Trigger and DAQ challenges at the LHC

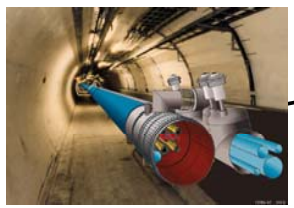
Paris Sphicas
CERN/EP and Univ. of Athens
Academic Training Lectures
March 31-April 2 2003

- Introduction
  - LHC: The machine and the physics
  - Trigger/DAQ architectures and tradeoffs
- Level-1 Trigger
  - Architectures, elements, performance
- DAQ
- High-Level trigger

LHC: physics goals and machine parameters

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 at LHC

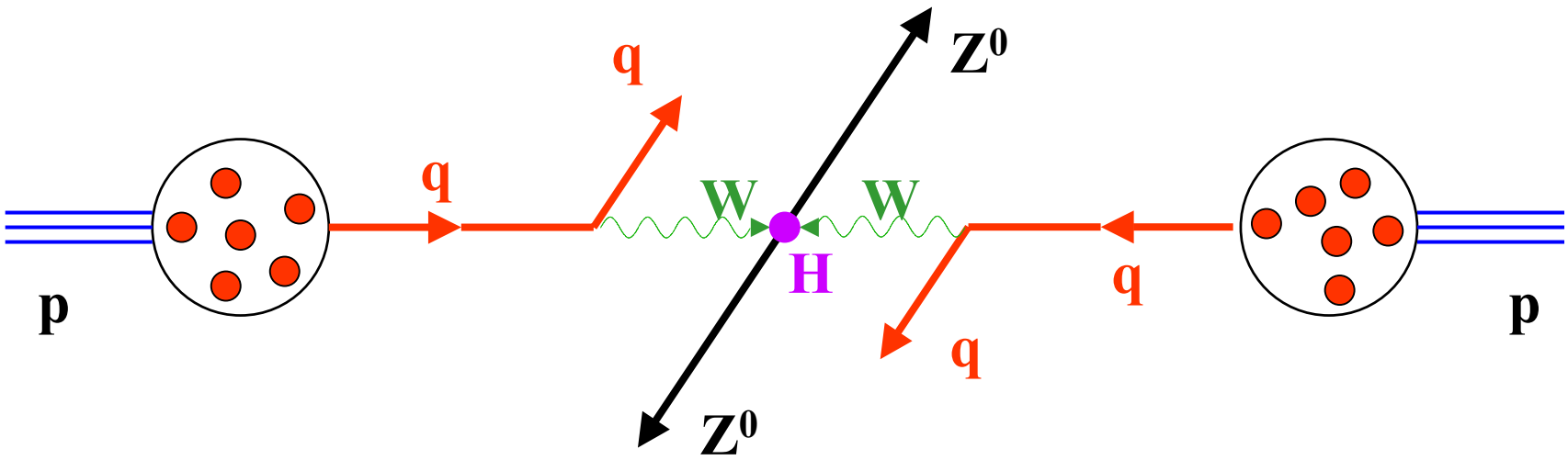
ATLAS A Toroidal LHC ApparatuS. (Study of Proton-Proton collisions)

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 collider)

Higgs Production in pp Collisions



$M_H \sim 1000$ GeV

$E_W \geq 500$ GeV

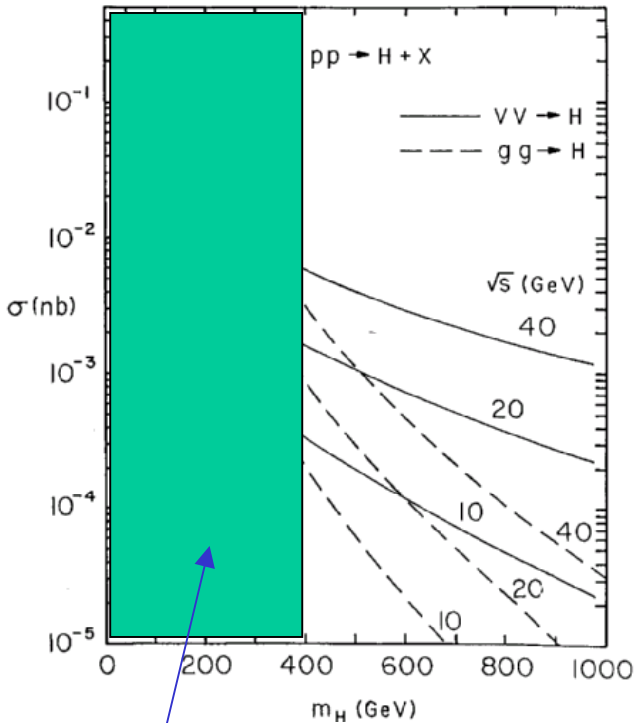
$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

