Triggers for top and 4^{th} Generation Quarks

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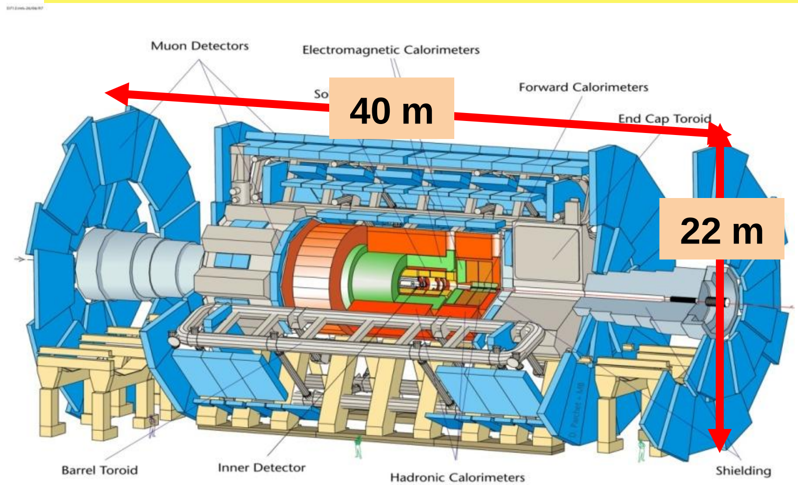
Workshop on single top and 4th generation quarks
DESY, Sept. 14th-15th, 2009

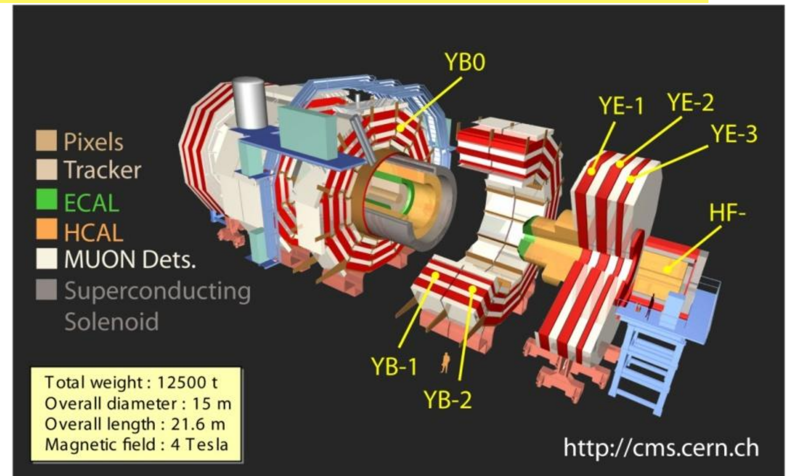
Results presented here have been collected from public documents
ATLAS Physics Performance Book, CMS Physics TDR,
ATLAS and CMS public physics pages,
conference articles and public talks

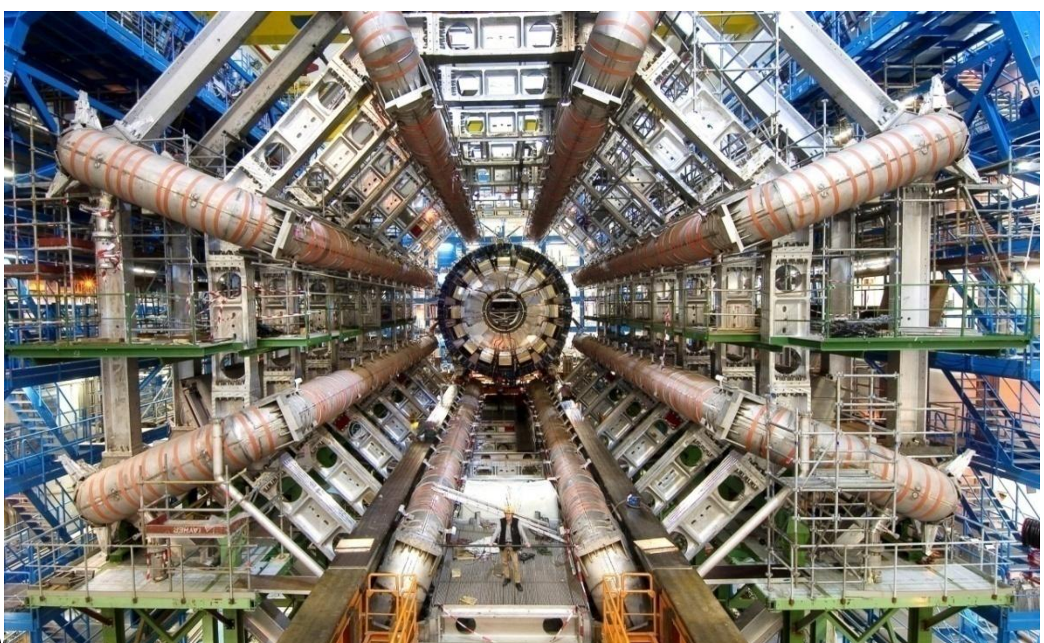
Thanks to the organizers of this very interesting workshop
and to colleagues in ATLAS and CMS
especially:
ATLAS: D.Berge, F. Ledroit , A. Lucotte, S. Mehlhase, P. Ryan, E. Ros, M. Zur Nedden,
CMS: J. Cuevas, A. Giammanco, S. Goy, G. Landsberg, C. Leonidopoulos, P. Lobelle,
E. Perez, W. Smith

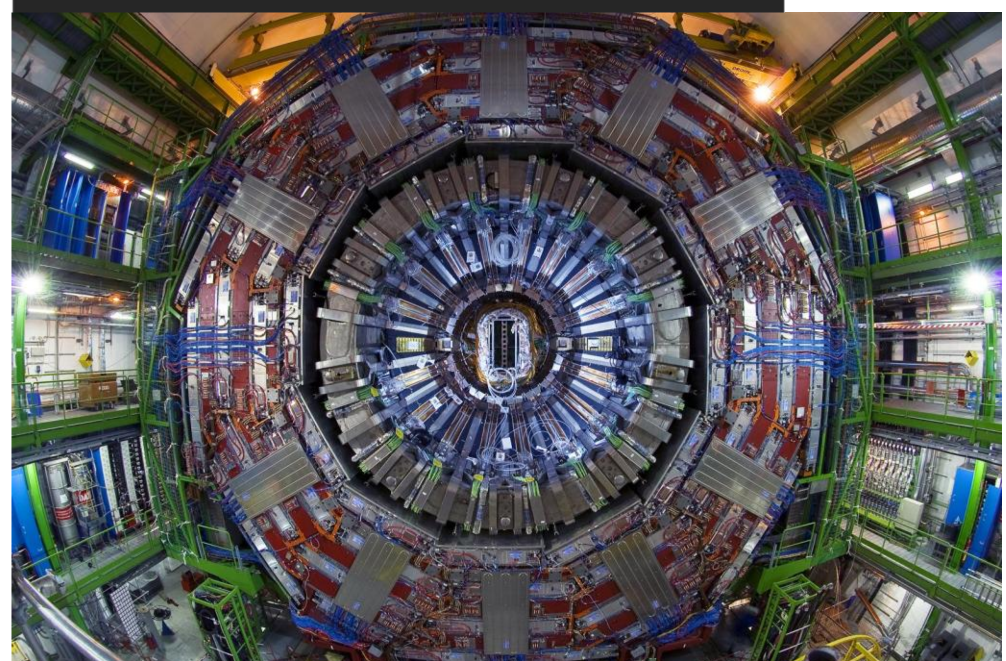
Outline

1. Overview of ATLAS and CMS Trigger Systems
2. Trigger Menu Development and Bandwidth Allocation
3. Triggers for top and 4th generation quarks

