Data Selection & Collection: Trigger & DAQ

EDIT 2012 Symposium

Wesley H. Smith

U. Wisconsin - Madison

February 17, 2012

Outline:

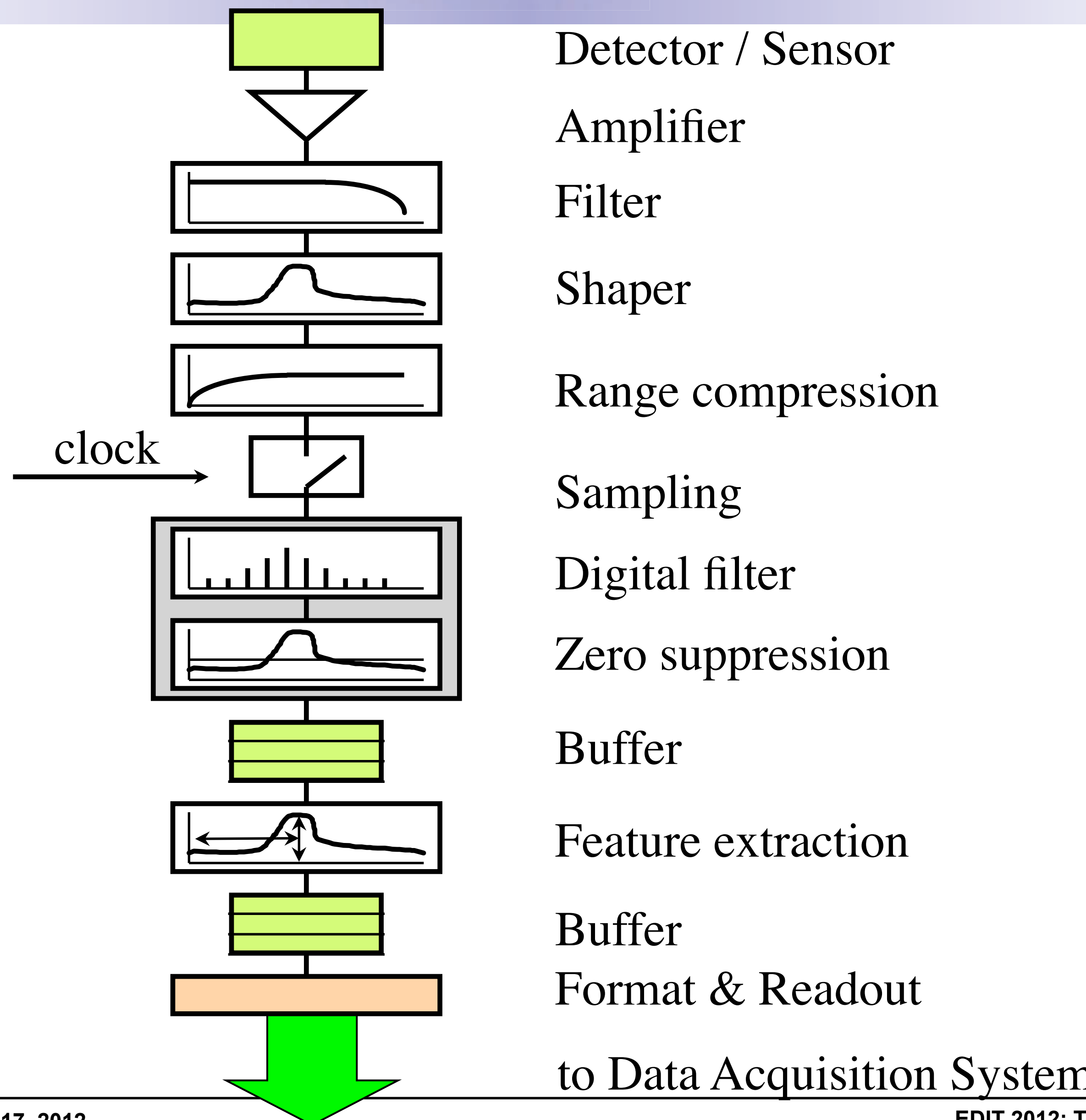
General Introduction to Detector Readout

Introduction to LHC Trigger & DAQ

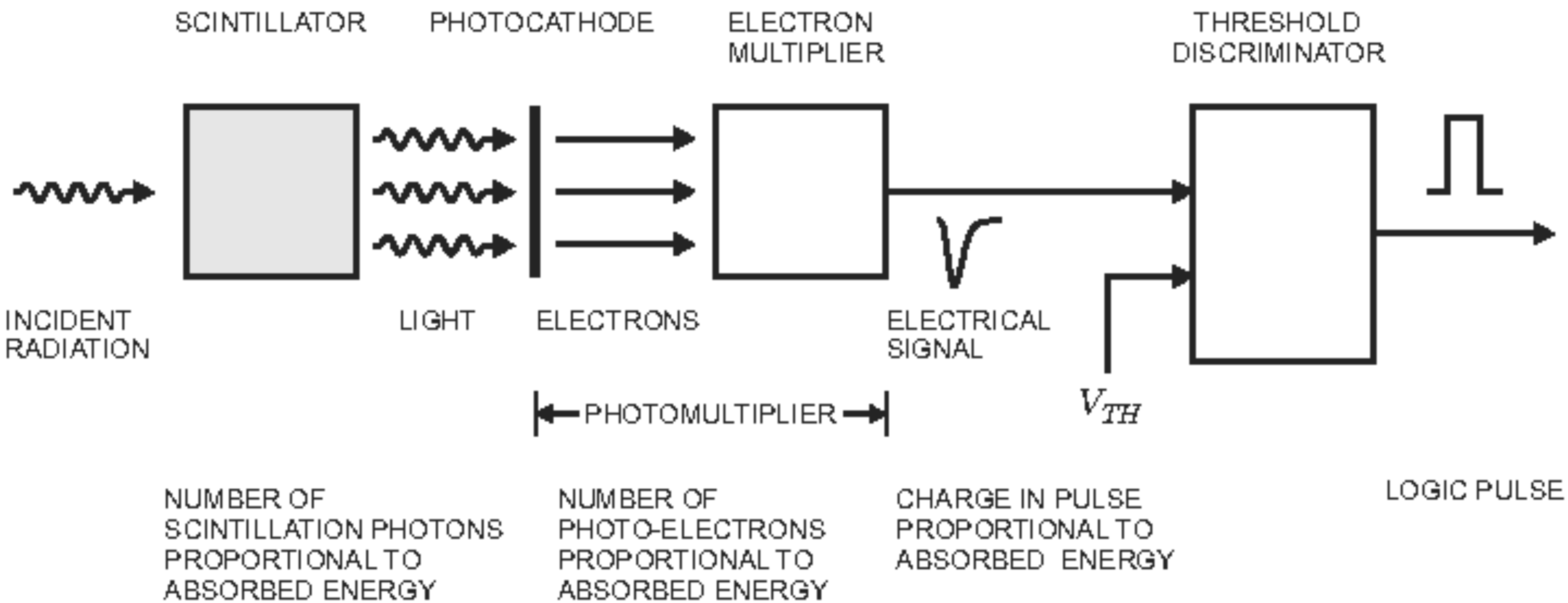
Challenges & Architecture

Examples: ATLAS & CMS Trigger & DAQ

Readout


clock
Detector / Sensor
Amplifier
Filter
Shaper
Range compression
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 ⇒**

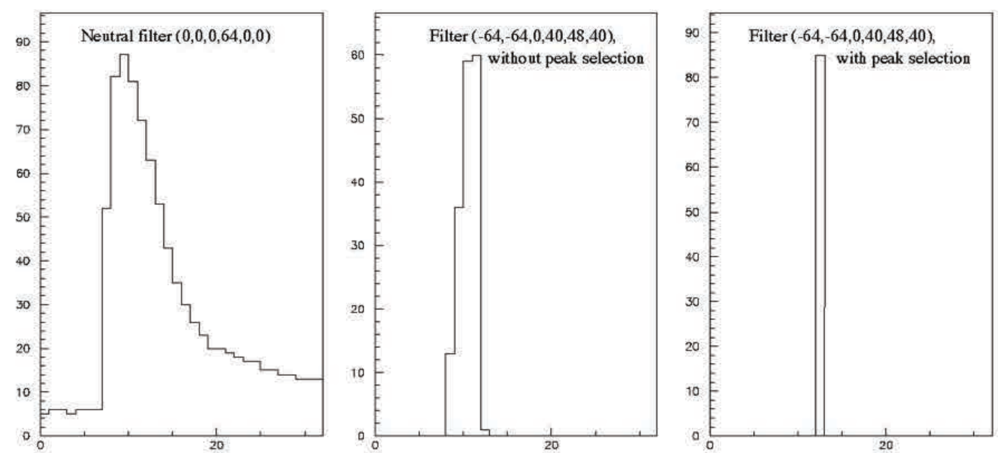
Example: Signals from scintillator every 25 ns

- **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

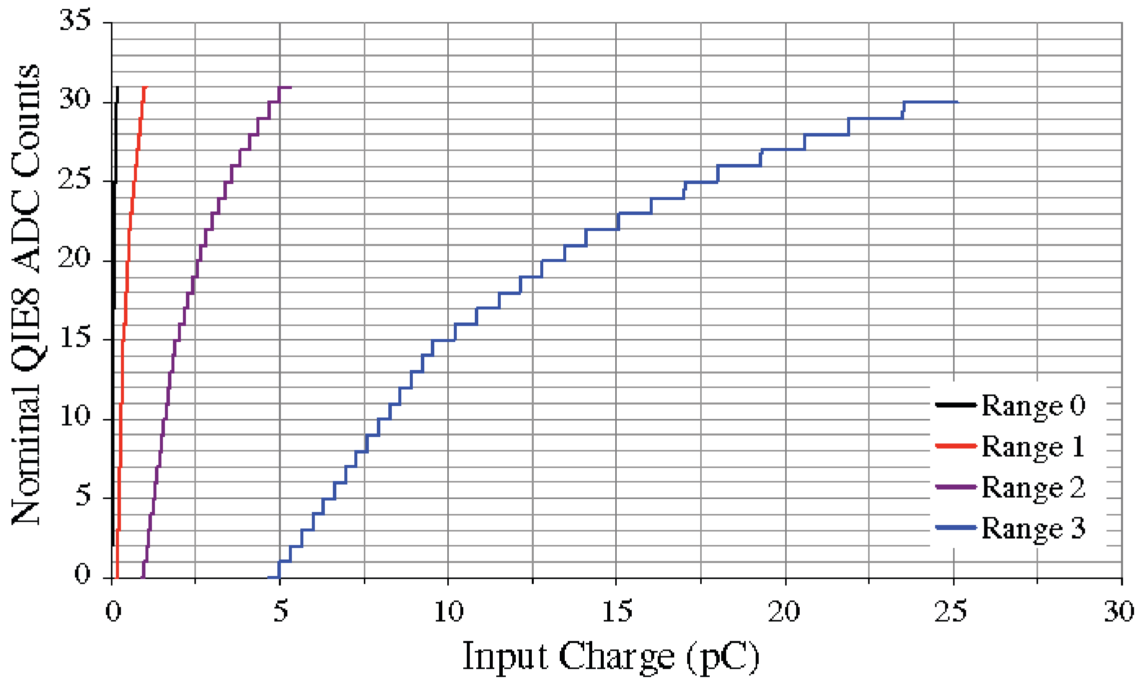
Signal can be discriminated against a threshold

- **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.

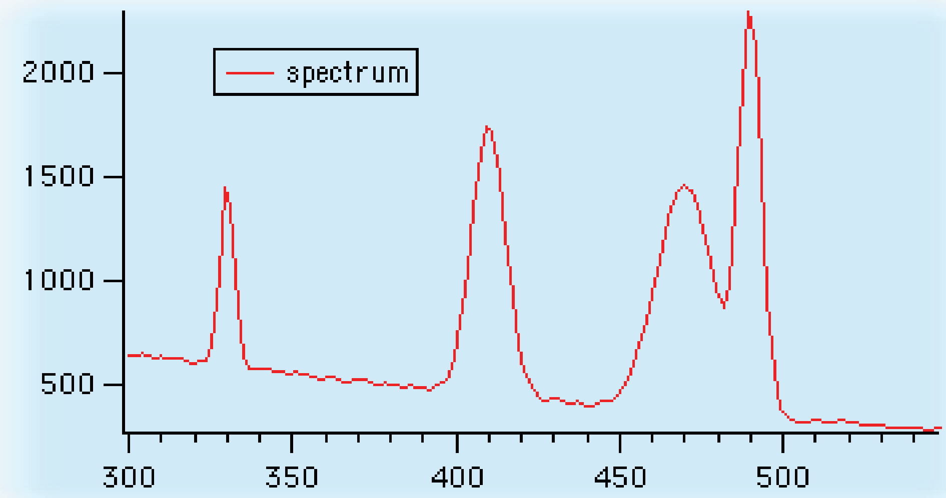
- **Have different ranges with different nos. of bits per pulse height**
- **Use nonlinear functions to match resolution**

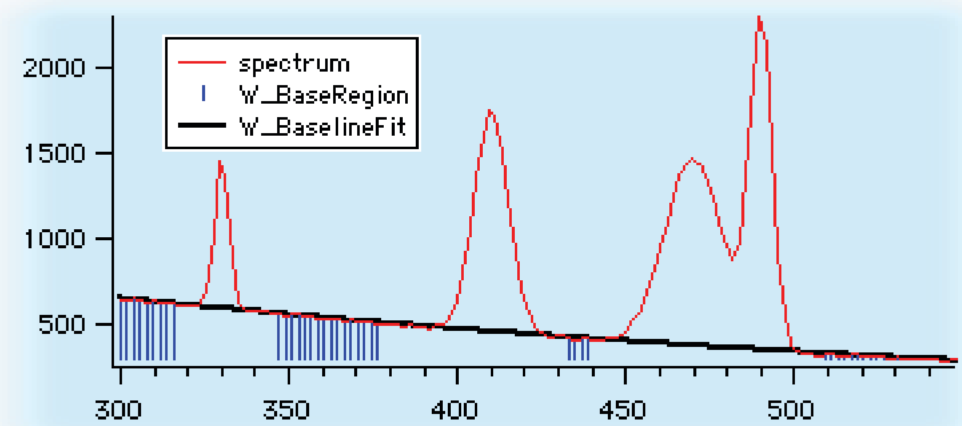


Baseline Subtraction

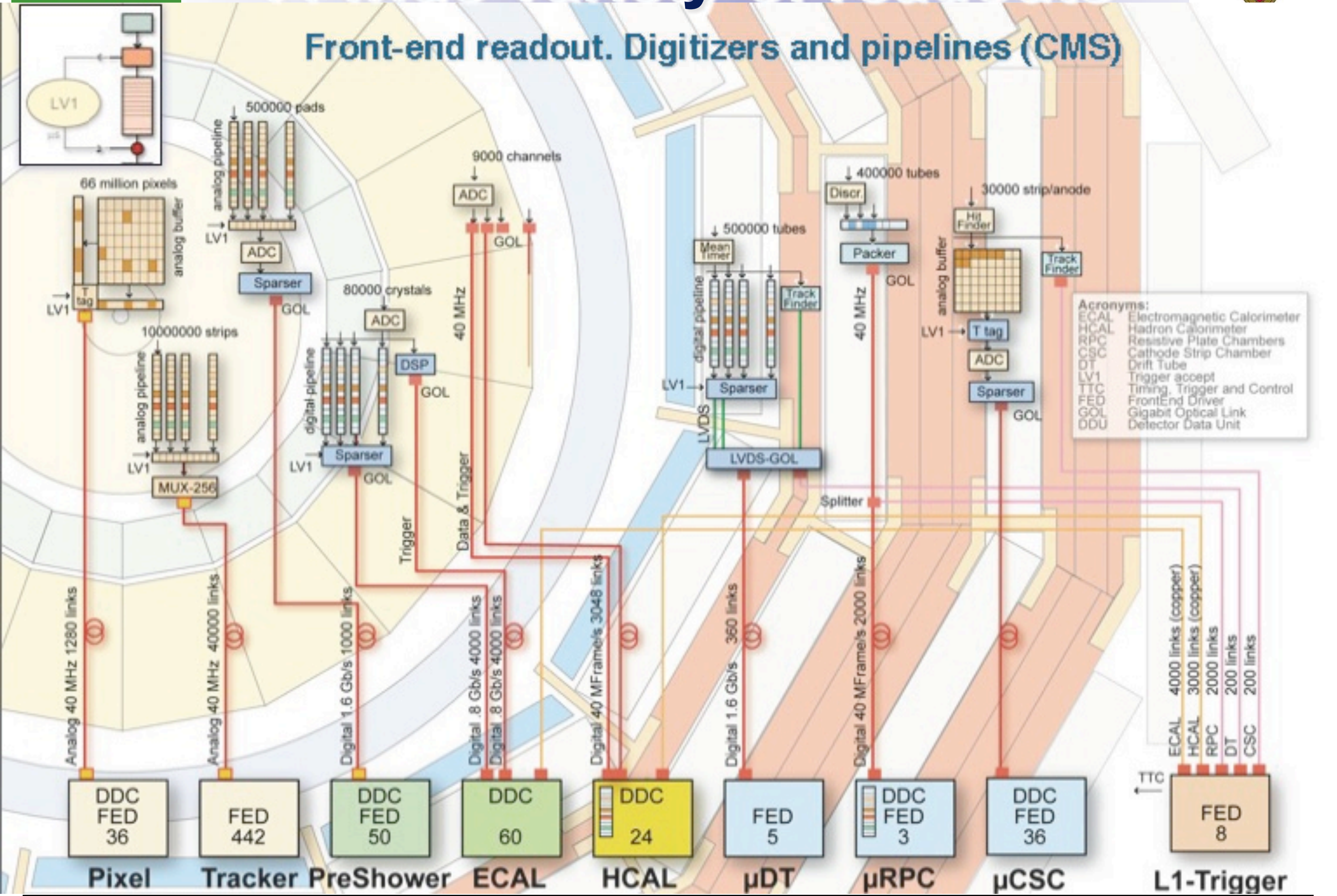
Wish to measure the integral of an individual pulse on top of another signal

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





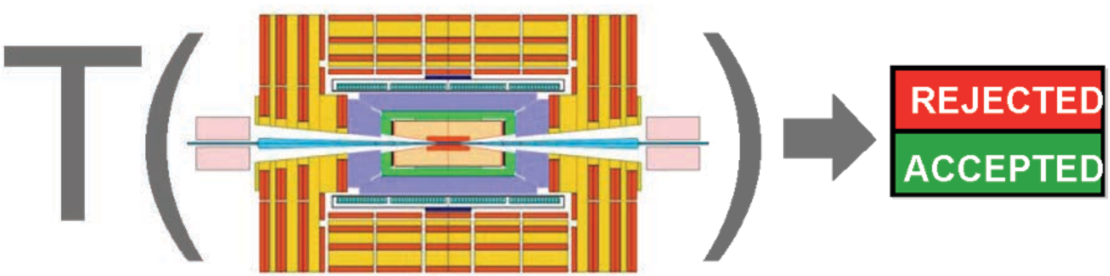
A wide variety of readouts



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 :



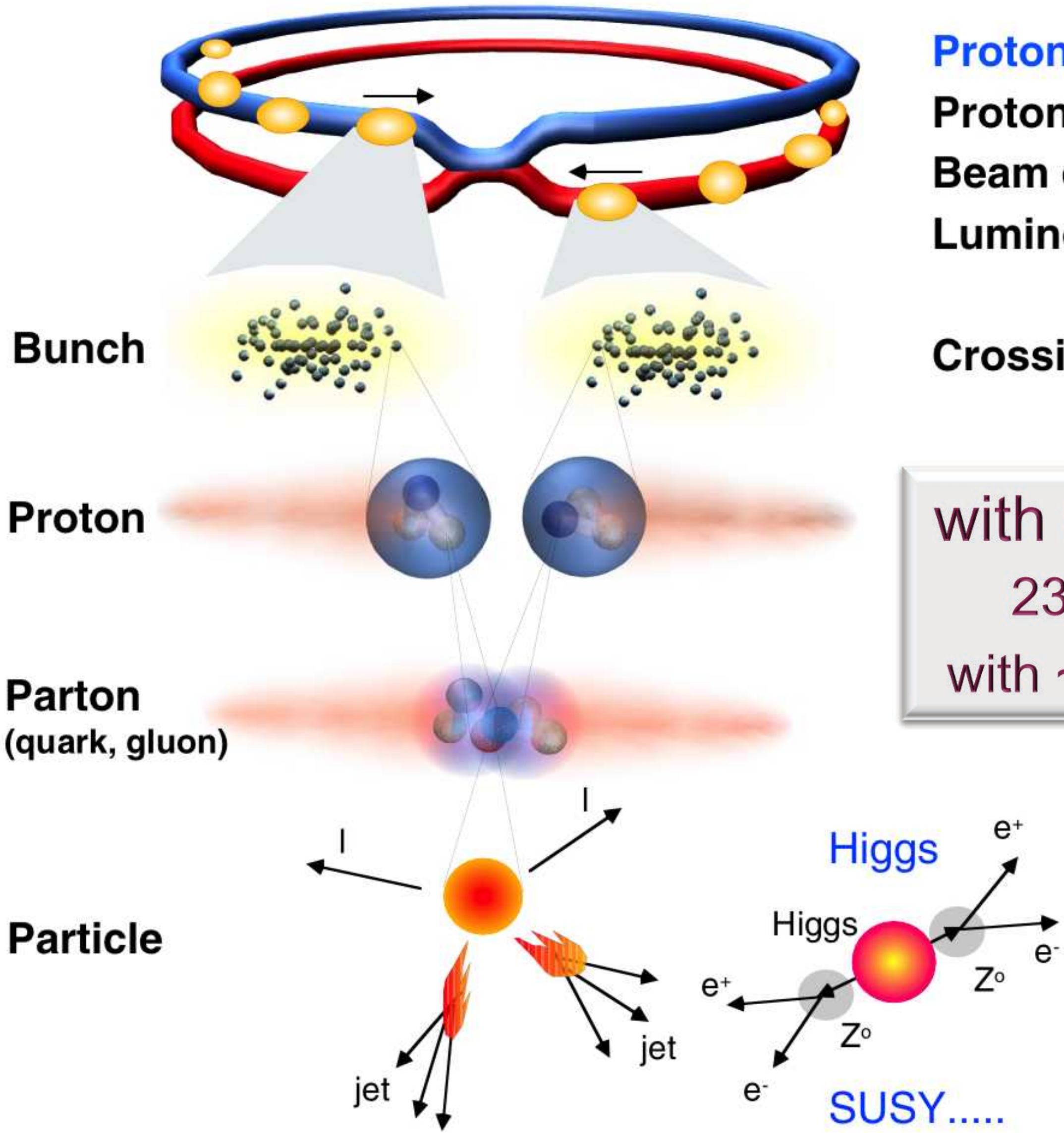
Event data & Apparatus
Physics channels & Parameters

• Detector data not (all) promptly available
• Selection function highly complex
$\Rightarrow$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

