CMS Muon and Calorimeter Trigger primtives

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On behalf of CMS Collaboration

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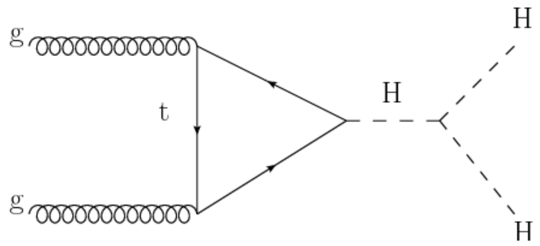
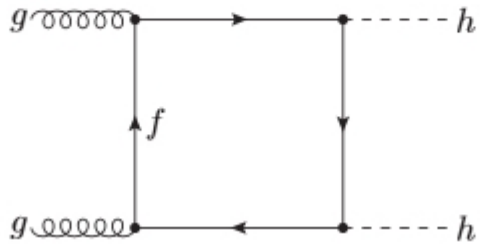
Outlook

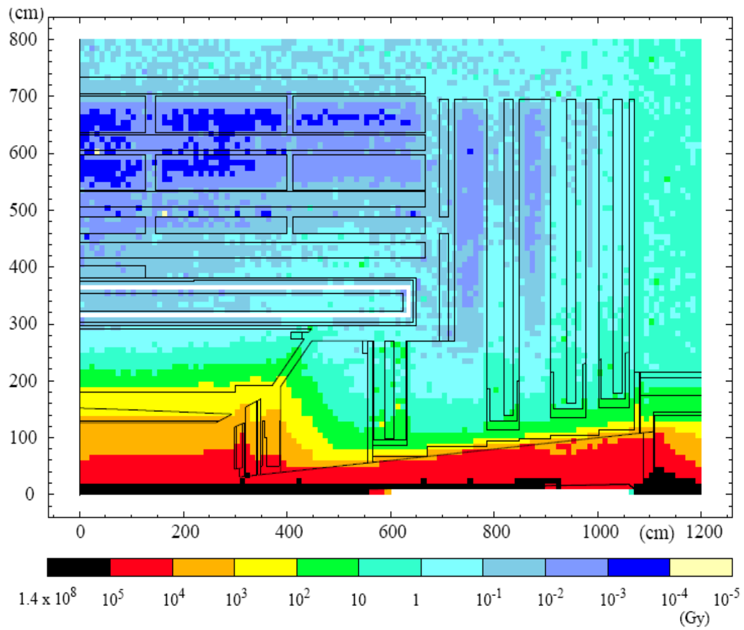
- In this talk:
  - Brief Introduction (Physics motivation for HL-LHC)
    - Requirement for the upgrade of CMS
  - The Phase-II upgrade
  - The CMS L1-Trigger upgrade for HL-LHC
    - Barrel Muon Upgrade (Drift Tubes)
    - Endcap Muon Upgrade (GEM)
    - Barrel Calorimeter Upgrade
    - Endcap Calorimeter Upgrade
  - Plans and Conclusion

Physics goal for HL-LHC

- HL-LHC (2026-203X) conditions:
  - $L_{inst.}=5\mathrm{x}10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-}$ @13TeV → $\langle PU \rangle \leq 200$
- Exploit the LHC at very high luminosity:
  - Precision measurements of H-sector (self-couplings)
  - W,Z trilinear and quadrilinear couplings
  - Rare H-decays + SUSY + Dark Matter
- HL-LHC challenges:
  - High luminosity → high pile-up
  - High n-fluence → degradation of PbWO4
  - Dose in forward region ~$3\mathrm{x}10^5$ Gy
  - huge amount of data reaching the online trigger
- The scientific goals require:
  - High efficieny on lepton/photon reconstruction
  - Trigger threshold don't compromise EWK physics
  - Jet energy resolution maintained at very high PU





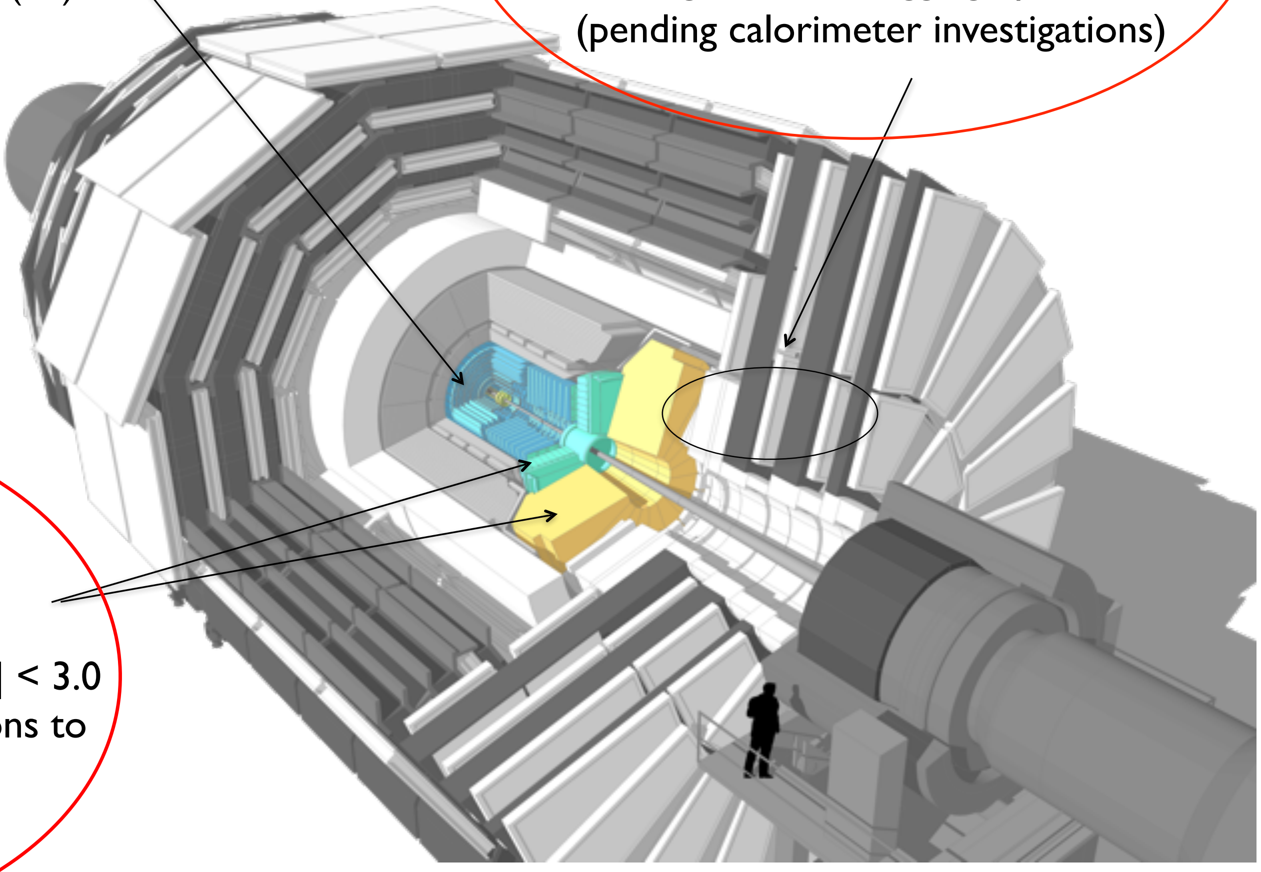


The CMS Phase-II Upgrade

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

These upgrades allow CMS to execute its physics program while receiving an average of 200 pile-up (PU) interactions per beam-crossing.

Muons
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Nominal coverage to $\eta \sim 2.4$
- Investigate Muon-tagging up to $\eta \sim 4$ (pending calorimeter investigations)



New Endcap Calorimeters
- Radiation tolerant - high granularity
- Nominal coverage $1.5 < |\eta| < 3.0$
- Investigate fast timing options to augment pile up rejection

The CMS Phase-II Upgrade

- The most demanding issue at HL-LHC is the handling of extreme data rates from increased granularity and much higher background

The performance of an hadron collider experiment is driven by the performance of the Level-1 Trigger

