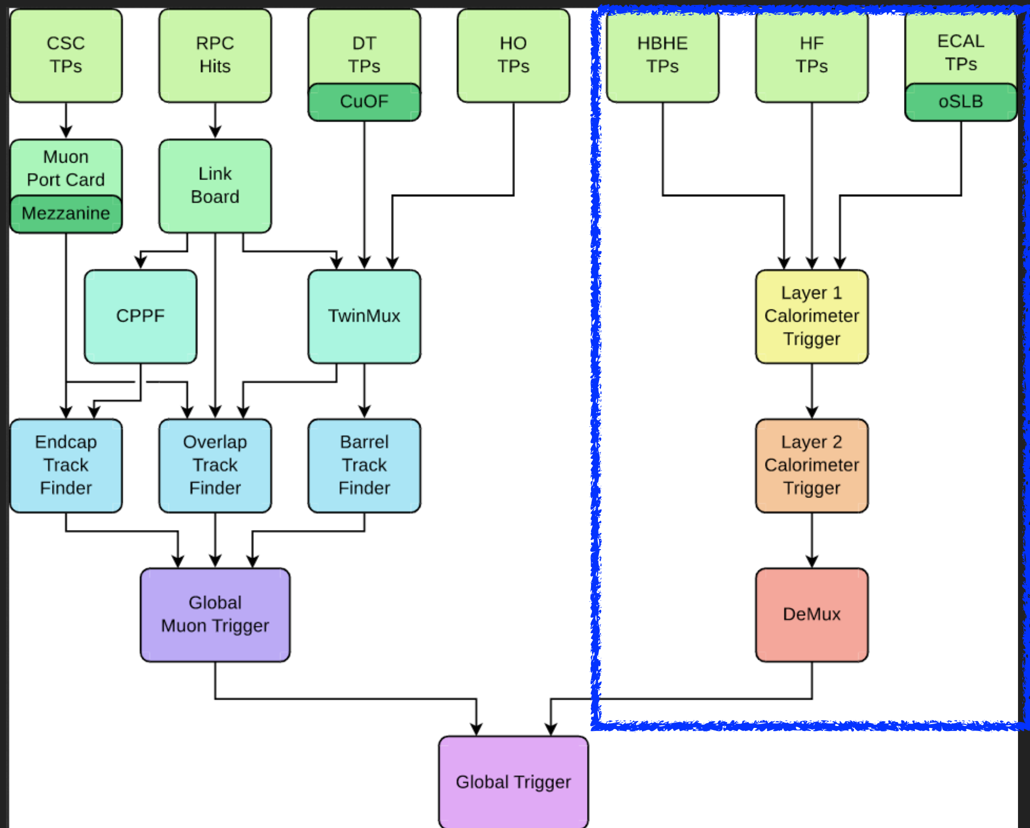
THE UPGRADED CALORIMETER TRIGGER FOR LHC PHASE I

THE CMS LEVEL-1 TRIGGER: INTRODUCTION & UPGRADE

Architecture overview: The CMS detector implements a sophisticated two-level trigger architecture composed a Level-1 (100kHz) and a High-Level-Trigger (HLT - 1kHz) achieving 10^5 rate reduction.



Level-1 Upgraded Trigger: Level-1 is implementing generic-designed electronics boards to process the data from the electromagnetic (ECAL) and hadronic (HCAL) calorimeters as well as the Muon system. Total Latency = 3.8 us



Motivation for the upgrade of the Level-1 Trigger:

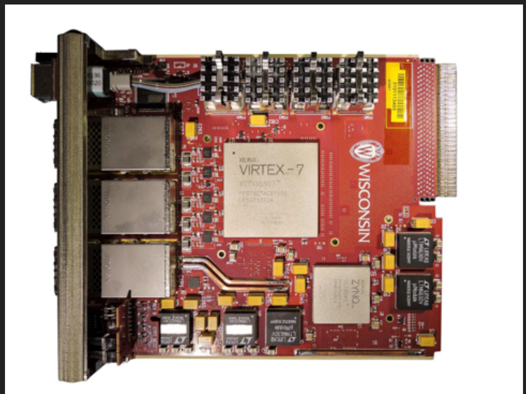
- Physics case: excellent single lepton (including Taus) efficiency w/ low thresholds (Higgs/EWK) & Jet/MET (top/SUSY) & dedicated VBF
- New LHC conditions: maintain performance with increased luminosity (2e34), higher Pile-Up (80, ~70 w/8b4e) while L1 bandwidth remains limited to 100kHz.

THE CMS LEVEL-1 TRIGGER: IMPLEMENTATION

Key technological changes

- Architecture: Organised in 2 Layers introducing Time-Multiplexed Trigger Vadatech Crates (μTCA). All calorimeter data sent to a single processing node: global view of the calorimeters
- FPGA & link: Xilinx Virtex VII XC7V690T, High-speed serial optical links (**10Gb/s**). Design of generic-processing boards to accommodate sophisticated algorithms & evolution
- Large optical patch panel : custom-made commercial solution (Molex Flexplane)
- Increased latency: for more flexibility at algorithm level

–> Replaced all hardware including Timing Control System and all software and databases

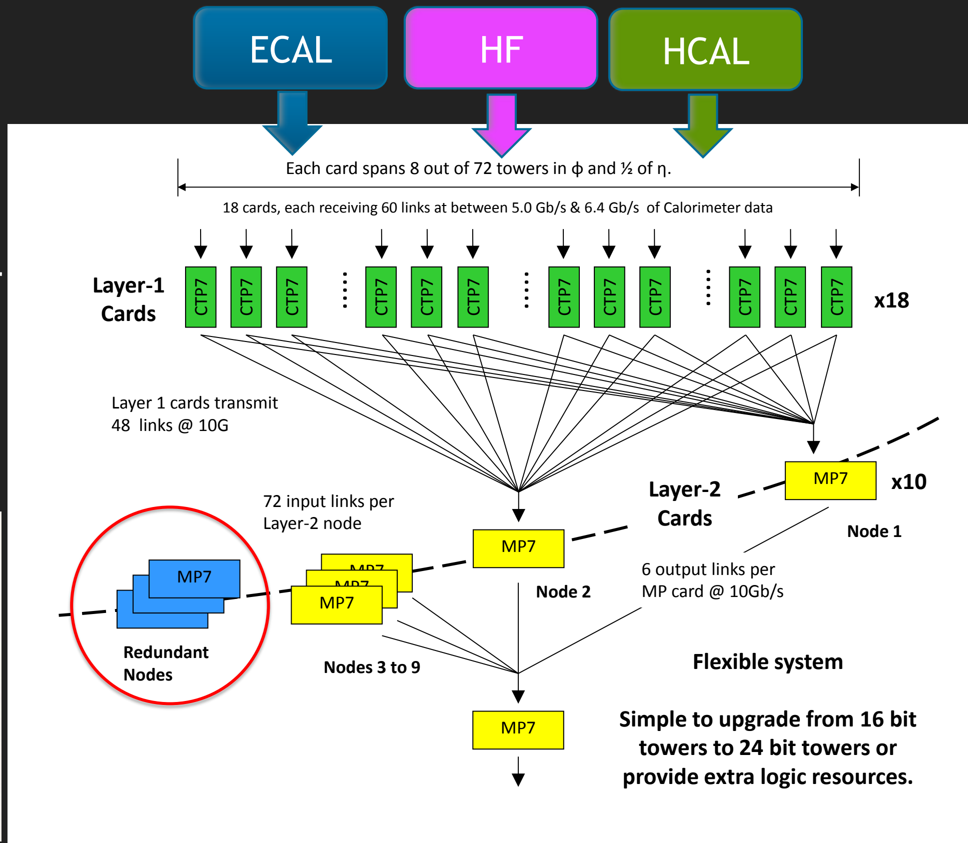


Layer-1 pre-processing:

