The next step in real time data processing for large scale experiments

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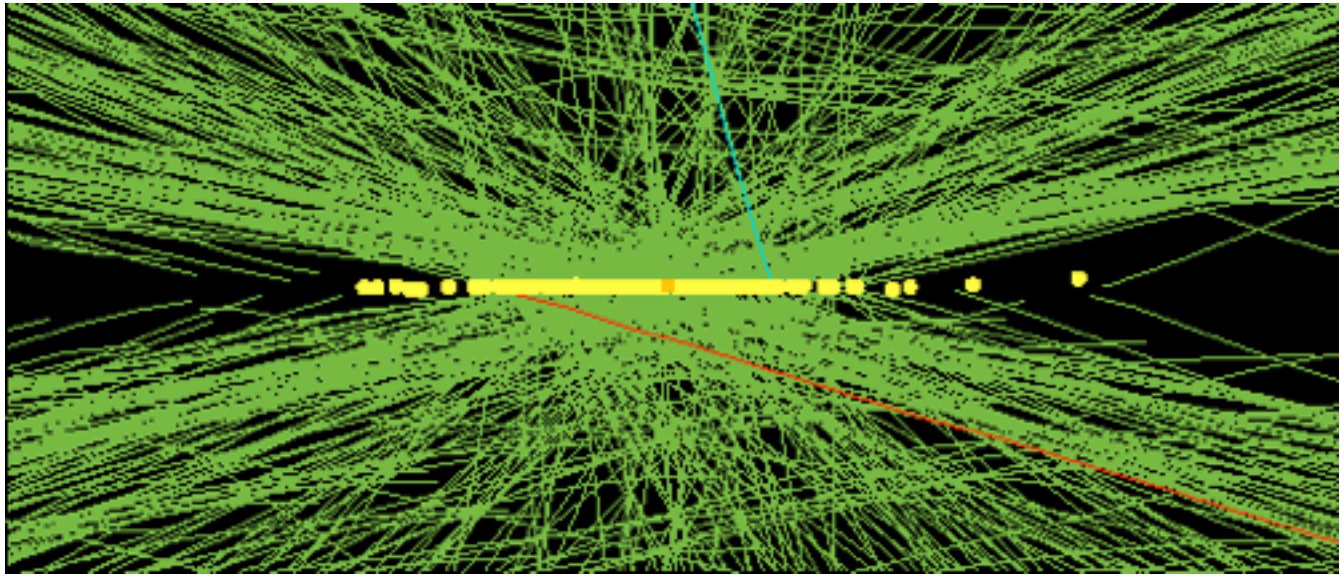
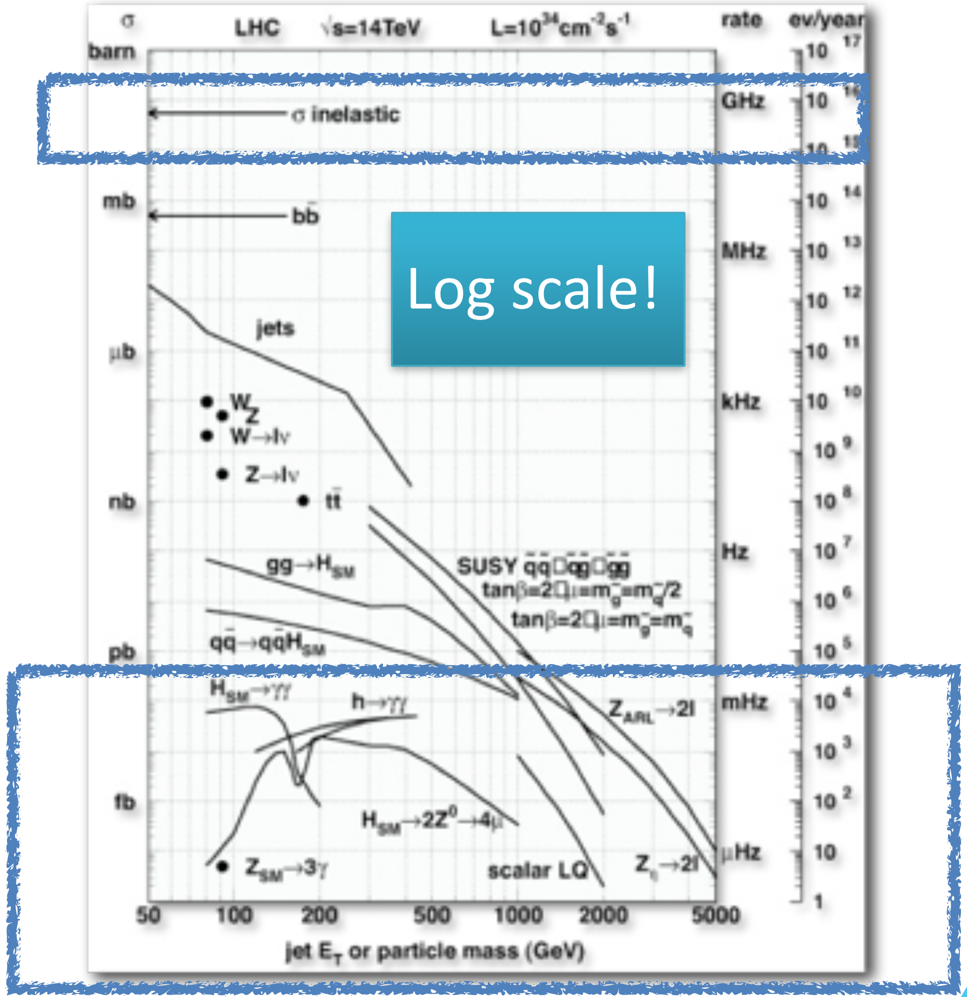
OUTLINE

/LHC @ CERN/

LHC is colliding protons at 13 TeV with peak crossing rate of 40 MHz

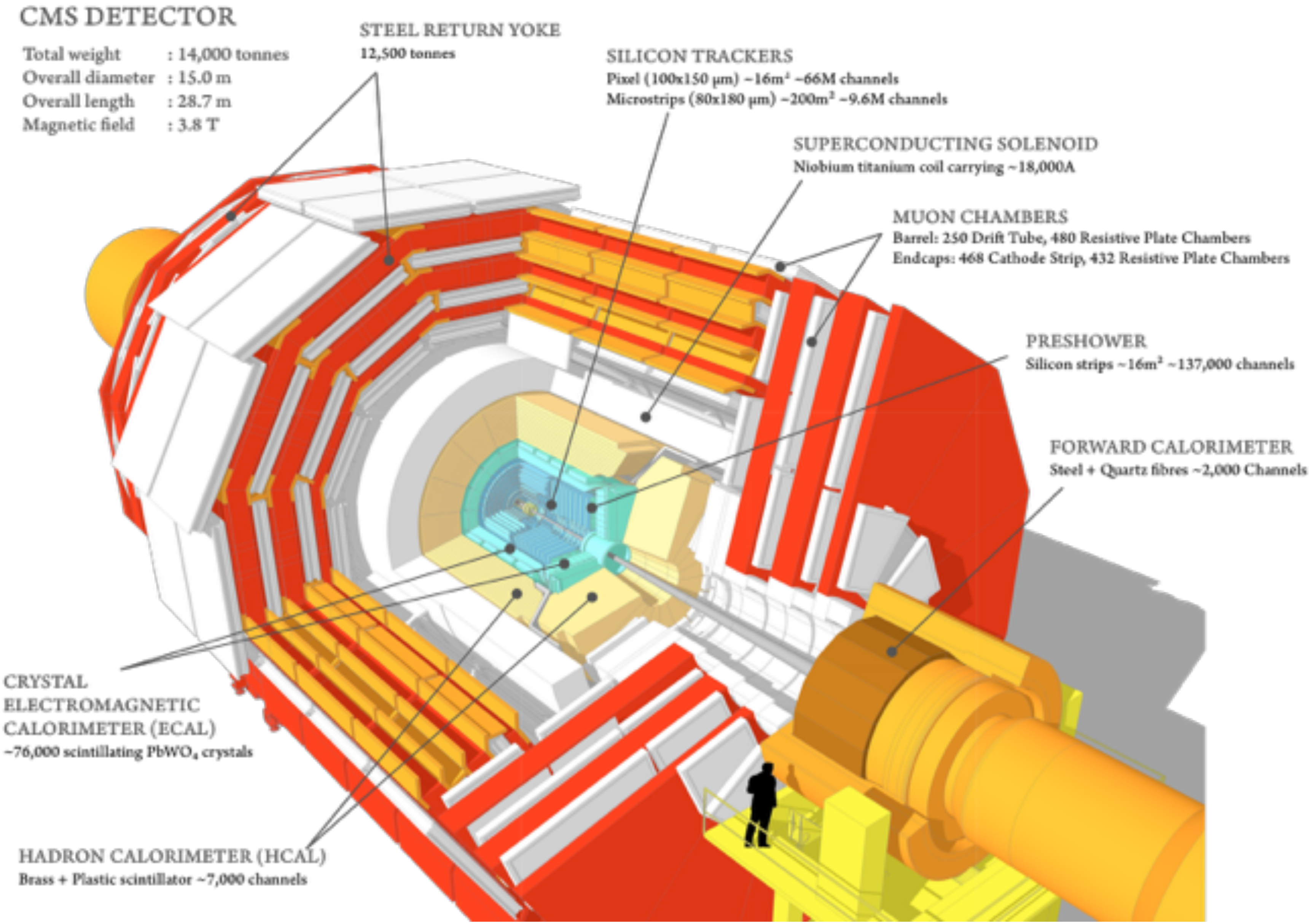


Multiple interactions per crossing (Pile-Up) also presents a significant challenge in identifying primary vertices of interest.

