THE CMS TRIGGER: THROUGH THE AGES

SUDAN PARAMESVARAN (UNIVERSITY OF BRISTOL)

UCL HEP SEMINAR - 26TH APRIL 2019

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?

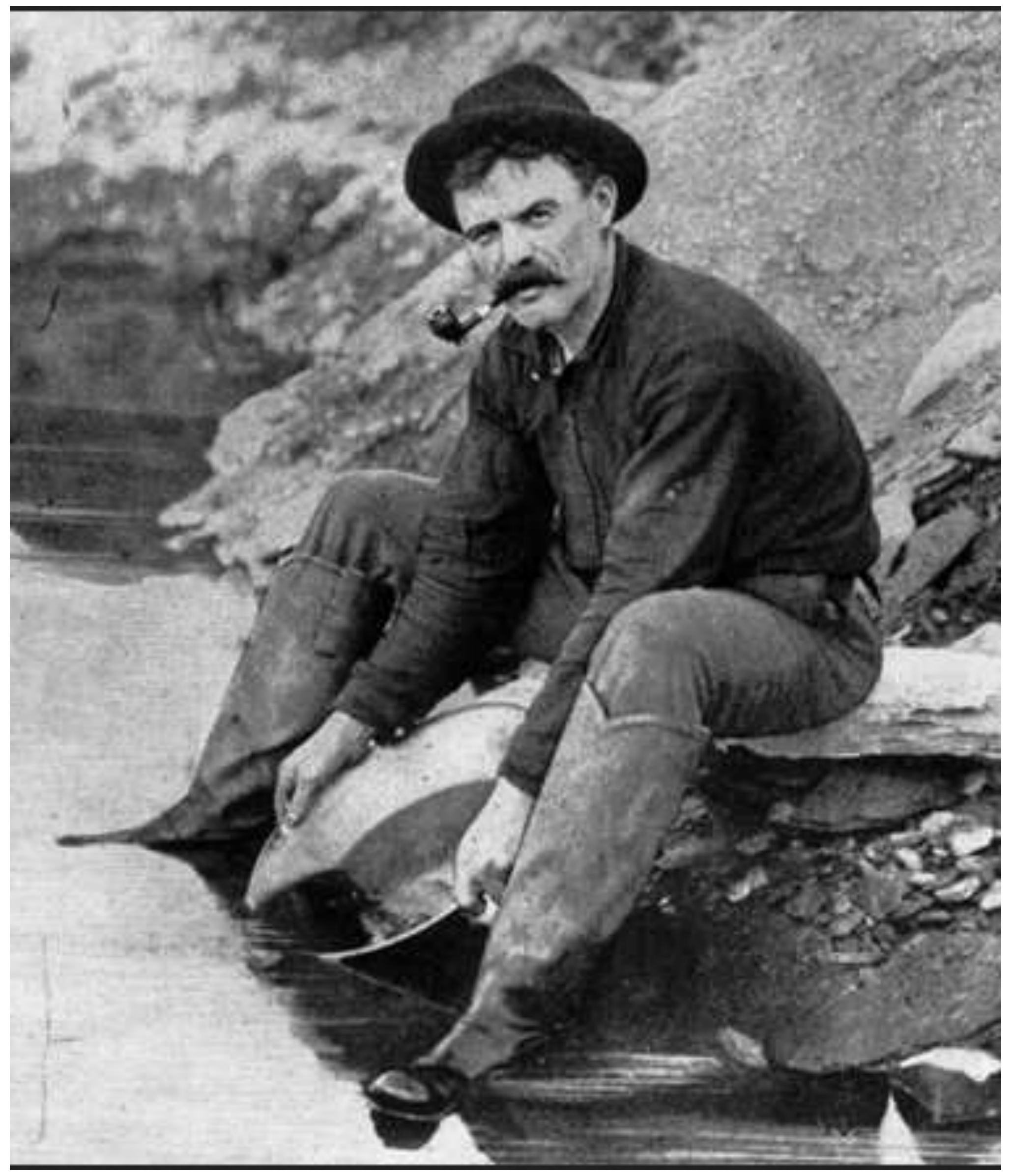
WHAT IS A TRIGGER?

Looking for the specks of gold
hidden in the water

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?



WHY DO WE NEED A TRIGGER?

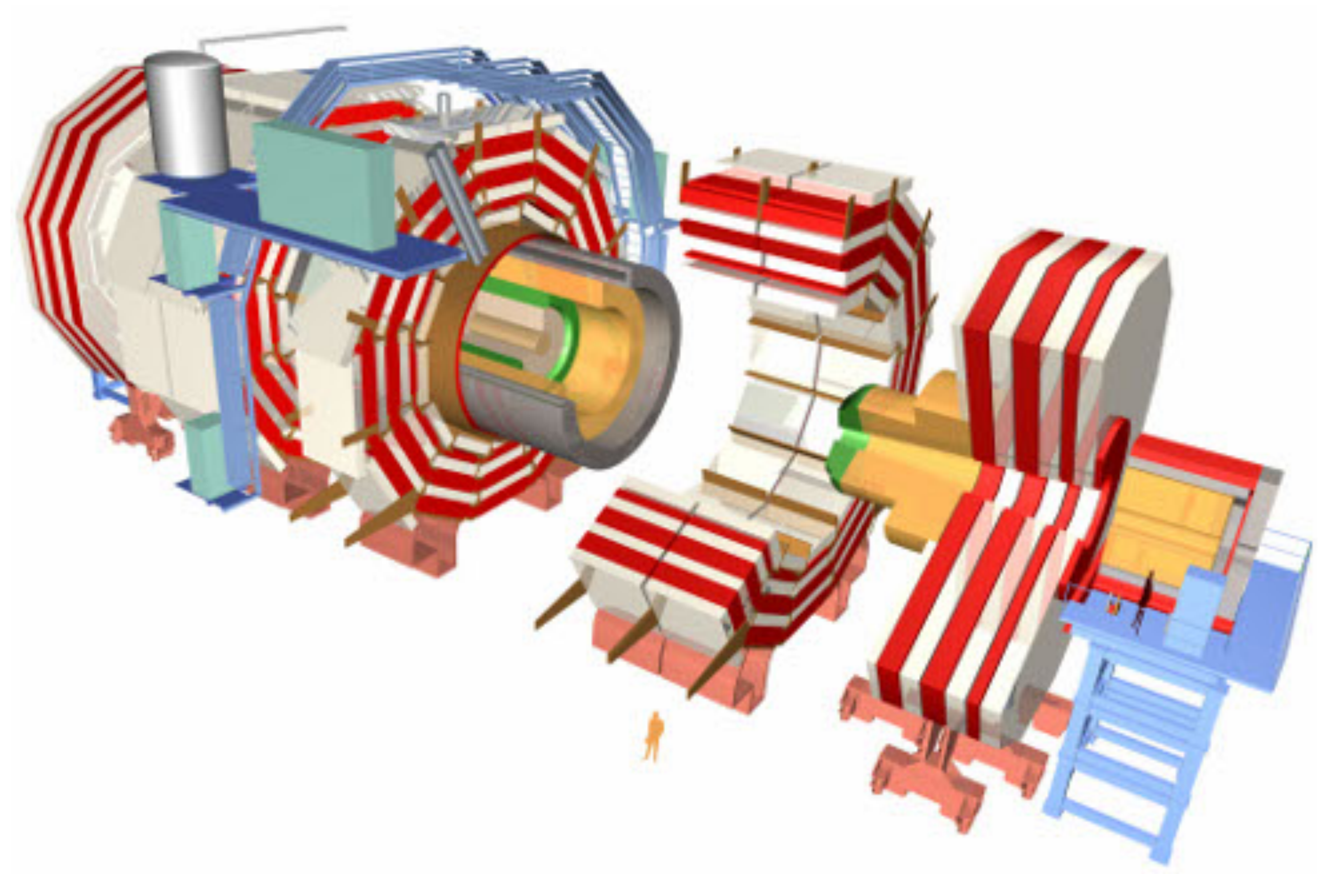
WHY DO WE NEED A TRIGGER?

To answer this question we first need to understand another concept:

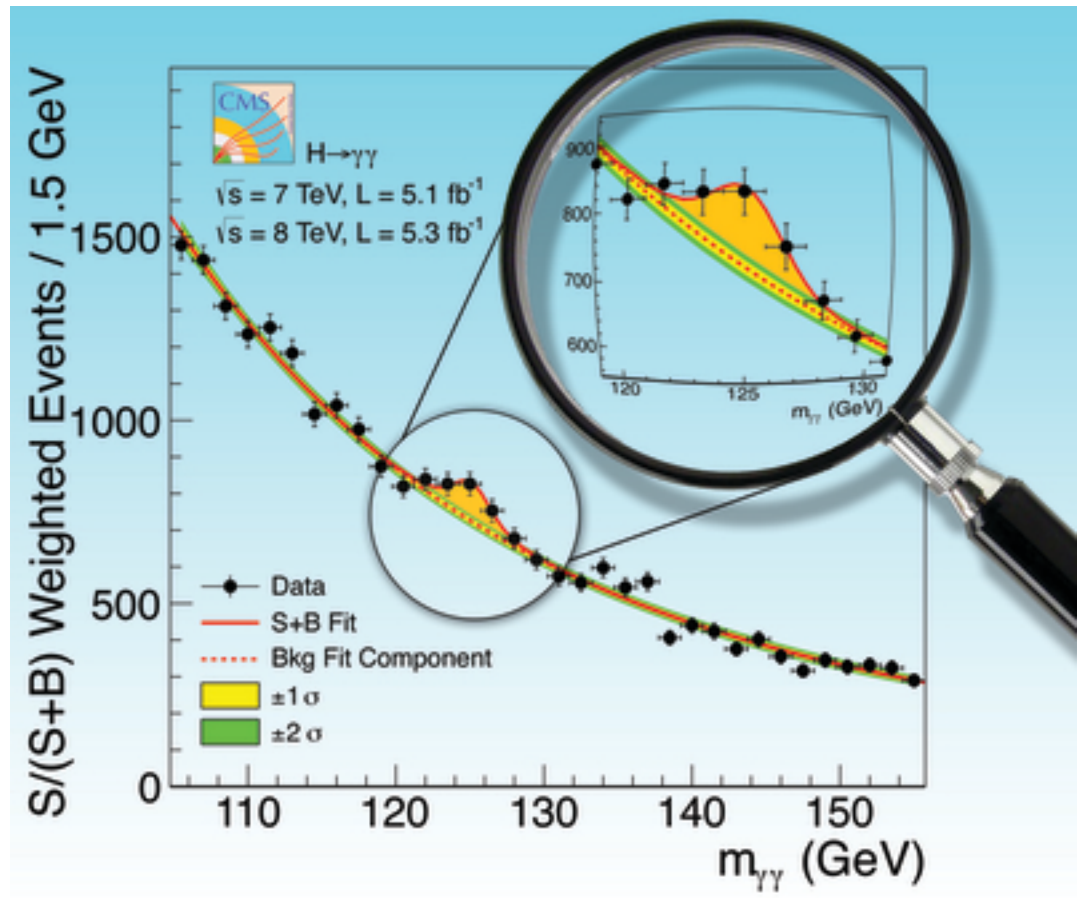
DAQ = DATA ACQUISITION

WHY DO WE NEED A TRIGGER?

To answer this question we first need to understand another concept:

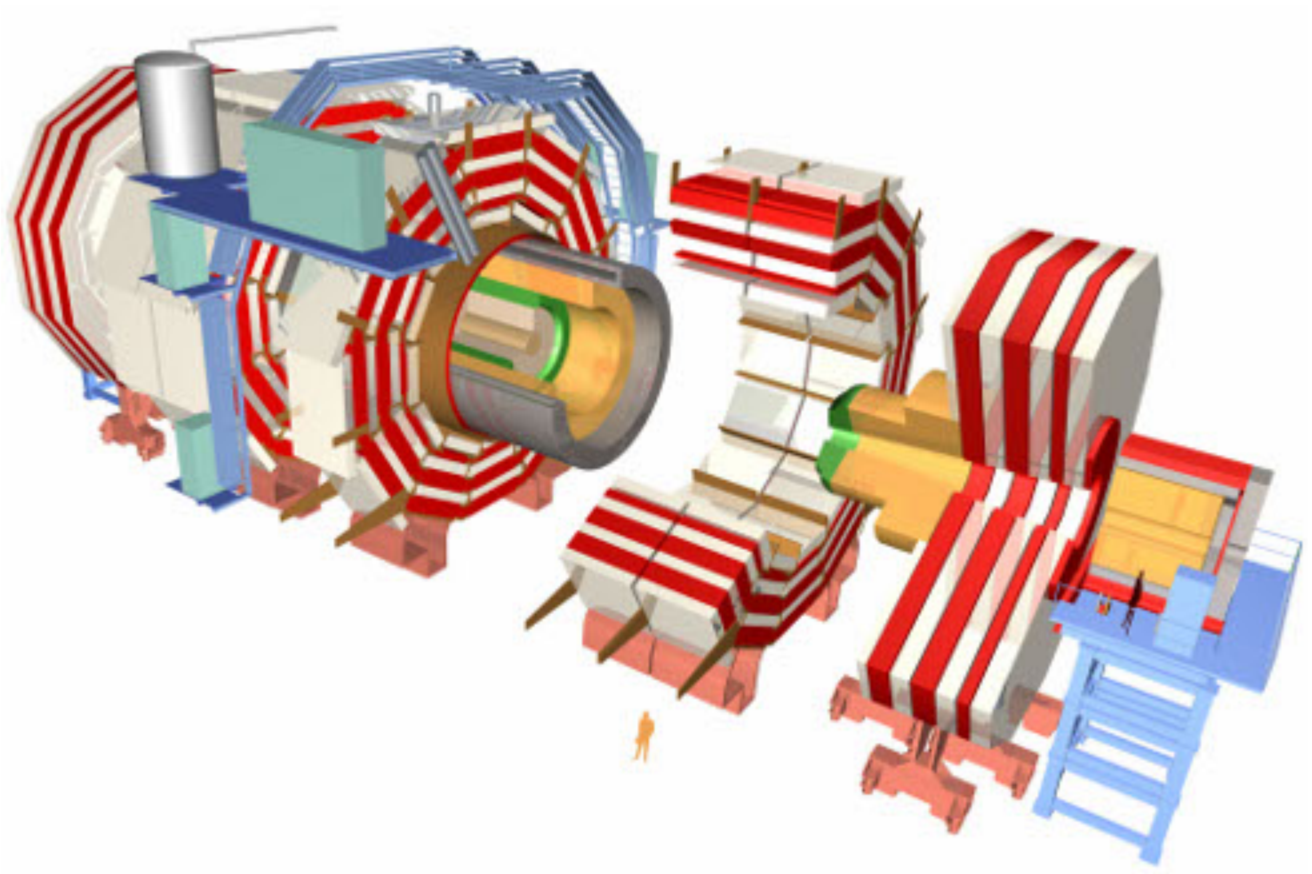


?



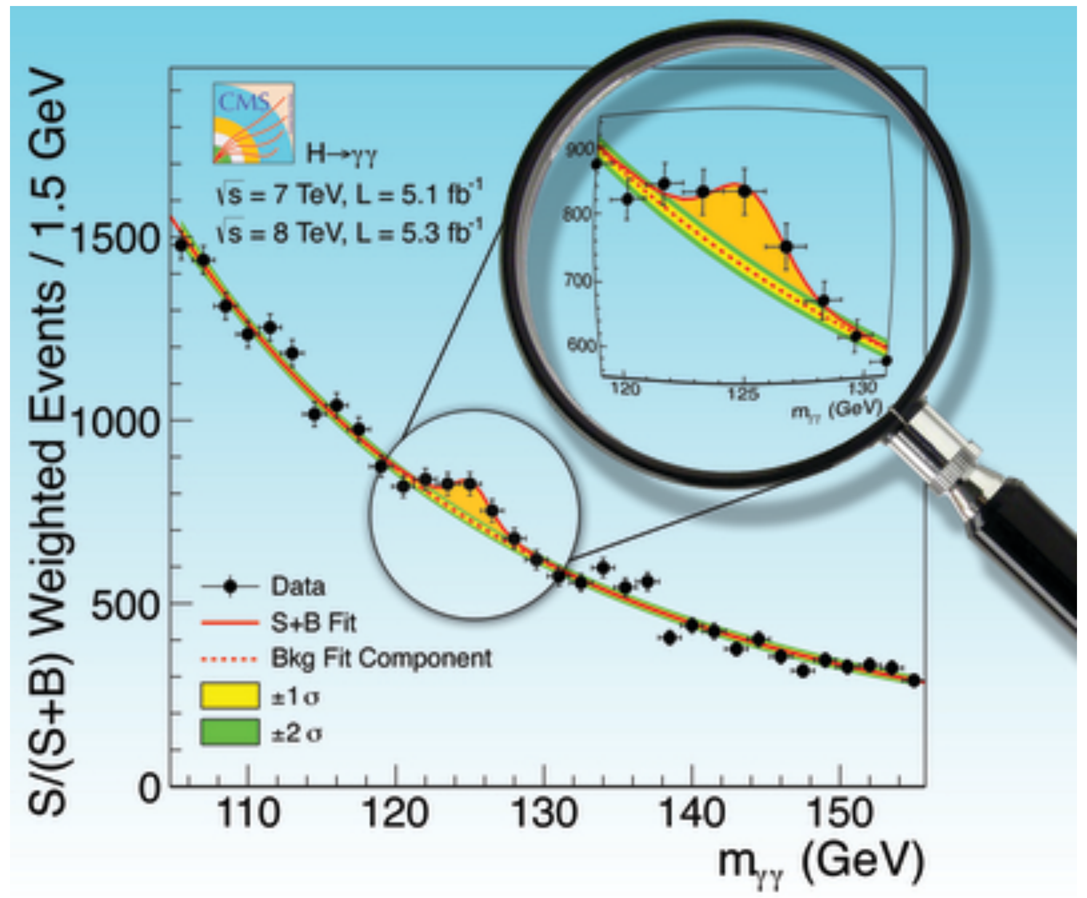
WHY DO WE NEED A TRIGGER?

To answer this question we first need to understand another concept:

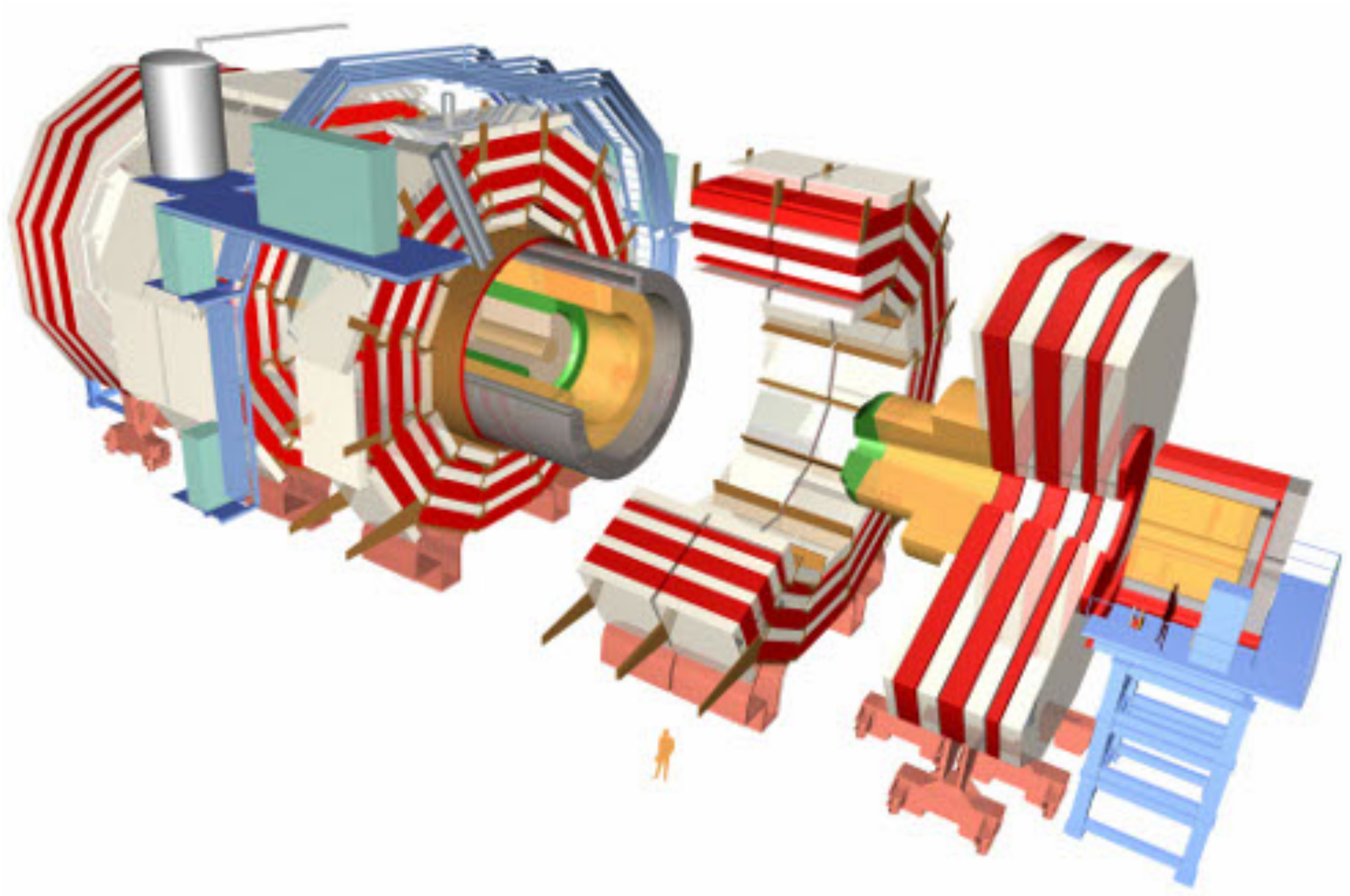


DAQ

data acquistion

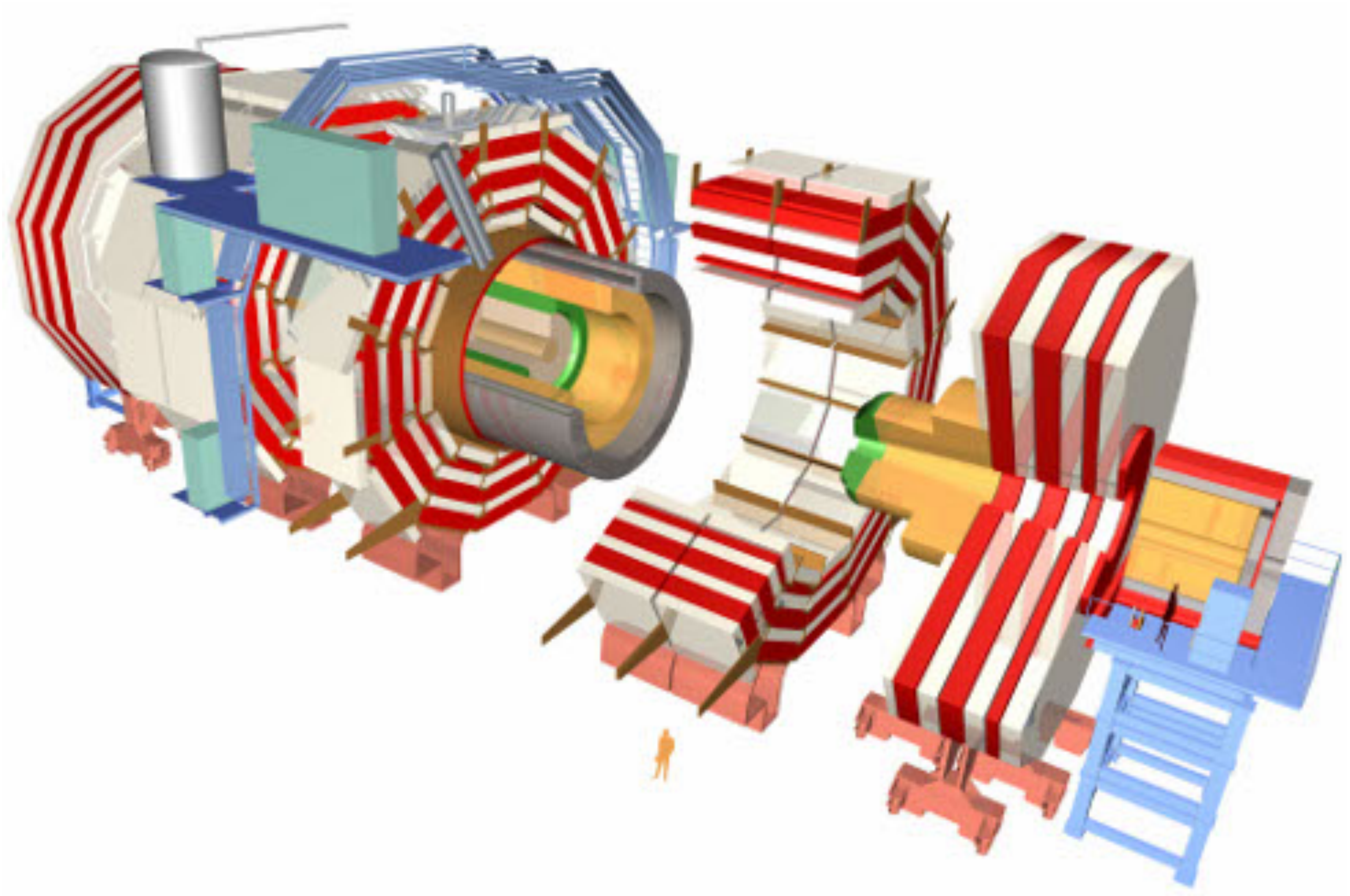


WHY DO WE NEED A TRIGGER?



~100 million channels

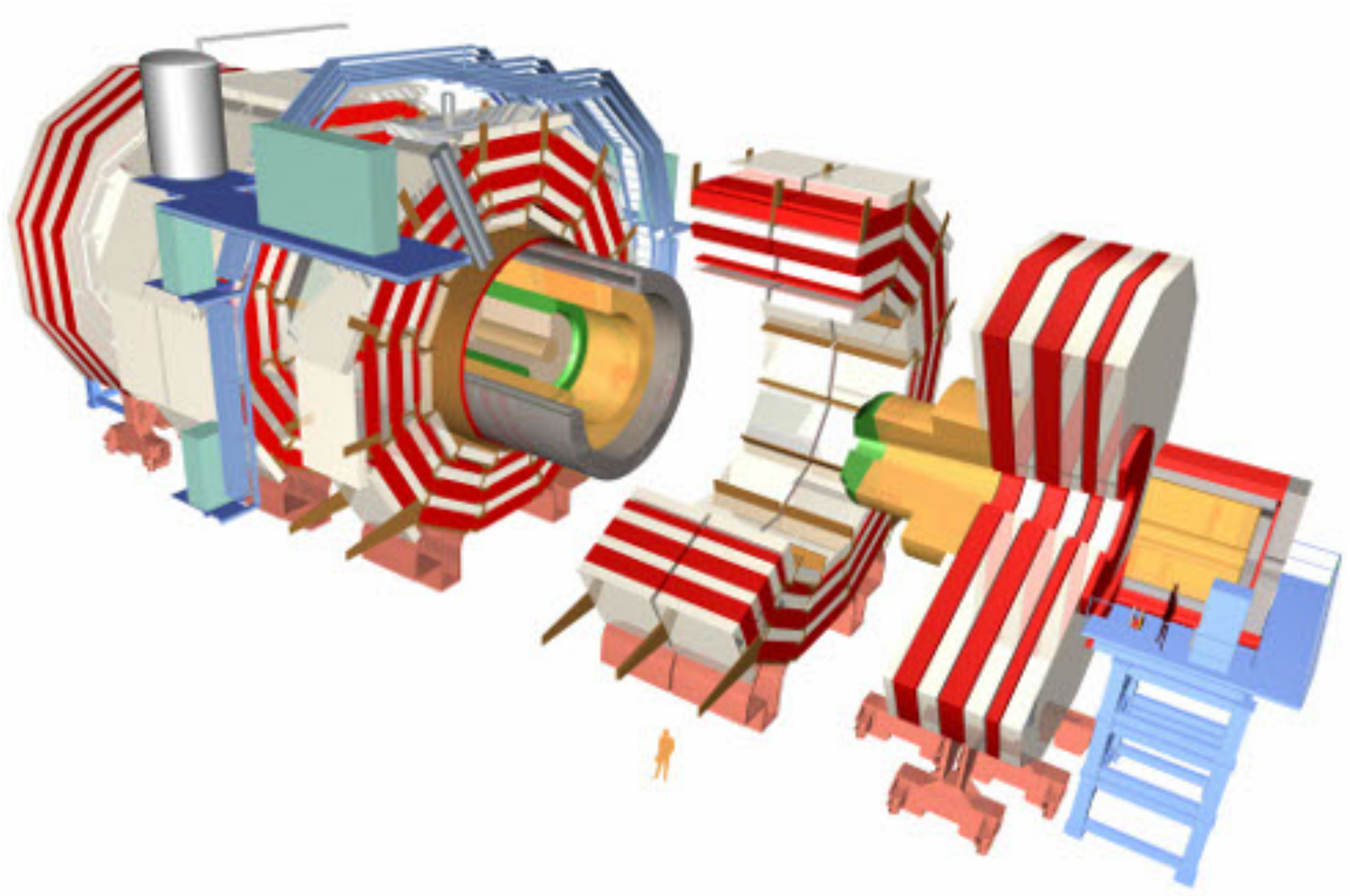
WHY DO WE NEED A TRIGGER?



