Online Event Selection at the LHC

Part I: Introduction

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Plan of the Lectures

Lecture 1: Introduction to online event selection at the LHC
Norbert Neumeister

Lecture 2: Regional and partial event reconstruction
Teddy Todorov

Lecture 3: Reconstruction of physics objects
Norbert Neumeister

Lecture 4: Algorithms for track reconstruction
Teddy Todorov

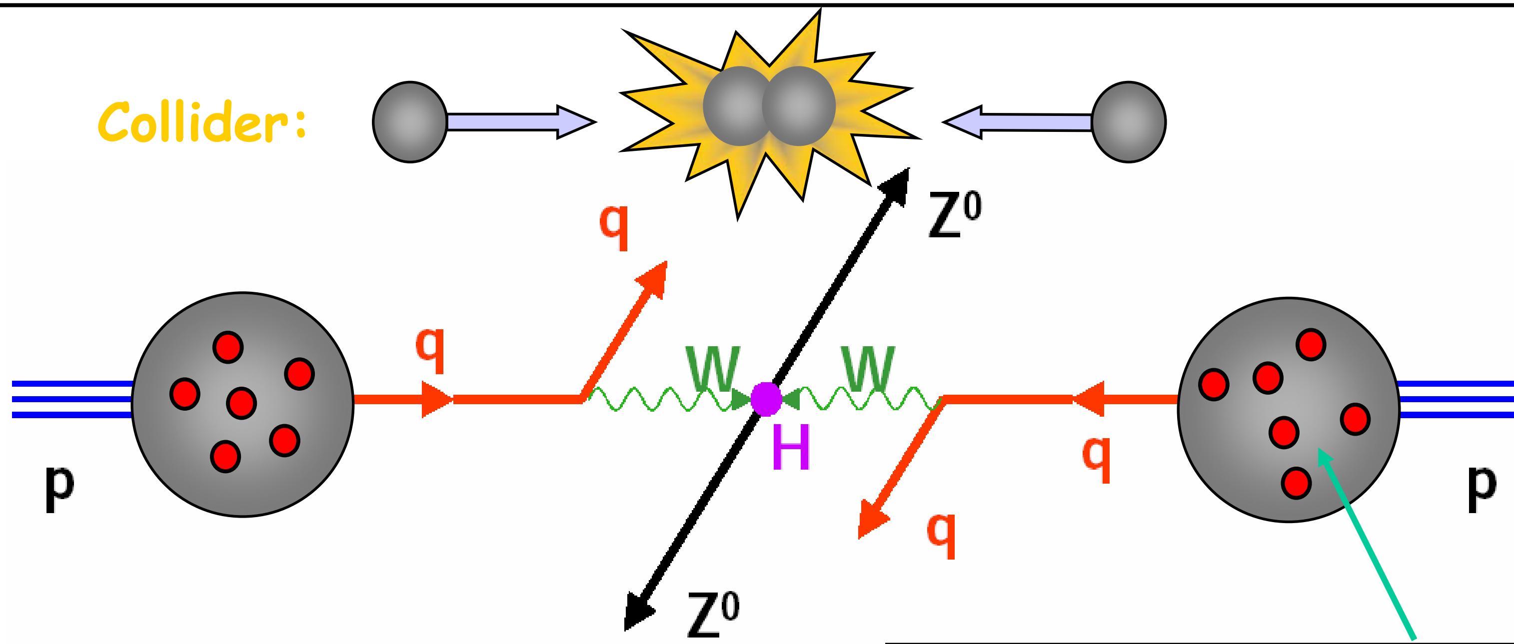
Exercises: Write your own event selection algorithm ☺
Norbert Neumeister, Teddy Todorov

Outline

- Large Hadron Collider
  - The machine and the physics
  - Physics selection strategy
- The Detectors
- Trigger and Data Acquisition Architectures
- Trigger Strategy
- Level-1 Trigger
- High-Level Trigger
  - Requirements
  - Strategy

Physics Goals, Machine Parameters and Detectors

Higgs Production in pp Collisions



M_H ~ 1000 GeV
$E_W \geq$ 500 GeV
$E_q \geq$ 1000 GeV
$E_p \geq$ 6000 GeV

Really colliding 'partons': **qg, qq, gg**
q can be a valence (u,d) or
a sea (virtual) quark (..,s,c,b…).
Momenta given by
Parton Distribution Functions
E_{Quark} is on average
only 1/6 of E_{Proton}

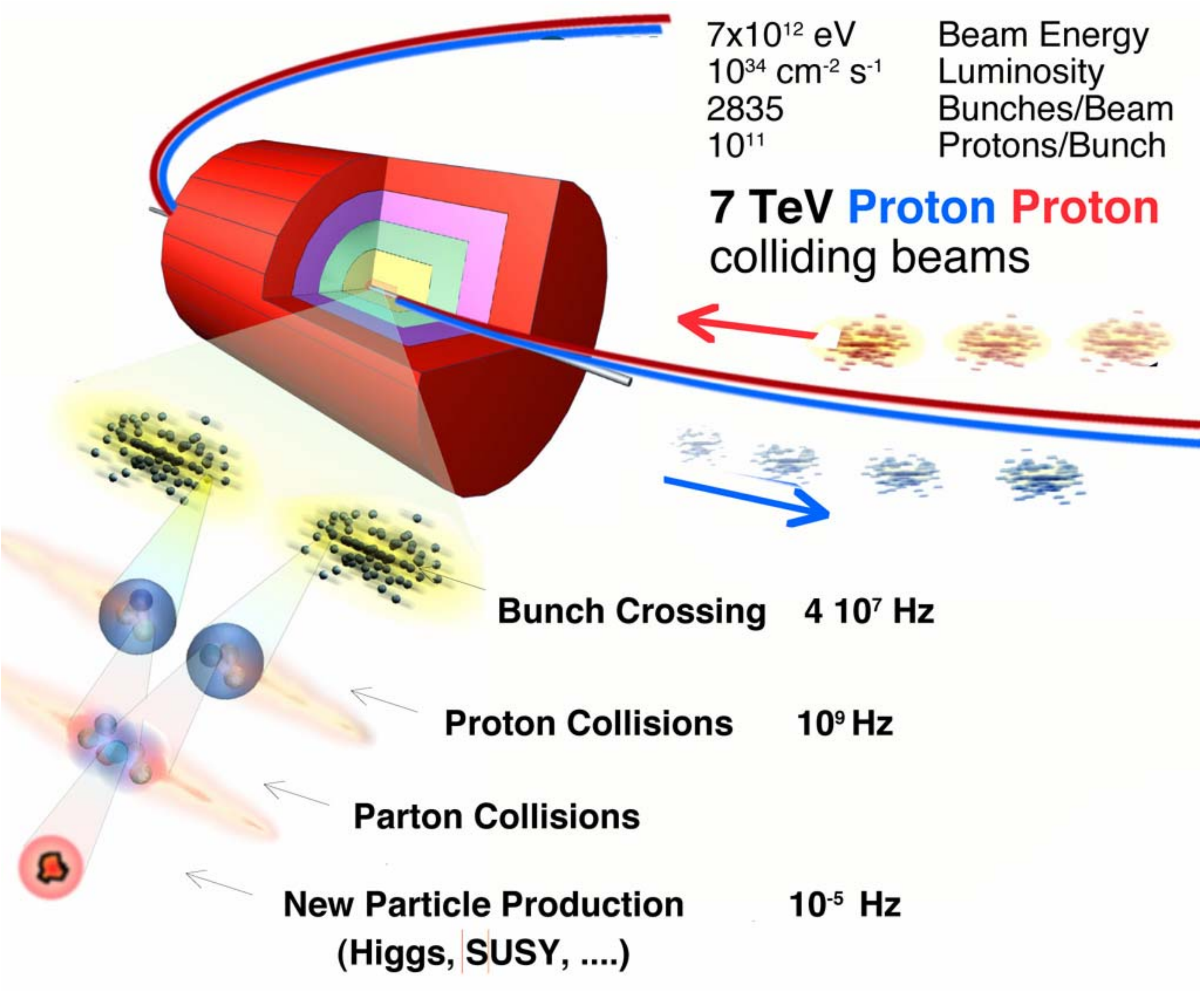
→ Proton-proton collider with $E_p \geq$ 7 TeV

Large Hadron Collider

- Will be installed in the existing LEP tunnel
  - need B = 8.4 T dipole magnets (limits energy)
- E_{cm} = 14 TeV
  - ~7 times higher than present highest energy machine (Tevatron: **2 TeV**)
- Under construction: *ready in 2007*
- Design luminosity: **L = 10^{34} $cm^{-2}s^{-1}$**
  - ~100 times larger than present machines (Tevatron: **10^{32} $cm^{-2}s^{-1}$**)
- Energy and luminosity gives LHC an accessible energy range extended by a factor of 10 compared to the Tevatron.
- Search for:
  - new massive particles up to m ~ 5 TeV
  - rare processes with small cross-sections
- One year at L = 10^{34} $cm^{-2}s^{-1}$ $\rightarrow \int L dt \approx$ 100 fb^{-1}

LHC @ CERN

Large Hadron Collider

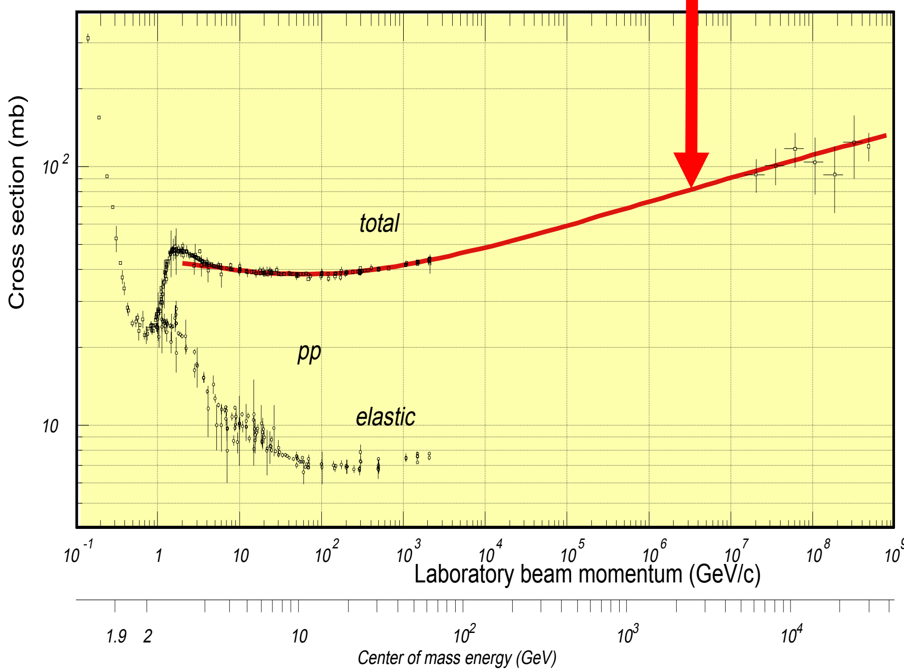


pp Cross Section and Pile-up

Interactions/s:

- Lum = 10^{34} $cm^{-2}s^{-1}$ = 10^{7} mb^{-1} Hz
- $\sigma_{inel}(pp)$ = 70 mb
- Interaction Rate, R = 7×10^{8} Hz

$\sigma(pp) \approx 70$ mb



Events / beam crossing:

- Δt = 25 ns = 2.5×10^{-8} s
- Interactions/crossing = 17.5

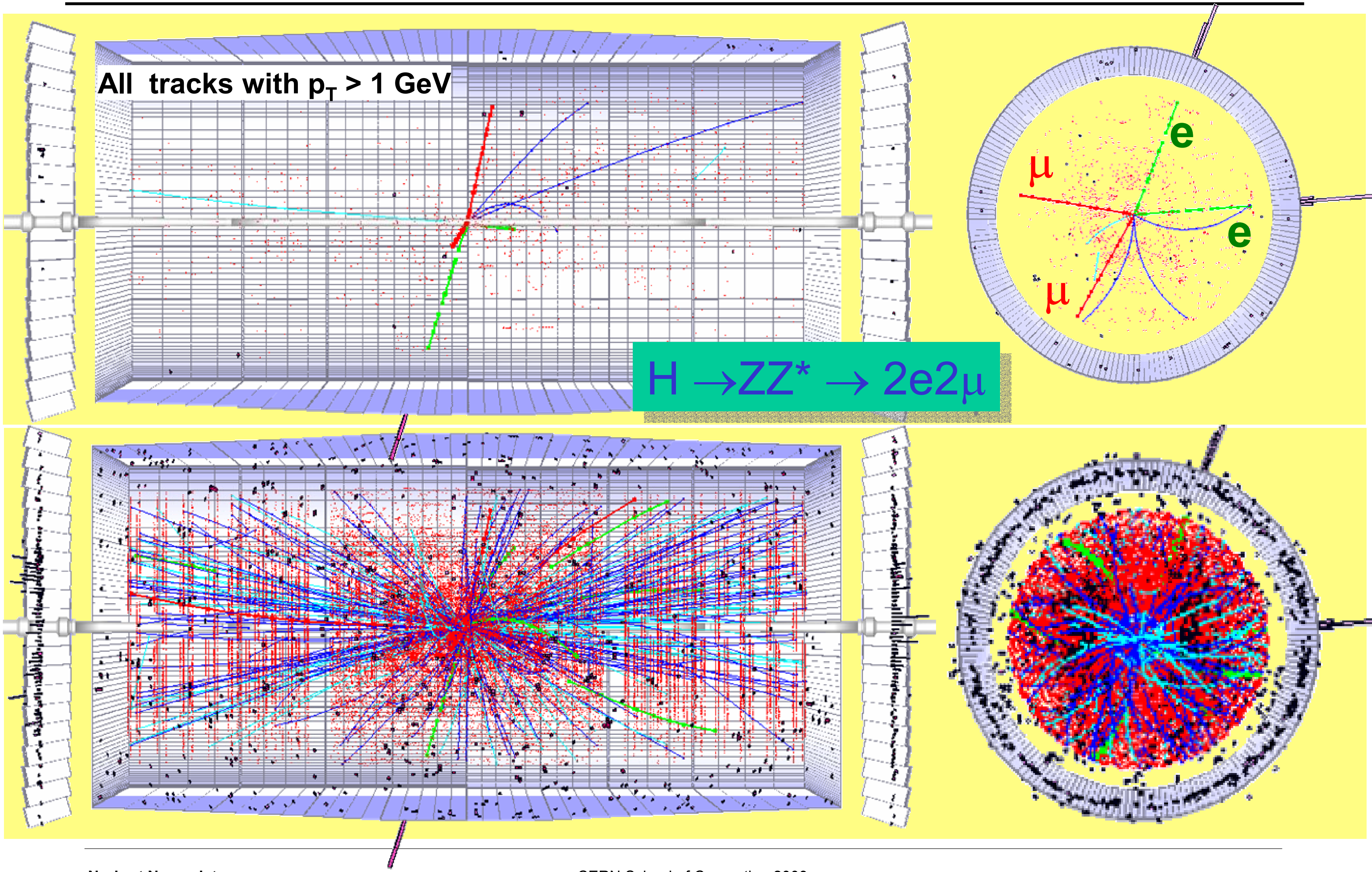
Not all proton bunches are full:

- Approximately 4 out of 5 are full
- Interactions/“active” crossings =
  17.5 × 3564/2835 = 23

Operating conditions:

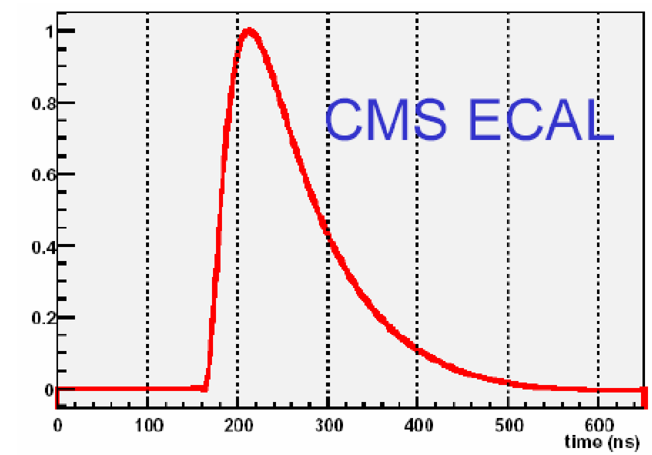
1) A “good” event containing a Higgs decay +
2) ~20 extra “bad” (minimum bias) interactions

