The new Global Muon Trigger of the CMS experiment

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Thomas Reis
CERN/EP-CMD
On behalf of the CMS Collaboration

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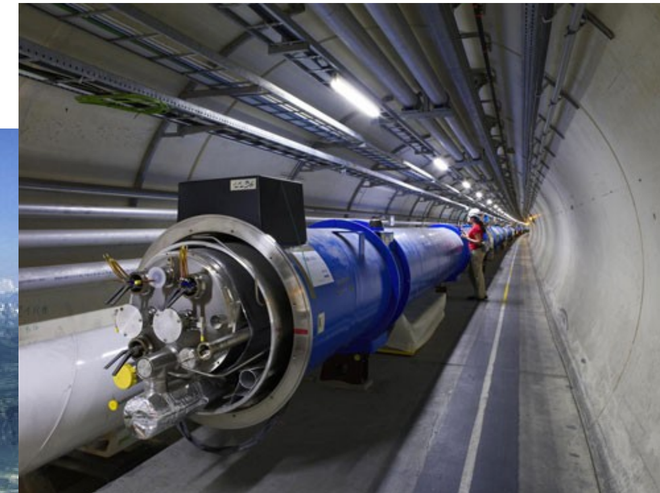
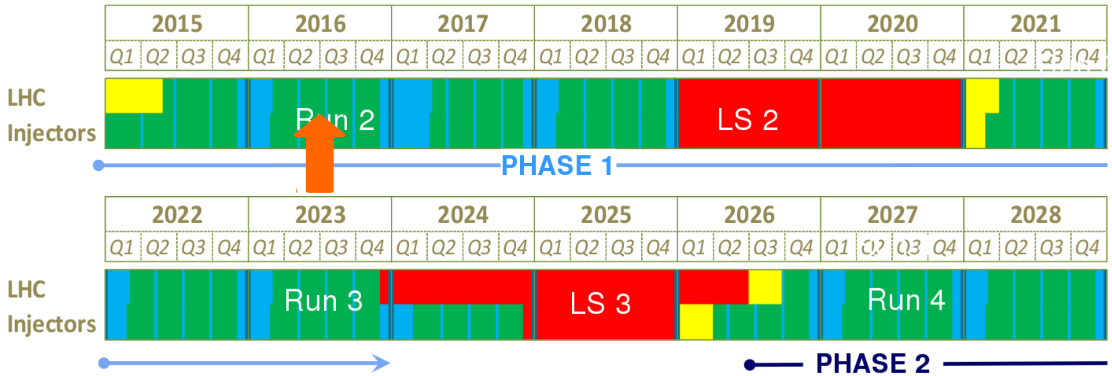
Large Hadron Collider

- 27 km circumference
- ~100 m underground
- 7 TeV nominal beam energy
- 40 MHz bunch crossing rate
- ~1 billion collisions / s
- 4 experiments



Large Hadron Collider

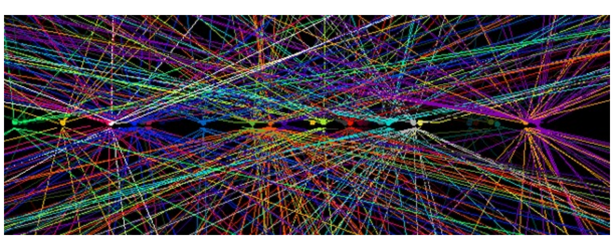


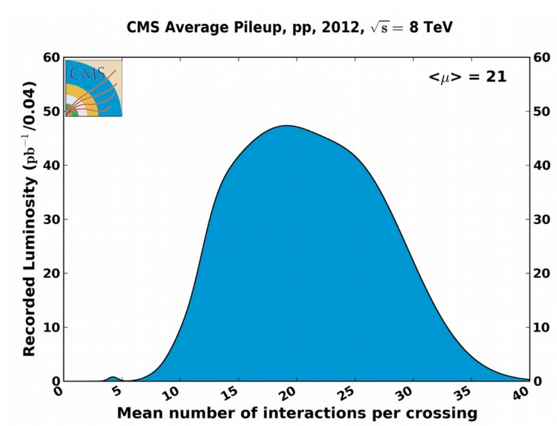
- LHC run 2:
  - 13 TeV pp centre-of-mass energy
  - Target ~100 fb^{-1} delivered luminosity
  - Increasing instantaneous luminosity
  - Increasing pileup

Pileup:

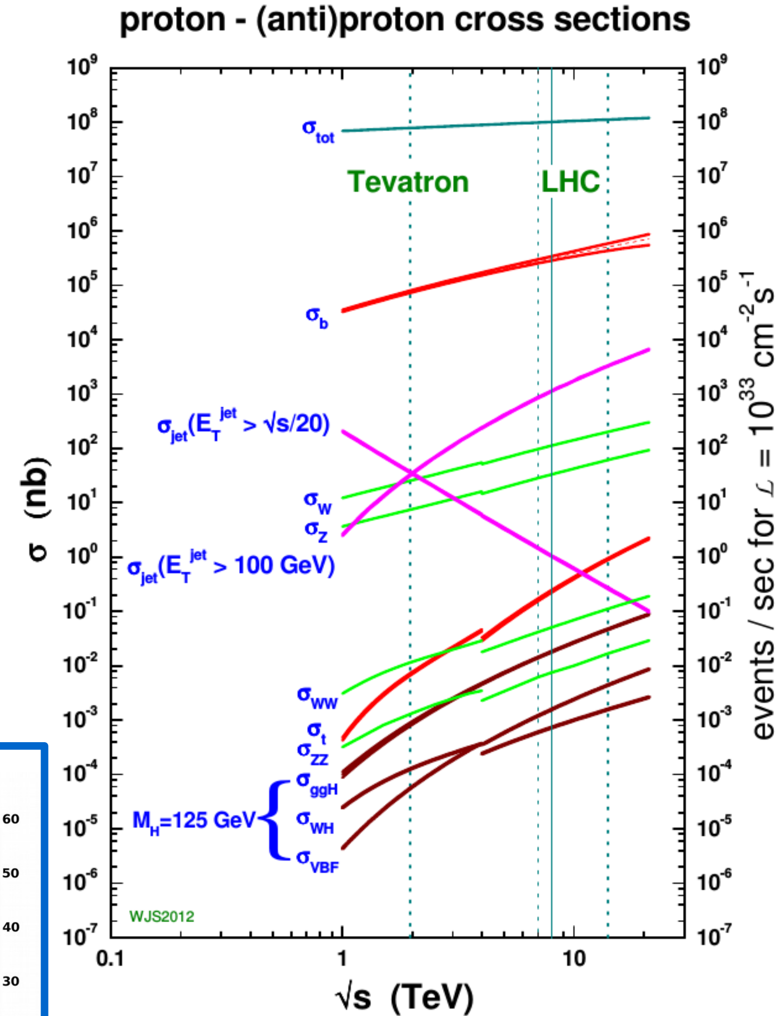
Several proton-proton collisions per bunch crossing (BX)

All created particles overlaid in the detector





What is how often produced?



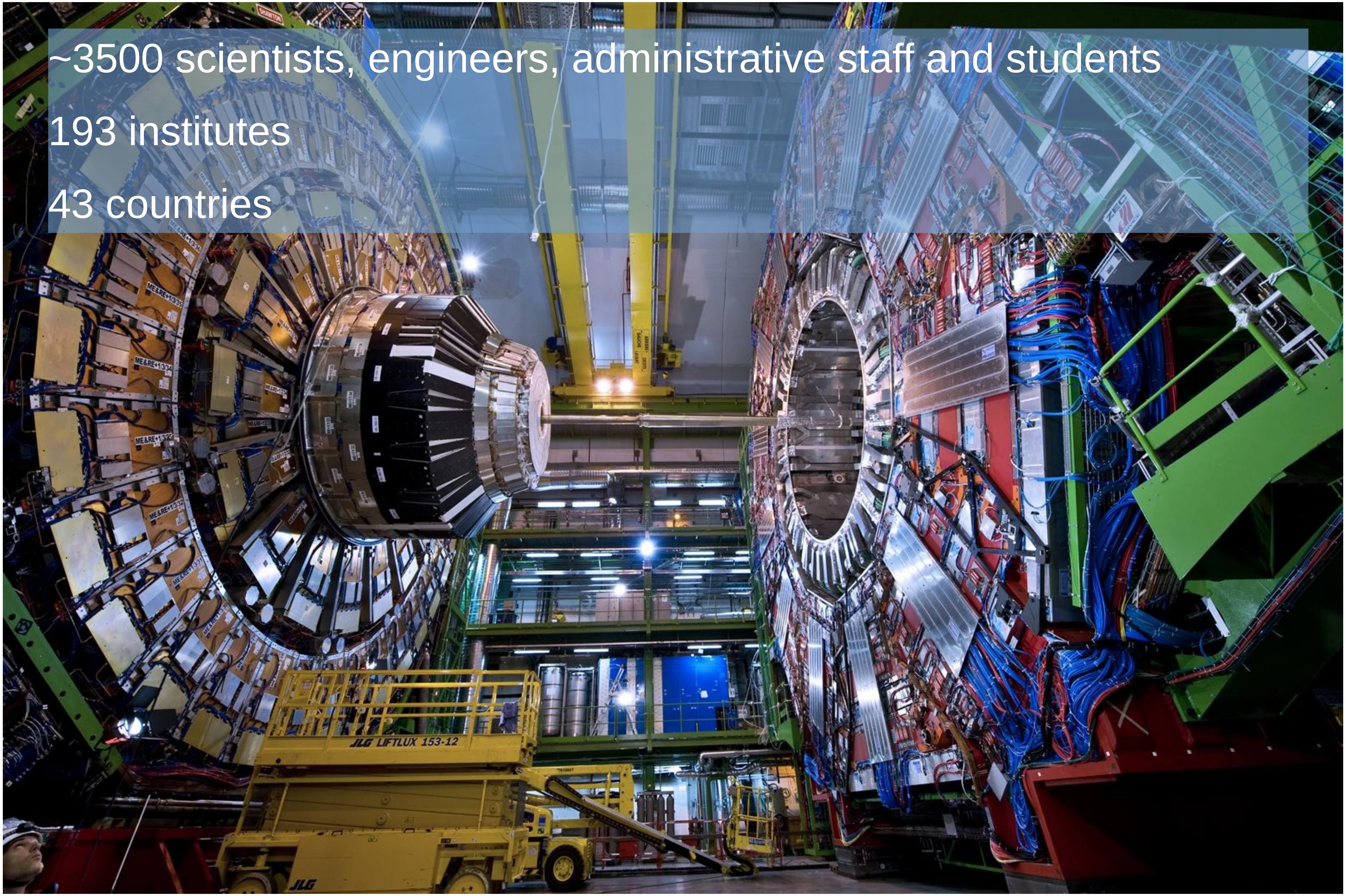
- Many interesting processes are rare. (currently ~1 Higgs boson produced / min, but few decay to golden channels)
- Require a lot of data to be studied.