~100 million channels

~1MB per event

WHY DO WE NEED A TRIGGER?

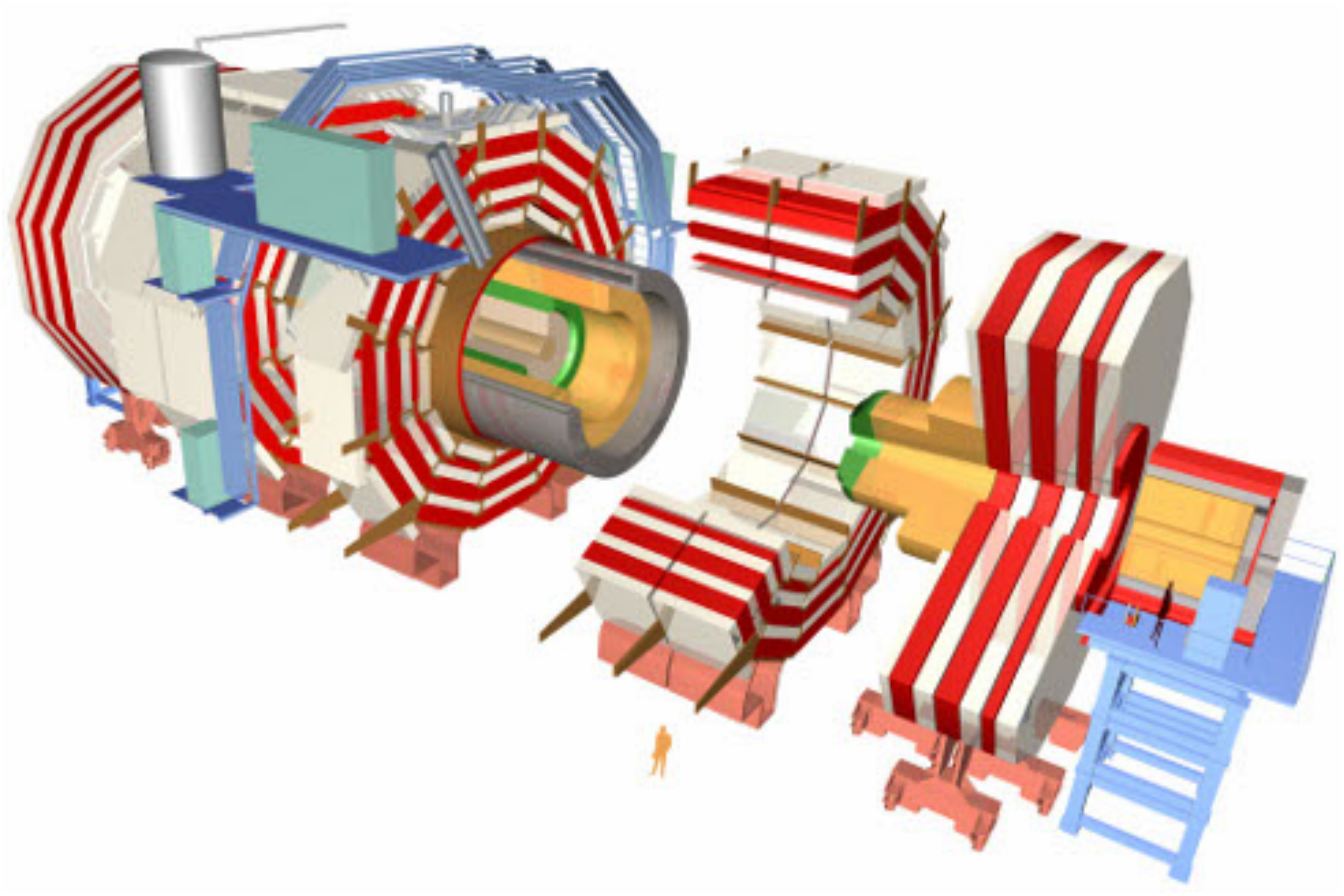


~100 million channels

~1MB per event

40 million collisions per second

WHY DO WE NEED A TRIGGER?



~100 million channels

~1MB per event

40 million collisions per second

↓

40 TB/s!!!!

WHY DO WE NEED A TRIGGER?

PROBLEM

Data volume is much too high - has to be reduced! (We can record ~1.5GB/s)

WHY DO WE NEED A TRIGGER?

PROBLEM

Data volume is much too high - has to be reduced! (We can record ~1.5GB/s)

SOLUTION

Store "interesting" physics only

EASIER SAID THAN DONE…

BASIC REQUIREMENTS OF TRIGGER SYSTEM

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.

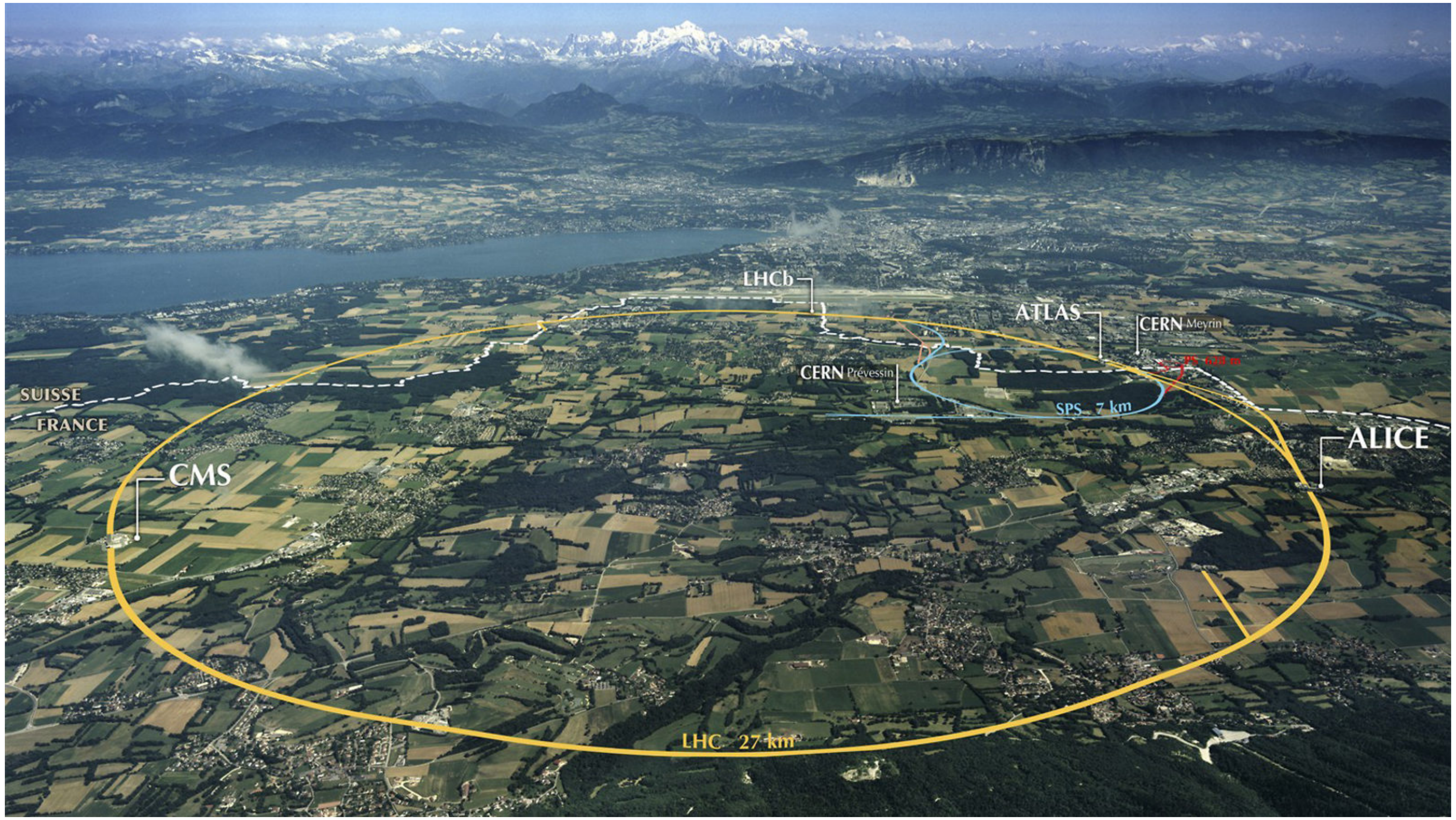
5 Affordability

Can't blow the experiment budget on the Trigger! Need to make a reliable system within limited budget.

LETS TAKE A LOOK AT THE CONDITIONS WE'RE PRESENTED WITH....LHC & CMS

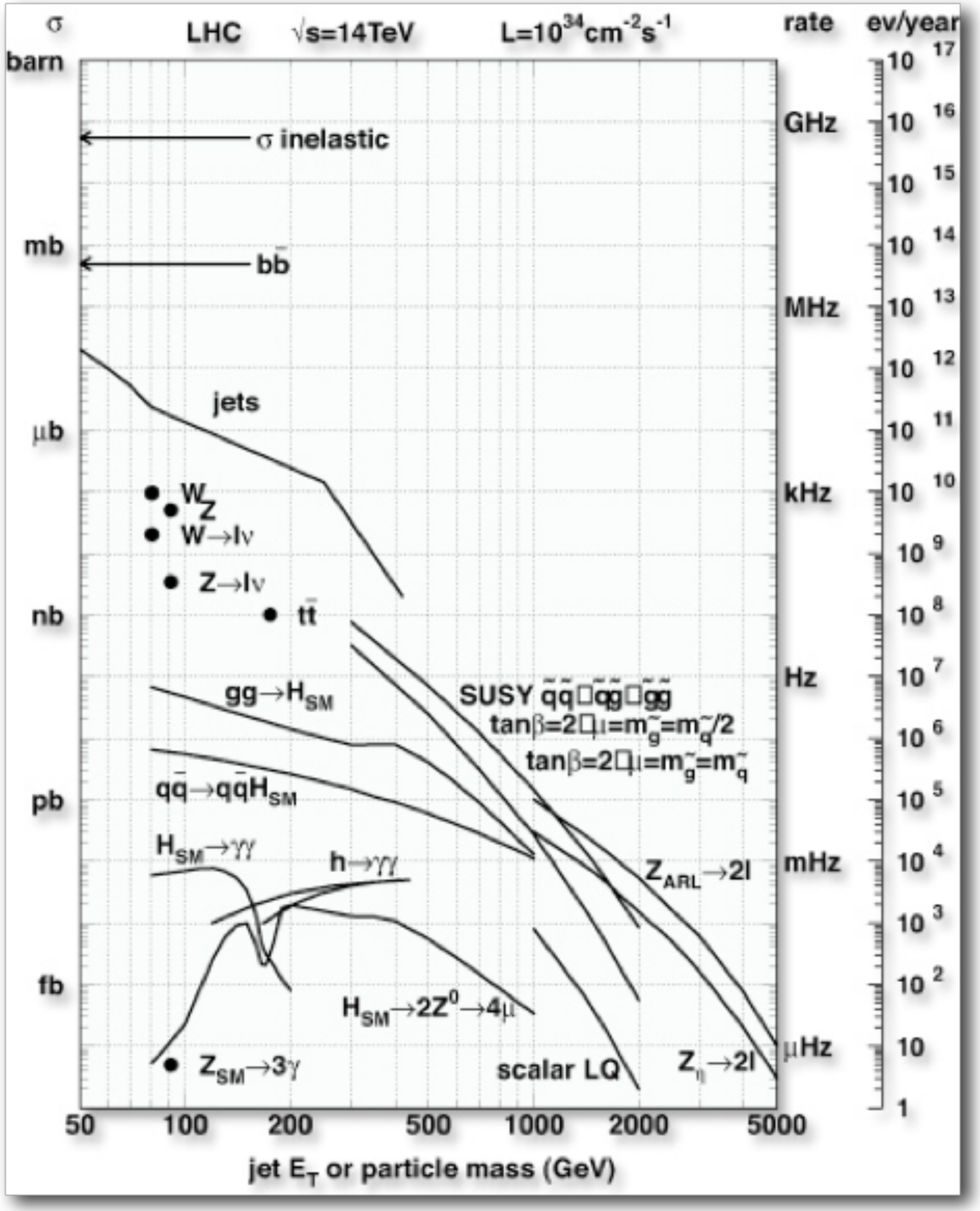
LHC @ CERN

- 27km tunnel, 100m underground
- proton-proton collisions @7,8,13 TeV
- Four major experiments: CMS, ATLAS, LHCb, ALICE
- collisions every 25ns, 40 Mhz collision rate

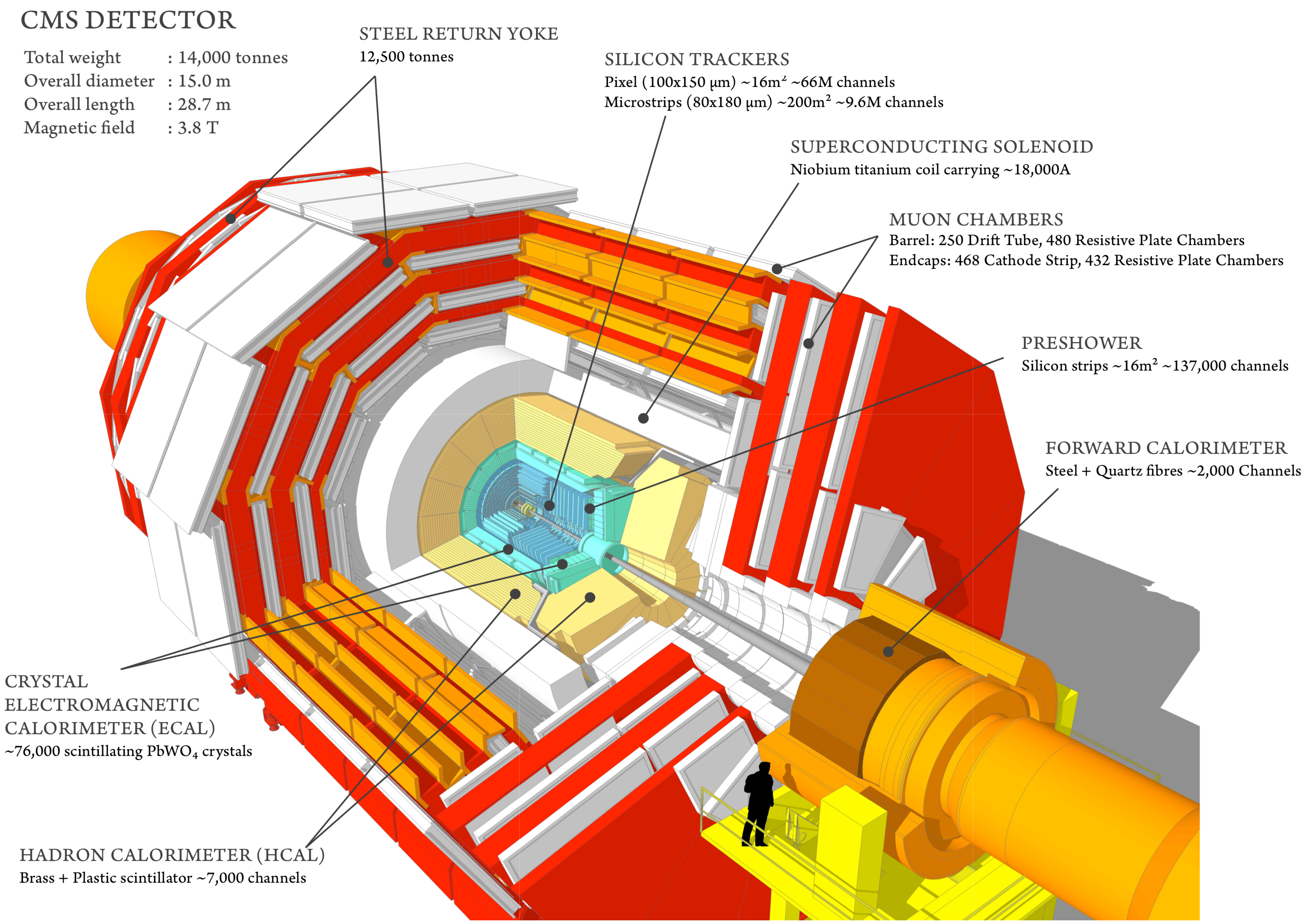


LHC @ CERN

- 27km tunnel, 100m underground
- proton-proton collisions @7,8,13 TeV
- Four major experiments: CMS, ATLAS, LHCb, ALICE

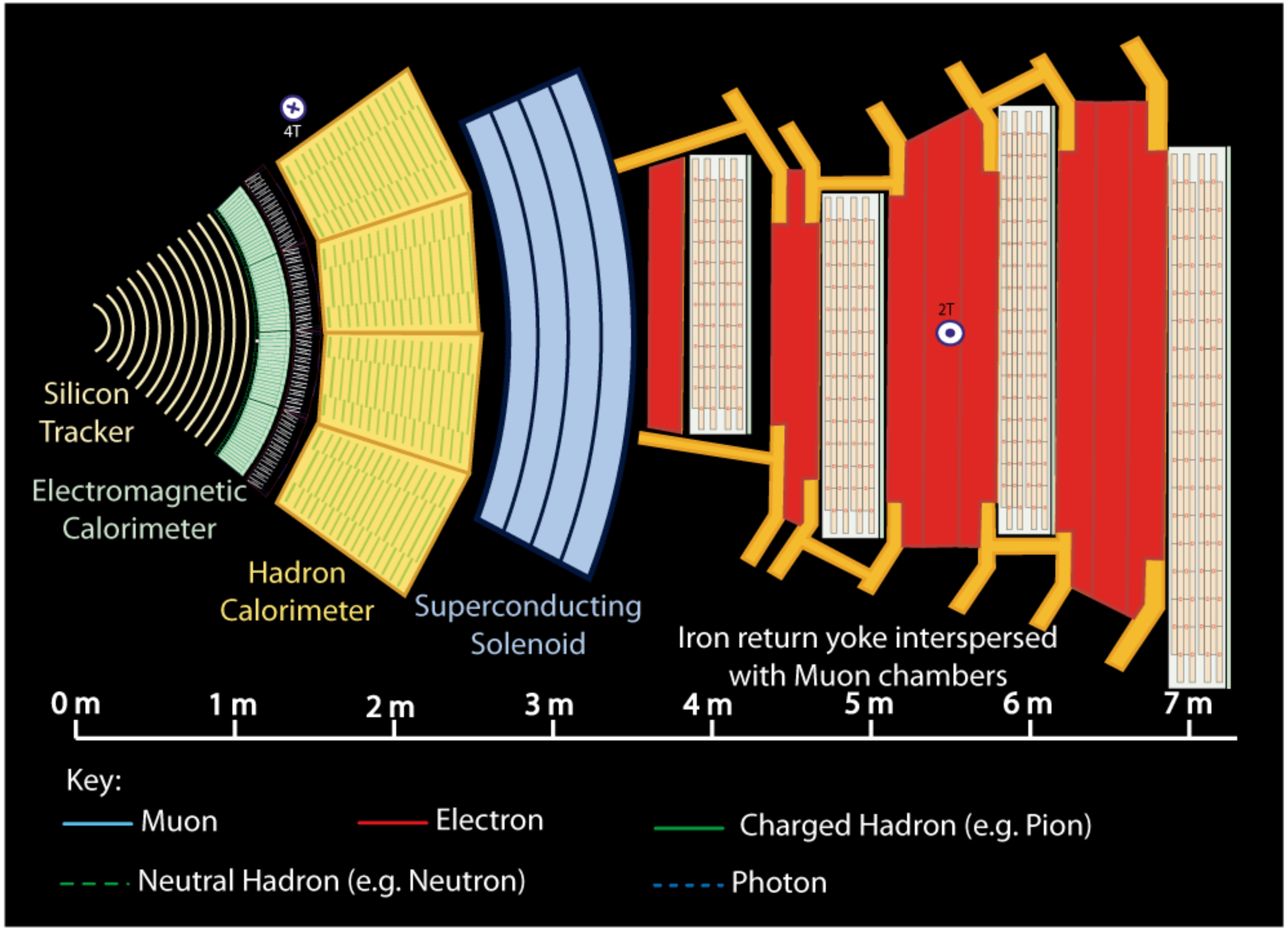


CMS @ LHC



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 $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

CMS @ LHC



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

CMS TRIGGER - RUN 1 (2010-2012)

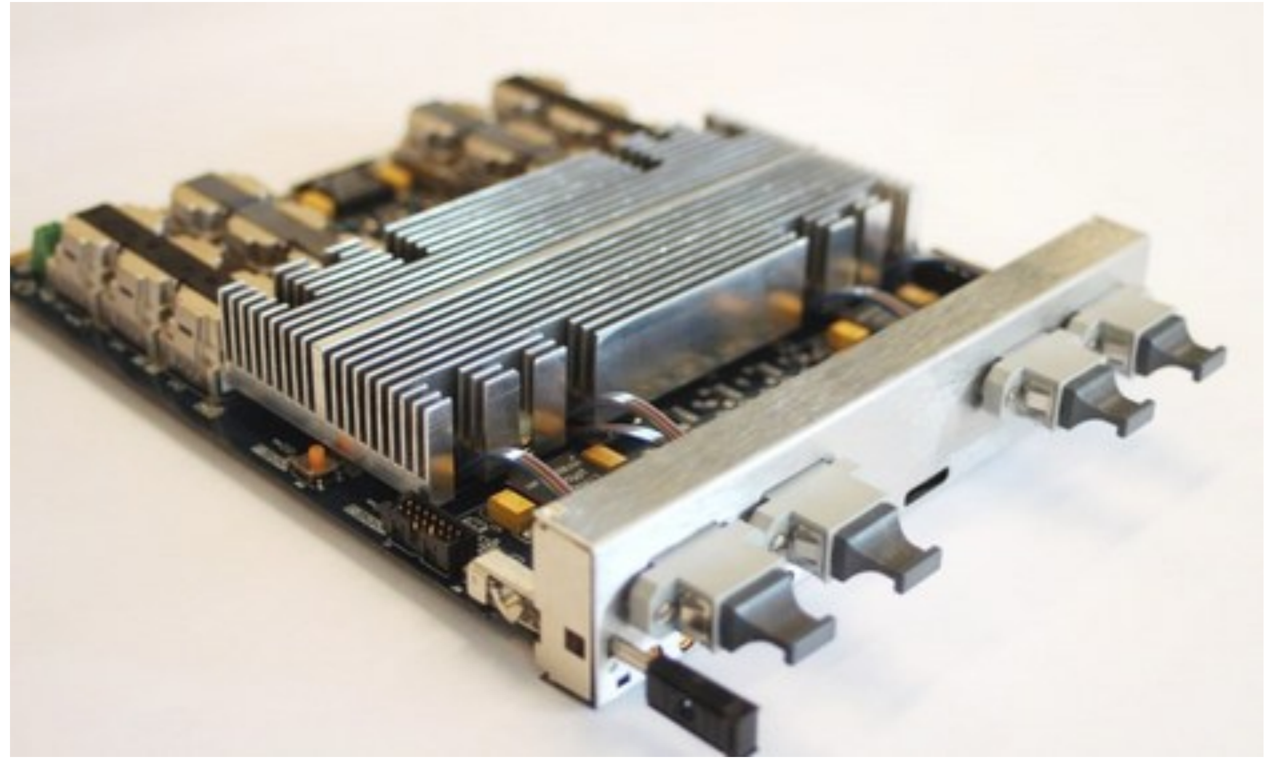
BASICS: TWO LEVEL TRIGGER SYSTEM

100 kHz output - 3us time to decide

1 kHz - 300ms (average)

LEVEL 1 TRIGGER (L1)

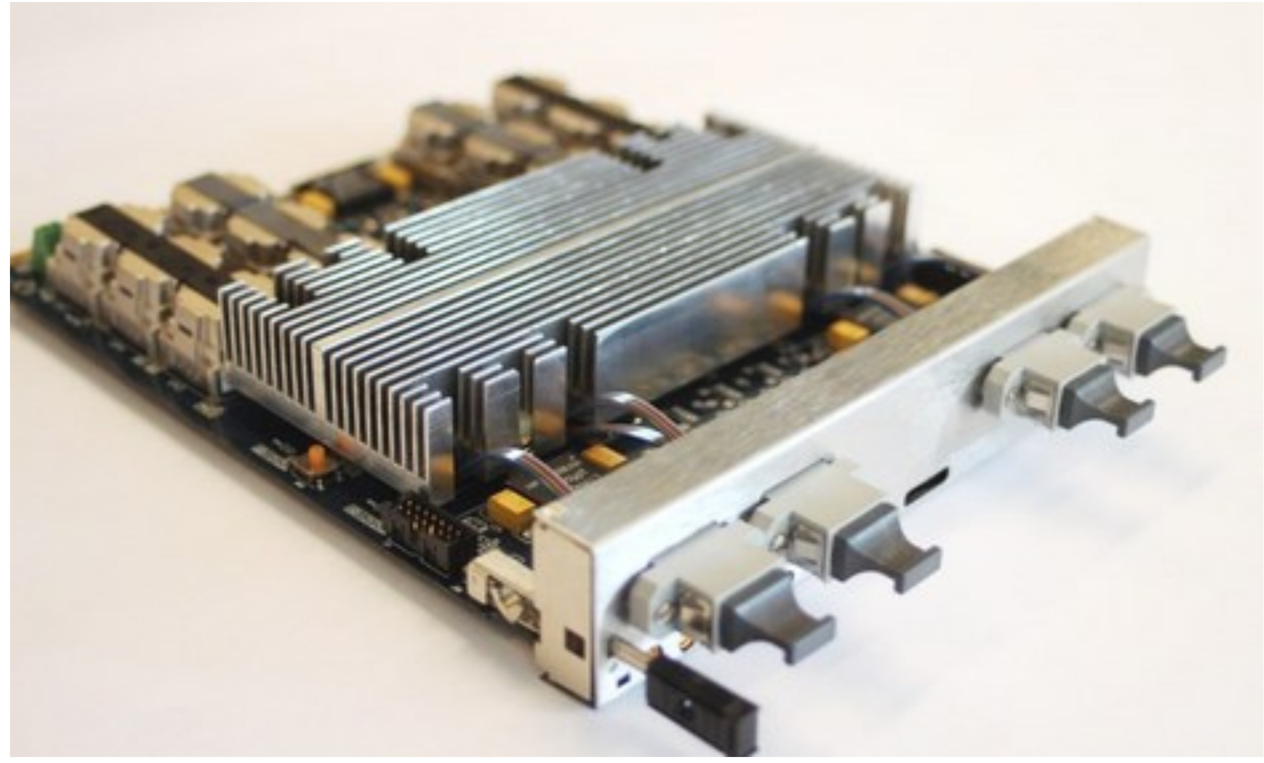
HIGH LEVEL TRIGGER
(HLT)



BASICS: TWO LEVEL TRIGGER SYSTEM

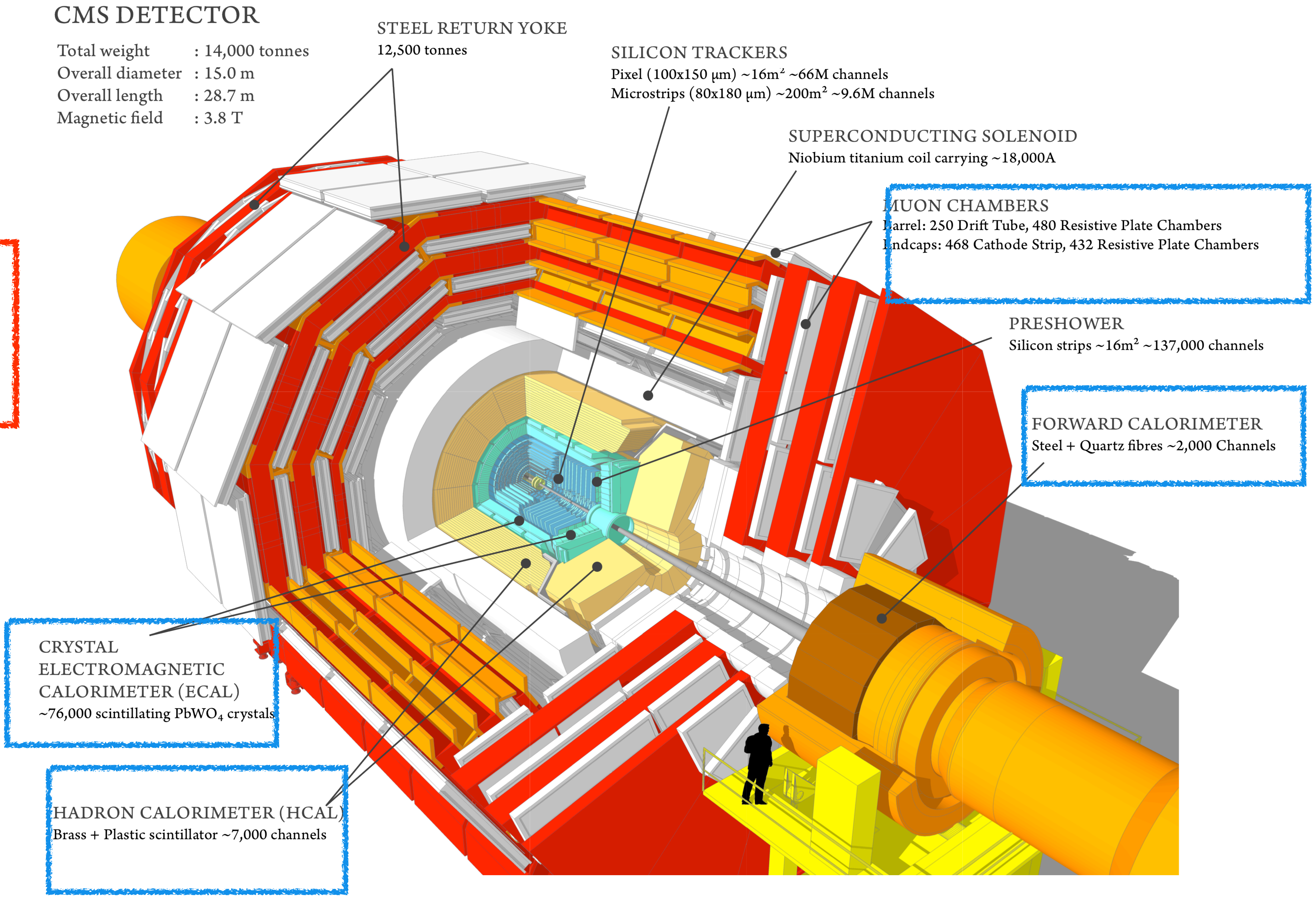
LEVEL 1 TRIGGER (L1)

