HL-LHC Trigger Upgrade

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Outline:

- Introduction to Trigger & Upgrade Requirements
- Strategy for Upgrade & starting point from Phase 1
- Need & use of a tracking trigger
- Architecture Options

Present CMS L1 Trigger System

Lv1 trigger is based on calorimeter & muon detectors.

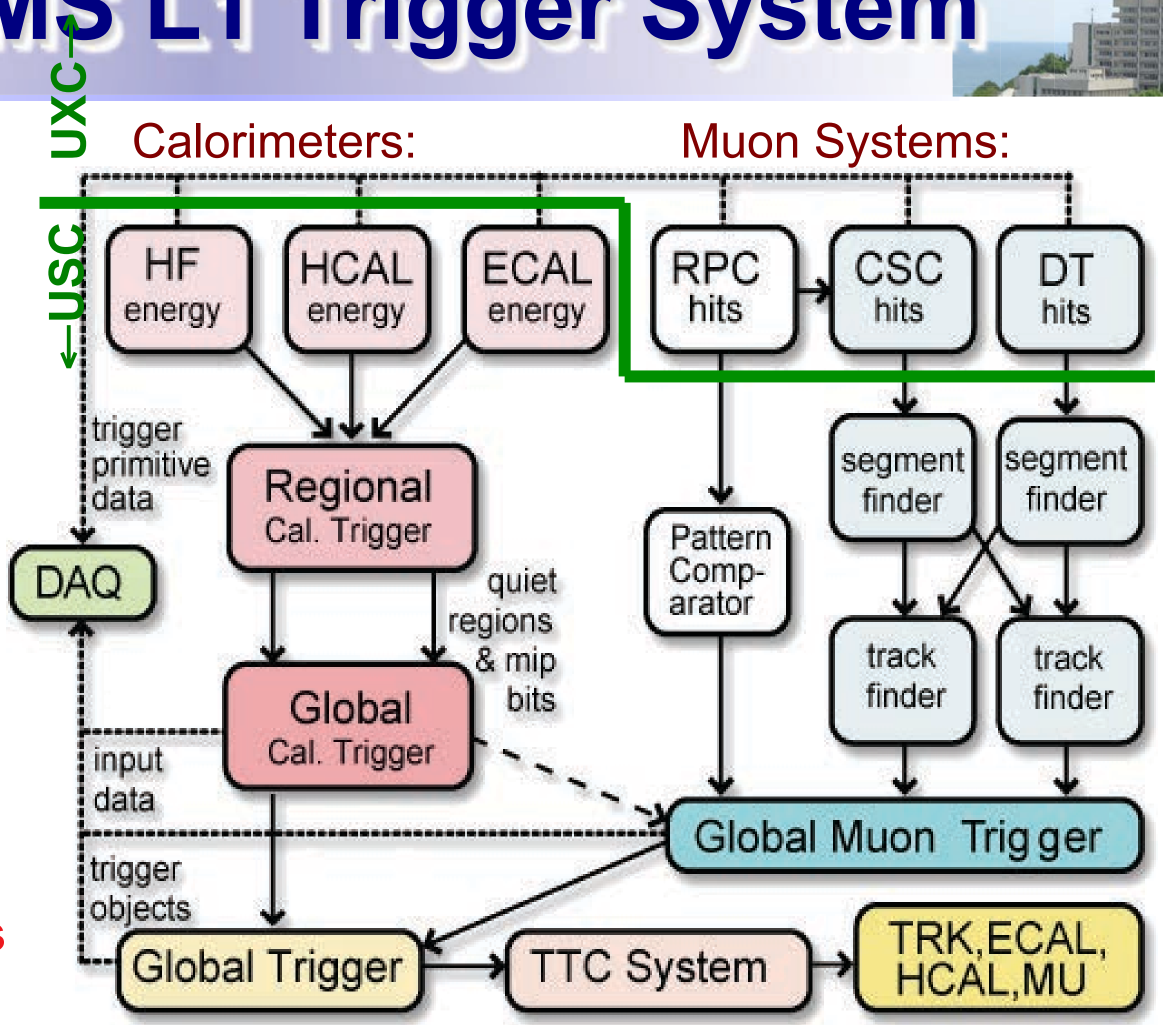
At L1 trigger on:

- **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

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

Phase 1: (until 2021)

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

Phase 2: High Lumi LHC (2023+)