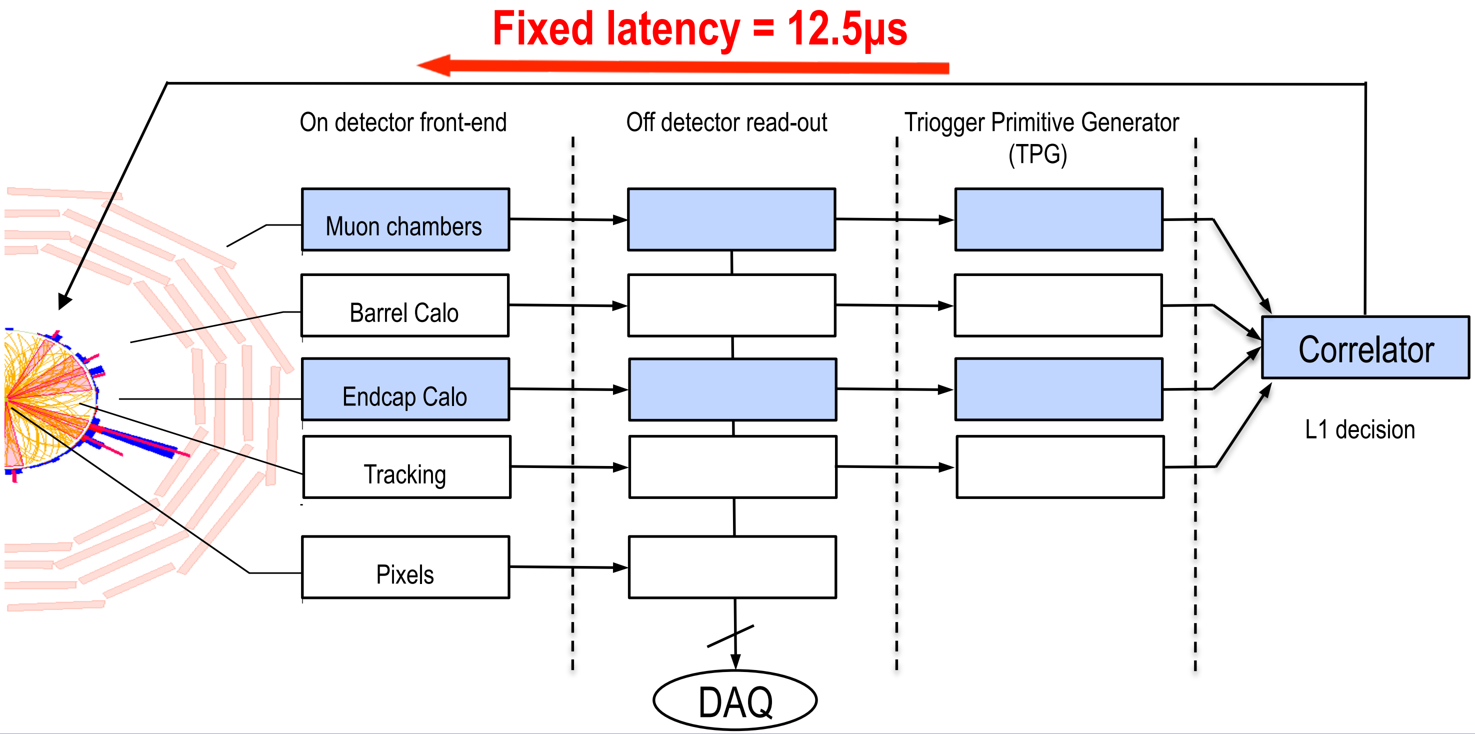
Enormous increase in background

Trigger trheshold, driven by the EWK energy scale, cannot increase

Radical, innovative approaches

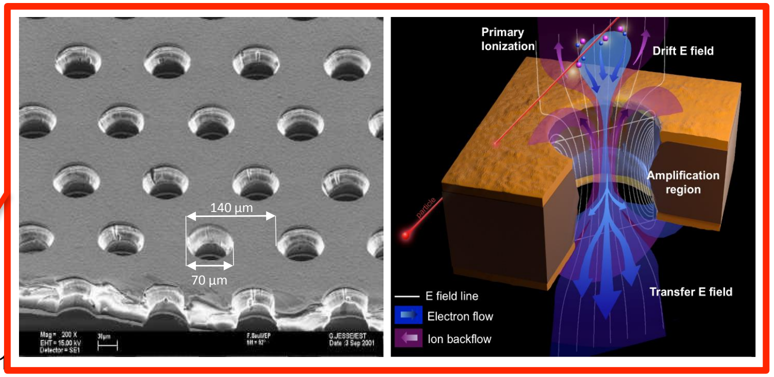
CMS L1-Trigger Phase-II Upgrade

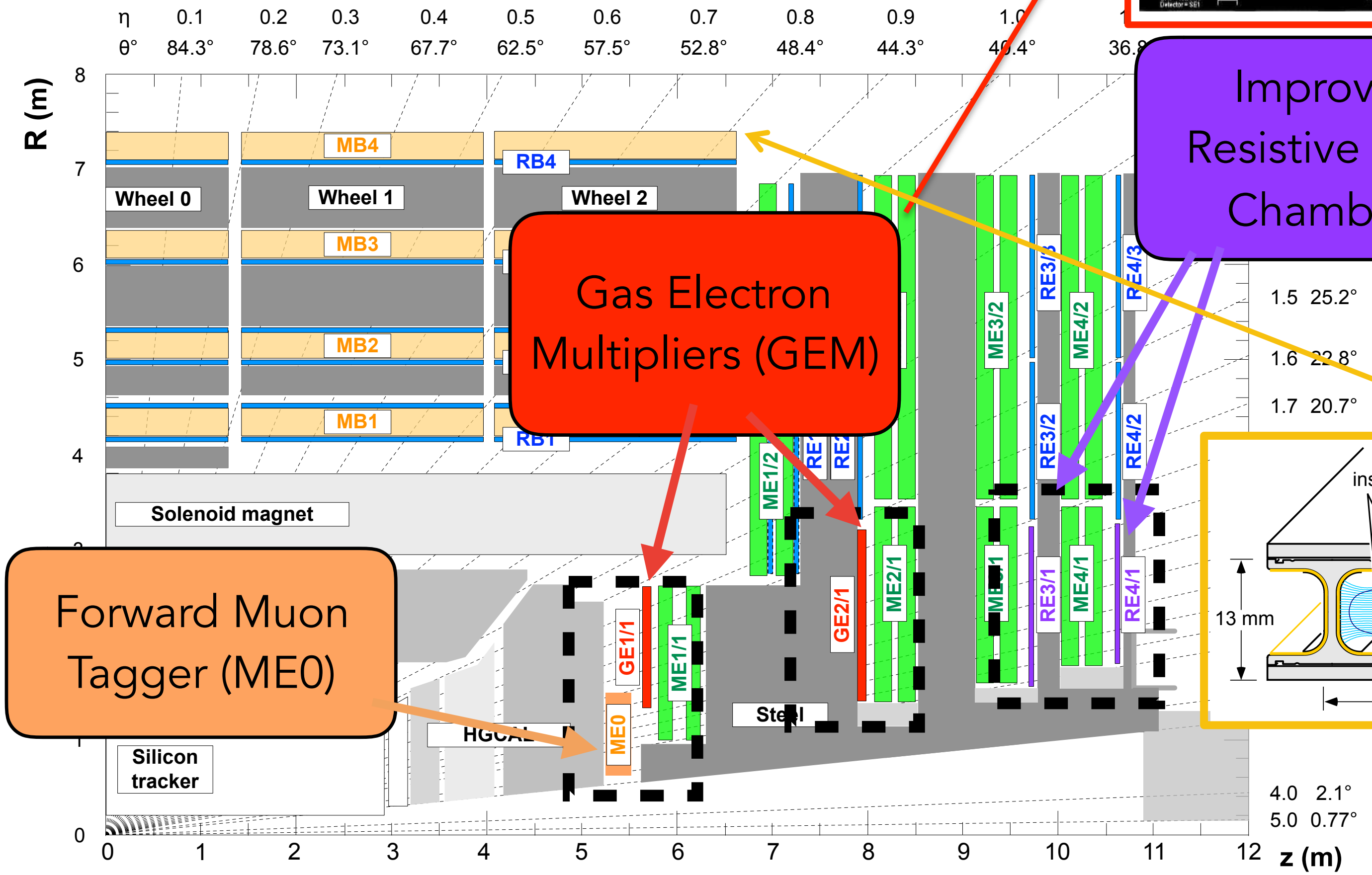
- The new L1-Trigger:
  - The CMS L1-Trigger system is required to select/reject each beam crossing and ➔ **First step of data analysis**
  - Time-multiplexed structure + tracker information + latest generation of FPGA + fast optical links ➔ For the first time **a full event** reconstruction **at L1** is possible
  - The input to the correlator will be **fitted tracks**, **calo-clusters** and **muon stubs**
  - Change in maximum rate: from actual **O(100kHz)➔O(1MHz)** + fixed latency (4μs➔12.5μs)

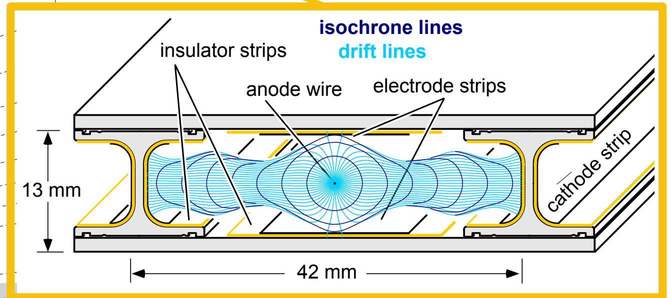


Muon Detector Upgrade

- In addition to the existing DT, RPC and CST:





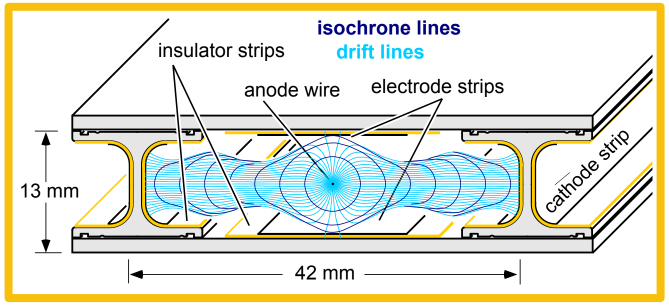


Barrel Muon Trigger Upgrade (DT)

- Motivation for the local DT trigger primitives generator upgrade[1]
  - The local DT-TPG is currently **hosted on-detector** and bound to DT readout (MiniCrate)
    - it is based on the BTI processor, which is a **synchronous fitter** sampling a range of bunch crossing hypotheses
  - The replacement of the MiniCrates is already planned for HL-LHC[2]: the readout and trigger electronics are aging because of radiation
    - the new MiniCrates will host only the readout: TDC signals will be driven off-detector on fast optical links using the CERN GBT protocol
      - The new trigger must be asynchronous

[1] N. Pozzobon, P. Zotto and F. Montecassiano A proposal for the upgrade of the muon Drift Tubes trigger for the CMS experiment at the HL-LHC. proceedings of the Connecting The Dots CTD 2016 workshop (HEPHY Wien, Feb. 2016) - Accepted by Eur. Phys. J. Web of Conference
[2] Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid, CERN-LHCC-2015-10 LHCC-P-008 CMS-TDR-15-02 ISBN 978-92-9083-417-5 1 June 2015

- A Hough Transform-based approach[2]
  - R&D activity ongoing in Padova



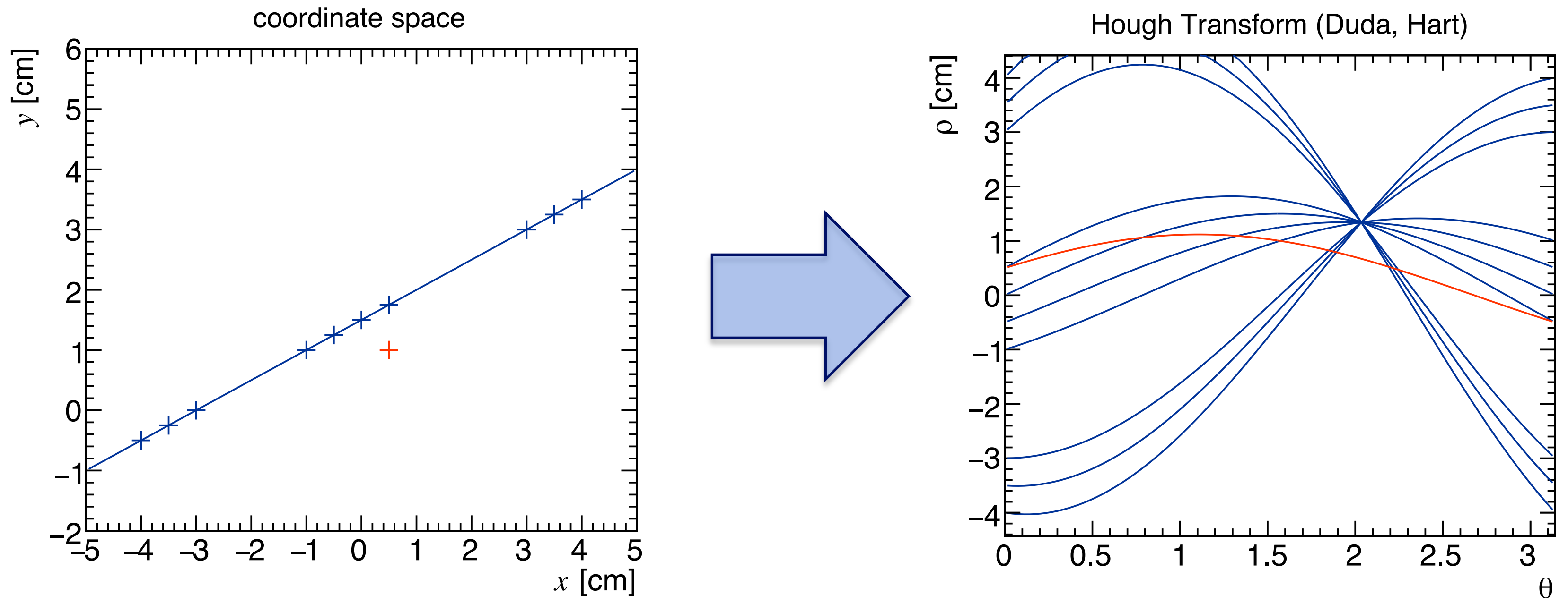
  - design of a **real-time pattern recognition algorithm**[2][3] to be implemented in logic devices for fast triggers or filters, requiring **high efficiency** and resolution on **reduced input** data samples
    - DT chamber layout = a telescopes of position-sensitive detectors, grouped together in layers and super-layers

  - Trigger on muons with a DT chamber means to recognise when the muon has traveled through the chamber and identify its approximately straight track segment

[1] N. Pozzobon, P. Zotto and F. Montecassiano A proposal for the upgrade of the muon Drift Tubes trigger for the CMS experiment at the HL-LHC. proceedings of the Connecting The Dots CTD 2016 workshop (HEPHY Wien, Feb. 2016) -] Accepted by Eur. Phys. J. Web of Conference
[3] Nucl. Instr. Meth. A 834 (2016) 81–97 N. Pozzobon, F. Montecassiano and P. Zotto A novel approach to Hough Transform for implementation in fast triggers. doi:10.1016/j.nima.2016.07.020
[4] N. Pozzobon, F. Montecassiano and P. Zotto Design of a Compact Hough Transform for a new L1 Trigger Primitives Generator for the upgrade of the CMS Drift Tubes muon detector at the HL-LHC -] Submitted for publication to IEEE Trans. Nucl. Sci.