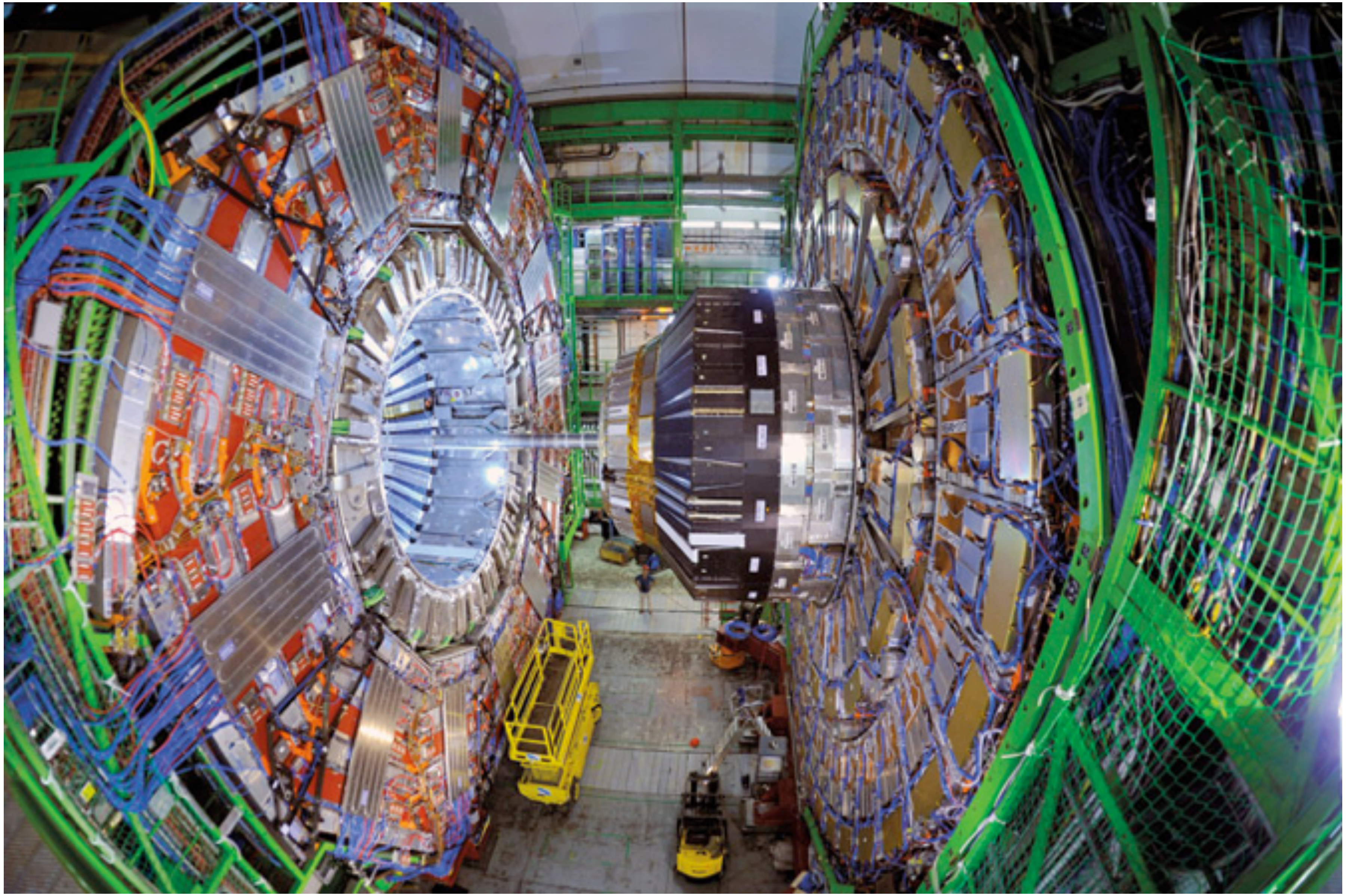


"Interesting" Physics signatures are rare!

/CMS/


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

/CMS/



Problem:

Peak crossing rate of 40MHz is much too high for us to record the data from every collisions. Bandwidth is much too high. (Nor would we want to)

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Peak crossing rate of 40MHz is much too high for us to record the data from every collisions. (Nor would we want to)

Solution:

Only record the measurements for a <u>subset</u> of observed interactions i.e record "interesting Physics only"

Easier said than done….

Basic requirements of Trigger systems

1 Real time processing

The trigger system has to decide in a very short space of time (us) whether to keep the event or discard it. It has to take a ‘quick look’ and then make a decision.

2 High rejection factor

Can conceivably store O(1000Hz) of data, so need to able to discard 10e5 events.

3 High efficiency for interesting events

Must be able to design algorithms that identify specific interesting signatures

4 Flexibility

Physics needs might evolve,and LHC conditions could change - so must be able to make changes relatively easily.

If you are not recording the interesting events, you could miss discoveries!

Basic requirements of Trigger systems

1 Real time processing

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4 **Flexibility**

Physics needs might evolve,and LHC conditions could change - so must be able to make changes relatively easily.

on the Trigger!
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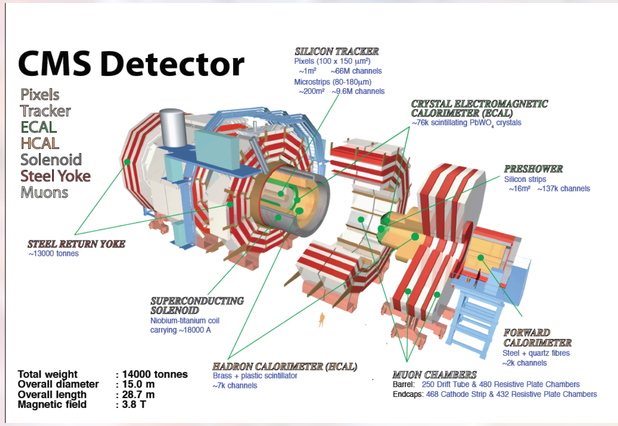
LHC IS A DISCOVERY MACHINE, DONT ALWAYS KNOW WHAT SIGNAL YOU ARE LOOKIN FOR!!!

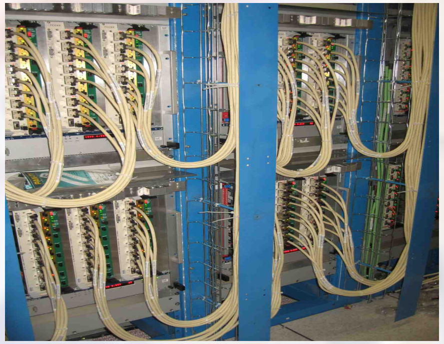
How is this achieved? Example:CMS Calorimeter Trigger

Detector information



Bunch crossing Input : 40 MHz

Level 1 Trigger - Electronics processing boards (FPGAs/ ASICS etc)



