LHC Physics
GRS PY 898 B8

Lecture #3

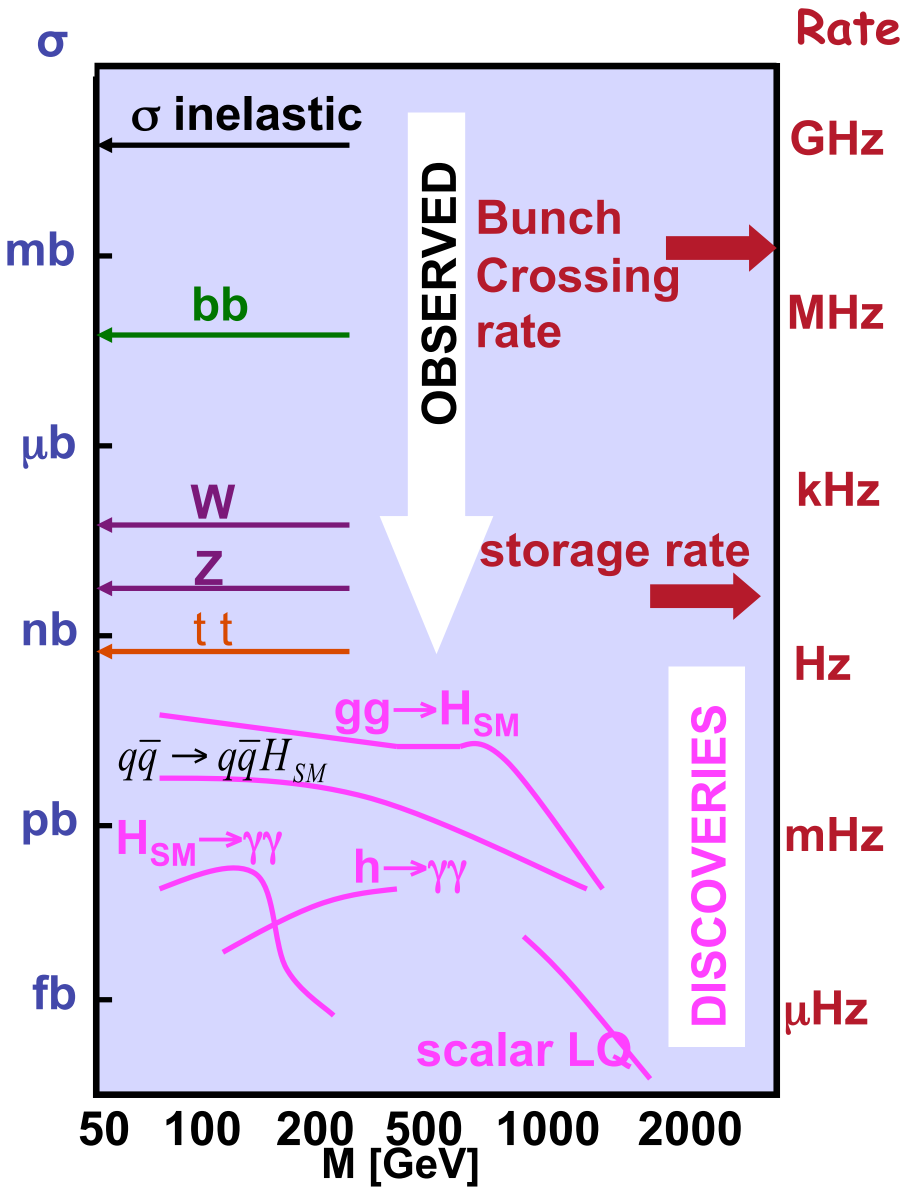
Tulika Bose

Trigger & DAQ: Part II

Seminar Topics

1) Higgs: overview of Higgs searches at LHC; One specific Higgs search (Phil)
2) SUSY: overview of SUSY searches at LHC; One specific SUSY search [jets/MET signatures only; no leptons] Adam
3) SUSY2: overview of SUSY searches at LHC; One specific SUSY search [leptonic signatures]
4) Exotica: overview of searches for new vector boson high mass states (W', Z', RS-Graviton...);
5) Exotica2: overview of alternative signatures (technicolor, Little Higgs, Composite Higgs, Twin Higgs...) David
6) Top quark physics at the LHC
7) Electroweak measurements at the LHC: Keith
8) QCD measurements at the LHC: John
9) B physics at the LHC
10) Model Independent Search methods (see for eg. http://cms-physics.web.cern.ch/cms-physics/public/EXO-08-005-pas.pdf)

Physics Selection @ LHC



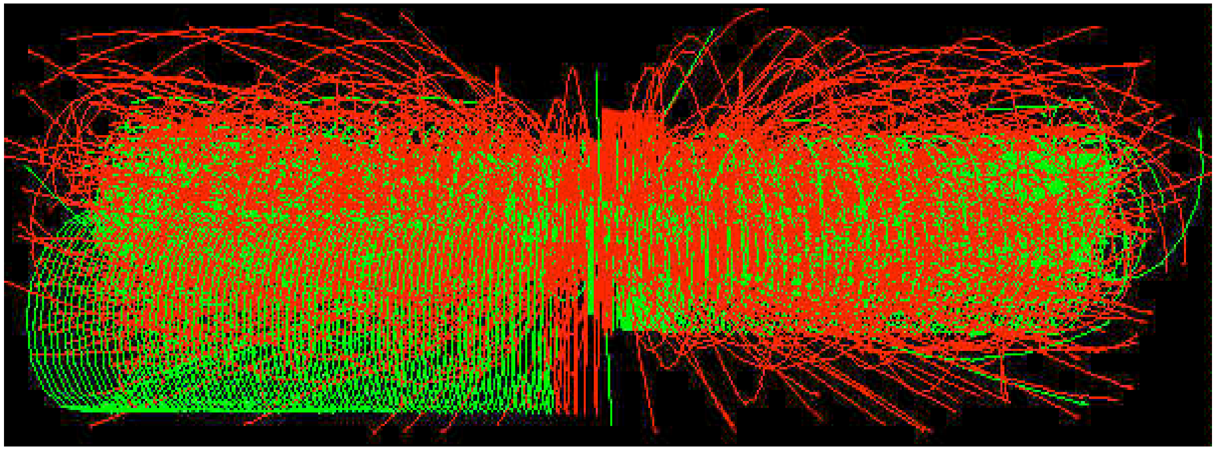
Cross sections for various processes vary over many orders of magnitude

Bunch crossing frequency: 40MHz
Storage rate ~ 200-300 Hz

→ online rejection: > 99.99%
→ crucial impact on physics reach

Keep in mind that what is discarded is lost forever

Challenges @ LHC



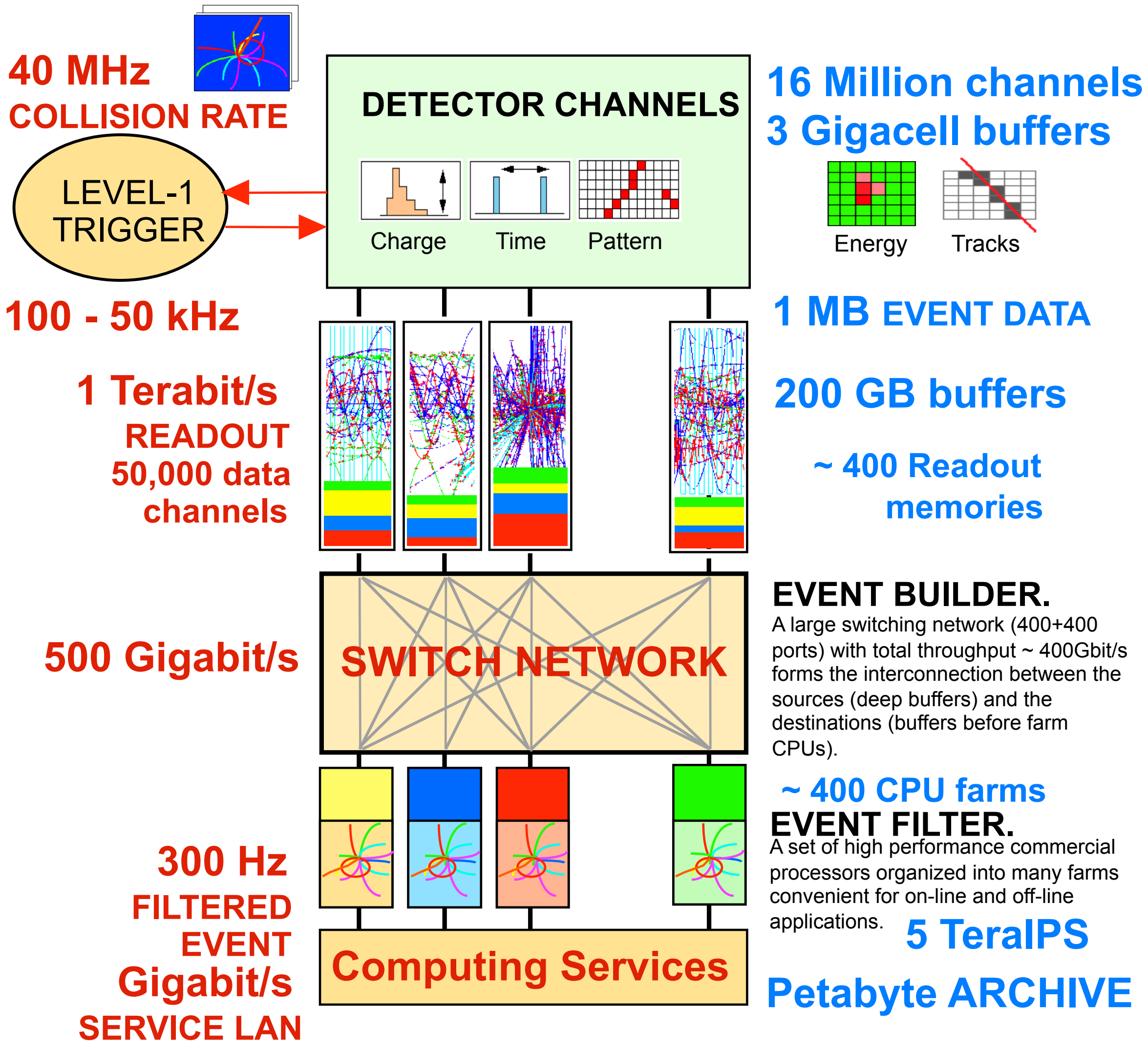
Challenges:

1 GHz of Input Interactions

Beam-crossing every 25 ns with ~ 25 interactions produces over 1 MB of data

Archival Storage at about 300 Hz of 1 MB events

Challenges @ LHC



40 MHz
COLLISION RATE

LEVEL-1
TRIGGER

100 - 50 kHz

1 Terabit/s
READOUT
50,000 data
channels

500 Gigabit/s

300 Hz
FILTERED
EVENT

Gigabit/s
SERVICE LAN

DETECTOR CHANNELS

Charge
Time
Pattern

SWITCH NETWORK

Computing Services

16 Million channels
3 Gigacell buffers

Energy
Tracks

1 MB EVENT DATA

200 GB buffers

~ 400 Readout
memories

EVENT BUILDER.
A large switching network (400+400 ports) with total throughput ~ 400Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs).

~ 400 CPU farms

EVENT FILTER.
A set of high performance commercial processors organized into many farms convenient for on-line and off-line applications.

5 TeraIPS

Petabyte ARCHIVE

Challenges:

1 GHz of Input Interactions

Beam-crossing every 25 ns with ~ 25 interactions produces over 1 MB of data

Archival Storage at about 300 Hz of 1 MB events

Challenges @ LHC

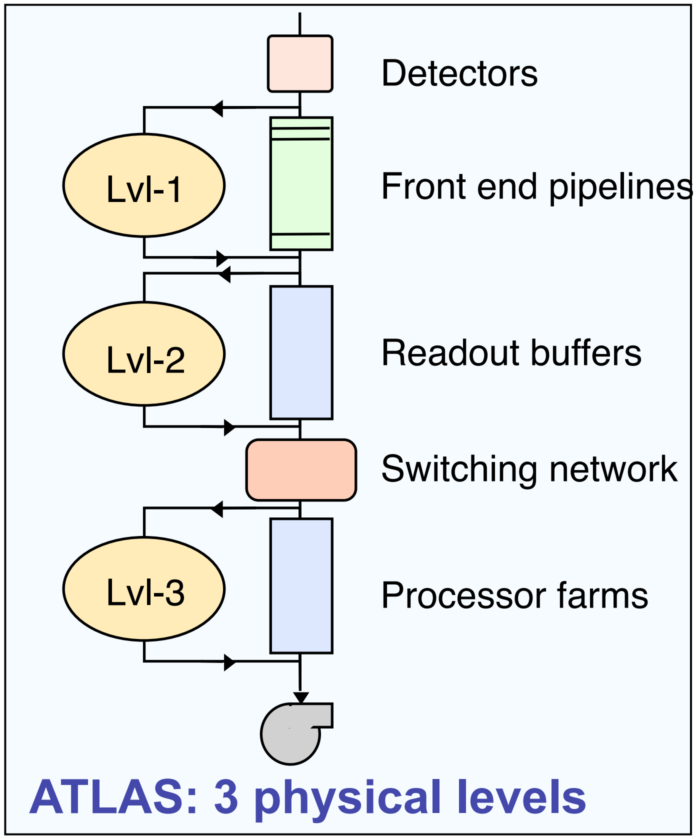
- # of channel ~ O(10^7). ~25 interactions every 25ns
  - Need large number of connections, need information super-highway
- Calorimeter information should correspond to tracker information
  - Need to synchronize detectors to better than 25ns
- Sometimes detector signal/time of flight > 25ns
  - Integrate information from more than one bunch crossing
  - Need to correctly identify bunch crossing
- Can store data at O(100 Hz)
  - Need to reject most events
- Selection is done Online in real-time
  - Cannot go back and recover events
  - Need to monitor selection

Trigger

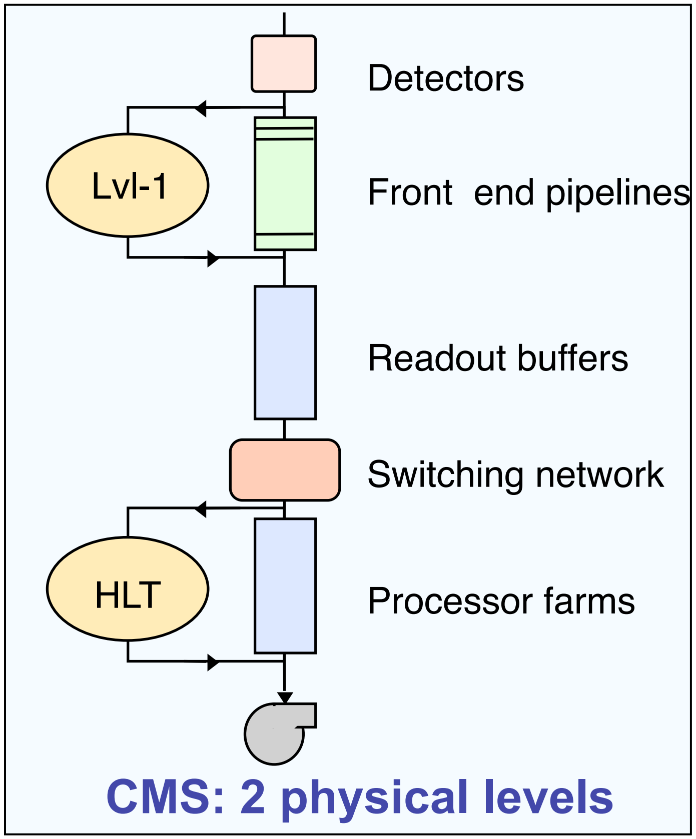
Multi-tiered trigger systems

Level-1 trigger: Integral part of all trigger systems – always exists
reduces rate to ~50-100kHz.

Upstream: further reduction needed – typically done in 1 or 2 steps

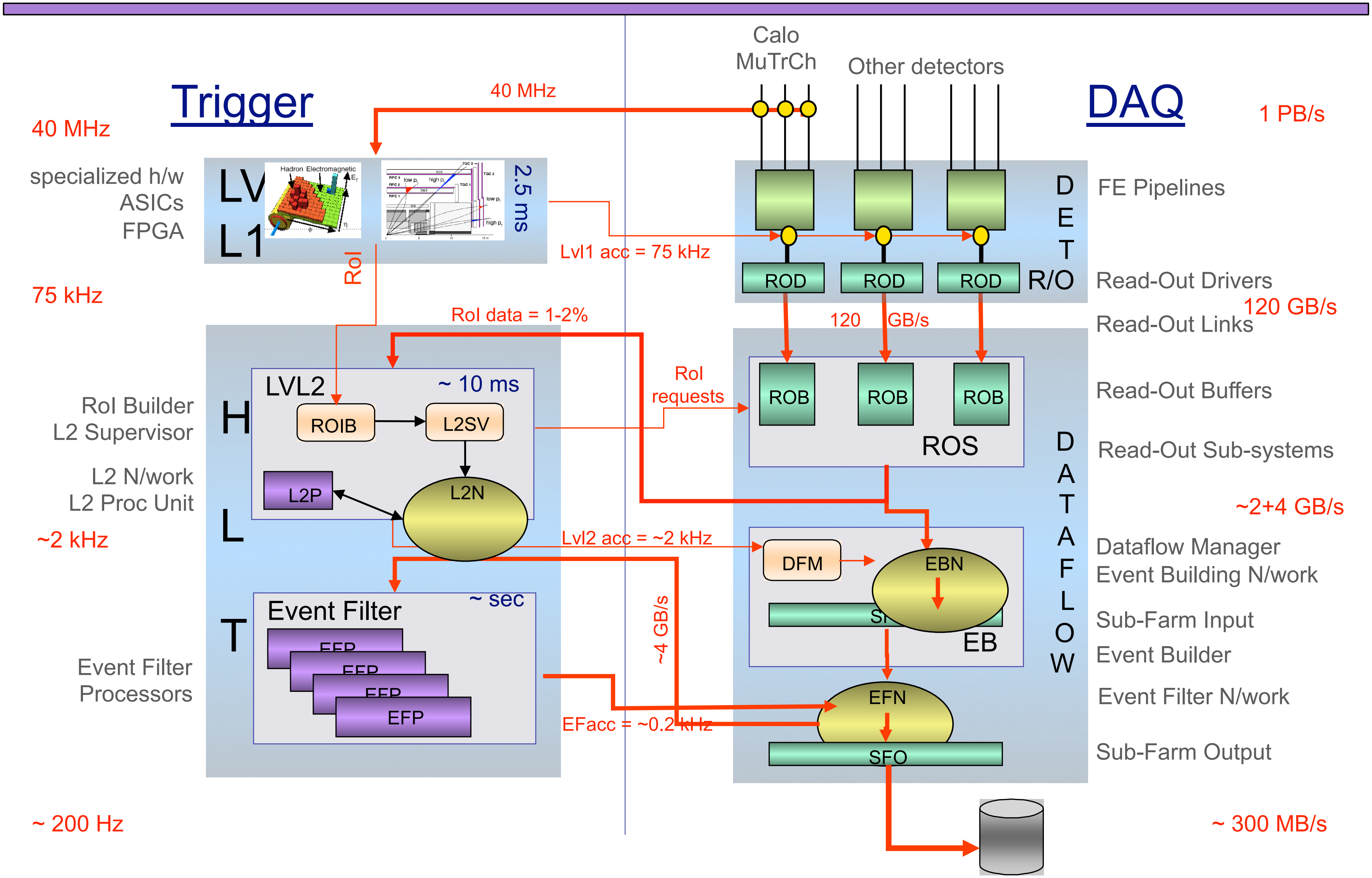


ATLAS: 3 physical levels



CMS: 2 physical levels

ATLAS Trigger/DAQ Architecture



Trigger

DAQ

40 MHz

1 PB/s

Calo
MuTrCh

Other detectors

specialized h/w
ASICs
FPGA

LV
L1

Hadron Electromagnetic

2.5 ms

RoI

Lvl1 acc = 75 kHz

D
E
T
R/O

FE Pipelines

ROD ROD ROD

Read-Out Drivers

75 kHz

RoI data = 1-2%

120 GB/s

Read-Out Links

120 GB/s

RoI Builder
L2 Supervisor

L2 N/work
L2 Proc Unit

~2 kHz

H
L
T

LVL2

~ 10 ms

ROIB

L2SV

L2P

L2N

RoI
requests

ROB ROB ROB

ROS

Read-Out Buffers

Read-Out Sub-systems

~2+4 GB/s

Lvl2 acc = ~2 kHz

DFM

EBN

SFI

EB

D
A
T
A
F
L
O
W

Dataflow Manager
Event Building N/work

Sub-Farm Input
Event Builder

~4 GB/s

Event Filter

~ sec

EFP
EFP
EFP
EFP

Event Filter
Processors

EFacc = ~0.2 kHz

EFN

SFO

Event Filter N/work

Sub-Farm Output

~ 200 Hz

~ 300 MB/s

L1 Trigger design goals

- Need large reduction in physics rate already at the first level (otherwise readout system becomes unaffordable)
  - $O(10^9)$ interaction rate → less than 100 kHz
    - Require complex algorithms to reject background while keeping signal

- An important constraint is to achieve this without significant "dead-time"
  - Information from all detector channels ($O(10^7)$ channels!) has to be held in local memory on detector pending the L1 decision
  - ~2.5 μs in ATLAS/~3.2 μs in CMS

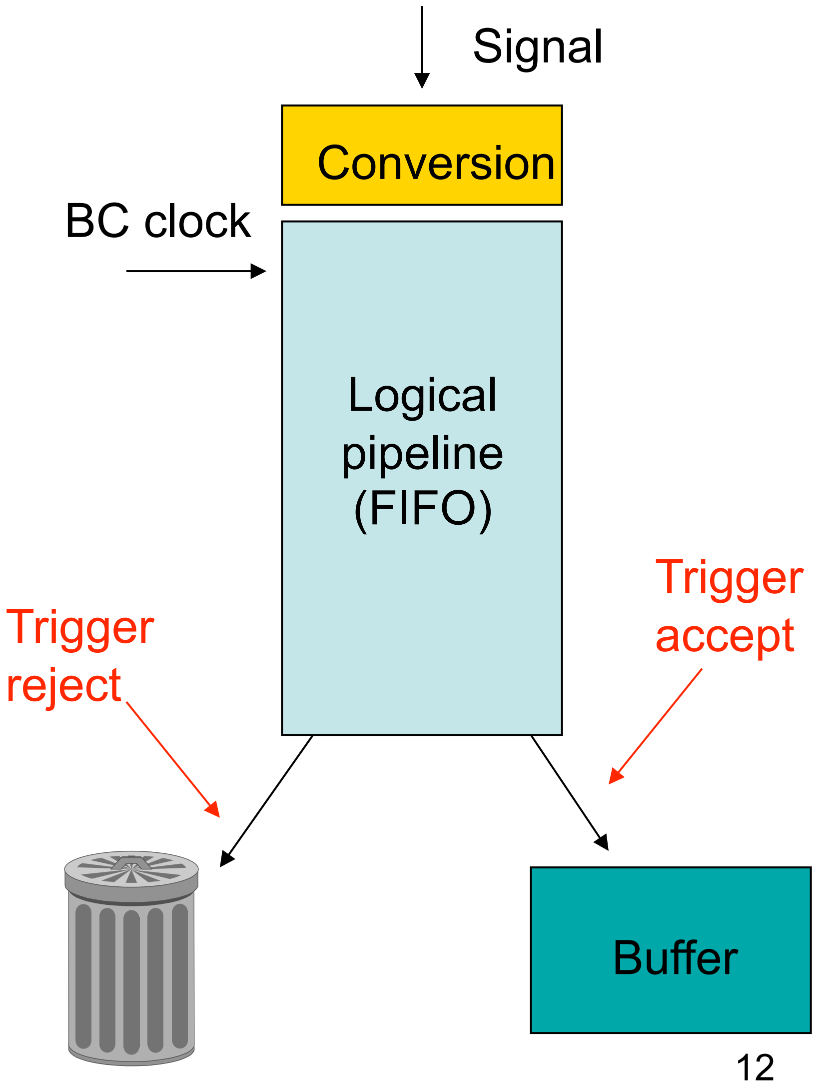
- Require flexibility to react to changing conditions (*e.g.* wide luminosity range) and — hopefully — new physics
  - Algorithms must be programmable (adjustable parameters at least)

Pipelined L1 trigger

- The time between LHC bunch crossings is 25ns
  - Too short to read out Megabytes of data for each event and to provide trigger decision
- The data is stored in a "pipeline" and the L1 decision is transmitted to the detector electronics within ~3μs of the crossing ("trigger latency")
  - Allows the L1 trigger to concurrently process many events
  - Can be achieved by "pipelining" the processing in custom trigger processors built using modern digital electronics
    - Break down processing into a series of steps, each of which can be performed within a single BX period
    - Many operations can be performed in parallel by having separate processing logic for each one
  - Note that the latency of the trigger is fixed
    - Determined by the number of steps in the calculation plus the time taken to move signals and data to and from the components of the trigger system

Pipelined readout

- In pipelined readout systems, the information from each bunch crossing, for each detector element, is retained during the latency of the LVL1 trigger (~3 μs)
- The information retained may be in several forms
  - Analog level (held on capacitor)
  - Digital value (e.g. ADC result)
  - Binary value (i.e. hit / no hit)



Preventing overflows

Trigger Rules (CMS)

- Level-1 Latency 3.2 μs (128 bunch crossings or bx)
- "Standard" trigger rules:
  - No more than 1 Level 1 Accept per 75 ns (> 2 bx btw. L1A),
    - Dead time 5×10^{-3} @ 100 KHz L1A rate
    - Required by tracker and preshower

  - No more than 2 Level 1 Accepts per 625 ns (25 bx)
    - Dead time 1.3×10^{-3} @ 100 KHz L1A rate

  - No more than 3 Level 1 Accepts per 2.5μs (100 bx)
    - Dead time 1.2×10^{-3} @ 100 KHz L1A rate

  - No more than 4 Level 1 Accepts per 6μs (240 bx)
    - Dead time 1.4×10^{-3} @ 100 KHz L1A rate

Total deadtime cost @ 100 KHz L1A rate of order of 0.9%.