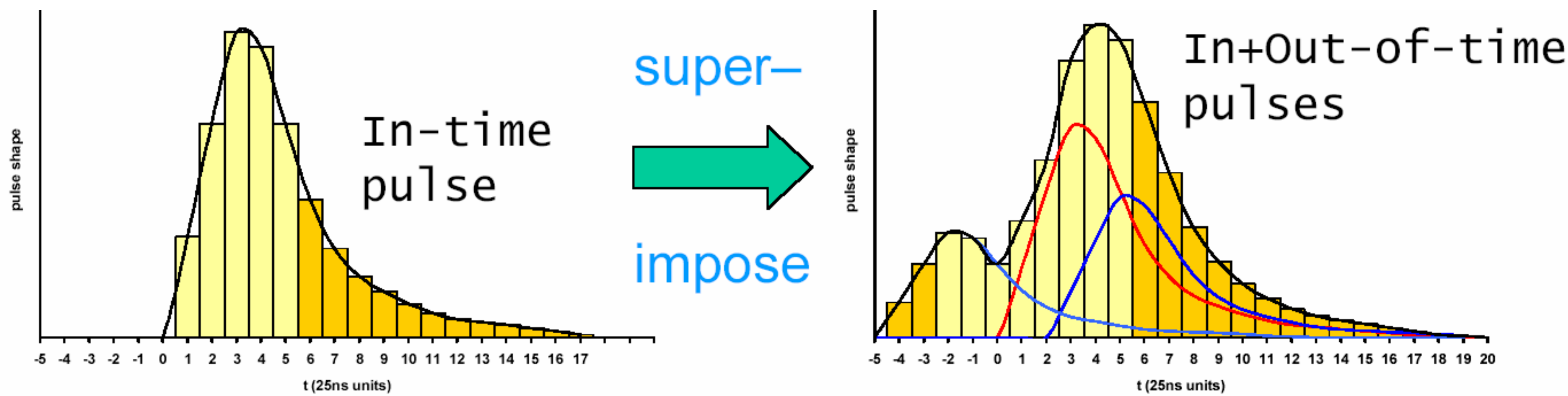
pp Collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$



Pile-up

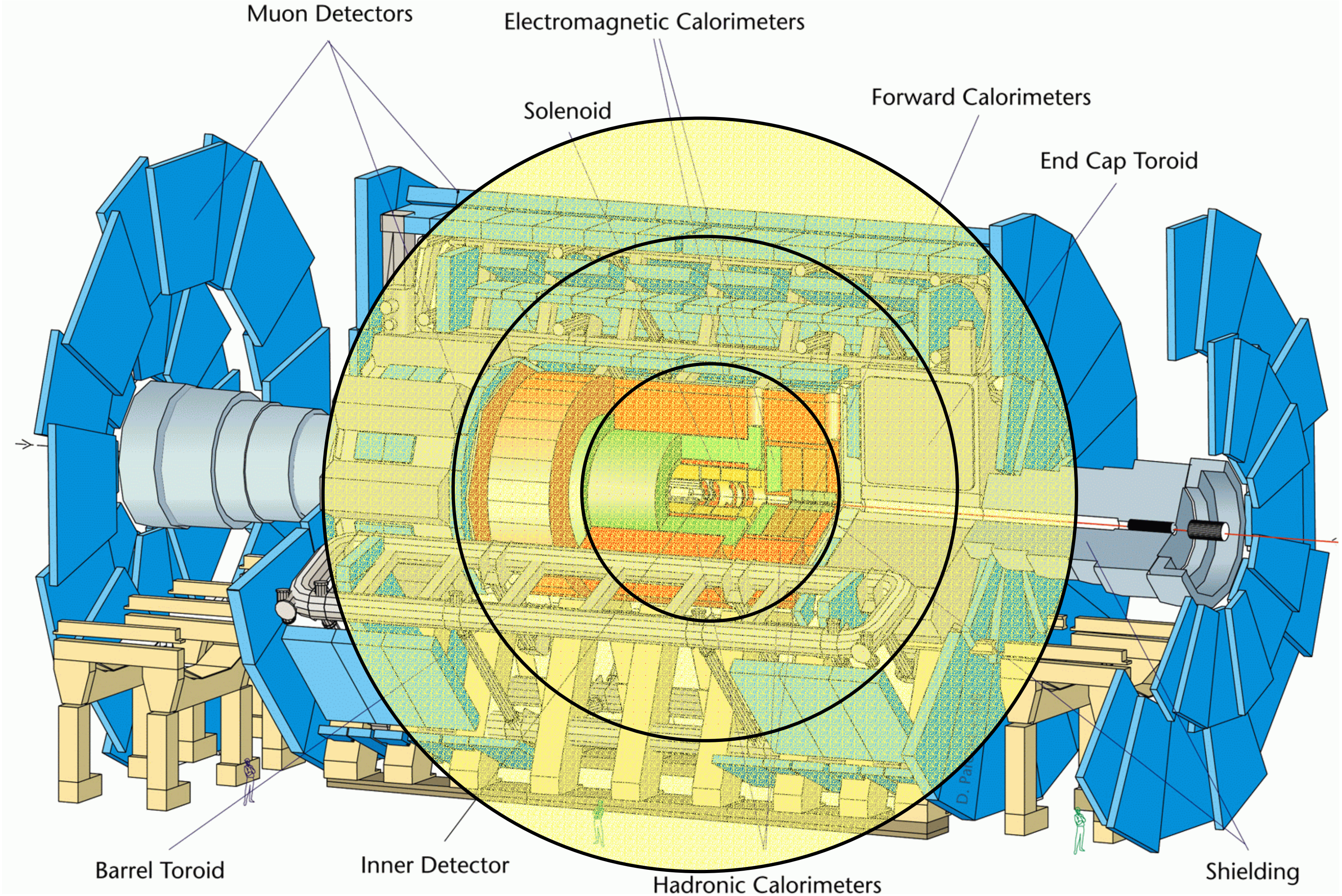
- "In-time" pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"





Time of Flight

c=30 cm/ns; in 25 ns, s=7.5 m

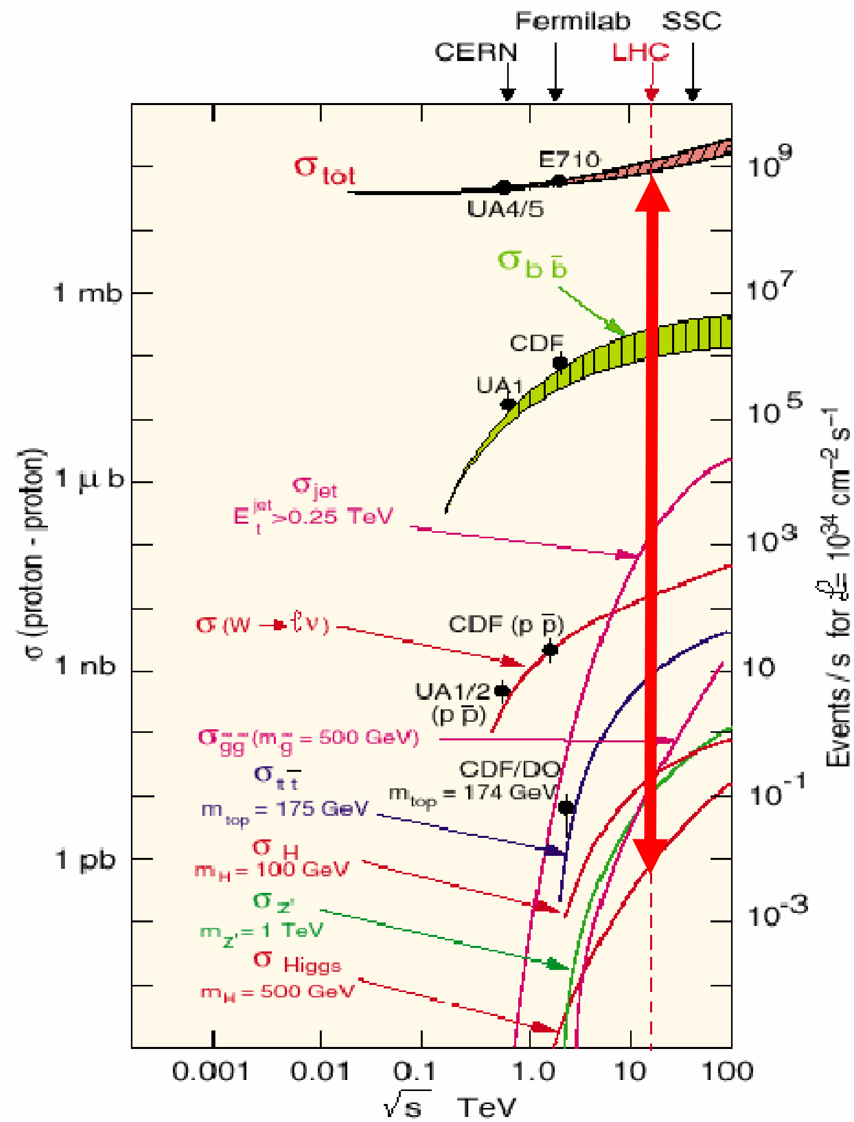


Trigger/DAQ Challenges

- Number of readout channels ≈ $O(10^7)$
  → need huge number of connections
- ~20 interactions every 25 ns
  → need information superhighway
- Calorimeter information should correspond to tracker info
  → need to synchronize detector elements to better than 25 ns
- In some cases: Detector signal > 25 ns
  → integrate more than one bunch crossing's worth of information
- In some cases: Time of Flight > 25 ns
  → need to identify bunch crossing
- Can store data at ≈100 Hz
  → need to reject most interactions
- **Trigger must be efficient, flexible and robust!**

Selectivity: The Physics

- **Cross-sections of physics processes vary over many orders of magnitude:**
  - inelastic: 10^9 Hz
  - $W \to l \nu$: 10^2 Hz
  - $t\bar{t}$ production: 10 Hz
  - Higgs (100 GeV/c^2) : 0.1 Hz
  - Higgs (600 GeV/c^2) : 10^{-2} Hz

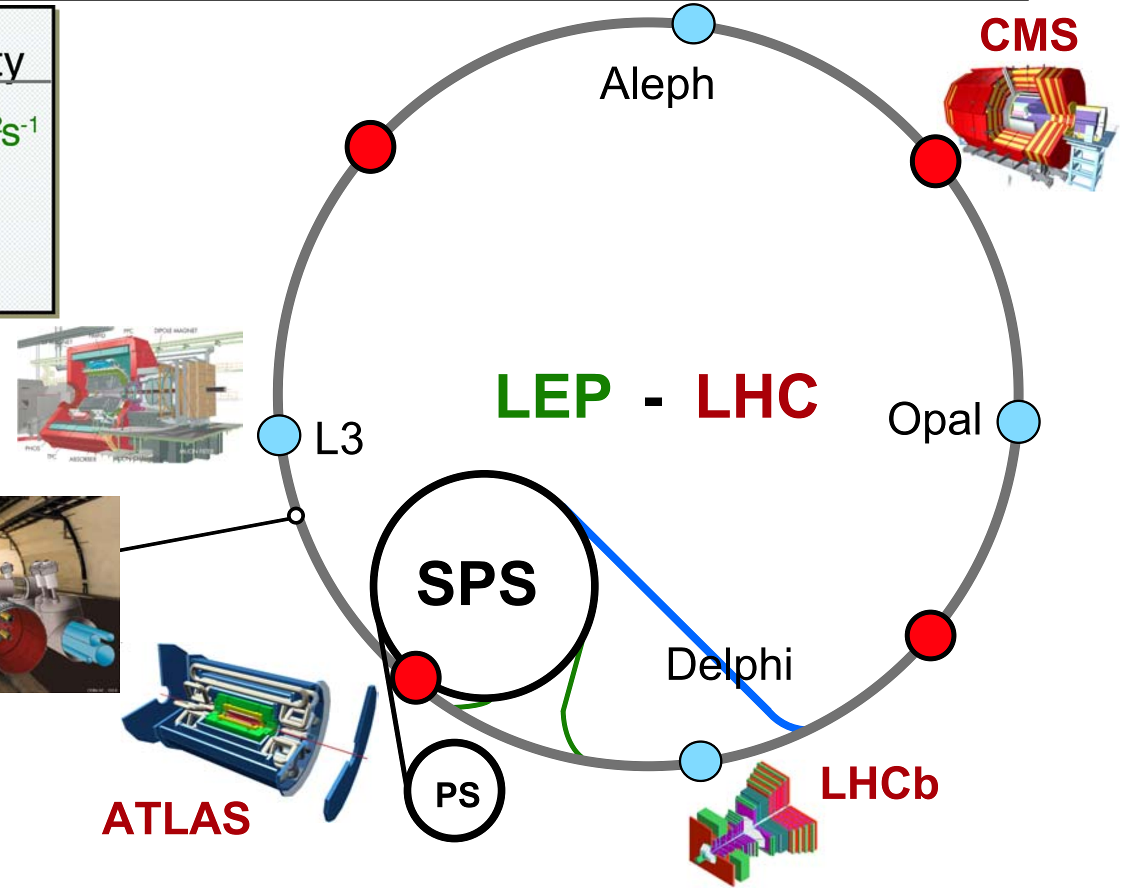


- **Selection needed: $1{:}10^{10\text{-}11}$**
  - before branching fractions

Experiments at the LHC

	Beams	Energy	Luminosity
LEP	e^+e^-	200 GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14 TeV	10^{34}
	$P_b P_b$	1312 TeV	10^{27}

Two super-conducting magnet rings in the LEP tunnel



Experiments:

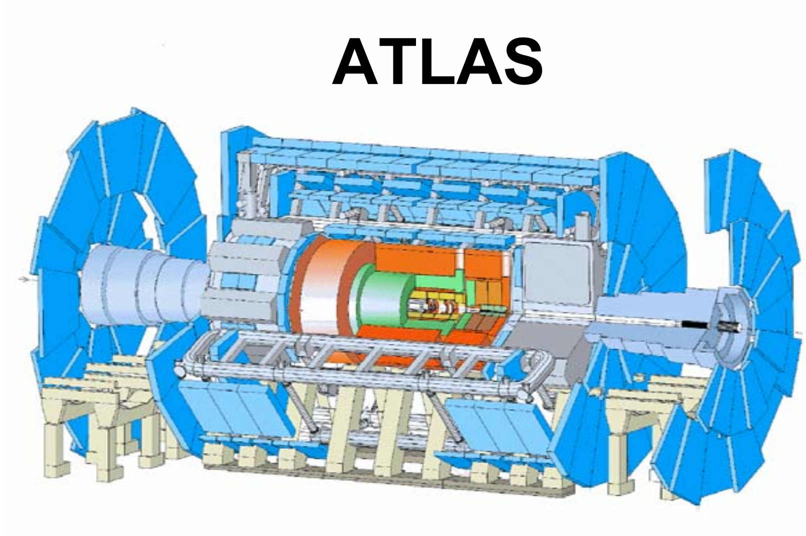
ATLAS A Toroidal LHC ApparatuS (Study of Proton-Proton collisions)

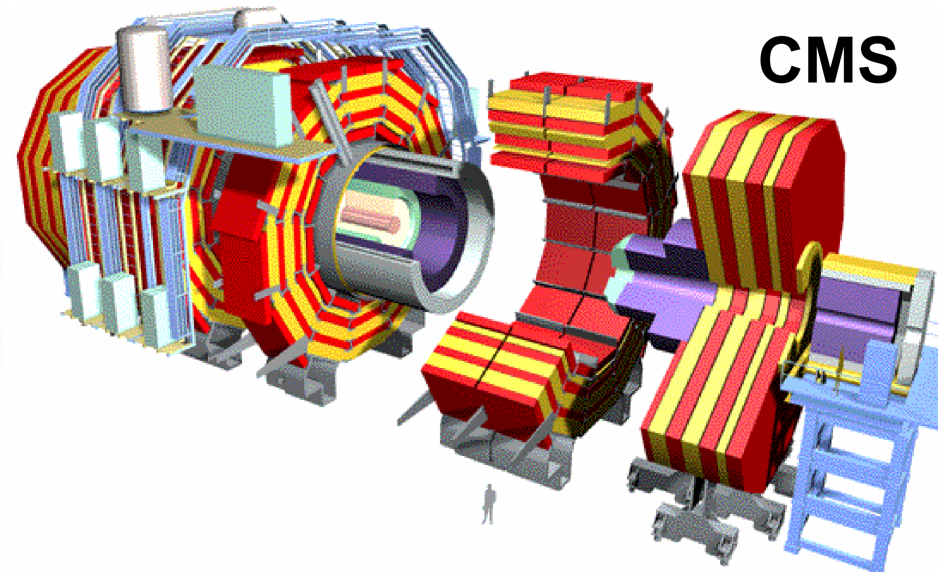
CMS Compact Muon Solenoid (Study of Proton-Proton collisions)

