Trigger Strategy for Alternative (non-SUSY) Signatures at the LHC

Tulika Bose
Brown University

(for the ATLAS & CMS Collaborations)

SUSY07, Karlsruhe
July 31st, 2007

Outline

- The LHC Trigger Challenge
- CMS High Level Trigger (HLT) Overview
- BSM (non-SUSY) Trigger Strategies at ATLAS and CMS
- CMS trigger-aware BSM (non-SUSY) analyses

ATLAS HLT & SUSY Trigger Strategies covered by A. De Santo

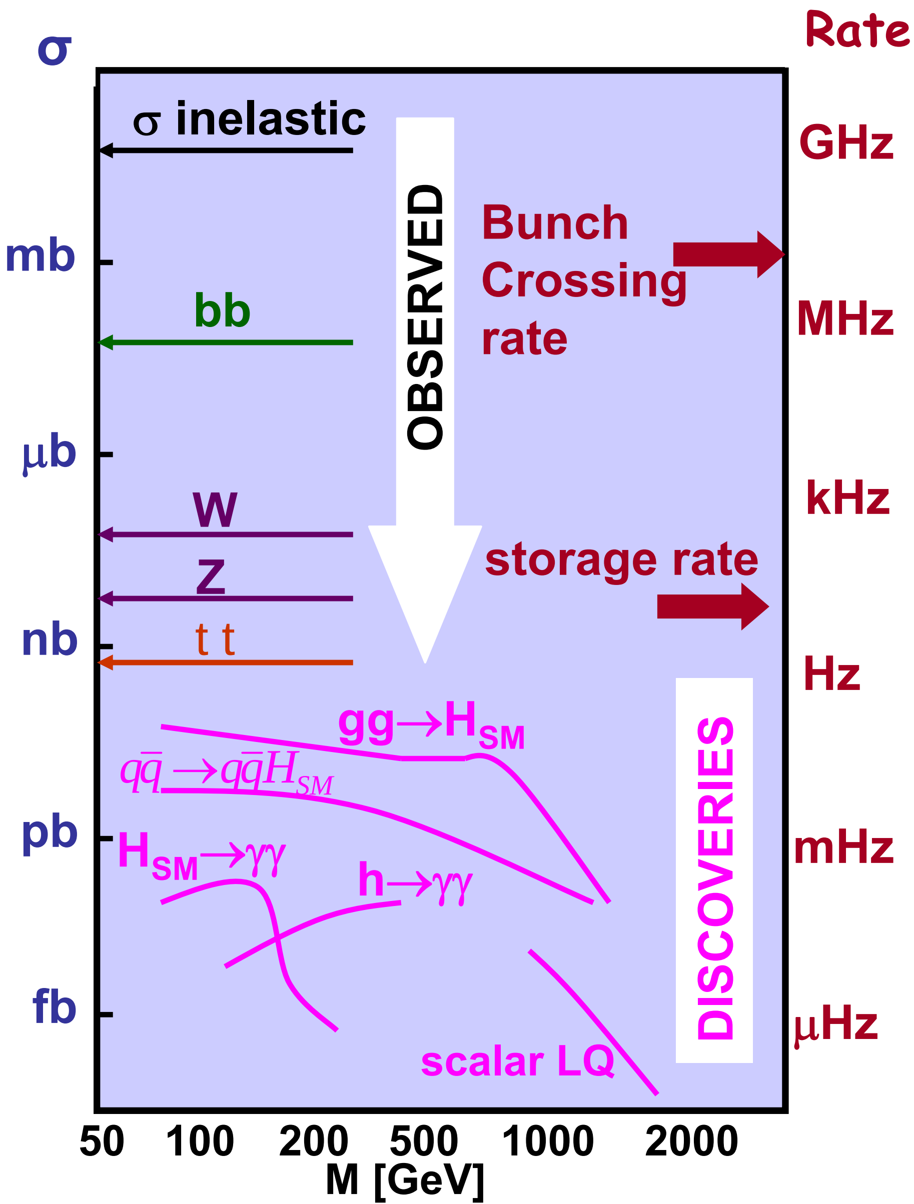
REFERENCES:

CMS Physics TDR II
http://cmsdoc.cern.ch/cms/cpt/tdr/

CMS HLT Report:
CERN-LHCC 2007-021, LHCC-G-134

ATLAS TDR

The LHC Trigger Challenge



Cross sections for various physics processes vary over many orders of magnitude

At the standard LHC luminosity:

$L = 10^{34}\ cm^{-2}s^{-1} = 10^{10}$ Hz/b

$\sigma_{inelastic}(pp) \sim 70$ mb

$\Rightarrow 7 \times 10^8$ interactions/s

Bunch crossing frequency: 32MHz

Storage rate ~ 200-300 Hz

→ online rejection: 99.999%

→ crucial impact on physics reach

Keep in mind that what is discarded is lost forever

General trigger strategy

Needed: An efficient selection mechanism capable of selecting interesting events - this is the **TRIGGER**

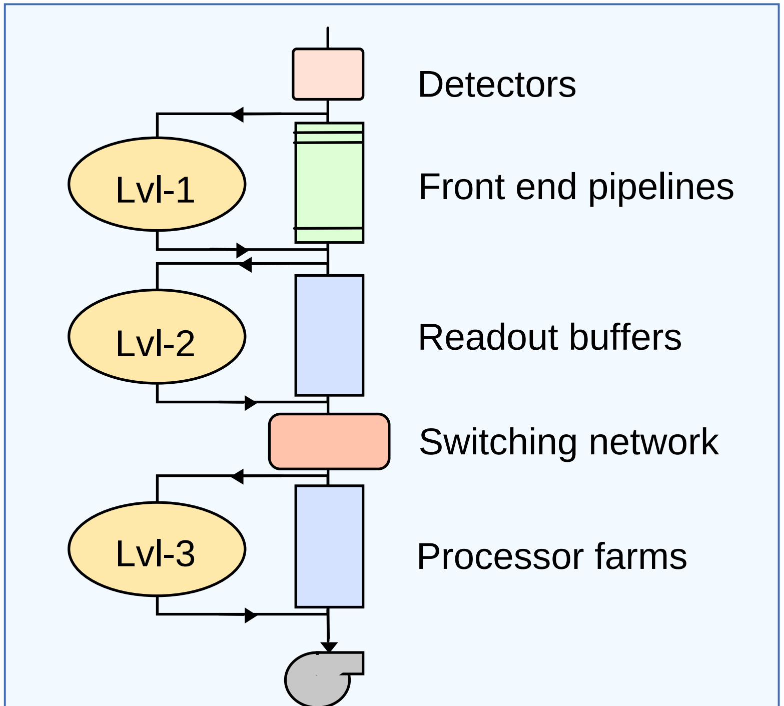
"Needle in a haystack"

General strategy:

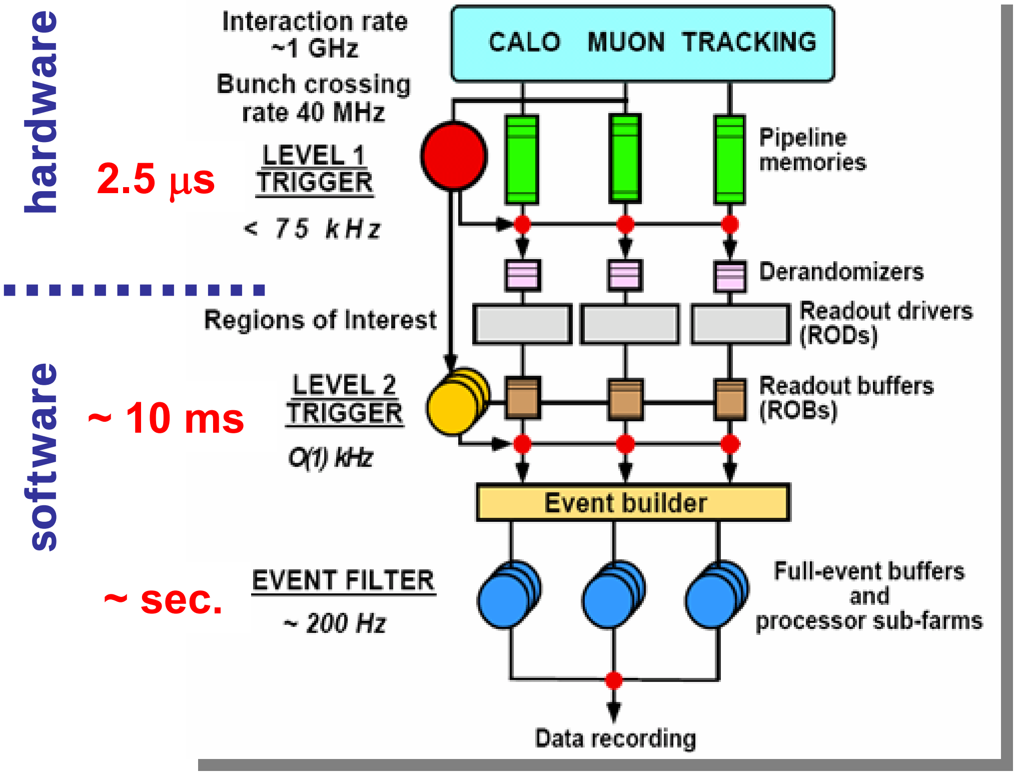
- System should be as inclusive as possible
- Robust
- Redundant
- Need high efficiency for selecting interesting processes for physics:
    - selection should not have biases that affect physics results
    - (understand biases in order to isolate and correct them)
- Need large reduction of rate from unwanted high-rate processes
    - instrumental background
    - high-rate physics processes that are not relevant (min. bias)

