Trigger & DAQ

Hadron Collider Physics Summer School

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Outline:

General Introduction to Detector Readout

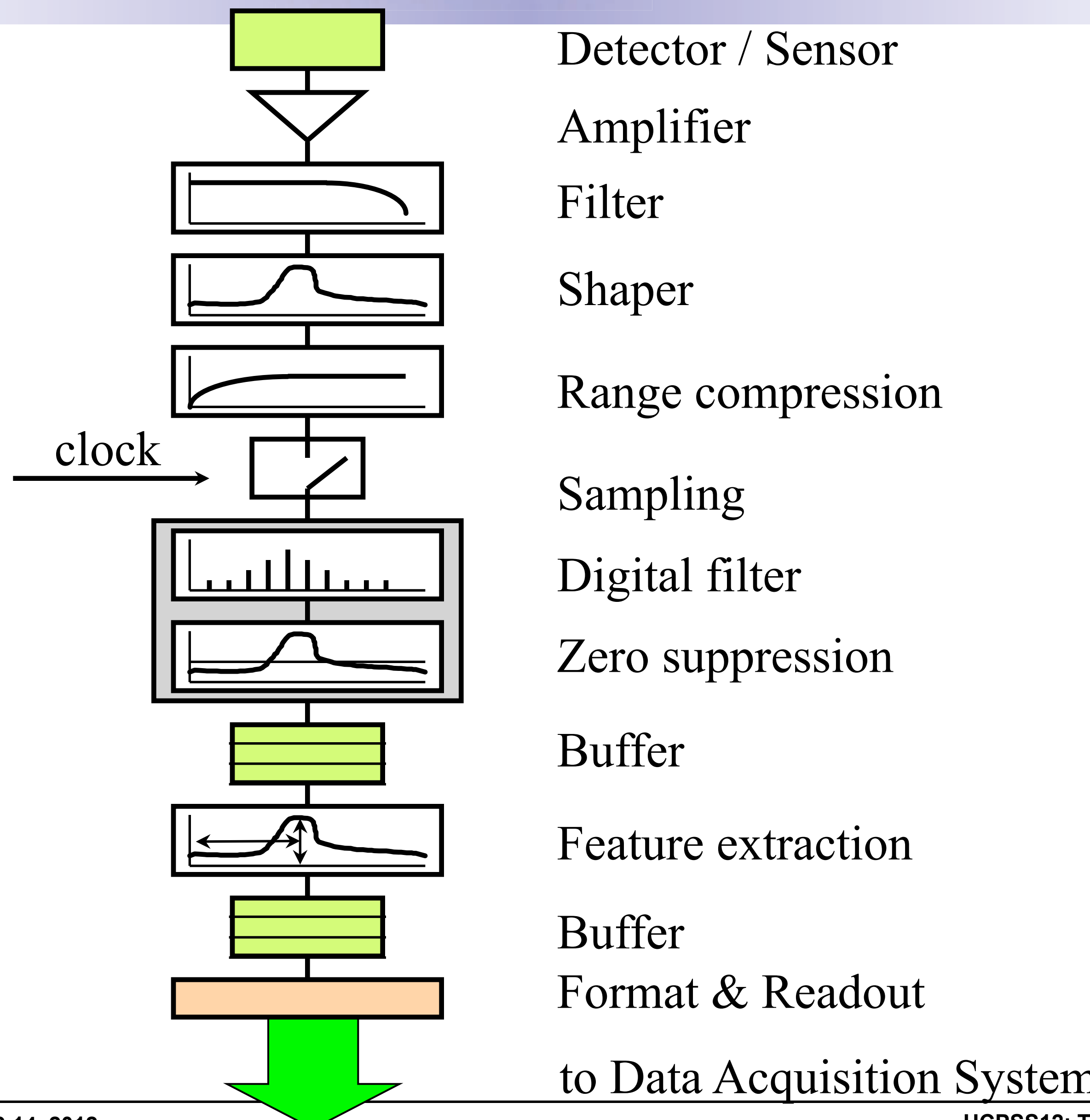
Introduction to LHC Trigger & DAQ

Challenges & Architecture

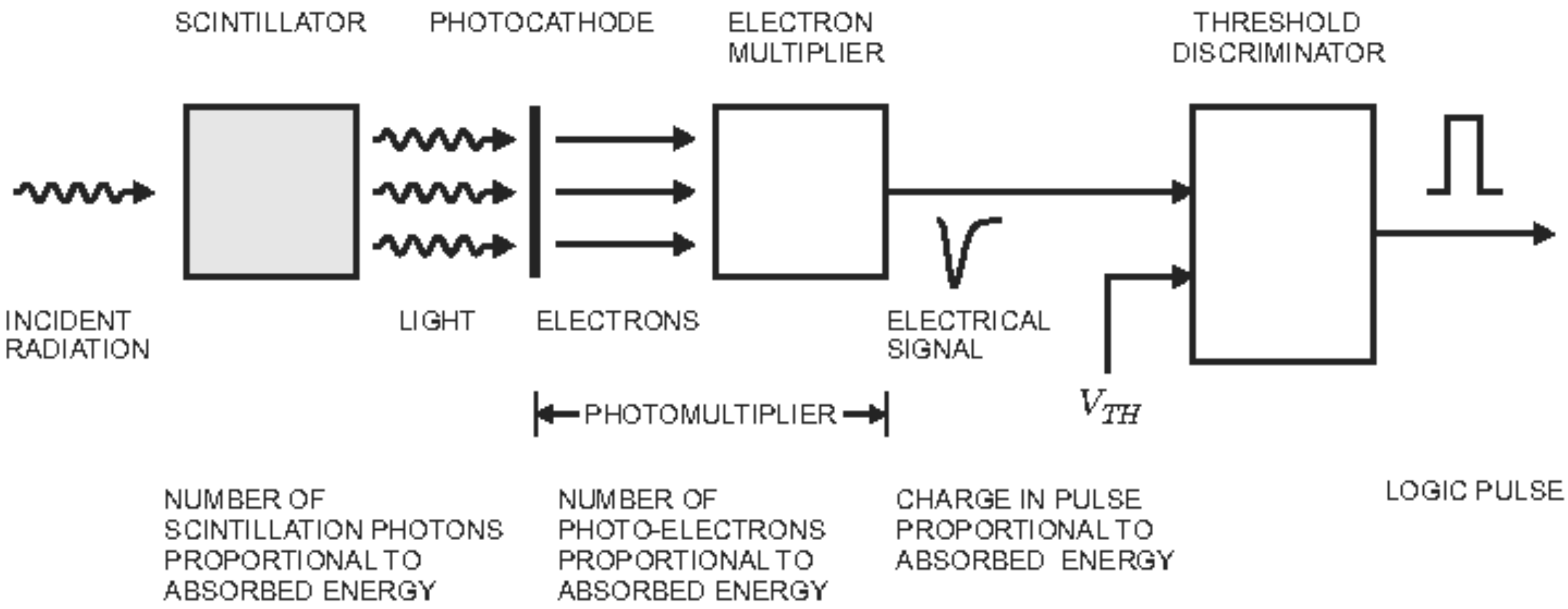
LHC Experiments Trigger & DAQ

The future of LHC Trigger & DAQ

Readout


Detector / Sensor
Amplifier
Filter
Shaper
Range compression
clock
Sampling
Digital filter
Zero suppression
Buffer
Feature extraction
Buffer
Format & Readout
to Data Acquisition System

Simple Example: Scintillator



from H. Spieler "Analog and Digital Electronics for Detectors"

Photomultiplier serves as the amplifier

Measure if pulse height is over a threshold

Filtering & Shaping

Purpose is to adjust signal for the measurement desired

- **Broaden a sharp pulse to reduce input bandwidth & noise**
  - Make it too broad and pulses from different times mix
- **Analyze a wide pulse to extract the impulse time and integral ⇒**

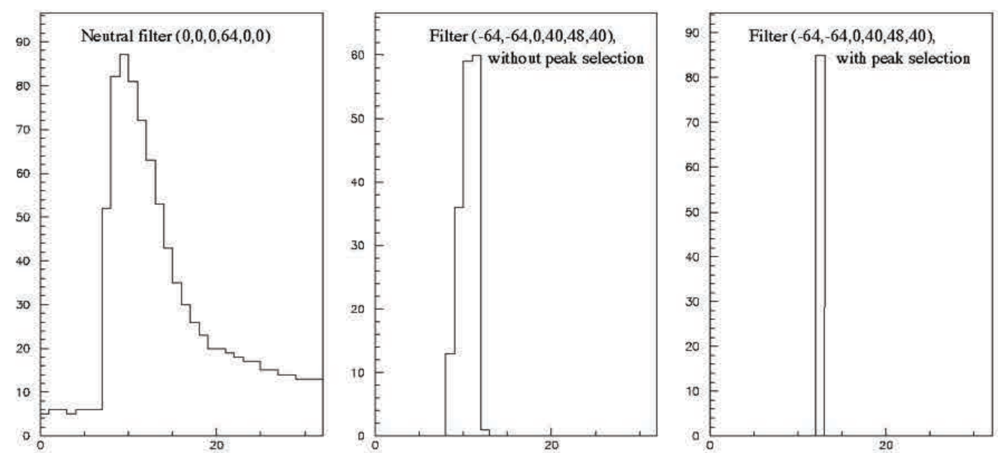
Example: Signals from scintillator every 25 ns

- **Need to sum energy deposited over 150 ns**
- **Need to put energy in correct 25 ns time bin**
- **Apply digital filtering & peak finding**
  - Will return to this example later

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)



Sampling & Digitization

Signal can be stored in analog form or digitized at regular intervals (sampled)

- **Analog readout: store charge in analog buffers (e.g. capacitors) and transmit stored charge off detector for digitization**
- **Digital readout with analog buffer: store charge in analog buffers, digitize buffer contents and transmit digital results off detector**
- **Digital readout with digital buffer: digitize the sampled signal directly, store digitally and transmit digital results off detector**
- **Zero suppression can be applied to not transmit date containing zeros**
  - Creates additional overhead to track suppressed data

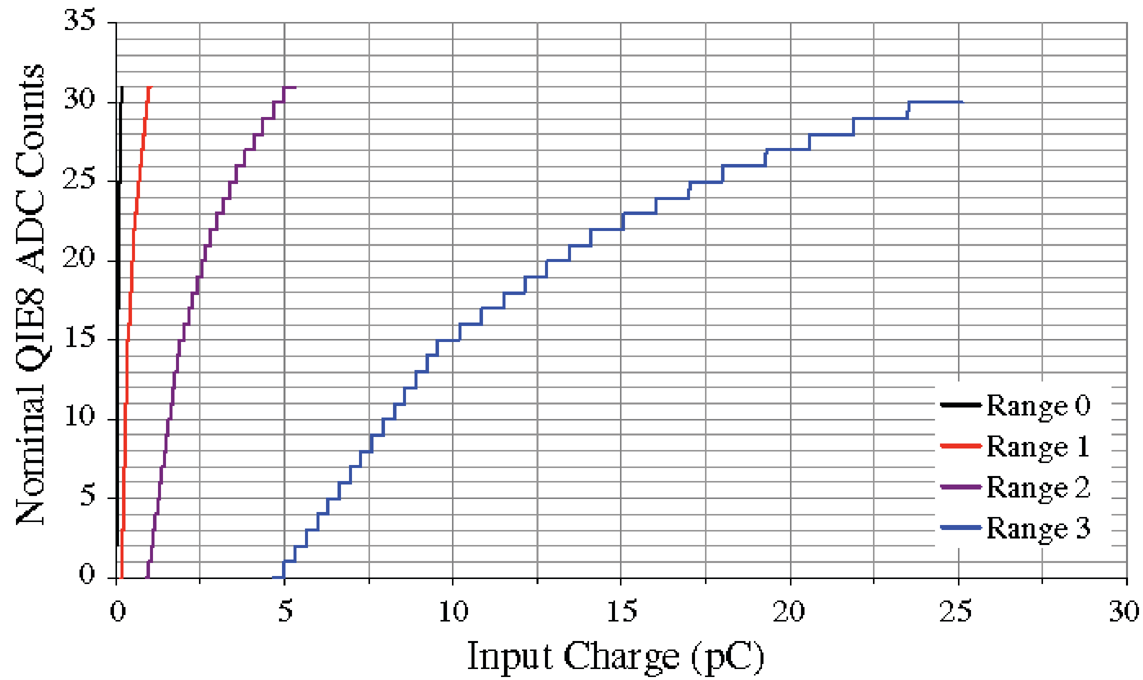
Signal can be discriminated against a threshold

- **Binary readout: all that is stored is whether pulse height was over threshold**

Range Compression

Rather than have a linear conversion from energy to bits, vary the number of bits per energy to match your detector resolution and use bits in the most economical manner.

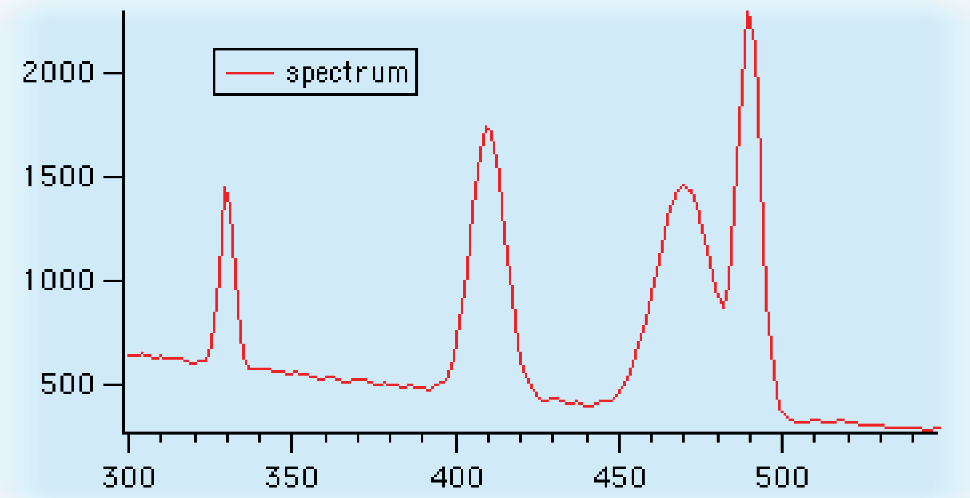
- **Have different ranges with different nos. of bits per pulse height**
- **Use nonlinear functions to match resolution**

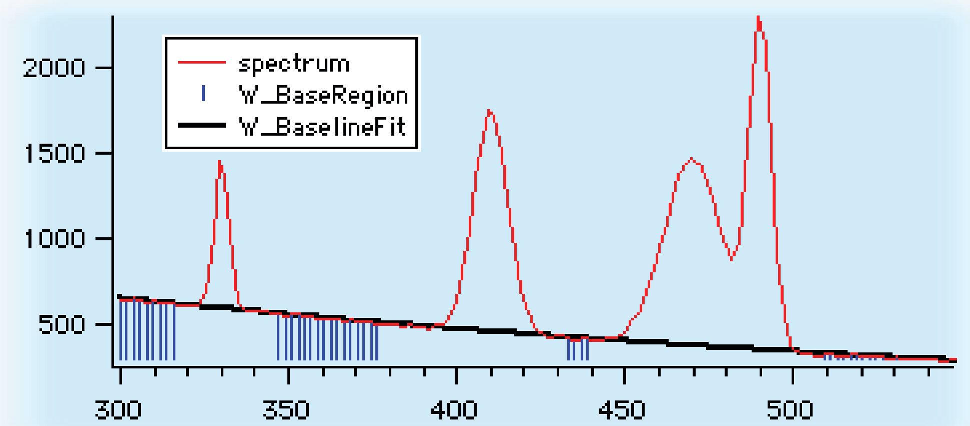


Baseline Subtraction

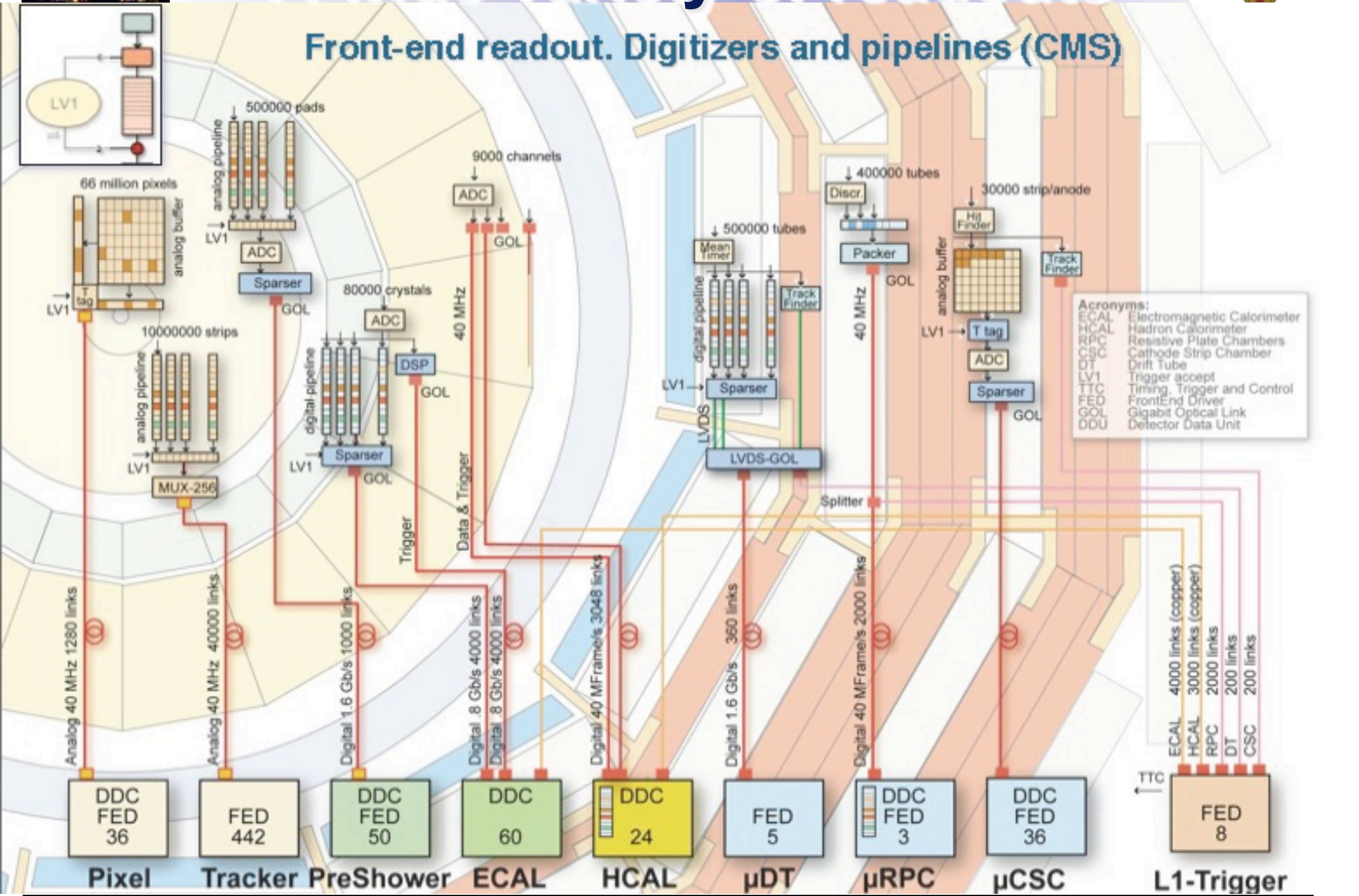
Wish to measure the integral of an individual pulse on top of another signal

- **Fit slope in regions away from pulses**
- **Subtract integral under fitted slope from pulse height**





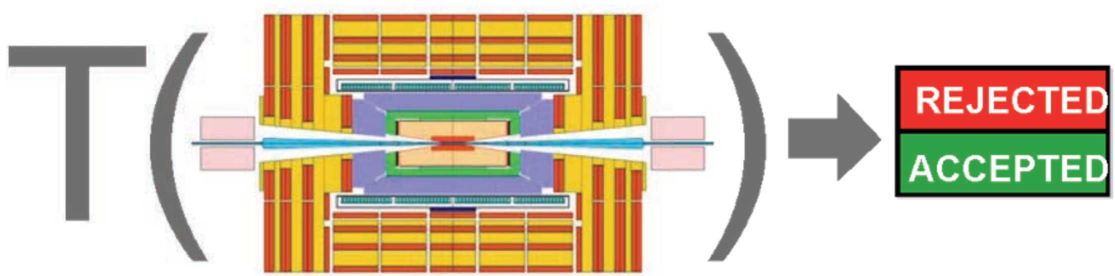
A wide variety of readouts



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

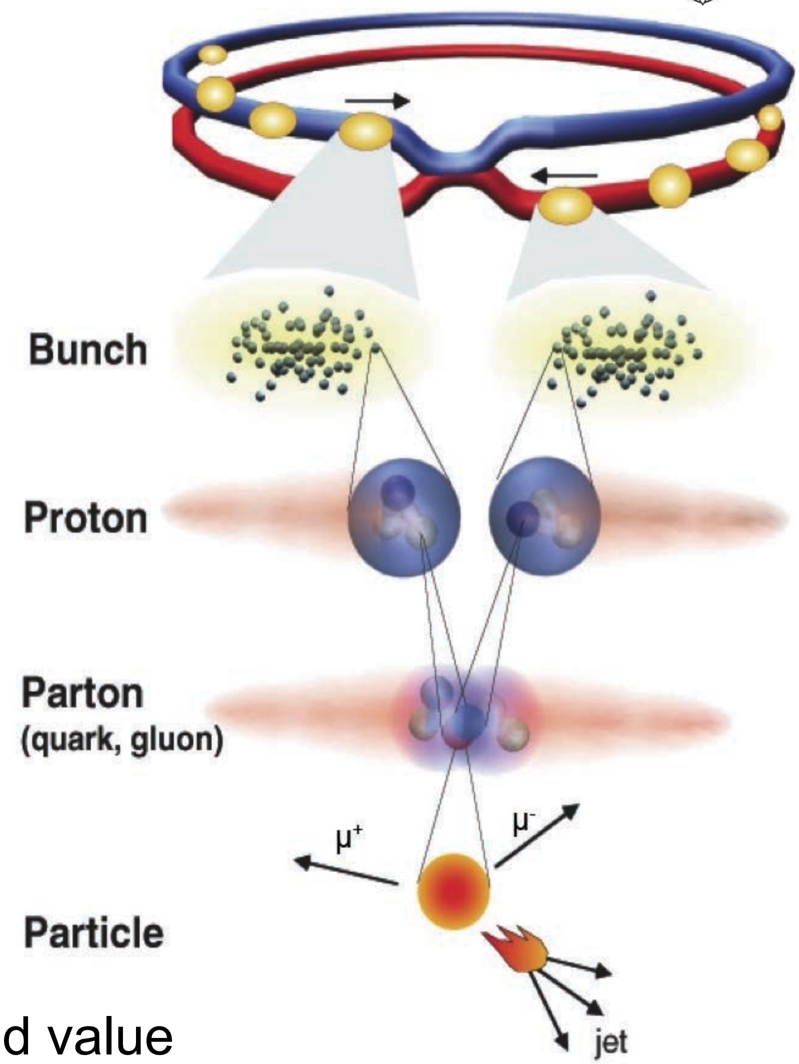
- Detector data not (all) promptly available
- Selection function highly complex

⇒T(...) is evaluated by successive approximations, the **TRIGGER LEVELS**

(possibly with zero dead time)

LHC now

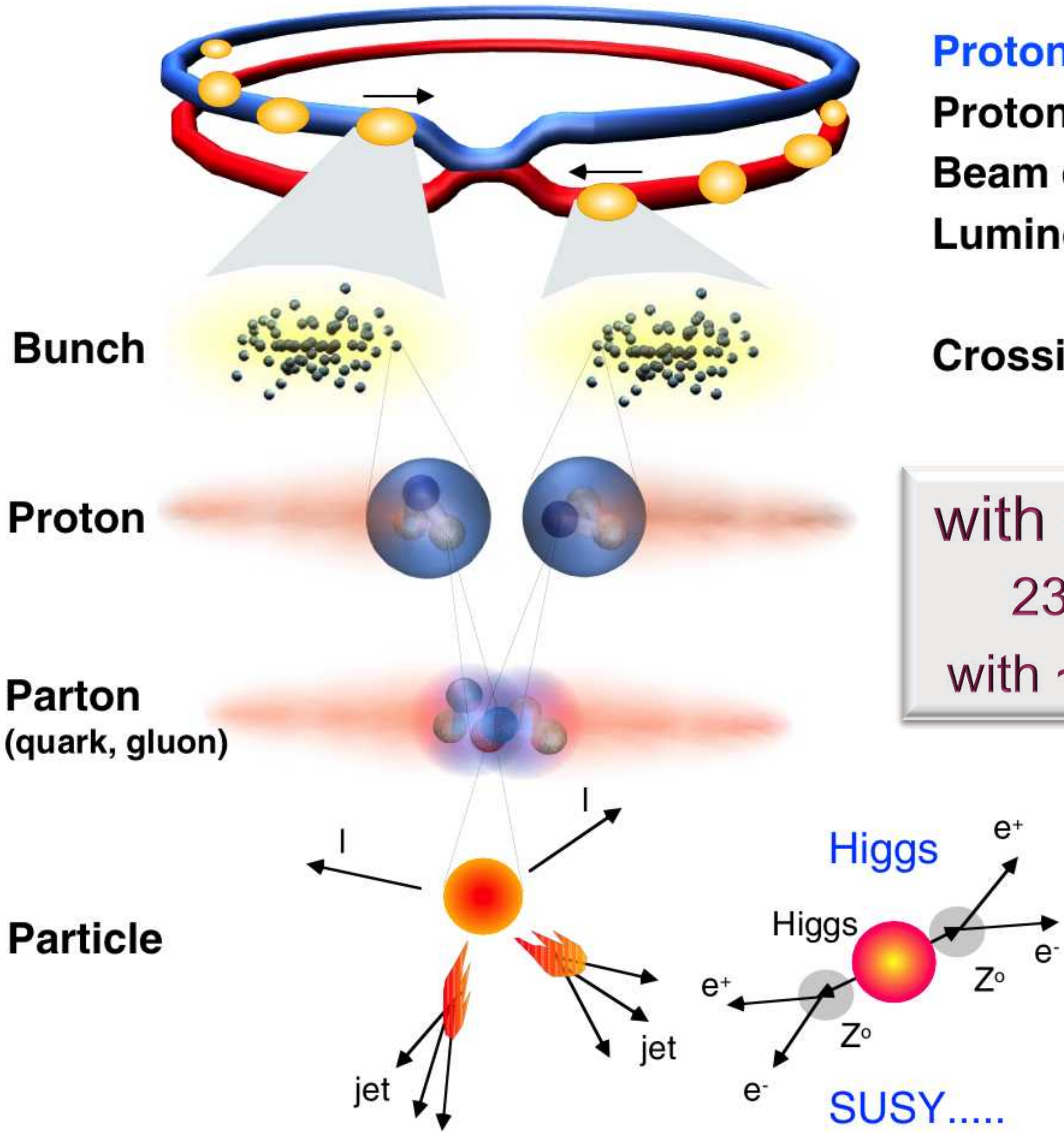
	Design	2010	2011	2012
Beam Energy (TeV)	7	3.5	3.5	4
Bunches/ Beam	2835	368	1380	1380
Proton/Bunch (10^{11})	1.15	1.3	1.5	1.5
Peak Lumi. (10^{32} cm^{-2} s^{-1})	100	2	30	60
Integrated Lumi. (fb^{-1})	100/yr	0.036	6	15*
Pile-Up	23	~1	20	30



Pile-Up – the number of proton interactions occurring during each bunch crossing

*expected value

More on LHC at Design



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

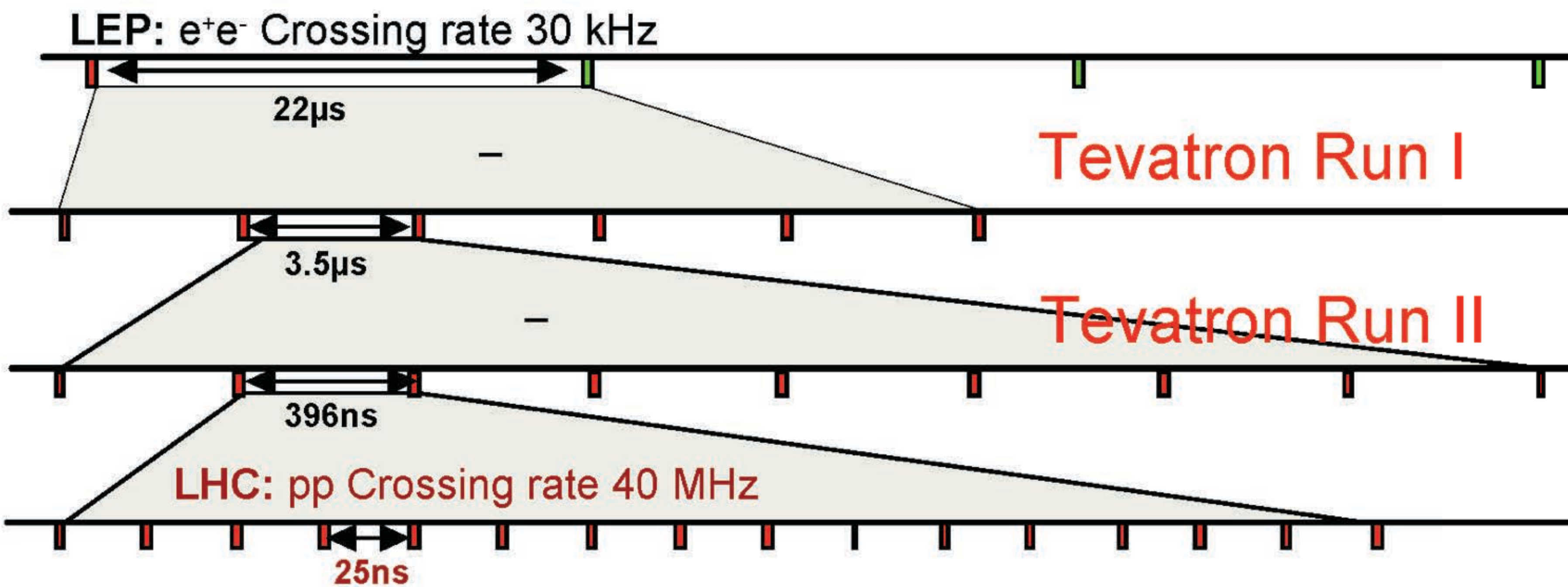
with every bunch crossing
23 Minimum Bias events
with ~1725 particles produced

