CMS101

Introduction to the CMS Trigger

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CMS Trigger & Data Acquisition

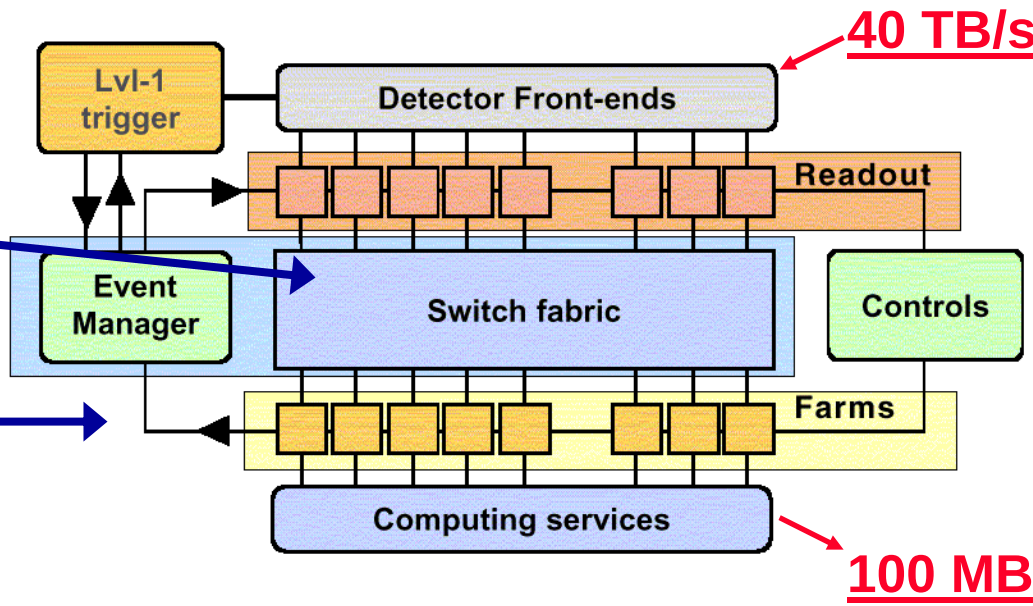
LHC beam crossing rate is 40 MHz ⇒ 1 GHz collisions

CMS has a multi-tiered system to handle this:

- ➔ **Level-1 trigger reduces rate from 40 MHz to 100 kHz (max)**
  - **Custom electronic boards and ASICs process calorimeter and muon data to select *objects***
- ➔ **High-Level triggers reduce rate from 100 kHz to O(100 Hz)**
  - **Filter farm runs online programs to select *physics channels***
  - **No custom Level-2 hardware**

Large switching network (~Tbit/s)

O(1000) node PC cluster



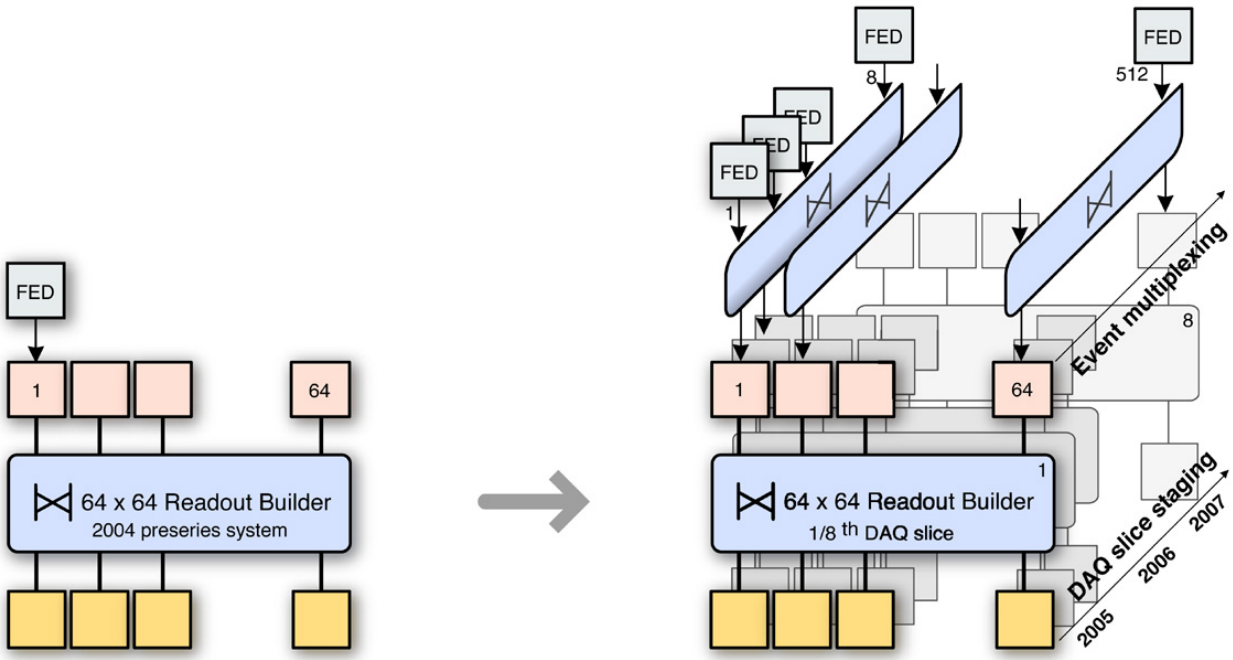
Trigger/DAQ Evolution

CMS DAQ is a number of functionally identical, parallel, small DAQ systems

- ➔ **Build up 512×512 switch from 8 64×64 switches (1/8th DAQ slice)**

Turn-on in 2007 expected to have 4 such slices (US contributes 1), yielding 50 kHz maximum L1A input rate to HLT

- ➔ **L1 fully scoped to deliver up to 100 kHz rate, and front-ends able to absorb 100 kHz rate**



The CMS Level-1 Trigger

Reduces data rate from 40 MHz to 100 kHz

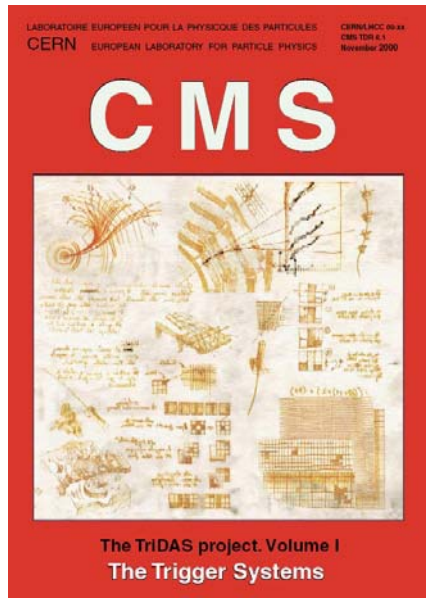
- ➔ Suppress background 400X while keeping high P_T physics
- ➔ Requires custom electronic hardware, some of which must be radiation hard

Only the muon and calorimeter systems participate

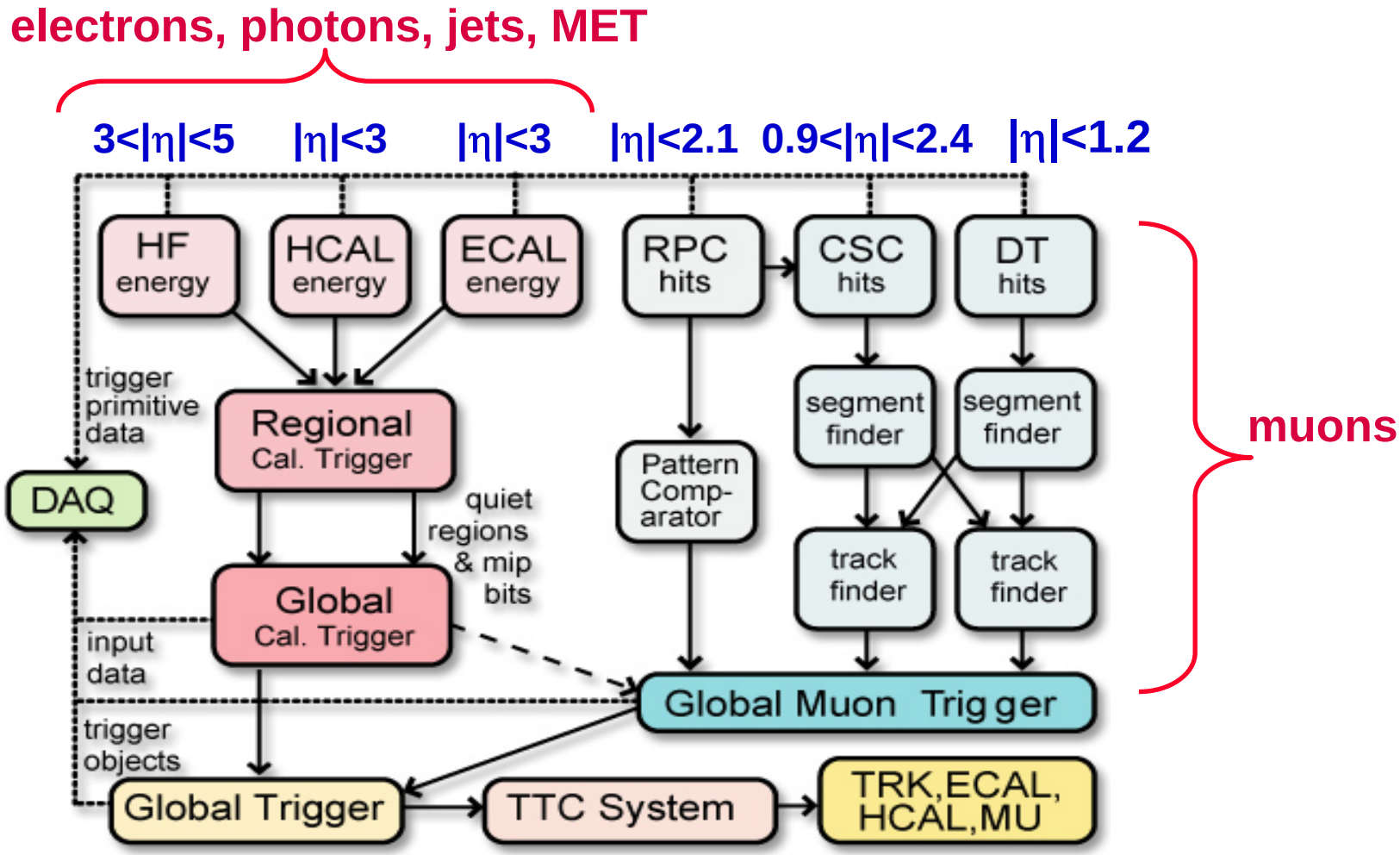
- ➔ Select muons, electrons, photons, jets, and MET
- ➔ Silicon tracker data is unavailable until the High-Level Trigger
  - Significant handicap compared to the Tevatron expts.

Hardware and simulation results described in Level-1 Technical Design Report:

- ➔ CERN/LHCC 2000-038
- ➔ Simulations based on GEANT and trigger emulation code

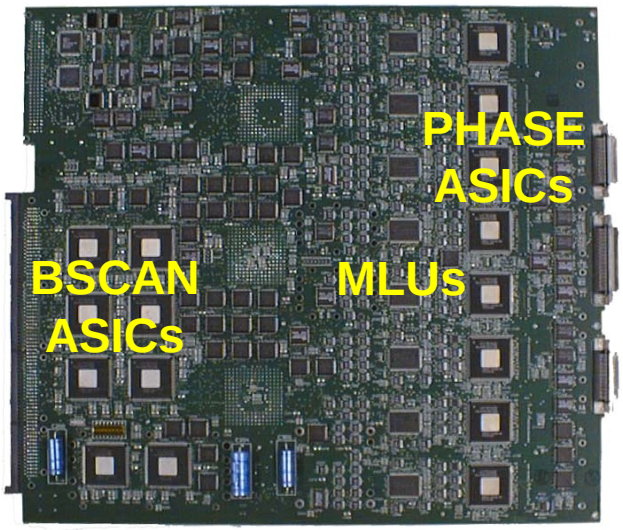


Level-1 Trigger Scheme

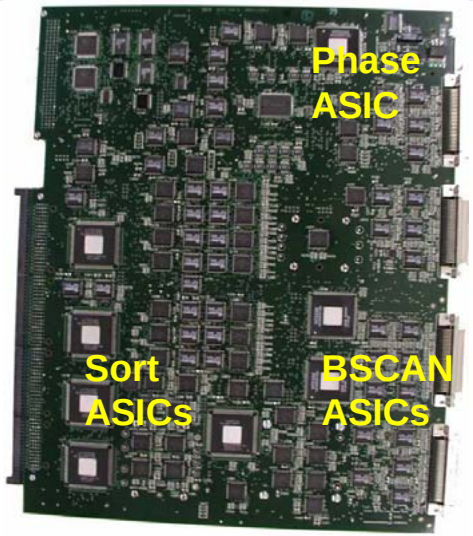


- ➔ **Algorithms are pipelined at 40 MHz for deadtime-free operation**
- ➔ **Total decision latency: 3.2 μs**

Level-1 Trigger Hardware (U.S.)

