LHC Trigger and DAQ

THE UNIVERSITY of WISCONSIN MADISON

Hadron Collider Physics Summer School

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Lectures 1 and 2

Outline:

Introduction to LHC Trigger and DAQ

Challenges & Architecture of ATLAS and CMS

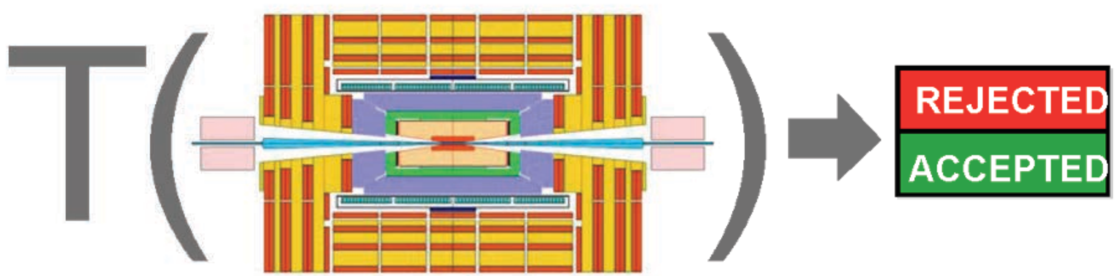
ATLAS and CMS Trigger and DAQ

The future of ATLAS and CMS 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

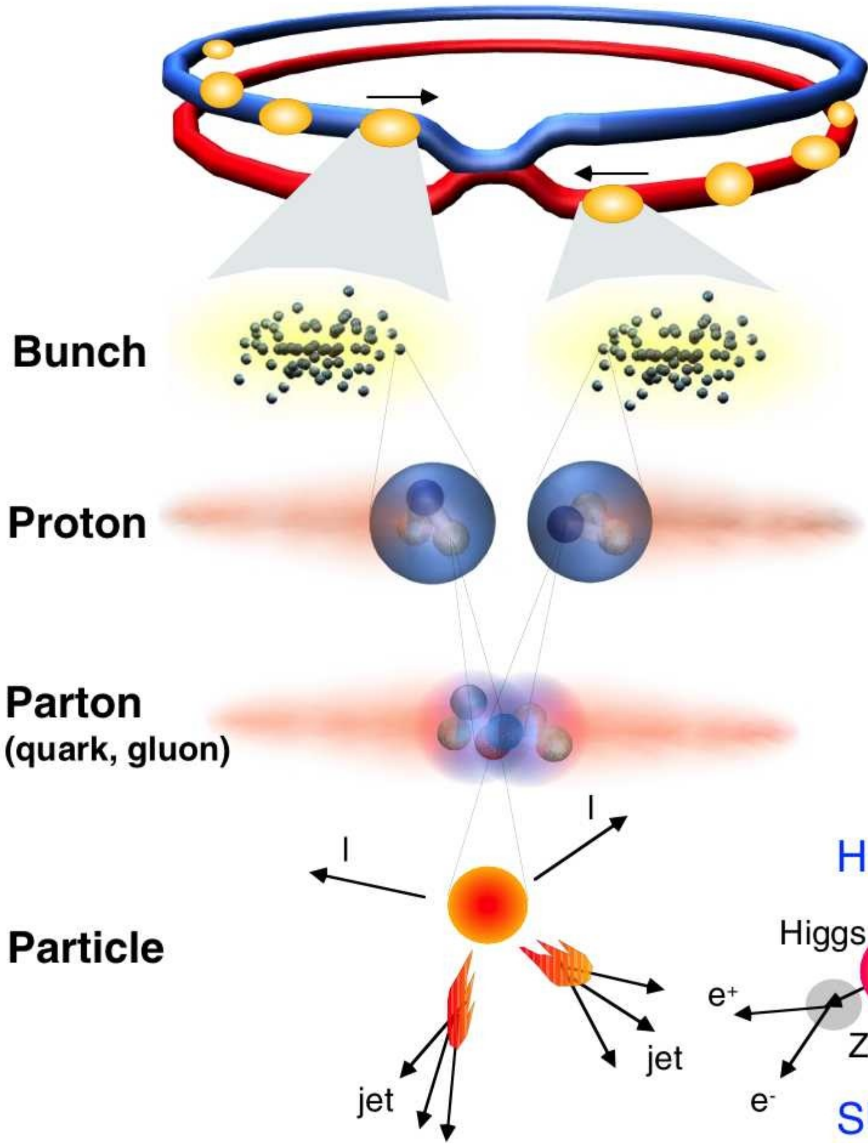
- Detector data not (all) promptly available
- Selection function highly complex

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

TRIGGER LEVELS

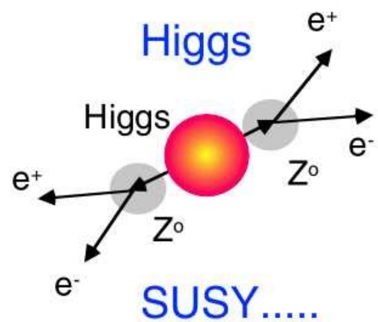
(possibly with zero dead time)

LHC Overview



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
~25 Minimum Bias events
with ~2000 particles produced



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

LHC Physics – Trigger Challenge

Electroweak Symmetry Breaking Scale

- **Higgs discovery and higgs sector characterization** ← Low ≅ 40 GeV; Low P_T γ, e, μ
- **Quark, lepton Yukawa couplings to higgs** ← Low P_T B, τ jets

New physics at TeV scale to stabilize higgs sector

- **Spectroscopy of new resonances (SUSY or otherwise)** ← Multiple low P_T objects
- **Find dark matter candidate** ← Missing E_T

Multi-TeV scale physics (loop effects)

- **Indirect effects on flavor physics (mixing, FCNC, etc.)**
  - B_s mixing and rare B decays ← ~ Dedicated triggers using displaced vertices
- **Lepton flavor violation**
  - Rare Z and higgs decays ← Low P_T leptons

Planck scale physics

- **Large extra dimensions to bring it closer to experiment**
- **New heavy bosons**
- **Blackhole production**

← High P_T leptons and photons; Multi particle and jet events

LHC Physics & Event Rates

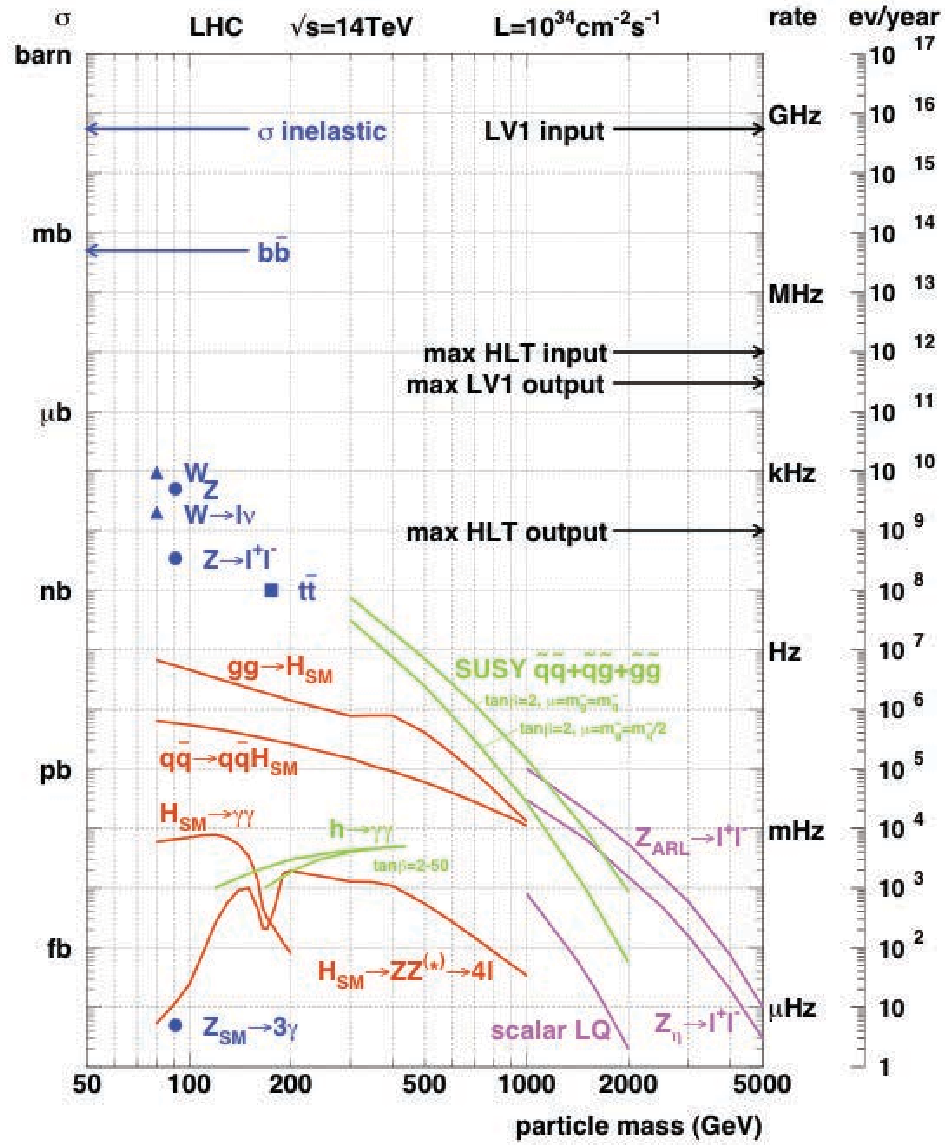
At design $L = 10^{34} cm^{-2}s^{-1}$

- **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**

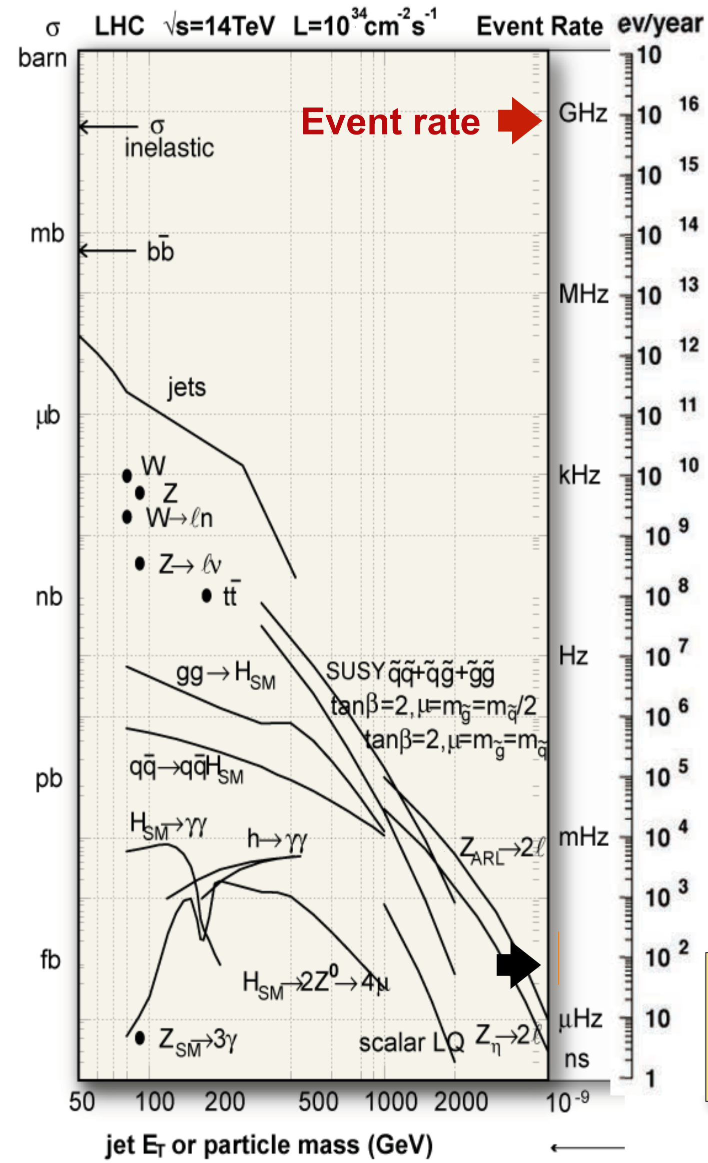
Can store ~ 1 kHz events

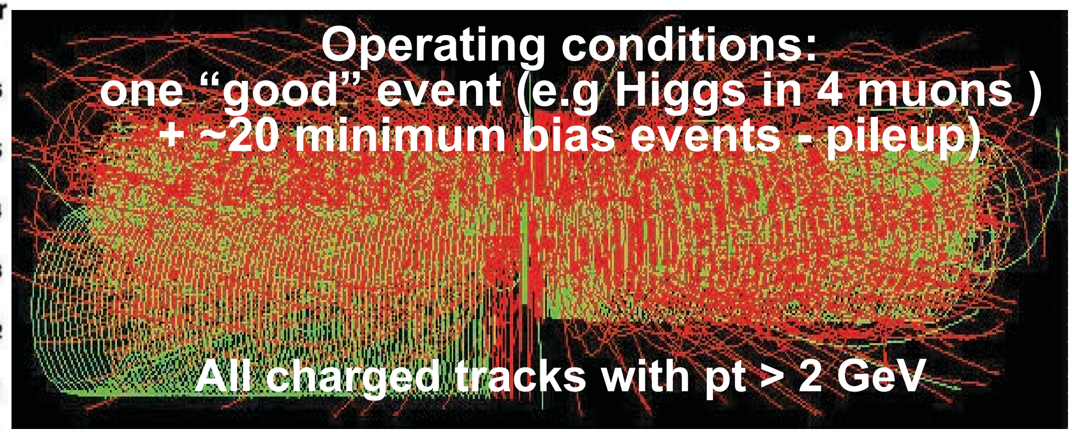
Select in stages

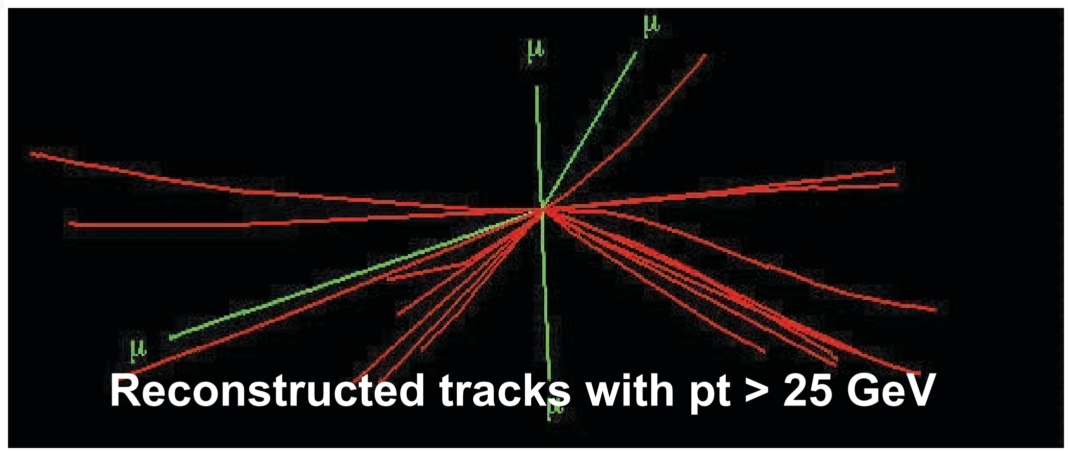
- **Level-1 Triggers**
  - 1 GHz to 100 kHz
- **High Level Triggers**
  - 100 kHz to 1 kHz



Collisions (p-p) at LHC

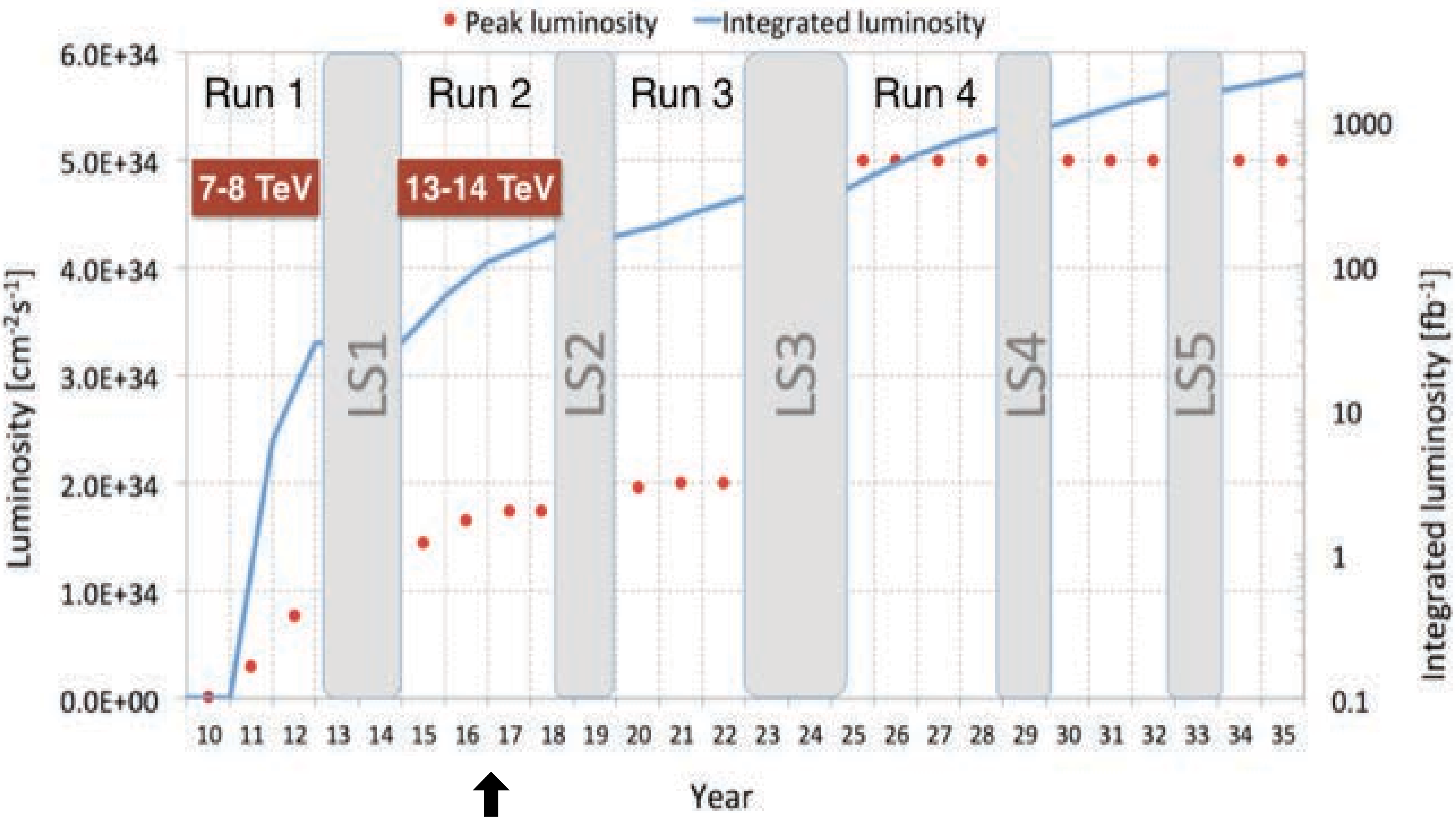






Event size: ~1 MByte
Processing Power: ~X TFlop

The LHC Plan

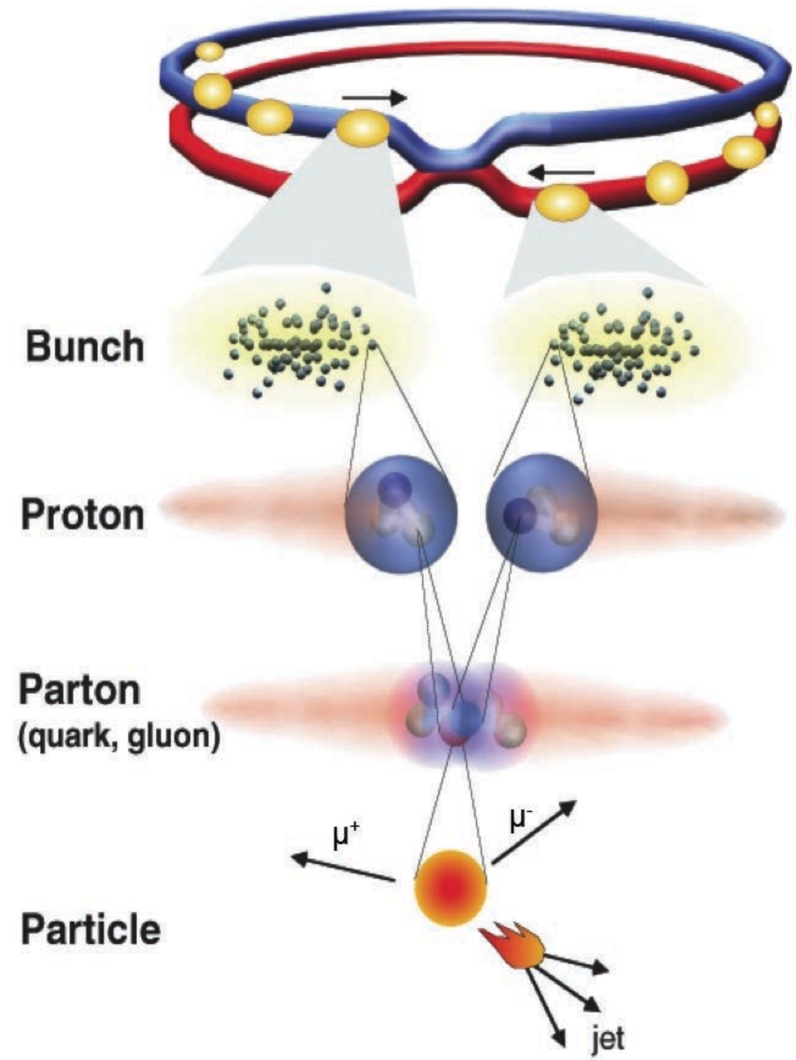


You are here!

LHC Run I Parameters

	Design	2010	2011	2012
Beam Energy (TeV)	***7***	***3.5***	***3.5***	***4***
Bunches/Beam	2808	368	1380	1380
Proton/Bunch (10^{11})	***1.15***	***1.3***	***1.5***	***1.7***
Peak Lumi. (10^{32} cm^{-2} s^{-1})	100	2	30	76
Integrated Lumi. (fb^{-1})	***100/yr***	***0.036***	***6***	***20***
Pile-Up	23	~1	10	20
Bunch Spacing	25 ns	50 ns	50 ns	50 ns

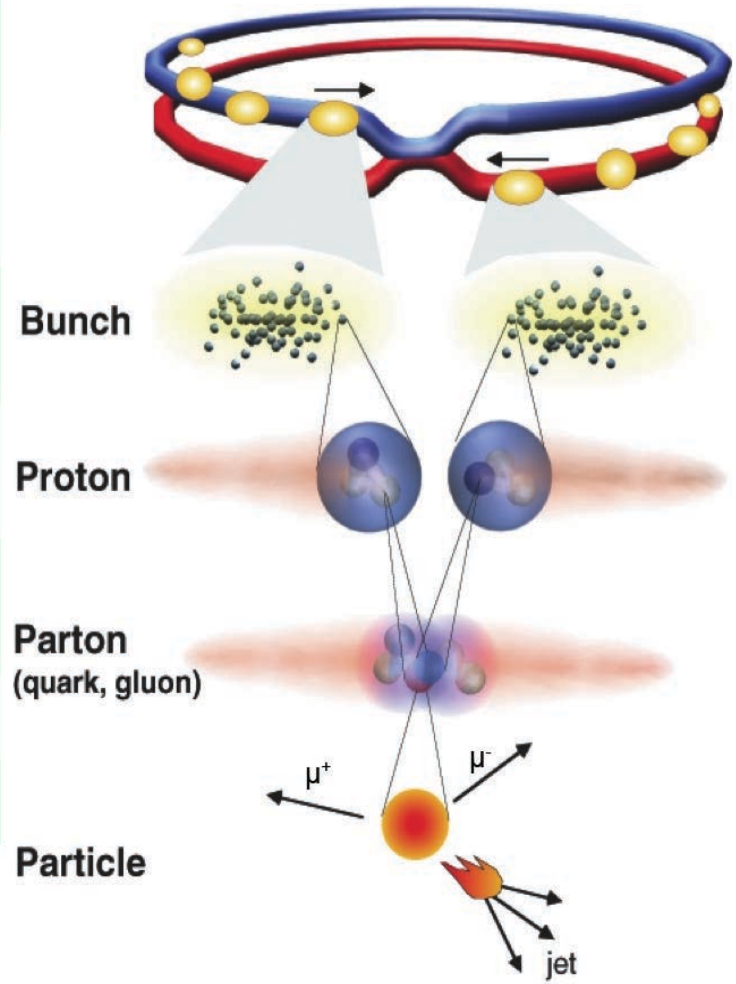
Pile-Up – the number of proton interactions occurring during each bunch crossing



HCPSS16

LHC Run 2 Parameters

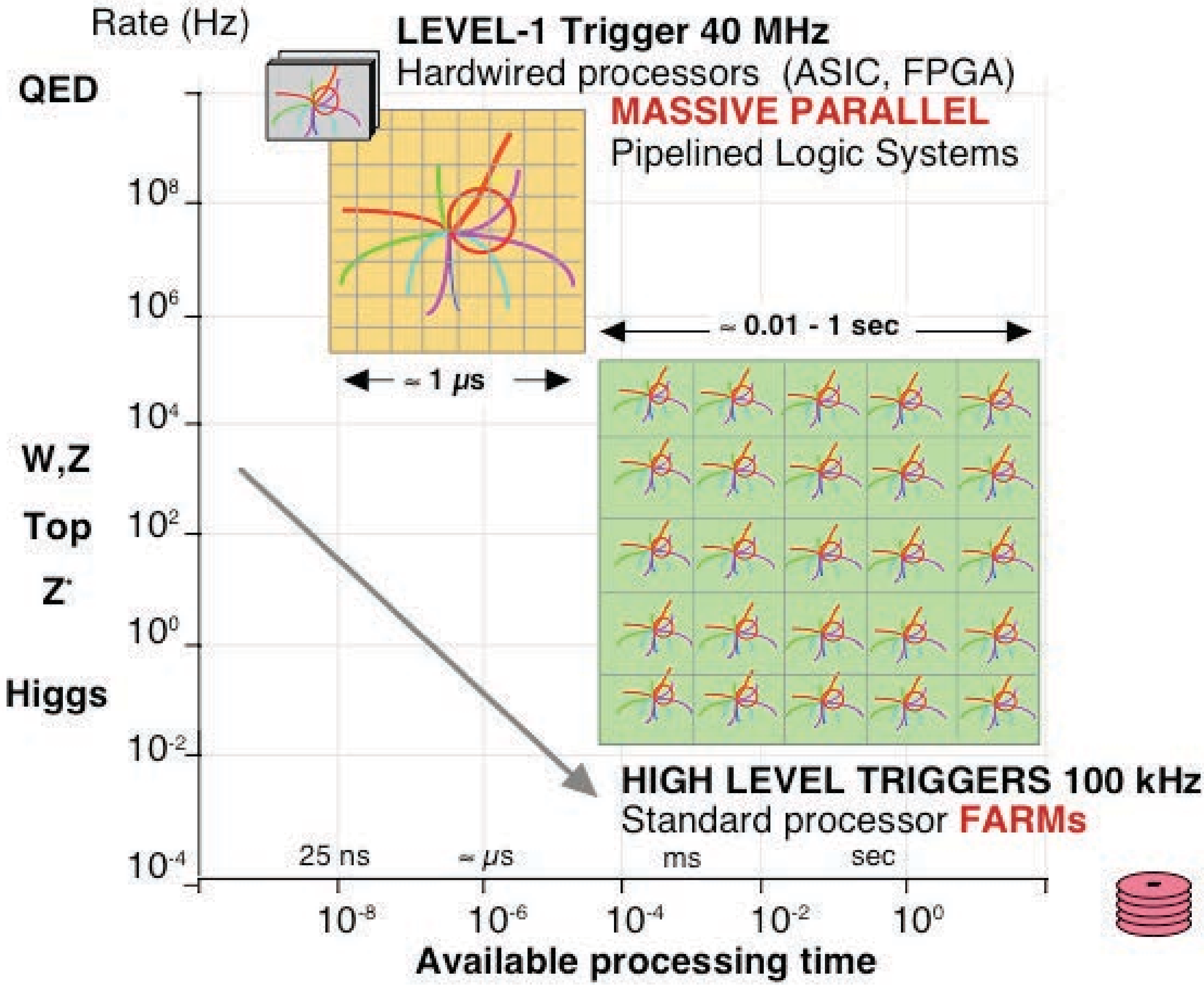
	Design	2015	2016	2017/8 (*)
Beam Energy (TeV)	***7***	***6.5***	***6.5***	***6.5/7***
Bunches/Beam	2808	2244	2748	2808
Proton/Bunch (10^{11})	***1.15***	***1.2***	***1.2***	***1.2***
Peak Lumi. (10^{32} cm^{-2} s^{-1})	100	51	100(*)	100
Integrated Lumi. (fb^{-1})	***100/yr***	***4***	***30(*)***	***70(*)***
Pile-Up	23	<20	40	40
Bunch Spacing	25 ns	50/25 ns	25 ns	25 ns



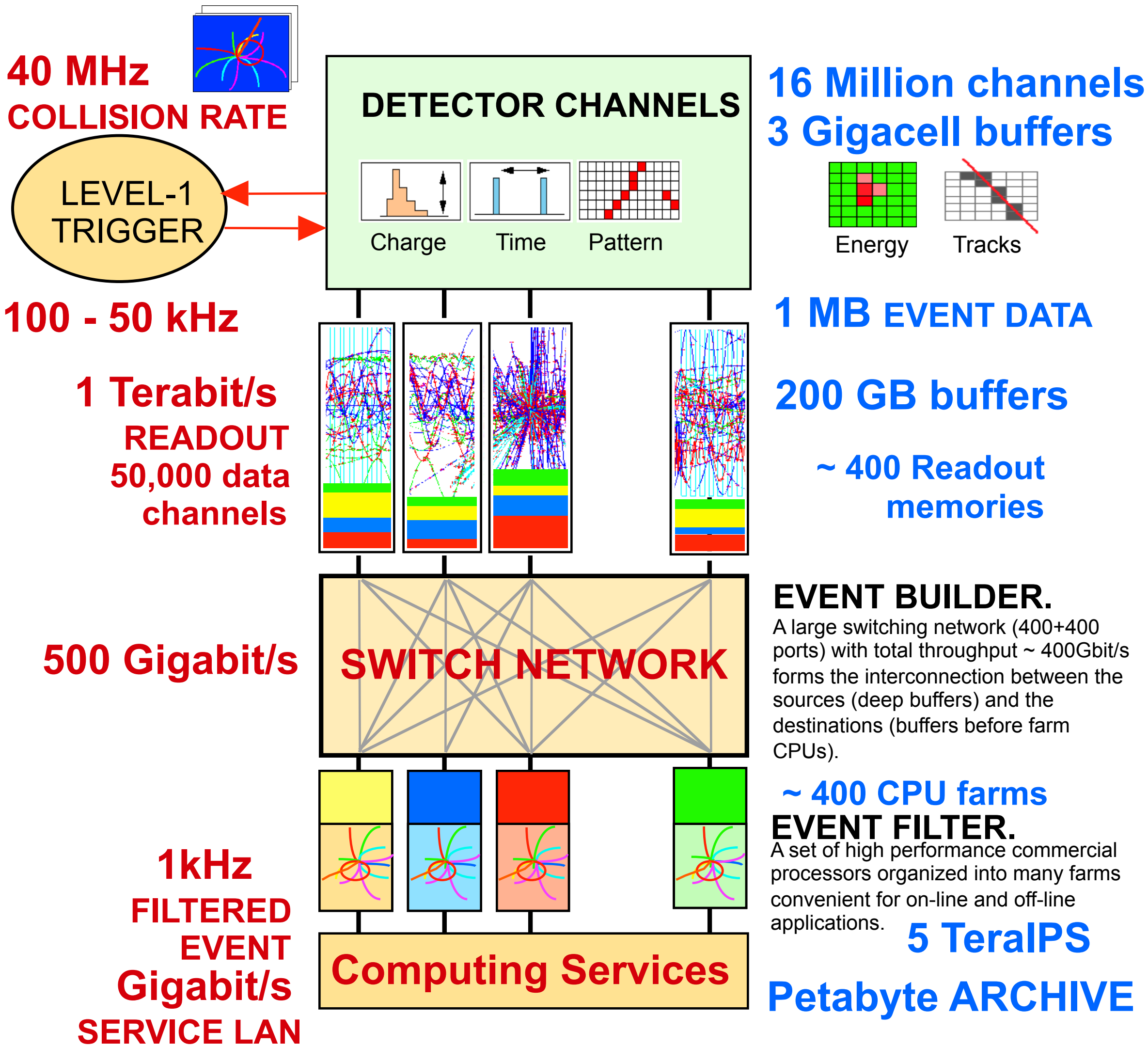
Pile-Up – the number of proton interactions occurring during each bunch crossing

*expected value

Processing LHC Data



LHC Trigger & DAQ Challenges



Challenges:

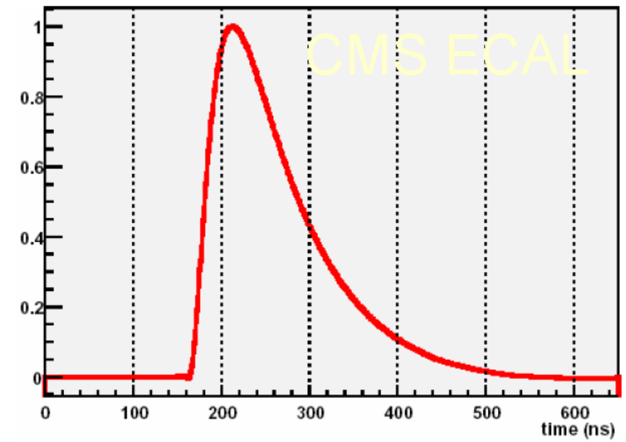
1 GHz of Input Interactions

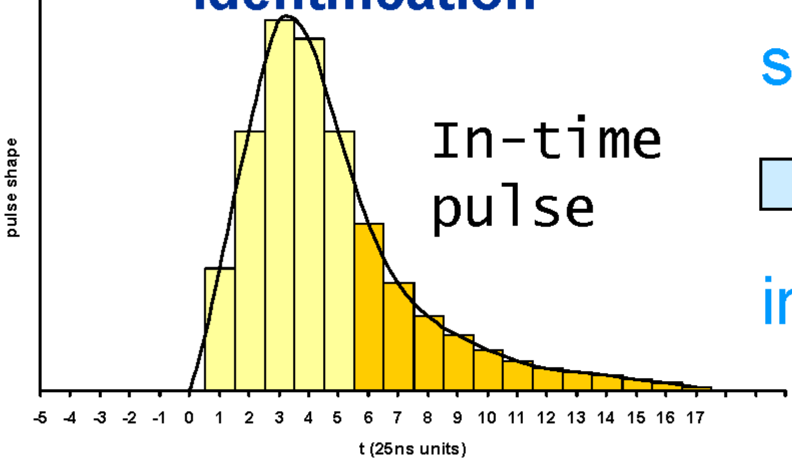
Beam-crossing every 25 ns with ~ 23 interactions produces over 1 MB of data

