Online Event Selection at the CMS experiment

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on behalf of the CMS Collaboration

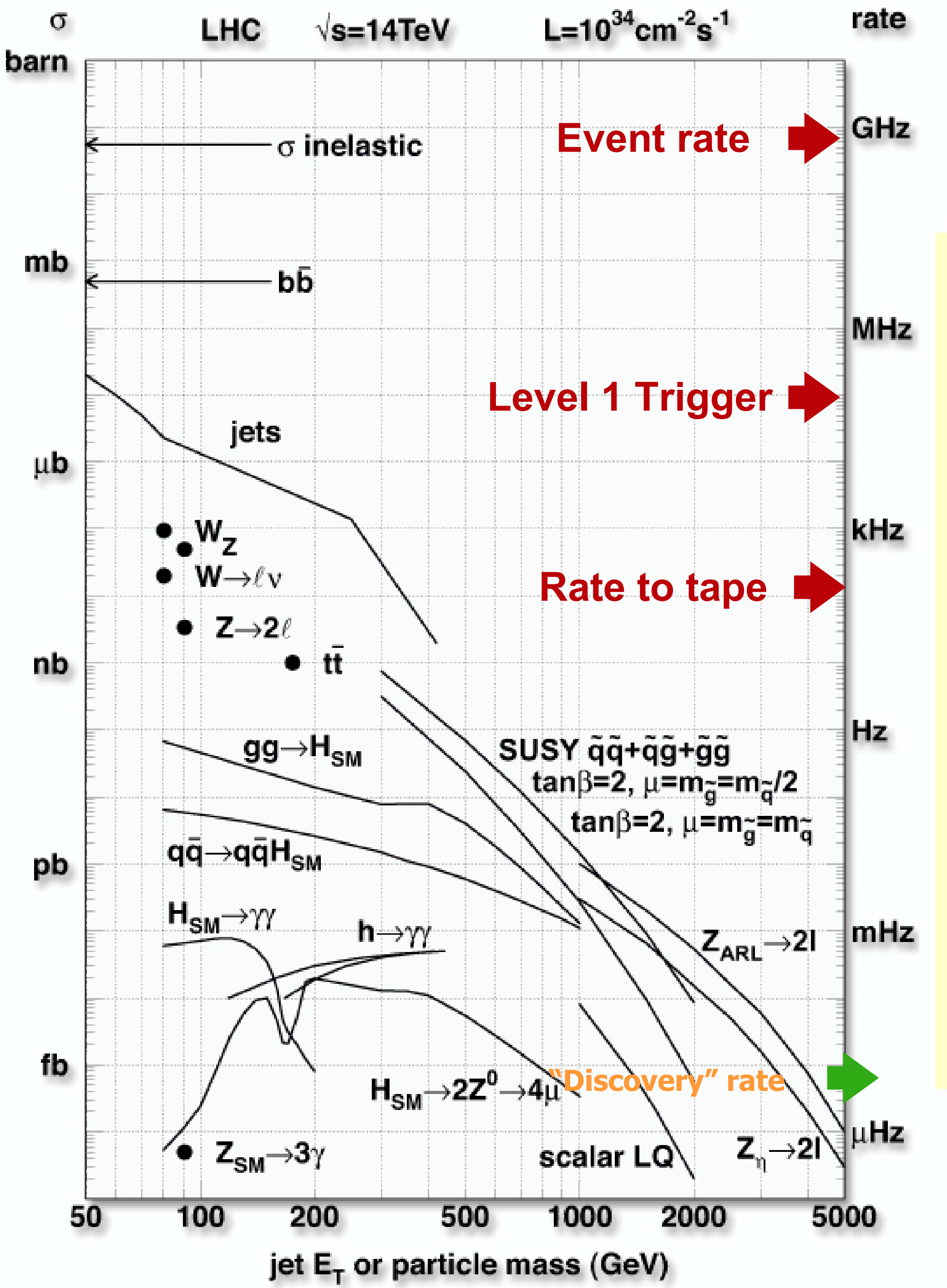
Outline:

- CMS trigger and DAQ Architecture
- Level-1 Trigger
- HLT principles
- HLT performance
- Summary

HLT = High-Level Trigger

"Level-1 TDR" - CERN/LHCC 2000-038
"DAQ & HLT TDR" - CERN/LHCC 2002-26

next: *Physics TDR*



CMS at LHC

LHC

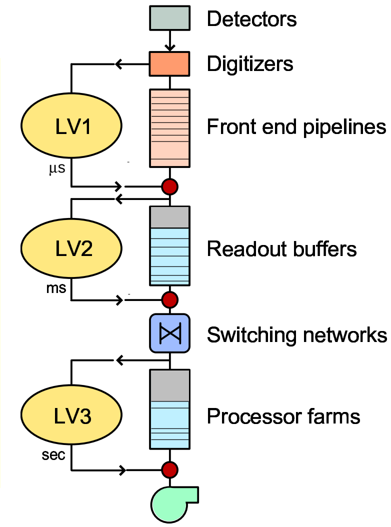
- 7+7 TeV protons
- bunch crossing rate: 40MHz
- High Luminosity: 10^{34}cm^{-2}s^{-1}
  Low Luminosity: $2 \cdot 10^{33}$cm^{-2}s^{-1}

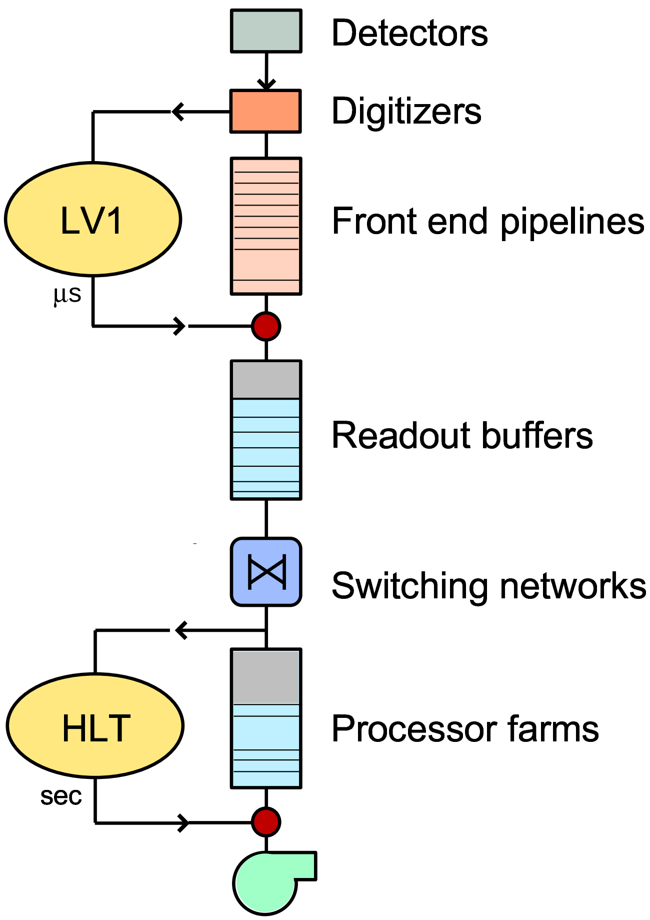
CMS: General purpose experiment

- 2 trigger levels
  – Max Level-1 output: 100kHz
  – High-Level Trigger output: O(100 Hz)
- Event selection 1 in $10^{\sim 13}$

CMS trigger principles

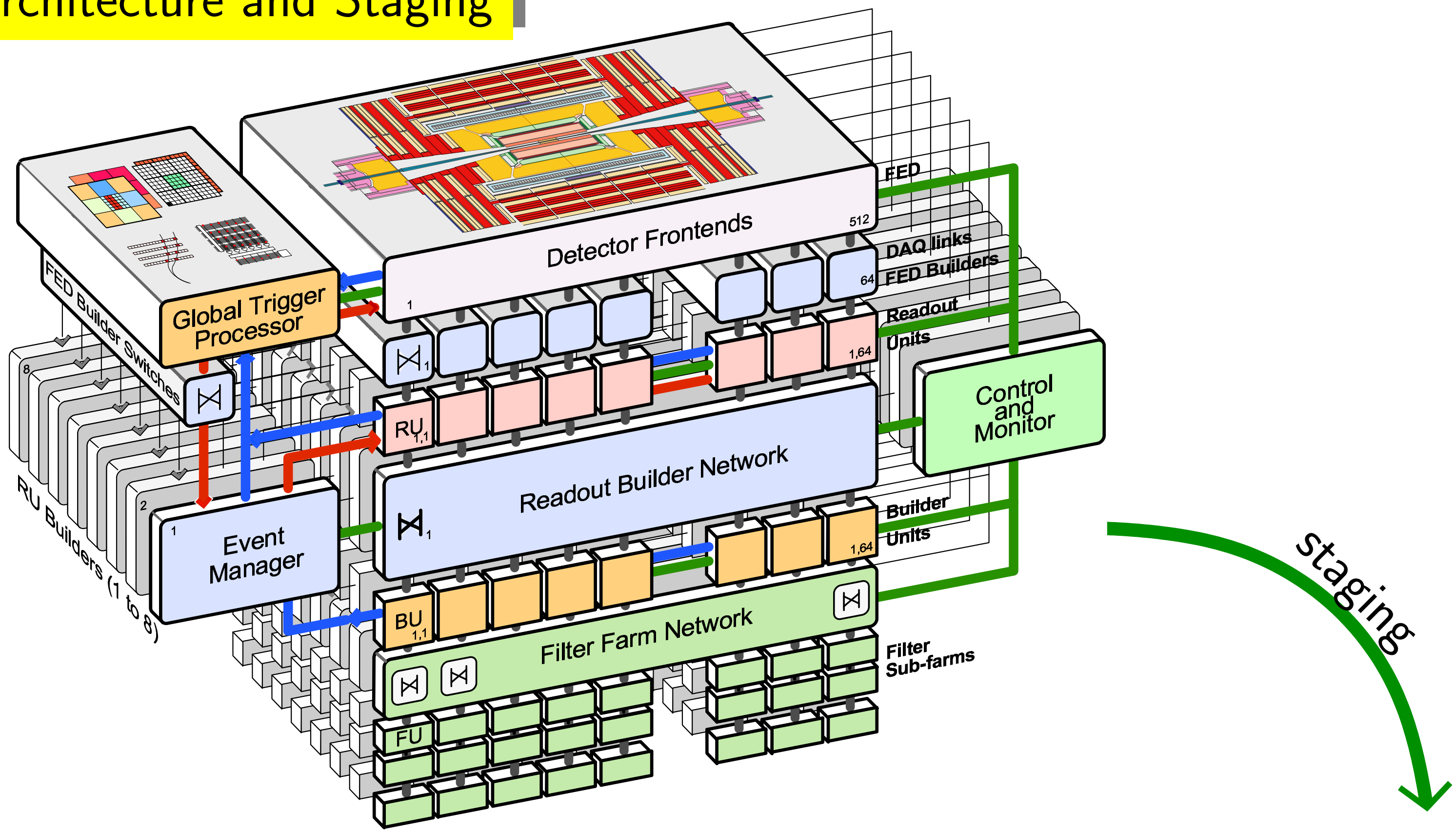
Traditional approach: Dedicated L2 hardware. Does not benefit from full granularity.