HIGH LEVEL TRIGGER (HLT)



CMS @ LHC

Not all detectors enter into the L1trigger



BASICS: LEVEL 1 CALORIMETER TRIGGER

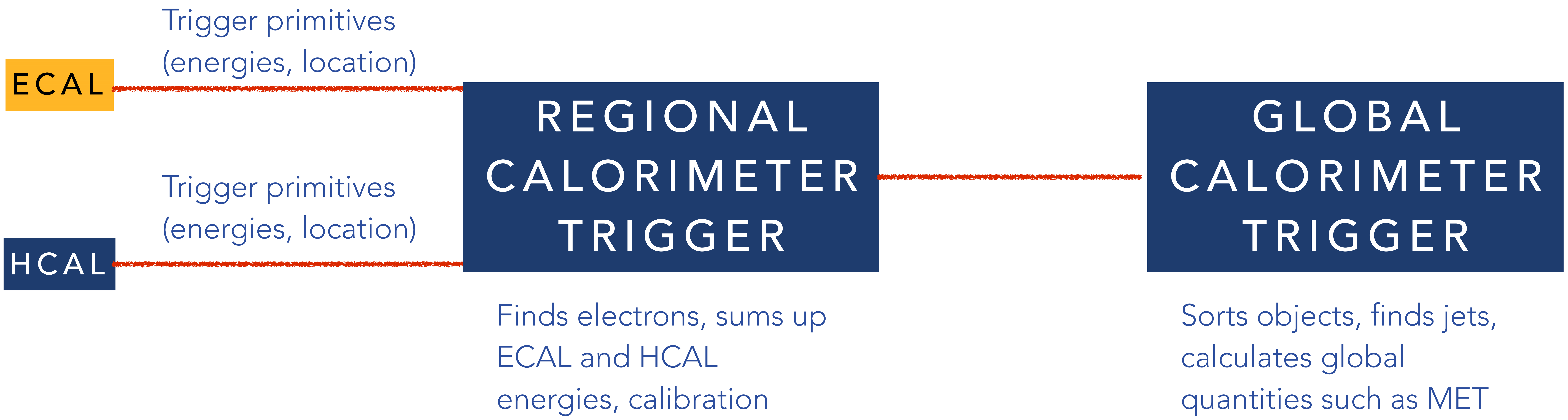
ECAL

HCAL

BASICS: LEVEL 1 CALORIMETER TRIGGER

Finds electrons, sums up ECAL and HCAL energies, calibration

BASICS: LEVEL 1 CALORIMETER TRIGGER



BASICS: LEVEL 1 CALORIMETER TRIGGER

GLOBAL CALORIMETER TRIGGER

Sorts objects, finds jets, calculates global quantities such as MET

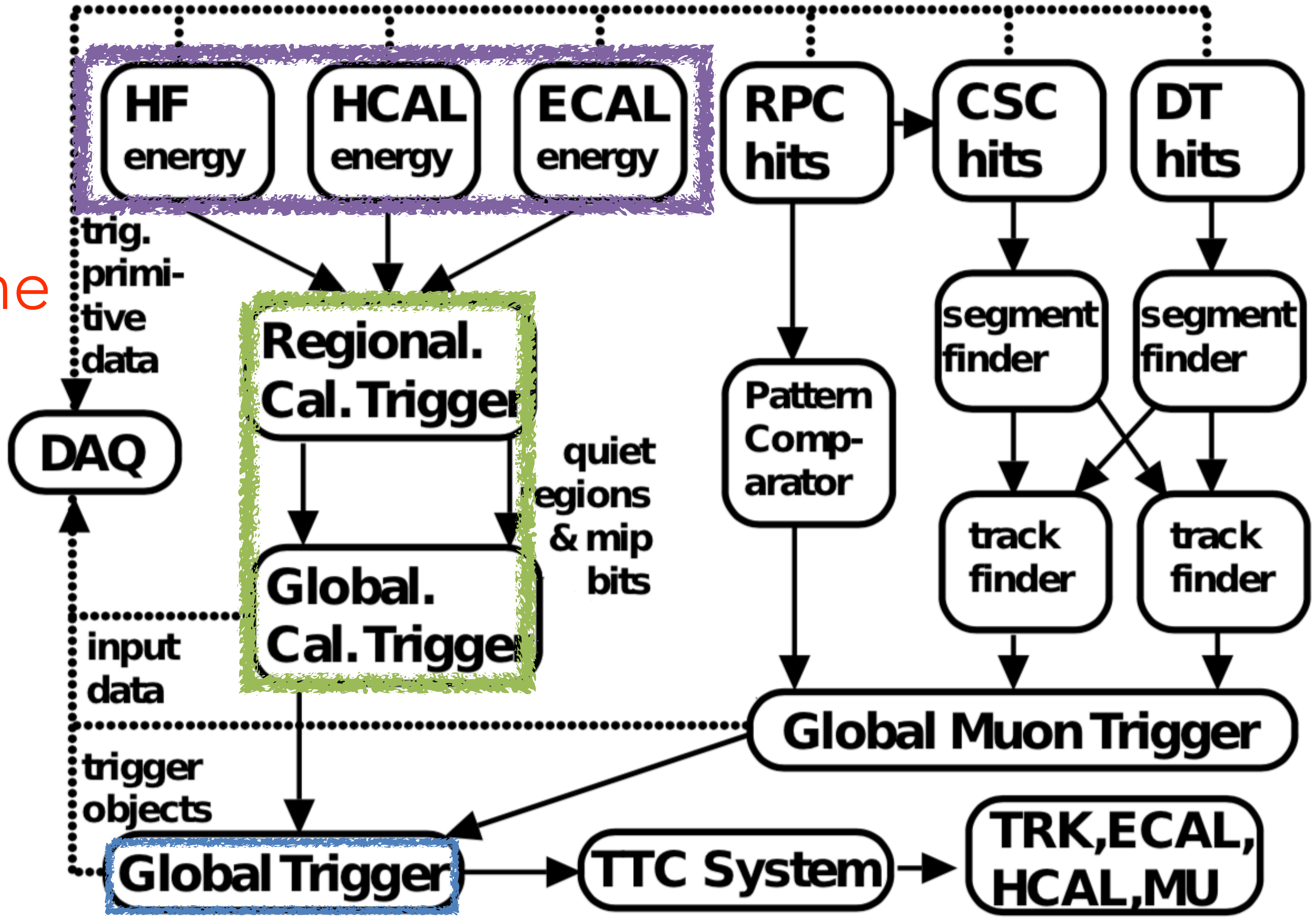
GLOBAL TRIGGER

Implements final decision (accept/reject). Based on objects received from upstream. Implements thresholds on objects

BASICS: LEVEL 1 TRIGGER

includes sending the data!

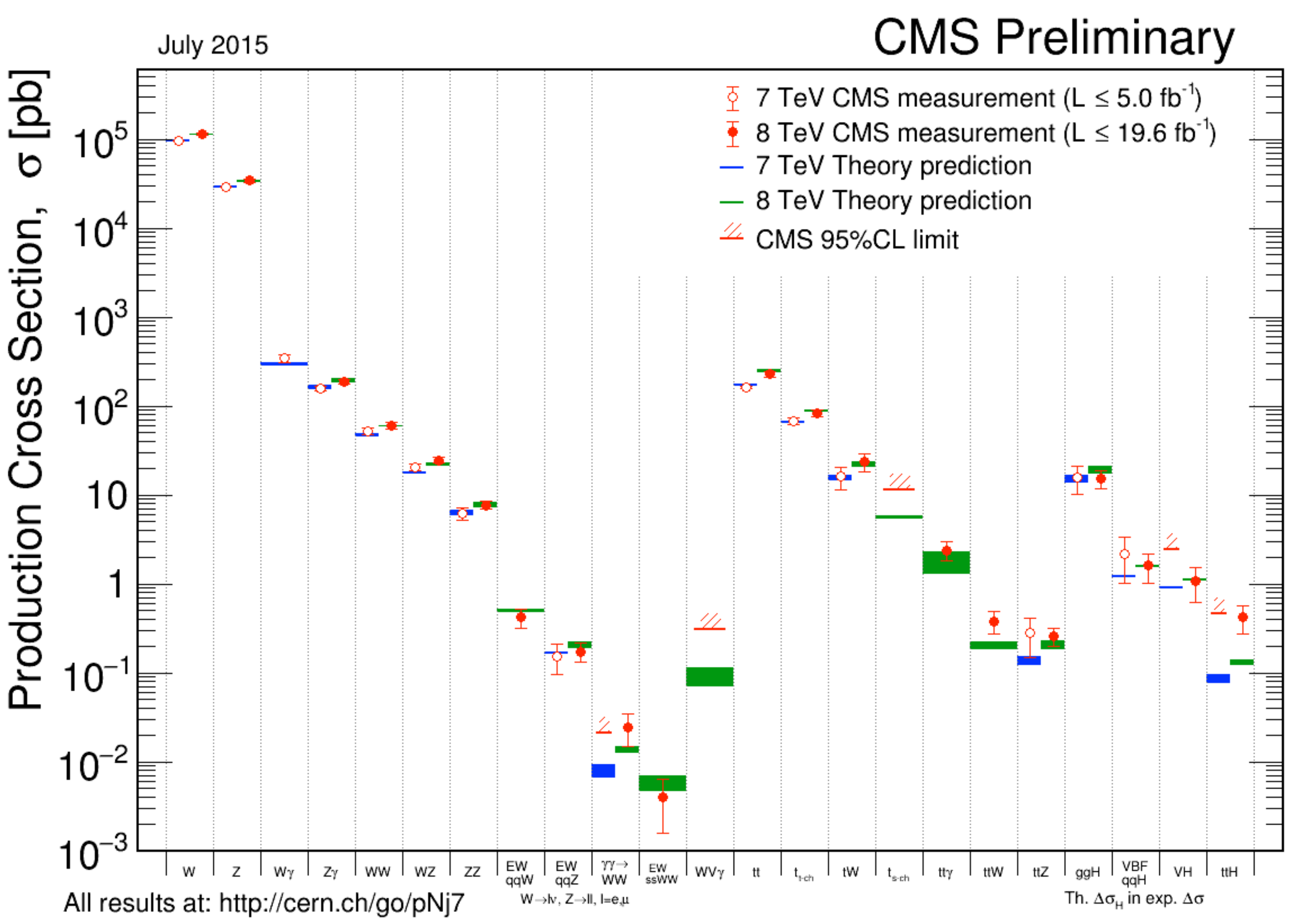
3us



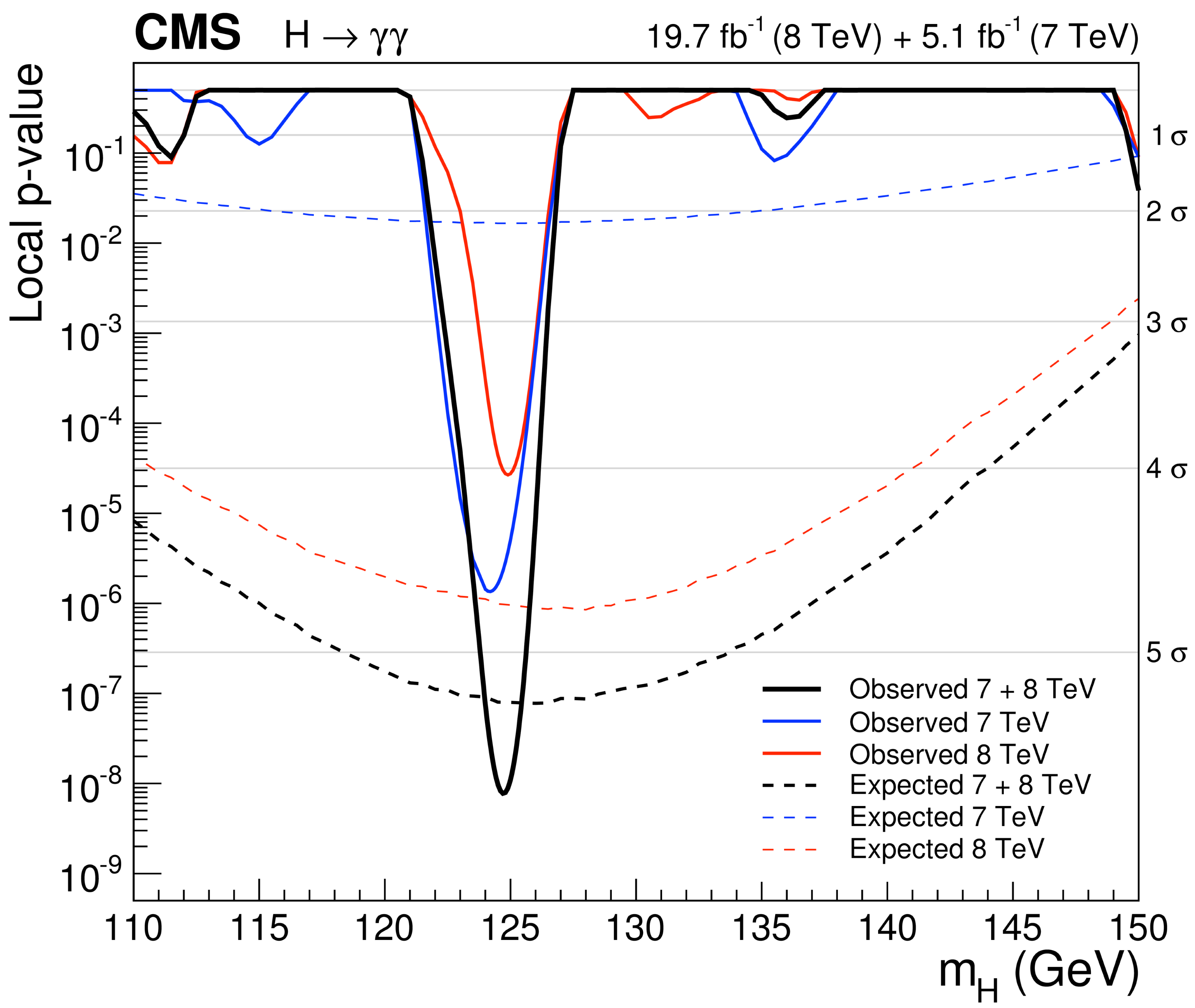
BASICS: LEVEL 1 CALORIMETER TRIGGER

- Driven by technology…
- ASICs - fixed algorithms (application-specific integrated circuits, fixed algorithms)
- early FPGA's - space limitations (field programmable field arrays - flexible)
- Parallel copper links
- Hard to move data around…

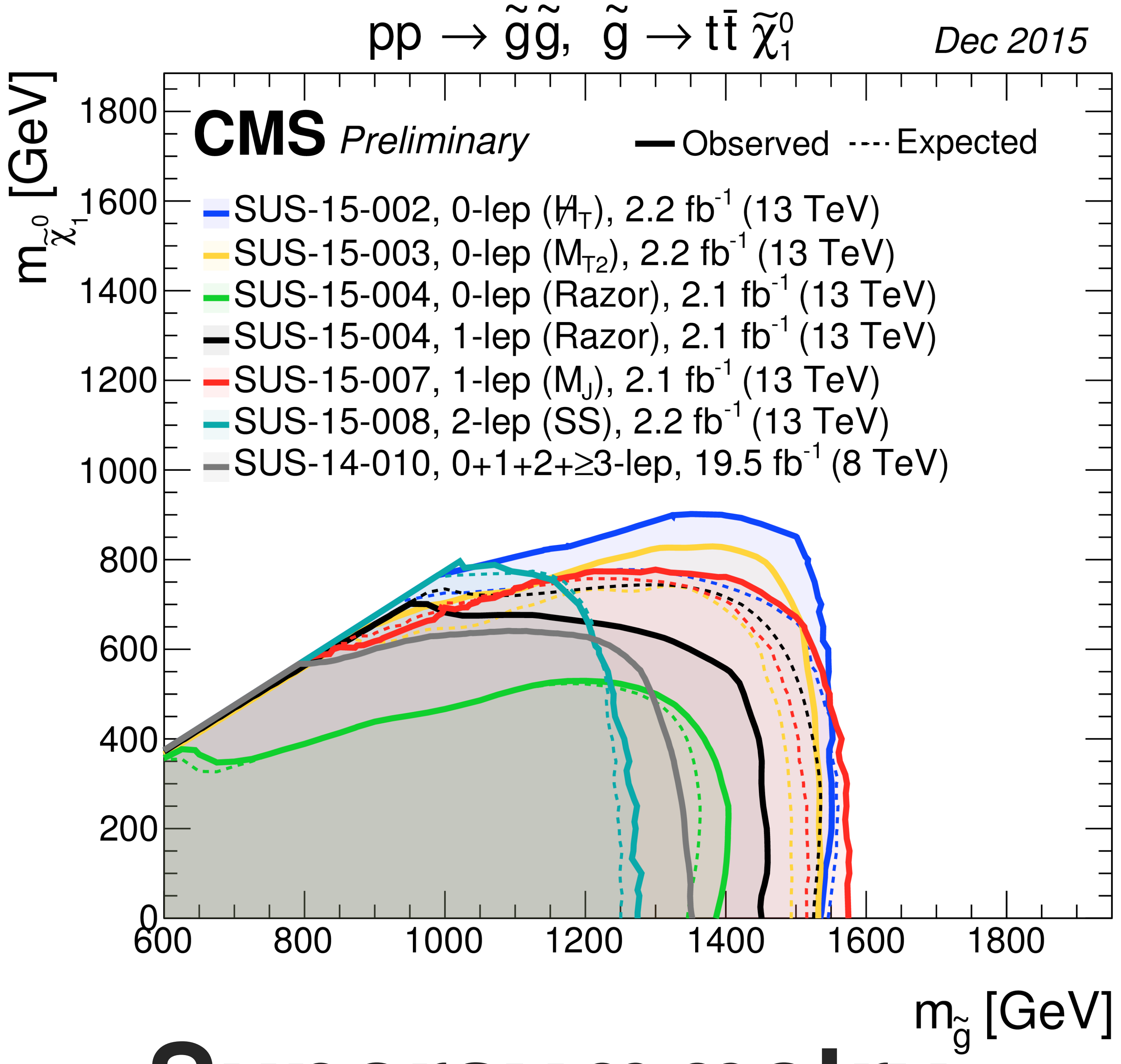
PERFORMED EXTREMELY WELL!



