CMS Triggers for LHC Startup

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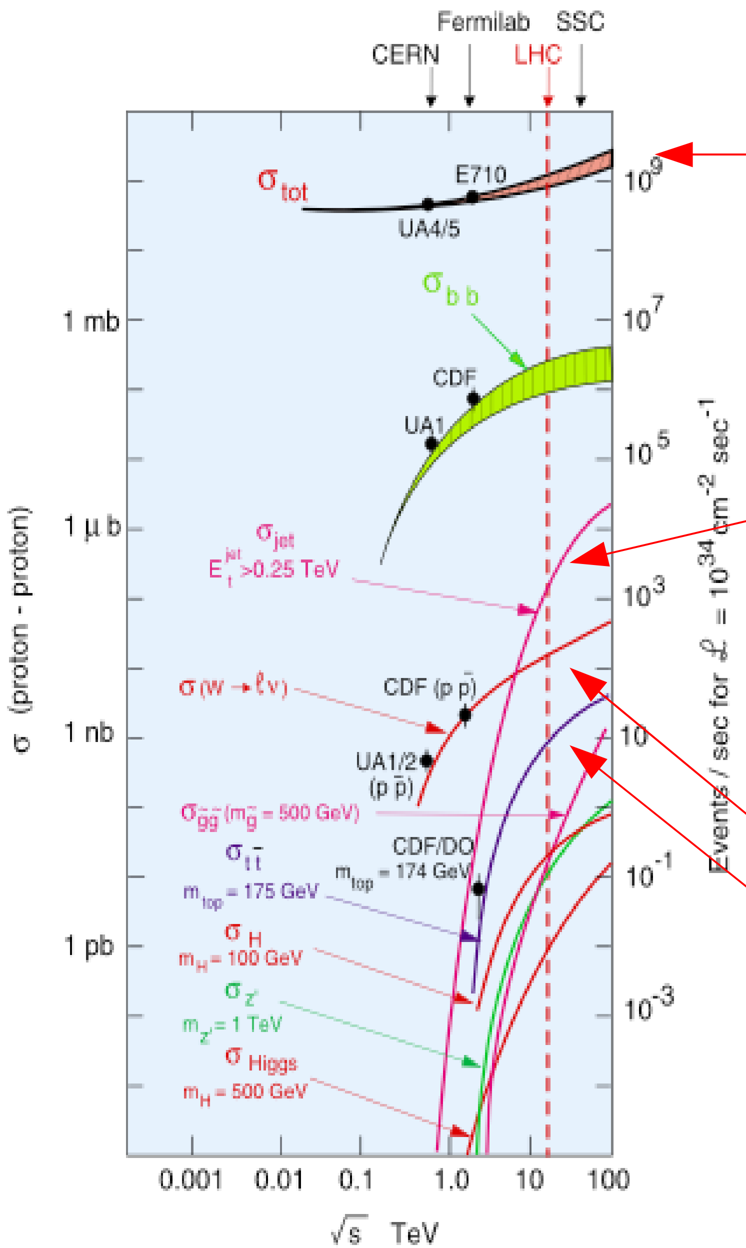
International Conference on Particle Physics
In Memoriam Engin Arik and Her Colleagues
Istanbul, 27-31 October 2008

- Introduction
- CMS Trigger System
- Trigger Strategy for Startup
    - Calibration, Alignment & early Physics
- Conclusion

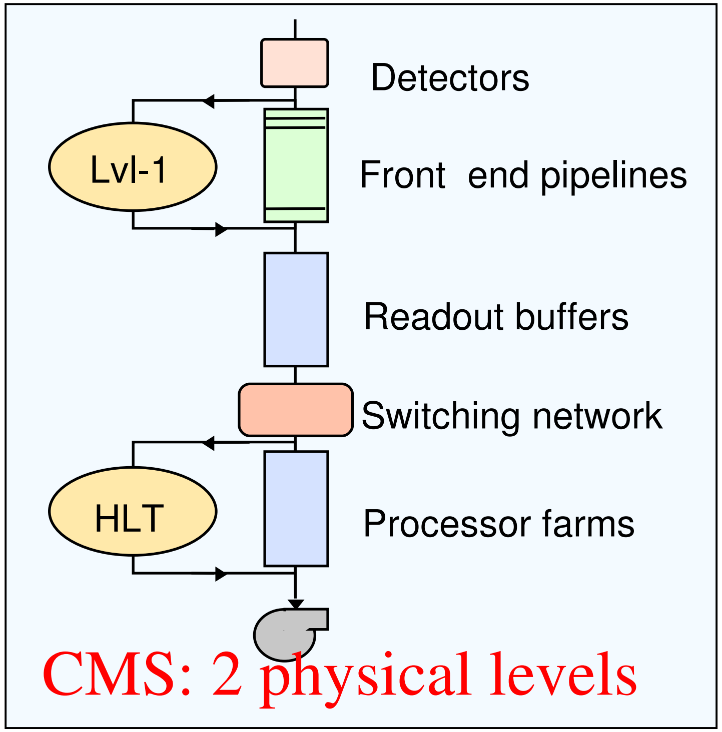
LHC Trigger Challenge



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

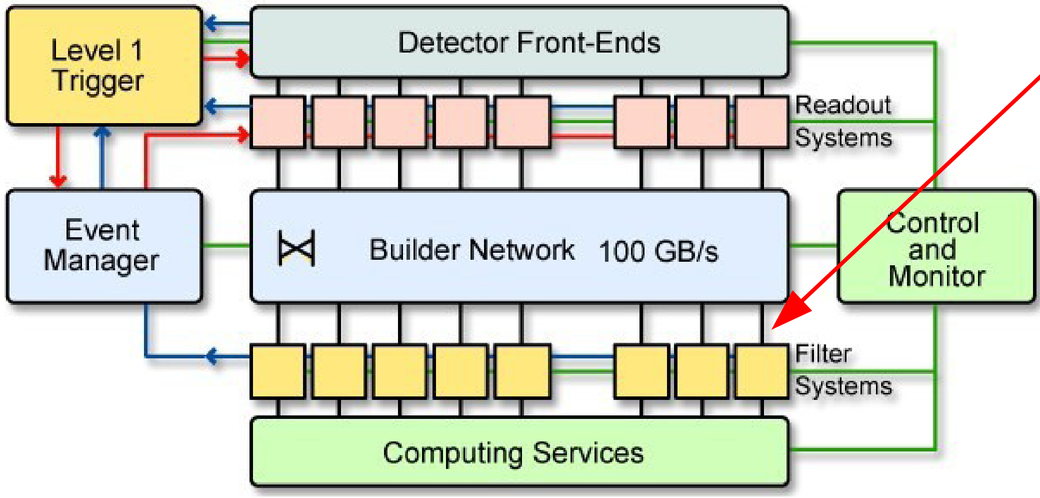
- 1 GHz input rate expected (total QCD)
  - 40 MHz bunch crossing rate
  - 20 pp events per crossing (pile-up)
- QCD background
  - Jet E_T > 250 GeV ~1 kHz
  - Jet Fluctuations ↣ Electron background
  - Decay of π, K, B ↣ Muon background
- Orders of magnitude higher cross section than SM candles & discovery channels
- Electroweak scale (W, Z, Higgs):
  - <100 Hz with Leptons/Photons E_T ~ 40 GeV
  - 10 Hz Top events
- TeV scale SUSY:
  - Multiple leptons, jets & LSP (missing E_T) with E_T < 100 GeV

CMS Trigger System



CMS has 2-Level trigger system:

- Level-1 (L1) reduces rate from 40 MHz to 100 kHz (custom fast processing electronic boards)
  - Using only coarsely segmented Object ID and isolation
  - No tracking!
- High Level Trigger (HLT) reduces rate from 100 kHz to 100 Hz (~1000 Standard CPUs)
  - Finer granularity
  - Track reconstruction (b, τ, electrons)
  - Kinematical cuts: Topology, invariant Mass