Barrel Muon Trigger Upgrade (DT)

- A Hough Transform-based approach[2]
  - Hough transform techniques are generally robust against spurious hits due to background or fake measurements
    - DT measurement carry an intrinsic left-right ambiguity, a Hough Transform-based technique can solve it



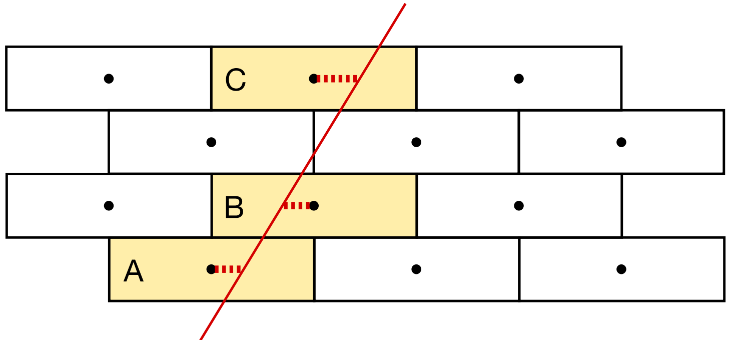
[3] Nucl. Instr. Meth. A 834 (2016) 81–97 N. Pozzobon, F. Montecassiano and P. Zotto A novel approach to Hough Transform for implementation in fast triggers. doi:10.1016/j.nima.2016.07.020

Barrel Muon Trigger Upgrade (DT)

- Key features of the algorithm*:
  - Clever partitioning of the input dataset into subsets that are processed in parallel to extract pattern parameters, and which are recombined in a later stage
  - Reduction of the typical computational load of the Compact Hough Transform* by processing N-ples of measurements simultaneausly, constraining a function of a single track parameter
    - Higher combinatorics are largely compensated by the reduction in the Hough Transform histogram size in the small input dataset

*patent applied for by Università degli Studi di Padova, 24th Feb 2016

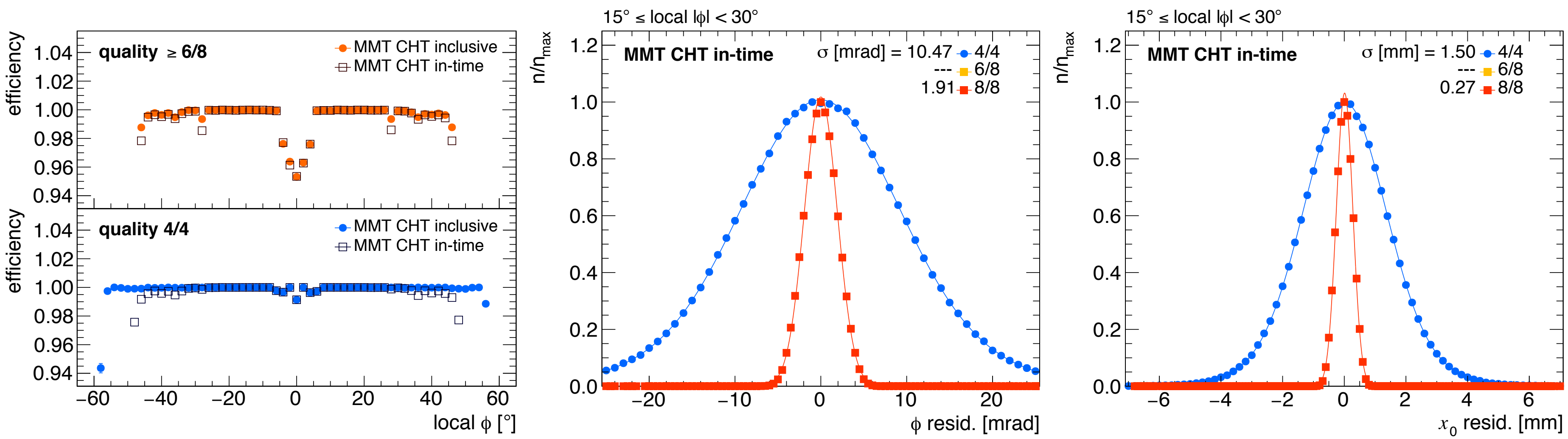
Barrel Muon Trigger Upgrade (DT)



- Majority Mean-Timer
  - A correct reconstruction of the drift distance relies on the identification of muon crossing time:
    - Possibility of resolving ambiguities by means of weighted average of reconstructed drift times is one of the key features of the CMS DT chambers design since the earliest studies,
    - Currently being used only in the offline calibration of drift velocity
  - A straight computation of the crossing time is possible for the majority of equations: all the equations can be made explicit in terms of it by applying the definition of drift time
  - The crossing time is obtained on a statistical basis from the evaluation of all the triplets of wires and left-right crossing hypotheses, without sampling the crossing time hypothesis: the most voted value is chosen to reconstruct the drift distances and positions that are input to the CHT

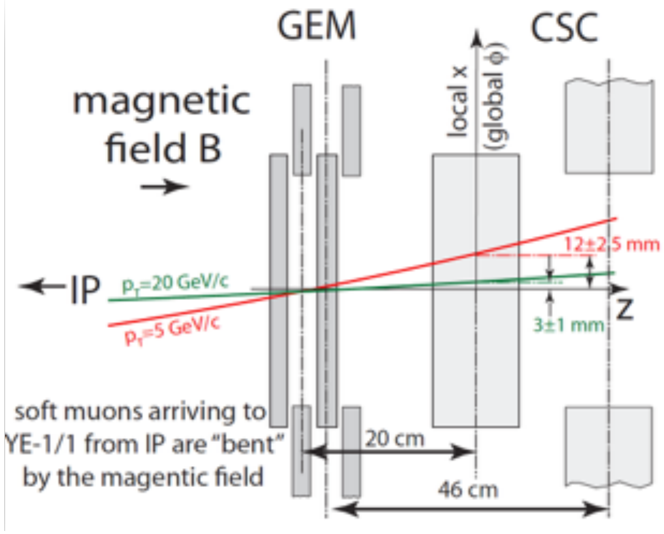
Performance Evaluation

- The design is driven by the request of a robust result, with an efficiency > 98% over a local φ range spanning ~100°,
- A resolution better than 30 mrad (3 mrad) for 4-point tracks (8-point tracks) in local φ, and better than 1.4 mm in intercept, fitting within few μs latency (not yet a final requirement)

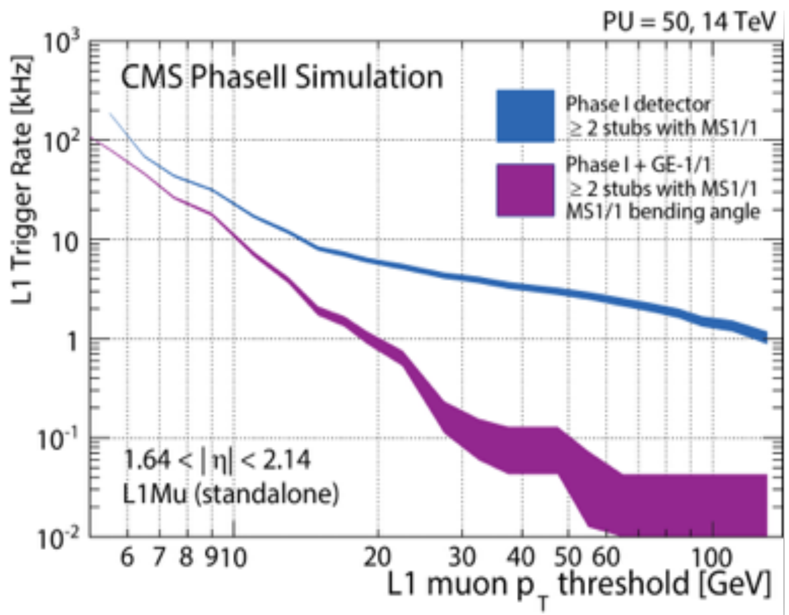


Endcap Muon Trigger Upgrade

- Motivation for muon trigger in the endcap:
  - Performance relies on optimal working of L1-CSC trigger
  - Deal with higher rate → maintain stub reconstruction efficiency + face with aging
  - Installation of new detectors (GEM + new RPC)



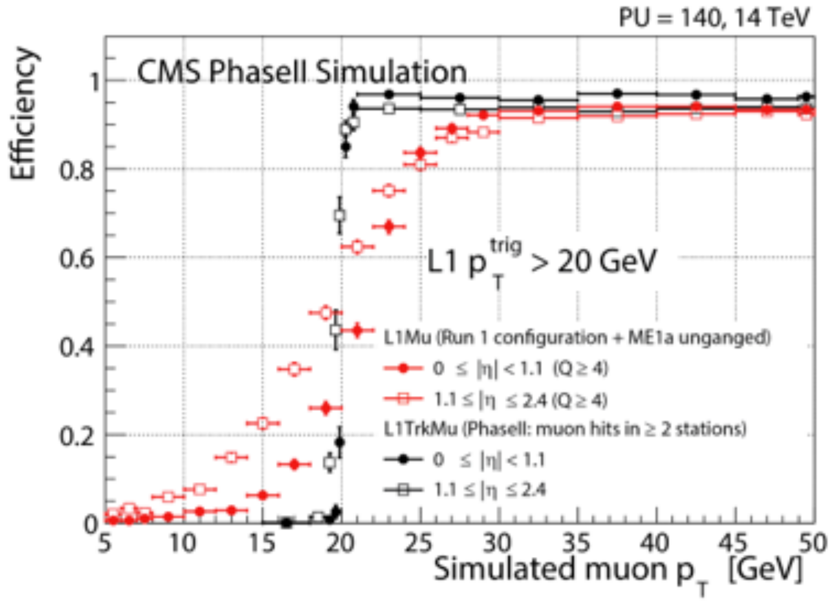
- Using GEM in front of CSC, will allow to measure the muon bending in the magnetic field
  - Distinguish between low and high p_T muon
  - Keep trigger rate under control



Endcap Muon Trigger Upgrade

- Algorithm & performance overview:
  - Algorithm for local trigger development from the technical proposal[2](high PU condition: **PU=140**)
  - Stubs reconstructed with **GEM+CSC**, bringing the **bending angle information**, are sent to the **track-finder**→Overall **improvement** ranging between **3%** and **10%**
  - Extra GEM and RPC recover efficiency losses in the track-finder, mainly due to CSC aging and mechanical spacers in large CSC

- Displaced L1-Mu trigger:
  - Prompt muon reconstructed by tracker and muon system → increase efficiency and dramatic reduce the rate
  - Design a Phase-II L1-Mu trigger that is efficient both to prompt and not-prompt muons



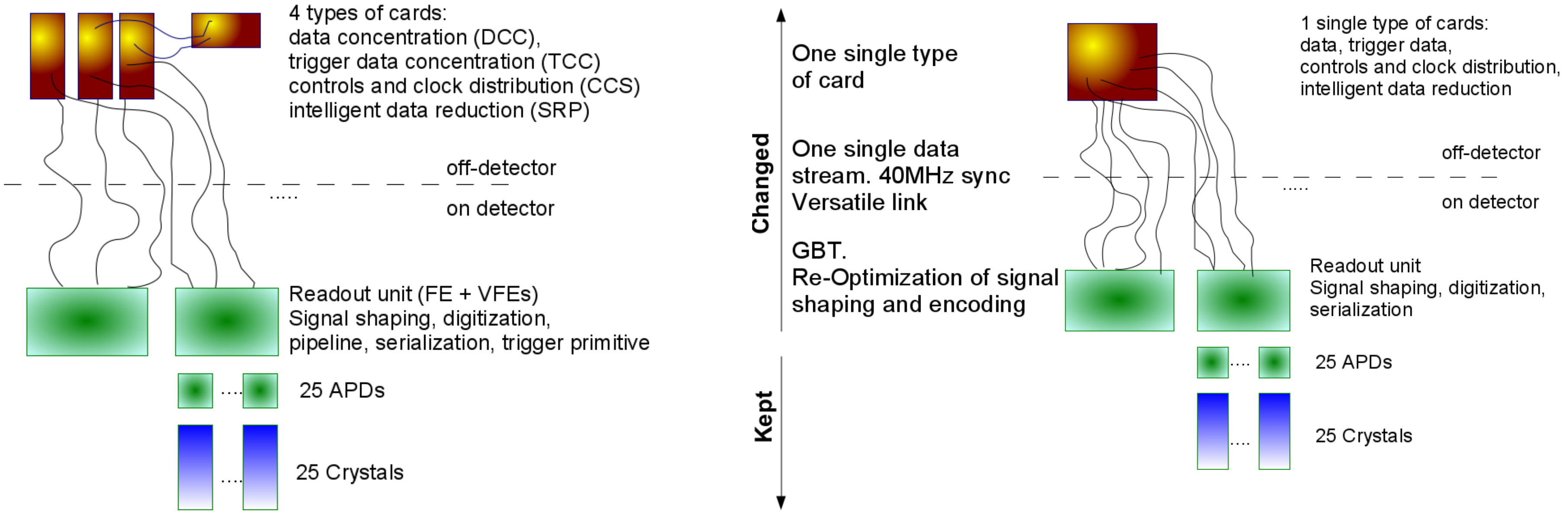
[2] Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid, CERN-LHCC-2015-10 LHCC-P-008 CMS-TDR-15-02 ISBN 978-92-9083-417-5 1 June 2015

