Calorimeter trigger for CMS phase-2

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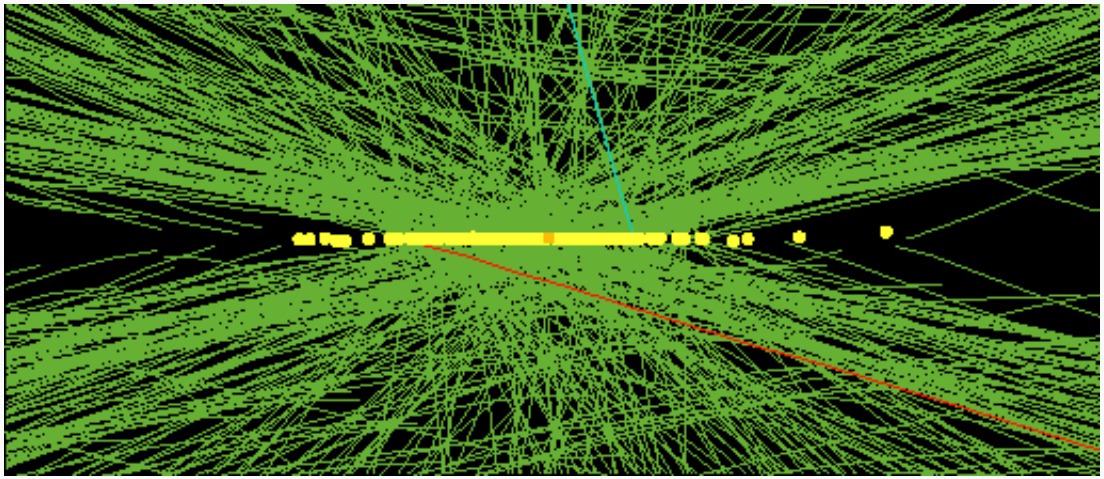
Triggering on new physics at the HL-LHC, workshop at Princeton University

Physics motivation

- Events with low p_T objects should be recorded to keep sensitivity to electroweak physics:
  - Higgs sector: H→ττ, H→ZZ→4l, H→BSM→SM, …
  - W and Z physics: precision measurements
  - …

- But major challenges in phase-2:
  - High luminosity
  - High pileup (140-200)



Trigger upgrades

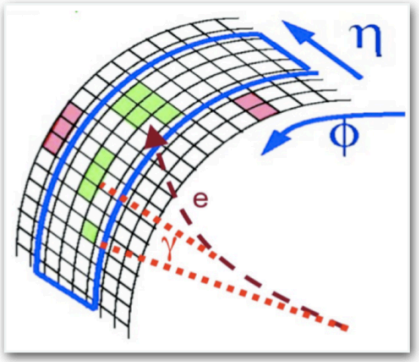
- Significant upgrades are needed to keep similar trigger thresholds as in phase-1

- Upgrades should aim at reaching **offline reconstruction performance at the L1 trigger level**. This would lead to:
  - Increase of the reconstruction efficiency
  - Sharpening of the trigger efficiency turn-on
  - Decrease of the background rates

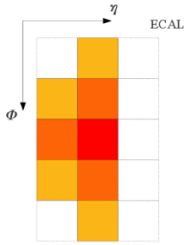
- Reaching offline reconstruction performance involves:
  - Using track information from track trigger
  - Increasing calorimeter trigger granularity