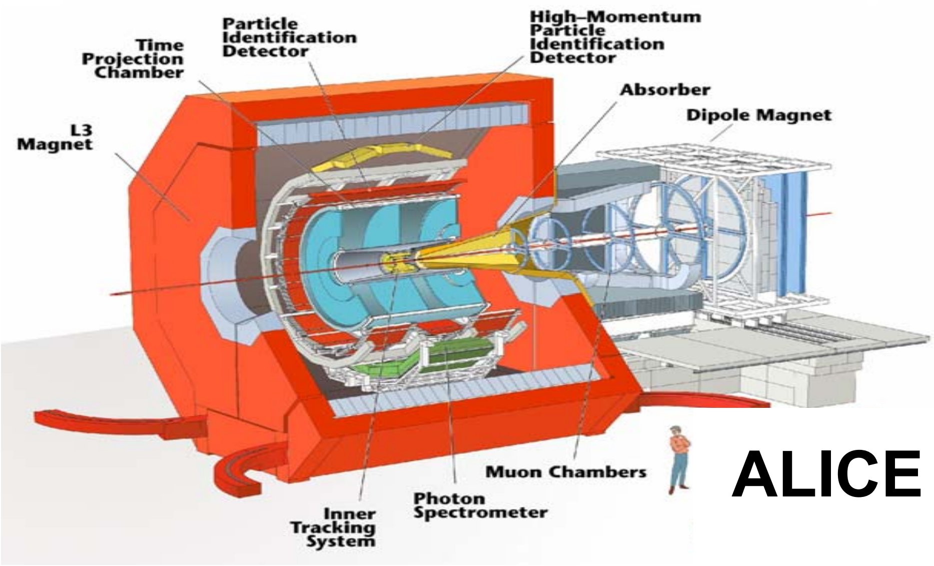
ALICE A Large Ion Collider Experiment (Study of Ion-Ion collisions)

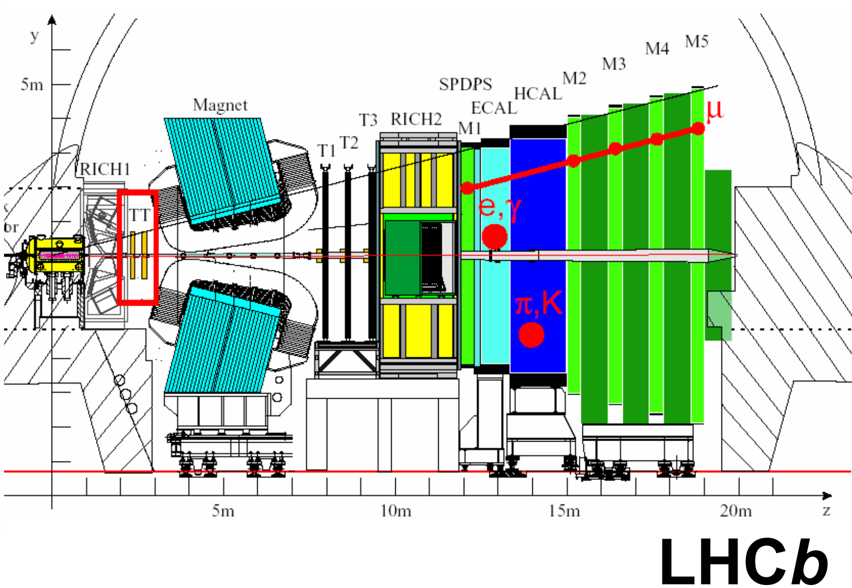
LHCb (Study of CP violation in B-meson decays at the LHC)

The LHC Detectors







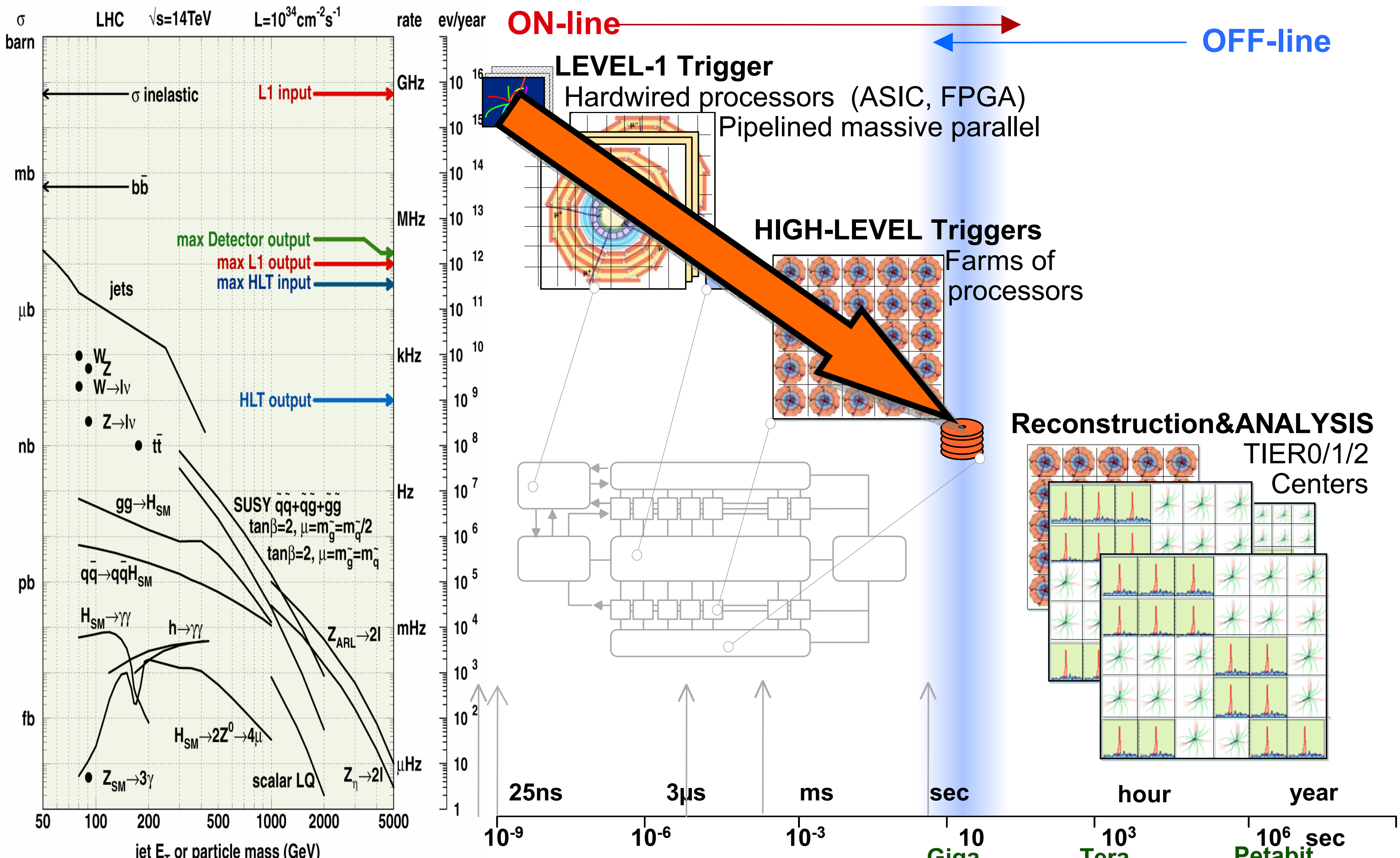


Selection Challenge

- **The challenge is the identification of the most interesting (and potentially entirely new) physics processes amidst the much more copious occurrence of well-understood and studied processes.**
- Out of a billion interactions/sec select one hundred for further analysis
  - **need to reject most interactions**
- Do it in steps / successive approximations:
  - **multi-level trigger**
- To achieve this level of sensitivity a detailed understanding of the underlying physics is essential
  - **high rejection power while preserving sensitivity for rare processes**
- It's On-Line (cannot go back and recover events)
  - **need to monitor selection**

➢ **On-line event selection ultimately determines the physics output of the LHC experiments**

Event Selection Stages



Trigger and DAQ Architecture

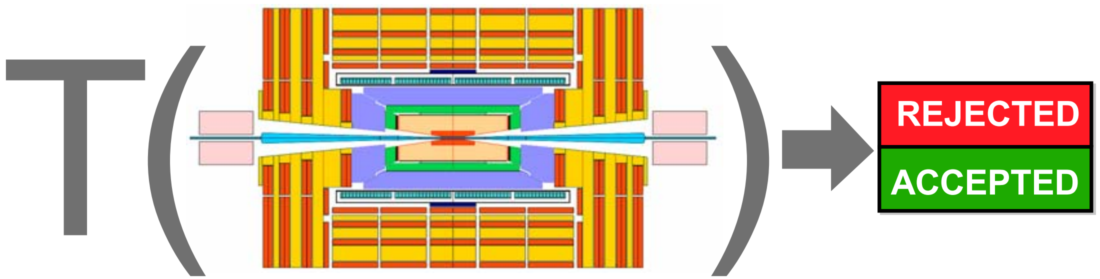
Triggering

Mandate:

"Look at (almost) all bunch crossings, select most interesting ones, collect all detector information and store it for off-line analysis"

P.S.: For a reasonable amount of money

The trigger is a function of:

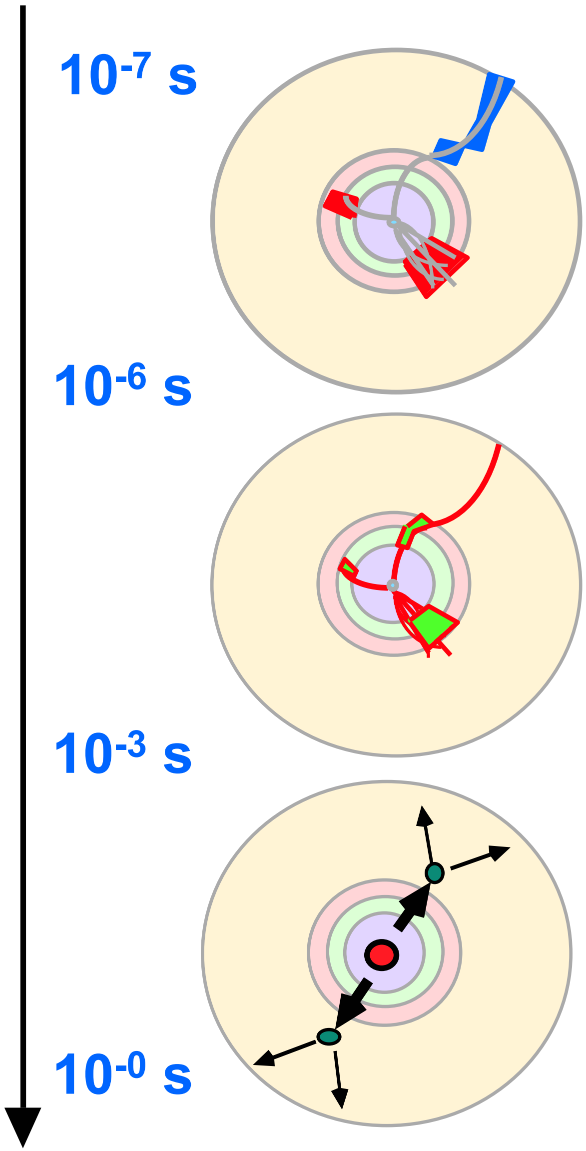


Event data & Apparatus
Physics channels & Parameters

Since the detector data are not all promptly available and the function is highly complex, T(…) is evaluated by successive approximations called:

TRIGGER LEVELS

Trigger Levels



Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^5 Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ...)

- Finer granularity precise measurement
- Kinematics: effective mass cuts and event topology
- Track reconstruction and detector matching

Level-3 events to tape 10...100 Hz

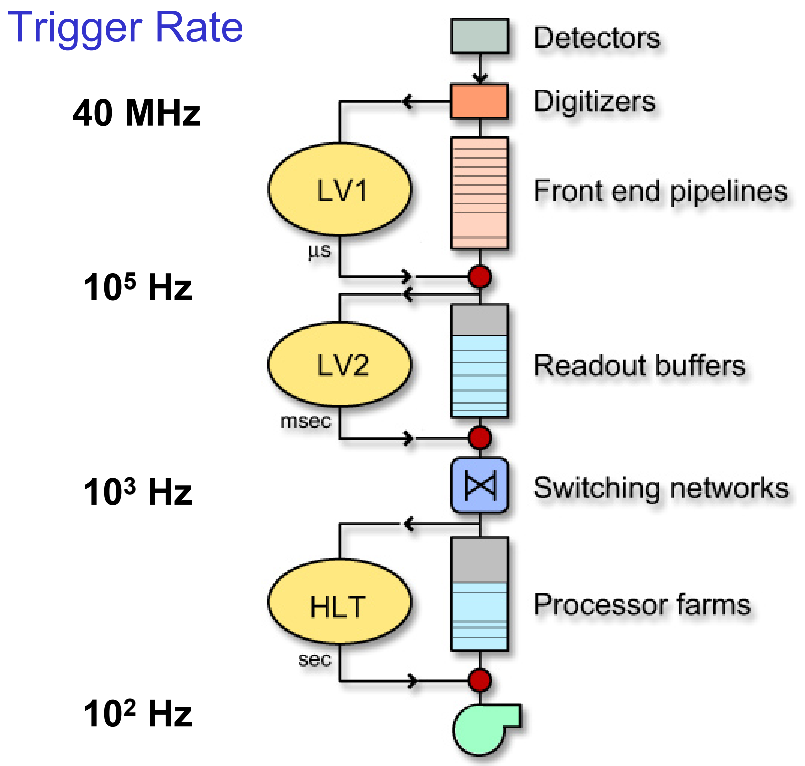
Physics process identification

- Event reconstruction and analysis

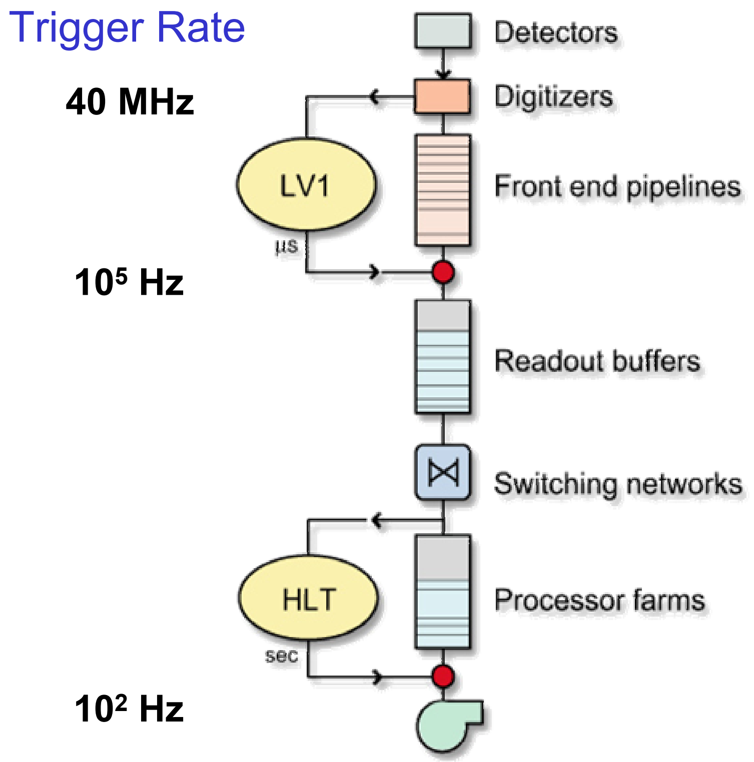
Trigger Strategy

- **Level-1 trigger: reduce 40 MHz to 10^5 Hz**
  - This step is always there
  - Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps

Traditional approach

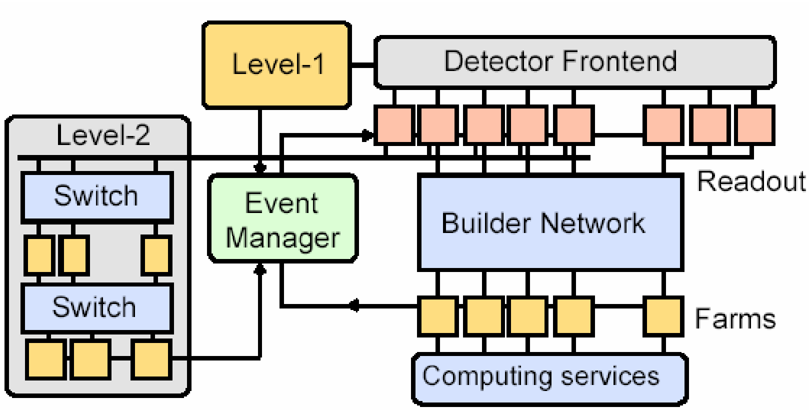


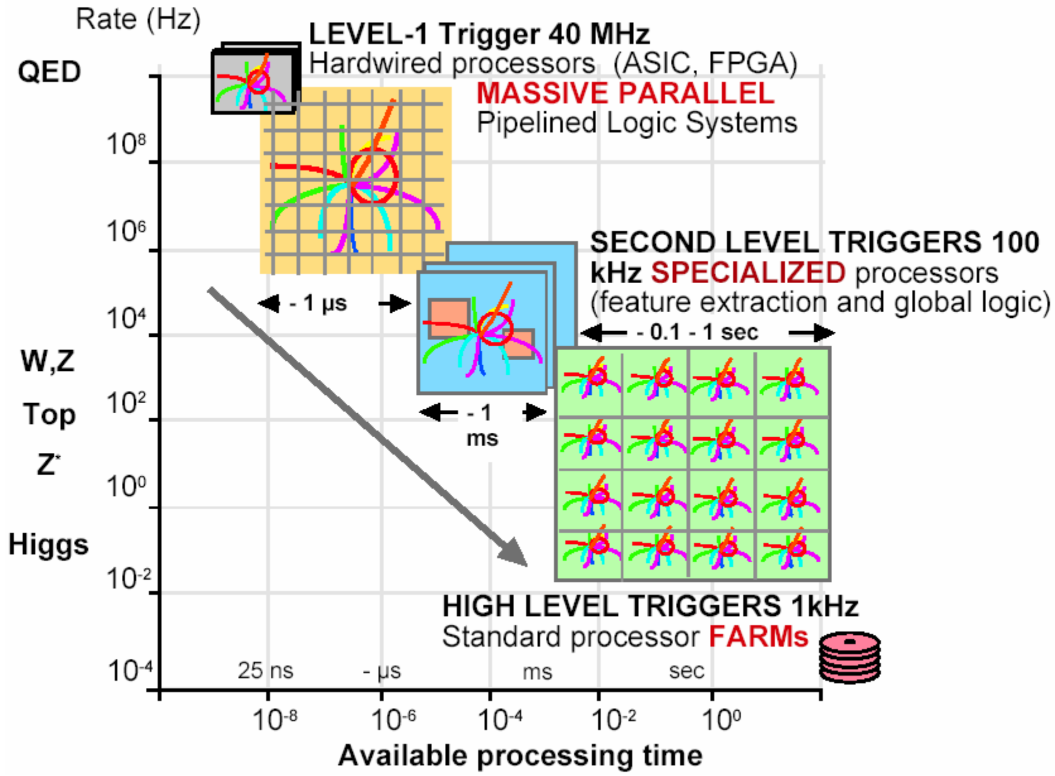
CMS approach



Three Physical Entities

- Additional processing in Level-2:
  - reduce network bandwidth requirements

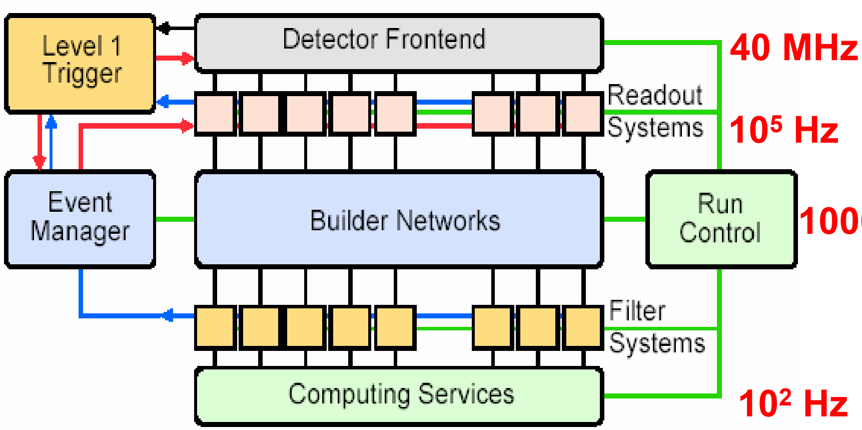


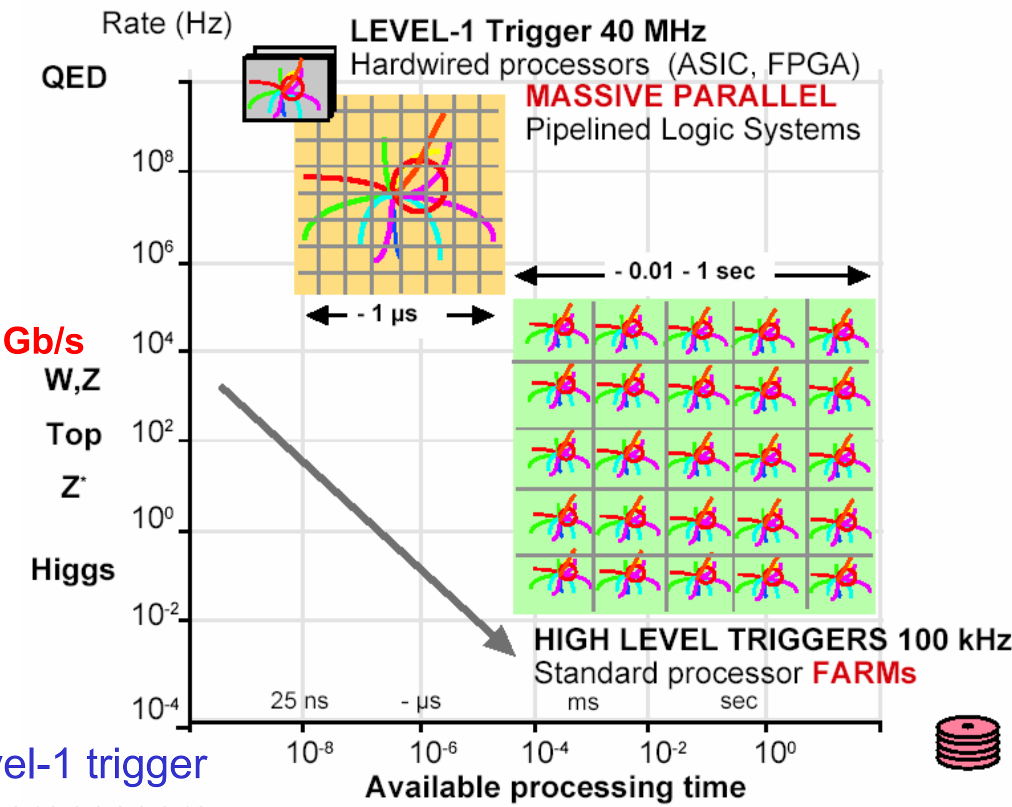


- **Level-1** (~µs)
  Clock driven (custom)
- **Level-2** (~ms)
  Event driven (custom)
- **HLT** (ms-sec)
  Event driven (PC farm)

Two Physical Entities

- Reduce number of building blocks
- Rely on commercial components (processing and communications)
- Upgrades and scales with the machine performance





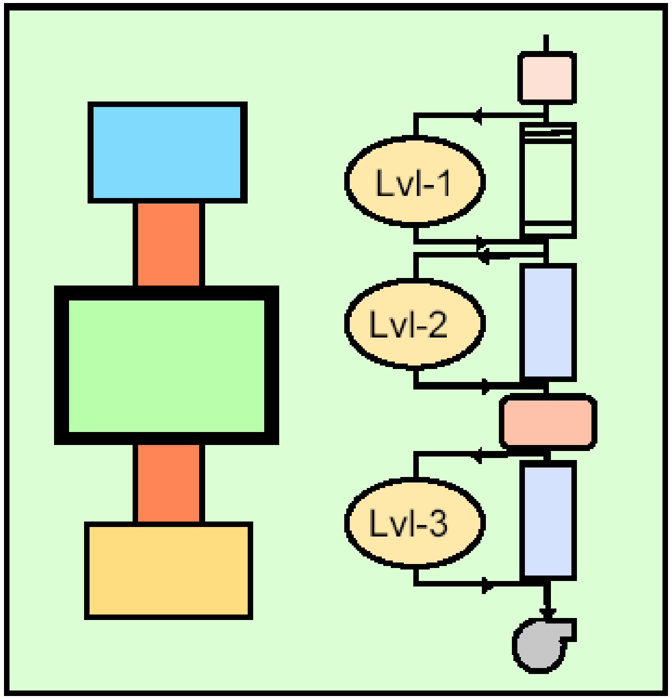
- Detector Front-ends: feed Level-1 trigger
- Readout Units: buffer events accepted by Level-1 trigger
- Switching network: interconnectivity with HLT processors
- Processor Farm: event filtering

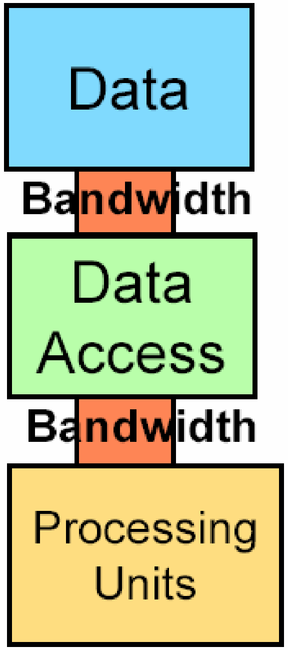
Comparison: 2 vs. 3 Physical Levels

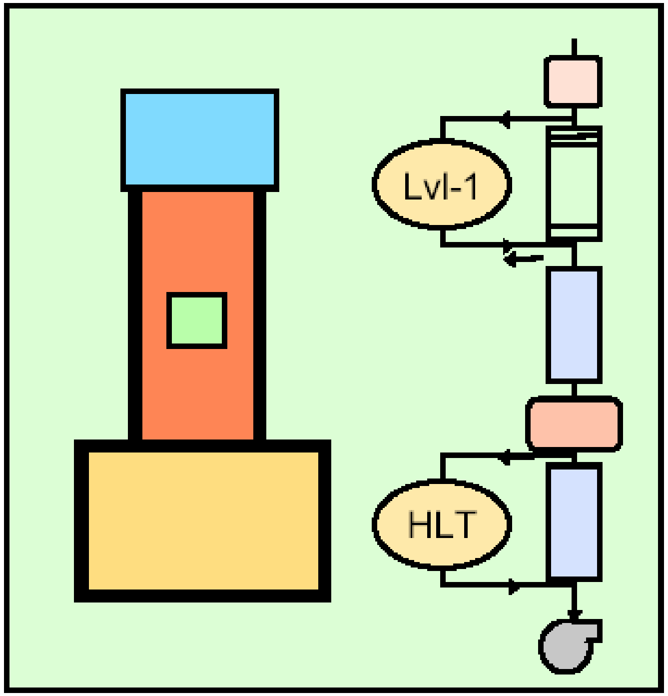
Three physical levels:
- Investment in:
  - Control Logic
  - Specialized processors

Model

Two physical levels:
- Investment in:
  - Bandwidth
  - Commercial processors

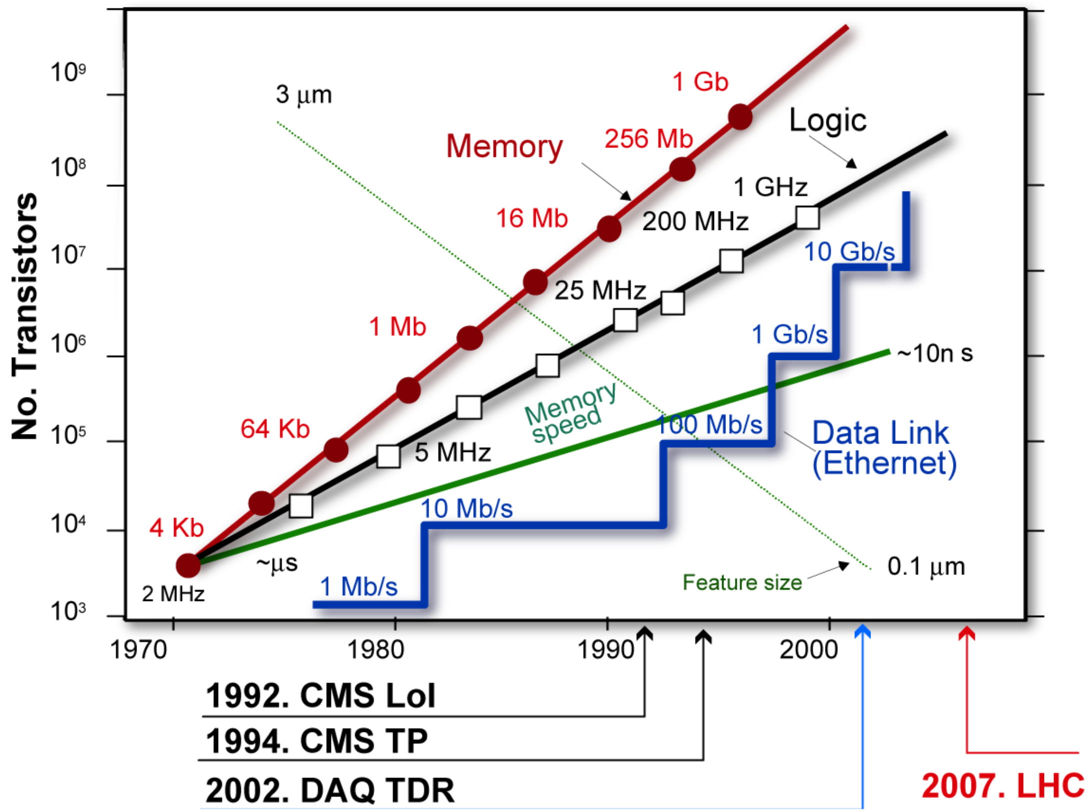






Technology Evolution

- Advantages of using processor farm for all selection beyond Level-1:
  - Benefit maximally from evolution of computing technology
  - Flexibility: no built-in design or architectural limitations — maximum freedom in what data to access and in sophistication of algorithms
  - Evolution, including response to unforeseen backgrounds
  - Minimize in-house elements
    - cost
    - maintainability
- Moore's law:
  - 2×CPU power every 1.5 years
    - ~7 - 8 × before LHC startup (2007)
- **Processing power increases by a factor 10 every 5 years**
- **Memory density increases by a factor 4 every two years**