Calorimeters Upgrade

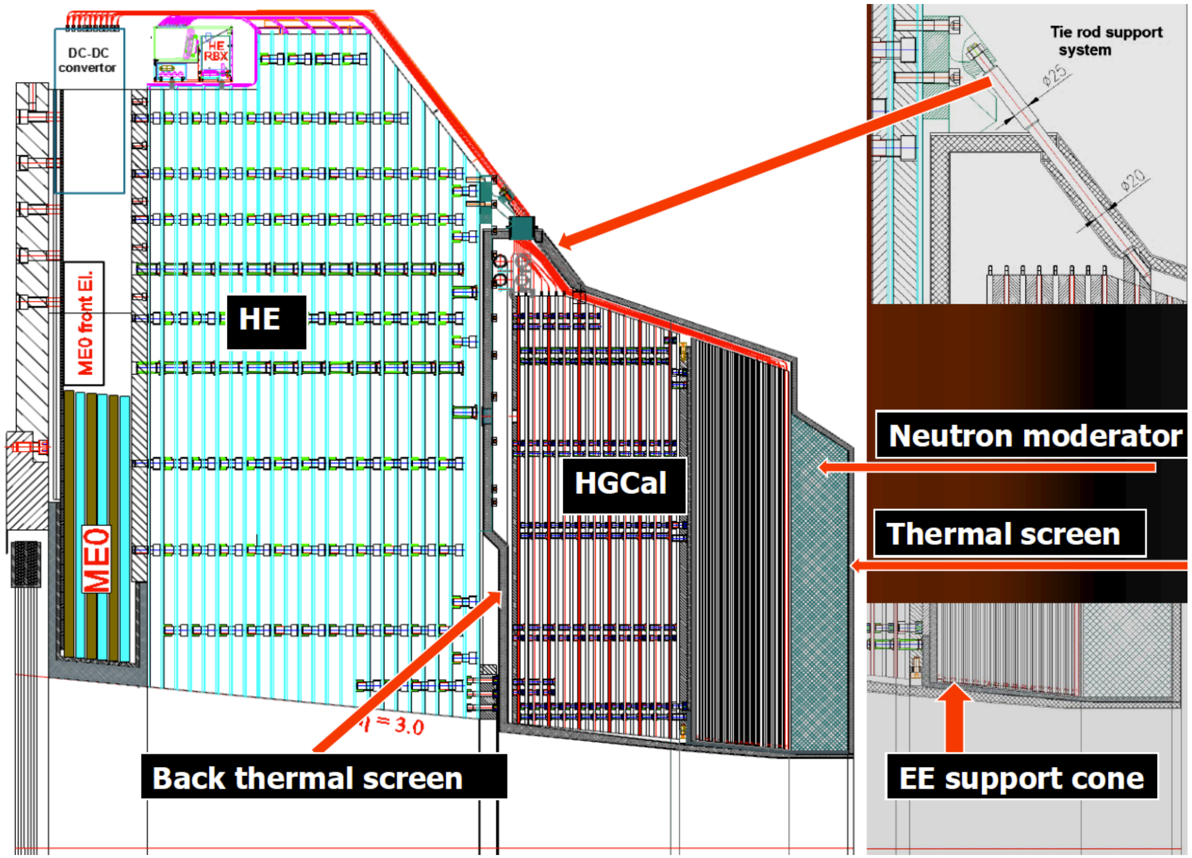
- Physics at HL-LHC requires precision calorimetry in both the barrel and endcap regions

  - To exploit the VBF signature to separate out the different Higgs boson production modes.
  - CMS decided to improve the existing calorimeters in the barrel region; while completely changing the endcaps
  - CMS will adopt two highly segmented sampling calorimeters to replace the existing ECAL+HCAL endcaps → HGCal.
  - This will increase from ~O(20K) up to ~O(6M) the number of channels to read out → much-improved pattern recognition for shower reconstruction
  - For L1 trigger → attempt to perform particle-flow event reconstruction

- ECAL+HCAL BARREL
  - Front-End + Off-Detector read out will be upgraded in order to provide full-resolution information on a single crystal basis (ECAL) and depth information (HCAL)



High Granularity sampling Calorimeter (HGCal)



HGC

Elecromagnetic (EE)
Si/W+Cu
25 X_0 (1.5 λ) 28 layers:
- 10 x 0.65 X_0
- 10 x 0.88 X_0
- 8 x 1.26 X_0

Hadronic (FH)
Stain. steel+Si
3.5 λ 12 layers:
- 12 x 0.3 λ

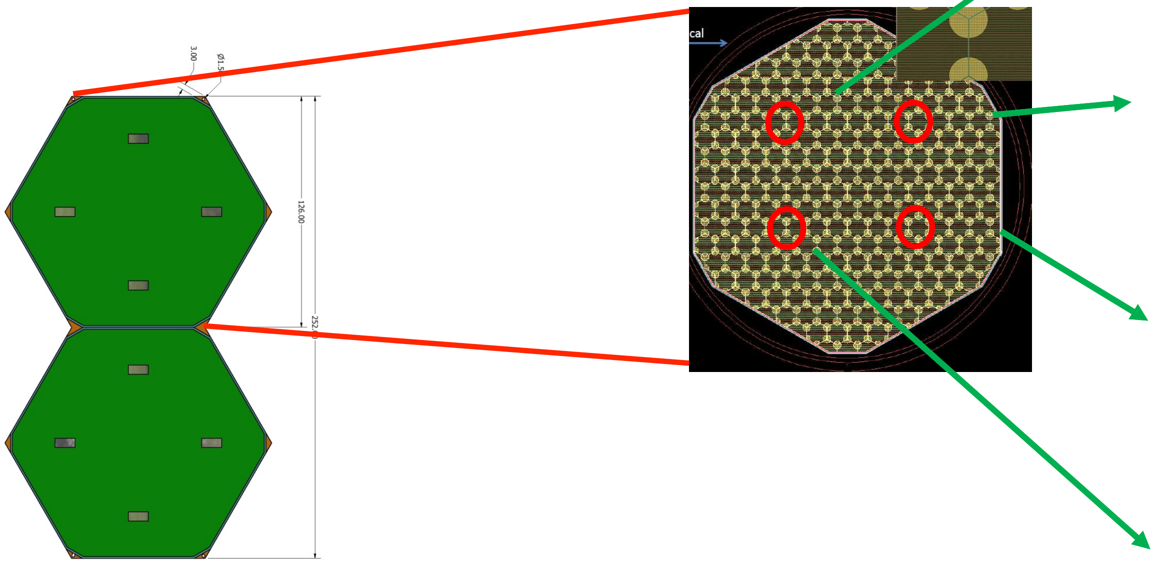
Hadronic (BH)
Stain. steel+scintillator
5 λ 12 layers/2 sampling
- 12 x 0.4 λ

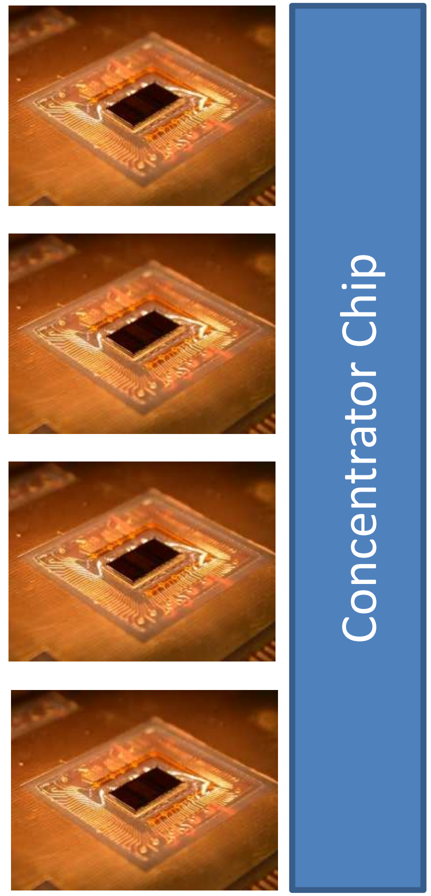
HGC readout

- Each wafer is made up of 128 (256) hexagonal 0.5 (1.0) cm^2cells
- 2(4) readout chips are plugged on each wafer

Depending on η

- Data are transmitted by **LpGBT**: ~8k links dedicated to trigger data (1TC = 4cells) and ~6k links dedicated to full resolution data

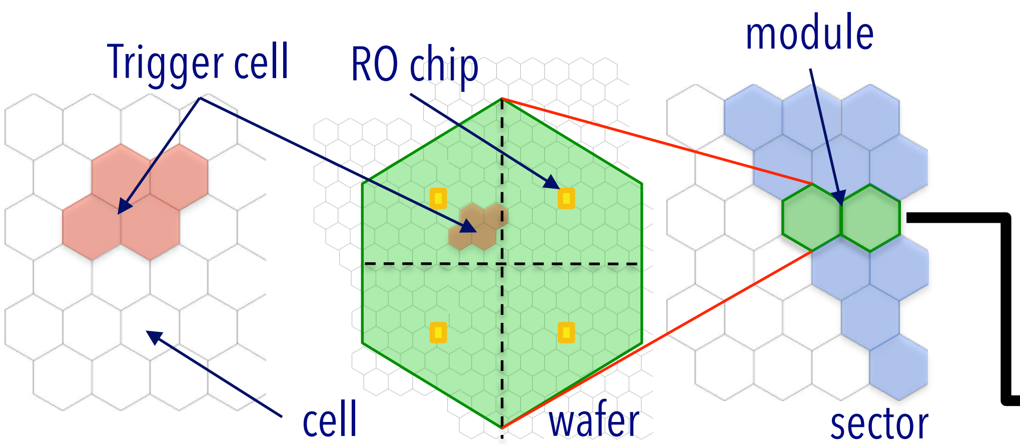




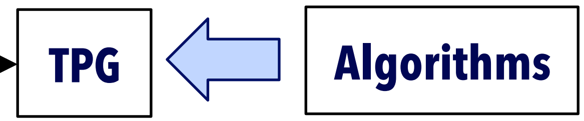
- ~14000 LpGBT links for 21700 modules!

HGC algorithms & data reduction

- Trigger cell = 4 hexagonal cells (64 or 32 per wafer)
- Important part of the HGCal trigger chain is the processing and data reduction in the front-end → selection of a maximum of the 10%-20% trigger cells per module
- The energy and the position of the selected TC is used as input to complex clustering algorithm (under study) → produce the trigger primitives to be sent to the correlator
- the algorithms and the hardware architecture are very inter-dependent. The architecture is putting constraints on the type of algorithms it is possible to implement as well as on the data format

