Trigger di primo livello per gli esperimenti ATLAS & CMS ad LHC

F.Pastore

INFN Sezione di Roma

II Workshop sulla fisica di ATLAS e CMS

Napoli, 13-15 Ottobre 2004

Outline

- LHC Physics Program
- Requirements for triqgger systems for experiments at the LHC
- ATLAS & CMS Level-1 Trigger systems
- Conclusions

The Large Hadron Collider

On a proton-proton beam

- CM Energy = 14 TeV
- $L = 10^{34}$ cm^{-2} s^{-1} (2x10^{33} cm^{-2} s^{-1} initial luminosity for 1.5 years)
- Bunch Spacing: 25 ns
  - Beam current = 0.56 A
  - Protons per bunch = 10^{11}
  - p-p interactions per bunch =~23
- Event size 1-2 Mbytes

=> Average of 600 Million Proton Interactions per second!!

We need highly efficient selection process.

For example, signal rate for SM H->$\gamma\gamma$ with a Higgs mass of 120GeV is about 10^{-13}

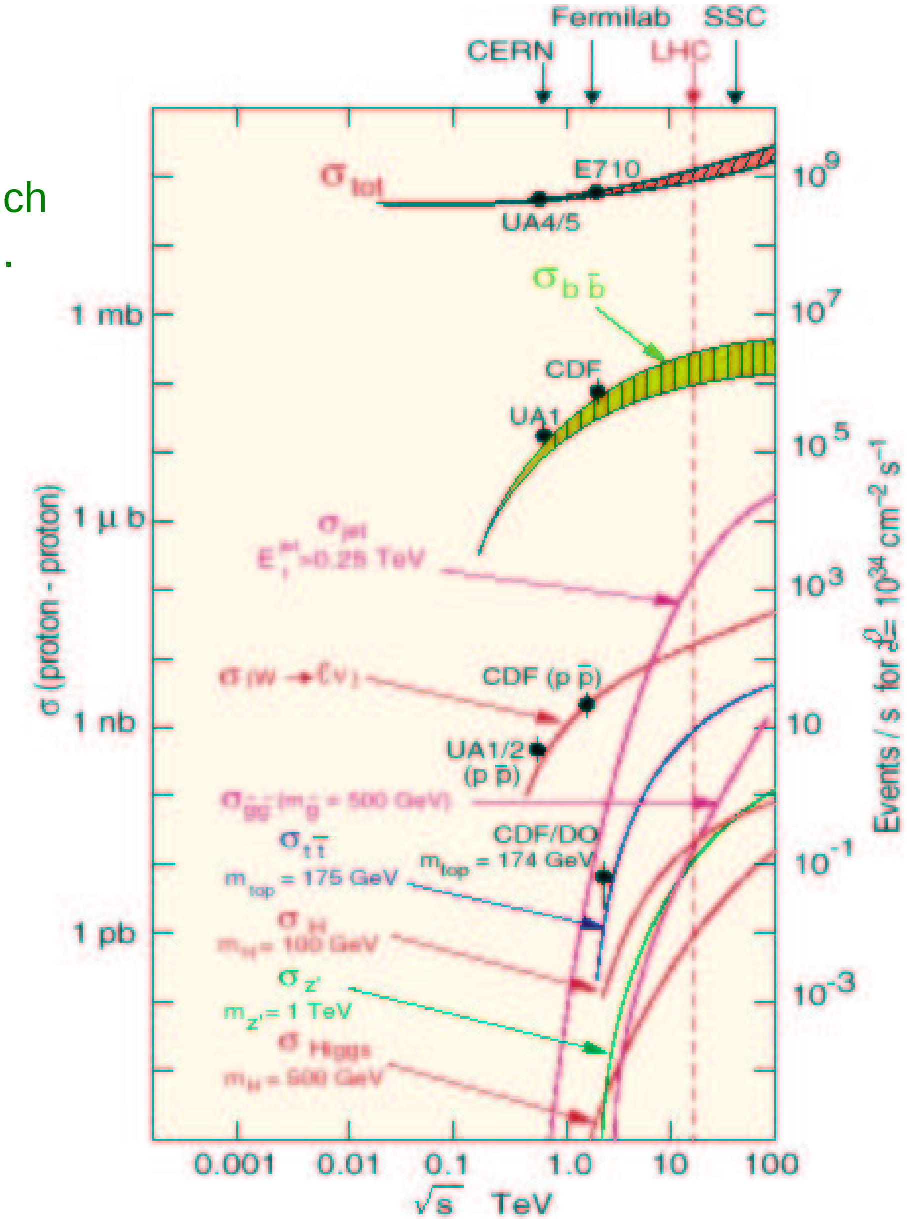
Proton-proton interactions

- High event rate: 1 Ghz
  the rate of these “minimum-bias” events is such that can have an impact on the Trigger system. Ex: the muon Trigger of ATLAS and CMS;

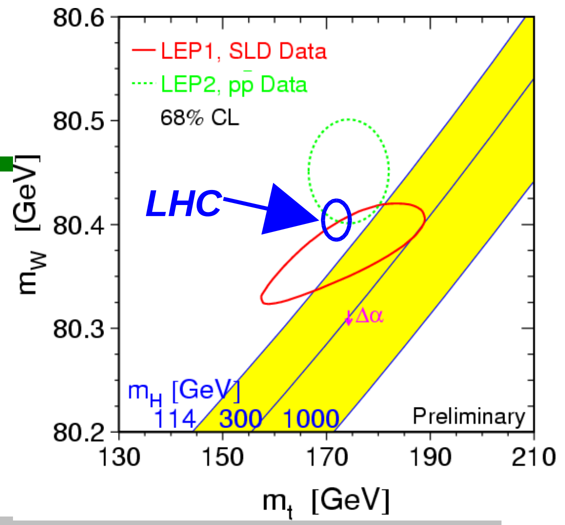
- LHC is a heavy-flavor factory:
  bb cross-section 500 b
  tt cross-section 1 nb

- LHC is a vector-bosons factory

- The event rate is huge
  big implications in the trigger/daq System



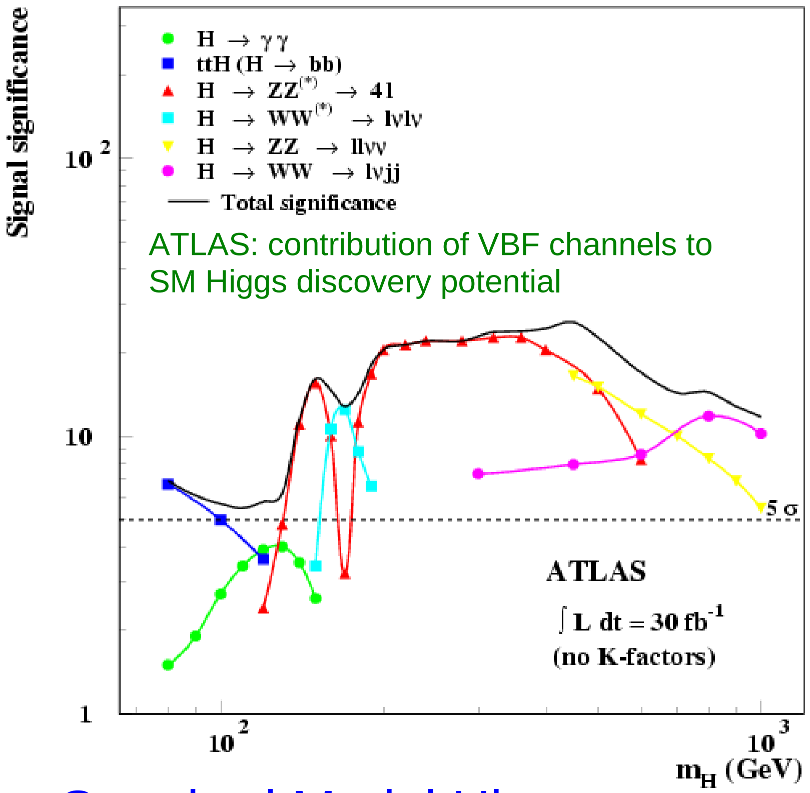
The LHC Physics Programme

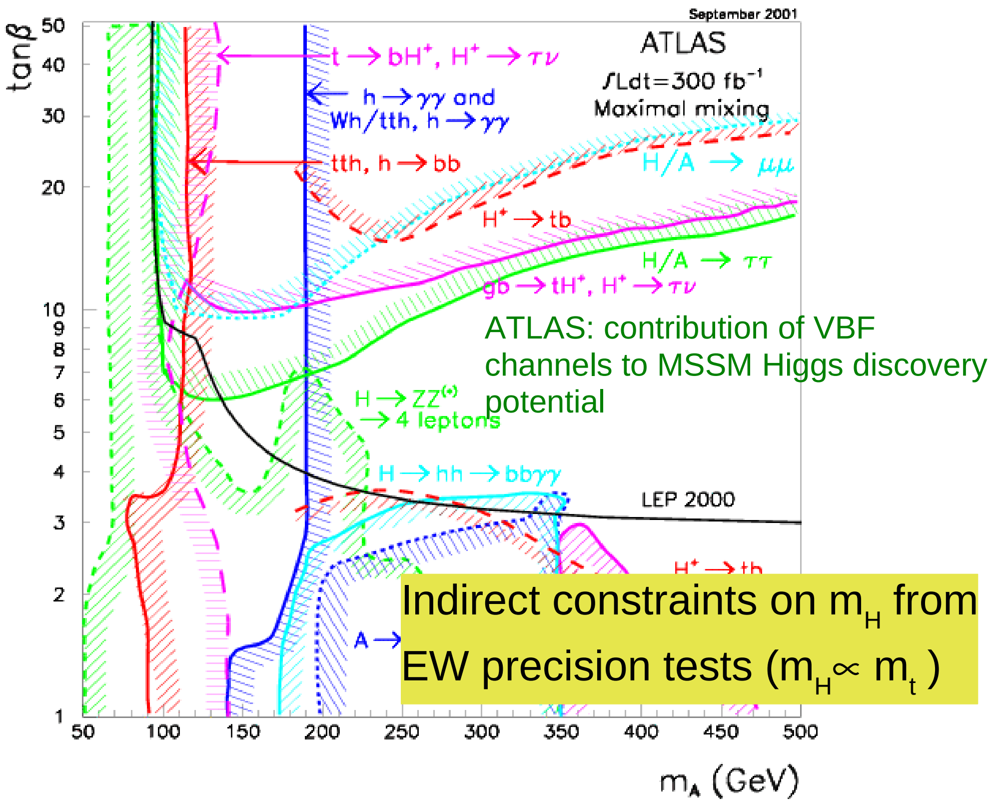


SM cannot be the ultimate theory:
- no gravity
- hierarchy problem

- Origin of the particle masses: search for the Higgs boson(s)
  - The LHC will search for a SM-like Higgs, covering whole range $m_H < 1$ TeV
  - SuSy prediction for light Higgs ($m_H < 135$ GeV)
- SuSy particles search
  - Jets and missing transverse energy (E_T)
- Standard Model Physics
  - Precision measurements with 10-30 fb^{-1}
- Origin of the Matter Anti-matter imbalance in the universe
  - SM CP-violation not sufficient; least tested aspect of the SM
- New Physics beyond the SM
  - Using inclusive triggers sensitive to unpredicted new physics

