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Triggering @ LHC

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Introduction

[1]trig·ger *noun* \'tri-gər\

Merriam-Webster

Definition of TRIGGER

1 **a :** a piece (as a lever) connected with a catch or detent as a means of releasing it; *especially* **:** the part of the action moved by the finger to fire a gun

b : a similar movable part by which a mechanism is actuated <*trigger* of a spray gun>

2 **:** something that acts like a mechanical trigger in initiating a process or reaction

?

— **trigger** *adjective*

— **trig·gered** *adjective*

Origin of TRIGGER

alteration of earlier *tricker*, from Dutch *trekker*, from Middle Dutch *trecker* one that pulls, from *trecken* to pull — more at TREK

First Known Use: 1621

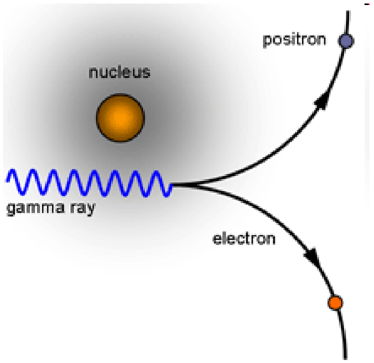
Triggering @ LHC

Challenge

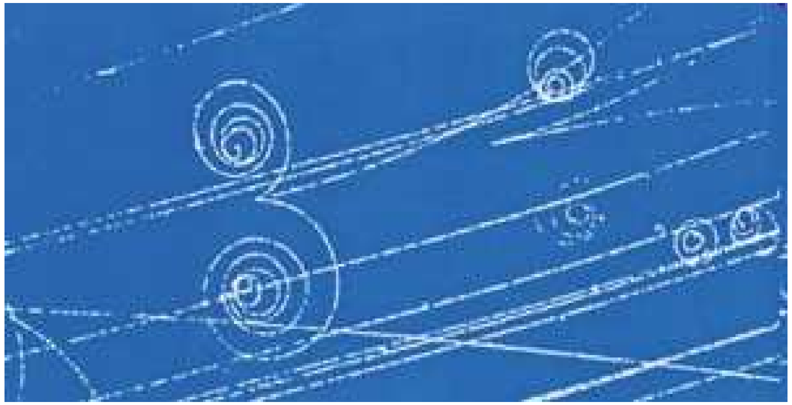
Implementation

Efficiencies

In Former Times



bubble chamber analysis

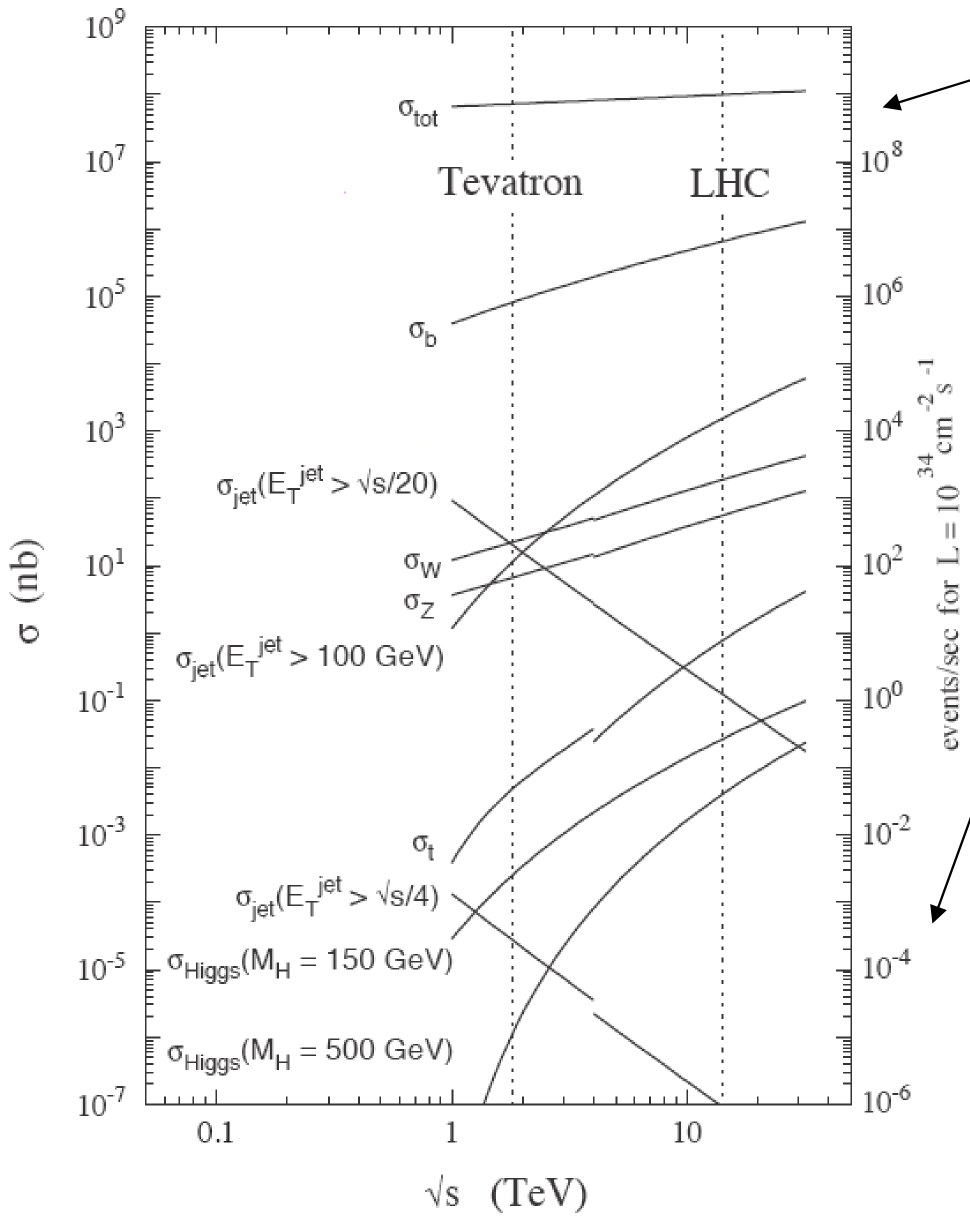


CERN PhotoLab

- Data acquisition (DAQ) was made by means of photographs
- Basically no first level trigger, later electronic signals used to trigger the camera
- Dead time during picture processing
- High-level trigger realised in human scanning teams

→ Slow operation rate, only most common processes accessible

What Is Different Today?



Most of the time we are here

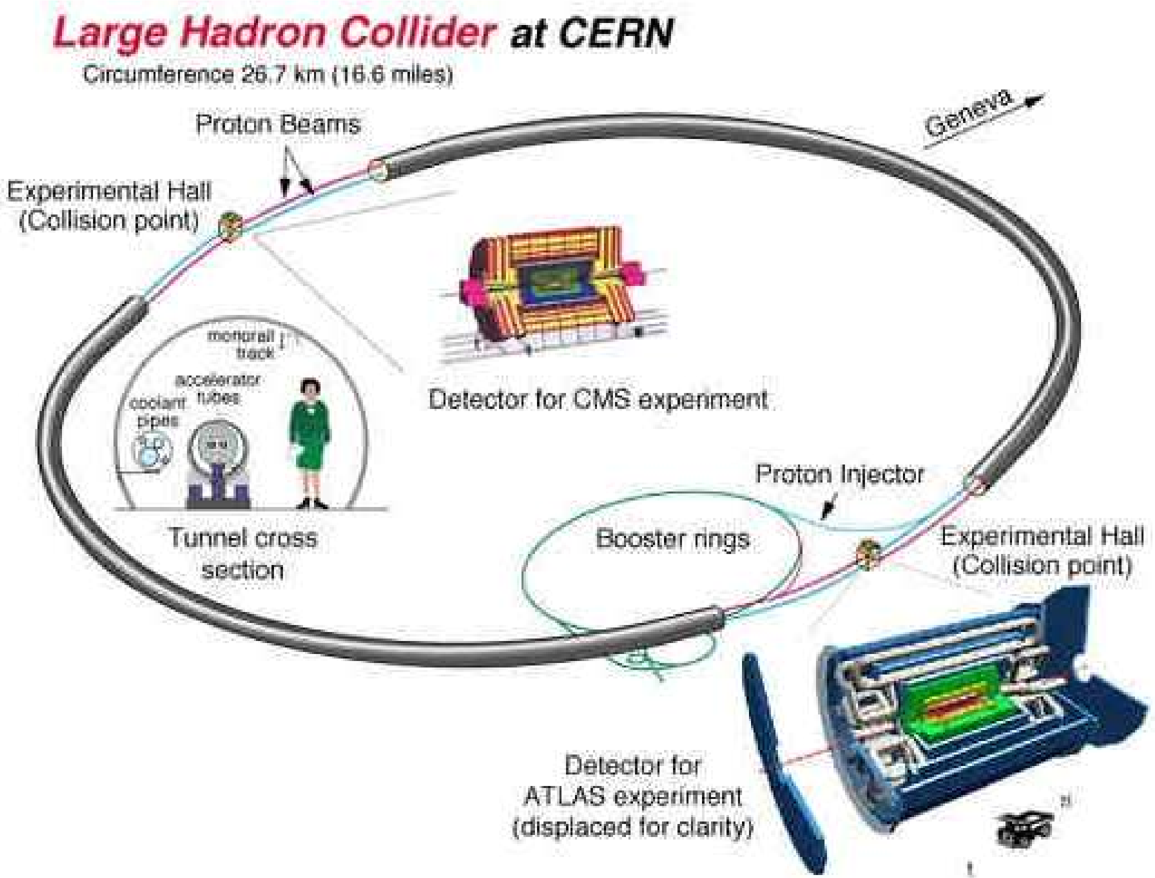
But here it gets really exciting!

During one LHC second
(at design luminosity)

- ~10^9 pp interactions
- ~10^3 W events
- ~500 Z events
- ~10 top events
- ~9 SUSY events (?)
- ~0.1 Higgs events (?)

→ But only 200 can be recorded!

The Discovery Machine



Large Hadron Collider LHC

Most powerful particle accelerator ever built

pp collisions at $\sqrt{s}$=14 TeV
(7 times higher than Tevatron)

Luminosity of $10^{34}cm^{-2}s^{-1}$
(100 times higher than Tevatron)

What does this actually mean?

LHC Luminosity

High instantaneous luminosity …

- increases available kinematic range (effective centre-of-mass energy depends on parton energy distribution in proton)
- is required to search for rare events

$$L = k\, N^2 f_R / (4\pi\, \sigma_x^* \sigma_y^*)$$

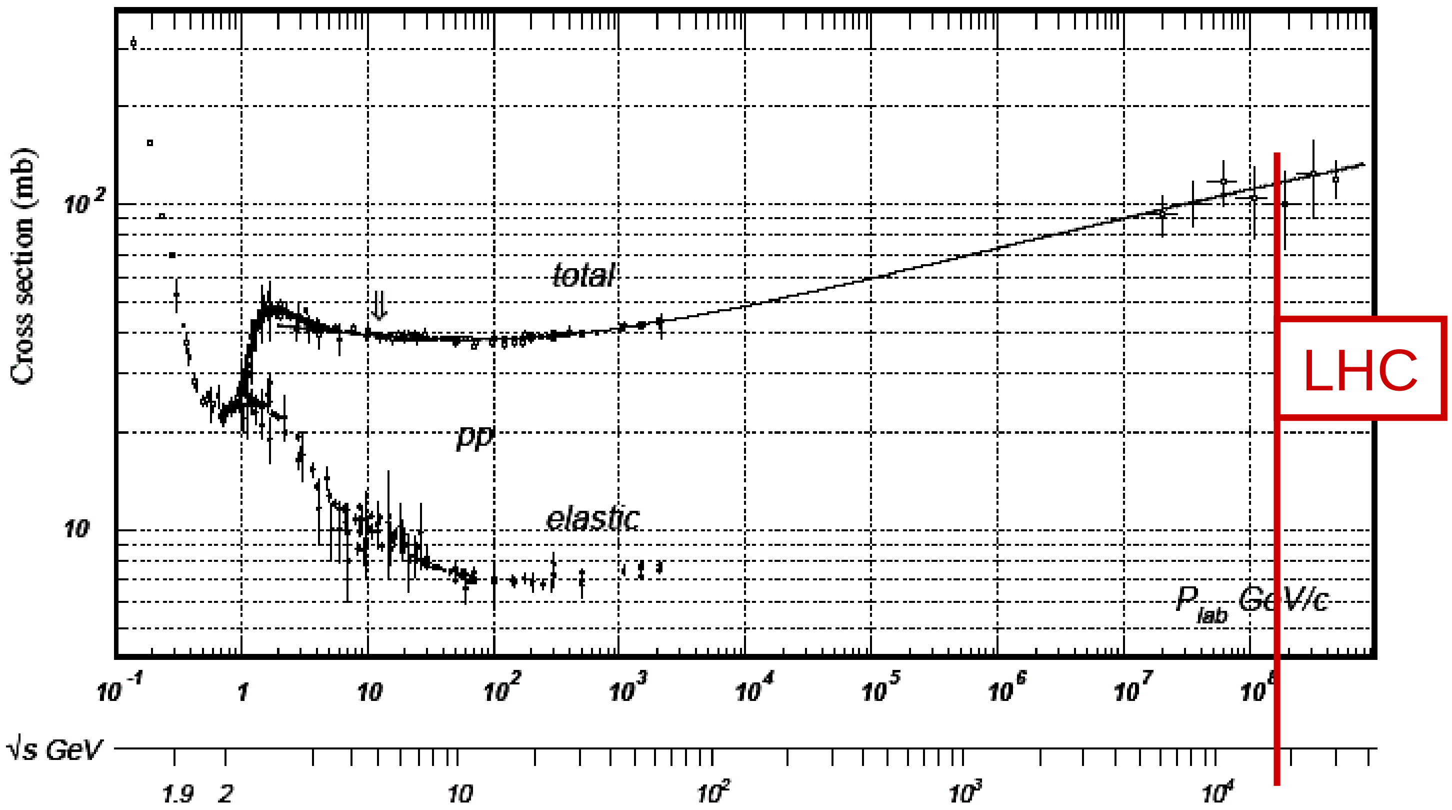
f_R = 11.25 kHz LHC revolution frequency
→ ring circumference / speed of light

LHC Machine Parameters		
Beam energy	E	7.0 TeV
Dipole magnetic field	B	8.4 T
Luminosity	L	10^{34} cm^{-2} s^{-1}
Injection energy	E_i	450 GeV
Circulating current/beam	I_{beam}	0.53 A
Number of bunches	k_b	2835
Time between bunches	τ_b	24.95 ns
Protons per bunch	n_b	1.05×10^{11}
Stored beam energy	E_s	334 MJ
r.m.s. beam radius at intersection point	σ^*	16 μm
Crossing angle	ϕ	200 μrad
Number of events per crossing	n_c	19
Beam lifetime	τ_{beam}	22 h
Luminosity lifetime	τ_L	10 h

… and requires …

- small transverse beam size of typically $\sigma_x^*=\sigma_y^*=16$ μm at 7 TeV
- dense proton bunches containing up to $N=10^{11}$ protons per bunch
- as many LHC bunches filled with protons as possible (k_{max}=2808 out of 3564), spaced by 25 ns from each other, corresponding to 7.5m
→ 40 MHz LHC bunch crossing rate

