Trigger and DAQ systems (at the LHC)

Paris Sphicas
CERN/PH and Univ. of Athens
Summer Student Lectures
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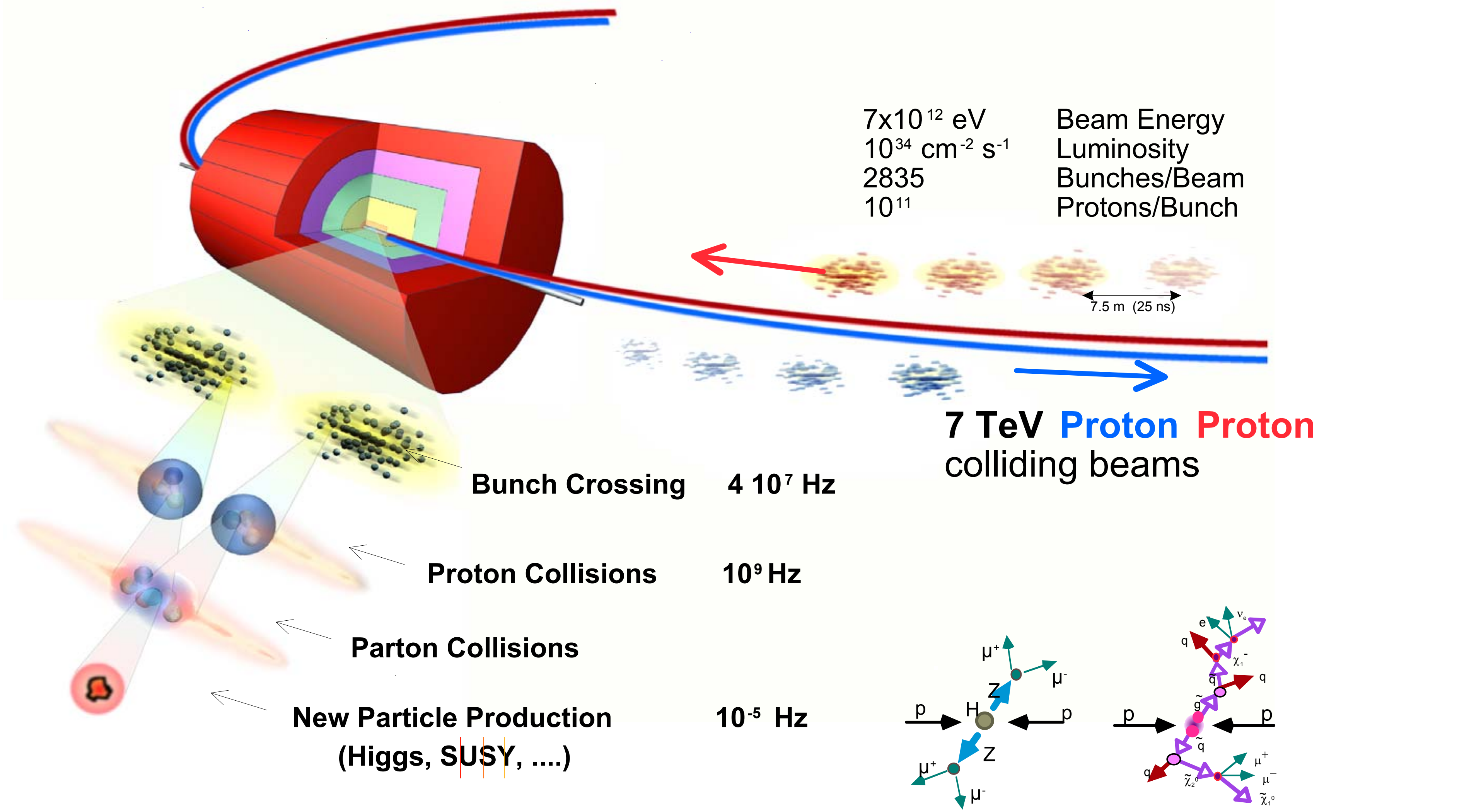
- **Introduction**
  - **The mission**
  - **LHC: The machine and the physics**
  - **Trigger/DAQ architectures and tradeoffs**
- **Level-1 Trigger**
  - **Architectures, elements, performance**
- **DAQ**
- **High-Level trigger**

Introduction:
Mission Make-it-Possible

Collisions at the LHC: summary



Selection of 1 event in 10,000,000,000,000

Trigger and Data Acquisition System

- **Mandate:**

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

  - P.S. For a reasonable number of CHF

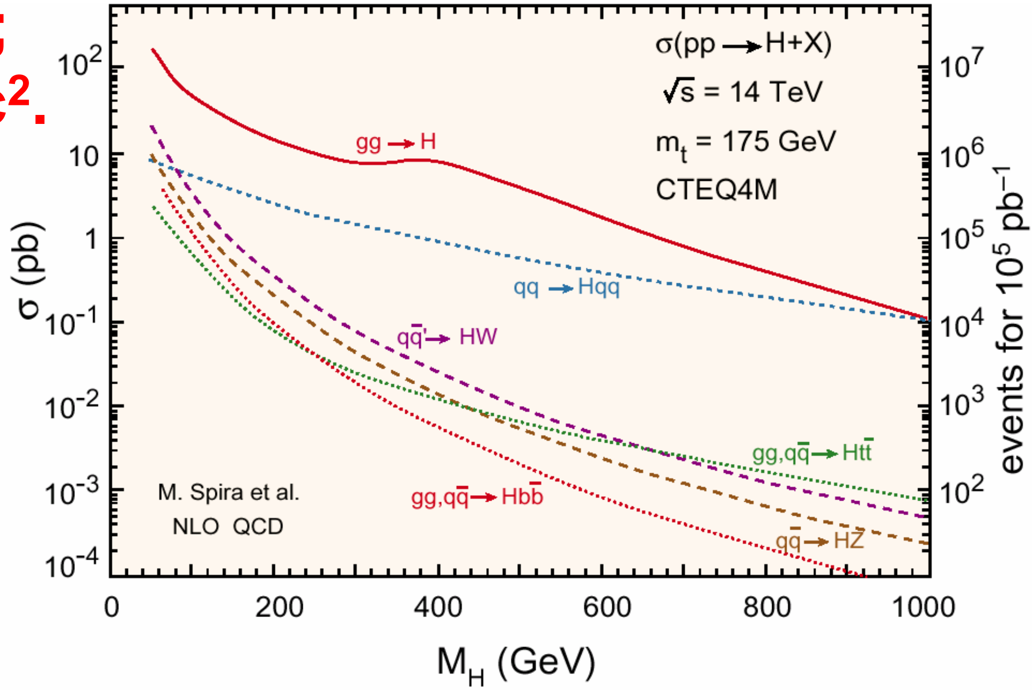
- **The photographer analogy:**
  - Trigger: the photographer/camera push-button combination
  - DAQ: burning the film, rolling out the picture, storing film
  - Quality of shot: number of pictures/second, number of pixels
    - And of course the photographer
  - Cost of shot: the camera (one-time); film (recurring); the shot itself (cannot take another picture for a short time after we push on the camera button)

- **Trigger/DAQ: the HEP experiment photographer. All physics analysis runs off of the film (s)he produces**

LHC: physics goals and machine parameters

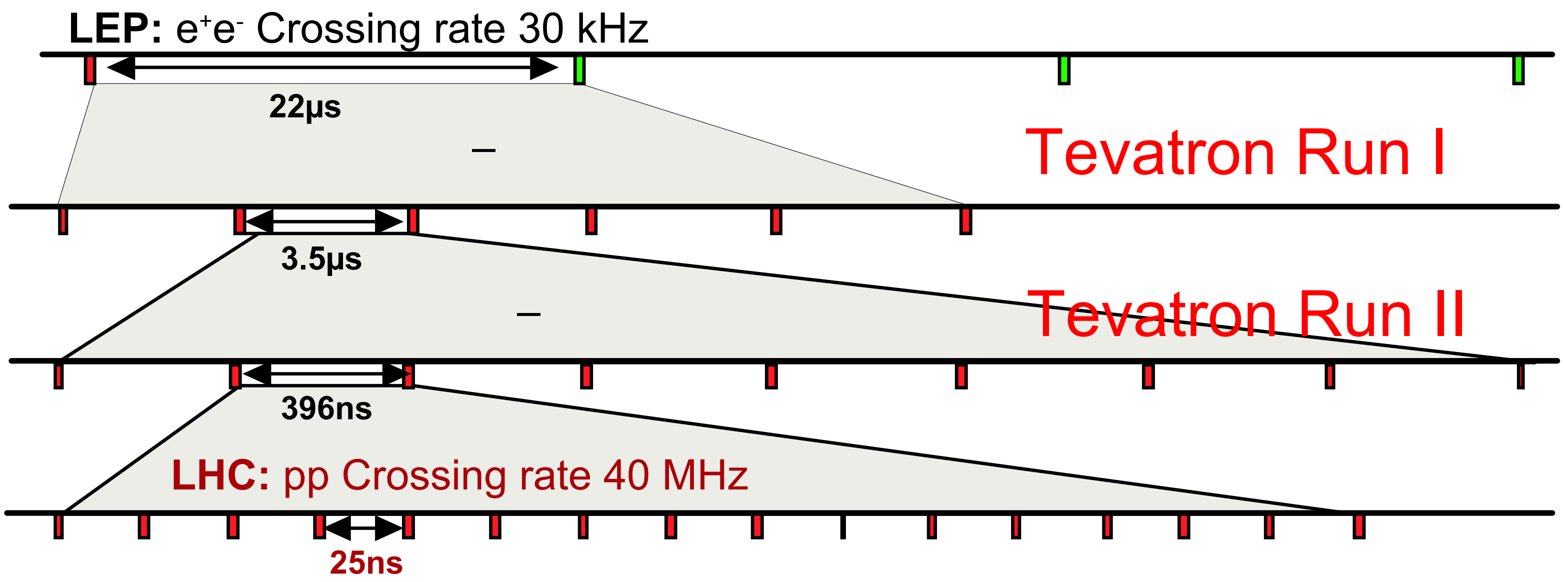
Higgs boson production at LHC

- **Primary physics goal: explore the physics of Electroweak symmetry breaking.**
  - In the SM: the Higgs
  - Energy of the collider: dictated by machine radius and magnets
  - Luminosity: determine from requirements
- **Higgs mass: unknown; could be up to ~1TeV/c^2.**
  - Wish to have ~20-30 events/year at highest masses
- **Luminosity needed: $10^{34}cm^{-2}s^{-1}$**
  - At 10^{11} protons/bunch, need ~3000 bunches



Beam crossings: LEP, Tevatron & LHC

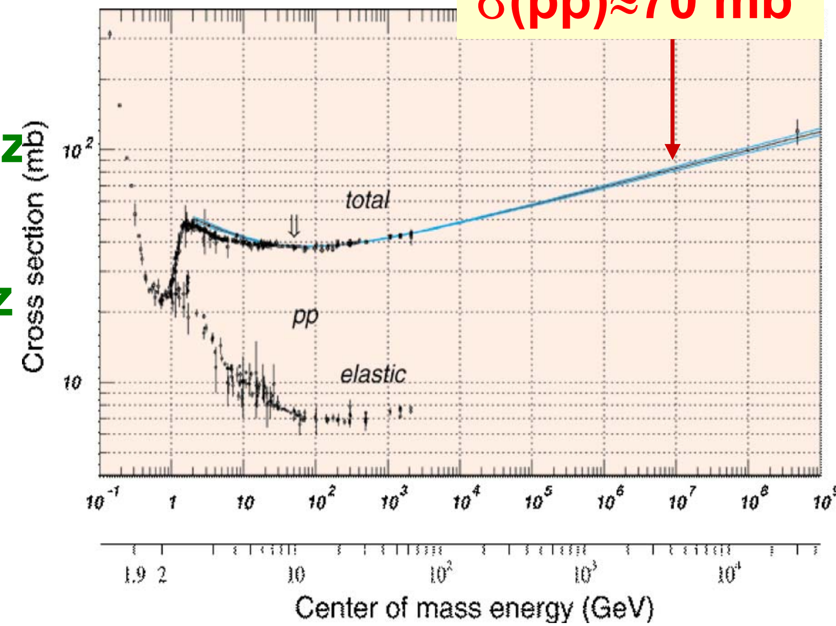
- **LHC will have ~3600 bunches**
  - **And same length as LEP (27 km)**
  - **Distance between bunches: 27km/3600=7.5m**
  - **Distance between bunches in time: 7.5m/c=25ns**



pp cross section and min. bias

- **# of interactions/crossing:**
  - **Interactions/s:**
    - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7$$mb^{-1}$Hz
    - σ(pp) = 70 mb
    - Interaction Rate, R = $7x10^8$ Hz
  - **Events/beam crossing:**
    - Δt = 25 ns = $2.5x10^{-8}$ s
    - Interactions/crossing=17.5
  - **Not all p bunches are full**
    - 2835 out of 3564 only
    - Interactions/"active" crossing = 17.5 x 3564/2835 = 23

