CMS Trigger Challenge

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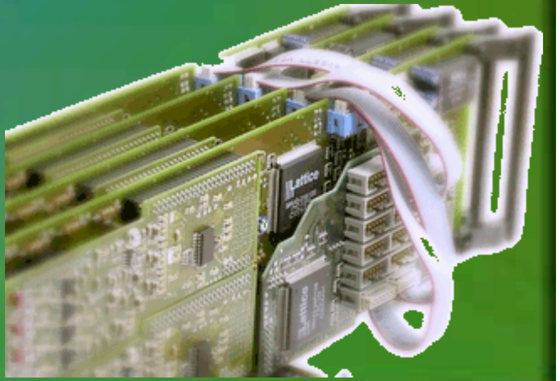
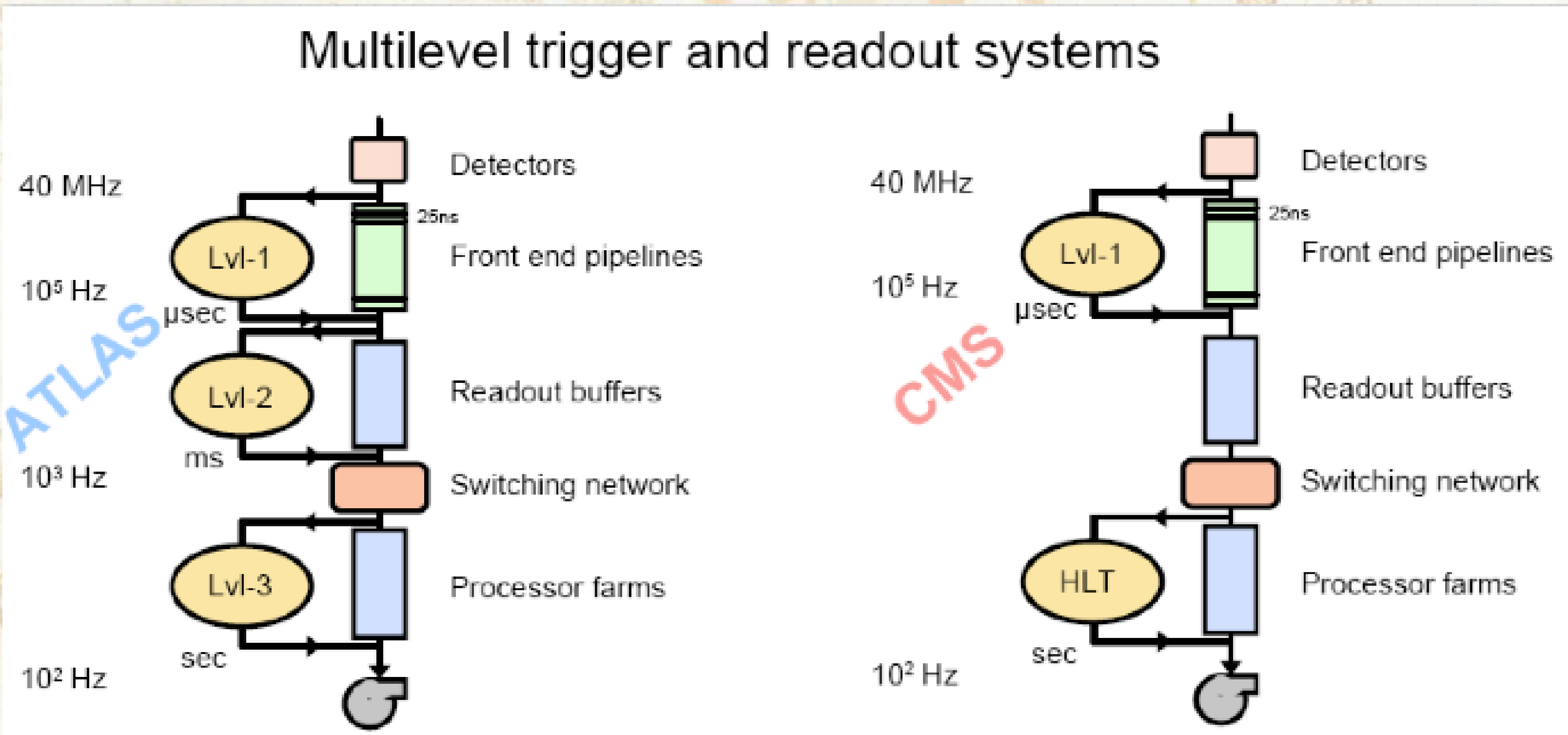
Detecting the Unexpected

Workshop at the UC Davis



Trigger Architecture

- Must reduce 32 MHz of input interactions to 100 Hz
  - Do it in steps/successive approximations: “Trigger Levels”