Event Rates



$$L * \sigma_{inel} = f = f_{BC} * \mu$$

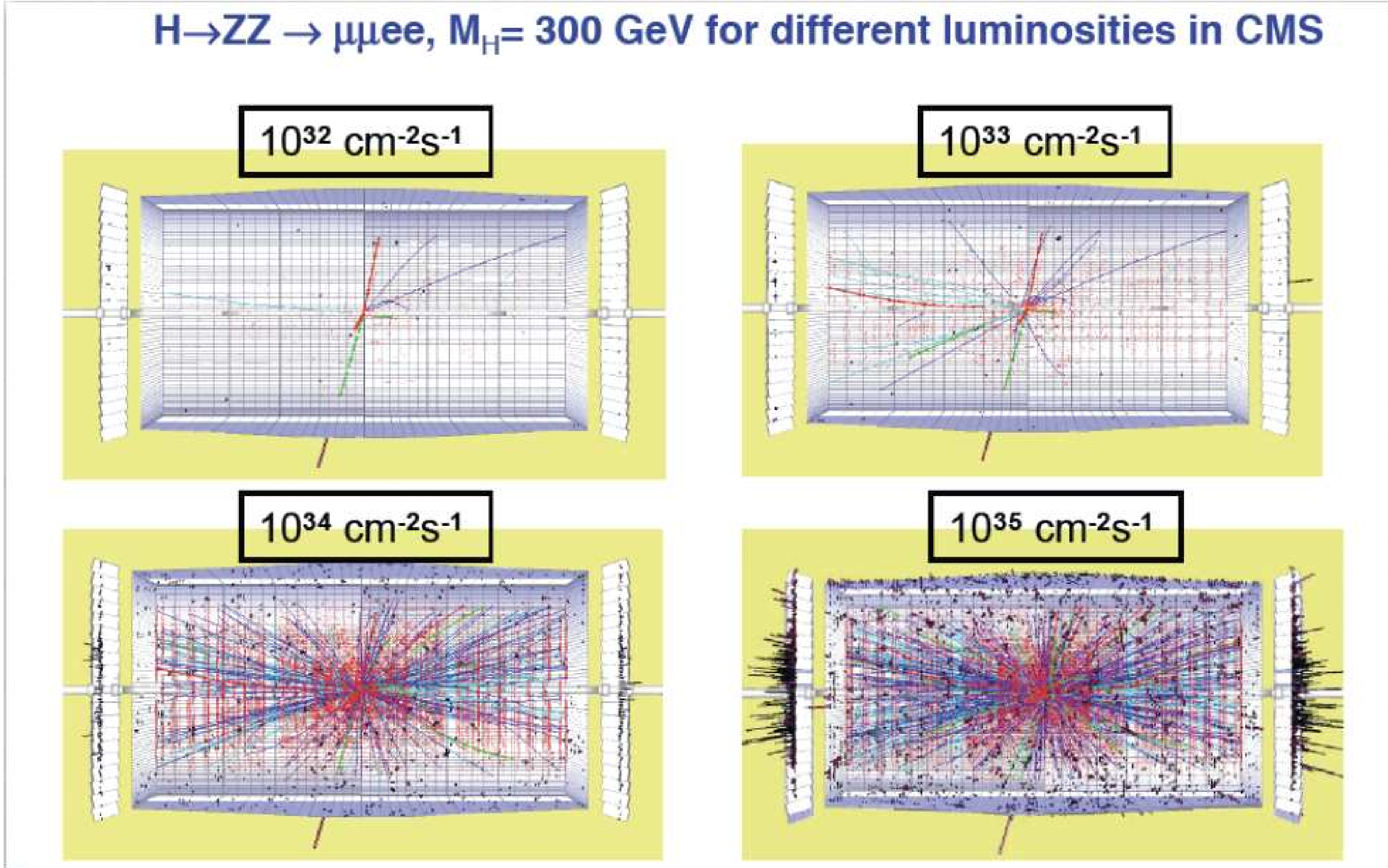
$\rightarrow \mu > 20$ events per BC

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

$\sigma_{inel} \sim 70$ mb

$f_{BC} = k\, f_R = 40$ MHz * 2808/3564

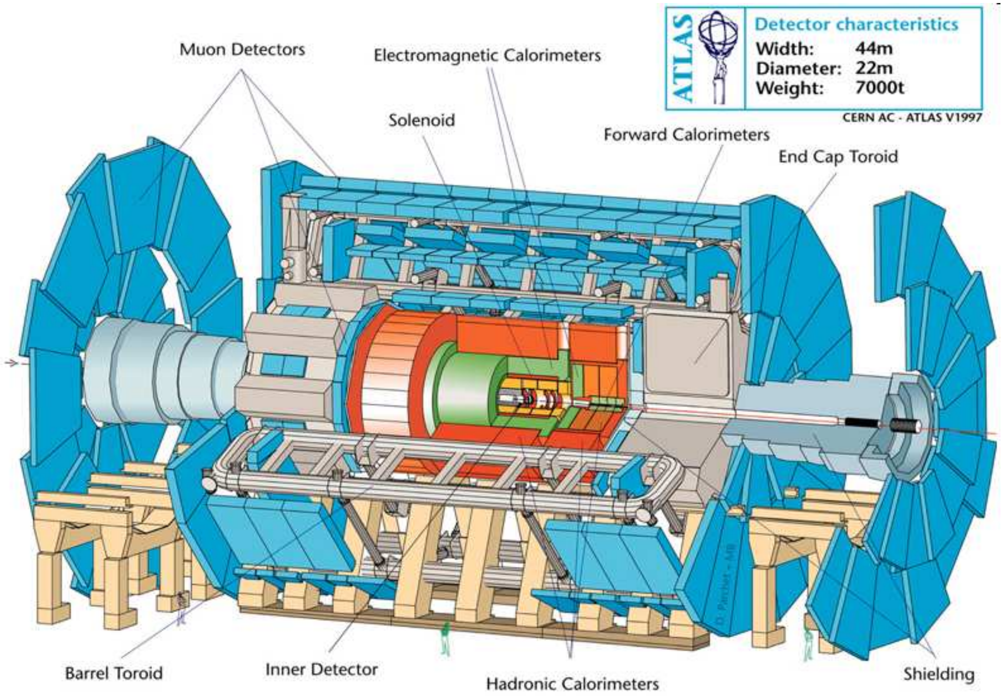
Event Multiplicities

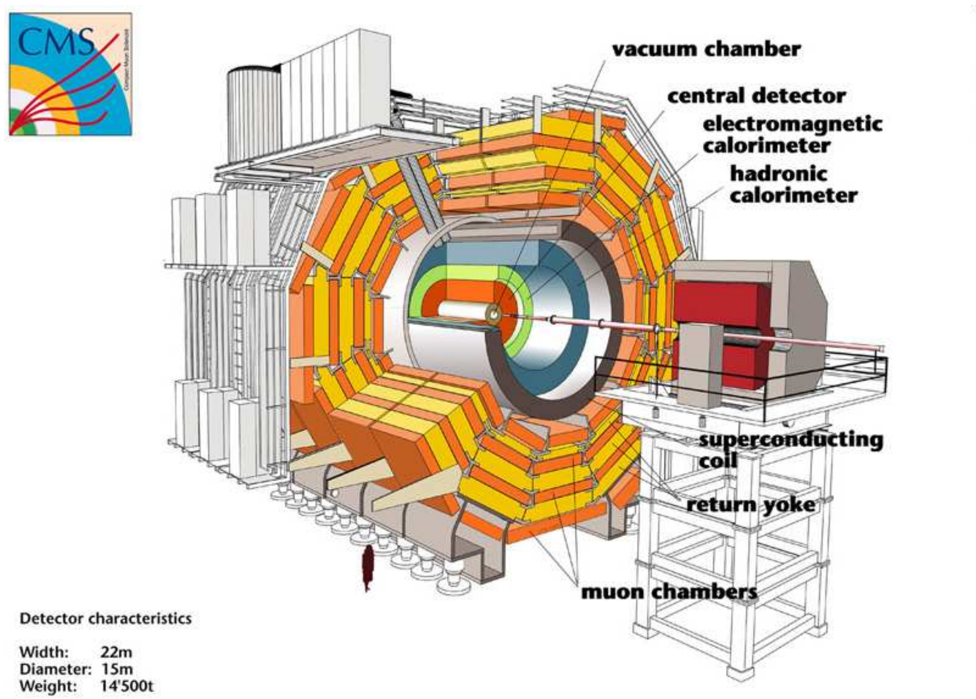


~20 minimum bias events piling up per BC → ~1700 charged particles per event

And where's the Higgs?

Another Constraint: Event Size





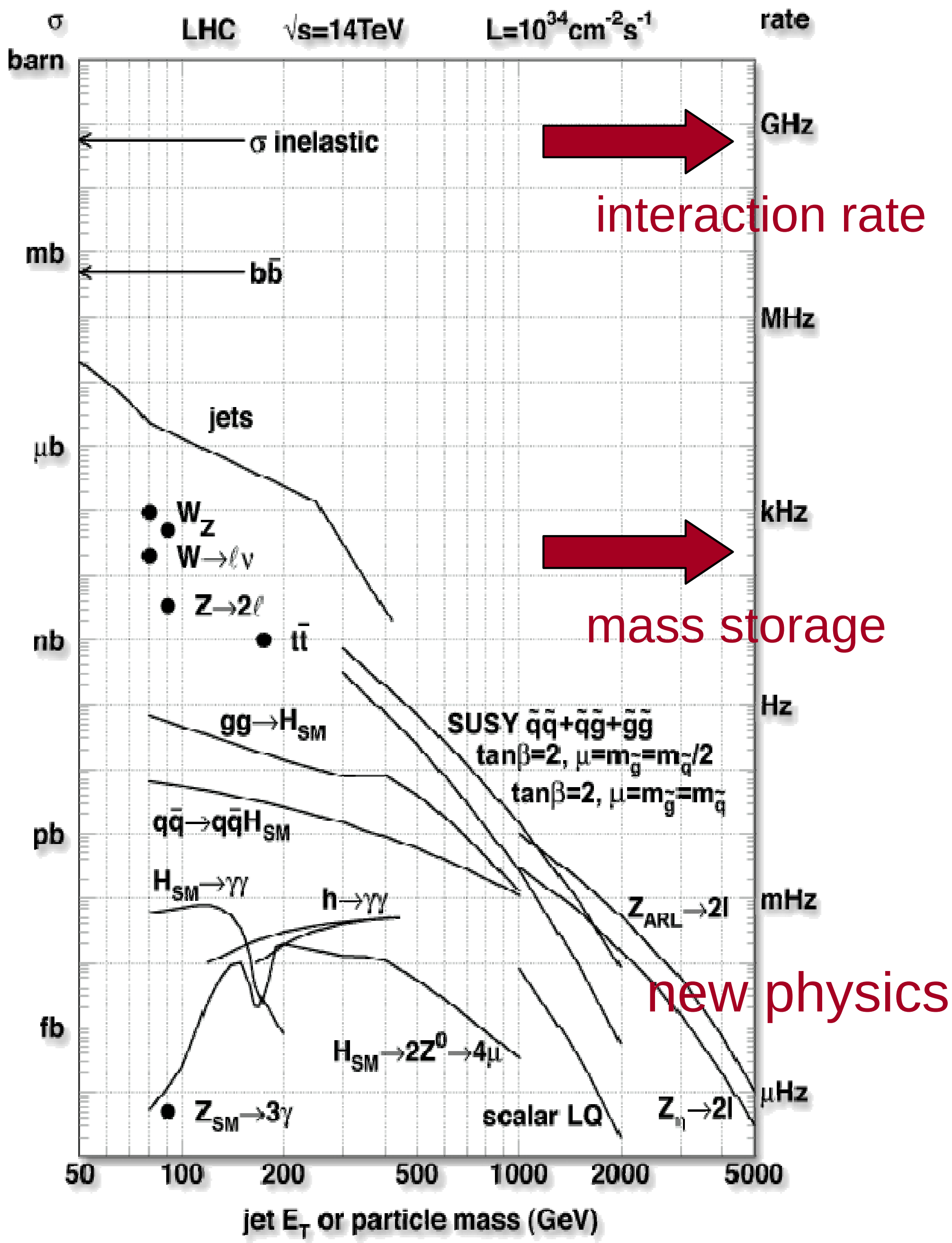
- Pile-up and sufficient precision
  → high resolution, small granularity
- Approx. 100 million readout channels
- Affordable mass storage ~ 300 MB/s

→ Storage rate < 200 Hz

Recorded	per event	per year
raw data	1.6 Mbytes	3 200 Tbytes
reconstructed data	1 Mbytes	2 000 Tbytes
physics data	0.1 Mbytes	200 Tbytes

(A terabyte is a million megabytes)

The Challenge



LHC 40 MHz bunch crossing rate

Pile-Up of 23 events

Interaction rate of ~1 GHZ

↓

Mass storage rate ~200 Hz

→ **Powerful trigger needed!**

Rate reduction by ~10^7

→ Highly selective while remaining efficient for rare events

New physics

→ Inclusive and fast (“searching”), minimisation of dead time

Large event size

→ Powerful network and computing resources

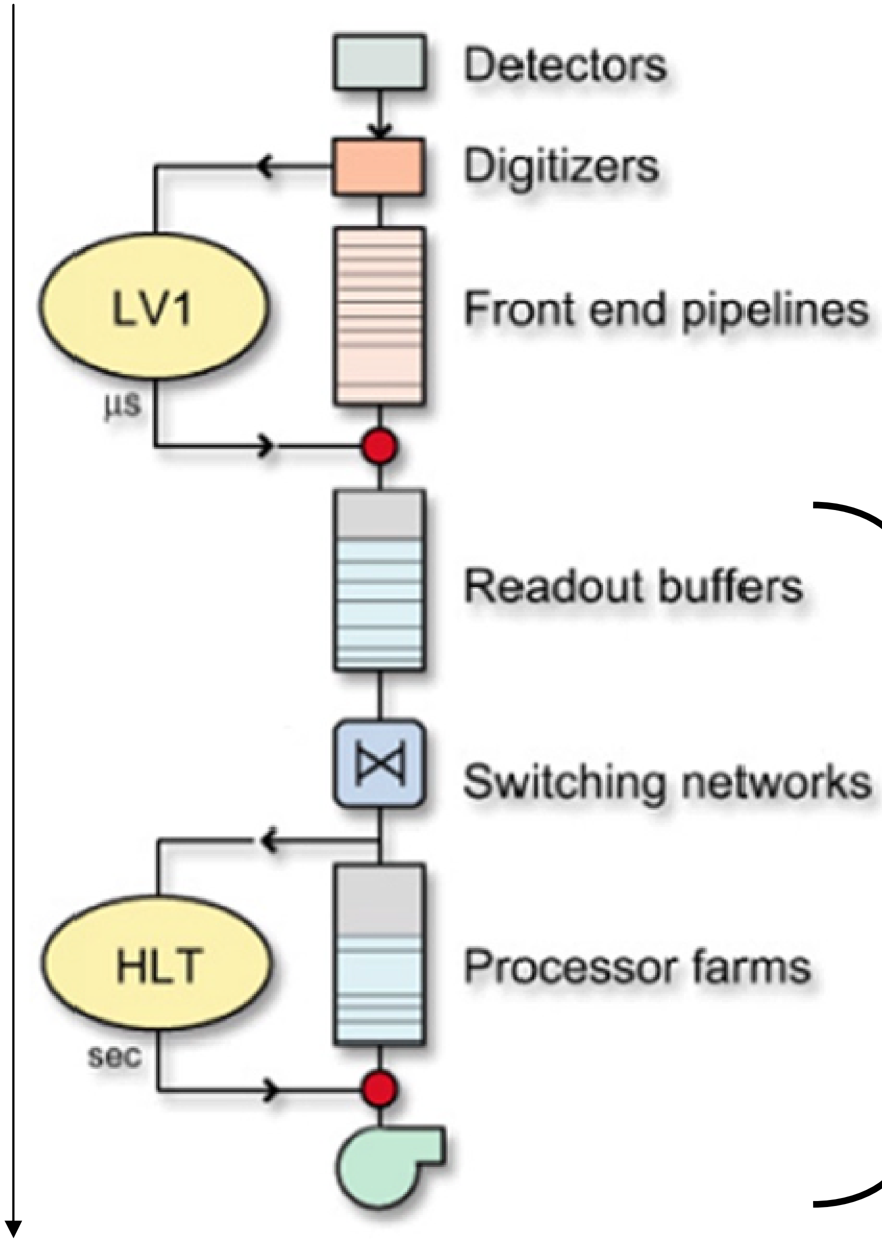
Trigger Concept

LVL1 Trigger

40 MHz
clock based
custom design
decision O(µs)

High Level Trigger

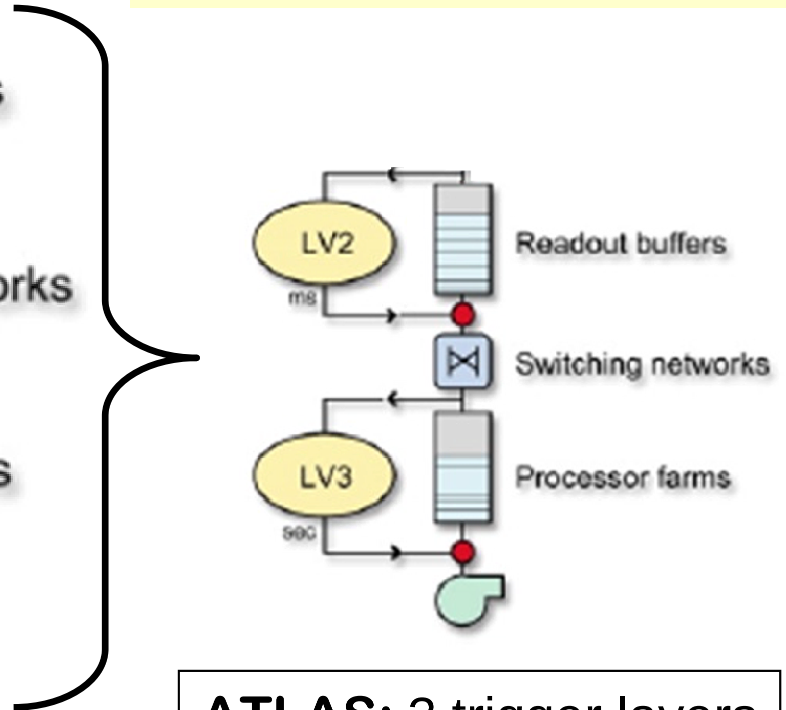
100 kHz
offline code
event driven
PC network
decision O(s)