Object signature – Phase-1 algorithms

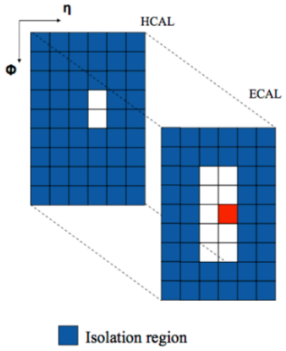
Electrons in CMS



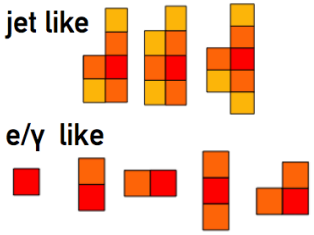
Cluster building



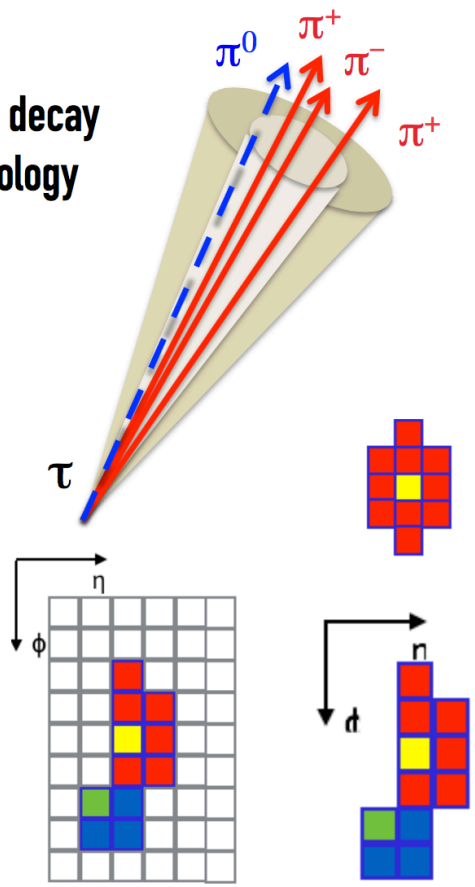
Isolation

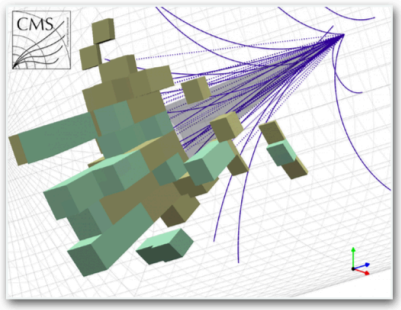


Cluster shapes



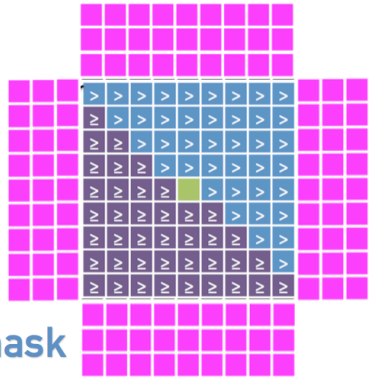
Tau decay topology





PUS areas

Seed tower



Veto mask

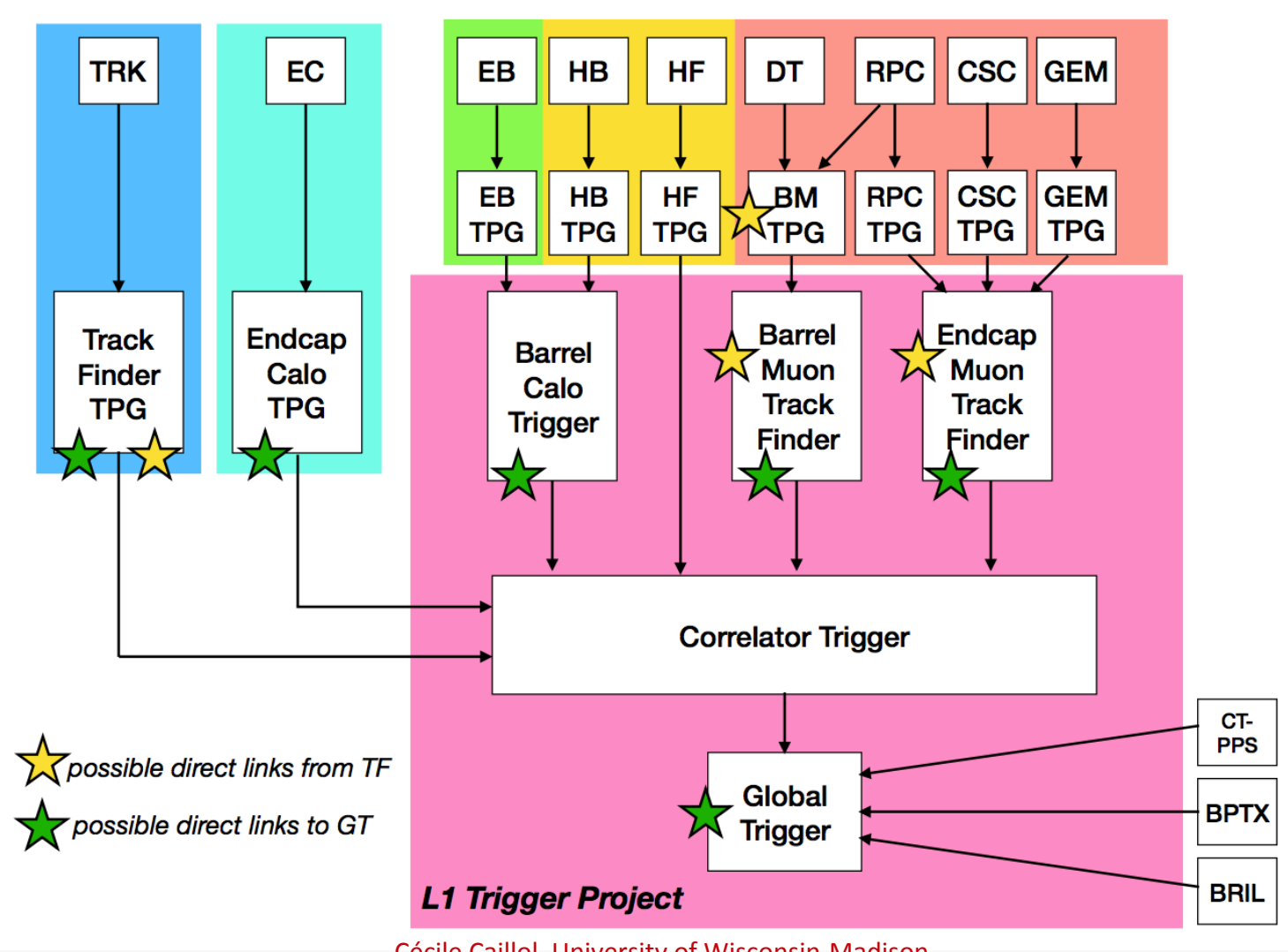
9x9 sliding window around seed tower

Electrons

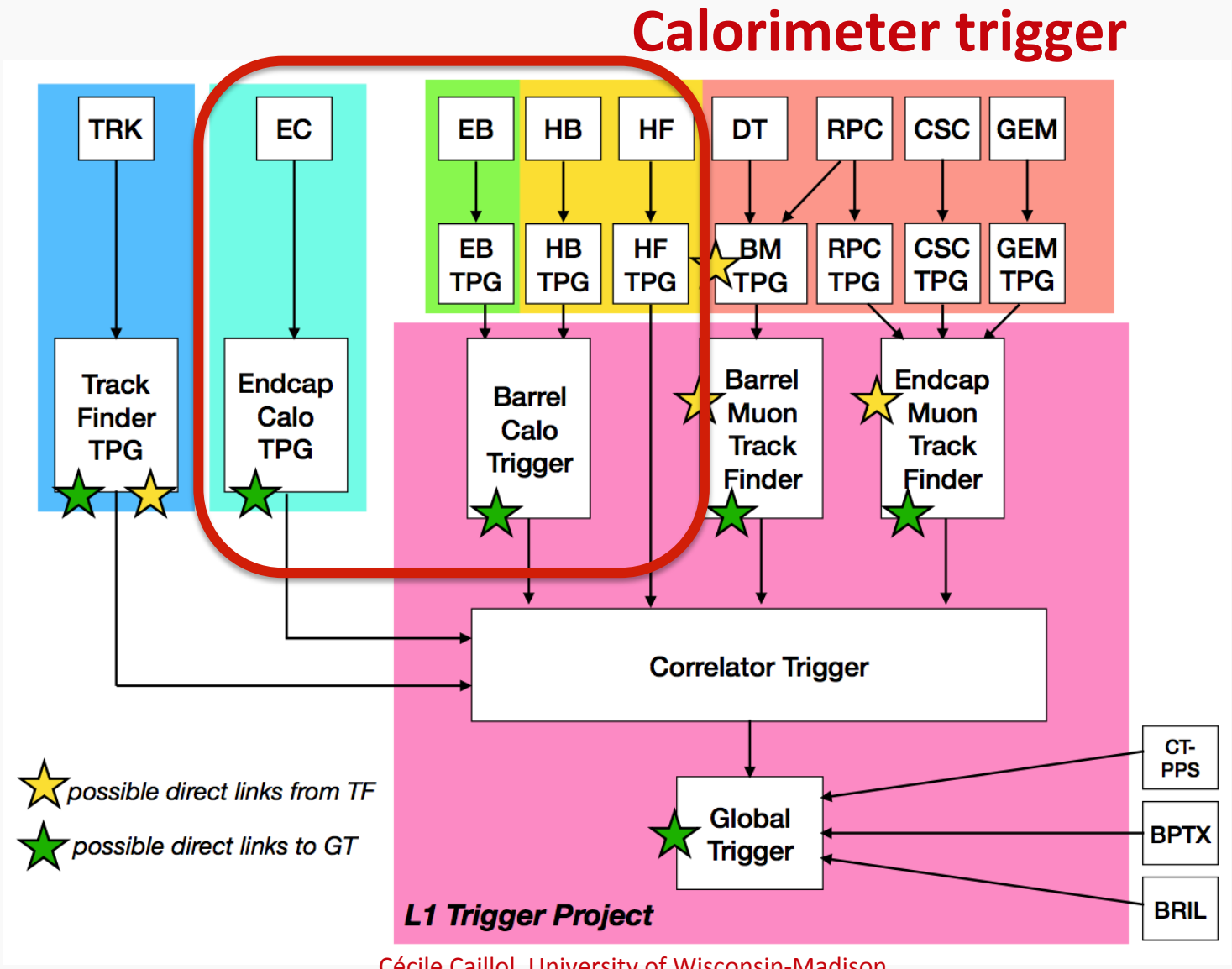
Taus

Jets

Phase-2 L1 overview



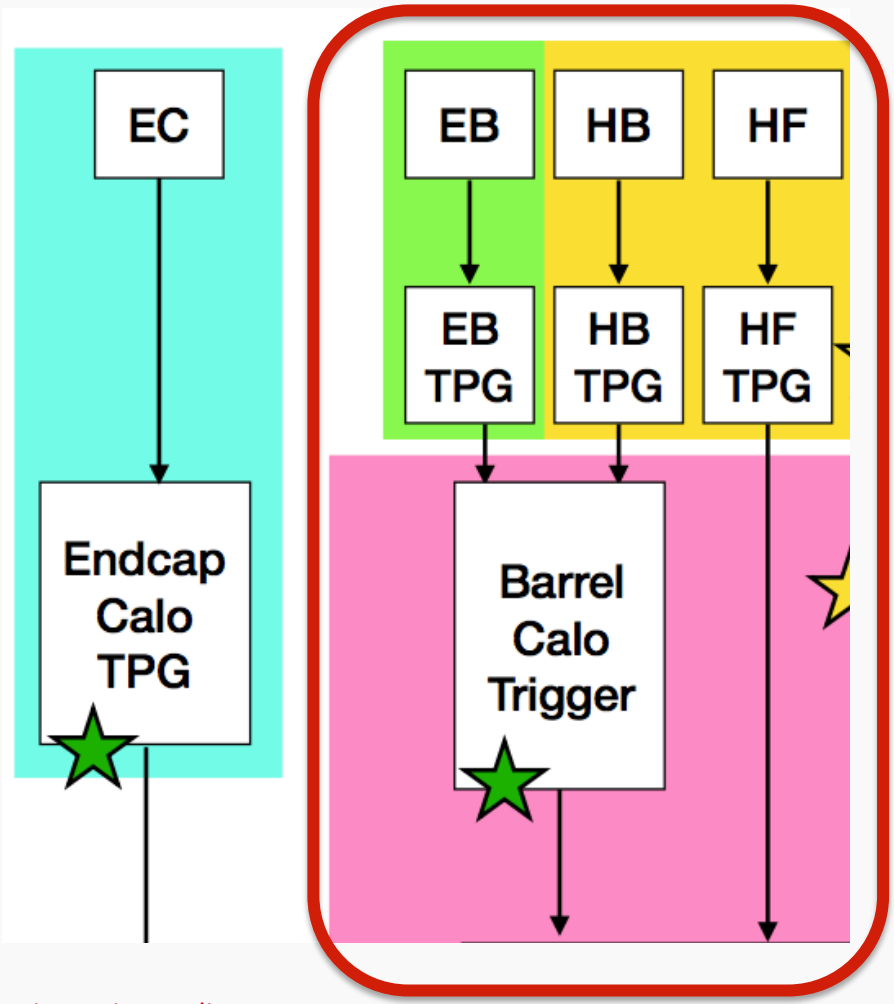
L1 overview


Calorimeter trigger
TRK
EC
EB
HB
HF
DT
RPC
CSC
GEM
EB TPG
HB TPG
HF TPG
BM TPG
RPC TPG
CSC TPG
GEM TPG
Track Finder TPG
Endcap Calo TPG
Barrel Calo Trigger
Barrel Muon Track Finder
Endcap Muon Track Finder
Correlator Trigger
CT-PPS
BPTX
BRIL
Global Trigger
possible direct links from TF
possible direct links to GT
L1 Trigger Project

Calorimeter trigger - Barrel

- Essentially same structure as for phase-1 upgrade
- **ECAL barrel (EB)**: increase of transverse granularity (unit size 25 times smaller than in phase-1)
- **HCAL barrel (HB)**
- **HCAL forward (HF)**