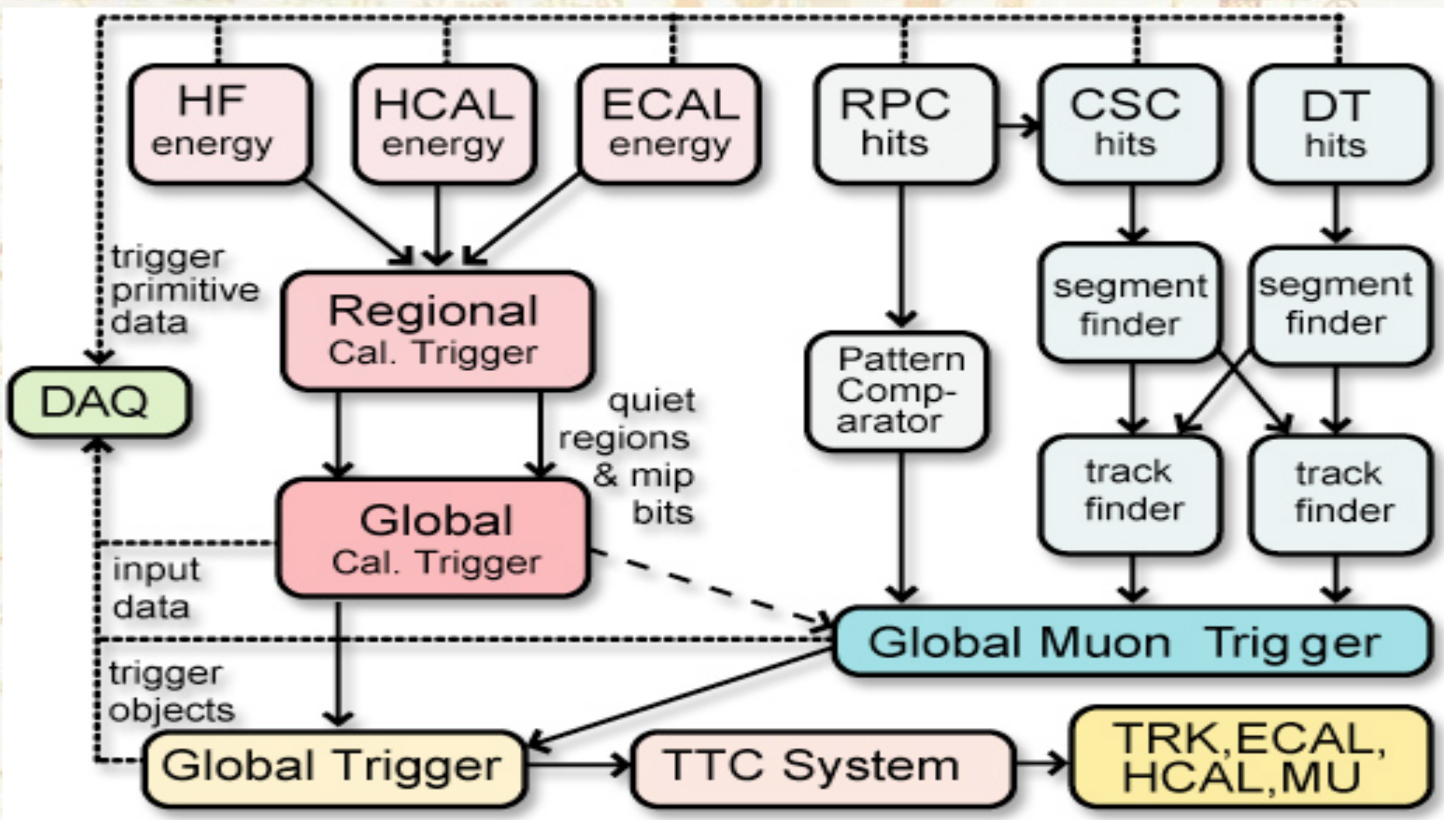


Recent progress in networking/switching has justified CMS choice

Level-1 Trigger Scheme

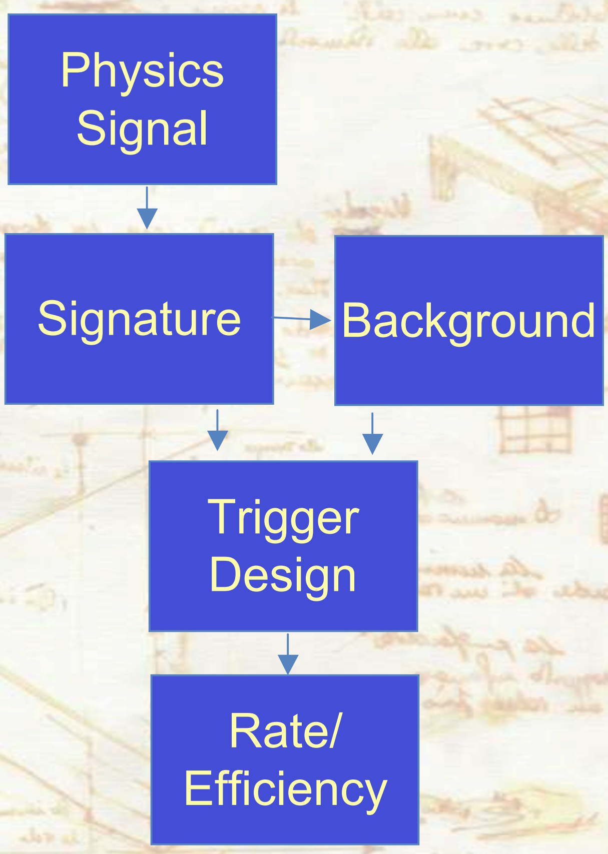
Electrons, Photons, Jets, ME_T — $3<|\eta|<5$, $|\eta|<3$, $|\eta|<3$

Muons — $|\eta|<2.1$, $0.9<|\eta|<2.4$, $|\eta|<1.2$

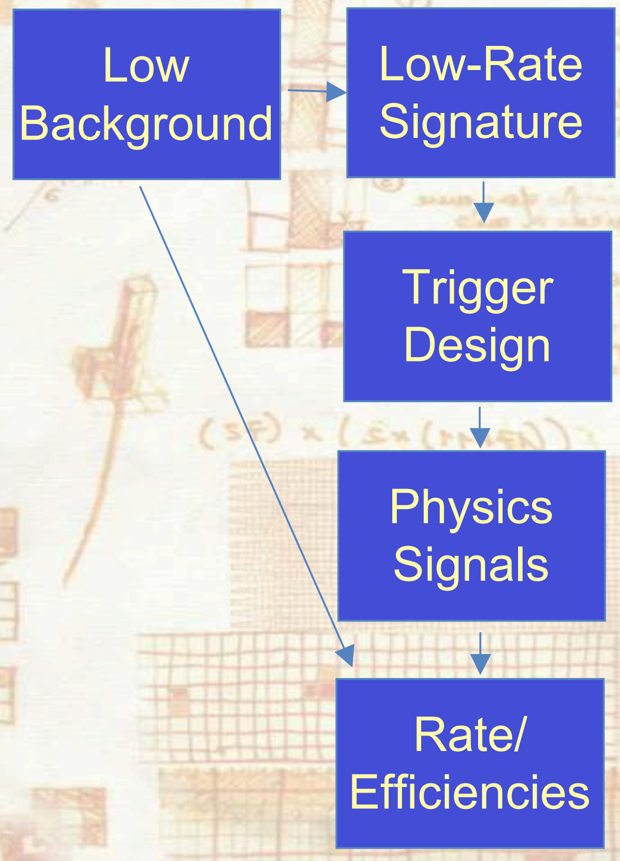


Trigger Design Strategies

- Traditional (top-down) design:



- Alternative (bottom-up) design:



Pro's and Con's

- Top-down Approach
- Examples:
  - e+jets trigger for top in lepton+jets
  - 2 jets + ME_T trigger for squark/gluino searches
- Pro's:
  - Optimum design for well-defined signals
  - Thorough threshold optimization
- Con's:
  - Inflexibility
  - Covers only a small fraction of allowed model space
  - No model – no trigger?