Several trigger levels with increasing complexity

LVL1: Short latency, high efficiency

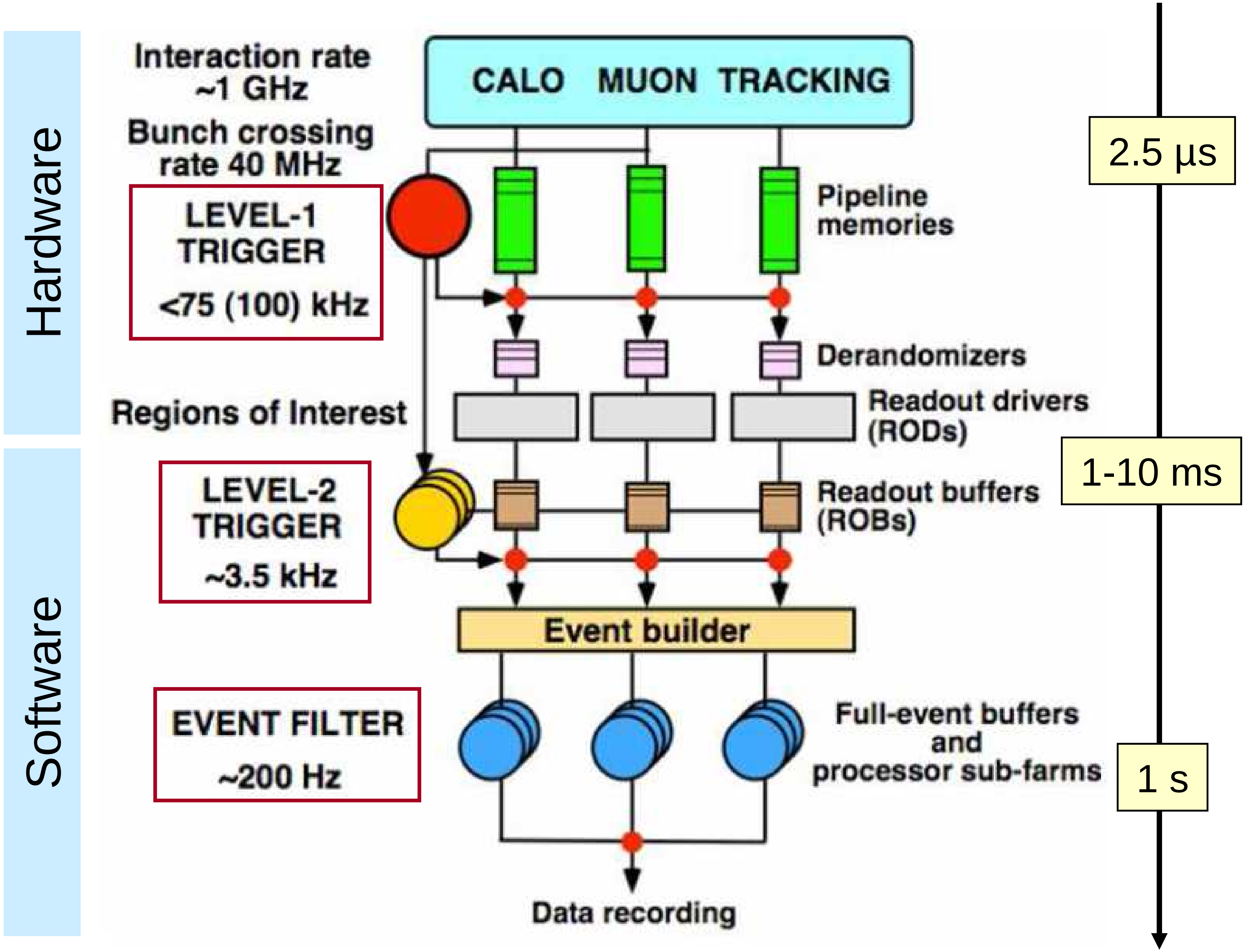
HLT: Fine grained selection and rejection



ATLAS: 3 trigger layers

ATLAS Trigger Overview

Three trigger layers



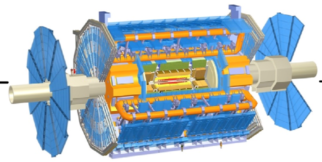
LVL1: Mainly calorimeter and muon data with reduced granularity

LVL2: “Regions of Interest” RoI data with full granularity from selected sub-detectors

EF: Refined selection based on full event readout

ATLAS Level-1 Trigger

Calorimeters



Muon Trigger Chambers

~7200 calorimeter trigger towers

O(1M) RPC/TGC channels

Calorimeter trigger

Pre-processor
(analogue ~ E_T)

Jet / Energy-sum Processor

Cluster Processor
(e/γ, τ/h)

3xJ5, … , XE15, … , TE10, …

TAU5, … , EM3, …

Muon trigger

Muon Barrel Trigger

Muon End-cap Trigger

Muon central trigger processor

MU0, …

e/γ, tau, jet,
ETsum, ETmiss

Design all digital, except input stage of calorimeter trigger Pre-processor

Central Trigger Processor (CTP)

Total 256 L1 trigger items describing object multiplicities above thresholds

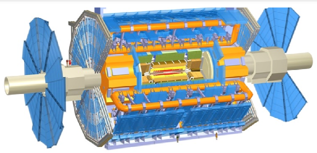
Local Trigger Processors (LTP)

Timing, Trigger, Control (TTC)

Latency limit: 2.5 μs

= 100 BC

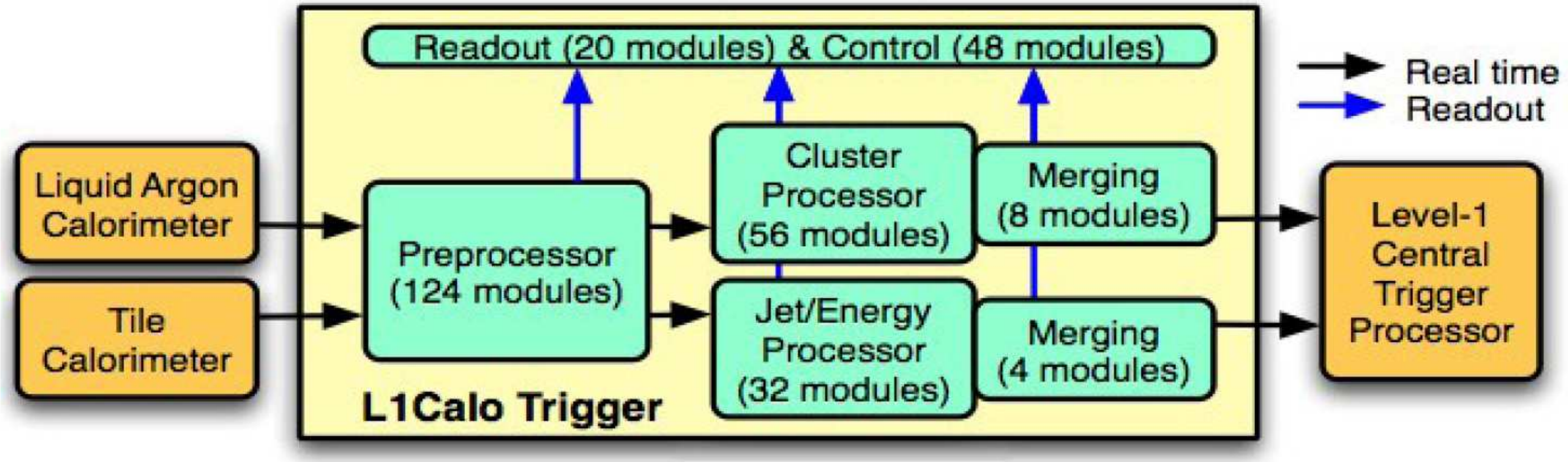
~75 kHz Level-1 Accepts initiating (partial) detector frontend readout



L1A

Data transfer to ROBs
(ReadOut Buffers)

ATLAS Level-1 Calorimeter Trigger



Fixed latency, pipe-lined, hardware based system using custom electronics

Nearly 300 VME modules of about 10 different types housed in 17 crates

Mixed-signal system

Entirely located off the detector in the service cavern USA15

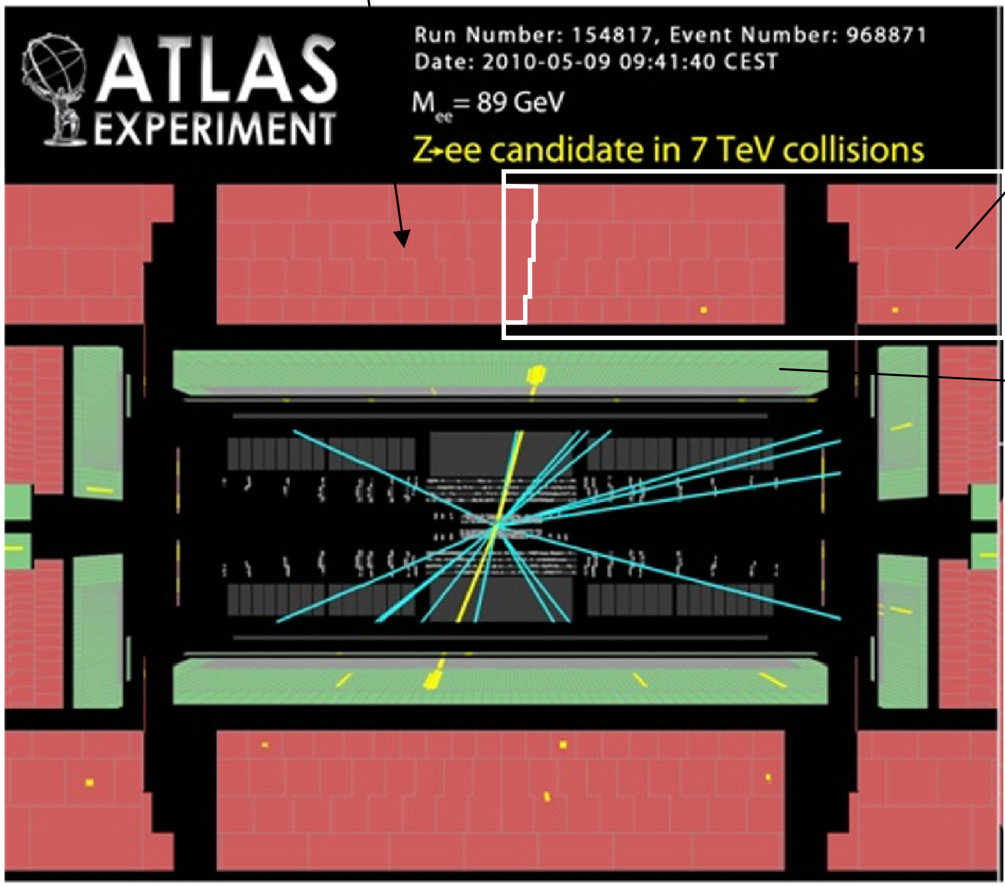
PreProcessor PPr: Digitisation and bunch crossing identification

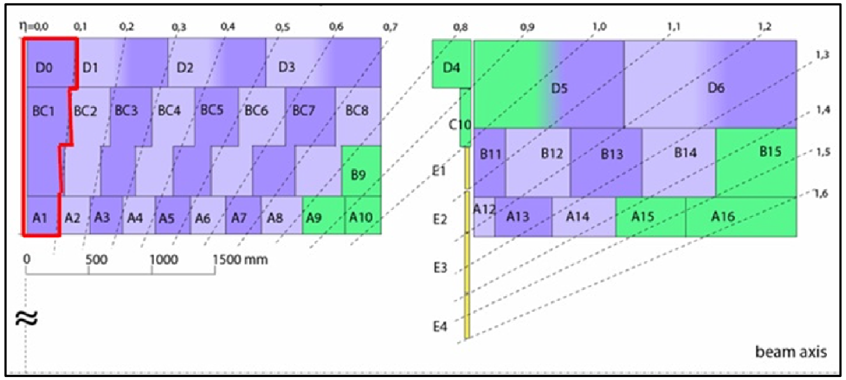
Cluster Processor CP: Identifies electrons, photons and hadrons

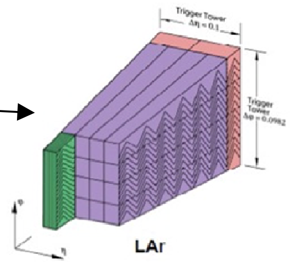
Jet/Energy Processor JEP: Jet finding and energy sums