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

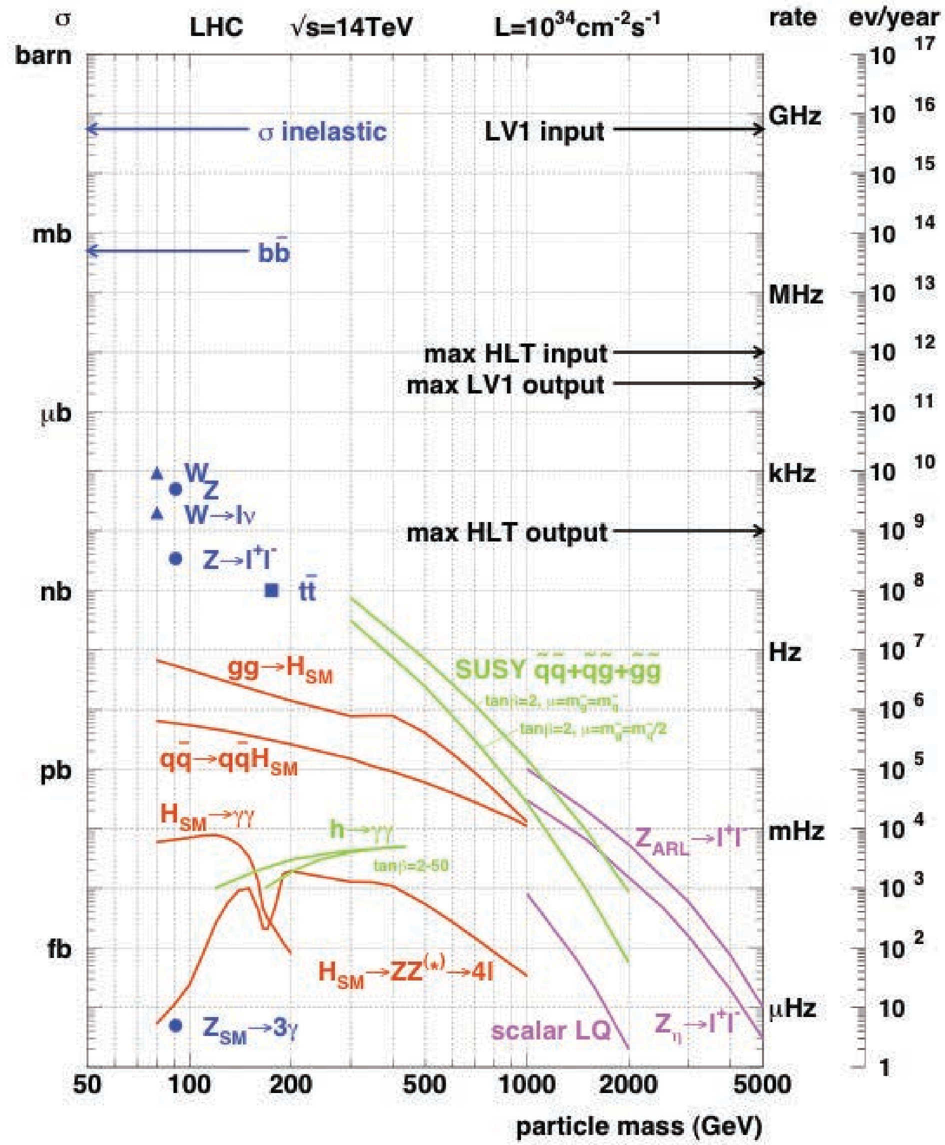
At design $L = 10^{34} cm^{-2}s^{-1}$

- **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**

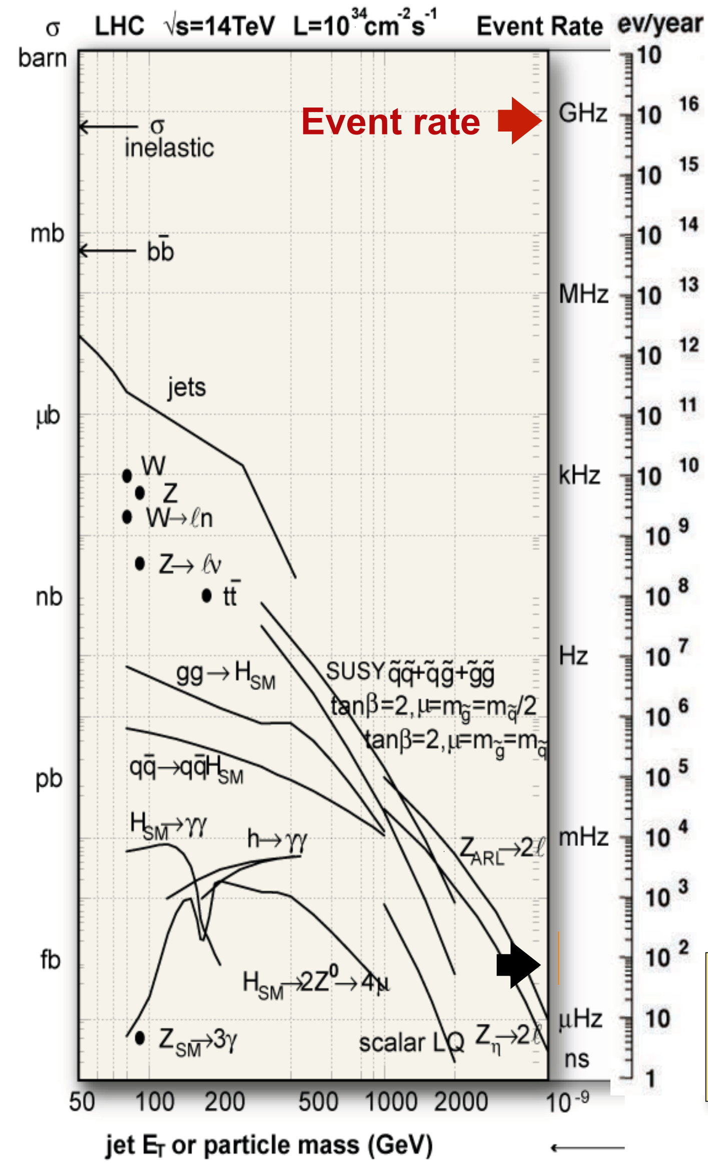
Can store ~ 300 Hz events

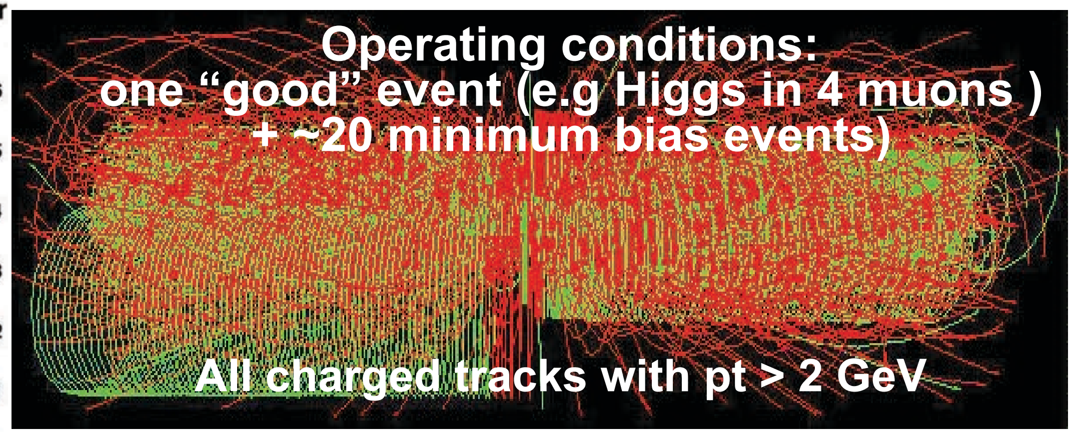
Select in stages

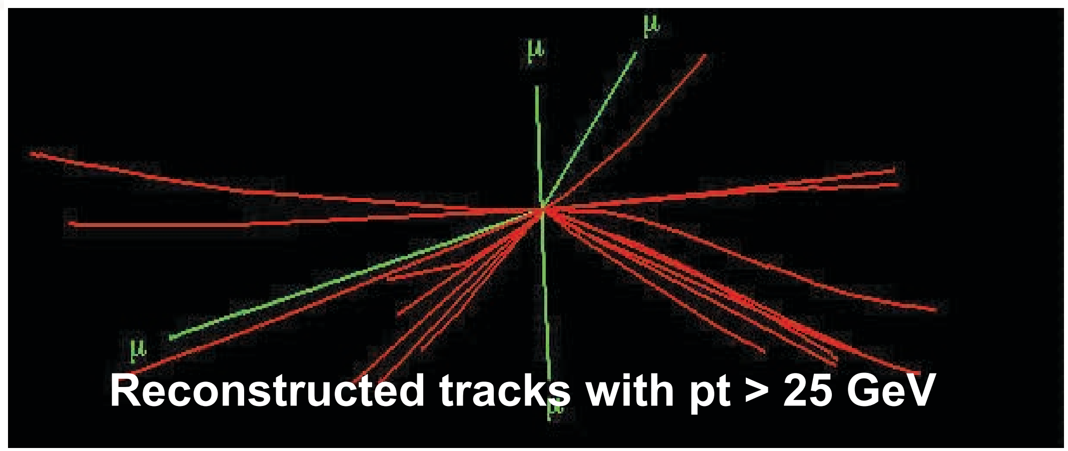
- **Level-1 Triggers**
  - 1 GHz to 100 kHz
- **High Level Triggers**
  - 100 kHz to 300 Hz



Collisions (p-p) at LHC

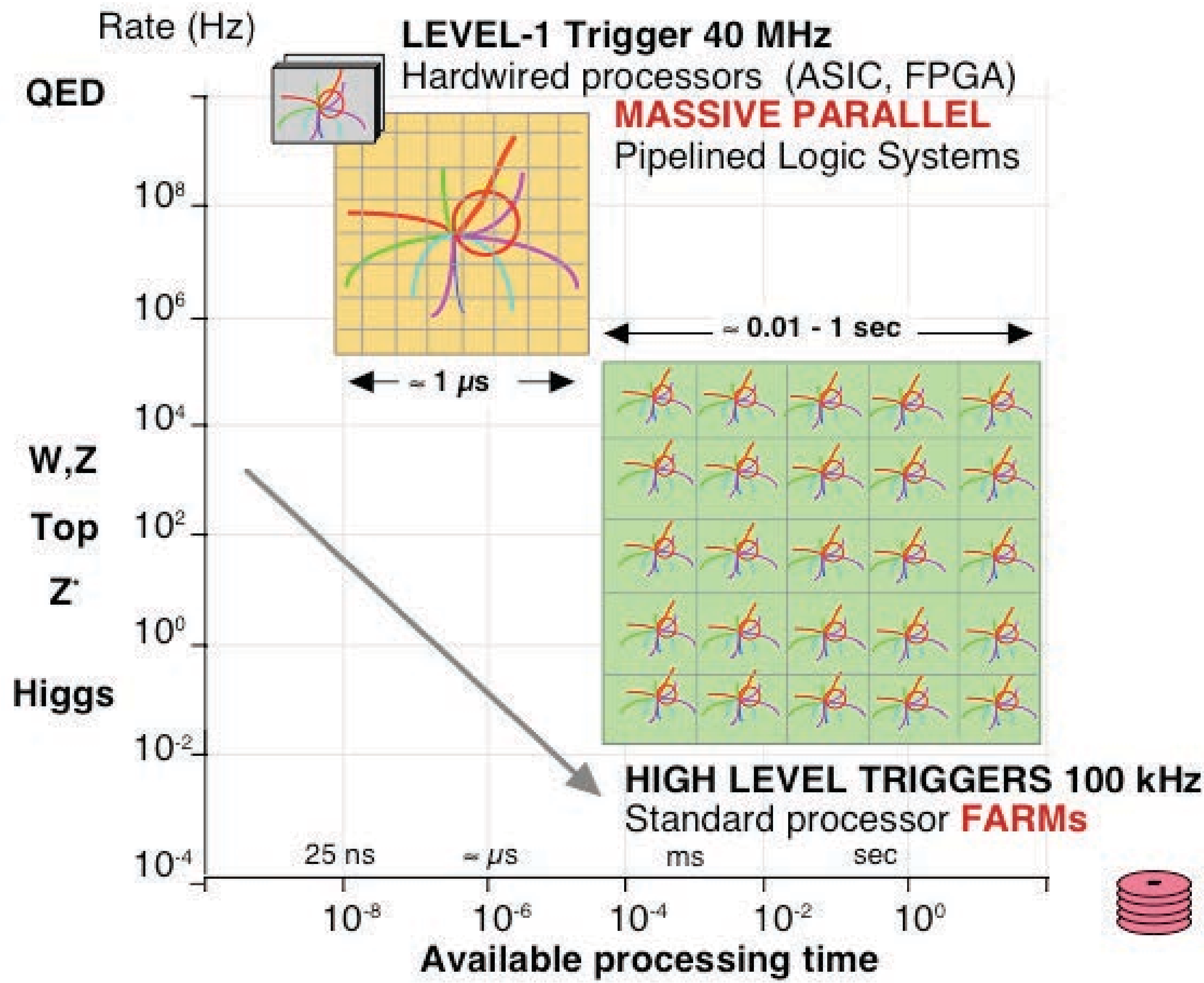




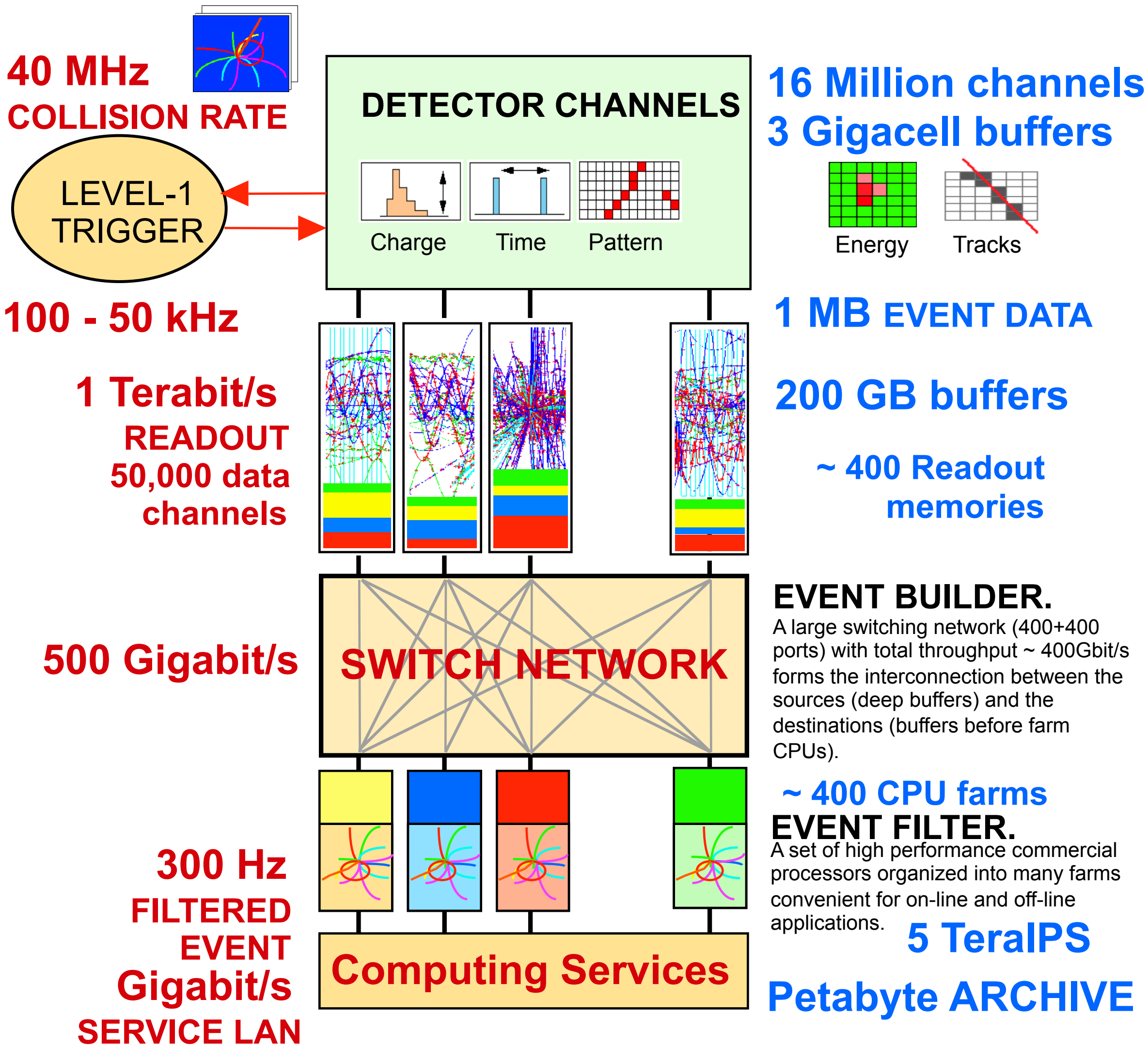


Event size:	**~1 MByte**
Processing Power:	**~X TFlop**

Processing LHC Data



LHC Trigger & DAQ Challenges



Challenges:

1 GHz of Input Interactions

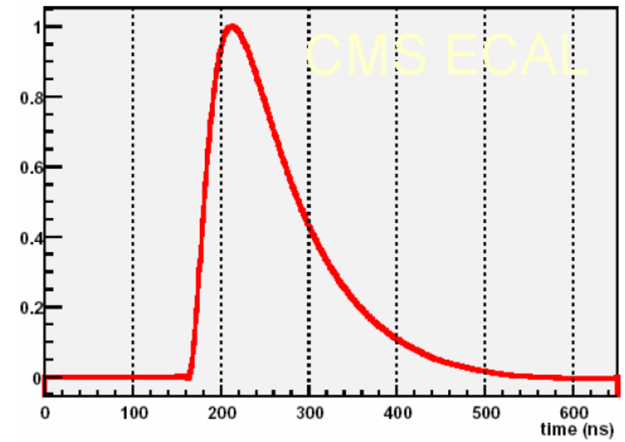
Beam-crossing every 25 ns with ~ 23 interactions produces over 1 MB of data

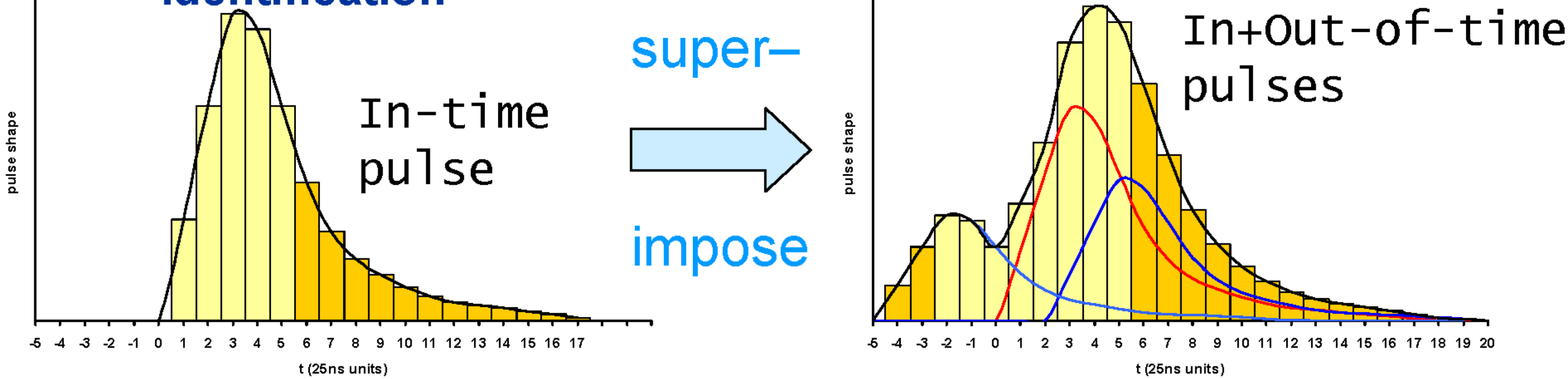
Archival Storage at about 300 Hz of 1 MB events

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"

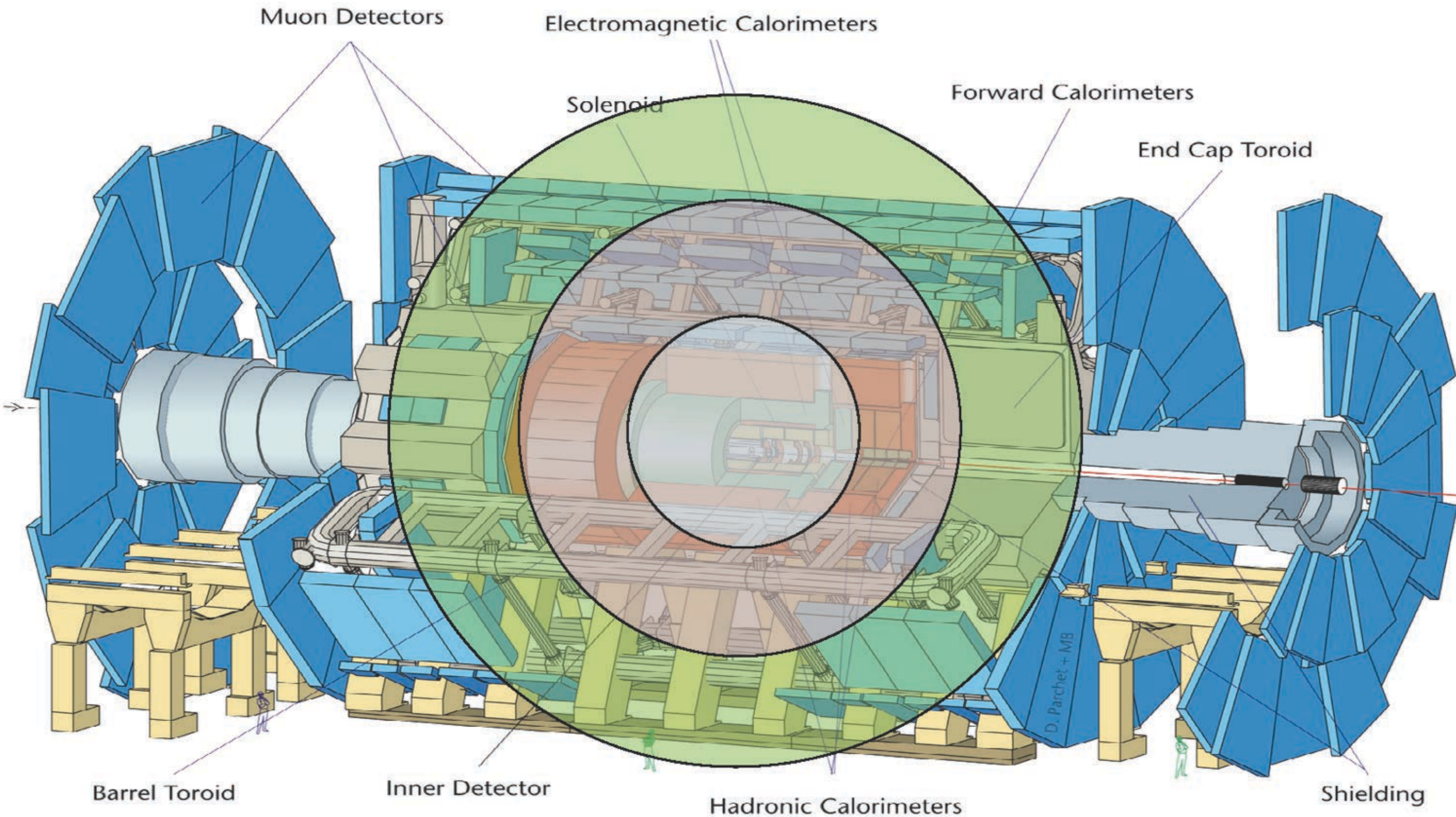




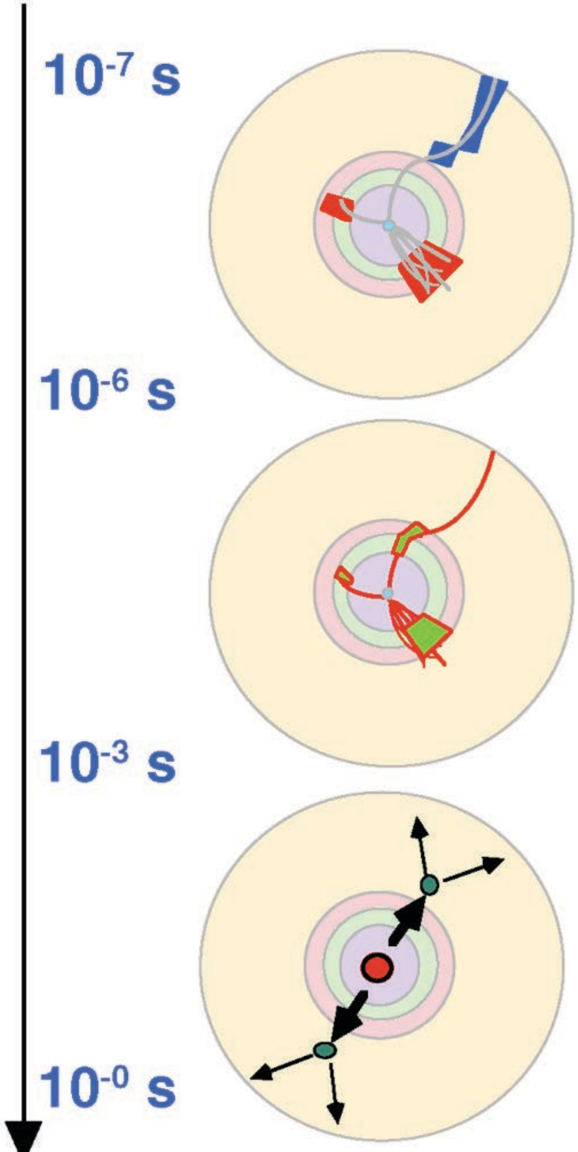
Challenges: Time of Flight

HCPSS12

c = 30 cm/ns → in 25 ns, s = 7.5 m



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, ..)

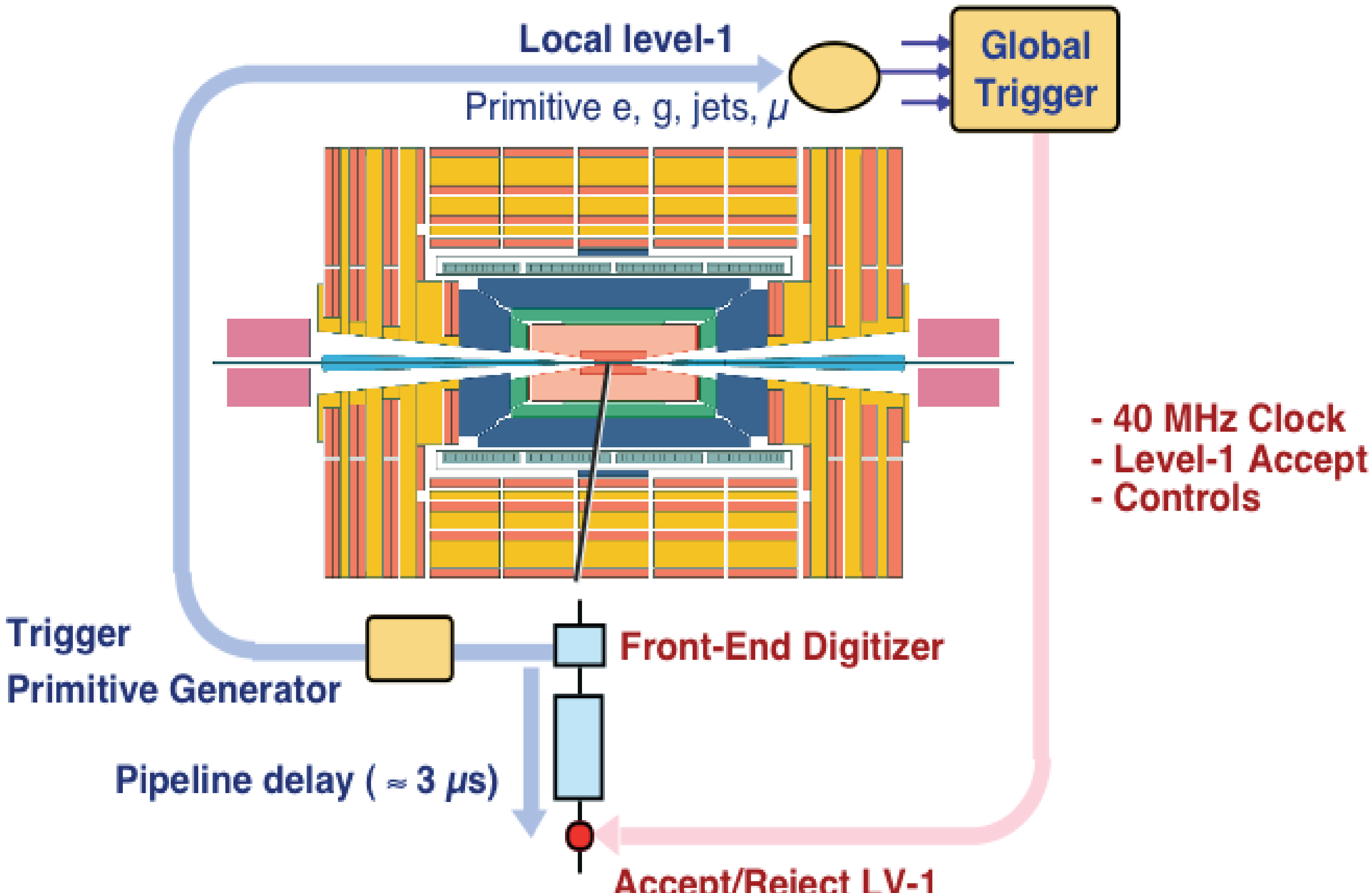
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