Electroweak symmetry breaking





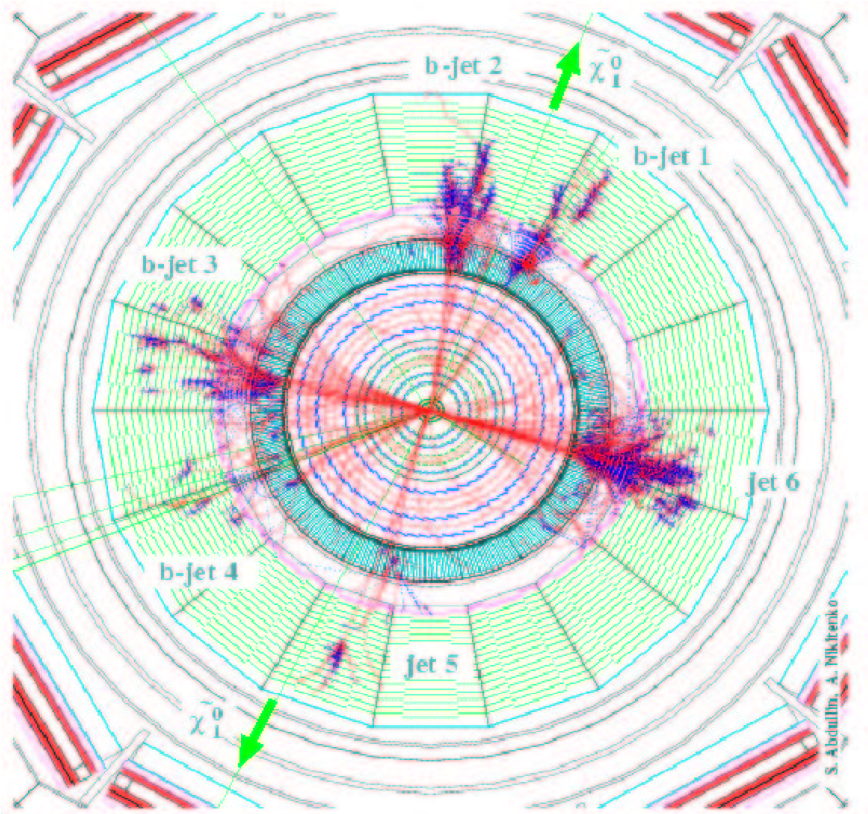
- Standard Model Higgs
  - Cover the full mass range with at least two decay modes
  - Relevant final states: **γγ - ttbb – 4l – lνlν – llνν – lljj** (l=e,μ)
- MSSM Higgs bosons
  - Additional final states relevant for H/A and H±: **ττ – μμ – τν – tb**

Selection signatures

Particles	Example of physics coverage
Electrons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Photons	Higgs (SM, MSSM), extra dimensions, SUSY
Muons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Jets	SUSY, compositeness, resonances
Jet + missing ET	SUSY, leptoquarks
Tau +missing ET	Extended Higgs models (e.g. MSSM), SUSY

Standard Model processes are mandatory to

- Understand background processes for discoveries and measurements (production of Wbb, ttbb, vector boson pairs, …)
- Understand detector performance (esp. during the first year(s))
    - Calibration / energy scale: $Z\rightarrow ee/\mu\mu$, $W\rightarrow jj$, $W\rightarrow e\nu$, $W\rightarrow \tau\nu$, Z+jet, $J/\psi\ \mu\mu$



SUSY events over all have high multeplicity jets, or leptons, and big missing transverse energy **(E_T^{miss}).**

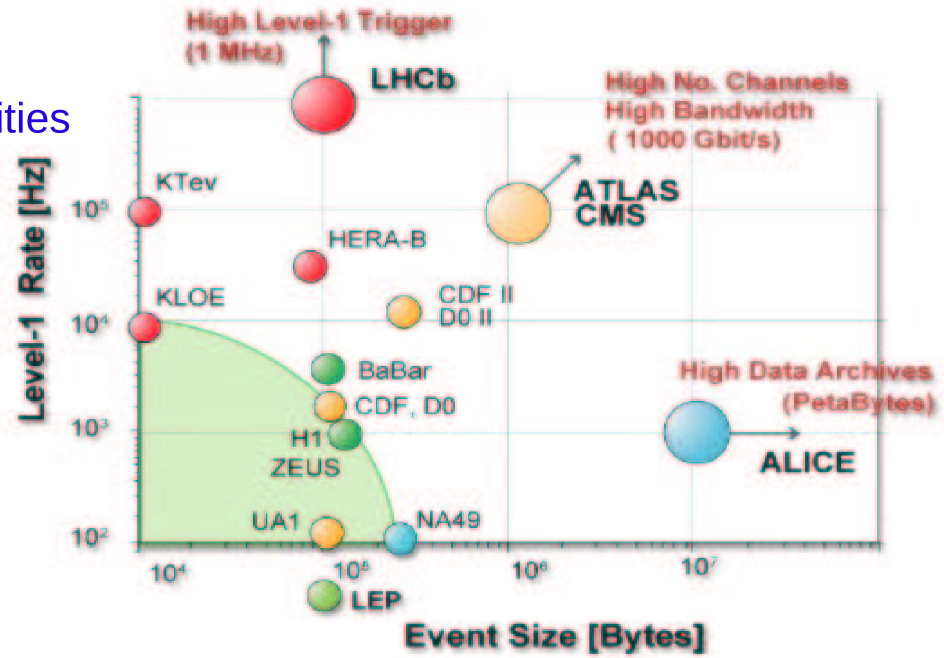
General trigger requirements

The role of the **trigger** is to make the online selection of particle collisions potentially containing interesting physics

- Need **high efficiency** for selecting processes of interest for physics analysis
  - Efficiency should be precisely known
  - should not have biases affecting physics results

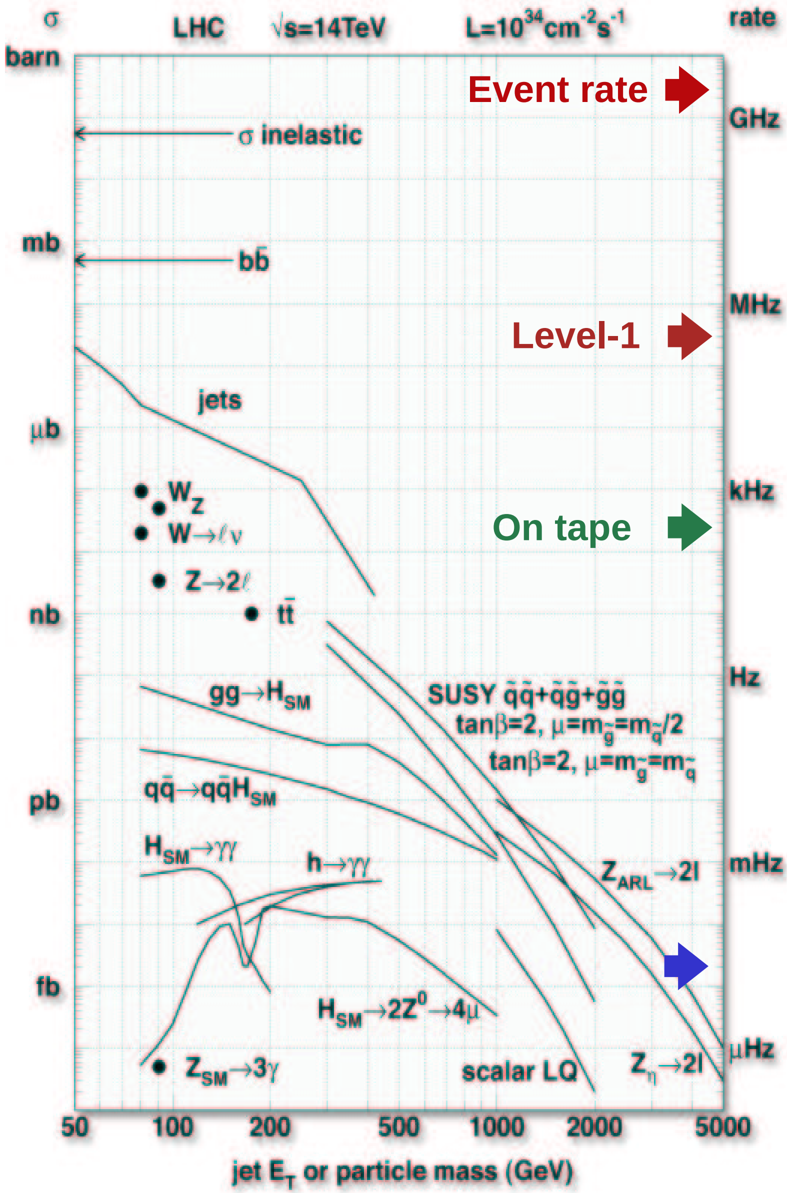
- Need **large reduction of rate** from unwanted high-rate processes (capabilities of DAQ and also offline farms)
  - Instrumental background
  - High-rate physics processes not relevant for analysis

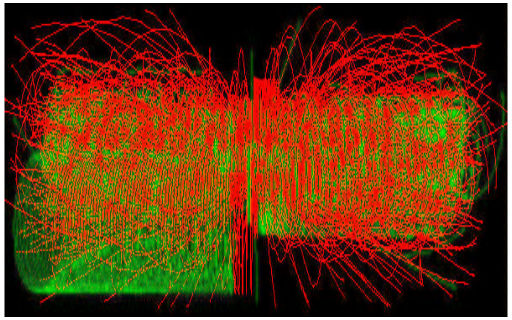
- System must be **affordable**
  - Limits complexity of algorithms that can be used



"During one second of CMS running, a data volume equivalent to 10,000 Encyclopaedia Britannica is recorded"

p-p collisions at LHC





ATLAS / CMS

Event Rates: ~10^9 Hz

Event size: ~1 MB

Level-1 Output	**100 kHz**
Mass storage	**10^2 Hz**
Event Selection:	**~$1/10^{13}$**

Why need *multi-level* triggers?