L1 Trigger 100kHz

Computing farm - 100s of CPUs

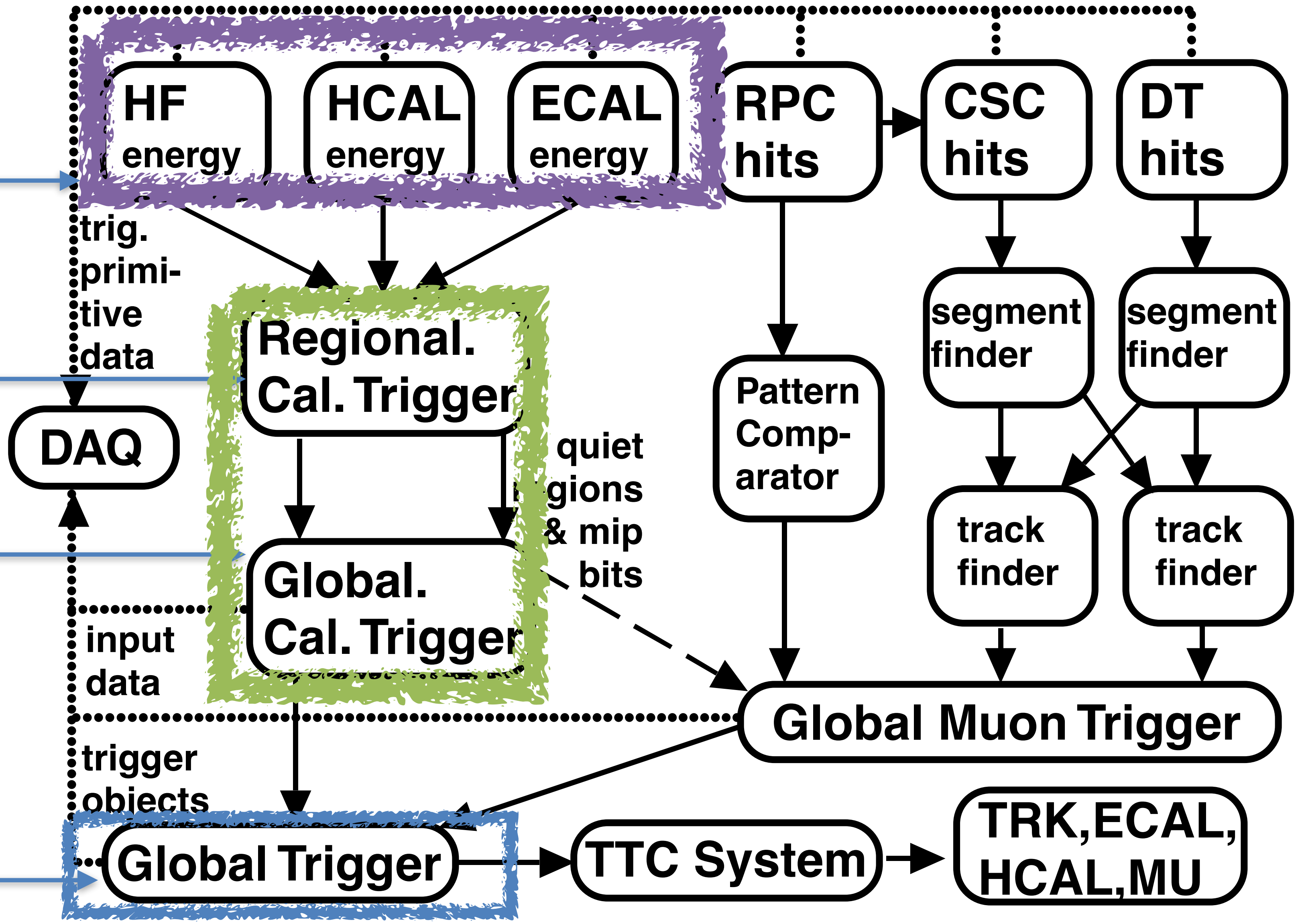
High Level Trigger Output: 300Hz

Original CMS L1 Trigger

Detector information

Calorimeter Trigger

Final decision



Original CMS L1 Calo Trigger

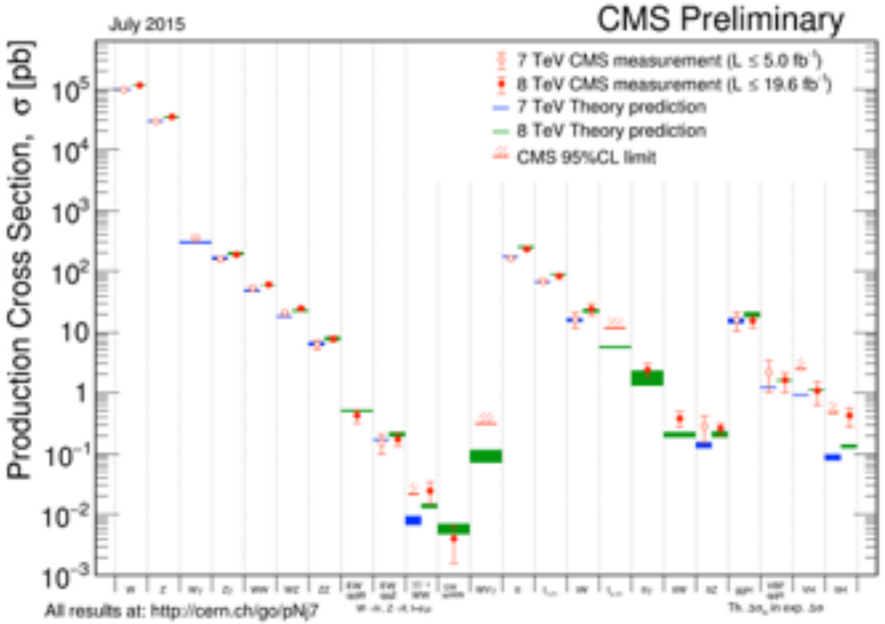
- Driven by technology…
- ASICs - fixed algorithms,
- early FPGA’s - space limitations
- Parallel copper links
- Hard to move data around…

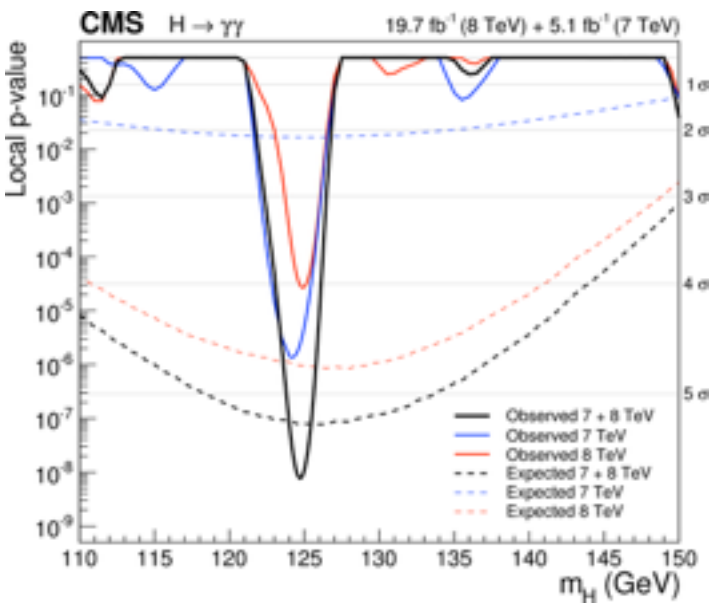
Key numbers:

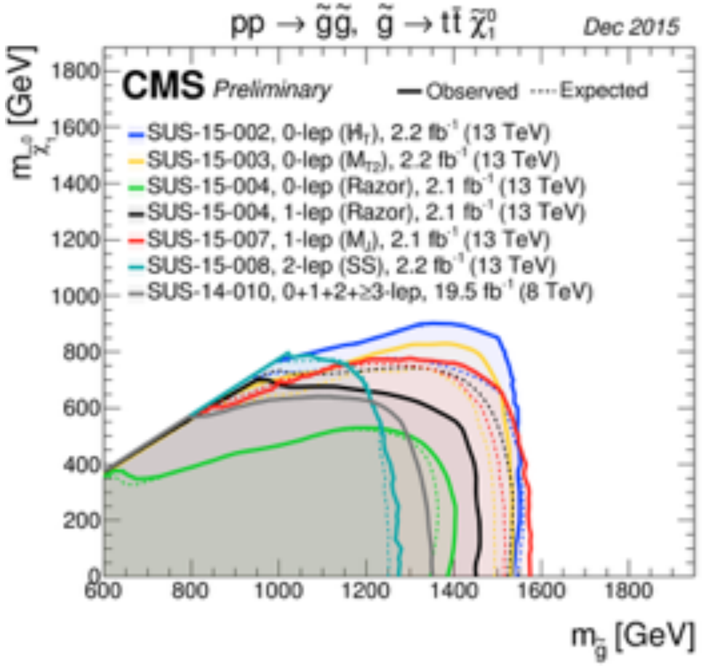
- 100KHz hard limit - maximum rate of recording events for next stage
- 3.2 micro seconds - maximum time before decision has to be made (front-end buffer size)

Original CMS Trigger

Performed extremely well!







Standard Model **Higgs** **Supersymmetry searches**

And many many more!!!

http://cms-results.web.cern.ch/cms-results/public-results/publications/

But Run 2 of the LHC presents new challenges…

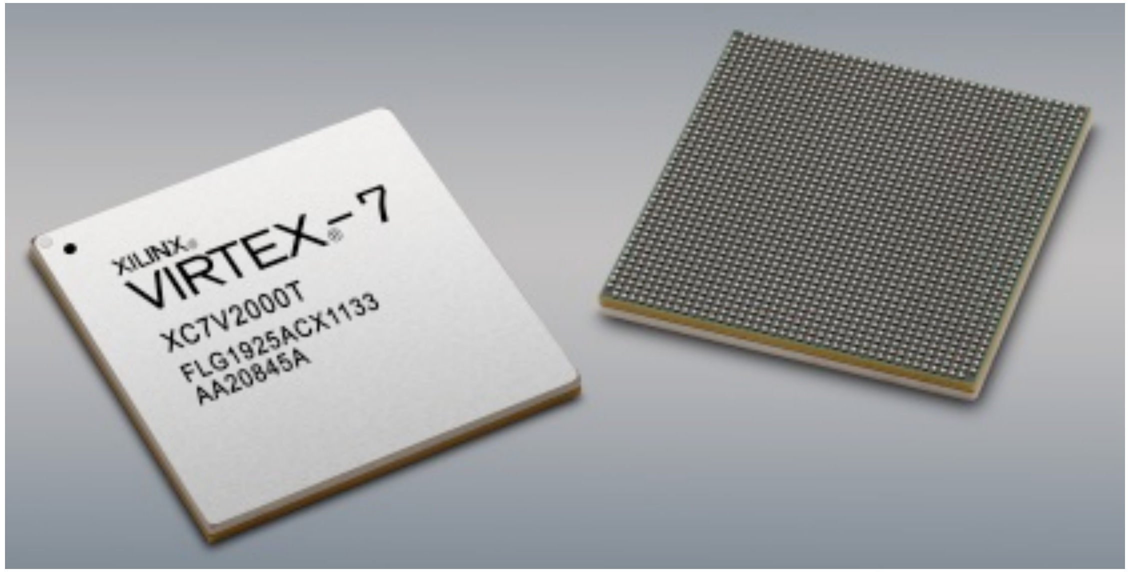
New LHC challenges

Luminosity to increase by up to x8
Energy to go from 8 TeV to 13 TeV
Multiple interactions per beam crossing to go up x2

CMS has a maximum first level acceptance rate of 100KHz…have to work within this number.
With the above LHC improvements, interesting physics events will be harder to separate from non-interesting ones….unless we upgrade!

Technology

- uTCA - modular open standard
- Uses Advanced Mezzanine Cards (AMCs)
- Commercially available
- Small form factor

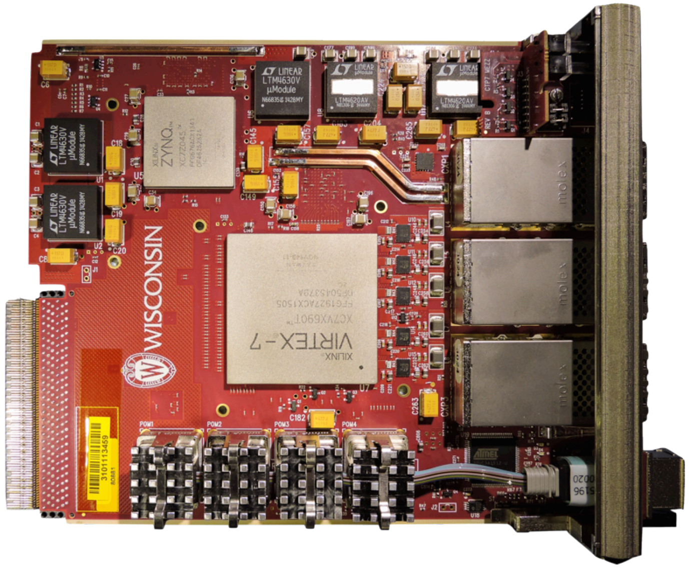


- Up to 2m logical cells
- Up to 2.8 Tb/s total serial bandwidth
- Up to 70% lower power

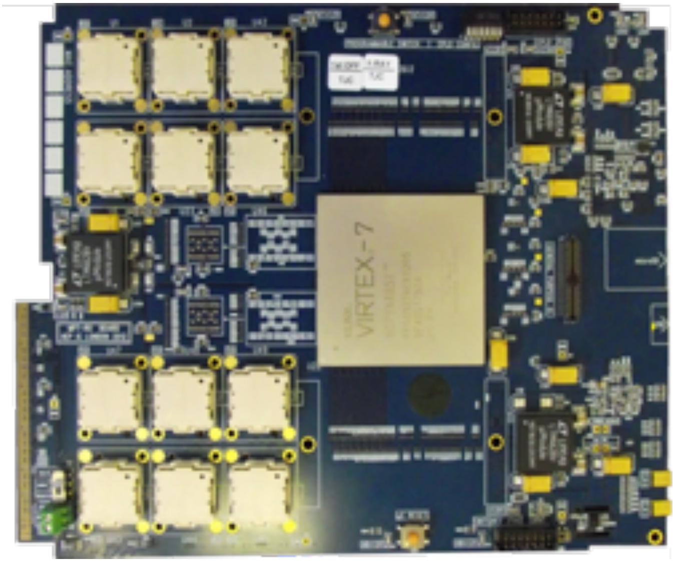
Drives us to think of ways to use this technology to do better

Trigger Hardware

- CTP7
- uTCA form factor
- Single Vertex 7 FPGA
- 67 optical inputs, 48 outputs
- ZYNQ processor running XiLinx PetaLinux for service tasks



- MP7
- uTCA form factor
- Single Vertex 7 FPGA
- 72 optical inputs, 72 outputs
- Dual 72 or 144MB QDR RAM clocked at 500 MHz



Fundamental design underwent a rethink…

Time-Multiplexed Trigger

What if we try and use one chip/board to process the WHOLE detector?