State-of-the-art technology

- ASICs (Application-Specific Integrated Circuits) used in some cases
  - Highest performance option, better radiation tolerance, lower-power consumption

- FPGAs (Field-Programmable Gate Arrays)
  - Impressive evolution with time; operating at 40MHz
  - Biggest advantage: flexibility
    - Can modify algorithms and their parameters in situ

- Communication technologies
  - High speed serial links (copper or fiber)
    - LVDS up to 10m and 400 Mb/s, G-link, Vitesse for longer distances and Gb/s transmission
  - Backplanes
    - Very large number of connections, multiplexing data, operate at ~160 Mb/s

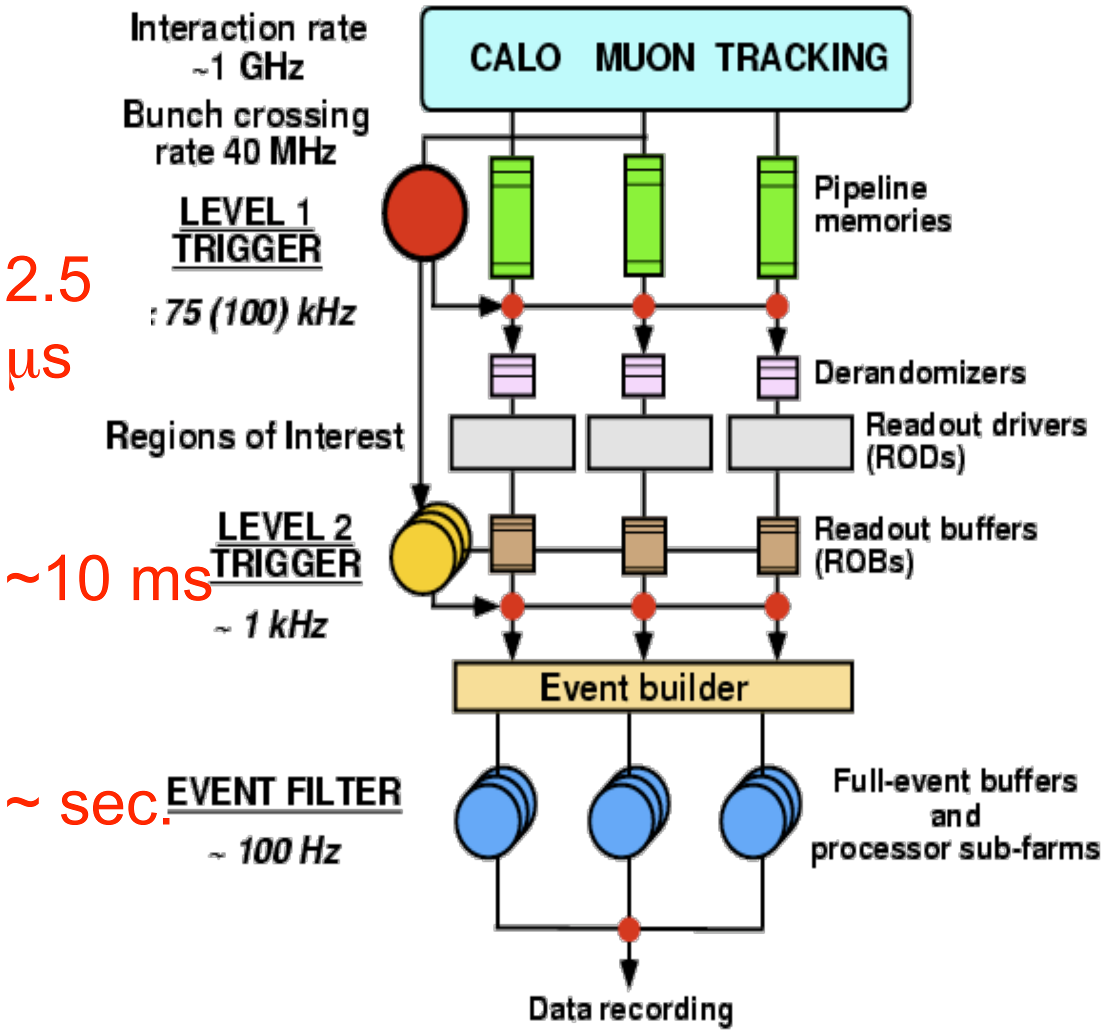
L1 selection criteria

- Features that distinguish new physics from the bulk of the cross-section for Standard Model processes at hadron colliders are:
  - In general, the presence of high-p_T particles (or jets)
    - *e.g.* these may be the products of the decays of new heavy particles
      - In contrast, most of the particles produced in minimum-bias interactions are soft (p_T ~ 1 GeV or less)
  - More specifically, the presence of high-p_T leptons (e, μ, τ), photons, and/or neutrinos
    - *e.g.* the products (directly or indirectly) of new heavy particles
      - These give a clean signature *c.f.* low-p_T hadrons in minimum-bias case, especially if they are "isolated" (*i.e.* not inside jets)
  - The presence of known heavy particles
    - *e.g.* W and Z bosons may be produced in Higgs particle decays
      - Leptonic W and Z decays give a very clean signature
        - » Also interesting for physics analysis and detector studies

L1 signatures and backgrounds

- L1 triggers therefore search for:
  - High-p_T muons
    - Identified beyond calorimeters; need p_T cut to control rate from $p^+ \rightarrow \mu\nu$, $K^+ \rightarrow \mu\nu$, as well as semi-leptonic beauty and charm decays
  - High-p_T photons
    - Identified as narrow EM calorimeter clusters; need cut on E_T; cuts on isolation and hadronic-energy veto reduce strongly rates from high-p_T jets
  - High-p_T electrons
    - Same as photon at L1 (matching track is required in subsequent selection)
  - High-p_T taus (decaying to hadrons)
    - Identified as narrow cluster in EM + hadronic calorimeters
  - High-p_T jets
    - Identified as cluster in EM + hadronic calorimeter — need to cut at very high p_T to control rate (jets are dominant high-p_T process)
  - Large missing E_T or total scalar E_T

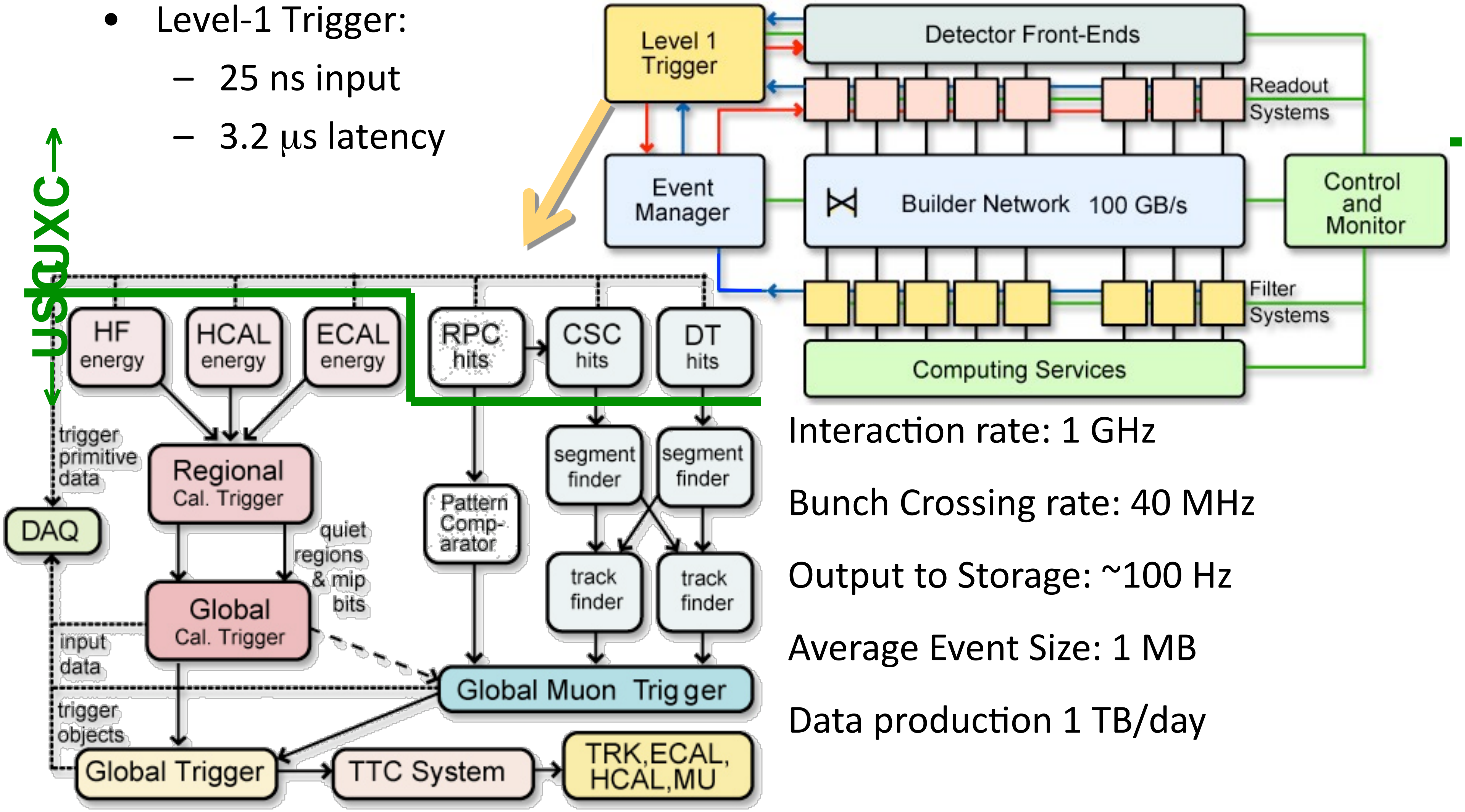
ATLAS Trigger Architecture



- LVL1 decision made with calorimeter data with coarse granularity and muon trigger chambers data.
  - Buffering on detector
- LVL2 uses Region of Interest data (~2%) with full granularity and combines information from all detectors; performs fast rejection.
  - Buffering in ROBs
- EventFilter refines the selection, can perform event reconstruction at full granularity using latest alignment and calibration data.
  - Buffering in EB & EF

CMS Level-1 Trigger & DAQ

- Overall Trigger & DAQ Architecture: 2 Levels:
- Level-1 Trigger:
  - 25 ns input
  - 3.2 μs latency



Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

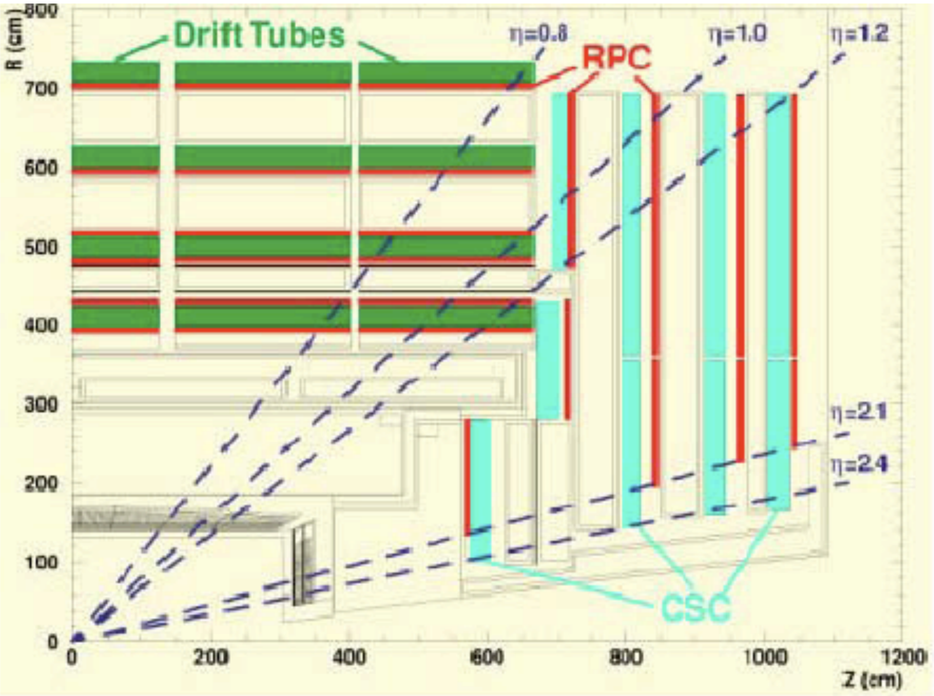
Output to Storage: ~100 Hz

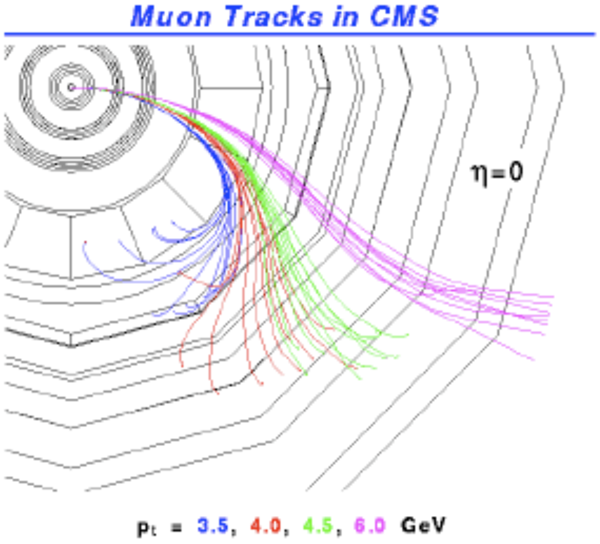
Average Event Size: 1 MB

Data production 1 TB/day

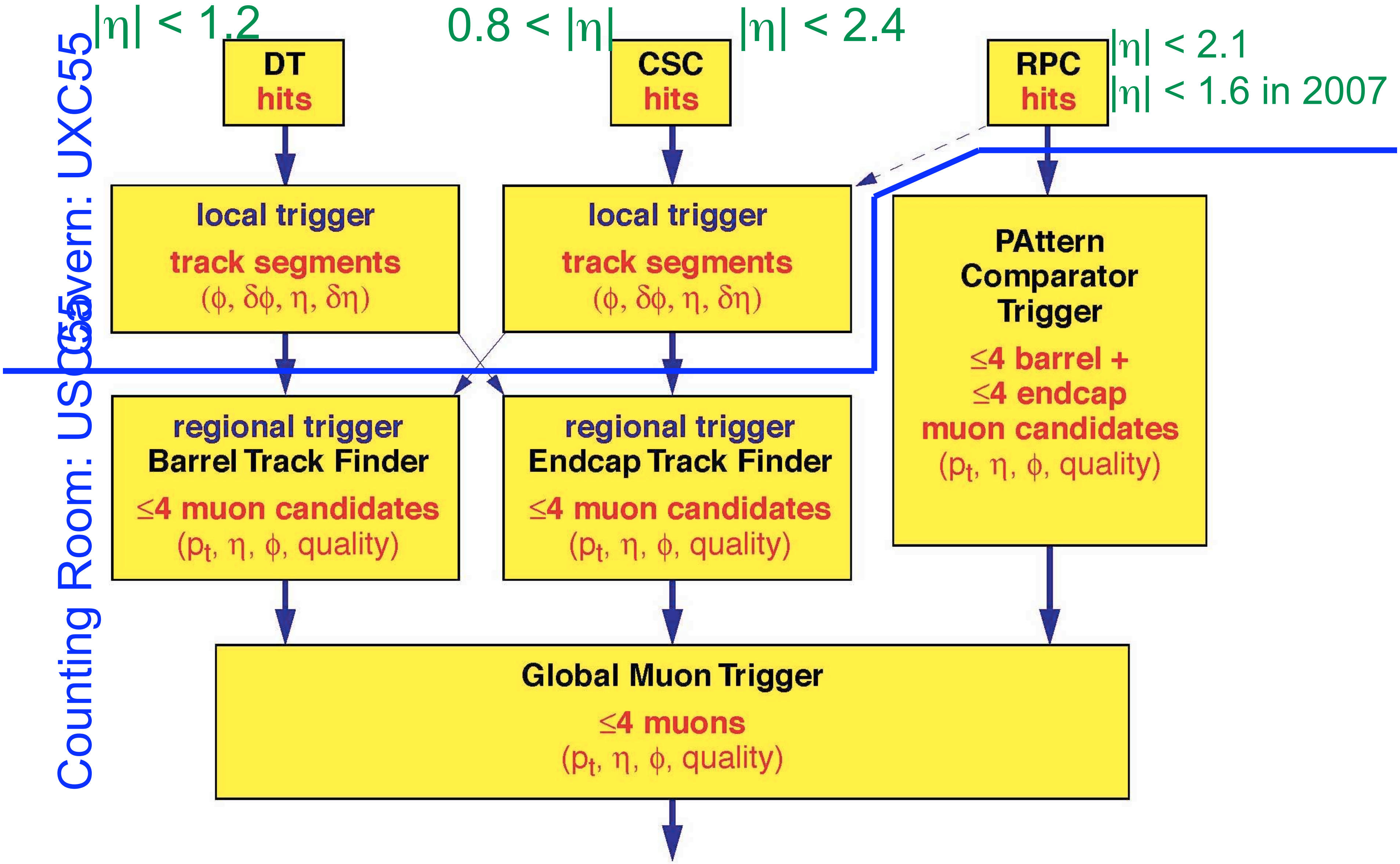
CMS L1 Muon Trigger

- Level-1 muon trigger info is obtained from:
  - Dedicated trigger detector (Resistive parallel plate chambers: RPC)
    - Excellent time resolution
  - Muon chambers with accurate position resolution
    - Drift Tubes (DT) in barrel
    - Cathode Strip Chambers (CSC) in endcaps
  - Bending in magnetic field =>
    - Determine pT
    - And cut on it





Muon Trigger Overview



$|\eta| < 1.2$

$0.8 < |\eta|$

$|\eta| < 2.4$

$|\eta| < 2.1$

$|\eta| < 1.6$ in 2007

Cavern: UXC55

Counting Room: USC55

DT
hits

CSC
hits

RPC
hits

local trigger
track segments
$(\phi, \delta\phi, \eta, \delta\eta)$

local trigger
track segments
$(\phi, \delta\phi, \eta, \delta\eta)$

PAttern
Comparator
Trigger
$\leq$4 barrel +
$\leq$4 endcap
muon candidates
$(p_t, \eta, \phi,$ quality$)$

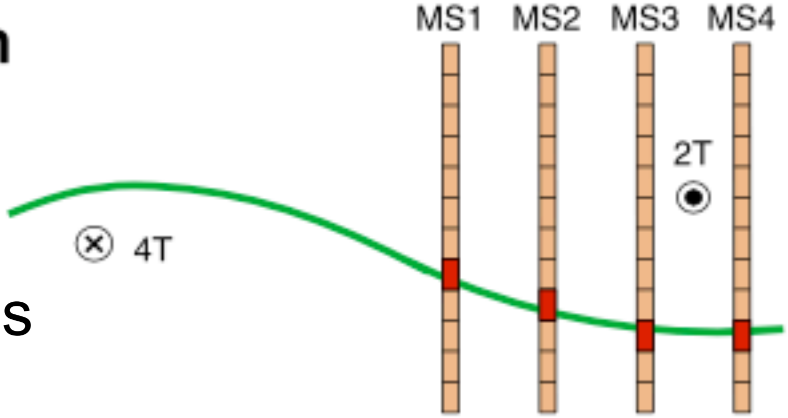
regional trigger
Barrel Track Finder
$\leq$4 muon candidates
$(p_t, \eta, \phi,$ quality$)$

regional trigger
Endcap Track Finder
$\leq$4 muon candidates
$(p_t, \eta, \phi,$ quality$)$

Global Muon Trigger
$\leq$4 muons
$(p_t, \eta, \phi,$ quality$)$

CMS Muon Trigger Primitives

RPC pattern recognition
- Pattern catalog
- Fast logic

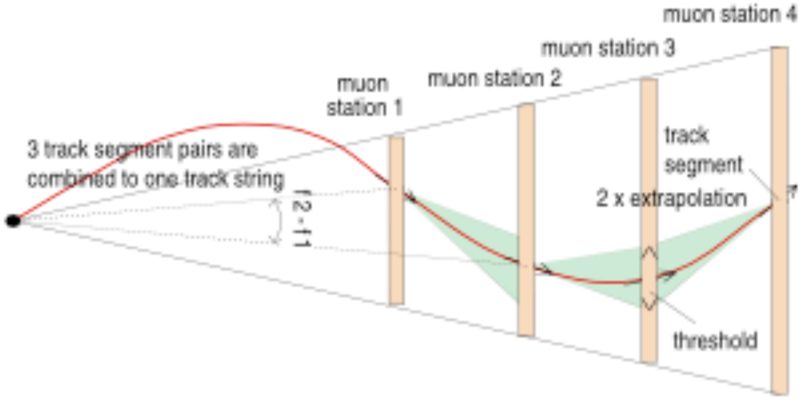


Memory to store patterns

Fast logic for matching

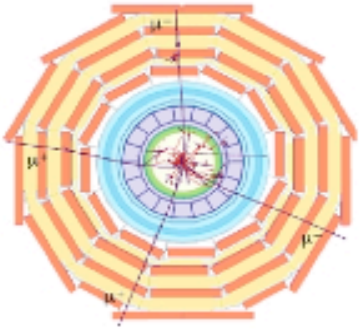
FPGAs are ideal

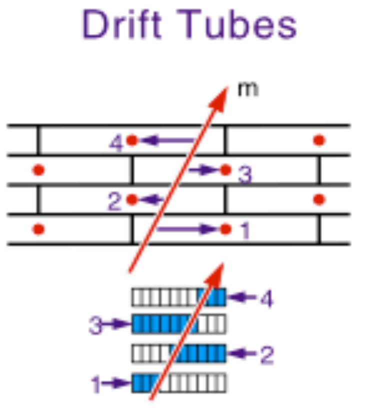
DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



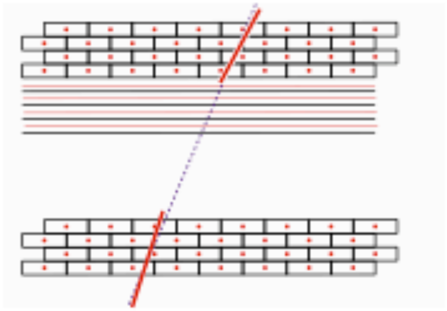
CMS Muon Trigger

Drift Tubes (DT)



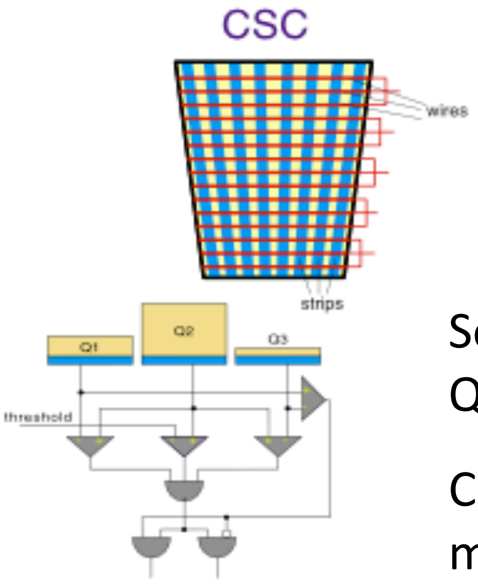


Meantimers recognize tracks and form vector / quartet.