This complicated process involves a multi-level trigger system…

The ATLAS Trigger System



"Traditional": 3 physical levels



ATLAS Trigger overview
covered in A. De Santo's talk

CMS Trigger Overview

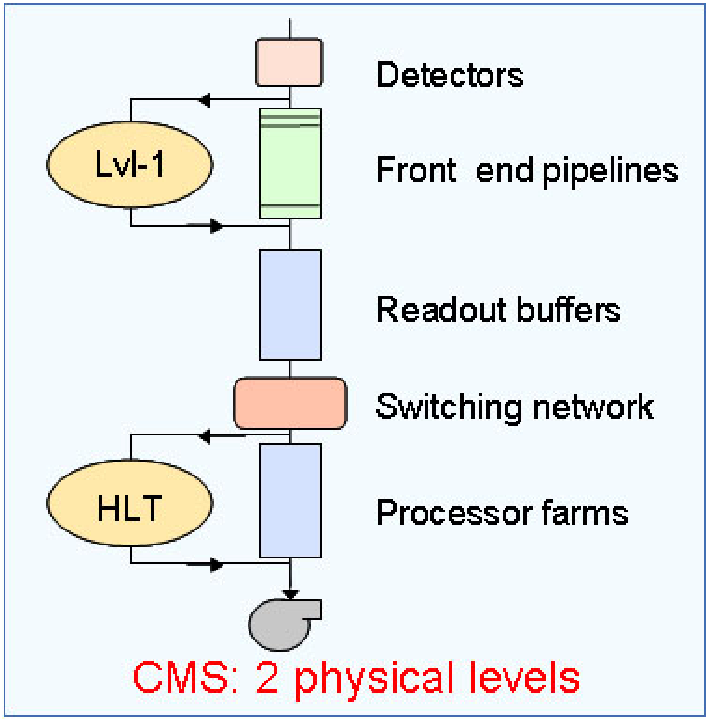
CMS has a two-tiered trigger system:

- Level-1 trigger reduces rate from 32 MHz to 100 kHz (max)
  Custom electronic boards and chips process calorimeter and muon data to select objects

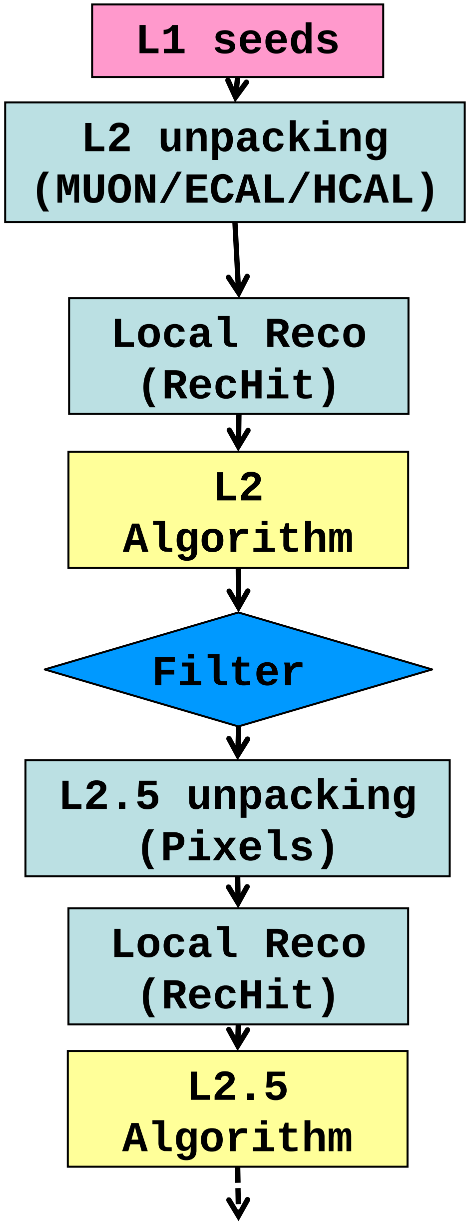
- High-Level Trigger (HLT) reduces rate from 100 kHz to O(100 Hz)
  Filter farm with commodity PCs

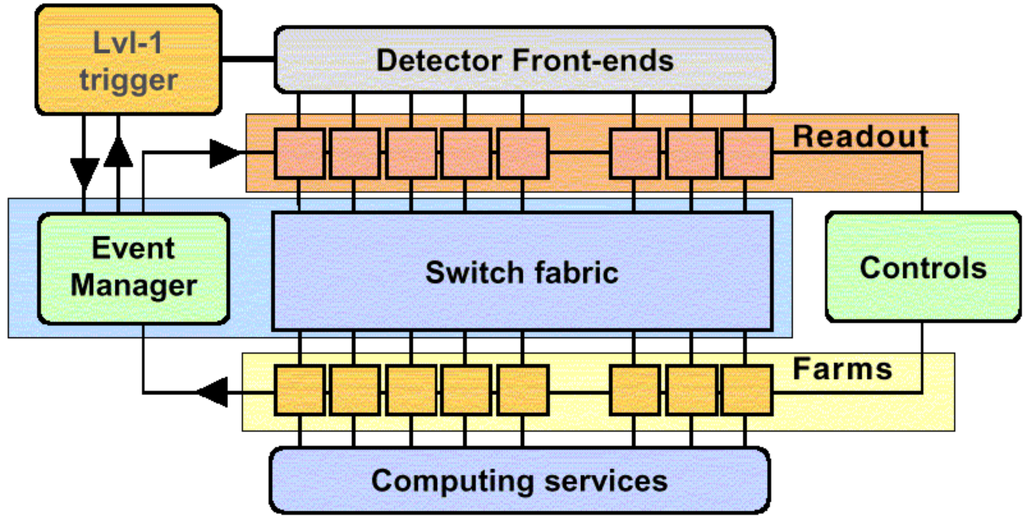
  Partial event reconstruction "on demand" using full detector resolution

Final rate will depend on data bandwidth, storage capability, and background rejection capability.



CMS HLT Overview





HLT filter algorithms are setup in various steps:

- Each HLT trigger path is a sequence of modules
- Processing of the trigger path stops once a module returns false
- Algorithms are essentially offline quality but optimized for fast performance

CMS HLT "Exercise"

CMS Report (LHCC): "What is the CPU performance of the HLT ?"