σ(pp)≈70 mb



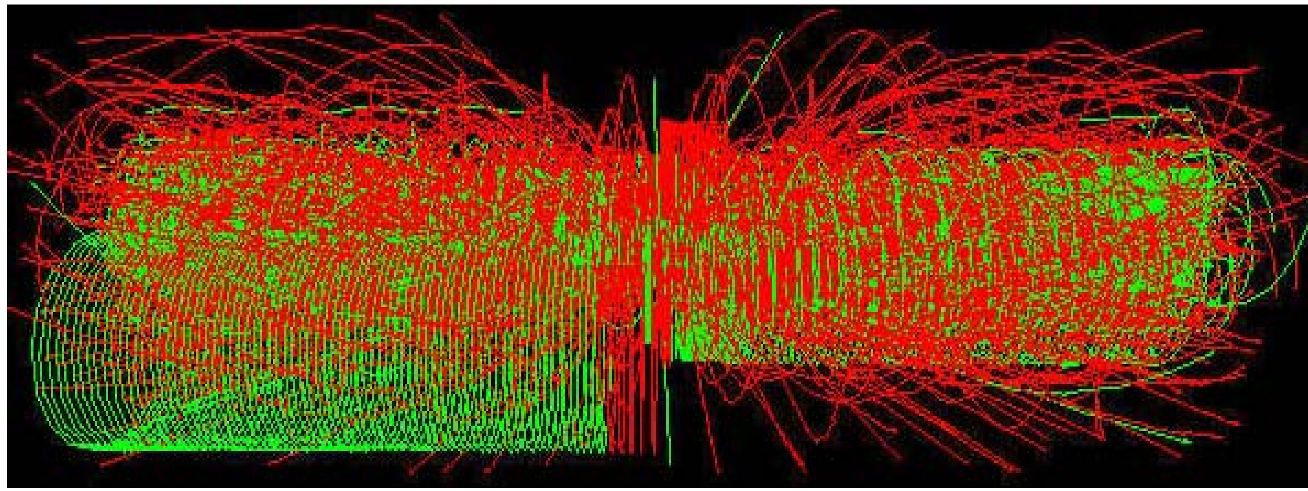
Operating conditions (summary):
1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

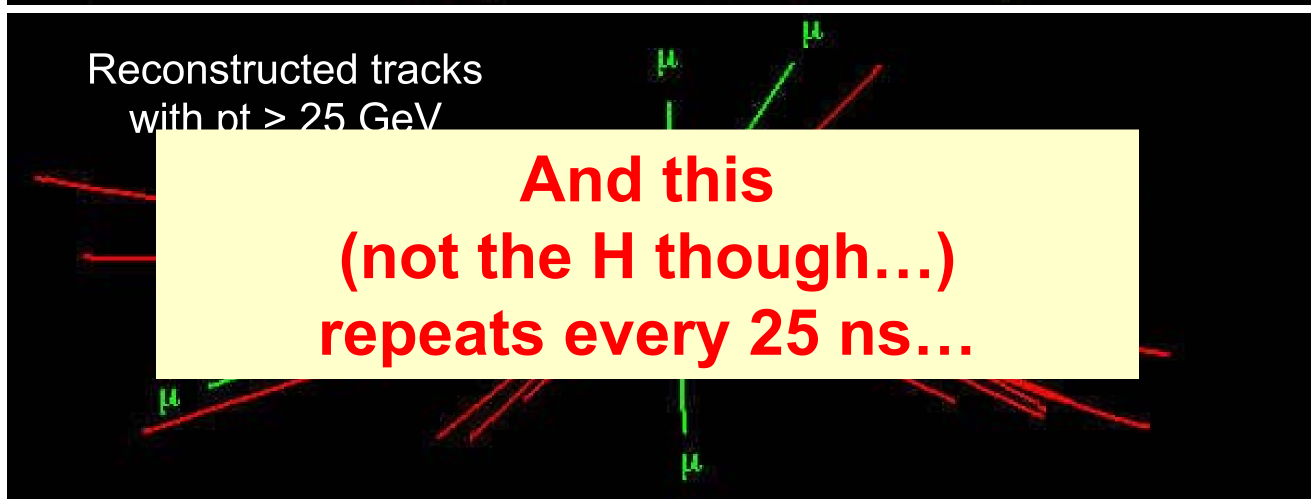
pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

- **20 min bias events overlap**
- **$H \rightarrow ZZ$**

$Z \rightarrow \mu\mu$

$H \rightarrow$ 4 muons: the cleanest ("golden") signature





And this (not the H though…) repeats every 25 ns…

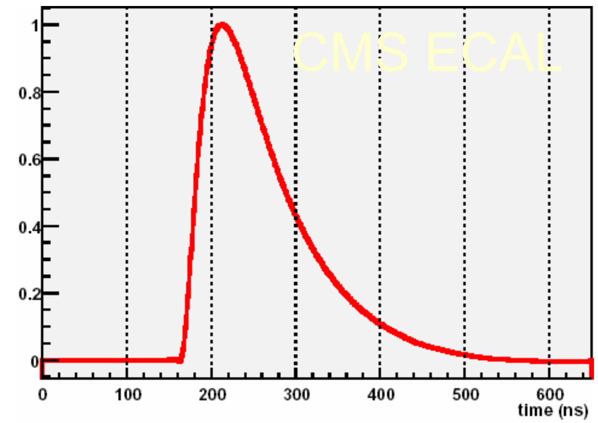
Impact on detector design

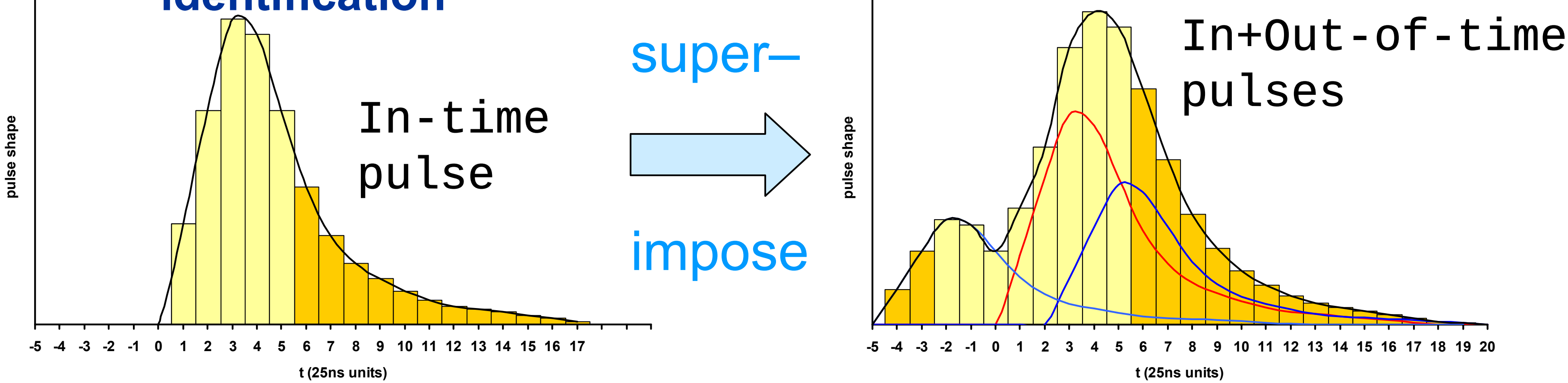
- **LHC detectors must have fast response**
  - Avoid integrating over many bunch crossings ("pile-up")
  - Typical response time : 20-50 ns
    - $\rightarrow$ integrate over 1-2 bunch crossings $\rightarrow$ pile-up of 25-50 min-bias events $\rightarrow$ very challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)
    - $\rightarrow$ large number of electronic channels
- **LHC detectors must be radiation resistant:**
  - high flux of particles from pp collisions $\rightarrow$ high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

Pile-up

- **"In-time" pile-up: particles from the same crossing but from a different pp interaction**

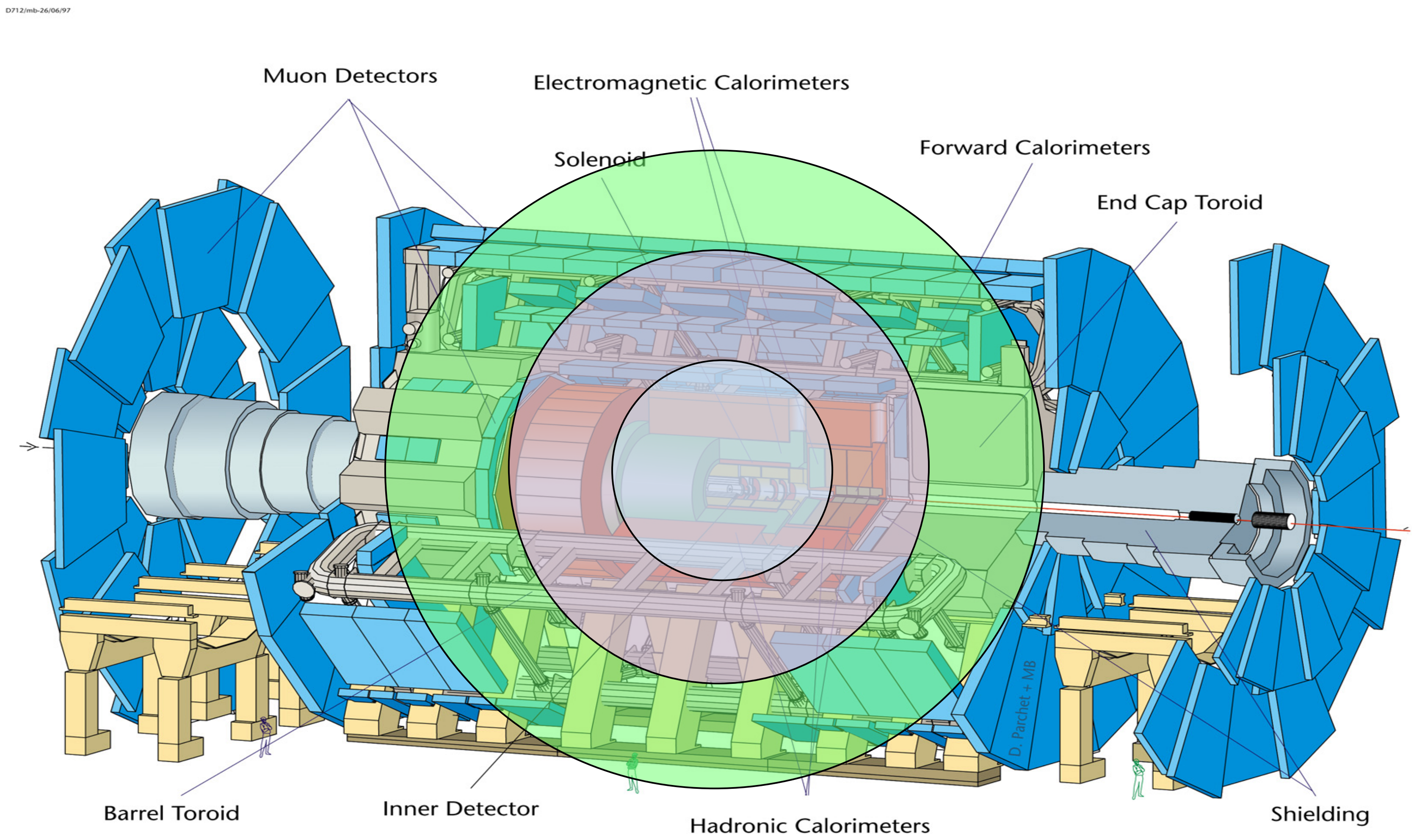
- **Long detector response/pulse shapes:**
  - **"Out-of-time" pile-up: left-over signals from interactions in previous crossings**
  - **Need "bunch-crossing identification"**