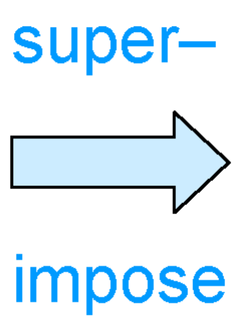
Archival Storage up to 1 kHz of 1 MB events

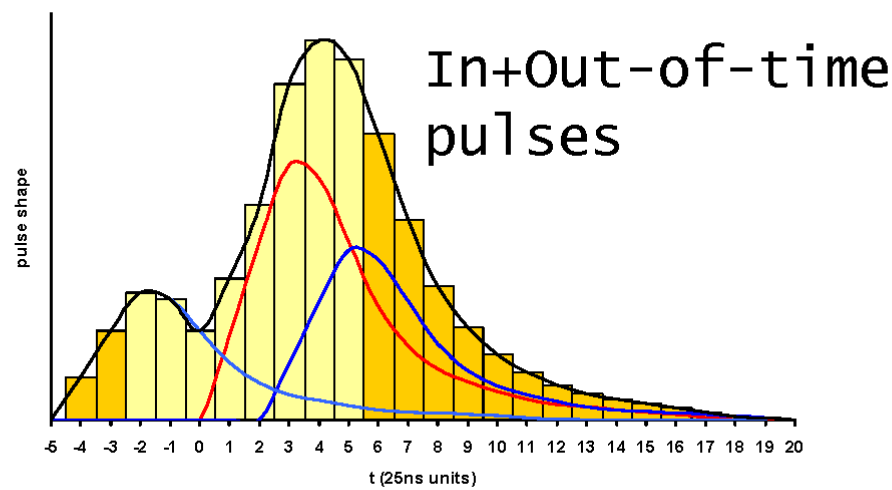
Challenges: Pile-up

- "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"



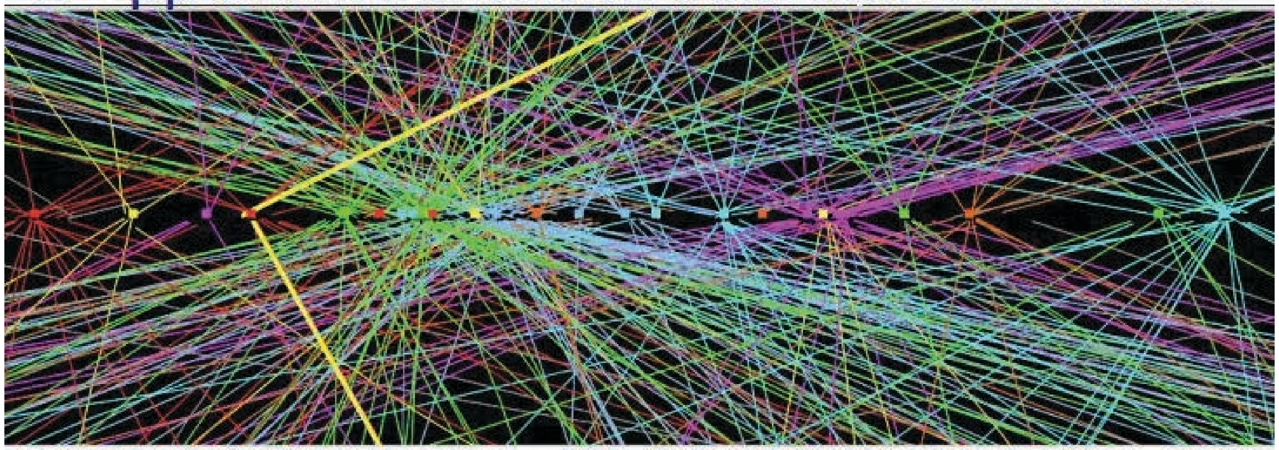




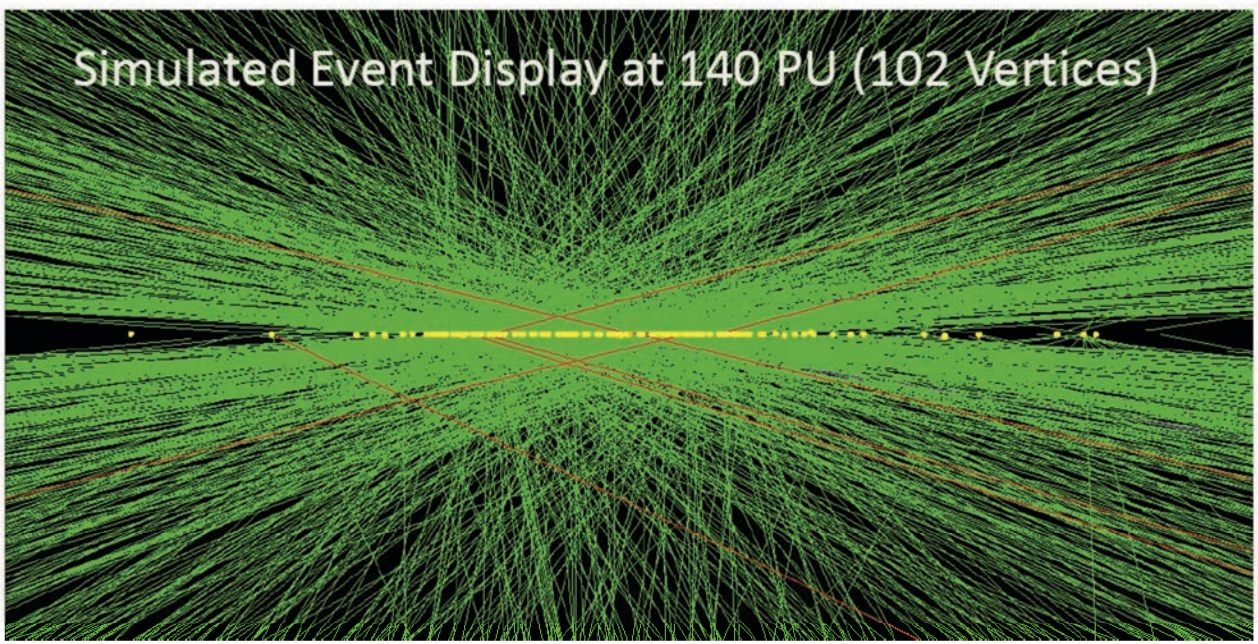


PileUp: major trigger problem

Z→μμ event from 2012 data with 25 vertices



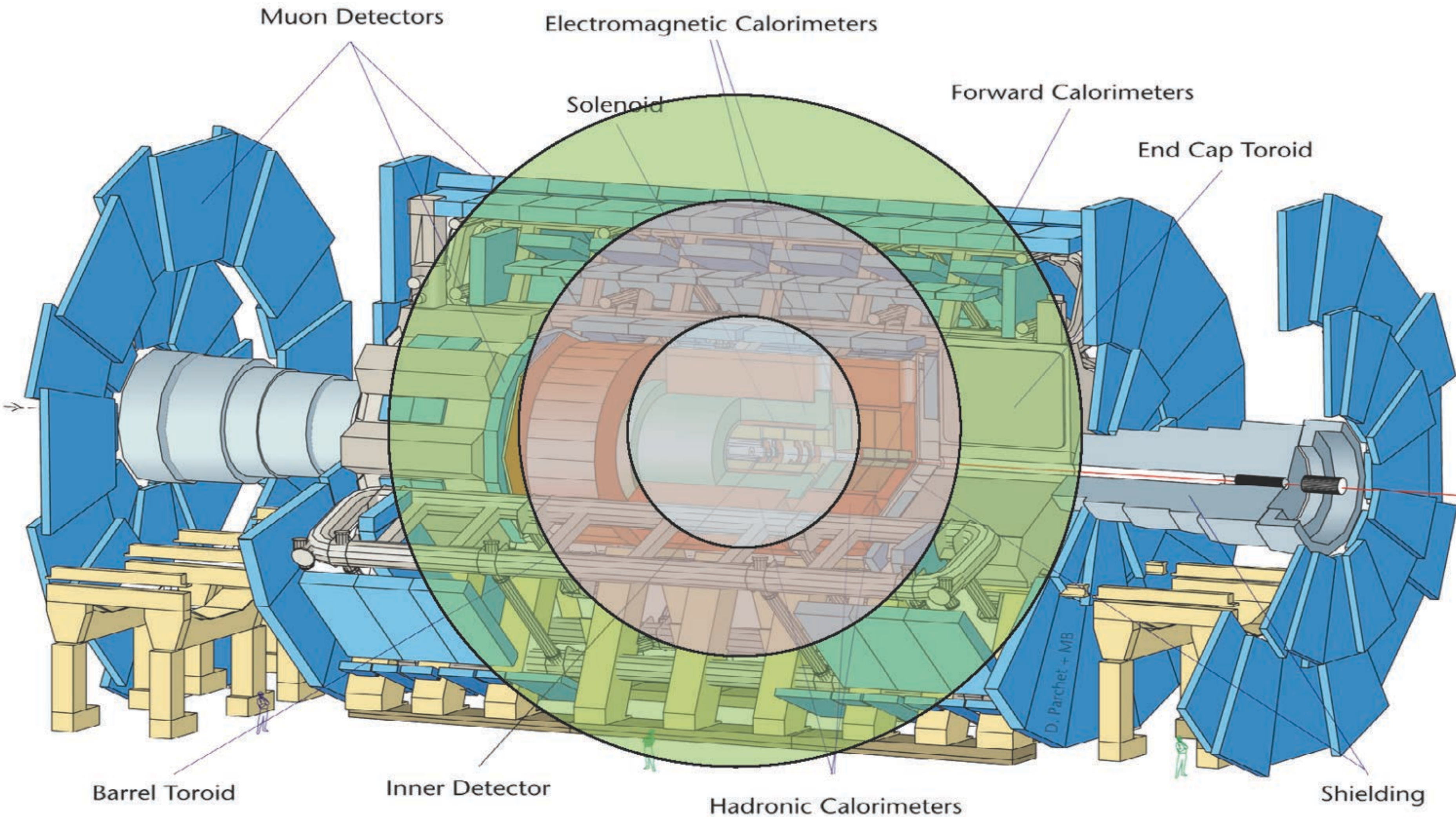
Now



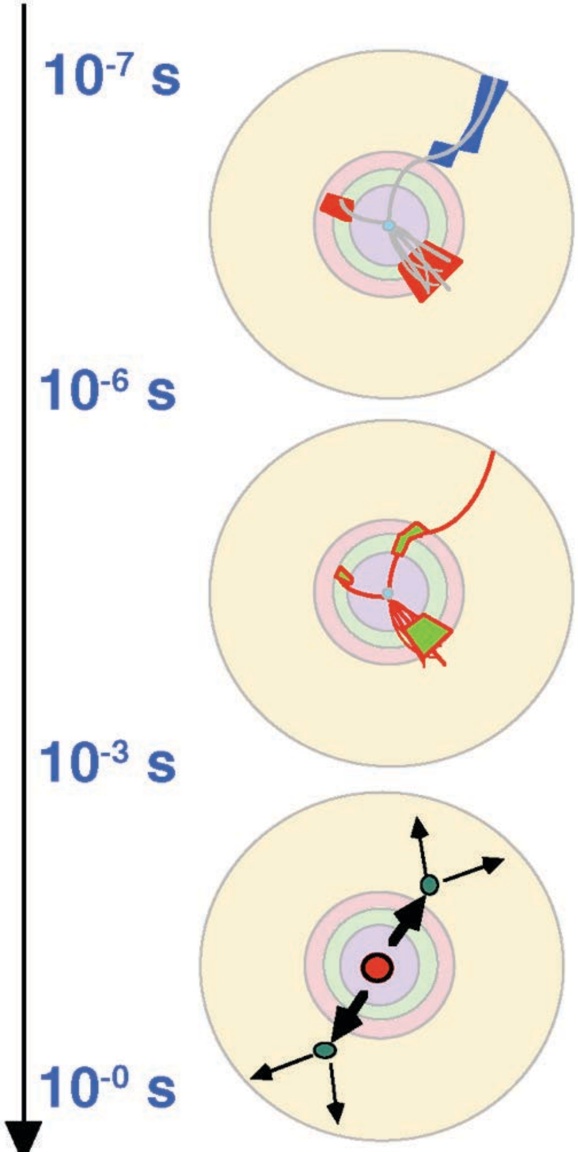
High Luminosity LHC: 2025

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, ..)

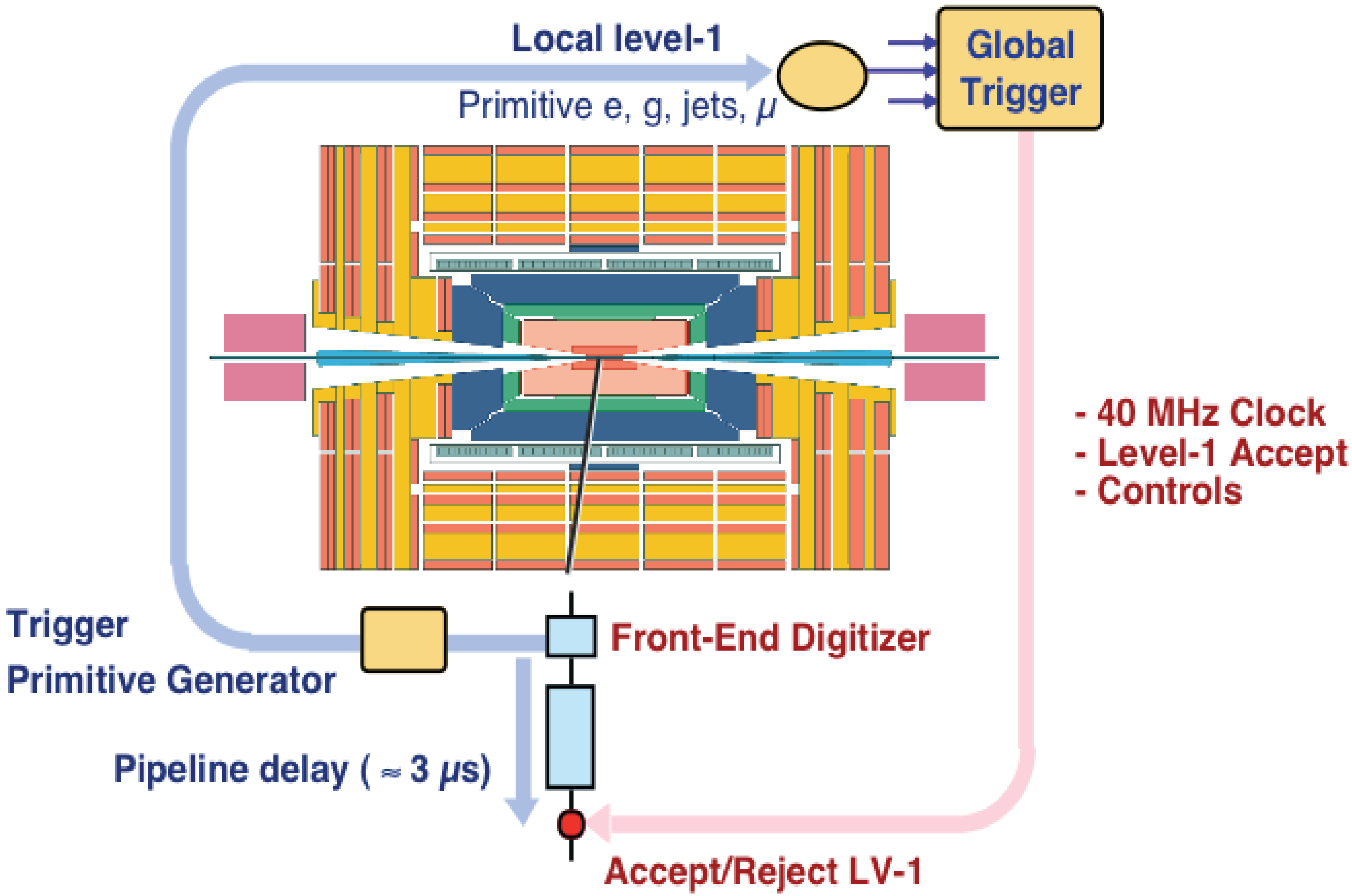
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

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

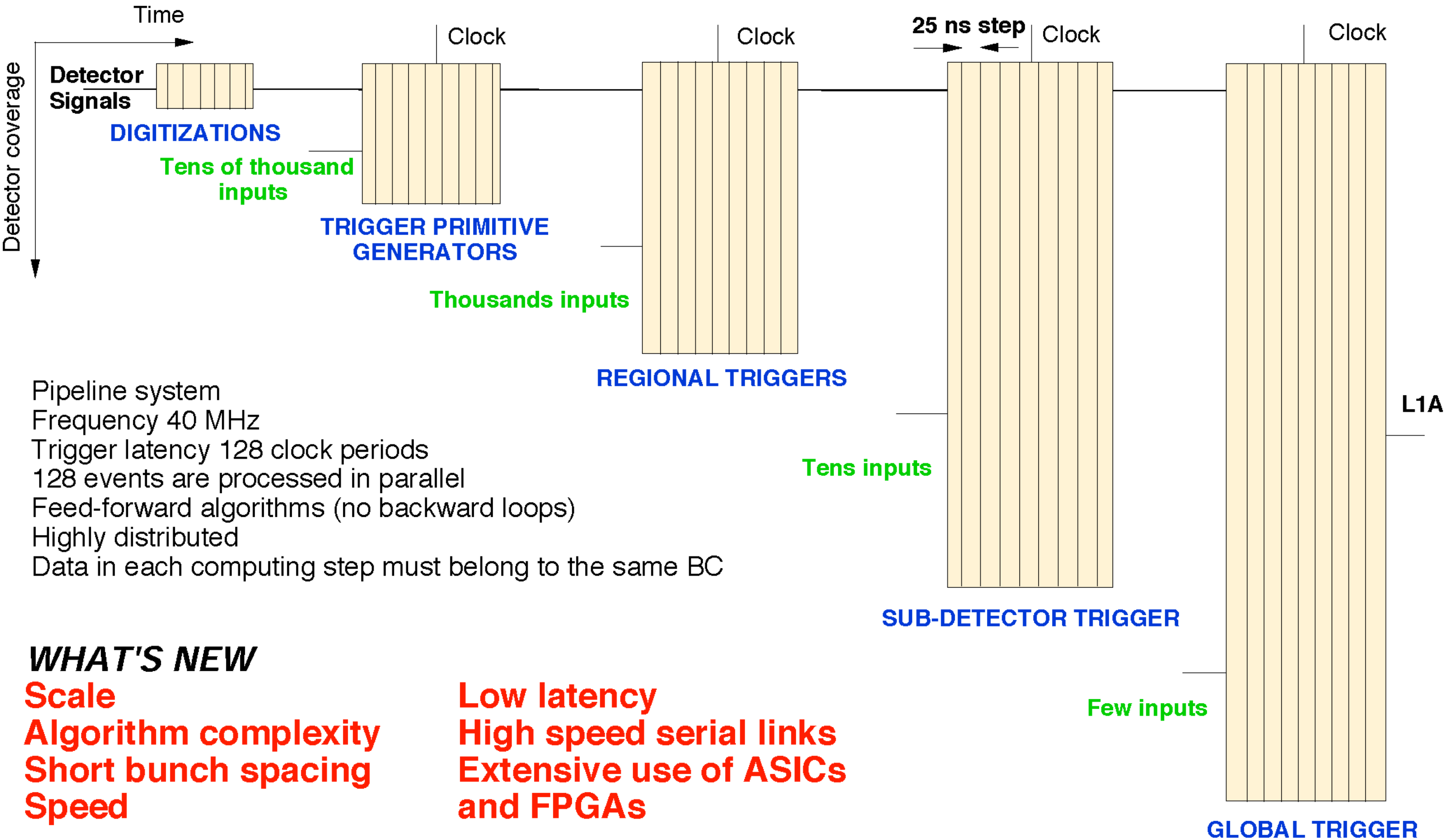
Physics process identification

- Event reconstruction and analysis

Level 1 Trigger Operation



Level 1 Trigger Organization



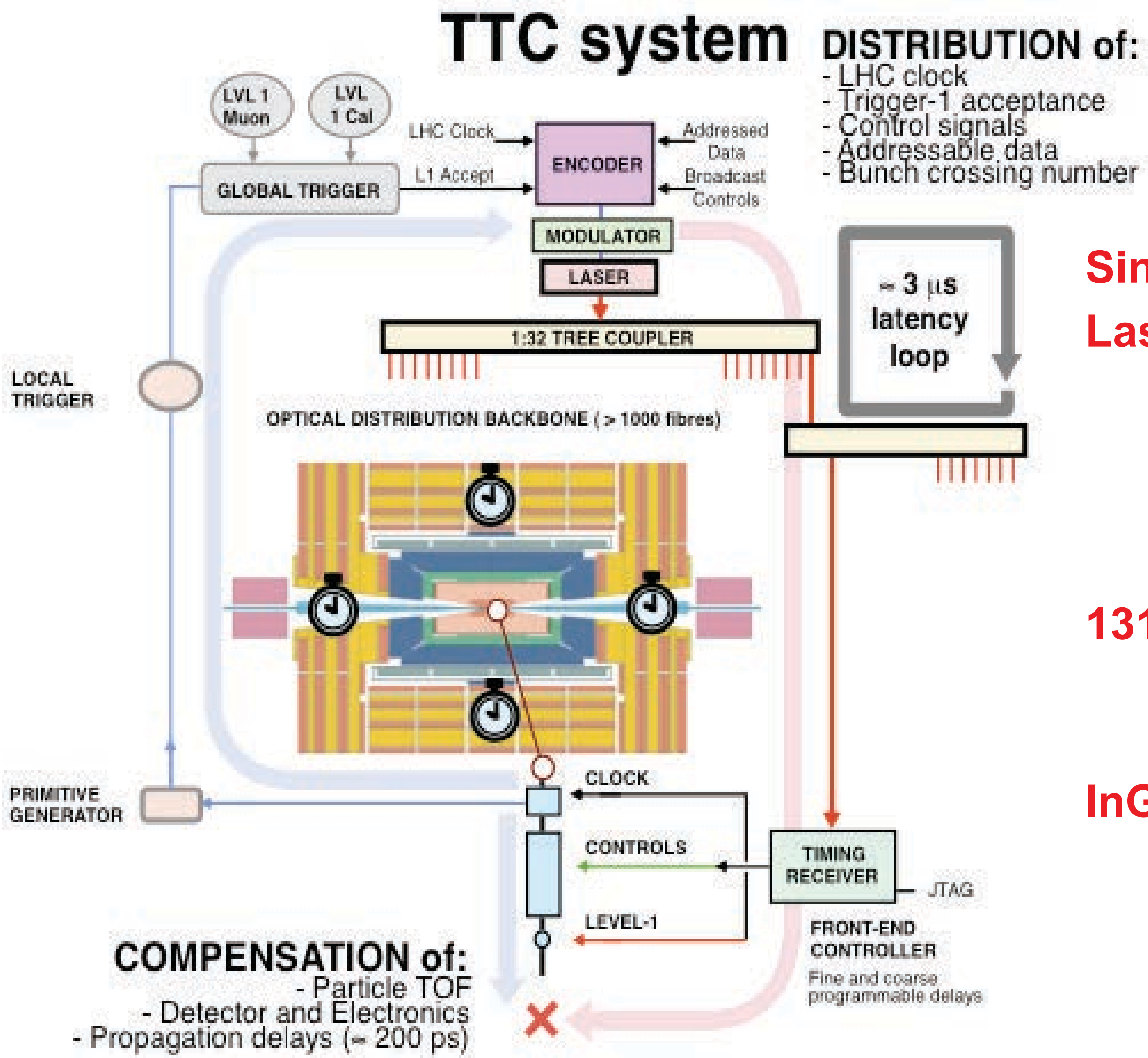
Pipeline system
Frequency 40 MHz
Trigger latency 128 clock periods
128 events are processed in parallel
Feed-forward algorithms (no backward loops)
Highly distributed
Data in each computing step must belong to the same BC

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**

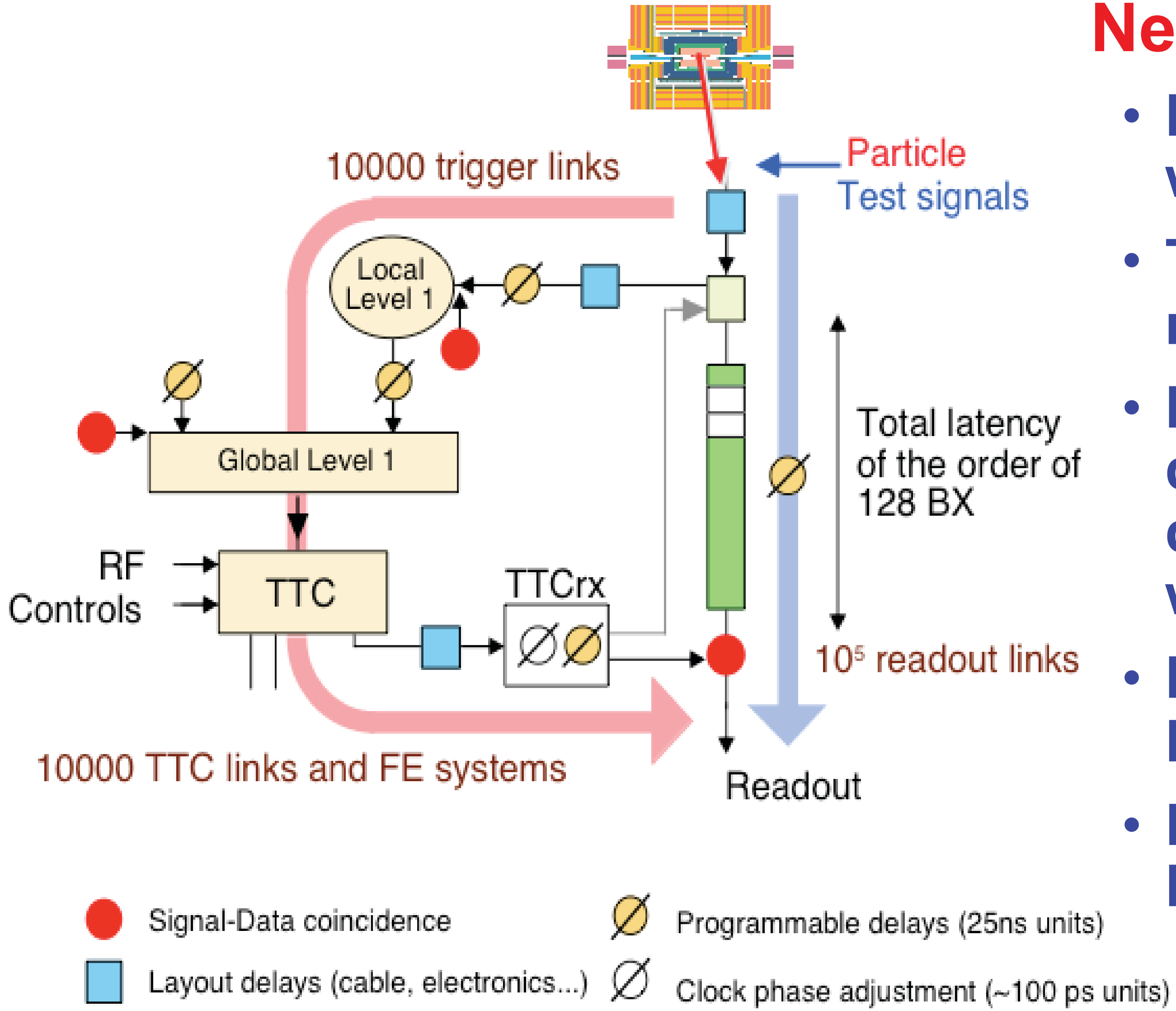
1310 nm Operation

- **Negligible chromatic dispersion**

InGaAs photodiodes

- **Radiation resistance, low bias**

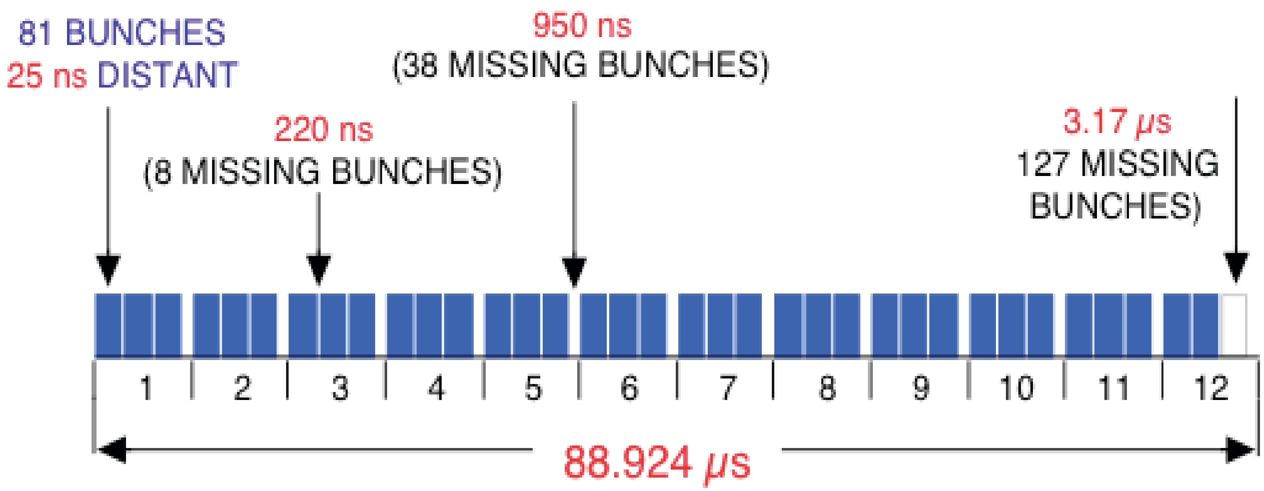
Detector Timing Adjustments



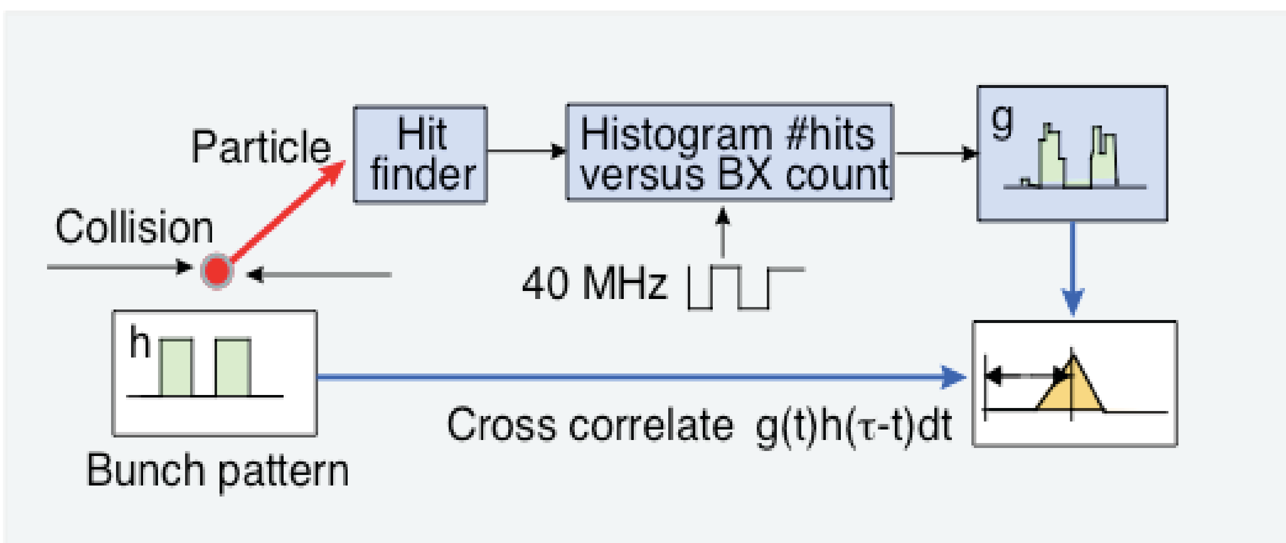
Need to Align:

- 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



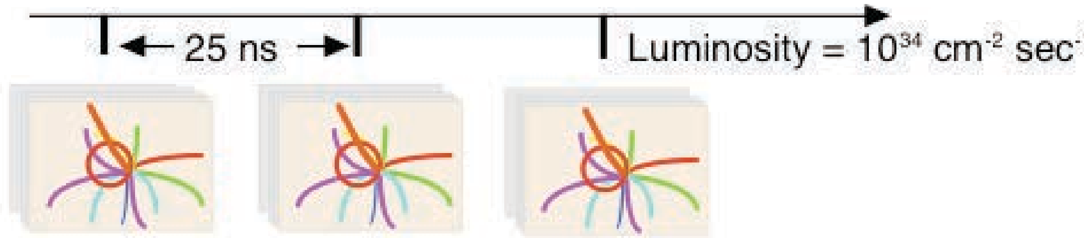
2835 out of 3564 p bunches are full, use this pattern:

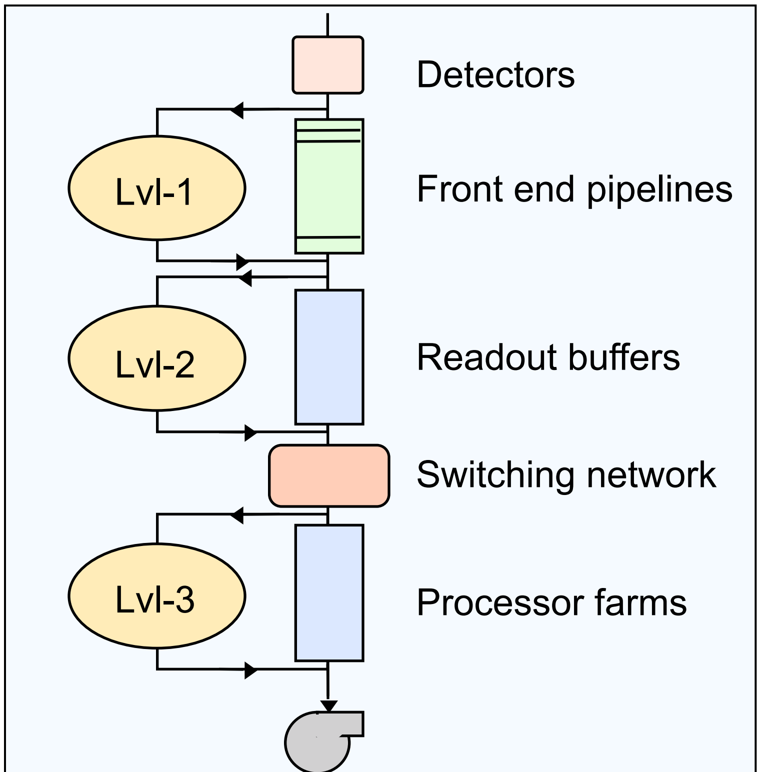


ATLAS & CMS Trigger & Readout Structure

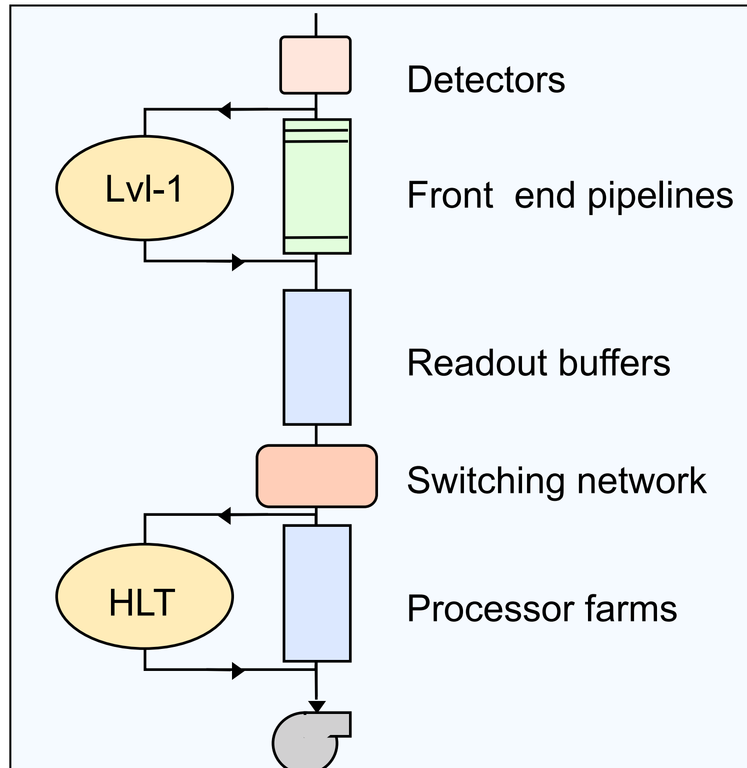
≈ 30 Collisions/25ns
(10^9 event/sec)

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





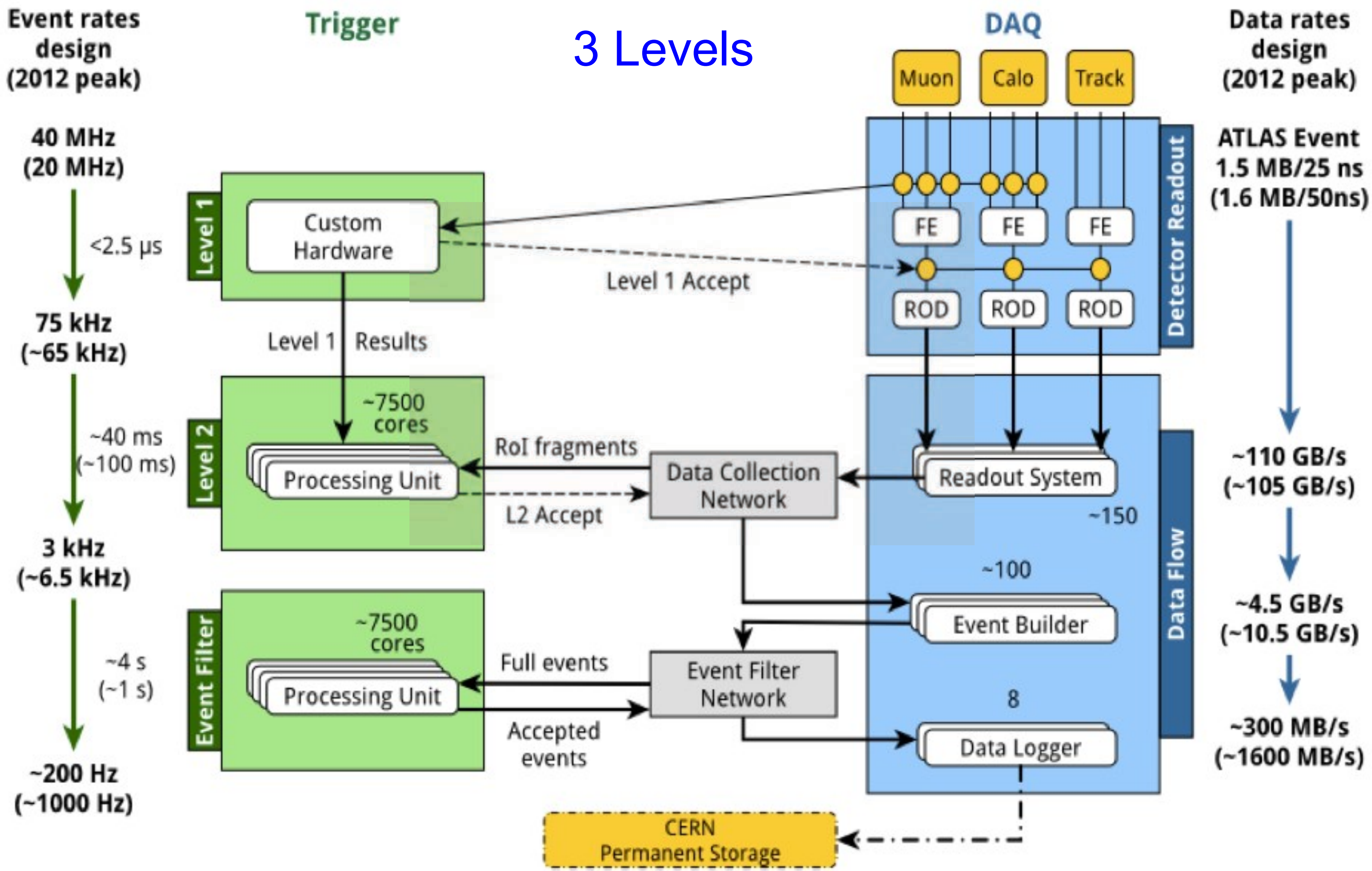
Run 1 ATLAS: 3 physical levels



CMS: 2 physical levels

ATLAS Run 1 Trigger & DAQ

3 Levels



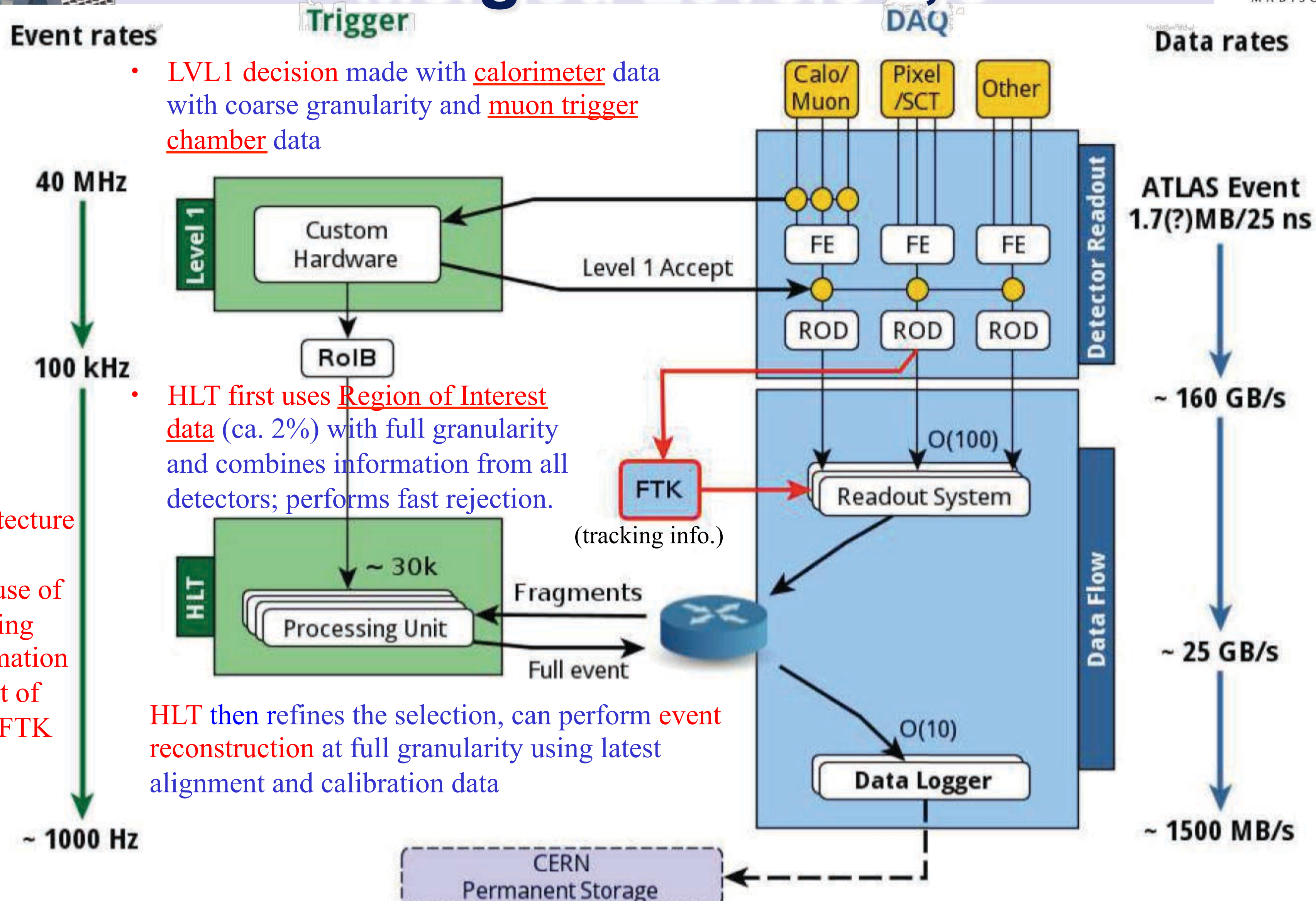
ATLAS Run 2 Trigger & DAQ: Merged Levels 2,3

- LVL1 decision made with calorimeter data with coarse granularity and muon trigger chamber data
- HLT first uses Region of Interest data (ca. 2%) with full granularity and combines information from all detectors; performs fast rejection.

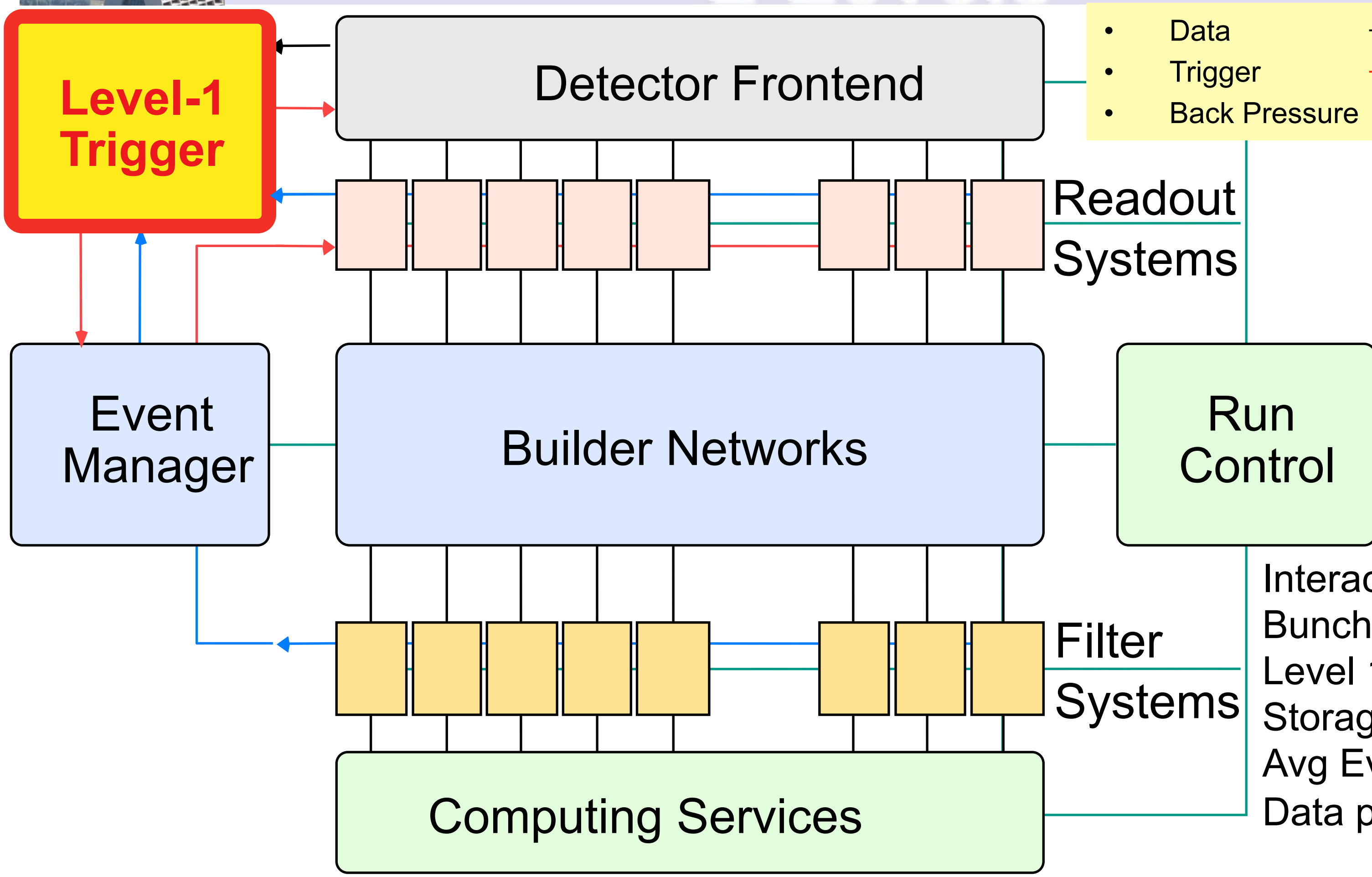
HLT then refines the selection, can perform event reconstruction at full granularity using latest alignment and calibration data

New HLT Architecture

New use of Tracking Information at start of HLT: FTK



CMS Run 1,2 Trigger & DAQ: 2 Levels



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

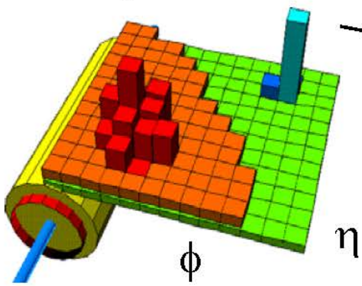
Interaction rate: 1 GHz
Bunch Xing rate: 40 MHz
Level 1 Output: 100 kHz
Storage Output: ~ 400 Hz
Avg Event Size: ~ 0.5 MB
Data production ~ 1 TB/day

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

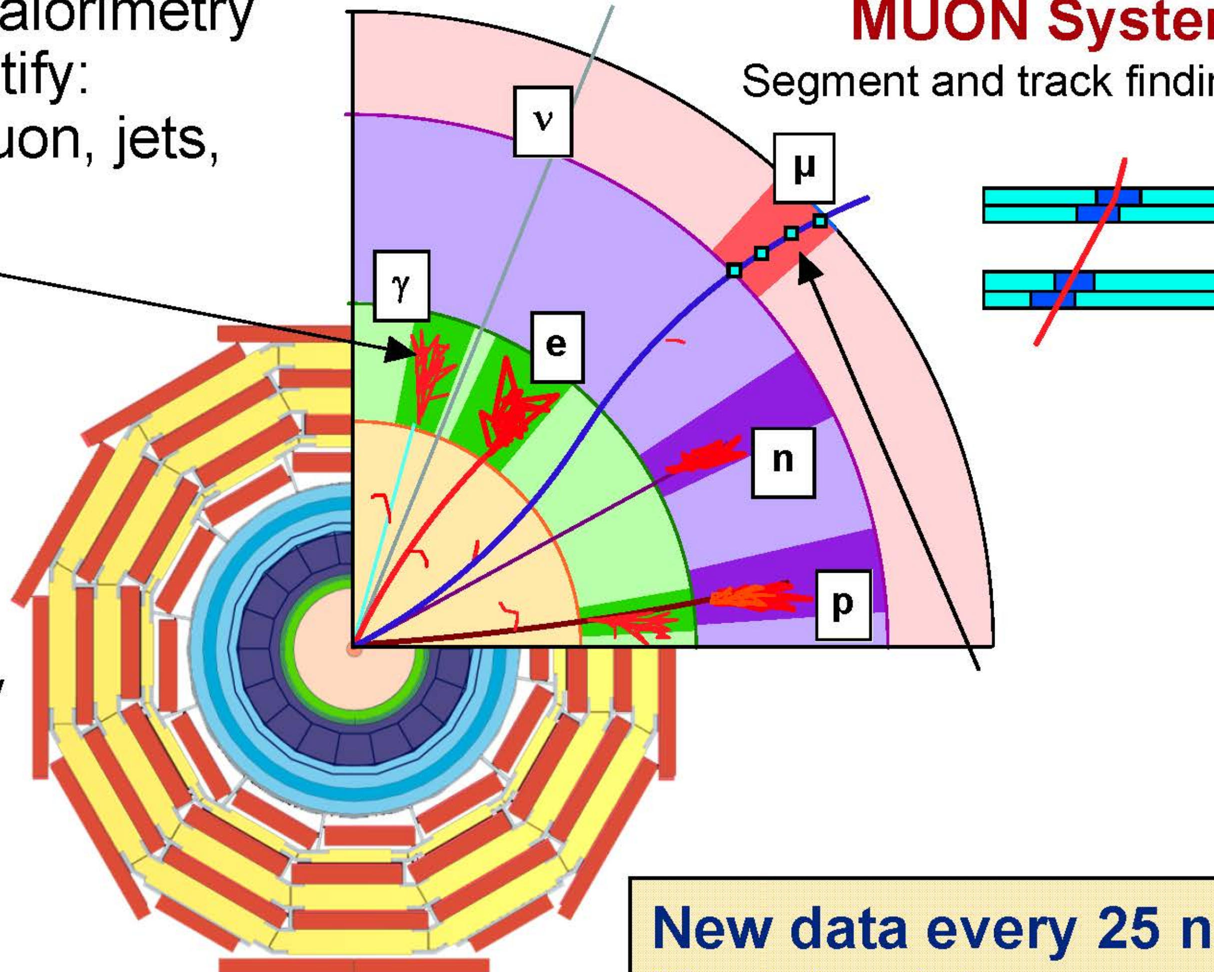
Readout buffers designed to accommodate Poisson fluctuations from 100 kHz Lv1 trigger rate.

Present ATLAS & CMS Level 1 Trigger Data

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



MUON System
Segment and track finding



CALORIMETERs
Cluster finding and energy deposition evaluation

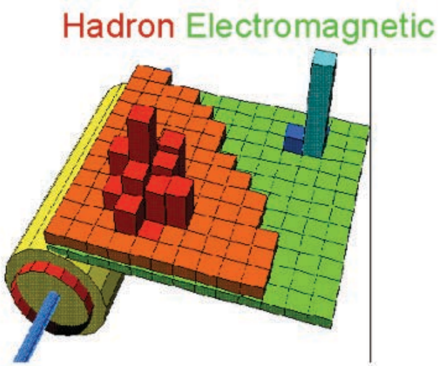
New data every 25 ns
Decision latency ~ μs

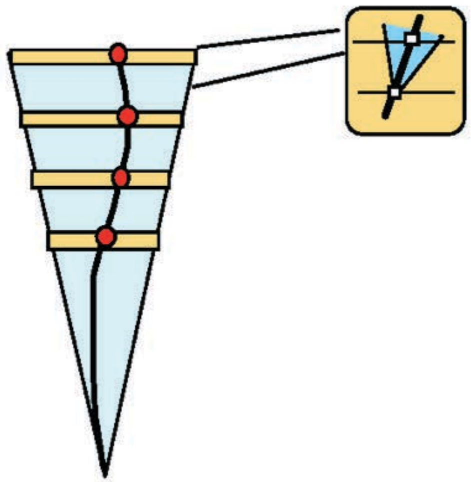
HCPSS16

Present ATLAS & CMS L1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

- **Pattern recognition much faster/easier**

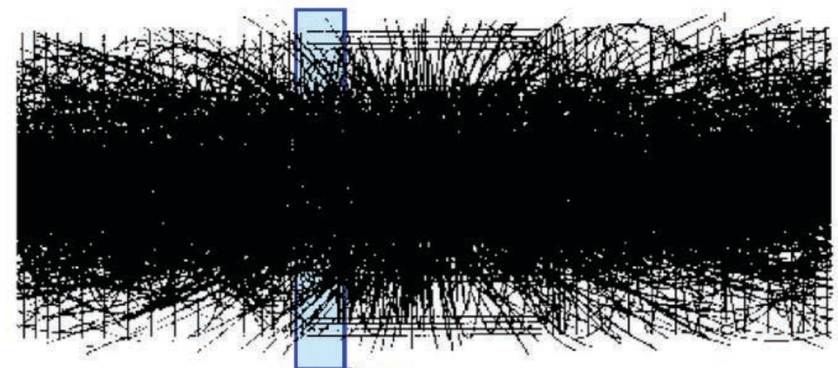


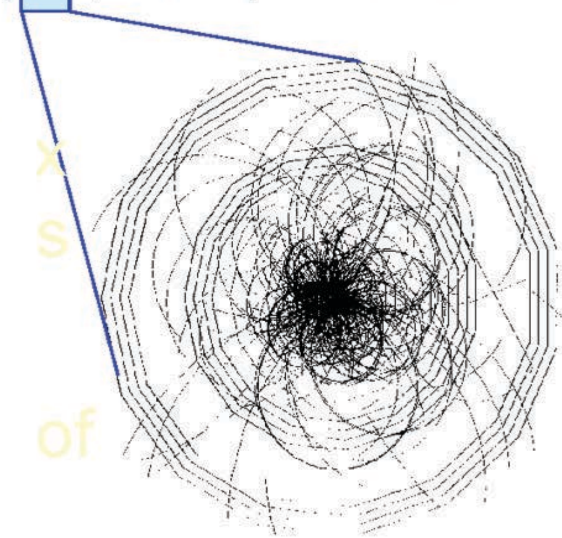


Simple Algorithms

Small amounts of data

- **Compare to tracker info**





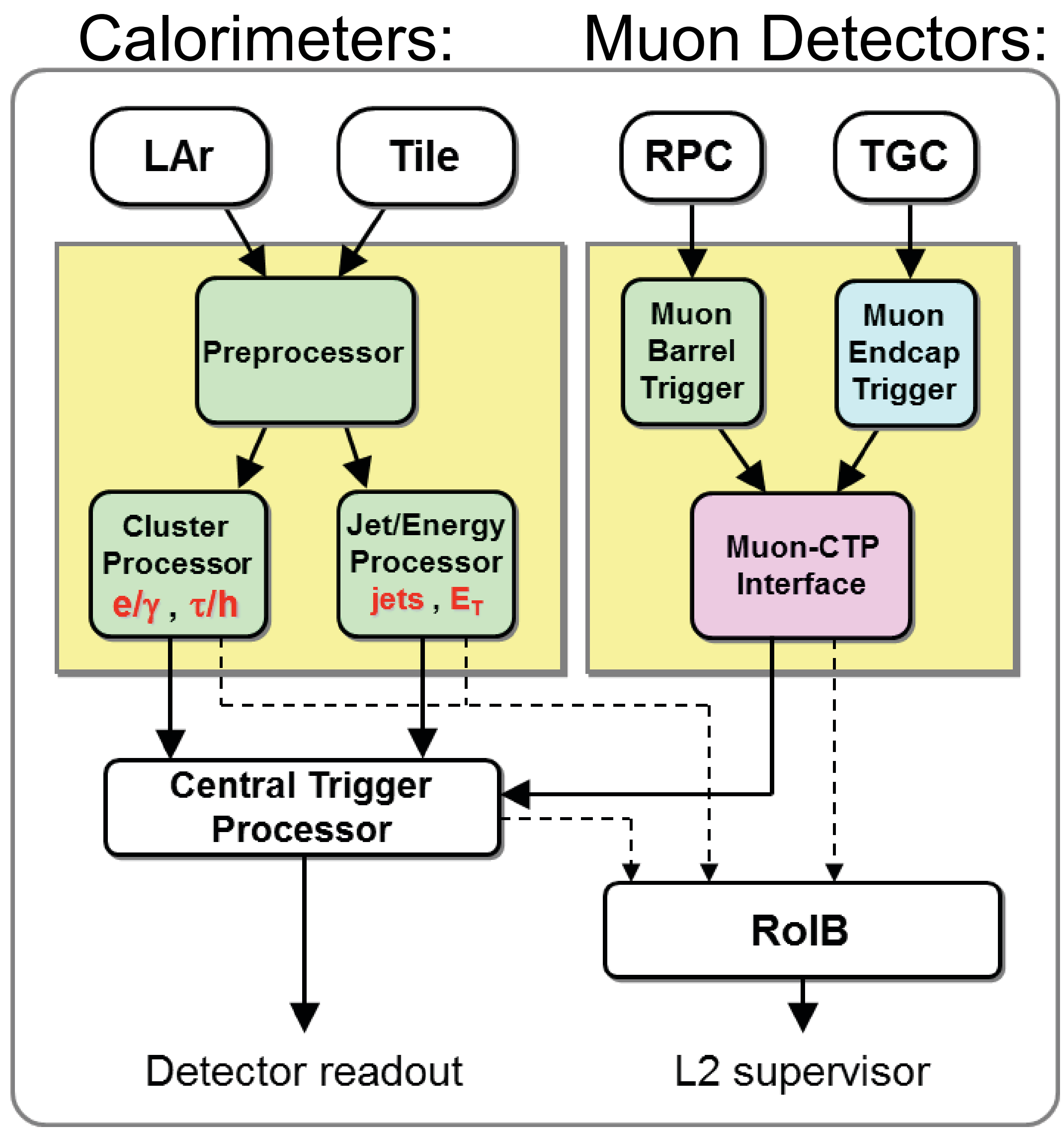
Complex Algorithms

Huge amounts of data

Run 1 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



ATLAS Run 1 RoI Mechanism

LVL1 triggers on high p_T objects

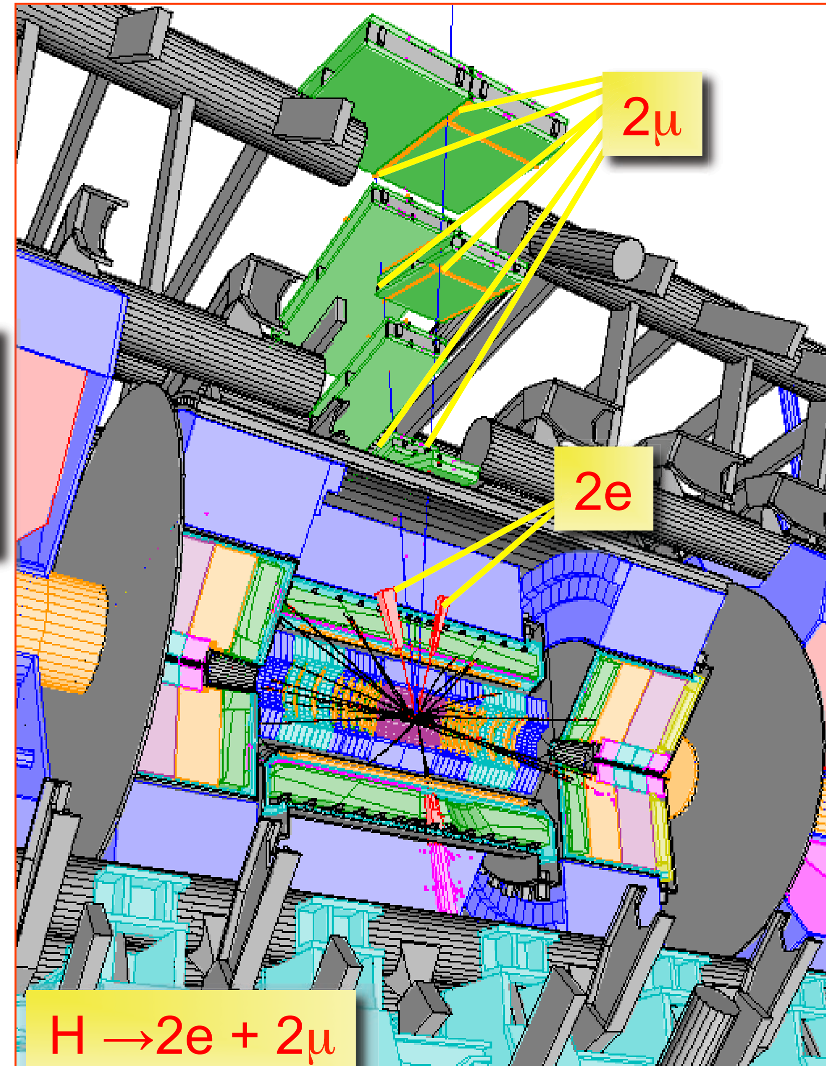
- **Calorimeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

LVL2 uses Regions of Interest as identified by Level-1

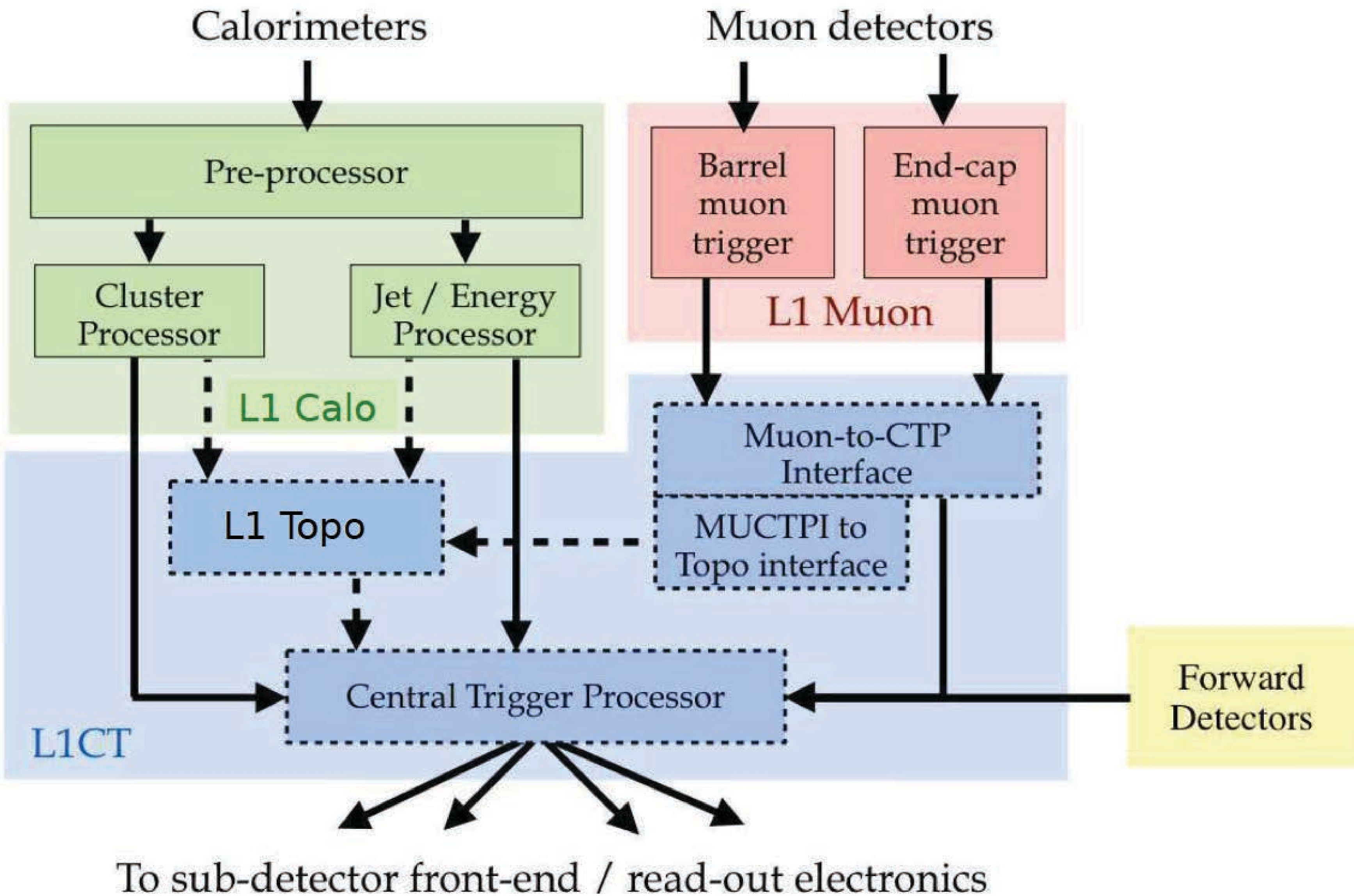
- Local data reconstruction, analysis, and sub-detector matching of RoI data

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



ATLAS Run 2 L1 Trigger



Run 1 CMS L1 Trigger System

Lv1 trigger is based on calorimeter & muon detectors.