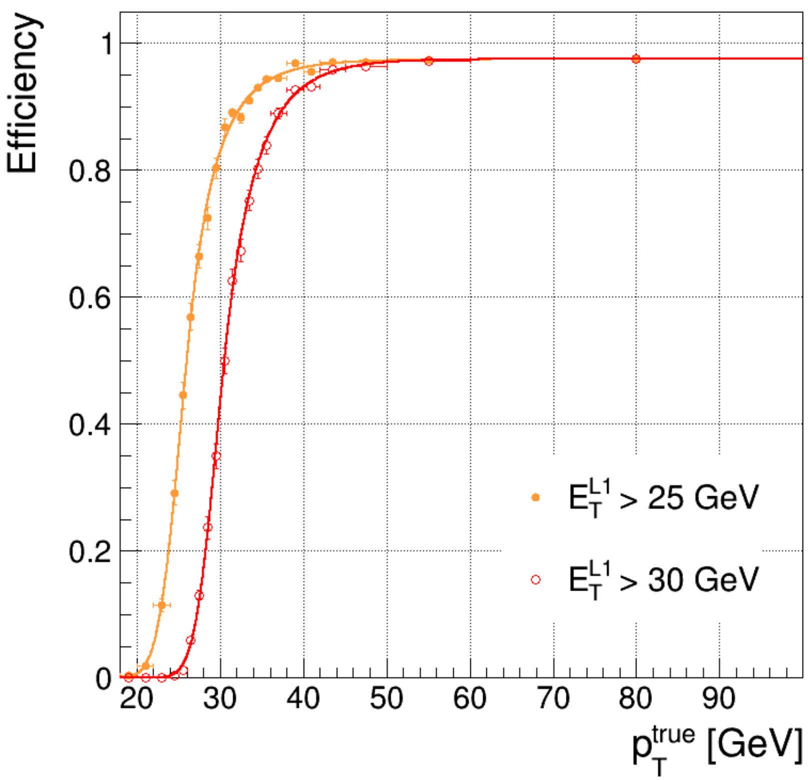


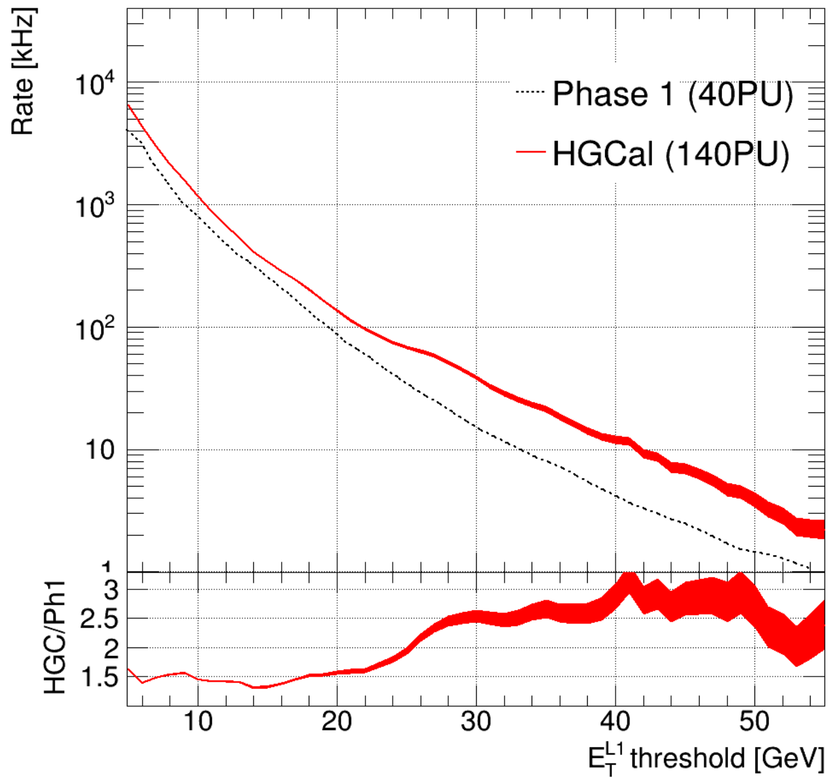
- Assuming **1LpGBT (8.96Gb/s) / module**:
  1.12 GB/s x 25 ns / bx = 28 B/bx
- Assuming data-format (**16b/TC**):
  (28 B/bx) / 2 B **~14TC/module (7TC/wafer)**



HGC TP-generation algorithms

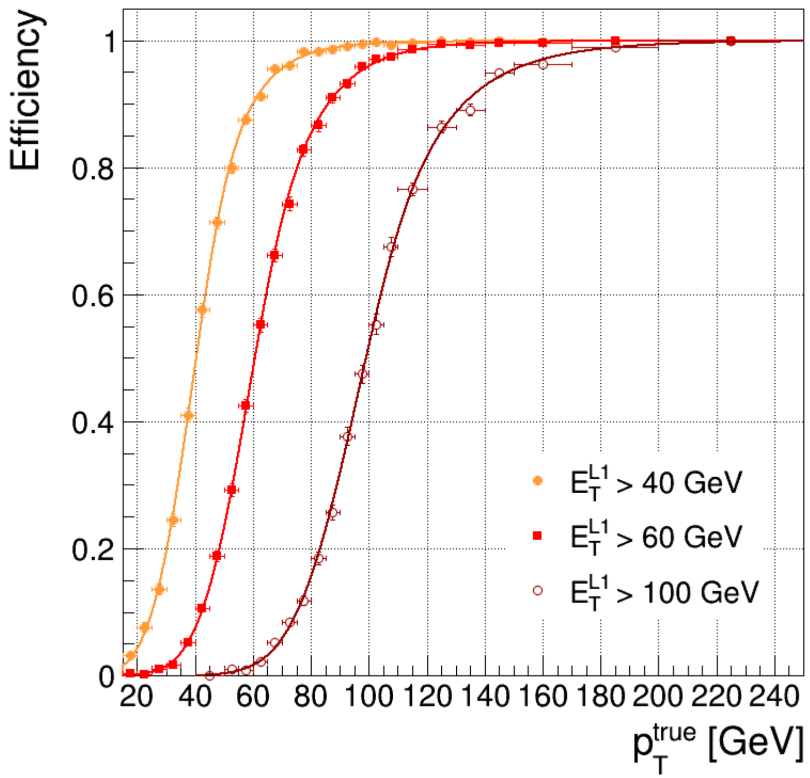
- Performance:
  - The expected performace have been evaluated using a 3D clustering approach
  - Other clustering possibilities are currently under study (from 2D→3Dclusters)
  - Result from the TP for the trigger efficiency (left) and rate (right) for electrons

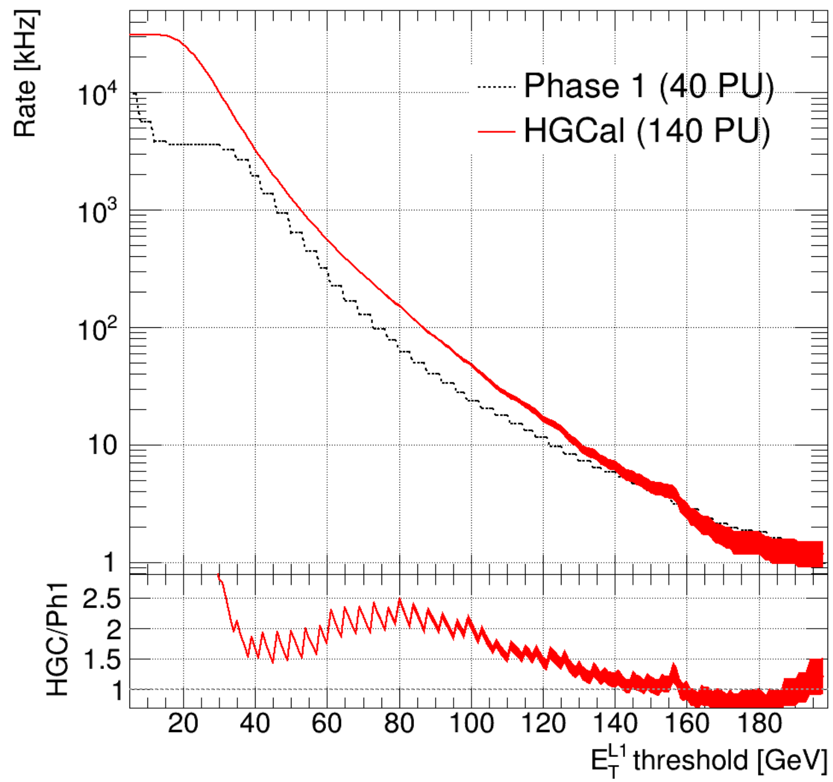




HGC TP-generation algorithms

- <u>Performance:</u>
  - The expected performace have been evaluated using a 3D clustering approach
  - Other clustering possibilities are currently under study (from 2D→3Dclusters)
  - Result from the TP for the trigger efficiency (left) and rate (right) for jets



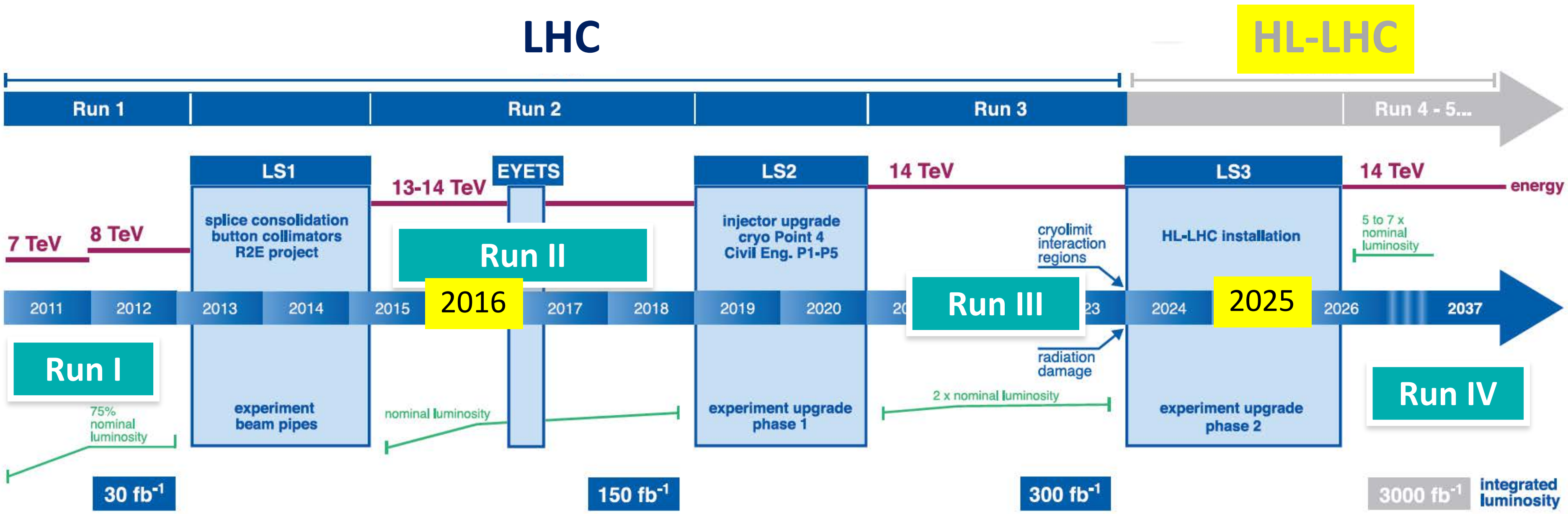


Conclusion

- To maintain (even improve) the CMS performance to preserve the physics discovery potential at the HL-LHC, CMS must undergo a major upgrade stage, called Phase-II upgrade (target 2026).
- Phase-II upgrade involves all the CMS subdetectors
- Looking to muon TPG upgrade: in the barrel there are already complex algorithms designed to generate the DT-TP, in the endcaps, new detectors like GEM/RPC will provide additional information to reduce the trigger rate
- Full granularity will be exploited by the upgraded barrel ECAL and time information will be available in the upgraded barrel HCAL
- Given the strategic importance of calorimetry (especially at high-η in tagging the VBF jets), a very innovative solution has been adopted for the endcap calorimeters upgrade: HGCal. The high granularity allows to perform shower studies and run complex algorithms for object identification
- Use of track info + high granularity(&time?) + last FPGA and fast optical links ➔ First time that there is the possibility to reconstruct the entire event at online trigger level with particle-flow-based algorithms. Complete inter-dependence between the architecture definition (number of trg-layer, links/layer) and the TPG algorithms

Back-Up

LHC/HL-LHC schedule



0.75 10^{34} cm^{-2}s^{-1}
50 ns bunch
high pile up ~40

1.5 10^{34} cm^{-2}s^{-1}
25 ns bunch
pile up ~40

1.7-2.2 10^{34} cm^{-2}s^{-1}
25 ns bunch
pile up ~60

~5(7.5!) 10^{34} cm^{-2}s^{-1}
25 ns bunch
pile up ~140 - 200

50 ⇒ 25 ns
bunch spacing

Physics goal for HL-LHC

- The scientific goals require:
  - Extreme demands on the lepton/photon reconstruction efficiency
  - Trigger thresholds don't compromise the ability to select W,Z^0 and H decays
  - Excellent vertex reconstruction for b-tagging
  - Jet energy resolution maintained at high PU (particularly at high-η, where the production of VBF-jets or the forward jets coming from vector boson scattering are enhanced)

Note: The objects reconstruction in CMS relies on the **Particle Flow algorithms**, thus, to reach the optimal reconstruction performance CMS must undergo a balanced upgrade of its subdetectors