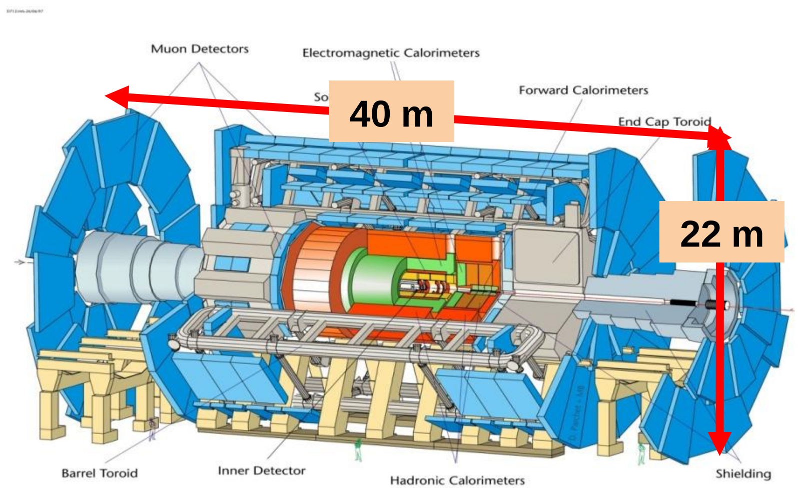


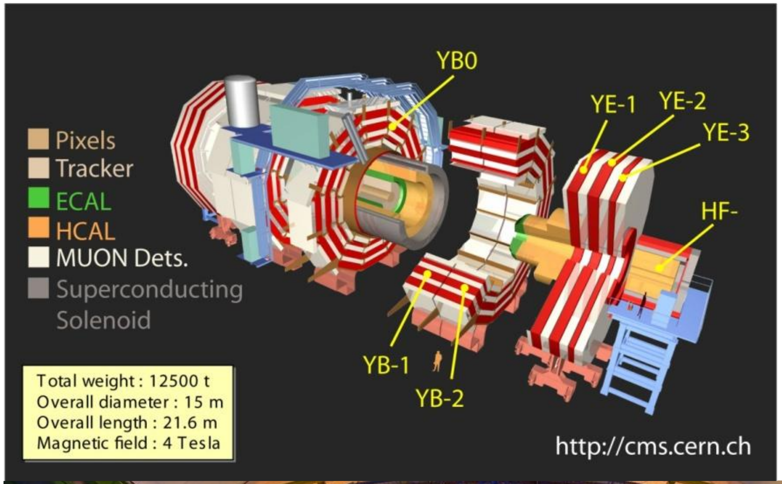


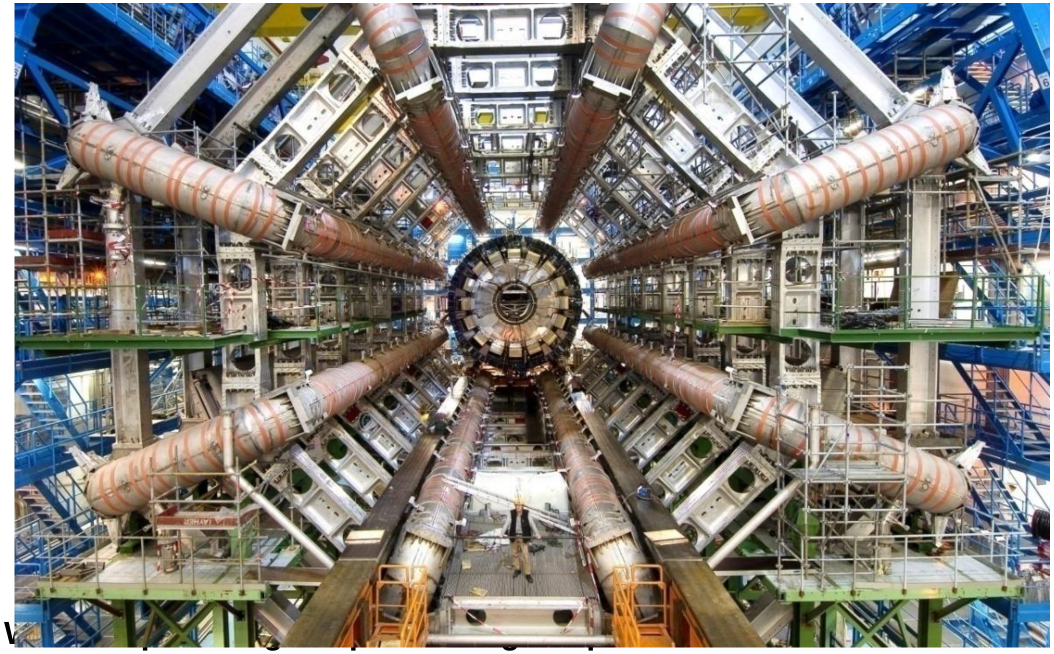


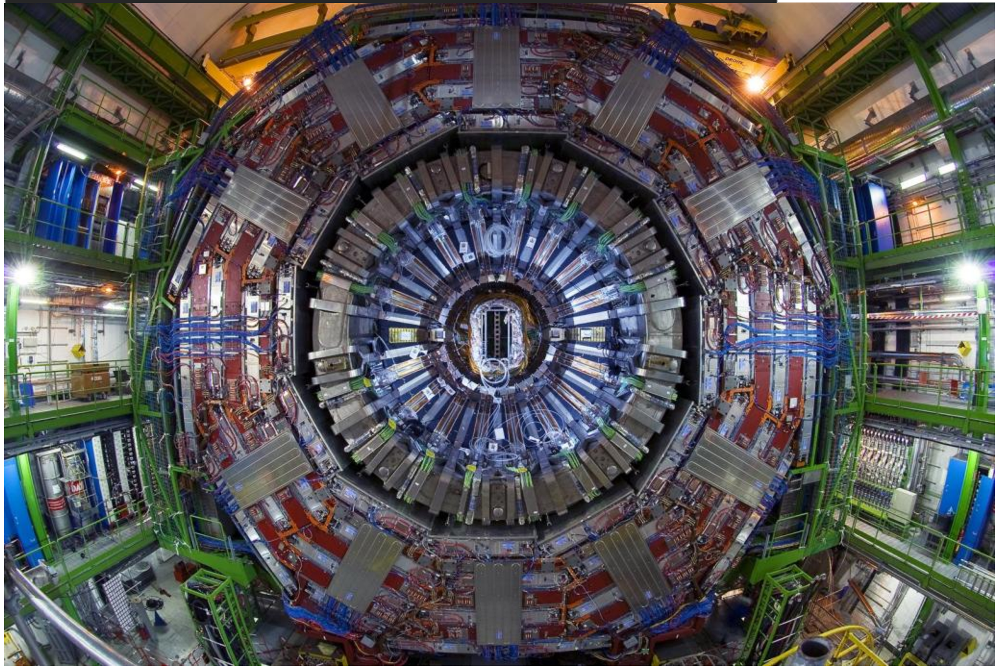


1. Overview of ATLAS and CMS Trigger Systems

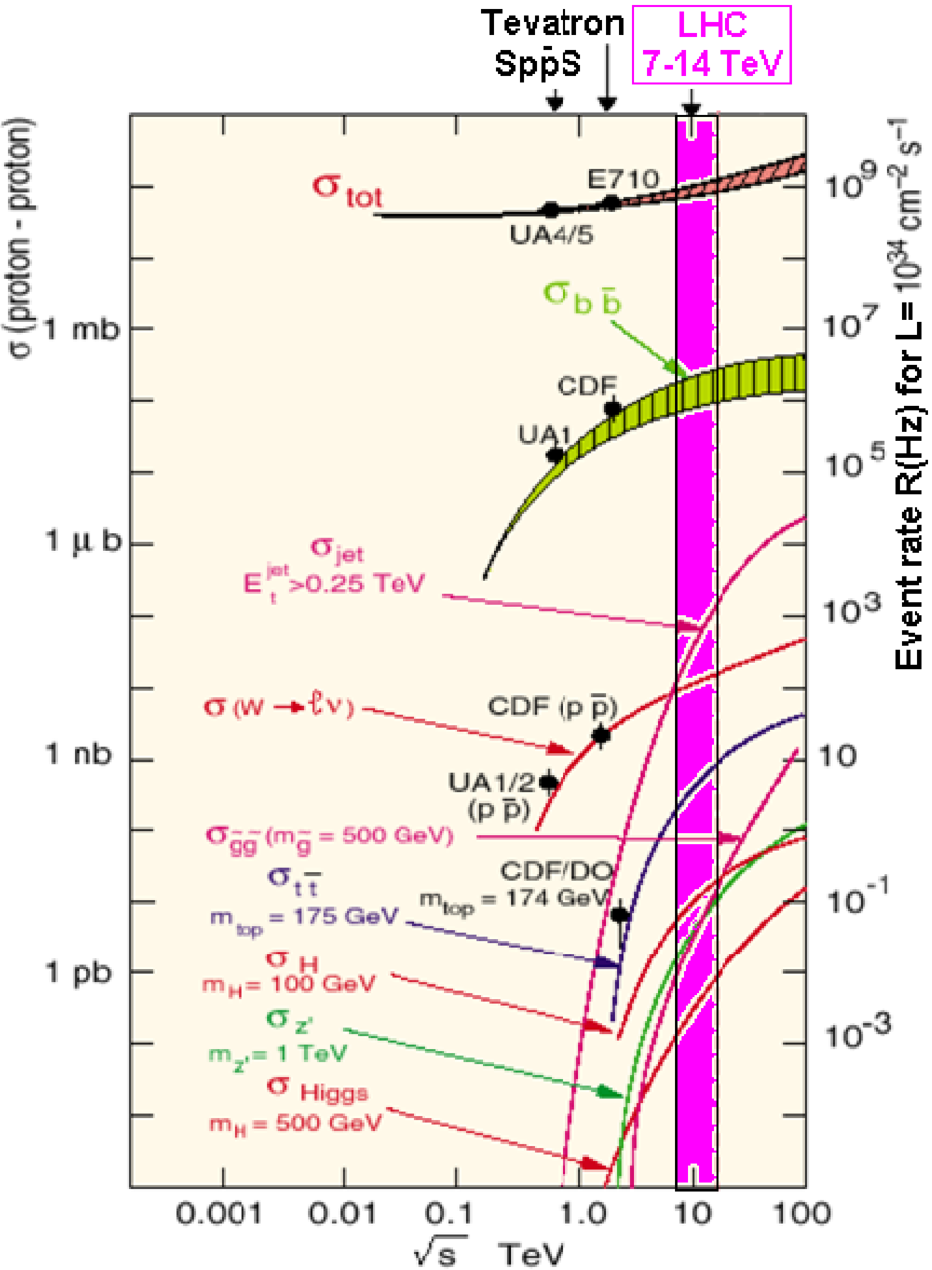








Trigger Challenges



1. High speed -> cope with high bunch cross. rate

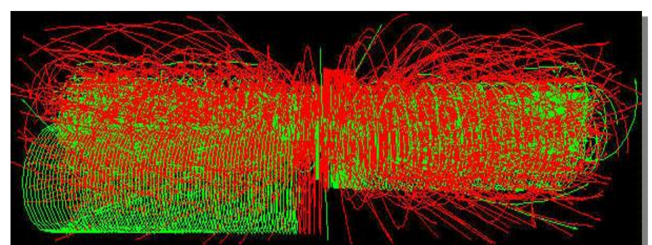
Bunch crossing rate B = 40 MHz-> trigger clock

2. High selectivity -> from 40 MHz to <~ 200 Hz (to storage) while retaining all the physics of interest

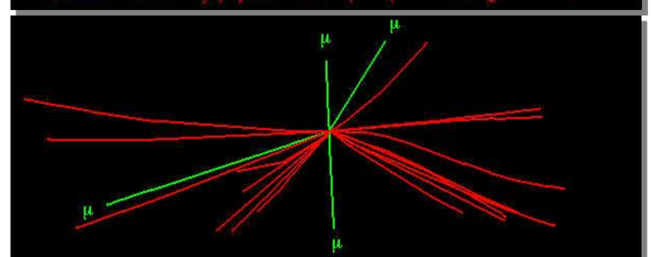
σ_{inel} **~ 80 mb ≥ 10⁸** σ_{tt} -> 1 in10^8 is a tt event

3. High granularity -> cope with high occupancy

At $L=10^{34} cm^{-2}s^{-1}$ -> Event Rate R = σ_{inel} L ~ 800 MHz
f = fraction of filled bunches ~ 0.8
Number of events/Bunch = R/(B f)~25
25 pile up events/bunch cross.w/ ~2000 particles produced

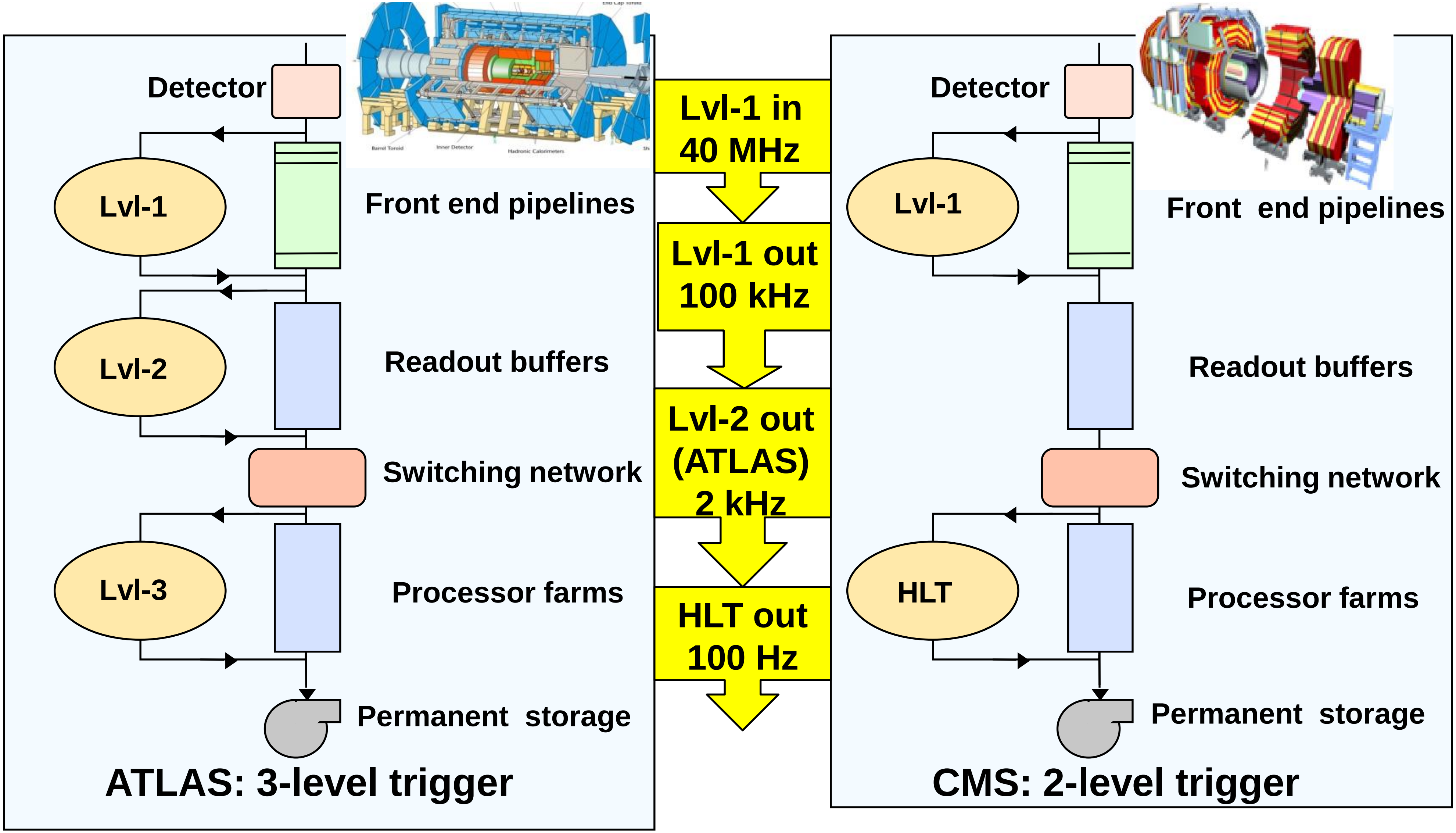


Operating conditions: An example: Higgs in 4 muons + ~20 minimum bias evts. Ch. tracks w/ pt > 2 GeV



Reconstructed tracks with pt > 25 GeV

ATLAS 3-Level Trigger vs CMS 2-Level Trigger



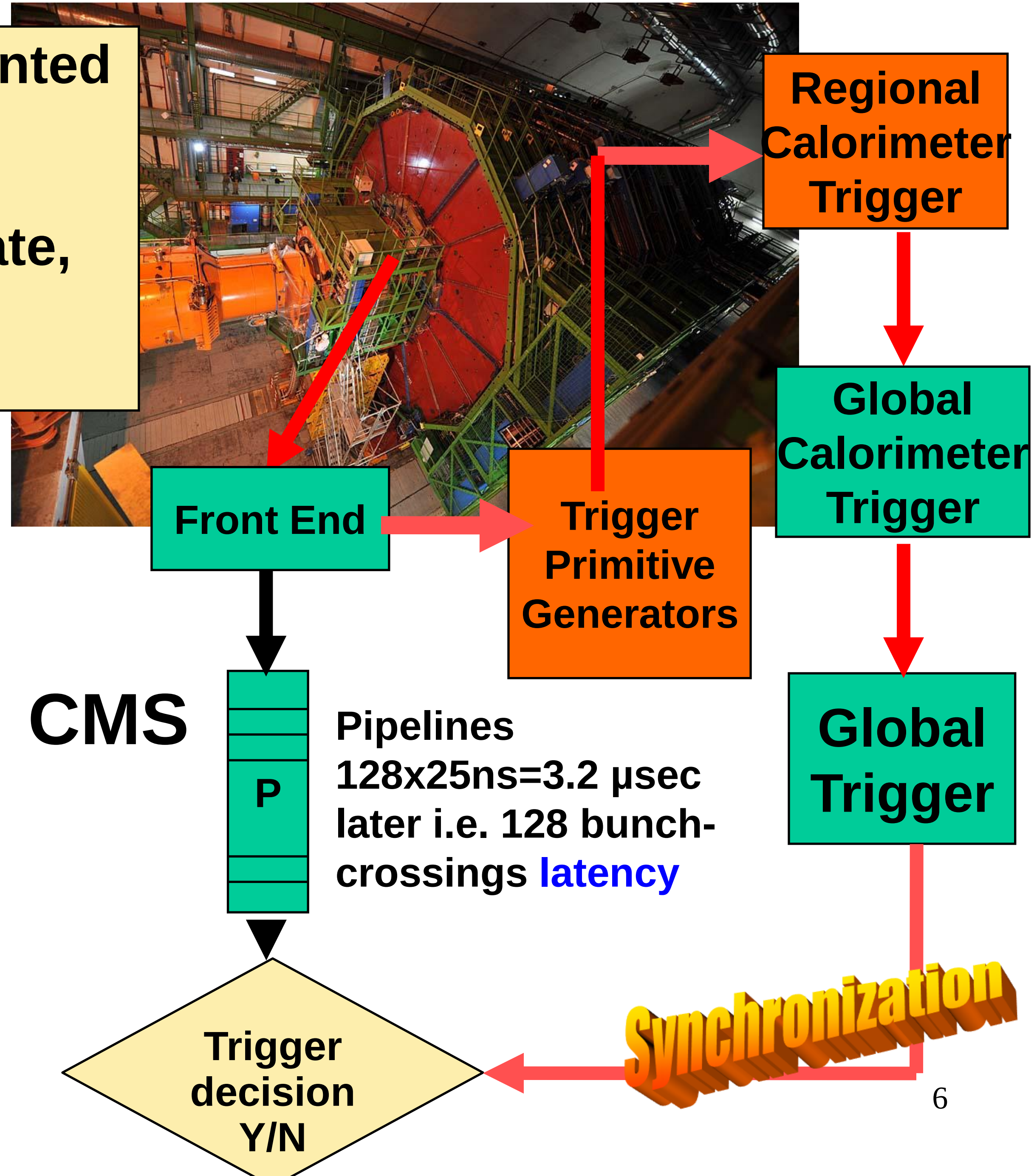
Level-1 trigger (Hardware, Firmware): reduce 40 MHz to 100 kHz

Level-2xLevel-3 or HLT (software): reduce 100 kHz to 100 Hz

Level-1 Trigger (Lvl-1T)