CERN-LHCC 2007-021

Focus:

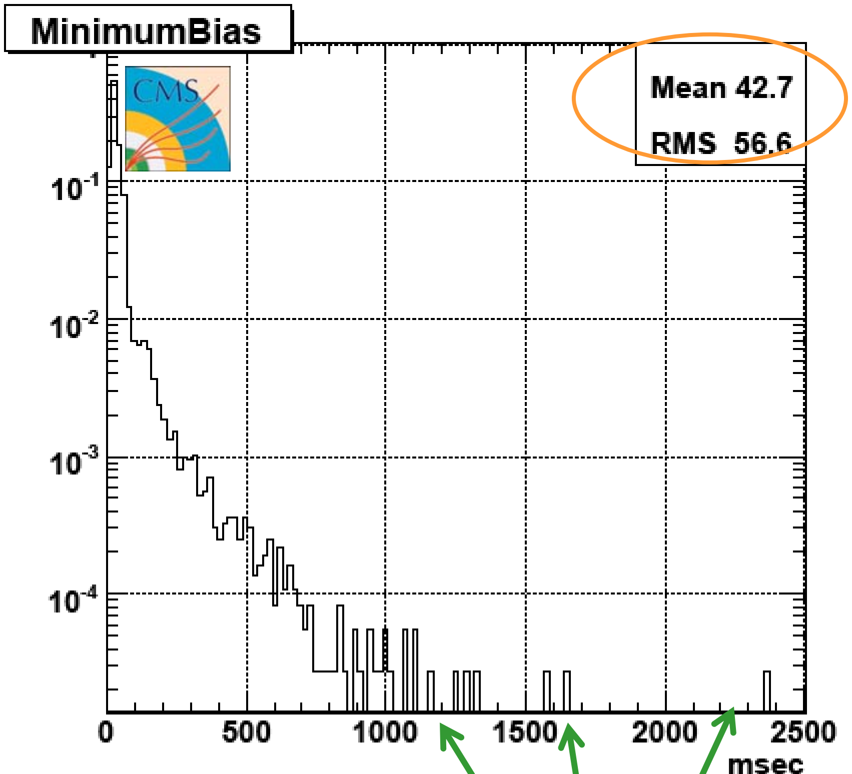
- Compile strawman Trigger Menu that covers CMS needs
- Determine CPU-performance of HLT algorithms
  - Implementation of 2008 physics-run (14 TeV) trigger menu

HLT cpu time budget ~ 40ms/event †

⇒ Select events that are "interesting enough" and bring down rate as quickly as possible

† DAQ-TDR (Dec 02):
"In 2007, for a L1 accept rate of 50 kHz & 2000 CPUs
we need an average processing time of 2000/50 kHz ~ 40 ms/evt"

CMS HLT Exercise result



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

Strong dependence of CPU-times on HLT input:
Safety factors used:
- factor of 3 in allocation of L1 bandwidth; only 17 kHz
- factor of 2 in HLT accept rate; only 150 Hz allocated

"Tails": Will eliminate with time-out mechanism

Auto-accept event if processing time exceeds e.g. 600 ms

This saves significant time in MC (probably much more in real data)

+ will keep events of "unexpected" nature

CMS HLT Trigger Rates

HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
Single Isolated μ	A_SingleMu7	11	18.3 ± 2.2	18.3
Single Relaxed μ	A_SingleMu7	16	22.7 ± 1.5	37.7
Double Relaxed μ	A_DoubleMu3	(3, 3)	12.3 ± 1.6	48.5
$\mu + \text{jet}$	A_Mu5_Jet15	(7, 40)	6.3 ± 0.7	60.8
$e + \mu$	$\star$	(8, 7)	0.5 ± 0.4	61.2
$e + \mu$ relaxed	$\star$	(10, 10)	0.1 ± 0.0	61.3
$\mu + \tau$	A_Mu5_TauJet20	(15, 20)	0.0 ± 0.0	61.3
Single-Jet	A_SingleJet150	200	9.3 ± 0.1	70.1
Double-Jet	A_SingleJet150 A_DoubleJet70	150	10.6 ± 0.0	74.4

"bread & butter" triggers for many BSM analyses

- μ: 50 Hz
- eγ: 30 Hz
- jets/MET/Ht: 30 Hz
- τ: 7 Hz
- b-jets: 10 Hz
- x-channels: 20 Hz
- prescaled: 15 Hz
- Total: 150 Hz

For complete "triggerlist" see CERN-LHCC 2007-021, LHCC-G-134

@ $L=10^{32}\ cm^{-2}\ s^{-1}$

CMS HLT Trigger Rates

HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
Single Jet Prescale 10	A_SingleJet100	150	3.5 ± 0.0	87.9
Single Jet Prescale 100	A_SingleJet70	110	1.5 ± 0.0	89.1
Single Jet Prescale 1000	A_SingleJet30	60	0.8 ± 0.4	89.9
VBF Double-Jet + $\not{E}_T$	A_ETM30	(40, 60)	0.2 ± 0.0	89.0
SUSY 2-jet+$\not{E}_T$	A_ETM30	(80,20,60)	2.0 ± 0.1	90.4
Acopl. Double-Jet + $\not{E}_T$	A_ETM30	(60, 60)	1.0 ± 0.0	90.4
Single Isolated e	A_SingleIsoEG12	15	17.1 ± 2.3	107.5
Single Relaxed e	A_SingleEG15	17	9.6 ± 1.3	109.3
Double Isolated e	A_DoubleIsoEG8	10	0.2 ± 0.1	109.4
Double Relaxed e	A_DoubleEG10	12	0.8 ± 0.1	109.9
Single Isolated γ	A_SingleIsoEG12	30	8.4 ± 0.7	118.1
Single Relaxed γ	A_SingleEG15	40	2.8 ± 0.2	118.5
Double Isolated γ	A_DoubleIsoEG8	(20,20)	0.6 ± 0.4	119.0
Double Relaxed γ	A_DoubleEG10	(20,20)	1.8 ± 0.5	120.1
High E_T e	A_SingleEG15	80	0.5 ± 0.0	120.4
High E_T e	A_SingleEG15	200	0.1 ± 0.0	120.4

"bread & butter" triggers for many BSM analyses

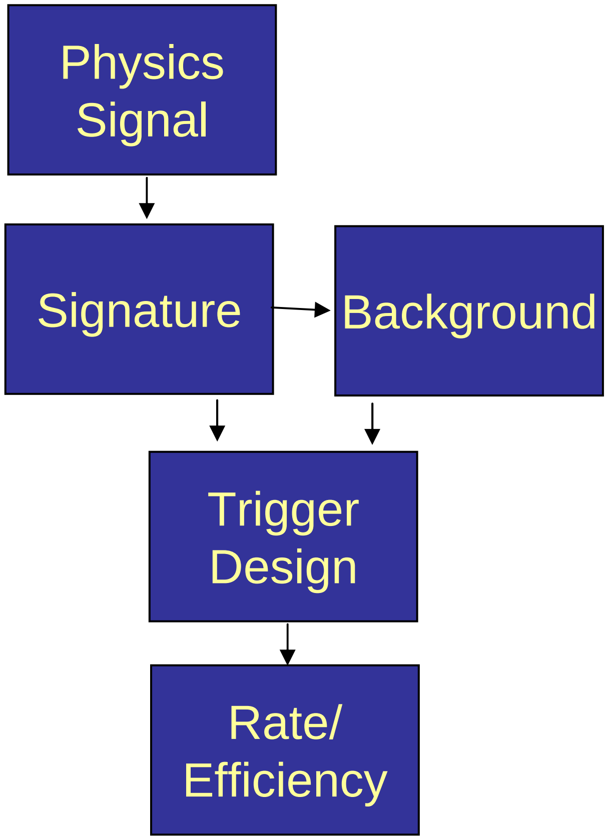
@ $L=10^{32}$ cm^{-2} s^{-1}

Similar trigger menus are being designed by ATLAS

Triggering on the unexpected

How does one trigger on the unknown ?

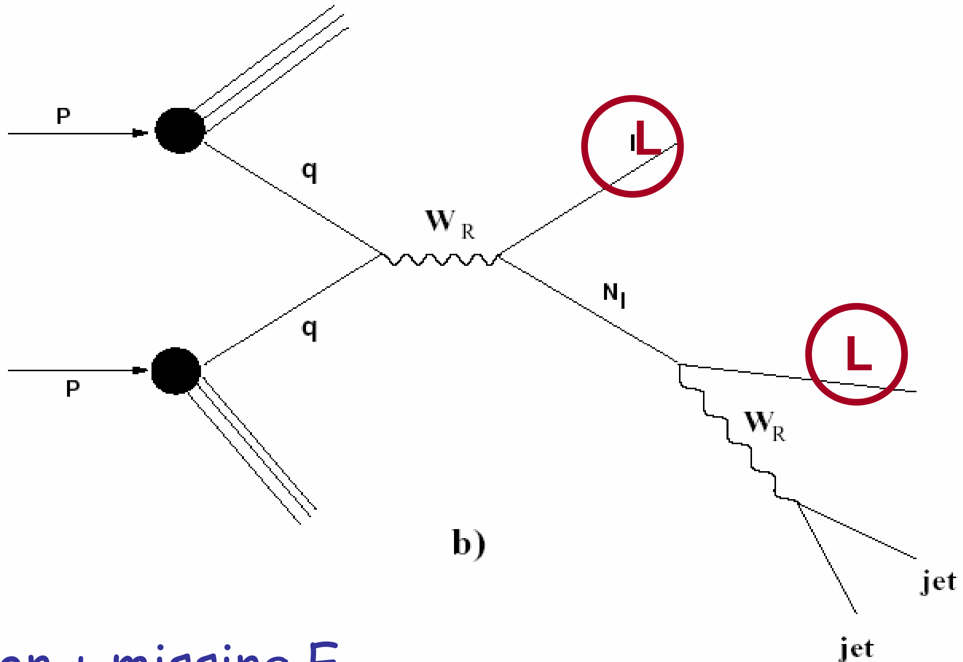
General Strategy



- Start by looking at various physics signals/signatures…
- Emphasize on robust inclusive e/μ, ee, μμ, eμ triggers, which may lead to early discoveries and surprises
  - τ/b/ME_T triggers will need more extensive commissioning and tuning

