The
CMS High Level Trigger

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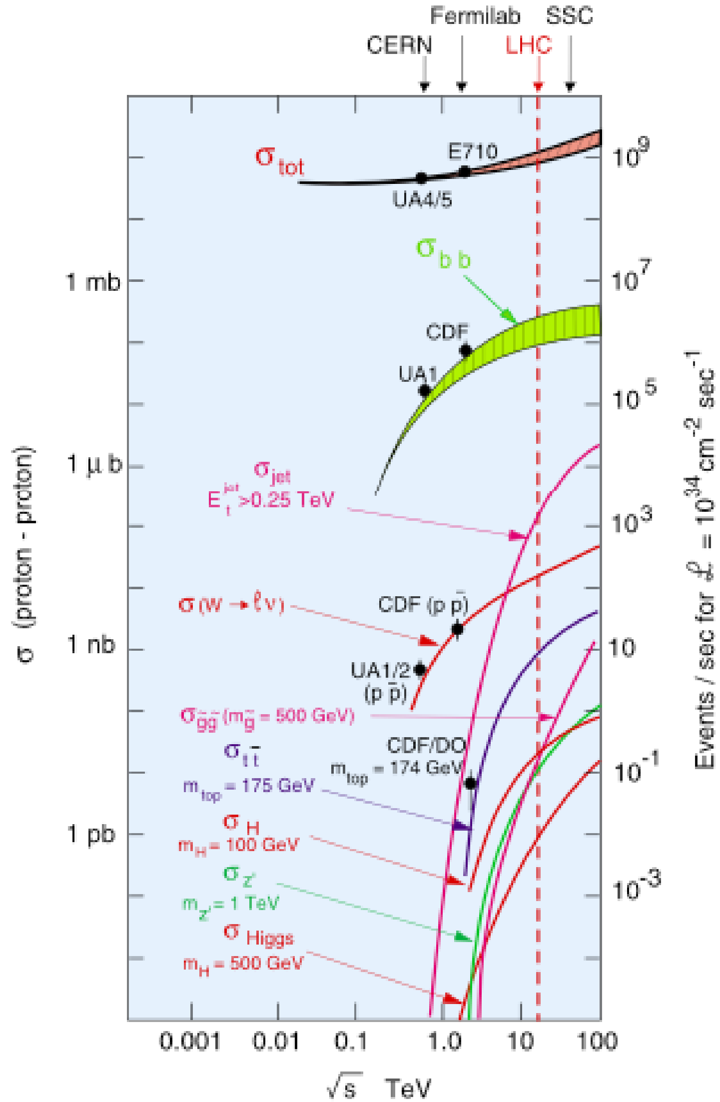
Introduction

- Introduction to the CMS trigger system
- Goals of the High Level Trigger "Exercise"
- Development of the Trigger menu
  - Level-1 and HLT Trigger paths and rates
- CPU performance of the HLT
  - Sensitivity to the input conditions
- Discussion of some of the associated uncertainties