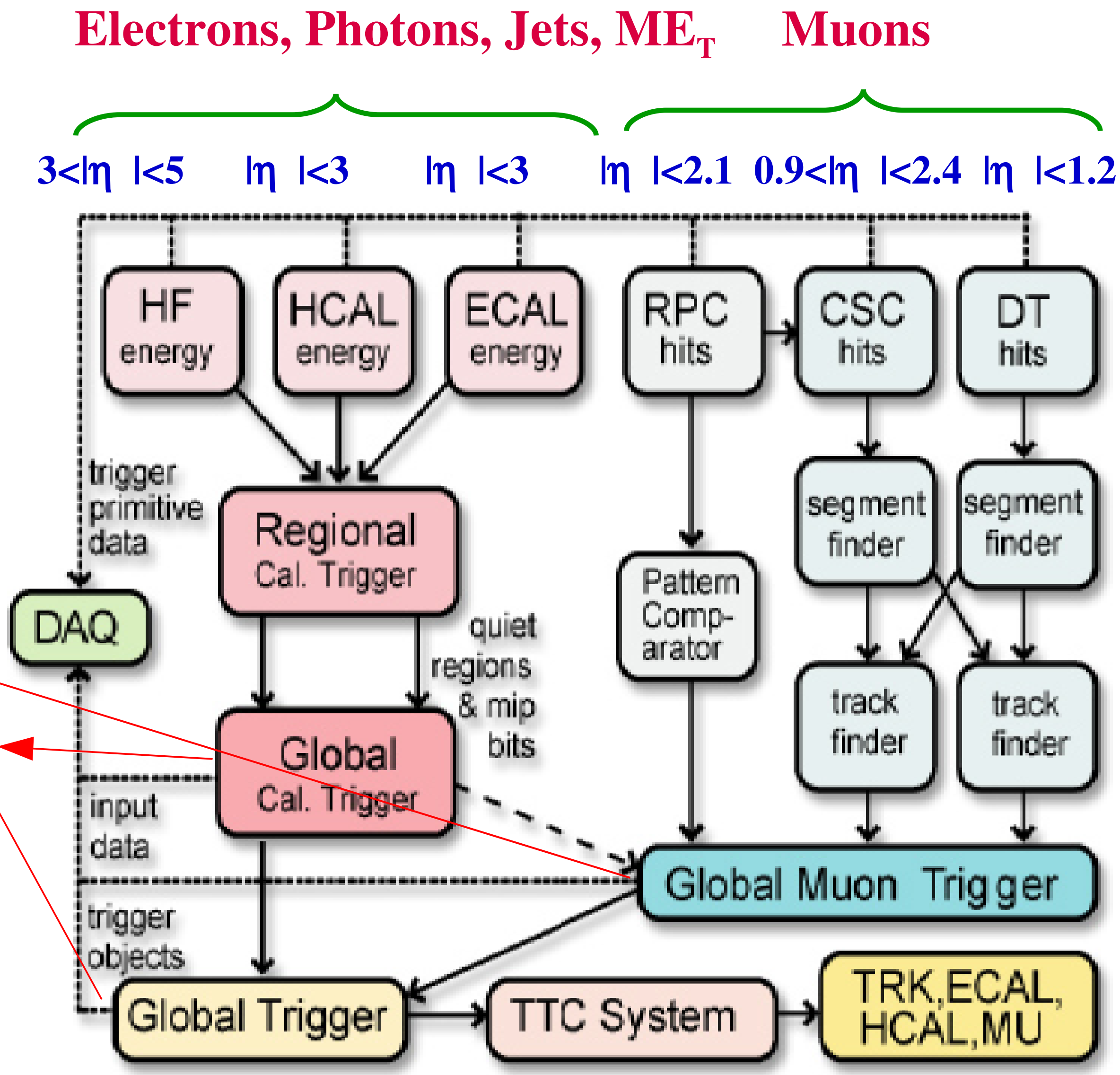


- Novel approach compared to traditional 3(4)-Level Trigger Systems
- Allows tuning of algorithms in most flexible way!

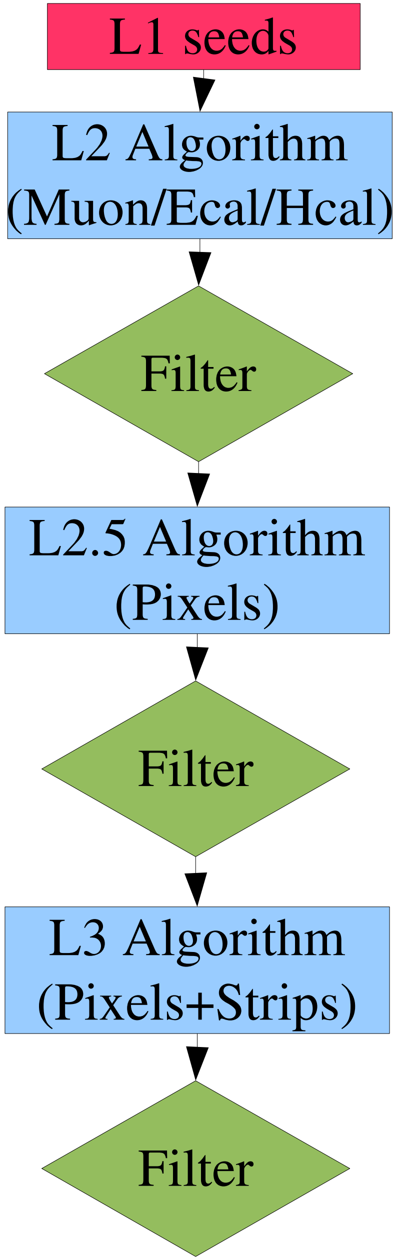
Level-1 Trigger System

CMS Level-1 trigger system:

- Level-1 reduces rate from 40 GHz to 100 kHz
- Custom fast processing electronics
- Pipelined (10^7 channels) for dead-time-free operation
- Latency: 3.2 μs (128 x 25 ns)
- Using only coarsely segmented Object ID and isolation
- No silicon tracking available!
- Global trigger has access to up to:
  - 4 muon candidates (position, sign, quality from GMT)
  - 4 central, forward, tau jet candidates, 4 (non-)isolated e/γ candidates, E_T, missing E_T (position from GCT)
- GT: 128 conditions can be combined to form 128 physics triggers
- Full readout capability not available at startup (4/8 DAQ slices installed by now ↣ 50 kHz)



High Level Trigger



<u>High Level Trigger</u>

- Reduces rate from 100 kHz to 100 Hz
- Runs on ~1000 Standard Dual Quad-Core CPUs at 2.6 GHz
- Software/reconstruction can be in principle with offline quality: Allows tuning of algorithms in most flexible way!

- Bandwidth/Timing constraint:
  - Each HLT trigger path is a sequence of filters
  - Moving from low (Calo, Muon) to high (Pixel, Strip) time consuming algorithms
  - All algorithms regional (except jets): Seeded by previous levels
  - Reco time is significantly improved by applying
    - regional data-unpacking (using small (η, φ) region)
    - local reconstruction (using one subdetector only)
  - Bandwidth:
    1 GB/s: Assuming event size of 1.5 MB ↣ 700 Hz peak output rate

  - Major exercise in 2007 with Xeon Core 2 3 GHz ($10^{32}cm^{-2}s^{-1}$)
    at 50 kHz input rate ↣ time budget ~40 ms/event
    Result: on average 43 ms/event

LHC Startup Phase

<u>LHC Stage A plans before September 19</u>:

- 30 days of collisions at low intensity, unsqueezed beams for machine comissioning
- Increase intensity, partially squeezed for further machine comissioning, CMS can do detector comissioning and look for early physics (rediscover SM):
  - 5 TeV Collsions, 75 ns bunch crossing time
  - Assume a few hours of beam time per day, 1-2 days per week
  - Integrated luminosity: Assume 72h data taking per beam configuration: O(10 pb^{-1})

Lyn Evans (ICHEP 2008)

Bunches	N	Int. Lumi. (pb^{-1})	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1 (3)	10^{10}	-	$1.1 \cdot 10^{27}$	<< 1
4	10^{10}	-	$4.5 \cdot 10^{27}$	<< 1
43	10^{10}	-	$5.0 \cdot 10^{28}$	<< 1
43	$4 \cdot 10^{10}$	0.21	$8.0 \cdot 10^{29}$	<< 1
43	$4 \cdot 10^{10}$	0.75	$2.9 \cdot 10^{30}$	0.36
156	$4 \cdot 10^{10}$	2.6	$1.0 \cdot 10^{31}$	0.36
156	$9 \cdot 10^{10}$	14	$5.4 \cdot 10^{31}$	1.8

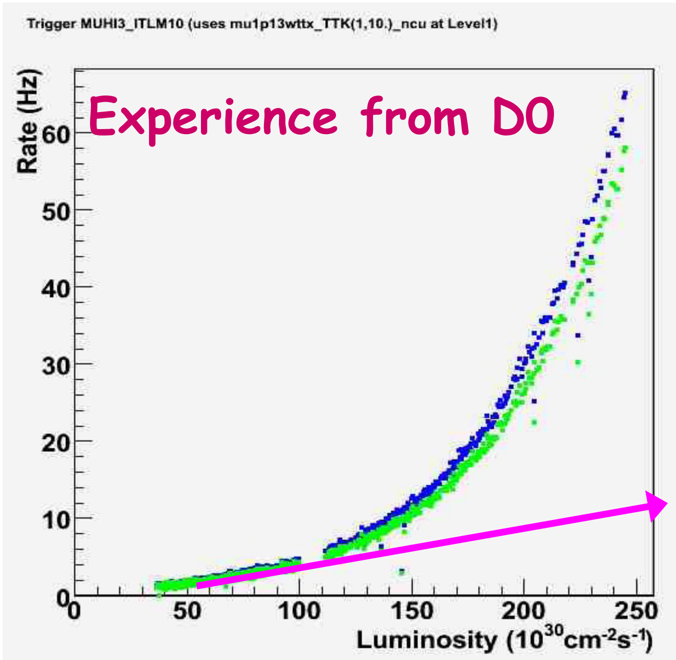
Strategy for LHC Startup

Motivation:

- Using Minbias & SM candles for calibration, alignment, energy scales (jets, missing E_T), trigger efficiencies, optimise lepton/photon ID, jet algo...
- Rediscover Standard Model (SM)

Contraints on Physics Trigger Menus:

- 4/8 „DAQ slices“ available: 50 kHz L1 bandwidth
- Latest studies assume 3/8 „DAQ slices“ available: 37 kHz L1 bandwidth
- Safety factor 3 for unknown QCD cross section :
  - L1: 12 kHz
  - HLT: 150 Hz (1GB/s; 100 MB/s reserved for alignment/calibration)



General Strategy: Grids of E_T/p_T per object

- Leptons: fine steps at low p_T, coarser steps at high p_T
- Jets: coarse E_T steps
- Relaxed triggers for unbiased studies ↣ efficiency studies, calibration, alignment
- In parallel: running standard physics triggers designed for higher luminosity ($\geq 10^{32}$ cm^{-2}s^{-1}) ↣ to be able to catch possible problems early
- ↣ Adjust only prescales of triggers as a function of luminosity: Most flexible & fast (non-linearities in the trigger response vs. Luminosity makes projections diffcult)

