Trigger & DAQ

Hadron Collider Summer School

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August 12,13 2008

Outline:

Introduction to LHC Trigger & DAQ

Challenges & Architecture

ATLAS, ALICE, CMS, LHCb Trigger & DAQ

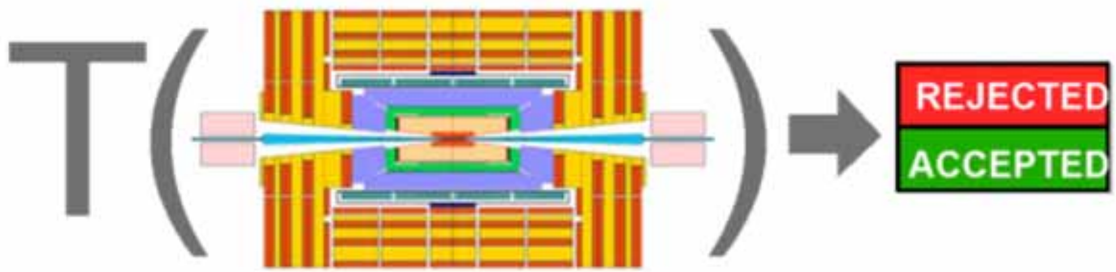
Detailed Example of CMS Trigger & DAQ

The Future: SLHC Trigger & DAQ

Triggering

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

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

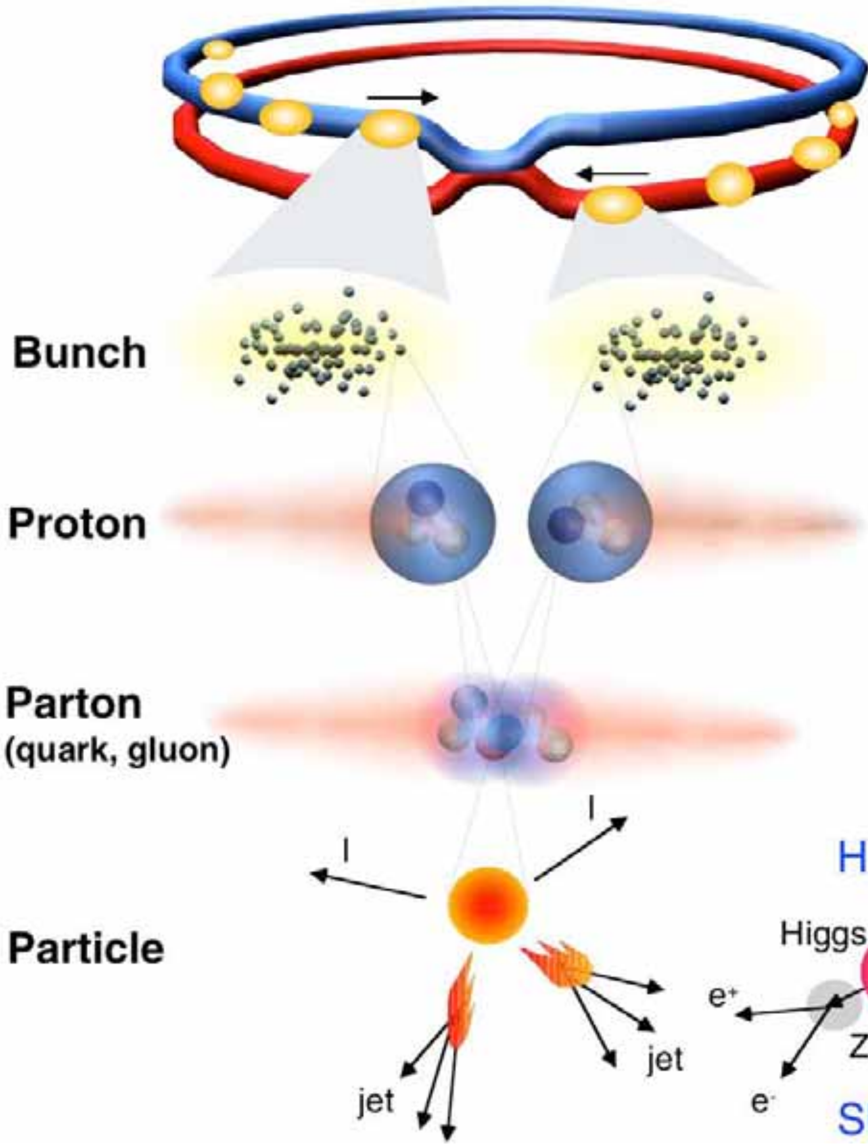
- Detector data not (all) promptly available
- Selection function highly complex

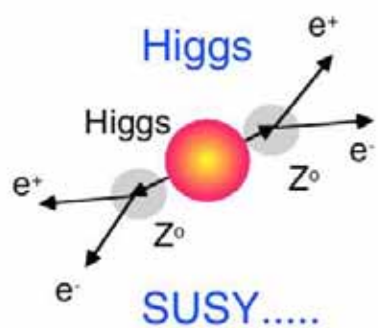
$\Rightarrow$T(...) is evaluated by successive approximations, the

TRIGGER LEVELS

(possibly with zero dead time)

LHC Collisions





Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz

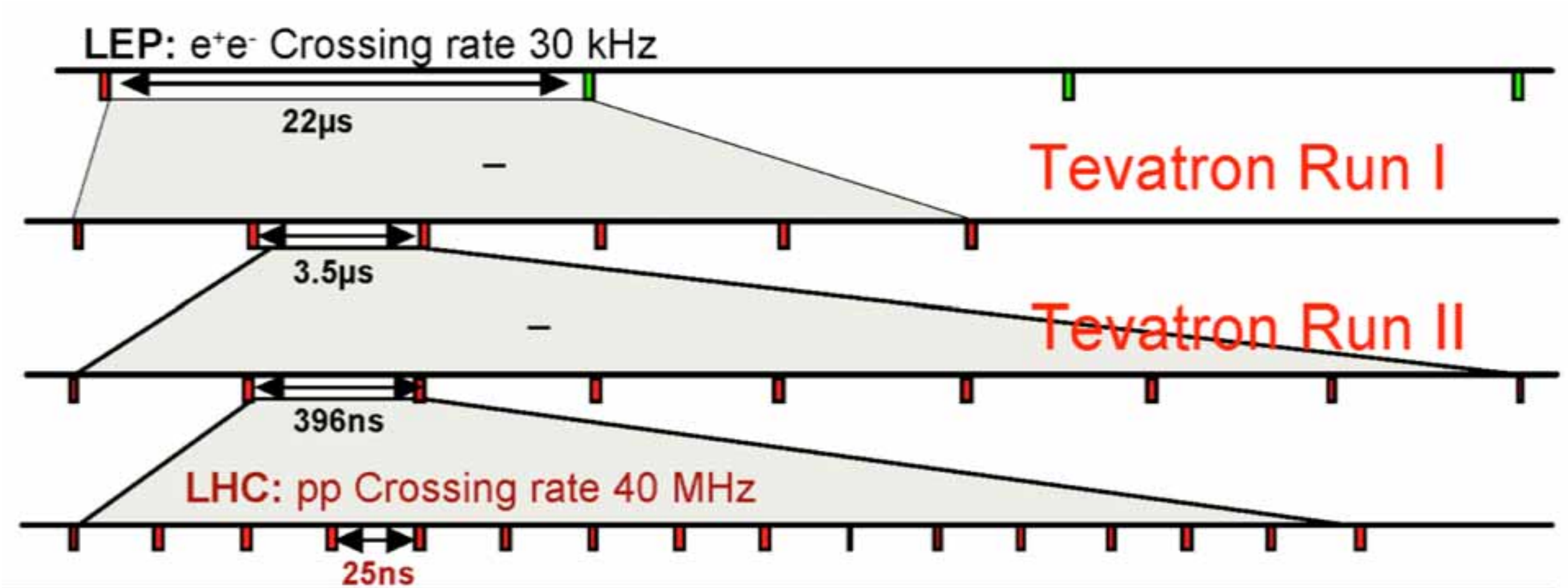
with every bunch crossing
23 Minimum Bias events
with ~1725 particles produced

Selection of 1 in 10,000,000,000,000

Beam Xings: LEP. TeV, LHC

LHC has ~3600 bunches

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



LHC Physics & Event Rates

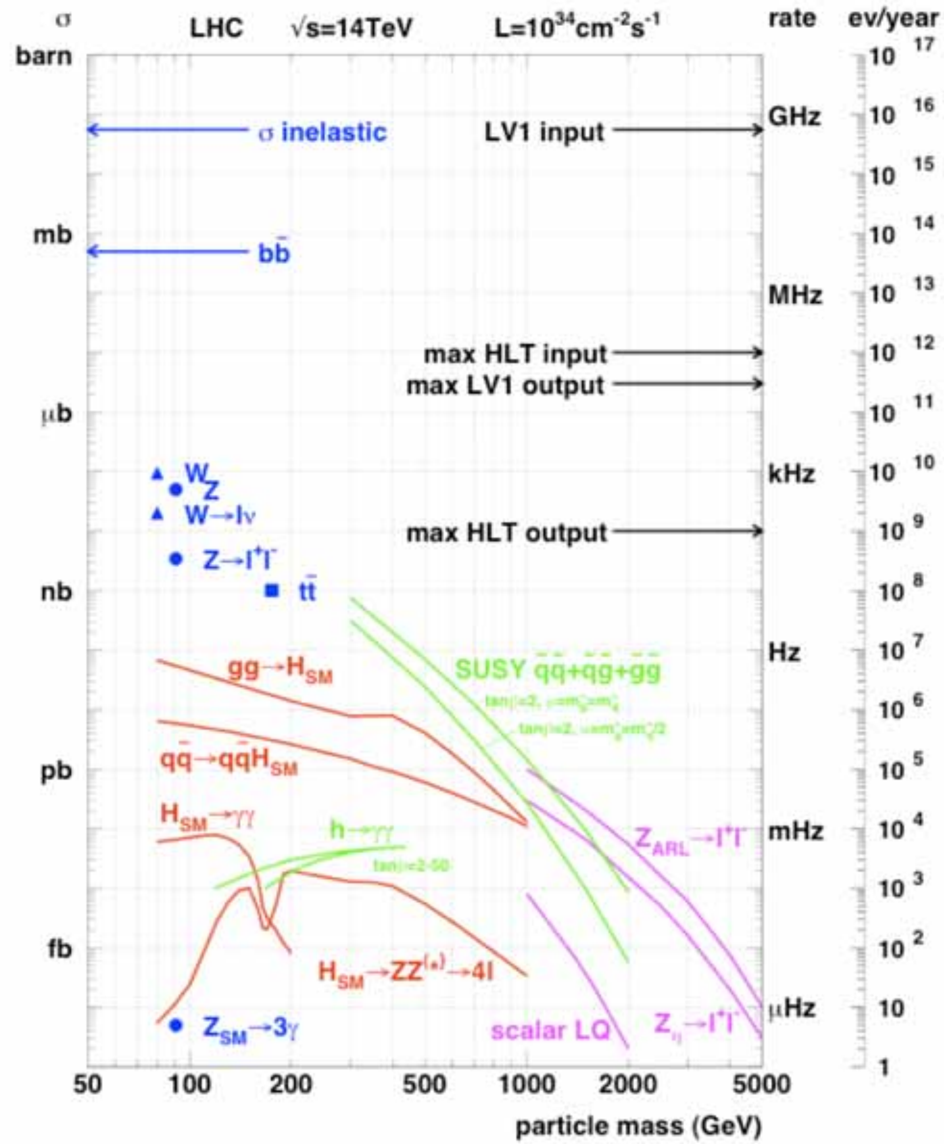
At design $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$

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

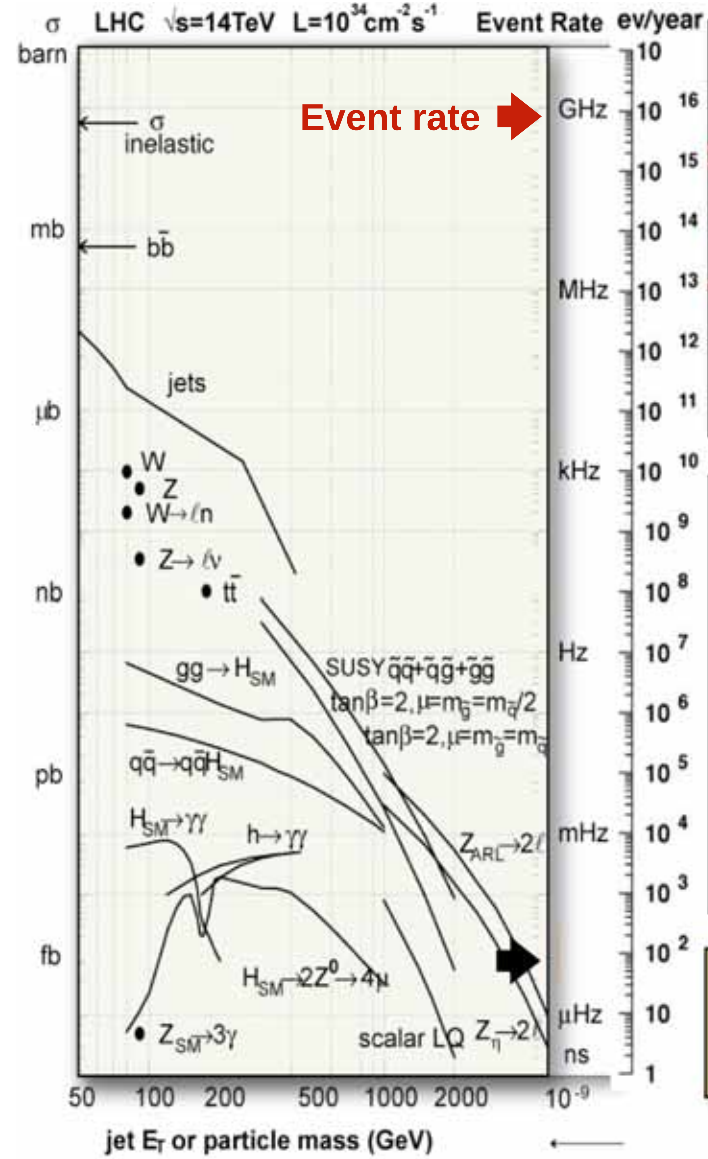
Can store ~ 300 Hz events

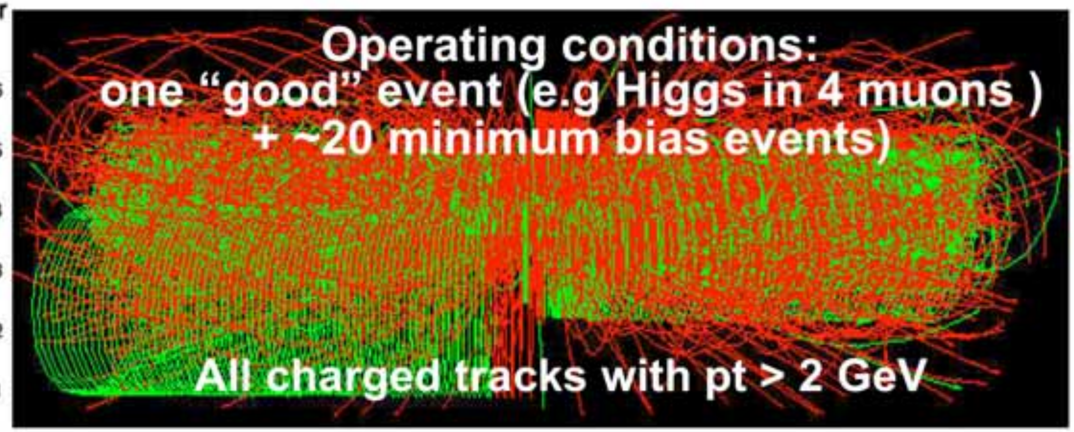
Select in stages

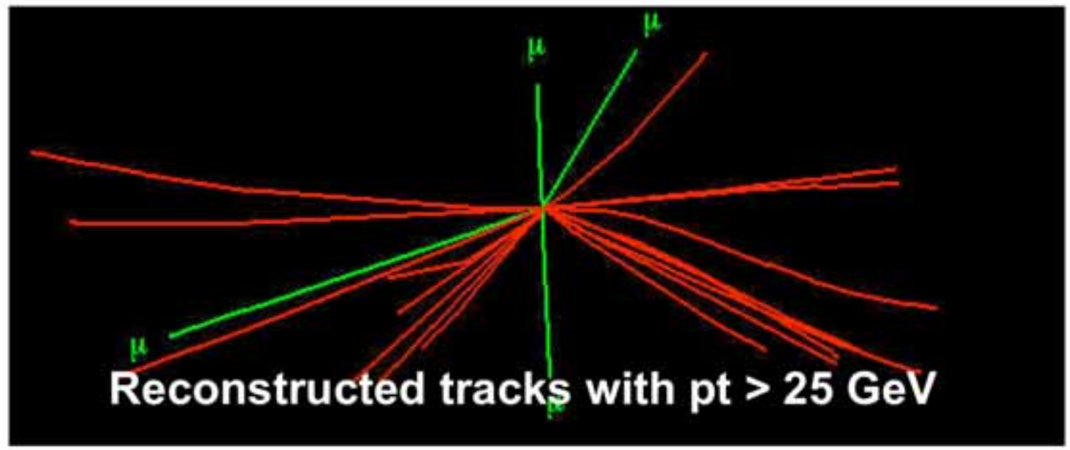
- **Level-1 Triggers**
  - 1 GHz to 100 kHz
- **High Level Triggers**
  - 100 kHz to 300 Hz



Collisions (p-p) at LHC

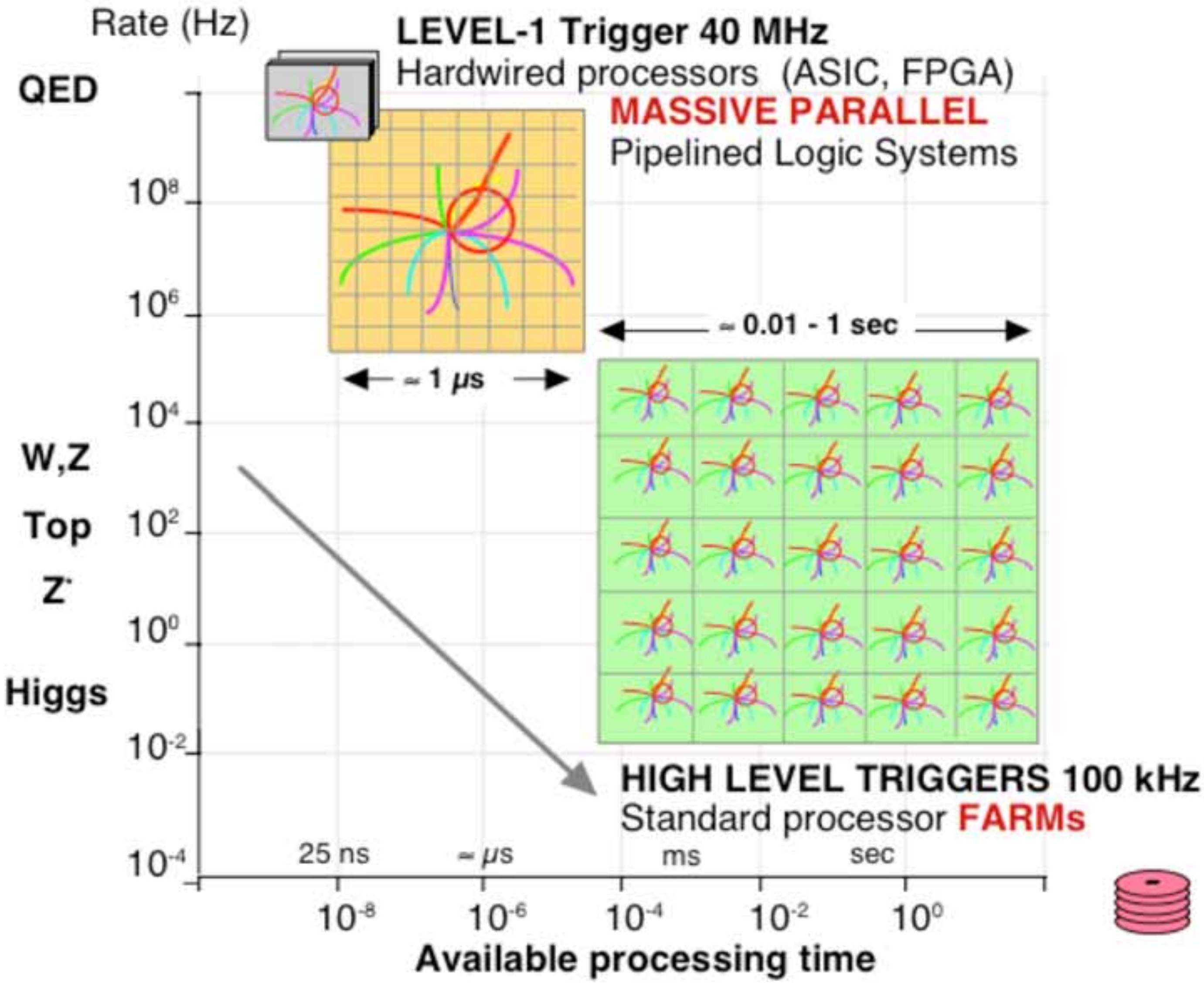




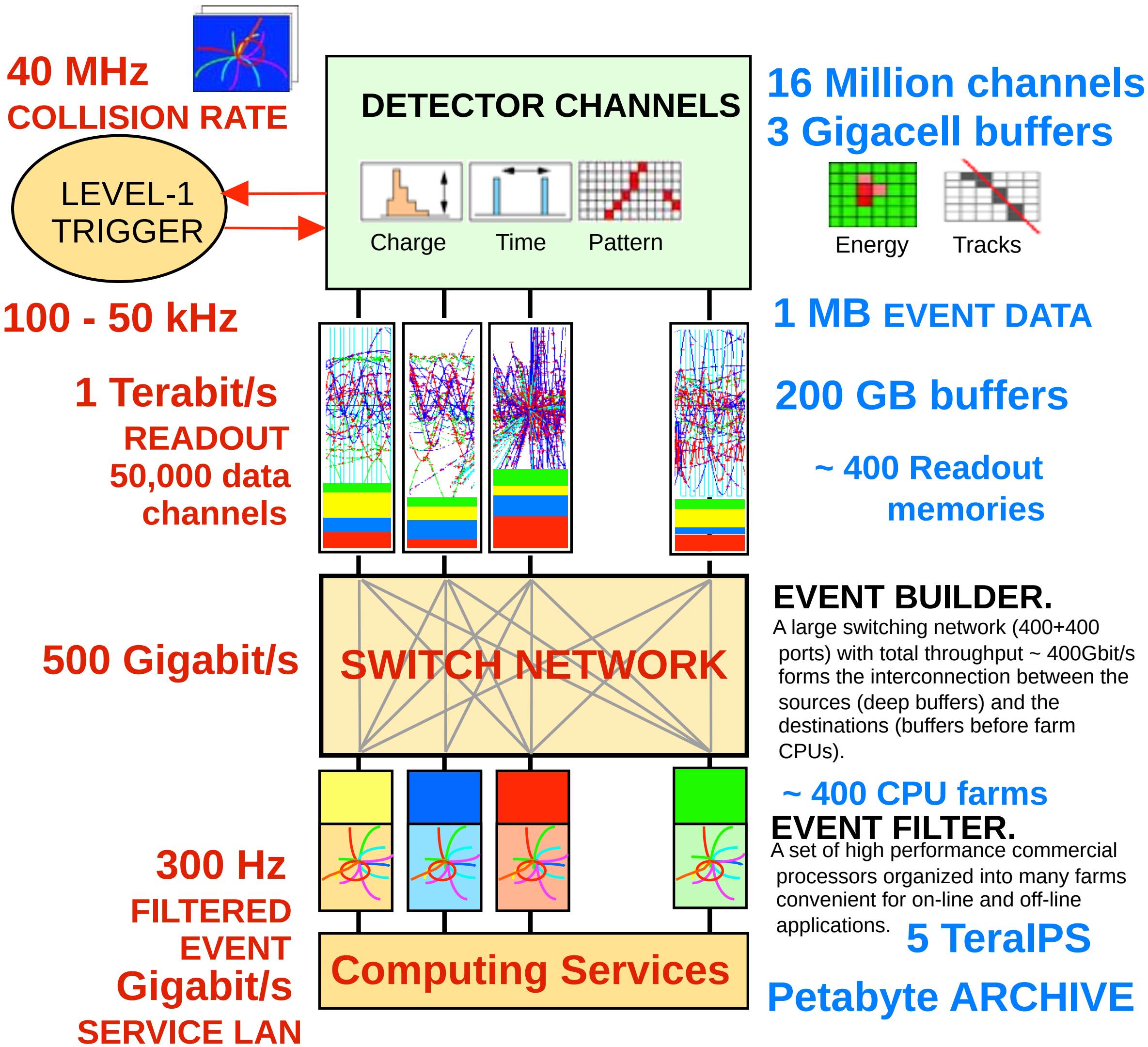


Event size:	~1 MByte
Processing Power:	~X TFlop

Processing LHC Data



LHC Trigger & DAQ Challenges



Challenges:

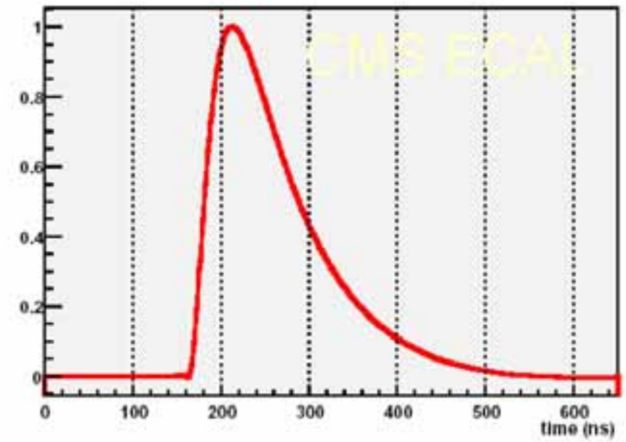
1 GHz of Input Interactions

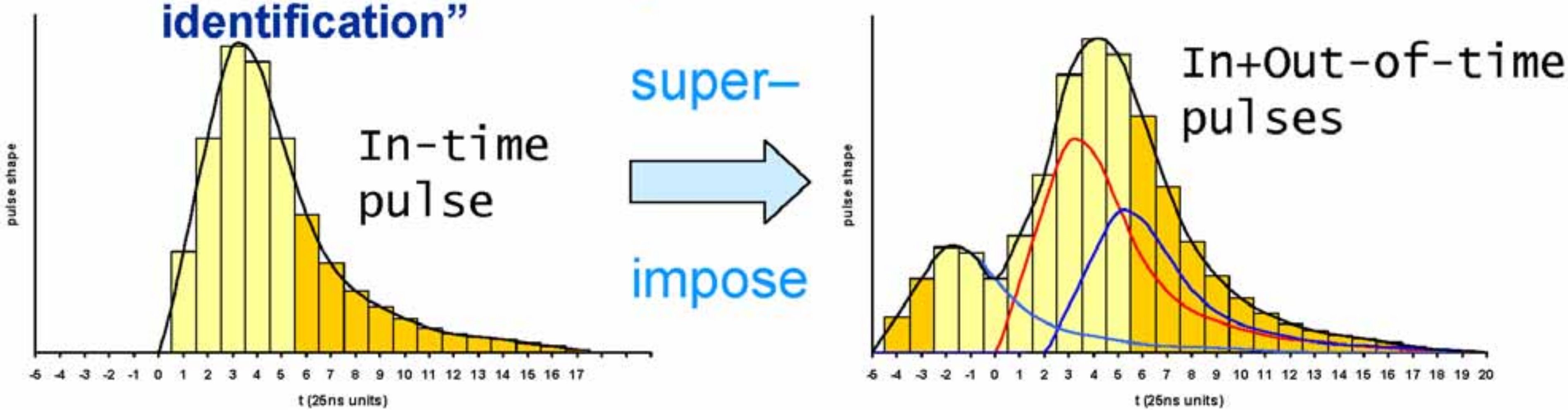
Beam-crossing every 25 ns with ~ 23 interactions produces over 1 MB of data

Archival Storage at about 300 Hz of 1 MB events

Challenges: Pile-up

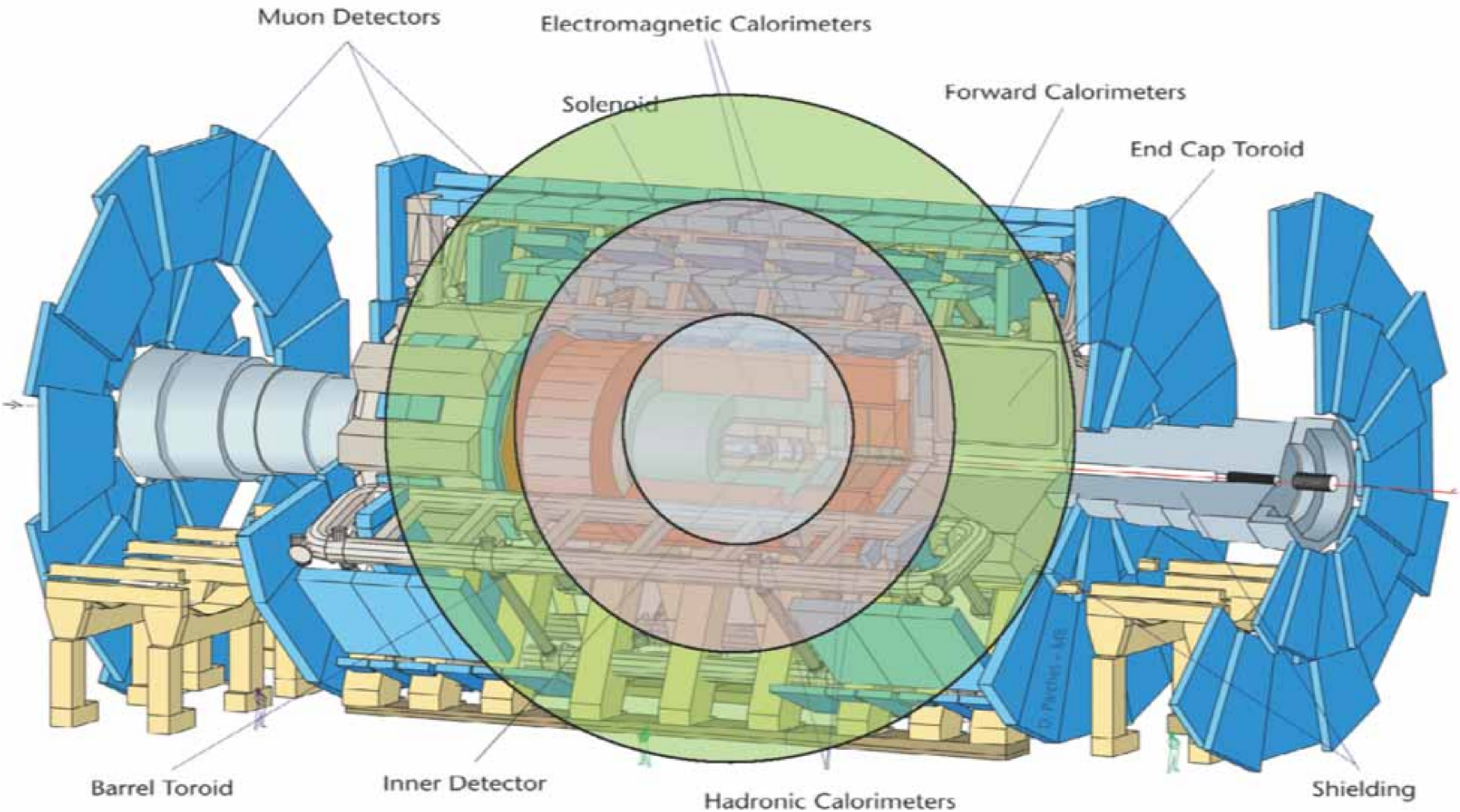
- "In-time" pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"





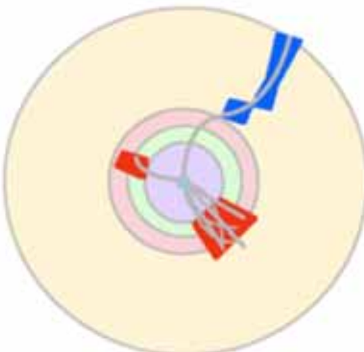
Challenges: Time of Flight

c = 30 cm/ns → in 25 ns, s = 7.5 m



LHC Trigger Levels

10^{-7} s



Collision rate 10^9 Hz

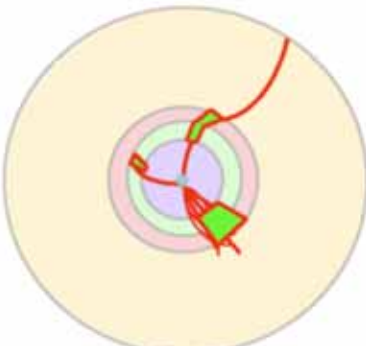
Channel data sampling at 40 MHz

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

10^{-6} s

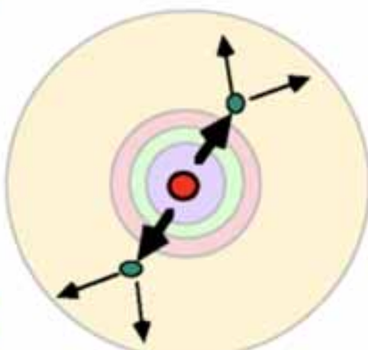


Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ..)