Analogue Input: Trigger Towers

Outer hadronic Tile Calorimeter







~7200 projective trigger towers

~250k calorimeter cells summed on detector to 7168 trigger towers

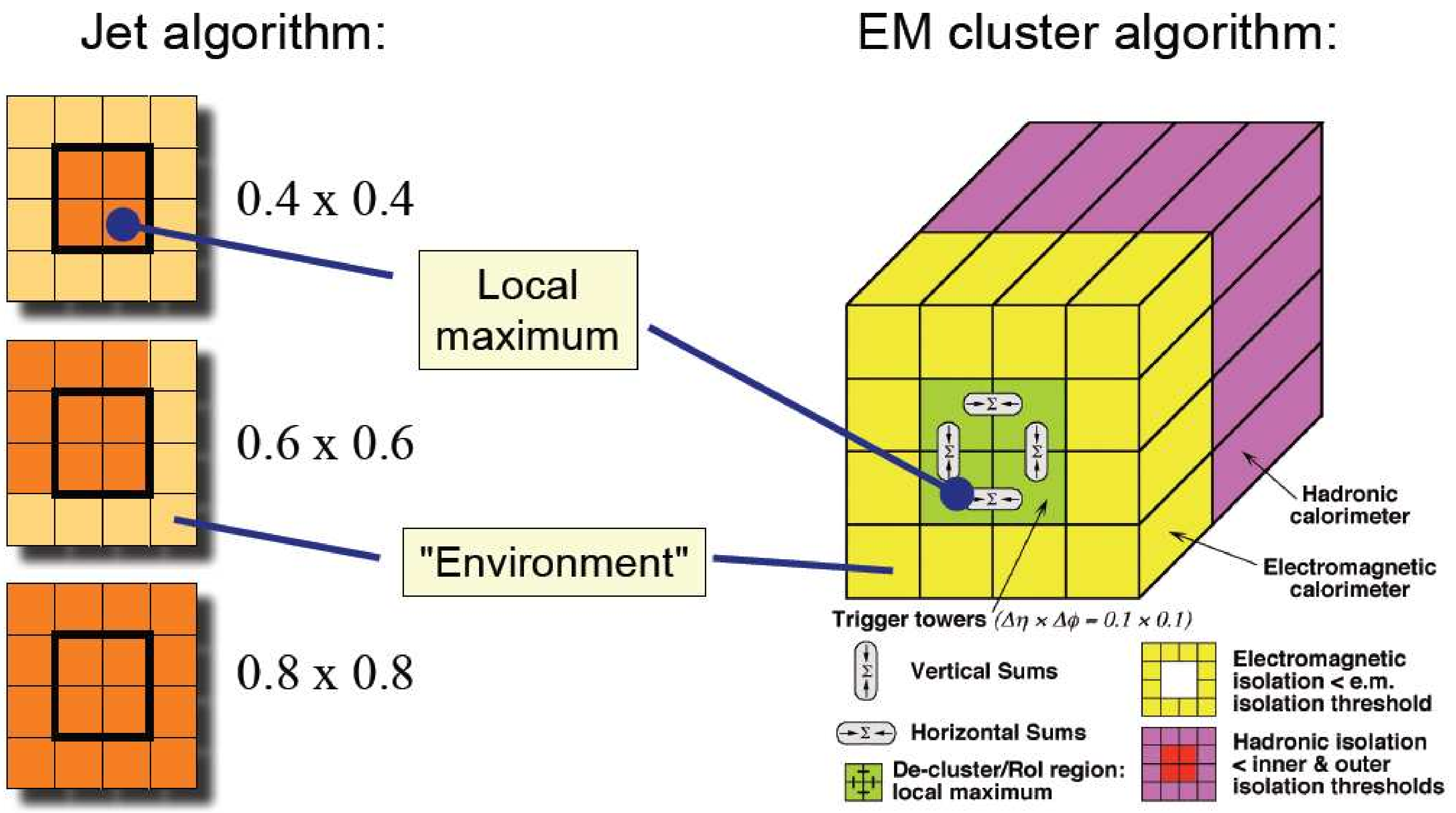
Granularity 0.1×0.1 in eta/phi

Analog signals routed to L1Calo PPr using up to 70m long cables

L1Calo PreProcessor
→ Digitization, BCID, Calibration

Inner electromagnetic / hadronic LArg Calorimeter

L1Calo Sliding Window Algorithms



Two independent processor subsystems (CP/JEP) using common architecture

Processor input is matrix of digitized trigger tower energies from PPr system

Search for local (isolated) maxima using overlapping, sliding windows

Multiplicities of programmable thresholds transferred to central trigger

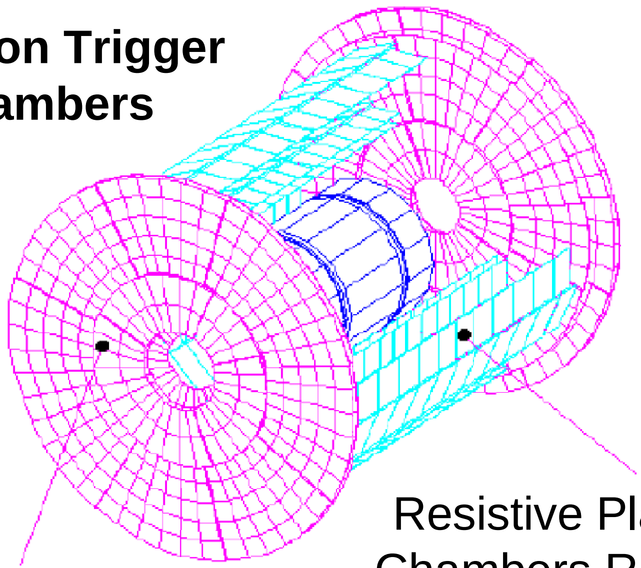
ATLAS L1Calo in USA15

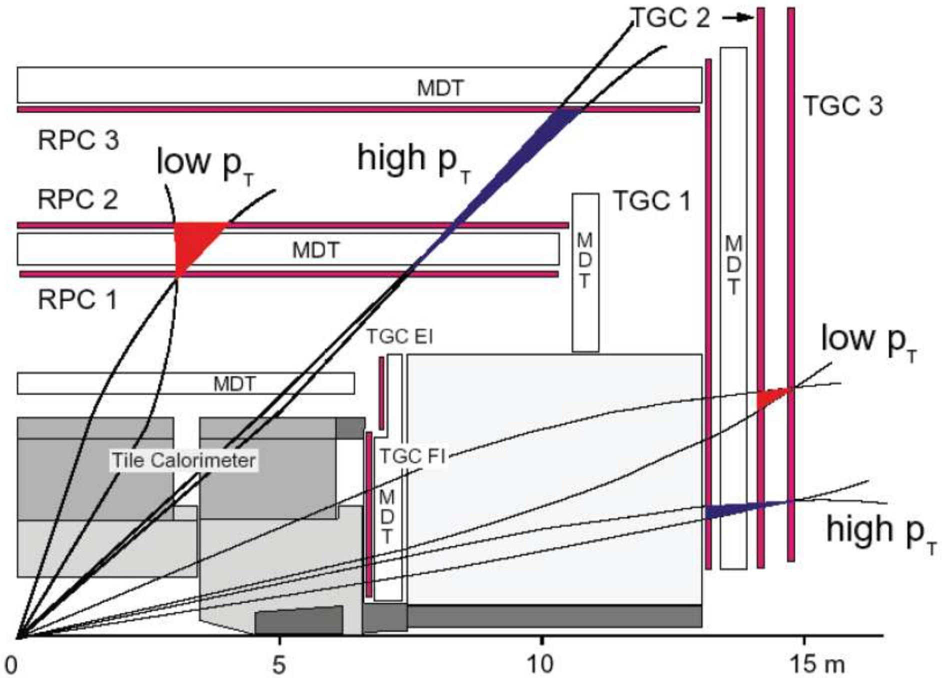
(Half of) Receivers and PreProceccors

Processors

Readout Drivers

ATLAS Level-1 Muon Trigger





Dedicated trigger chambers with good timing resolution, divided into 208 sectors

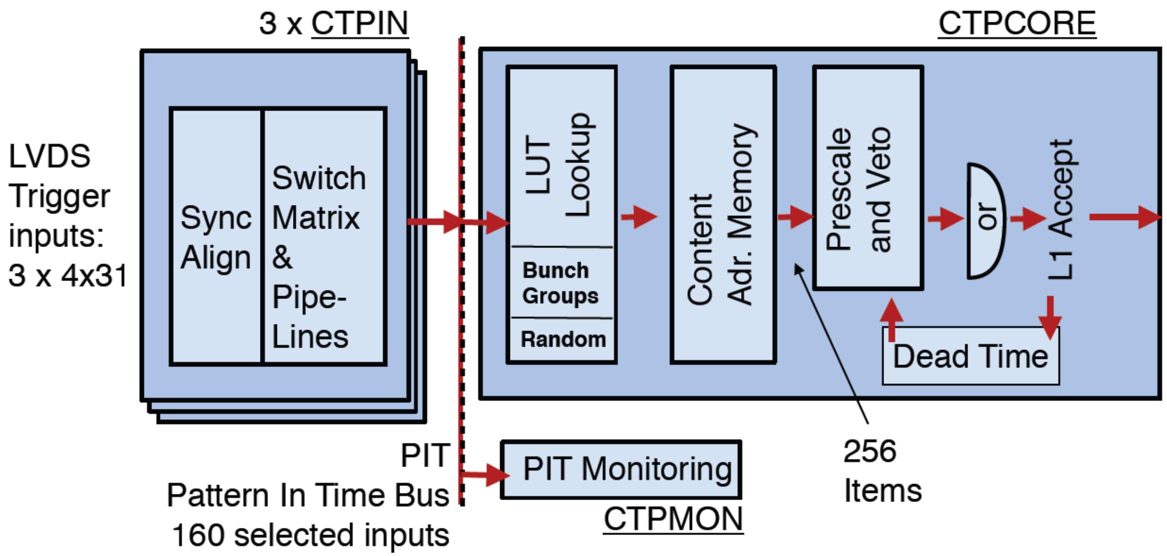
Muon candidates identified by coincidences of hits in different layers

MuCTPI collects sector muon candidates, removes ovelraps and forms total muon multiplicities at 6 different P_T thresholds

Barrel: |eta| < 1.1
Tracking with MDT
Trigger with RPC

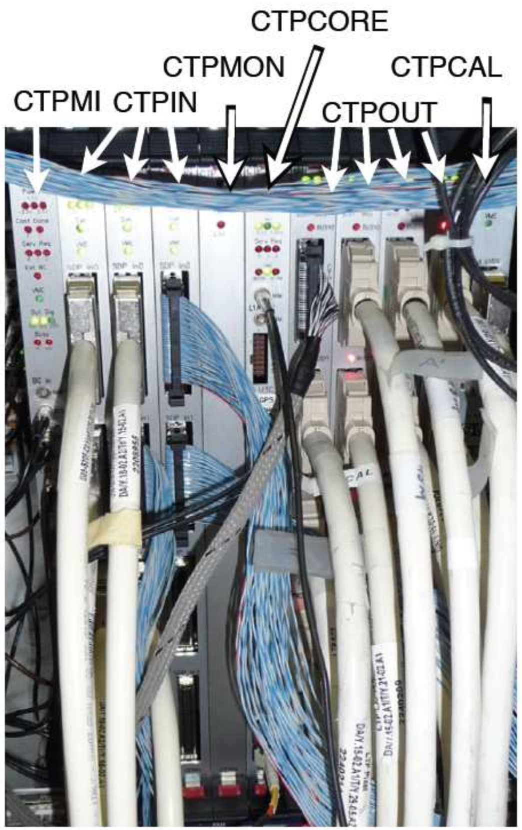
Endcaps: 1< |eta| < 2.7
Tracking with MDT and CSC
Trigger with TGC

ATLAS Central Trigger Processor



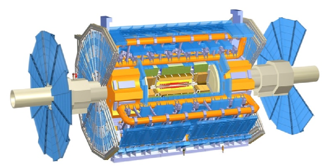
Central Trigger Processor

CTP = Single 9U VME crate

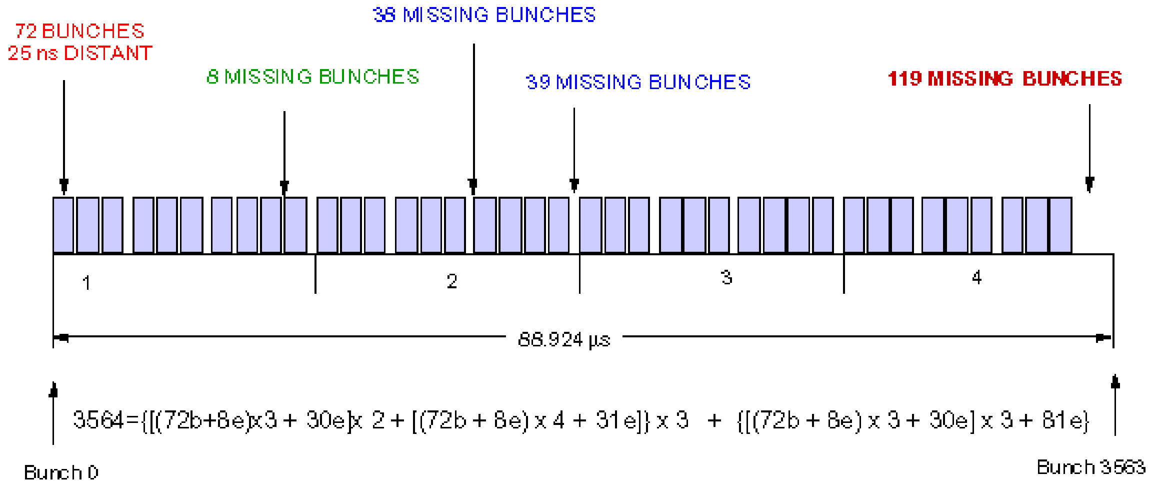


- CTP retrieves signals from the LVL1 subsystems and combines them based on a trigger menu
- Application of internal signals (*bunch group*, random rates)
- 256 trigger items, e.g. EM15, XE10, MU10+JET25
- Application of *prescale factors*
- Veto evaluation and dead time (prevent reading overlapping events and buffer overflows)

→ Level-1 decision is OR of actual trigger items → L1A →



Bunch Groups

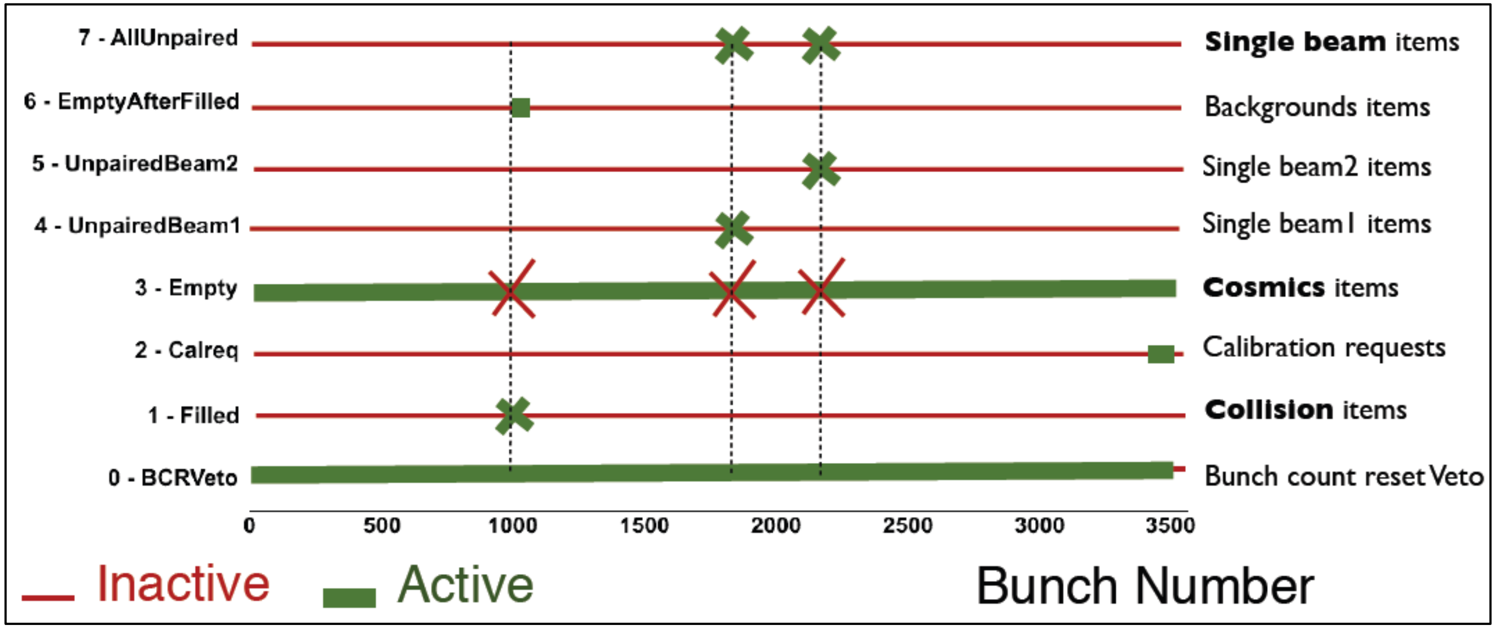


At maximum 2808 of 3564 proton bunches filled ← 0xDEC

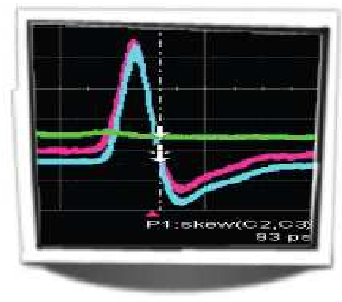
Today 104 filled bunches, 93 colliding in ATLAS/CMS