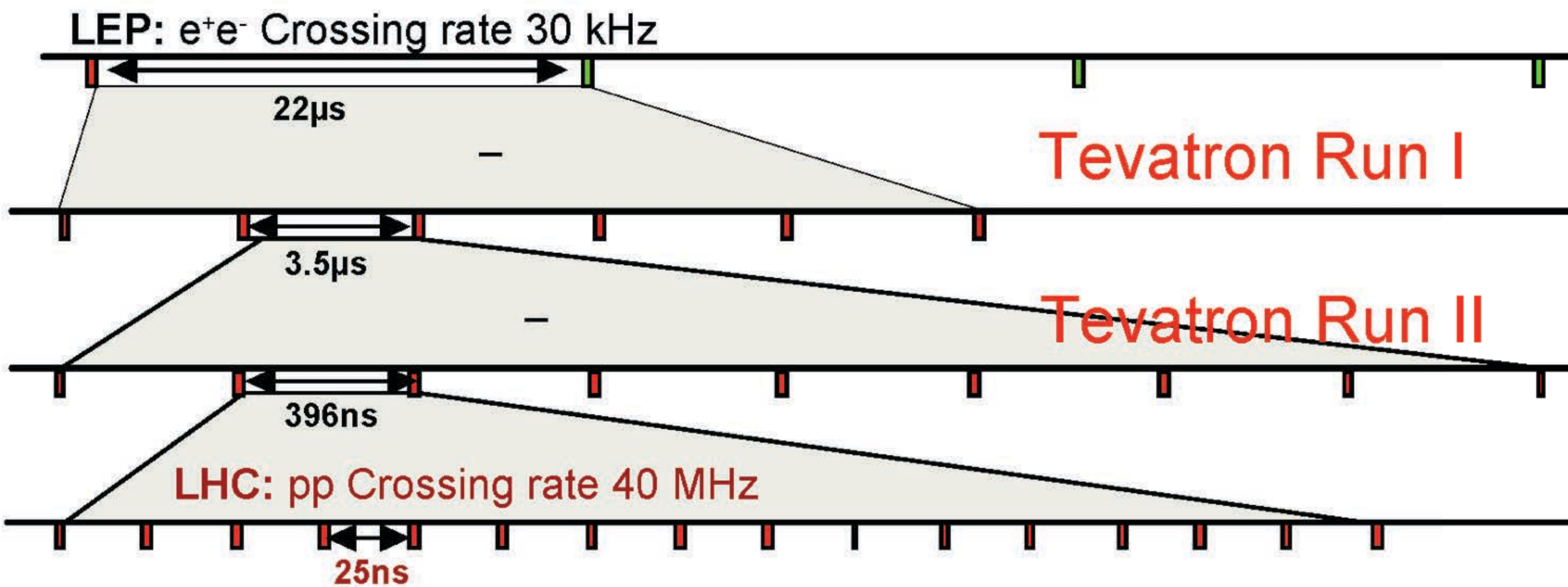
with every bunch crossing
23 Minimum Bias events
with ~1725 particles produced

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

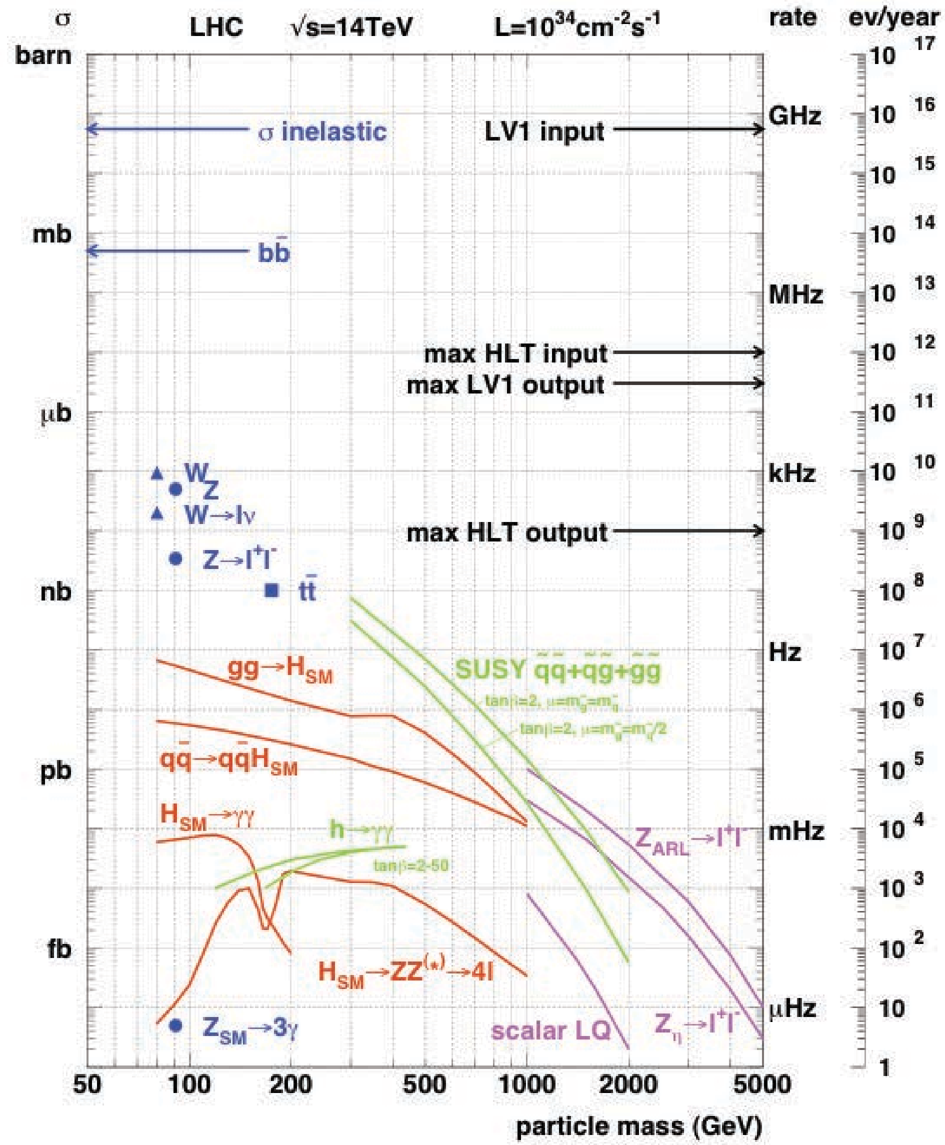
At design *L* = 10^{34}cm^{-2}s^{-1}

- **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**

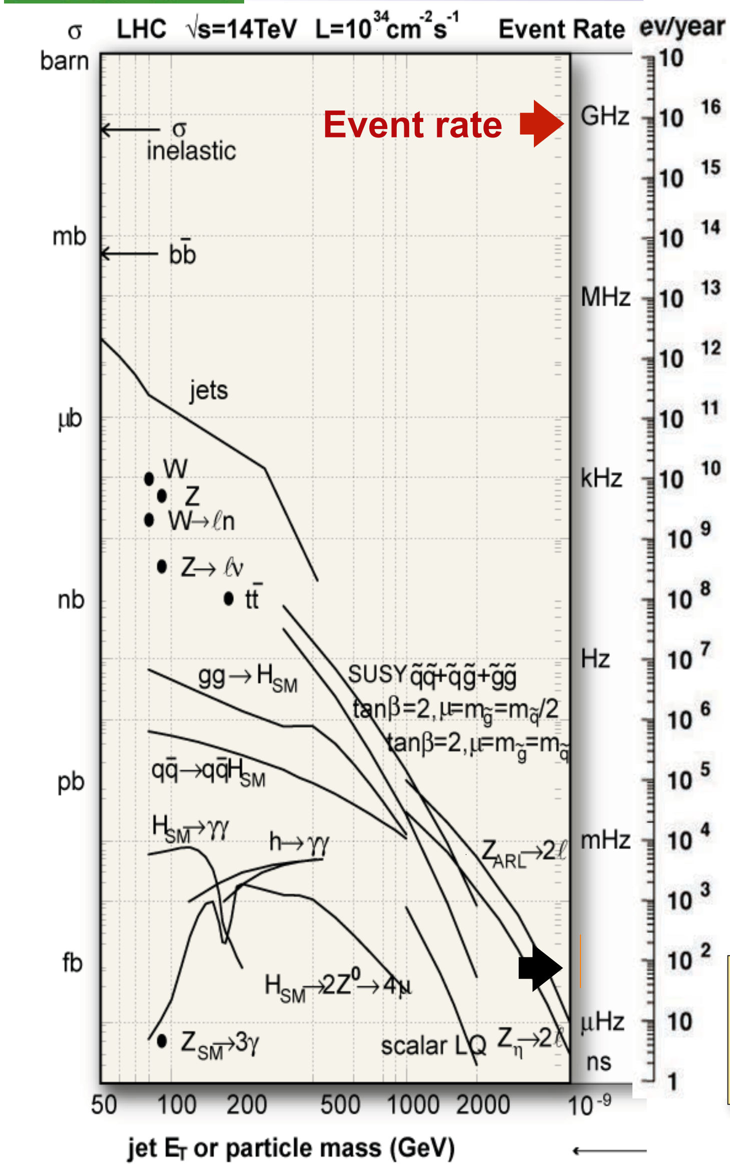
Can store ~ 300 Hz events

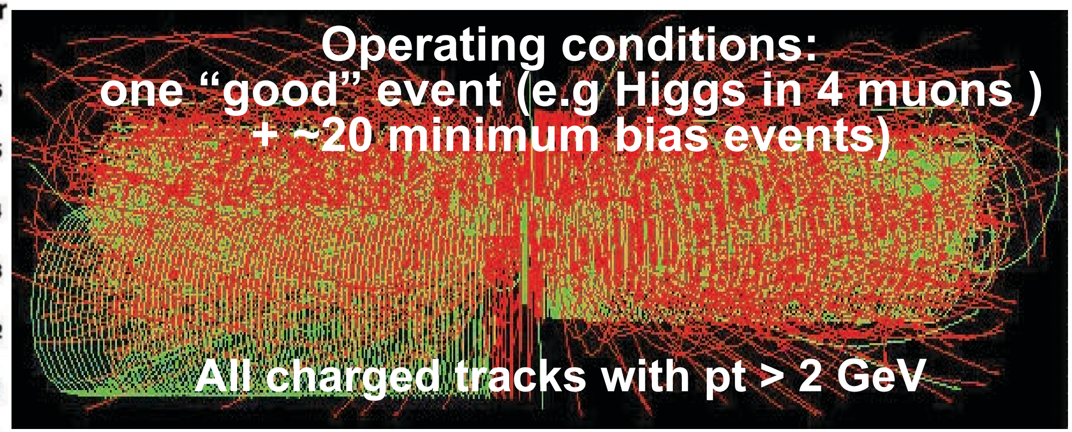
Select in stages

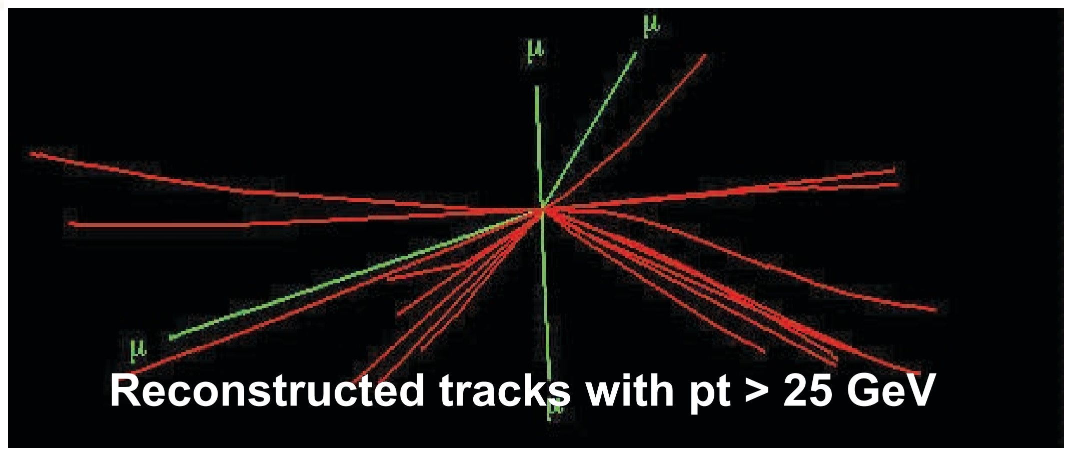
- **Level-1 Triggers**
  - 1 GHz to 100 kHz
- **High Level Triggers**
  - 100 kHz to 300 Hz



Collisions (p-p) at LHC

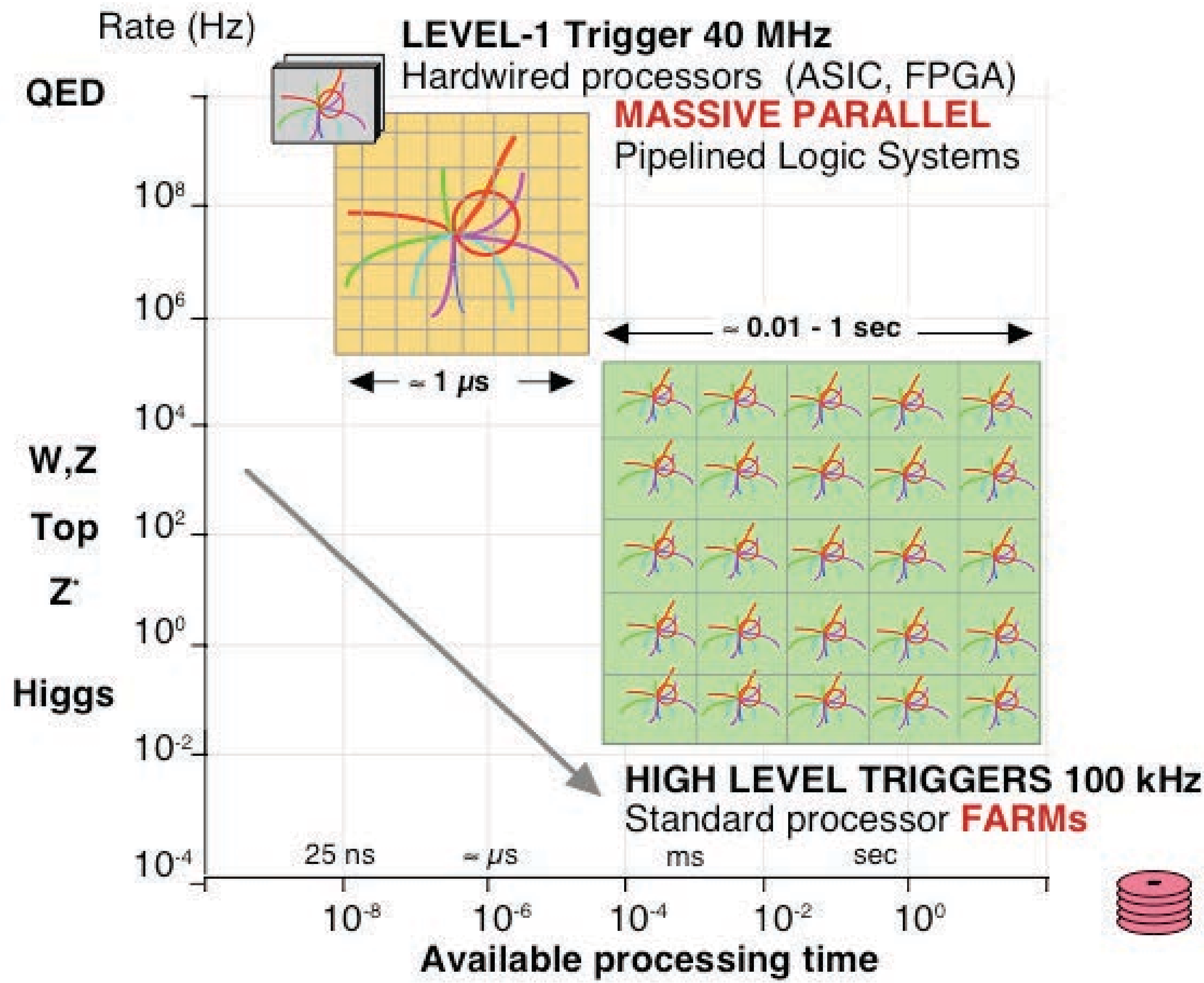




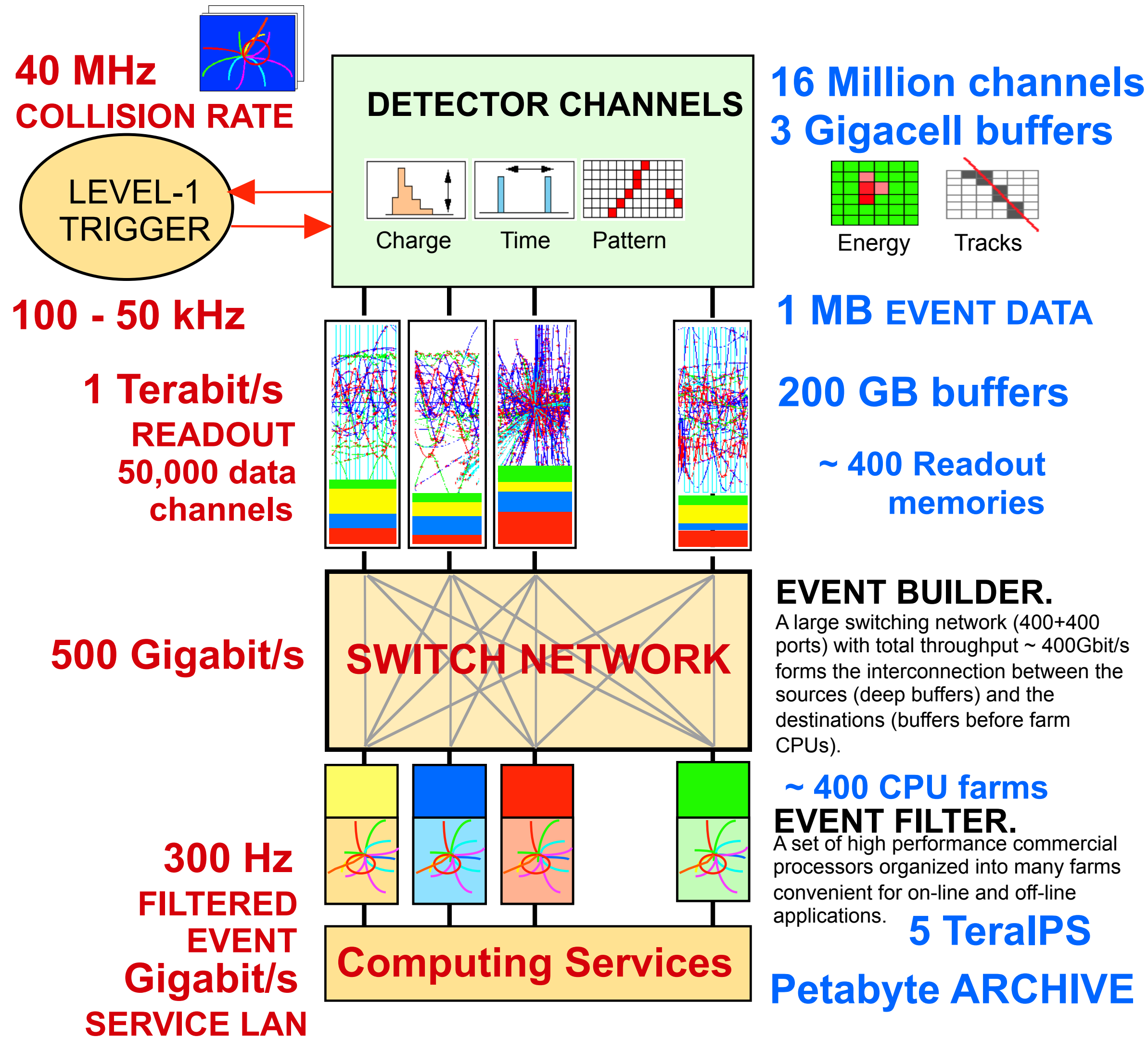


Event size:	**~1 MByte**
Processing Power:	**~X TFlop**

Processing LHC Data



LHC Trigger & DAQ Challenges



Challenges:

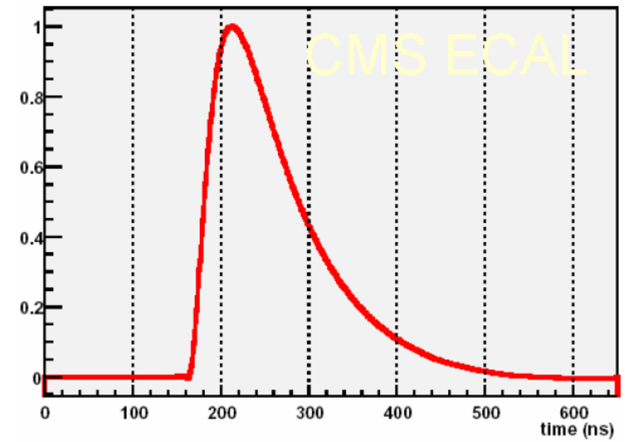
1 GHz of Input Interactions

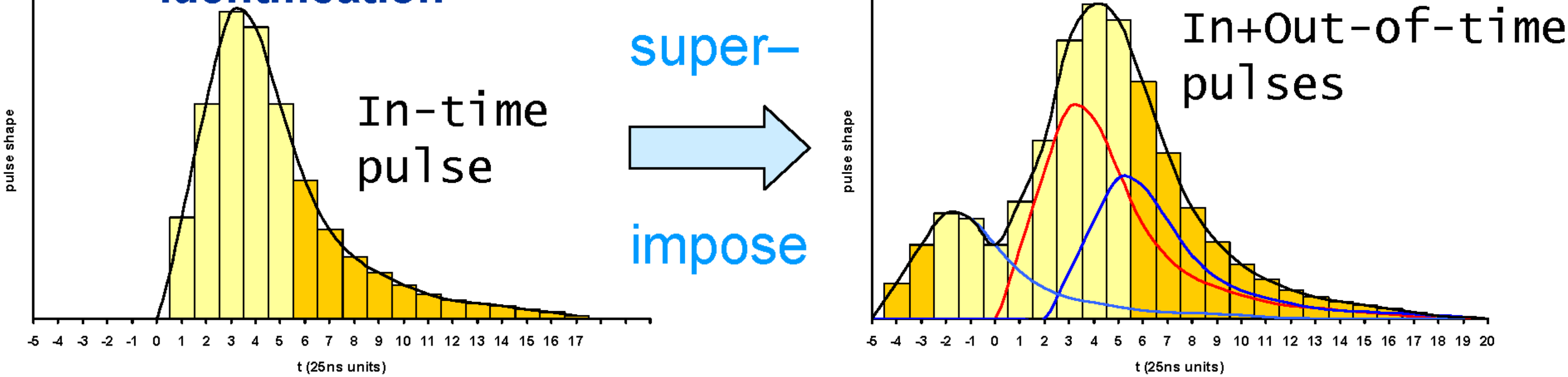
Beam-crossing every 25 ns with ~ 23 interactions produces over 1 MB of data

Archival Storage at about 300 Hz of 1 MB events

Challenges: Pile-up

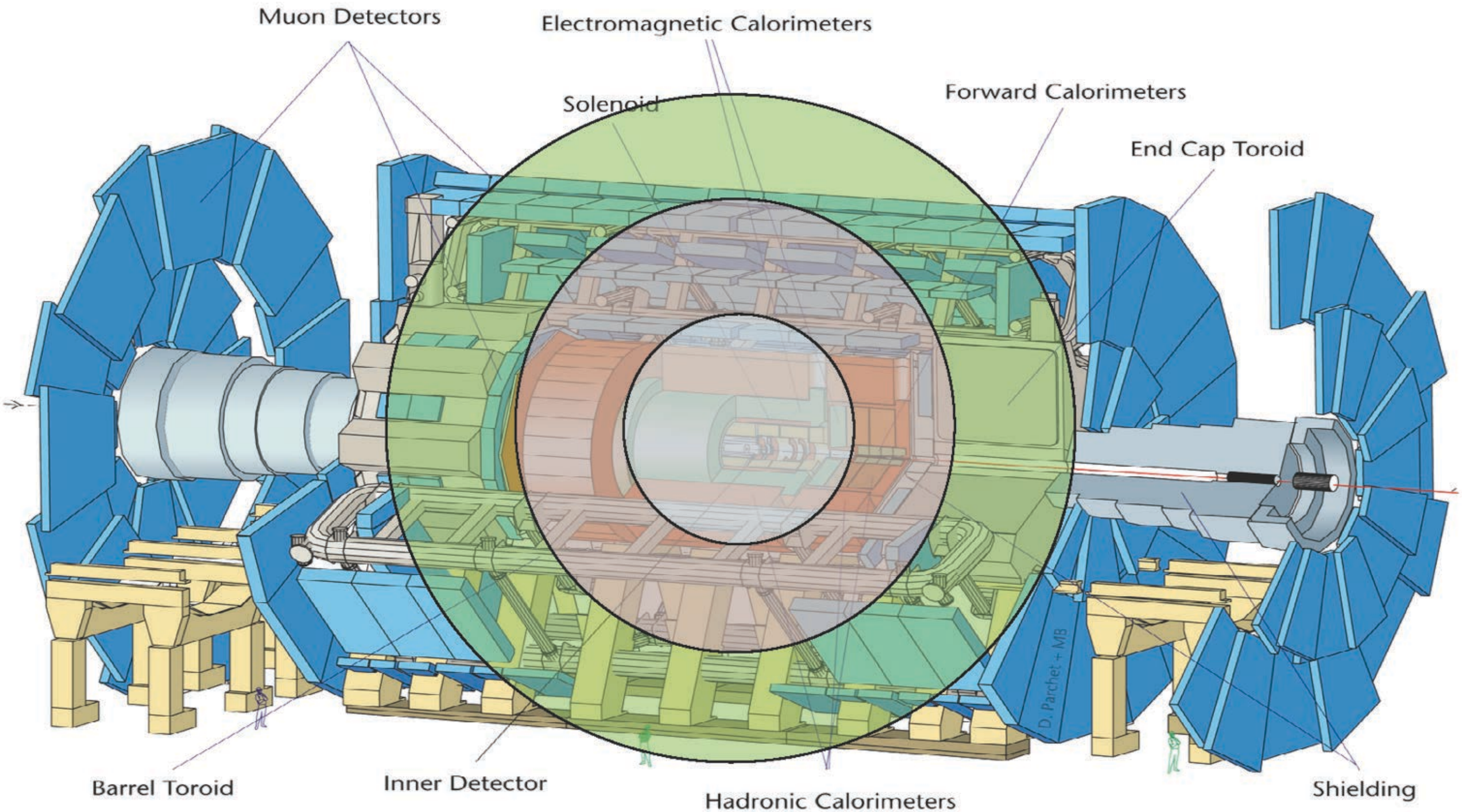
- "In-time" pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"