CMS Collaboration

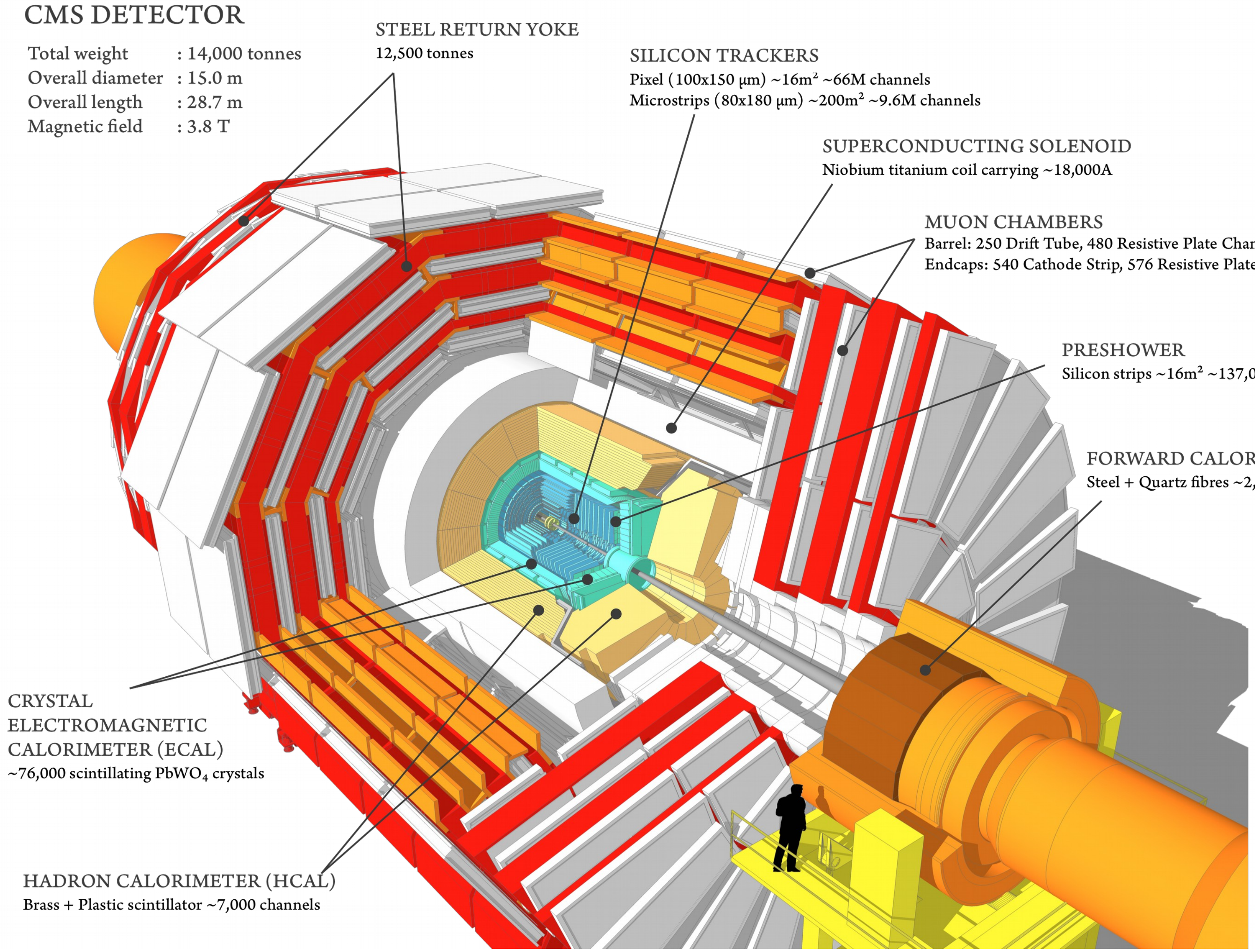
~3500 scientists, engineers, administrative staff and students

