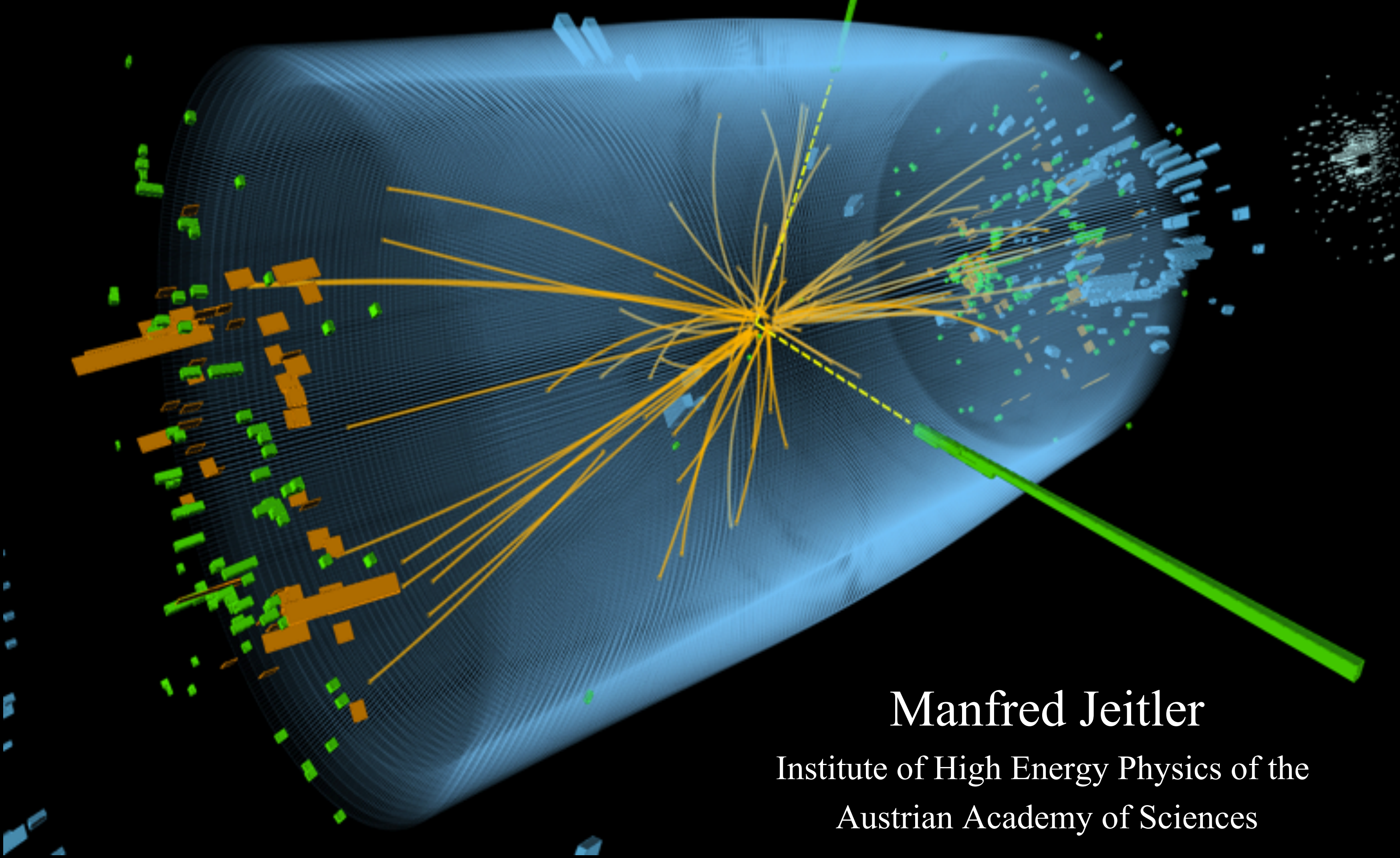
The CMS Trigger System and its upgrade

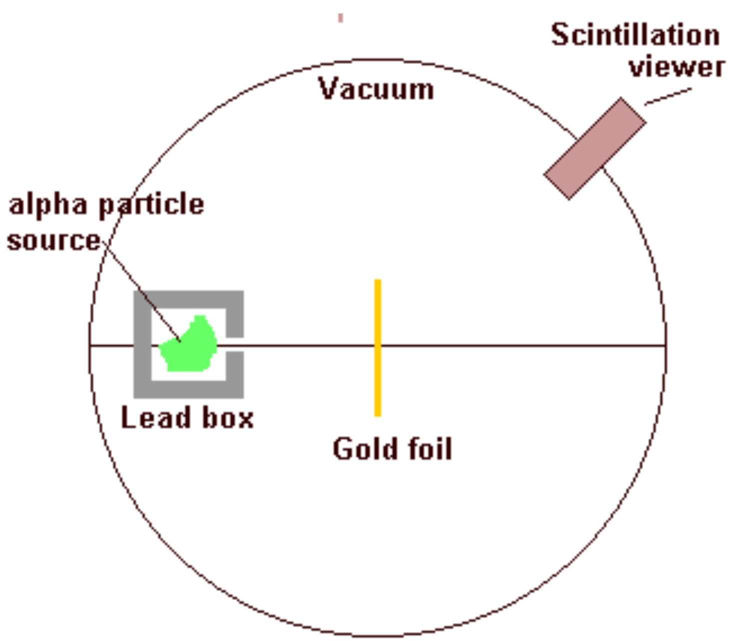


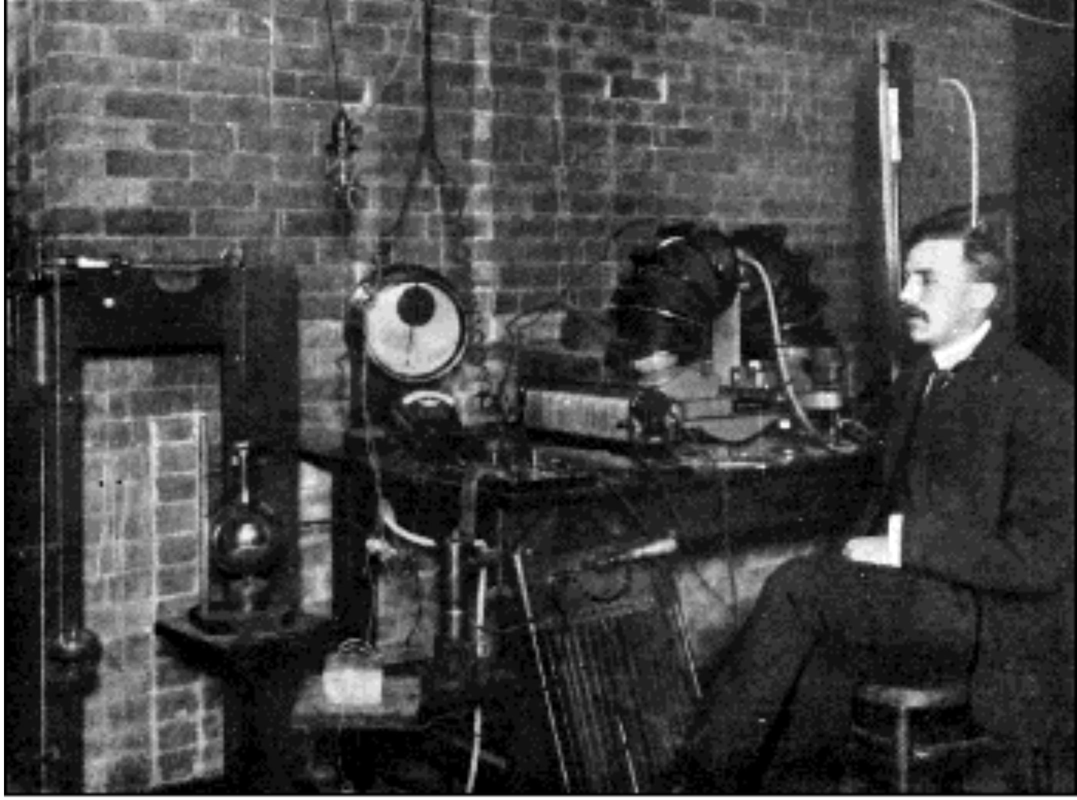
Manfred Jeitler

Institute of High Energy Physics of the Austrian Academy of Sciences

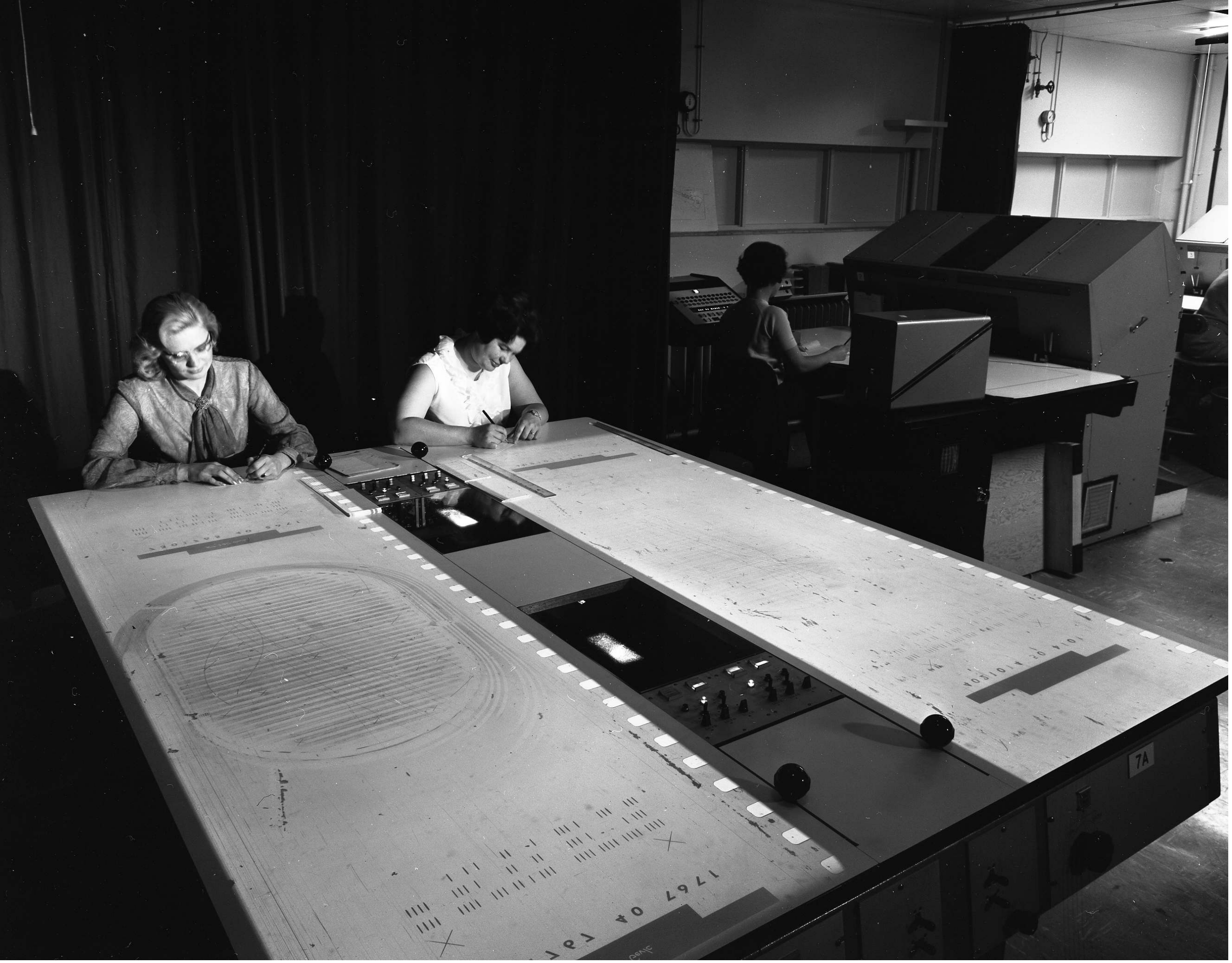

trigger
funclub-shoot.clan.su

- first particle physics experiments needed no trigger
- were looking for most frequent events
- people observed all events and then saw which of them occurred at which frequency



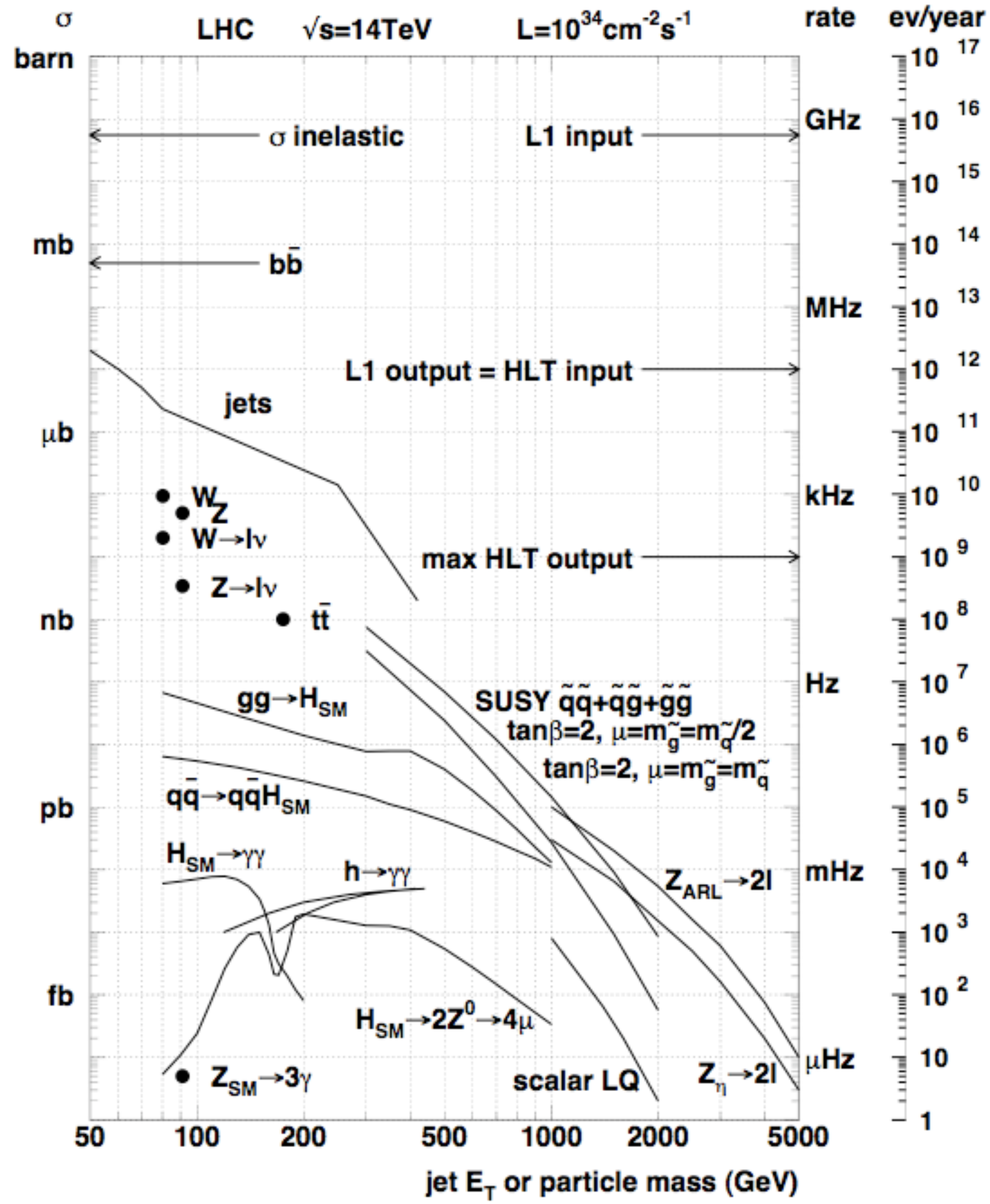


Ernest Rutherford with Gold Foil Experiment



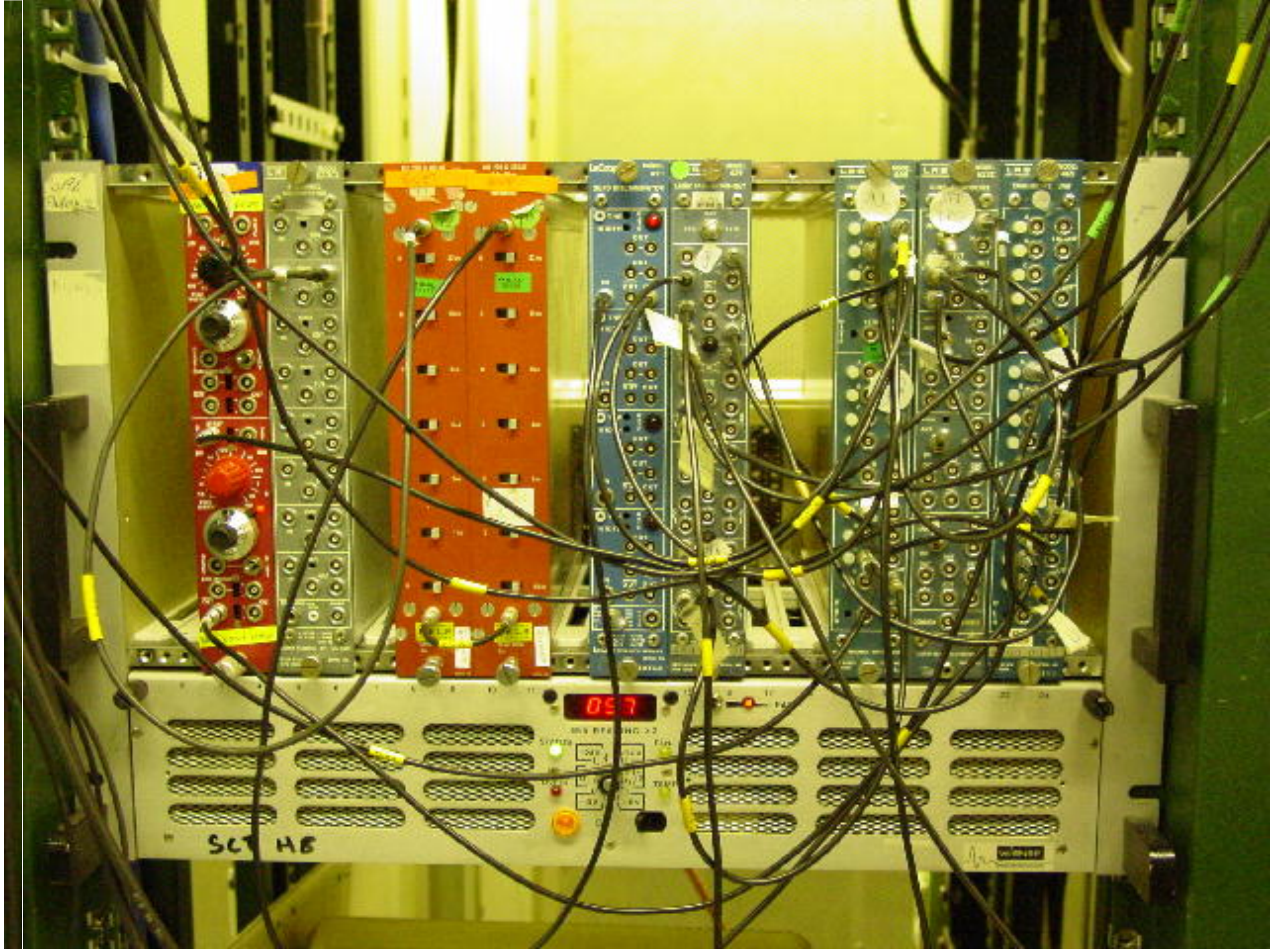
- later physicists started to look for rare events
  - “frequent” events were known already
- searching “good” events among thousands of “background” events was partly done by auxiliary staff
  - “scanning girls” for bubble chamber photographs

- due to the extremely small cross sections of processes now under investigation it is impossible to check all events "by hand"
  - ~ 10^{13} background events to one signal event
- it would not even be possible to read out and record all data in computer memories
- we need a fast, automated decision ("trigger") if an event is to be recorded or not



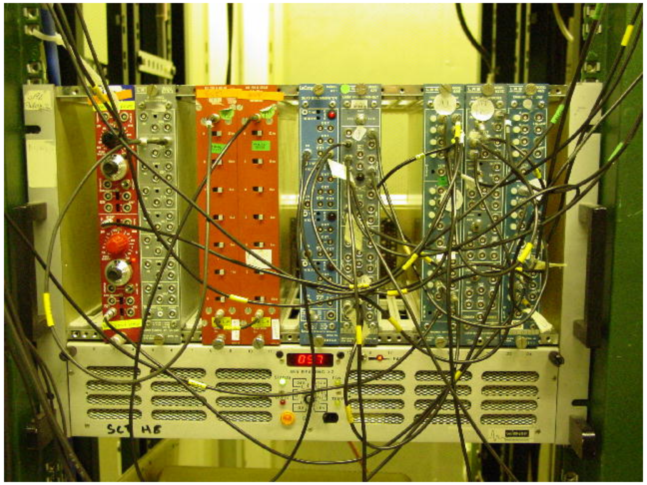
detectors yielding electrical output signals allow to select events to be recorded by electronic devices

- thresholds (discriminators)
- logical combinations (AND, OR, NOT)
- delays
- available in commercial "modules"
- connections by cables ("LEMO" cables)



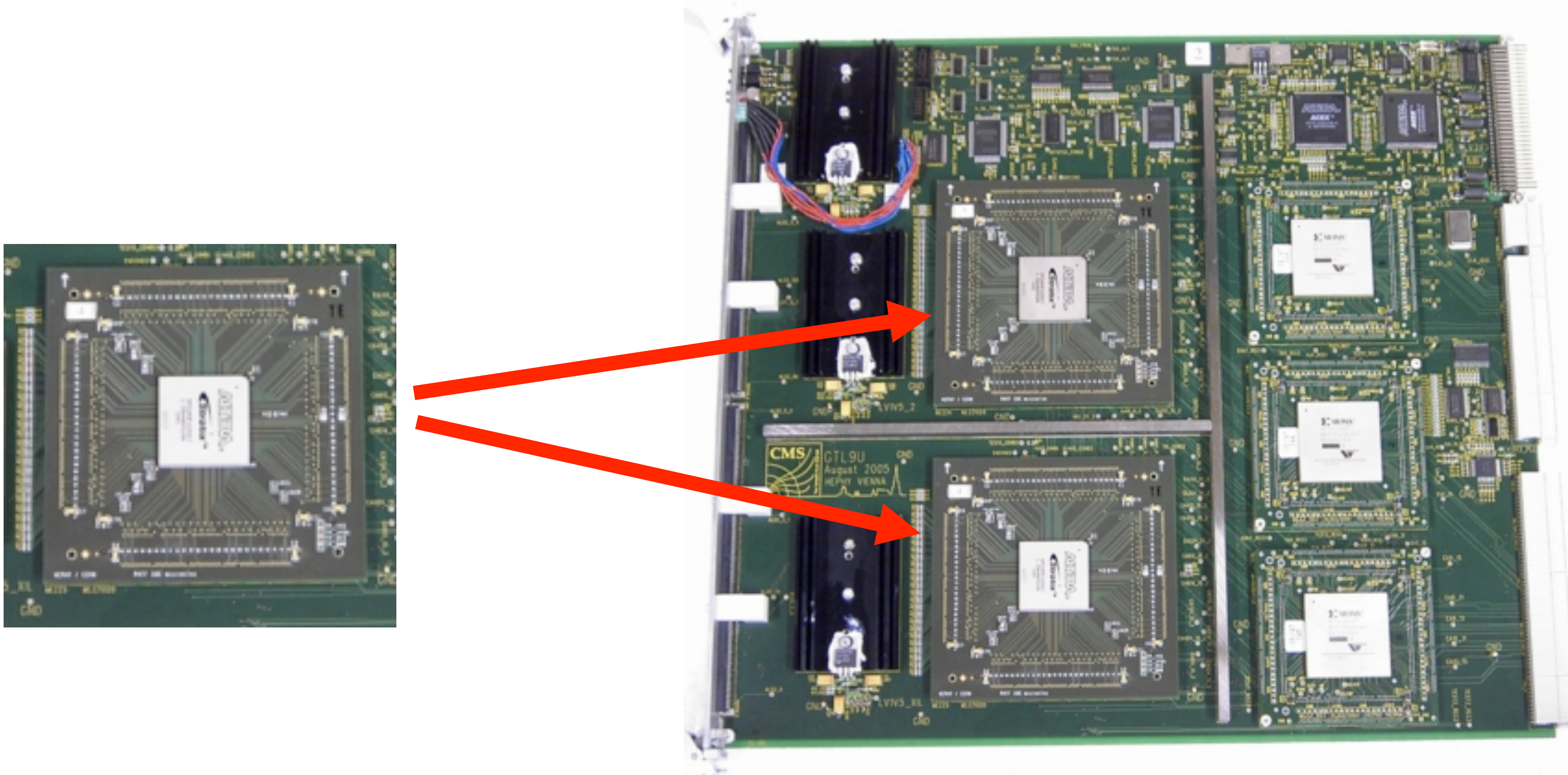
- because of the enormous amounts of data at major modern experiments electronic processing by such individual modules is impractical
  - too big
  - too expensive
  - too error-prone
  - too long signal propagation times
- ⇒ use custom-made highly integrated electronic components ("chips")

400 x



⇒ 1 x

~ 10 logical operations / module ⇒ ~ 40000 logical operations in one chip example: trigger logic of the L1-trigger of the CMS experiment