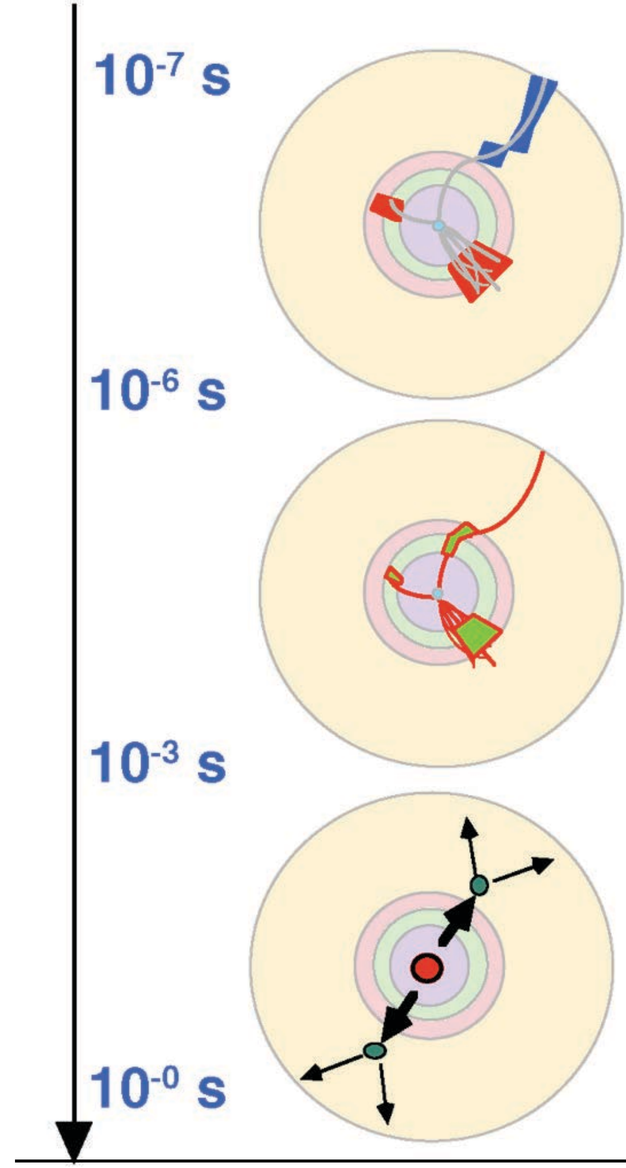


Challenges: Time of Flight

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, ..)

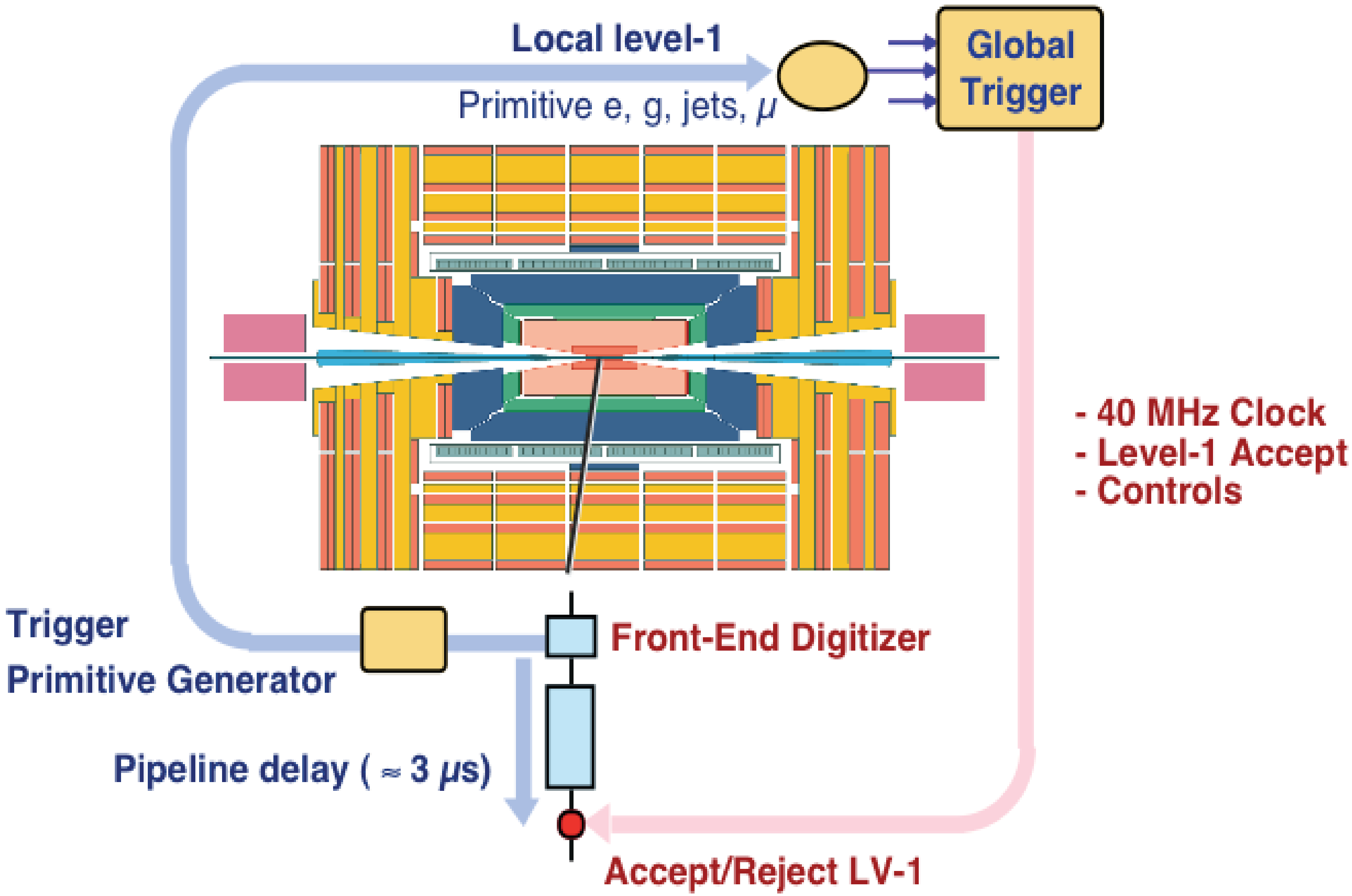
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

Level-3 events to tape 100- 300 Hz

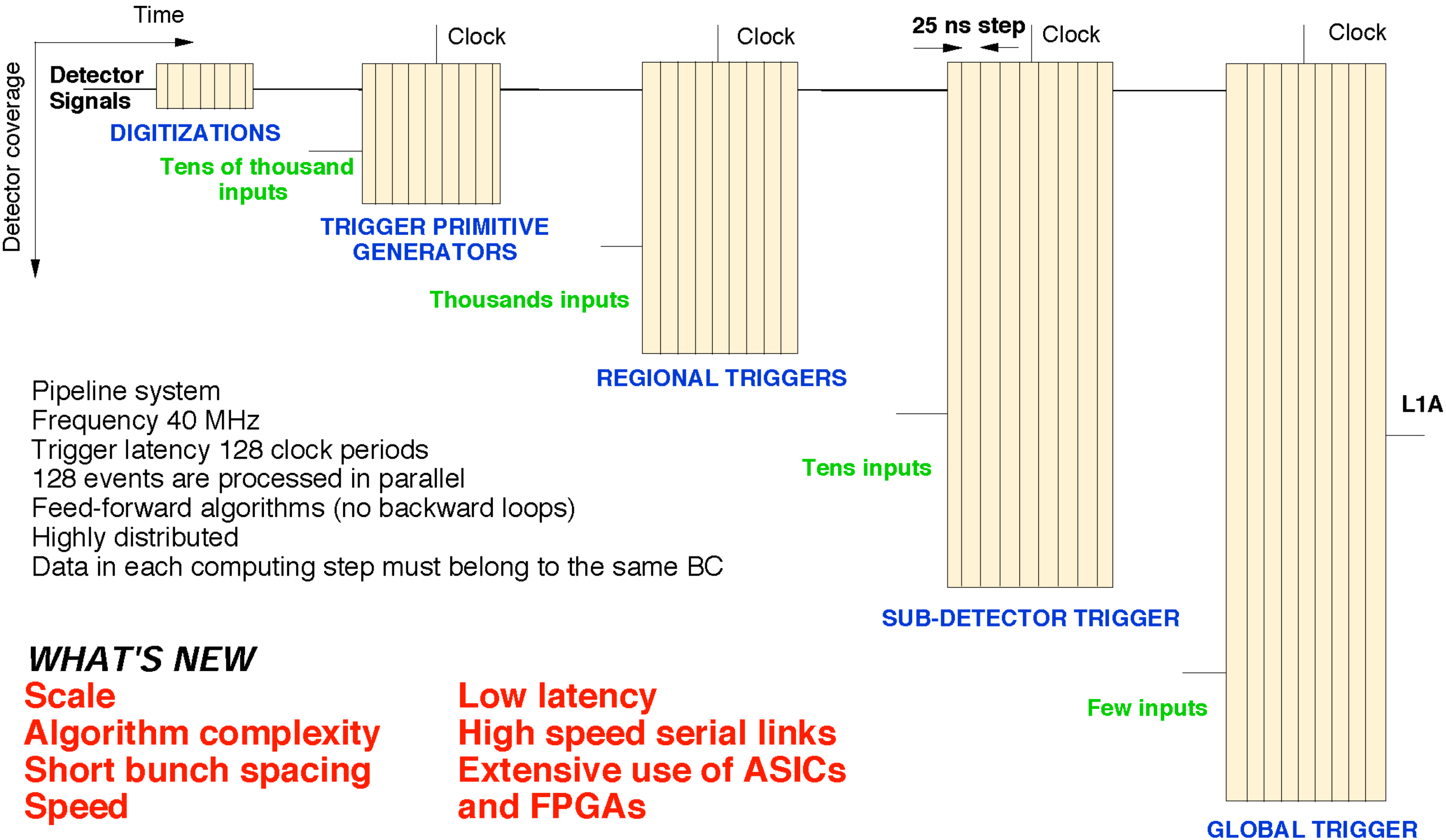
Physics process identification

- Event reconstruction and analysis

Level 1 Trigger Operation



Level 1 Trigger Organization



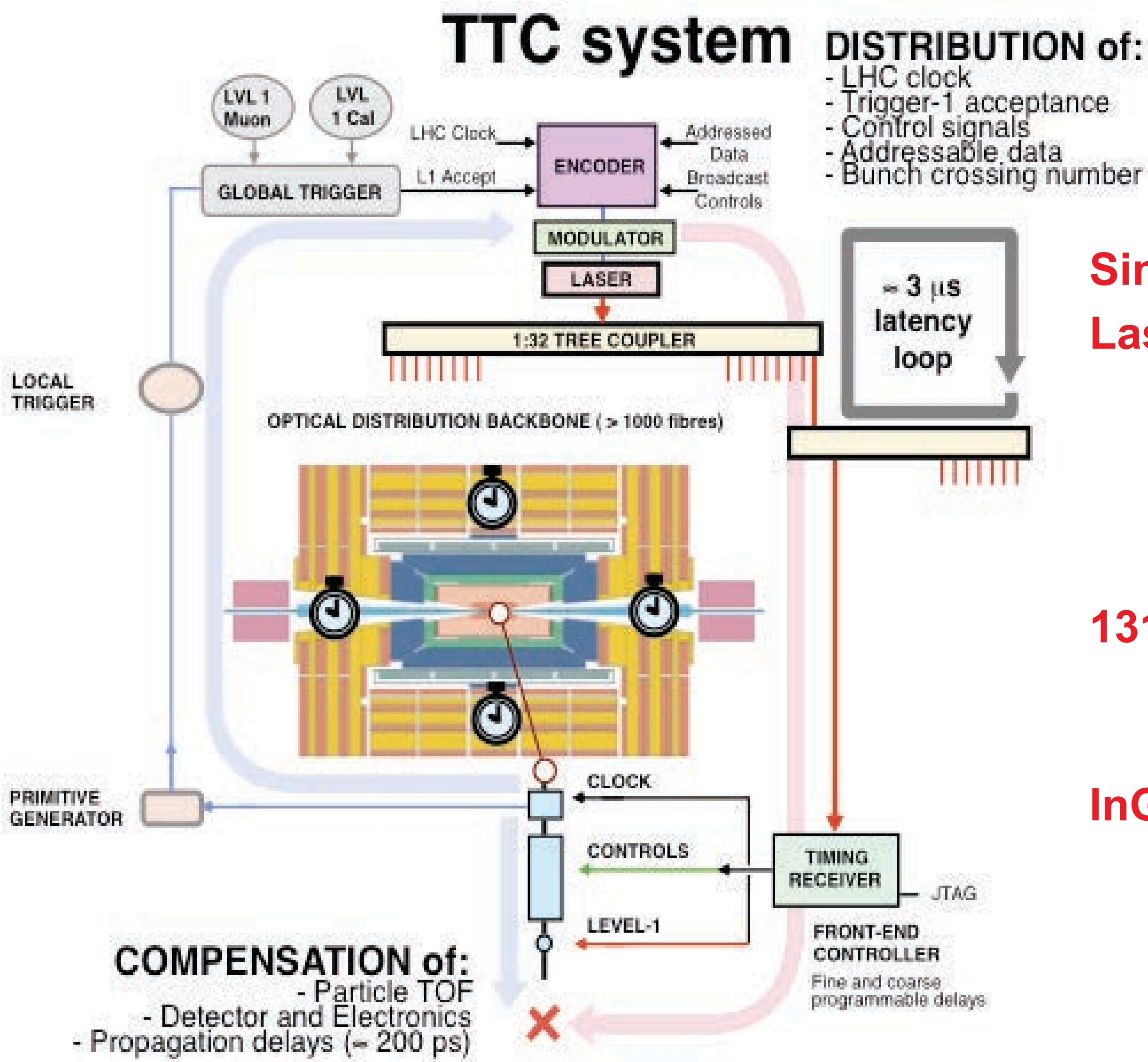
Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

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**

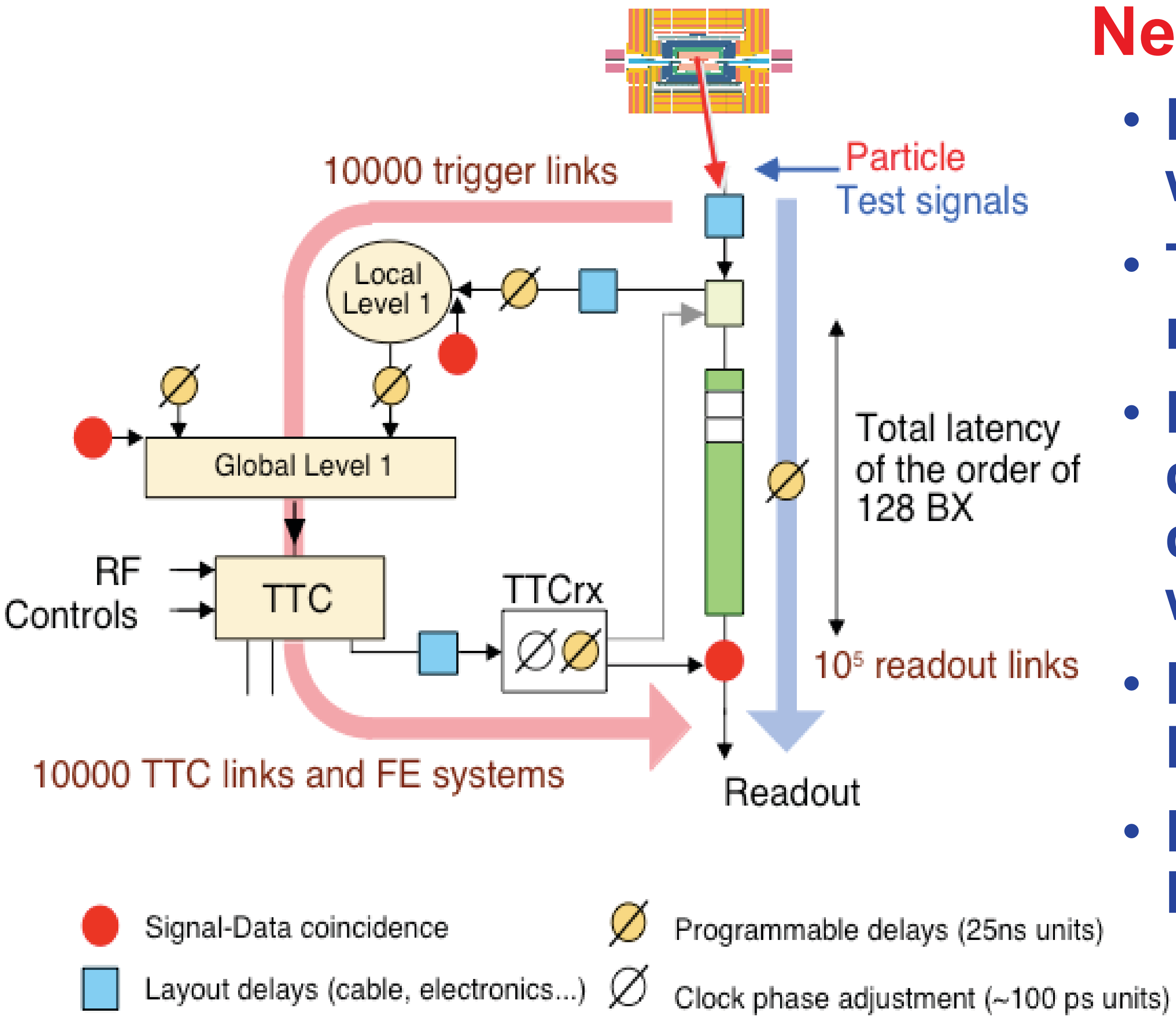
1310 nm Operation

- **Negligible chromatic dispersion**

InGaAs photodiodes

- **Radiation resistance, low bias**

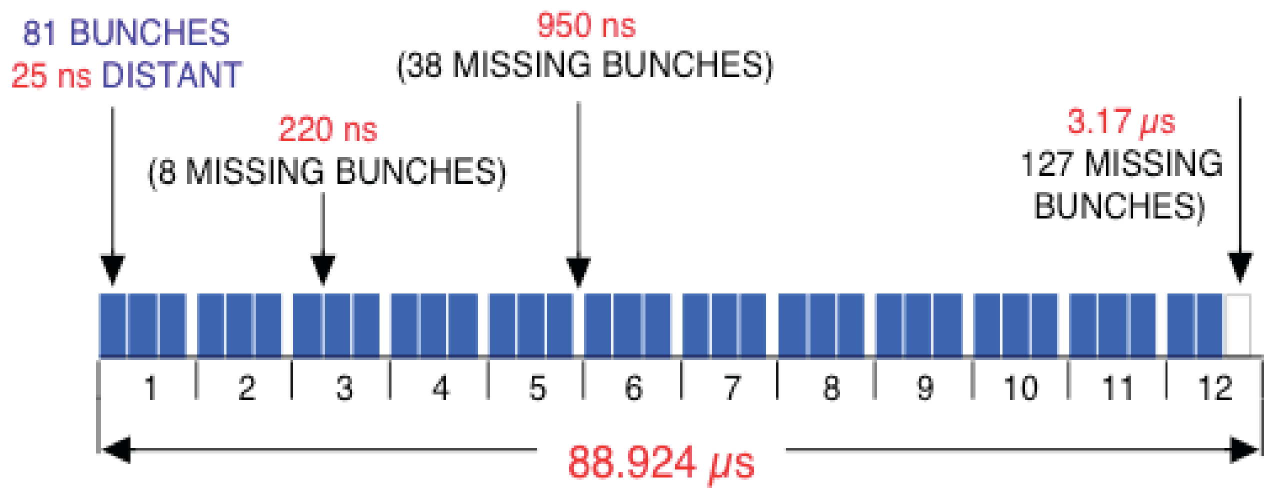
Detector Timing Adjustments



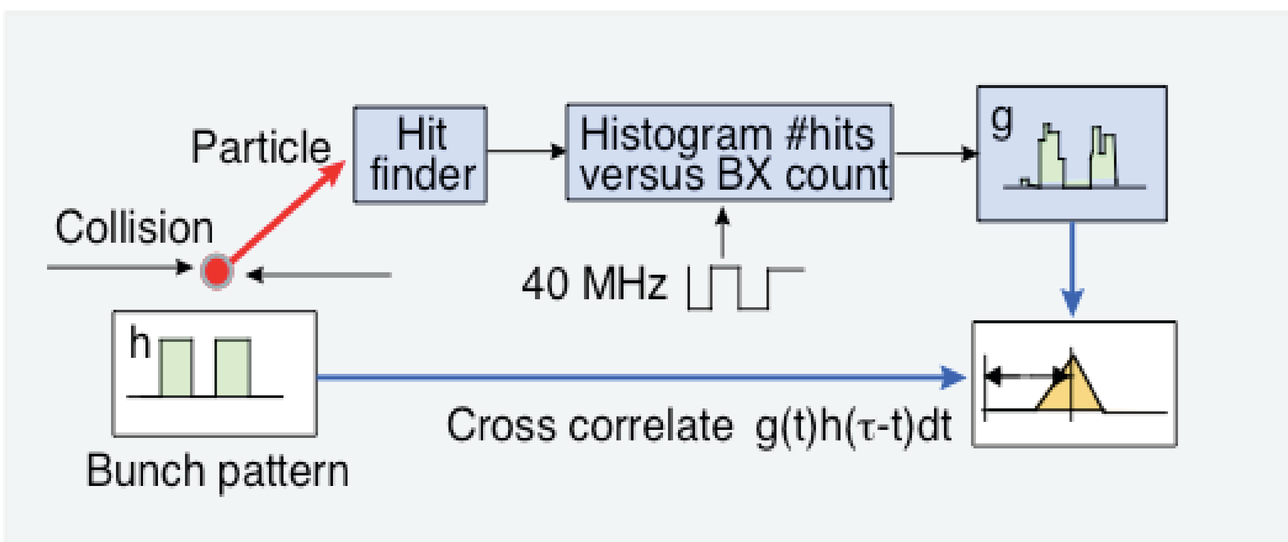
Need to Align:

- 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

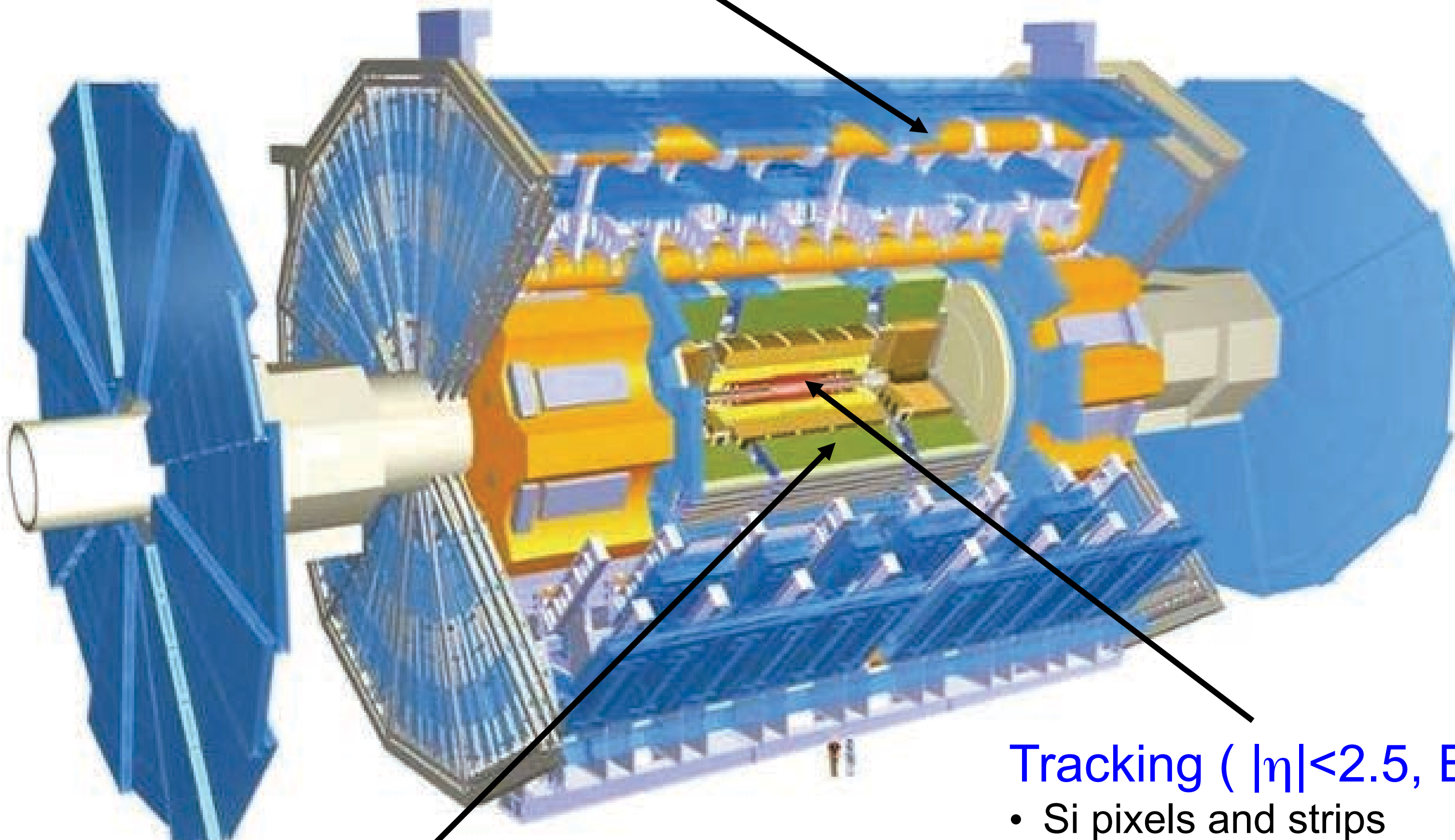


2835 out of 3564 p bunches are full, use this pattern:



ATLAS Detector Design

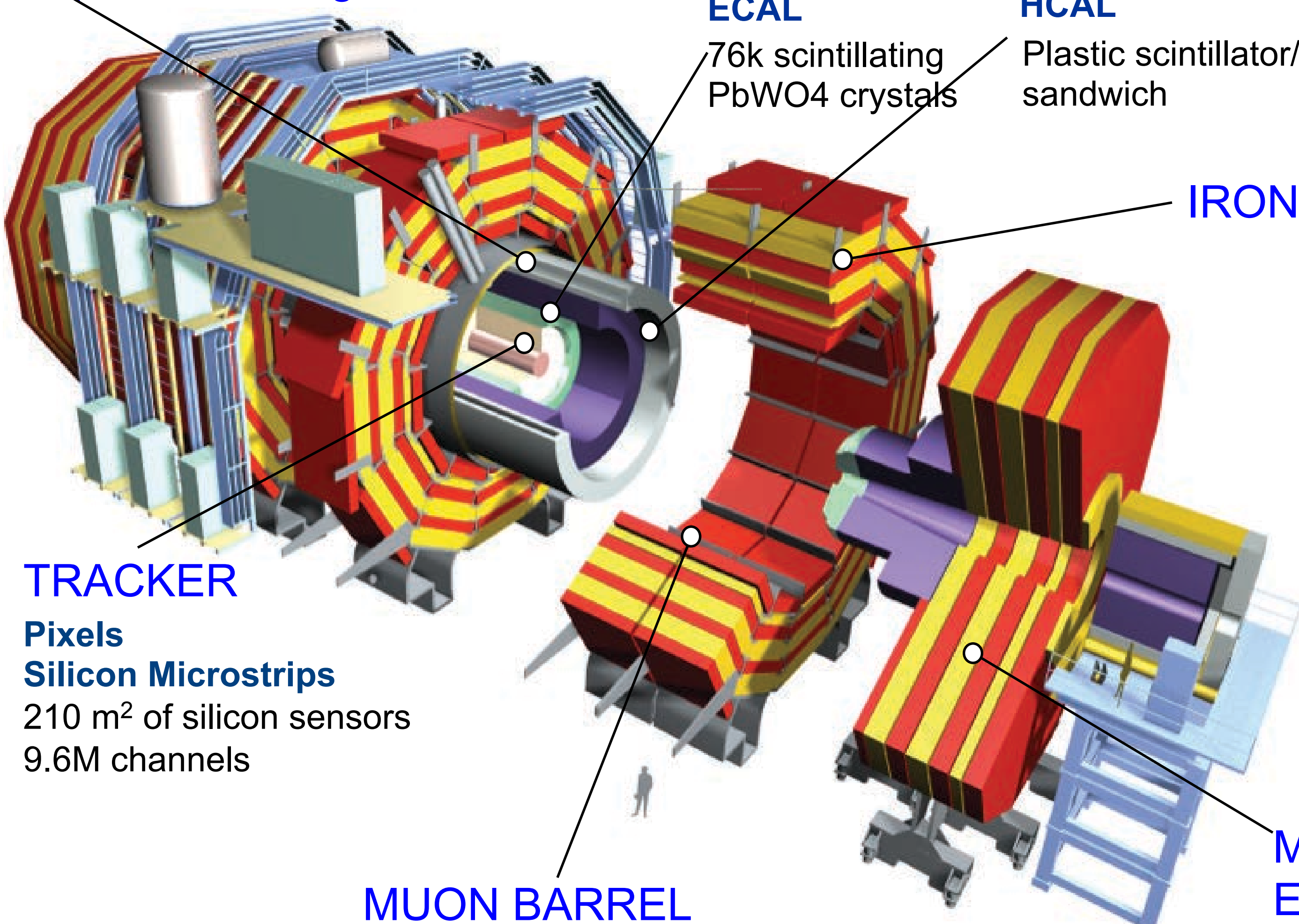
Muon Spectrometer (|η|<2.7)
- air-core toroids with muon chambers



Tracking (|η|<2.5, B=2T)
- Si pixels and strips
- TRD (e/π separation)

Calorimetry (|η|<5)
- EM : Pb-LAr
- HAD : Fe/scintillator (central), Cu/W-Lar (fwd)

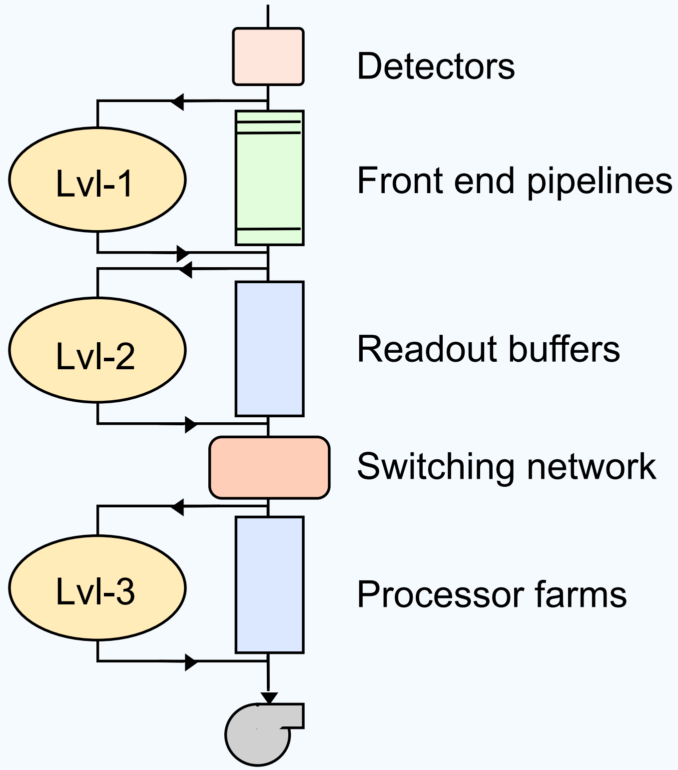
CMS Detector Design



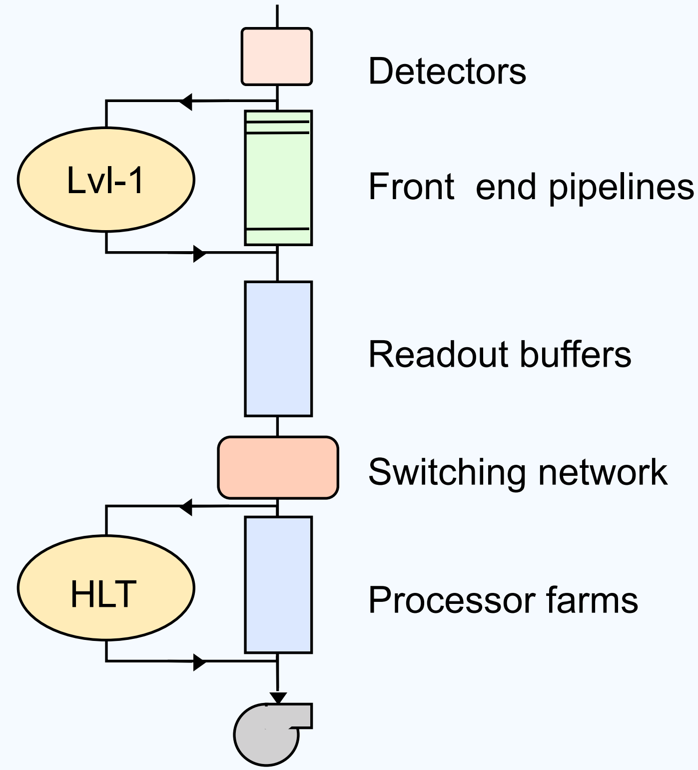
ATLAS & CMS Trigger & Readout Structure

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

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



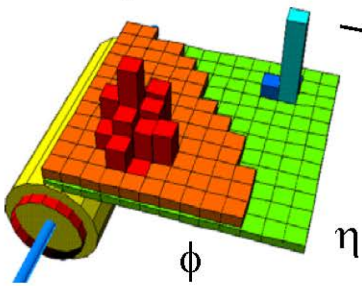
ATLAS: 3 physical levels

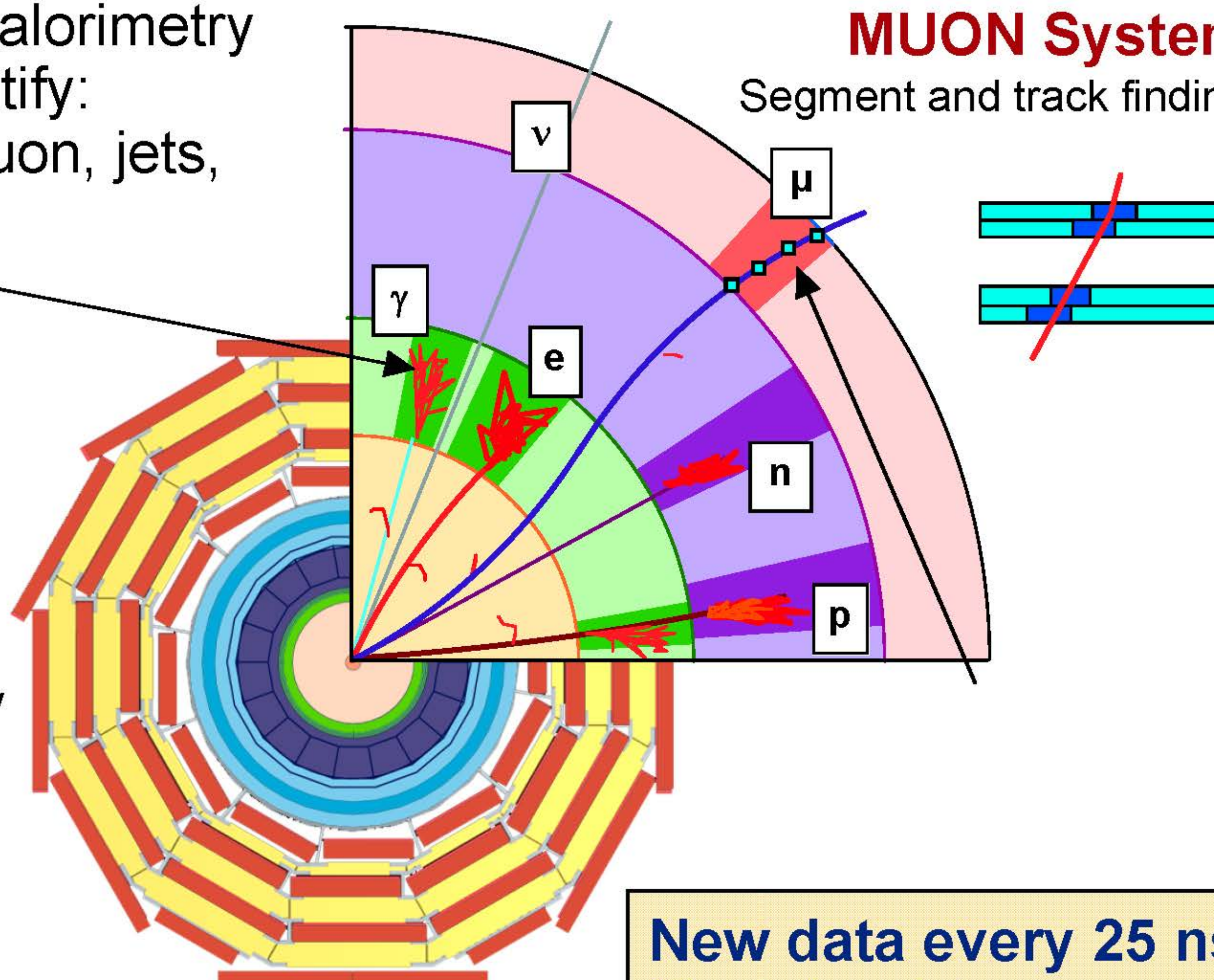


CMS: 2 physical levels

ATLAS & CMS Trigger Data

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





MUON System

Segment and track finding

CALORIMETERs

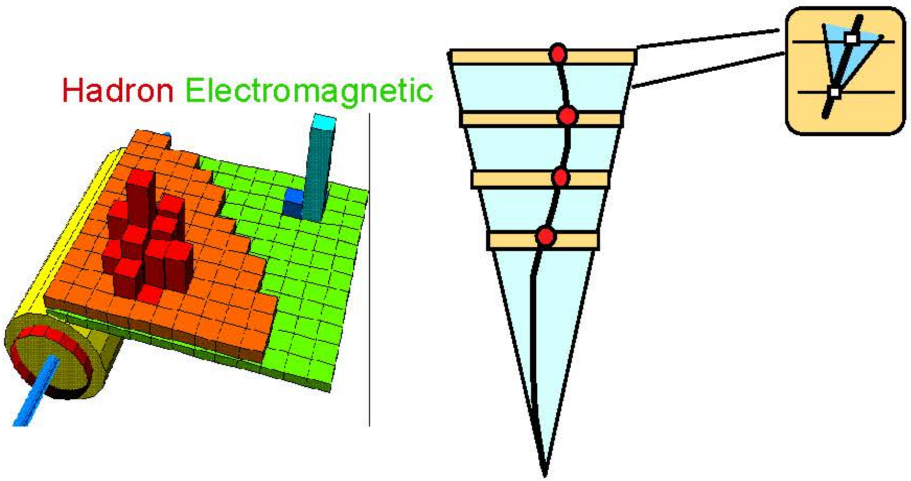
Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ μs

ATLAS & CMS Level 1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

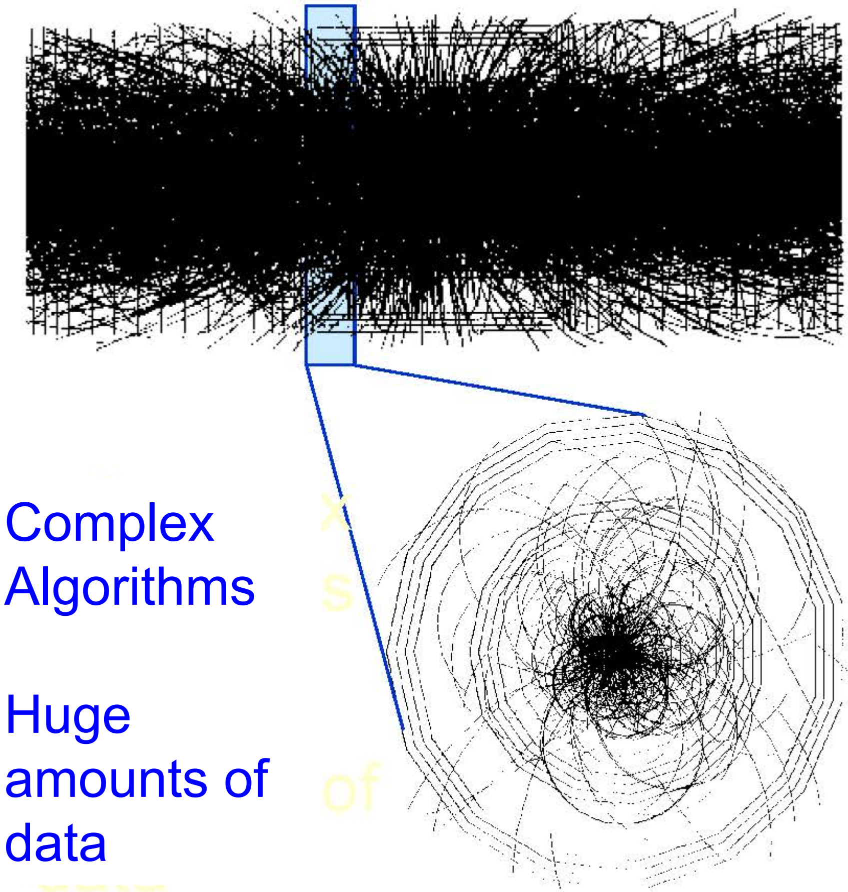
- **Pattern recognition much faster/easier**