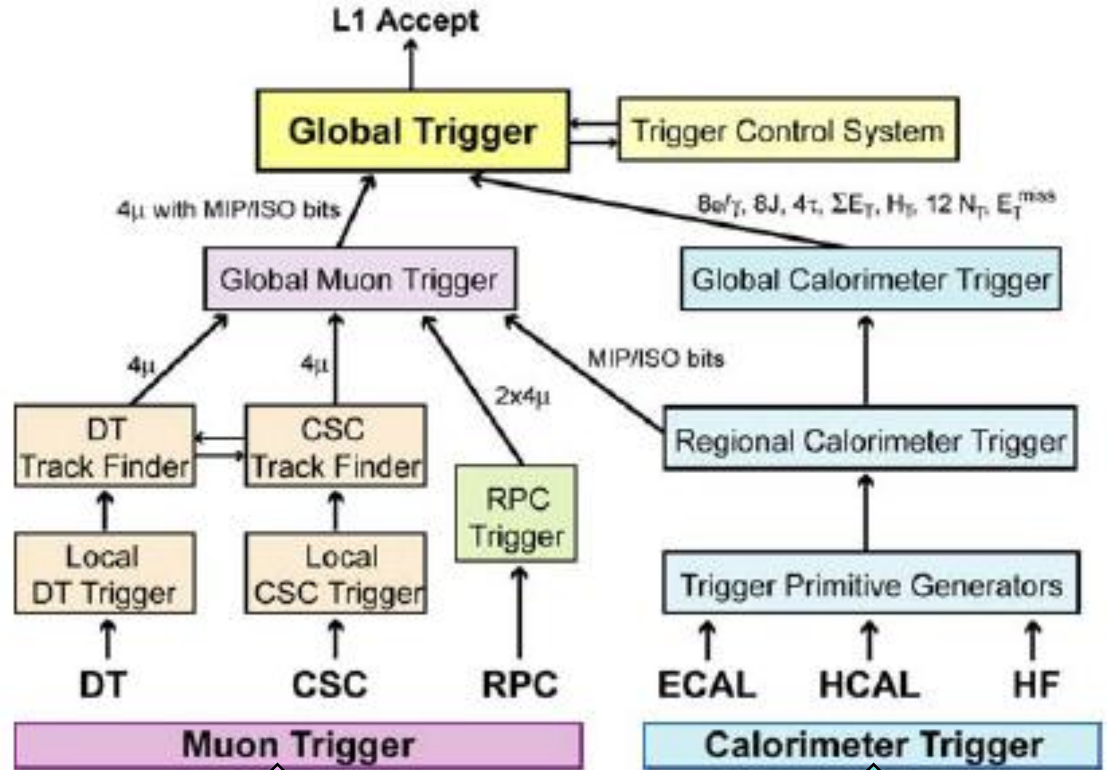
The Level-1 trigger, implemented using custom electronics, inspects events at the full bunch-crossing rate, while selecting 100 kHz for further processing

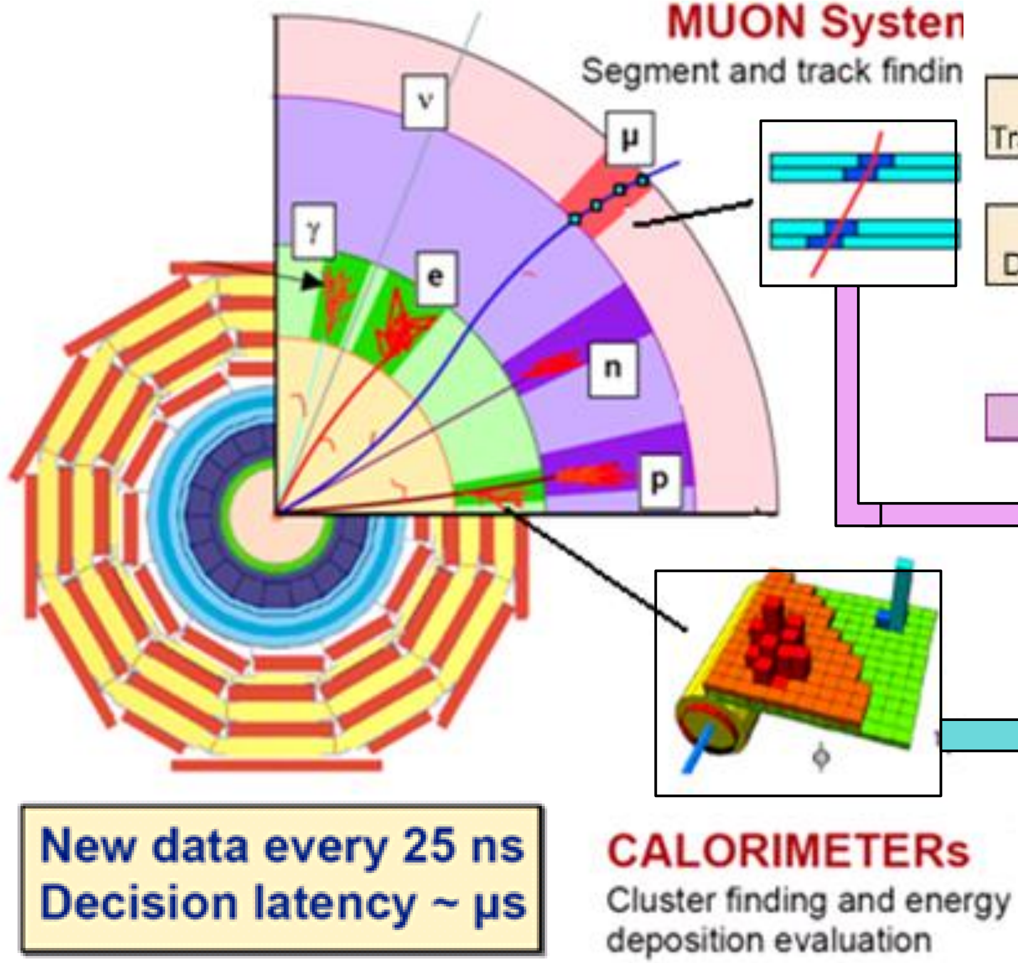
- Detector data stored in **Front End Pipelines.**
- Trigger decision derived from **Trigger Primitives** generated on the detector.
- Regional Triggers search for **jets, isolated e/γ and μ and compute the transverse, missing energy** of the event.
- **Event Selection Algorithms run on the Global Triggers**



Lvl-1T Data Flow

Use prompt data, calorimeters and muon data, to identify high P_T muons, electrons, jets, missing E_T





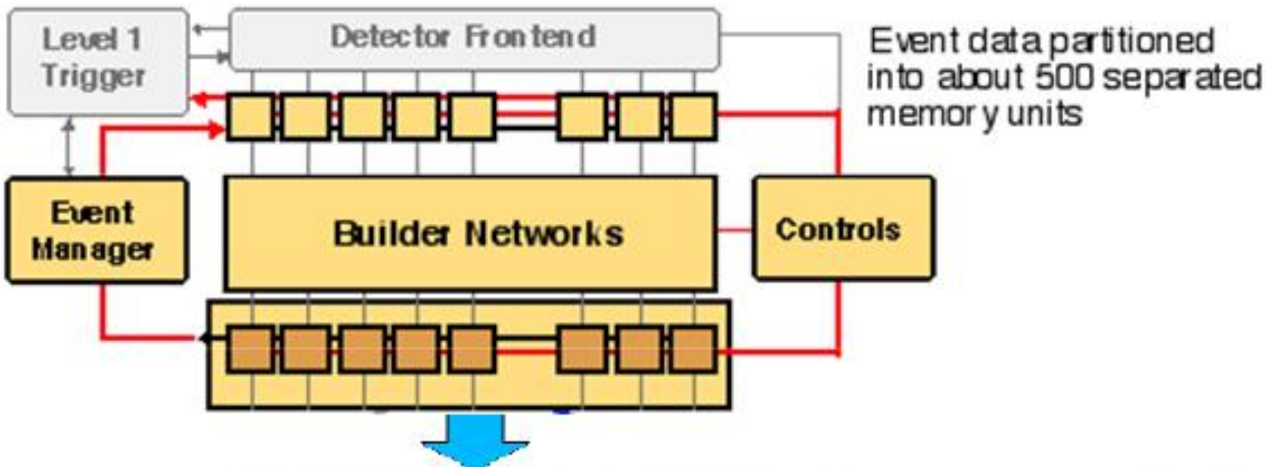
New data every 25 ns
Decision latency ~ μs

ATLAS and CMS similar Lvl-1 Data Flow

CMS High Level Trigger and DAQ

Further online selection is performed in the high-level trigger (HLT) which reduces the 100 kHz input stream to 100 Hz of events written to permanent storage.
The HLT system consists of a large cluster of commercial CPUs : the HLT Filter Farm

L1 Input rate <~40 MHz
L1 latency: 3.2 μs
L1 Output rate:
100kHz-50kHz (startup)



L2 and L3 merged into
High Level Trigger (HLT)

HLT ~ startup: 50kHz input rate
~2000 CPUs
~40 ms average per event

Farm of processors
ONE event, ONE processor
- High latency (larger buffers)
- Simpler I/O
- Sequential programming

The High Level Trigger is purely software-based and achieves a 1/1000 rate reduction by executing offline-quality algorithms.

ATLAS HLT Selection Strategy

Credit: J. Haller

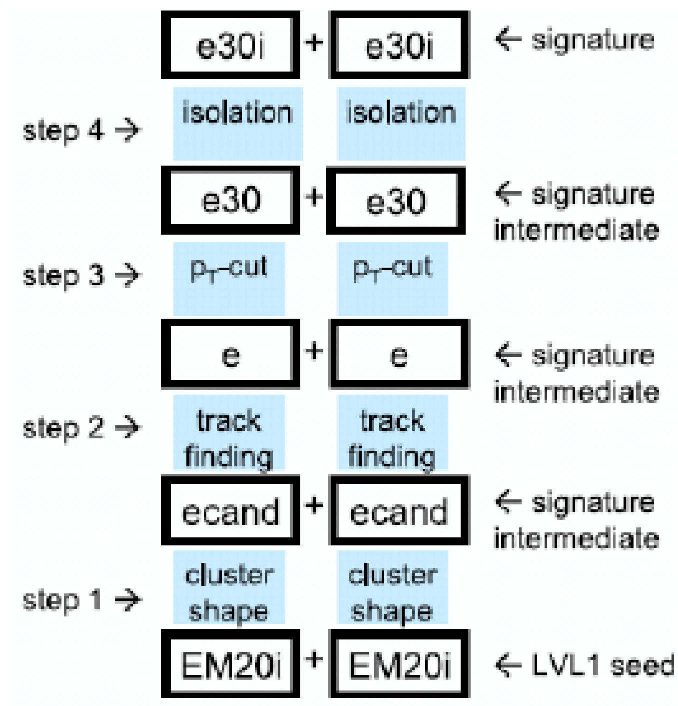
<u>fundamental principles</u>:

1) step-wise processing and decision
- inexpensive (data, time) algorithms first, complicated algorithms last.
- early reject

2) seeded reconstruction
- algorithms use results from previous steps
- initial seeds for LVL2 are LVL1 RoIs

→ LVL2 confirms & refines LVL1
→ EF confirms & refines LVL2
note: EF tags accepted events according to physics selection (→ streams, offline analysis!)

Example: Dielectron Trigger

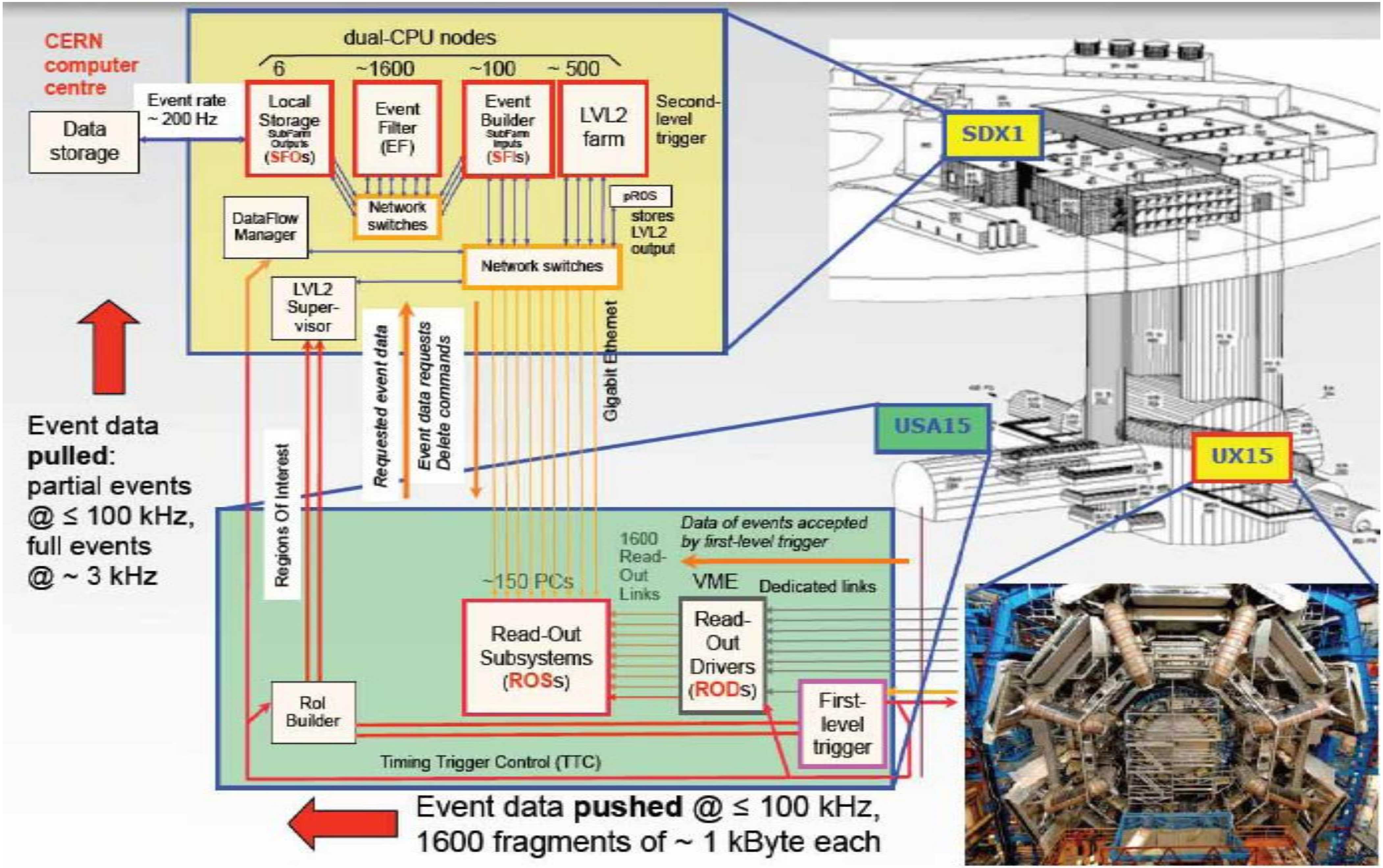


<u>ATLAS trigger terminology:</u>
- Trigger chain
- Trigger signature (called item in LVL1)
- Trigger element