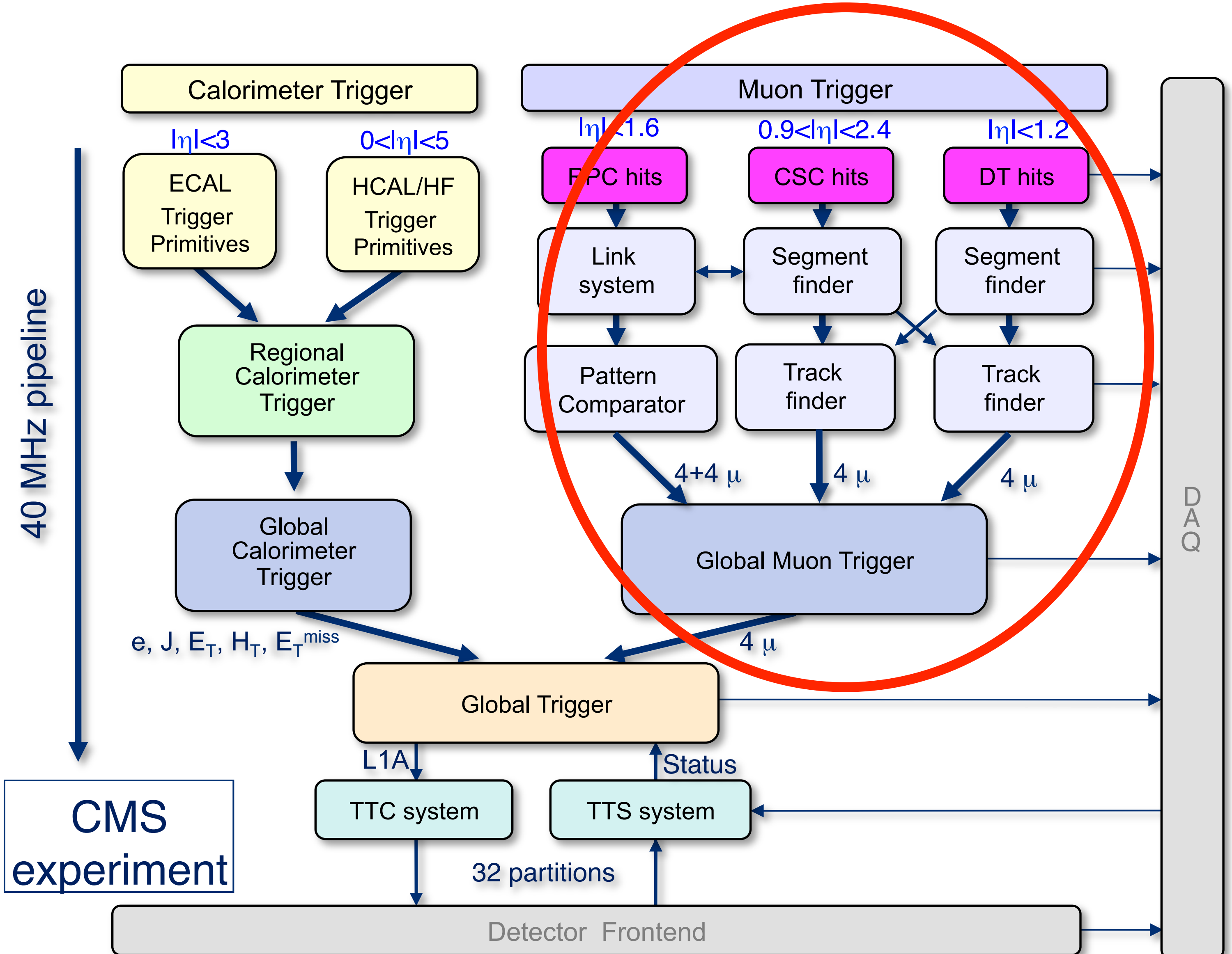


The present CMS trigger system

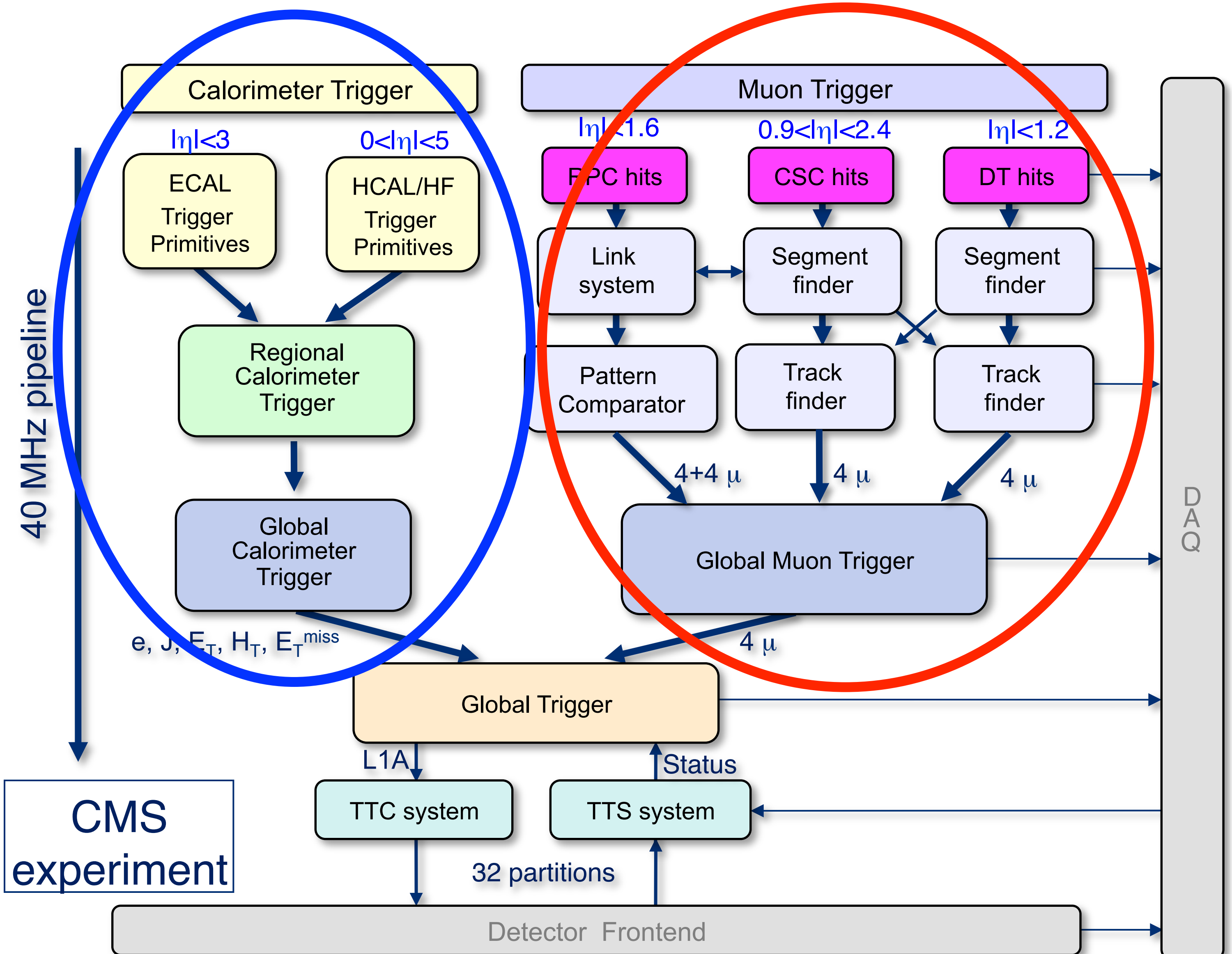
- two-tier trigger setup:
- Level-1 Trigger ("L1")
  - reduce LHC's 40-MHz bunch-crossing rate to 100 kHz
  - hardware based (custom electronics)
  - pipe-lined architecture
  - L1-accept: read out full CMS detector
- High-Level Trigger ("HLT")
  - reduce 100 kHz to a few hundred Hz
  - computer farm running CMS analysis software

The good ones go into the pot,
The bad ones go into your crop.

The present CMS Level-1 Trigger



The present CMS Level-1 Trigger



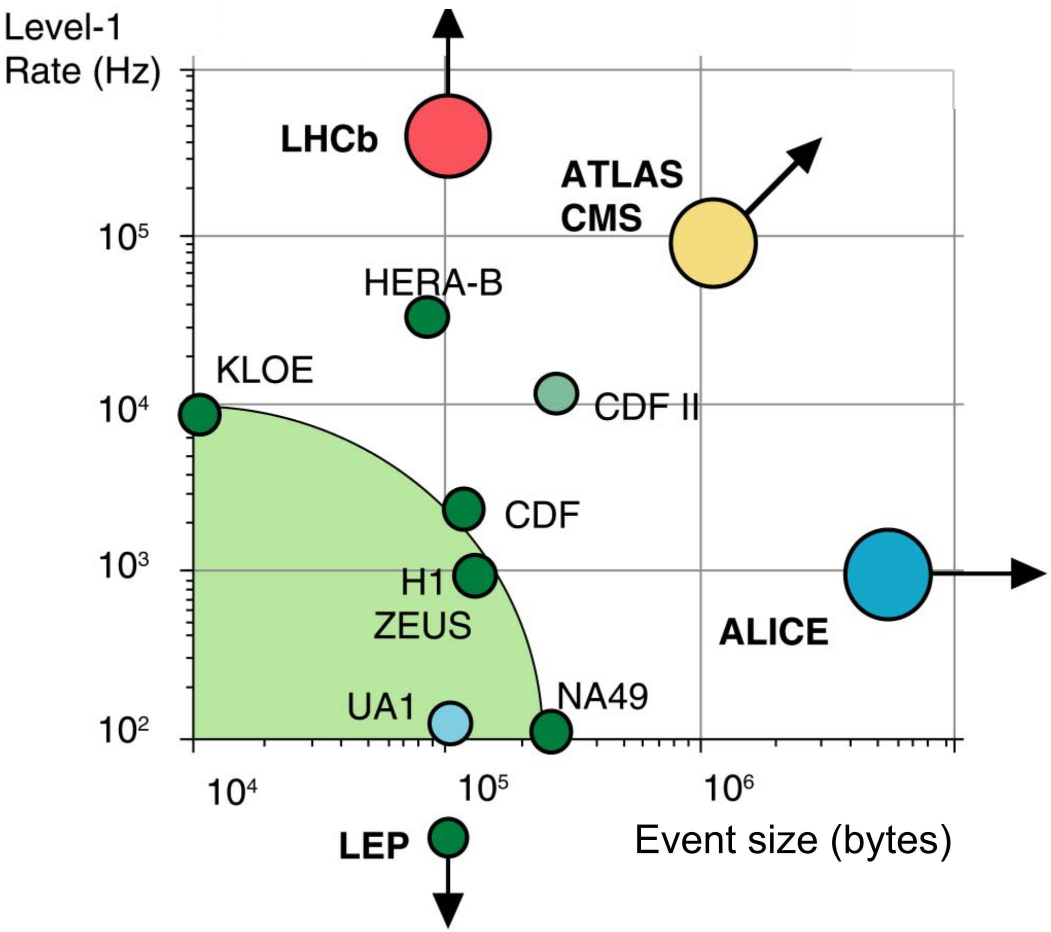
When do we trigger ?

- „bunch" structure of the LHC collider
  - „bunches" of particles
  - 40 MHz
    - a bunch arrives every 25 ns
    - bunches are spaced at 7.5 meters from each other
    - bunch spacing of 125 ns for heavy-ion operation
- at nominal luminosity of the LHC collider (10^{34} cm^{-2} s^{-1}) we will have over 40 proton-proton interactions for each collision of two bunches
  - only a small fraction of these "bunch crossings" contains at least one collision event which is potentially interesting for searching for "new physics"
  - in this case all information for this bunch crossing is recorded for subsequent data analysis and background suppression
  - luminosity quoted for ATLAS and CMS
    - reduced luminosity for LHCb (b-physics experiment)
    - heavy-ion luminosity much smaller

the LHC experiments

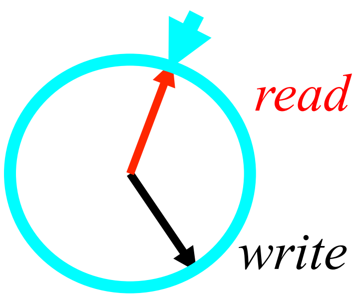
- 4 major experiments
- 3 different main physics goals
  - "general purpose": Higgs, Susy, ... : ATLAS+CMS
  - b-physics: LHCb
  - heavy ion physics: ALICE
- different emphasis on trigger:
  - ATLAS+CMS: high rates, many different trigger channels
  - LHCb: lower luminosity, need very good vertex resolution (b-decays)
  - ALICE: much lower luminosity for heavy ions, lower event rates, very high event multiplicities

trigger:		*first level*	*high level*
ATLAS, CMS	40 MHz →	100 kHz →	100 Hz
LHCb	40 MHz →	1 MHz →	2 kHz
ALICE	10 kHz →	1 kHz →	100 Hz



How do we trigger ?

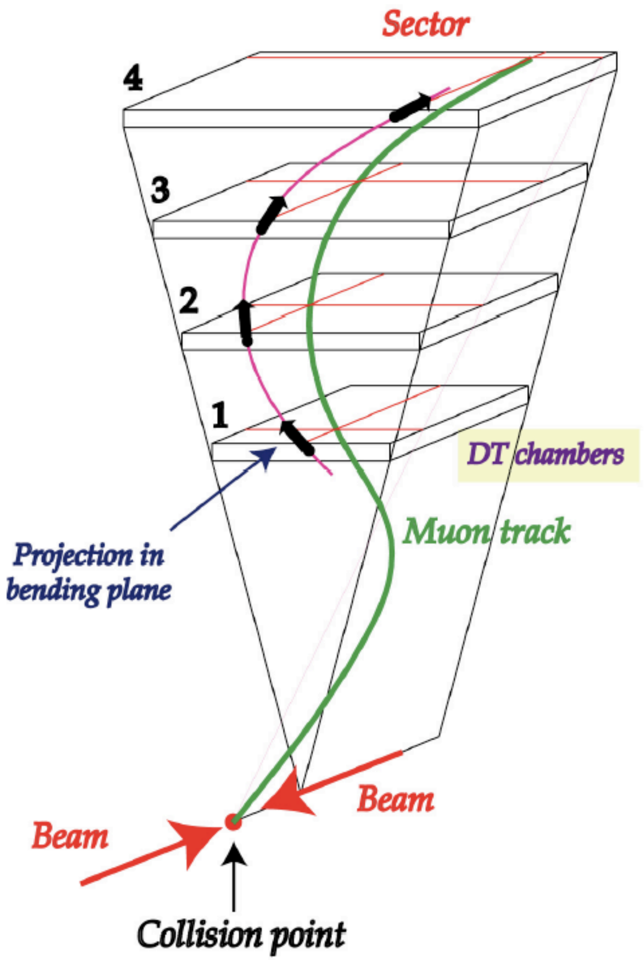
- use as much information about the event as possible
  - allows for the best separation of signal and background
  - ideal case: "complete analysis" using all the data supplied by the detector
- problem: at a rate of 40 MHz it is impossible to read out all detector data
  - (at sensible cost)
- have to take preliminary decision based on part of the event data only
- be quick
  - in case of positive trigger decision all detector data must still be available
  - the data are stored temporarily in a "pipeline" in the detector electronics
    - "short term memory" of the detector
    - "ring buffer"
    - in hardware, can only afford a few μs
- how to reconcile these contradictory requirements ?

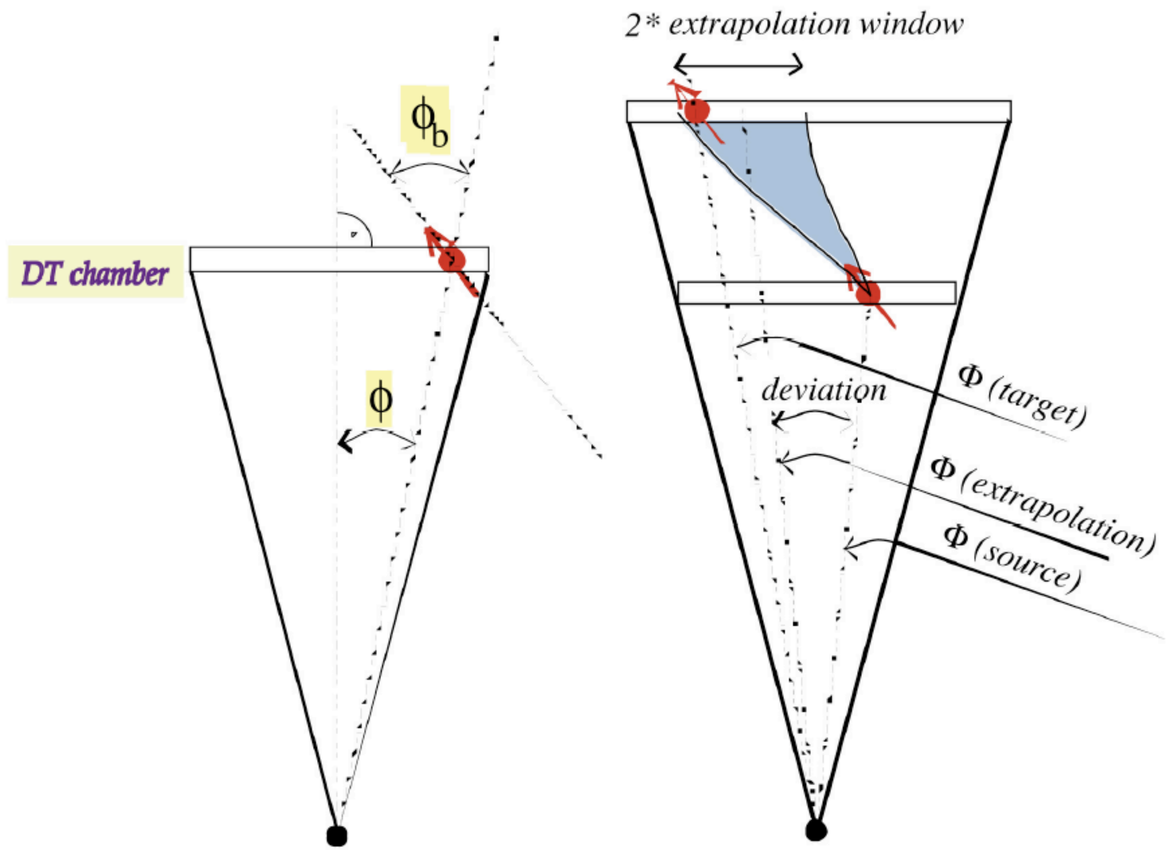


$\Rightarrow$ *multi-level trigger*

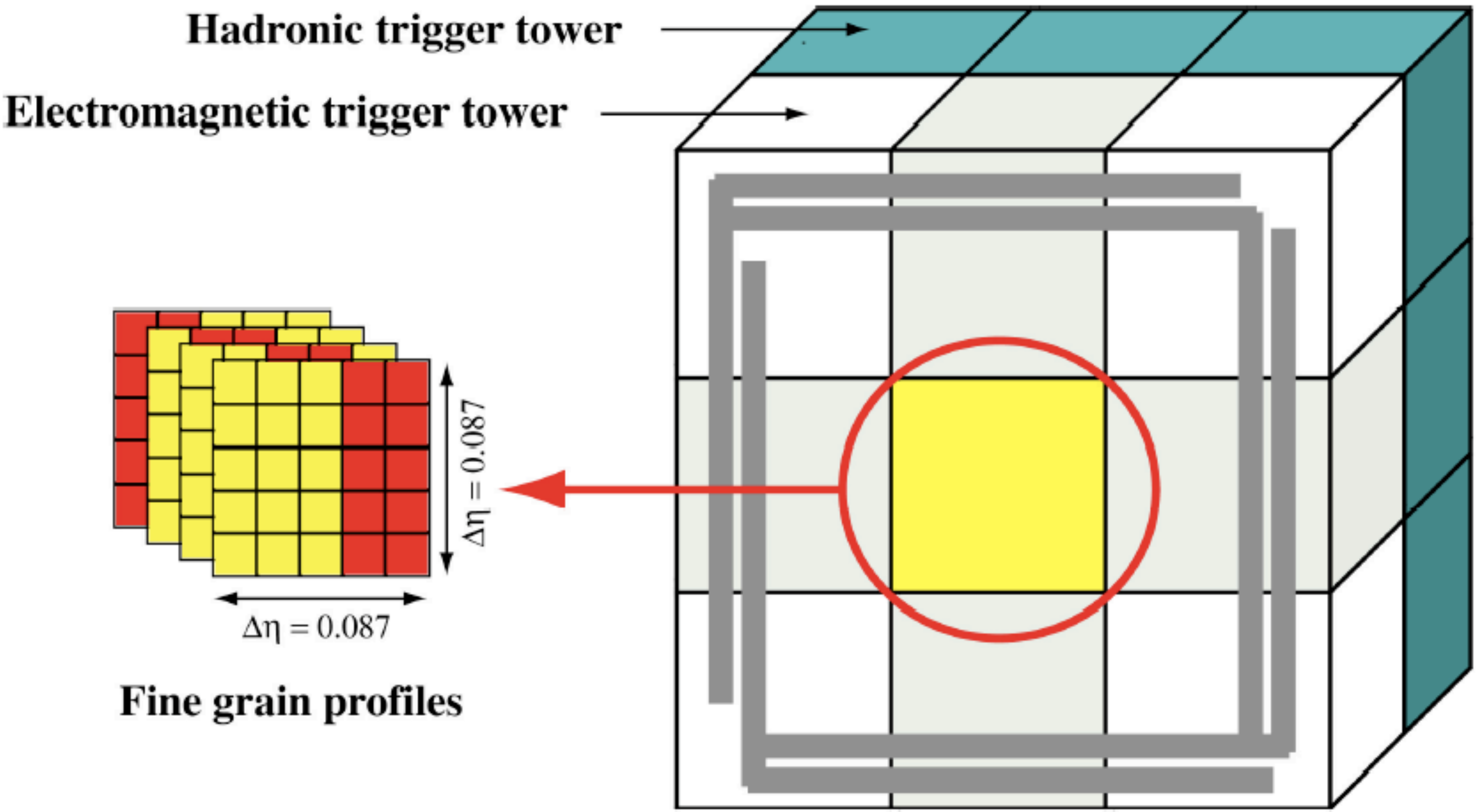
- first stage takes preliminary decision based on part of the data
  - rate is already strongly reduced at this stage
  - ~1 GHz of events (= 40 MHz bunch crossings) → ~100 kHz
  - only for these bunch crossings are all the detector data read out of the pipelines
  - still it would not be possible (with reasonable effort and cost) to write all these data to tape for subsequent analysis and permanent storage
- the second stage can use all detector data and perform a "complete analysis" of events
  - further reduction of rate: ~100 kHz → ~100 Hz
  - only the events thus selected (twice filtered) are permanently recorded

how to find muon tracks ? (CMS: solenoidal field)





calorimeter trigger



How does the trigger actually select events ?

- the first trigger stage has to process a limited amount of data within a very short time
  - relatively simple algorithms
  - special electronic components
    - ASICs (Application Specific Integrated Circuits)
    - FPGAs (Field Programmable Gate Arrays)
  - something in between "hardware" and "software": "firmware"
    - written in programming language ("VHDL") and compiled
    - fast (uses always same number of clock cycles)
    - can be modified at any time when using FPGAs

```
pre_algo_a(54) <= tau_2_s(2);
pre_algo_a(55) <= tau_2_s(1);
pre_algo_a(56) <= muon_1_s(10) AND ieg_1_s(2);
pre_algo_a(57) <= muon_1_s(6) AND ieg_1_s(28);
pre_algo_a(58) <= muon_1_s(8) AND (ieg_1_s(25) OR eg_1_s(7));
pre_algo_a(59) <= muon_1_s(9) AND (jet_1_s(9) OR fwdjet_1_s(5) OR tau_1_s(26));
pre_algo_a(60) <= muon_1_s(4) AND (jet_1_s(8) OR fwdjet_1_s(4) OR tau_1_s(25));
pre_algo_a(61) <= muon_1_s(7) AND (jet_1_s(4) OR fwdjet_1_s(20) OR tau_1_s(16));
pre_algo_a(62) <= muon_1_s(3) AND (jet_1_s(20) OR fwdjet_1_s(15) OR tau_1_s(10));
pre_algo_a(63) <= muon_1_s(2) AND tau_1_s(9);
pre_algo_a(64) <= muon_1_s(1) AND tau_1_s(20);
pre_algo_a(65) <= ieg_1_s(26) AND (jet_1_s(7) OR fwdjet_1_s(3) OR tau_1_s(24));
pre_algo_a(66) <= ieg_1_s(24) AND (jet_1_s(19) OR fwdjet_1_s(14) OR tau_1_s(8));
pre_algo_a(67) <= ieg_1_s(10) AND (jet_1_s(5) OR fwdjet_1_s(1) OR tau_1_s(19));
pre_algo_a(68) <= ieg_1_s(9) AND (jet_1_s(3) OR fwdjet_1_s(19) OR tau_1_s(15));
pre_algo_a(69) <= ieg_1_s(8) AND tau_1_s(7);
```

ex

ved)

How does the trigger actually select events ?

- the first trigger stage has to process a limited amount of data within a very short time
  - relatively simple algorithms
  - special electronic components
    - ASICs (Application Specific Integrated Circuits)
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  - something in between "hardware" and "software": "firmware"
    - written in programming language ("VHDL") and compiled
    - fast (uses always same number of clock cycles)
    - can be modified at any time when using FPGAs
- the second stage ("High-Level Trigger") has to use complex algorithms
  - not time-critical any more (all detector data have already been retrieved)
  - uses a "computer farm" (large number of PCs)
  - programmed in high-level language (C++)

LHC / CMS schedule

- now: just finished first "long shutdown" ("LS 1")
- **phase-1 upgrade**

- 2023-2025: third "long shutdown" ("LS 3")
- silicon strip tracker upgrade
- use tracker in Level-1 Trigger: "**phase-2 upgrade**"

CMS trigger upgrade

- upgrade of LHC
  - higher energy: 8 → 13 TeV collision energy in 2015
    - » higher cross-sections → higher rates
  - higher luminosity:
    - » 0.7×10^{34} $cm^{-2}s^{-1}$ in 2012
    - » → > 10^{34} $cm^{-2}s^{-1}$ in 2015
    - » → > 5×10^{34} $cm^{-2}s^{-1}$ at High-Luminosity LHC (HL-LHC)
  - higher pile-up (from 30 in 2013 to 140 at HL-LHC)
  - narrower bunch spacing (50 ns → 25 ns)
- Higgs precision measurements
- search for new physics
- → upgrade CMS trigger
  - to keep physics potential
  - else: would have to raise thresholds more and more

Level-1 Trigger phase-1 upgrade strategy

- task: reduce rates and occupancy while keeping efficiency
- calorimeter trigger
  - higher precision in coordinates (η, φ) and transverse energy (E_T)
  - flexibility for improved and more complex algorithms (pile-up subtraction, tau-jets etc.)
  - more candidate objects
- muon trigger
  - higher precision in coordinates (η, φ) and transverse momentum (p_T)
  - more candidate objects
  - combine candidates from different detectors at track-finder level
  - profit from additional chambers in endcaps (YE04 and RE04)
- global trigger
  - more algorithms (current limit: 128)
  - more sophisticated algorithms:
  - *now*: multiple objects, simple angular correlations
  - *future*: invariant mass, transverse mass, complex correlations

Level-1 Trigger phase-1 upgrade technology

- current system consists of many different custom-built electronics modules
  - VME based
  - digital electronics implemented in FPGAs and ASICs
  - maintenance and spare-module management problematic
- in future aim for higher integration
  - use larger FPGAs
  - build system in more compact way (fewer boards)
- use standardized electronics where possible
  - custom built but same for many systems
  - partly also COTS (Commercial off-the-shelf) components
  - new form factor: µTCA (Micro Telecommunications Computing Architecture)
- use optical links
  - higher data rates (higher precision, more trigger objects)
  - less space for connectors (µTCA instead of 9U-VME)