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

10^{-3} s



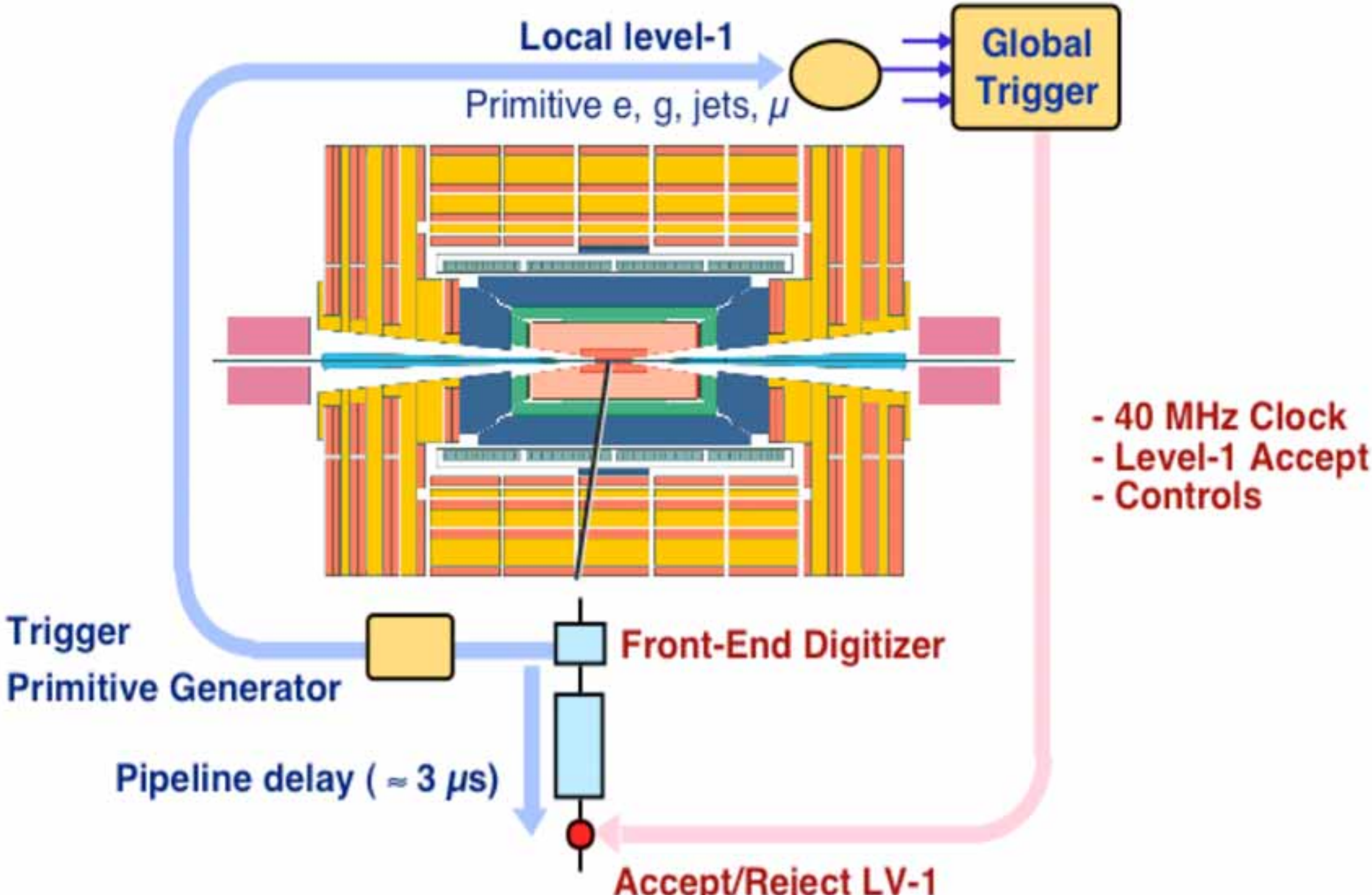
Level-3 events to tape 100- 300 Hz

Physics process identification

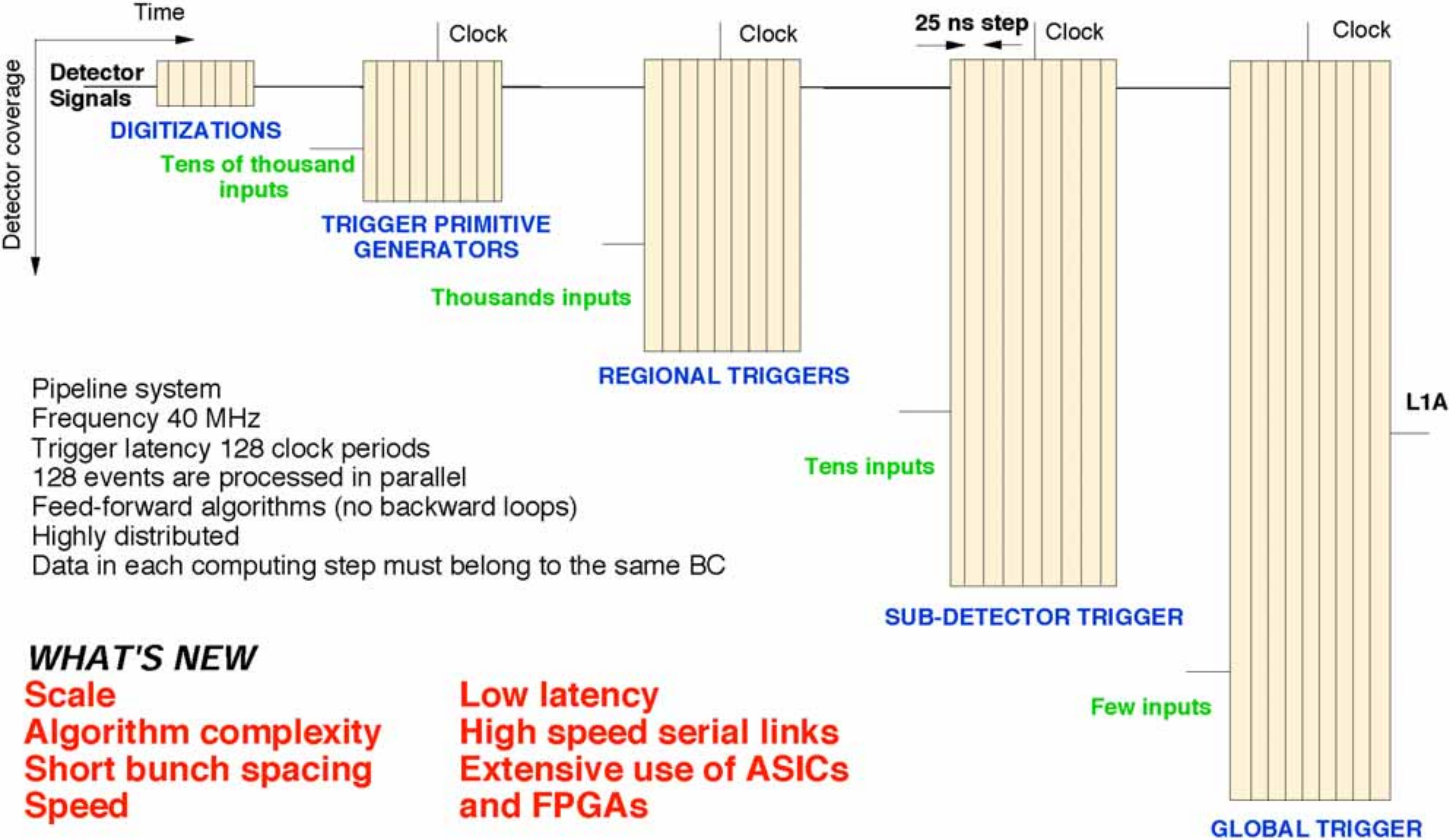
- Event reconstruction and analysis

10^{-0} s

Level 1 Trigger Operation



Level 1 Trigger Organization



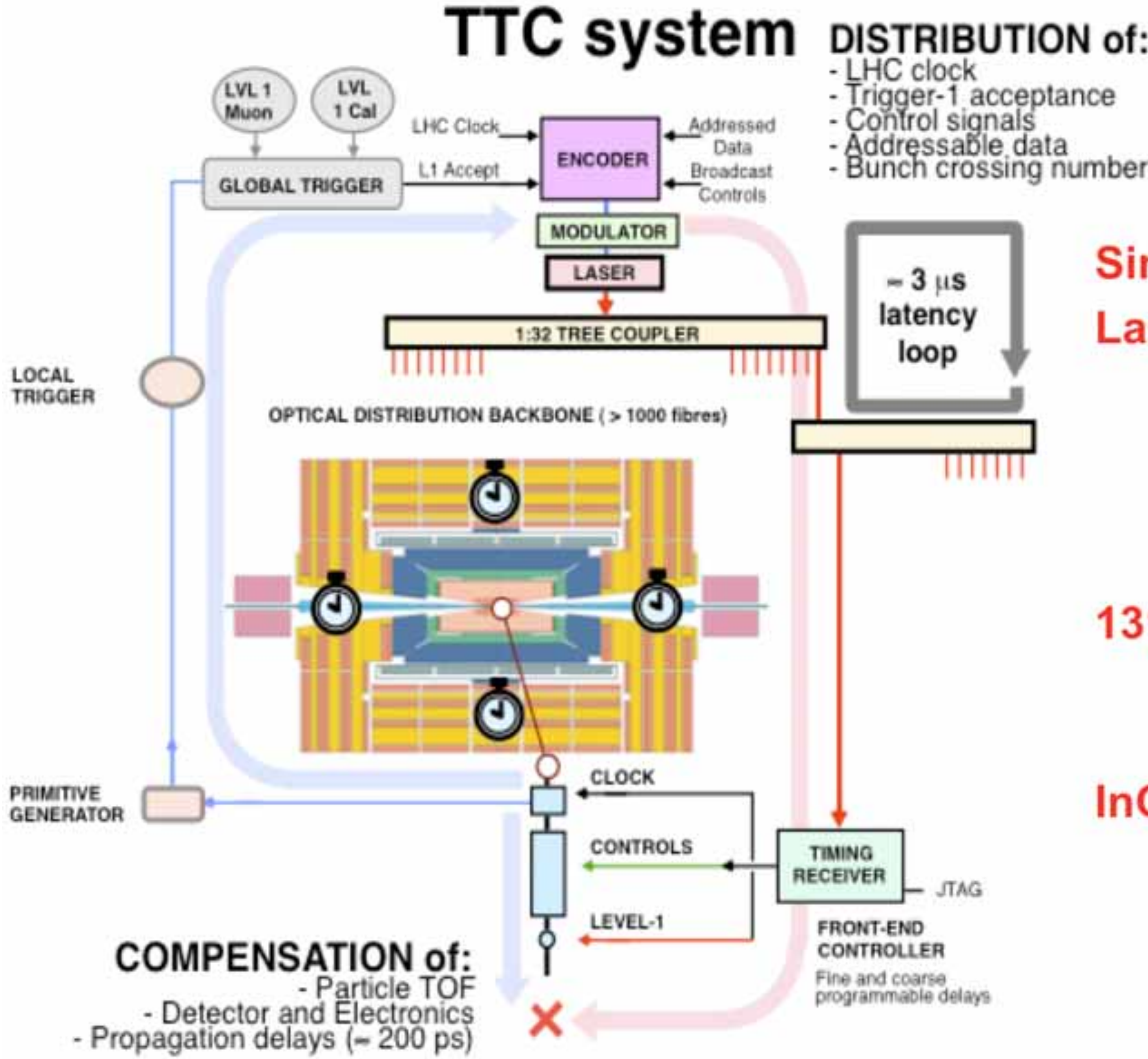
Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

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



Optical System:

Single High-Power Laser per zone

- **Reliability, transmitter upgrades**
- **Passive optical coupler fanout**

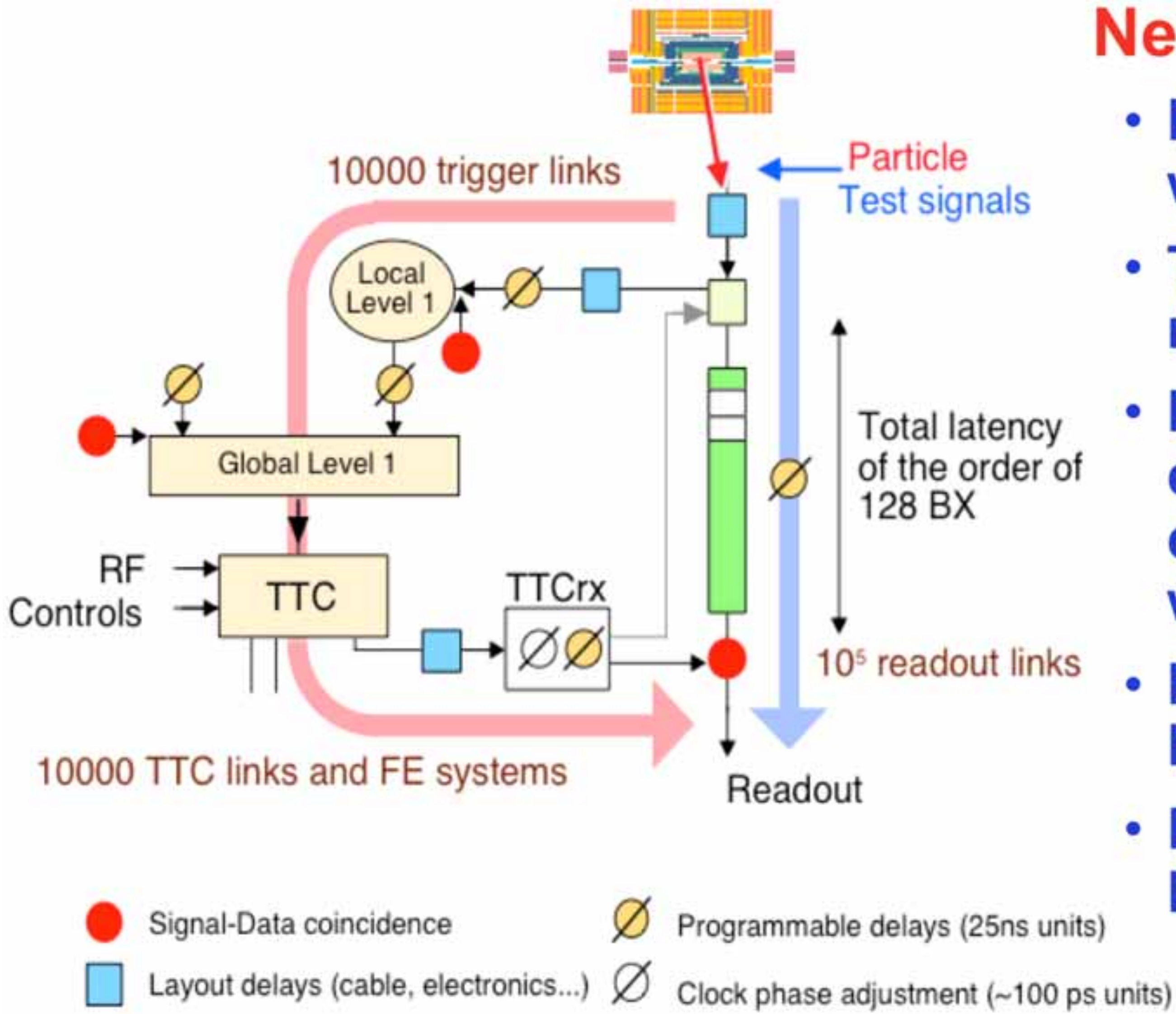
1310 nm Operation

- **Negligible chromatic dispersion**

InGaAs photodiodes

- **Radiation resistance, low bias**

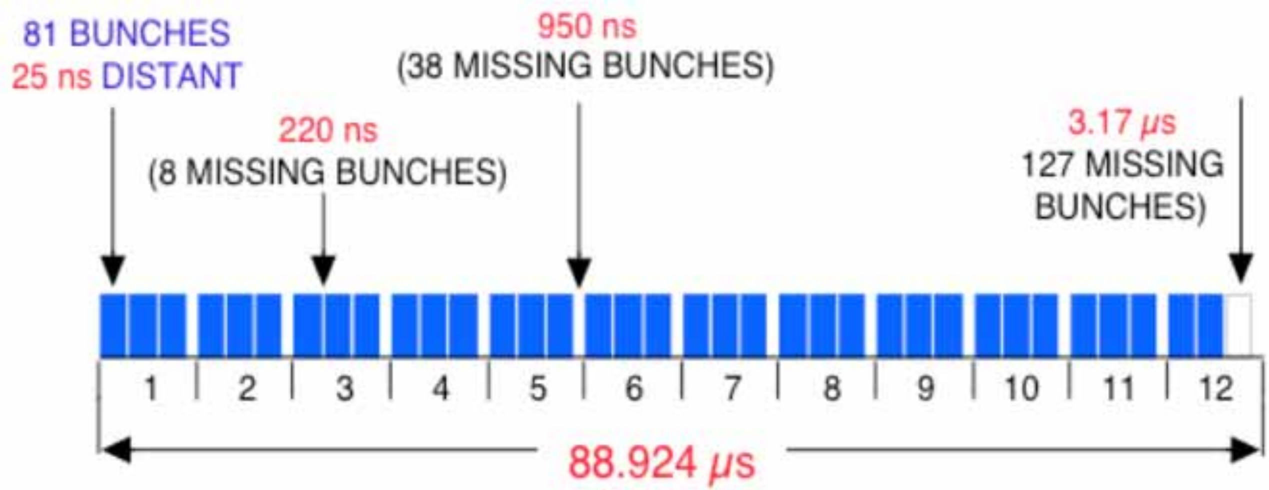
Detector Timing Adjustments



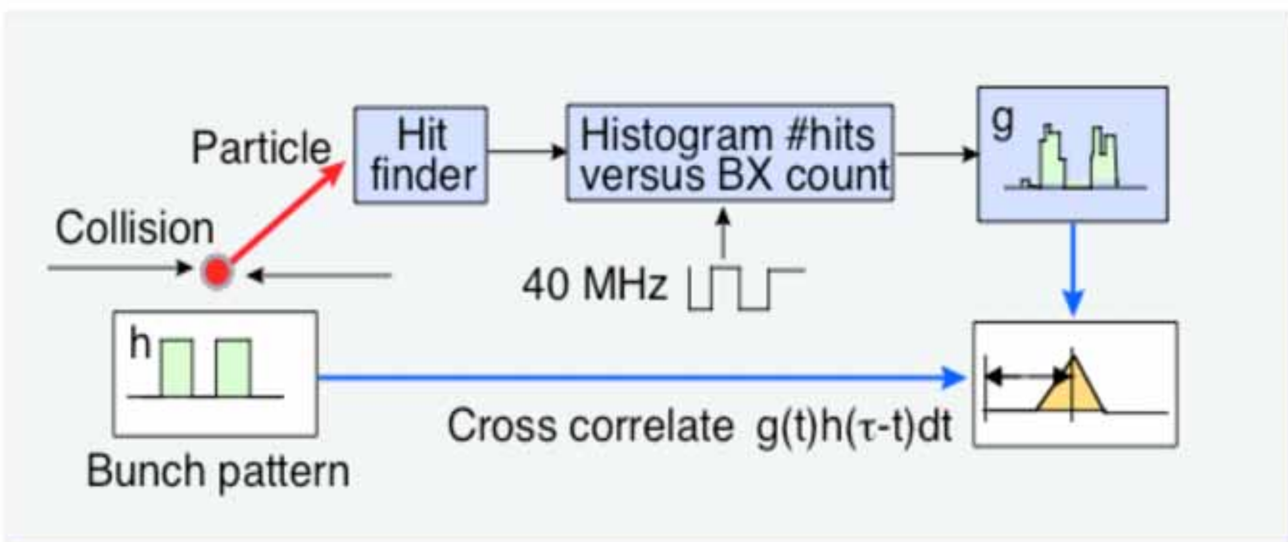
Need to Align:

- 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

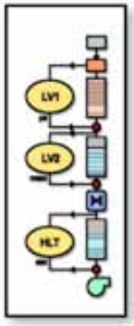


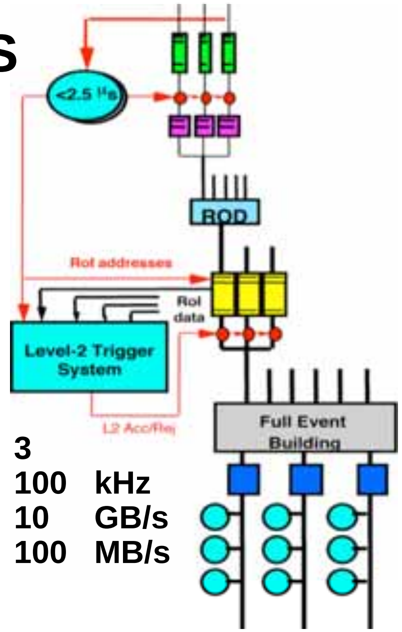
2835 out of 3564 p bunches are full, use this pattern:



Trigger & DAQ at LHC

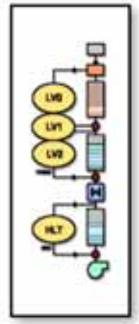
ATLAS

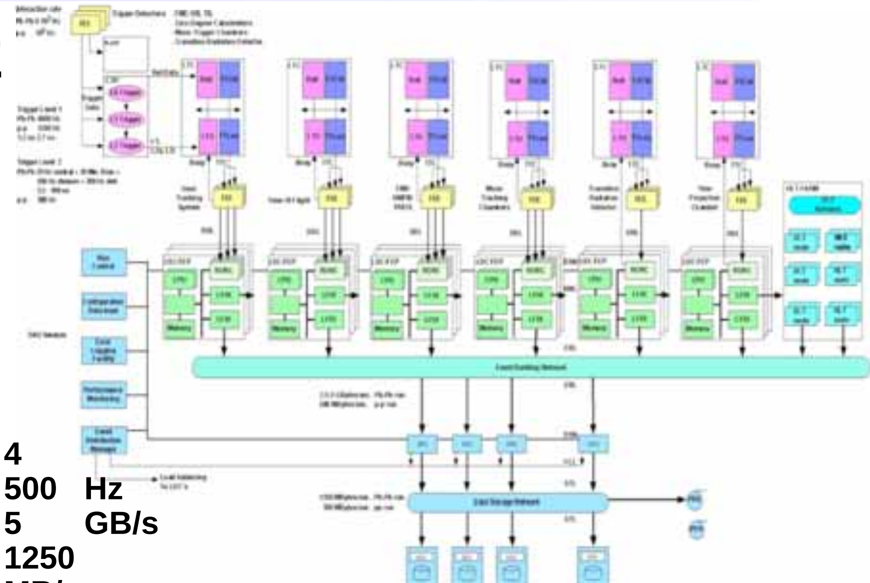




Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

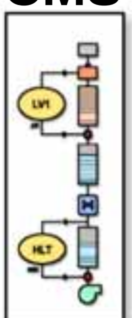
ALICE

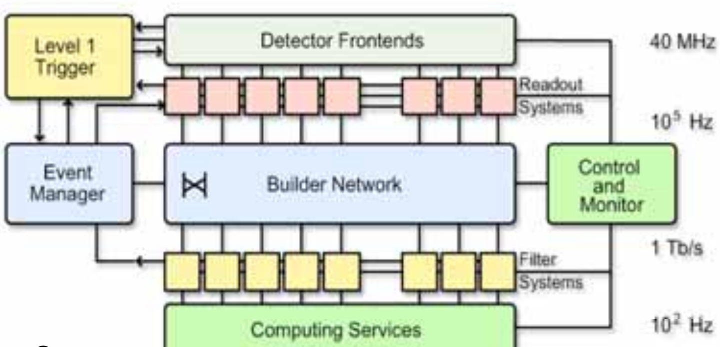




Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250 MB/s	

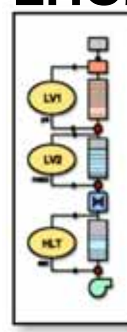
CMS





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

LHCb



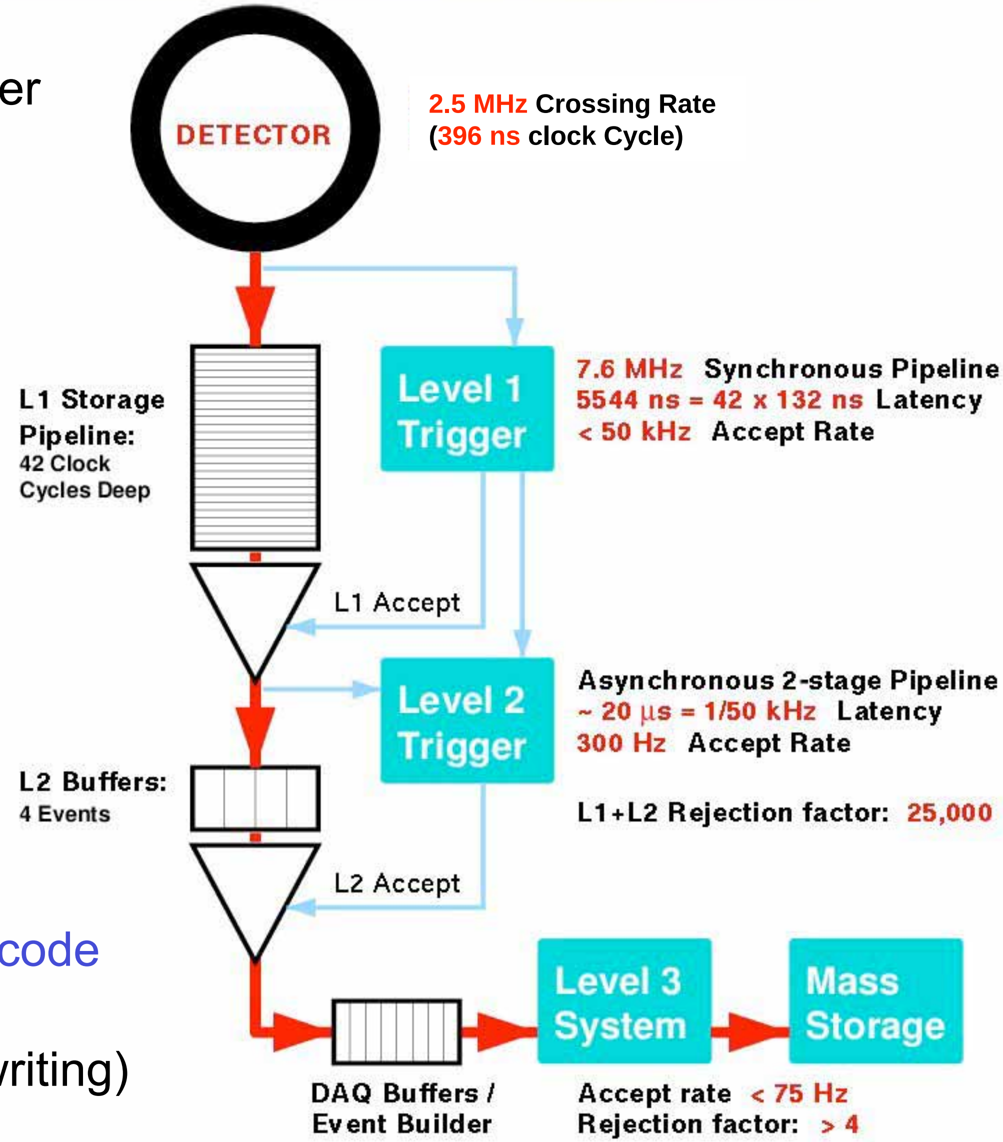
Levels	3	
LV-1 rate	1	MHz
Readout	4	GB/s
Storage	40	MB/s

Tevatron: CDF Trigger

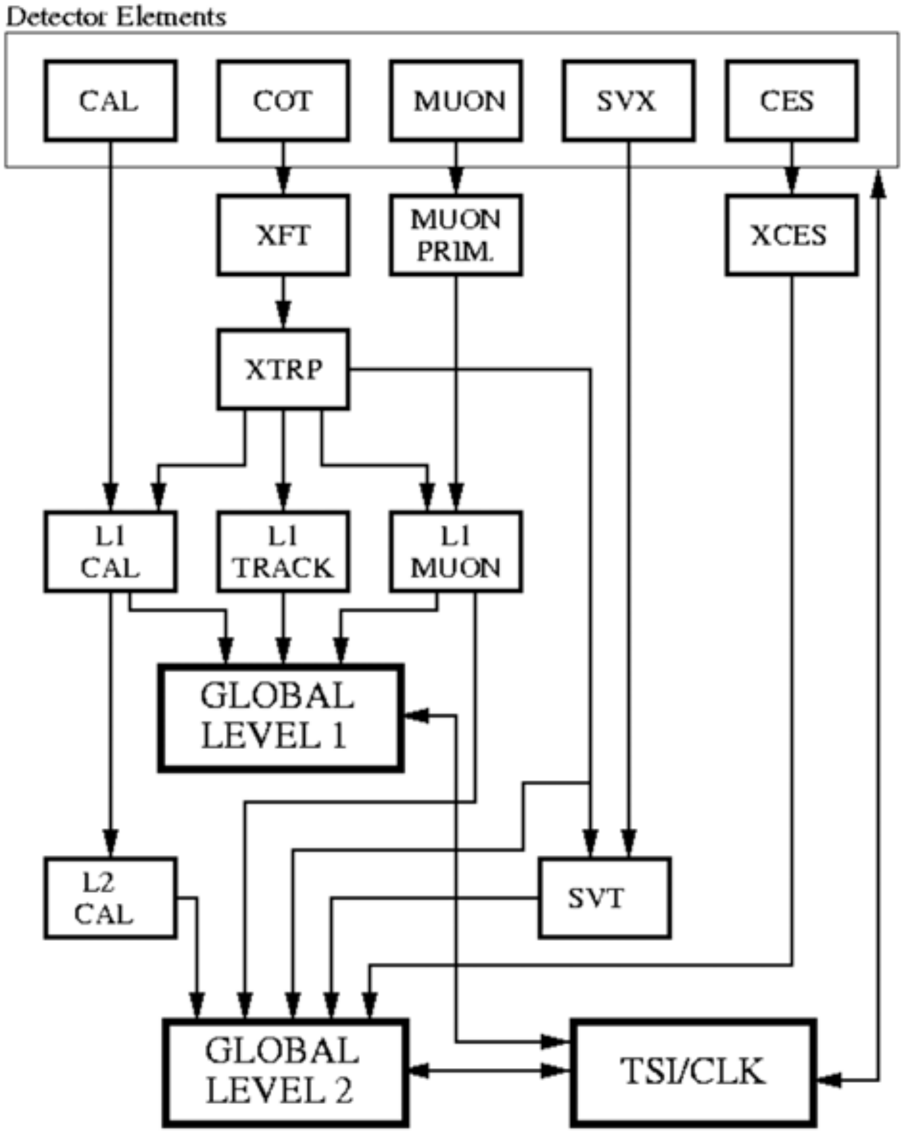
- Level-1 : synchronous hardware trigger
  - L1 decision every 396 ns (2.5 MHz) at 5.5 μs after beam collision
  - L1 accept ~ 50KHz (limited by L2)

- Level-2 : mainly hardware with simple software for trigger decision
  - Parallel preprocessing for full detector
  - Avg L-2 processing time ~30 μs
  - L2 accept ~350Hz

- Level-3 : ~200 Dual CPU with Linux
  - Direct copy of offline reconstruction code
    - Full event reconstruction
  - L3 accept ~ 80Hz (limited by tape writing)



CDF L1, L2 Trigger Systems



L1: Cal, Track, Muon, L1Global

main L1 primitives:

- L1 track (phi, p_T)
- EM cluster (EM, HAD/EM)
- Electron (EM cluster+XFT)
- Jet cluster (EM+HAD)
- Muon (Muon tower + XFT)
- Missing Et, SumEt

L1 triggers:

- inclusive and simple combinations

L2:

- SVT (phi, pT, d0)
- L2Cal : EM and Jet clusters,

Isolated clusters

- EM ShowerMax
- L2Global

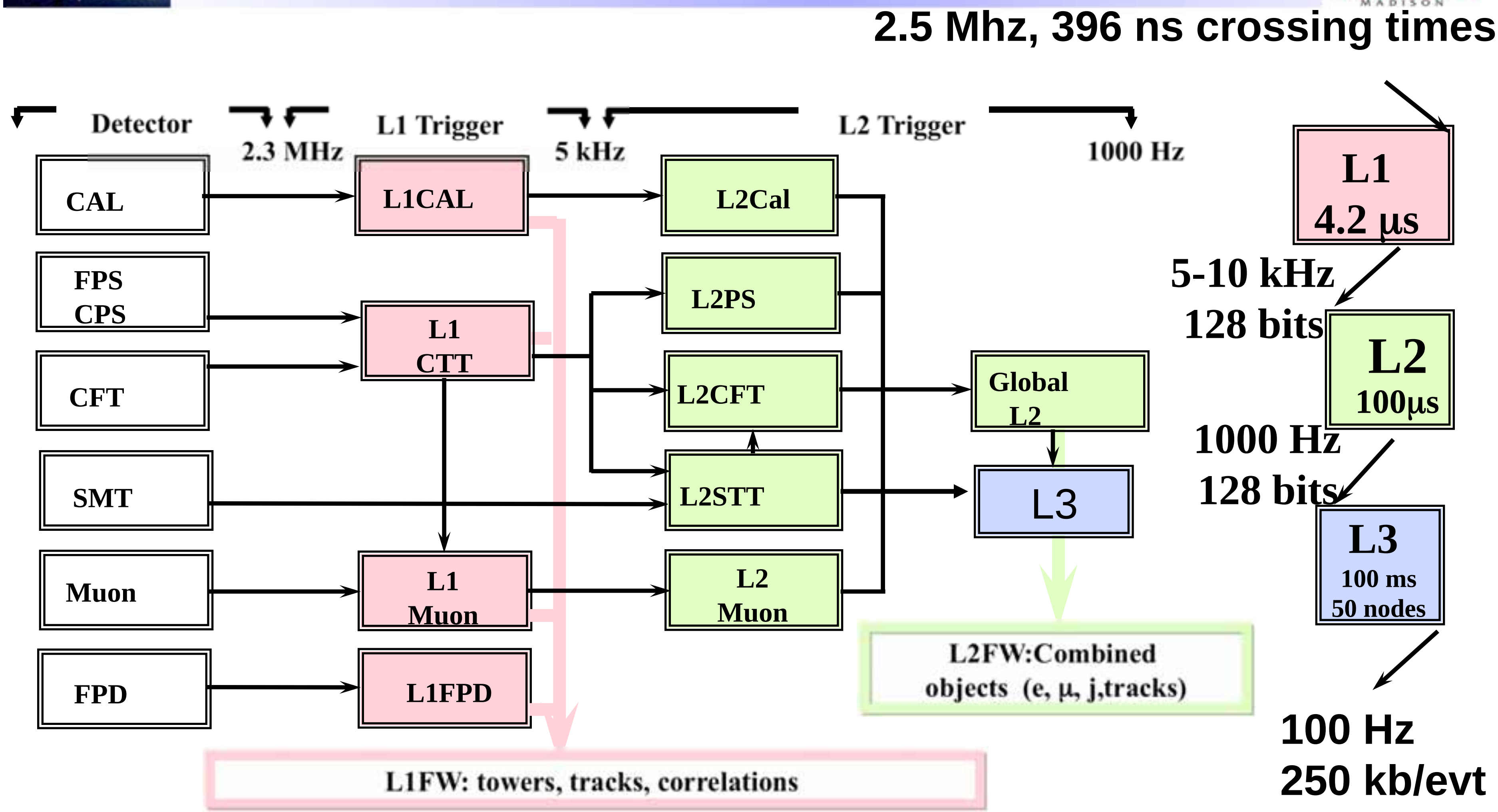
L2 objects

- e, μ, γ, jets, met, sumEt
- tau, displaced track, b-jet
- isolated e and γ

L2 triggers

- inclusive and complex combinations

DØ Trigger System



Deadtime: <5%

DØ Level 1 & 2 Triggers

Level 1

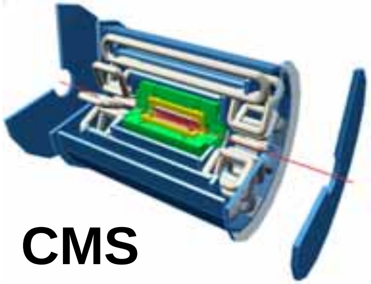
- **Central Track Trigger (CTT) uses axial layers of Central Fiber Tracker**
  - provides track terms in 4 pT bins, isolation terms, sends track lists to L1 cal/μ
- **Calorimeter**
  - course 0.2 x 0.2 eta-phi towers
  - Cal-CTT match (L1 tau trigger)
- **Muon**
  - Scintillator and wire hits
  - Muon-CTT match

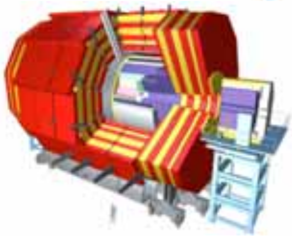
Level 2

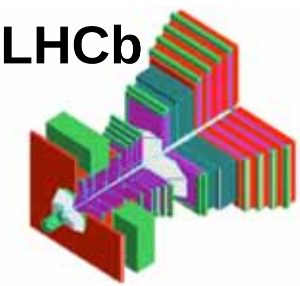
- **Silicon track trigger**
  - Better track p_T resolution
  - Primary vertex finding
  - Track impact parameter significance terms
- **L1 Muon and Calorimeter (jet and electron) objects are refined**
- **Global variables allowing combinations of objects**

LHC trigger & DAQ Summary

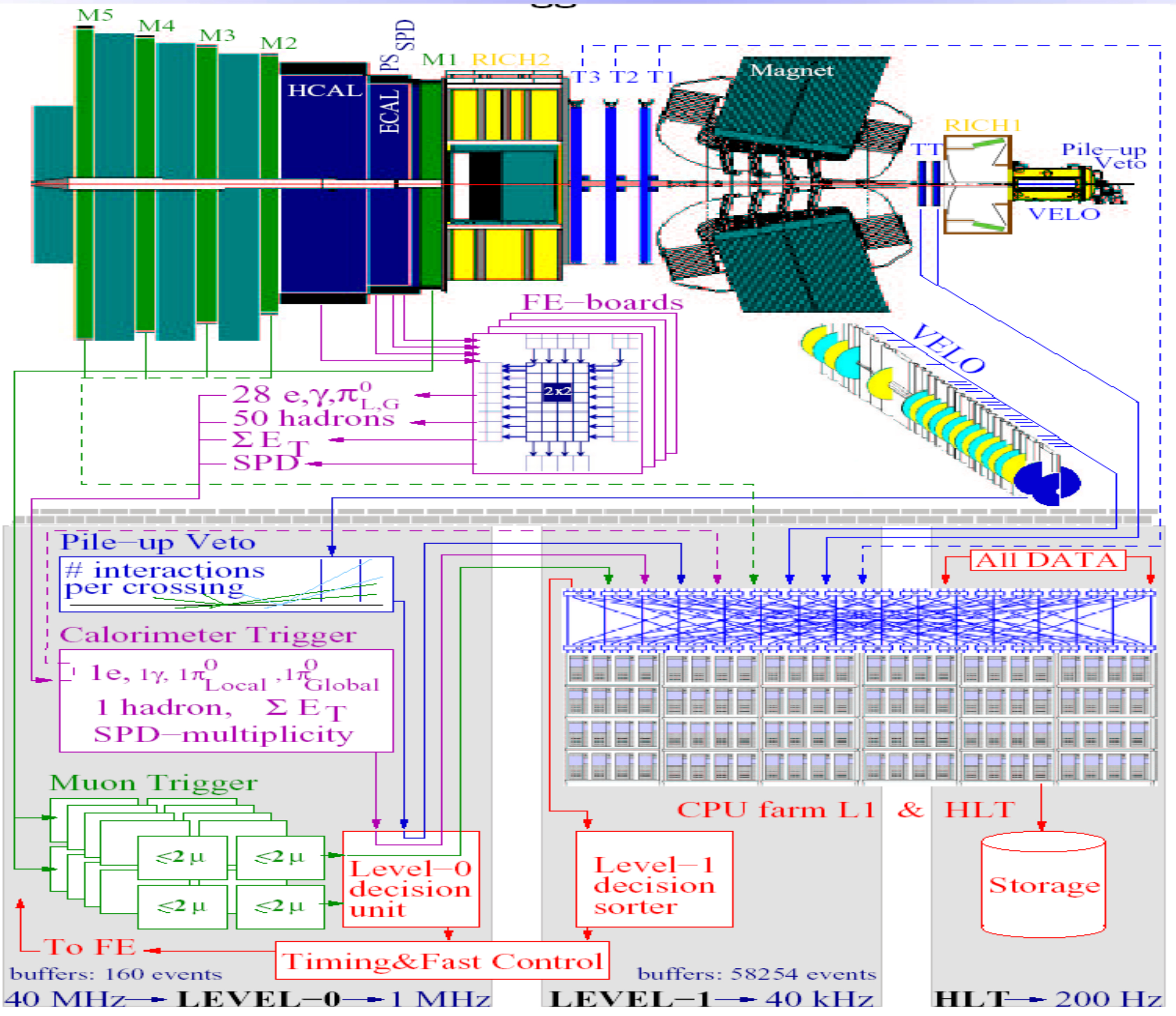
	No.Levels Trigger	First Level Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS	3	10^5 LV-2 10^3	10^6	10	100 (10^2)
CMS	2	10^5	10^6	100	100 (10^2)
LHCb	3	LV-0 10^6 LV-1 4 10^4	2x10^5	4	40 (2x10^2)
ALICE	4	Pp-Pp 500 p-p 10^3	5x10^7 2x10^6	5	1250 (10^2) 200 (10^2)