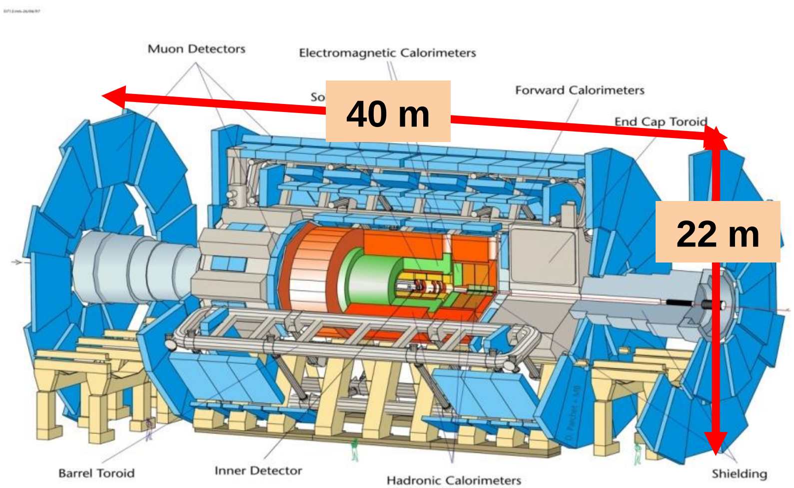
CMS HLT Selection Strategy is quite similar

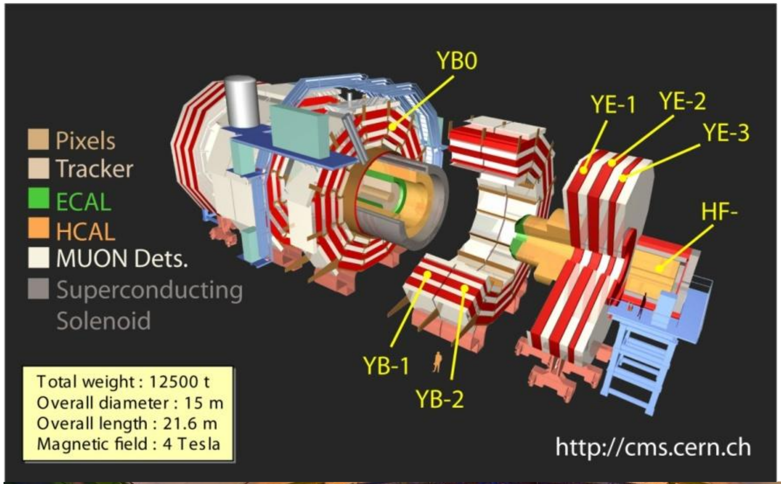
ATLAS Trigger and DAQ Architecture

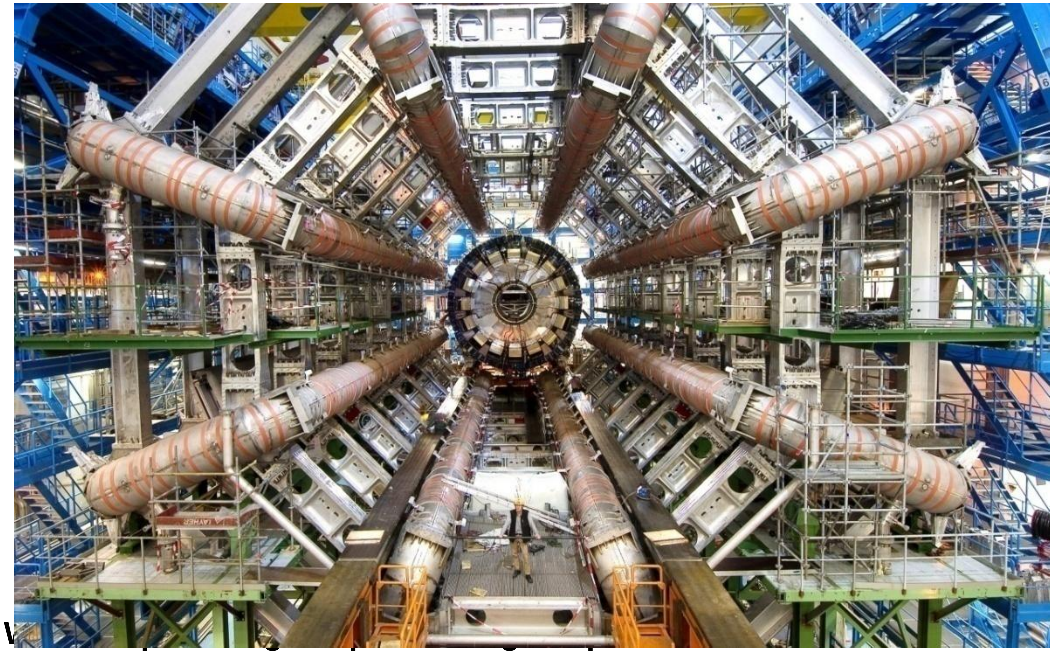
Credit: J. Haller

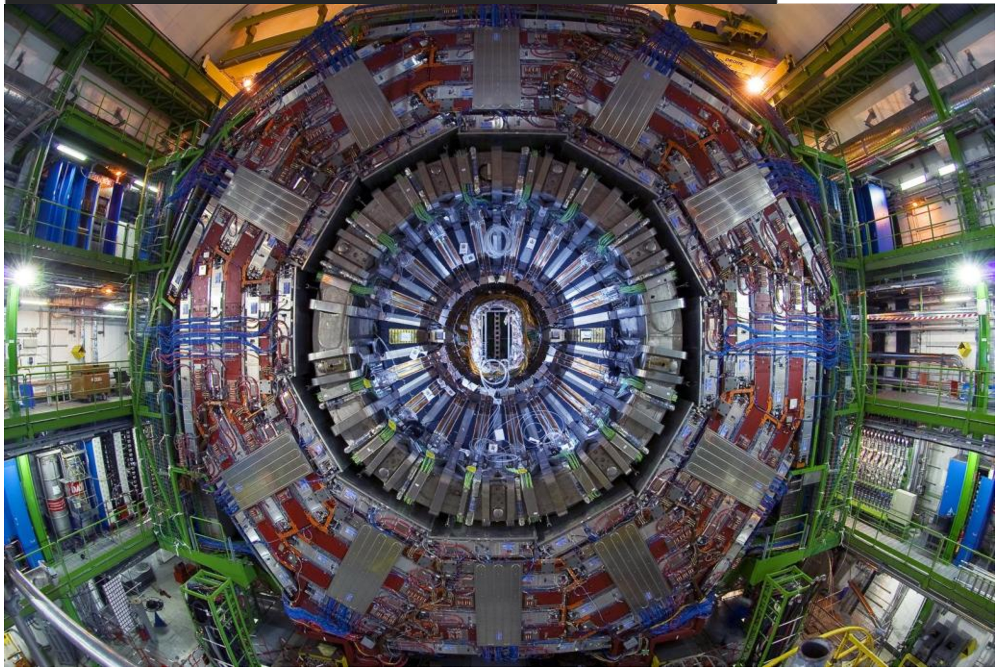


2. Trigger Menu Development and Bandwidth Allocation









The trigger criteria must be adapted to the plan and goals of the experiment at each luminosity

The Plan: from start-up to discovery

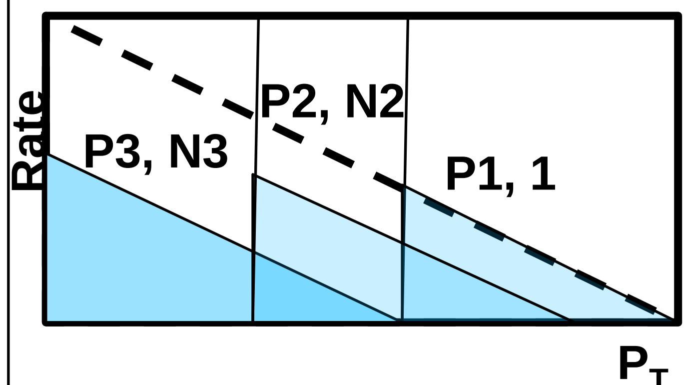
Luminosity range	Goals	Definition of Signal	Definition of Background
$10^{29}s^{-1}cm^{-2}$-$10^{31}s^{-1}cm^{-2}$	Calibrate and align all the sub-detectors	QCD events	Machine, detector noise
$10^{31}s^{-1}cm^{-2}$-$10^{33}s^{-1}cm^{-2}$ @ **$10^{32}s^{-1}cm^{-2}$** collect O(100/pb)/mo, O(1/fb)/ y (Tevatron now: ~4/fb/expt)	Measure the Standard Model processes: b-phys. , W/Z ,top Use them for more refined detector calibration	Standard Model processes: b-phys., W/Z ,top	As above and QCD events
$10^{33}s^{-1}cm^{-2}$-$10^{34}s^{-1}cm^{-2}$	Detector well calibrated and response well understood Enter the "Discovery Mode¨	New "expected" Physics: Higgs Supersymmetry New unknown: ???	As above and Standard Model processes

Define trigger criteria to optimize trigger performance in serving the above plan

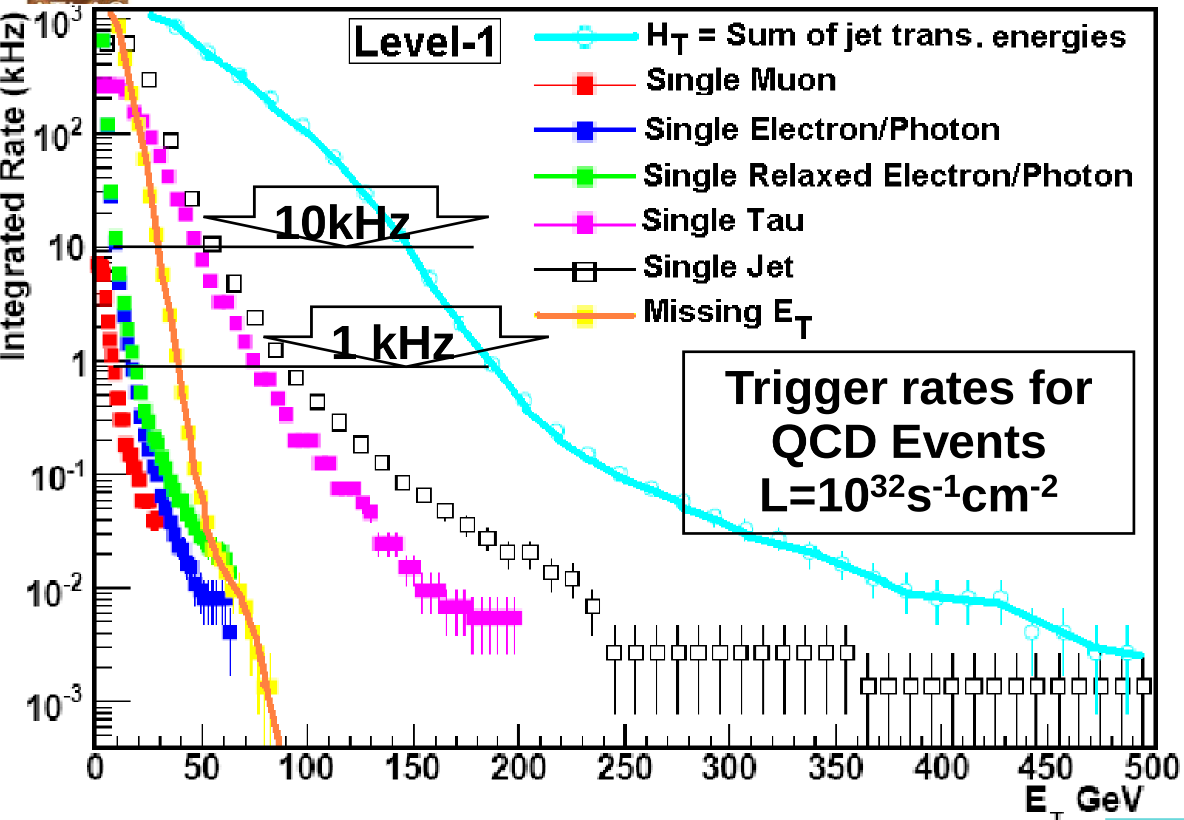
Trigger menu, paths and their use

Trigger type/path	Trigger conditions	Purpose
Inclusive Single object: IsoMuon, NoIsoMuon, RelaxElectron, Electron, Others…. Double-object: DoubleNoIsoMuon, DoubleRelaxElectron, Others….	See prescale table and rate plot below	High P_T triggers used for: high-P_T signals (W,Z, top, Higgs, …) Low P_T triggers used for: - Low P_T signals (b-physics...) - Background measurements - Trigger efficiency measurement - Detector calibration
Exclusive Cross-object: NoIsoMuon+3jets, RelaxElectron+NoIsoMuon, Others….	Low P_T thresholds allowed (lower than for Inclusive single object triggers) because of low rate. Prescale factors may be needed at higher luminosities	Cross-object triggers used for specific selections of interest both for Standard Model process and for new physics searches

P_T Threshold	Prescale factor
P1	1
P2 (< P1)	N2 (>1)
P3 (<P2)	N3 (>N2)



Example: Lvl-1T Bandwidth Allocation & Rates



Design tables for 17kHz L1 output rate
1/3 actual initial capability of 50 kHz

How do we allocate bandwidth between the different triggers?

For **single object triggers**:
- Muon rates are low
- Electron rates are high at low Et
- Jet rates are high also at high Et

For **double object triggers** (not shown here) rates are one to more orders of magnitude lower than for single object triggers: allow to keep low thresholds at small bandwidth cost.