CTP7 Calorimeter Trigger Processor: Collecting and processing all calorimeter data + DAQ readout for monitoring

Layer-2 Data processing:

MP7 Master Processor hosting all triggering algorithms + DAQ readout for monitoring



THE CMS LEVEL-1 TRIGGER: ALGORITHMS

Calorimeter algorithms features: **benefiting from full calorimeter tower granularity**

- Dynamic clustering to optimize signal reconstruction and bkg rejection
- Optimised identification (H/E, shower shapes etc..) and lepton isolation
- Implement pile-up mitigation (only based on calorimeter information) for physics objects
- Improve position/energy resolution to provide useful object correlations

–> The implementation in powerful hardware to provide enough flexibility to adapt algorithms to LHC running conditions, integrate improvement from detector upgrades and physics needs.

Run I calo trigger granularity

14 (η) x 18(ϕ)

Run II calo trigger granularity

56 (η) x 72(ϕ)

Reminder: Trigger primitives are local energy deposit into calorimeter sent to the Level-1 calorimeter trigger. For example: ECAL TP = sum of 25 crystal ET

THE CMS LEVEL-1 TRIGGER: ALGORITHMS

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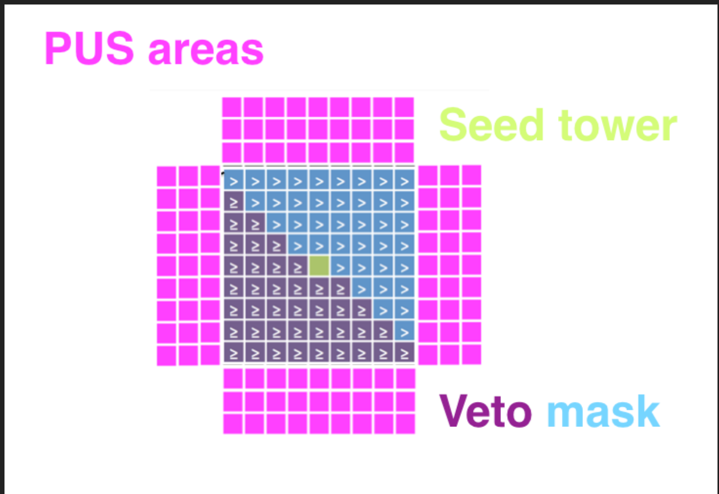
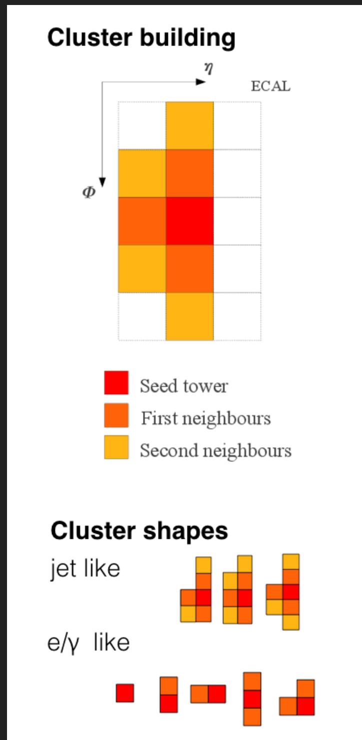
JETS & SUMS



Jets&Sums 9x9 sliding window = offline cone (ak4). PU subtraction applied to jets and missing ET

EGAMMA

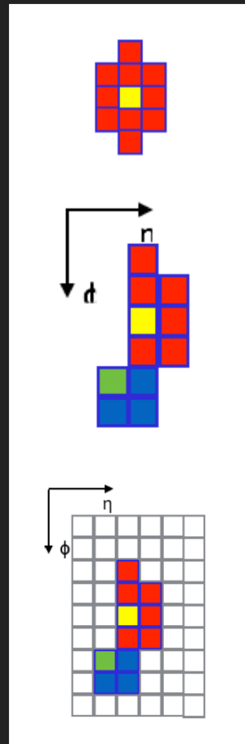


TAU LEPTONS

Electron finder: dynamic clustering to recover energy loss due to tracker material. Cluster Shape used remove pile-up induced candidates

Tau lepton finder: Combine EG cluster merging (multiple-prong object)

Isolation & ID: LUT depending on pT, Eta and pile-up. Multiple working points (Loose & Tight). Reoptimised at data taking start.



See Zhenbin Wu's talk on "Triggering on electrons, photons, tau leptons, jets and sums with the CMS Level-1 trigger"

THE CMS LEVEL-1 TRIGGER: ALGORITHMS & PERFORMANCE

Calorimeter algorithms features: benefiting from full calorimeter tower granularity

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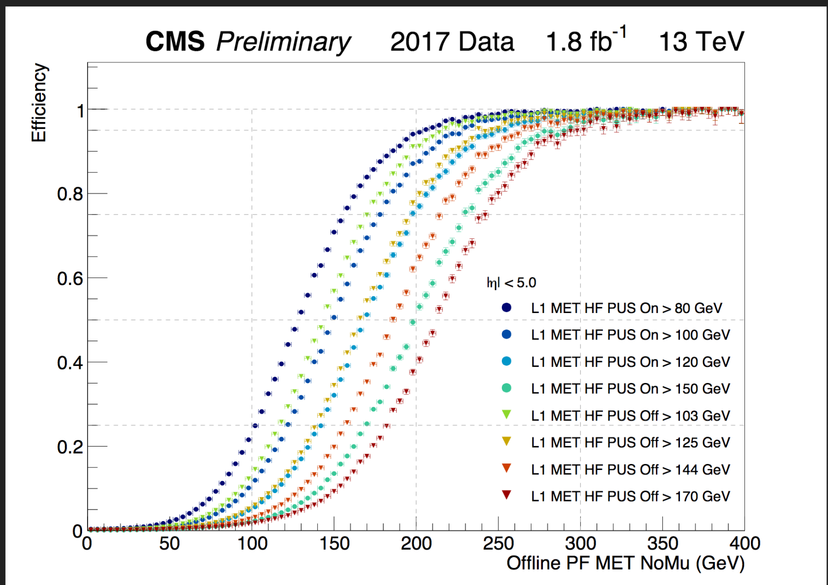