LHCb Trigger



LHCb: Two SW Trigger Levels

Both Software Levels run on commercial PCs

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

LHCb Trigger Features

Two data streams to handle:

- Level-1 trigger: 4.8 kB @ 1.1 MHz
- High Level Trigger: 38 kB @ 40 kHz

Fully built from commercial components

(Gigabit) Ethernet throughout

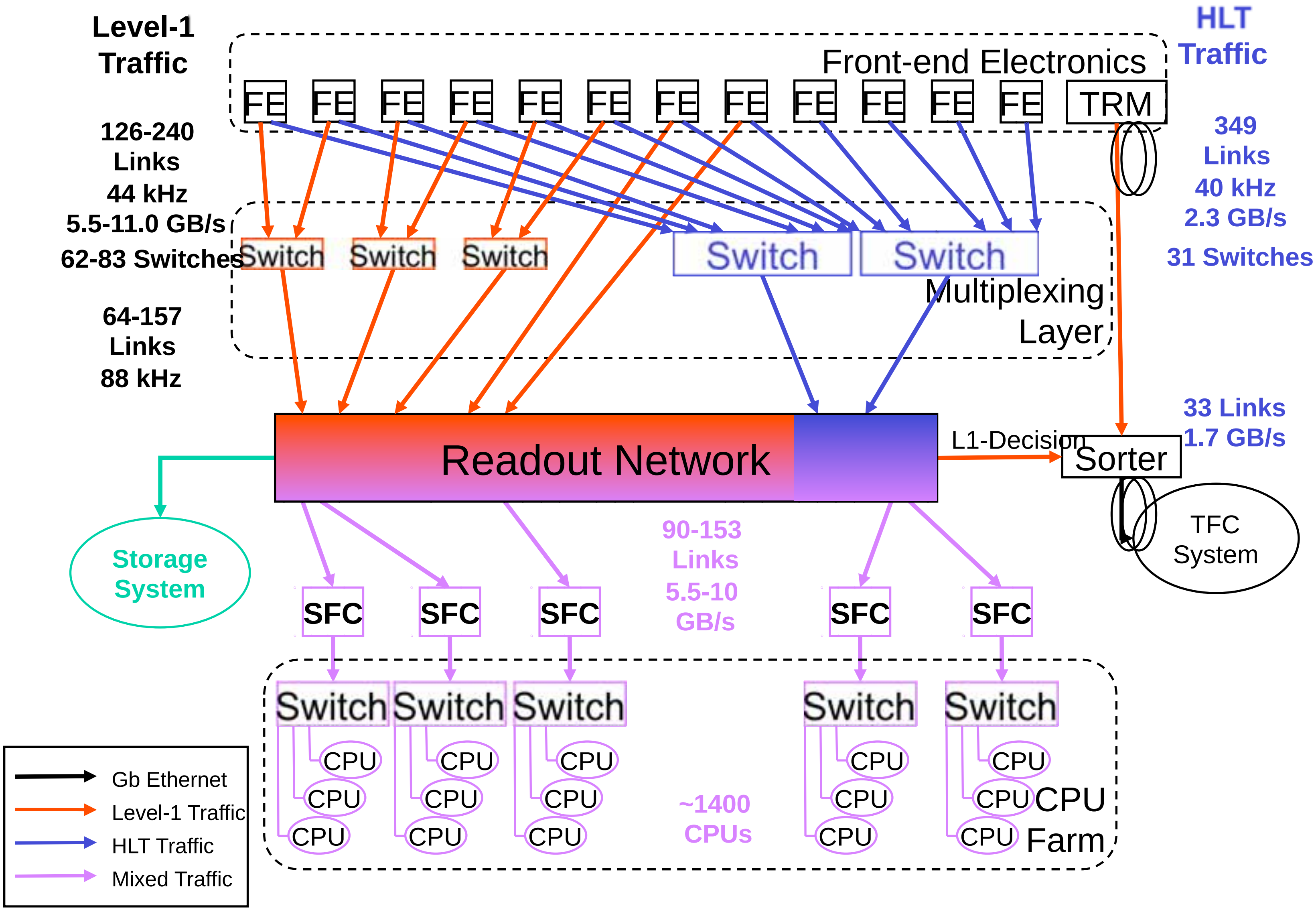
Push-through protocol, no re-transmissions

Centralized flow control

Latency control for Level-1 at several stages

Scalable by adding CPUs and/or switch ports

LHCb Architecture



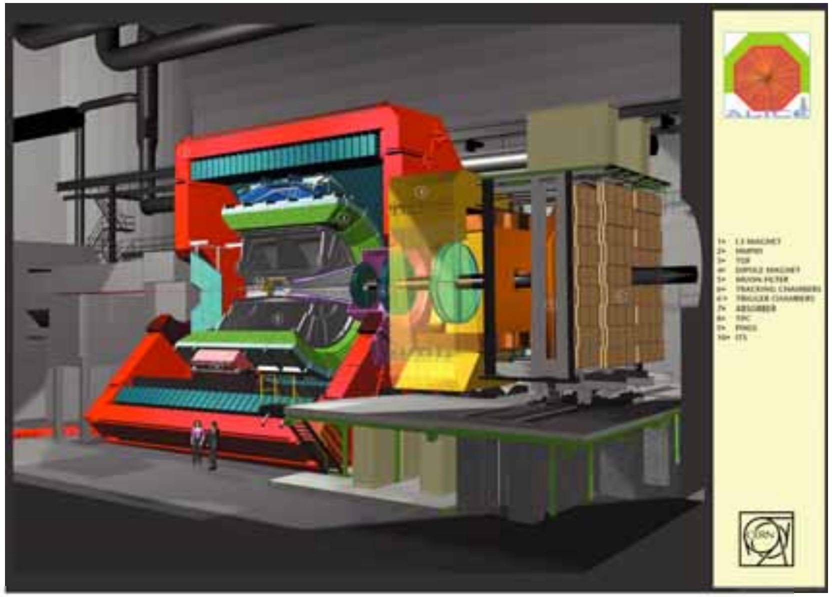
ALICE Data rates

ALICE data rates (TPC only)

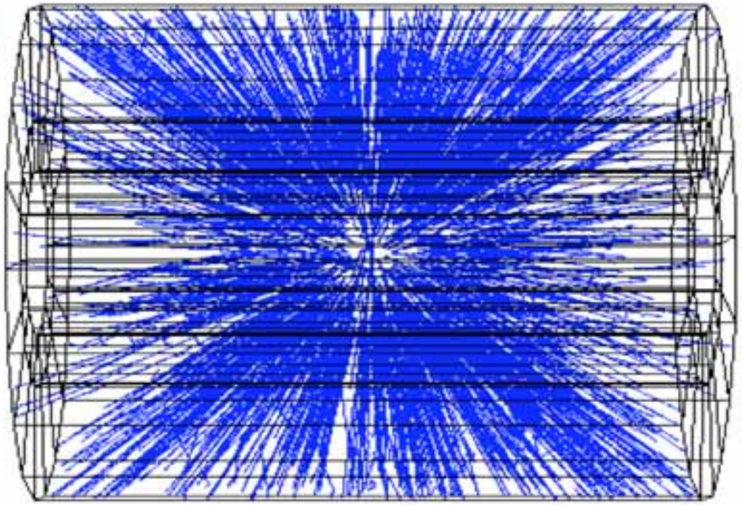
- Event rates
  - Central Pb-Pb: < 200 Hz (past/future protected)
  - Min. bias pp: < 1000 Hz (roughly 25 piles)

- Event sizes (after zero suppression)
  - Pb Pb: ~75 Mbyte
  - pp: ~2.5 Mbyte

- Data rates
  - Pb Pb: < **15 Gbyte/sec**
  - pp: ~2.5 Gbyte/sec



TPC is the largest data source with 570132 channels, 512 timebins and 10 bit ADC value.

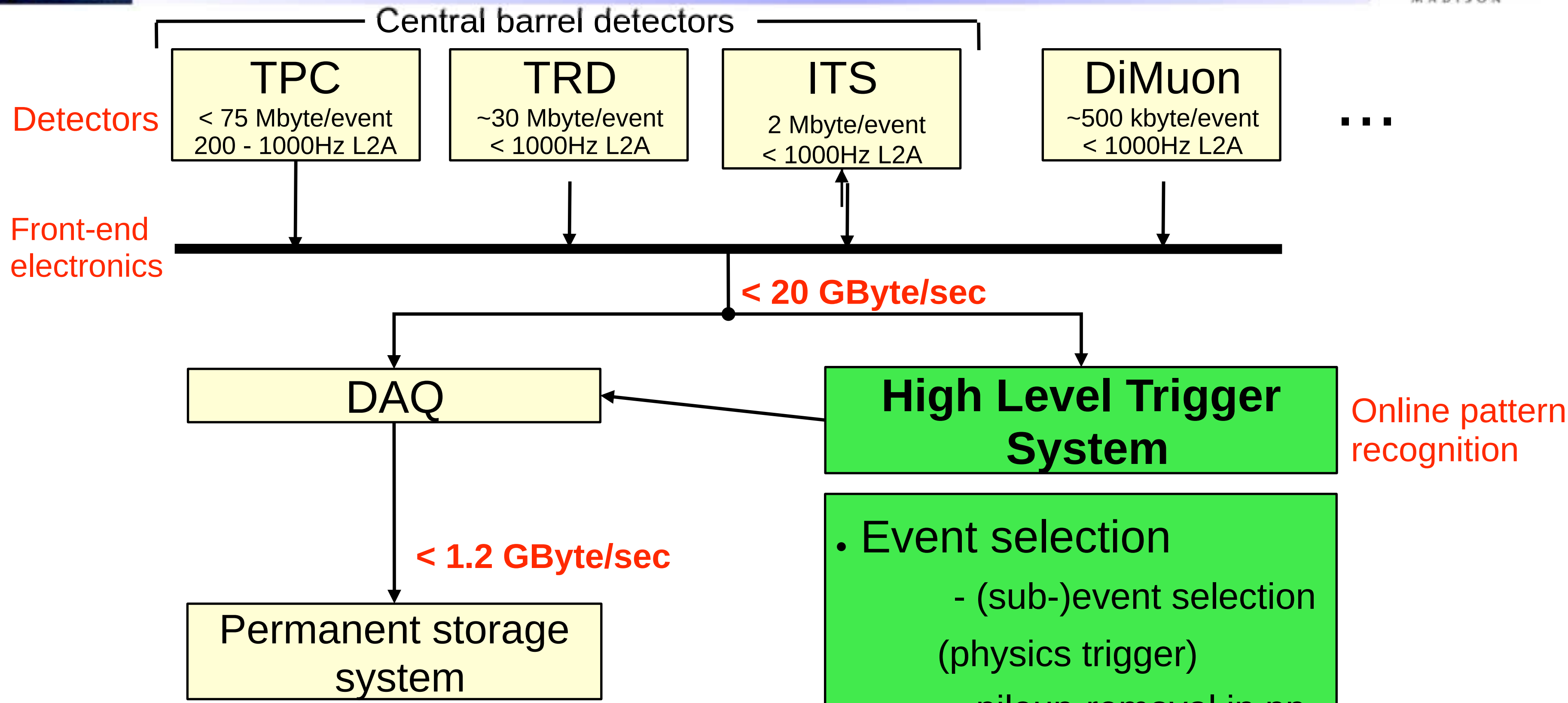


Data rate exceeds by far the foreseen total DAQ bandwidth of **~1.2 Gbyte/sec**

ALICE Trigger Features

- 3 decision levels: L0: 1.2 μs, L1: 6.5 μs, L2: 88 μs
- Parallel decisions at each level –different groups of detectors (clusters) are reading out different events at the same time
- All the readout detectors (max. 24) are partitioned in up to 6 dynamically partitioned independent detector clusters
- 4 past/future protection circuits for each decision level shared among all detectors, which protects the system against pile-up
- 50 trigger classes (combination of input signals and trigger vetos) for each level
- 24 L0 trigger inputs
- 20 L1 trigger inputs
- 6 L2 trigger inputs

ALICE Higher Level Trigger



- Event selection
  - (sub-)event selection (physics trigger)
  - pileup-removal in pp
- Data compression
  - Entropy coding, ...
  - TPC data modeling

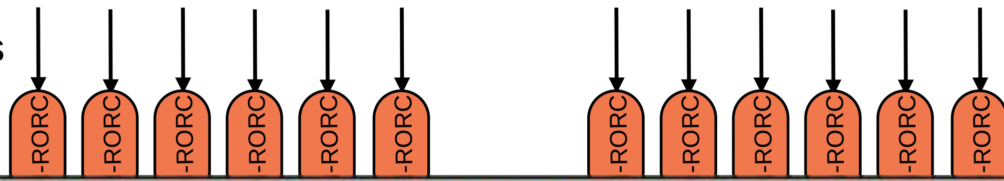
Inspected events per year (in TPC)

	No HLT	With HLT
Pb-Pb	10^7	20 * 10^7
p-p	10^9	10 * 10^9

HLT data flow architecture

36 TPC sectors, ITS, TRD, DiMuon and triggers:
~250 H-RORCs

Optical links



H-RORC: ReadOut Receiver Card
(FPGA Co-Processors)

Generic PC-farm of 500-1000 nodes

Track finding on sector level

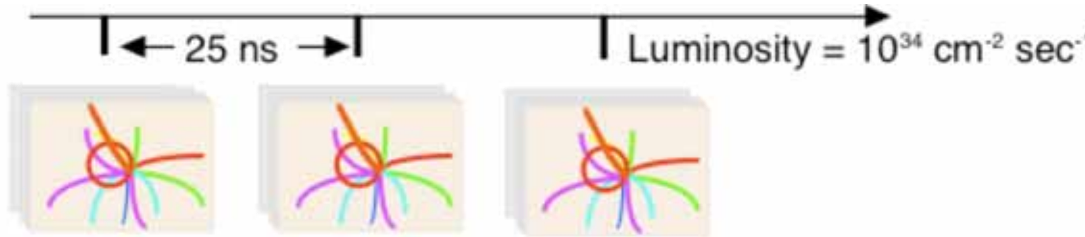
Detector/sector merging and track fitting

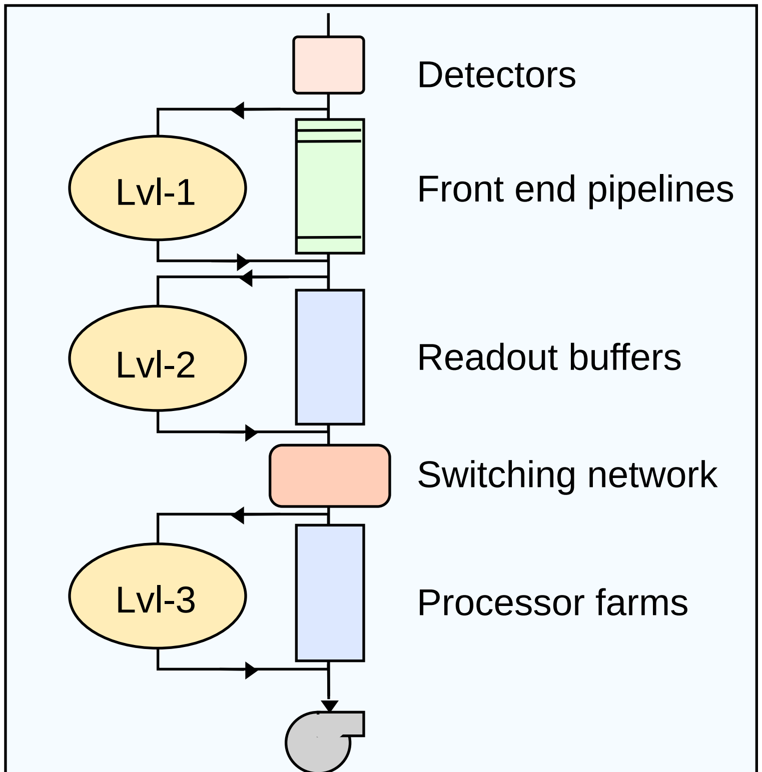
Trigger decision

ATLAS & CMS Trigger & Readout Structure

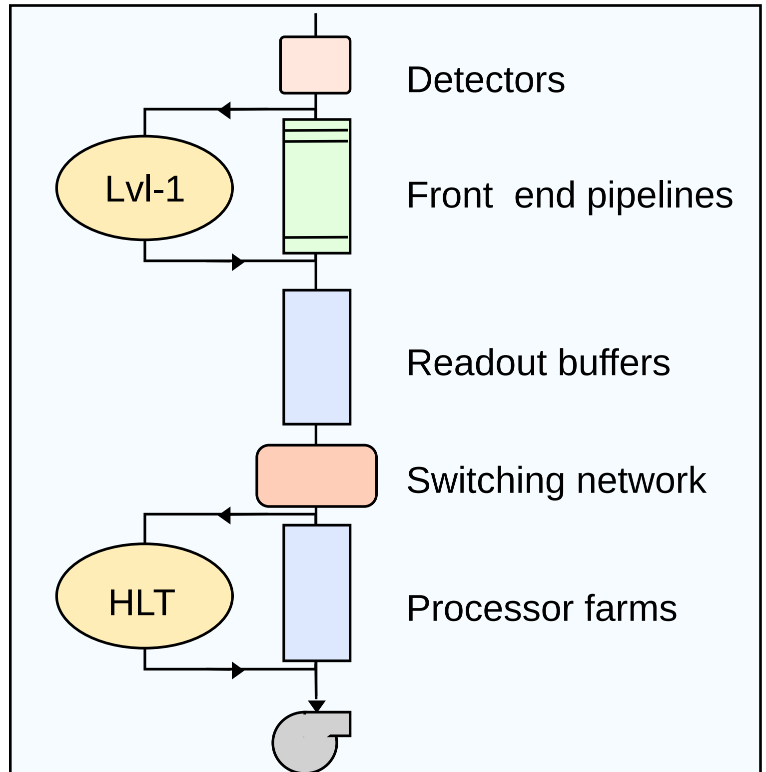
≈ 30 Collisions/25ns
(10^9 event/sec)

10^7 channels
(10^{16} bit/sec)





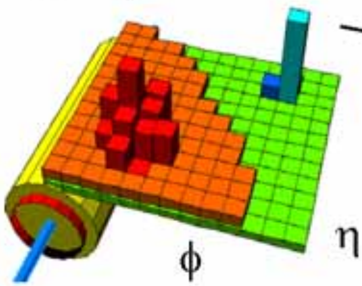
ATLAS: 3 physical levels



CMS: 2 physical levels

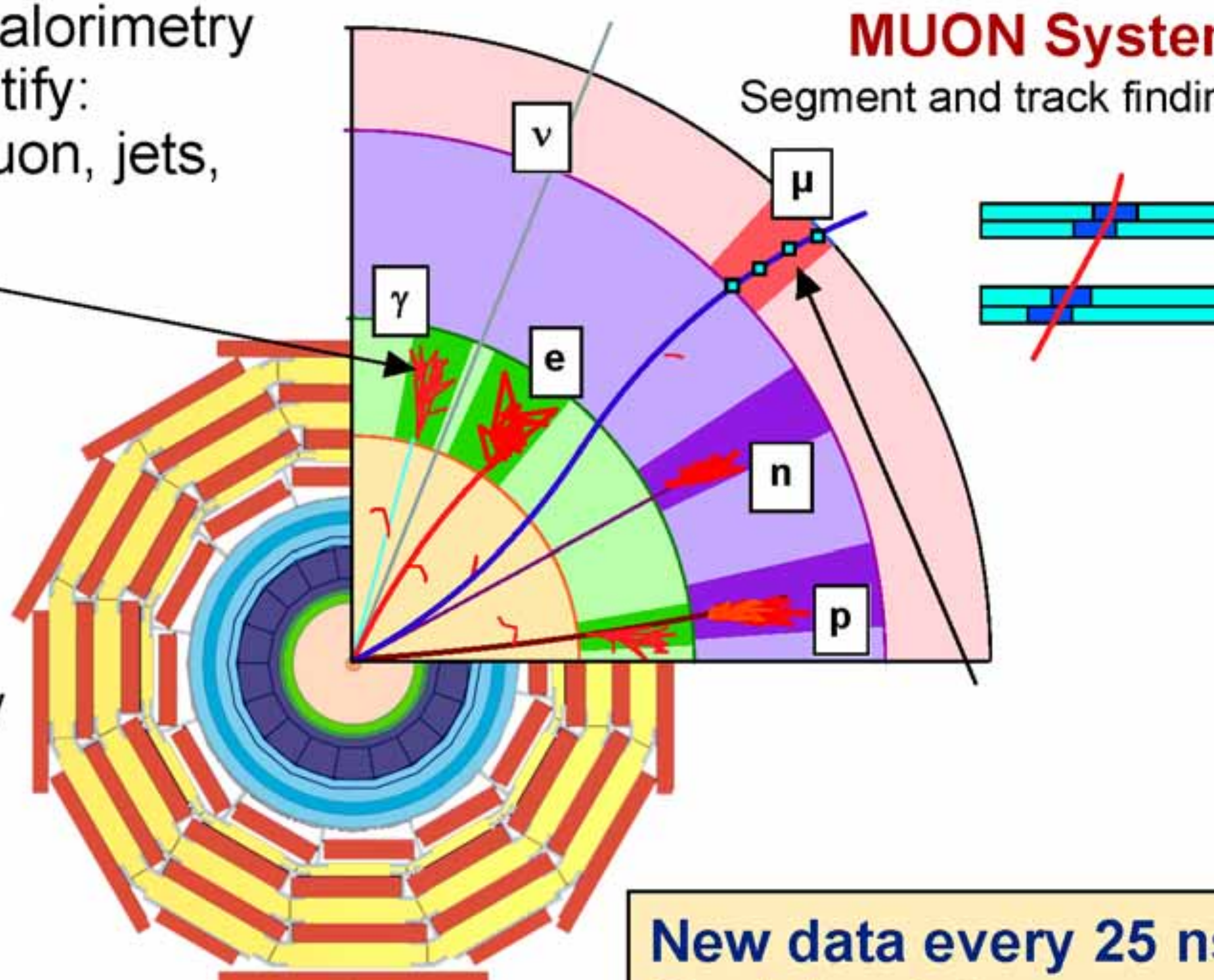
ATLAS & CMS Trigger Data

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



CALORIMETERs

Cluster finding and energy deposition evaluation



MUON System

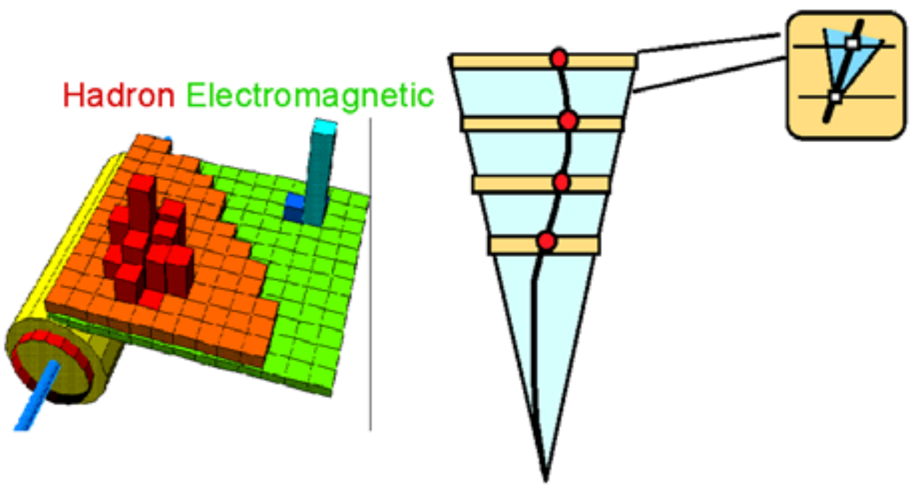
Segment and track finding

New data every 25 ns
Decision latency ~ μs

ATLAS & CMS Level 1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

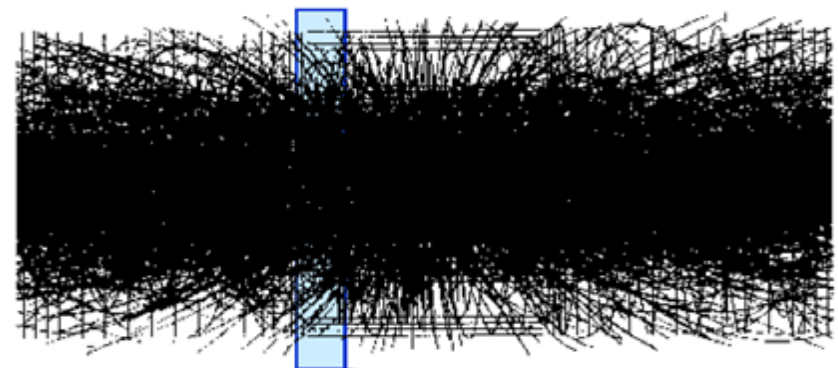
- **Pattern recognition much faster/easier**



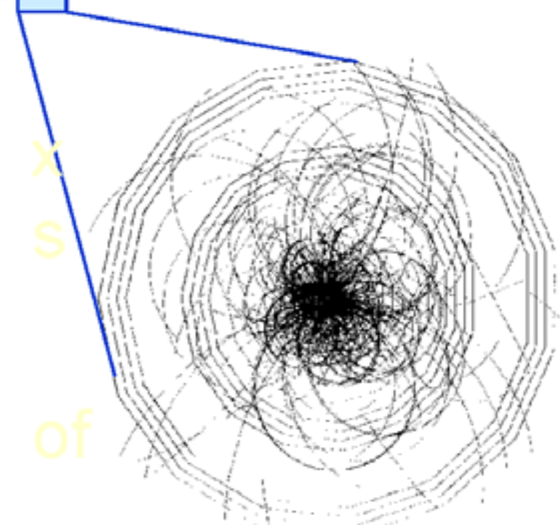
Simple Algorithms

Small amounts of data

- **Compare to tracker info**

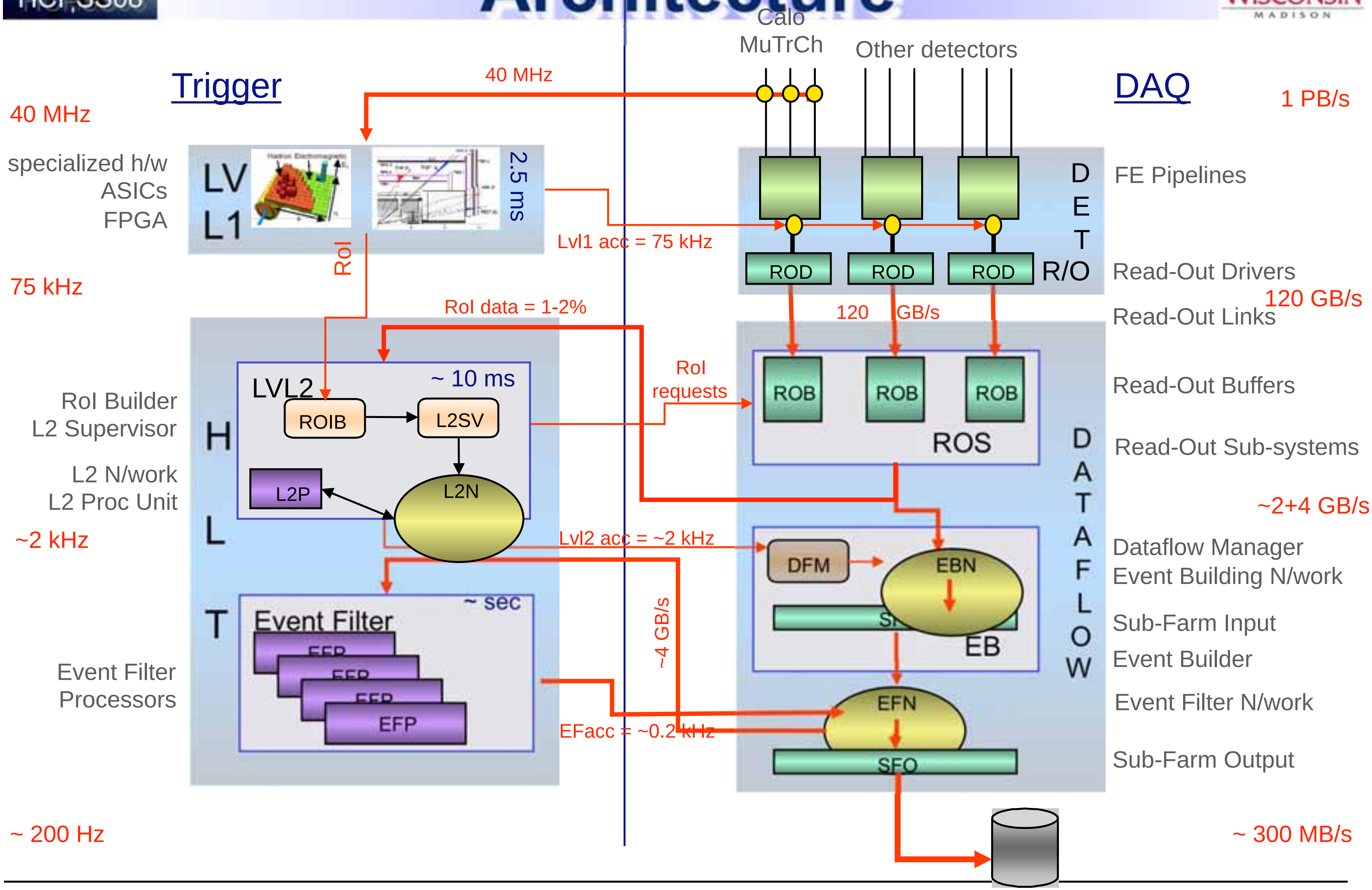


Complex Algorithms

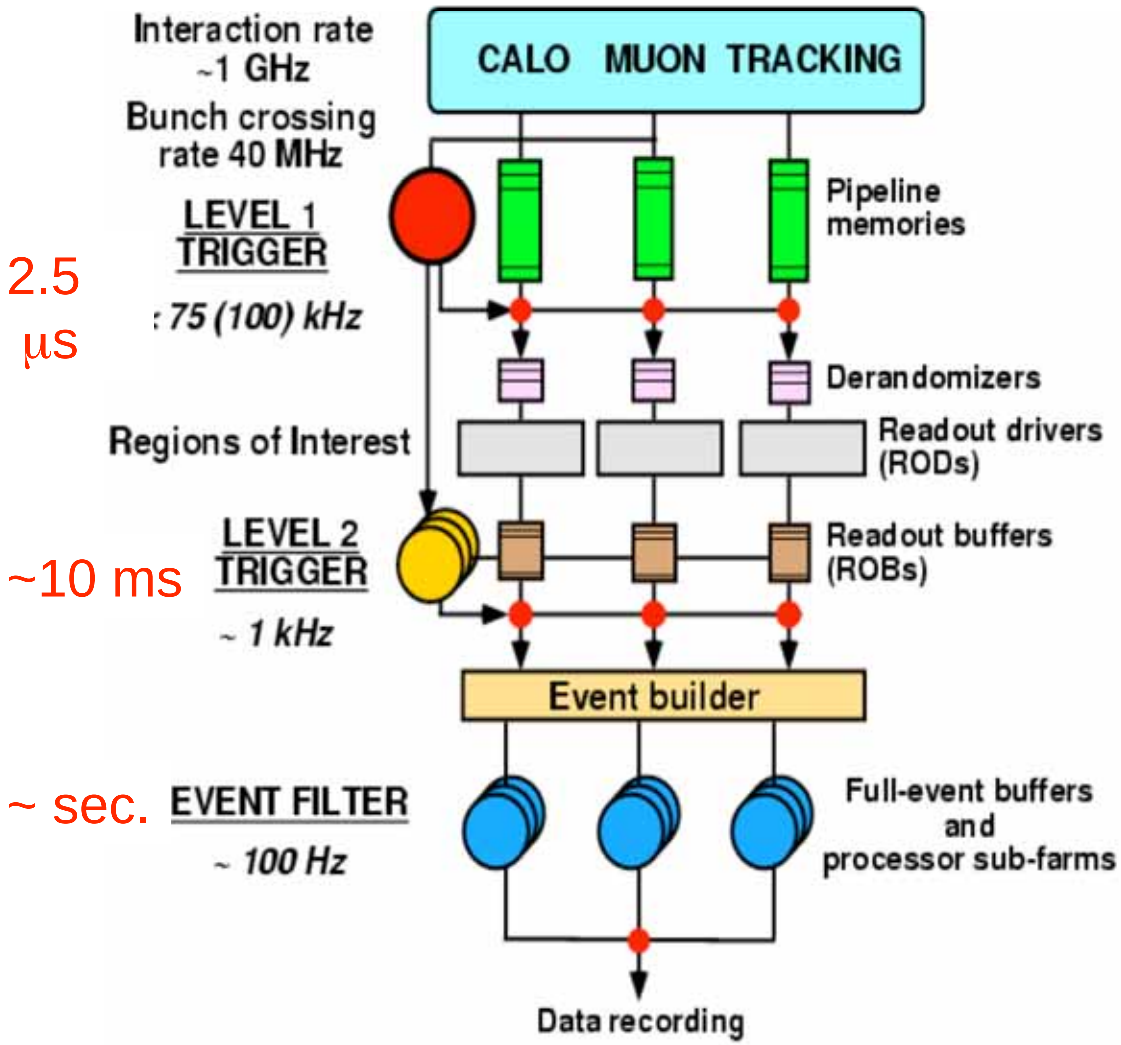


Huge amounts of data

ATLAS Trigger & DAQ Architecture

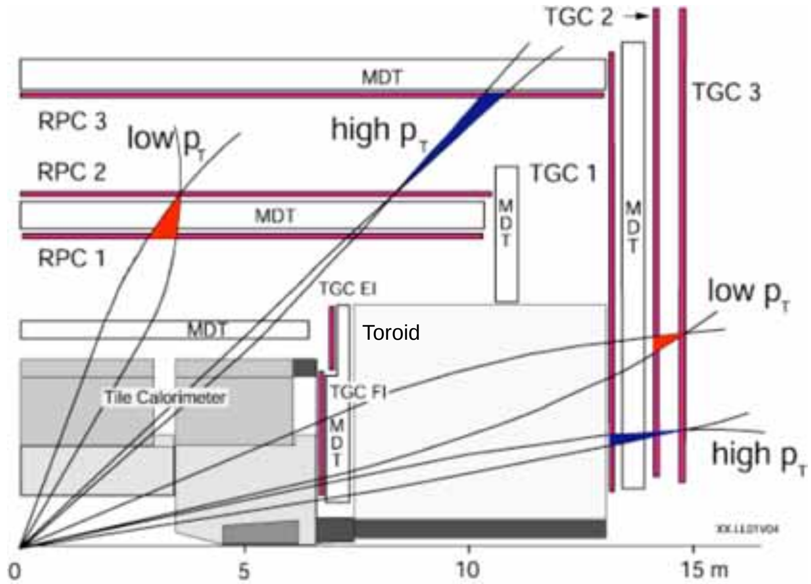


ATLAS Three Level Trigger Architecture



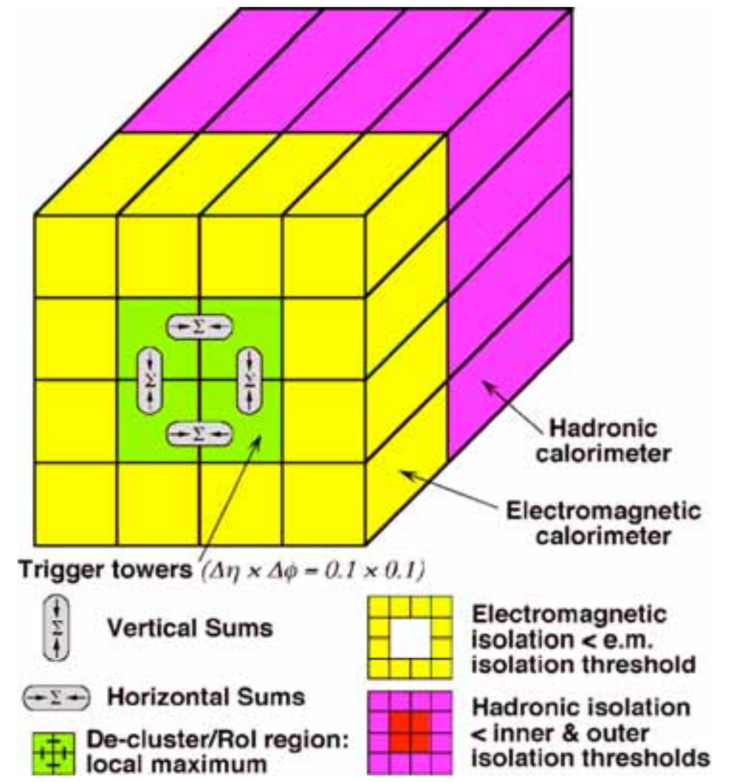
- **LVL1 decision** made with **calorimeter** data with coarse granularity and **muon trigger chambers** data.
  - Buffering on detector
- **LVL2 uses Region of Interest data** (ca. 2%) with full granularity and combines information from all detectors; performs fast rejection.
  - Buffering in ROBs
-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