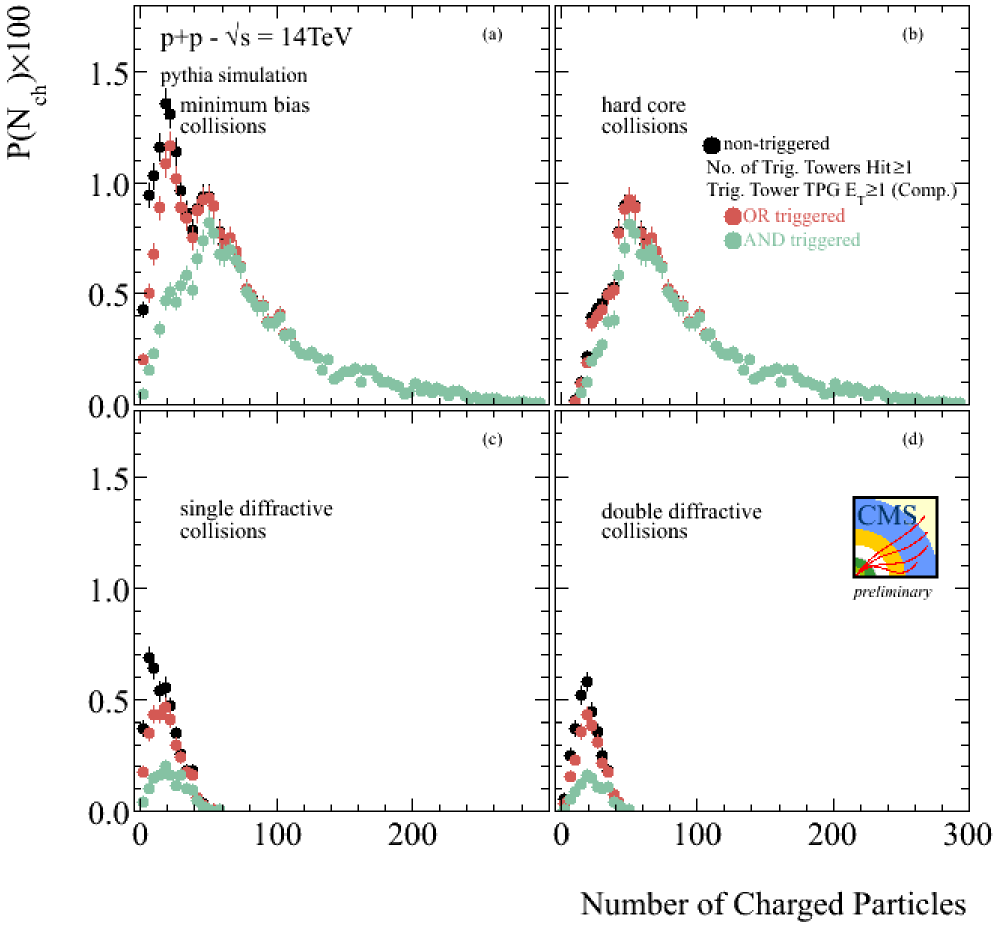
Triggers for Minbias

Minbias (MB) triggers (L1):

- Motivation: new accelerator, detector! Need to understand data taking, selection and detector performance using a zero/minimum bias data sample Limitation: Bandwidth (high prescales)
- Zerobias: trigger on bunch crossing

- MB based on forward Hcal (HF): 3< η <5
  - Counting towers above threshold
  - Rates & efficiencies depend on noise
  - Single-sided or double-sided coincidence (latter rejects gas/halo background)
  - Alternative: Sum E_T of HF Rings

- MB based on Ecal (less noisy)
  - Single Ecal tover > 2 GeV
  - Double Ecal towers > 1 GeV

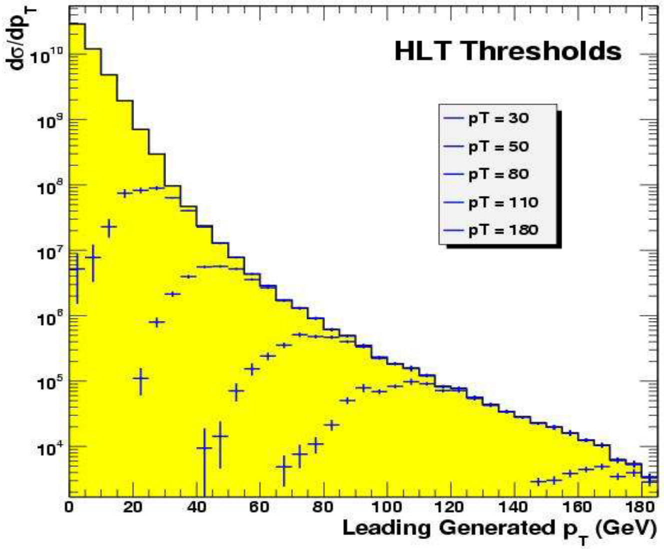


Triggers for Jets

Example grid of jet triggers:

- Coarse E_T grid
- Same Menu runs up to $10^{32}\,cm^{-2}s^{-1}$ by just changing prescales
- Use lower threshold paths to measure higher threshold trigger efficiencies (Minbias for lowest)

$\mathcal{L}$		$8.0 \cdot 10^{29}\,cm^{-2}s^{-1}$		$2.9 \cdot 10^{30}\,cm^{-2}s^{-1}$	
HLT Threshold (GeV)	L1 Trigger	Prescale	Individual Rate (Hz)	Prescale	Individual Rate (Hz)
—	L1_SingleJet15	1000	6	5000	4
30	L1_SingleJet15	25	21	250	6
50	L1_SingleJet30	5	9	10	12
80	L1_SingleJet50	1	5	5	3
110	L1_SingleJet70	1	1	1	3
180	L1_SingleJet70	1	0.1	1	0.2
250	L1_SingleJet70	1	0	1	0



- Also included are complementary average E_T Dijet paths designed to measure η dependence of jet response (see also Hcal calibration later)

Triggers for Missing ET

Similar as for jet triggers: $\mathcal{L}$ $8.0 \cdot 10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $2.9 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

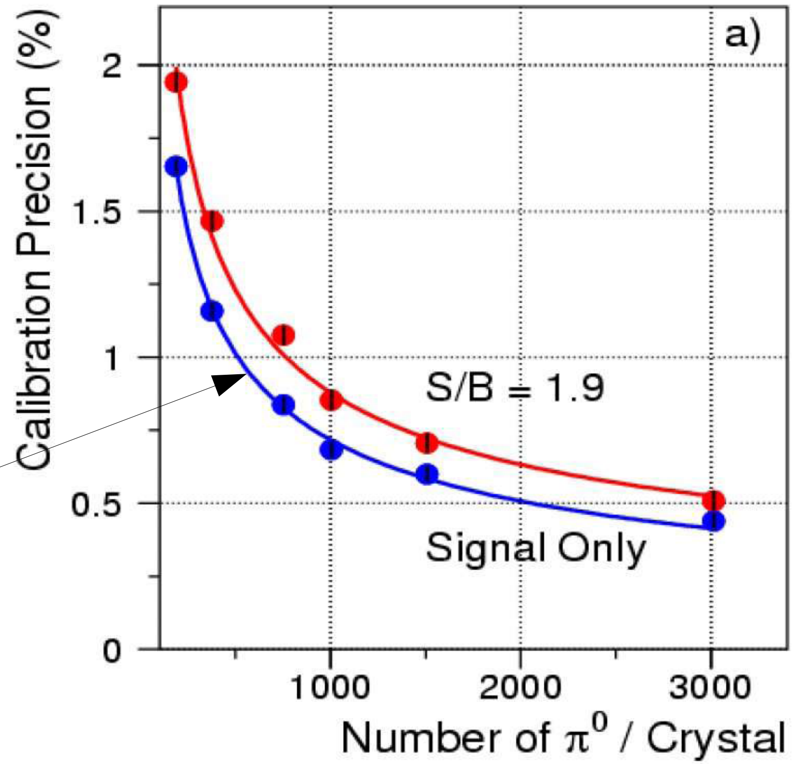
- Same Menu runs up to $10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by just changing prescales
- Use lower threshold paths to measure higher threshold trigger efficiencies (Minbias for lowest)

HLT Threshold (GeV)	L1 Trigger	Prescale ($8.0 \cdot 10^{29}$)	Individual Rate (Hz) ($8.0 \cdot 10^{29}$)	Prescale ($2.9 \cdot 10^{30}$)	Individual Rate (Hz) ($2.9 \cdot 10^{30}$)
–	L1_ETM20	50	8	250	6
25	L1_ETM20	50	0.6	250	0.5
35	L1_ETM30	1	3	10	1.1
50	L1_ETM40	1	0.8	1	0.4
65	L1_ETM50	1	0	1	0.1
75	L1_ETM50	1	0	1	0.1

Triggers for Calibration: Ecal

Ecal calibration

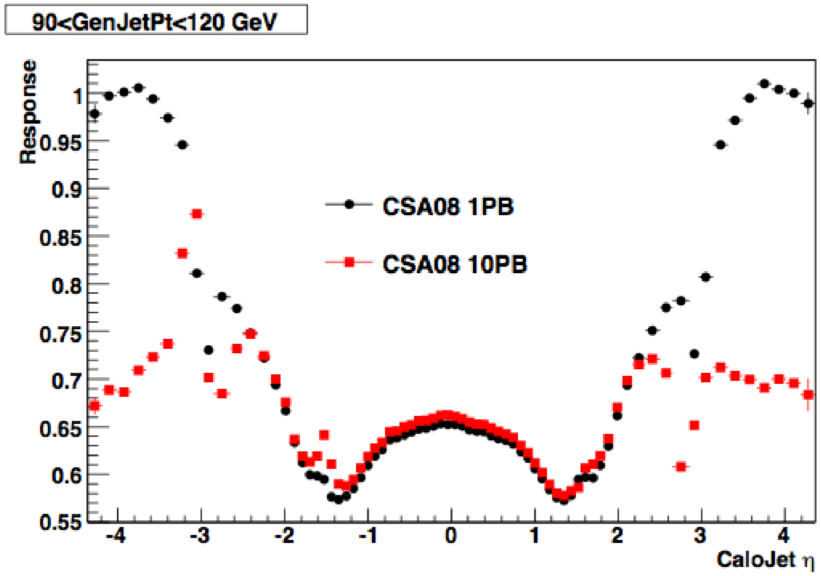
- ϕ-symmetry (1-10 pb^{-1})
  - Intercalibration of crystals at constant η assuming homogeneity of energy
    - L1: Zero-/Minium-Bias, very low threshold of L1 e/γ seeds (single/double > 2/1 GeV)
    - HLT: At least one RecHit with $E_T > 0.15/0.65$ GeV for EB/EE
  - ϕ-Invariance not exact: inhomogenious tracker material (1-2% precision in barrel)
- Z→ee triggers (1-10 pb^{-1}): Region η-rings calibration assuming almost flat distribution and exploiting invariant mass peak (absolute energy scale)
  - Single-/Double-Electron $E_T > 10/15$ GeV
  - Tight selection for brem-free electrons: expected precision is 4% in endcap
- Alternatively using unconverted photons from π^0 (10-100 pb^{-1}): Absolute energy scale by exploiting invariant mass at different point than Z
  - L1: $p_T(e/\gamma) > 5$ GeV
  - HLT: 90 MeV < $M(\gamma\gamma)$ < 160 MeV
  - Precision expected: 1% in barrel