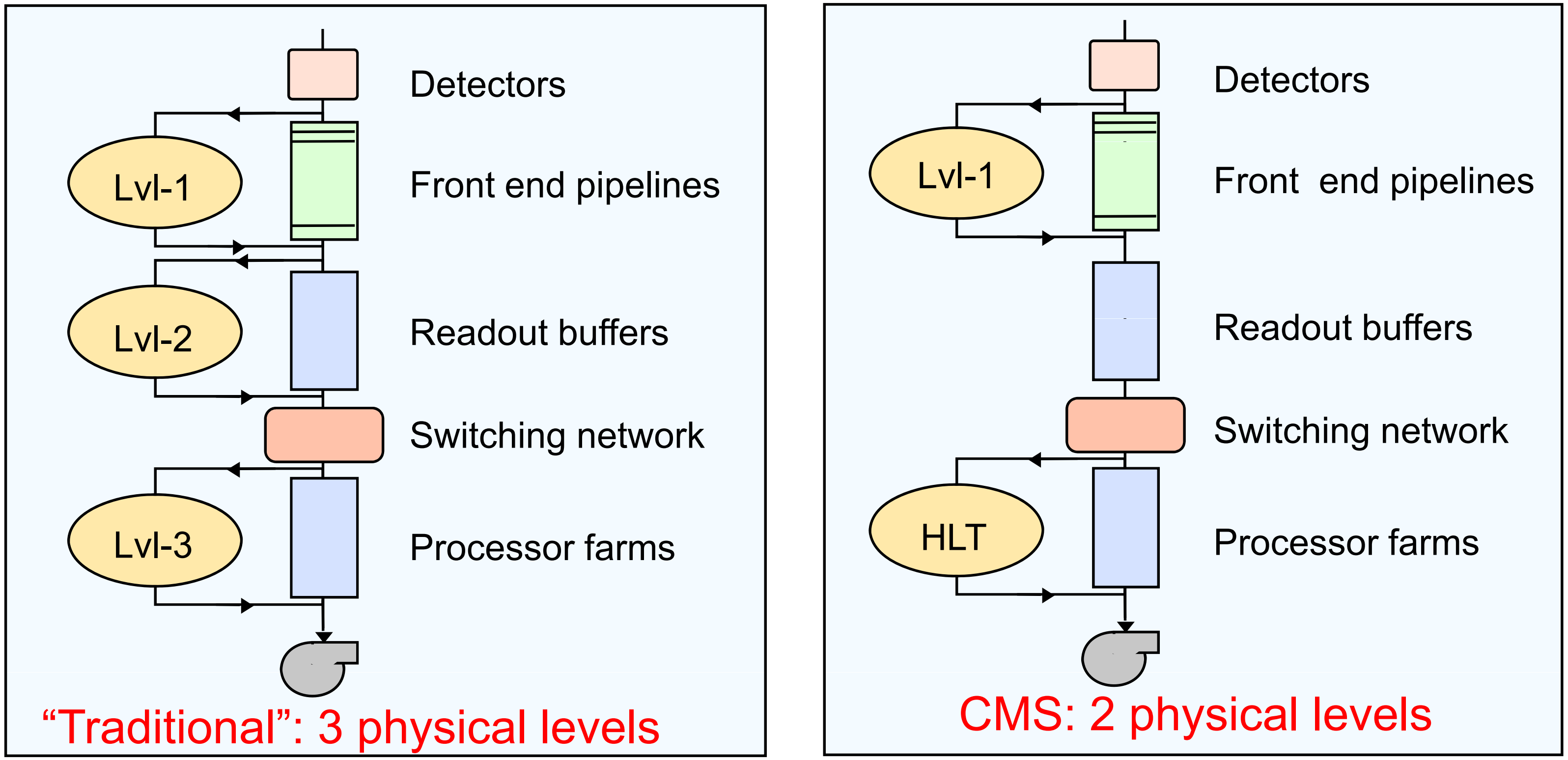
Trigger Challenges

- Filter out the "interesting" interactions from the "uninteresting" ones
- Input Rate:
  - ~10^9 interactions/second at design luminosity
  - (L = 10^{34} $cm^{-2}s^{-1}$)
- Output rate:
  - Ultimately limited by speed a which we can write events to tape (~150 Hz)



