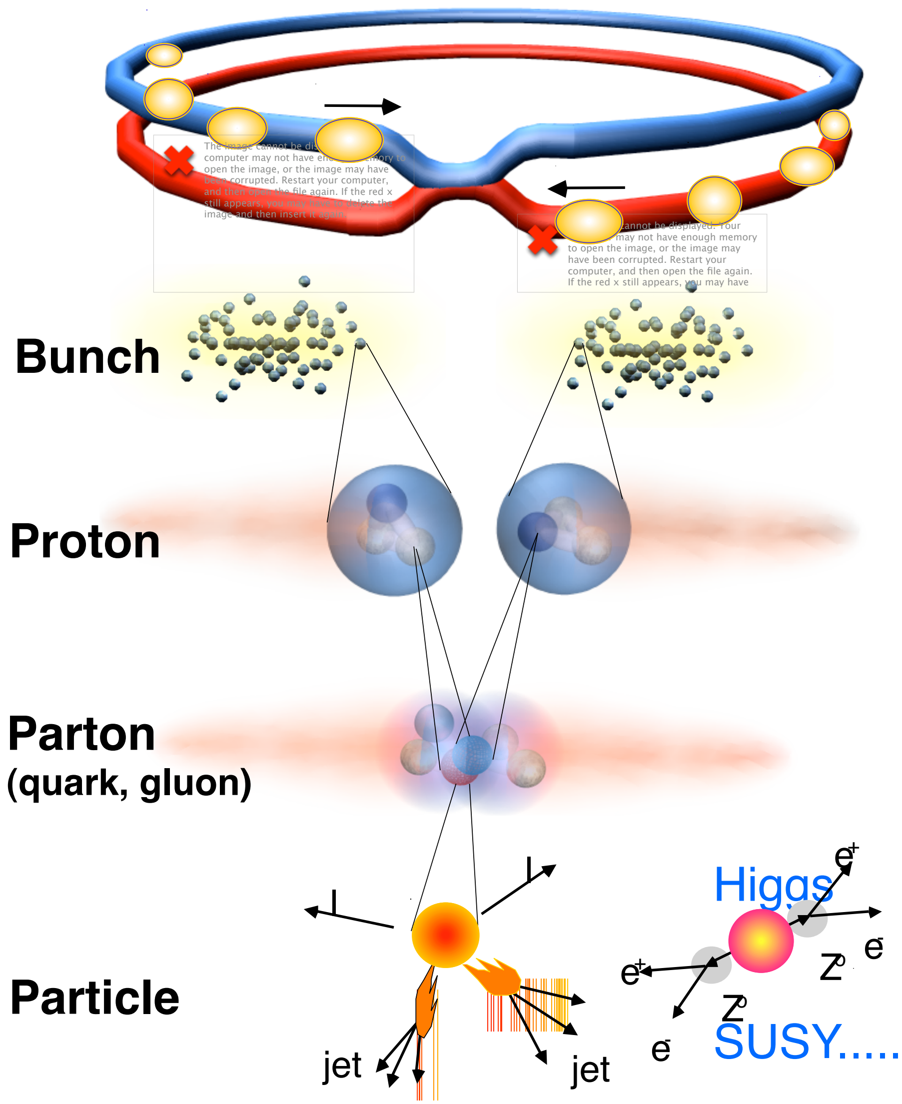
LHC Physics
GRS PY 898 B8

Lecture #3

[Tulika Bose](#)

Trigger & DAQ: Part 1

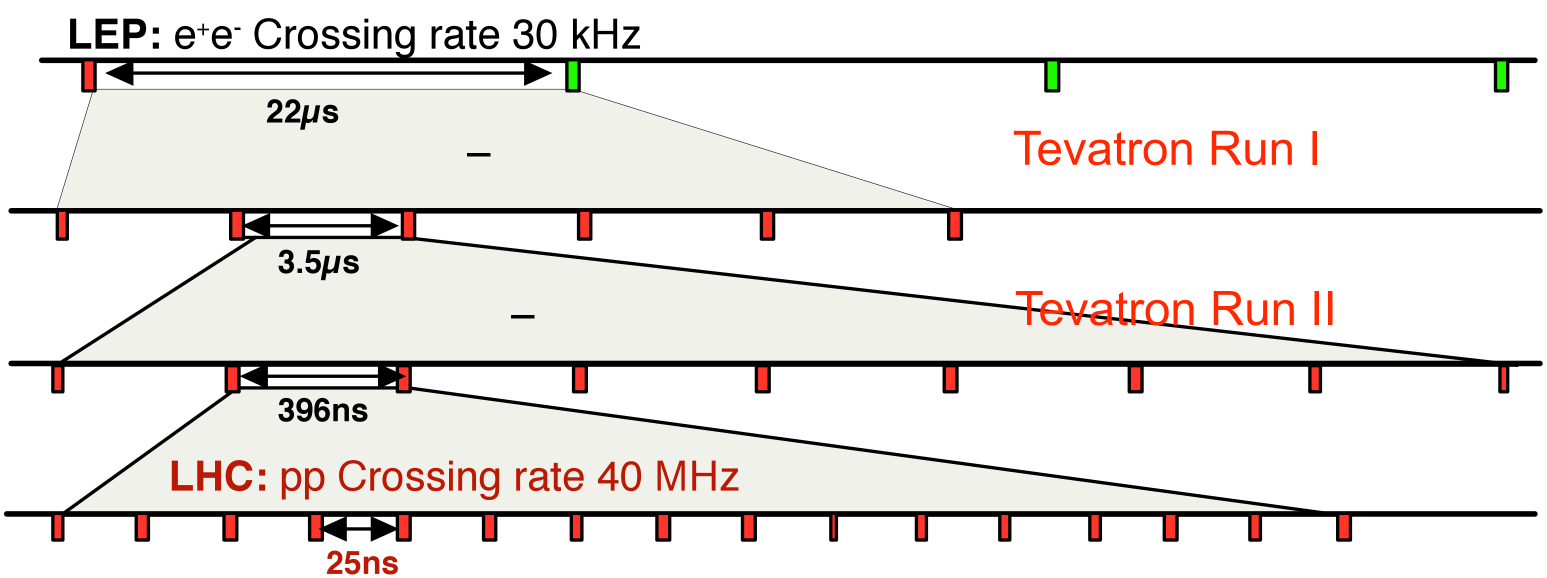
LHC



Proton - Proton	**3564 bunch/beam**
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**$10^{34} cm^{-2}s^{-1}$**

Beam crossings: LEP, Tevatron & LHC

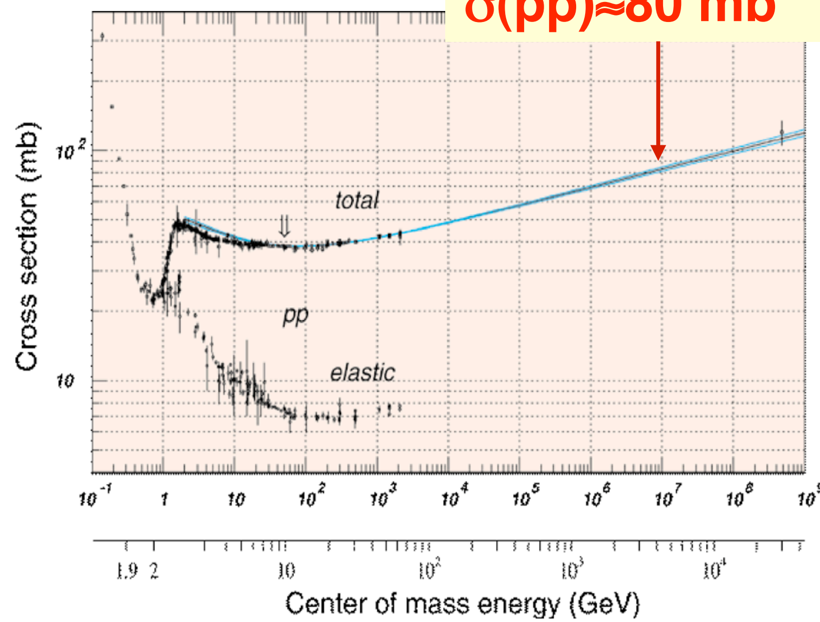
- LHC: ~3600 bunches (3564 bunches or 2808 filled bunches)
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns



pp cross section and min. bias

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}$Hz
    - σ(pp) = ~80 mb
    - Interaction Rate, R = $8x10^8$ Hz!
  - Events/beam crossing:
    - Δt = 25 ns = $2.5x10^{-8}$ s
    - Interactions/crossing=20.0
  - Not all p bunches are full
    - 2808 out of 3564 only
    - Interactions/"active" crossing = 20.0 x 3564/2835 = 25

σ(pp)≈80 mb



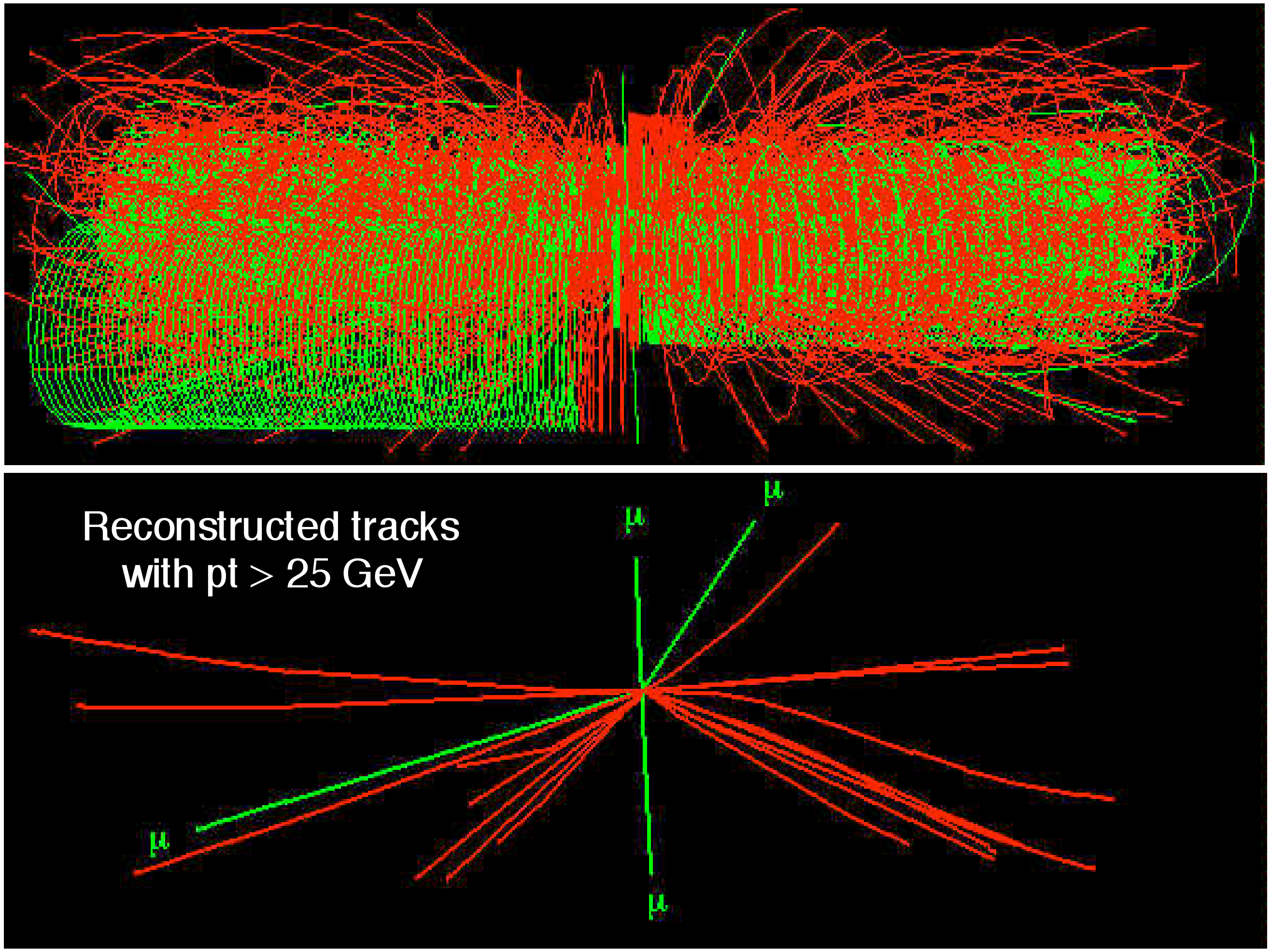
Summary of operating conditions:

A "good" event (say containing a Higgs decay) + ~25 extra "bad" minimum bias interactions

pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

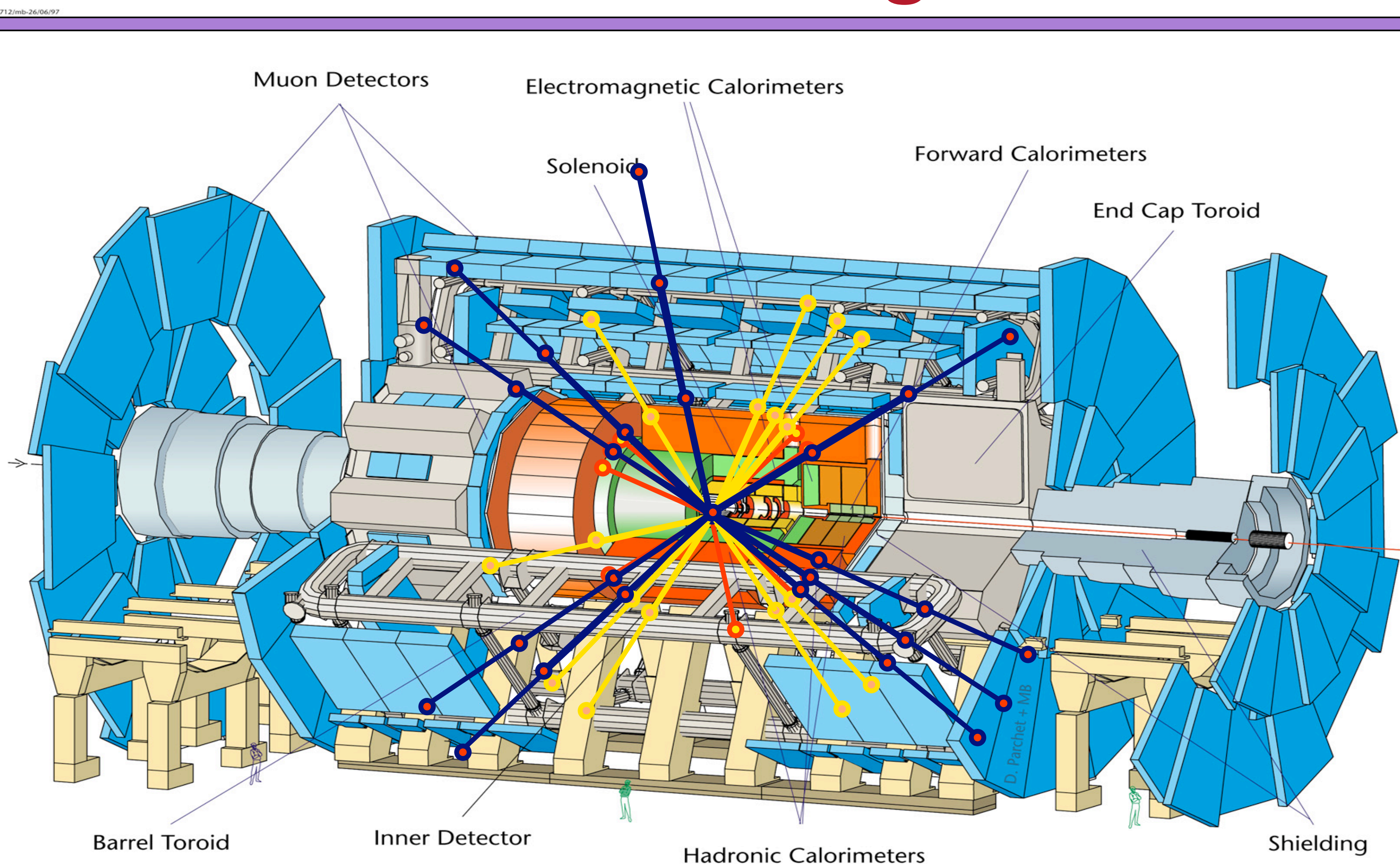
25 min bias events overlap

- H→ZZ (Z →μμ)
- H→ 4 muons: the cleanest (“golden”) signature



And this (not the H though…) repeats every 25 ns…

The challenge



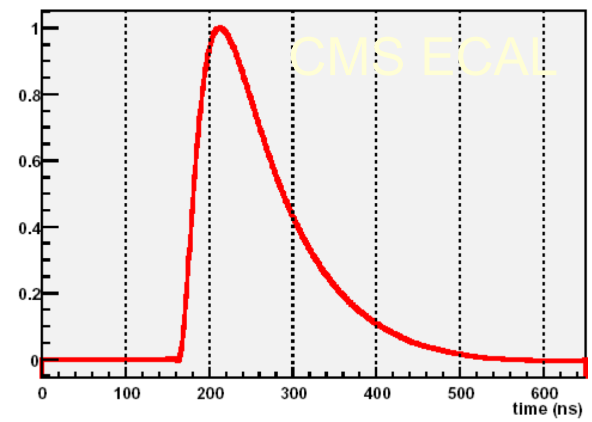
Interactions every 25 ns …

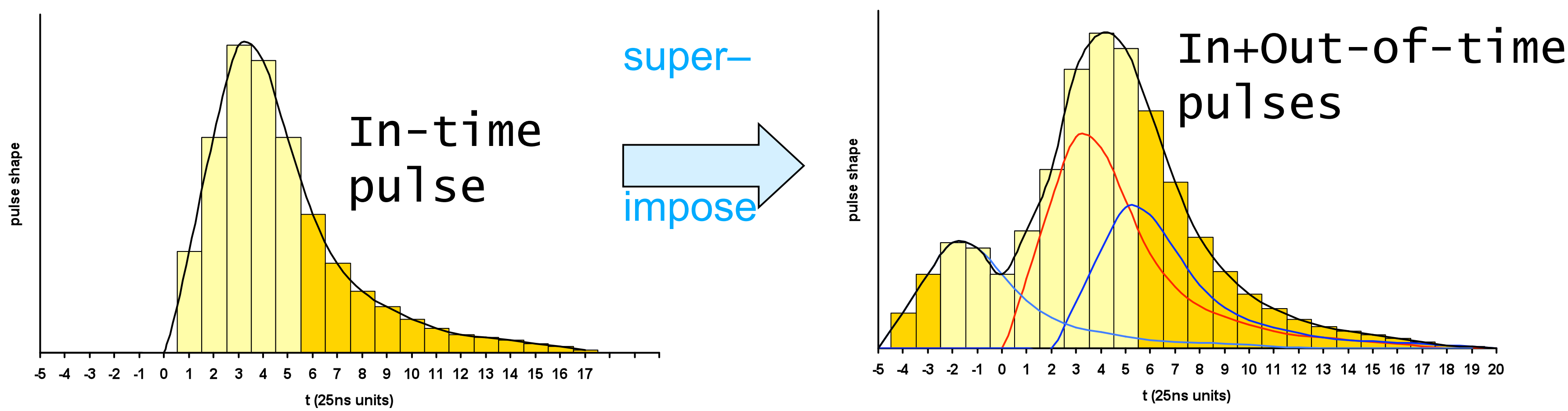
- **In 25 ns particles travel 7.5 m**

Pile-up

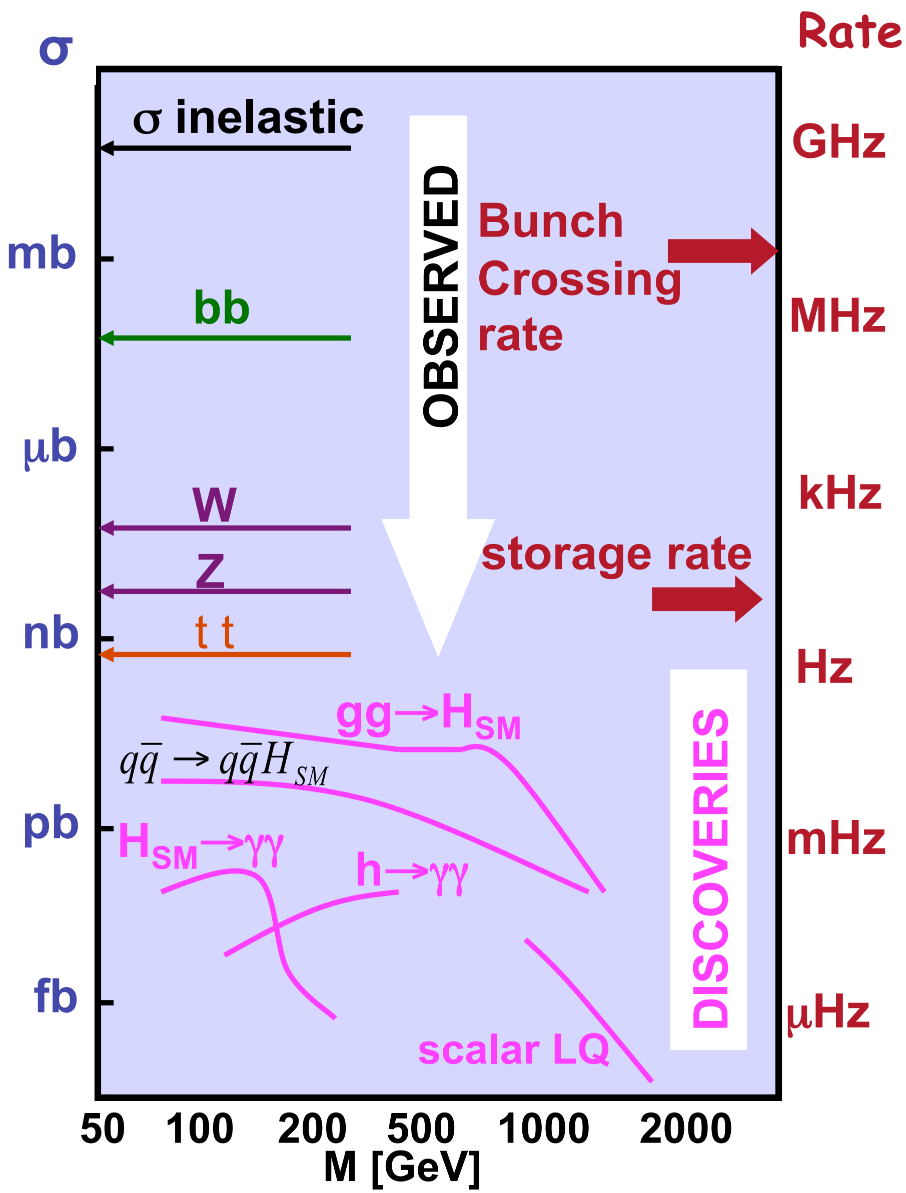
• "In-time" pile-up: particles from the same crossing but from a different pp interaction

- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"





Physics Selection @ LHC



Cross sections for various processes vary over many orders of magnitude

Bunch crossing frequency: 40MHz
Storage rate ~ 200-300 Hz

→ online rejection: > 99.99%
→ crucial impact on physics reach

Keep in mind that what is discarded is lost forever

The Challenge @ LHC

The Challenge

Process	σ (nb)	Production rates (Hz)
Inelastic	~10^8	~10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
$H(100\,\mathrm{GeV})$	0.05	0.1
$Z'(1\,\mathrm{TeV})$	0.05	0.1
$\tilde{g}\tilde{g}\,(1\,\mathrm{TeV})$	0.05	0.1
$H(500\,\mathrm{GeV})$	10^{-3}	10^{-2}