Triggers for Calibration: Hcal

Hcal calibration

- ϕ-symmetry (1-10 pb^{-1}): similar to Ecal – expected precision 3-6%
- Isol. track trigger: Compare track p_T to Hcal energy
  - L1: Jet triggers
  - HLT: p_T(pixel track) > 20 GeV
  - Precision: 2-3%
- Jet energy scale using Di-jet events (10-100 pb^{-1})
  - Di-jet balancing
    - Incl. jets (likely prescaled ↣ DiJetAverage)
    - Uniform response vs. η
  - Cross check with: Z/γ+jet



•Standard HCAL calibration scheme

•After dijet balancing

E/Hcal calibration

- Calibrations need maximal rate (millions of events) to be fast and accurate
- But will exceed bandwith & CPU timing if everything written & reconstructed
  - Writing minimal output stream
  - CPU: Regional unpacking & reconstruction around L1 seed

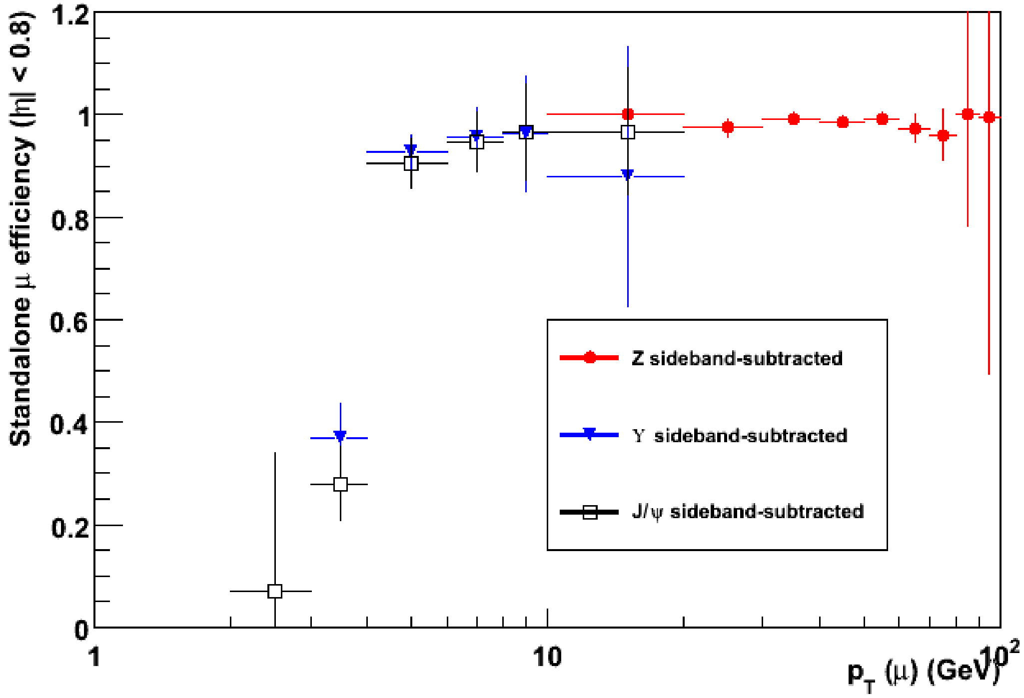
Triggers for Muons

Check Muon algorithms:

- No L1 quality cuts, any hit at 1st muon station, no HLT ➻ test L1 track finders, quality cuts
- L1 threshold 3 GeV (kinematic limit), HLT passthrough ➻ test HLT algorithms
- Release cut on impact parameter ➻ insensitive to pixel mis-alignment & beamspot offset
- Thresholds from 3 GeV in 2 GeV steps: isolated & non-isolated (check isolation effect)

Different double muon triggers to measure efficiency for different SM candles (Z, Y, J/Ψ)

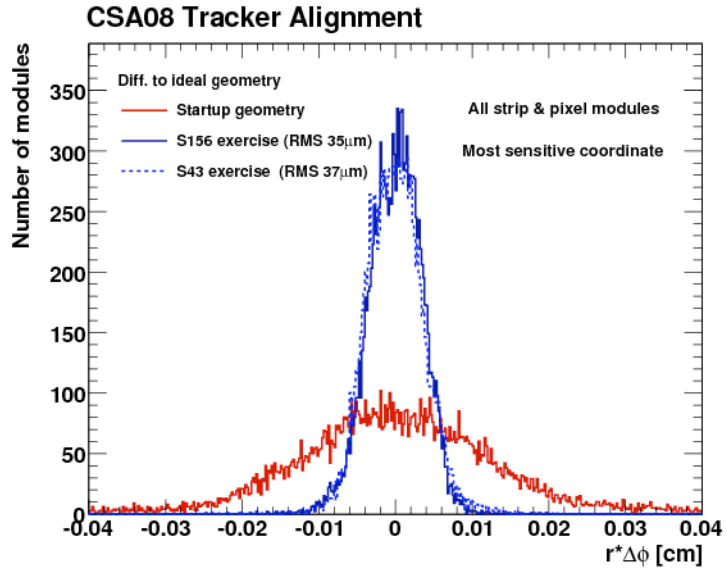
- J/Ψ
  - $p_T > 3$ GeV
  - $2.9 < M(\mu\mu) < 3.3$ GeV
  - Rate (1E32): 2 Hz
- Y
  - $p_T > 3$ GeV
  - $8 < M(\mu\mu) < 12$ GeV
  - Rate (1E32): 2 Hz
- Z
  - $p_T > 7$ GeV
  - $80 < M(\mu\mu) < 100$ GeV
  - Rate (1E32): 0.1 Hz



Triggers for Alignment

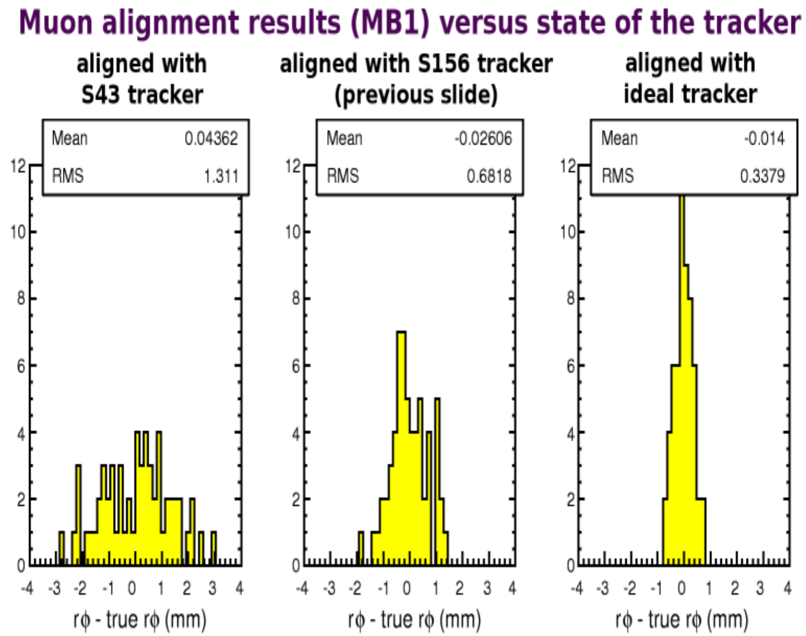
Tracker alignment:

- 1-10 pb^{-1}: High-p_T isolated hadrons pile-up free events through minbias/dijet triggers
- 10 pb^{-1}: Muons from J/Ψ and Y events selected with single muon, J/Ψ, Y triggers. Precision: ~100 μm
- 10-100 pb^{-1}: High-p_T muons from $Z\rightarrow\mu\mu$, $W\rightarrow\mu\nu$ events with low threshold single/double muon triggers. Precision: 0.1-1 μm
  - S43: 1 pb^{-1}
  - S156: 10 pb^{-1}



Muon alignment:

- Clean source of high-p_T muons:
  - Select $W\rightarrow\mu\nu$ and $Z\rightarrow\mu\mu$ events with single isolated muon triggers
  - 10 pb^{-1}: 10^3 μ allow rough alignment: ΔR ~1mm, $\Delta\phi$ ~ 0.3 mrad



Triggers for Electrons & Photons

Check Electron algorithms:

- Lowest threshold trigger starts at 10 GeV in 5 GeV steps
- To study effects due to mis-calibration and mis-alignment at startup
  - Different isolations (track, Hcal): No/Loose/Tight
  - Different pixel matching windows: Large/Startup/Normal
- Can also use offline reconstructed electrons to study and tune isolation & matching windows
- $Z \rightarrow ee$ events to measure trigger effciency

Check Photon algorithms:

- Lowest threshold unprescaled trigger start from 10 GeV
- To study effects due to mis-calibration and mis-alignment at startup
  - Different isolations (track, Ecal, Hcal): No/Loose/Tight
- Study jet energy scale with γ+jets events