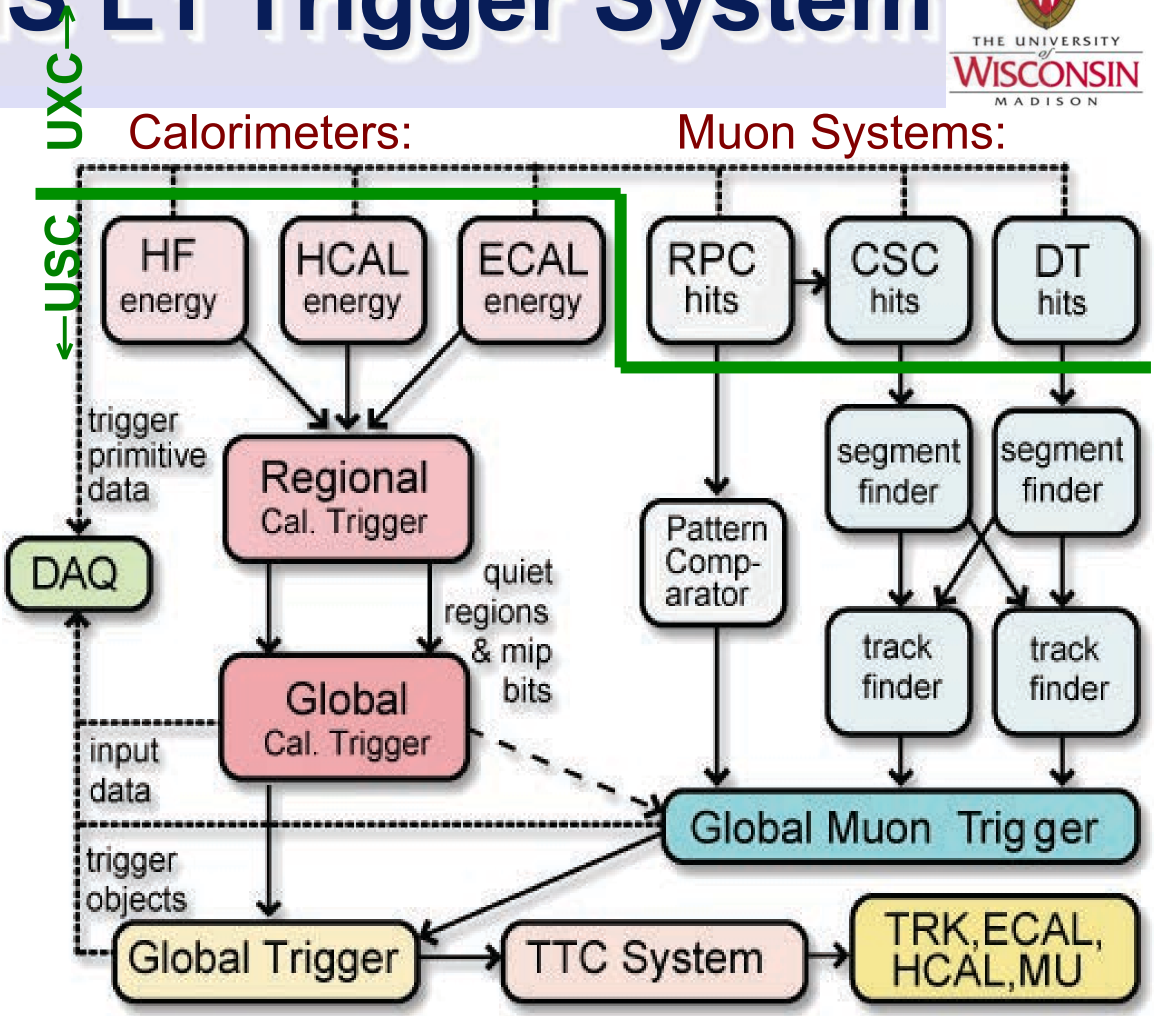
At L1 trigger on:

- 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

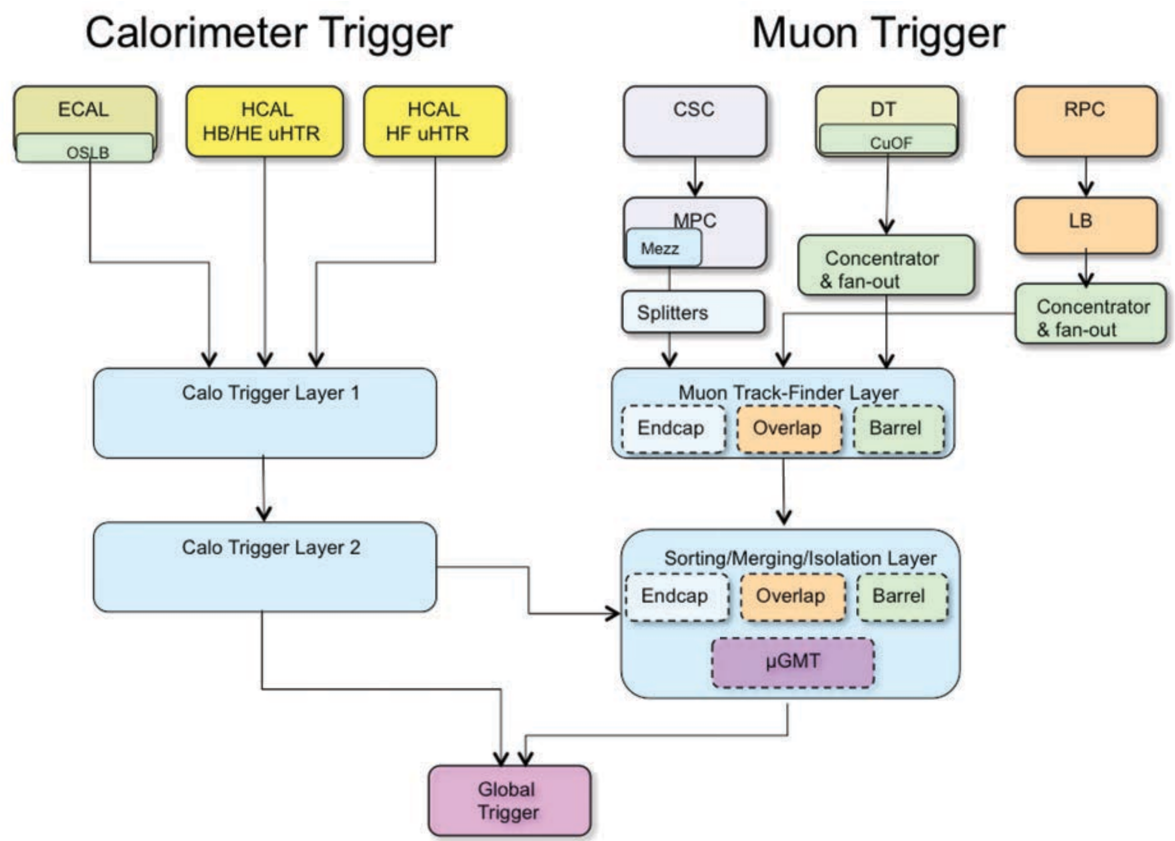
Run 2 CMS L1 Trigger System

Lv1 trigger is based on calorimeter & muon detectors.

Increased η and φ granularity of the objects

Larger object available to the GlobalTrigger algorithms
- 12 highest E_t $e^\pm/\gamma$
- 12 highest E_t jets
- 8 highest E_t tau-jets
- 8 highest P_t muons

Larger reach of topological cuts at GlobalTrigger & so Higher Level Triggers can seed on them

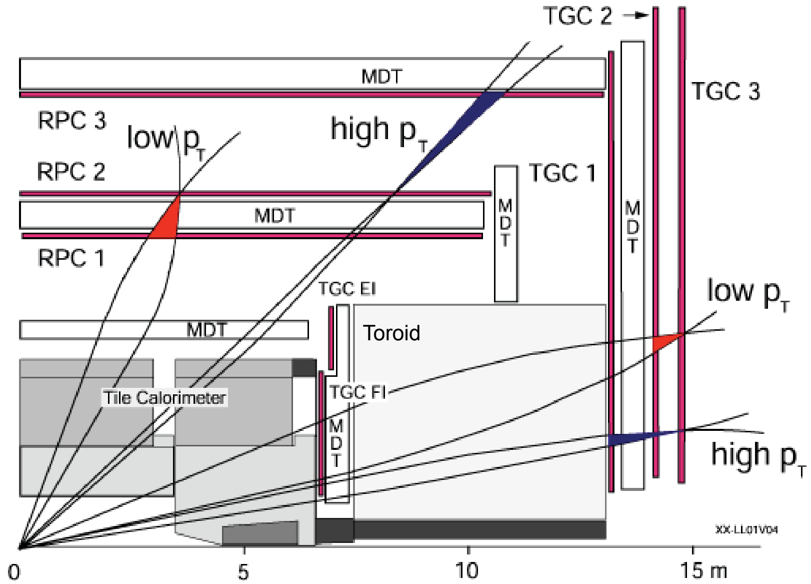


Generate L1A and send via TCDS distribution to detector front-ends to initiate readout

Maximum round-trip latency 4 μs

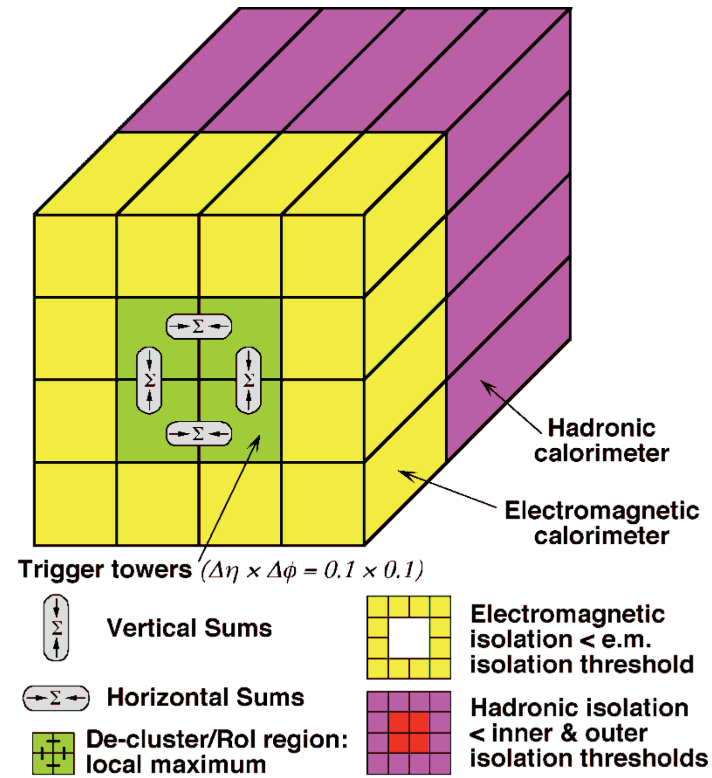
Data stored in on-detector pipelines

ATLAS Run 1 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)



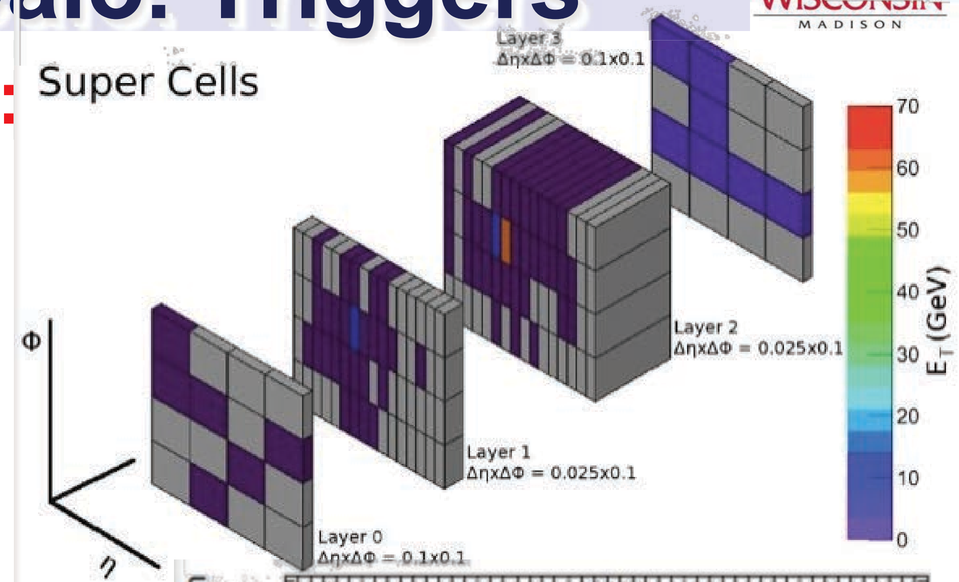
Calorimetry Trigger looking for e/γ/τ + jets

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

ATLAS Phase-1 (LS2) Upgrade Calo. Triggers

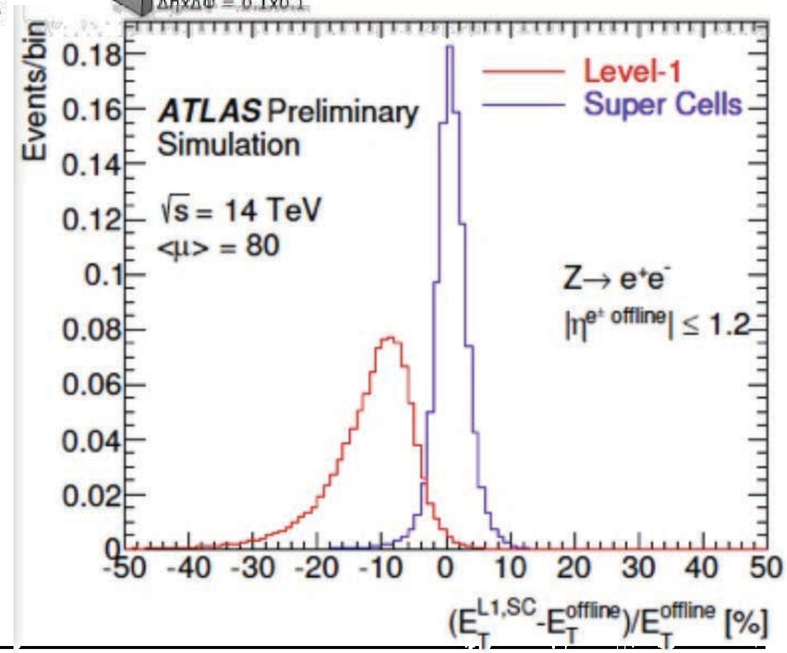
Calo. Trig: Improvements: Feature Extractor Processors

- Higher granularity in eta 0.025
  - present $\eta \times \phi = 0.1 \times 0.1$
- Segmentation in depth
- Higher resolution (E_T: 0.125 GeV/count, now is 1 GeV/count)



Expected Improvement wrt. Run 1 System

- At Pileup of 80:

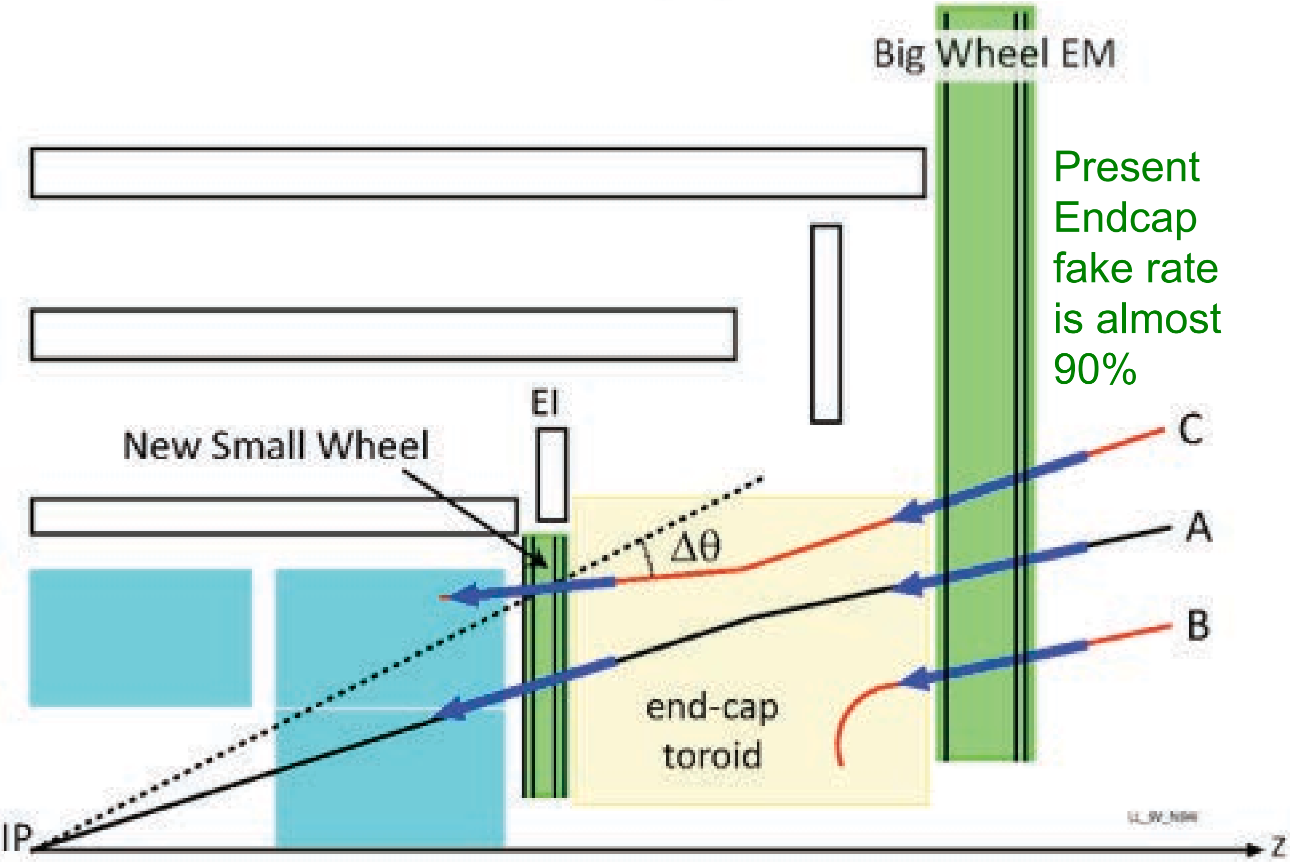


ATLAS Phase-1 (LS2) Upgrade Muon Triggers

THE UNIVERSITY of WISCONSIN MADISON

Muon. Trig: Improvements:

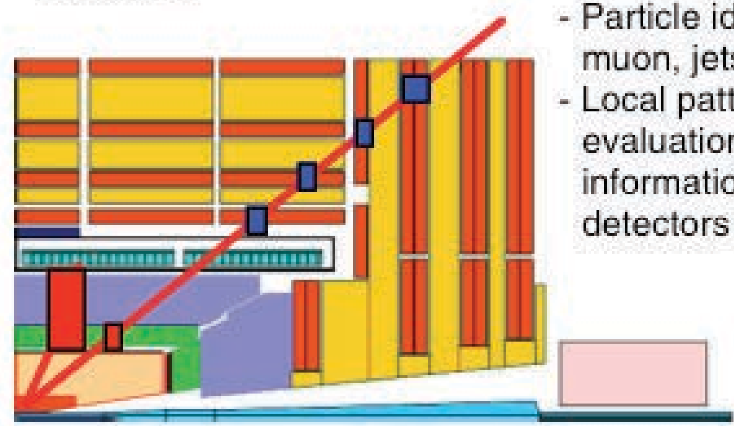
- **New Small Wheel**
- **Rejects tracks not from IP:**
  - B: creation within toroid
  - C: multiple scattering
- **Matching θ btw. Big Wheel and NSW**



Angular resolution of 1 mrad (trigger)
- After phase-2 BW upgrade
- Until LS3: NSW confirmation of BW tracks with angular cut of +- 7 mrad

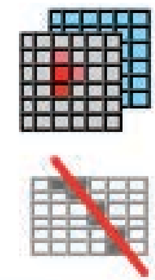
CMS Trigger Levels

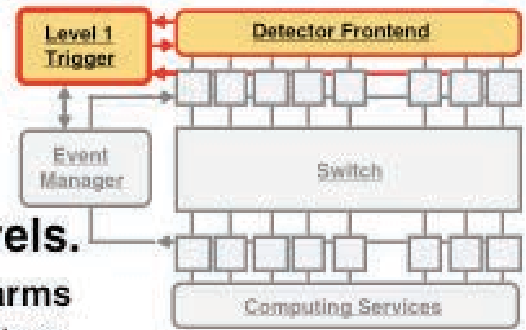
40 MHz



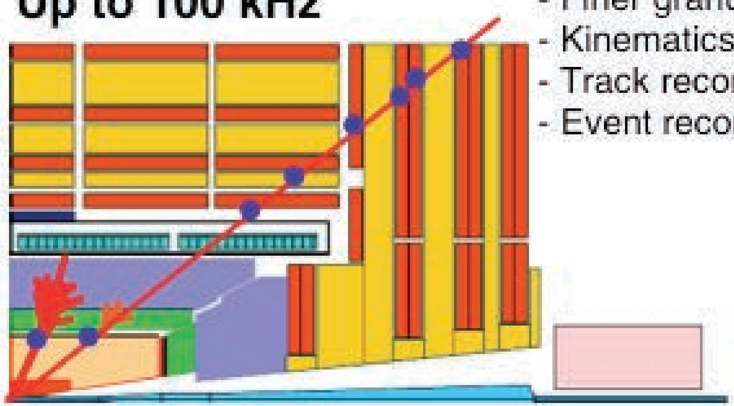
Level-1. Specialized processors

- 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

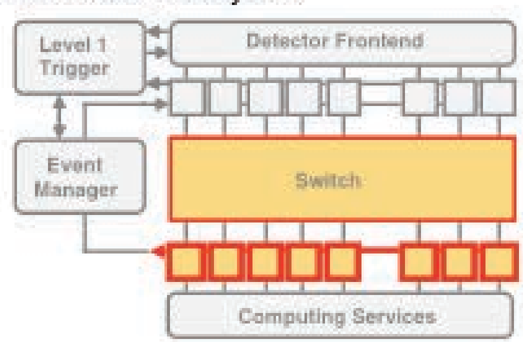


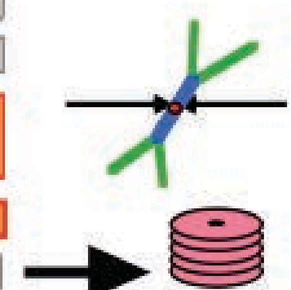
High trigger levels.

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

≈ 1kHz



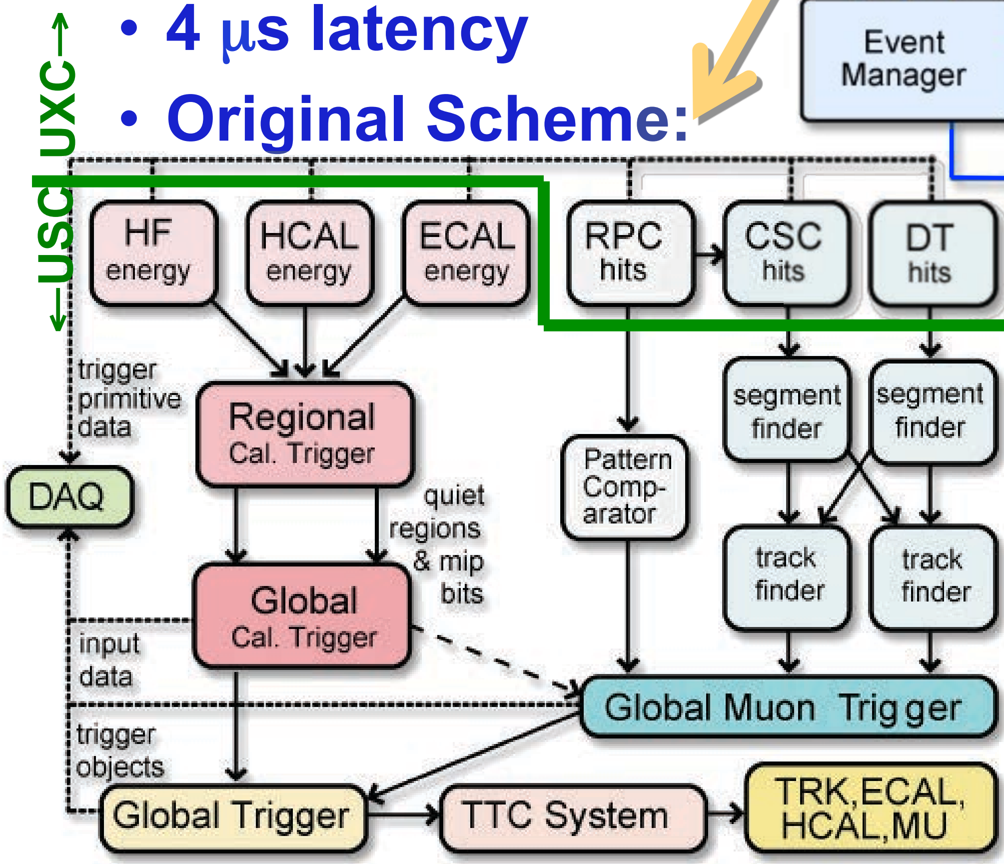


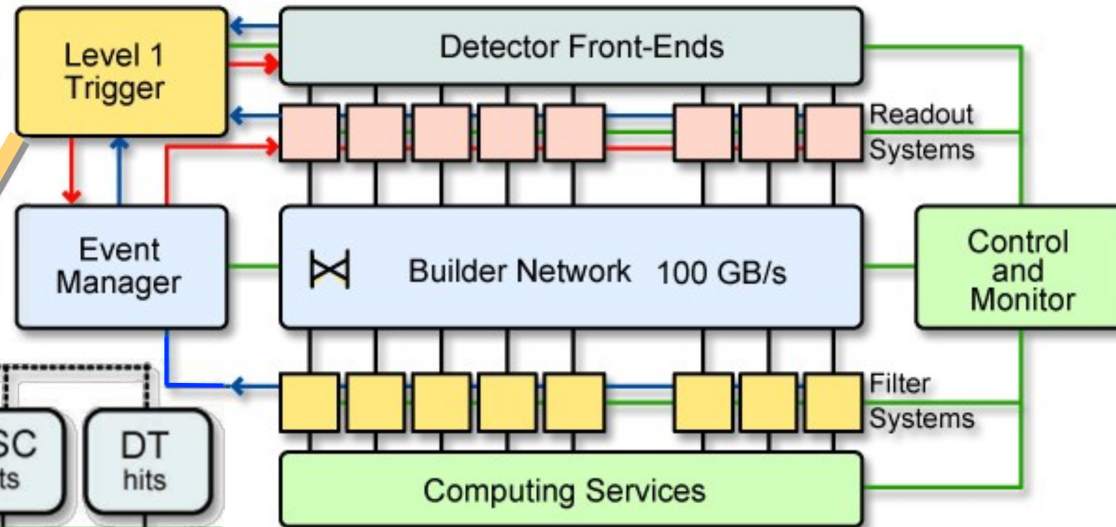
CMS Level-1 Trigger & DAQ

Overall Trigger & DAQ Architecture: 2 Levels:

Level-1 Trigger:

- 25 ns input
- 4 μs latency
- Original Scheme:





Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

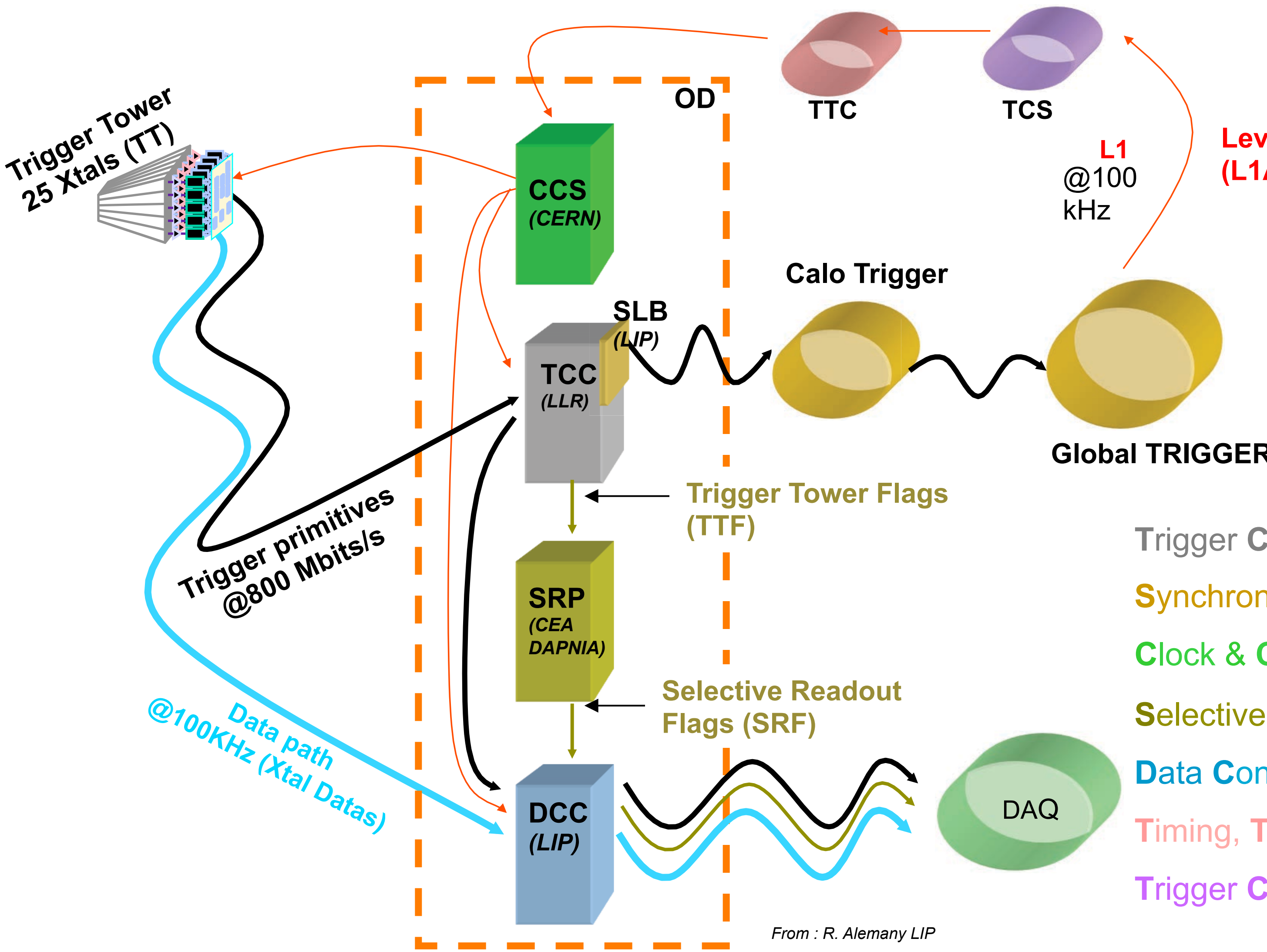
Level 1 Output: 100 kHz

Output to Storage: 1kHz

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

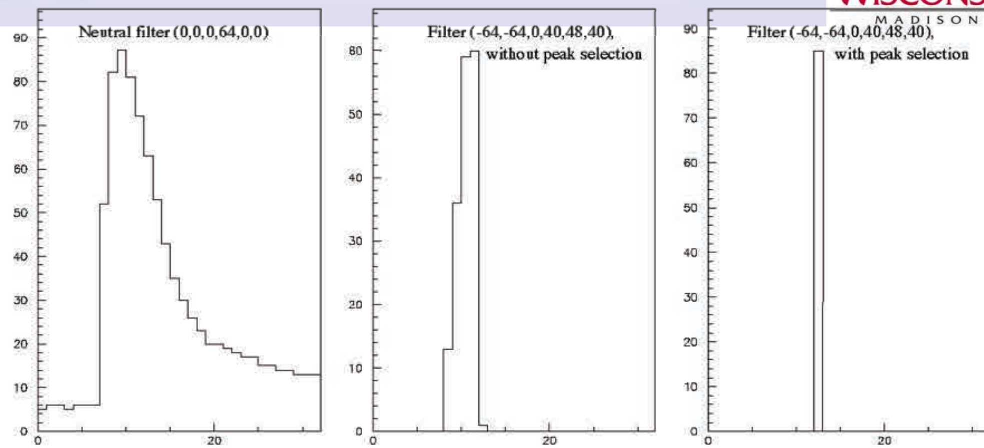
Trigger Control System

ECAL Trigger Primitives

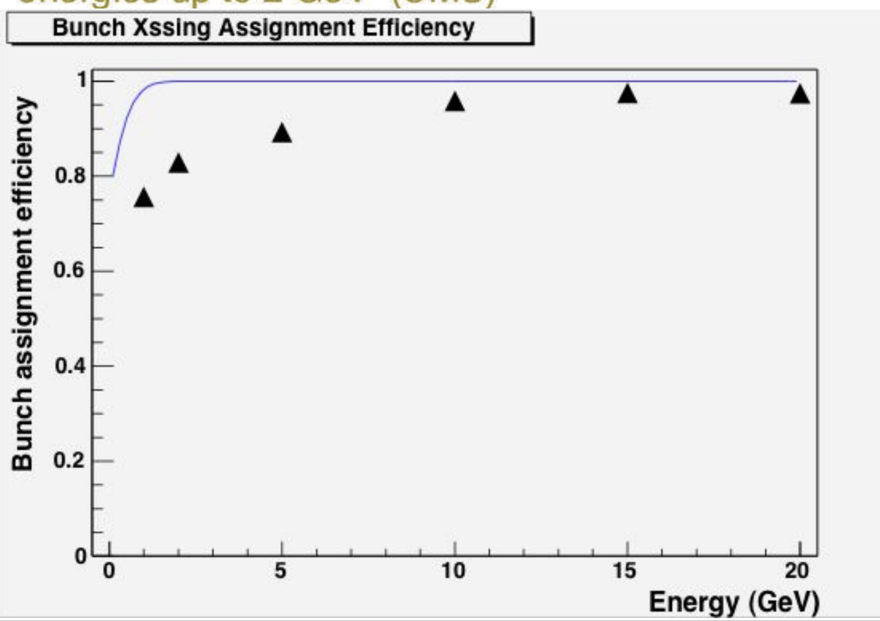
In the trigger path, **digital filtering** followed by a **peak finder** is applied to energy sums **(L1 Filter)**

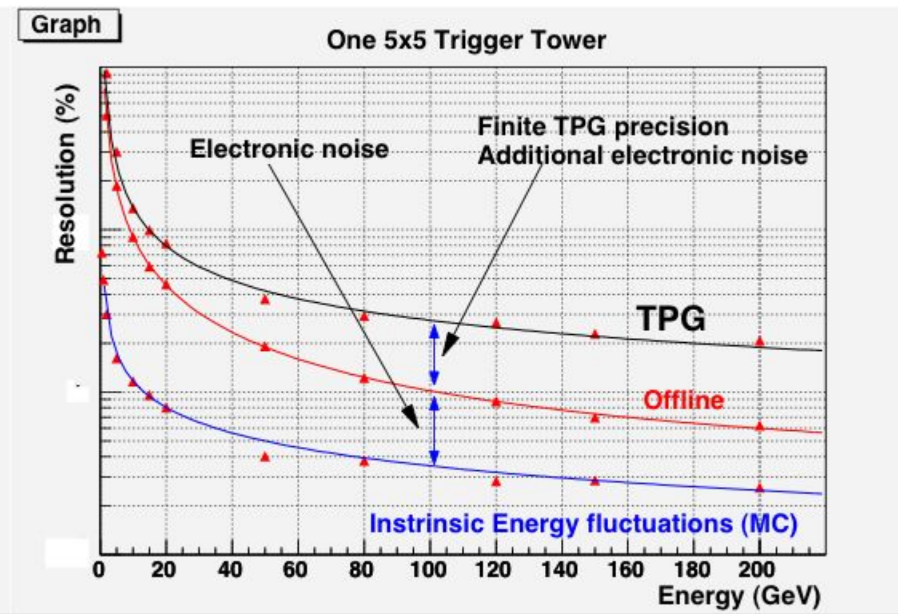
Efficiency for energy sums above 1 GeV should be close to 100% (depends on electronics noise)

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: Basics

Trigger Primitive Generator

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

Regional Calorimeter Trigger

E_T cut — + Max ( ) > Threshold

AND

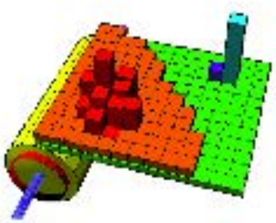
Longitudinal cut (H/E) — / < 0.05

AND

Isolation, Hadronic & EM — < 2 GeV

AND

One of (, , ,) < 1 GeV



↓

ELECTRON or PHOTON

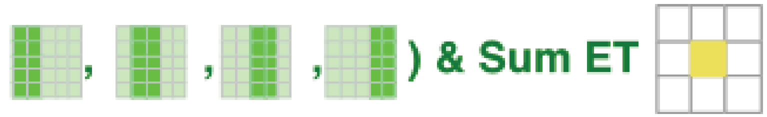
CMS Electron/Photon Algorithm: Run 2 Version