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

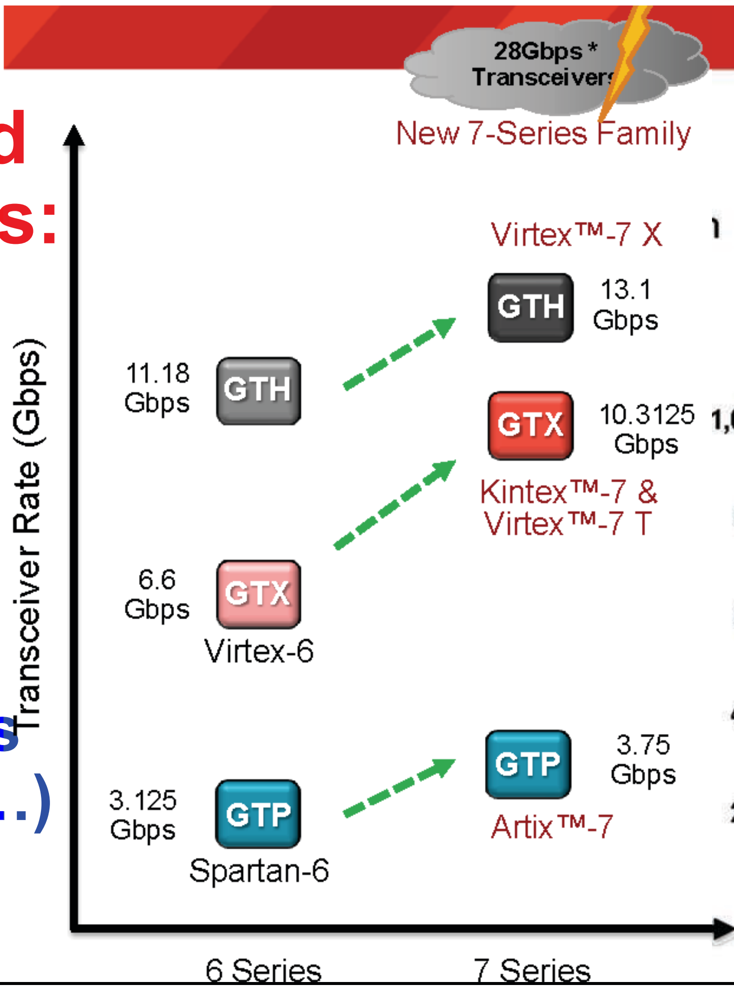
Tools for Upgrades: FPGAs

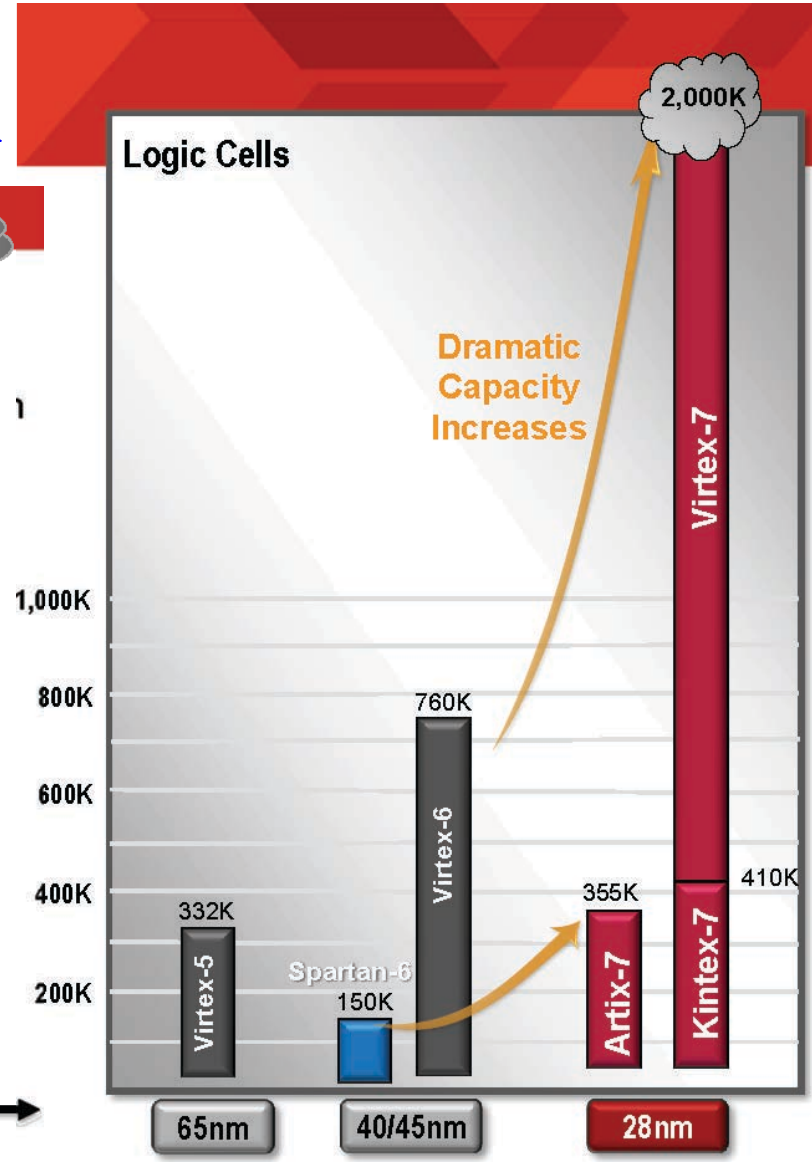
Logic Cells

- 28 nm: > 2X gains over 40 nm→

On-Chip High Speed Serial Links:

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

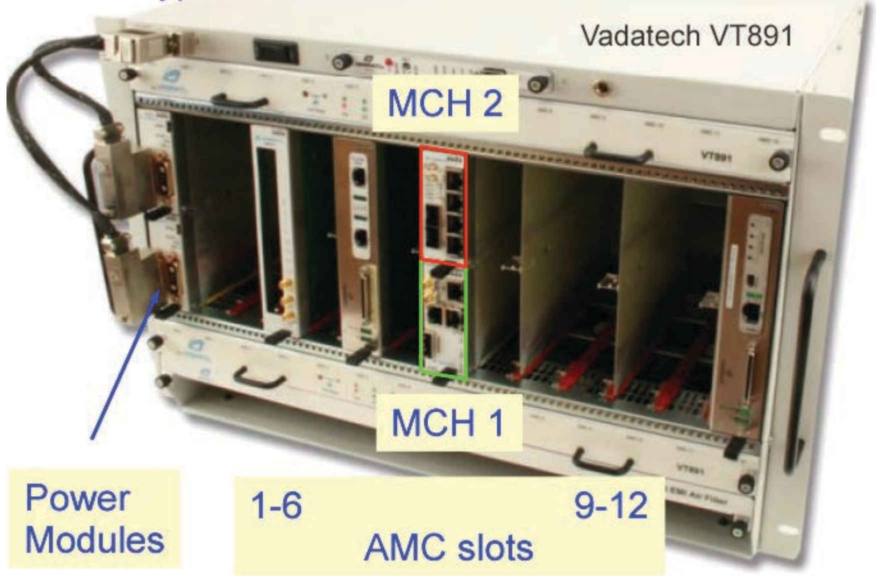




Tools for Upgrades: µTCA

- Advanced Telecommunications Computing Architecture ATCA
- µTCA Derived from AMC std.
  - Advanced Mezzanine Card
  - Up to 12 AMC slots
    - *Processing modules*
  - 1 or 2 MCH slots
    - *Controller Modules*
- 6 standard 10Gb/s point-to -point links from each slot to hub slots (more available)
- Redundant power, controls, clocks
- Each AMC can have in principle (20) 10 Gb/sec ports
- Backplane customization is routine & inexpensive

Typical MicroTCA Crate with 12 AMC slots



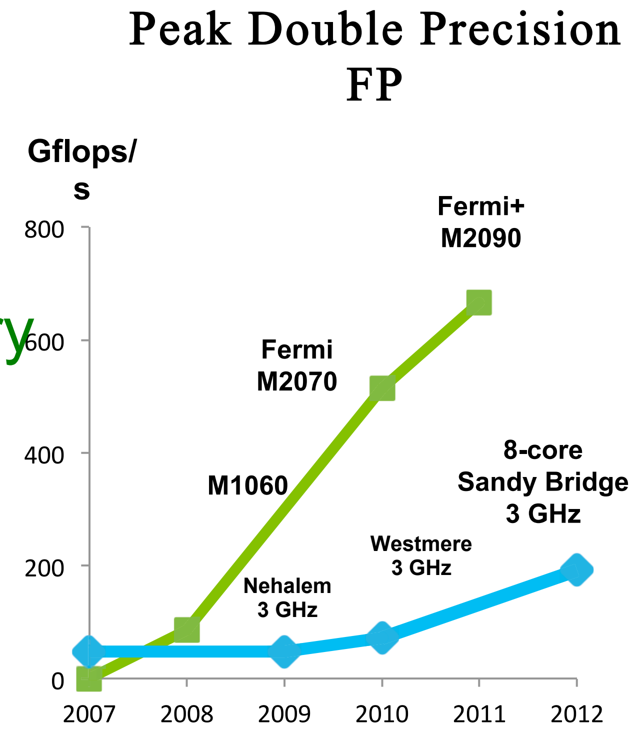
Single Module (shown): 75 x 180 mm
Double Module: 150 x 180mm

Tools cont'd: CPU, GPU, PCIe

CPU Gains for High Level Triggers: Moore's Law

GPU Enhancement of HLT →

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



Enhancement of detector to DAQ readout:

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

CMS Upgrade Trigger Strategy

Constraints

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

Example: strategy for Phase 1 Calorimeter Trigger

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

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

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

Starting Point: Phase 1 Trig.

High efficiency triggers with suitable rate for physics relevant for >100 fb^{-1} regime

- **Rate reduction > factor of 2 required**
  - $2x10^{34}$ @ 25 ns bunch xing or 10^{34} @ 50 ns ➔ same pileup
- **Threshold limiting physics is for higgs studies**
  - 30-40 GeV thresholds to trigger on W and Z (assoc. or decay)
  - Tau and b-jets play a role, especially MSSM
- **Double and cross triggers w/ topological constraints**
  - Improved position resolution needed (also eventually needed for combination with Phase 2 L1 tracking trigger)

Input trigger data remains same for muon & calorimeter

- **One or two bits more from HCAL with depth information**
- **More CSC muon segments sent to track-finder**

Algorithms providing > x2 reduction in rate and better efficiency than current trigger with pileup included

Algorithms shown to be possible to implement in firmware using input trigger data