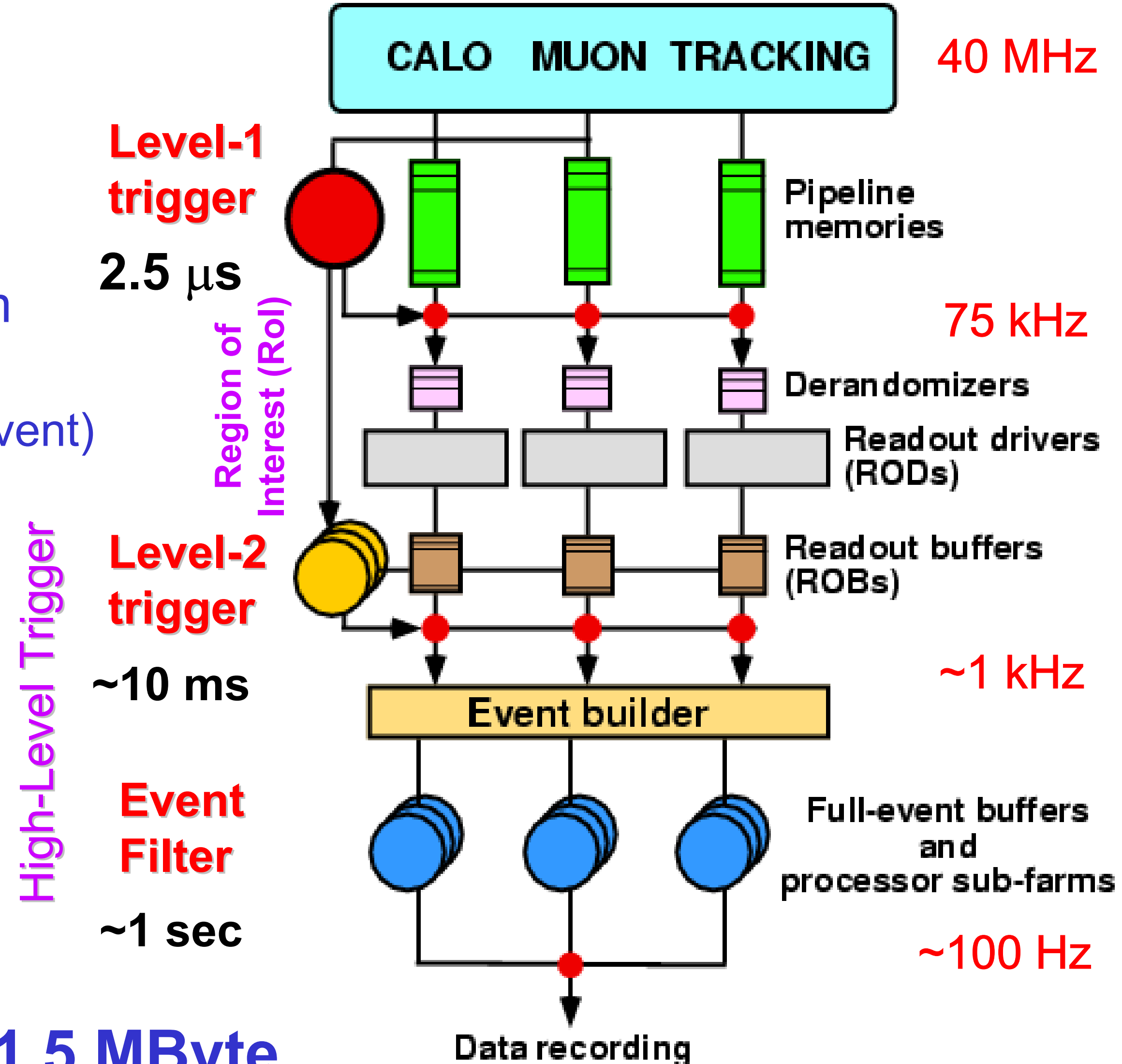
ATLAS Data Flow

Level-1: coarse granularity calorimeter and muon data

Level-2: full granularity data from all detectors;
Regions of Interest (ROI) from Level-1 to reduce data access to ROBs (~ 2% of full event)

	Level 2
ave. latency	~10 ms
input rate	75-100 kHz
data access	event fragments
characteristic	fast rejection

	Event Filter
ave. latency	~1 s
input rate	1-2 kHz
data access	full event
characteristic	precise selection

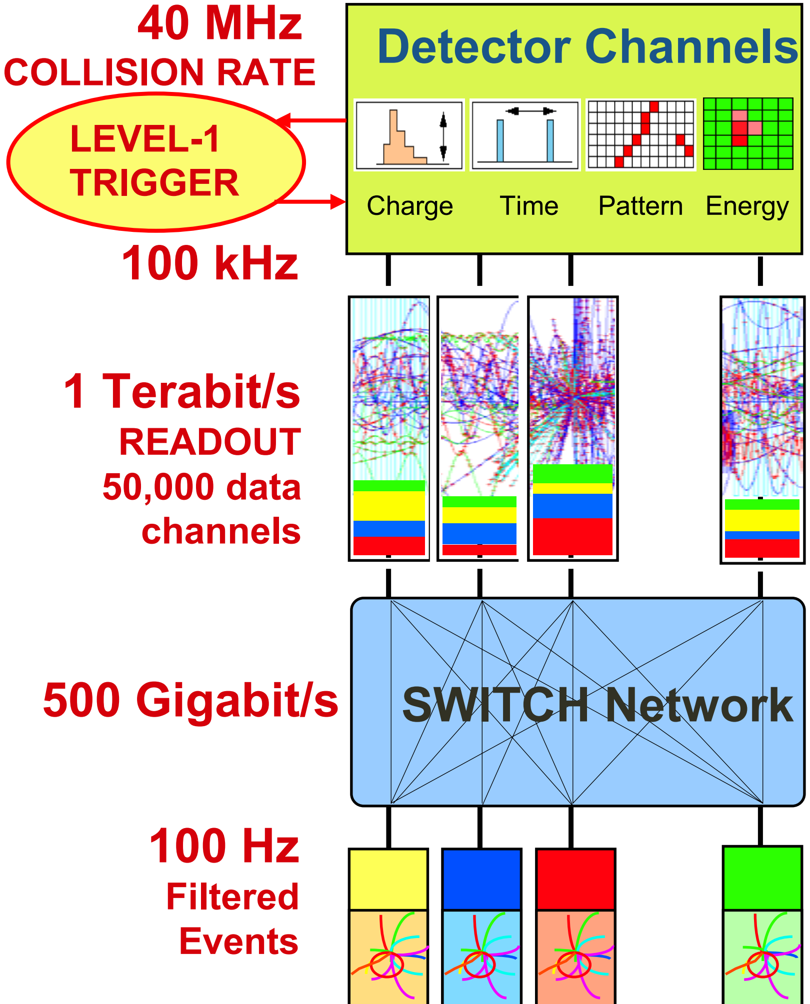


Average event size: ~1.5 MByte

ATLAS Trigger Overview

- **Level-1:** hardware trigger, 40 MHz → 75 kHz, 2.5 μs maximum latency
  - Looks for regions of potentially interesting activity, with high p_T objects
  - Region of Interest (RoI): muon, electromagnetic, tau/hadronic, jet clusters
  - Uses data from calorimeters and muon spectrometer
  - Does not combine information of more than one detector
- **Level-2:** software trigger, 75 kHz → 1 kHz, 10 ms average latency
  - Data are held in readout buffers (ROB) during Level-2 processing
  - Selection software run by Processing Application on one node of Level-2 farm
  - Input (seed) is Level-1 RoI (type, position, p_T threshold passed) so that typically only few % of full event information in the ROBs need to be transferred to Level-2
  - Feature extraction in RoI region by specialized algorithms that are optimized for speed and cover all sub-detectors sequentially
  - For events accepted by Level-2 EventBuilder builds full event
- **EventFilter:** software trigger, 1 kHz → 100 Hz, 1 sec average latency
  - Full event from EventBuilder passed to EventFilter farm
  - Independent Processing Applications run selection algorithms on farm nodes
  - Selection software consists of offline-type algorithms that have access to latest calibration and alignment data

CMS Data Flow



40 MHz
COLLISION RATE

LEVEL-1 TRIGGER

100 kHz

1 Terabit/s
READOUT
50,000 data channels

500 Gigabit/s

100 Hz
Filtered Events

Gigabit/s
SERVICE LAN

Computing services

16 Million channels

3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
~400 Readout memories

EVENT BUILDER

A large switching network (400+400 ports) with a total throughput of ~400 Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs).
The Event Manager distributes event building commands (assigns events to destinations).

5 TeraIPS

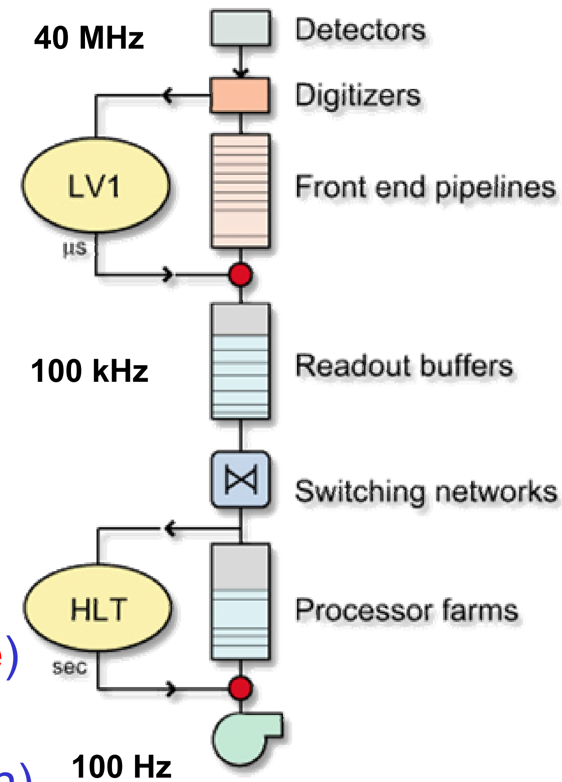
EVENT FILTER

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

Petabyte ARCHIVE

CMS Trigger Overview

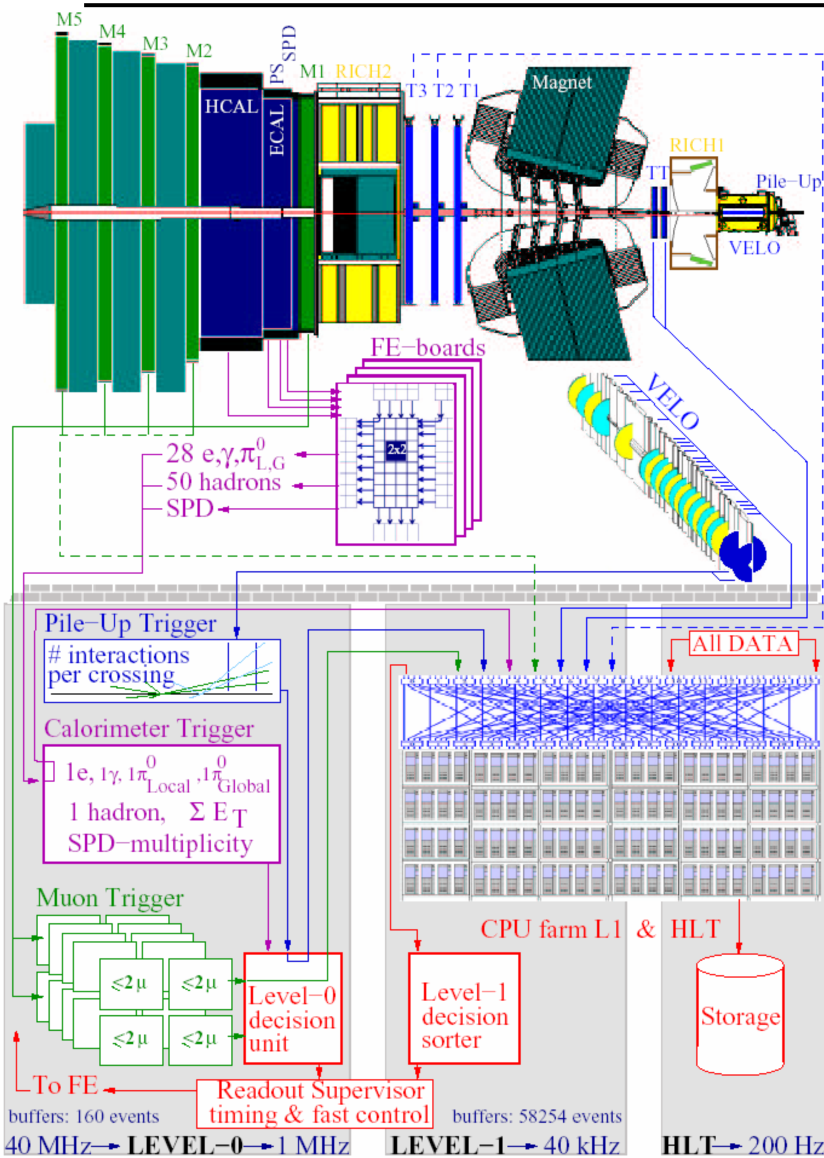
- **Level-1:** hardware trigger, 40 MHz → 100 kHz (75 kHz)
  - Only calorimeter and muon information used
  - Electron/photon triggers
  - Jet and missing E_T triggers
  - Muon triggers
  - L1 decision based on trigger objects with η/φ information
  - Custom-built electronics
  - Latency: < 3.2 μs (128 bx)



- **HLT:** software trigger, 100 kHz → $O(10^2)$Hz
  - Beyond Level-1 there is a High-Level Trigger running on a single processor farm (no dedicated L2 hardware)
  - DAQ designed to accept Level-1 rate of 100 kHz
  - Access to full event data (full granularity and resolution)
  - Rejection factor of 1000
  - ~1000 processor units

Average event size: ~1 MByte

LHCb Trigger Overview

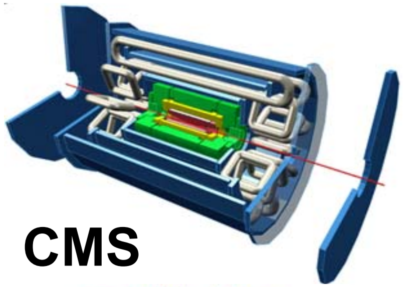
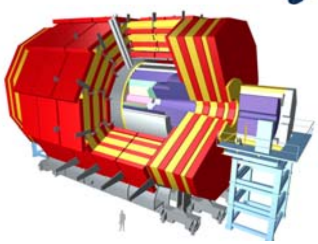
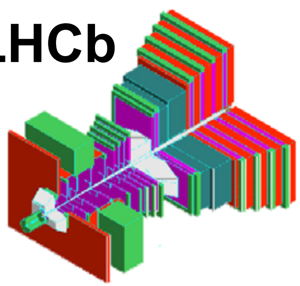
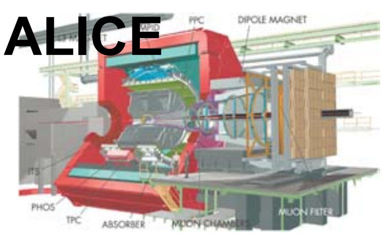


- Design Luminosity: L = 2×10^{32} $cm^{-2}s^{-1}$
- **$\sigma_{vis} \approx$ 60 mb → ~10 MHz event rate**
- **100 kHz B event rate; but low BR!**