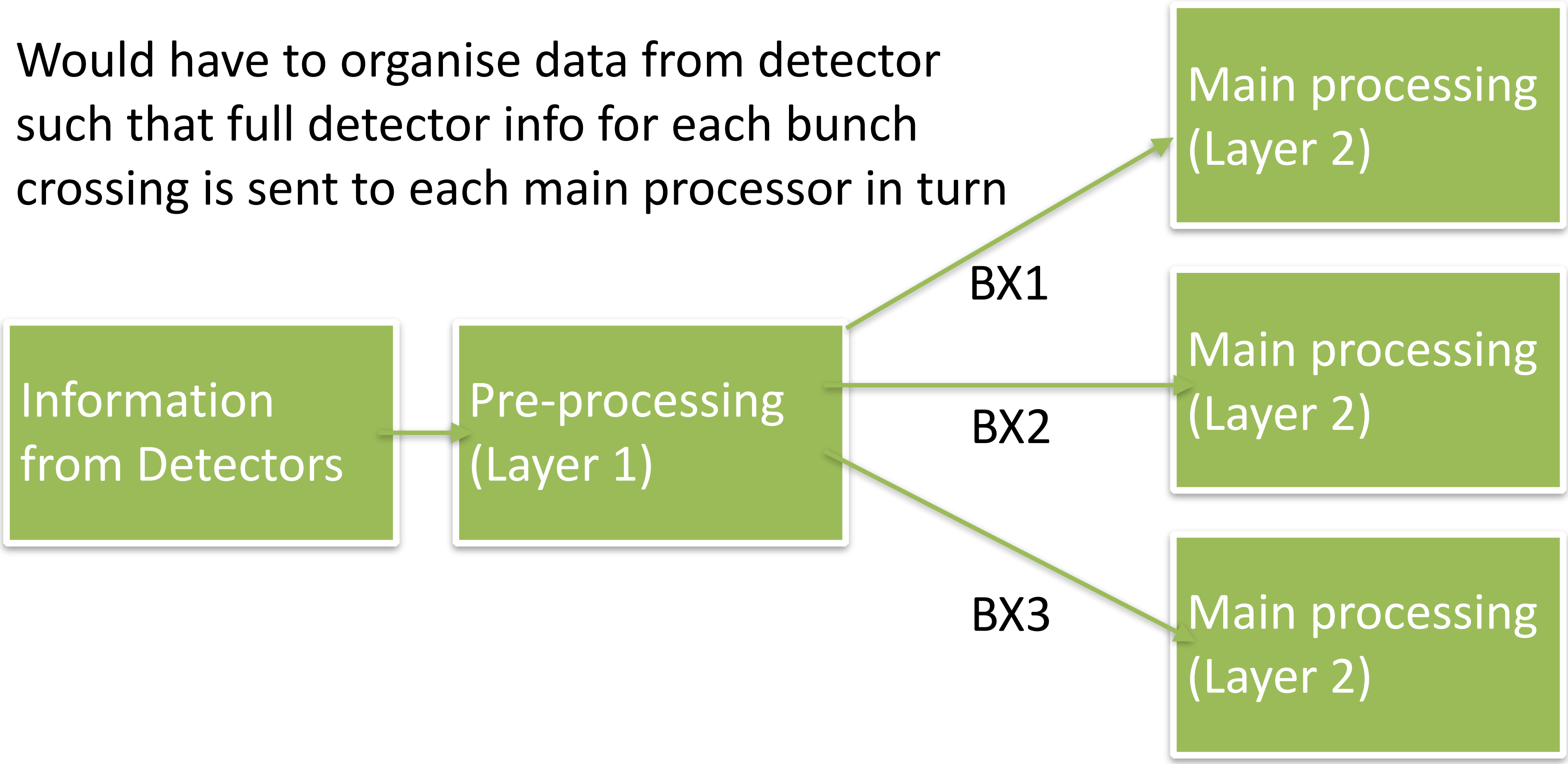
- No overlap/boundary between boards to consider
- Each board would be identical, containing full suite of algorithms
- Each board would have access to full information on event
- Could rotate through boards sequentially.

Would need to make use of latest generation of FPGA’s and optical links in order to achieve best performance. Larger space of new FPGAs enables full suite of improved algorithms to be placed into one chip.

Time-Multiplexed Trigger

What if we try and use one chip/board to process the WHOLE detector?

Would have to organise data from detector such that full detector info for each bunch crossing is sent to each main processor in turn



Time-Multiplexed Trigger

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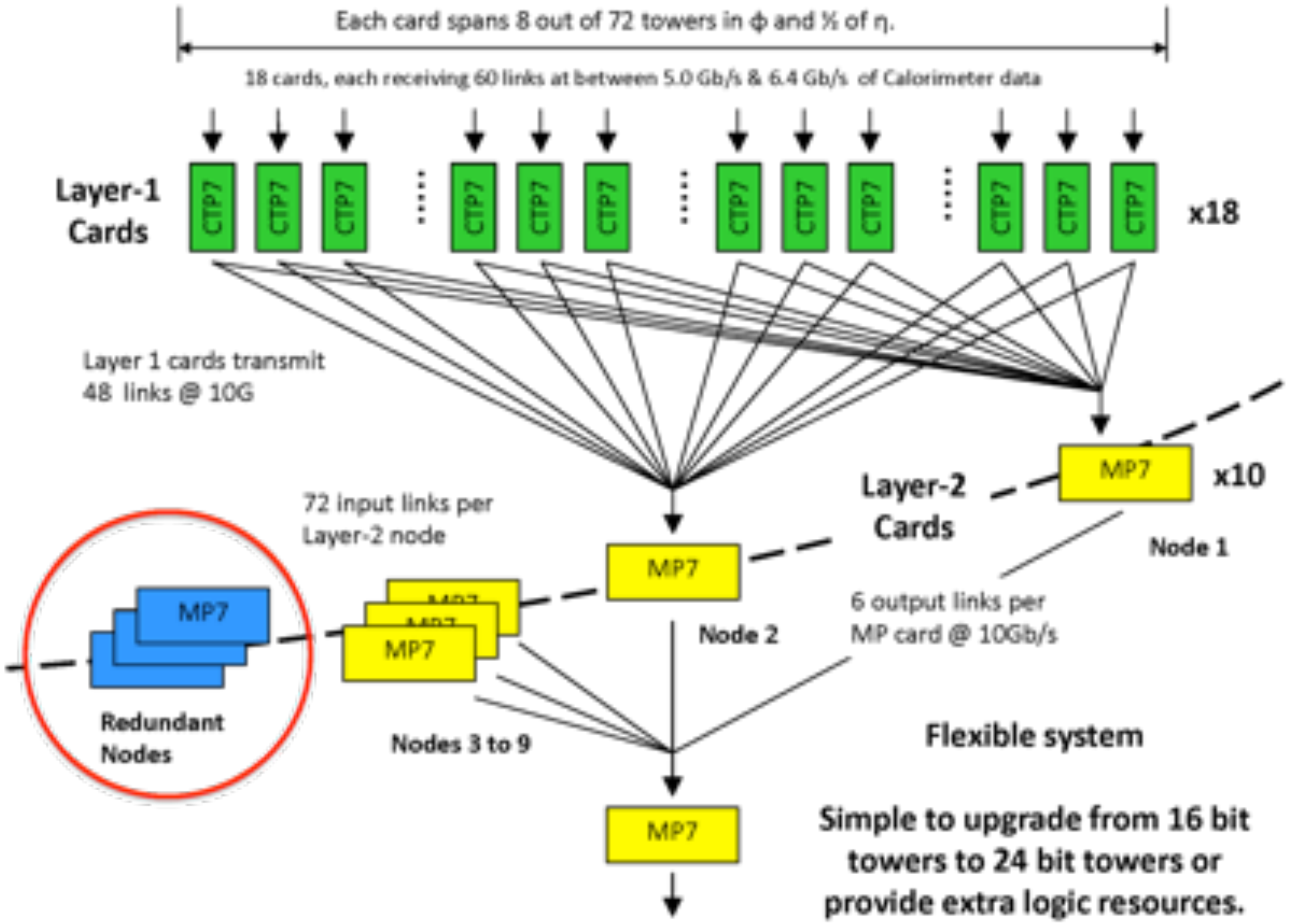
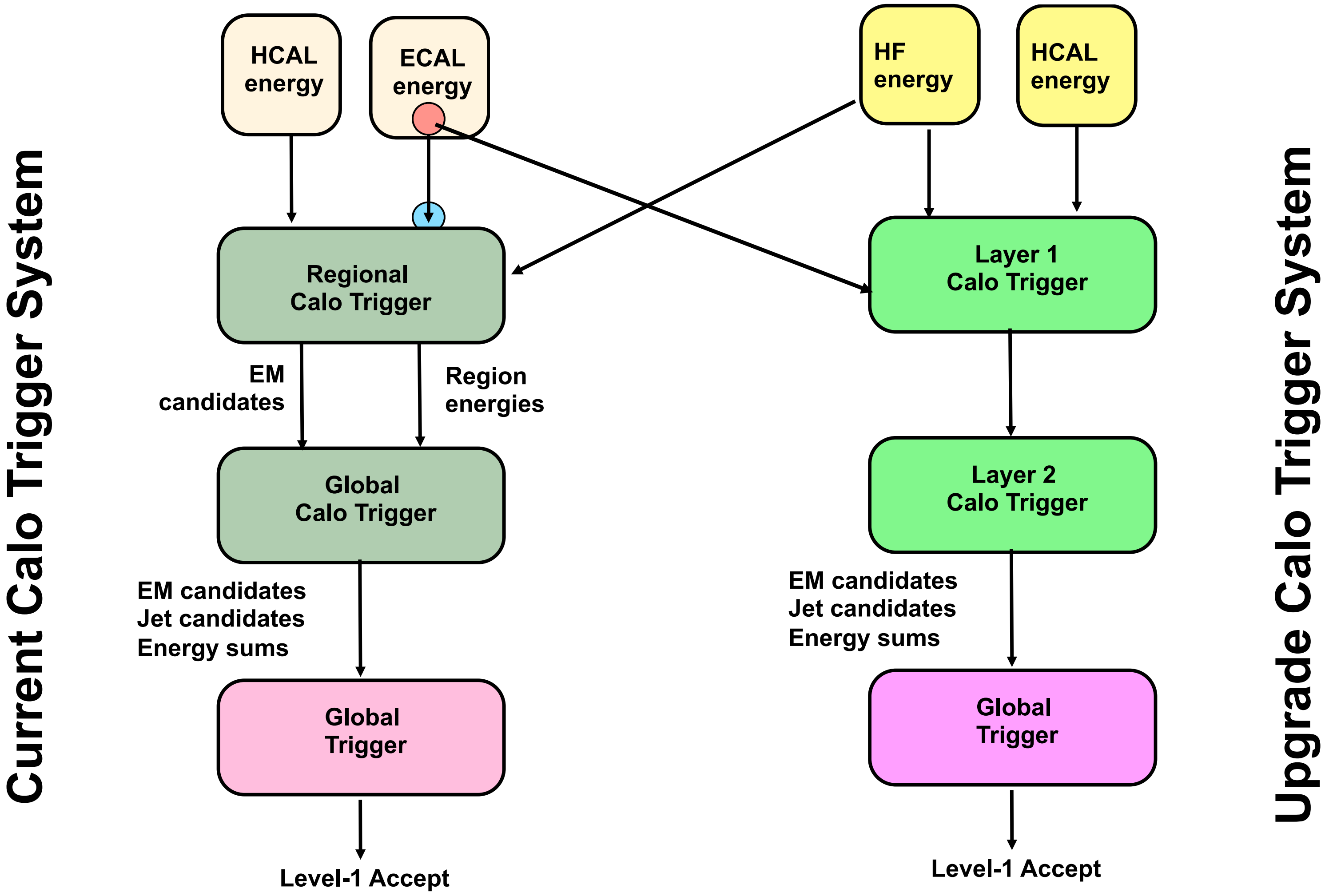
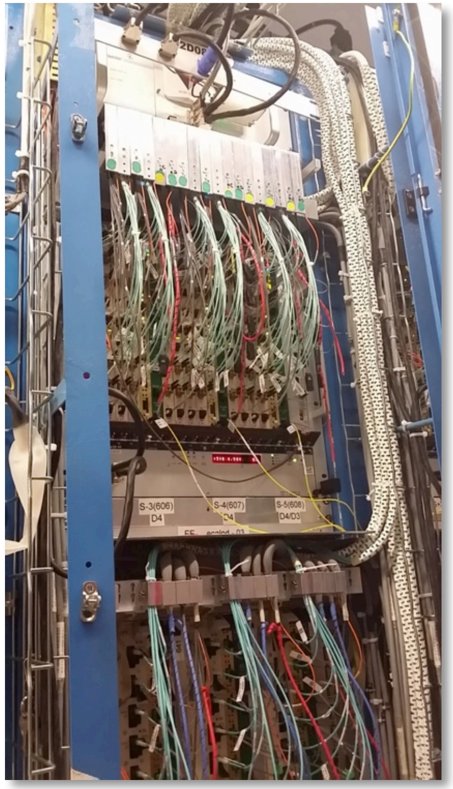