CMS CSC Trigger Upgrade

Improve redundancy

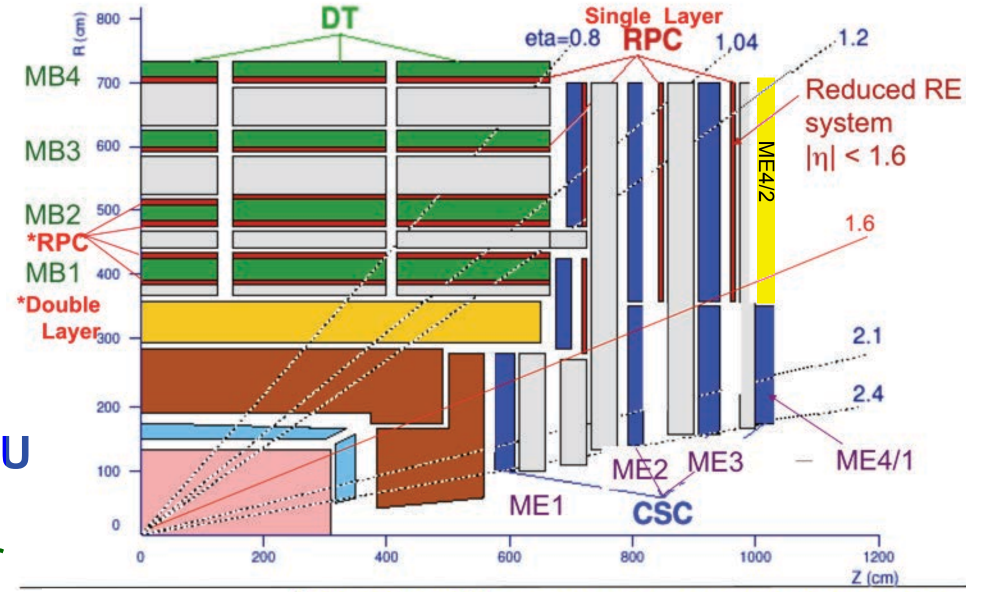
- Add station ME-4/2 covering η=1.1-1.8
- Critical for momentum resolution

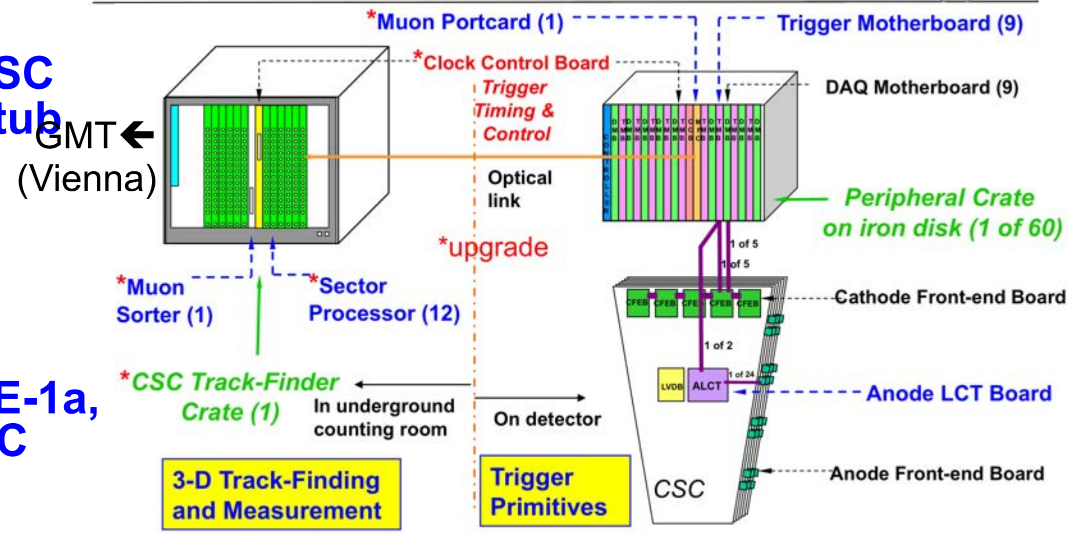
Upgrade electronics to sustain higher rates

- New Front End boards for station ME-1/1
- Forces upgrade of downstream EMU electronics
  - Particularly Trigger & DAQ Mother Boards
- Upgrade Muon Port Card and CSC Track Finder to handle higher stub rate

Extend CSC Efficiency into η=2.1-2.4 region

- Robust operation requires TMB upgrade, unganging strips in ME-1a, new FEBs, upgrade CSCTF+MPC

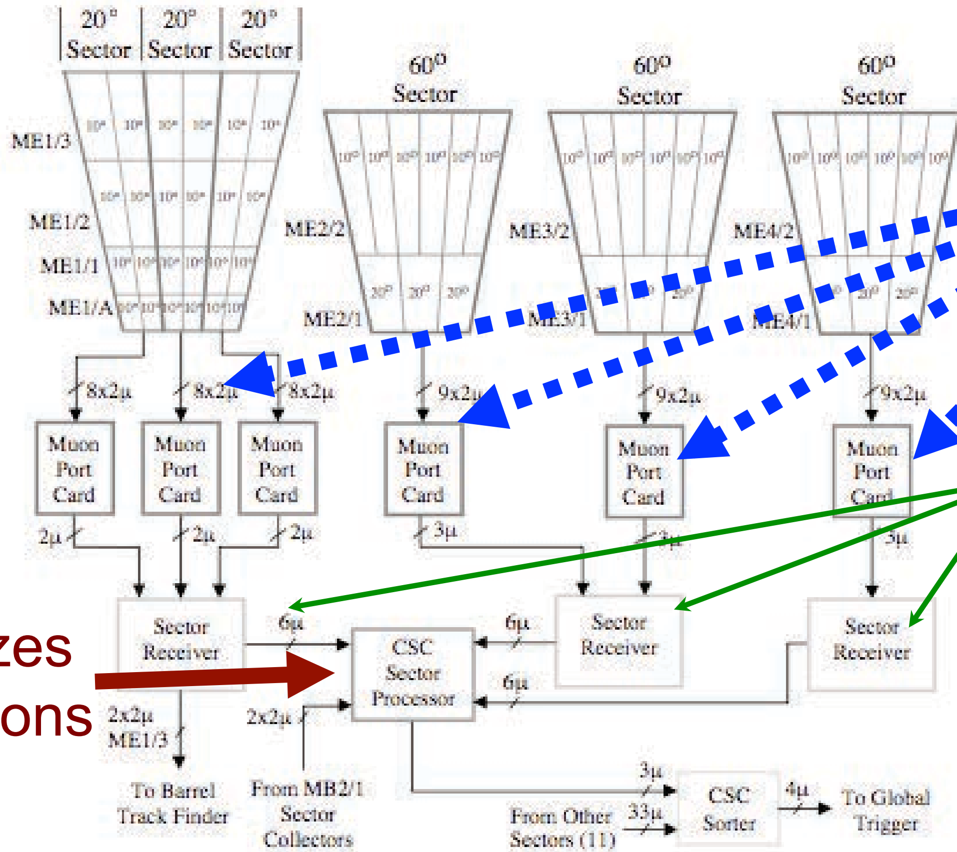




CSC Trigger Upgrade

- gather all information that chambers can report
- sort them out at Sector Processor: pattern recognition logic
- develop better p_t estimation algorithms