- Bottom-Up Approach
- Example:
  - Low-threshold μe trigger for generic searches
  - H_T trigger
- Pro's:
  - Casting net for large variety of signals, possibly missed by the dedicated triggers
  - Largely model-indpendent trigger
- Con's:
  - Non-optimum (purely rate-driven) design
  - Loss of efficiency compared to dedicated triggers

HLT Trigger Table for 2x10^{33} cm^{-2}s^{-1}

From Physics TDR, vol. 2

Trigger	L1 bits used	L1 Prescale	HLT Threshold (GeV)	HLT Rate (Hz)
Inclusive e	2	1	26	23.5 ± 6.7
e-e	3	1	12, 12	1.0 ± 0.1
Relaxed e-e	4	1	19, 19	1.3 ± 0.1
Inclusive γ	2	1	80	3.1 ± 0.2
γ-γ	3	1	30, 20	1.6 ± 0.7
Relaxed γ-γ	4	1	30, 20	1.2 ± 0.6
Inclusive μ	0	1	19	25.8 ± 0.8
Relaxed μ	0	1	37	11.9 ± 0.5
μ-μ	1	1	7, 7	4.8 ± 0.4
Relaxed μ-μ	1	1	10, 10	8.6 ± 0.6
$\tau + E_T^{miss}$	10	1	65 (E_T^{miss})	0.5 ± 0.1
Pixel τ-τ	10, 13	1	—	4.1 ± 1.1
Tracker τ-τ	10, 13	1	—	6.0 ± 1.1
$\tau + e$	26	1	52, 16	< 1.0
$\tau + \mu$	0	1	40, 15	< 1.0
b-jet (leading jet)	36, 37, 38, 39	1	350, 150, 55 (see text)	10.3 ± 0.3
b-jet (2nd leading jet)	36, 37, 38, 39	1	350, 150, 55 (see text)	8.7 ± 0.3
Single-jet	36	1	400	4.8 ± 0.0
Double-jet	36, 37	1	350	3.9 ± 0.0
Triple-jet	36, 37, 38	1	195	1.1 ± 0.0
Quadruple-jet	36, 37, 38, 39	1	80	8.9 ± 0.2
E_T^{miss}	32	1	91	2.5 ± 0.2
jet + E_T^{miss}	32	1	180, 80	3.2 ± 0.1
acoplanar 2 jets	36, 37	1	200, 200	0.2 ± 0.0
acoplanar jet + E_T^{miss}	32	1	100, 80	0.1 ± 0.0
2 jets + E_T^{miss}	32	1	155, 80	1.6 ± 0.0
3 jets + E_T^{miss}	32	1	85, 80	0.9 ± 0.1
4 jets + E_T^{miss}	32	1	35, 80	1.7 ± 0.2
Diffractive	See Ref. [10]	1	40, 40	< 1.0
$H_T + E_T^{miss}$	31	1	350, 80	5.6 ± 0.2
$H_T + e$	31	1	350, 20	0.4 ± 0.1
Inclusive γ	2	400	23	0.3 ± 0.0
γ-γ	3	20	12, 12	2.5 ± 1.4
Relaxed γ-γ	4	20	19, 19	0.1 ± 0.0
Single-jet	33	10	250	5.2 ± 0.0
Single-jet	34	1 000	120	1.6 ± 0.0
Single-jet	35	100 000	60	0.4 ± 0.0
Total HLT rate				119.3 ± 7.2

EM Trigger Suite

- Extensive suite of single and double EM triggers, including prescaled background triggers

7	A_SingleIsoEG5	5	10000
8	A_SingleIsoEG8	8	1000
9	A_SingleIsoEG10	10	100
10	A_SingleIsoEG12	12	1
11	A_SingleIsoEG15	15	1
12	A_SingleIsoEG20	20	1
13	A_SingleIsoEG25	25	1
14	A_SingleEG5	5	10000
15	A_SingleEG8	8	1000
16	A_SingleEG10	10	100
17	A_SingleEG12	12	100
18	A_SingleEG15	15	1
19	A_SingleEG20	20	1
20	A_SingleEG25	25	1

47	A_DoubleIsoEG8	8	1
48	A_DoubleIsoEG10	10	1
49	A_DoubleEG5	5	10000
50	A_DoubleEG10	10	1
51	A_DoubleEG15	15	1

L1 Trigger	Trigger Name	HLT Threshold (GeV)
A_SingleIsoEG12	Single Electron	15
A_SingleEG15	Relaxed Single Electron	17
A_DoubleIsoEG8	Double Electron	10
A_DoubleEG10	Relaxed Double Electron	12
A_SingleIsoEG12	Single Photon	40
A_SingleEG15	Relaxed Single Photon	60
A_DoubleIsoEG8	Double Photon	20, 20
A_DoubleEG10	Relaxed Double Photon	20, 20
A_SingleEG15	Relaxed Single EM High Et	80
A_SingleEG15	Relaxed Single EM Very High Et	200

L1 / HLT

Signal process	Acceptance	Single	Relaxed Single	Double	Relaxed Double	Total
$Z \to ee$	89.9	96.0	97.0	77.3	86.9	
$W \to e\nu$	41.0	85.5	88.2	0.0	0.0	
$H \to \gamma\gamma (m_H = 120\text{ GeV})$	93.1	97.9	99.9	78.1	94.3	

Table 3.2: Detector acceptance (%) and Level-1 trigger efficiencies relative to the acceptance (%) for EM trigger paths.