Trigger Architecture

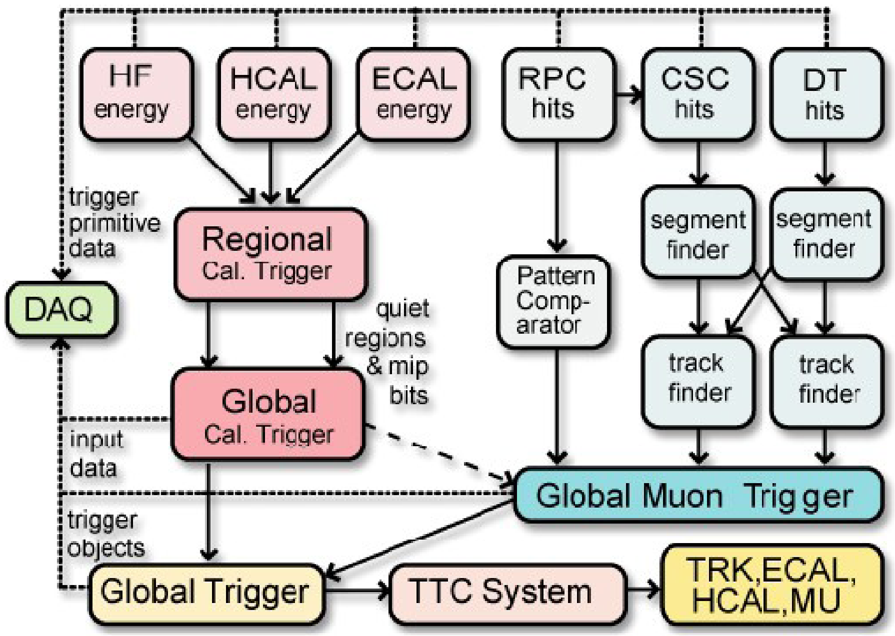
- 2-tiered trigger design



- Possible because of large, fast switching network

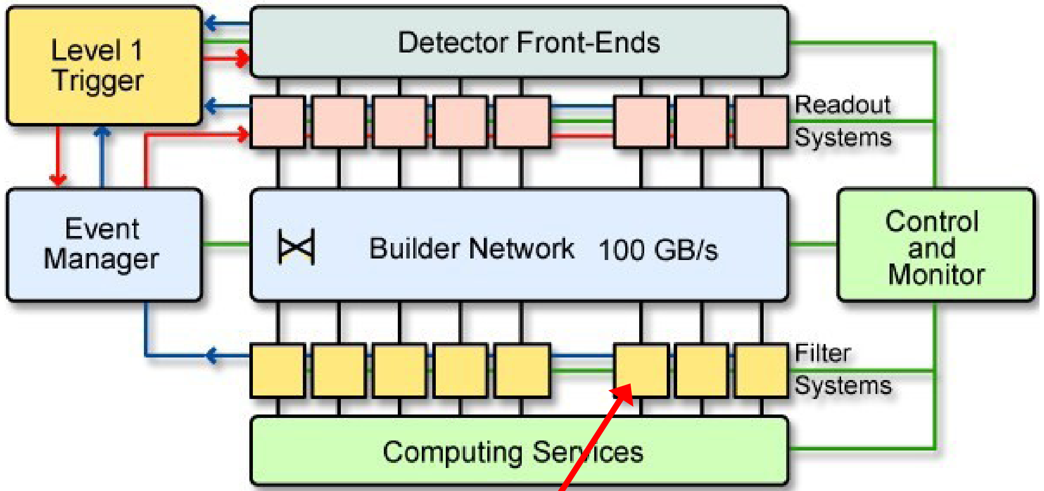
The Level-1 Trigger

- Reduce data rate from 40 MHz to 50 kHz while keeping the interesting physics events
  – Custom electronic boards and chips
- Selects muons, electrons, photons, jets
  – E_T and location in detector
- Also Missing E_T, Total E_T, H_T, and jet counts
- Total decision latency: 3.2 μs



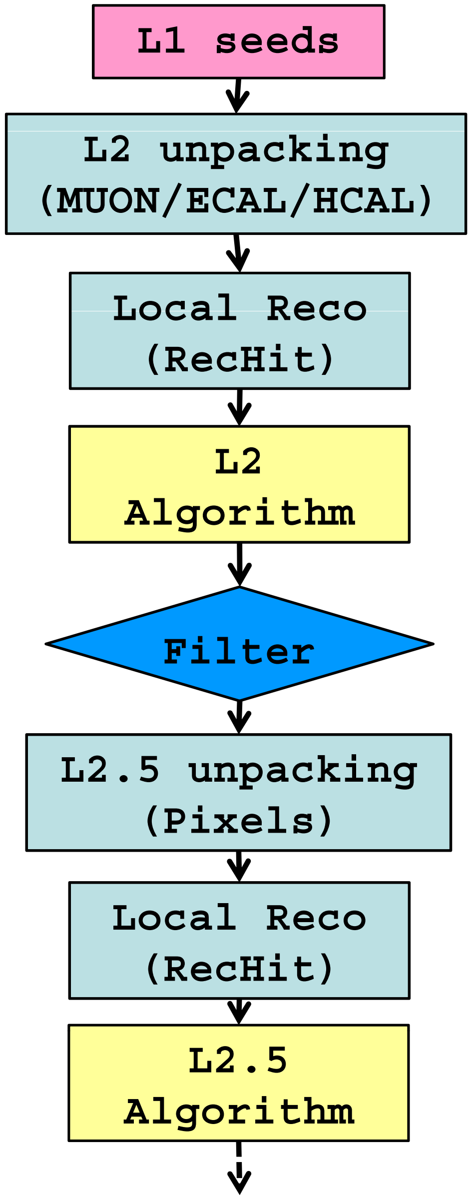
High Level Trigger (HLT)

- High-Level triggers reduce rate from 50 kHz to O(150 Hz)
- HLT does event reconstruction "on demand" seeded by the L1 objects found, using full detector resolution
- Algorithms are essentially offline quality but optimized for fast performance



~1000 dual processor PC cluster

HLT Algorithm Design



- Each HLT trigger path is a sequence of modules
- Processing of the trigger path stops once a module returns false
- Reconstruction time is significantly improved by doing regional data-unpacking and local reconstruction across HLT
- All algorithms (except for Jets) regional
  - Seeded by previous levels (L1, L2, L2.5)

"Local": using one sub-detector only
"Regional": using small (η, φ) region

The HLT "Exercise"

Determine CPU-performance for early physics-run Trigger Menu

- Driven by need to purchase Filter Farm at end of 2007
- Design for $L = 10^{32}\ cm^{-2}\ s^{-1}$
  - Maximum luminosity in 2008
- Assuming an L1 output rate of 50 kHz and a 2000 CPU Filter Farm:
  - ➢ **HLT CPU time budget ~ 40ms/event**

HLT Timing Considerations

HLT Timing is influenced by:

- Trigger menu (L1T & HLT)
  - Determined by physics priorities
- Input L1Trigger rate
  - Limited by bandwidth
  - Parameters of various L1T algorithms, e.g., H/E
- HLT algorithms and configuration
  - Standard trigger paths at HLT seeded by L1 trigger bits
  - Order of modules and filters in a path
  - Parameters of the modules and filters