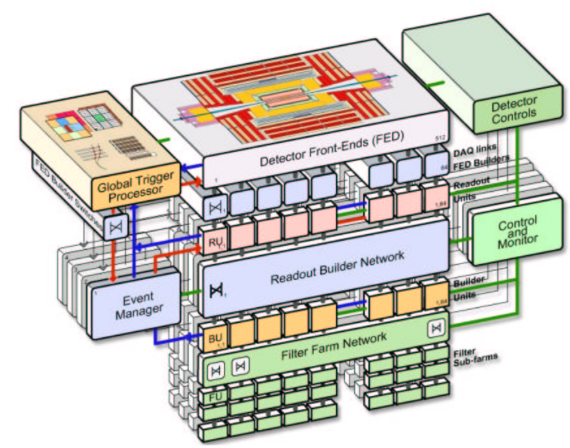




CMS Approach: do without dedicated L2 hardware. After Level-1 there is a High-Level Trigger running on a single processor farm.
Advantage: The only limitation is available CPU. Maximal Flexibility. Full granularity and resolution.
Caveats: A lot of data to handle. Challenging.

DAQ Architecture and Staging





- DAQ designed to accept Level-1 rate of 100 kHz
- Modular DAQ: 8×12.5 kHz DAQ units.
  4 Slices at startup (50 kHz).
- HLT output $O(10^2)$ Hz - rejection of 1000.

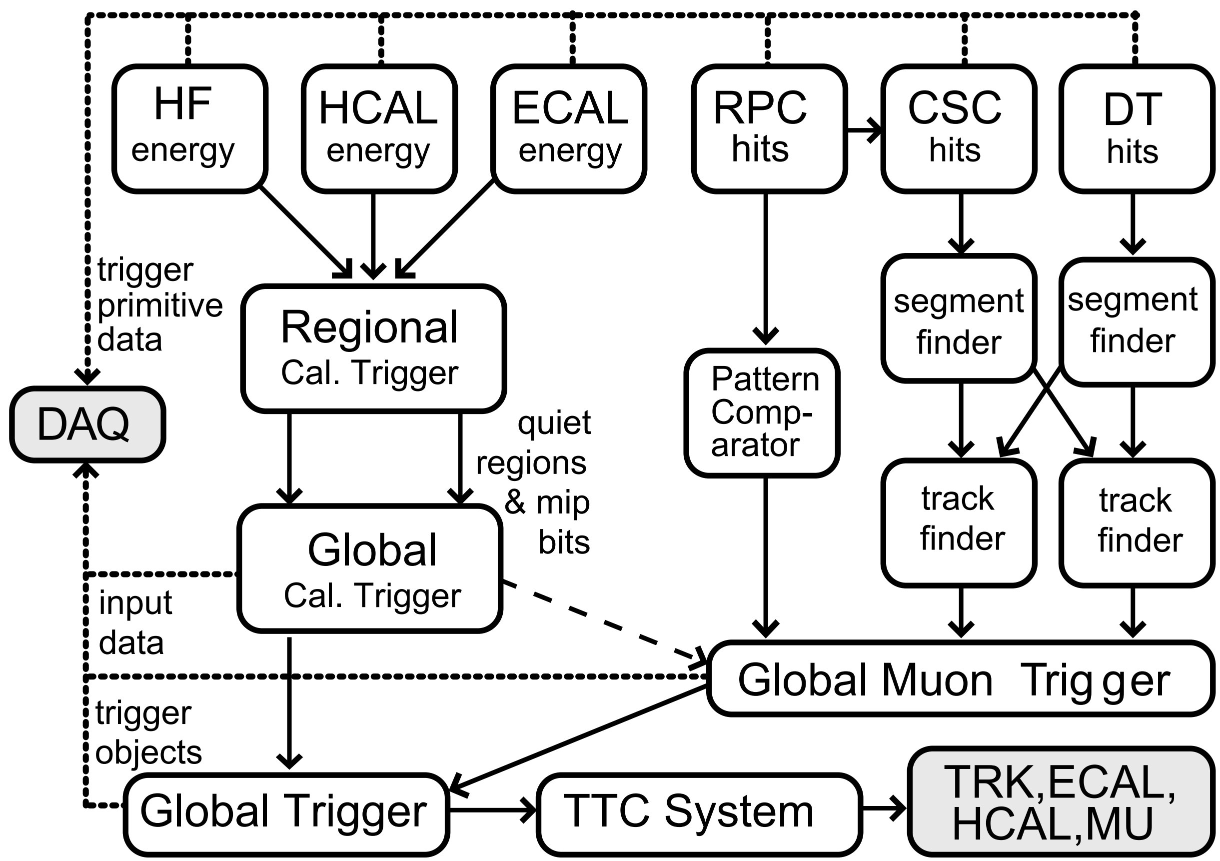
Level−1

Overview

Requirements driven by LHC discovery physics:

- Identify high-p_T leptons (including taus) and photons. Single and Combined triggers.
- All trigger thresholds and conditions must be programmable (large uncertainties in backgrounds and signals)
- Need to include overlapping and min-bias triggers to well understand efficiencies
- Large rejections factors needed: 40MHz ($\times \sim 20$ ev/bx) $\rightarrow$ 100 kHz.

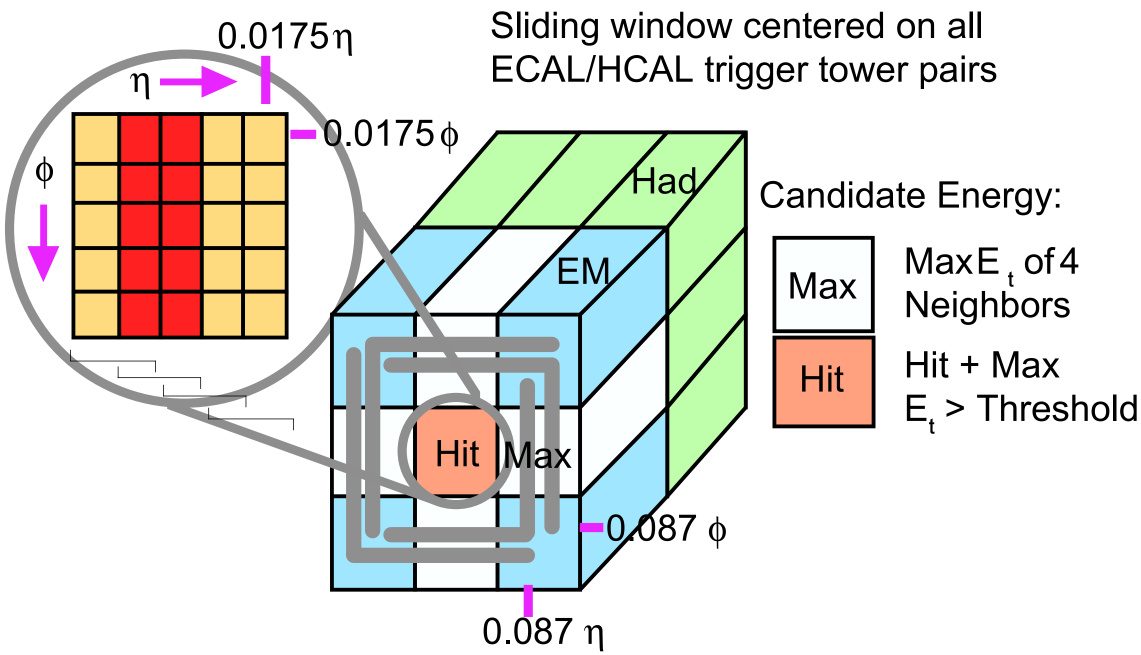
- Level-1 uses muon and calorimeter detector data only
- Special-purpose hardware (ASICS) but also FPGAs
- Data stored on detector during fixed Level-1 latency. 128BX $= 3.2\mu$s
- Data read on Level-1 accept. Proceed via event builder switch to HLT