LVL1 - 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)

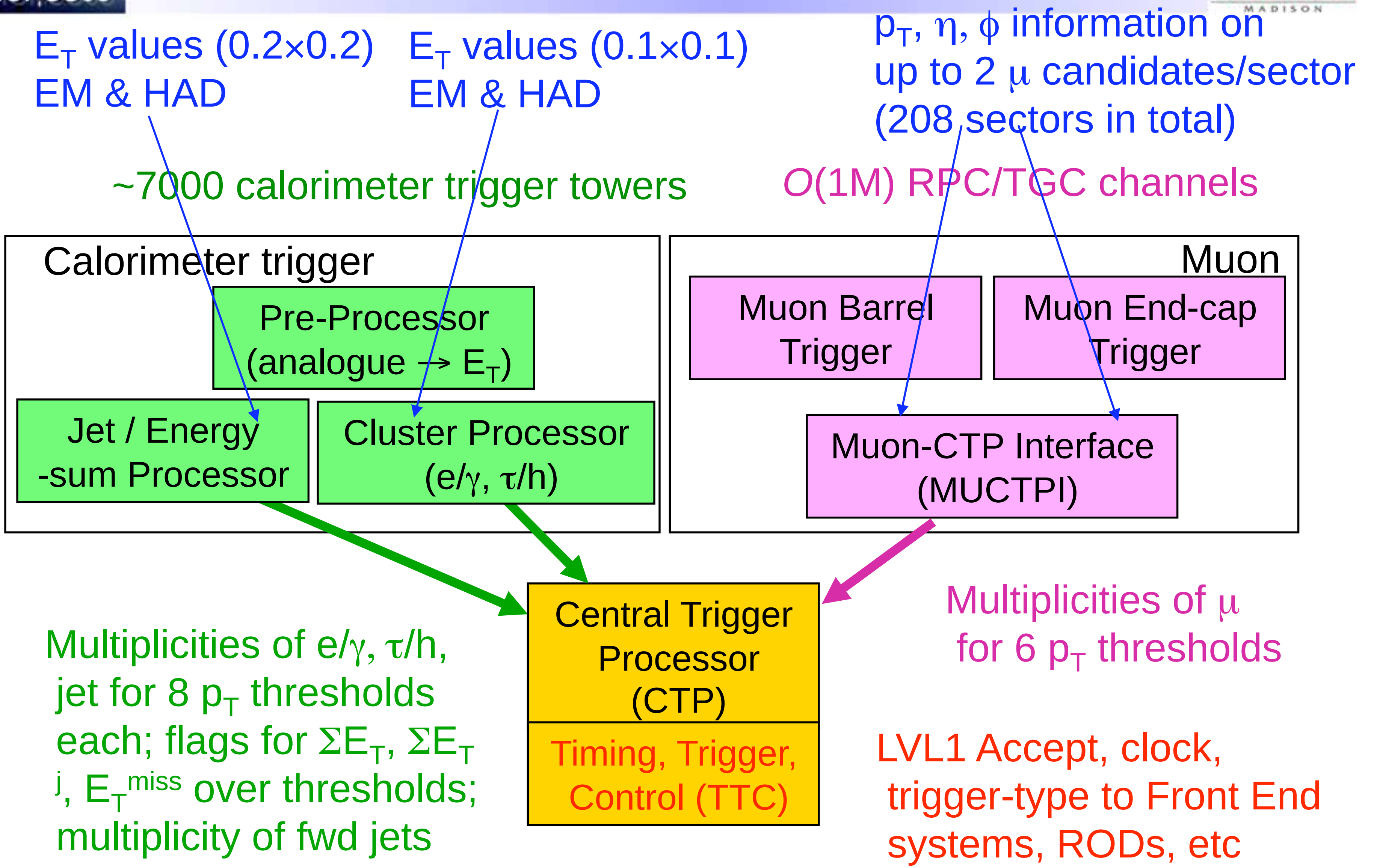
Trigger efficiency 99% (low-p_T) and 98% (high-p_T)



Calorimetry Trigger looking for e/γ/τ + jets

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

ATLAS LVL1 Trigger



RoI Mechanism

HCPSS08

THE UNIVERSITY of WISCONSIN MADISON

LVL1 triggers on high p_T objects

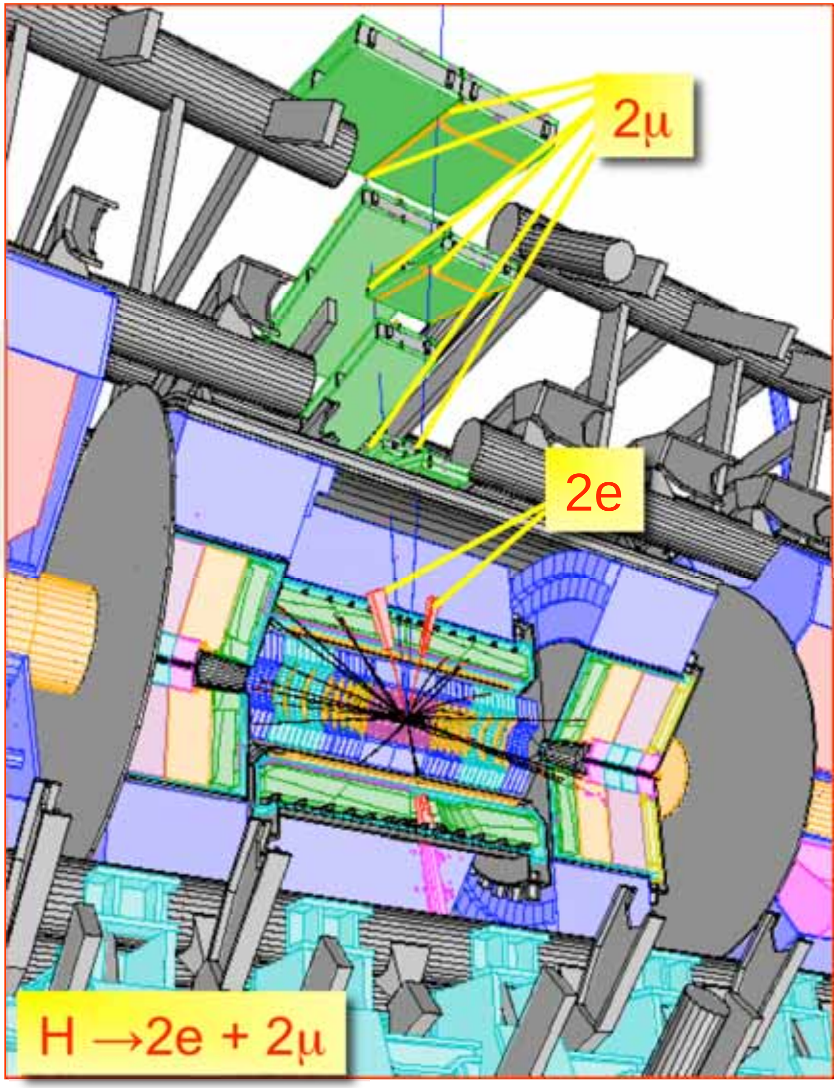
- **Calorimeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

LVL2 uses Regions of Interest as identified by Level-1

- Local data reconstruction, analysis, and sub-detector matching of RoI data

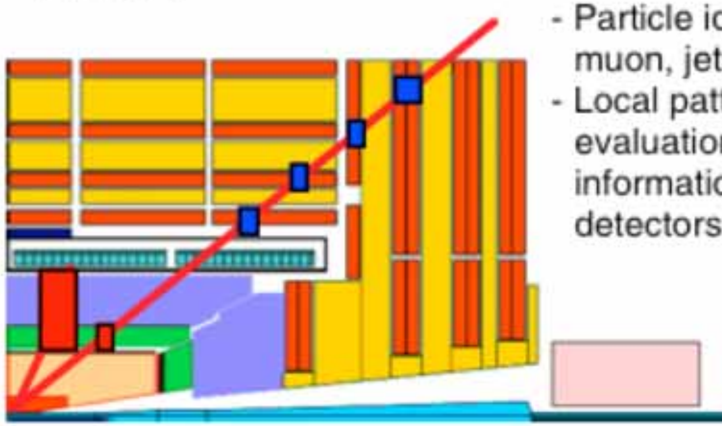
The total amount of RoI data is minimal

- ~2% of the Level-1 throughput but it has to be extracted from the rest at 75 kHz



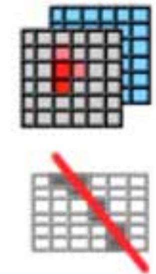
CMS Trigger Levels

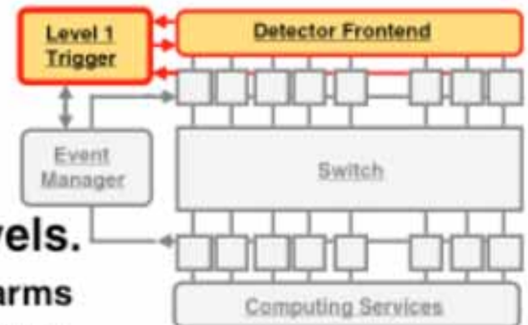
40 MHz



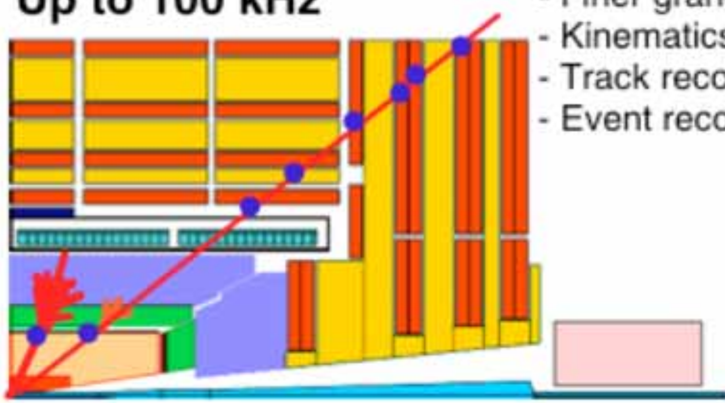
Level-1. Specialized processors

- 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

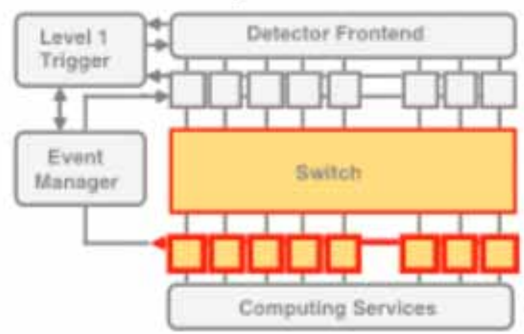


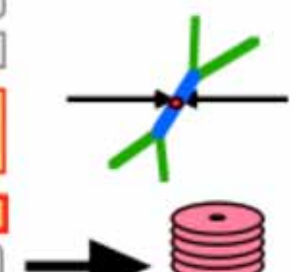
High trigger levels.

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



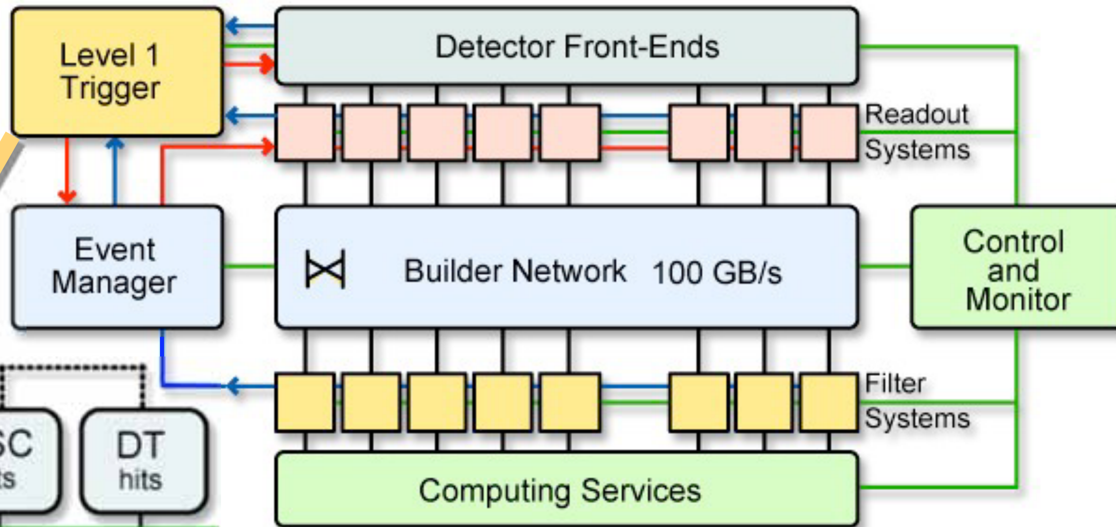


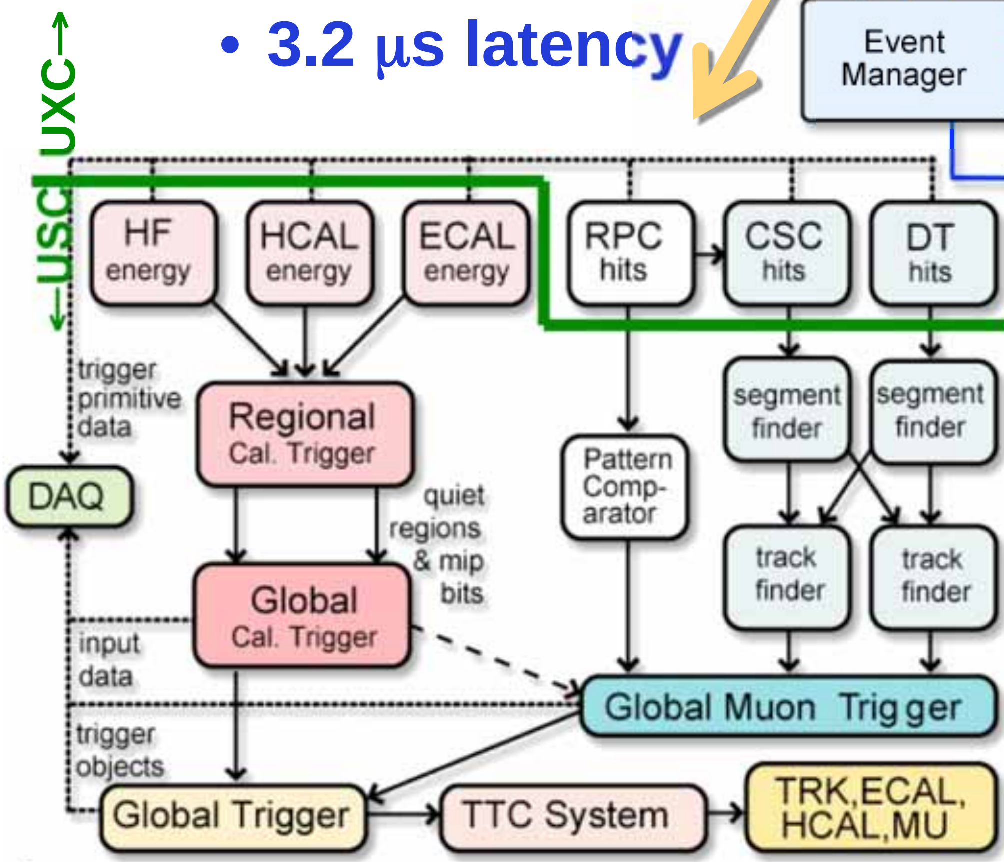
CMS Level-1 Trigger & DAQ

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

Level 1 Output: 100 kHz (50 initial)

Output to Storage: 100 Hz

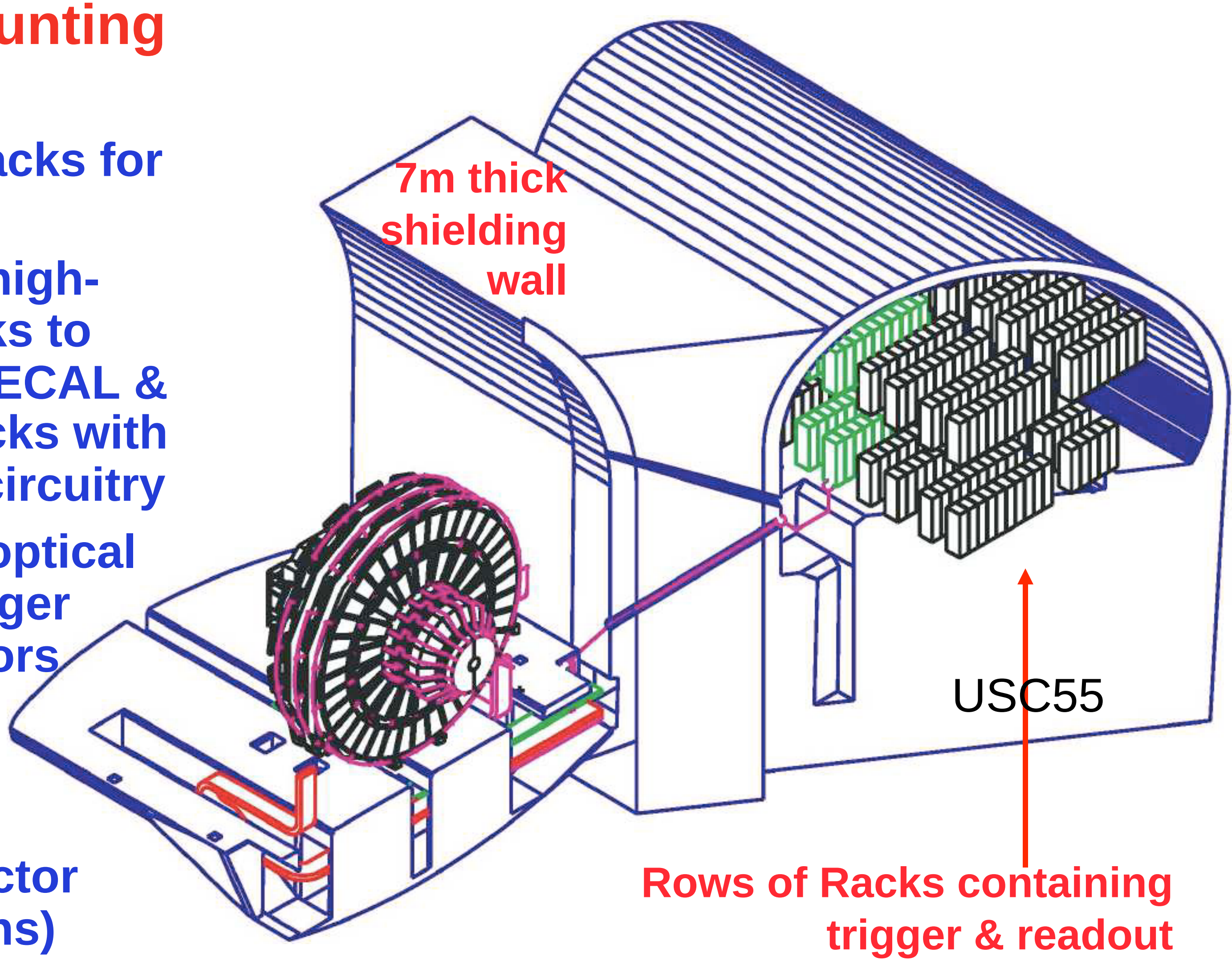
Average Event Size: 1 MB

Data production 1 TB/day

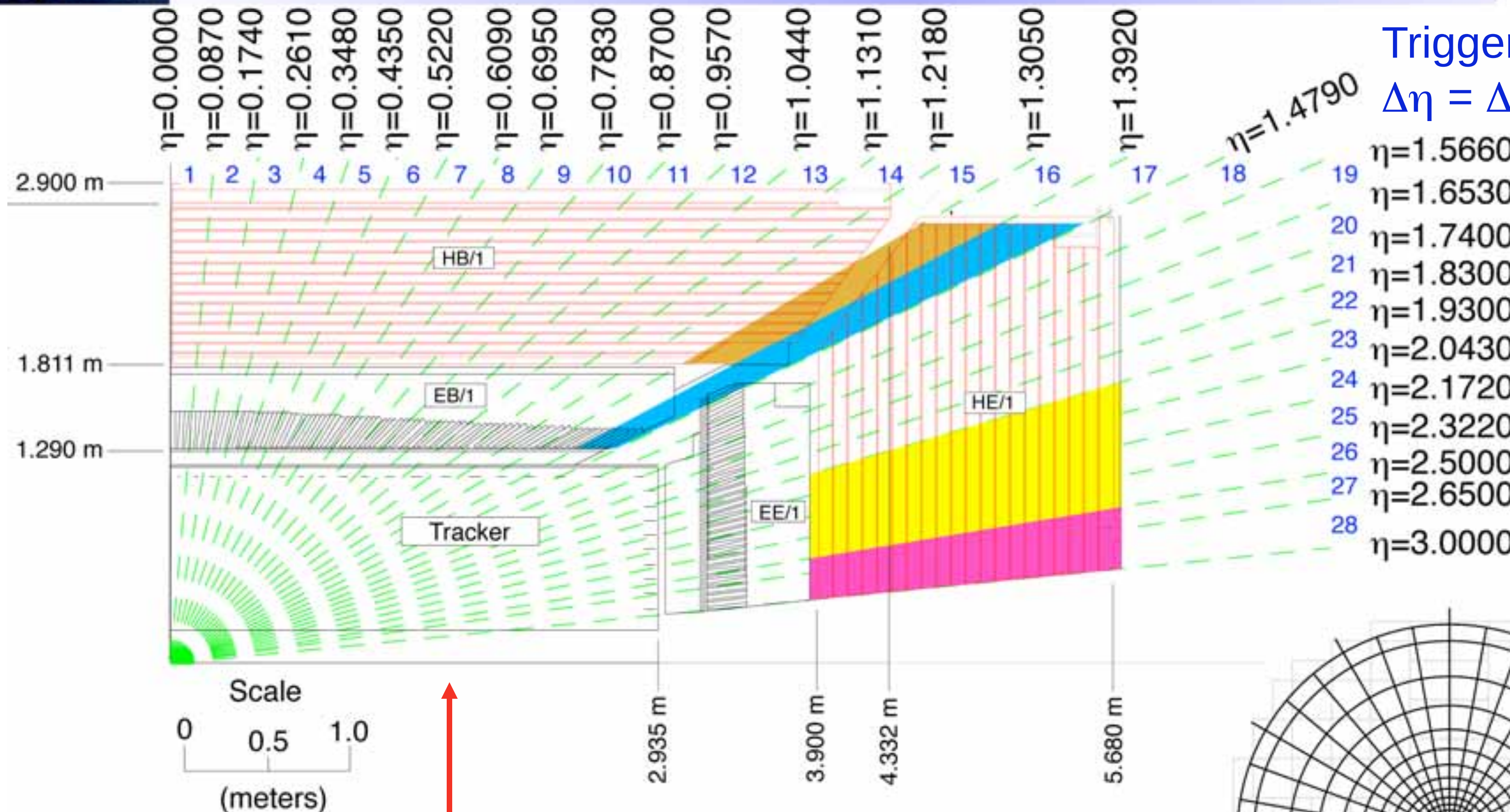
L1 Trigger Locations

Underground Counting Room

- Central rows of racks for trigger
- Connections via high-speed copper links to adjacent rows of ECAL & HCAL readout racks with trigger primitive circuitry
- Connections via optical fiber to muon trigger primitive generators on the detector
- Optical fibers connected via "tunnels" to detector (~90m fiber lengths)



CMS Calorimeter Geometry



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

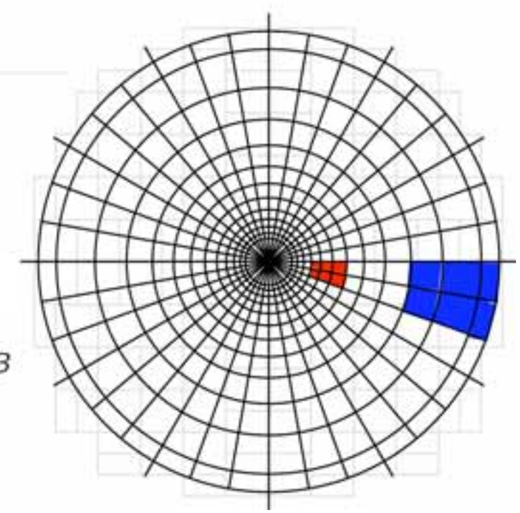
EB, EE, HB, HE map to 18 RCT crates

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

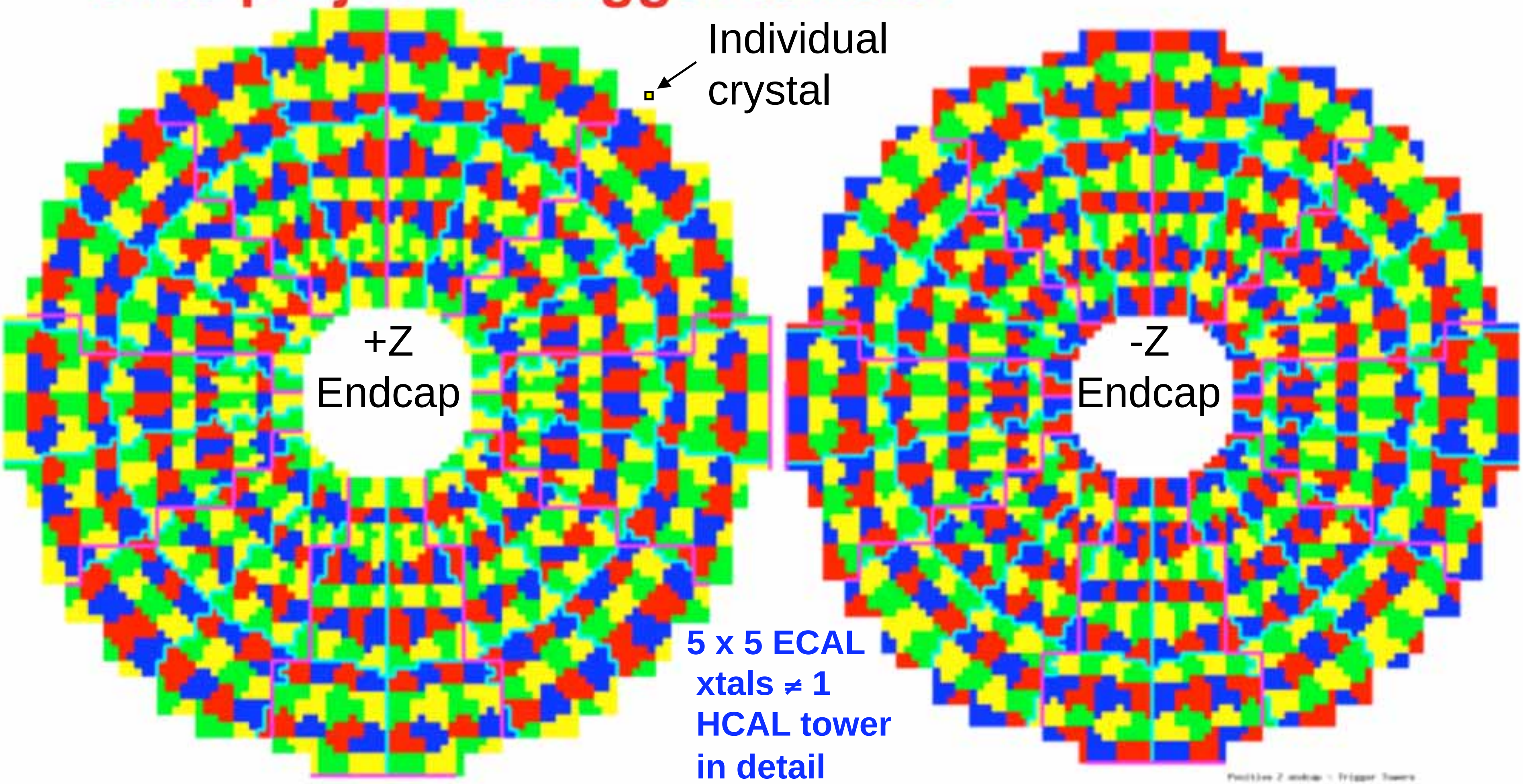
Trigger Tower segmentation: 18φ × 4η × 2F/B



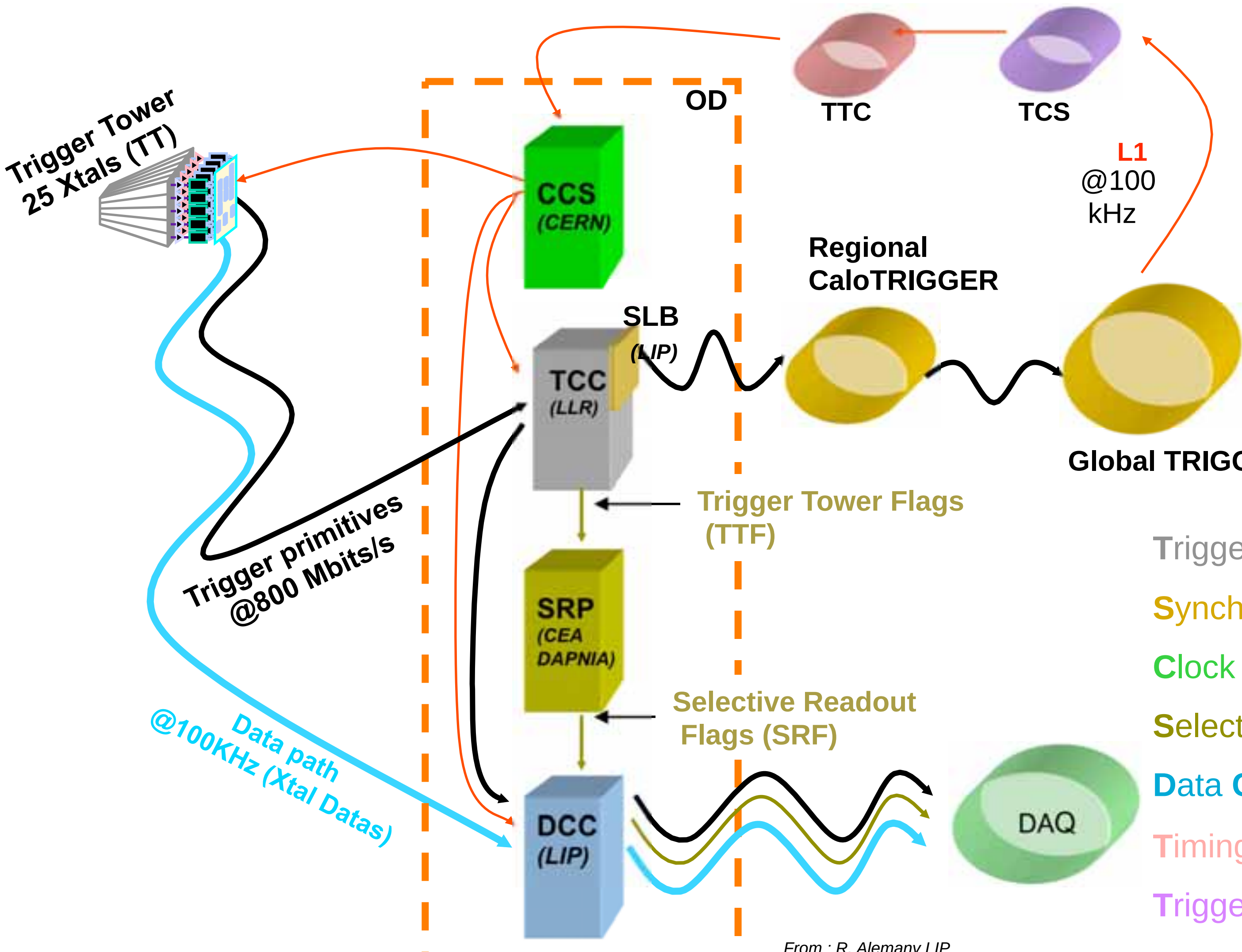
1 trigger tower (.087η x .087φ) = 5 x 5 ECAL xtals = 1 HCAL tower

ECAL Endcap Geometry

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



Calorimeter Trigger Processing



Trigger Concentrator Card

Synchronisation & Link Board

Clock & Control System

Selective Readout Processor

Data Concentrator Card

Timing, Trigger & Control

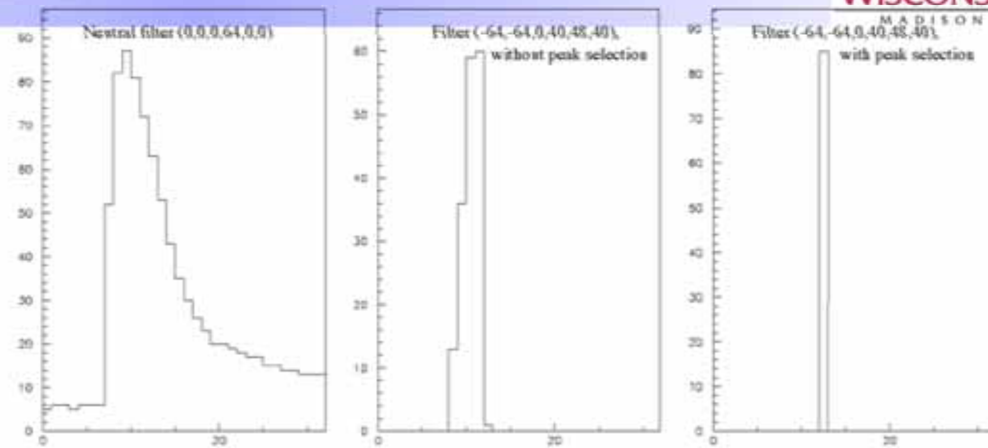
Trigger Control System

ECAL Trigger Primitives

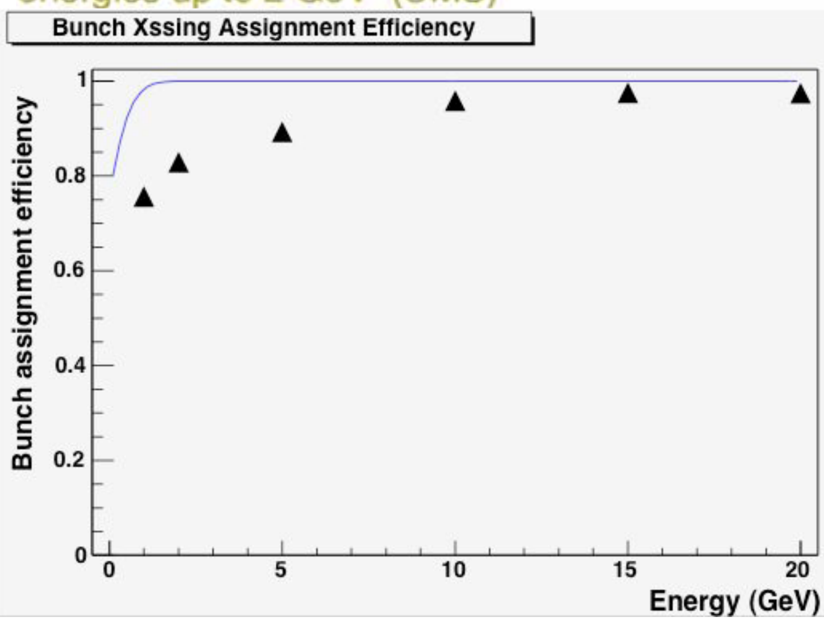
In the trigger path, **digital filtering** followed by a **peak finder** is applied to energy sums **(L1 Filter)**