Physics triggers only "wanted" for filled (paired) bunches

→ Bunch group mechanism



Example configuration with 2 paired and 2 unpaired bunches



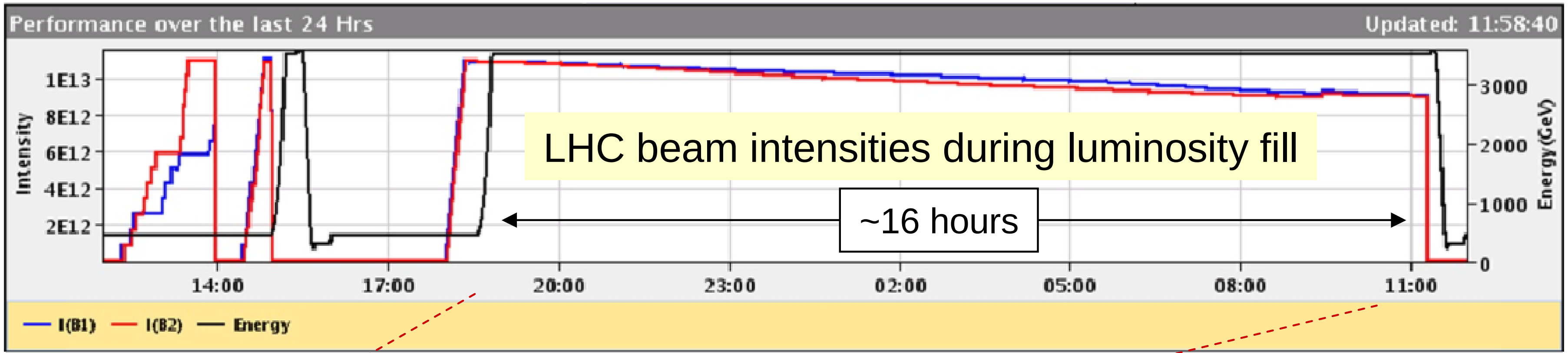
Bunch structure measured using beam pickups

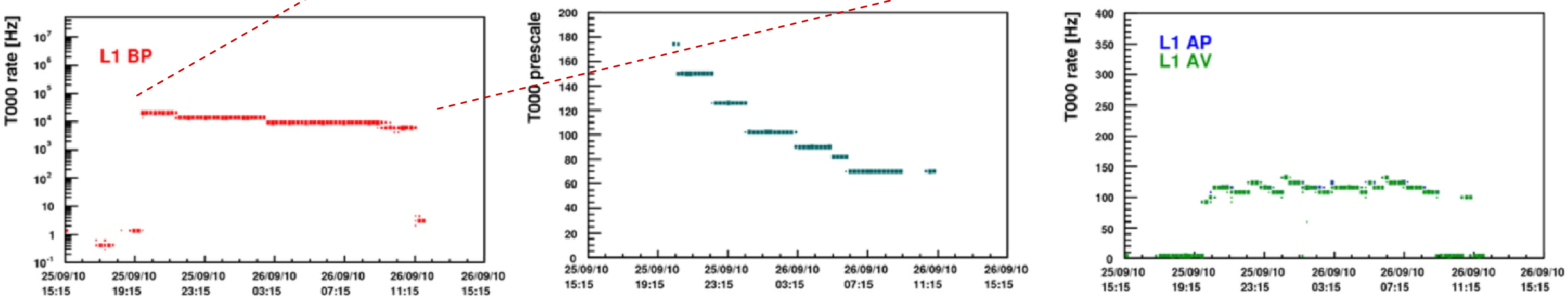
Bunch groups used in trigger definition

Prescales

Prescale = A downscale factor *d* which can be applied such that in average only every *d*-th selected event (raw bit) is kept by the system (actual bit)

→ Simple and effective mechanism for rate (and luminosity!) restriction





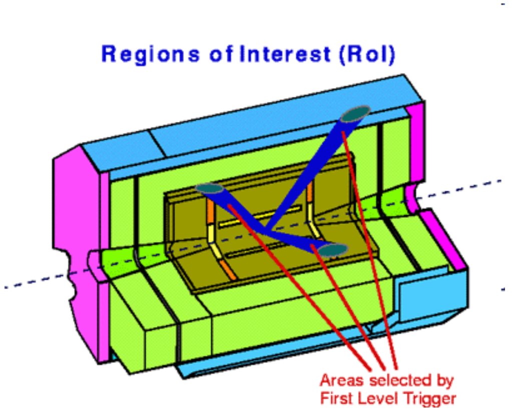
L1 raw rate

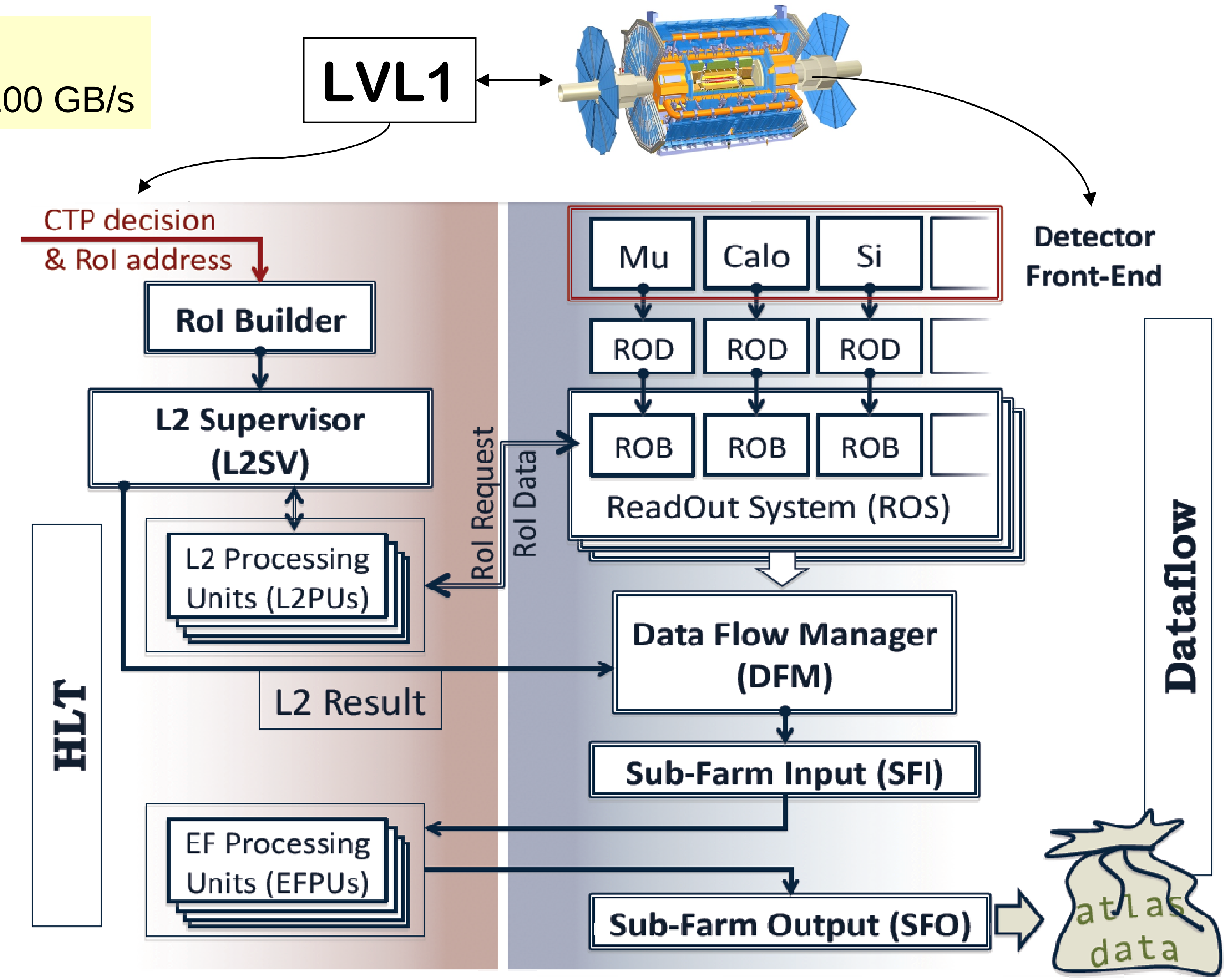
Prescale

L1 rate after prescale

ATLAS High Level Trigger

Massive L1 data flow
~ 1 MB * 100 kHz → 100 GB/s





ATLAS: Intermediate trigger level based on partial event readout for RoIs

CMS: HLT input rate tamed by factorising event building (large network bandwidth)

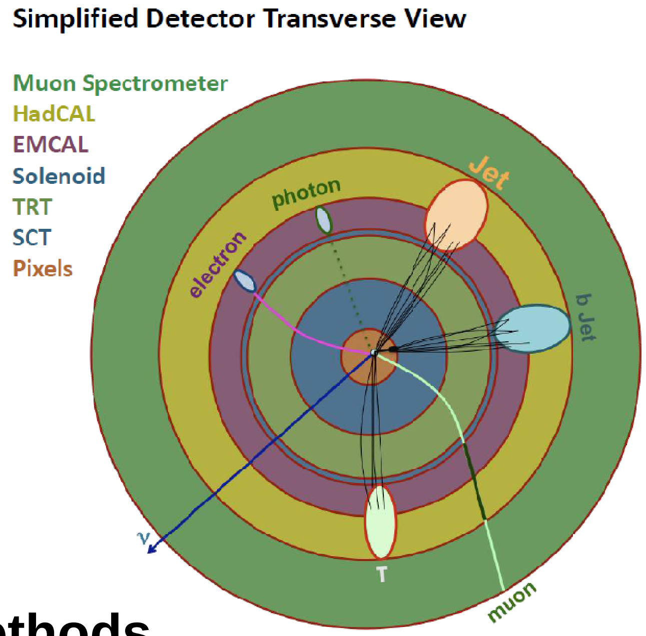
ATLAS HLT PC Farms

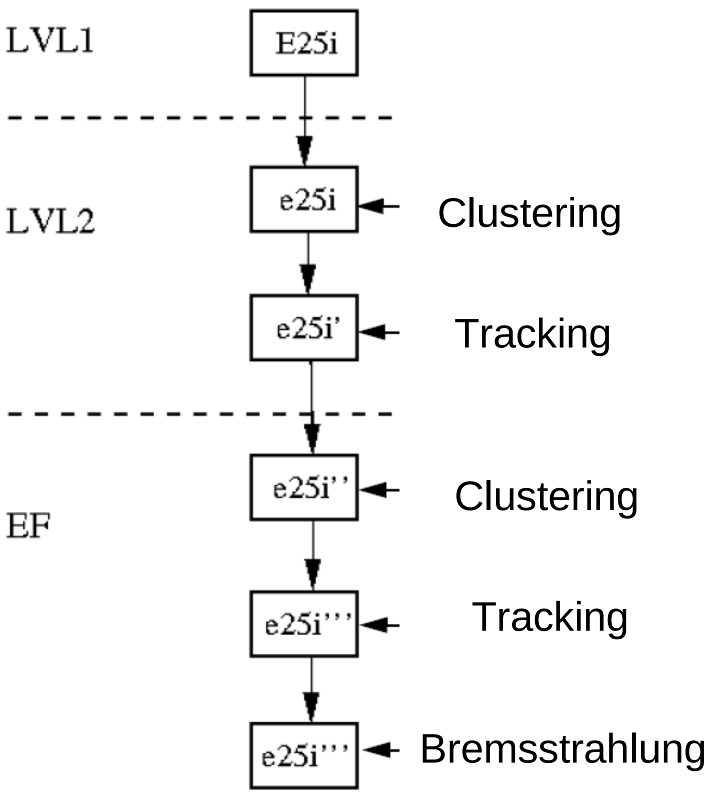
XPUs = Interchangeable processing units (can be used for L2 or EF)

Trigger Chains

ATLAS General strategy

- Chains, stepwise processing, fast event rejects
- Seeded algorithms using results from previous steps as input
- Streaming for offline analysis based on different trigger signatures





HLT Reduction methods

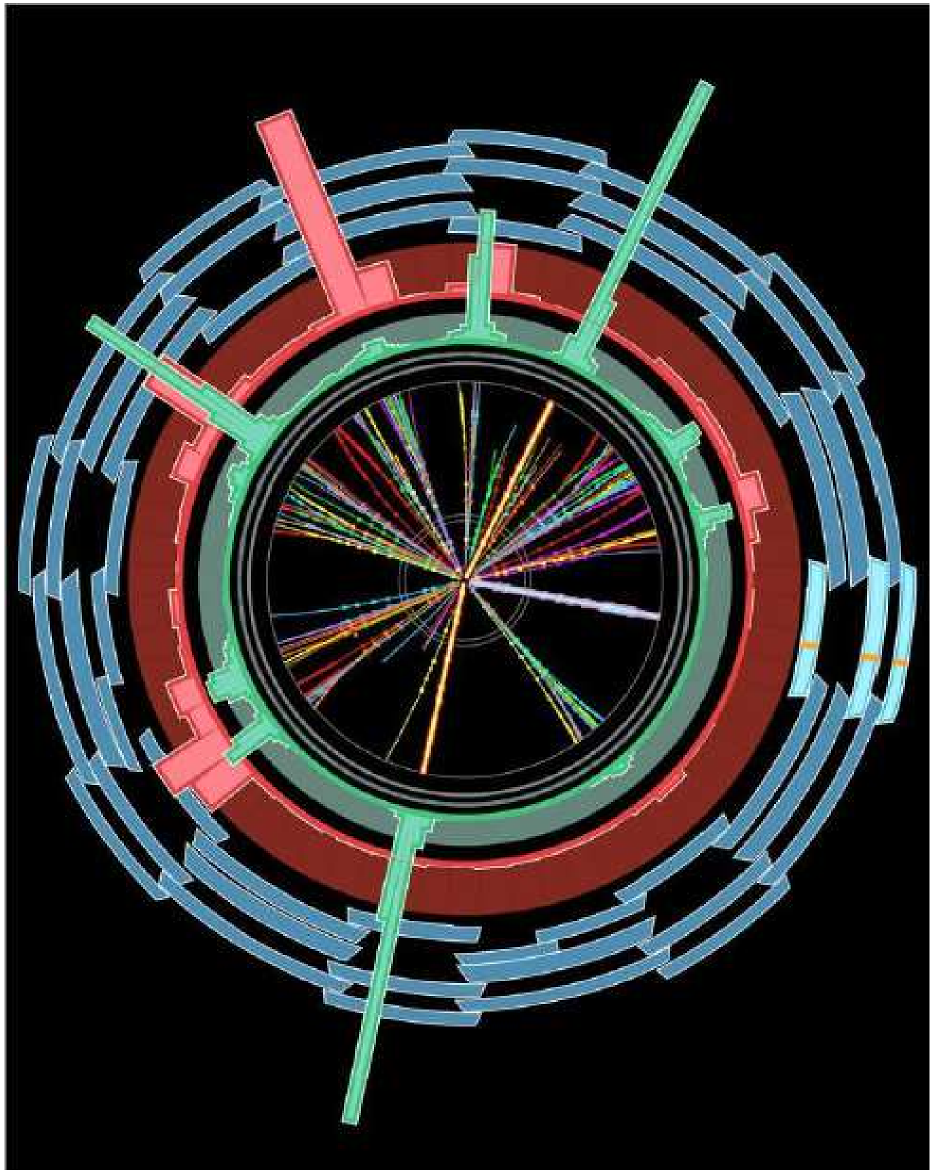
Muons: Sharpen P_T threshold using full muon info and inner tracking