HLT Threshold (GeV)	L1 Trigger	Isolation Criteria	Prescale
–	L1_SingleEG5	None	Yes
10	L1_SingleEG5	None	Yes
		Loose	
15	L1_SingleEG10	None	Yes
		Loose	
20	L1_SingleEG12	None	Yes(?)
		Loose	No
		10^{32}	No
25	L1_SingleEG15	None	No
		Loose	
		10^{32}	

Conclusion

- LHC is a challenge for the CMS trigger system
- CMS has implemented a non-standard 2 Level trigger system for data reduction from 40MHz to 100 Hz
  - Level-1: Custom fast processing electronics
  - HLT: Standard CPU filter farm – offline software – high flexibility

- Trigger menus for first data are in place and studied at realistic conditions ($<10^{32}\ cm^{-2}s^{-1}$)
  - Flexible & robust enough to cope with the unexpected
  - At startup focus on comissioning of detector performance, data readout & selection
    - applying dedicated triggers: minbias, calibration, alignment
  - Selection of Standard Model candles for comissioning & early physics
    - Unprescaled low threshold triggers which likely be prescaled for higher luminosity

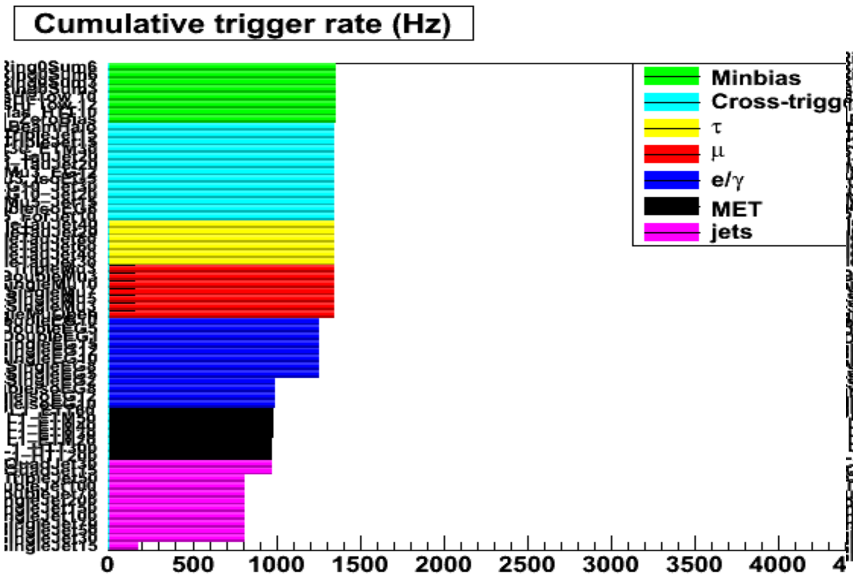
- Same menu will be basis for higher statistics SM measurements at $L \geq 10^{32}\ cm^{-2}s^{-1}$
  - Older studies on efficiencies and rates exist
  - But need to be confirmed by experience with very first data

We are looking forward (and are prepared) to restarting in Spring 2009!

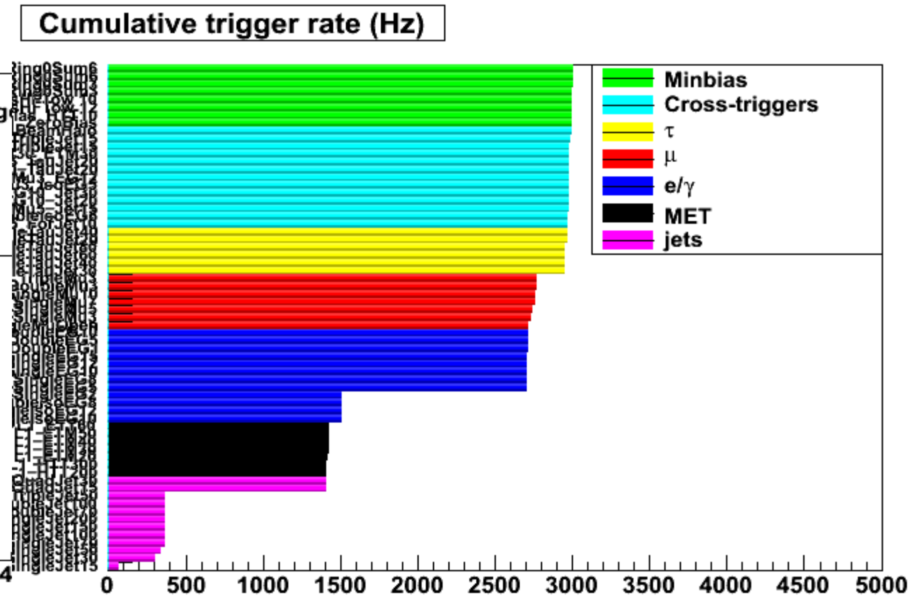
Backup

Expected Rates

- L1:

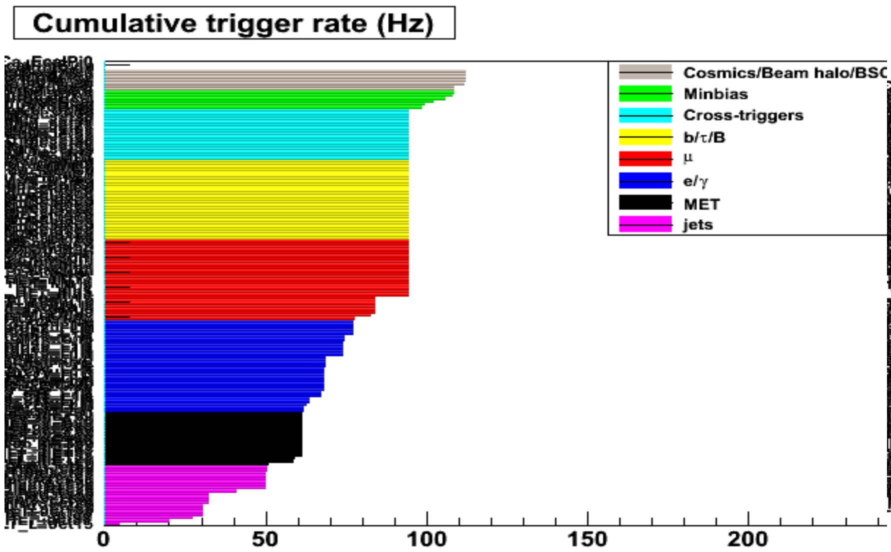


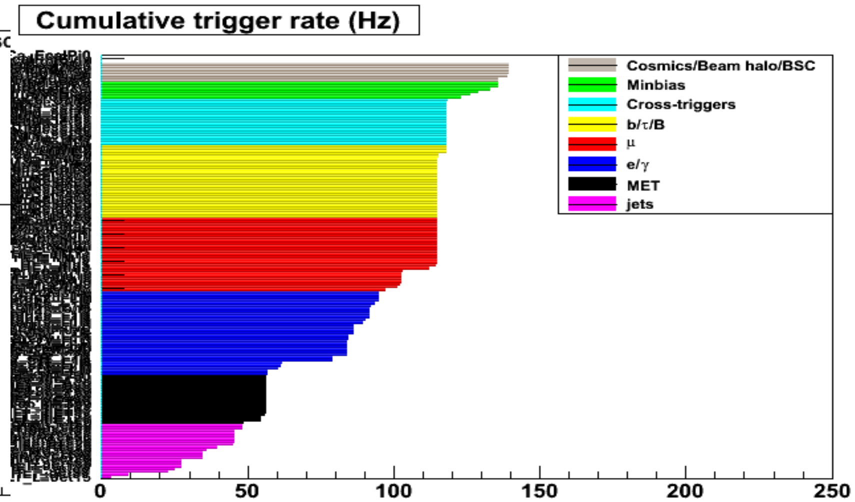
L = 8E29



L = 3E30

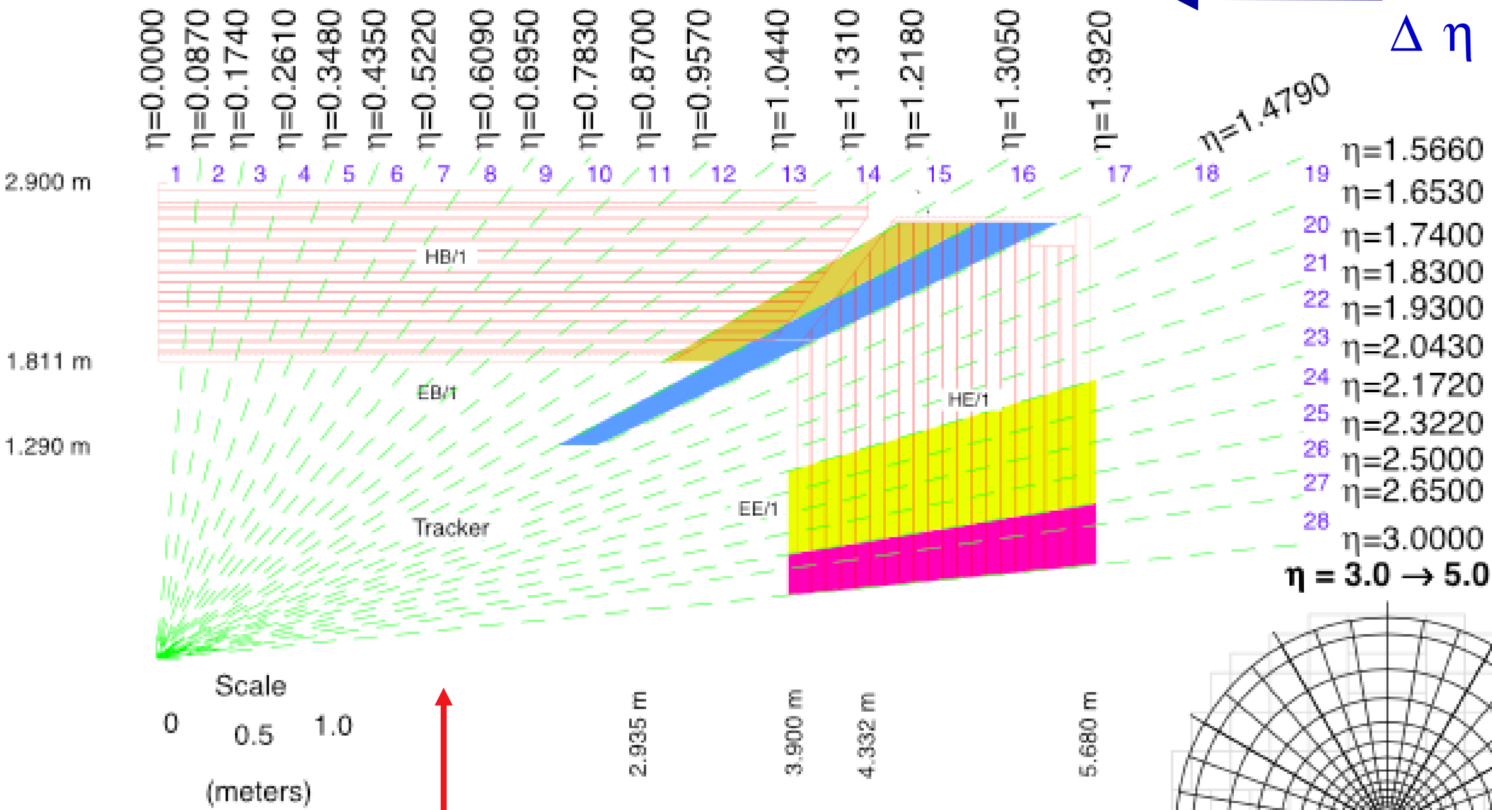
- HLT:



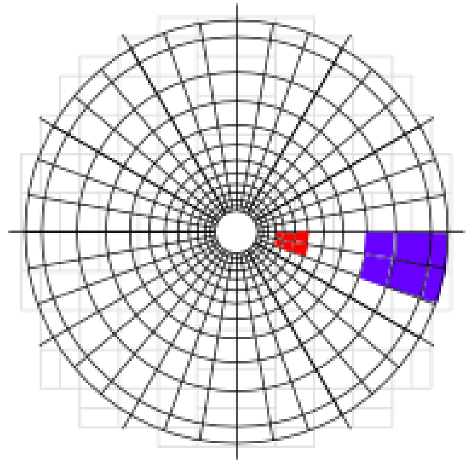


Calorimeter Trigger Geometry

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



η = 3.0 → 5.0 :



2 CMS HF Calorimeters mapping onto Trigger System Jet/Summary Card

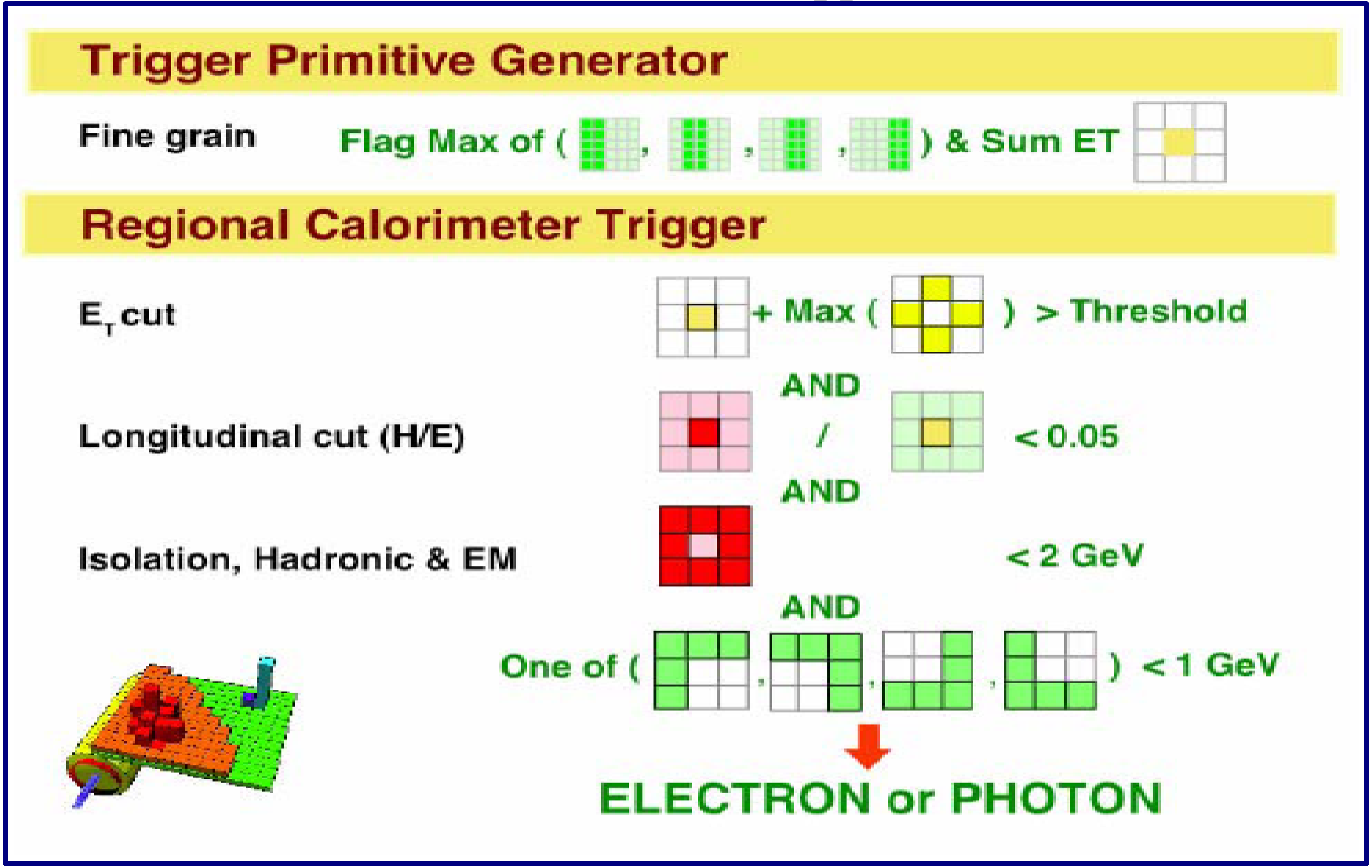
Readout segmentation: 36ϕ × 12η × 2z × 2F/B