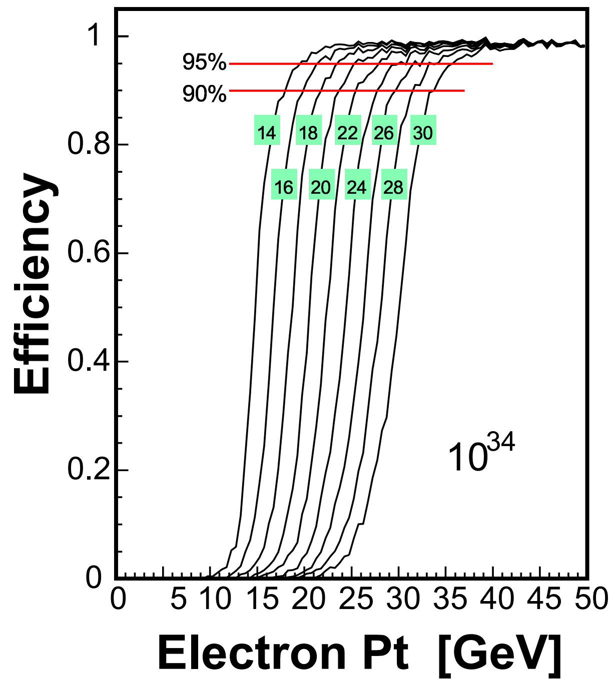
Electron/Photon

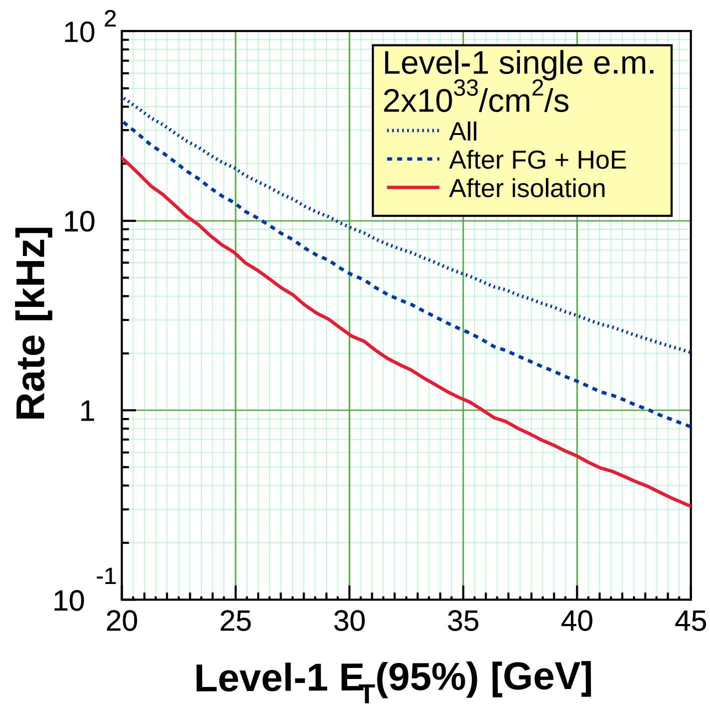
Trigger based on 3x3 trigger towers. Each tower consists of one HCAL tower and 5x5 crystals barrel ECAL (varies in endcap). e/γ identification criteria:

- h/e fraction
- Fine shape in ECAL (most of energy collected in 2x5 strip)
- Isolation in both ECAL and HCAL sections



Steep curves allow sharp cuts. Good control of rates. 4 isolated and 4 non-isolated e/γ candidates passed to global trigger



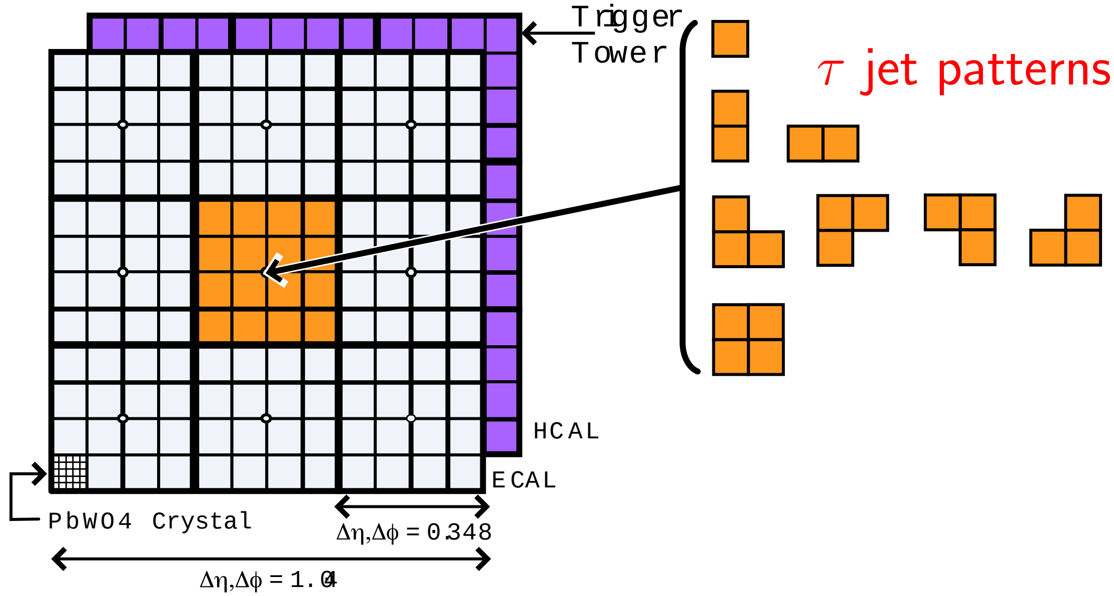


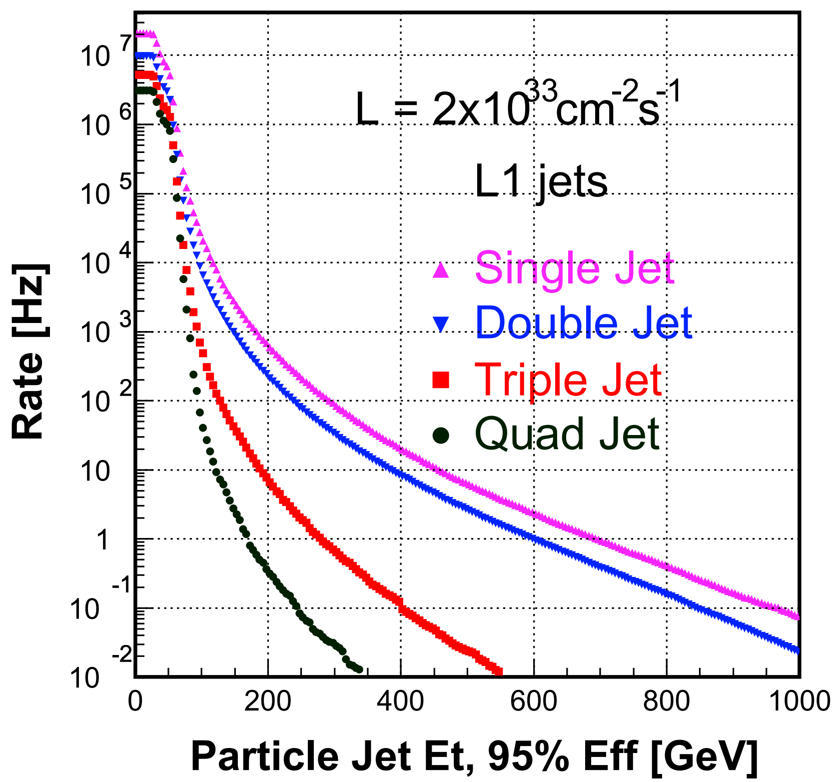
Jet and Tau

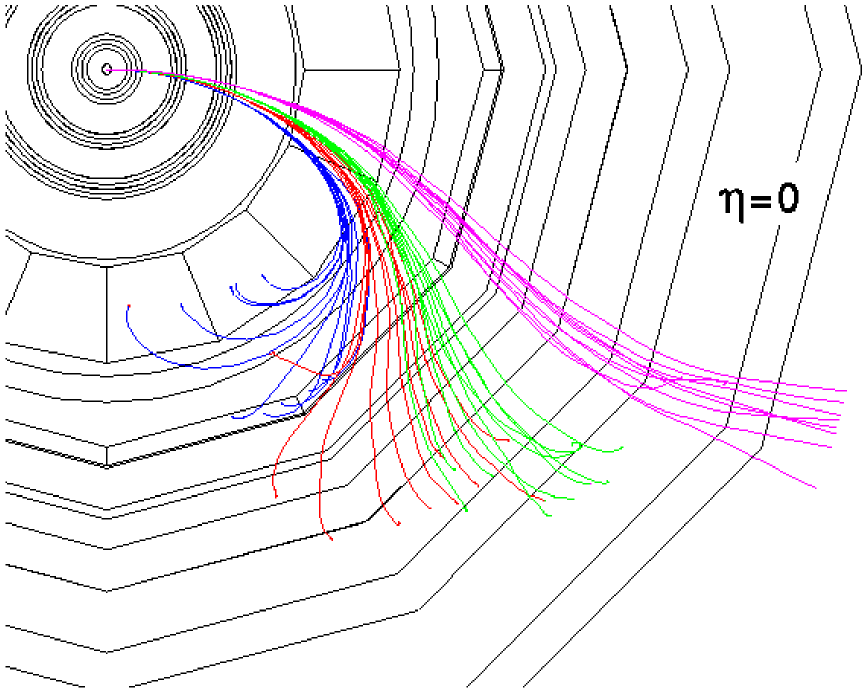
Trigger region: 4×4 towers.
Sliding window: 3×3 regions.
Central has maximal E_T.
Jet E_T summed in sliding window.