Level-3 events to tape **100- 400 Hz**

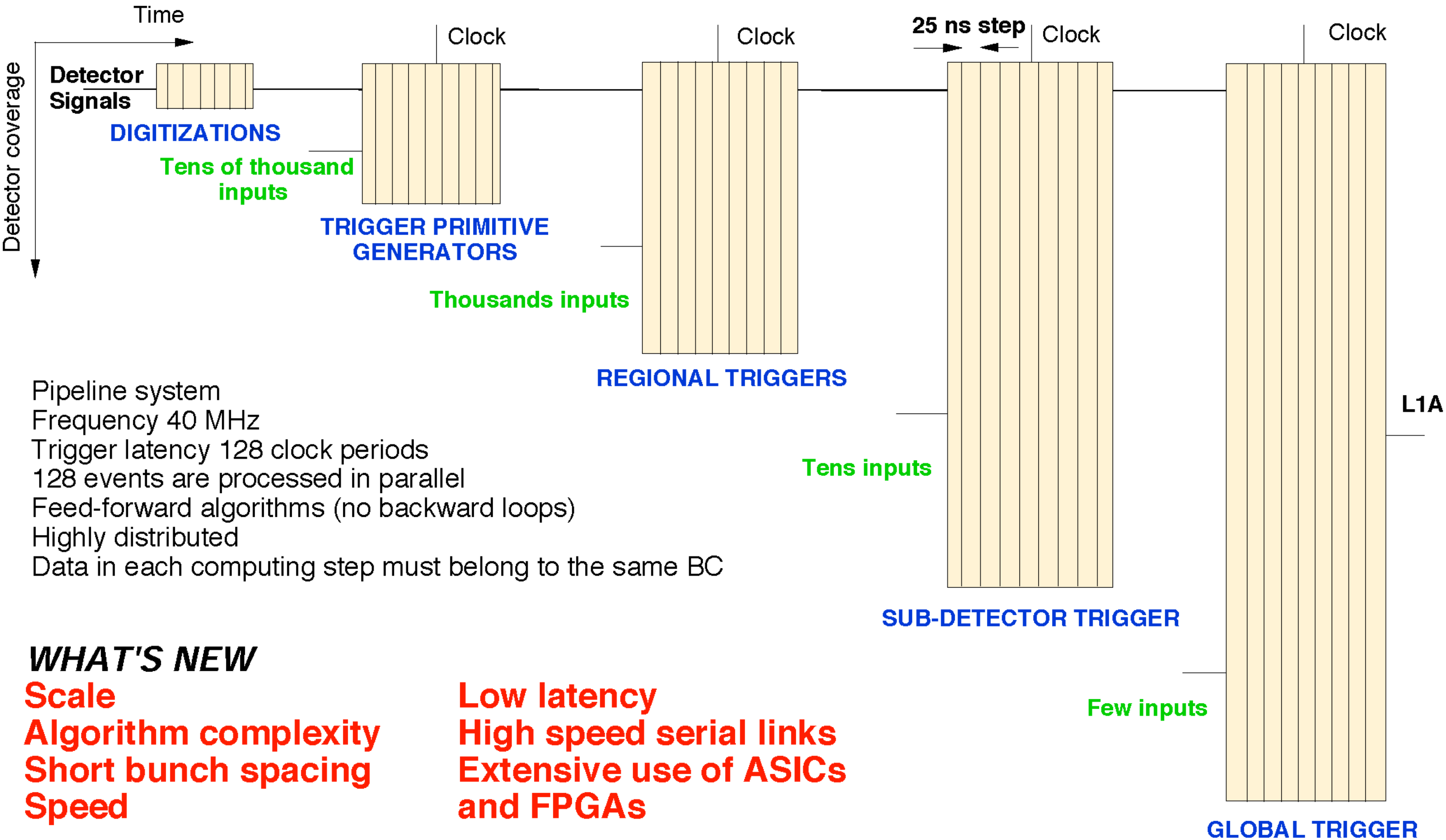
Physics process identification

- Event reconstruction and analysis

Level 1 Trigger Operation



Level 1 Trigger Organization

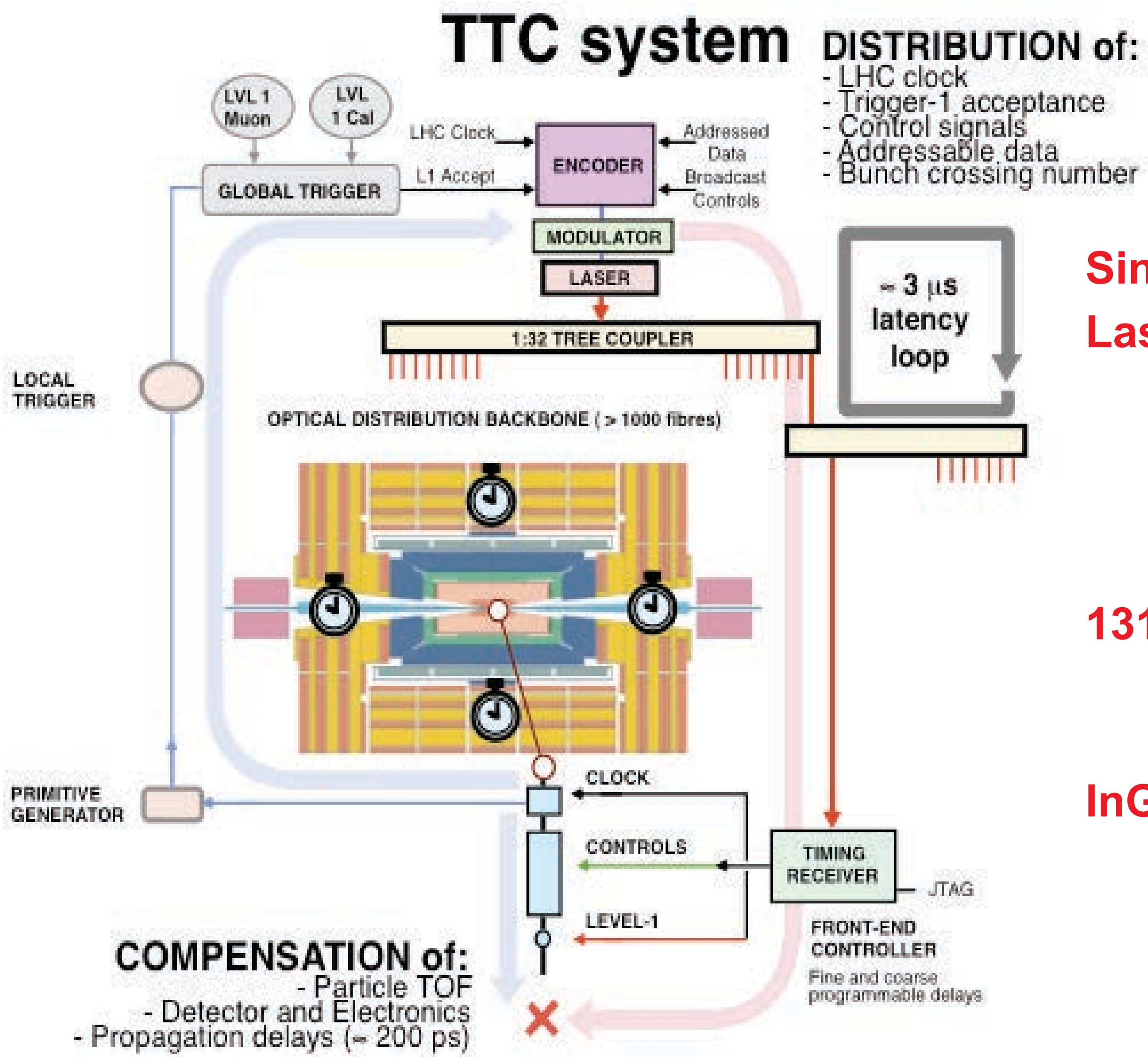


Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

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**

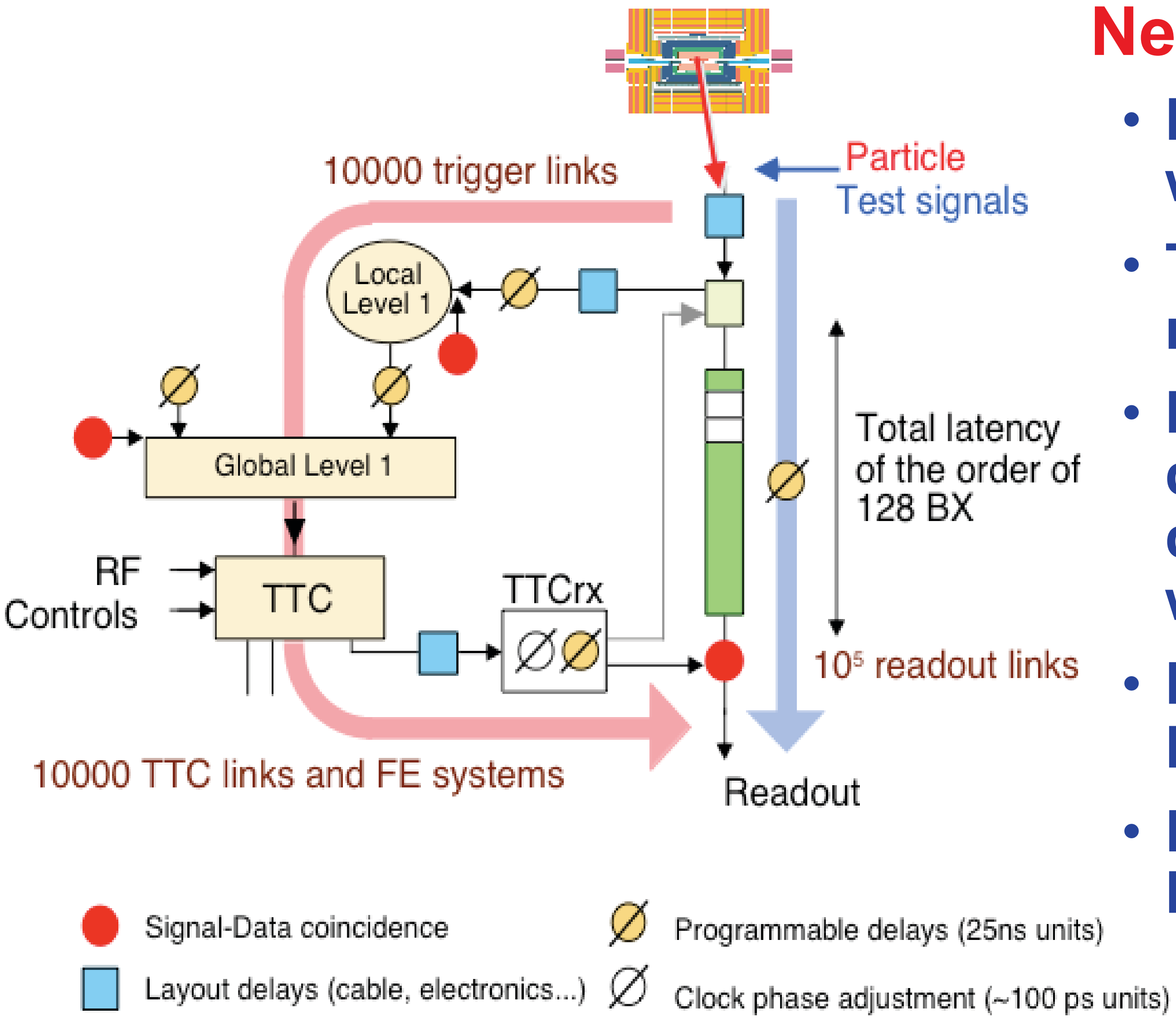
1310 nm Operation

- **Negligible chromatic dispersion**

InGaAs photodiodes

- **Radiation resistance, low bias**

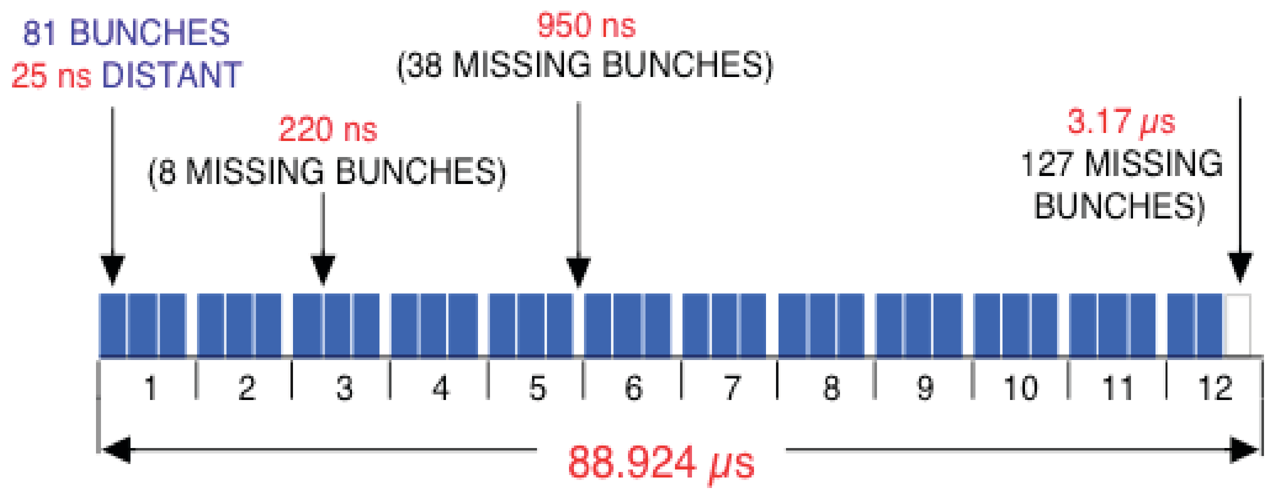
Detector Timing Adjustments



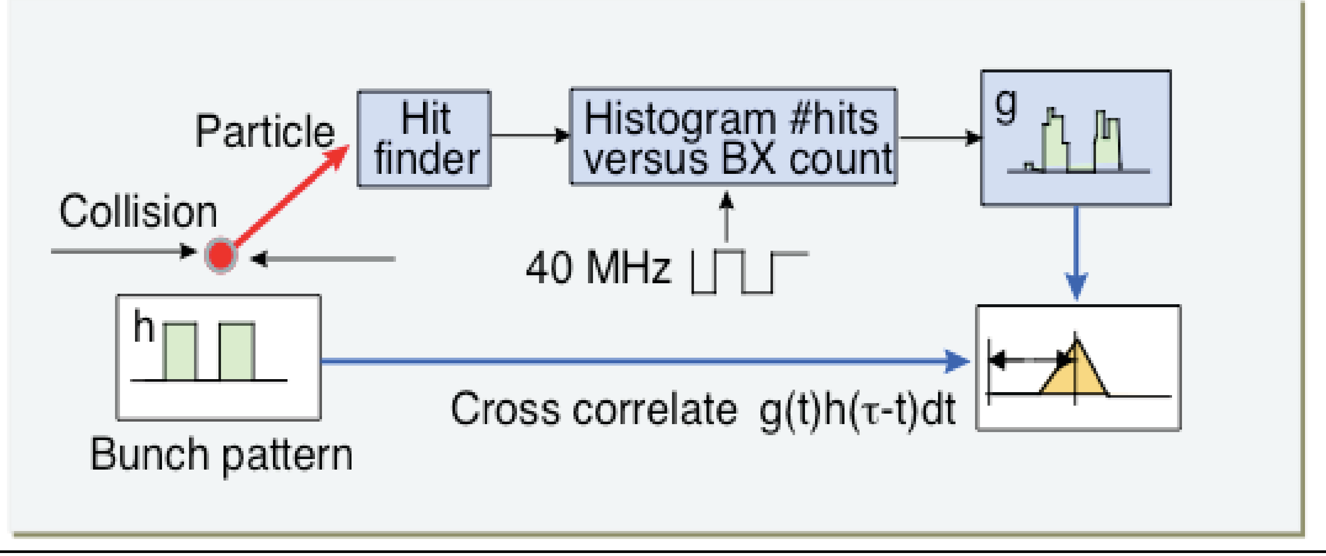
Need to Align:

- 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



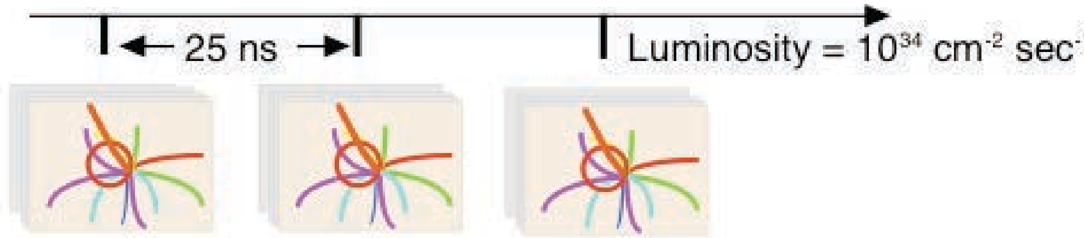
2835 out of 3564 p bunches are full, use this pattern:

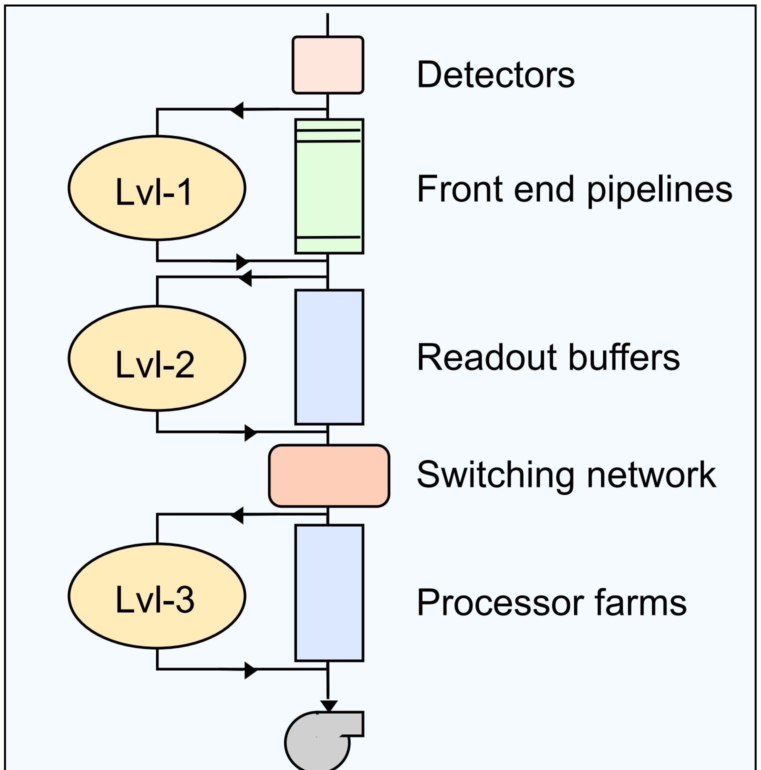


ATLAS & CMS Trigger & Readout Structure

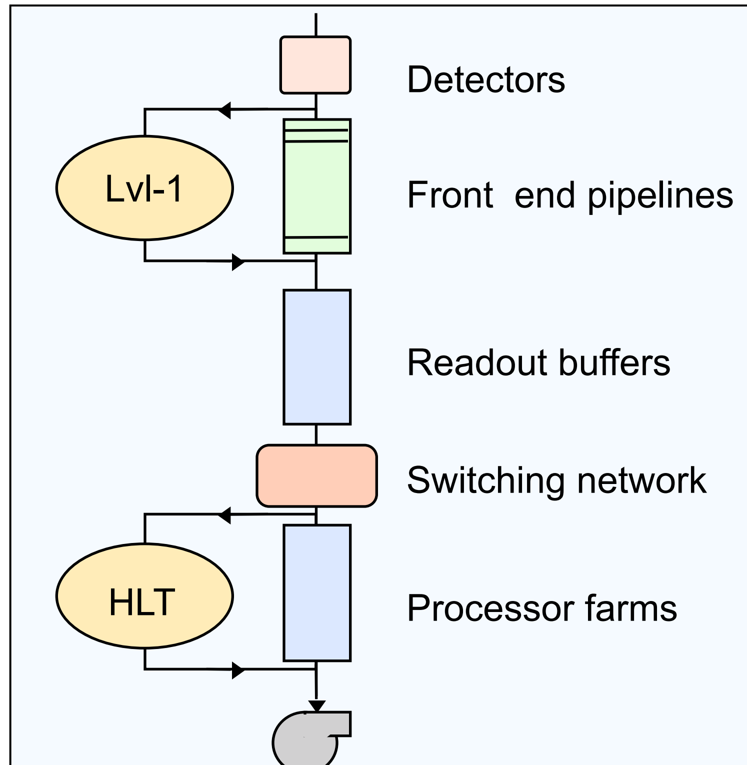
≈ 30 Collisions/25ns
(10^9 event/sec)

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



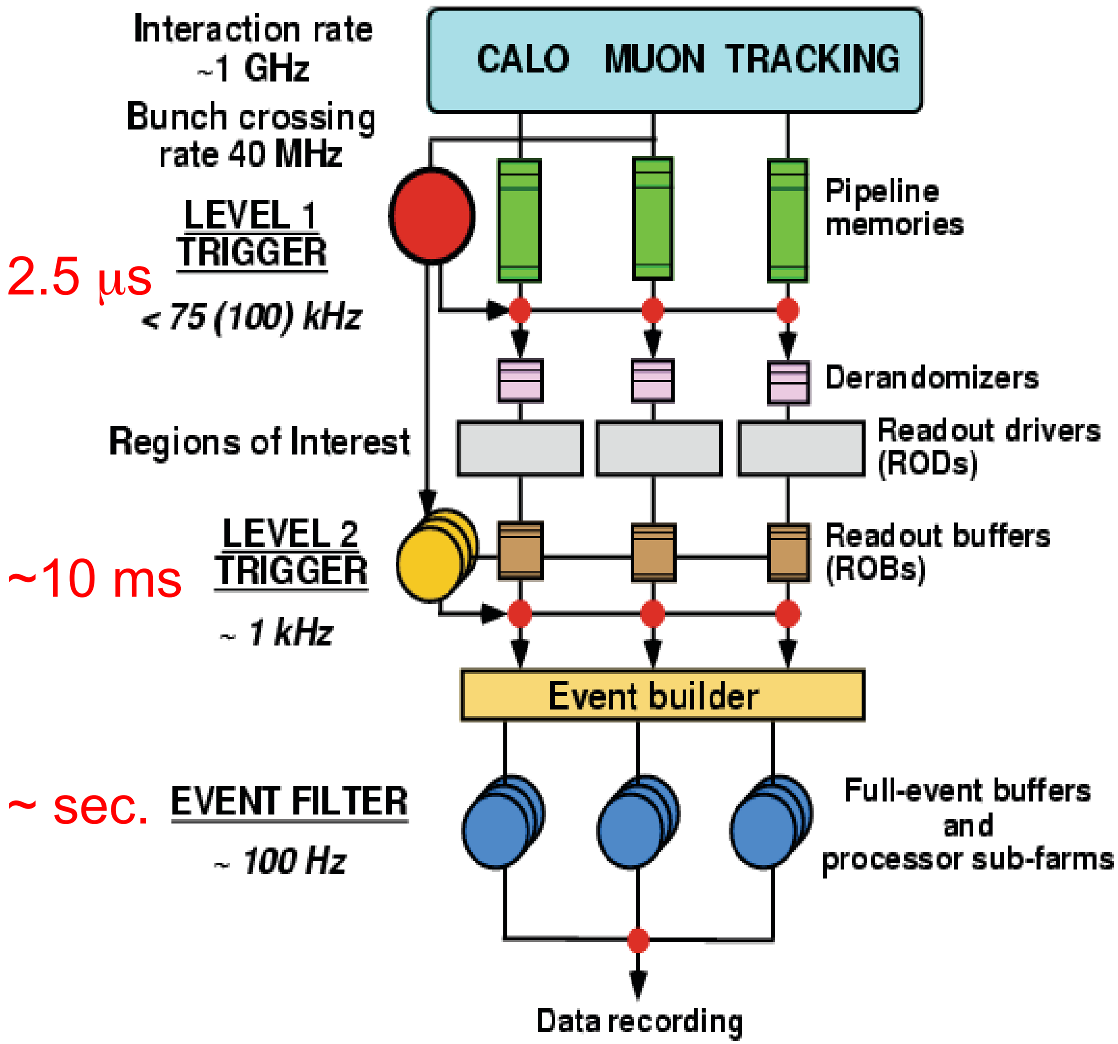


ATLAS: 3 physical levels



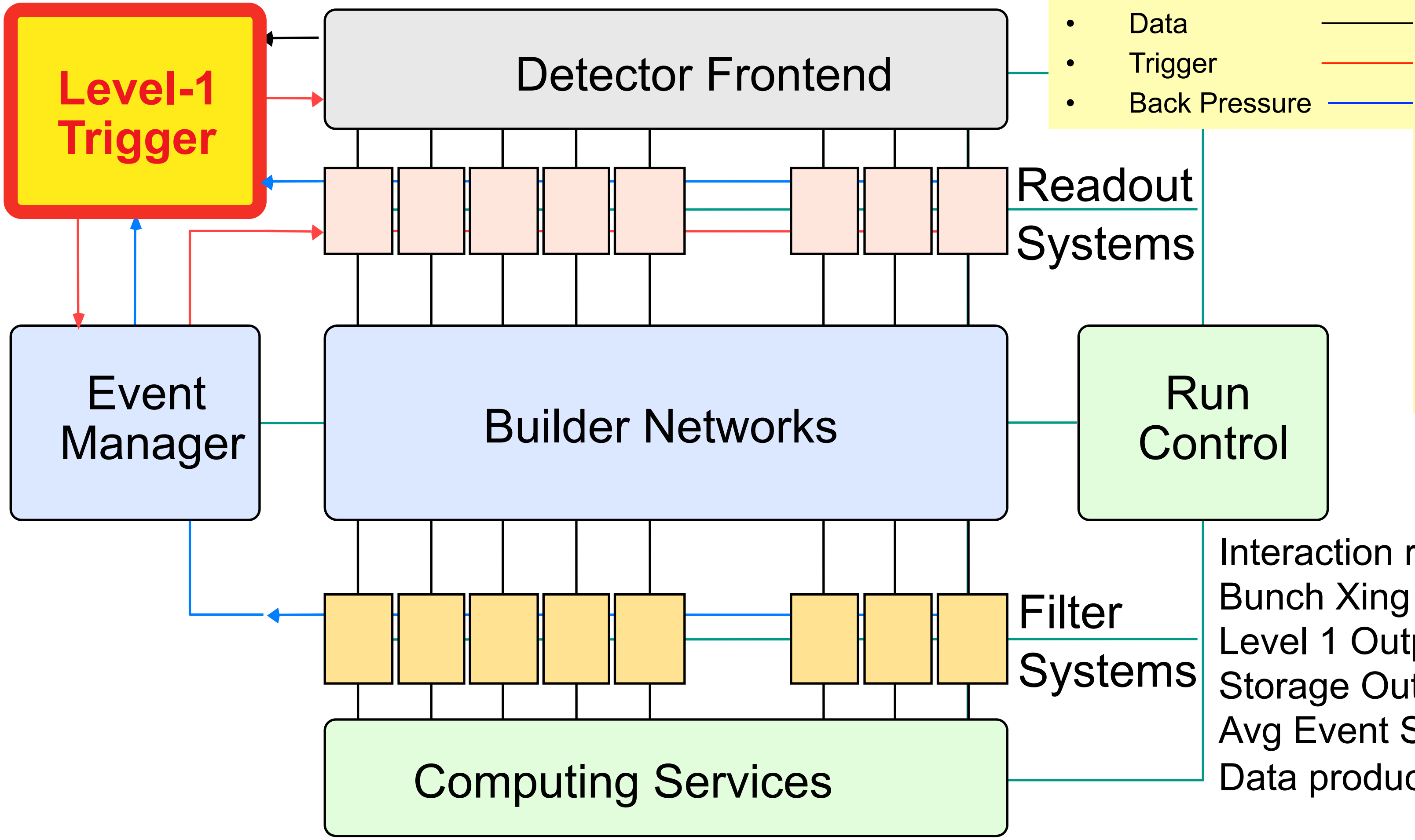
CMS: 2 physical levels

ATLAS Three Level Trigger Architecture



- **LVL1 decision made with calorimeter data with coarse granularity and muon trigger chamber 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 Readout Buffers**
- **EventFilter refines the selection, can perform event reconstruction at full granularity using latest alignment and calibration data.**
  - **Buffering in EB & EF**

CMS 2-Level Trigger & DAQ



The Lv1-Accept decision causes the readout system to respond with backpressure information.

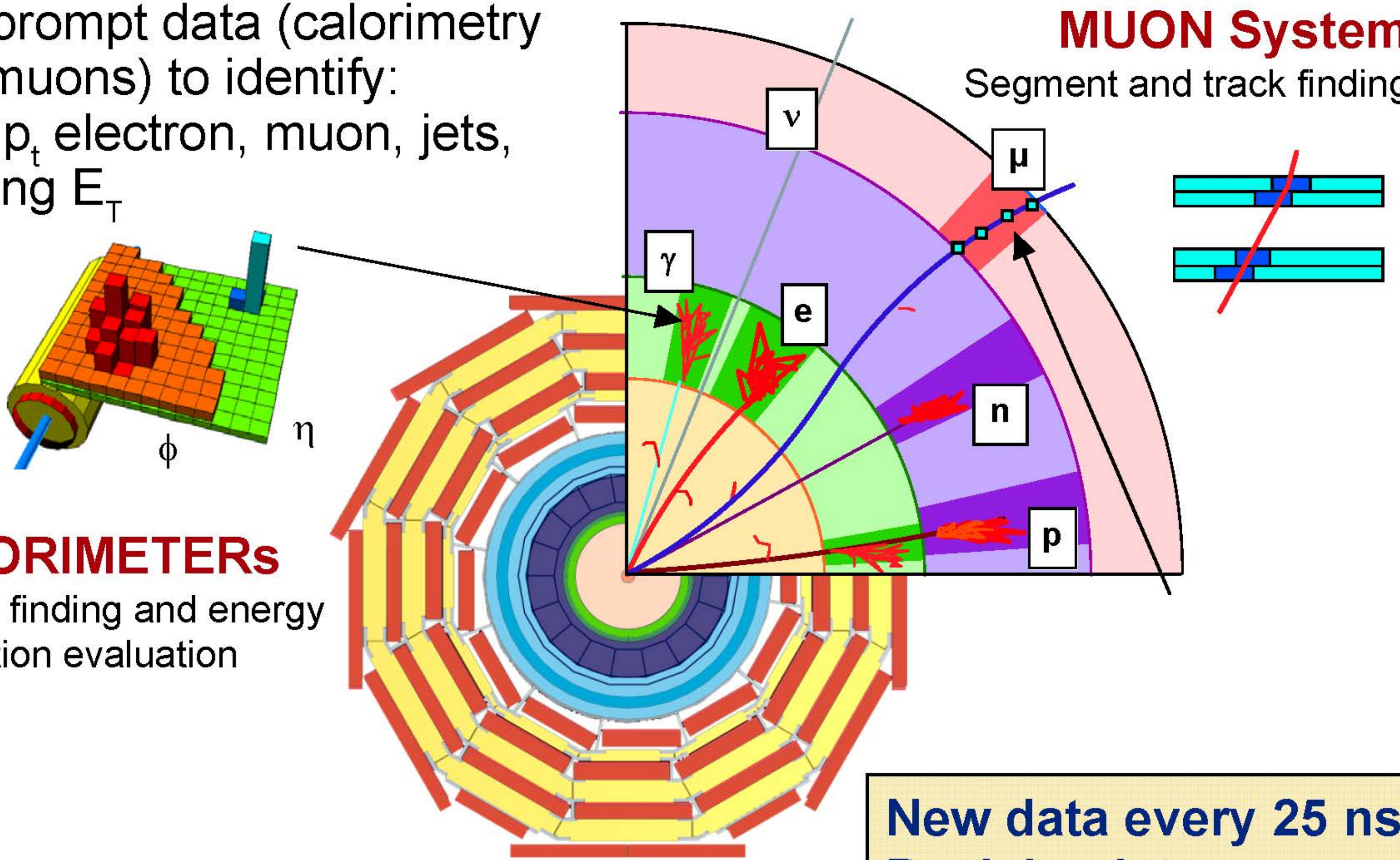
Interaction rate: 1 GHz
Bunch Xing rate: 40 MHz
Level 1 Output: 100 kHz
Storage Output: ~ 400 Hz
Avg Event Size: ~ 0.5 MB
Data production ~ 1 TB/day

Lv1 decision is distributed to front-ends & readout via TTC system (red).

Readout buffers designed to accommodate Poisson fluctuations from 100 kHz Lv1 trigger rate.

Present ATLAS & CMS Level 1 Trigger Data

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



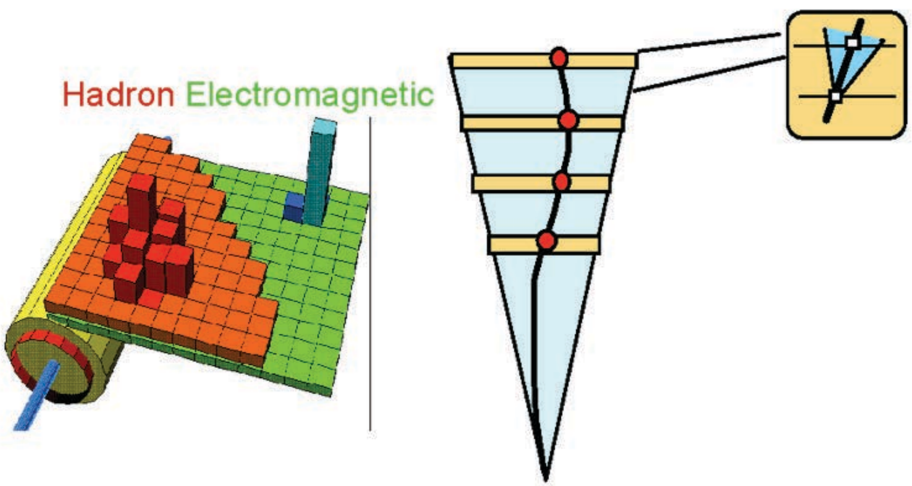
CALORIMETERs
Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ μs

Present ATLAS & CMS L1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

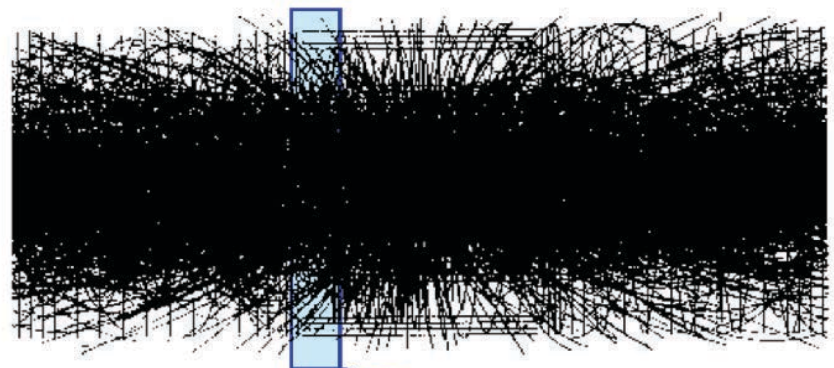
- **Pattern recognition much faster/easier**



Simple Algorithms

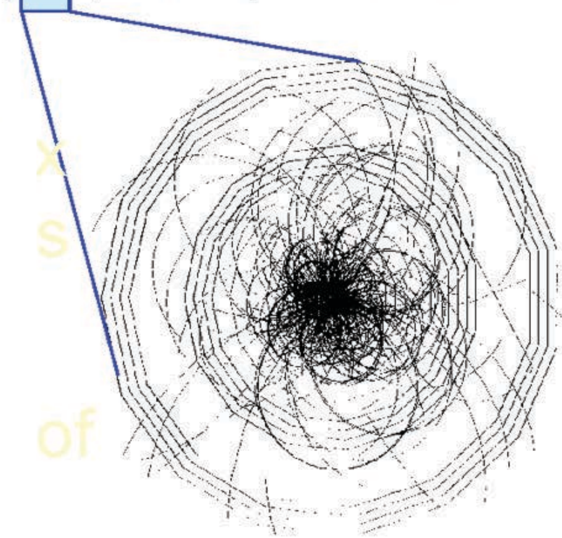
Small amounts of data

- **Compare to tracker info**



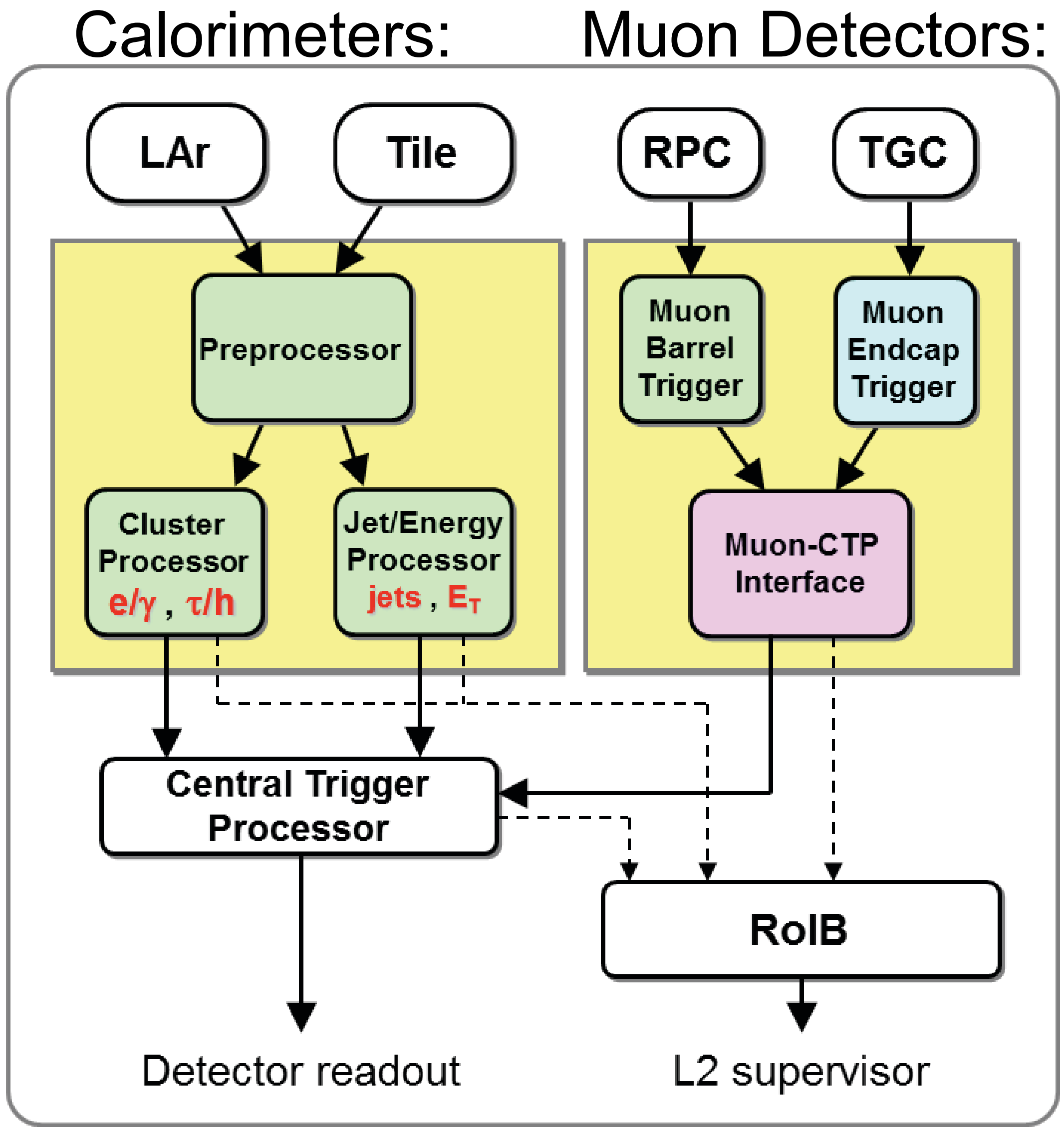
Complex Algorithms

Huge amounts of data



Present ATLAS L1 Trigger

- Process reduced granularity data from calorimeter and muon detectors
- Trigger decision based on object multiplicities
- Generate L1A and send via TTC distribution to detector front-ends to initiate readout
- Maximum round-trip latency 2.5 us
  - Data stores in on-detector pipelines
- Identify regions-of-interest (RoI) to seed L2 trigger
- Custom built electronics
- Synchronous, pipelined processing system operating at the bunch crossing rate



Present CMS L1 Trigger System

HCPSS12

Lv1 trigger is based on calorimeter & muon detectors.