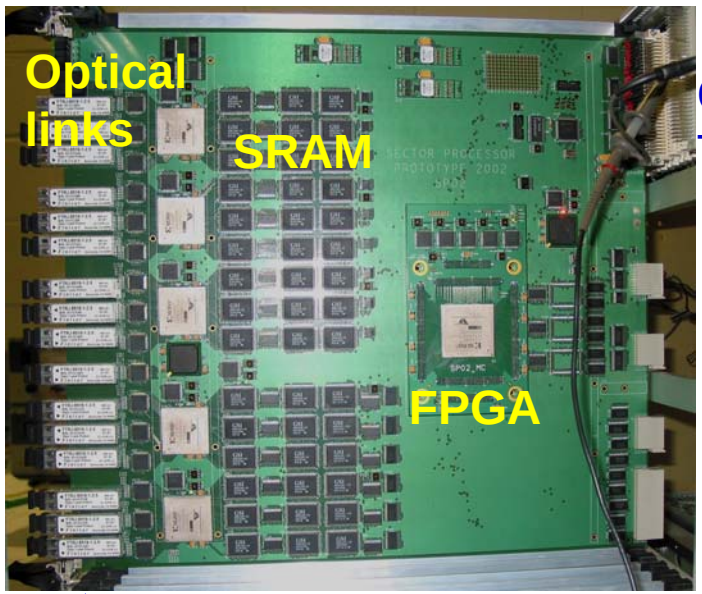


RCT Receiver card



RCT Jet/Summary card

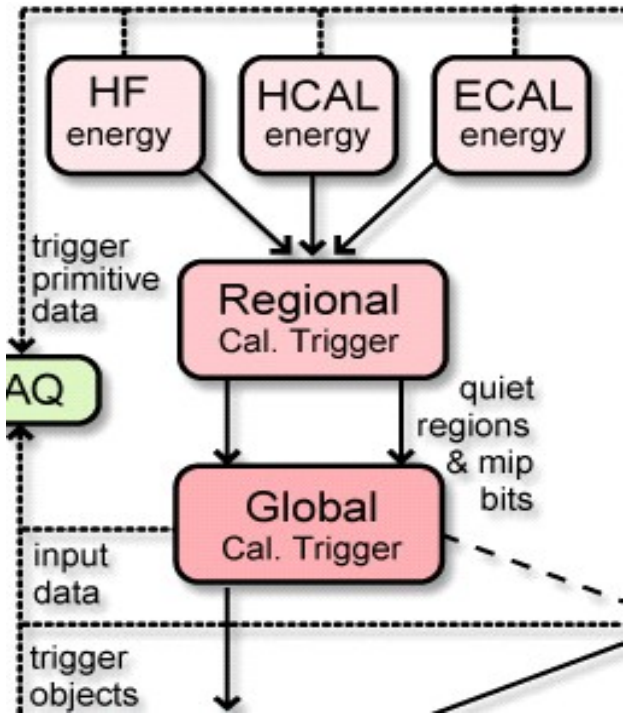
RCT Electron isolation card



CSC
Track-Finder

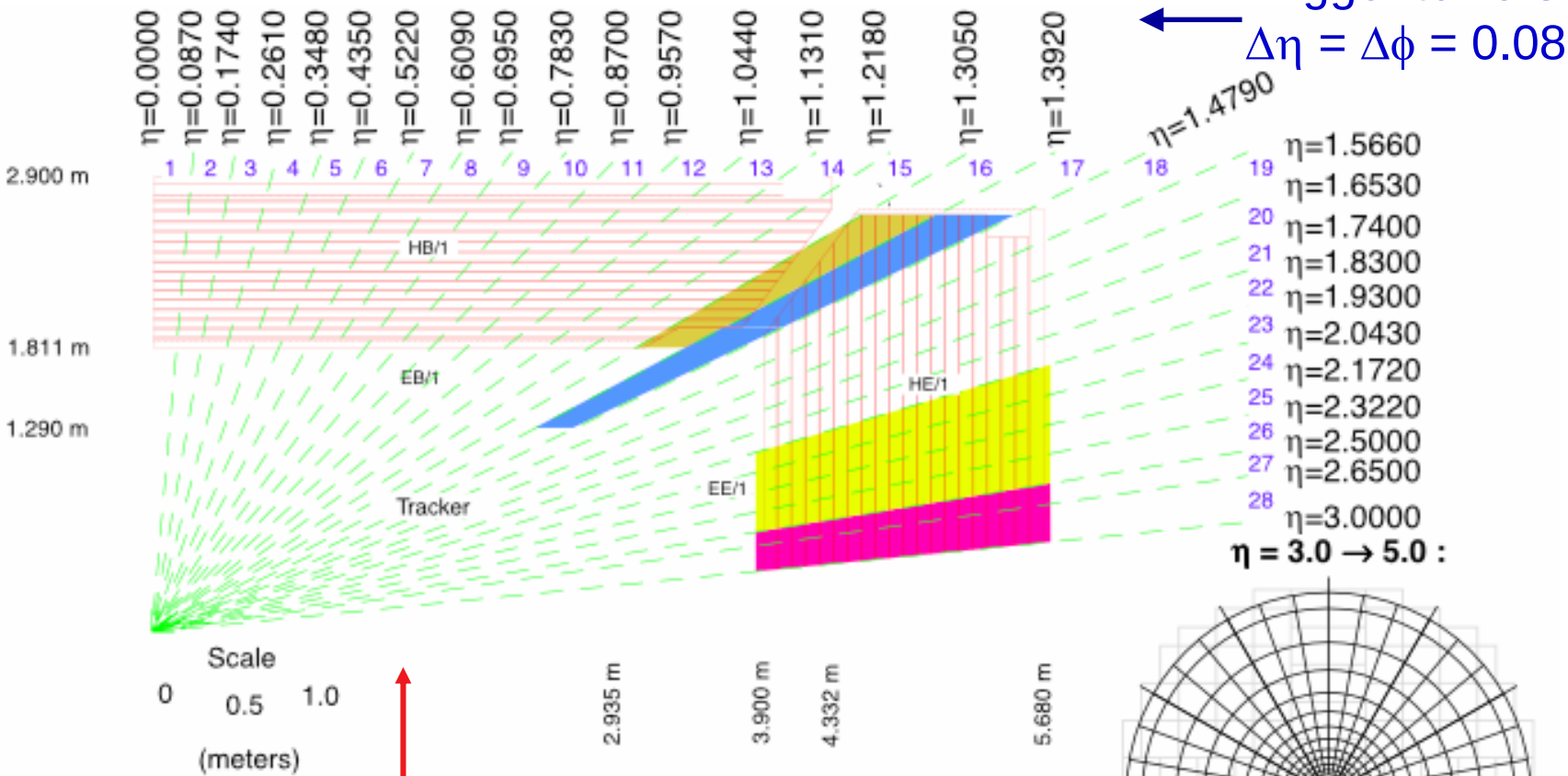
- **Custom ASICs**
- **Large FPGAs**
- **SRAM**
- **Gbit/s Optical links**
- **Dense boards**

Level-1 Calorimeter Trigger Scheme



Calorimeter Trigger Geometry

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



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

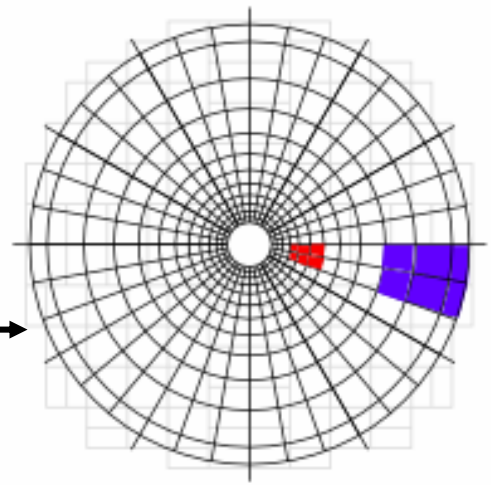
Provide e/γ and jet, τ, E_T triggers

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

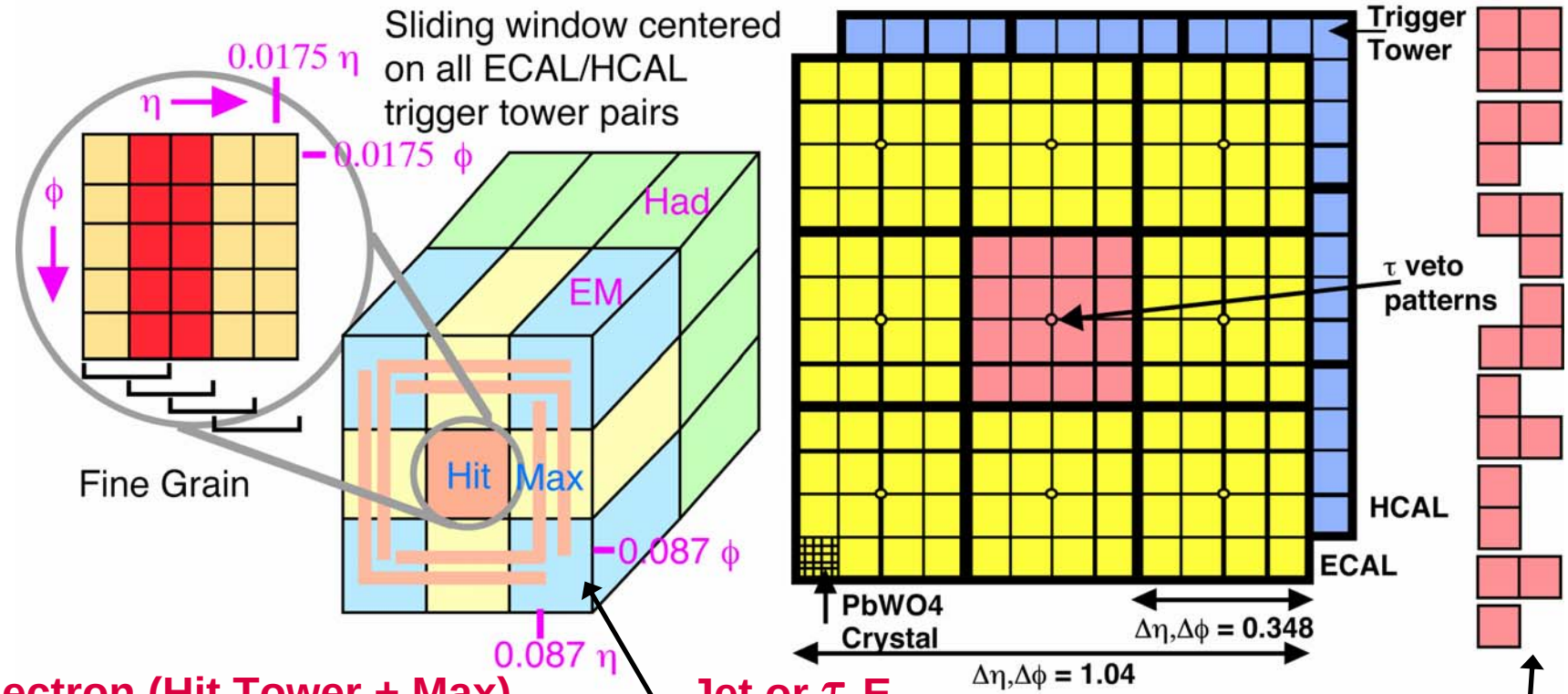
Readout segmentation: 36ϕ × 12η × 2z × 2F/B

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

η = 3.0 → 5.0 :



Level-1 Calorimeter Trigger Algorithms



Electron (Hit Tower + Max)

- ➔ 2-tower ΣE_T + Hit tower *H/E*
- ➔ Hit tower 2x5-crystal strips >90% of E_T in 5x5 (Fine Grain)

Isolated Electron (3x3 Tower)

- ➔ Quiet neighbors: all towers pass Fine Grain & *H/E*
- ➔ One group of 5 EM E_T < Thr.