- Tau jet identified by τ-pattern shape.
- Various combinations of thresholds possible
- Cuts on jet multiplicities
- Also: Missing E_T, ΣE_T, ΣE_T^{JET} triggers

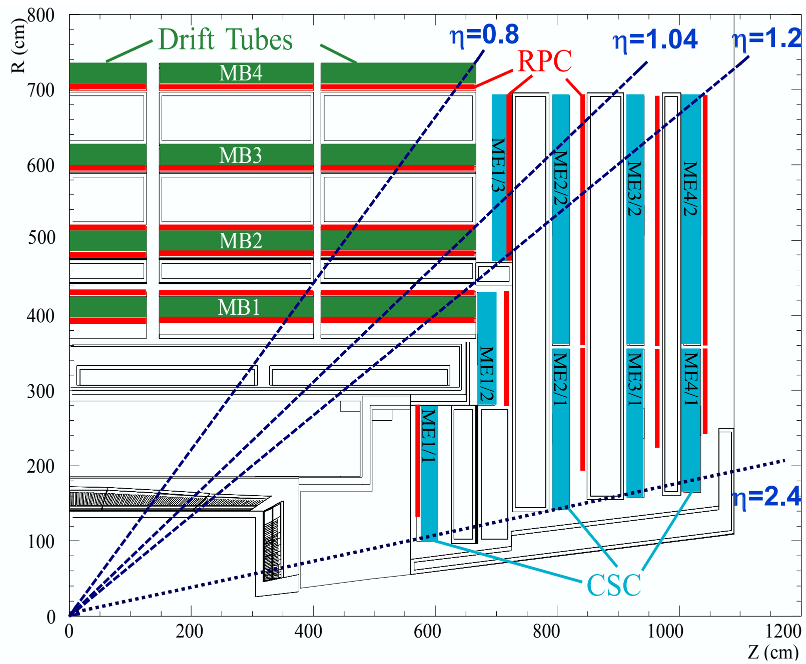
High rates or high cuts.





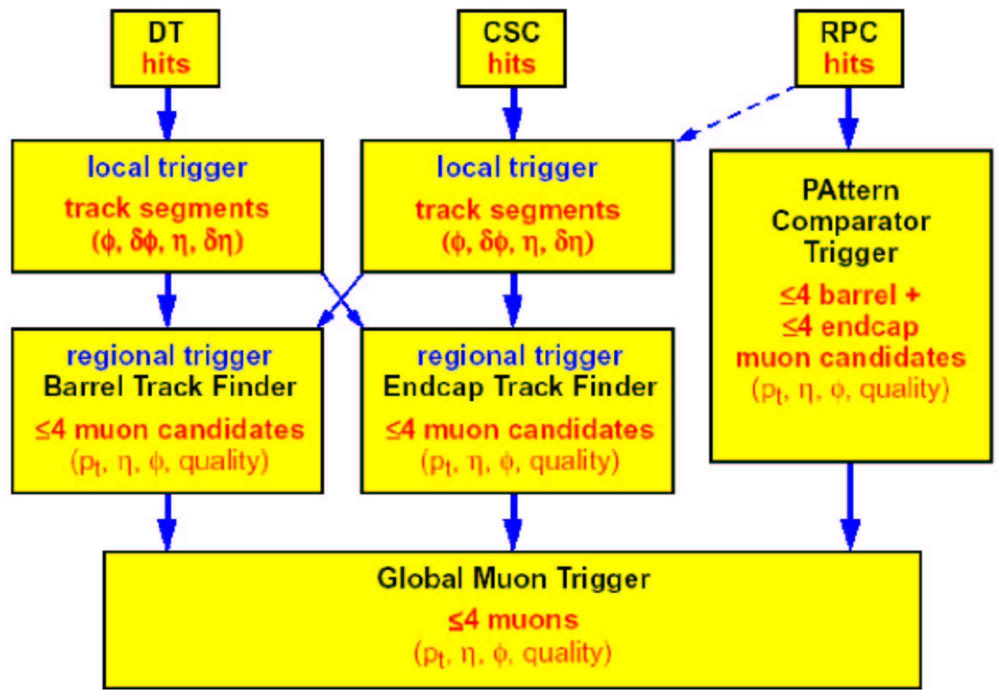


p_t = 3.5, 4.0, 4.5, 6.0 GeV



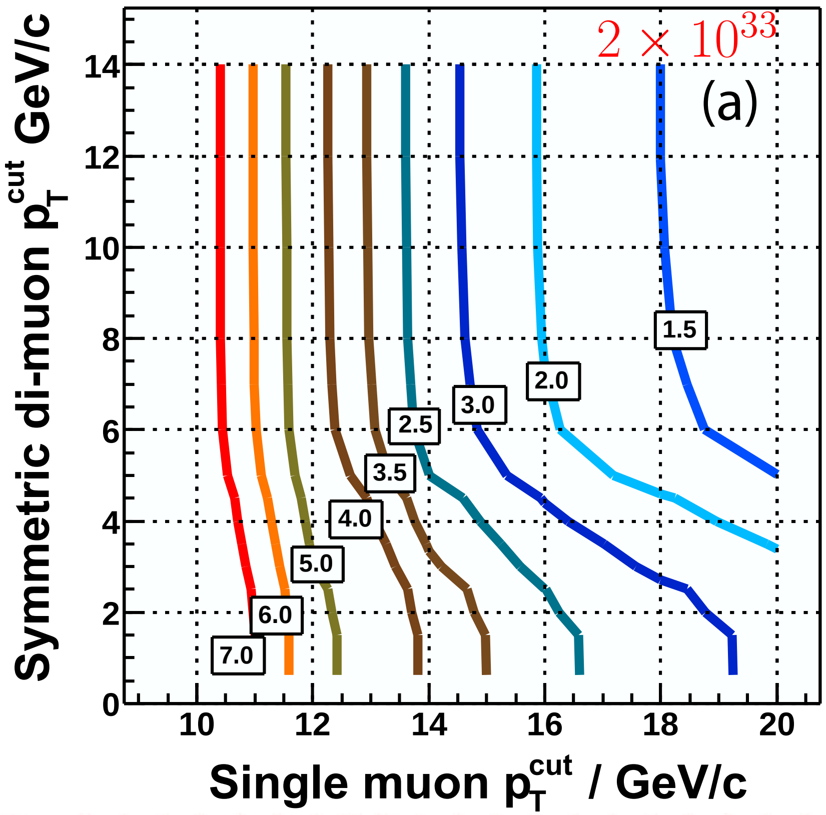
Muon

DT = Drift Tubes
RPC = Resistive Plate Chamber
CSC = Cathode Strip Chamber
GMT = Global Muon Trigger



L1 trigger in the range $|\eta| < 2.1$.
Recent change: RPC in $|\eta| < 1.6$.

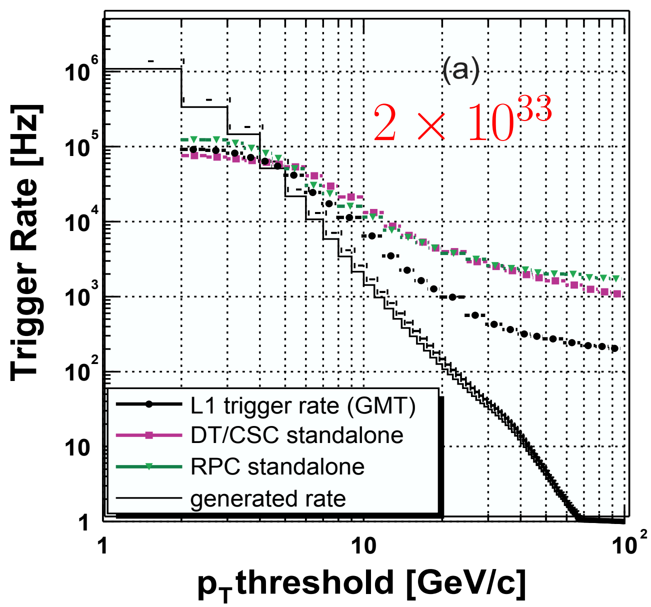
Muon

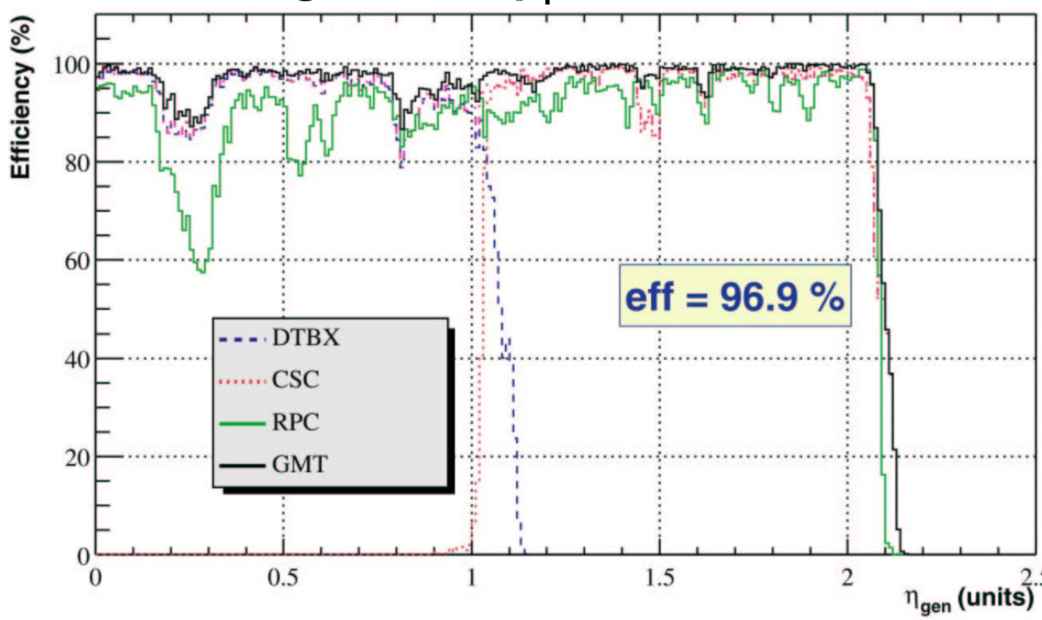


Three systems are complementary:

- gain in efficiency.
- gain in rate.