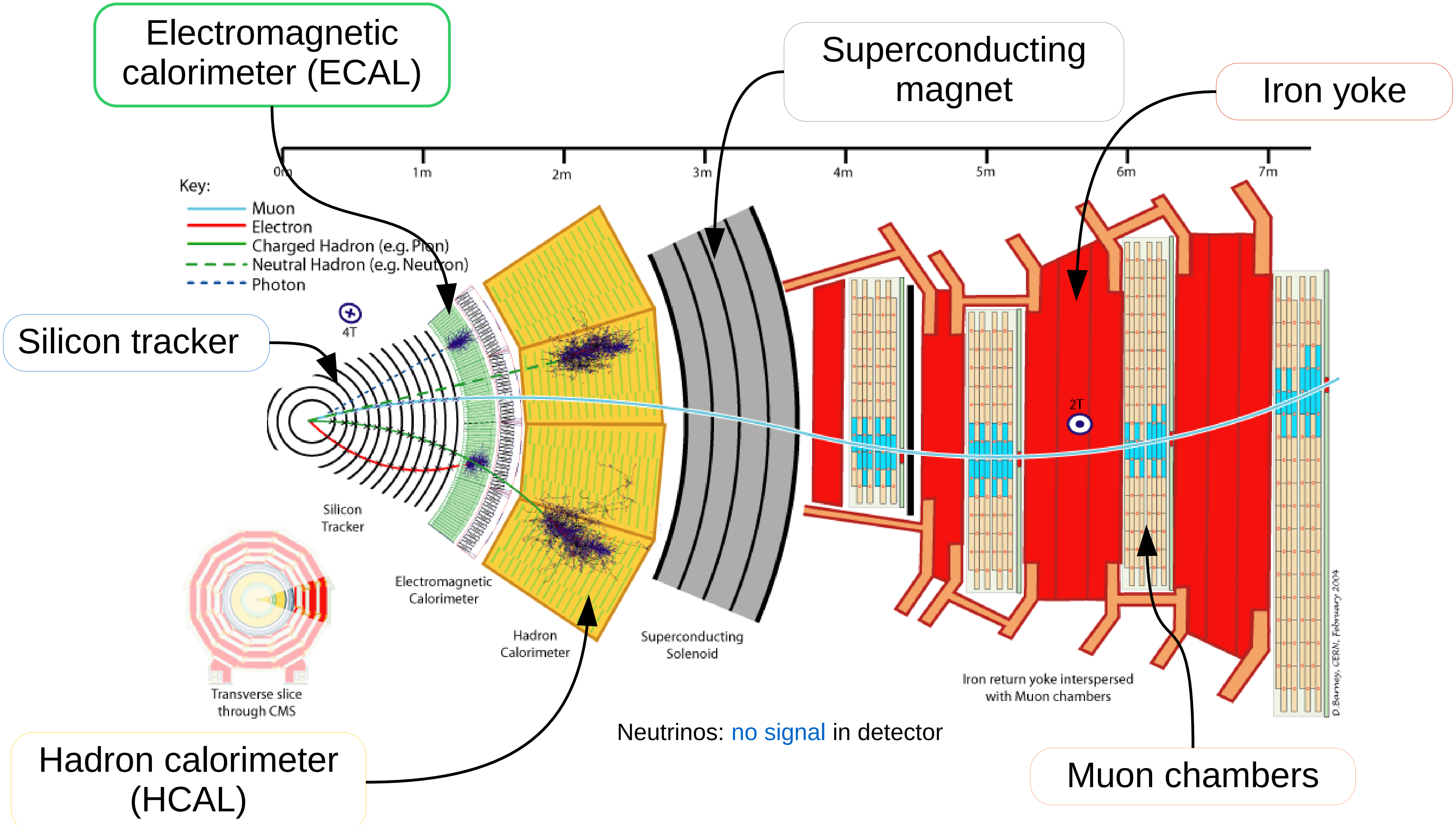
193 institutes

43 countries



Compact Muon Solenoid



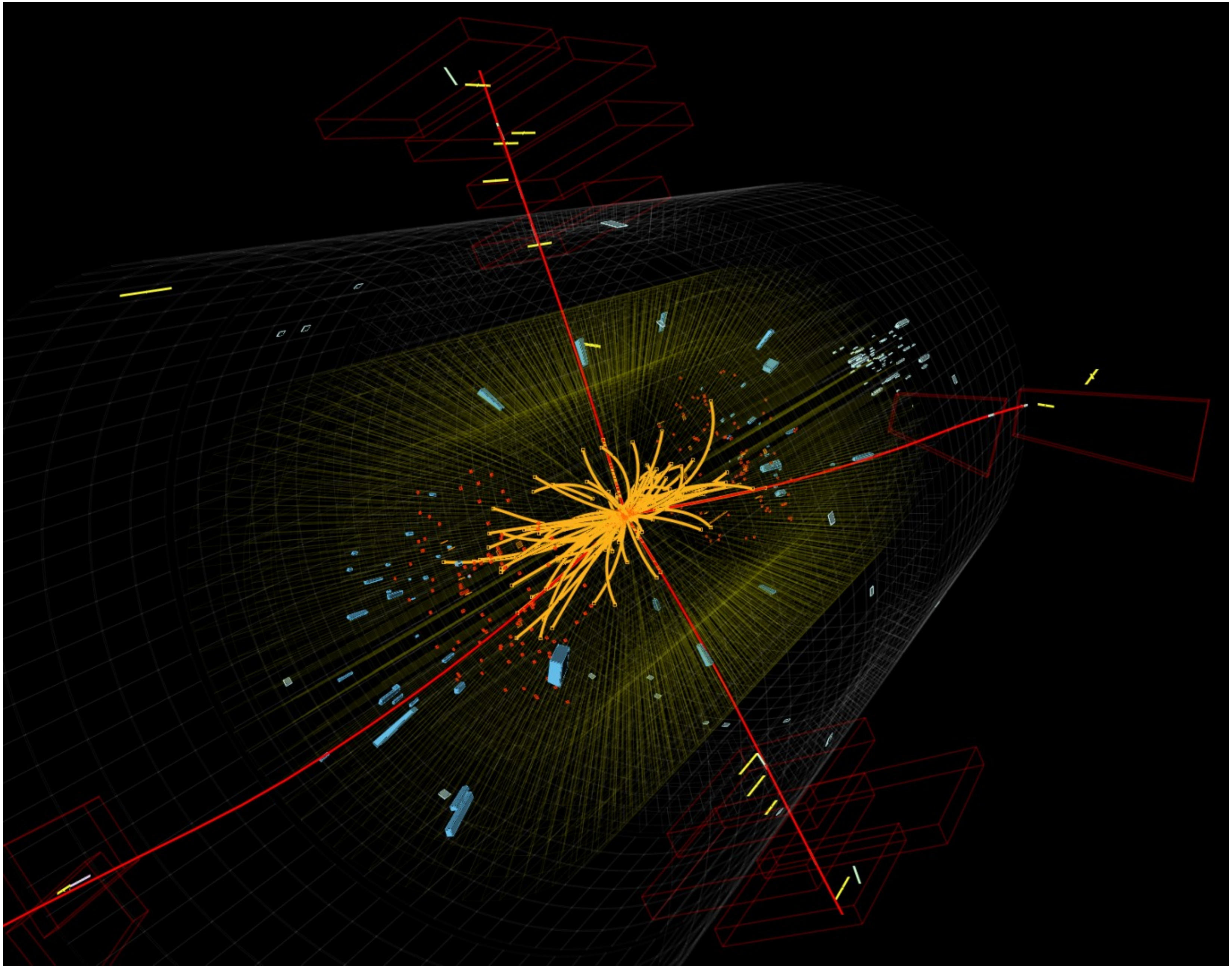


Neutrinos: no signal in detector

Radius 7.5 m

Particles from previous collision are still in the detector when protons from the next bunch collide

CMS - event



Trigger

- Only a small fraction of the 40 MHz LHC collision rate can be analysed
- CMS uses a 2-level trigger system to select interesting events for analysis

L1 trigger

2016 upgrade

- Custom HW in μTCA standard
- 3.8 μs latency
- High granularity data kept in readout buffer until L1 decision
- 100 kHz output rate
- Trigger control and distribution system (TCDS) delivers trigger signal to front end electronics
  - Can throttle the trigger
- Silicon tracker not used at L1
  - Presentation by T. Schuh
  - Poster by L. Calligaris

DAQ event building

100 kHz

High Level Trigger (HLT)

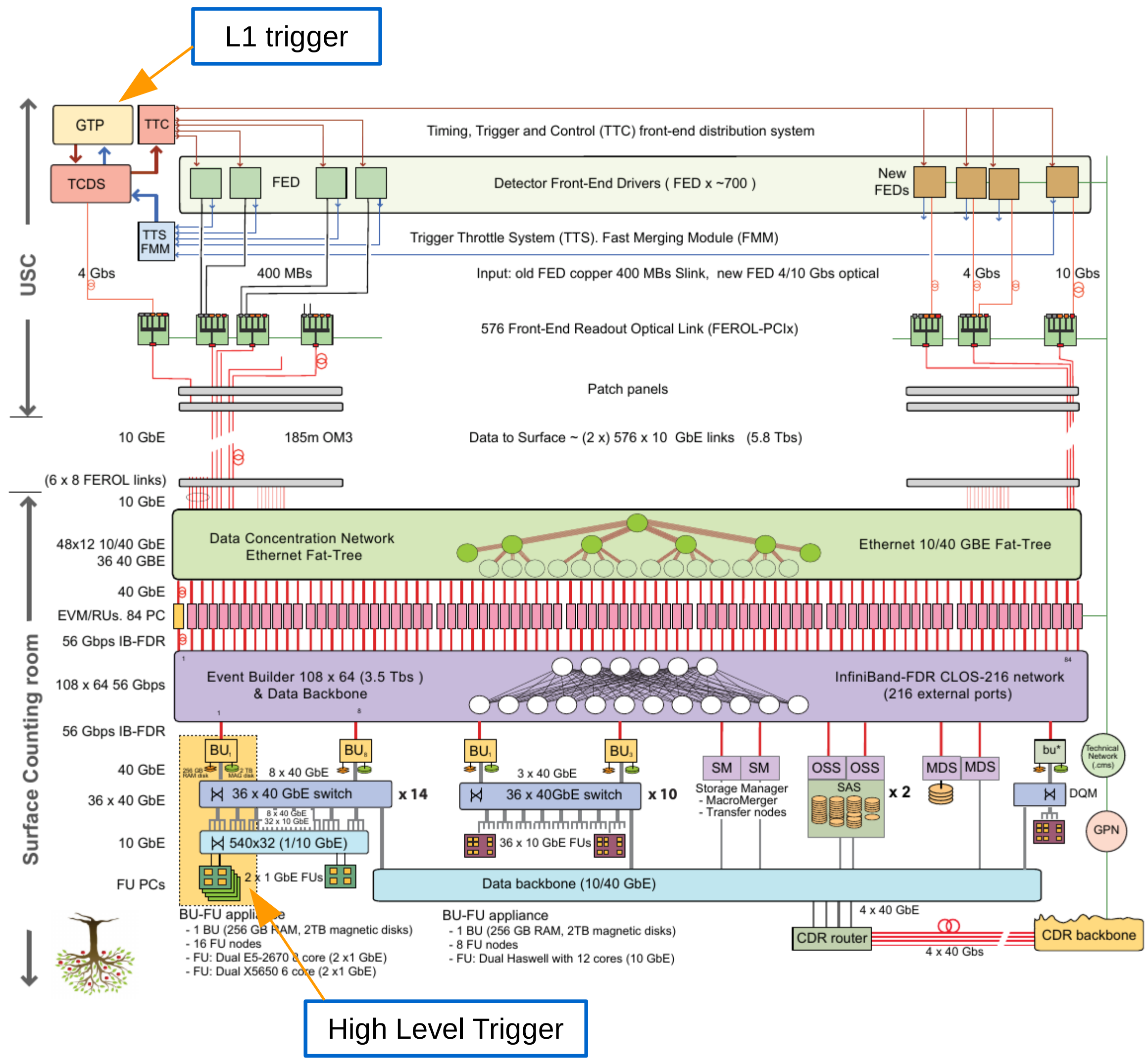
- Entirely in software
- Processor farm with ~20000 cores
- Working on full events built by DAQ
- File based (On RAM disks)
  - Decouple online SW from HLT SW
- 1 kHz output rate
- HLT farm used for cloud computing during technical stops of the LHC
  - Ongoing work to also use it between collision runs