Multi-level triggers provide:

- Rapid rejection of high-rate backgrounds without incurring (much) dead-time ⇒

Fast first-level trigger (custom electronics)

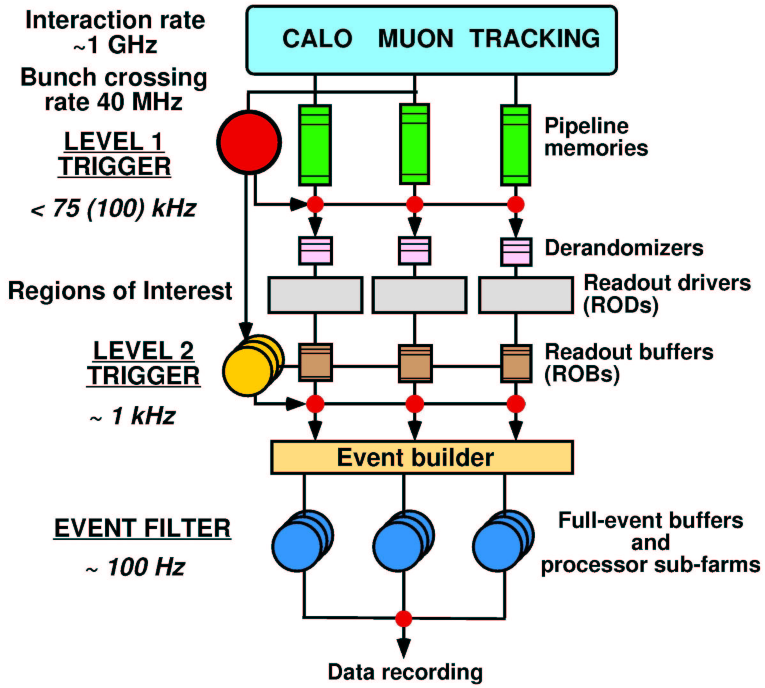
  - Needs high efficiency, but rejection power can be *comparatively* modest
  - Short latency is essential since information from all (up to $O(10^8)$) detector channels needs to be buffered (often on detector) pending result

- High overall rejection power to reduce output to mass storage to affordable rate ⇒

one or more "High" Trigger Levels:

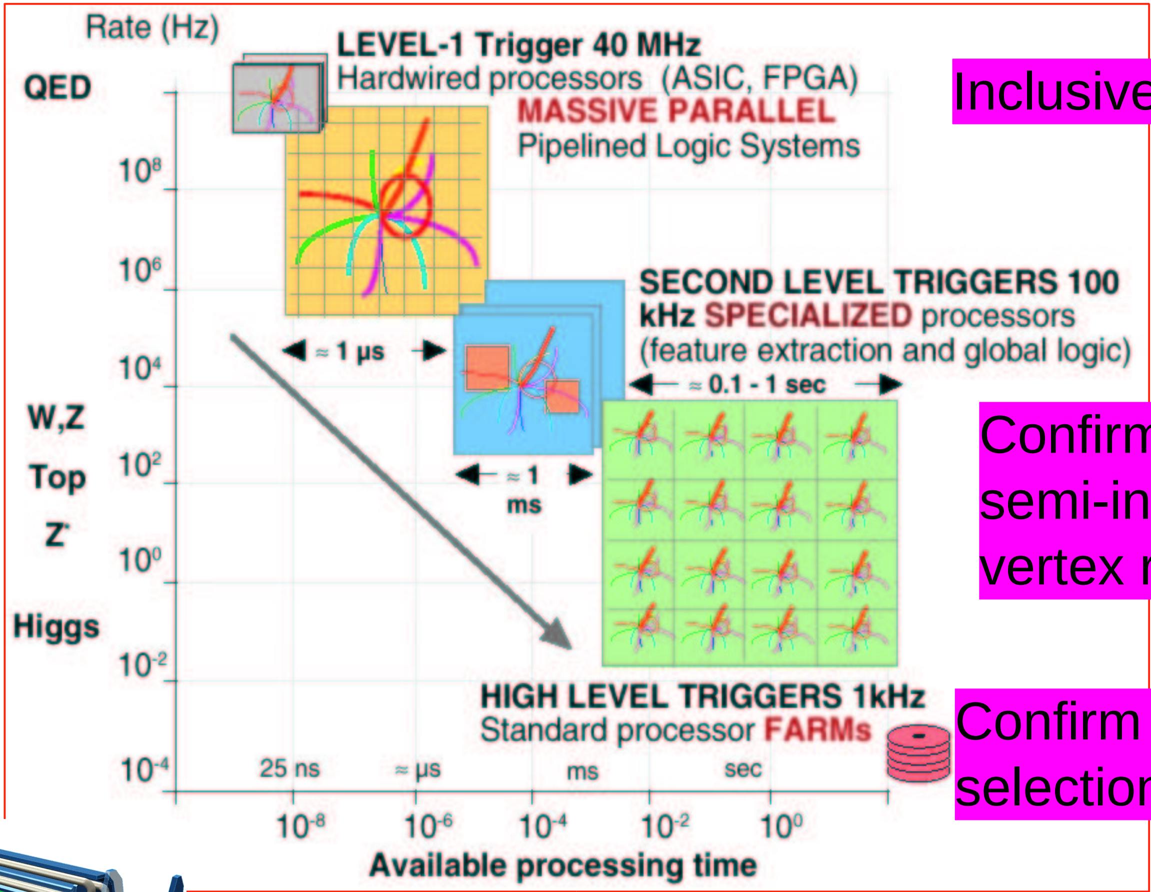
  - Progressive reduction in rate after each stage of selection allows use of more and more complex algorithms at affordable cost
  - Final stages of selection, running on computer farms, can use comparatively very complex (and hence slow) algorithms to achieve the required overall rejection power

Exp.	No of Levels
ATLAS	3
CMS	2
LHCb	3
ALICE	4



ATLAS Trigger

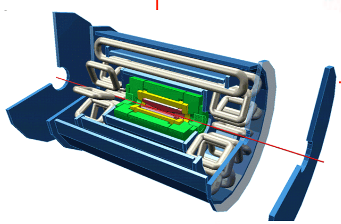
Trigger Rate reduction

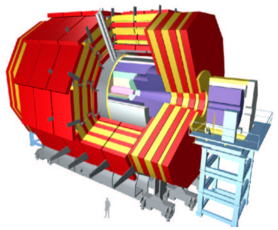


Inclusive trigger

Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

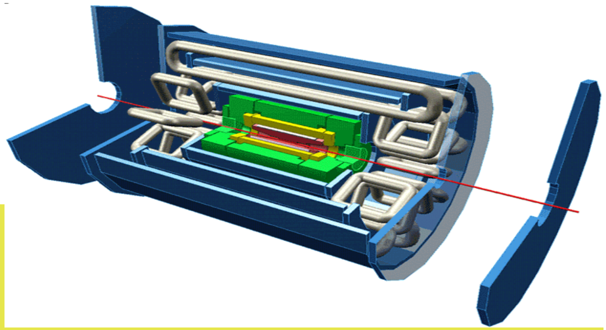
Confirm L2, more refined topology selection, near offline





	N.of Levels	First Level Rate (Hz)	Event Size (Byte)	ReadOut Bandwd (GB/s)	FilterOut MB/s
ATLAS	3	10^5 (LV-2 10^3)	10^6	10	100
CMS	2	10^5	10^6	10^2	100

Trigger baselines and remarks

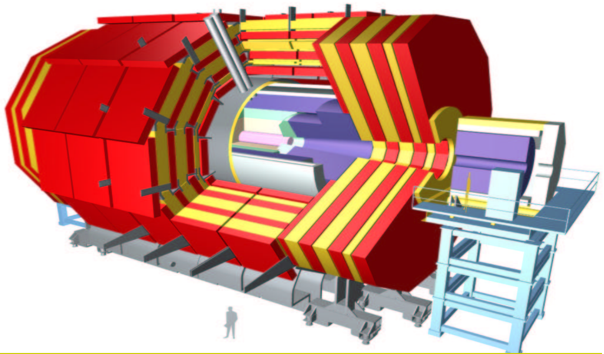


ATLAS

- L2 trigger operates on "ROIs" , nominally 2% of event data, at output of Level-1 (75 kHz, 1MB events, 20 kB ROI data)
- Full event build at L2 rate of ~1 kHz, sent to Event Filter (EF) farm

Risk: not yet completely clear that small ROIs provide enough information

⇒Able to shift boundary between L2, EF somewhat



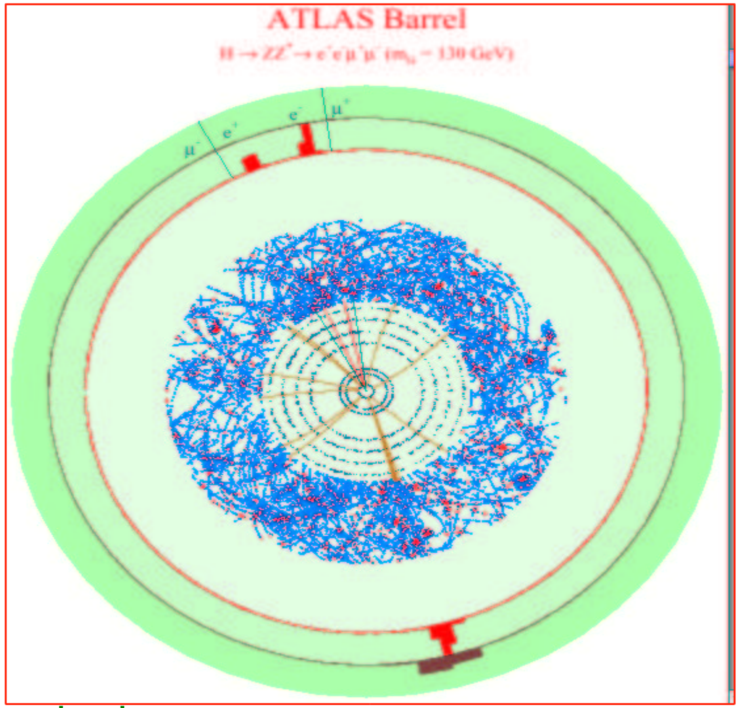
CMS

- Build full events at output of Level-1 : 100 kHz, 1MB events

Risk: there is a lot of data to handle

⇒ Able to fall back to a partial-readout Level 2 model

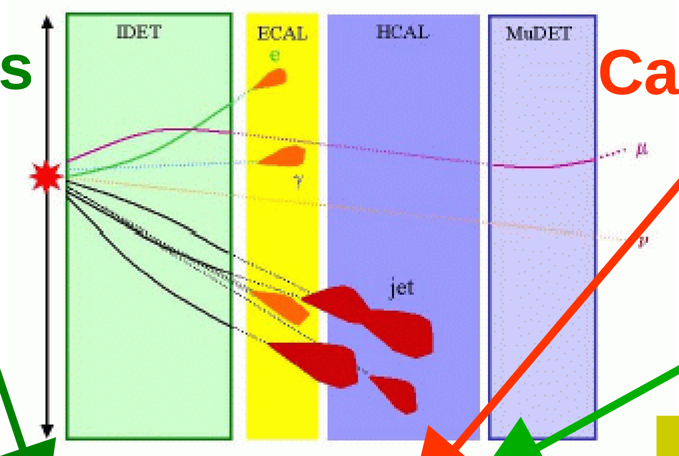
First Level Trigger Requirements



- Rate reduction of a factor of 10^4-10^5
- Each single Bunch Crossing must be processed, so data are held in pipeline
  - Also electronics must be structured in pipelines, each component repeating its specific actions every 25 ns. Pipelines allow a fixed latency of up to 2.5 μs for a trigger decision, then events are sent to ROD
  - Fast dectector responses and data movement are required
  - Logic decisions are taken by custom hardware systems (FPGAs and ASICs)
- BC identification is crucial in order to select the event among hundreds filling the detector each moment
- Redondance of selection criteria ("trigger menus") leads to high trigger efficiency and the possibility to measure it from the data
  - Concurrently select events of a wide range of physics studies
- Must be sufficiently flexible to face possible variations of LHC luminosity, one order of magnitude at least
  - Event characteristics vary with luminosity, due to changings in pile-up, so it's not a simple events rescaling but events with different number of muons, clusters,... must be managed