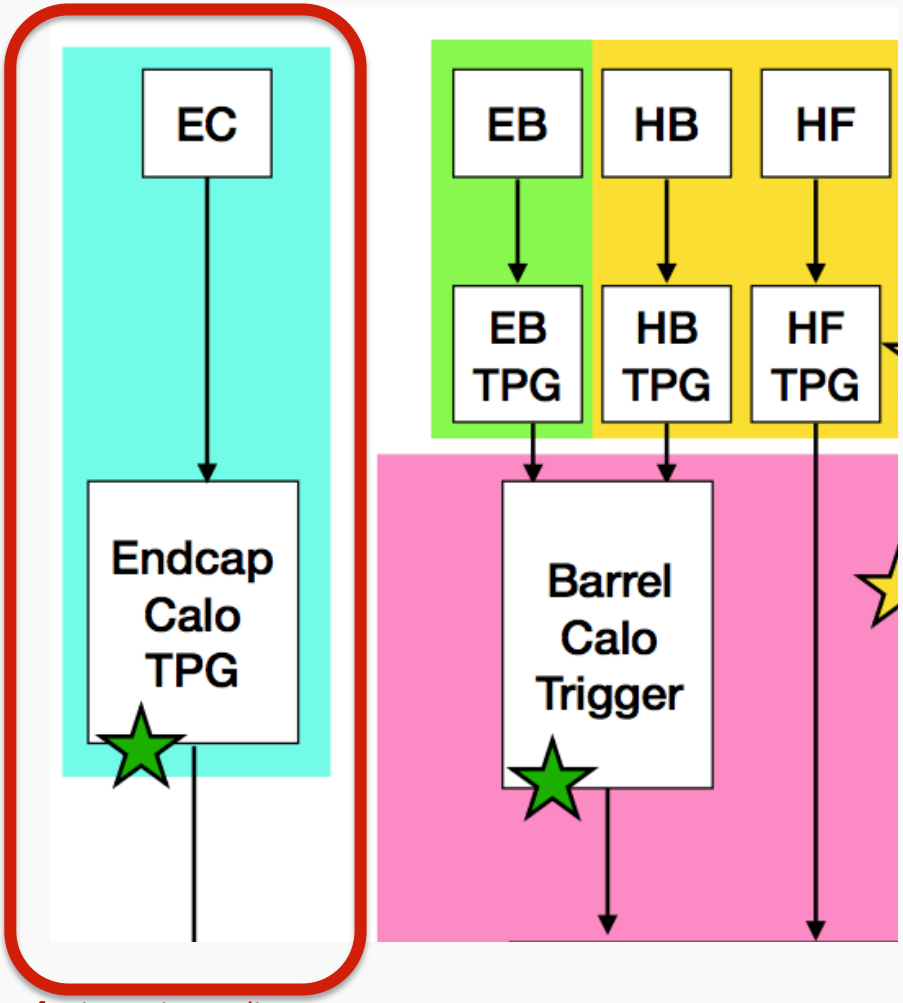
Barrel calorimeter trigger



Calorimeter trigger - Endcap

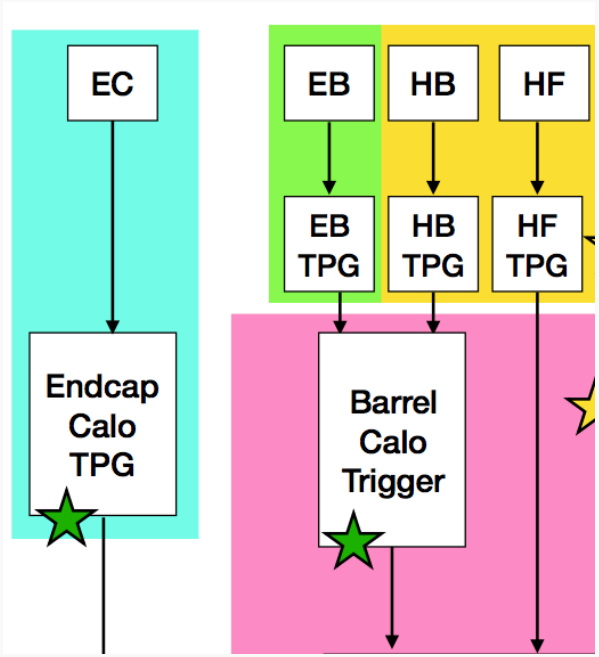
- Completely new 3D structure
- High granularity sampling calorimeter
- Time-multiplexed architecture

Endcap calorimeter trigger



Phase-2 calorimeter trigger

- Tiled multilayer architecture:
  - **Layer-1 (regional)**: Crates assigned to particular regions receive information from different subdetectors
  - **Layer-2 (global)**: The information from the different regions is combined

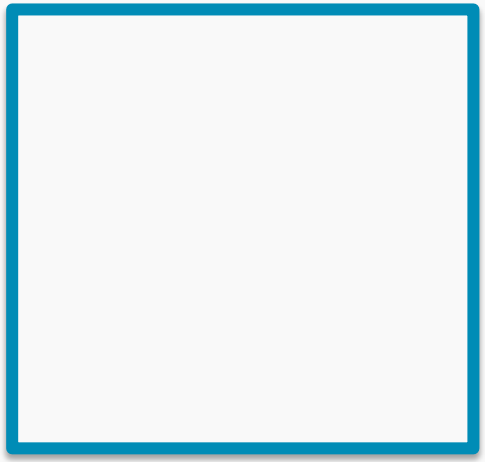


- Xilinx FPGA package C2104 (max 104 optical links)

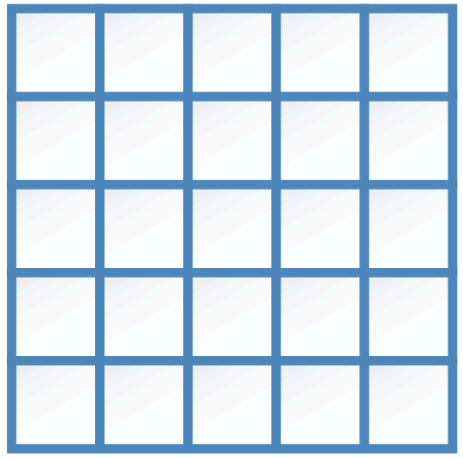
- Calorimeter objects can then be matched to tracks from the track trigger

EB – ECAL barrel

- **Phase-1**: 1 trigger tower with dimension 0.085 x 0.085



- **Phase-2**: the ECAL units are crystals (crystal dimension: 0.0175 x 0.0175), and 5x5 crystals are covered by a front-end card
- Increase of granularity → better position and energy **resolution**, better **shape** distinction between signal and backgrounds, better **matching** to tracks



EB – Trigger primitives

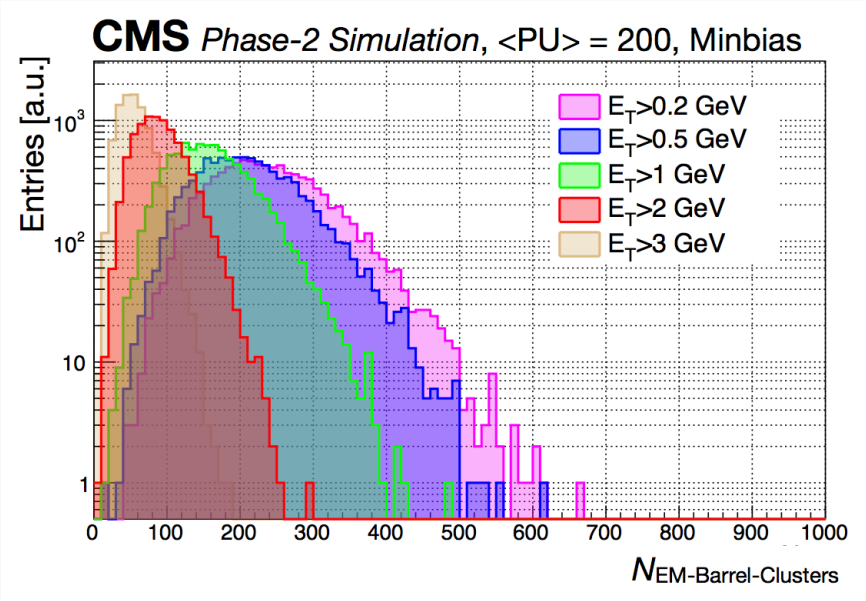
- Two possibilities:
  - Send single crystal information
  - Cluster crystals and send information about clusters
- **Crystal** primitive (baseline):
  - 16 bits: E_T (10), time (5), spike flag (1)
- **Cluster** primitive:
  - Example with 40 bits: Also includes the position of the cluster and the number of crystals in the cluster
- Primitives sent to correlator of global trigger
- Trigger primitive generator entirely located in back-end electronics (for phase-1: on-detector electronics)