General guidelines:

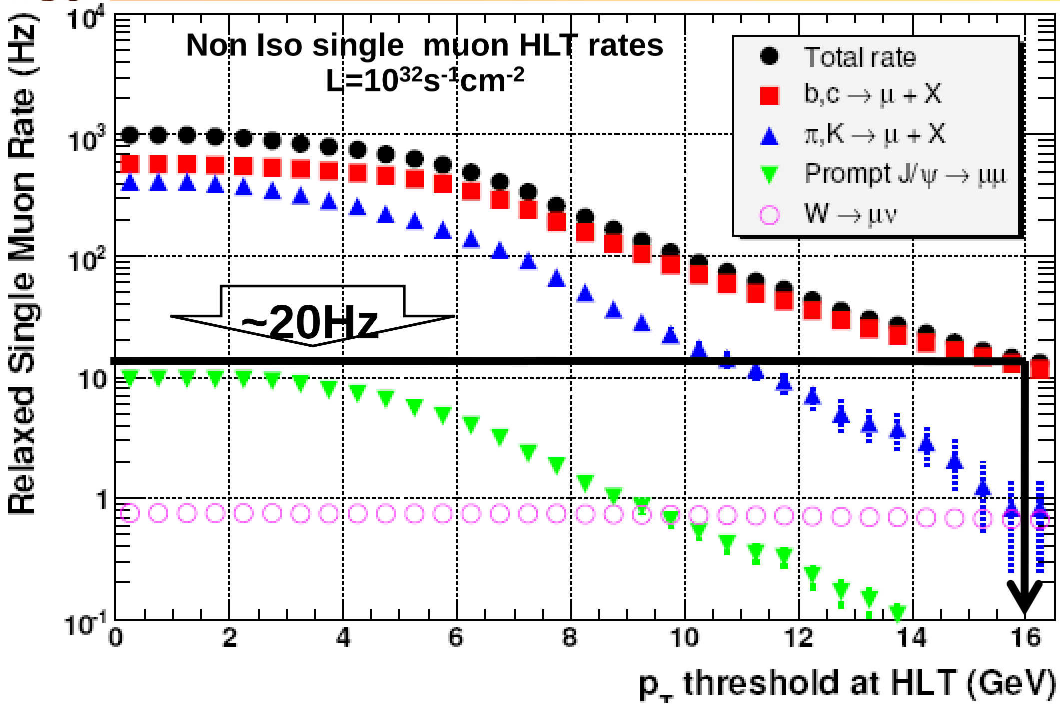
Keep muons down to tow pT at modest bandwidth cost

Give higher bandwidth to electron/photons for further processing in the HLT

Give even higher bandwidth to energy and jet triggers (energy calibration)

Trigger class	Allowed Rate
Muon (single or double)	2 kHz
Electron/photon (single or double)	3 kHz
Jets or Total Transverse Energy	6 kHz
Tau jets	3 kHz
Combination of triggering objects	3 kHz
Total Level-1 output rate	17 kHz

Example: HLT Bandwidth Allocation & Rates



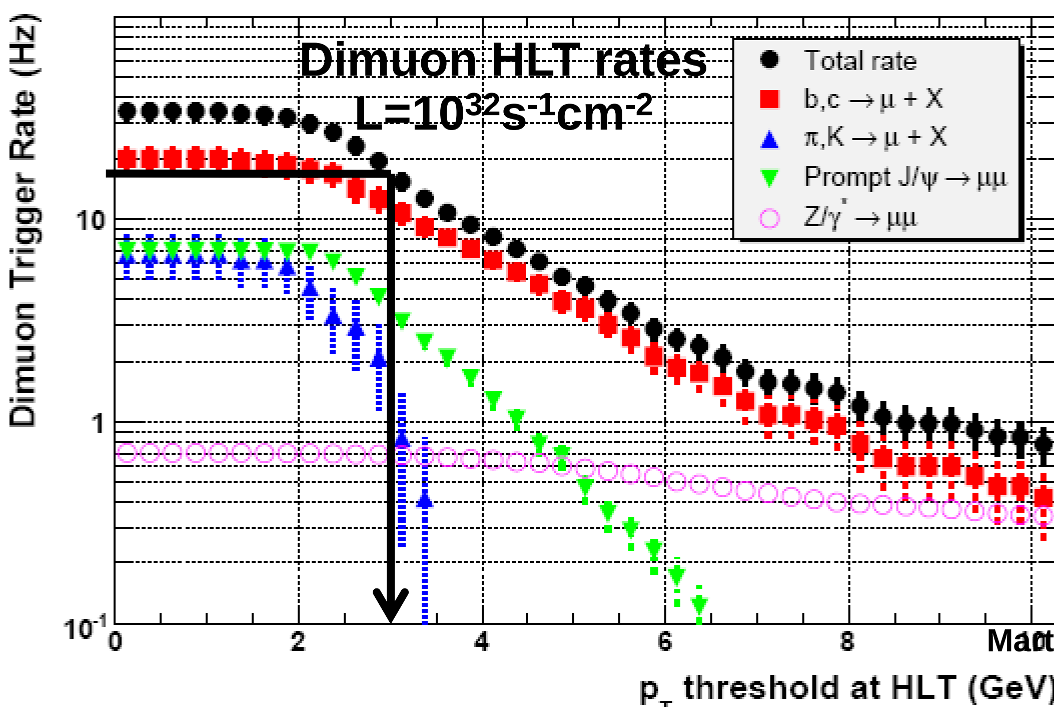
Design HLT tables for 150 Hz HLT output rate
50% of actual initial capability of 300 Hz

Share bandwidth according to detector and physics priorities at the given luminosity

Examples of **muon and electron (next page) triggers rates and tables** at **L=10^{32}s^{-1}cm^{-2}:**

At this luminosity set **muon trigger thresholds** as **low as possible** (detector and physics studies)

Allow **1/3 of total bandwidth for muon triggers**



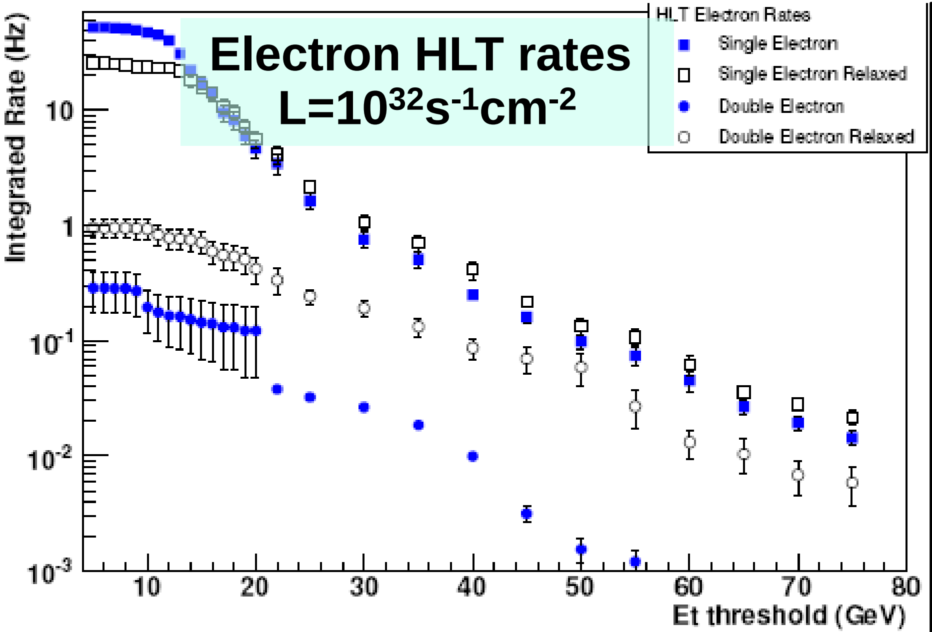
Muon HLT table -Total rate: 50 Hz

Trigger	Threshold (GeV)	Note
1μ	16	
1μ	11	isolation
2μ	3	

Muon HLT – Signal efficiencies

Signal	HLT Single Relaxed muon eff.(%)	HLT Double muon eff.(%)
$Z \to \mu\mu$	98.6	91.2
$W \to \mu\nu$	86.9	-

Example: HLT Bandwidth Allocation & Rates



Electrons/Photons HLT table Total rate: 30 Hz		
Trigger	Threshold (GeV)	Notes
1e	17	
1e	15	isolation
2e	12	
2e	10	isolation
1γ	40	
1γ	30	isolation
2γ	20	
2γ	20	isolation
High-E_T EM	80	looser cuts
Very high-E_T EM	200	looser cuts

Overview of bandwidth sharing among the different trigger classes a L=$10^{32}s^{-1}cm^{-2}$

Trigger class	Allowed Rate
Muon (single or double)	50 Hz
Electron/photon (single or double)	30 Hz
Single jet or multi-jet or Missing Transverse Energy (MET)	30 Hz
Tau and b-jets	20 Hz
Combination of triggering objects	20 Hz
Total HLT output rate	150 Hz

Given the relatively low trigger thresholds affordable at this luminosity

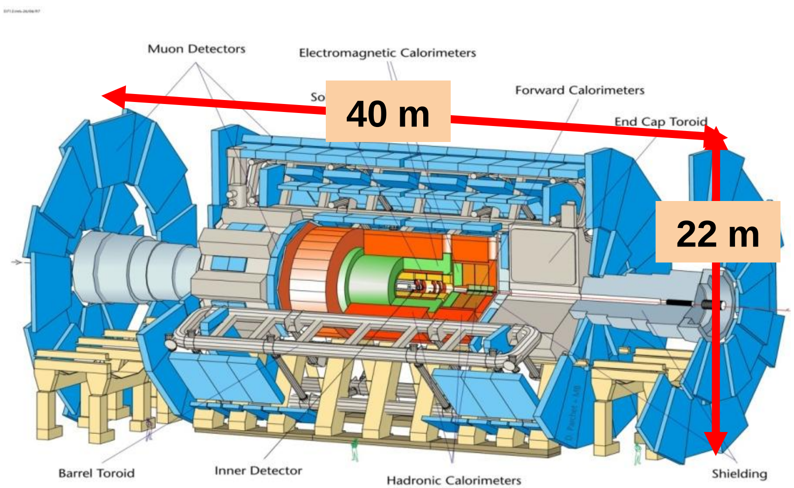
Signal (W/Z, top, Higgs, etc) efficiencies are high: 70 to 100% depending on topology

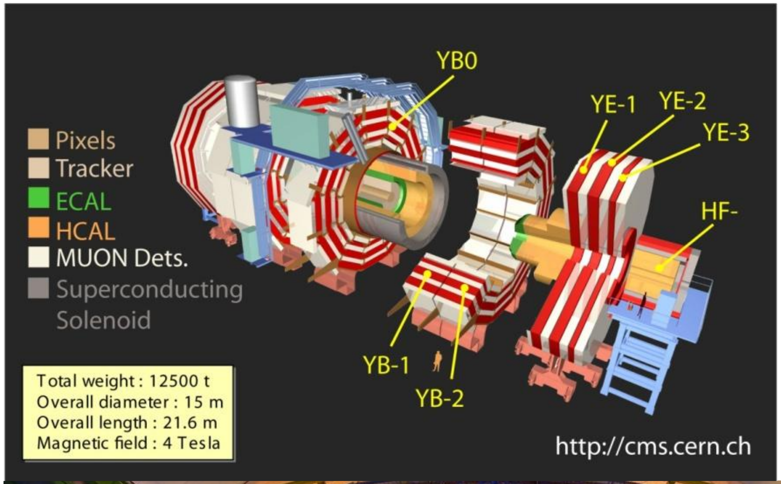
LHC 2009-10 Planned Operations

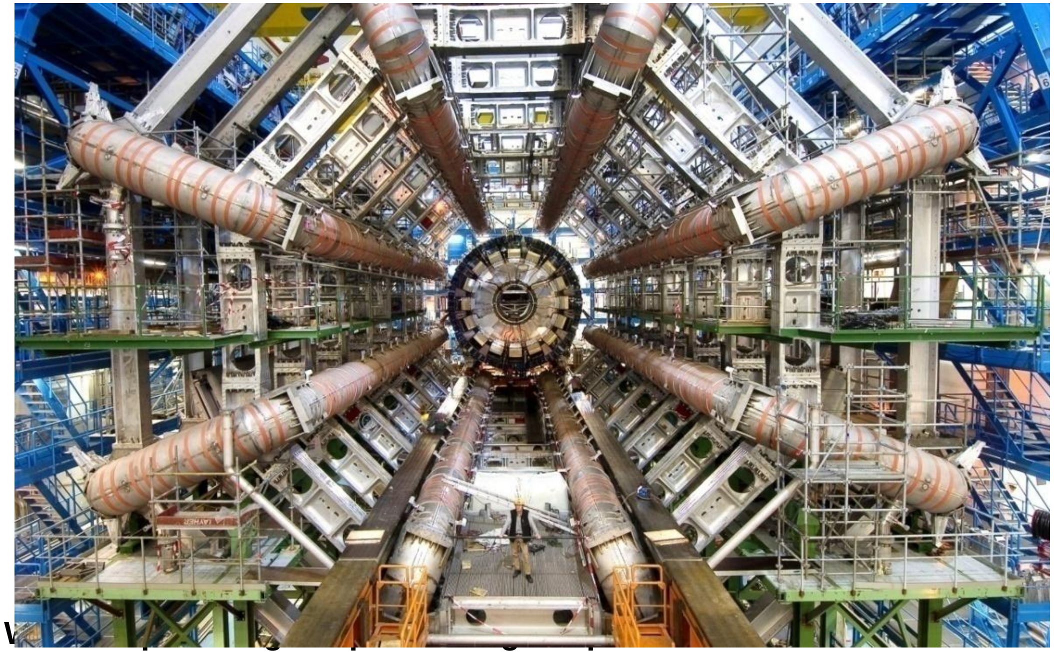
M. Lamont

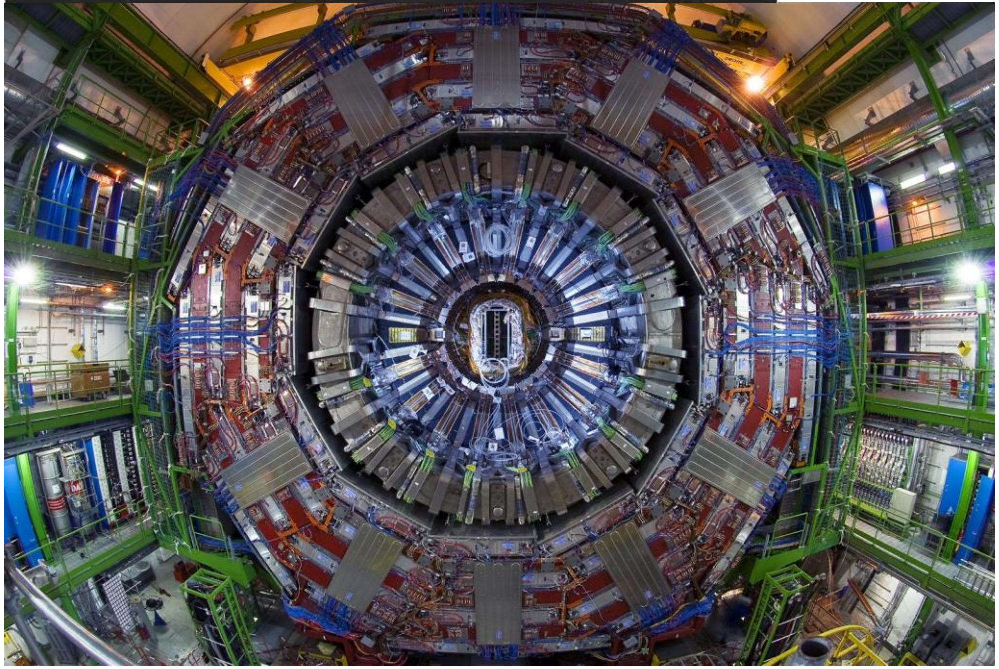
Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3	3.5 TeV	43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12