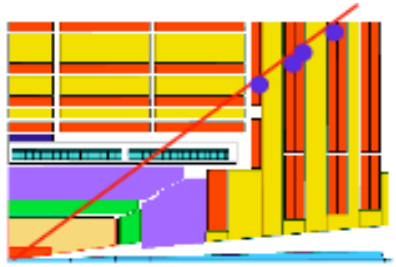


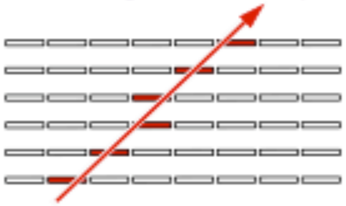
Correlator combines them into one vector / station.

Cathod Strip Chambers (CSC)



Comparators give 1/2-strip resol.





Hit strips of 6 layers form a vector.

Sort based on P_T, Quality - keep loc.

Combine at next level - match

Sort again – Isolate…

Top 4 highest P_T and quality muons with location coord.

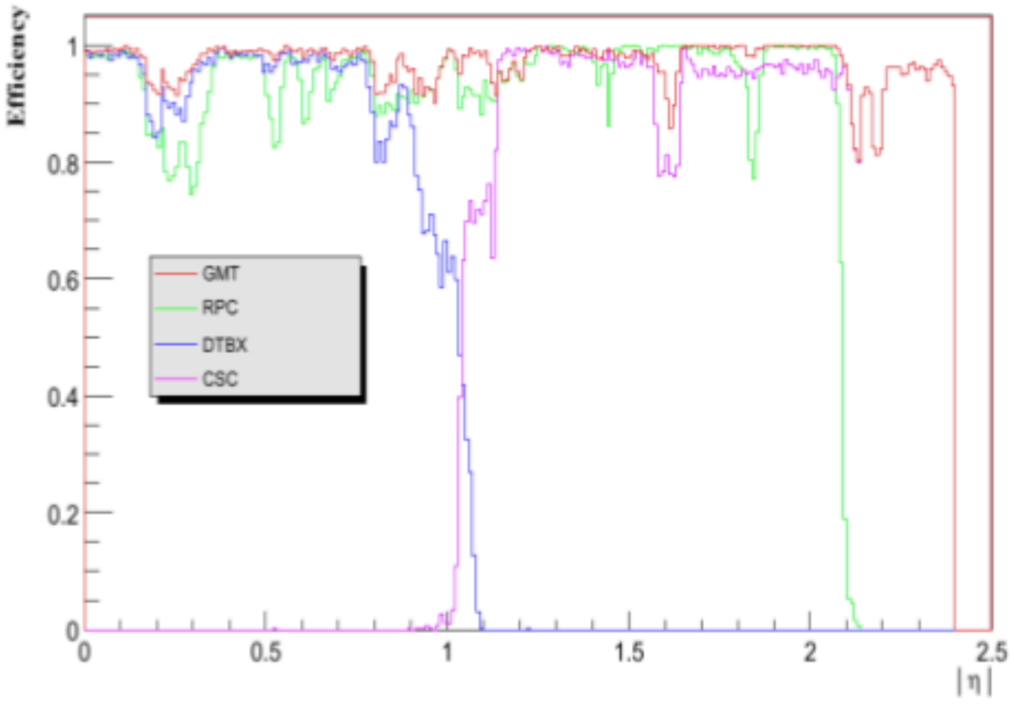
Hardware Implementation:

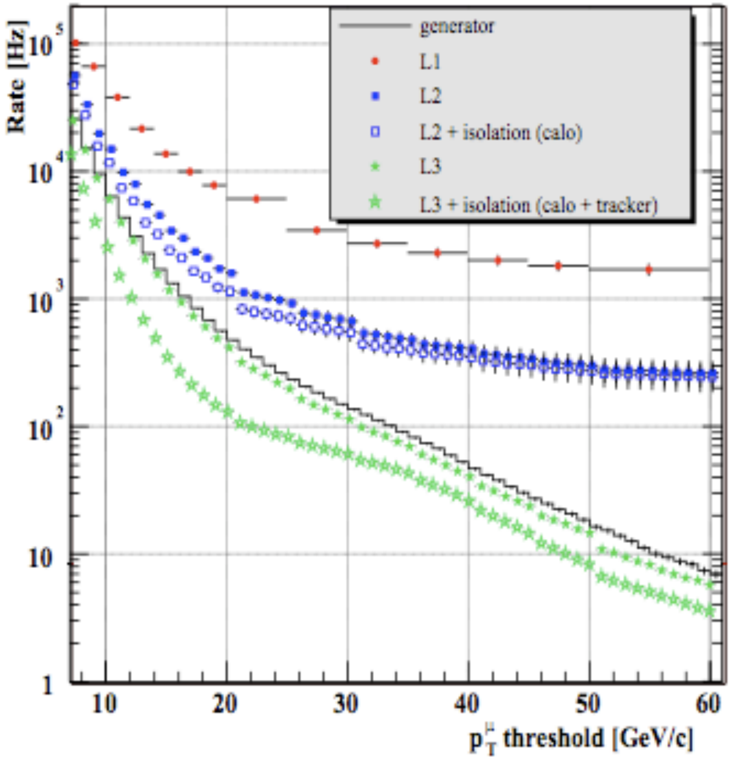
ASICs for Trigger Primitive Generators

FPGAs for Track finder processors

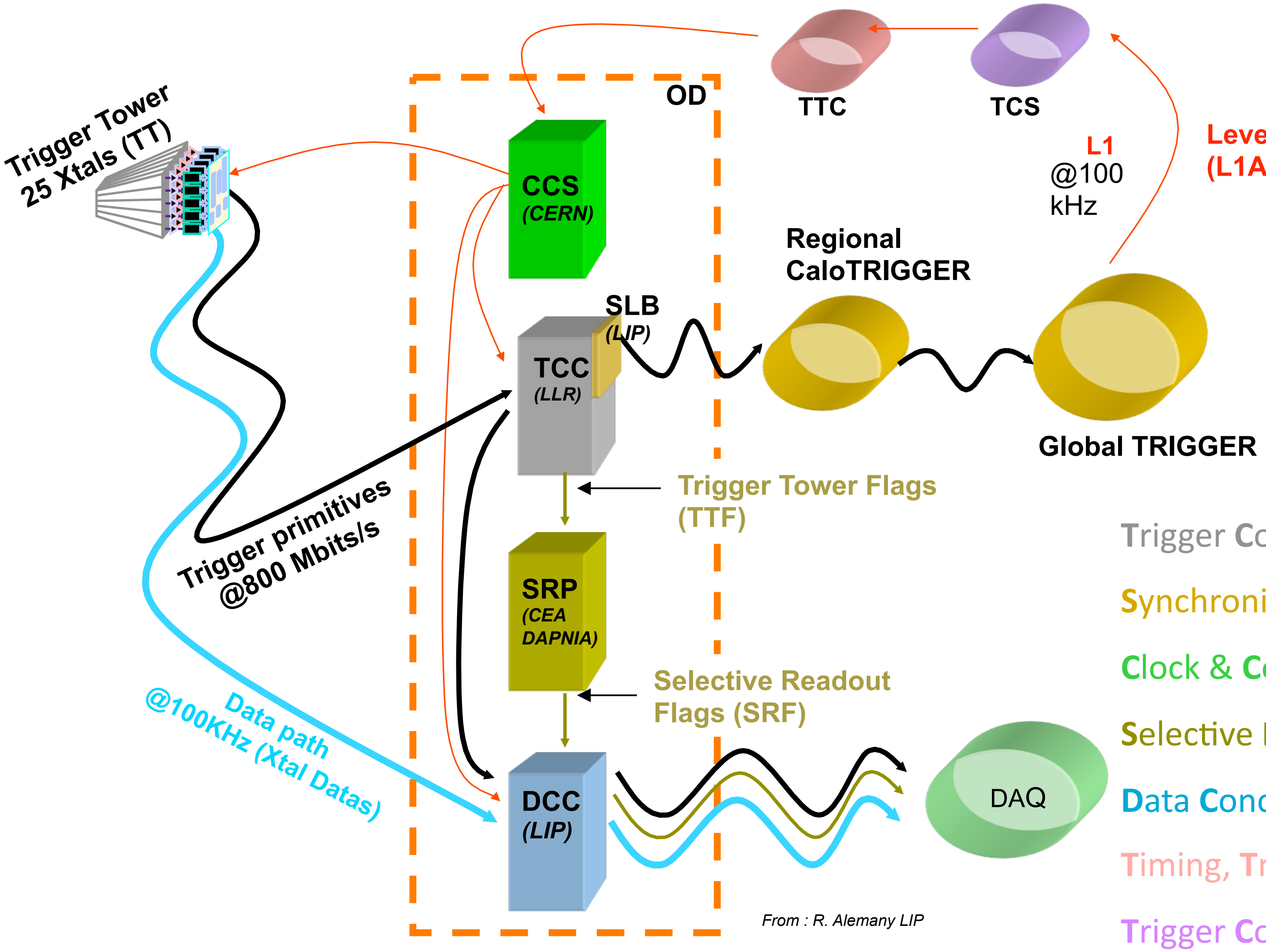
L1 Global Muon Trigger

- Combines information from different trigger decisions (RPC, DT, CSC)
  - Match muon candidates
  - Use complementarity of the sub-systems
  - Maximize efficiency, minimize rate
  - Identify 4 “best” muons and pass them onto the Global Trigger





Calorimeter Trigger Processing



From : R. Alemany LIP

Trigger Concentrator Card

Synchronisation & Link Board

Clock & Control System

Selective Readout Processor

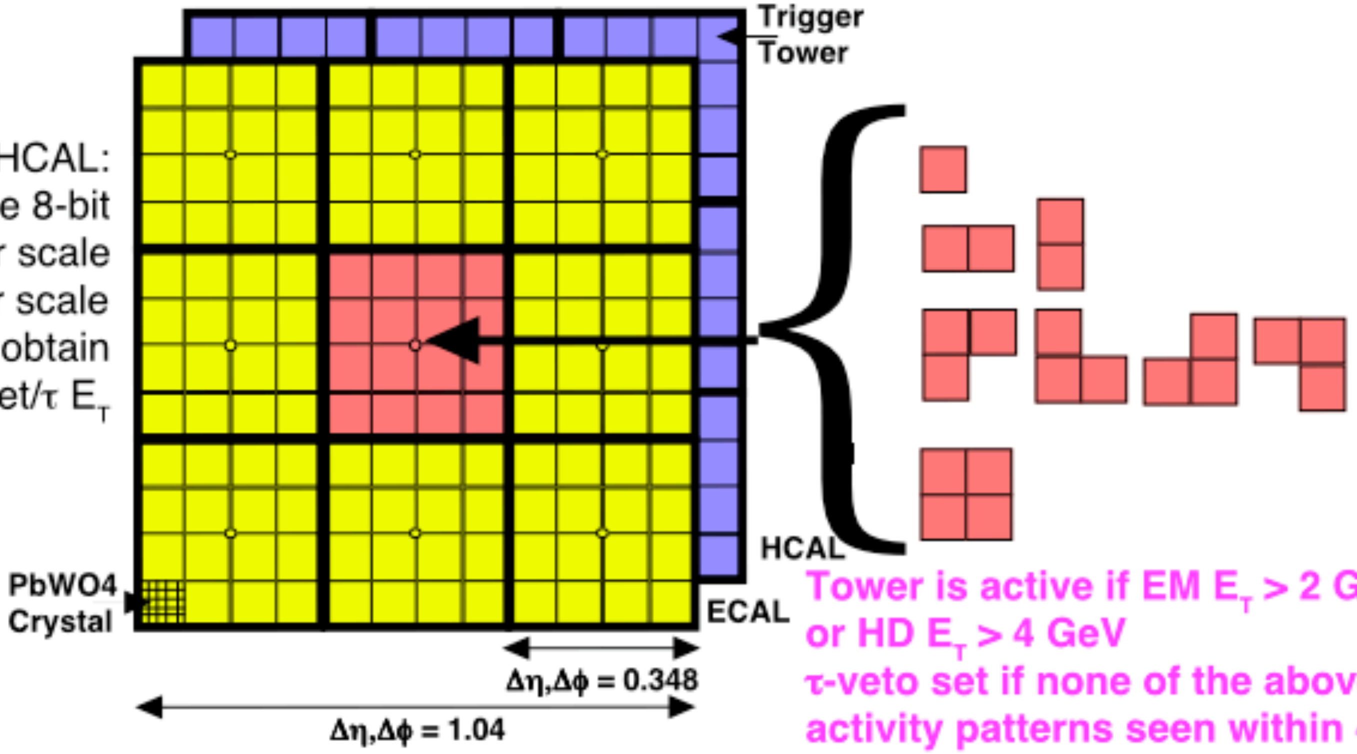
Data Concentrator Card

Timing, Trigger & Control

Trigger Control System

CMS Jet/τ Algorithm

Input from E/HCAL:
Programmable 8-bit
non-linear scale
Converted to linear scale
and summed to obtain
10-bit range jet/τ E_T



Tower is active if EM $E_T > 2$ GeV
or HD $E_T > 4$ GeV
τ-veto set if none of the above
activity patterns seen within 4x4

Jet or τ E_T

- 12x12 trigger tower E_T sums in 4x4 region steps with central region > others
- Larger trigger towers in HF but ~ same jet region size, 1.5 η x 1.0 ϕ

τ algorithm (isolated narrow energy deposits), within $-2.5 < \eta < 2.5$

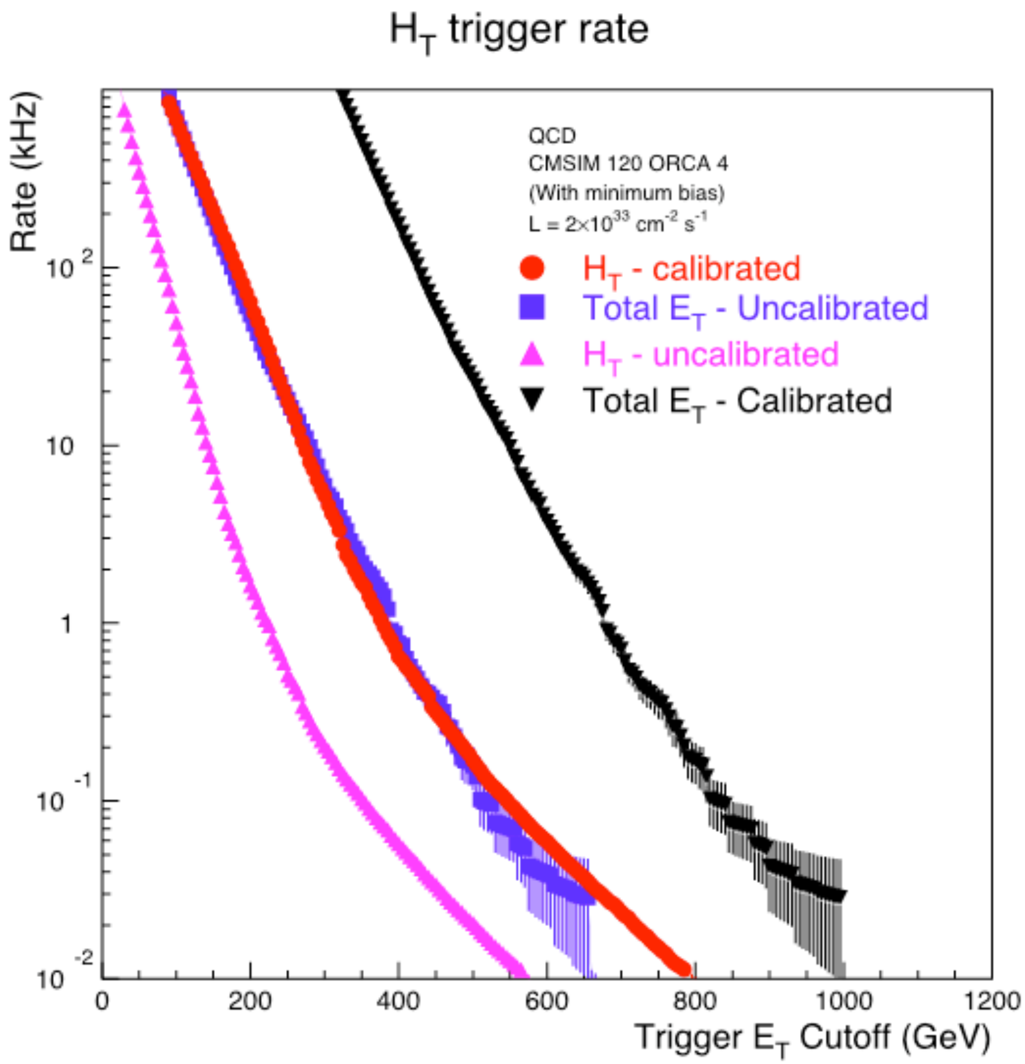
- Redefine jet as τ jet if none of the nine 4x4 region τ-veto bits are on

Output

- Top 4 τ-jets and top 4 jets in central rapidity, and top 4 jets in forward rapidity

H_T Trigger

- Total scalar E_T integrates too much noise and is not easily calibrated
  - At L1 tower-by-tower E_T calibration is not available
- However, jet calibration is available as function of (E_T, η, ϕ)
- Therefore, H_T which is the sum of scalar E_T of all high E_T objects in the event is more useful for heavy particle discovery/study
  - SUSY sparticles
  - Top



Global Trigger

- A very large OR-AND network which allows specification of complex conditions:
  - 1 electron with pT > 20 GeV OR 2 electrons with pT > 14 GeV OR 1 electron with pT > 12 GeV AND 1 jet with pT > 40 GeV
  - The top-level logic requirements (1 electron + 1 jet for eg.) constitute a “Trigger table”
    - Allocating rates to different trigger conditions is a complex process that requires optimization of physics efficiencies versus backgrounds, rates and machine conditions

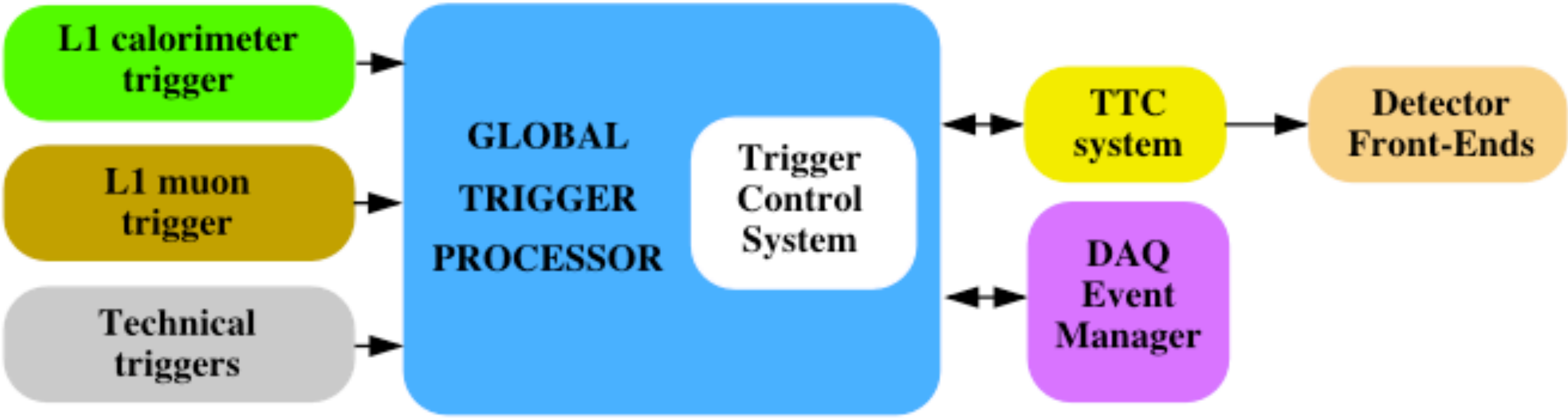
CMS Global Trigger

Input:

- Jets: 4 Central, 4 Forward, 4 Tau-tagged, & Multiplicities
- Electrons: 4 Isolated, 4 Non-isolated
- 4 Muons (from 8 RPC, 4 DT & 4 CSC w/P_t & quality)
  - All above include location in η and ϕ
- Missing E_T & Total E_T