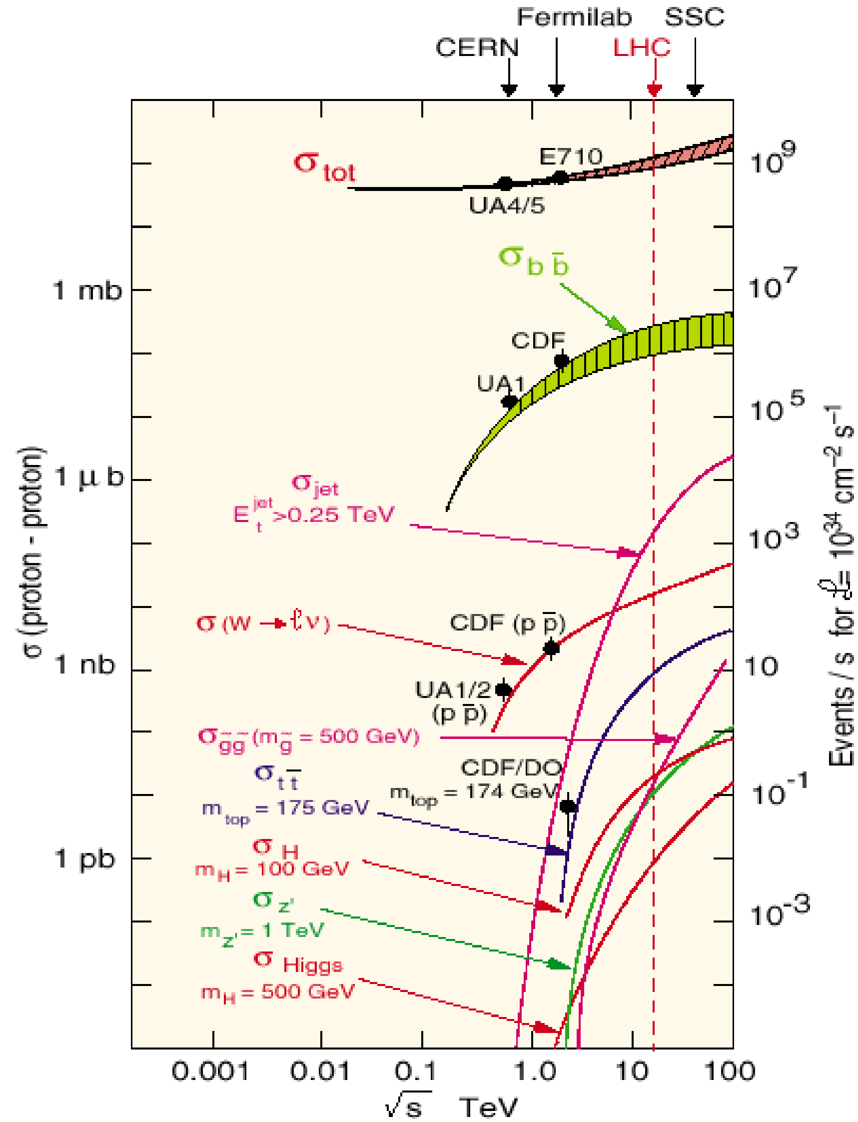
Time of Flight

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

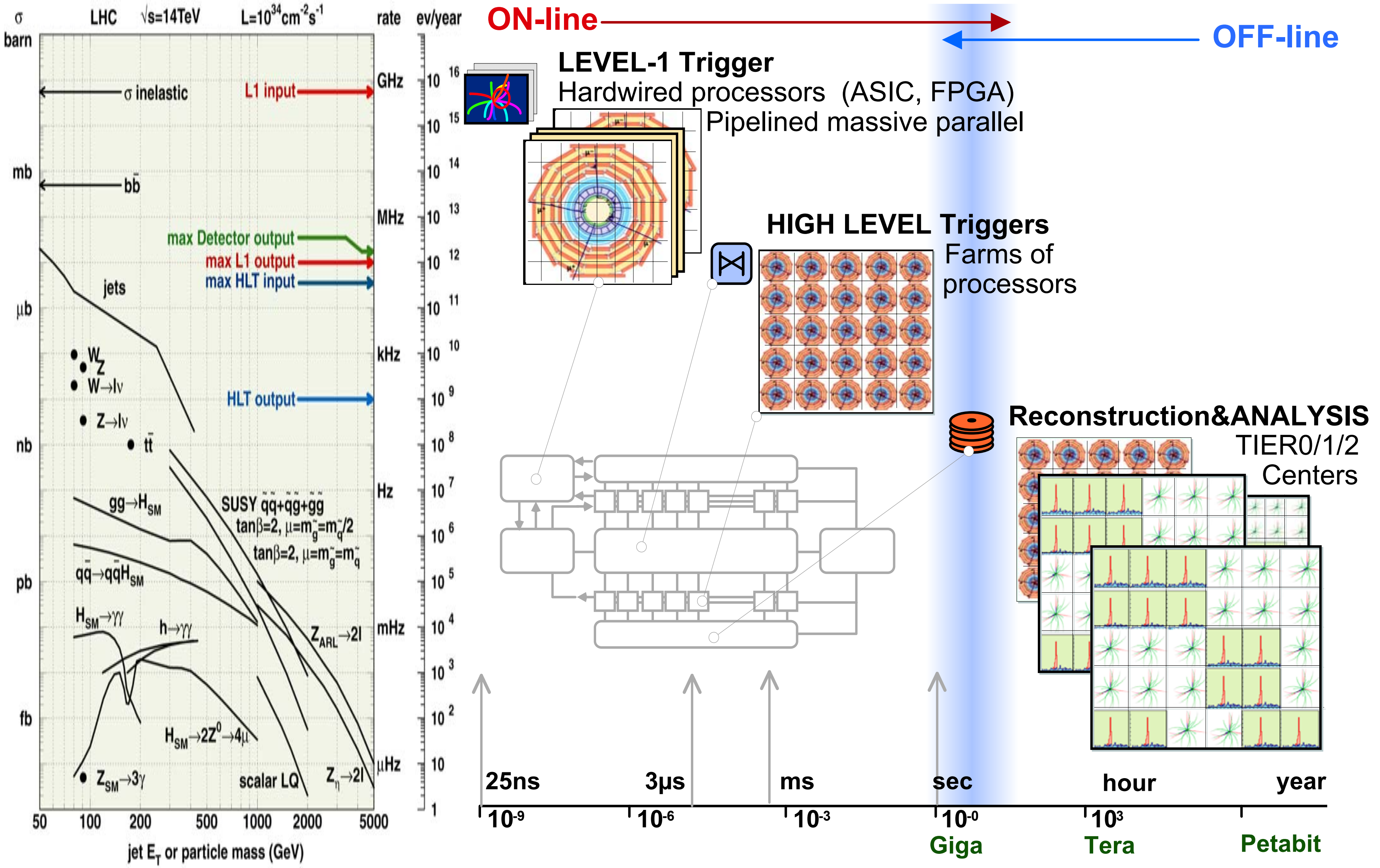


Selectivity: the physics

- **Cross sections for various physics processes vary over many orders of magnitude**
  - **Inelastic: 10^9 Hz**
  - **$W \to \ell \nu$: 10^2 Hz**
  - **t t production: 10 Hz**
  - **Higgs (100 GeV/c^2): 0.1 Hz**
  - **Higgs (600 GeV/c^2): 10^{-2} Hz**
- **Selection needed: $1:10^{10-11}$**
  - **Before branching fractions...**



Physics selection at the LHC



Trigger/DAQ requirements/challenges

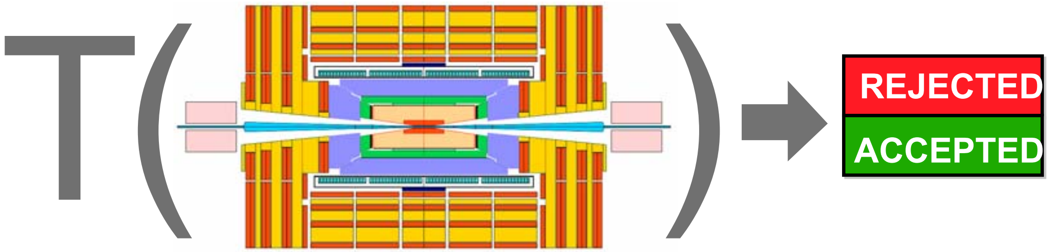
- **N (channels) ~ O(10^7); ≈20 interactions every 25 ns**
  - need huge number of connections
  - need information super-highway
- **Calorimeter information should correspond to tracker info**
  - need to synchronize detector elements to (better than) 25 ns
- **In some cases: detector signal/time of flight > 25 ns**
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing...
- **Can store data at ≈ 10^2 Hz**
  - need to reject most interactions
- **It's On-Line (cannot go back and recover events)**
  - need to monitor selection

Trigger/DAQ: architectures

Triggering

- **Task: inspect detector information and provide a first decision on whether to keep the event or throw it out**

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

- **Detector data not (all) promptly available**
- **Selection function highly complex**

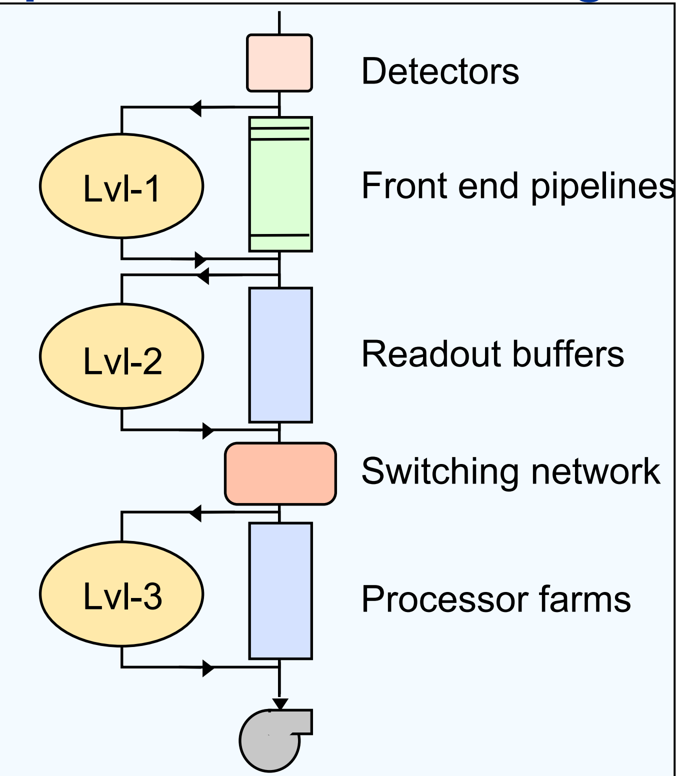
⇒T(...) is evaluated by successive approximations, the

TRIGGER LEVELS

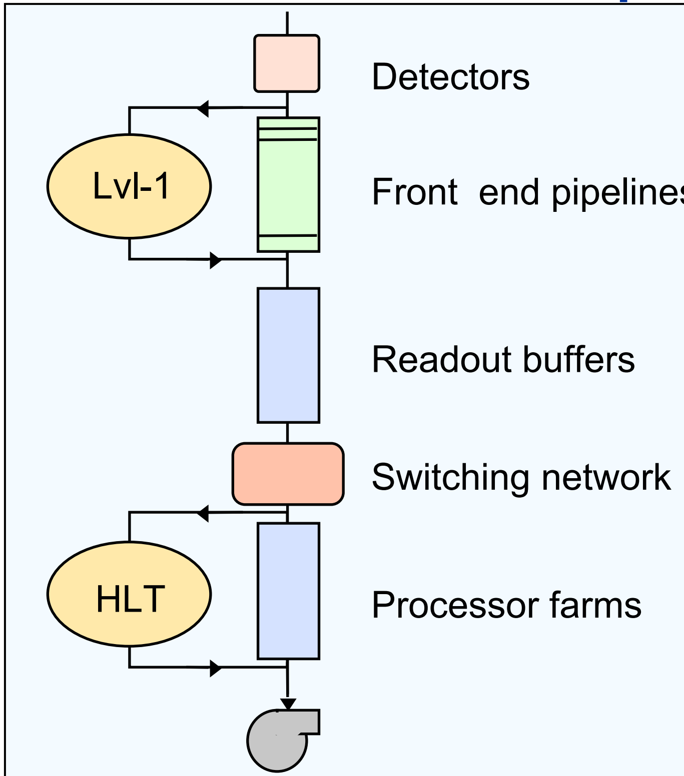
(possibly with zero dead time)