Level-1 Trigger Menu

- L1 Menu optimized to fit within the L1 bandwidth
  - Allow a safety factor of 3 to account for uncertainties in the trigger rate determination, e.g. underestimate of input cross sections, poor beam conditions, detector performance, etc.
    - 17 kHz instead of nominal 50 kHz allowed by DAQ
- All L1 bits matched to HLT paths to help ensure proper estimation of HLT processing times
- Realistic menu including double and mixed triggers for specific physics channels

L1 Trigger Menu: Single and Double

L1 Trigger	Threshold (GeV)	Prescale	Rate (kHz)
A_SingleMu3	3	1000	0.01 ± 0.00
A_SingleMu5	5	1000	0.00 ± 0.00
A_SingleMu7	7	1	1.11 ± 0.04
A_SingleMu10	10	1	0.47 ± 0.03
A_SingleMu14	14	1	0.18 ± 0.02
A_SingleMu20	20	1	0.09 ± 0.01
A_SingleMu25	25	1	0.06 ± 0.01
A_SingleIsoEG5	5	10000	0.00 ± 0.00
A_SingleIsoEG8	8	1000	0.01 ± 0.00
A_SingleIsoEG10	10	100	0.04 ± 0.01
A_SingleIsoEG12	12	1	2.47 ± 0.06
A_SingleIsoEG15	15	1	1.10 ± 0.04
A_SingleIsoEG20	20	1	0.32 ± 0.02
A_SingleIsoEG25	25	1	0.14 ± 0.01
A_SingleEG5	5	10000	0.00 ± 0.00
A_SingleEG8	8	1000	0.01 ± 0.00
A_SingleEG10	10	100	0.04 ± 0.01
A_SingleEG12	12	100	0.03 ± 0.01
A_SingleEG15	15	1	1.51 ± 0.05
A_SingleEG20	20	1	0.52 ± 0.03
A_SingleEG25	25	1	0.25 ± 0.02
A_SingleJet70	70	100	0.02 ± 0.01
A_SingleJet100	100	1	0.43 ± 0.02
A_SingleJet150	150	1	0.07 ± 0.01

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L1 Trigger	Threshold (GeV)	Prescale	Rate (kHz)
A_SingleJet200	200	1	0.02 ± 0.01
A_SingleTauJet40	40	1000	0.02 ± 0.01
A_SingleTauJet80	80	1	0.68 ± 0.03
A_SingleTauJet100	100	1	0.20 ± 0.02
A_HTT250	250	1	2.56 ± 0.06
A_HTT300	300	1	0.65 ± 0.03
A_HTT400	400	1	0.08 ± 0.01
A_HTT500	500	1	0.02 ± 0.00
A_ETM20	20	10000	0.00 ± 0.00
A_ETM30	30	1	5.69 ± 0.09
A_ETM40	40	1	0.40 ± 0.02
A_ETM50	50	1	0.05 ± 0.01
A_ETM60	60	1	0.01 ± 0.00
A_DoubleMu3	3	1	0.28 ± 0.02
A_DoubleIsoEG8	8	1	0.28 ± 0.02
A_DoubleIsoEG10	10	1	0.08 ± 0.01
A_DoubleEG5	5	10000	0.00 ± 0.00
A_DoubleEG10	10	1	0.19 ± 0.02
A_DoubleEG15	15	1	0.05 ± 0.01
A_DoubleJet70	70	1	0.58 ± 0.03
A_DoubleJet100	100	1	0.11 ± 0.01
A_DoubleTauJet20	20	1000	0.02 ± 0.01
A_DoubleTauJet30	30	100	0.08 ± 0.01
A_DoubleTauJet40	40	1	2.36 ± 0.06