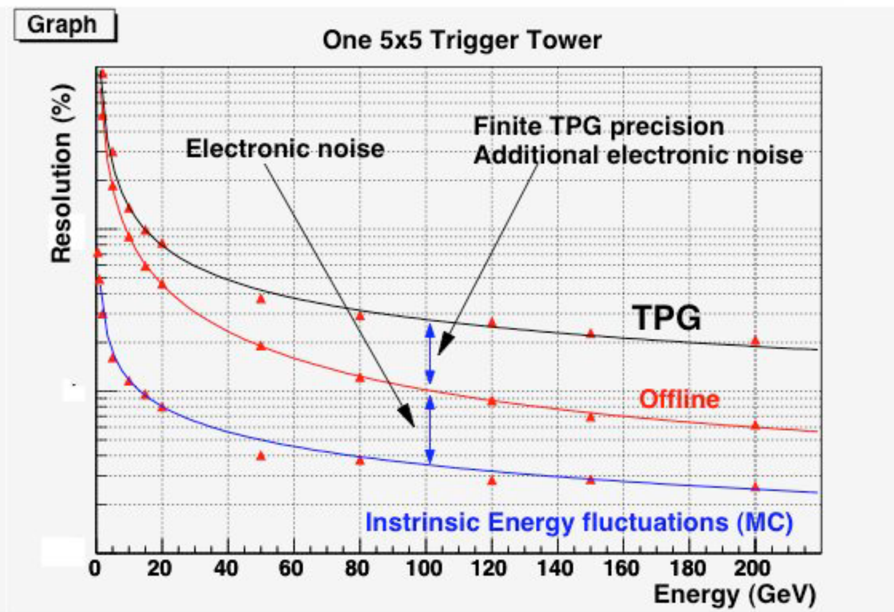
Efficiency for energy sums above 1 GeV should be close to 100% (depends on electronics noise)

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/Photon Algorithm

Trigger Primitive Generator

Fine grain — Flag Max of (, , ,) & Sum ET

Regional Calorimeter Trigger

E_T cut — + Max ( ) > Threshold

AND

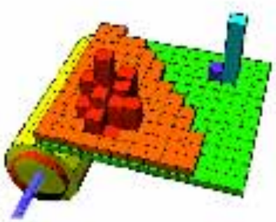
Longitudinal cut (H/E) — / < 0.05

AND

Isolation, Hadronic & EM — < 2 GeV

AND

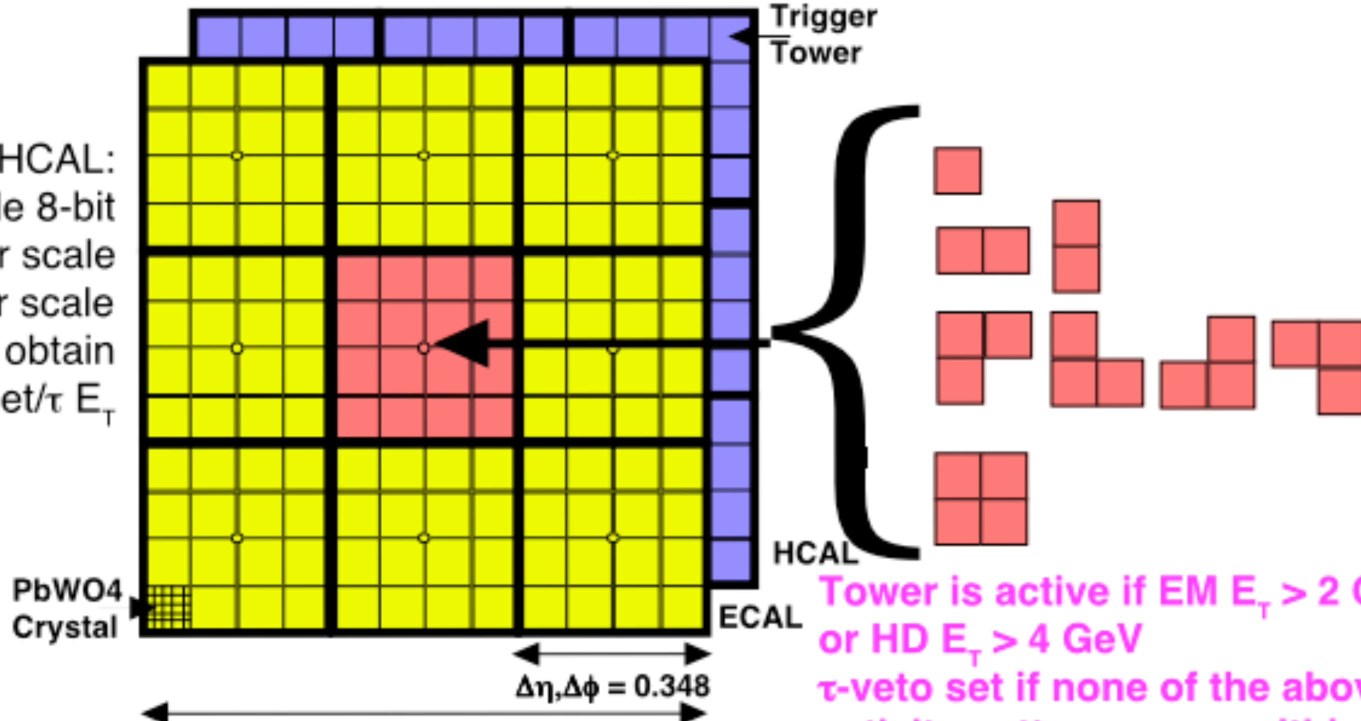
One of (, , ,) < 1 GeV



ELECTRON or PHOTON

CMS τ / Jet Algorithm

Input from E/HCAL:
Programmable 8-bit non-linear scale
Converted to linear scale and summed to obtain 10-bit range jet/τ E_T



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 < η < 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

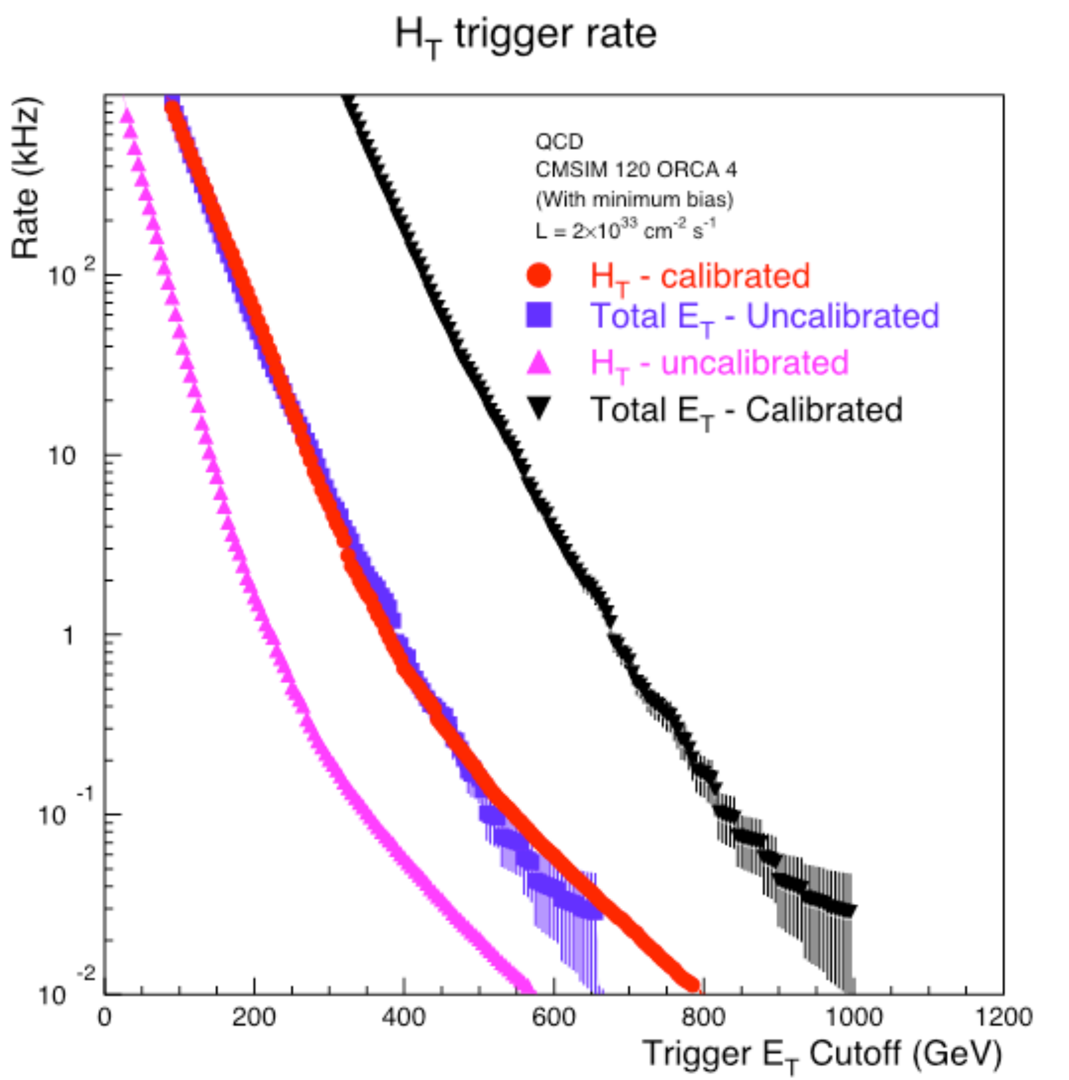
Total scalar E_T integrates too much noise and is not easily calibrated

- At L1 tower-by-tower E_T calibration is not available

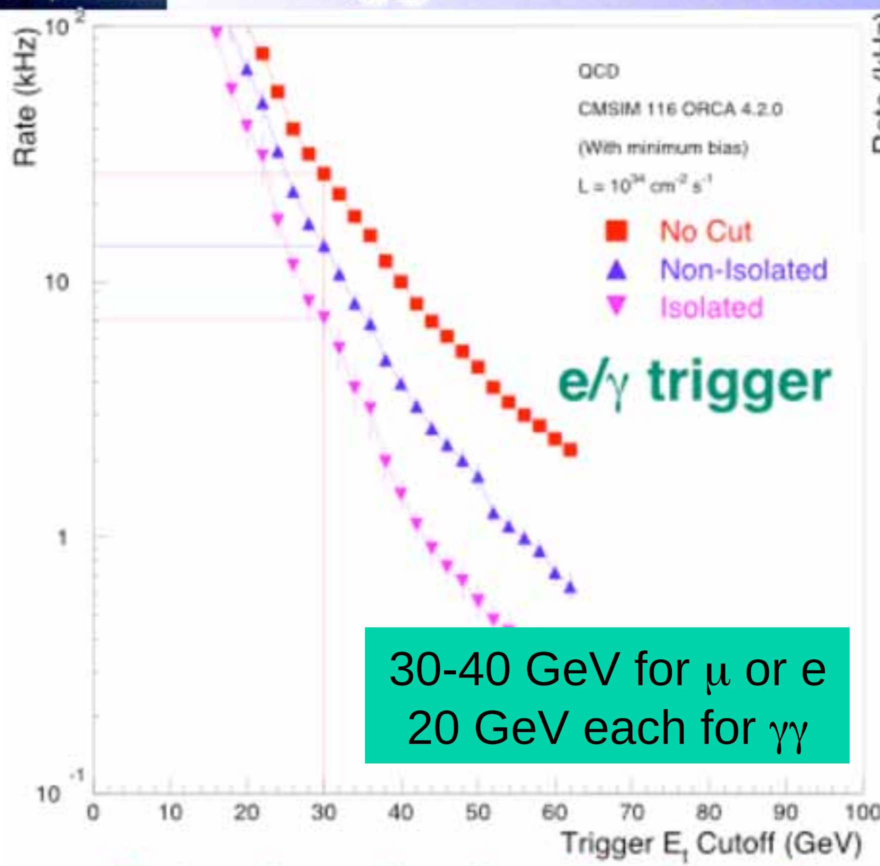
However, jet calibration is available as function of (E_T, η, ϕ)

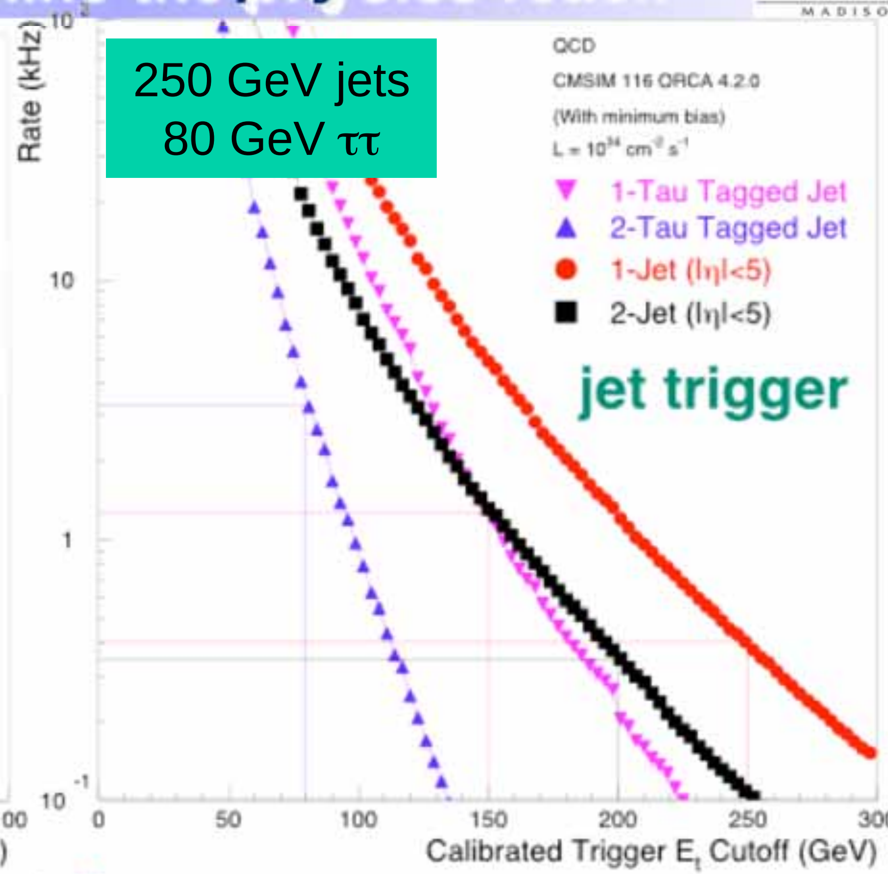
Therefore, H_T which is the sum of scalar E_T of all high E_T objects in the event is more useful for heavy particle discovery/study

- SUSY sparticles
- Top



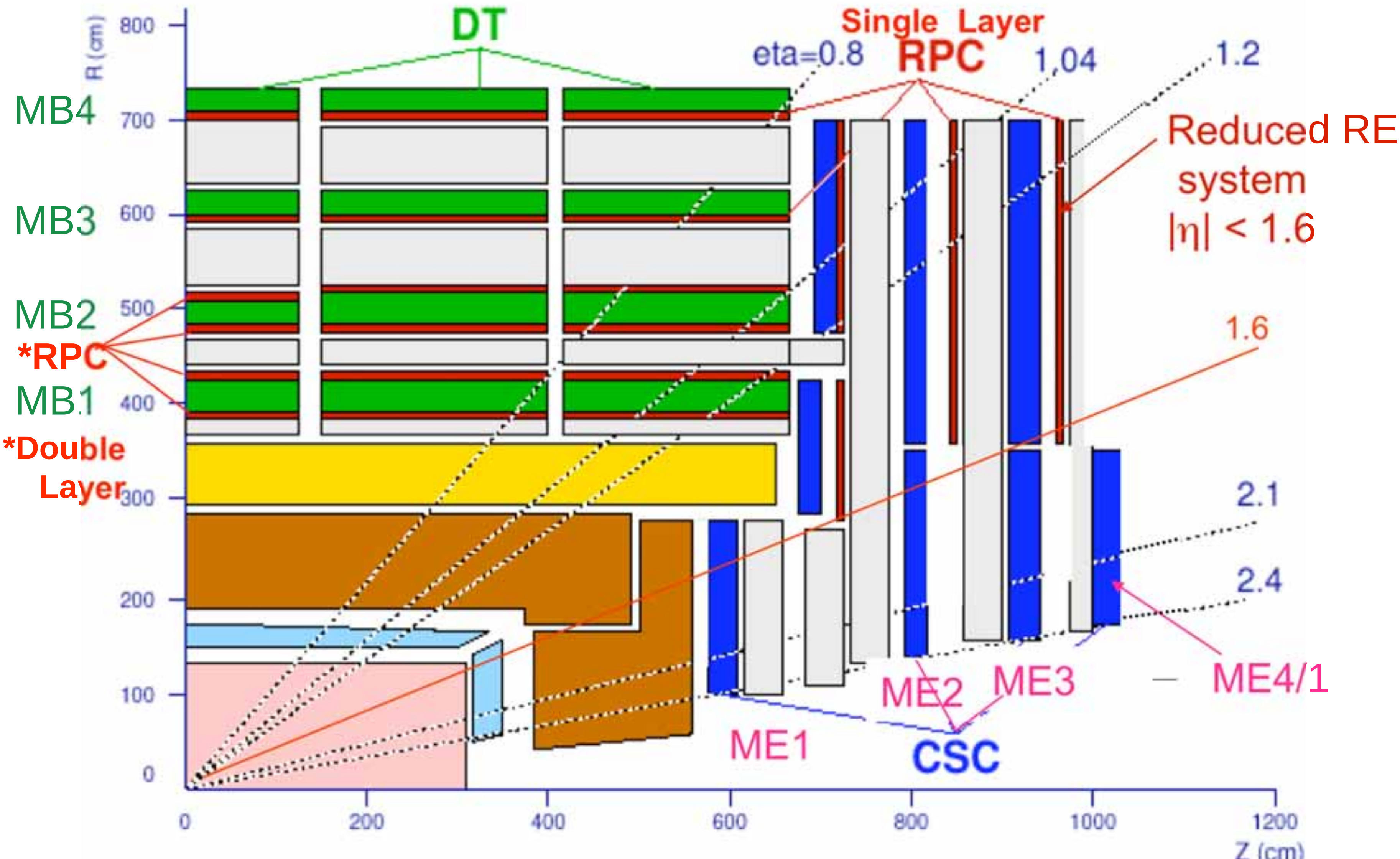
Level-1 Trigger Rates:
Trigger cuts determine the physics reach



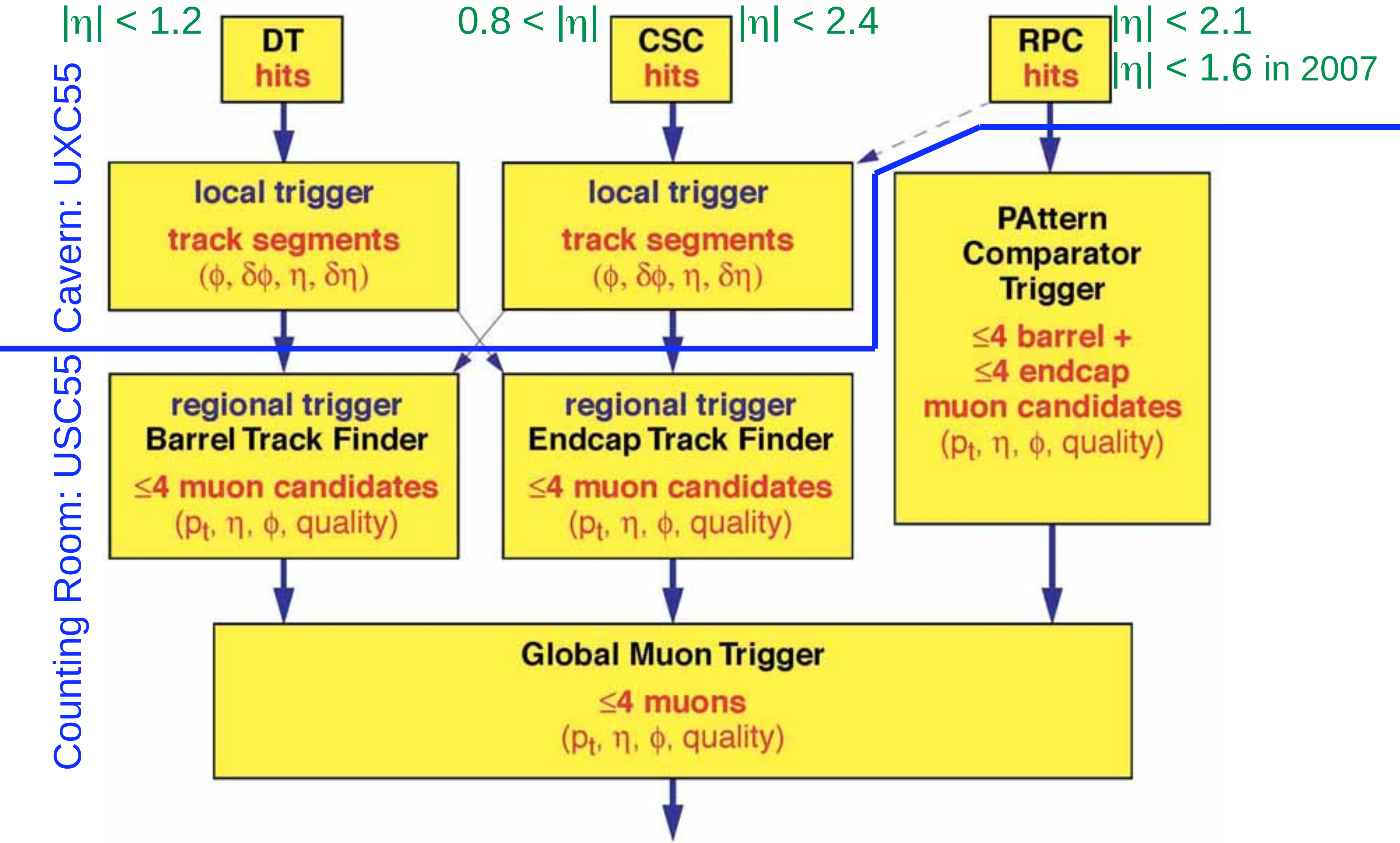


- **Efficiency for H→γγ and H→4 leptons = >90% (in fiducial volume of detector)**
- **Efficiency for WH and ttH production with W→lν = ~85%**
- **Efficiency for qqH with H→ττ (τ→1/3 prong hadronic) = ~75%**
- **Efficiency for qqH with H→invisible or H→bb = ~40-50%**

CMS Muon Chambers

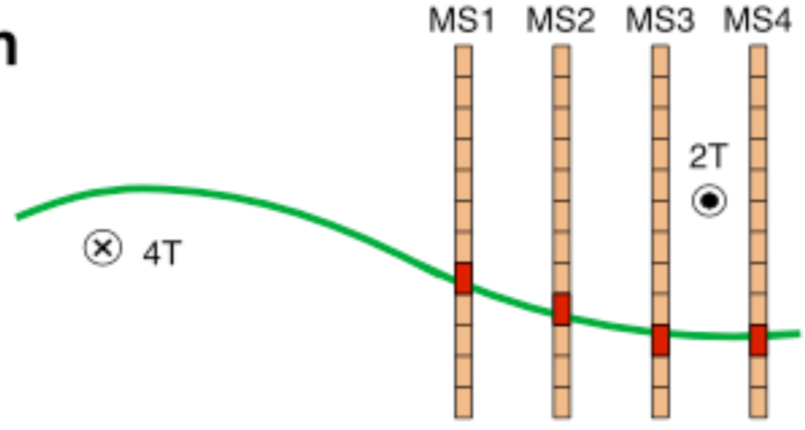


Muon Trigger Overview



CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

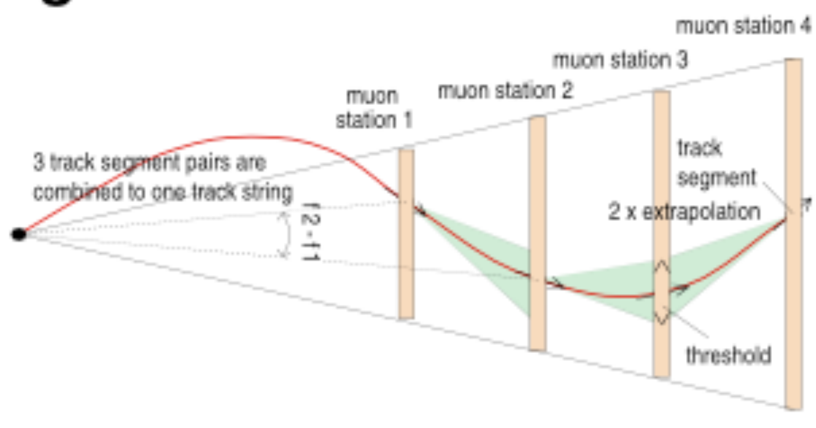


Memory to store patterns

Fast logic for matching

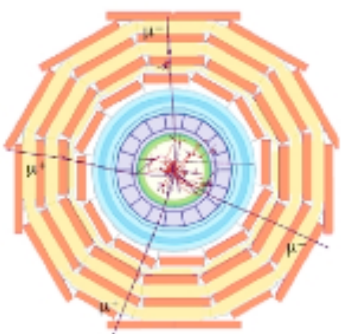
FPGAs are ideal

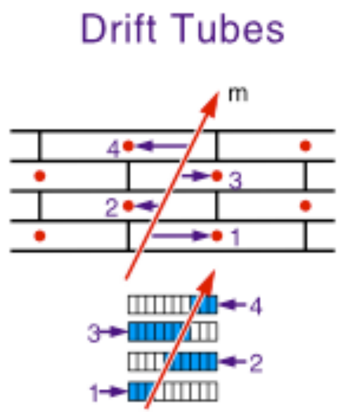
DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



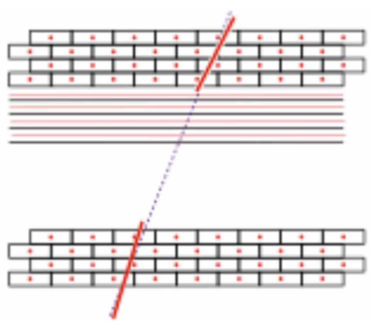
CMS Muon Trigger Track Finders

Drift Tubes (DT)



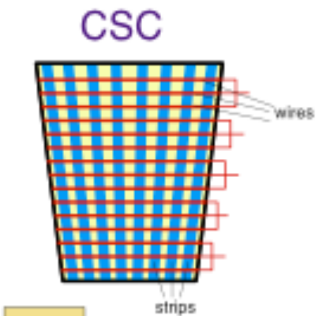


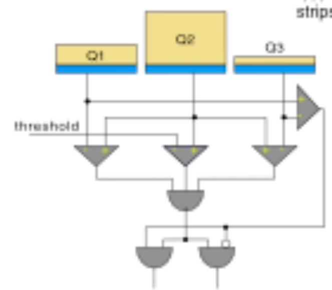
Meantimers recognize tracks and form vector / quartet.



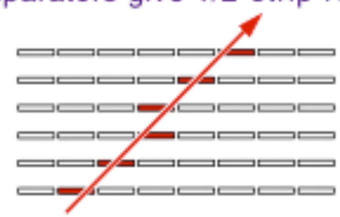
Correlator combines them into one vector / station.

Cathod Strip Chambers (CSC)

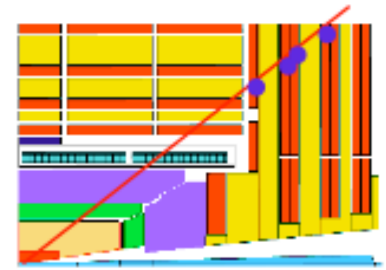




Comparators give 1/2-strip resol.



Hit strips of 6 layers form a vector.



Sort based on P_T, Quality - keep loc.

Combine at next level - match

Sort again - Isolate?

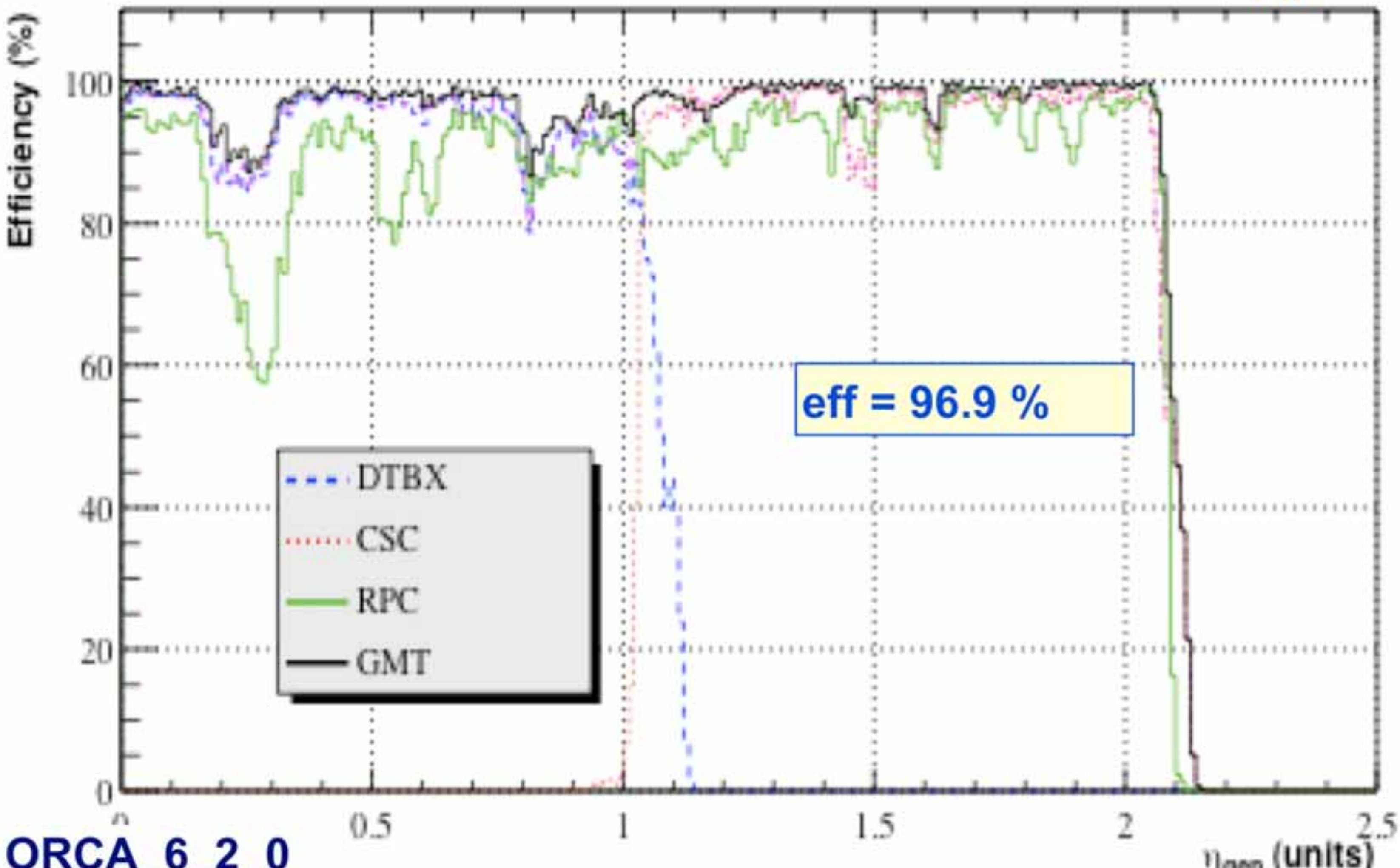
Top 4 highest P_T and quality muons with location coord.