1 kHz

Storage

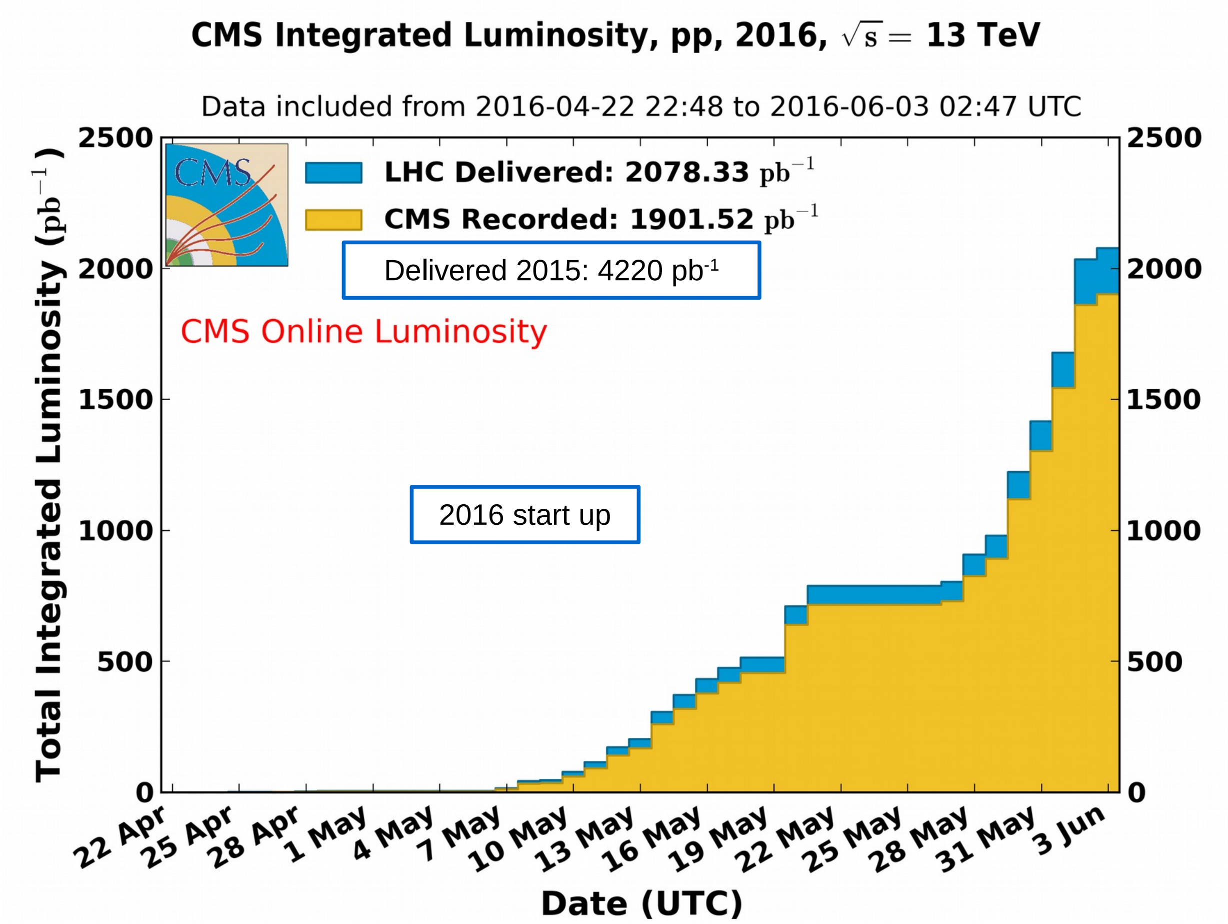
Data Acquisition

- DAQ2 operating since 2015 run
  - Dedicated talk by J. Hegeman
- Readout and build events at L1 trigger rate (100 kHz)
- Event size O(1 MB)
- High throughput system (200 GB/s)
- Lossless system
  - Backpressure is generated if event building cannot keep up
  - Throttles trigger if needed



CMS status

- LHC start up very fast, despite problems in accelerator chain and incidents with local fauna
- Data taking efficiency by luminosity greater 91%

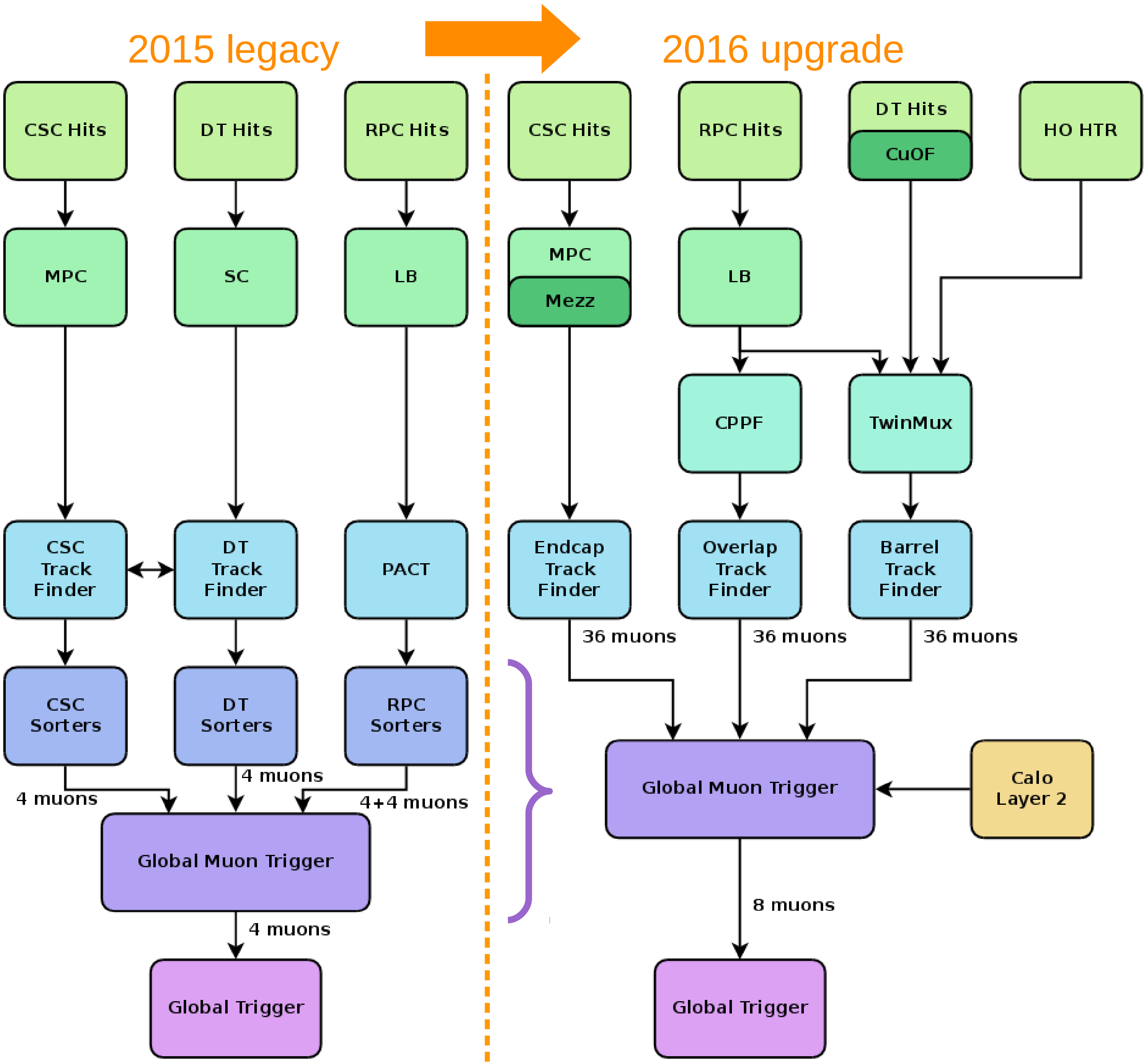


Upgraded Global Muon Trigger

Why upgrade the trigger?

- Higher LHC performance in run 2
  - Higher centre-of-mass energy of 13 TeV (7/8 TeV in run 1)
  - Increased luminosity
  - Higher pileup
  - Increased trigger output rate would require major detector upgrades
- A more selective trigger is needed
  - Making use of capabilities of new FPGAs and fast serial links
    - Higher precision in particle parameter measurements
    - Implement more sophisticated algorithms
- More trigger algorithms in the menu
  - Previously limited to 128 algorithms
  - Now max. 512 algorithms
- Several components showed signs of ageing
- Move to common HW for different subsystems

Upgraded muon trigger

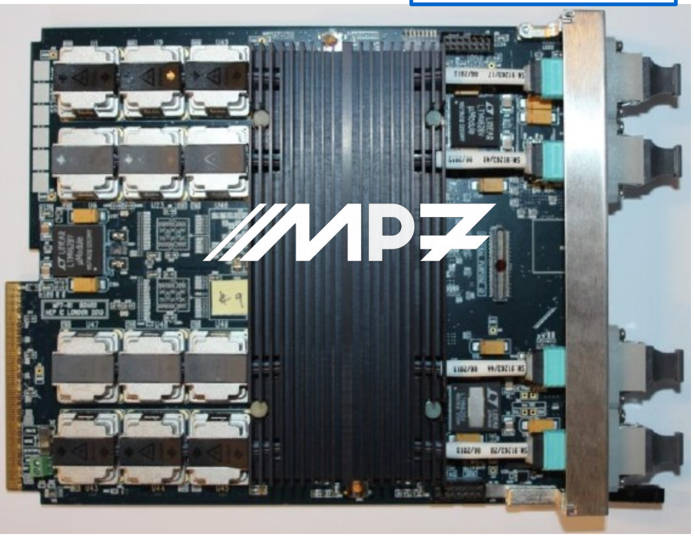


- Moving from a subdetector centred concept to a geometry centred concept
- Based on common HW designs
- 3 muon track finders (TF) for different η regions
  - Barrel muon TF (BMTF)
  - Overlap muon TF (OMTF)
  - Endcap muon TF (EMTF)
- Global Muon Trigger performs sorting, duplicate removal and calculates muon isolation
- Best 8 muon candidates are sent to the upgraded Global Trigger