L1TEmulator Developers +
Werner Sun, Sridharda Dasu, Pedram Bargassa

L1 Trigger Menu: Mixed

A_Mu3_IsoEG5	3,5	1	0.95 ± 0.04
A_Mu5_IsoEG10	5,10	1	0.04 ± 0.01
A_Mu3_EG12	3,12	1	0.09 ± 0.01
A_Mu3_Jet15	3,15	20	0.30 ± 0.02
A_Mu5_Jet15	5,15	1	1.62 ± 0.05
A_Mu3_Jet70	3,70	1	0.10 ± 0.01
A_Mu5_Jet20	5,20	1	1.18 ± 0.04
A_Mu5_TauJet20	5,20	1	0.66 ± 0.03
A_Mu5_TauJet30	5,30	1	0.38 ± 0.02
A_IsoEG10_Jet15	10,15	20	0.15 ± 0.01
A_IsoEG10_Jet30	10,30	1	1.95 ± 0.05
A_IsoEG10_Jet20	10,20	1	3.04 ± 0.06
A_IsoEG10_Jet70	10,70	1	0.26 ± 0.02
A_IsoEG10_TauJet20	10,20	1	1.95 ± 0.05
A_IsoEG10_TauJet30	10,30	1	1.33 ± 0.04
A_TauJet30_ETM30	30,30	1	1.96 ± 0.05
A_TauJet30_ETM40	30,40	1	0.26 ± 0.02
A_TripleMu3	3	1	0.01 ± 0.00
A_QuadJet30	30	1	0.58 ± 0.03
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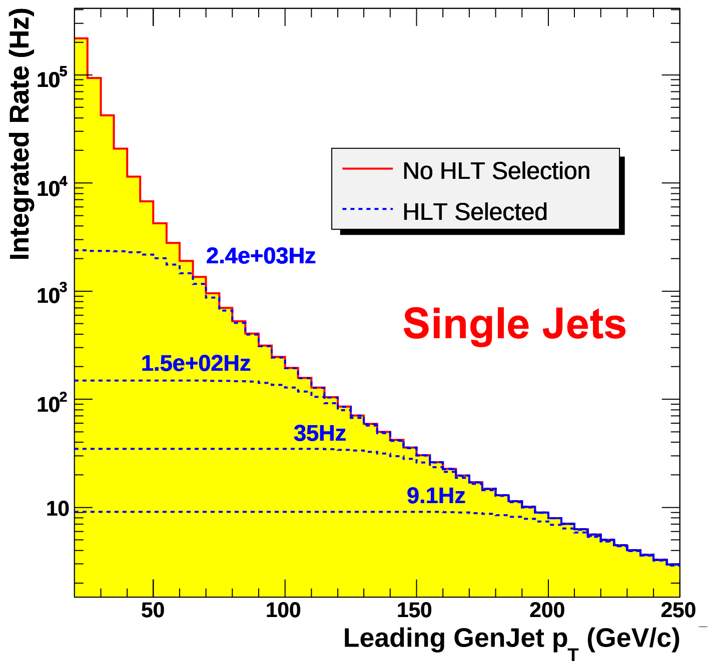
L1 Trigger	Threshold (GeV)	Prescale	Rate (kHz)
A_MinBias_HTT10	10	large	0.40 ± 0.00
A_ZeroBias	0	large	0.40 ± 0.00
Total L1 Trigger Rate (kHz)			16.67 ± 0.15

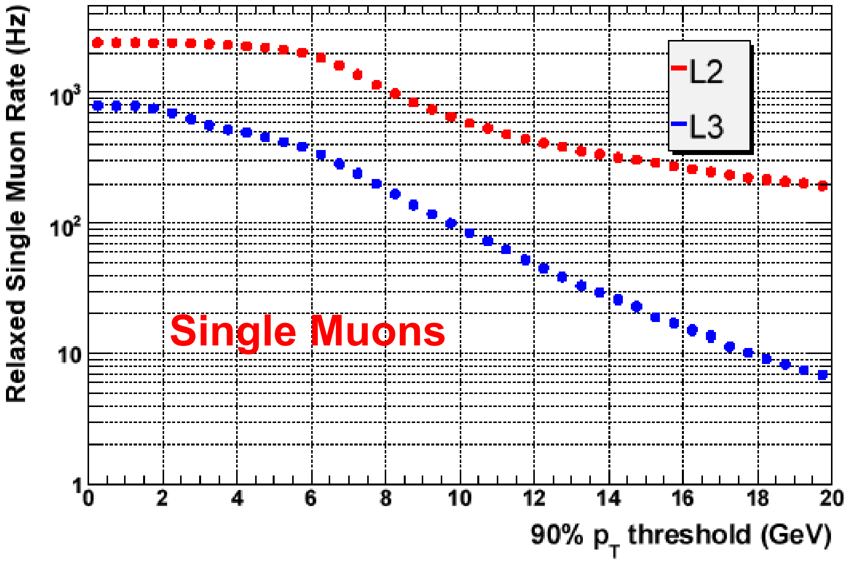
Table 9.1: Trigger table showing L1 rates at chosen thresholds for $\mathcal{L} = 10^{32}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

- μ: 1.5 kHz
- eγ: 2.5 kHz
- jets: 3.5 kHz
- τ: 3 kHz
- MET: 5.5 kHz
- x-channels: 8 kHz
- Total: 17 kHz