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

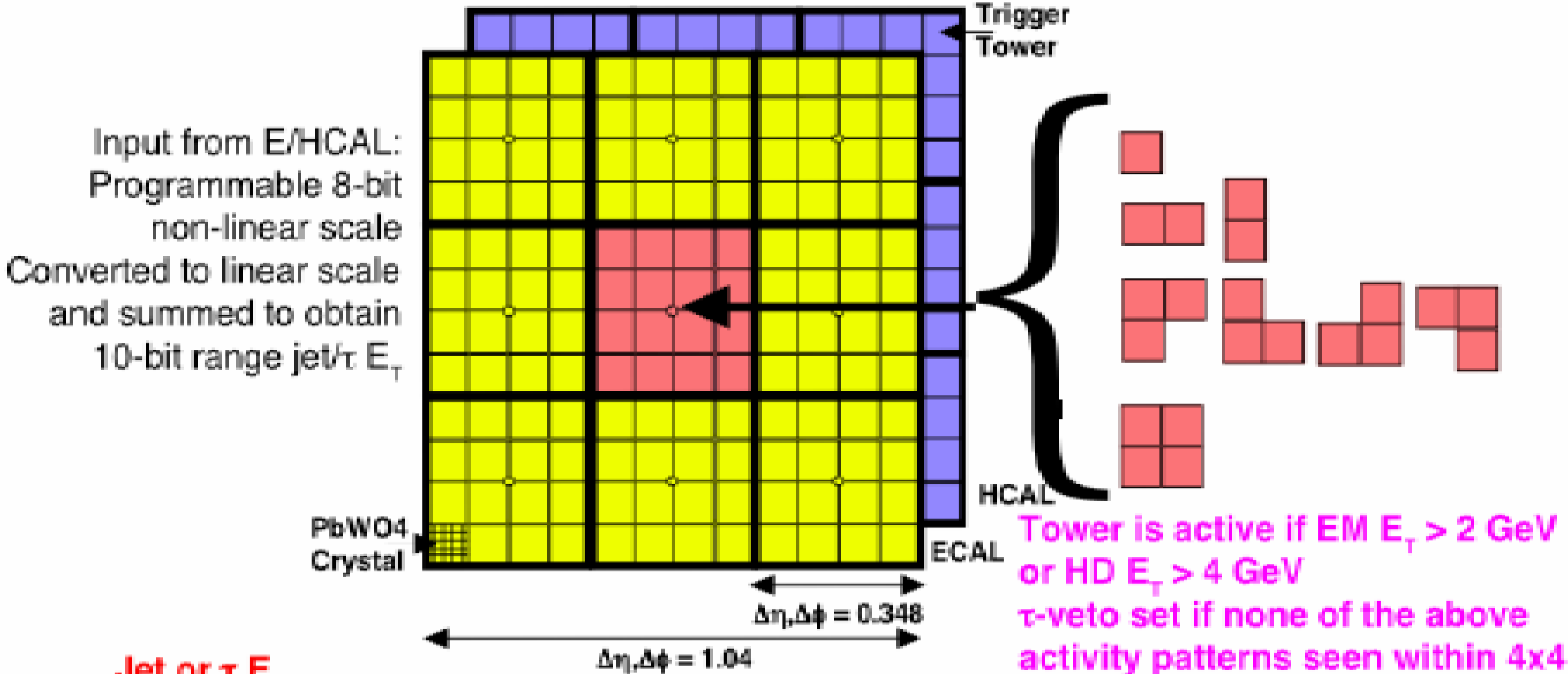
EB, EE, HB, HE map to 18 RCT crates

Provide e/γ and jet, τ , E_T triggers

Level-1 EM Trigger



Level-1 Jet/Tau Trigger



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

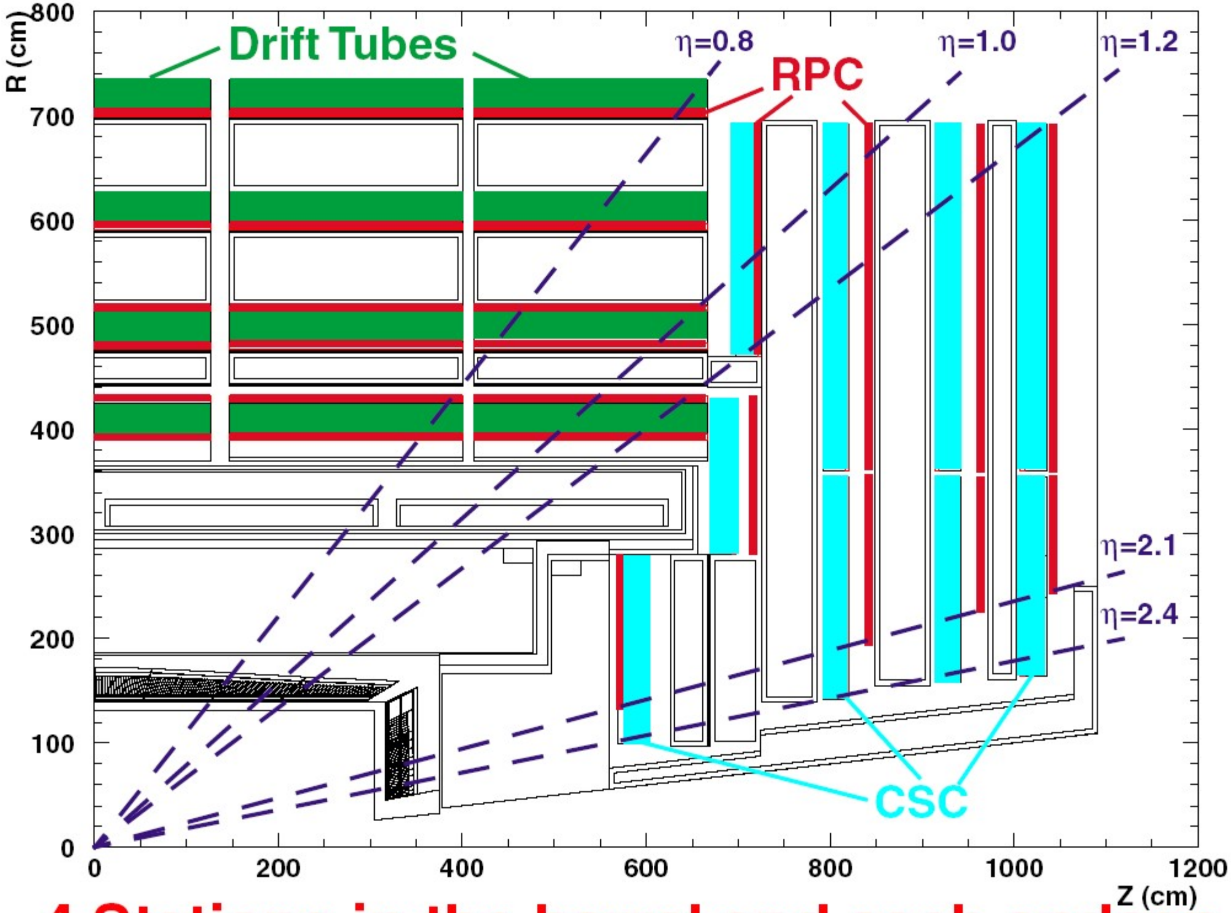
τ algorithm (isolated narrow energy deposits), within $-2.5 < \eta < 2.5$

- 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

Level-1 Muon Trigger Geometry



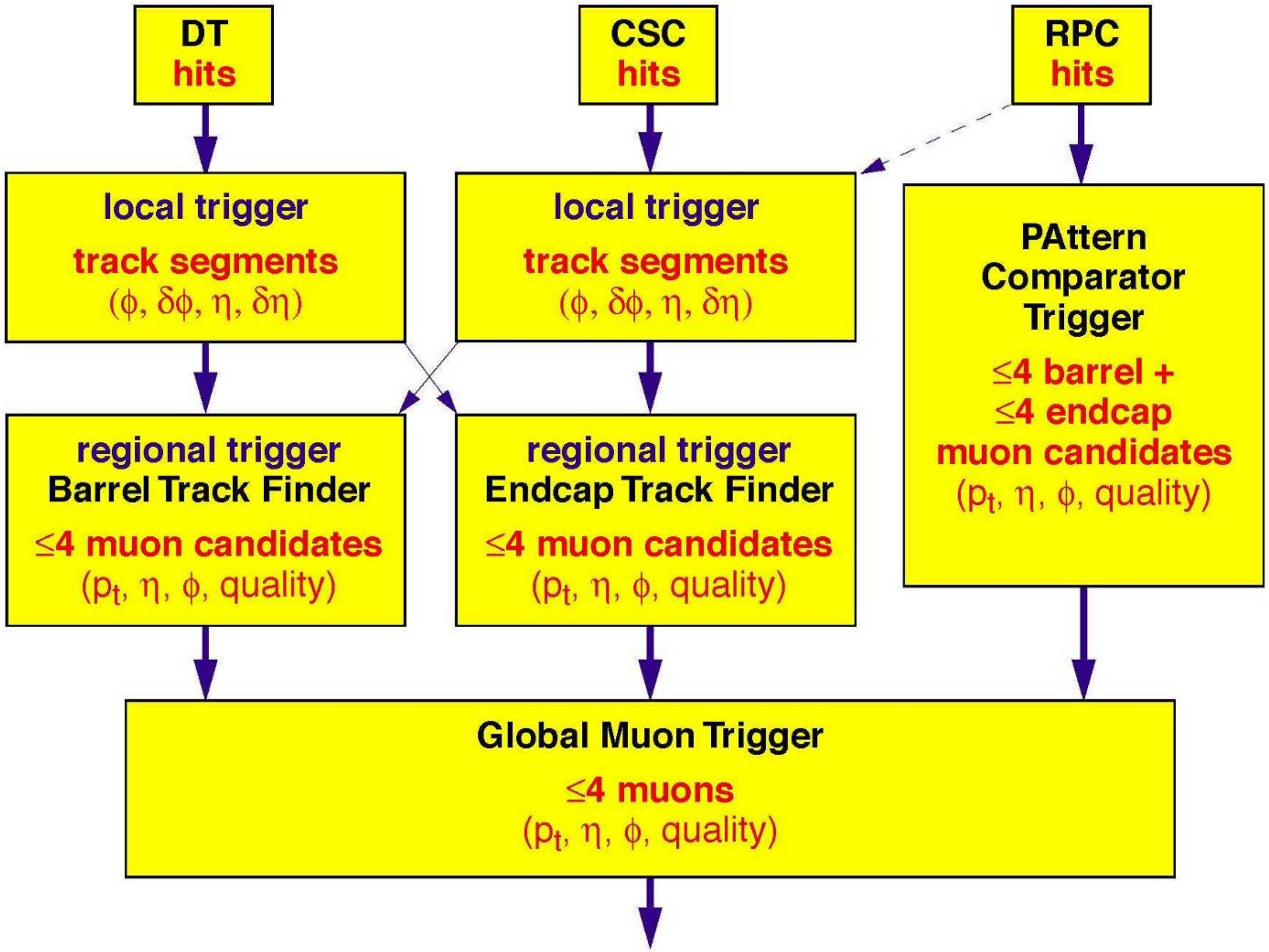
4 Stations in the barrel and each endcap

- RPC: resistive plate chamber system
- CSC: cathode strip chamber system
- DT: drift-tube system

Initial coverage of RPC is staged to $\eta < 1.6$

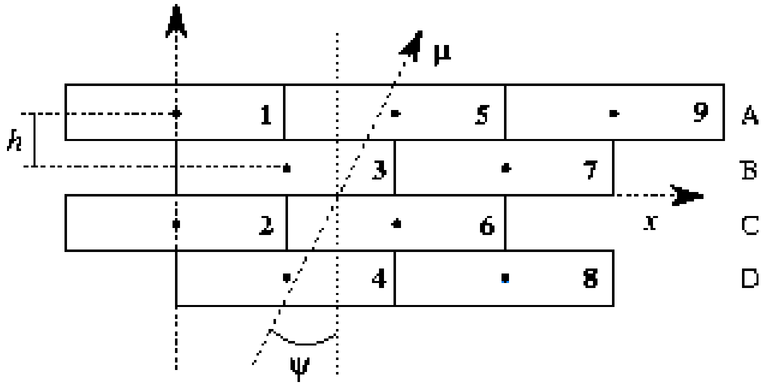
Initial coverage of CSC 1st station is staged to $\eta < 2.1$