3. Triggers for Top and 4th Generation Quarks

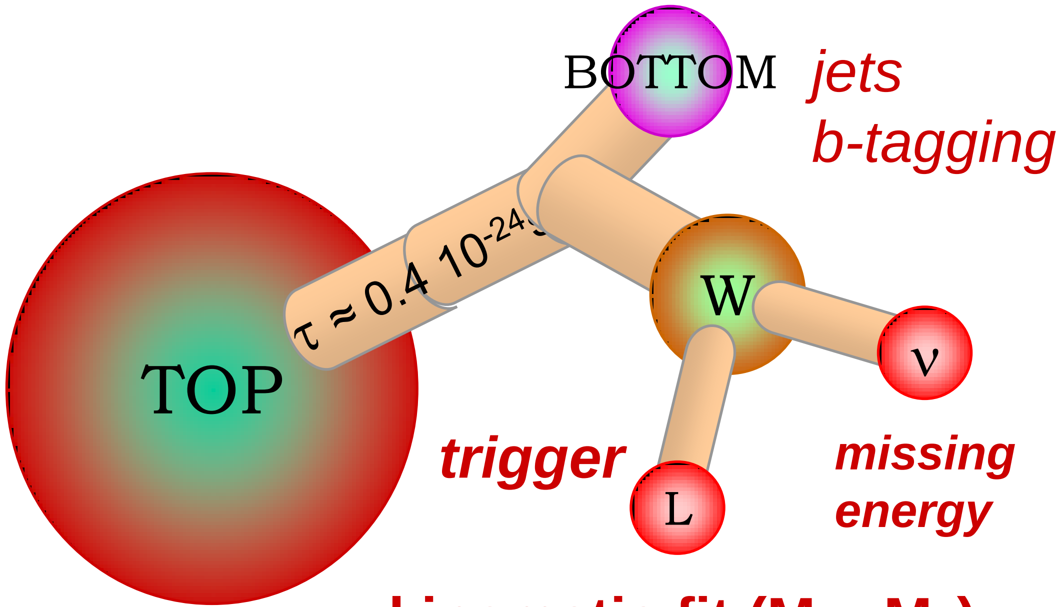








Top Topology



kinematic fit (M_W, M_t)

tt events caracterized by:
- **central leptons (|η| < 2)**
- **moderate lepton P_T**
- **moderate Jet E_T & E_T^{miss}**
- **high jet multiplicity**

- **for background reduction use**
  b-tagging
  reconstructed masses M_W, M_t

√s	σ_{tt}	Luminosity	
		10^{34} cm^{-2}s^{-1}	10^{32} cm^{-2}s^{-1}
14 TeV	~850 pb	~8.5 Hz	0.08 Hz
10 TeV	~400 pb	~4 Hz	0.04 Hz

Final states for detection:
-semileptonic: 1 lepton+(=>4) jets
-dilepton : 2 leptons+(=>2) jets
-multijets: (=>4,5,6) jets

For early measurements
final states w/ leptons preferred
(can be selected w/ high efficiency)
-> use single lepton triggers (mainly)

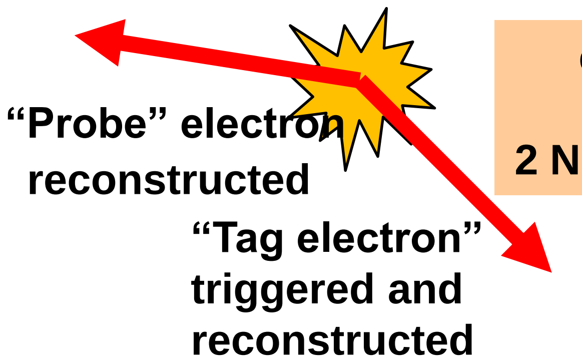
Measuring Trigger Efficiencies

Use data (not MC generator information) to determine trigger efficiencies

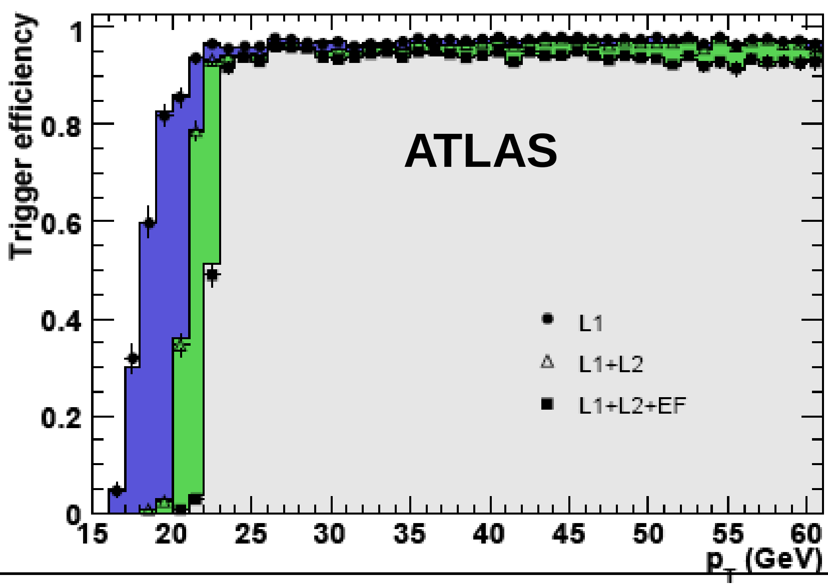
1. Single lepton trigger efficiency from **“tag-and-probe” methods** using events with 2 reconstructed leptons (eg Z) (ATLAS and CMS)

2. Single lepton trigger efficiency in top-like (lepton+jets) events selected eg with a multijet trigger -> use eg for efficiency stability monitoring as a function of jet multiplicity (CMS)

“Tag & Probe” method



electron trigger efficiency=
$2\ N_{probe} / (N_{tag} + N_{probe})$



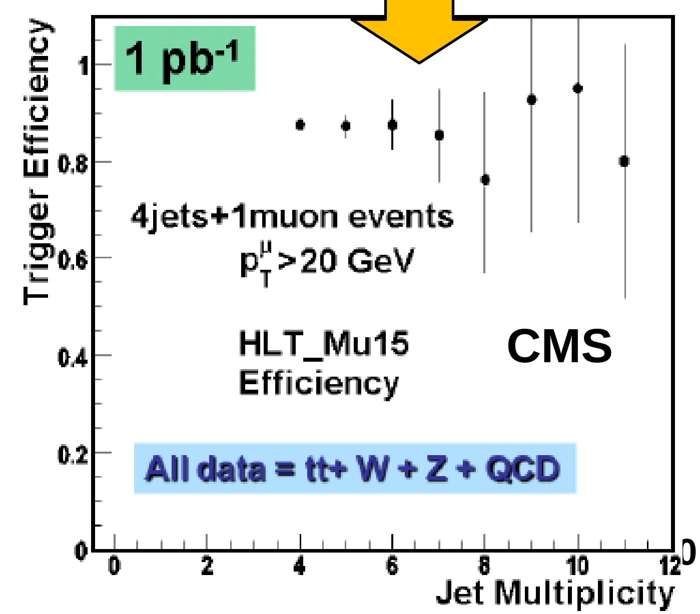
“Orthogonal” trigger method

Out of FourJet triggered events N_{trig}(4jet) select top-like events w/ offline reconstructed =>4 jets and1 muon N_{reco}(mu+jets)

Out of N_{reco}(¨mu+jets) count those passing the muon trigger N_{trig} (mu)

efficiency muon trig.= N_{trig} (mu)/ N_{reco}(mu+jets)

Muon trigger efficiency in multijets+mu events vs jet multiplicity



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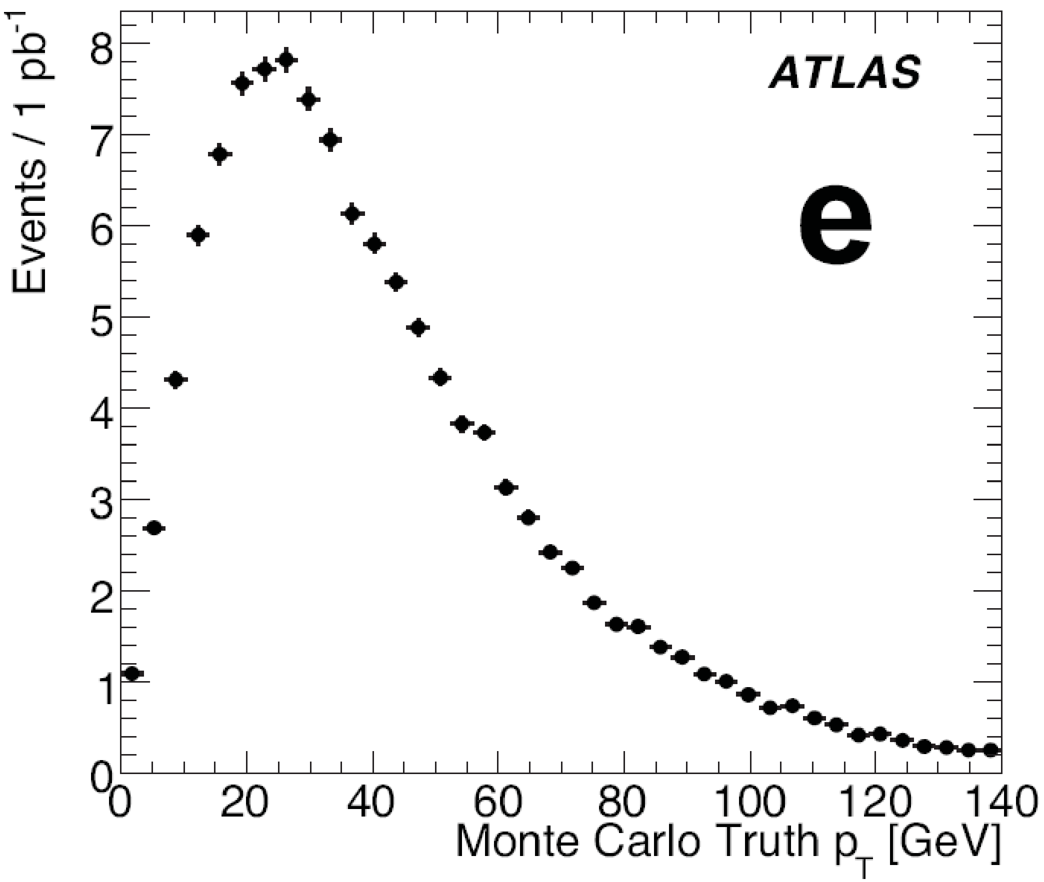
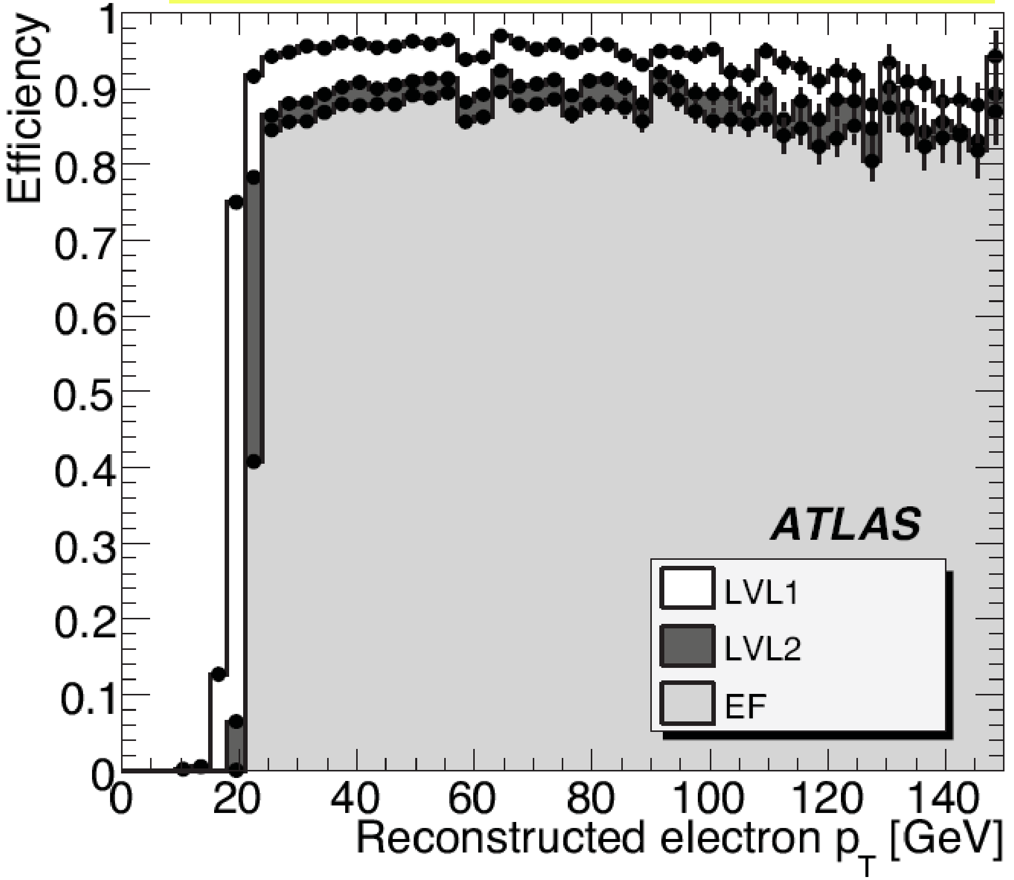
UCD