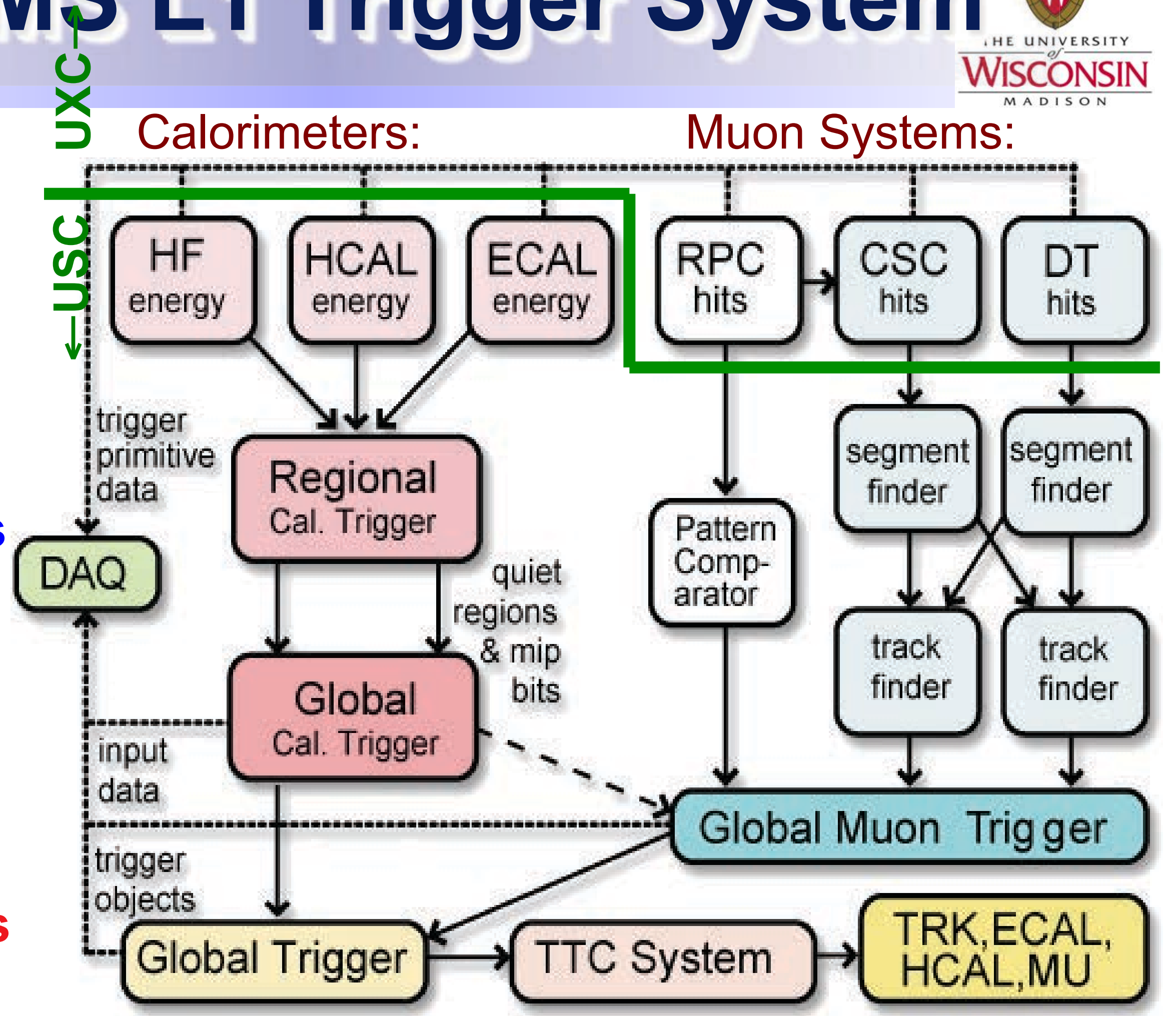
At L1 trigger on:

- 4 highest E_t $e^{\pm}/\gamma$
- 4 highest E_t central jets
- 4 highest E_t forward jets
- 4 highest E_t tau-jets
- 4 highest P_t muons

For each of these objects rapidity, η, and φ are also transmitted to Global Trigger for topological cuts & so Higher Level Triggers can seed on them.

Also trigger on inclusive triggers:

- E_t , MET, H_t

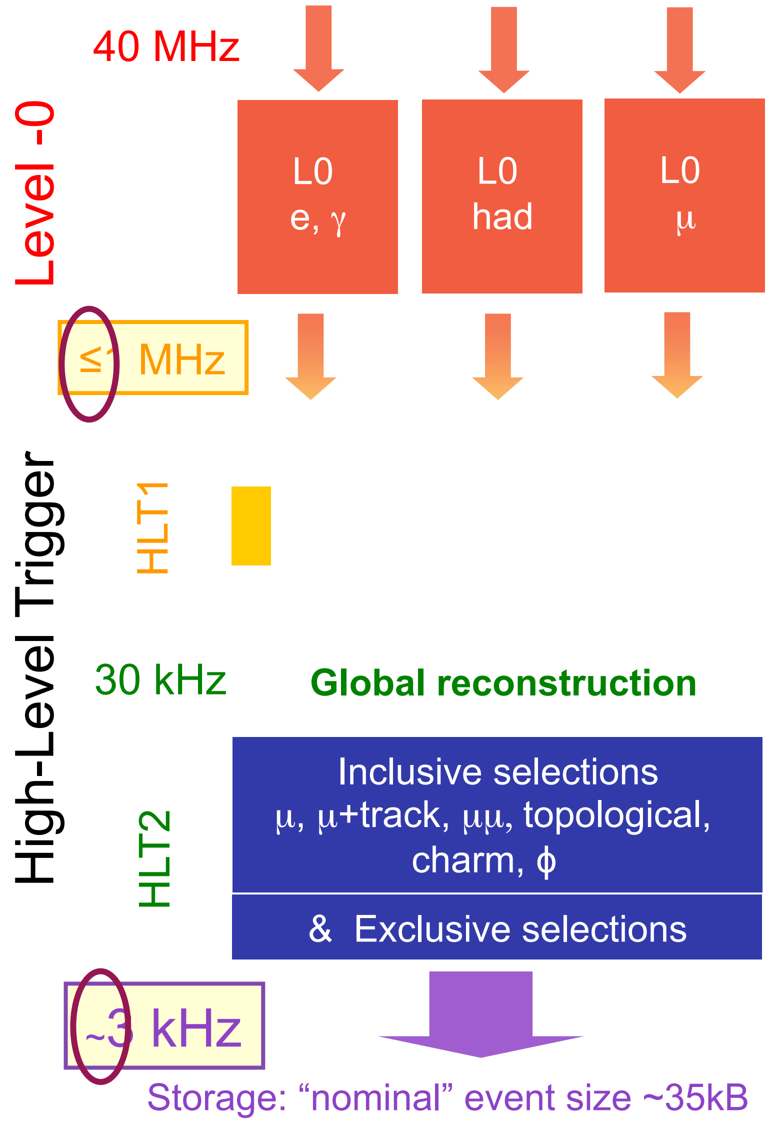


Generate L1A and send via TTC distribution to detector front-ends to initiate readout

Maximum round-trip latency 4 μs

Data stored in on-detector pipelines

Present LHCb Trigger & DAQ



Level 0: Hardware

Both Software Levels run on commercial PCs

Level-1:

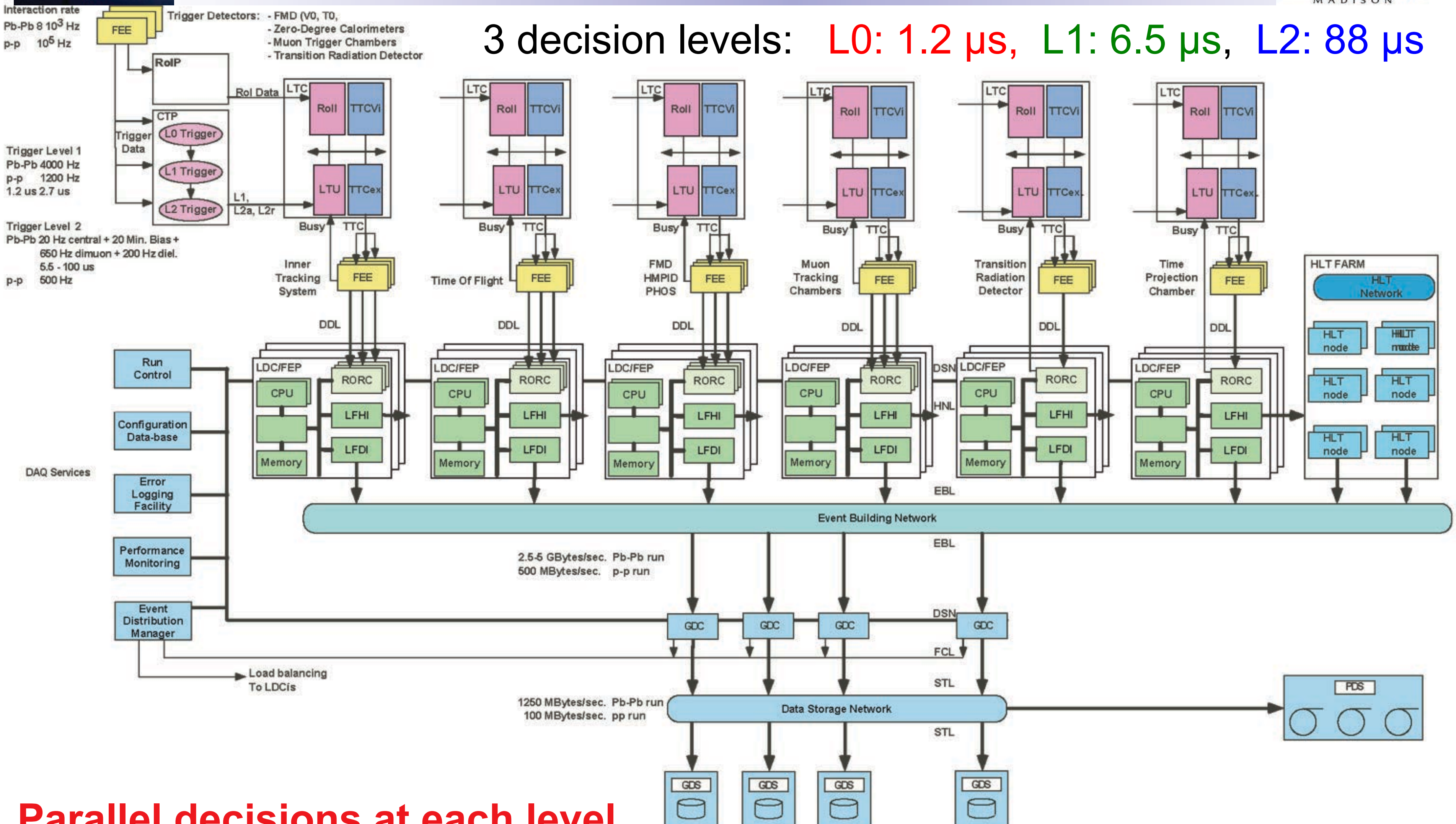
- **Input: 4.8 kB @ 1.1 MHz**
- **uses reduced data set: only part of the sub-detectors (mostly Vertex-detector and some tracking) with limited-precision data**
- **reduces event rate by selecting events with displaced secondary vertices**

High Level Trigger (HLT)

- **Input: 38 kB @ 30 kHz**
- **uses all detector information**
- **Output 3 kHz for permanent storage**

Present Alice Trigger & DAQ

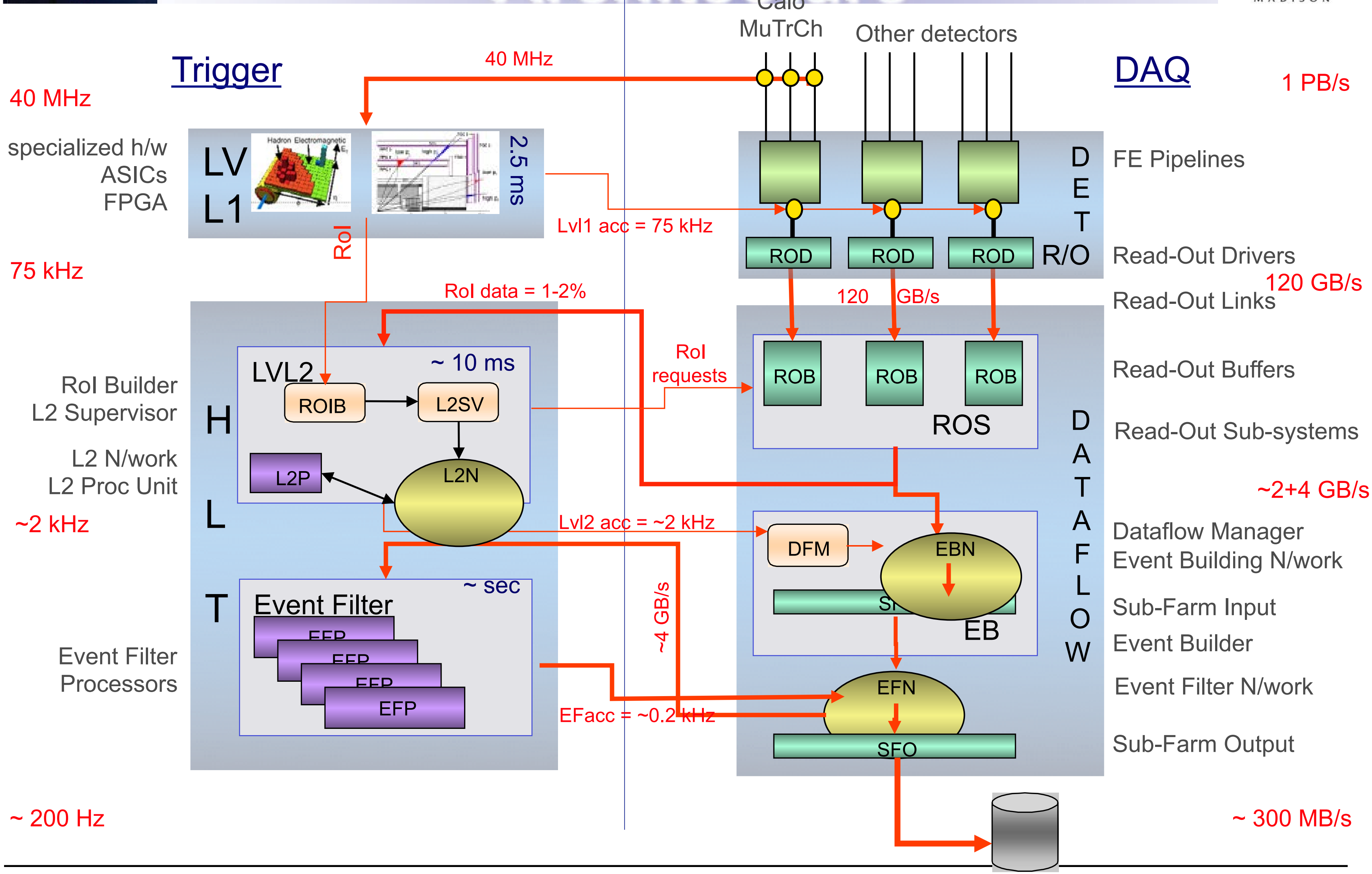
3 decision levels: L0: 1.2 μs, L1: 6.5 μs, L2: 88 μs



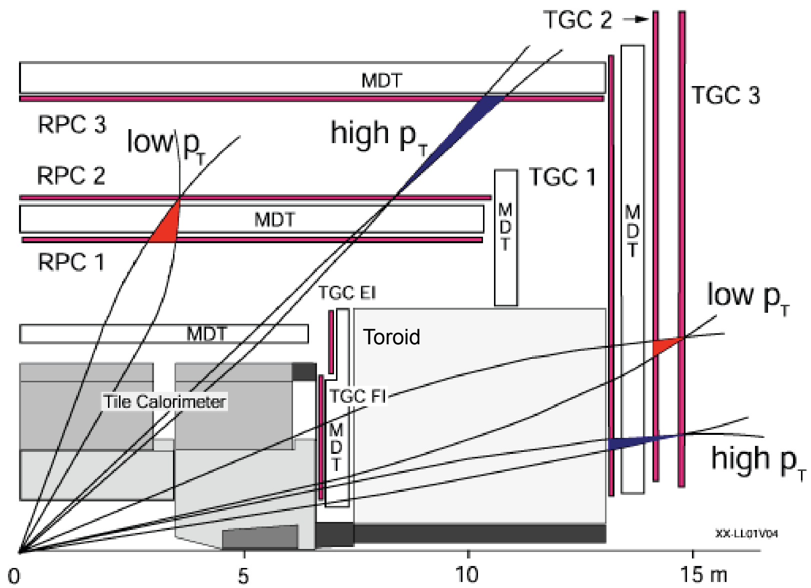
Parallel decisions at each level

- different groups of detectors (clusters) are reading out different events at same time

ATLAS Trigger & DAQ Architecture

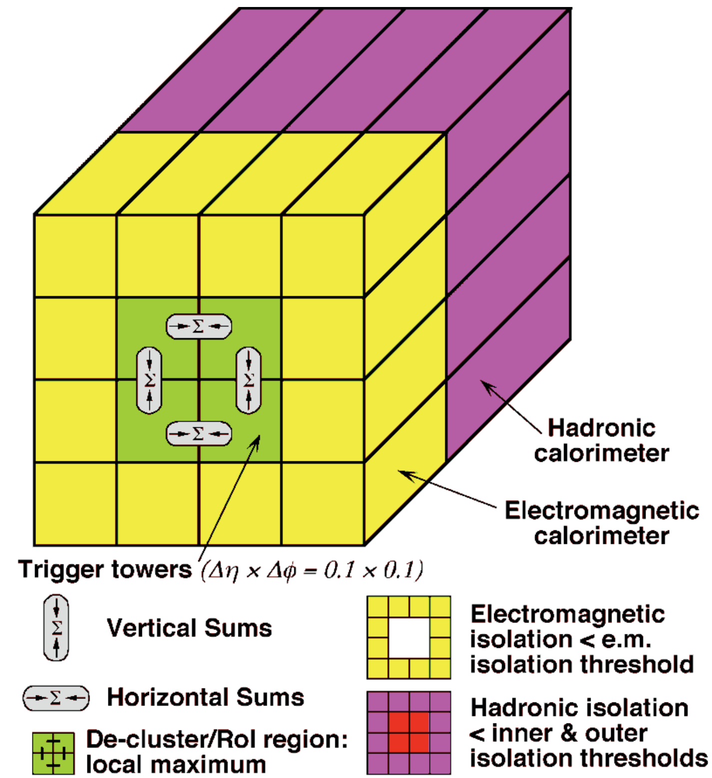


ATLAS Level-1 Trigger - Muons & Calorimetry



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)

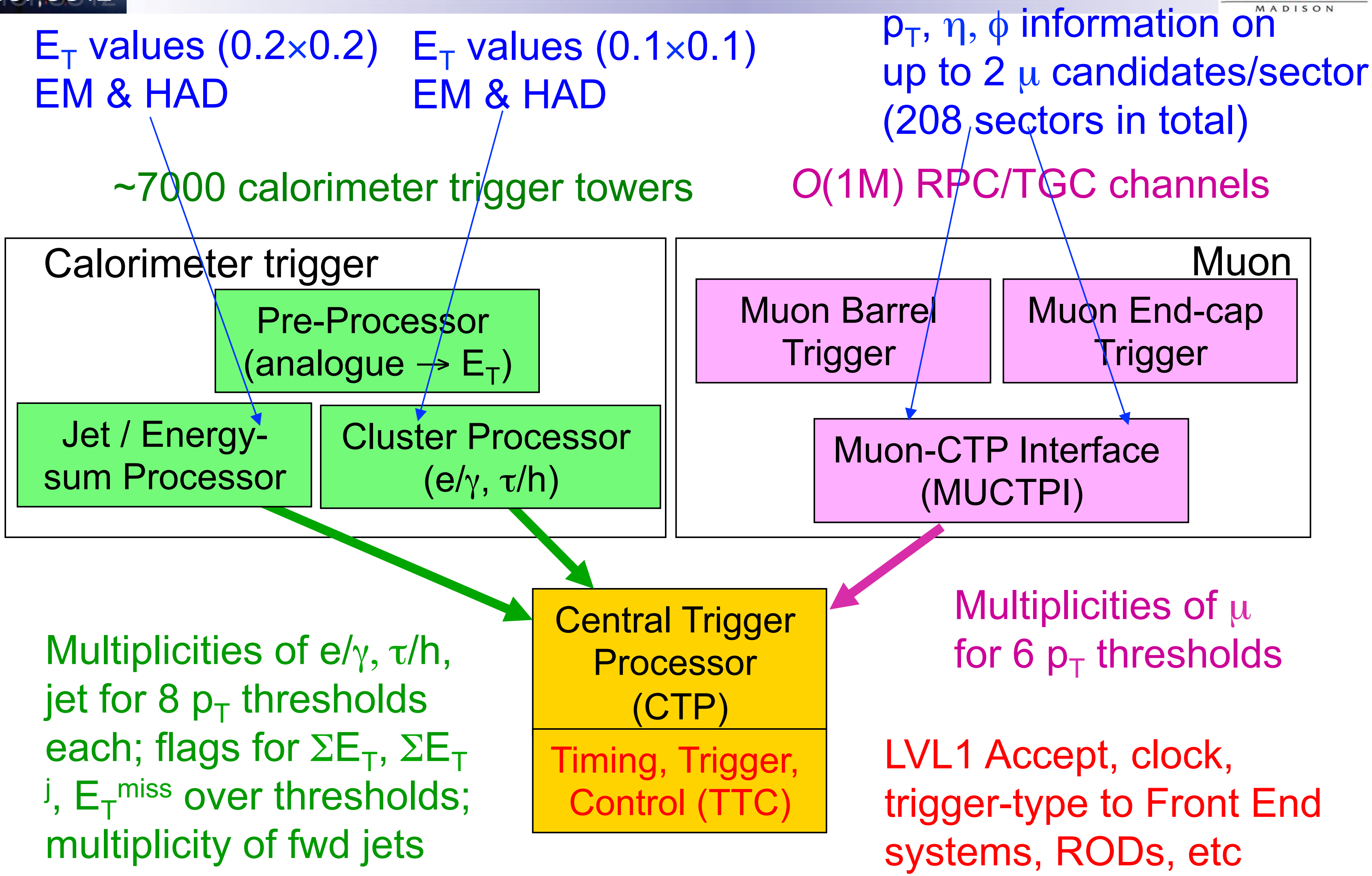
Trigger efficiency 99% (low-p_T) and 98% (high-p_T)



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

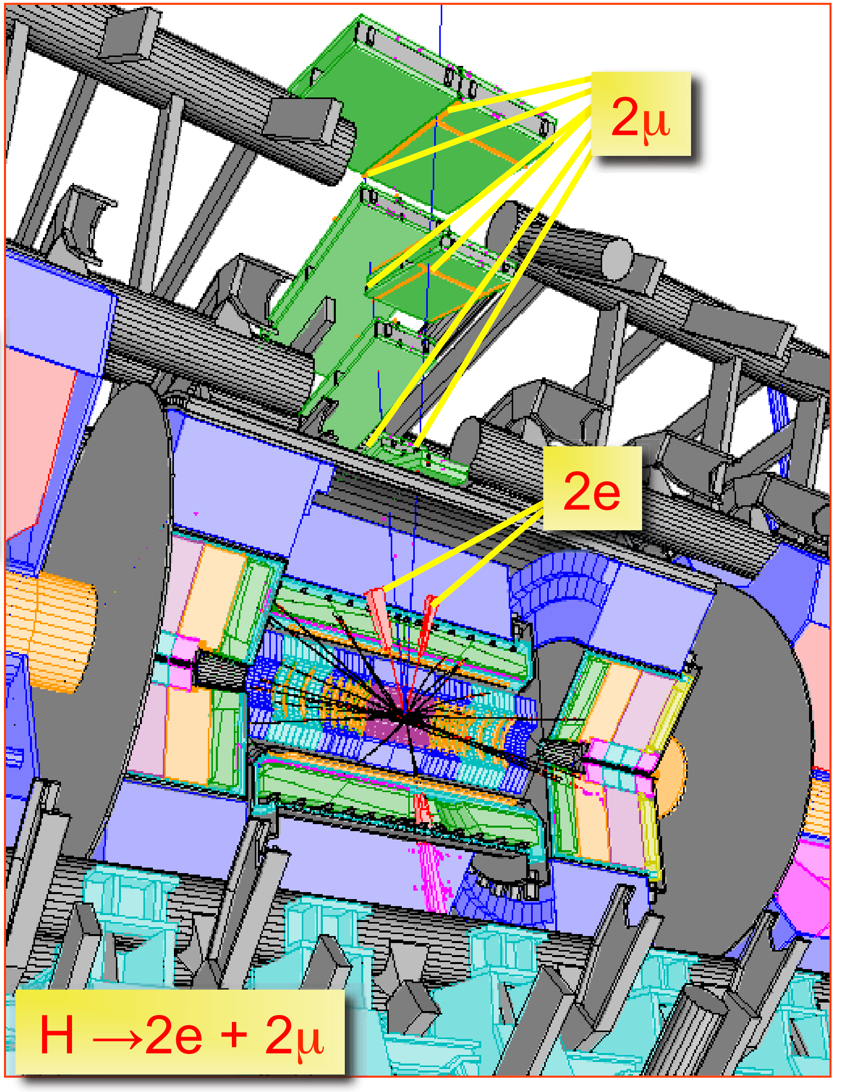


RoI Mechanism

LVL1 triggers on high p_T objects
- **Calorimeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

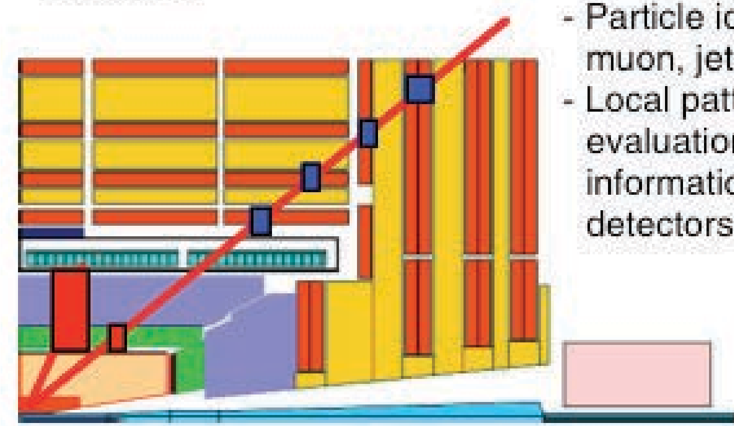
LVL2 uses Regions of Interest as identified by Level-1
- Local data reconstruction, analysis, and sub-detector matching of RoI data

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



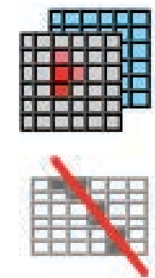
CMS Trigger Levels

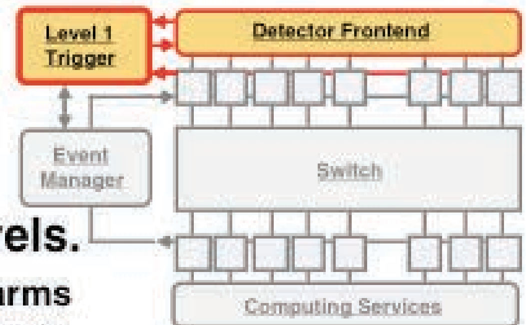
40 MHz



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



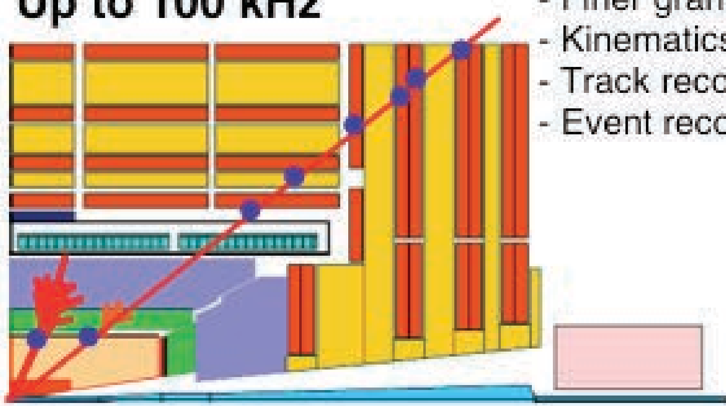


Up to 100 kHz

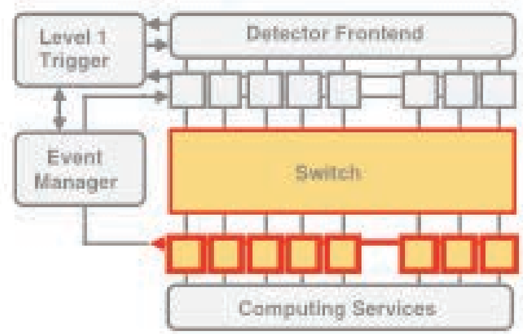
High trigger levels.