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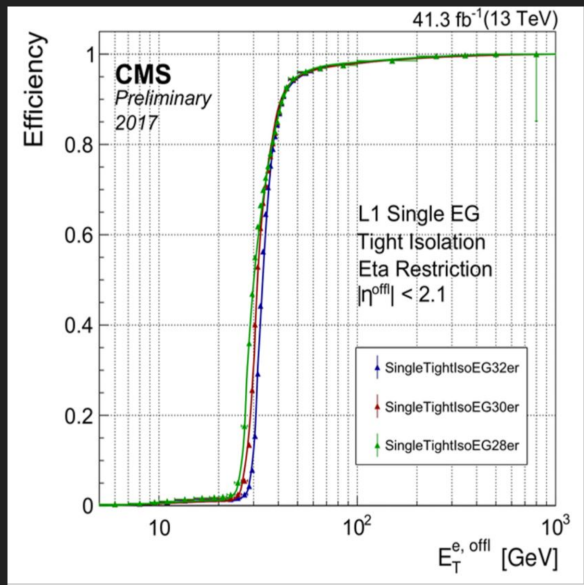
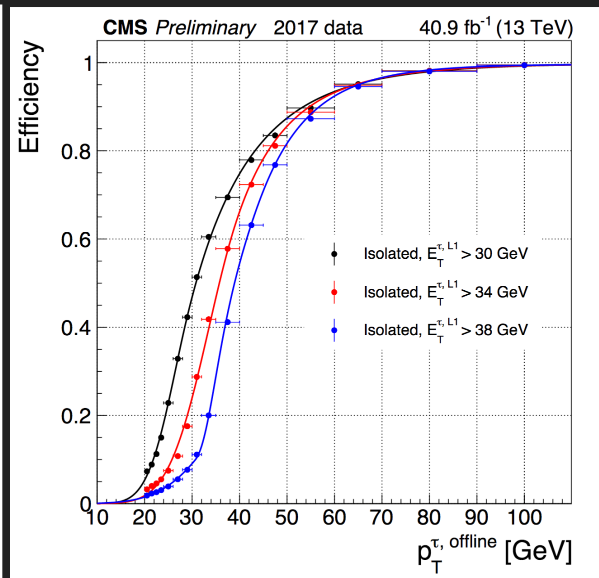


TAU LEPTONS



Missing transverse energy

L1_ETMHF110_HTT60 (SUSY)
L1_ETMHF120

Isolated Electron

DoubleEG_25_15 (Higgs) , TripleEG_18_17_8, DoubleEG_LooseIso24_10 or L1_LooseIsoEG24er2p1_HTT100er (TOP)

Isolated Tau lepton

L1_DoubleIsoTau34er2p1 (Higgs) unprescaled until 2e34, L1_IsoTau40er_ETM100 (Higgs)

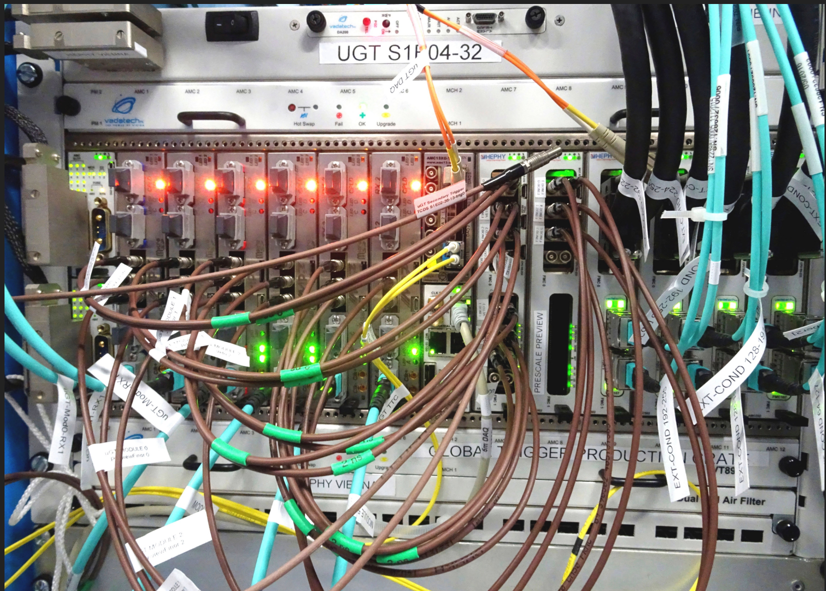
See Zhenbin Wu's talk on "Triggering on electrons, photons, tau leptons, jets and sums with the CMS Level-1 trigger"

THE CMS LEVEL-1 TRIGGER: GLOBAL TRIGGER

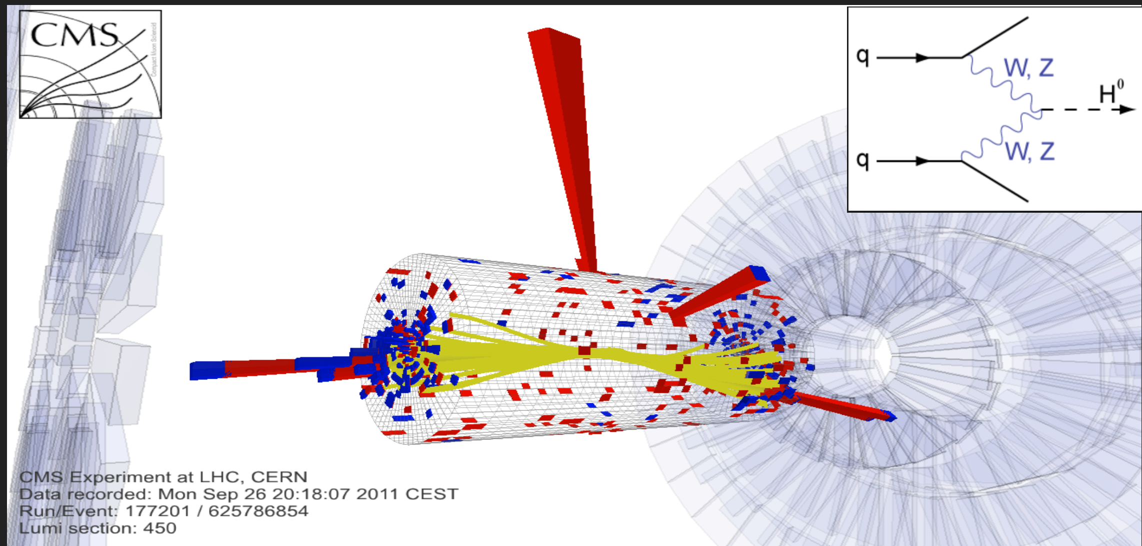
Final level-1 trigger decision

- Receiving trigger objects (muons (from uGMT), electrons, tau leptons, jets and sums) from Layer-2 calorimeter trigger. Implemented complex object correlations (including variables using invariant mass) and algorithms tailored for physics analyses
  –> introducing the first dedicated VBF trigger and W trigger (MT)
- Implementing multiple processing boards to accommodate 512 algorithms (could be more!)
- Evolution of the trigger menu with luminosity and pile-up conditions

–> Implementing twice as much cross-triggers in 2017 to provide efficient triggering w/ low thresholds



Level-1 Global trigger: implementing 6 processing boards (instead of 3 in 2016)
–> Enhanced selectivity (2017: 486 algorithms implemented)



First dedicated VBF trigger implemented in the core of the level-1 decision
–> significant gain in acceptance for a large panel of physics analyses.