Full throughput MPC handle all 18 muons deliver to SP



SP analyzes combinations

Sector Receivers are now integrated onto the Sector Processor board

Phase 1 DT Upgrade

Sector Collector moves to USC55 – all DT information available

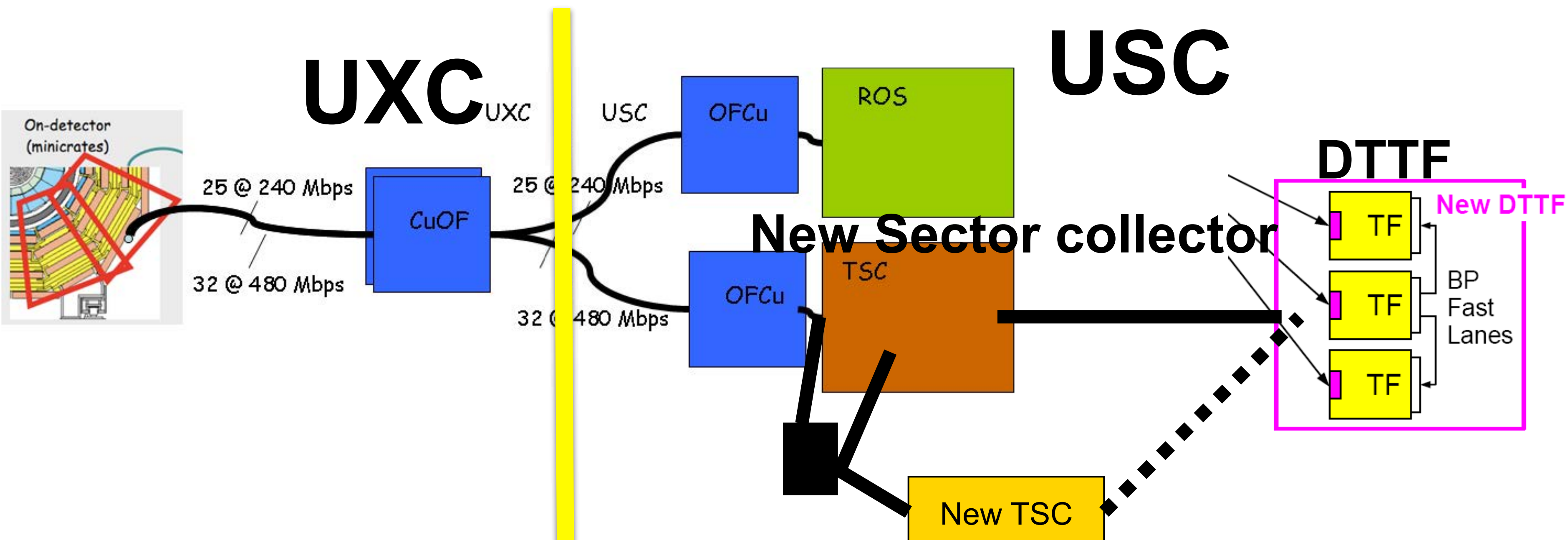
Optical fibers from Minicrates split for running a new system in parallel

At trigger level can test new algorithms exploiting single chamber (or even single Super-Layer) triggers in difficult regions

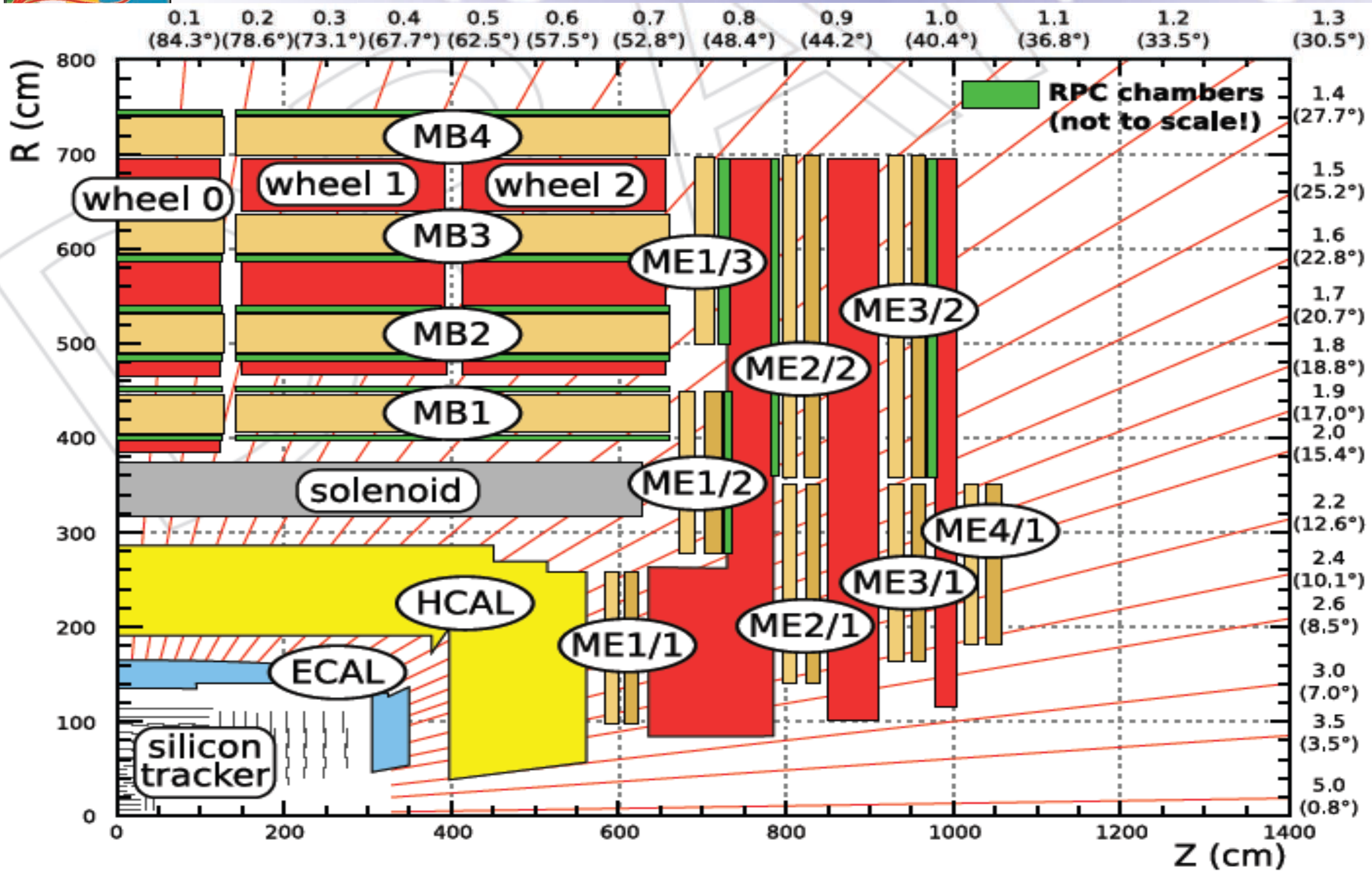
Can study new algorithms to improve redundancy with RPC

- also available on fibers in USC

DT/RPC coincidence at station level can improve BX ID in high PU



Upgrade Overlap Region



Trigger logic:

- CSCTF ≥ 3 CSC
- DTTF ≥ 2 DTs
- RPC 3 of 4 or 4 of 6 RPC
- Overlap DT&CSC, RPC not used

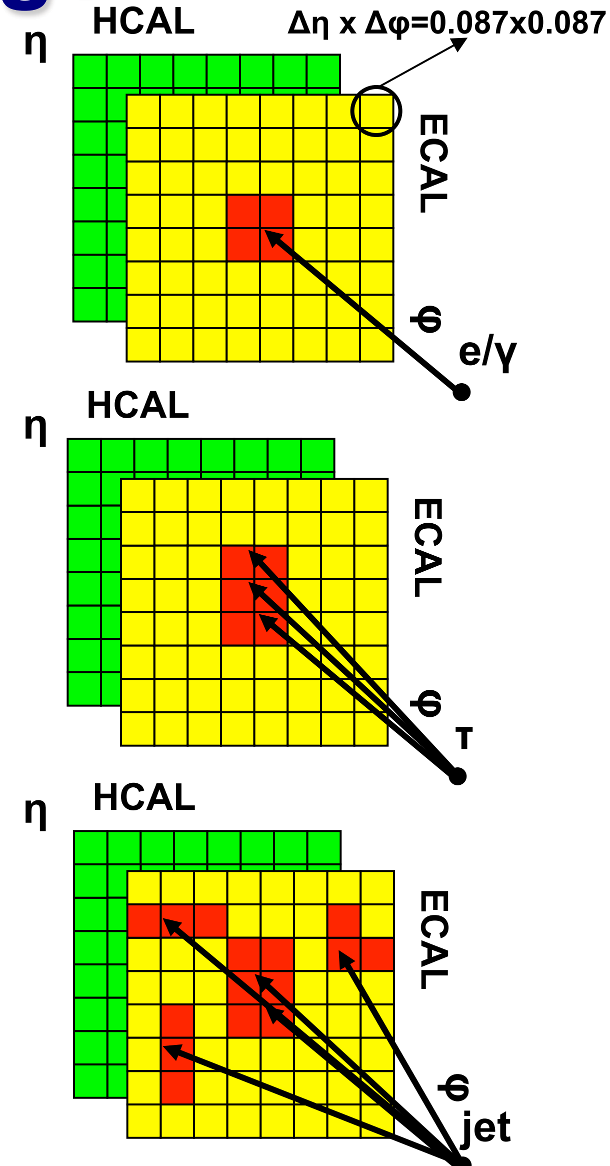
Coincidence of signals from single DT, CSC, RPC can be exploited for improving efficiency in difficult regions