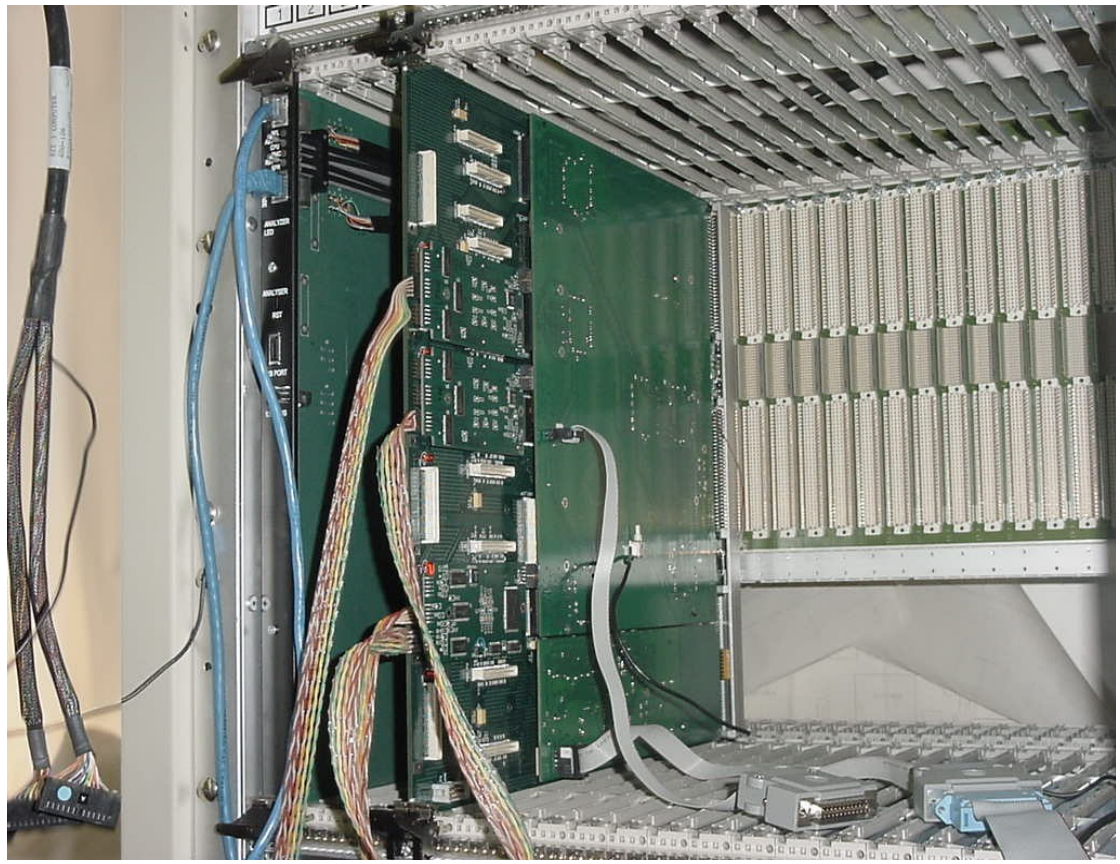
The Solution

The Trigger

The Challenge

Process	σ (nb)	Production rates (Hz)
Inelastic	~10^8	~10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
$H(100\ \mathrm{GeV})$	0.05	0.1
$Z'(1\ \mathrm{TeV})$	0.05	0.1
$\tilde{g}\tilde{g}\ (1\ \mathrm{TeV})$	0.05	0.1
$H(500\ \mathrm{GeV})$	10^{-3}	10^{-2}

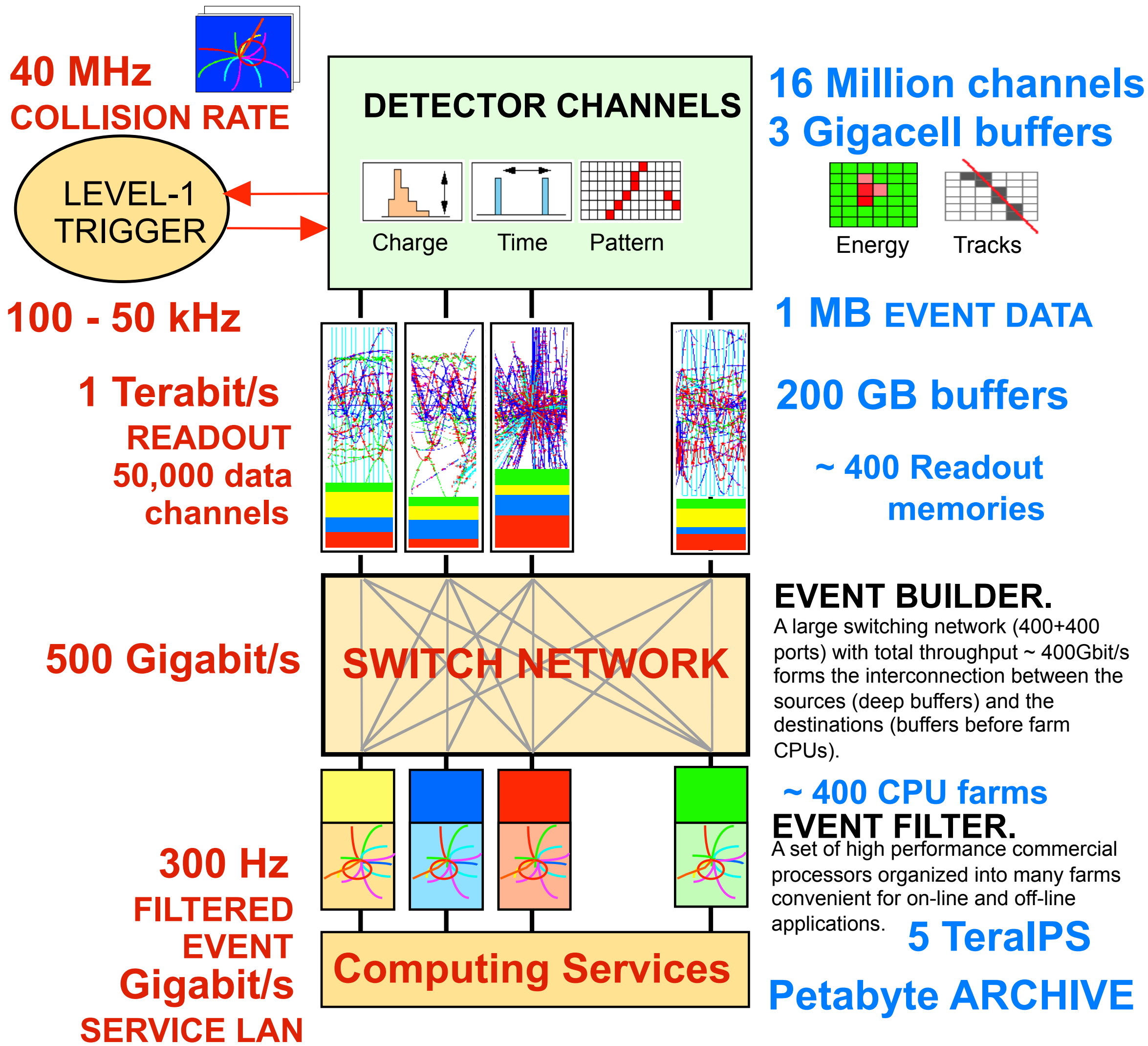
The Solution



Trigger/DAQ challenges @ LHC

- # of channel ~ O(10^7). ~25 interactions every 25ns
  - Need large number of connections
  - Need information super-highway
- Calorimeter information should correspond to tracker information
  - Need to synchronize detectors to better than 25ns
- Sometimes detector signal/time of flight > 25ns
  - Integrate information from more than one bunch crossing
  - Need to correctly identify bunch crossing
- Can store data at O(100 Hz)
  - Need to reject most events
- Selection is done Online in real-time
  - Cannot go back and recover events
  - Need to monitor selection

Trigger/DAQ Challenges



Challenges:

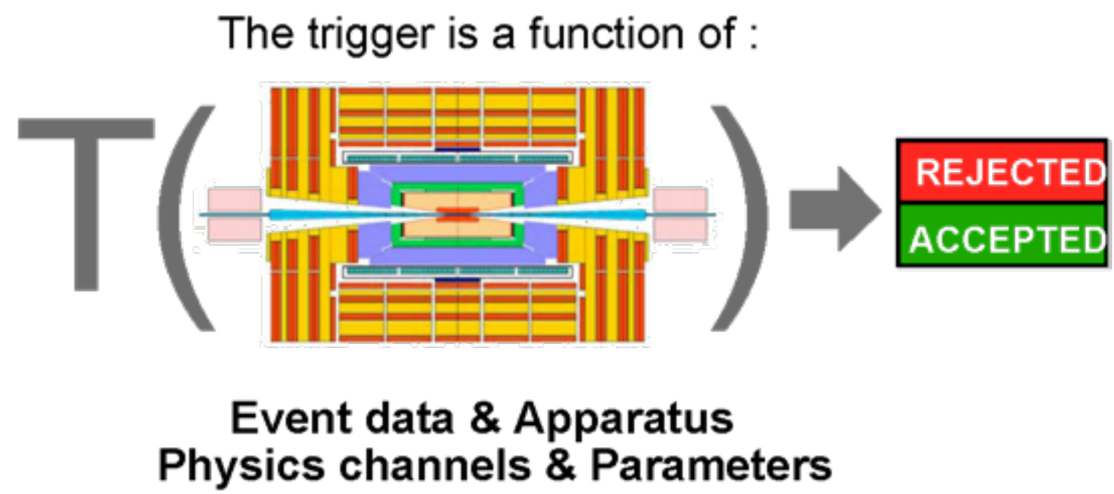
1 GHz of Input Interactions

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

Archival Storage at about 300 Hz of 1 MB events

Triggering

- **Task: inspect detector information and provide a first decision on whether to keep the event or throw it out**



• Detector data not (all) promptly available
• Selection function highly complex
⇒T(...) is evaluated by successive approximations, the

TRIGGER LEVELS

(possibly with zero dead time)

General trigger strategy

Needed: An efficient selection mechanism capable of selecting interesting events
- this is the **TRIGGER**

"Needle in a haystack"

General strategy:

- System should be as inclusive as possible
- Robust
- Redundant
- Need high efficiency for selecting interesting processes for physics:
    - selection should not have biases that affect physics results
    - (understand biases in order to isolate and correct them)
- Need large reduction of rate from unwanted high-rate processes
    - instrumental background
    - high-rate physics processes that are not relevant (min. bias)

This complicated process involves a multi-level trigger system…

Multi-level trigger systems

- L1 trigger:
  - Selects 1 out of 10000 (max. output rate ~100kHz)

- This is NOT enough
  - Typical ATLAS and CMS event size is 1MB
  - 1MB x 100 kHz = 100 GB/s!

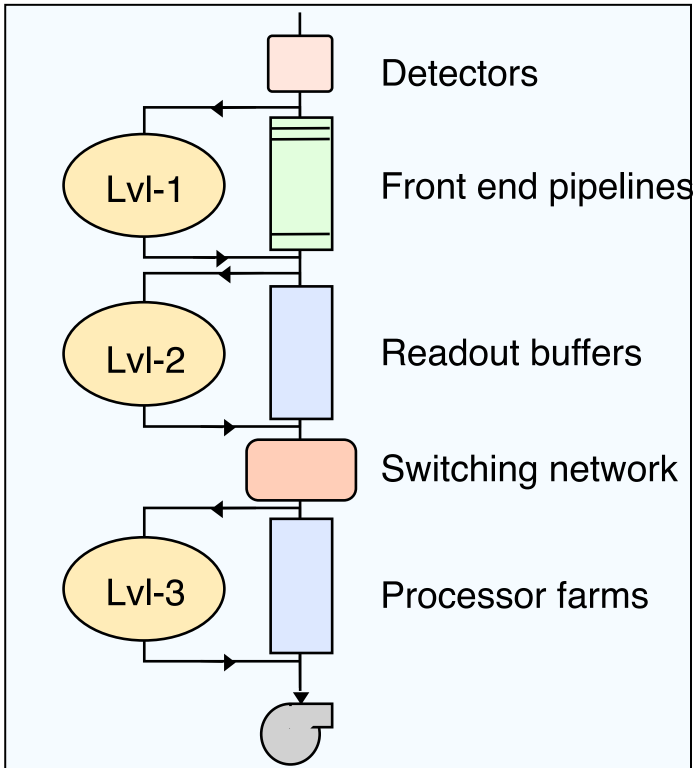
- What is the amount of data we can reasonably store these days ?
  - 100 MB/s

⇒ Additional trigger levels are needed to reduce the fraction of "less interesting" events before writing to permanent storage

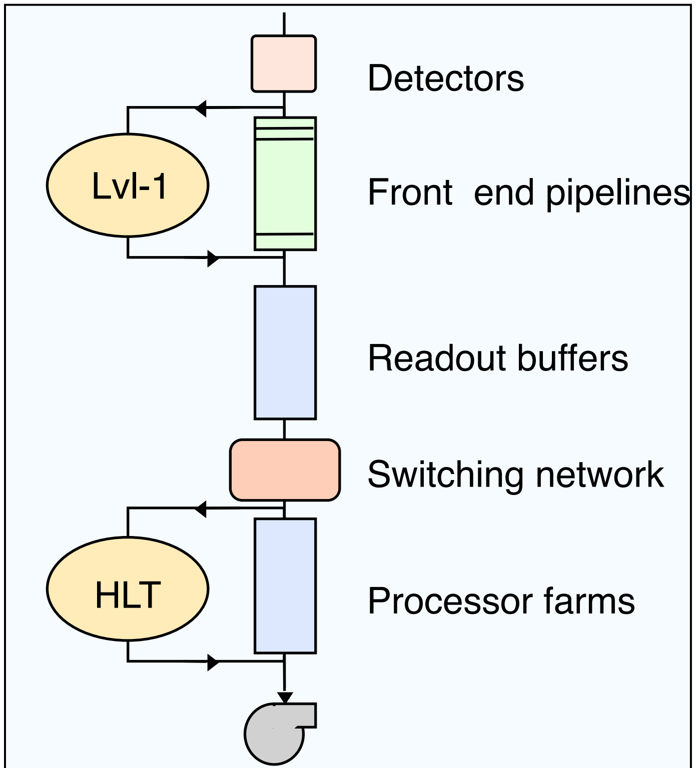
Multi-tiered trigger systems

Level-1 trigger: Integral part of all trigger systems – always exists
reduces rate to ~50-100kHz.

Upstream: further reduction needed – typically done in 1 or 2 steps



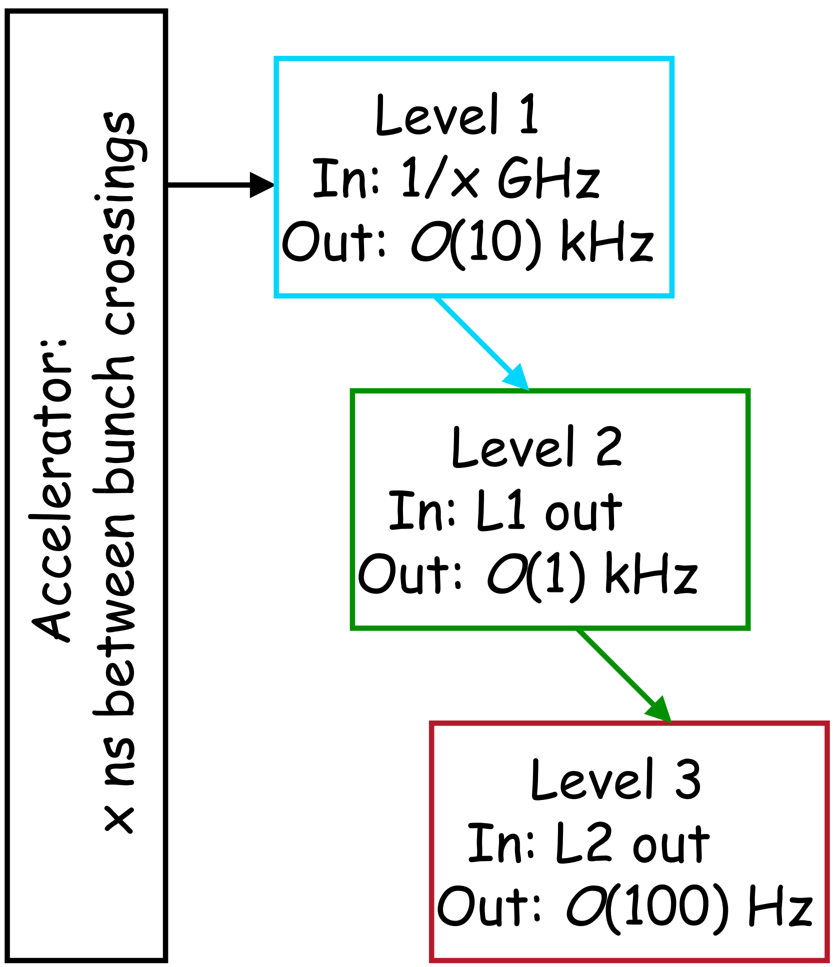
ATLAS: 3 physical levels



CMS: 2 physical levels

A multi-tiered Trigger System

Traditional 3-tiered system

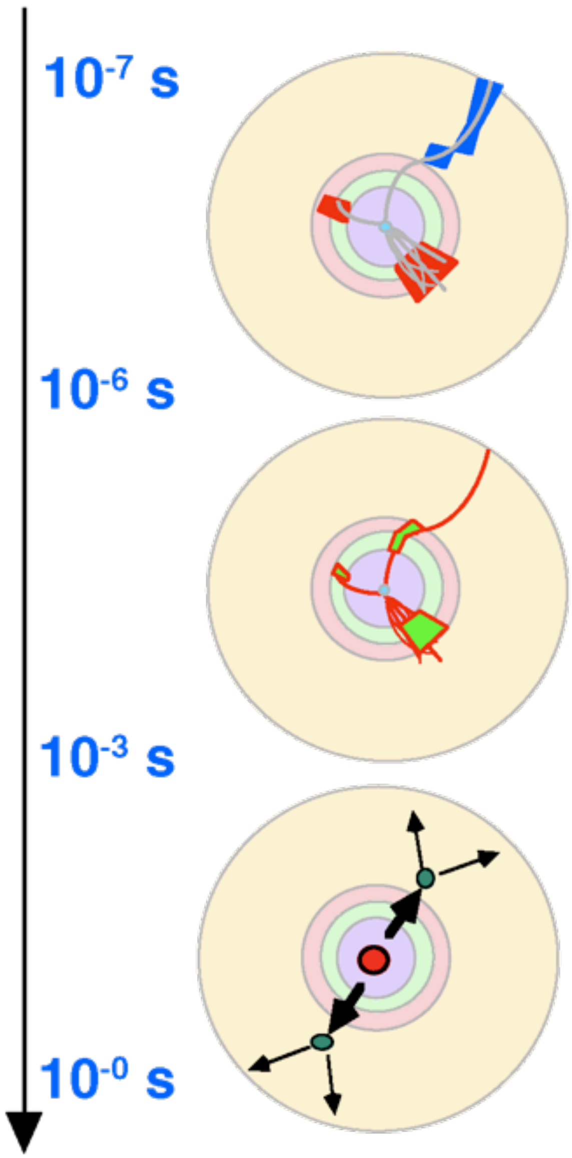


Pipelined,
Hardware only, coarse readout,
~few μs latency

Hardware/Software mix,
L1 inputs, ~100 μs latency

CPU farm, access to full event information, $O(1)$s/event

LHC 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

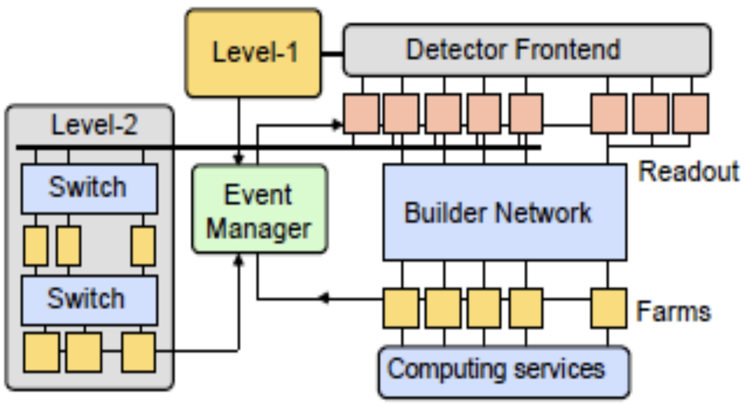
Level-3 events to tape **100- 300 Hz**

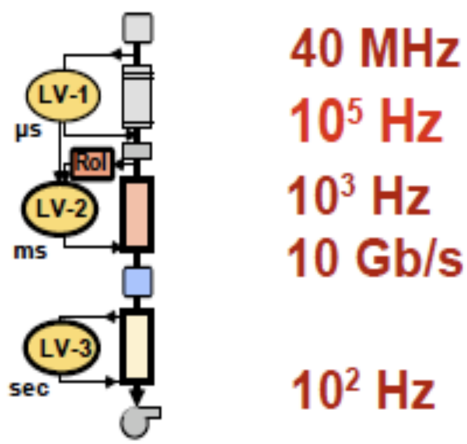
Physics process identification

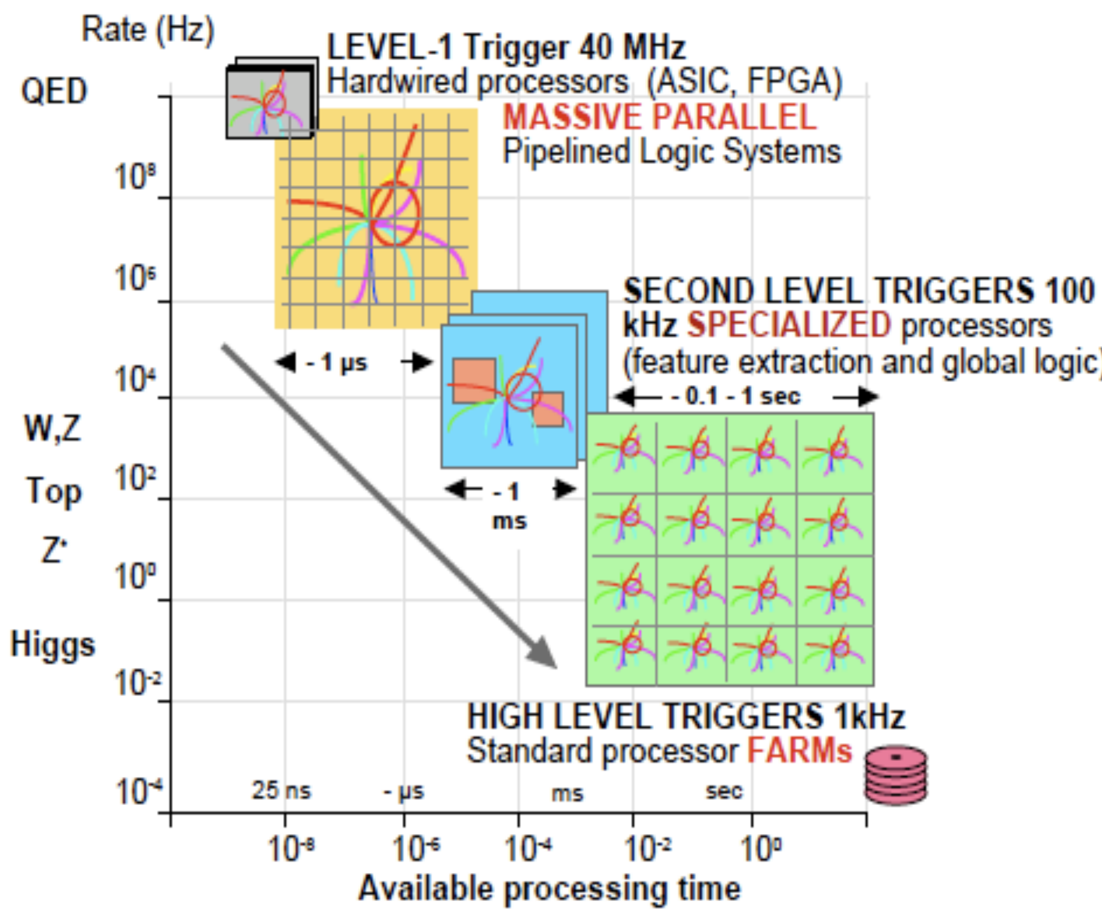
- Event reconstruction and analysis

Three-tiered system

Additional processing at Level-2: reduce bandwidth requirements



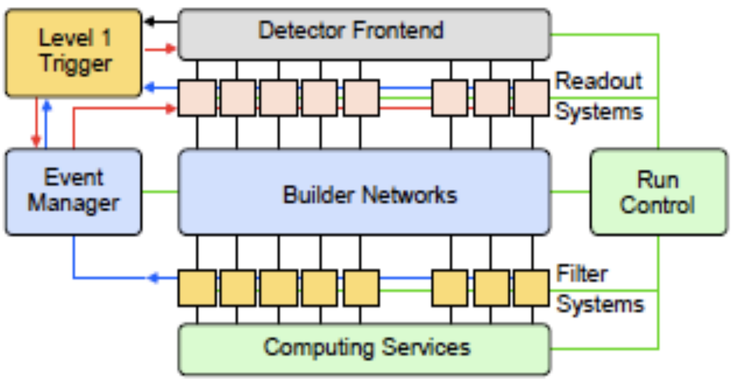


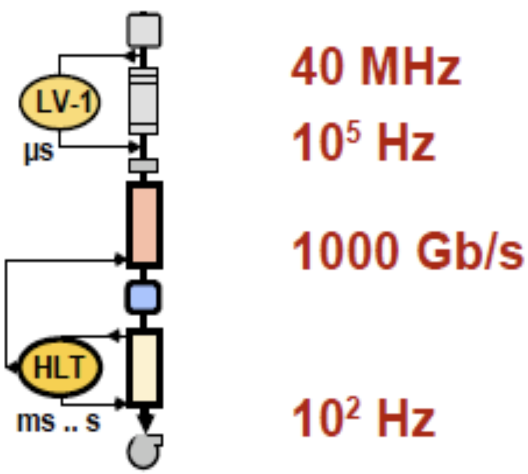


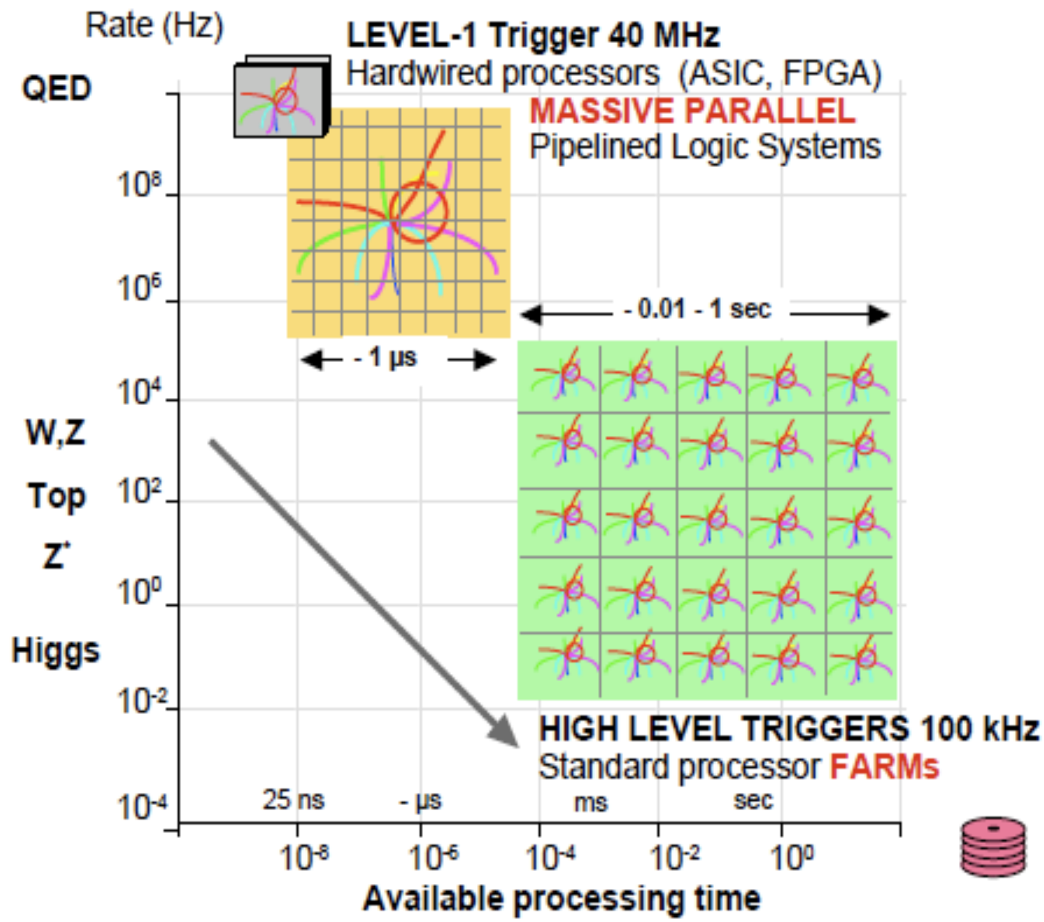
Two-tiered system

Two-level processing:

- Reduce number of building blocks
- Rely on commercial components for processing and communication

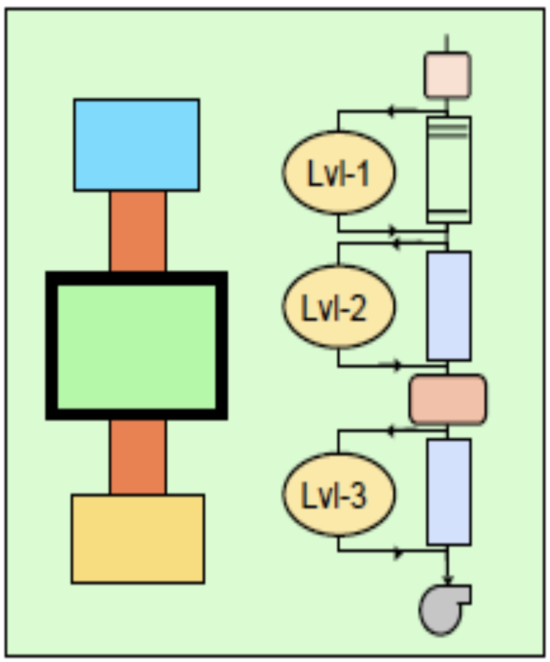


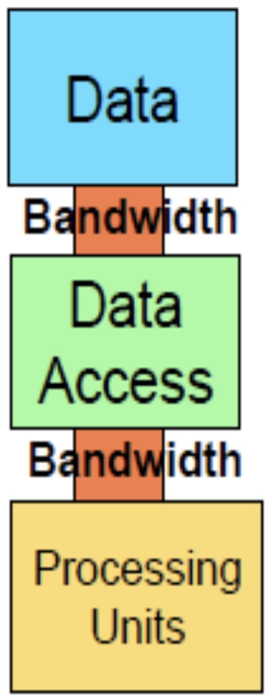


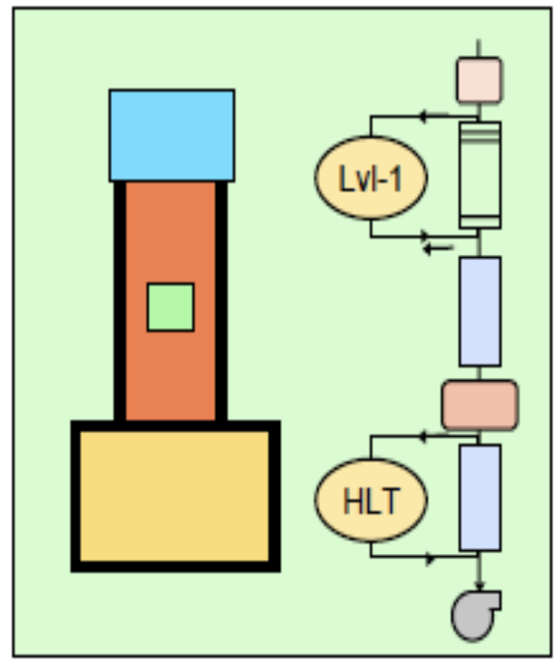


Comparison

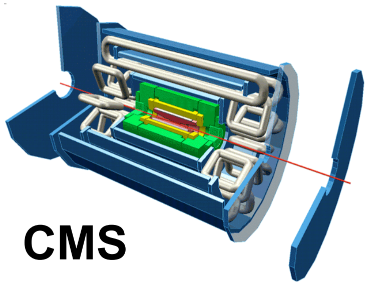
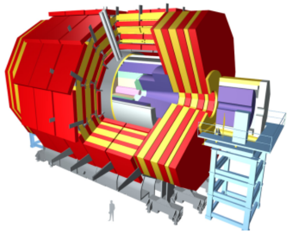
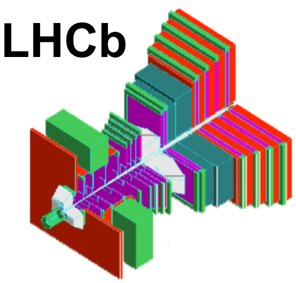
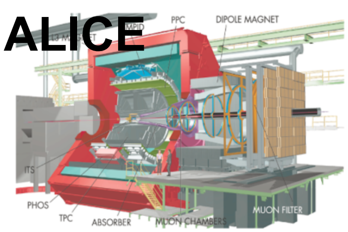
- Three physical entities
  - Invest in
    - Control logic
    - Specialized processors
- Two physical entities
  - Invest in
    - Bandwidth
    - Commercial processors



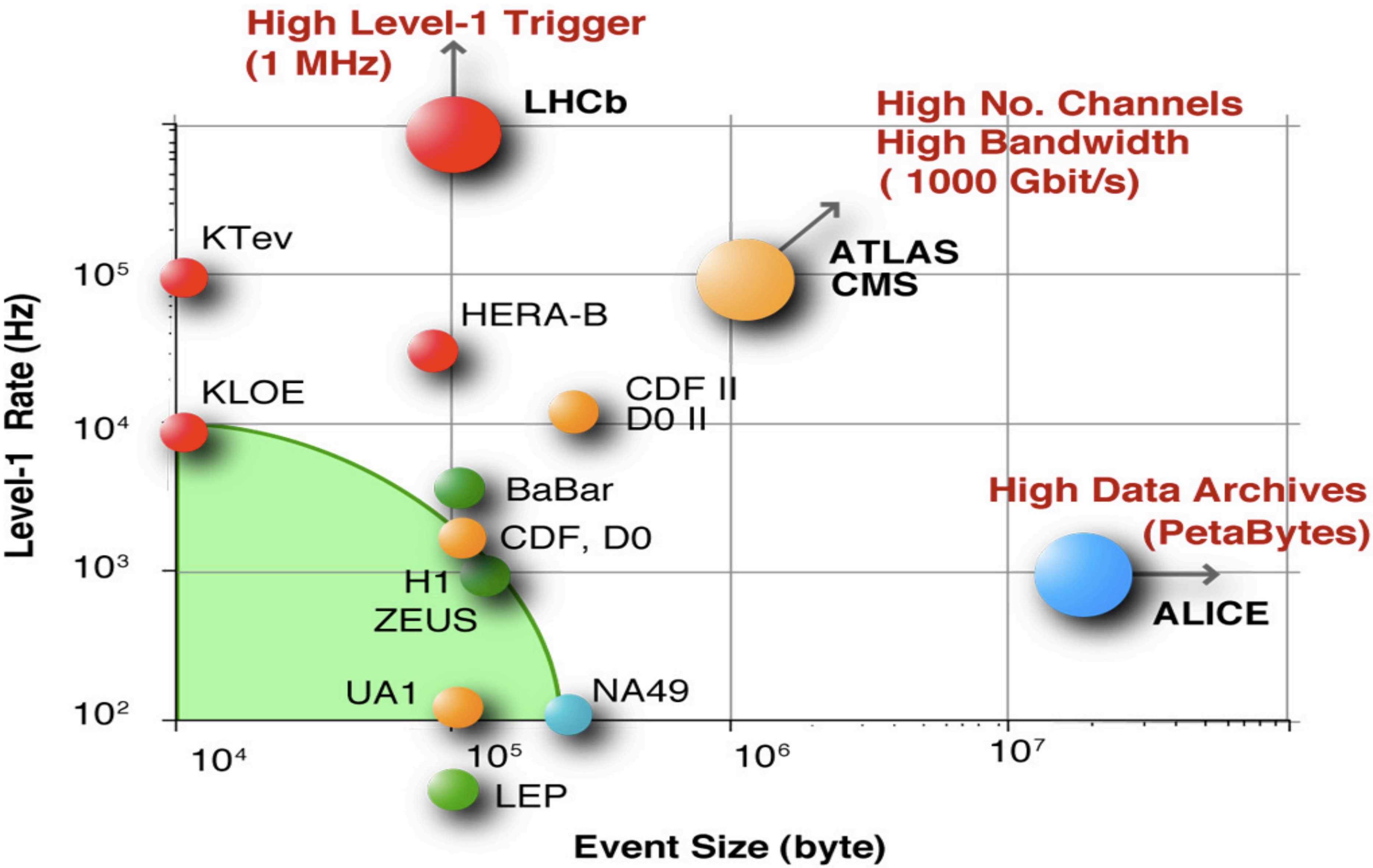




LHC Trigger/DAQ Summary

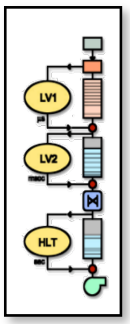
	No.Levels Trigger	First Level Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS 	**3**	10^5 LV-2 10^3	10^6	**10**	**100** (10^2)
CMS 	**2**	10^5	10^6	**100**	**100** (10^2)
LHCb 	**3**	LV-0 10^6 LV-1 $4\ 10^4$	$2x10^5$	**4**	**40** ($2x10^2$)
ALICE 	**4**	Pp-Pp **500** p-p 10^3	$5x10^7$ $2x10^6$	**5**	**1250** (10^2) **200** (10^2)

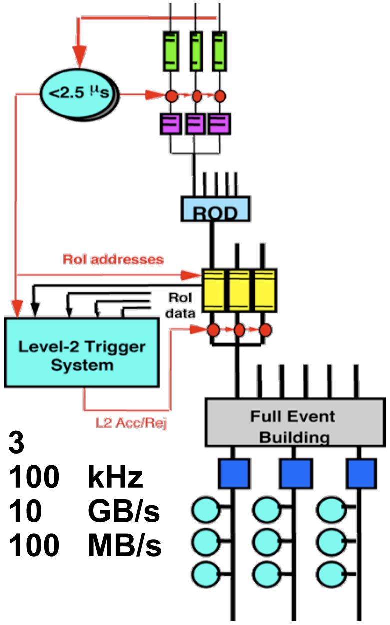
Trigger/DAQ systems



Trigger & DAQ at LHC

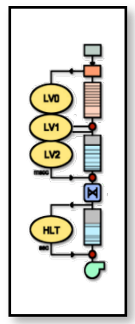
ATLAS

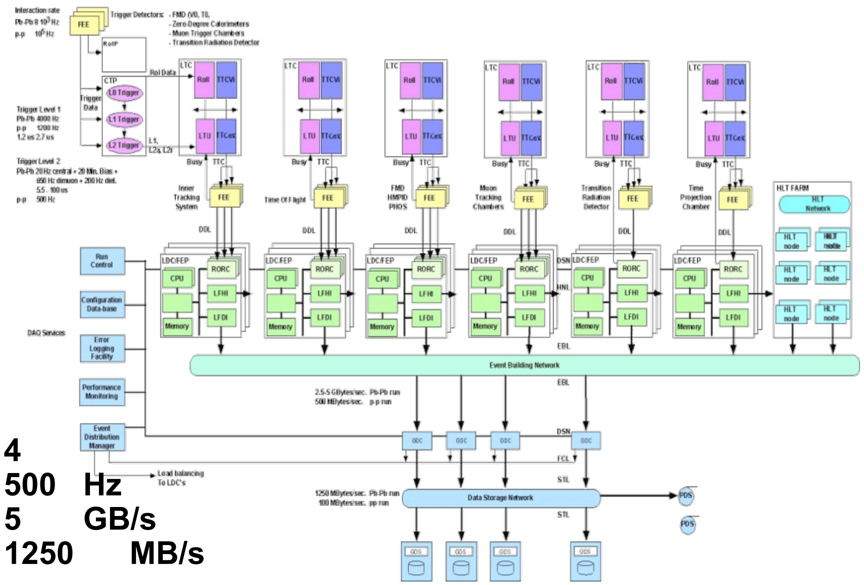




Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

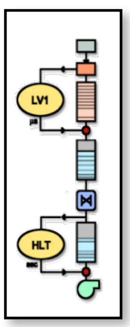
ALICE

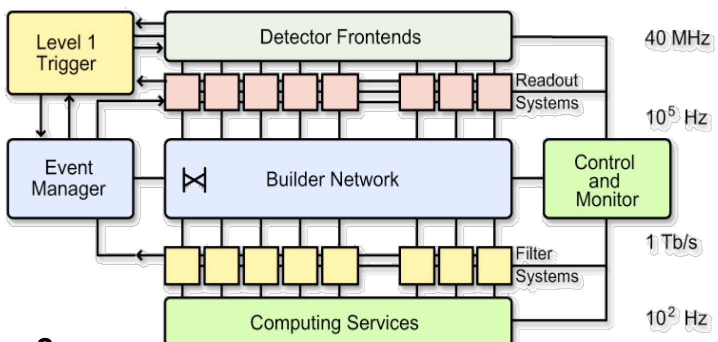




Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250	MB/s

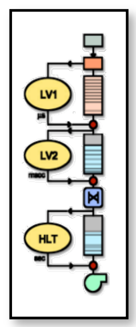
CMS





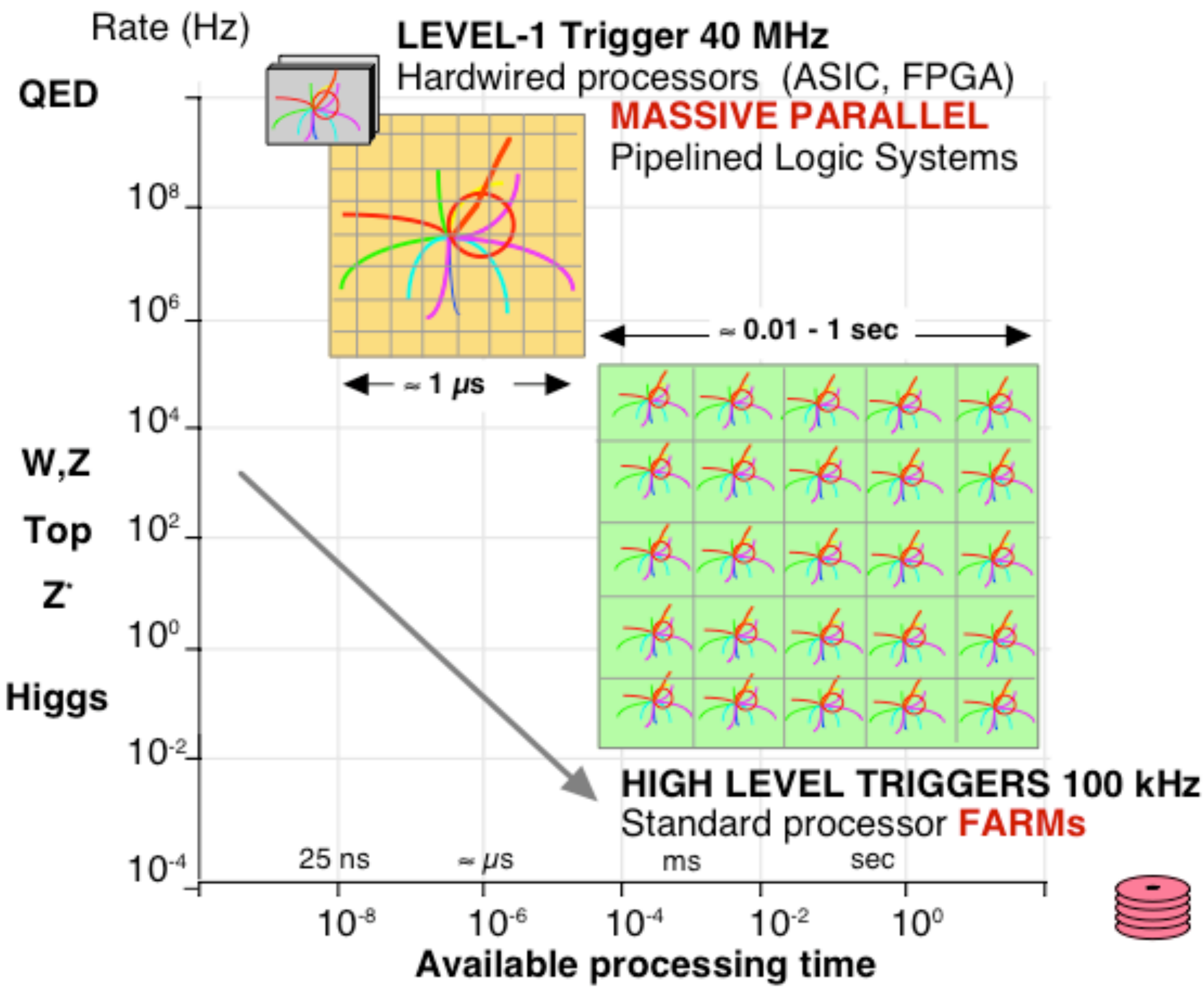
Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

LHCb



Levels	3	
LV-1 rate	1	MHz
Readout	4	GB/s
Storage	40	MB/s

Processing LHC Data

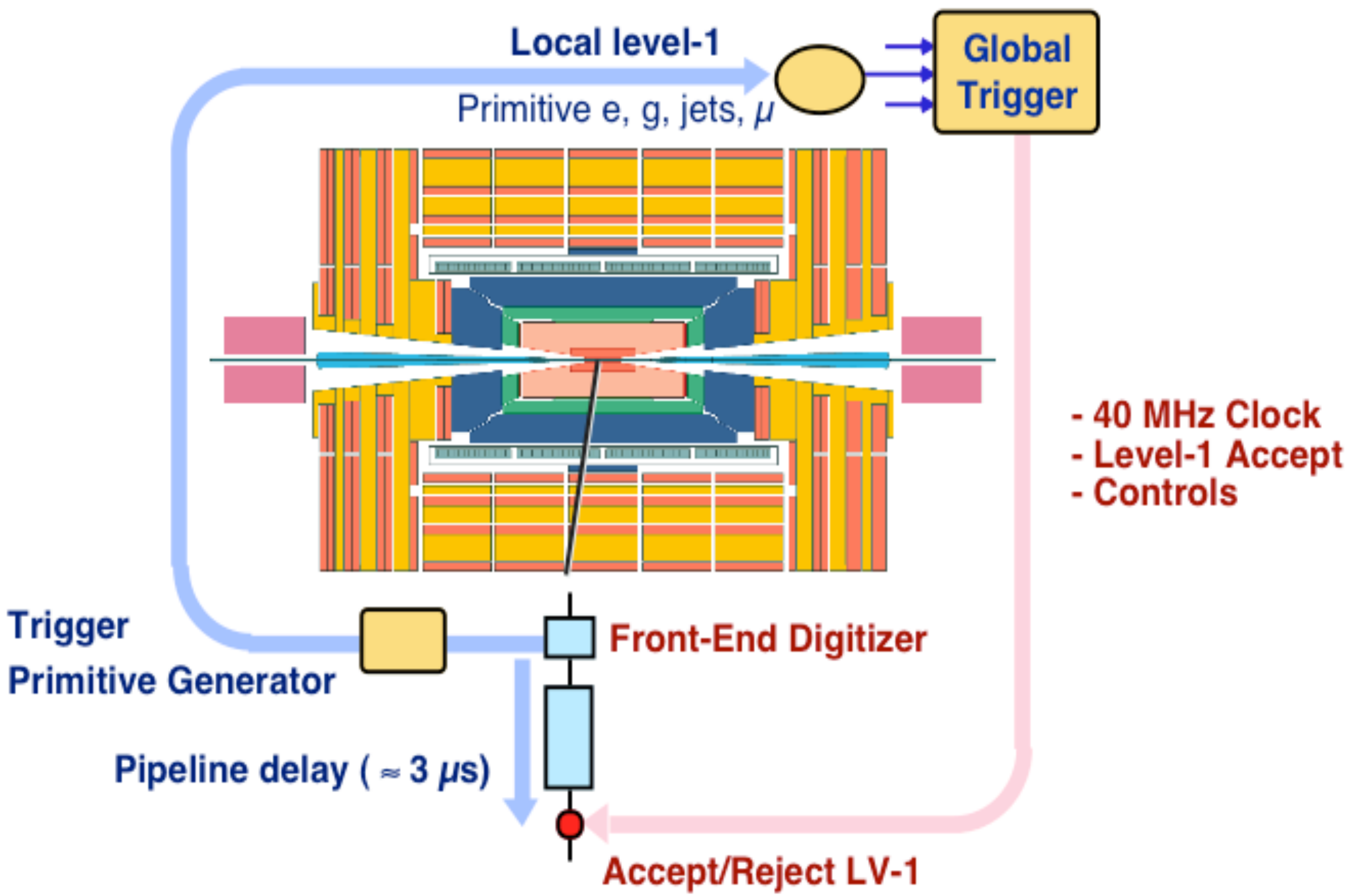


Level-1 algorithms

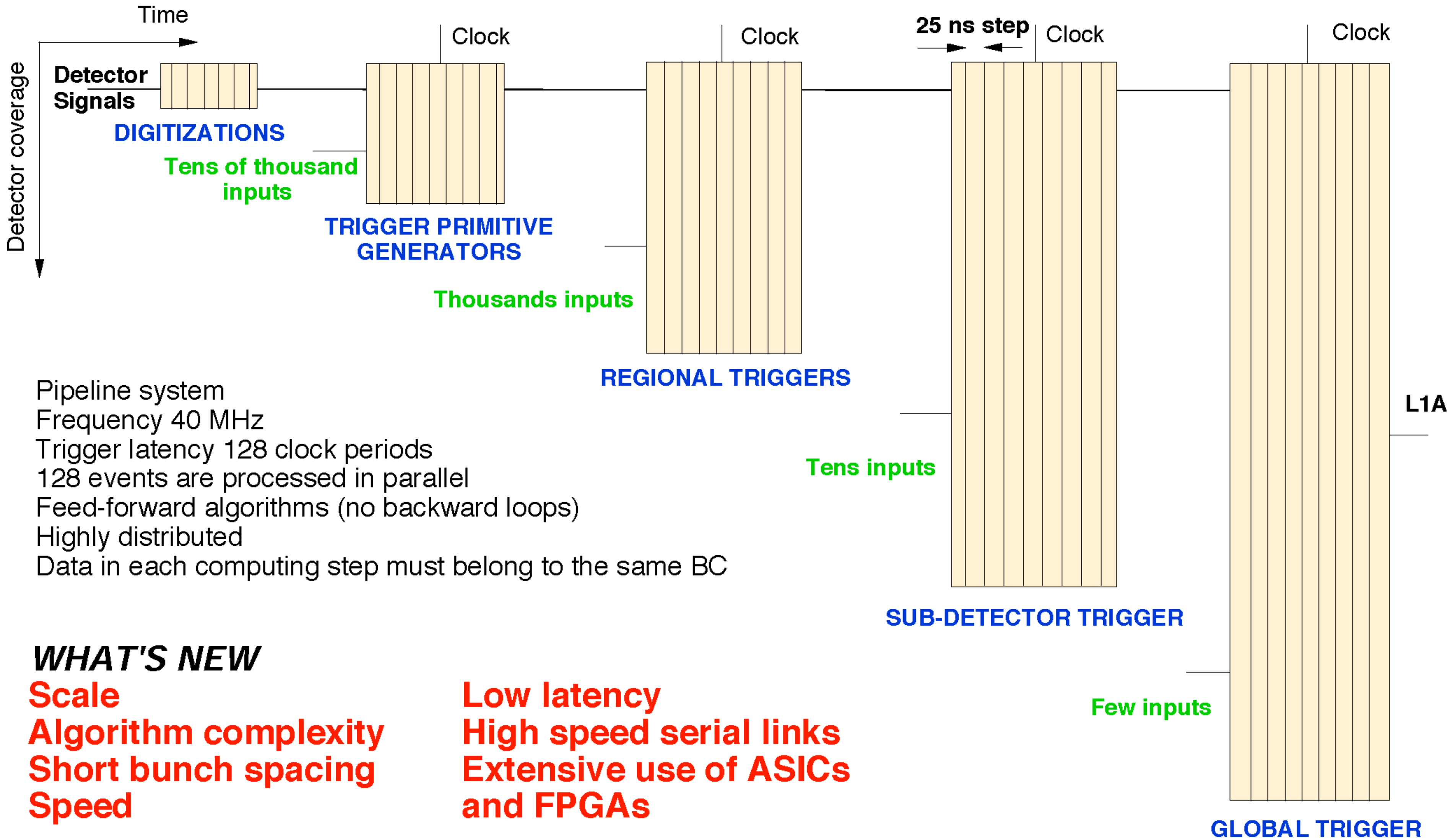
- Physics concerns:
  - pp collisions produce mainly low pT hadrons with pT ~ 1 GeV
  - Interesting physics has particles with large transverse momentum
    - W->eν : M(W) = 80 GeVl pT (e) ~ 30-40 GeV
    - H(120 GeV) → γγ ; pT(γγ) ~ 50-60 GeV