"Alternatives" signatures

1) Di-lepton, di-jet, di-photon resonances
   - Z' (leptons, jets),
   - RS Extra dimensions (leptons, photons, jets)
   - Z_{KK} in TeV^{-1}
   - heavy neutrino from right-handed W (di-lepton + di-jets)



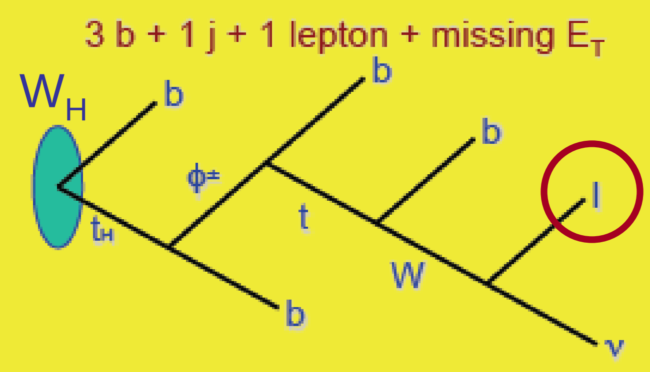
2) Single photon + missing E_T
   - ADD direct graviton emission

"Alternatives" signatures

3) Single lepton + jets/missing ET

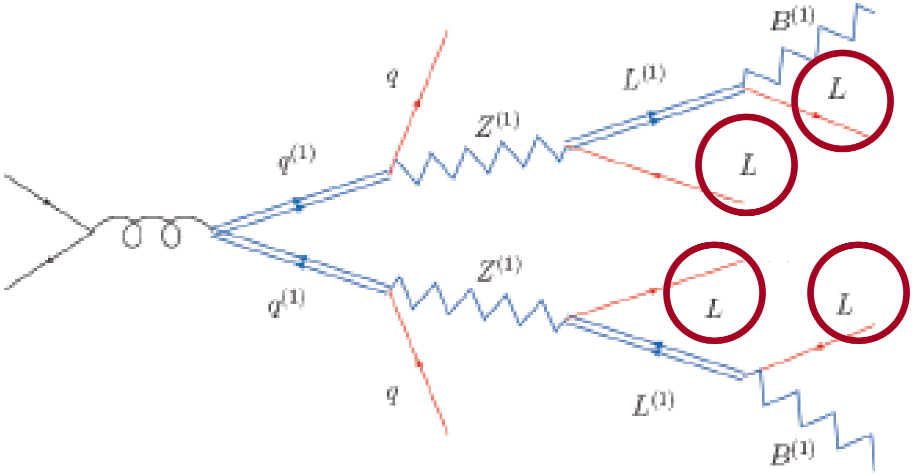
- W' (lepton+ missing ET)
- Twin Higgs (lepton + jets + missing ET)

$W_H \rightarrow t_H$ b



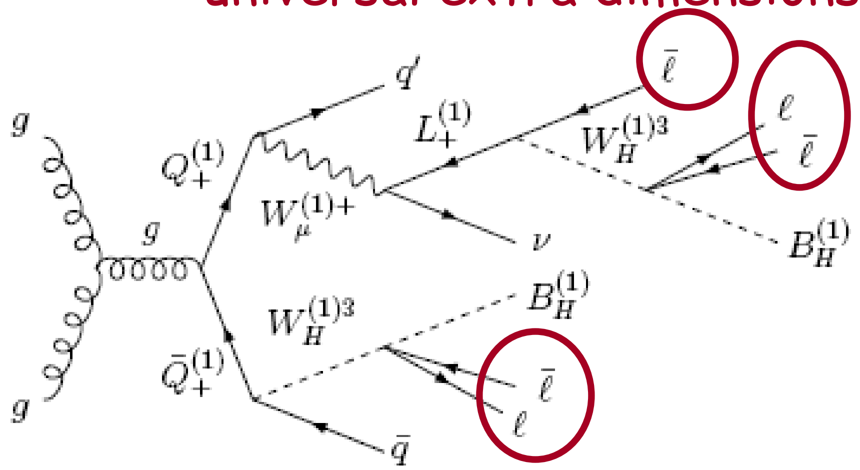
4) (a) Multi-lepton + multi-jet

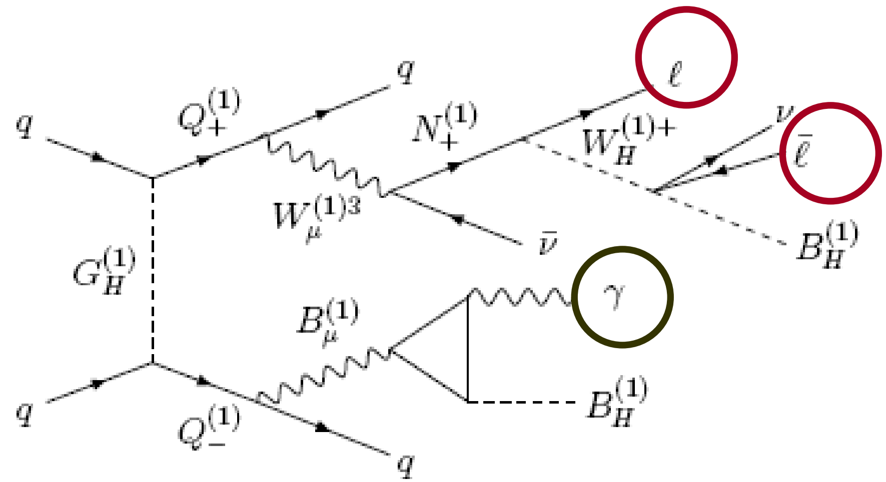
- Technicolor, littlest Higgs, universal extra dimensions



“Alternatives” signatures

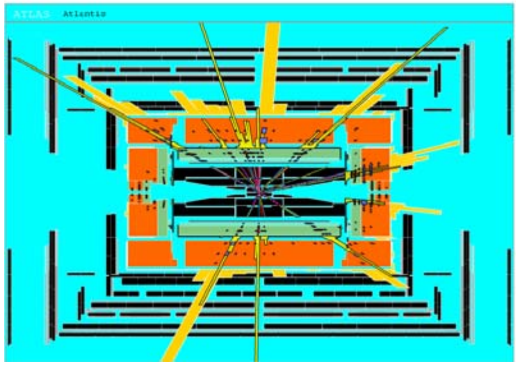
4) (b) Multi-leptons + photons
- universal extra dimensions