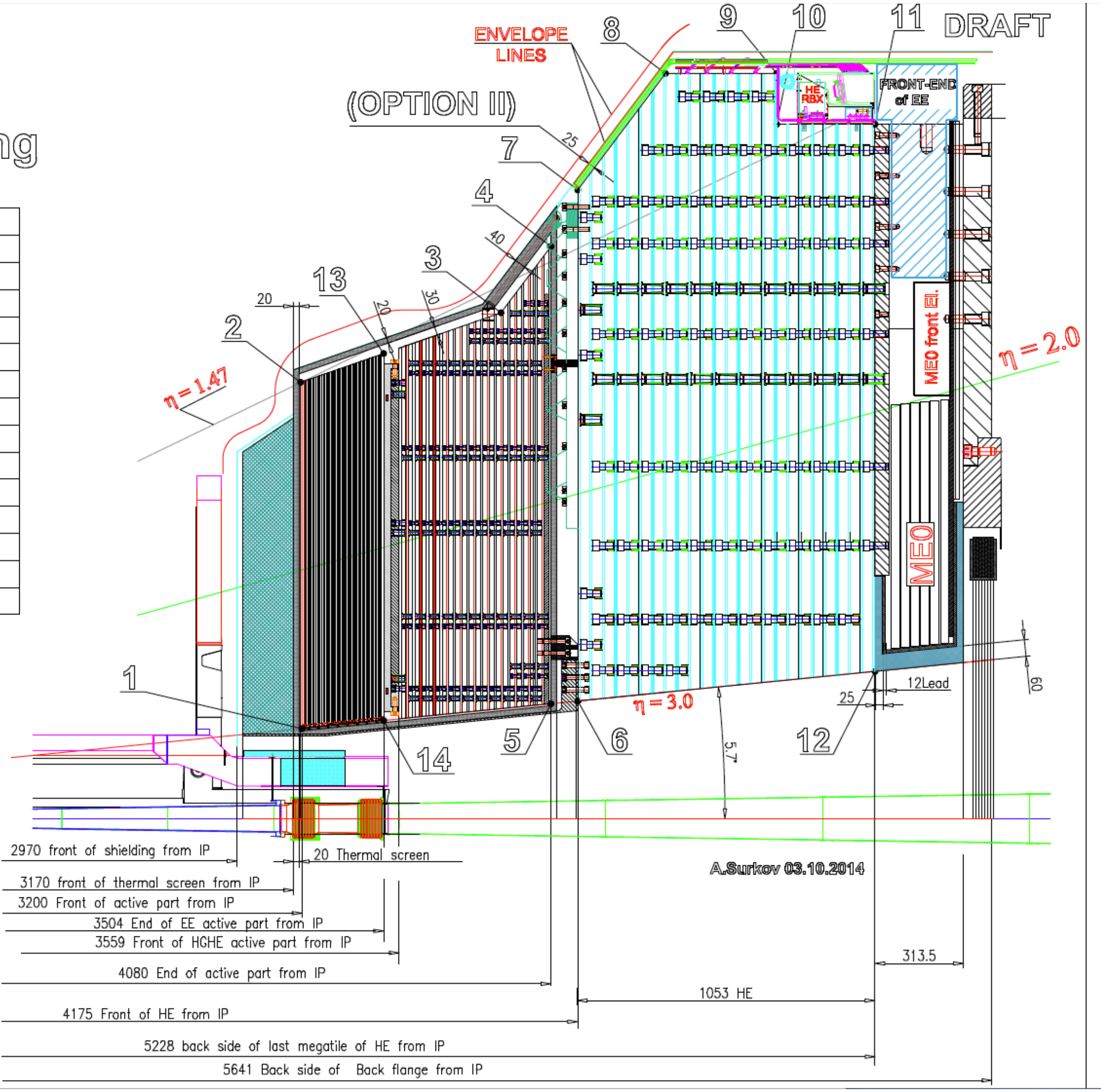
The CMS Phase-II Upgrade

- The algorithm is designed for parallel processing of symmetric groups of 18 wires each (macro-cells), one per super-layer at a time
- The straight track direction is searched for in the 1D HT histogram, built from pairs of hits, which is incremented for track slope values m meeting the condition $|\Delta x + m \cdot \Delta z| < \varepsilon$
- The CHT is differently tuned for single-super-layer subsets (1-SL CHT) and for the two-super-layers subset (2-SL CHT)

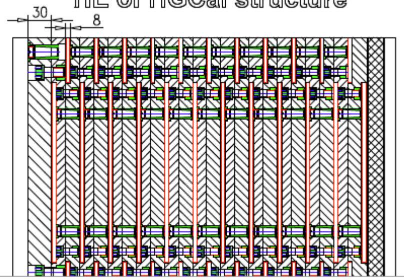
Back-Up

HGCal/HE/ME0 parameter drawing

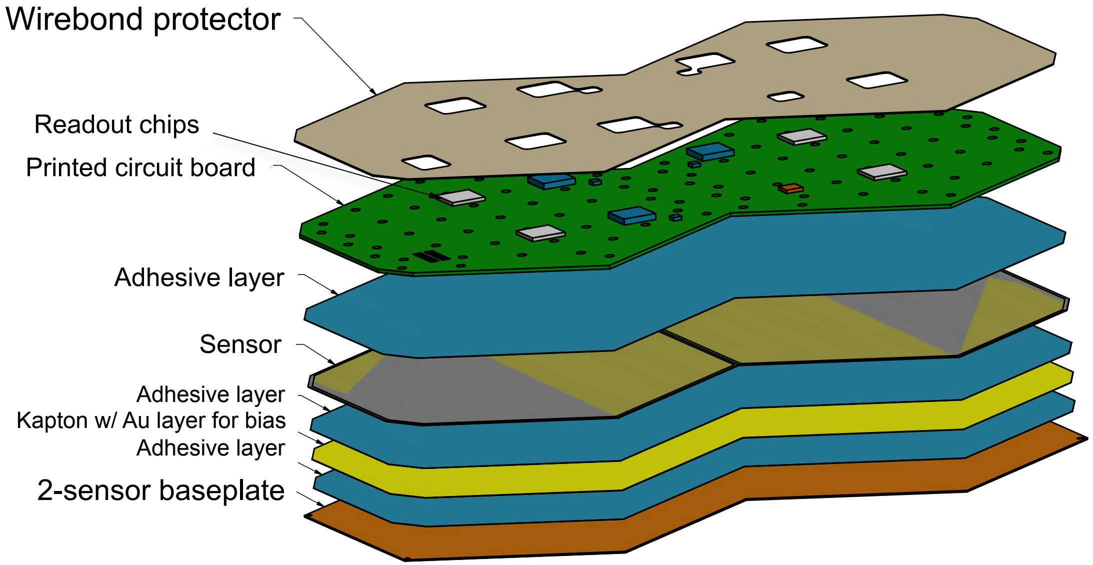
P- s	Z (mm)	Y (mm)
1	3200	319
2	3200	1545.3
3	3904	1791.5
4	4081	2026.5
5	4081	407
6	4176	417
7	4176	2226.5
8	4486	2639
9	4880	2639
10	4880	2458
11	5228	2458
12	5228	522
13	3504	1647
14	3504	348

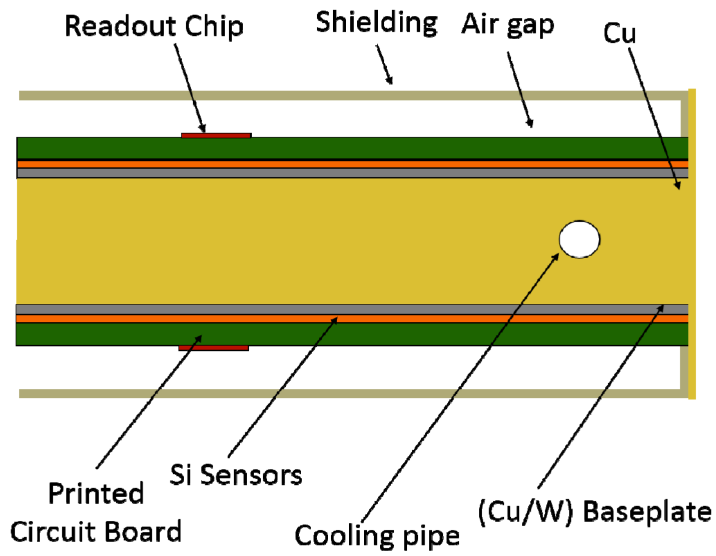


HE of HGCal structure



- The cassette is built up on either side of a 6 mm-thick copper plate containing cooling channels.
- Pairs of hexagonal silicon sensor wafers are mounted on a PCB
- The other faces of the sensors are glued to a tungsten-copper baseplate