HCPSS16

THE UNIVERSITY of WISCONSIN MADISON

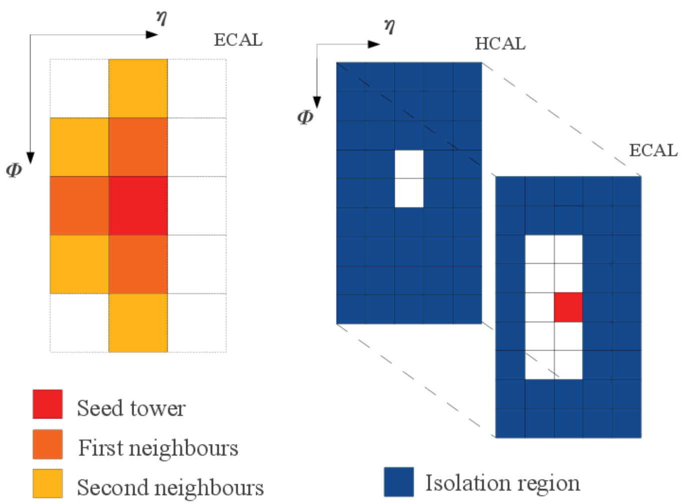
Trigger Primitive Generator

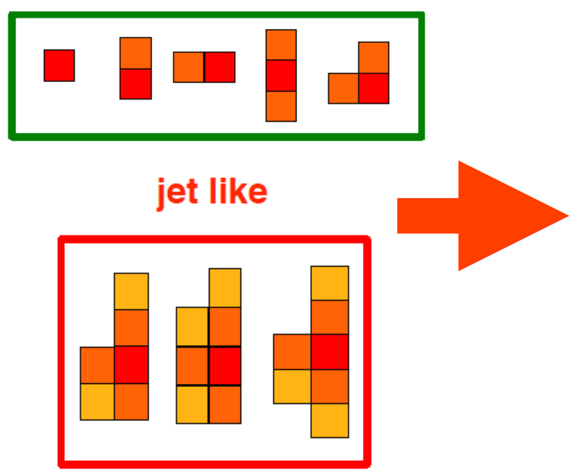
Fine grain Flag Max of (, , ,) & Sum ET



EGamma Identification

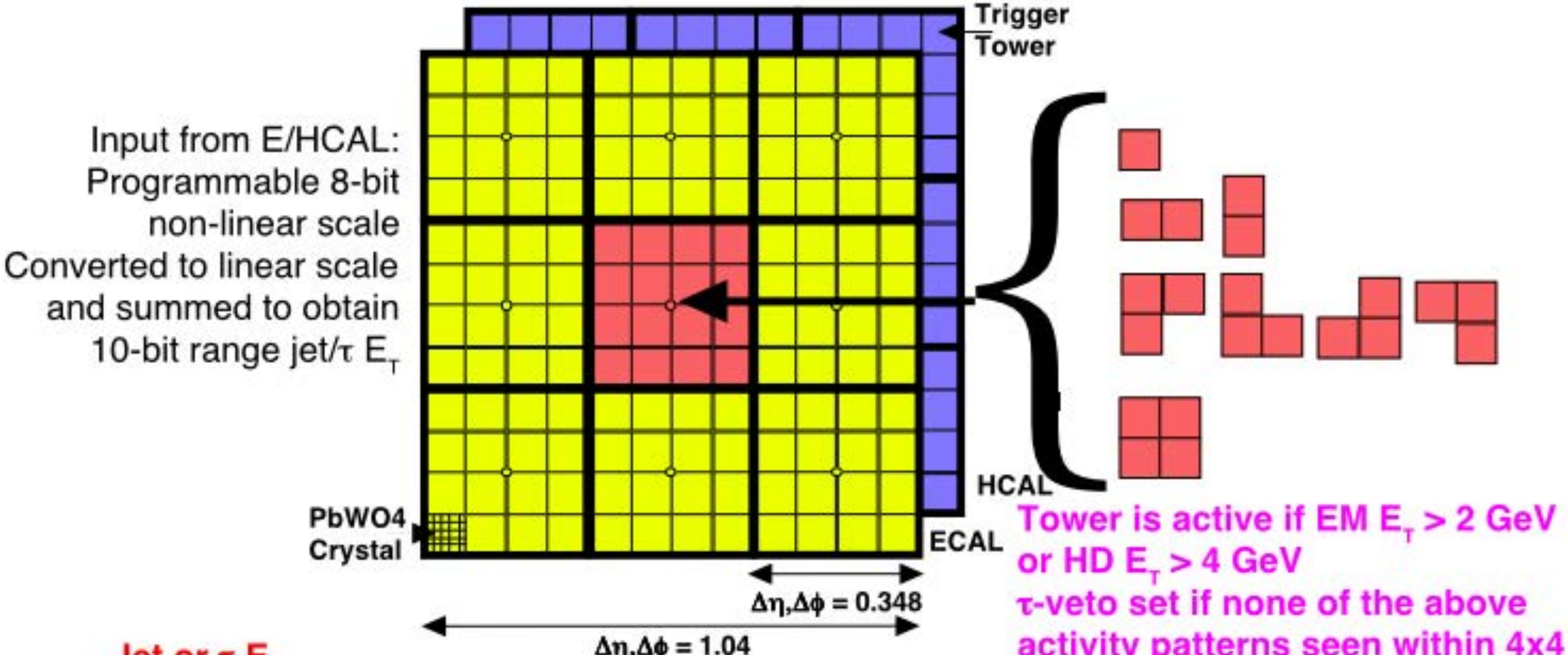
Dynamic clustering around a seed trigger tower (ET>2GeV)
Shape identification: based on ET, eta and cluster shape





ELECTRON OR PHOTON

CMS τ / Jet Algorithm: Run 1



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

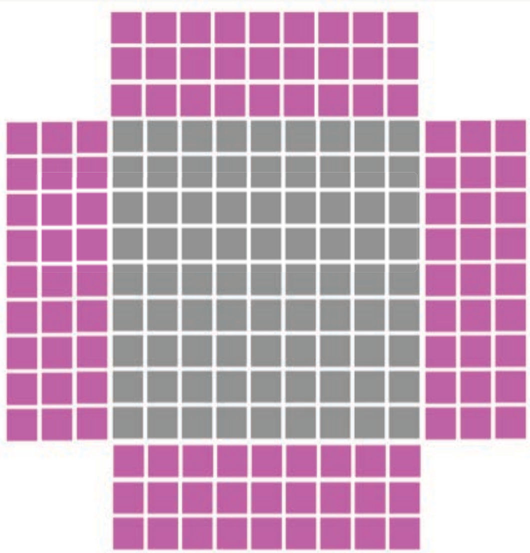
Output

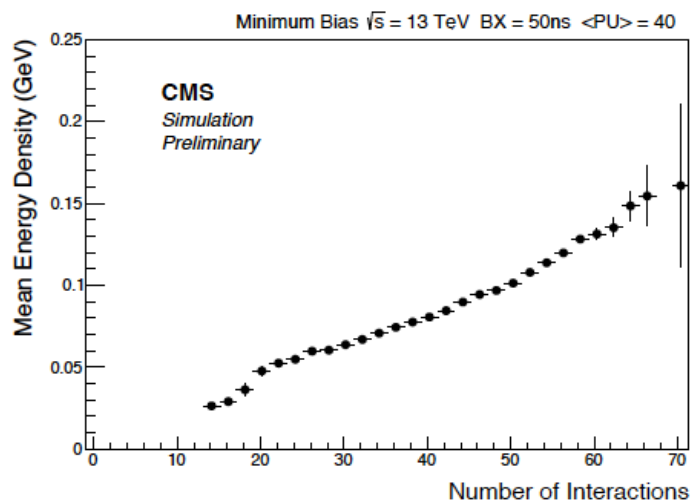
- Top 4 τ-jets and top 4 jets in central rapidity, and top 4 jets in forward rapidity

CMS Jet Algorithms: From 2016

Sliding-Window Algorithm, centred on a local maximum ET trigger tower

- 9x9 trigger towers considered - corresponding to anti-kt jets of R=0.4
- jet position from the central (local maximum) TT
- jet ET from the 9x9 TT sum
- inequality mask to avoid self veto & double counting





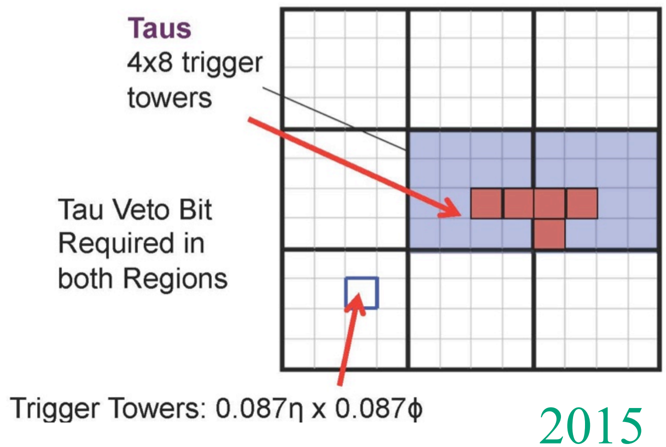
PileUp rejection based on a "donut" algorithm

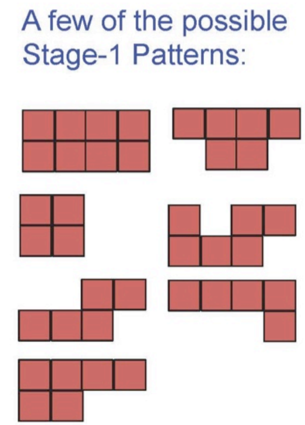
- energy in the four 3x9 trigger towers blocks around the jet used to estimate pile-up energy density

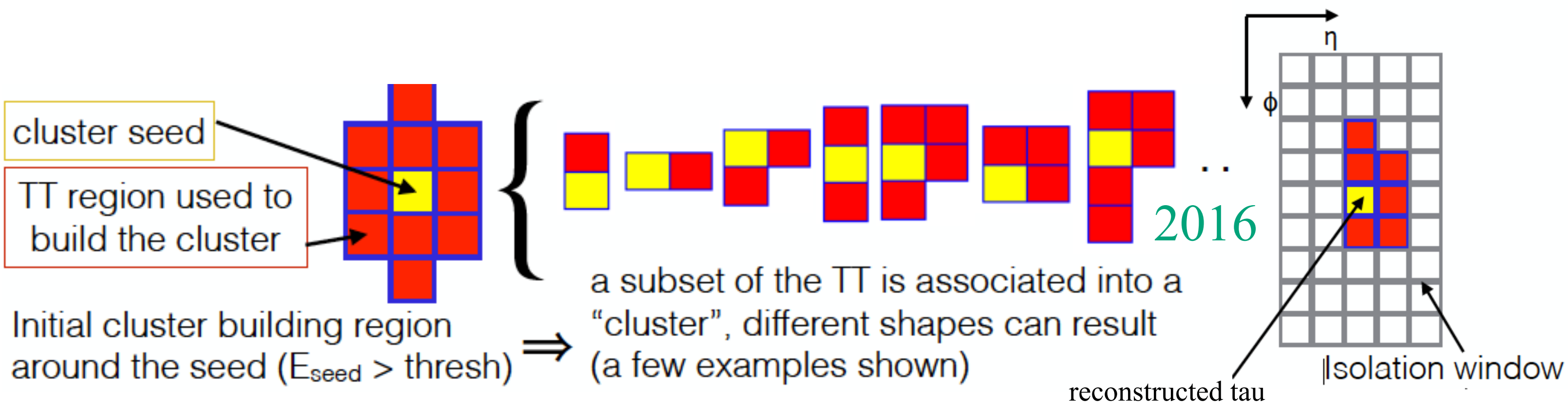
CMS τ algorithms: Run II

Topology can be used to distinguish hadronically decaying taus from taus:

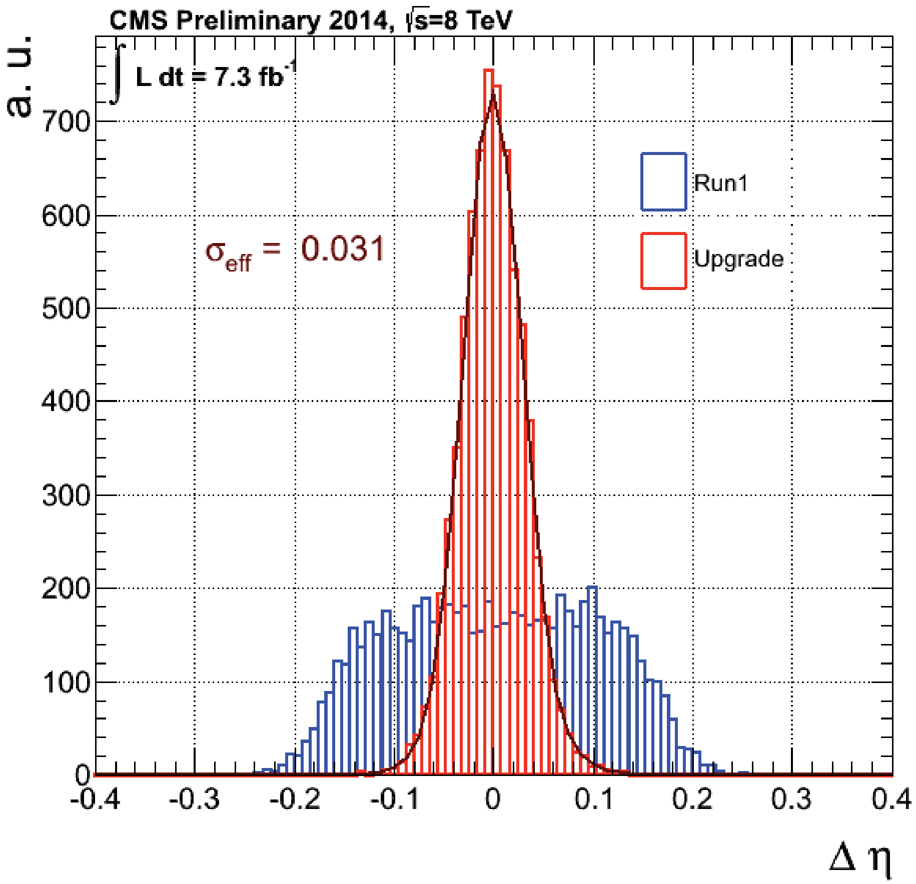
- Enhanced position resolution by increasing granularity
- Introduce isolation as a handle to control rate
- Better energy resolution with specific calibration sequences

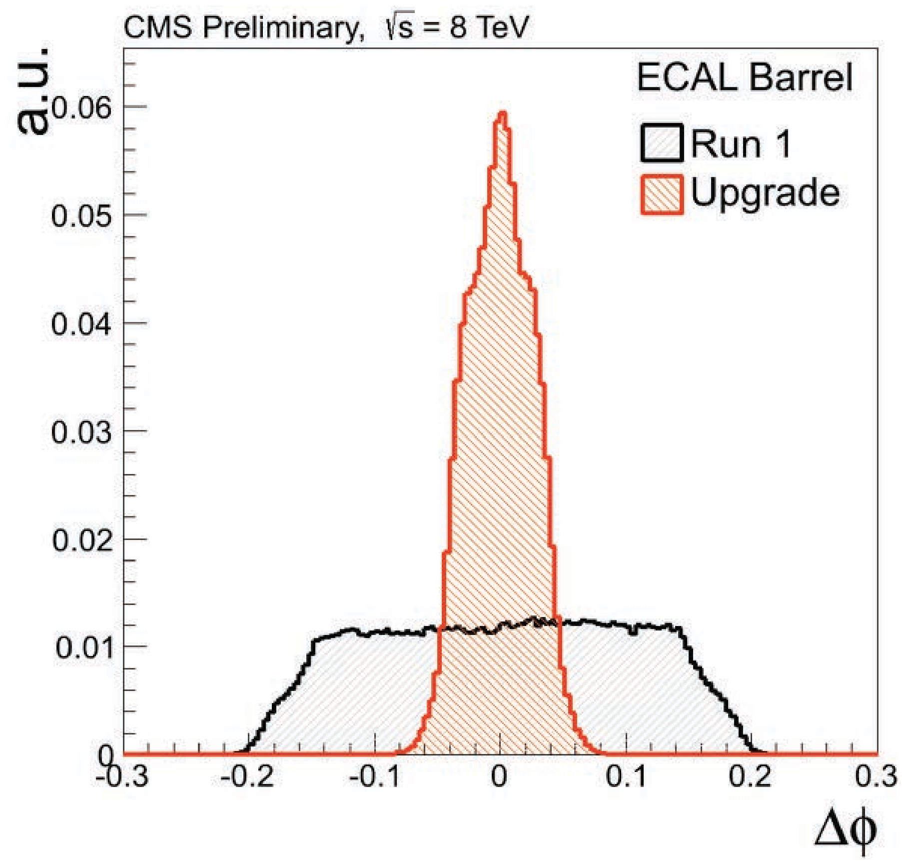






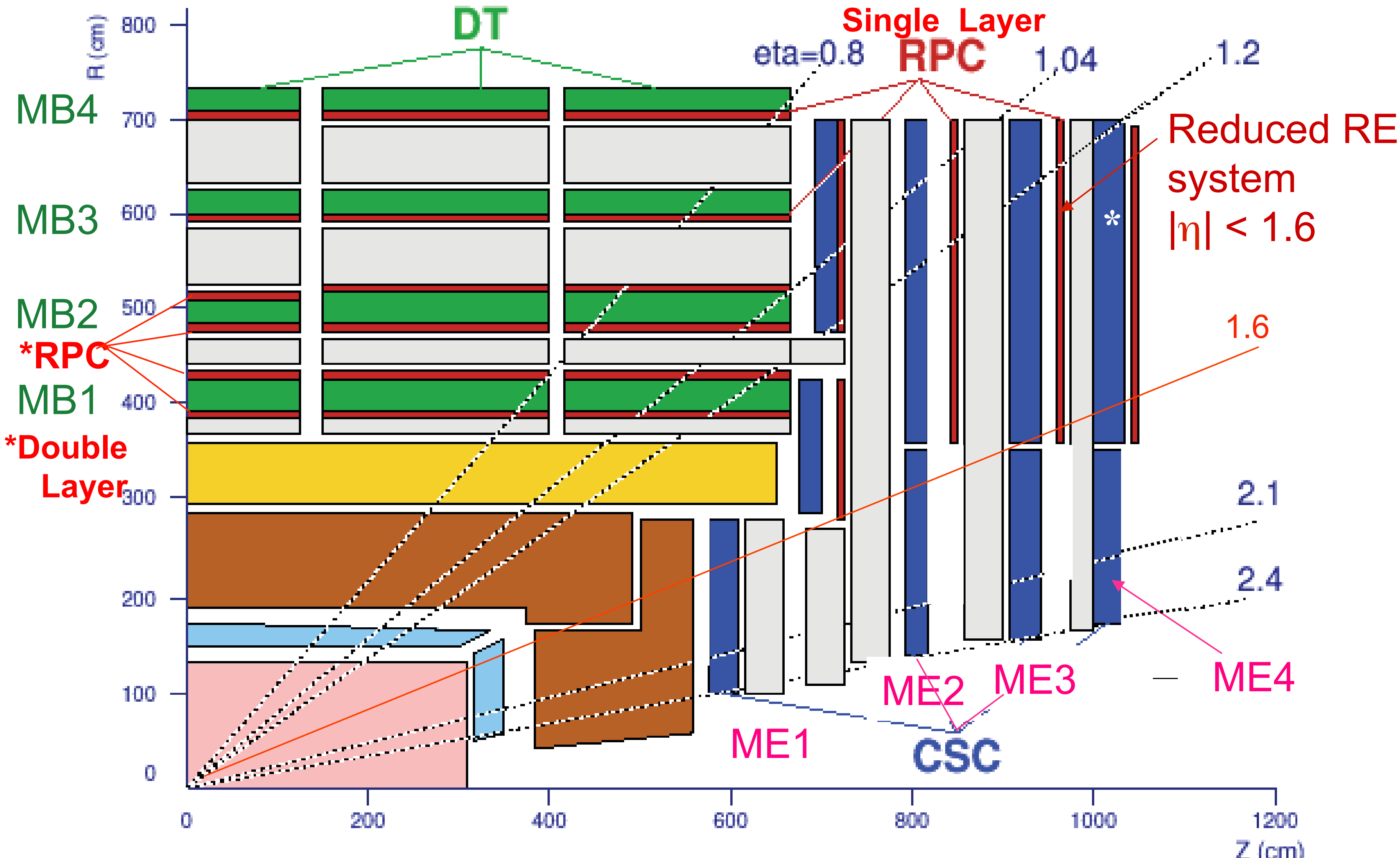
Position Resolution Improvement



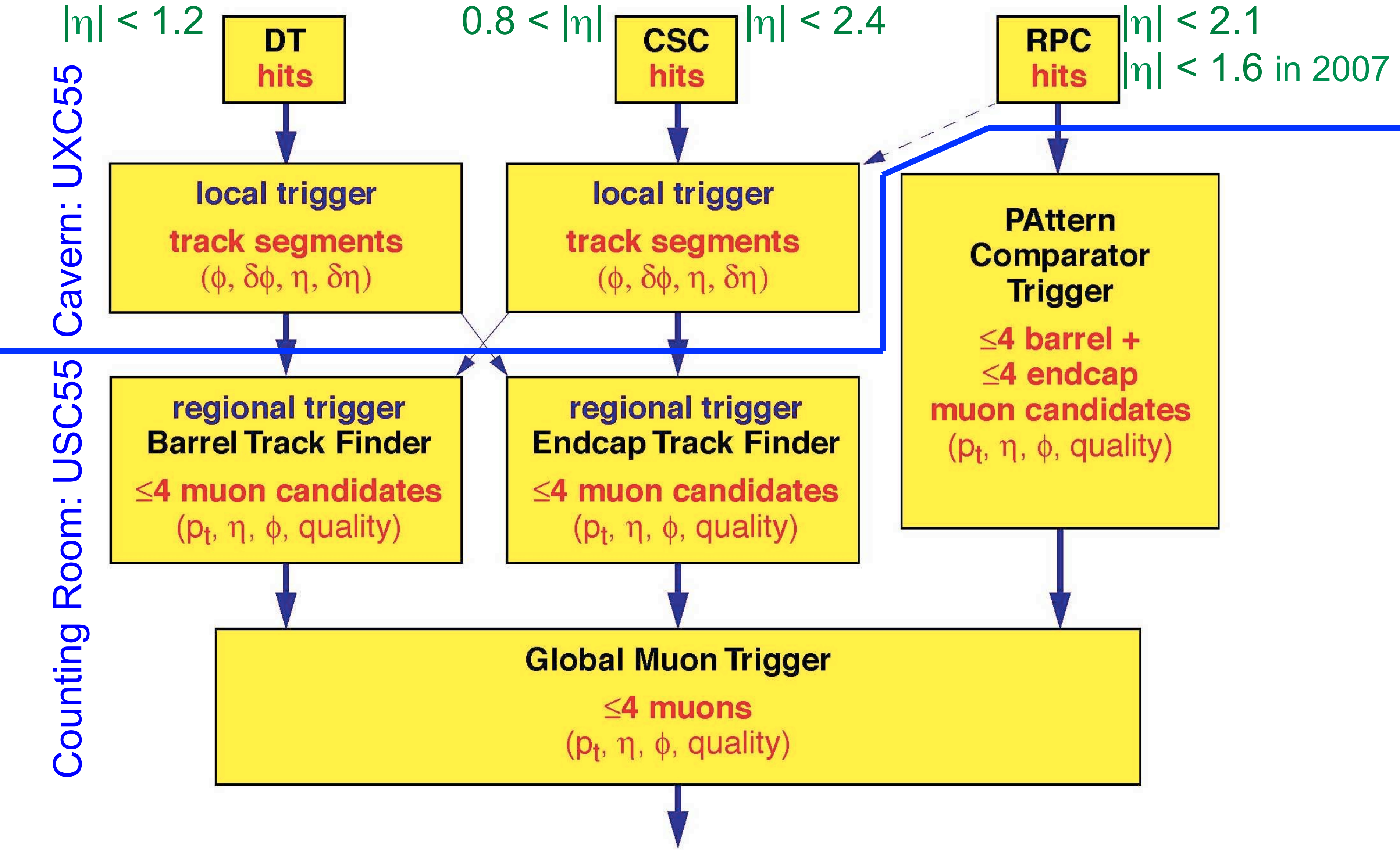


Being able to access tower level granularity for the position strongly enhances the position resolution of electrons and taus

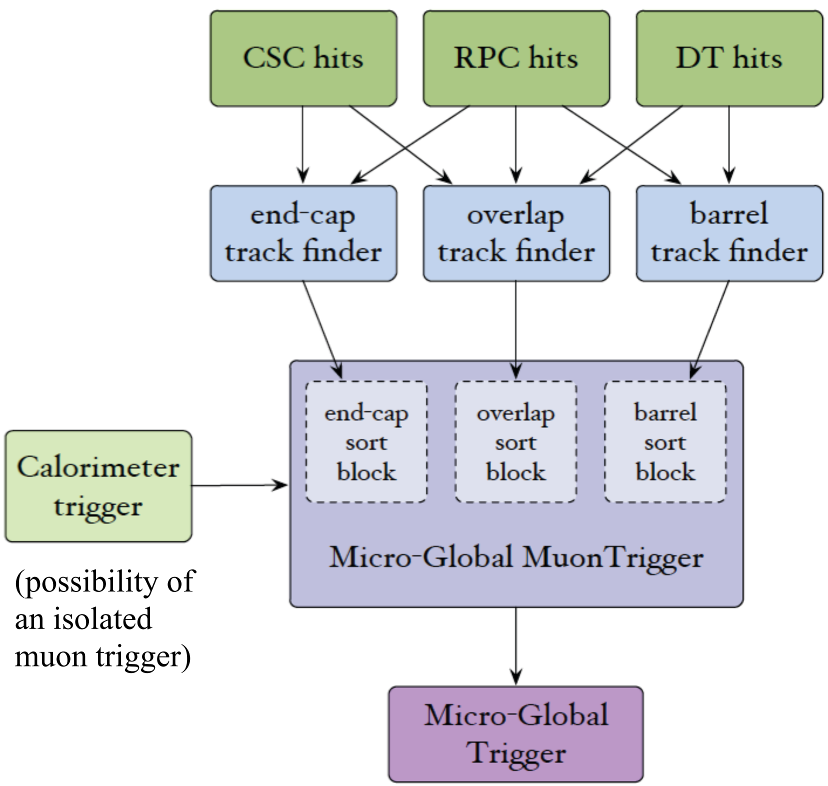
CMS Muon Chambers (> 2014*)



CMS Run 1 Muon Trigger



CMS Run 2 Muon Trigger



BARREL MUON TRACK FINDER:
- DT + RPC Hits
- $0.8 < |\eta|$
- Optical links from the fronted of the DTs to the track finder boards (MP7)

ENDCAP MUON TRACK FINDER:
- CSC+RPC Hits
- $1.25 < |\eta| < 2.5$
- Optical signals sent from the CSC and RPC to the trigger boards (MTF7)
- Will include GEM detectors in the future

OVERLAP MUON TRACK FINDER
- DT+RPC+CSC
- $1.25 < |\eta| < 2.5$

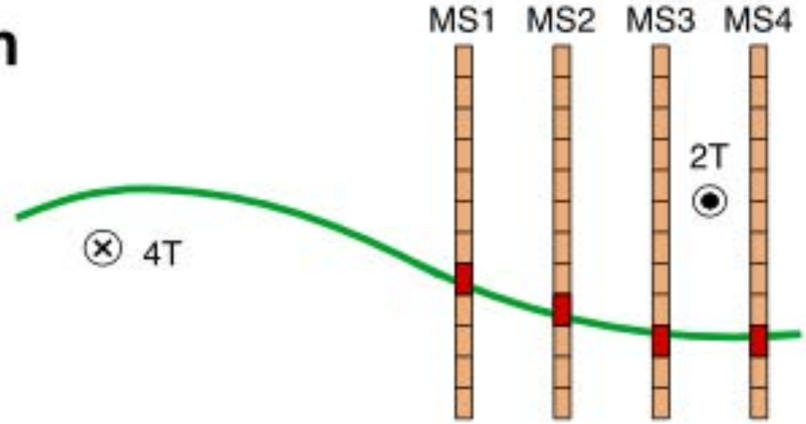
All track finders assign eta/phi/pt and quality

GLOBAL MUON TRIGGER
- Receives muons raking according to pt accuracy
- Sorts and sends the 8 highest ranking ones to the GT

HCPSS16

CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

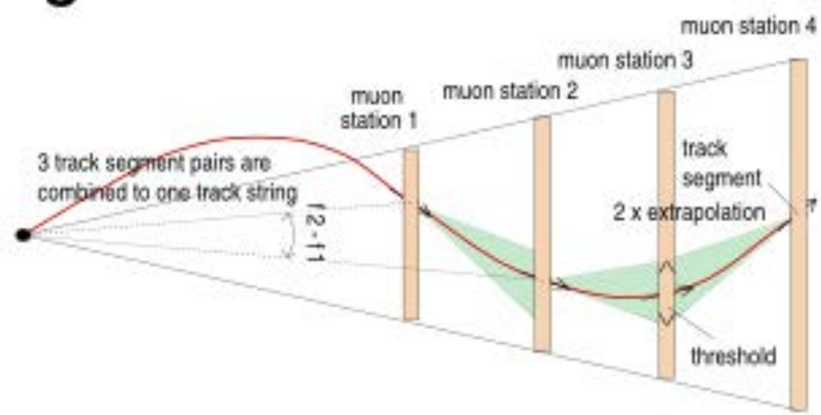


Memory to store patterns

Fast logic for matching

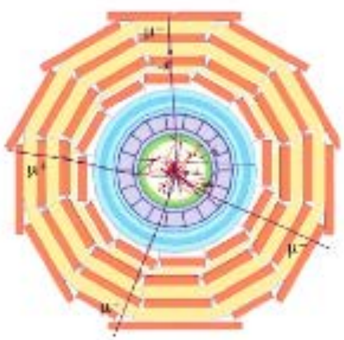
FPGAs are ideal

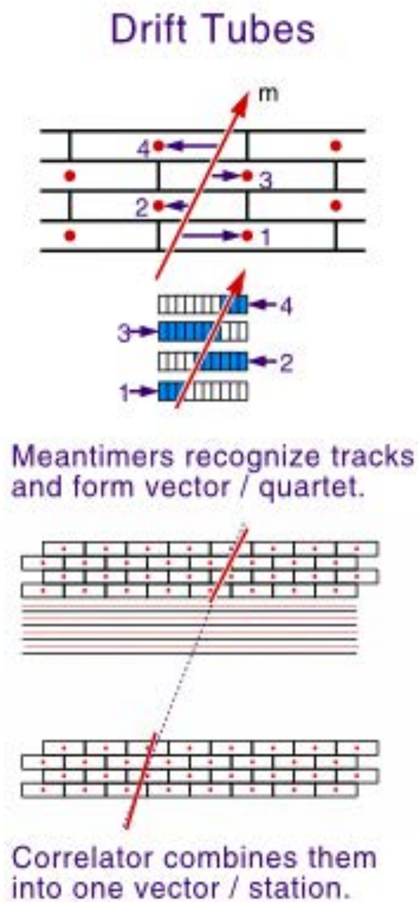
DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



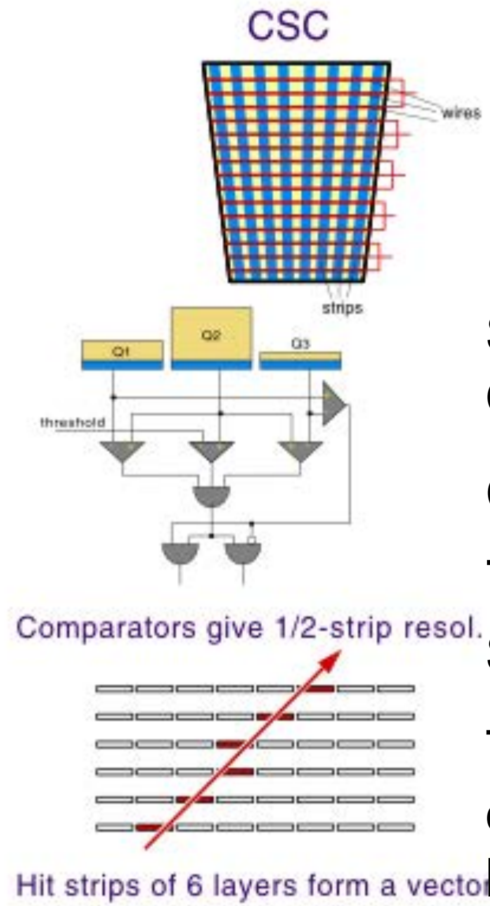
CMS Muon Trigger Track Finders

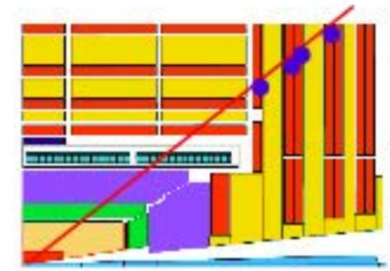
Drift Tubes (DT)





Cathod Strip Chambers (CSC)





Sort based on P_T, Quality - keep loc.

Combine at next level - match

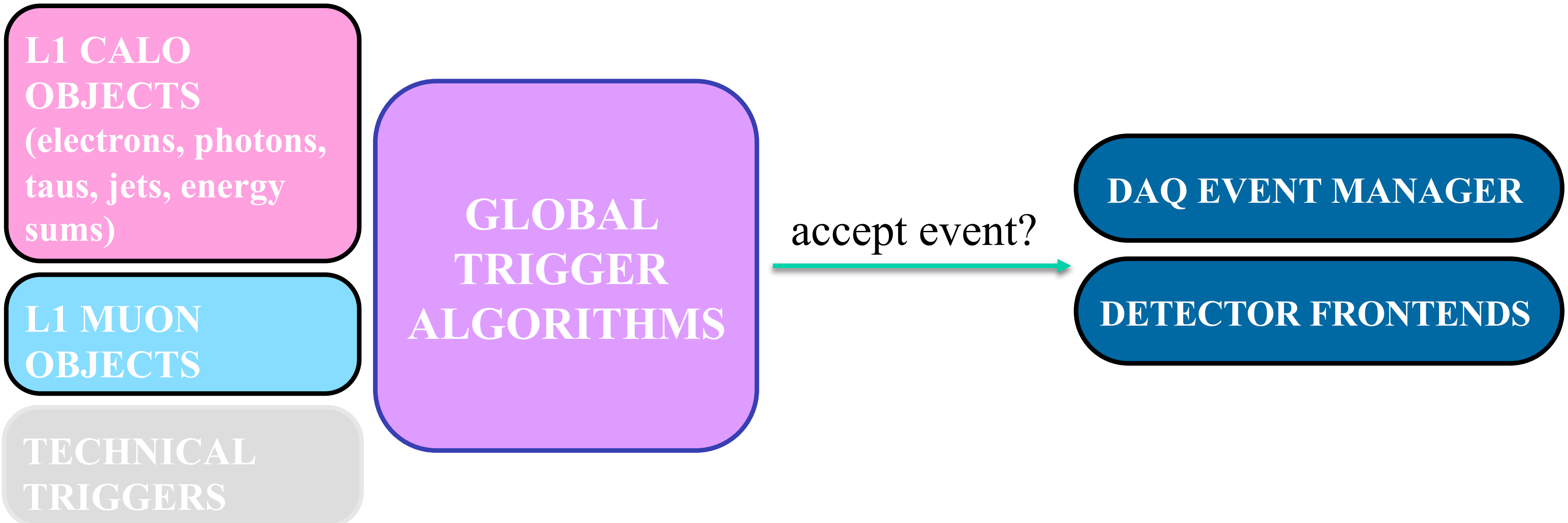
Sort again - Isolate?