Hardware

- Trigger processor: Master Processor 7 (MP7)
  - Advanced mezzanine card (AMC) in µTCA standard
  - Generic design for stream data processor
    - Used by several other CMS systems as well
      - e.g. GT, BMTF, Calorimeter trigger
  - Based on Xilinx Virtex-7 690 FPGA
  - 72 optical Rx & 72 optical Tx links at 10 Gb/s

Imperial College

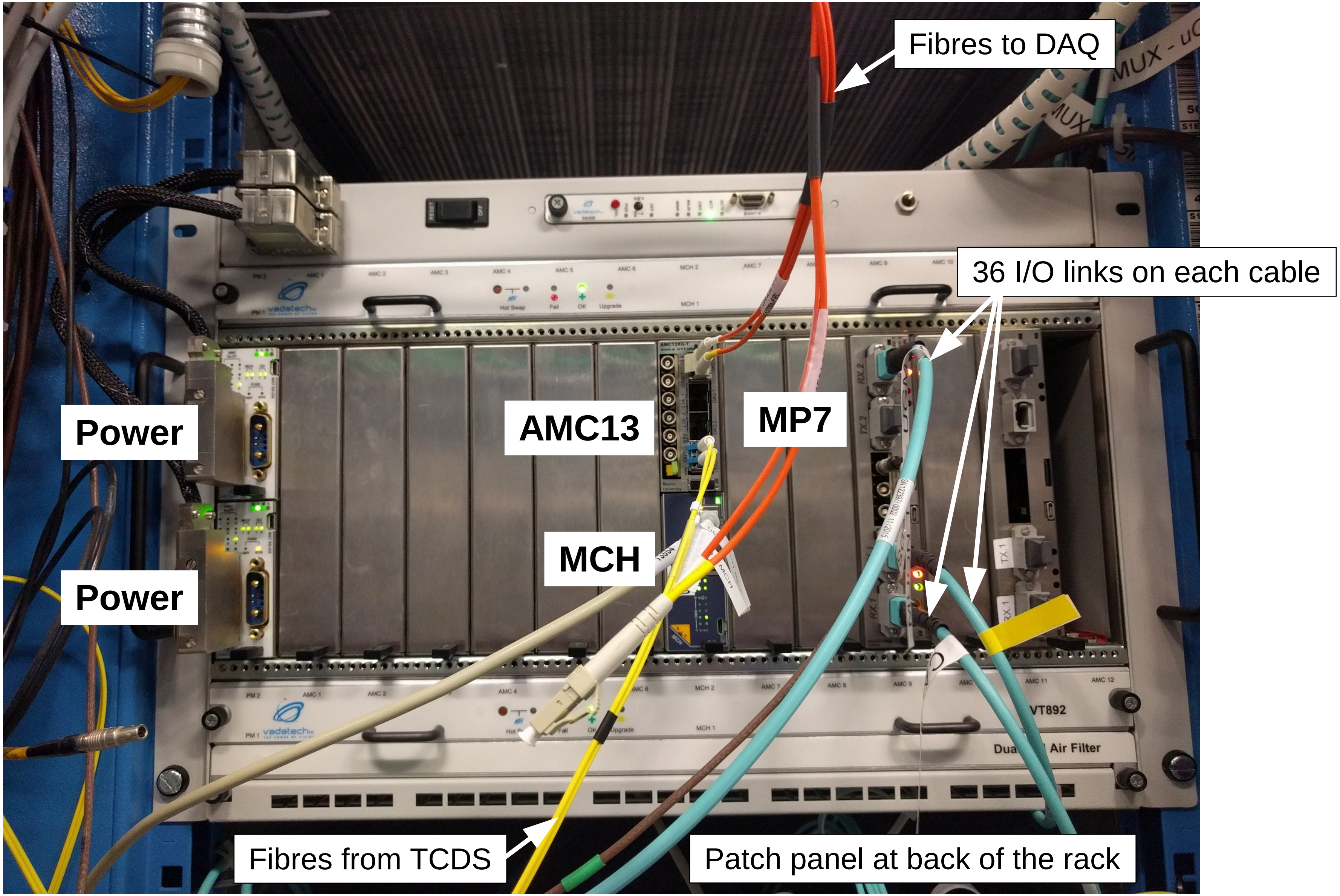


- DAQ link: AMC13
  - A 13th AMC in the second µTCA carrier hub (MCH) slot of the crate
  - 10 Gb/s optical links to central DAQ
  - Distributes LHC clock, timing and control signals to MP7 over backplane