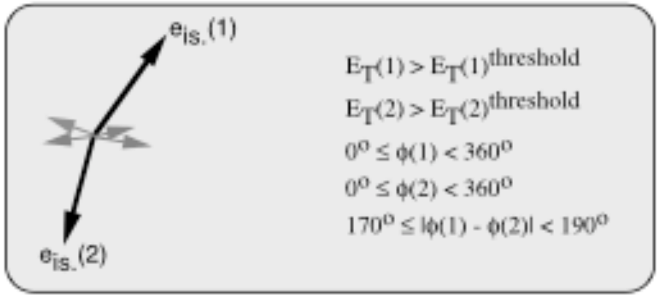
Output

- L1 Accept from combinations & proximity of above

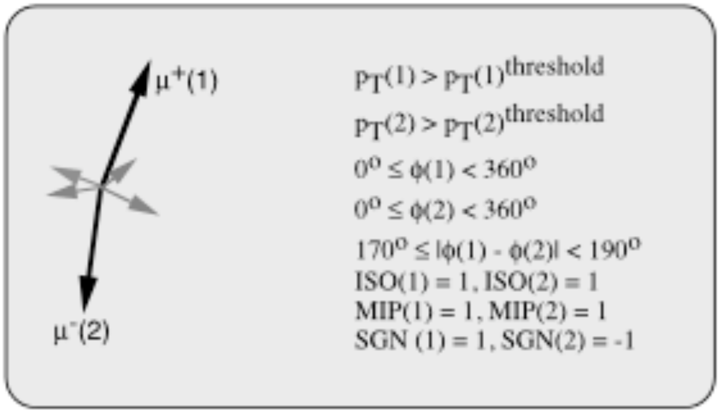


Global L1 Trigger Algorithms

Particle Conditions

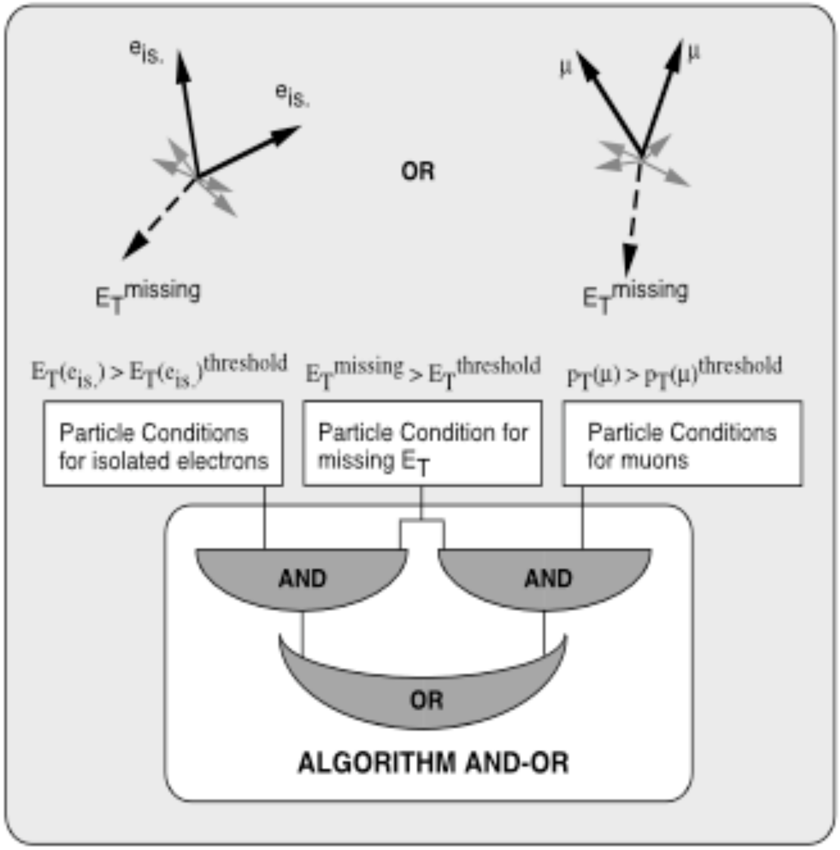


$E_T(1) > E_T(1)^{threshold}$
$E_T(2) > E_T(2)^{threshold}$
$0^o \leq \phi(1) < 360^o$
$0^o \leq \phi(2) < 360^o$
$170^o \leq |\phi(1) - \phi(2)| < 190^o$



$p_T(1) > p_T(1)^{threshold}$
$p_T(2) > p_T(2)^{threshold}$
$0^o \leq \phi(1) < 360^o$
$0^o \leq \phi(2) < 360^o$
$170^o \leq |\phi(1) - \phi(2)| < 190^o$
$ISO(1) = 1, ISO(2) = 1$
$MIP(1) = 1, MIP(2) = 1$
$SGN(1) = 1, SGN(2) = -1$

Logical Combinations

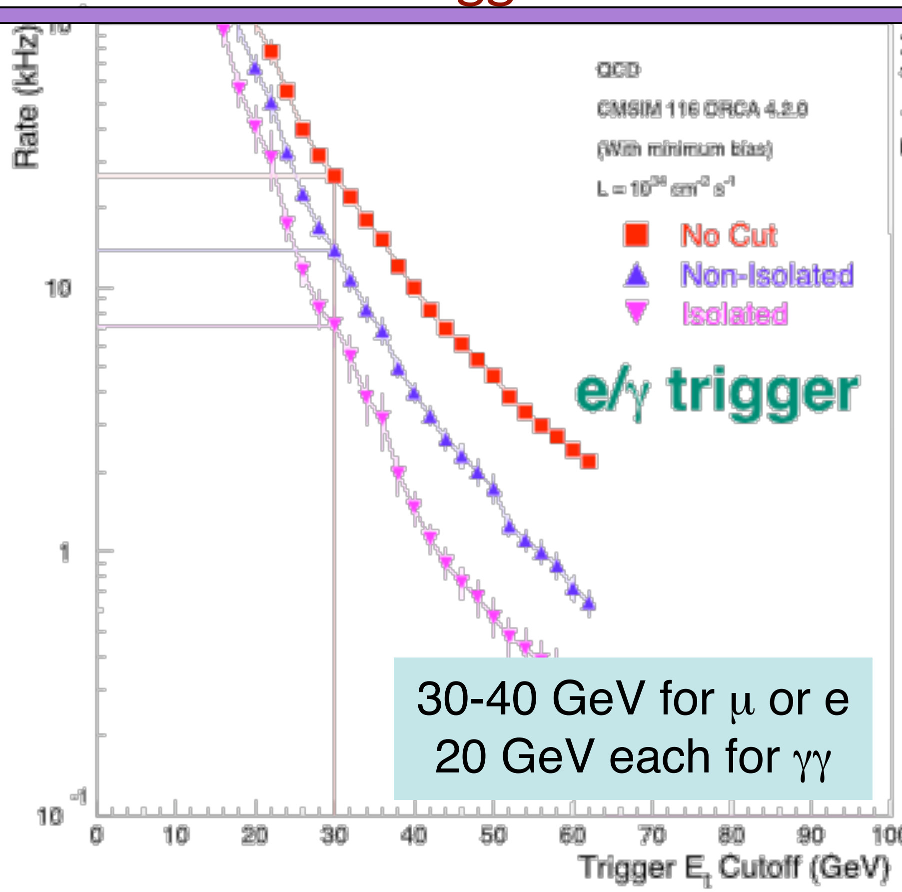


$E_T(e_{is.}) > E_T(e_{is.})^{threshold}$
$E_T^{missing} > E_T^{threshold}$
$p_T(\mu) > p_T(\mu)^{threshold}$

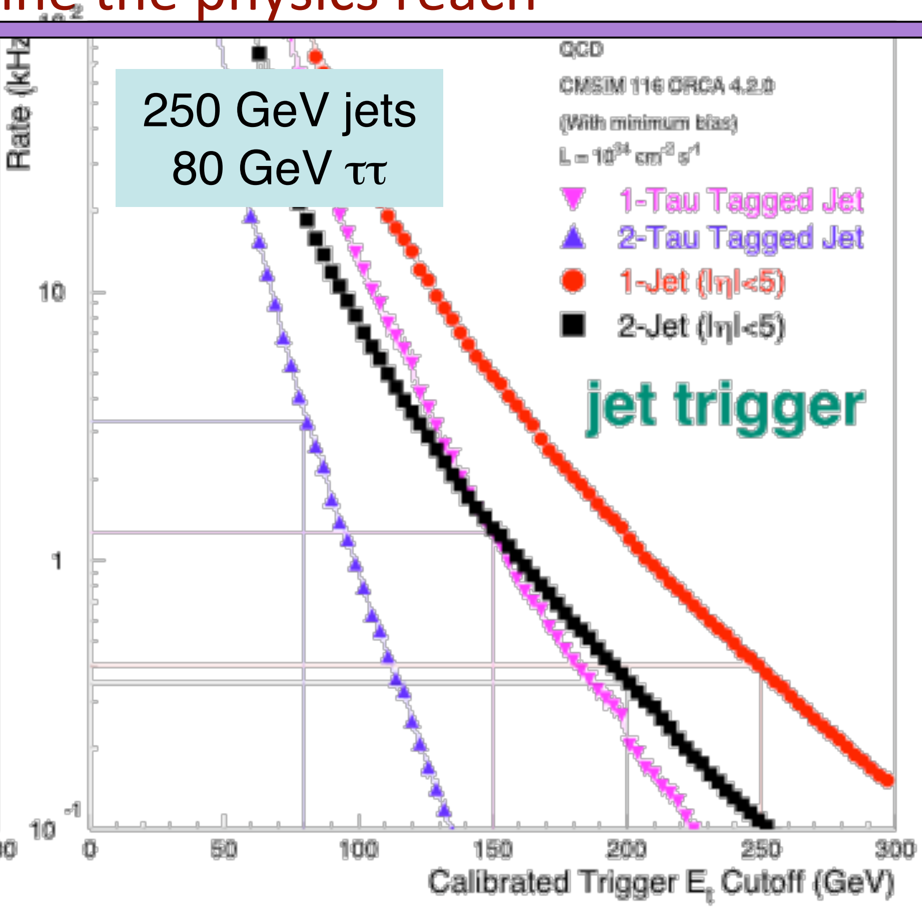
Flexible algorithms implemented in FPGAs
100s of possible algorithms can be reprogrammed

Level-1 Trigger Rates:

Trigger cuts determine the physics reach



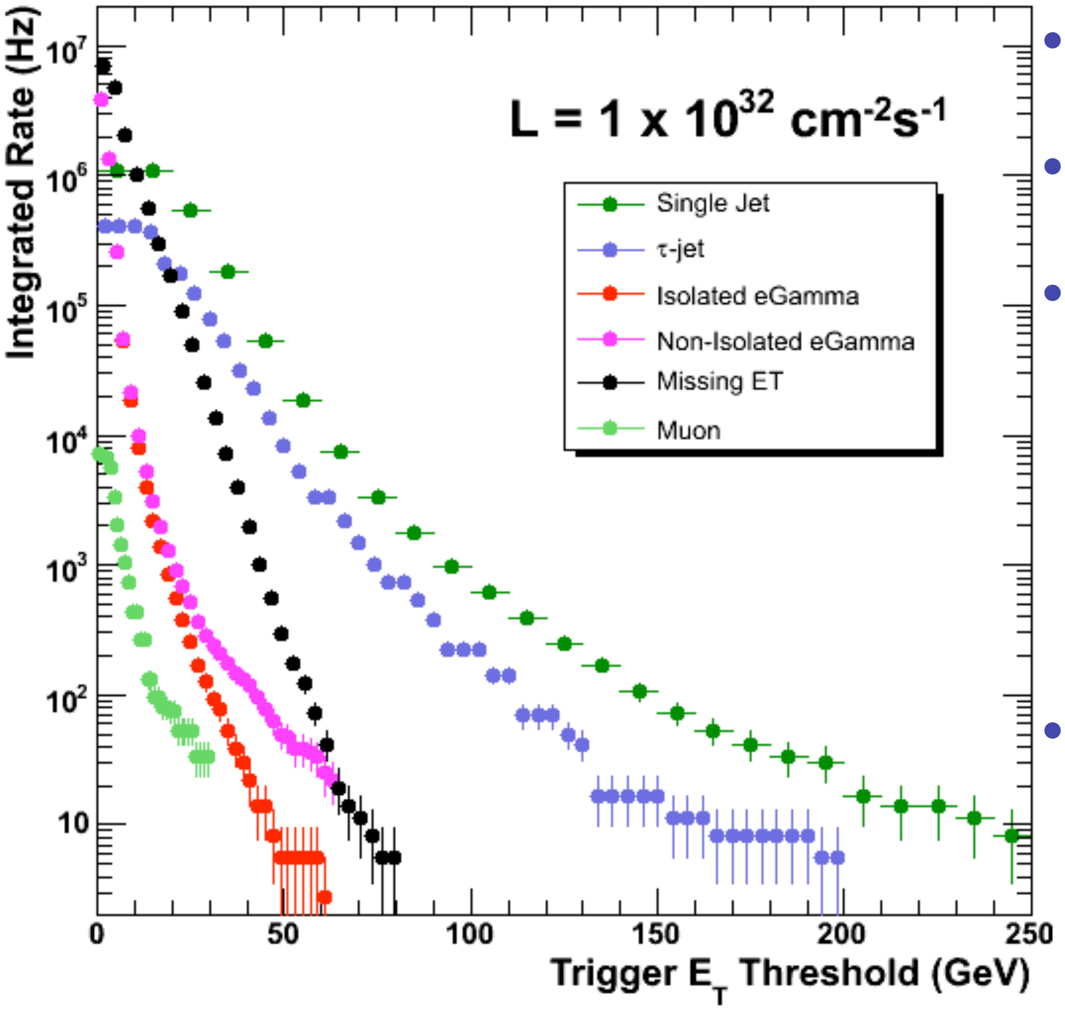
30-40 GeV for μ or e
20 GeV each for γγ



250 GeV jets
80 GeV ττ

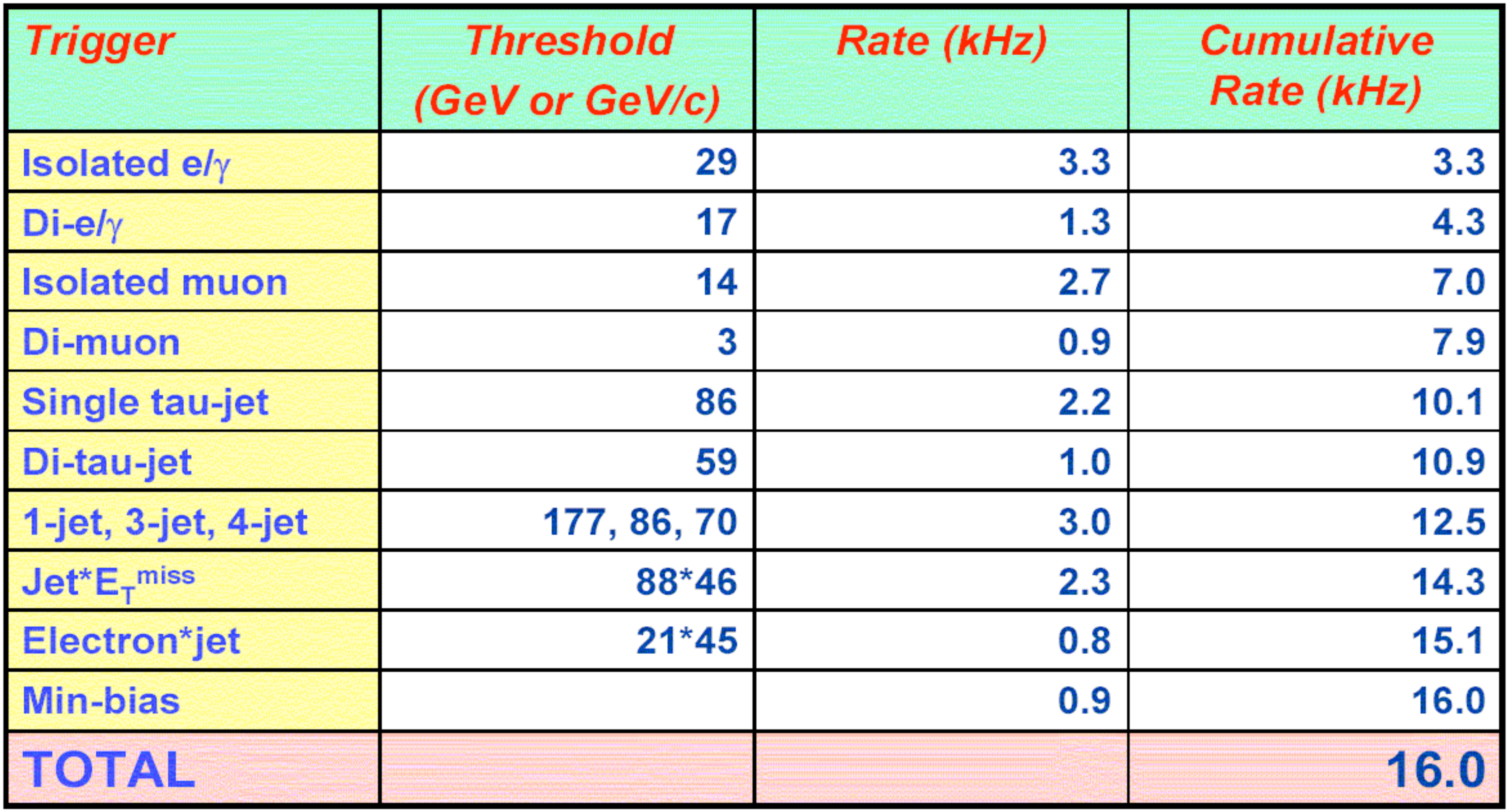
- Efficiency for H→γγ and H→4 leptons = >90% (in fiducial volume of detector)
- Efficiency for WH and ttH production with W→lν = ~85%
- Efficiency for qqH with H→ττ (τ→1/3 prong hadronic) = ~75%
- Efficiency for qqH with H→invisible or H→bb = ~40-50%

L1 Trigger Table



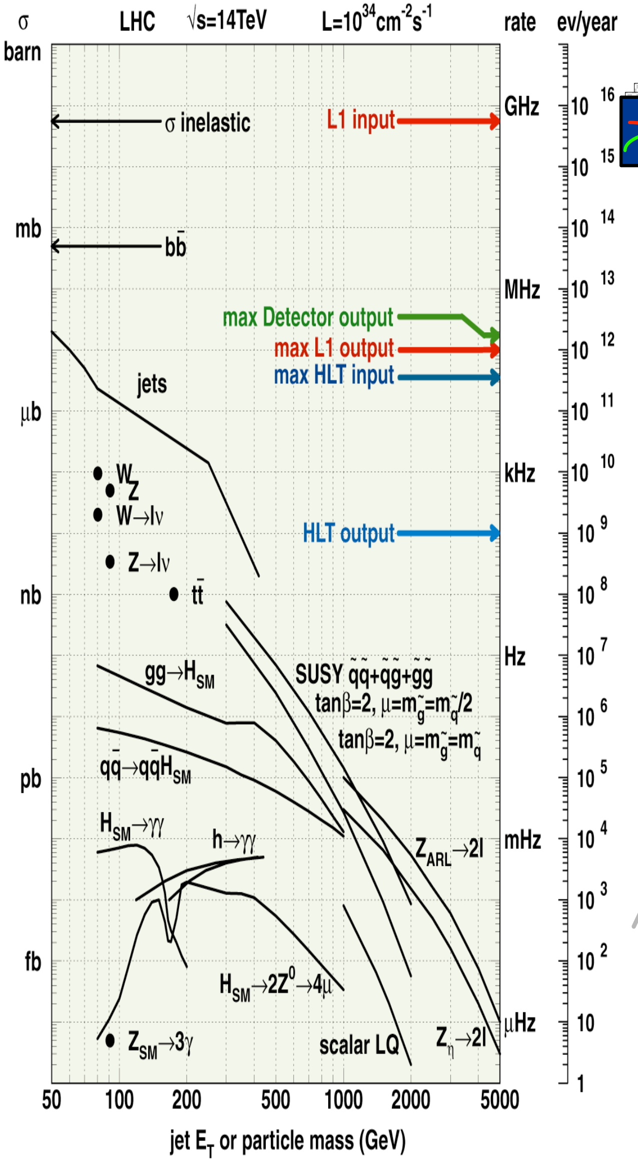
- Determined by the physics priorities of the experiment
- L1 table optimized to fit within the L1 bandwidth
- Allow a safety factor of 3
  - underestimation of input cross sections, poor beam conditions, detector performance, etc.
  - 17 kHz instead of nominal 50 kHz allowed by DAQ at startup
- Realistic menu including double and mixed triggers for specific physics channels

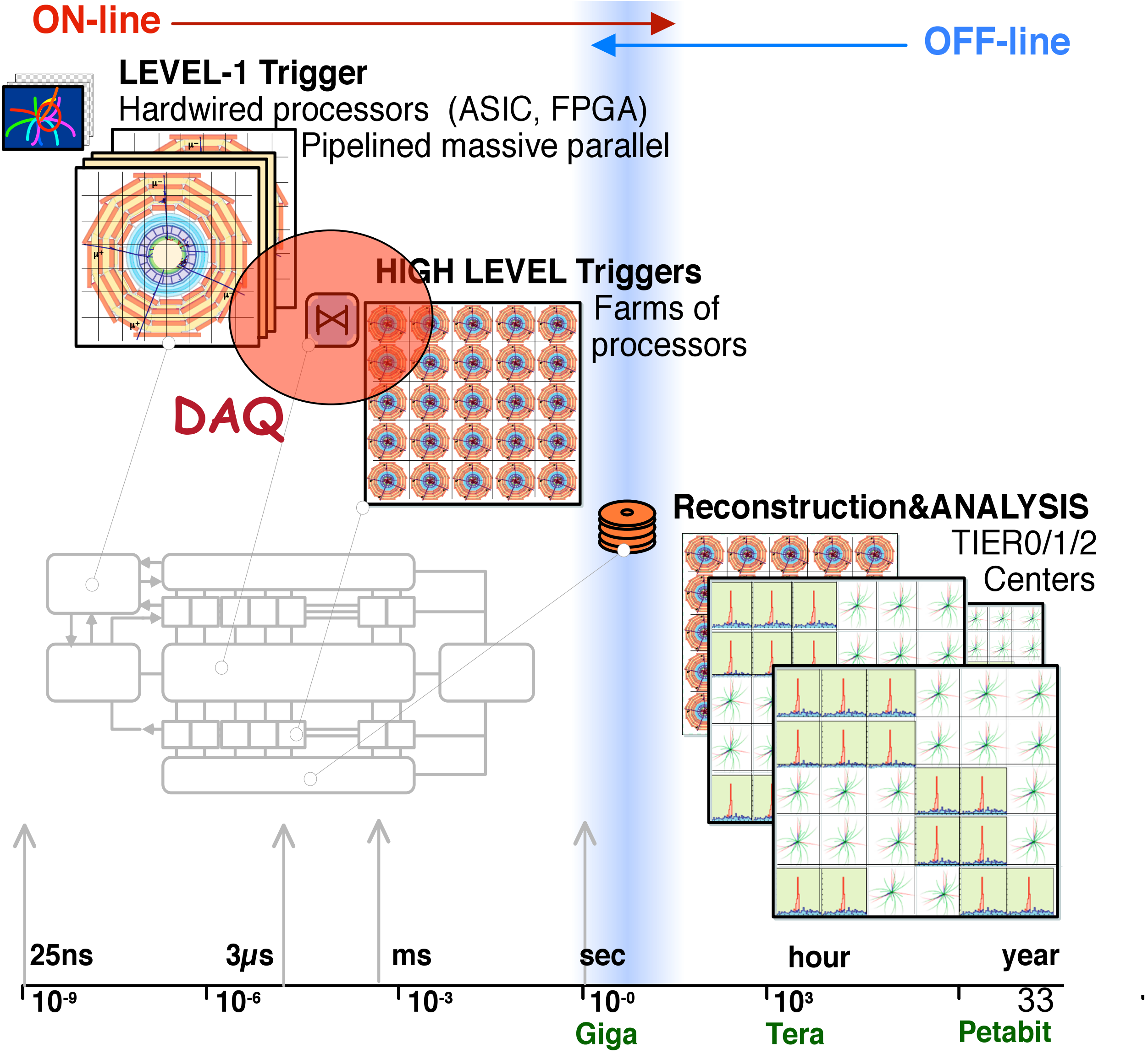
Example Level-1 Trigger Table (DAQ TDR: 2 x 10^{33})



Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			**16.0**

× 3 safety factor ⇒ 50 kHz (expected start-up DAQ bandwidth)





ON-line

OFF-line

LEVEL-1 Trigger

Hardwired processors (ASIC, FPGA)

Pipelined massive parallel

HIGH LEVEL Triggers

Farms of processors

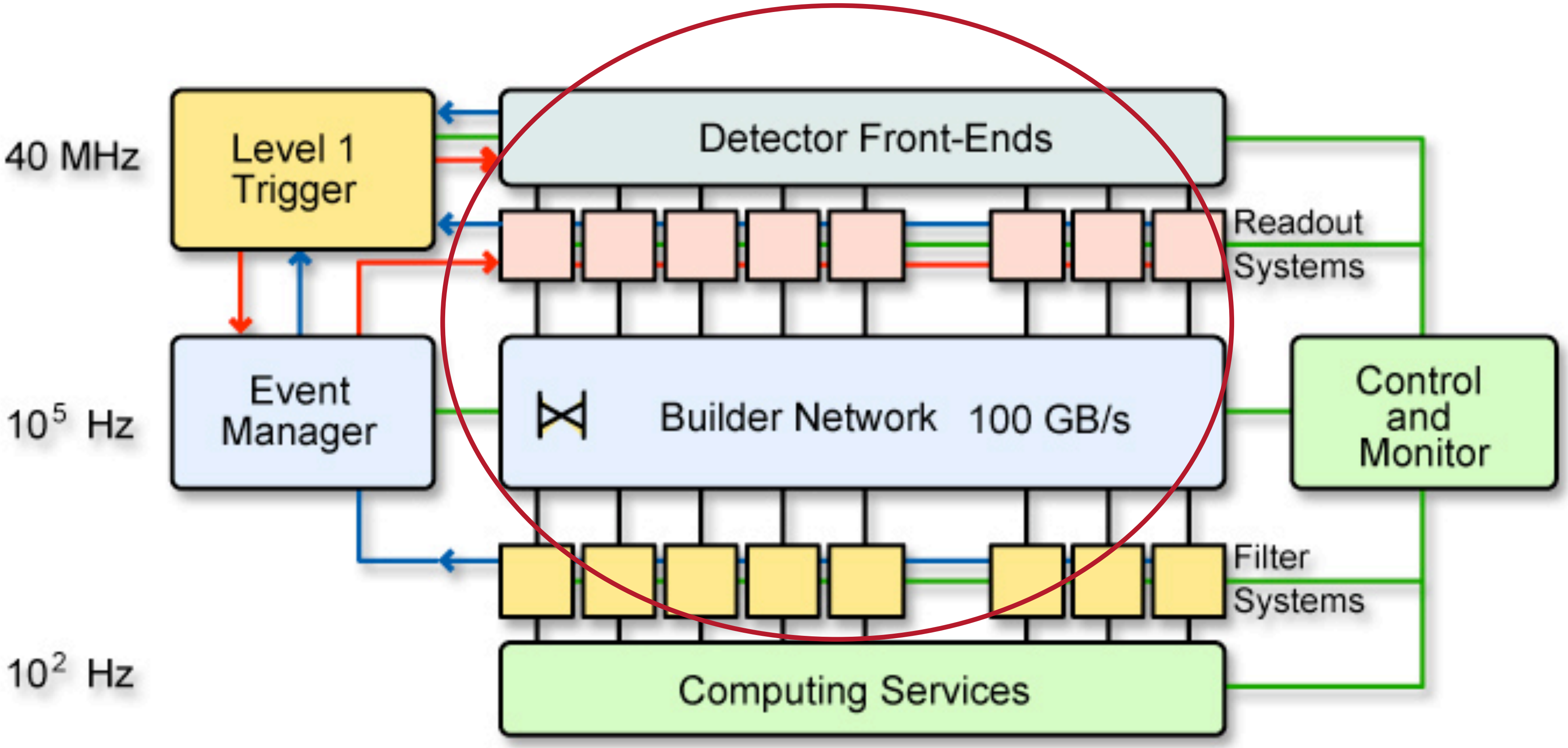
DAQ

Reconstruction&ANALYSIS

TIER0/1/2 Centers

DAQ

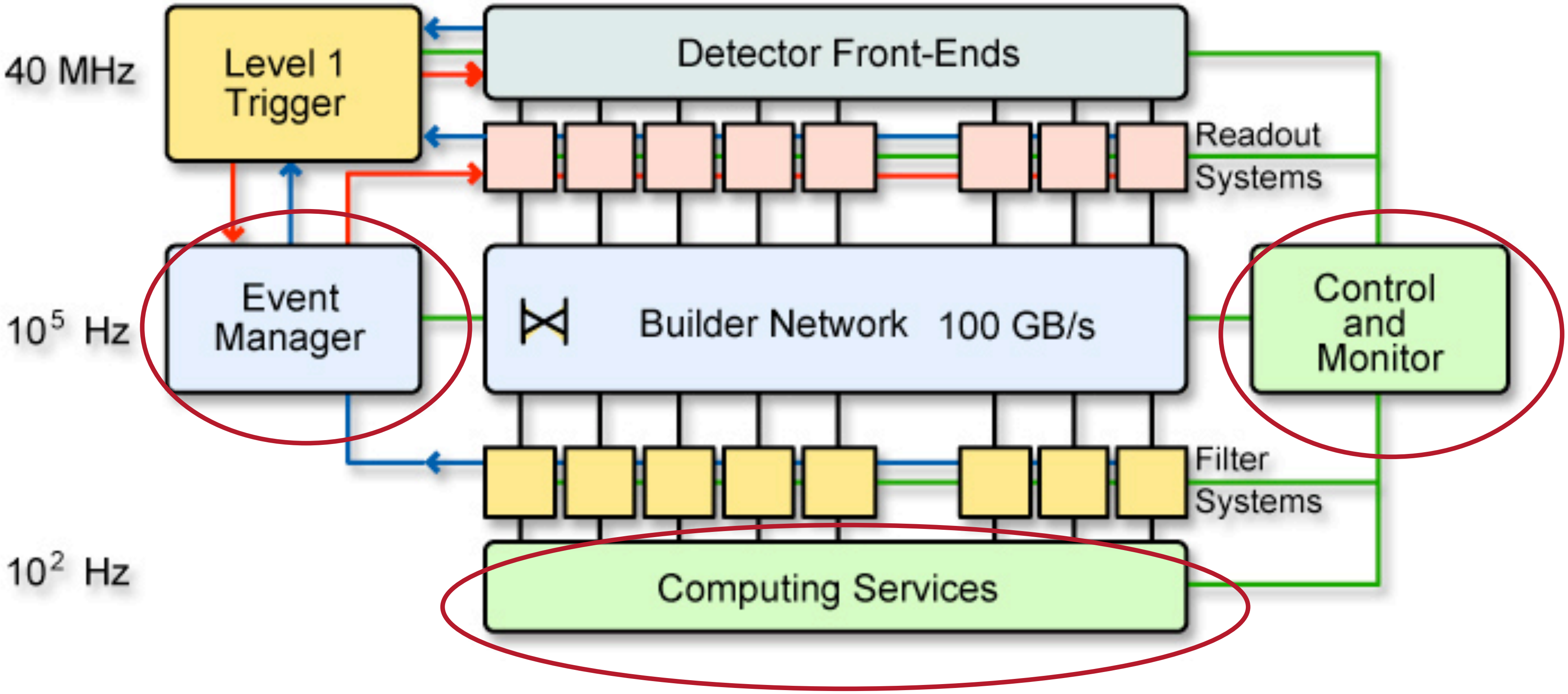
DAQ Overview



DAQ Architecture

- Detector Front-ends:
  - Modules which store data from detector front-end electronics upon a L1 accept
- Readout systems:
  - Modules which read data from front-end systems and store the data until it is sent to the processors for analysis
- Intermediate trigger level (a la ATLAS)
  - Local detector data (partially assembled) provides an intermediate trigger level
- Builder network:
  - Collection of networks (switches) provide interconnections between the Readout and Filter systems, assembles events
- Filter Systems:
  - Processors which execute HLT algorithms to select interesting events for offline processing

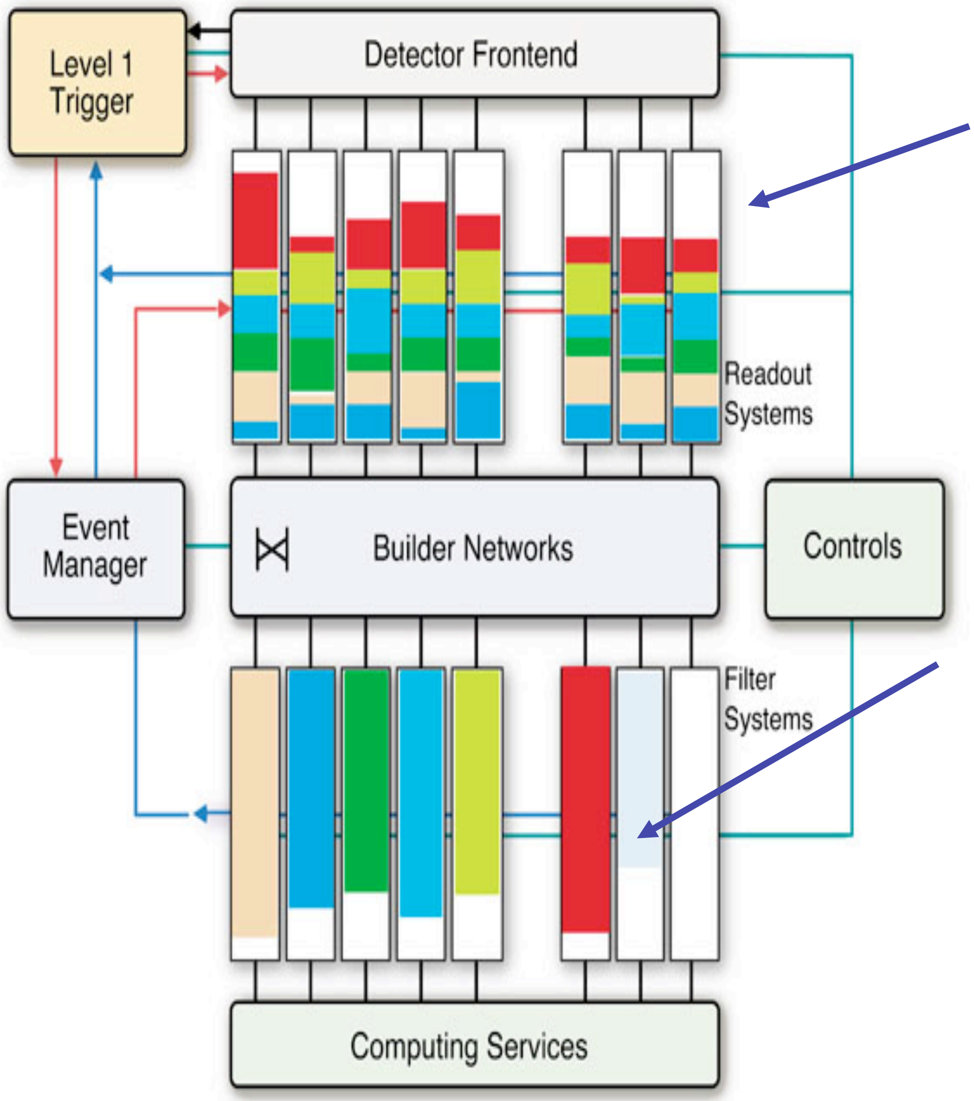
DAQ Overview



DAQ Architecture

- Event Manager:
  - Responsible for controlling the flow of data (events) in the DAQ system
  - Simplifies overall system synchronization
- Computing systems:
  - Processors which receive filtered events from the Filter farms
- Controls:
  - Entities responsible for the user interface, configuration and monitoring of the DAQ

Event Builder Scheme



Event fragments are stored in independent physical memories

Each full event should be stored in one physical memory of the processing unit (commodity PC)

The Event Builder builds full events from event fragments.

- must interconnect all data sources to destinations

⇒ Huge network switch

Event Building with a Switch

SWITCH : Networking device that connects network segments

Allows one to send data from a PC connected to a port (input port) to a PC connected to another port (output port) directly without duplicating the packet to all ports (i.e. an "intelligent" hub)

Switch inspects data packets as they are received, determines the source and destination device of that packet and forwards it appropriately

Conserves network bandwidth and optimizes data transfers

A switch you may be familiar with:

8-port consumer grade switch

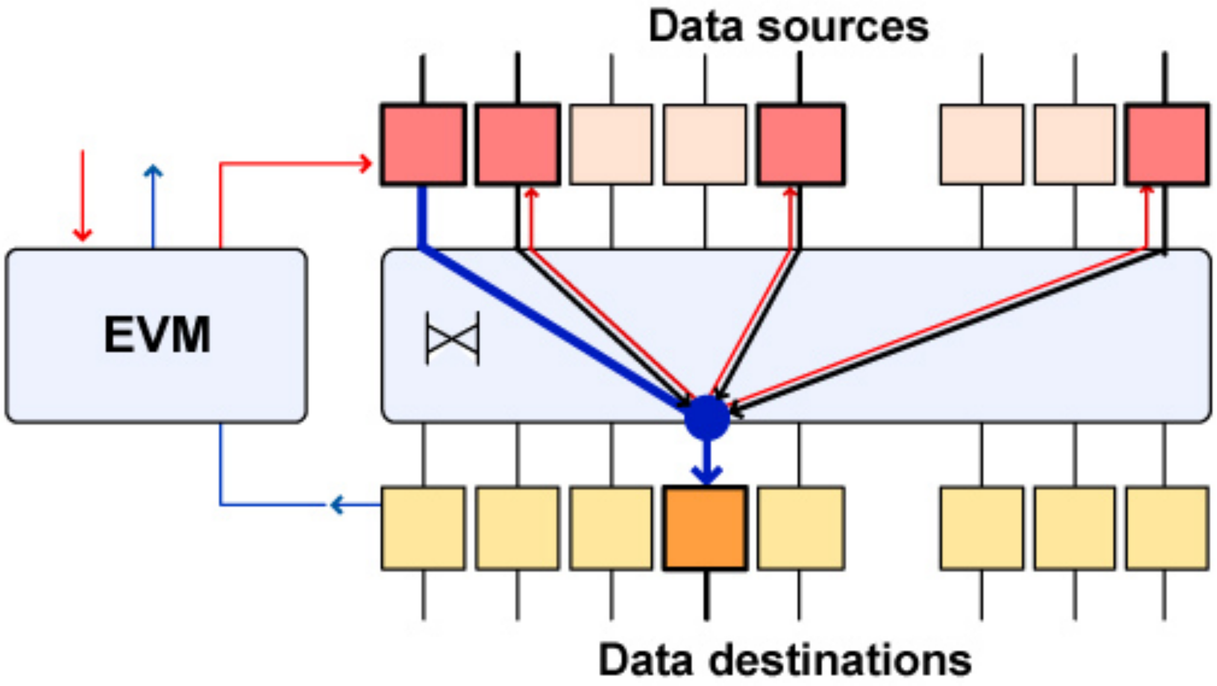
HEP Switching Technologies

Gigabit Ethernet:
64 ports @ 1.2 Gb/s

Myricom Myrinet:
64 ports @ 2.5 Gb/s

Traffic Issues

READOUT BUFFERS



EVB Traffic "Jam":

All sources send to the same destination concurrently
⇒ congestion

Event Builder congestion should not lead to readout buffer overflow:

Need traffic shaping!

Dealing with traffic

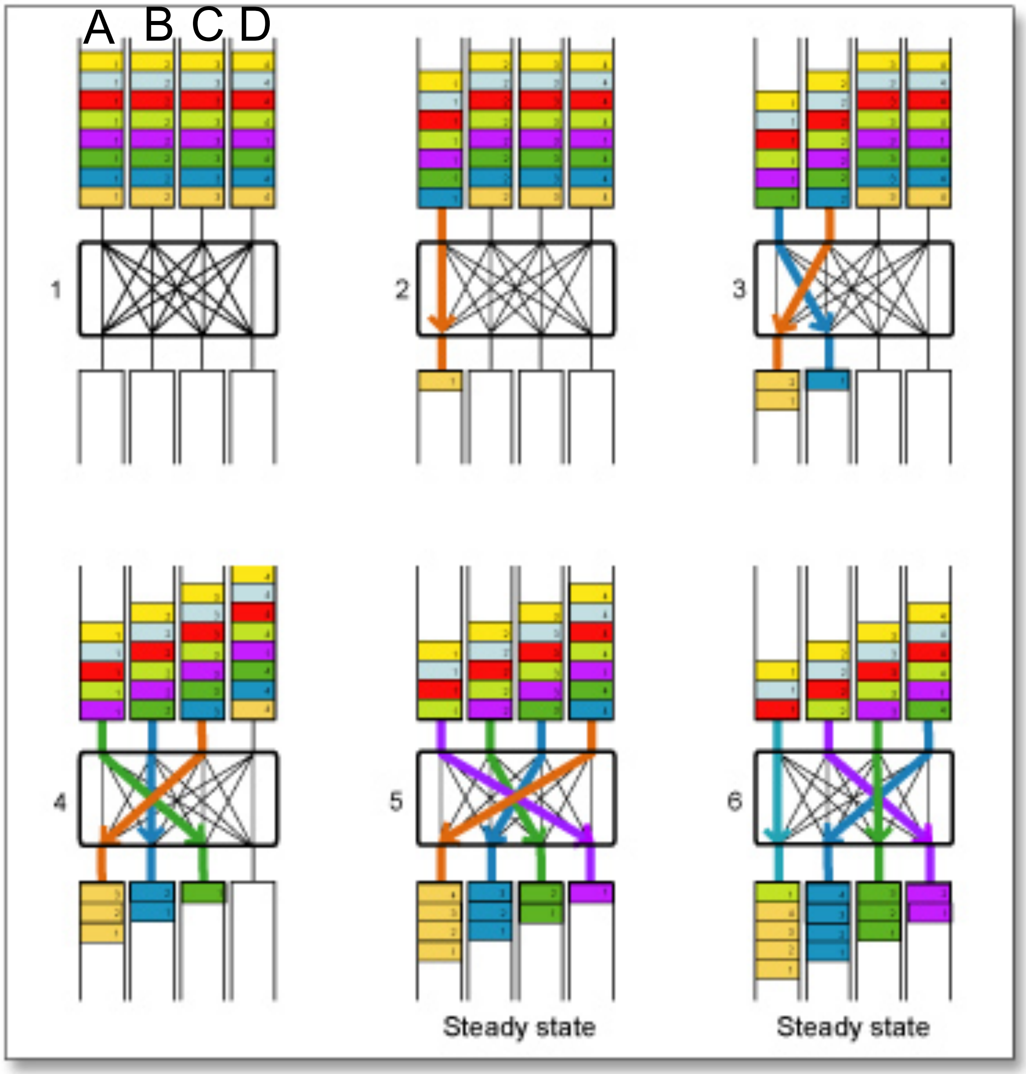
Barrel Shifter:

The sequence of send from each source to each destination follows the cyclic permutations of all destinations

Allow to reach a throughput closer to 100% of input bandwidth

Additional traffic shaping techniques being used as well

Barrel shifter



Strategies

The massive Level-1 data rate poses problems even for network-based event building — ATLAS and CMS have adopted different strategies:

ATLAS: Uses Region-of-Interest (RoI) mechanism with sequential selection to access the data only as required – i.e. only move data needed for Level-2 processing

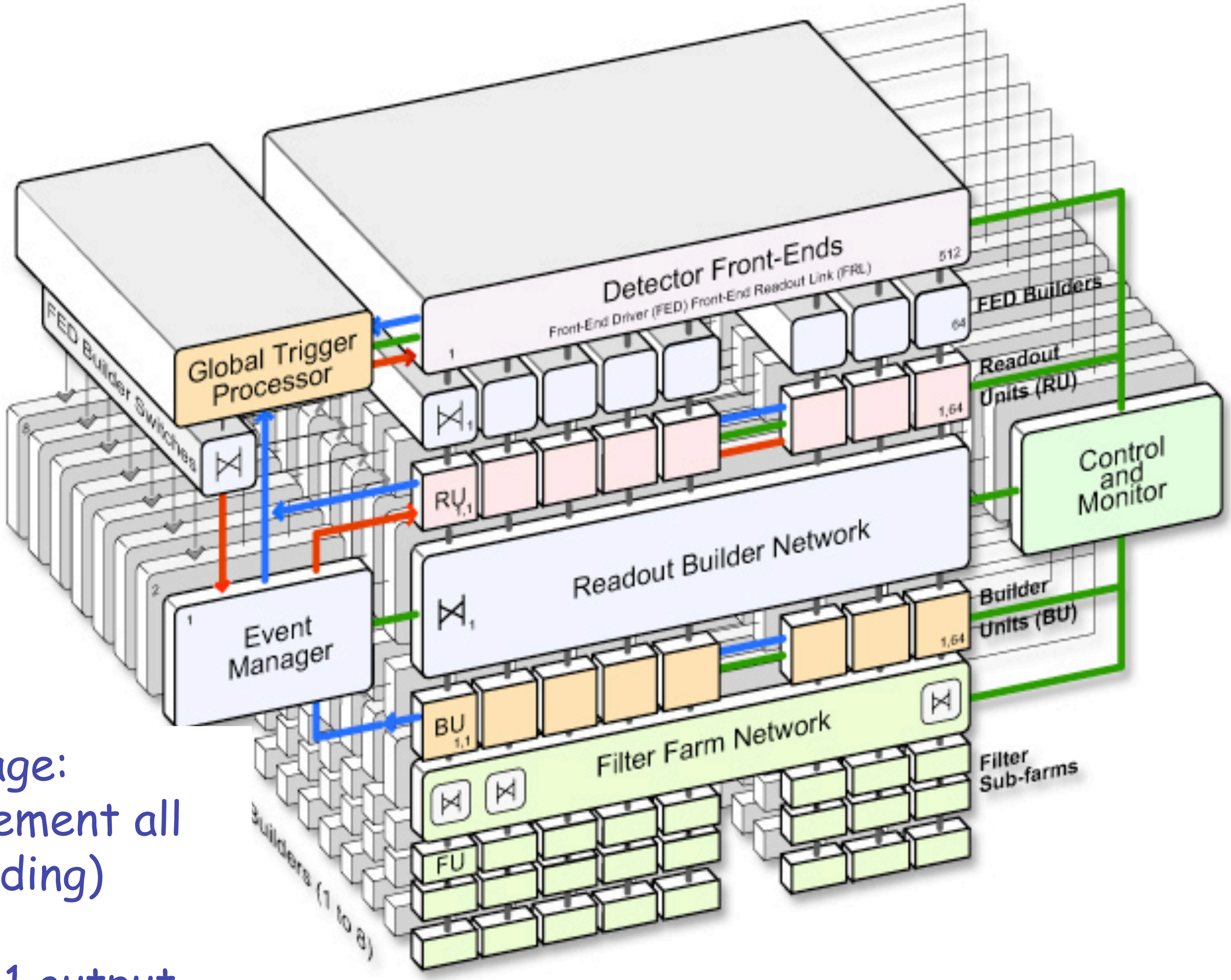
- Reduces by a substantial factor the amount of data that needs to be moved from the Readout Systems to the Processors
- Relatively complicated strategies needed to serve the data selectively to the Level-2 processors ⇒ more complex software