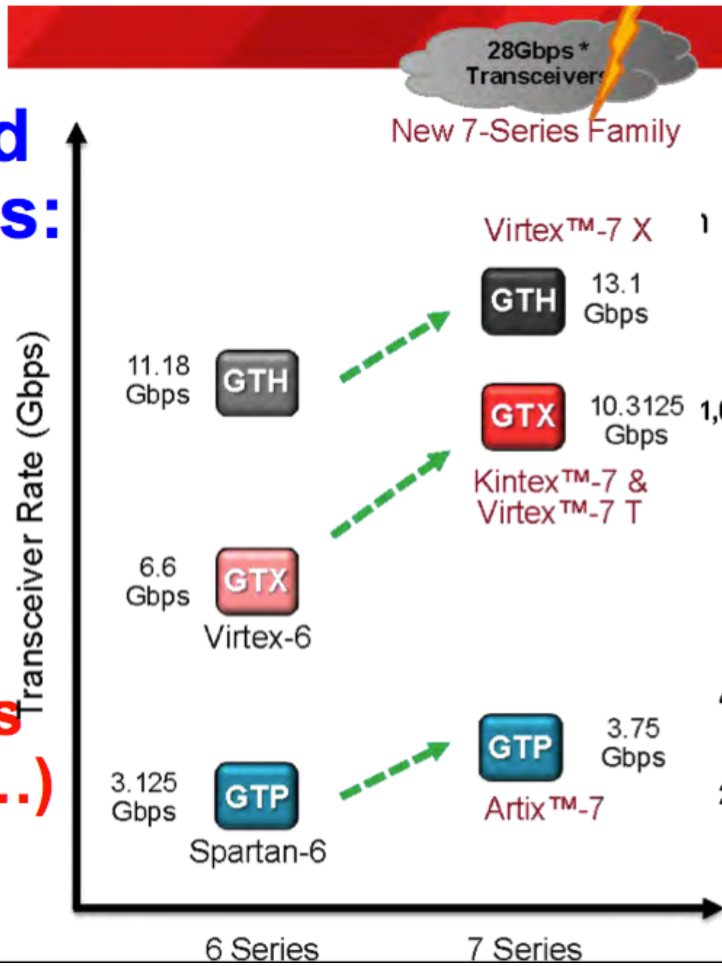
Progress in FPGAs

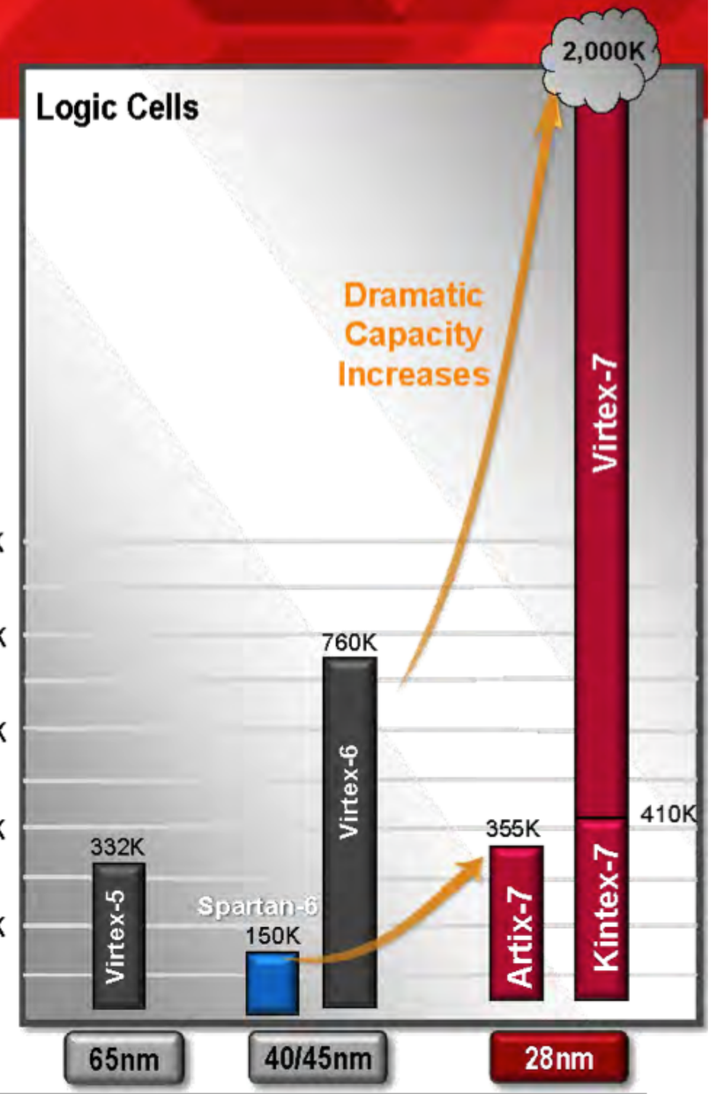
Logic Cells

- 28 nm: > 2X gains over 40 nm→

On-Chip High Speed Serial Links:

- Connect to new compact high density optical connectors (SNAP-12…)





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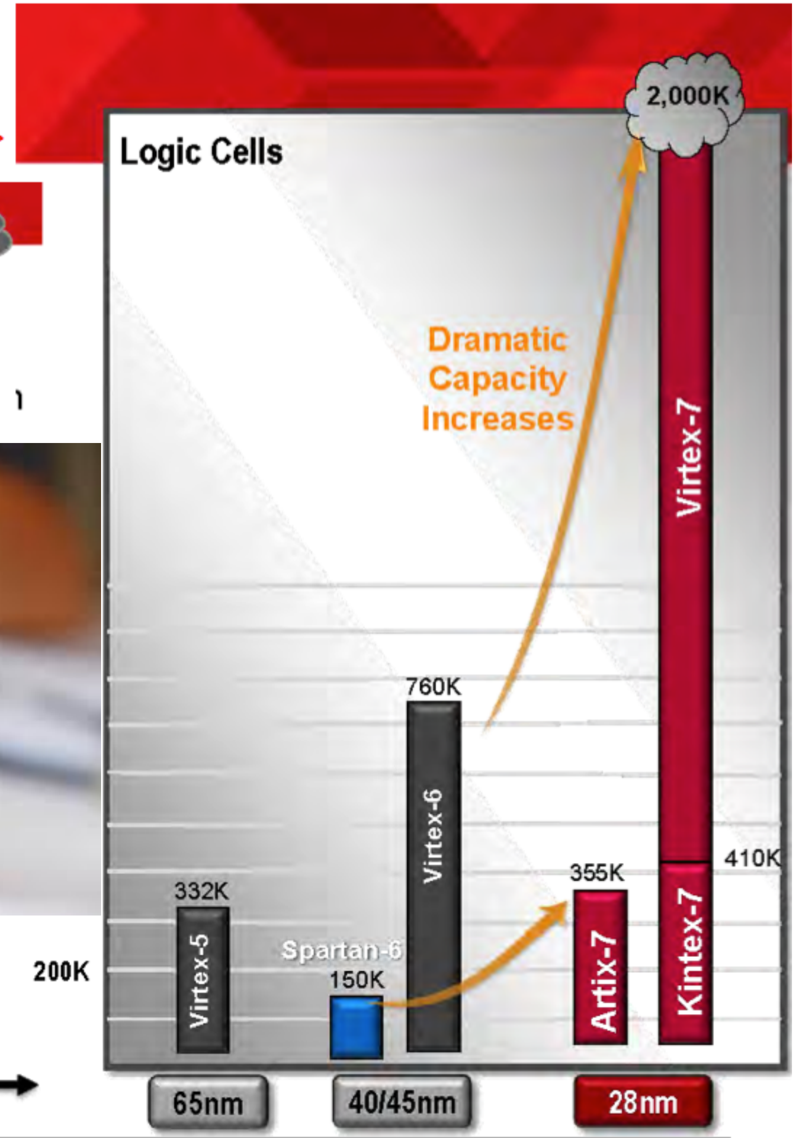
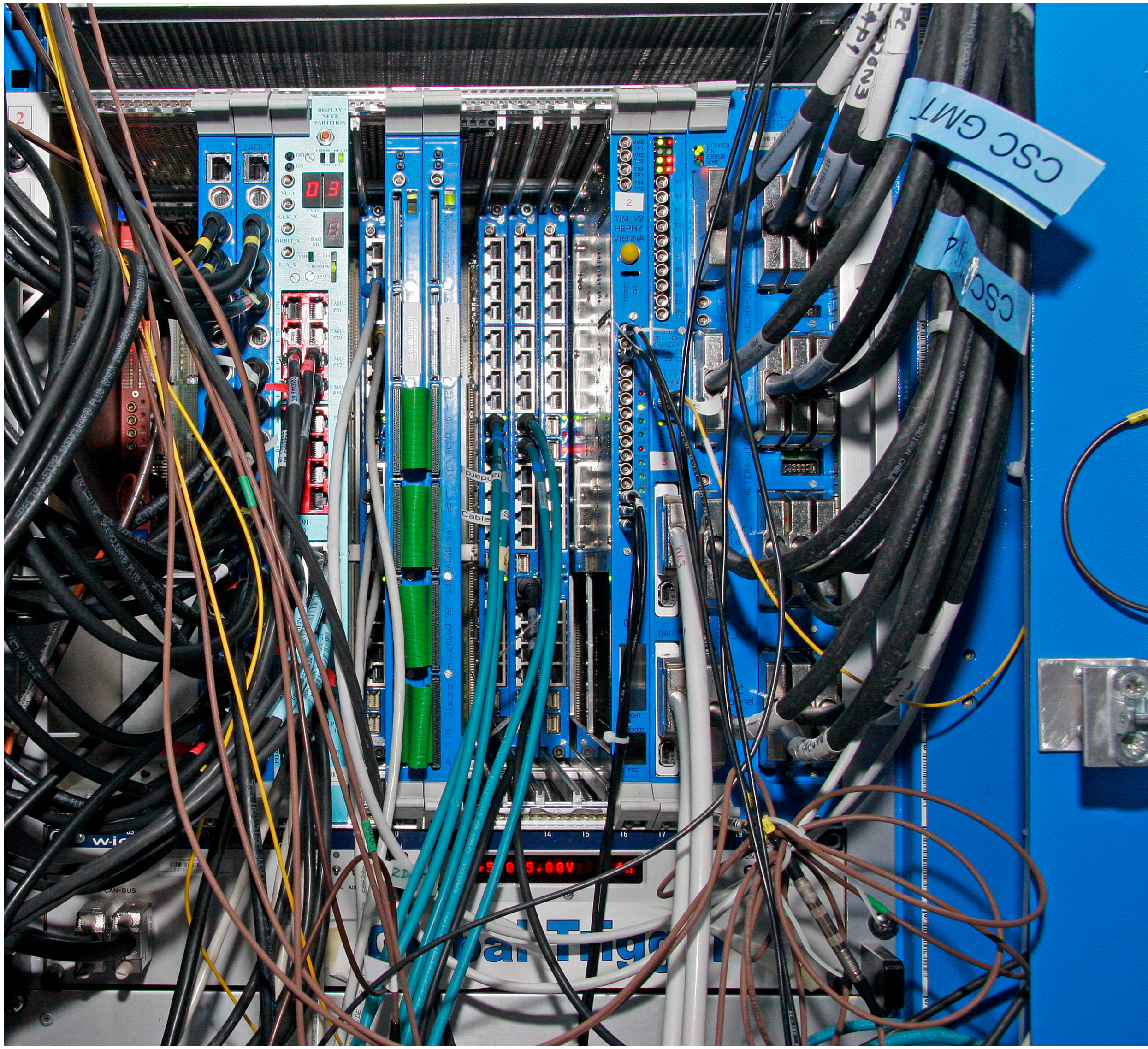


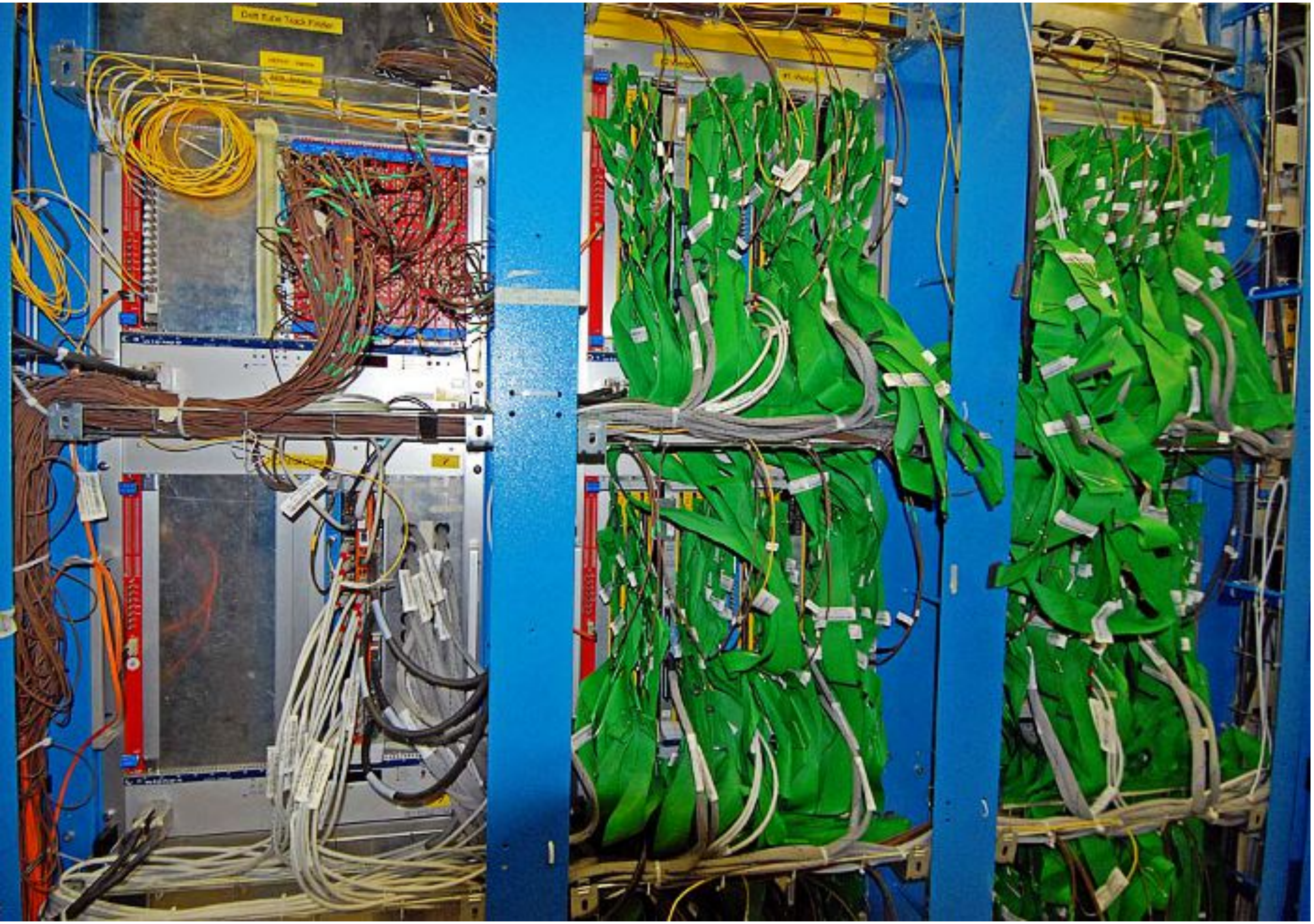
Original system: many different custom-built electronics modules (VME)

Example:

Global Trigger (left)
and
Global Muon Trigger (right)



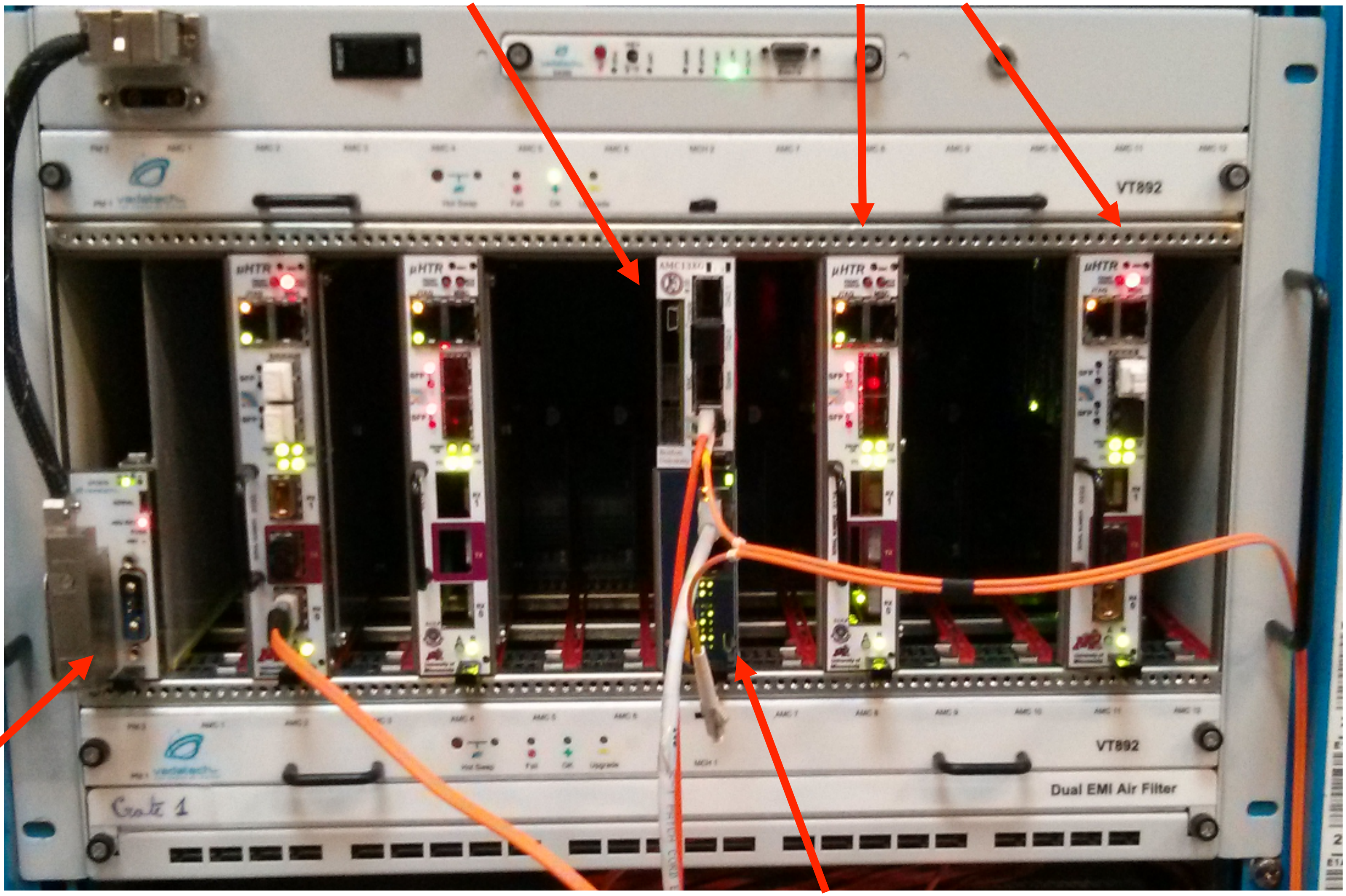
Original system: many parallel galvanic connections



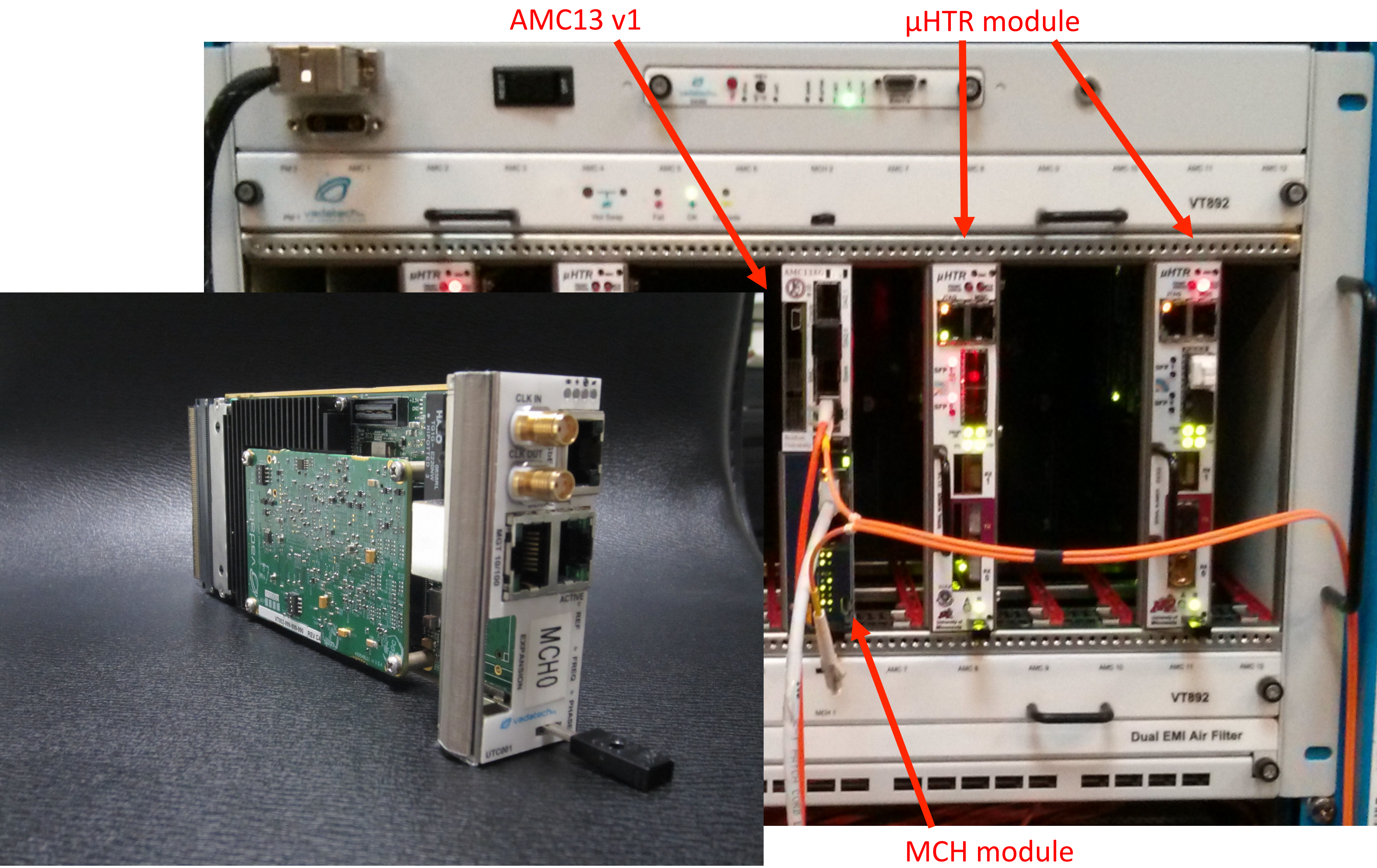
Example:

Drift Tube Track Finder (part of muon trigger)

μTCA crate


AMC13 v1
μHTR module
Power module
MCH module
VT892
Dual EMI Air Filter
Crate 1

μTCA crate


AMC13 v1
μHTR module
MCH module
VT892
VT892
Dual EMI Air Filter
CLK IN
CLK OUT
MCH0
ACTIVE
EXPANSION

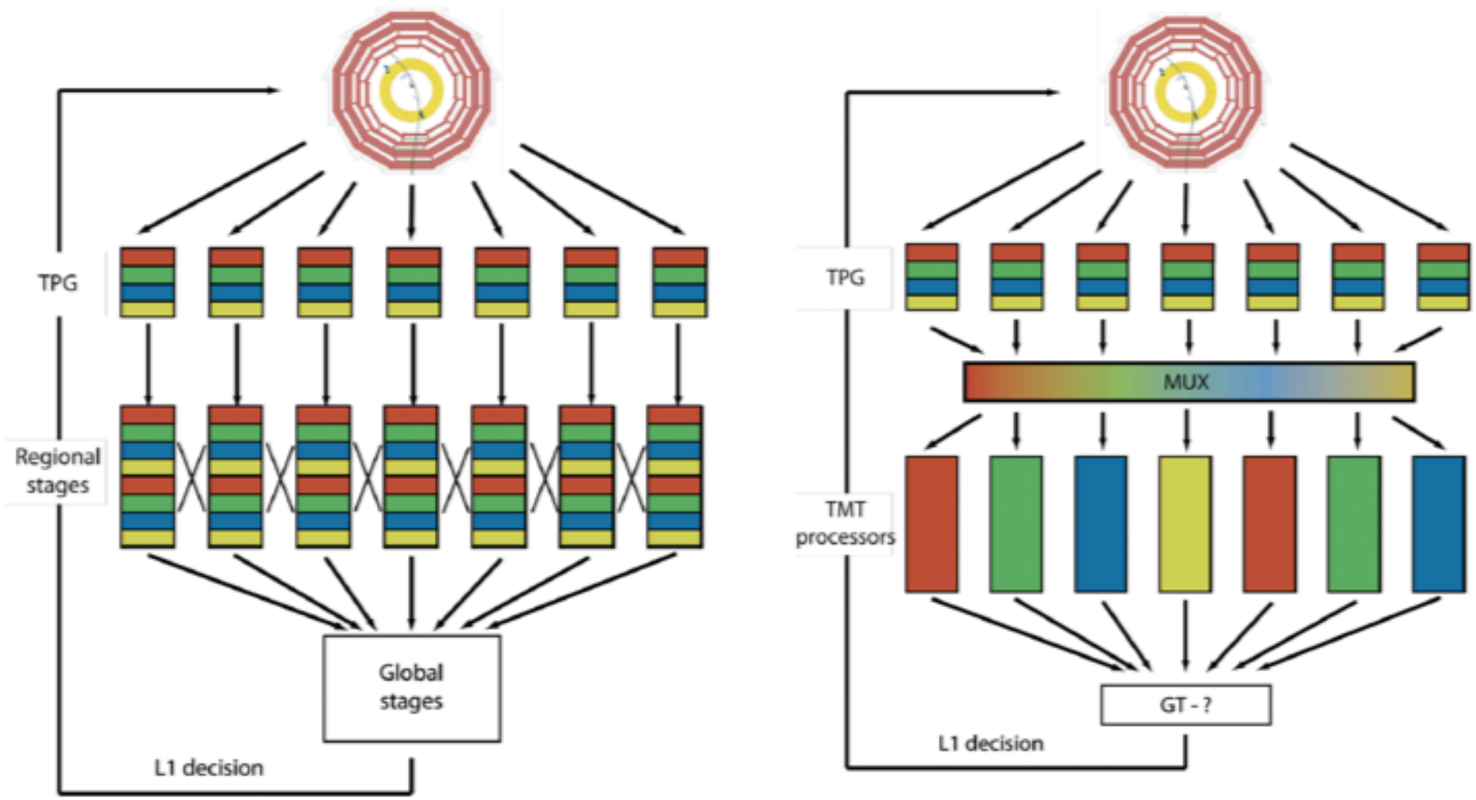
Level-1 Trigger latency

- presently ~ 4 μs
  - ~ 160 clock cycles
  - limited by tracker pipeline length
- will be increased only during tracker upgrade
  - Long Shutdown 3: phase-2 upgrade
  - ~2023
- phase-1 trigger upgrade will have to fit into same latency budget
  - challenge because of optical links
    - parallel-serial conversion (SerDes) needs time
  - we have some reserve

Muon trigger upgrade

- make use of redundant systems already at track-finder level
  - so far candidates from CSC/RPC and DT/RPC combined only after track finding, in Global Muon Trigger
- 3 regional systems: Barrel Track Finder (DT+RPC), Endcap Track Finder (CSC+RPC), Overlap Track Finder (DT+CSC+RPC)
- high rate particularly problematic in end caps
  - Cathode Strip Chambers (CSC) and Resistive-Plate Chambers (RPC)
  - outermost chambers being added now
  - improve p_T resolution and thus reduce rate
  - current design ($\Delta\varphi$ comparisons) does not scale well
  - → switch to pattern matching system to accommodate higher occupancy
- Drift Tube trigger relocation
  - moved front-end electronics ("sector collectors") from experimental cavern to electronics cavern
  - all trigger electronics close to Global Trigger, always accessible in radiation-safe area