Boston University

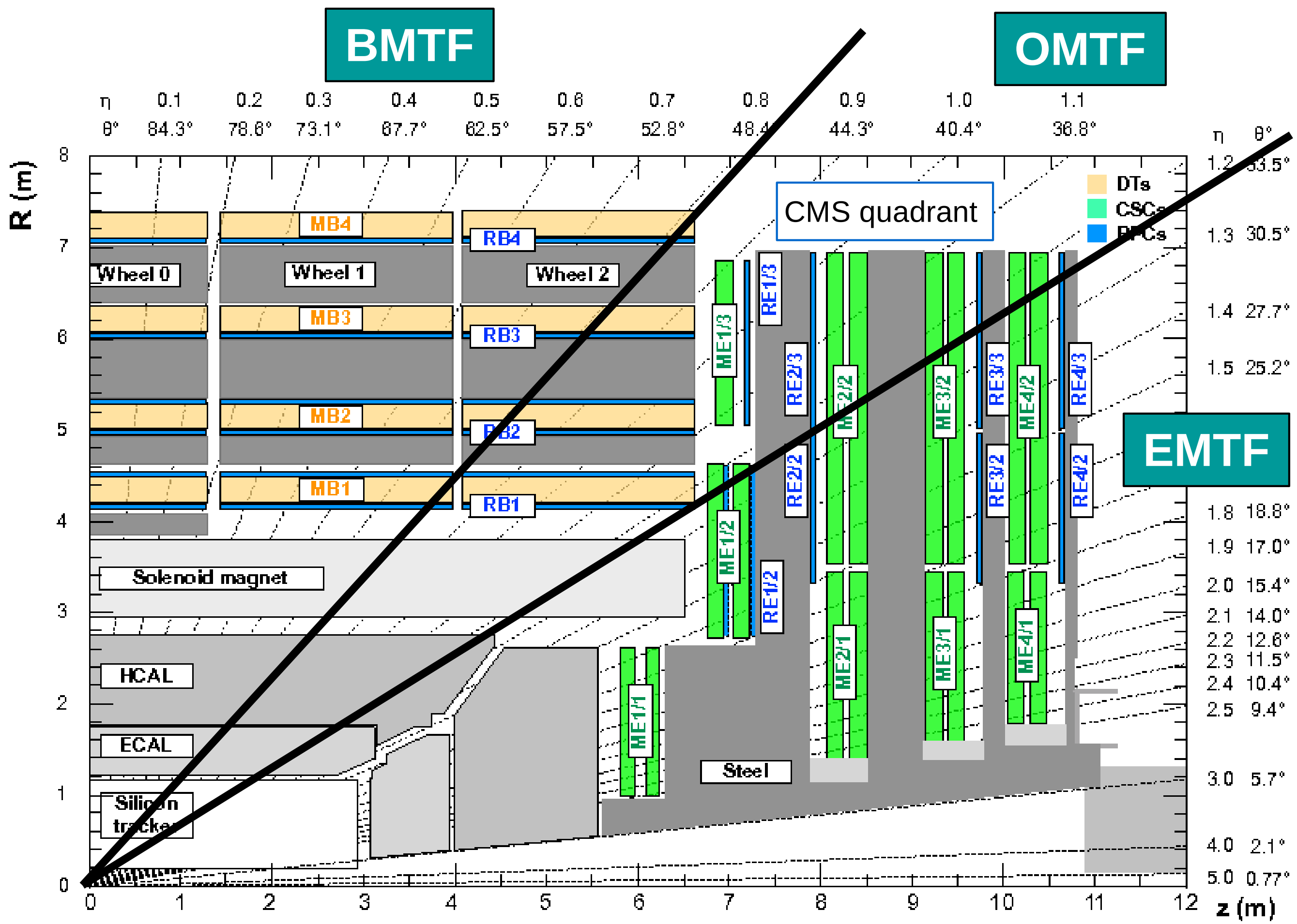
GMT installation

Global muon trigger installation in the CMS service cavern



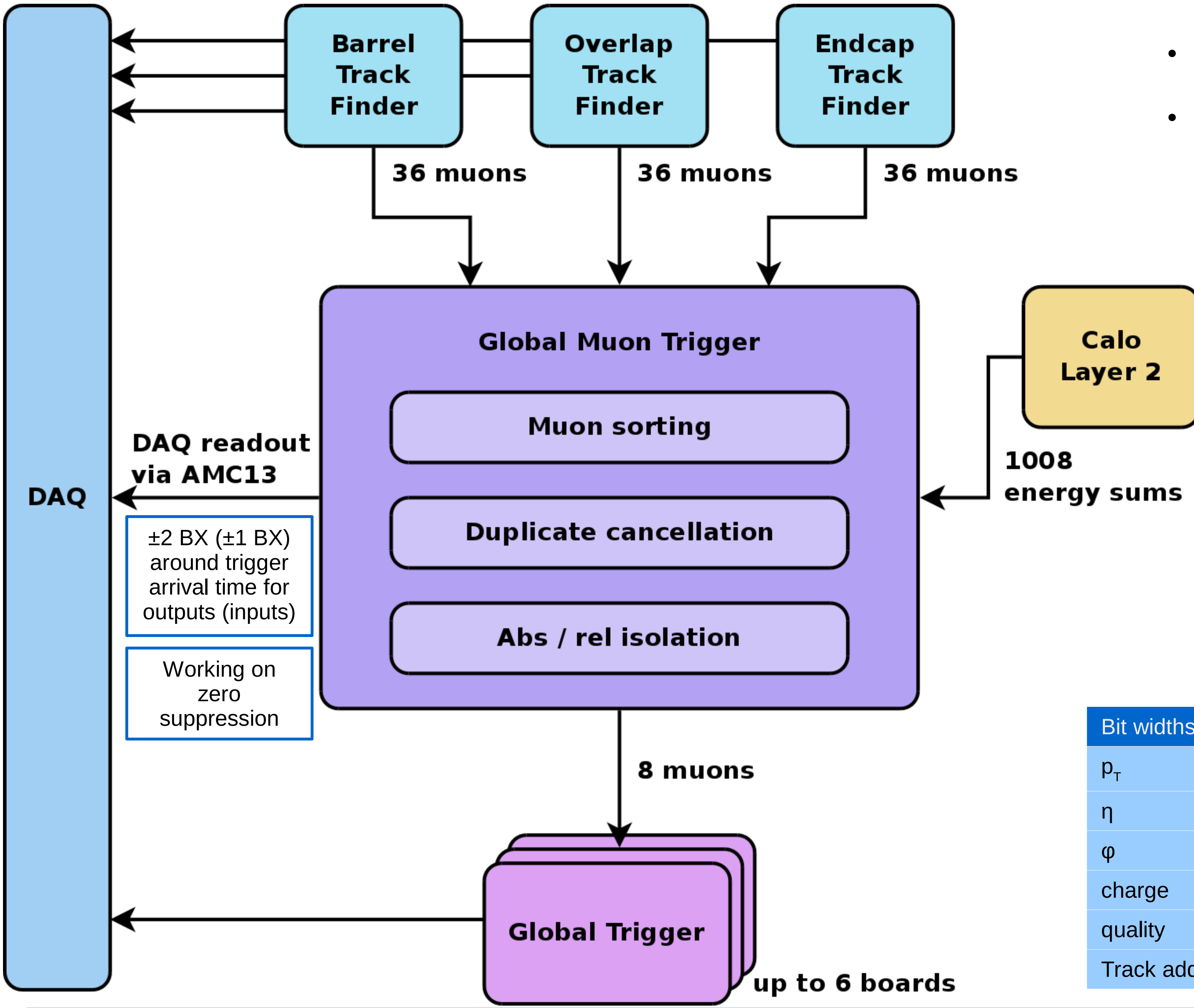
Track finders

- Barrel Track Finder
  - DT and RPC
  - |η| < 0.83
  - 2D track finding
  - 12 wedges in φ
- Overlap Track Finder
  - DT, CSC and RPC
  - 0.83 < |η| < 1.24
  - Pattern finding
  - 6 sectors in φ on each detector side
- Endcap Track Finder
  - CSC and RPC
  - |η| > 1.24
  - 3D track finding
  - 6 sectors in φ on each detector side



Pseudorapidity: $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$

Upgraded Global Muon Trigger

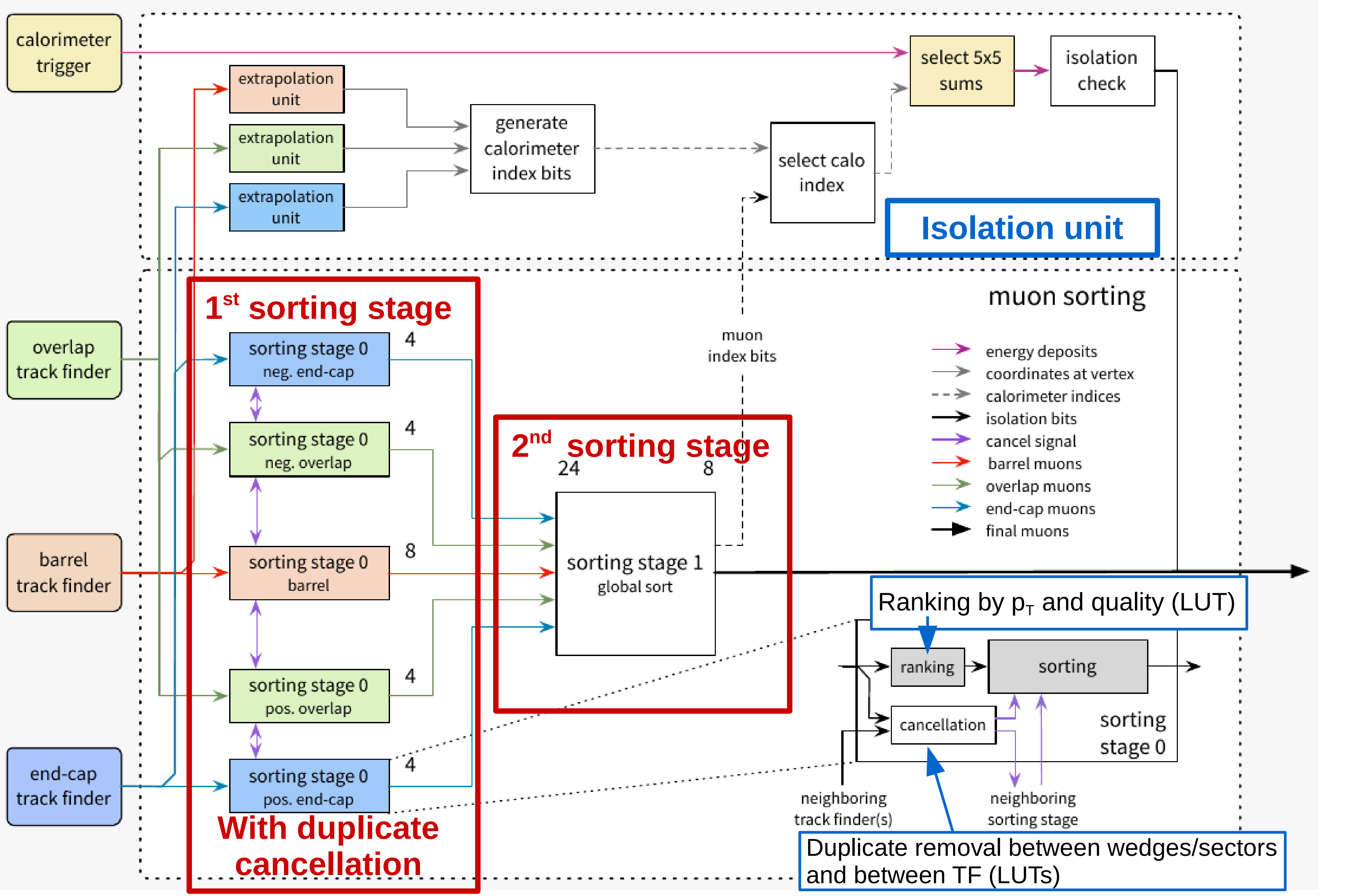


- One MP7 board
- One AMC13

100 ns (4 BX) algo latency
+ 5 BX for (de-)serialisation

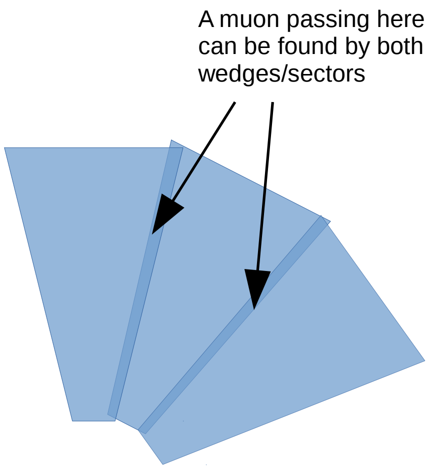
Bit widths	Legacy	Upgrade
p_T	5	9
η	6	9
φ	8	10
charge	2	2
quality	3	4
Track address	n/a	29

Global Muon Trigger algorithm

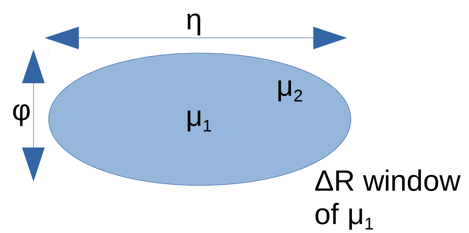


Duplicate muon removal

- The same muon can be found twice (~1% of the muons)
  - Due to overlap of adjacent track finder wedges/sectors or adjacent TF
  - This would increase the trigger rate for double muon triggers



