Triggering LHC Experiments

Wesley H. Smith

University of Wisconsin - Madison

Outline:

- Introduction: ATLAS, CMS, LHCb, ALICE
- Architecture
- Calorimeter Triggers
- Muon Triggers
- Global/Central Triggers & Control
- Conclusions

LHC Physics & Event Rates

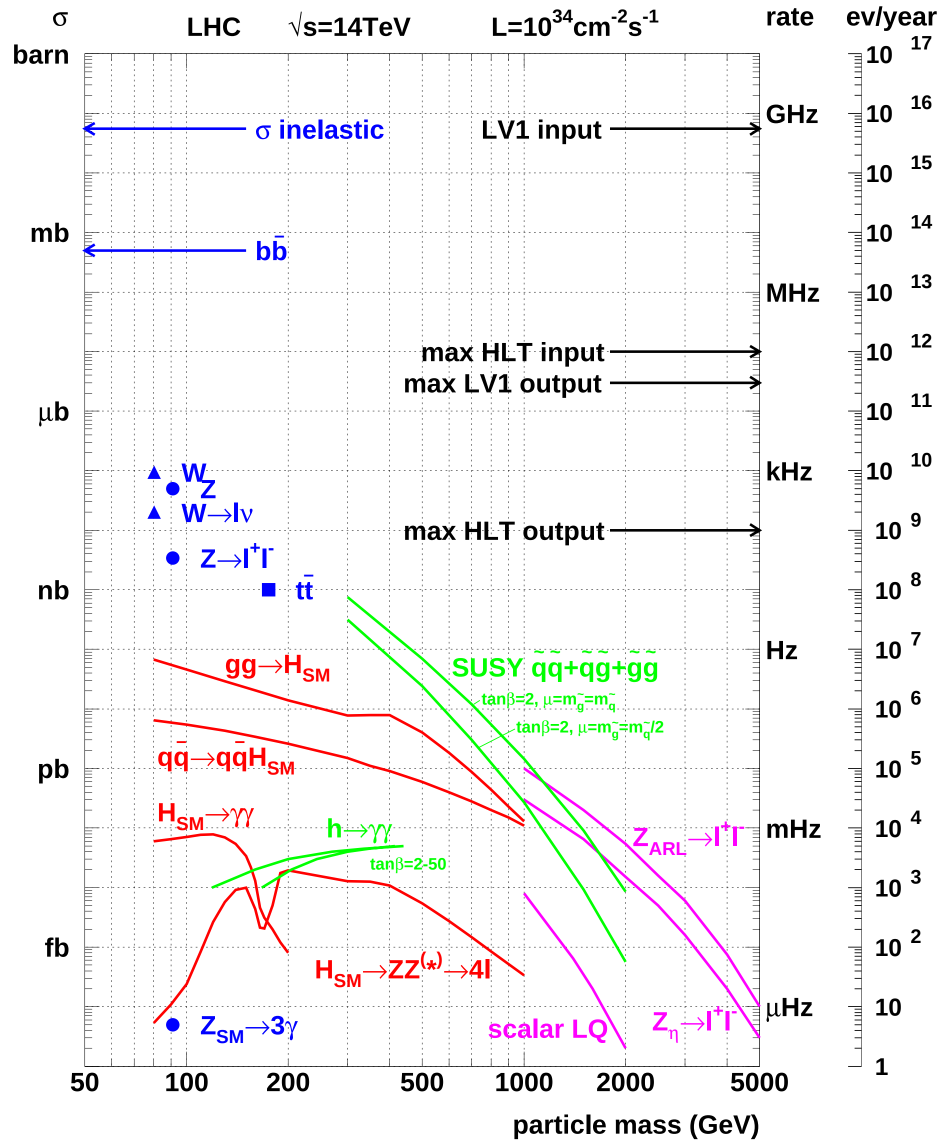
At design $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$

- 17 pp events per 25 ns crossing
  - ~ 1 GHz input rate
  - "Good" events contain ~ 20 bkg. events
- 1 kHz W events
- 10 Hz top events
- < 10^4 detectable Higgs decays/year

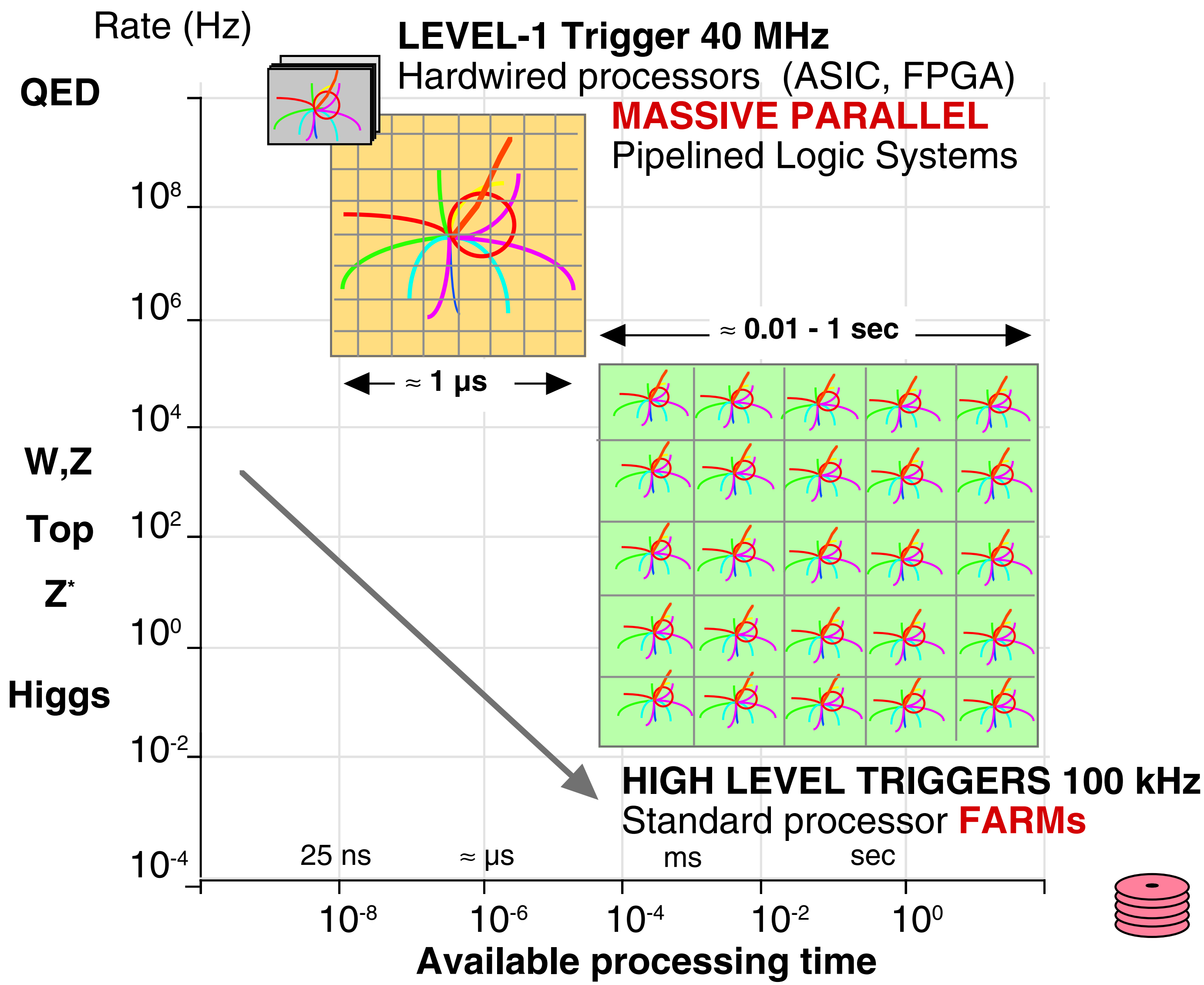
Can store ~ 100 Hz of events

Select in stages

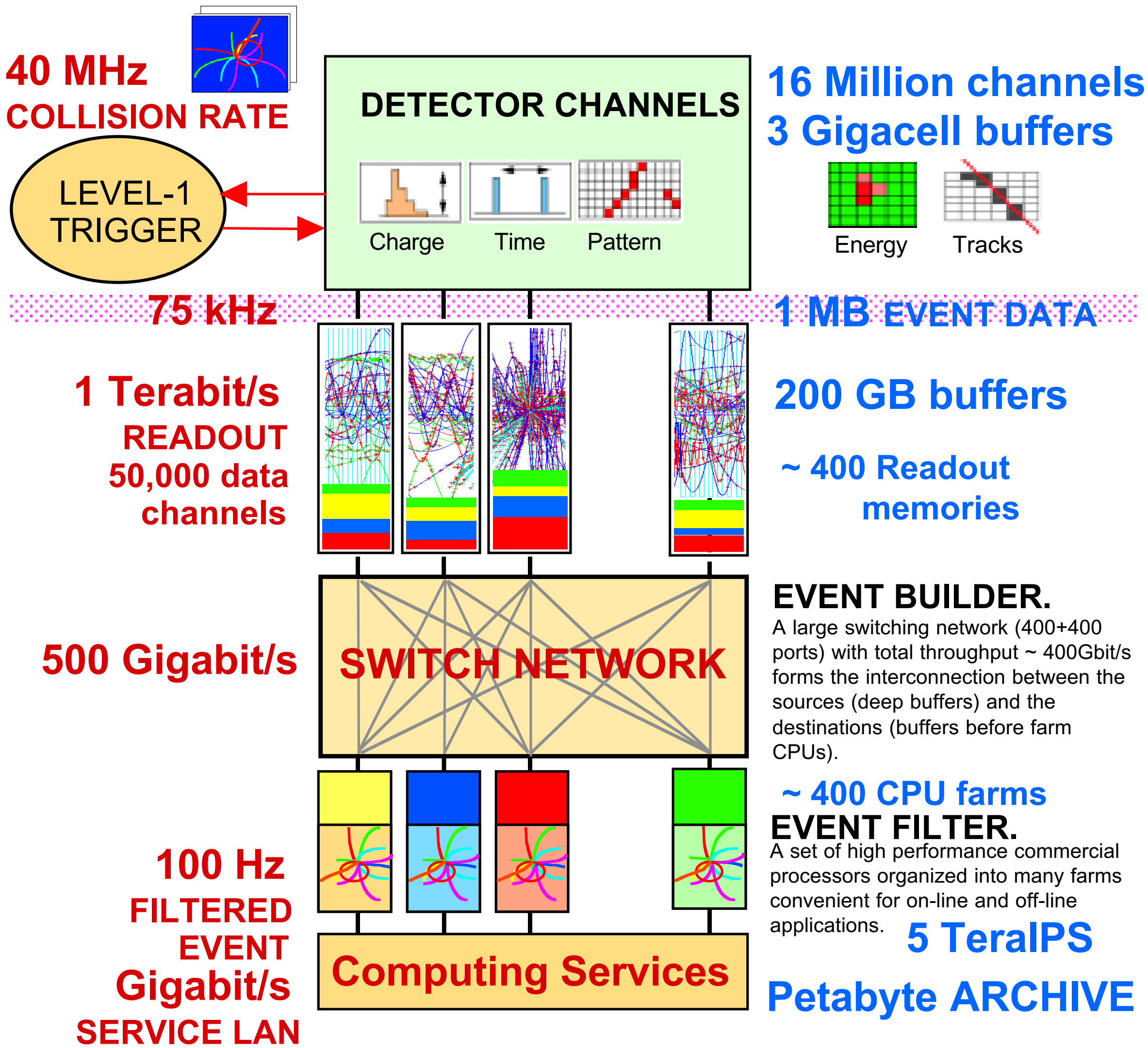
- Level-1 Triggers
  - 1 GHz to 100 kHz
- High Level Triggers
  - 100 kHz to 100 Hz



Processing LHC Data



Overview of Trigger & DAQ



Challenges:

1 GHz of Input Interactions

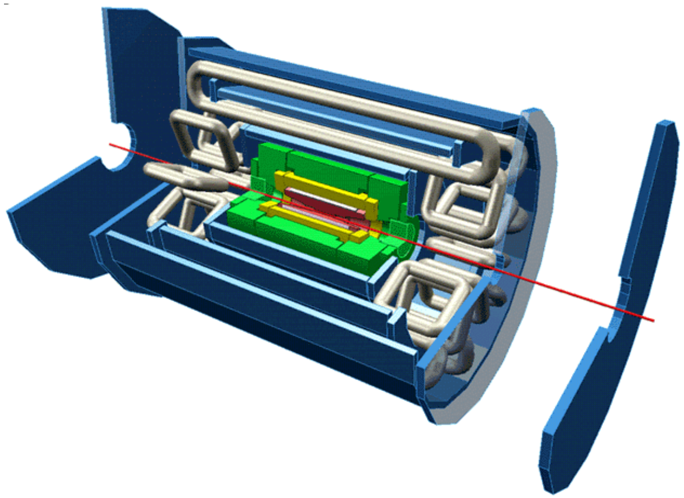
Beam-crossing every 25 ns with ~17 interactions produces over 1 MB of data

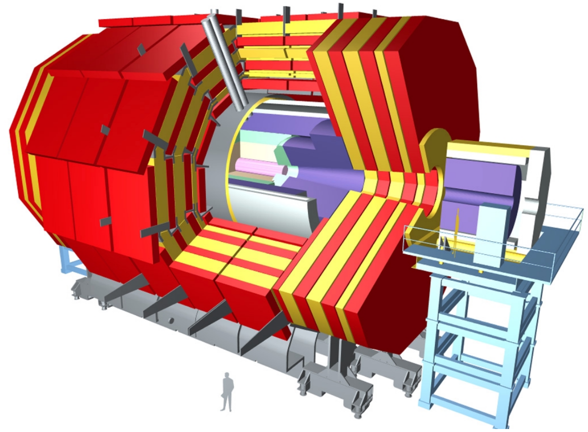
Archival Storage at about 100 Hz of 1 MB events

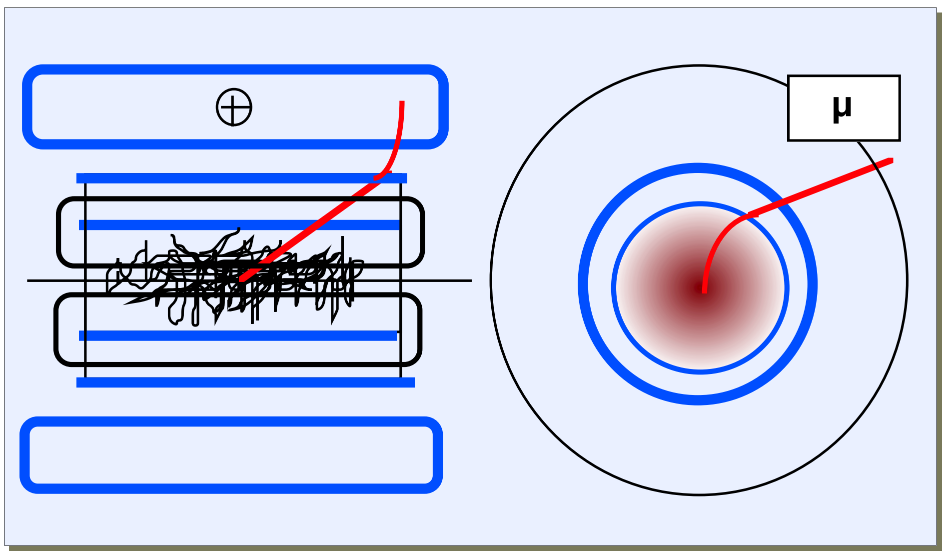
LHC pp experiments

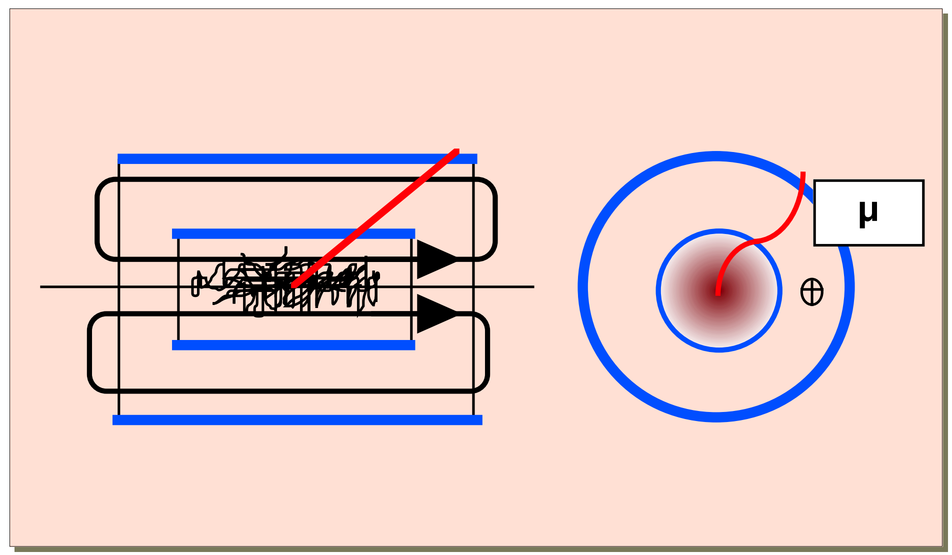
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid

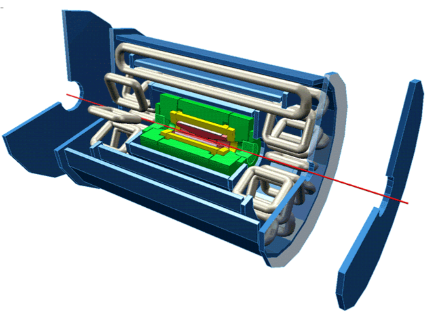


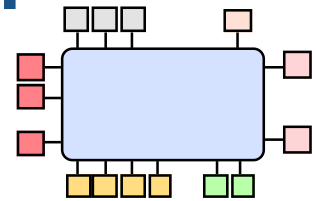


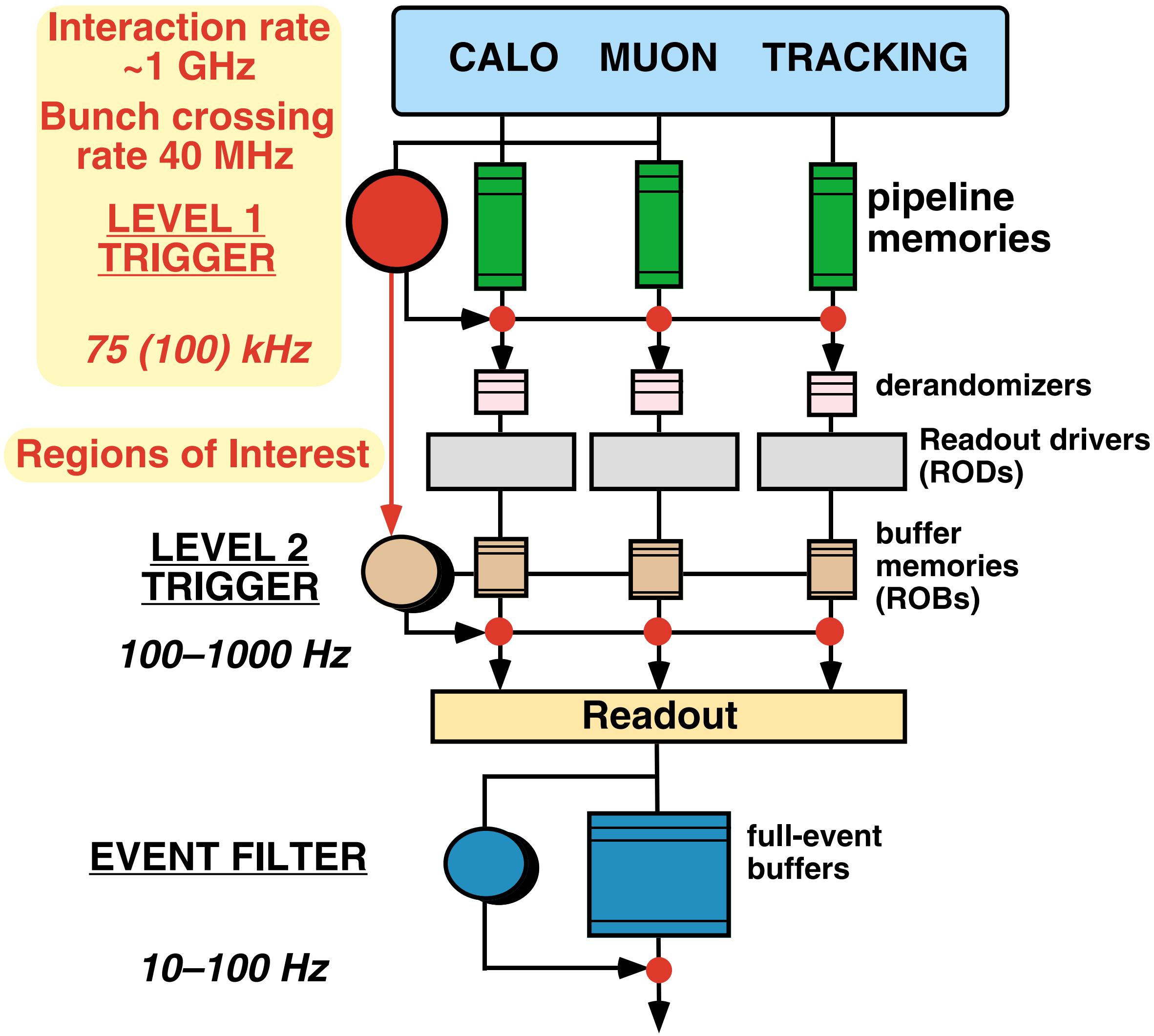




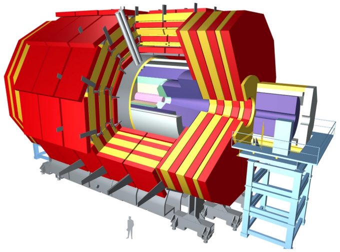
ATLAS Trigger and DAQ system

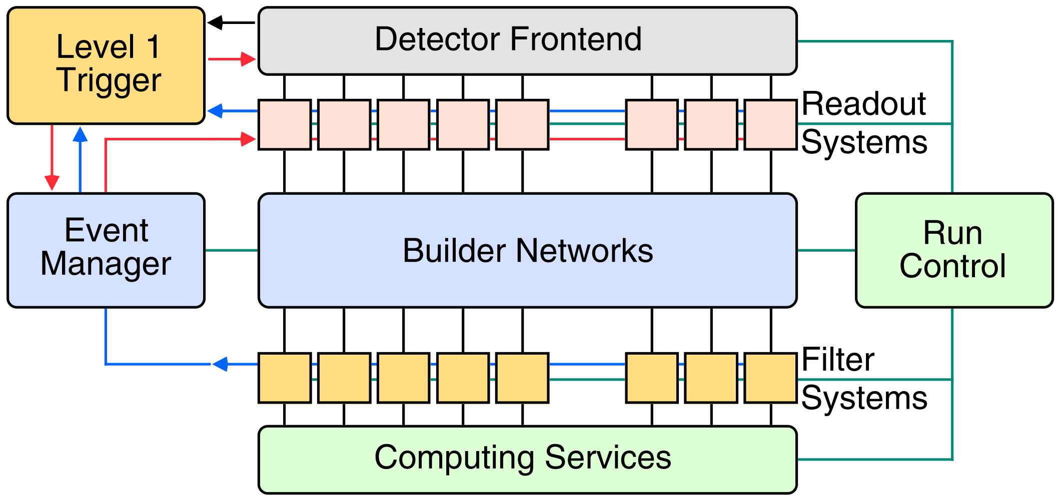


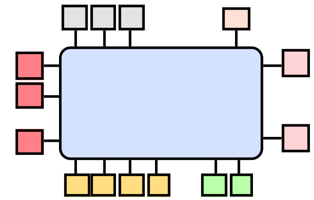




CMS Trigger and DAQ system







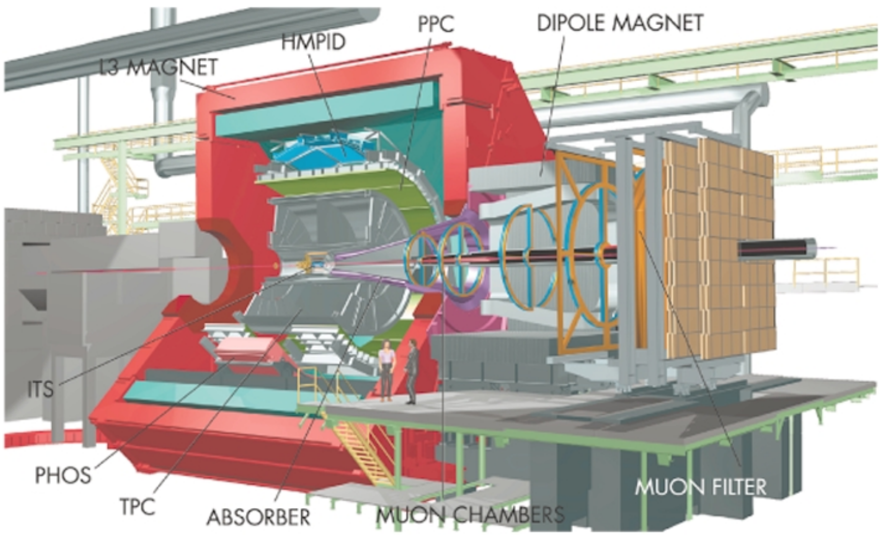
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	≈ 1 Mbyte
Event Flow Control	≈ 10^6 Mssg/s
No. of In-Out units (200-5000 byte/event)	1000
Readout network (512-512 switch) bandwidth	≈ 500 Gbit/s
Event filter computing power	≈ 5 10^6 MIPS
Data production	≈ Tbyte/day
No. of readout crates	≈ 250
No. of electronics boards	≈ 10000

LHC Ion-Ion collision and B-decay experiments

ALICE

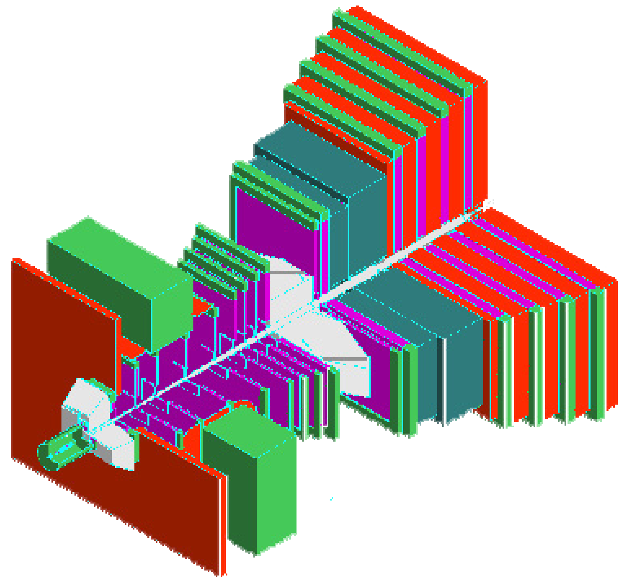
A Large Ion Collider Experiment

The ALICE Collaboration proposes to build a dedicated heavy-ion detector to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.

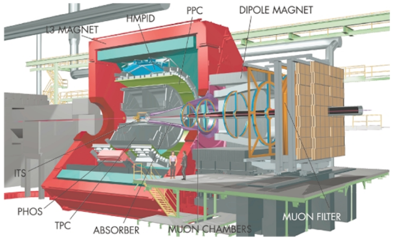


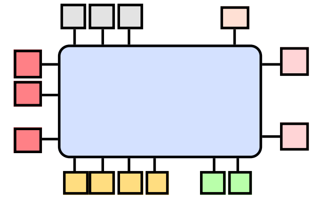
LHCb

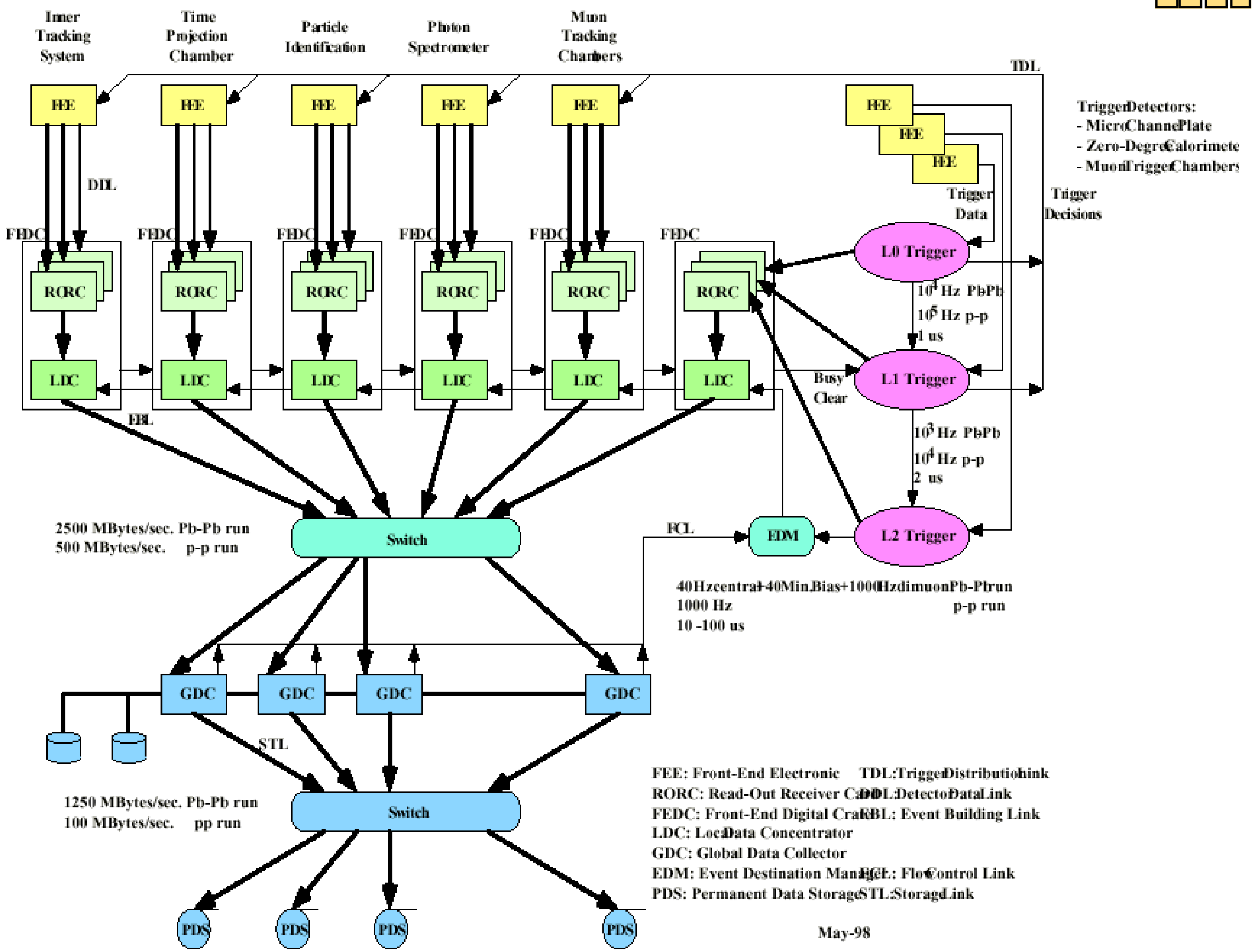
(Study of CP violation in B-meson decays at the LHC collider)



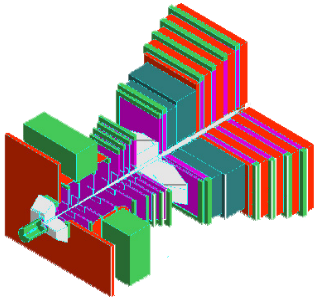
Alice Trigger and DAQ system

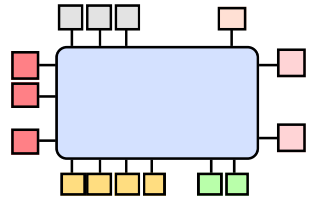


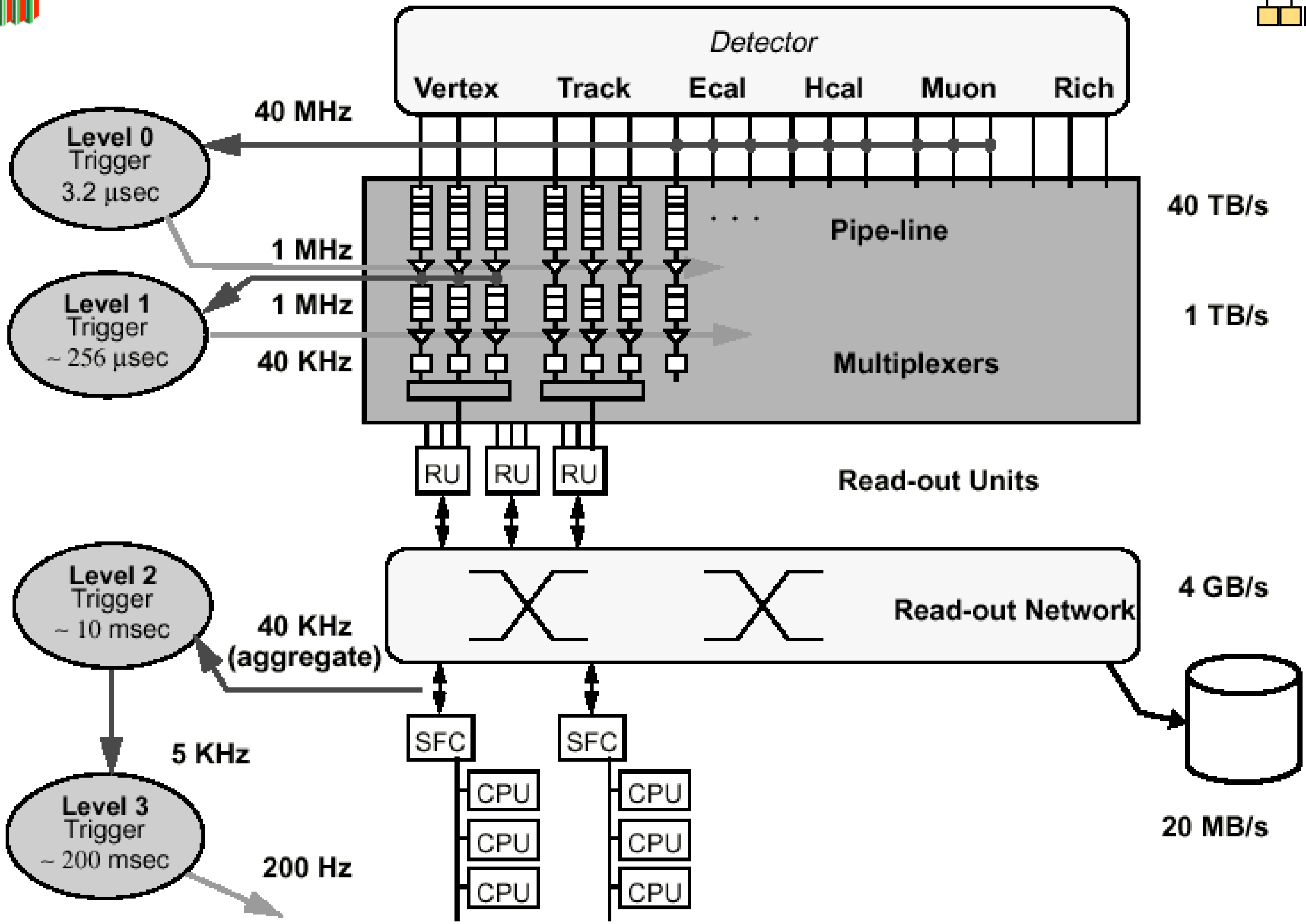




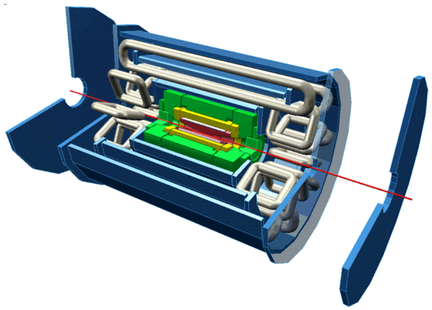
LHCb Trigger and DAQ system

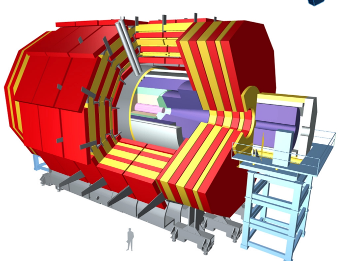


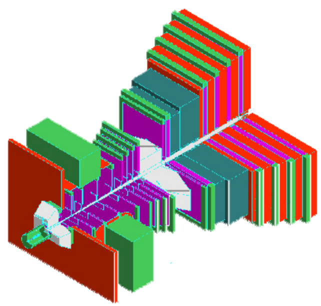


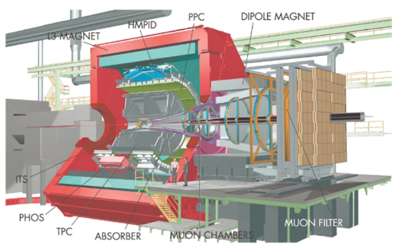


LHC experiments trigger and DAQ summary



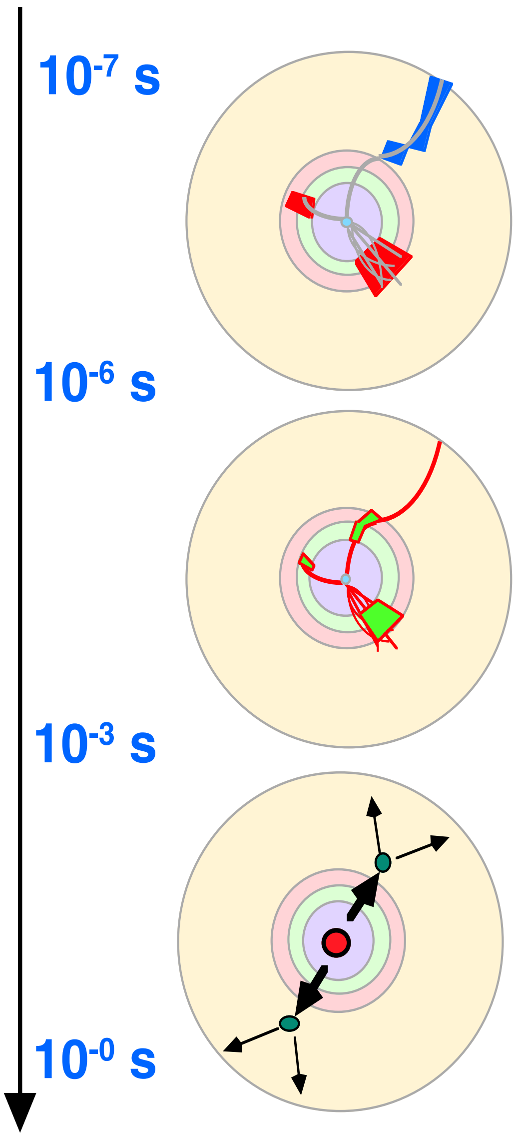






	Level-1 kHz	Event MByte	Storage MByte/s
ATLAS	100	1	100
CMS	100	1	100
LHCb	400	0.1	20
ALICE	1	25	1500

Trigger Levels



Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^5 Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ..)

- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

Level-3 events to tape 10..100 Hz

Physics process identification

- Event reconstruction and analysis

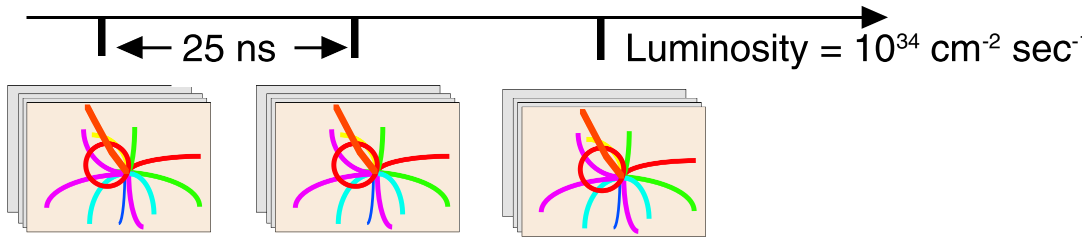
Trigger & Readout Structure

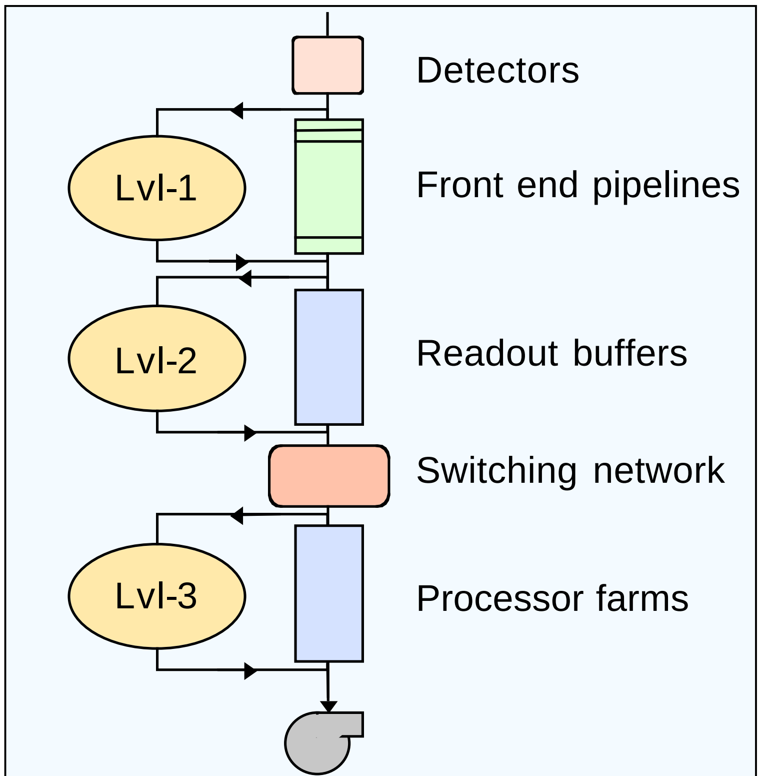
≈ 30 Collisions/25ns

(10^{9} event/sec)

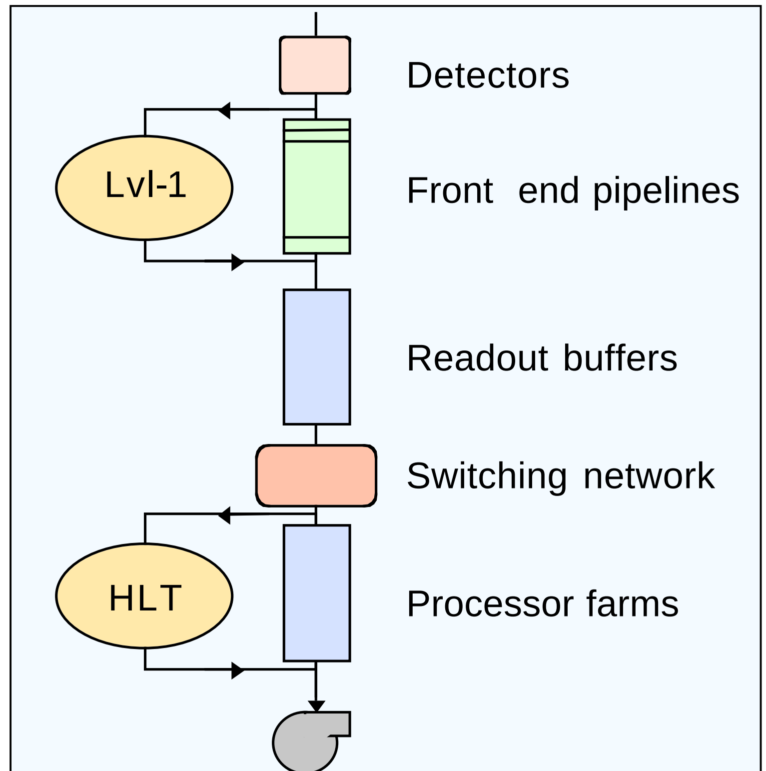
10^{7} channels

(10^{16} bit/sec)