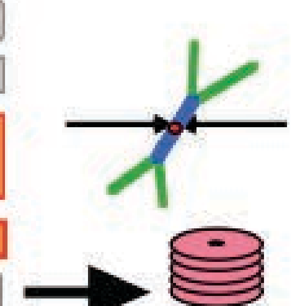
Network and CPU farms

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



≈ 400 Hz



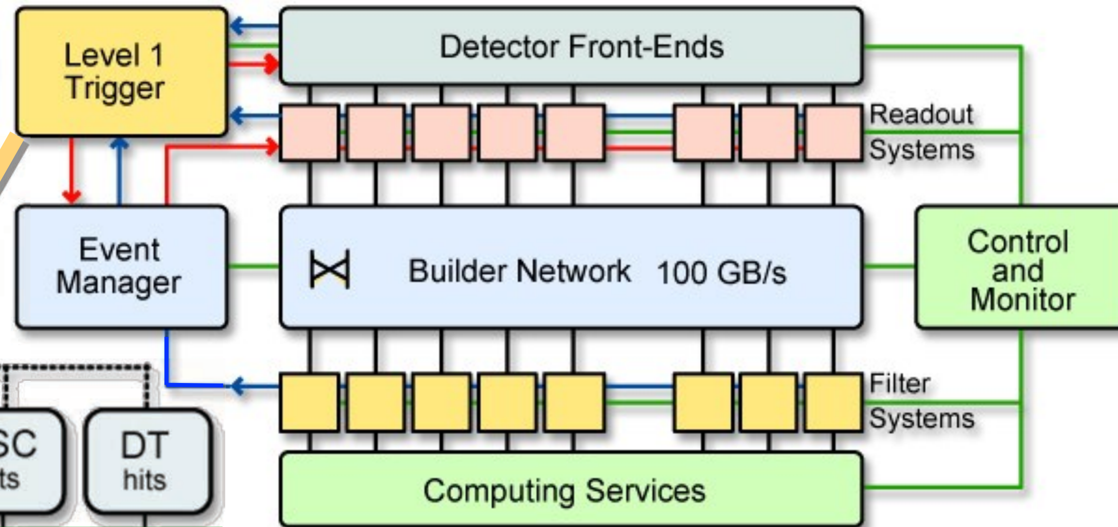


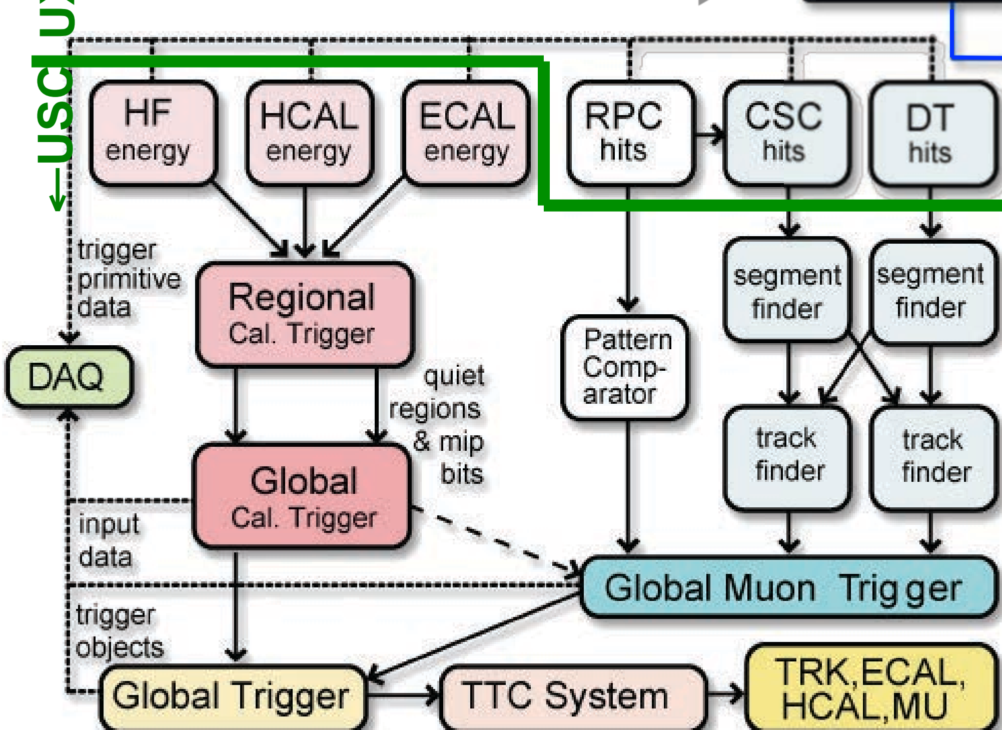
CMS Level-1 Trigger & DAQ

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

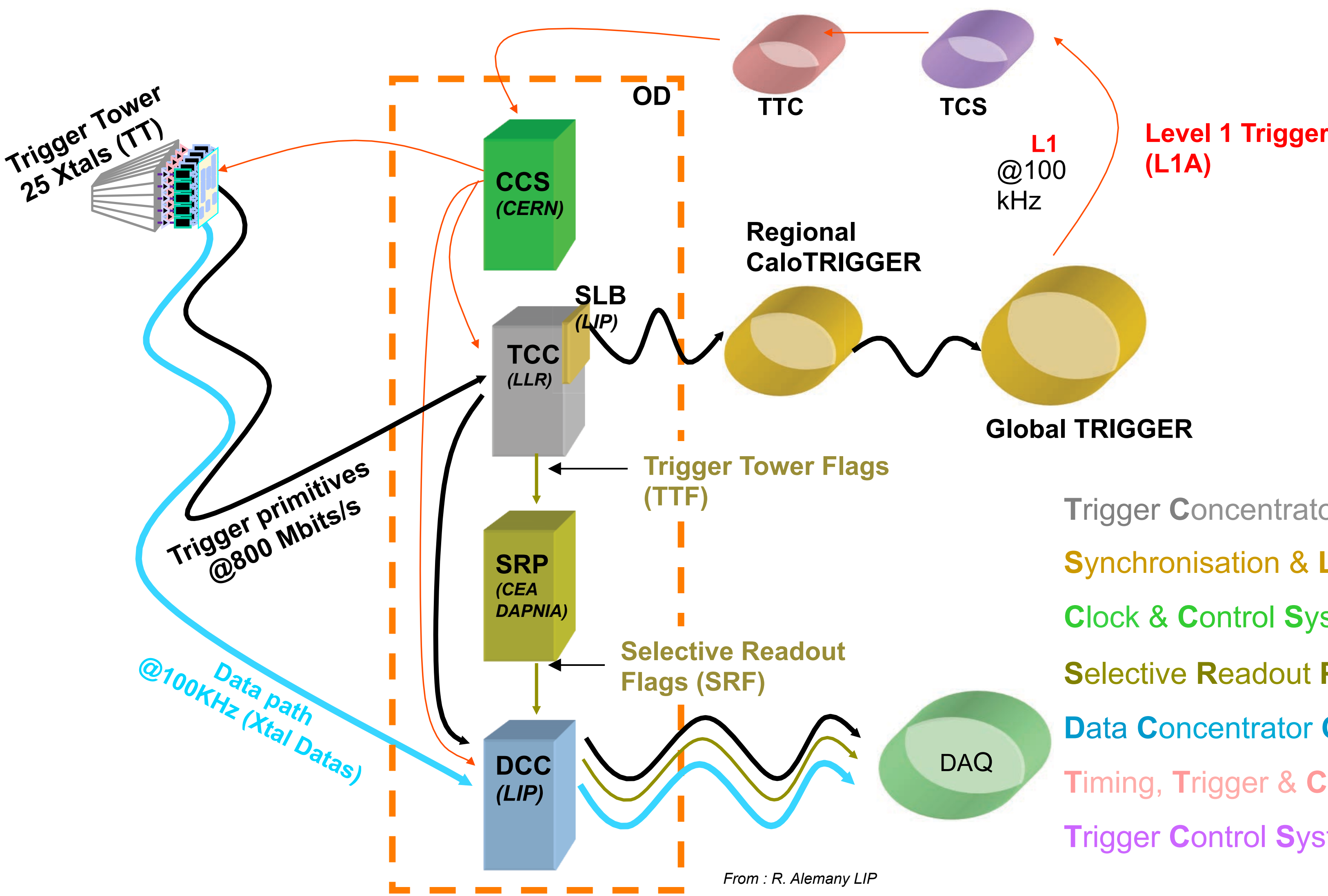
Level 1 Output: 100 kHz

Output to Storage: 400 Hz

Average Event Size: 1 MB

Data production 1 TB/day

Calorimeter Trigger Processing



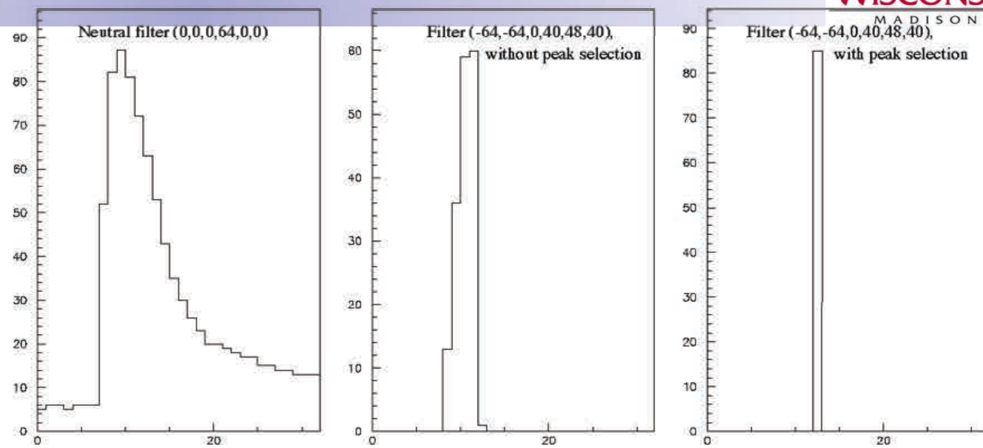
Trigger Concentrator Card
Synchronisation & Link Board
Clock & Control System
Selective Readout Processor
Data Concentrator Card
Timing, Trigger & Control
Trigger Control System

ECAL Trigger Primitives

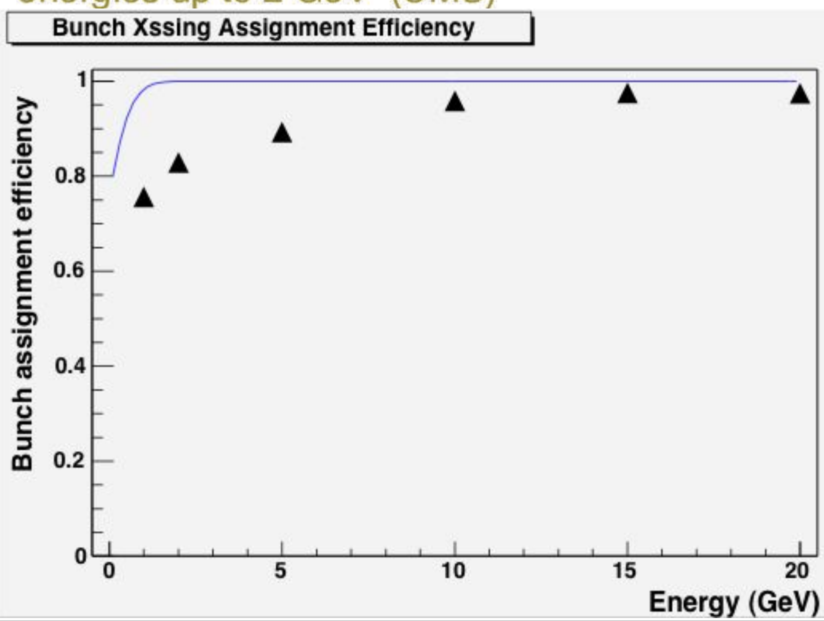
In the trigger path, **digital filtering** followed by a **peak finder** is applied to energy sums **(L1 Filter)**

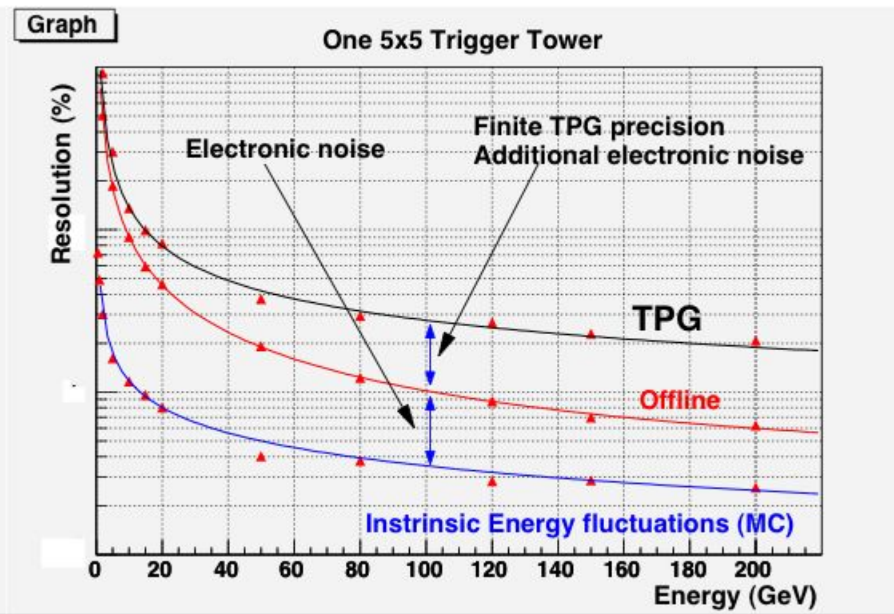
Efficiency for energy sums above 1 GeV should be close to 100% (depends on electronics noise)

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

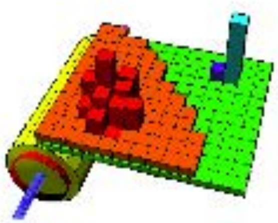
Longitudinal cut (H/E) — / < 0.05

AND

Isolation, Hadronic & EM — < 2 GeV

AND

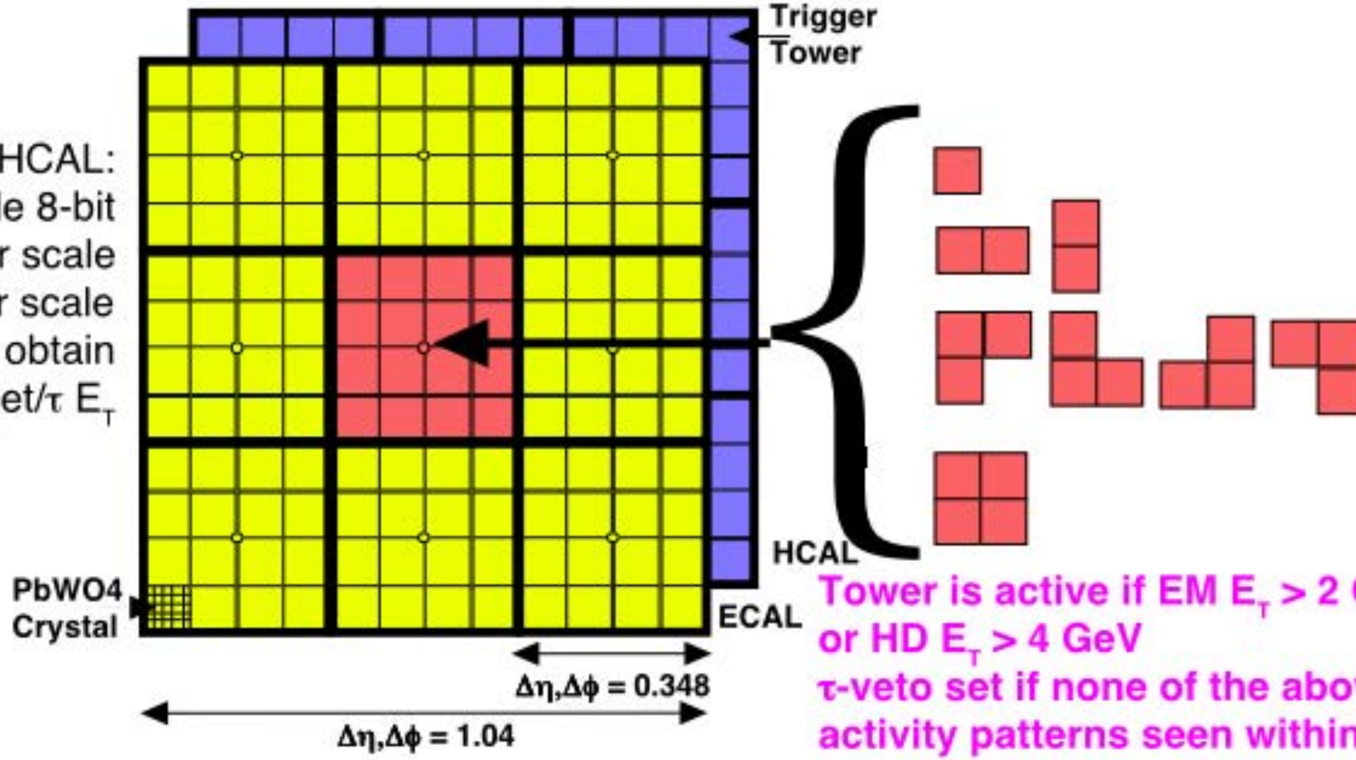
One of (, , ,) < 1 GeV



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

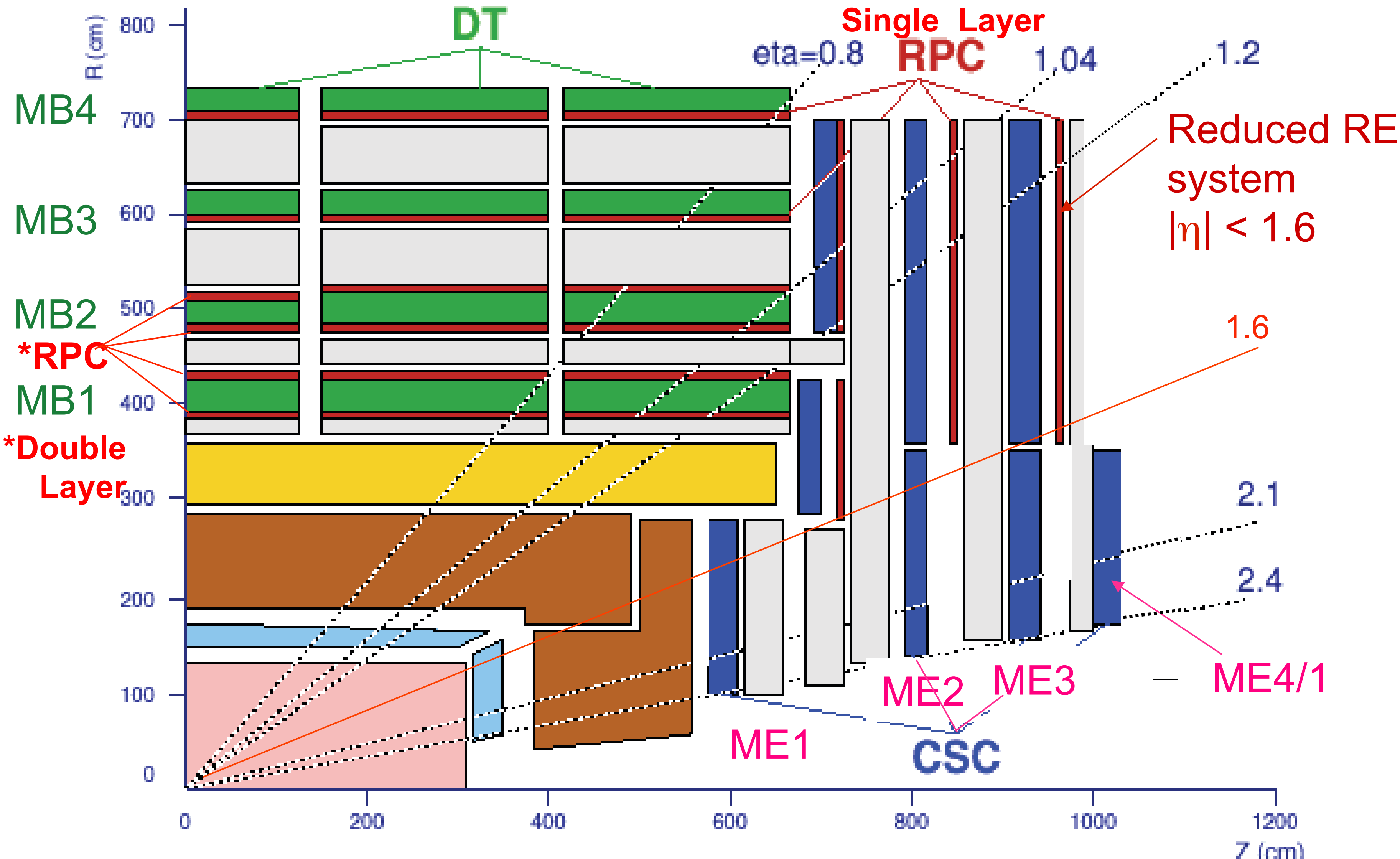
τ algorithm (isolated narrow energy deposits), within -2.5 < η < 2.5

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

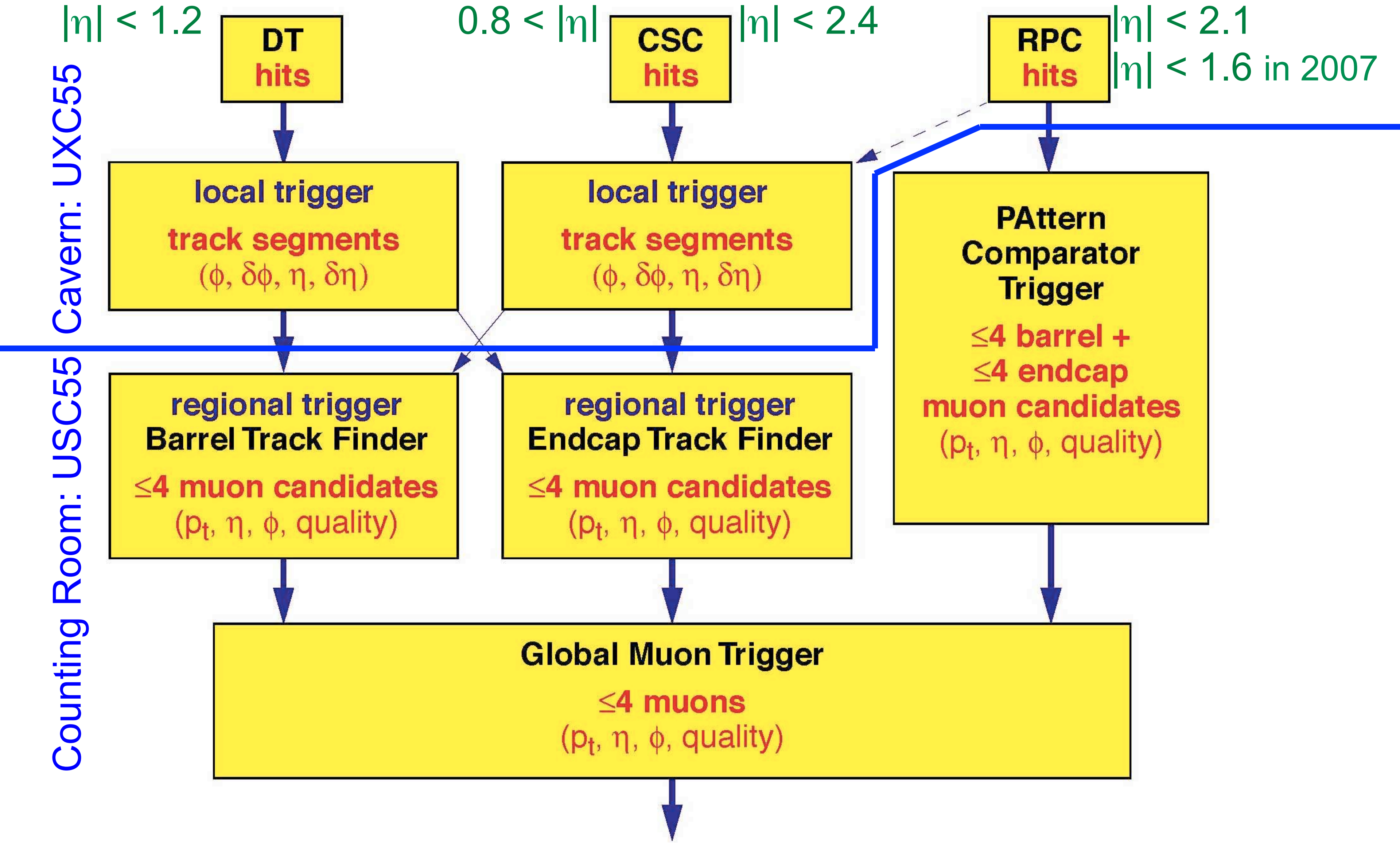
Output

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

CMS Muon Chambers

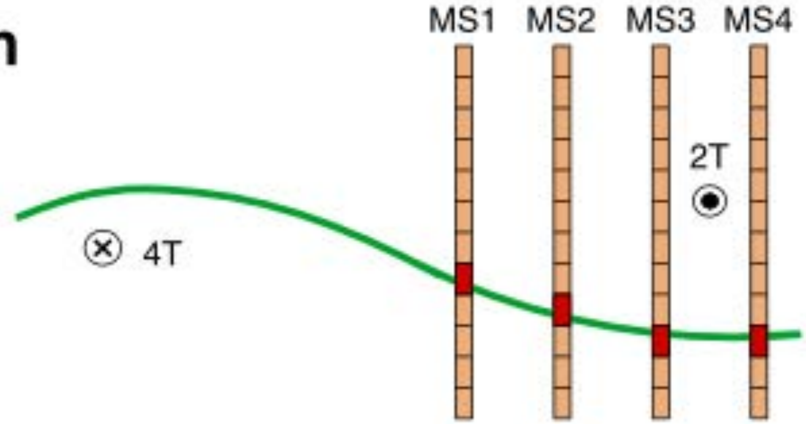


Muon Trigger Overview



CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

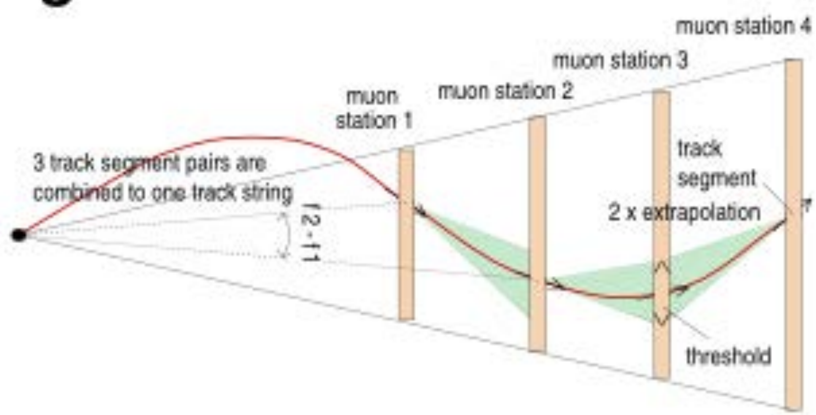


Memory to store patterns

Fast logic for matching

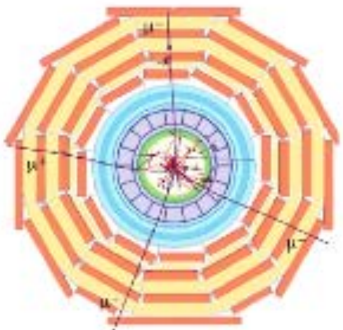
FPGAs are ideal

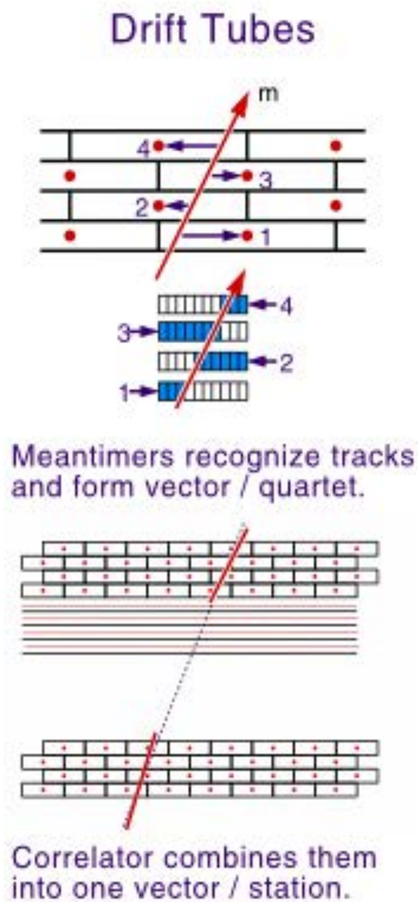
DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



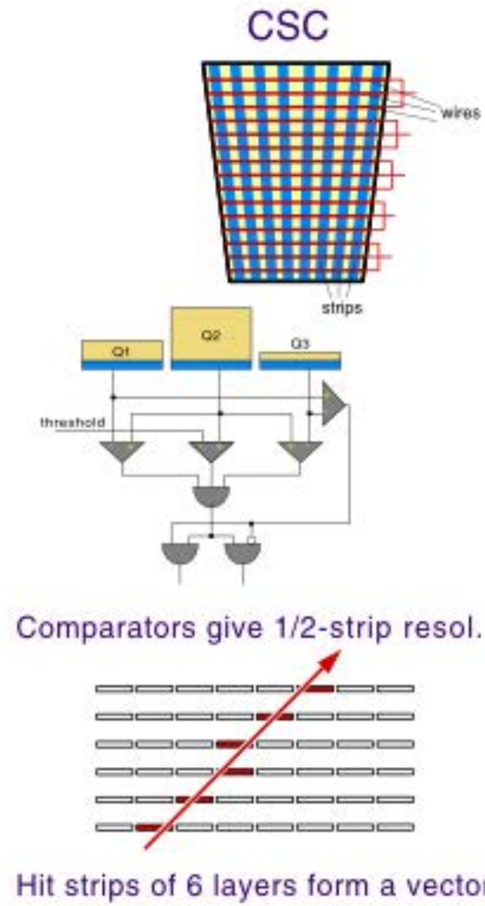
CMS Muon Trigger Track Finders

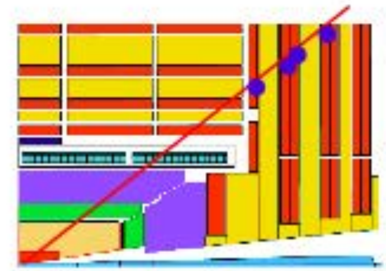
Drift Tubes (DT)





Cathod Strip Chambers (CSC)