Online Selection Flow in pp

- **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**



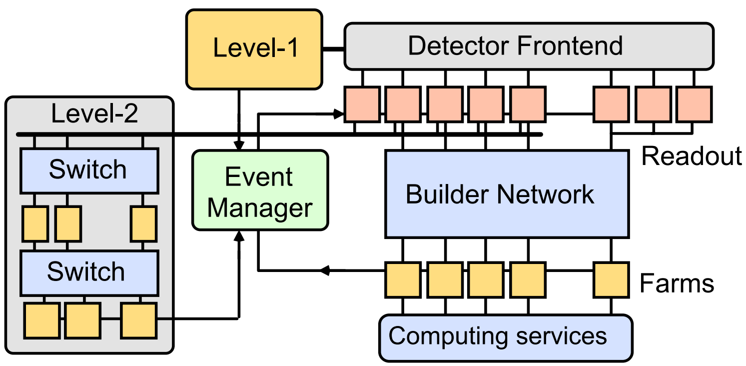
"Traditional": 3 physical levels

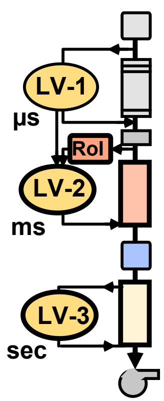


CMS: 2 physical levels

Three physical entities

- **Additional processing in LV-2: reduce network bandwidth requirements**





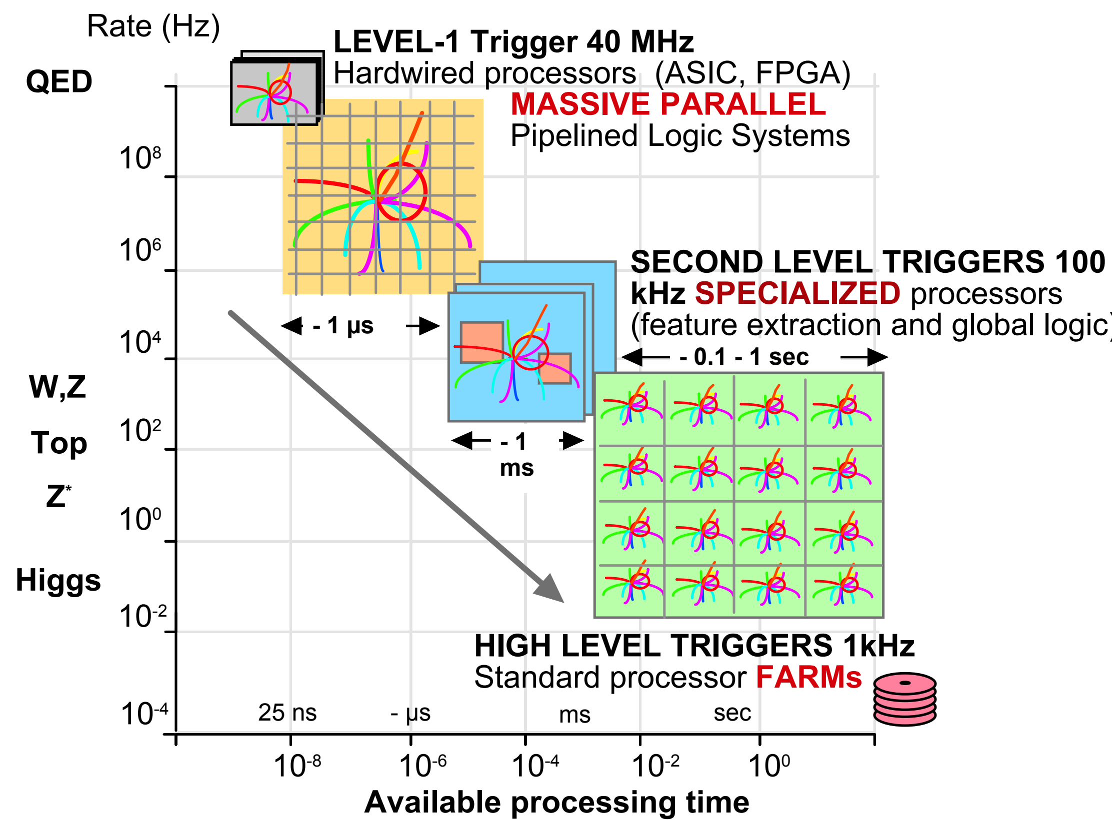
40 MHz

10^5 Hz

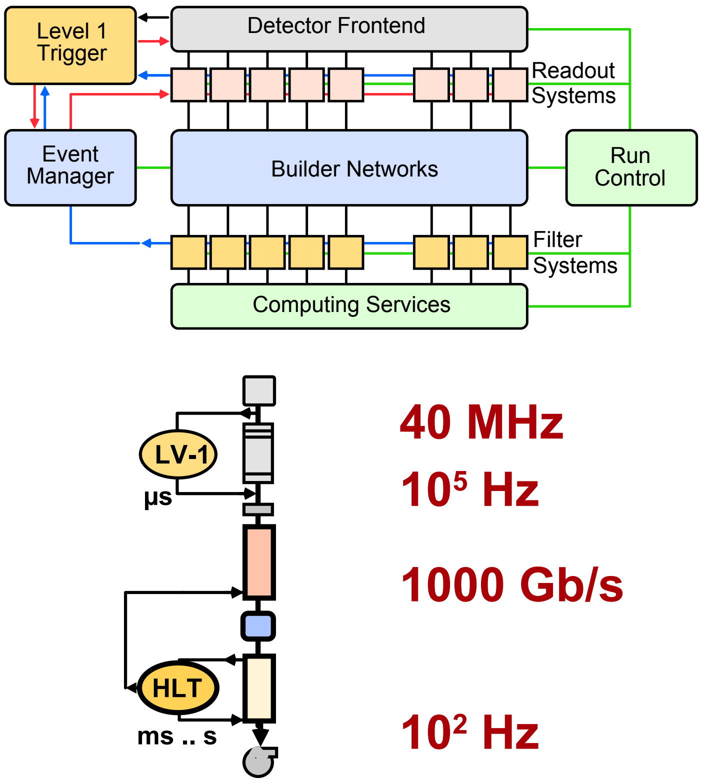
10^3 Hz

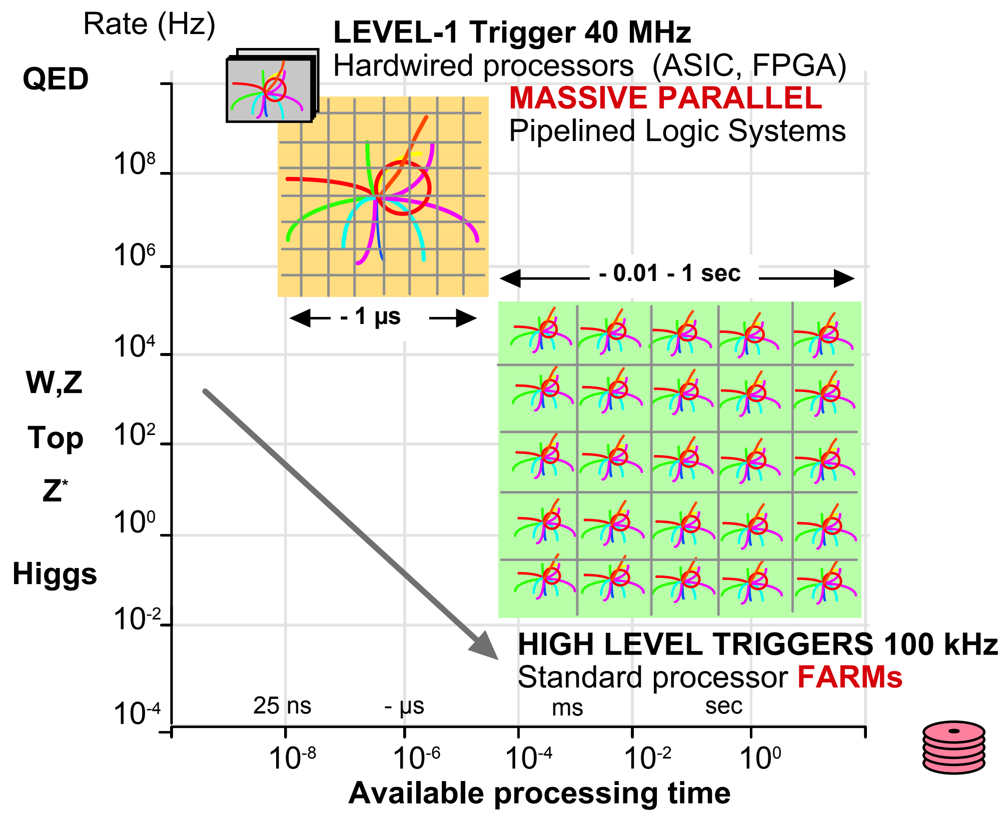
10 Gb/s

10^2 Hz



Two physical entities

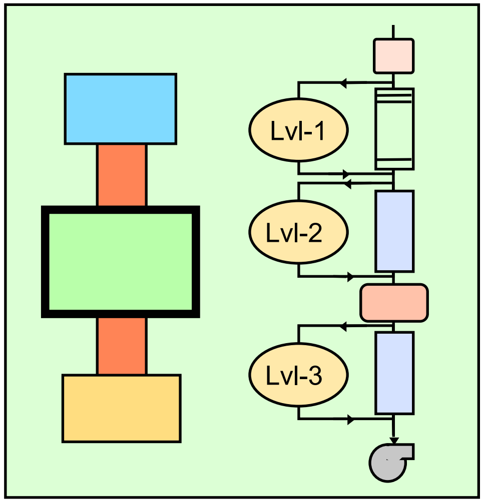




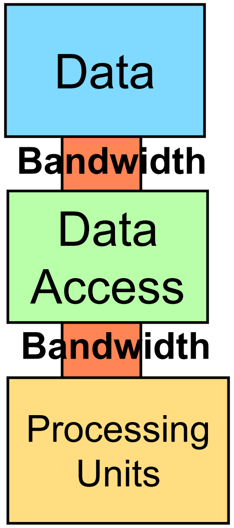
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Comparison of 2 vs 3 physical levels

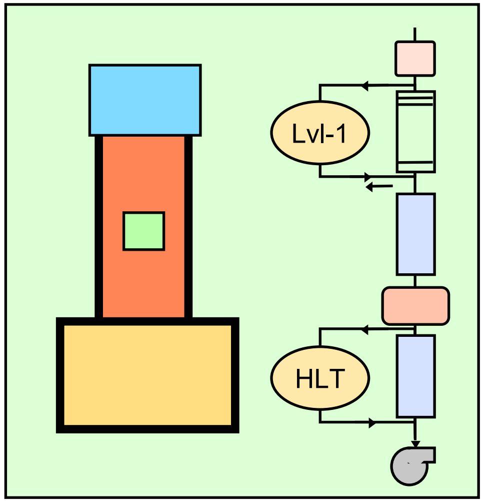
- **Three Physical Levels**
  - Investment in:
    - Control Logic
    - Specialized processors



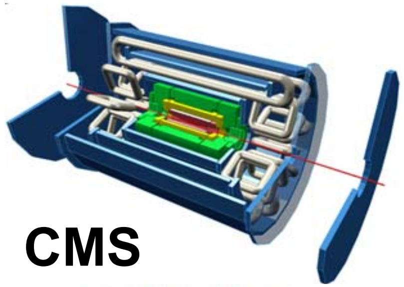
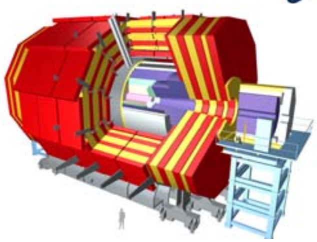
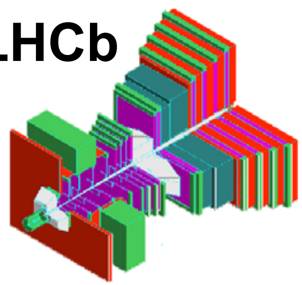
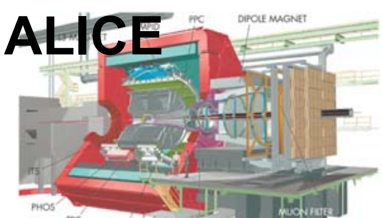
Model