Match with RPC

Improve efficiency and quality

Single muon trigger efficiency vs. η

|η| < 2.1



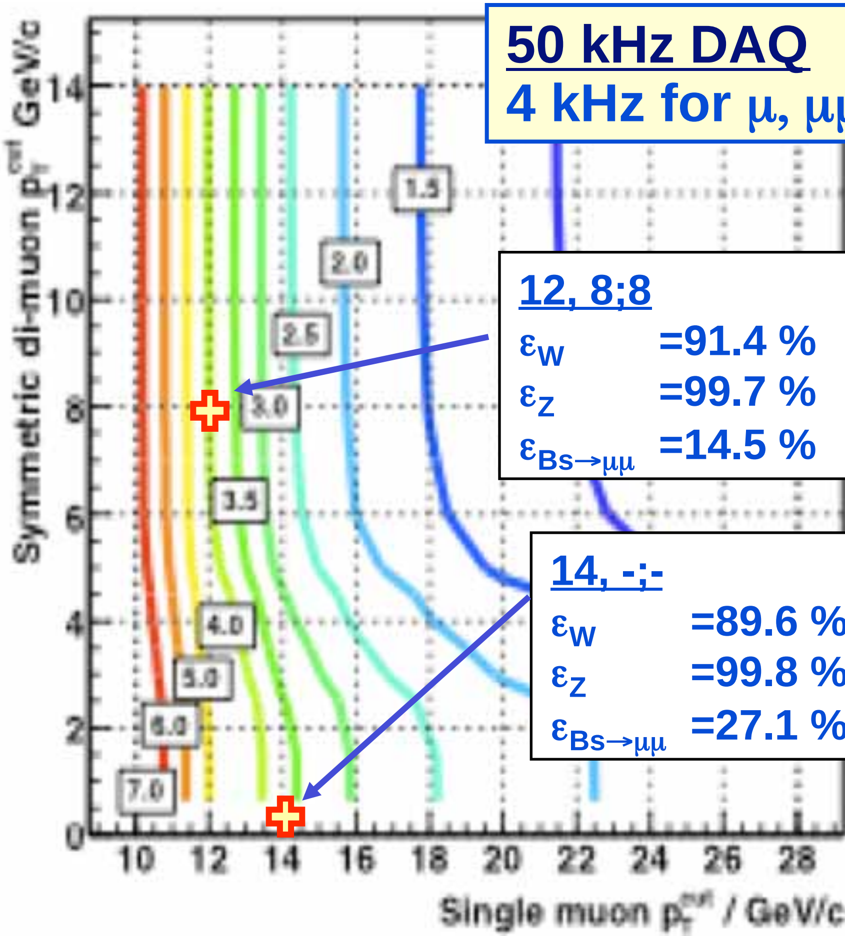
ORCA_6_2_0

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

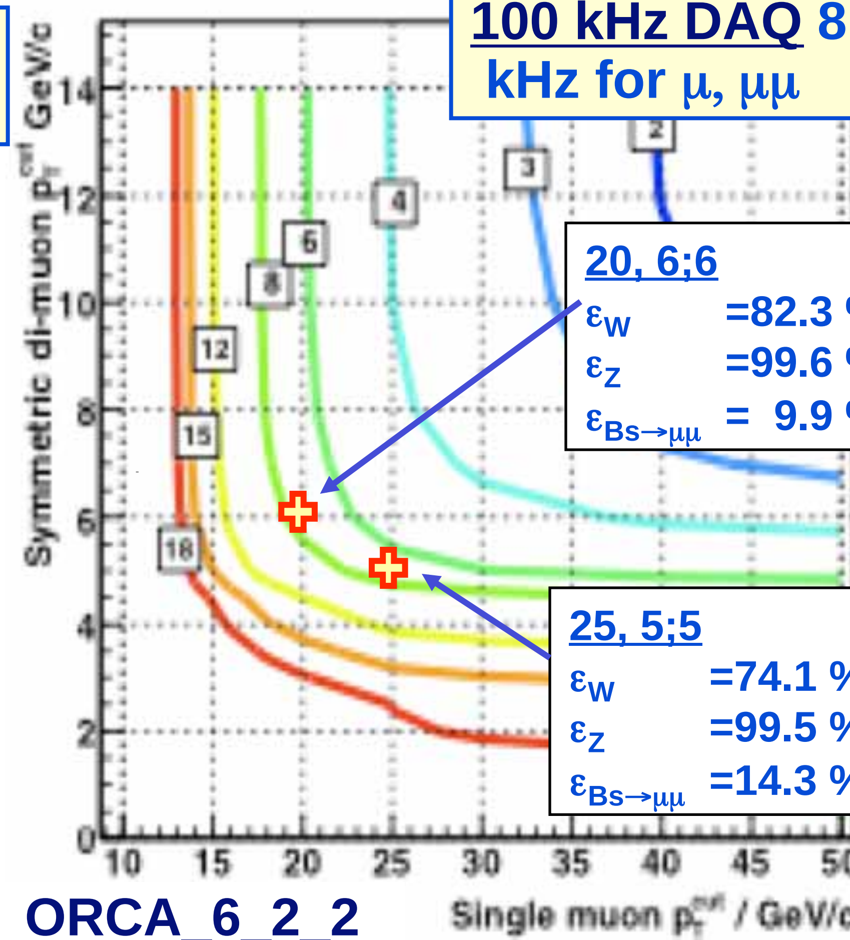
$|\eta| < 2.1$



50 kHz DAQ
4 kHz for μ, μμ

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

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



100 kHz DAQ 8 kHz for μ, μμ

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

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

ORCA_6_2_2

✚ working points selected as examples

$L = 2\times10^{33} cm^{-2}s^{-1}$

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

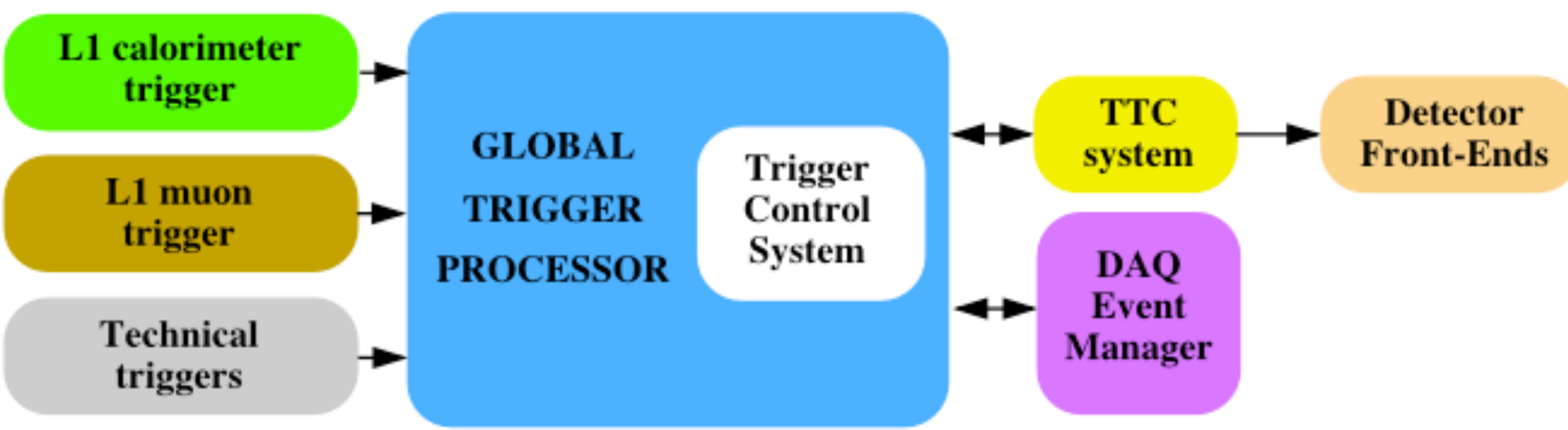
CMS Global Trigger
- Vienna

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

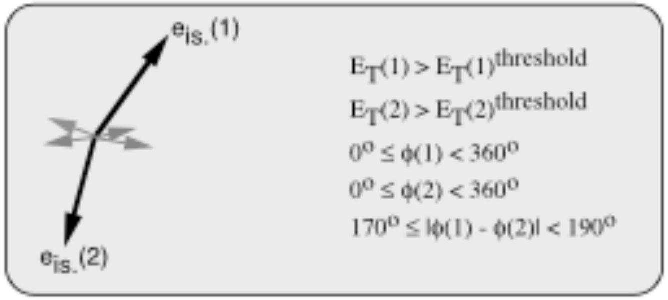
Output

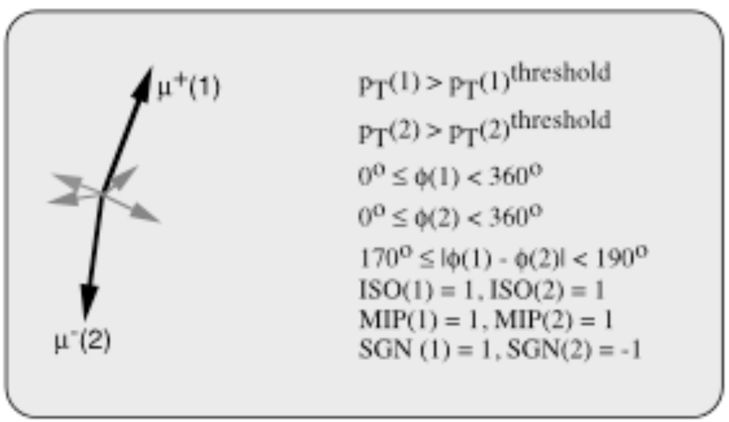
- L1 Accept from combinations & proximity of above



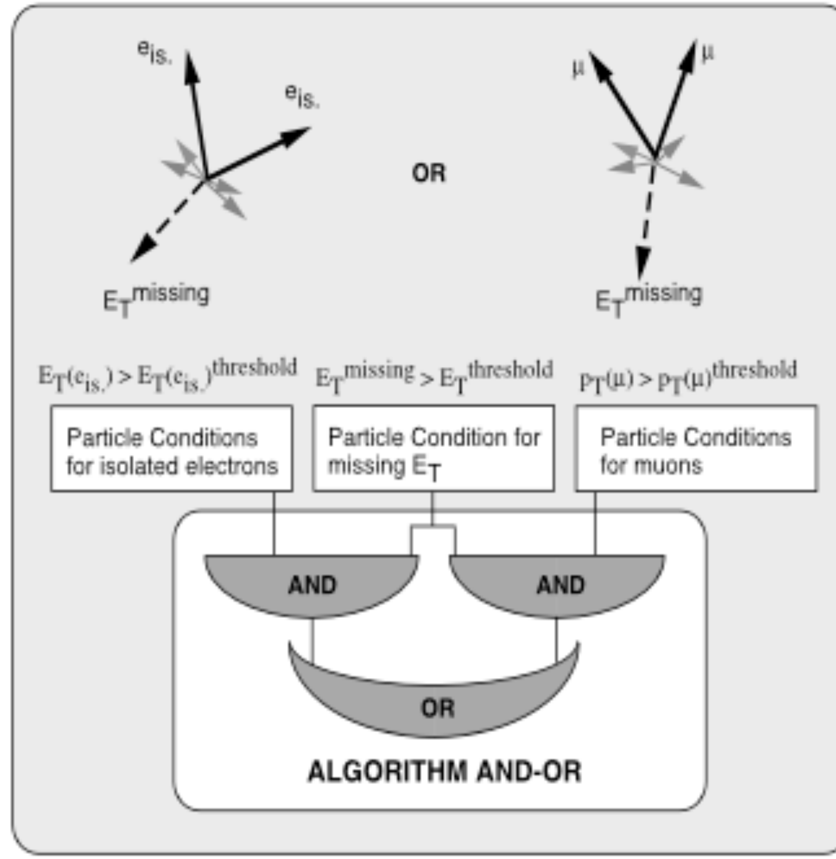
Global L1 Trigger Algorithms

Particle Conditions





Logical Combinations



Flexible algorithms implemented in FPGAs

100s of possible algorithms can be reprogrammed

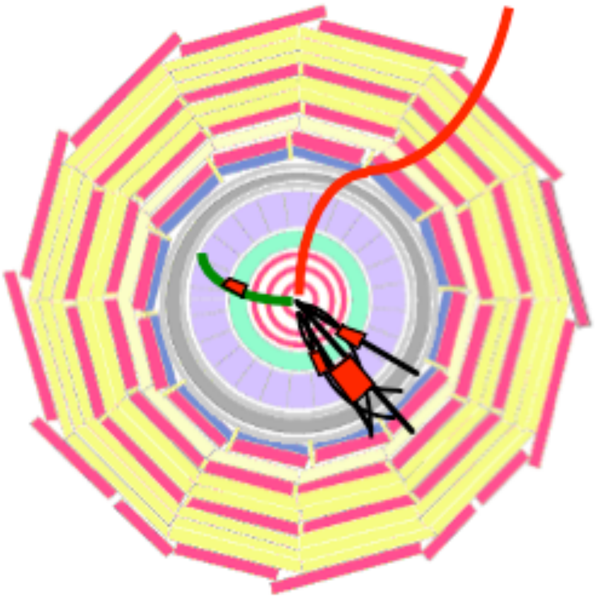
Example Level-1 Trigger Table
(DAQ TDR: $L = 2 \times 10^{33}$)

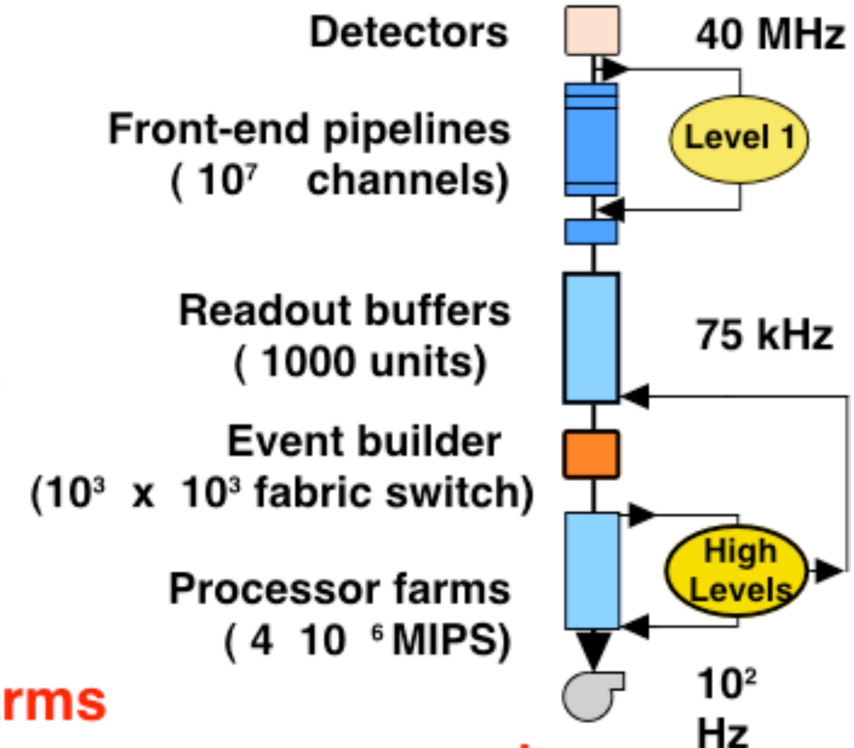
Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias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

High Level Trigger Strategy



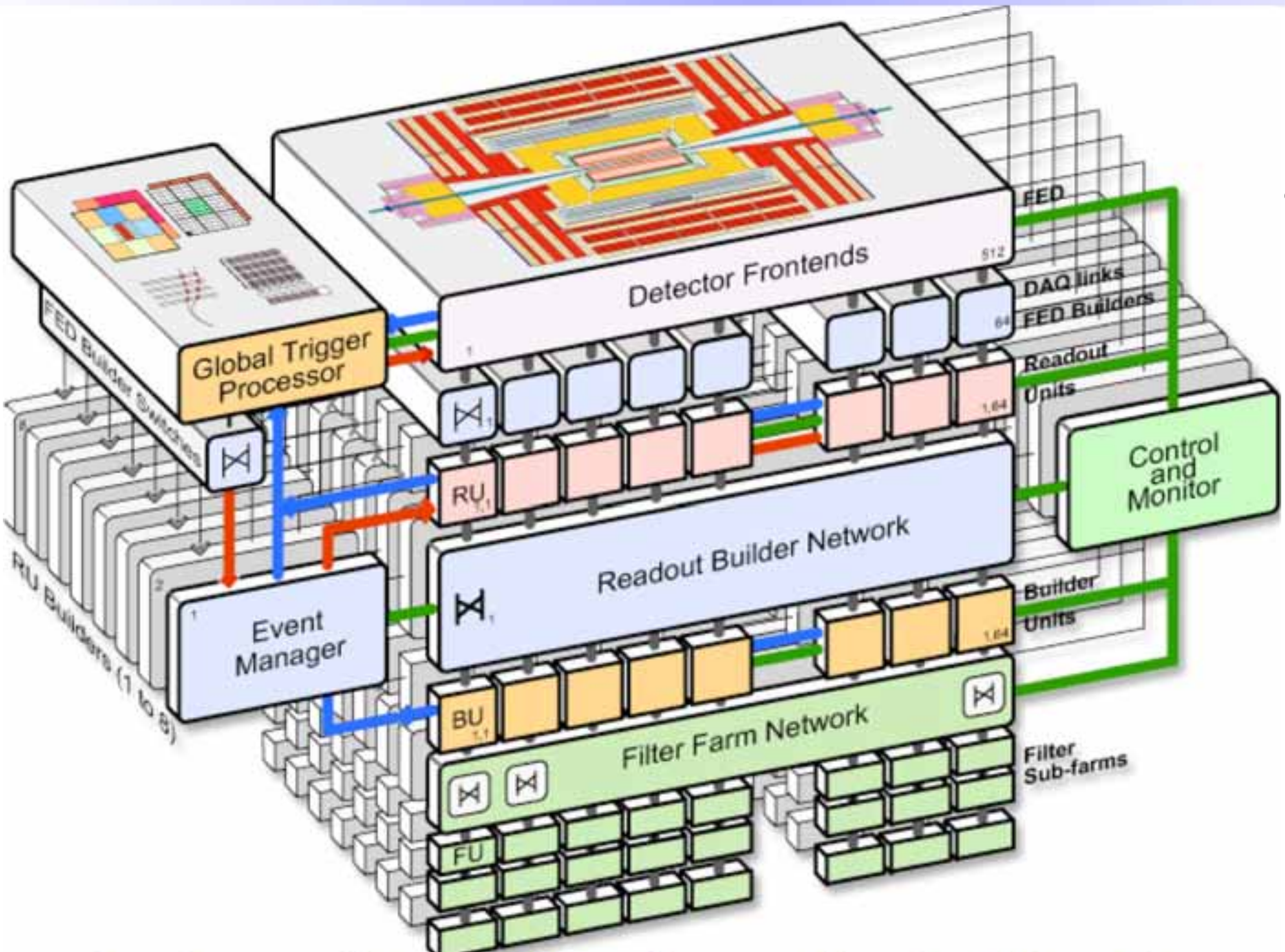


High level triggers. CPU farms

- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,τ-jet tagging
- Full event reconstruction and analysis

Successive improvements : background event filtering, physics selection

High-Level Trig. Implementation



8 "slices"

All processing beyond Level-1 performed in the Filter Farm

Partial event reconstruction "on demand" using full detector resolution

Start with L1 Trigger Objects

Electrons, Photons, τ-jets, Jets, Missing E_T, Muons

- HLT refines L1 objects (no volunteers)

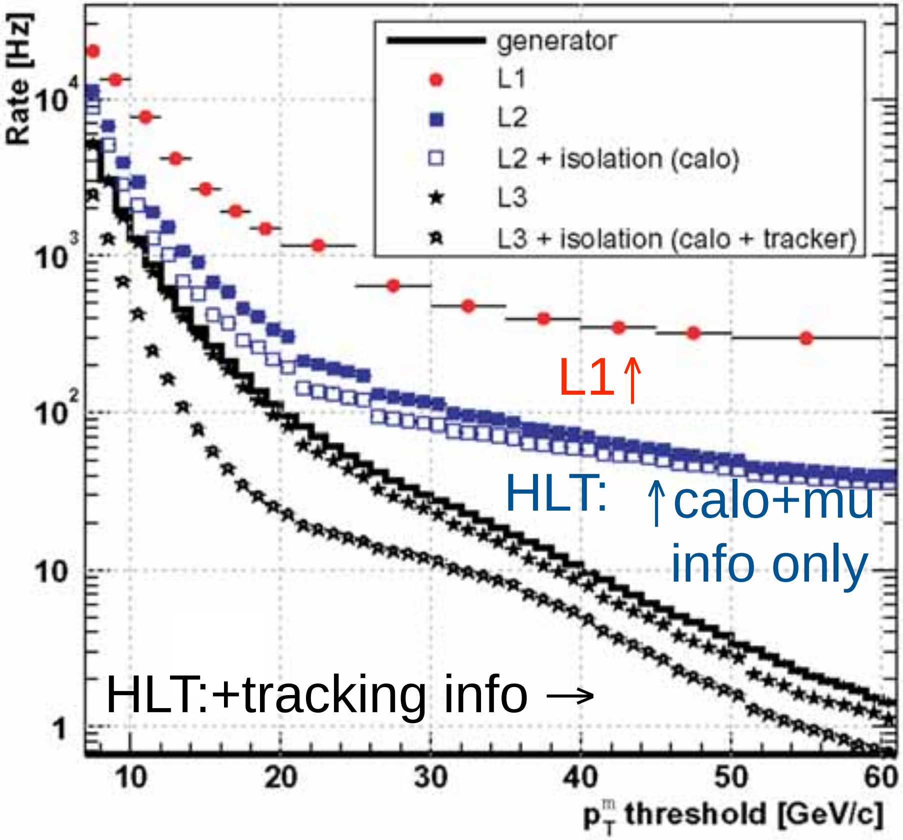
Goal

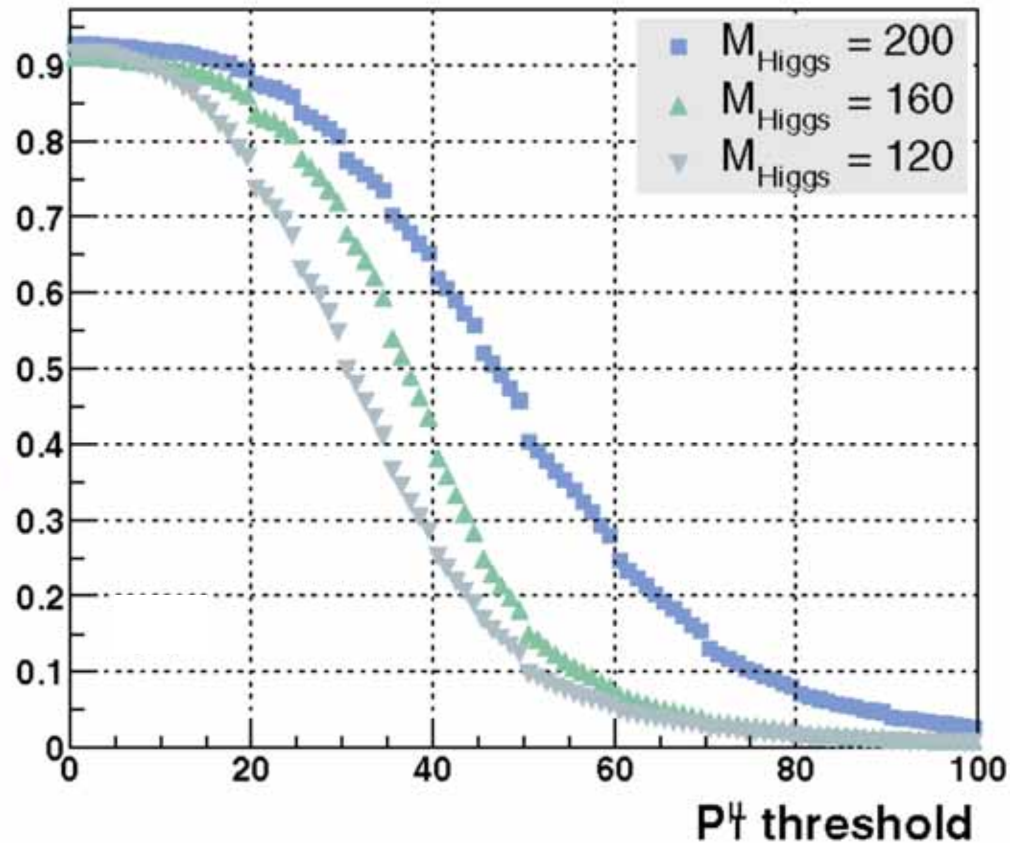
- Keep L1T thresholds for electro-weak symmetry breaking physics
- However, reduce the dominant QCD background
  - From 100 kHz down to 100 Hz nominally

QCD background reduction

- Fake reduction: e±, γ, τ
- Improved resolution and isolation: μ
- Exploit event topology: Jets
- Association with other objects: Missing E_T
- Sophisticated algorithms necessary
  - Full reconstruction of the objects
  - Due to time constraints we avoid full reconstruction of the event - L1 seeded reconstruction of the objects only
  - Full reconstruction only for the HLT passed events

Muon Higher Level Trigger





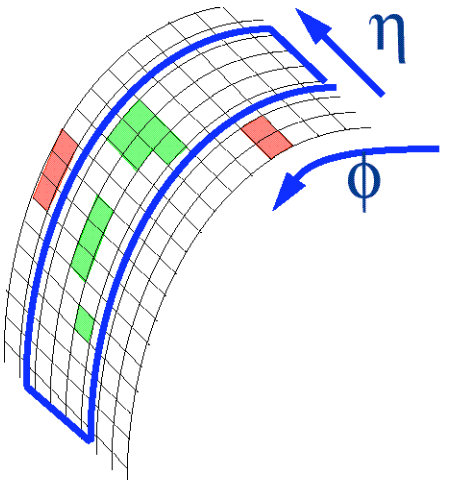
Trigger rates vs. muon p_T threshold through levels of HLT processing at $L = 2 \times 10^{33}$

Efficiency for Higgs selection vs. muon p_T threshold for different Higgs masses

Electron selection: Level-2

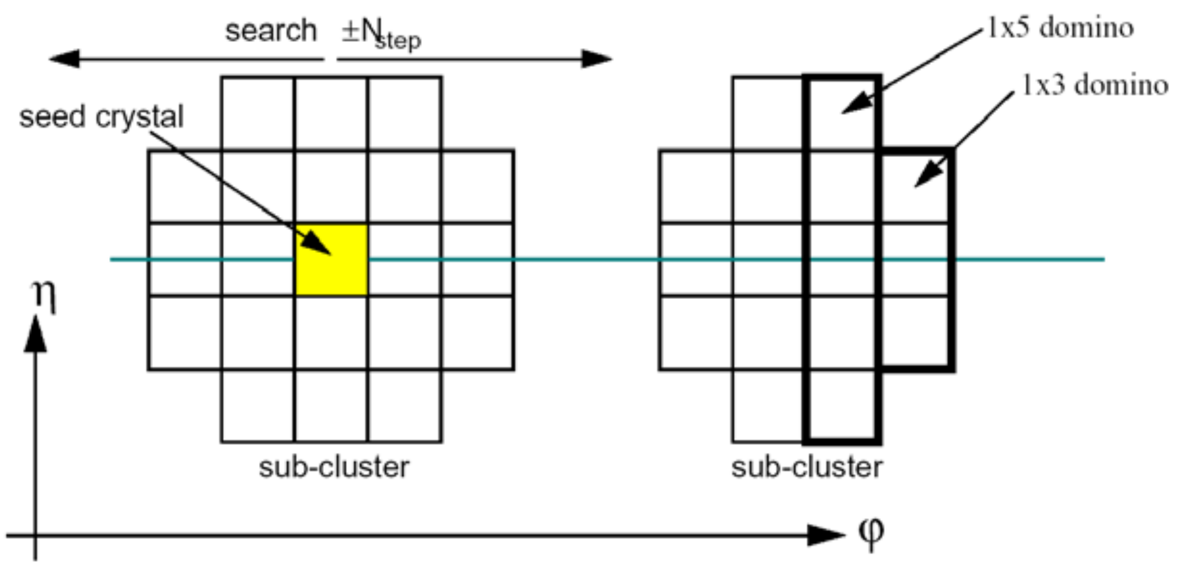
"Level-2" electron:

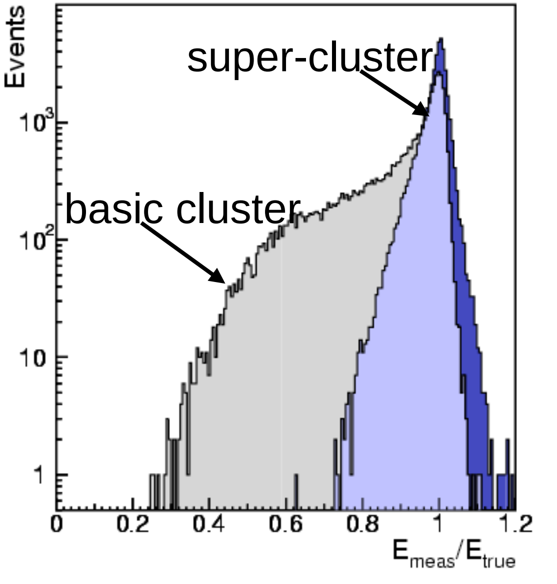
- Search for match to Level-1 trigger
  - Use 1-tower margin around 4x4-tower trigger region
- Bremsstrahlung recovery "super-clustering"
- Select highest E_T cluster



Bremsstrahlung recovery:

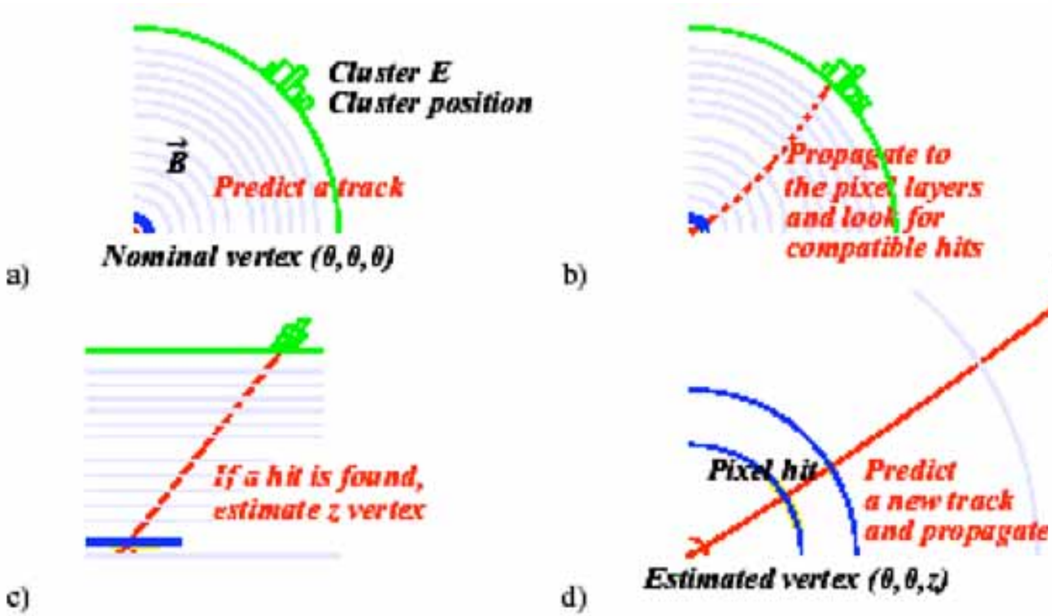
- Road along ϕ — in narrow η-window around seed
- Collect all sub-clusters in road → "super-cluster"

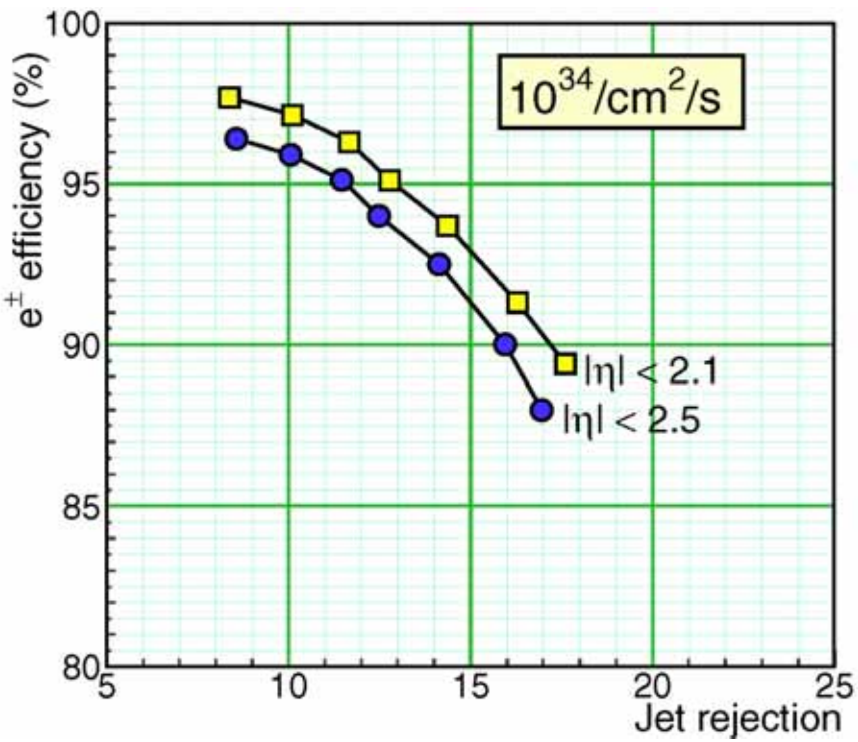




CMS tracking for electron trigger

Present CMS electron HLT

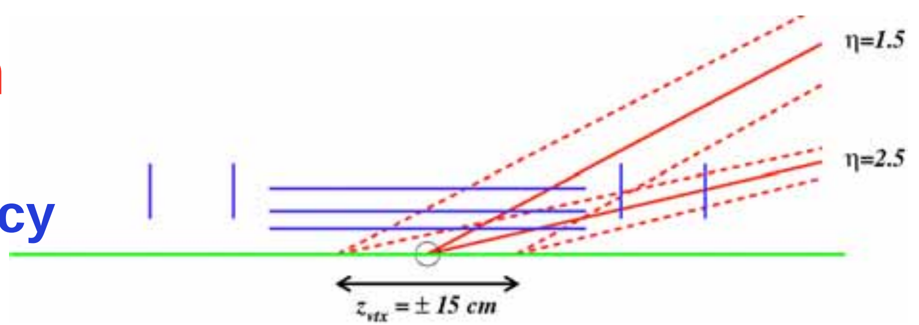




Factor of 10 rate reduction

γ: only tracker handle: isolation

- **Need knowledge of vertex location to avoid loss of efficiency**



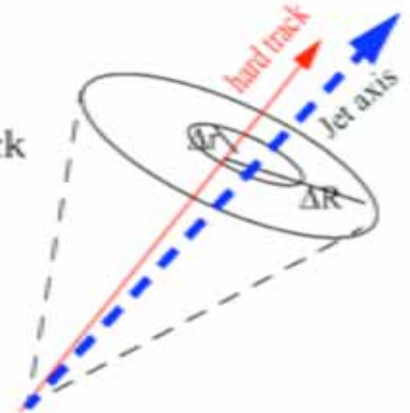
τ-jet tagging at HLT

τ-jet ($E_t^{\tau\text{-jet}} > 60$ GeV) identification (mainly) in the tracker:

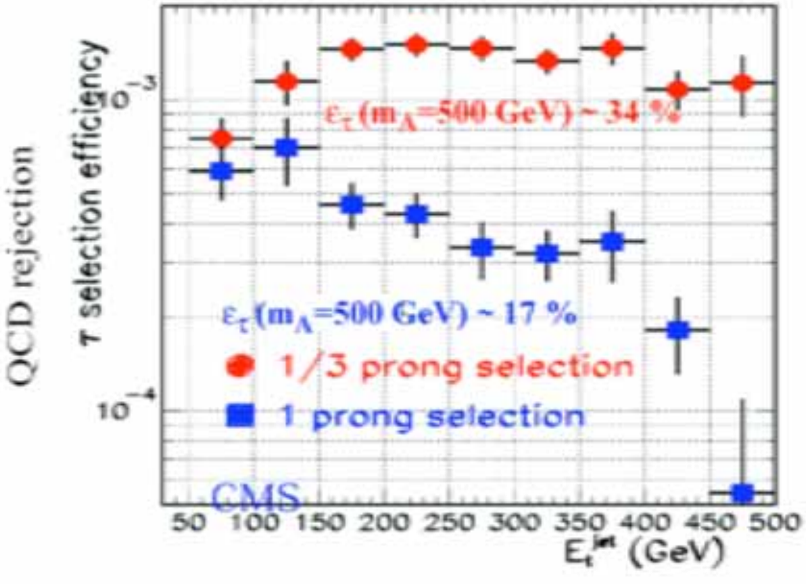
Hard track, $p_t^{max} > 40$ GeV, within $\Delta R < 0.1$ around calorimeter jet axis

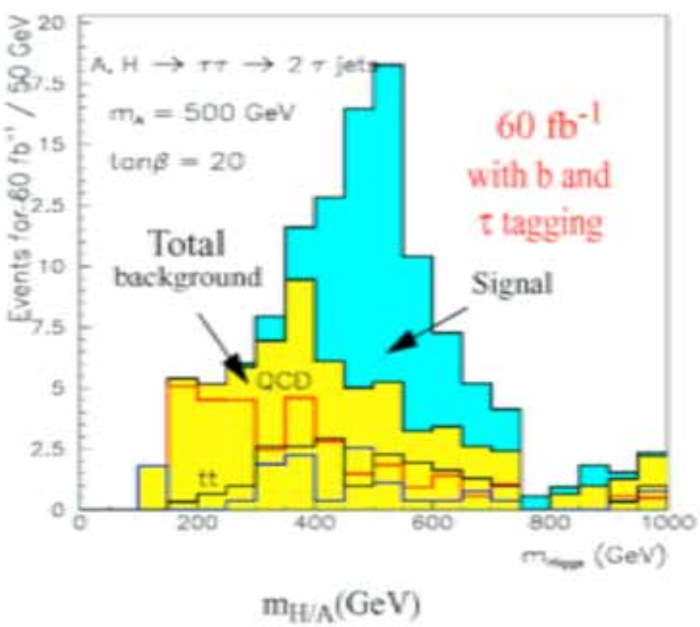
Isolation: no tracks, $p_t > 1$GeV, within $0.03 < \Delta R < 0.4$ around the hard track

For 3-prong selection 2 more tracks in the signal cone $\Delta r < 0.03$



QCD jet rejection from isolation and hard track cuts





Further reduction by ~ 5 expected for 3-prong QCD jets from τ vertex reconstruction (CMS full simulation)

B and τ tagging

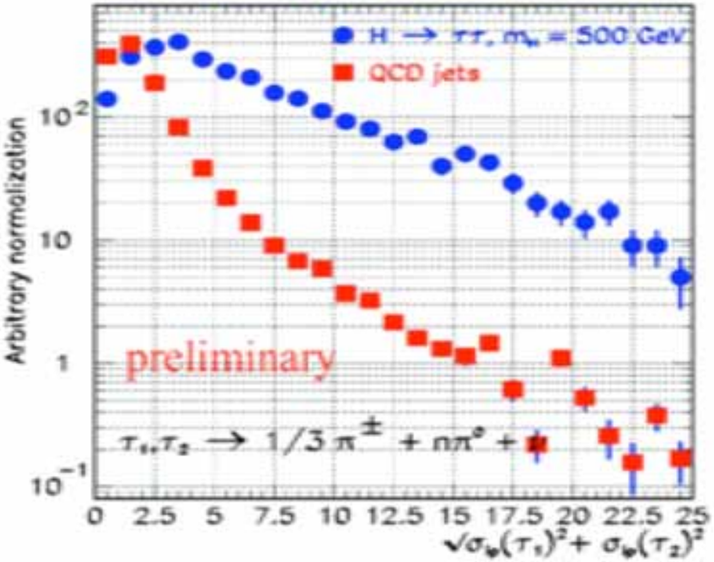
Soft b-jets with a wide η-range:

Efficiency to tag one b-jet ~ 35% for ~1% mistagging rate (CMS)

τ - tagging with impact parameter measurement

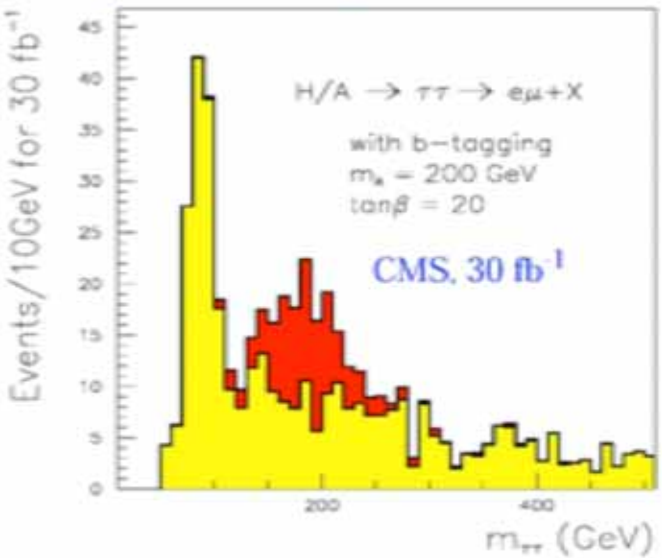
combining the ip measurements of the hard tracks in the two τ's (τ -> hadron, τ -> lepton) into one variable: $\sqrt{\sigma_{ip}(\tau_1)^2 + \sigma_{ip}(\tau_2)^2}$

CMS full simulation for H -> ττ -> 2 τ–jets and QCD events



Expect rejection of 5 - 10 against QCD background and backgrounds with W -> lν, Z -> ll