Electrons: Match inner track, higher granularity information

Photons: Inner track veto, higher granularity information

Energy sums: Correct L1 saturation, correct muon P_T in L1 missing E_T

ATLAS Trigger Execution



A proton-proton collision

Tracking system

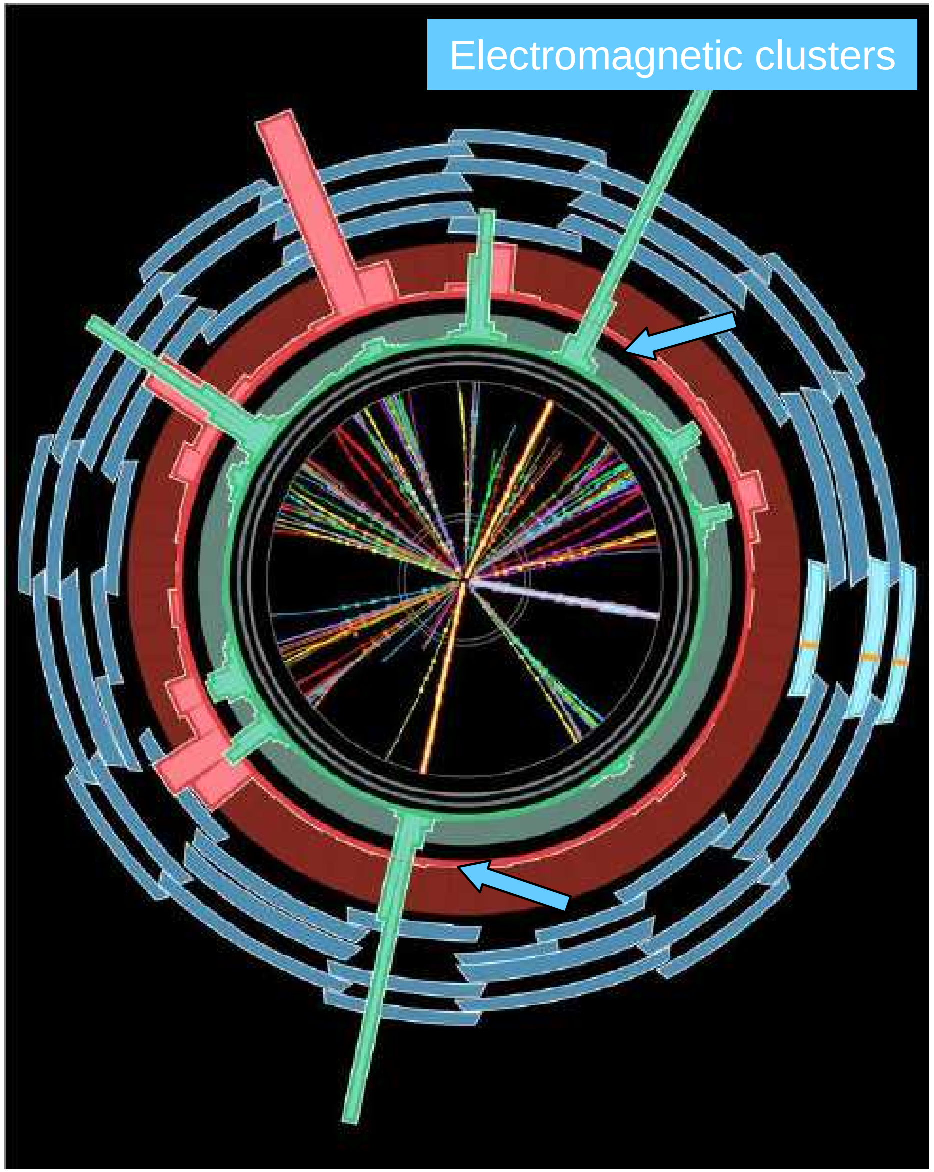
EM Calorimeter

HAD Calorimeter

Muon system

ATLAS Trigger Execution

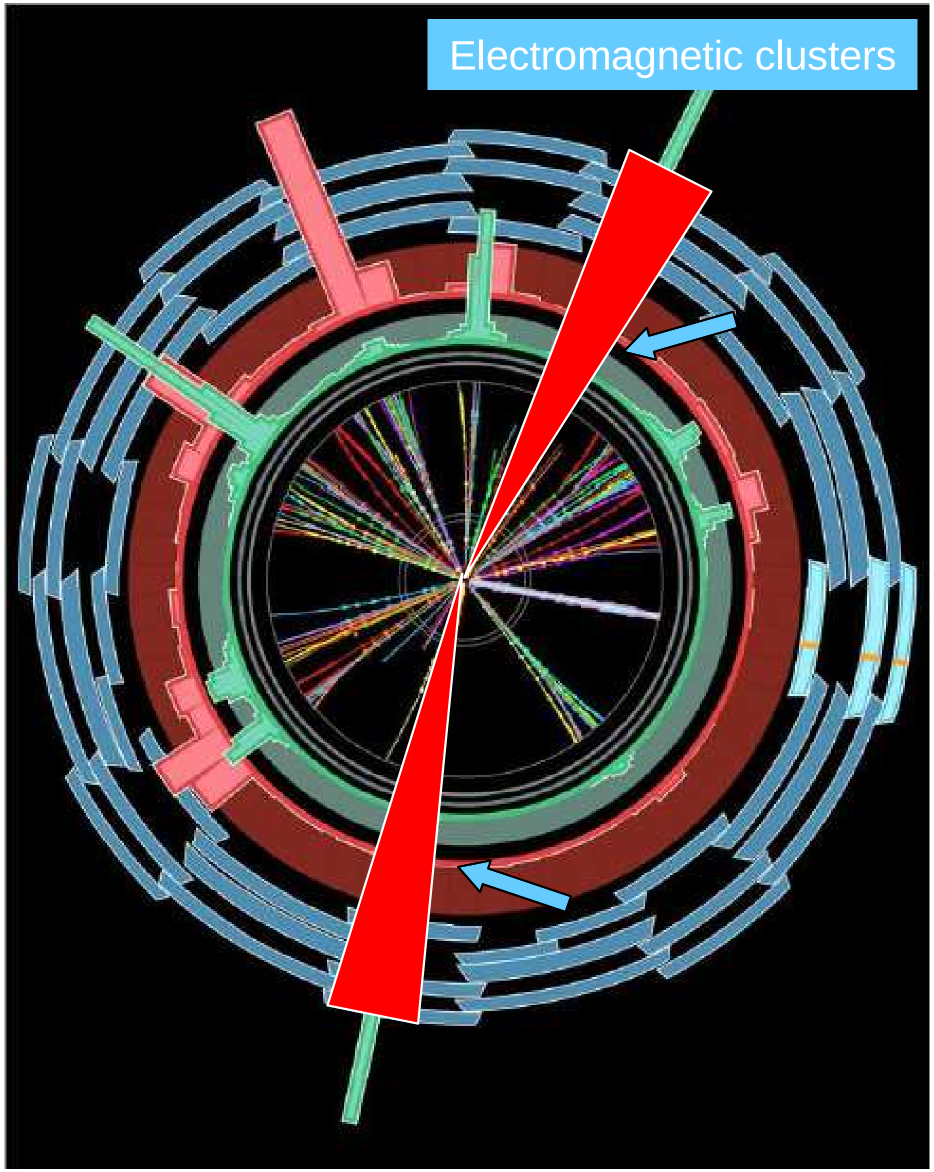
EM RoI



LVL1

EM RoIs identified, thresholds passed, coordinates passed to LVL2

ATLAS Trigger Execution

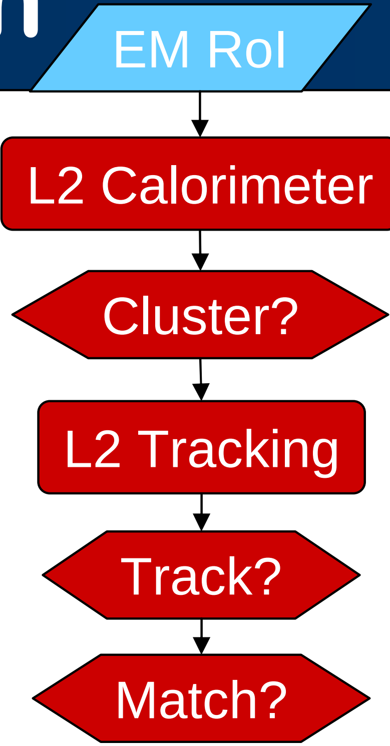


LVL1

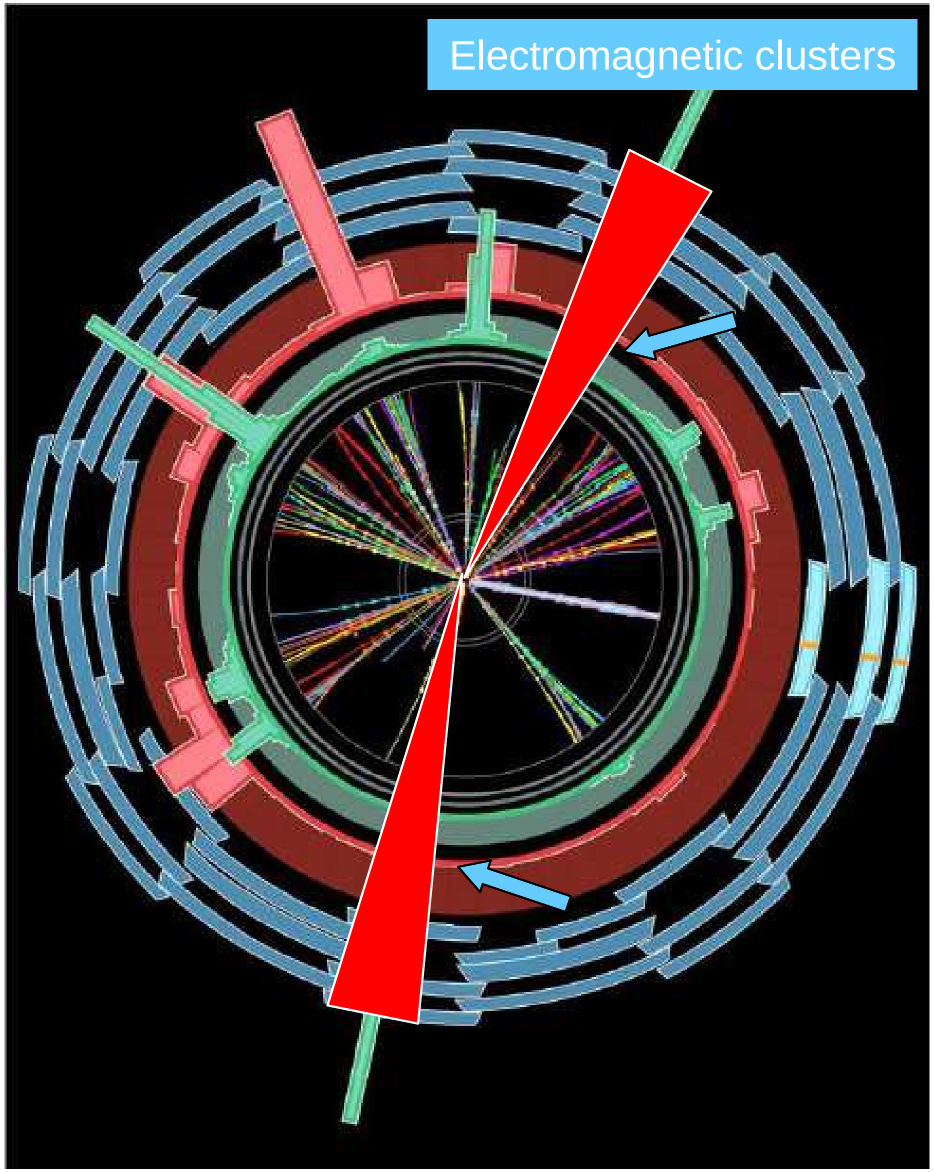
EM RoIs identified, thresholds passed, coordinates passed to LVL2

LVL2 seeded by LVL1

Fast reconstruction algorithms within RoI, only detector information needed requested



ATLAS Trigger Execution



LVL1

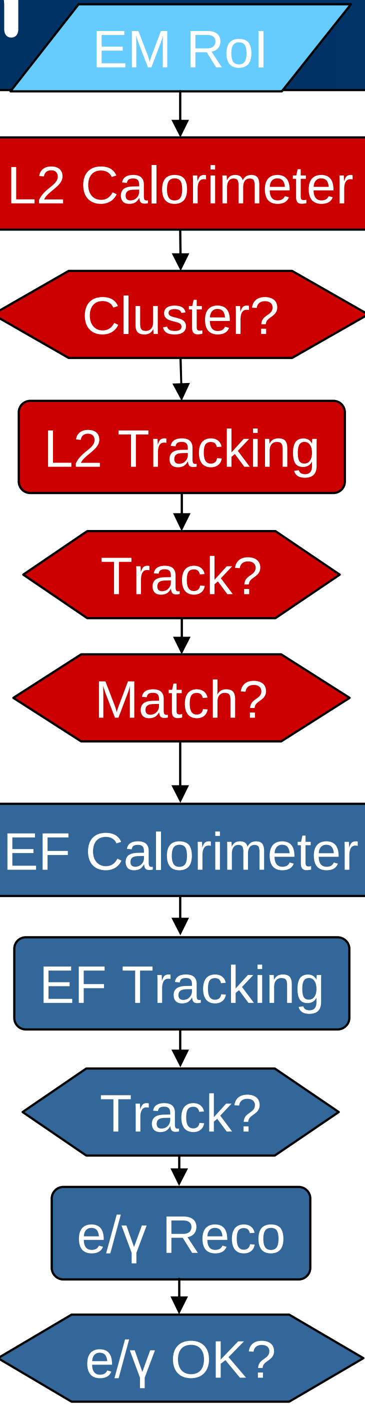
EM RoIs identified, thresholds passed, coordinates passed to LVL2