THE CMS LEVEL-1 TRIGGER: OPERATING @ HIGH-LUMINOSITY

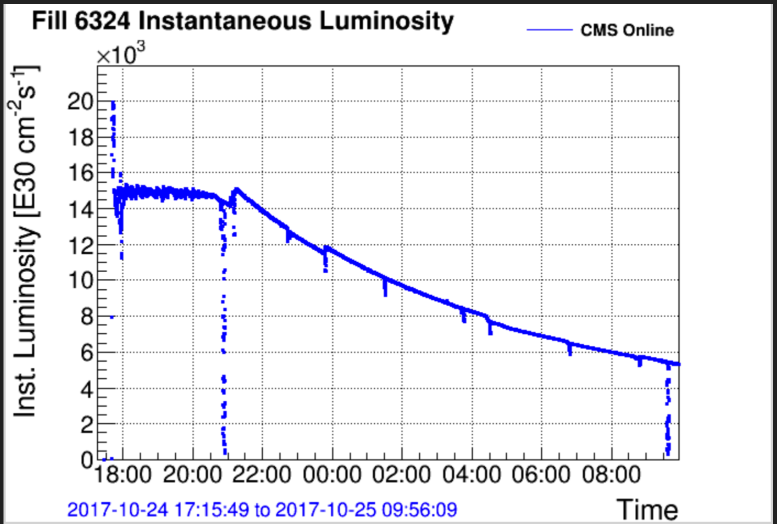
Since the beginning of Run II, the level-1 trigger has been operating in harsh conditions

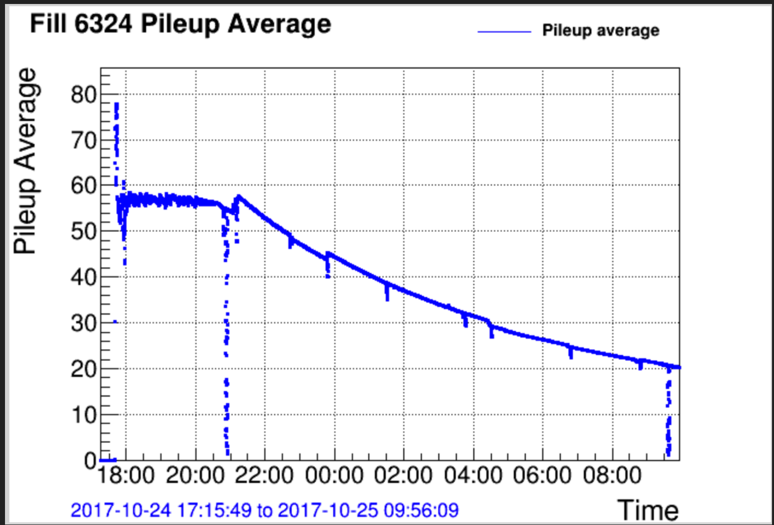
- Facing High instantaneous luminosity and pile-up conditions: 2.1e34 and PU~70 *–> adapting trigger menu (physics threshold) to this intense regime.*
- Increase of out-of-time pile-up seen in the forward region of the calorimeters. Effect enhanced by the LHC bunch structures (8b4e) *–>sizeable impact on sum triggers (missing transverse energy)*
- Detector related effects : change of the ECAL crystal response with time (corrected using a laser monitoring), anomalous signal in ECAL Barrel APDs, noise from coming from ageing electronics….

  –> Need to mitigate these effect @ the trigger level

–> All these have been addressed profiting from the flexibility of the system and the improvement of algorithms including new features available (depths in HCAL EE, finer H/E for EG candidates etc…)

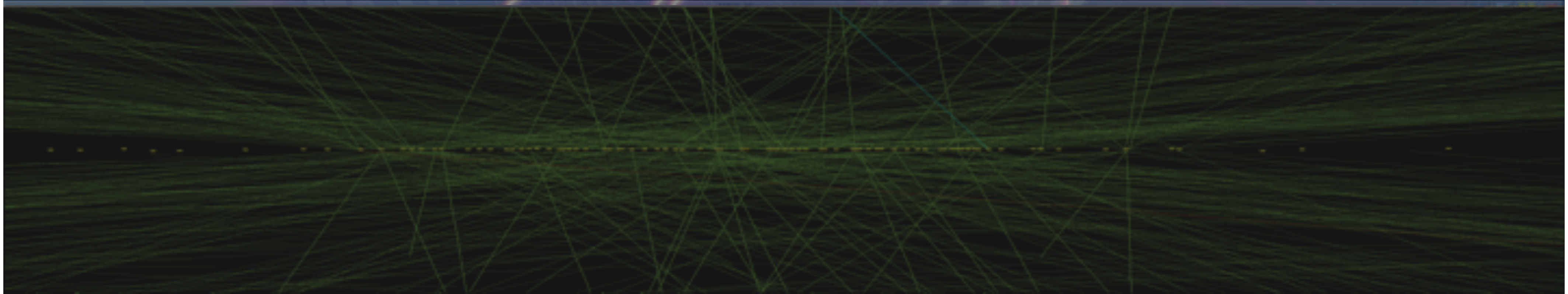
–> The experienced acquired during these years of operation are helping guiding the design of the Phase II trigger system.





See Amina's Zghiche talk on "Performance of the CMS electromagnetic calorimeter during LHC Run II"

DESIGN OF THE PHASE II CALORIMETER TRIGGER

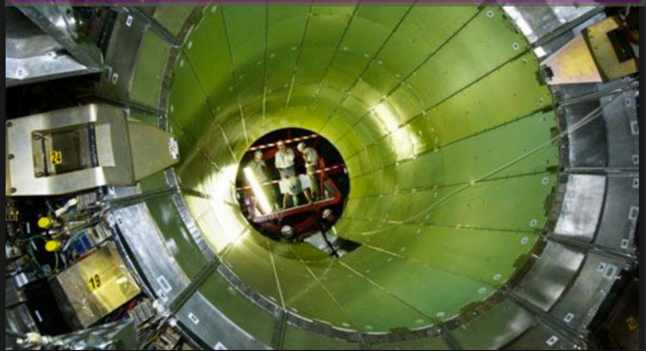


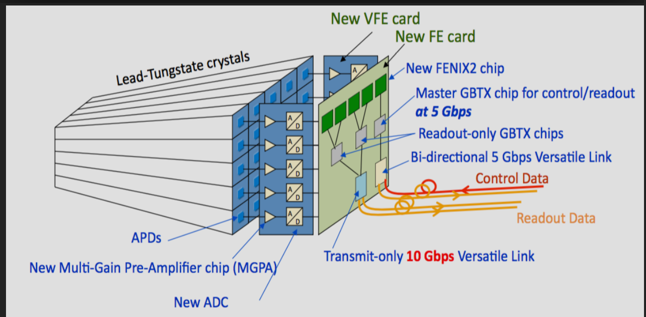
A NEW REALM OF TRIGGERING: HIGH-GRANULARITY