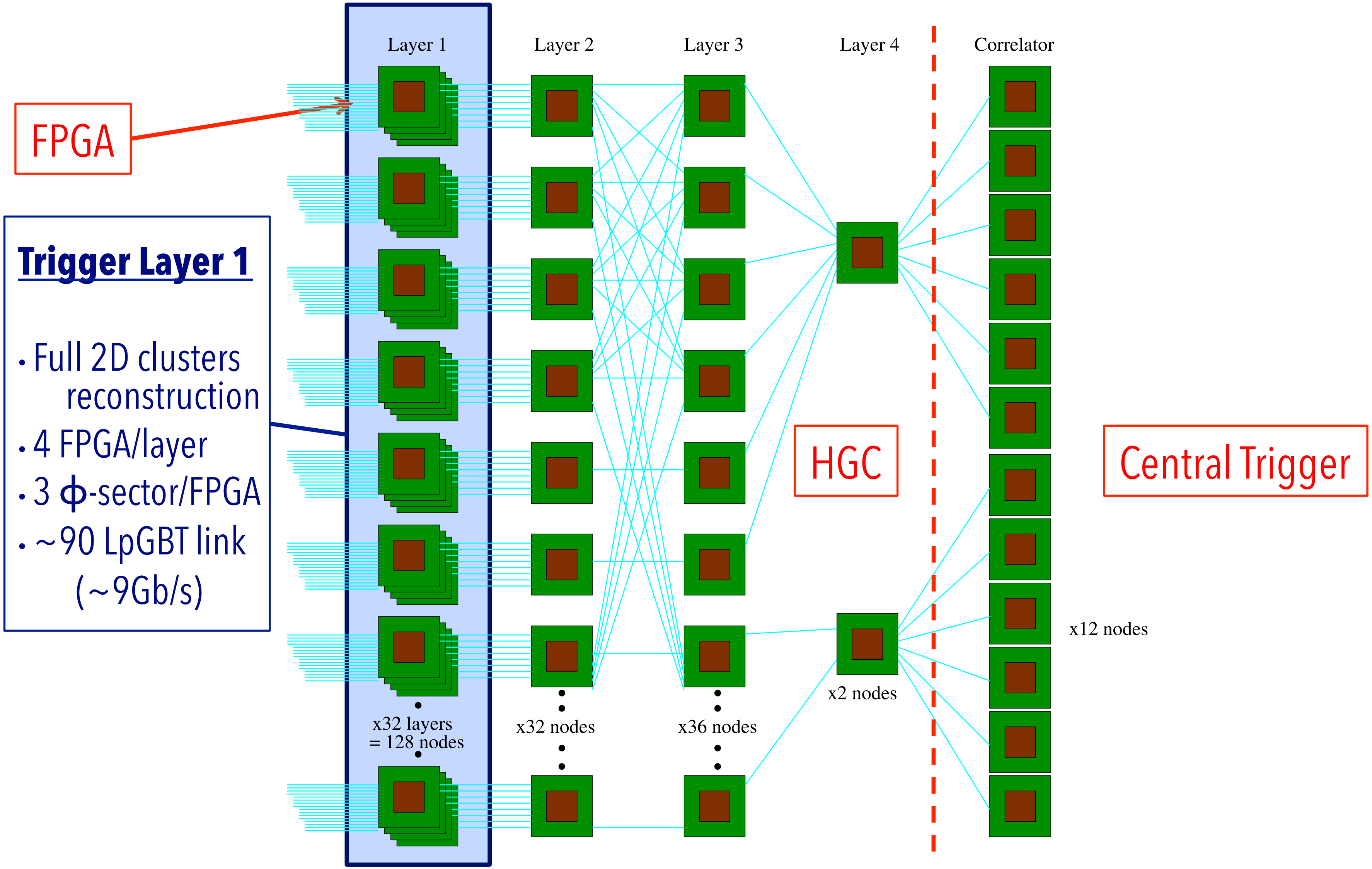




Possible trigger architecture

Trigger Layer 1

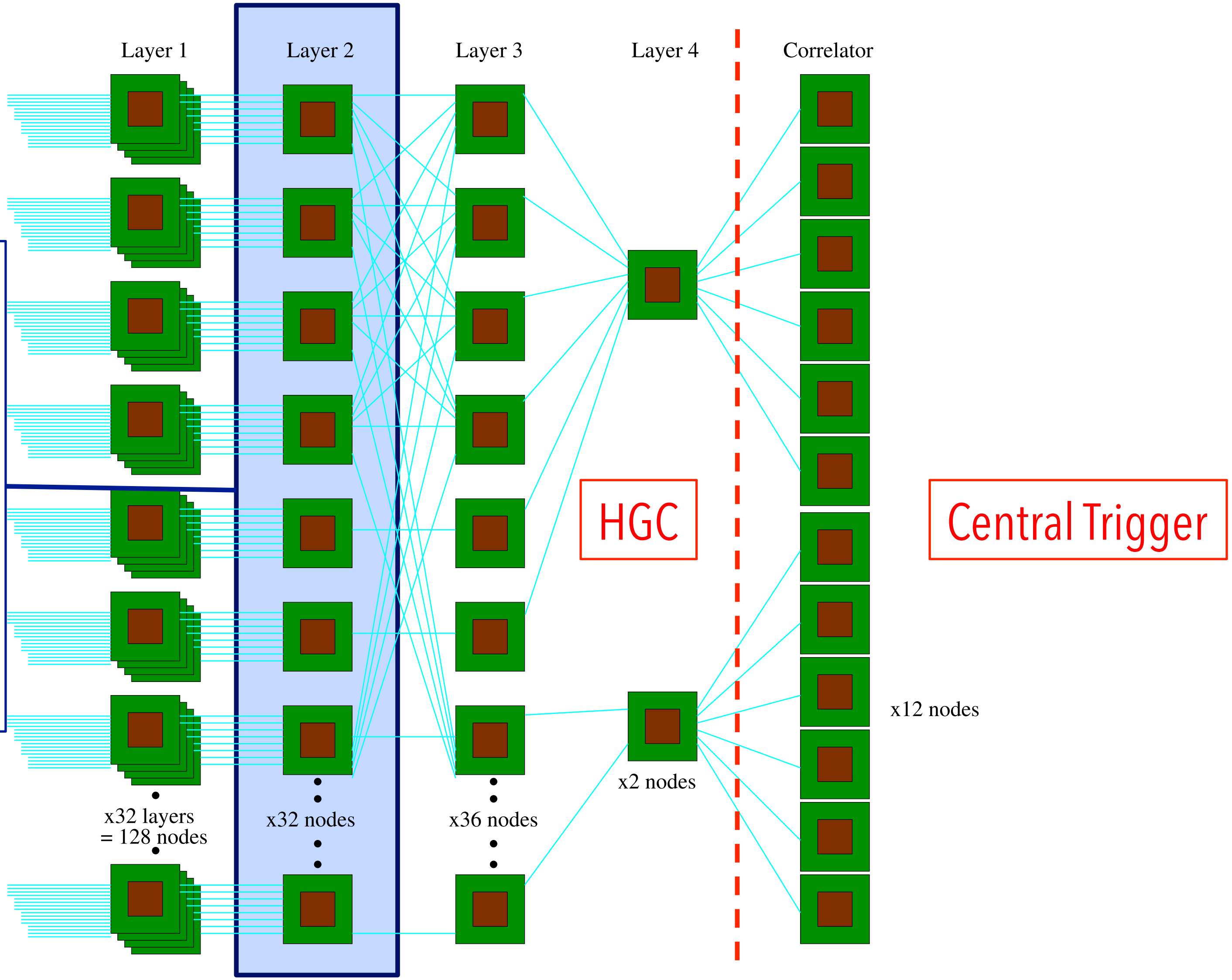
- Full 2D clusters reconstruction
- 4 FPGA/layer
- 3 ϕ-sector/FPGA
- ~90 LpGBT link (~9Gb/s)



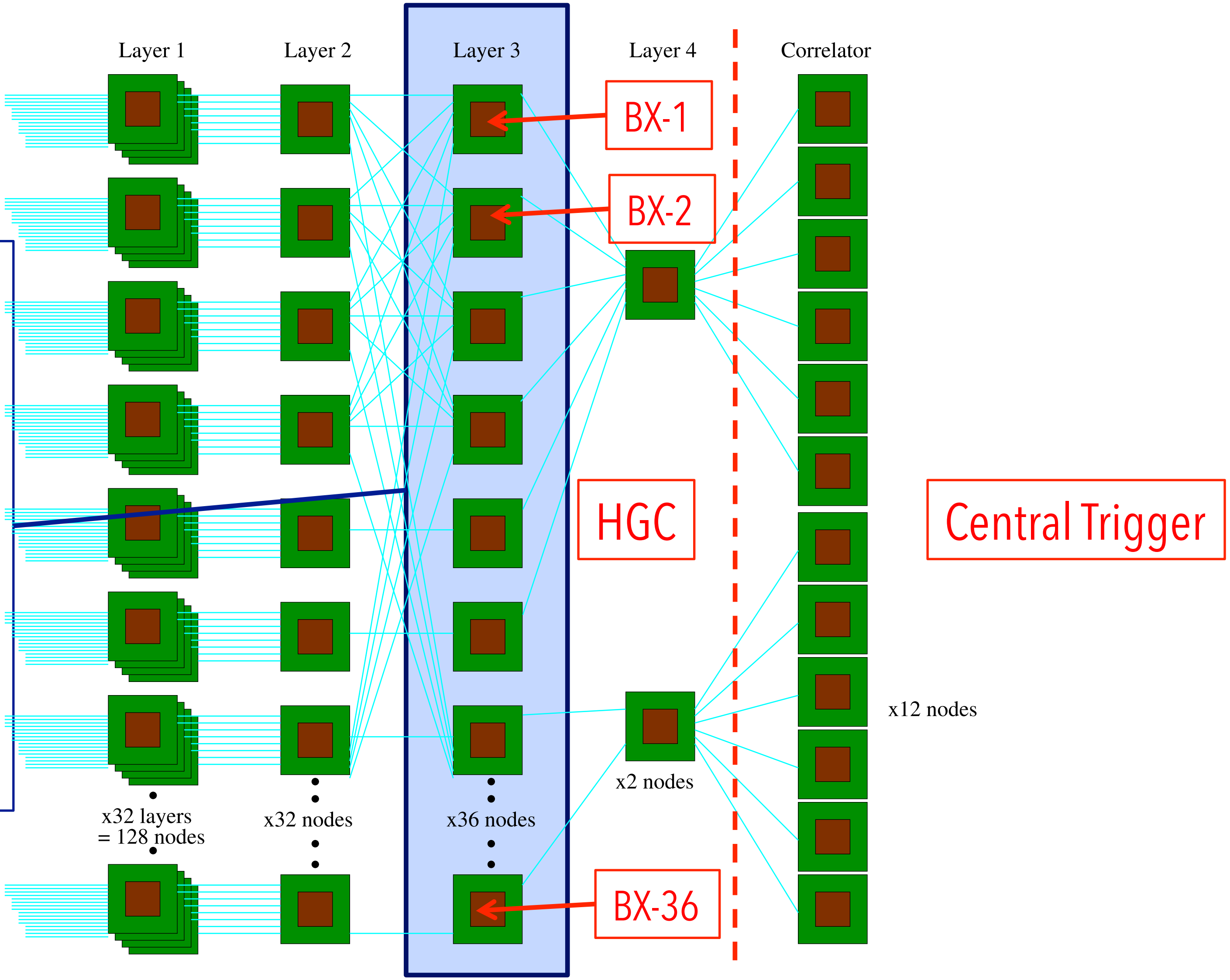
Possible trigger architecture

Trigger Layer 2

- Assuming data reduction x3
- Cluster from 1 layer can go into 1 node
- cluster merging at sector edges
- ϕ-ordering



Possible trigger architecture



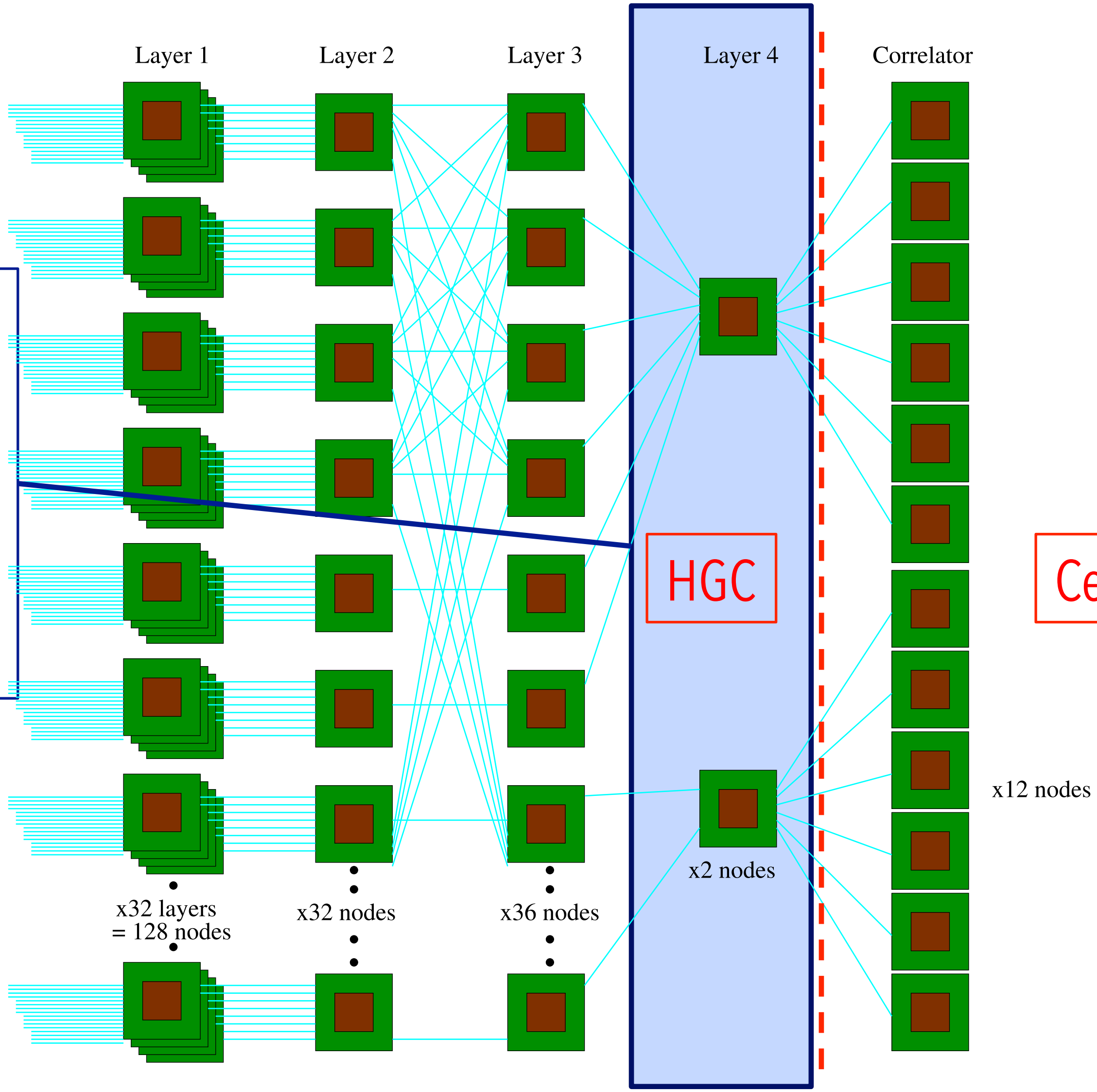
Trigger Layer 3

- Build 3D clusters
- 36-fold mplex
- 1 node/BX
- Compromise between input links and latency
- Each node see 1 endcap