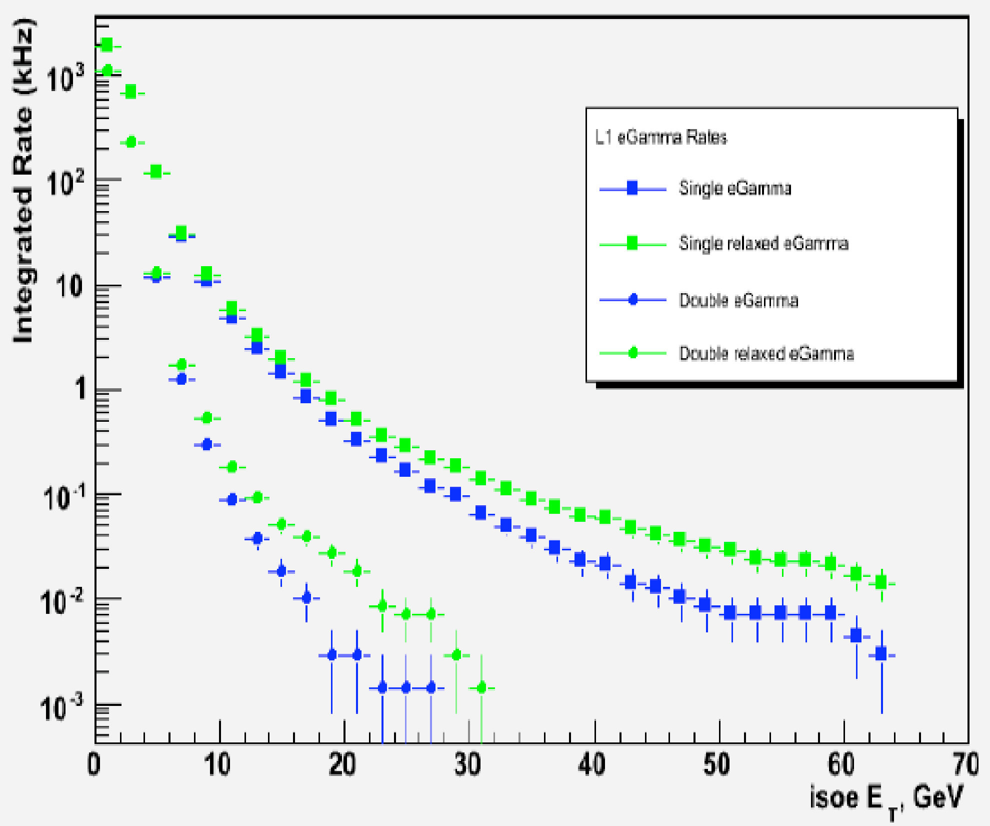
Signal process	Isolated single electron	Relaxed single electron	Isolated double electron	Relaxed double electron	Total
$Z \to ee$	79.9	82.8	49.3	56.0	
$W \to e\nu$	58.2	58.2	0.0	0.0	

Signal process	Isolated single photon	Relaxed single photon	Isolated double photon	Relaxed double photon	Total
$H \to \gamma\gamma$ (m_H=120 GeV)	71.4	42.7	59.6	71.5	

Signal process	single high energy egamma	Single very high energy egamma	Total
$Z' \to ee (M \geq 200\text{ GeV})$	72 %	7.5 %	
$Z' \to ee (M \geq 500\text{ GeV})$	93 %	71.5 %	
$Z' \to ee (M \geq 1000\text{ GeV})$	96 %	93 %	
$Z' \to ee (M \geq 1600\text{ GeV})$	94 %	97 %	
$Z' \to ee (M \geq 2000\text{ GeV})$	94 %	98 %	

EM trigger Rates

- Rates are under control and add up to ~5 kHz



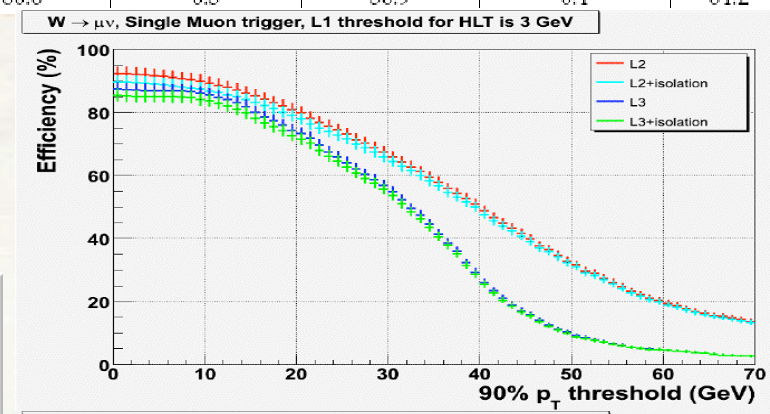
A_SingleIsoEG5	: Individual :	4.43	+- 2.60	Pure :	4.42
A_SingleIsoEG8	: Individual :	25.06	+- 5.91	Pure :	24.94
A_SingleIsoEG10	: Individual :	114.87	+- 11.63	Pure :	110.94
A_SingleIsoEG12	: Individual :	5450.12	+- 76.81	Pure :	5269.47
A_SingleIsoEG15	: Individual :	2404.75	+- 45.80	Pure :	0.00
A_SingleIsoEG20	: Individual :	765.67	+- 21.61	Pure :	0.00
A_SingleIsoEG25	: Individual :	301.60	+- 12.04	Pure :	0.00
A_SingleEG5	: Individual :	7.58	+- 2.63	Pure :	7.54
A_SingleEG10	: Individual :	148.53	+- 13.08	Pure :	81.59
A_SingleEG15	: Individual :	89.61	+- 7.05	Pure :	27.44
A_SingleEG20	: Individual :	117.13	+- 7.66	Pure :	26.17
A_SingleEG25	: Individual :	482.74	+- 13.41	Pure :	141.91
A_DoubleIsoEG8	: Individual :	642.01	+- 21.95	Pure :	204.69
A_DoubleIsoEG10	: Individual :	204.42	+- 11.11	Pure :	0.00
A_DoubleEG5	: Individual :	2.09	+- 1.24	Pure :	0.60
A_DoubleEG10	: Individual :	426.00	+- 14.17	Pure :	43.43
A_DoubleEG15	: Individual :	64.44	+- 3.71	Pure :	0.00