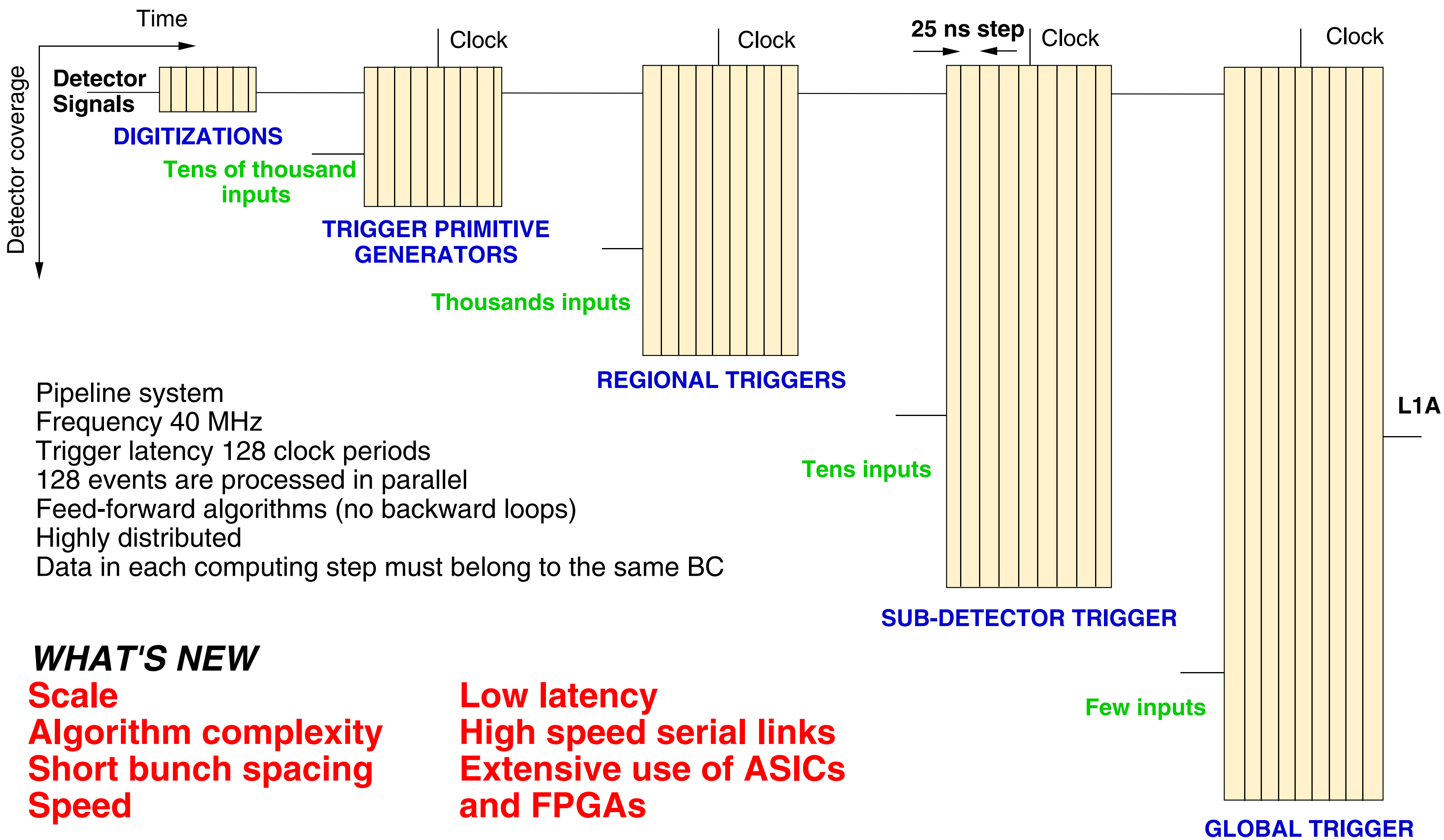


ATLAS: 3 physical levels



CMS: 2 physical levels

Level 1 Trigger Organization



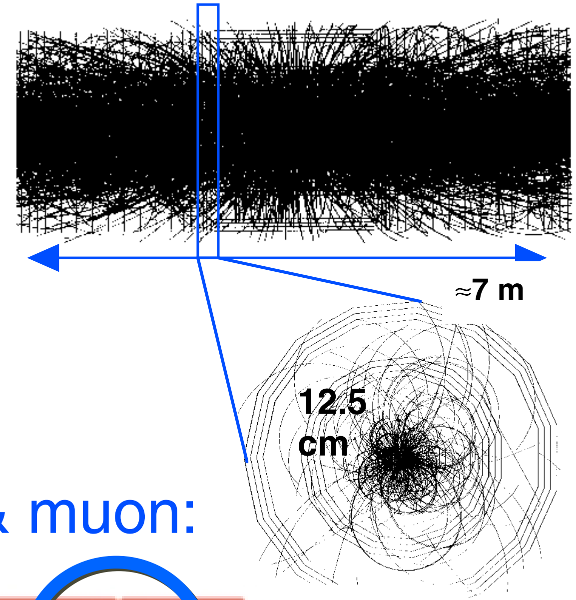
Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

WHAT'S NEW

Scale
Algorithm complexity
Short bunch spacing
Speed
Low latency
High speed serial links
Extensive use of ASICs and FPGAs

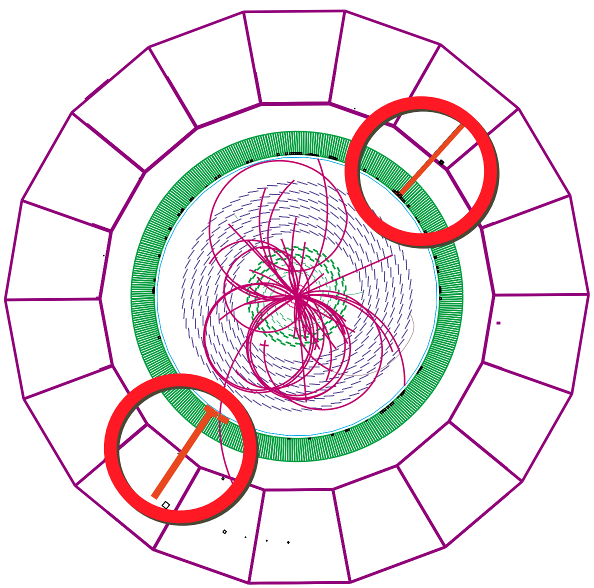
Level-1 : only calorimeters & muons ....

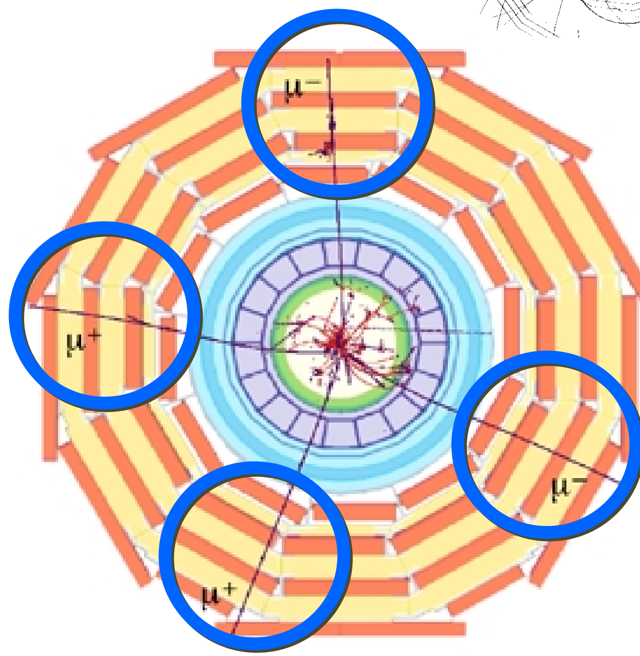
Compare to Central tracking at L = 10^{34}
(50 ns integration, ≈1000 tracks)



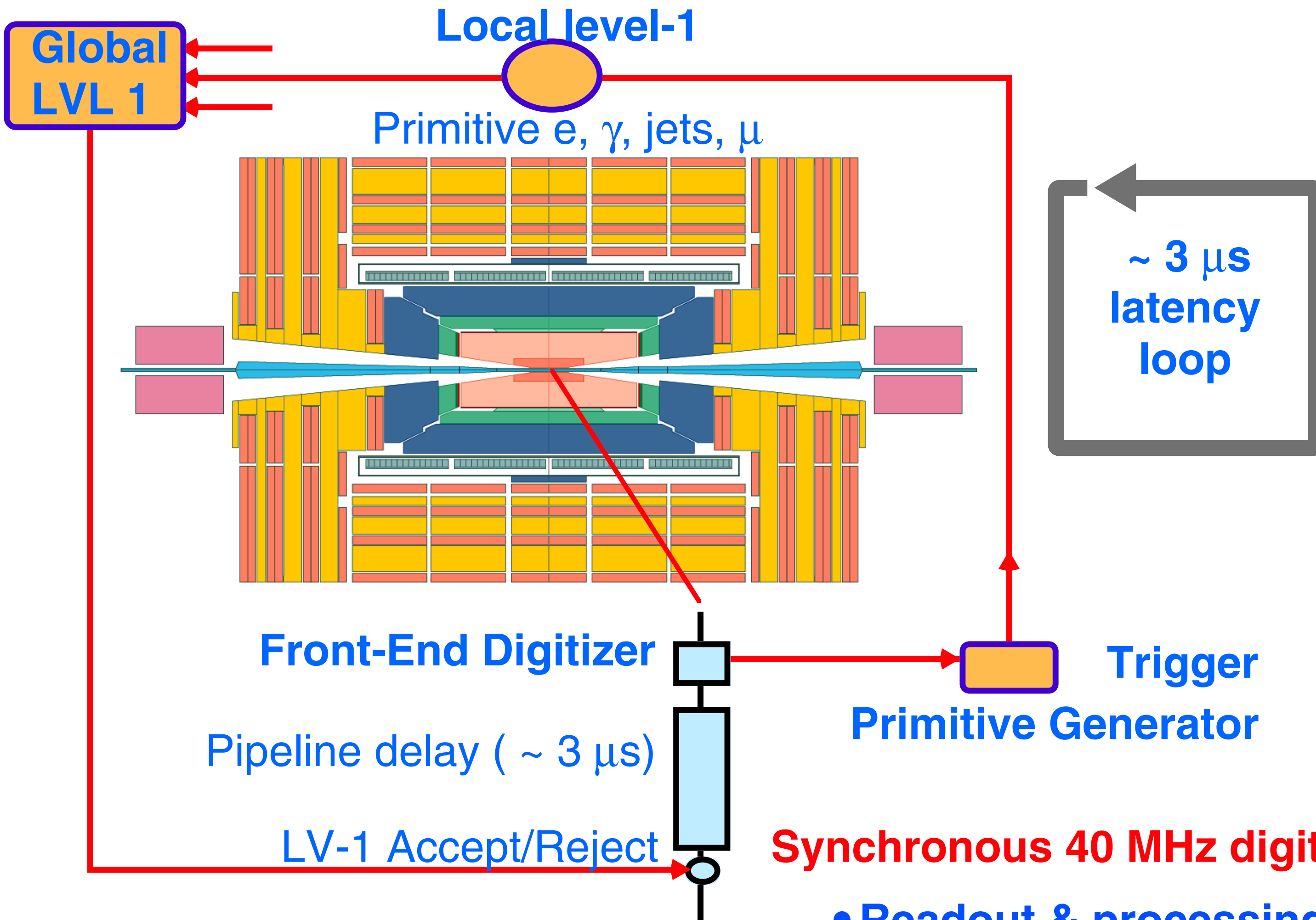
Algorithm Complexity
+
huge amount of data

Pattern recognition much easier on calo & muon:





LHC Level 1 Pipeline



Synchronous 40 MHz digital system

- **Readout & processing latency < 1μs**
- **Signal distribution latency ~ 2 μs**

Trigger Electronics Locations

In Underground Shielded Room:

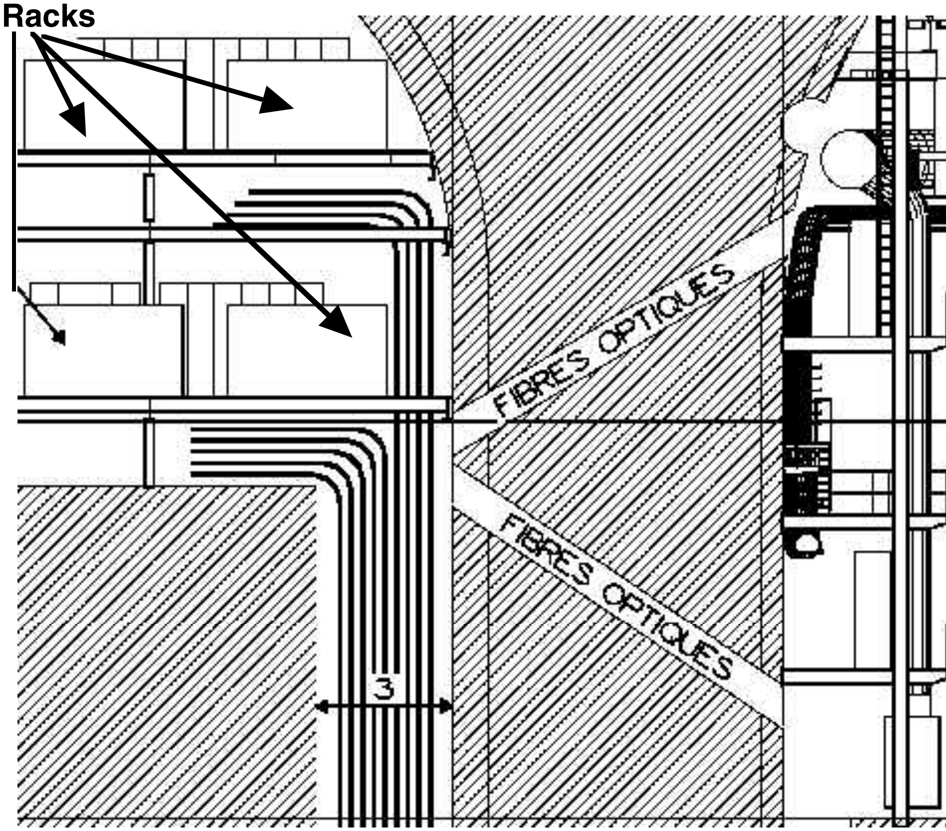
- Muon track-finding & pt assignment
- Calorimeter object identification & energy summation
- Global trigger & control

On Detector:

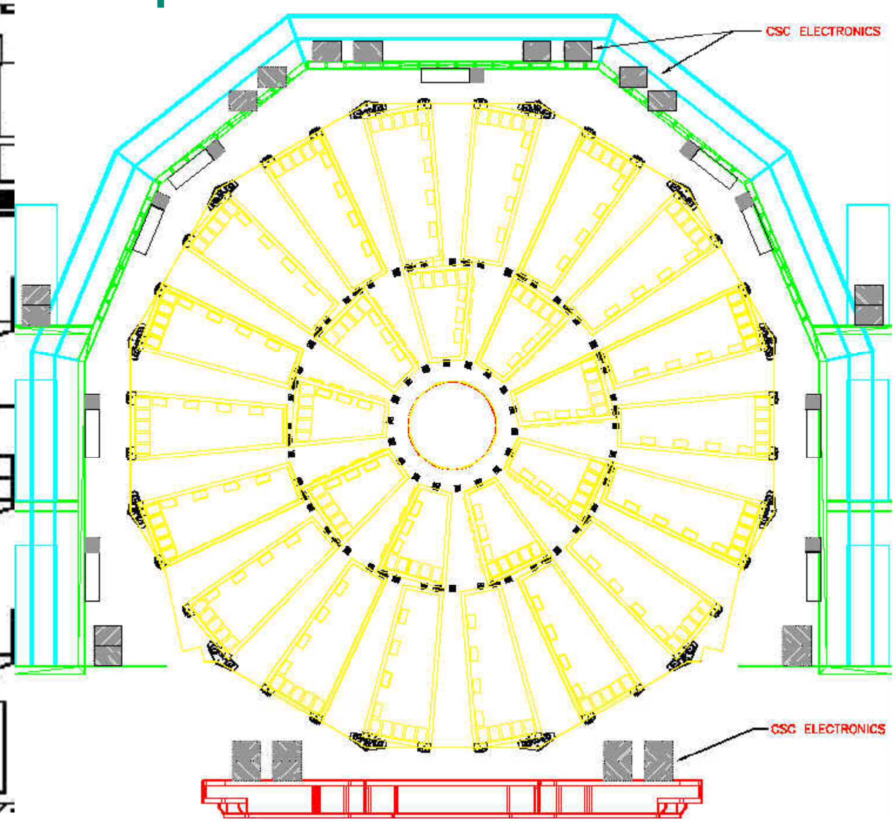
- Muon Hits or Segments
- Calorimeter energy analog summation (ATLAS) or digitization (CMS)

Electronics

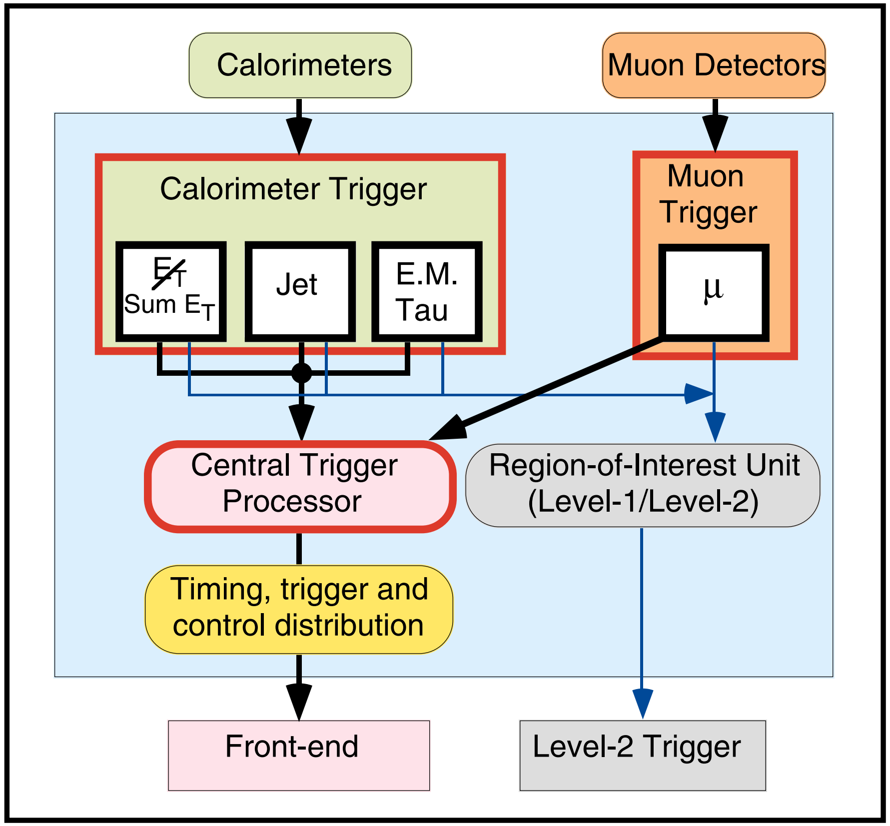
Racks



CMS picture



Level-1 Trigger architecture



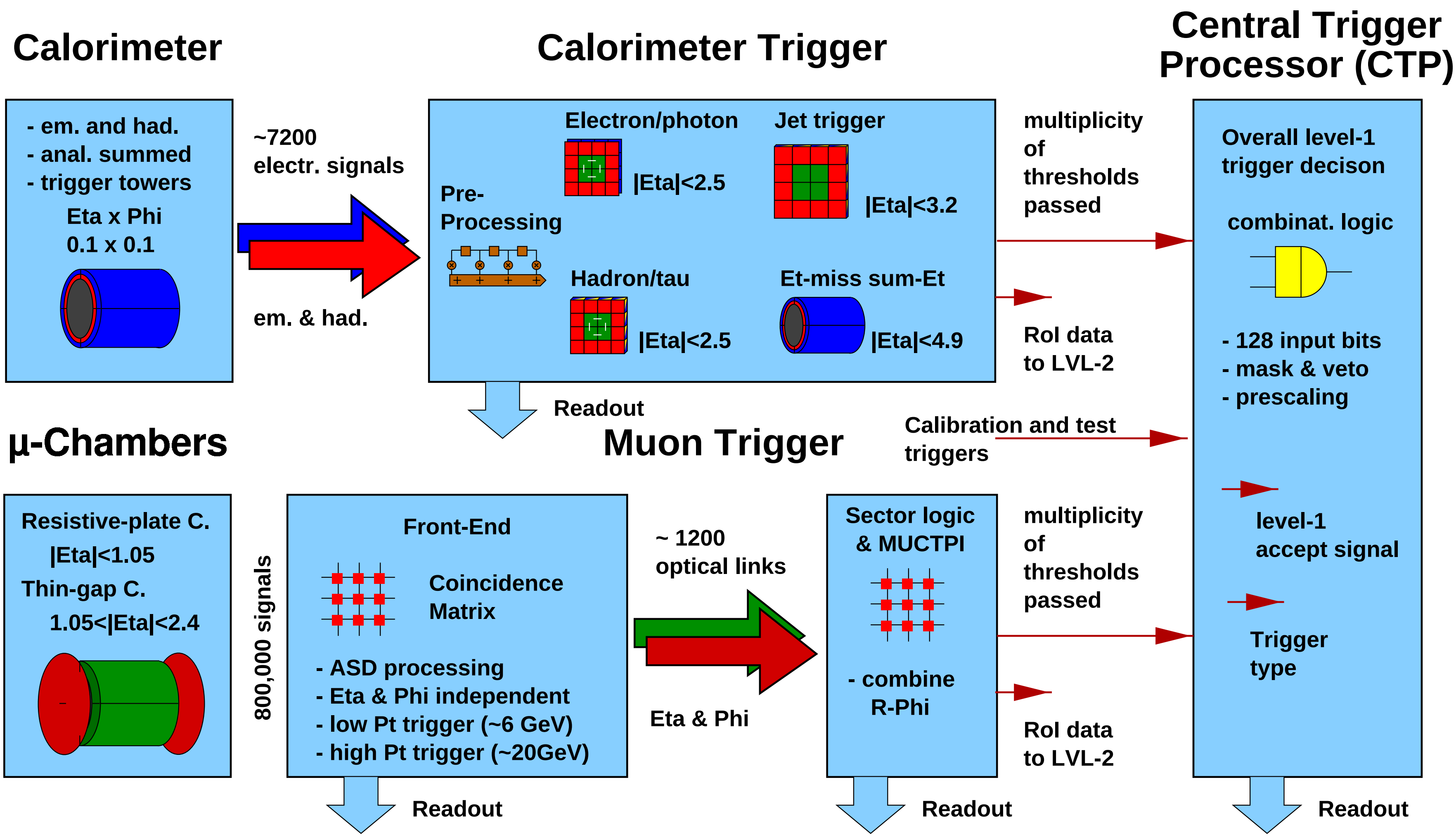
ATLAS:

- **Regional triggers: calo & muon**
- **Results merged into Central Trigger Processor & sent to ROIs**
- **Final Level-1 accept $\rightarrow$ front-ends**

CMS:

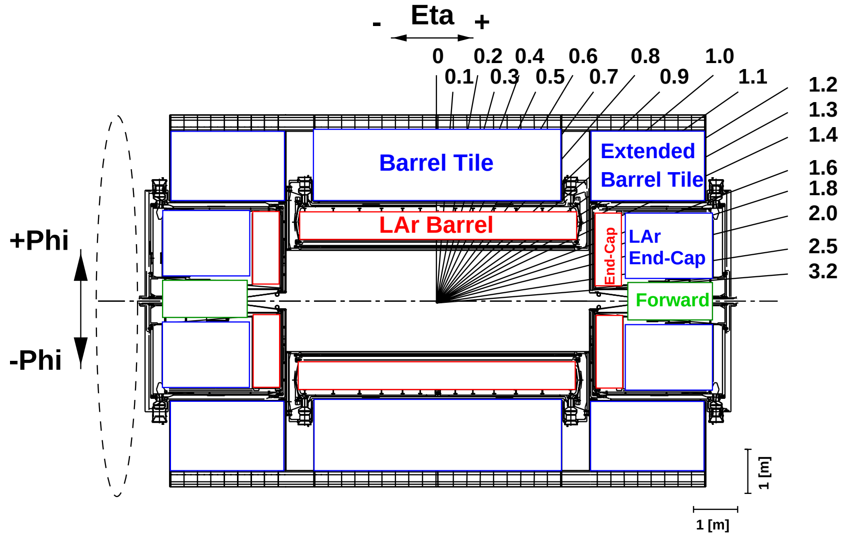
- **Same, except for no ROIs**

ATLAS Level-1 Trigger

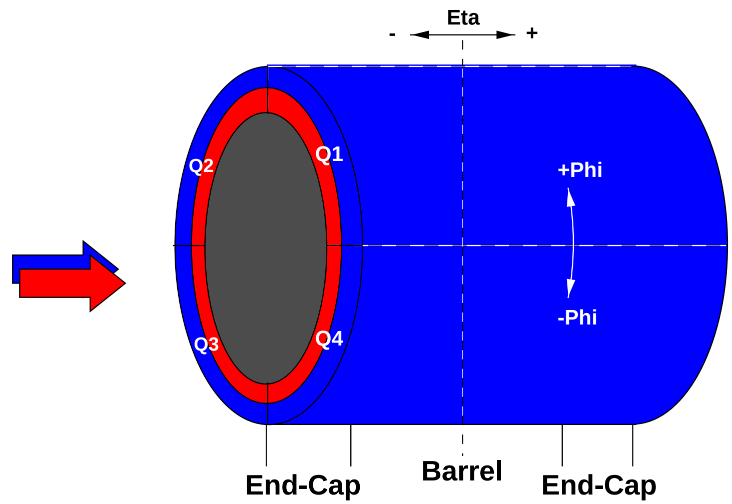


ATLAS Calorimeter

Atlas calorimetry



Mapping to Quadrants in Phi



- Trigger tower Matrix:

Eta x Phi = 0.1 x 0.1 |Eta| < 2.5

Variations up to |Eta| < 4.9

- Optimise fan-out between modules:

Phi/Quadrant architecture, only one-slot connections

- Each quadrant is mapped into:

2 Preprocessor crates,
1 Cluster Processor crate and
1 Jet Energy-Sum Processor crate.

ATLAS L1 Calorimeter Trigger

Preprocessor (PPr)

Cluster Processor

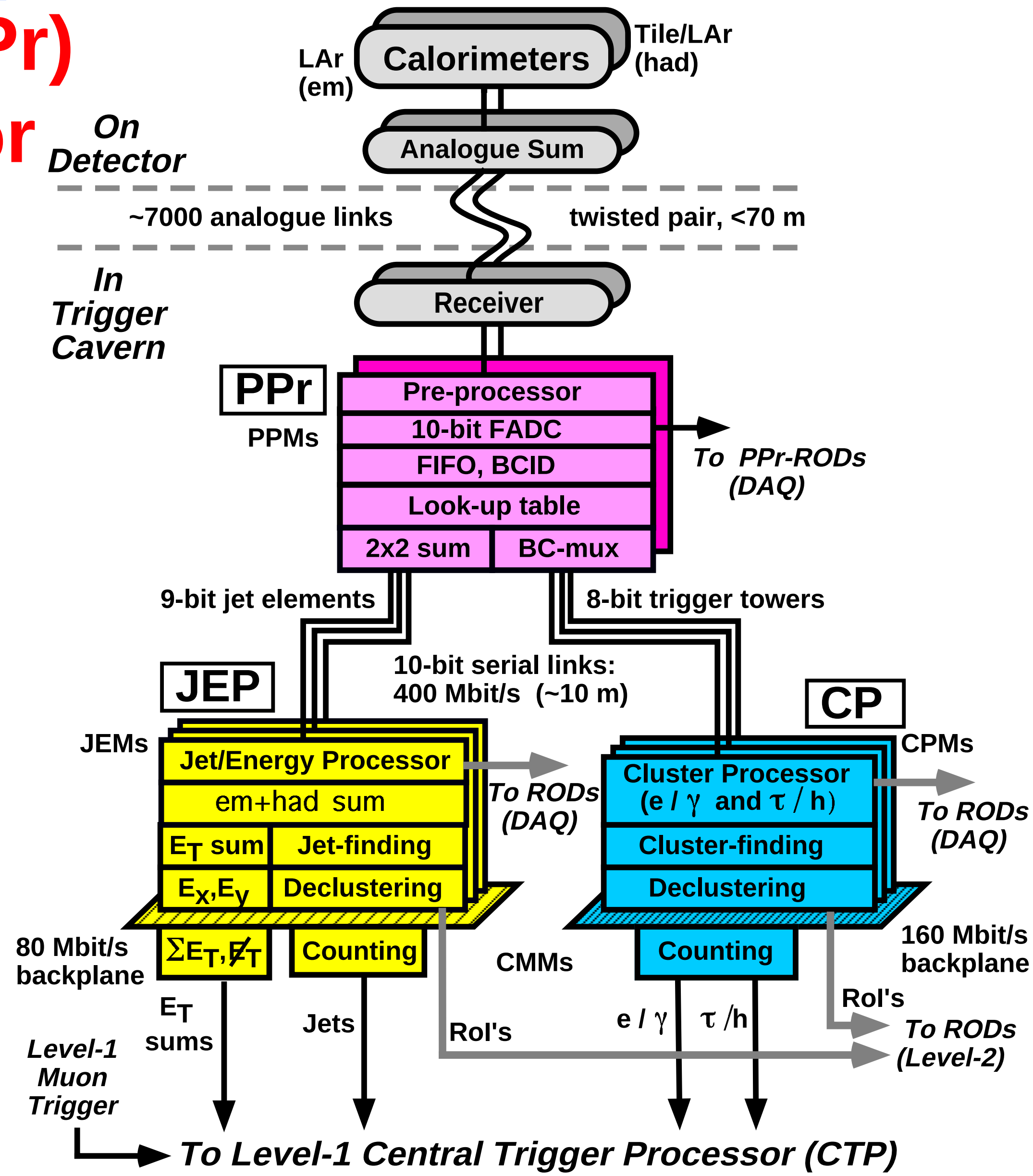
- Electron/Photon
- Hadron/Tau

Jet/Energy Sum Processor (JEP)

- Jet
- Missing-E_T
- Total Scalar E_T

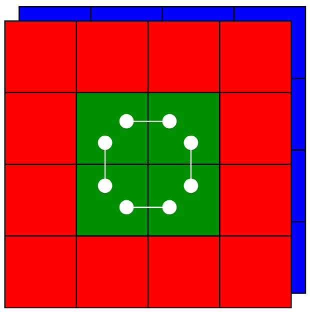
Output

- Central Trigger Processor
- Level-2 Regions of Interest

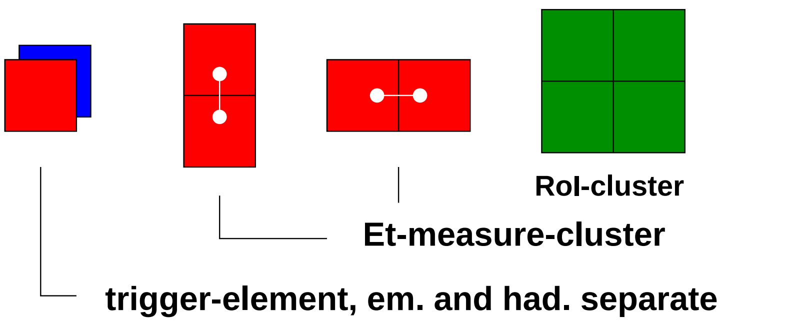


ATLAS L1 Electron & Tau Triggers

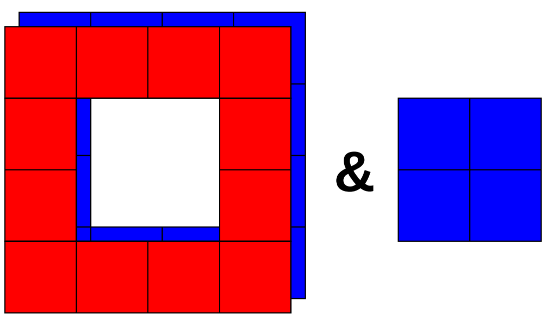
Electron/photon trigger



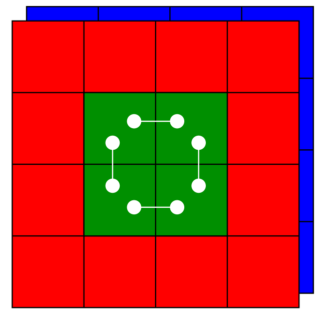
4 x 4 window
0.1 x 0.1 elements
step by 1 element
|Eta|<2.5



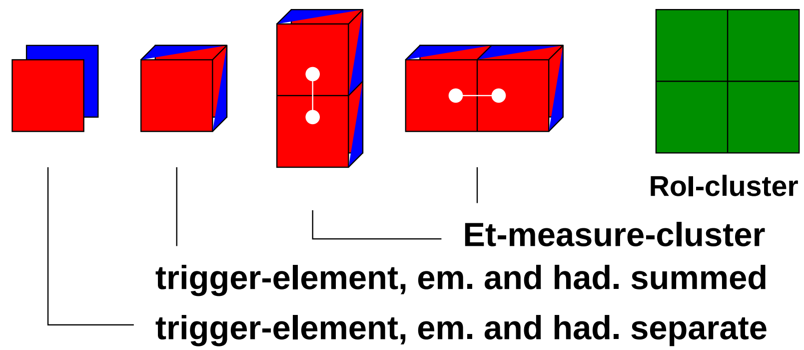
Isolation:



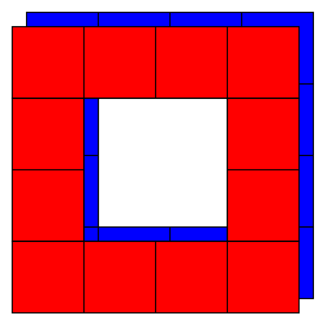
Hadron/tau trigger



4 x 4 window
0.1 x 0.1 elements
step by 1 element
|Eta|<2.5

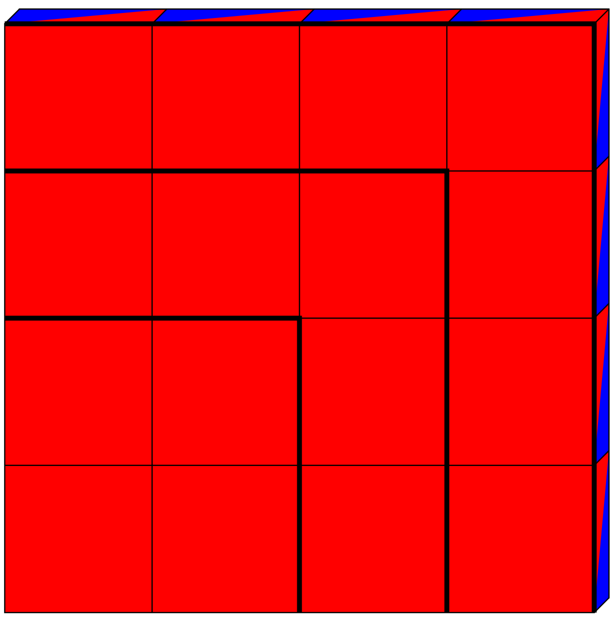


Isolation:

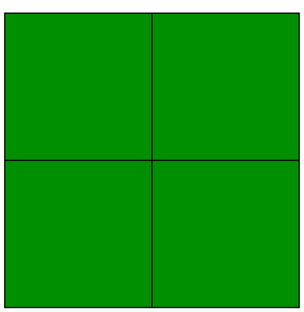


ATLAS L1 Jet & Et-miss Triggers

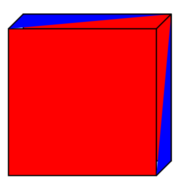
Jet trigger



programmable
4 x 4 or 3 x 3 or
2 x 2 window
0.2 x 0.2 jet-elements
step by 1 jet-element
|Eta| < 3.2

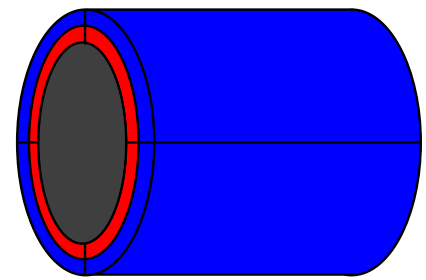


RoI-cluster



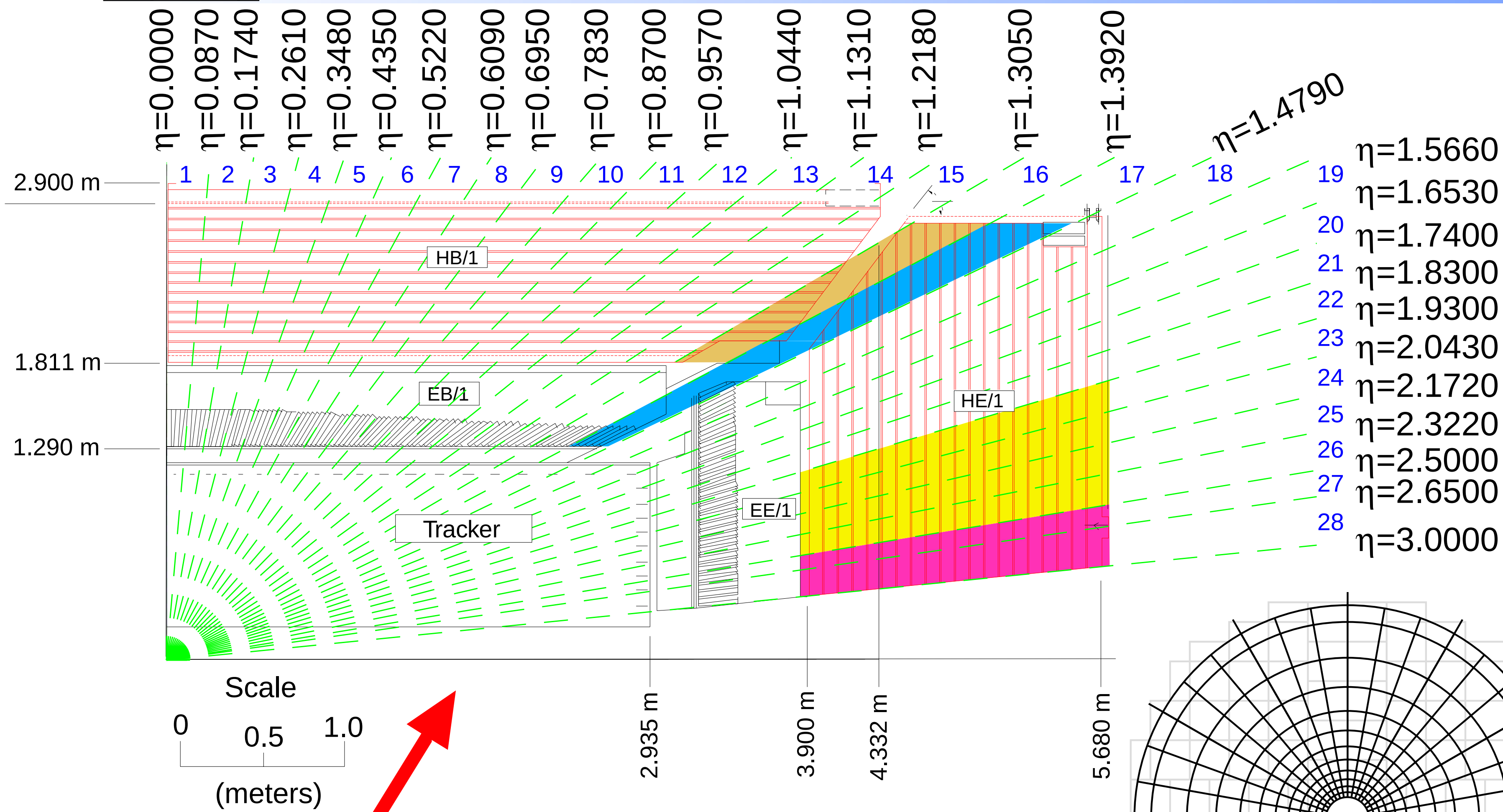
Jet-element, em. + had. summed

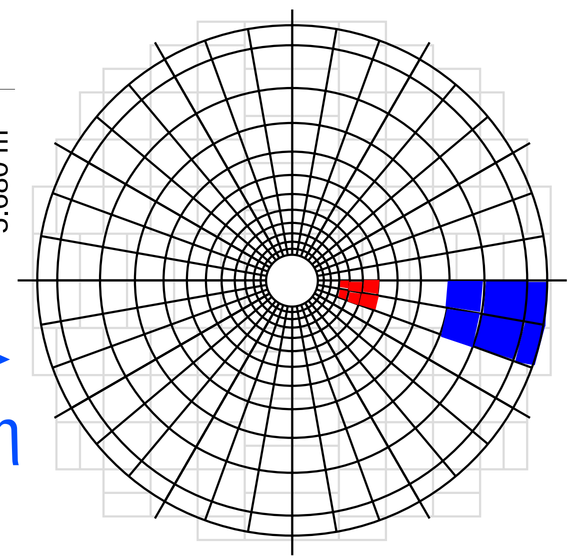
Et-miss / sum-Et trigger



sum of Et
sum of Ex and Ey
|Eta| < 4.9

CMS Calorimeter Geometry

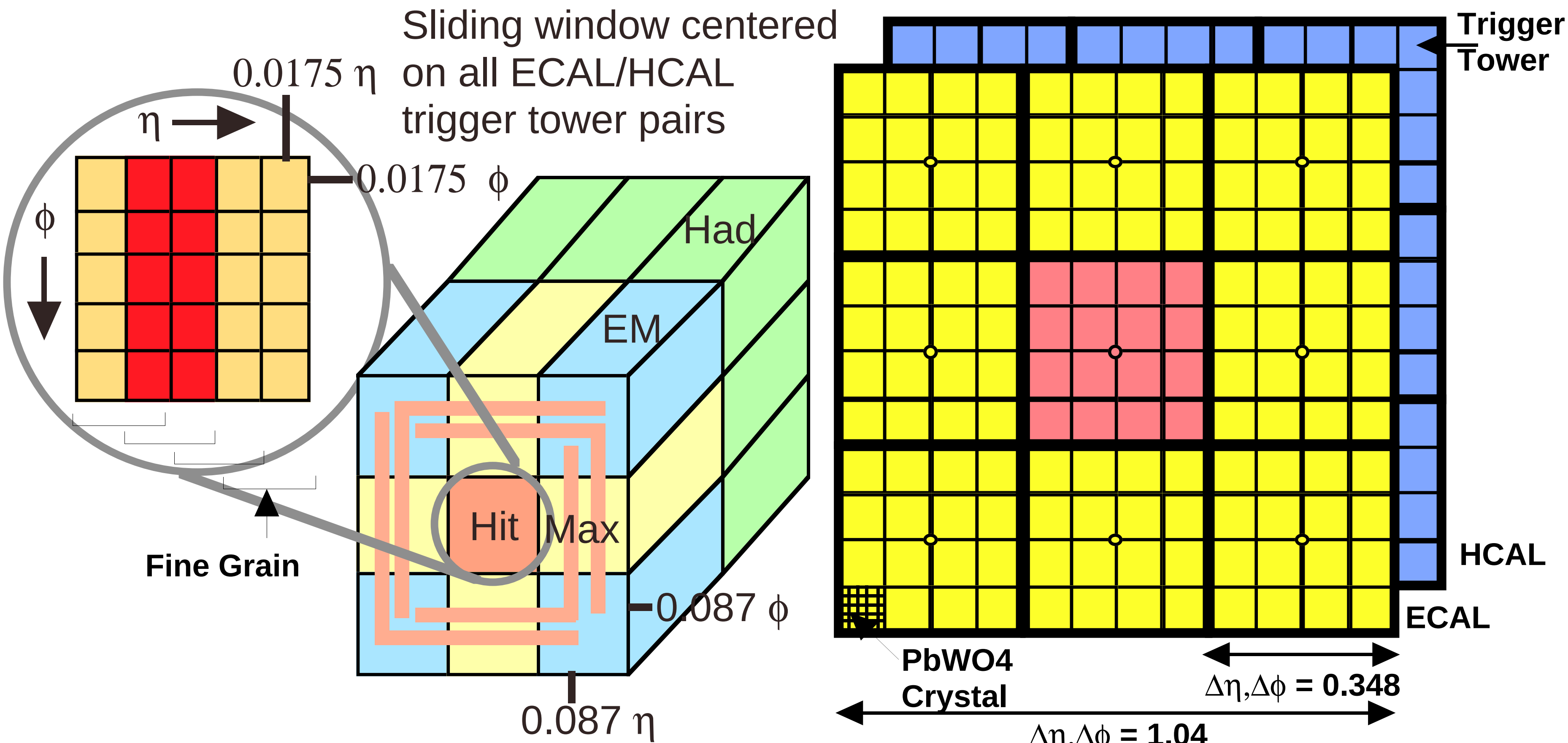




Barrel & Endcap:
E & H: 72 ϕ x 56 η
(|η| < 3.0)