- Requirements
  - Impose high thresholds
    - Implies distinguishing particles
      - possible for electrons, muons and jets; beyond that need complex algorithms
  - Some typical thresholds:
    - Single muon with pt > 20 GeV
    - Single e/γ with pT > 30 GeV
    - Single jet with pT > 30 GeV

Level 1 Trigger Operation



Level 1 Trigger Organization



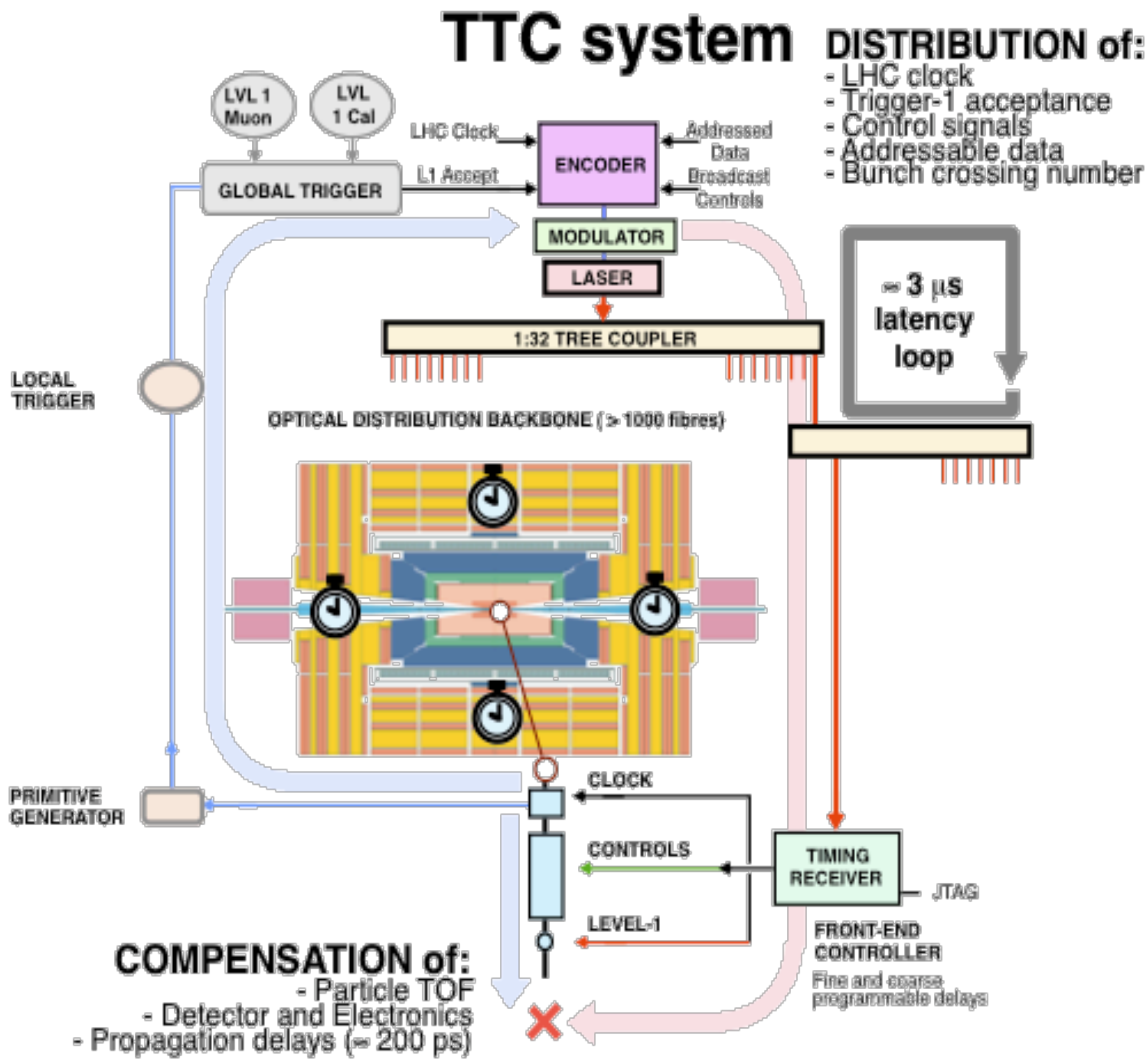
Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

WHAT'S NEW

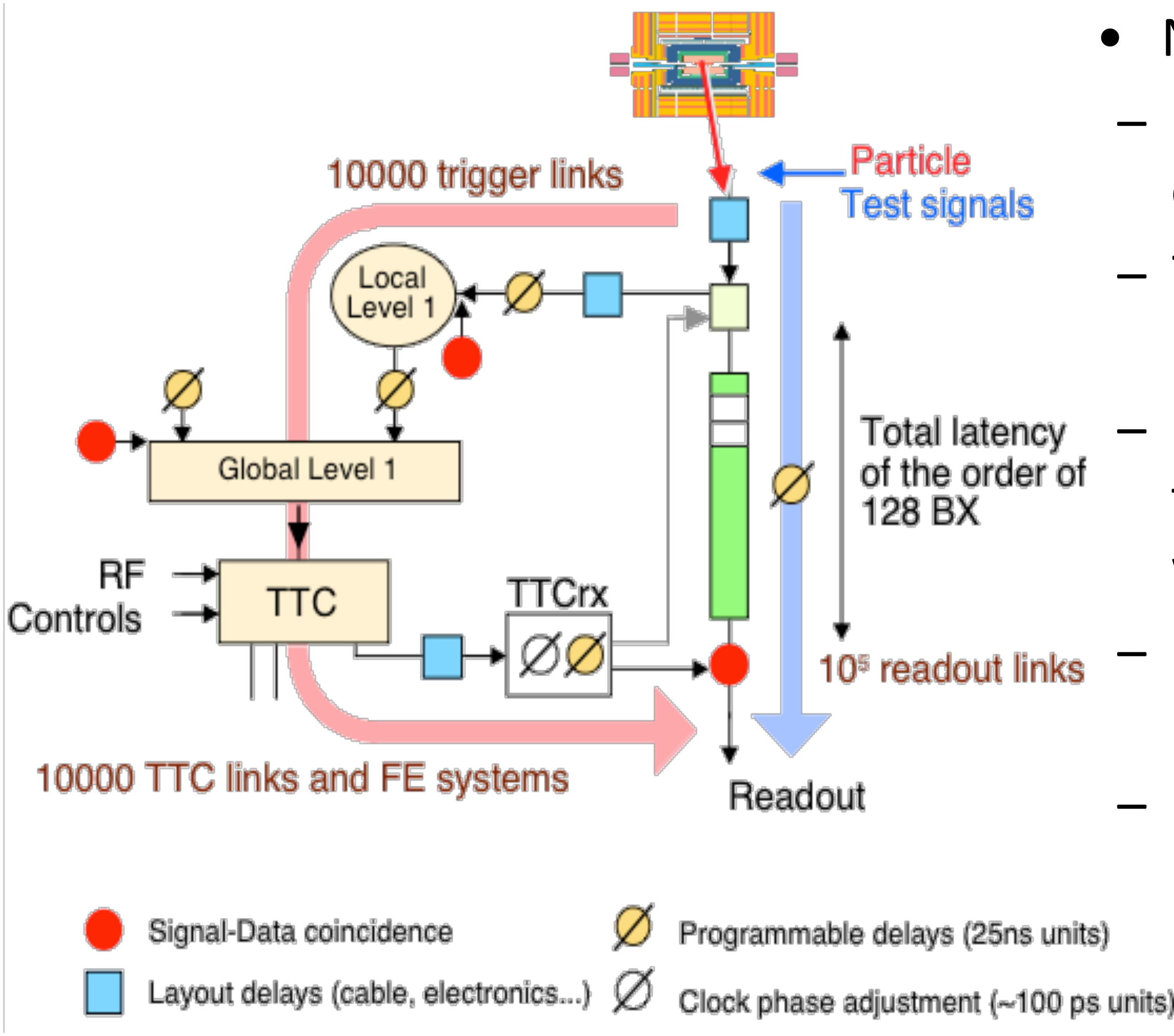
Scale
Algorithm complexity
Short bunch spacing
Speed

Low latency
High speed serial links
Extensive use of ASICs and FPGAs

Trigger Timing & Control

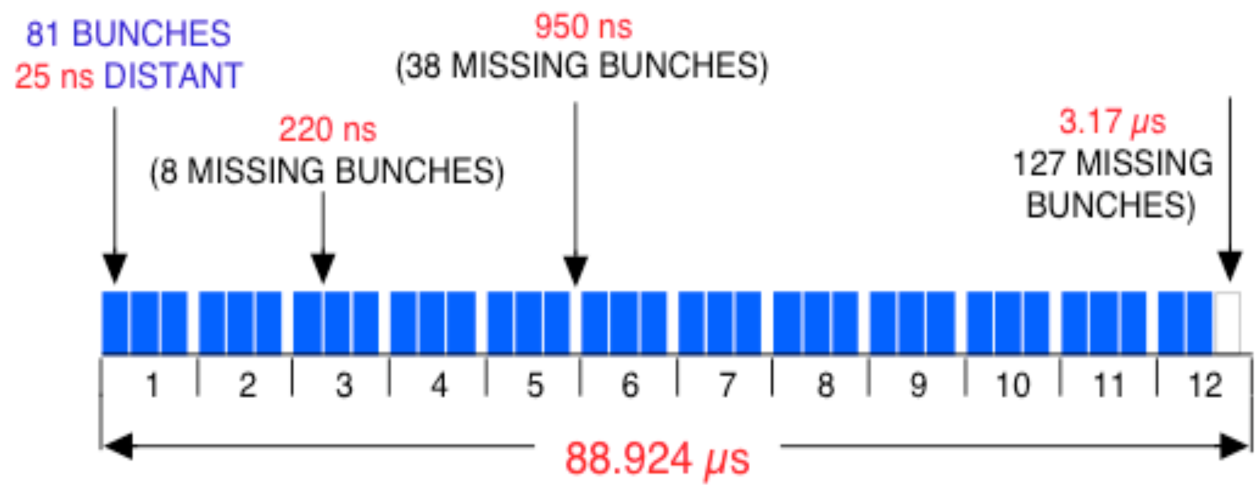


Detector Timing Adjustments

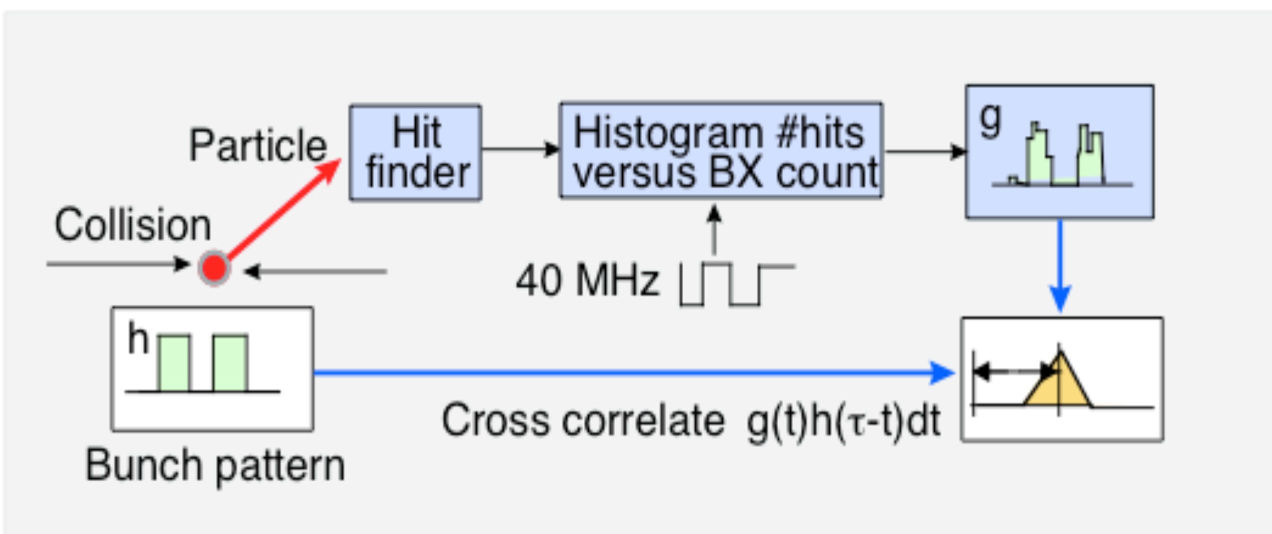


- Need to Align:
  - Detector pulse w/ collision at IP
  - Trigger data w/ readout data
  - Different detector trigger data w/each other
  - Bunch Crossing Number
  - Level 1 Accept Number

Synchronization Techniques

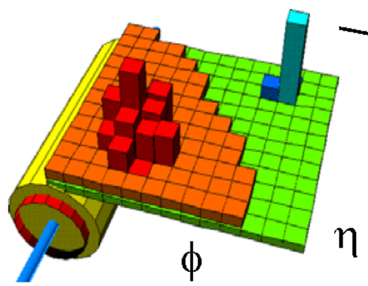


2835 out of 3564 p bunches are full, use this pattern:



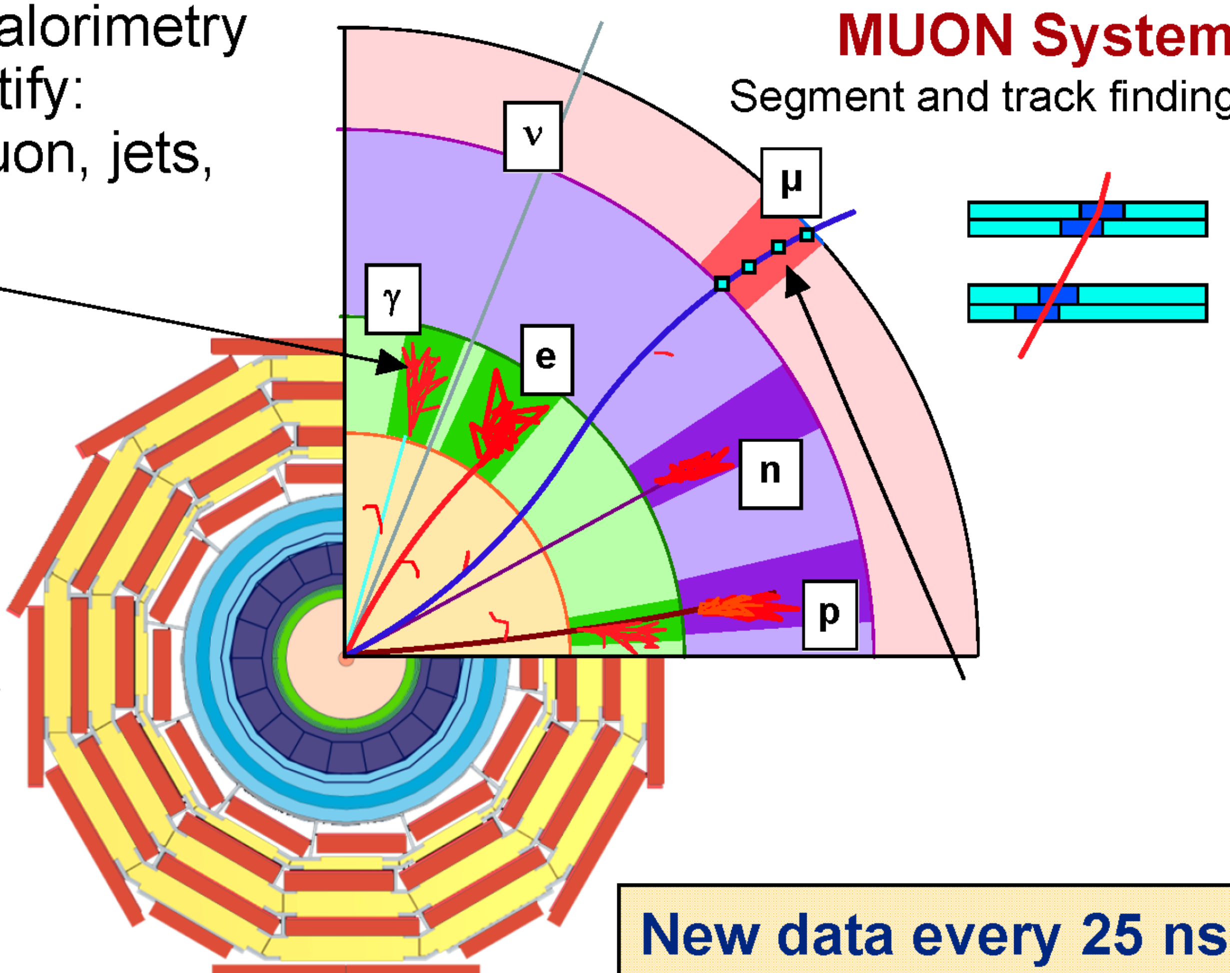
Particle signatures

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



CALORIMETERs

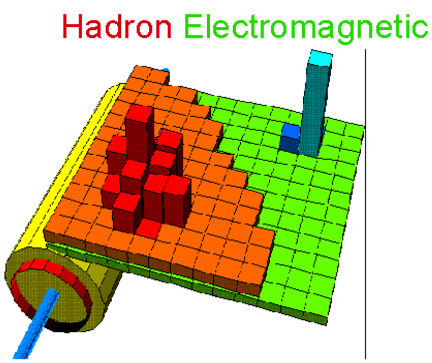
Cluster finding and energy deposition evaluation