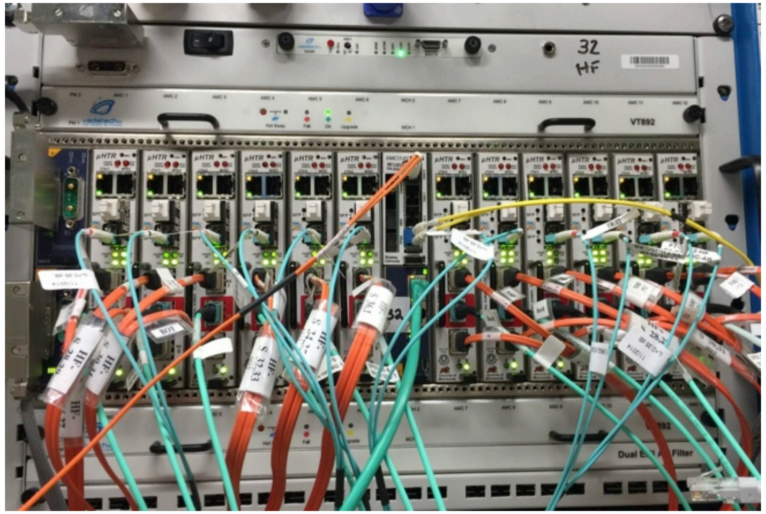
Time-Multiplexed Trigger

- Devised plan of installing and commissioning new system in parallel with legacy Trigger.