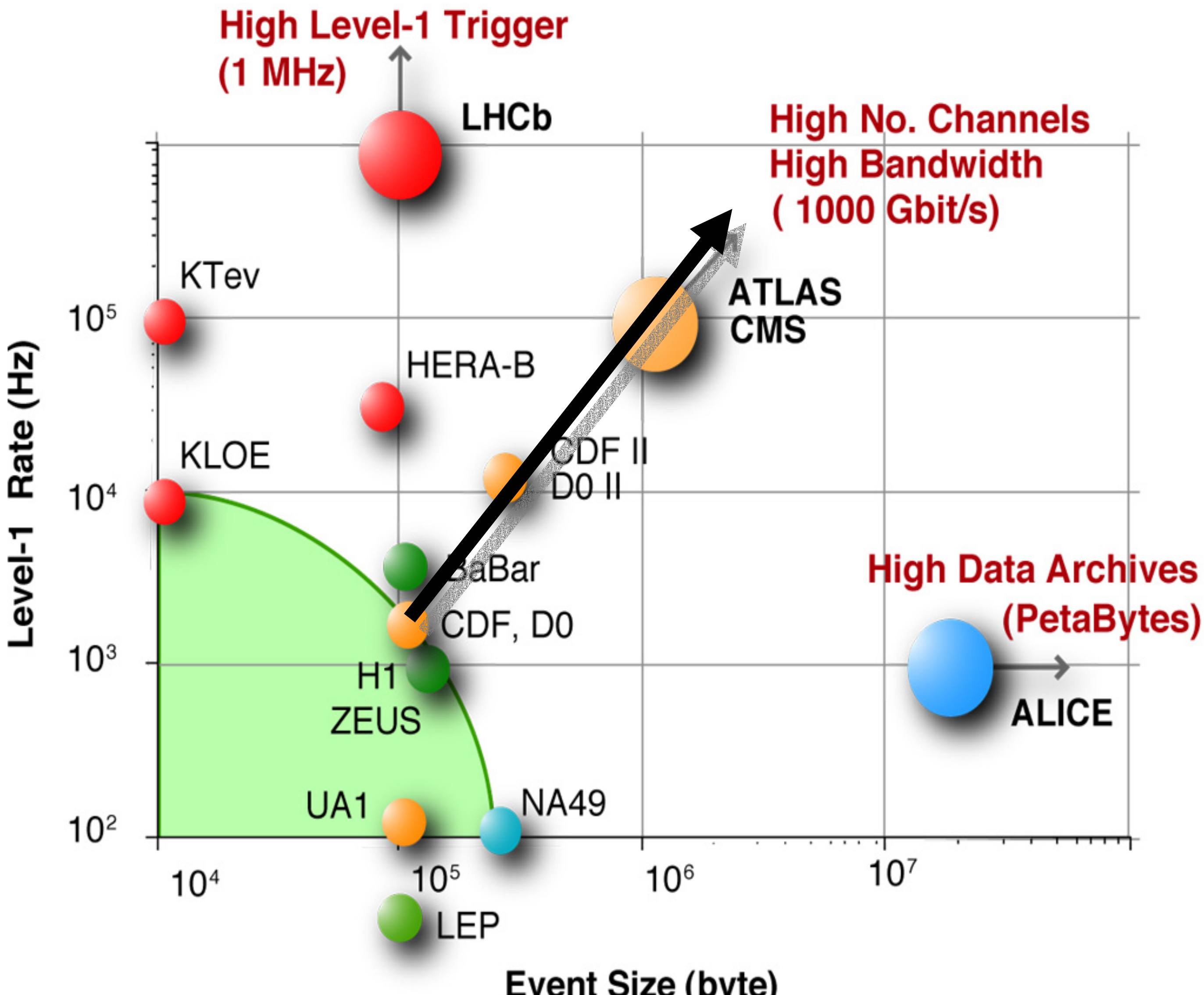
- **Level-0:** hardware trigger, 10 MHz → 1 MHz
  - Select high E_T candidates (leptons, hadrons, photons)
  - Calorimeters, muon chambers and pile-up veto
  - Pile-Up detector is used to recognize multiple interactions per crossing
  - Executed in full custom electronics
  - Latency: 4 μs (2 μs for processing)
- **Level-1:** software trigger, 1 MHz → 40 kHz
  - Uses Level-0 objects, VELO (Vertex Locator) and TT (Trigger Tracking)
  - Selects tracks with large impact parameter
  - 58 ms max latency
- **HLT:** software trigger, 40 kHz → 200 Hz
  - Uses full event data apart from the RICH

Level-1 and HLT share a commodity farm of 1400 CPUs; same network for event building
Event size: ~30 kByte

Trigger/DAQ Parameters

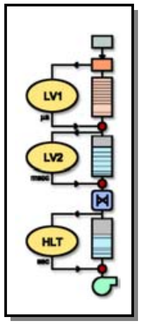
	No. Levels Trigger	First Level Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS 	3	10^5 LV-2 10^3	10^6	10	100 (10^2)
CMS 	2	10^5	1.5×10^6	100	150 (10^2)
LHCb 	3	LV-0 10^6 LV-1 4×10^4	3×10^4	4	6 (2×10^2)
ALICE 	4	Pp-Pp 500 p-p 10^3	5×10^7 2×10^6	5	1250 (10^2) 200 (10^2)

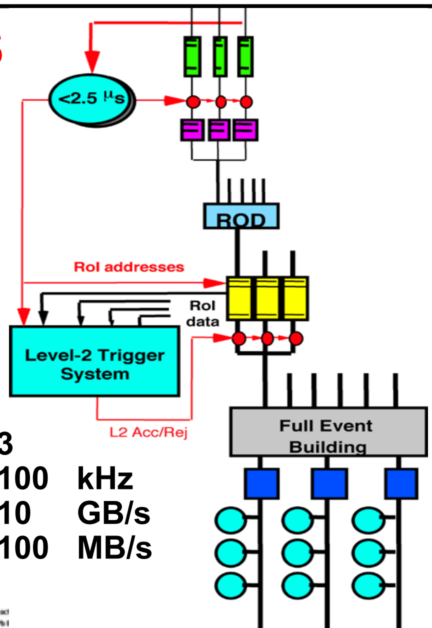
Trigger/DAQ Systems



DAQ Overview

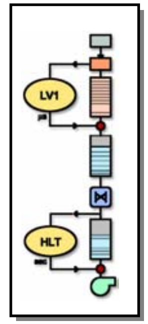
ATLAS

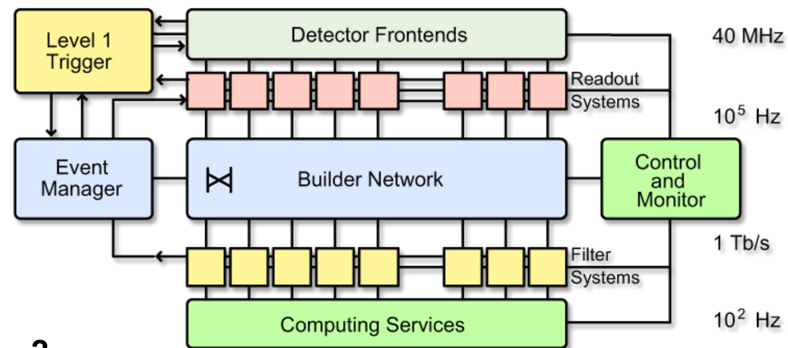




Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

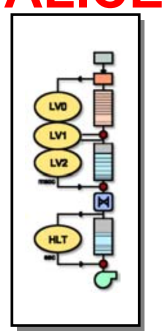
CMS

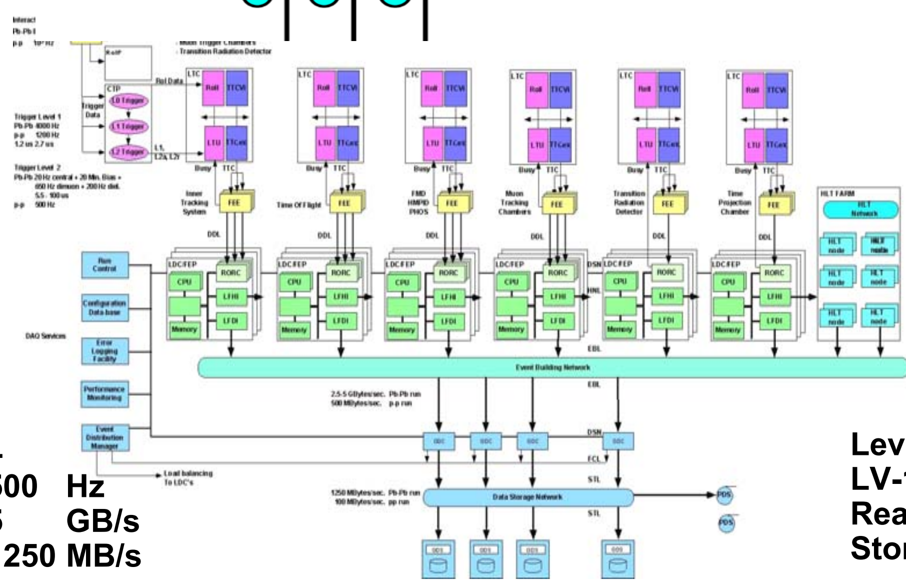




Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

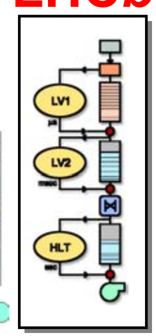
ALICE

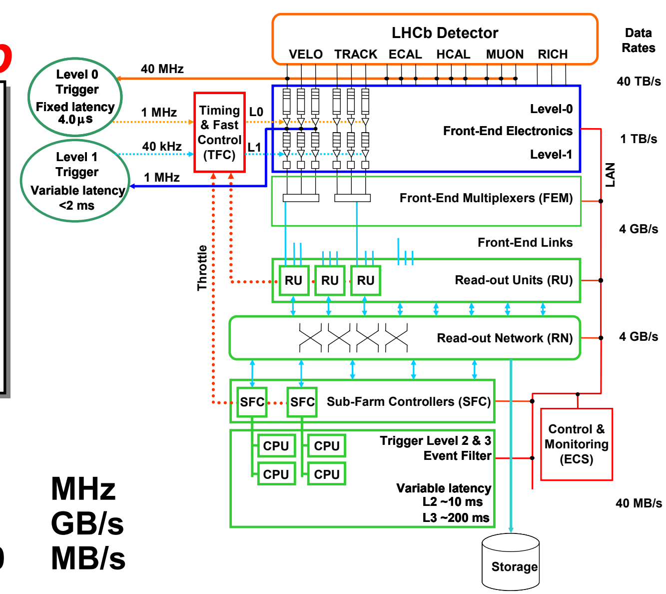




Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250	MB/s

LHC*b*





Levels	3	
LV-1 rate	1	MHz
Readout	4	GB/s
Storage	40	MB/s

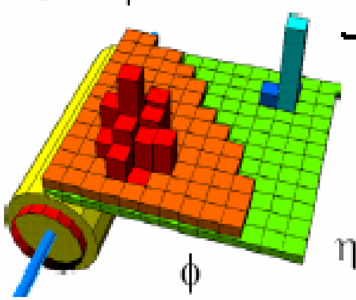
Level-1 Trigger

Level-1 Trigger Algorithms

- **Physics facts:**
  - pp collisions produce mainly hadrons with p_T~1 GeV
  - Interesting physics (old and new) has particles (leptons and hadrons) with large transverse momenta:
    - **W $\rightarrow$ eν:** M(W)=80 GeV/c^2; p_T(e) ~ 30-40 GeV
    - **H(120 GeV) $\rightarrow$ $\gamma\gamma$:** $p_T(\gamma)$ ~ 50-60 GeV
- **Basic requirements:**
  - Impose high thresholds on particles
    - Implies distinguishing particle types; possible for electrons, muons and “jets”; beyond that, need complex algorithms
  - Typical thresholds:
    - Single muon with p_T>20 GeV (rate ~ 10 kHz)
      - Di-muons with P_T>6 (rate ~ 1 kHz)
    - Single e/γ with p_T>30 GeV (rate ~ 10-20 kHz)
      - Di-electrons with P_T>20 GeV (rate ~ 5 kHz)
    - Single jet with p_T>300 GeV (rate ~ 0.2-0.4 kHz)