Jet or τ E_T

- ➔ 12x12 trig. tower ΣE_T sliding in 4x4 steps w/central 4x4 E_T > others

τ: isolated narrow energy deposits

- ➔ Energy spread outside τ veto pattern sets veto
- ➔ Jet ≡ τ if all 9 4x4 region τ vetoes off

Level-1 Global Calorimeter Trigger

Implements sliding window jet cluster algorithm

Sorts electron and jet objects

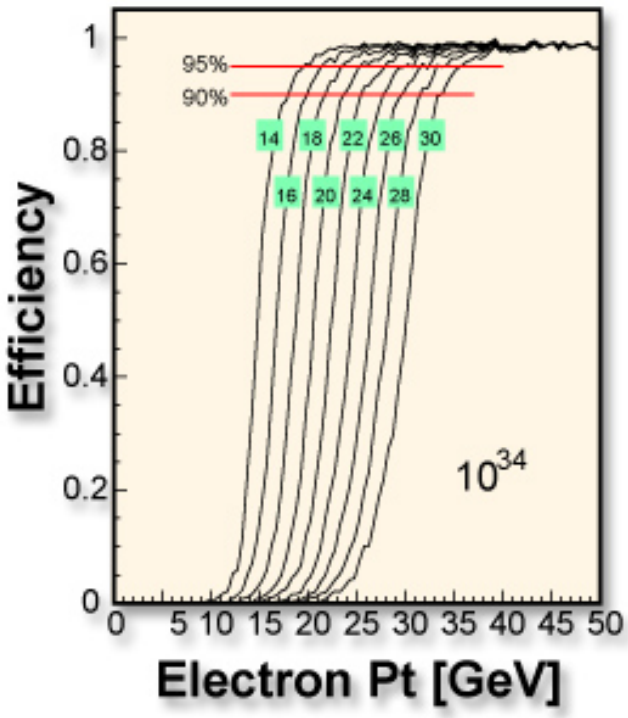
Computes energy and missing E_T sums

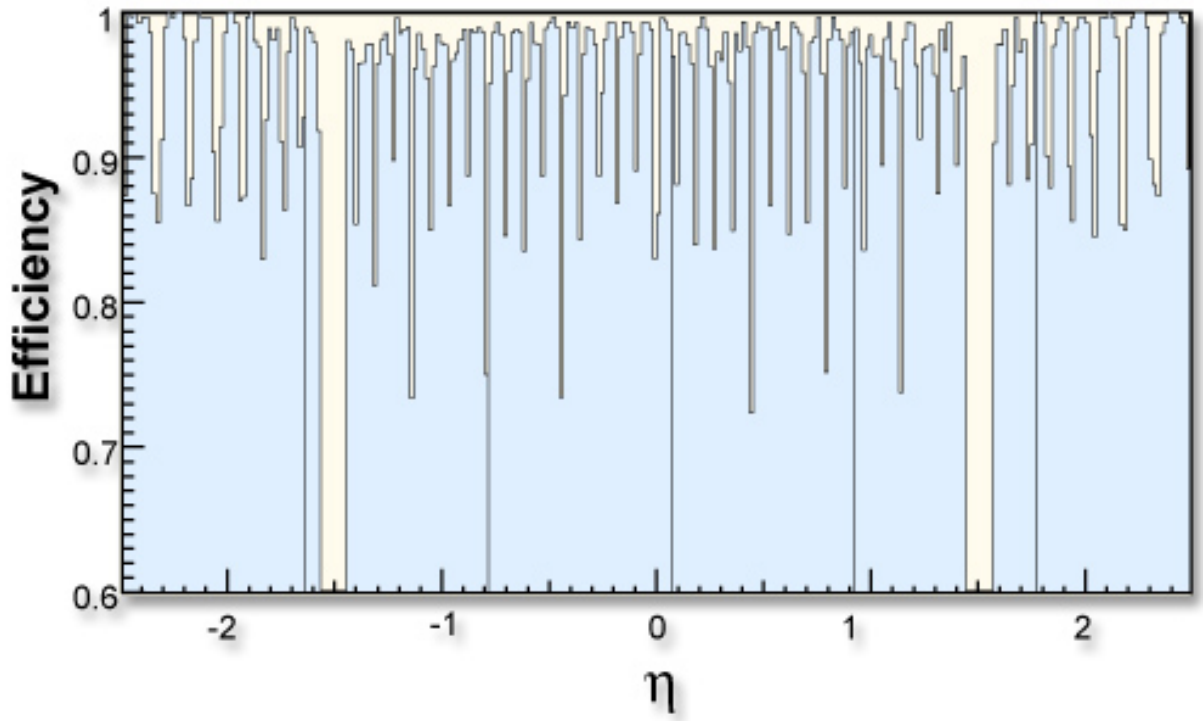
Output to Global Trigger:

- **4 non-isolated e/γ**
- **4 isolated e/γ**
- **4 central jets**
- **4 forward jets**
- **4 τ objects**
- **Total E_T**
- **MET**
- **MET ϕ angle**