First Level Trigger Overview

Muon detector signals



Calorimeter signals

BUSY signals

Search for **high-p_T:**

muons
electrons/photons
taus/hadrons
jets

Calculate E_T, missing E_T

Form trigger decision for each BC based on combinations of above

Decision every 25 ns
Latency ~few μs

First-level Trigger

Yes/No

Introduce deadtime to avoid data loss or buffer overflow in front-end electronics

Distribute first-level trigger decision to front-end electronics

Less than 3 μs for trigger decision, while data are held in pipelines

Level-1 Trigger p_T cut

- In contrast to particles produced in typical pp collisions (typical hadron $p_T \sim 1$ GeV), products of new physics are expected to have large p_T
  - E.g. if $m_H \sim 100$ GeV $\Rightarrow p_T \sim 50$ GeV
- At low p_T, muons from K and π decays, and from b- and c-quarks are the large background: precise measurement of p_T is needed. Since they are produced in jets, isolation criteria based on energy deposited around the muon in the calorimeter or trackers are used
- Typical first-level trigger thresholds for LHC design luminosity
  - Single muon $p_T > 20$ GeV (rate ~ 10 kHz)

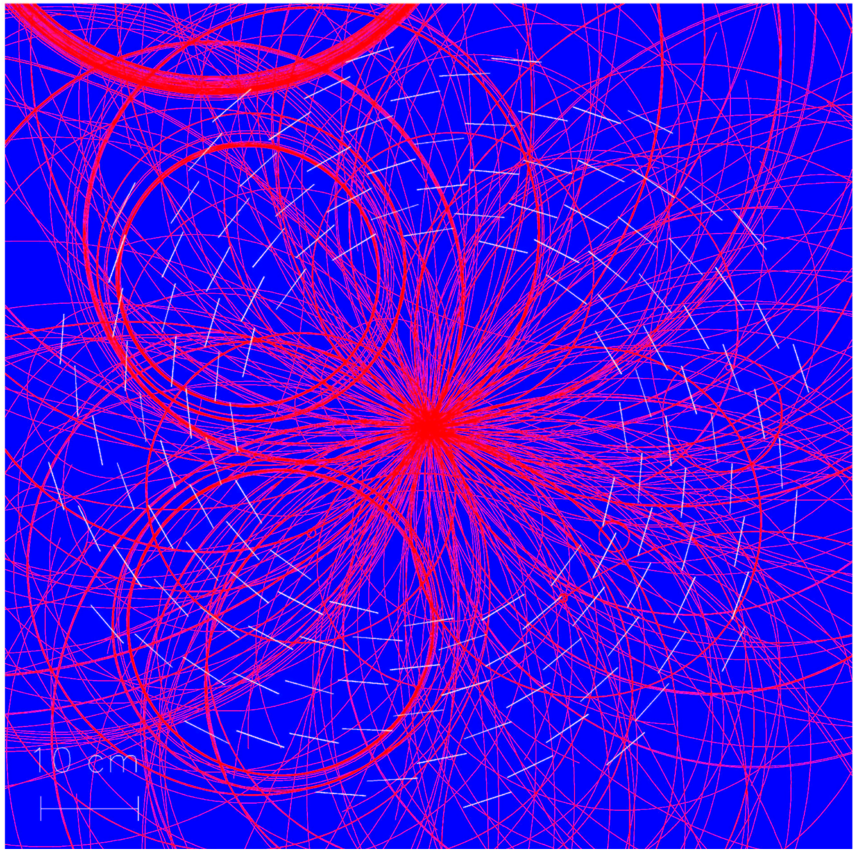
    Pair of muons each with $p_T > 6$ GeV (rate ~ 1 kHz)
  - Single e/γ $p_T > 30$ GeV (rate ~ 10-20 kHz)

    Pair of e/γ each with $p_T > 20$ GeV (rate ~ 5 kHz)
  - Single jet $p_T > 300$ GeV (rate ~ 200 Hz)

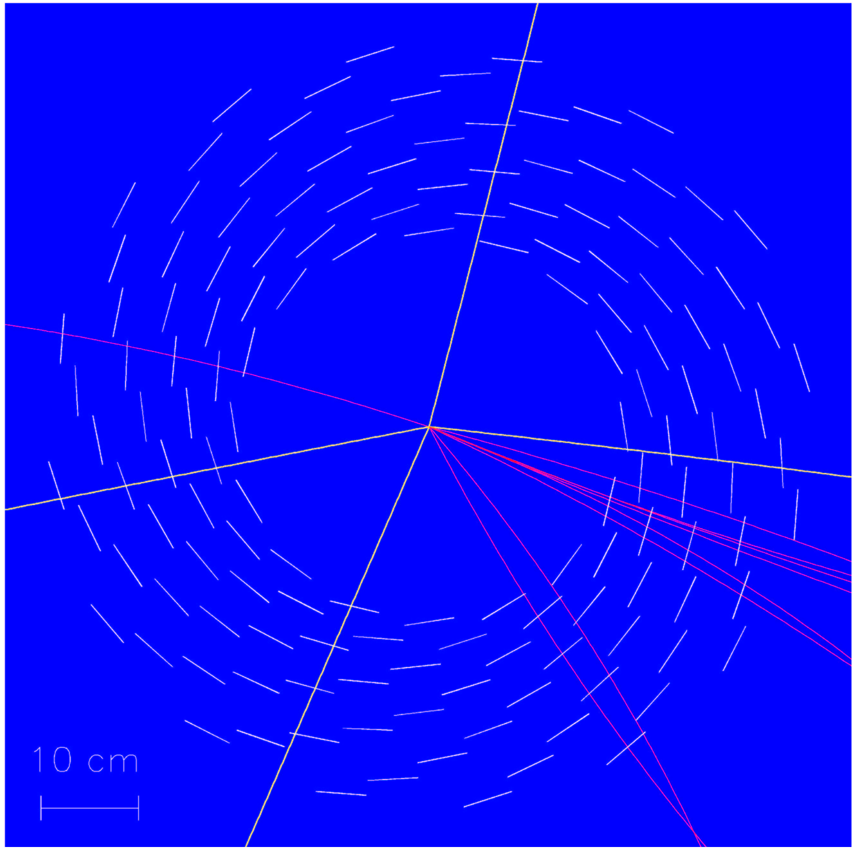
    Jet $p_T > 100$ GeV and missing-$p_T > 100$ GeV (rate ~ 500 Hz)

    Four or more jets $p_T > 100$ GeV (rate ~ 200 Hz)
- Very inclusive triggers keep the thresholds sufficiently low to be sensitive to decay products of new particles and to leptons from Z and W decays. (LHC is a discovery machine!)
  - Also important to understand the background and low energy spectrums.
  - Ensure safe overlap with potential RunII at the Tevatron