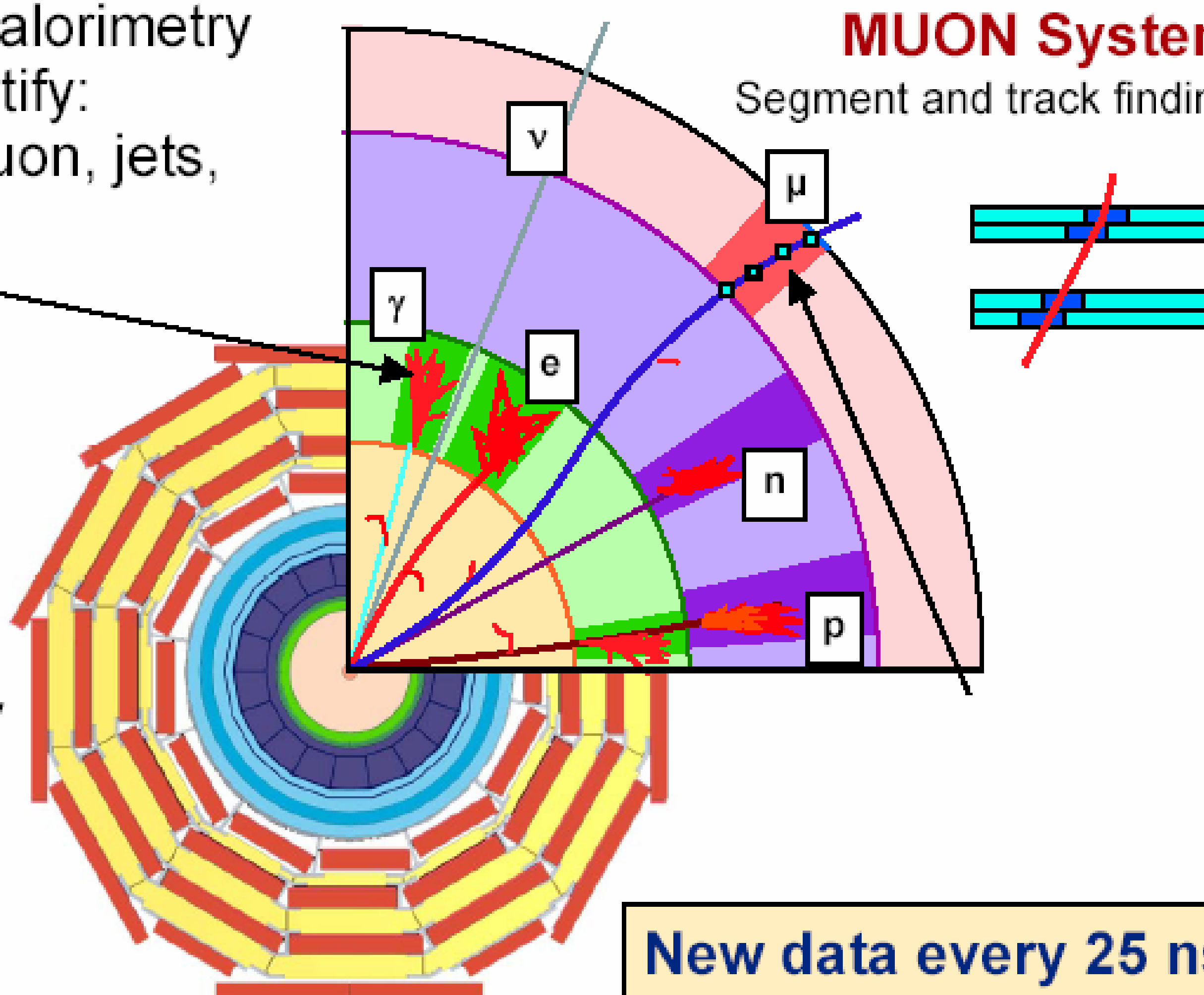
Signatures in the Detector

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



MUON System

Segment and track finding



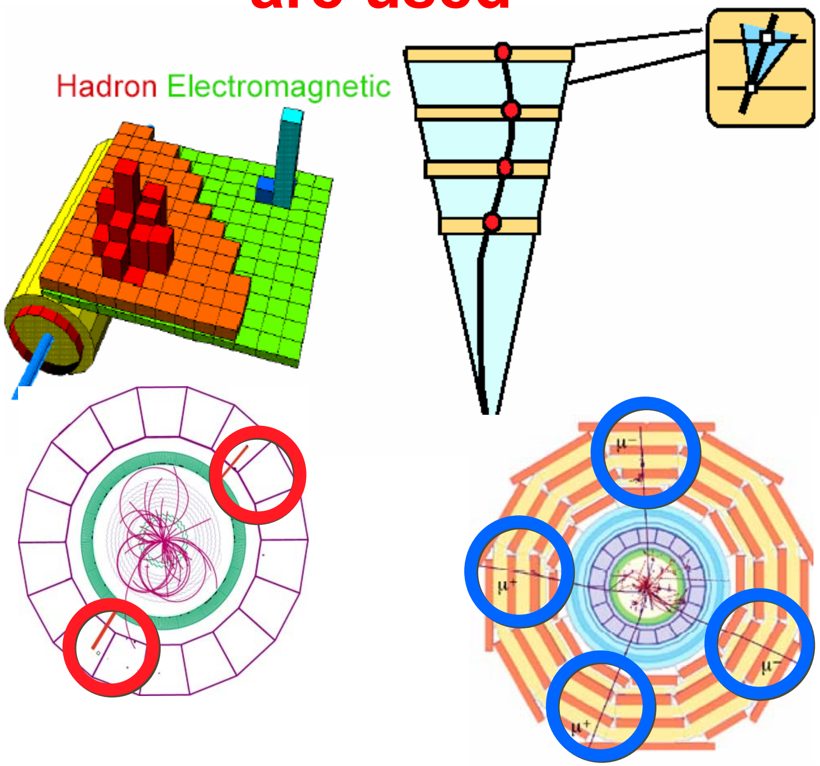
CALORIMETERs

Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ µs

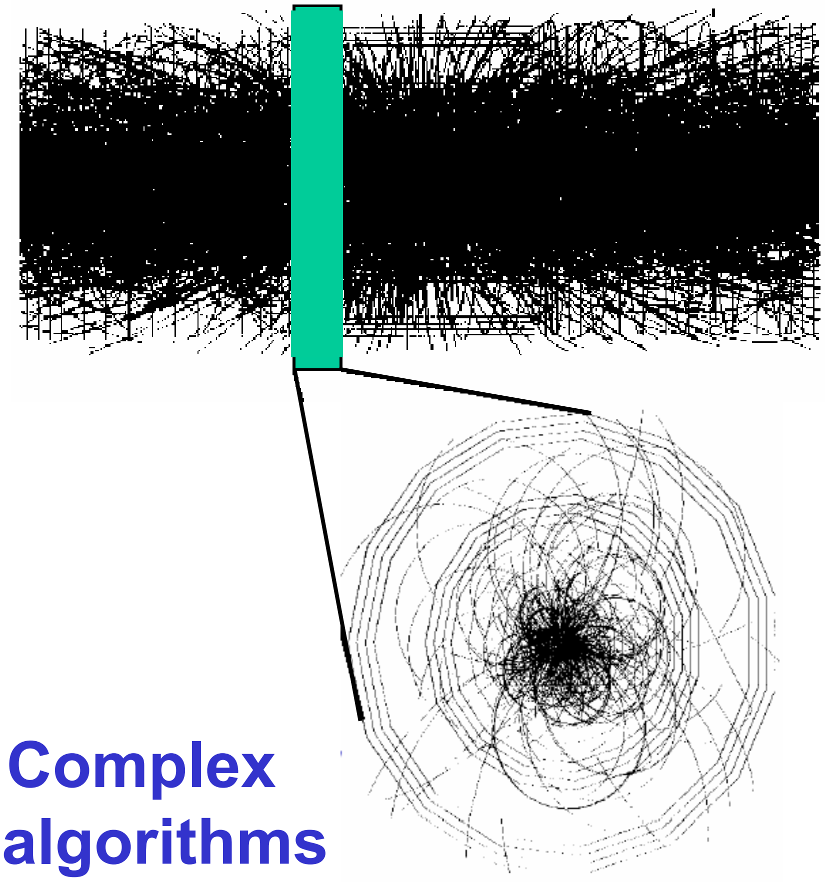
Level-1 Trigger

Only Calorimeters and Muons are used



- Simple algorithms
- Small amounts of data
- Local decision

Compare to tracker info



- Complex algorithms
- Huge amounts of data
- Need to link sub-detectors

CMS Level-1 Strategy

- **Level-1 decision based on trigger objects** (with η/φ information):
  - muons, e/γ, μ, jets, tau-jets, missing E_T, total energy
- **Trigger objects are determined in 3 steps:**

Local

- Energy measurement in single calorimeter cells or groups of cells (towers)
- Determination of hits or track segments in muon detectors
- Algorithms run on coarse local data
- Generate "Trigger Primitives"

Regional

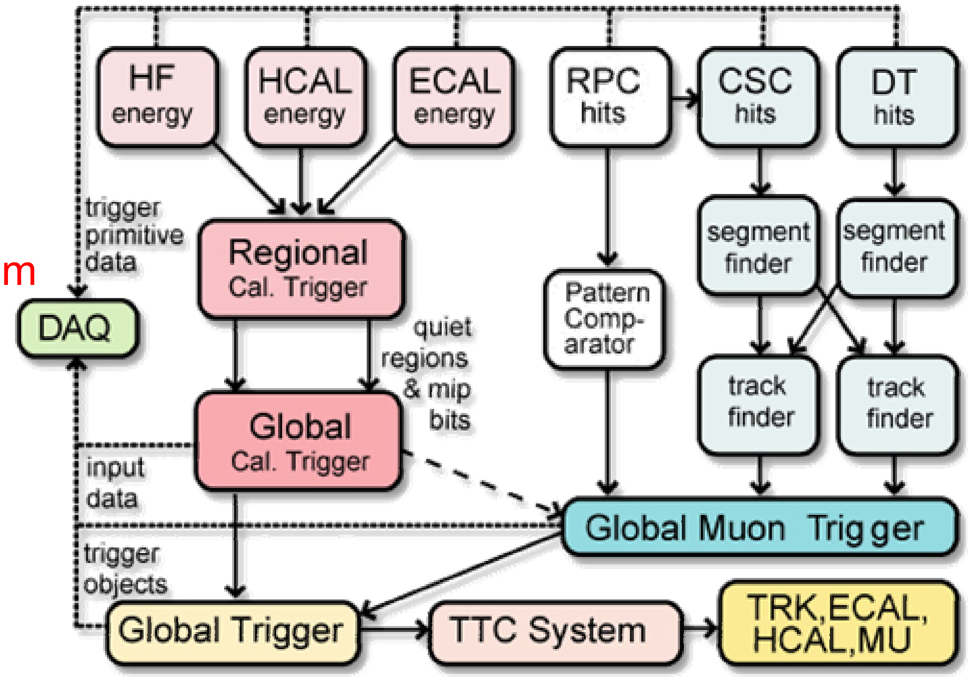
- Identify particle signature
- Measurement of p_T/E_T, location (η/φ) in detector and quality of "reconstruction"

Global

- Sort candidates by p_T and quality keeping best 4 of each object type
- Location of each candidate tracked to global level
- Set trigger conditions: Thresholds (p_T/E_T, N_{Jets}), etc.
- Seeds for High-Level Triggers

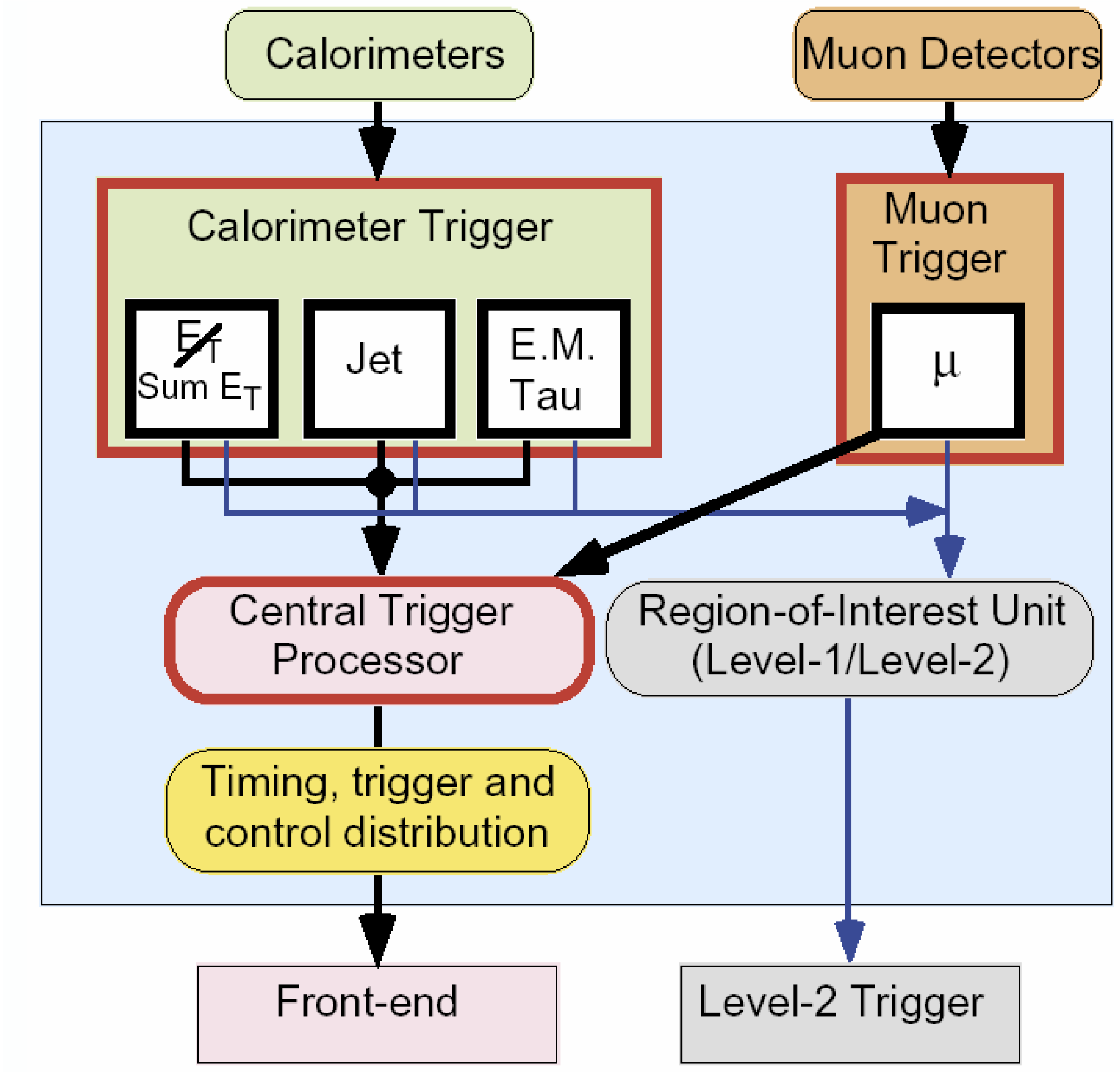
CMS Level-1 Trigger

- Information from calorimeters and muon detectors
- Custom-built electronics for trigger processors (ASICs, FPGAs)
- Synchronous, pipelined
  - Processing logic: 25 ns pipelined system
  - Must work dead time free
  - Latency: < 3.2 μs (128 bx)
  - readout + processing: < 1μs
  - signal collection + distribution: ~2μs
- Max. output rate: 100 kHz
- Organized in 3 subsystems:
  - Muon Trigger, Calorimeter Trigger, Global Trigger



- Backgrounds are huge
  - Large rejection factor: 40 MHz (×20 events/crossing) $\rightarrow$ 100 kHz
  - Rates: steep functions of thresholds

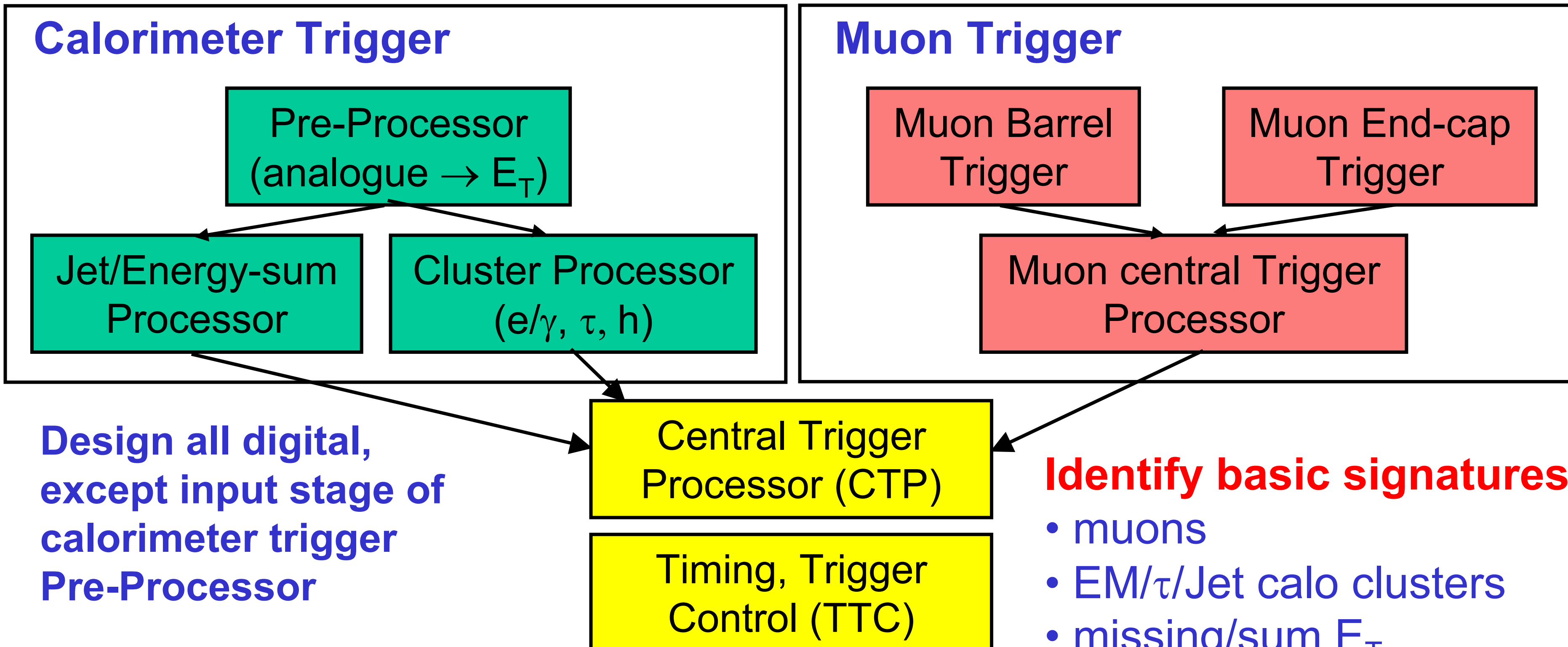
ATLAS Level-1 Trigger



ATLAS Level-1 Trigger

~7000 calorimeter trigger towers
(analogue sum on detectors)

O(1M) RPC/TGC channels



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

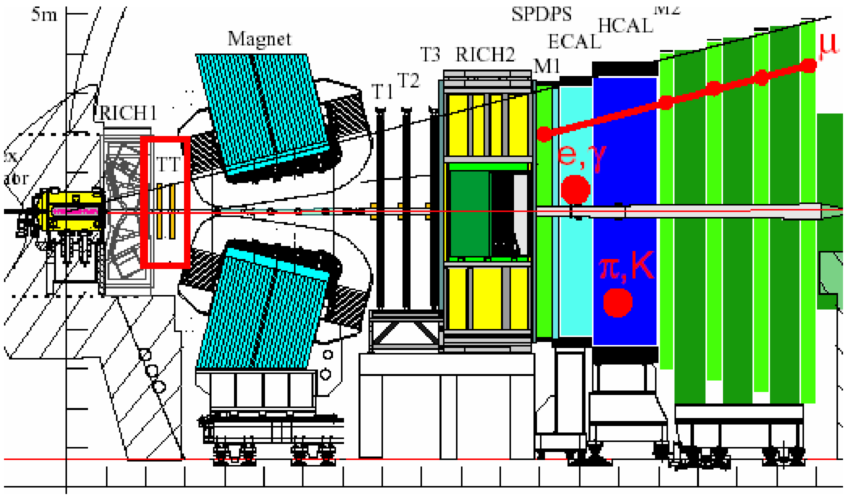
Identify basic signatures:

- muons
- EM/τ/Jet calo clusters
- missing/sum E_T

- Decision based on **multiplicities** of trigger objects
- Programmable thresholds
- Latency limit: 2.5 μs