Signal superimposed on the total background for m_A = 200 GeV, tanβ =20



Example HLT Trigger Menu (L=2x10^{33})

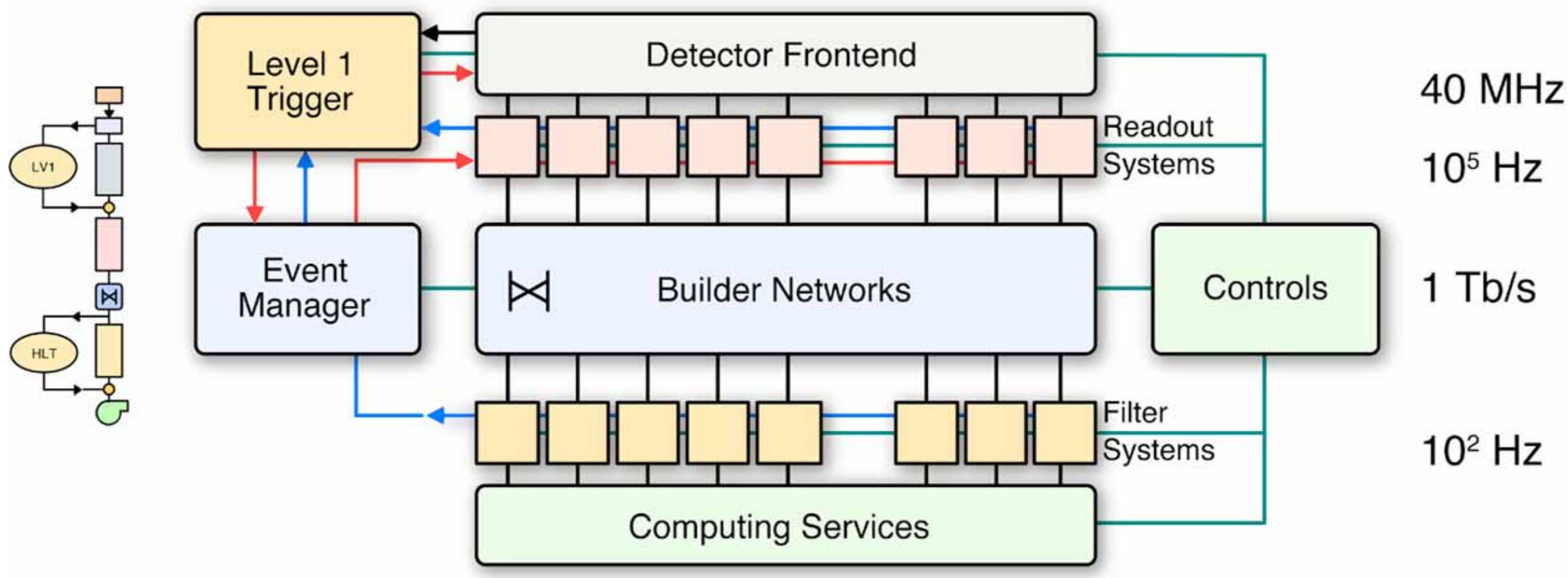
Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
Inclusive electron	29	33	33
Di-electrons	17	1	34
Inclusive photons	80	4	38
Di-photons	40, 25	5	43
Inclusive muon	19	25	68
Di-muons	7	4	72
Inclusive τ-jets	86	3	75
Di-τ-jets	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
Electron * tau	19 * 45	2	90
Inclusive *b*-jets	237	5	95
Calibration and other events (10%)		10	105
TOTAL			**105**

SUSY Efficiencies (MSUGRA benchmark)

$m(\tilde{g})$ (GeV/c^2)	$m(\tilde{u}_L)$ (GeV/c^2)	$m(\tilde{\chi}_1^0)$ (GeV/c^2)
466	410	70
447	415	66
349	406	45

	Level-1 Trigger		High-Level Trigger	
SUSY point	1 Jet >79 GeV+ E_T^{miss}>46 GeV	3 jets, E_T>86 GeV	1 Jet >180GeV+ E_T^{miss}>123 GeV	4 jets, E_T>113 GeV
	efficiency (%)	efficiency (%) (cumulative efficiency)	efficiency (%)	efficiency (%) (cumulative efficiency)
4	88	60 (92)	67	11 (69)
5	87	64 (92)	65	14 (68)
6	71	68 (85)	37	16 (44)
4R	67	89 (94)	27	28 (46)
5R	58	90 (93)	17	30 (41)
6R	47	84 (87)	9	20 (26)
Background	rate (kHz)	rate (kHz) (cumulative rate)	rate (Hz)	rate (Hz) (cumulative rate)
	2.3	0.98 (3.1)	5.1 Hz	6.8 (11.8)

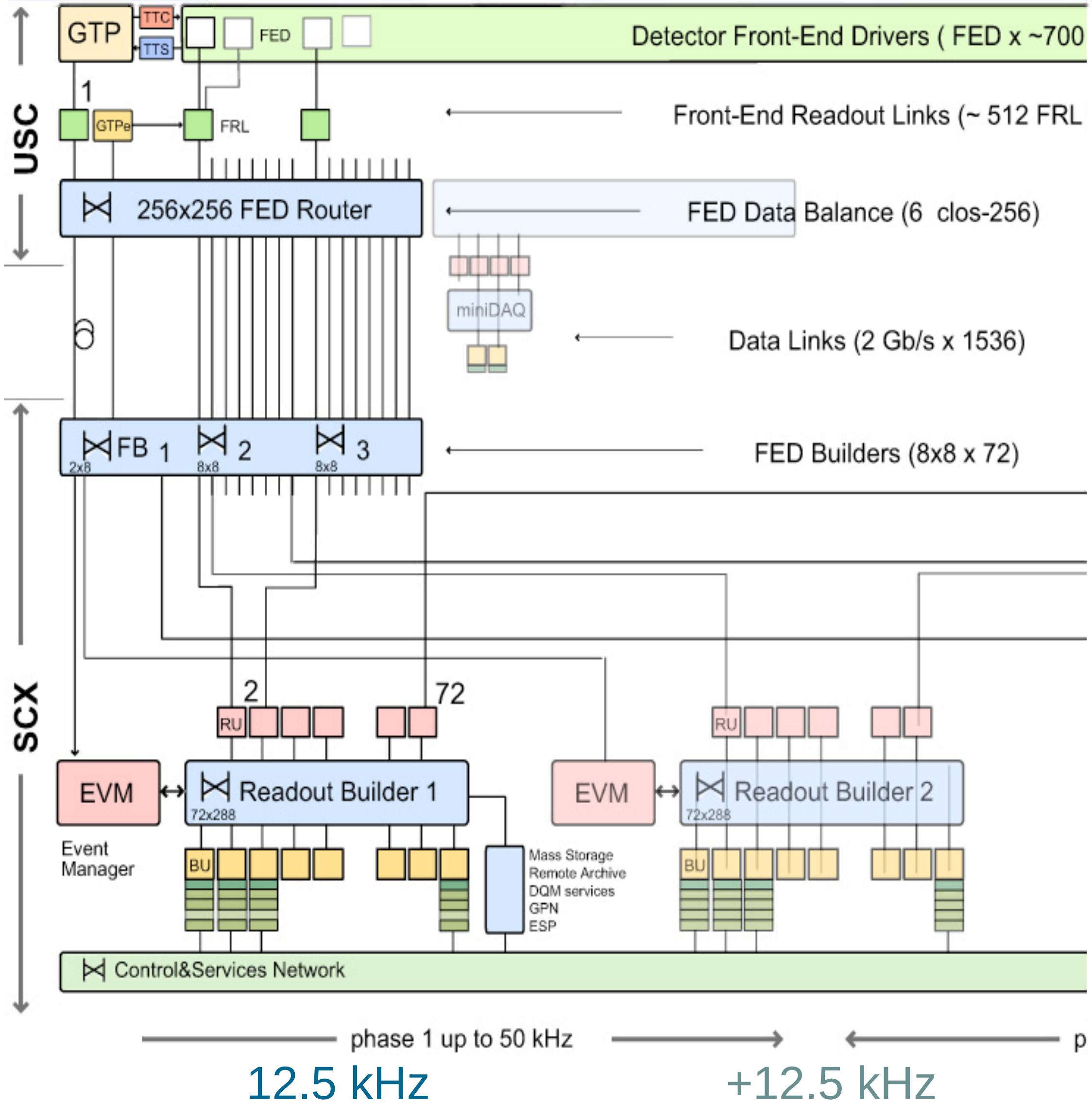
CMS DAQ baseline structure

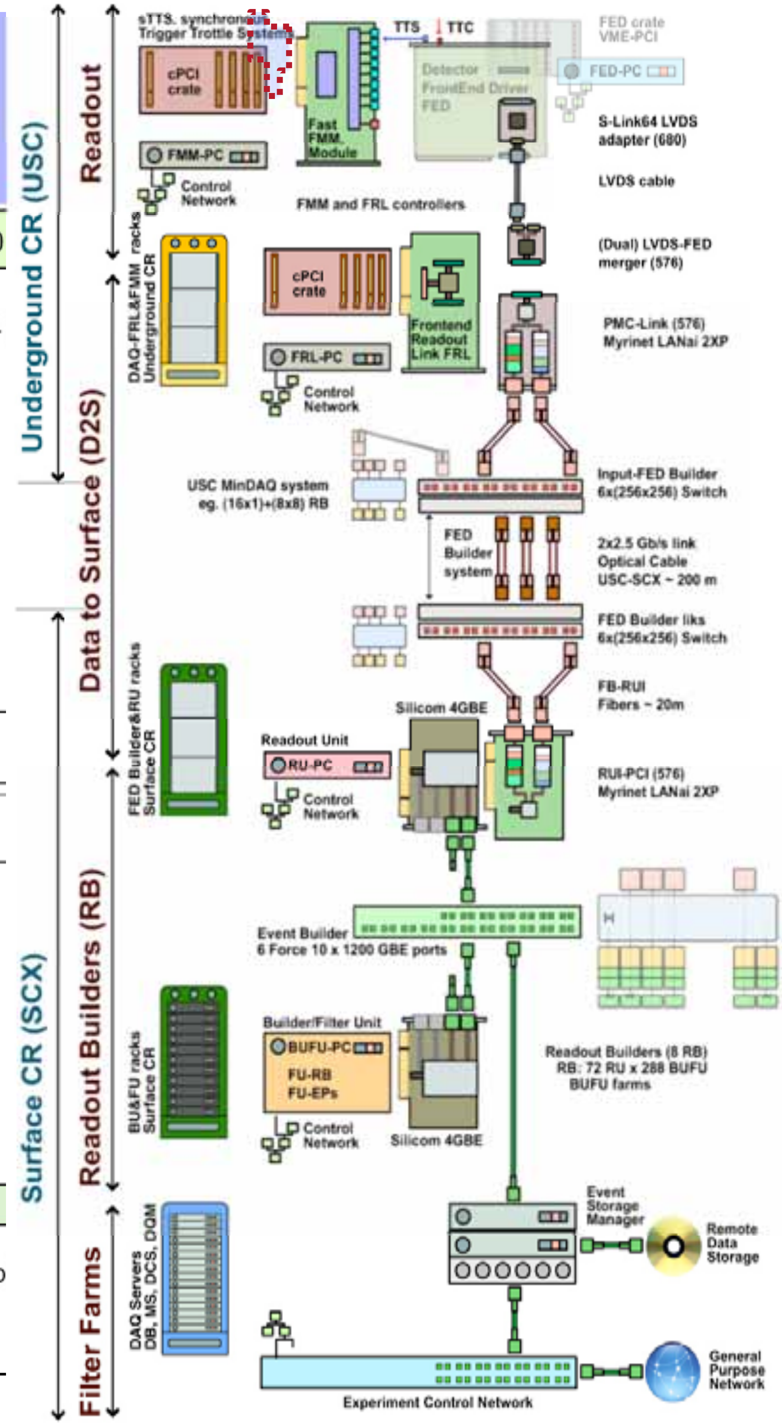


Collision rate		40 MHz
Level-1 Max. trigger rate		**100 kHz(*)**
Average event size	**≈**	**1 Mbyte**
Event Flow Control	≈	10^6 Mssg/s

No. of In-Out units	≈ 500
Readout network bandwidth	**≈ 1 Terabit/s**
Event filter computing power	**≈ 5 TFlop**
Data production	≈ Tbyte/day
No. of PC motherboards	≈ Thousands

CMS DAQ Details

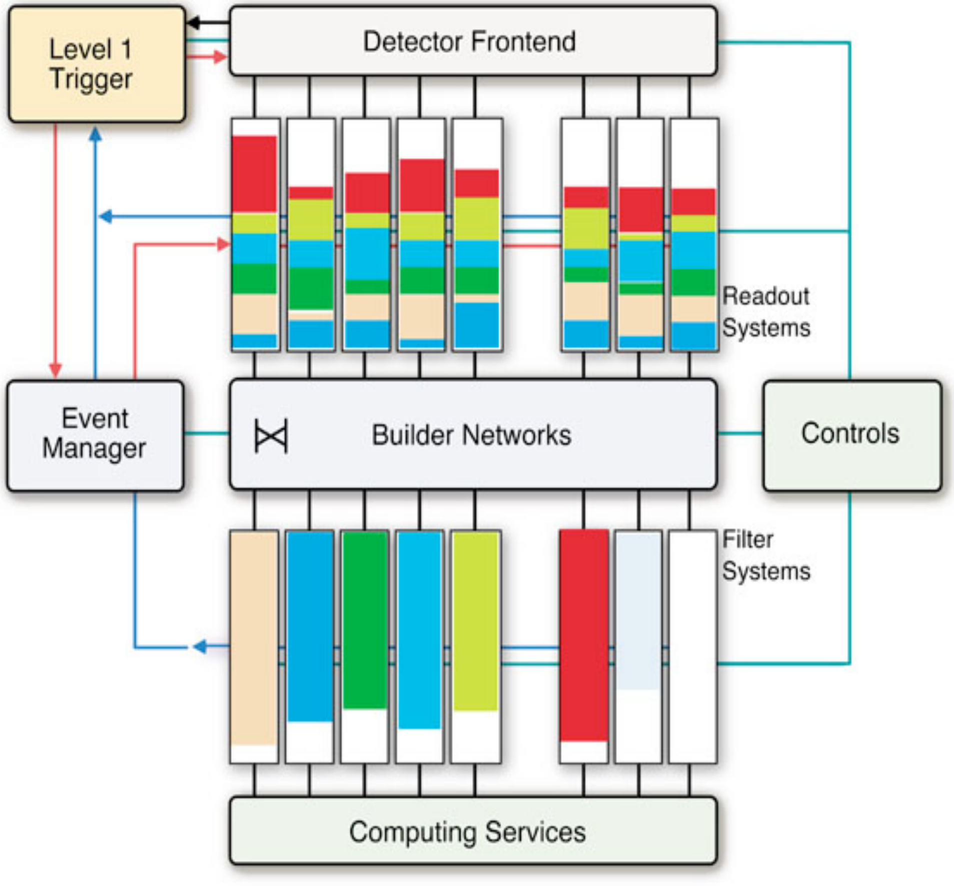




Building the event

Event builder :

Physical system interconnecting data sources with data destinations. It has to move each event data fragments into a same destination



Event fragments :

Event data fragments are stored in separated physical memory systems

Full events :

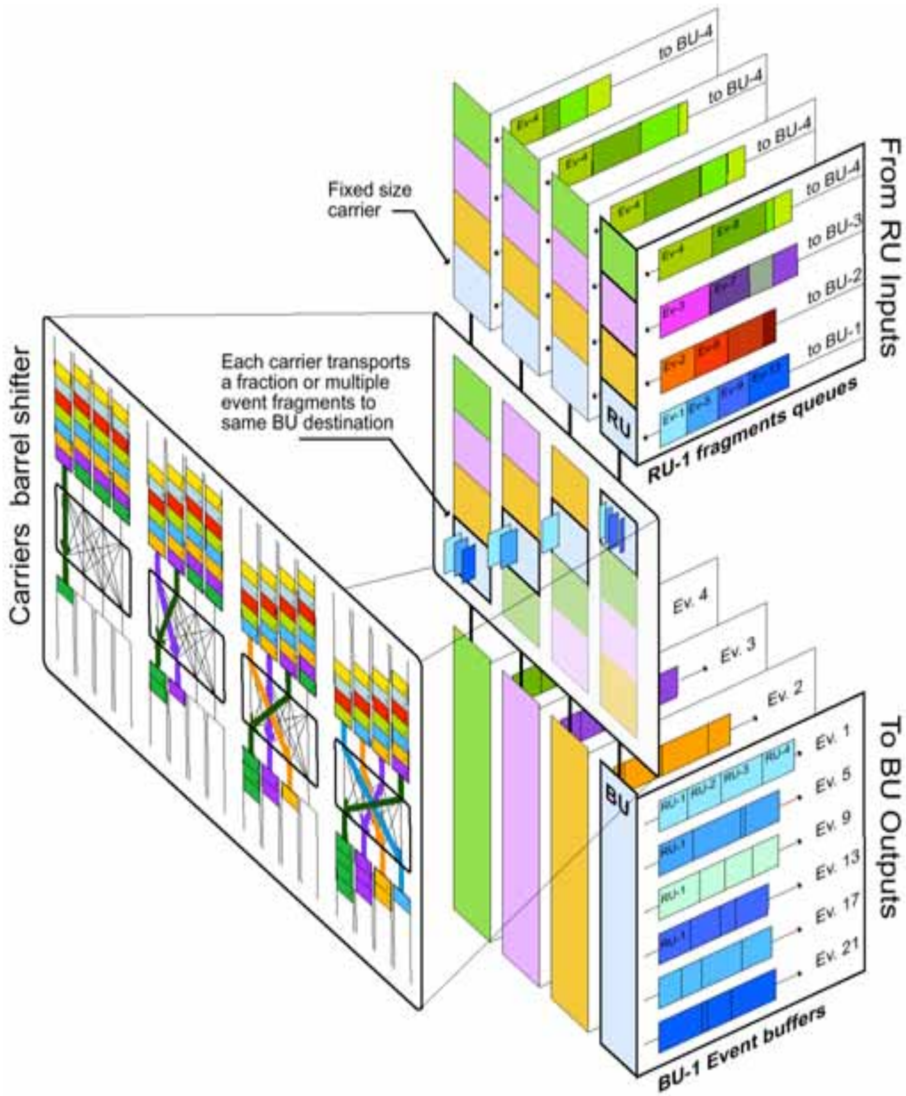
Full event data are stored into one physical memory system associated to a processing unit

Hardware:

Fabric of switches for builder networks

PC motherboards for data Source/Destination nodes

Myrinet Barrel-Shifter



BS **implemented in firmware**

- Each source has message queue per destination
- Sources divide messages into fixed size packets (carriers) and cycle through all destinations
- Messages can span more than one packet and a packet can contain data of more than one message
- No external synchronization (relies on Myrinet back pressure by HW flow control)

zero-copy, **OS-bypass**

principle works for multi stage switches

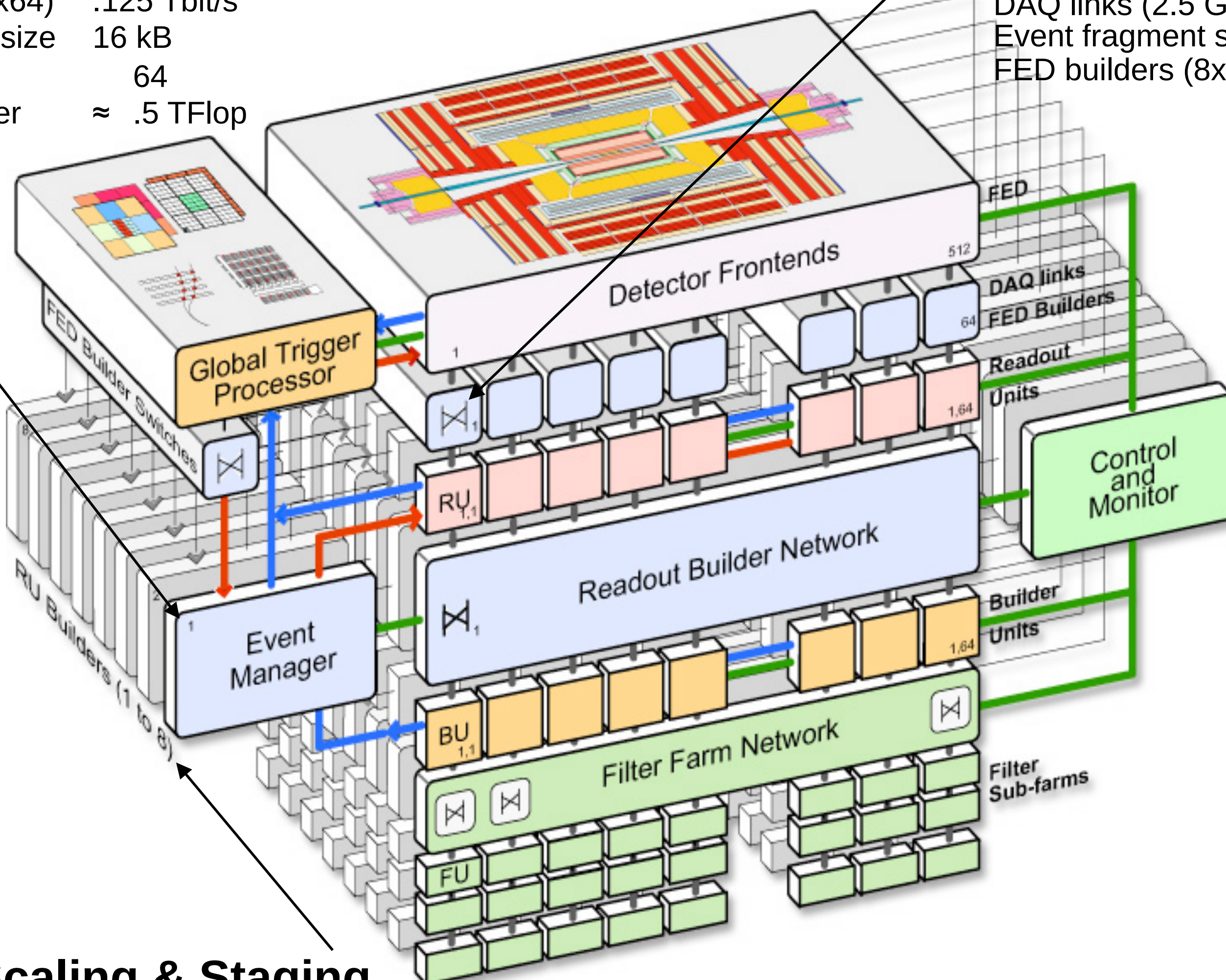
CMS DAQ in 3-D

DAQ unit (1/8th full system):

Lv-1 max. trigger rate	12.5 kHz
RU Builder (64x64)	.125 Tbit/s
Event fragment size	16 kB
RU/BU systems	64
Event filter power	≈ .5 TFlop

Data to surface:

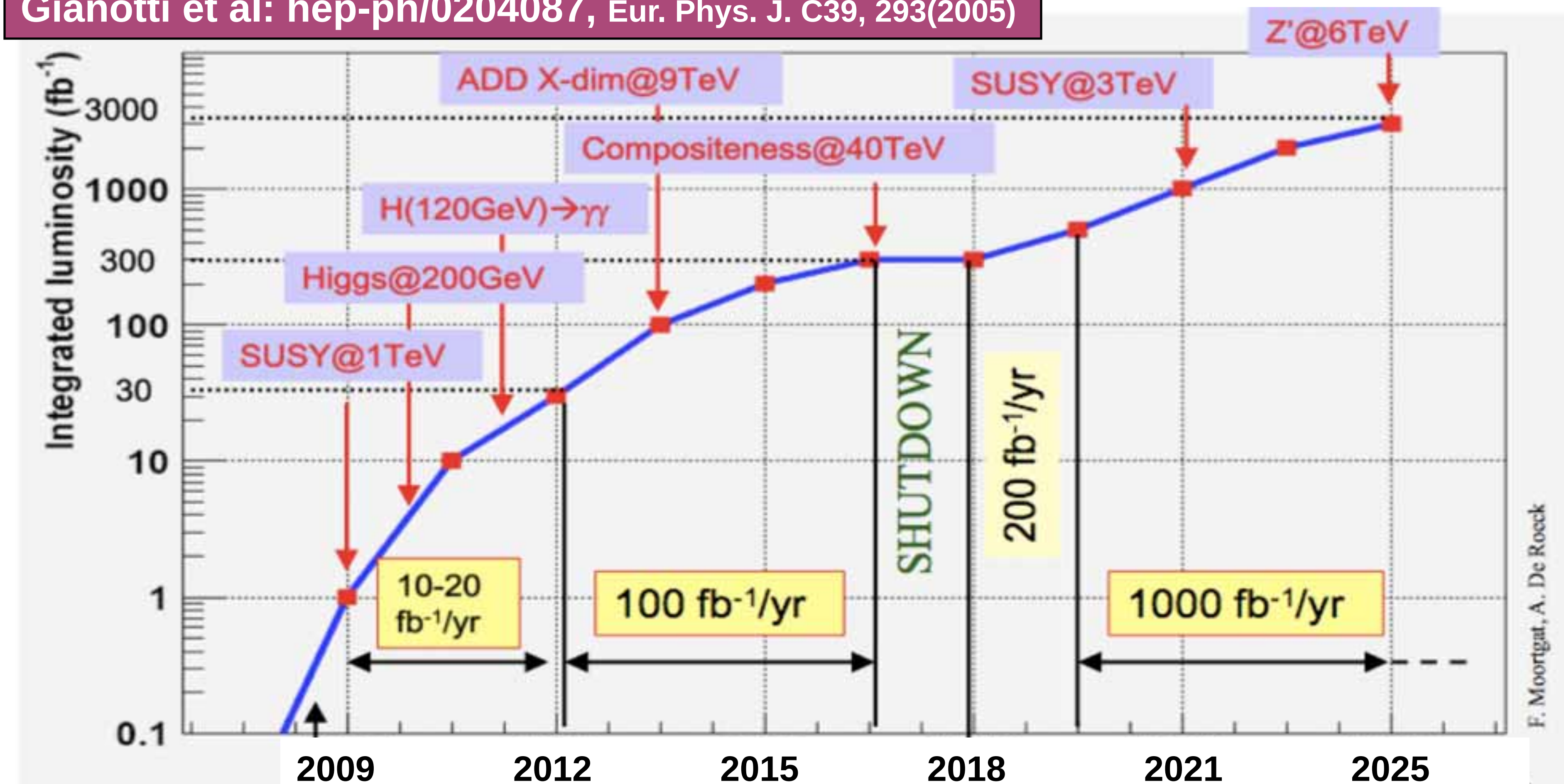
Average event size		1 Mbyte
No. FED s-link64 ports	>	512
DAQ links (2.5 Gb/s)		512+512
Event fragment size		2 kB
FED builders (8x8)	≈	64+64



DAQ Scaling & Staging

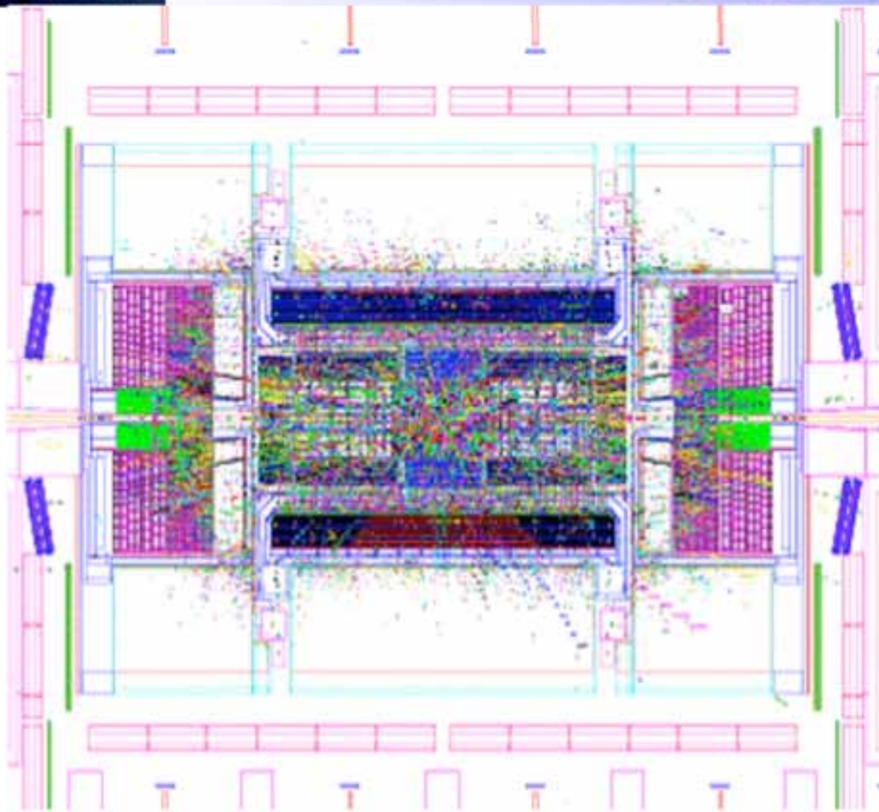
LHC → SLHC physics evolution

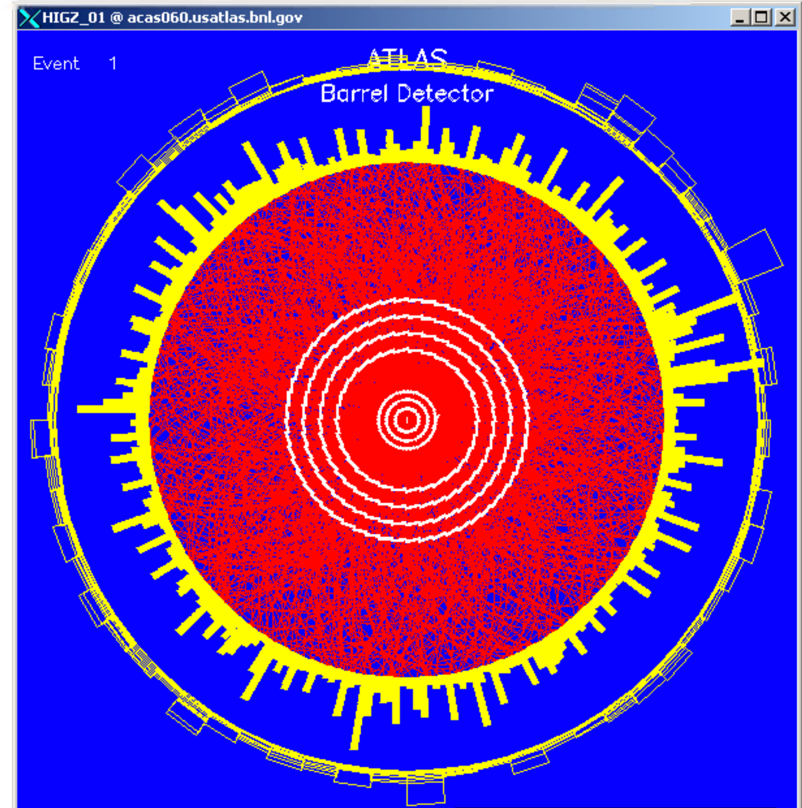
De Roeck, Ellis, Gianotti: hep-ph/0112004
Gianotti et al: hep-ph/0204087, Eur. Phys. J. C39, 293(2005)



Timescale adjusted

Expected Pile-up at Super LHC
in ATLAS at 10^{35}





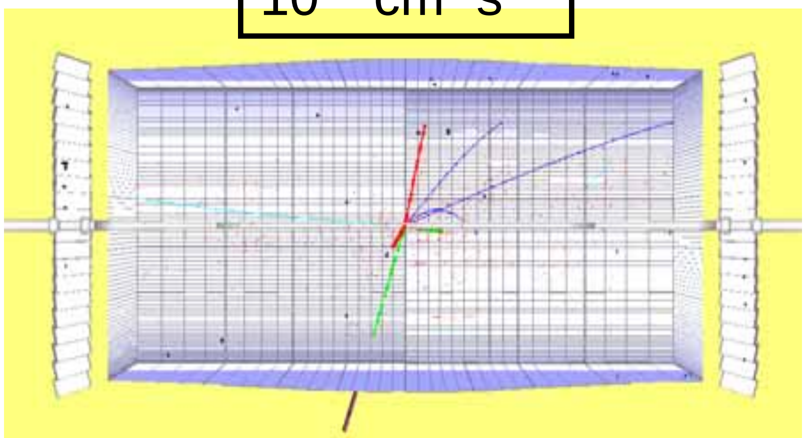
$N_{ch}(|y| \leq 0.5)$

- 230 min.bias collisions per 25 ns. crossing
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks
- requires upgrades to detectors

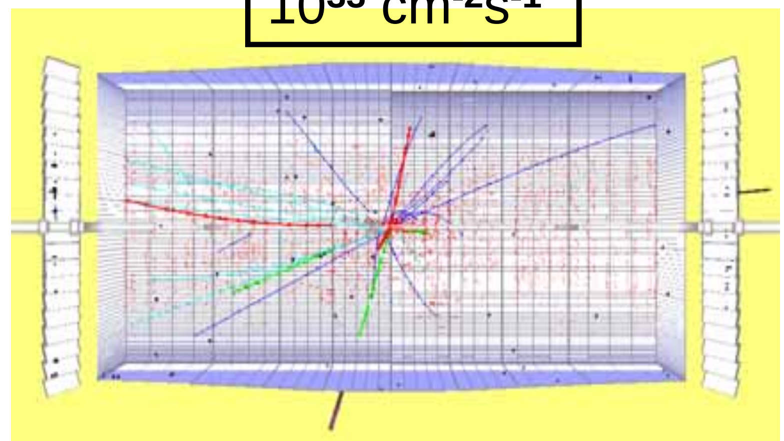
Detector Luminosity Effects

$H \rightarrow ZZ \rightarrow \mu\mu ee$, $M_H = 300$ GeV for different luminosities in CMS

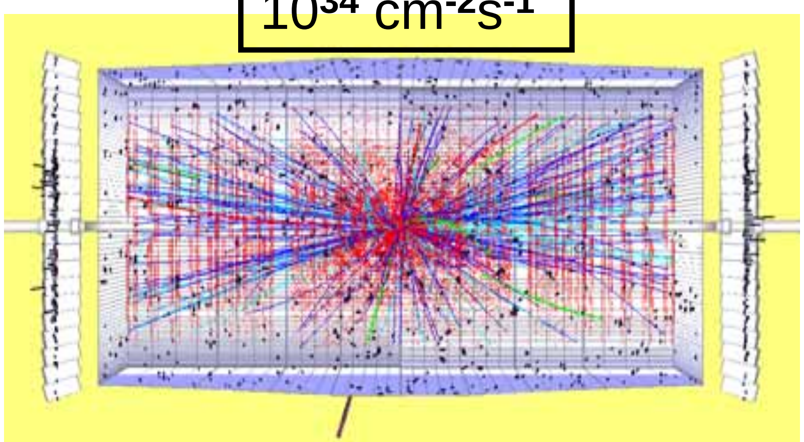
10^{32} cm^{-2}s^{-1}



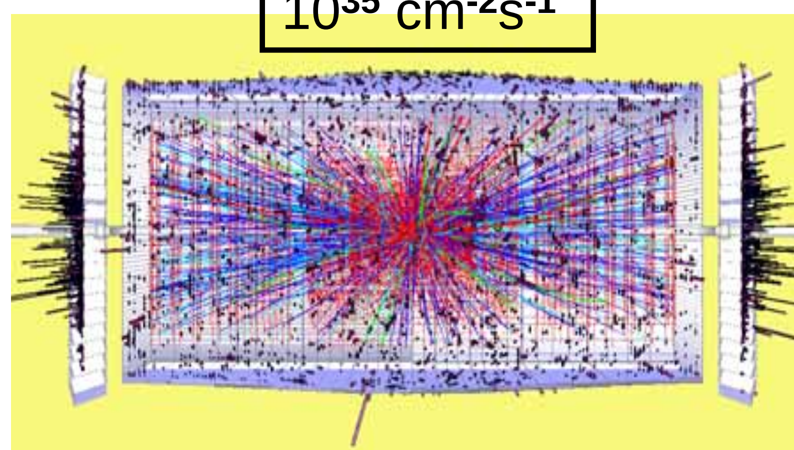
10^{33} cm^{-2}s^{-1}



10^{34} cm^{-2}s^{-1}



10^{35} cm^{-2}s^{-1}



SLHC Level-1 Trigger @ 10^{35}

Occupancy

- **Degraded performance of algorithms**
  - Electrons: reduced rejection at fixed efficiency from isolation
  - Muons: increased background rates from accidental coincidences
- **Larger event size to be read out**
  - New Tracker: higher channel count & occupancy → large factor
  - Reduces the max level-1 rate for fixed bandwidth readout.