Top 4 highest P_T and quality muons with location coord.

Match with RPC

Improve efficiency and quality

CMS Global Trigger Runs 1&2



L1Menu: list of all the operational GT algorithms for a particular moment of data taking

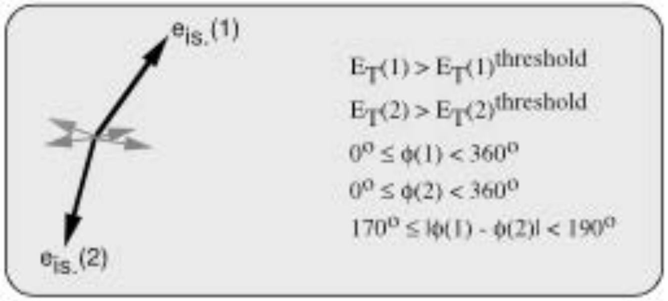
Basic algorithms: counting single or multiple particles with energy above a threshold in a pseudorapidity range (eg: SingleMu16; DoubleEG20_10)

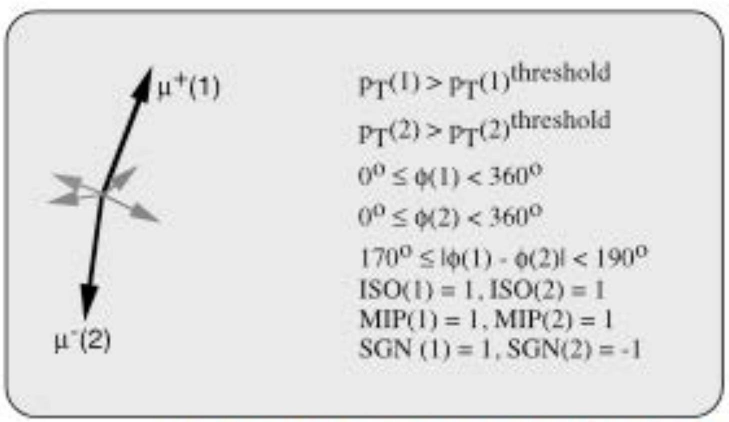
Complex algorithms take into account topological correlations of the candidates (eg: $\Delta\eta$ or invariant mass)

Output of the GT: L1 Accept after the check of the different combinations

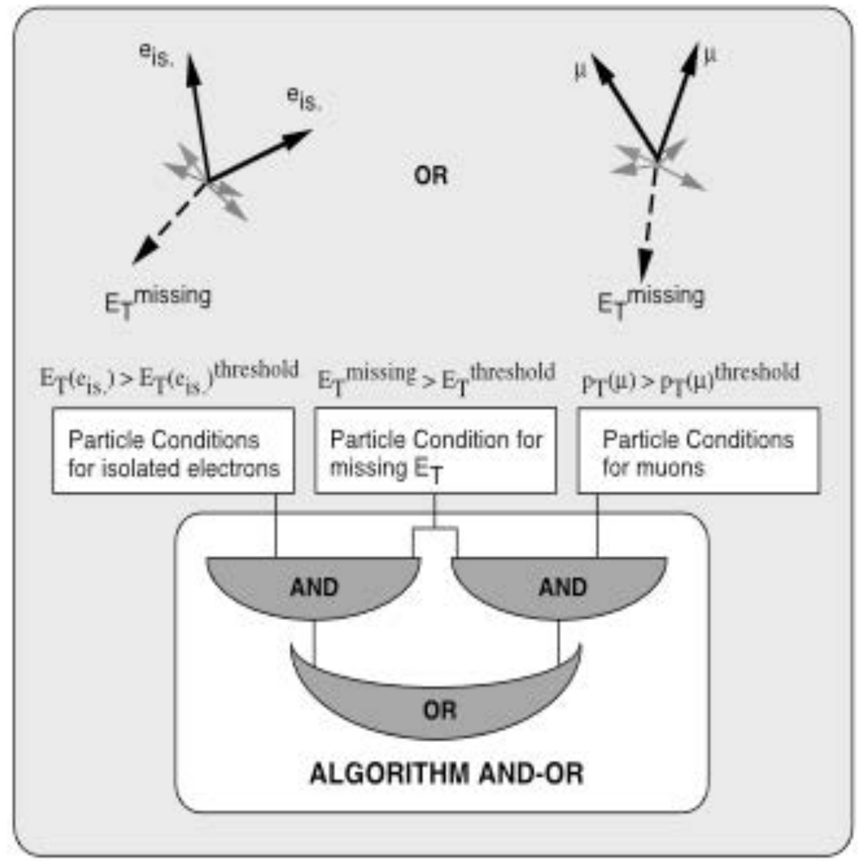
Global L1 Trigger Algorithms (Runs 1 & 2)

Particle Conditions





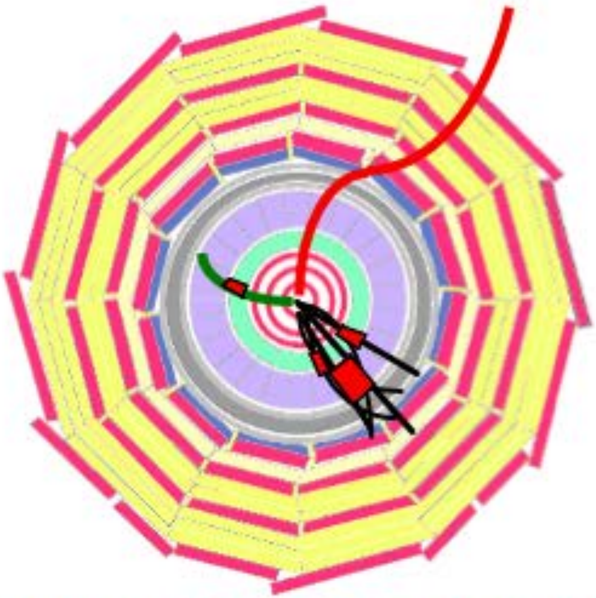
Logical Combinations

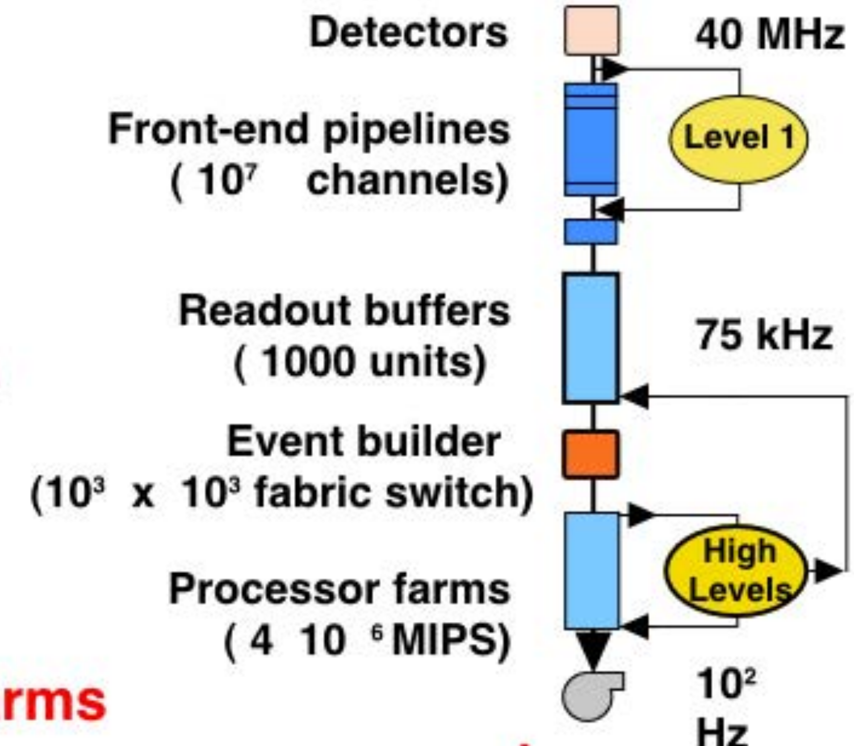


Flexible algorithms implemented in FPGAs

100s of possible algorithms can be reprogrammed

High Level Trigger Strategy





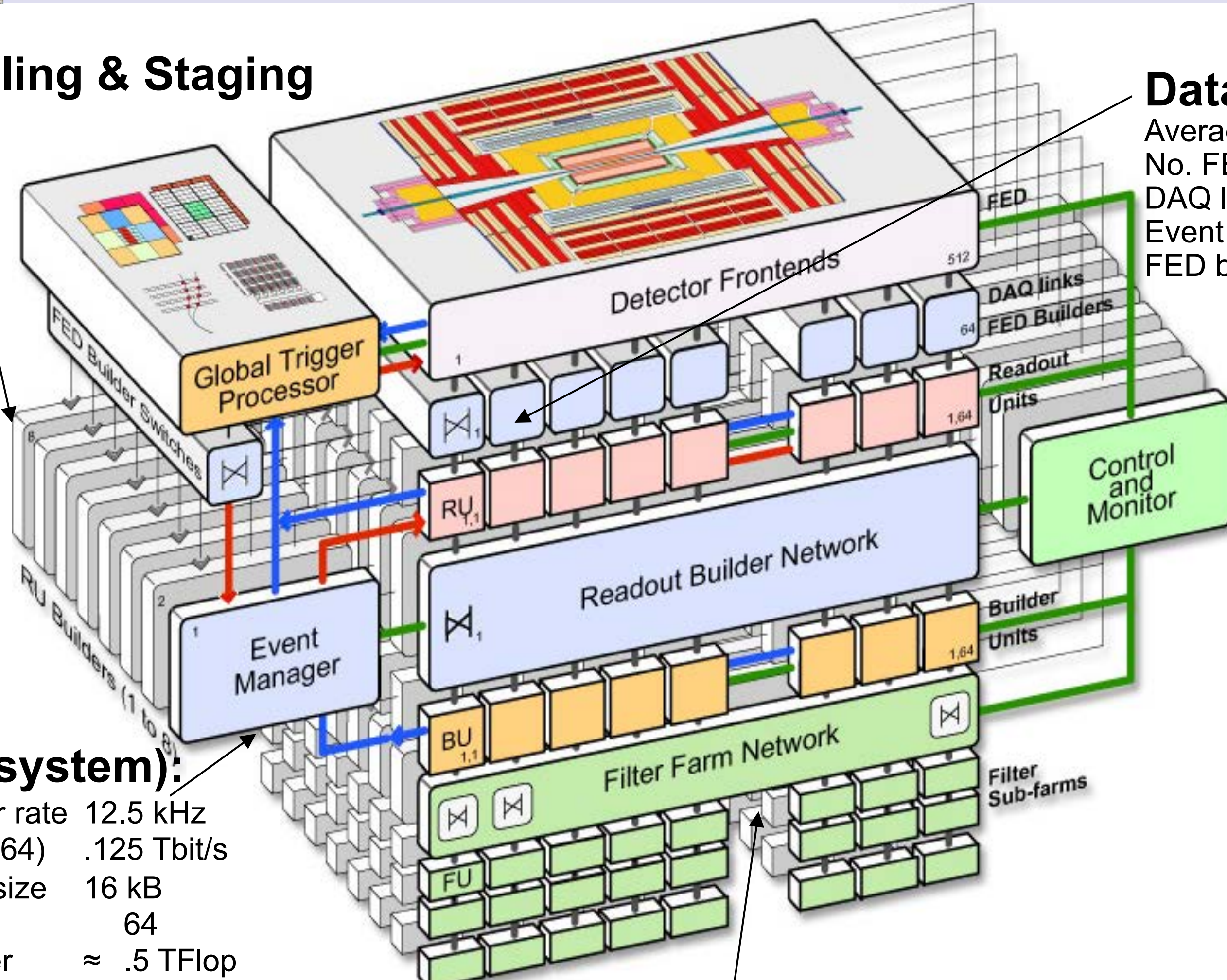
High level triggers. CPU farms

- 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+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)

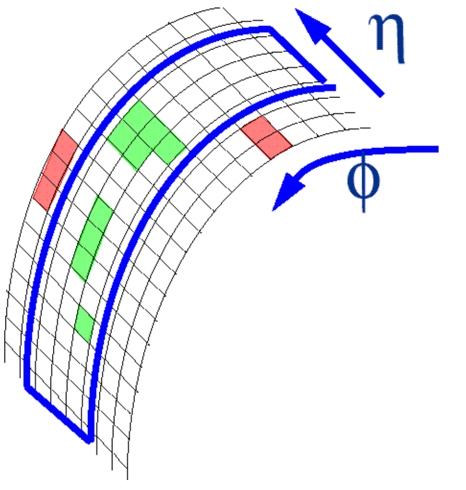
Goal

- 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

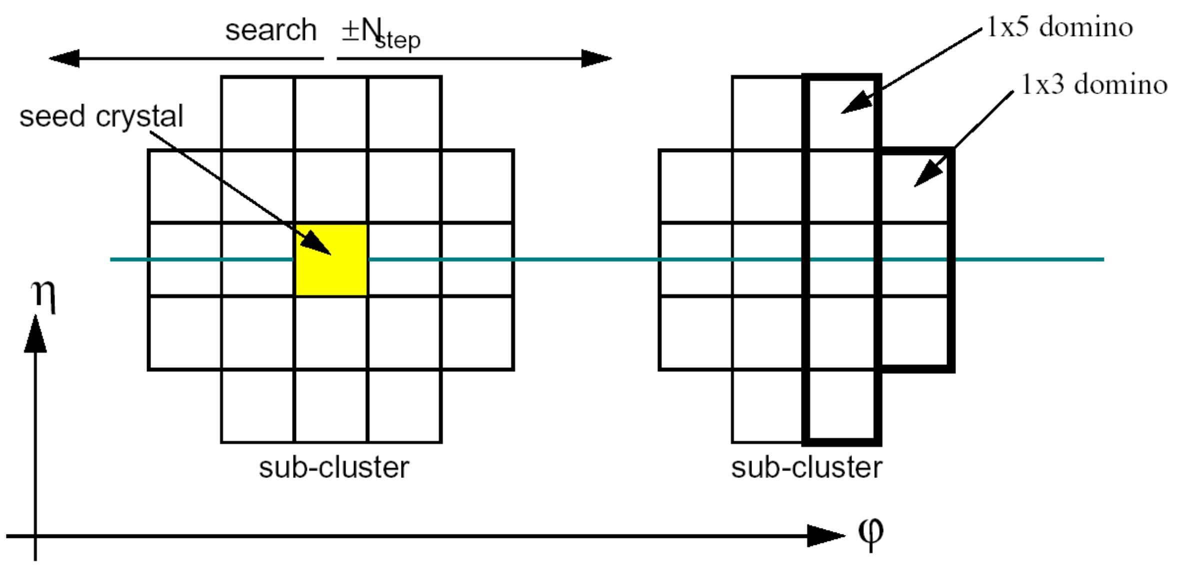


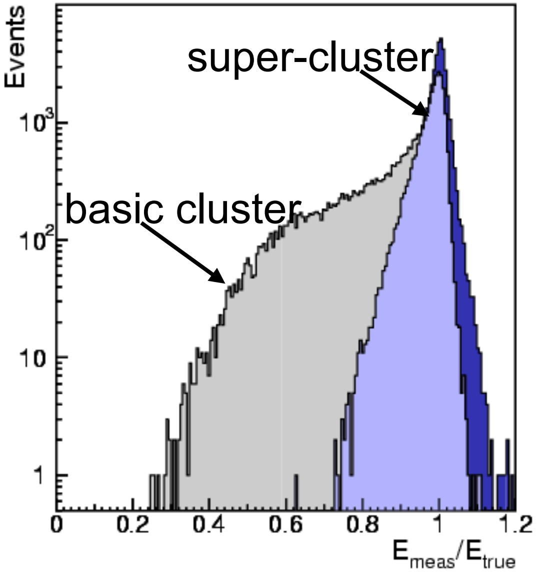
"Level-2" electron:

- 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"

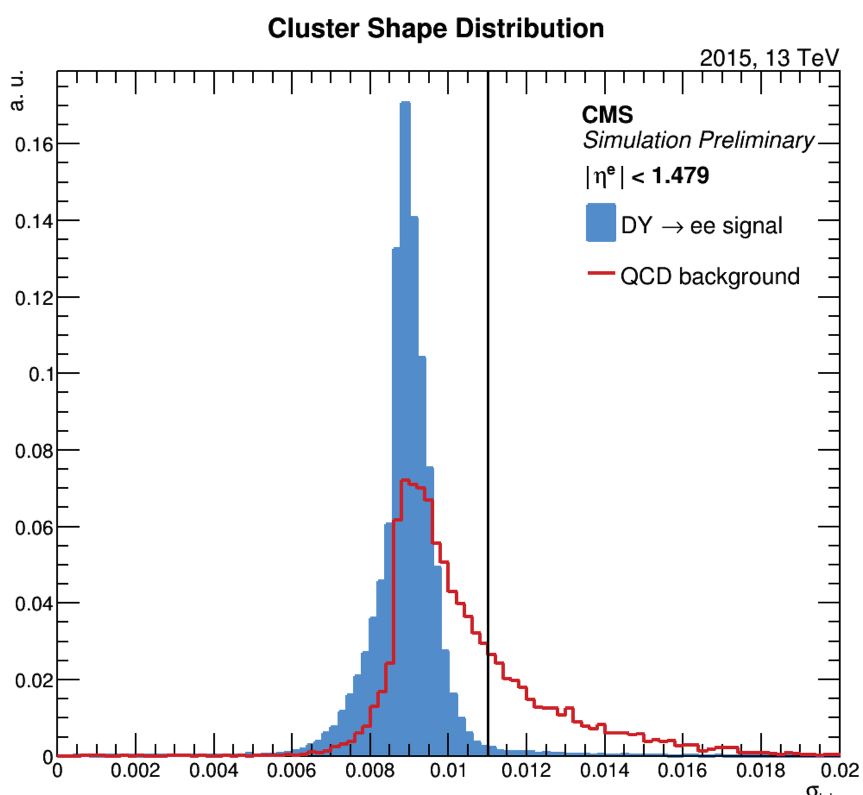


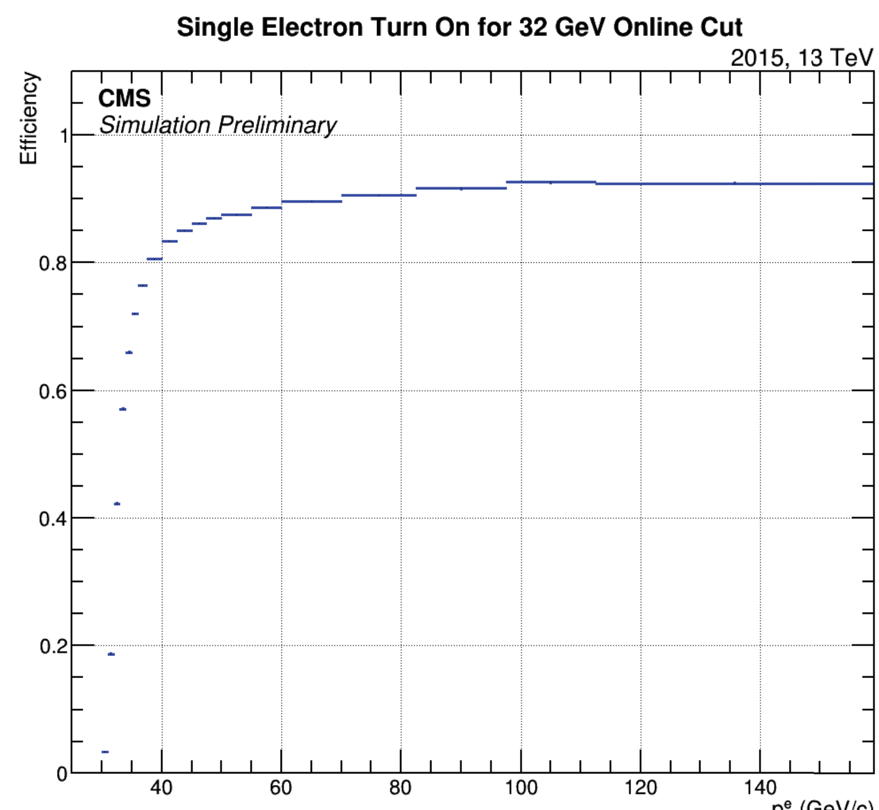


Electrons at HLT

Cluster shape discrimination and isolation techniques similar or identical to the ones used offline after full reconstruction:

- precise energy and position determination
- enhanced background rejection





Muon HLT

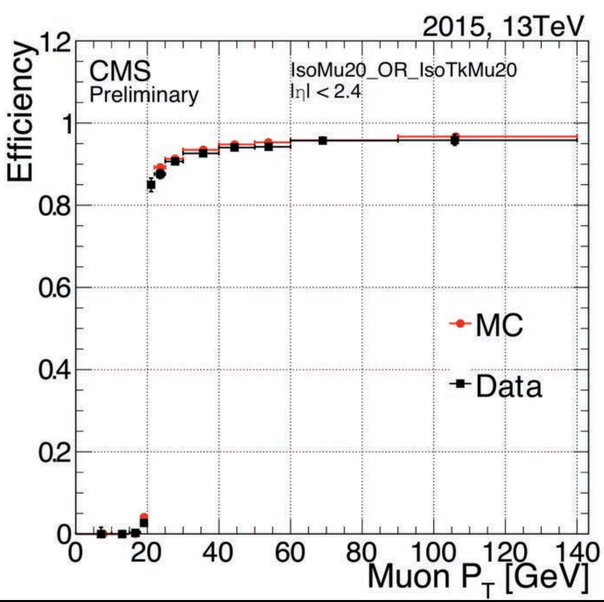
Similar reconstruction to the offline one: tracker and muon chambers hits available for a full fit to the trajectory of the muon

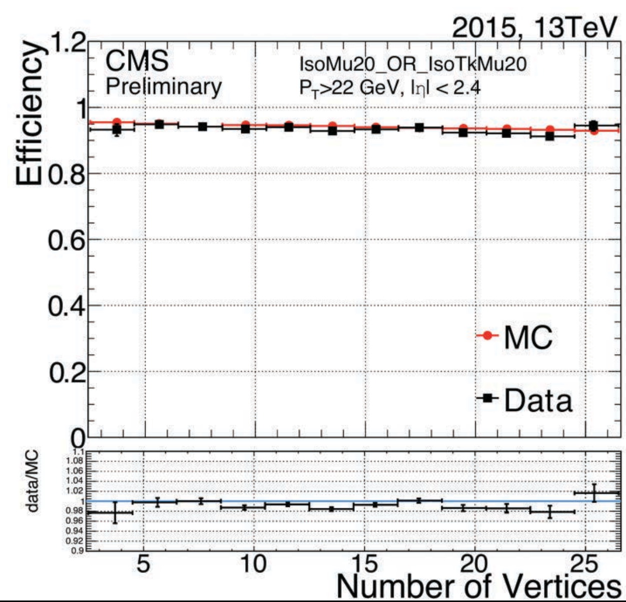
- "Standalone" track reconstruction in the muon chambers only
- "Combined" reconstruction uniting Muon+Tracker

Outside-In and Inside-Out track fitting; track reconstruction quality; and depth of penetration in the system used to reduce misidentification

Isolation around the muon direction can be used to reduce rate

Typically high efficiencies and robustness versus pileup



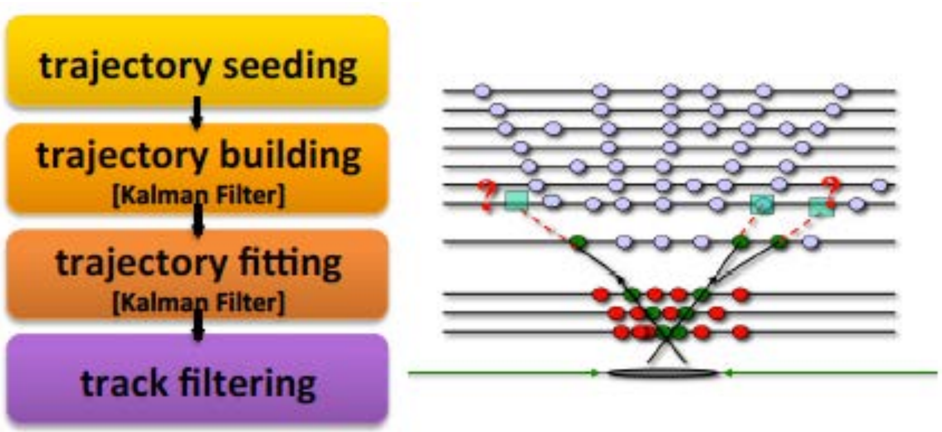


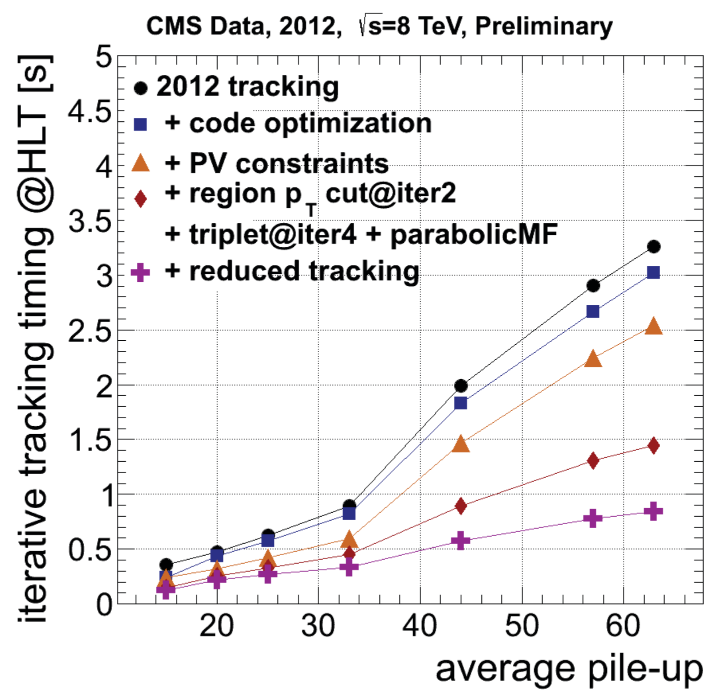
Tracking & B tagging @ HLT

Offline algorithms for track reconstruction are too slow O(10s) to be used online

—> Iterative tracking algorithm used to achieve O(100ms):

- **Each step reconstructs a specific subset of tracks (prompt, low/high pt, displaced)…**
- **First reconstruct the most energetic tracks (high pt seeds)—> remove hits associated to found tracks —> repeat pattern recognition with looser criteria**





Tracking & B tagging @ HLT

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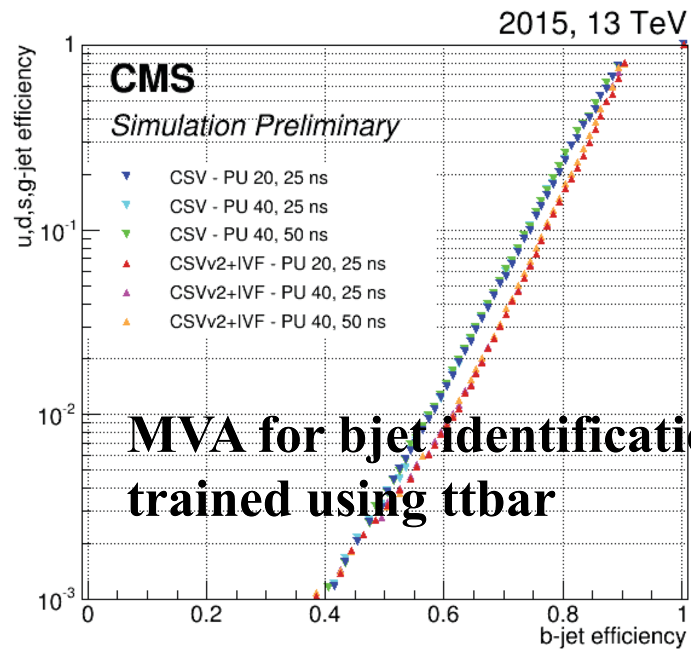
- **Each step reconstructs a specific subset of tracks (prompt, low/high pt, displaced)…**
- **First reconstruct the most energetic tracks (high pt seeds)—> remove hits associated to found tracks —> repeat pattern recognition with looser criteria**

Good HLT track reconstruction —> Fast primary vertex identification

—> impact parameter of tracks can be identified and used to tag displaced vertices

—> identify inclusive secondary vertices to tag events with a b-quark decay

—> similar algorithms to offline

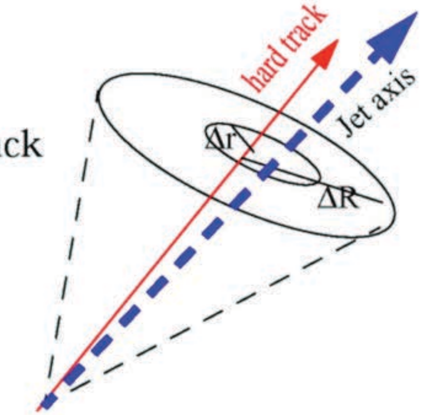


MVA for bjet identification trained using ttbar

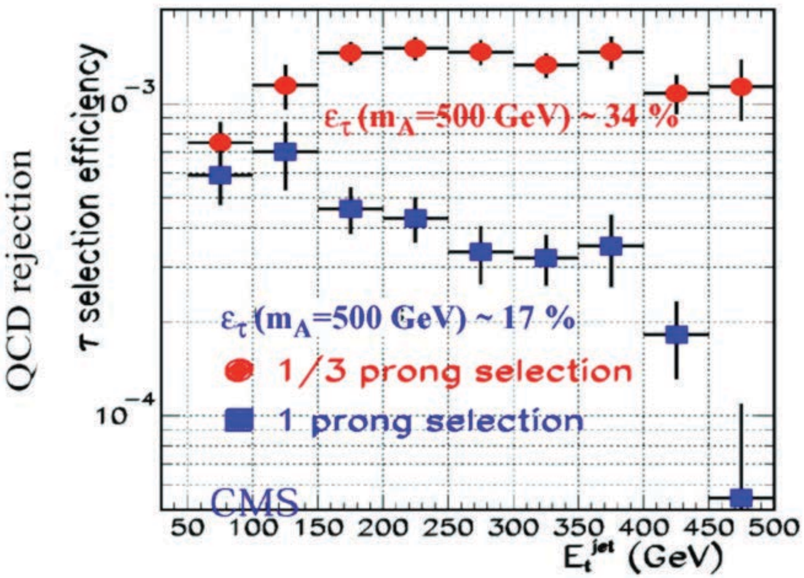
τ-jet tagging at HLT

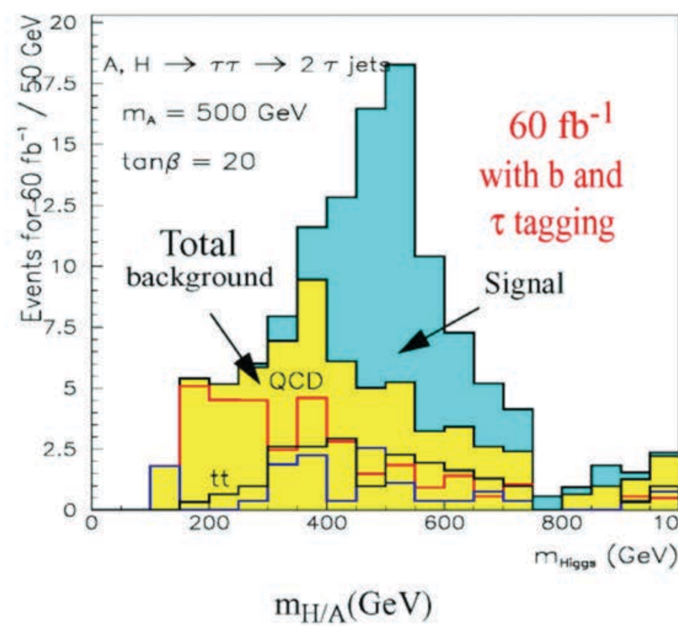
τ-jet ($E_t^{\tau\text{-jet}} > 60$ GeV) identification (mainly) in the tracker:

- **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 $\Delta r < 0.03$



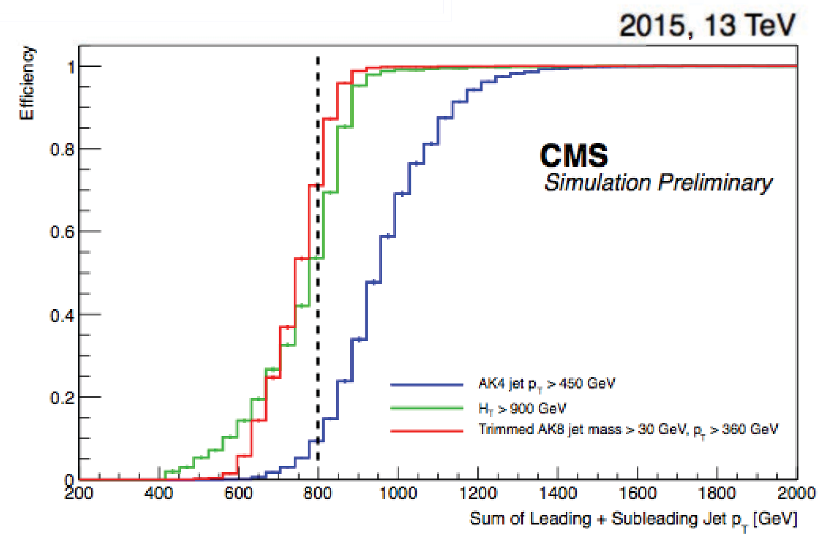
QCD jet rejection from isolation and hard track cuts