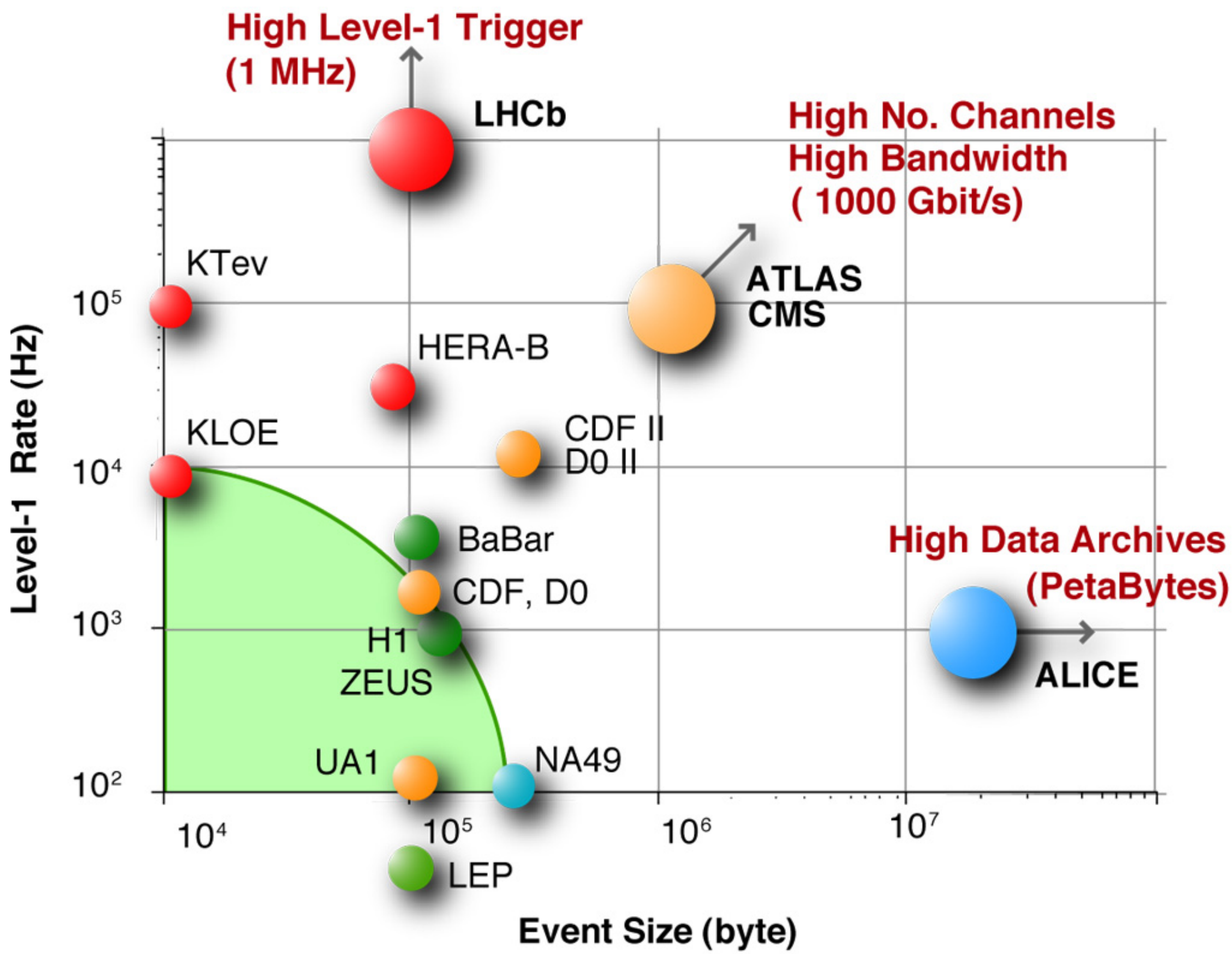
- **Two Physical Levels**
  - Investment in:
    - Bandwidth
    - Commercial Processors



Trigger/DAQ parameters: summary

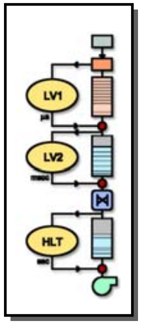
	No.Levels Trigger	Level-1 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS 	**3**	**10^5** LV-2 **10^3**	**10^6**	**10**	**100** (10^2)
CMS 	**2**	**10^5**	**10^6**	**100**	**100** (10^2)
LHCb 	**3**	LV-0 **10^6** LV-1 **$4\ 10^4$**	**$2x10^5$**	**4**	**40** ($2x10^2$)
ALICE 	**4**	Pp-Pp **500** p-p **10^3**	**$5x10^7$** **$2x10^6$**	**5**	**1250** (10^2) **200** (10^2)

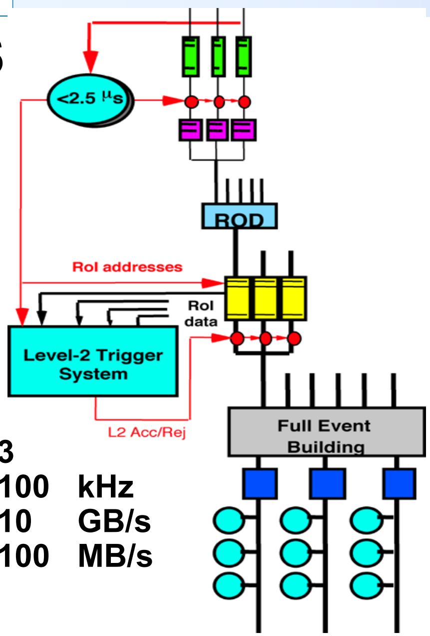
Trigger/DAQ systems: present & future



Trigger/DAQ systems: grand view

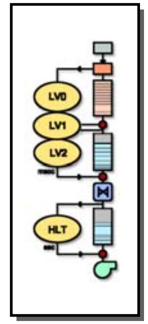
ATLAS

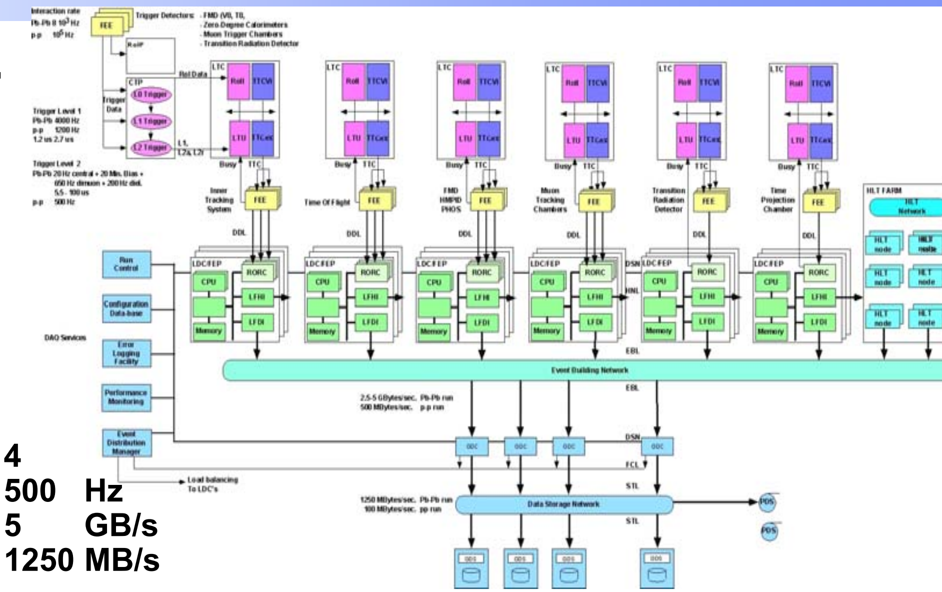




Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

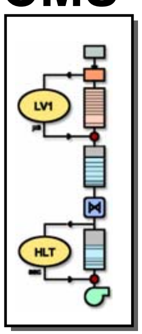
ALICE

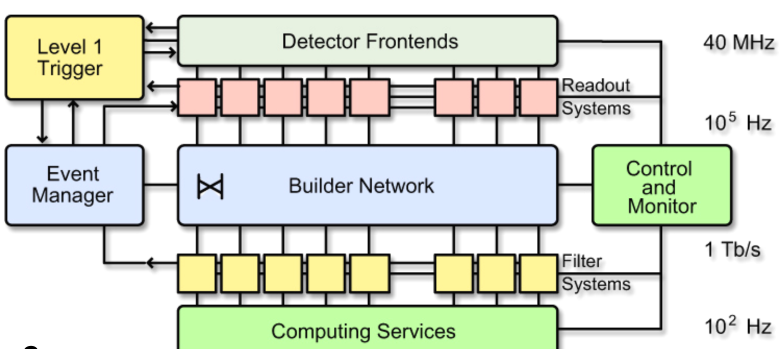




Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250	MB/s

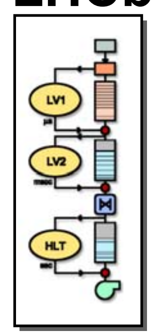
CMS

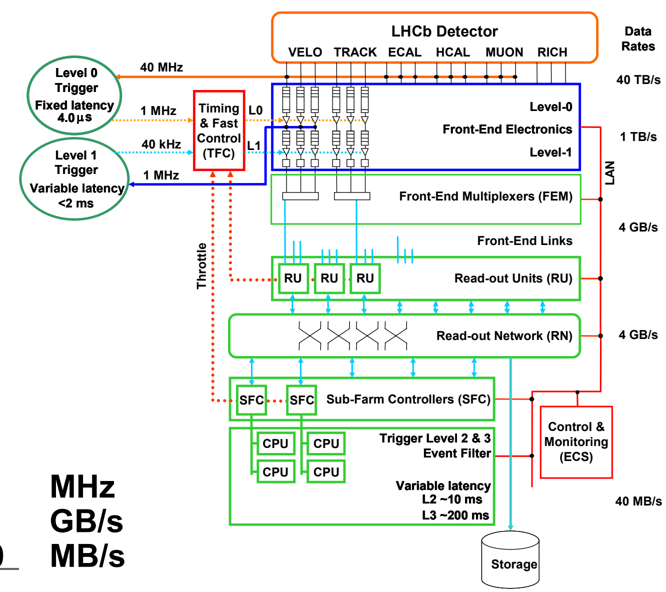




Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

LHCb





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

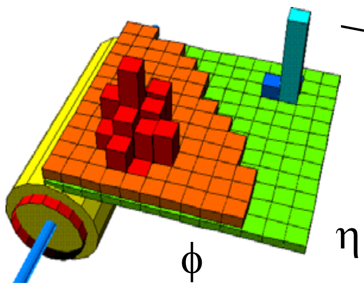
Level-1 Trigger

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:
    - $W \rightarrow e\nu$: $M(W)=80\ GeV/c^2$; $P_T(e) \sim 30\text{-}40$ GeV
    - $H(120\ GeV) \rightarrow \gamma\gamma$: $P_T(\gamma) \sim 50\text{-}60$ 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)
      - ➔ Dimuons with P_T>6 (rate ~ 1 kHz)
    - Single e/γ with P_T>30 GeV (rate ~ 10-20 kHz)
      - ➔ Dielectrons with P_T>20 GeV (rate ~ 5 kHz)
    - Single jet with P_T>300 GeV (rate ~ 0.2-0.4 kHz)

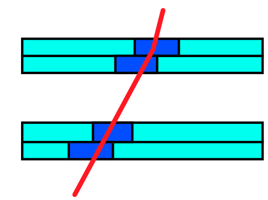
Particle signatures in the detector(s)