Forward:
H only: 18 ϕ x 4 η
(3.0 < |η| < 5.0)

Cal. Trigger Algorithms



Electron

- **2-tower ΣE_T + H/E**

Isolated Electron

- **2x5-crystal strips>90% energy in 5x5 (Fine Grain)**
- **Neighbor EM + Had Quiet**

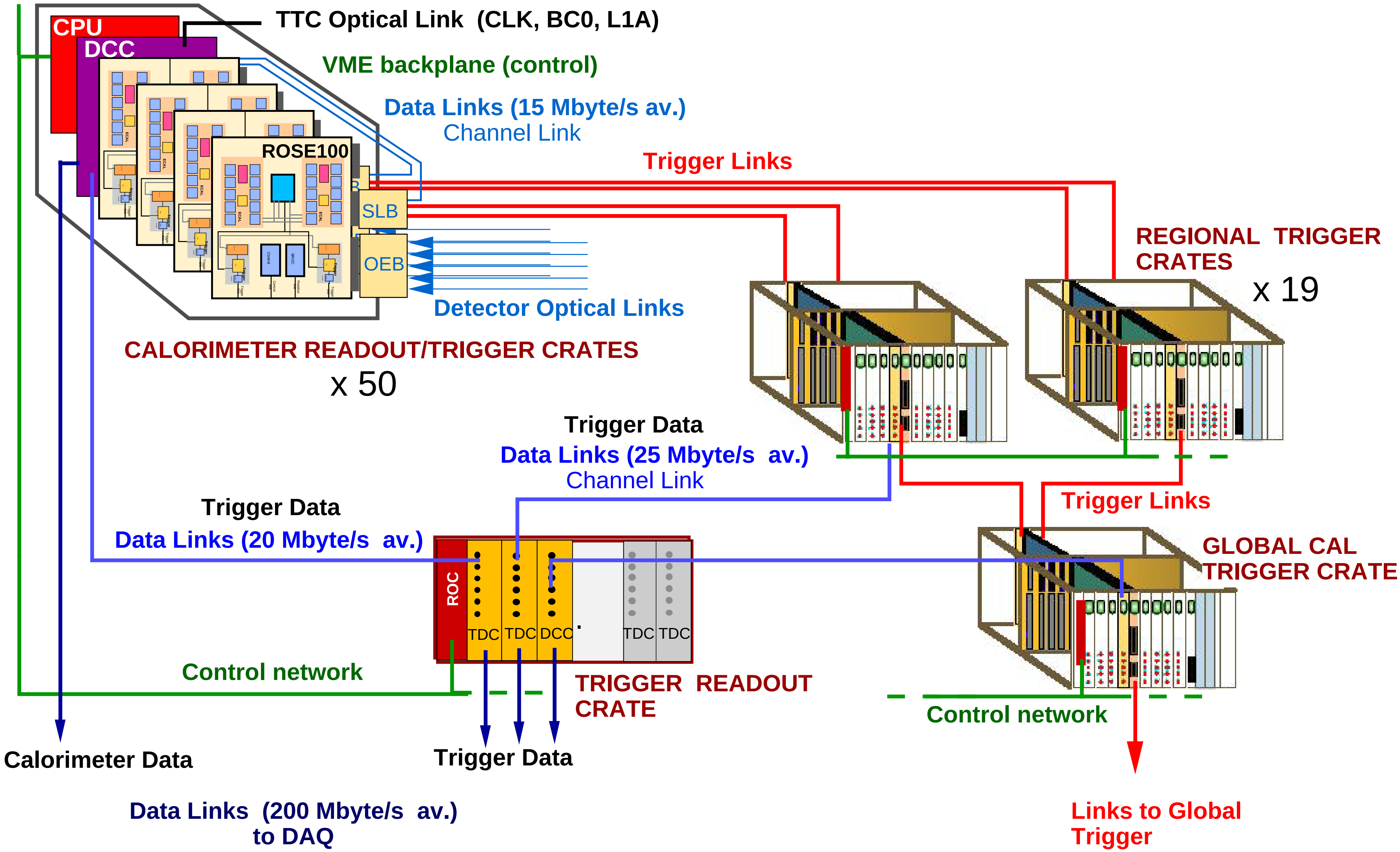
Jet or τ E_T

- **12x12 trig. tower ΣE_T sliding in 4x4 steps w/central 4x4 > rest**

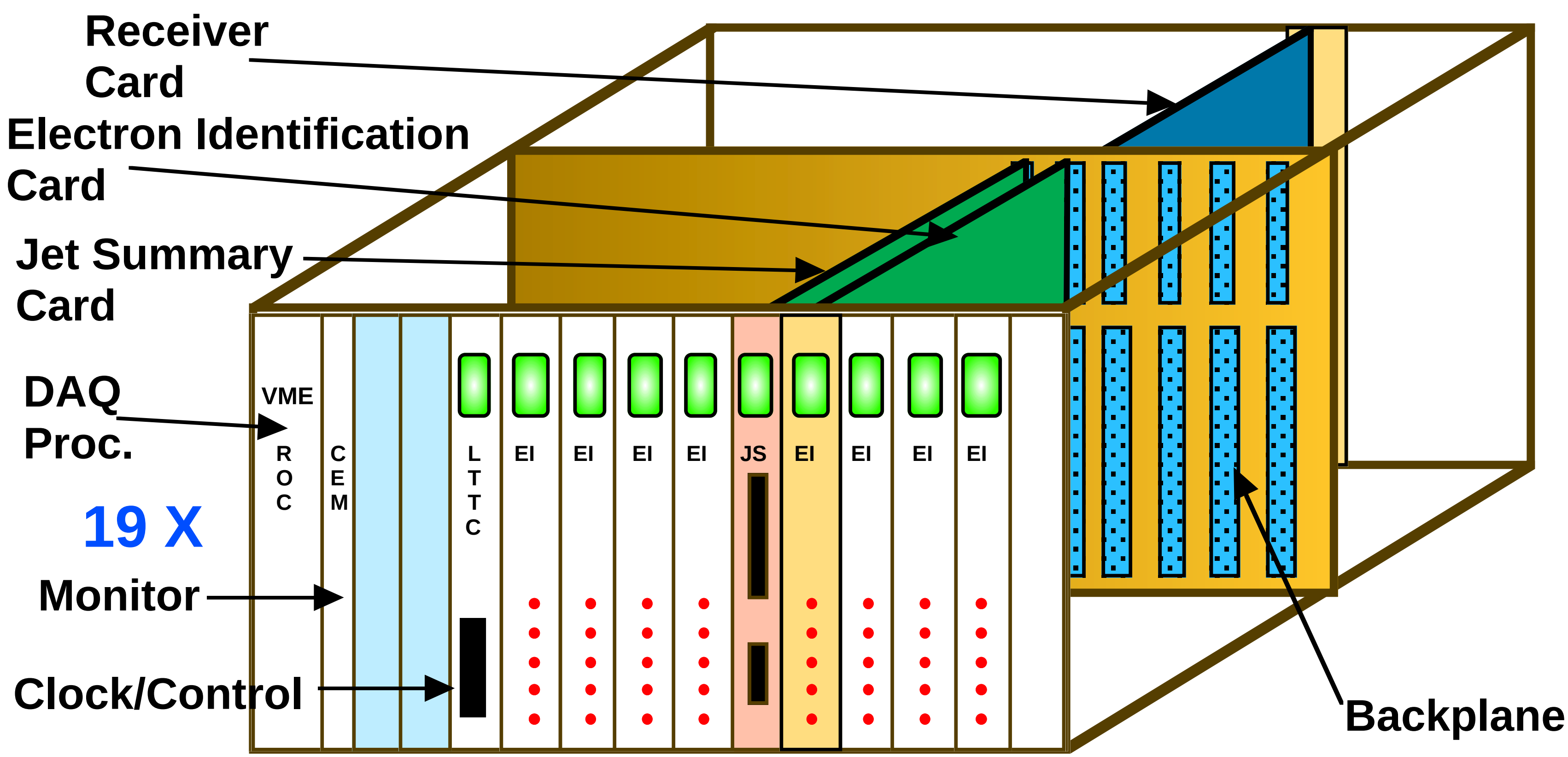
τ algorithm (isolated narrow energy deposits)

- **Call Jet τ if all 9 4x4 region τ-vetoes off**
- **τ-veto: > 2 active E or H towers in 4x4**

CMS Cal. Trig. & Readout Layout



CMS Regional Calorimeter Crate



Data from calorimeter FE on Cu links @ 1.2 Gbaud (ptyp. tstd.)

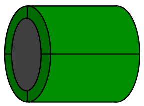
- Into 133 rear-mounted Receiver Cards **(ptyp. tstd. w/ ASICs)**

160 MHz point to point backplane (ptyp. tstd.)

- 19 Clock&Control **(ptyp. tstd.)**, 133 Electron ID **(ptyp. tstd.)** 19 Jet/Summary Cards -- all (incl. RC) operate @ 160 MHz

ATLAS Muon System

Resistive-plate chambers (RPCs) for Barrel region



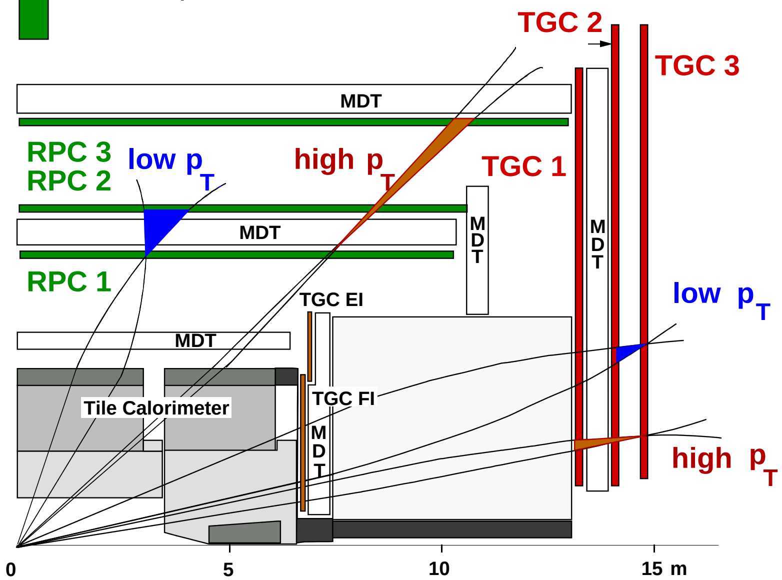
|Eta|<1.05

- Wireless strip detector in Eta & Phi
  easy to cover large area
- 3 stations
- 430,000 channels

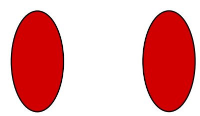
- Measurement of muon trajectories in 3 stations
- Two Pt threshold ranges:

Low-Pt: (6-10 GeV)	3-fold coincidence, 3 thresholds
High-Pt: (8-35 GeV)	3-fold coincidence, 3 thresholds

- Signal processing on detector: 800,000 channels



Thin-gap chambers (TGCs) for End-Caps



1.05<|Eta|<2.4

- Finer granularity needed
  Chambers outside toroidal field
  Trigger stations close together
- Strips in Phi, wires in R
- 3 stations + EI / FI
- High-rate capability needed for backgrounds in forward region
- 370,000 channels

ATLAS L1 Muon Trigger

RPC front-end electronics

RPCs for Barrel
|Eta|<1.05

- ASD processing
- 430,000 chan.
- 55,000 boards

Coincidence Matrix boards

CM ASIC

- 320 MHz ASIC
- find tracks sep. for Eta / Phi
- coincidence
- readout
- 3,328 boards

Pad boards logic
Pad = 0.2 x 0.2

- combines:
  1. Eta with phi
  2. low with high Pt
- assign RoIs of size 0.1 x 0.1
- solve overlaps

~800 optical links

Sector logic
64 sectors

- reduce to sector granularity
- keep 2 highest Pt candidates for each sector

TGC front-end electronics

TGCs for End-Cap
1.05<|Eta|<2.4

- strips in Phi
- wires in R
- ASD processing
- BCID in patch p.
- 370,000 chan.

Slave Boards Coincidence:

- Eta & Phi separ.
- Includes low Pt
- FPGA / ASIC
- readout

High-Pt boards

- coincidence for high Pt only
- readout
- assign RoIs of size 0.1 x 0.1

~600 optical links

Sector logic
144 sectors

R-Phi Coincidence

- keep 2 highest Pt candidates for each sector

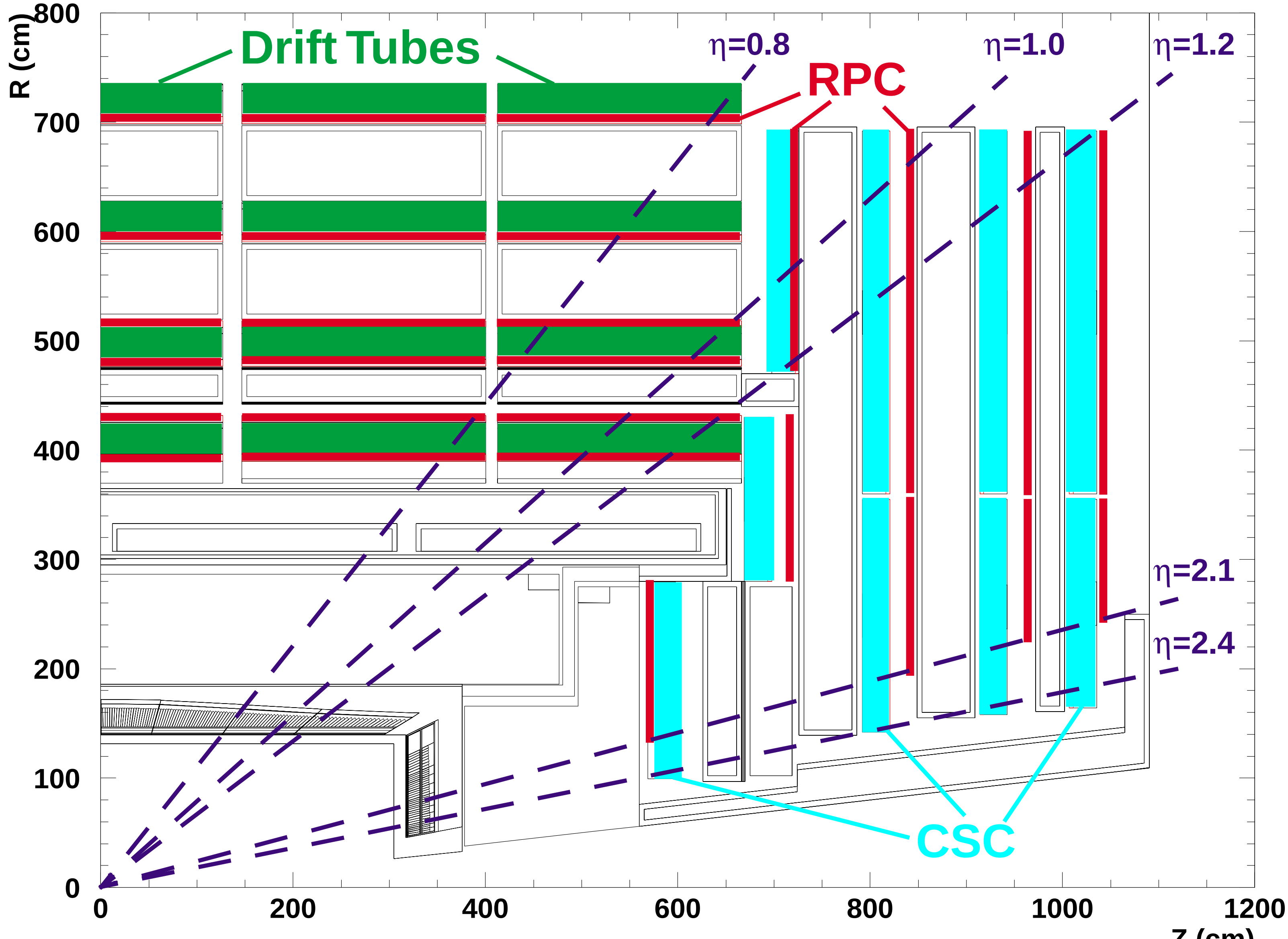
MUCTPI

- combine sector results for 6 thresholds
- multiplicity
- declustering of overlap
- readout
- FPGA implemented

multiplicity of μ-candidates for 6 thresholds

RoI data to LVL-2

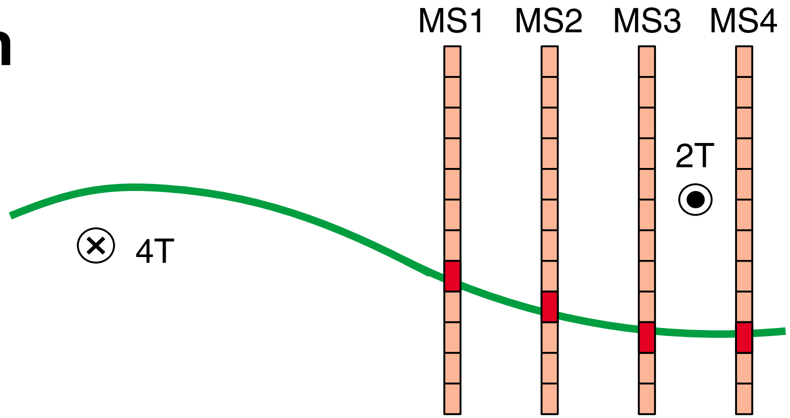
CMS Muon Trigger Geometry



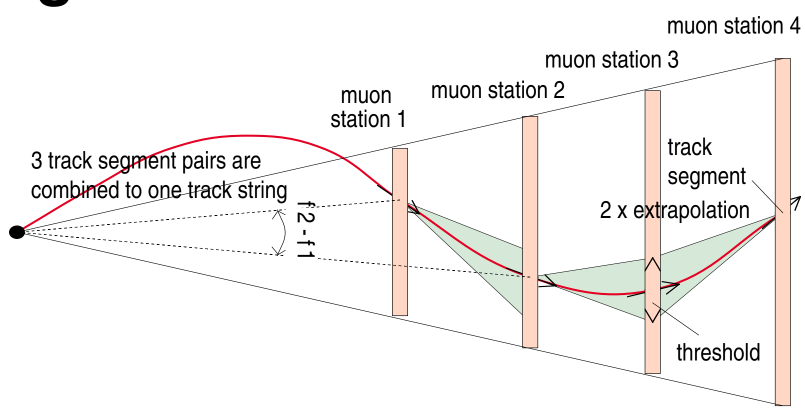
4 Stations in the barrel and each endcap

CMS Muon trigger system

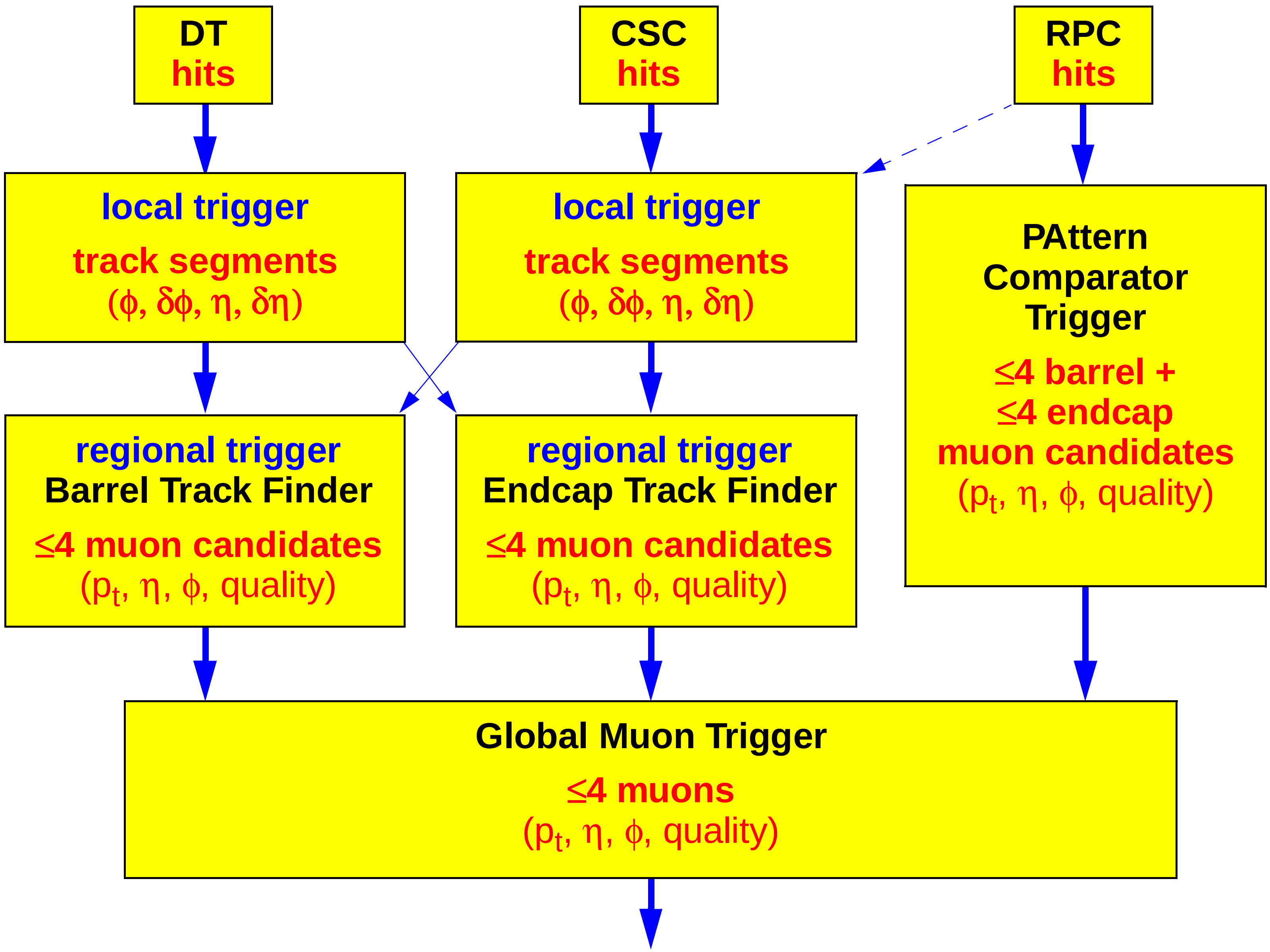
RPC pattern recognition
- Pattern catalog
- Fast logic



DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value

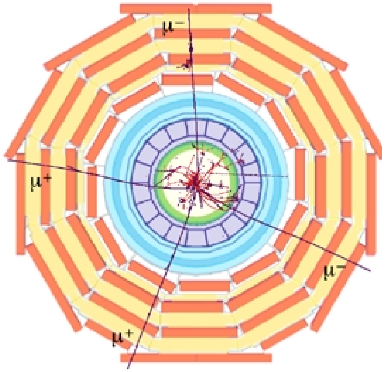


CMS Muon Trigger Overview

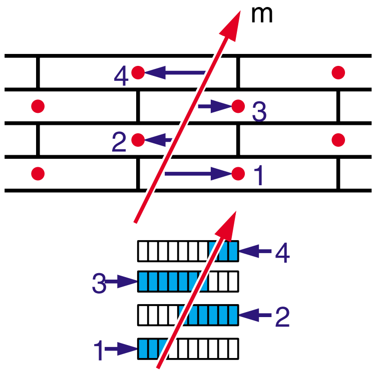


CMS muon tracker finders

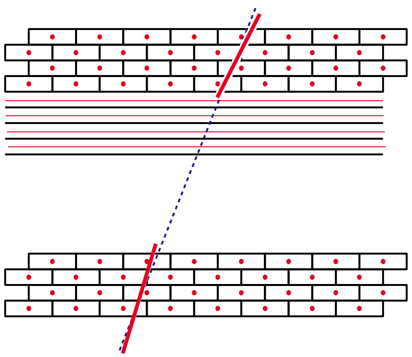
Drift Tubes (DT)



Drift Tubes



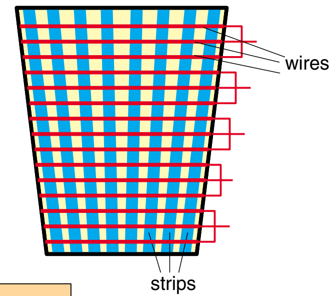
Meantimers recognize tracks and form vector / quartet.