The phase II calorimeter trigger will benefit from an enhanced granularity

Changes to the trigger primitives: finer calorimeter information

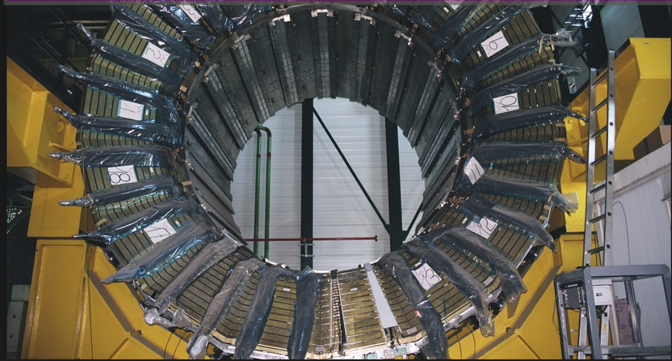
ECAL (barrel)

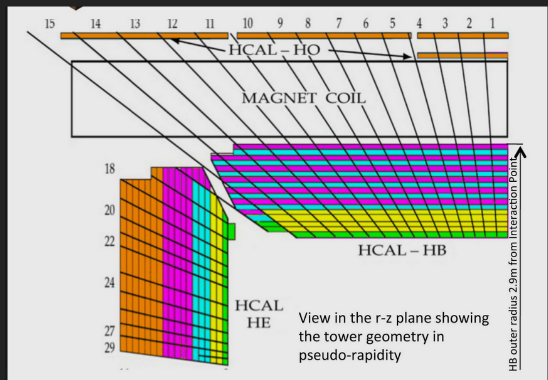




Access to crystal info instead of TT towers. 61200 crystals
x25 finer granularity

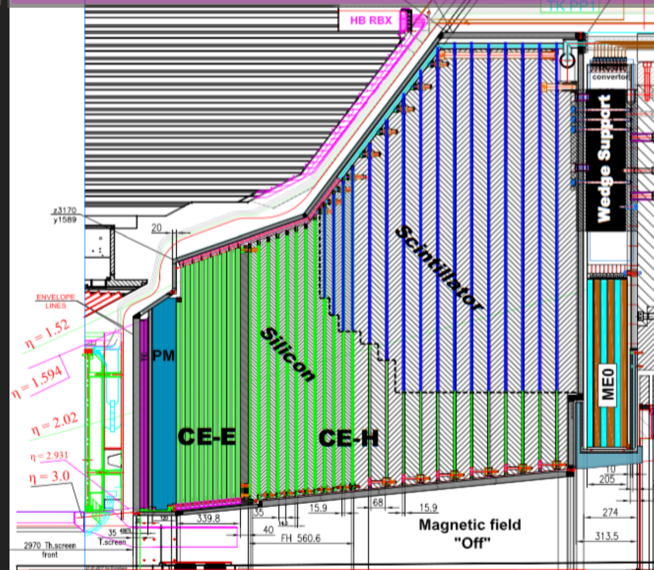
HCAL (barrel & forward)





Access to all HCAL TT depths
x7 finer granularity

HGCAL (endcap)



52 layers (28 EM & 24 HAD)
(1/2 of EM layers in trigger)
x500 finer granularity
(compared to 1684 Trigger Towers ECAL EE-HCAL HE)

–> Huge data volume to be processed efficiently to fit algorithms within latency budget.

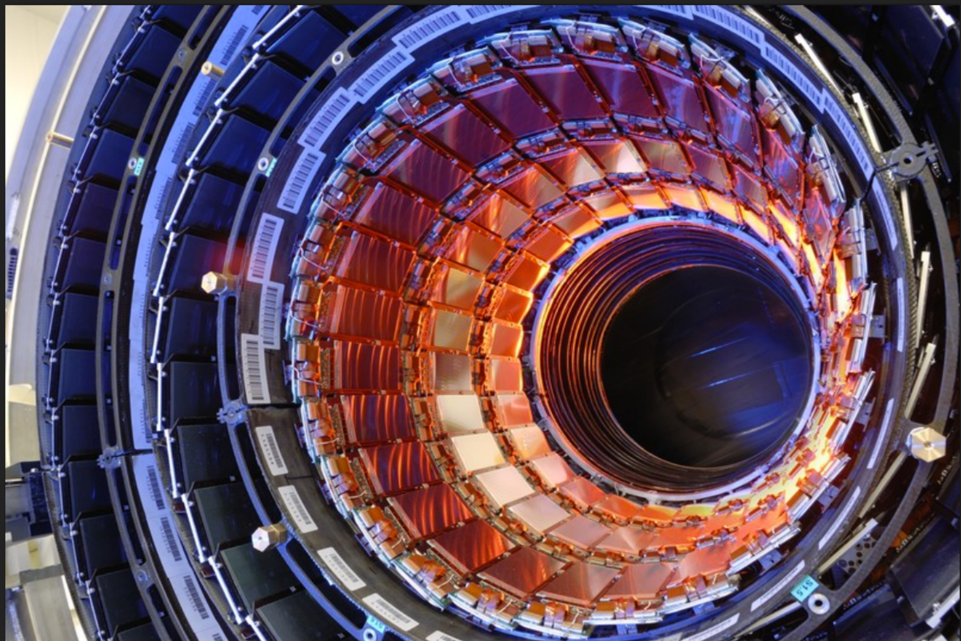
See Nural Akchurin's talk on "Overall status of the CMS High Granularity Calorimeter"

A NEW REALM OF TRIGGERING: TRACKING @ LEVEL-1

The phase II calorimeter trigger will benefit from an enhanced granularity

Changes to the trigger primitives: the addition of the track trigger primitives

Tracker CMS will install a new Pixel and Tracker



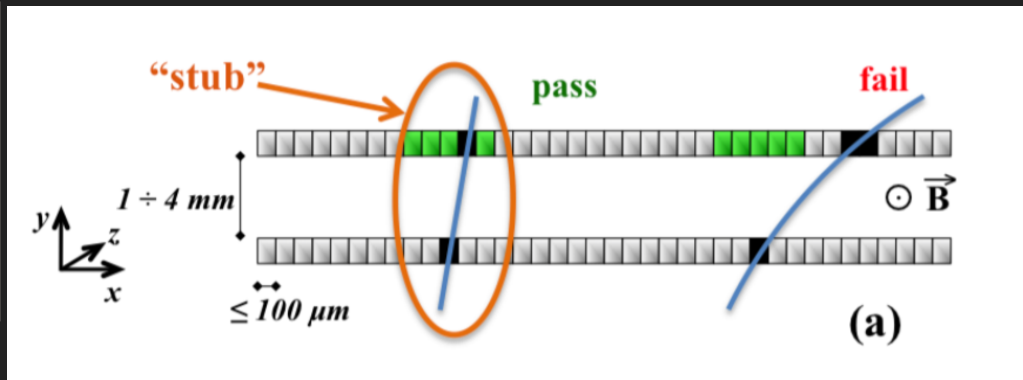
Improvements to the Calorimeter objects including tracking information:

- *Improved lepton reconstruction and identification by matching with tracks*
- *Improved lepton isolation : EG & Tau leptons*
- *Vertexing: jets and sum triggers, track-based lepton isolation etc…*
- *PU estimator (not only calorimeter-based as done for Phase I)*
- *etc…*

—> significantly reducing the trigger rate associated with these algorithms.