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

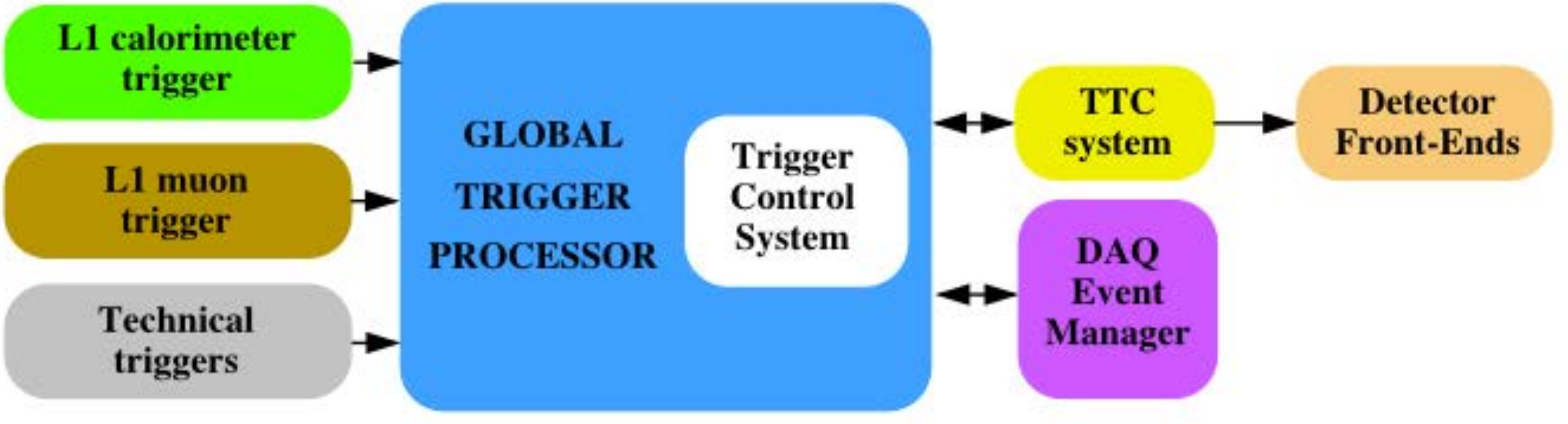
CMS Global Trigger

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

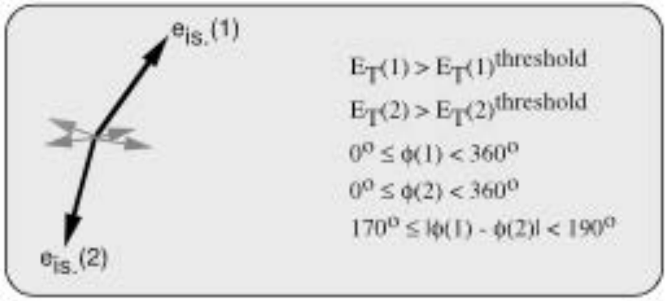
Output

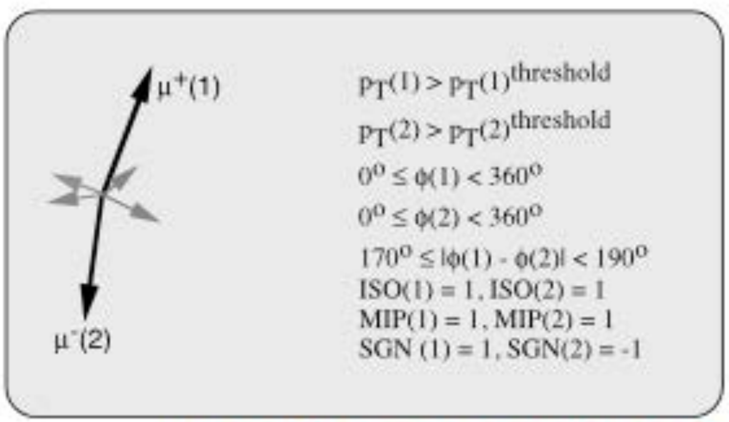
- L1 Accept from combinations & proximity of above



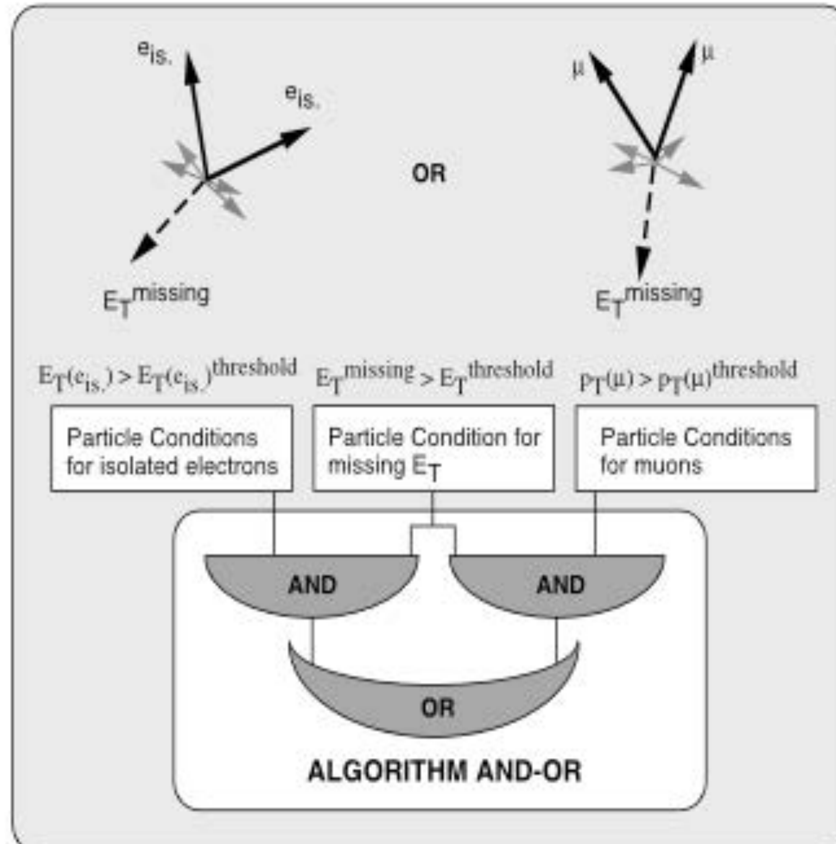
Global L1 Trigger Algorithms

Particle Conditions



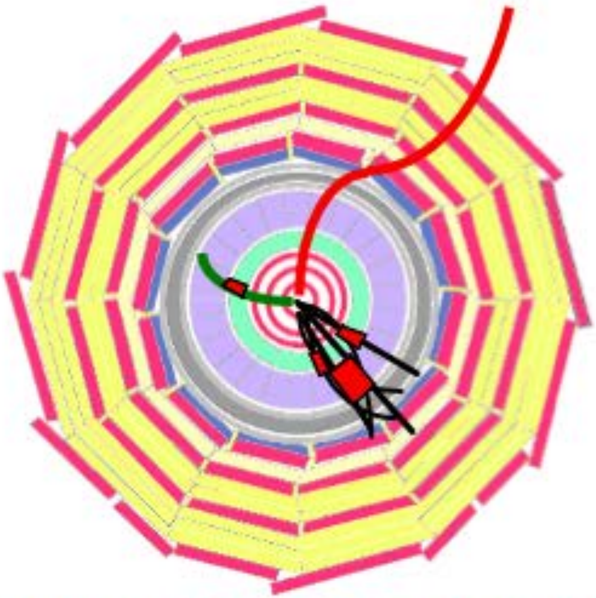


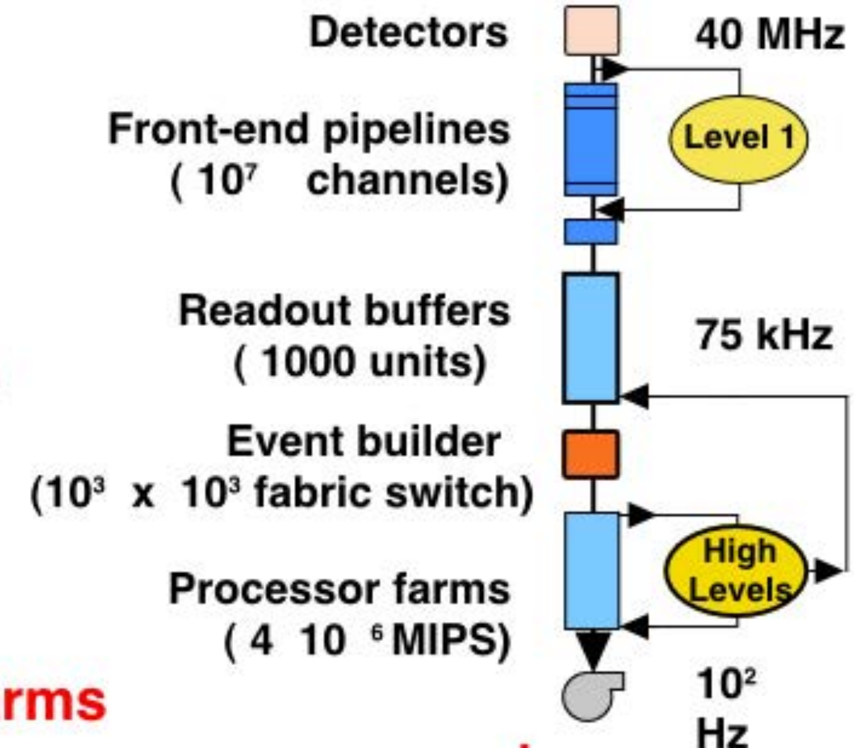
Logical Combinations



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

High Level Trigger Strategy





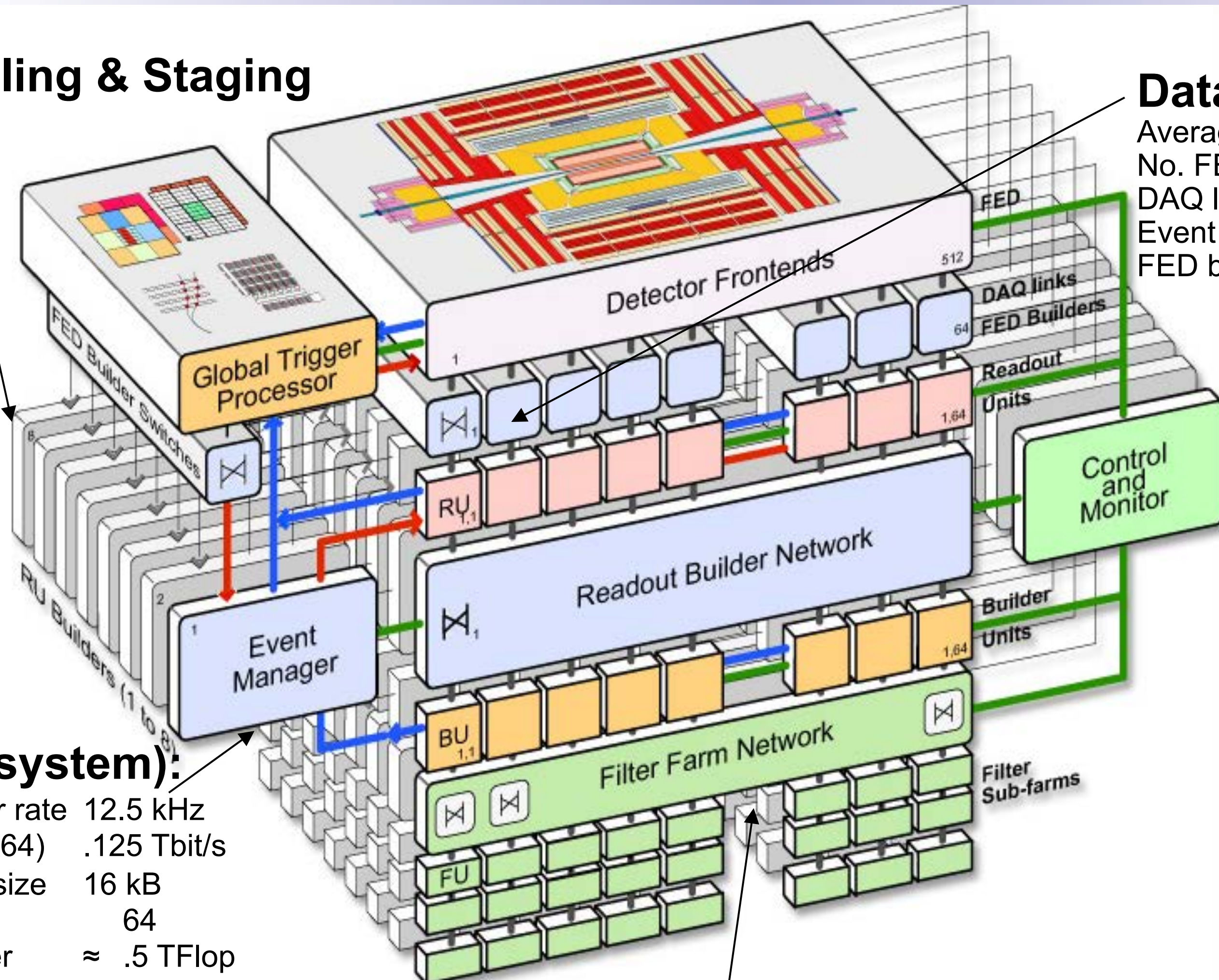
High level triggers. CPU farms

- 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

CMS DAQ & HLT

DAQ Scaling & Staging



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 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

HLT: 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

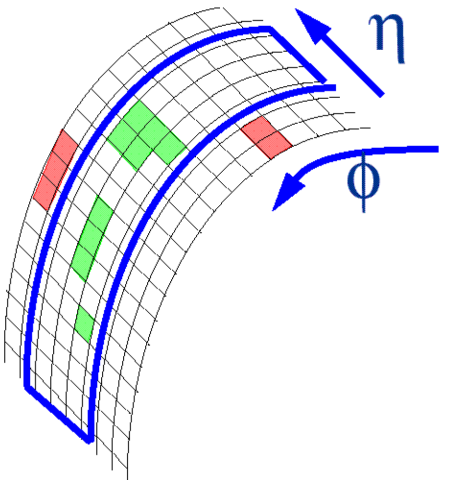
Electron selection: Level-2

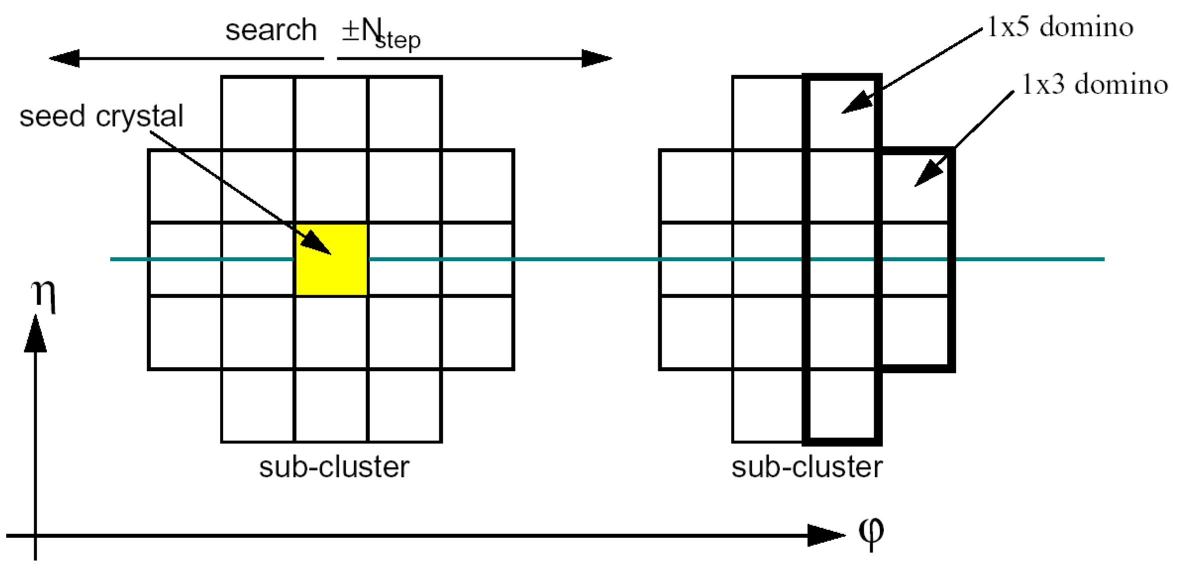
"Level-2" electron:

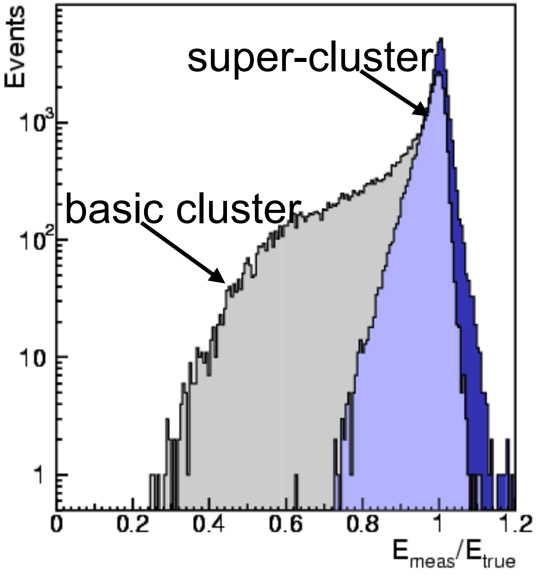
- **Search for match to Level-1 trigger**
  - Use 1-tower margin around 4x4-tower trigger region
- **Bremsstrahlung recovery "super-clustering"**
- **Select highest E_T cluster**

Bremsstrahlung recovery:

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

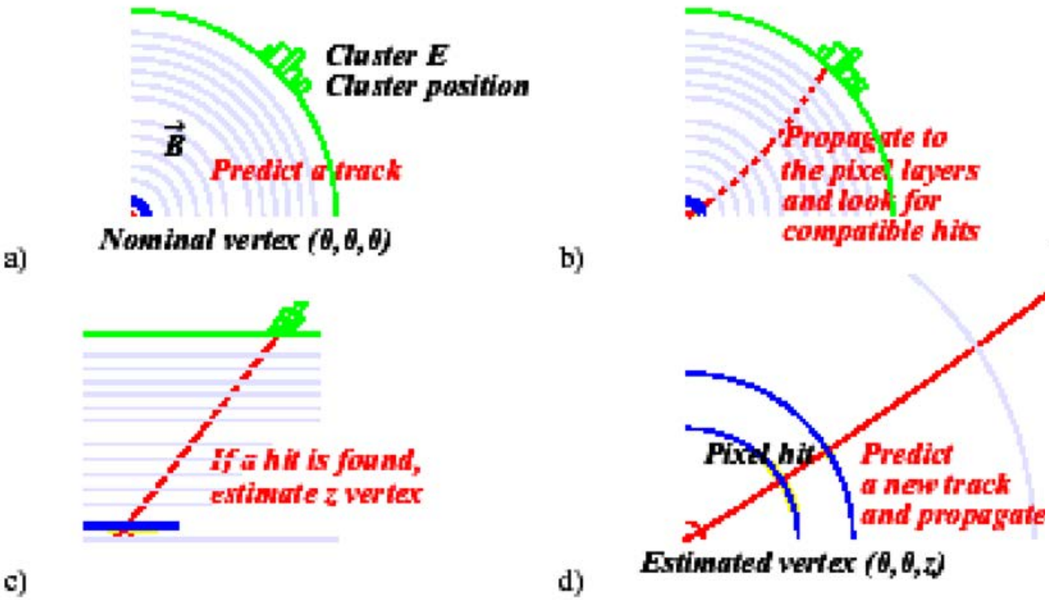


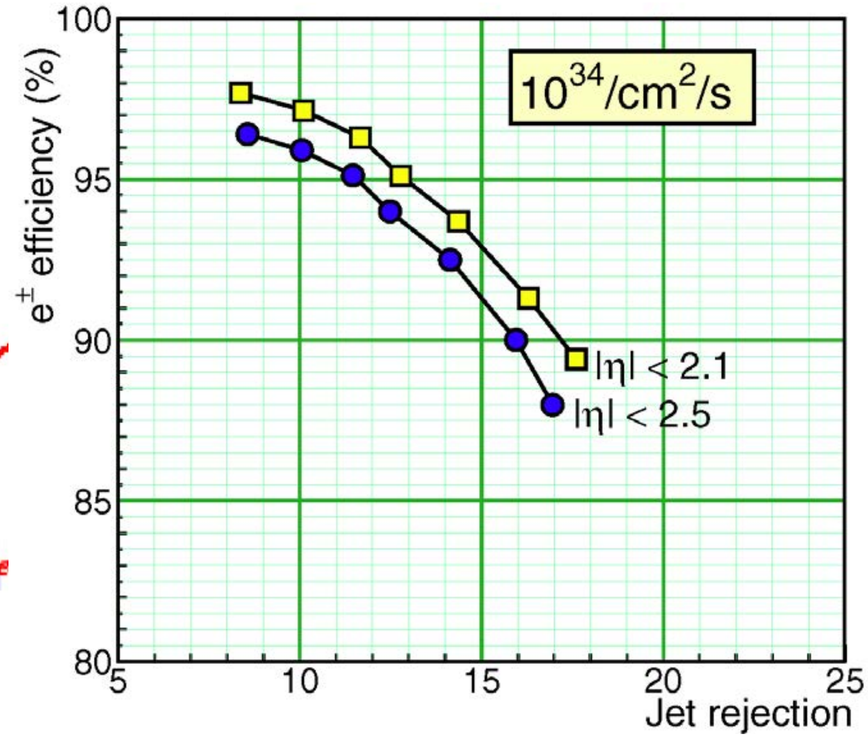




CMS tracking for electron trigger

Present CMS electron HLT

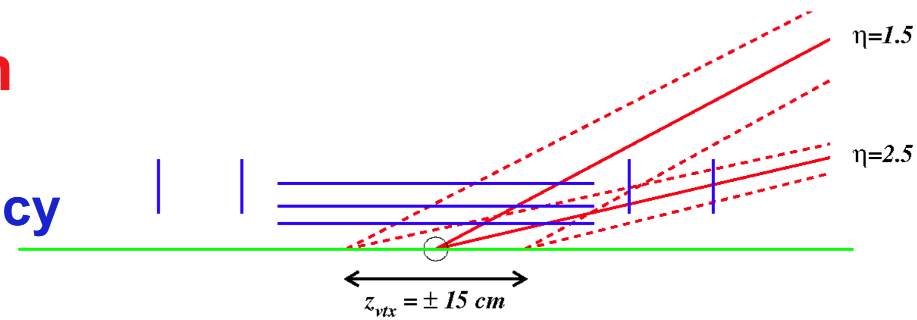




Factor of 10 rate reduction

γ: only tracker handle: isolation

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

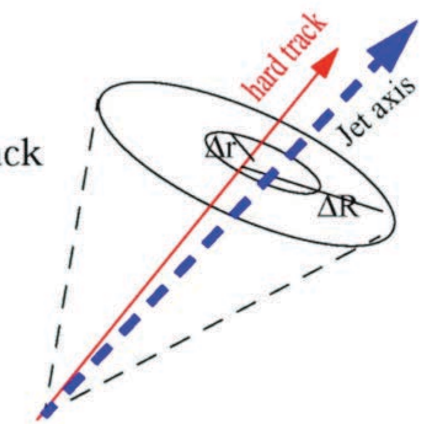


τ-jet tagging at HLT

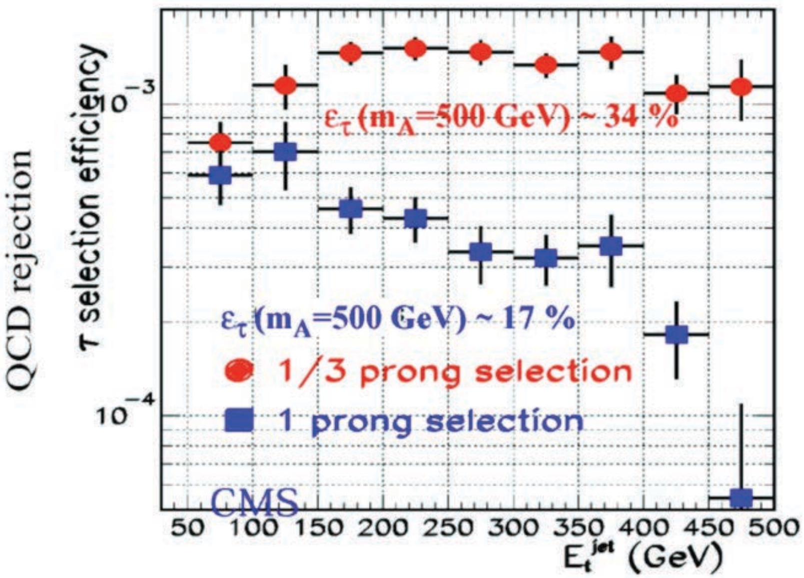
THE UNIVERSITY of WISCONSIN MADISON

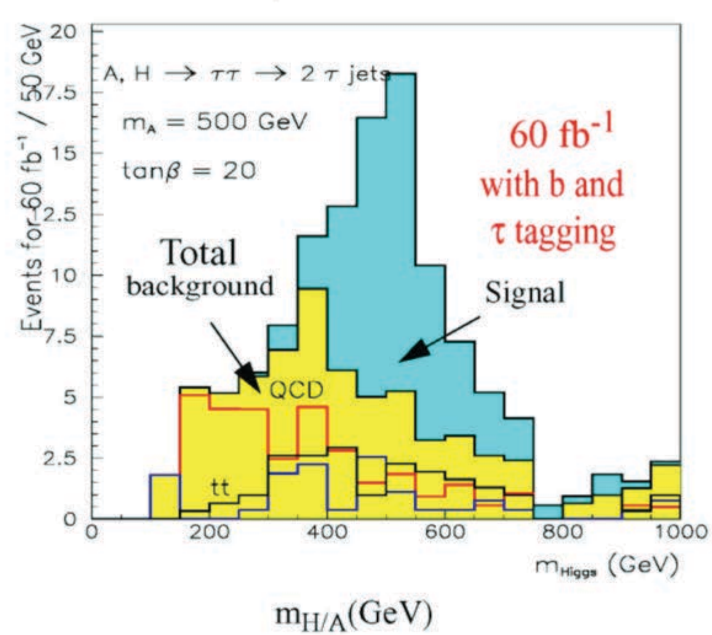
τ-jet ($E_t^{\tau\text{-jet}} > 60$ GeV) identification (mainly) in the tracker:

- 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:

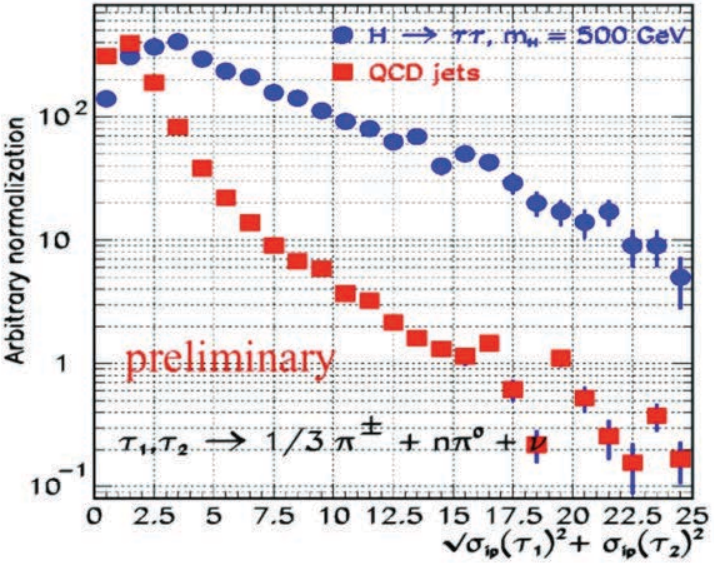
Efficiency to tag one b-jet ~ 35% for ~1% mistagging rate (CMS)

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: $\sqrt{\sigma_{ip}(\tau_1)^2 + \sigma_{ip}(\tau_2)^2}$

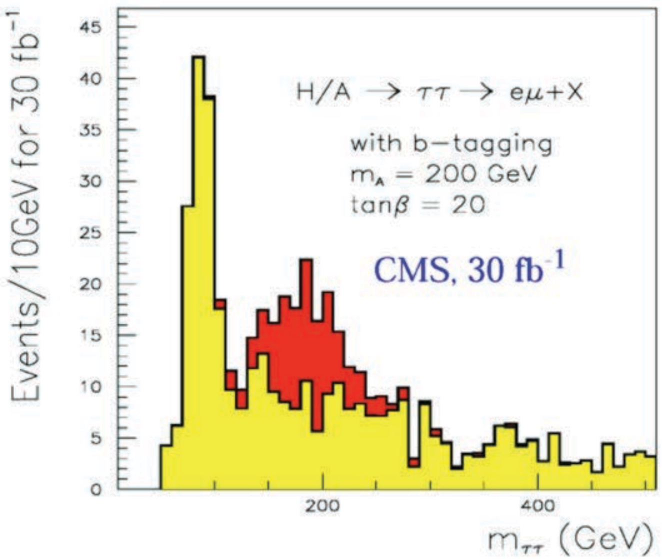
CMS full simulation for

H -> ττ –> 2 τ–jets and QCD events



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

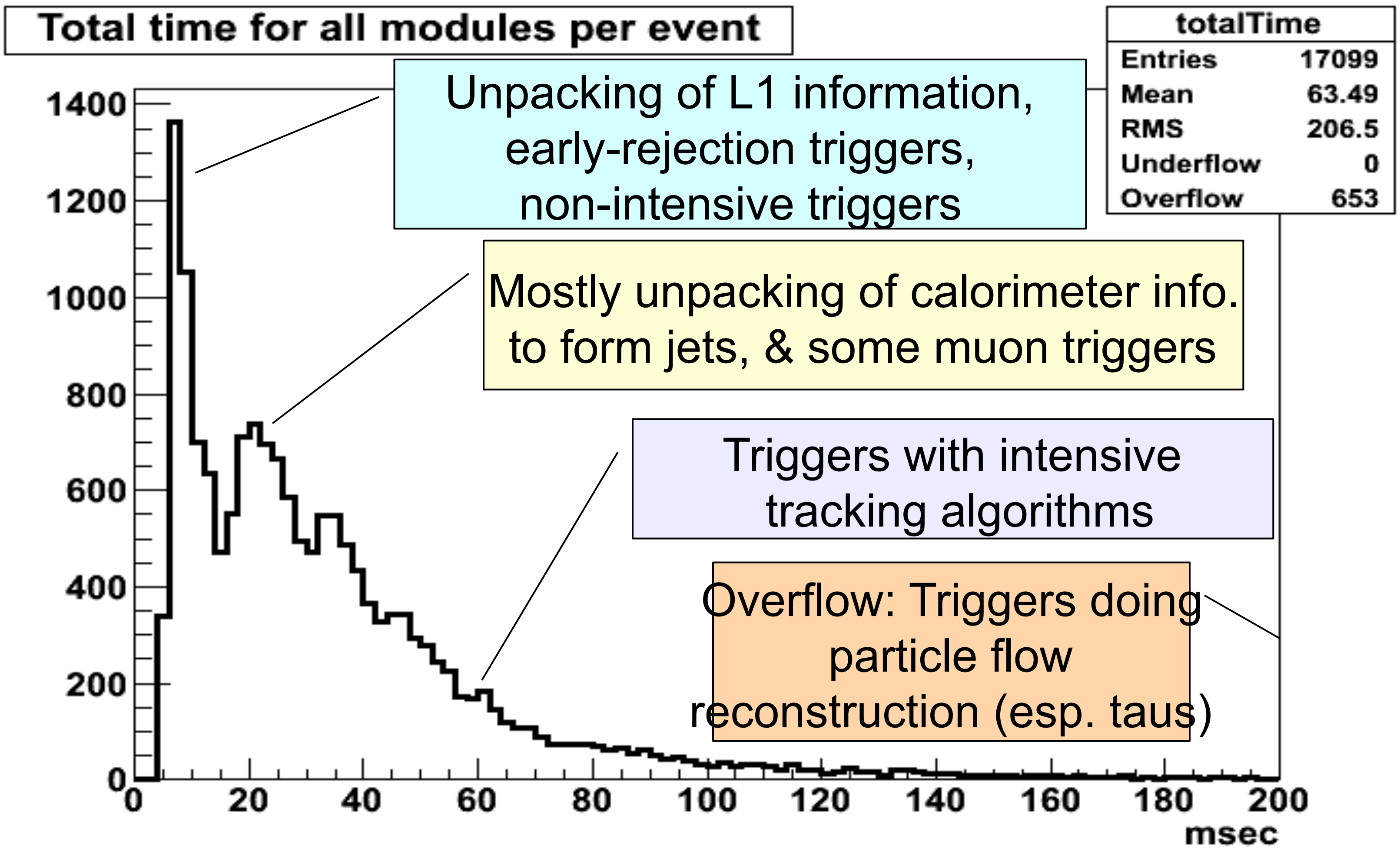
Signal superimposed on the total background for m_A = 200 GeV, tanβ =20



CMS HLT Time Distribution (example from early 2011)