Electron/photon Level-1 Efficiencies

Response to electrons

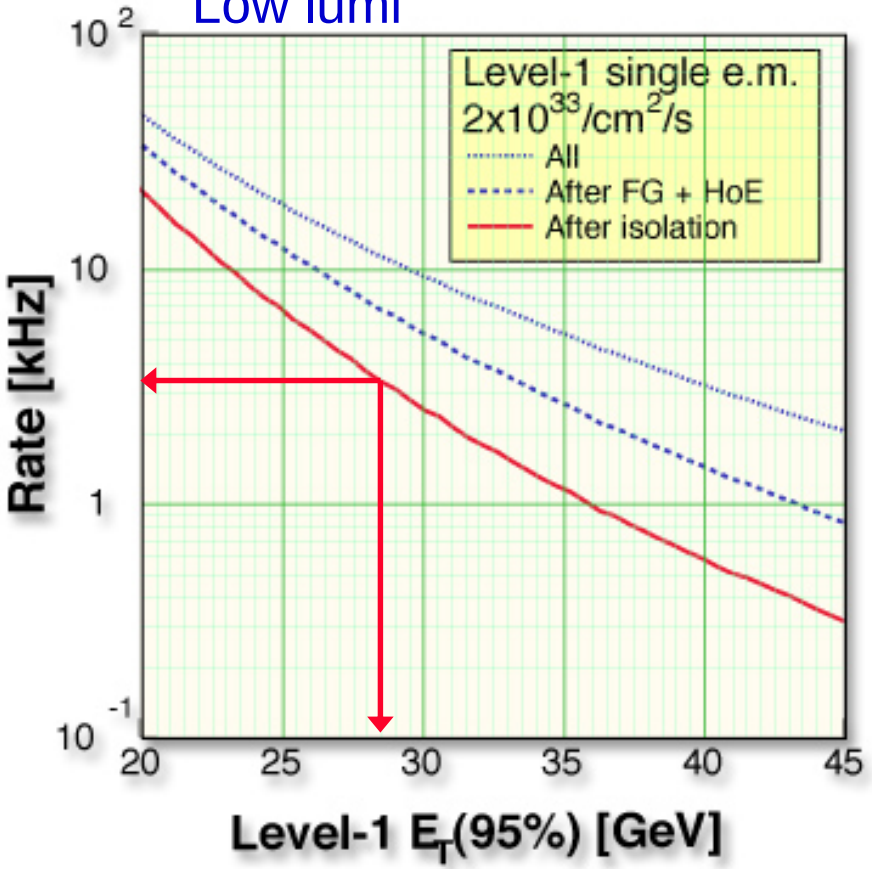




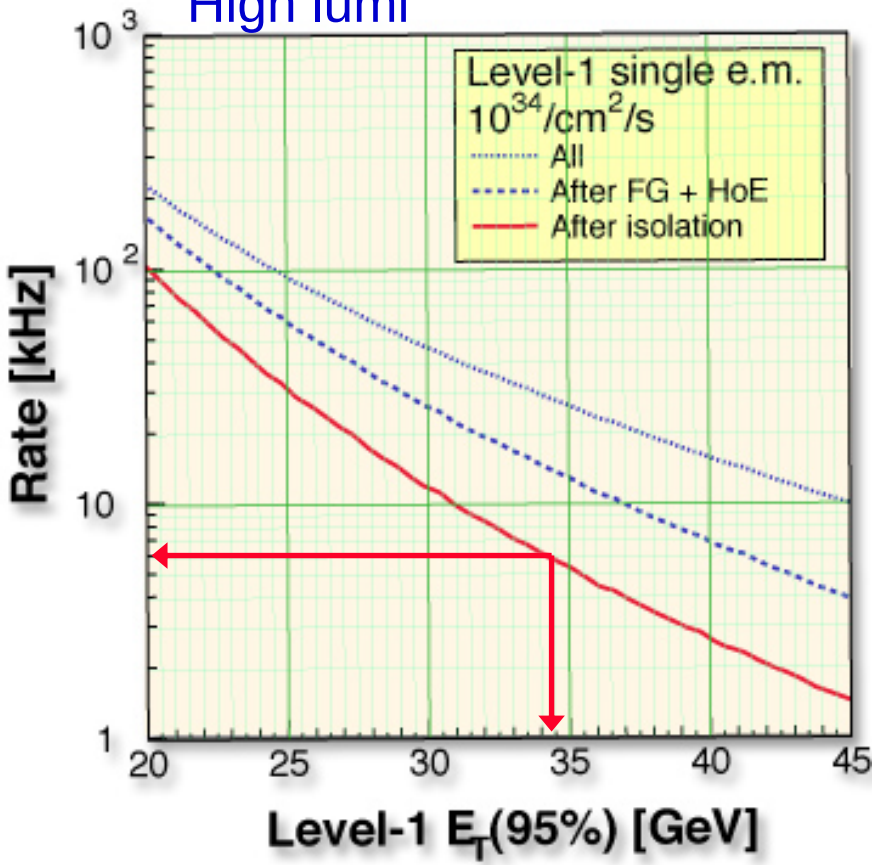
Single Electron/photon Level-1 Rates

Rate from jet background

Low lumi

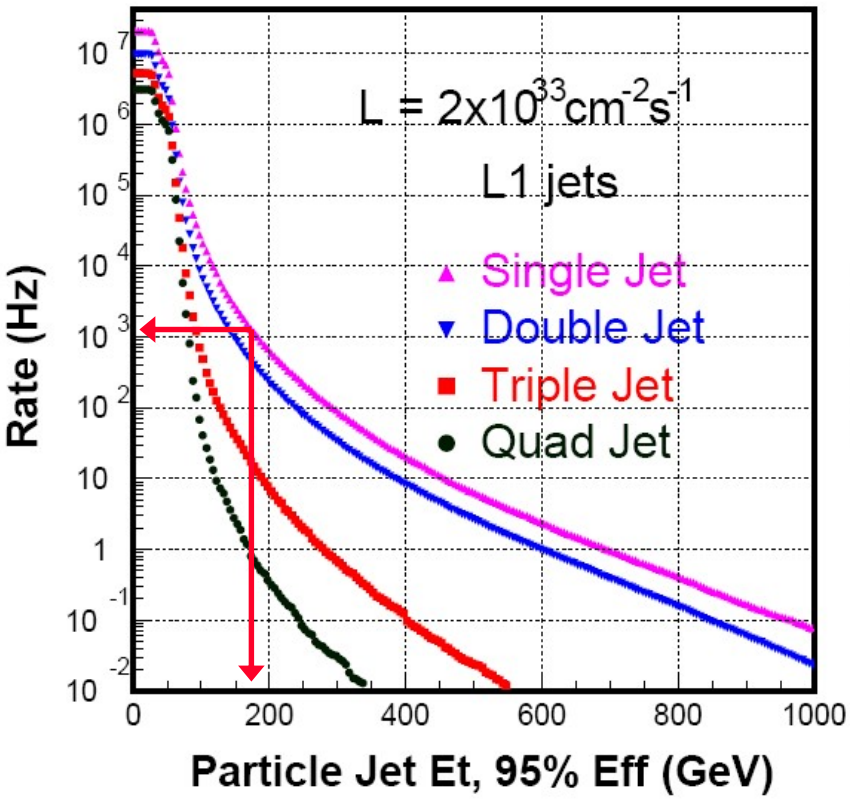


High lumi

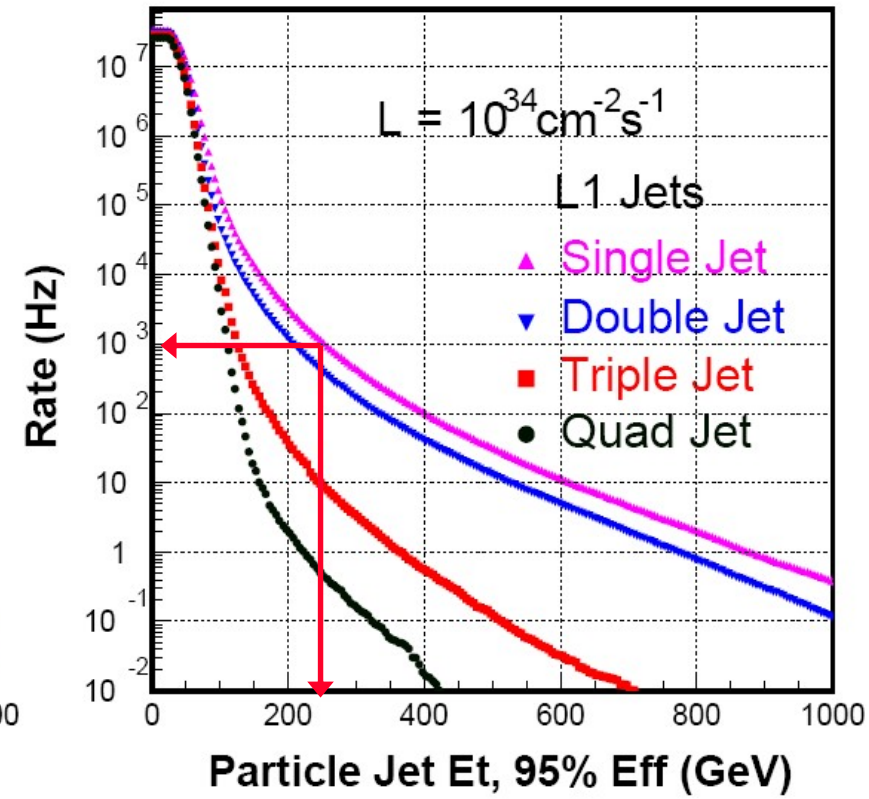


Level-1 Jet Trigger Rate

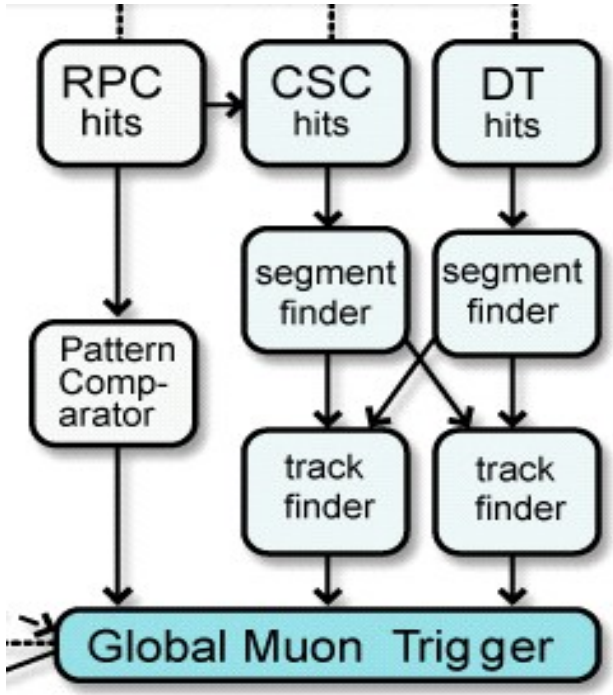
Low lumi



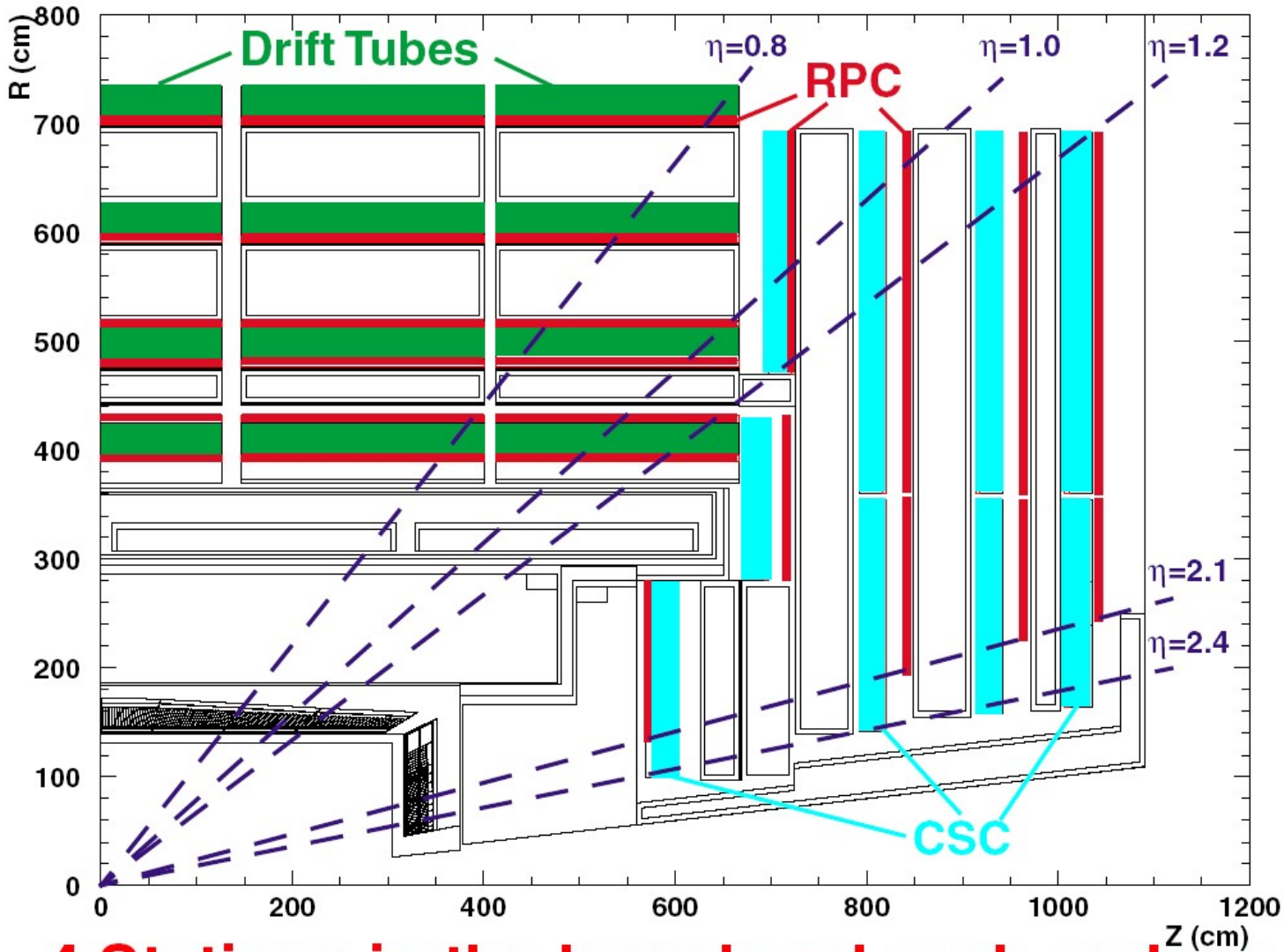
High lumi



Level-1 Muon Trigger Scheme



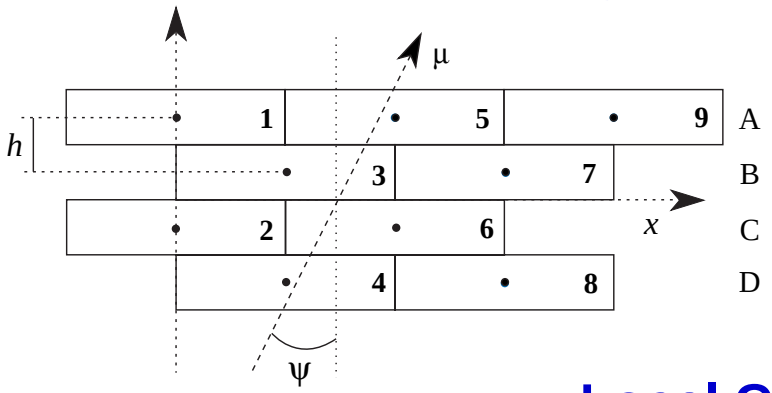
Muon Trigger Geometry



4 Stations in the barrel and each endcap

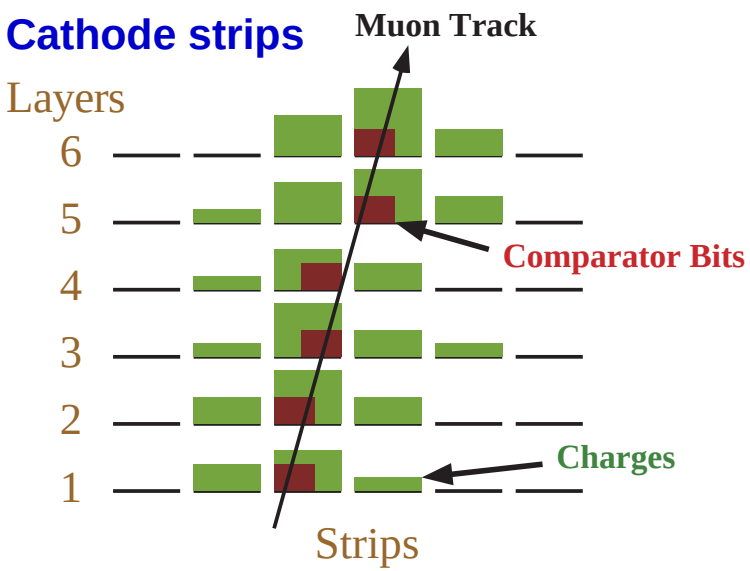
DT and CSC Local Triggers

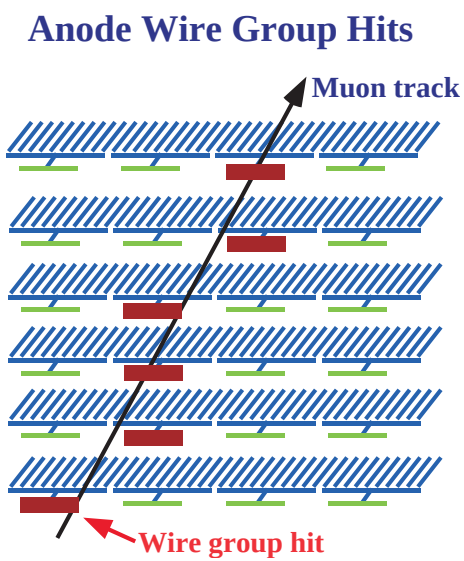
Both are multi-layer detectors



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

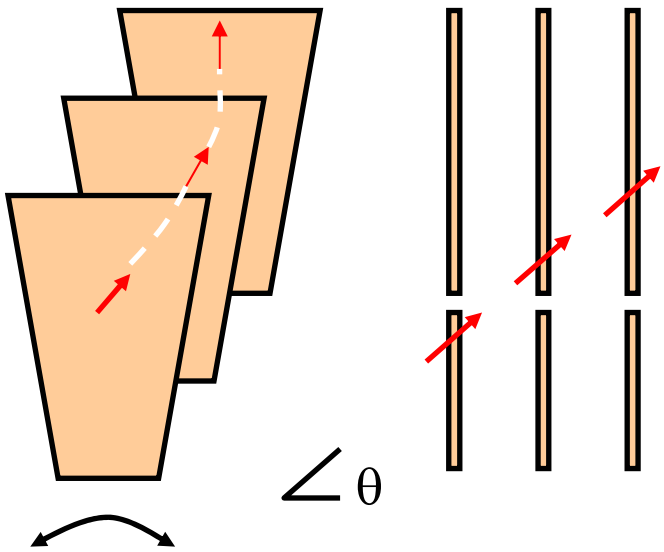
Local Charged Track (LCT) logic identifies track stubs in CSCs (in ϕ and η)



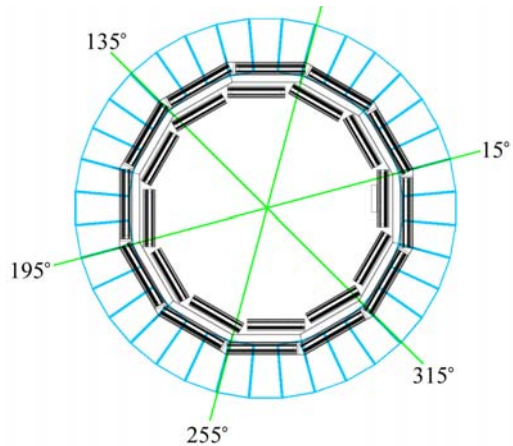


Track-Finding

- DT and CSC Track-Finders link local track segments into distinct tracks
  - 2-D tracks for DT, 3-D tracks for CSC
- RPC Pattern Comparator Trigger applies coincidence logic along roads in η and ϕ with $\Delta\eta \times \Delta\phi = 0.1 \times 0.005$
- Standalone momentum measurement using B-field in yoke
  - Require < 25% P_T resolution for sufficient rate reduction
- Highest quality candidates sent to Global Muon Trigger