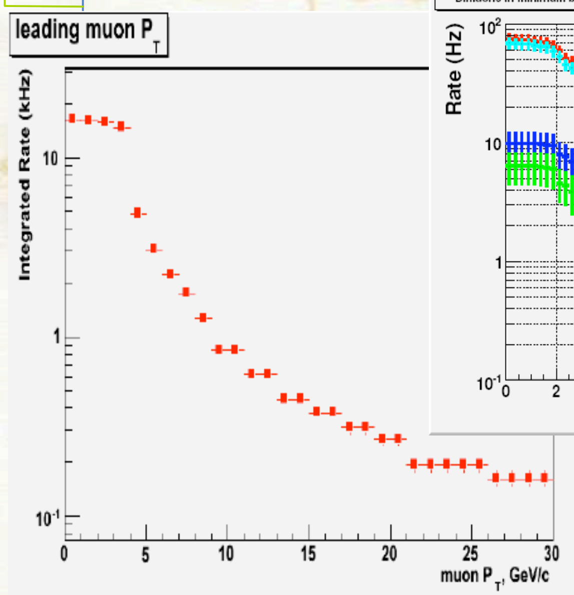
Muon Triggers

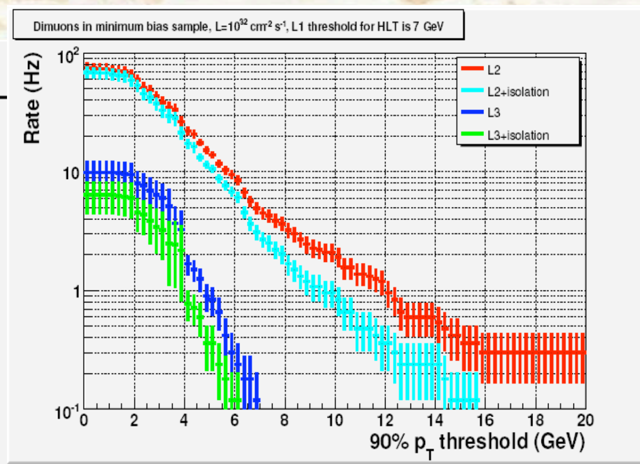
- Similar well-thought suite of muon triggers

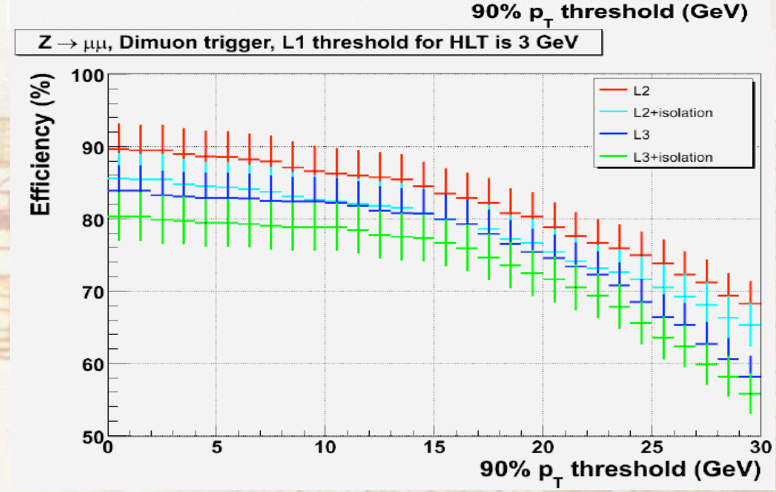
0	A_SingleMu3	3	1000
1	A_SingleMu5	5	1000
2	A_SingleMu7	7	1
3	A_SingleMu10	10	1
4	A_SingleMu14	14	1
5	A_SingleMu20	20	1
6	A_SingleMu25	25	1
46	_A DoubleMu3	3	1
91	A_TripleMu3	3	1

Signal	Single Isolated muon eff.(%)	Double Isolated muon eff.(%)	Single Relaxed muon eff.(%)	Double Relaxed muon eff.(%)	Total (%)
$Z \to \mu\mu$	91.3	68.8	90.5	67.7	93.7
$W \to \mu\nu$	60.6	0.3	56.9	0.1	64.2





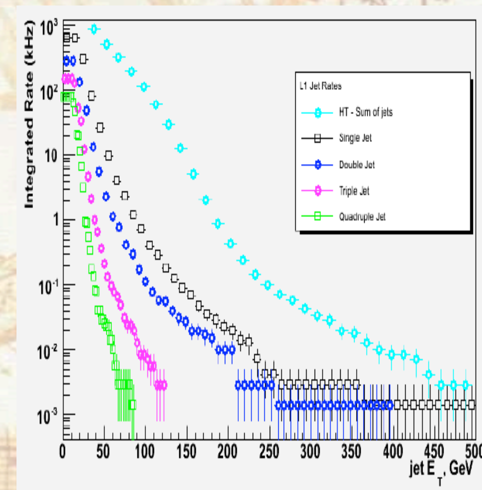


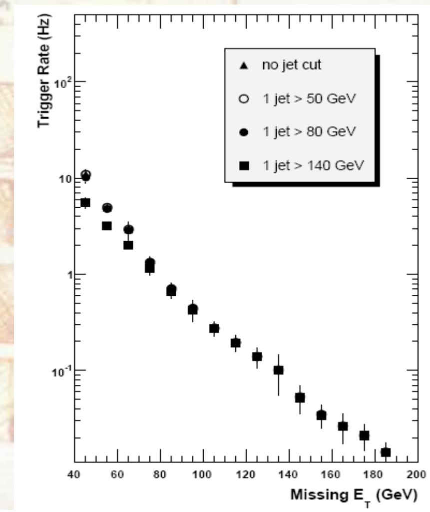


Jets/MET Triggers

- Well-designed suite of jet/MET triggers
- Challenge to keep it at higher luminosities

23	A_SingleJet30	30	10000
24	~~A_SingleJet50~~	50	
25	A_SingleJet70	70	100
26	A_SingleJet100	100	1
27	A_SingleJet150	150	1
28	A_SingleJet200	200	1
37	A_HTT250	250	1
38	A_HTT300	300	1
39	A_HTT400	400	1
40	A_HTT500	500	1
41	A_ETM20	20	10000
42	A_ETM30	30	1
43	A_ETM40	40	1
44	A_ETM50	50	1
45	A_ETM60	60	1
52	A_DoubleJet70	70	1
53	A_DoubleJet100	100	1
94	A_TripleJet50	50	1
110	A_QuadJet30	30	1





Trigger	Level-1 Prescale	Level-1 Threshold (GeV)	Level-1 Rate/ Prescale (Hz)	HLT Threshold (GeV)	HLT Rate (Hz)
HIGH	1	200	17	250	3.0
MED	10^2	70	12	120	1.1
LOW	10^4	30	—	60	???
Double jet	1	200 (1j),100 (2j)	—	200	2.9
Triple jet	1	200 (1j),100 (2j),50 (3j)	—	100	3.4
Quadruple jet	1	200 (1j),100 (2j),50 (3j),30 (4j)	—	80	1.0
$\not{E}_T$	1	50	—	75	1.1
jet + $\not{E}_T$	1	50 ($\not{E}_T$)	—	180,65	1.0
2 jets + $\not{E}_T$	1	50 ($\not{E}_T$)	—	155,65	0.3
3 jets + $\not{E}_T$	1	50 ($\not{E}_T$)	—	85,65	0.2
4 jets + $\not{E}_T$	1	50 ($\not{E}_T$)	—	35,65	0.4
acoplanar 2 jets	1	200 (1j),100 (2j)	—	155,155	0.4
acoplanar jets + $\not{E}_T$	1	50 ($\not{E}_T$)	—	100,70	0.5
$H_T + \not{E}_T$	1	300 (H_T)	—	350,80	1.5
$H_T + e$	1	300 (H_T)	—	350,20	—
VBF jet + $\not{E}_T$ ‡	1	60 ($\not{E}_T$)	—	40,80	0.05