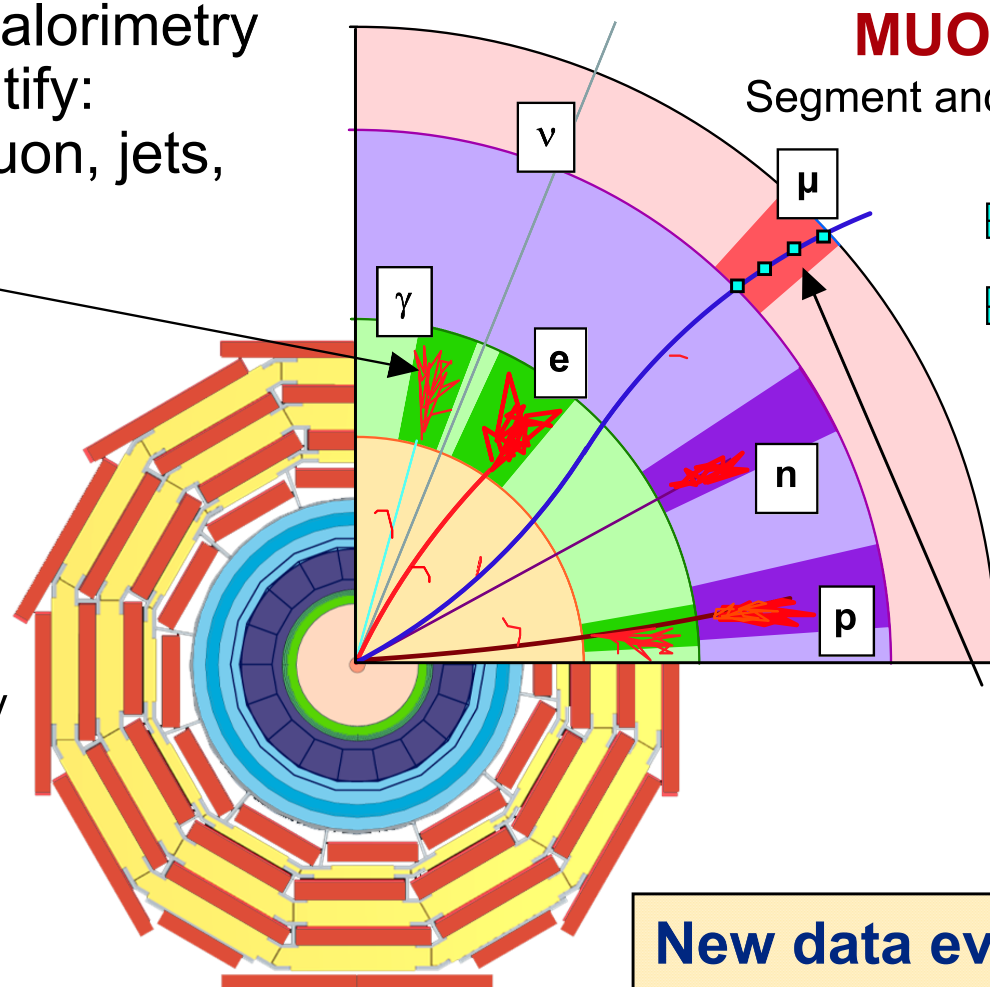
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



MUON System

Segment and track finding





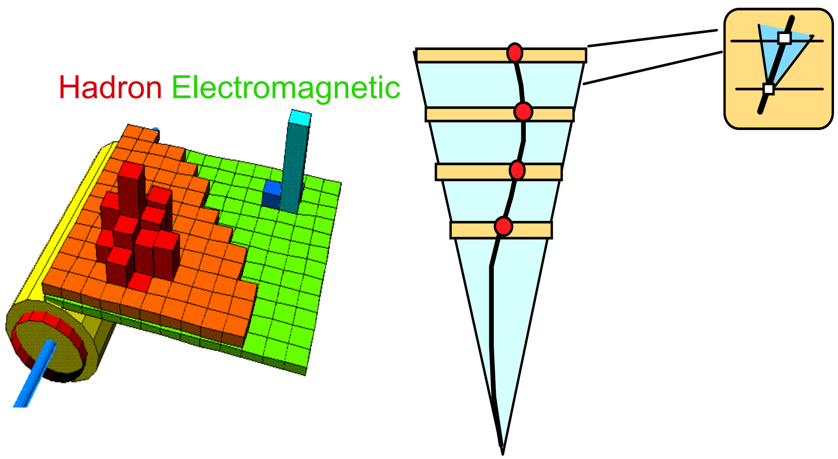
CALORIMETERs

Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ μs

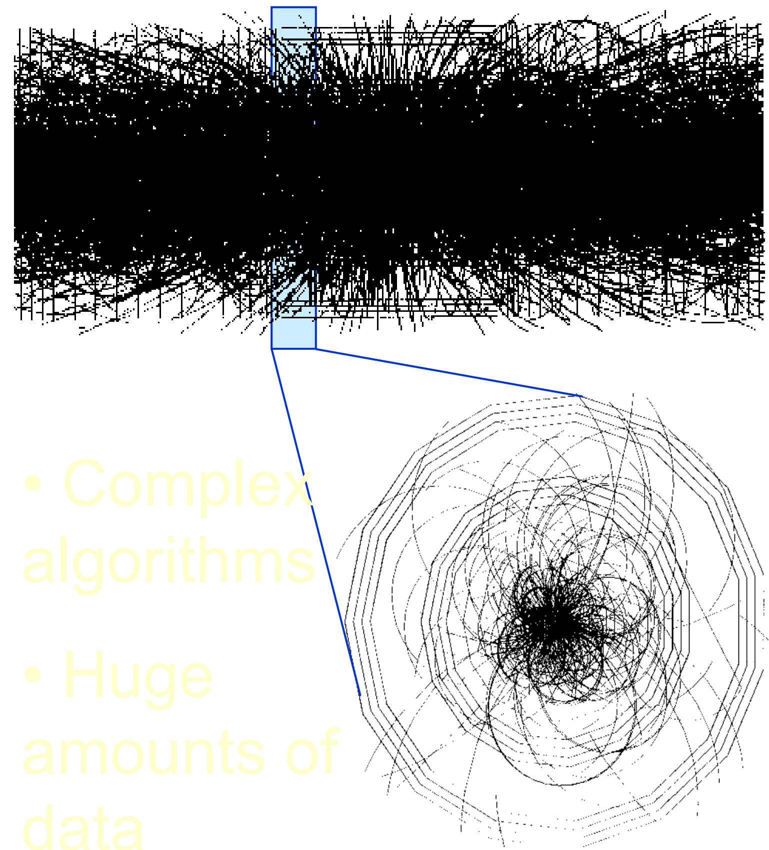
At Level-1: only calo and muon info

- **Pattern recognition much faster/easier**



- Simple algorithms
- Small amounts of data
- Local decisions

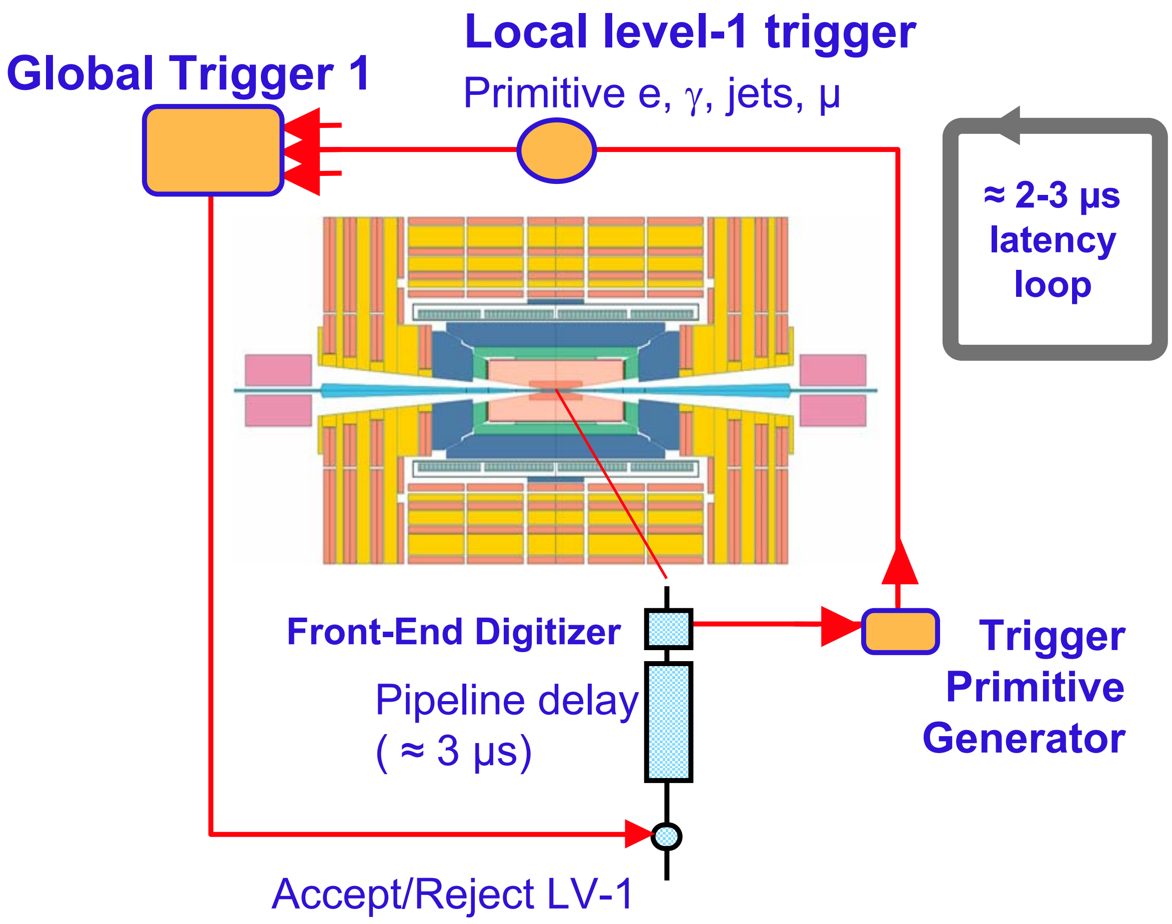
- **Compare to tracker info**



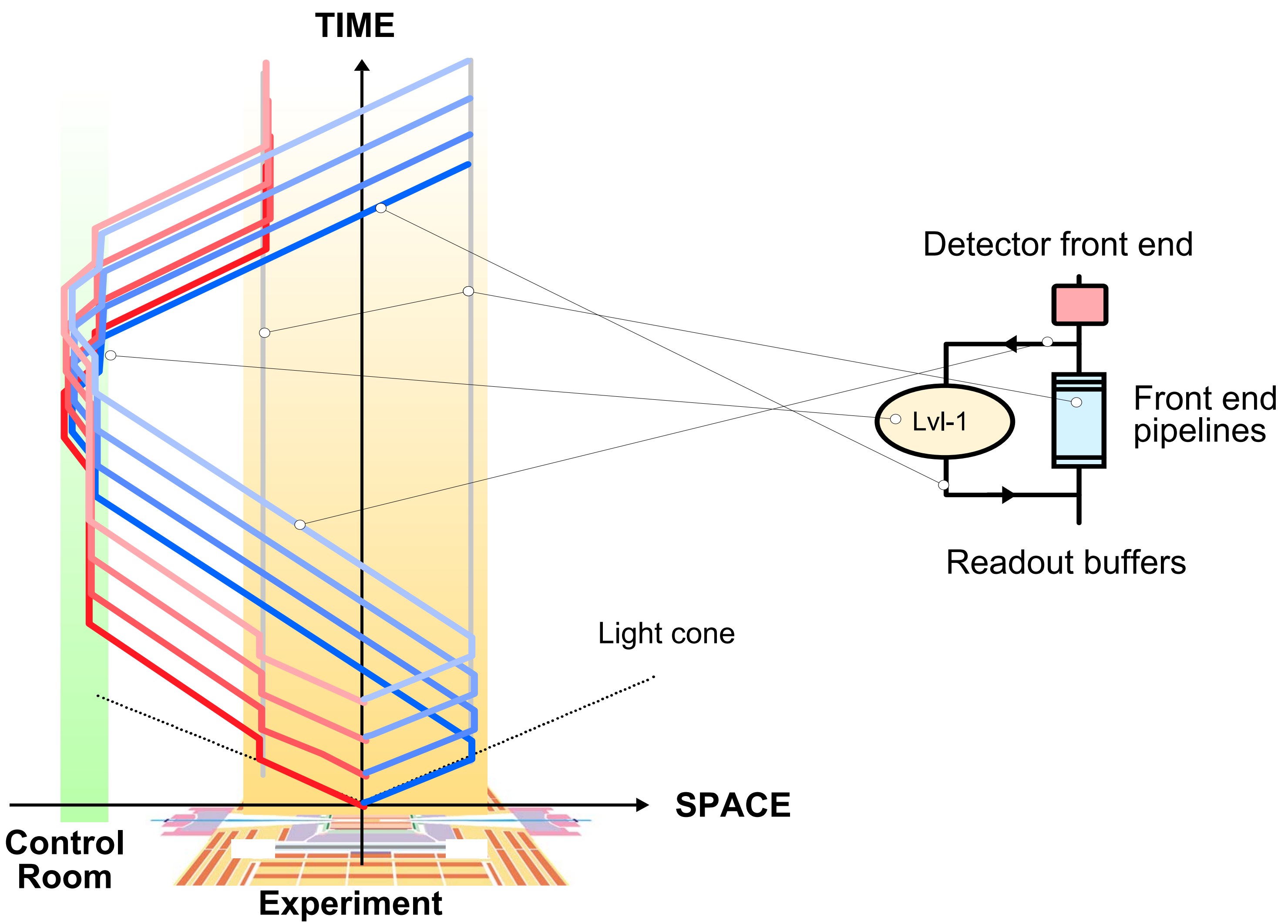
- Complex algorithms
- Huge amounts of data
- Need to link sub-detectors