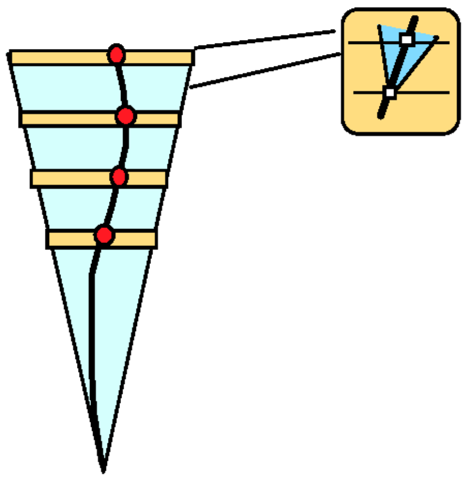


New data every 25 ns
Decision latency ~ µs

ATLAS & CMS Level 1: Only Calorimeter & Muon

- **Pattern recognition much faster/easier**

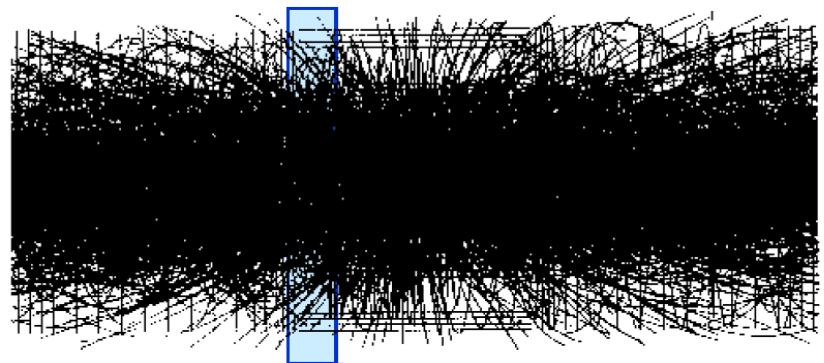


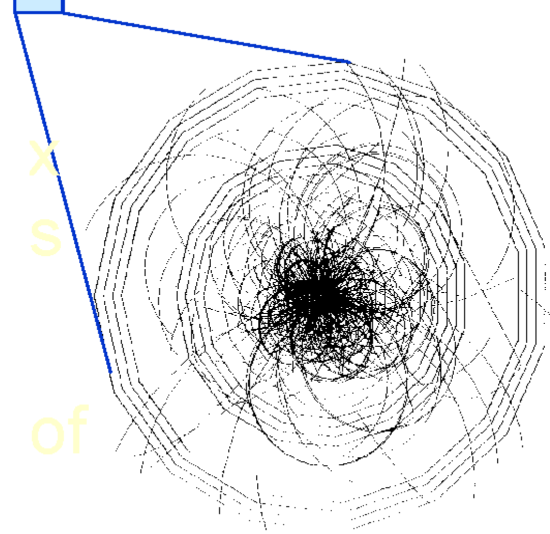


Simple Algorithms

Small amounts of data

- **Compare to tracker info**



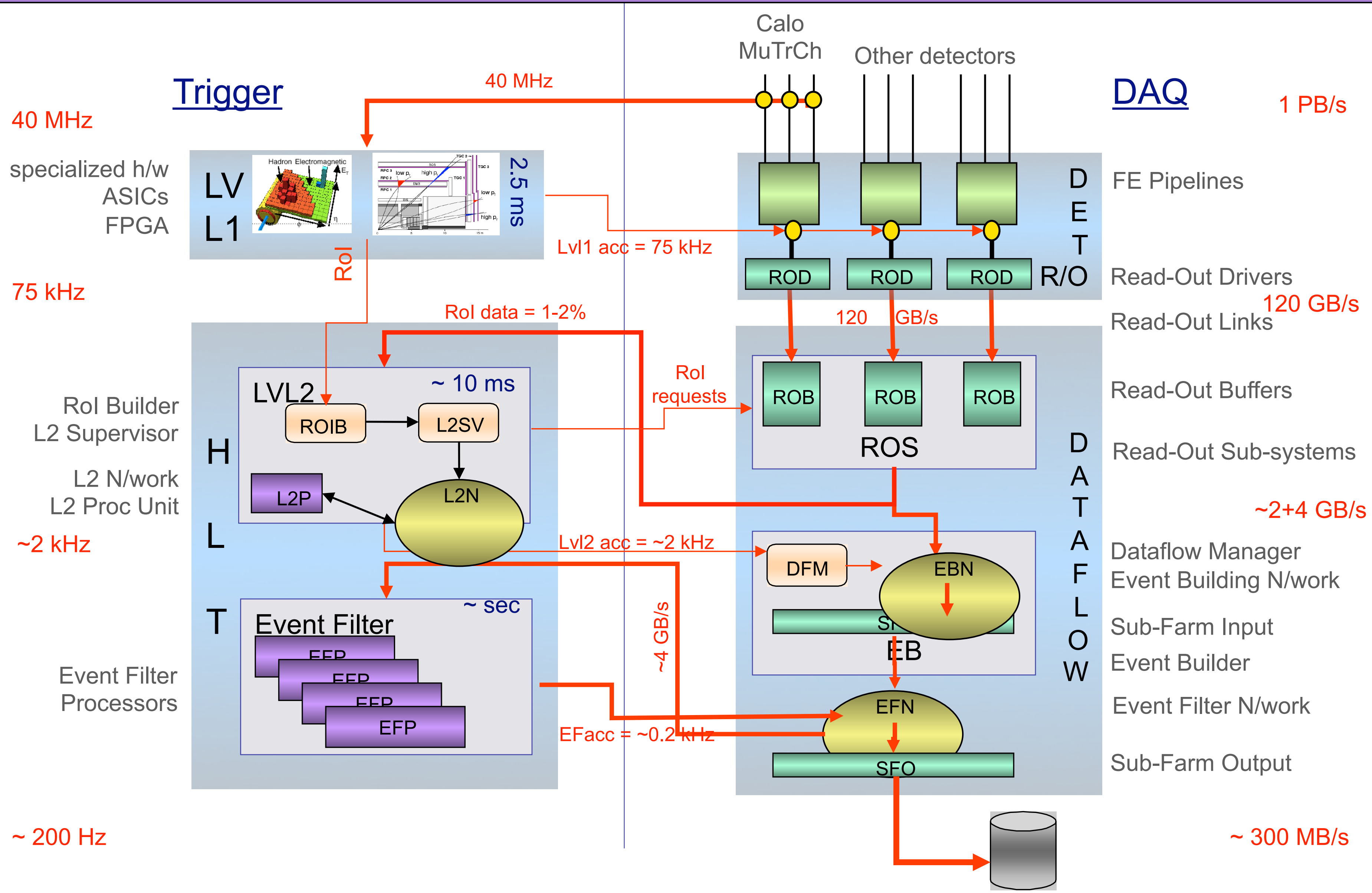


Complex Algorithms

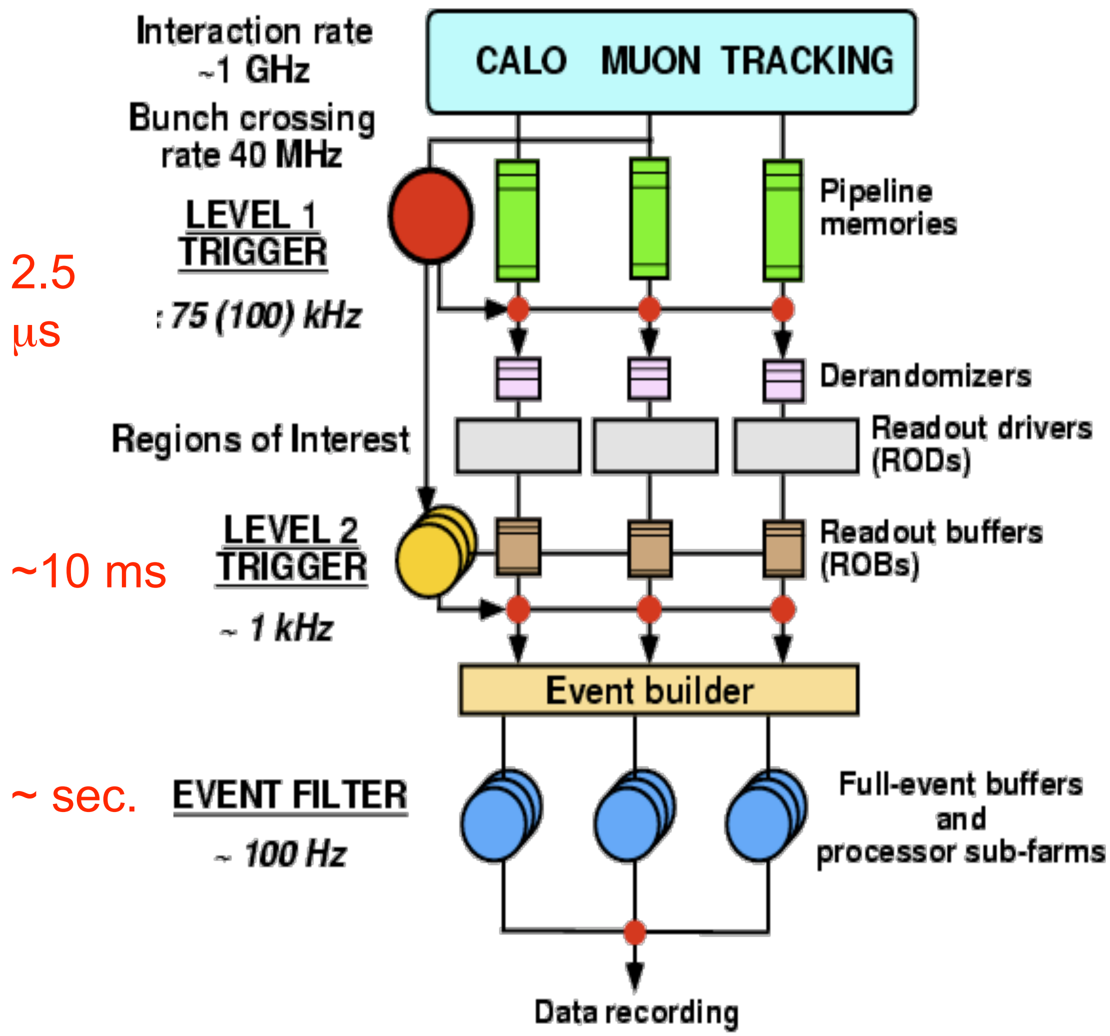
Huge amounts of data

High Occupancy in high granularity tracking detectors

ATLAS Trigger/DAQ Architecture

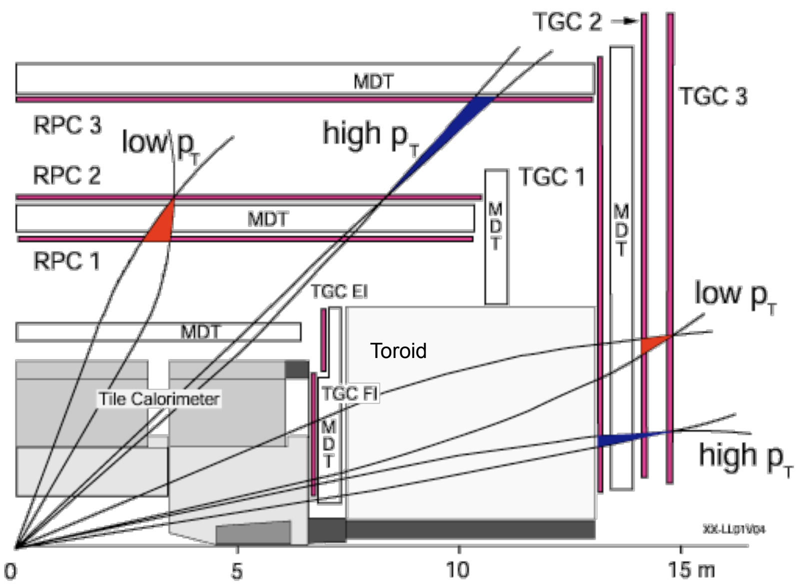


ATLAS Trigger Architecture



- LVL1 decision made with calorimeter data with coarse granularity and muon trigger chambers data.
  - Buffering on detector
- LVL2 uses Region of Interest data (~2%) with full granularity and combines information from all detectors; performs fast rejection.
  - Buffering in ROBs
- EventFilter refines the selection, can perform event reconstruction at full granularity using latest alignment and calibration data.
  - Buffering in EB & EF

Level1 - Muons & Calorimetry

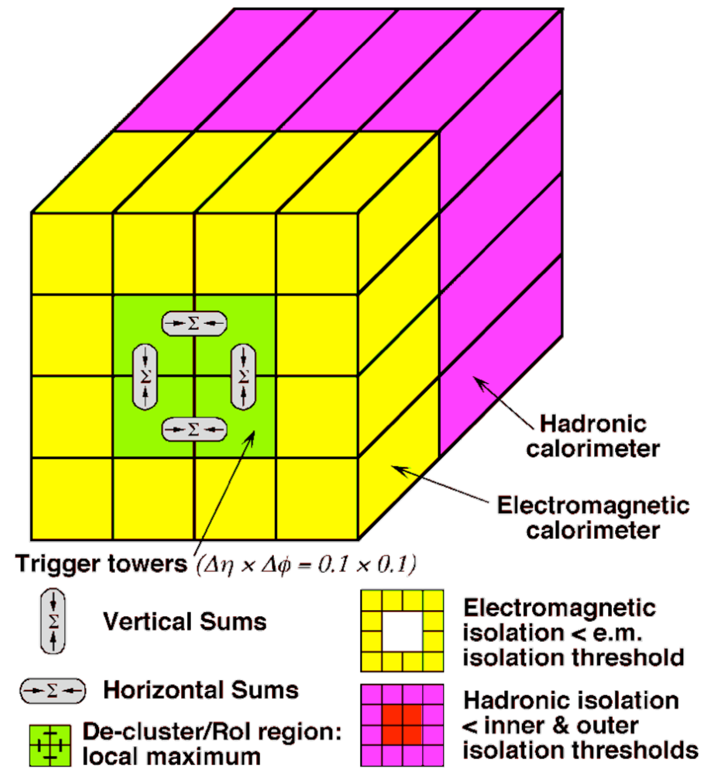


Muon Trigger looking for coincidences in muon trigger chambers

2 out of 3 (low-p_T; >6 GeV) and

3 out of 3 (high-p_T; > 20 GeV)

Trigger efficiency 99% (low-p_T) and 98% (high-p_T)

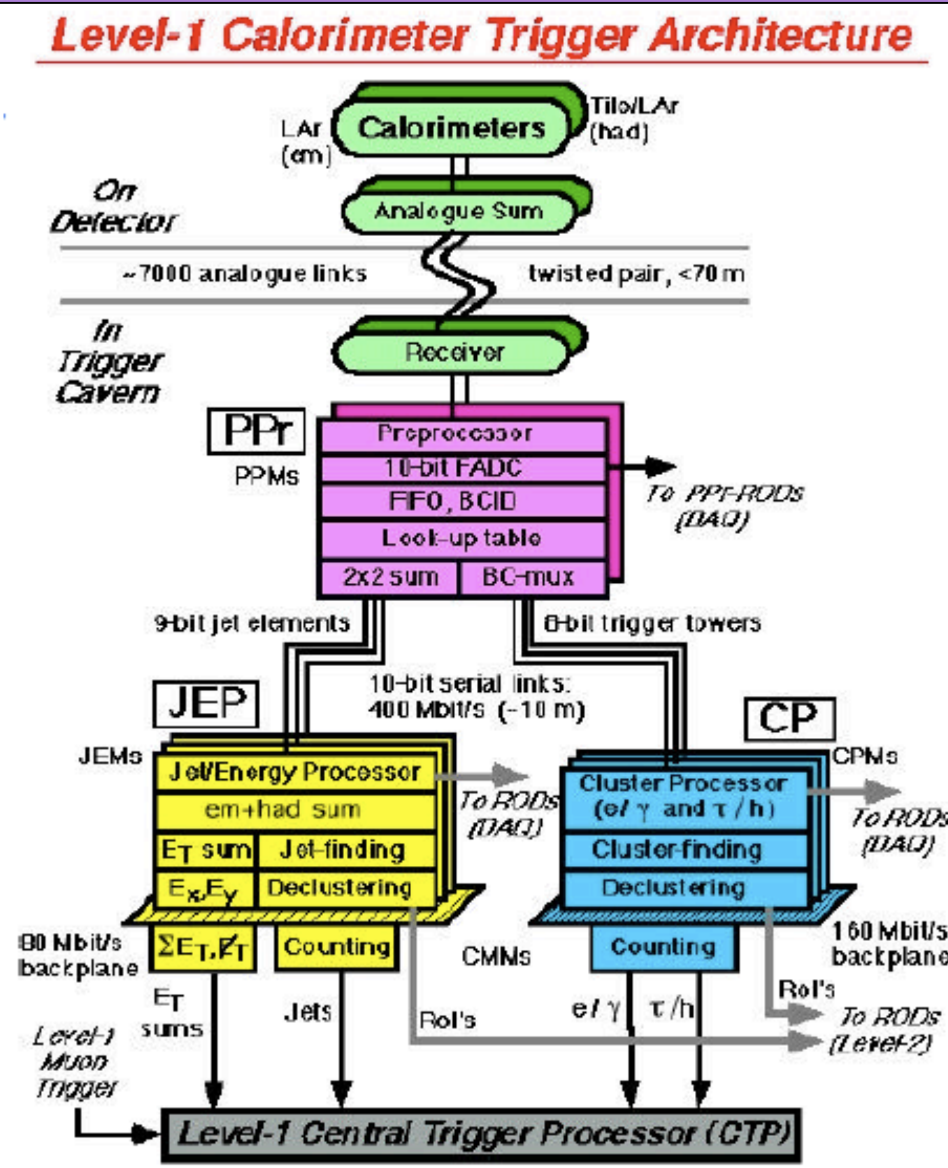


Calorimeter Trigger looking for e/γ/t + jets

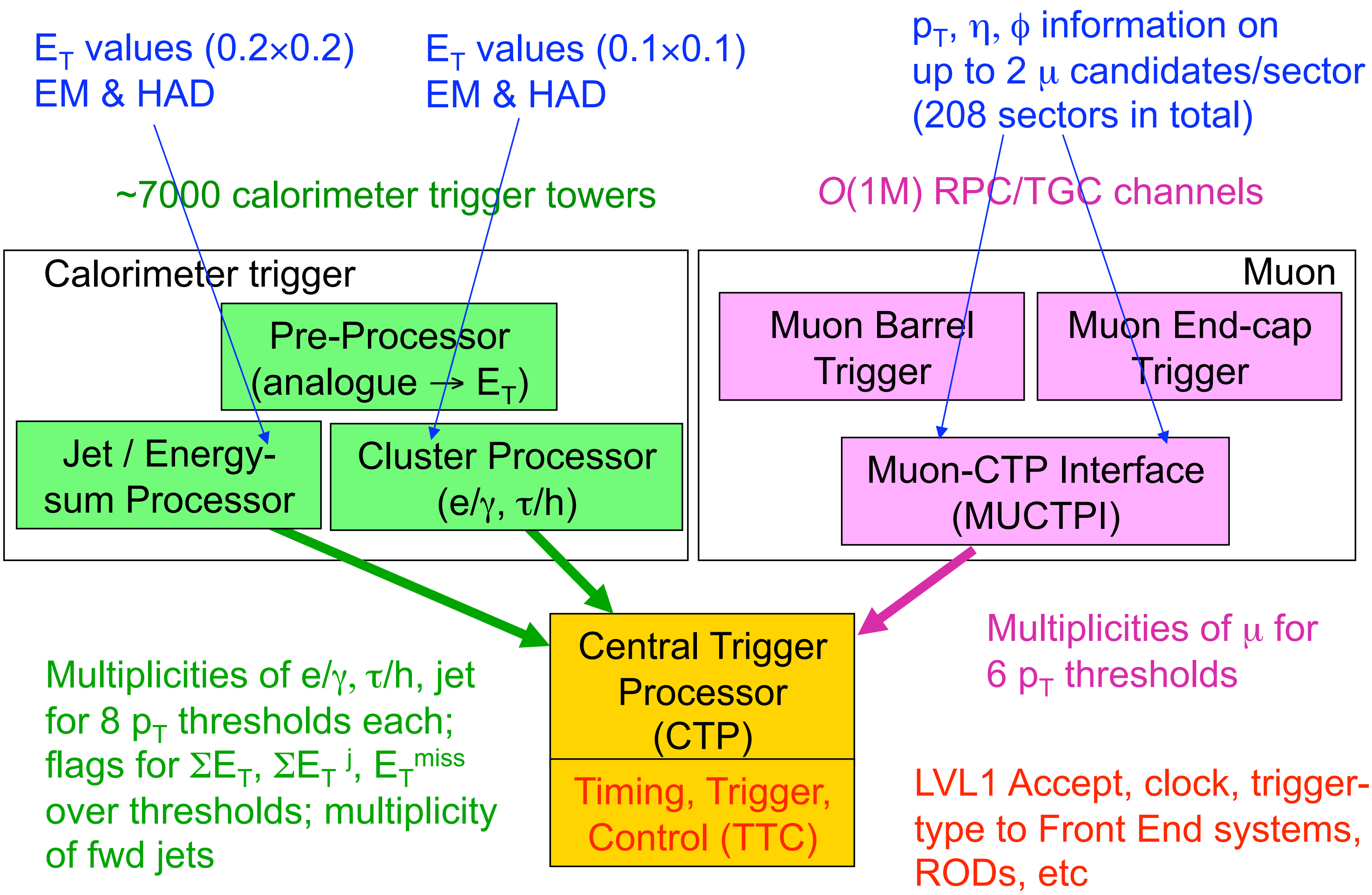
- Various combinations of cluster sums and isolation criteria
- $\Sigma E_T^{em,had}$, E_T^{miss}

ATLAS L1 Cal. Trigger data-flow

- On-detector:
  - Analog sums to form trigger towers (trigger primitives)
- Off-detector:
  - Receive data, digitize, identify bunch crossing, compute ET
  - Send data to cluster processer and jet energy processor
- Local processor crates
  - form sums, comparisons as per algorithm, decide on objects found
- Global Trigger: decision



ATLAS L1 Trigger

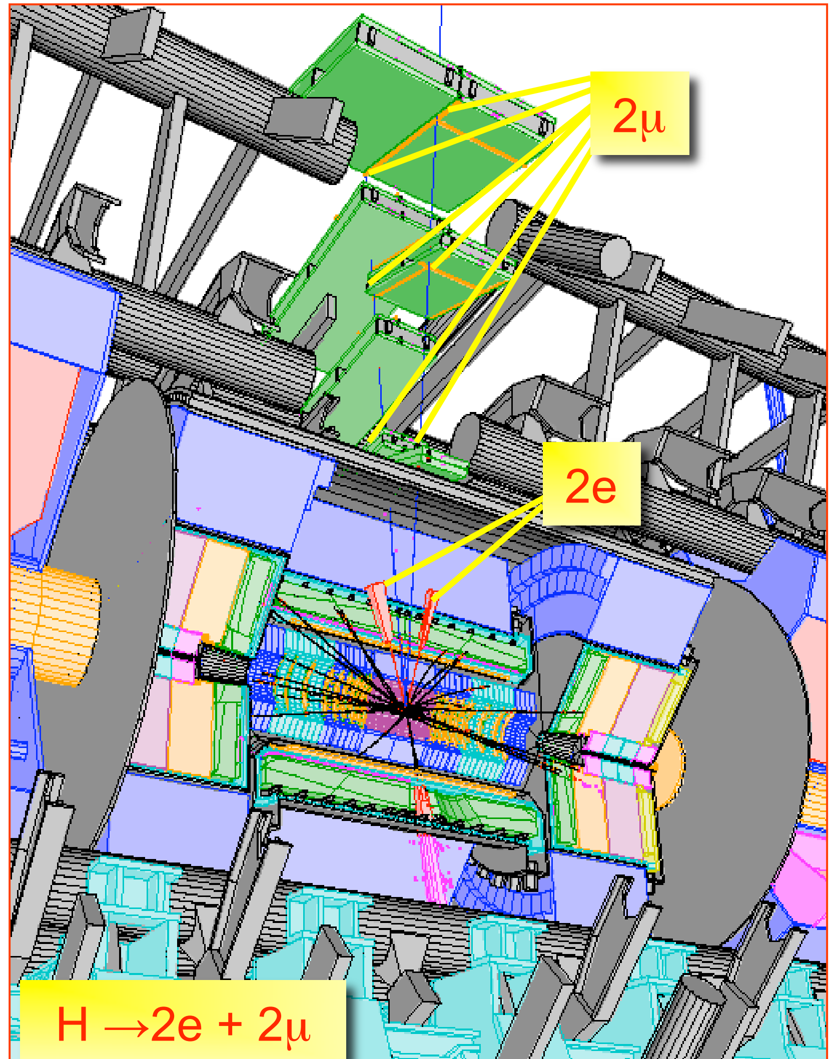


RoI Mechanism

- Level-1 triggers on high p_T objects
  - Calorimeter cells and muon chambers to find e/γ/τ-jet/μ candidates above thresholds

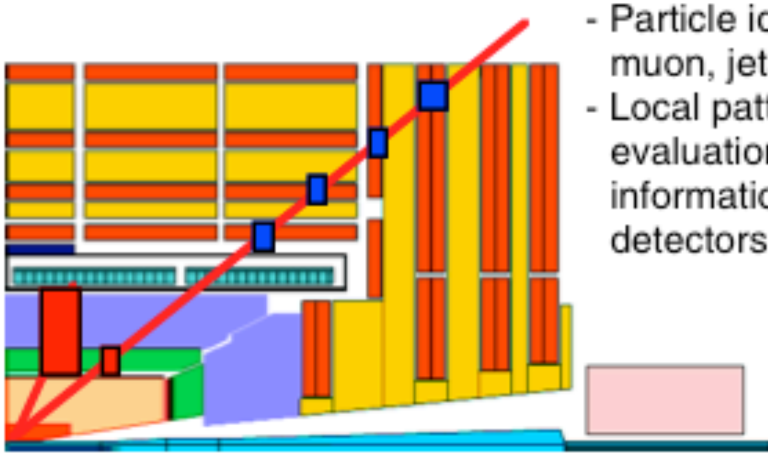
- Level-2 uses Regions of Interest as identified by Level-1
  - Local data reconstruction, analysis, and sub-detector matching of RoI data

- The total amount of RoI data is minimal
  - ~2% of the Level-1 throughput but it has to be extracted from the rest at 75 kHz



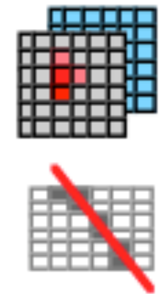
CMS Trigger Levels

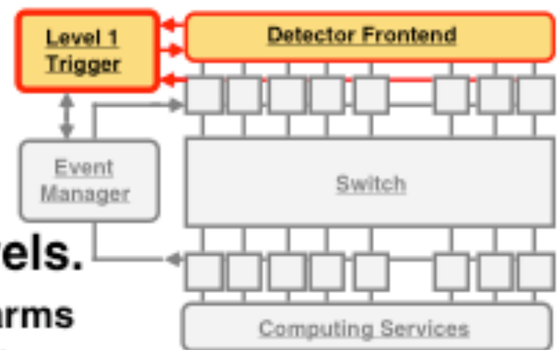
40 MHz



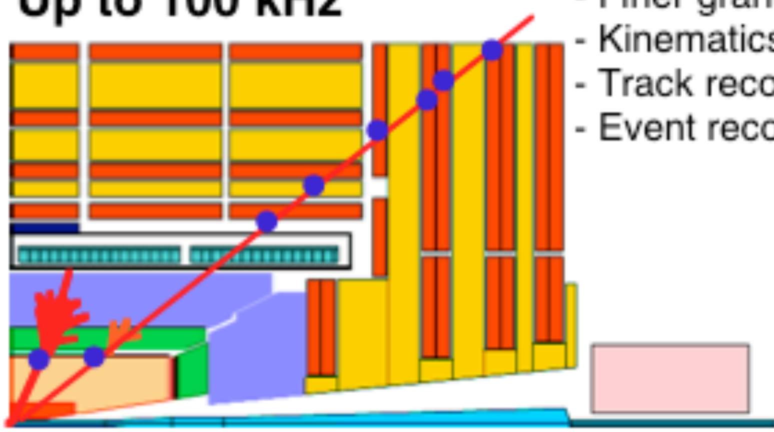
Level-1. Specialized processors

- Particle identification: high p_T electron, muon, jets, missing E_T
- Local pattern recognition and energy evaluation on prompt macro-granular information from calorimeter and muon detectors





Up to 100 kHz

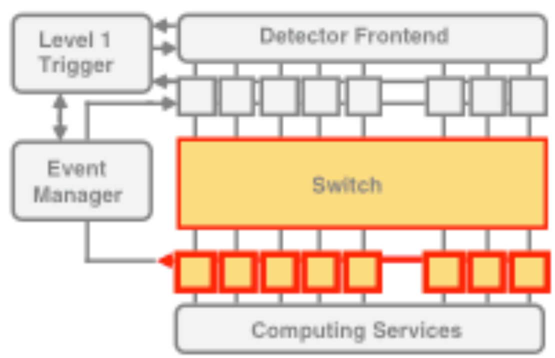


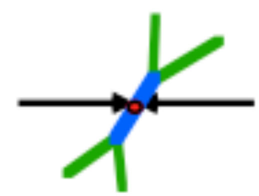
High trigger levels.