Table 4.1: Jet and $\not{E}_T$ triggers for $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

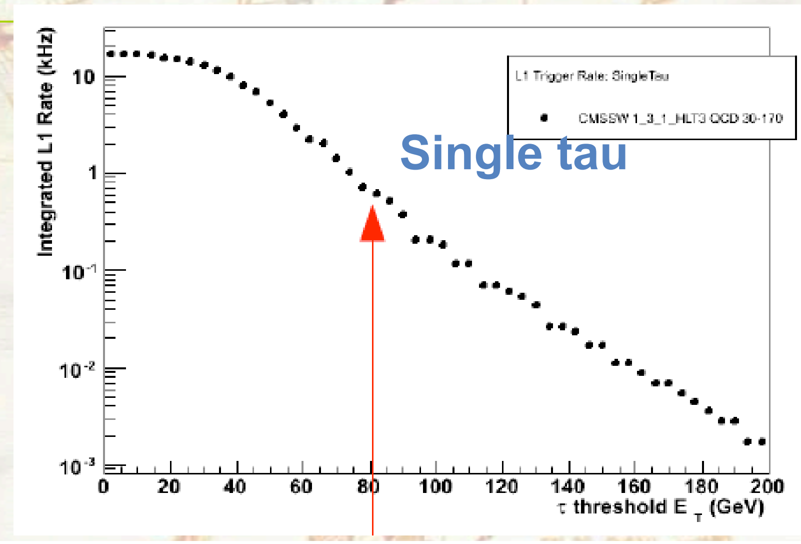
Triggers with Taus

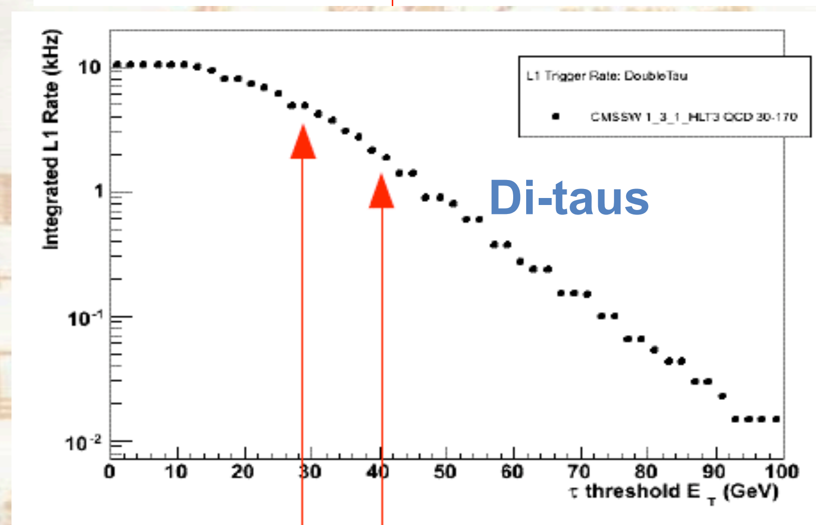
- Based on the "tau-jets" found by the L1 Calorimeter Trigger

32	A_SingleTauJet40	40	1000
33	A_SingleTauJet80	80	1
34	A_SingleTauJet100	100	1
54	A_DoubleTauJet20	20	1000
55	A_DoubleTauJet30	30	100
56	A_DoubleTauJet40	40	1
71	A_IsoEG10_TauJet20	10, 20	1
72	A_IsoEG10_TauJet30	10, 30	1
88	A_TauJet30_ETM30	30, 30	1
89	A_TauJet30_ETM40	30, 40	1

Table 5.1: Efficiencies, purities and rates for Level-1 tau trigger paths.

Samples/Trigger	SingleTau		DoubleTau		SingleTauMET	
	Eff.	Purity	Eff.	Purity	Eff.	Purity
$Z \to \tau\tau$	9%	6%	18%	13%	18%	12%
$W \to \tau\nu$	4%	3%	–	–	12%	20%
$H^{\pm} \to \tau\nu$ ($m_H = 200$ GeV/c^2)	62%	37%	–	–	83%	41%
$H^{\pm} \to \tau\nu$ ($m_H = 400$ GeV/c^2)	71%	50%	–	–	90%	50%
QCD ($\hat{p}_T$ = 15-300 GeV/)	200 Hz		1800 Hz		700 Hz	





A No-Lose Trigger Conjecture

- Conjecture: *if we can discover it, we should be able to trigger on it!*
- Idea based on multiple discussions with the LHC phenomenologists,
- Two scenarios:
  - Low-mass – high rate, soft final state particles
  - High-mass – low rate, hard final state particles or large multiplicity
- Key observation:
  - Low-rate signal can be only found in low-background samples
    - Hence should be possible to design trigger with $S/\sqrt{B}$ factor of 10-1000 worse than offline, but still high, i.e. a LOW-RATE trigger!
    - Example: heavy Higgs in $2e2\mu$ or $4e/\mu$
  - High-rate signal can be found even if the efficiency is low
    - Hence can go for decays with low branching fraction and more complicated signatures or raise thresholds to fit the bandwidth
    - Example: use $h \to \gamma\gamma$, rather than $h \to bb$ for low-mass Higgs
- Shell and armor race: theorists design a new model; we design a trigger
  - Can we get ahead in this game?
  - Yes, by designing generic feature triggers and the “last-resort” trigger!

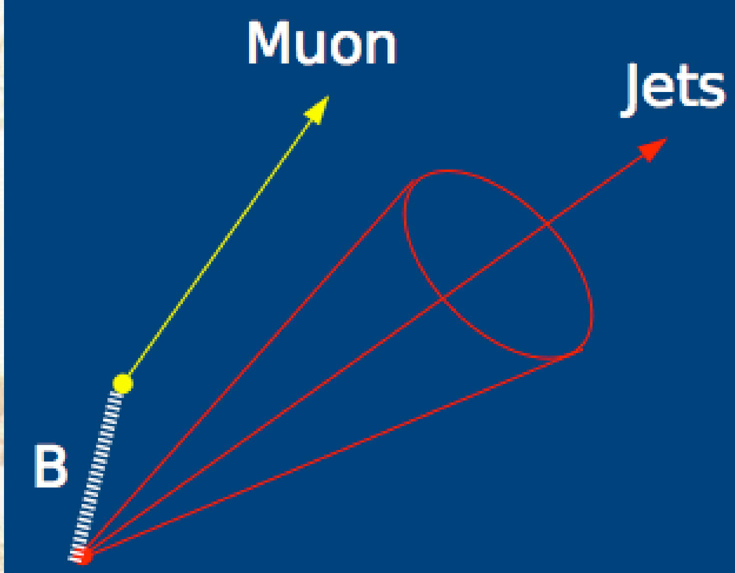
What's Common About New Physics?