LVL2 seeded by LVL1

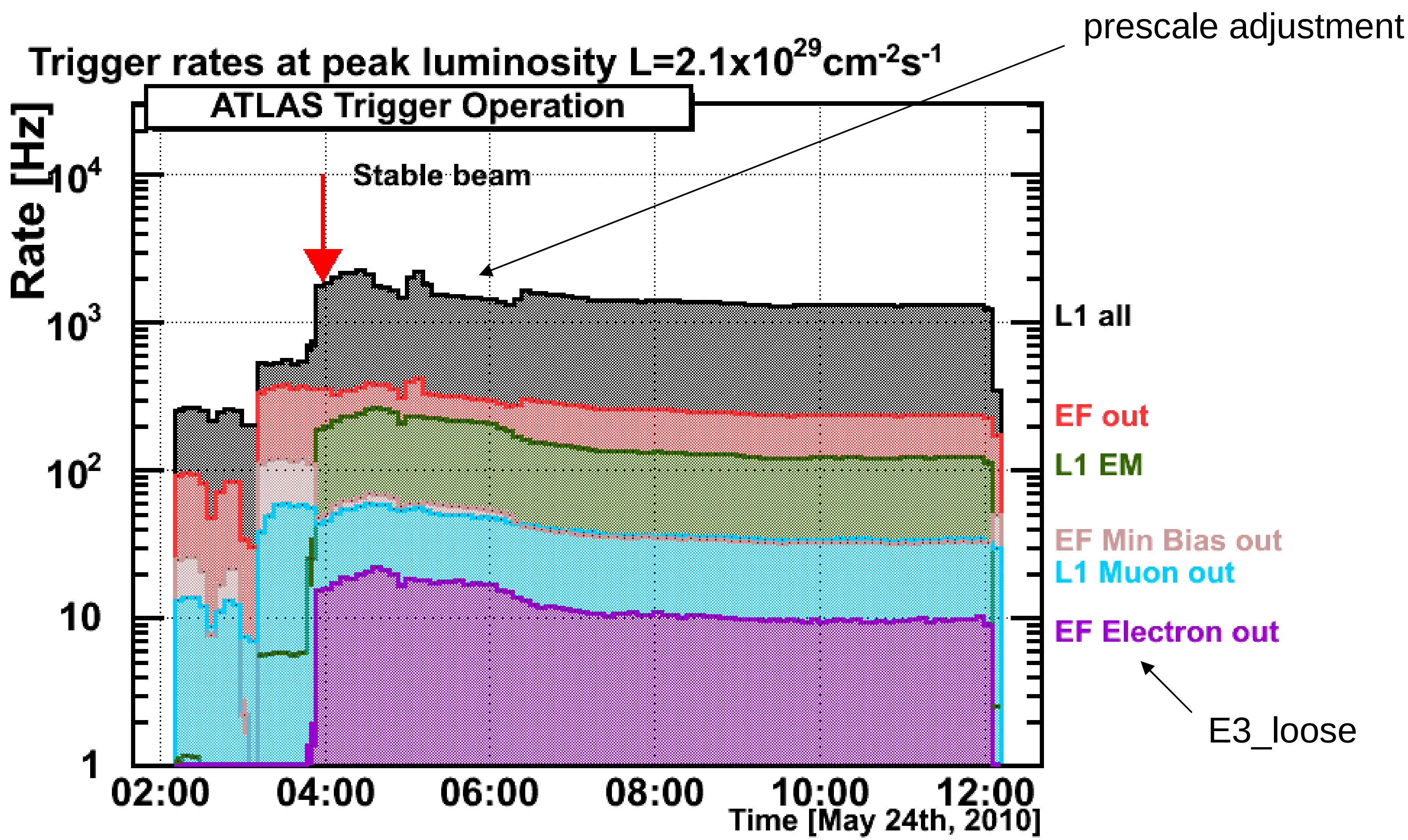
Fast reconstruction algorithms within RoI, only detector information needed requested

EF seeded by LVL2

Full offline reconstruction algorithms, refined alignment and calibration

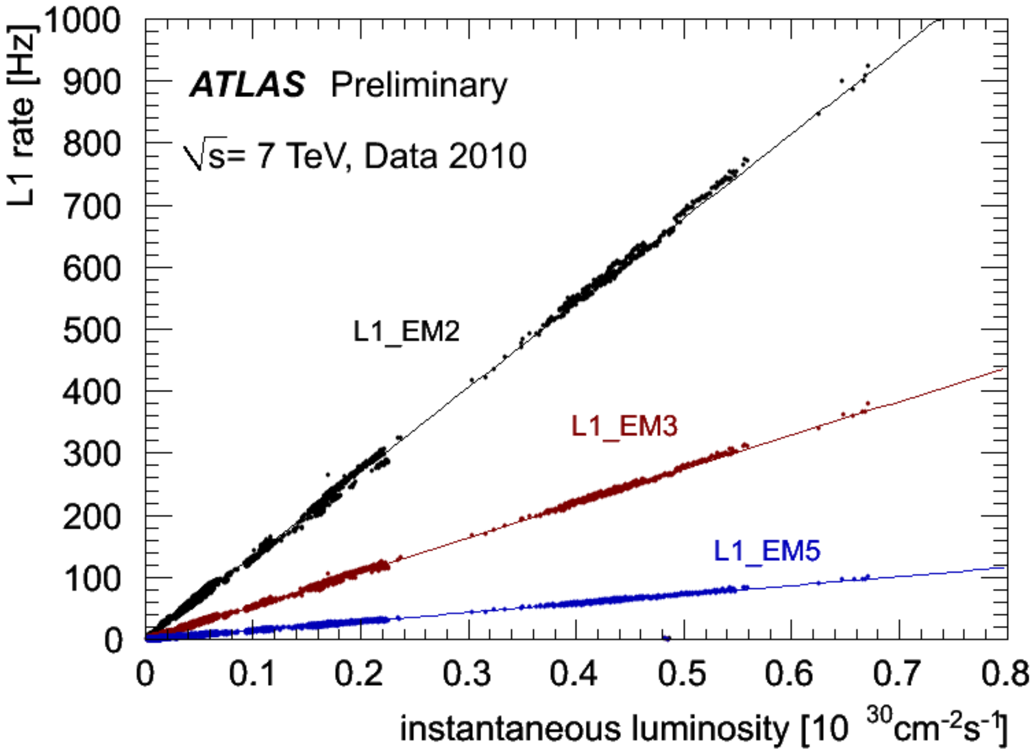


ATLAS Trigger Rates



Online rates with HLT rejection enabled for low threshold EM triggers (EM2, EM3)

Trigger Rates



L1_EM rates scaling with luminosity

Rates dominated by QCD background
(no L1 isolation or had. leakage criteria yet)

Purity versus signal efficiency!

Any process rate: $R = L * \sigma$
(L = inst. luminosity, σ = cross section)

For physics σ independent of L

"Trigger cross sections"

$$\sigma_{trig} = A/L + B + \underbrace{C\,L + D\,L^2}_{\text{grow terms}}$$

constant rate
(e.g.cosmics)

constant σ

Extra powers of L can be caused by

- overlapping objects from different interactions
- luminosity dependent fake

High purity triggers: $R \sim L$

Trigger Efficiency

Goal of the trigger is to maximise collection of data for various physics process analysis of interest → Aim for high efficiency

Trigger efficiency = Ratio of events which actually have been triggered and those which should have caused the trigger (of interest)

Important quantity for analysis as it is usually **NOT** equal to 1

→ Direct ingredient in every quantitative measurements such as

cross section: $\sigma = N / (\varepsilon_{trig}\, L_{int}\, C)$

ε_{trig} trigger efficiency

L_{int} integrated luminosity

C reconstruction efficiency, detector acceptance etc.

Events rejected by trigger are lost forever (remember factor 10^7 rejection)

→ Monitoring of trigger (in-) efficiency crucial for successful operation

Another source of inefficiency: Trigger dead time

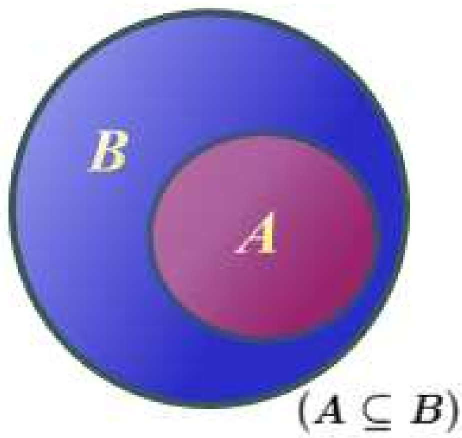
Trigger Efficiency Calculation

→ Should (must) be determined from real data as trigger hardware usually not perfectly emulated in Monte Carlo simulation

Trigger efficiency For an unbiased event sample fulfilling a given analysis selection the number of events accepted by a raw trigger item divided by the original number of events

→ By definition the efficiency depends on the offline event selection

→ Relies on unbiased event selection, i.e. the reference sample must be collected based on information independent from that used by the studied trigger (different detector components)



Methods (determined by availability of unbiased reference)

- Orthogonal signatures (e..g. tracks/calorimeter or muon/ETmiss)
- Double object final states (tag and probe)
- Bootstrap (looser trigger used to study tighter one, e.g. EM5 vs. EM20)

Trigger Efficiency Notes

Assuming an unbiased reference sample with N_0 events fulfilling the offline event selection and containing N^i events passing the trigger decision on level i

$\varepsilon^{L1} = N^{L1} / N_0$	$\varepsilon^{L1+L2} = N^{L1+L2} / N_0$	$\varepsilon^{L2} = N^{L1+L2} / N^{L1}$
L1 only efficiency	L1/L2 combined efficiency	L2 only efficiency

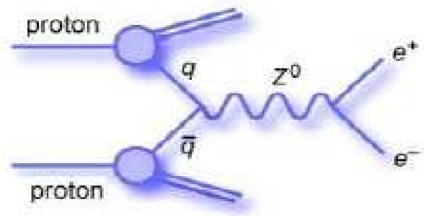
- Usually (for data analysis) N_0 contains further correction factors such as reconstruction efficiencies and detector acceptance. Those factors usually need to be derived in further analysis, e.g. from simulation studies

- Some caution with prescaled triggers
  - Prescales usually vary during the data taking period
  - Danger of additional uncertainties for short runs or large prescales
  - Proper use of raw and actual trigger information might be important

- Combination of prescaled triggers (in multi-level) systems!

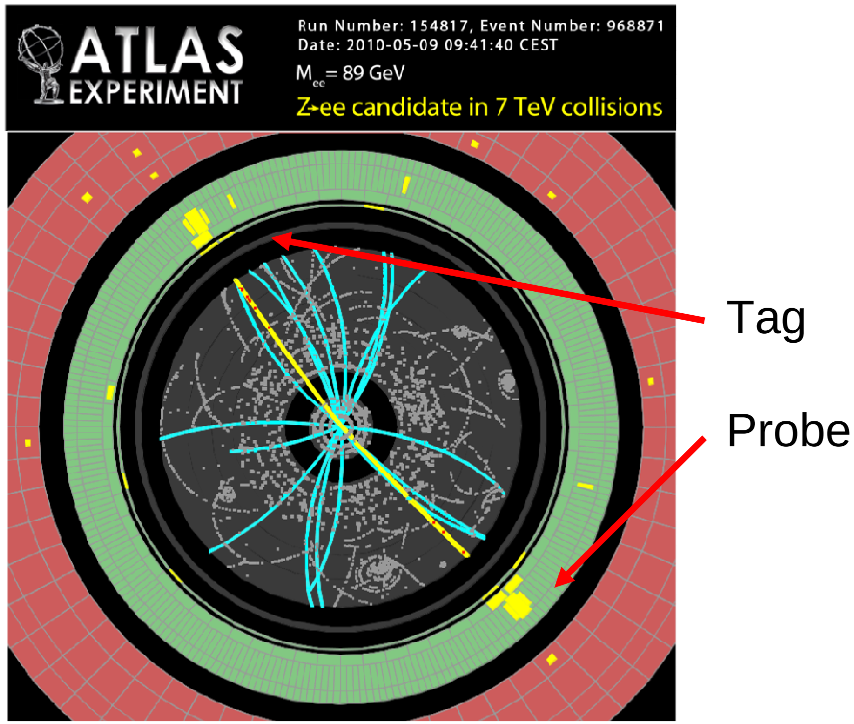
Tag & Probe For Electrons

Based on double object final state, e.g $Z \rightarrow ee$



Example offline selection:

- 2 good electrons (cluster/track match)
- Opposite charge
- Restrict inv. mass $70 < M_{ee} < 100$GeV



Trigger on “tag” electron and measure efficiency to trigger on 2nd electron (“probe”)

Diagnostic sample: N1 events where at least one electron passes trigger

Control sample: N2 events where at least two electrons pass trigger

$$\epsilon = 2N_2/(N_1 + N_2)$$

Global efficiency (electrons non-distinguishable); different statistics applies for differential efficiency

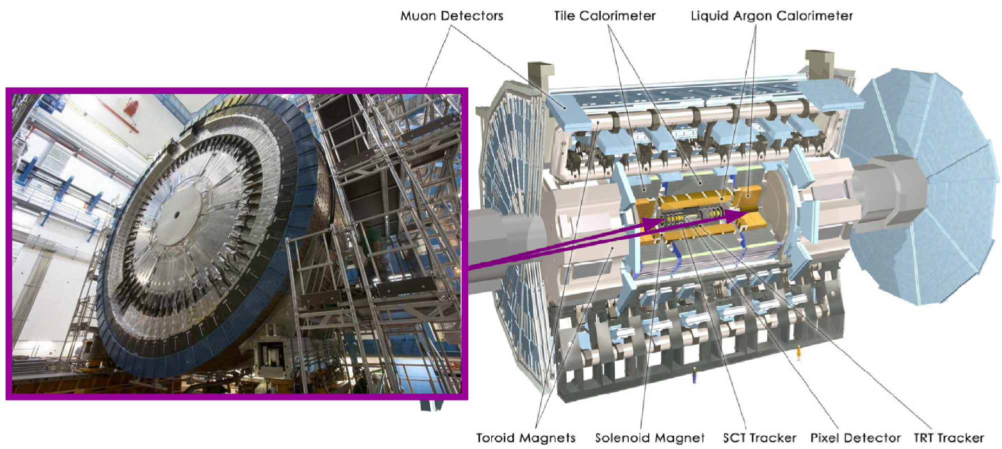
Orthogonal Triggers for Electrons

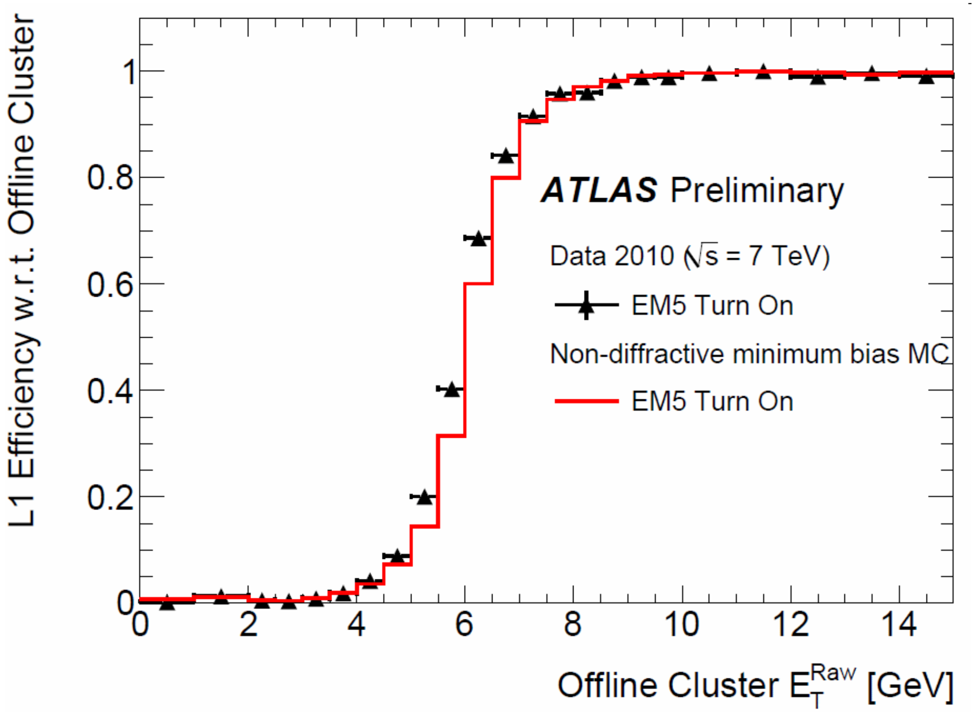
Need unbiased event sample collected by independent trigger

For early data, e.g.