Standard Model



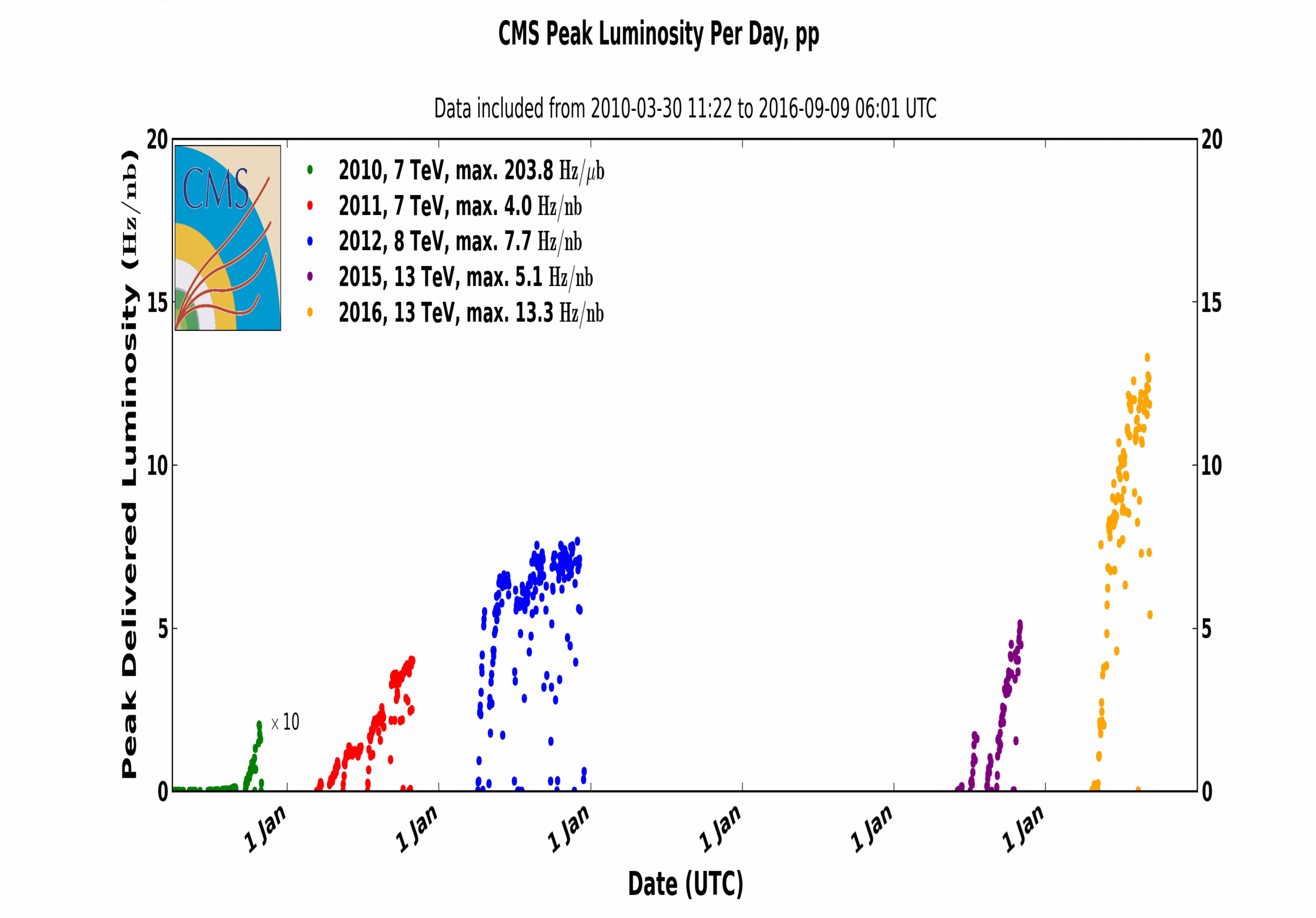
Higgs



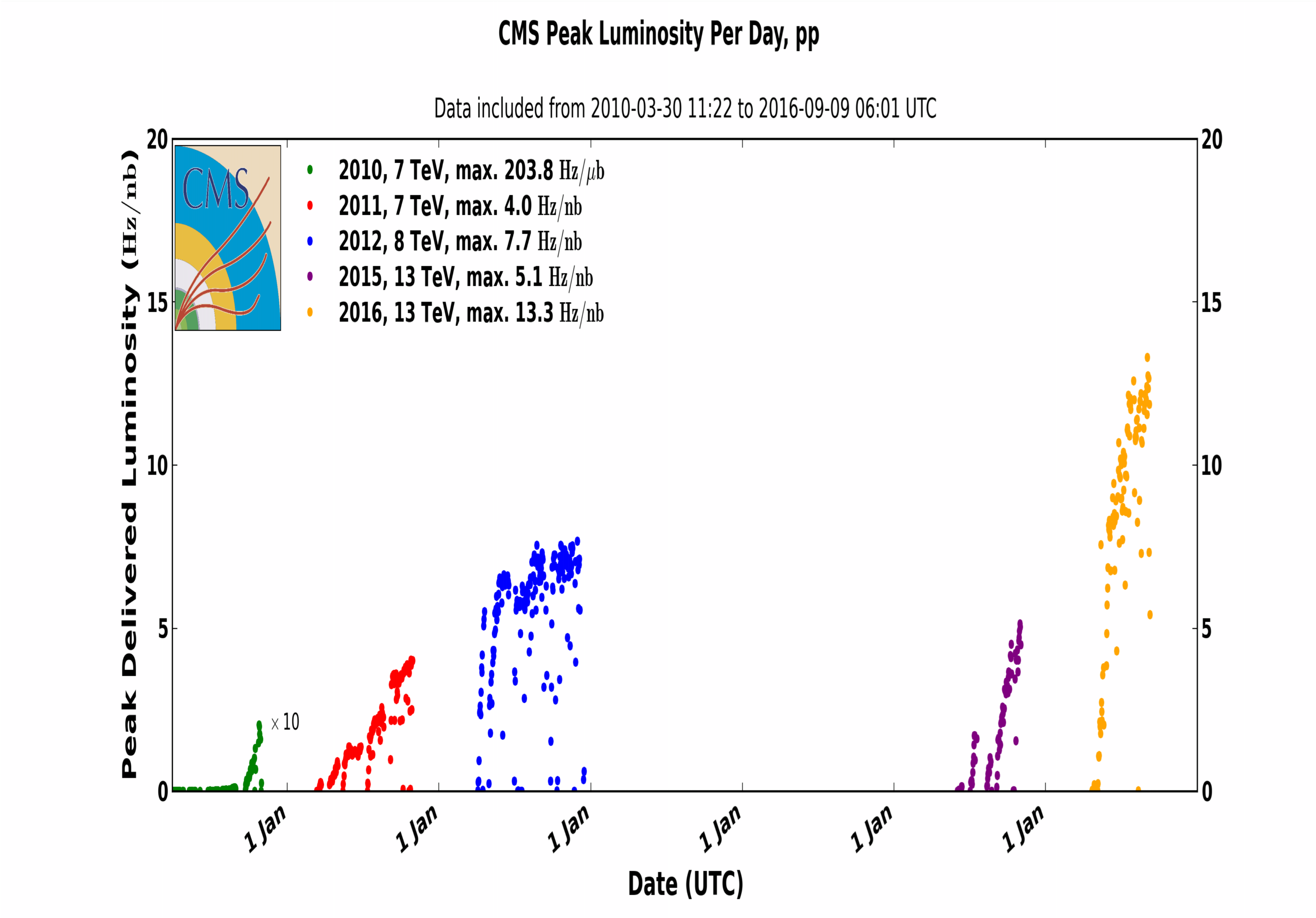
Supersymmetry searches

BUT RUN 2 PRESENTED NEW CHALLENGES…

NEW CONDITIONS



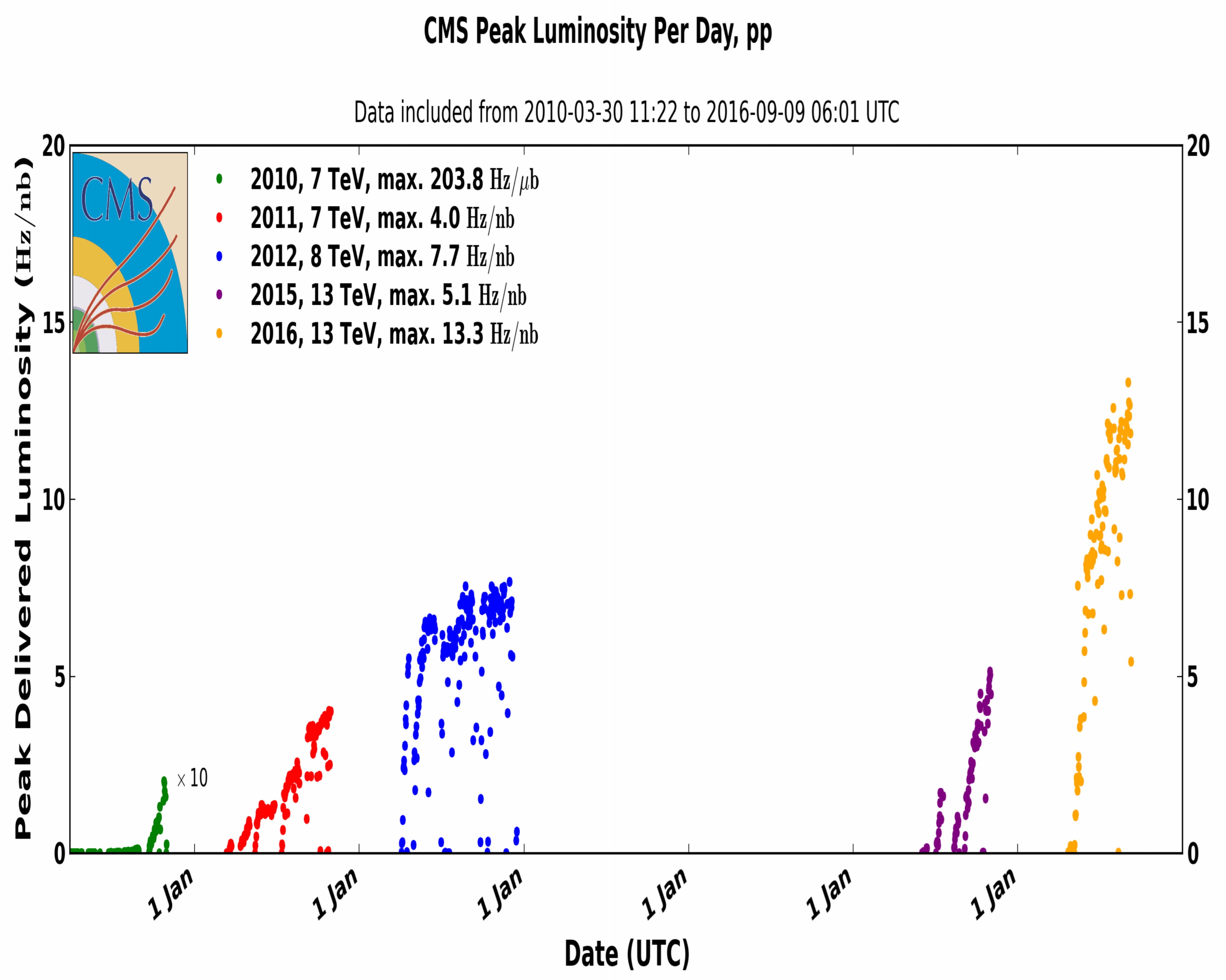
NEW CONDITIONS

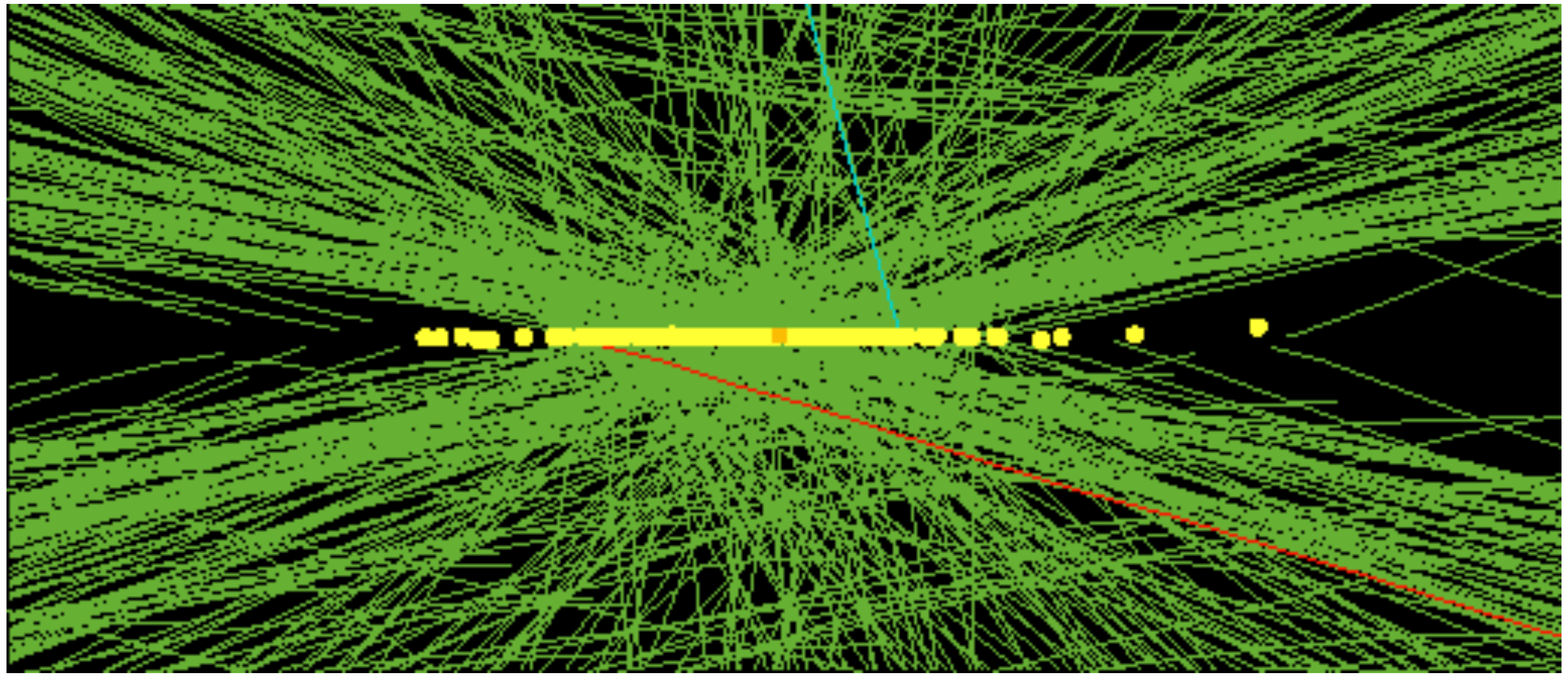


8 TeV → 13 TeV

NEW CONDITIONS

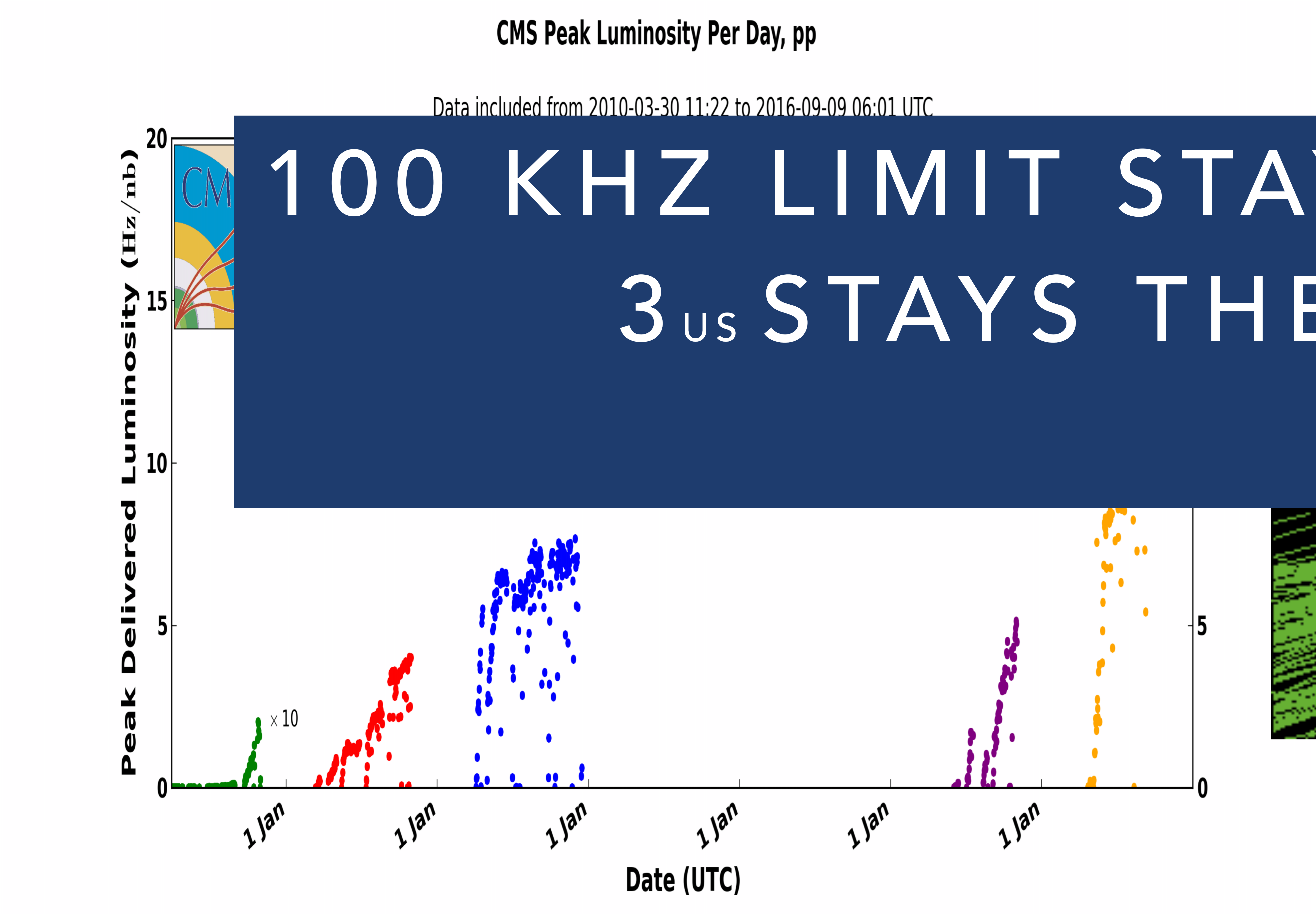
8 TeV → 13 TeV

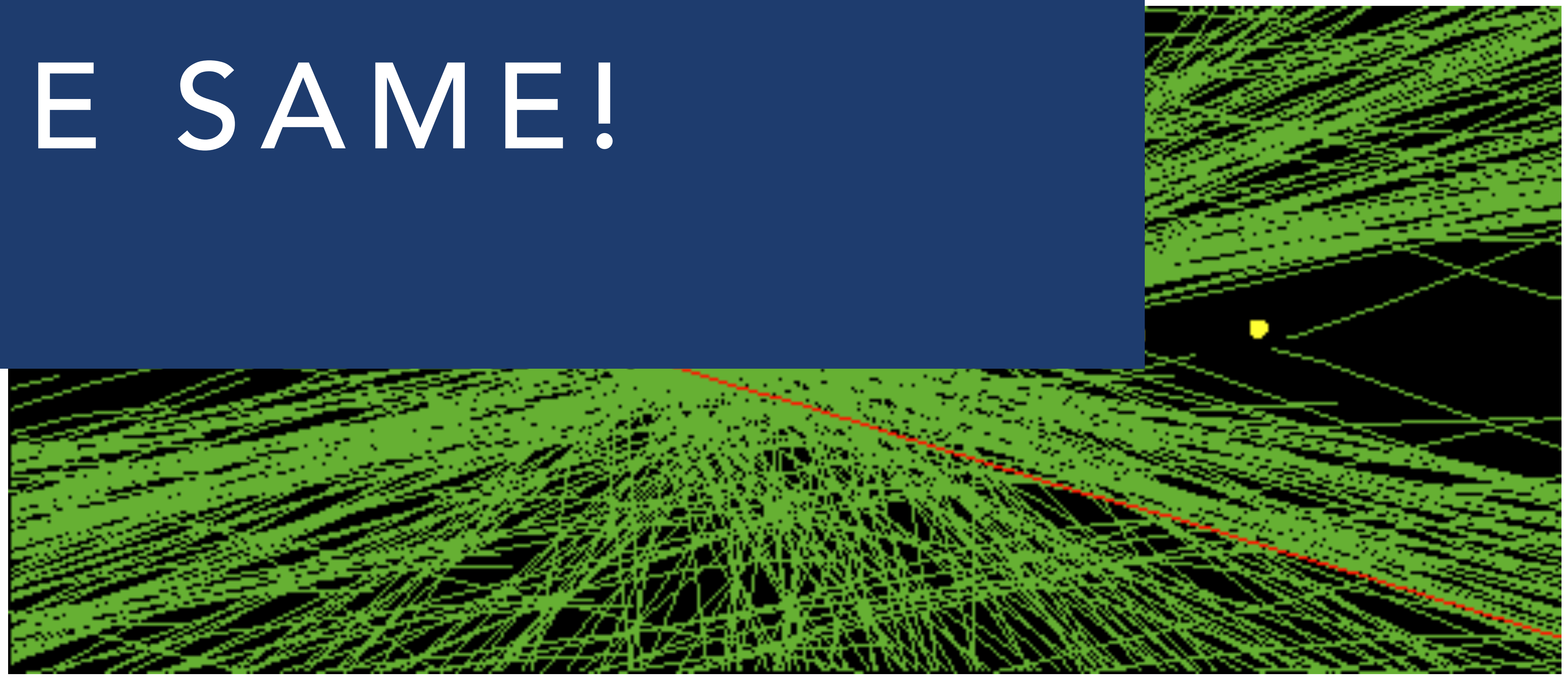




NEW CONDITIONS

8 TeV ⟶ 13 TeV





100 KHZ LIMIT STAYS THE SAME!

3 US STAYS THE SAME!

NEW IDEAS NECESSARY

NEW IDEAS NECESSARY

But need to maintain robustness, flexibility, and of course physics reach! (and don't forget cost!)

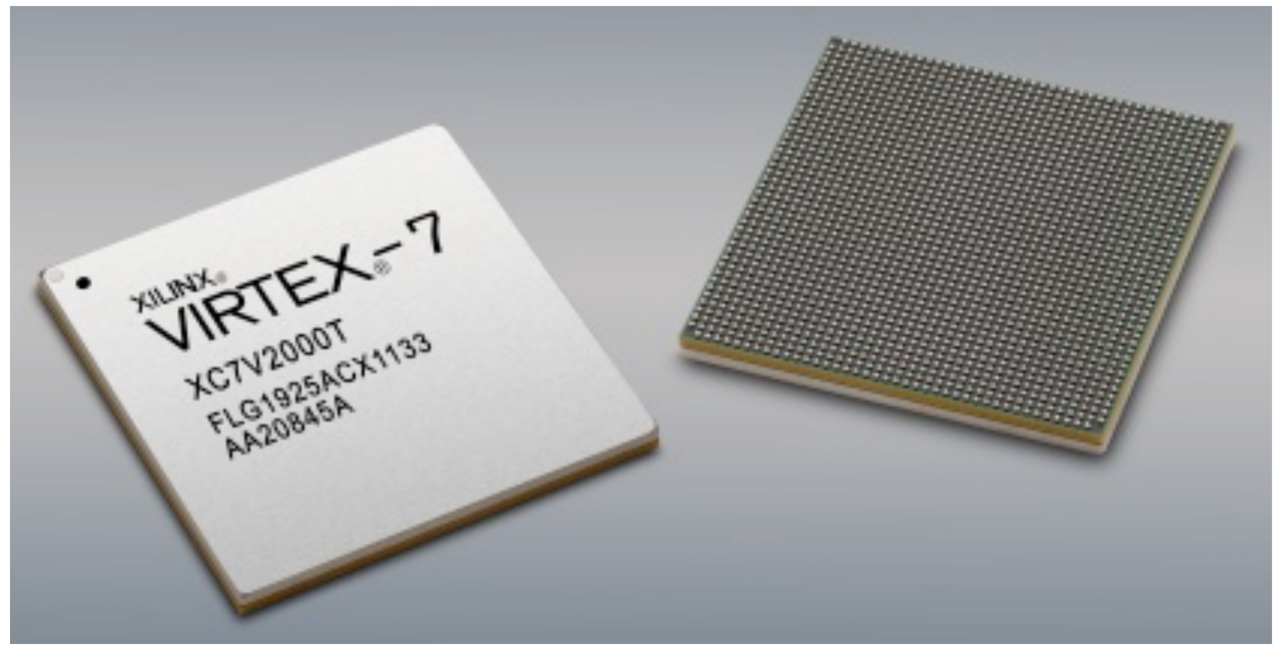
NEW IDEAS NECESSARY

But need to maintain robustness, flexibility, and of course physics reach! (and don't forget cost!)

Only possible by making use of new technologies

NEW IDEAS NECESSARY

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



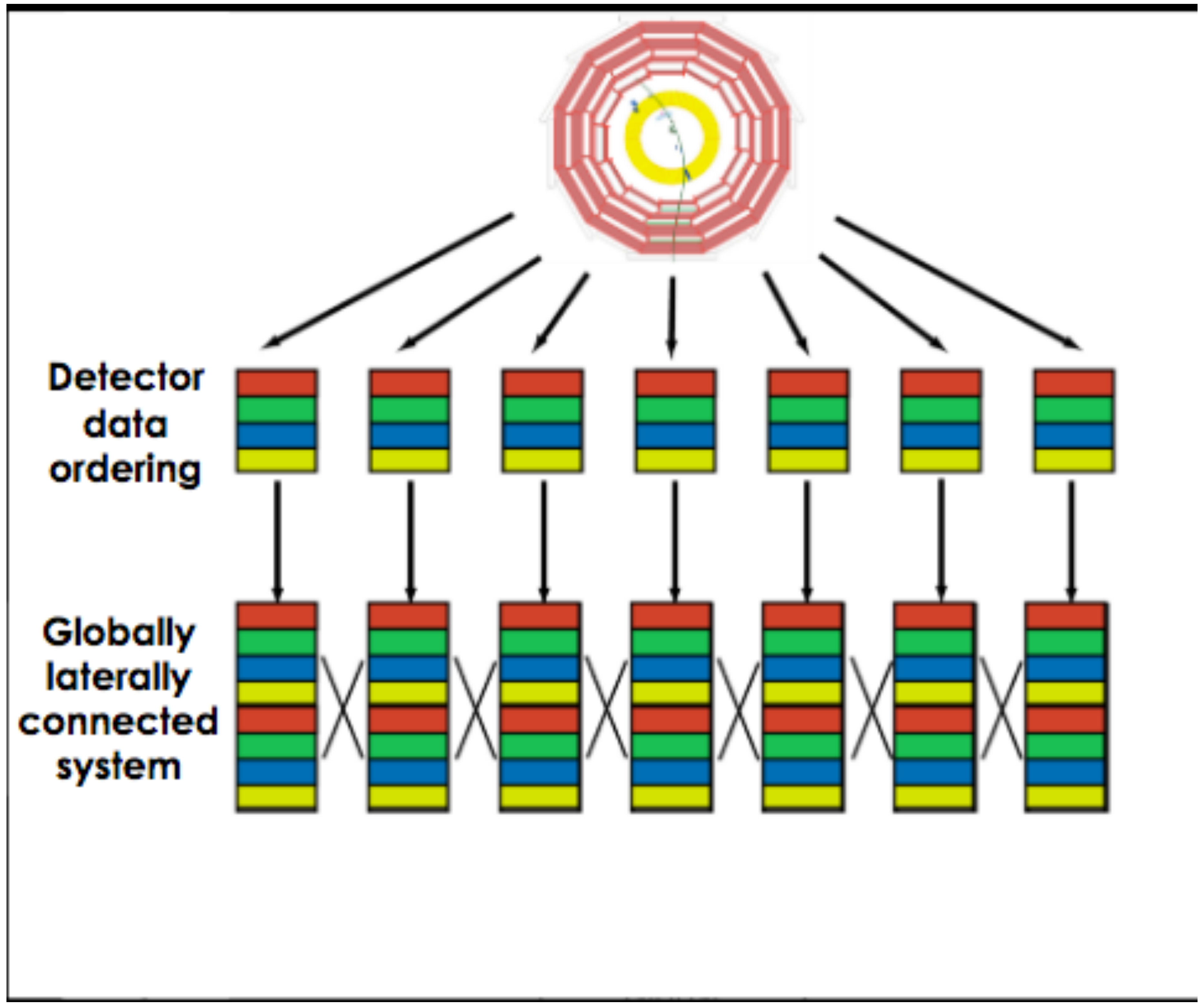
- Up to 2m logical cells
- Up to 2.8 Tb/s total serial bandwidth
- low power consumption

- High speed optical links
- 10 Gb/s

AND PERHAPS USING THIS NEW TECHNOLOGY TO DEVELOP NEW ARCHITECTURES?

TRIGGER ARCHITECTURE CHOICE

Run 1 trigger



- Regional segmentation
- Necessitates sharing of boundary information with adjoining board
- Specific firmware for specific boards

TRIGGER ARCHITECTURE CHOICE

- Using the new technology (optical links, larger FPGAs…) leads to other ideas

TRIGGER ARCHITECTURE CHOICE

- Using the new technology (optical links, larger FPGAs…) leads to other ideas

- **What if we try to optimise the data for processing?**

TRIGGER ARCHITECTURE CHOICE

- Using the new technology (optical links, larger FPGAs…) leads to other ideas

- **What if we try to optimise the data for processing?**

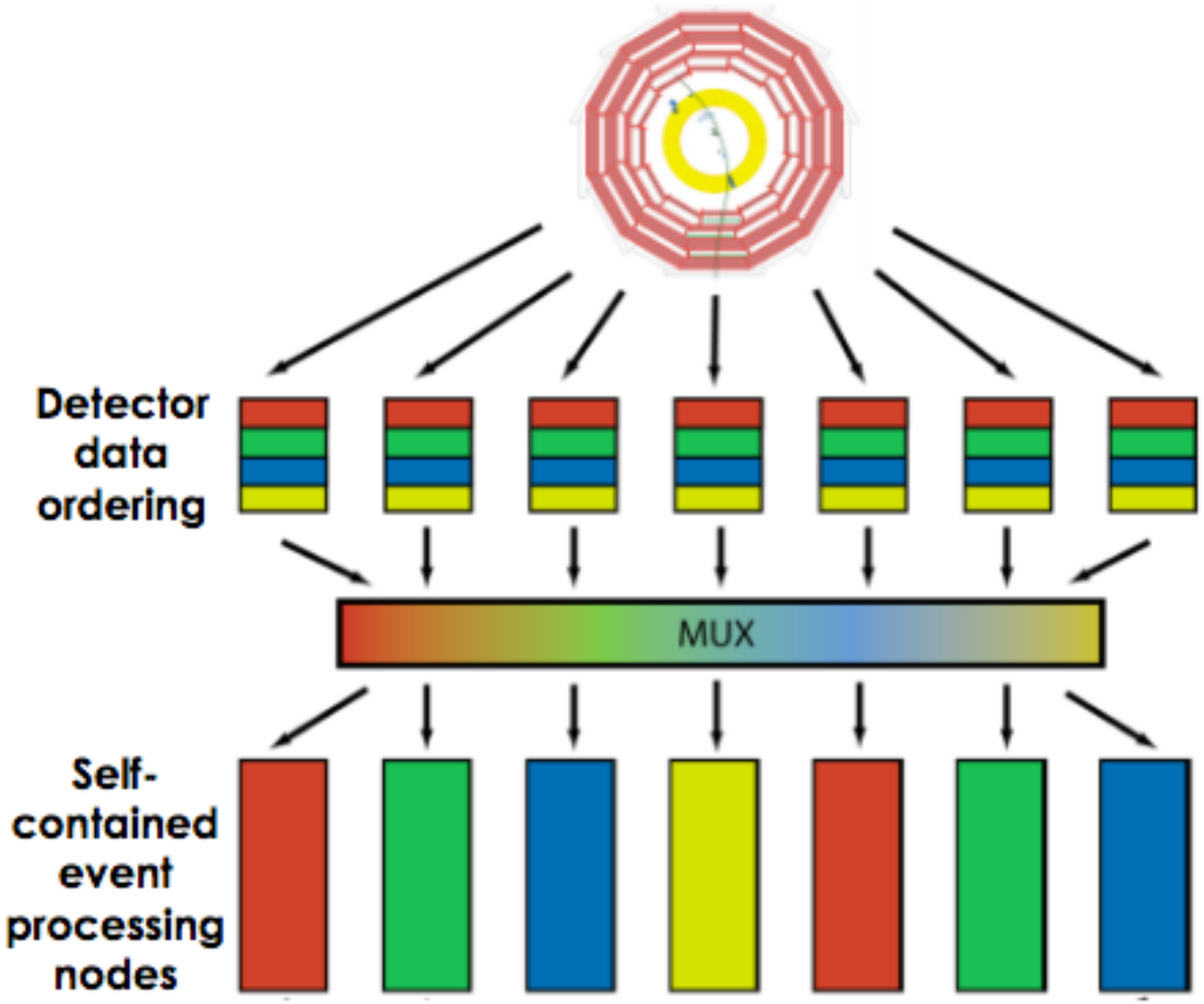
- **Can spread out over time and reuse FPGA resources?**

TRIGGER ARCHITECTURE CHOICE

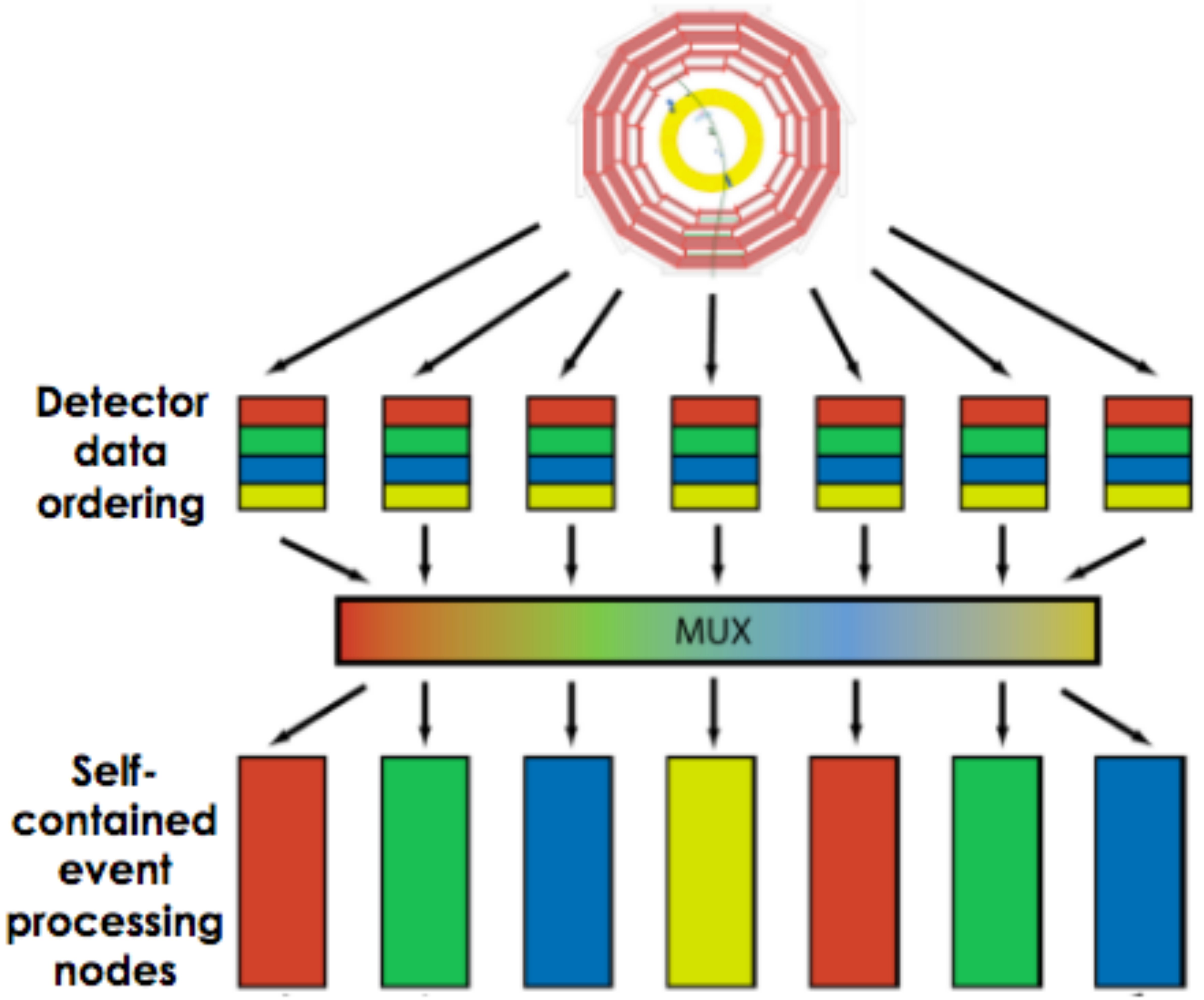
- Using the new technology (optical links, larger FPGAs…) leads to other ideas

- **What if we try to optimise the data for processing?**
- **Can spread out over time and reuse FPGA resources?**
- **Eliminate boundaries?**