- Start with a few very general features of new physics:
  - Either pair- or singly produced
  - Has relatively high s-hat
  - To be produced, must couple to gluons, quarks, and/or W/Z/γ
  - Prompt or cascade decays into SM particles
    - Cascades often carried by intermediate vector bosons, thus expect leptons in the final state
  - May have couplings proportional to mass and prefer decays into third-generation
    - Both tau's and b's decay with emission of electrons and muons sizeable fraction of the time

Generalized Exotics Triggers

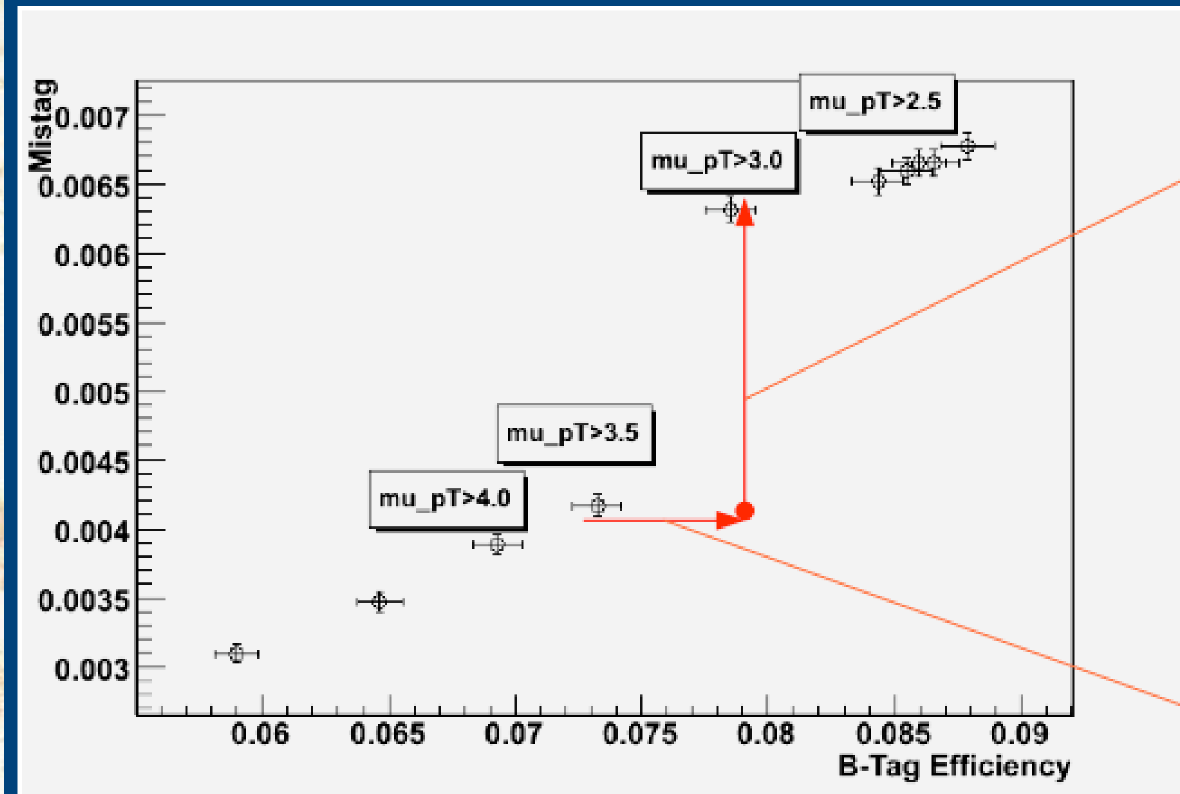
- Go for high s-hat:
  - High-threshold single and di-object triggers
  - H_T trigger for high-multiplicity decays
  - H_T + ME_T trigger for high-multiplicity events with large fraction of invisible particles
  - Multiplicity trigger
  - Sphericity trigger
- Go for semi-soft leptons from cascade decays:
  - Multiobject e/μ+X and ee/eμ/$\mu\mu$+X triggers; H_T is a good choice for X
- Go for the third generation:
  - Leptonic τ+X, mixed $\tau\tau$+X, hadronic high p_T $\tau\tau$+X
  - A suite of b-tagged triggers (including jet+muon tag at L1!)
- CMS-specific: given the simplicity of L1 triggers and high available L1 bandwidth, most rejection power has to come from the HLT
  - Staged rate rejection L2 → L3 → …
  - Object quality and topological requirements at each level to control rate

B-Tagging at L1



- Mean lifetime of b meson is ~1.2 ps (~360um).
- Most light jets don't decay leptonically.
- Identify b-jet by the angular separation between jets & muon.