Level-1 Trigger: decision loop

- **Synchronous 40 MHz digital system**
  - **Typical: 160 MHz internal pipeline**
  - **Latencies:**
    - **Readout + processing: < 1μs**
    - **Signal collection & distribution: ≈ 2μs**
- **At Lvl-1: process only calo+μ info**



Signaling and pipelining



Lvl-1 trigger architecture: ATLAS

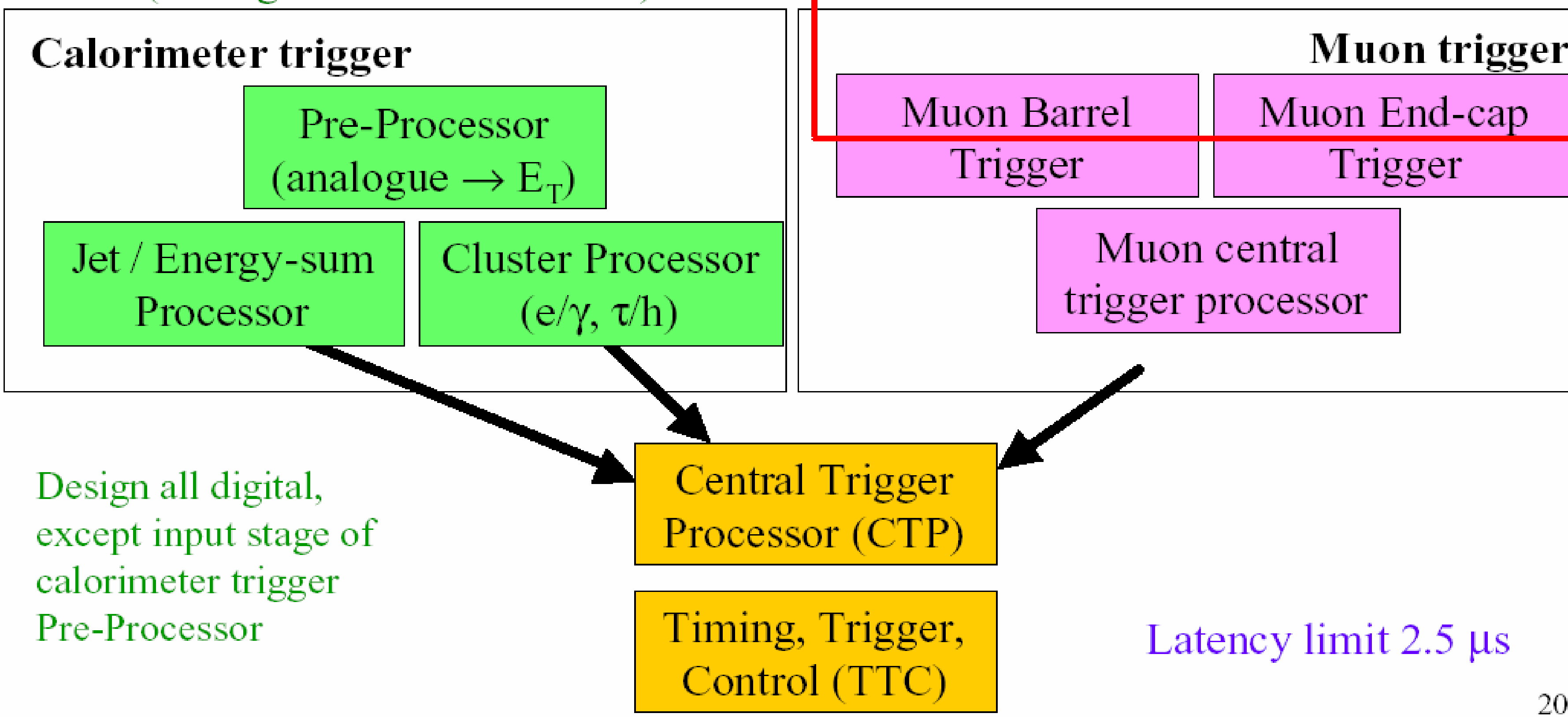
CMS ~ similar

~7000 calorimeter trigger towers
(analogue sum on detectors)

CAVERN

Radiation tolerance, cooling, grounding, magnetic field, no access

O(1M) RPC/TGC channels



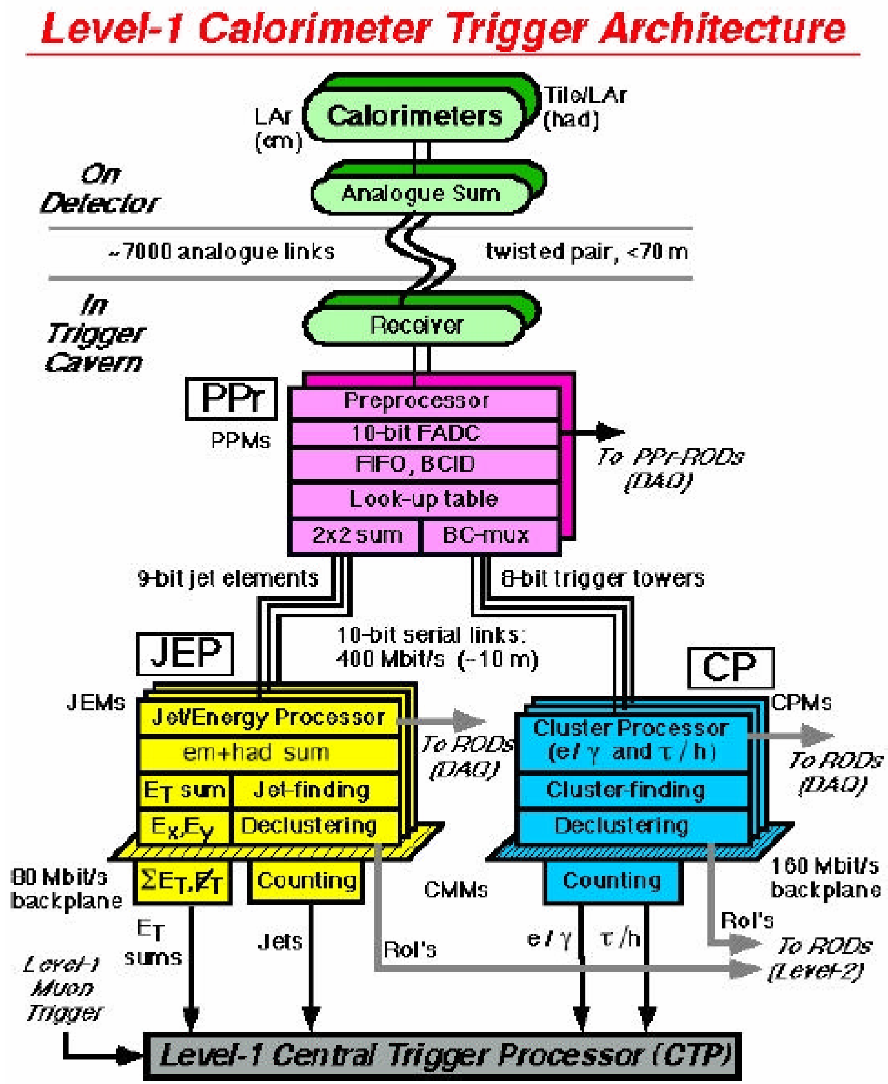
Design all digital, except input stage of calorimeter trigger Pre-Processor

Latency limit 2.5 μs

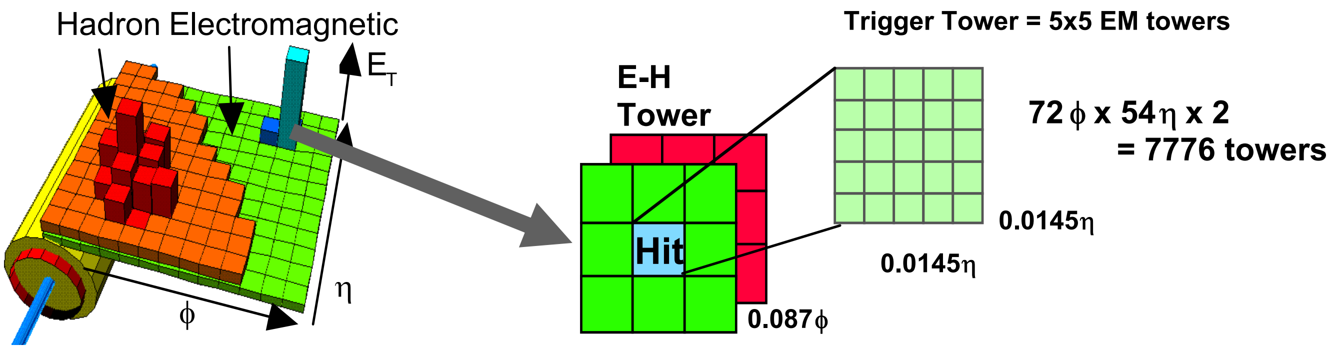
20

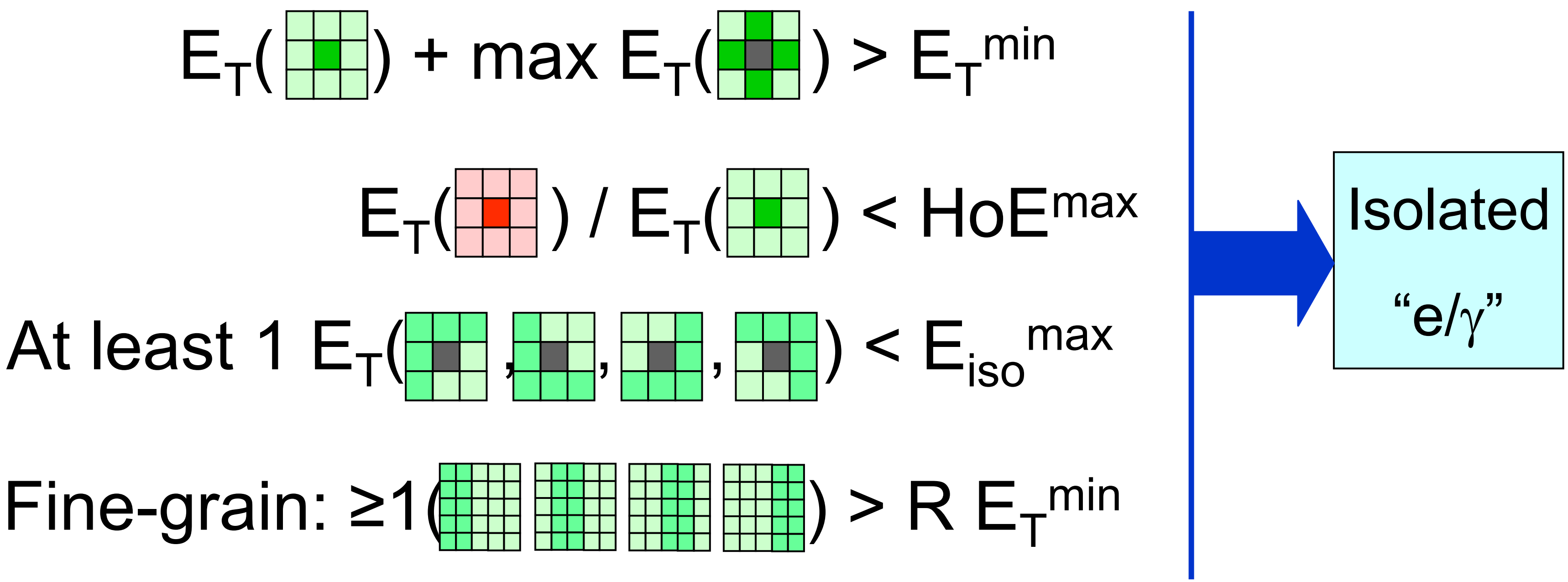
Level-1 trigger data flow: ATLAS

- **On-detector:**
  - analog sums to form trigger towers
- **Off-detector:**
  - Receive data, digitize, identify bunch crossing, compute E_T
  - Send data to Cluster Processor and Jet Energy Processor crates
- **Local processor crates:**
  - Form sums/comparisons as per algorithm, decide on objects found
- **Global Trigger: decision**