TIME-MULTIPLEXED TRIGGER

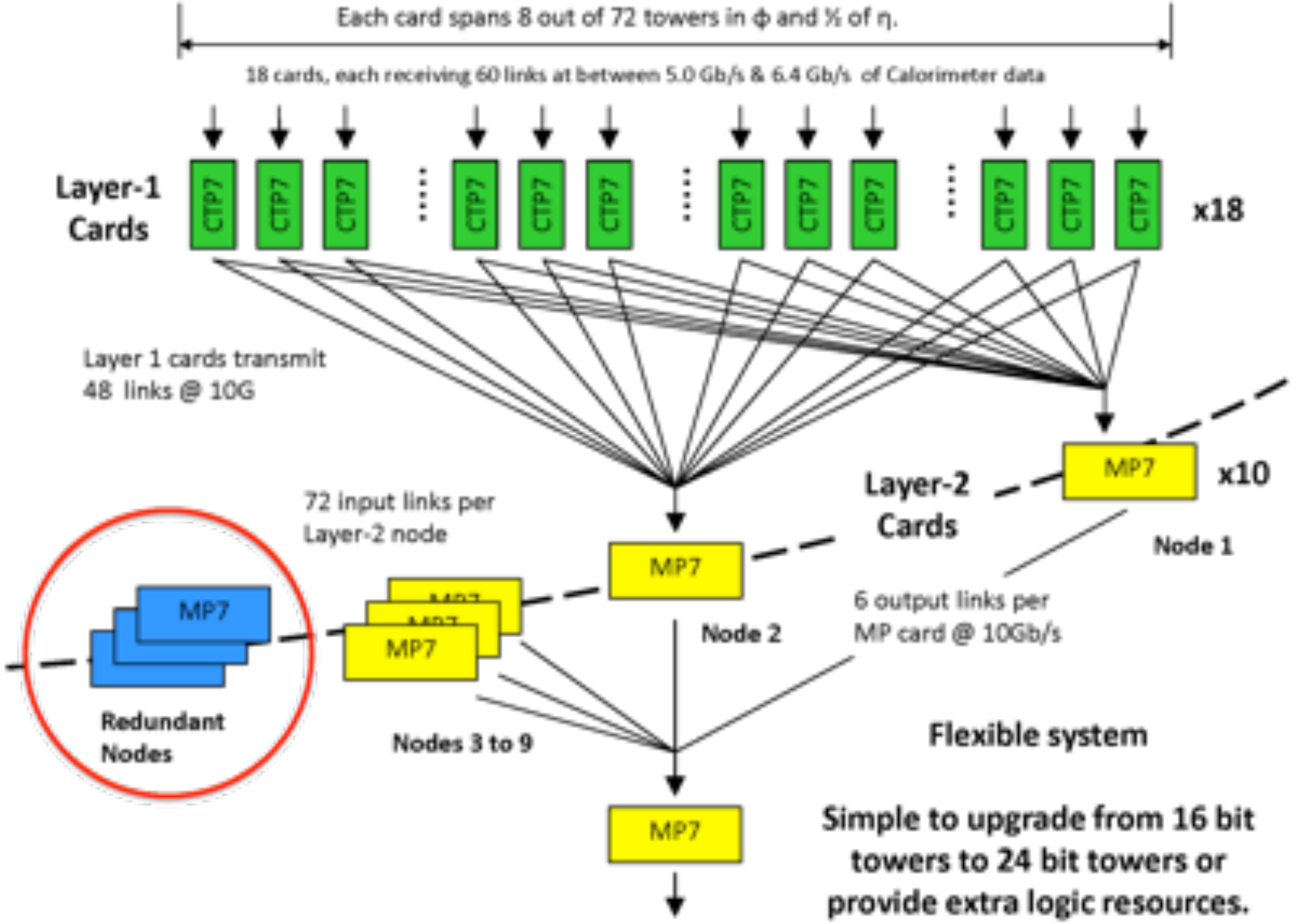


TIME-MULTIPLEXED TRIGGER



Chosen as the CMS Calorimeter Trigger for Run II and Run III

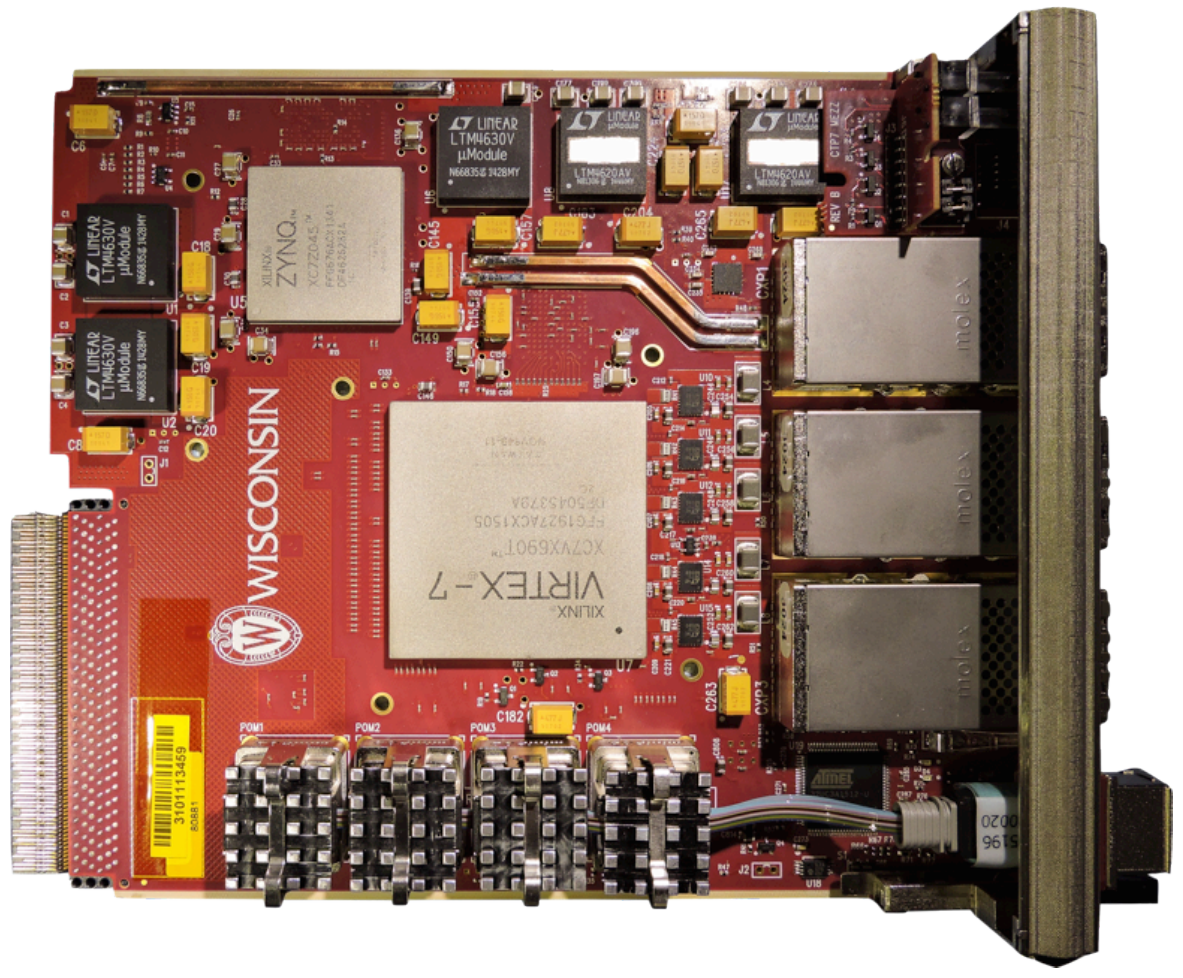
TIME-MULTIPLEXED TRIGGER



All calorimeter algorithms, e/g, jets, taus, sums,contained in processing layer!!

DEVELOPED NEW CARDS WITH CUTTING EDGE TECHNOLOGY - GENERIC USE

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

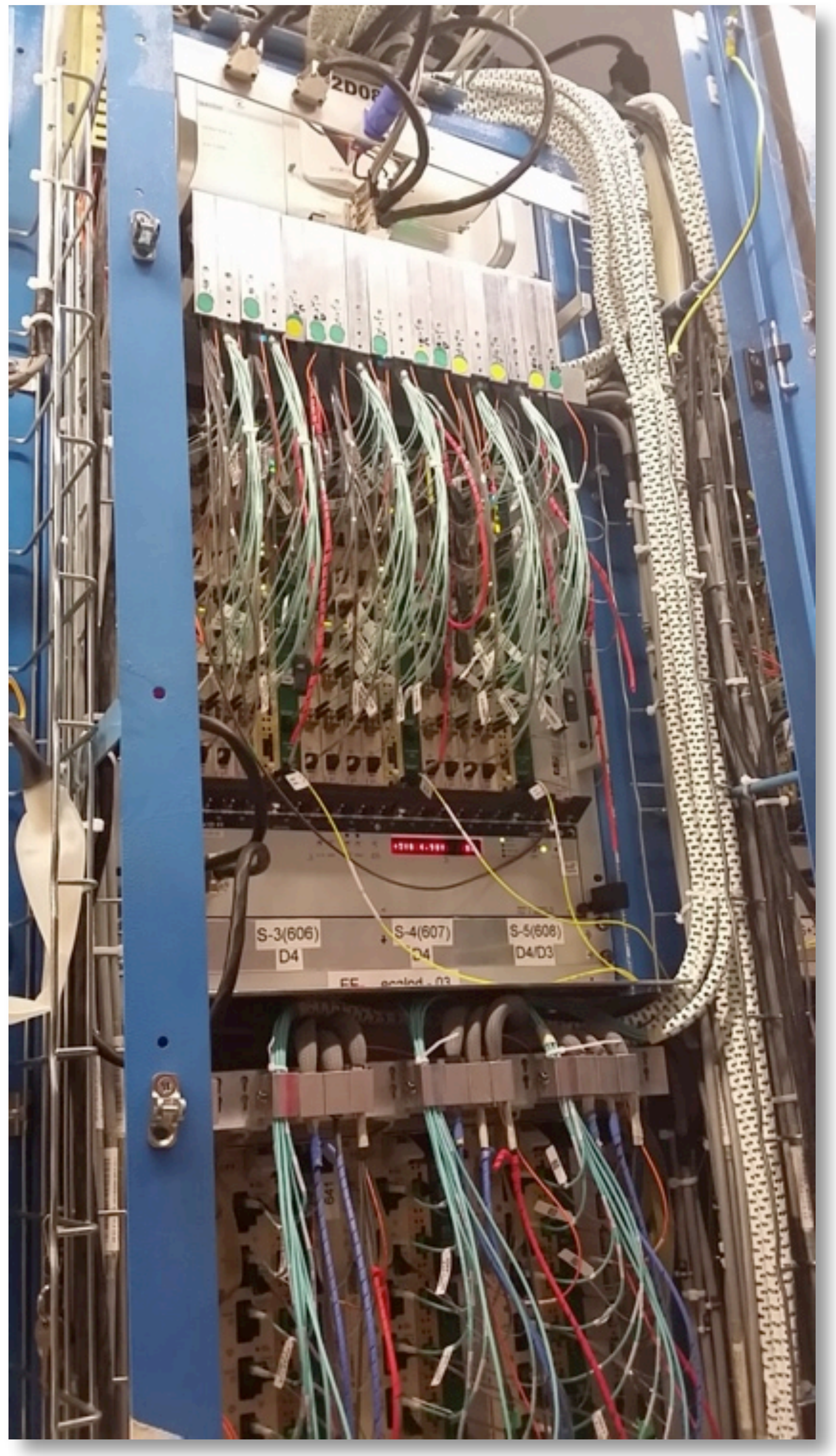


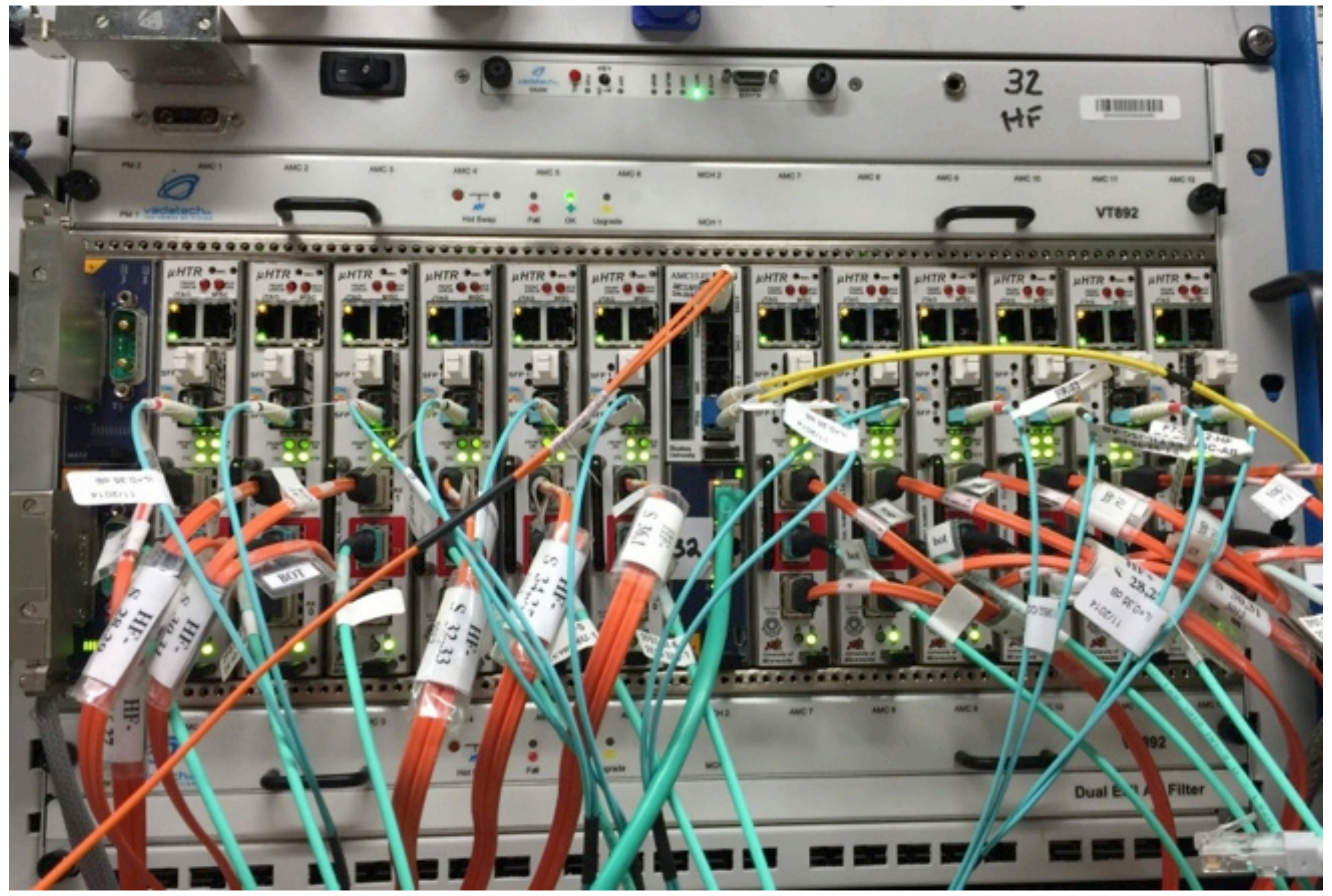
- MP7
- uTCA form factor
- Single Vertex 7 FPGA
- 72 optical inputs, 72 outputs
- Dual 72 or 144MB QDR RAM clocked at 500 MHz

HOW DID WE BUILD IT?

Starts with the Calorimeters

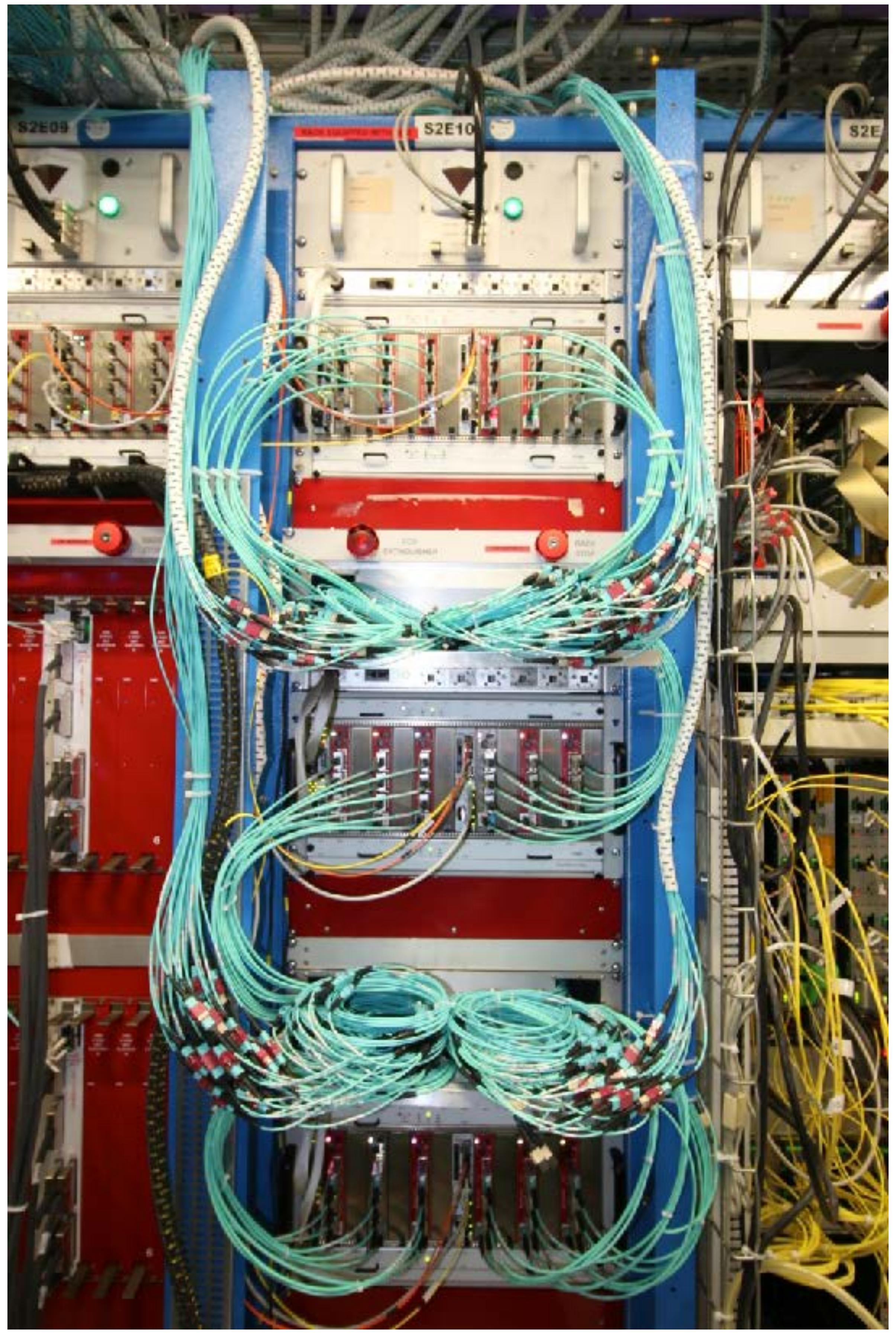
Replaced copper links by optical
1152 links!!





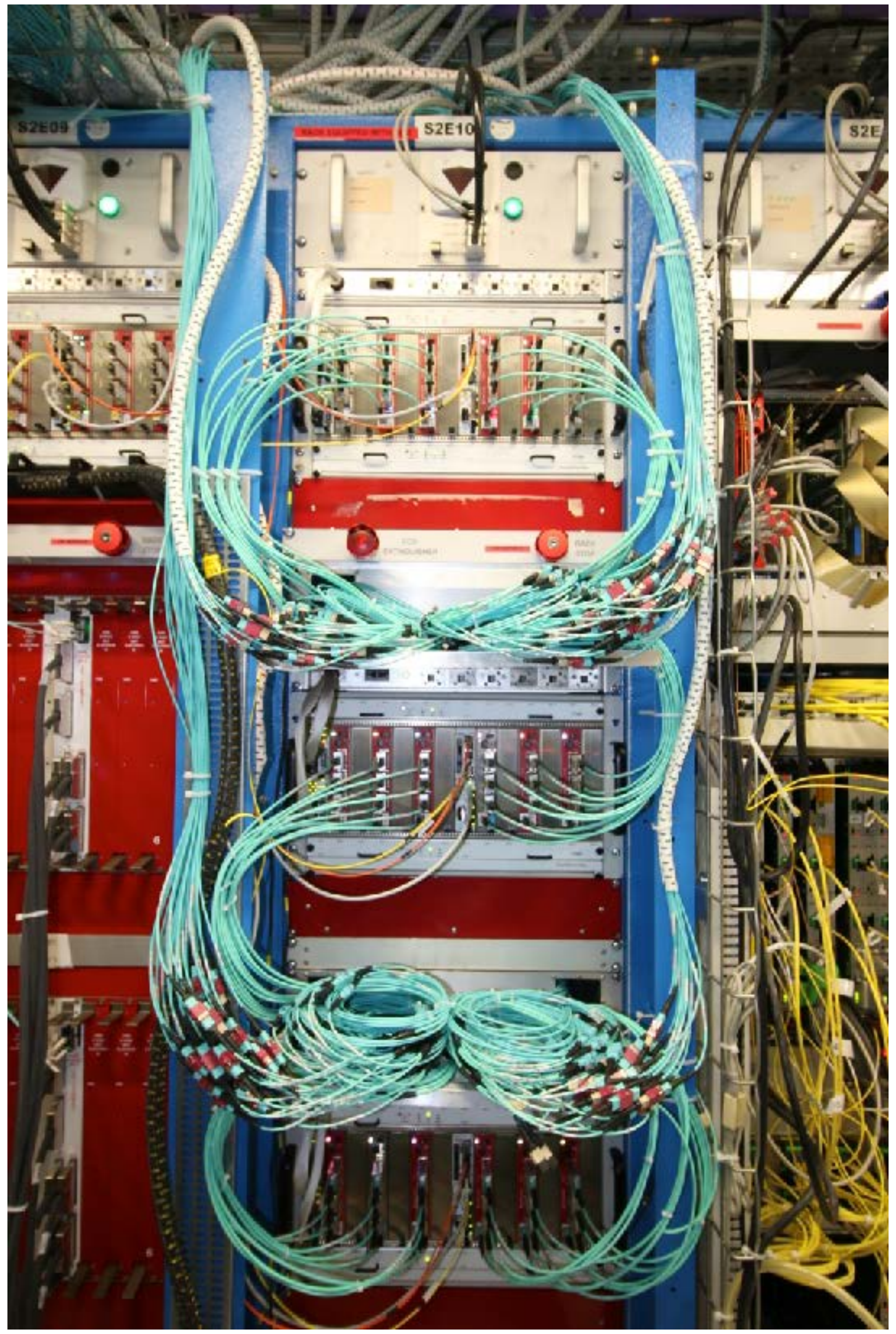
HOW DID WE BUILD IT?

Then move to pre-processing layer collecting, processing calorimeter data

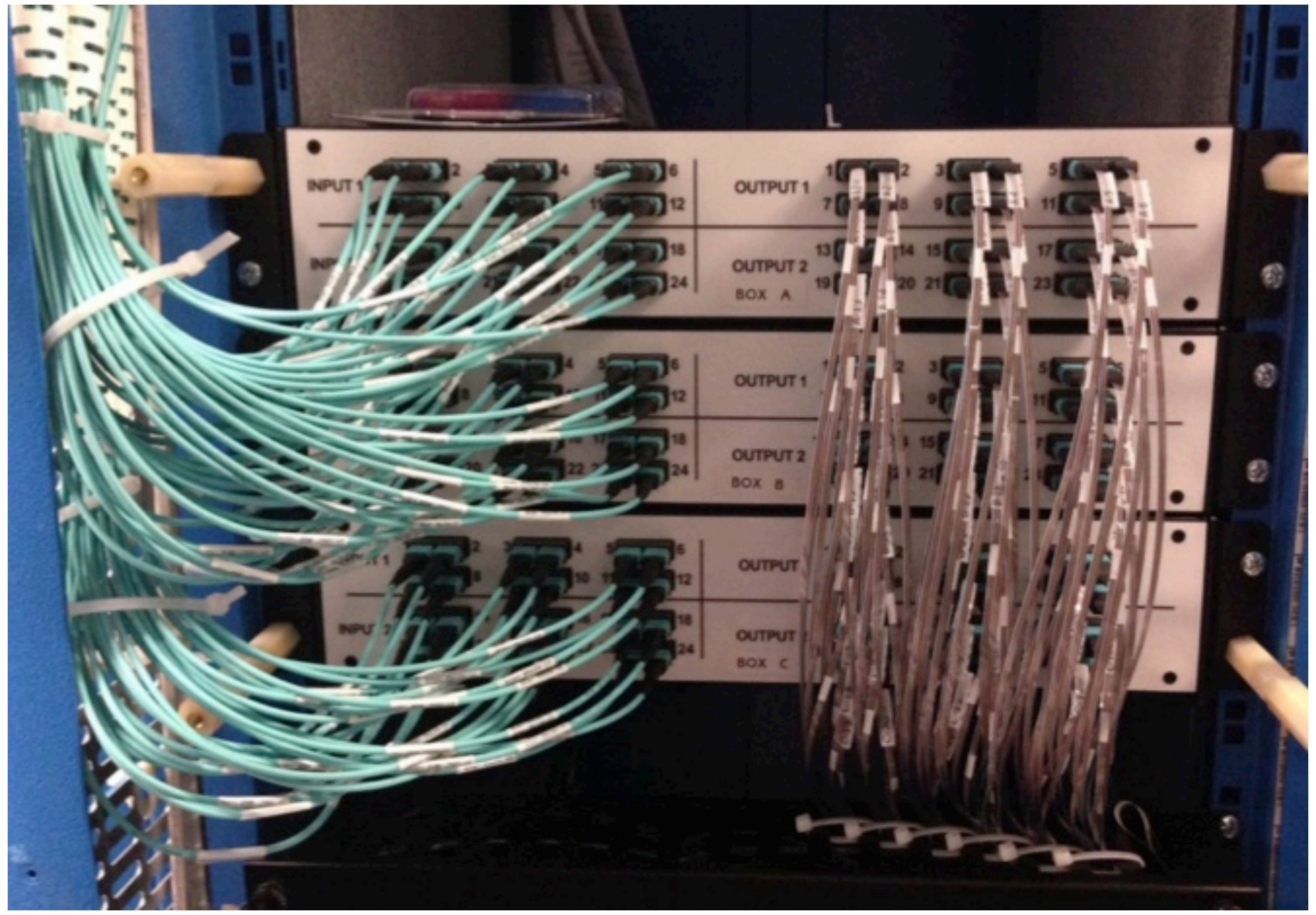


HOW DID WE BUILD IT?