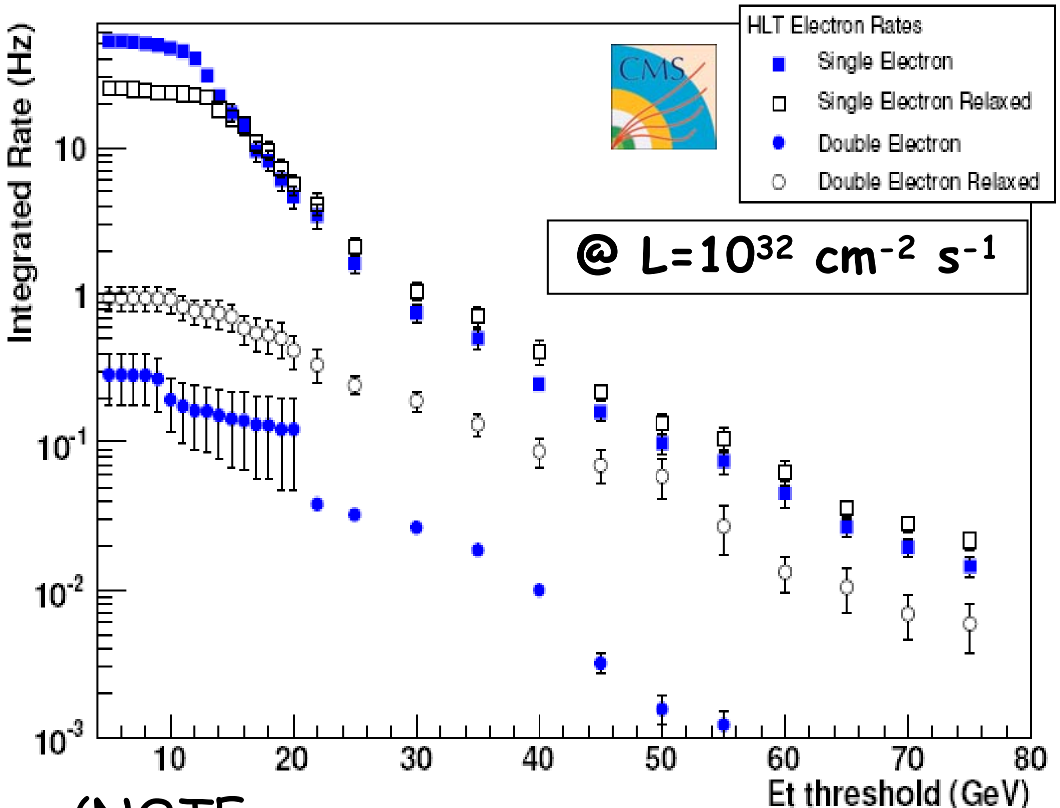
5) Same sign di-leptons
- same-sign top

6) Black Holes
- High multiplicity events, jets/lepton ratio of 5:1



Having robust lepton triggers will be crucial !

(Cross-channel triggers like leptons + jets v. important too.)



Let us now look at some examples of BSM analyses and triggers used...

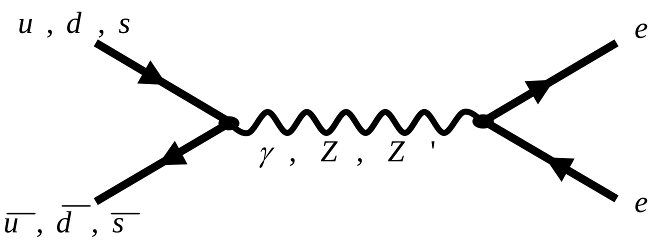
(NOTE:
Many BSM signatures involve 3rd generation particles: b's and τ.
Though challenging, triggers for these need to be commissioned at the same time)

Di-lepton final states

1) GUTs, superstring-inspired, left-right, little Higgs models, etc…

➔ new gauge bosons W′ and Z′ (or KK modes)

Clean decay channels: Z′ → e^+e^- or $\mu^+\mu^-$



Z′ → e^+e^- Analyses:

Trigger: single or double electron triggers

CMS: new "High ET EM" triggers with high ET thresholds

- (ET thresholds: 80 GeV and 200 GeV; relaxed isolation criteria)

HLT trigger path	E_T threshold (GeV)
Single isolated electron	15
Single relaxed electron	17
Double isolated electron	10
Double relaxed electron	12
Single isolated photon	30
Single relaxed photon	40
Double isolated photon	20
Double relaxed photon	20
Single high energy EM	80
Single very high energy EM	200

Signal Efficiencies : (L1 eff=100%)

Signal process	single high energy EM	Single very high energy EM	Total
$Z' \to ee$ ($M \geq 200$ GeV)	67	7.0	67
$Z' \to ee$ ($M \geq 500$ GeV)	91	69	93
$Z' \to ee$ ($M \geq 1000$ GeV)	94	92	98
$Z' \to ee$ ($M \geq 2000$ GeV)	90	97	98
$G \to \gamma\gamma$ ($M \geq 2000$ GeV)	91	97	98

Di-lepton final states

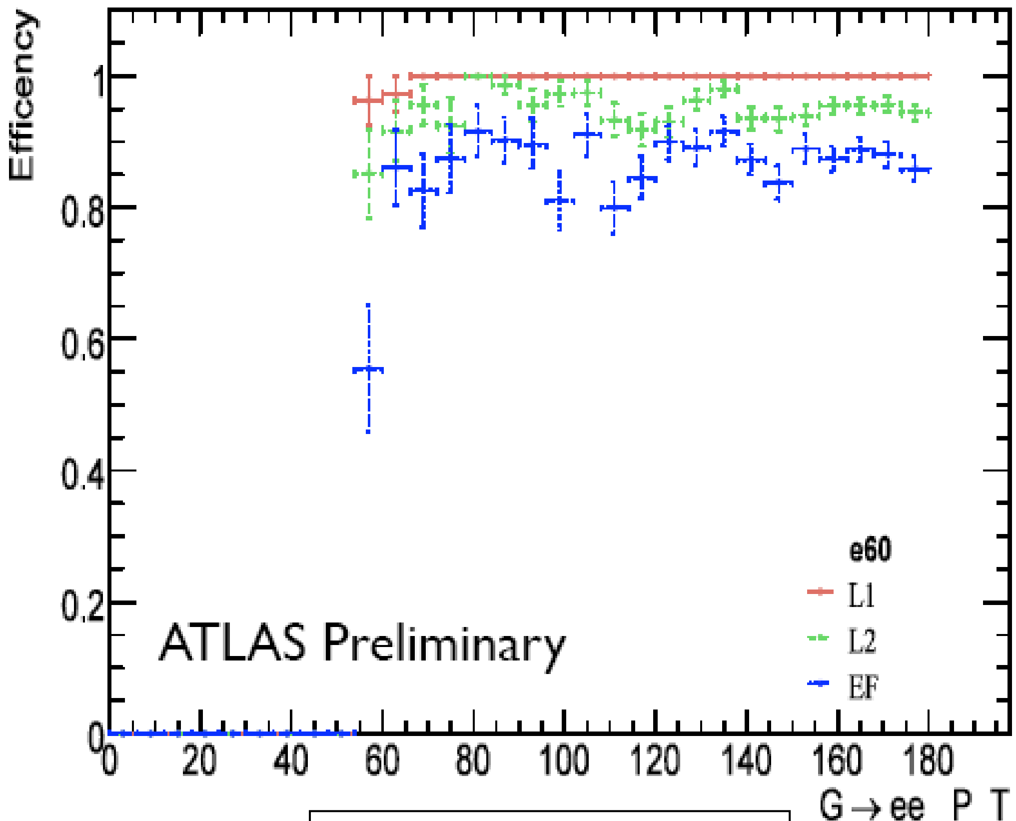
"e60": ET > 60 GeV Trigger

ATLAS Plans:
Expect to run with a loose "em100" trigger with no L2/EF cuts for as long as possible (Estimated rate: 1 Hz @ 10^{31} $cm^{-2}s^{-1}$)

L2/EF cuts will be optimized based on that data

Also run di-EM triggers:
2e15:2em13@L1 (150 Hz)
2e15@EF (1Hz)

Efficiency of "e60" trigger Vs electron p_T based on a sample of 500 GeV RS G→ee



@ L=10^{31} cm^{-2} s^{-1}

Photons

1) Di-photon resonances (RS Extra dimensions):

Trigger: Photon triggers;

2) Direct graviton emission in ADD type of Extra Dimensions framework

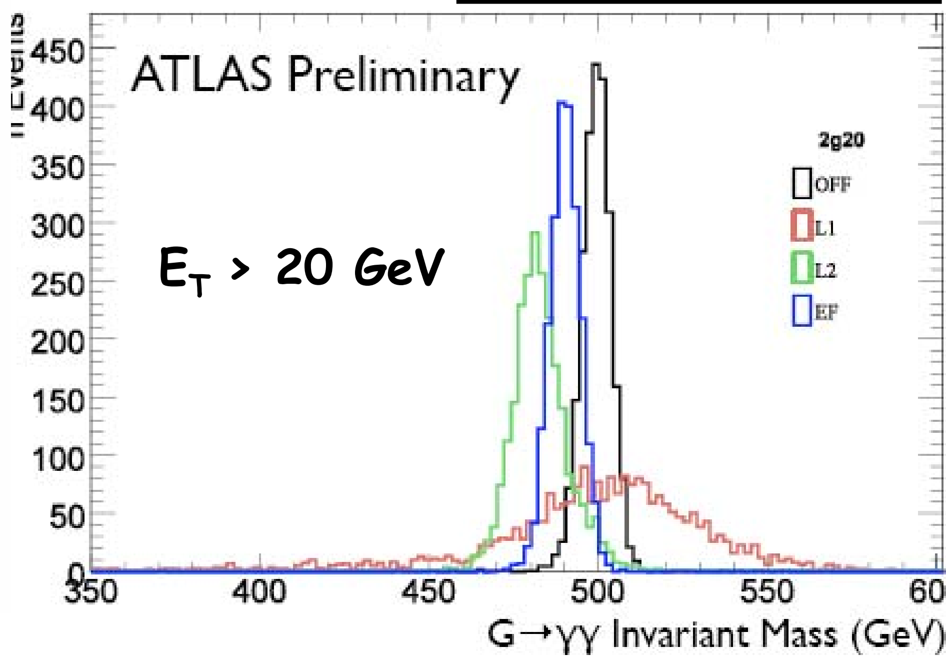
Signature: single, high p_T photon; large ME_T back-to-back with the photon