Simple Algorithms

Small amounts of data

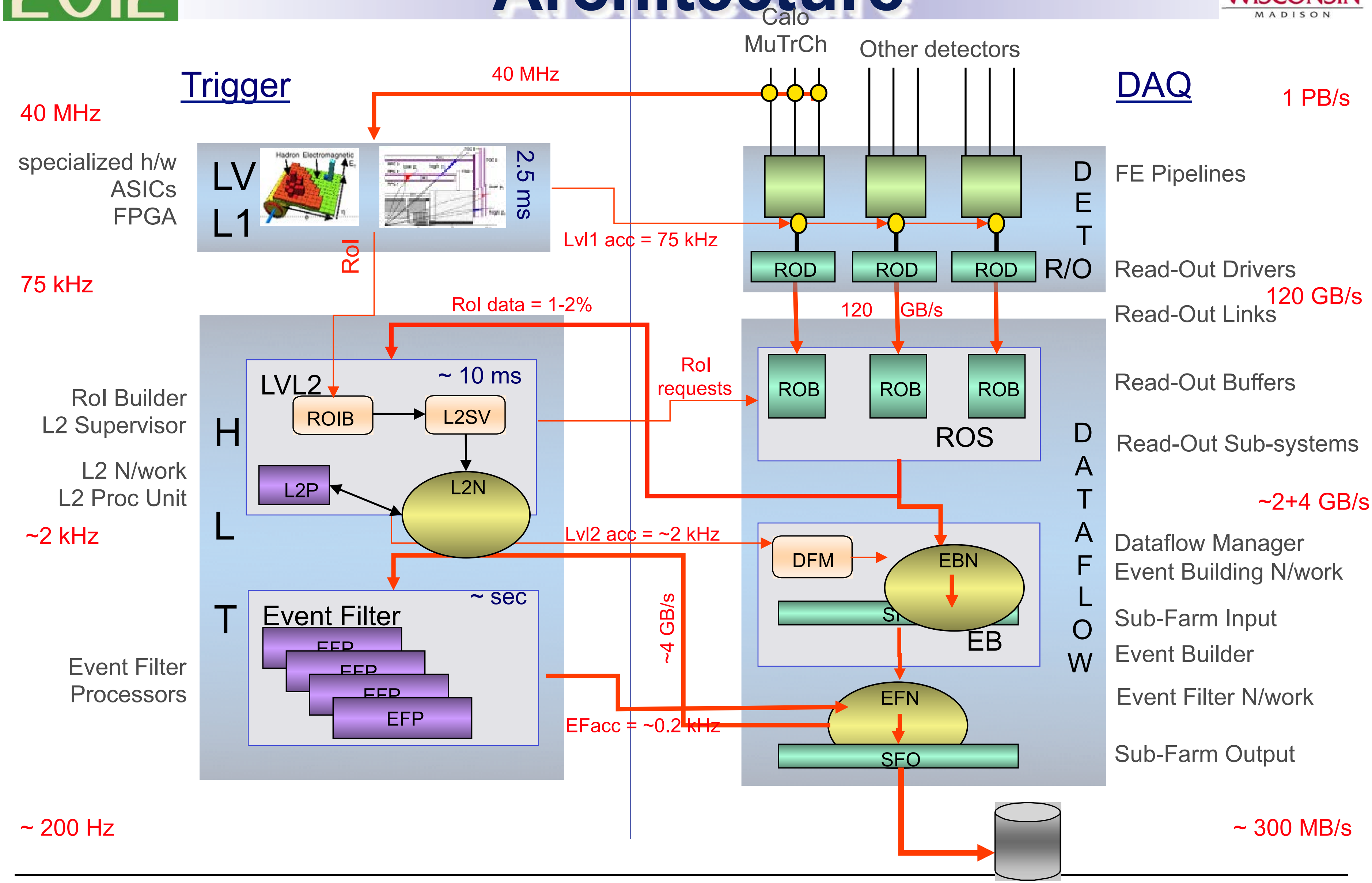
- **Compare to tracker info**



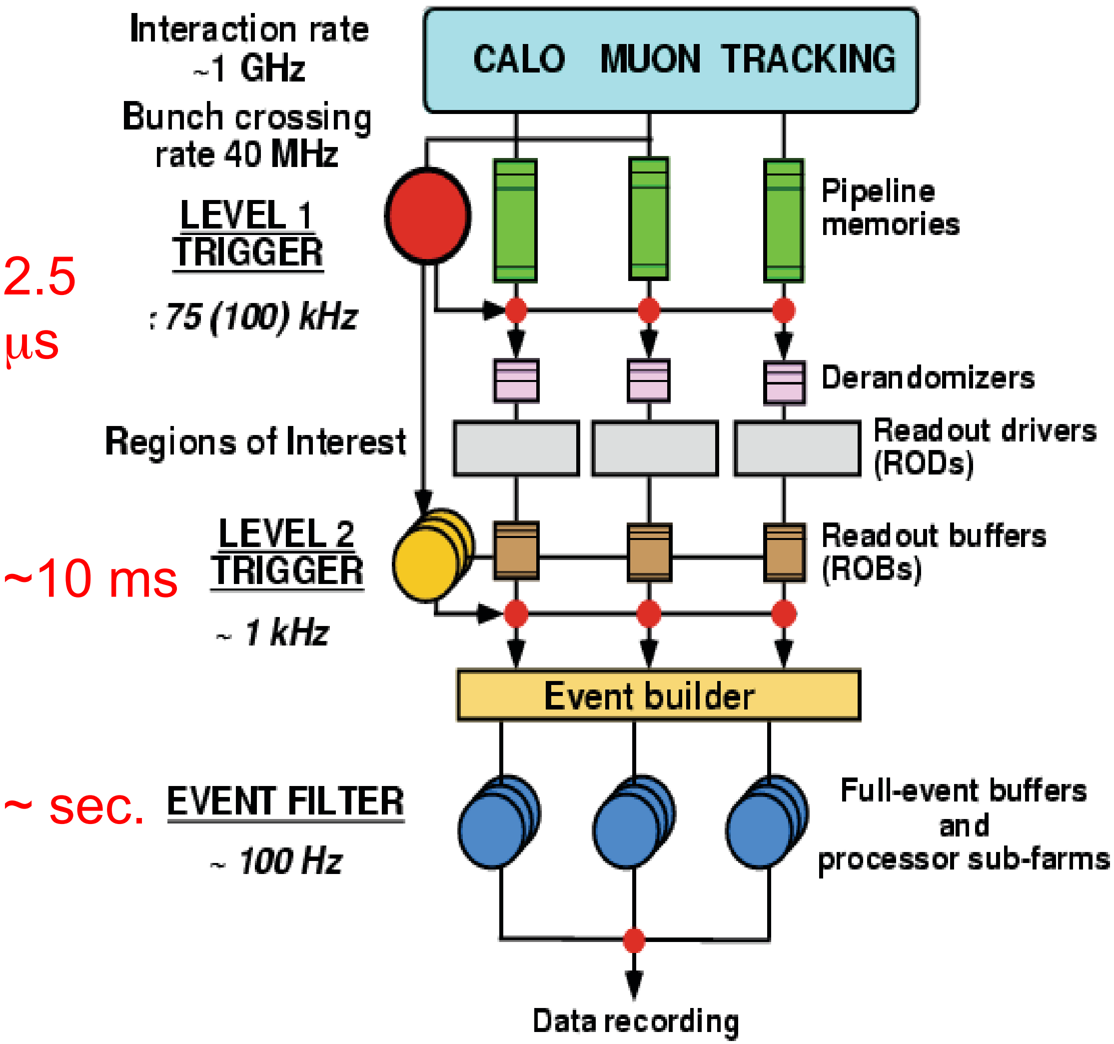
Complex Algorithms

Huge amounts of data

ATLAS Trigger & DAQ Architecture

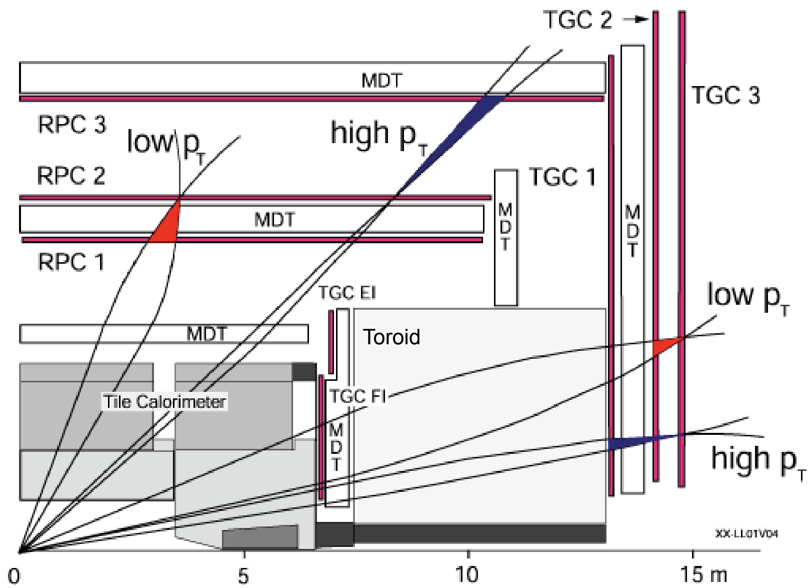


ATLAS Three Level Trigger Architecture



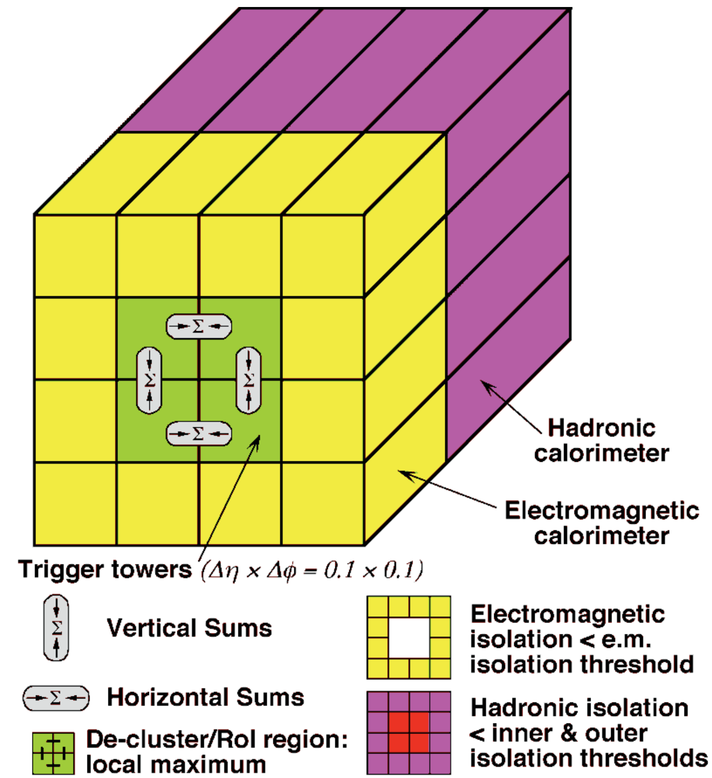
- **LVL1 decision made with calorimeter data with coarse granularity and muon trigger chambers data.**
  - **Buffering on detector**
- **LVL2 uses Region of Interest data (ca. 2%) with full granularity and combines information from all detectors; performs fast rejection.**
  - **Buffering in ROBs**
-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

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)

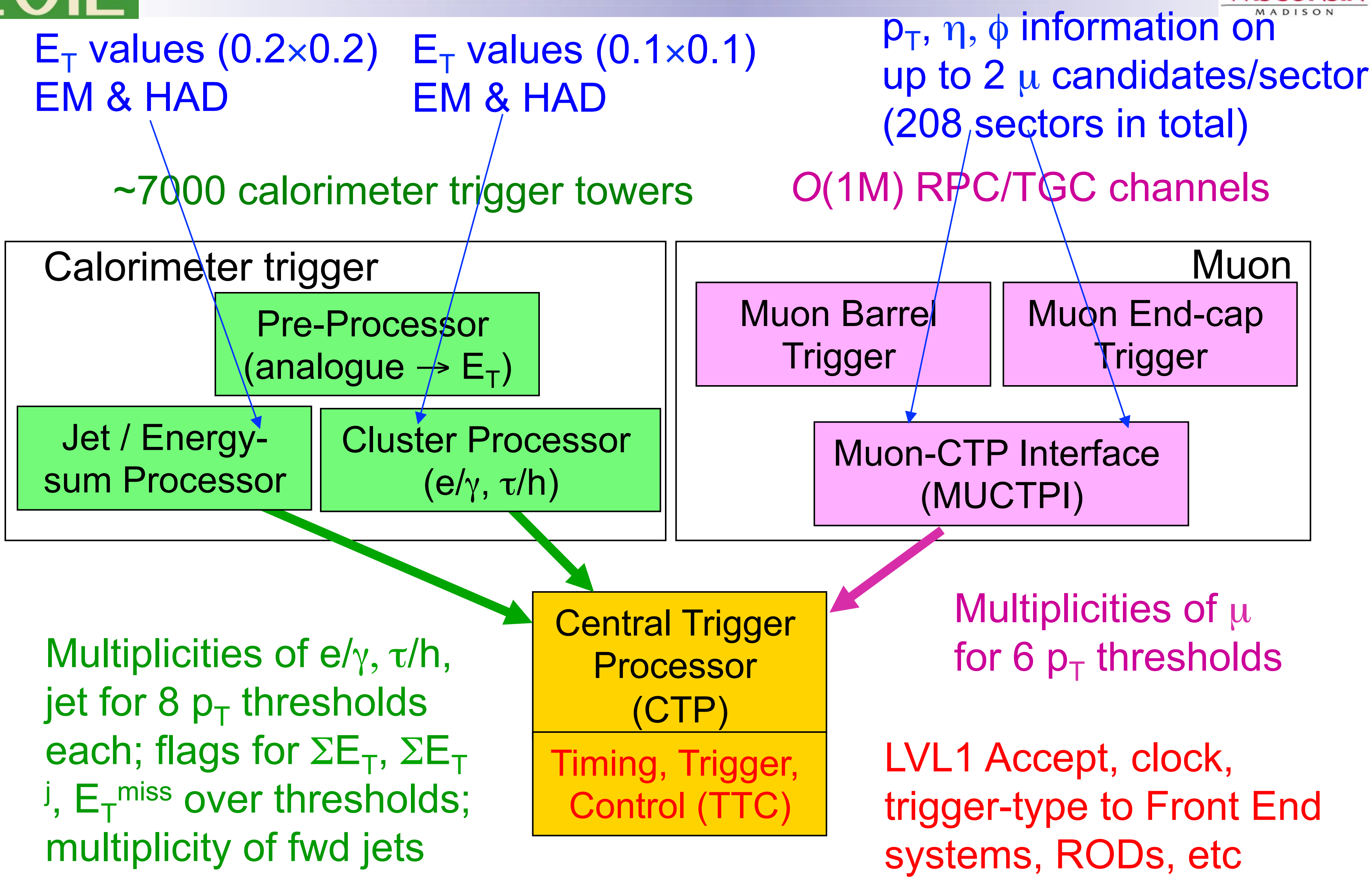
Trigger efficiency 99% (low-p_T) and 98% (high-p_T)



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

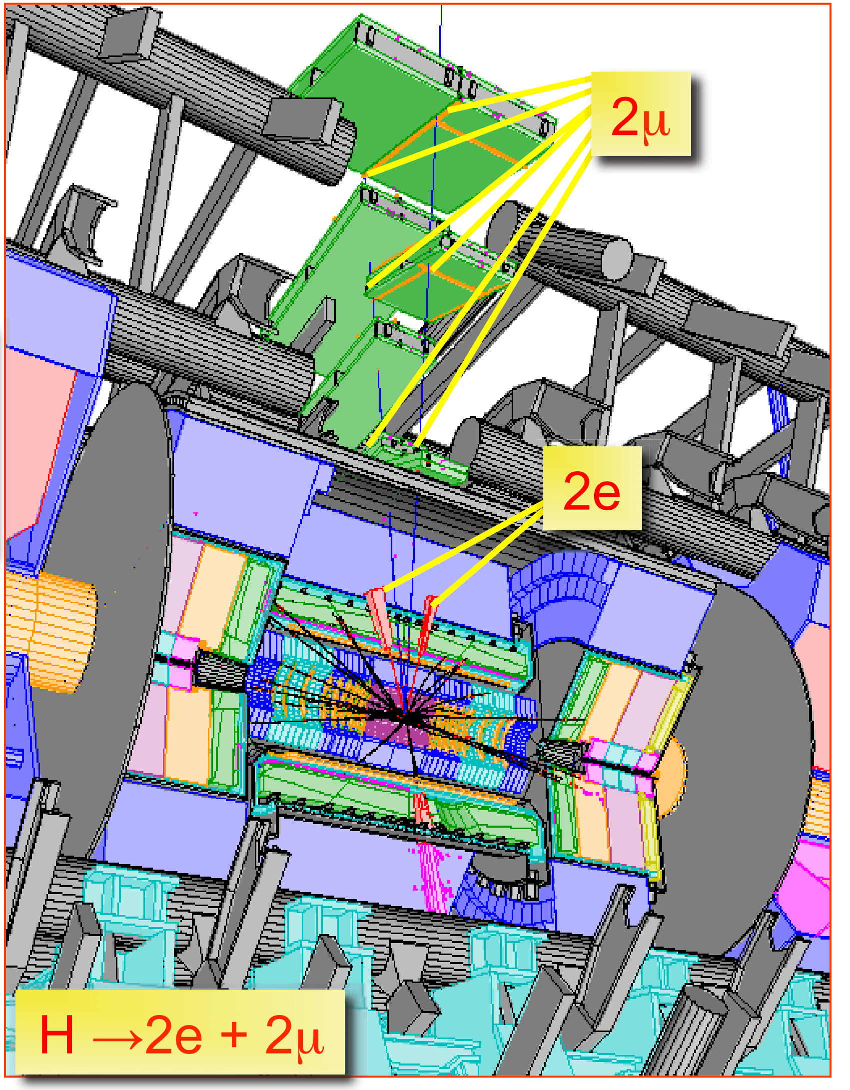
- **Caloriemeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

LVL2 uses Regions of Interest as identified by Level-1

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

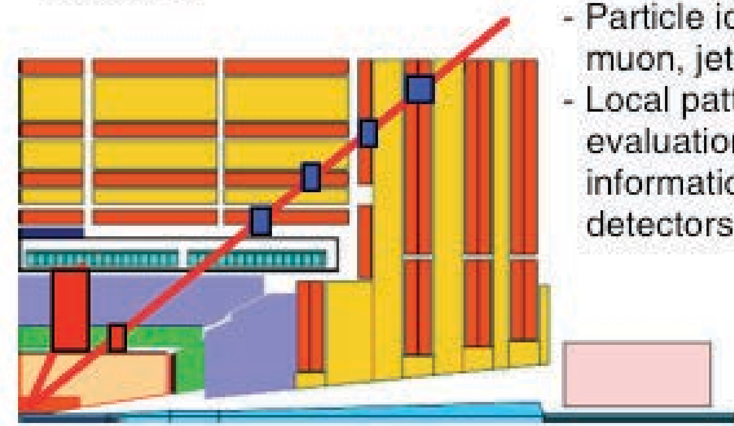
The total amount of RoI data is minimal

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



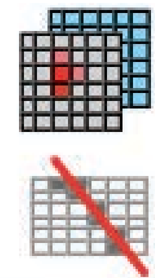
CMS Trigger Levels

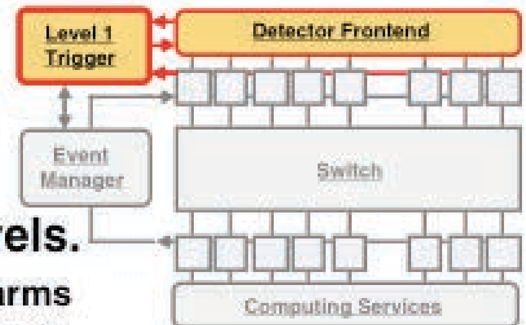
40 MHz



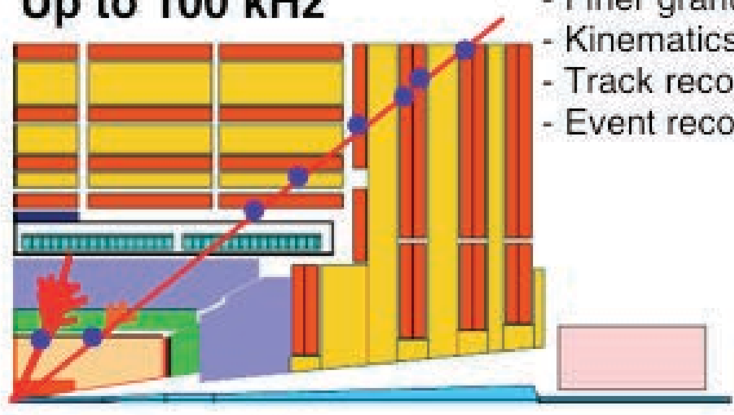
Level-1. **Specialized processors**

- 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

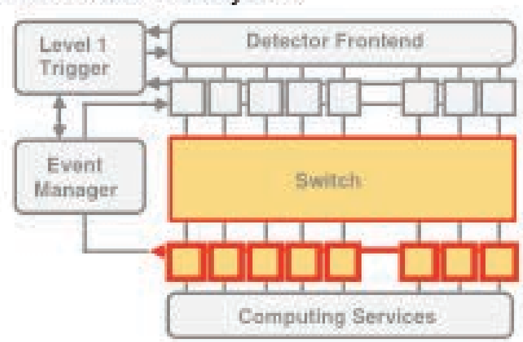


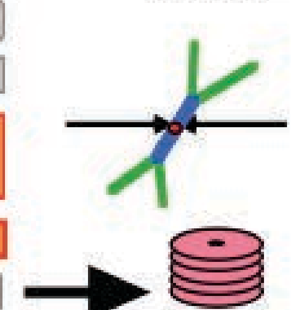
High trigger levels.

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



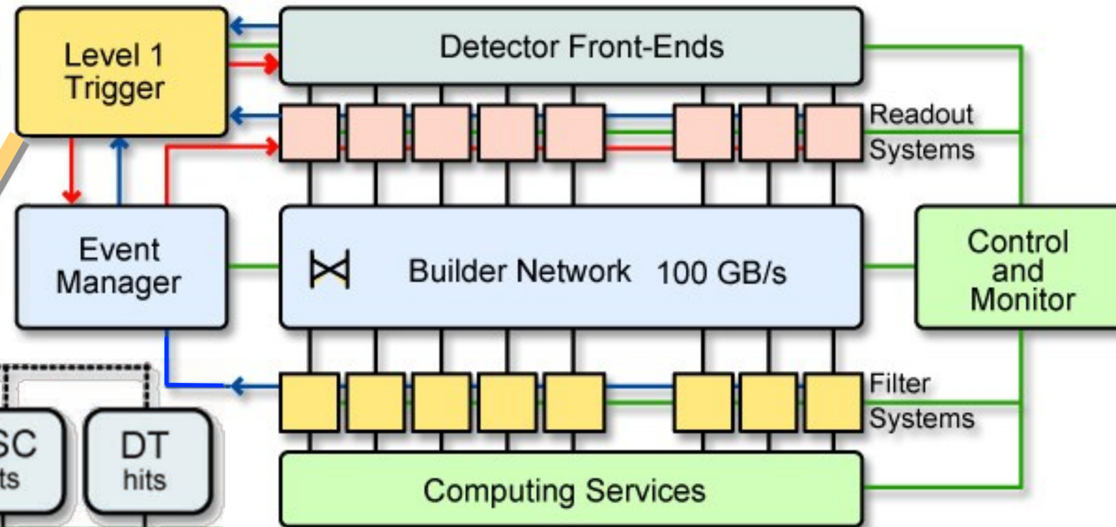


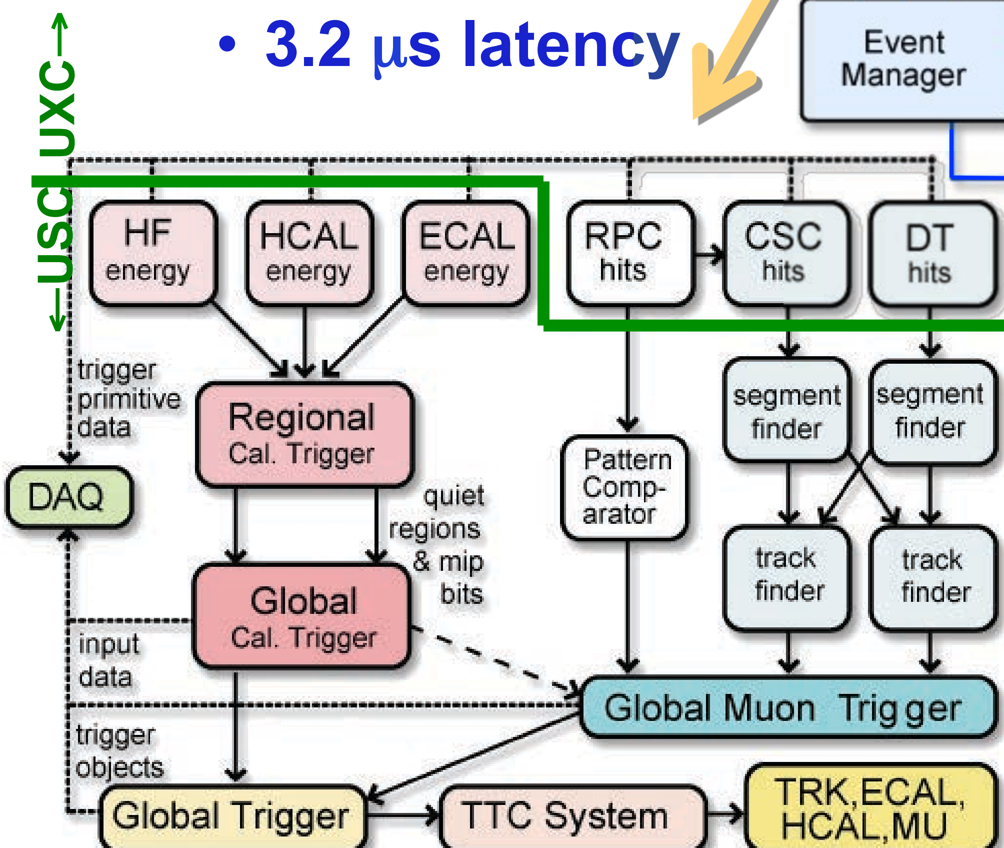
CMS Level-1 Trigger & DAQ

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

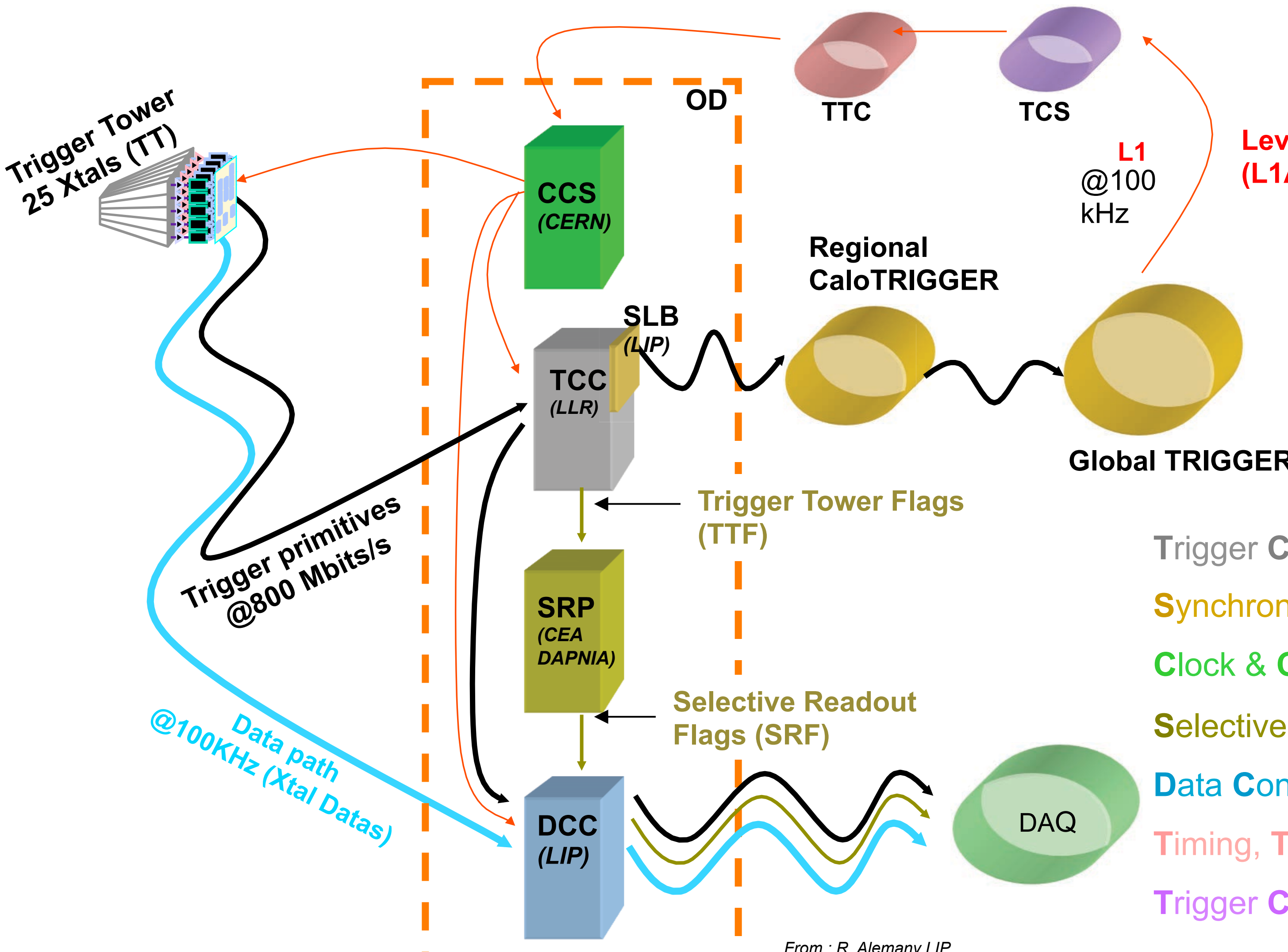
Level 1 Output: 100 kHz (50 initial)