Trigger Rates

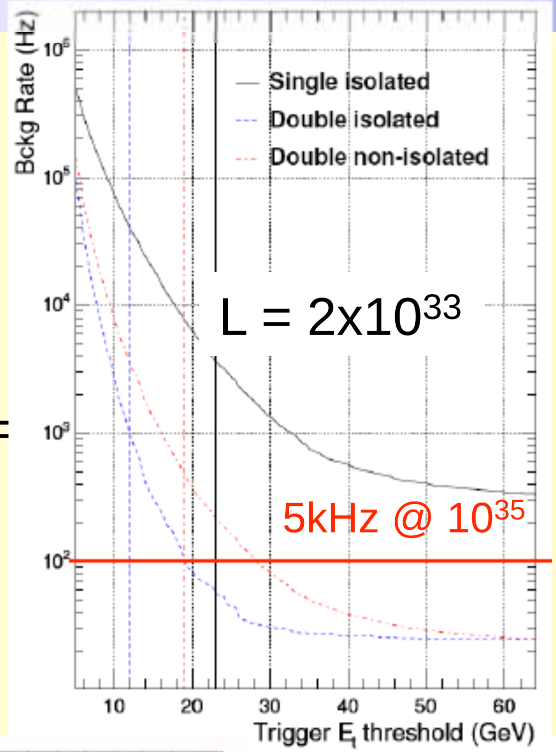
- **Try to hold max L1 rate at 100 kHz by increasing readout bandwidth**
  - Avoid rebuilding front end electronics/readouts where possible
    - **Limits: ⟨readout time⟩ (< 10 μs) and data size (total now 1 MB)**
  - Use buffers for increased latency for processing, not post-L1A
  - May need to increase L1 rate even with all improvements
    - **Greater burden on DAQ**
- **Implies raising E_T thresholds on electrons, photons, muons, jets and use of multi-object triggers, unless we have new information ⇒Tracker at L1**
  - Need to compensate for larger interaction rate & degradation in algorithm performance due to occupancy

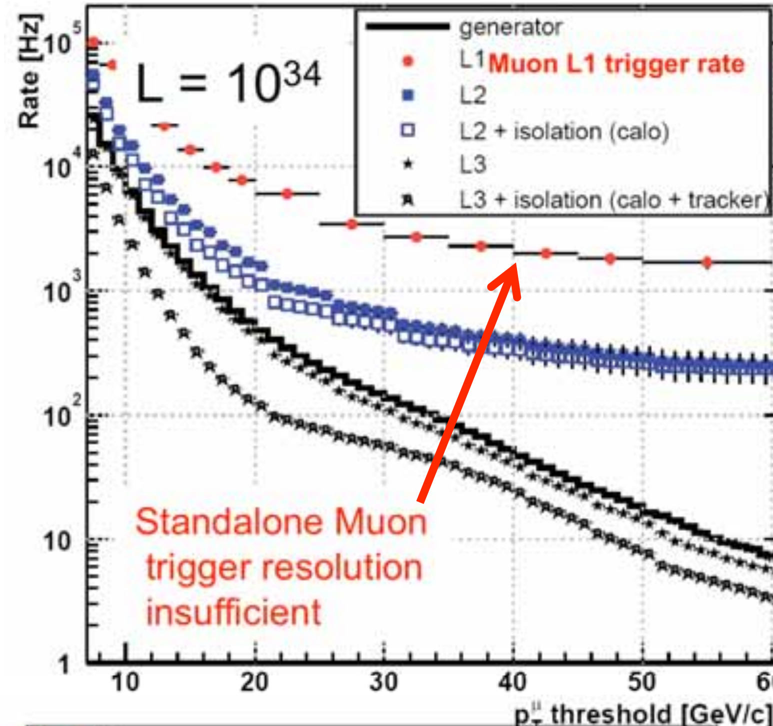
Radiation damage -- Increases for part of level-1 trigger located on detector

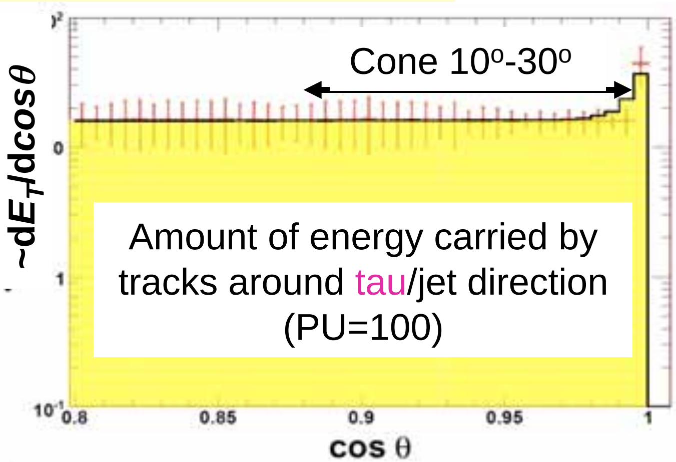
Tracking needed for L1 trigger

Single electron trigger rate

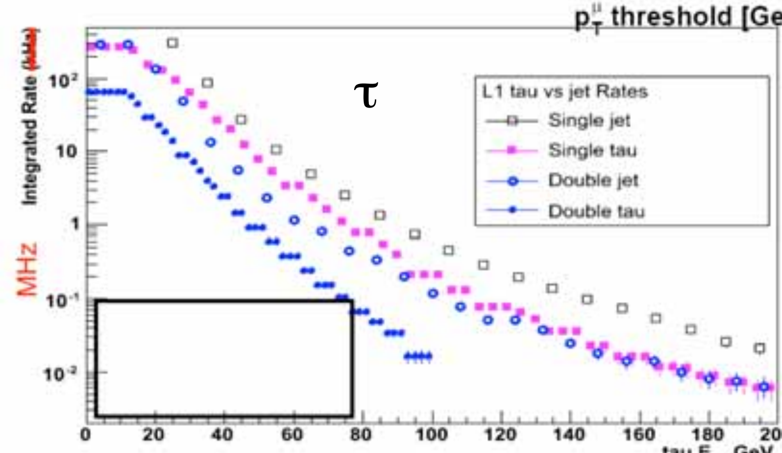
Isolation criteria are insufficient to reduce rate at L = 10^{35} cm^{-2}.s^{-1}







We need to get another x200 (x20) reduction for single (double) tau rate!



Use of CMS L1 Tracking Trigger

Combine with L1 μ trigger as is now done at HLT:

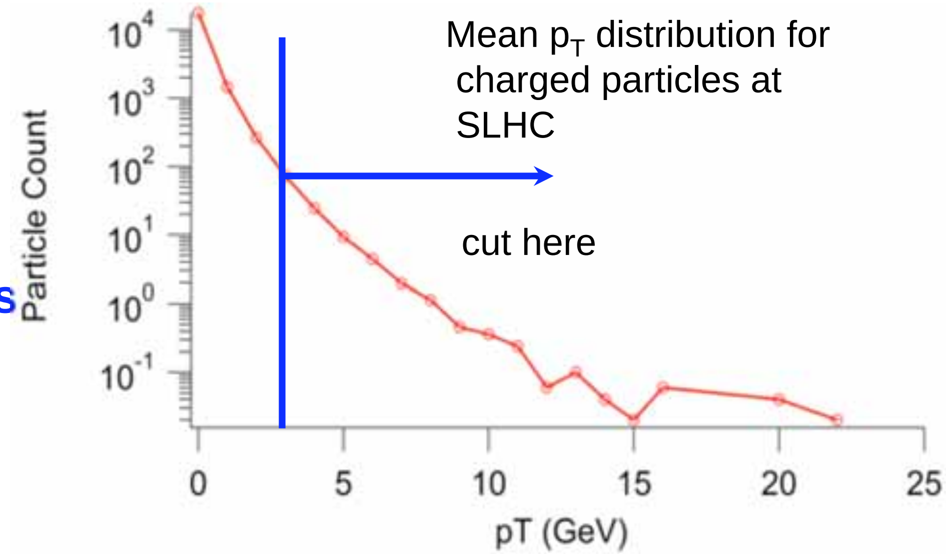
- **Attach tracker hits to improve P_T assignment precision from 15% standalone muon measurement to 1.5% with the tracker**
  - Improves sign determination & provides vertex constraints
- **Find pixel tracks within cone around muon track and compute sum P_T as an isolation criterion**
  - Less sensitive to pile-up than calorimetric information *if* primary vertex of hard-scattering can be determined (~100 vertices total at SLHC!)

To do this requires η-ϕ information on muons finer than the current 0.05-2.5°

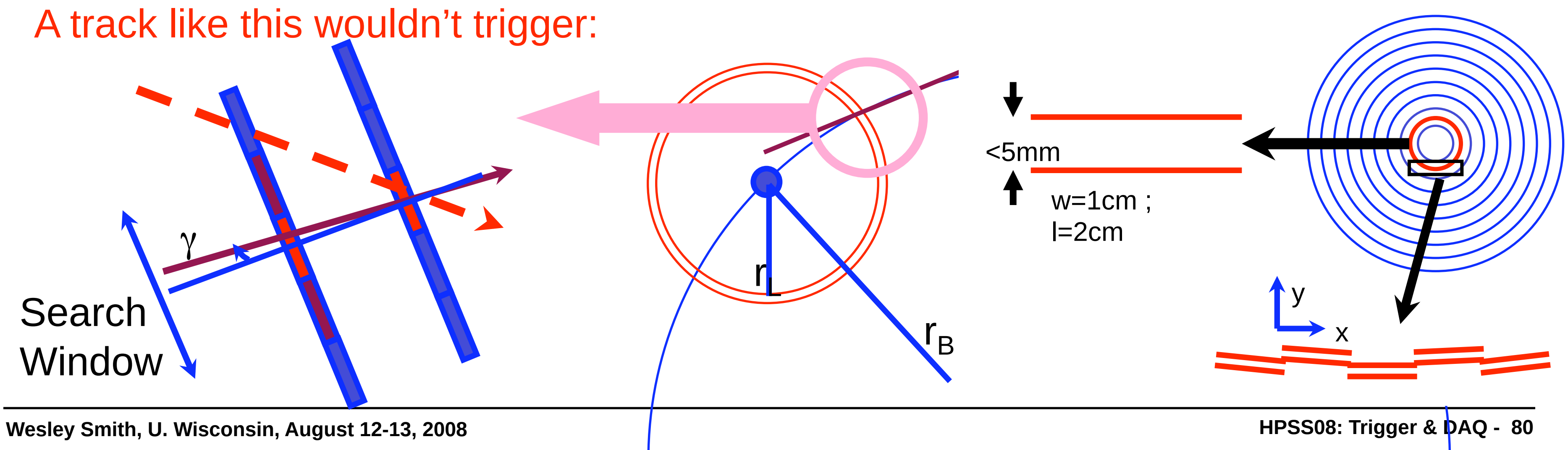
- **No problem, since both are already available at 0.0125 and 0.015°**

CMS ideas for trigger-capable tracker modules -- very preliminary

- Use close spaced stacked pixel layers
- Geometrical p_T cut on data (e.g. ~ GeV):
- Angle (γ) of track bisecting sensor layers defines p_T ($\Rightarrow$ window)
- For a stacked system (sepn. ~1mm), this is ~1 pixel
- Use simple coincidence in stacked sensor pair to find tracklets
- More details & implementation next slides



A track like this wouldn't trigger:



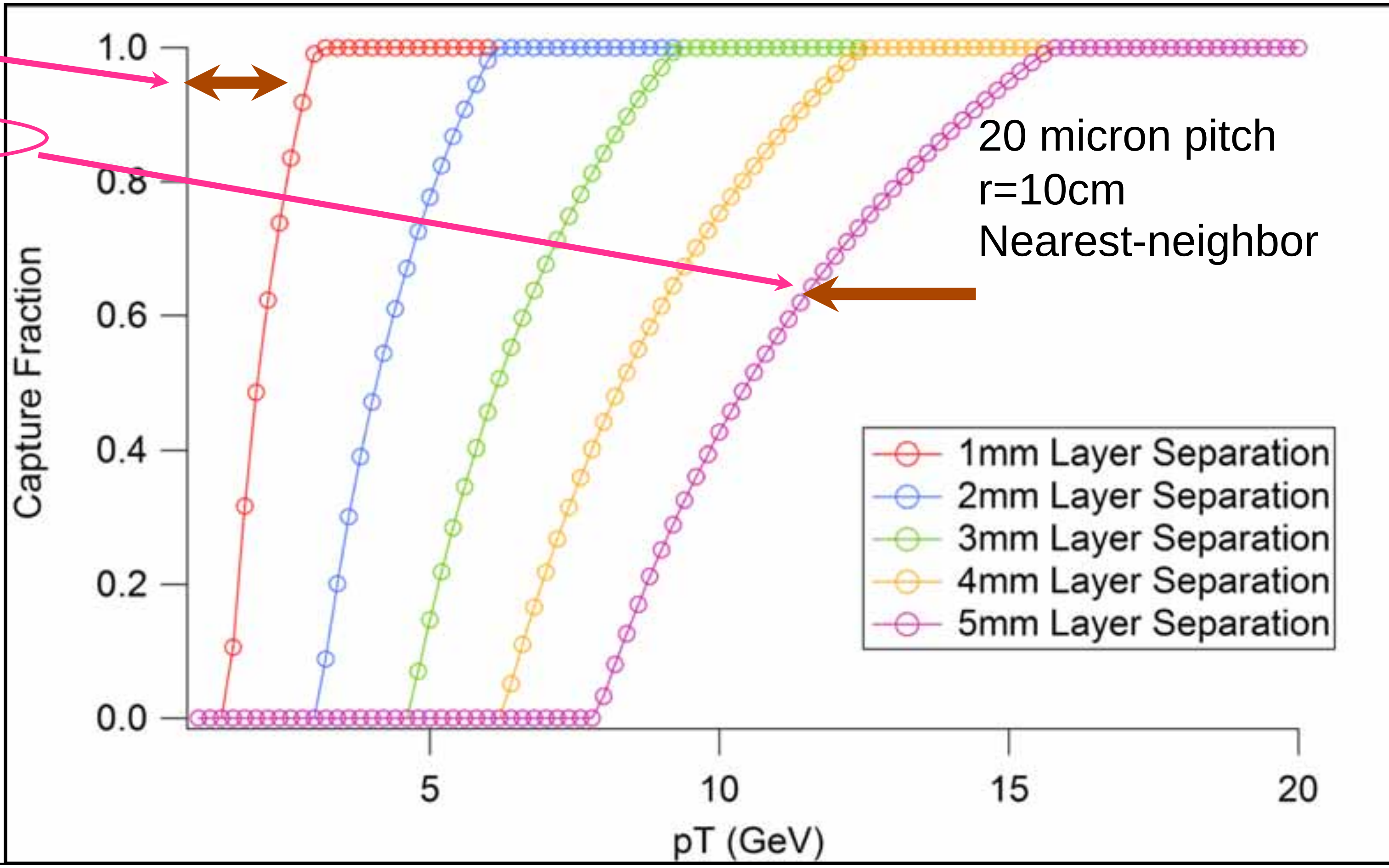
p_T Cuts in a Stacked Tracker – p_T Cut Probabilities

- **Depends on:**

Layer Sepn. & Radius

Pixel Size

Search Window

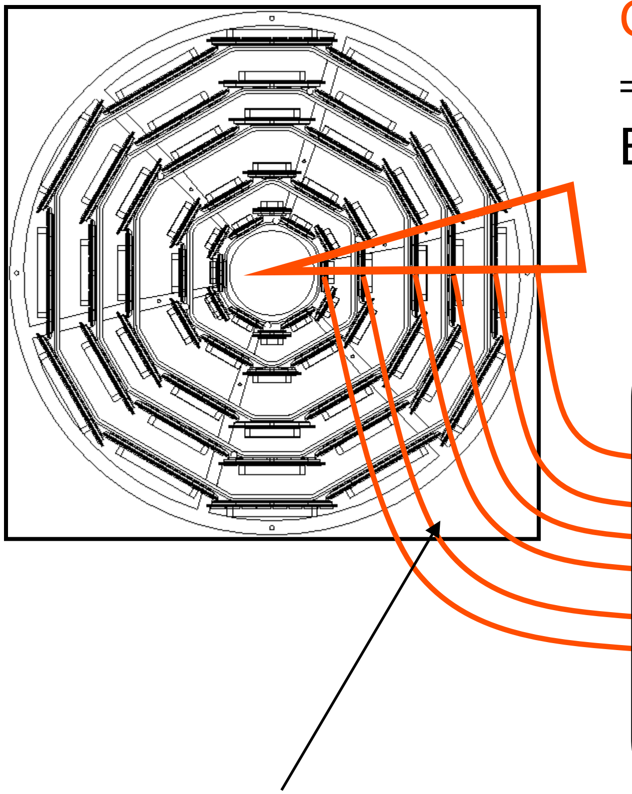


20 micron pitch
r=10cm
Nearest-neighbor

There is an additional 'blurring' caused by charge sharing…

Alternative Tracking Trigger: Associative Memories (from CDF SVX)

Challenge: input Bandwidth
⇒divide the detector in thin ϕ sectors.
Each AM searches in a small $\Delta\phi$



Data links

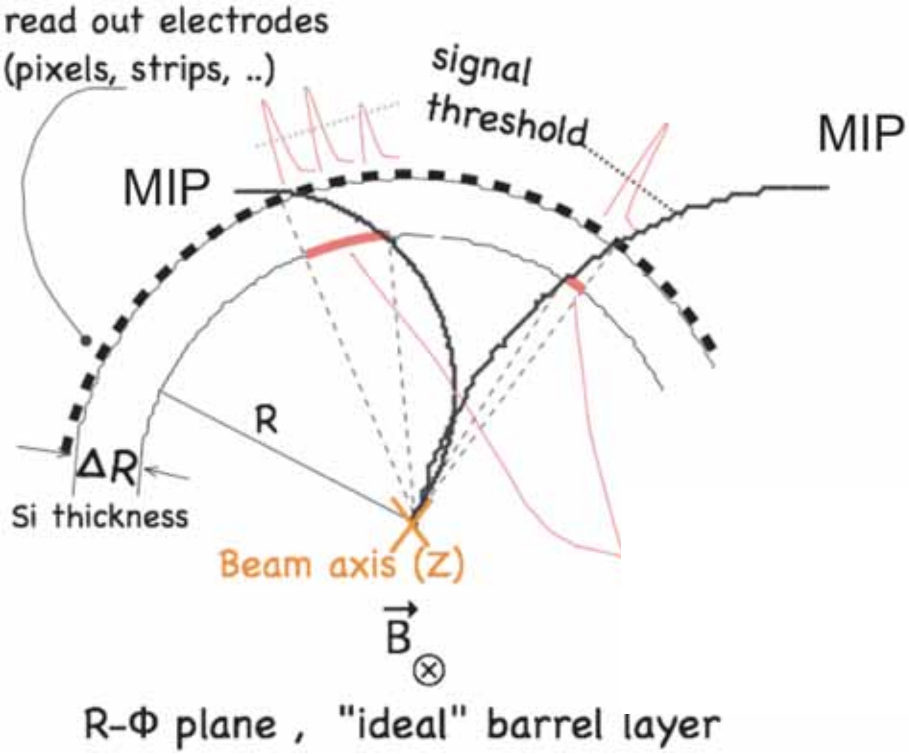
OFF DETECTOR

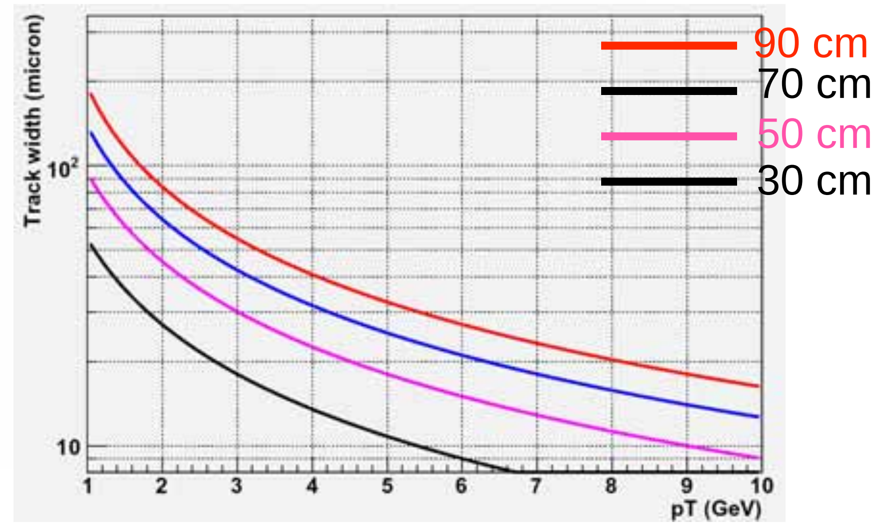
1 AM for each enough-small $\Delta\phi$
Patterns
Hits: position+time stamp
All patterns inside a single chip
N chips for N overlapping events identified by the time stamp

Event1 AMchip1	Event2 AMchip2	Event3 AMchip3	• • • • •	EventN AMchipN

-- F. Palla, A. Annovi, *et al.*

Cluster width discrimination





Discrimination of low p_T tracks made directly on the strip detector by choosing suitable pitch values in the usual range for strip sensors.

(Needed because 25M channels x 4% occupancy would require 6000 2.8 Gbps links at 100 kHz.)

In the region above 50 cm, using 50µm pitch, about 5% of the total particles leave cluster sizes with ≤2 strips

- No. of links (2.5Gbps) ~300 for whole tracker (assuming 95% hit rejection)

Once reduced to ~100 KHz, it would only need few fast readout links to readout the entire Tracker

CMS SLHC Trigger Implementation Goals

Modular

- Develop modules independently
- Share across subsystems

Compact

- Fewer crates → fewer interconnections
- Smaller circuit boards

Flexible

- FPGAs
- Programmably routable backplanes
  - Need flexibility in routing of data and processed results

Higher density inputs

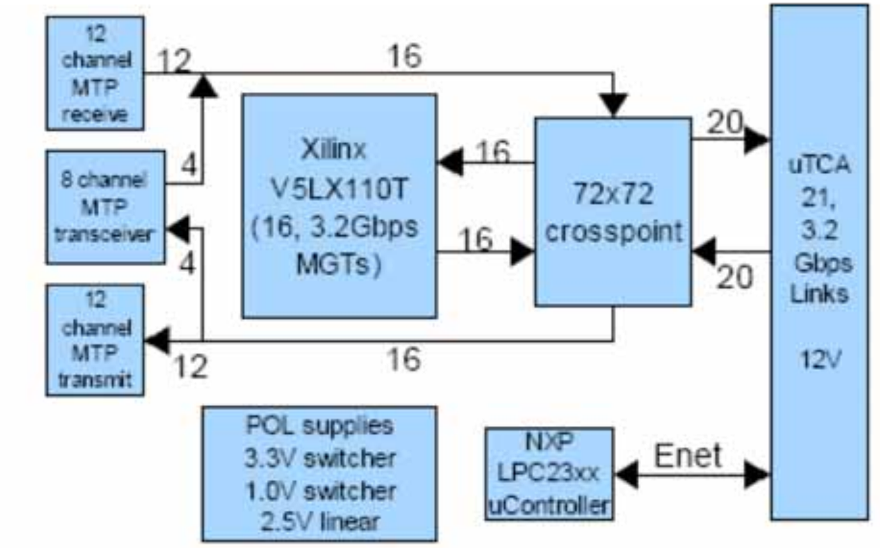
- Bring more in more information on a finer grain scale

More general & modular firmware

- Less device dependence
- Sharing of firmware modules & development

Proto. Generic Trigger System

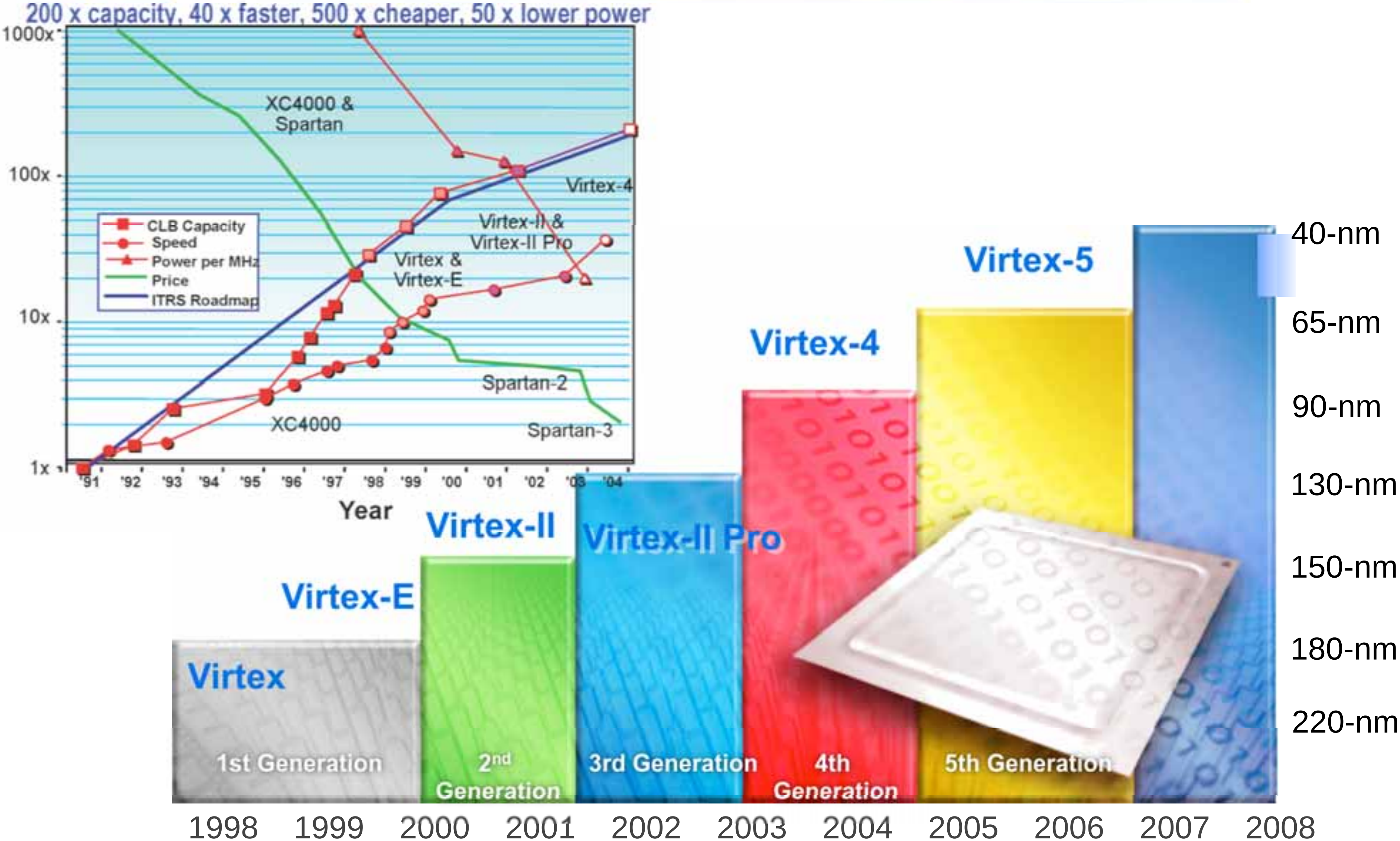
Concept for Main Processing Card



uTCA Crate and Backplane

- **The Main Processing Card (MPC):**
  - **Receives and transmits data via front panel optical links.**
  - **On board 72x72 Cross-Point Switch allows for dynamical routing of the data either to a V5 FPGA or directly to the uTCA backplane.**
  - **The MPC can exchange data with other MPCs either via the backplane or via the front panel optical links.**
- **The Custom uTCA backplane:**
  - **Instrumented with 2 more Cross-Point Switches for extra algorithm flexibility.**
  - **Allows dynamical or static routing of the data to different MPCs.**

FPGA Progress



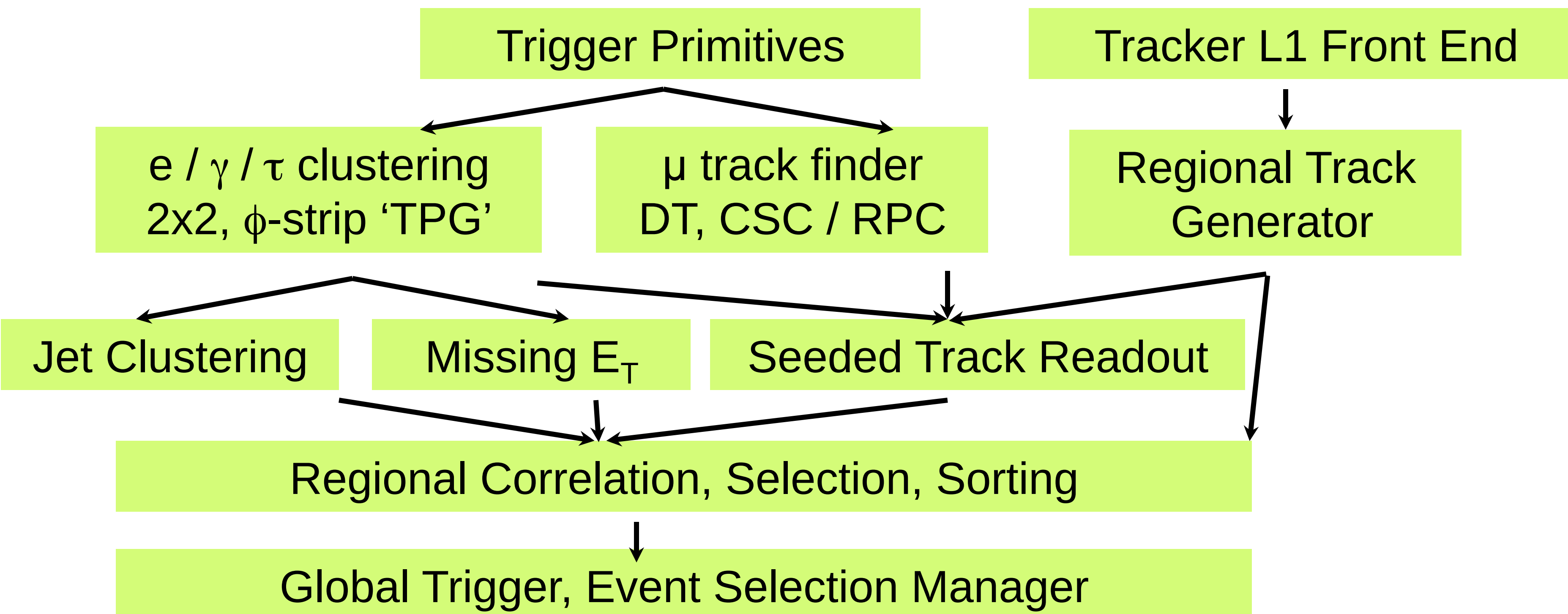
CMS L1 Trigger Stages

Current for LHC:

TPG ⇒ RCT ⇒ GCT ⇒ GT

Proposed for SLHC (with tracking added):

TPG ⇒ Clustering ⇒ Correlator ⇒ Selector



CMS Level-1 Latency

Present CMS Latency of 3.2 μsec = 128 crossings @ 40MHz

- Limitation from post-L1 buffer size of tracker & preshower
- Assume rebuild of tracking & preshower electronics will store more than this number of samples

Do we need more?

- Not all crossings used for trigger processing (70/128)
  - It's the cables!
- Parts of trigger already using higher frequency

How much more? Justification?

- Combination with tracking logic
- Increased algorithm complexity
- Asynchronous links or FPGA-integrated deserialization require more latency
- Finer result granularity may require more processing time
- ECAL digital pipeline memory is 256 40 MHz samples = 6.4 μsec
  - Propose this as CMS SLHC Level-1 Latency baseline

SLHC DAQ

SLHC Network bandwidth at least 5-10 times LHC

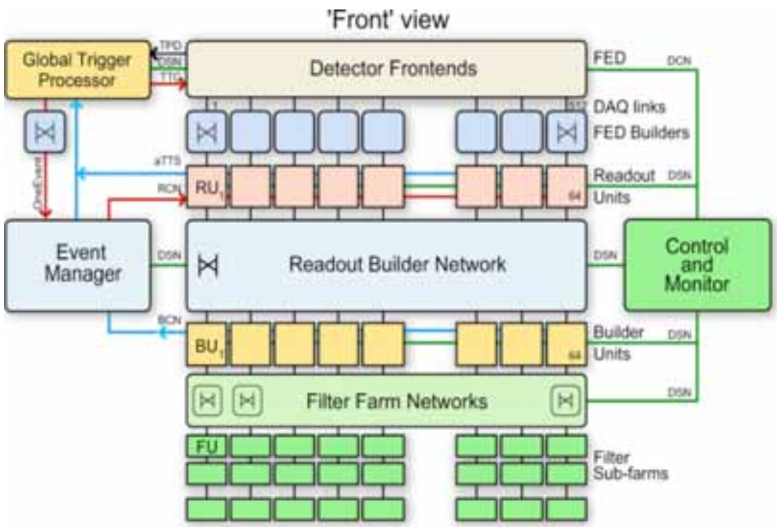
- **Assuming L1 trigger rate same as LHC**
- **Increased Occupancy**
- **Decreased channel granularity (esp. tracker)**

Upgrade paths for ATLAS & CMS can depend on present architecture

- **ATLAS: Region of Interest based Level-2 trigger in order to reduce bandwidth to processor farm**
  - Opportunity to put tracking information into level-2 hardware
  - Possible to create multiple slices of ATLAS present RoI readout to handle higher rate
- **CMS: scalable single hardware level event building**
  - If architecture is kept, requires level-1 tracking trigger

CMS DAQ: Possible structure upgrade

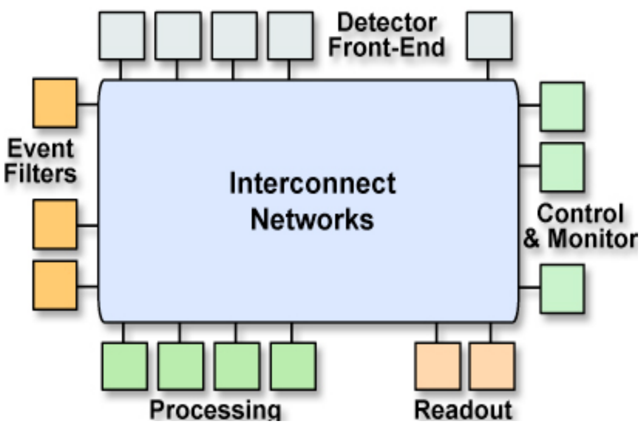
- S. Cittolin



LHC DAQ design:

A network with Terabit/s aggregate bandwidth is achieved by two stages of switches and a layer of intermediate data concentrators used to optimize the EVB traffic load.

RU-BU Event buffers ~100GByte memory cover a **real-time interval of seconds**



SLHC DAQ design:

A **multi-Terabit/s network** congestion free and scalable (as expected from communication industry).

In addition to the Level-1 Accept, the Trigger has to transmit to the FEDs additional information such as the event type and the event destination address that is the processing system (CPU, Cluster, TIER..) where the event has to be built and analyzed.

The event fragment delivery and therefore the **event building will be warranted by the network protocols** and (commercial) network internal resources (buffers, multi-path, network processors, etc.)

Real time buffers of Pbytes temporary storage disks will cover a **real-time interval of days**, allowing to the event selection tasks a better exploitation of the available distributed processing power.

New SLHC Fast Controls, Clocking & Timing System (TTC)

Drive High-Speed Links

- **Design to drive next generation of links**
  - Build in very good peak-to-peak jitter performance

Fast Controls (trigger/readout signal loop):

- **Provides Clock, L1A, Reset, BC0 in real time for each crossing**
- **Transmits and receives fast control information**
- **Provides interface with Event Manager (EVM), Trigger Throttle System**
  - For each L1A (@ 100 kHz), each front end buffer gets IP address of node to transmit event fragment to
  - EVM sends event building information in real time at crossing frequency using TTC system
    - **EVM updates 'list' of avail. event filter services (CPU-IP, etc.) where to send data**
    - **Info.is embedded in data sent into DAQ net which builds events at destination**
  - Event Manager & Global Trigger must have a tight interface
- **This control logic must process new events at 100 kHz → R&D**

Trigger & DAQ Summary:
LHC Case

Level 1 Trigger

- **Select 100 kHz interactions from 1 GHz (10 GHz at SLHC)**
- **Processing is synchronous & pipelined**
- **Decision latency is 3 μs (x~2 at SLHC)**
- **Algorithms run on local, coarse data**
  - Cal & Muon at LHC (& tracking at SLHC)
  - Use of ASICs & FPGAs (mostly FPGAs at SLHC)

Higher Level Triggers

- **Depending on experiment, done in one or two steps**
- **If two steps, first is hardware region of interest**
- **Then run software/algorithms as close to offline as possible on dedicated farm of PCs**