Trigger primitives (TF-TPG): Building Stubs from inner and outer layers —> Tracks Optimising track information by removing low-pT: TF -TPG (built&sent ~ 5us)

Note: ~200 Tracks /event @200 PU w/ pT > 3GeV



A NEW REALM OF TRIGGERING: FULL DETECTOR VIEW @ L1

The phase II calorimeter trigger architecture provides global detector view

Organisation of the data flow and overall infrastructure of the trigger

Improved triggering with full detector view:

- *Trigger decision not only based on calorimeter information. Tracking requires larger latency: L1Rate 750 kHz & 12.5 us latency*
- *Sophisticated clustering algorithms deployed in the detector back-end electronics.*
- *Building trigger objects @ Correlator level. Bringing HLT @ Level-1*

–> increased selectivity achieved

Number of links compared to Phase I trigger:

–> Phase I ~1152 links : Phase II ~ 1000 links

(up to 28 Gb/s vs 10 Gb/s in Phase I)

Total bandwidth:

–> Phase I ~1.8 Tb/s : Phase II ~ 50 Tb/s

Options to send clusters and/or trigger towers to correlator is investigated

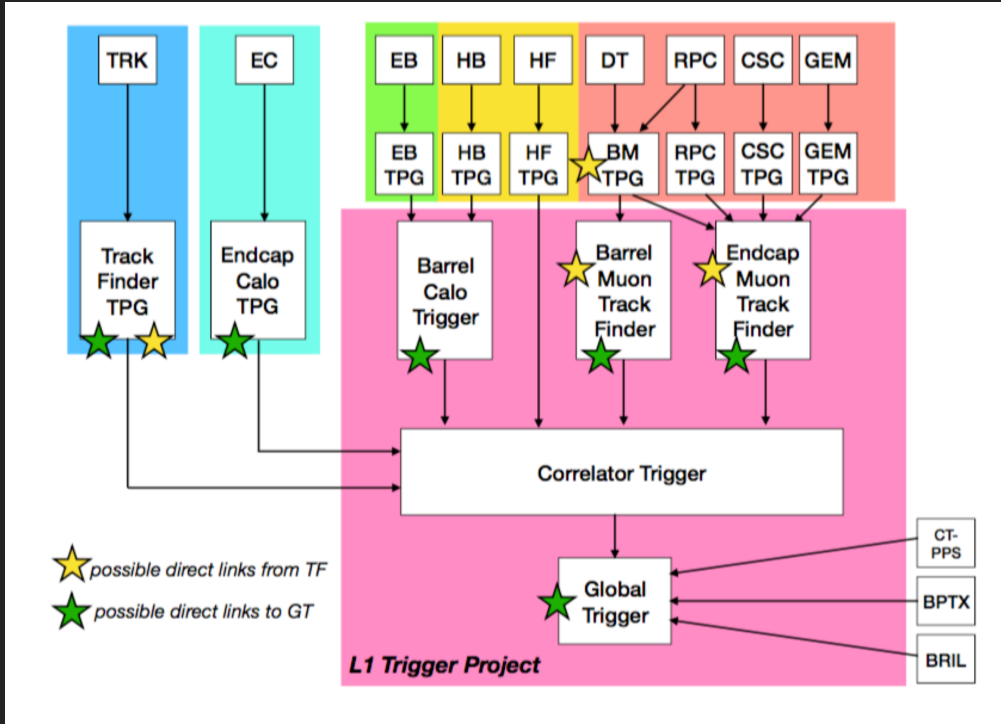


Table 2.1: Summary of the logical input data to the Phase-2 L1 trigger.

Detector	Object	N bits/object	N objects	N bits/BX	Required BW (Gb/s)
TRK	Track	100	400	40 000	1 600
EB	Crystal	16	61 200	979 200	39 168
HB	Tower	16	2 304	36 864	1 475
HF	Tower	10	1 440	13 824	553
EC	Cluster	200	400	80 000	3 200
EC	Tower	16	2 400	38 400	1 536

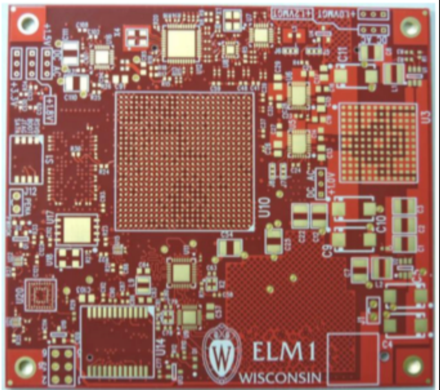
A NEW REALM OF TRIGGERING: FULL DETECTOR VIEW @ L1

The phase II calorimeter trigger architecture provide global detector view

The new technologies provide ways to implement sophisticated algorithms and object correlation.

From the technological development during Phase-1:

- *The phase I trigger processors CTP7 and MP7 were not designed to fulfill a specific role, but rather, to generic-stream processing engines. Already used as demonstrators to build track triggers/Calorimeter readout for Phase II*
- *Our experience from Run I helps us approach large scale data processing with original trigger architectural choices. Implement flexible correlator at higher level –> more selectivity*

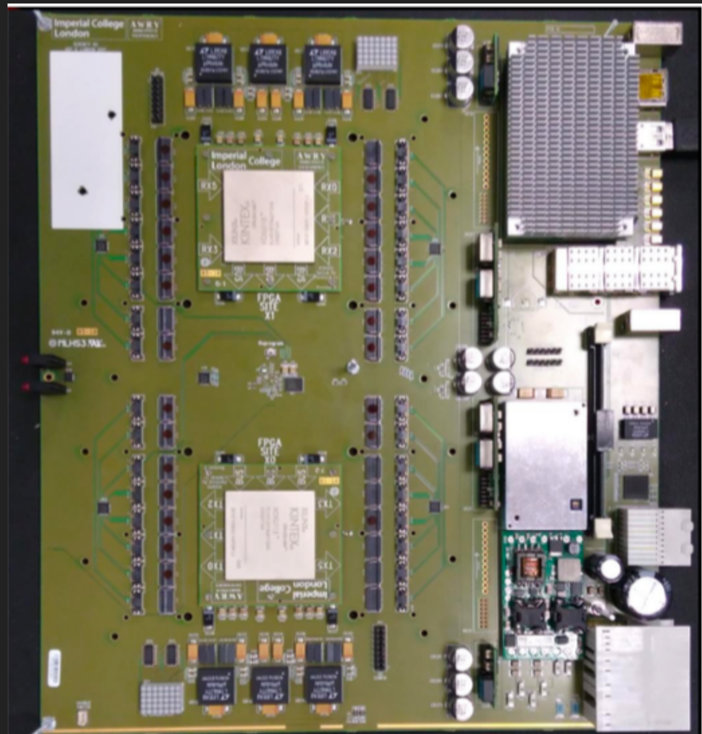


Example of boards under development:

Left: An ATCA service card with just the core infrastructure. **Right:** Embedded Linux Mezzanine (ELM) card built to study on-board ZYNQ-based embedded Linux configuration and control management for ATCA blades

Extended use of HLS (High-Level-Synthesis): Using HLS to enable algorithm design w/ account hardware constraints.