Network and CPU farms

- Clean particle signature
- Finer granularity precise measurement
- Kinematics. effective mass cuts & event topology
- Track reconstruction and detector matching
- Event reconstruction and analysis

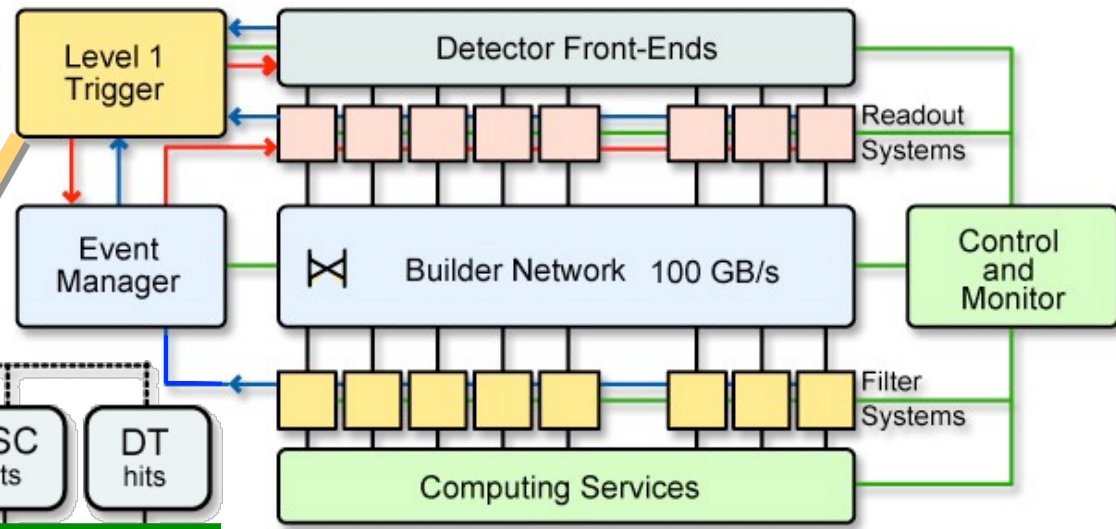
≈ 100 Hz

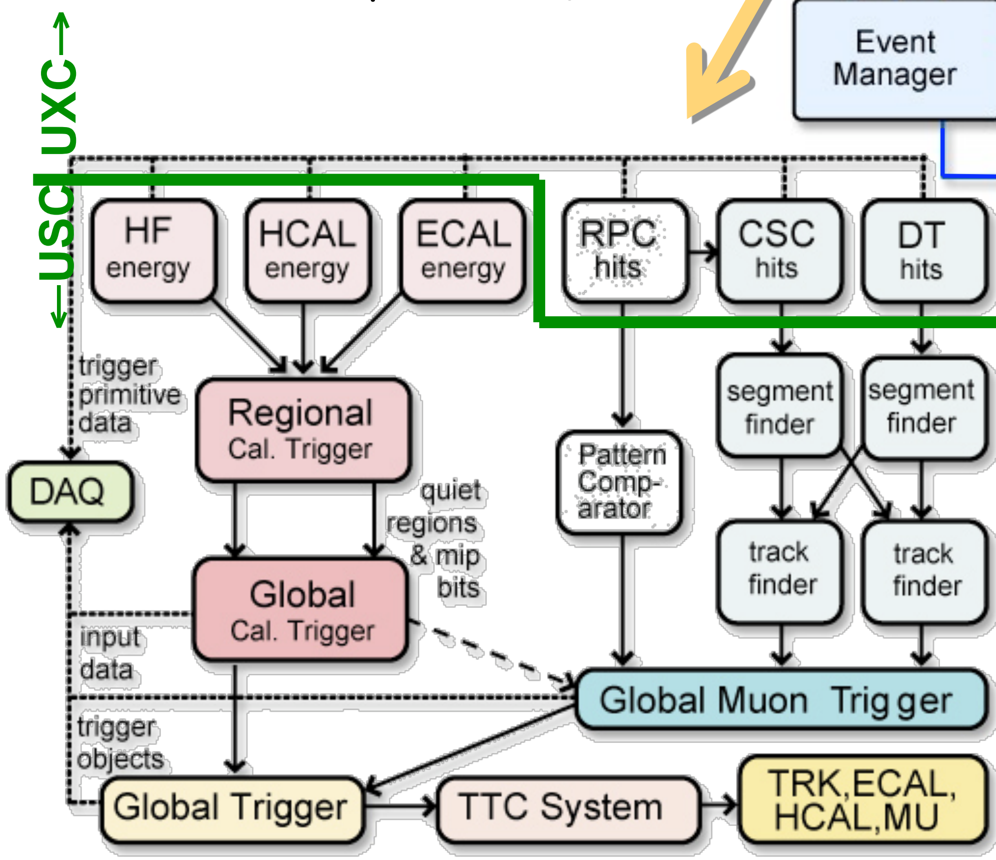




CMS Level-1 Trigger & DAQ

- Overall Trigger & DAQ Architecture: 2 Levels:
- Level-1 Trigger:
  - 25 ns input
  - 3.2 μs latency





Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

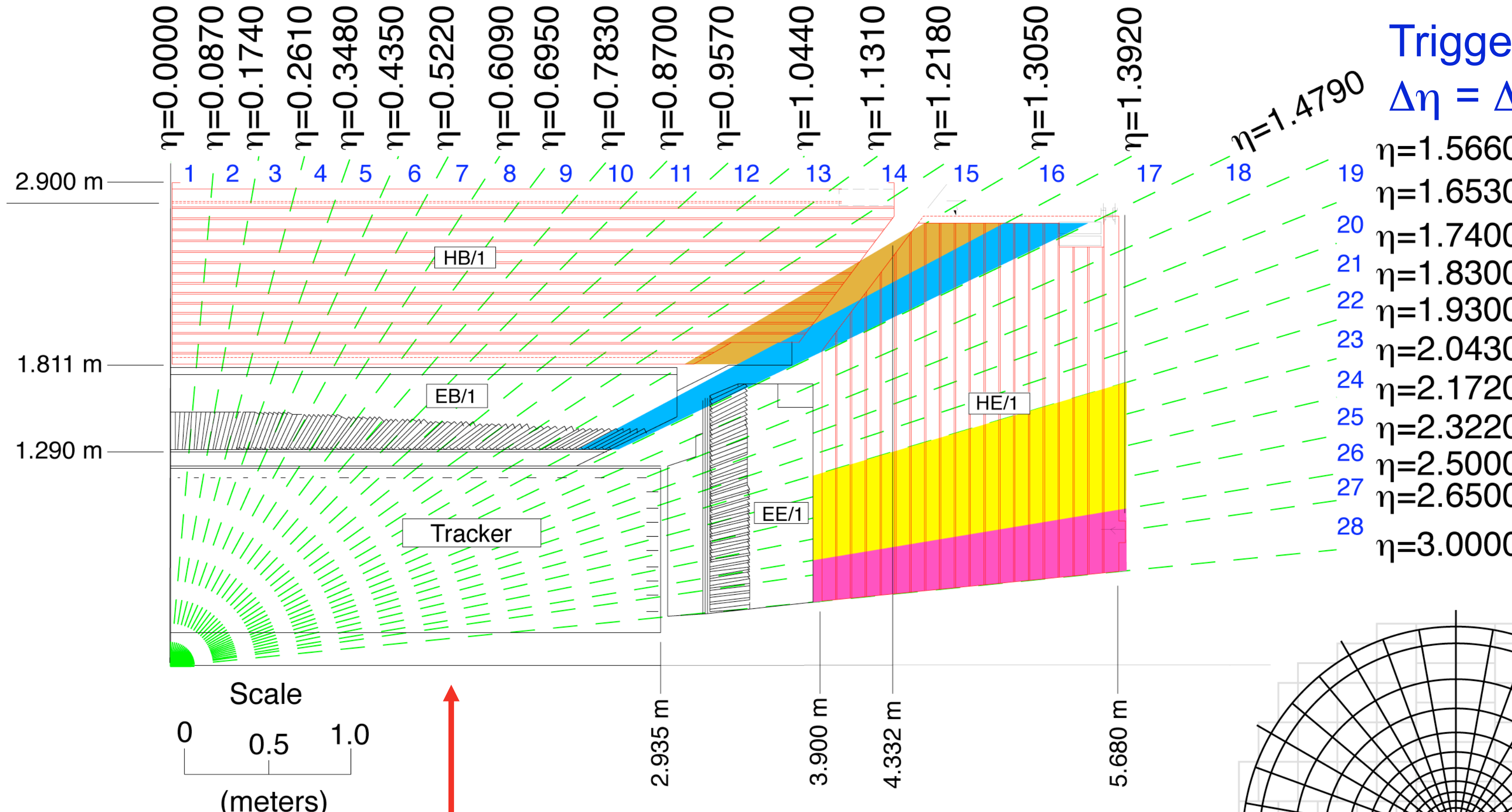
Output to Storage: ~100 Hz

Average Event Size: 1 MB

Data production 1 TB/day

CMS Calorimeter Geometry

Trigger towers:
$\Delta\eta = \Delta\phi = 0.087$



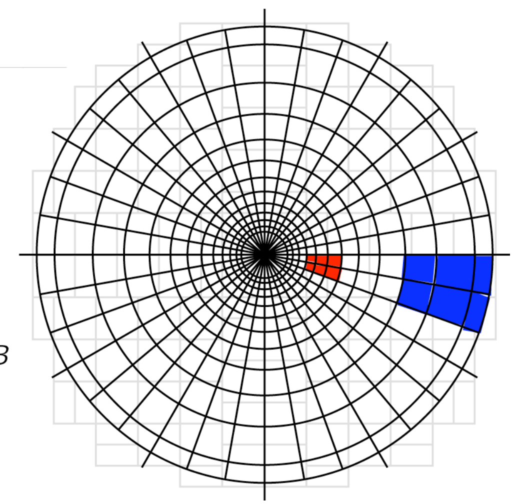
EB, EE, HB, HE map to 18 RCT crates

Provide e/γ and jet, τ, E_T triggers

2 HF calorimeters map on to 18 RCT crates

Readout segmentation: 36φ × 12η × 2z × 2F/B

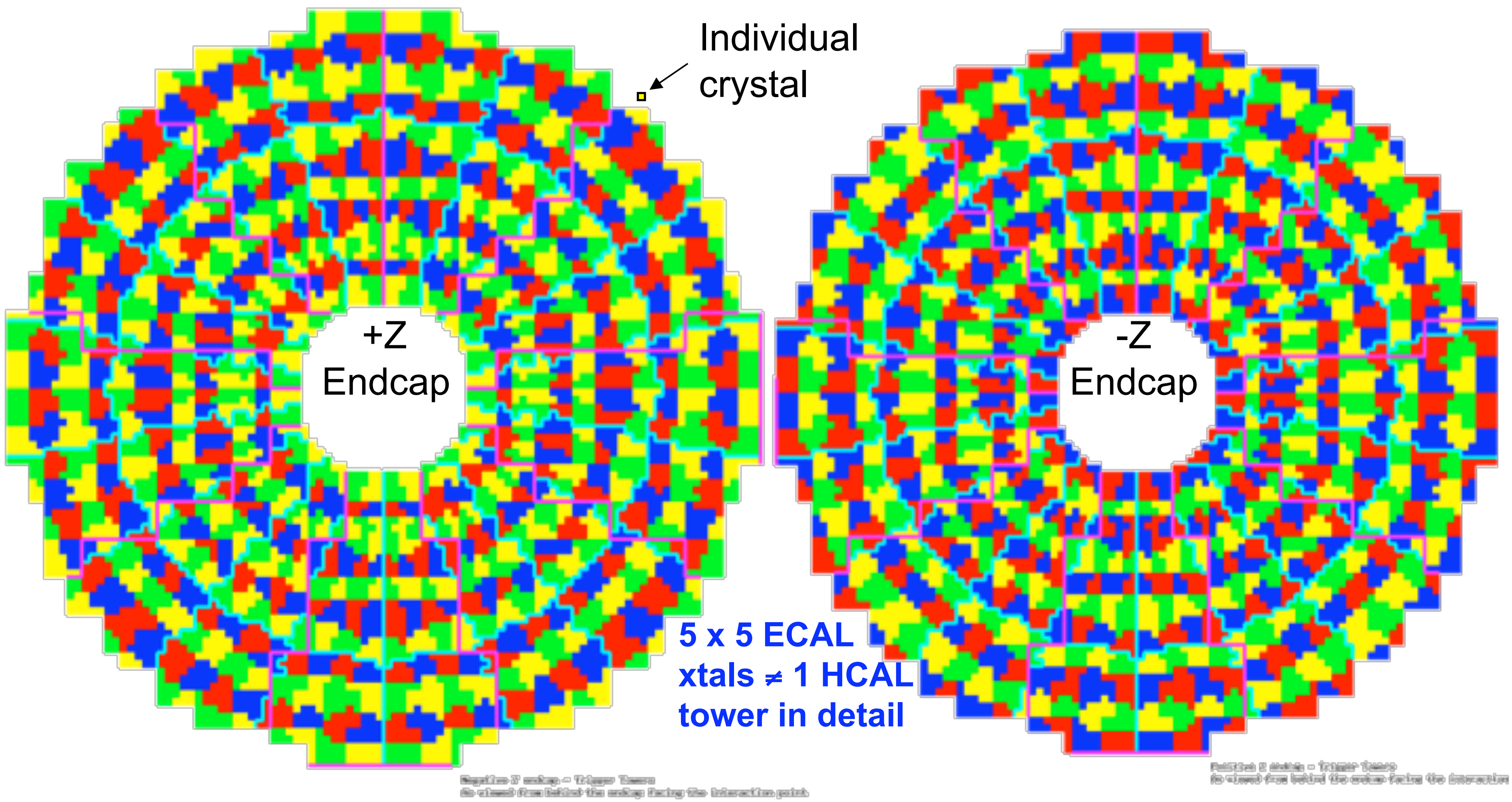
Trigger Tower segmentation: 18φ × 4η × 2F/B



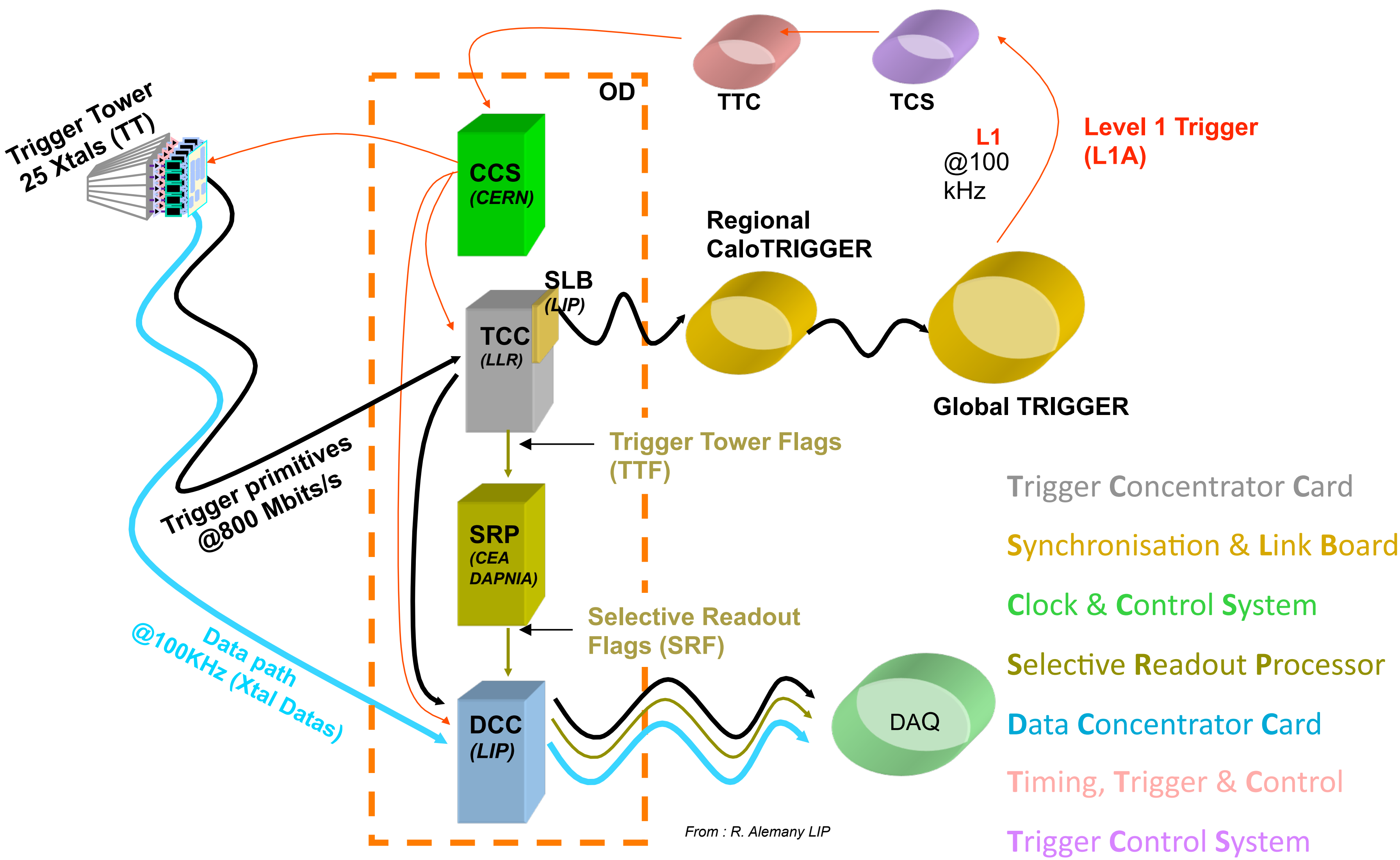
1 trigger tower (.087η x .087φ) = 5 x 5 ECAL xtals = 1 HCAL tower

ECAL Endcap Geometry

- Map non-projective x-y trigger crystal geometry onto projective trigger towers:

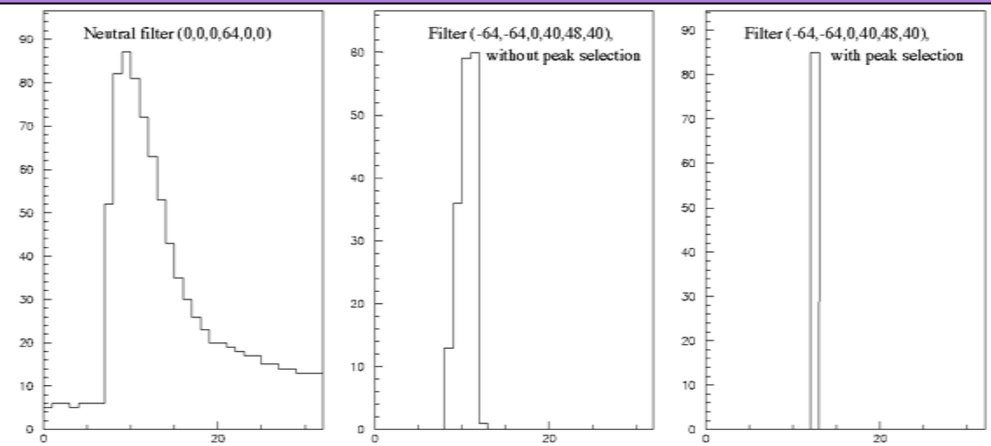


Calorimeter Trigger Processing



ECAL Trigger Primitives

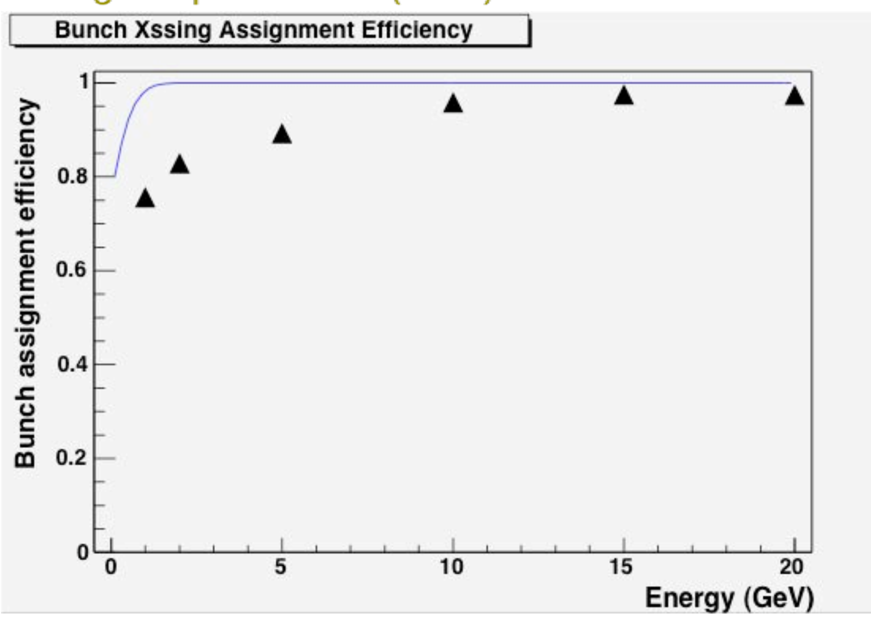
In the trigger path, **digital filtering** followed by a **peak finder** is applied to energy sums **(L1 Filter)**

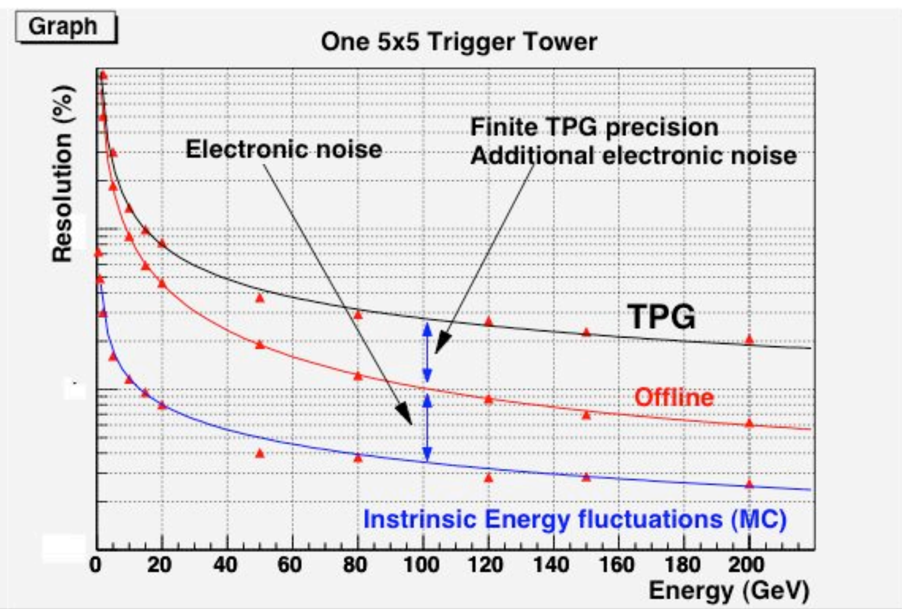


Efficiency for energy sums above 1 GeV should be close to 100% (depends on electronics noise)

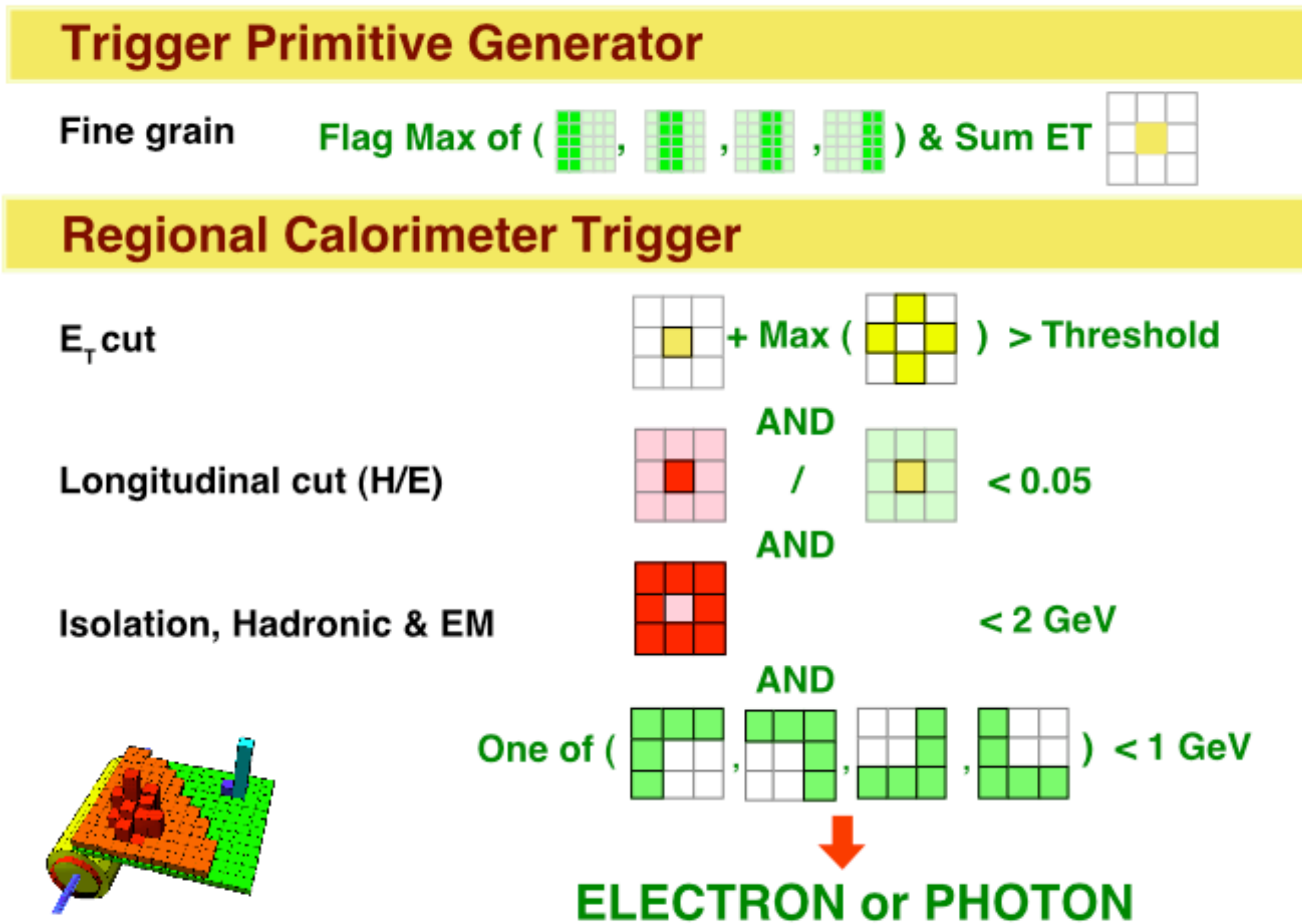
Pile-up effect: for a signal of 5 GeV the efficiency is close to 100% for pile-up energies up to 2 GeV (CMS)

Test beam results (45 MeV per xtal):