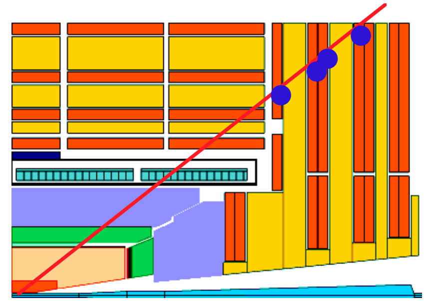


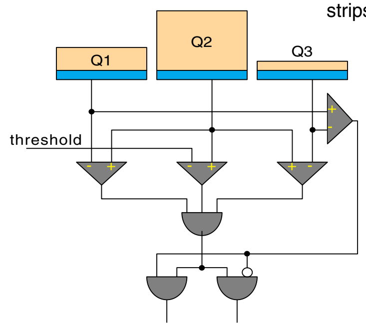
Correlator combines them into one vector / station.

Cathod Strip Chambers (CSC)

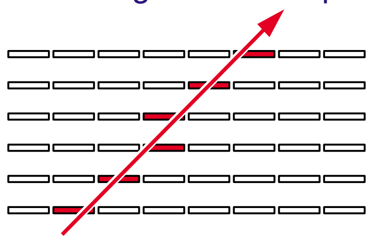
CSC





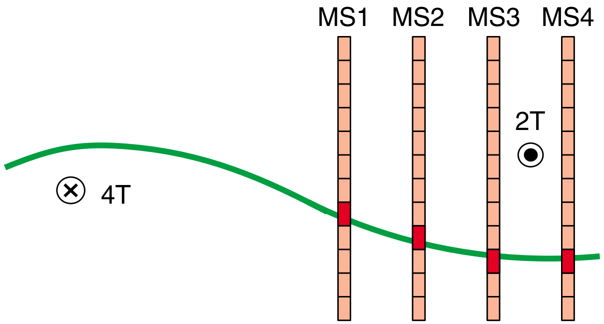


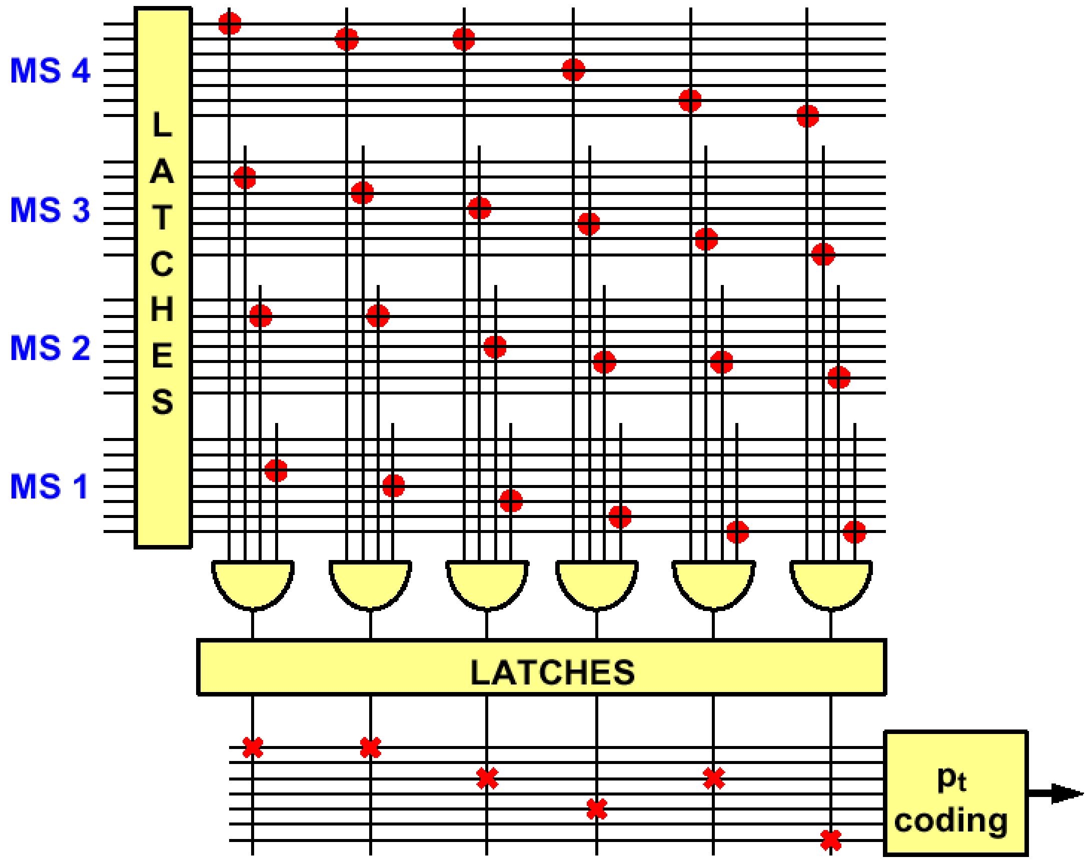
Comparators give 1/2-strip resol.



Hit strips of 6 layers form a vector.

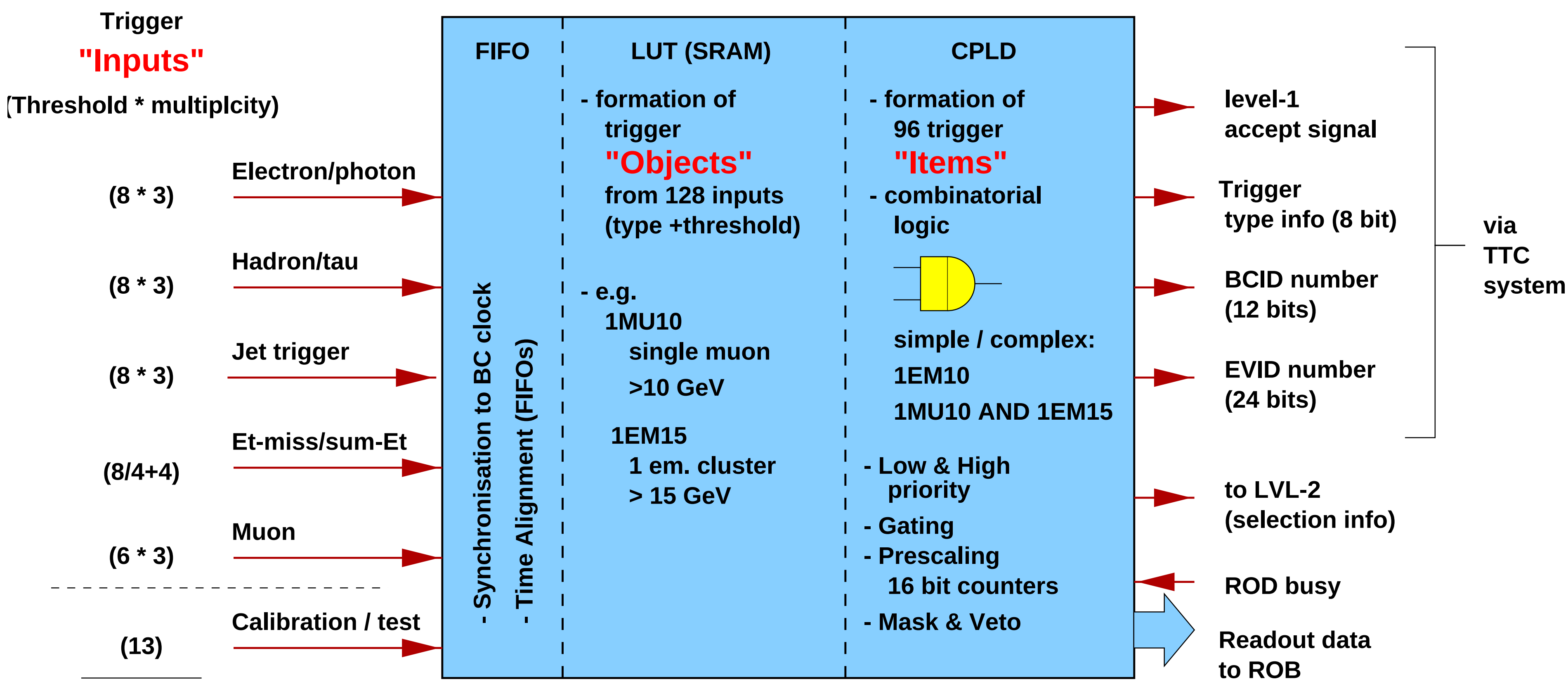
RPC muon trigger (CMS)





PRINCIPLE: pattern of hit strips is compared to predefined patterns corresponding to various pt

ATLAS L1 Central Processor



119 bits
(128 foreseen)

- Latency
  < 4 BC (100ns)
- 1 printed circuit board

- Dead time handling
  - peak: 0-16 dead BC following trigger (4 are normal)
  - average: 1-32 triggers in 0-1.7 ms (8 in 80 us are normal)

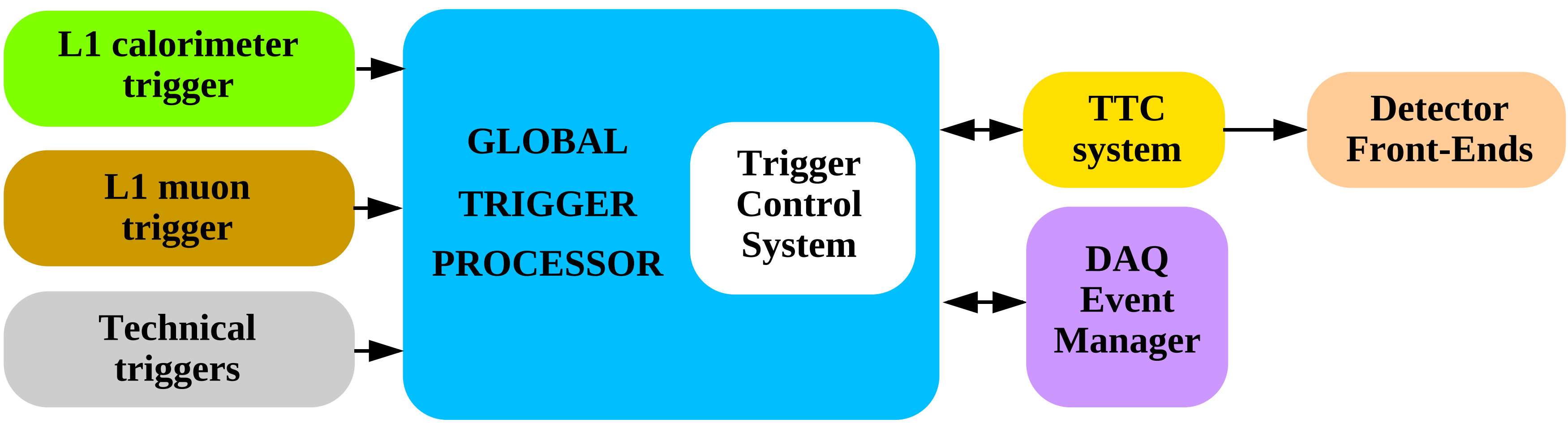
CMS Global Trigger

Input:

- Jets: 4 Central, 4 Forward, 4 Tau-tagged, & Multiplicities
- Electrons: 4 Isolated, 4 Non-isolated
- 4 Muons (from 8 RPC, 4 DT & 4 CSC w/P_t & quality)
  - All above include location in η and ϕ
- Missing E_T & Total E_T

Output

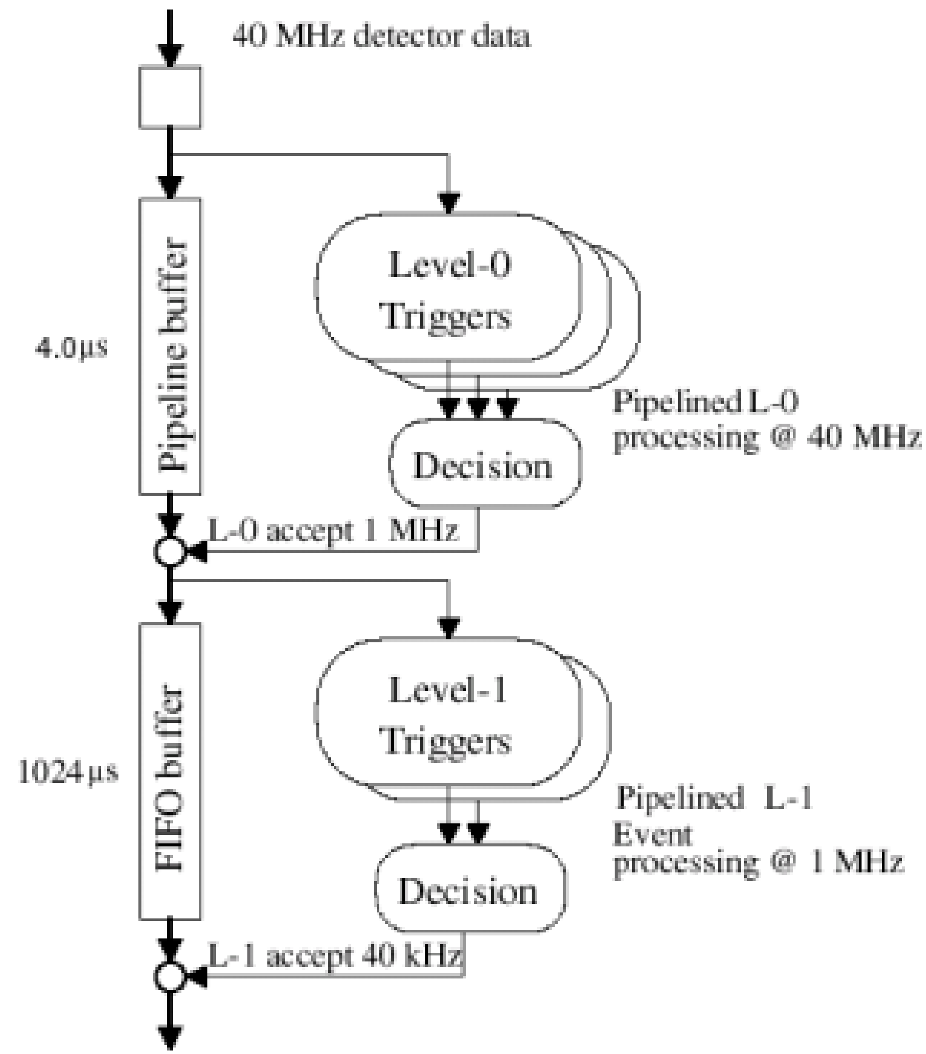
- L1 Accept from combinations & proximity of above



LHCb Trigger

◆ Two hardware levels

- Level 0 reduces the rate to 1 MHz in 4 µs
  - Select high P_T particles
  - Reject multiple interactions
- Level 1 reduces the rate to 40 kHz in 1000 µs
  - Identification of a secondary vertex
- DAQ input at 40 kHz

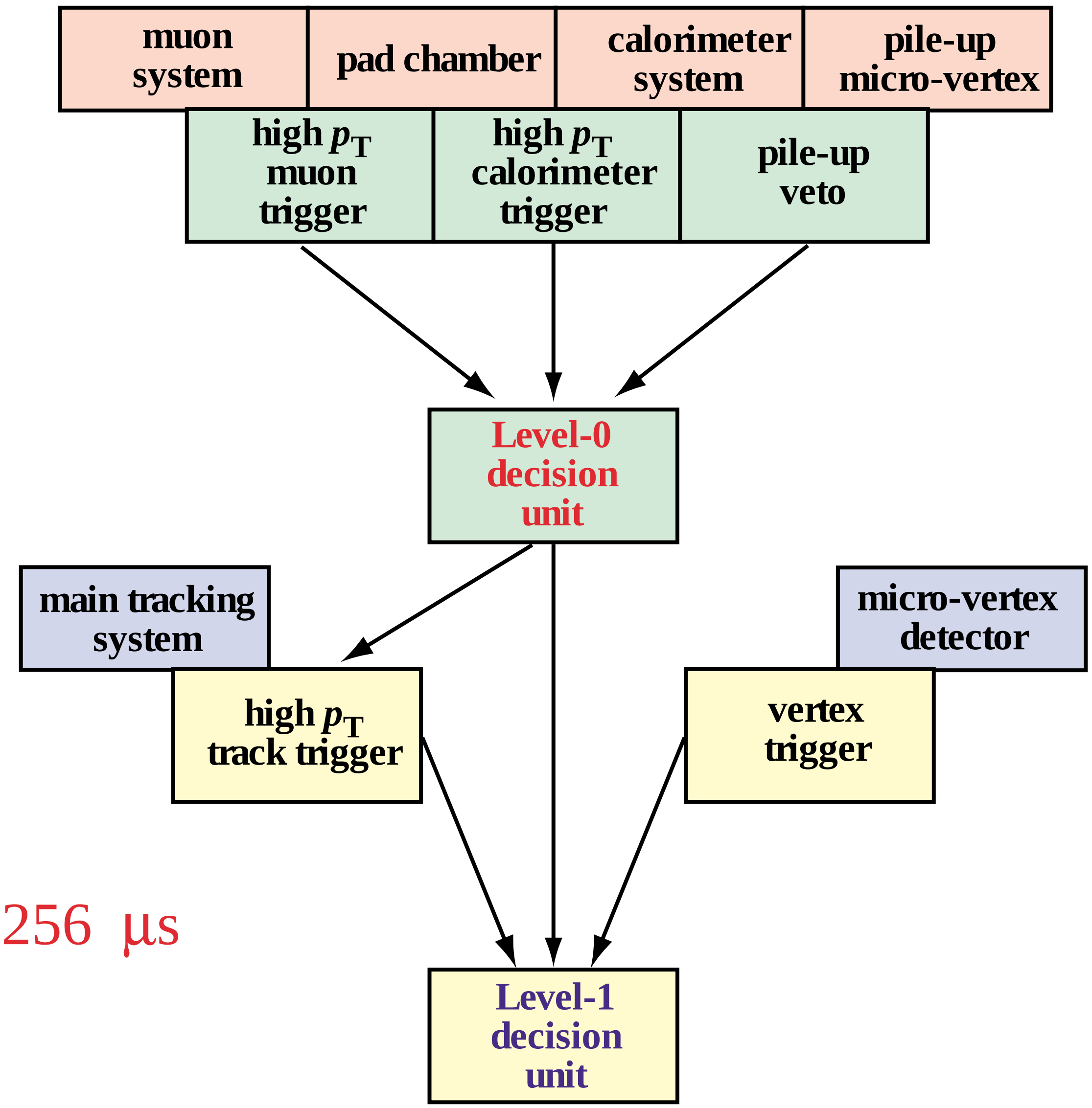


◆ Software filtering

- Two software filtering stages to reduce the rate to 200 Hz

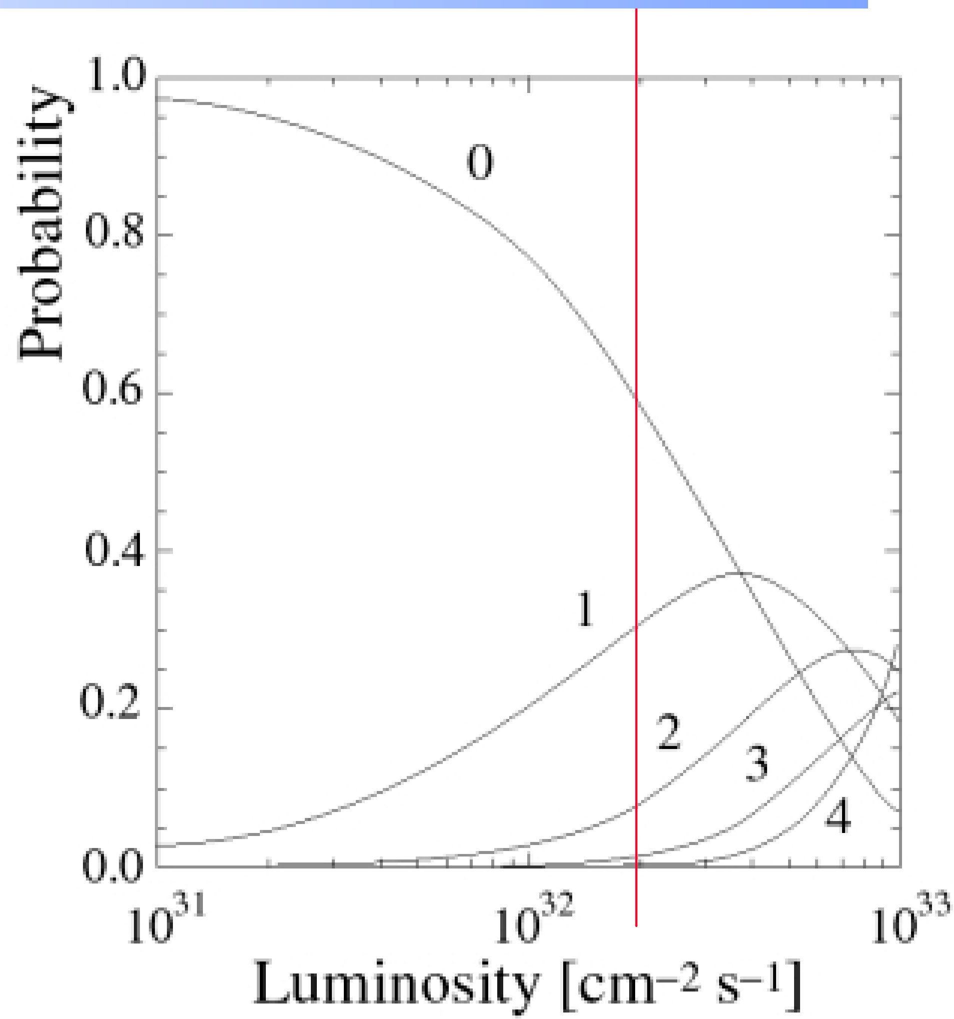
LHCb Level 0 & Level 1

- Level-0
  - Calorimeter triggers
  - Muon trigger
  - Pile-up veto
- Level-1
  - Vertex trigger
- Basic requirements
  - Level-0 latency < 3.2 μs, rate reduction to < 1 MHz
  - Level-1 latency variable < 256 μs (average 120 μs), rate reduction to < 40 kHz