Quantity	N bits
E_T	10
Time	5
Spike flag	1
Total	16

Quantity	N bits
E_T	10
Time	5
η	8
ϕ	8
$N_{crystal}$	8
Spike flag	1
Total	40

EB – Cluster primitive

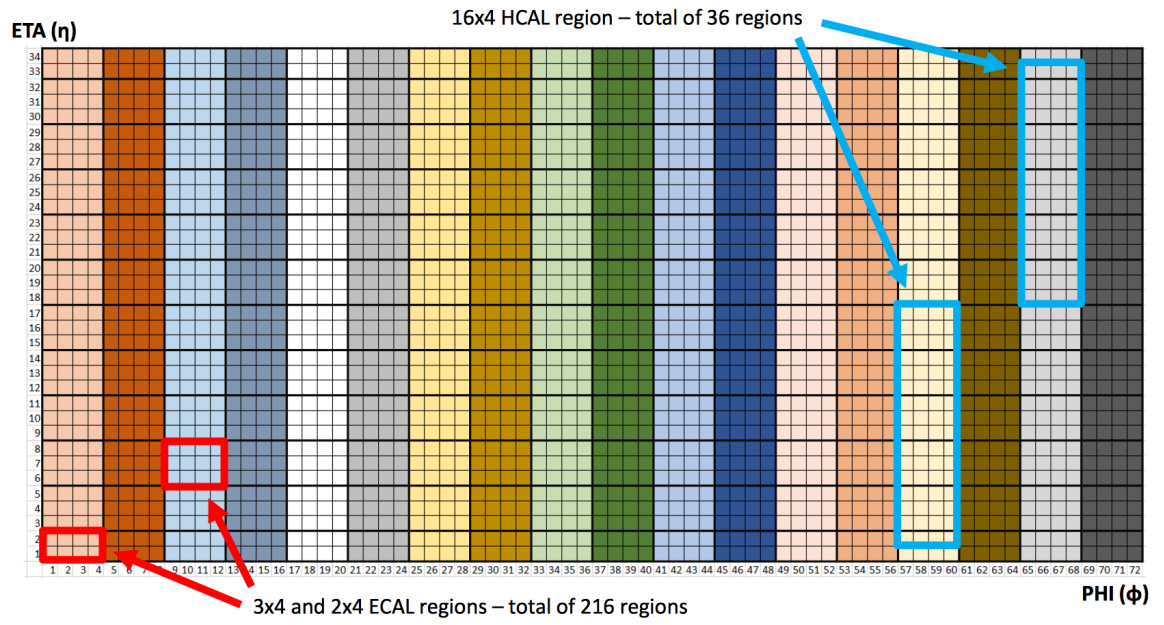
- Not the preferred solution, only if processing or bandwidth becomes constrained
- Capacity to transmit of order 1000 clusters per bunch to limit truncation effects to 10^{-4} (for PU = 200)



- A 16-bit word that sums the crystal energy within a region of 25 × 25 crystals should be sent to account for unclustered energy.

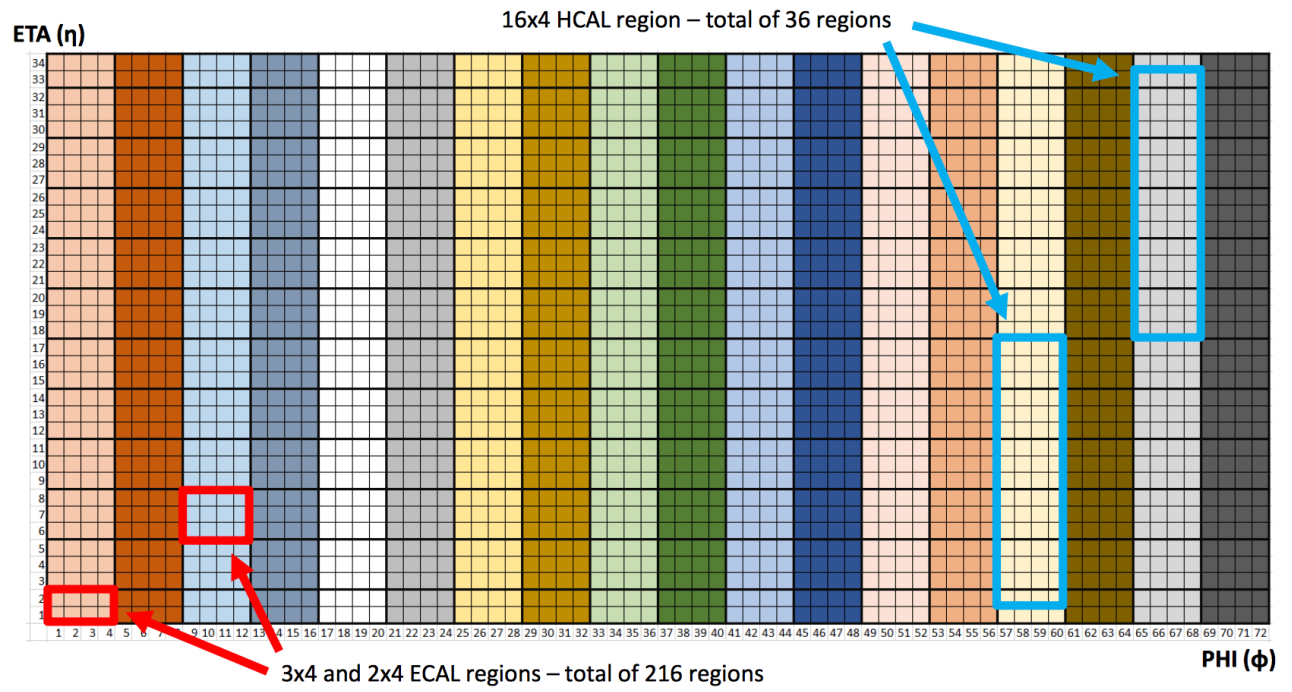
EB – Region definition

- Each front-end card collects data from a 5 × 5 array of crystals at 160 MHz
- 12 such cards send data to a single back end-card, via 48 upstream links and 12 downstream links
- Each back-end card covers 300 crystals ($\eta \times \varphi = 0.26 \times 0.35$)
- 216 back-end cards (in 18 crates) cover the ECAL barrel



Hadron Barrel (HB)

- Back-end divided in 16η x 4ϕ regions and tower level energies are sent out with 16Gbps links at 16bit/tower.
- Total of **36 regions**, each processed by a single FPGA.



Hadron Barrel (HB)

- Back-end divided in 16η x 4ϕ regions and tower level energies are sent out with 16Gbps links at 16bit/tower.
- Total of **36 regions**, each processed by a single FPGA.

- Same hardware as developed for EB

- The Phase-2 upgrade of the HB calorimeter replaces the back-end electronics, and partially replaces a few front layer scintillator tiles

Hadron forward (HF)

- The HF detector will continue to operate with the Phase-1 front-end and back-end electronics.

- Phase-1 HB and HE back-end cards will be reused to increase HF back-end to sustain the rates expected in phase-2