$\rightarrow$ Proton Proton Collider with $E_p \geq 7$ TeV

A machine for EWK Symmetry Breaking

- Superconducting SuperCollider (SSC)
  - Would have 2nd-generation results
- Large Hadron Collider
  - Use existing LEP tunnel



D.Dicus, S. Willenbrock

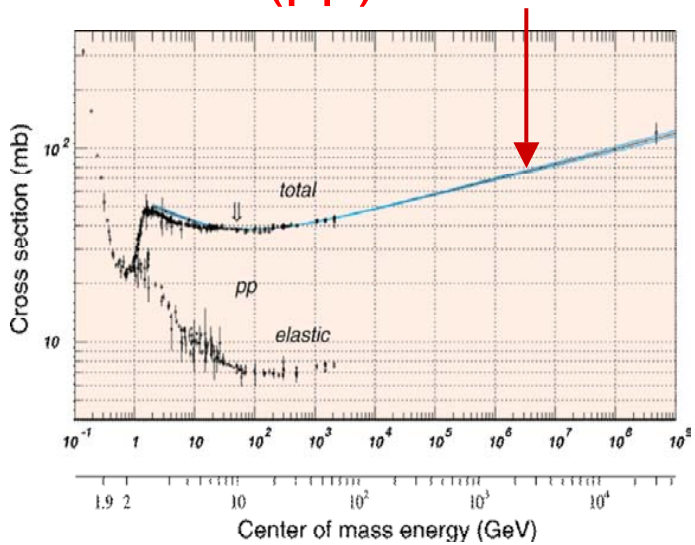
Phys.Rev.D32:1642,1985

Not true any more (M_T=175 GeV)

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
    - Approximately 4 out of 5 (only) are full
    - 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

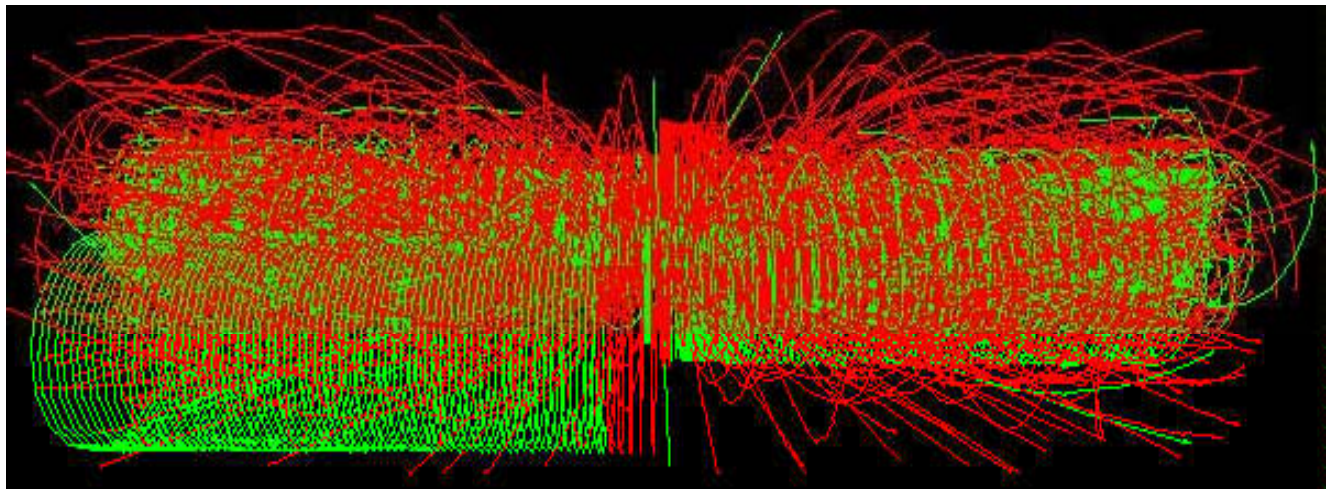
pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