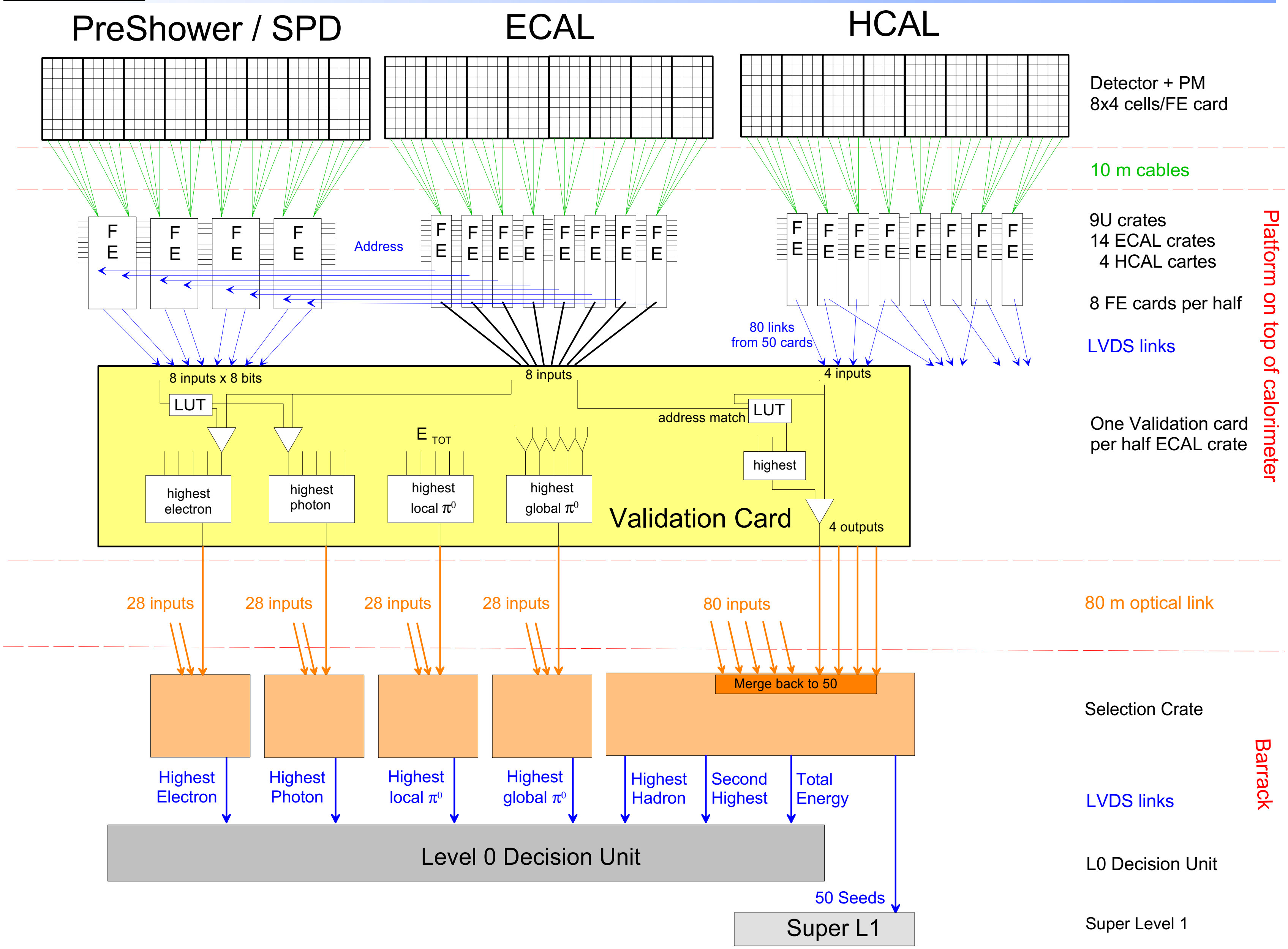


LHCb Level 0

- LHC repetition rate 40 MHz
  - But only ~76 % have colliding bunches at LHCb
- LHCb works at 'low' luminosity, to have a single interaction per crossing
  - Nominally 2 x10^{32} $cm^{-2}s^{-1}$
  - Double and multiple interactions are rejected as soon as possible, using a pile-up VETO at Level 0
- Rate of interaction:
  - Single : 9.4 MHz
  - Multiple : 3.0 MHz
- Accepted rate 1 MHz
  - Factor 10 reduction on single interactions
  - In fact a bit more as multiple interactions are not all vetoed.



LHCb Calorimeter Trigger



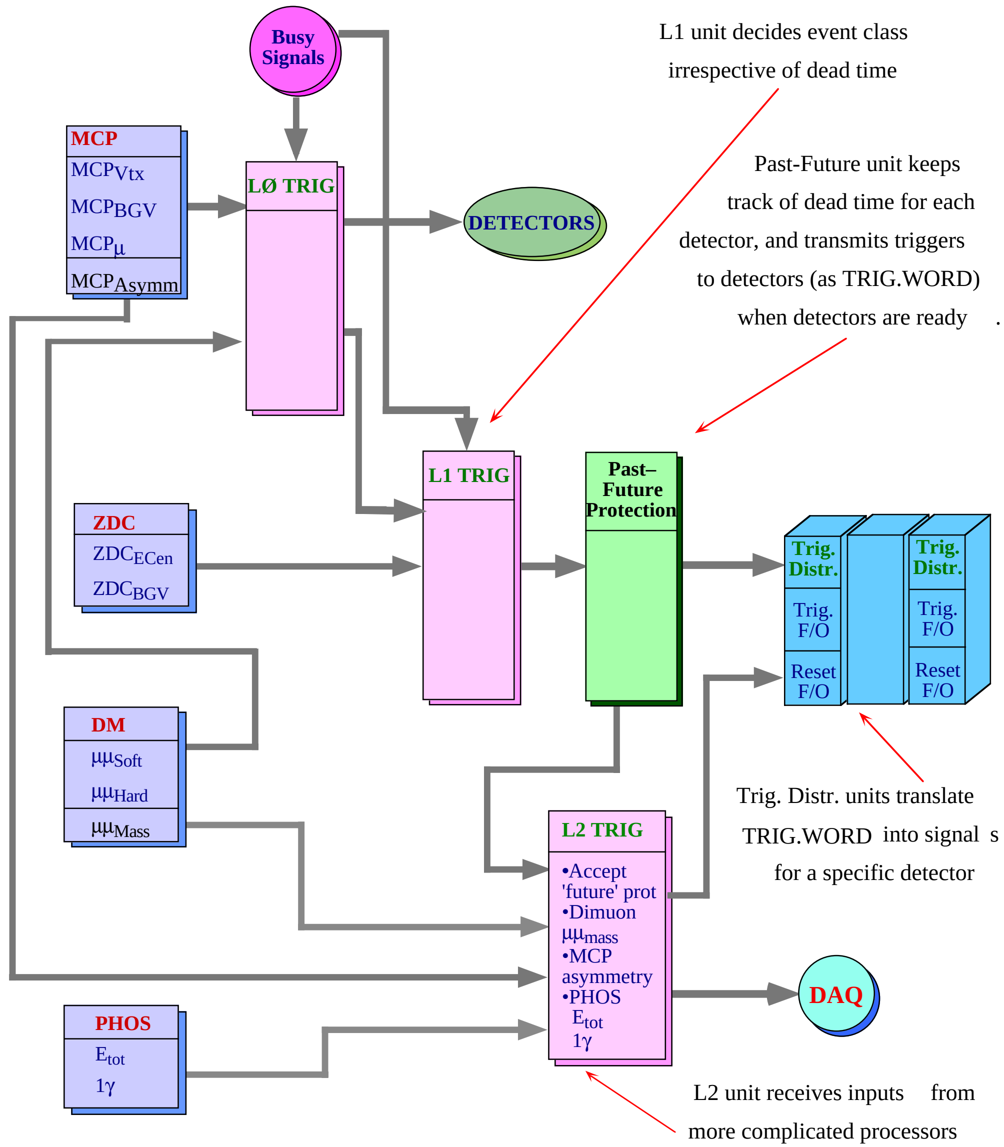
Alice vs. ATLAS & CMS

- ***ALICE is very different from CMS and ATLAS!***

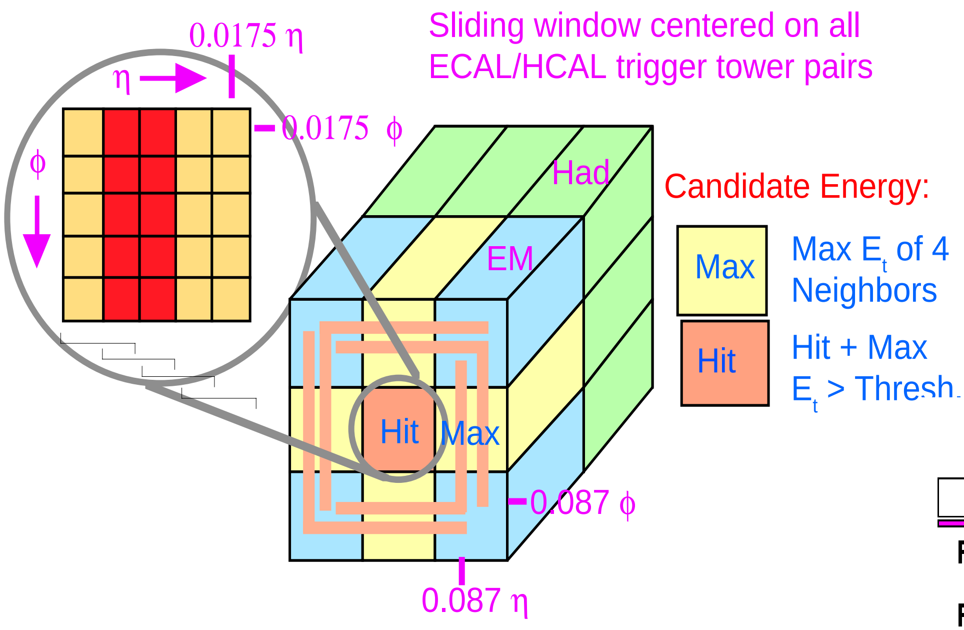
	ALICE			CMS/ATLAS
	Pb–Pb	*Ca–Ca*	*p–p*	*p–p*
Bunch-crossing period (ns)	125	125	25	25
$\mathcal{L}$ (cm^{-2} s^{-1})	10^{27}	3×10^{27} 10^{29} (μμ)	10^{30}	10^{34}
σ minimum bias (barn)	8	3	0.1	0.1
d*N*(charged)/dη	8000	1200	8	8 (×18)
Minimum bias rate (Hz)	8000	8000 3×10^{5} (μμ)	10^{5}	10^{9}
Level-1 trigger rejection	10^{-1}			10^{-4}
Event storage rate (Hz)	40 1000 (μμ)	150 1000 (μμ)	1000	100
Event size (bytes)	33–39 M 0.25 M (μμ)	5–6 M 0.1 M (μμ)	0.5 M	1 M
Data storage rate (bytes/s)	10^{9}			10^{8}
Data storage (bytes/yr)	10^{15}			10^{15}

Alice Level 0 & Level 1

- Level-0
  - Minimum-bias trigger
  - Dimuon trigger
- Level-1
  - Centrality trigger
- Past–future protection
- Basic requirements (Pb–Pb)
  - Must protect TPC for ±100 μs if pile-up, but can have non-TPC events which read out quickly
  - Level-0 latency < 1.2 μs, rate reduction to ~1 kHz
  - Level-1 latency < 2.7 μs, rate reduction ~factor 2

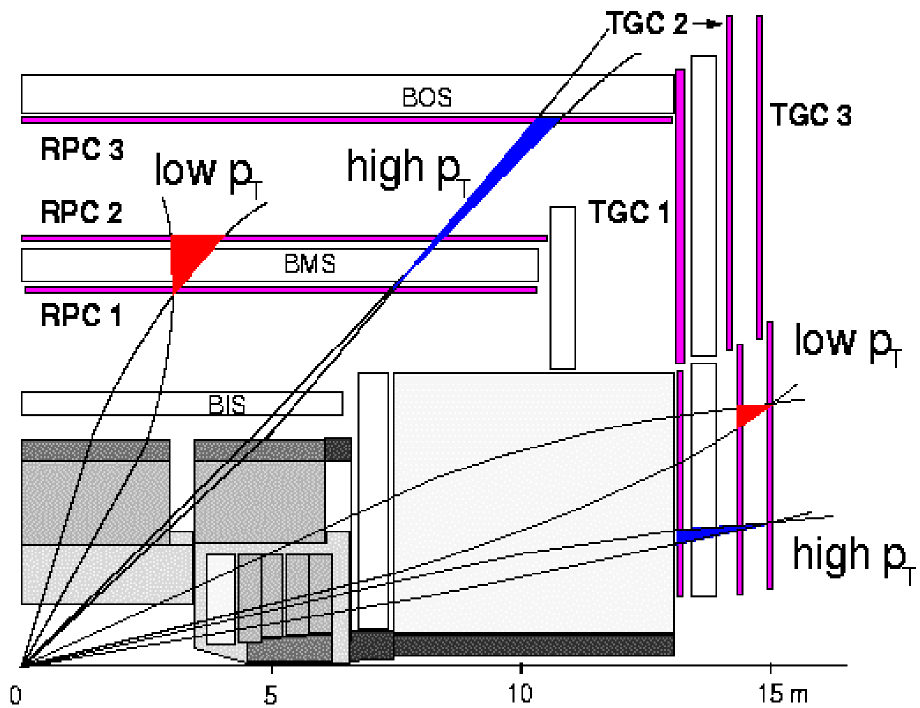


Digital ASICs for Pattern Logic

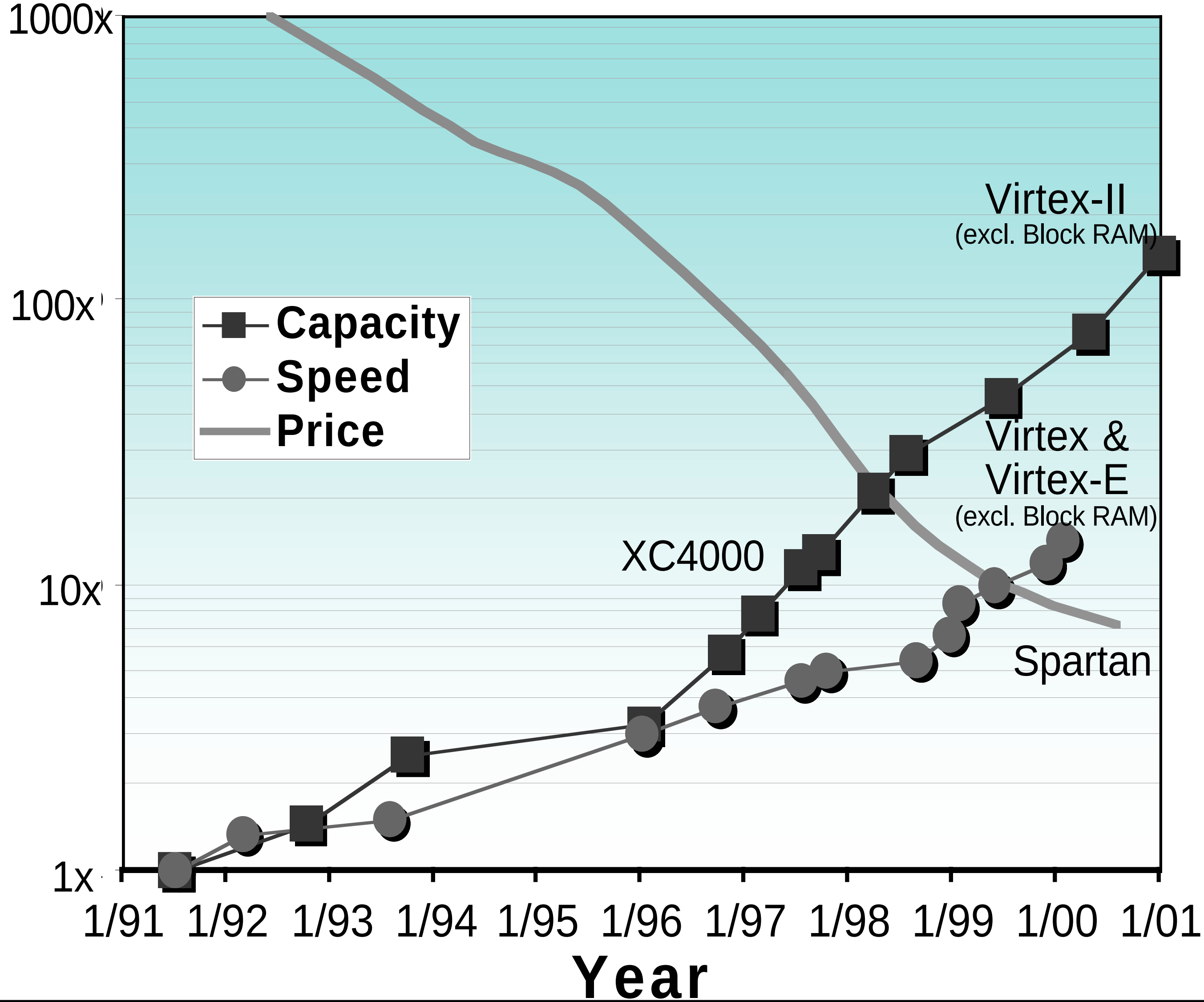


CMS Calorimeter Regional Trigger Electron Isolation ASIC: 160 MHz 0.6 μm high-integration GaAs custom gate array

ATLAS Muon Trigger high & low p_t coincidence logic in 0.6 μm and 0.35 μm CMOS full-custom ASICs