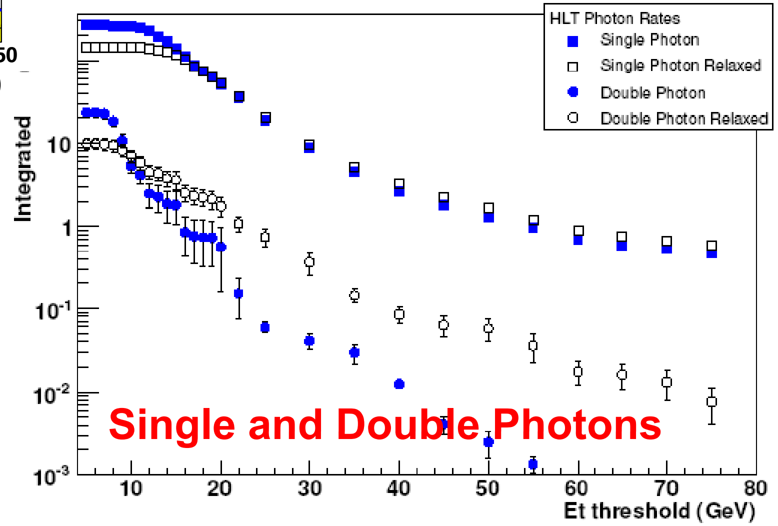
HLT Rates



Integrated Rate (Hz)
No HLT Selection
HLT Selected
2.4e+03Hz
1.5e+02Hz
35Hz
9.1Hz
Single Jets
Leading GenJet p_T (GeV/c)



Relaxed Single Muon Rate (Hz)
L2
L3
Single Muons
90% p_T threshold (GeV)



HLT Photon Rates
Single Photon
Single Photon Relaxed
Double Photon
Double Photon Relaxed
Integrated
Single and Double Photons
Et threshold (GeV)

HLT Menu

e, γ, τ + X

HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)
Single Isolated e	A_SingleIsoEG12	15	17.3 ± 2.3
Single Relaxed e	A_SingleEG15	17	9.3 ± 1.3
Double Isolated e	A_DoubleIsoEG8	10	0.2 ± 0.1
Double Relaxed e	A_DoubleEG10	12	0.9 ± 0.2
Single Isolated γ	A_SingleIsoEG12	30	8.3 ± 0.7
Single Relaxed γ	A_SingleEG15	40	2.8 ± 0.2
Double Isolated γ	A_DoubleIsoEG8	(20,20)	0.6 ± 0.4
Double Relaxed γ	A_DoubleEG10	(20,20)	1.9 ± 0.5
High E_T e	A_SingleEG15	80	0.5 ± 0.2
High E_T e	A_SingleEG15	200	0.1 ± 0.0
Lifetime b-tag 1-jet	$\diamond$	180	1.5 ± 0.2
Lifetime b-tag 2-jets	$\diamond$	120	2.4 ± 0.3
Lifetime b-tag 3-jets	$\diamond$	70	1.9 ± 0.1
Lifetime b-tag 4-jets	$\diamond$	40	2.1 ± 0.1
Lifetime b-tag H_T	$\diamond$	470	2.9 ± 0.1
Charged Higgs τ	A_SingleTauJet80	15	0.2 ± 0.0
$\tau + \not{E}_T$	A_TauJet30_ETM30	15	1.8 ± 0.2
Double τ (Calo+Pixel)	A_DoubleTauJet40	15	5.0 ± 0.7
e + b-jet	A_IsoEG10_Jet20	(10, 35)	0.1 ± 0.0
e + jet	A_IsoEG10_Jet30	(12, 40)	11.9 ± 1.2
$e + \tau$	A_IsoEG10_TauJet20	(12, 20)	0.1 ± 0.2
Prescaled e/γ	A_SingleIsoEG5	—	3.0 ± 0.0
Prescaled μ	See Table 2.6		3.0 ± 0.0
Min.Bias	A_MinBias_HTT10	—	0.5 ± 0.0
Pixel Min.Bias	A_ZeroBias	—	0.5 ± 0.0
Zero Bias	A_ZeroBias	—	1.0 ± 0.0
Total HLT rate (Hz)			**150 ± 4.9**

Monica Vazquez Acosta
Marco Pieri,
Alessio Ghezzi, …

Ian Tomalin

Simone Gennai

Greg Landsberg, Duong Nguyen, Len Christofek, Nadia Eram

Marta Felcini

HLT
Sing
Doub
Trip
Qua
Acopl. D
Acopl. Sing
Acopl. Dou
Single-J
Double-
Triple-J
Quad-J
VBF Doub
H_T
SUSY 2
Single Jet
Single Jet I
Single Jet P