Effect of p_T cut in minimum-bias events



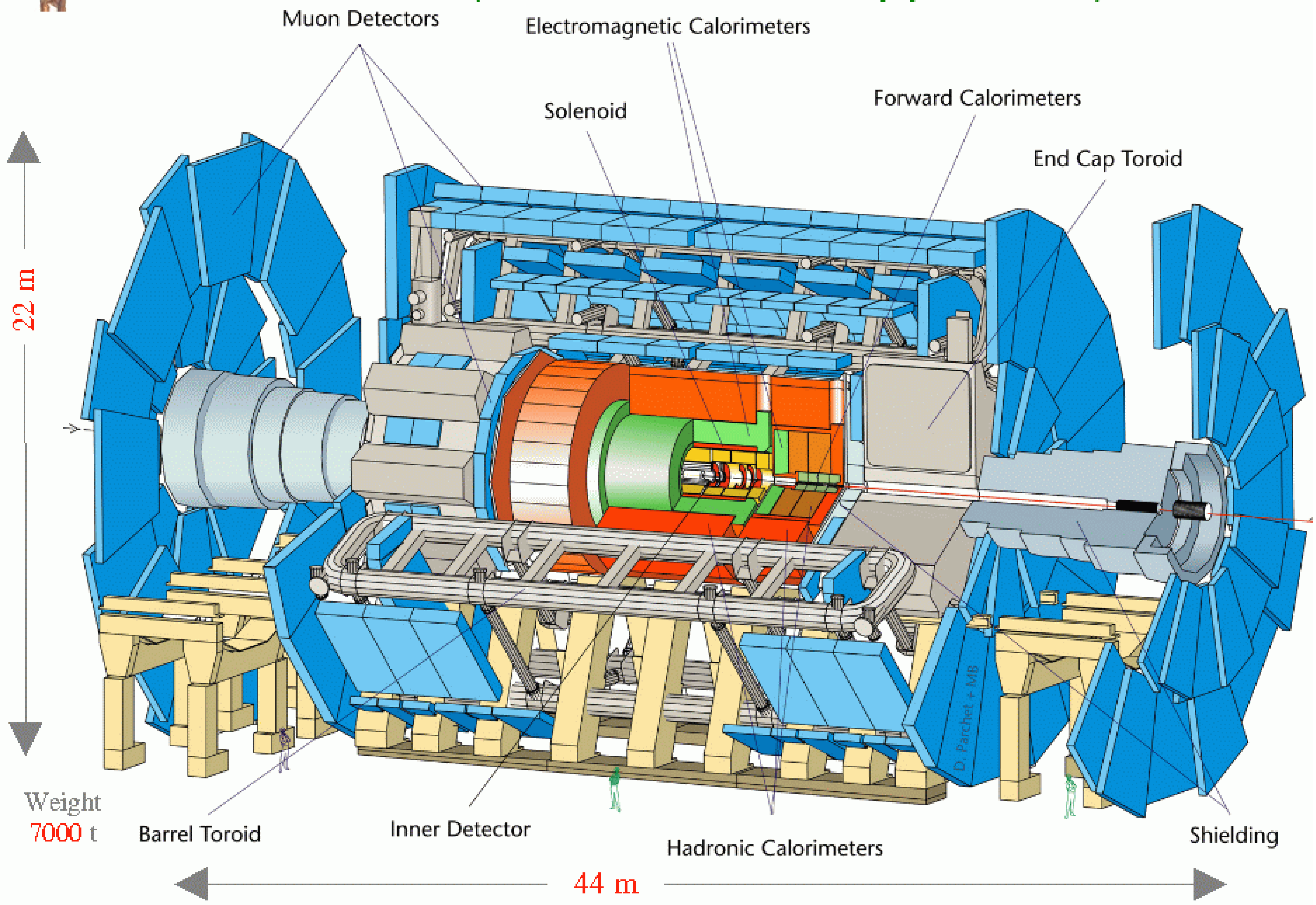
All tracks



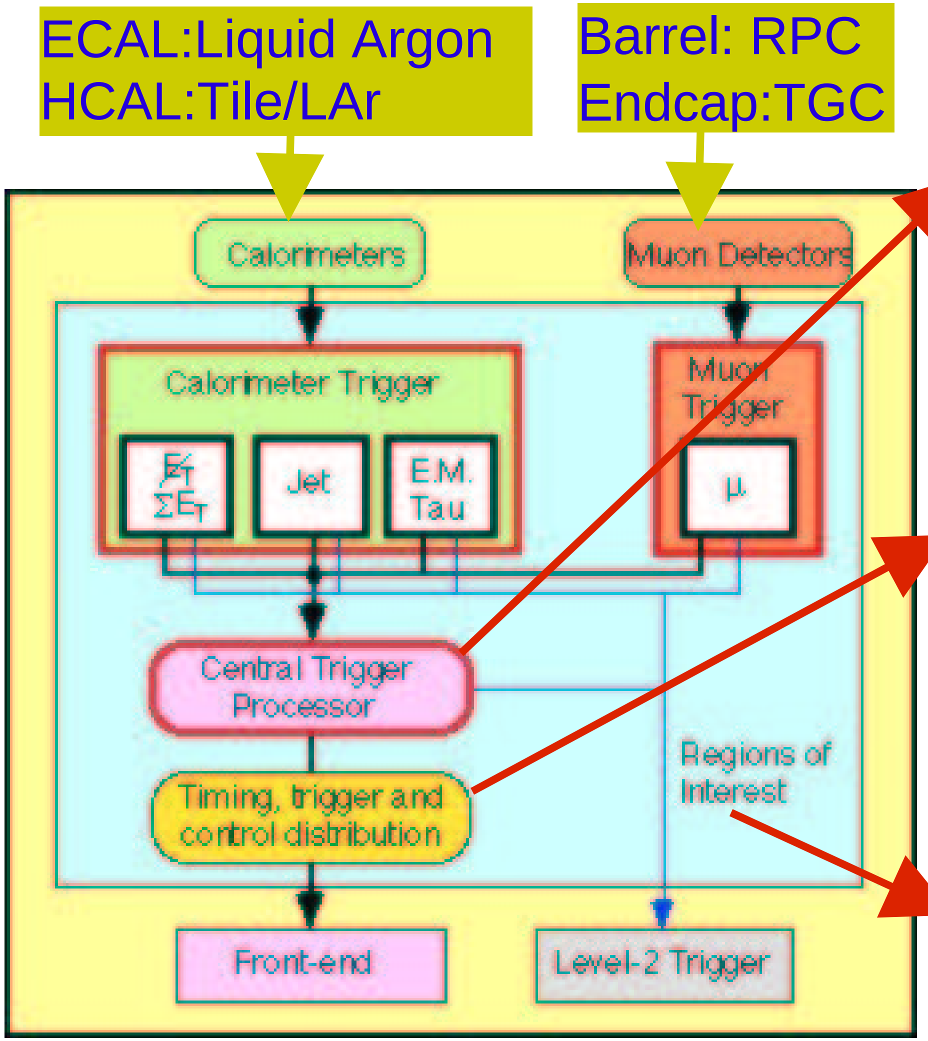
$p_T > 2$ GeV

Simulated H ⇒4μ event + 17 minimum-bias events

ATLAS (A Toroidal Lhc ApparatuS)



ATLAS Level-1 Trigger Structure



CTP makes the final decision based on multeplicities of identified trigger objects, using p_T thresholds and global energy variables

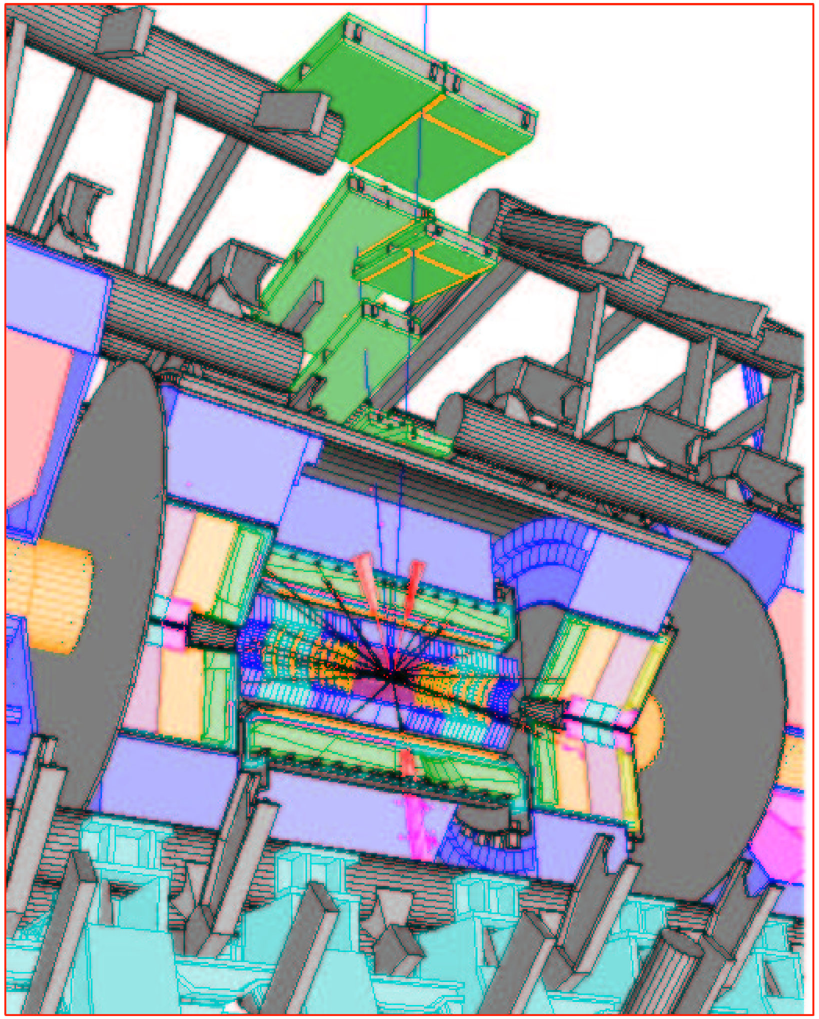
Decisions are sent via the TTC system to the Front End electronics

For accepted events the LVL1 trigger sends readout information to the RoI Builder which assembles the list of RoIs for the event, to be used by LVL2

ATLAS Trigger Segmentation: the Region of Interest

The Level-1 selection is dominated by local signatures

- Based on coarse granularity (calo, mu trig chamb), w/out access to inner tracking
- Important further rejection can be gained with local analysis of full detector data



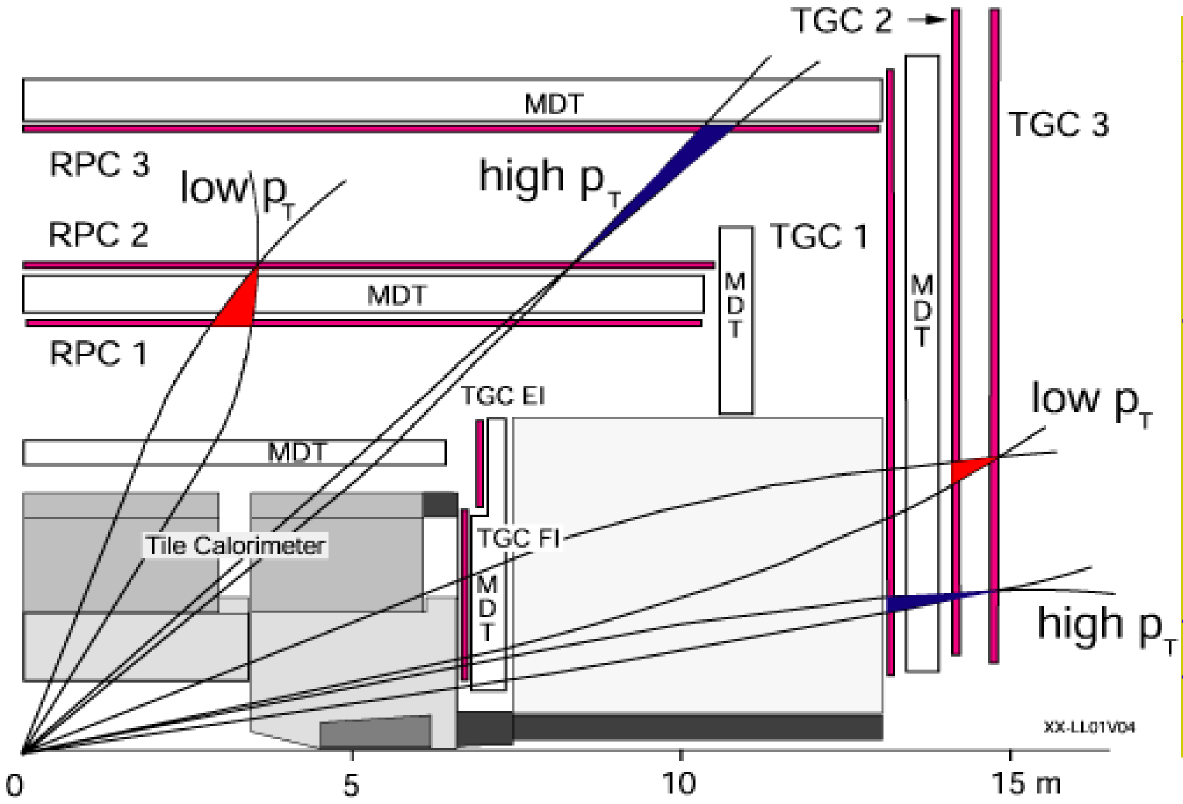
The geographical addresses of interesting signatures identified by the LVL1 (Regions of Interest)

- Allow access to local data of each relevant detector
- Sequentially

Typically, there are less than 2 RoIs per event accepted by LVL1 (~1.6)

The resulting total amount of RoI data is minimal : a few % of the Level-1 throughput

ATLAS LVL1 Muon Trigger



Algorithm requires coincidence of hits within a road, which is related to the p_T threshold applied.