Calorimeter trigger

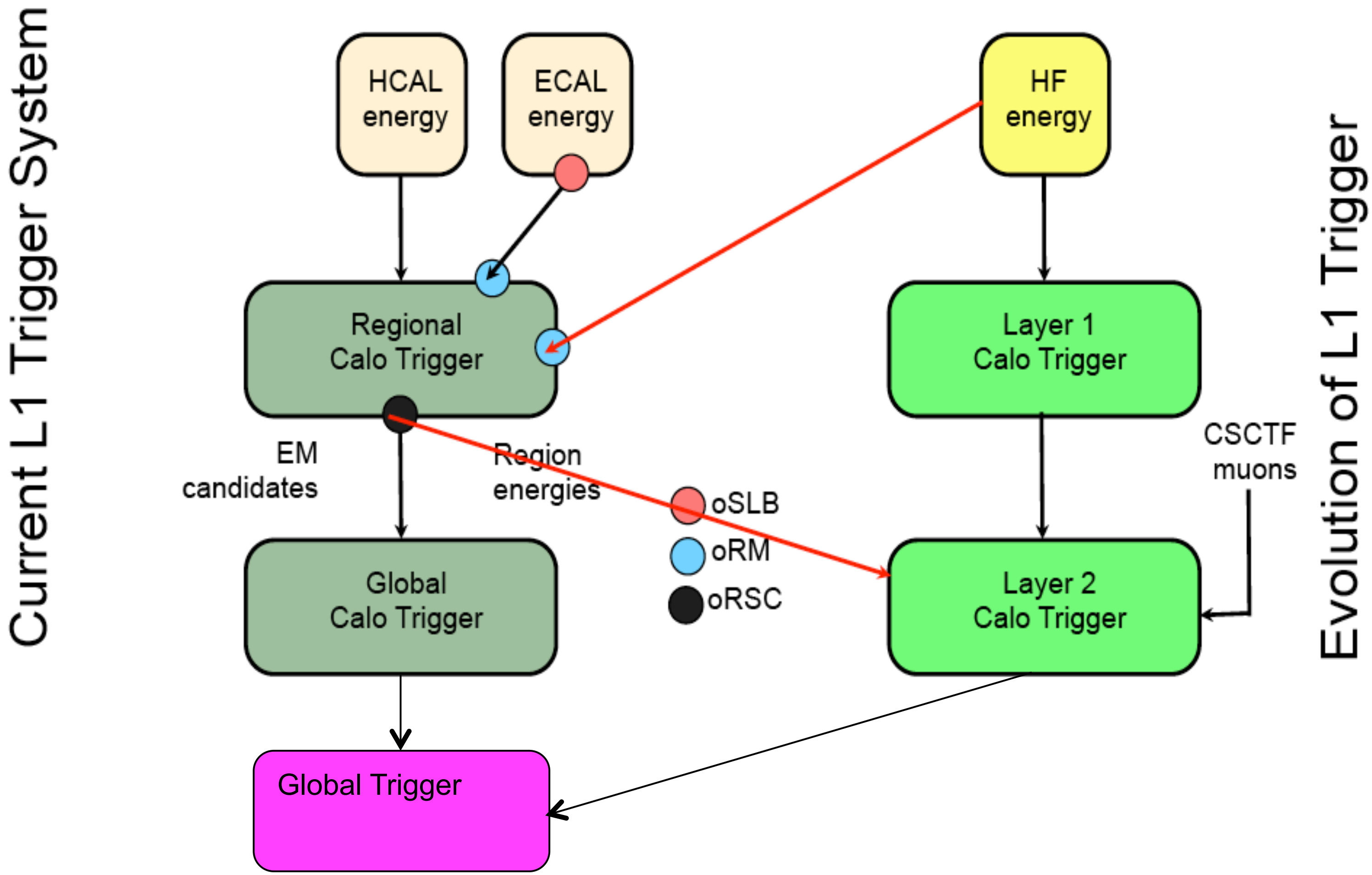


transition from parallel triggering systems to ***time-multiplexed trigger***

- processors take turns
- each processor gets all the data for a given bunch crossing
- same hardware with different connections could run parallel triggering system

Stage-1 Upgrade of Level-1 in 2015

- to profit from improvements in calorimeter algorithms early on



Level-1 Global Trigger upgrade

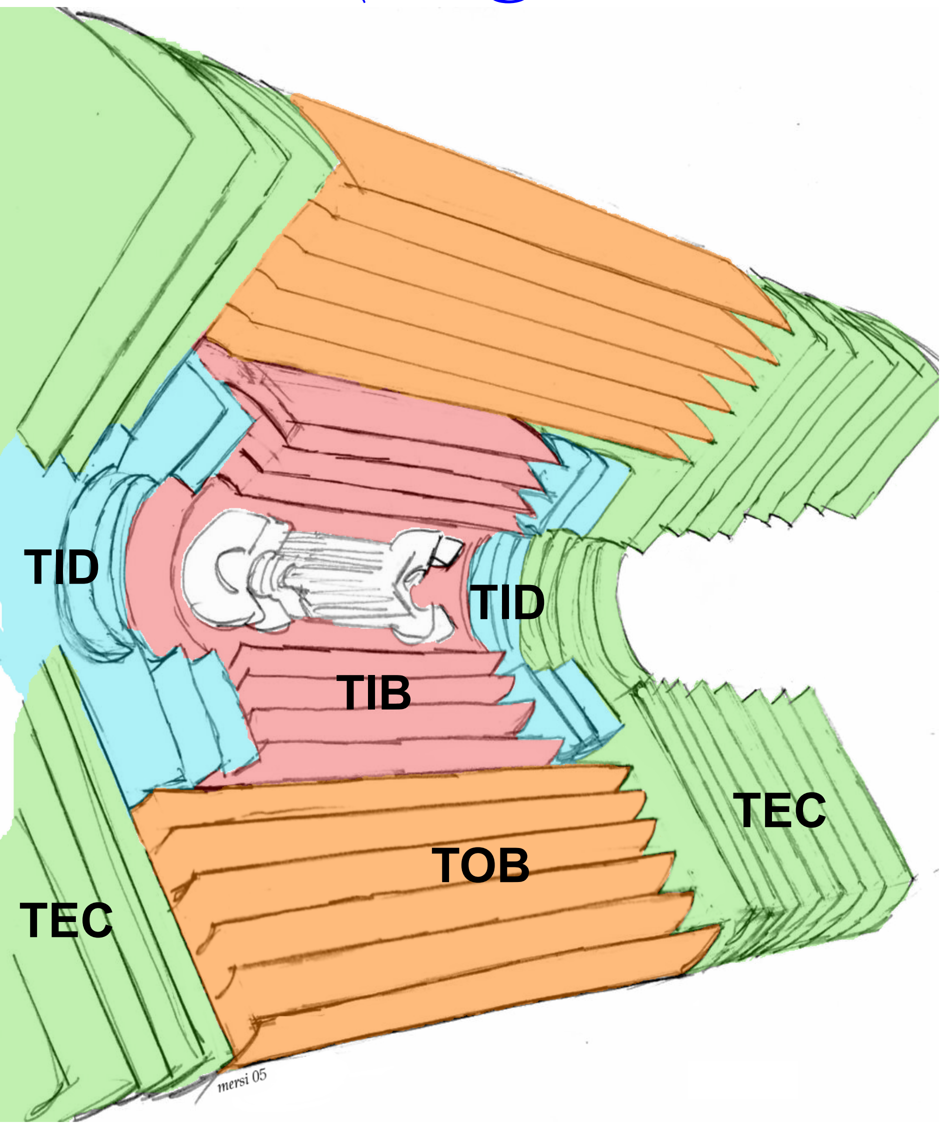
- again centralizing all final decision taking in one crate
- Global Trigger Logic in one μTCA module
  - if needed, several modules can run in parallel for more trigger algorithms
- use of big FPGA (Xilinx Virtex-7) will allow much more complex logic
  - large number of high-speed IO links and logic cells
  - big lookup tables, floating-point operations in DSPs
- Trigger Control System moves to different crate
  - combined with trigger distribution system (TTC) into "TCDS" (Trigger Control and Distribution System)

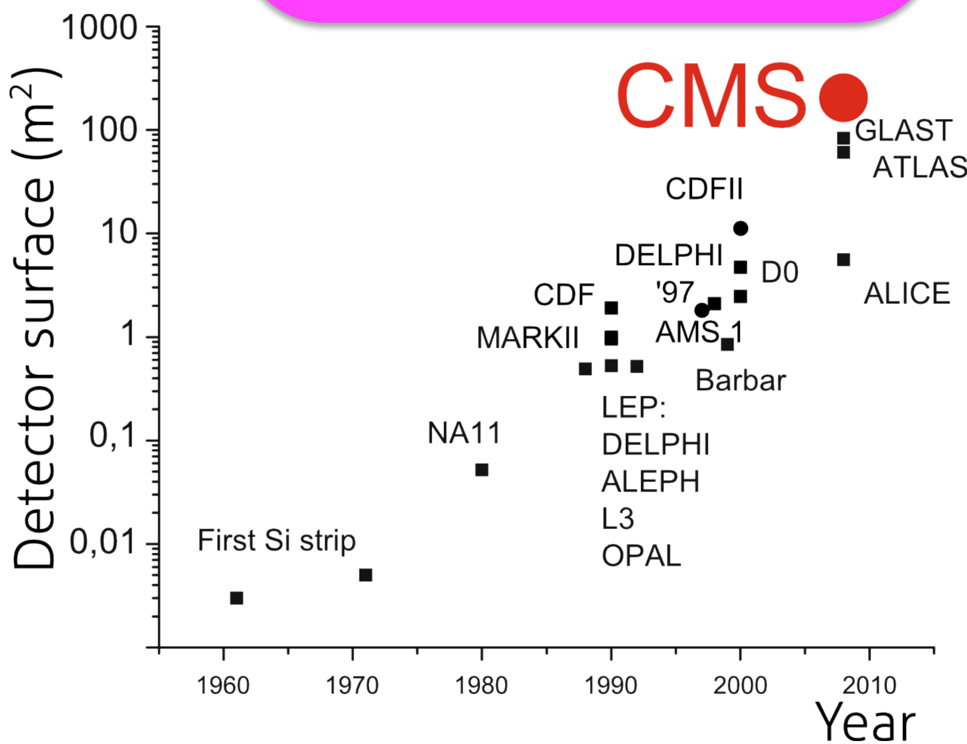
Parallel running of old and new system in 2015

- running "old" and "new" systems in parallel
  - trigger with old system
  - record decision proposed by new system
- study and debug new system
- switch to new system during short shutdown
  - Year-end technical stop
- upgrade work must not jeopardize data taking!

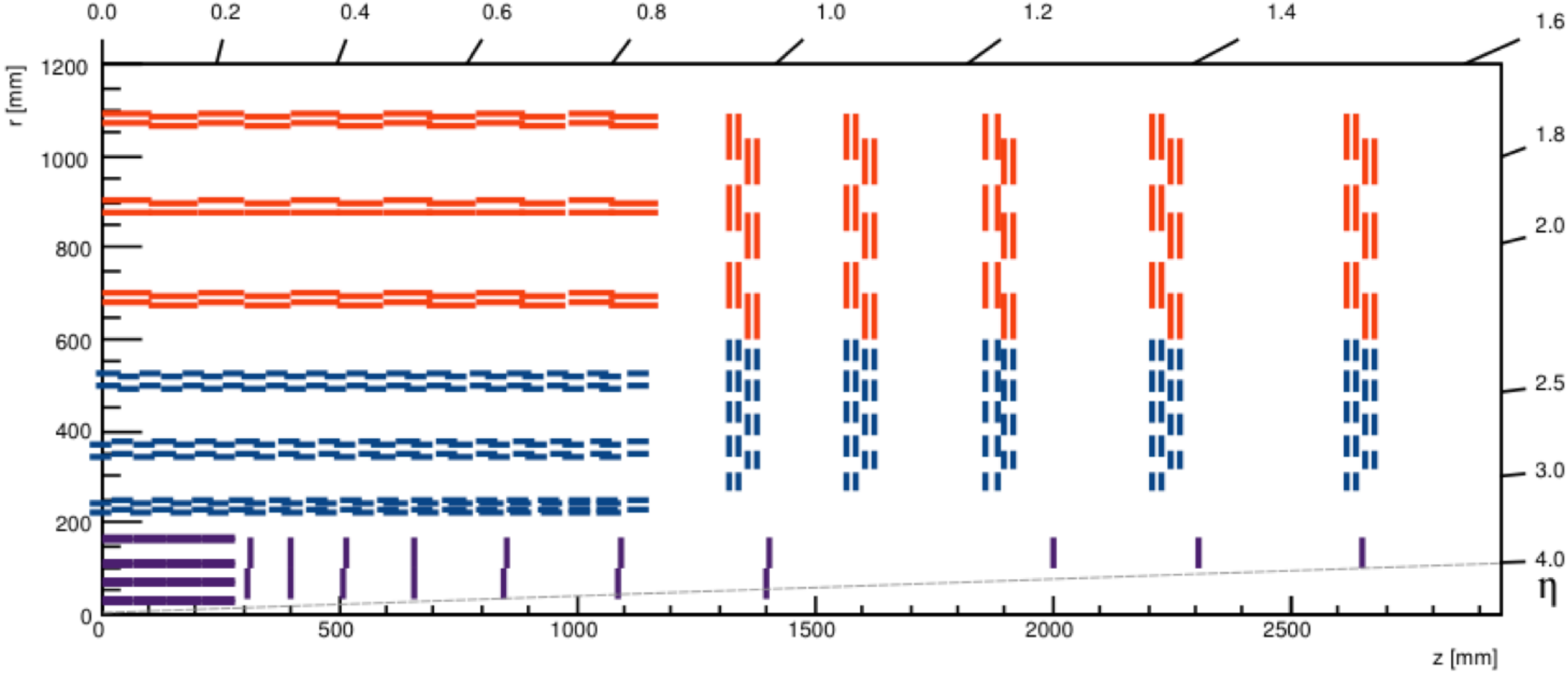
Level-1 Tracker (original detector)

Volume	23 m^3
Active area	210 m^2
Modules	15'148
Front-end chips	72'784
Read-out channels	9'316'352
Bonds	24'000'000
Optical channels	36'392
Raw data rate:	1 Tbyte/s
Power dissipation:	30 kW
Operating T:	−10°C





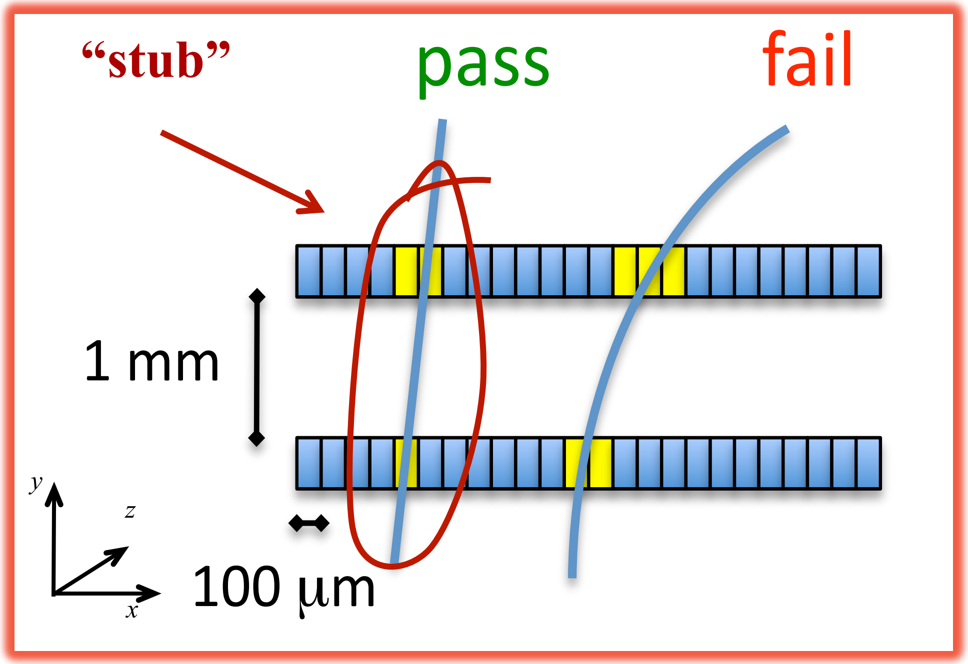
Level-1 Tracker trigger: new tracker layout



- roughly same total sensor area and number of sensors
- number of readout channels up by almost one order of magnitude

Phase-2 upgrade: Level-1 Tracker trigger

- at present, Silicon Strip Tracker only in High-Level Trigger
- plan to use it in Level-1 Trigger after tracker replacement
  - after 2022, during Long Shutdown 3
  - tracker information available as "seeds" to High-Level Trigger
- idea: select high-momentum tracks at local level
  - look for low bending (close azimuth in adjacent strip modules)

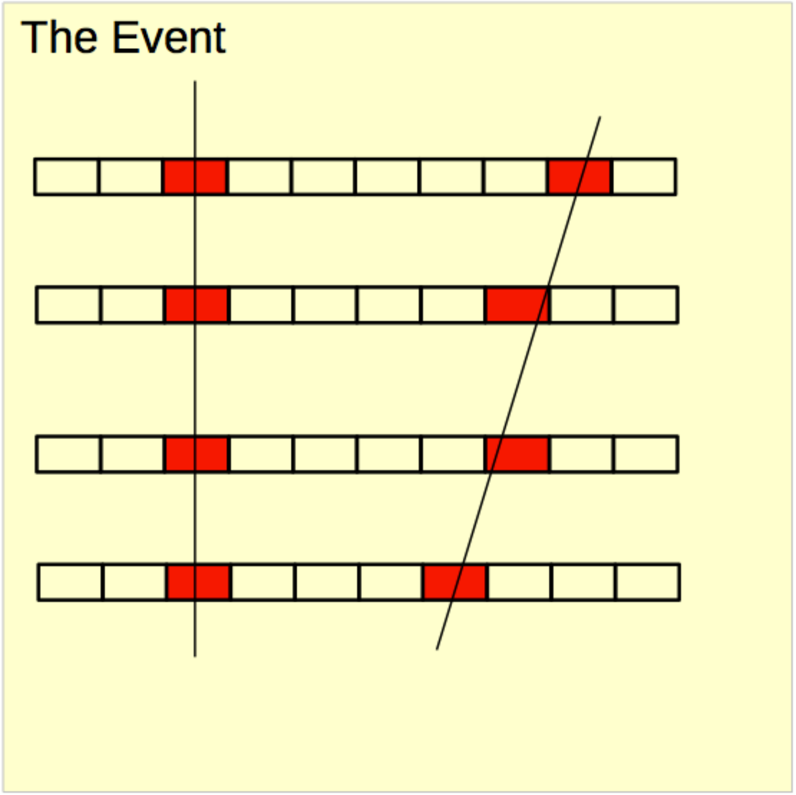


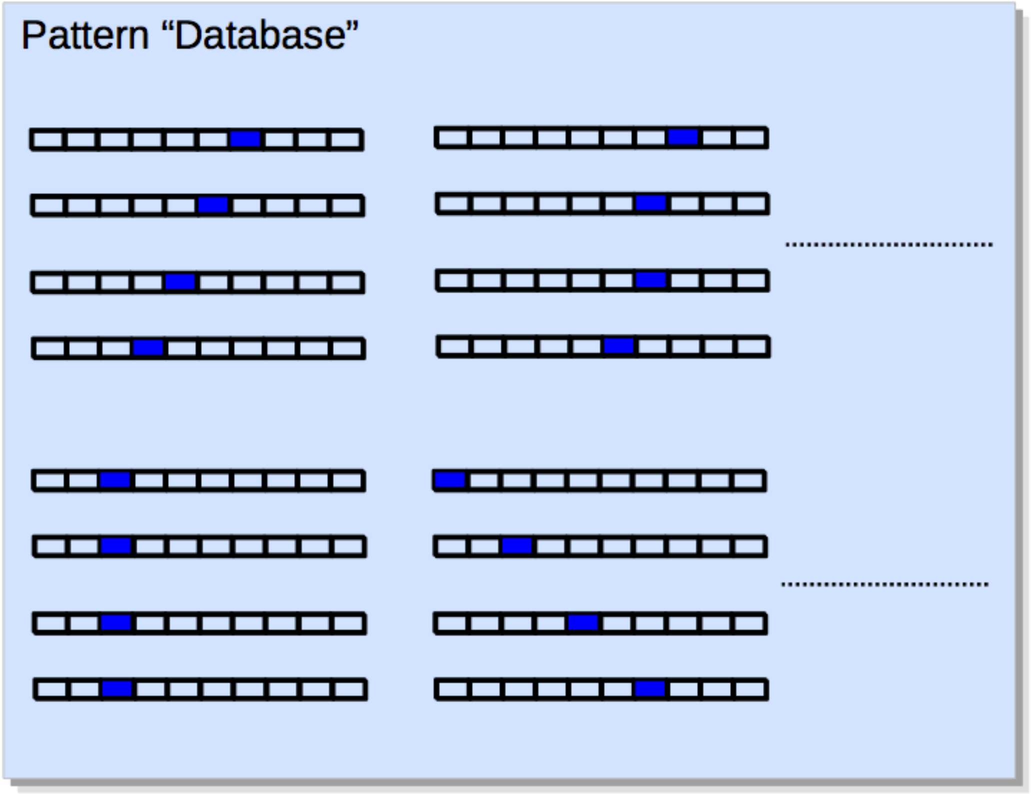
Tracker trigger concept

- Silicon modules provide at the same time "Level-1 data" (@ 40 MHZ), and "readout data" (upon Level-1 trigger)
  - whole tracker sends out data at each bunch crossing: "push path"
- Level-1 data require local rejection of low-p_T tracks
- tracker modules with p_T discrimination ("p_T modules")
- Level-1 "stubs" are processed in the back-end

- Pixel option
  - possibly also use Pixel detector in "pull" architecture
  - longer latency needed (20 μs)

Track Trigger: pattern recognition

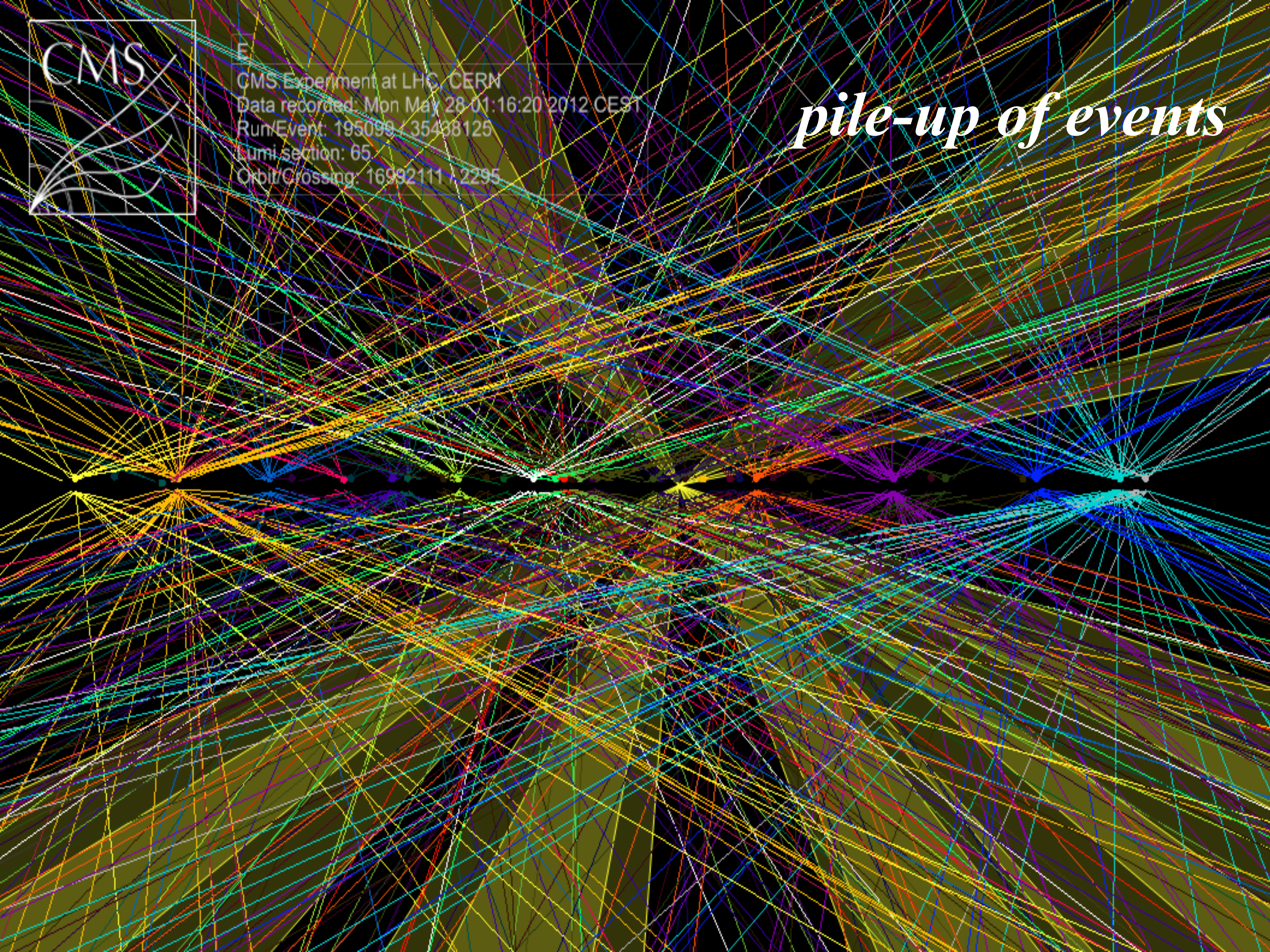




- pattern recognition using "associative memory"
  - CAM = "content addressable memory"
- by comparing with patterns find candidates ("roads")

Track trigger: goals

- presence of track match validates a calorimeter or muon trigger object,
  - e.g. discriminating electrons from hadronic ($\pi^0 \rightarrow \gamma\gamma$) backgrounds in jets
- link precise tracker system tracks to muon system tracks
  - improve precision on the p_T measurement
  - sharpen thresholds in muon trigger
- check isolation of candidate (e, γ, μ or τ)
- primary z-vertex location within 30-cm "luminous region"
  - from projecting tracks found in trigger layers
  - discrimination against pile-up events in multi-object triggers (e.g. lepton-plus-jet triggers)


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
pile-up of events

High Level Trigger (HLT)

- now: ~ 13 000 CPU cores
- more and faster computers will allow for more calculation time
  - more complex algorithms
  - ~ 100 → ~ 1000 ms per event
- improving the object reconstruction and physics selection to bring it closer to the offline version

- phase 2: higher pileup and input rate
- use L1 Track trigger info at very first stage of HLT processing
  - reduce HLT processing time (unpacking)

Scenario for phase-2 upgrade

Tracker replacement allows for

- Track Trigger
- increased latency (10-20 μs)
  - replace ECAL electronics, for 20 μs also endcap muon (CSC) electronics
- finer granularity
  - use single-crystal granularity in ECAL instead of "trigger towers"
- L1 trigger rate 0.5 – 1 MHz
  - up from 100 kHz
  - replace muon Drift Tube electronics
  - needed for hadronic triggers (do not benefit so much from Track Trigger)
  - HLT should cope with this (estimate 50x increase; Moore's law)
- HLT output rate of 10 kHz

Summary

- LHC development makes trigger upgrade mandatory
  - else we lose much of the data
- Phase 1 upgrade underway
  - commission in 2015
  - full deployment in 2016
- Phase 2 upgrade > 2022
  - Track Trigger
  - increase latency to 10 or 20 μs
  - L1 rate ~ 0.5-1 MHz
  - HLT rate ~ 10 kHz

BACKUP

LHC / CMS schedule

- 2013-2014 first "long shutdown" ("LS 1")
  - part of trigger electronics being upgraded: "**phase-1 upgrade**"
- 2015-2017 data taking @ ($\sqrt{s}$ = 13 TeV)
  - LHC may exceed design luminosity (10^{34} $cm^{-2}s^{-1}$) and run at higher than design pile-up !
    - original design: ~20 interactions per bunch crossing
  - during this period evolve to improved system
  - Pixel detector replacement at end of 2016
- 2018-2019 second "long shutdown" ("LS 2")
- 2023-2025 third "long shutdown" ("LS 3")
  - silicon strip tracker upgrade
  - plans to use tracker in Level-1 Trigger: "**phase-2 upgrade**"

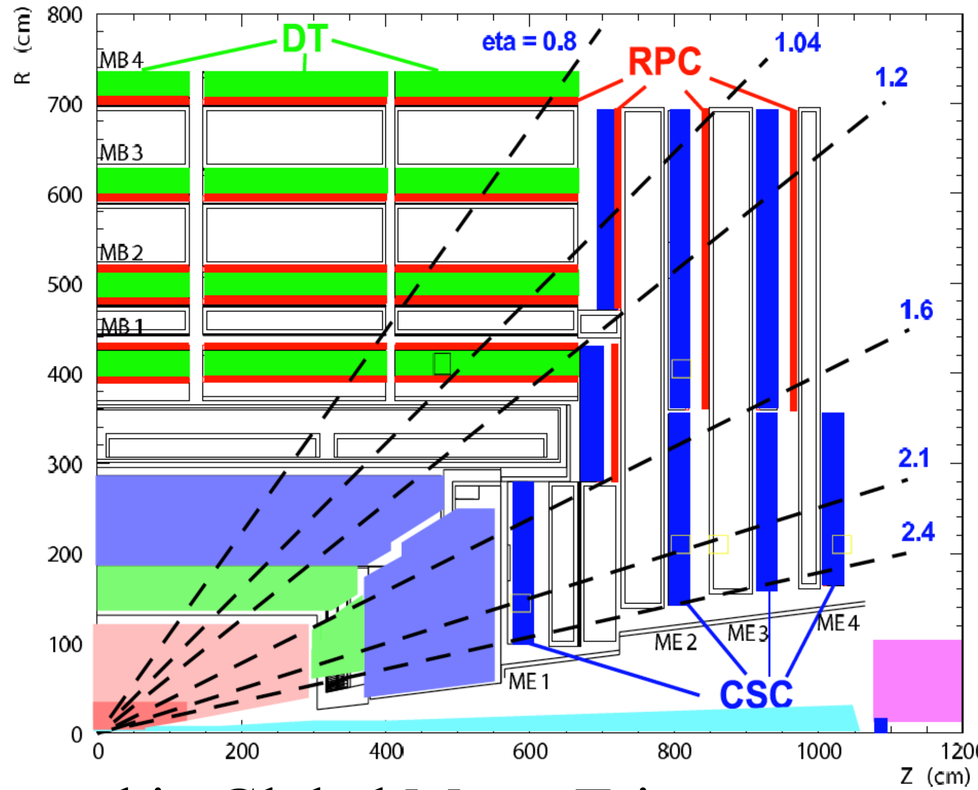
- *schedule may change over time*

Why upgrade the CMS trigger?