Possible trigger architecture

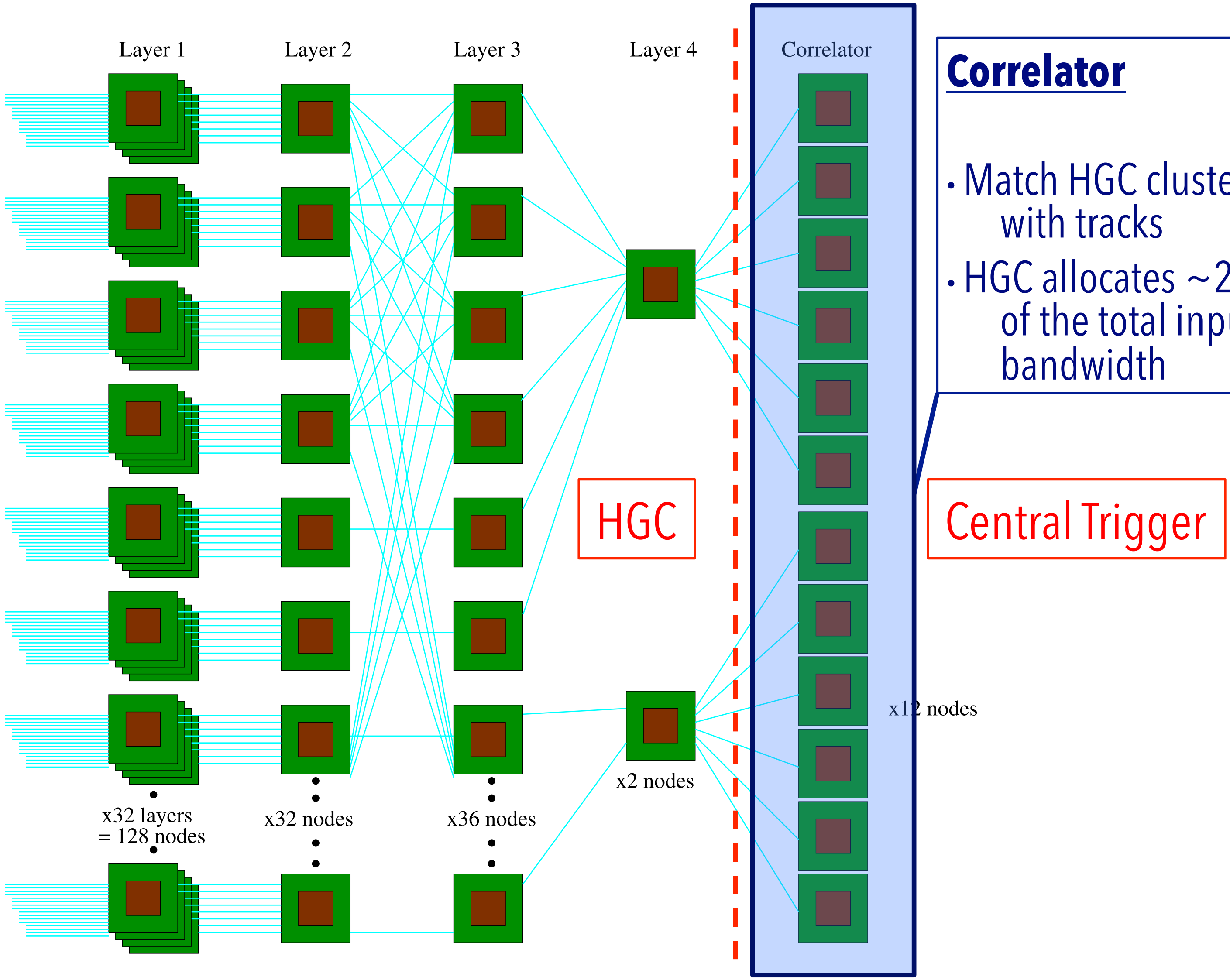
Trigger Layer 4

- Pipeline the correct bunch crossing to the Correlator



Central Trigger

Possible trigger architecture



Correlator

- Match HGC clusters with tracks
- HGC allocates ~25% of the total input bandwidth

Truth clustering

SimClustering can be used to begin to develop higher-level object algorithms while final clustering algorithm is still being developed

- **"Perfect clustering":**
  - Collection of all the recHit (Energy, position) associated to a simHit coming from a simulated particle trajectory
  - Reliable simulation of the cluster behaviour in the hypothesis to collect all the information from every HGC cells involved in the incoming particle shower
  - Make use of HyDRA framework (developed @IC) to associate tracks and hits to allow simple access to reconstructed + simulated information for development of clustering and particle flow
  - Clusters with perfect sharing of recHit energy between overlapping clusters, and perfect connection of separated pieces of a single shower

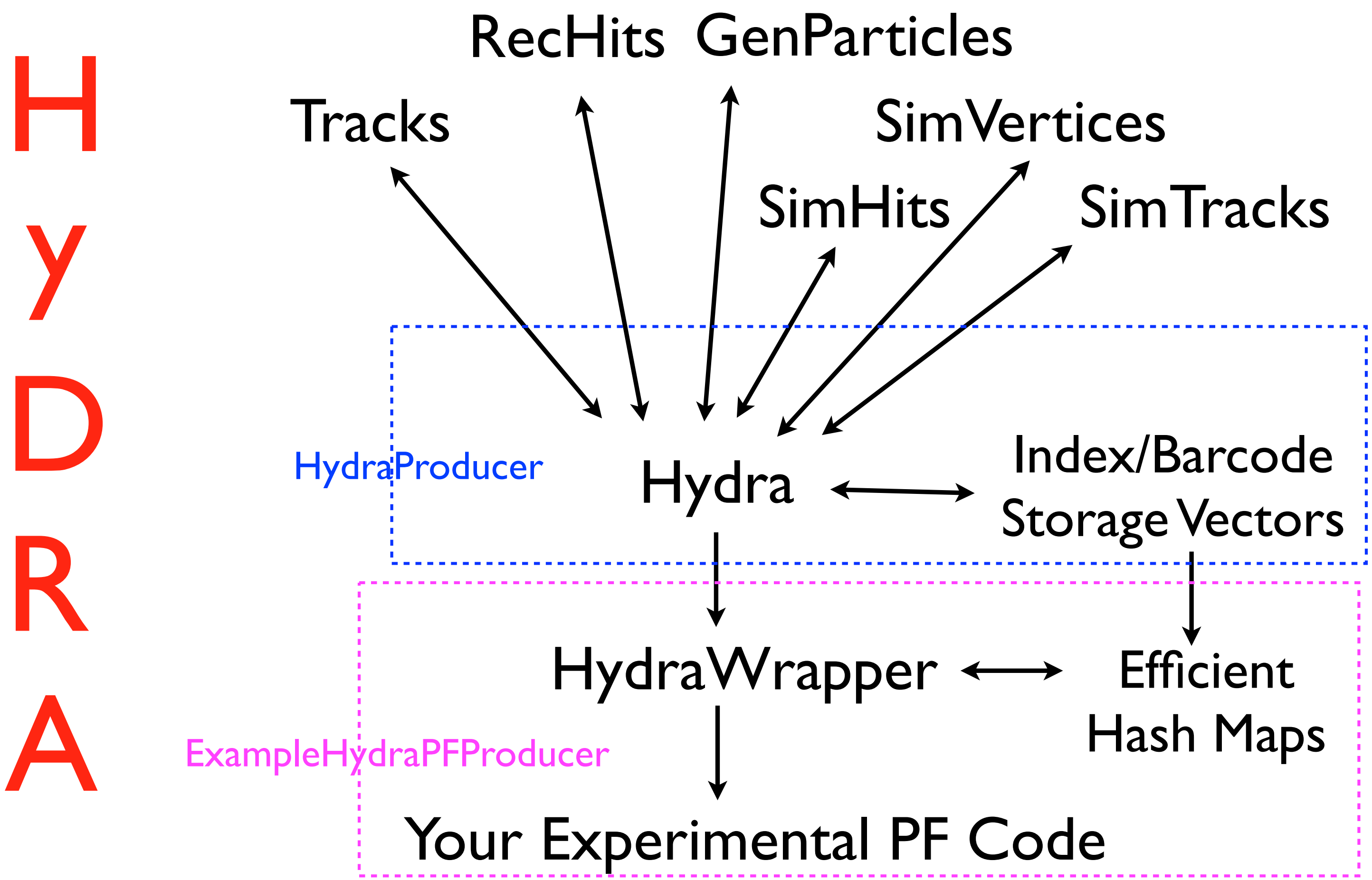
Truth clustering

- **Truth clustering is particle dependent:**
  - Different particles release energy in different ways in HGC
  - Studies on μ,τ,γ and QCD events → different particle **FOOTPRINTS**
  - Possibility to extract useful information to develop real clustering algos:

→size of the cluster, layers involved, shower shapes, etc…

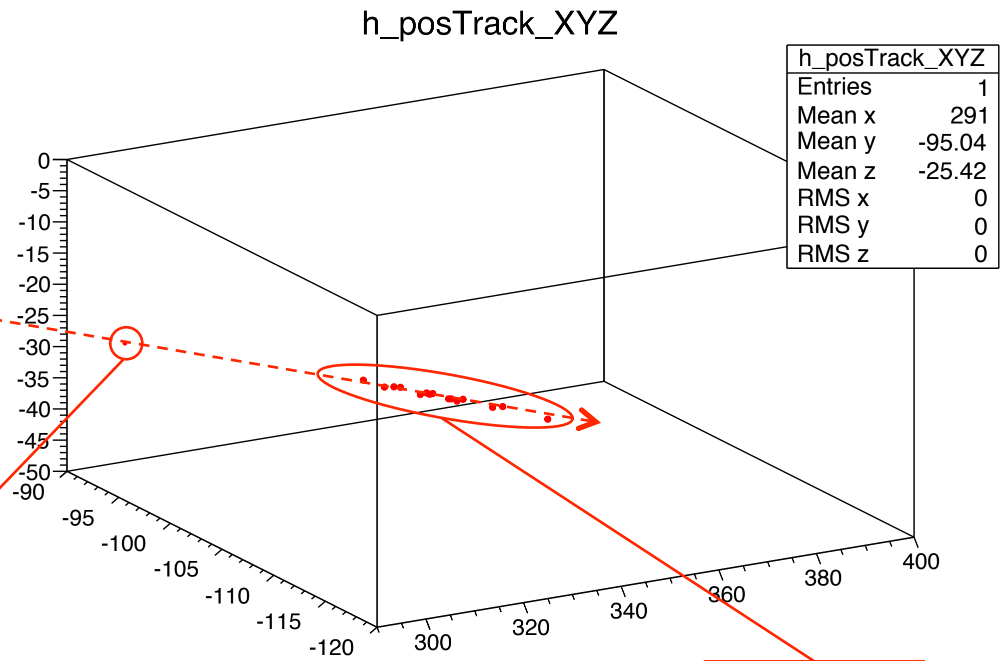
HyDRA in a nutshell

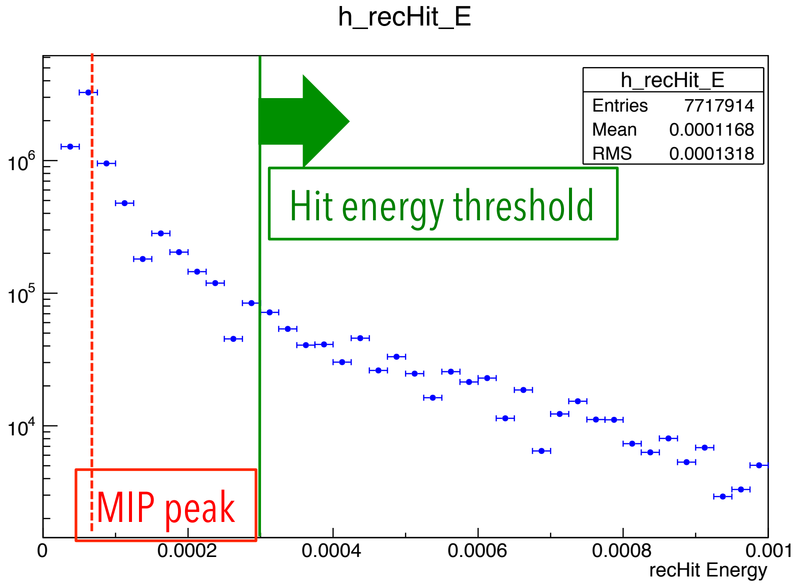
- **High y Rapidity Dev Reco Association:**



More on truth clustering – μ studies

- **MIPs Studies:**
  - Identification of the MIPs peak
  - Definition of the threshold to apply on the recHits = 5xMIP





- **MIPs Calibration (next step)**