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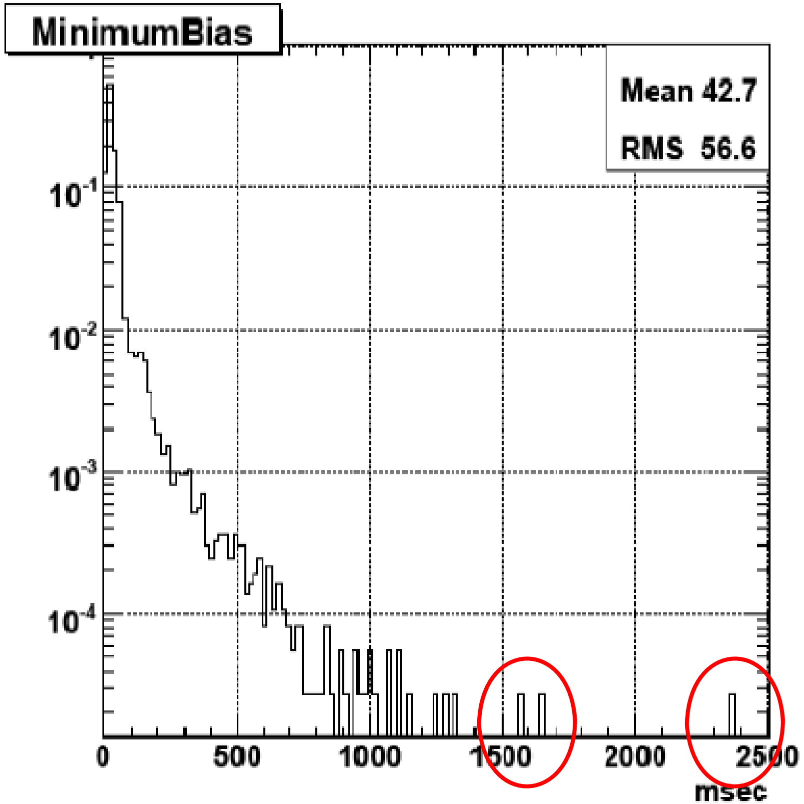
Same-si
μ-base
Pre
μ-based
μ-based
μ-based
μ-base
$b \rightarrow$
μ
$\mu + \mu$-
μ
$e + \mu$

HLT Processing Times

- 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



Time Plot: Tulika & Simone

HLT Processing Times (2)

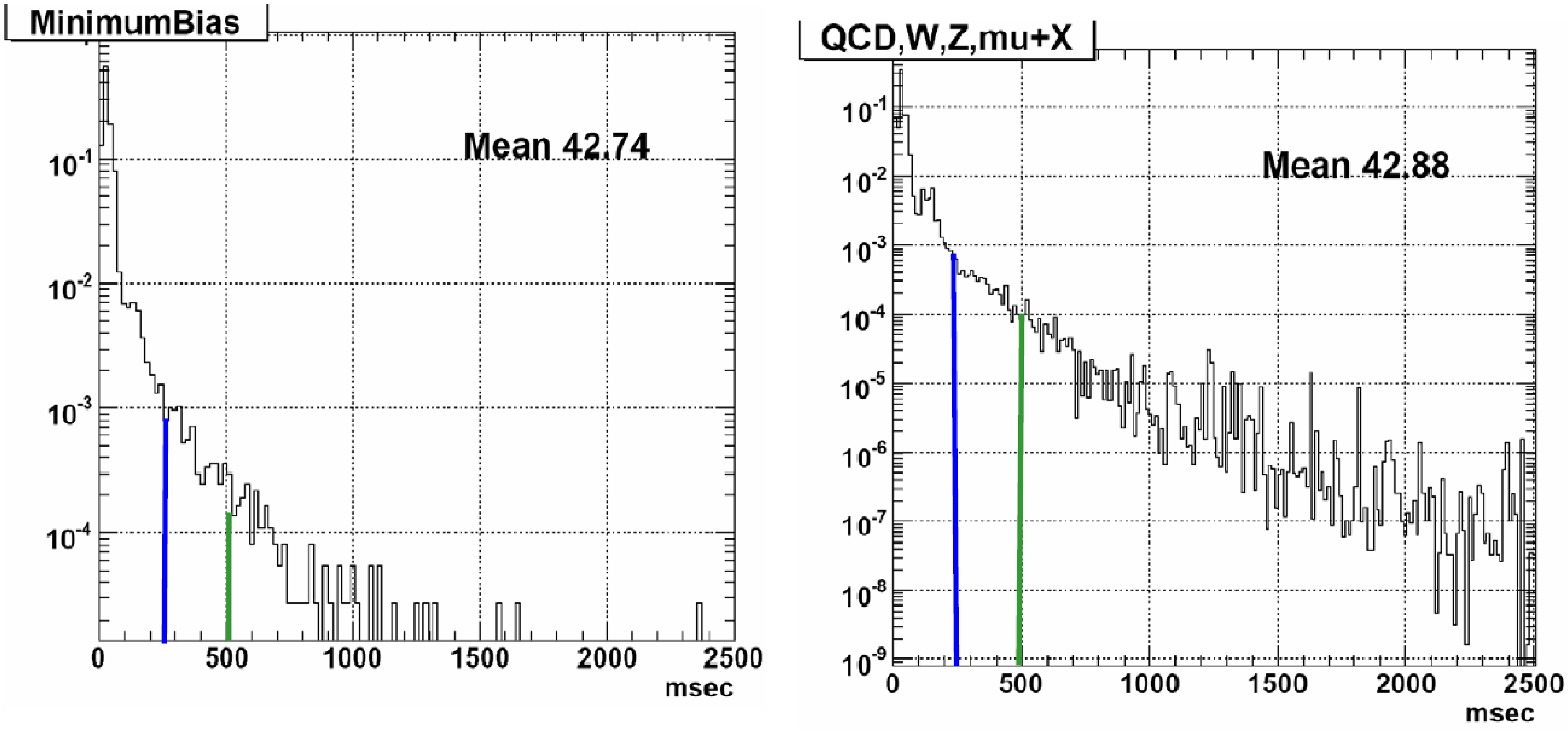
- Calculate ave. processing times for different QCD, W/Z, μ-enriched samples
  - Weight by combined cross-section and L1 selection efficiency, add them up
- Compared weighted sum with result obtained on L1-accepted min. bias events