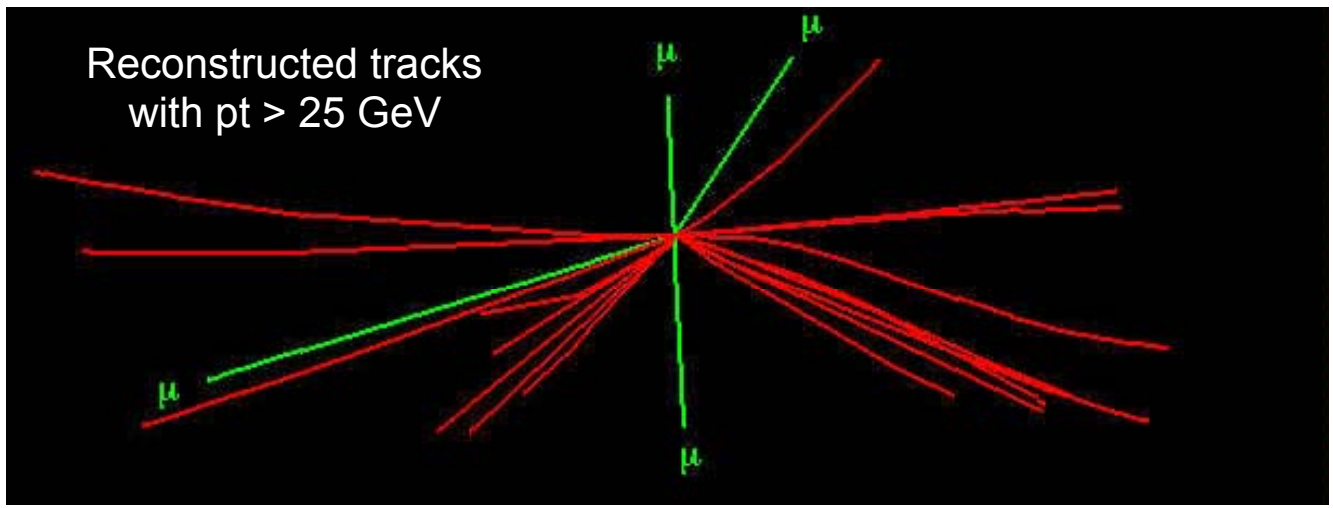
- 20 min bias events overlap
- H→ZZ

Z →μμ

H→ 4 muons: the cleanest ("golden") signature

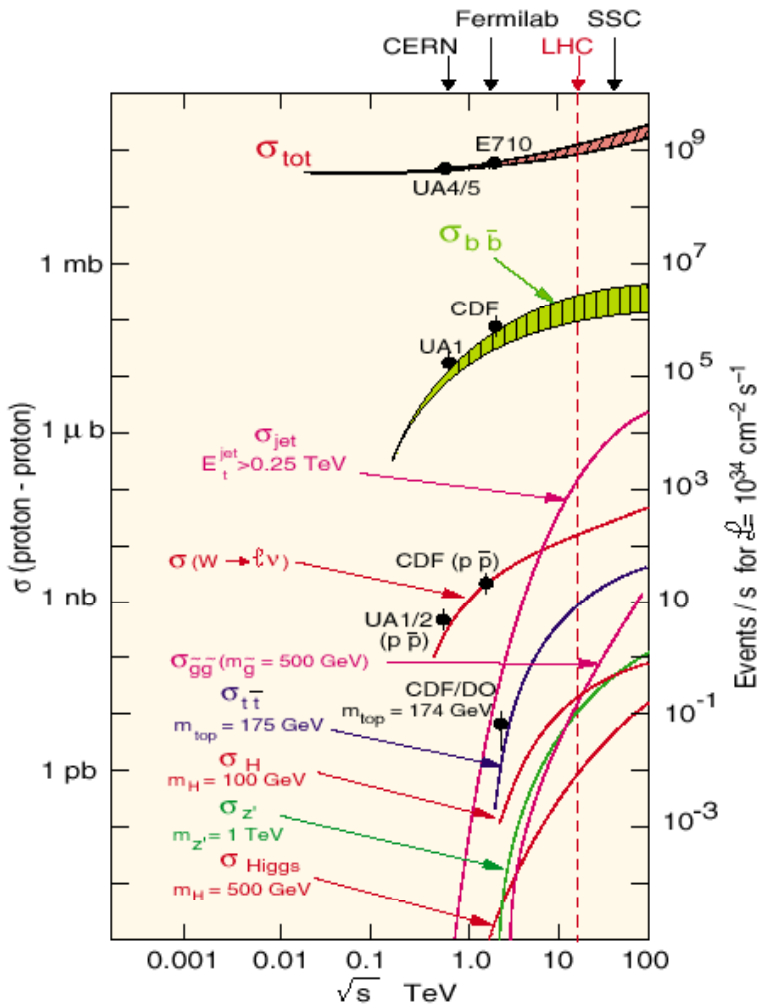
And this (not the H though…) repeats every 25 ns…