Output to Storage: 100 Hz

Average Event Size: 1 MB

Data production 1 TB/day

Calorimeter Trigger Processing



Trigger Concentrator Card

Synchronisation & Link Board

Clock & Control System

Selective Readout Processor

Data Concentrator Card

Timing, Trigger & Control

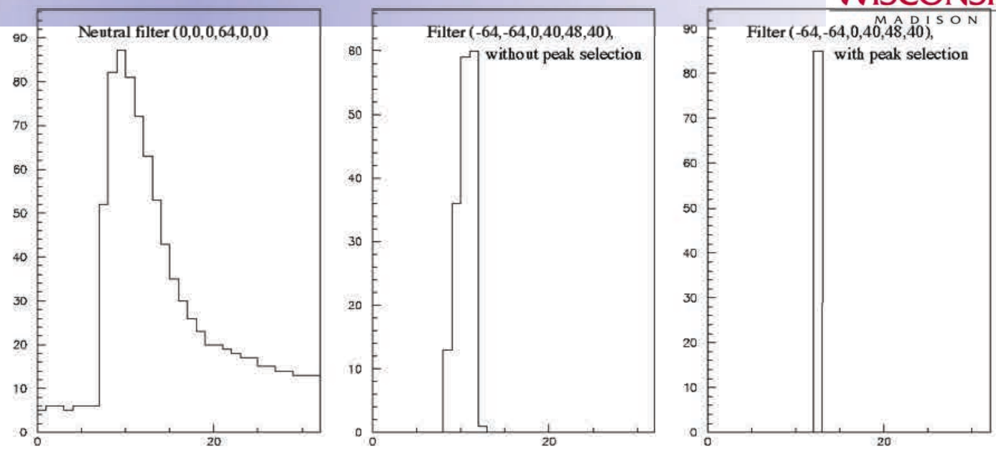
Trigger Control System

ECAL Trigger Primitives

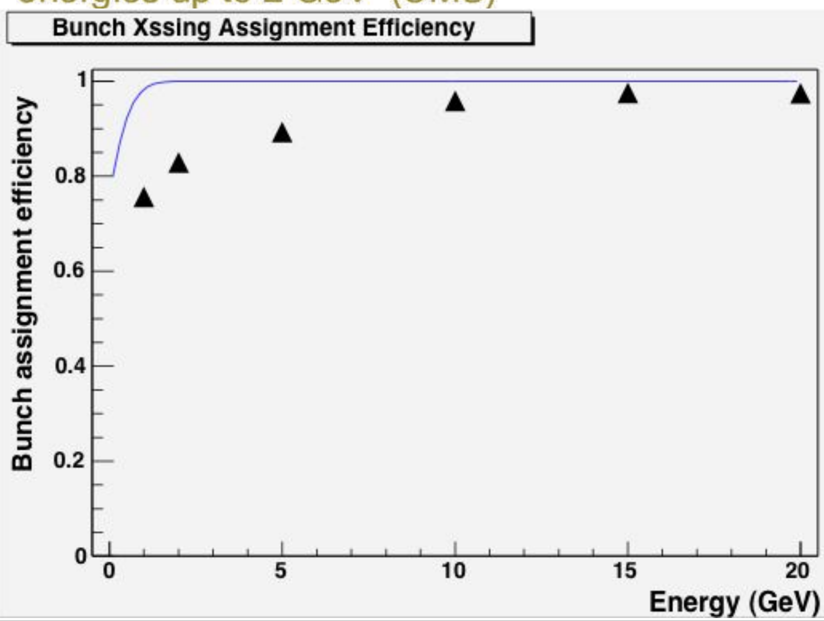
In the trigger path, **digital filtering** followed by a **peak finder** is applied to energy sums **(L1 Filter)**

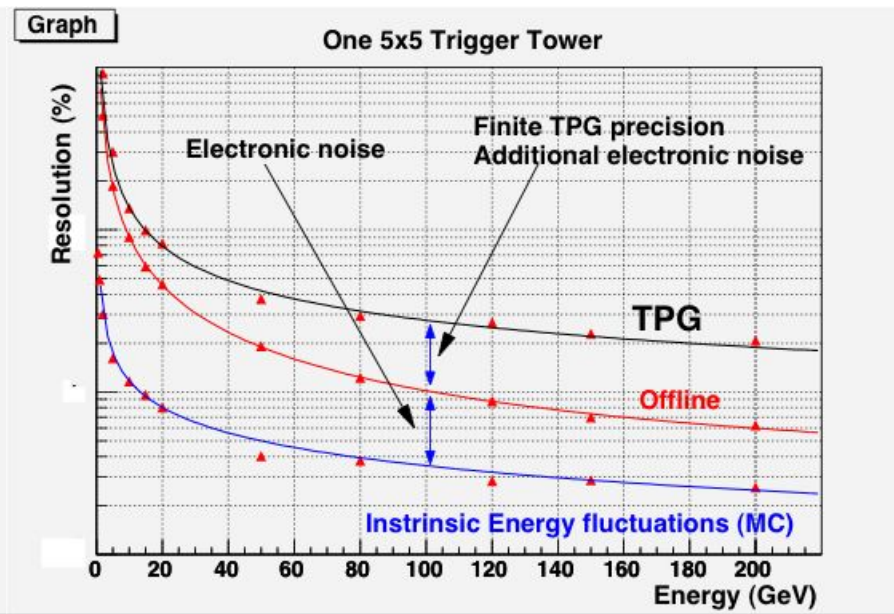
Efficiency for energy sums above 1 GeV should be close to 100% (depends on electronics noise)

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

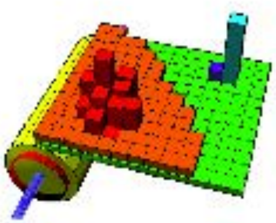
AND

Longitudinal cut (H/E) — / < 0.05

AND

Isolation, Hadronic & EM — < 2 GeV

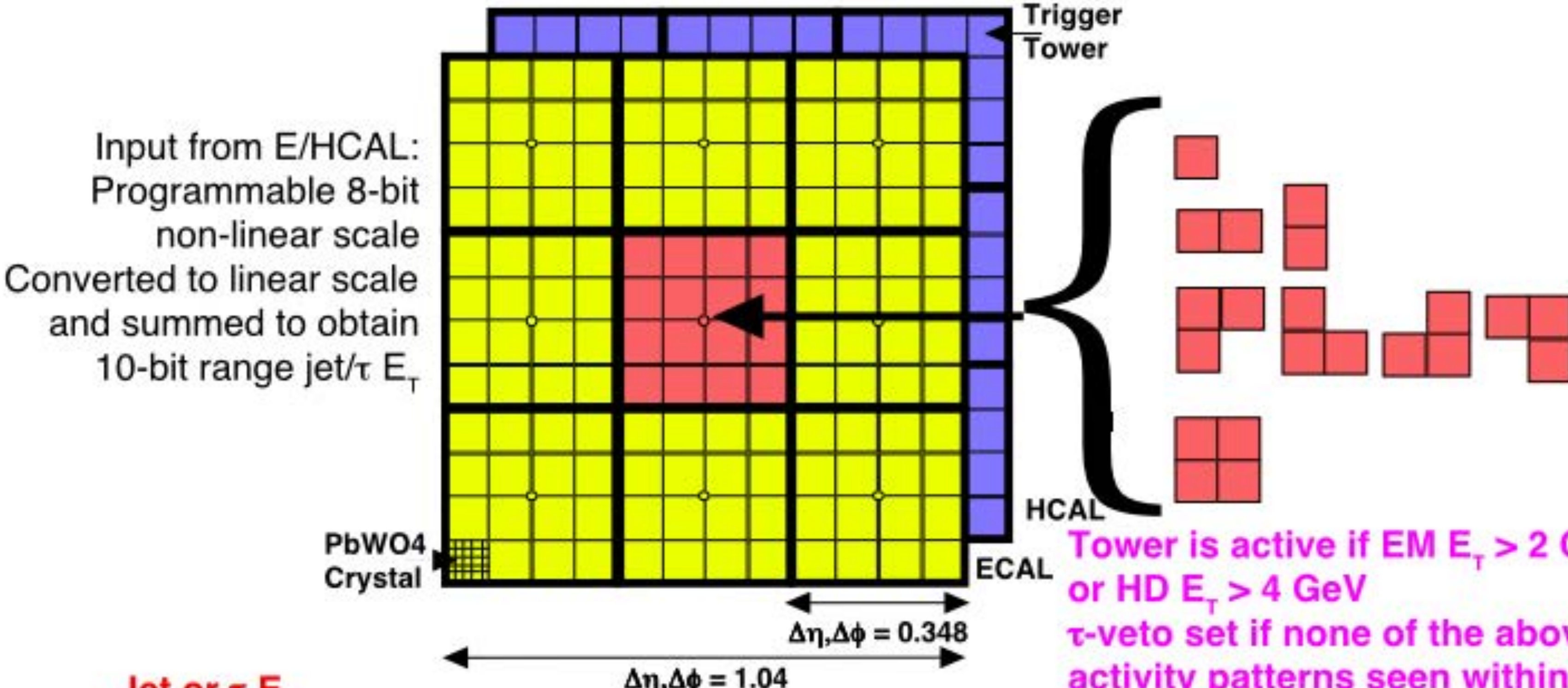
AND



One of (, , ,) < 1 GeV

ELECTRON or PHOTON

CMS τ / Jet Algorithm



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

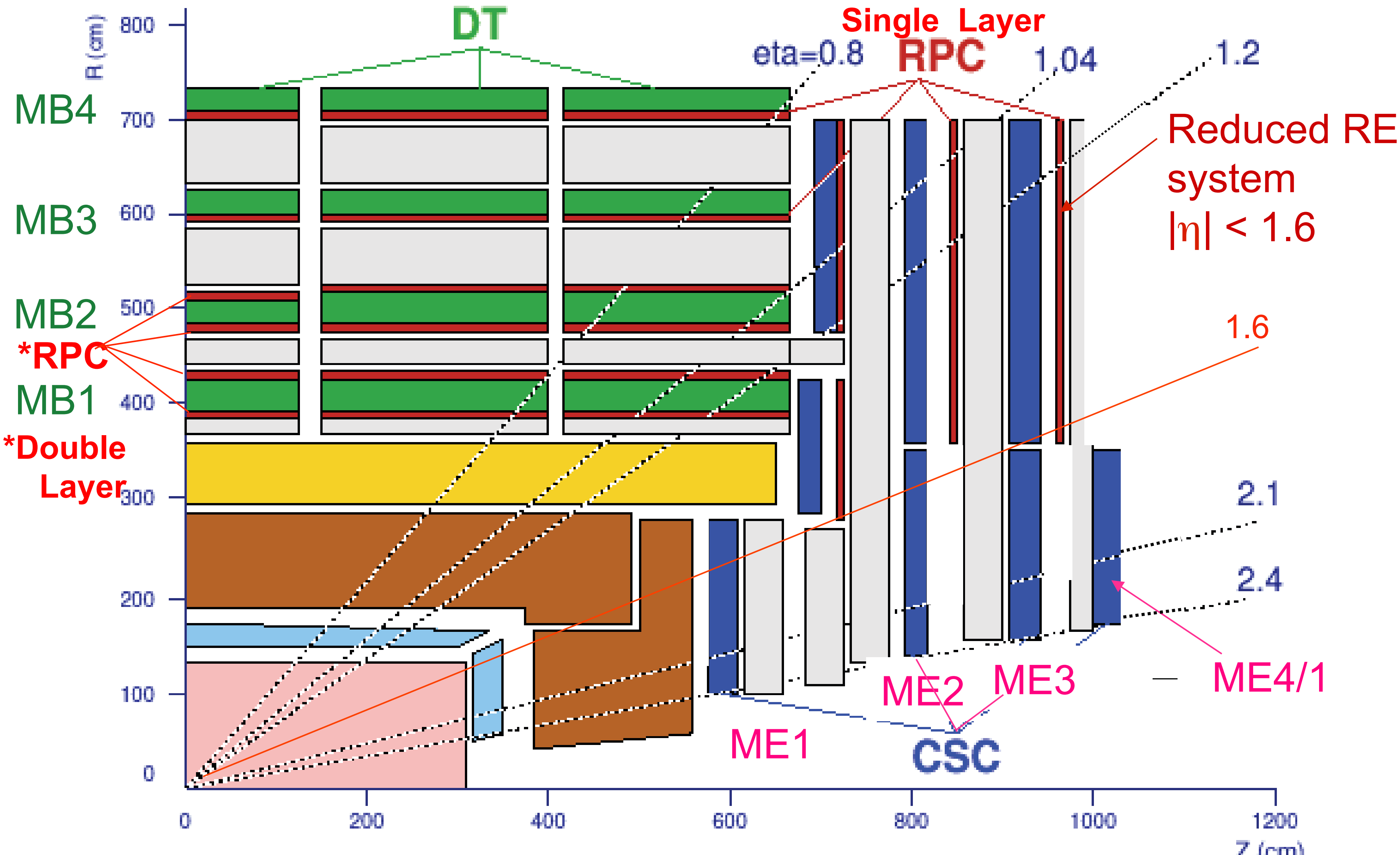
τ algorithm (isolated narrow energy deposits), within -2.5 < η < 2.5

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

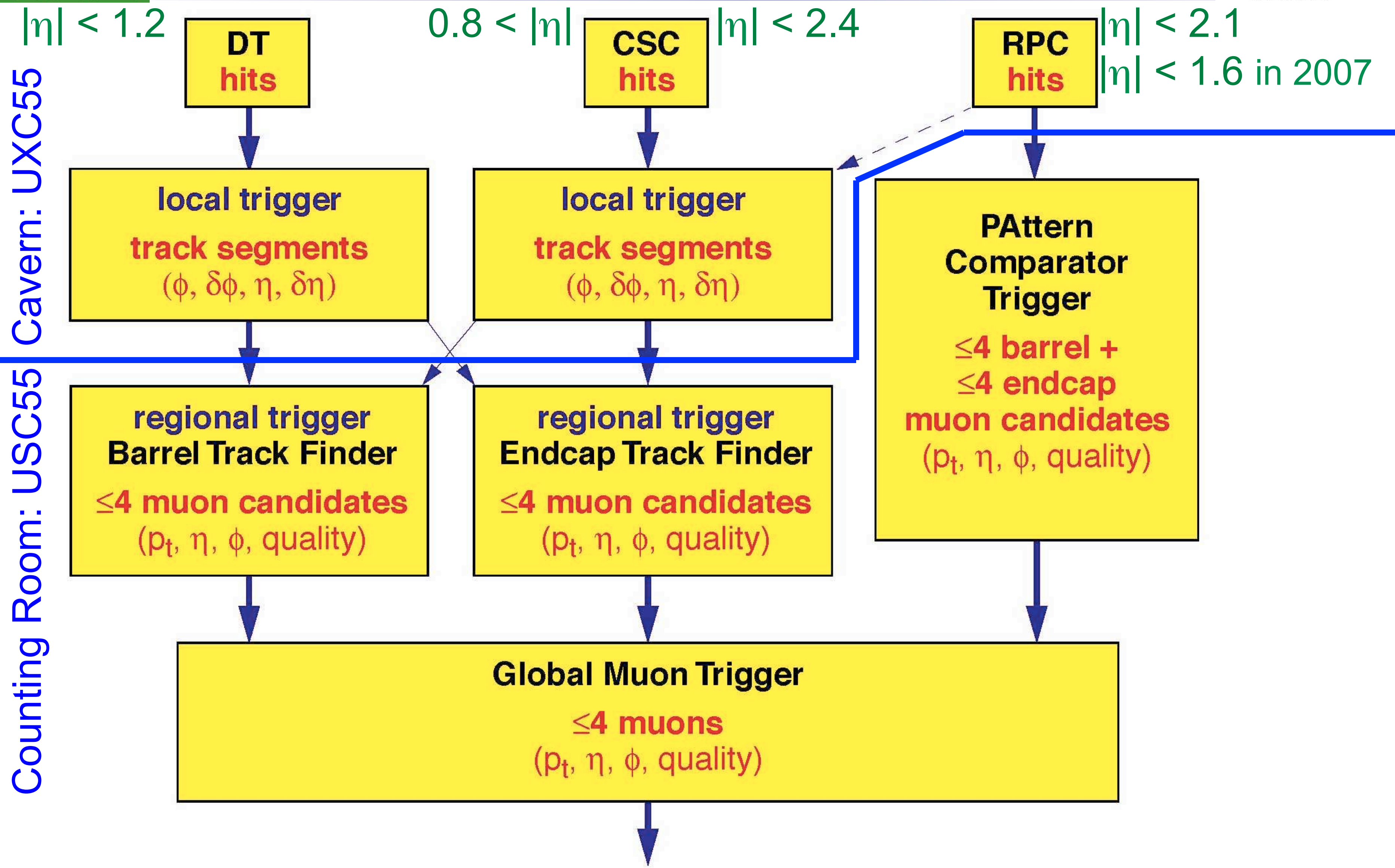
Output

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

CMS Muon Chambers

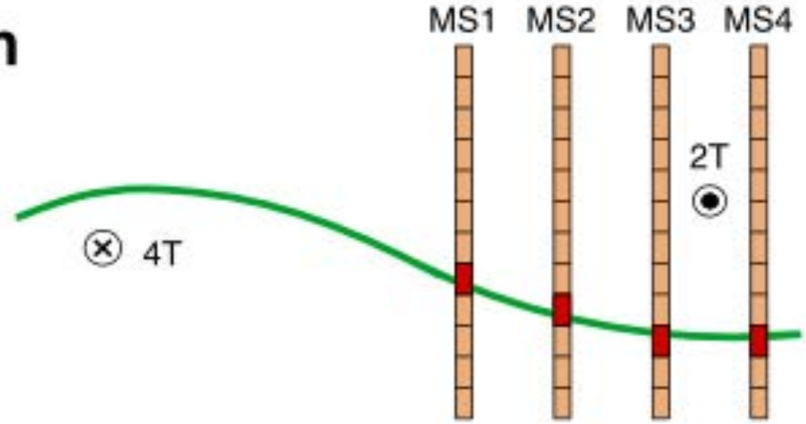


Muon Trigger Overview



CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

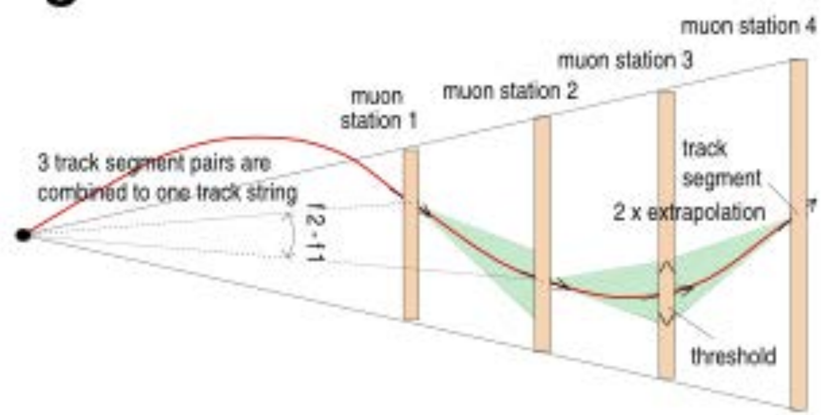


Memory to store patterns

Fast logic for matching

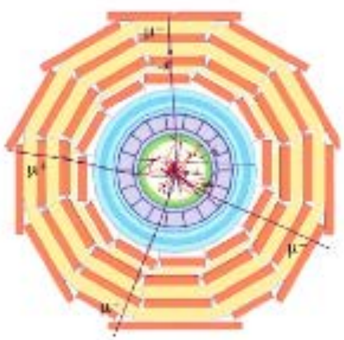
FPGAs are ideal

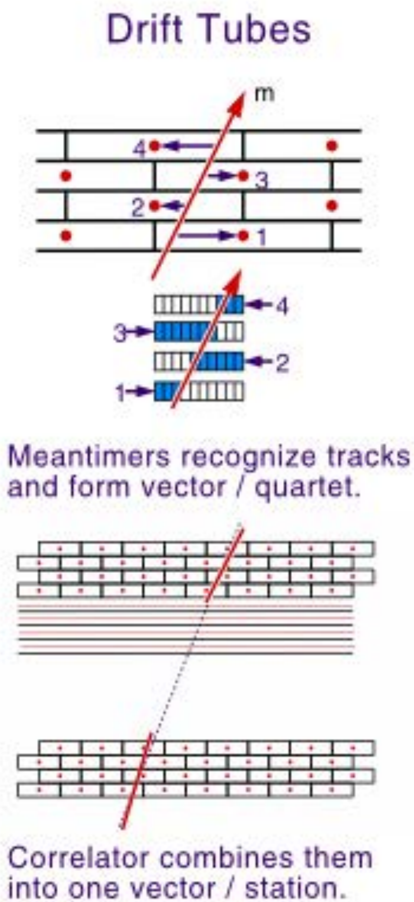
DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



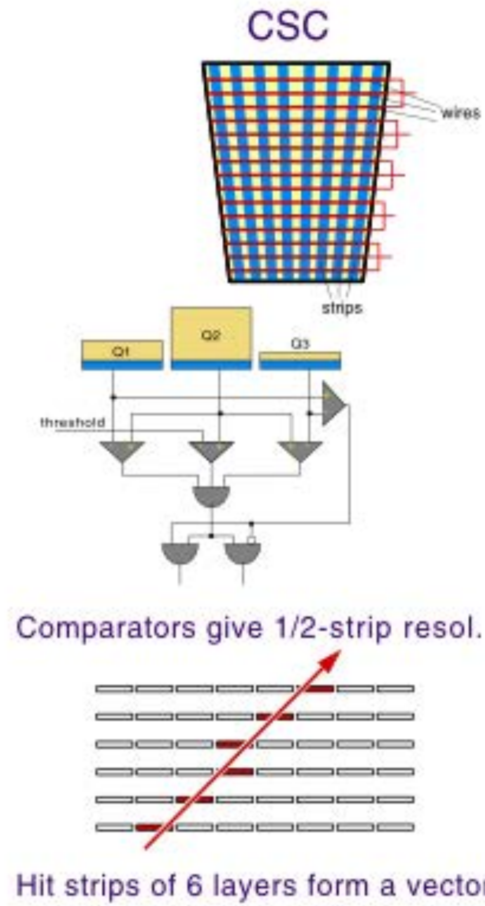
CMS Muon Trigger Track Finders

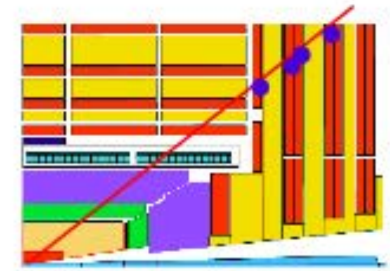
Drift Tubes (DT)