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

Jets and Energy Sums

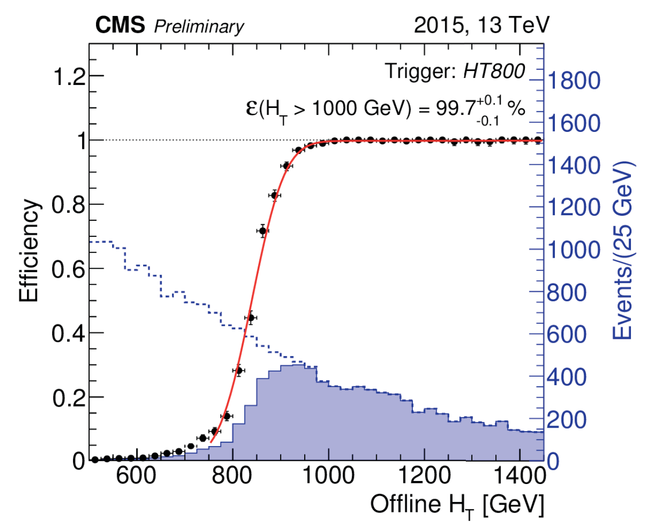


Again, the techniques are now very close to offline ones

Both simple calorimetric based and PF-based algorithms are available for Jets, missing energy and HTT

Jet clustering:

- **anti-kt jet with a 0.4 cone as the default jet algorithm**
- **anti-kt jets with 0.8 cone to trigger on boosted topologies (top, W,Z,Higgs tagging)**
- **offline-like pile up subtraction**

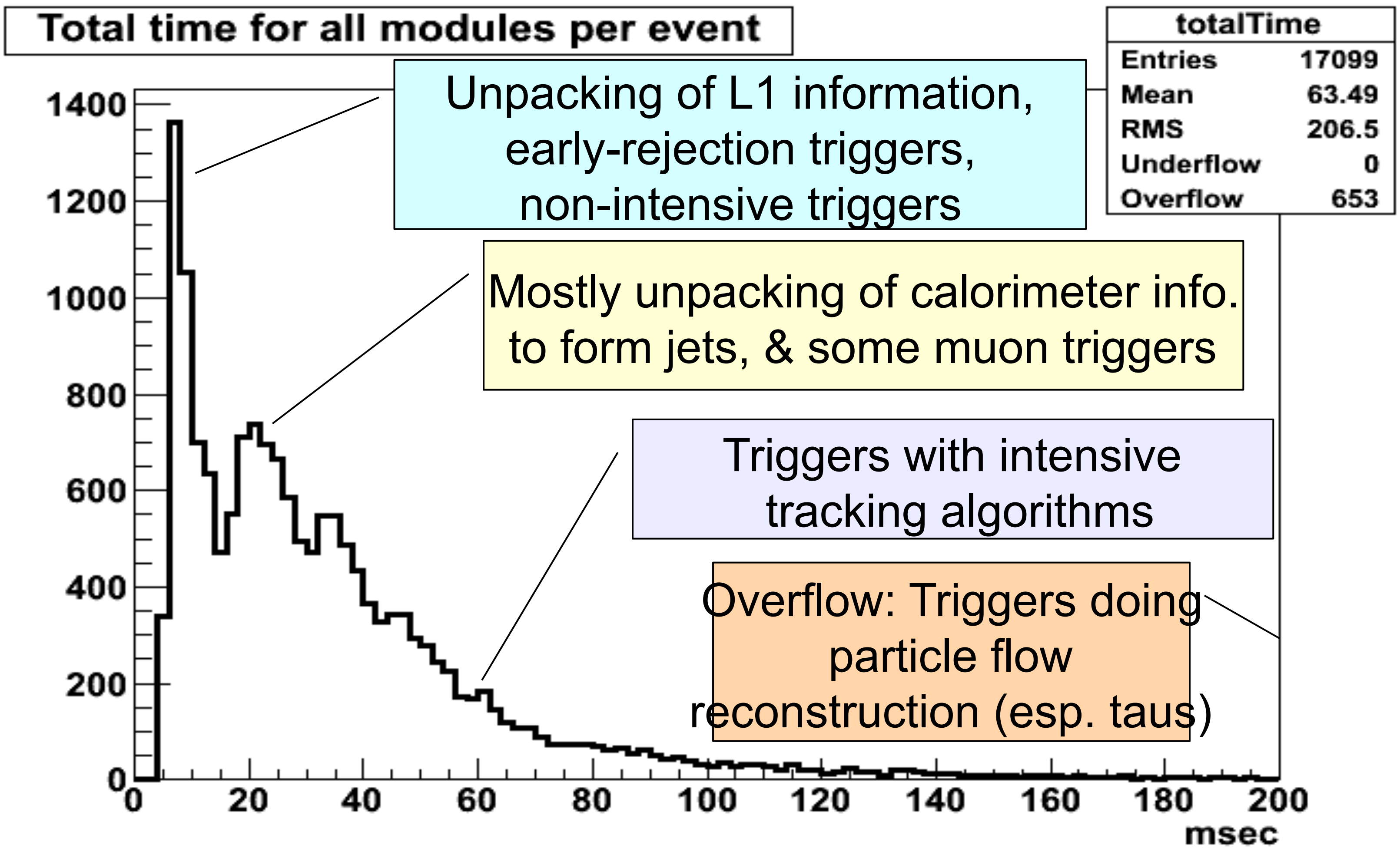


ParticleFlow: Comprehensive event reconstruction algorithm that aim to identify all the particles in the event. Heavily used in CMS to exploit the excellent track reconstruction of the detector

CMS HLT Time Distribution (example from early 2011)

Prescale set used: 2E32 Hz/cm²

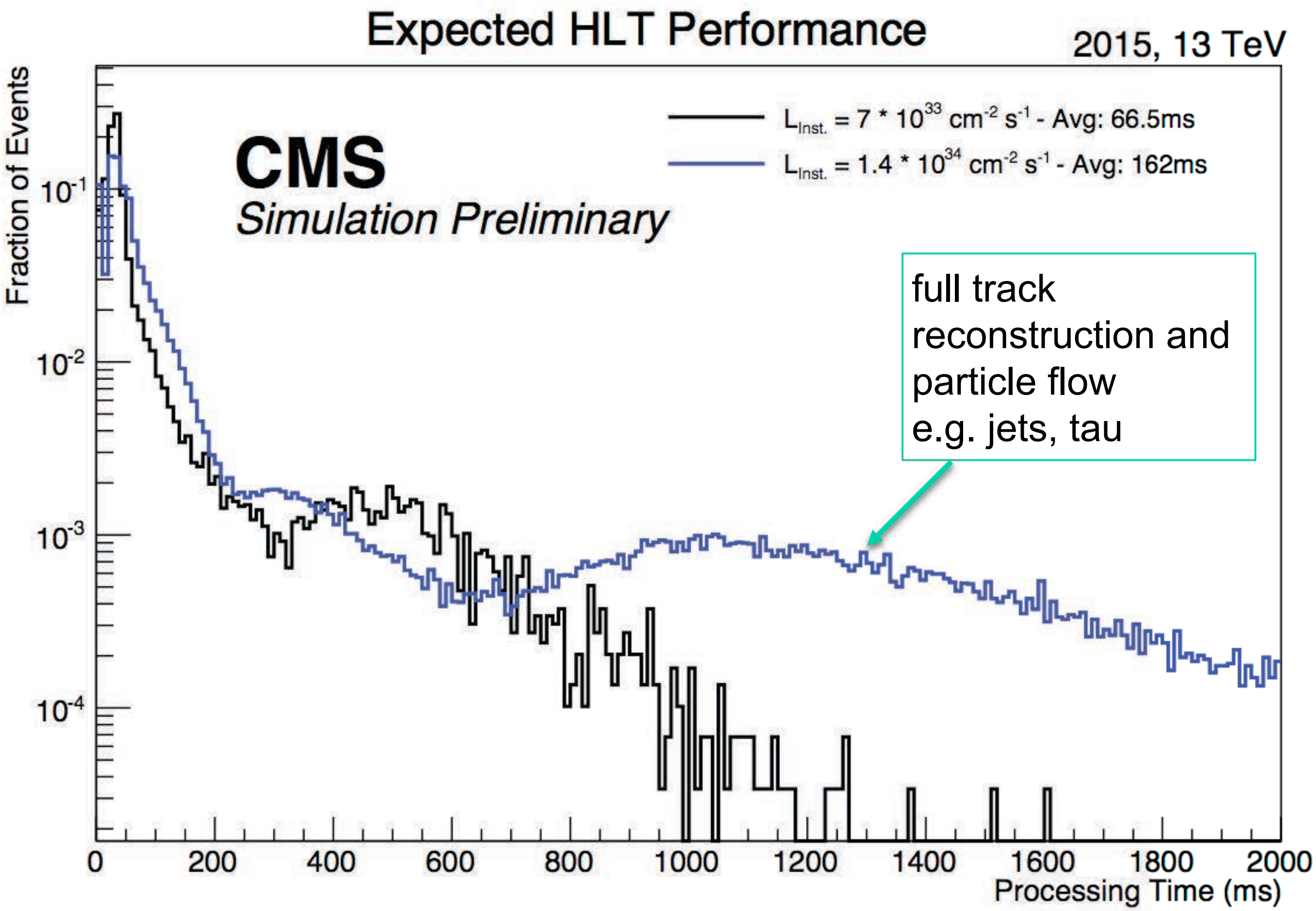
Sample: MinBias L1-skim 5E32 Hz/cm² with 10 Pile-up



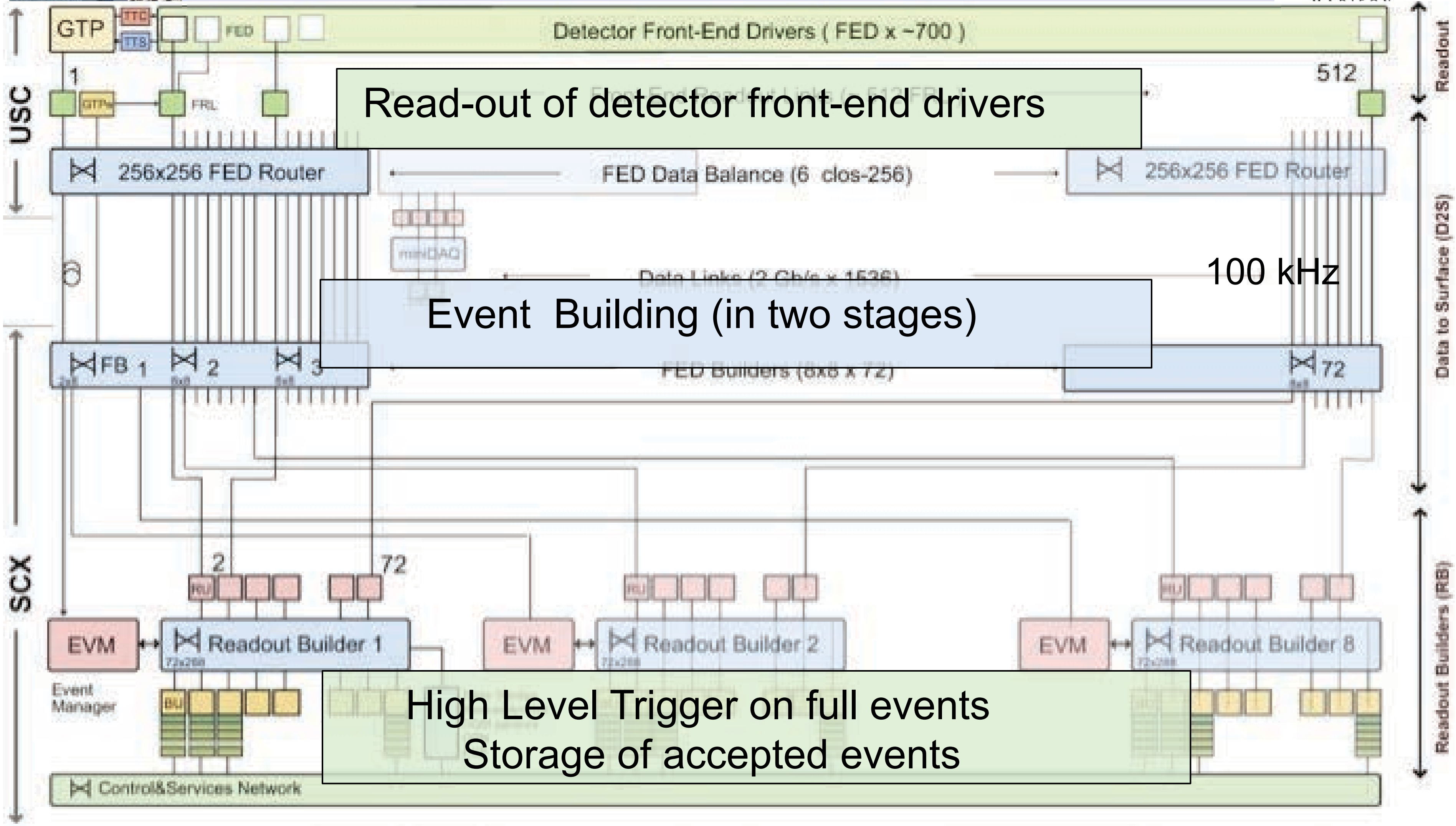
HLT Time Distribution: Run 2

Monte Carlo simulation, MinimumBias @ 13TeV

Black: 20 PU   Blue: 40 PU



CMS DAQ for Run 1



Read-out of detector front-end drivers

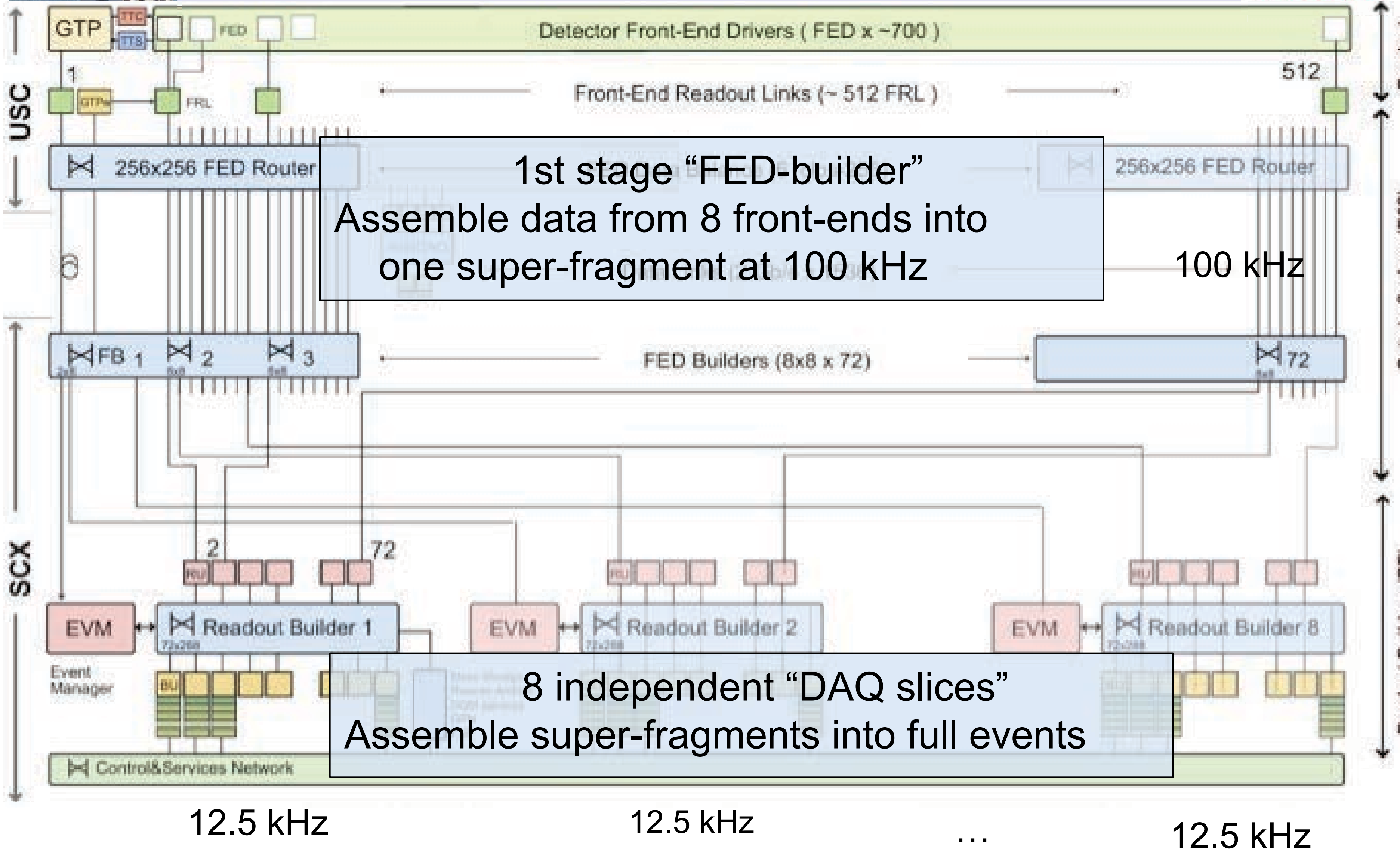
100 kHz

Event Building (in two stages)

High Level Trigger on full events
Storage of accepted events

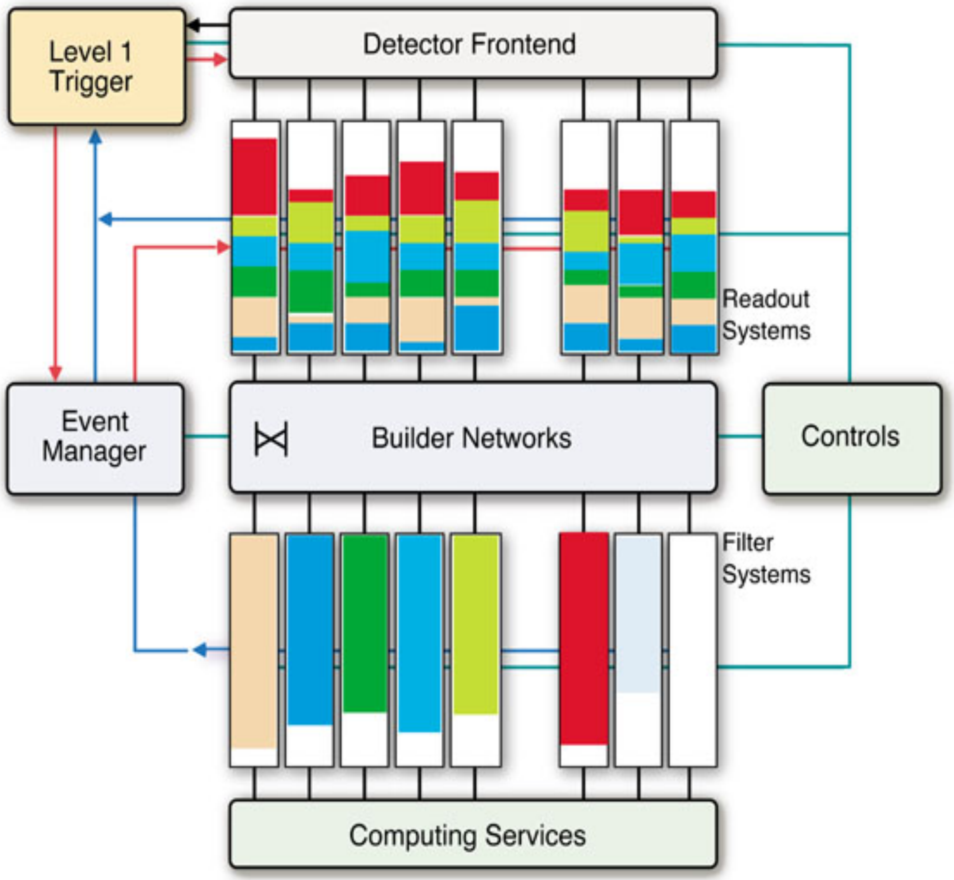
12.5 kHz 12.5 kHz … 12.5 kHz

CMS Run 1 2-Stage Event Builder



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

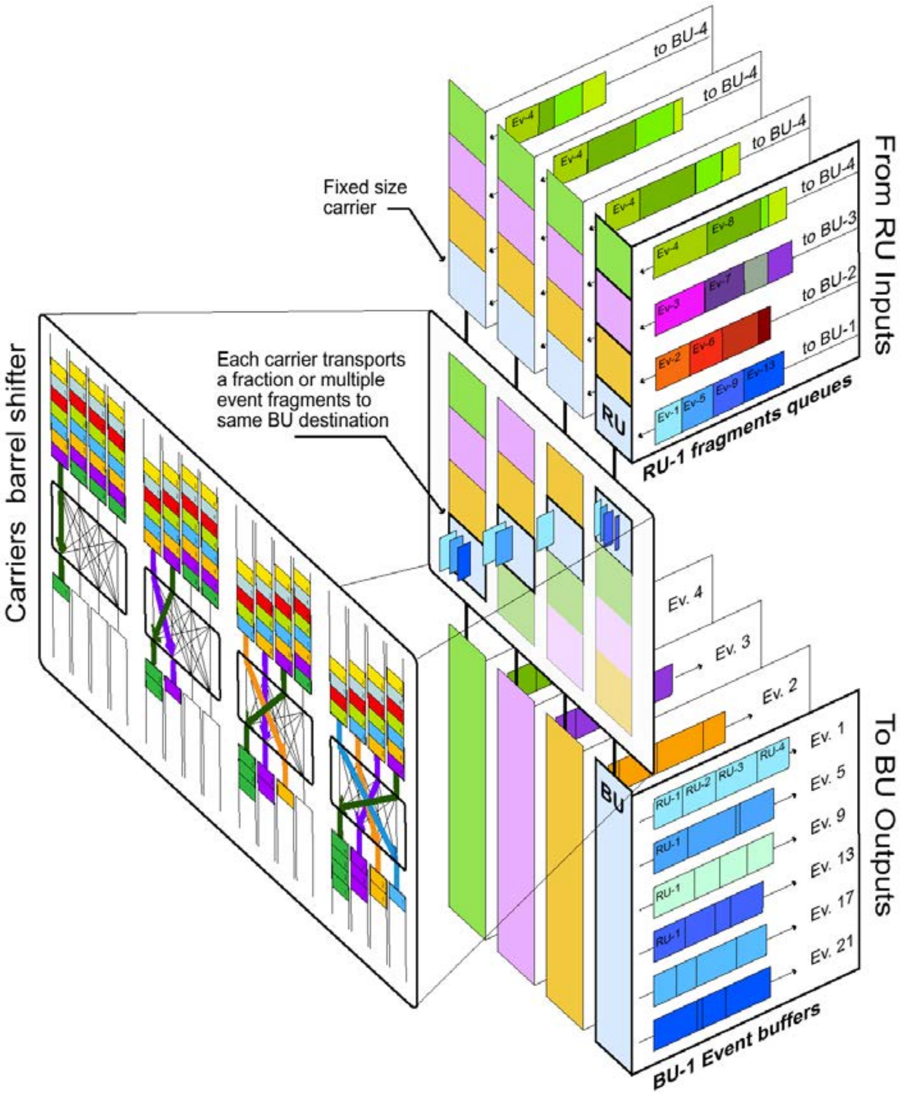


Event fragments :
Event data fragments are stored in separated physical memory systems

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

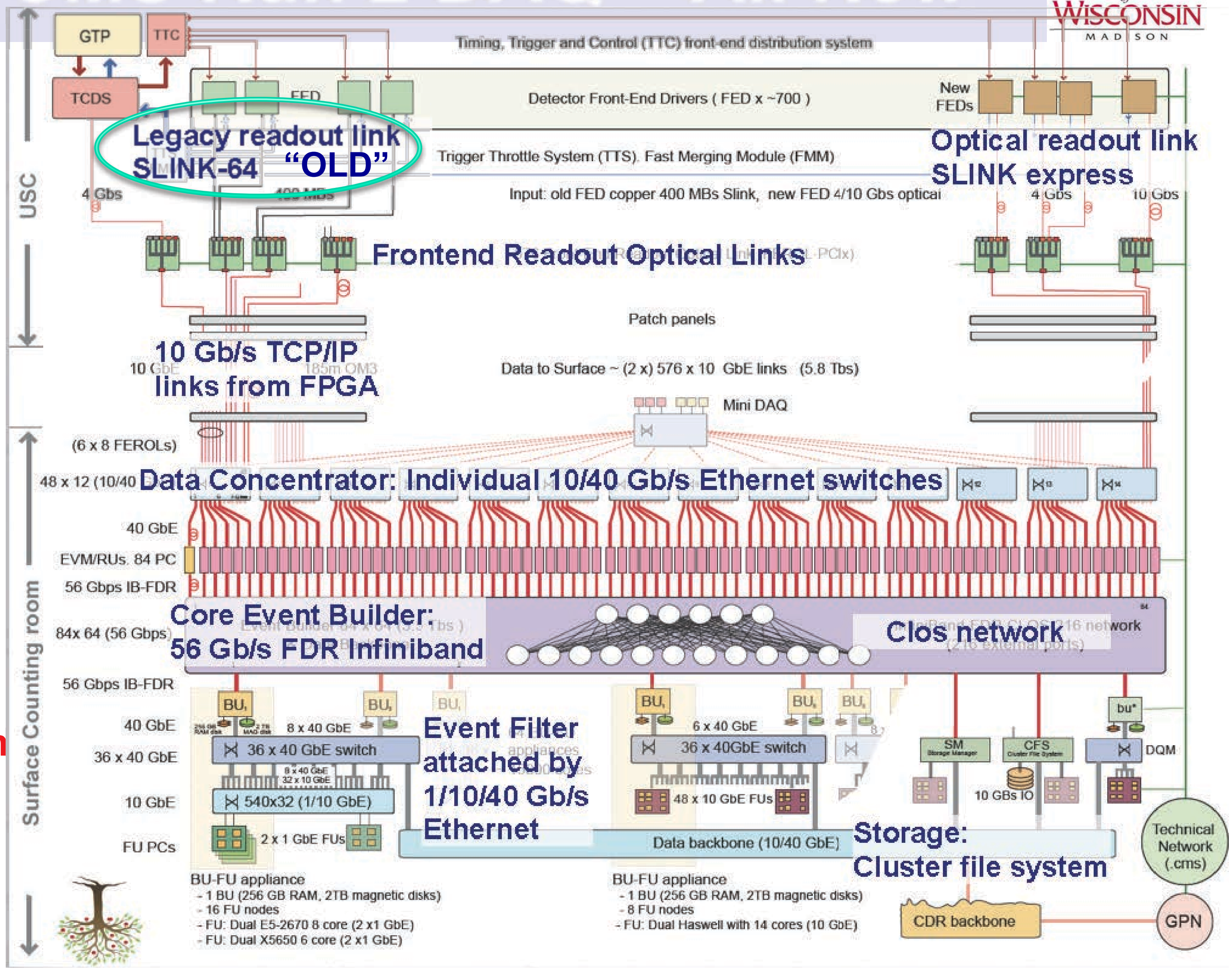
Barrel-Shifter



- 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 Network back pressure by HW flow control)
- zero-copy, **OS-bypass**
- **principle works** for multi-stage switches

CMS Run 2 DAQ ~ All New

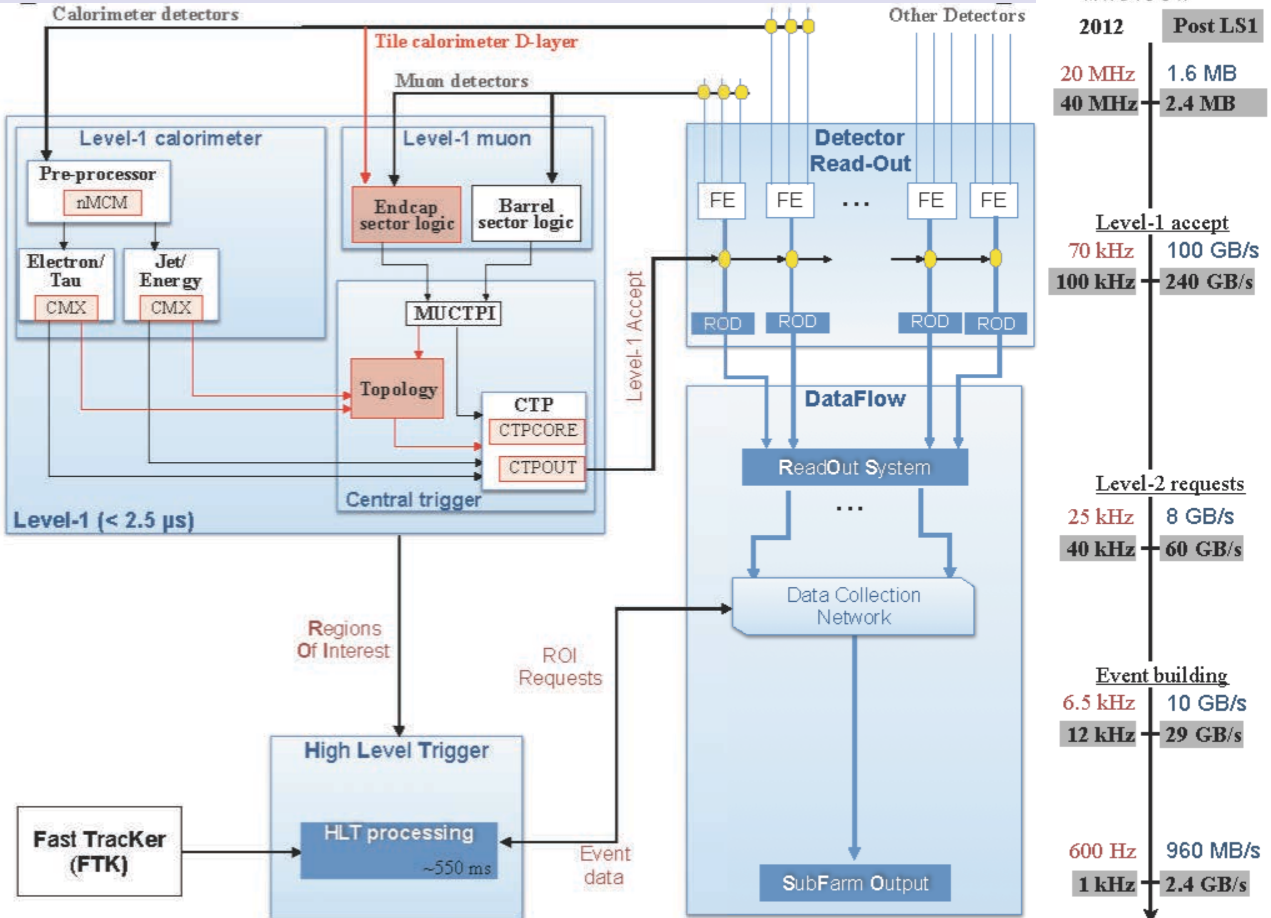
- 10 GbE replacing Myrinet
- New µTCA readouts interfaced thru BU AMC13
- New CPUs
- Infiniband switches
- DAQ is an order of magnitude smaller!
- Filter Farm: CMSSW from files
- Distributed file system for backend



ATLAS Run 2 v. 1 TDAQ

Run2 system:

- new L1CALO pre-processor and interface to Central trigger.
- new muon chambers and Tile calorimeter input to endcap L1MUON.
- Central Trigger with new Topology Trigger and Central Trigger Processor modules.
- initial deployment of Fast Tracker (FTK) in HLT (Next slide)



Beyond Run 2 (Pre HL-LHC):

- **Cal Trig: Increased granularity for better isolation**
- **Mu Trig: Endcap suppresses fakes using New Small Wheel**

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.**

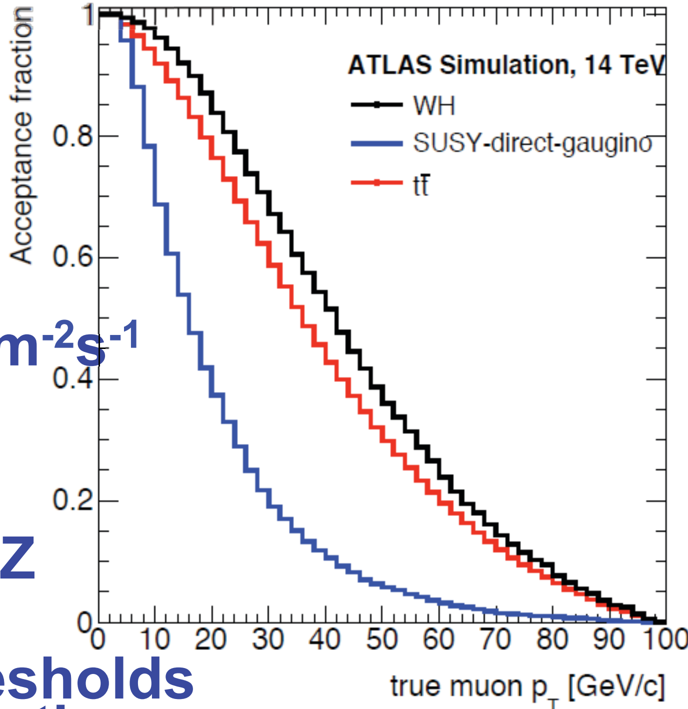
Addresses two time-consuming stages in tracking

- **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, CMS Trigger HL-LHC Upgrades

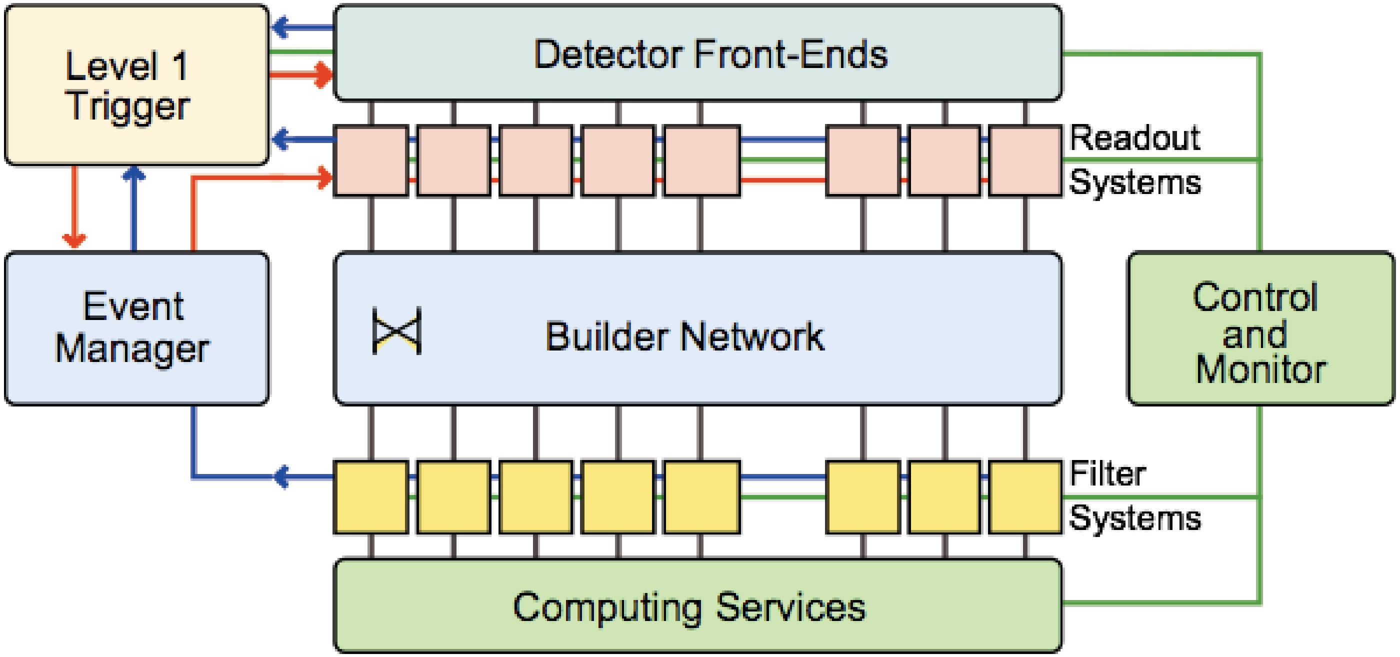
Maintain current physics sensitivity at HL-LHC challenging for trigger