Considering deep learning and iterative algorithms ….



Other example of boards: CMS Serenity board

ATCA Format 96 I/O 16-25 Gb/s. Ultrascale FPGAs

CALORIMETER TRIGGER ALGORITHMS: STANDALONE & TRACKING

The phase II calorimeter trigger can implement sophisticated algorithms

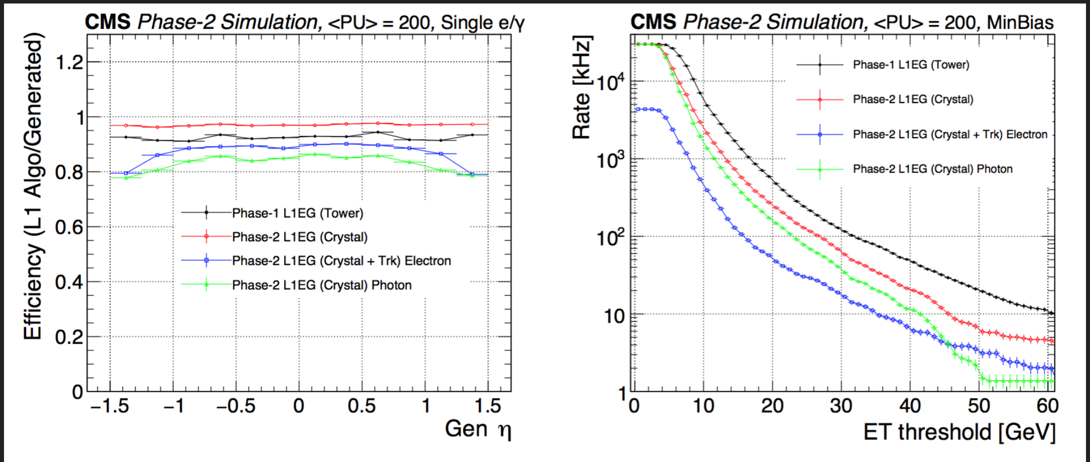
–> Getting closer to performance of the offline reconstruction algorithms

The approach adopted here:

- Standalone algorithms –> building finer clusters w/ Pile-Up subtraction
- Building trigger candidates with tracks (matching standalone objects w/ tracks)

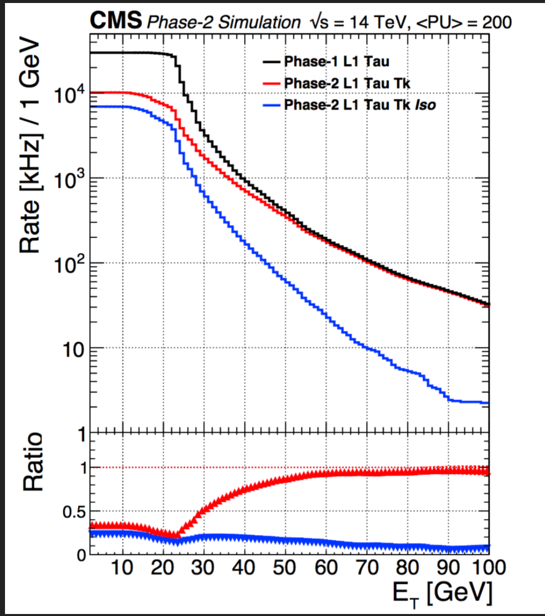
Example of track-matched objects performance with EG and Tau leptons:

Electron trigger algorithm (Barrel)



Efficiency/Rate for electrons: improved track matching with crystals-based clustering. Large threshold reduction achieve with small efficiency loss
Note: Track matching/reco inefficiency included

Tau lepton trigger algorithm (barrel)



Rate for tau leptons: A combination of track-matching and track-based isolation allows to achieve a substantial rate reduction.

CALORIMETER TRIGGER ALGORITHMS: IMAGING CALO TO TRIGGER

The phase II calorimeter trigger can implement sophisticated algorithms

–> Combining a track and a calorimeter into one: High-granularity Calorimeter (HG-CAL)

–> 6M channels available over 52 layers (900k channels dedicated to trigger): goal is to achieve an unprecedented spacial resolution and shower separation to optimise matching with tracks @ L1

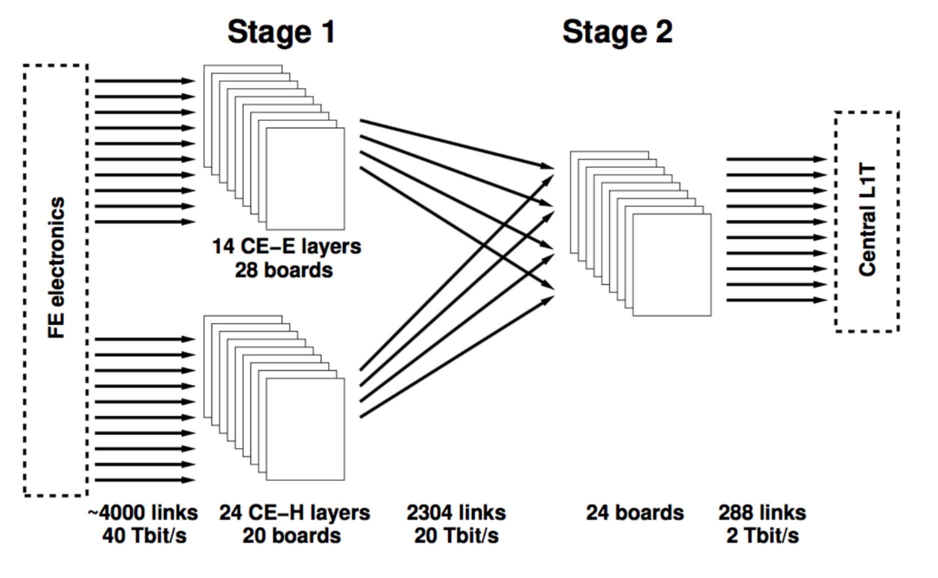
Possibility to perform 2D & 3D clustering

–> From Trigger Cells built at the Front-End Level:

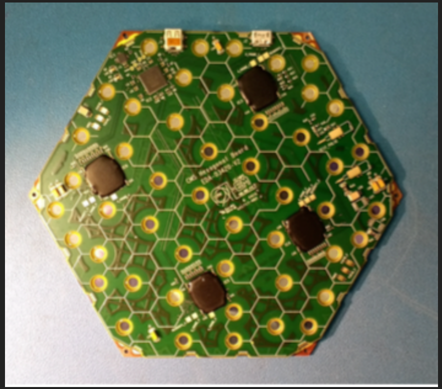
- 2D clustering/Layer (@ Stage 1)
- 3D clustering (combining 2D clusters @ Stage2)