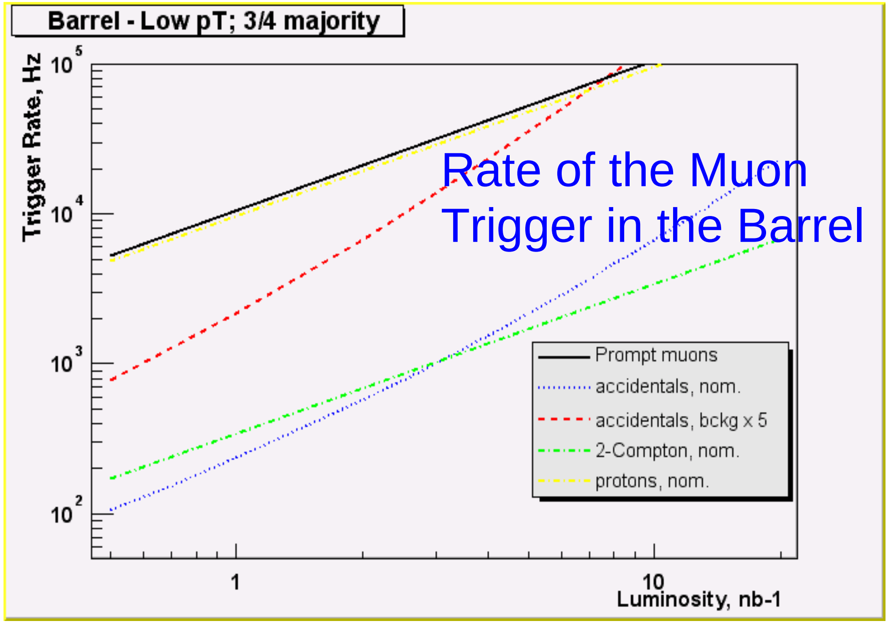
Two algorithms are applied: Low and High p_T.

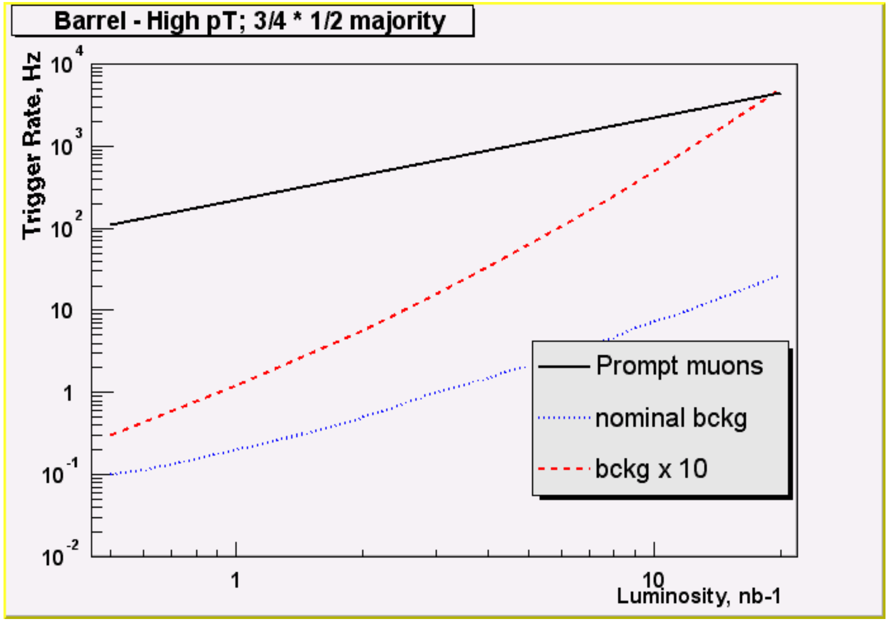
Programmable coincidence logic allows multiple thresholds to be used at the same time, 3 for each Low and High algorithm

Fast and high redundancy system

1. Wide p_T-threshold range
2. Safe Bunch Crossing Identification
3. Strong rejection of fake muons (induced by noise and physics background)

ATLAS LVL1 Trigger: performances



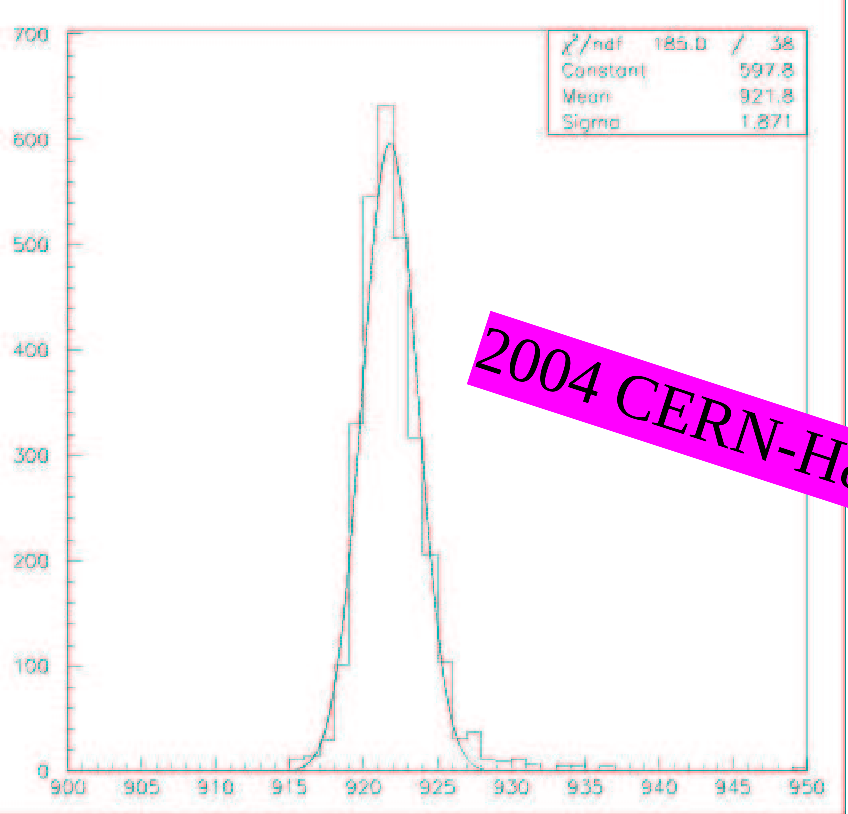


- Requirement for cosmic-ray and beam-halo triggers included in design
  - e.g. trigger ASICs include programmable delays to compensate for TOF of down-going cosmic-ray muons in barrel
- Projectivity constraints mainly from cabling between planes of trigger chambers. However system is flexible, e.g. can change coincidence requirements

The total expected rate in ATLAS at L=10^{34} is about 40 kHz (whith a safety factor of 2).

Rate is dominated by the single EM trigger which has a rate of more than 20kHz

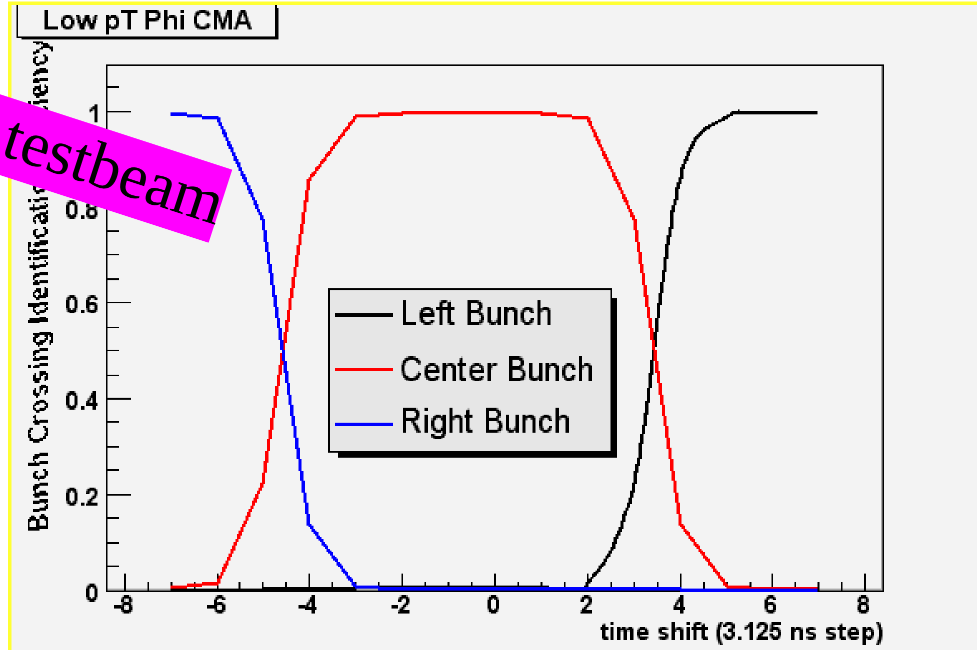
ATLAS: RPC trigger BC capability, 25 ns run