- EWK, top (and Higgs) scale physics remain critical for HL-LHC
- Cannot fit same "interesting" physics events in trigger at 13-14 TeV, 5×10^{34} $cm^{-2}s^{-1}$



- **Increasing p_T thresholds reduces signal efficiency**
  - Trigger on lepton daughters from $H \rightarrow ZZ$ at $p_T \sim 10$-20 GeV
  - Very easy to reach the worst case: thresholds increase beyond energy scale of interesting processes
- **Backgrounds from HL-LHC pileup further reduces the ability to trigger on rare decay products**
  - Leptons, photons no longer appear isolated and are lost in QCD backgrounds
  - Increased hadronic activity from pileup impacts jet p_T and MET measurements

CMS HL-LHC Evolution

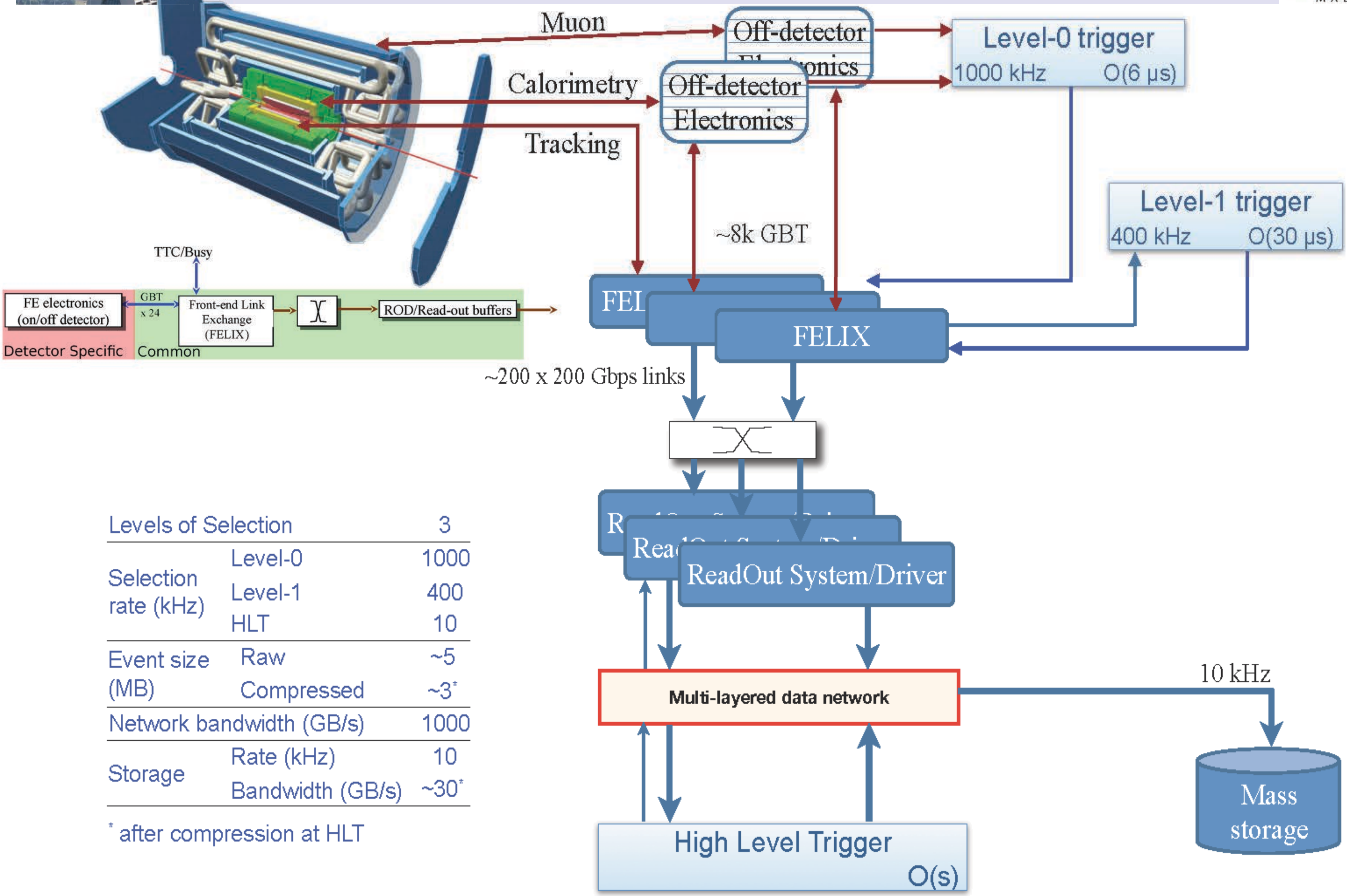


40 MHz
100 kHz → 750 kHz

2 Tbps → ~50 Tbps
1 kHz → ~7.5 kHz

HL- LHC: Lumi = 5 - 7 x 10^{34}
<PU> = 140 - 200 (increase × 6 - 8 v. run 1)
E = 13-14 TeV (increase ~ 2 v. run 1)
25 nsec bunch spacing (reduce × 2 v. run 1)
Integrated Luminosity > 250 fb^{-1} per year

ATLAS HL-LHC Evolution



Levels of Selection		3
Selection rate (kHz)	Level-0	1000
	Level-1	400
	HLT	10
Event size (MB)	Raw	~5
	Compressed	~3*
Network bandwidth (GB/s)		1000
Storage	Rate (kHz)	10
	Bandwidth (GB/s)	~30*

* after compression at HLT

ATLAS & CMS L1 Tracking Trigger

Reduces Leptonic Trigger Rate

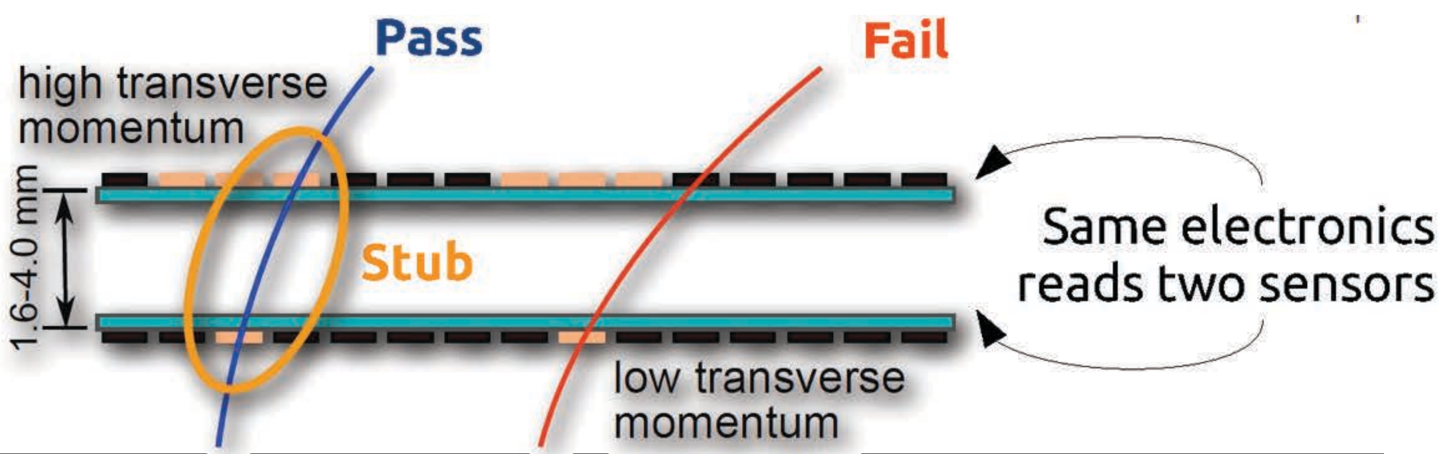
- Validate calorimeter or muon trigger object, e.g. discriminating electrons from hadronic ($\pi^0 \rightarrow \gamma\gamma$) backgrounds in jets
- Addition of precise tracks to improve precision on p_T measurement, sharpening thresholds in muon trigger
- Degree of isolation of e, γ, μ or τ candidate
- Requires calorimeter trigger trigger at the finest granularity to reduce electron trigger rate

Other Triggers

- Primary z-vertex location within 30 cm luminous region derived from projecting tracks found in trigger layers,
- Provide discrimination against pileup events in multiple object triggers, e.g. in lepton plus jet triggers.

Example: CMS Track Trigger design finds stubs with $p_T \gtrsim 2$:

Thanks to CMS 3.8 T magnetic field!



ATLAS & CMS @ HL-LHC

An introductory Summary

ATLAS*:

- **Divide L1 Trigger into L0, L1 of latency 6, 30 μsec, rate ≤ 1 MHz, ≤ 400 kHz, HLT output rate of 5-10 kHz**
  - Calorimeter readout at 40 MHz w/backend waveform processing (140 Tbps)
- **L0 uses Cal. & μ Triggers, which generate track trigger seeds**
- **L1 uses Track Trigger and more fine-grained calorimeter trigger information.**

CMS:

- **L1 Trigger latency: 12.5 μsec**
- **L1 Trigger rate: 500 kHz (PU=140), 750 kHz (PU=200)**
- **L1 uses Track Trigger, finer granularity μ & calo. Triggers**
- **HLT output rate of 5 kHz (PU=140), 7.5 kHz (PU=200)**

CMS Level-1 Tracking Trigger

Require:

- Highest possible efficiency over all η for isolated high P_T tracks
- Good efficiency for tracks in jets for vertex identification
- P_T > 2-3 GeV (small difference within this range)
  - Expect ~ 115 charged tracks with P_T > 2 GeV at PU = 140
  - Design for 300 tracks per bunch crossing
- Vertex resolution ~ 1 mm

Use:

- Charged Lepton ID
- Improve P_T resolution of charged leptons
- Determine isolation of leptons and photons
- Determine vertex of charged leptons and jet objects
- Determine primary vertex and MET from L1 Tracks from this vertex

Pixel Trigger Option

- Under consideration for now, but need a strong physics case
- Challenging to meet 12.5 μsec latency

CMS Estimation of required HL-LHC HLT Capabilities

Observation so far

- **Required HLT power scales linearly with pile-up**
  - This has been observed for PU in the range of 10-40
    - **Conservatively assume this continues – needs verification**

Assuming

- **Linear scaling with average PU up to 2000**
- **A factor 1.5 due to energy increase to 13 TeV**
  - Also conservative – takes into account complexity of events selected by L1 Trigger scaling with energy
  - Operation after LS1 with 6.5 TeV per beam will quickly allow refining this estimate

	LHC Run-I	LHC Phase-I upgr.	HL-LHC Phase-II upgr.	
Energy	7-8 TeV	13 TeV	13 TeV	
Peak Pile Up (Av./crossing)	35	50	140	200
Level-1 accept rate (maximum)	100 kHz	100 kHz	500 kHz	750 kHz
Event size (design value)	1 MB	1.5 MB	4.5 MB	5.0 MB
HLT accept rate	1 kHz	1 kHz	5 kHz	7.5 kHz
HLT computing power	0.2 MHS06	0.4 MHS06	6 MHS06	13 MHS06
Storage throughput (design value)	2 GB/s	3 GB/s	27 GB/s	42 GB/s

ATLAS Estimation of required HL-LHC HLT capabilities

Processing time extrapolations to PU = 200

- Run 4 rejection requirements similar/better than in Run 1-2 → 1k/100k vs 10k/400k

A factor O(50) in HLT compute power needed wrt to Run 1

Moore's law on a ~10 years period predicts a factor 100 increase

- Compute power requirements within expected technology envelope → HLT farm of similar size wrt to Run 1

BUT

- Software will have evolve to be at least as efficient as today on future technologies (GPGPU, Many-cores, ARM64, ...)

Assume a similar packaging → ~50 racks

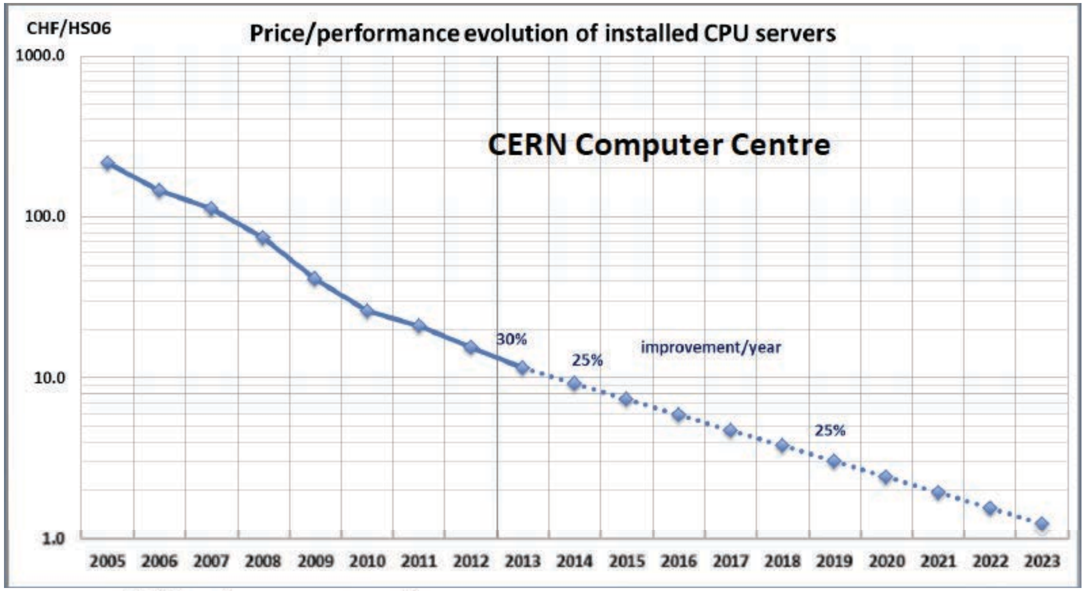
Network:

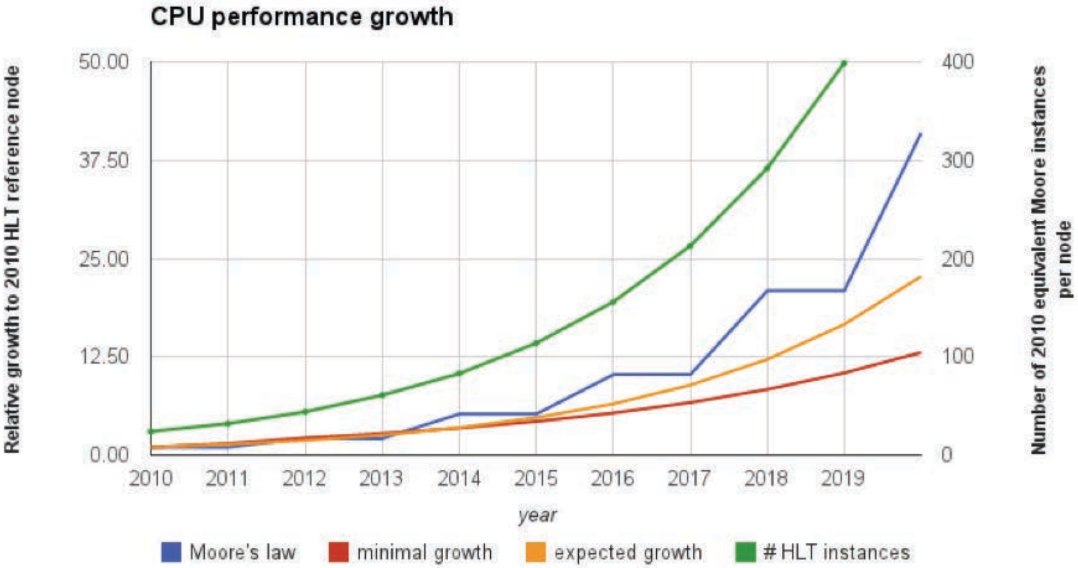
- 5MB@400kHz → ~20 Tbps
- Reasonable to assume
  - 100 Gbps per CPU socket (computing unit)
  - established (>)400 Gbps technology
    - Infiniband EDR x12 → 300 Gbps
- Total number of ports ~unchanged
- Network topology and link speeds mix & match depend on compute power packaging

Higher Level Trigger Performance

25% performance improvement per year is not the same as doubling performance every 2 years (more like 3)

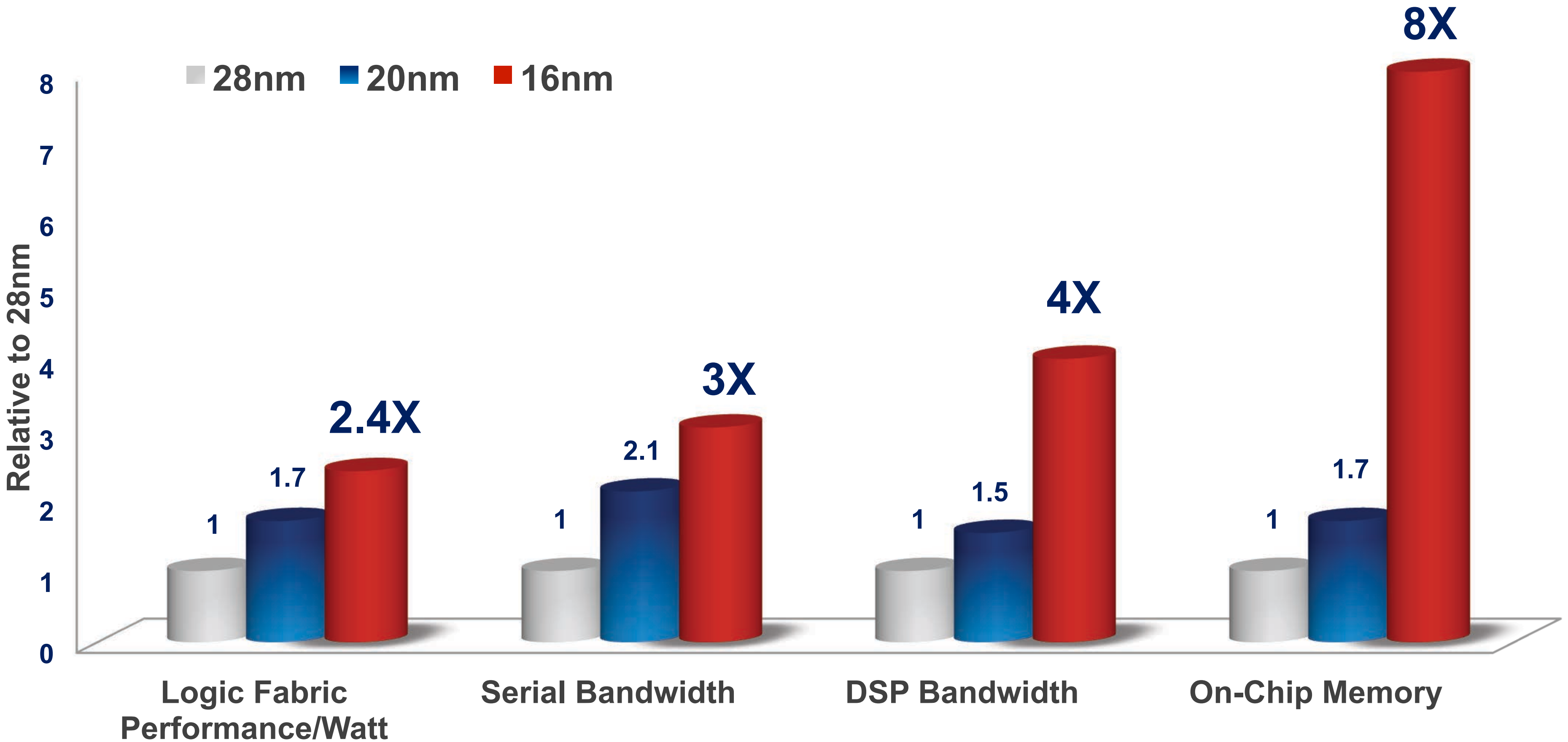
However also important to notice that this is a power law, so small changes in assumed %/year lead to big differences on 10-20 year timescale..





Tools for Triggers: FPGAs

Example: Xilinx Virtex 7 (28 nm), Ultrascale (20 nm), Ultrascale + (16 nm)



Enhanced Fabric with FinFET performance	Up to 128 transceivers at up to 32.75 Gb/s	~12,000 DSP slices running at ~900 MHz	UltraRAM for SRAM device replacement

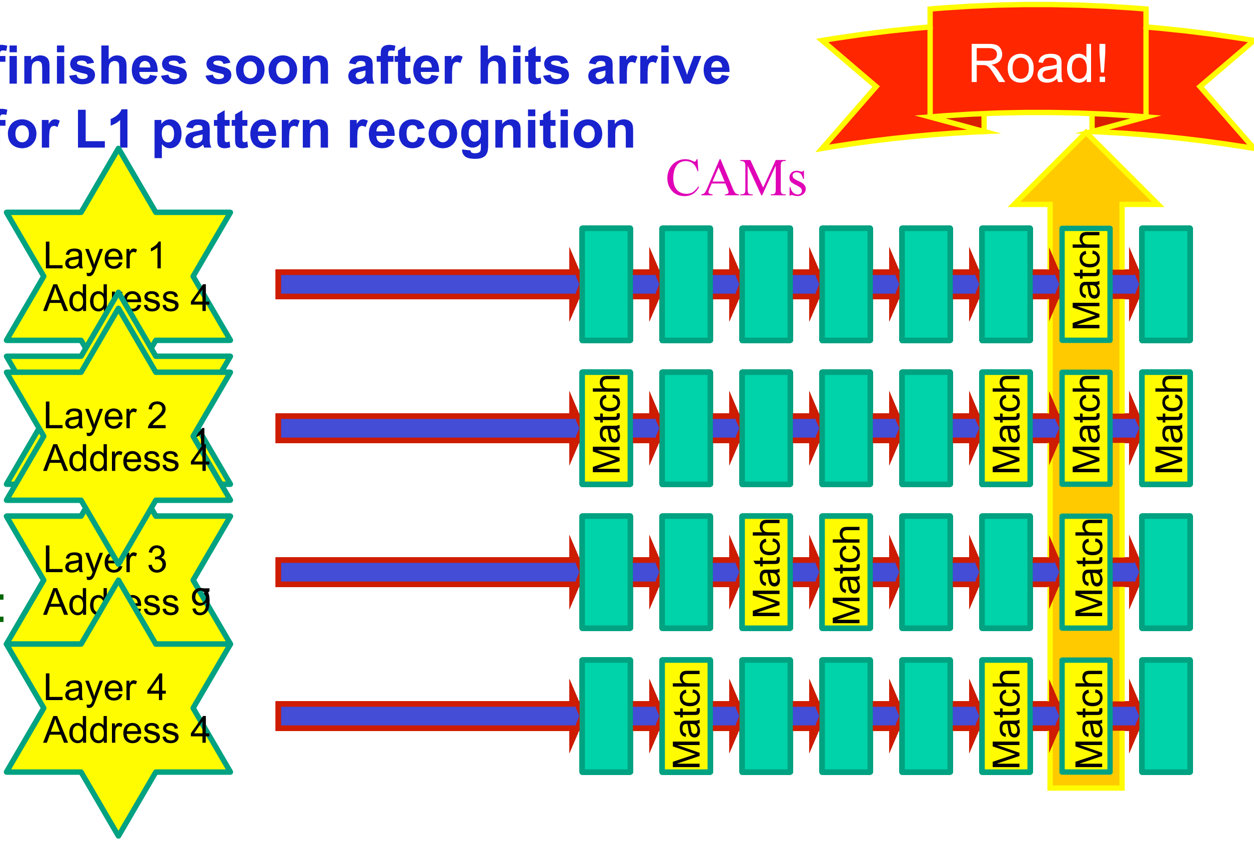
FPGA Examples: Xilinx devices

	KINTEX 7	KINTEX UltraSCALE	VIRTEX 7	VIRTEX UltraSCALE
Logic Cells (LC)	478	1,161	1,995	4,407
Block RAM (BRAM) (Mbits)	34	76	68	132
DSP-48	1,920	5,520	3,600	2,880
Peak DSP Performance (GMACs)	2,845	8,180	5,335	4,268
Transceiver Count	32	64	96	104
Peak Transceiver Line Rate (Gb/s)	12.5	16.3	28.05	30.5
Peak Transceiver Bandwidth (Gb/s)	800	2,086	2,784	5,886
PCI Express Blocks	1	6	4	6
Memory Interface Performance (Mb/s)	1,866	2,400	1,866	2,400
I/O Pins	500	832	1,200	1,456

Tool for Tracking Triggers: Associative Memories

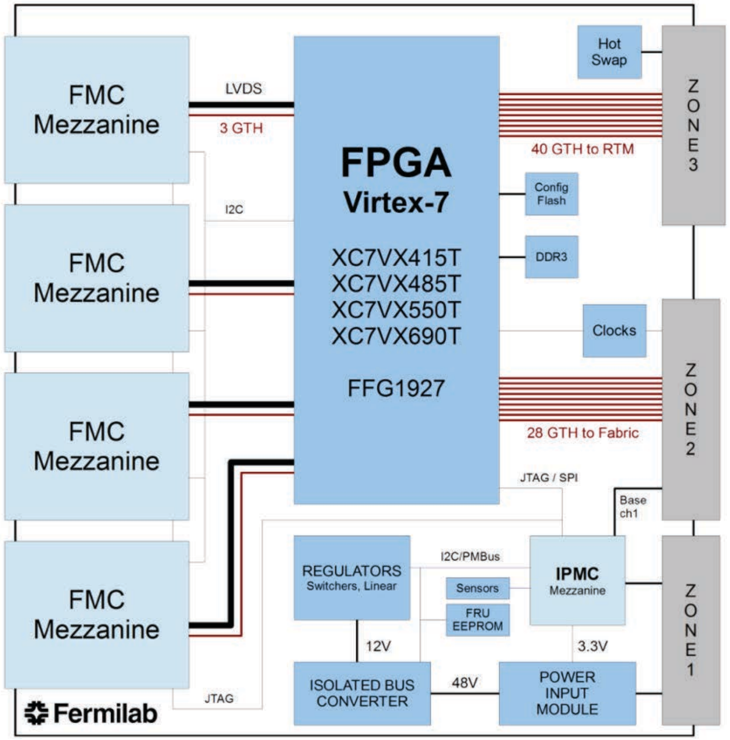
Pattern Recognition Associative Memory (PRAM)

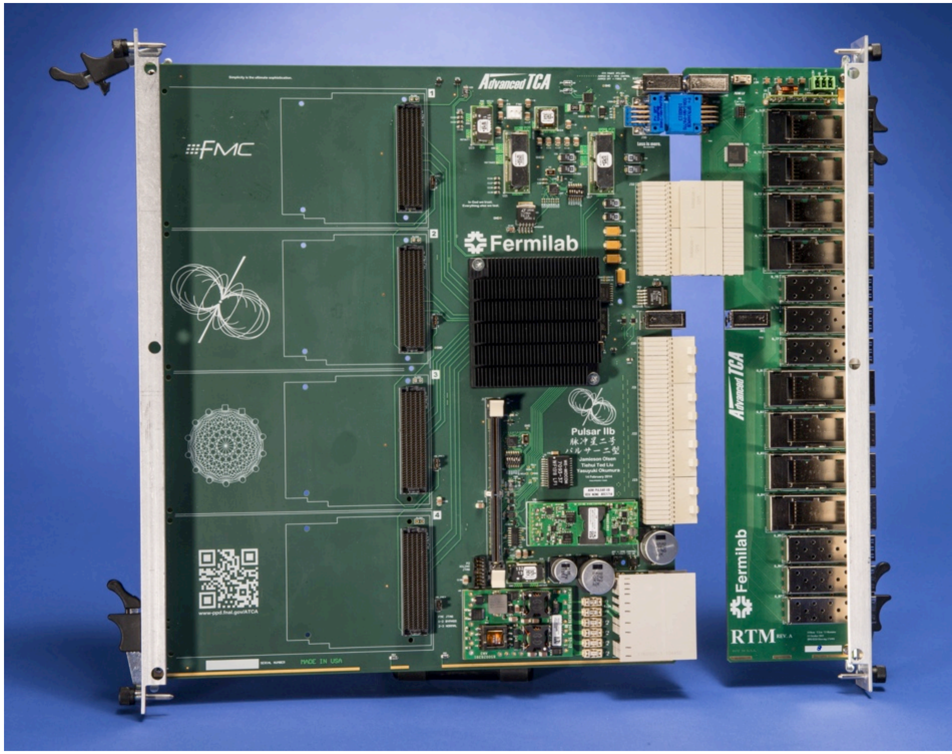
- Based on CAM cells to match and majority logic to associate hits in different detector layers to a set of pre-determined hit patterns
  - Example of FTK planned for ATLAS Level 2 Trigger in Phase 1
- highly flexible/configurable, much less demand on detector design
- Pattern recognition finishes soon after hits arrive
- Potential candidate for L1 pattern recognition
- However: Latency
- Challenges:
  - Increase pattern density by 2 orders of magnitude
  - Increase speed x 3
  - Same Power
  - Use 3D architecture: Vertically Integrated Pattern Recognition AM - VIPRAM



Tools for Trigger/DAQ: ATCA

- Advanced Telecommunications Computing Architecture
- Example: Pulsar Card (FNAL, UIC, Northwestern) for CMS Track Trigger
  - Use FPGAs for low latency
  - FPGAs are directly connected to the full mesh fabric channels
  - No network switch
  - Low overhead serial protocols
  - High bandwidth I/O via serial links on Rear Transition Module and mezzanines



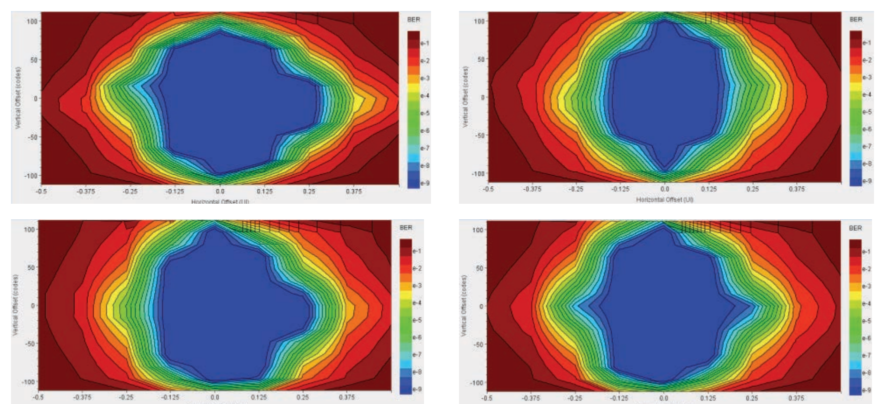


ATCA Backplane example: Pulsar IIb

HCPSS16

THE UNIVERSITY of WISCONSIN MADISON

- Full shelf tests with all lanes running at 10 Gbps
  - BER = $2x10^{-16}$
- Evaluating latest high performance 40G+ full mesh backplanes from ASIS-PRO, COMTEL, and Pentair/Schroff



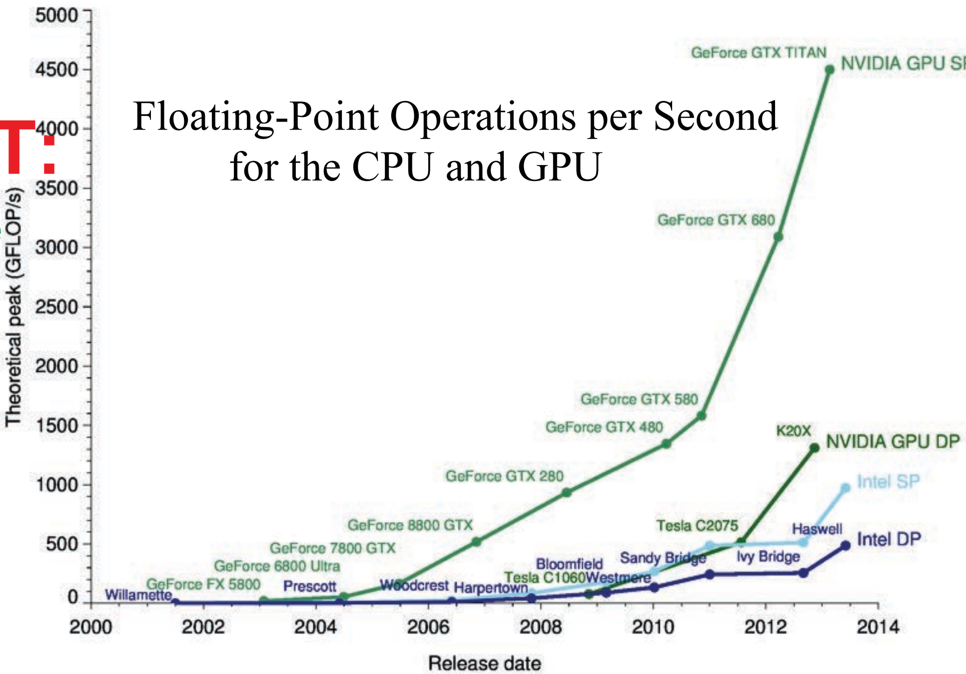
Tools cont'd: CPU, GPU, PCIe

CPU Gains for High Level Triggers: Moore's Law

- **e.g. Xeon Phi Co-processor**
  - 1.2 TeraFlop/s double precision peak performance today

GPU Enhancement of HLT:

- GPU uses a highly scalable architecture that closely tracks Moore's Law
- High performance memory system with ≥ 5x bandwidth vs. CPU
- Better performance / Watt vs. CPU
- Hardware and software support for moving data directly from network interface to GPU memory



Enhancement of detector to DAQ readout:

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

Trigger & DAQ Summary
Continuously Evolving

ATLAS and CMS Level-1 Trigger (pre-LS3)

- Select 100 kHz interactions from 1 GHz
- Processing is synchronous & pipelined
- Decision latency is 3 μs
- Algorithms run on local, coarse cal & muon data
    - Use of ASICs & FPGAs

ATLAS Level-1 Trigger (post-LS3):

- Divide L1 Trigger into L0, L1 of latency 6, 30 μsec, rate ≤ 1 MHz, ≤ 0.4 MHz
- L0 uses Cal. & μ Triggers, which generate track trigger seeds
- L1 uses Track Trigger & more muon detectors & more fine-grained calorimeter trigger information.

CMS Level-1 Trigger (post LS3):

- L1 Trigger latency, rate: 12.5 μsec, .5 – .75 MHz (140 – 200 PU)
- L1 uses Track Trigger, finer granularity μ & calo. Triggers

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
- Pre-LS3 output rate of < 1 kHz.
- Post LS3 HLT output rate of 5 – 10 (ATLAS)/7.5 (CMS) kHz (140 – 200 PU)