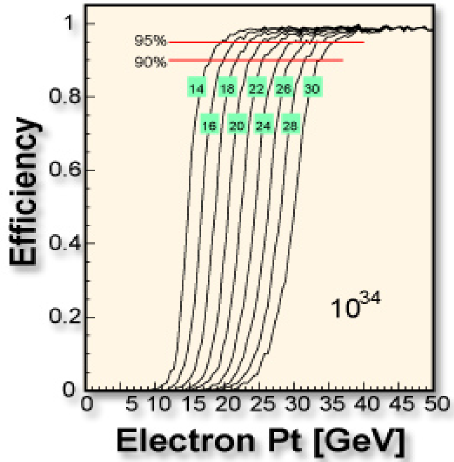
Lvl-1 Calo Trigger: e/γ algorithm (CMS)

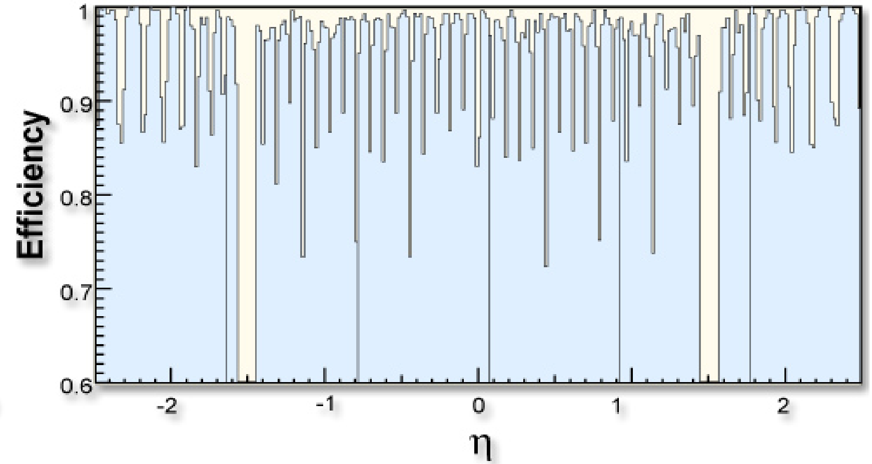


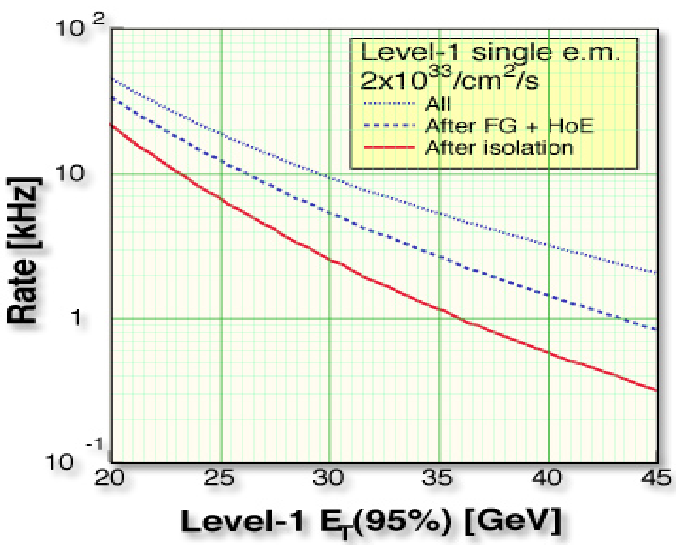


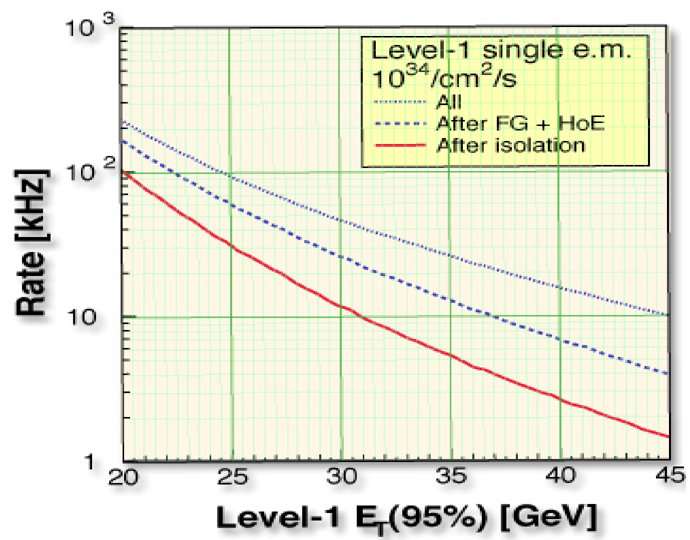
Lvl-1 Calo e/γ trigger: performance

- **Efficiencies and Trigger Rates**









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**

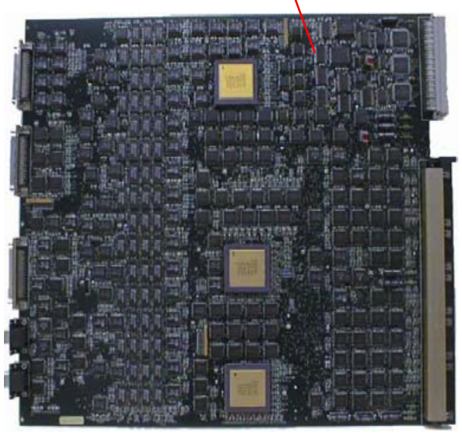
Lvl-1 Calo Trigger: prototypes

Trigger Crate
(160 MHz backplane)

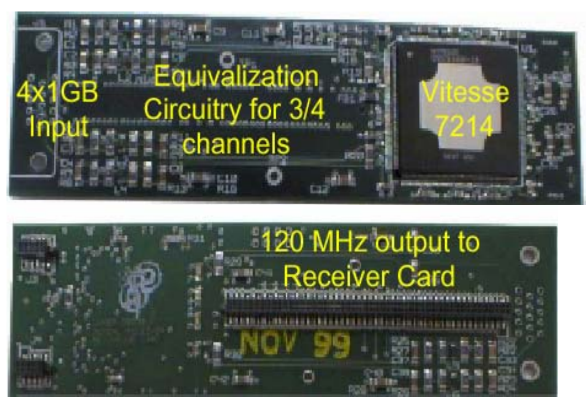
Back

Front

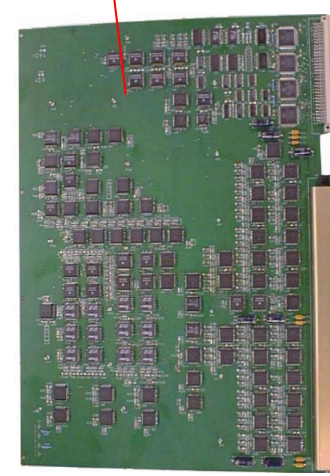
Receiver Card



Links

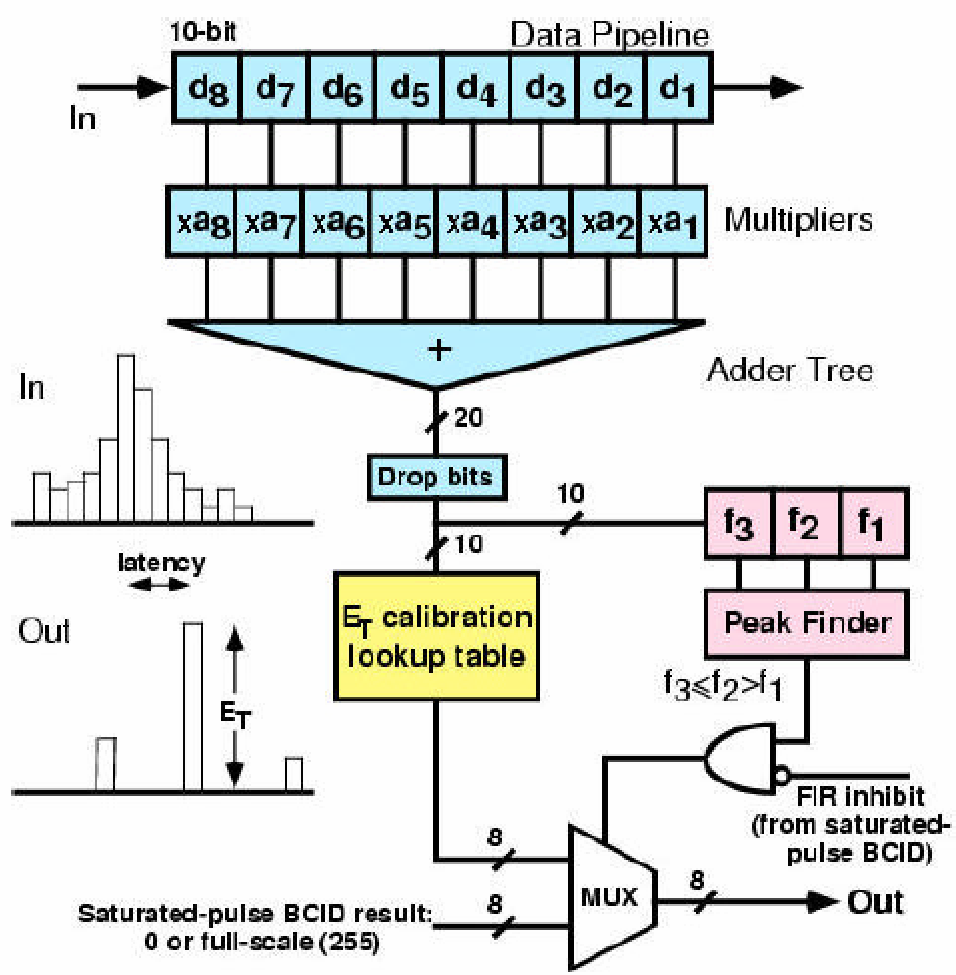


Electron (isolation) Card



Bunch-crossing identification

- **Need to extract quantities of the bunch-crossing in question (and identify the xing)**
- **FIR (finite impulse response filter)**
  - Feed LUT to get E_T
  - Feeds peak-finder to identify bunch-xing
  - Special handling of very large pulses (most interesting physics…)
- **Can be done in an ASIC (e.g. ATLAS)**



Global Trigger

- A very large OR-AND network that allows for the specification of complex conditions:
  - 1 electron with P_T>20 GeV OR 2 electrons with P_T>14 GeV OR 1 electron with P_T>16 and one jet with P_T>40 GeV…
  - The top-level logic requirements (e.g. 2 electrons) constitute the "trigger-table" of the experiment
    - Allocating this rate is a complex process that involves the optimization of physics efficiencies vs backgrounds, rates and machine conditions
      - → More on this in the HLT part

Summary

- **Some challenges of unprecedented scale**
  - Interaction rate and selectivity
  - Number of channels and synchronization
  - Pile-up and bunch-crossing identification
  - Deciding on the fate of an event given ~3 μs
    - Of which most is spent in transportation
- **Trigger levels: the set of successive approximations (at the ultimate save-or-kill decision)**
  - Number of physical levels varies with architecture/experiment
- **Level-1 is always there, reduces 40 MHz to 40-100 kHz**
  - Level-0 may be used to (a) reduce initial rate to ~ 1MHz allow for slightly more complex processing (e.g. simple tracking)