GMT selection based on candidate p_T and quality.





L1 trigger table ($2 \cdot 10^{33}$cm^{-2}s^{-1})

Safety factor of three is superimposed for simulation uncertainties, beam conditions,... Thus output rate: $50 \text{ kHz} \Longrightarrow 16 \text{ kHz}$ at startup ($2 \cdot 10^{33}$cm^{-2}s^{-1}). Bandwidth is allocated in equal parts to electron/photons, muons, taus, and jet+combined triggers. Priority: discovery physics.

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/γ, 2e/γ	29, 17	4.3	4.3
1μ, 2μ	14, 3	3.6	7.9
1τ, 2τ	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet * Miss-E_T	88 * 46	2.3	14.3
e * jet	21 * 45	0.8	15.1
Min-bias		0.9	16.0

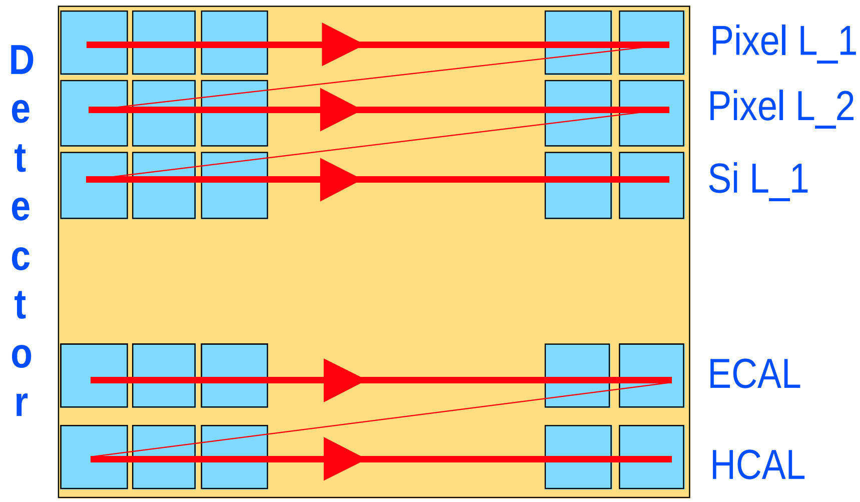
HLT

Principles

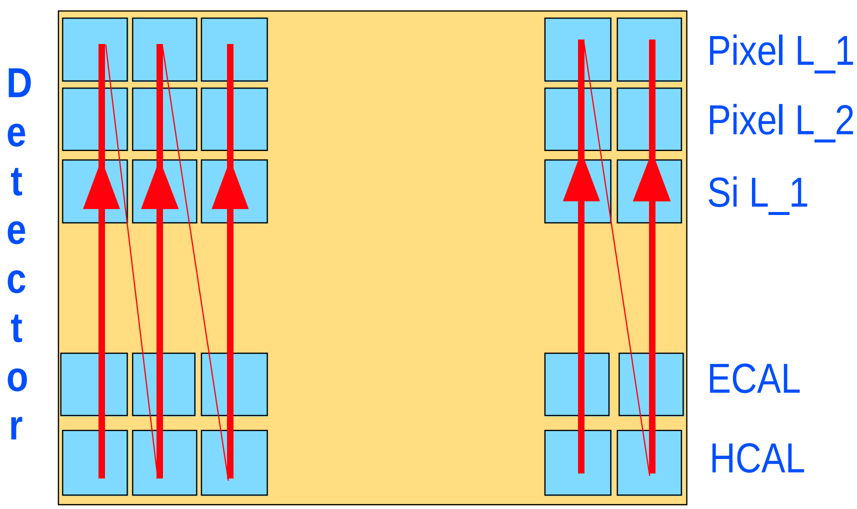
- Runs on CPU farm (1 ev/processor at a time). Available CPU is a limitation (→ timing). Uses full granularity and resolution. C++.
- Must provide sufficient rate reduction 100(50) kHz $\Longrightarrow$ O(10^2) Hz. Selection 1 ev in ∼1000.
- Must satisfy physics requirements: inclusive selection, high efficiency.
- Must not required precise knowledge of calibration/run conditions.
- Two strategies:
  - Fast but not accurate reconstruction
  - Use minimal amount of precise information.

  Both ways used to optimize event rejection speed. Second is preferred. Code as close as possible to offline reconstruction.
- Reconstruction on demand: do not reconstruct until necessary
- Regional reconstruction (→)
- Partial and conditional track reconstruction (→).

Global and Regional reconstruction

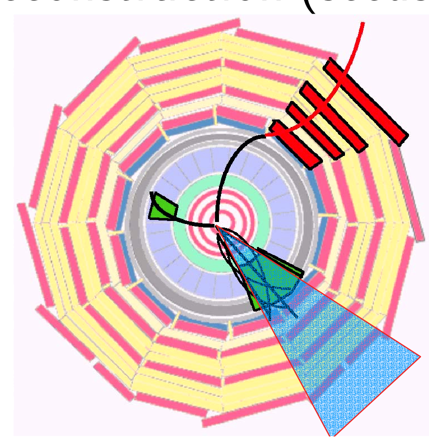


GLOBAL: Reconstruct raw data detector by detector, link detectors to make objects. Needed when no seed given. Also: global tracking, ΣE_T, Missing E_T, "other side of lepton"



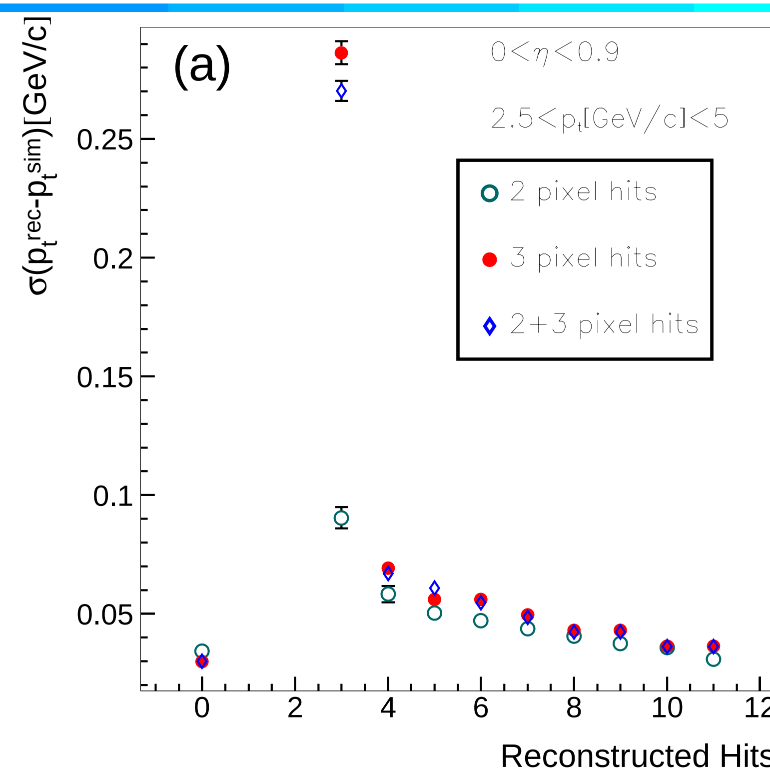
REGIONAL: Reconstruct data only where it is needed. Slices of appropriate size. Need to know where to start reconstruction (seeds from Level-1, Level-2).