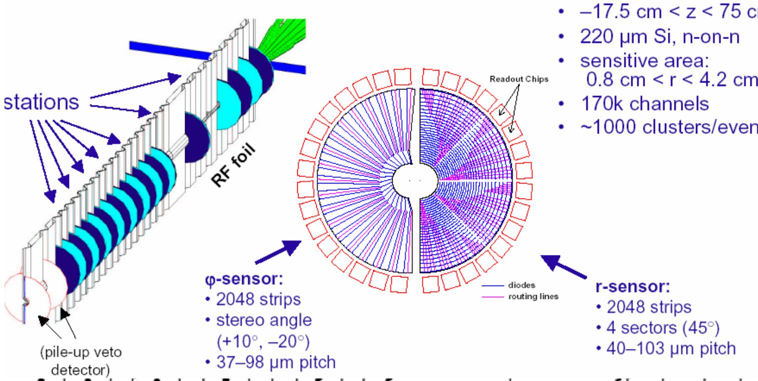
LHCb Level-1 Trigger Strategy

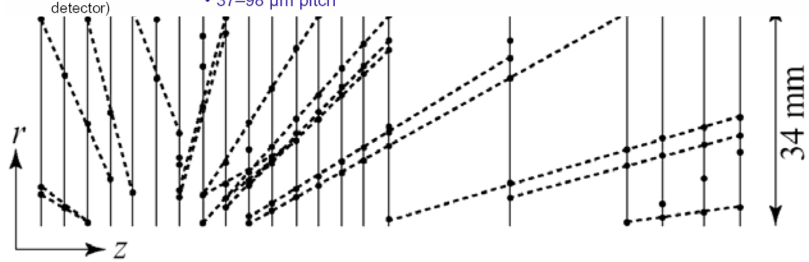
- **Select events containing B hadrons** (heavy and long-lived):
  - high transverse momentum (p_T)
  - large impact parameter (relative to primary vertex)
- Detector Input:
  - VELO: VErtex LOcator (impact parameter)
  - Trigger Tracker } p_T
  - Level-0 decision unit } p_T
- Measure impact parameter with the Vertex Locator (21 stations of silicon)
- Reconstruct only tracks with large impact parameter
- P_T measurement:
  - Fringe field before magnet
  - Trigger Tracker: two layers of silicon
  - Calorimeter clusters and muon track segments (after magnet) found at Level-0
  - Match with VELO tracks



measure impact parameters with the **VE**rtex **LO**cator:

- 21 stations, each with 2 r- and 2 φ-sensors
- –17.5 cm < z < 75 cm
- 220 μm Si, n-on-n
- sensitive area: 0.8 cm < r < 4.2 cm
- 170k channels
- ~1000 clusters/event to L1





LHCb Level-0/1 Trigger

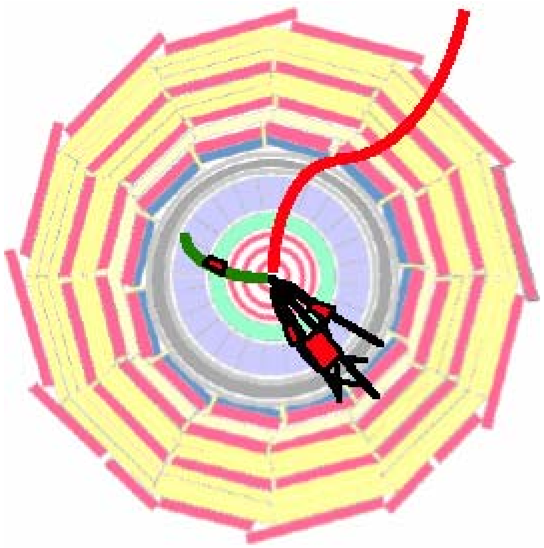
- Level-0 is a hardware trigger:
  - High p_T muons, EM particles or hadrons
  - Pile-up veto (to select single-interaction crossings)
  - Input: 40 MHz
  - Output: 1 MHz
- Level-1 is a software trigger:
  - Maximum flexibility at an early stage
  - Perform track reconstruction
  - Level-1 farm is part of online farm
    - Level-1 events size and global event size not so different
    - 1200 processors foreseen (Level-1 and HLT)
    - flexible allocation between Level-1 and HLT; currently 800 processors for Level-1
  - Level-1 buffer holds 58k events => > 50 ms latency

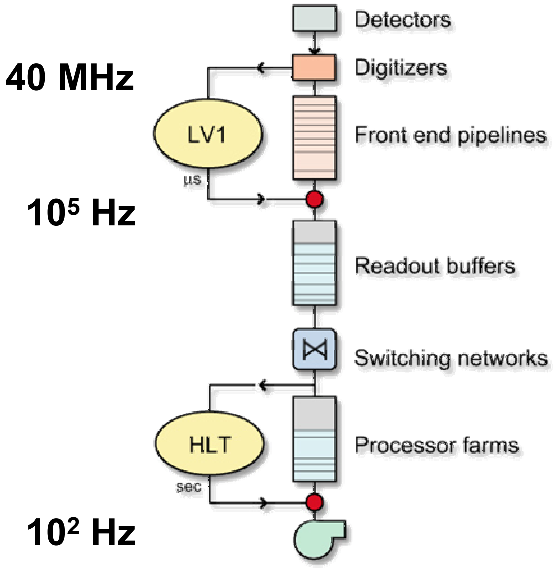
Technologies in Level-1 Systems

- **ASICs** (Application-Specific Integrated Circuits) used in some cases
  - Highest-performance option, better radiation tolerance and lower power consumption (a plus for on-detector electronics)
- **FPGAs** (Field-Programmable Gate Arrays) used throughout all systems
  - Impressive evolution with time: Large gate counts and operating at 40 MHz (and beyond)
  - Biggest advantage: flexibility
    - Can modify algorithms (and their parameters) in situ
- Communication technologies
  - High-speed serial links (copper or fiber)
    - LVDS up to 10 m and 400 Mb/s; HP G-link, Vitesse for longer distances and Gb/s transmission
  - Backplanes
    - Very large number of connections, multiplexing data; operating at ~160 Mb/s

High-Level Trigger

High-Level Trigger Overview





High-Level Trigger, CPU farms

- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation,…)
- Track reconstruction and detector matching
- Kinematics: Effective mass cut and topology
- Full event reconstruction and analysis

Successive improvements: background event filtering, physics selection

HLT Requirements

- **Runs on CPU farm**
  - A **single processor** analyzes one event at a time
- HLT (or Level-3) has access to **full event data** (full granularity and resolution)
  - **Only limitations:**
    - **CPU time**
    - **Output selection rate (~10^2 Hz)**
    - **Precision of calibration constants**
- Main requirements:
  - **Satisfy physics program: high efficiency**
  - **Selection must be inclusive (to discover the unpredicted as well)**
  - **Must not require precise knowledge of calibration/run conditions**
  - **Efficiency must be measurable from data alone**
  - **All algorithms/processors must be monitored closely**

HLT Software

- **Robust, high quality reconstruction software**
  - Offline reconstruction without final calibration, etc.
  - Ease of maintenance, but also understanding of the detector
  - Able to include major improvements in offline reconstruction
- **Regional/Partial reconstruction**
  - Using data in a region around a "seed"
    - Faster processing
    - Ability to reject events using only a small fraction of the event data
  - Reconstruction/selection applied to regions only
  - Need seeds: use objects from previous level
    - ➢ Region of Interest Builder (ATLAS)
    - ➢ Level-1 trigger objects (CMS)
- **Reconstruction on demand**
  - Reject events as soon as possible, avoid unnecessary calculations
  - Access data as needed
- **Once trigger rate is low enough (≈1 kHz) apply full reconstruction**

HLT Example

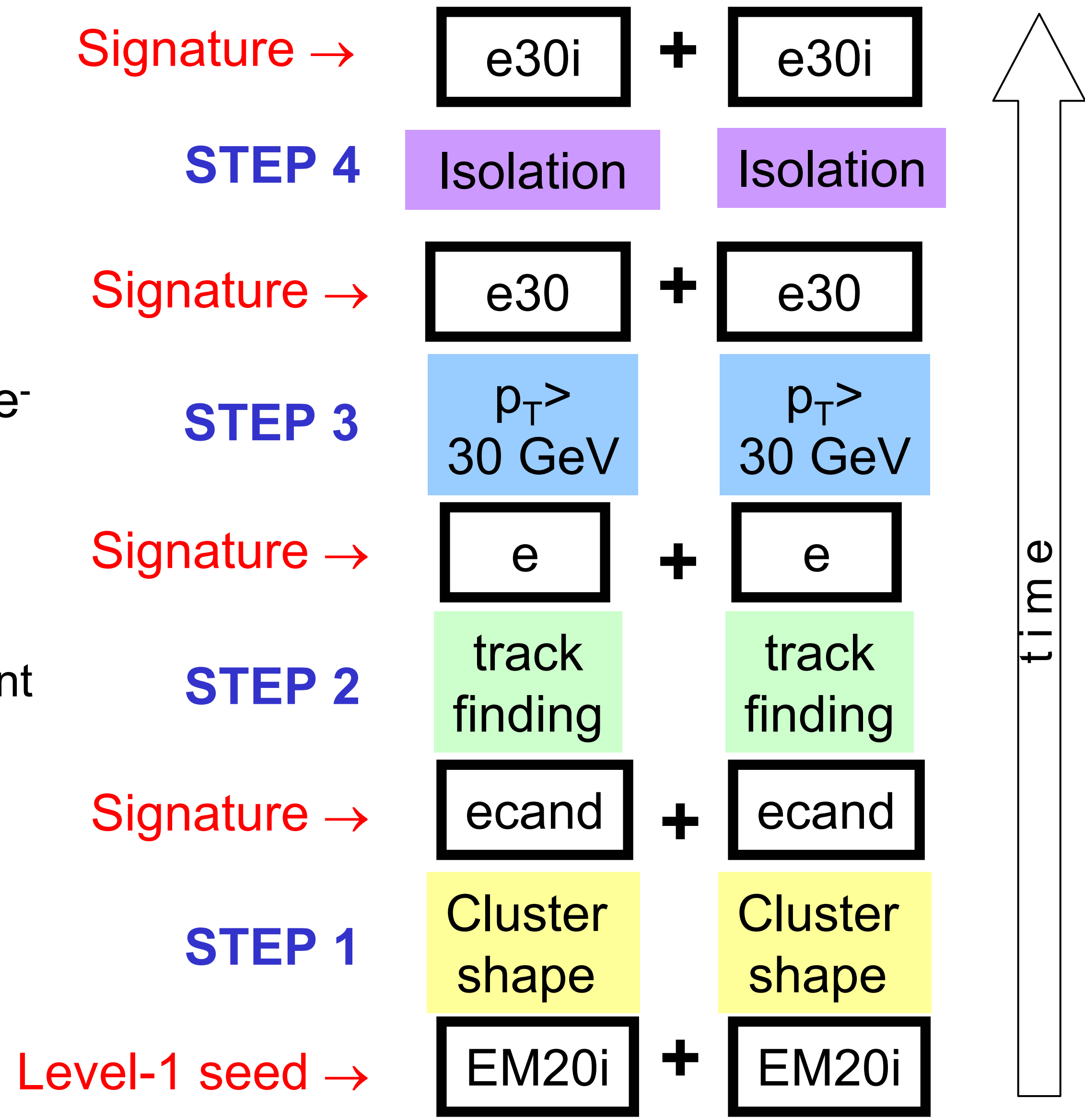
Example:

- Level-1 finds 2 isolated EM clusters with each p_T>20 GeV
- Possible signature for $Z \rightarrow e^+e^-$

Method:

- Validate step-by-step
- Check intermediate signatures
- Reject at earliest possible moment

Managed by HLT Steering

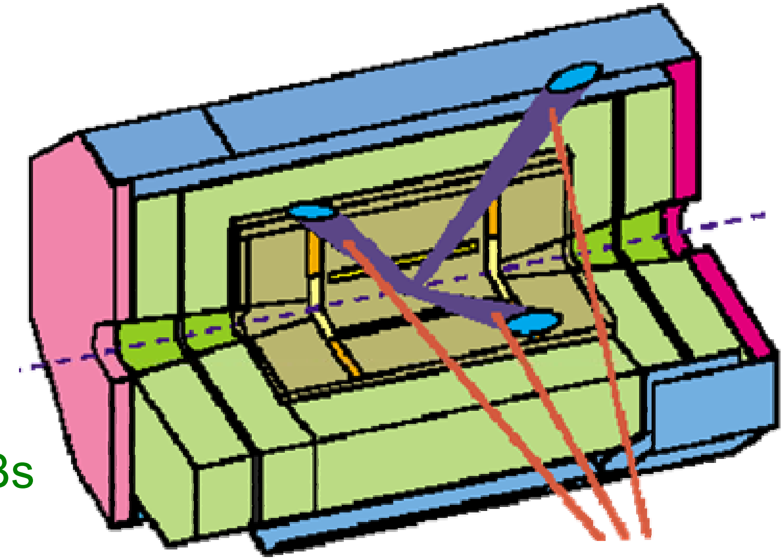


ATLAS High-Level Trigger

- Use simple inclusive high-p_T signatures
  - Can do exclusive signatures in HLT if necessary
- **Level-2**
  - Use seeding (ROIs) to reduce data access and processing time
  - Reconstruct physics objects in stages by a sequence of algorithms requesting data as needed
  - Algorithms at Level-2 have access to Level-1 RoIs
  - Specialized Level-2 algorithms
  - Reject early without executing the rest of the algorithms if not necessary
  - Code to be run in multi-threaded environment
- **Event Filter** based on offline reconstruction code
  - Full event in memory
  - Refine Level-2
  - Event classification
  - Monitoring
- Common framework compatible with offline
  - Flexible boundary between Level-2 and Event Filter

ATLAS Level-2 Trigger

- Driven by Level-1 information
  - Crucial parameters: data routing and CPU time (latency)
  - ROIBuilder: custom hardware to combine ROI pointers
  - Supervisor farm: collect info, allocate event to processor, distribute result to ROBs
  - Processor farm: collect data from ROBs execute algorithm decision to supervisor farm



- Regions of Interest
  - Different geometrical region descriptions (cone, region following a track, etc.)
  - If Level-2 delivers a factor 100 rejection, then input to Level-3 is 1-2 kHz
  - At an event size of 1-2 MB, this needs 1-4 GB/s
    - Dividing this into ~100 receivers implies 10-40 MB/s sustained – certainly doable
  - Elements needed: ROIBuilder, Level-2 processing unit

CMS High-Level Trigger

- The entire HLT runs on a single CPU farm
- Goals:
  - Validate Level-1 decision
  - Refine E_T/p_T thresholds
  - Reject backgrounds
  - Perform physics selection
- Selection must meet physics goals
  - Output rate to permanent storage limited to $O(10^2)$ Hz
- Processing time
  - Estimated processing time: up to 1 s for certain events, average 50 ms
  - About 1000 processor units needed
- Bandwidth:
  - Interconnection of processors and front-end
  - Front-end has O(1000) modules → necessity for large switching network
  - Average event size 1 MB → for maximum Level-1 rate need 100 GByte/s capacity

High-Level Trigger Resources

- **Rejection:**
  - **1:1000 selection**
- **Algorithms:**
  - Algorithms can almost be as sophisticated as in offline analysis
  - Avoid unnecessary calculations; **reject as soon as possible**
  - Hence, internal “logical” trigger levels:
    - Level-2: use calorimeter and muon detectors
    - Level-2.5: also use tracker pixel detectors
    - Level-3: use of full information, including tracker
  - In principle continuum of steps possible
  - Regional reconstruction: e.g. tracks in a given road or region
- **Resources/CPU time:**
  - **100 kHz → 10 μs/event**
  - **If T_j is the time taken by the Level-J decision (J=2,3,…) and the rejection factors are R_J**

$$T_{tot} = T_2 + T_3 / R_2 + T_4 / (R_3 R_2) + \ldots$$

- **A 50 kHz system at startup will need ~2000 CPU’s**

Summary

- LHC is *the* machine to study electro-weak symmetry breaking
  - Capable of finding a Higgs with M up to 1 TeV
  - Given existing tunnel and magnet technology leads to E_{cm} = 14 TeV and very high luminosities
  - **A number of severe challenges as a result:**
    - Interaction rate and physics selectivity, triggering, electronics (fast, pipelined), radiation environment, pile-up
- Trigger Levels: set of successive approximations: number of physical levels varies with architecture/experiment
- The Level-1 trigger takes the LHC experiments from 40 MHz to 40-100 kHz
  - Custom hardware, huge fan-in/out problem, fast algorithms on coarse-grained, low-resolution data
- Depending on the experiment, the next filter is carried out in one or two steps
  - Commercial hardware, large networks, Gb/s links
  - If Level-2 present: low throughput needed
- High-Level Trigger: run software/algorithms as close as possible to offline
  - Solution is straightforward: large processor farm of PCs
- **Event selection at the LHC is a difficult task but will determine the ultimate physics output!**