Installation underground



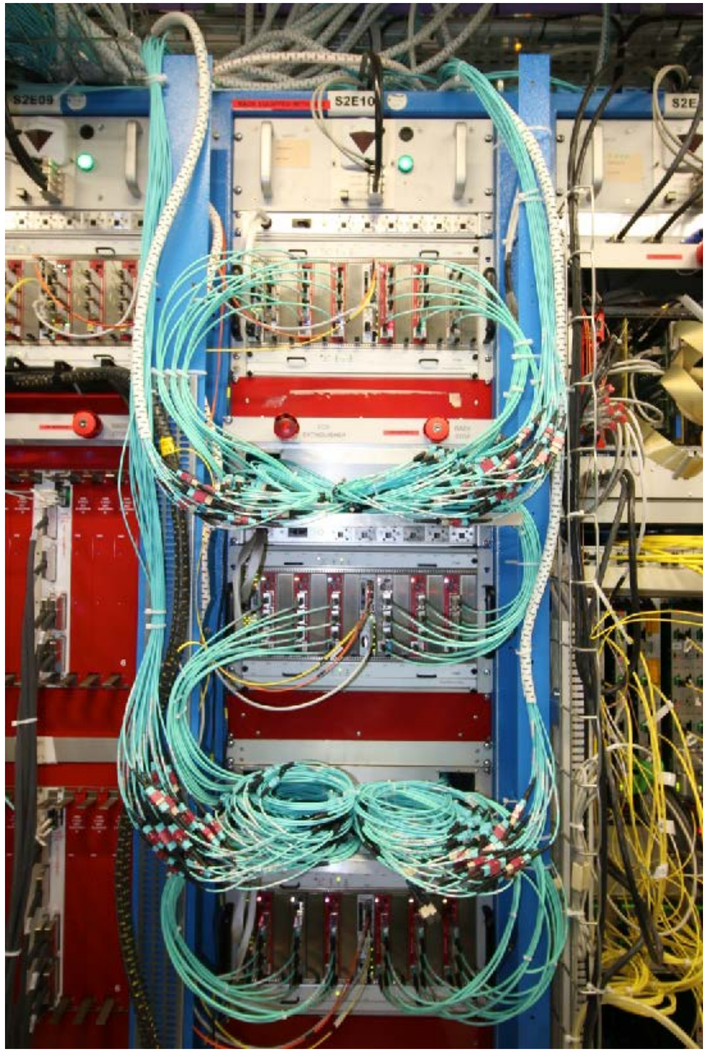


HCAL

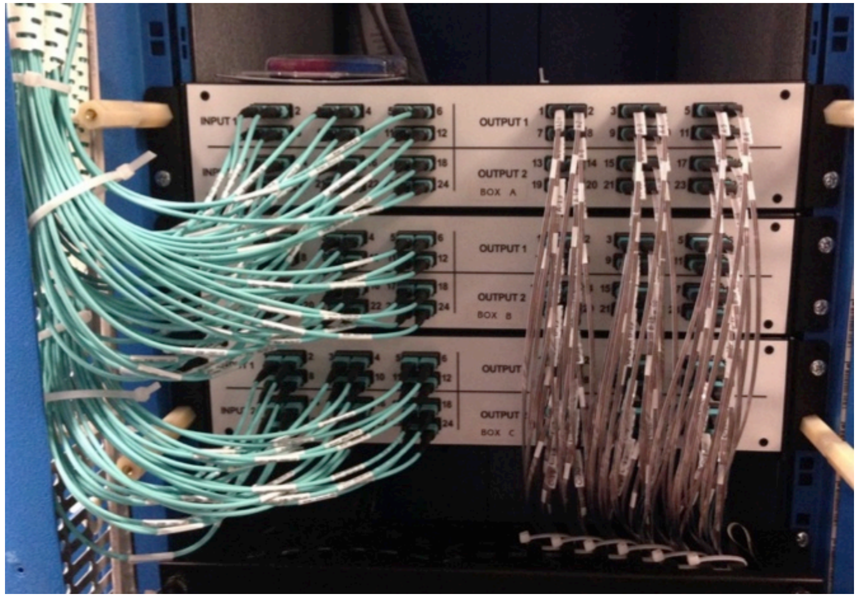
ECAL

ECAL HCAL

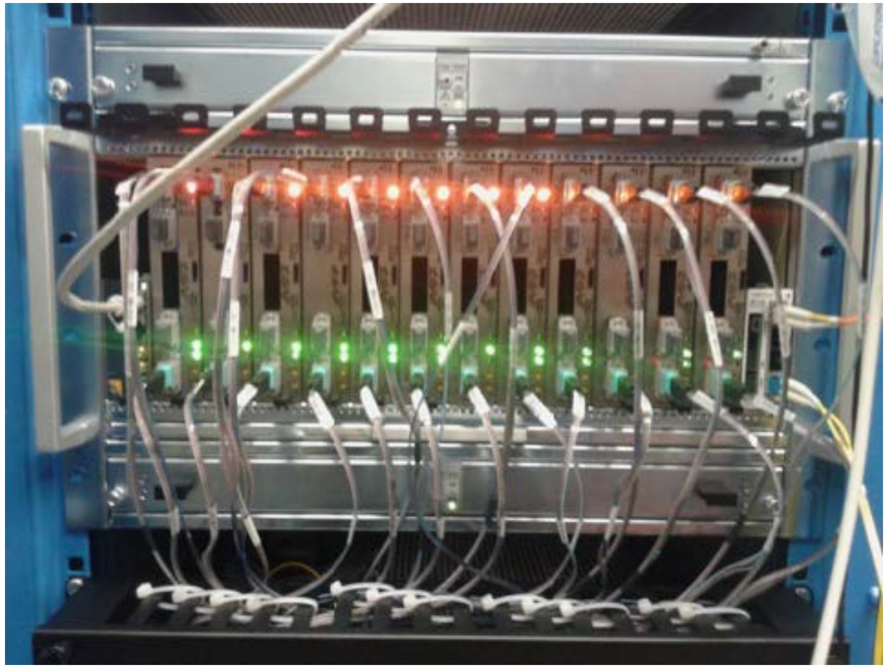
Installation underground



Layer 1



Multiplexer



Layer 2

Layer 1-Layer 2 interconnect

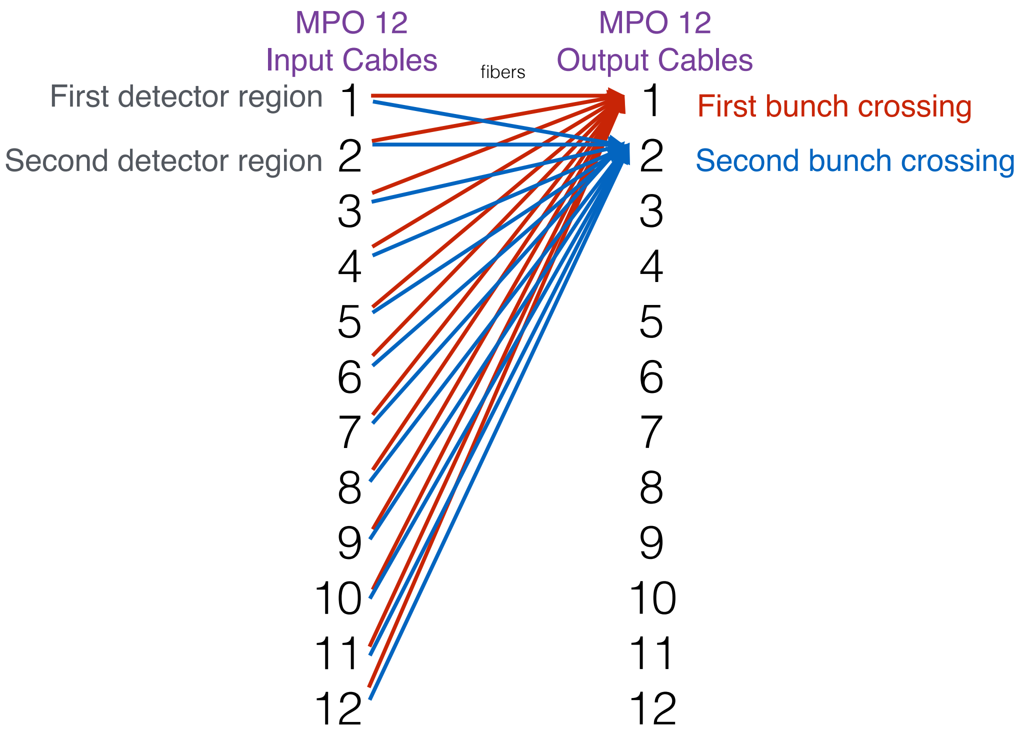
For time-multiplexed trigger architecture, need each of the Layer 1 boards to send information to each of the Layer 2 boards.

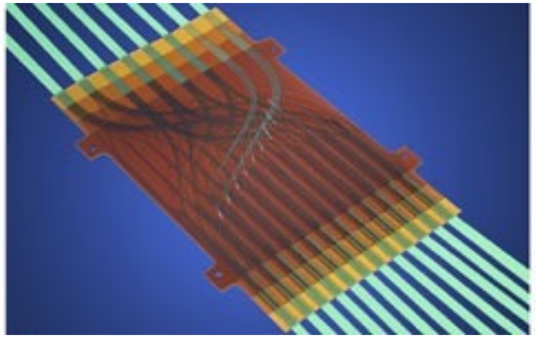
Have 18 Layer 1 boards with 48 outputs on each: 864 links coming into a patch panel, 864 coming out to Layer 2 boards.

Doing this using standard patch panels would take an entire rack of space! (coupled with ensuring 1728 fibres were connected correctly).

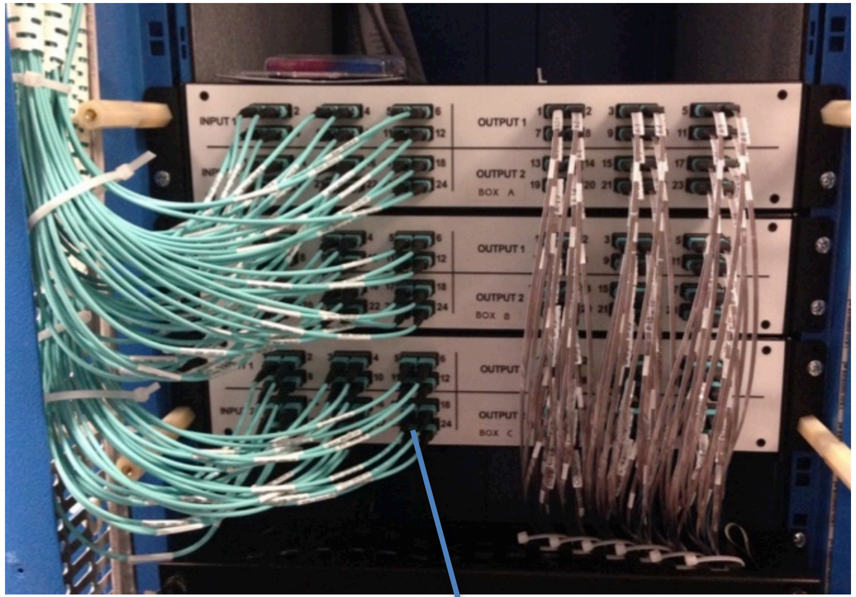
Looked into using a new technology, Molex FlexPlane.

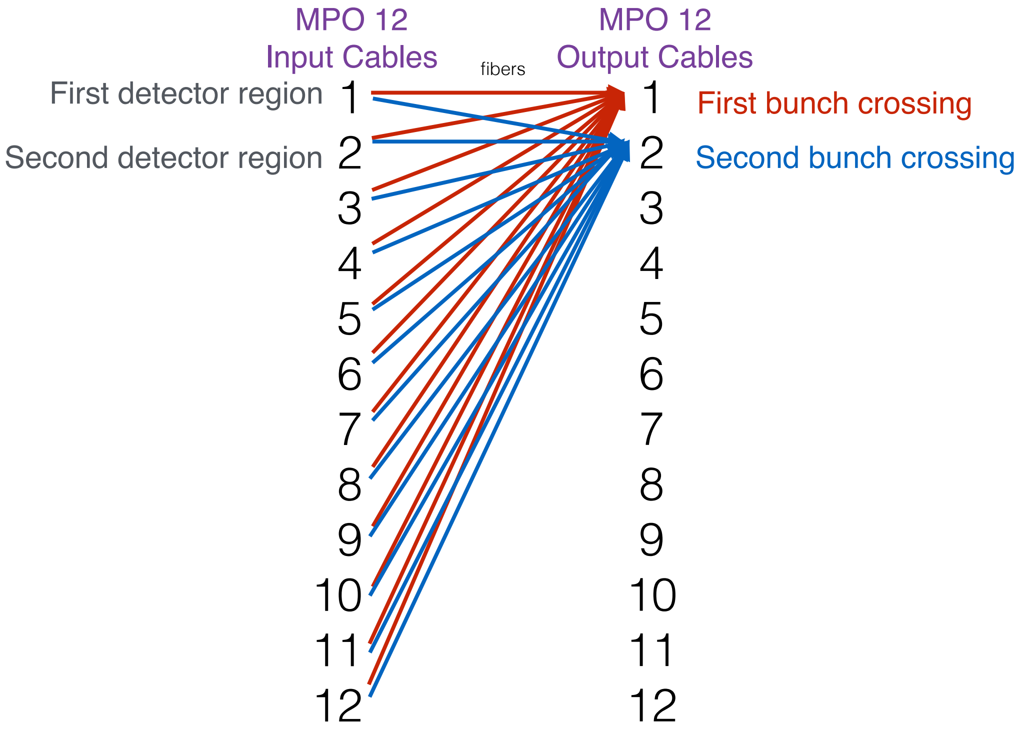
The mesh fabric inside the patch panel would do all the routing internally, we would just need to plug in the MPO12 inputs and outputs.



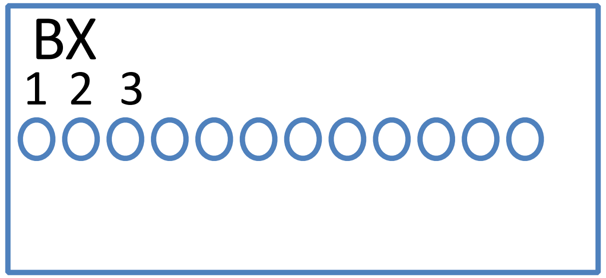


Layer 1-Layer 2 interconnect





MPO12 ribbon



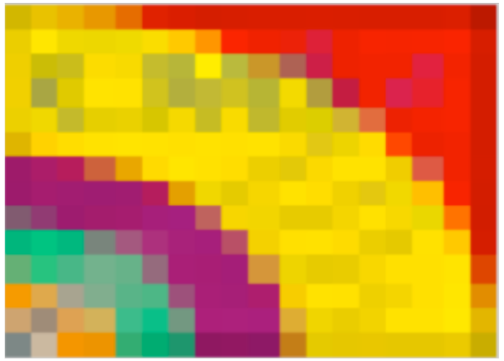
- **Each MPO12 ribbon brings one part of the detector., e.g. Phi 0,1, Eta +ve.**
- **But on each individual link, a consecutive BX**

What goes in the chip?

High-granularity algorithms - Electron/Photon

Key advantage of the upgraded Trigger is that we now have tower level granularity - leads to improved energy and position resolution.

Developed algorithms that exploit this improvement.