CMS: Event building is factorized into a number of slices each of which sees only a fraction of the rate

- Requires large total network bandwidth (⇒ cost), but avoids the need for a very large single network switch

CMS DAQ Slices

Eight slices:
Each slice sees
only 1/8th of
the events



Additional advantage:
Don't have to implement all
slices initially (funding)
At startup:
4 slices =>50kHz L1 output

- Level-2 (ATLAS):
  - Region of Interest (ROI) data is ~1% of total
  - Smaller switching network is needed (not in # of ports but in throughput)
  - But adds:
    - Level-2 farm
    - Lots of control and synchronization
  - Problem of large network → problem of Level-2

- Combined HLT (CMS):
  - Needs very high throughput
  - Needs large switching network
  - But it is:
    - Simpler data flow and operations
    - More flexible (the entire event is available to the HLT – not just a piece of it)
  - Problem of selection → problem of technology

High Level Trigger

HLT Guidelines

- Strategy/design:
  - Use offline software as much as possible
    - Easy to maintain (software can be easily updated)
    - Uses our best (bug-free) understanding of the detector
- Boundary conditions:
  - Code runs in a single processor, which analyzes one event at a time
  - Have access to full event data (full granularity and resolution)
  - Limitations:
    - CPU time
    - Output selection rate: ~100 Hz
    - Precision of calibration constants

HLT Requirements

- Flexible:
  - Working conditions at 14 TeV are difficult to evaluate (prepare for different scenarios)
- Robust:
  - HLT algorithms should not depend in a critical way on alignment and calibration constants
- Inclusive selection:
  - Rely on inclusive selection to guarantee maximum efficiency to new physics
- Fast event rejection:
  - Event not selected should be rejected as fast as possible (i.e. early on in the processing)
- Quasi-offline software:
  - Offline software used online should be optimized for performance
  - (we need to select events that are "interesting enough")

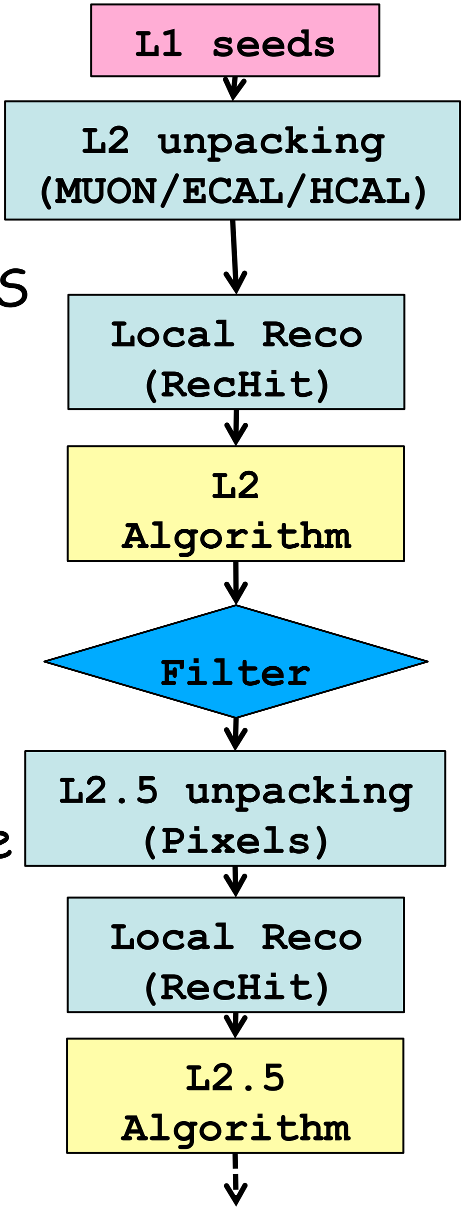
HLT Processing

High Level Triggers (> Level 1) are implemented more or less as advanced software algorithms

- Run on standard processor farms with Linux as OS
- cost effective since Linux is free

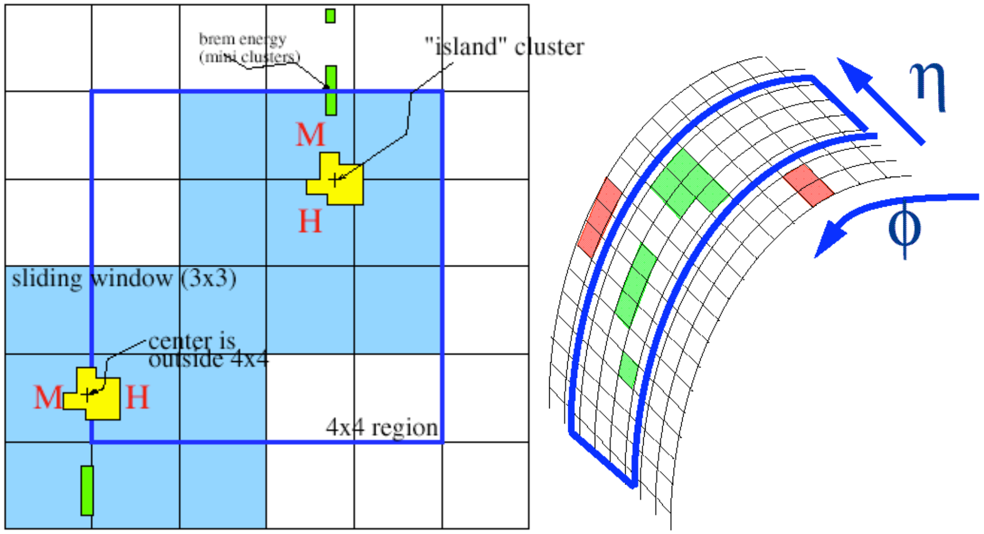
HLT filter algorithms are setup in various steps:

- 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

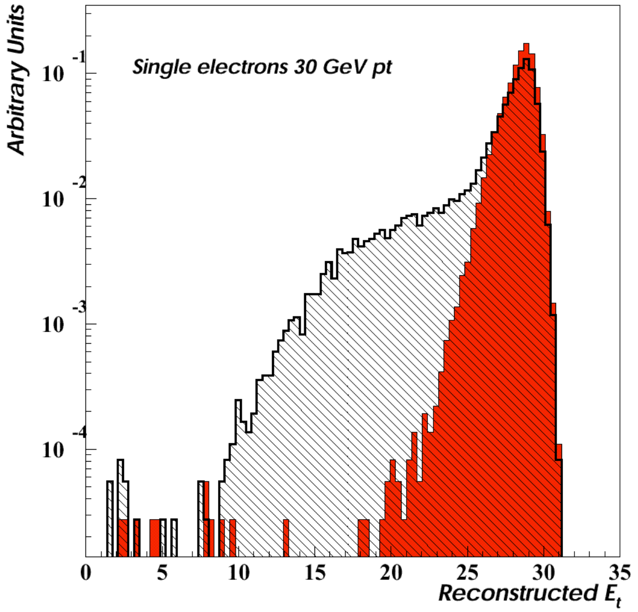


Example Trigger Path: CMS E/γ

- "Level-2" (CAL info only):
  - Confirm L1 candidates
  - Apply "clustering"
  - Supercluster algorithm recovers bremmstrahlung
  - Select highest E_T cluster



- "Level-2.5" (pixel only)
  - CAL particles traced back to vertex detector



- "Level-3"
  - Track reconstruction starting with L 2.5 seed & track quality cuts (electrons)
  - High Et cut (photons)

Trigger Menus

Need to address the following questions:

- What to save permanently on mass storage ?
  - Which trigger streams should be created ?
  - What is the bandwidth allocated to each stream ?
  - (Usually the bandwidth depends on the status of the experiment and its physics priorities)
- What selection criteria to apply ?
  - Inclusive triggers (to cover major known or unknown physics channels)
  - Exclusive triggers (to extend the physics potential of certain analyses – say b-physics)
  - Prescaled triggers, triggers for calibration & monitoring

General rule :

Trigger tables should be flexible, extensible (to different luminosities for eg.), and allow the discovery of unexpected physics.

Performance is a key factor too…

CMS HLT "Exercise"

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

CERN-LHCC 2007-021

Focus:

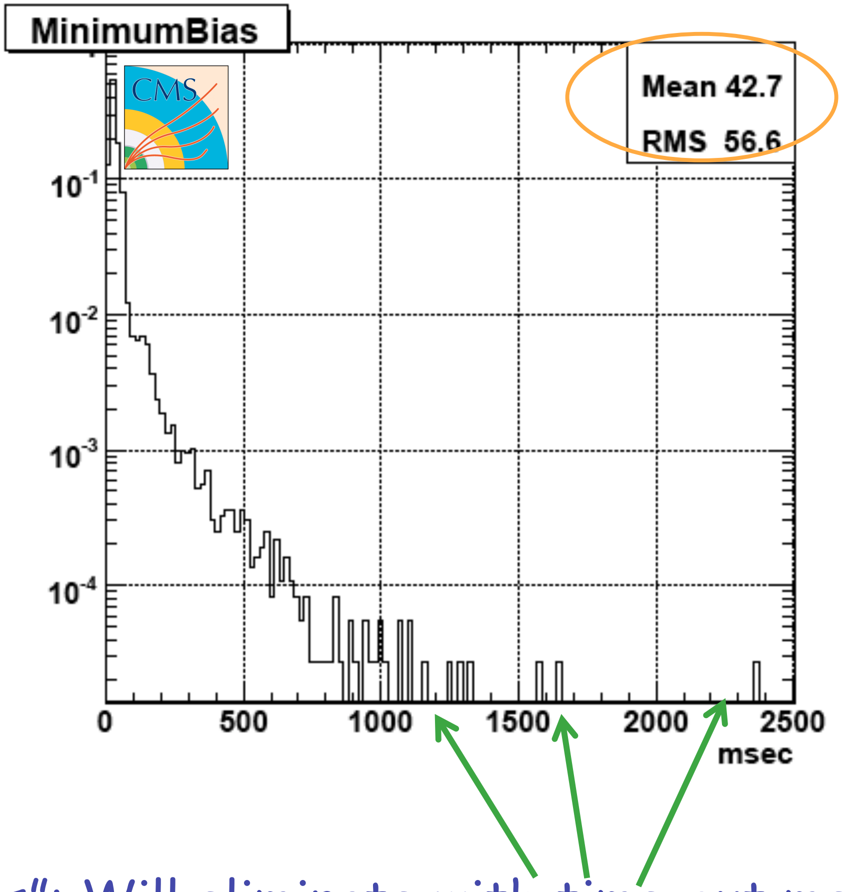
- Compile strawman Trigger Menu that covers CMS needs
- Determine CPU-performance of HLT algorithms
    - Implementation of 2008 physics-run (14 TeV) trigger menu
- (Study motivated by the need to purchase the Filter Farm by end 2007)

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

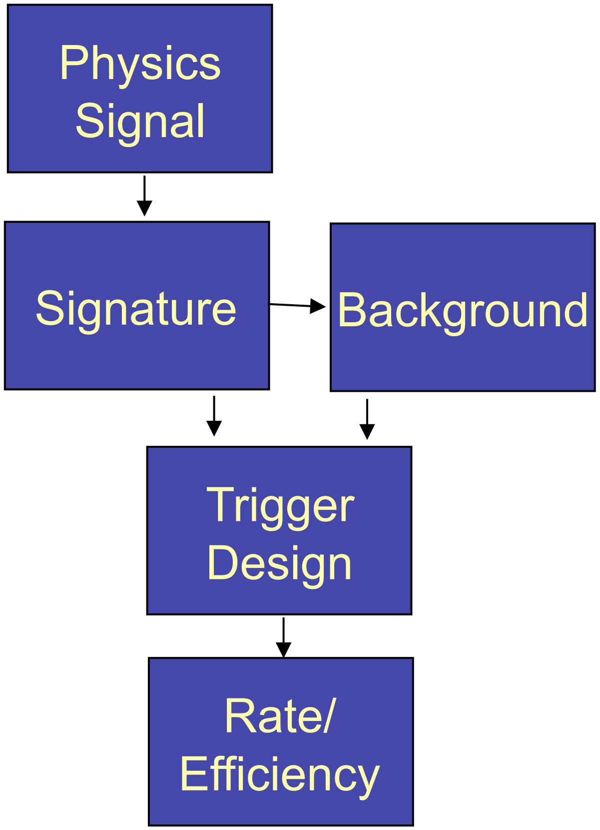
"Tails": Will eliminate with time-out mechanism

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

Triggering on the unexpected

How does one trigger on the unknown ?

General Strategy



Start by looking at various physics signals/signatures…

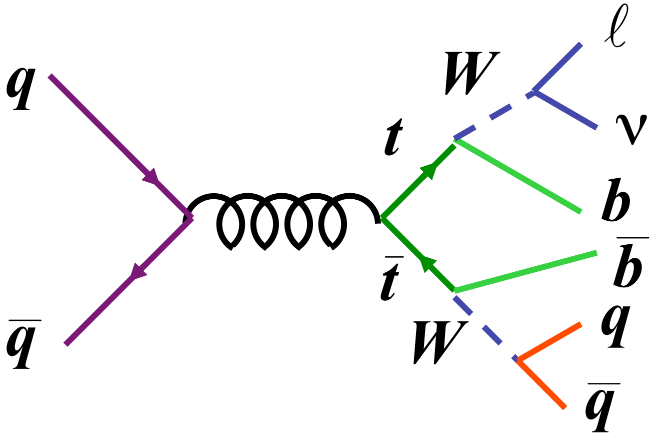
What are the main backgrounds ?

Design a trigger using the above info

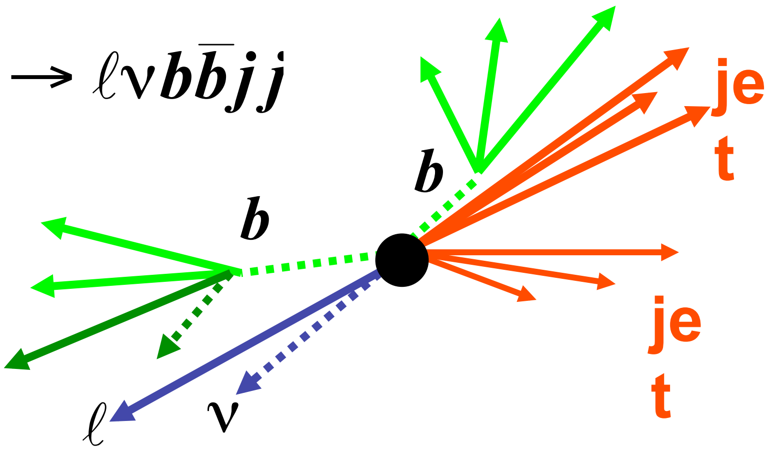
Estimate rates and efficiencies

Recognizing physics

Object	High E_T Leptons	High E_T Jets	Missing E_T	Displ. Vertices
Bgrd QCD	rare	low E	all visible	rare
W/Z	✓	✓	W	—
$p\bar{p} \to b\bar{b}$ $b \to J/\psi K_s$	low E $J/\psi \to l^+l^-$	— —	— —	✓ ✓
Top $t \to bW$	✓	✓	✓	✓
Higgs $pp \to hW/Z$ $h \to bb$	✓	✓	✓	✓
W′	✓	✓	✓	✓

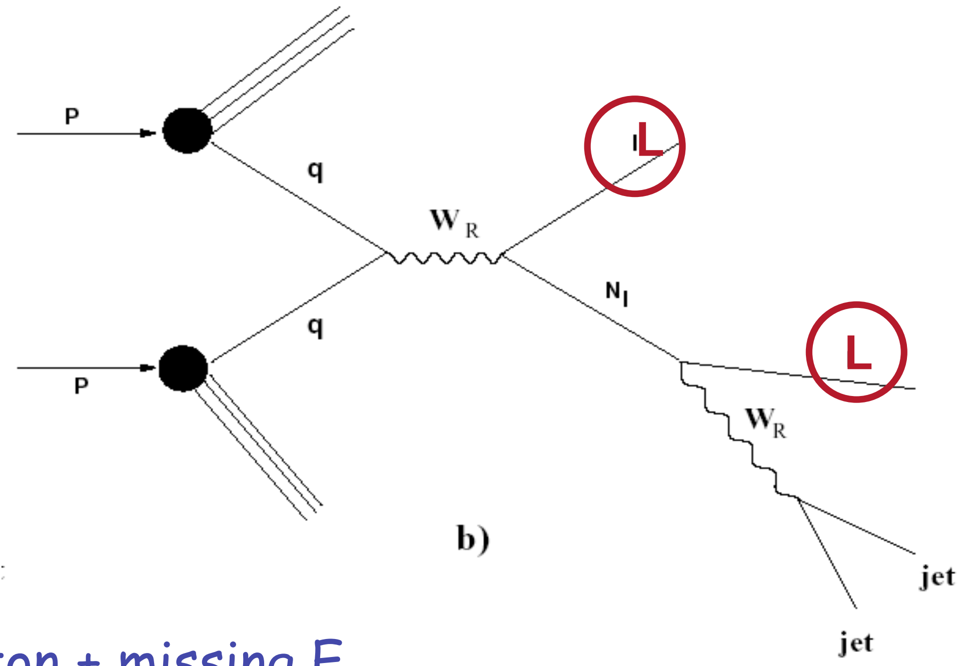


$$p\bar{p} \to t\bar{t} \to \ell\nu b\bar{b}jj$$



“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)



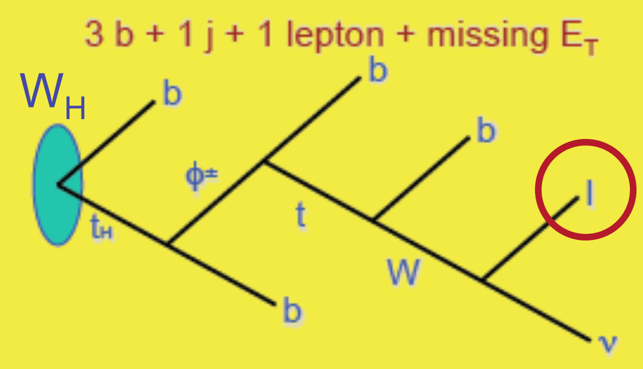
3) Single photon + missing E_T
   - ADD direct graviton emission

"Alternatives" signatures

3) Single lepton + jets/missing ET

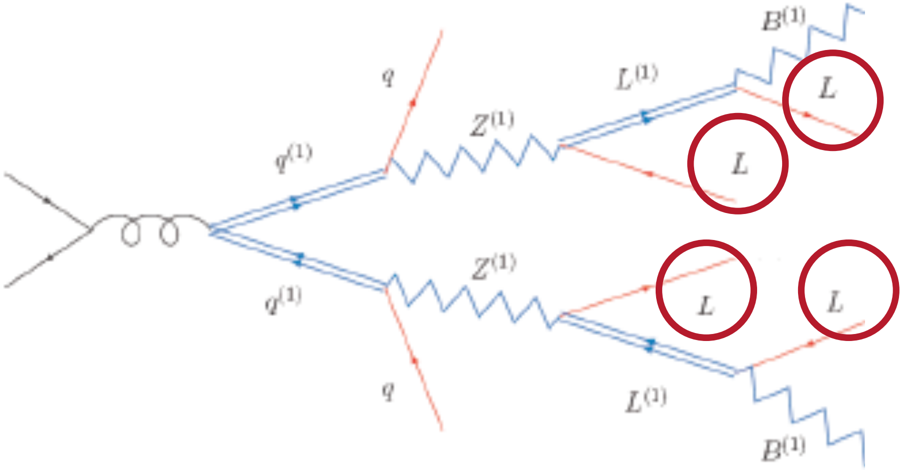
- W' (lepton+ missing ET)
- Twin Higgs (lepton + jets + missing ET)

$W_H \rightarrow t_H\ b$



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

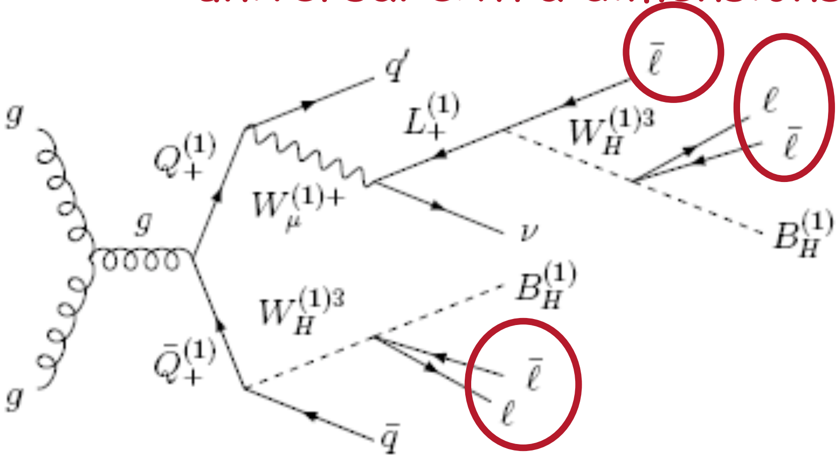
- Technicolor, littlest Higgs, universal extra dimensions

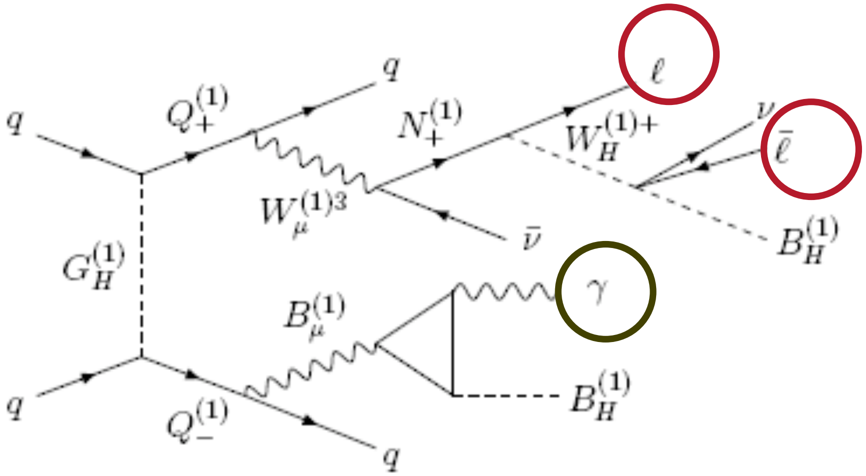


“Alternatives” signatures

4) (b) Multi-leptons + photons

- universal extra dimensions



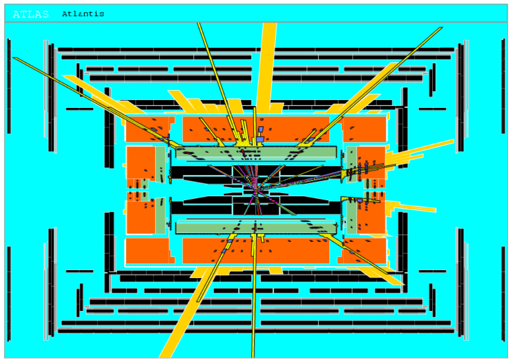


5) Same sign di-leptons

- same-sign top

8) Black Holes

- High multiplicity events, jets/lepton ratio of 5:1

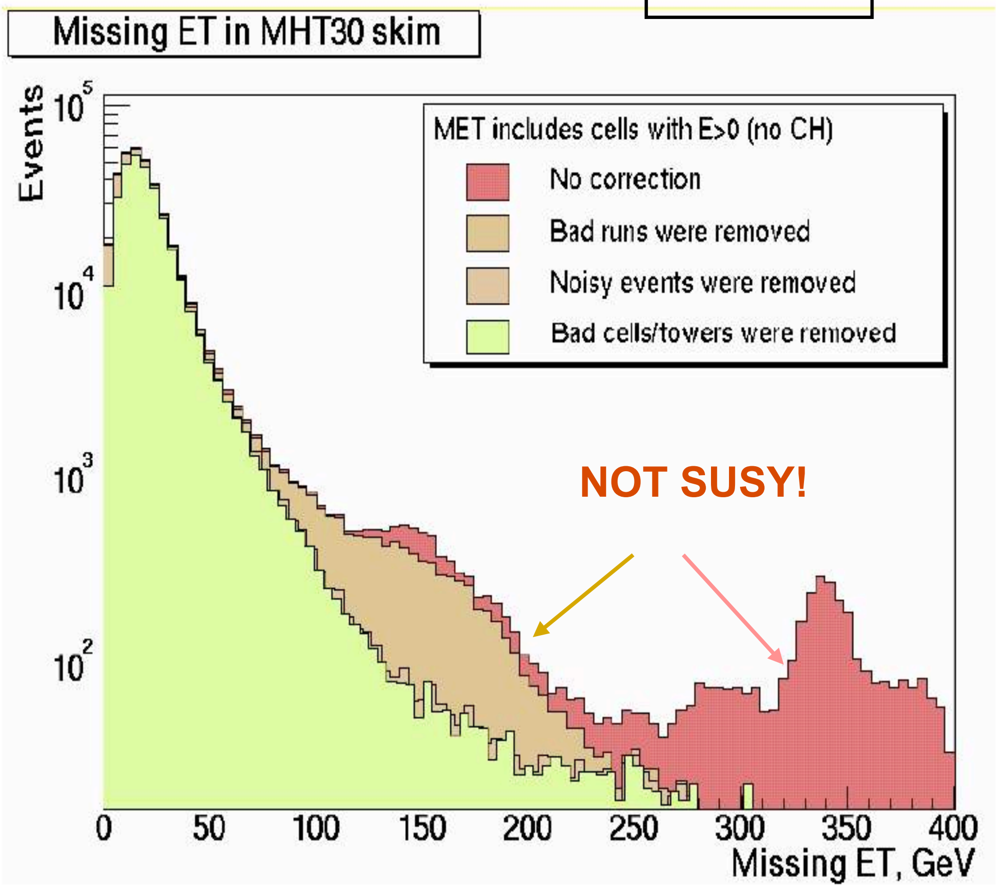


Having robust lepton and jets triggers will be crucial !