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

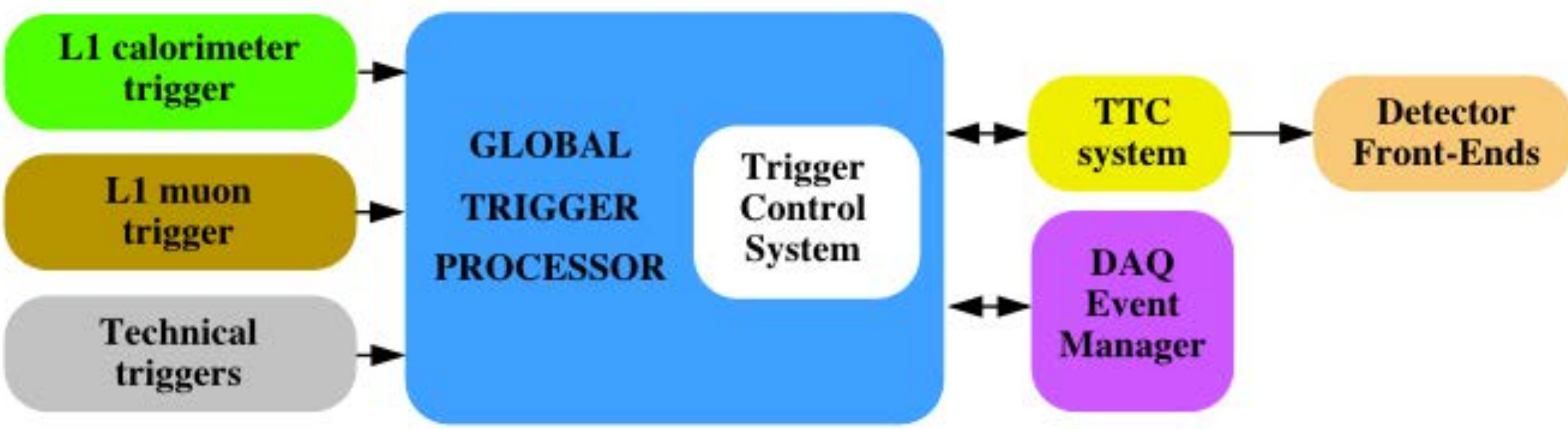
CMS Global Trigger

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

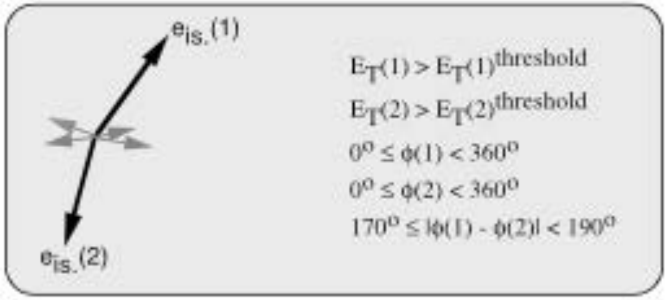
Output

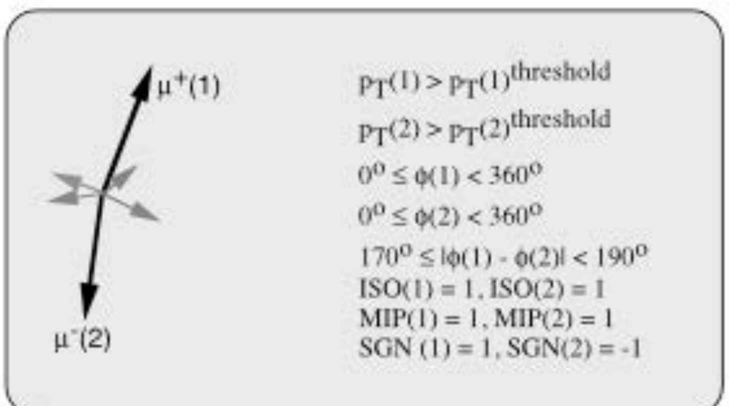
- L1 Accept from combinations & proximity of above



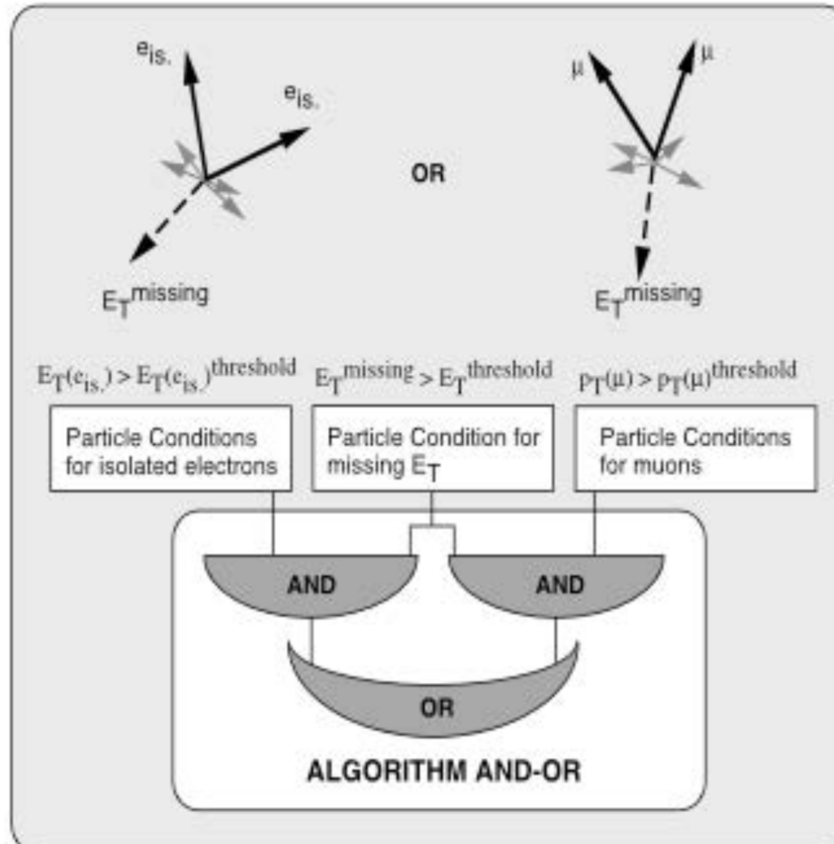
Global L1 Trigger Algorithms

Particle Conditions





Logical Combinations

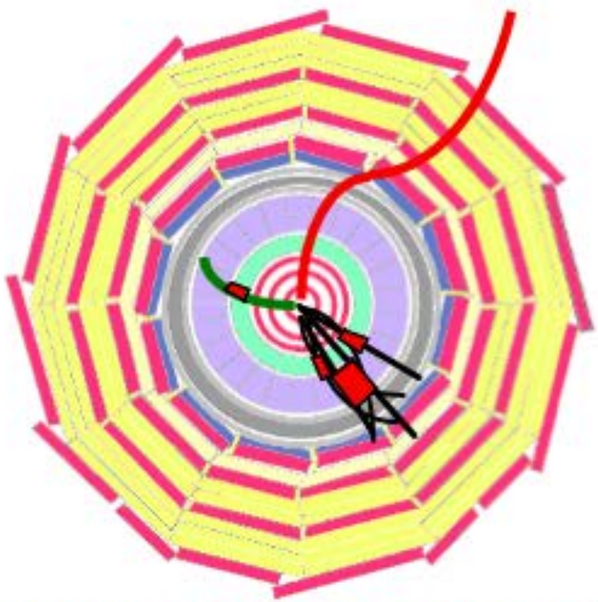


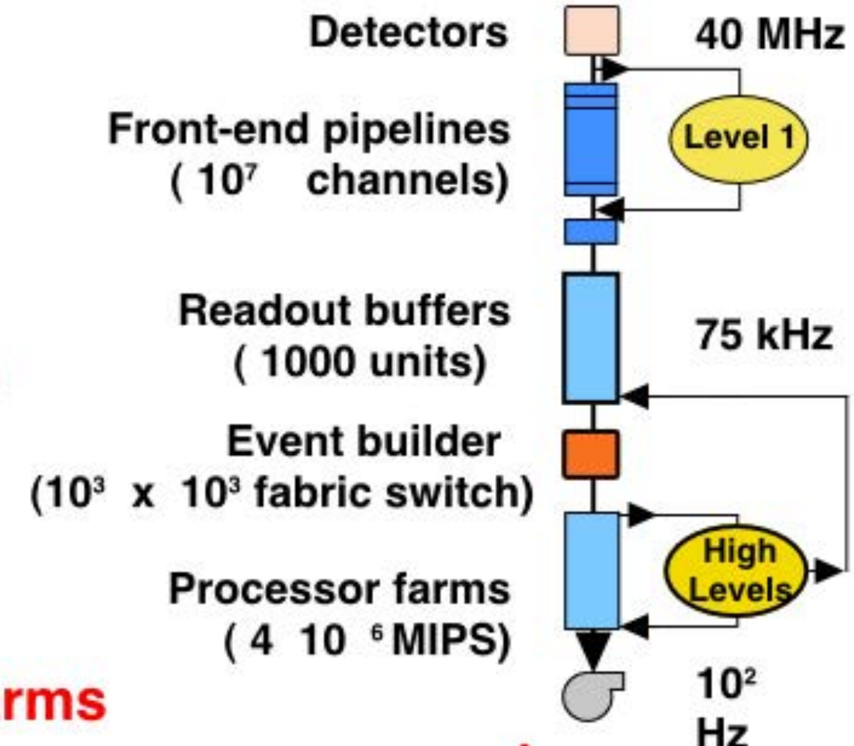
Flexible algorithms implemented in FPGAs
100s of possible algorithms can be reprogrammed

EDIT 2012

High Level Trigger Strategy

THE UNIVERSITY of WISCONSIN MADISON





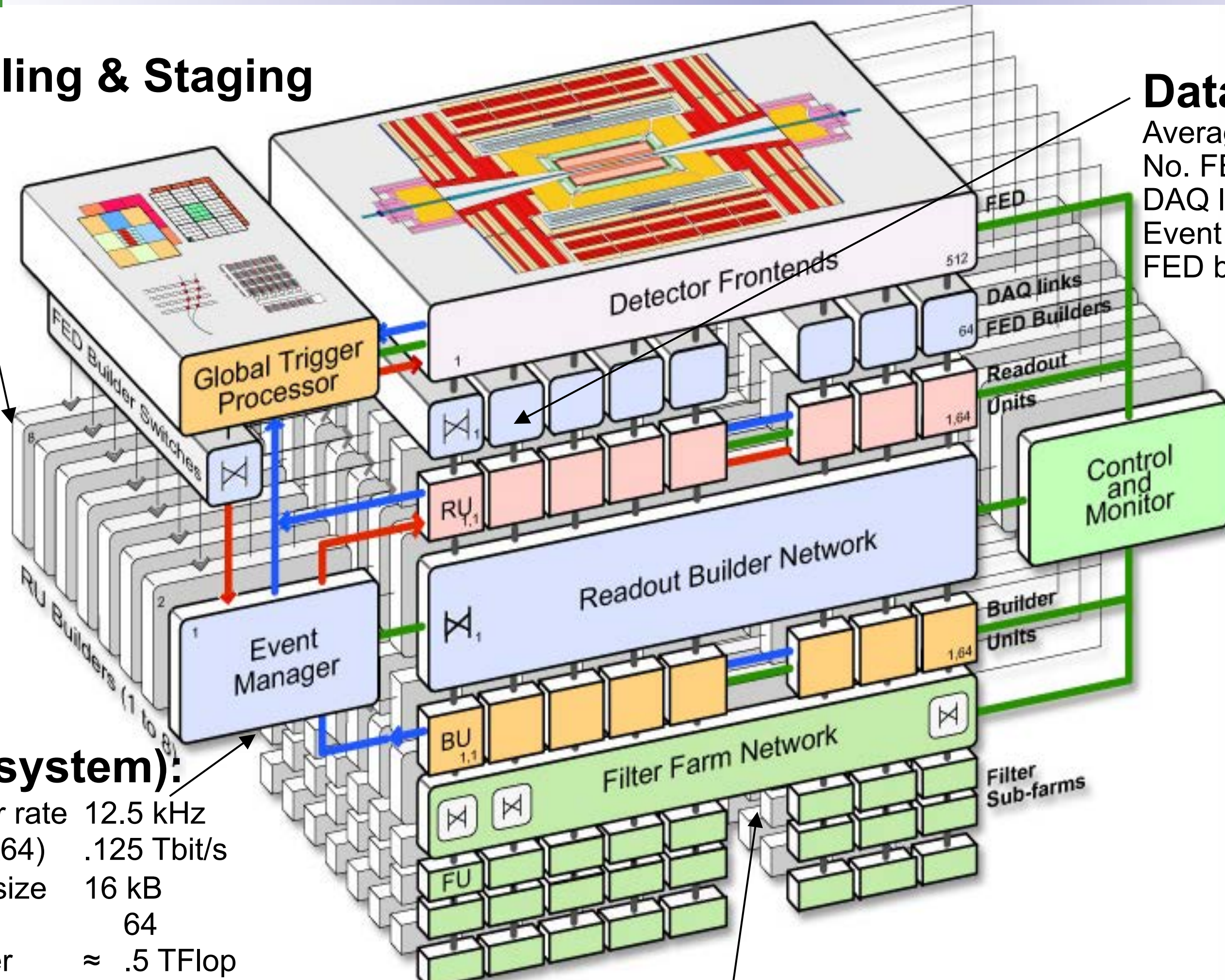
High level triggers. CPU farms

- 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+51
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)**

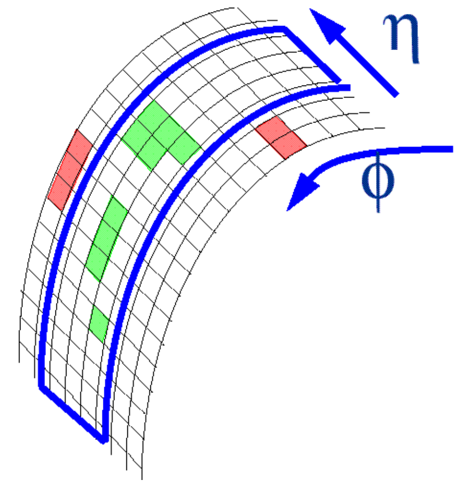
Goal

- **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

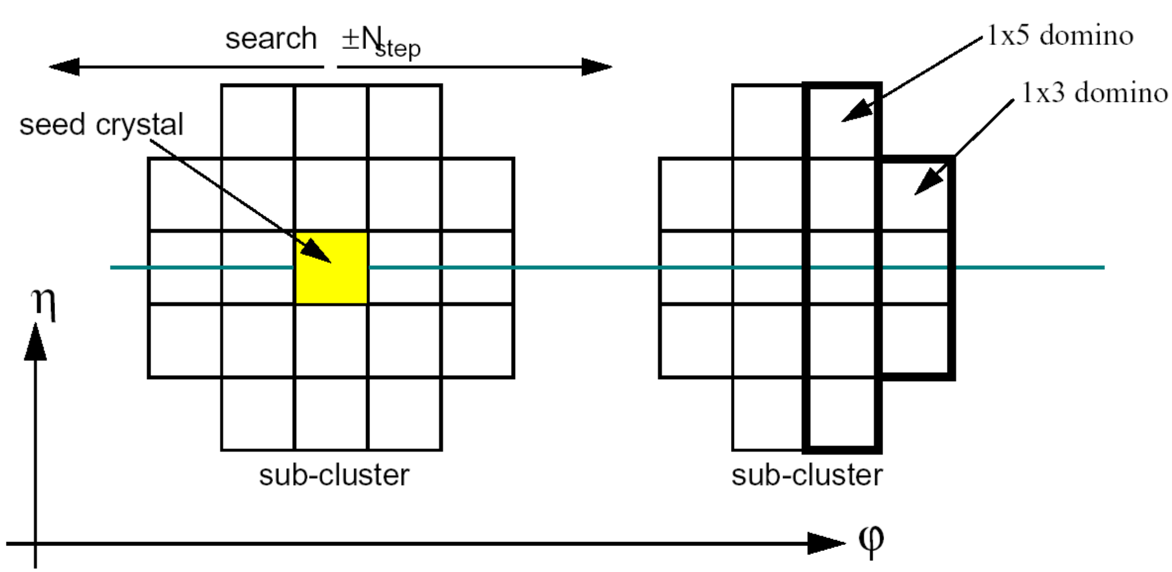


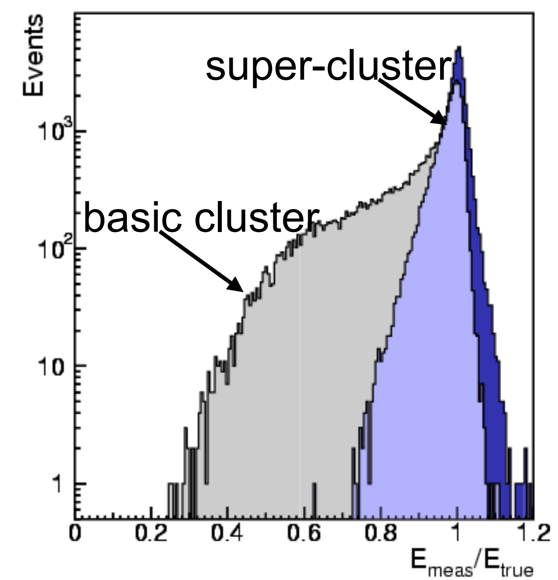
"Level-2" electron:

- **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:

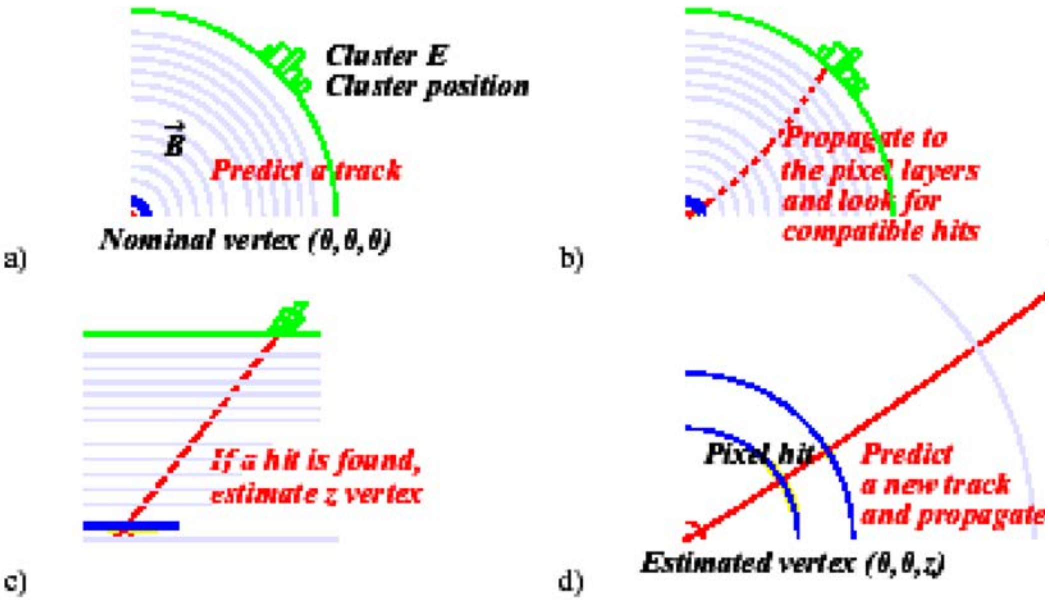
- **Road along φ — in narrow η-window around seed**
- **Collect all sub-clusters in road → "super-cluster"**

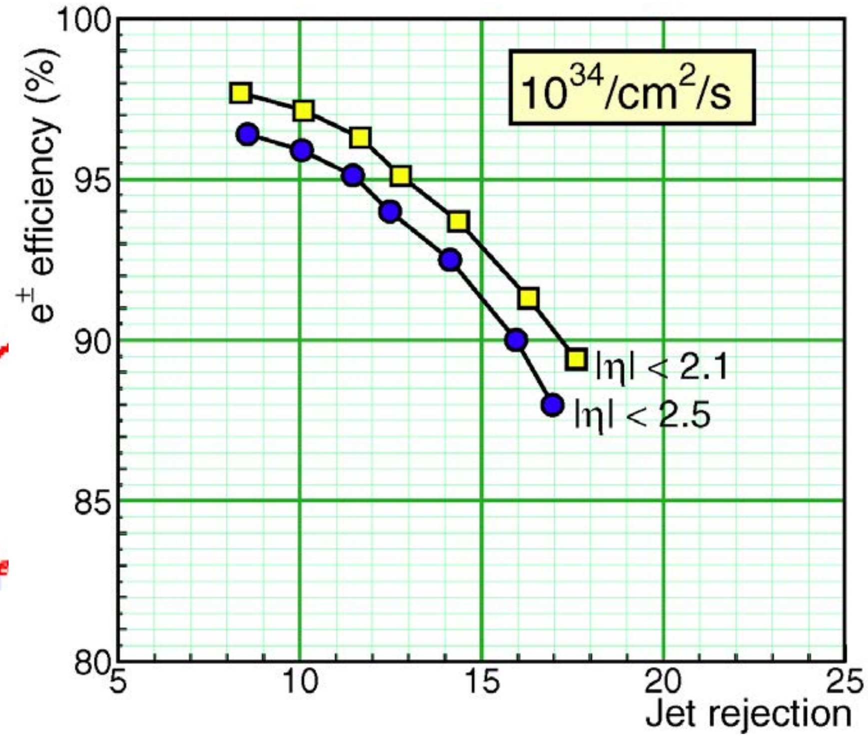




CMS tracking for electron trigger

Present CMS electron HLT

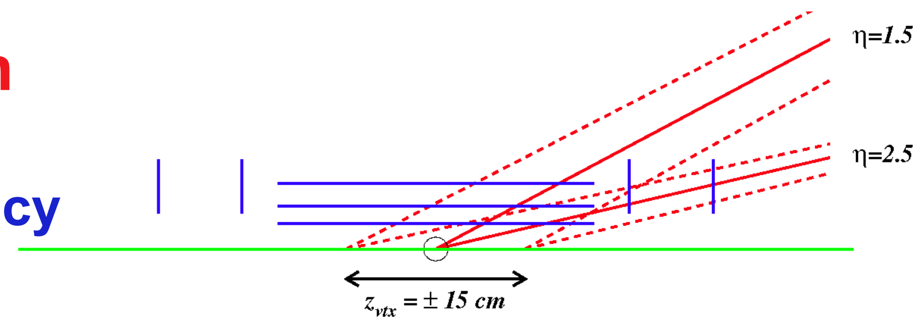




Factor of 10 rate reduction

γ: only tracker handle: isolation

- Need knowledge of vertex location to avoid loss of efficiency



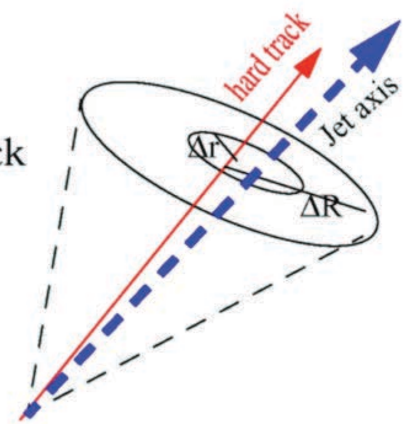
τ-jet tagging at HLT

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

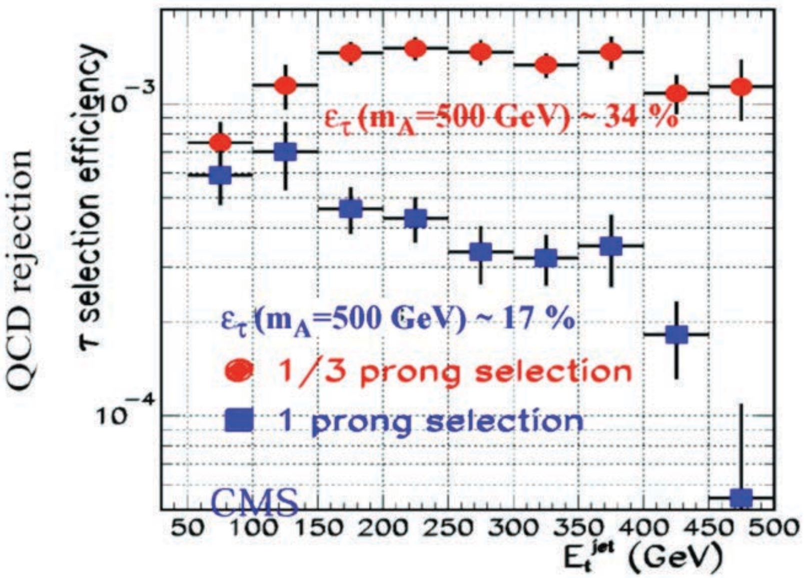
Hard track, $p_t^{max} > 40$ GeV, within $\Delta R < 0.1$ around calorimeter jet axis