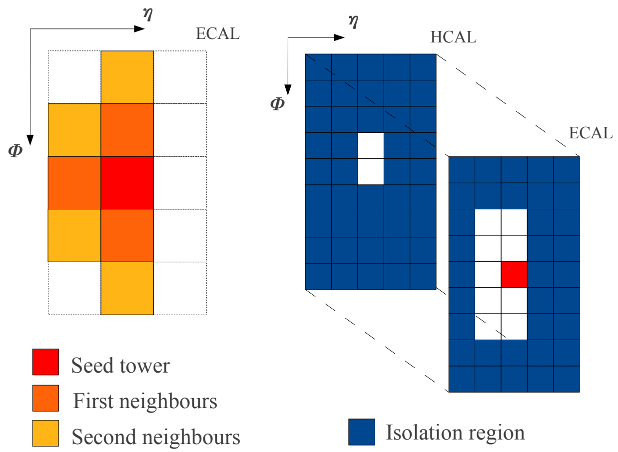


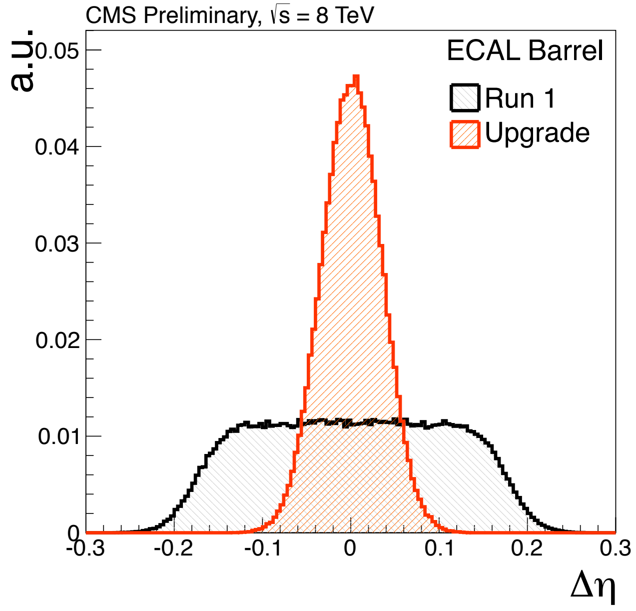
Region Granularity

Trigger Tower Granularity

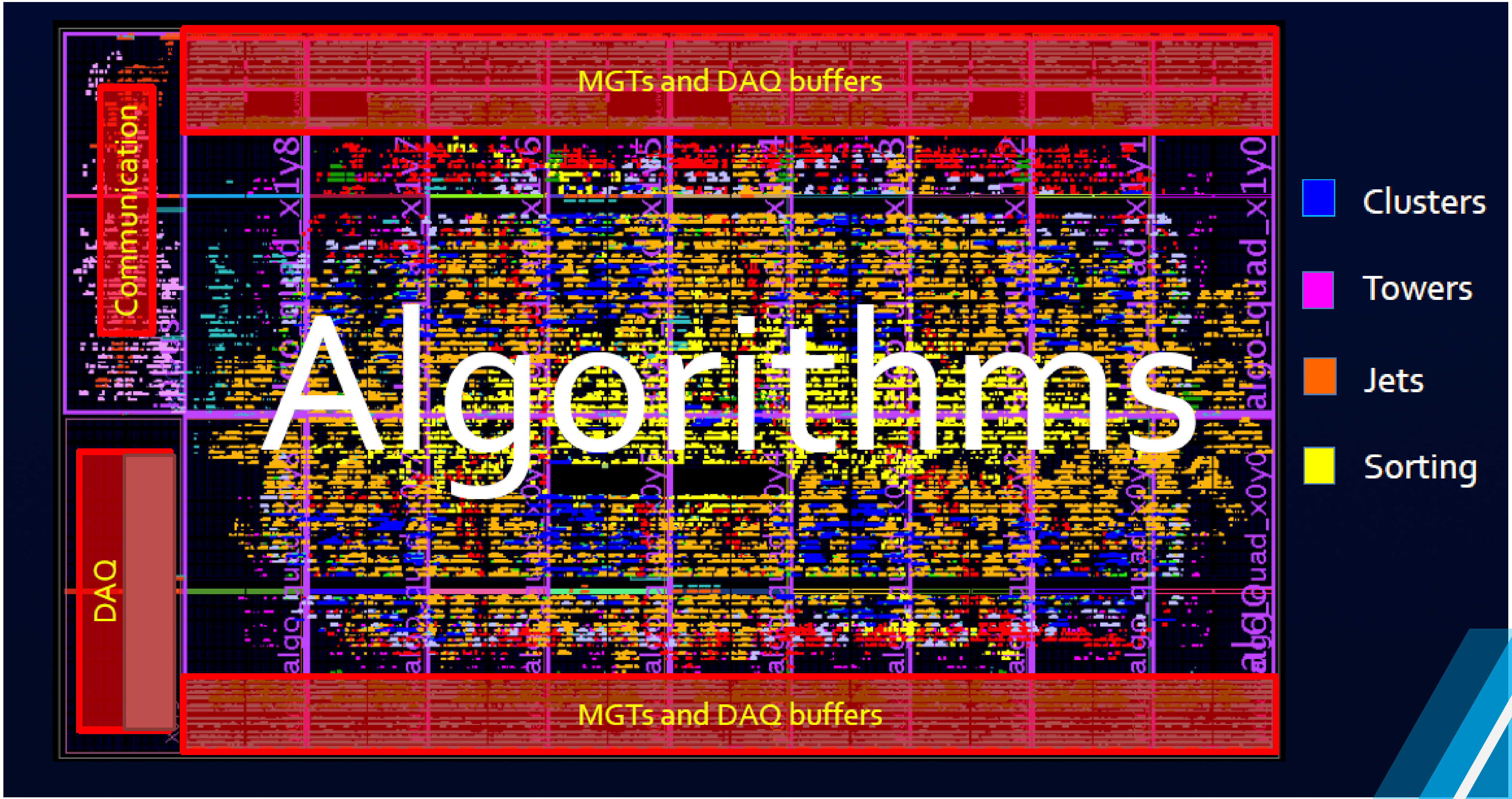
Electron/Photon finder:

- Clusters are seeded by local maxima of energy above fixed threshold
- Position of the candidate is an energy-weighted average centred on the seed tower.
- A candidate is considered isolated if the total energy in the blue region is less than a given value





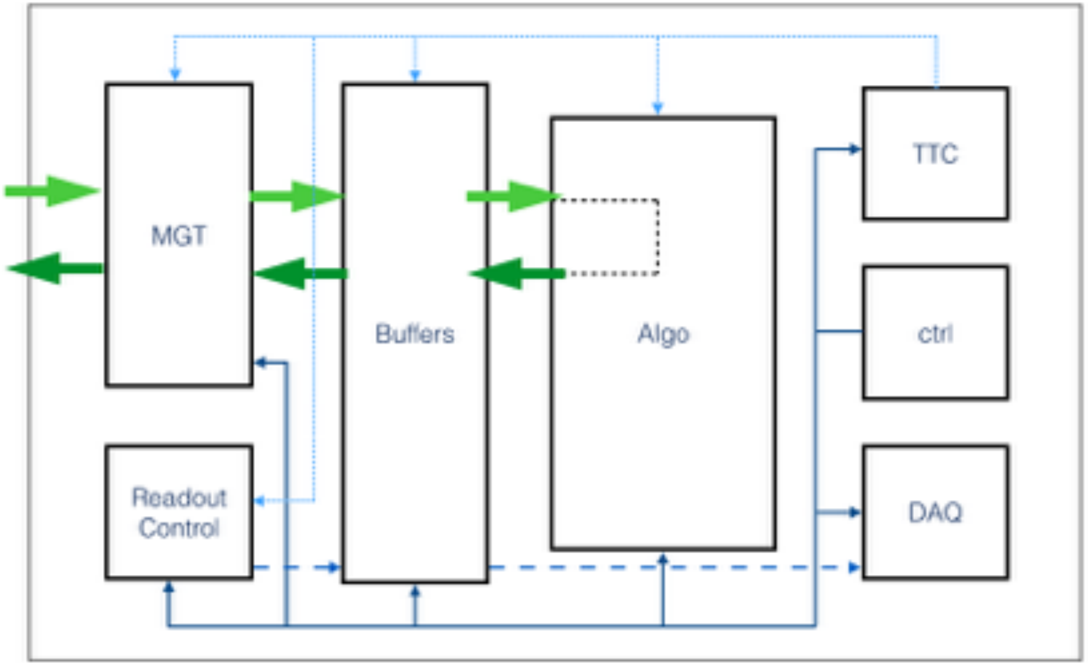
High-granularity algorithms - inside the chip



Infrastructure

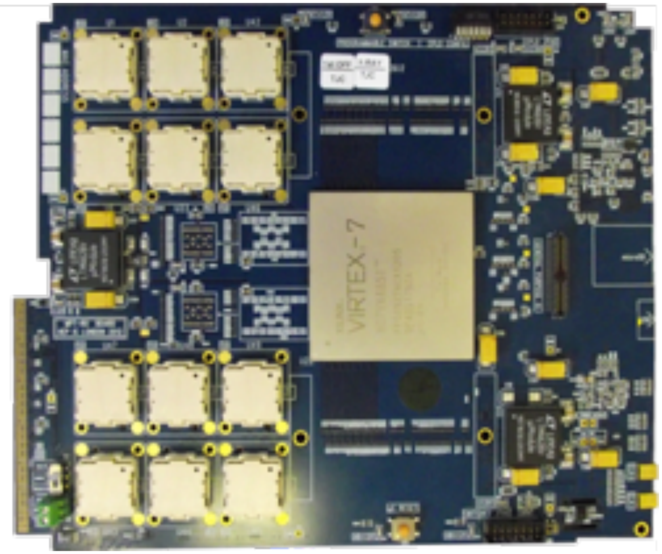
Can see from the previous page that in addition to the hardware, firmware algorithms etc, there is HUGE amount of infrastructure firmware and software which is required to ensure the Trigger system operates at all!