Then move to pre-processing layer collecting, processing calorimeter data

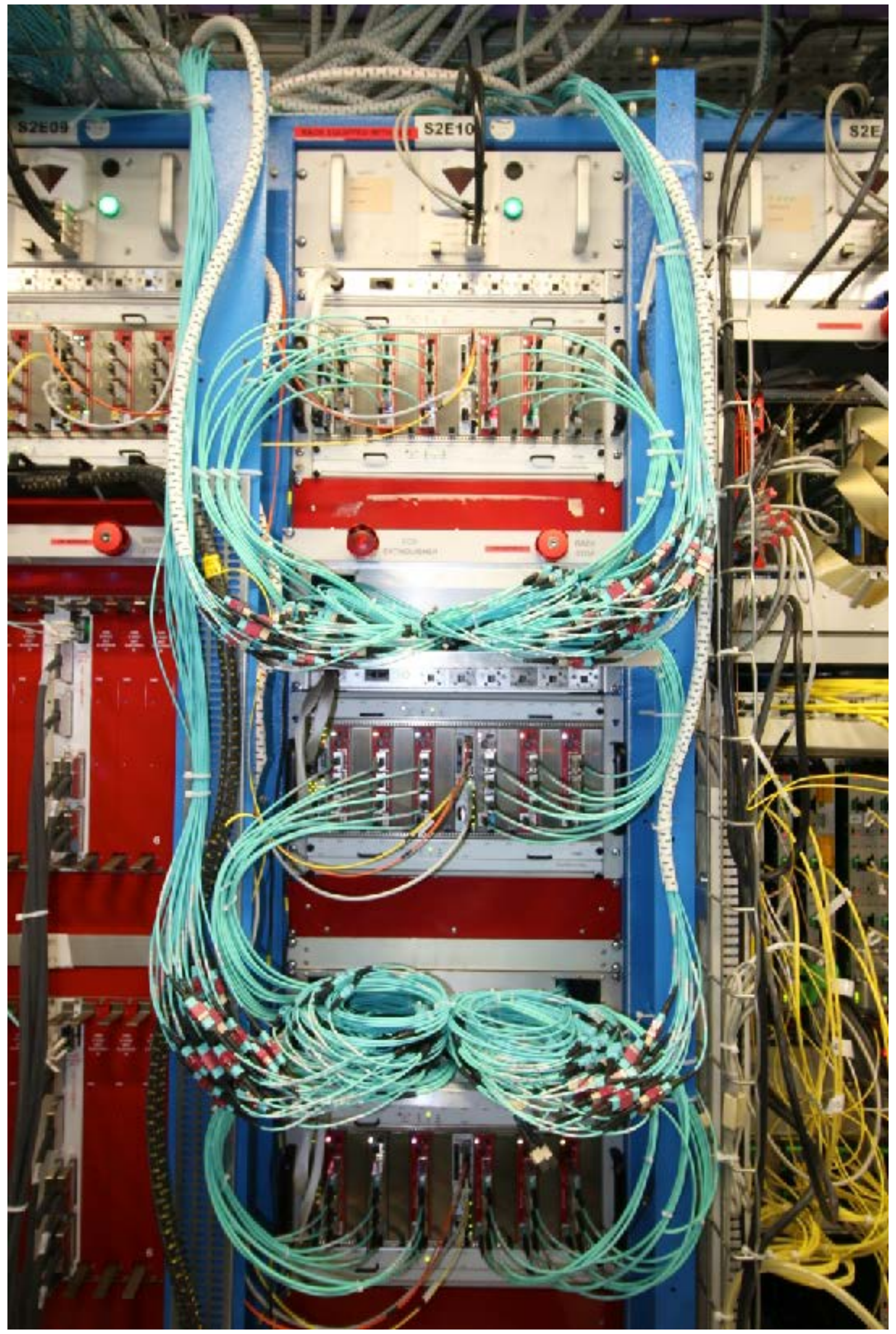


Multiplexing

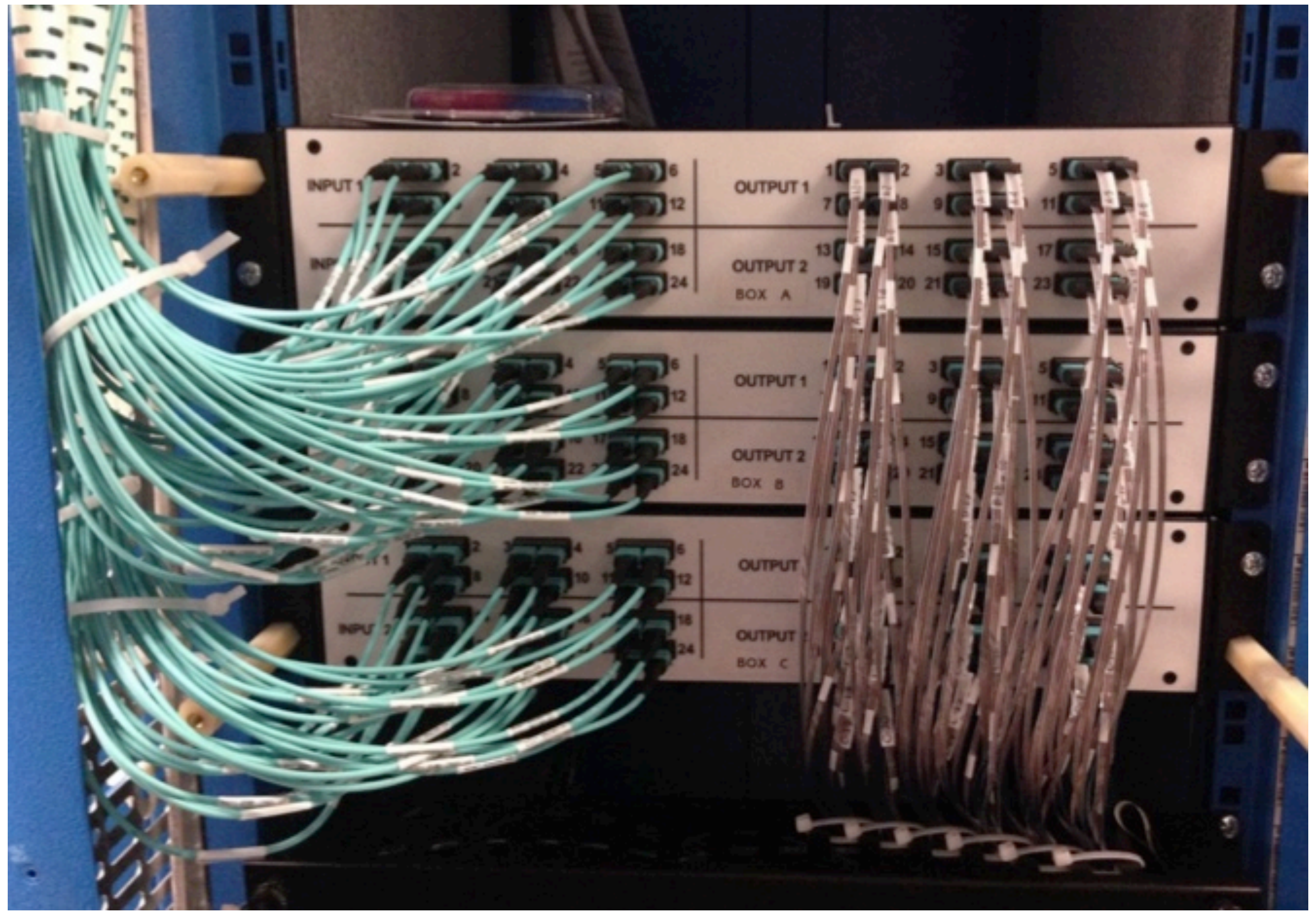


HOW DID WE BUILD IT?

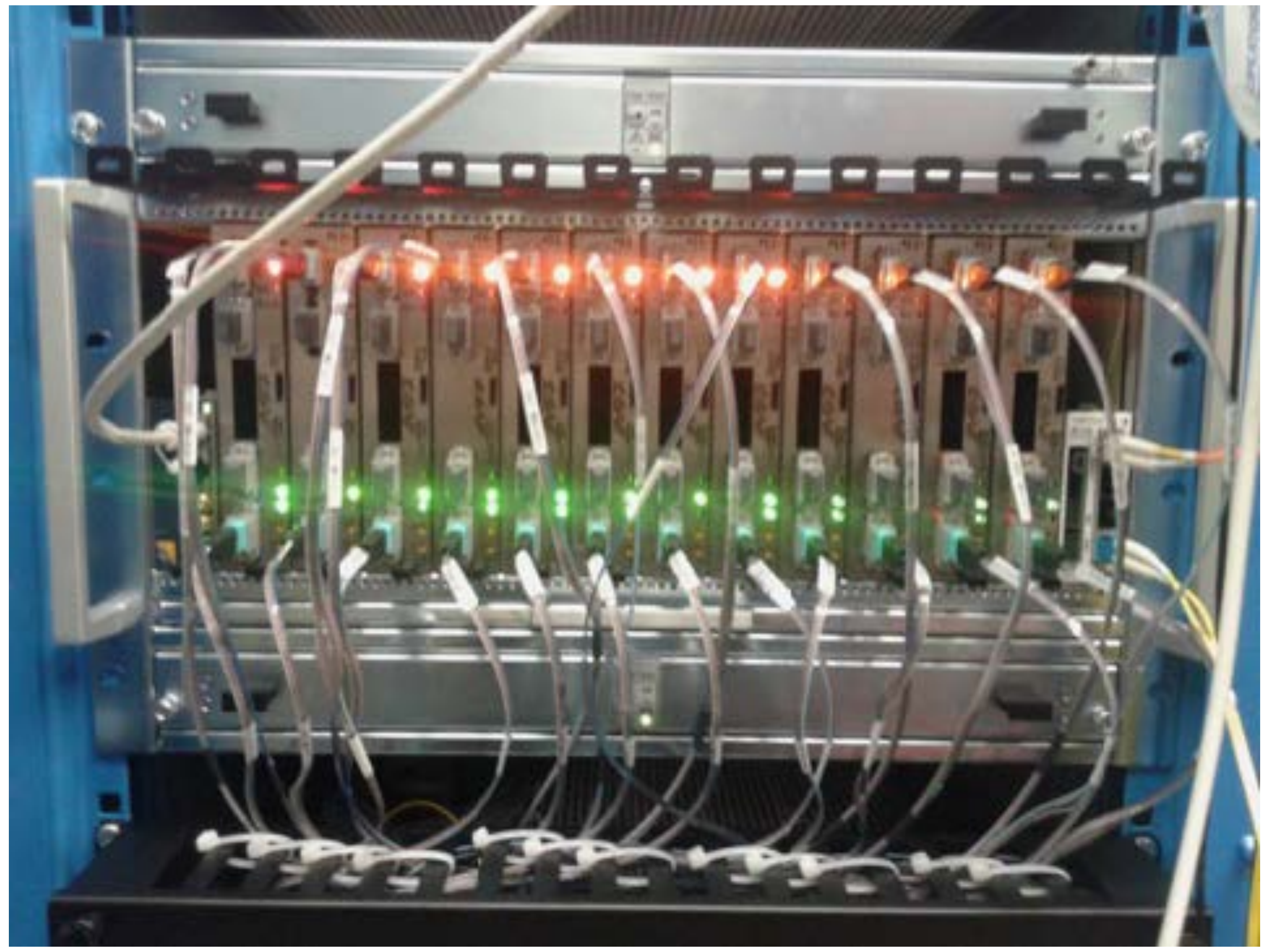
Then move to pre-processing layer collecting, processing calorimeter data



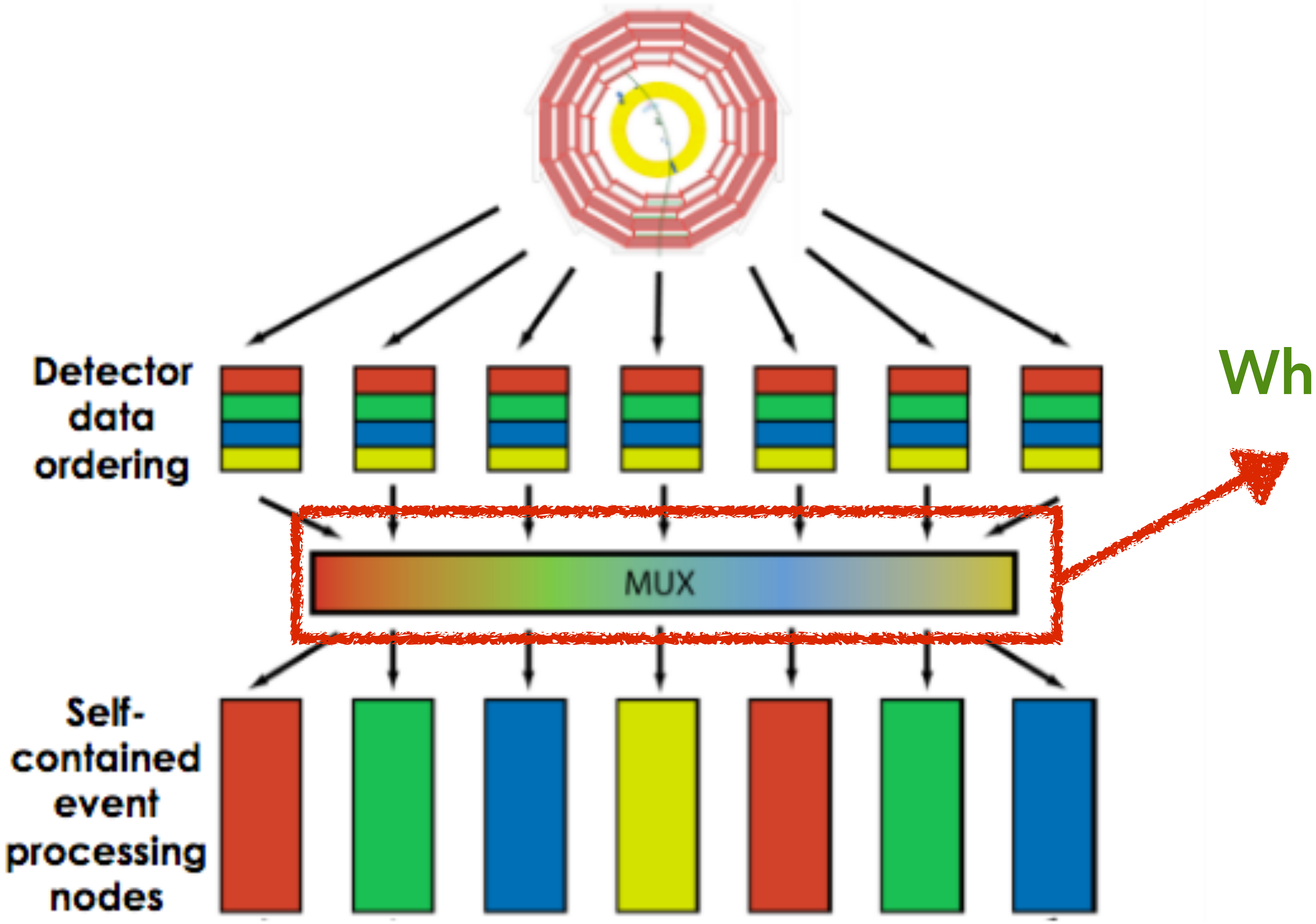
Multiplexing



Algorithm layer
9 nodes
Each node identical



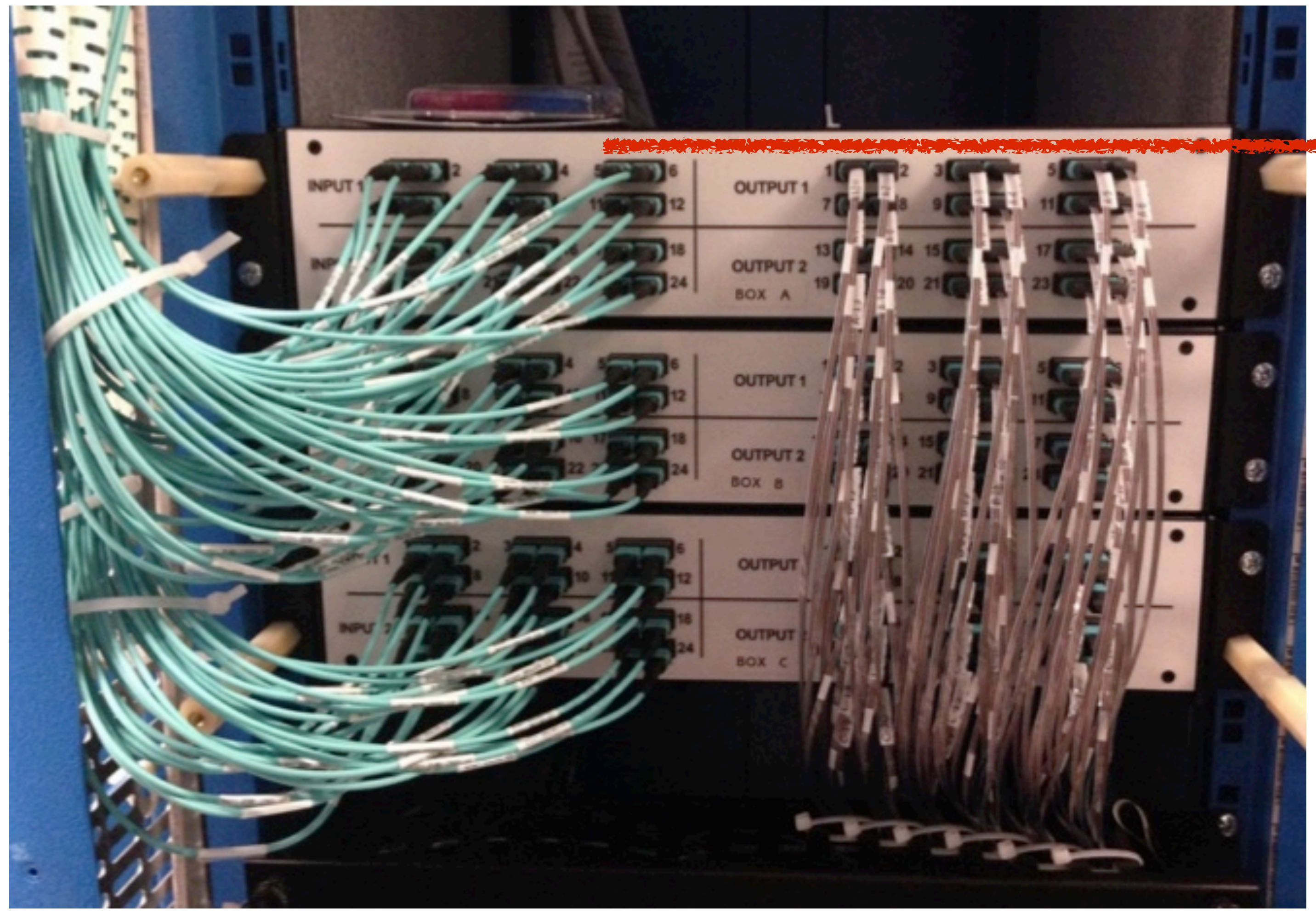
HOW DOES THE MULTIPLEXER WORK?



What goes on in this box?

HOW DOES THE MULTIPLEXER WORK?

INPUT



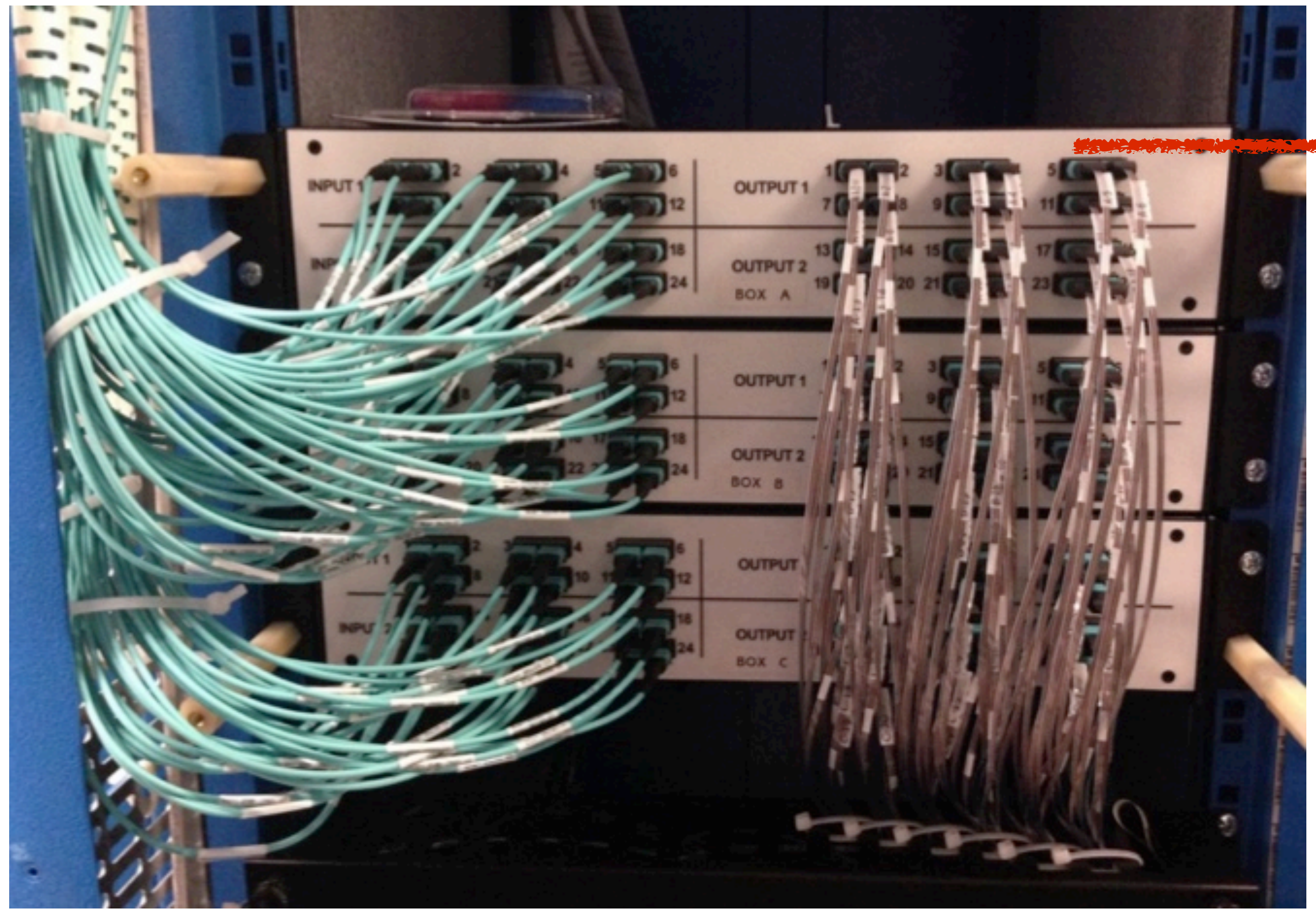
MPO12 ribbon

BX 1 2 3

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

HOW DOES THE MULTIPLEXER WORK?

OUTPUT



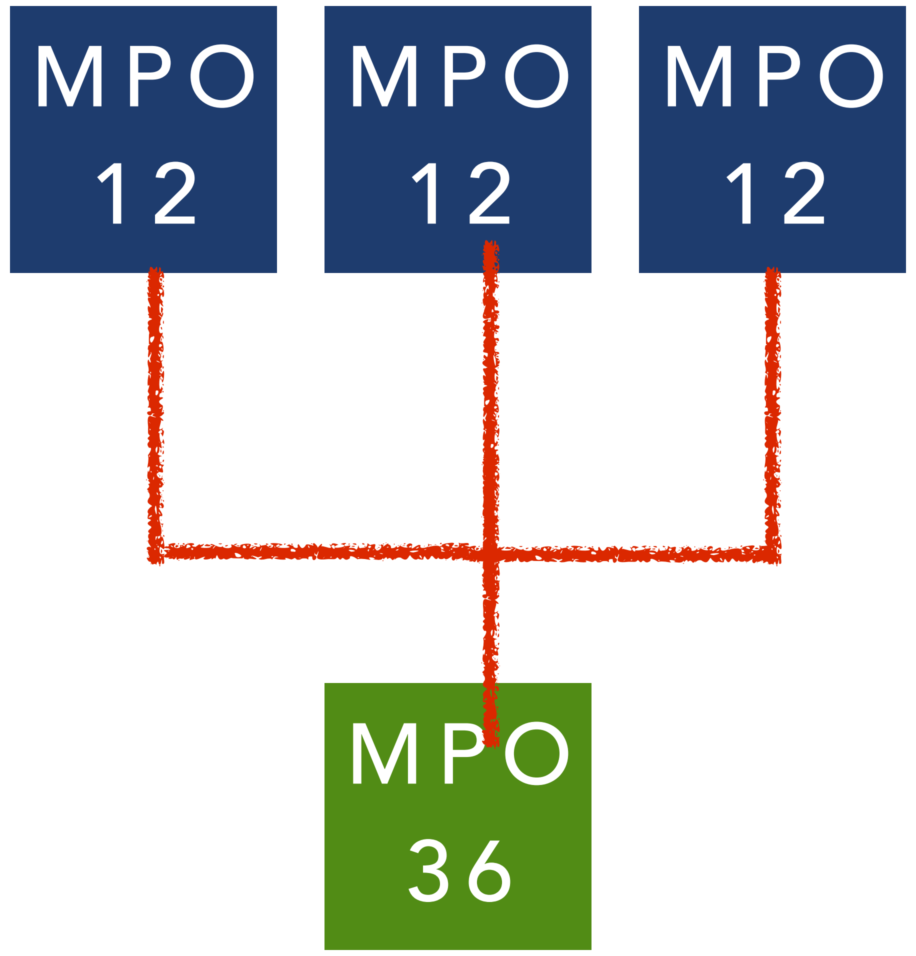
MPO12 ribbon

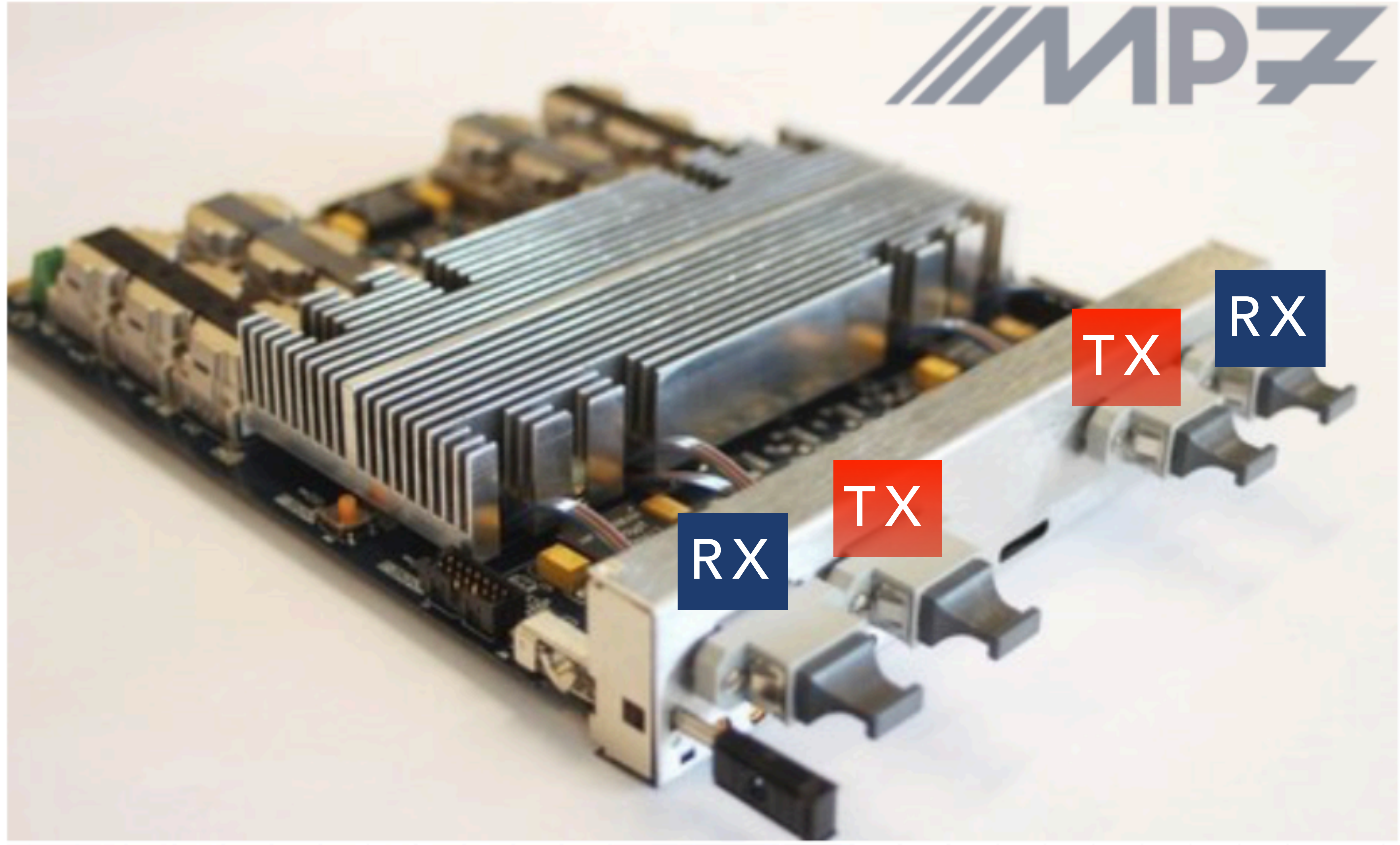
BX 111

- Each MPO12 ribbon groups data from the same BX, but different regions of the detector

HOW DOES THE MULTIPLEXER WORK?

- To get information from the whole calorimeter - need 72 links (calorimeter split into 72 regions).

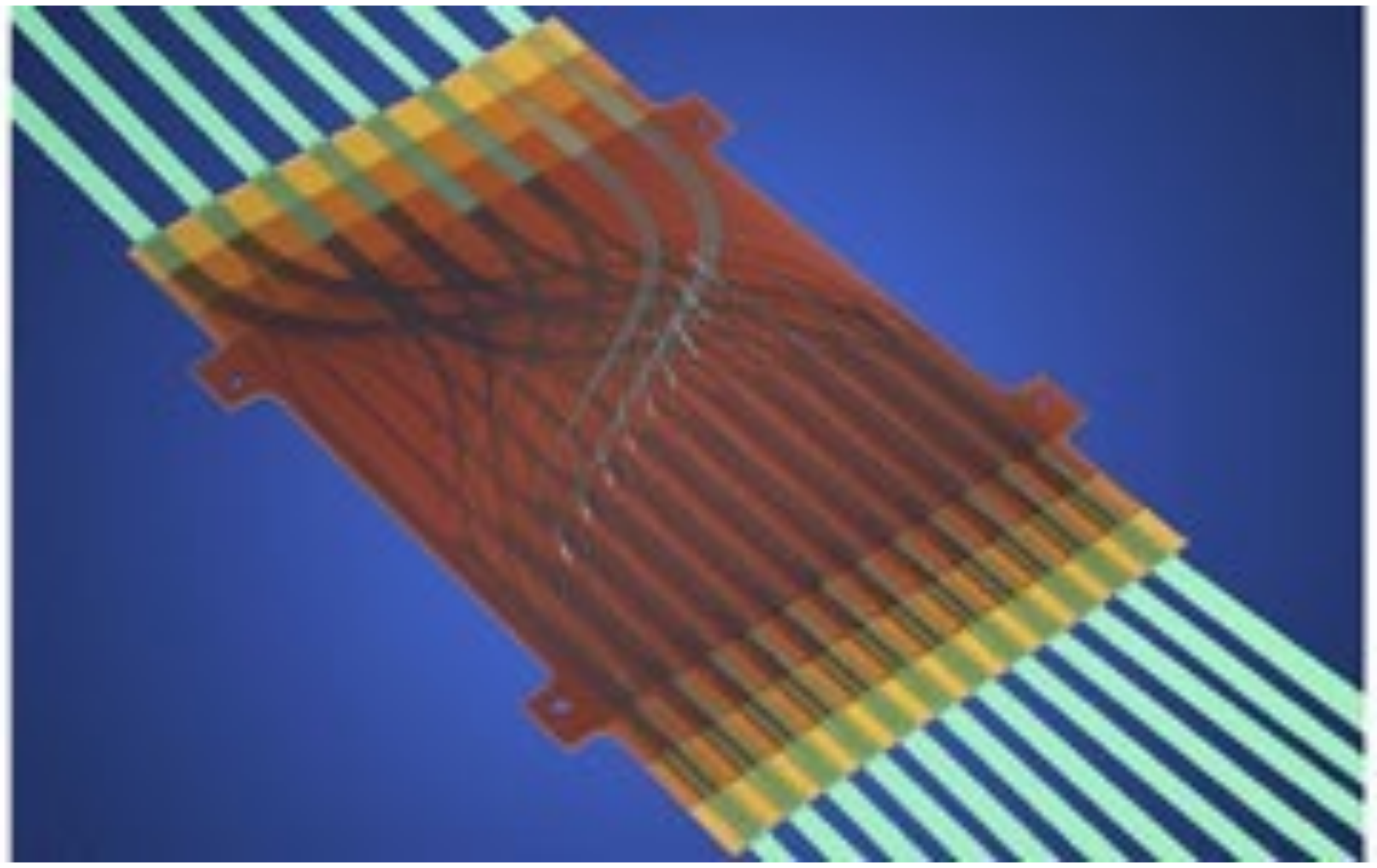




HOW DOES THE MULTIPLEXER WORK?