CMS Phase 1 Upgrade Calorimeter Trigger

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

Rate reductions x4 w/improved efficiency

Implemented in 4 μTCA Crates



CMS Level-1 Trigger → $5x10^{34}$

Occupancy

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

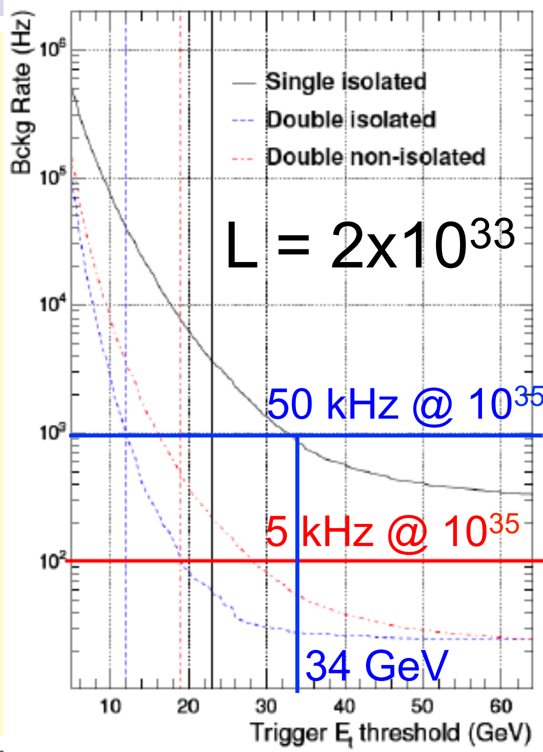
Trigger Rates

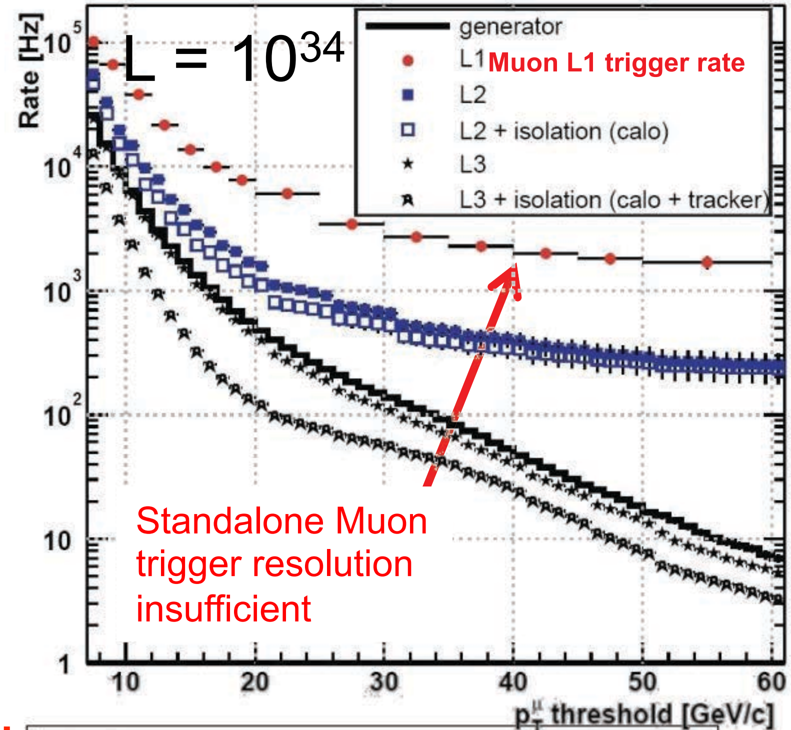
- **Try to hold max L1 rate at 100 kHz by increasing readout bandwidth**
  - Avoid rebuilding front end electronics/readouts where possible
    - **Limits: ⟨readout time⟩ (< 10 μs) and data size (total now 1 MB)**
  - Use buffers for increased latency for processing, not post-L1A
  - May need to increase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

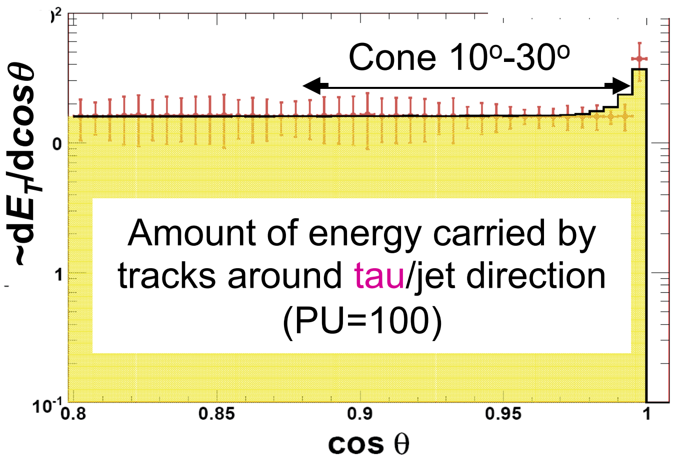
Tracking needed for L1 trigger

Single electron trigger rate: *Isolation criteria are insufficient to reduce rate at* L = 10^{35} $cm^{-2}s^{-1}$

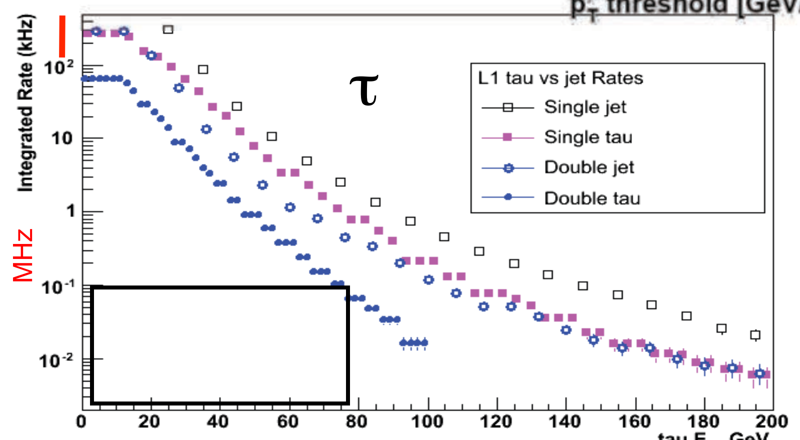
(Or $5x10^{34}$ at 50 ns)