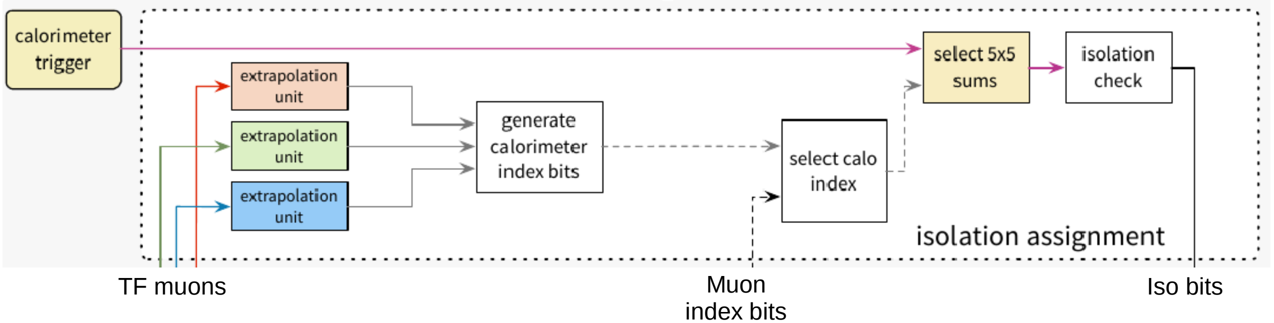
- Two methods of cancelling duplicates
  - Track address based (Track Address: Track segments used to build the muon)
    - Used to cancel duplicates between BMTF wedges
    - A tracks are marked as duplicates if they share one common segment
    - Plan to used address based cancel out also for EMTF muons
  - Muon coordinate based
    - Different address schemes between TF require duplicate cancel out by muon track coordinates
    - Tracks within the cancel out window are marked as duplicates
    - Cancel out window $\Delta R^2 = f_1 * \Delta\eta^2 + f_2 * \Delta\phi^2$
    - Window shape tunable by factors f_1 and f_2



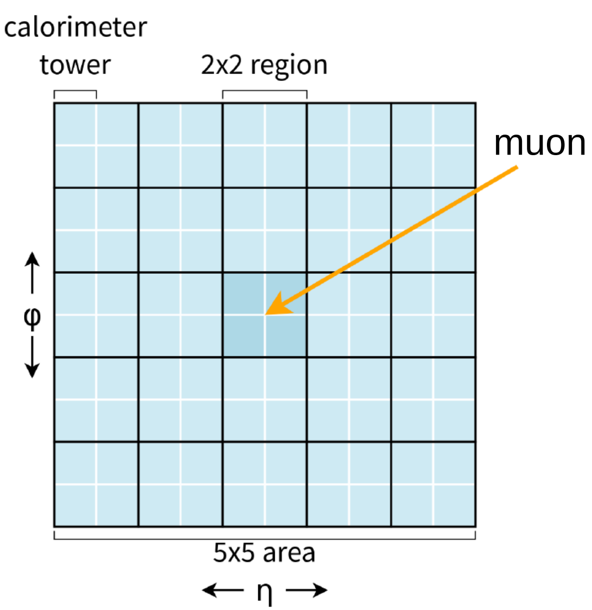
- If a duplicate is found the muon with higher quality is kept
- Tuning needed to keep real close-by di-muons
- Cancel out unit catches ~80% of duplicate muons while keeping ~70% efficiency for di-muons

Isolation

- The GMT receives 1008 energy sums from the calorimeter trigger on 28 optical links
  - 36 (φ) * 28 (η)
  - 5 bit per sum
  - Sums over 5x5 calo regions



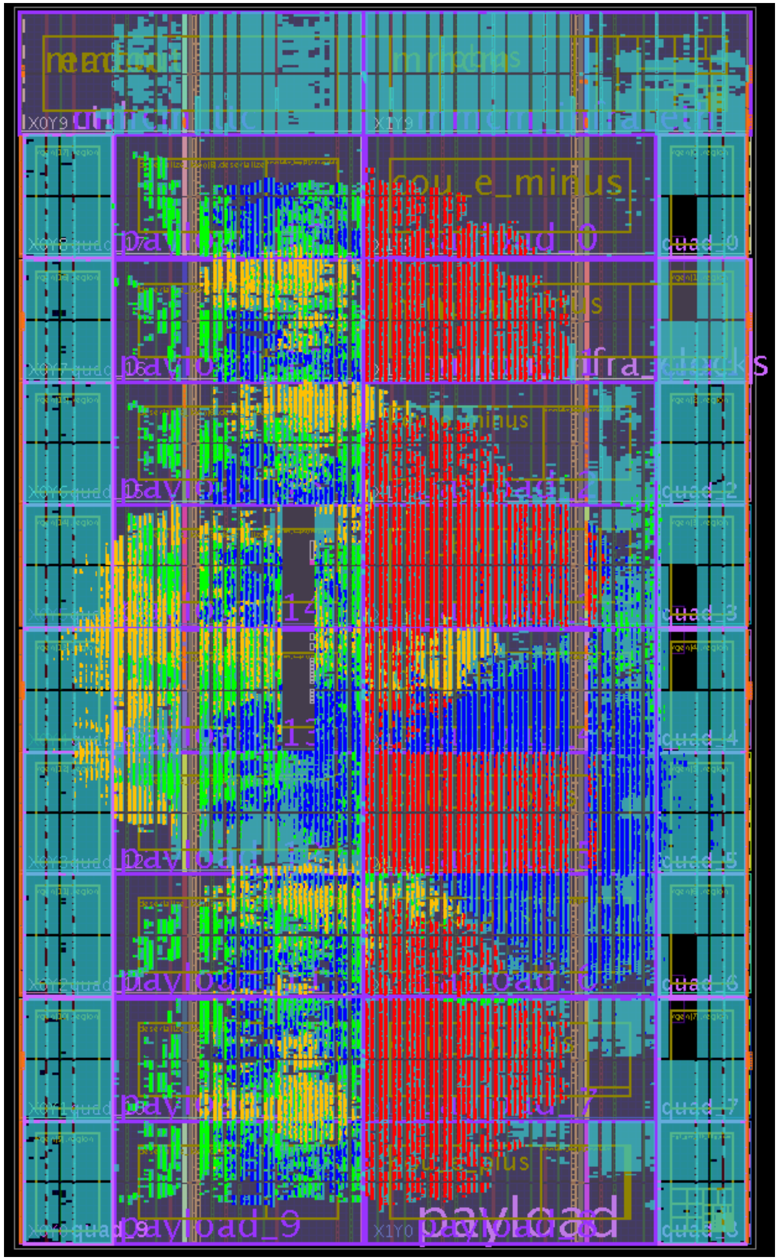
- Muon coordinates are extrapolated to the vertex (LUTs)
- Muons are matched to corresponding energy sum index (LUTs)
- For each muon two isolations are calculated (LUTs)
  - Absolute isolation
  - Relative isolation
    - Energy sum relative to muon p_T
- Isolation bits are merged with output muons



- Algorithm in FW but not commissioned yet
- Other isolation algorithms are under study

Firmware

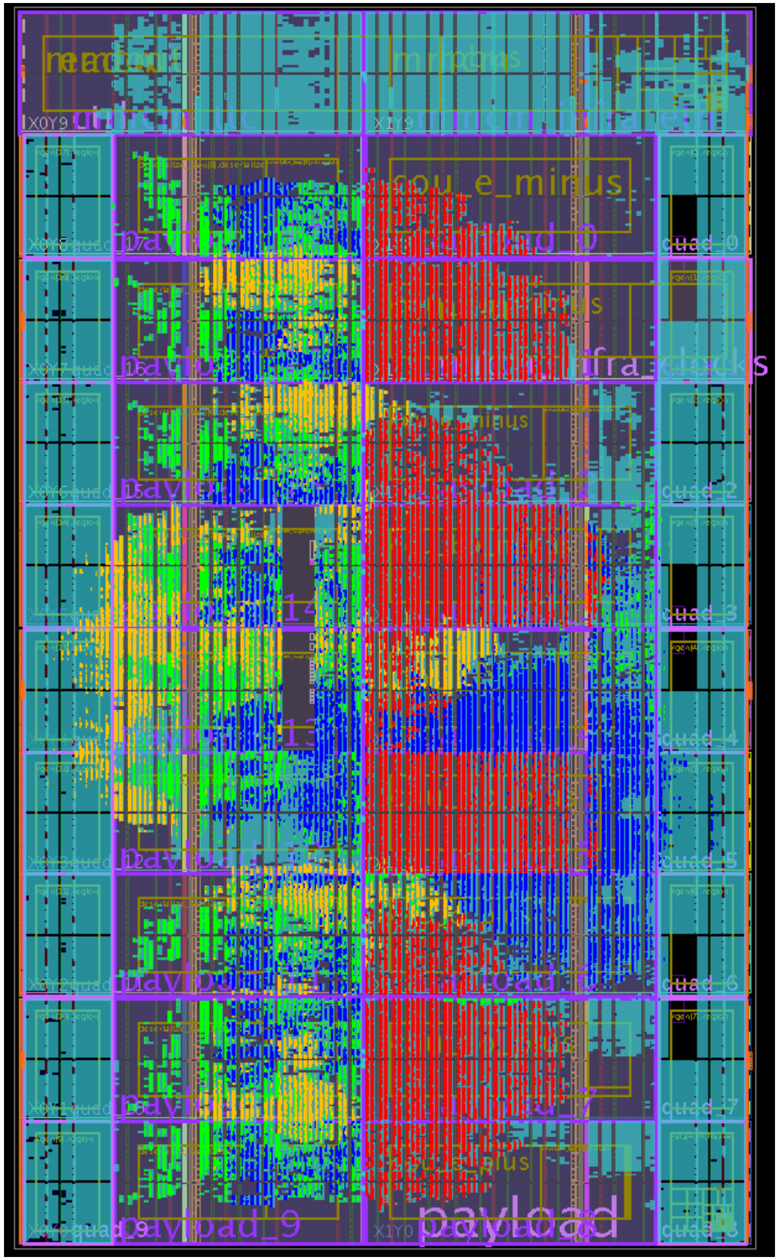
- Virtex-7 690 T
- Pipelined logic
  at 240 MHz and 40 MHz
- Resource utilisation
  - Logic: 51%
  - Block RAM: 32%
  - Inputs 10 Gb/s: 64/72
  - Outputs 10 Gb/s: 36/72