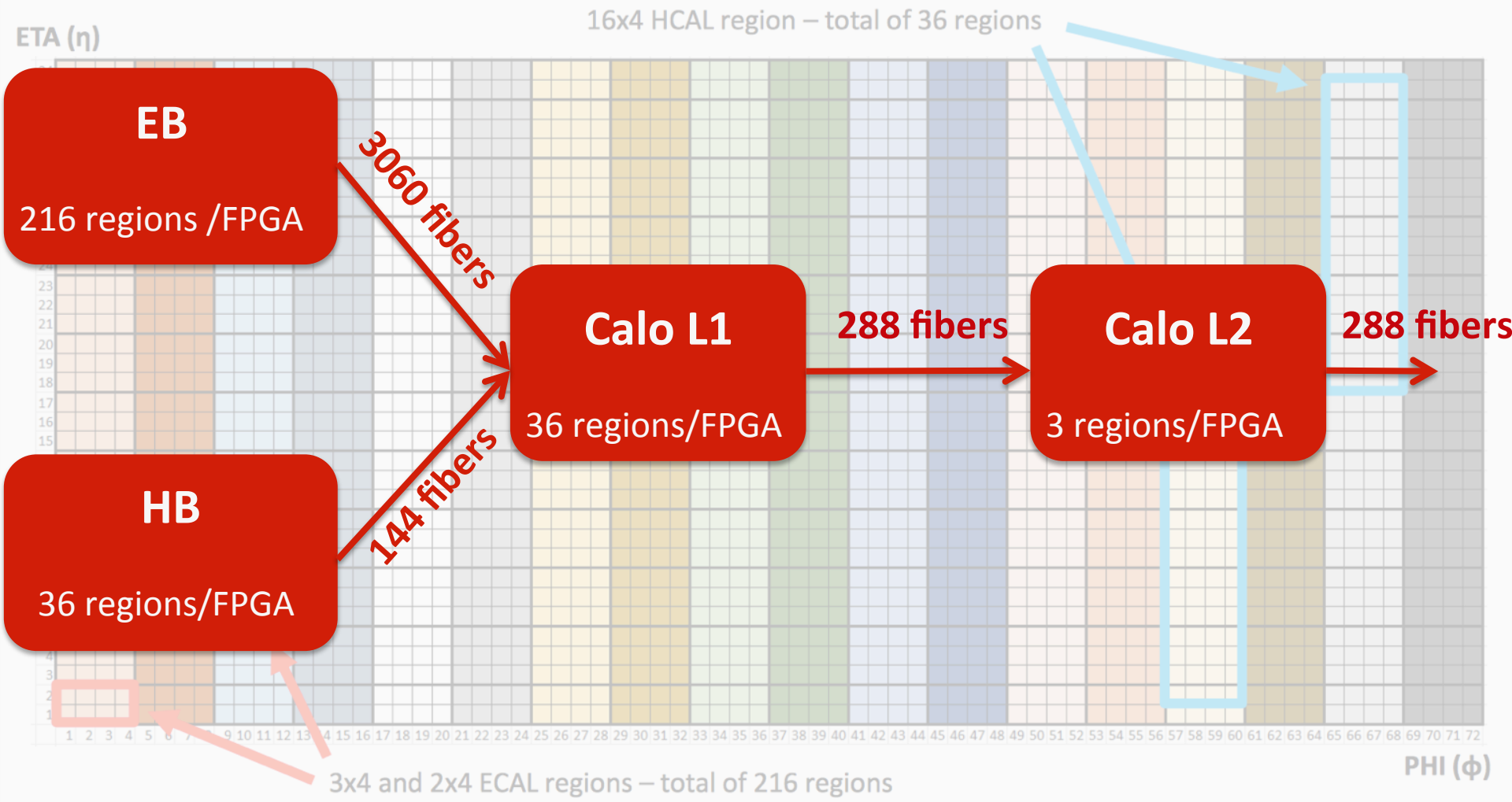
HB and HF – Trigger primitive

- HB units are trigger towers of 0.0875 x 0.0875 (25 times bigger than the EB units)

- HB trigger primitives correspond to these trigger towers, with 16 bits

Quantity	N bits (HB)	N bits (HF)
E_T	10	8
Feature bits	6	2
Total	16	10

Recap - Barrel calorimeter layout



High-granularity endcap calorimeter (EC)

- Completely new high granularity sampling calorimeter, using silicon and scintillators as sensitive elements
- 52 sensitive layers (28 in ECAL and 24 in HCAL)
- Trigger cells correspond to 4 cm^2 in the silicon regions
- 3D high granularity makes PF algorithm possible at L1
- Dimensions of the trigger towers: 0.0875 x 0.0875, same as in the barrel

EC – Trigger primitives

1. Form 2D clusters from trigger cells in a single layer, and sum tower data into a single η, φ grid
2. Combine the 2D clusters in depth to form 3D clusters, and combine all the single-layer tower map data with an appropriate weighting into the complete transverse energy tower map.

- The completed tower maps and 3D clusters form the ECT primitives that are transmitted to the L1 trigger.

- Time-multiplexing to transfer all the 2D clusters and tower maps for a single bunch crossing into one FPGA, feasible in 4µs

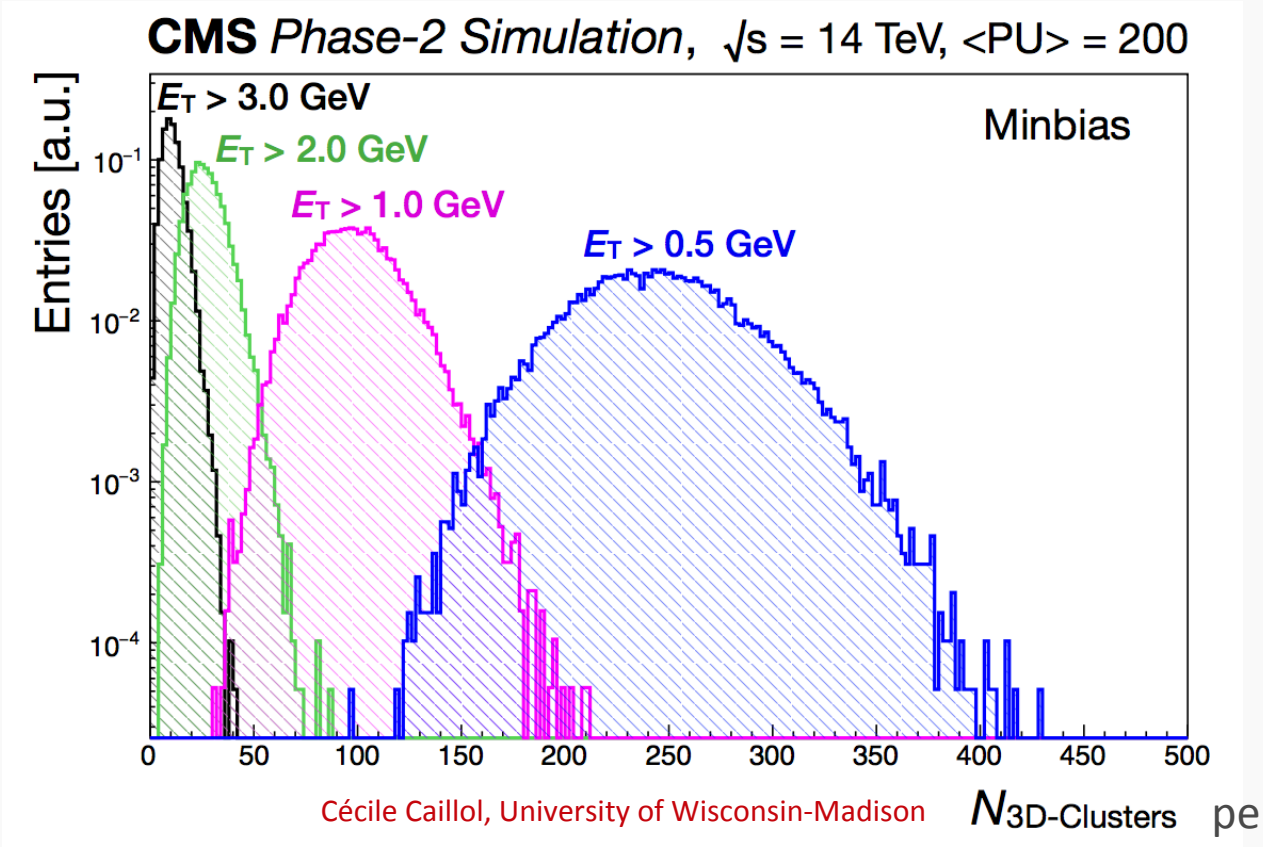
EC – Trigger pimitives

- Typical size of a 3D cluster should be around 200 bits (minimum 128 bits)

Quantity	N bits	Comment
E_T	2×16	with and without PU subtraction
Endcap	1	
f_{EE}	13	E_T fraction in EE
f_{BH}	12	E_T fraction in BH
L_{max}	6	Max energy layer
η	11	Shower start
ϕ	11	Shower start
z	10	Shower start
N_{cells}	8	
Quality	12	
Extra flags	12	
Minimum total	128	

EC – Trigger primitives

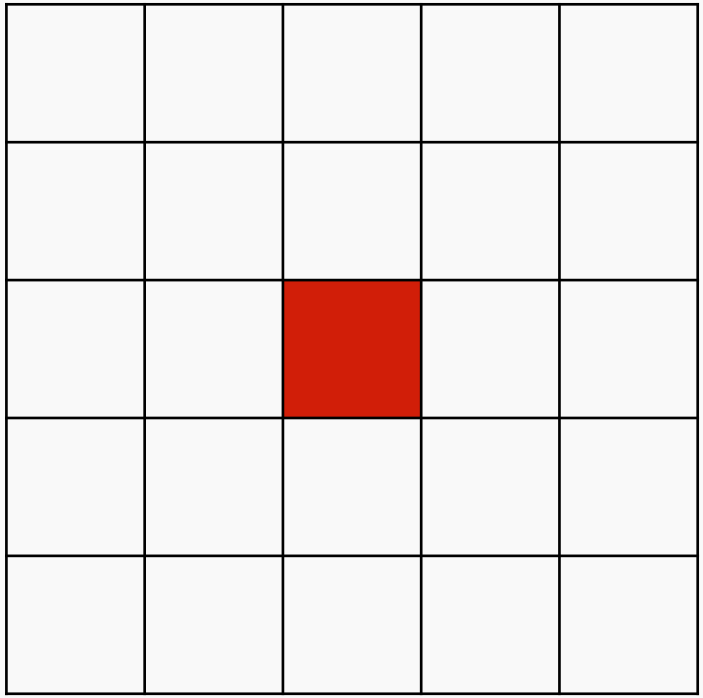
- E_T threshold needed to reduce bandwidth
- Threshold such that clusters can be matched to tracks (2-3 GeV) → ~1 GeV
- Bandwidth of 80 kb per bunch crossing, corresponding to 200 clusters per endcap, needed for this threshold