Electron Trigger Performance

electron from t->bW->bev



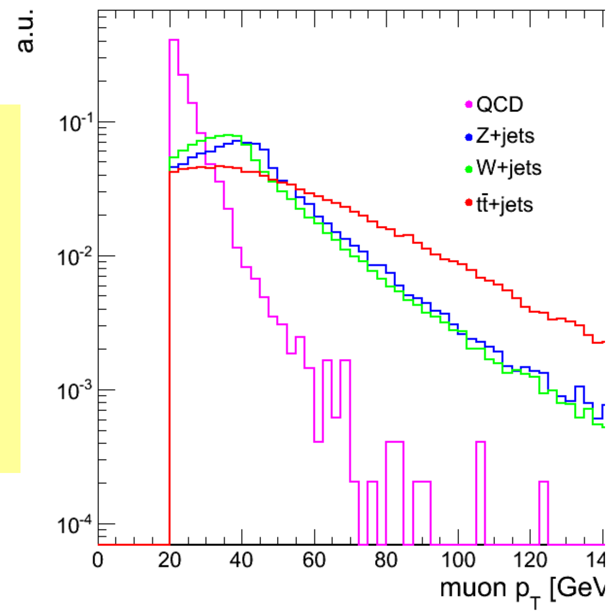
reconstructed isolated electron(*)

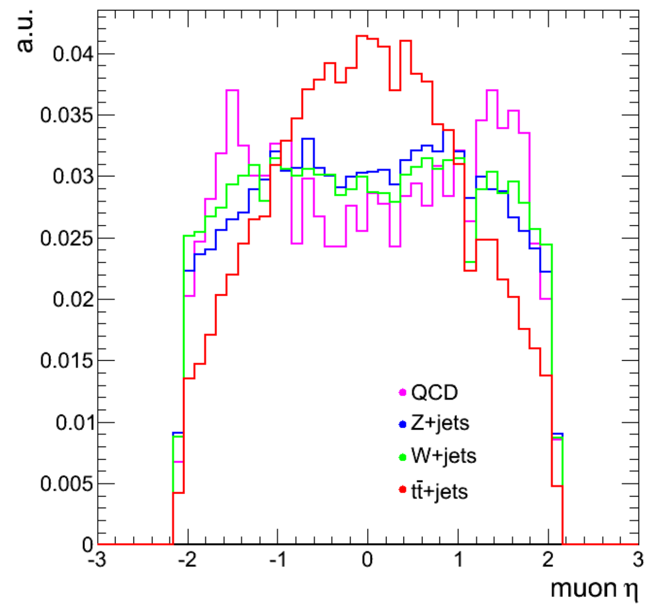


(*)Offline requirements: reconstructed isolated electron with pT > 20 GeV,
miss-ET > 20 GeV, 3 reco. jets with pT > 40 GeV, 4 reco. jets with pT > 20 GeV

Muon Trigger Performance

Muon transverse momentum
and
pseudo-rapidity distributions
after muon identification and
isolation requirements
(muon selection for top analysis)

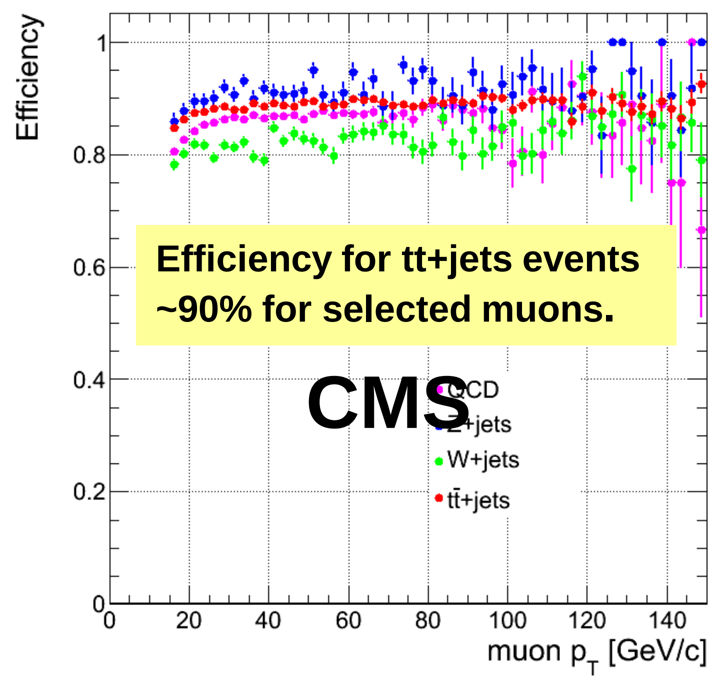


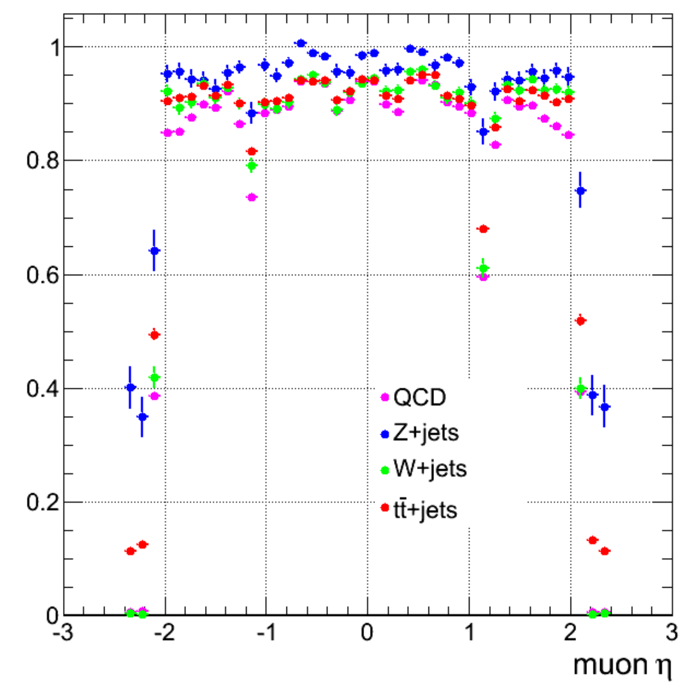


Efficiencies for accepting a top analysis selected muons by the HLT-Mu9 trigger as a function of muon p_T and η,

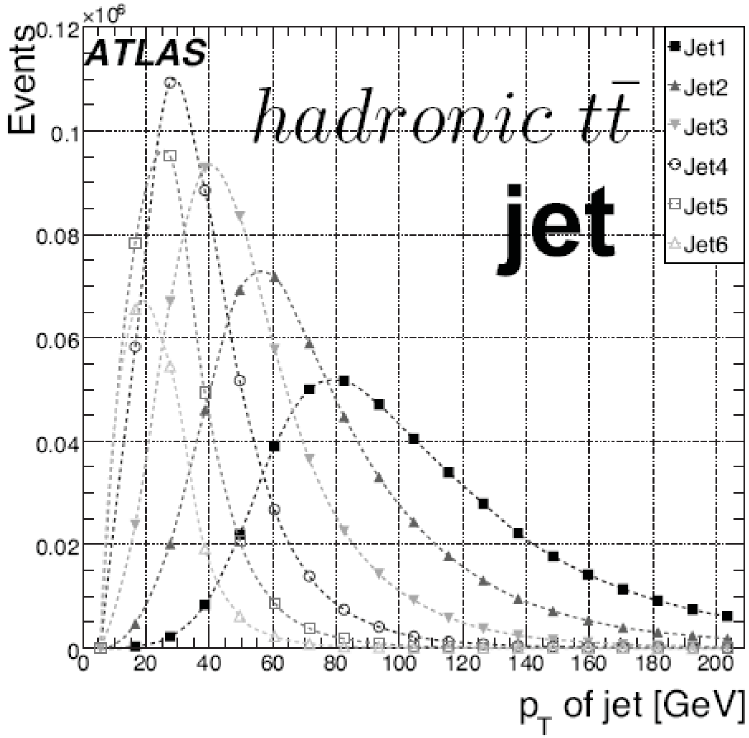
The efficiency is defined as the number of selected muons that pass the HLT over the total number of selected muons.

Efficiency for tt+jets events ~90% for selected muons.

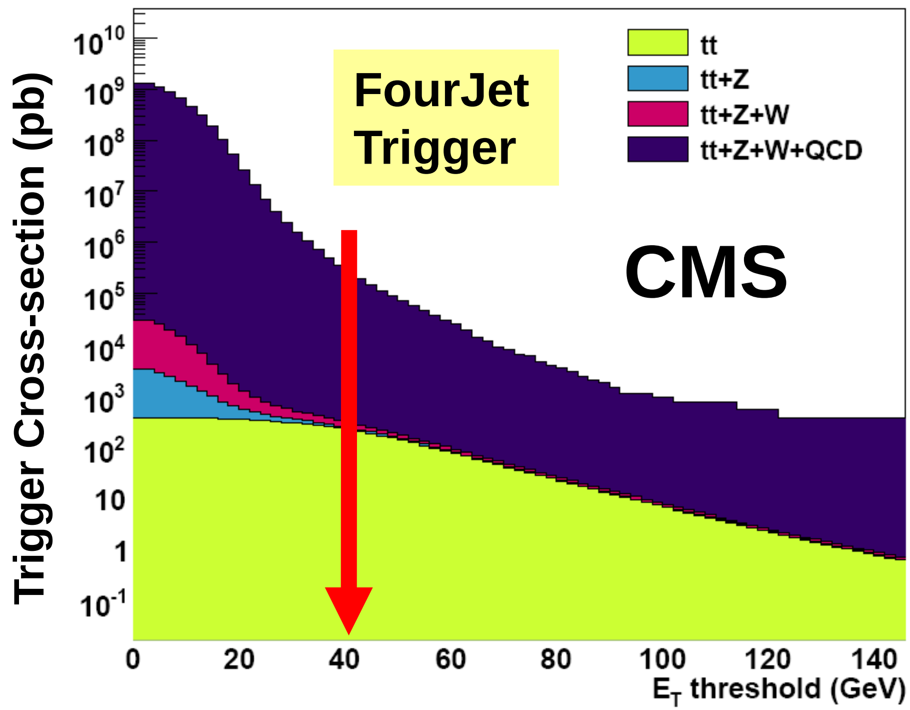




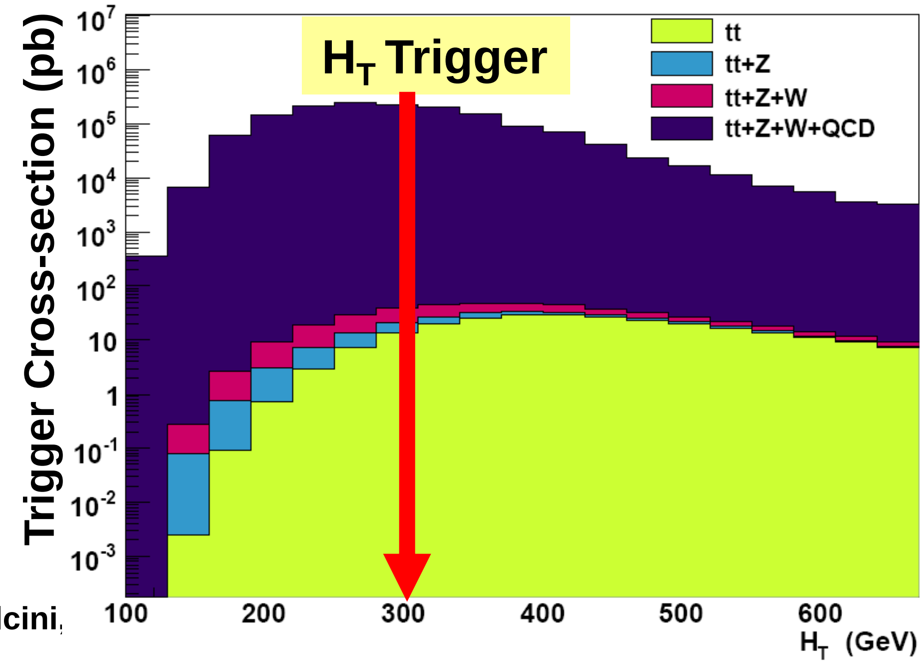
MultiJet and HT Trigger Performance



ATLAS



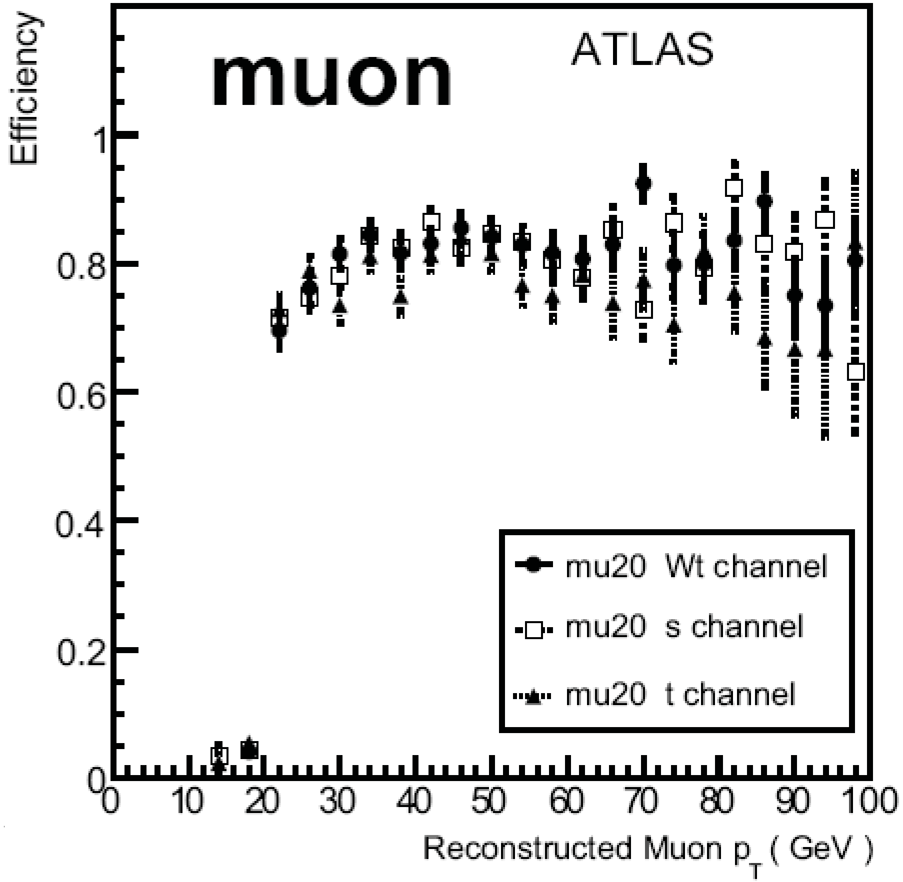
Proc.	EF_j160		EF_4j50	
	Eff. [%]	Rate [Hz]	Eff. [%]	Rate [Hz]
$t\bar{t}_{lep}$	11.2	$5.1*10^{-4}$	9.9	$4.5*10^{-4}$
$t\bar{t}_{had}$	12.9	$4.8*10^{-4}$	21.0	$7.7*10^{-4}$
QCD	-	1.3	-	$5.5*10^{-1}$
W+jet	-	$4.9*10^{-4}$	-	$1.0*10^{-4}$