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

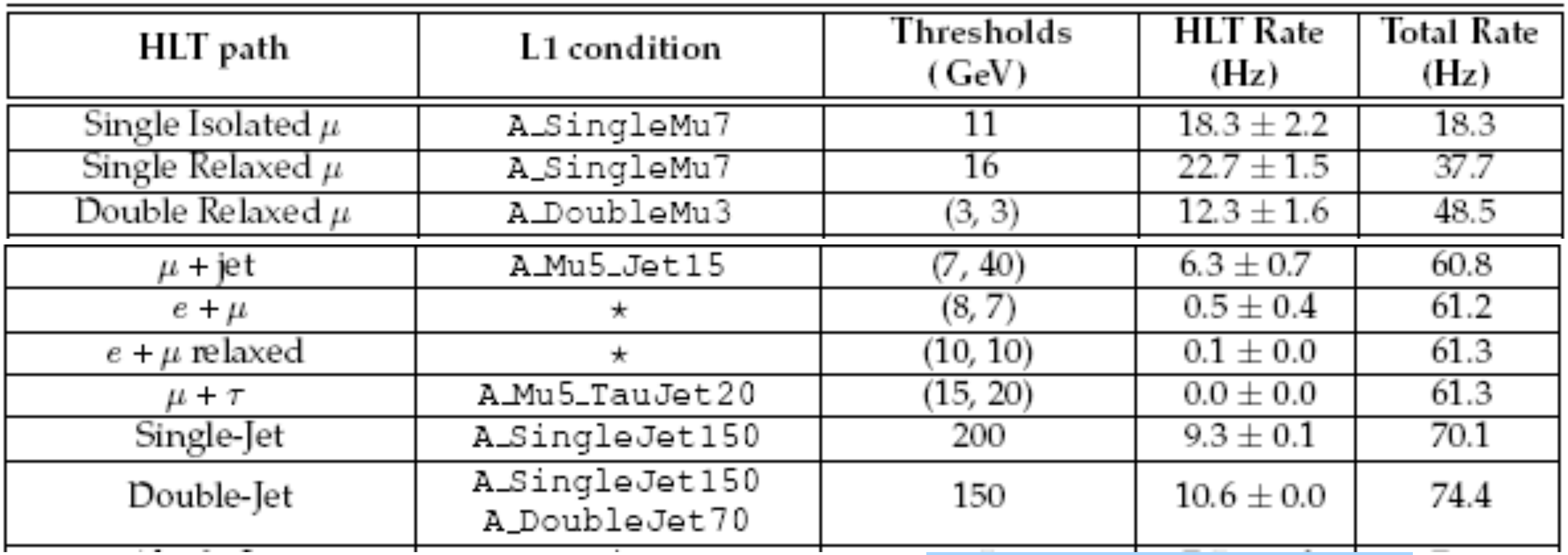
(NOTE:
Many BSM signatures involve 3rd generation particles: b's and τ and also MET
Though challenging, triggers for these need to be commissioned at the same time)

MET at DØ



NOT SUSY!

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
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

"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

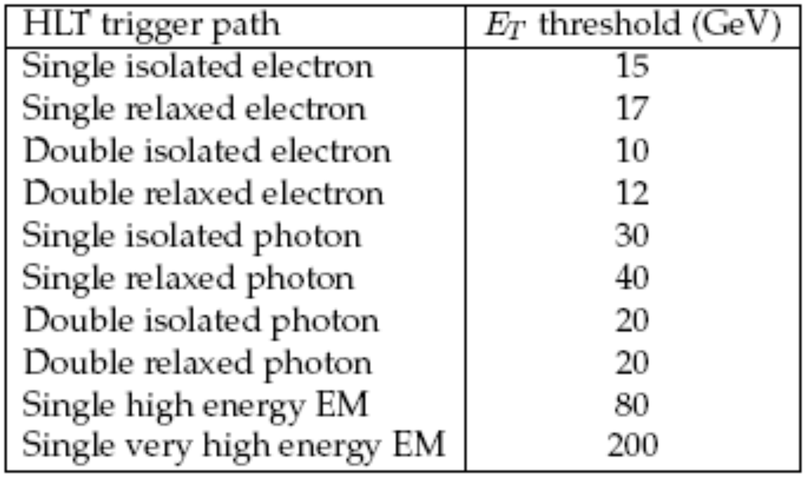
HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
Single Jet Prescale 10	`A_SingleJet100`	150	3.5 ± 0.0	87.9
Single Jet Prescale 100	`A_SingleJet70`	110	1.5 ± 0.0	89.1
Single Jet Prescale 1000	`A_SingleJet30`	60	0.8 ± 0.4	89.9
VBF Double-Jet + $\not\!\!E_T$	`A_ETM30`	(40, 60)	0.2 ± 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

Similar trigger menus are being designed by ATLAS

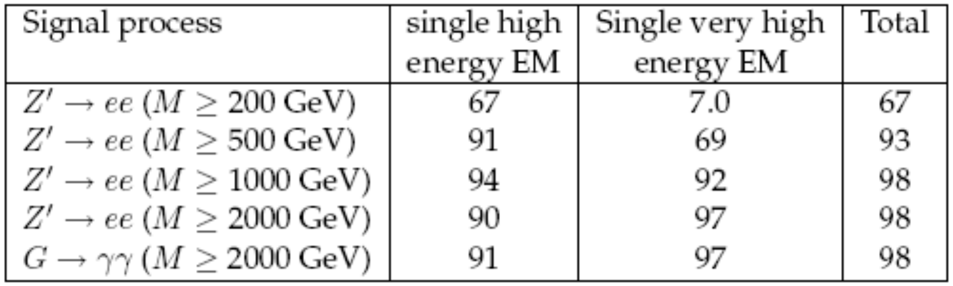
@ $L=10^{32}$ cm^{-2} s^{-1}

Lepton thresholds/efficiencies



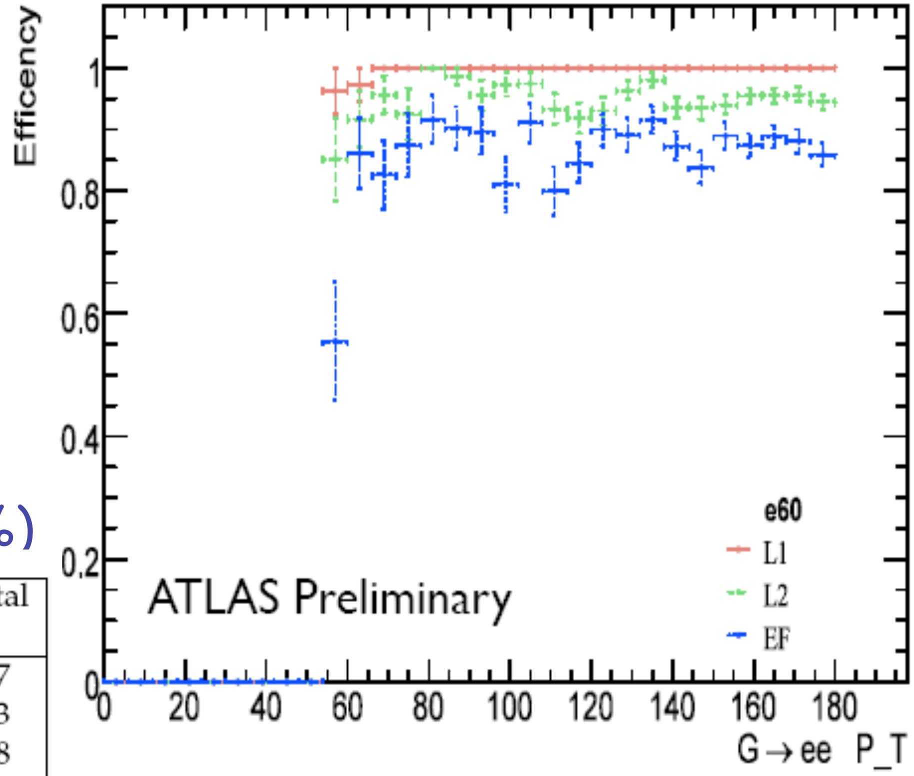
HLT trigger path	E_T threshold (GeV)
Single isolated electron	15
Single relaxed electron	17
Double isolated electron	10
Double relaxed electron	12
Single isolated photon	30
Single relaxed photon	40
Double isolated photon	20
Double relaxed photon	20
Single high energy EM	80
Single very high energy EM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

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

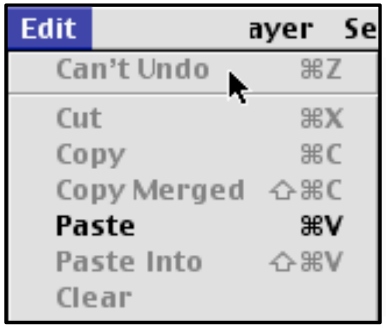


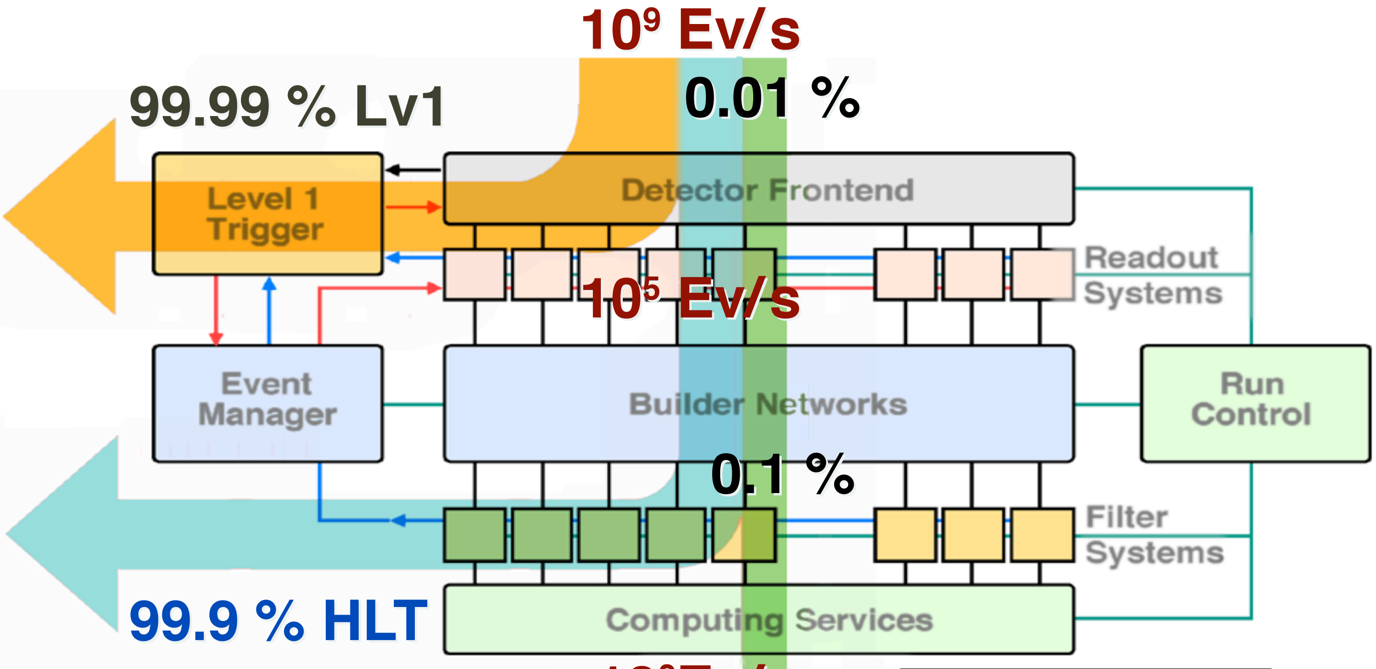
@ $L=10^{31}$ cm^{-2} s^{-1}

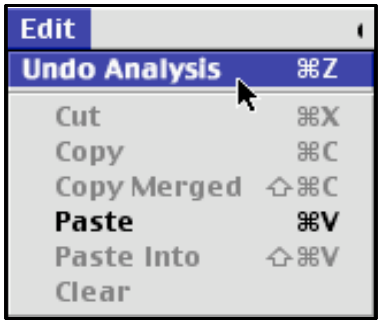
Summary

- Triggering at the LHC is a real challenge
- Sophisticated multi-tiered trigger systems have been designed by ATLAS and CMS
- Trigger menus for early physics runs 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!

Trigger: A tricky business







Will your favorite new physics signal be included in the small fraction of selected events?

Last Resort Trigger

- General trigger strategies work, 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:
  - Electron/photons with large impact parameter resulting in a "funny" cluster profile
  - 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
  - …

Last Resort Trigger

- Proposal:
  - Take advantage of the sequential nature of HLT processing
  - Let individual HLT paths 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 in the path
  - 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…
  - Cuts designed to keep very low output rate (« 1 Hz)
- The LRT could allow 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

BACKUP

Compact Muon Solenoid (CMS) DETECTOR

EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(GeV)} \oplus 0.5\%$

CALORIMETERS

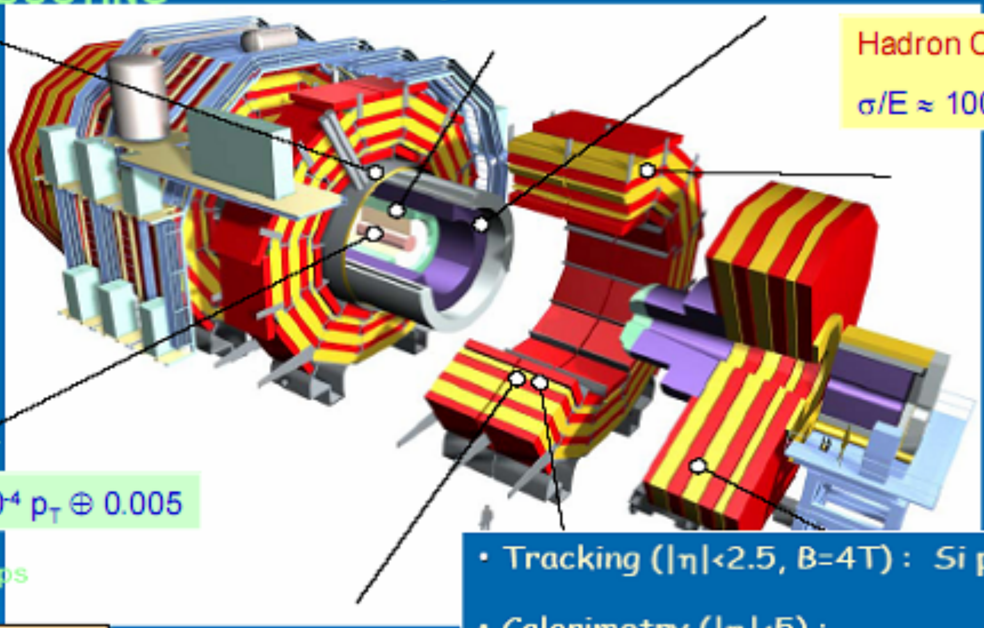
Scintillating PbWO4 crystals

ECAL

HCAL

Plastic scintillator/brass sandwich

SUPERCONDUCTING COIL



Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(GeV)} \oplus 5\%$

IRON YOKE

TRACKER

$\sigma/p_T \approx 1.5 \times 10^{-4}\, p_T \oplus 0.005$

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 ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

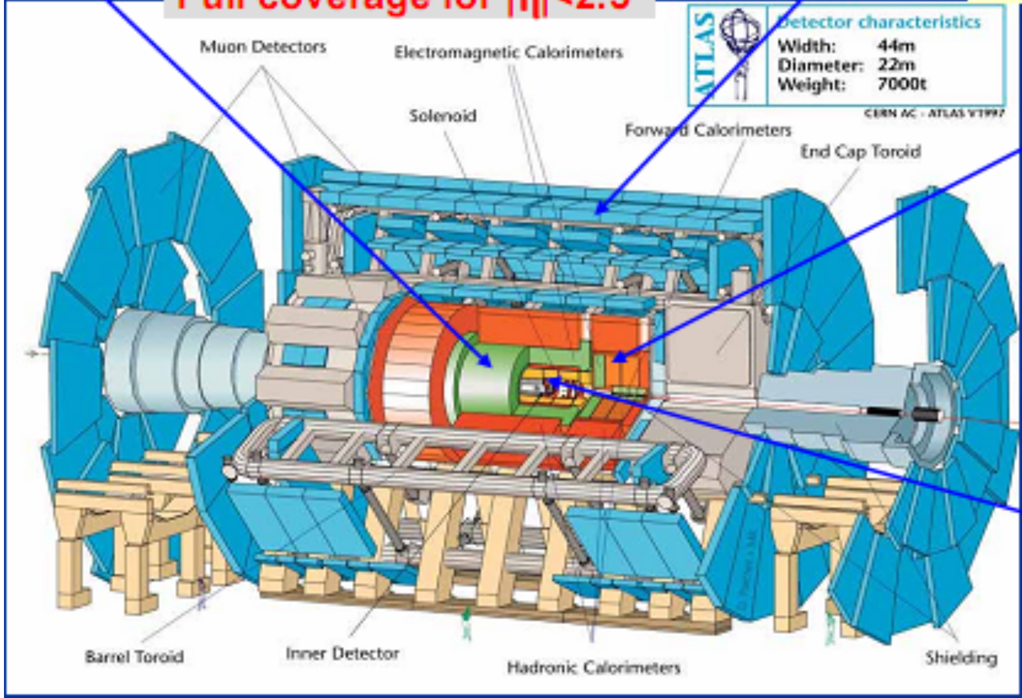
A Toroidal LHC AppartuS (ATLAS) DETECTOR

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

excellent electron/photon identification

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

Full coverage for $|\eta|<2.5$



Precision Muon Spectrometer,

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

Fast response for trigger

Good *p* resolution

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

Hadron Calorimeters,

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

Good jet and E_T miss performance

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

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

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

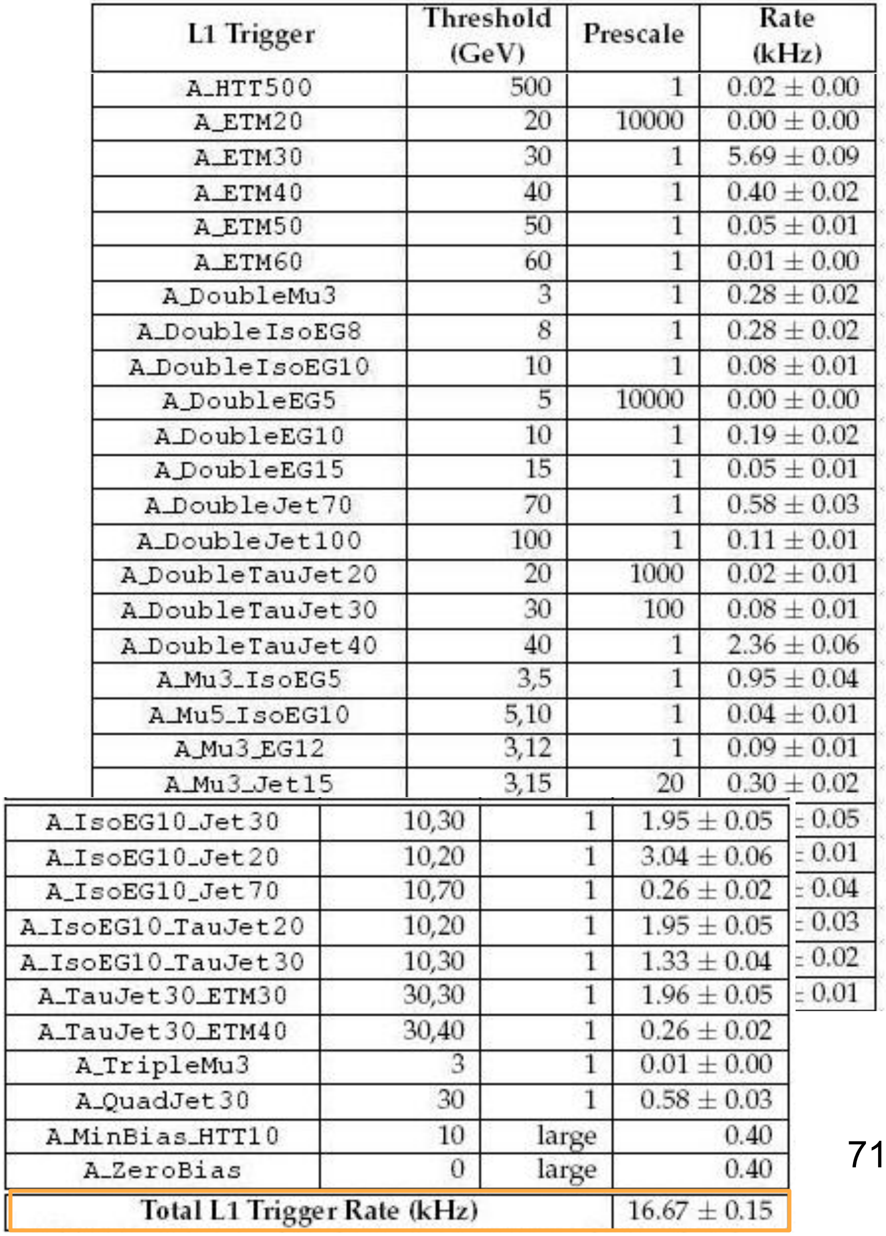
Good impact parameter res.