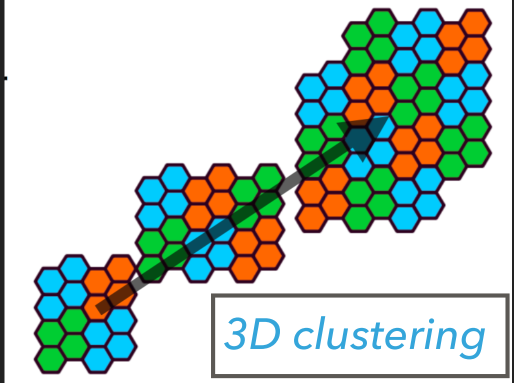
Enhanced Standalone objects produced at Level-1. Along with 3D clusters :

–> *benefiting from the longitudinal information to provide ID variables largely reducing the rate*



HGCAL Back-end Electronics: implementing a Time-Multiplexed Architecture as Phase I trigger (24 depth implemented vs 9 in Phase I)

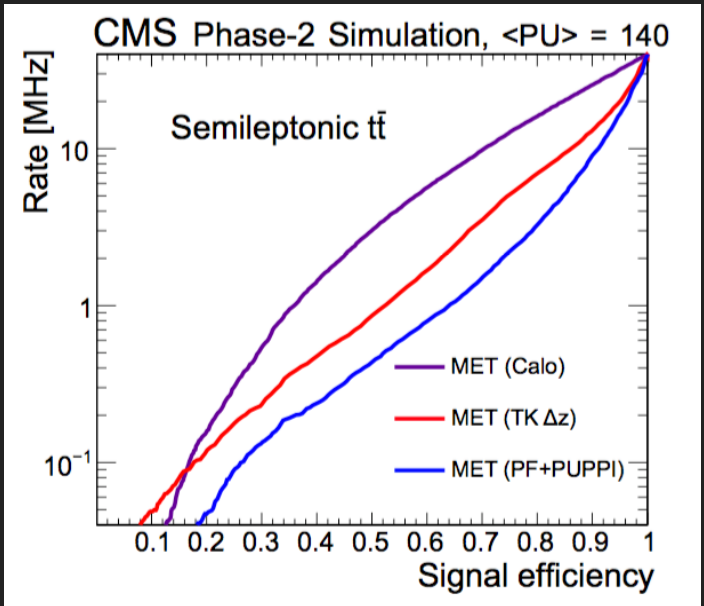




See Thomas Strebler's talk on "Design and object performance of CMS High Granularity Calorimeter Level1 Trigger"

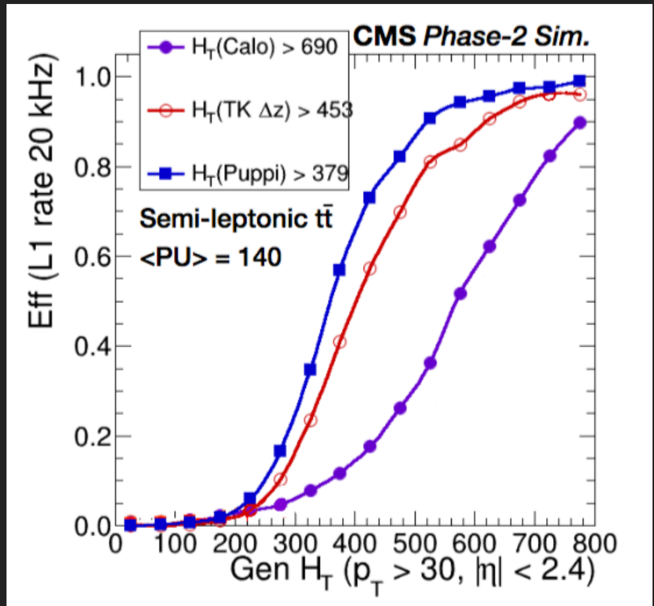
CALORIMETER TRIGGER ALGORITHMS: PARTICLE FLOW OBJECTS

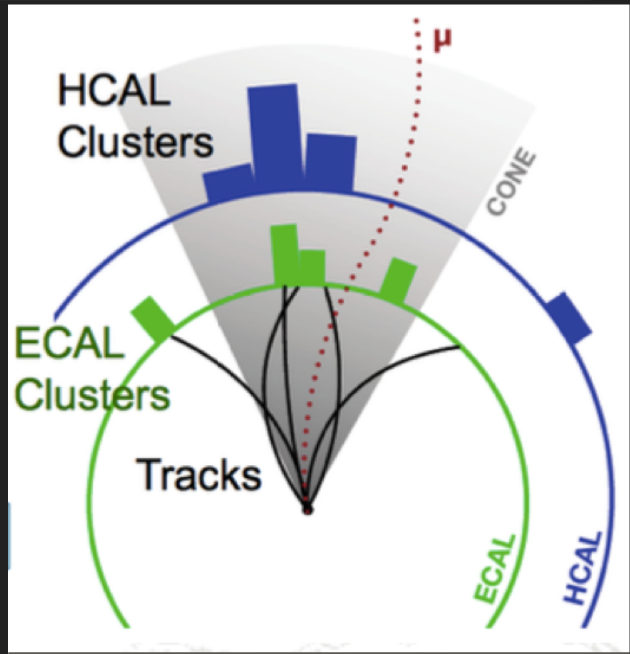
Particle Flow within the Level-1 trigger hardware: With the addition of tracking information, Level-1 algorithms can match the performance of HLT/Offline algorithms
–> Enhanced particle separation and identification –> improved response/spacial resolution
Phase II Correlator can be used to combine all detector info to provide higher level objects: prompt muons, electrons, photons, taus, jets and global quantities: ETM, Sums etc…
Approach used here: **Combine PFlow & PileUP per particle Identification (PUPPI)**



Missing transverse energy: *Calo vs track-MET and MET (PF-PUPPI)*

Hadronic transverse energy: *PF-PUPPI performance on tt*





PFlow: reconstructing all particles in the event

–> Demonstrating the L1 PF & PUPPI algorithms performance on ETM and HT.
–> Encouraging results from the firmware implementation: Phase II trigger R&D program

SUMMARY

- **Phase I upgraded calorimeter trigger is showing excellent performance:**
  acceptance for physics has been maintained in harsh LHC conditions (peak luminosity of 2.1e34) –> Technological choices made demonstrated the flexibility of the system to adapt to physics needs by providing enhanced selectivity.
  Running experience is certainly crucial to guide the design of the Phase II trigger

- **The Phase II upgraded calorimeter trigger is being designed to face even harsher environment.**
  The technological choices are based on experience acquired with Phase I upgrade. New technologies certainly allow to contemplate exciting opportunities to implement even more sophisticated algorithms
  –> Introduction of finer calorimeter granularities into the trigger
  –> First introduction of tack information in the level-1 trigger decision
  –> High-level objects and Particle flow algorithm in the heart of the hardware trigger

BACKUPS