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

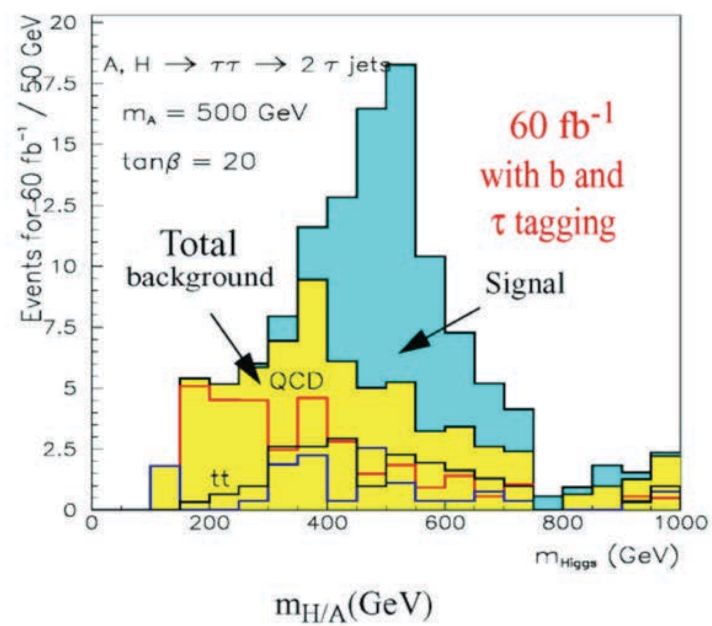
For 3-prong selection 2 more tracks in the signal cone $\Delta r < 0.03$



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:

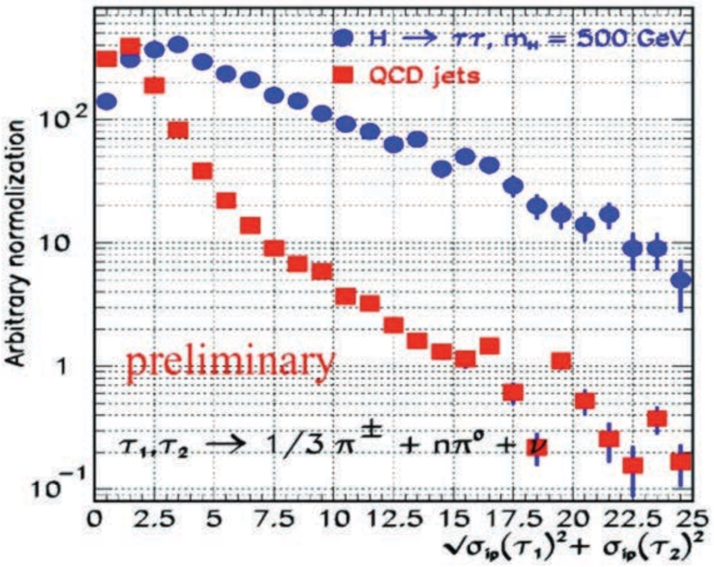
Efficiency to tag one b-jet ~ 35% for ~1% mistagging rate (CMS)

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

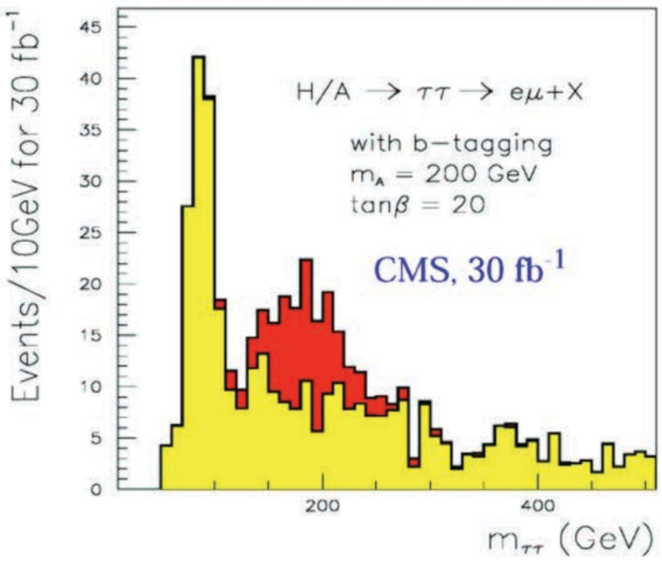
CMS full simulation for

H -> ττ –> 2 τ–jets and QCD events



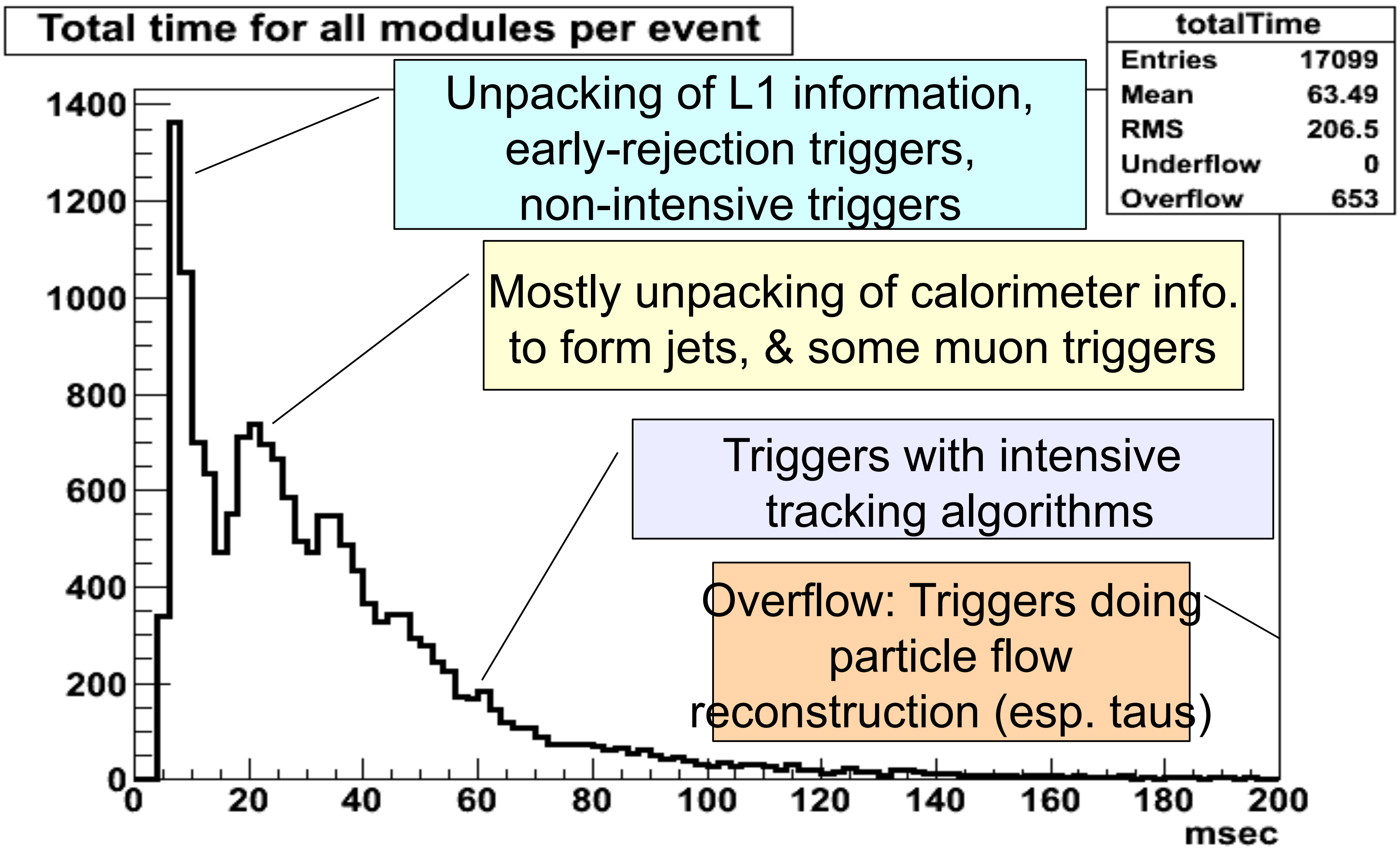
Expect rejection of 5 - 10 against QCD background and backgrounds with W -> *l*ν, Z -> *ll*

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

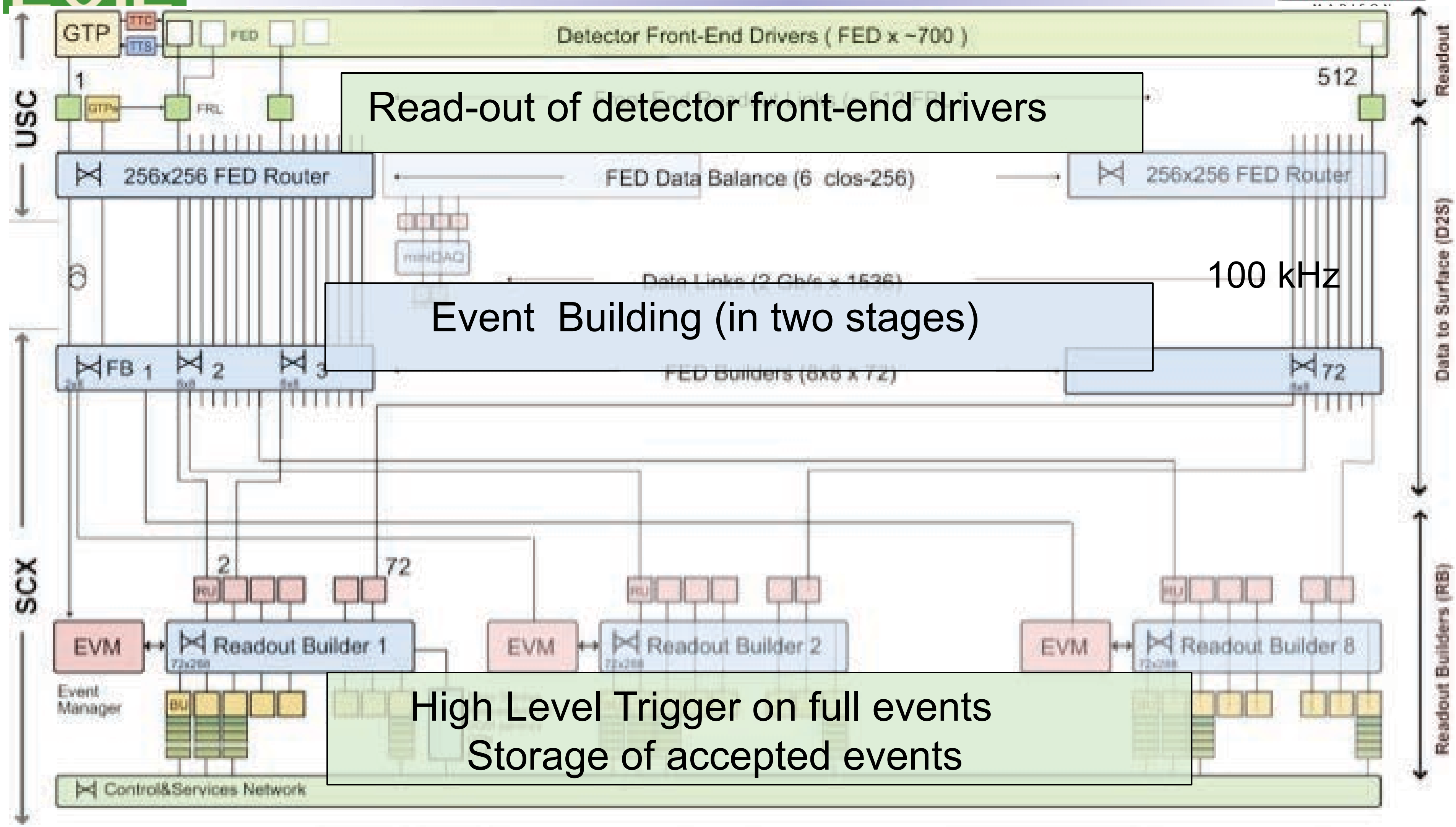


CMS HLT Time Distribution

Prescale set used: 2E32 Hz/cm²
Sample: MinBias L1-skim 5E32 Hz/cm² with 10 Pile-up

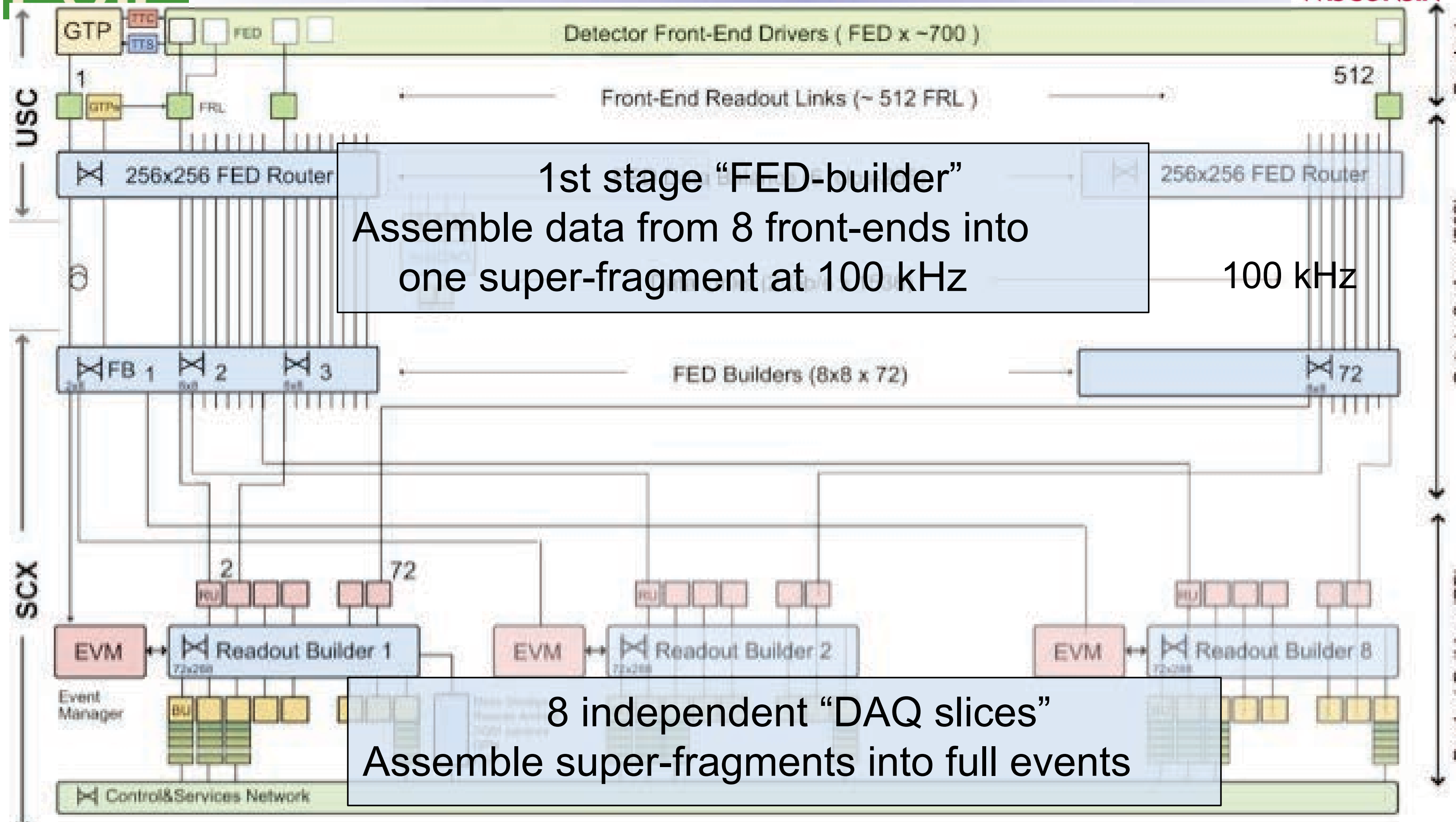


CMS DAQ



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

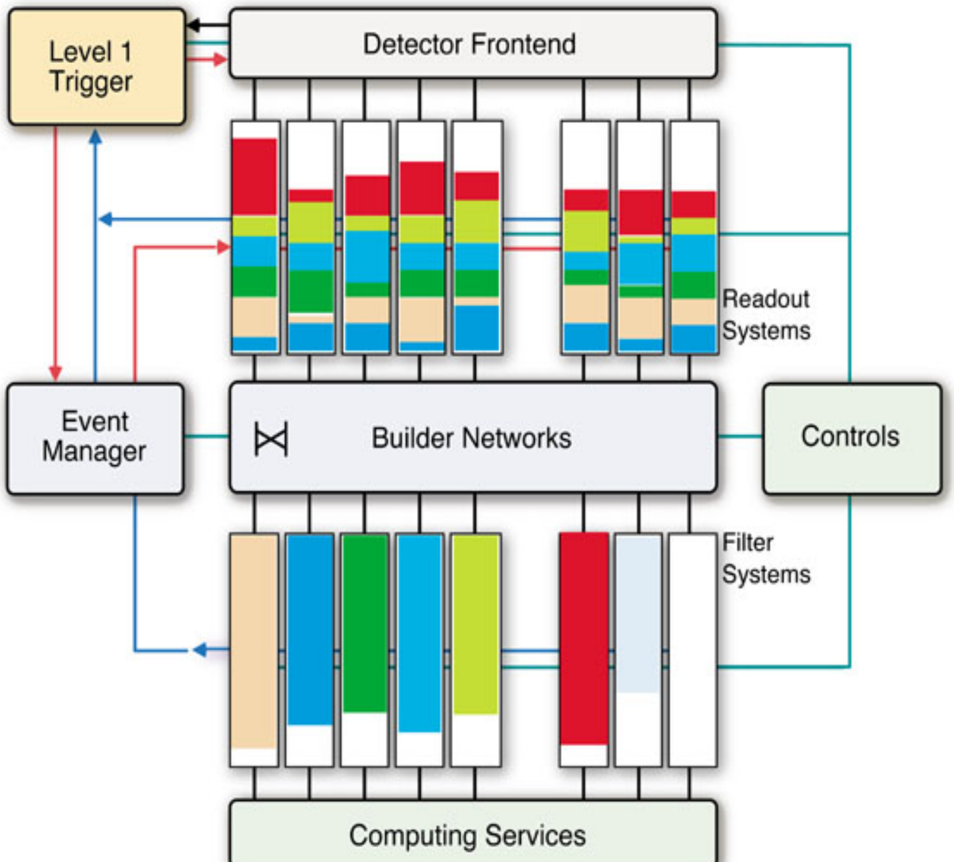
100 kHz

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

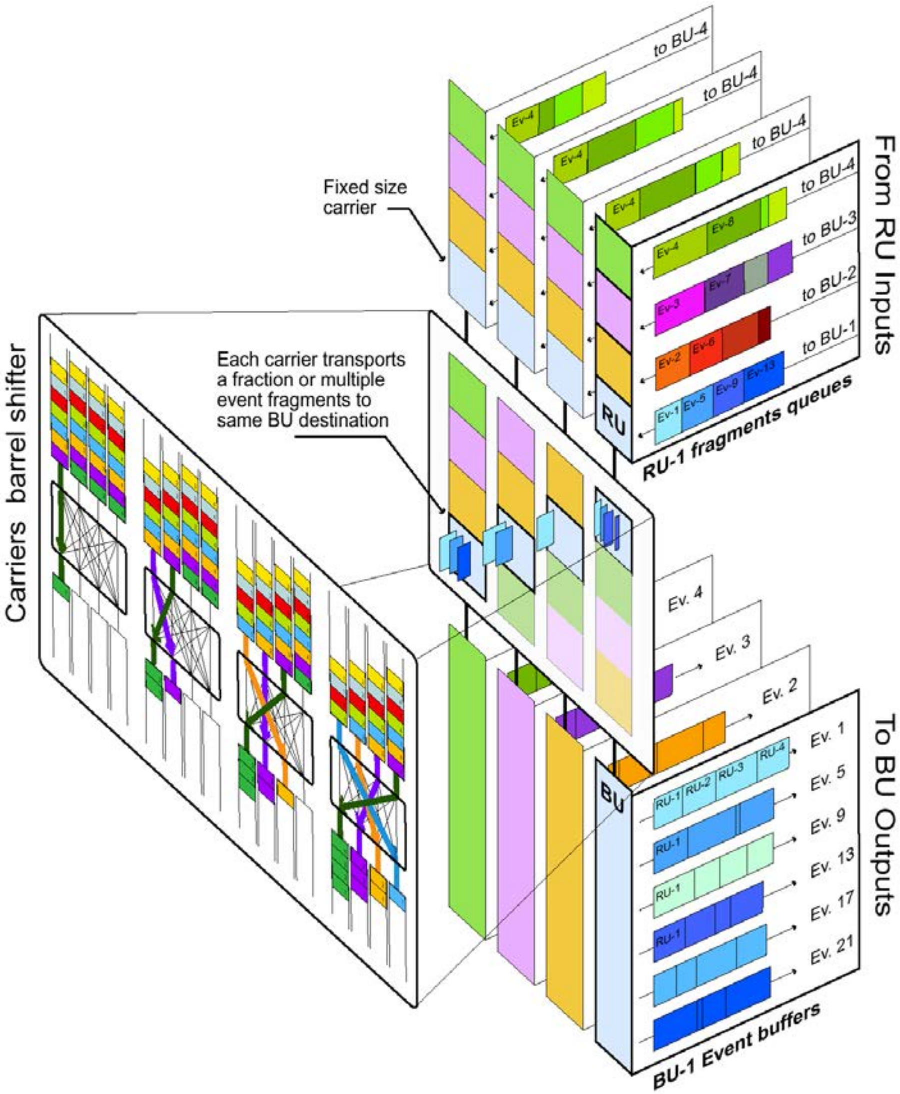


Event fragments :
Event data fragments are stored in separated physical memory systems

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)

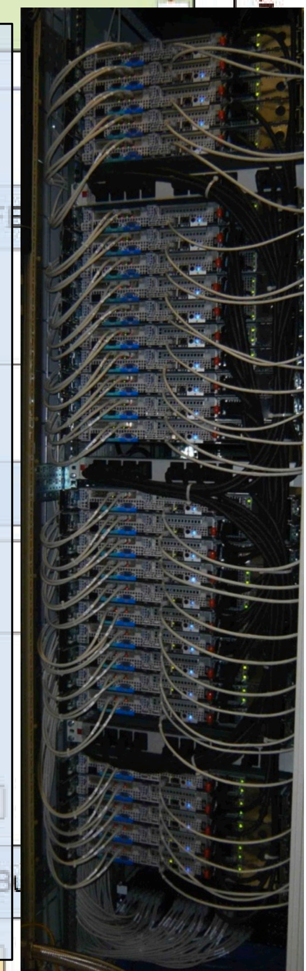
zero-copy, **OS-bypass**

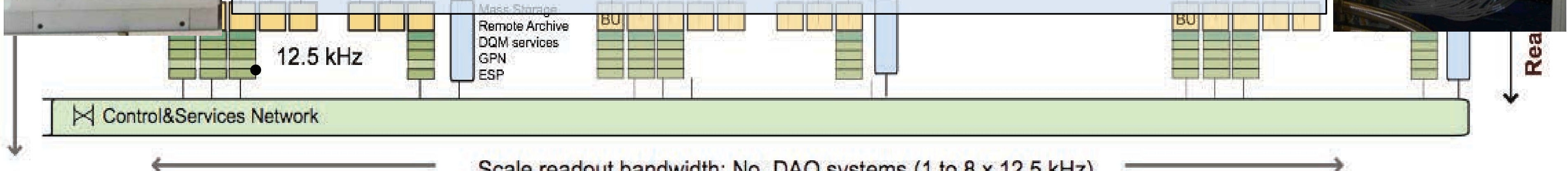
principle works for multi-stage switches

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





Trigger & DAQ Summary:
LHC Case

Level 1 Trigger

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