Readout system time resolution
σ=1.9 ns

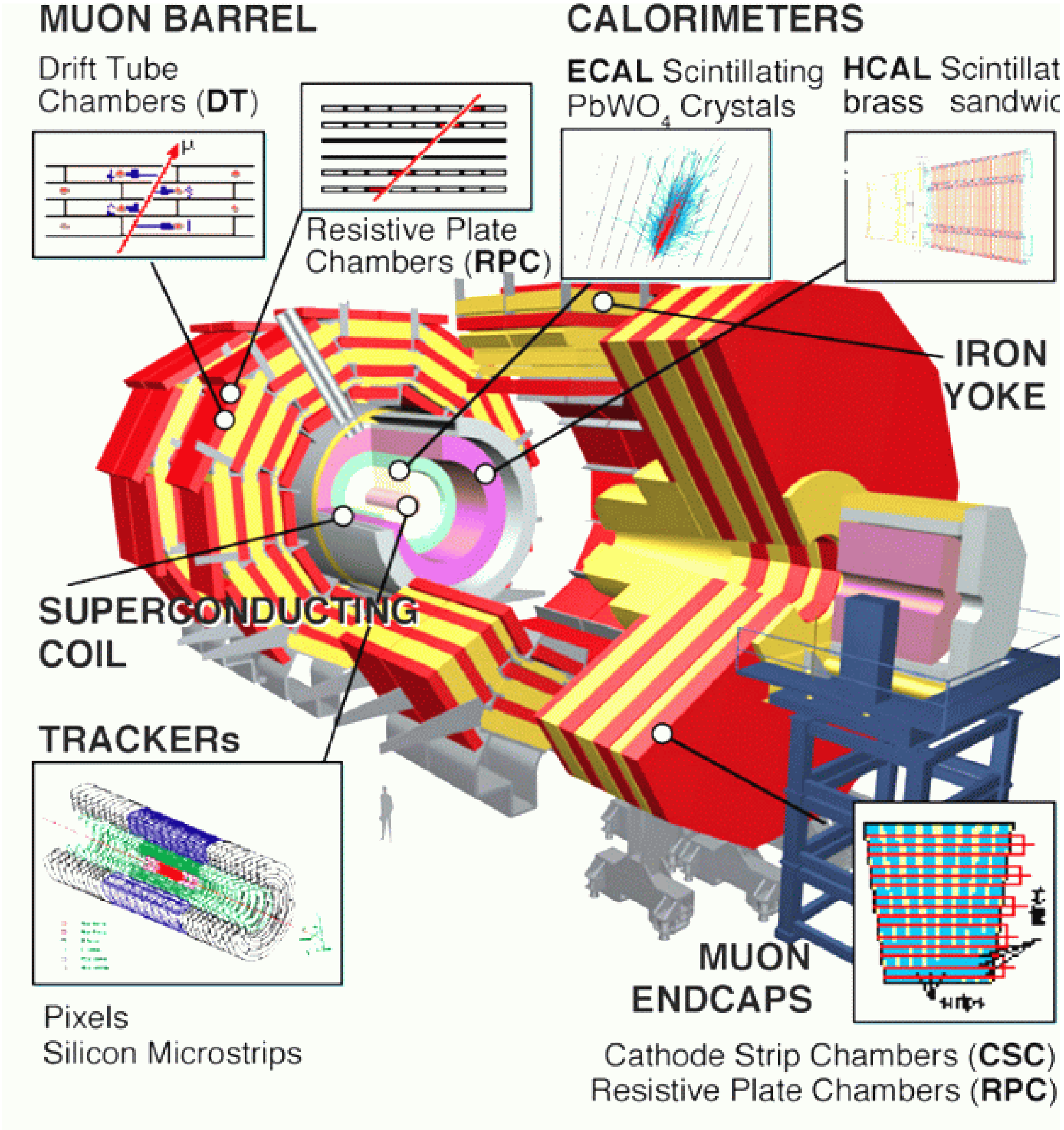
CM ASIC uses 1BC/8 LSB time interpolator to measure time of arrival of RPC hits and trigger output

2004 CERN-H8 testbeam



Low-Pt trigger Bunch counter
Identification efficiency vs pipeline delay

CMS (Compact Muon Solenoid)

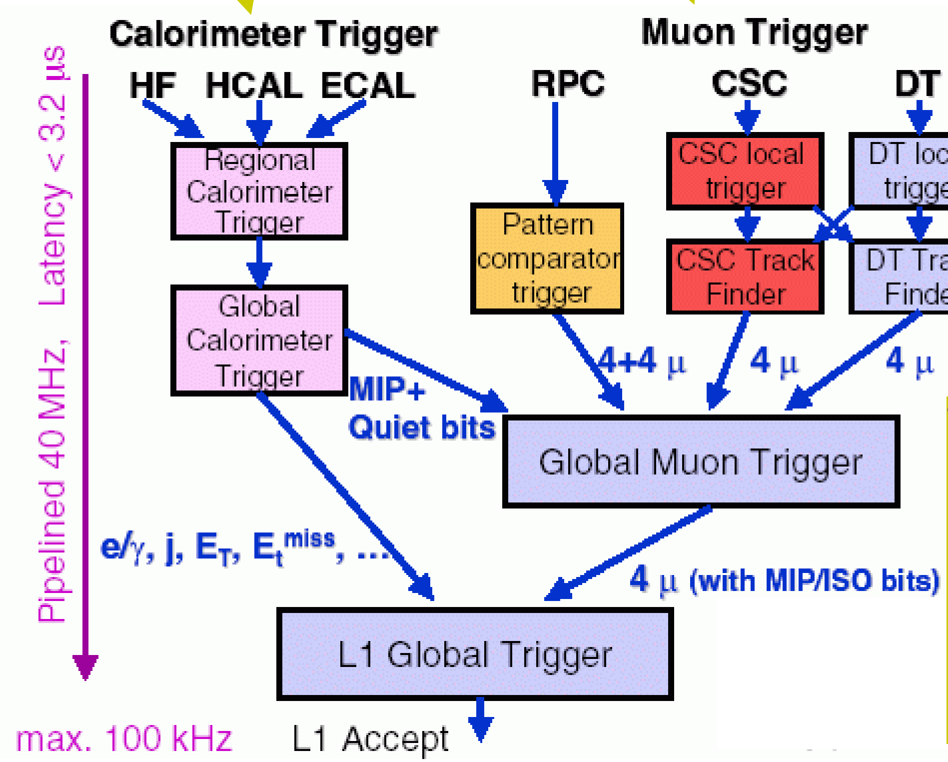


Total weight : 12,500 t	Overall length : 21.6 m
Overall diameter : 15 m	Magnetic field : 4 Tesla

CMS Level-1 Trigger

ECAL: lead-Tungstate Crystals
HCAL: sc+cupper absorber plates
HCAL Forward: sc+steel absorber plates

Barrel: Drift Tubes
EndCaps: Cathod Strip Chambers
Barrel + EndCaps: RPC (for BC identification)



Trigger decision is held in 3.2 μs, but only 1 μs is needed, rest is due to cable length

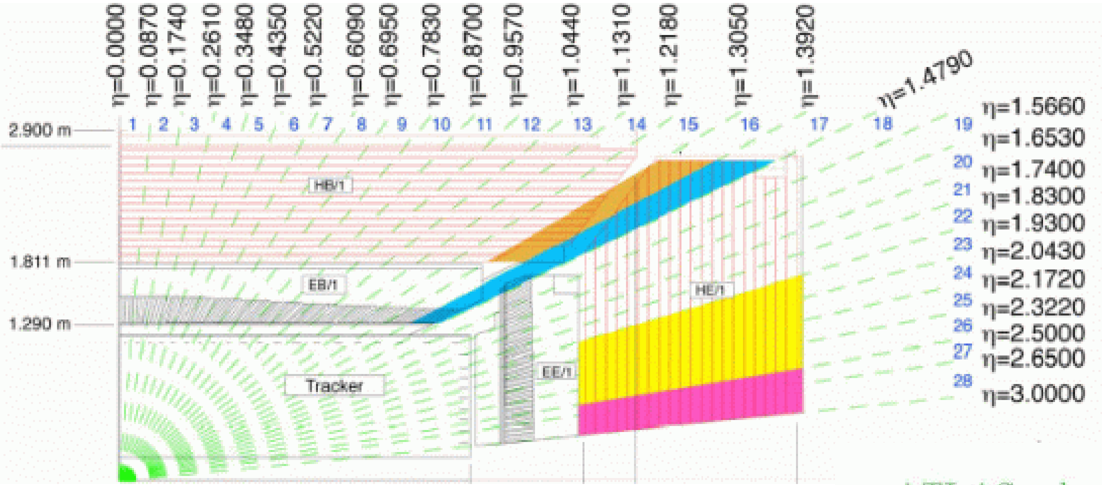
The Global Muon Trigger receives 4 muons candidate of maximum p_T, selects the best quality candidates (n.of hits, matched track segments, responses by the 3 detectors) $\Delta\eta x \Delta\phi$ = 0.35x0.35 rad

The Global Calorimeter Trigger selects the best 4 e,γ (separately single and not), τ and jets. It calculates the total E_T and the E_T missing vector

The Global Trigger applies the thresholds and performs the trigger algorithms.

Up to 128 algorithms can run in parallel: arbitrary combinations of trigger objects passing thresholds and topological correlations

CMS calorimeter trigger



Segmentation

Barrel: Energy Tower=25 ECAL crystals ($5\eta x 5\phi$)