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
$pp \to \mu X$	42.96 ± 0.37	$(1.03 \pm 0.01) \times 10^7$	74
$W \to e\nu$	93.18 ± 0.59	$(7.36 \pm 0.05) \times 10^2$	280
$W \to \mu\nu$	84.67 ± 0.80	$(8.29 \pm 0.08) \times 10^2$	123
$Z \to ee$	99.54 ± 0.67	$(8.16 \pm 0.05) \times 10^2$	739
$Z \to \mu\mu$	98.99 ± 1.20	$(7.82 \pm 0.09) \times 10^2$	184
Weighted sum of QCD, W, Z and $pp \to \mu X$ contributions			42.9 ± 5.6

Tulika Bose

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

HLT Processing Times (3)



Time Plot: Tulika & Simone

Timing Improvements Since Early 2007

HLT CPU time budget ~ 40ms/event

- Early 2007: > 450 ms
  - HCAL: use zero-suppressed data (100 → ~2-3 ms)
  - ECAL: optimize data-unpacking (200 → ~15 ms)
  - EgammaHLT: regional reconstruction
- Last May:120-140 ms
  - MuonHLT: regional reconstruction, improved L2 muon propagator
  - Optimization of tau, b-jet algorithms: fast rejection earlier in path
  - Switch from Pentium IV/AMD to Core-2 machines (~35%)
    - Data cache (memory allocation) more important than clock speed
- Early June:70 ms
  - Faster siStrip unpacking code
  - Regional ECAL unpacking implemented for egamma, muonHLT
- Middle of June:43 ms

Sensitivity to the Trigger Menu

Try an alternate trigger table within the bandwidth restrictions of L1T to HLT (17 kHz)

- Motivated by increasing the W/Z efficiencies of the τ hadronic channels
  - L1 Single-tau: 80 → 60 GeV; L1 Double-tau: 40 → 35 GeV
  - eff(W): 10% →17% ; eff(H200): 15% →32% ; eff(H400): 28% →44%
  - Replace "MET" by "MET + HT" condition for jet triggers to balance L1
  - <T>: 43 ms →45.8 ms (min.bias),
    : 45.2 ±3.4 ms (QCD/W/Z/μ mix)

Sensitivity to the Trigger Menu (2)

Raise L1 thresholds to $L = 2 \times 10^{33}\ cm^{-2}\ s^{-1}$ menu from PTDRv2

- Contributions from high-P_T QCD bins become more relevant
- Assume average HLT processing time per sample remains ~same
  - In reality, it will increase because of pile-up
- <T>: 45.2 ms $\rightarrow$55.6 ±4.2 ms (QCD/W/Z/μ mix)
  - CPU-processing times still under control

Systematic Uncertainties

- Overall rate uncertainties are accounted for by the x3 safety factor. However, there are systematic effects to be considered
  - QCD background and b cross section uncertainties
  - $pp \rightarrow eX$ is underestimated
- Noise, calibration and alignment contributions
  - Study assumes default noise, good calibration and perfect alignment
  - Reality will be different, especially at the startup
  - More energy in the detector longer it takes to process
- Calibration and other triggers not included yet
  - Adds to processing time

Summary

We made it to 43 ms!

- Thanks to all involved. The HLT Exercise was a CMS-wide effort.
- Physics and CPU performance consistent with the CMS physics program and resources
  - A realistic global trigger menu for early physics run conditions ($L = 10^{32}\ cm^{-2}s^{-1}$) is in place
- The exercise is fully documented in a note submitted to LHCC: **CERN-LHCC 2007-021, LHCC-G-134**
  - "What is the CPU performance of the HLT?"
  - 56 pages, ~80 authors