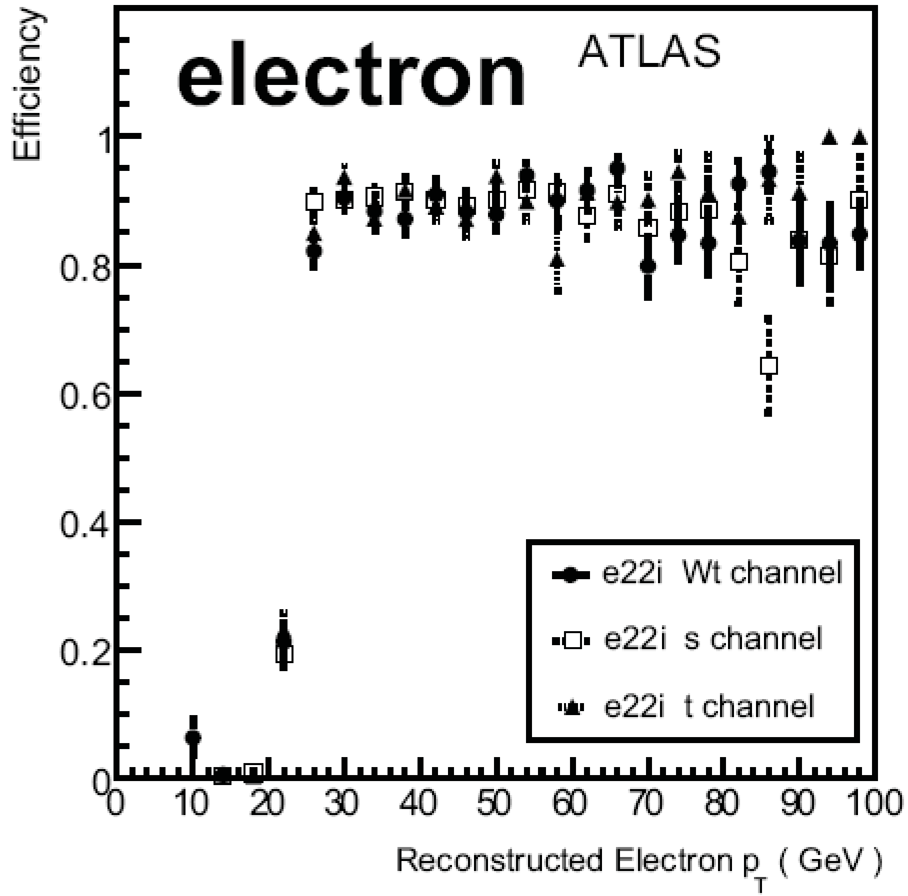


Trigger Performance for Single Top

Final state:
- **high-p_T lepton (W decay)**
- **missing-E_T**
- **1-3 jets**

Sample	Muon channel		Electron channel	
	Trigger	Efficiency [%]	Trigger	Efficiency [%]
Wt	mu06	88.4	e22i	87.1
	mu20	82.5	e22i or e55	90.6
s	mu06	88.0	e22i	89.2
	mu20	82.6	e22i or e55	90.7
t	mu06	86.0	e22i	89.5
	mu20	79.6	e22i or e55	90.6





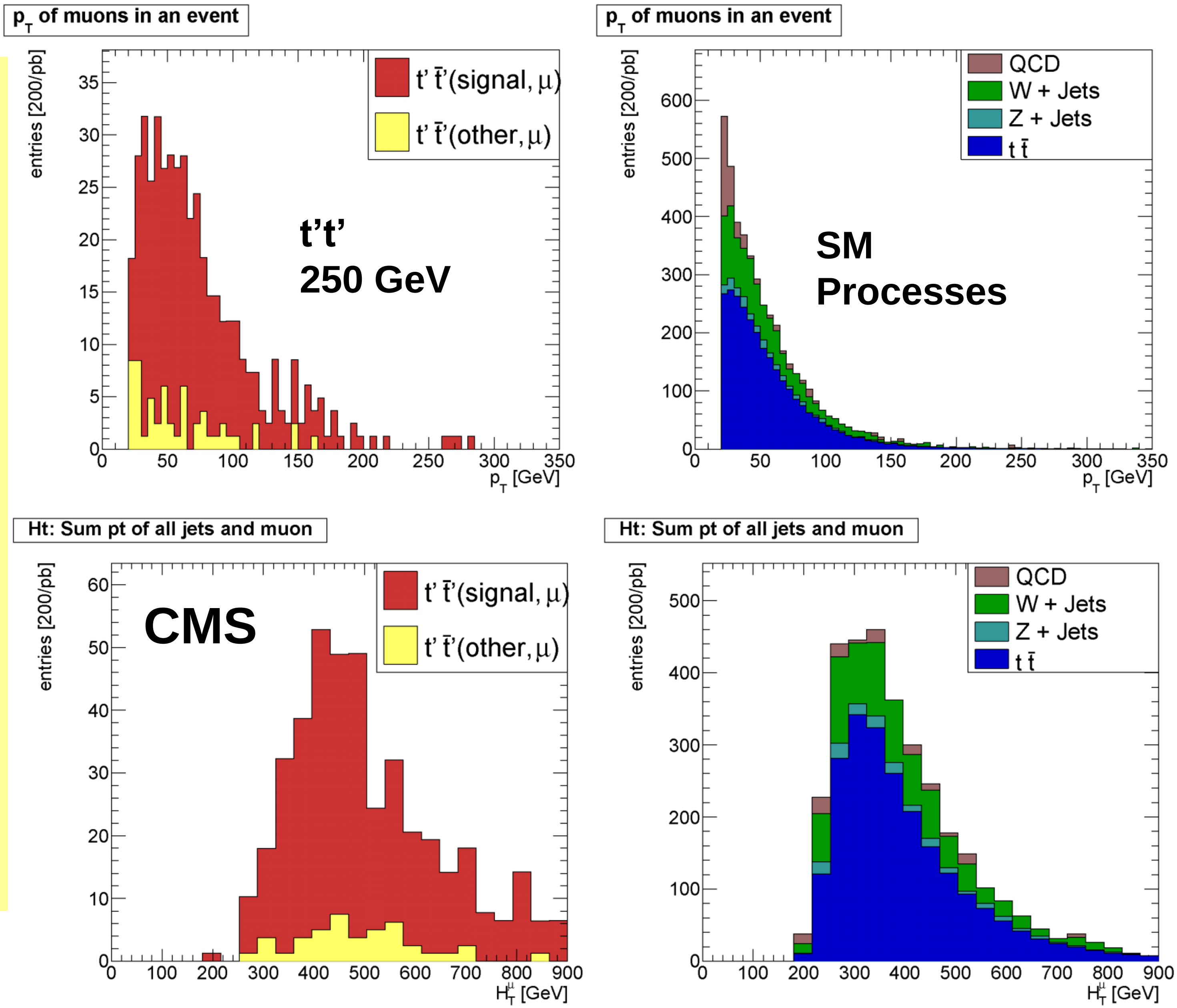
Trigger Performance for 4th Generation Quarks

4th Generation Quarks production and decay

t'(b') ->b(c) W
b'->tW -> bWW

induces jjWW or jjWWWW final states with lepton, jets $p_{T,}$ H_T significantly higher (depending on $M_{t'}$) than for top events

Îf lepton and H_T triggers are highly efficient for top they are also expected to have **high efficiency for 4th Generation Quarks**



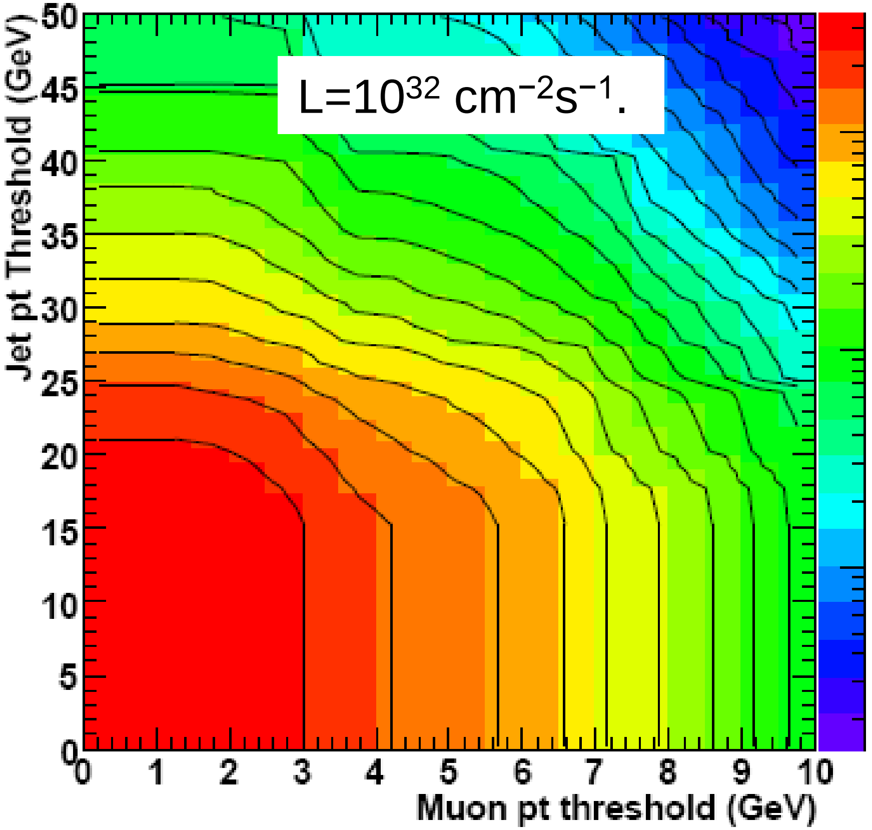
Top Triggers for Higher Luminosity

At higher luminosities -> Multiple object triggers

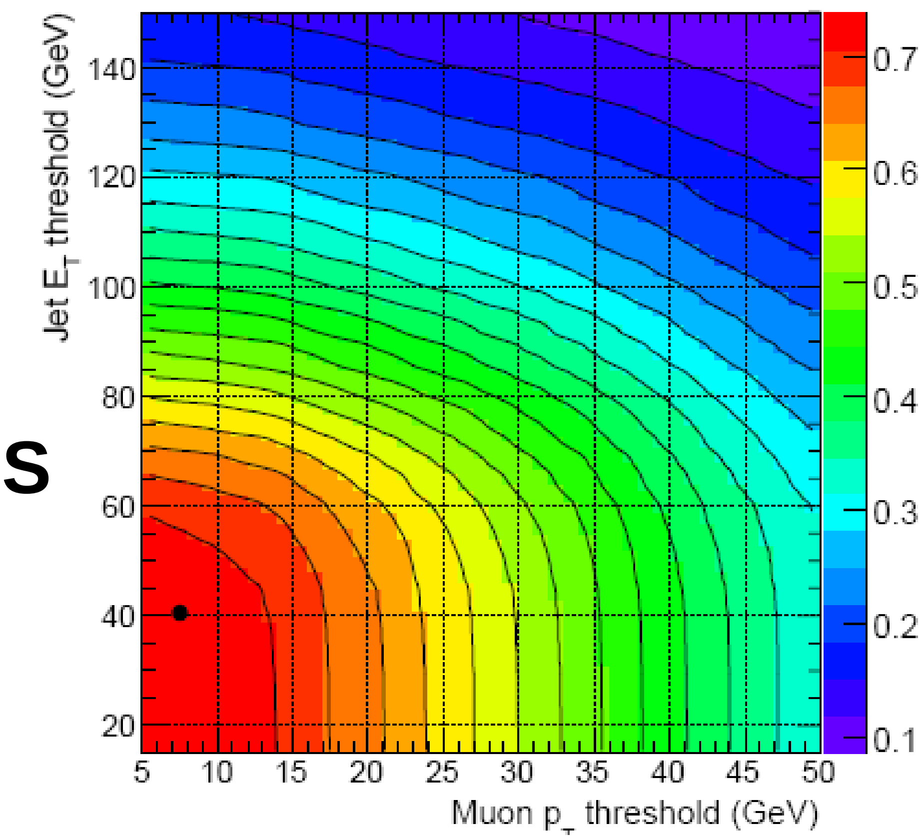
Trigger on moderately high P_T objects (10-20 GeV lepton, 30-50 GeV jets) exploiting high object multiplicity to reduce rate while retaining high signal efficiency

HLT rate, in Hz, of the **muon+1 jet path**
Muon (10 GeV) + jet (40 GeV) Rate ~0.5 Hz

HLT efficiency of the **muon+1 jet path** on tt evts
Muon (10 GeV) + jet (40 GeV) Eff(tt) ~80%



CMS



Summary and Conclusions

ATLAS and CMS experiments are ready to collect collision data
Trigger menus have been developed for a luminosity range likely to be covered in 2009-10
Their performance will be optimized based on measurements with collision data
In all cases **trigger efficiencies for top events are and will be kept very high (~90%)**
in view of **prompt SM measurements and new physics discoveries**