- Manually connecting the 864 fibres in and out - and using conventional patch panels would have taken an entire rack

- Decided to use MOLEX flexplane mesh - specified the link routing. (and double and triple checked!)



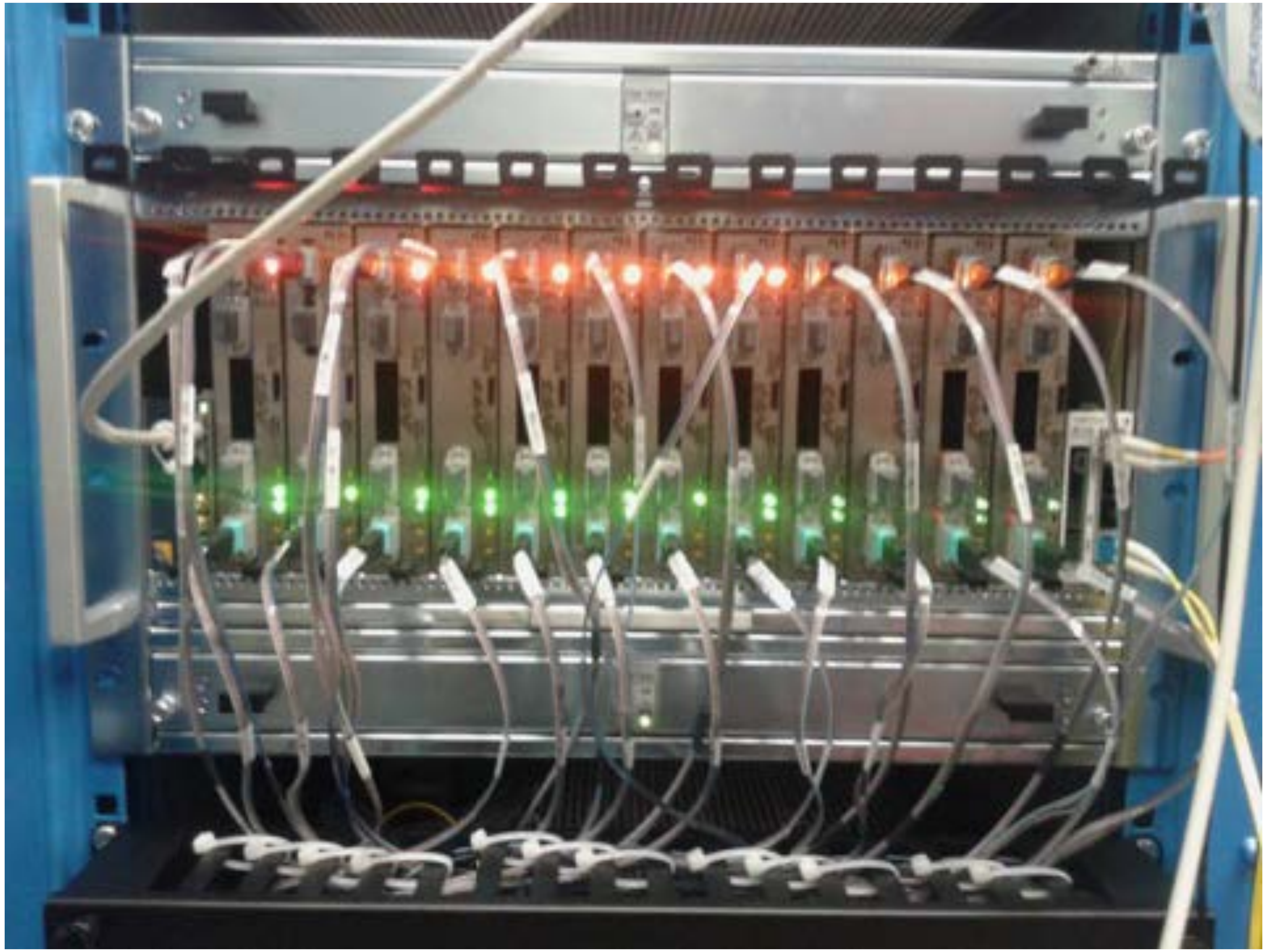
Once this is defined and produced, no room for errors…

ALGORITHM PROCESSING

9 cards - full suite of calo algorithms on each one, identical firwmare, round-robin style through the BXs

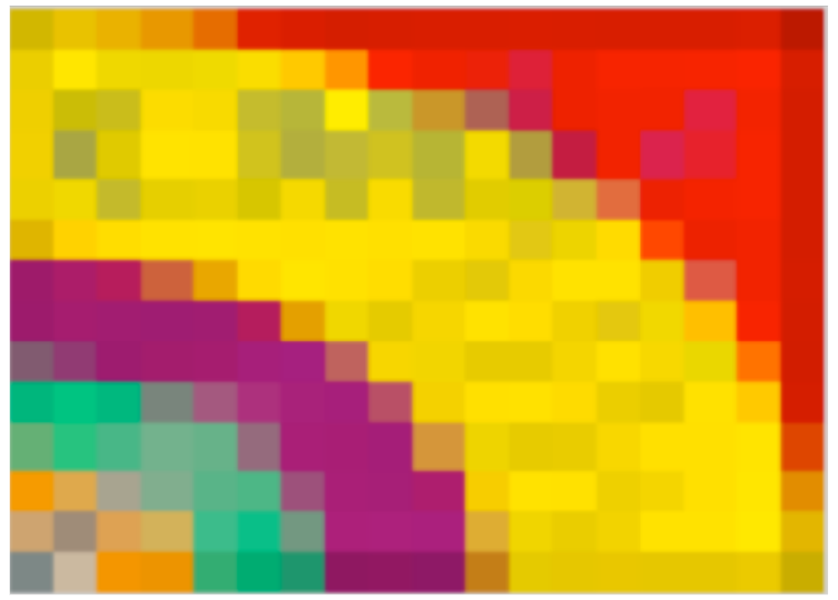
hot spare also!

Algorithm layer



WHAT GOES IN THE CHIPS?

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

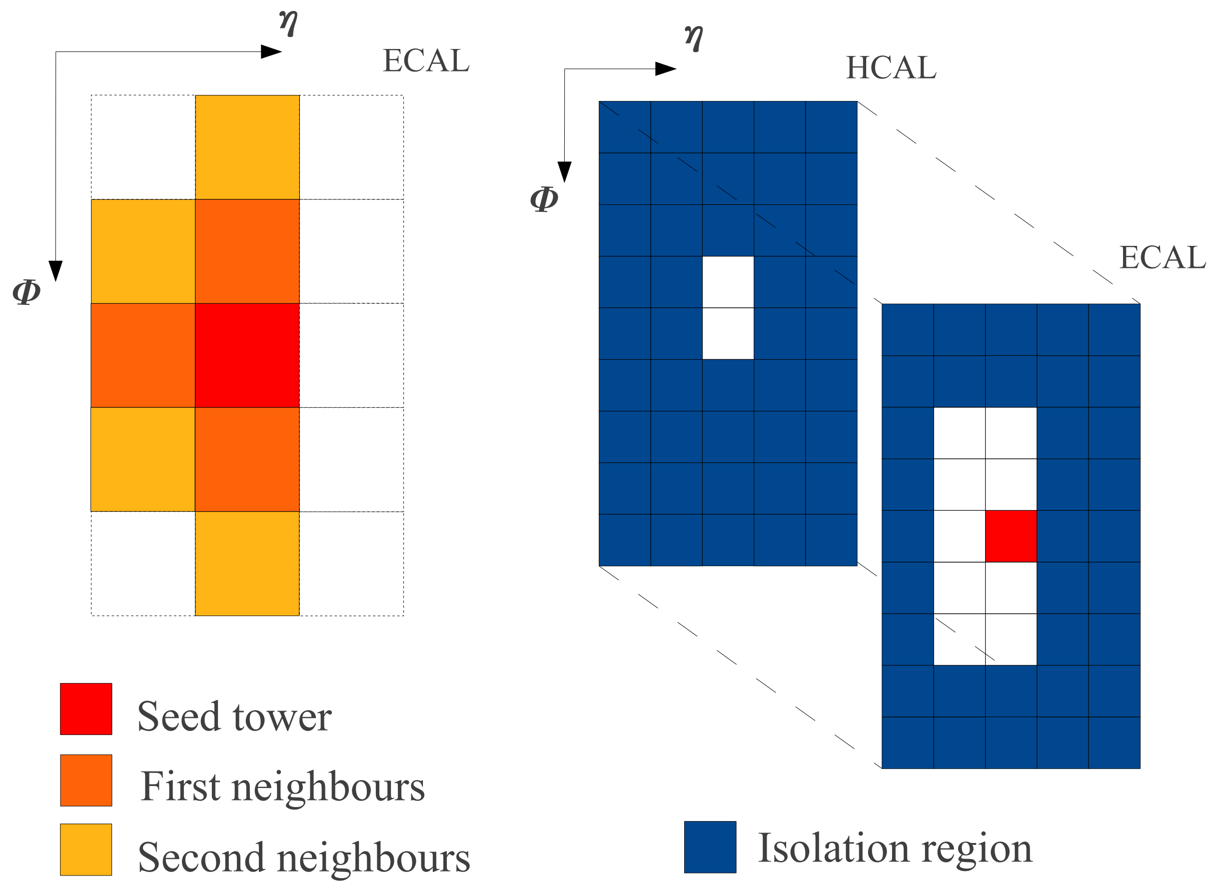


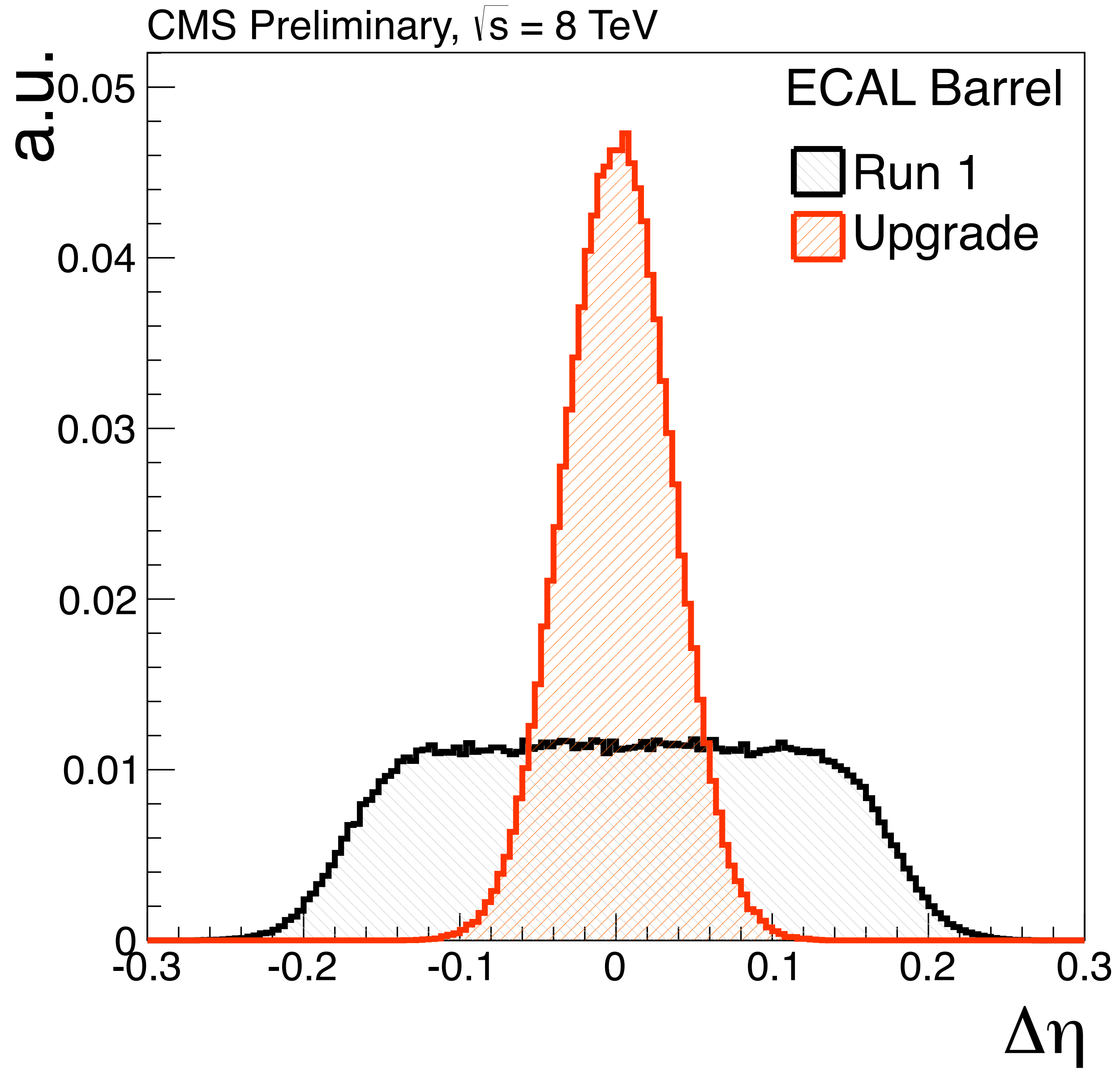
Region Granularity

Trigger Tower Granularity

Electron/Photon finder:

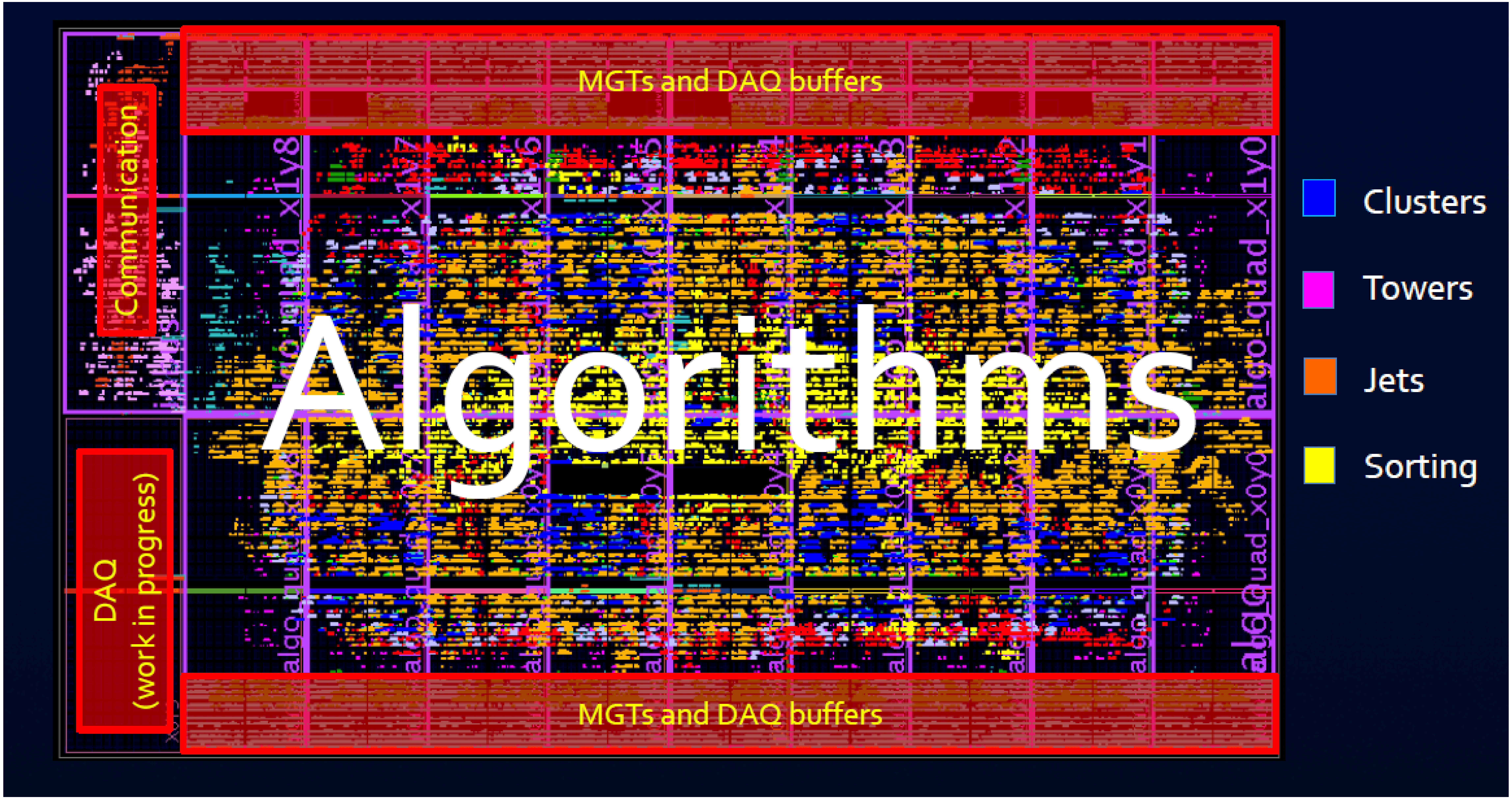
- Clusters are seeded by local maxima of energy above fixed threshold
- Position of the candidate is an energy-weighted average centred on the seed tower.
- A candidate is considered isolated if the total energy in the blue region is less than a given value





SOME LESSONS LEARNED…

WHAT GOES IN THE CHIPS?

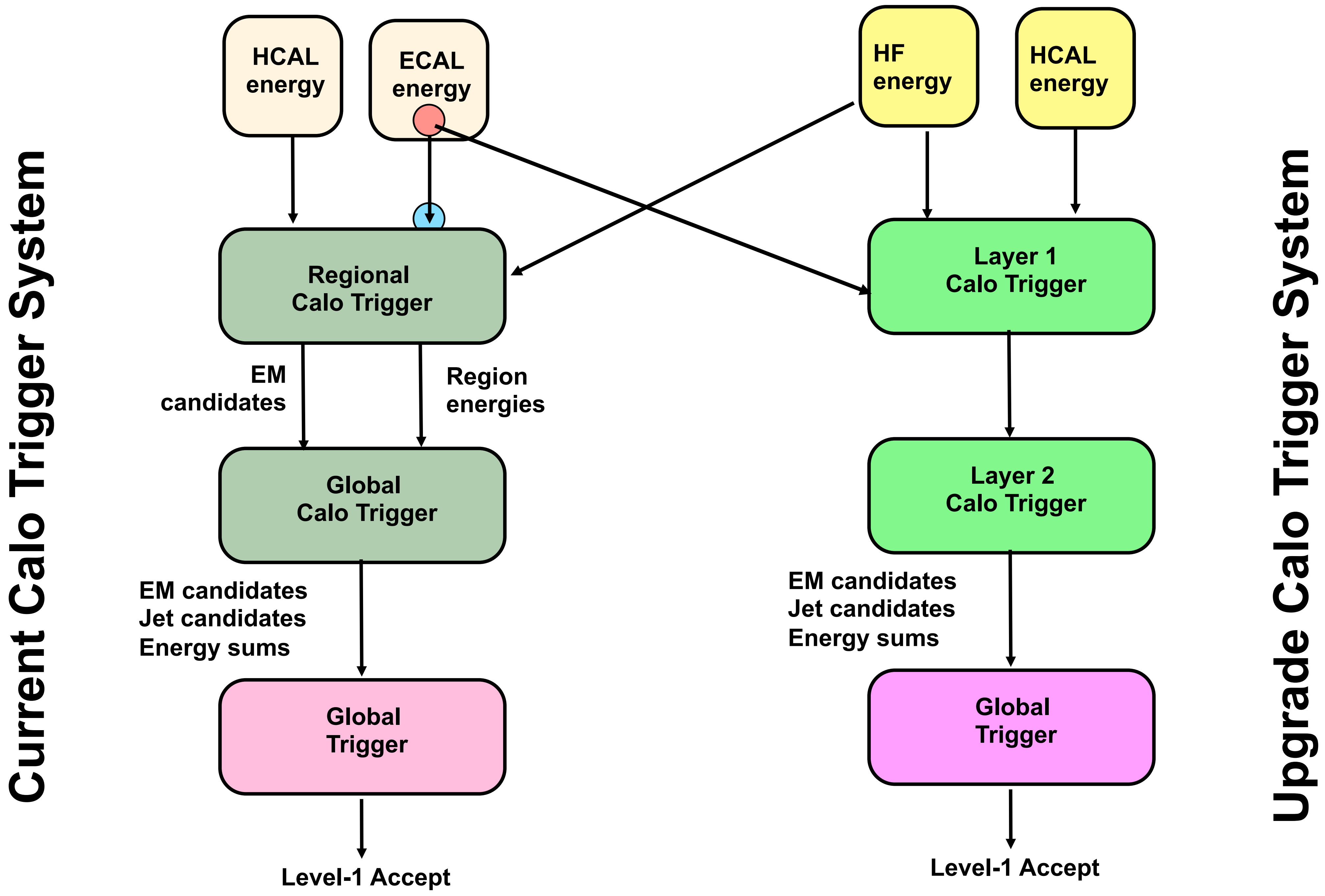


COMMONALITY

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!

PARALLEL RUNNING



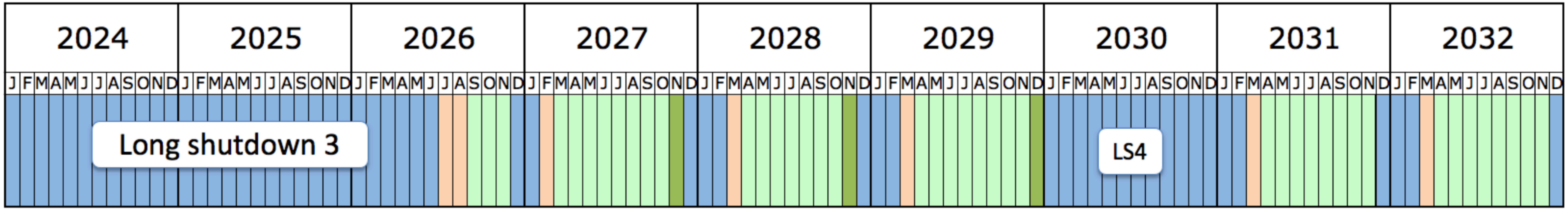
- All Calorimeter Trigger boards installed and commissioned in 2015.
- In order to validate algorithm performance, reliability etc, this trigger was included in a number of proton-proton Collision runs at the tail end of 2015.
- Collected > 3 billion events with this new Trigger!

LHC CAN EXCEED EXPECTATIONS!

- Make sure algorithms are as flexible and configurable as possible!
    - Change of filling schemes (e.g. what happened in 2017 with 8b4e)
    - Quickly rising instantaneous luminosity

HL-LHC TRIGGERING

REMINDER: CURRENT SCHEDULE



REMINDER: CURRENT SCHEDULE

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong 7.5\ 10^{34}\ cm^{-2}s^{-1}$ and **Ultimate Integrated** $L_{int\ ult} \sim 4000\ fb^{-1}$

LHC should not be the limit, would Physics require more...

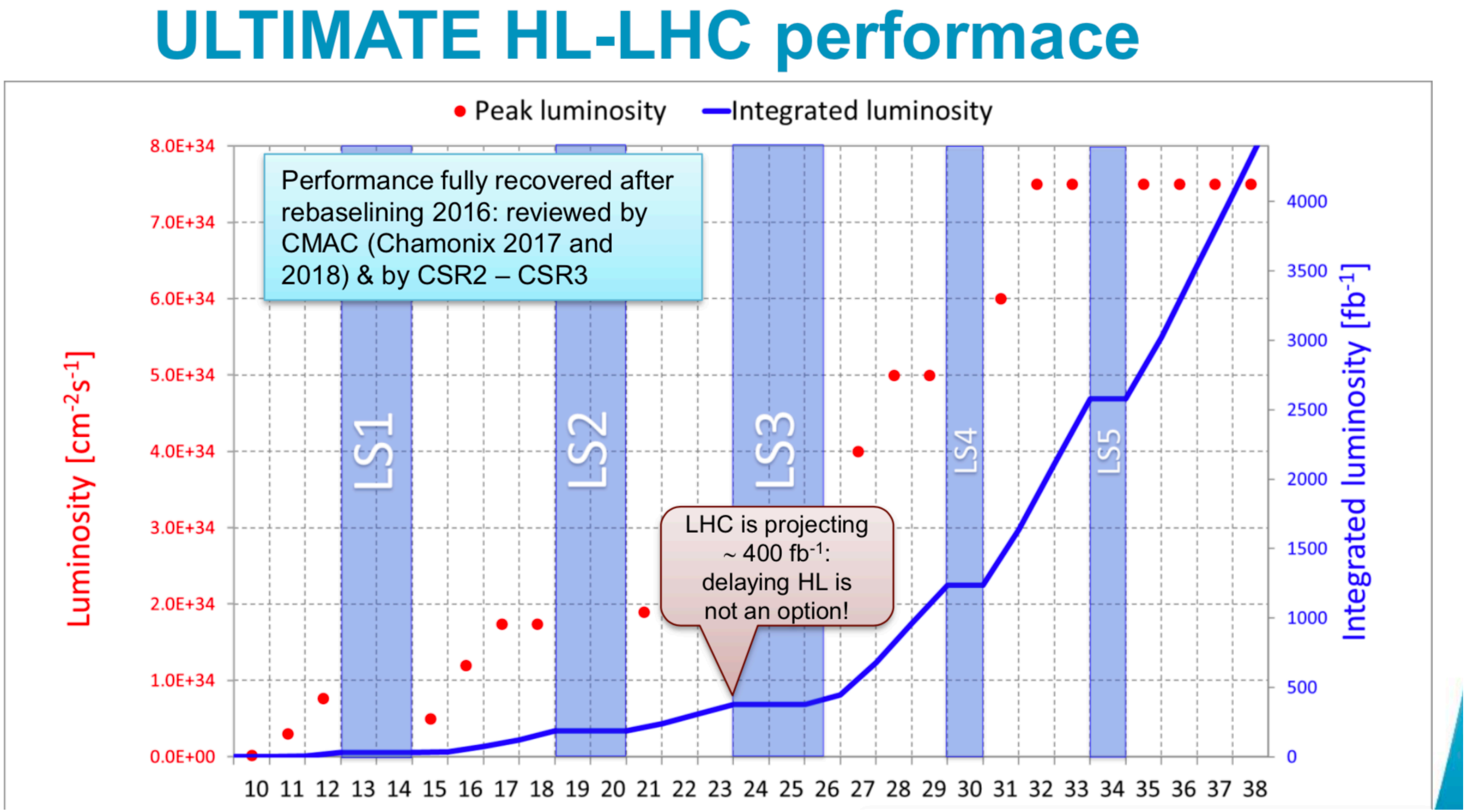
Project approved by CERN Council in June 2016

HiLumi HL-LHC PROJECT

Lucio Rossi - 8th HiLumi Collaboration Meeting 2018

PU CAN GO TO ~ 200!!!

REMINDER: CURRENT SCHEDULE



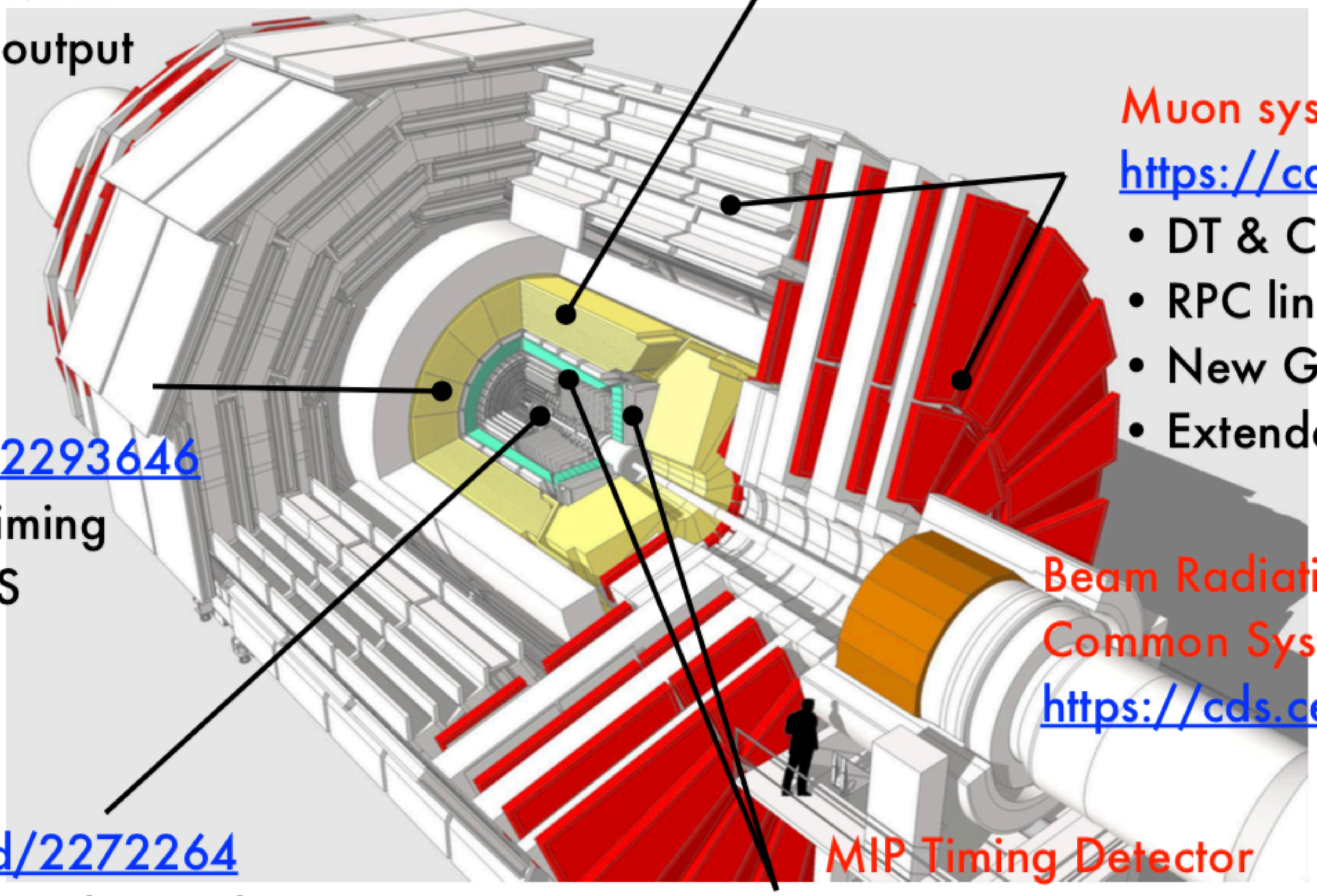
HOW DO WE PREPARE FOR THIS?