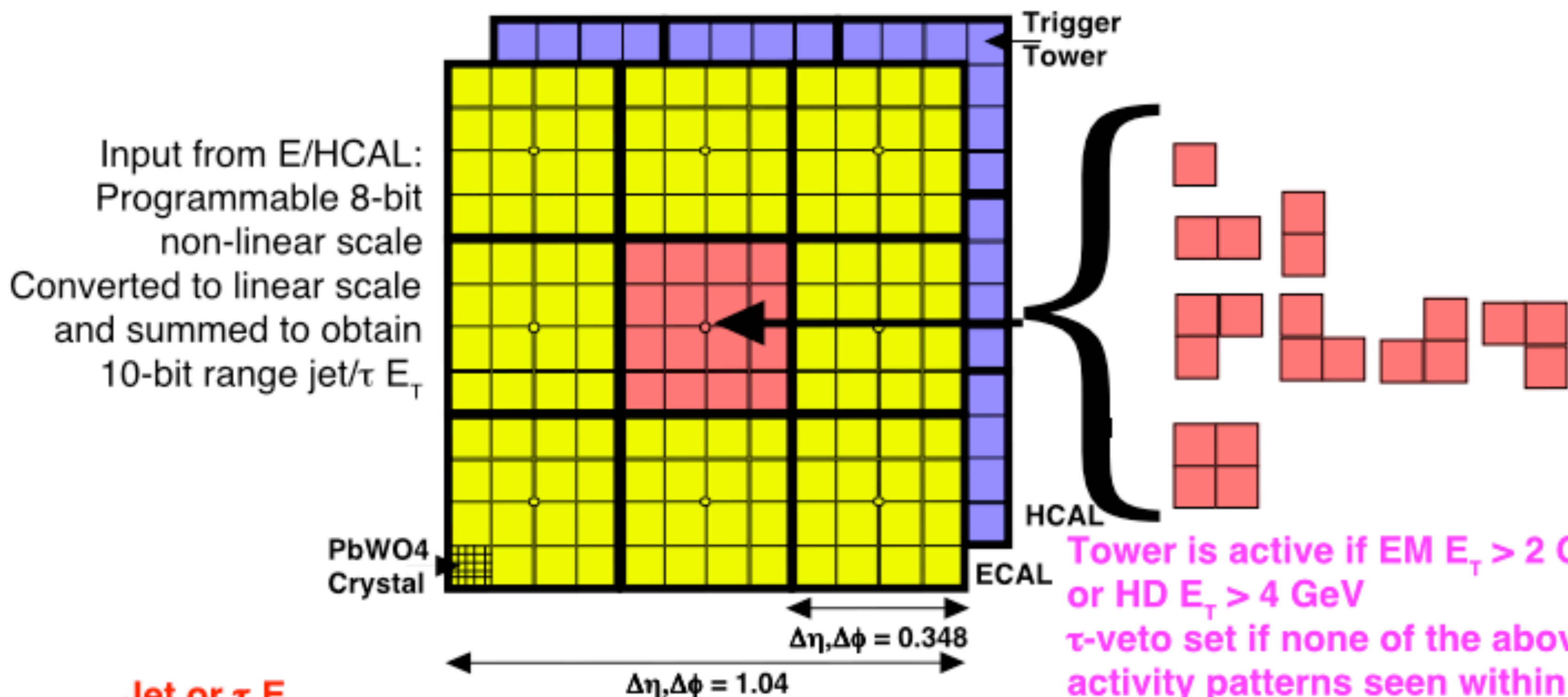




CMS Electron/γ Algorithm



CMS τ / Jet Algorithm



Tower is active if EM $E_T > 2$ GeV or HD $E_T > 4$ GeV
τ-veto set if none of the above activity patterns seen within 4x4

Jet or τ E_T

- 12x12 trigger tower E_T sums in 4x4 region steps with central region > others
- Larger trigger towers in HF but ~ same jet region size, 1.5 η x 1.0 ϕ

τ algorithm (isolated narrow energy deposits), within $-2.5 < \eta < 2.5$

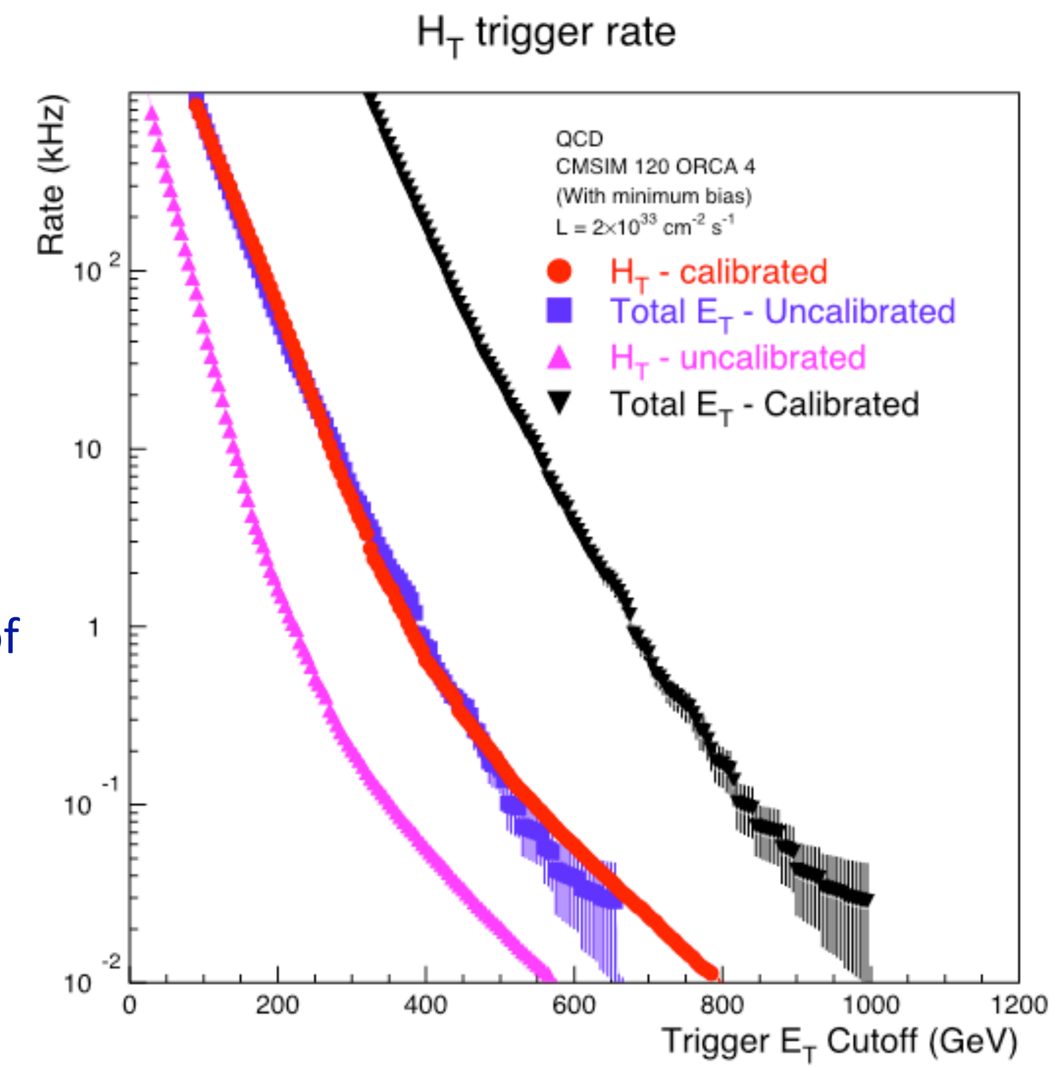
- Redefine jet as τ jet if none of the nine 4x4 region τ-veto bits are on

Output

- Top 4 τ-jets and top 4 jets in central rapidity, and top 4 jets in forward rapidity

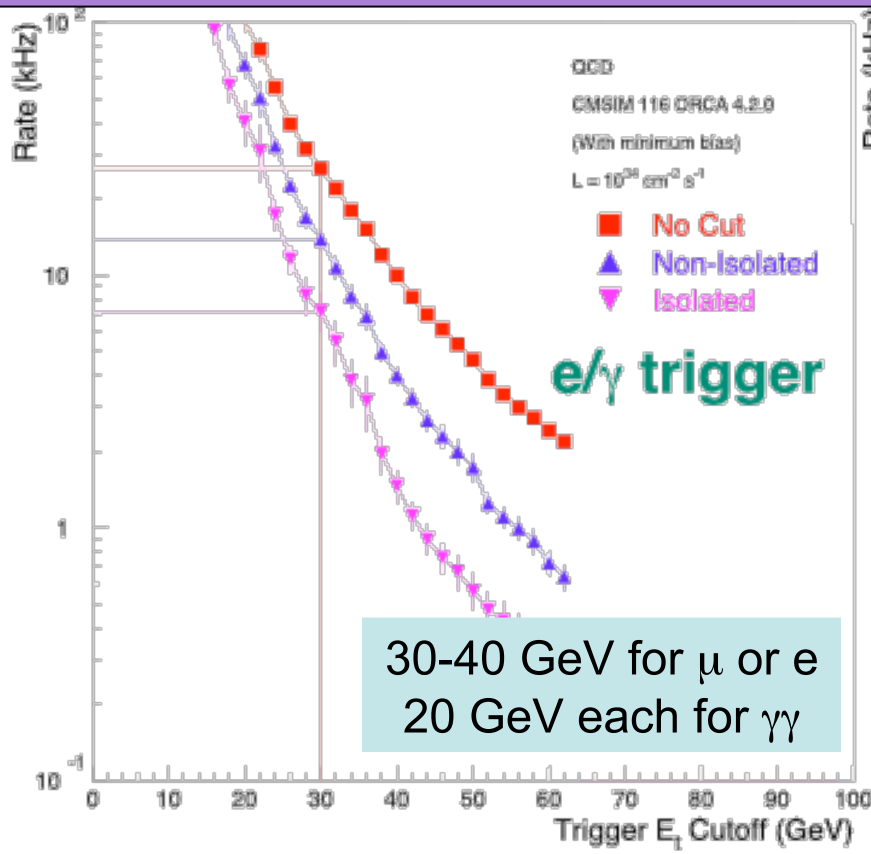
H_T Trigger

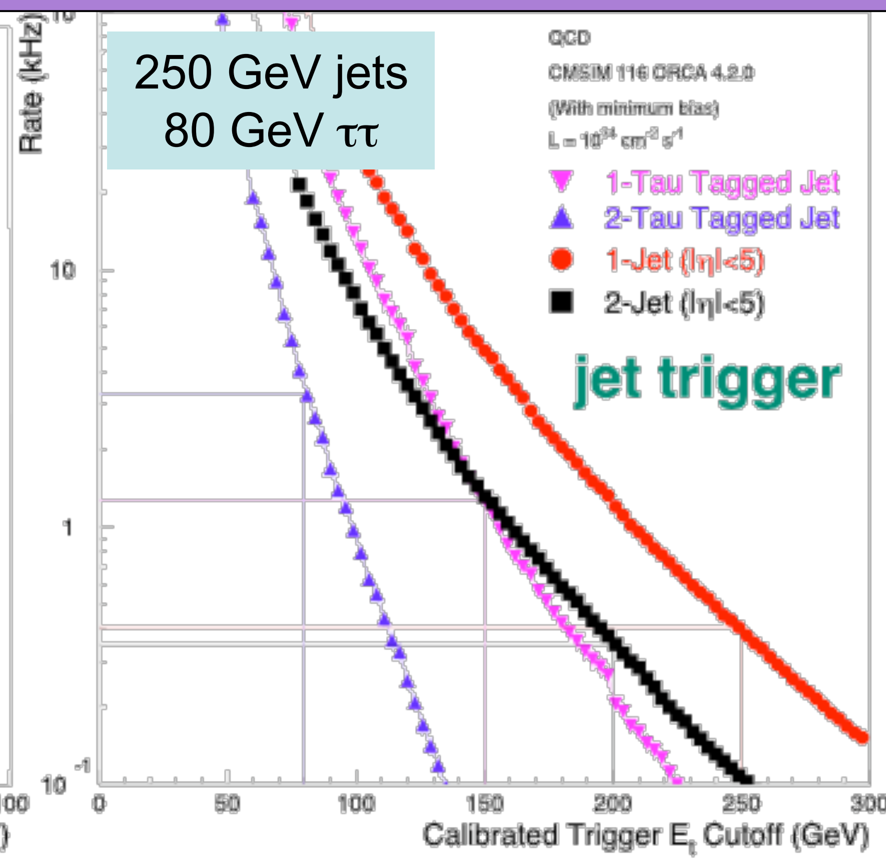
- Total scalar E_T integrates too much noise and is not easily calibrated
  - At L1 tower-by-tower E_T calibration is not available
- However, jet calibration is available as function of (E_T, η, ϕ)
- Therefore, H_T which is the sum of scalar E_T of all high E_T objects in the event is more useful for heavy particle discovery/study
  - SUSY sparticles
  - Top



Level-1 Trigger Rates:

Trigger cuts determine the physics reach

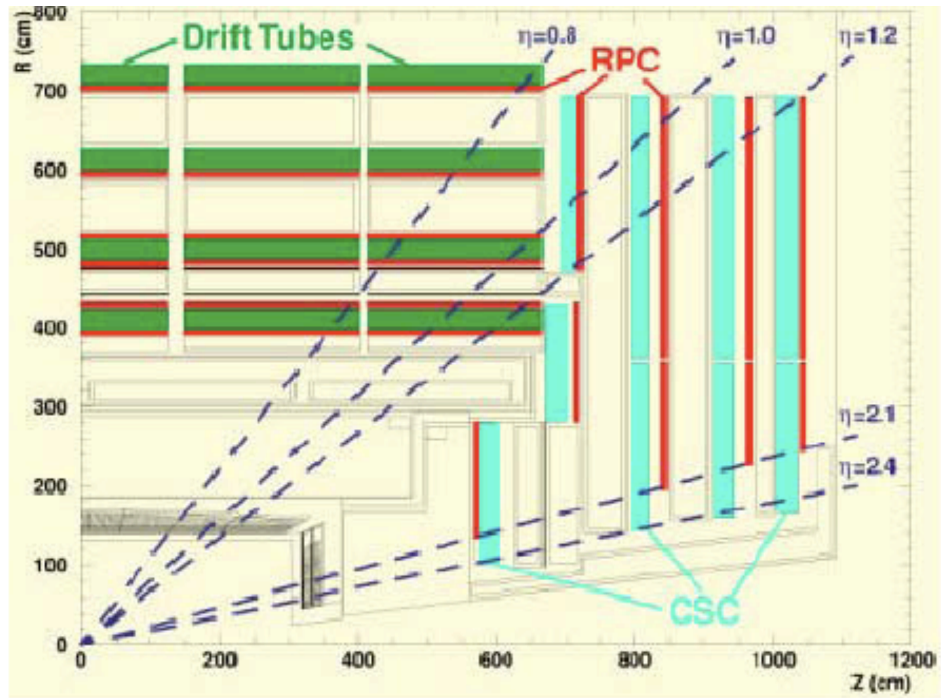


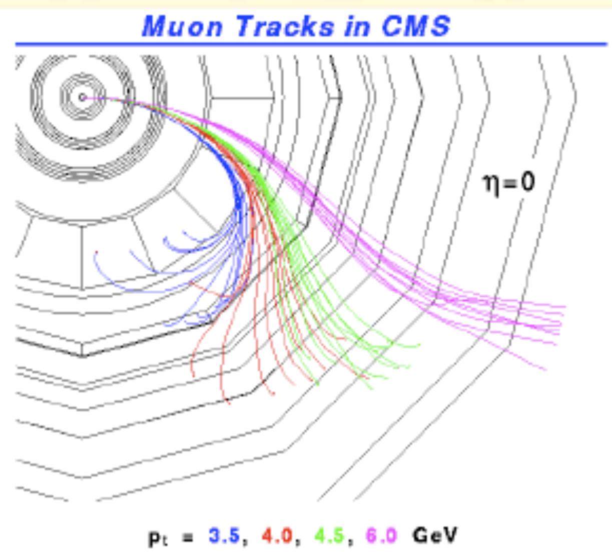


- **Efficiency for H→γγ and H→4 leptons = >90% (in fiducial volume of detector)**
- **Efficiency for WH and ttH production with W→lν = ~85%**
- **Efficiency for qqH with H→ττ (τ→1/3 prong hadronic) = ~75%**
- **Efficiency for qqH with H→invisible or H→bb = ~40-50%**

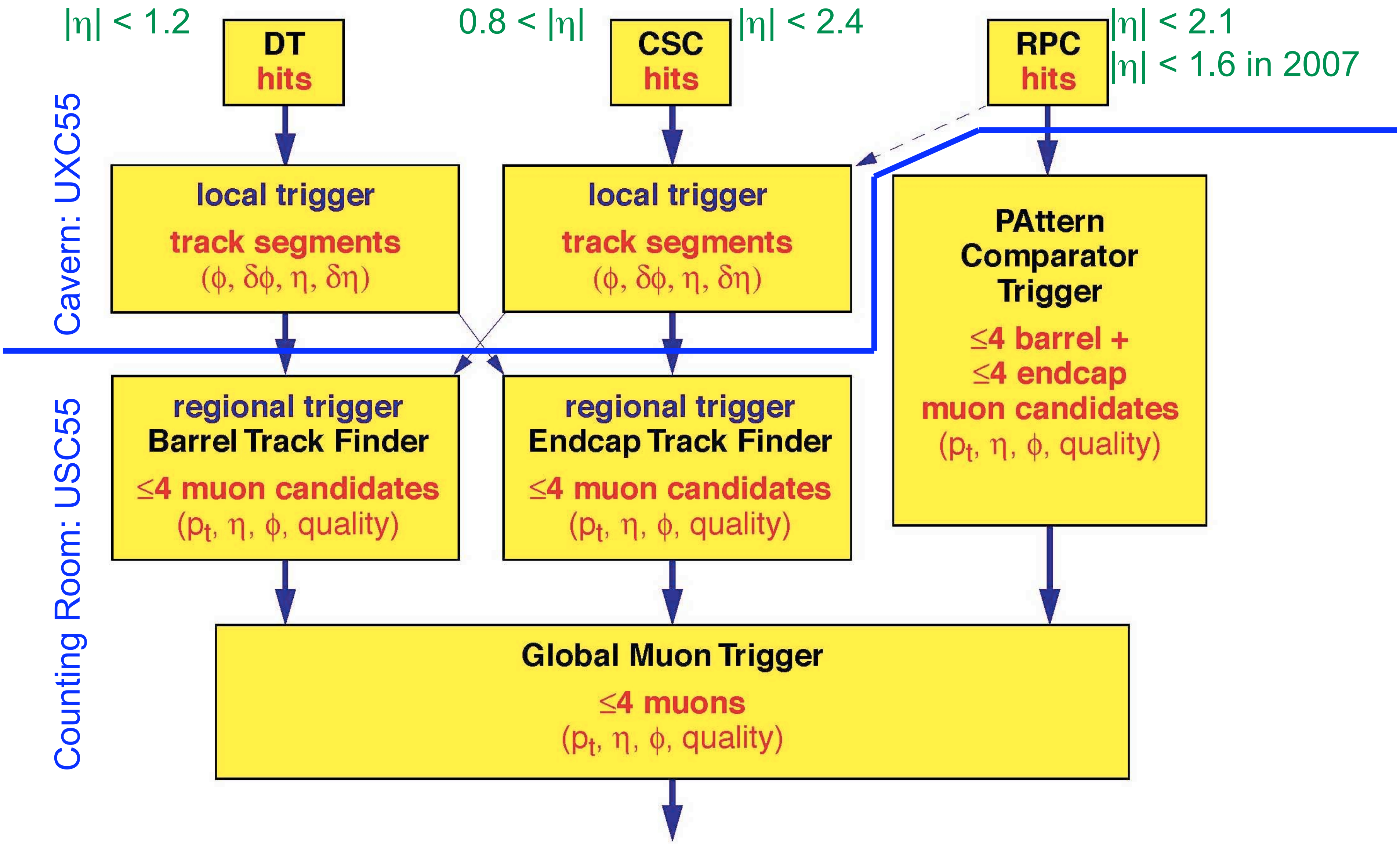
CMS Level-1 Muon Trigger

- Level-1 muon trigger info is obtained from:
  - Dedicated trigger detector (Resistive paralle plate chambers: RPC)
    - Excellent time resolution
  - Muon chambers with accurate position resolution
    - Drift Tubes (DT) in barrel
    - Cathode Strip Chambers (CSC) in endcaps
  - Bending in magnetic field =>
    - Determine pT
    - And cut on it



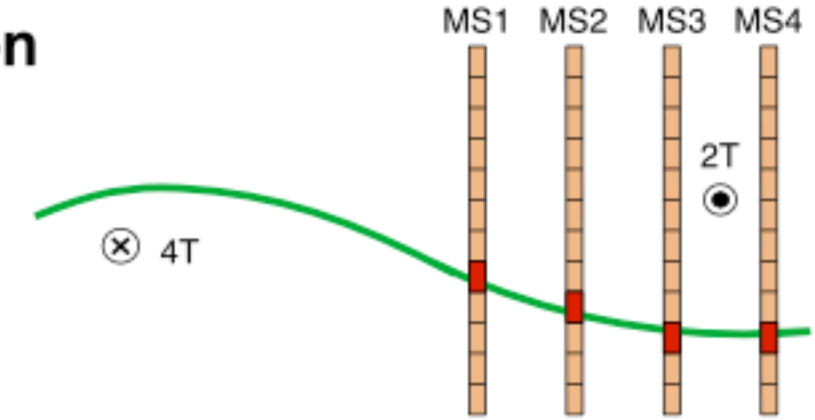


Muon Trigger Overview



CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

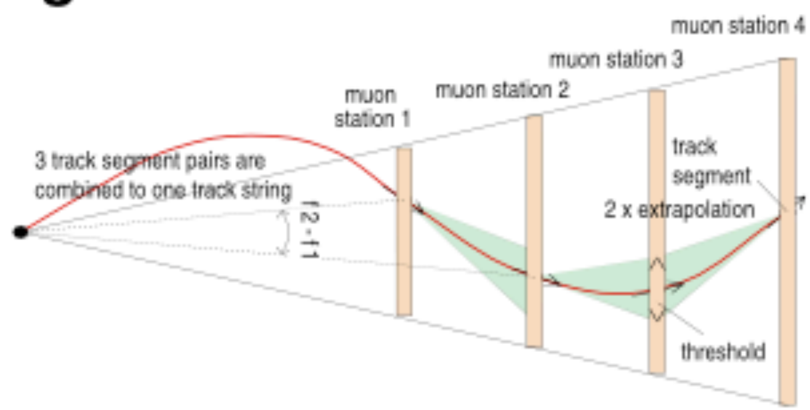


Memory to store patterns

Fast logic for matching

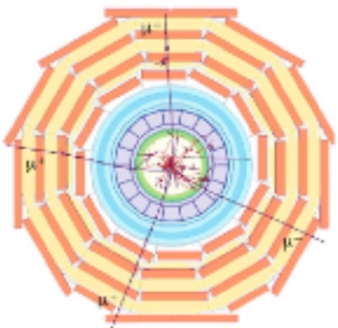
FPGAs are ideal

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

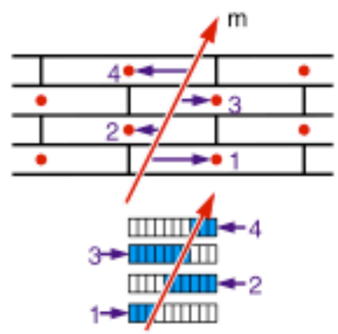


CMS Muon Trigger

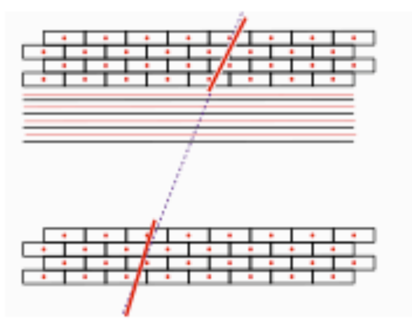
Drift Tubes (DT)



Drift Tubes



Meantimers recognize tracks and form vector / quartet.



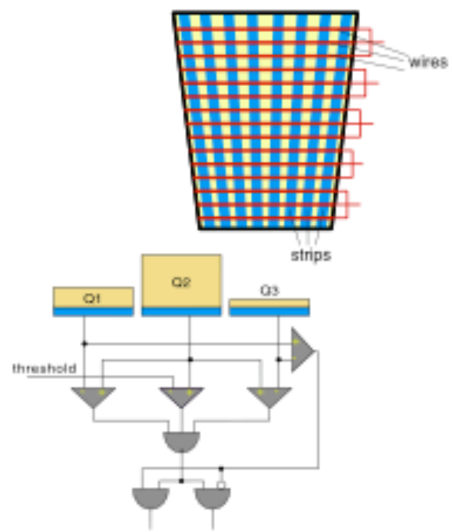
Correlator combines them into one vector / station.

Match with RPC

Improve efficiency and quality

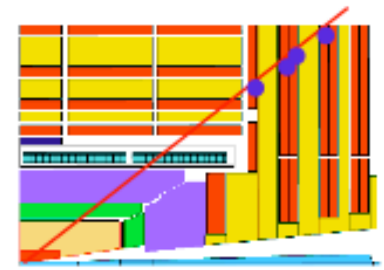
Cathod Strip Chambers (CSC)

CSC



Comparators give 1/2-strip resol.