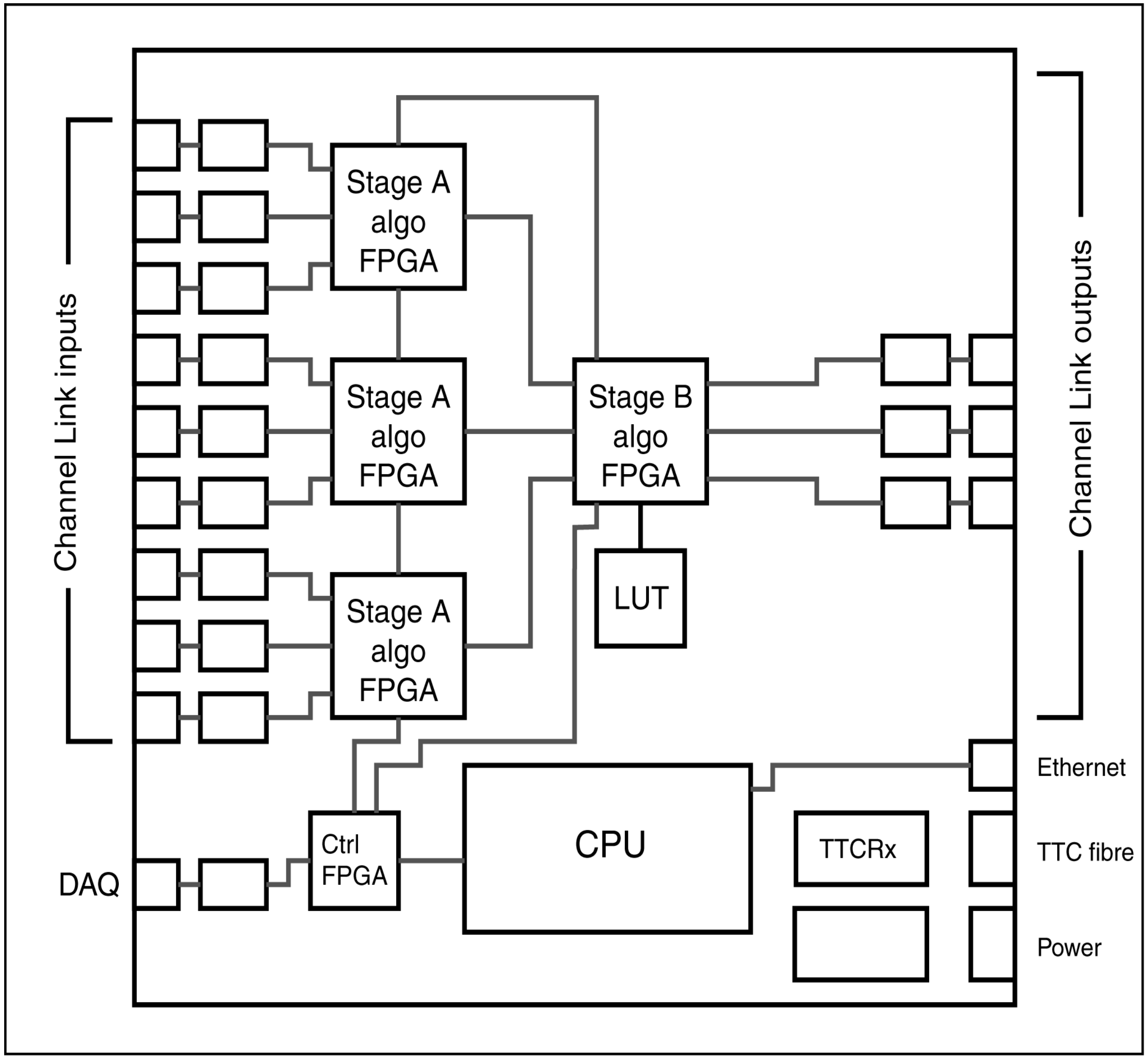
FPGA Revolution



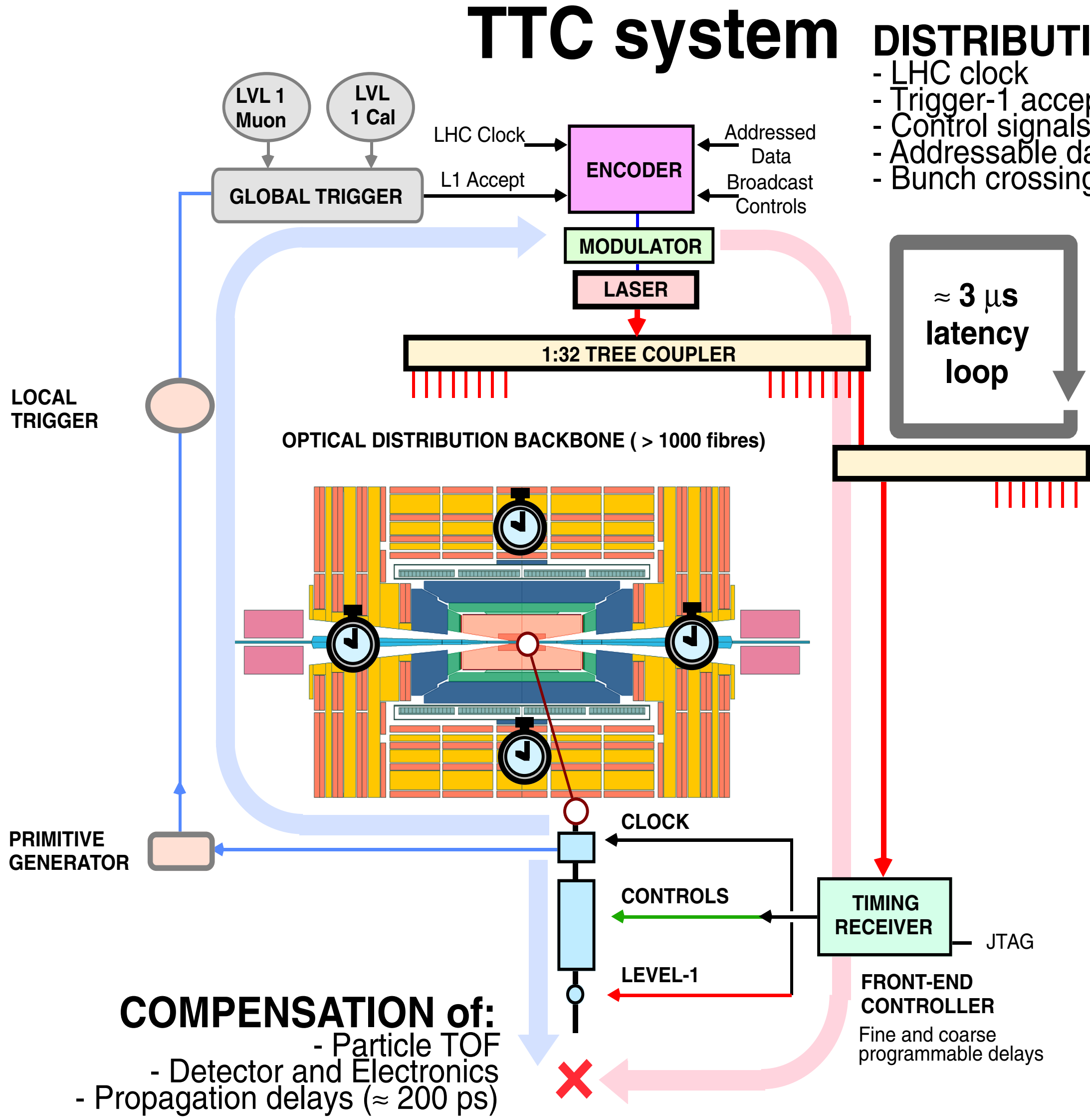
Use of FPGAs

Example:
CMS Cal Global Trig

- Summing
- Sorting
- Selecting
- Monitoring
- Whatever
  - (flexible)



Trigger Timing & Control



DISTRIBUTION of:
- LHC clock
- Trigger-1 acceptance
- Control signals
- Addressable data
- Bunch crossing number

COMPENSATION of:
- Particle TOF
- Detector and Electronics
- Propagation delays (≈ 200 ps)

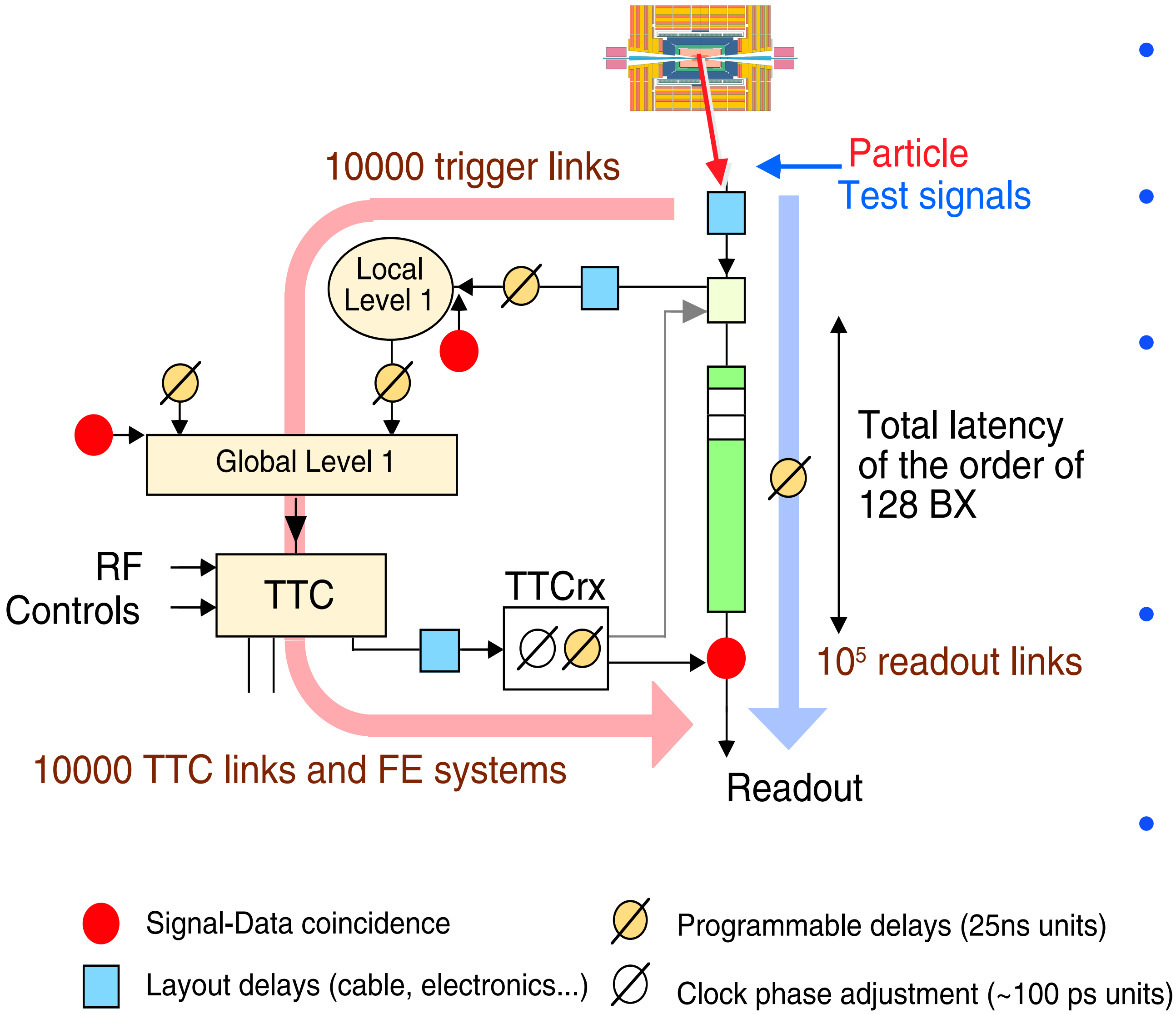
Optical System:

Single High-Power Laser per zone
- Reliability, transmitter upgrades
- Passive optical coupler fanout

1310 nm Operation
- Negligible chromatic dispersion

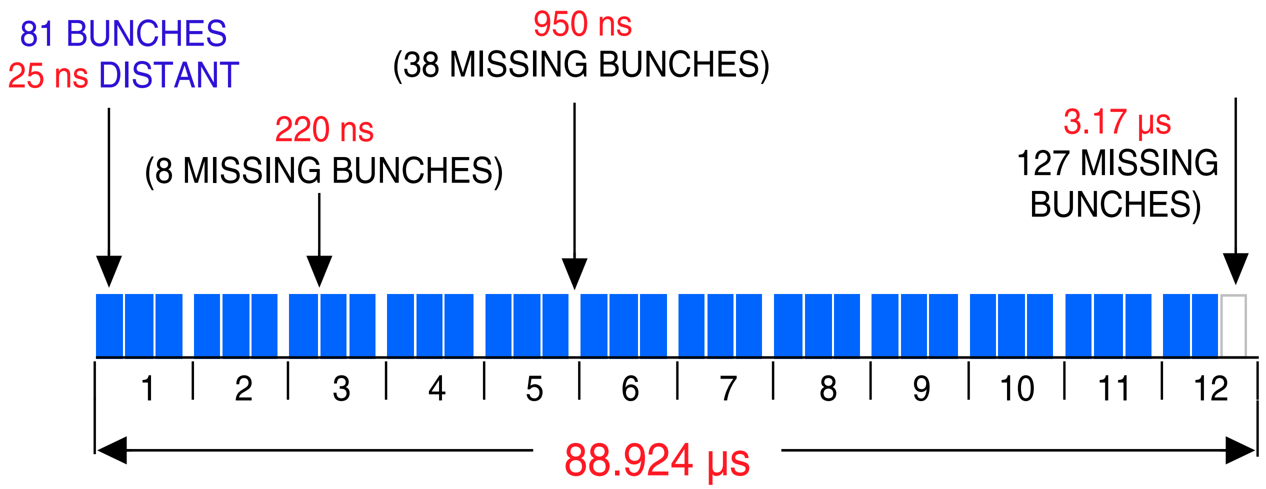
InGaAs photodiodes
- Radiation resistance, low bias

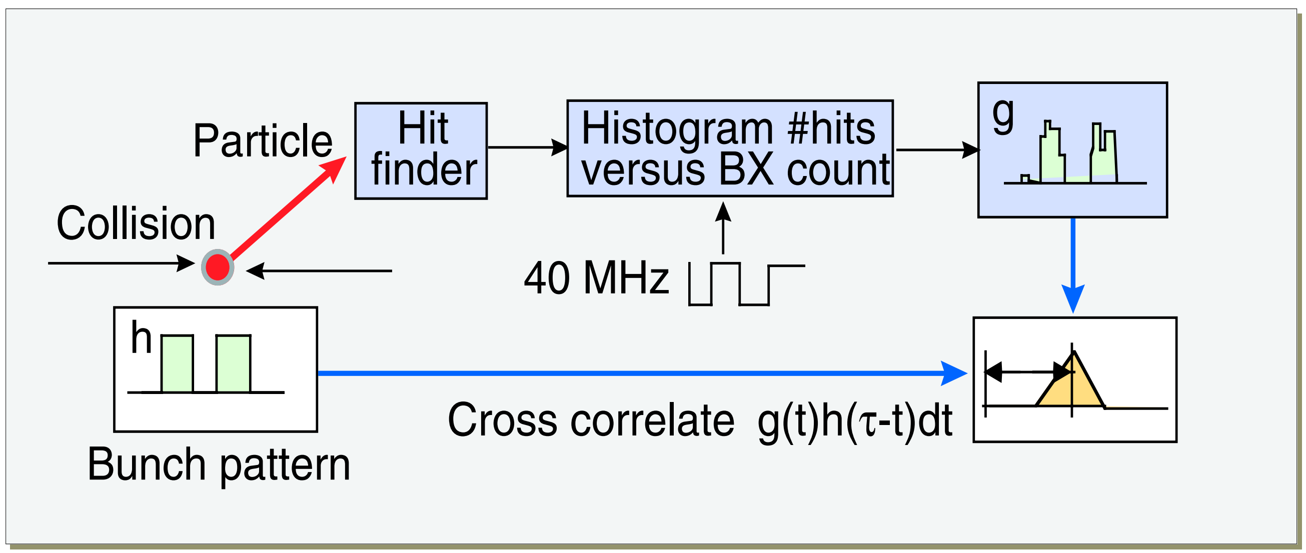
Detector Timing Adjustments



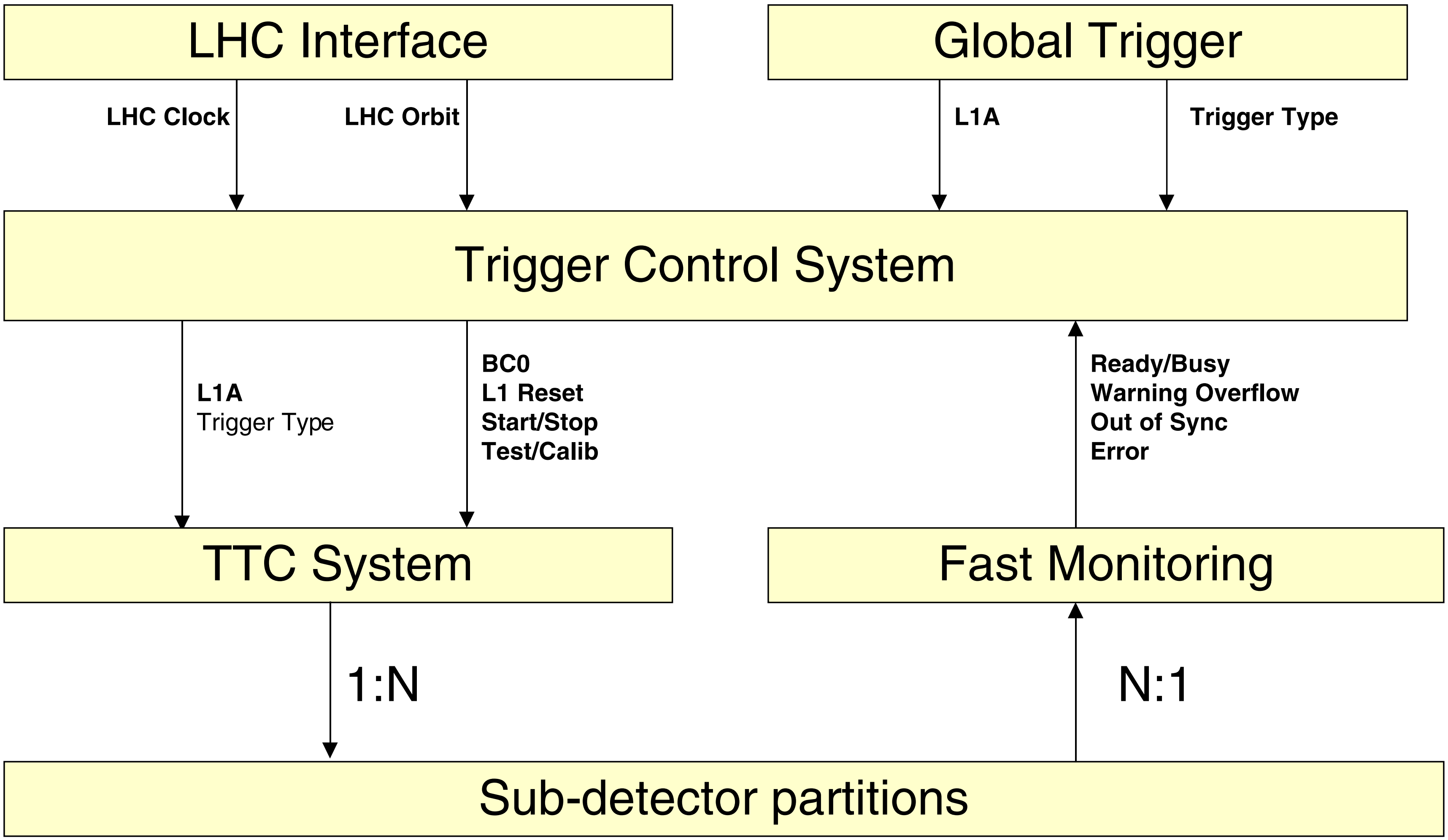
- Detector pulse w/collision at IP
- Trigger data w/ readout data
- Different detector trigger data w/each other
- Bunch Crossing Number
- Level 1 Accept Number

Synchronization Techniques



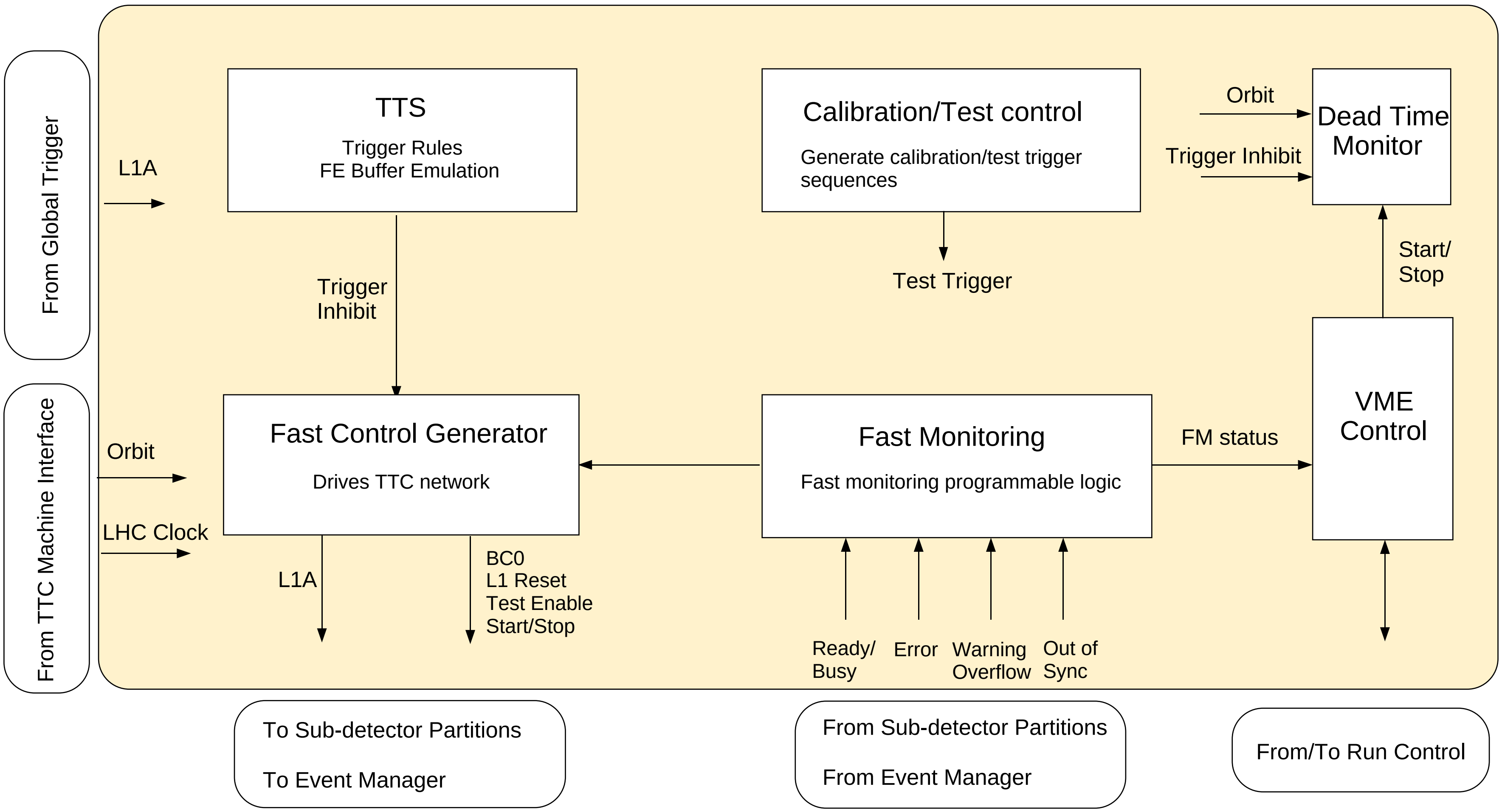


Trigger & Readout Control



CMS Trigger Control

- L1Accept, LHC Clock, Bunch Crossing 0, Calibration Trigger
- Trigger rules prevent overflows. Deadtime is monitored.
- Fast monitoring:Buffer overflow signal starts L1A throttling
- System is divisible into independently operating partitions



LHC Trigger Conclusions

The design challenges of LHC experiments have been met with innovative systems involving:

- Extraction, processing and analysis of 40 Terabits of information per second
- Detailed pattern-recognition of calorimeter & muon chamber signals using pipelined logic with 25-ns steps (or faster)
- Reduction of 1 GHz of interactions to 100 Hz with high efficiency for discovery physics
- Nanosecond-level synchronization of Millions of channels of data
- Use of FPGAs, high-speed digital ASICs, high-speed optical links

Moving from prototypes into system construction in the next ~ 2 years

Acknowledgements

Special Thanks to:

- **Eric Eisenhandler, ATLAS**
  - "Hardware Triggers at the LHC", 1998 LHC Electronics Workshop, Rome.
- **Ulrich Pfieffer, ATLAS**
- **Alexander Walsch, LHCb**
- **Olivier Callot, LHCb**
- **Sergio Cittolin, CMS**
- **Joao Varela, CMS**

Whose slides were used in preparation of this presentation