- CSC and DT sectors align for overlap region



Global Muon Trigger

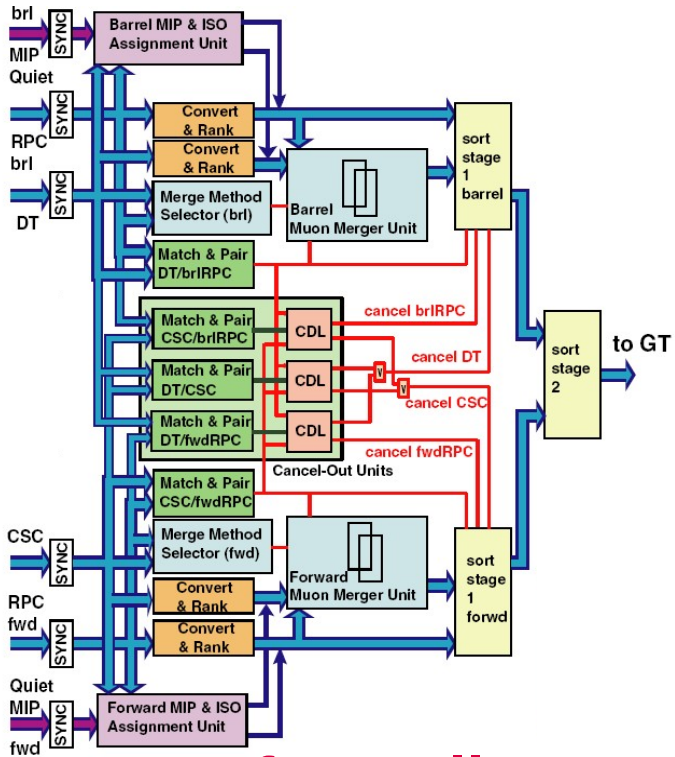
252 MIP bits
252 Quiet bits

4 μ RPC brl

4 μ DT

4 μ CSC

4 μ RPC fwd

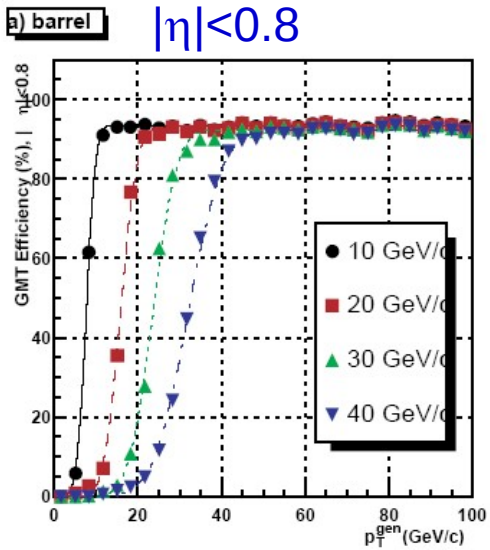


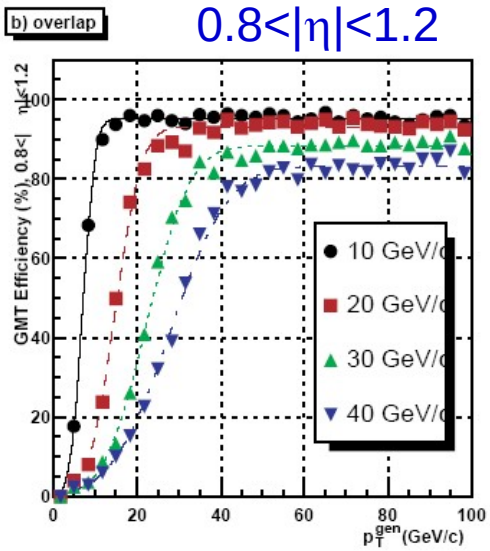
Best 4 μ

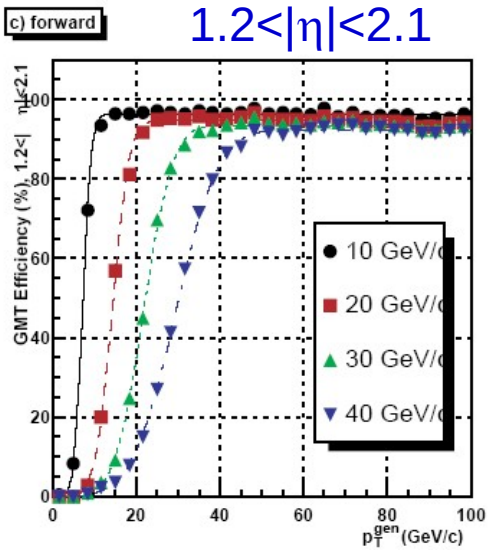
Combines/matches muons from all 3 systems:

- ➔ Maximize efficiency
- ➔ Minimize rate
- ➔ Cancel duplicates
- ➔ Apply calorimeter isolation or MIP
- ➔ Programmable P_T thresholds from 1 to 140 GeV/c

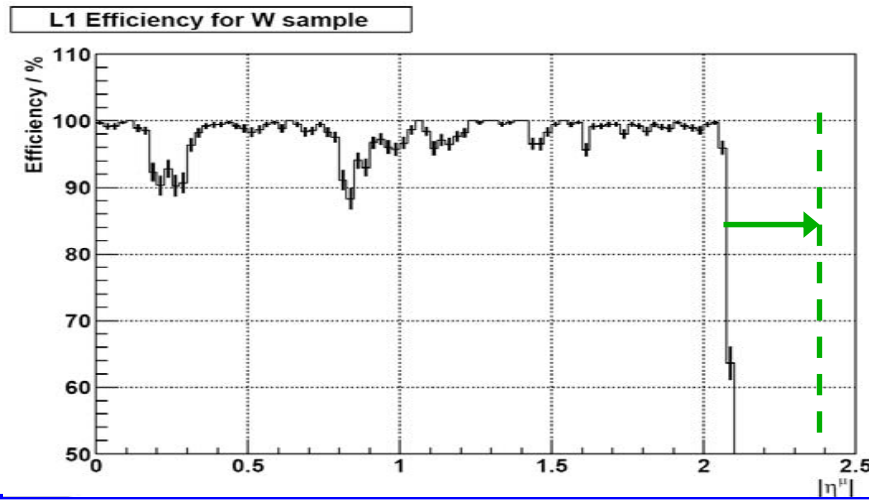
Level-1 Muon Efficiency







P_T



η

Di-muon trigger coverage extends to |η|<2.4

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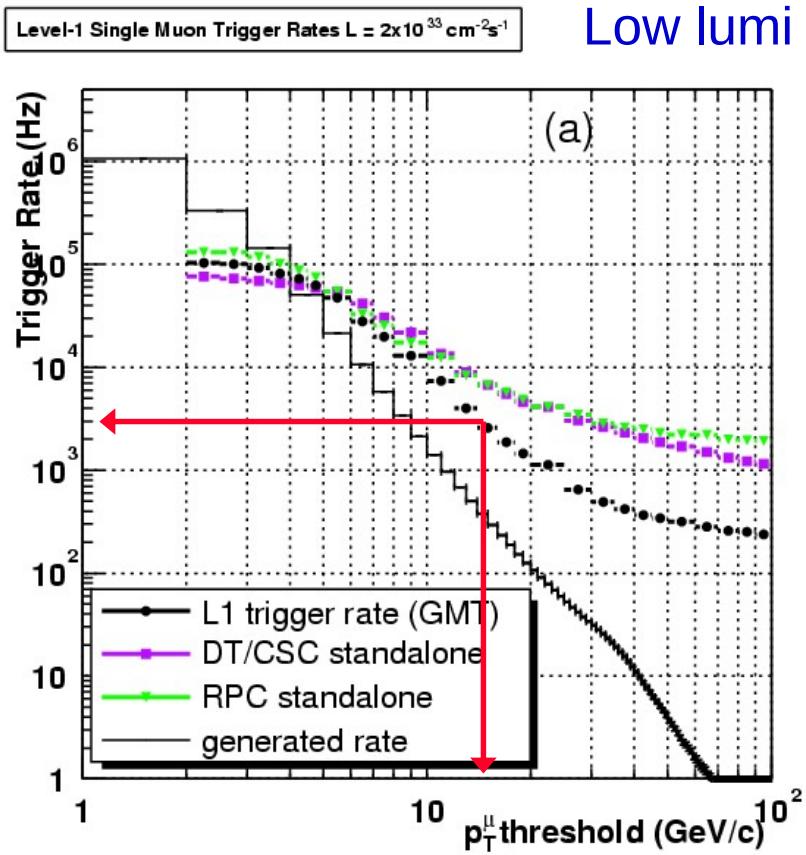
Single Muon Level-1 Rate

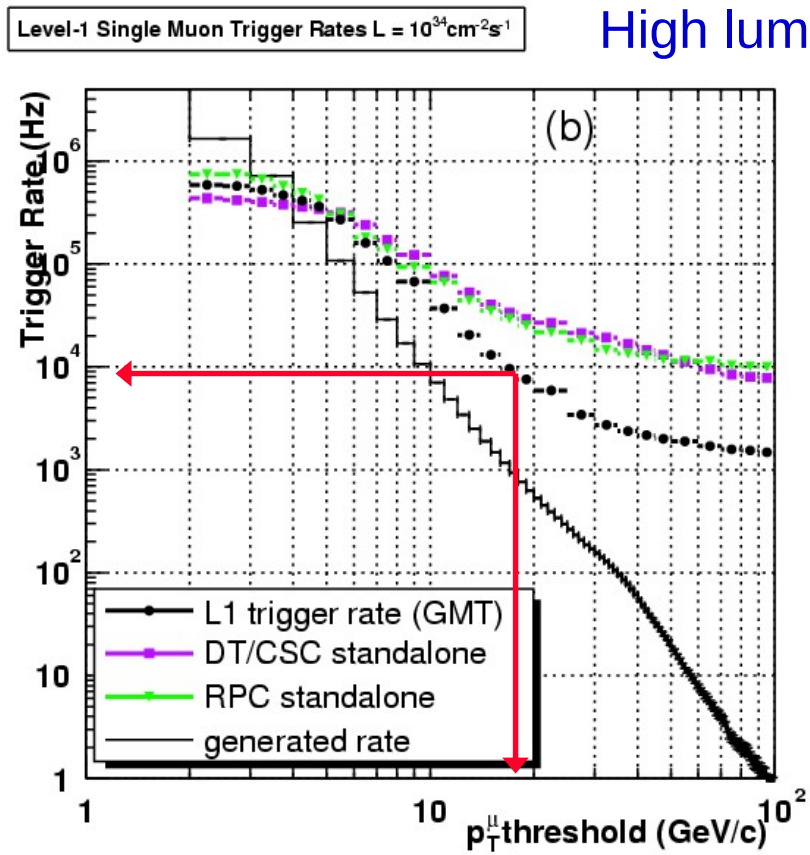
Rate comes from real muons!

Limited P_T resolution flattens rate curve for high thresholds

Low lumi



High lumi



Level-1 Global Trigger

A maximum of 128 trigger lines can be implemented

- ➔ e.g. 1e, 2μ, 1μ+1e, etc.