- radiation damage to inner detectors (Pixels, Silicon Strips) and on-detector electronics
  - replacement planned from the beginning
  - put as many systems as possible out of radiation area (move to "electronics cavern")
- obsolescence
  - long preparation times for big experiments
  - newer electronics will improve reliability and performance
- **higher performance**
  - higher LHC luminosity and pileup
  - need better detector resolution and more sophisticated triggering algorithms
- *must not jeopardize performance of detector during data taking!*

Level-1 Muon trigger

- three technologies
  - Drift Tubes (DT, in barrel)
  - Cathode Strip Chambers (CSC, in endcaps)
  - Resistive Plate Chambers (RPC, everywhere)
- redundant
- complementary technologies
- geometrical overlap



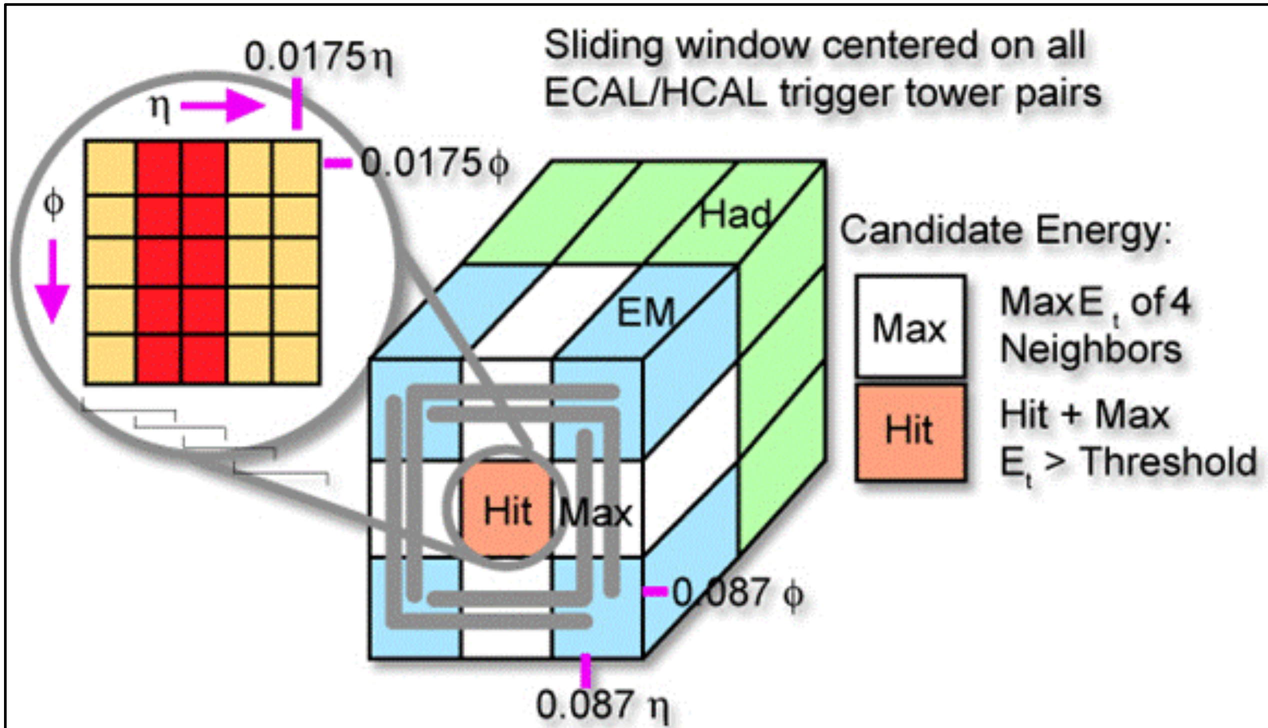
- muons from all 3 systems processed in Global Muon Trigger

final muon candidates determined by

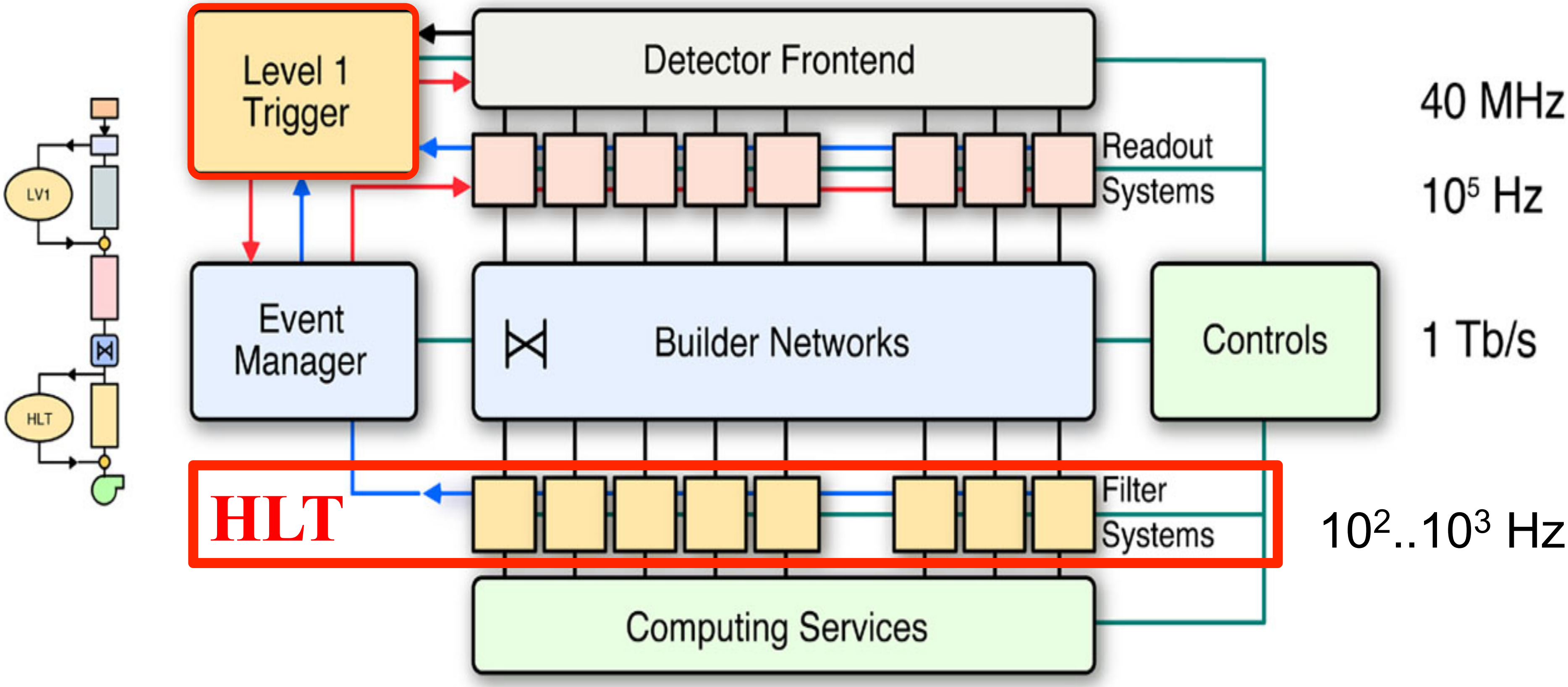
- quality (e.g. number of hits)
- correlation between systems (RPC+DT, RPC+CSC)
- transverse momentum

Level-1 Calorimeter trigger

- Electromagnetic Calorimeter (ECAL)
  - block of 5x5 lead-tungstate crystals forms a “trigger tower”
- Hadronic Calorimeter (HCAL)
- combination of signals from both calorimeters allows to determine candidates for
  - e/gamma (discriminated only at High-Level Trigger)
  - jets (“central” and “forward”)
  - tau jets
- as well as
  - total and missing energy
  - total and missing hadronic energy



CMS Trigger & DAQ Systems



ATLAS & CMS Triggered vs. Triggerless Architectures

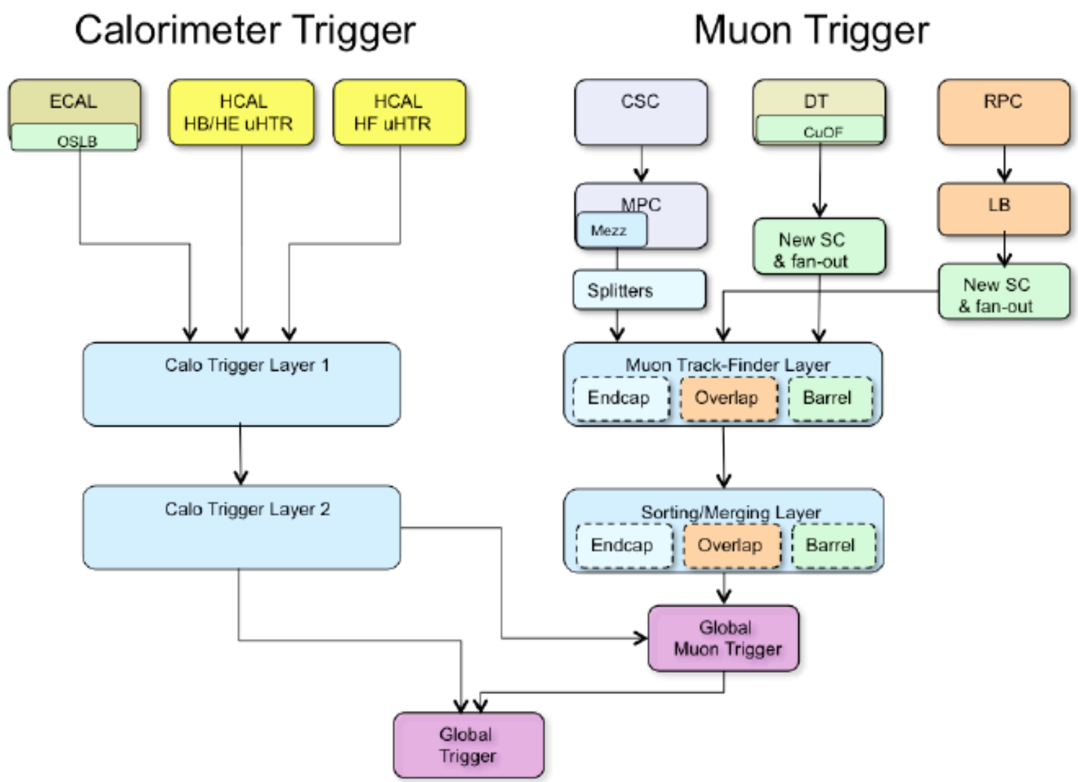
1 MHz (Triggered):

- **Network:**
  - 1 MHz with ~5 MB: aggregate ~40 Tbps
  - Links: Event Builder-cDAQ: ~ 500 links of 100 Gbps
  - Switch: almost possible today, for 2022 no problem
- **HLT computing:**
  - General purpose computing: 10(rate)x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~50 wrt today maybe for ~same costs**
  - Specialized computing (GPU or else): Possible

40 MHz (Triggerless):

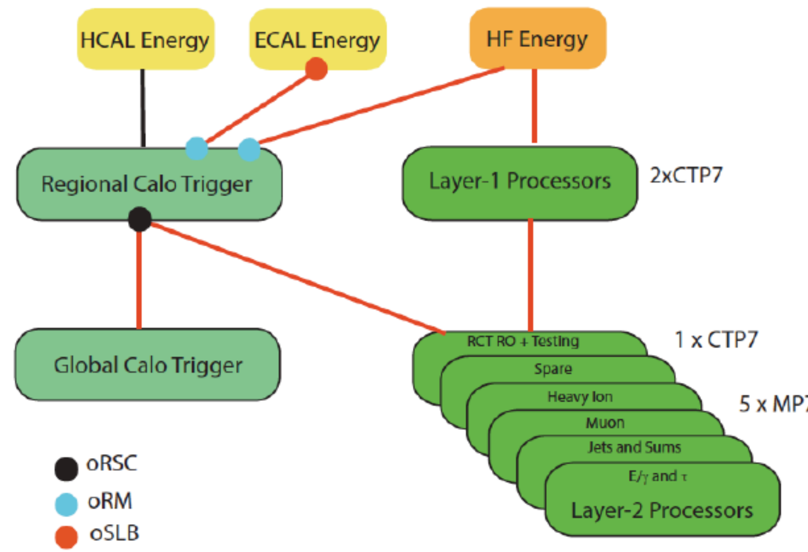
- **Network:**
  - 40 MHz with ~5 MB: aggregate ~2000 Tbps
  - Event Builder Links: ~2,500 links of 400 Gbps
  - Switch: has to grow by factor ~25 in 10 years, difficult
- **Front End Electronics**
  - Readout Cables: Copper Tracker! – Show Stopper
- **HLT computing:**
  - General purpose computing: 400(rate) x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~2000 wrt today, but too pessimistic since events easier to reject w/o L1**
    - **This factor looks impossible with realistic budget**
  - Specialized computing (GPU or …)
    - **Could possibly provide this …**

L1 trigger upgrade



- L1 trigger upgrade for the Phase 1
  - Upgrade CALO trigger, muon track finder and global trigger, as described in the TDR
  - This will be fully operational from 2016 but it will be commissioned in parallel during 2015

Stage-1 Upgrade in 2015



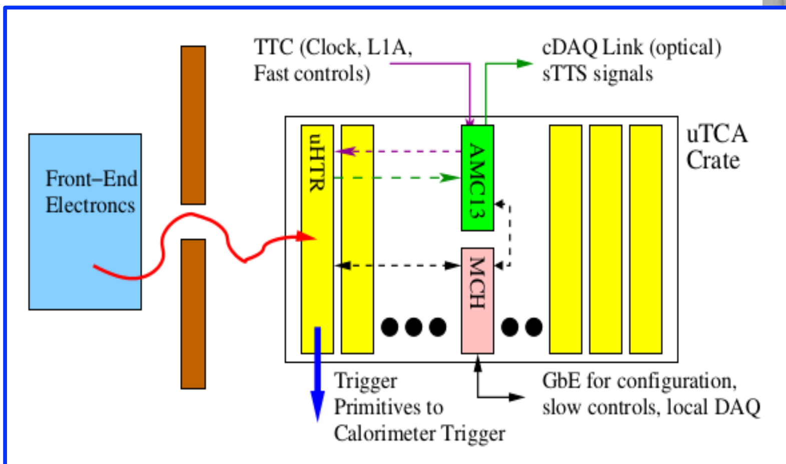
- **Replace current GCT**
  - **With pre-production upgrade processors**
  - **Use current RCT**
    - Reprogram it to provide 2x1 and 4x4 calo tower clusters with with total E_T sum and EM id
    - oRSC to connect RCT to the new GCT
      - **These cards are the only new design specific for Stage-1**
      - **Retain data path to legacy GCT for easy rollback**
  - **Use current GT**
  - **oSLB and oRM mezzanines already planned for LS1, as well as uHTR for HF**
    - To allow parallel commissioning of full L1 upgrade

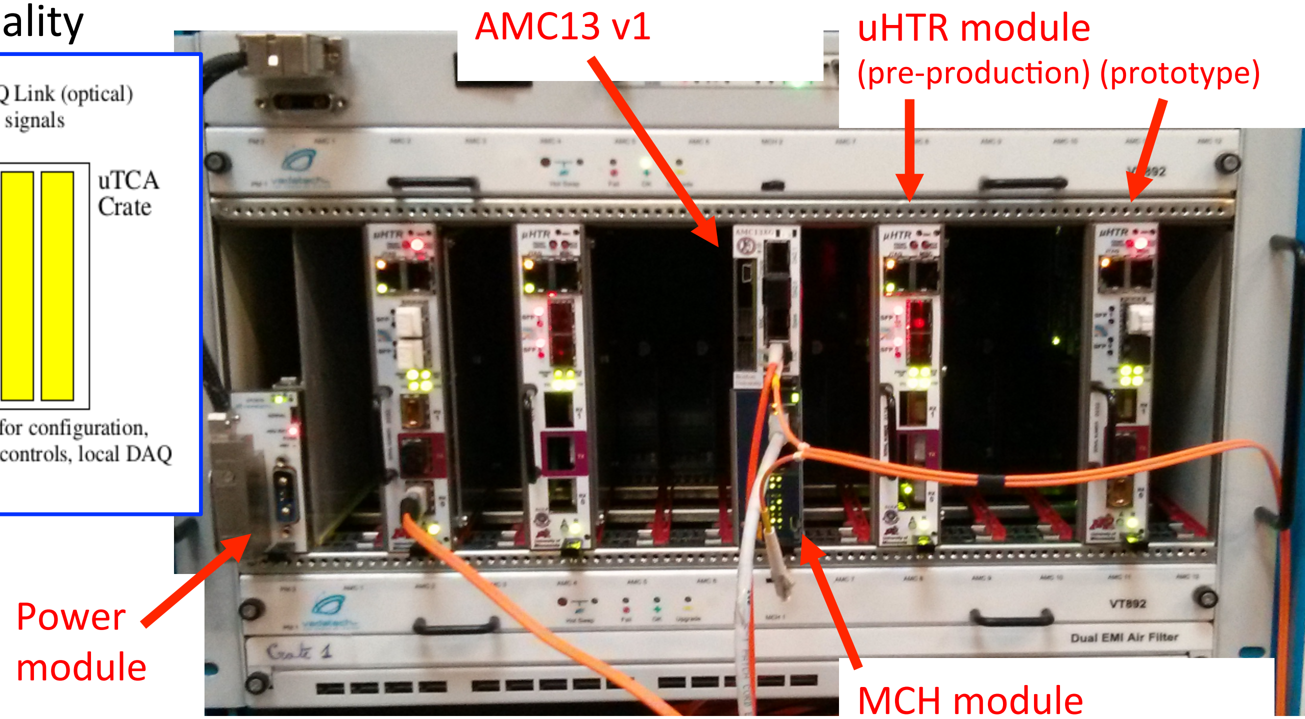
- **Significant performance improvements possible in:**
  - **Jets and energy sums**
    - From PU subtraction
  - **EG**
    - From isolation, with PU subtracted
  - **Taus**
    - From 2x1 EG object without E/H cut

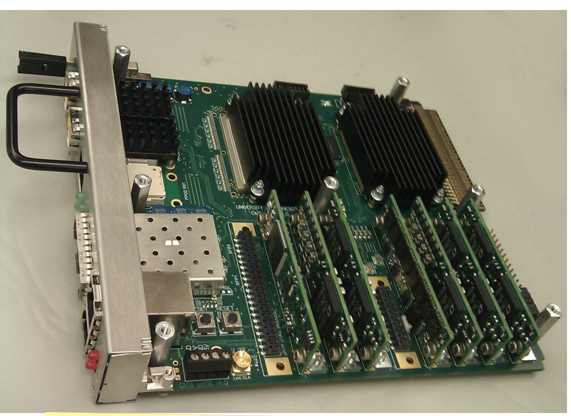
Commercial μTCA module
MCH (MicroTCA Carrier Hub)

HCAL Backend Electronics : HF will upgrade to uTCA in LS1

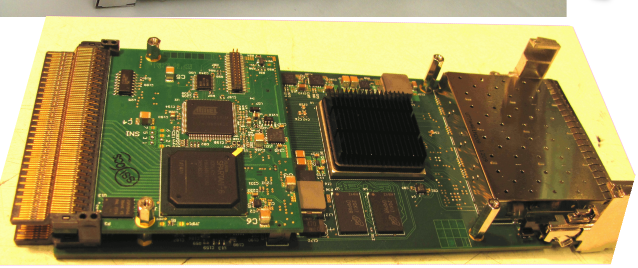
TDR concept is becoming reality







- Pre-production HF uHTRs recently completed at Saha (India)
- Successful Electronics System Review in June
- Installation targeted for early 2014



- 10 Gbps-capable pre-production AMC13 (AMC13XG) recently delivered at Boston University
- Development and testing firmware with uHTR underway

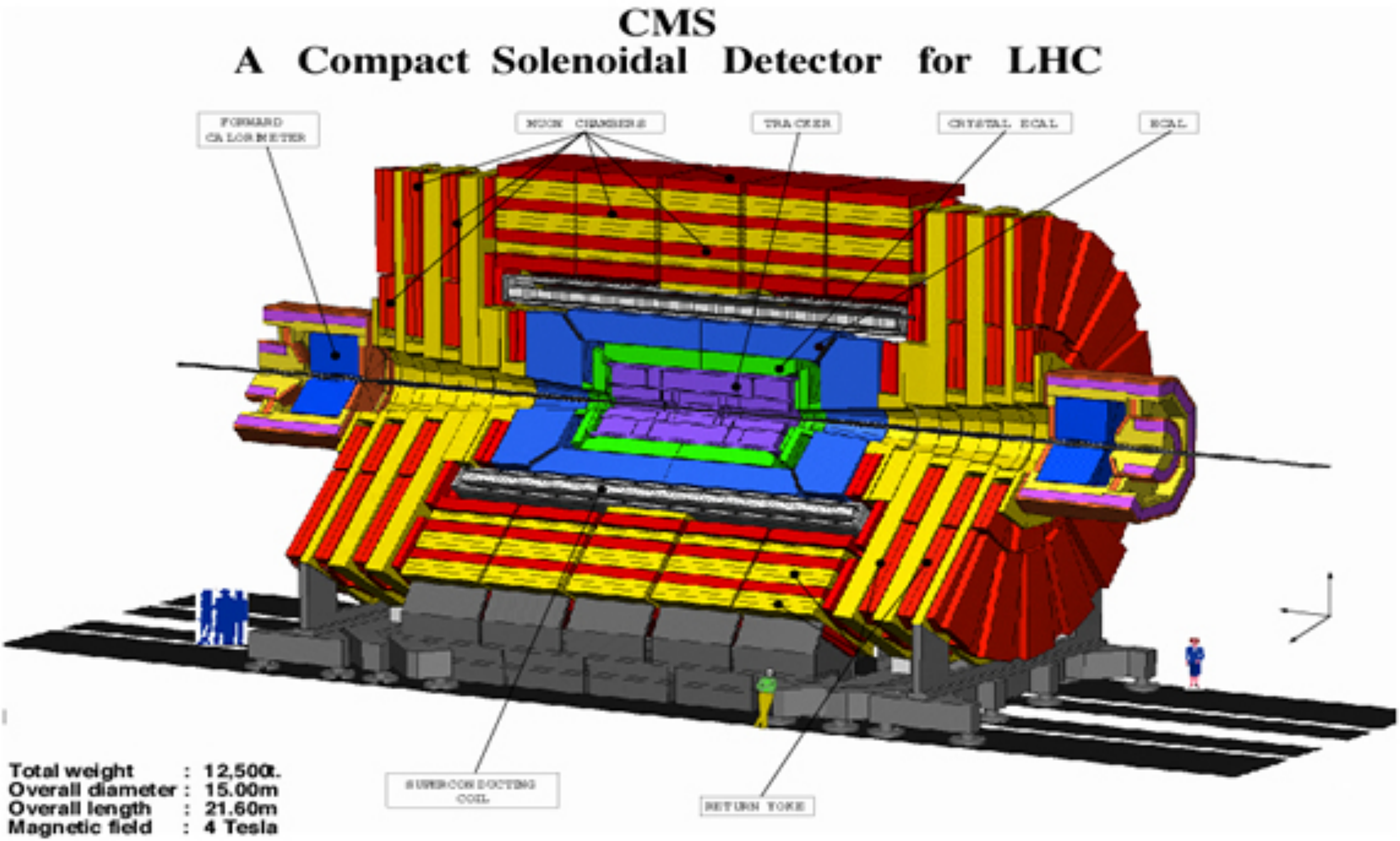
LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

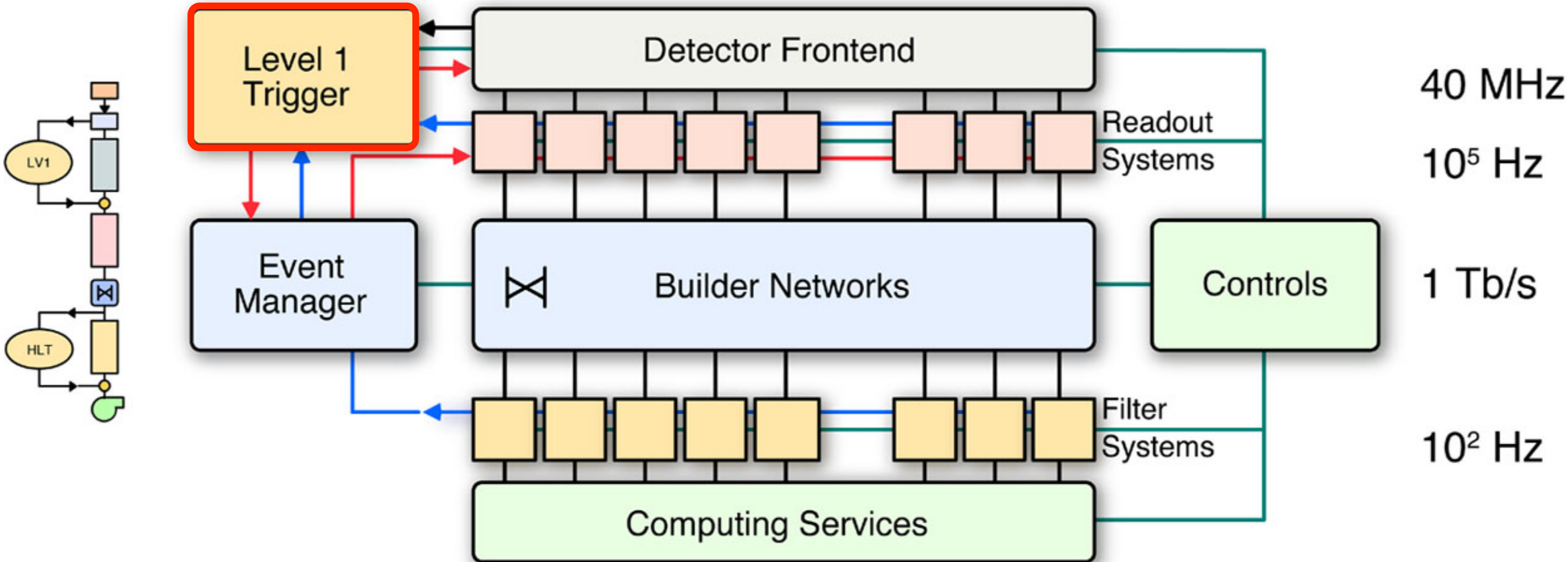
LS2	starting in 2018 (July)		18 months + 3months BC (Beam Commissioning)
LS3	LHC: starting in 2023	=>	30 months + 3 BC
	injectors: in 2024	=>	13 months + 3 BC