Trigger: Single photon trigger; (ME_T trigger)

@ $L=10^{32}$ cm^{-2} s^{-1}

HLT trigger path	E_T threshold (GeV)
Single isolated electron	15
Single relaxed electron	17
Double isolated electron	10
Double relaxed electron	12
Single isolated photon	30
Single relaxed photon	40
Double isolated photon	20
Double relaxed photon	20
Single high energy EM	80
Single very high energy EM	200

@ $L=10^{31}$ cm^{-2} s^{-1}



Single lepton + ME_T

3) W' – a charged spin-1 boson; hypothetical heavy partner of the W

- Reference Model by Altarelli, Mele, Ruiz-Altaba with same W' couplings to fermions as for W
- Trigger : single muon triggers

Muon Trigger Menu

@ L=10^{32} cm^{-2} s^{-1}

HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
Single Isolated μ	A_SingleMu7	11	18.3 ± 2.2	18.3
Single Relaxed μ	A_SingleMu7	16	22.7 ± 1.5	37.7
Double Relaxed μ	A_DoubleMu3	(3, 3)	12.3 ± 1.6	48.5
$J/\psi \to \mu\mu$	A_DoubleMu3	(3, 3) $M_{\mu\mu} \in [2.9, 3.3]$	2.0 ± 0.8	49.4
$\Upsilon \to \mu\mu$	A_DoubleMu3	(3, 3) $M_{\mu\mu} \in [8, 12]$	1.8 ± 0.5	50.5
$Z \to \mu\mu$	A_DoubleMu3	(7, 7) $M_{\mu\mu} \in [80, 100]$	0.1 ± 0.0	50.5
Triple Relaxed μ	A_TripleMu3	(3, 3, 3)	0.1 ± 0.0	50.5
Same-sign double μ	A_DoubleMu3	(3, 3)	5.7 ± 1.2	52.5

Start with "mu20" (Muon E_T > 20 GeV cut at L1 only);
Rate estimated at 14 Hz @ 10^{31} cm^{-2} s^{-1}
In parallel have triggers with cuts at L2, EF

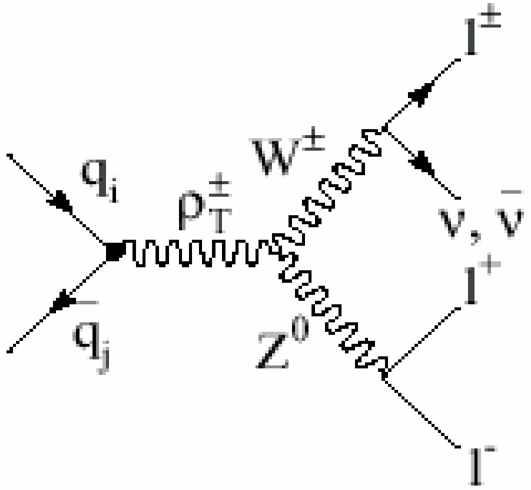
High multiplicity final states

4) Technicolor: Dynamical EWSB via new strong interaction

- Predicts new techni-fermions, techni-hadrons

Signal: $\rho_{TC} \rightarrow W\,Z$

- (clean with leptonic W & Z decays)



5) Same sign top

$tt/\bar{t}\bar{t}$ (+jets) topologies predicted where both leptons have equal charge (FCNC, Top-color assisted Technicolor)
Signal: t-tbar -> $\bar{b}$ W $\bar{b}$ W -> b l1 ν b l2 ν with (l1, l2 = μ or e)

Trigger: single/di-lepton triggers (also e+μ triggers)
CMS: Same-sign di-muon trigger (with relaxed isolation criteria)