Topological cuts can be defined

- ➔ e.g. 2 jets not back-to-back in ϕ

Only place where thresholds are applied

Level-1 decision is transmitted to the Trigger Throttle System, which in turn transmits a Level-1 Accept via the Trigger Timing and Control system to the detector front-end read-out electronics

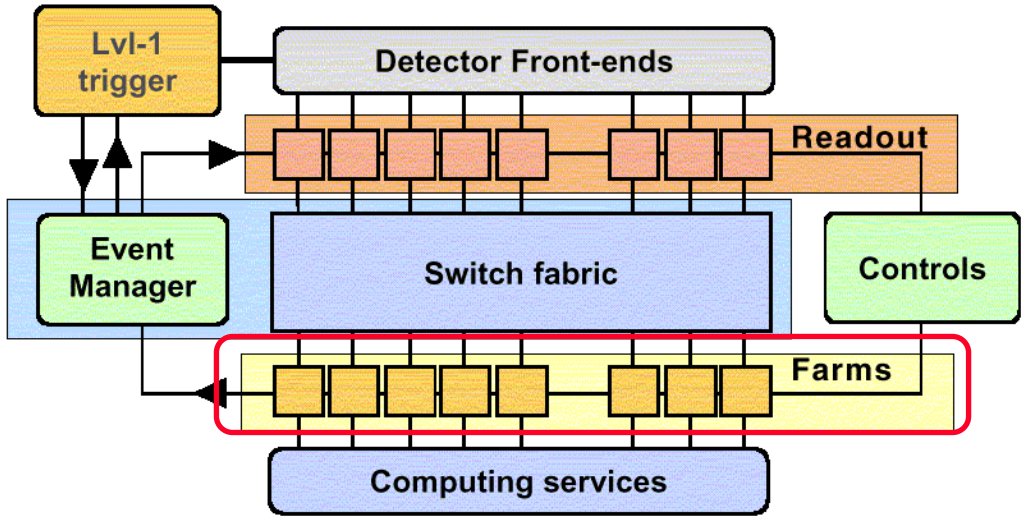
Example Level-1 Trigger Table (L=2×10^{33})

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			16.0

× 3 safety factor ⇒ 50 kHz (expected start-up DAQ bandwidth)

Only muon trigger has low enough threshold for B-physics

The High-Level Triggers



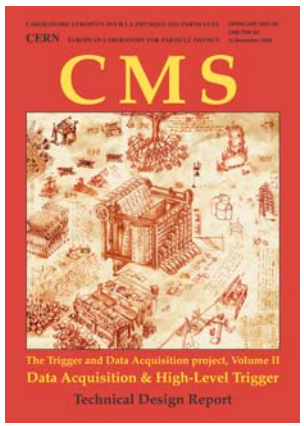
CMS does not have a custom Level-2 trigger in hardware

Everything beyond Level-1 performed in the Filter Farm

HLT does partial event reconstruction “on demand” using full detector resolution

Historically, Level-2 uses only calorimeter + muon and Level-3 uses tracker (90% of data volume)

Documented in DAQ & HLT TDR CERN/LHCC 2002-26



The CMS High-Level Triggers

Reduces rate from 100 kHz to O(100 Hz)

- ➔ Final rate will depend on data bandwidth, storage capability, and background rejection capability
- ➔ Deployed as software filters running in an online computer farm (~1000 PCs)
  - Software is in principle the same as used offline

Starts with a data sample already enriched in physics!

- ➔ Level-1 already applied a factor 400 background rejection

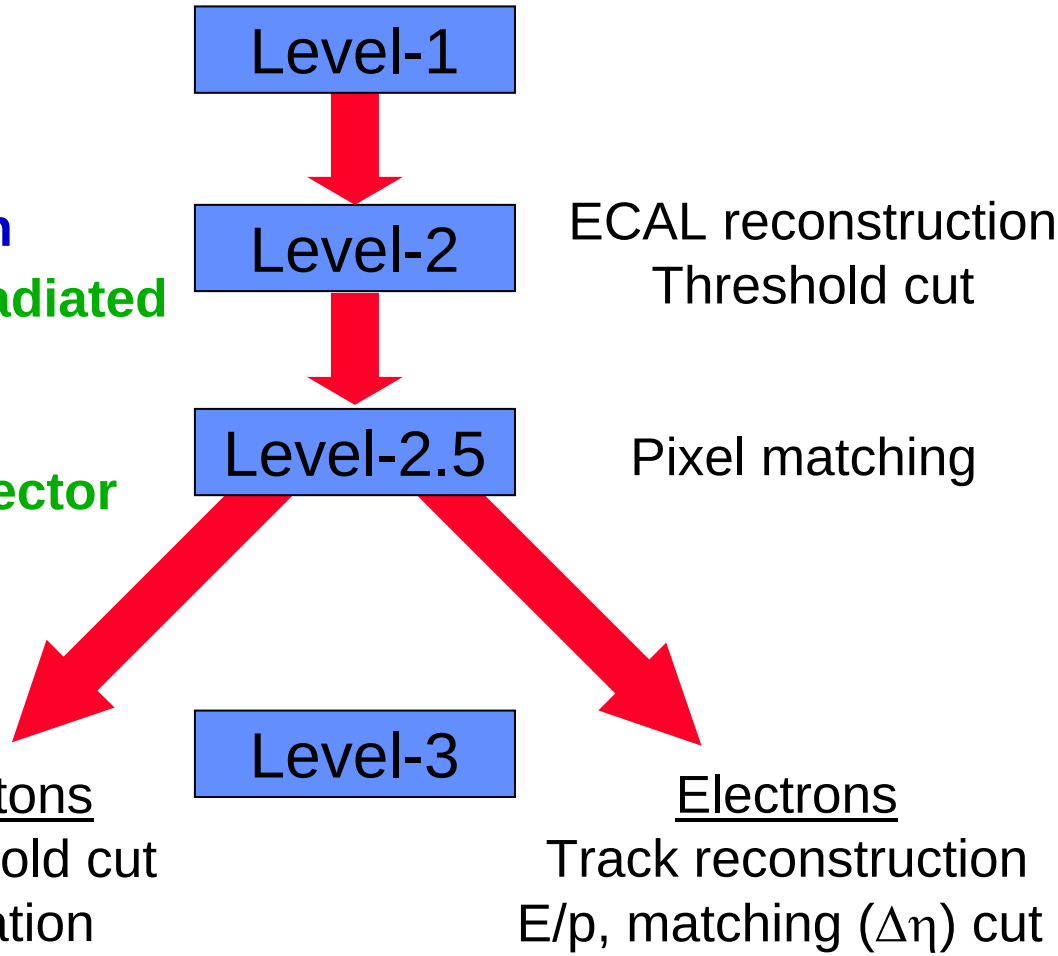
What can be done:

- ➔ Electrons: require high-P_T track match to veto π^0 fakes, recover bremsstrahlung
- ➔ Photons: veto tracks
- ➔ Muons: require high-P_T track match to improve momentum resolution
- ➔ Jets: run standard jet algorithms
- ➔ Tracks: improve measurement of impact parameter, p_T and charge
- ➔ Apply isolation criteria to all leptons
- ➔ Apply topology and invariant mass cuts

HLT selection: electrons and photons

- Issue is electron reconstruction and rejection
- Higher E_T threshold on photons

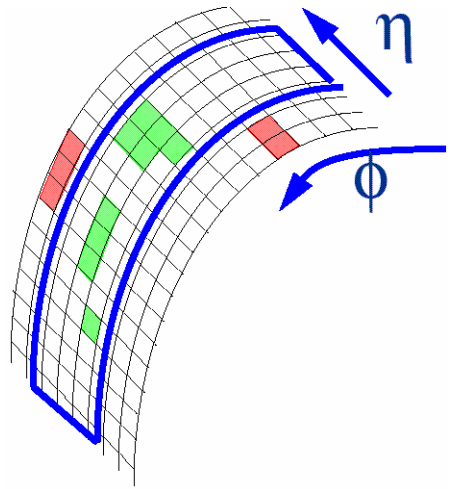
- Electron reconstruction
  - key is recovery of radiated energy
- Electron rejection
  - key tool is pixel detector



Electron selection: Level-2

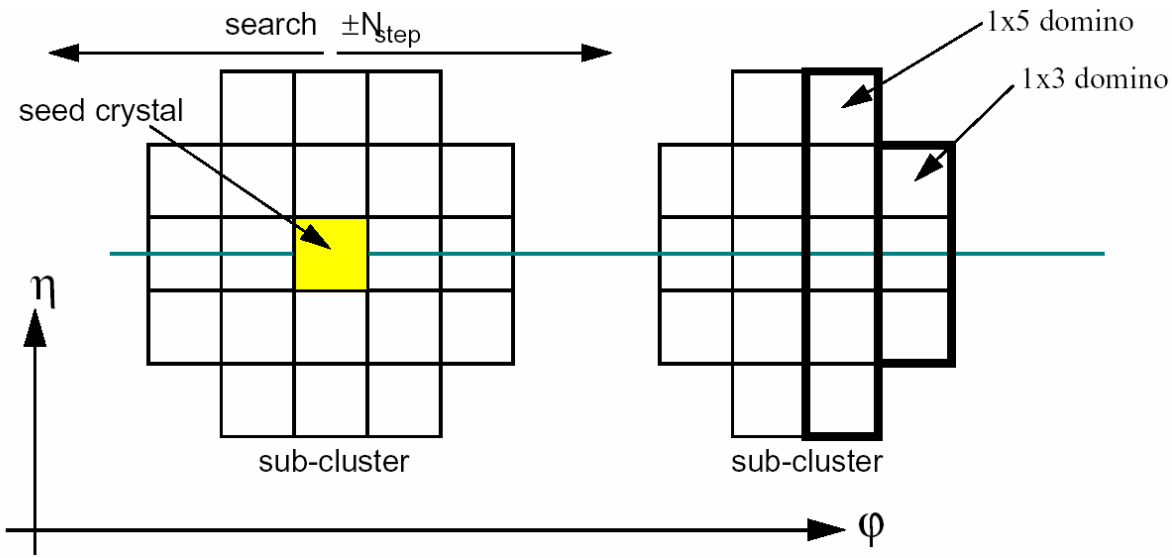
"Level-2" electron:

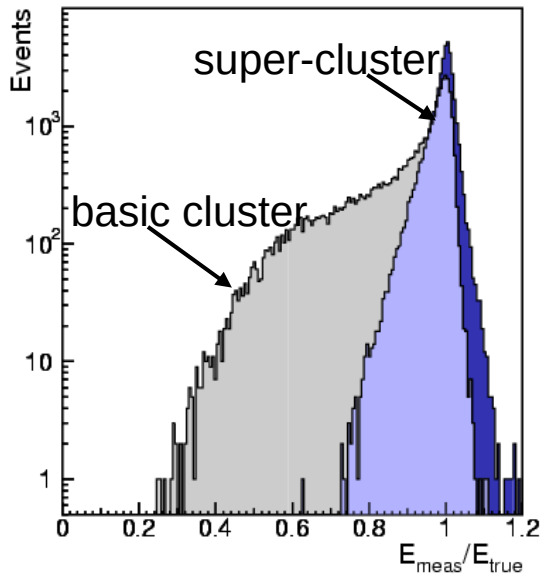
- Search for match to Level-1 trigger
  - Use 1-tower margin around 4x4-tower trigger region
- Bremsstrahlung recovery "super-clustering"
- Select highest E_T cluster



Bremsstrahlung recovery:

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

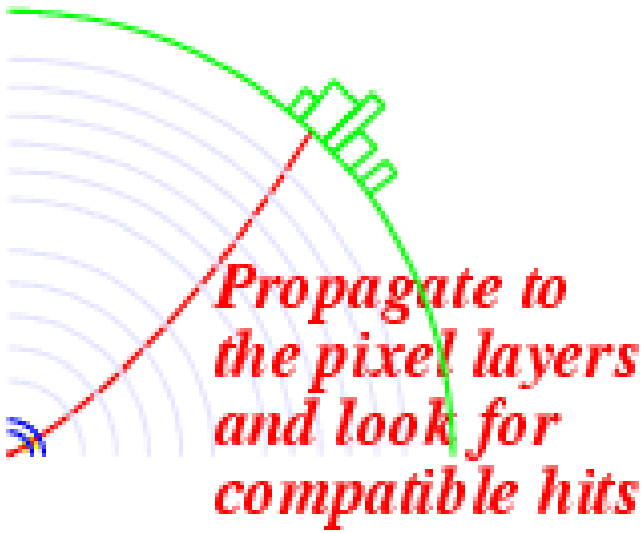


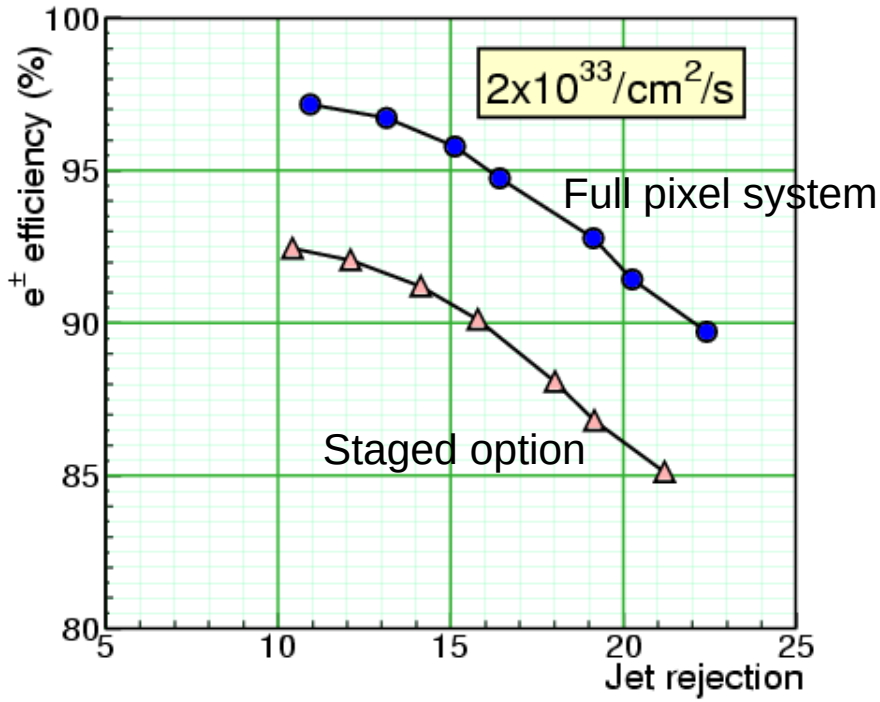


Electron selection: Level-2.5

"Level-2.5" selection: use pixel information

- ➔ Very fast, large rejection with high efficiency (>15 for ε=95%)
  - Before most material ⇒ before most bremsstrahlung, and before most conversions
  - Number of potential hits is 3: demanding ≥ 2 hits quite efficient