HOW DO WE PREPARE FOR THIS?

L1 Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1 trigger at 40 MHz
- PF-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
http://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC link-board
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

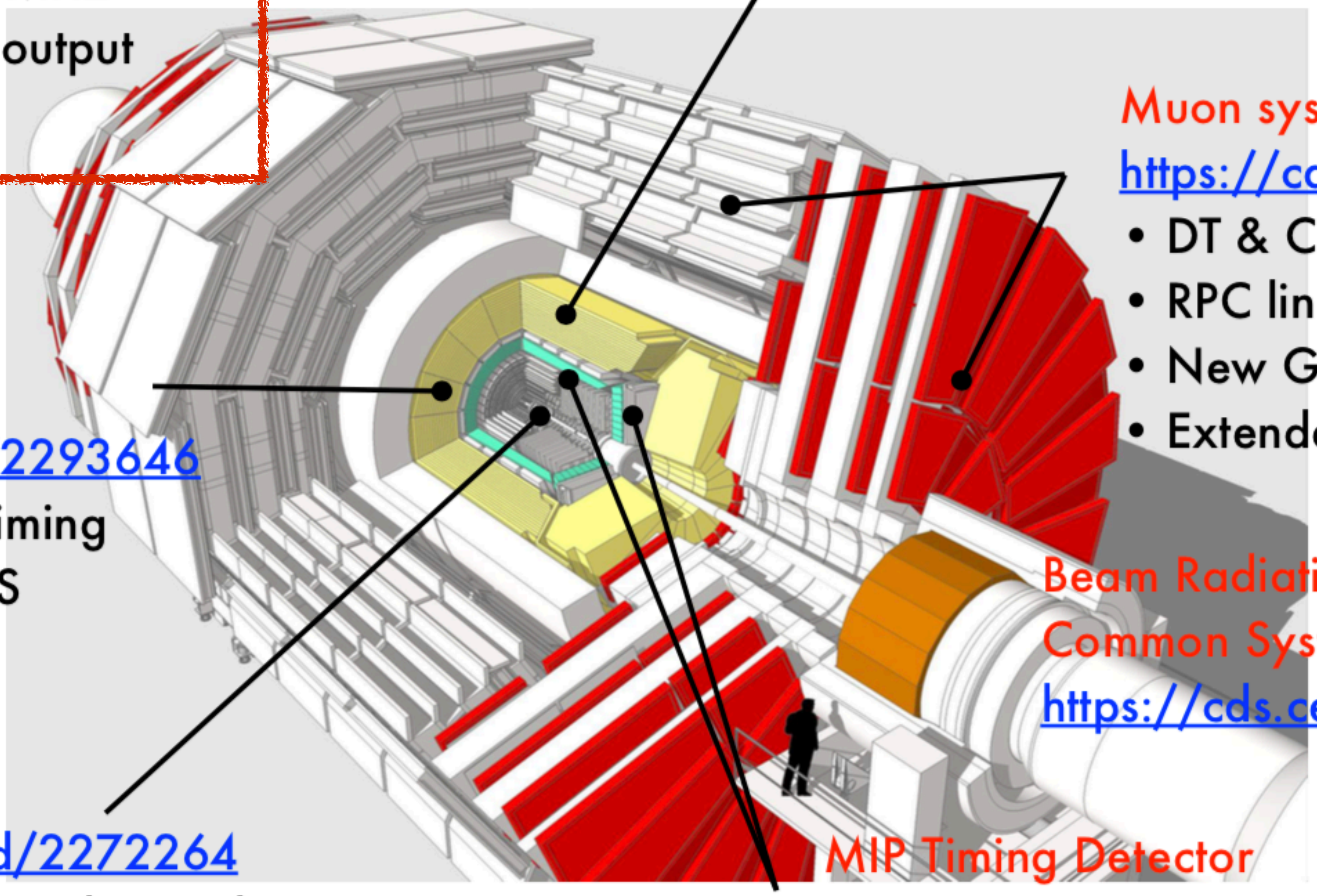
Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and pixels increased granularity
- Design for tracking in L1 Trigger
- Extended coverage to $|\eta| \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

HOW DO WE PREPARE FOR THIS?

L1 Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1 trigger at 40 MHz
- PF-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
http://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC link-board
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

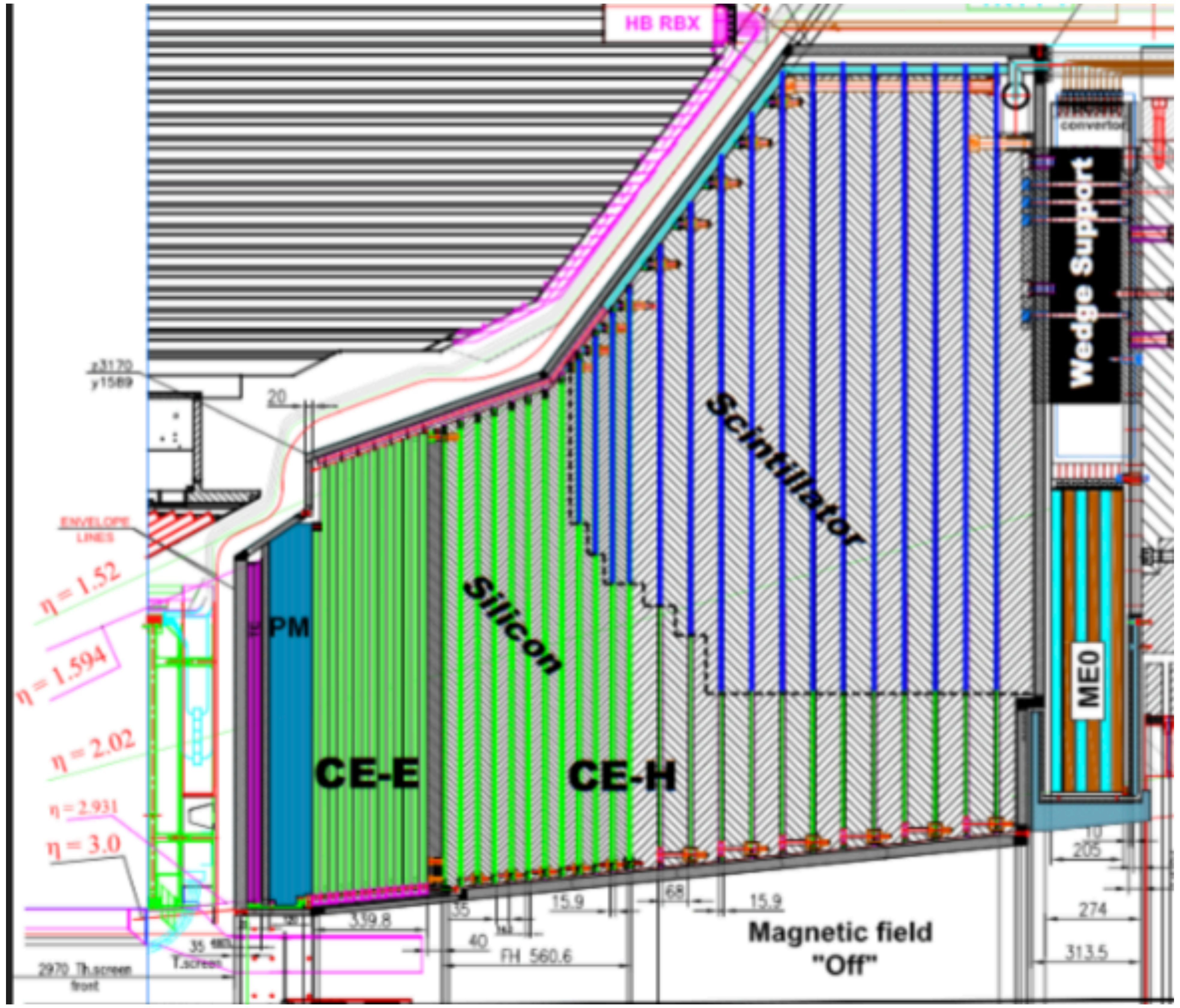
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and pixels increased granularity
- Design for tracking in L1 Trigger
- Extended coverage to $|\eta| \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

TRIGGERING HAS TO EVOLVE!

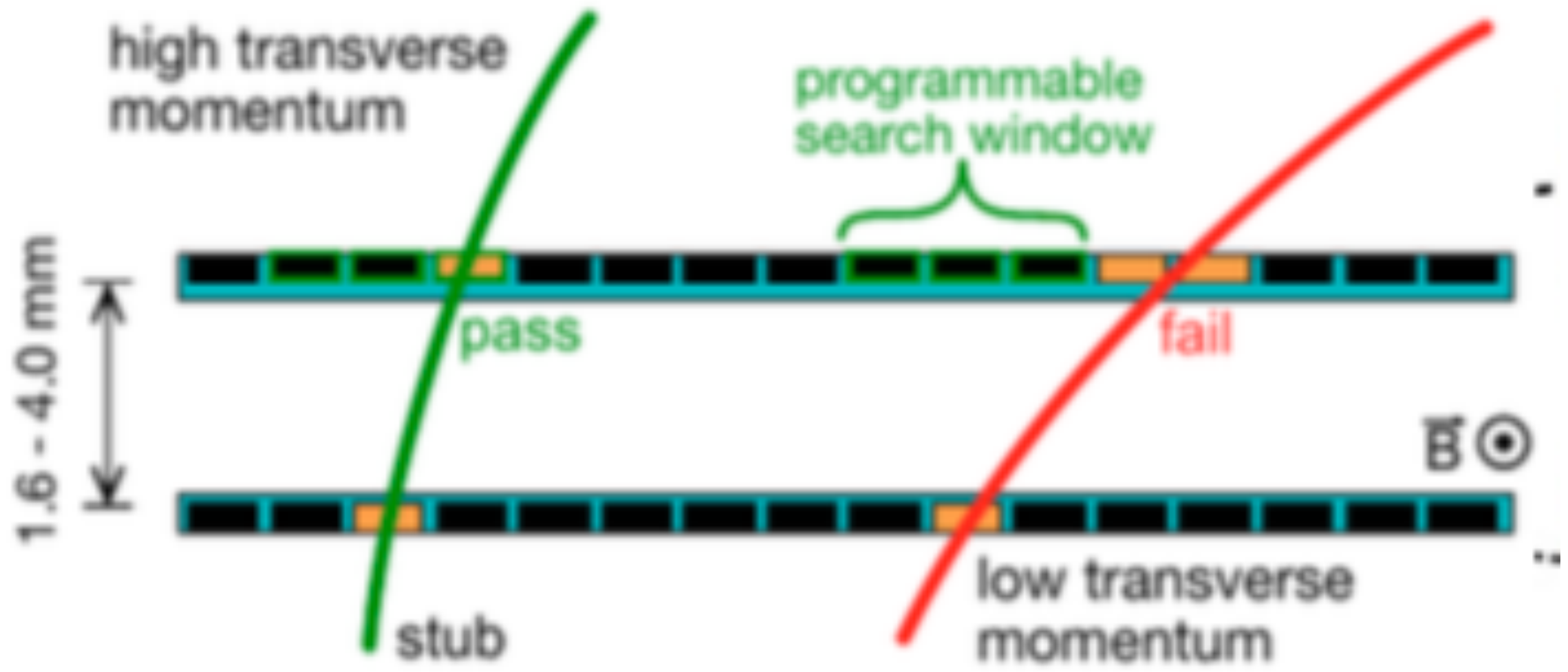
- Finer granularity information from the calorimeters
  - ECAL barrel = x25 finer granularity
  - HCAL barrel = x7 finer granularity
  - High Granularity EndCap calorimeter = x500 finer granularity!



TRIGGERING HAS TO EVOLVE!

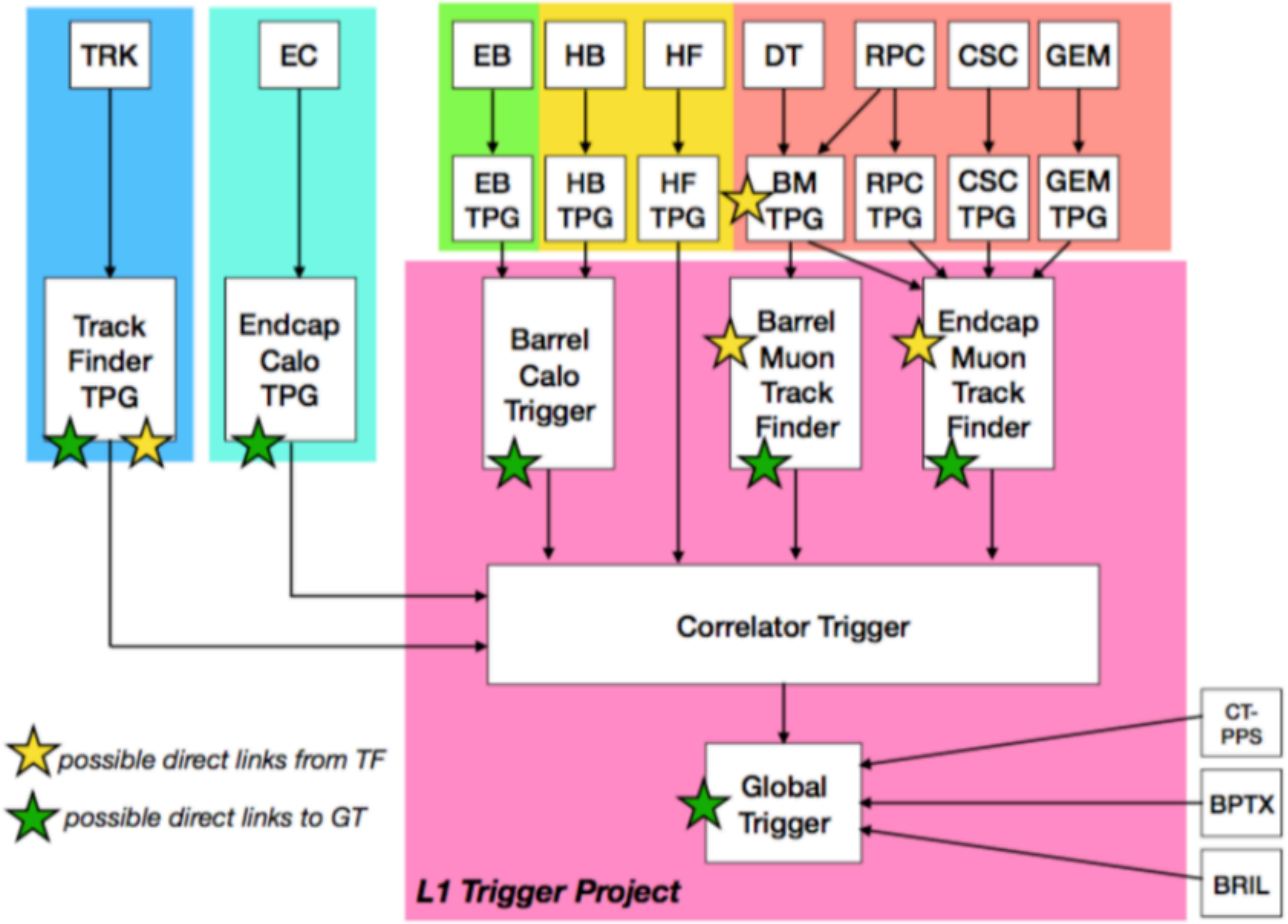
- New Pixel and Strip trackers being installed
- Tracking information at Level 1!

- Remove low momentum tracks by requiring hits in 2 close strip sensors



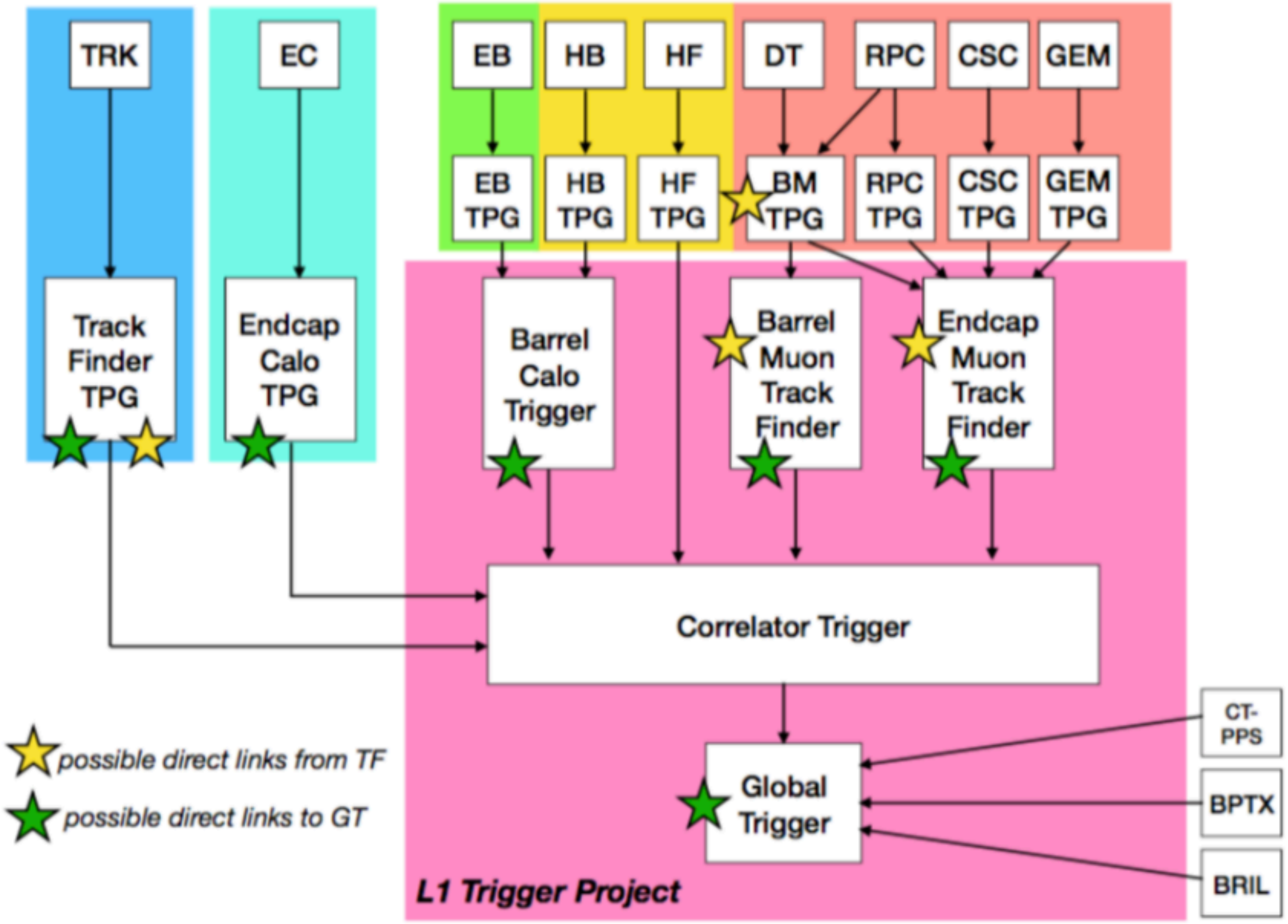
TRIGGERING HAS TO EVOLVE!

- Latency up from 4us to 12.5us
- Output 750 kHz



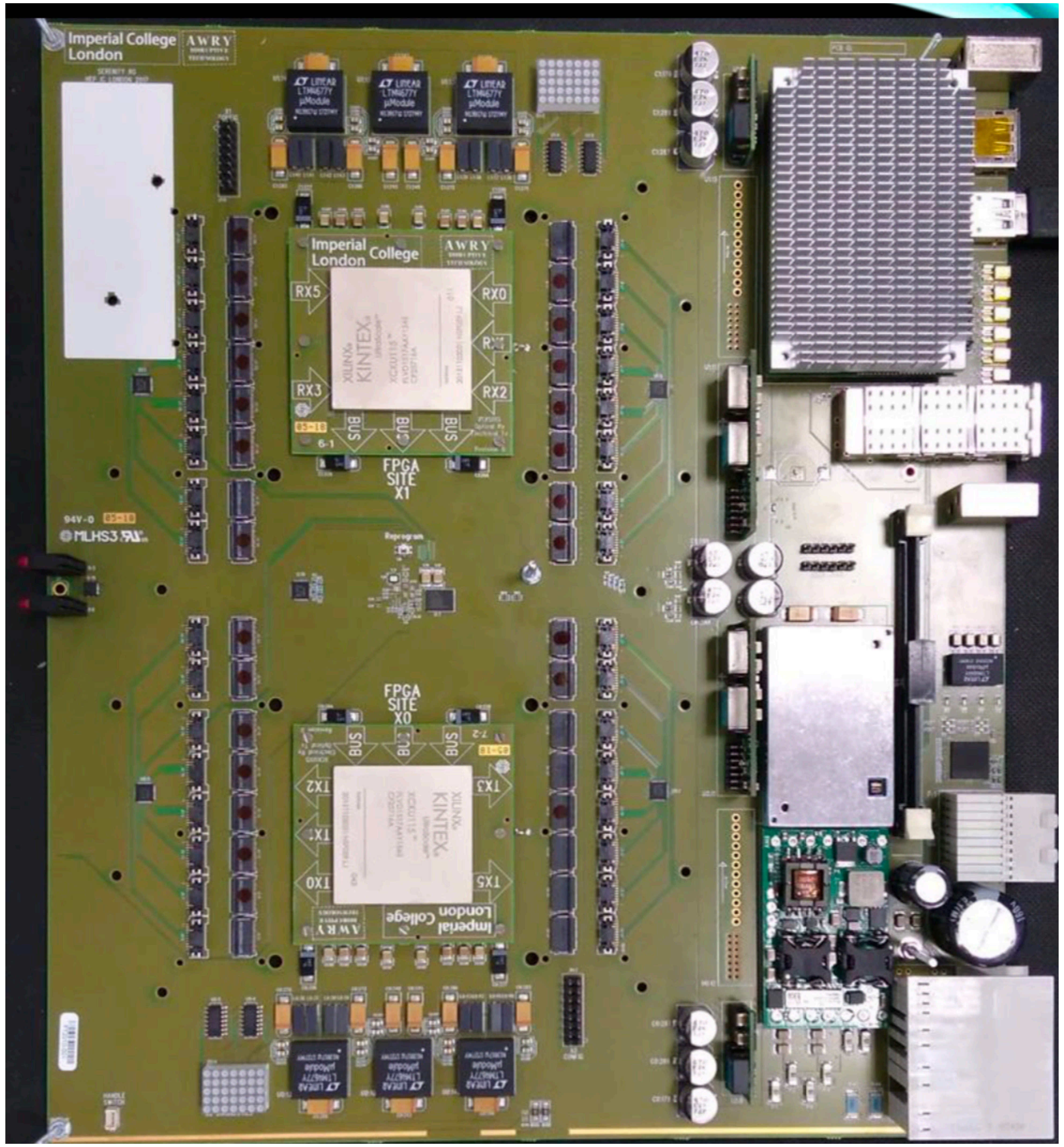
HOW CAN WE BUILD THIS?

- Latency up from 4us to 12.5us
- Output 750 kHz

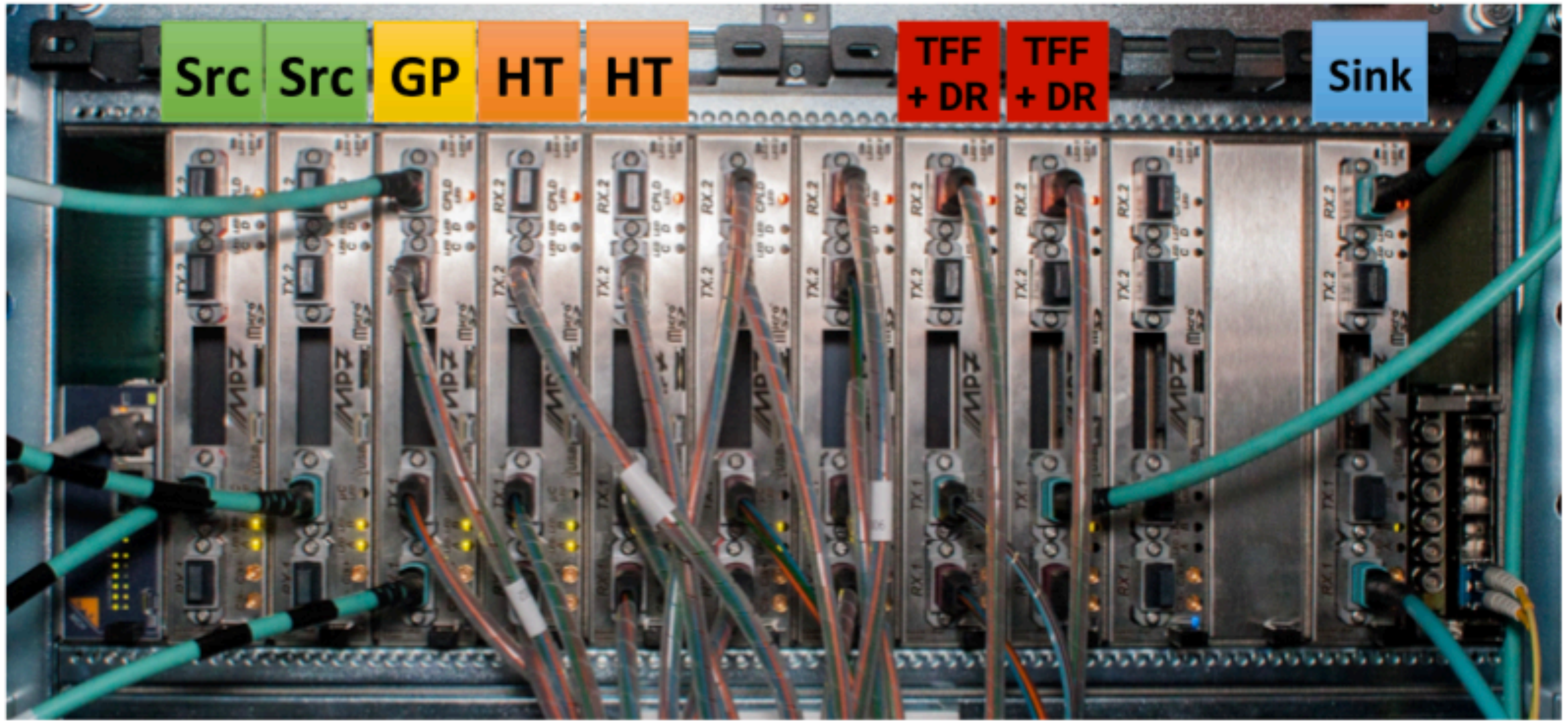


NEW TECHNOLOGY REQUIRED

- Moving to ATCA from uTCA
  - Larger form factor
- Having FPGA's on daughter cards provides flexibility to adapt boards to the purpose
- Maintain Phase 1 idea of generic stream processing boards.



BUT ALSO TEST WITH WHAT WE HAVE!



Used MP7's to build a slice of a track-trigger and demonstrate the feasibility! Excellent way to educate us on how to build our track trigger, and where potential issues could lie.

SUMMARY - I

- **Triggering is a fundamental concept of extracting useful physics from hadron colliders**
    - **Really the first stage of a Physics analysis**
    - **Also an extremely interesting environment to work in- brings together hardware, firmware, software and cutting edge technology**

SUMMARY - II

- The CMS Level 1 trigger has evolved considerably from Run 1 to Run 2, and now and even bolder system is being designed for HL-LHC
- Important to stay on top of the technological curve, and to think of new ideas using this technology which can benefit the Physics!

<u>**Lots of opportunities for innovation!!**</u>

It's not always glamorous though….

THANK YOU FOR YOUR ATTENTION!