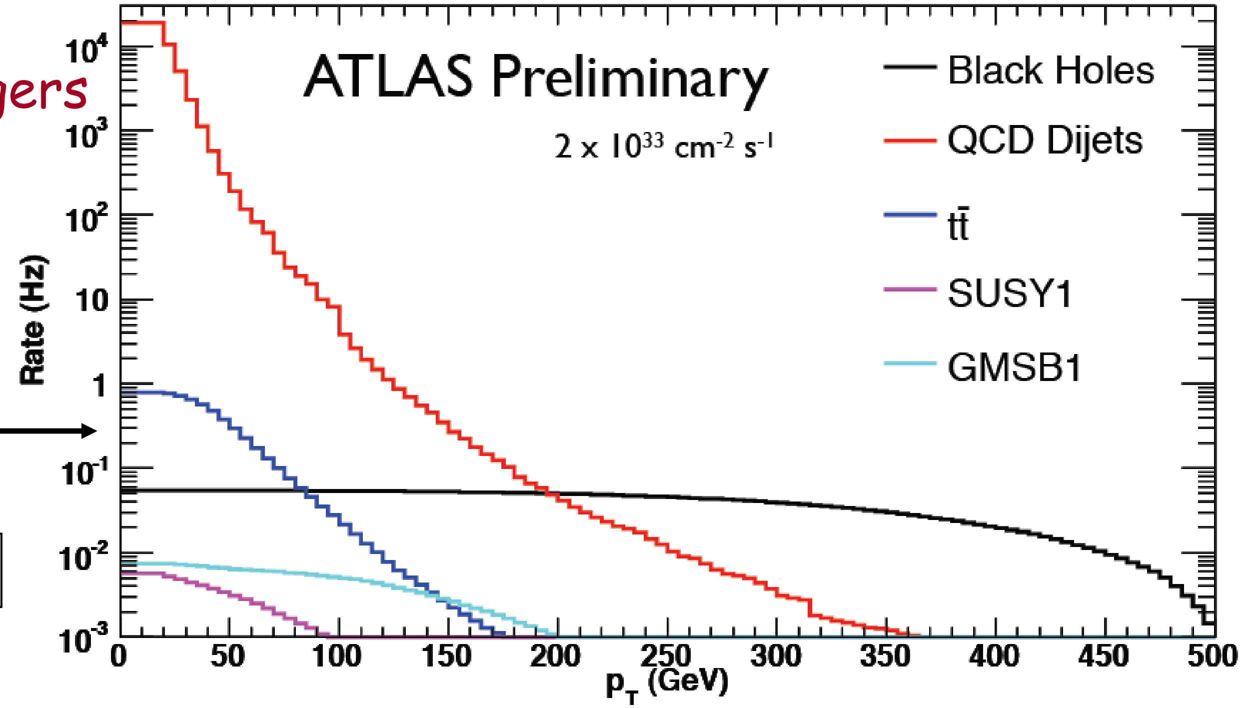
High-multiplicity final states

6) Black Holes

Single lepton, photon triggers are very efficient
Use jet triggers as well

@ L=10^{33} cm^{-2} s^{-1}

Rate for 4JX trigger as a function of 4th jet pT cut



Multi-jet Trigger Menu

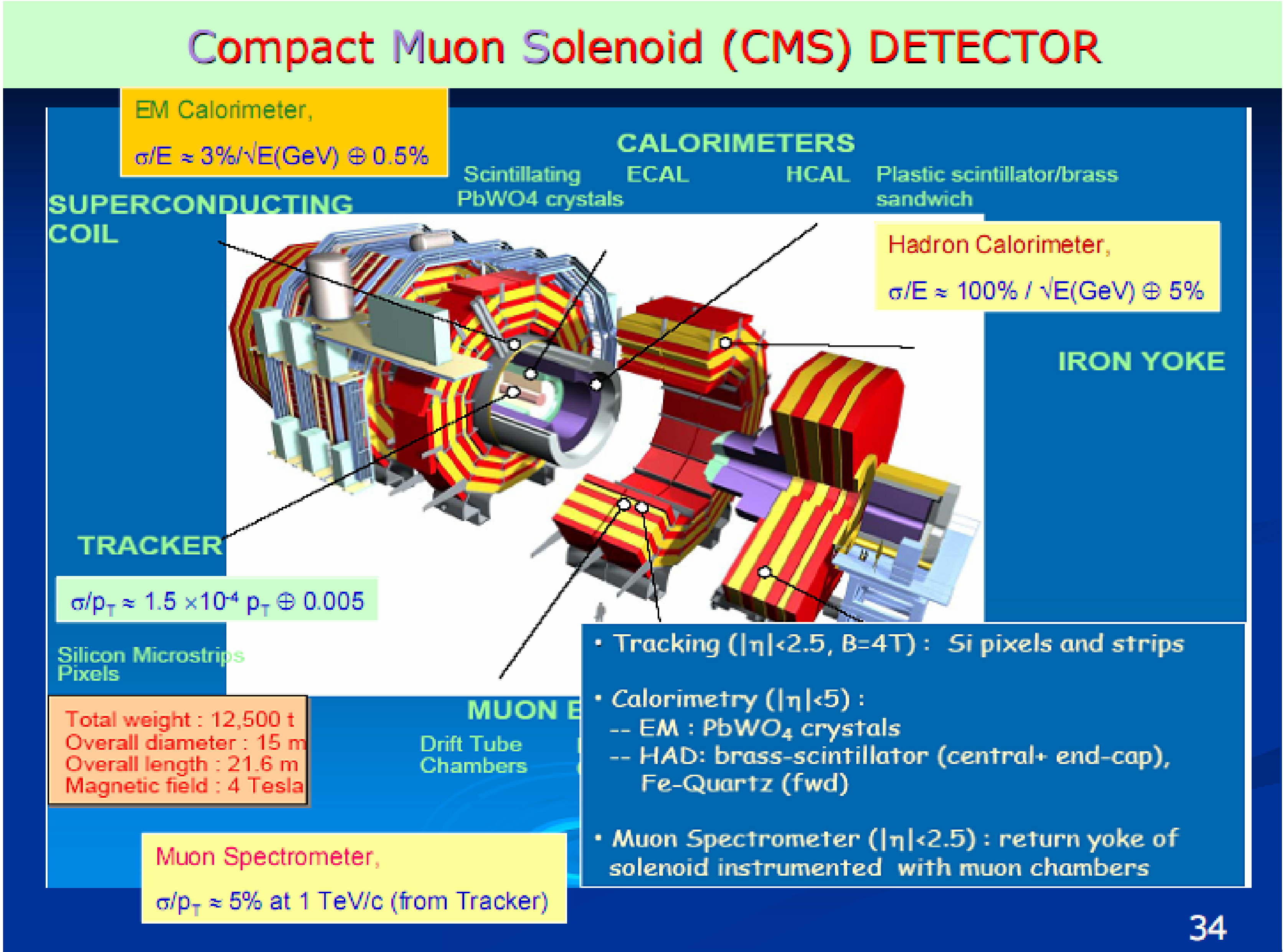
@ L=10^{32} cm^{-2} s^{-1}

HLT	L1 condition	HLT thres.(GeV)	Rate
Double-Jet	A_SingleJet150 A_DoubleJet70	150	10.6 ± 0.0
Triple-Jet	†	85	7.5 ± 0.1
Quad-Jet	‡	60	3.9 ± 0.1

Summary

- Triggering at the LHC is a real challenge
- BSM trigger strategies rely on inclusive selection of electrons, muons, photons…
- Sophisticated multi-tiered trigger systems have been designed by ATLAS and CMS
- Trigger menus for early physics runs (2008) are being laid out
  - Tools are in place and strategies are being optimized
- These strategies cover final states predicted by most BSM models
- Perhaps the most important strategy? KEEP AN OPEN MIND!

BACKUP


Compact Muon Solenoid (CMS) DETECTOR
EM Calorimeter,
σ/E ≈ 3%/√E(GeV) ⊕ 0.5%
CALORIMETERS
Scintillating PbWO4 crystals
ECAL
HCAL
Plastic scintillator/brass sandwich
SUPERCONDUCTING COIL
Hadron Calorimeter,
σ/E ≈ 100% / √E(GeV) ⊕ 5%
IRON YOKE
TRACKER
σ/p_T ≈ 1.5 ×10^-4 p_T ⊕ 0.005
Silicon Microstrips
Pixels
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
MUON E
Drift Tube Chambers
• Tracking (|η|<2.5, B=4T) : Si pixels and strips
• Calorimetry (|η|<5) :
-- EM : PbWO4 crystals
-- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
• Muon Spectrometer (|η|<2.5) : return yoke of solenoid instrumented with muon chambers
Muon Spectrometer,
σ/p_T ≈ 5% at 1 TeV/c (from Tracker)
34

A Toroidal LHC AppartuS (ATLAS) DETECTOR

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \to \gamma\gamma$)

Precision Muon Spectrometer,

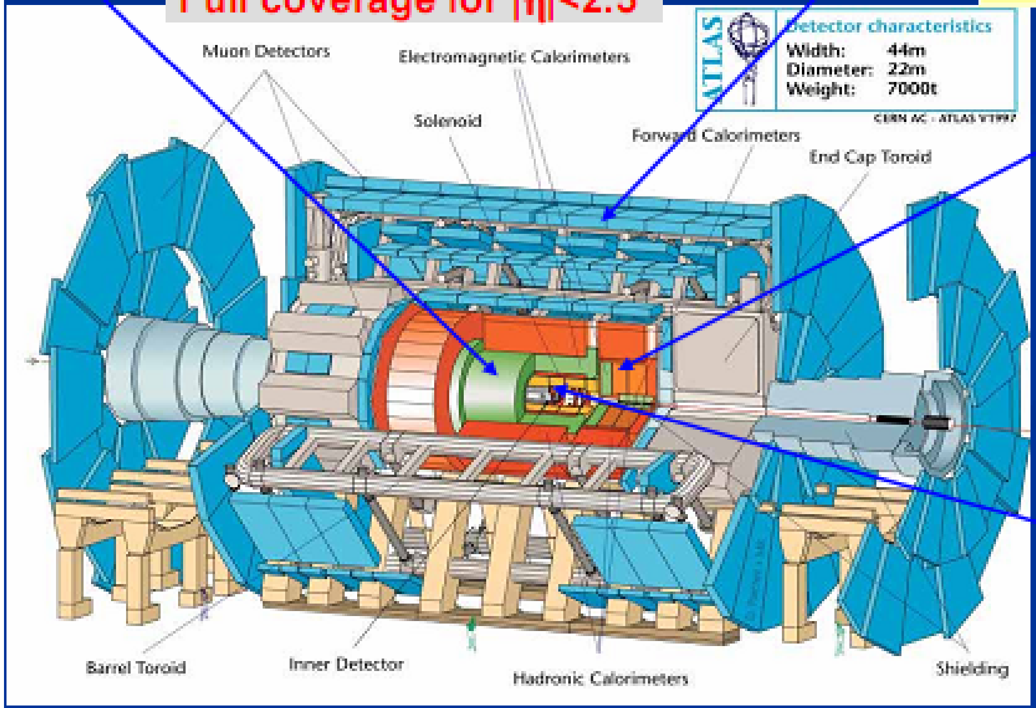
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(GeV)} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

$\sigma/p_T \approx 5 \times 10^{-4}\ p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)=15\mu m@20GeV$ (e.g. $H \to bb$)

Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

CMS L1 Trigger Rates

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
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

L1 Trigger	Threshold (GeV)	Prescale	Rate (kHz)	
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	
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_IsoEG10_Jet30	10,30	1	1.95 ± 0.05	: 0.05
A_IsoEG10_Jet20	10,20	1	3.04 ± 0.06	: 0.01
A_IsoEG10_Jet70	10,70	1	0.26 ± 0.02	: 0.04
A_IsoEG10_TauJet20	10,20	1	1.95 ± 0.05	: 0.03
A_IsoEG10_TauJet30	10,30	1	1.33 ± 0.04	: 0.02
A_TauJet30_ETM30	30,30	1	1.96 ± 0.05	: 0.01
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	
A_MinBias_HTT10	10	large	0.40	
A_ZeroBias	0	large	0.40	
Total L1 Trigger Rate (kHz)			16.67 ± 0.15	