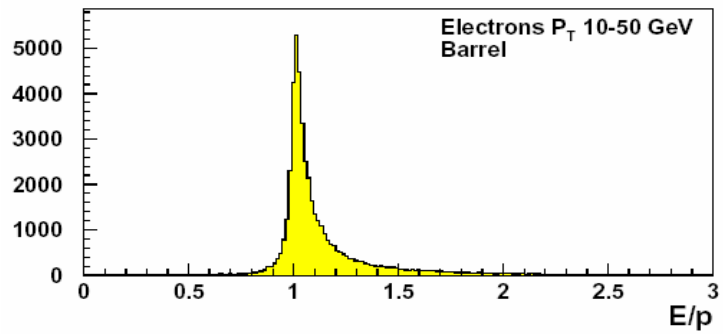


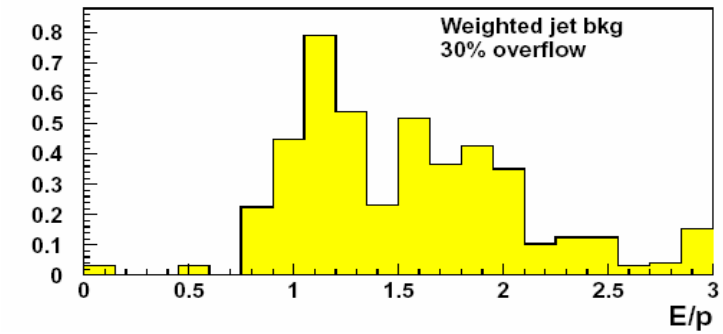


Electron selection: Level-3

"Level-3" selection

- Full tracking, loose track-finding (to maintain high efficiency)
- Cut on E/p everywhere, plus
  - Matching in η (barrel)
  - h/e (endcap)
- Isolation (used for photons)





2×10^{33} cm^{-2}s^{-1}

	Signal	Background	Total
Single e	$W \rightarrow e\nu$: 10 Hz	$\pi^{\pm}/\pi^0$ overlap: 5 Hz π^0 conversions: 10 Hz b/c $\rightarrow$ e: 8 Hz	33 Hz
Double e	$Z \rightarrow ee$: 1 Hz	~0	1 Hz
Single γ	2 Hz	2 Hz	4 Hz
Double γ	~0	5 Hz	5 Hz
			43 Hz

Muon HLT Selection

Standalone Muon Reconstruction: "Level-2"

- Seeded by Level-1 muons
- Local reconstruction exploiting full detector resolution (100μm)
- Kalman filtering technique applied to DT/CSC/RPC track segments
- "GEANE"-like algorithm used for propagation through iron
- Trajectory building works from inside out
- Track fitting works from outside in
- Fit track with beam constraint
- Isolation based on ΣE_T from calorimeter towers in cone around μ

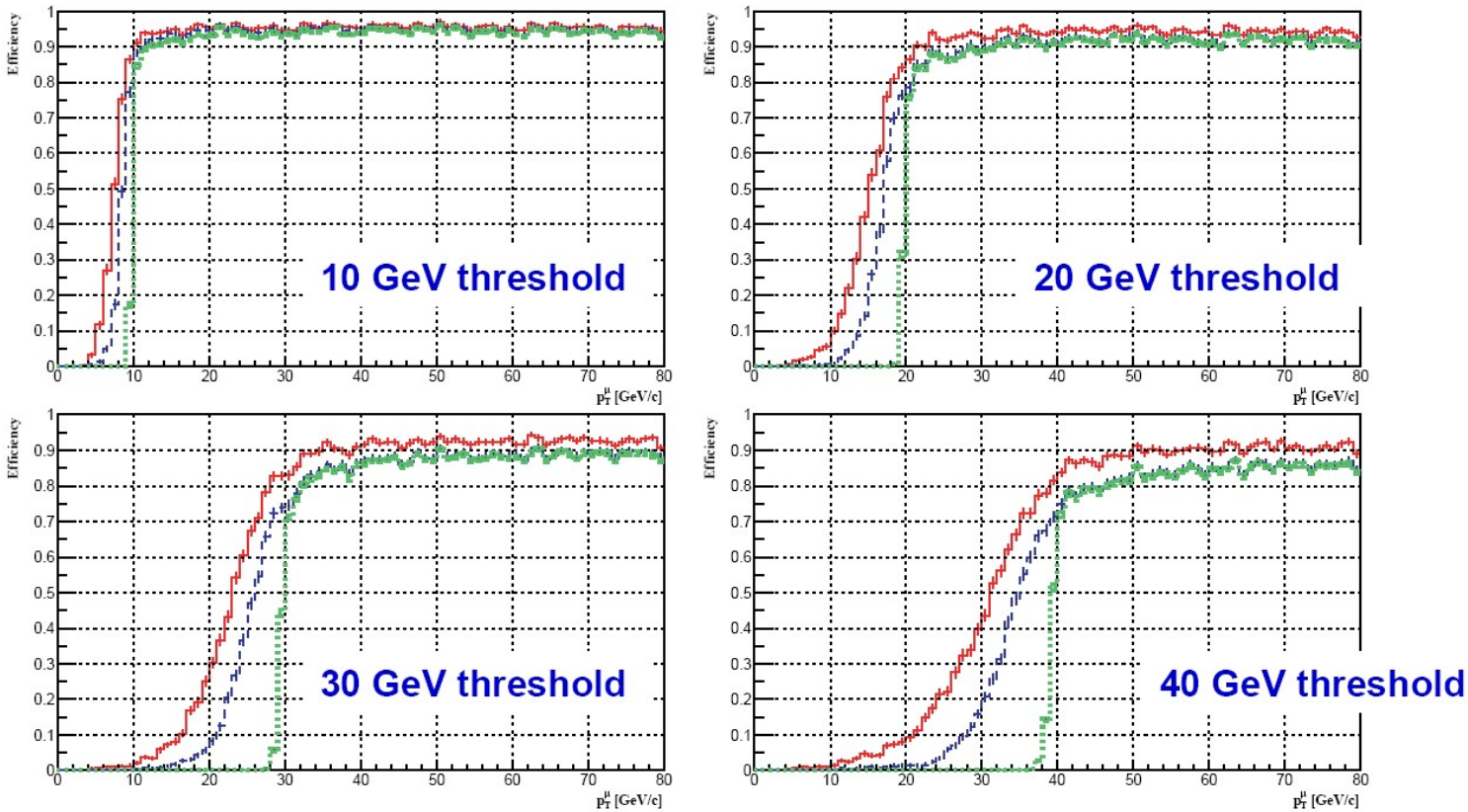
Inclusion of Tracker Hits: "Level-3"

- Define a region of interest through tracker based on Level-2 track with parameters at vertex
- Find pixel seeds, and propagate from innermost layers out, including muon
- Isolation based on ΣP_T from pixel/tracker tracks in cone around μ

Muon HLT Efficiency vs. P_T Threshold

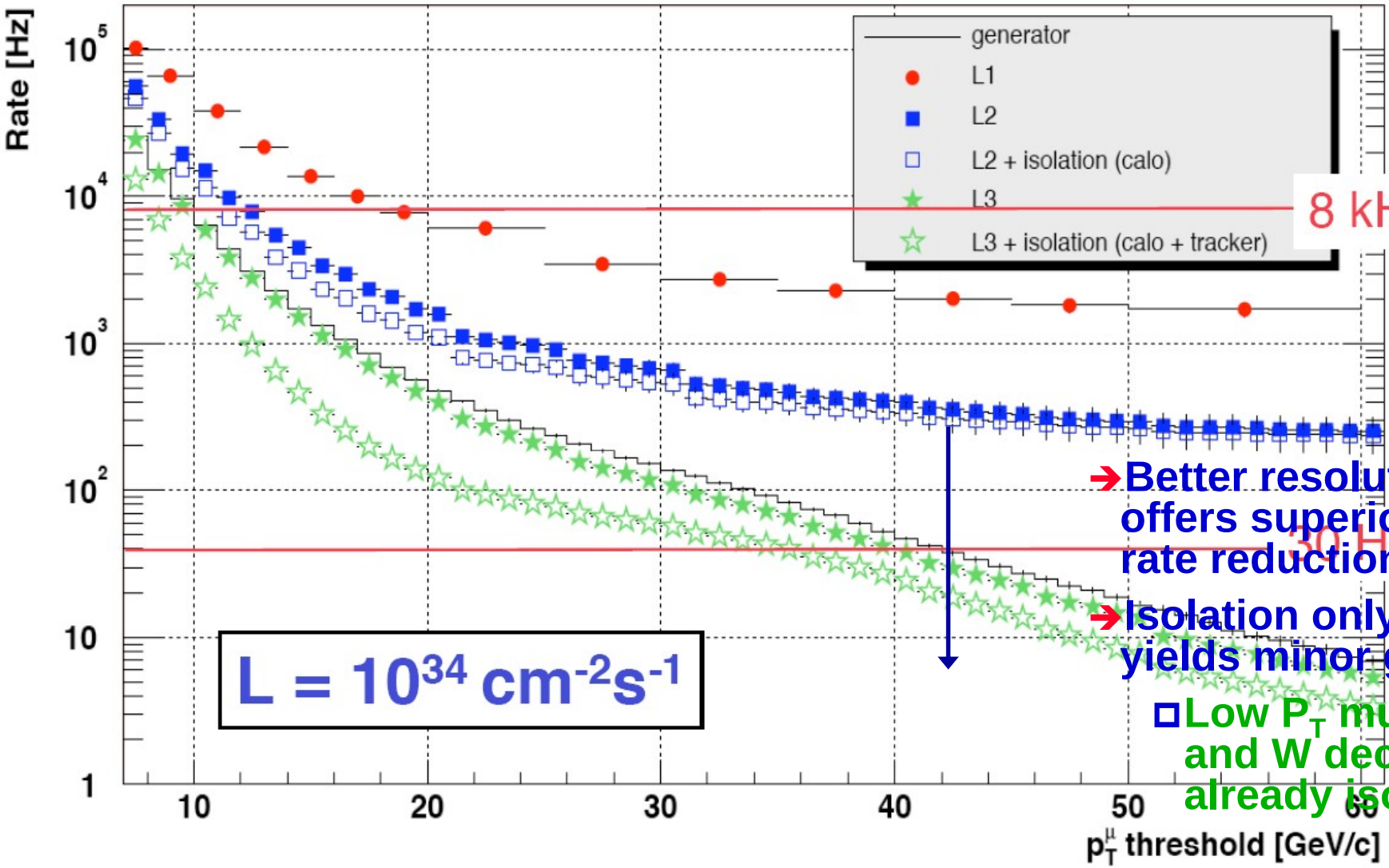
Level-1, Level-2, Level-3

Single muons with $|\eta|<2.1$



Thresholds sharpen with improved P_T resolution (15% without tracker, 1.5% with tracker)

L1, L2, L3 Trigger Rates @ High Lumi



Muon HLT Results

$L=2\times10^{33}\ s^{-1}cm^{-2}$

Level	Rate (Hz) Single	Rate (Hz) Double	Efficiency for $W\to\mu\nu$ Relative	Efficiency for $W\to\mu\nu$ Absolute	Efficiency for $t\bar{t}\to\mu+X$ Relative	Efficiency for $t\bar{t}\to\mu+X$ Absolute	Efficiency for $Z\to\mu\mu$ Relative	Efficiency for $Z\to\mu\mu$ Absolute
Level-1	2700	900		0.90		0.94		0.99
Level-2	335	25	0.89	0.80	0.93	0.88	0.99	0.98
Calo isolation	220	20	0.97	0.77	0.90	0.79	0.98	0.95
Level-3	100	10	0.93	0.74	0.95	0.84	0.99	0.97
Level-3+calo +tracker isolation	25	4	0.94	0.69	0.86	0.72	0.95	0.92
Total	29			0.69		0.72		0.92