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

*The Compact **MUON** Solenoid*



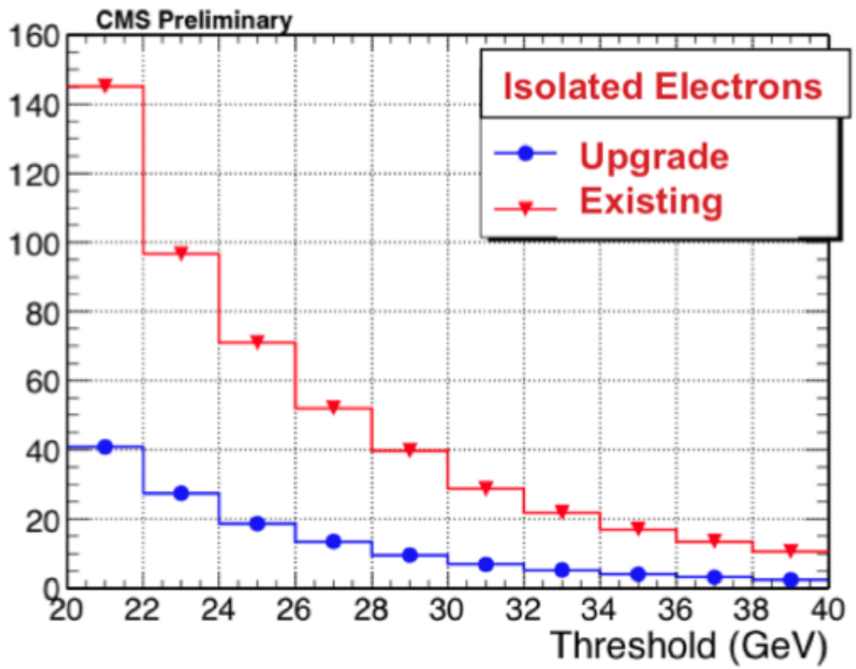
CMS Trigger & DAQ Systems

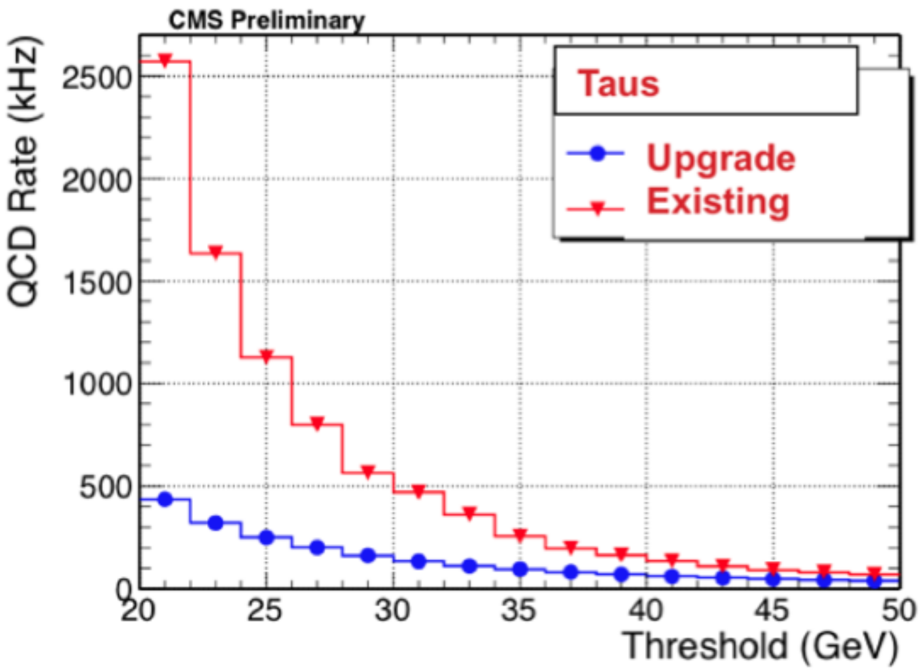


- LHC beam crossing rate is 40 MHz & at full Luminosity of 10^{34} $cm^{-2}s^{-1}$ yields 10^9 collisions/s
- Reduce to 100 kHz output to High Level Trigger and keep high-P_T physics
- Pipelined at 40 MHz for dead time free operation
- Latency of only 4 μsec for collection, decision, propagation

Calorimeter trigger upgrade

- improve resolution in coordinates
  - azimuth φ and pseudorapidity η
- improve identification of tau jets
  - better isolation criteria
- further improve e/gamma isolation determination

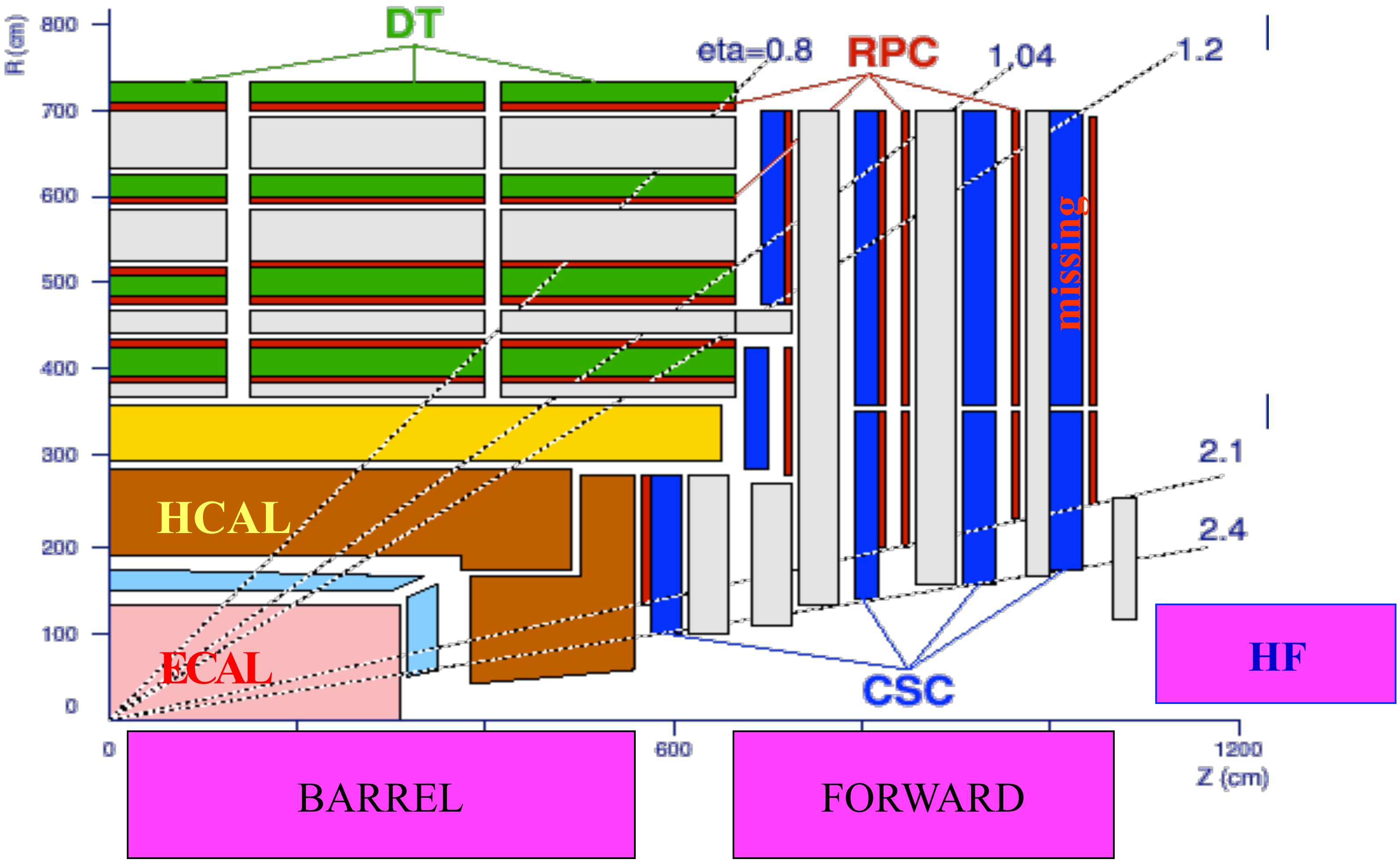




signals used by the first-level trigger

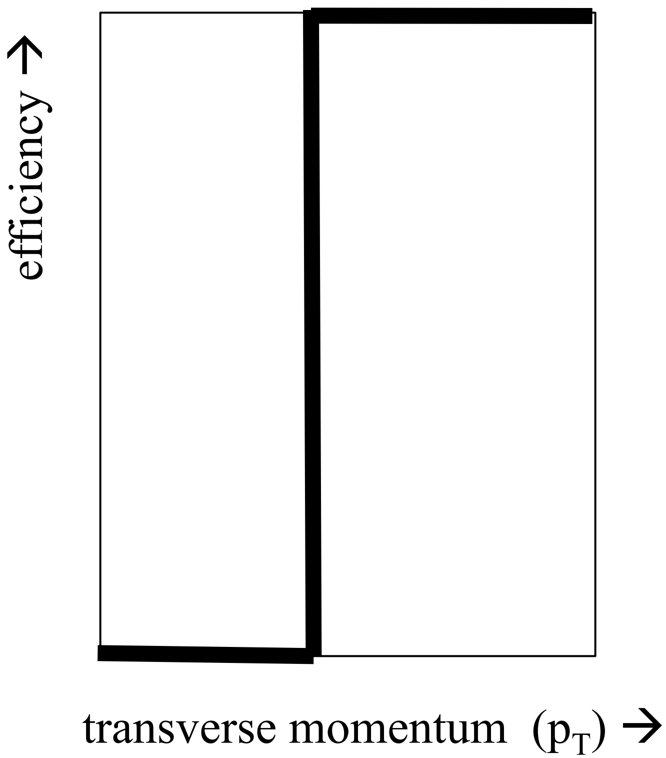
- muons
  - tracks
  - several types of detectors (different requirements for barrel and endcaps):
  - in ATLAS:
    - RPC (Resistive Plate Chambers): barrel
    - TGC ("Thin Gap Chambers"): endcaps
    - not in trigger: MDT ("Monitored Drift Tubes")
  - in CMS:
    - DT (Drift Tubes): barrel
    - CSC (Cathode Strip Chambers): endcaps
    - RPC (Resistive Plate Chambers): barrel + endcaps
- calorimeters
  - clusters
  - electrons, jets, transverse energy, missing transverse energy
  - electromagnetic calorimeter
  - hadron calorimeter
- only in high-level trigger: tracker detectors
  - silicon strip and pixel detectors, in ATLAS also straw tubes
  - cannot be read out quickly enough

TRIGGER COMPONENTS

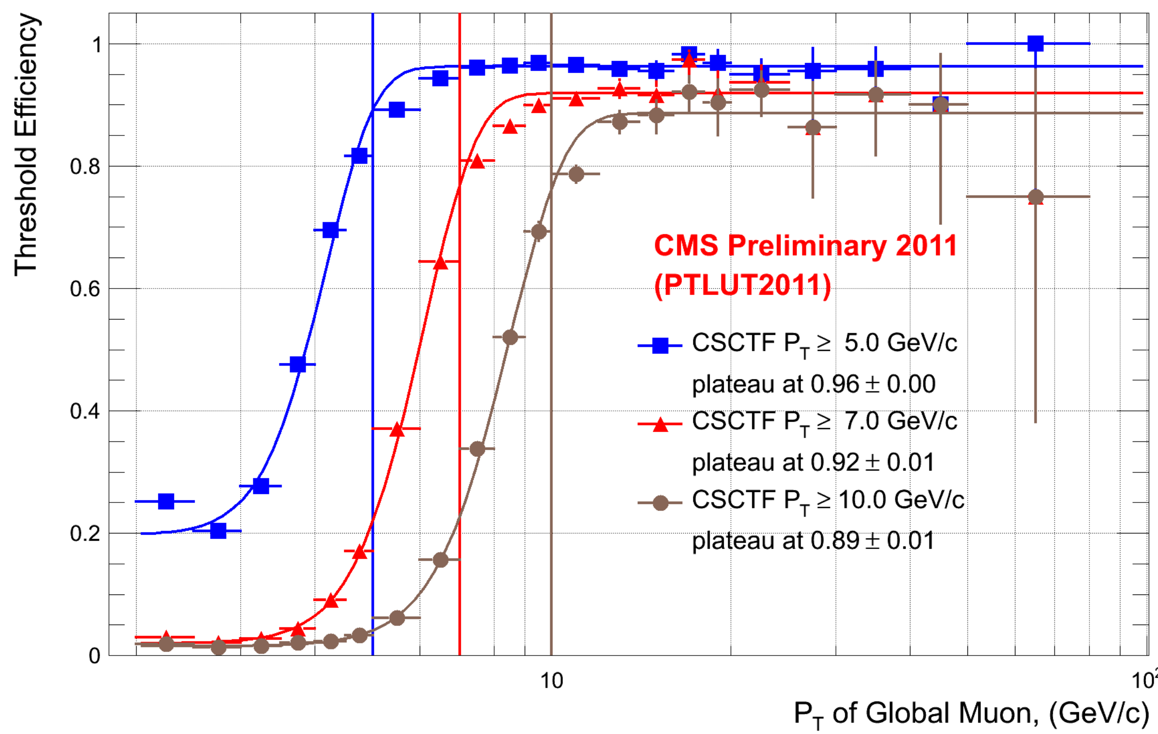


turn-on curves

ideal:



reality:

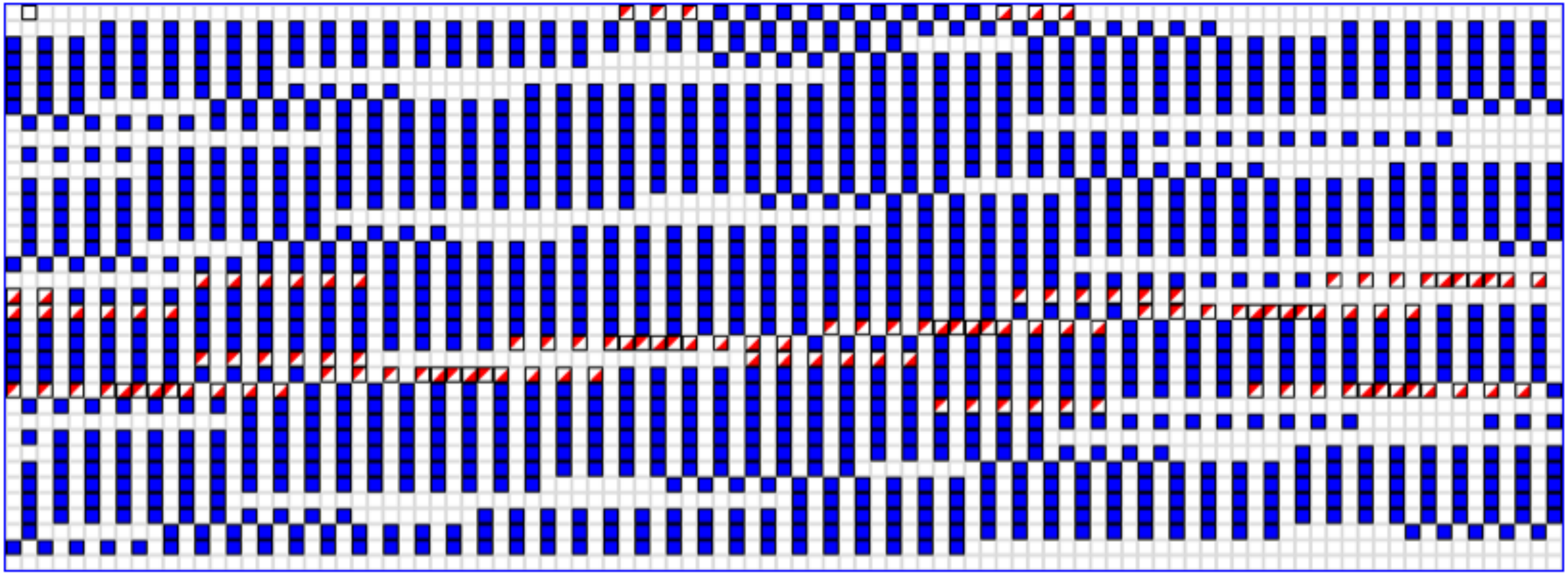


LHC bunch-filling scheme

LHC orbit with 3564 “bunch crossings”
(colliding bunches in CMS: blue; single bunches in CMS: red/white):

Fill 2129 Bunch Pattern at CMS *1317 luminosity bunch pairs – $\times 10^{27} cm^{-2} sec^{-1}$*

BX 0 → 98



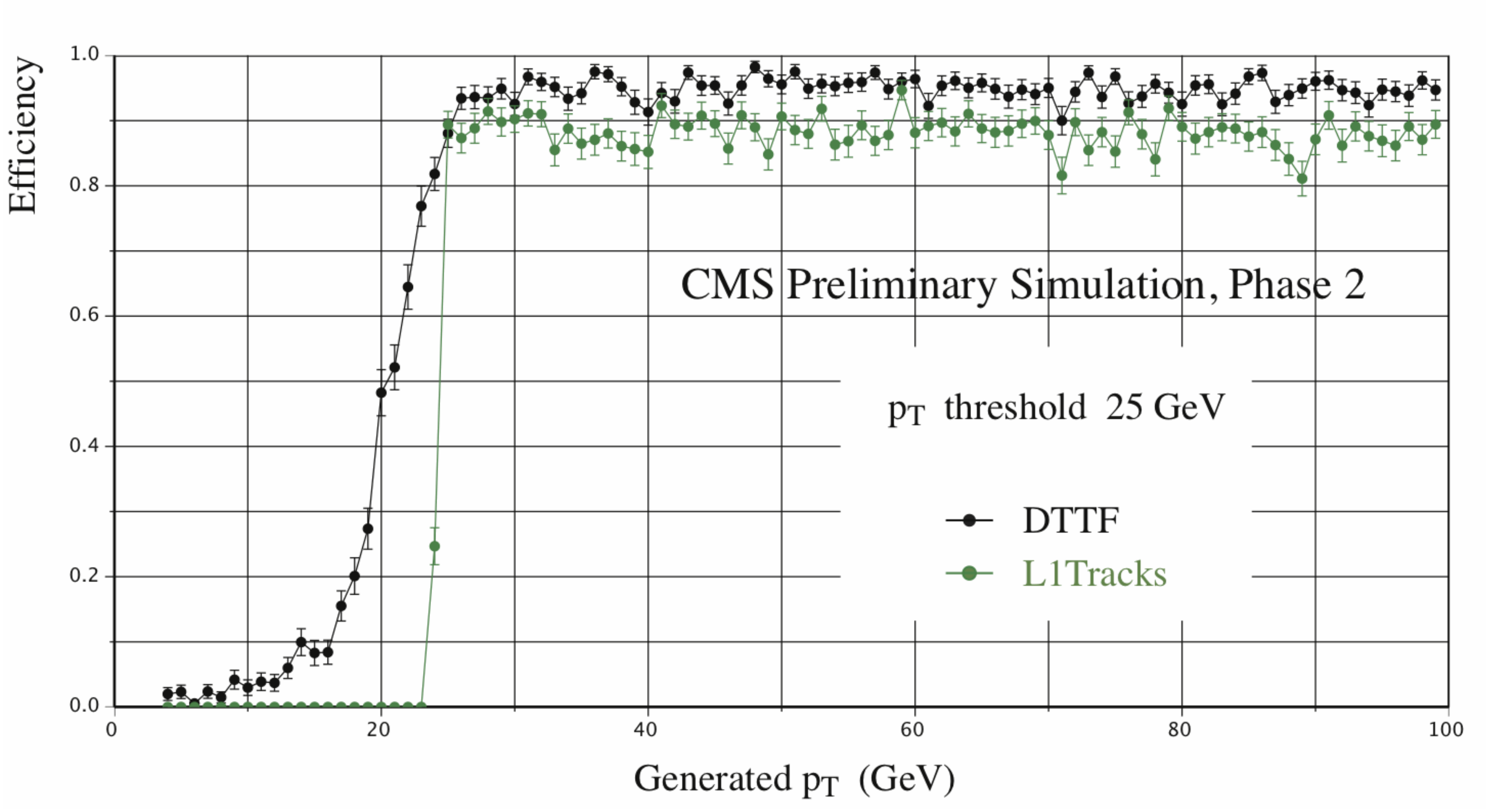
BACKUP
Track Trigger

Trigger, Threshold	Algorithm	Rate reduction	Full eff. at the plateau	Comments
Single Muon, 20 GeV	Improved Pt, via track matching	~ 13 ($\mid \eta \mid < 1$)	~ 90 %	Tracker isolation may help further.
Single Electron, 20 GeV	Match with cluster	> 6 (current granularity) >10 (crystal granularity) ($\mid \eta \mid < 1$)	90 %	Tracker isolation can bring an additional factor of up to 2.
Single Tau, 40 GeV	CaloTau – track matching + tracker isolation	O(5)	O(50 %) (for 3-prong decays)	
Single Photon, 20 GeV	Tracker isolation	40 %	90 %	Probably hard to do much better.
Multi-jets, HT	Require that jets come from the same vertex			Performances depend a lot on the trigger & threshold.

Tracker trigger concept

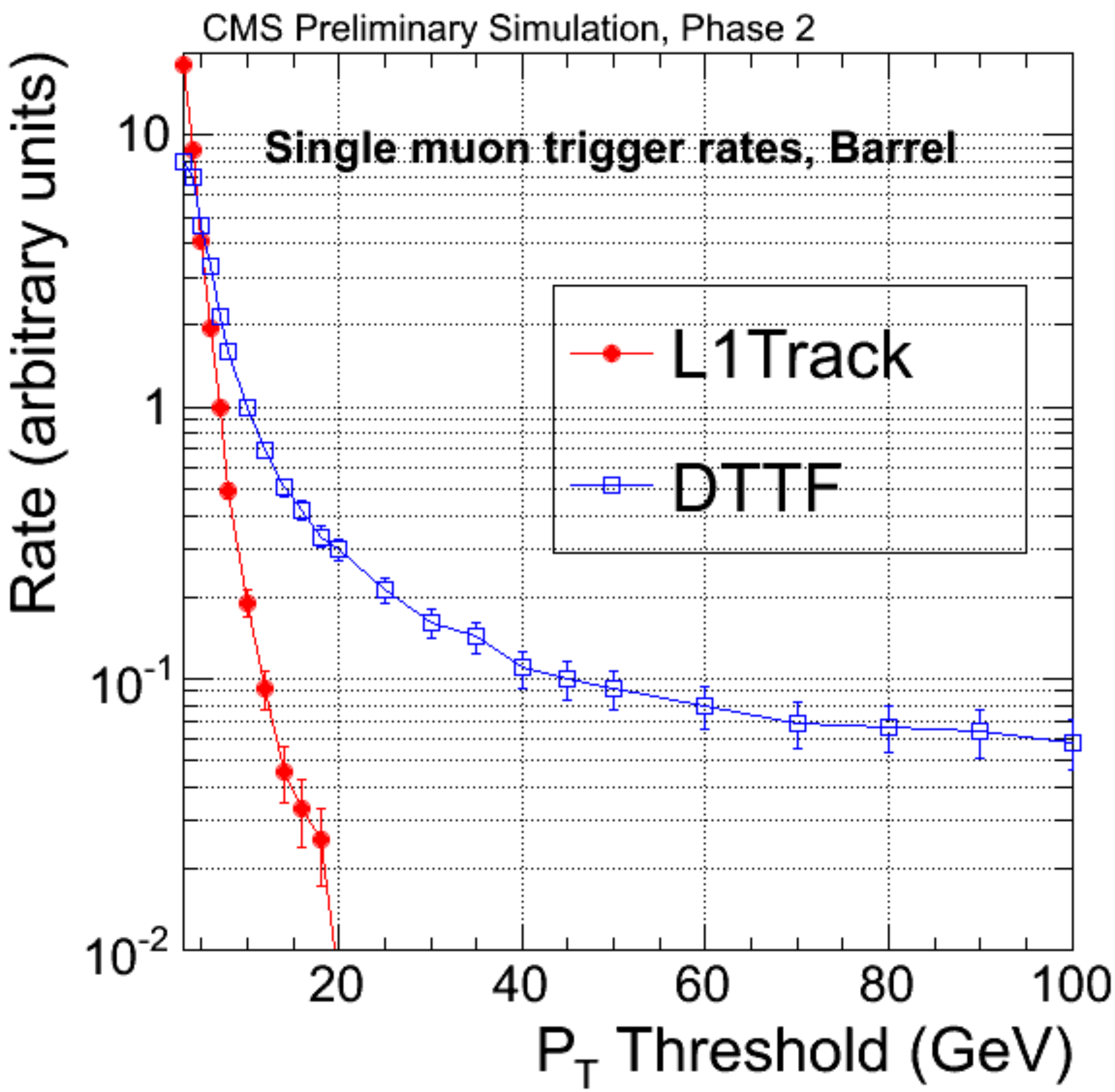
- Silicon modules provide at the same time "Level-1 data" (@ 40 MHZ), and "readout data" (upon Level-1 trigger)
  - whole tracker sends out data at each bunch crossing: "push path"
- Level-1 data require local rejection of low-p_T tracks
  - reduce data volume and simplify track finding @ Level-1
  - Threshold of ~ 2 GeV ⇒ data reduction of one order of magnitude or more
- tracker modules with p_T discrimination ("p_T modules")
  - correlate signals in two closely-spaced sensors
  - exploit the strong magnetic field of CMS
- Level-1 "stubs" are processed in the back-end
  - form Level-1 tracks with p_T above ~2 GeV
- Pixel option
  - possibly also use Pixel detector in "pull" architecture
  - longer latency needed (20 μs)

Muons : turn-on curves



Much sharper turn-on curves w.r.t. DTTF, as expected from the much better PT resolution. Hence the contribution from mis-measured low PT muons (which makes most of the DTTF rate) is dramatically reduced.

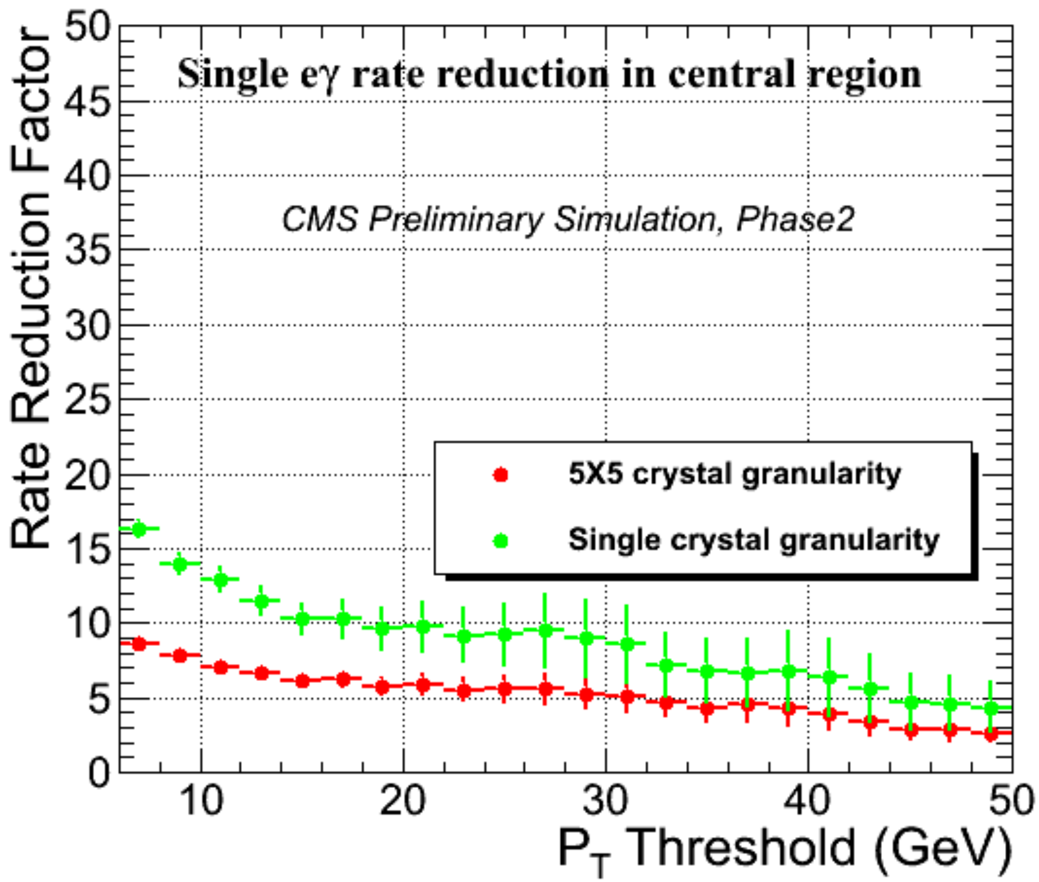
Muons : rates



- DTTF : Flattening of the rates at high threshold

- Matching the DT primitives with L1Tracks : large rate reduction, > 10 at threshold > ~ 14 GeV.