EndCap: 10 to 25 crystals per Tower, no $\eta x \phi$ geometry

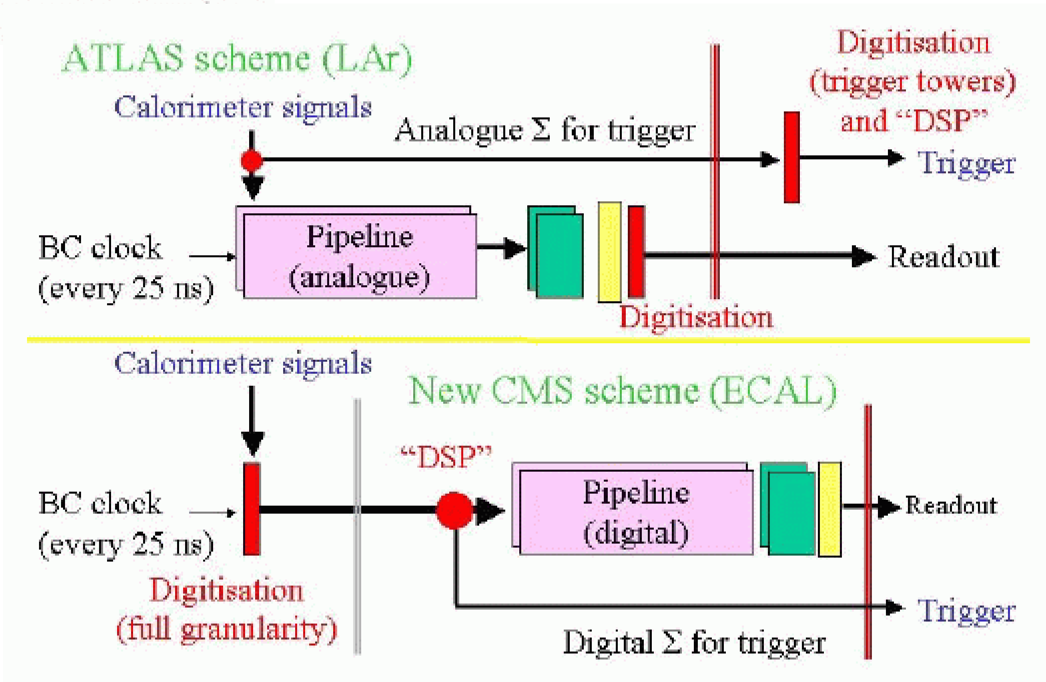
HCAL: follows the ECAL geometry

HF: used for seamless jets and missing E_T, coarser segmentation in ϕ

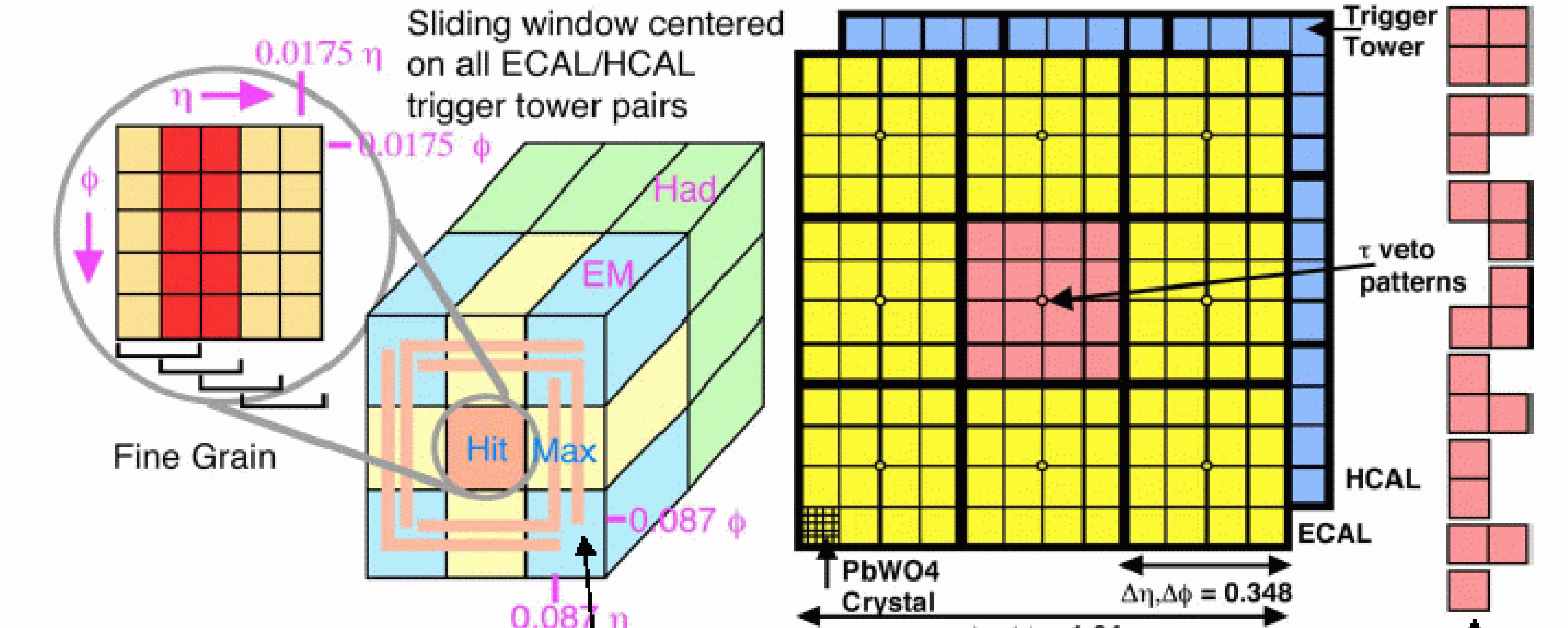
On-detector electronics digitizes analog signals at 40MHz with the full detector granulanity

Off-detector the trigger towers are formed by digital summation

The signal is processed in order to associate the measured energy to the correct BC. This is done with a Finite Impulse Response filter, that sends its results to a look-up table to convert to E_T and to a peak finder which determines the BC



CMS Calo Trigger Algorithms



Electron (Hit Tower + Max)

- 2-tower ΣE_T + Hit tower H/E
- Hit tower 2x5-crystal strips >90% E_T in 5x5 (Fine Grain)

Isolated Electron (3x3 Tower)

- Quiet neighbors: all towers pass Fine Grain & H/E
- One group of 5 EM E_T < Thr.

Jet or τ E_T

- 12x12 trig. tower ΣE_T sliding in 4x4 steps w/central 4x4 E_T > others

τ: isolated narrow energy deposits

- Energy spread outside τ veto pattern sets veto
- Jet ≡ τ if all 9 4x4 region τ vetoes off

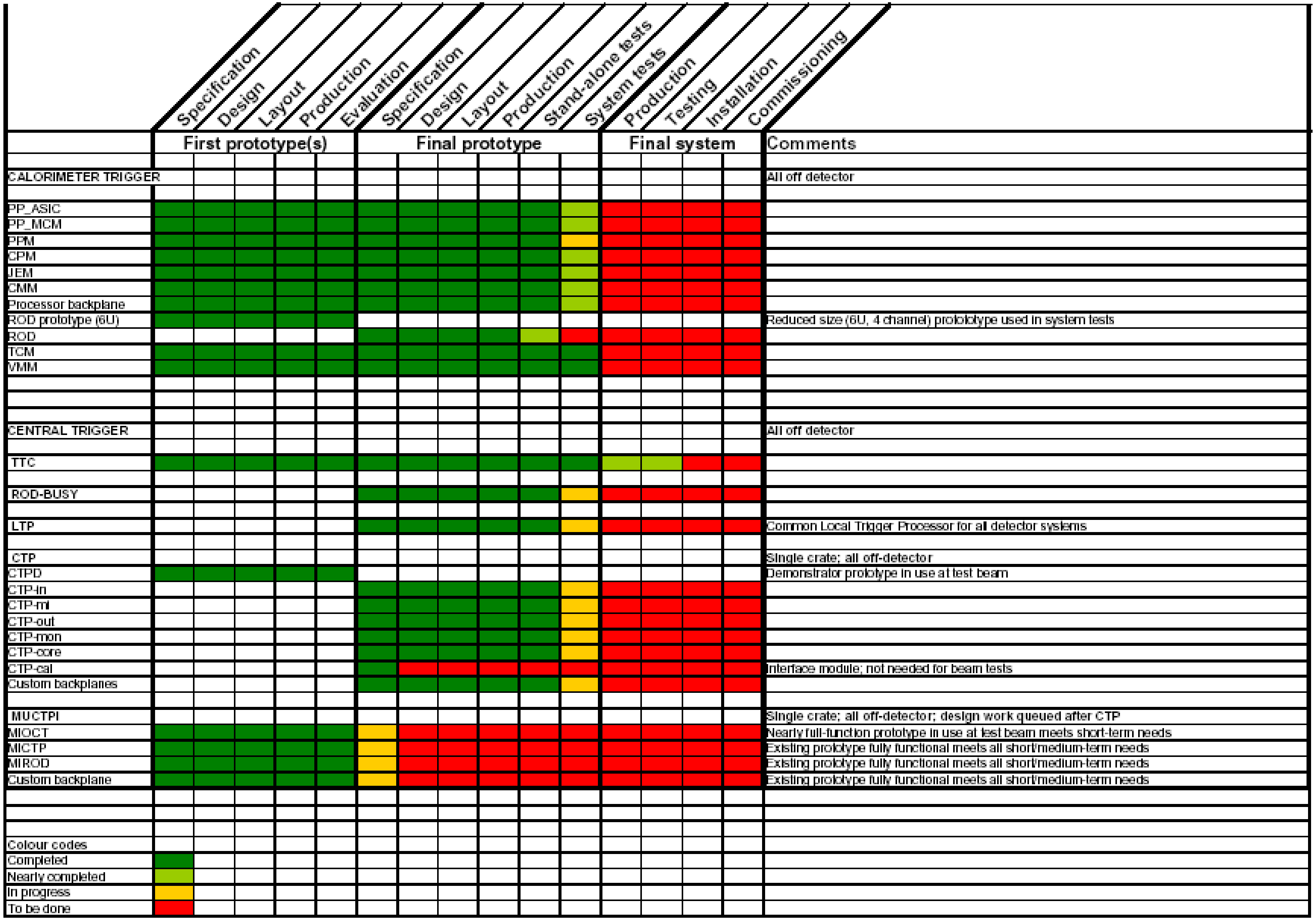
Conclusions

- First-level triggers for both ATLAS and CMS represent a huge challenge. They have a direct impact on the exploitation of the physics program
- Multi-Level selection can handle the high p-p collision rate and rejects events with no physics interest
  - 100 kHz is only 10^{-4} of the interaction rate!
- The implementation is based on new technologies for data taking and transport
- System scalability is essential to face staging/deferral scenarios of the LHC detectors
- Trigger systems flexibility important for event selection of unknown physics

ATLAS Commissioning

- Full system of prototype level-1 trigger now being evaluated at the test-beam
  - First time for calorimeter trigger and CTP
  - Builds on previous test-beam experience for muon trigger
- Full set of algorithmic slices
  - Calorimeters - Receivers - Pre-Processor - Cluster Processor - CTP
  - Calorimeters - Receivers - Pre-Processor - Jet/energy Processor - CTP
  - RPCs - Splitters/Pads - Sector Logic - MUCTPI - CTP
  - TGCs - PS packs - HPT - Sector Logic - MUCTPI - CTP
- Readout and control paths functional
  - But not yet final RODs at test-beam

	Specification	Design	Layout	Production	Evaluation	Specification	Design	Layout	Production	Stand-alone tests	System tests	Production	Testing	Installation	Commissioning	
	First prototype(s)					Final prototype						Final system				Comments
MUON TRIGGER																
Barrel																
On-detector part																
CM_ASIC																Critical item; very urgent to produce prototypes of final design
Splitter boards																Preproduction completed
Motherboards																Preproduction completed
Daughterboards																Preproduction completed
Mechanics																Preproduction completed
Pad boards																
Motherboards																
Pad-OR																
CM-eta																Prototype uses previous prototype ASIC
CM-phi																Prototype uses previous prototype ASIC
Mechanics																
On-detector cables																
Optical link																
Off-detector part																
RX boards																
Custom backplane																
Sector Logic boards																Demonstrator prototype can be used with MUCTPI link
Link to MUCTPI																
ROD boards																
Endcap																
On-detector part																
PP_ASIC																
SLB_ASIC																Minor bug fix required; existing prototype OK for chamber & system tests
HPT_ASIC																
PS boards																
Motherboards																
Daughterboards																
DCS board																
Service board																
Mechanics																
On-detector cables																
Near-detector part																
HPT																
SSW																Full-function prototype exists; final version will use anti-fuse FPGAs
HSC																
Off-detector part																
Sector Logic Boards																
ROD																Prototype exists with reduced # channels (used in test beam)
CCI																
Colour codes																
Completed																
Nearly completed																
In progress																
To be done																


Specification
Design
Layout
Production
Evaluation
Specification
Design
Layout
Production
Stand-alone tests
System tests
Production
Testing
Installation
Commissioning
First prototype(s)
Final prototype
Final system
Comments
CALORIMETER TRIGGER
All off detector
PP_ASIC
PP_MCM
PPM
CPM
JEM
CMM
Processor backplane
ROD prototype (6U)
Reduced size (6U, 4 channel) prototype used in system tests
ROD
TCM
VMM
CENTRAL TRIGGER
All off detector
TTC
ROD-BUSY
LTP
Common Local Trigger Processor for all detector systems
CTP
Single crate; all off-detector
CTPD
Demonstrator prototype in use at test beam
CTP-in
CTP-mi
CTP-out
CTP-mon
CTP-core
CTP-cal
Interface module; not needed for beam tests
Custom backplanes
MUCTPI
Single crate; all off-detector; design work queued after CTP
MIOCT
Nearly full-function prototype in use at test beam meets short-term needs
MICTP
Existing prototype fully functional meets all short/medium-term needs
MIROD
Existing prototype fully functional meets all short/medium-term needs
Custom backplane
Existing prototype fully functional meets all short/medium-term needs
Colour codes
Completed
Nearly completed
In progress
To be done