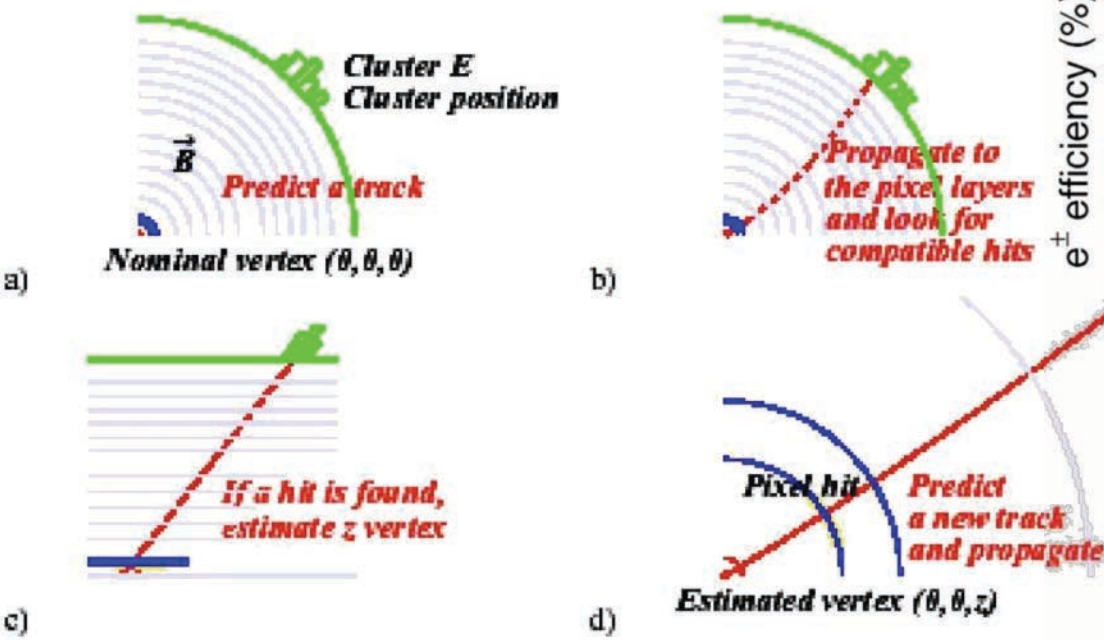


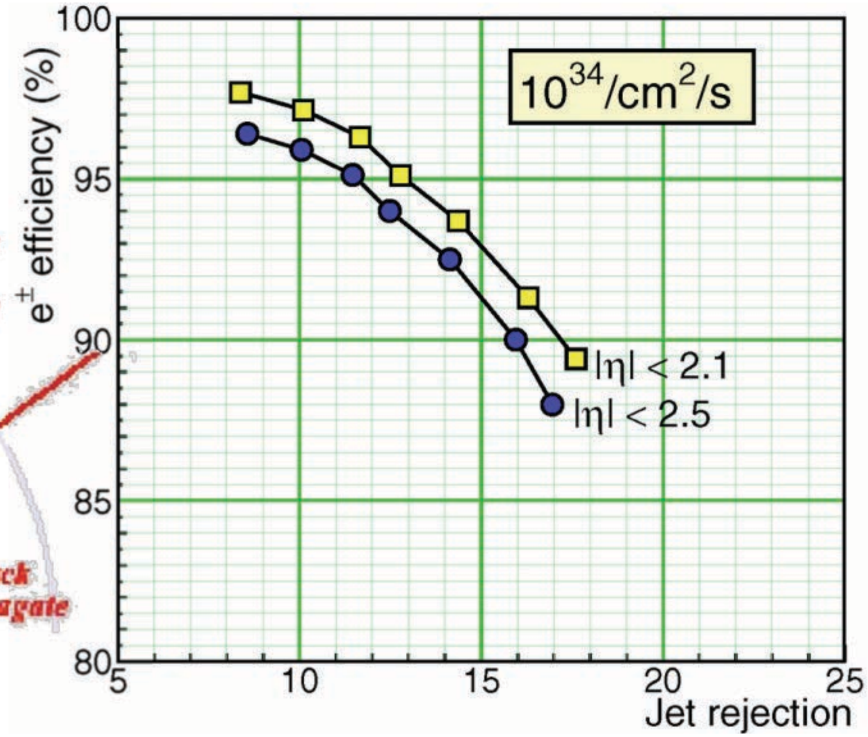


We need to get another x200 (x20) reduction for single (double) tau rate!