Trigger algorithm – Electron example

- Algorithm developed for EB
- Electron identification at L1 strongly based on calorimeter trigger
- Rate reduced by matching calo objects to tracks

Seed crystal with E_T > 1 GeV



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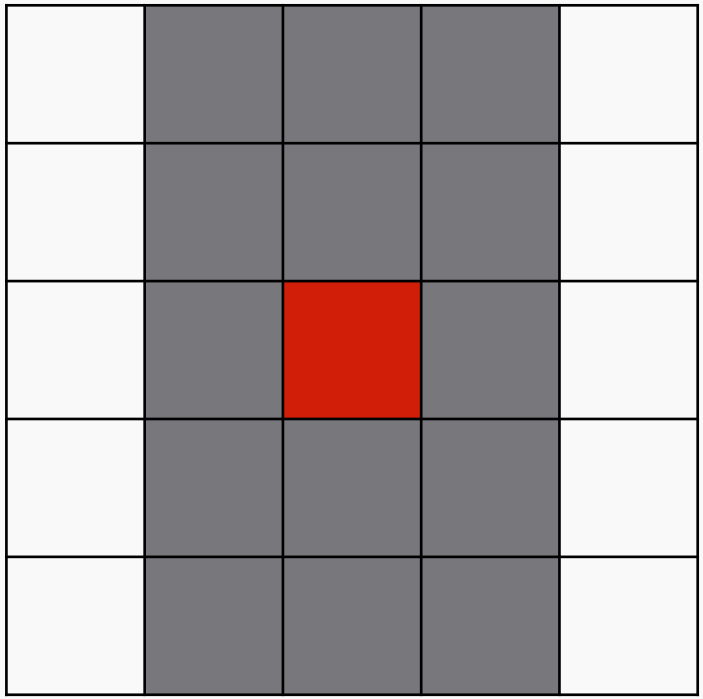
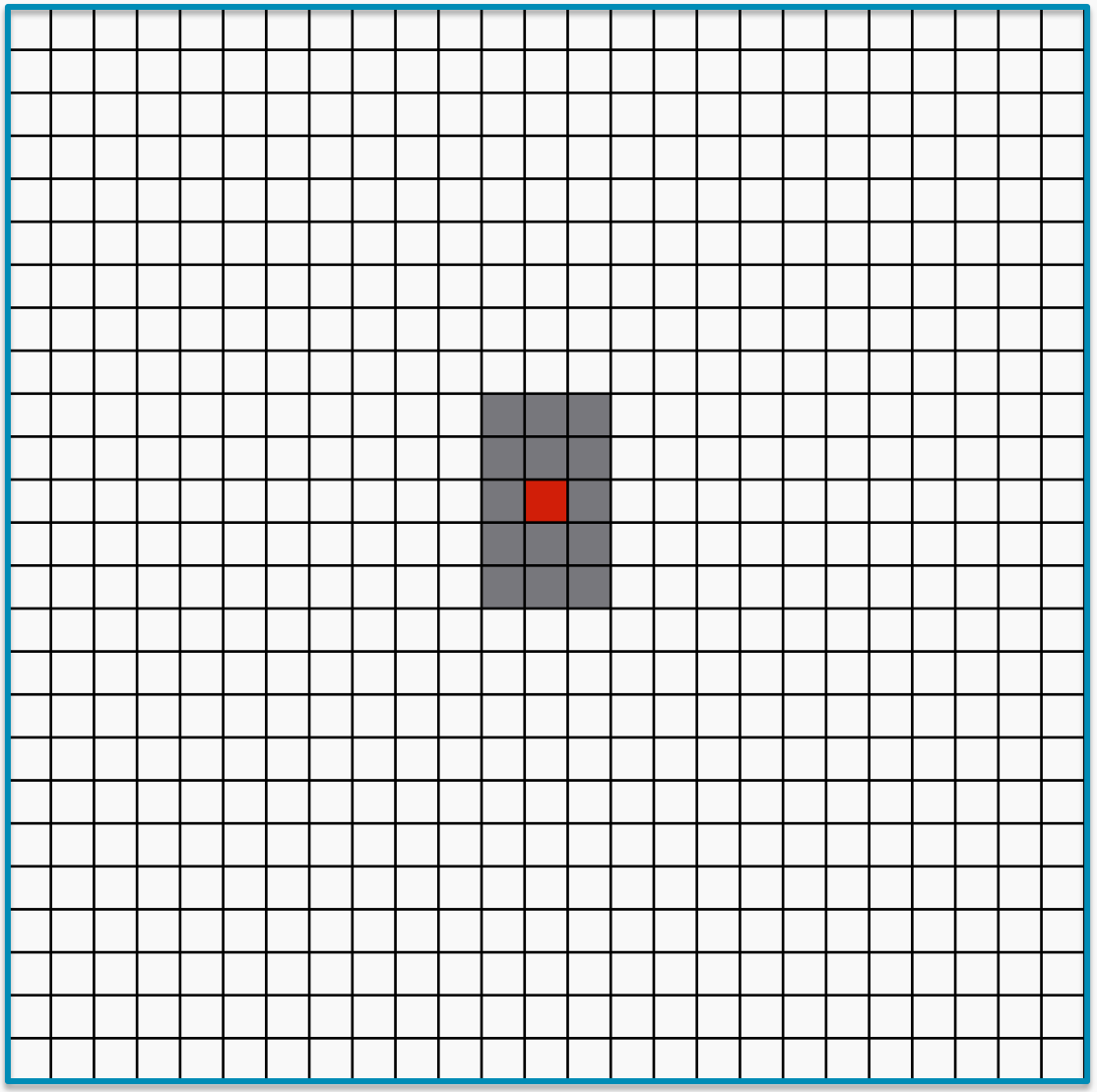


Cluster energy in 3x5 crystals around the seed

Position of the cluster determined from energy-weighted crystals

Electron algorithm

- Discriminating variables against jets:
  - Relative isolation: Energy in cluster / energy in 27 x 27