$\sigma(d_0)=15\mu m@20GeV$ (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
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
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
$J/\psi \to \mu\mu$	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
$b \to \mu$ tag 1-jet Prescale 20	A_Mu5_Jet15	20 $\Delta R(\mu, j) < 0.4$	4.0 ± 0.1	56.1
$b \to \mu$ tag 2-jets	A_Mu5_Jet15	120, $p_T^{\mathrm{rel}}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.5 ± 0.0	56.1
$b \to \mu$ tag 3-jets	A_Mu5_Jet15	70, $p_T^{\mathrm{rel}}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.3 ± 0.0	56.1
$b \to \mu$ tag 4-jets	A_Mu5_Jet15	40, $p_T^{\mathrm{rel}}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	0.4 ± 0.0	56.1
$b \to \mu$ tag H_T	A_HTT250	300, $p_T^{\mathrm{rel}}(\mu) > 0.7$ $\Delta R(\mu, j) < 0.4$	2.6 ± 0.2	56.6
$b \to J/\psi(\mu\mu)$	A_DoubleMu3	(4, 4) $M_{\mu\mu} \in [2.95, 3.25]$	0.7 ± 0.1	56.8
$\mu + b$-jet	A_Mu5_Jet15	(7, 35)	0.1 ± 0.0	56.8
$\mu + b \to \mu$-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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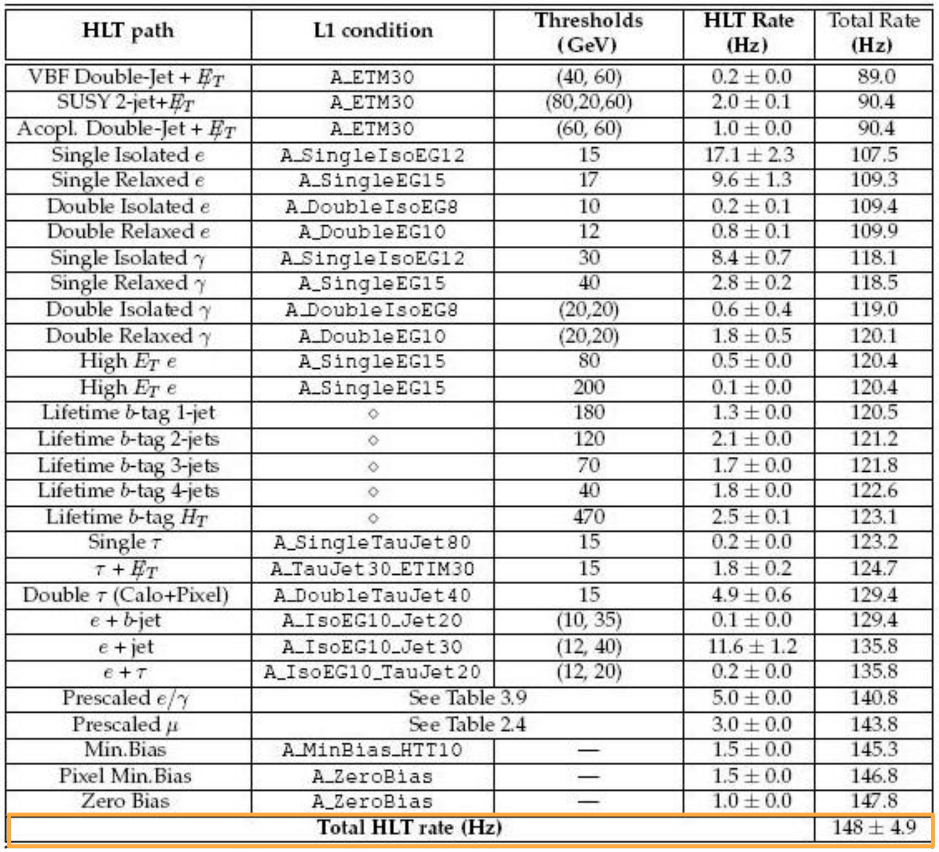
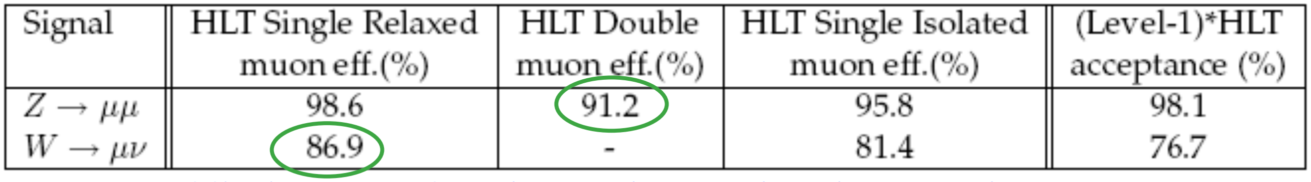


HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
VBF Double-Jet + $\not{E}_T$	A_ETM30	(40, 60)	0.2 ± 0.0	89.0
SUSY 2-jet+$\not{E}_T$	A_ETM30	(80,20,60)	2.0 ± 0.1	90.4
Acopl. Double-Jet + $\not{E}_T$	A_ETM30	(60, 60)	1.0 ± 0.0	90.4
Single Isolated e	A_SingleIsoEG12	15	17.1 ± 2.3	107.5
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
$\tau + \not{E}_T$	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

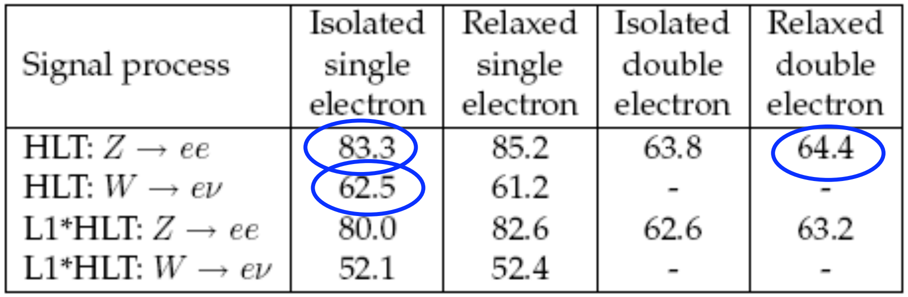
CMS Trigger Efficiencies



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

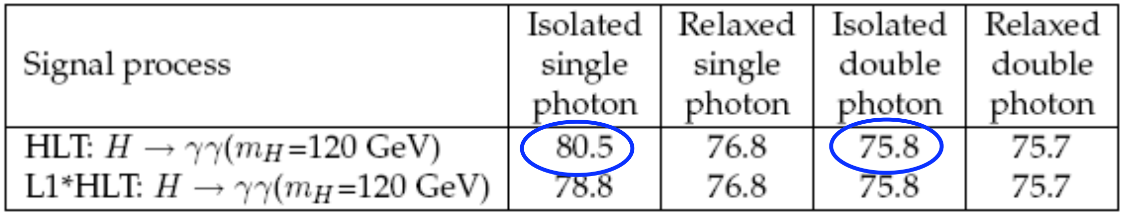
Muons

HLT efficiency for benchmark channels



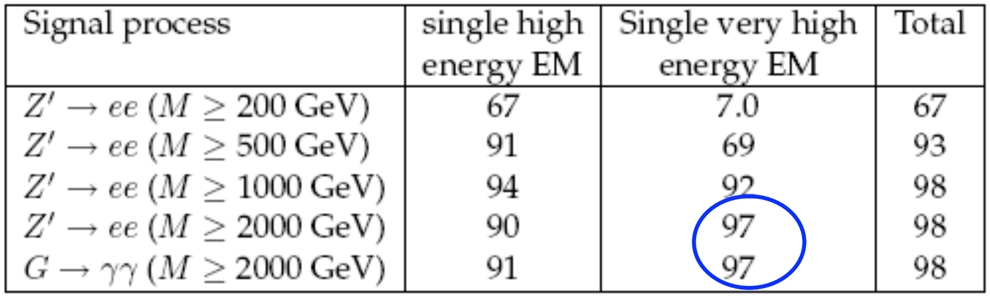
Signal process	Isolated single electron	Relaxed single electron	Isolated double electron	Relaxed double electron
HLT: $Z \to ee$	83.3	85.2	63.8	64.4
HLT: $W \to e\nu$	62.5	61.2	-	-
L1*HLT: $Z \to ee$	80.0	82.6	62.6	63.2
L1*HLT: $W \to e\nu$	52.1	52.4	-	-

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

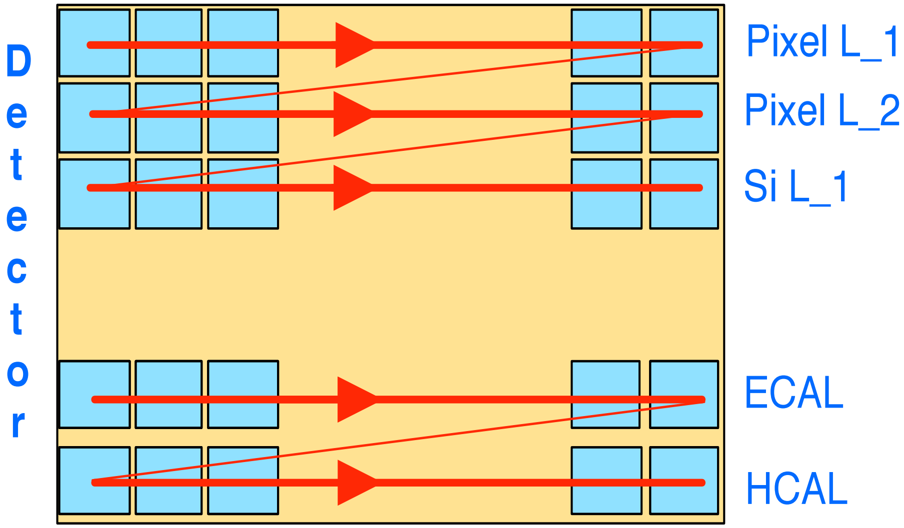


Signal process	single high energy EM	Single very high energy EM	Total
$Z' \to ee$ ($M \geq 200$ GeV)	67	7.0	67
$Z' \to ee$ ($M \geq 500$ GeV)	91	69	93
$Z' \to ee$ ($M \geq 1000$ GeV)	94	92	98
$Z' \to ee$ ($M \geq 2000$ GeV)	90	97	98
$G \to \gamma\gamma$ ($M \geq 2000$ GeV)	91	97	98

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

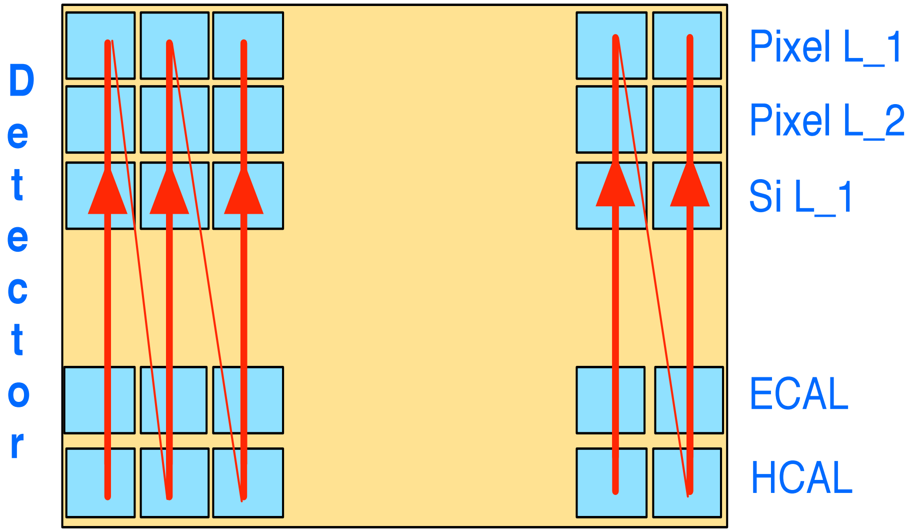
Good *W/Z* efficiencies
for muon, egamma HLT

Global or Regional



Global

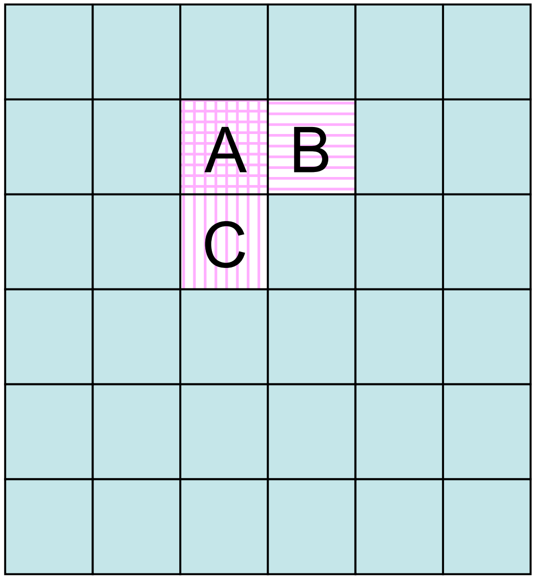
- process (e.g. DIGI to RHITs) each detector fully
- then link detectors
- then make physics objects



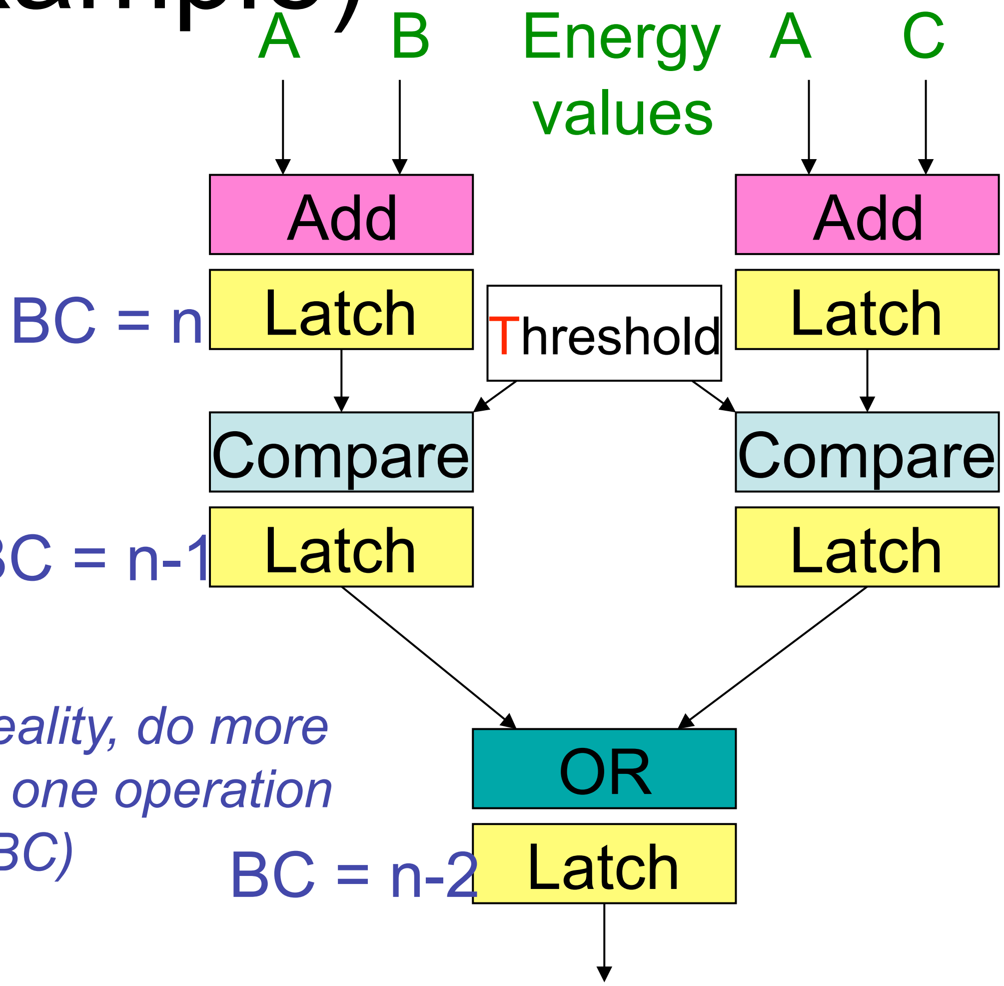
Regional

- process (e.g. DIGI to RHITs) each detector on a "need" basis
- link detectors as one goes along
- physics objects: same

Pipelined LVL1 trigger (example)



EM Calorimeter
(~3500 trigger towers)



A B Energy values A C

Add

Add

BC = n

Latch

Threshold

Latch

Compare

Compare

BC = n-1

Latch

Latch

OR

BC = n-2

Latch

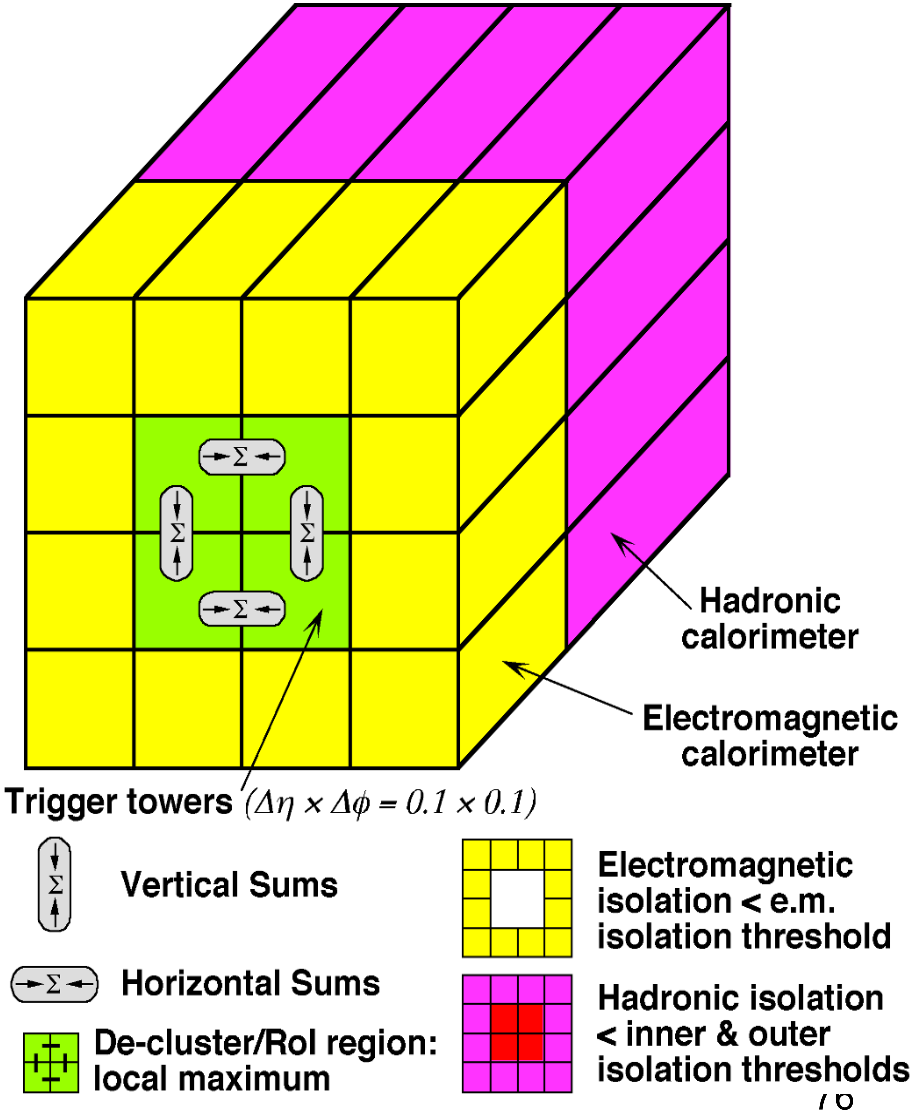
Output

(In reality, do more than one operation per BC)

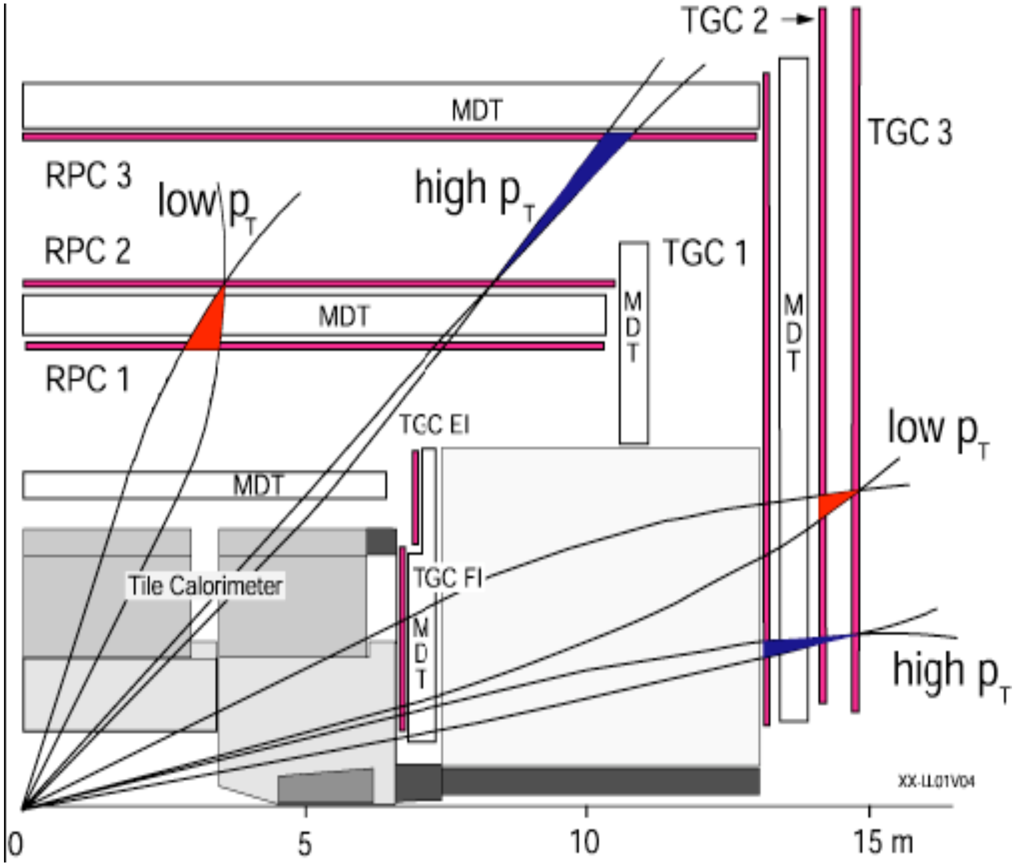
Output = (A+B)>T <u>OR</u> (A+C)>T

ATLAS e/γ trigger

- ATLAS e/g trigger is based on 4×4 “overlapping, sliding windows” of trigger towers
  - Each trigger tower 0.1×0.1 in h×f
    - h pseudo-rapidity, f azimuth
  - ~3500 such towers in each of the EM and hadronic calorimeters
- There are ~3500 such windows
  - Each tower participates in calculations for 16 windows
    - This is a driving factor in the trigger design



ATLAS LVL1 μ trigger



- ATLAS LVL1 μ trigger is based on coincidences among hits within “window” in layers of RPCs (TGCs). Window size determines p_T threshold.
  - Low p_T trigger use inner 2 layers (3 thresholds)
  - High p_T trigger use outer 2 layers (+ low p_T trigger) (3 thresholds)