CMS High Level Trigger Rates

HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
Single Isolated μ	A_SingleMu7	11	18.3 ± 2.2	18.3
Single Relaxed μ	A_SingleMu7	16	22.7 ± 1.5	37.7
Double Relaxed μ	A_DoubleMu3	(3, 3)	12.3 ± 1.6	48.5
$J/\psi \rightarrow \mu\mu$	A_DoubleMu3	(3, 3) $M_{\mu\mu} \in [2.9, 3.3]$	2.0 ± 0.8	49.4
$\Upsilon \rightarrow \mu\mu$	A_DoubleMu3	(3, 3) $M_{\mu\mu} \in [8, 12]$	1.8 ± 0.5	50.5
$Z \rightarrow \mu\mu$	A_DoubleMu3	(7, 7) $M_{\mu\mu} \in [80, 100]$	0.1 ± 0.0	50.5
Triple Relaxed μ	A_TripleMu3	(3, 3, 3)	0.1 ± 0.0	50.5
Same-sign double μ	A_DoubleMu3	(3, 3)	5.7 ± 1.2	52.5
$b \rightarrow \mu$ tag 1-jet Prescale 20	A_Mu5_Jet15	20 $\Delta R(\mu, j) < 0.4$	4.0 ± 0.1	56.1
$b \rightarrow \mu$ tag 2-jets	A_Mu5_Jet15	120, $p_T^{rel}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.5 ± 0.0	56.1
$b \rightarrow \mu$ tag 3-jets	A_Mu5_Jet15	70, $p_T^{rel}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.3 ± 0.0	56.1
$b \rightarrow \mu$ tag 4-jets	A_Mu5_Jet15	40, $p_T^{rel}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.4 ± 0.0	56.1
$b \rightarrow \mu$ tag H_T	A_HTT250	300, $p_T^{rel}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	2.6 ± 0.2	56.6
$b \rightarrow J/\psi(\mu\mu)$	A_DoubleMu3	(4, 4) $M_{\mu\mu} \in [2.95, 3.25]$	0.7 ± 0.1	56.8
μ + b-jet	A_Mu5_Jet15	(7, 35)	0.1 ± 0.0	56.8
$\mu + b \rightarrow \mu$-jet	A_Mu5_Jet15	(7, 20)	0.1 ± 0.1	56.8
μ + jet	A_Mu5_Jet15	(7, 40)	6.3 ± 0.7	60.8
$e + \mu$	$\star$	(8, 7)	0.5 ± 0.4	61.2
$e + \mu$ relaxed	$\star$	(10, 10)	0.1 ± 0.0	61.3
$\mu + \tau$	A_Mu5_TauJet20	(15, 20)	0.0 ± 0.0	61.3
Single-Jet	A_SingleJet150	200	9.3 ± 0.1	70.1
Double-Jet	A_SingleJet150 A_DoubleJet70	150	10.6 ± 0.0	74.4
Triple-Jet	†	85	7.5 ± 0.1	78.8
Quad-Jet	‡	60	3.9 ± 0.1	80.5
$\not\!\!E_T$	A_ETM40	65	4.9 ± 0.7	84.0
Acopl. Double-Jet	A_SingleJet150 A_DoubleJet70	125	1.4 ± 0.0	84.0
Acopl. Single-Jet + $\not\!\!E_T$	A_ETM30	(100, 60)	1.6 ± 0.0	84.2
Single-Jet + $\not\!\!E_T$	A_ETM30	(180, 60)	2.2 ± 0.1	84.4
Double-Jet + $\not\!\!E_T$	A_ETM30	(125, 60)	1.0 ± 0.0	84.4
Triple-Jet + $\not\!\!E_T$	A_ETM30	(60, 60)	0.6 ± 0.0	84.4
Quad-Jet + $\not\!\!E_T$	A_ETM30	(35, 60)	1.2 ± 0.1	84.6
H_T + $\not\!\!E_T$	A_HTT300	(350, 65)	4.4 ± 0.1	86.2
Single Jet Prescale 10	A_SingleJet100	150	3.5 ± 0.0	87.9
Single Jet Prescale 100	A_SingleJet70	110	1.5 ± 0.0	89.1
Single Jet Prescale 1000	A_SingleJet30	60	0.8 ± 0.4	89.9

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HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
VBF Double-Jet + $\not\!\!E_T$	A_ETM30	(40, 60)	0.2 ± 0.0	89.0
SUSY 2-jet+$\not\!\!E_T$	A_ETM30	(80,20,60)	2.0 ± 0.1	90.4
Acopl. Double-Jet + $\not\!\!E_T$	A_ETM30	(60, 60)	1.0 ± 0.0	90.4
Single Isolated e	A_SingleIsoEG12	15	17.1 ± 2.3	107.5
Single Relaxed e	A_SingleEG15	17	9.6 ± 1.3	109.3
Double Isolated e	A_DoubleIsoEG8	10	0.2 ± 0.1	109.4
Double Relaxed e	A_DoubleEG10	12	0.8 ± 0.1	109.9
Single Isolated γ	A_SingleIsoEG12	30	8.4 ± 0.7	118.1
Single Relaxed γ	A_SingleEG15	40	2.8 ± 0.2	118.5
Double Isolated γ	A_DoubleIsoEG8	(20,20)	0.6 ± 0.4	119.0
Double Relaxed γ	A_DoubleEG10	(20,20)	1.8 ± 0.5	120.1
High E_T e	A_SingleEG15	80	0.5 ± 0.0	120.4
High E_T e	A_SingleEG15	200	0.1 ± 0.0	120.4
Lifetime b-tag 1-jet	$\diamond$	180	1.3 ± 0.0	120.5
Lifetime b-tag 2-jets	$\diamond$	120	2.1 ± 0.0	121.2
Lifetime b-tag 3-jets	$\diamond$	70	1.7 ± 0.0	121.8
Lifetime b-tag 4-jets	$\diamond$	40	1.8 ± 0.0	122.6
Lifetime b-tag H_T	$\diamond$	470	2.5 ± 0.1	123.1
Single τ	A_SingleTauJet80	15	0.2 ± 0.0	123.2
τ + $\not\!\!E_T$	A_TauJet30_ETIM30	15	1.8 ± 0.2	124.7
Double τ (Calo+Pixel)	A_DoubleTauJet40	15	4.9 ± 0.6	129.4
e + b-jet	A_IsoEG10_Jet20	(10, 35)	0.1 ± 0.0	129.4
e + jet	A_IsoEG10_Jet30	(12, 40)	11.6 ± 1.2	135.8
$e + \tau$	A_IsoEG10_TauJet20	(12, 20)	0.2 ± 0.0	135.8
Prescaled e/γ	See Table 3.9		5.0 ± 0.0	140.8
Prescaled μ	See Table 2.4		3.0 ± 0.0	143.8
Min.Bias	A_MinBias_HTT10	—	1.5 ± 0.0	145.3
Pixel Min.Bias	A_ZeroBias	—	1.5 ± 0.0	146.8
Zero Bias	A_ZeroBias	—	1.0 ± 0.0	147.8
Total HLT rate (Hz)				148 ± 4.9

CMS Trigger Efficiencies

Signal	HLT Single Relaxed muon eff.(%)	HLT Double muon eff.(%)	HLT Single Isolated muon eff.(%)	(Level-1)*HLT acceptance (%)
$Z \to \mu\mu$	98.6	91.2	95.8	98.1
$W \to \mu\nu$	86.9	-	81.4	76.7

Muons

HLT efficiency for benchmark channels

Signal process	Isolated single electron	Relaxed single electron	Isolated double electron	Relaxed double electron
HLT: $Z \to ee$	83.3	85.2	63.8	64.4
HLT: $W \to e\nu$	62.5	61.2	-	-
L1*HLT: $Z \to ee$	80.0	82.6	62.6	63.2
L1*HLT: $W \to e\nu$	52.1	52.4	-	-

Electrons

Signal process	Isolated single photon	Relaxed single photon	Isolated double photon	Relaxed double photon
HLT: $H \to \gamma\gamma(m_H$=120 GeV)	80.5	76.8	75.8	75.7
L1*HLT: $H \to \gamma\gamma(m_H$=120 GeV)	78.8	76.8	75.8	75.7

Photons

Signal process	single high energy EM	Single very high energy EM	Total
$Z' \to ee$ ($M \geq$ 200 GeV)	67	7.0	67
$Z' \to ee$ ($M \geq$ 500 GeV)	91	69	93
$Z' \to ee$ ($M \geq$ 1000 GeV)	94	92	98
$Z' \to ee$ ($M \geq$ 2000 GeV)	90	97	98
$G \to \gamma\gamma$ ($M \geq$ 2000 GeV)	91	97	98

High-E_T EM candidates
(apply high E_T cuts, loosen-up isolation)

Good *W/Z* efficiencies
for muon, egamma HLT