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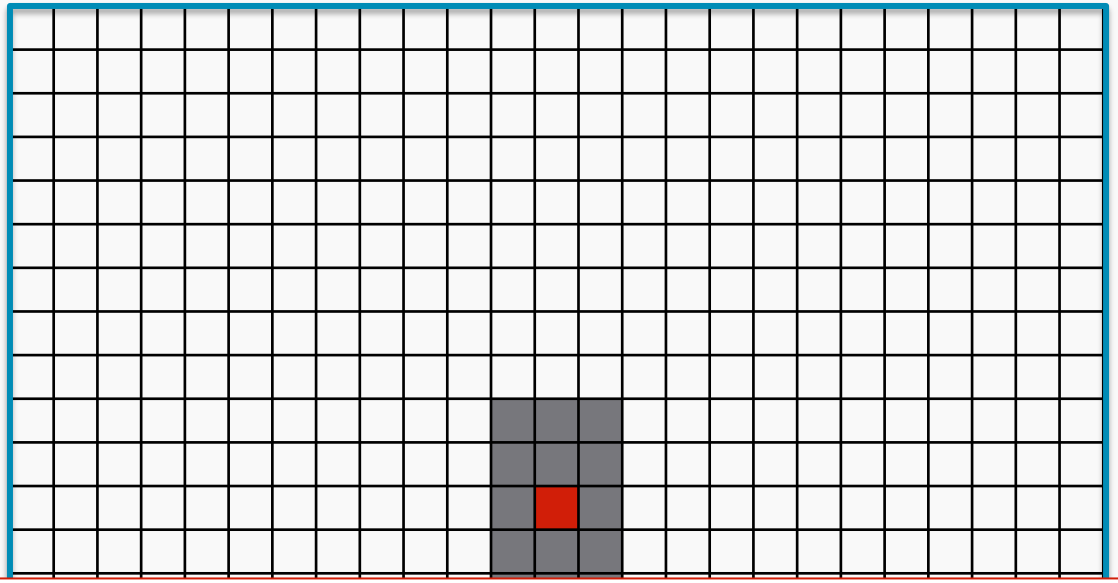
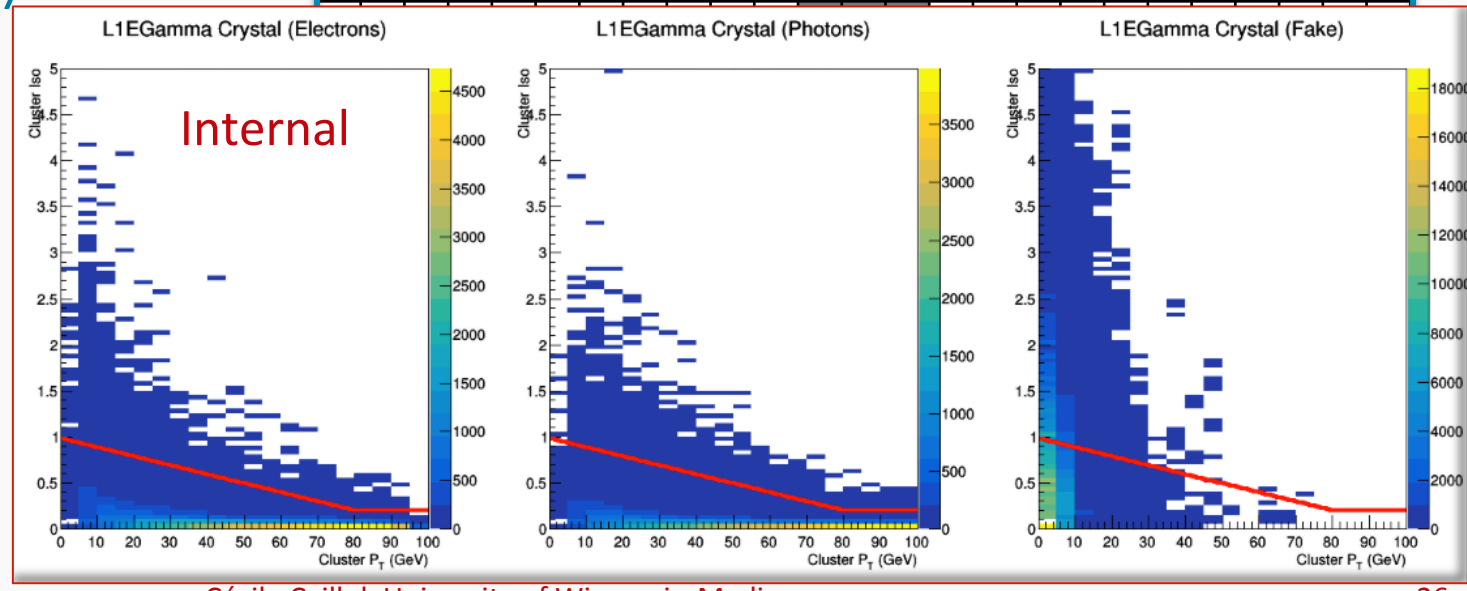
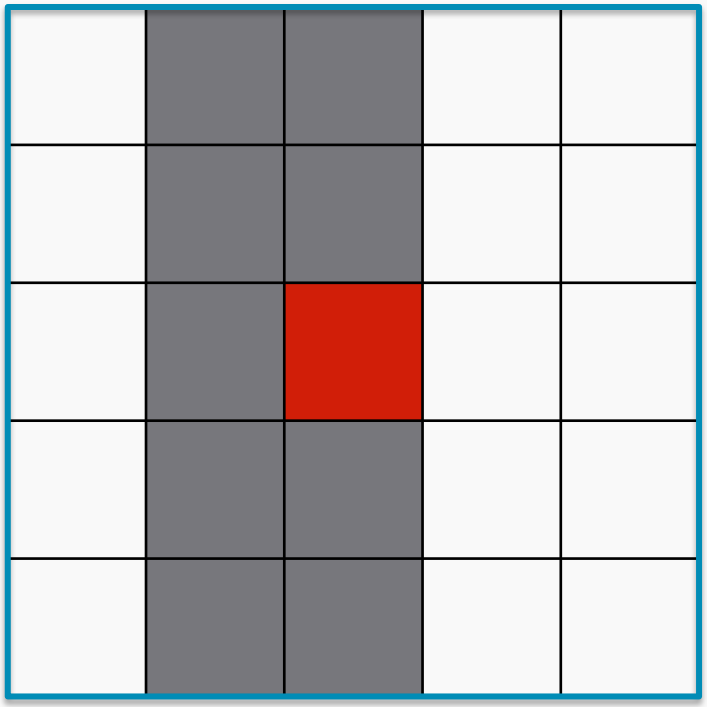




Electron algorithm

- Discriminating variables against jets:
  - Relative isolation
  - **Shower shape:**
    Max energy in 2x5 / Energy in 5x5



Electron algorithm

Internal

- Discrim
  variables a
  jets:
  - Relative
  - **Shower shape:**
    Max energy in
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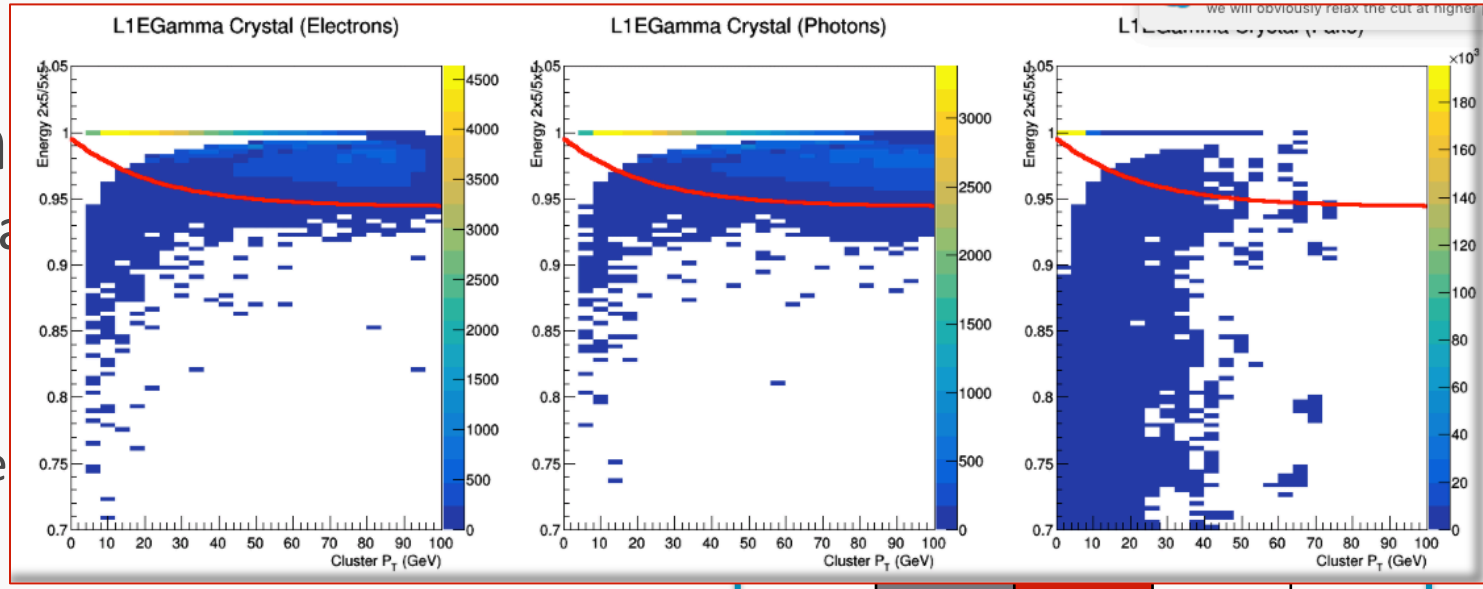
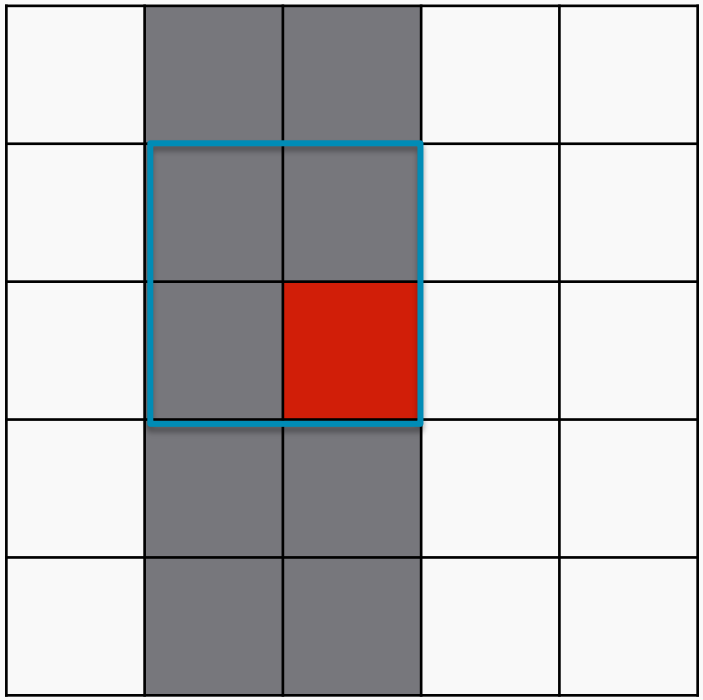


Photon algorithm

- Additional shape variable:
  - Photon shower shape (max energy in 2x2 / max energy in 2x5)