Hit strips of 6 layers form a vector



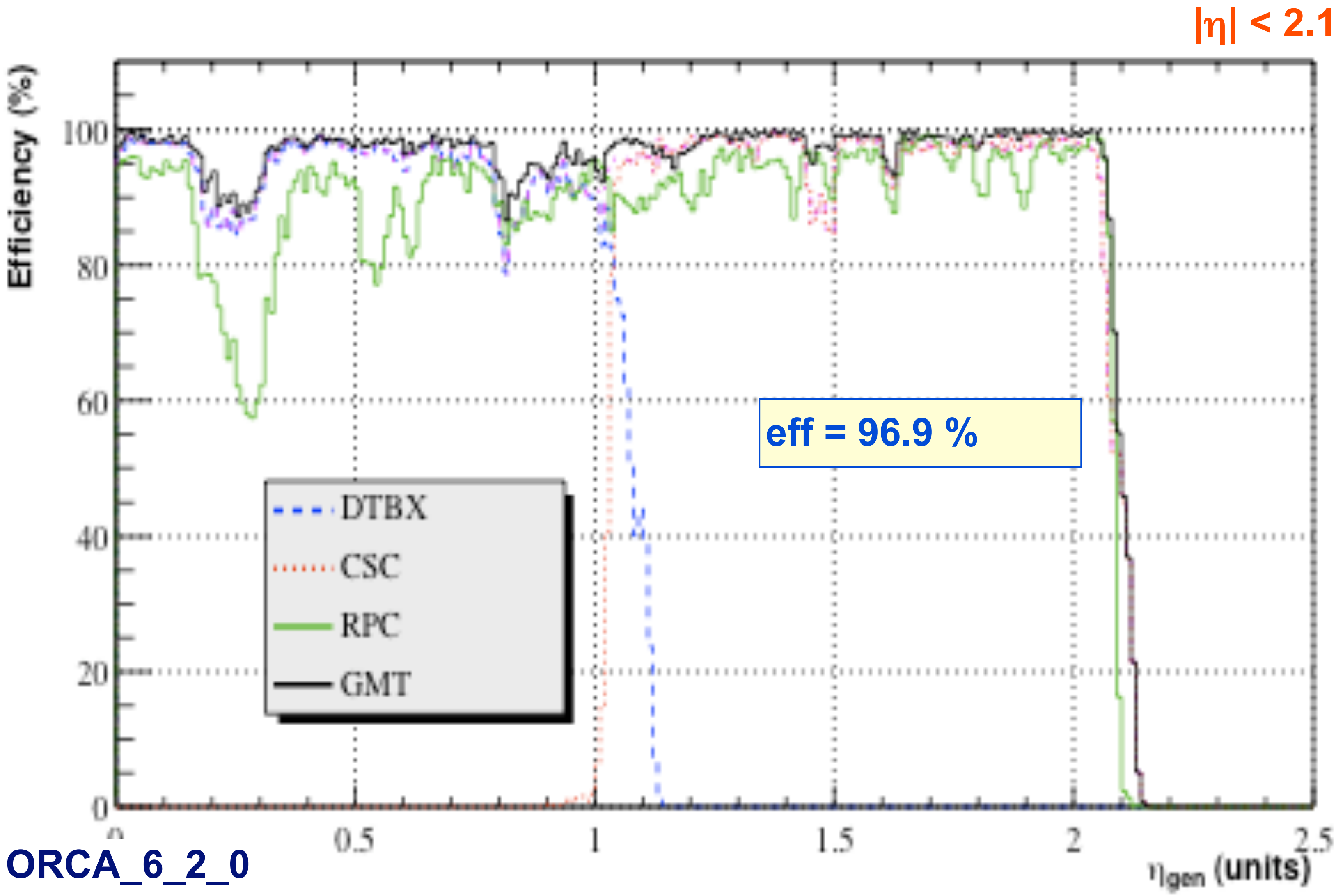
Sort based on P_T, Quality - keep loc.

Combine at next level - match

Sort again – Isolate…

Top 4 highest P_T and quality muons with location coord.

Single muon trigger efficiency vs. η



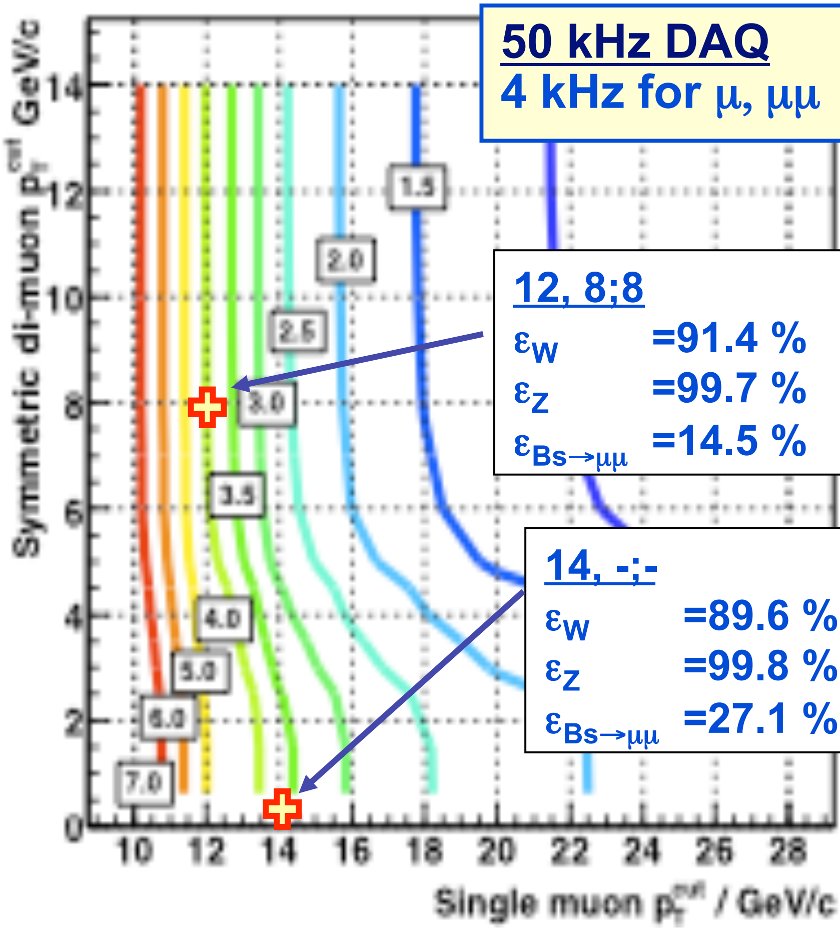
ORCA_6_2_0

η (*)efficiency to find muon of any p_T in flat p_T =3-100 GeV sample

L1 single & di-muon trigger rates

trigger rates in kHz

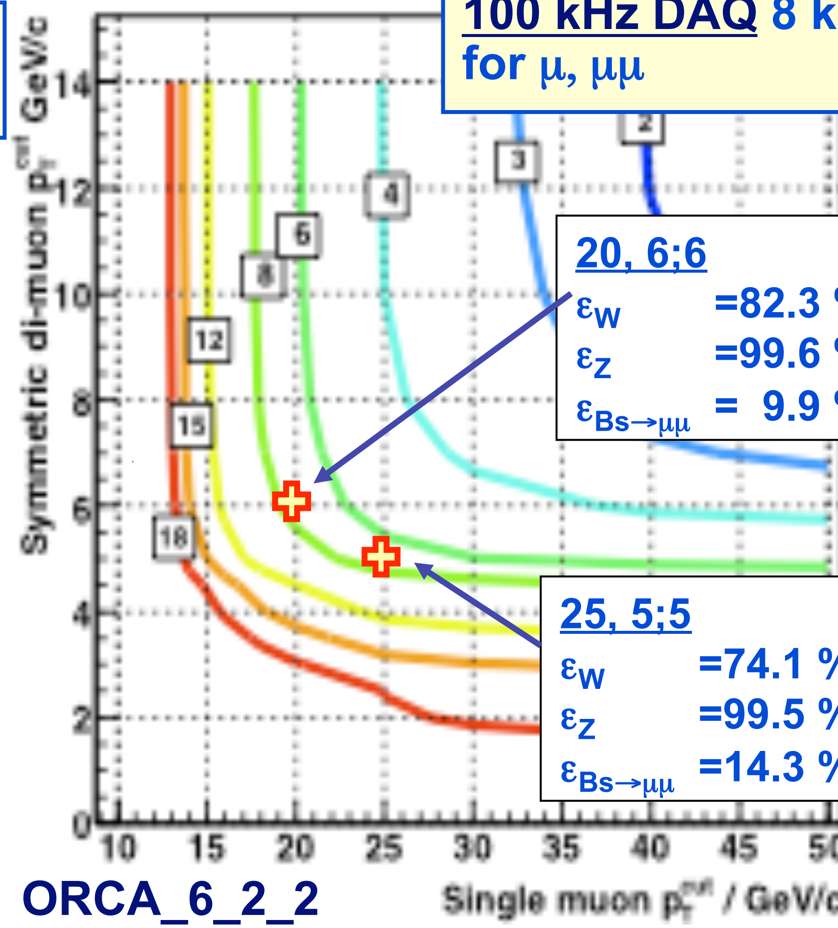
|η| < 2.1



50 kHz DAQ
4 kHz for μ, μμ

12, 8;8
ε_W =91.4 %
ε_Z =99.7 %
$\varepsilon_{Bs\to\mu\mu}$ =14.5 %

14, -;-
ε_W =89.6 %
ε_Z =99.8 %
$\varepsilon_{Bs\to\mu\mu}$ =27.1 %



100 kHz DAQ 8 kHz
for μ, μμ

20, 6;6
ε_W =82.3 %
ε_Z =99.6 %
$\varepsilon_{Bs\to\mu\mu}$ = 9.9 %

25, 5;5
ε_W =74.1 %
ε_Z =99.5 %
$\varepsilon_{Bs\to\mu\mu}$ =14.3 %

ORCA_6_2_2

✚ working points selected as examples

$L = 2x10^{33} cm^{-2}s^{-1}$

$L = 10^{34} cm^{-2}s^{-1}$

Global Trigger

- A very large OR-AND network which allows specification of complex conditions:
  - 1 electron with pT > 20 GeV OR 2 electrons with pT > 14 GeV OR 1 electron with pT > 12 GeV AND 1 jet with pT > 40 GeV
  - The top-level logic requirements (1 electron + 1 jet for eg.) constitute a "Trigger table"
    - Allocating rates to different trigger conditions is a complex process that requires optimization of physics efficiencies versus backgrounds, rates and machine conditions
    - More on this in the next lecture

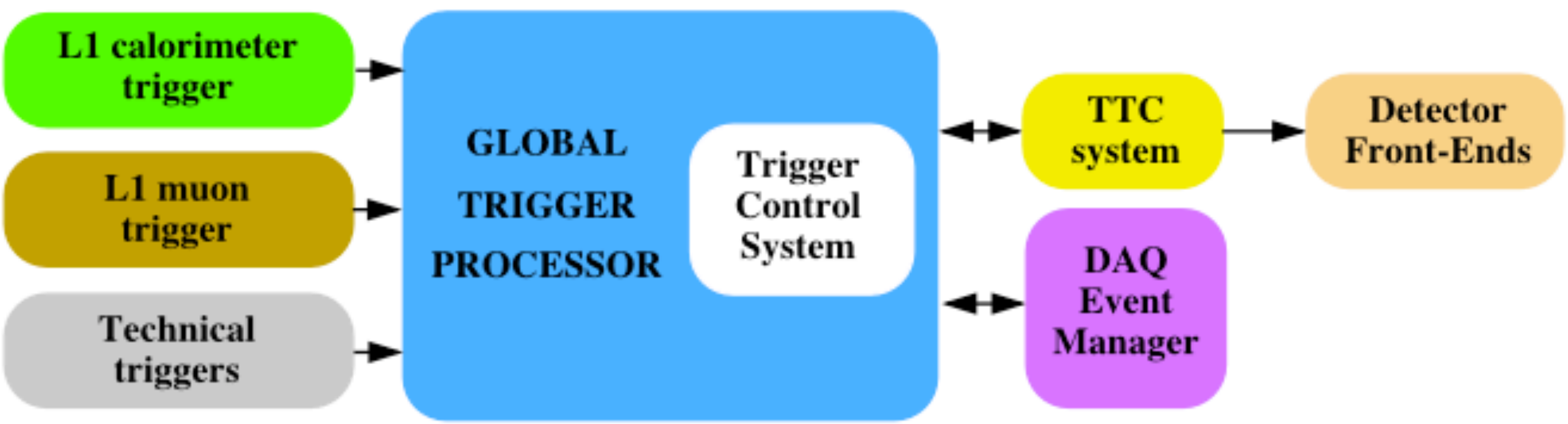
CMS Global Trigger

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

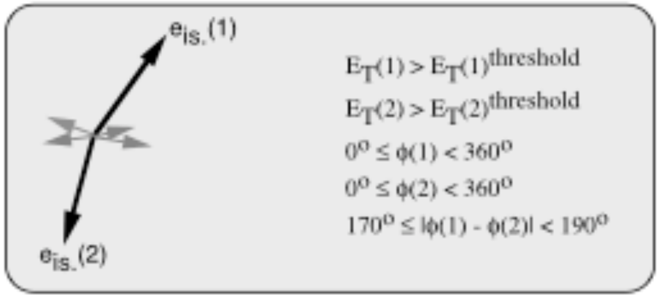
Output

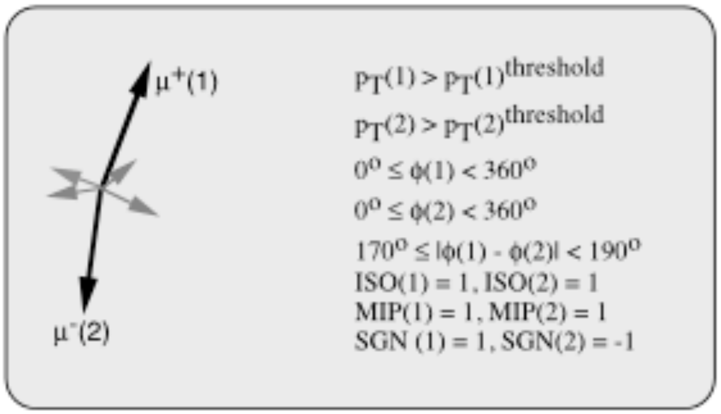
- L1 Accept from combinations & proximity of above



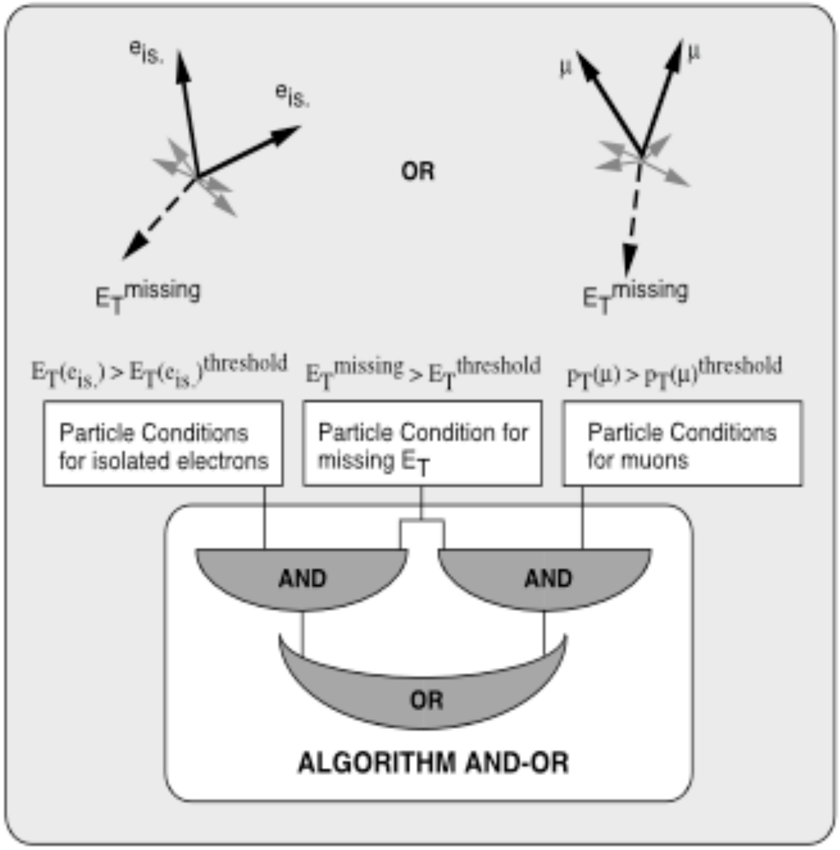
Global L1 Trigger Algorithms

Particle Conditions





Logical Combinations



Flexible algorithms implemented in FPGAs
100s of possible algorithms can be reprogrammed

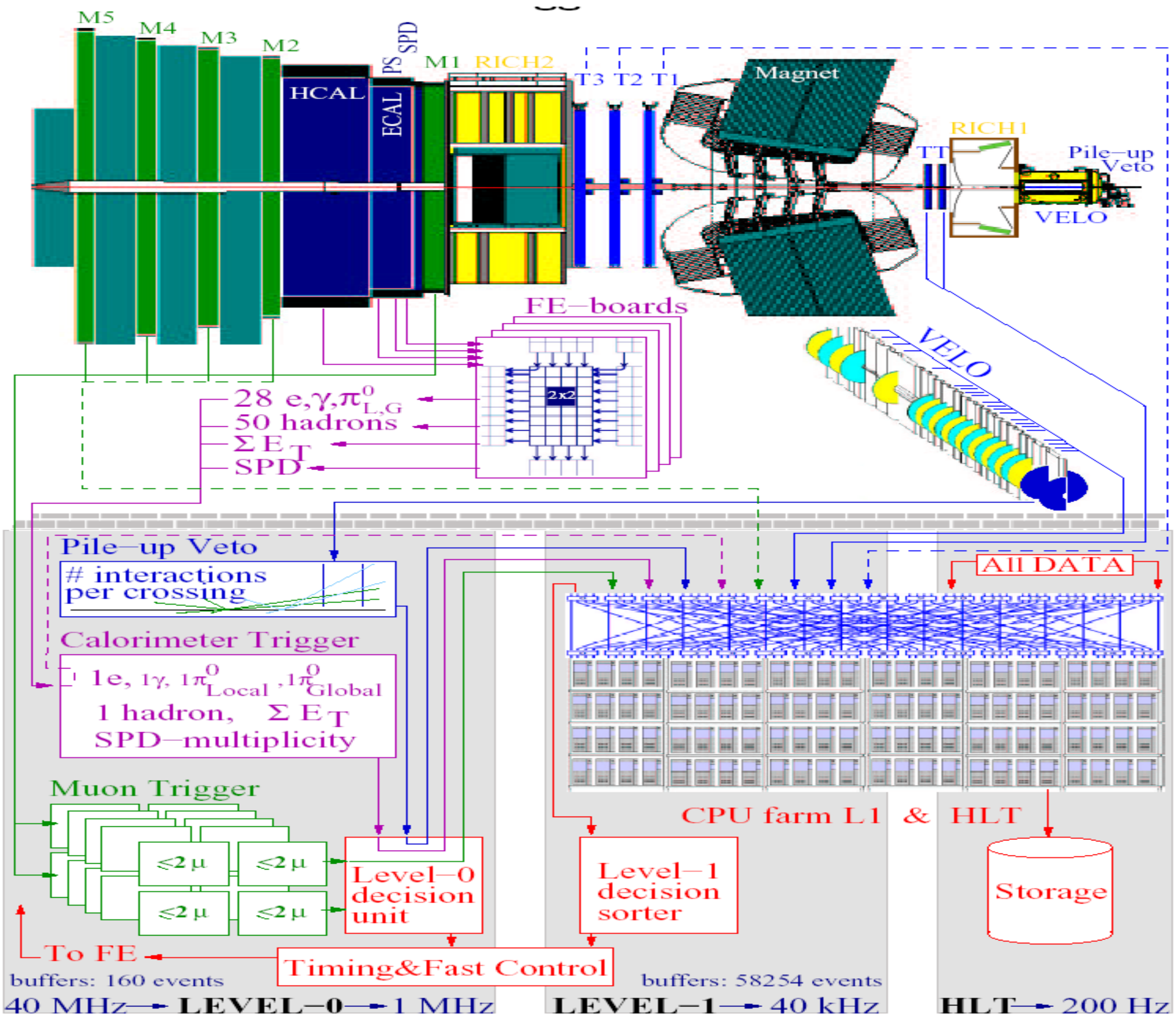
Example Level-1 Trigger Table (DAQ TDR: *L*=2

Trigger	*Threshold (GeV or GeV/c)*	*Rate (kHz)*	*Cumulative Rate (kHz)*
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			**16.0**

× 3 safety factor ⇒ 50 kHz (expected start-up DAQ bandwidth)

Only muon trigger has low enough threshold for B-physics (aka $B_s \rightarrow \mu\mu$)

LHCb Trigger

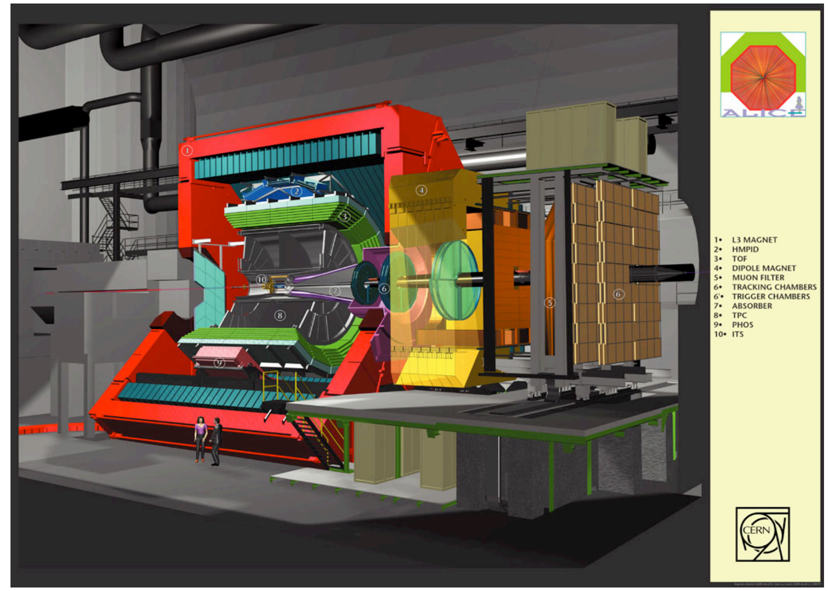


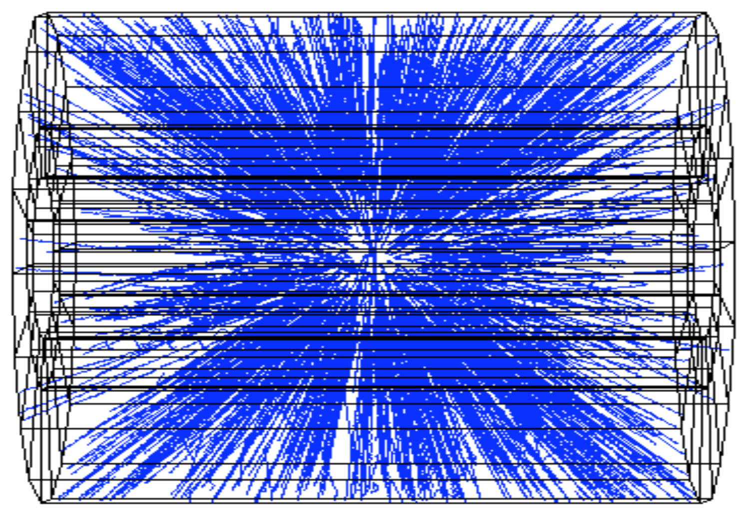
LHCb Trigger Levels

- First level trigger : here called Level-0
  - Selects high pT particles (muons, egamma…)
  - Reduces input rate of 10MHz to 1.1 MHz
  - Custom boards
- Followed by two software-based trigger levels
- Level-1
  - uses reduced data set: only part of the sub-detectors (mostly Vertex-detector and some tracking) with limited-precision data
  - has a limited latency, because data need to be buffered in the front-end electronics
  - reduces event rate from 1.1 MHz to 40 kHz, by selecting events with displaced secondary vertices
- High Level Trigger (HLT)
  - uses all detector information
  - reduces event rate from 40 kHz to 200 Hz for permanent storage

ALICE Implementation

- Heavy ions runs
  - L=10^{27} $cm^{-2}s^{-1}$
  - Interaction rate < 10 kHz
  - Very high multiplicity and huge events size (~50MB)
  - Modest requirements on lower level triggers
- pp (or pA) runs
  - Interaction rate up to 200kHz
  - Small event size (~2MB)
  - Strong requirements on lower level triggers
- To accommodate all the different running conditions, the first level trigger is split in 3 distinct levels
  - L0, L1 and L2





Summary

- LHC : a very challenging environment
  - Interaction rate and selectivity
  - Number of channels and synchronization
  - Pile-up and bunch-crossing identification
  - Making a decision to accept/reject an event given ~3ms

- Trigger level: set of successive approximations
  - Number of physical levels varies with experiment/architecture

- Level-1 is always present and is responsible for reducing the rate to acceptable values (< 100kHz) for processing by the (more precise) High Level Trigger

References

ATLAS Technical Design Reports: http://atlas.web.cern.ch/Atlas/internal/tdr.html

CMS Trigger Technical Design Report: http://cmsdoc.cern.ch/cms/TDR/TRIGGER-public/trigger.html

P. Sphicas: http://indico.cern.ch/conferenceDisplay.py?confId=a032525

W. Smith:
http://indico.fnal.gov/materialDisplay.py?contribId=8&sessionId=22&materialId=slides&confId=1965