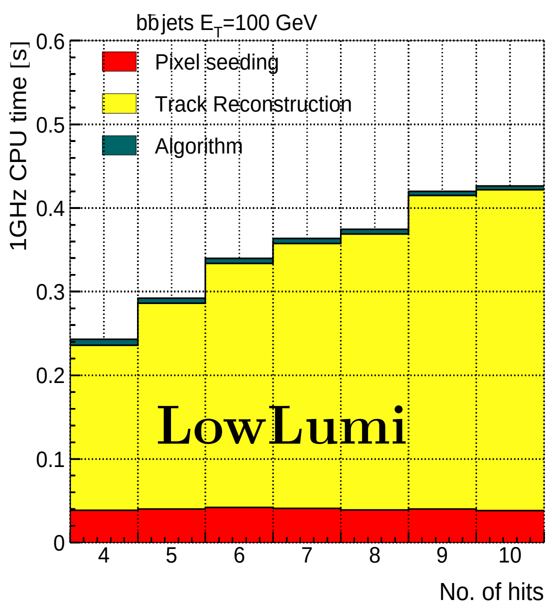
example: Track in the region of interest defined by a jet. Typical cone size: $\Delta R = 0.2 - 0.5$



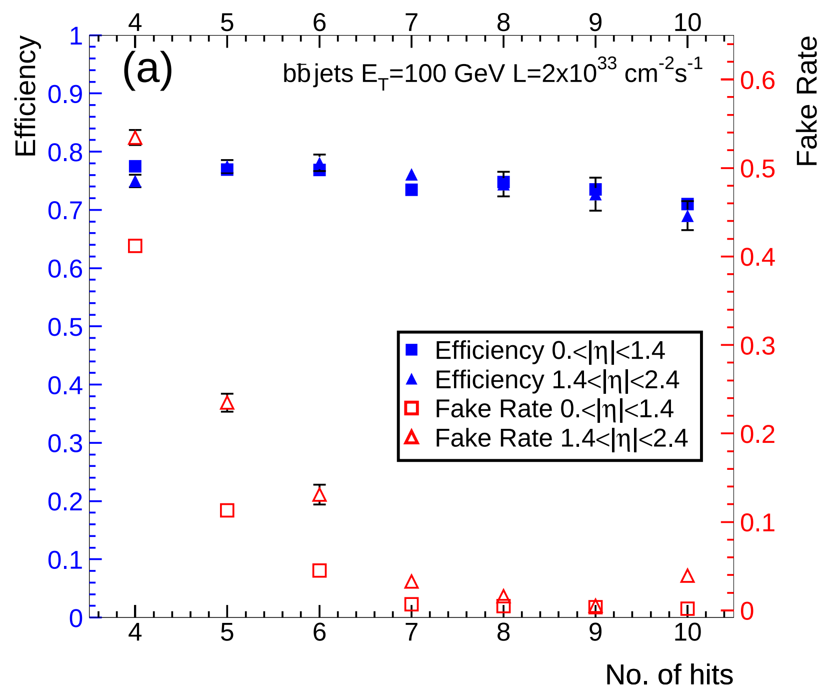
Partial and Conditional track reconstruction

- Stop tracking when combinatorics is solved and/or precision is sufficient for analysis.
- Stop track reconstruction if track does not match kinematics requirements.



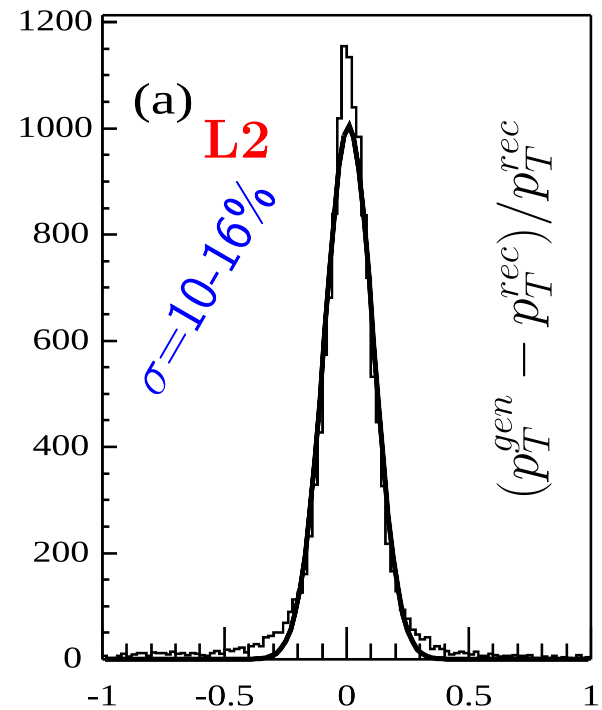


- Time used for track reconstruction increases linearly with number of hits.

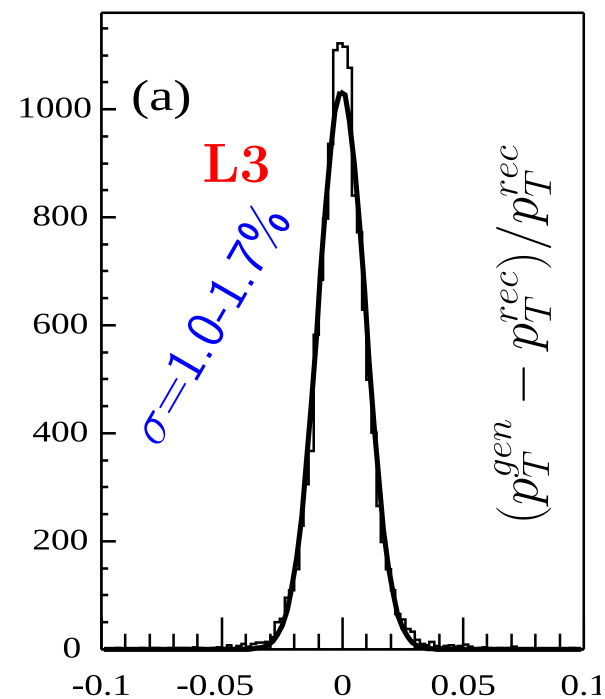


Muons – reconstruction

- L2: Reconstruction in Muon System Only
  - Regional reconstruction seeded by Level-1 muon,
  - Kalman Filter Fit collecting DT/CSC/RPC segments/hits; GEANE is used for propagation through CMS,
  - Add beam spot constraint to the fit.



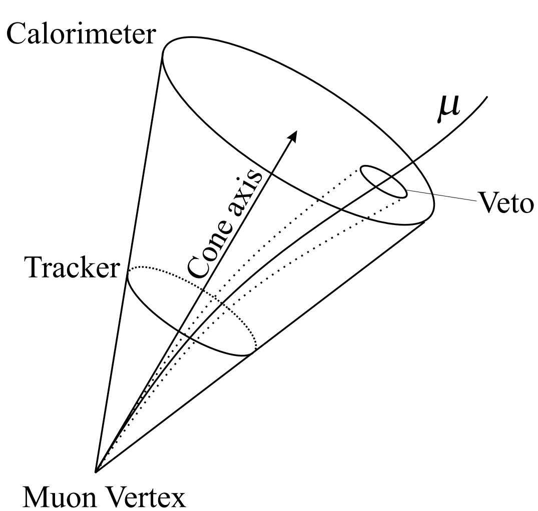
- L3: Inclusion of Tracker Data
  - Define a region of interest around L2 muon,
  - Find seeds compatible with L2 kinematic requirements; Seeds are formed by pairs of pixel hits,
  - Kalman Filter Fit in the tracker,
  - Update trajectory with hits from Muon Detector.



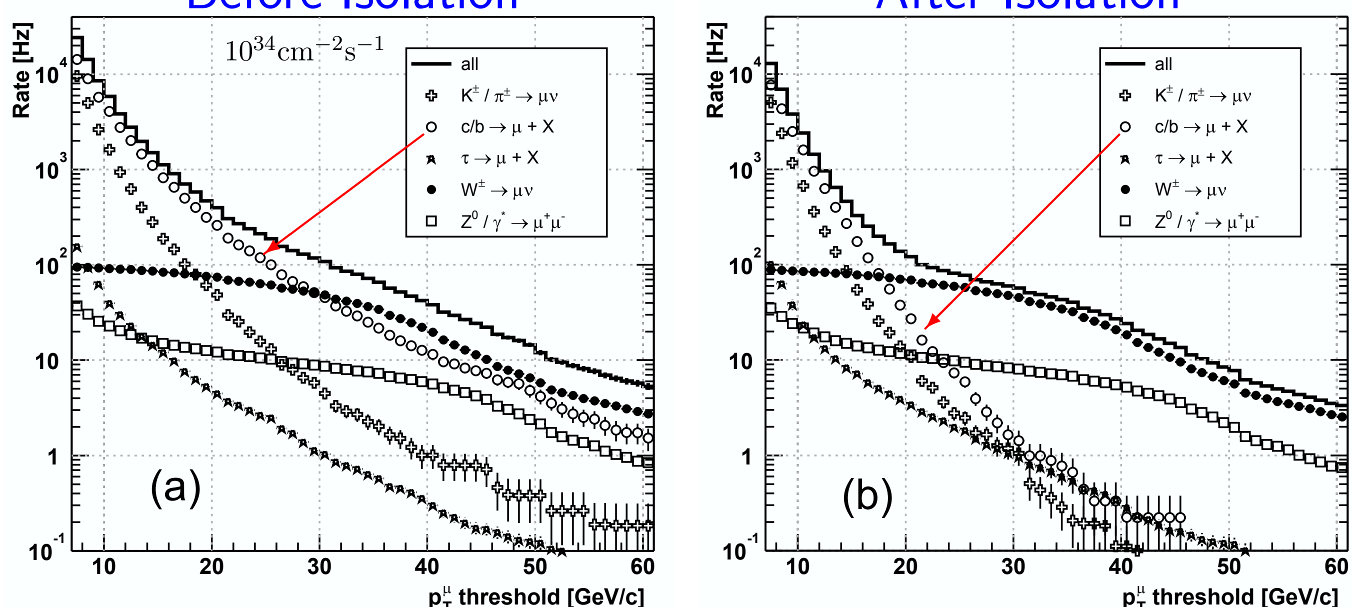
Muons – Isolation

A tool to reject muons from K, π, b, c decays which are often a background for discovery physics. Isolation is based on the $\Sigma\, E_T$ or $\Sigma\, p_T$ in a cone around the muon.