Present CMS electron HLT

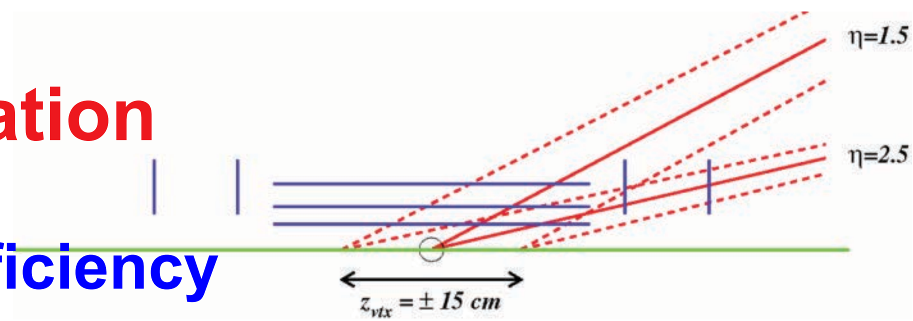




Factor of 10 rate reduction

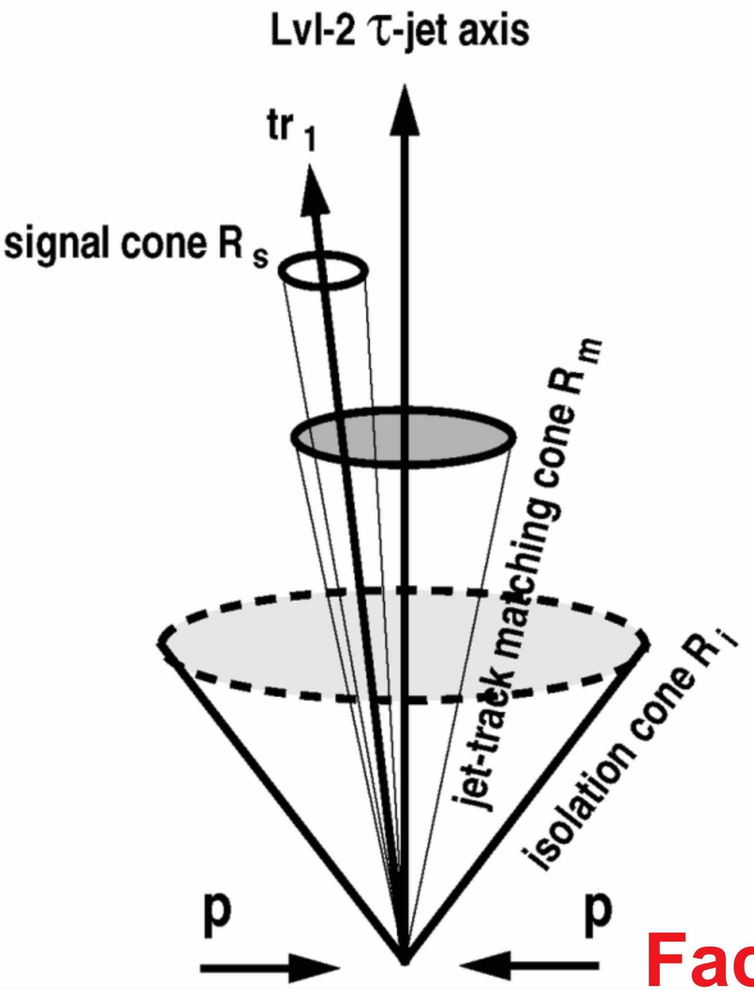
γ: only tracker handle: isolation

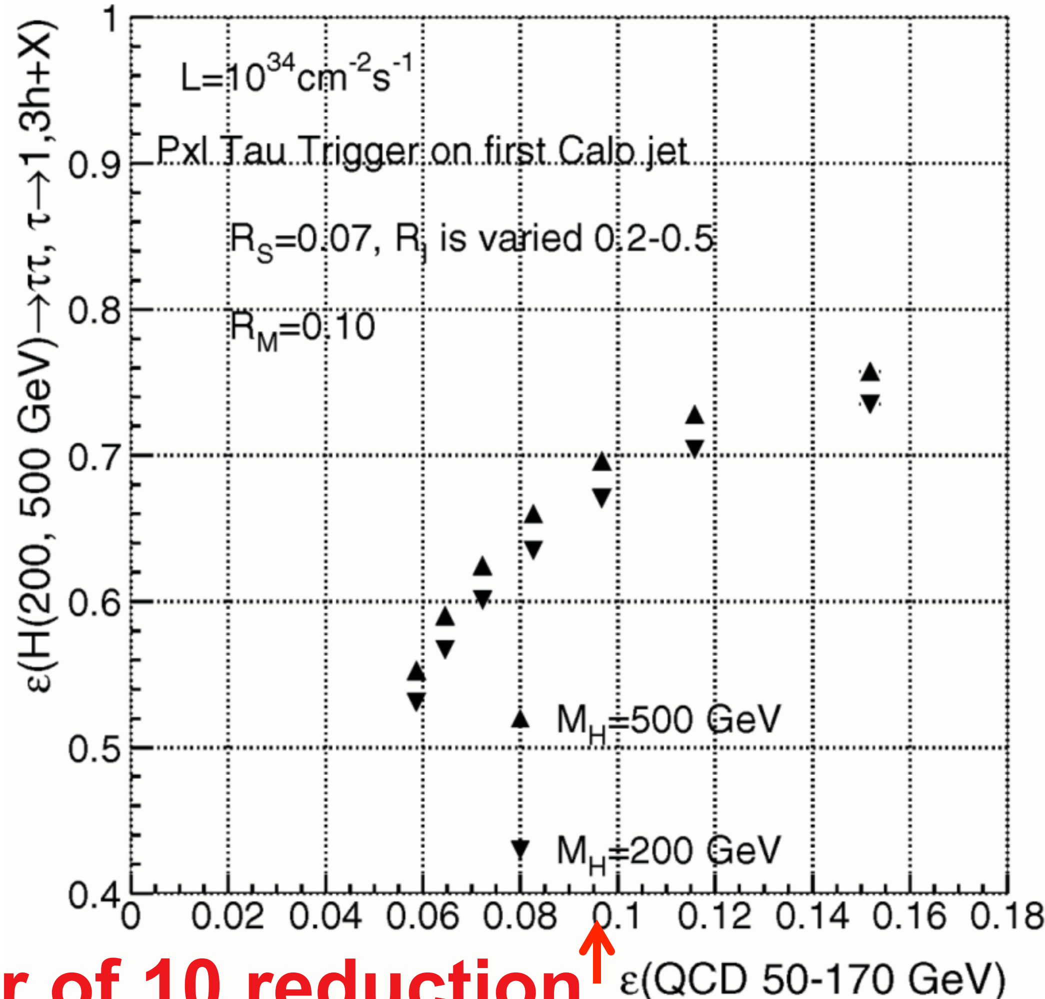
- **Need knowledge of vertex location to avoid loss of efficiency**



Tracking for τ-jet isolation

τ-lepton trigger: isolation from pixel tracks outside signal cone & inside isolation cone





Factor of 10 reduction

CMS L1 Track Trigger for Muons

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

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

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

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

CMS Phase 2: Tracker input to L1 Trigger

Use of Tracker input to Level-1 trigger

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

Full-scope objectives:

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

Track trigger data at 40MHz

Attempt to minimize power for readout of track trigger data

Requirement: achieve a trigger rate reduction of ~10

- **with 40 MHz tracker readout – penalty is power**
- **most of time spent on "useless" processing of most of data**
  - not evident that it adds much to find vectors most of which are unrelated to trigger object

If present L1 trigger transmitted to tracker, read out limited number of faces

- **$\Delta\Phi = 0.087 \approx 1$ azimuthal face at $R = 25$cm**
- **if ~3/64 faces read out at 1MHz => rate reduction ≈ 850**
- **penalty is latency: tracker data only available after L0 trigger + ~1μs**

CMS Track Trigger Architectures: Phase 2

"Push" path:

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

"Pull" path:

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

"Afterburner" path:

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

Phase 2 CMS Level-1 Latency

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

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

Do we need more?

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

How much more? Justification?

- Combination with tracking logic
- Increased algorithm complexity
- Asynchronous links or FPGA-integrated deserialization require more latency
- Finer result granularity may require more processing time
- ECAL digital pipeline memory is 256 40 MHz samples = 6.4 μsec
  - This is CMS SLHC Level-1 Latency baseline (use 6.0 μsec)

CMS Readout Options

Read out all detectors after 6 μsec at L1 rate

- Pro: Don't need to rebuild ECAL FE
- Con: Still have subset of calorimeter & muon detector information used to triggering

Read out calorimeter & muon detectors in real time at 40 MHz, tracker at L1 rate after L1 latency

- Pro: Do have to rebuild ECAL FE
- Pro: Have all muon & calorimeter information available for L1 Trigger Decision
- Pro: Can increase latency to limit of buffering of tracker data
- Pro: Can increase L1 Trigger Rate to limit of tracker readout power (100 $\rightarrow$ 200 $\rightarrow$ 500 kHz)
- Con: Need to rebuild all FE electronics

Intermediate situation

- Still have to rebuild all FEE but only have partial calorimeter and muon trigger information at L1.

Actions:

- Trigger Performance & Strategy Working Group is meeting with detector groups during CMS week to determine limitations, options

Private Track Trigger Level-0

Cal & Muon triggers would produce L0 after 3 µsec with request for tracking information at the rate of 1 MHz.

Request only goes to regions of tracker where candidate was found (0.5 µsec) Tracker then send out information for these regions only in 5 bx (~ 0.1 µsec data + 0.5 µsec trans.) & data would then be combined in L1 correlation logic, resulting in a L1A combining tracking, muon and cal information after 6 µsec.

- Correlation logic + Global Trigger start at ~ 4.1 µsec, finish at ~ 5.5 µsec – needs to be fast!

Reduces the data transmitted from the tracker to L1 trigger logic ✕ 40 (40 MHz ➔1 MHz) times the frequency of tracker regions found with candidates. This could exceed 2 orders of magnitude.

Hybrid: tracking trigger info. for high p_T correlation sent only if above a high enough threshold in real time & "stored" trigger information used for lower thresholds & isolation provided after L0 signal to specific tracker region.

Not "classical" L1.5. No FE would see "L0". Only on-detector tracking trigger logic in specific ROI would see L0. Rest of CMS would see the standard L1A after 6 µsec. In this way the trigger remains a "simple" architecture.

Approximate Private L0 Timeline

- Cal & Muon triggers produce L0: 3.0 μsec
- Transmit L0 to Tracker RoIs: 0.5 μsec ➔3.5 μsec
- Send RoI track trigger info in 5 b.x. = 0.1 μsec ➔3.6 μsec
- Transmit RoI Track Trig. data to Correlators: 0.5 μsec ➔4.1 μsec
- Correlate Track, Muon, Cal Trigs: 0.5 μsec ➔4.6 μsec
- Global Trigger: 0.5 μsec ➔5.1 μsec
- Transmit L1A back to front ends: 0.5 μsec ➔5.6 μsec
- Contingency: 0.4 μsec ➔6.0 μsec

IMPORTANT: This proposal allows us to have a L1 tracking trigger with presently "achievable" technology in a feasible tracker. If more performant solutions are developed, we can send out tracking trigger data without a L0. This lets us get started.