Level-1 Muon Trigger Overview

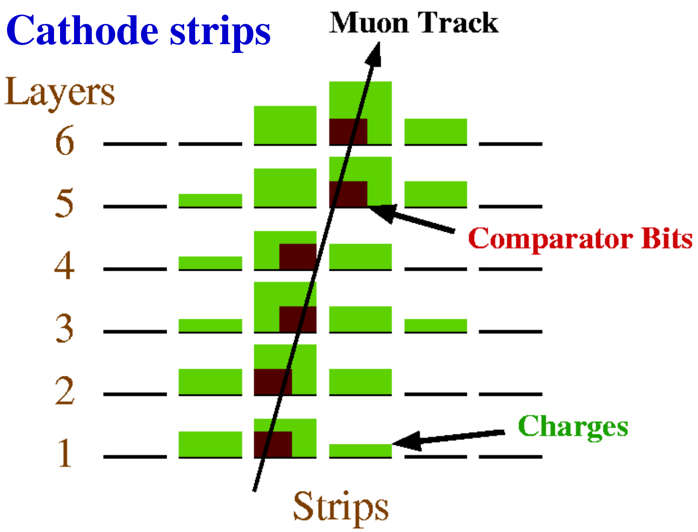


Level-1 Muon Track Finding

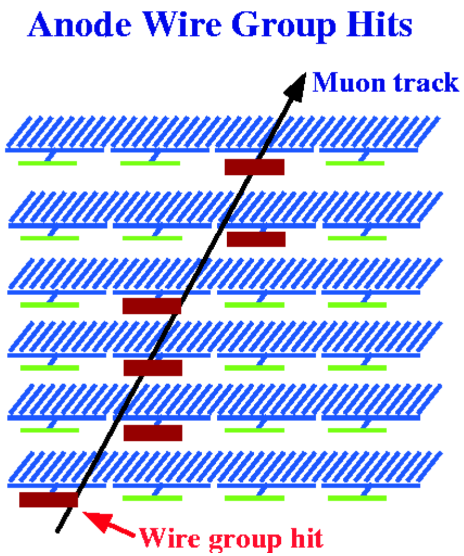
Both are multi-layer detectors



Bunch & Track Identifier (BTI) uses shift registers to search for patterns in drift tubes (ϕ and θ) and to assign correct BX



Local Charged Track (LCT) logic identifies track stubs in CSCs (in ϕ and η) and assigns BX



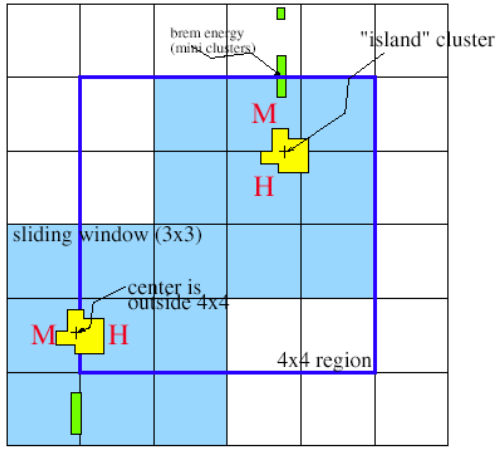
HLT Algorithms

Jets: Iterative cone algorithm (same as offline)

Missing E_T: Vector sum of Tower E_T

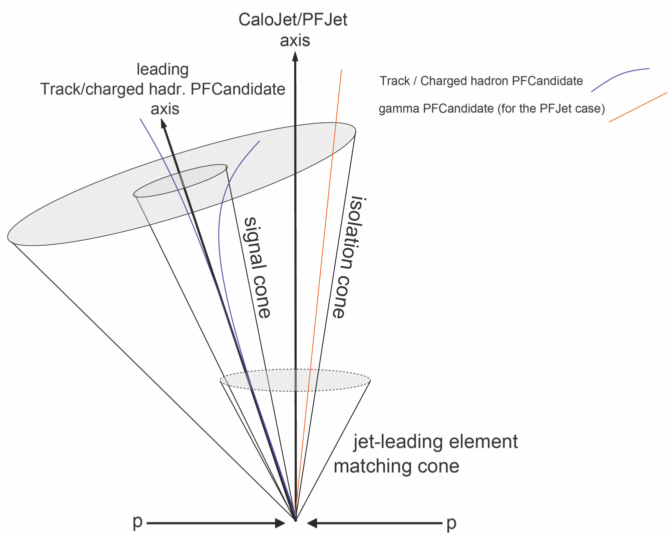
Muons

- L2: Local Kalman Filter from muon system only, seeded by L1, p_T cut, E/Hcal isolation
- L3: Global refit including tracker, p_T cut, track isolation



Electrons/Photons:

- L2: Cluster reconstruction in 4x4 towers, matching with L1 seed, H/E cut, E_T cut, Hcal isolation, Brem recovery
- L2.5: Pixel reco (at least 2 hits) & L1 matching (electron only)
- L3: Loose track reconstruction, E/p cut (electron only), track isolation

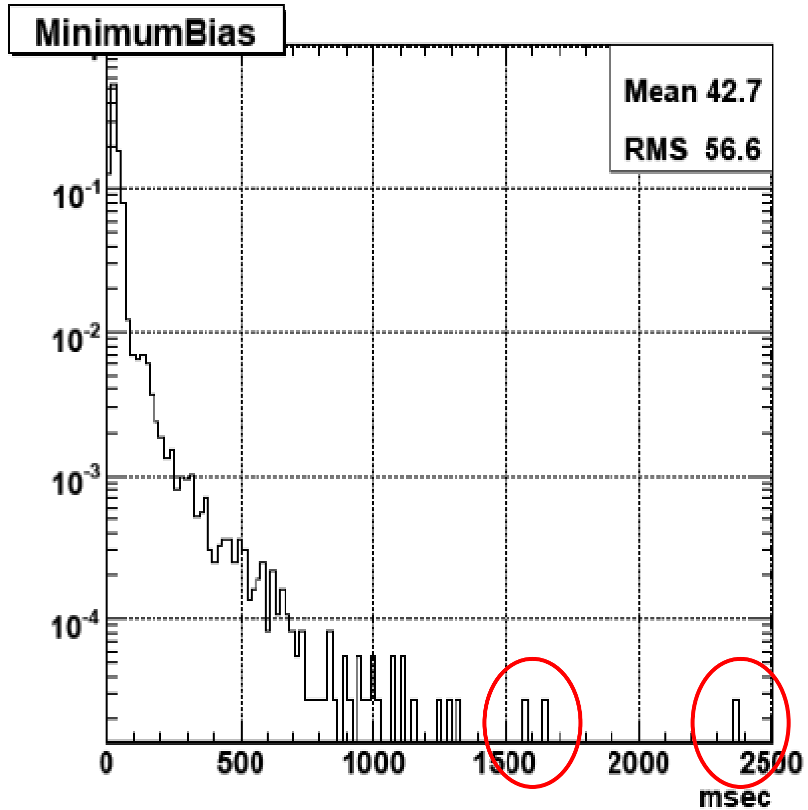


Taus:

- L2: Jet matching, Ecal isolation
- L2.5: Pixel matching, pixel track reconstruction, leading track p_T cut, pixel isolation
- L3: Tracker reconstruction, p_T cut

HLT Processing Timing

- Average time needed to run full Trigger Menu on L1-accepted events: 43 ms/event
  - Core 2 5160 Xeon processor running at 3.0 GHz
- CPU times strongly dependent on HLT input
- "Tails" have a significant impact on the average time
  - Will eliminate with time-out mechanism



HLT Processing Timing cont.

- Calculate ave. processing times for different QCD, W/Z, μ-enriched samples
  - ➢ Weight by combined cross-section and L1 selection efficiency, add them up
- Compared weighted sum with result obtained on L1-accepted min. bias events

Sample	L1 efficiency (%)	L1 eff. $\times \sigma$ (pb)	Average time (ms)
Minimum bias	0.19 ± 0.01	$(1.50 \pm 0.09) \times 10^8$	42.7
QCD $\hat{p_T} \in [0, 15]$ GeV/c	0.08 ± 0.01	$(4.36 \pm 0.49) \times 10^7$	31
QCD $\hat{p_T} \in [15, 20]$ GeV/c	2.08 ± 0.11	$(3.04 \pm 0.17) \times 10^7$	36
QCD $\hat{p_T} \in [20, 30]$ GeV/c	5.75 ± 0.18	$(3.64 \pm 0.11) \times 10^7$	40
QCD $\hat{p_T} \in [30, 50]$ GeV/c	21.70 ± 0.41	$(3.54 \pm 0.07) \times 10^7$	47
QCD $\hat{p_T} \in [50, 80]$ GeV/c	63.36 ± 0.84	$(1.37 \pm 0.02) \times 10^7$	53
QCD $\hat{p_T} \in [80, 120]$ GeV/c	95.96 ± 1.23	$(2.96 \pm 0.04) \times 10^6$	73
QCD $\hat{p_T} \in [120, 170]$ GeV/c	99.87 ± 1.18	$(4.93 \pm 0.06) \times 10^5$	143
QCD $\hat{p_T} \in [170, 230]$ GeV/c	100.00 ± 0.00	$(1.01 \pm 0.00) \times 10^5$	264
QCD $\hat{p_T} \in [230, 300]$ GeV/c	100.00 ± 0.00	$(2.45 \pm 0.00) \times 10^4$	385
$pp \rightarrow \mu X$	42.96 ± 0.37	$(1.03 \pm 0.01) \times 10^7$	74
$W \rightarrow e\nu$	93.18 ± 0.59	$(7.36 \pm 0.05) \times 10^3$	280
$W \rightarrow \mu\nu$	84.67 ± 0.80	$(8.29 \pm 0.08) \times 10^3$	123
$Z \rightarrow ee$	99.54 ± 0.67	$(8.16 \pm 0.05) \times 10^2$	739
$Z \rightarrow \mu\mu$	98.99 ± 1.20	$(7.82 \pm 0.09) \times 10^2$	184
Weighted sum of QCD, W, Z and $pp \rightarrow \mu X$ contributions			42.9 ± 5.6

Table 8.4 Average processing wall-clock times for running the High-Level Trigger Menu at $\mathcal{L} = 10^{32}$ cm^{-2} s^{-1} on Level-1-accepted events at an idle Core 2 5160 Xeon 3.0 GHz machine.