- Calorimeter Isolation
  E_T in calorimeter towers. Can be applied already at L2. Sensitive to pile-up
- Tracker Isolation
  $\Sigma\, p_T$ of tracks around L3 muon. Tracks from simplified Pixel Detector based reconstruction or Full Tracker reconstruction (regional and conditional)



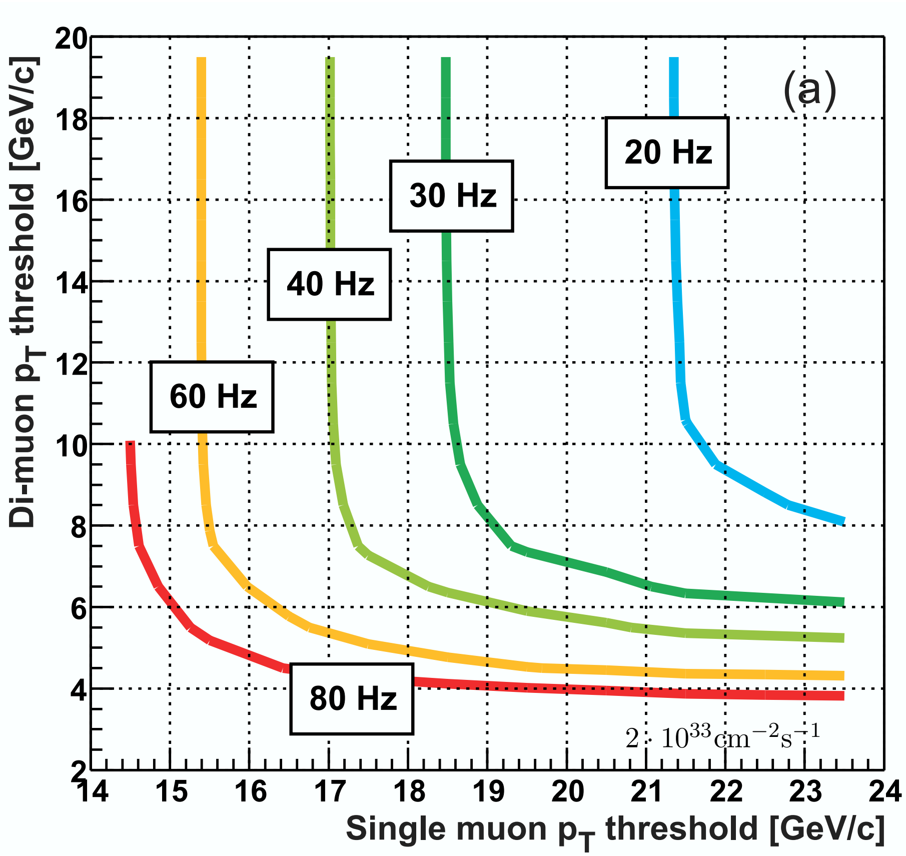
Before Isolation | After Isolation

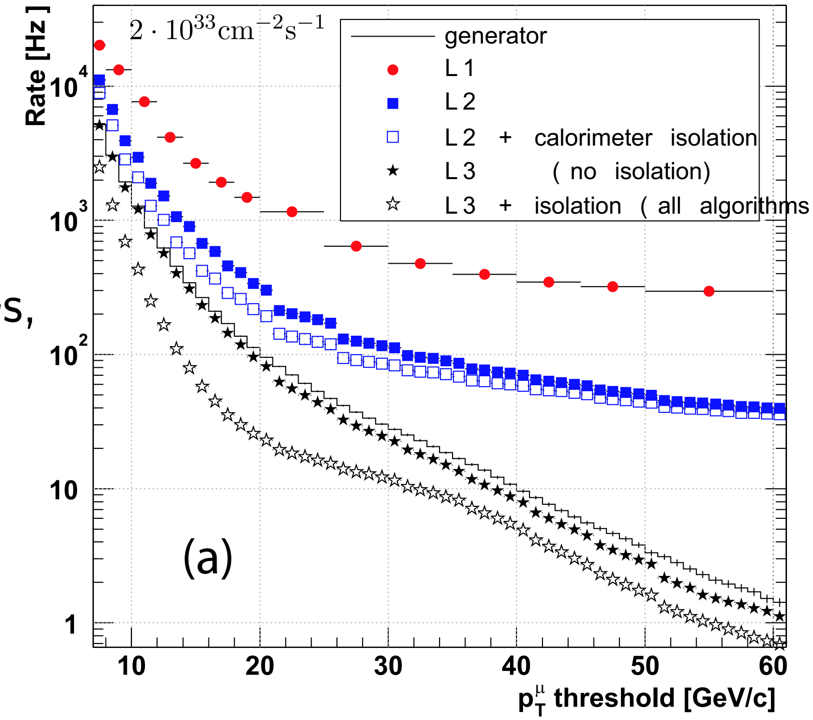


Isolation cuts are against B physics!

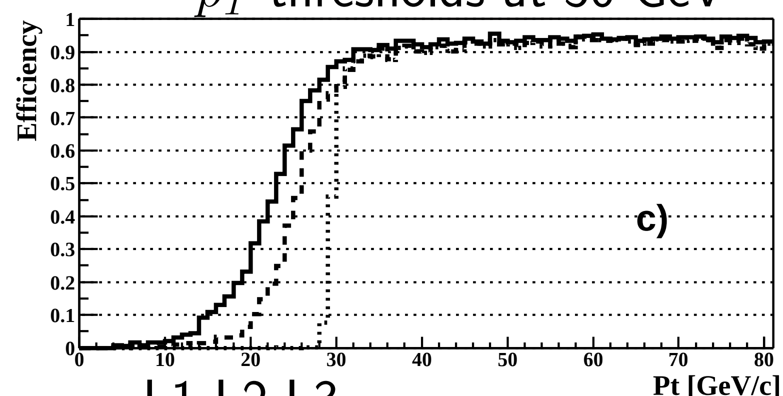
Muons – rates

- L1, L2 rate (almost) saturates at very high p_Ts,
- sharp L3 cut and steep rate curves.





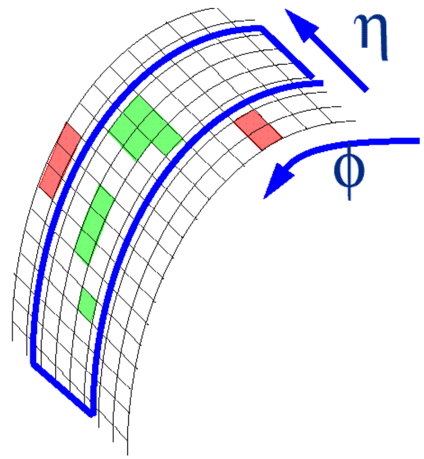
p_T thresholds at 30 GeV

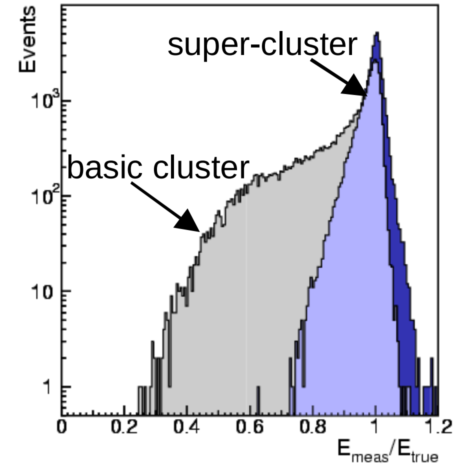


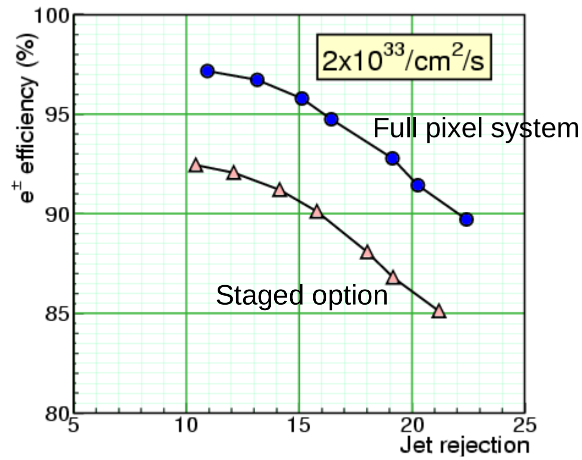
L1 L2 L3

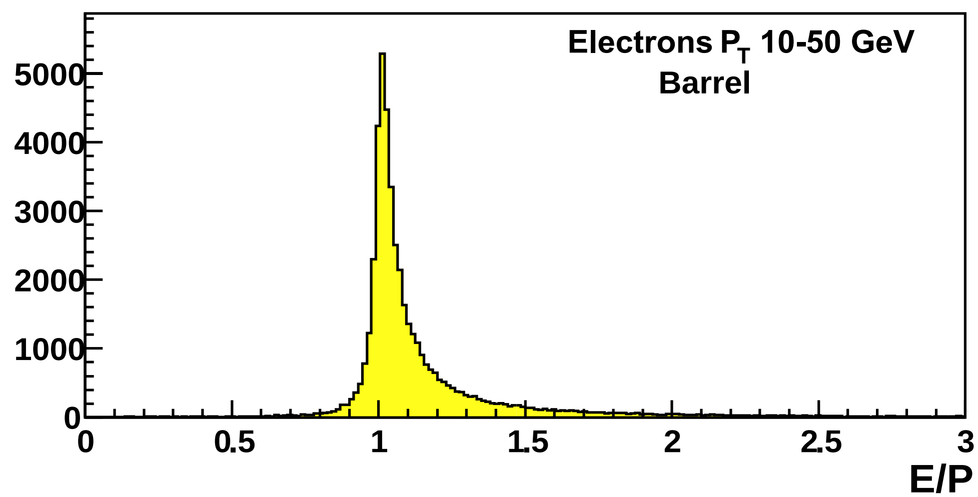
Electrons and Photons

- L2: Reconstruct clusters (full granularity) to match Level-1 candidates.
  Bremsstrahlung recovery with "super clustering" ($\sim\ 1X_0$ in Tracker) .
- L2.5: confirm electrons with pixel detector hits. Reject $\pi^0 \rightarrow 2\gamma$ background (high E_T cut for photons).
- L3: Electrons: Track reconstruction, E/p, η-matching;
  Photons: Threshold cut, Isolation.