Photon algorithm

- Additional shape variable:
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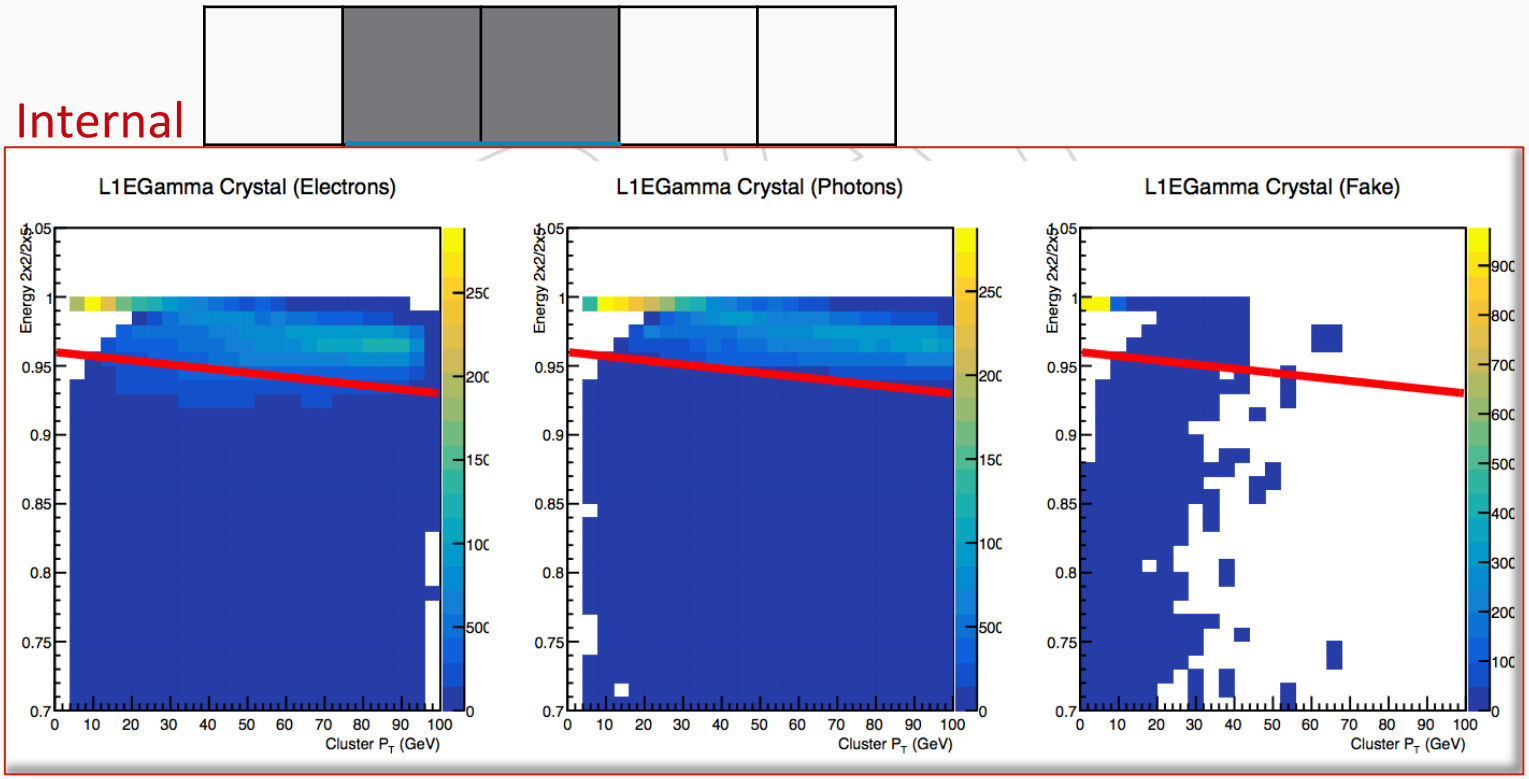
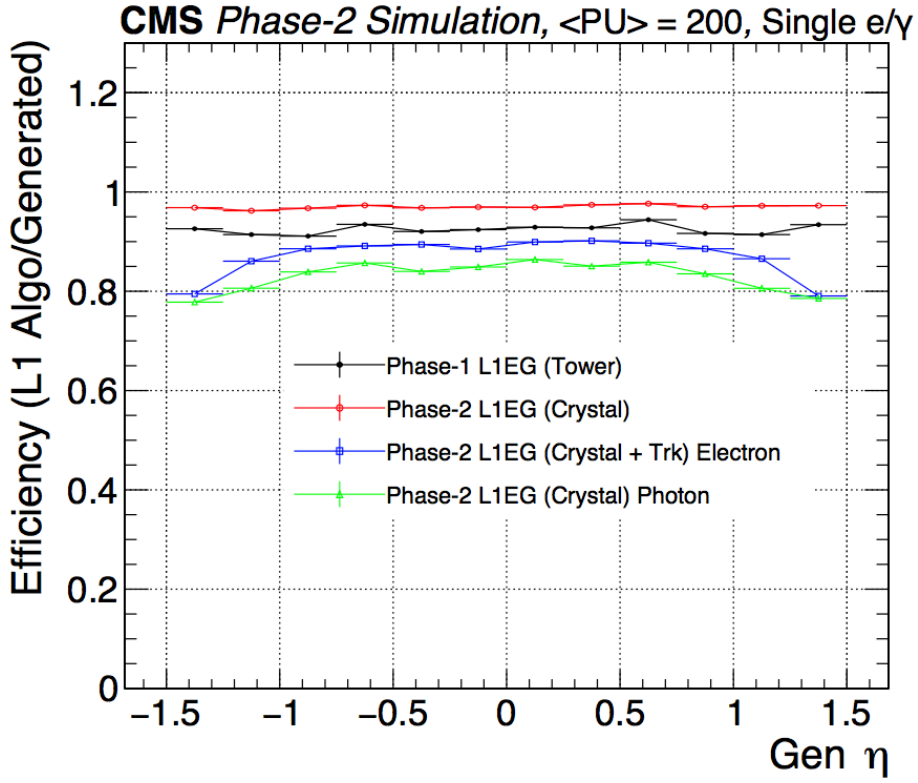
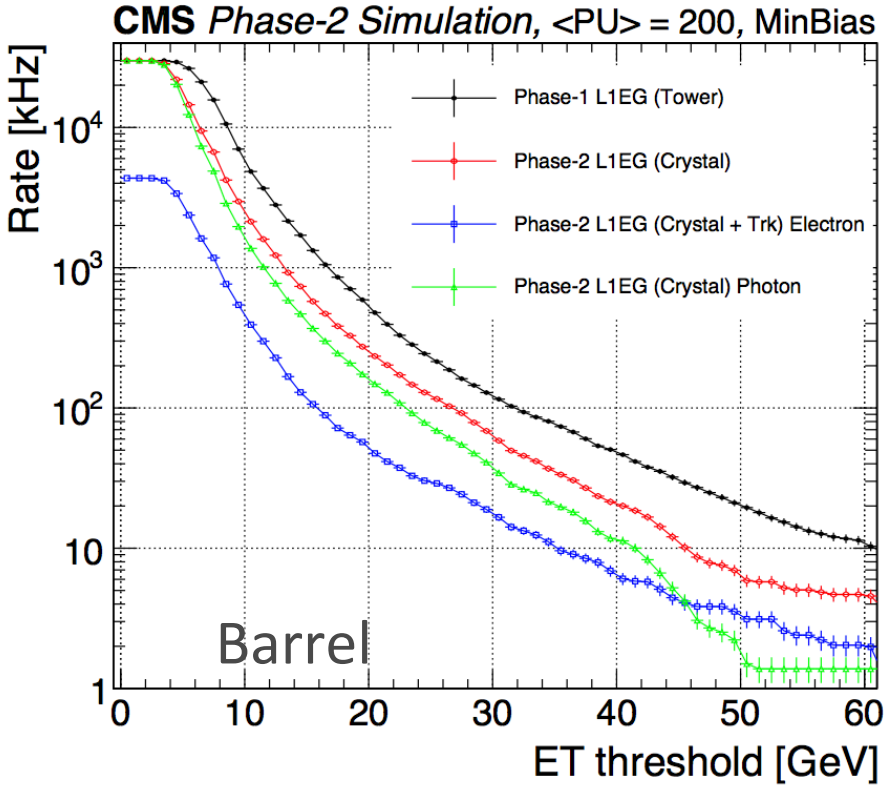
Internal



Electron algorithm

- Phase-2 calo-based only algorithm performs better than phase-1 because of higher granularity
- Matching the objects to tracks can further reduce the rate by an order of magnitude





Conclusion and prospects

- Geometry and trigger primitives defined for phase-2 calorimeter trigger
- Algorithms for specific objects developed to check performance
- Hardware R&D on the way:
  - Virtex-7 µTCA and ATCA cards
  - Embedded Linux
  - High level synthesis (HLS) coding