ATLAS Minimum Bias Scintillator

(mounted on LArg endcap crystat)





L1 efficiency for trigger selecting EM clusters above 5 counts (~5 GeV)

Shape reasonably well modelled

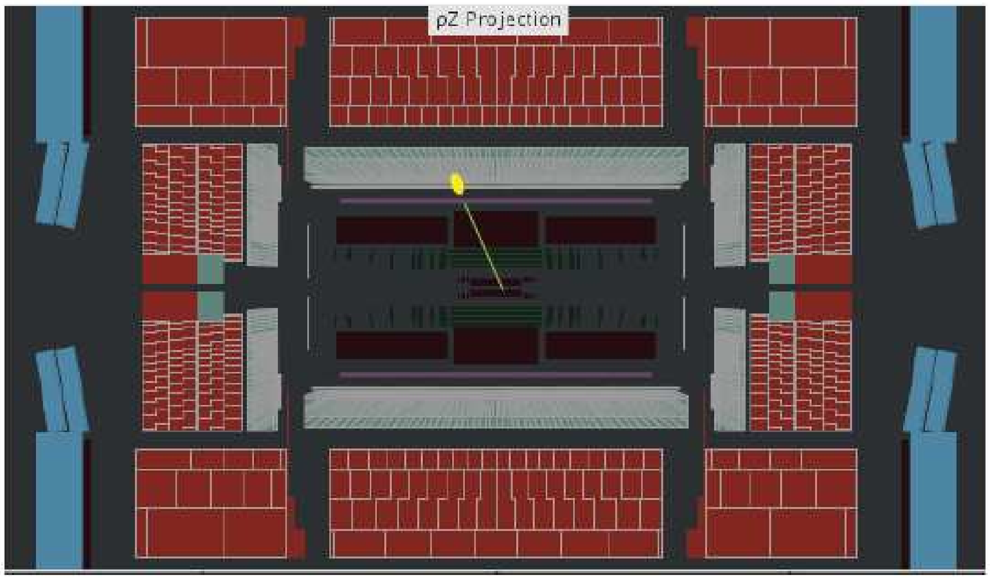
MBTS completely independent, but

- genuine EM objects rare, mostly studying background to EM objects
- Increasingly heavy prescaled
- Slowly dying (expected radiation)

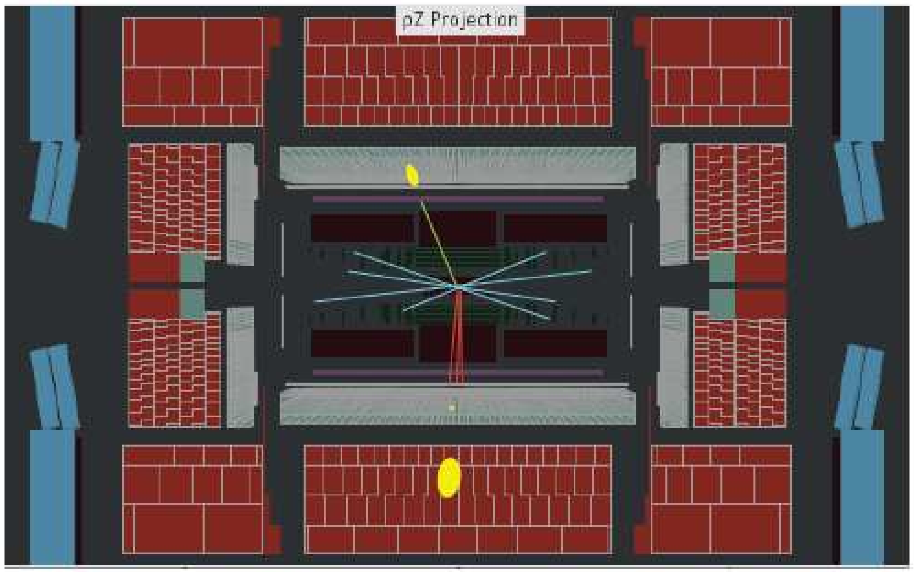
Jet 'Tag & Probe' for Electrons

The reference sample ... a matter of independency and statistics!

- Use electrons in jet triggered sample to study EM trigger efficiency
- To avoid bias, need to ensure that EM object is NOT the cause of the jet trigger
- Apply strict offline isolation criteria in eta/phi plane



Events to be ignored



Events to be studied

ongoing

Conclusions

LHC is most powerful particle accelerator ever built and allows for first time to deeply explore TeV scale → Highest energies at highest luminosities

Triggering at LHC is a challenge, powerful selection needed in order to fit the best possible physics cocktail into the available bandwidth

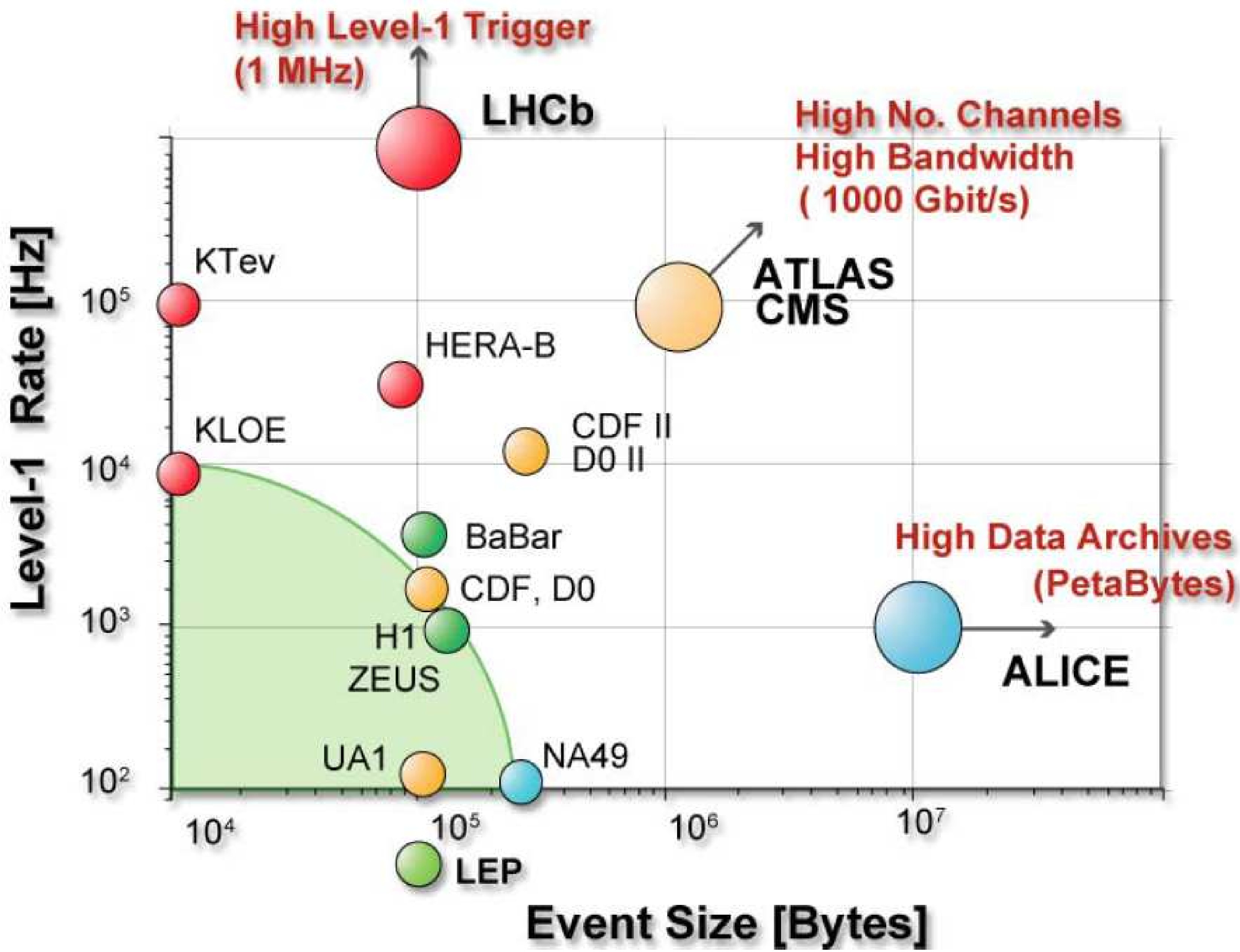
Both ATLAS and CMS triggers are separated into fast first level hardware trigger and software based higher level triggers performing fine grained selection and rejection

Understanding and correct measurement of trigger efficiencies is crucial for both successful detector operation and precise data analysis

Thanks for your attention!

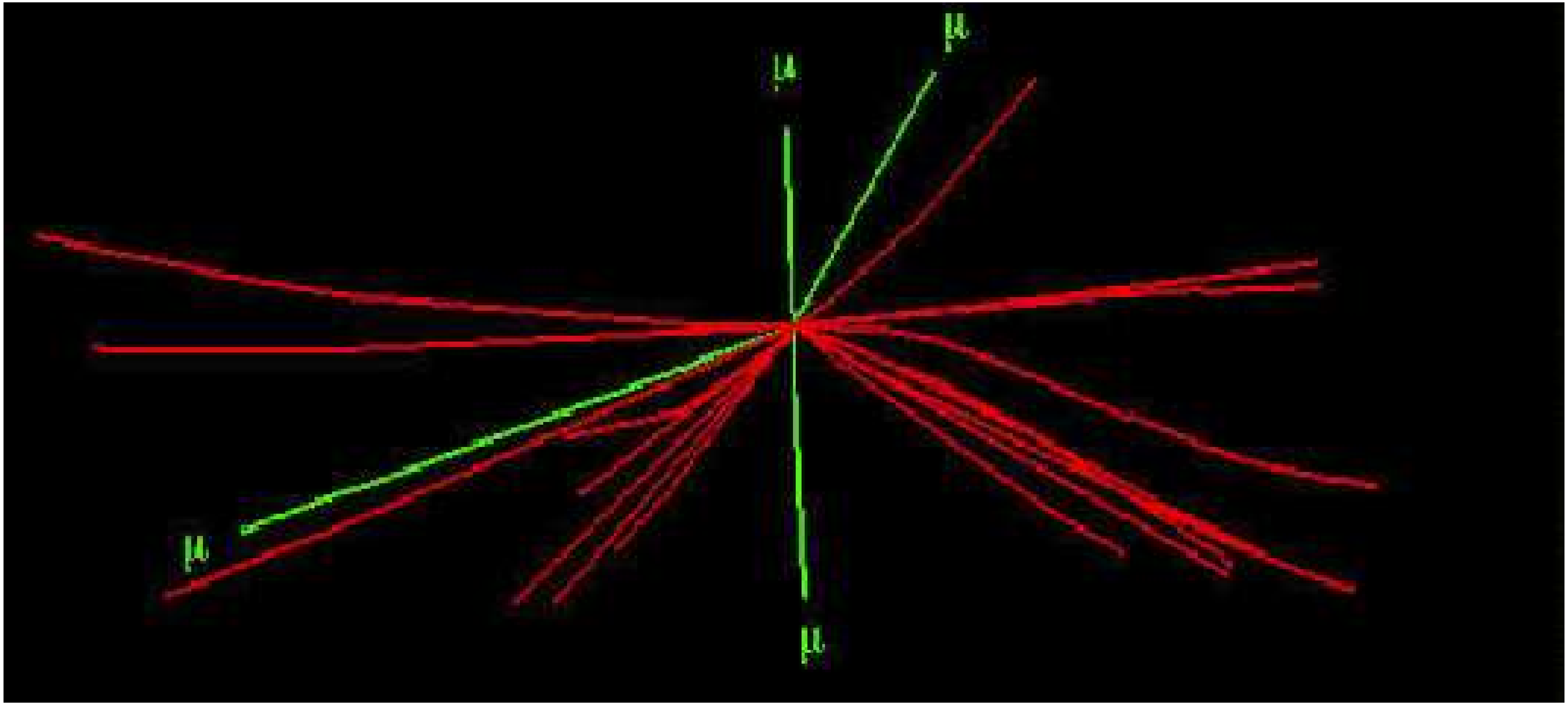
… and apologies to my CMS colleagues for spending an intolerable amount of time talking about ATLAS. I am convinced that changing all figures shown into corresponding CMS ones would not alter the message.

TDAQ Trends



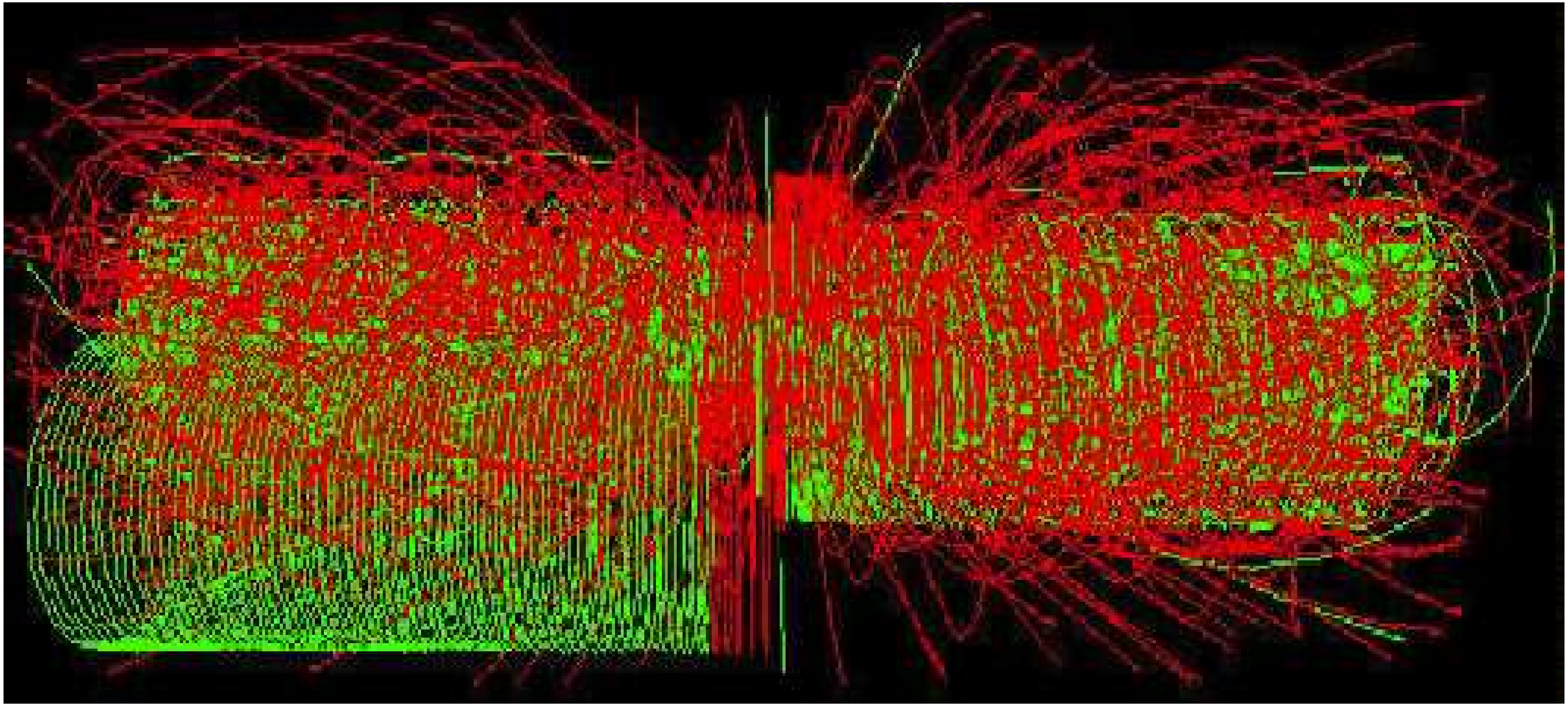
High Level-1 Trigger
(1 MHz)
LHCb
High No. Channels
High Bandwidth
(1000 Gbit/s)
KTev
ATLAS
CMS
HERA-B
KLOE
CDF II
D0 II
BaBar
High Data Archives
(PetaBytes)
CDF, D0
H1
ZEUS
ALICE
UA1
NA49
LEP
Level-1 Rate [Hz]
10^5
10^4
10^3
10^2
10^4
10^5
10^6
10^7
Event Size [Bytes]

Event Signatures



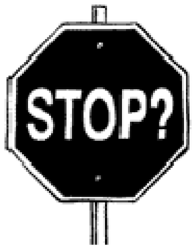
Higgs → 4μ

Event Signatures



Higgs → 4μ

+30 Min Bias Events



How do the interesting events (only) get to tape?