Electrons



Rate reduction brought by matching L1EG to L1Tkstubs in the central region (| eta | < 1)

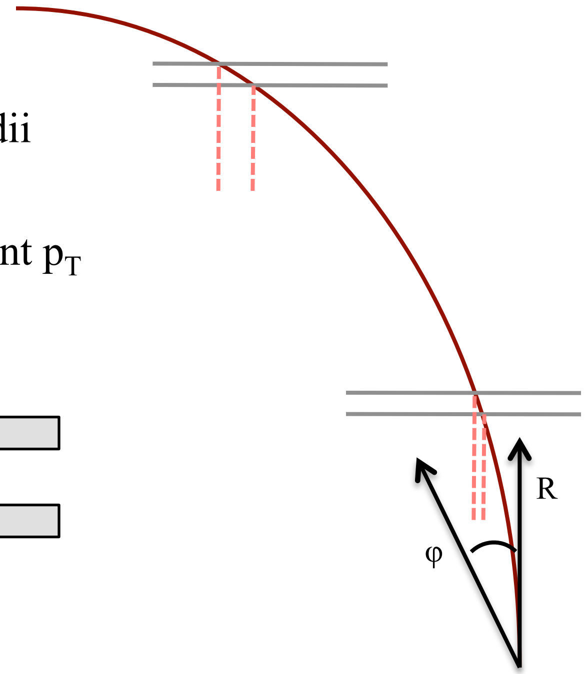
Red : with the current L1Cal granularity.

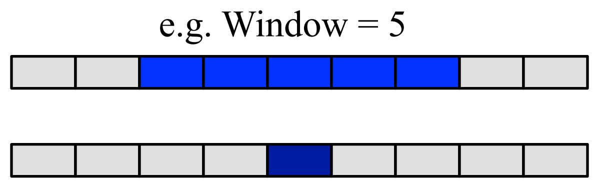
Green : if crystal-level information is available for L1EG. The better position resolution for the L1EG object improves the performance of the matching to the tracker.

(NB : the pure calorimetric L1EG rates could also be reduced with the finer granularity. Not taken into account here.)

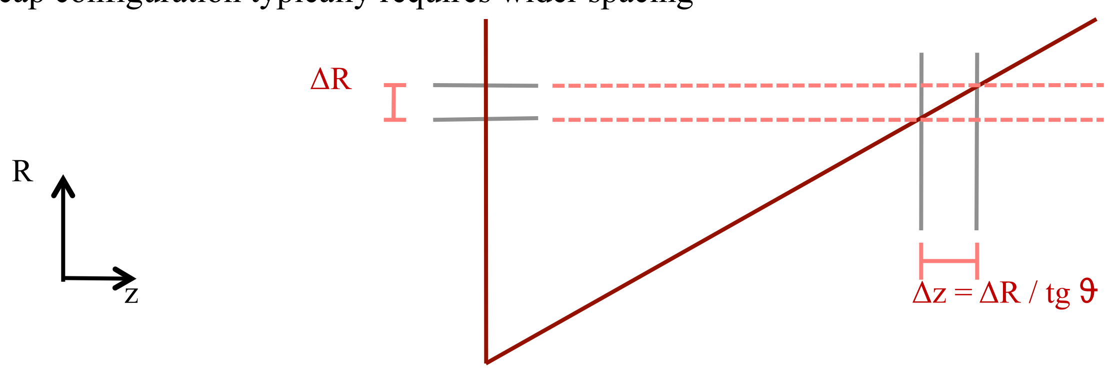
p_T modules: working principle

- measure p_T via $\Delta(R\varphi)$ over a given ΔR
- for a given p_T, $\Delta(R\varphi)$ increases with R
  - same geometrical cut corresponds to harder p_T cuts at large radii
  - at low radii, rejection power limited by pitch
  - optimize selection window and/or sensors spacing for consistent p_T selection through the tracking volume



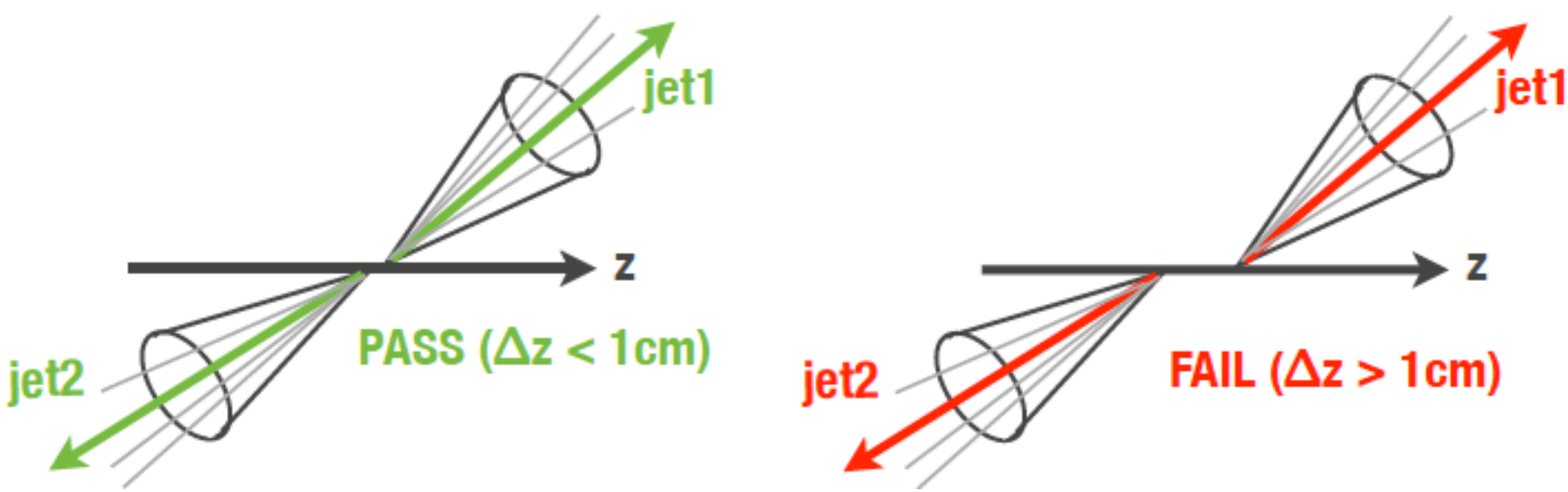


- barrel: ΔR is given directly by the sensors spacing
- end-cap: dependence on detector location
  - End-cap configuration typically requires wider spacing

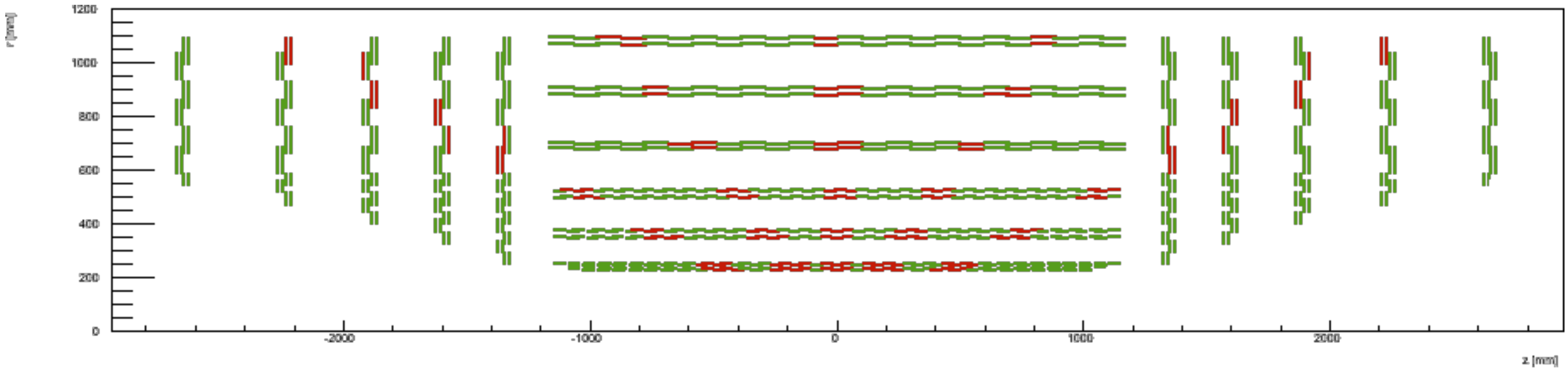


Jets

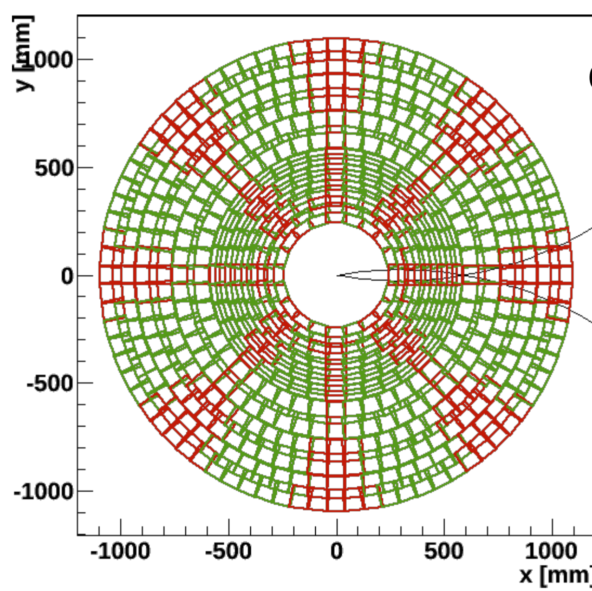
- Associate jets to nearby L1 tracks to determine z position
  - **(1)** Select tracks with dR(track, jet) < 0.40
    - *$|z_{track}| < 25$ cm*
    - *$chi2_{track} < 100$*
  - **(2)** p_T averaged z position of selected tracks → *initial jet z position "z_1(jet)"*
  - **(3)** Remove outliers in two steps & recalculate z position
    - *First outlier step:* $|z_{track} - z_1(jet)| <$ **5cm** → *updated z position "z_2(jet)"*
    - *Second outlier step:* $|z_{track} - z_2(jet)| <$ **1cm** → *final z position "z_{final}(jet)"*



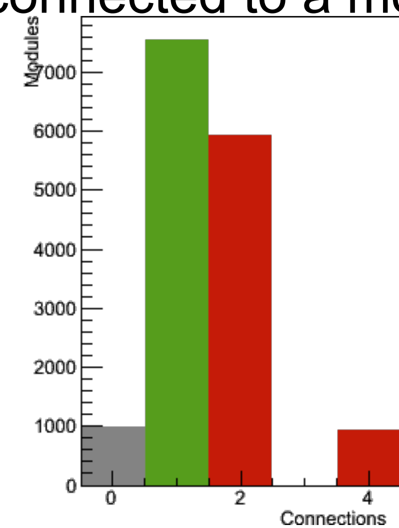
Track finding @ Level-1



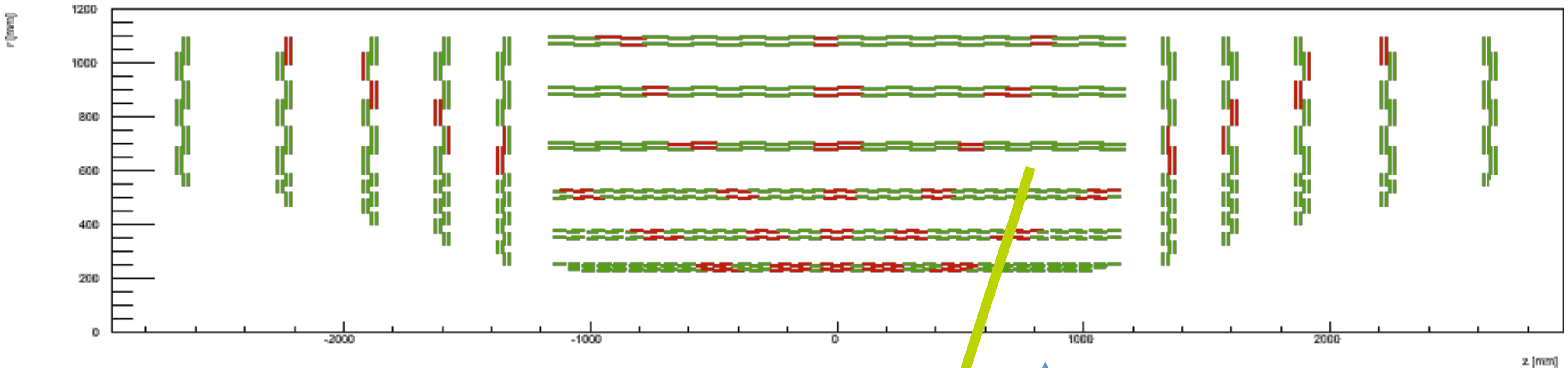
- Each sector independent
- Overlap regions depend on
  - Luminous region Δz
  - Minimum p_T cut



Number of sectors connected to a module

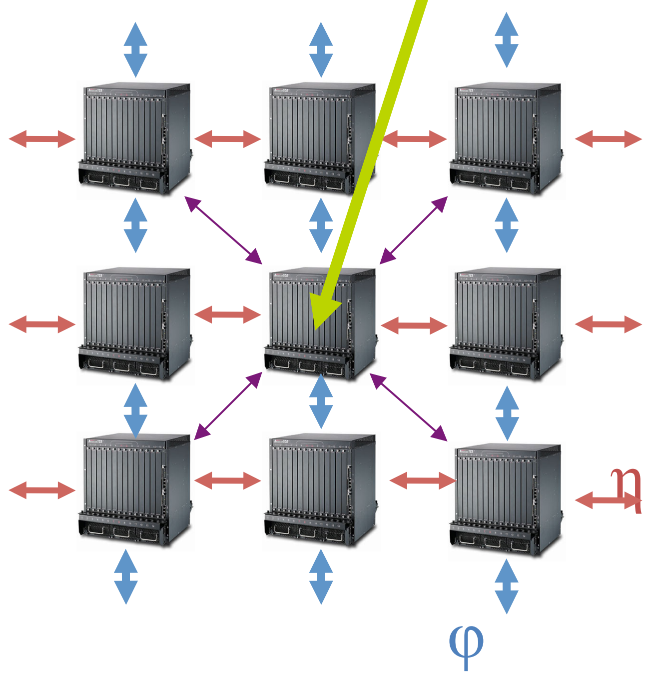


Track finding @ Level-1



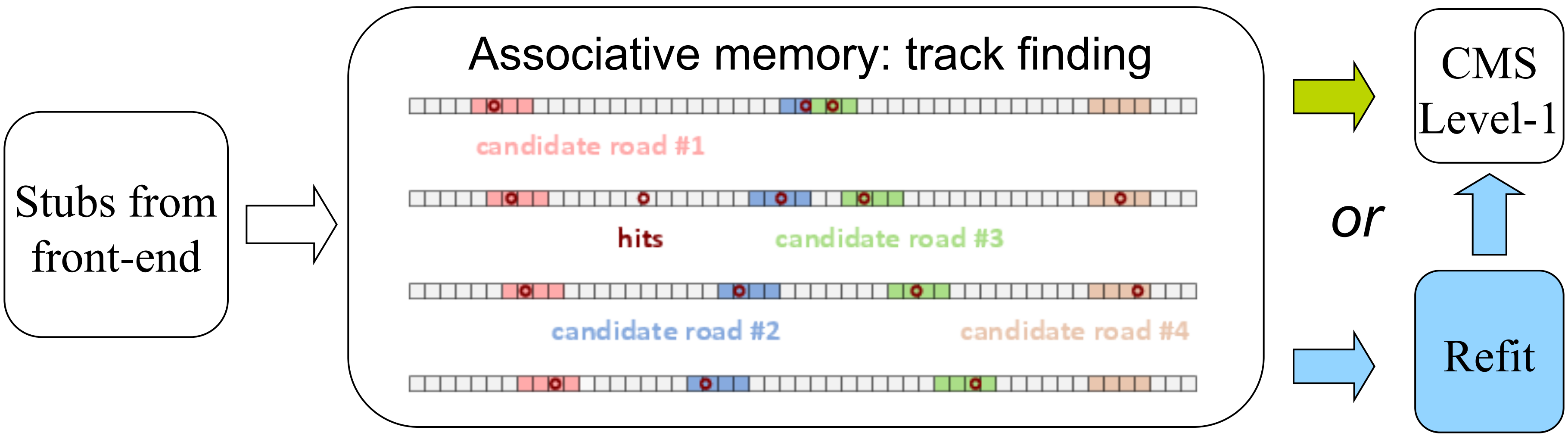
Simple
Trigger Tower
Interconnections

Each box represents
a trigger tower



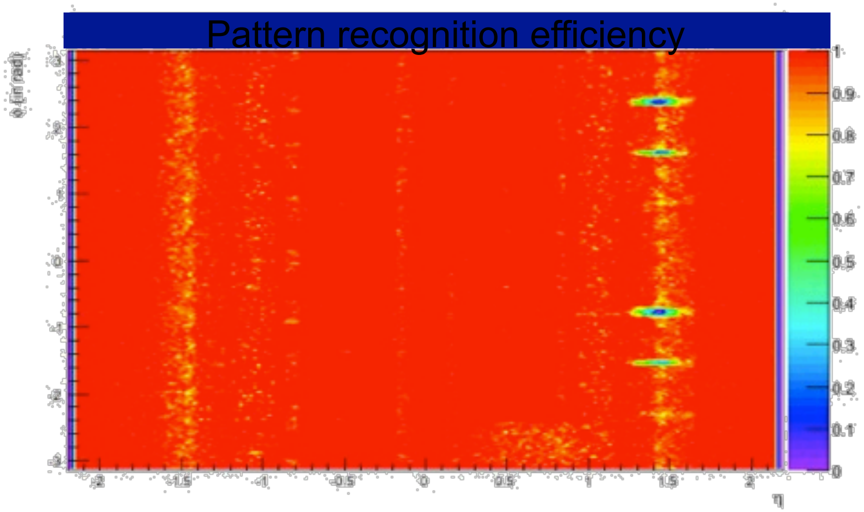
Track finding at Level-1

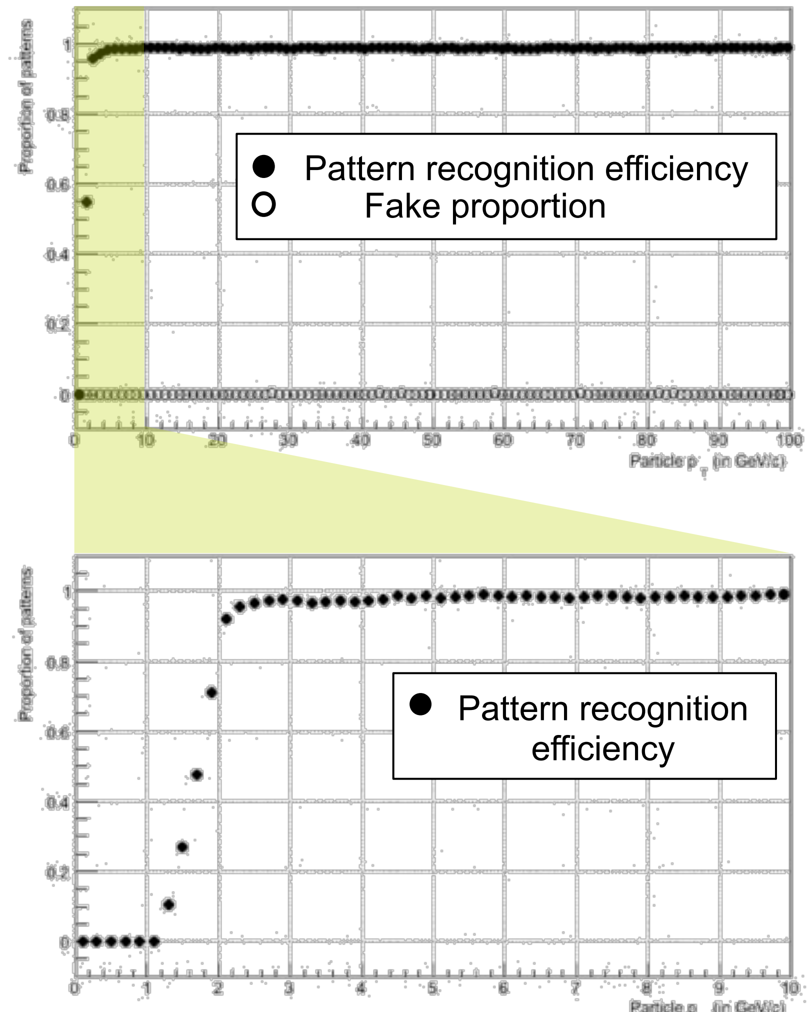
- Within a latency of O(μs): Associative Memories
  - Pattern matching using AM technologies dates back to CDF SVT to enhance collection of events with long-lived hadrons
  - HL-LHC: much higher occupancy, higher event rates, higher granularity
  - Plan of development
    - **Software emulation** (ongoing)
    - Build a **demonstrator system** using ATLAS **F**ast**T**rac**K**er boards (started)
    - Develop dedicated AM chips and boards



Trigger board emulation

VERY preliminary results!

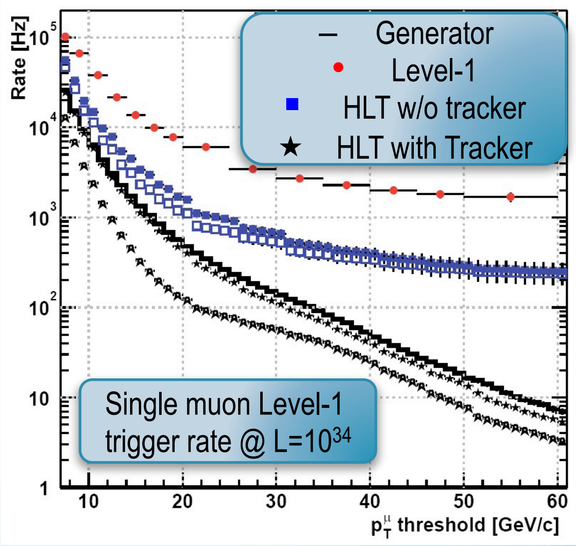




- Preliminary studies indicate that full efficiency can be achieved over the whole η range
  - Sharp turn-on curve of the efficiency around ~1.5 GeV/c
- Implementation in hardware?

Basic requirements and guidelines – II

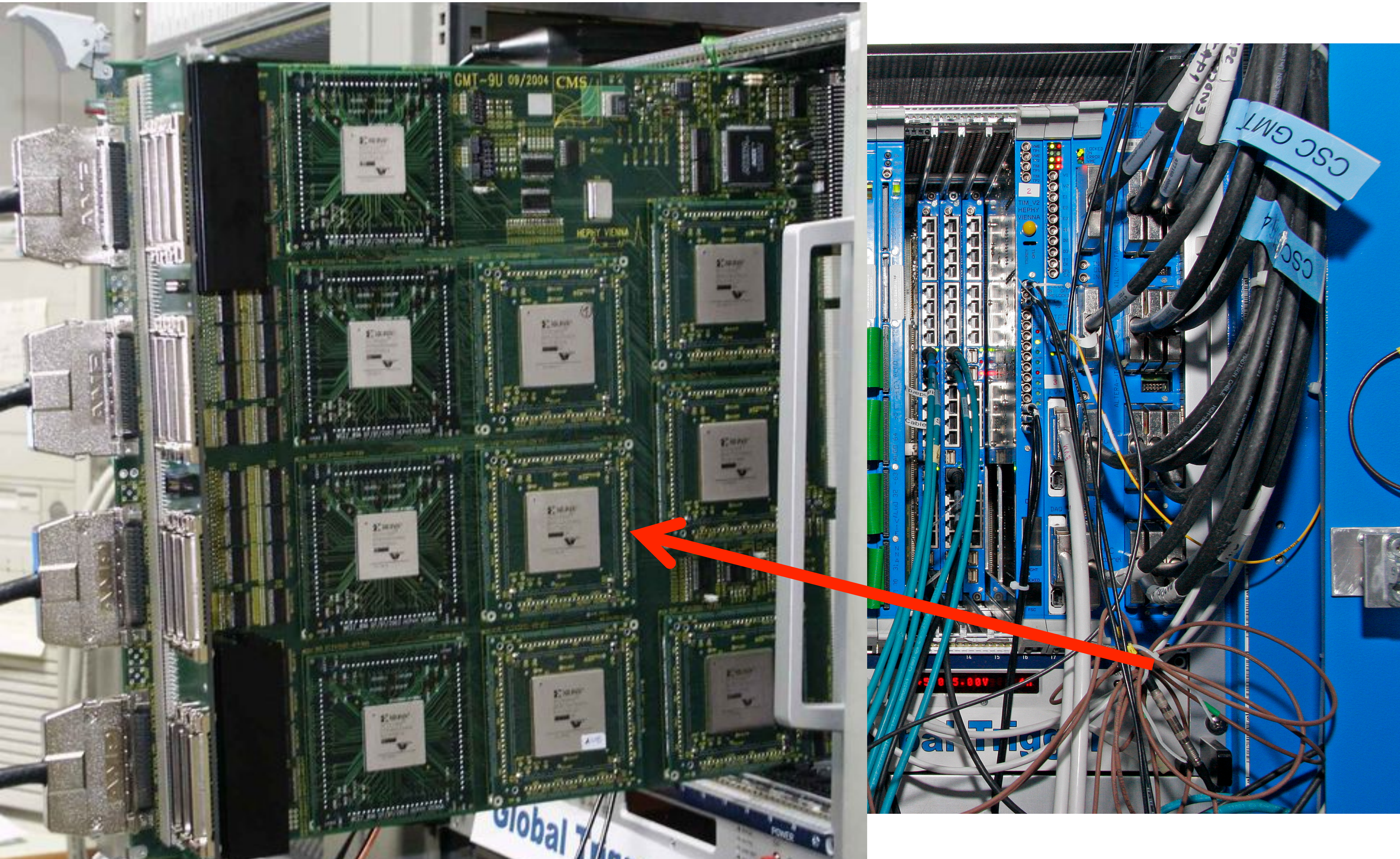
- Tracker input to Level-1 trigger
  - μ, e and jet rates would substantially increase at high luminosity
    - Even considering “phase-1” trigger upgrades
  - Increasing thresholds would affect physics performance
    - Performance of algorithms degrades with increasing pile-up
      - Muons: increased background rates from accidental coincidences
      - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation
  - Even HLT without tracking seems marginal
  - Add tracking information at Level-1
    - Move part of HLT reconstruction into Level-1!