- **Have to be able to control the electronics boards, set-up the clocking, transceivers, link aligment etc**
- **Have to be able to debug any potential problems, need various test modes and monitoring to do this.**
- **Developed a new online Software framework - SWATCH - in order to simplify the framework of common software objects for the upgraded trigger.**



Commonality

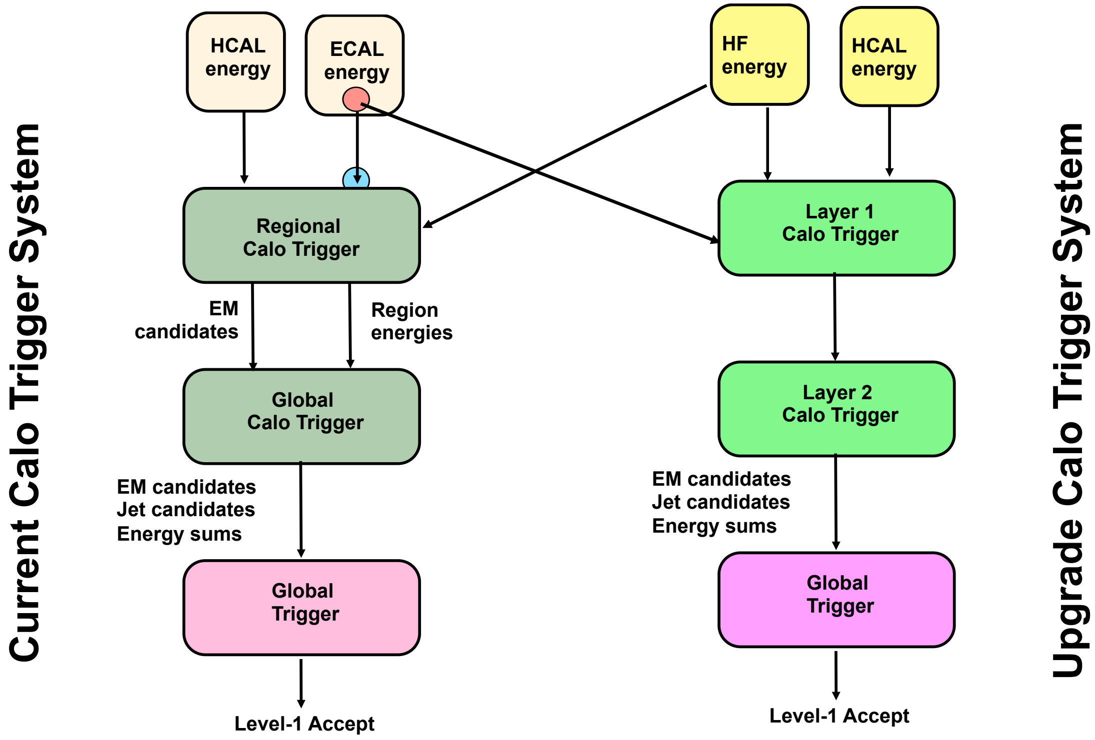
Another important lesson for us in this upgrade was the need to make as much hardware, firmware, software as COMMON as possible.



MP7 card used in the muon system and in the Global Trigger.
Infrastructure firmware the same, just need to plug in a different algorithm.
Ensures commissioning is more straightforward - reduces duplication of effort!

Aiming to follow this principle in the next phase of upgrades also.

Parallel running



- All Calorimeter Trigger boards installed and commissioned in 2015.
- In order to validate algorithm performance, reliability etc, this trigger was included in a number of proton-proton Collision runs at the tail end of 2015.
- Collected > 3 billion events with this new Trigger!
- Operated reliably and first indications are that Trigger is working as expected, ready to deploy in 2016!

Summary

- LHC conditions for Run 2 demand new Trigger for CMS.
- Novel Time-Multiplexed Architecture researched and developed for the Calorimeter Trigger
- Installed and commissioned during 2015, including new boards, optical fibres, patch panels etc
- Operated in parallel during actual proton-proton LHC collisions at the end of 2015
- Currently analysing data, expect to see great improvements over Run 1 Trigger!

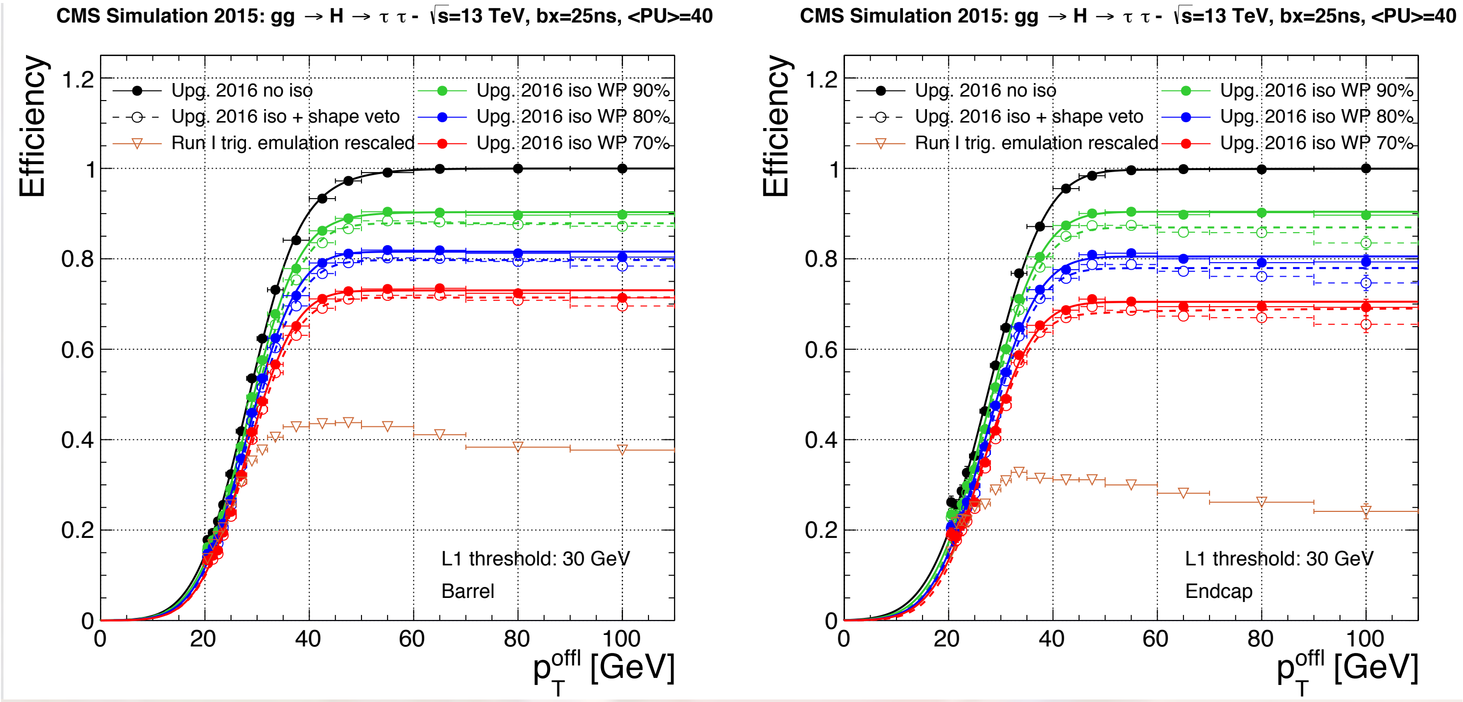
Technology advances drove us to research and implement new ways of processing data online - remarkable progress - shows the need to stay on top of the game - always thinking of new ways to improve!
Next steps…how do we include information from the Tracker?!

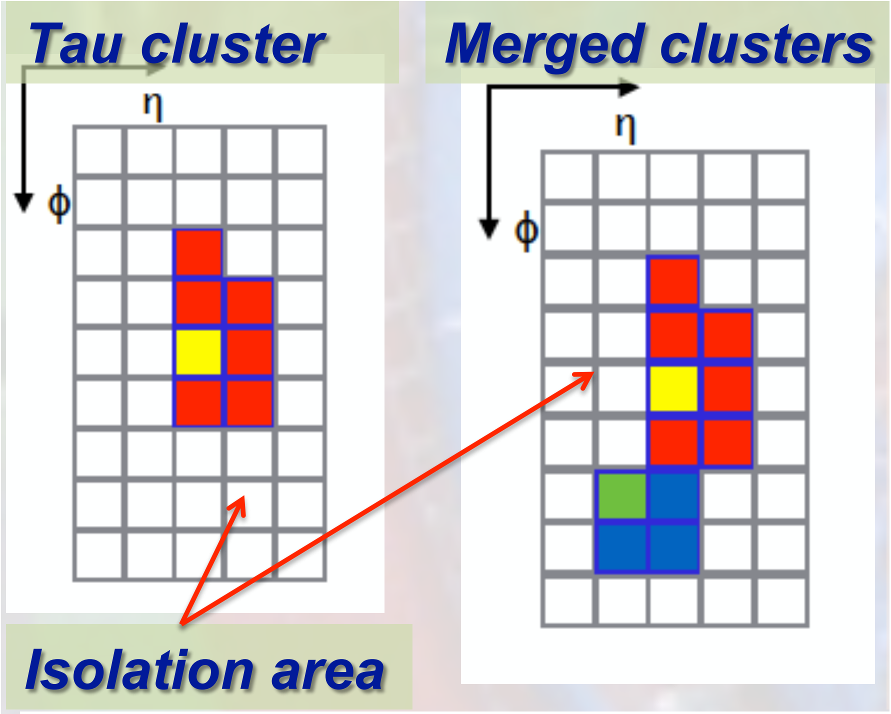
Back-ups

High-granularity algorithms - Tau

Tau finder:

- Candidates built using electron/photon algorithm but summing ECAL + HCAL energies

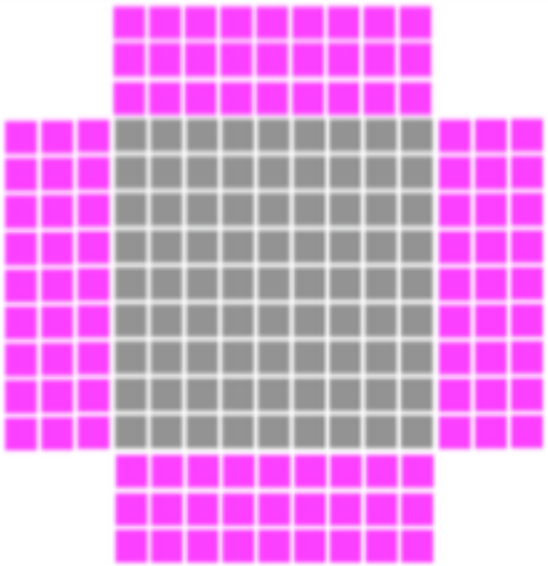




High-granularity algorithms - Jet finder

Jet finder:

- a 9x9 trigger tower (ECAL + HCAL) sliding window is implemented.



PileUp subtraction:

- towers in each of the 3 x 9 sides summed, total energy in lowest 3 sides subtracted from jet energy..