$p_T>20$

30 Hz output rate

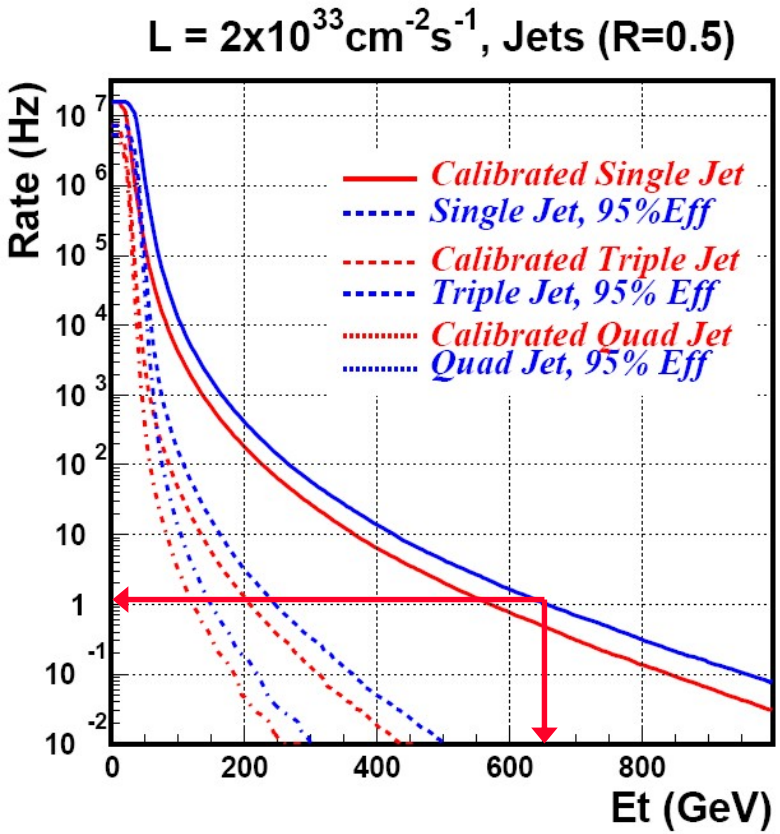
Efficiencies

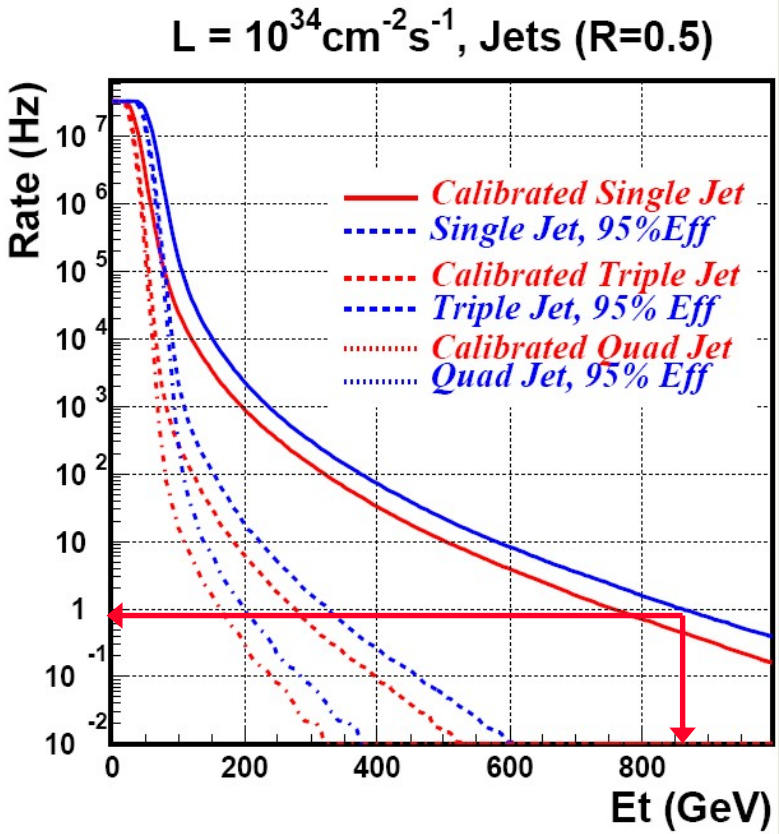
$H \to ZZ^* \to \mu\mu\mu\mu$ $\quad \varepsilon \approx 98\%$ for M=150 GeV

$H \to WW^* \to \mu\mu\ \nu\nu$ $\quad \varepsilon \approx 92\%$ for M=160 GeV

Jet Selection: Level-2

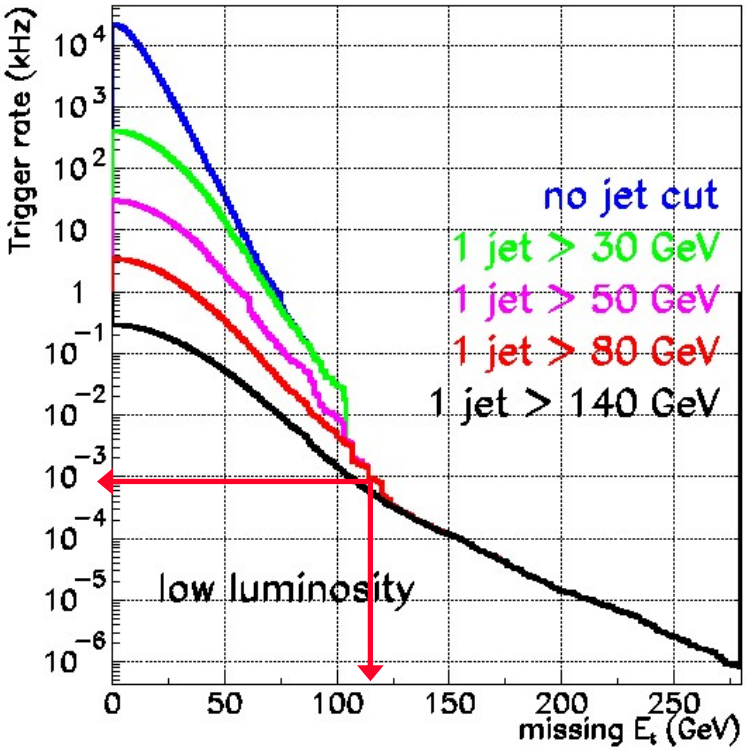
Cone algorithm, $R = 0.5$

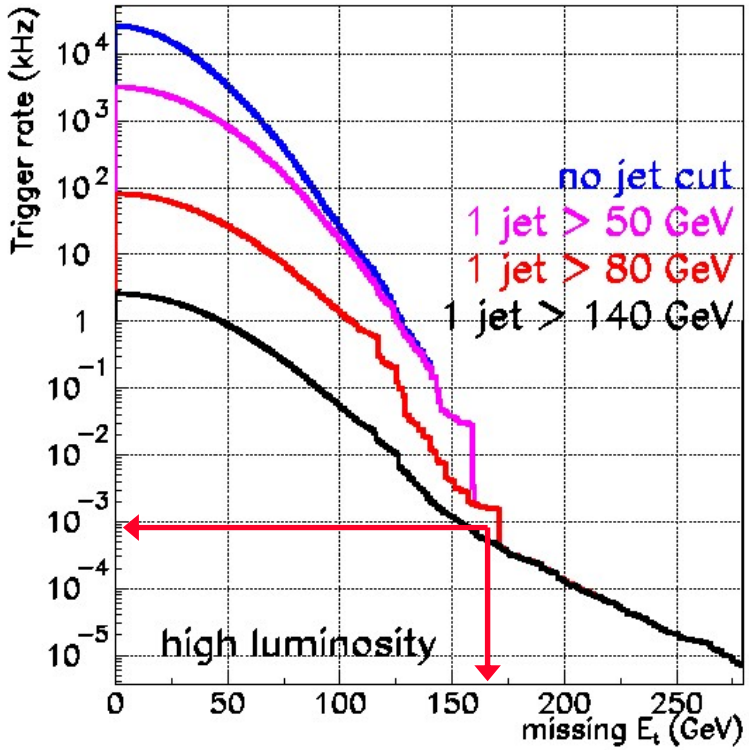




Single-jet E_T thresholds expected to be very high

Jets + MET Triggers

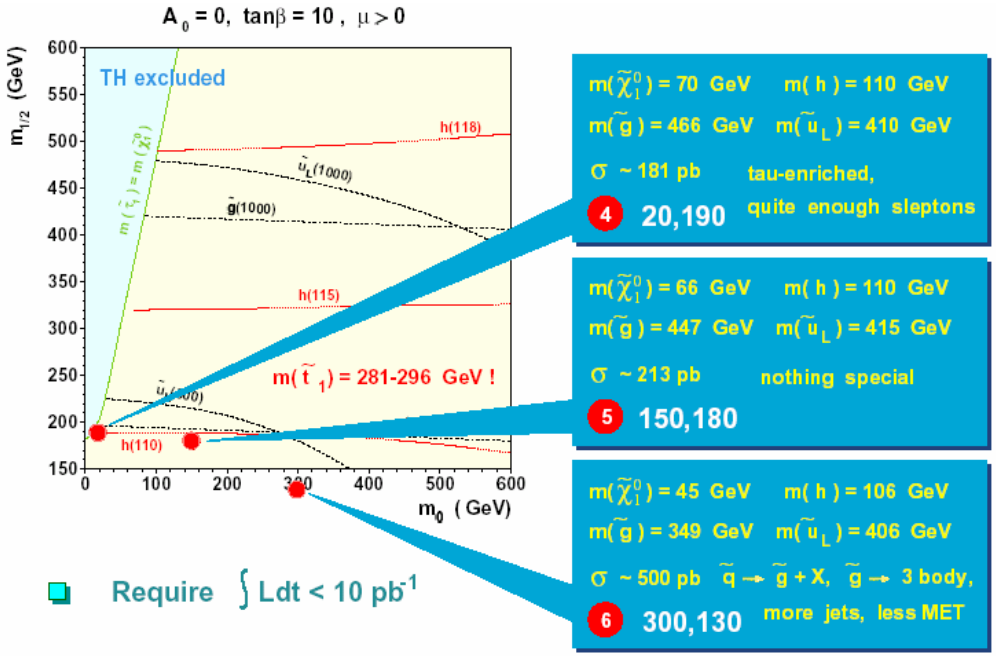




➔ **Reconstructed MET rate below 100 GeV mainly from calorimeter coverage and energy resolution**

Inclusive SUSY Trigger Exercise

- Consider several points in the $m_0 - m_{1/2}$ plane near the Tevatron reach (most difficult for LHC)



Possible triggers at Level-2:

- 1 jet E_T>180 GeV & MET>120
- 4 jets E_T>110 GeV

Overall efficiency to pass both Level-1 and Level-2:

- ε=0.63, 0.63, 0.37 (4) (5) (6)
- Background rate of ~12Hz @ L = 2×10^{33} dominated by QCD jets
- Trigger becomes more efficient at high luminosity since one expects to explore higher masses
- More exclusive triggers can further improve efficiency

Example HLT Trigger Menu (L=2×10^{33})

- 1e: P_T > 30 GeV
- 2e: P_T > 15 GeV
- 1γ: P_T > 80 GeV
- 2γ: P_T > 40, 25 GeV
- 1μ: P_T > 20 GeV
- 2μ: P_T > 7 GeV
- 1τ: P_T > 85 GeV
- 2τ: P_T > 60 GeV
- 1 jet: E_T > 660 GeV
- 1 jet + MET: E_T > 180, 120 GeV
- 3 jets: E_T > 250 GeV
- 4 jets: E_T > 110 GeV

Estimated rate to tape ~100 Hz

Summary

Trigger system applies an overall factor of 10^6 filtering while maintaining good efficiency

Level-1:

- First factor of 1000
- Hadronic tau trigger implemented
- Sliding window jet triggers
- Isolated and non-isolated lepton triggers (without central tracking)
- 128 trigger lines available

HLT:

- Second factor of 1000
- Access to full event information
- Partial reconstruction based on the calorimeter and muon systems initially (verify and improve Level-1 decision), followed by pixel + tracker information for final rejection
- Lots of flexibility

Your analysis may require yet another factor 10^6 rejection!