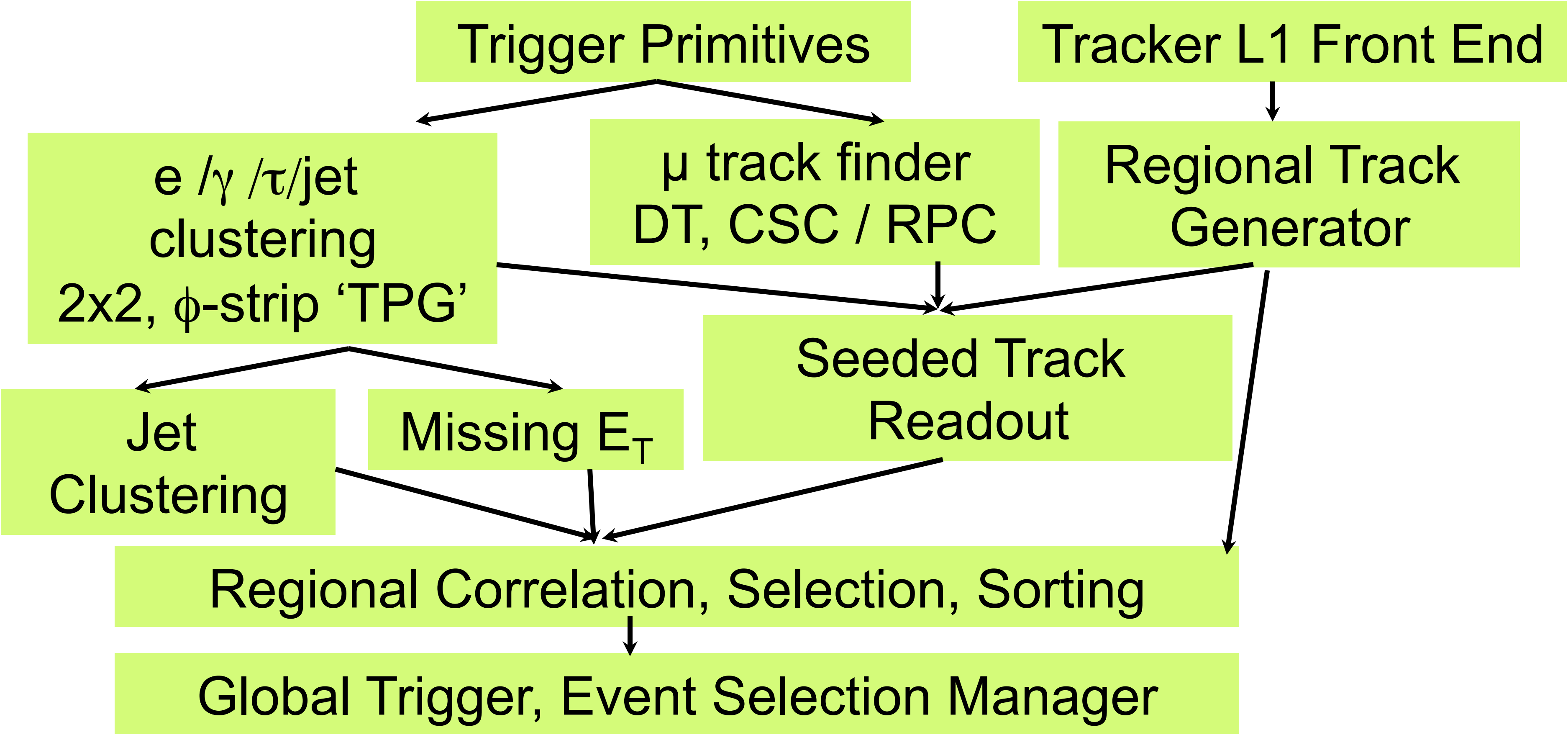
CMS L1 Trigger Stages

Current for LHC:

TPG → RCT → GCT → GT

One option for HL-LHC (with tracking added):

TPG → Clustering → Correlator → Selector



Trigger Summary

Trigger upgrades critical to harvesting physics from $1x10^{34}$ to $5x10^{34}$

Tracking Trigger is needed for HL-LHC

- Calorimetric Isolation ineffective at high pileup
- Resolution of stand-alone muon trigger insufficient at high Pt

3 places where L1 Tracking Trigger can be used:

- Push, Pull, Afterburner

Information from L1 Tracking Trigger can be combined with muon and calorimeter L1 triggers or used standalone

Various Architectures for HL-LHC under study

- Full readout at 40 MHz option for some detectors

New Trigger Performance & Strategy WG will be tackling these issues

- Your input is welcome!

Backup

CMS Track Trigger: General concept

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

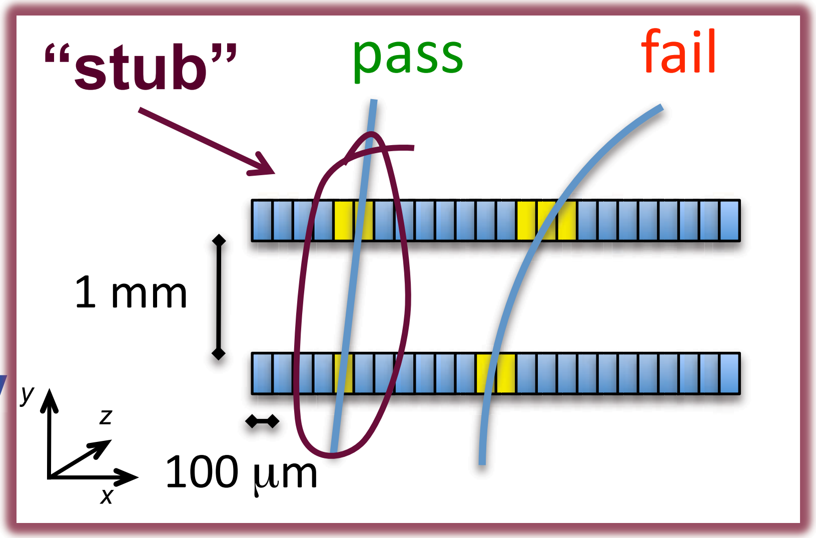
- **The whole tracker sends out data at each BX: "push path"**

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

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

Design modules with p_T discrimination ("p_T modules")

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



Level-1 "stubs" processed in back-end

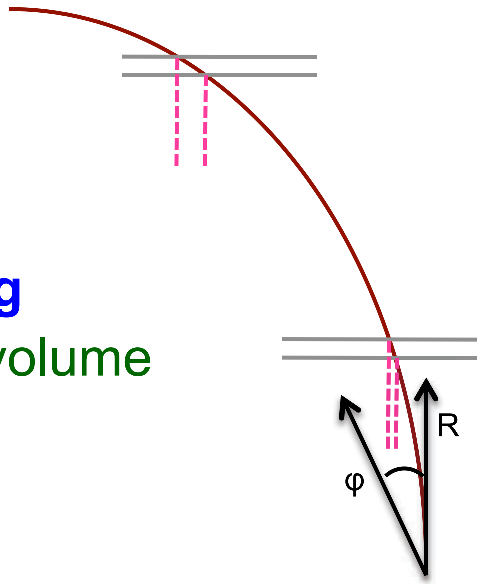
- **Form Level-1 tracks, p_T above 2-2.5 GeV**
  - Improve different trigger channels

CMS Track Trigger p_T modules: working principle

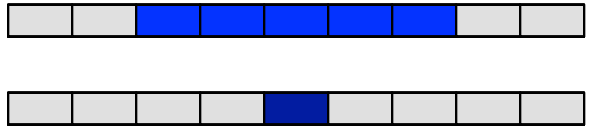
Sensitivity to p_T from measurement of $\Delta(R\varphi)$ over a given ΔR

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

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



e.g. Window = 5



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

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

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