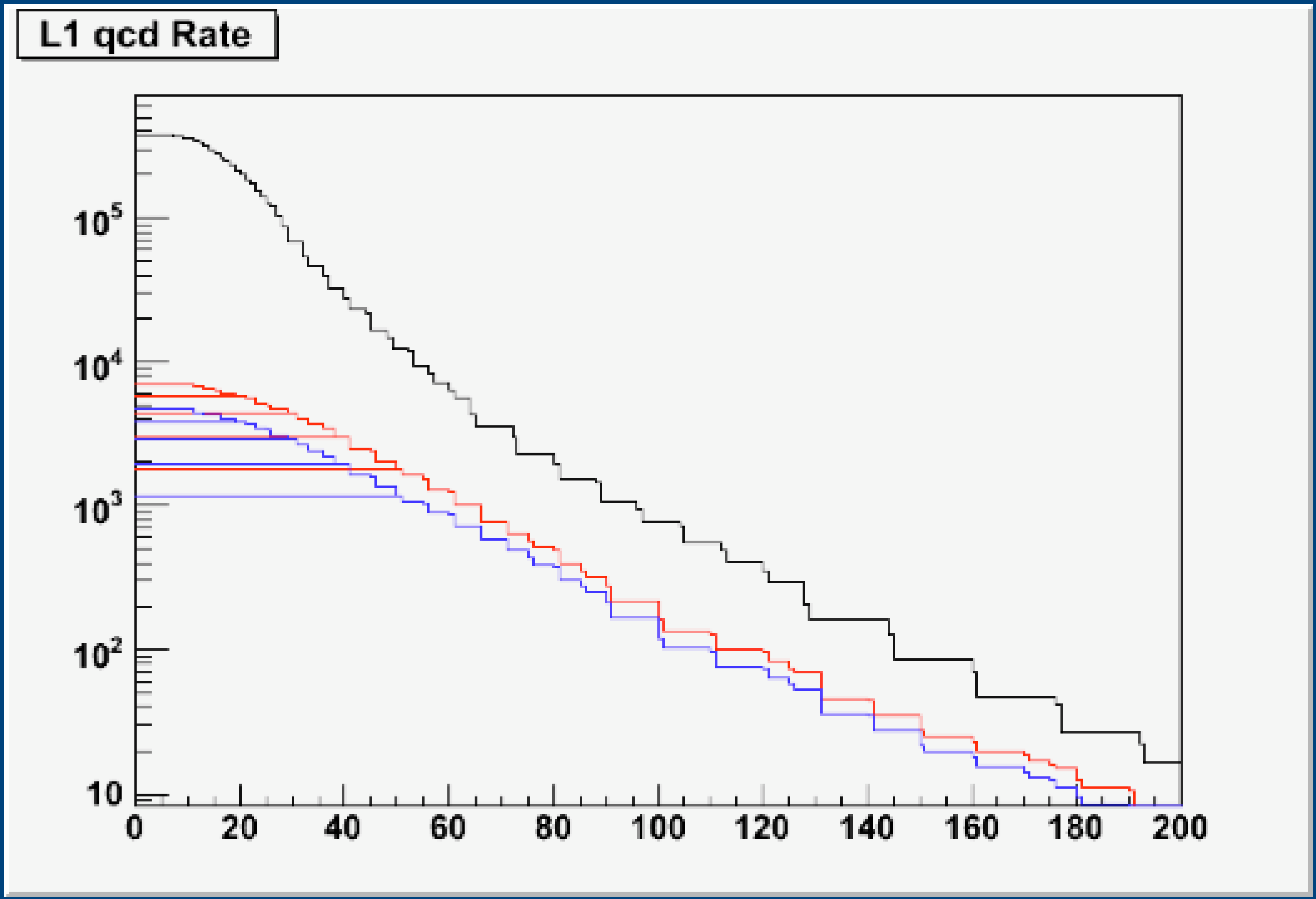
Rejection vs Efficiency



Mistag increase 51.6% from 0.41% to 0.63%.

B-Tag efficiency increase only 7.2%, from 7.3% to 7.9%.

L1 Rate



L1 qcd Rate
10
10^2
10^3
10^4
10^5
0
20
40
60
80
100
120
140
160
180
200

Example

- $H^0 \to A^0 A^0 \to$ bbar bbar events
- Standard configuration file with the following:
  - H^0 mass = 130 GeV
  - A^0 mass = 50 GeV
  - A^0 lifetime = 66.7 ps
  - Production via $gg \to H^0$ (process 152)
- The H^0 can only decay to A^0s and the latter decay to bbar over 99% of the time
- Pythia cross-section: 16.9 pb

L1 Trigger Results

Trigger	Efficiency	Bkgd Rate (kHz)
L1_HTT250	0.2676	2.56
L1_DoubleTauJet40	0.2570	2.36
L1_IsoEG10_Jet20	0.2324	3.04
L1_IsoEG10_Jet30	0.2136	1.95
L1_IsoEG10_TauJet20	0.2136	1.95
L1_QuadJet30	0.1936	0.58
L1_SingleEG15	0.1884	1.51
L1_IsoEG10_TauJet30	0.1844	1.33

Luminosity = 10E32 $cm^{-2}s^{-1}$

- All background rates from HLT exercise
- Note: IsoEG10_Jet30 and IsoEG10_TauJet20 do in fact have the same rates (not a typo)

HLT Results

Trigger	Efficiency	Rate (mHz)	Bkgd Rate (Hz)
HLT1jet	0.0248	0.0419	9.3
HLT2jet	0.0172	0.0291	10.6
HLT1MET	0.0166	0.0281	4.9
HLT3jet	0.0160	0.0270	7.5
HLT1MET1HT	0.0152	0.0257	4.4
HLT1jet1MET	0.0132	0.0223	2.2
HLT4jet	0.0100	0.0169	3.9
HLTBHT	0.0100	0.0169	2.5

Luminosity = 10E32 $cm^{-2}s^{-1}$

- This is total efficiency, L1 included
- Approximately 5 events per day

When General Triggers Fail…

- The above strategy works in general, but what if an object fails "standard quality" cuts?
  – More likely to happen at the HLT, as L1 quality requirements are, in general, fairly loose
- Examples:
  – Jets from slow-particle decays, which lack tracking confirmation
  – Electron/photons with large impact parameter resulting in a "funny" cluster profile
  – Events with "mixed" timing (e.g., calorimeter and muon or track are offset in time)
  – Events with abnormally high multiplicity of relatively soft objects
  – b-tagged jets with extremely large impact parameter
  – Funny tracking patterns in roads defined by L1 candidates
  – Abnormally large fraction of L1 triggers fired with no HLT triggers to pass
  – Abnormal density of tracks within HLT roads
  – …

The "Last Resort" Trigger

- Possible remedy:
  - Let individual HLT trigger set a "weirdness flag" when the event fails the trigger, but in the process something in the event is found to look fairly strange (e.g., one of the cuts is failed by a very large margin)
- Run the "Last Resort" HLT filter as the last one before rejecting the event
  - Try to rescue these weird events by analyzing "weirdness flags" set by individual paths and/or based on global event properties
    - Forcefully accepts the event if several such flags are set
    - Accepts the event if large number of L1 triggers is fired
    - Accepts the event if abnormally high multiplicity of high-p_T L1 objects have been found
  - Cuts designed to keep very low output rate (« 1 Hz)
- The LRT clearly fails the no-volunteer concept
  - Can't measure efficiency or luminosity presicely
  - However, allows for an early warning system for "weird" events, which may indicate hardware failure or interesting, exotic physics
  - Designated triggers can then be developed for particular exotic signatures found by the LRT without compromising taking these data