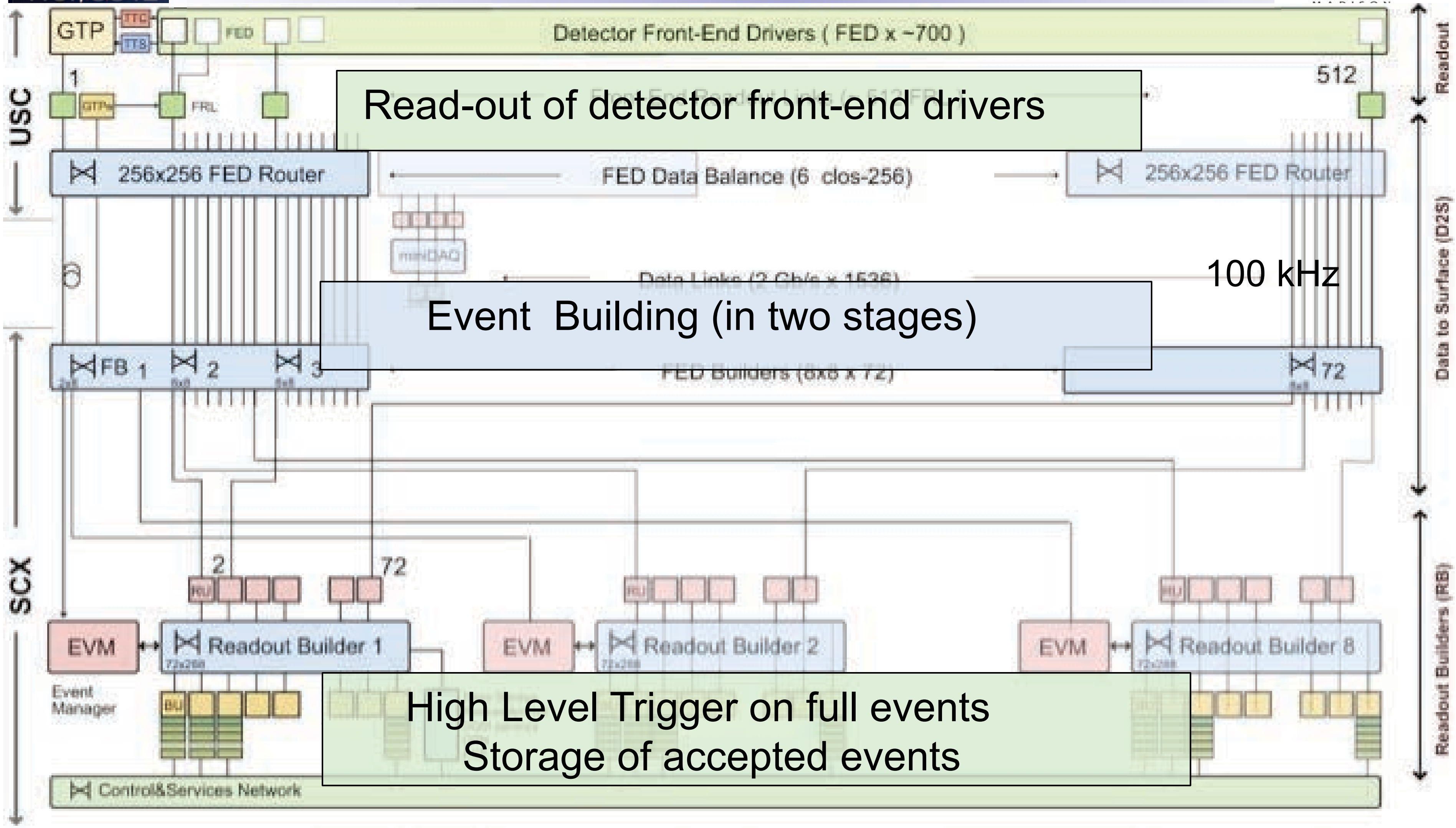
Prescale set used: 2E32 Hz/cm²

Sample: MinBias L1-skim 5E32 Hz/cm² with 10 Pile-up



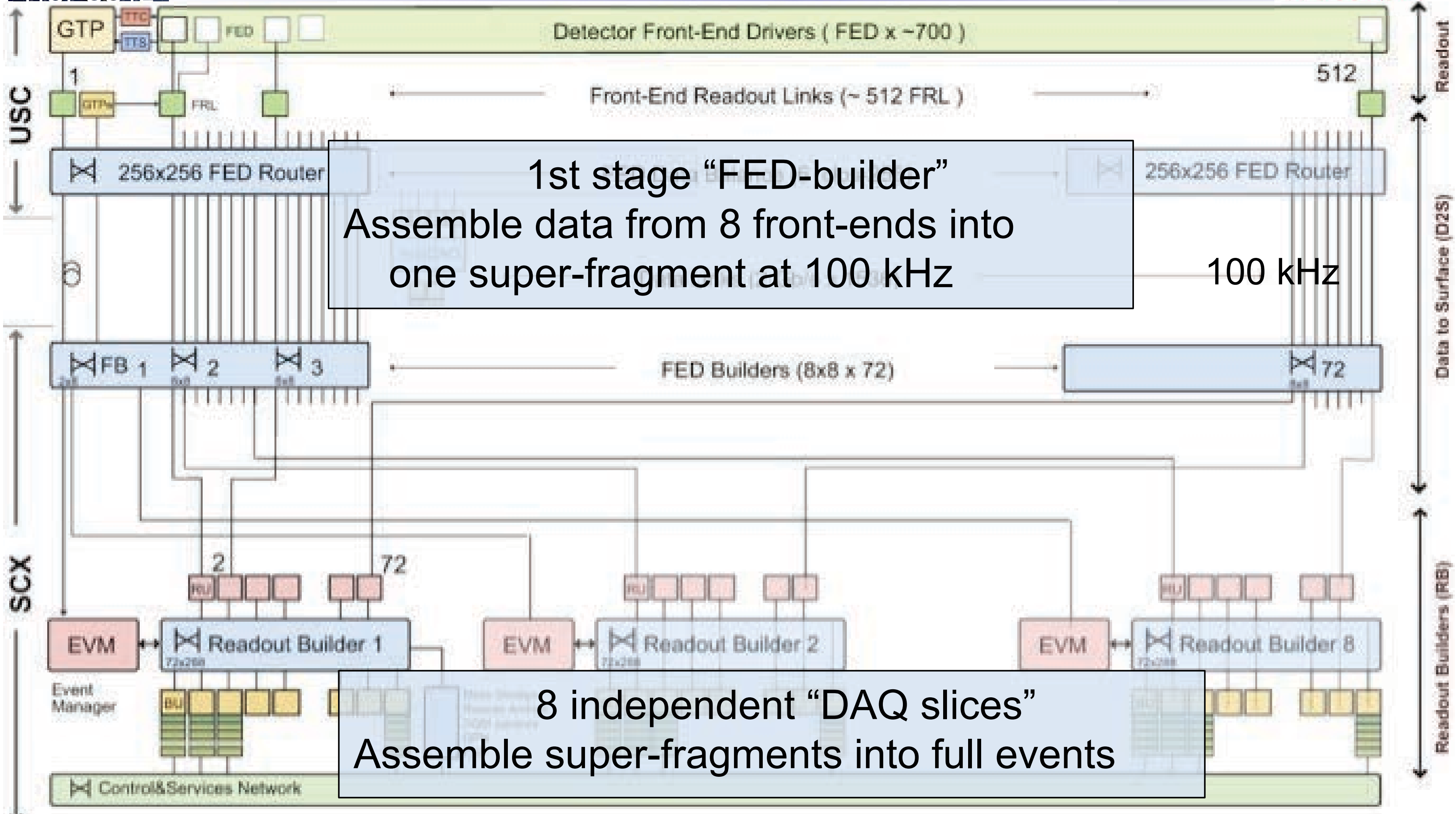
HCPSS12

CMS DAQ



12.5 kHz 12.5 kHz … 12.5 kHz

2-Stage Event Builder



1st stage “FED-builder”
Assemble data from 8 front-ends into one super-fragment at 100 kHz

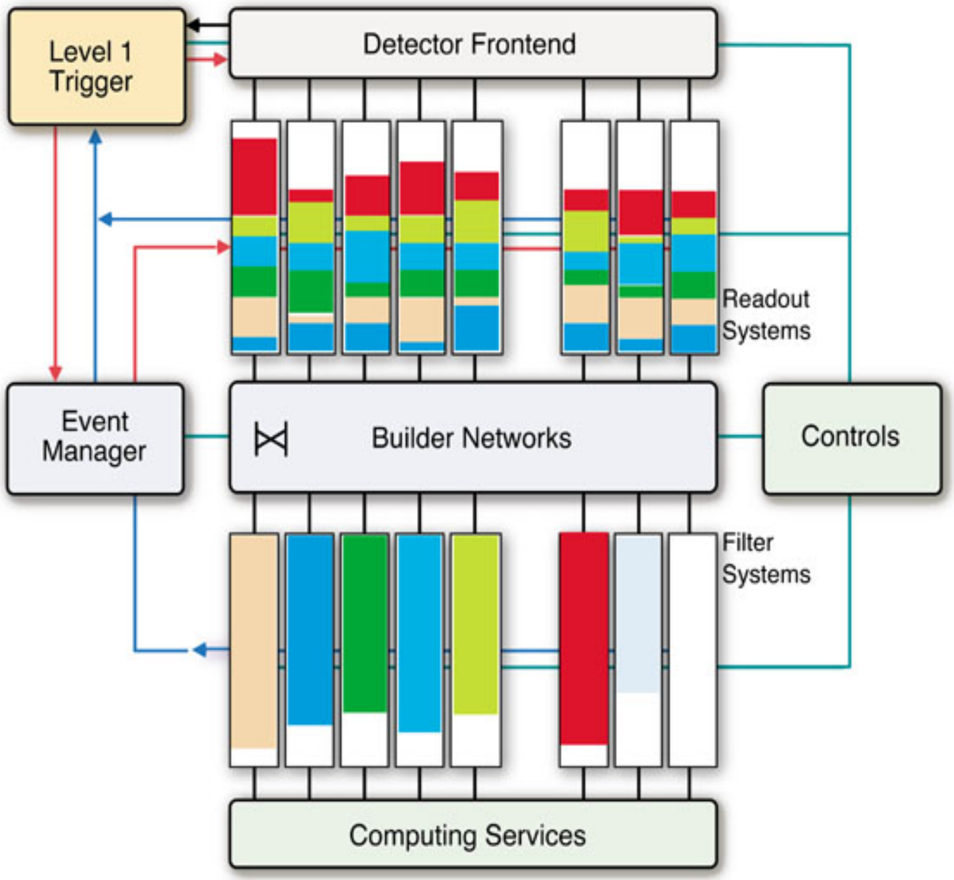
100 kHz

8 independent “DAQ slices”
Assemble super-fragments into full events

12.5 kHz   12.5 kHz   …   12.5 kHz

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

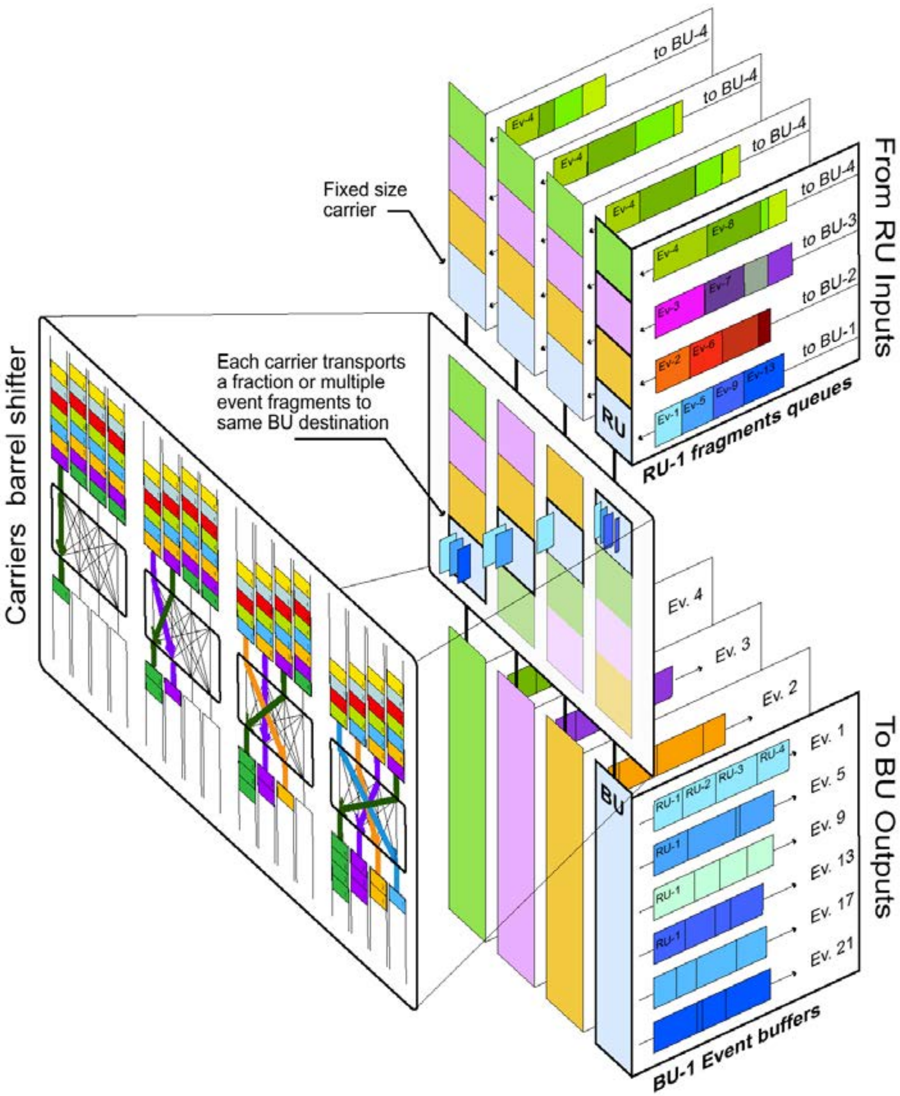


Event fragments :
Event data fragments are stored in separated physical memory systems

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)

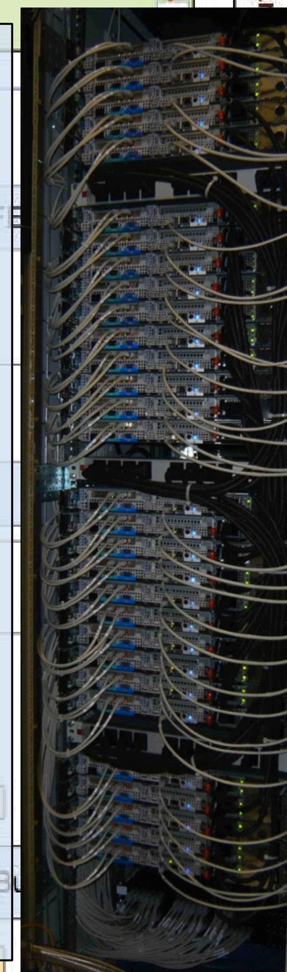
zero-copy, **OS-bypass**

principle works for multi-stage switches

EVB – HLT installation

- EVB – input "RU" PC nodes
  - 640 times dual 2-core E5130 (2007)
  - Each node has 3 links to GbE switch
- Switches
  - 8 times F10 E1200 routers
  - In total ~4000 ports
- EVB – output + HLT node ("BU-FU")
  - 720 times dual 4-core E5430, 16 GB (2008)
  - 288 times dual 6-core X5650, 24 GB (2011)
  - Each node has 2 links to GbE switch

HLT Total: 1008 nodes, 9216 cores, 18 TB memory
@100 kHz: ~90 ms/event
Can be easily expanded by adding PC nodes and recabling EVB network



ATLAS & CMS High Luminosity Motivation

Establish nature of Higgs boson and of EWSB:

- fundamental or composite?
- how many doublets? singlets? charged H's?

Need to measure, as accurately as possible:

- Higgs couplings to fermions, gauge bosons & self-couplings
- Rare decay modes, possible Flavor Changing Neutral Current
- WW scattering at high E
- Gauge boson self-couplings

Example:

- For light Higgs: $H \rightarrow Z\gamma$ @ 3.5/11 σ with 600/6000 fb^{-1} or $H \rightarrow \mu^+\mu^-$ < 3.5σ for 600 fb^{-1} and ~ 7σ for 6000 fb^{-1}

Requirements for LHC phases of the upgrades: ~2010-2030

Phase 1: (until 2021)

- Goal of extended running in second half of decade to collect ~100s/fb
- 80% of this luminosity in last three years of this decade
- About half the luminosity would be delivered at luminosities above the original LHC design luminosity
- Trigger & DAQ systems should be able to operate with a peak luminosity of up to 2×10^{34}

Phase 2: High Lumi LHC (2023+)

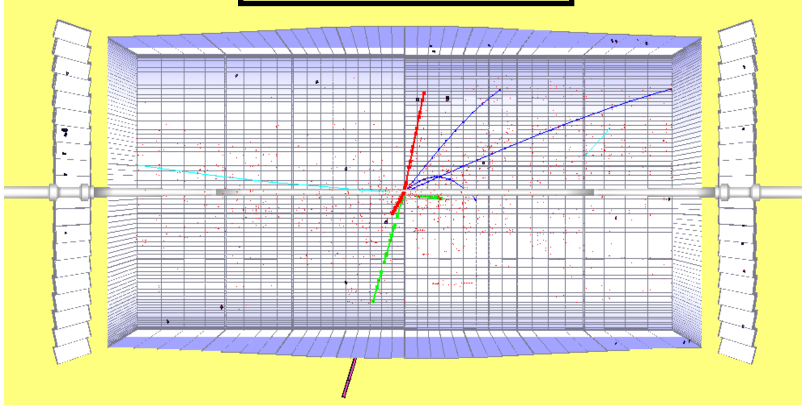
- Continued operation of the LHC beyond a few 100/fb will require substantial modification of detector elements
- Goal is to achieve 3000/fb in phase 2
- Need to be able to integrate ~300/fb-yr
- Will require new tracking detectors for ATLAS & CMS
- Trigger & DAQ systems should be able to operate with a peak luminosity of up to 5×10^{34}

HCPSS12

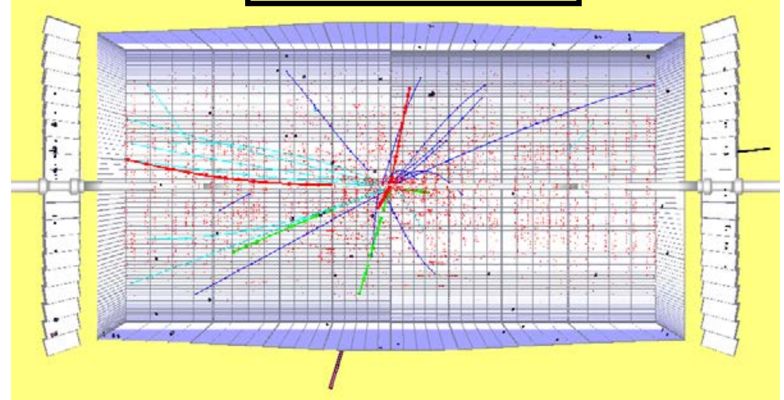
Detector Luminosity Effects

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

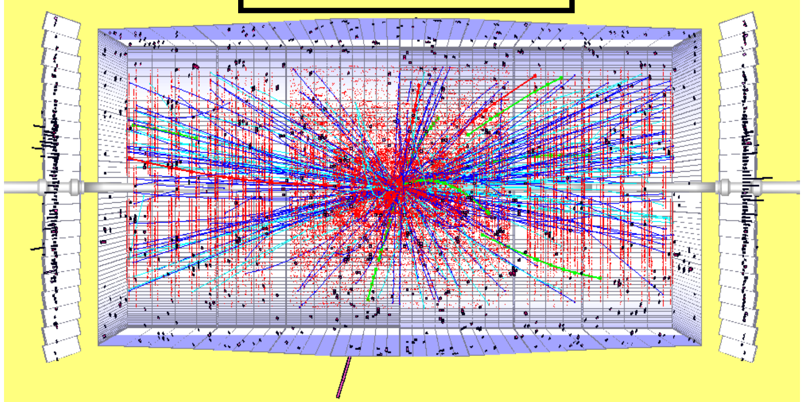
10^{32} cm^{-2}s^{-1}



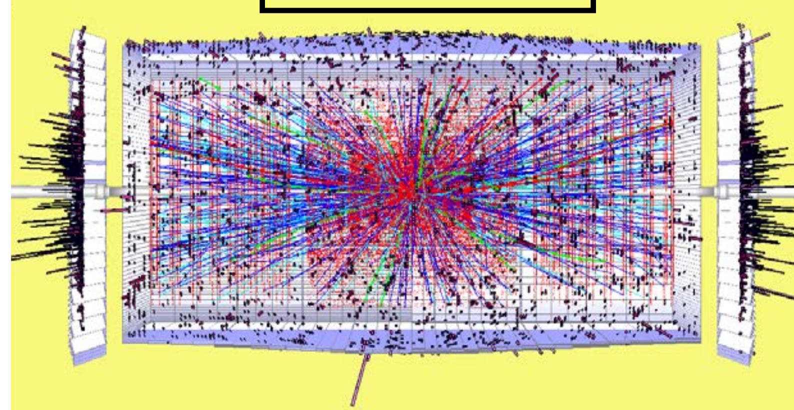
10^{33} cm^{-2}s^{-1}



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



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



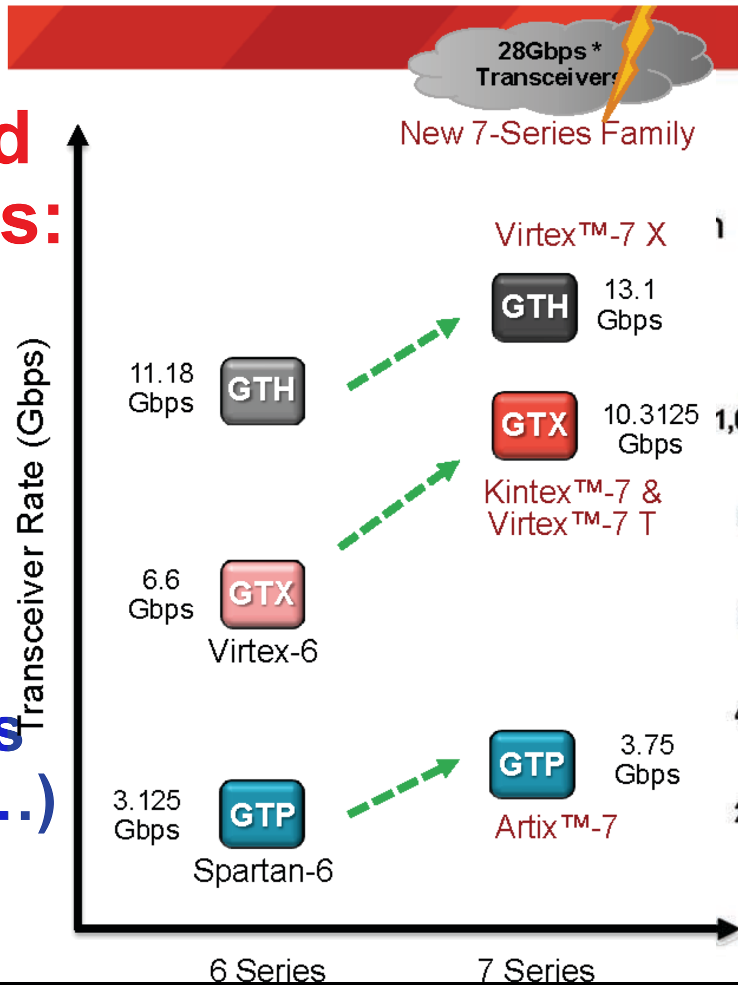
Tools for Upgrades: FPGAs

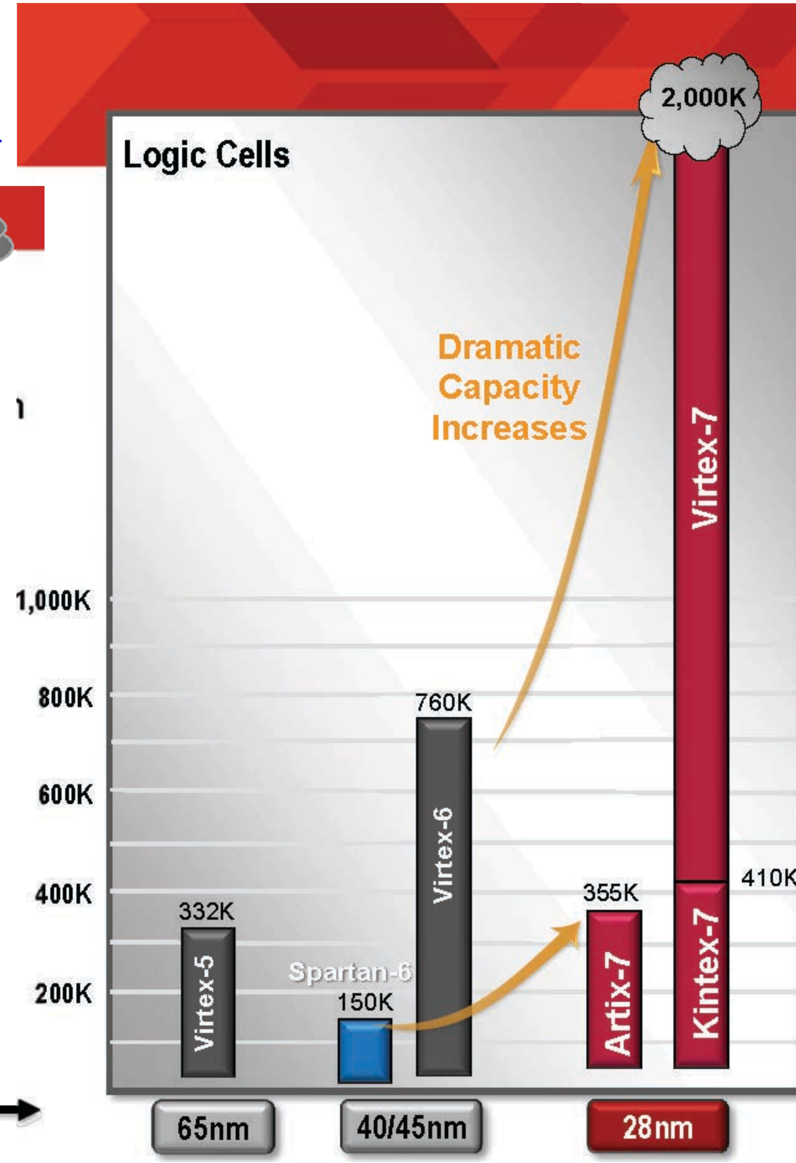
Logic Cells

- 28 nm: > 2X gains over 40 nm→

On-Chip High Speed Serial Links:

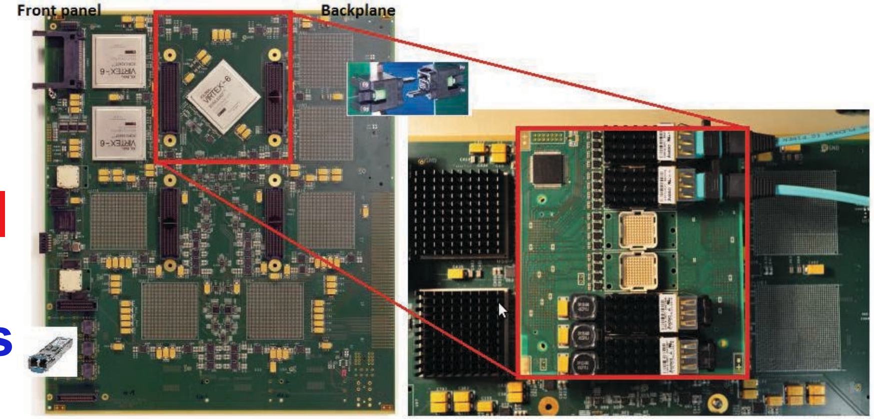
- Connect to new compact high density optical connectors (SNAP-12…)



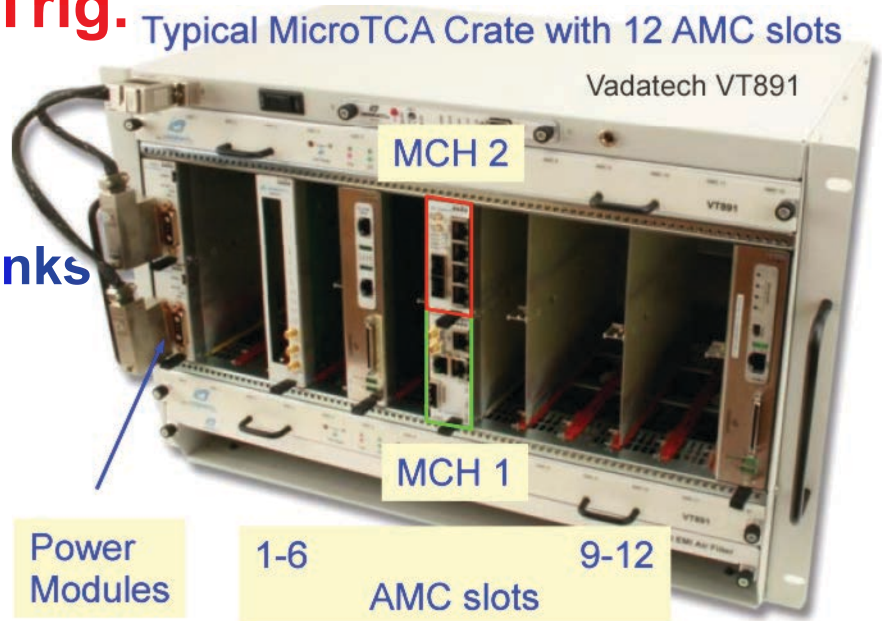


Tools for upgrades: ATCA

- **Advanced Telecommunications Computing Architecture ATCA**
- **Example: ATLAS Upgrade Calorimeter Trigger Topological Processor Card**
  - **12-chan. ribbon fiber optic modules**
  - **Backpl. opt. ribbon fiber connector**



- **Example: μTCA derived from AMC std. used by CMS HCAL, Trig.**
  - **Advanced Mezzanine Card**
  - **Up to 12 AMC slots**
    - *Processing modules*
  - **6 standard 10Gb/s point-to -point links slot to hub slots (more cavailable)**
  - **Redundant power, controls,clocks**
  - **Each AMC can have in principle (20) 10 Gb/sec ports**
  - **Backplane customization is routine & inexpensive**

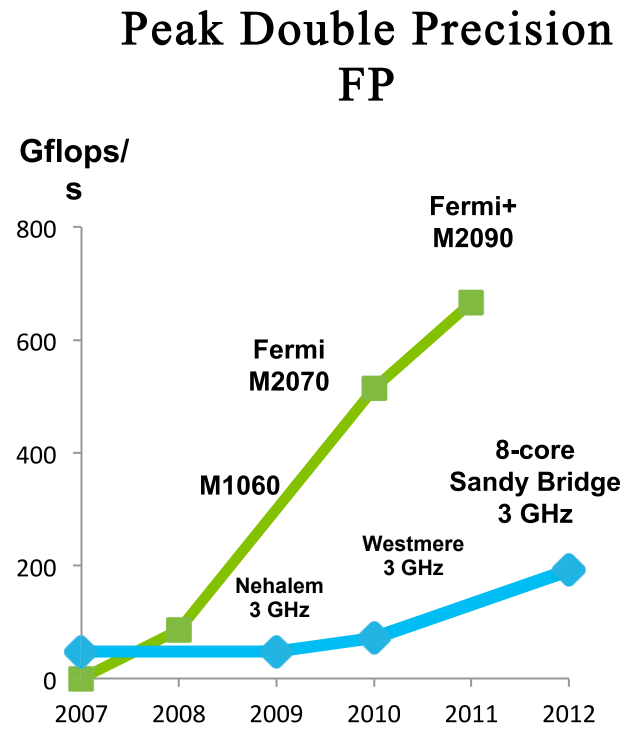


Tools cont'd: CPU, GPU, PCIe

CPU Gains for High Level Triggers: Moore's Law

GPU Enhancement of HLT →

- GPU performance tracks Moore's Law, since GPU architecture is scalable:
  - Large Increase in memory bandwidth x10 in Gbytes/s
  - Power efficient x3 with latest GPU card
  - Well suited to tracking, fitting algorithms



Enhancement of detector to DAQ readout:

- **PCI Express Gen3 Cards now available**
- **Up to 56Gb/s InfiniBand or 40 Gigabit Ethernet per port**

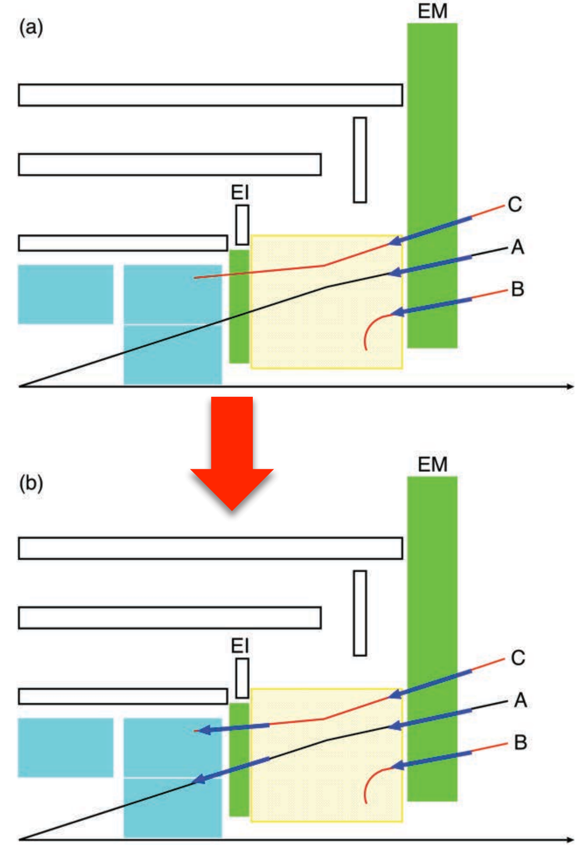
ATLAS Upgrade Trigger Strategy

Near Future (2014)

- New calorimeter trigger & central trigger processor modules provide topological triggers, more triggers

Phase 1:

- "New Small Wheel" provides inner track segments to reduce endcap muon trigger rate
- Muon trigger upgrade to provide topological triggers
- Calorimeter trigger digital "preprocessor" & feature extractors allow use of finer granularity information
- Latency & L1 Trigger Rate stay same through phase 1



Phase 2 Options:

- Divide L1 trigger into L0, L1 of latency 5, 20 μsec, rate < 500, 200 kHz
- L0 uses Calo & Muon Triggers, generates track trigger seeds
- L1 uses track trigger & more muon detectors & more fine-grained calorimeter trigger information.