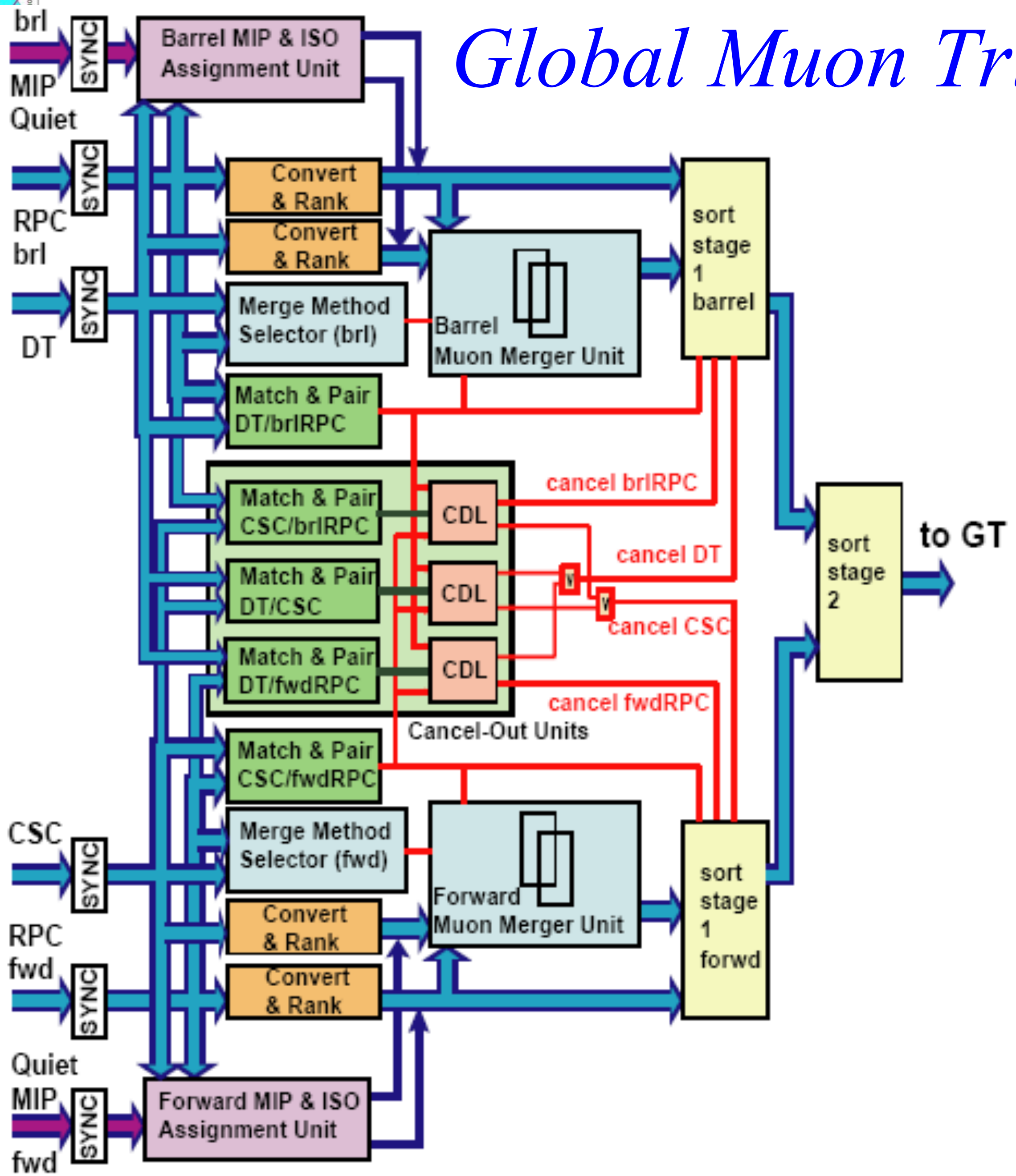
- Goal for “track trigger”:
  - Reconstruct tracks above 2 GeV
  - Identify the origin along the beam axis with ~ 1 mm precision

BACKUP
muons

Level-1 muon trigger

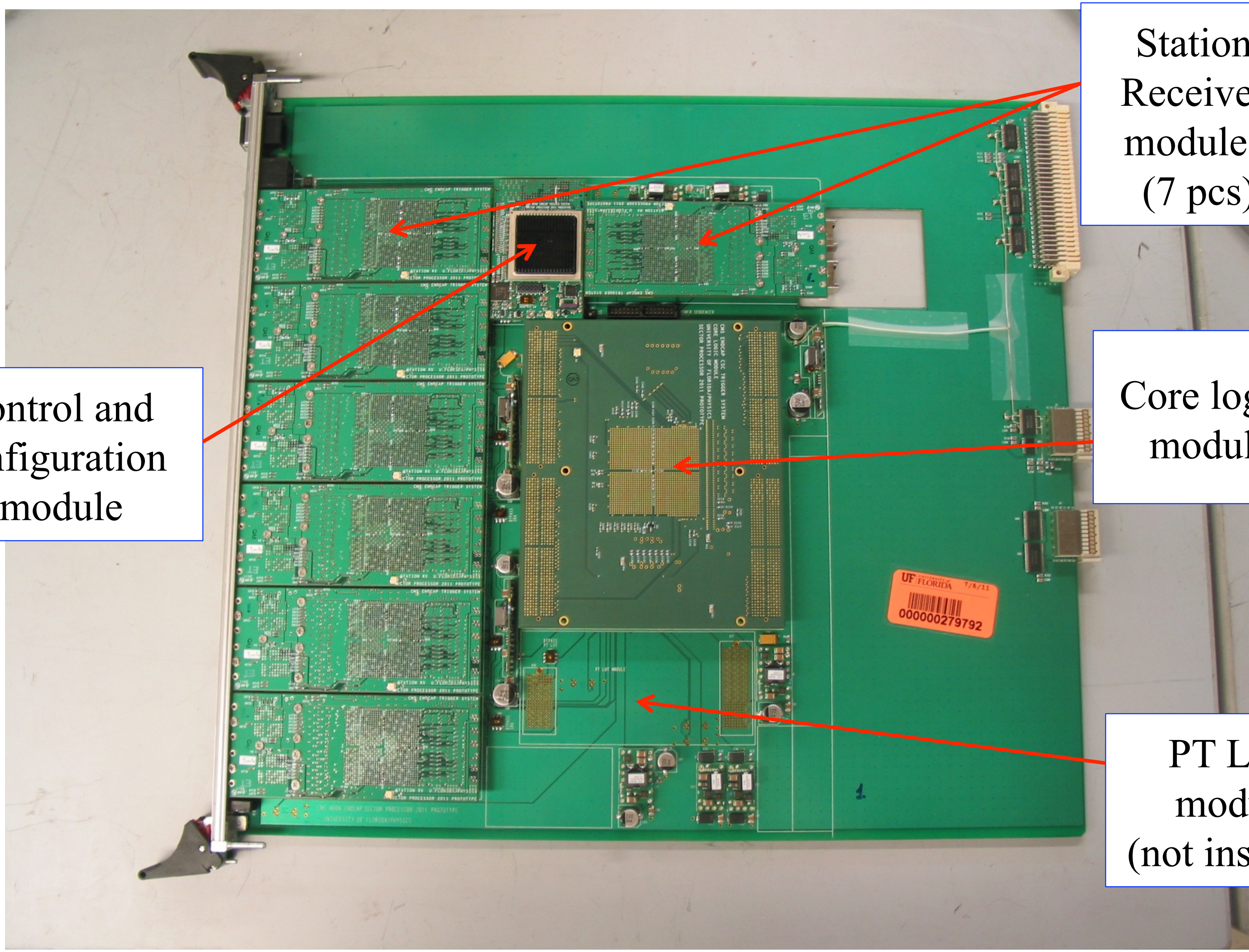


Global Muon Trigger



- match & merge
  - barrel: DT-RPC
  - endcap: CSC-RPC
- cancel duplicates
  - overlap region: DT-CSC
- sort by momentum and quality

CSC Sector processor 2010-2011 prototype, Florida

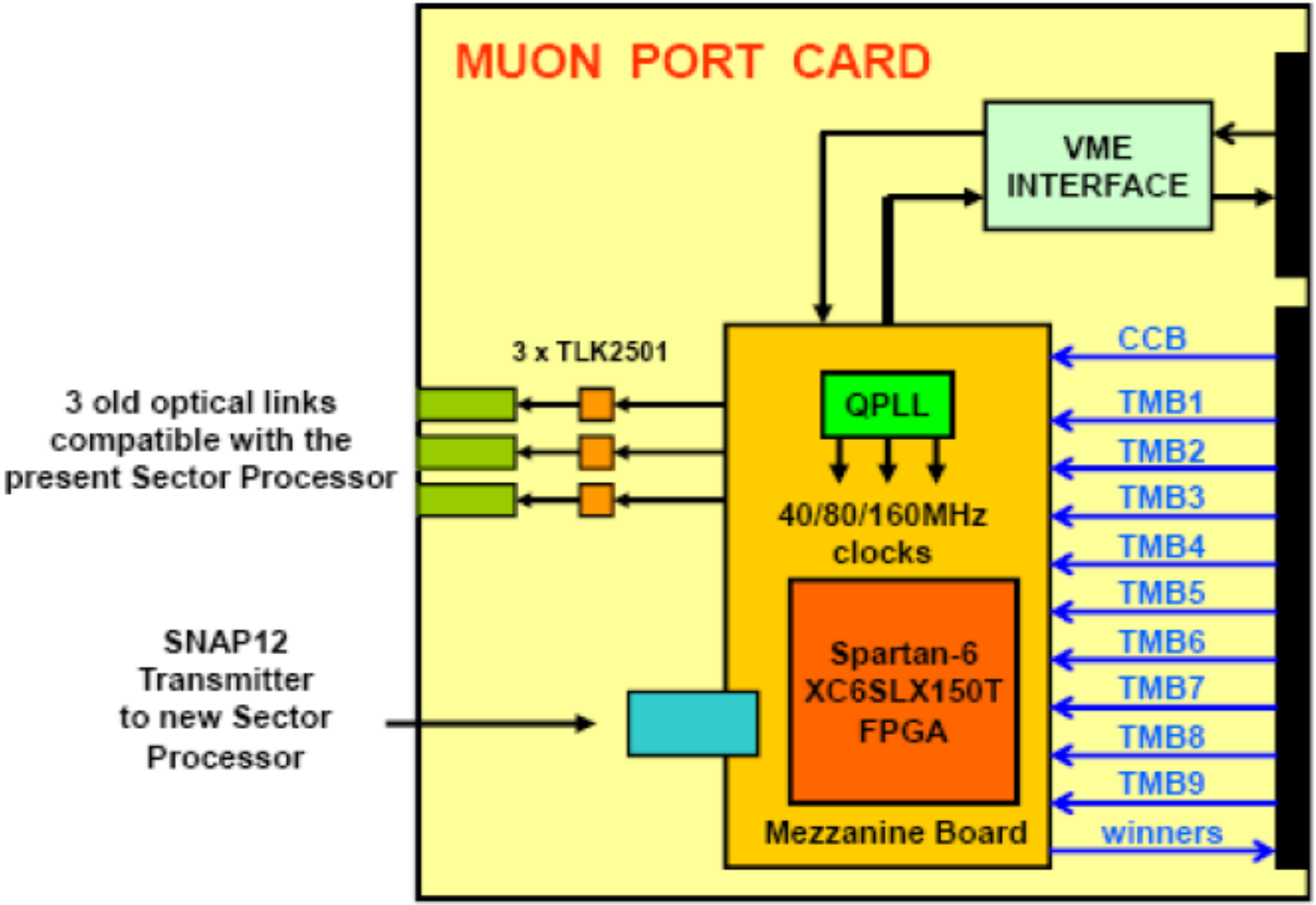


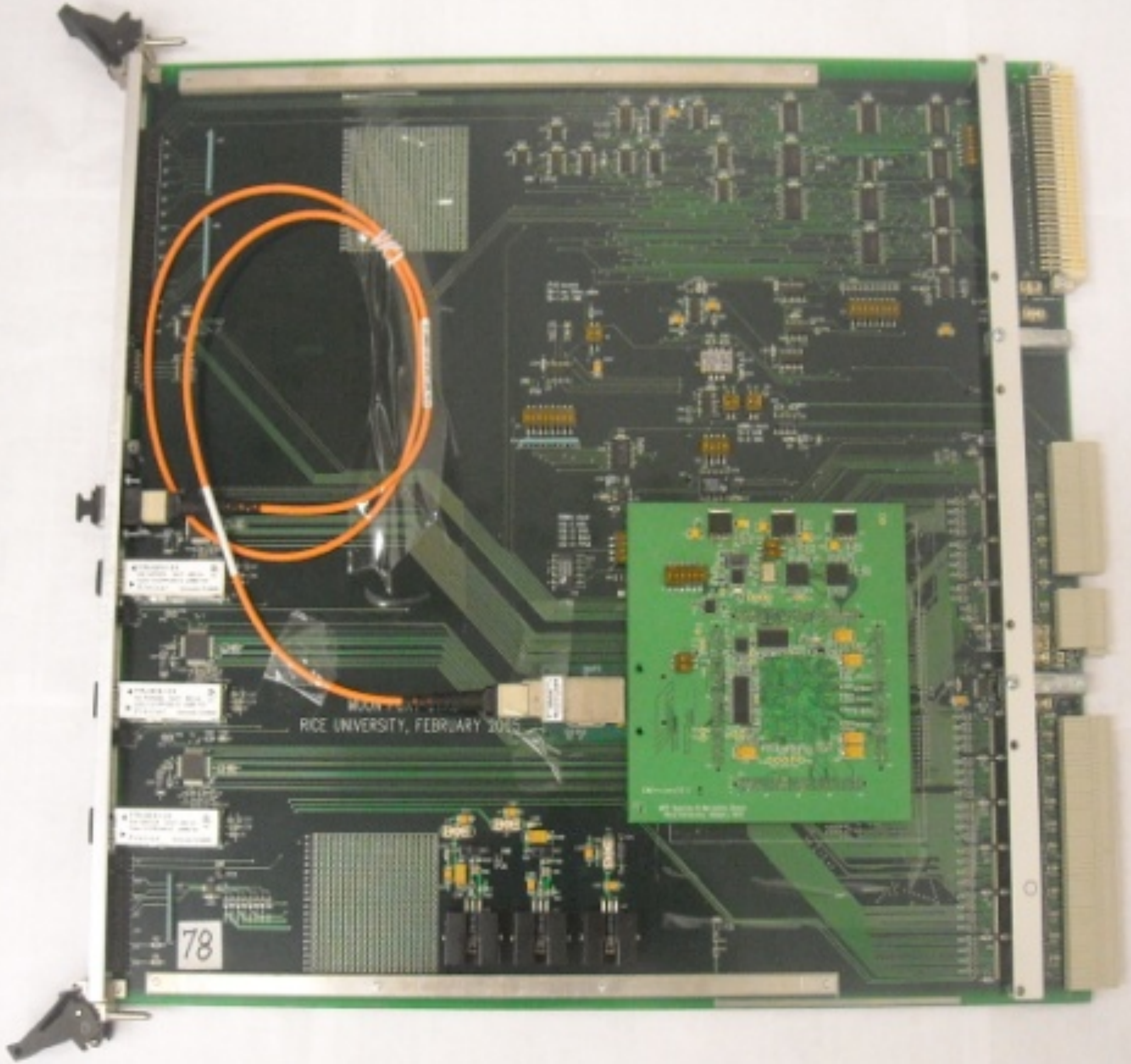
Station Receiver modules (7 pcs)

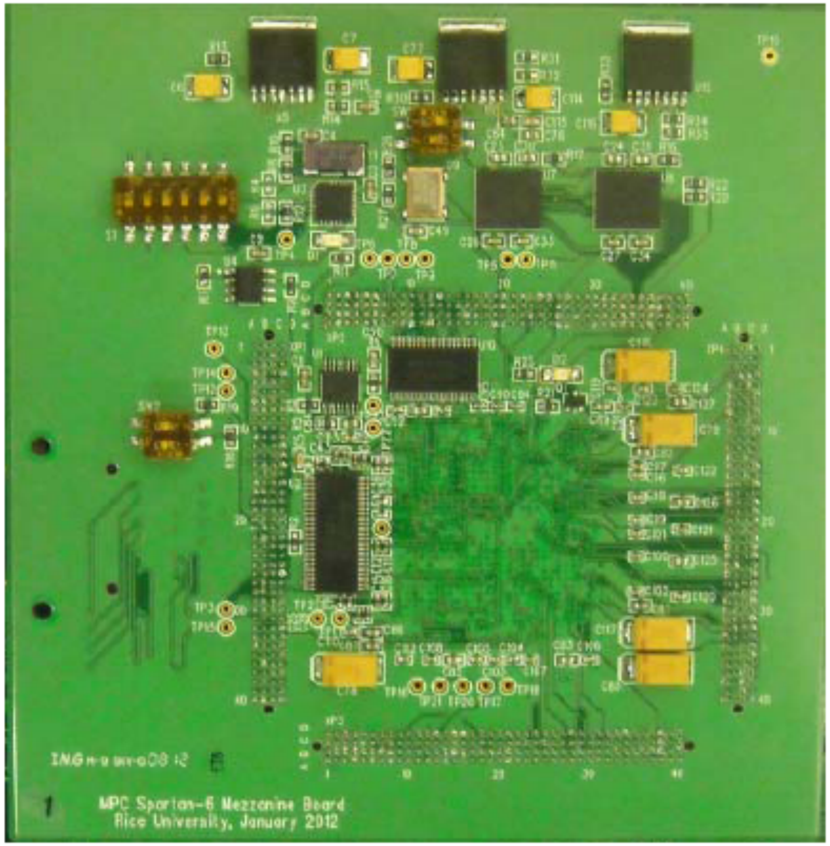
Control and configuration module

Core logic module

PT LUT module (not installed)


MUON PORT CARD
VME
INTERFACE
3 x TLK2501
QPLL
40/80/160MHz
clocks
Spartan-6
XC6SLX150T
FPGA
Mezzanine Board
CCB
TMB1
TMB2
TMB3
TMB4
TMB5
TMB6
TMB7
TMB8
TMB9
winners
3 old optical links
compatible with the
present Sector Processor
SNAP12
Transmitter
to new Sector
Processor


RICE UNIVERSITY, FEBRUARY
78


MPC Spartan-6 Mezzanine Board
Rice University, January 2012


Test of MPC to SP10 communication.
8 fibers, 3.2 Gbps each, no errors

MPC prototype (Rice)
Based on Spartan-6

SP10 prototype (Florida)

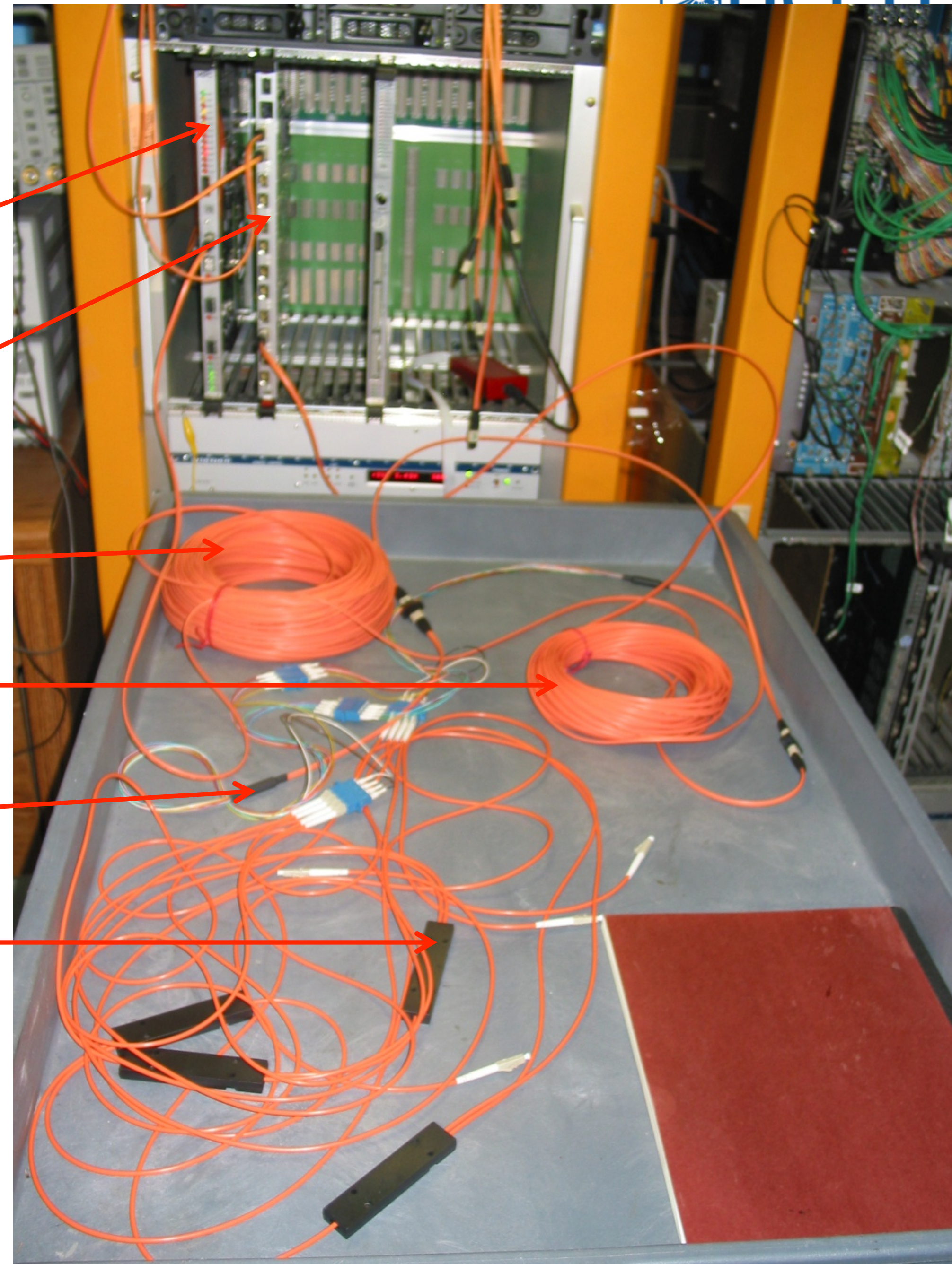
100 meter fiber (12-core)

25 meter fiber (12-core)

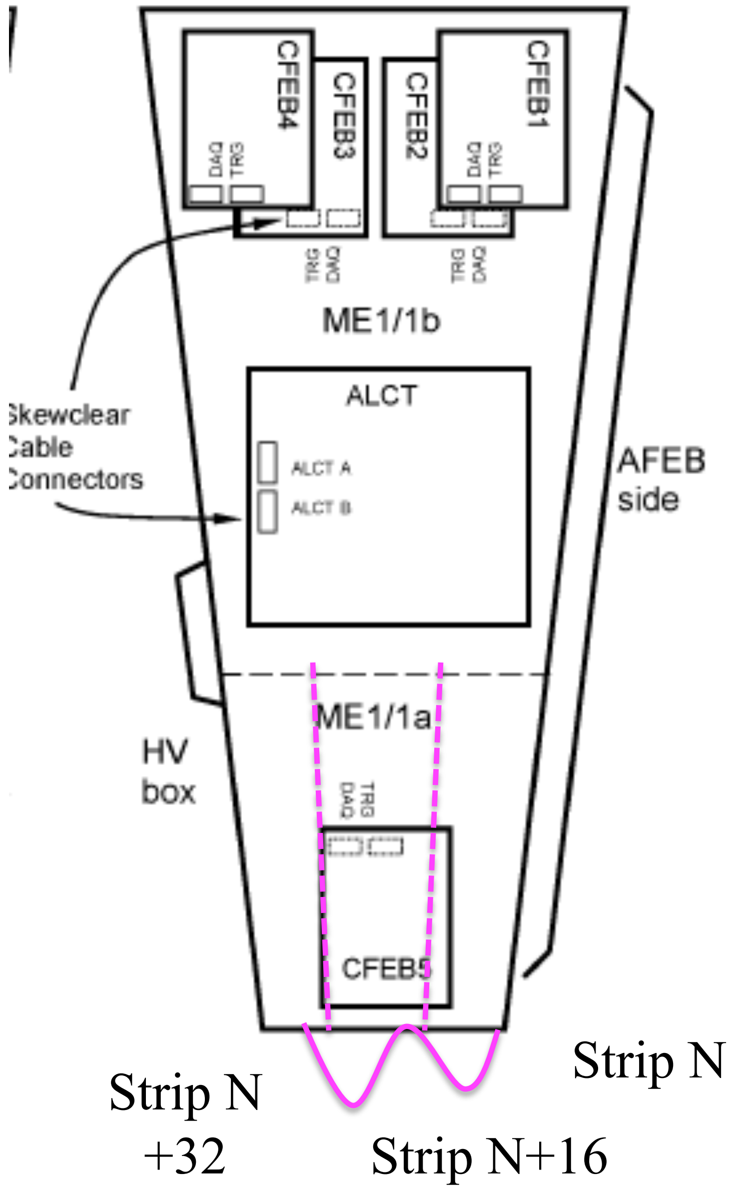
12-core fiber fanout (2 pcs)

50/50% optical splitter (4 pcs)

Total optical path length: 125 meters + fanouts and splitters



YE-1 chambers with even phi indices,
YE+1 chambers with odd phi indices



ME11a structure

ME1/1 view (from CMS IN-2007/024)

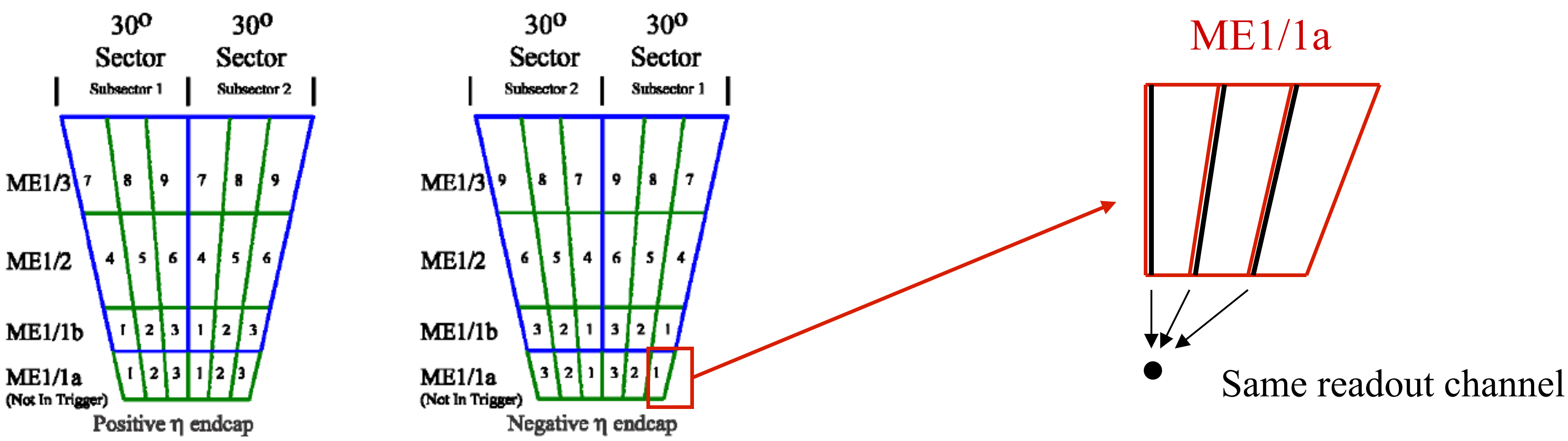


Figure 9. Numbering of CSC chambers within ME1 trigger sectors, as viewed from the IP.

- The 48 strips of ME1/1a are ganged 3:1 in 16 readout channels
- e.g. strips 1 (2), 17 (18) and 33 (34) are ganged together into the 1^{st} (2^{nd}) readout channel
- In the CSCTF LUTs the ϕ value is shifted to the middle of the CFEB
- We will mistake the ϕ assignment at most by 1/3 (with the older assignment up to 2/3)

Rates and efficiencies of current and upgraded calorimeter trigger