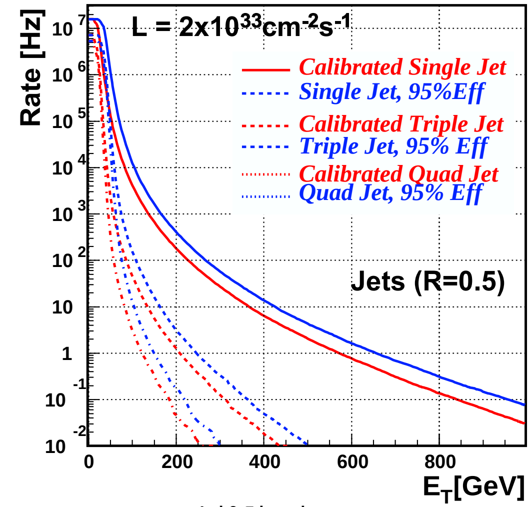






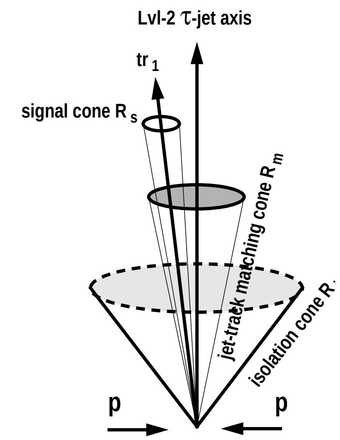
Jets and MET

- Jet reconstruction with iterative cone algorithm
- E_T miss reconstruction: vector sum of towers above thresholds



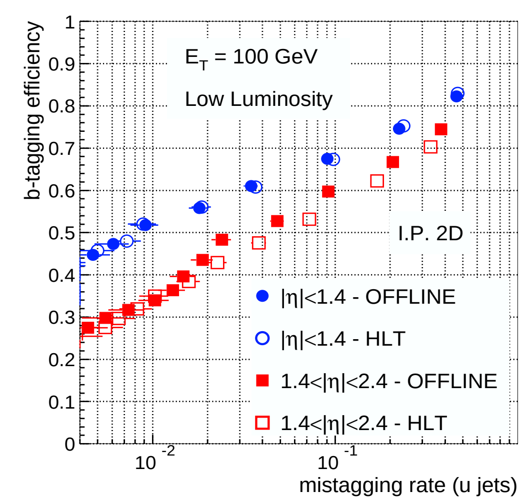
Taus

- L2: Narrow jet surrounded by isolation region.
- L2.5/L3: Pixel reconstruction or Full Tracker reconstruction. Check for leading track in the calorimeter defined matching cone. No tracks in bigger isolation cone.



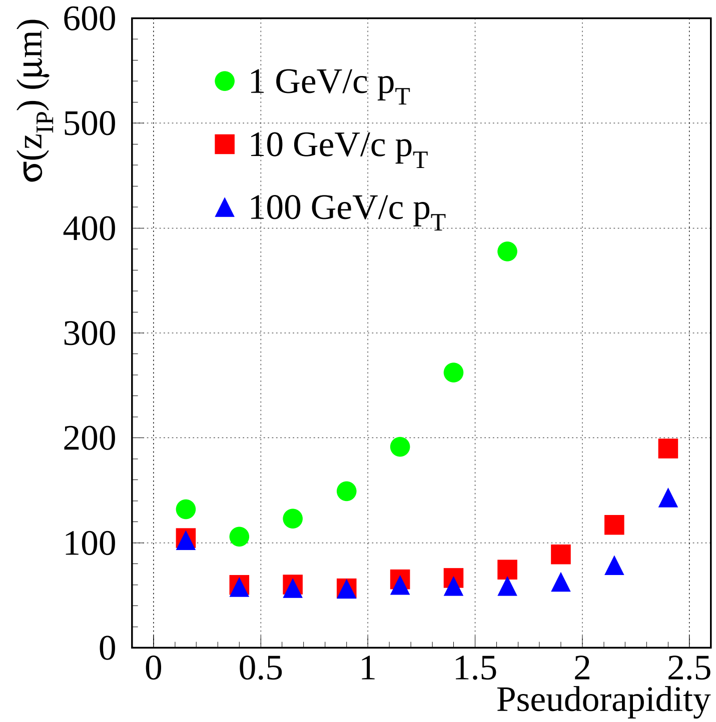
b-tagging

- algorithm(s) rely on large value of the b-hadron proper time (large impact parameter comparing to tracks from u,d jets),
- tracking region defined by calorimeter jet,
- regional and conditional tracking,
- HLT performance close to offline.



Primary Vertex reconstruction

Pixel detector allows for standalone global (or regional) track reconstruction with good space accuracy. Input to PV finding algorithms.



	High Lumi		Low Lumi	
Event Type	Closest PV Eff	Tagged PV Eff	Closest PV Eff	Tagged PV Eff
$q\bar{q}$ $E_T^{Jet} = 100$ GeV	0.99	0.97	0.98	0.97
$b\bar{b}$ $E_T^{Jet} = 100$ GeV	0.99	0.90	1.00	0.96
QCD $\hat{p}_T = 120 \div 170$ GeV/c	1.00	0.97	1.00	0.96
QCD $\hat{p}_T = 50 \div 80$ GeV/c	0.97	0.80	0.98	0.92
$B_s \rightarrow \mu\mu$	0.97	0.50	0.96	0.71
$h \rightarrow ZZ$ $m_h = 130$ GeV/c^2	0.98	0.95	0.99	0.98
$h \rightarrow WW$ $m_h = 140$ GeV/c^2	0.99	0.85	0.97	0.94
$h \rightarrow \gamma\gamma$ $m_h = 115$ GeV/c^2	0.96	0.52	0.94	0.75

HLT trigger table - rates $(2 \cdot 10^{33} cm^{-2} s^{-1})$

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (Hz)	Cumul rate (Hz)
1e, 2e	29, 17	34	34
1γ, 2γ	80, (40*25)	9	43
1μ, 2μ	19, 7	29	72
1τ, 2τ	86, 59	4	76
Jet * Miss-E_T	180 * 123	5	81
1-jet, 3-jet, 4-jet	657, 247, 113	9	89
e * jet	19 * 52	1	90
Inclusive b-jets	237	5	95
Calibration/other		10	105

HLT trigger table - efficiencies $(2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1})$

efficiencies to example signals:

channel	*Efficiency* (fiducial obj.)
$H(115\text{GeV})\rightarrow\gamma\gamma$	77%
$H(160\text{GeV})\rightarrow\text{WW}^*\rightarrow 2\mu$	92%
$H(150\text{GeV})\rightarrow\text{ZZ}\rightarrow 4\mu$	98%
$A/H(200\text{GeV})\rightarrow 2\tau$	45%
SUSY (~ 0.5 TeV sparticles)	$\sim$ 60%
with R_P - violation	$\sim$ 20%
$W\rightarrow e\nu$	42%
$W\rightarrow\mu\nu$	69%
$t\rightarrow\mu X$	72%

Timing Performance $(2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1})$

Numbers for a 1 GHz Pentium III (DAQ TDR, December 2002).

Trigger	CPU (ms)	Rate (kHz)	Total (s)
1e/γ, 2e/γ	160	4.3	688
1μ, 2μ	710	3.6	2556
1τ, 2τ	130	3.0	390
Jets, Jet * Miss-E_T	50	3.4	170
e * jet	165	0.8	132
B-jets	300	0.5	150

note: uncertainties, expected improvements, raw data checking and formatting not counted, does safety factor 3 requires same CPU?,....

note: CPU dominated by GEANE propagations – now under replacement.

Weighted average for all trigger streams $\simeq$ 300 ms/L1 event (2002).
Moore's law: 2xCPU each 1.5 years $\longrightarrow$ $\simeq$40ms/L1 event in 2007.
40 ms/ev $\times$ 50 kHz = 2000 processors $\longrightarrow$ filter farm of $\sim$ 1000 dual CPU boxes.

Is there a place for B-physics?

Some Standard Model physics not included in standard HLT selection (example B-physics). However we want to do it at low luminosity and during luminosity drops through fill. B-physics dedicated algorithms at HLT are high efficient with low CPU cost. B-physics limitations due to Level-1 trigger. $\Longrightarrow$ talk by Nancy Marinelli.
There is a room for B-physics.

Summary

- Event selection at LHC is challenging,
- CMS trigger with only two physics layers,
  - Level-1: partially programmable hardware,
  - HLT: great flexibility at processor farm.

- High-Level Trigger selection of 1:1000 is possible at single processor farm.

- The CMS High-Level Trigger selection optimized for discovery physics,
- There is a room for exclusive B-physics.