CMS Upgrade Trigger Strategy

HCPSS12

Constraints

- **Output rate at 100 kHz**
- **Input rate increases x2/x10 (Phase 1/Phase 2) over LHC design (10^{34})**
  - Same x2 if crossing freq/2, e.g. 25 ns spacing → 50 ns at 10^{34}
- **Number of interactions in a crossing (Pileup) goes up by x4/x20**
- **Thresholds remain ~ same as physics interest does**

Example: strategy for Phase 1 Calorimeter Trigger

- **Present L1 algorithms inadequate above 10^{34}**
  - Pileup degrades object isolation
- **More sophisticated clustering & isolation deal w/more busy events**
  - Process with full granularity of calorimeter trigger information
- **Should suffice for x2 reduction in rate as shown with initial L1 Trigger studies & CMS HLT studies with L2 algorithms**

Potential new handles at L1 needed for x10 (Phase 2: 2023+)

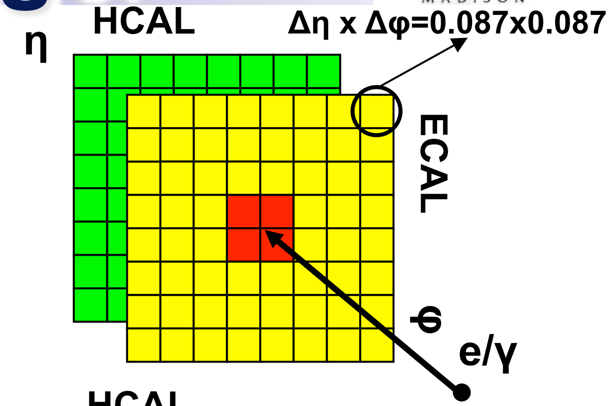
- **Tracking to eliminate fakes, use track isolation.**
- **Vertexing to ensure that multiple trigger objects come from same interaction**
- **Requires finer position resolution for calorimeter trigger objects for matching (provided by use of full granularity cal. trig. info.)**

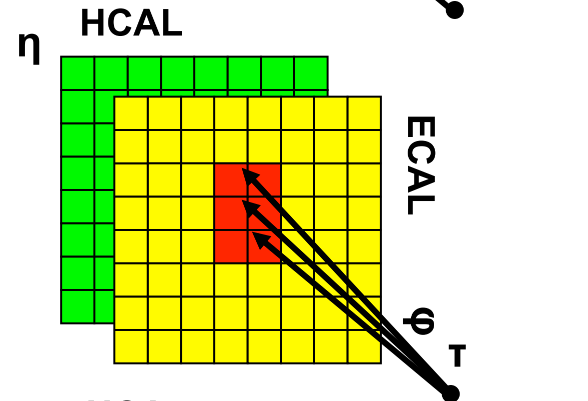
CMS Phase 1 Upgrade Calorimeter Trigger

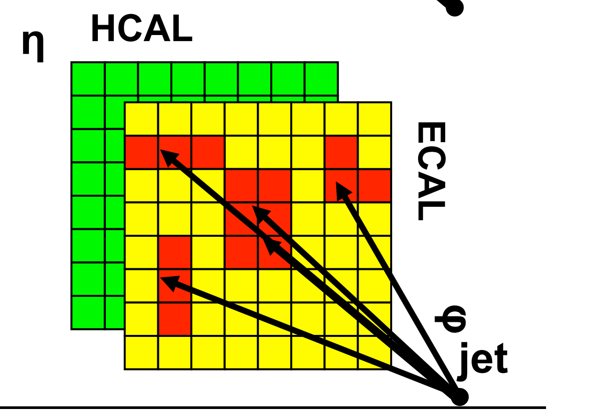
- **Particle Cluster Finder**
  - **Applies tower thresholds to Calorimeter**
  - **Creates overlapped 2x2 clusters**
- **Cluster Overlap Filter**
  - **Removes overlap between clusters**
  - **Identifies local maxima**
  - **Prunes low energy clusters**
- **Cluster Isolation and Particle ID**
  - **Applied to local maxima**
  - **Calculates isolation deposits around 2x2,2x3 clusters**
  - **Identifies particles**
- **Jet reconstruction**
  - **Applied on filtered clusters**
  - **Groups clusters to jets**
- **Particle Sorter**
  - **Sorts particles & outputs the most energetic ones**
- **MET,HT,MHT Calculation**
  - **Calculates Et Sums, Missing Et from clusters**

Rate reductions x4 w/improved efficiency

Implemented in 4 μTCA Crates







CMS Phase 2: Tracker input to L1 Trigger

Use of Tracker input to Level-1 trigger

- μ, e and jet rates would exceed 100 kHz at high luminosity
  - Even considering "phase-1" trigger upgrades
- Increasing thresholds would affect physics performance
  - Performance of algorithms degrades with increasing pile-up
    - Muons: increased background rates from accidental coincidences
    - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation
- Add tracking information at Level-1
  - Move part of HLT reconstruction into Level-1!

Full-scope objectives:

- Reconstruct "all" tracks above 2 - 2.5 GeV
- Identify the origin along the beam axis with ~ 1 mm precision

CMS Track Trigger Architectures: Phase 2

"Push" path:

- L1 tracking trigger data combined with calorimeter & muon trigger data regionally with finer granularity than presently employed.
- After regional correlation stage, physics objects made from tracking, calorimeter & muon regional trigger data transmitted to Global Trigger.

"Pull" path:

- L1 calorimeter & muon triggers produce a "Level-0" or L0 "pre-trigger" after latency of present L1 trigger, with request for tracking info at ~1 MHz. Request only goes to regions of tracker where candidate was found. Reduces data transmitted from tracker to L1 trigger logic by 40 (40 MHz to 1 MHz) times probability of a tracker region to be found with candidates, which could be less than 10%.
- Tracker sends out info. for these regions only & this data is combined in L1 correlation logic, resulting in L1A combining track, muon & cal. info..
- Only on-detector tracking trigger logic in specific region would see L0

"Afterburner" path:

- L1 Track trigger info, along with rest of information provided to L1 is used at very first stage of HLT processing. Provides track information to HLT algorithms very quickly without having to unpack & process large volume of tracker information through CPU-intensive algorithms. Helps limit the need for significant additional processor power in HLT computer farm.

CMS Track Trigger: General concept

Silicon modules provide at same time "Level-1 data" (@ 40 MHz) & "readout data" (@ 100 kHz, upon Level-1 trigger)

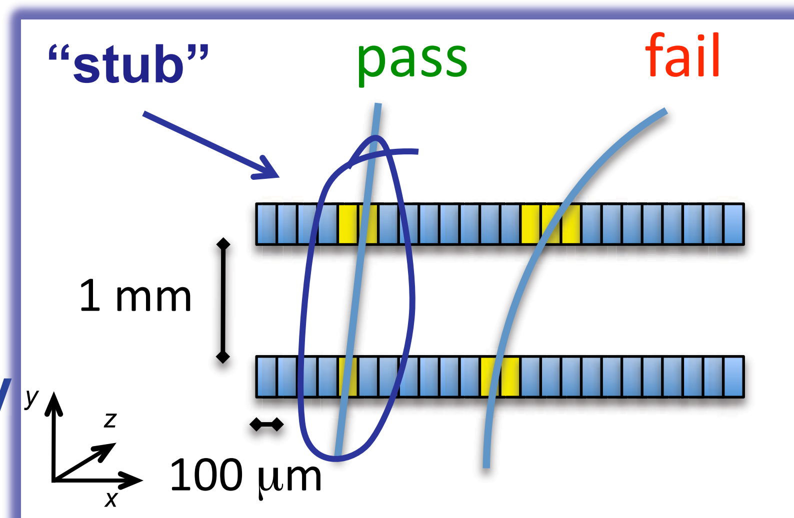
- The whole tracker sends out data at each BX: "push path"

Level-1 data require local rejection of low-p_T tracks

- To reduce the data volume, and simplify track finding @ Level-1
  - Threshold of ~ 1-2 GeV ⇒ data reduction of > one order of magnitude

Design modules with p_T discrimination ("p_T modules")

- Correlate signals in two closely-spaced sensors
  - Exploit CMS strong magnetic field



Level-1 "stubs" processed in back-end

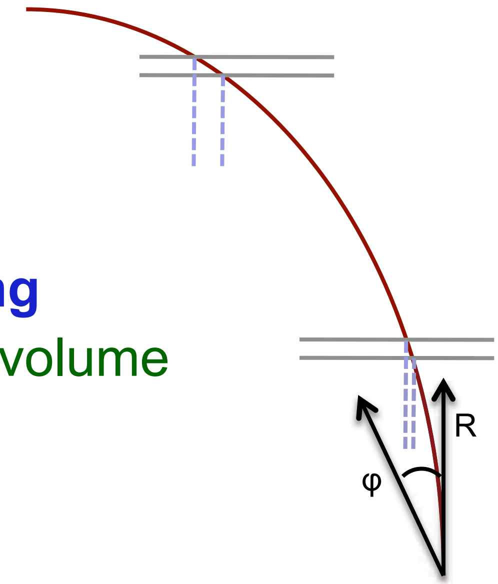
- Form Level-1 tracks, p_T above 2-2.5 GeV
  - Improve different trigger channels

CMS Track Trigger p_T modules: working principle

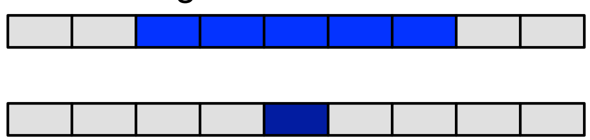
Sensitivity to p_T from measurement of $\Delta(R\varphi)$ over a given ΔR

For a given p_T, $\Delta(R\varphi)$ increases with R

- **Same geometrical cut, corresponds to harder p_T cuts at large radii**
- **At low radii, rejection power limited by pitch**
- **Optimize selection window and/or sensors spacing**
  - To obtain consistent p_T selection through tracking volume



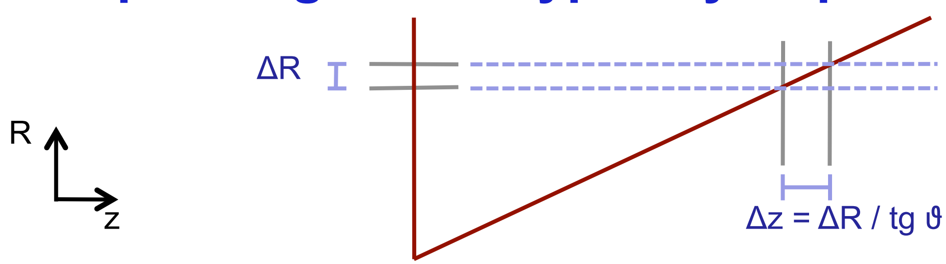
e.g. Window = 5



In the barrel, ΔR is given directly by the sensors spacing

In the end-cap, it depends on the location of the detector

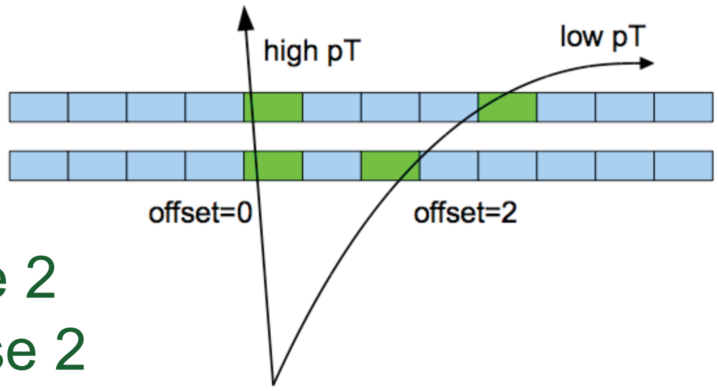
- **End-cap configuration typically requires wider spacing**



ATLAS Trigger Upgrades

Various projects being pursued:

- **Track trigger**
  - Fast Track Finder (FTK), hardware track finder for ATLAS (at L1.5)
    - **Phase 1**
  - ROI based track trigger at L1 – Phase 2
  - Self seeded track trigger at L1 – Phase 2



- **Combining trigger objects at L1 & topological "analysis"**
  - Phase 1 & 2
- **Full granularity readout of calorimeter**
  - requires new electronics – Phase 2
- **Changes in muon systems (small wheels), studies of an MDT based trigger & changes in electronics – Phase 1**
- **Upgrades of HLT farms**

Some of the changes are linked to possibilities that open when electronics changes are made (increased granularity, improved resolution & increased latency)

ATLAS FastTracKer (FTK)

For Phase 1:

Dedicated hardware processor completes GLOBAL track reconstruction by beginning of level-2 processing.

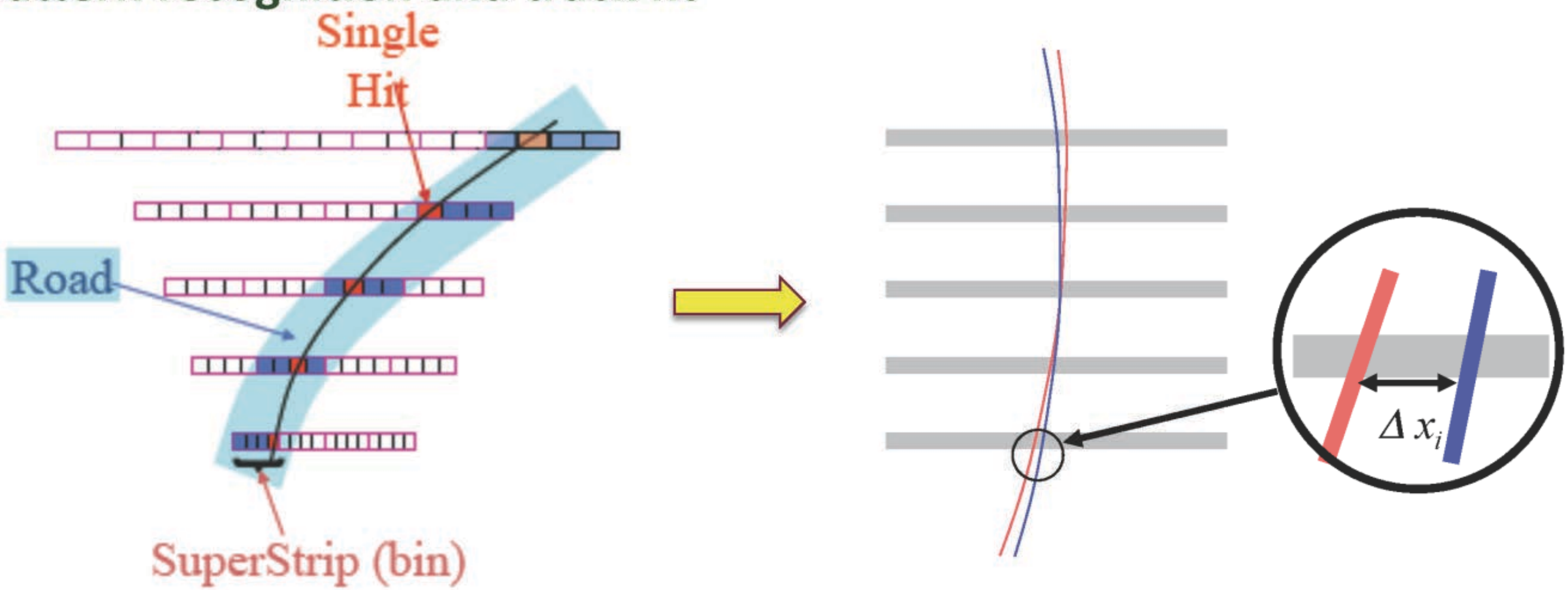
- **Allows very rapid rejection of most background, which dominates the level-1 trigger rate.**
- **Frees up level-2 farm to carry out needed sophisticated event selection algorithms.**

Addresses two time-consuming stages in tracking

- **Pattern recognition – find track candidates with enough Si hits**
  - 10^9 prestored patterns simultaneously see each silicon hit leaving the detector at full speed.
- **Track fitting – precise helix parameter & χ^2 determination**
  - Equations linear in local hit coordinates give near offline resolution

ATLAS FTK Approach

Use hardware to perform the global tracking in two steps
pattern recognition and track fit



Pattern recognition in coarse resolution (superstrip➔road)

Track fit in full resolution (hits in a road)

$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$

Design: FTK completes global tracking in 25 μsec at 3×10^{34}.

Current level-2 takes 25 msec per jet or lepton at 3×10^{34}.

ATLAS L1 Track Trigger Design Options for Phase 2

Region Of Interest based Track Trigger at L1

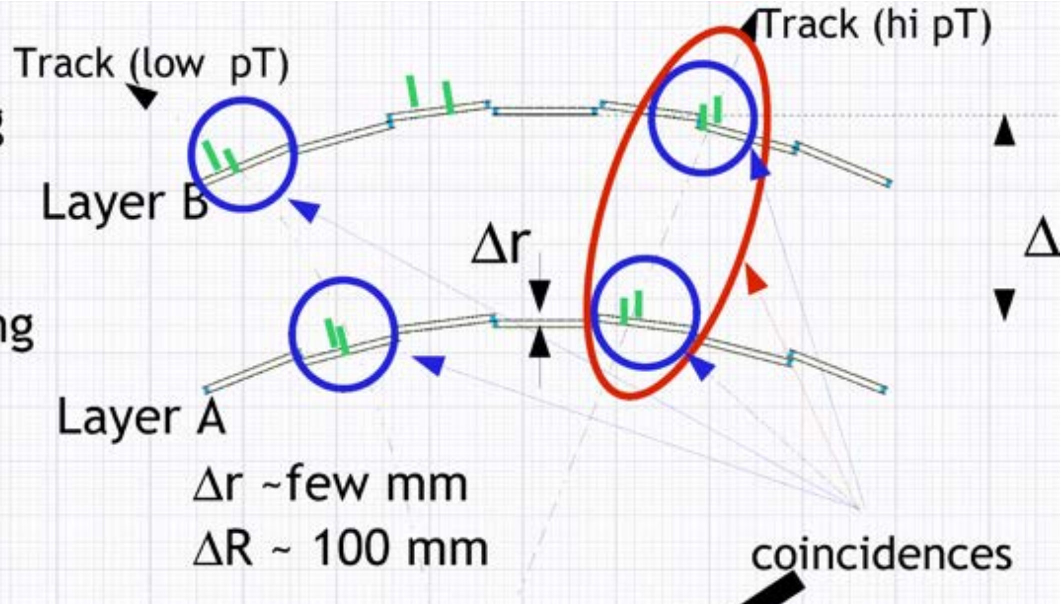
- **uses ROIs from L1Calo & L1Muon to seed track finding**
- **has a large impact on the Trigger architecture**
  - requires significantly lengthened L1 pipelines and fast access to L1Calo and L1Muon ROI information
  - could also consider seeding this with an early ("Level-0") trigger, or sending a late ("Level-1.5") track trigger
- **smaller impact on Silicon readout electronics**

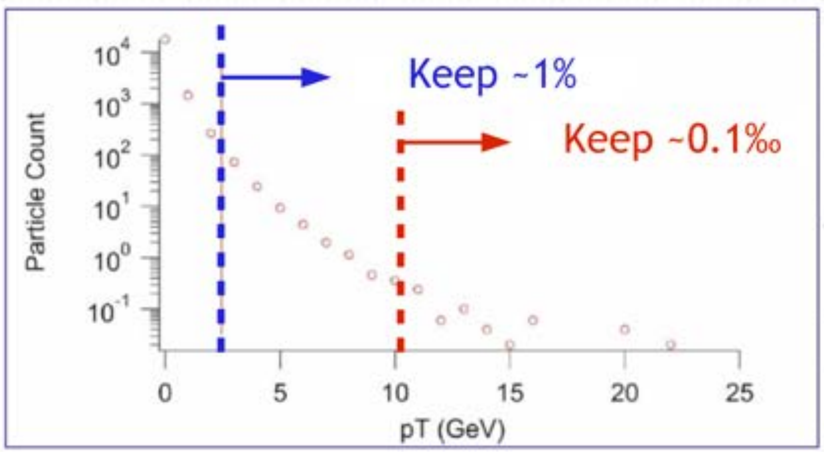
Self-Seeded Track Trigger at L1

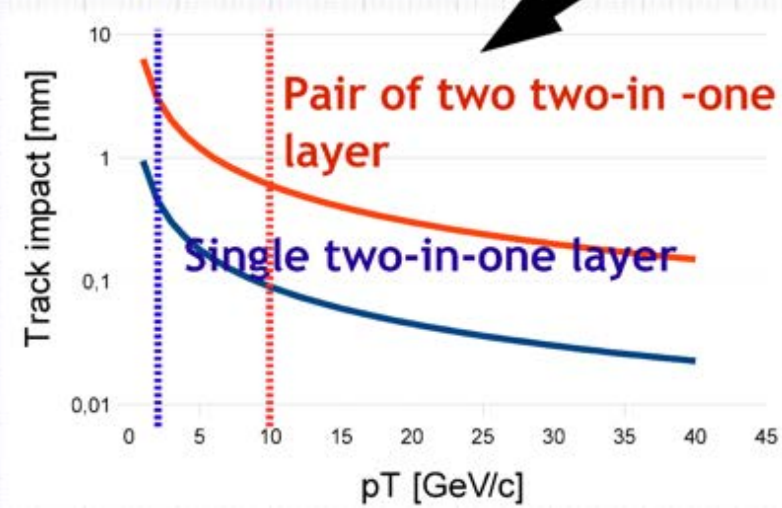
- **independent of other trigger information**
- **has a large impact on Silicon readout electronics**
  - requires fast access to Silicon detector data at 40 MHz
- **smaller impact on the Trigger architecture**

ATLAS Self-Seeded L1 Track Trigger with Doublet Layers

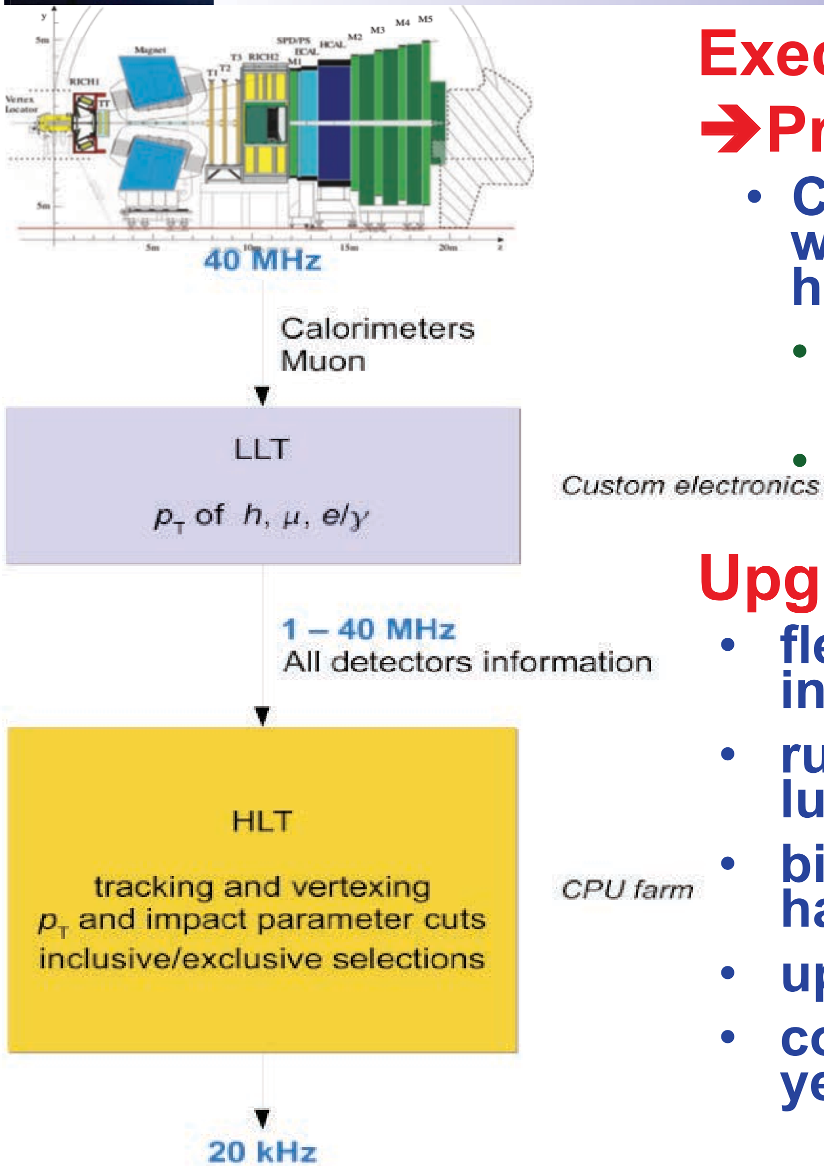
- Moderate pT dependent discrimination of hits using coincidences in closely spaced double layers
- High pT discrimination using coincidences between several doublet layers
- Has to operate at full BCO frequency (40 MHz)







LHCb Upgrade Trigger & DAQ



Execute whole trigger on CPU farm

➔Provide ~40 MHz detector readout

- **Cannot satisfy present 1 MHz requirement w/o deeply cutting into efficiency for hadronic final states**
  - worst state is $\phi\phi$, but all hadronic modes are affected
  - Can ameliorate this by reading out detector & then finding vertices

Upgrade Trigger & DAQ

- **flexible software trigger with up to 40 MHz input rate and 20 kHz output rate**
- **run at ~ 5-10 times nominal LHCb luminosity → L ~ 1-2 · 10^{33} cm^{-2} s^{-1}**
- **big gain in signal efficiency (up to x7 for hadron modes)**
- **upgrade electronics & DAQ architecture**
- **collect ≥ 5/fb per year and ~ 50/fb in 10 years**

ALICE Upgrade

Run at high rates, 50 kHz Pb-Pb (*i.e.* $L = 6 \times 10^{27}\ cm^{-1}s^{-1}$), with minimum bias (pipeline) readout (max readout with present ALICE set-up ~500Hz)

- Factor 100 increase in recorded luminosity
- Improve vertexing and tracking at low p_t

Pb-Pb run complemented by p-Pb & pp running

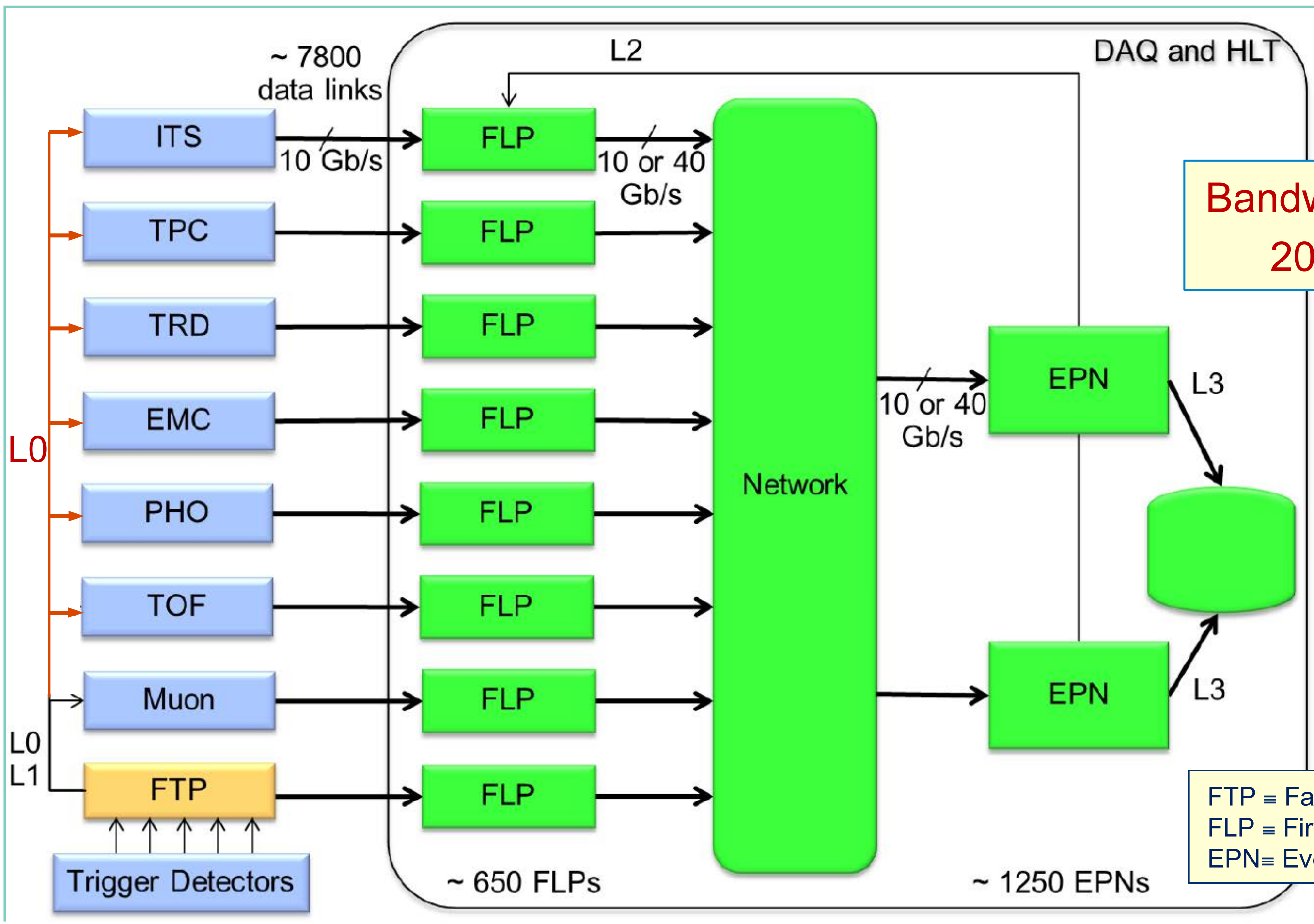
Entails building High-rate upgrade for readout of TPC, TRD, TOF, CALs, Muons, DAQ/HLT

Two HLT scenarios for the upgrade:

- Partial event reconstruction (clustering and tracking): Factor of ~20 → Rate to tape: 20 kHz
  - clusters (associated with tracks) information recorded on tape
- Full event reconstruction: additional reduction factor ~3 → Rate to tape > 50 kHz
  - track parameters recorded on tape

ALICE Upgrade Readout & Online Systems Architecture

Readout scheme



Bandwidth to tape
20 Gbyte/s

FTP ≡ Fast Trigger Processor
FLP ≡ First Level Processor
EPN≡ Event processor Node

LHC Online Systems Upgrade

- Very significant challenges to operate trigger & DAQ systems for high rate experiments.
- Very substantial assets to bring to bear on these challenges from commercial world: ATCA, FPGAs, high speed links (transceivers), optical connectors …
- Exploiting these assets enables physics input to drive much more precise selection of events and processing of a much higher volume of data.
  - e.g. a level-1 tracking trigger for ATLAS & CMS
- There is considerable technical difficulty involved in successfully exploiting these advances in technology and implementing them in running experiments in a controlled and adiabatic manner.

Trigger & DAQ Summary

Level 1 Trigger

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

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**