- Links, readout, IPbus
- Muon deserialisation / serialisation
- Cancel out
- Sorting
- Isolation

Firmware

- Initially developed with Xilinx ISE
  - Needed SmartXplorer for parallel implementation runs on a cluster of 5 machines
  - Took at least 13h for the implementation
  - Needed to floor plan entire design to achieve timing closure
- Change to Vivado reduced implementation time to 2h
  - Still need some floor planing constraining several functional blocks to clock regions



- Links, readout, IPbus
- Muon deserialisation / serialisation
- Cancel out

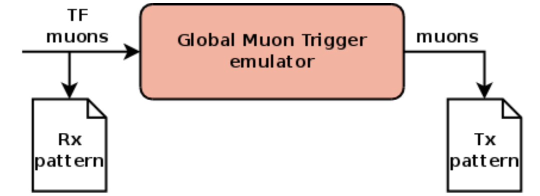
Constrained to clock region

- Isolation
- Sorting

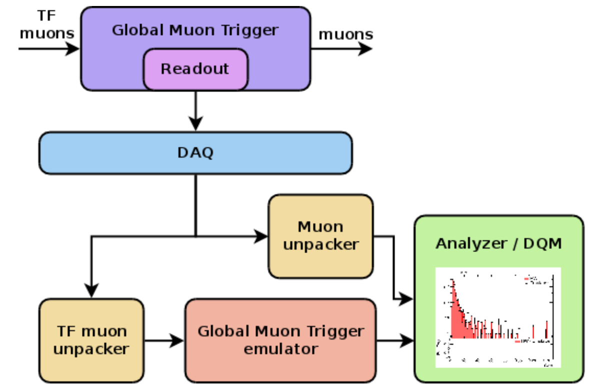
Partly constrained

Trigger emulation

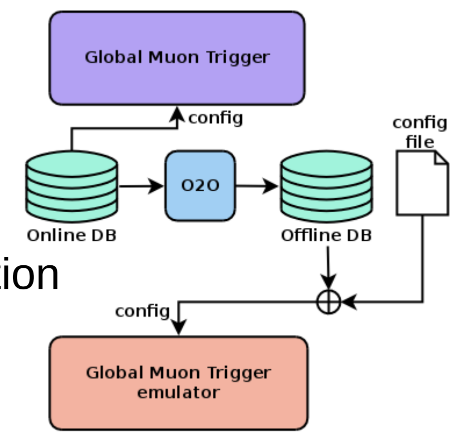
- Trigger emulator software within the CMS software framework
  - Use cases:
    - Rate and efficiency studies
    - Production of Monte Carlo simulated samples
    - Algorithm studies
    - Creating test patterns for firmware validation on test bench
    - Calculating LUTs for duplicate cancel out and sorting
    - Planned: Online DQM comparisons with FW



- 100% agreement between HW output and emulator
  - Verified with test patterns from simulated samples
  - Compared unpacked data from collision events with emulator output

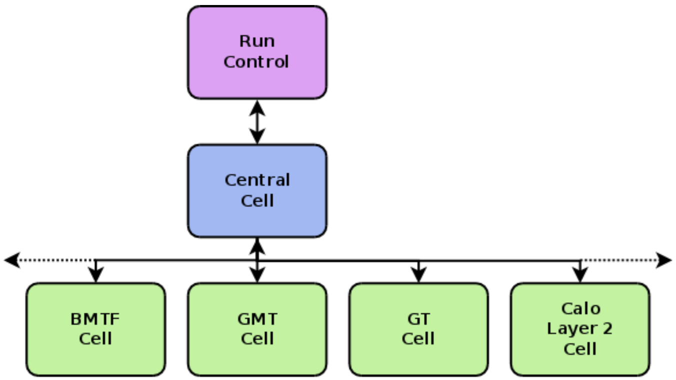


- Written in C++
- Emulator configuration
  - Automated from offline conditions synchronized to online DB configuration
    - O2O: Online to offline DB configuration transfer
  - Manually from configuration file for studies

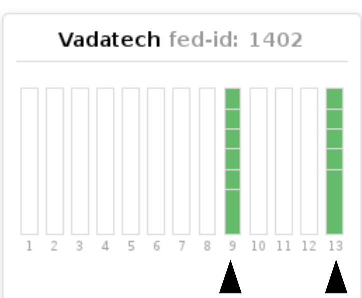


Control and monitoring software

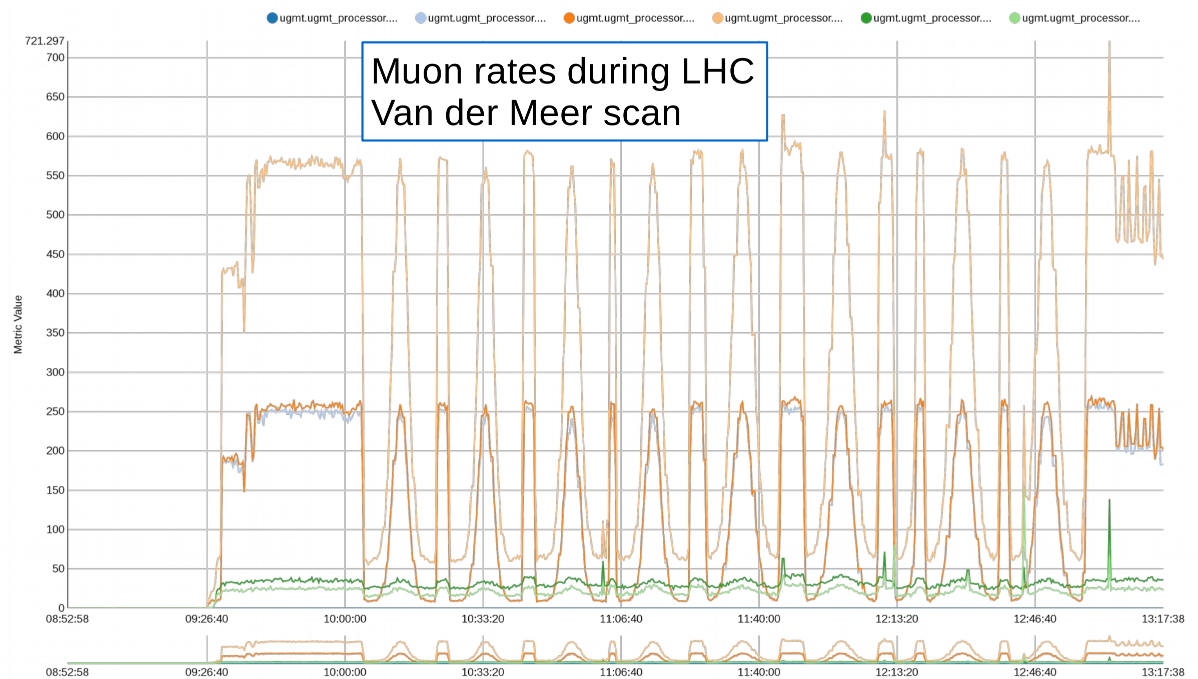
- Common control and monitoring software (SWATCH) is used to configure and monitor the system (Dedicated presentation by T. Williams)



- Centrally controlled run control state machine
  - Load configuration and LUTs from online DB at configure
- Monitoring status registers from MP7 and AMC13
  - Muon counters at input, after first and second sorting stages
  - Bunch counter mismatches
  - Disabled inputs
  - Input/Output link status
  - DAQ readout status



MP7 status AMC13 status



Summary

- CMS L1 trigger was upgraded to µTCA based system

- New global muon trigger uses generic, FPGA based, trigger processor board with 144 optical inputs and outputs at 10 Gb/s
  - Sorting of muons from regional muon track finders including regional sorting previously done on independent boards
  - Removal of duplicate muons from overlap areas
  - Absolute and relative isolation bits assignment for muons sent to global trigger
  - Firmware implemented and 100% compatible with software emulation

- New global muon trigger has been commissioned and is used for data taking since March 2016
  - Preliminary studies show lower rates while maintaining similar efficiencies as in 2015