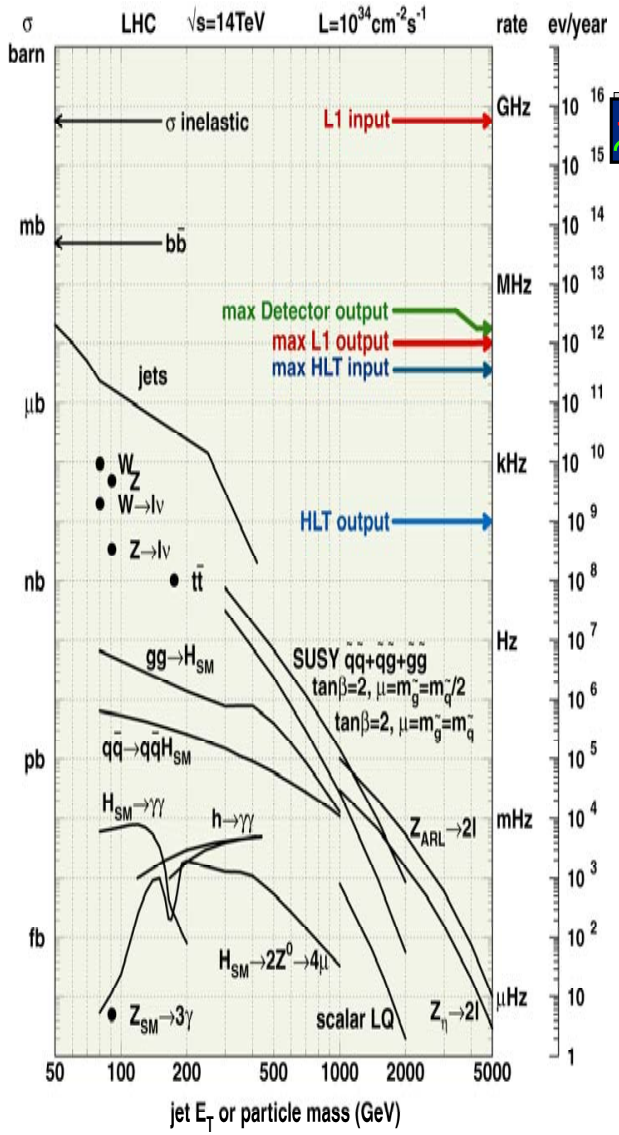


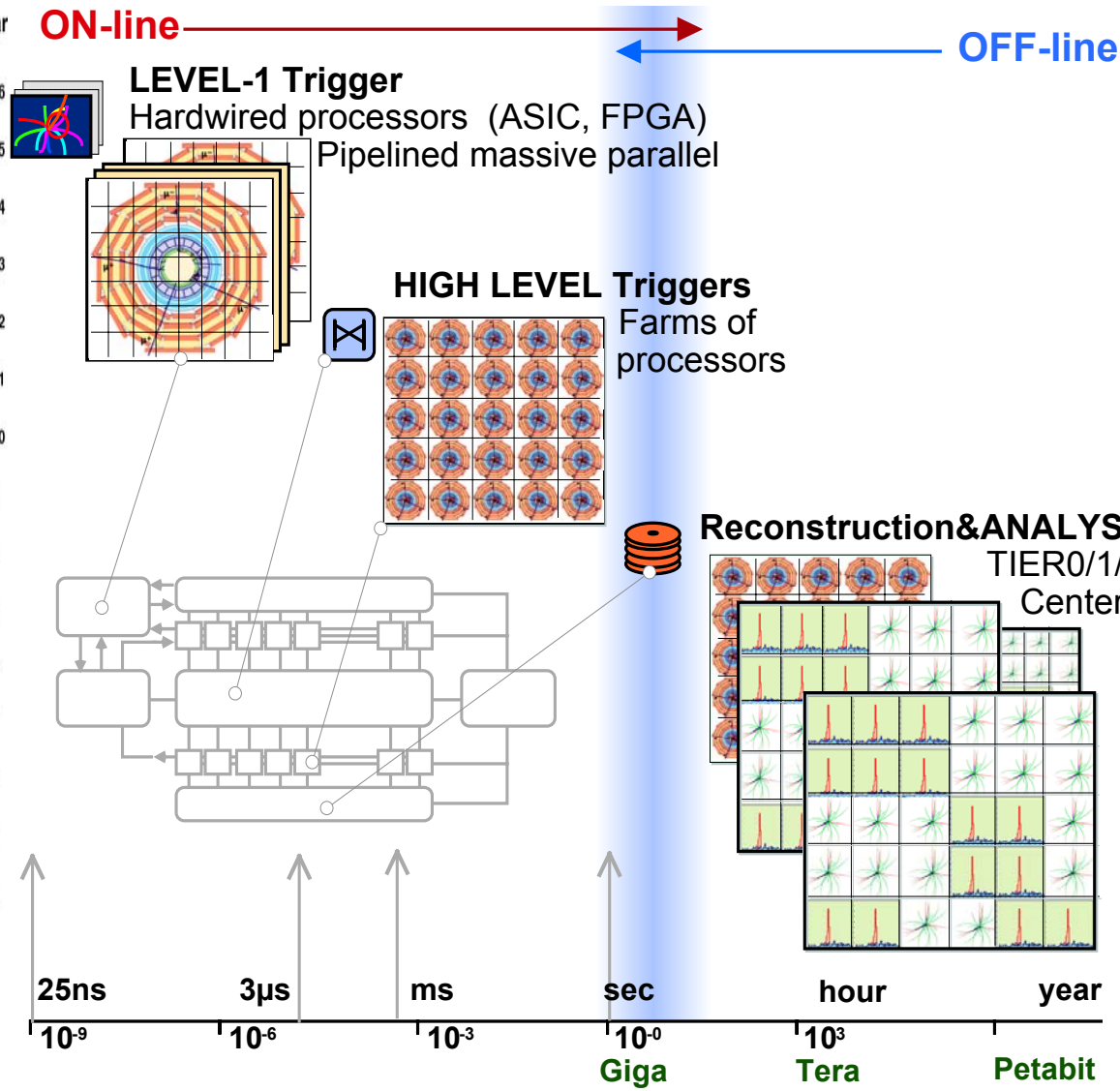
Selectivity: the physics

- Cross sections for various physics processes vary over many orders of magnitude
  - Inelastic: 10^9 Hz
  - $W \rightarrow \ell \nu$: 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: $1:10^{10-11}$
  - Before branching fractions...



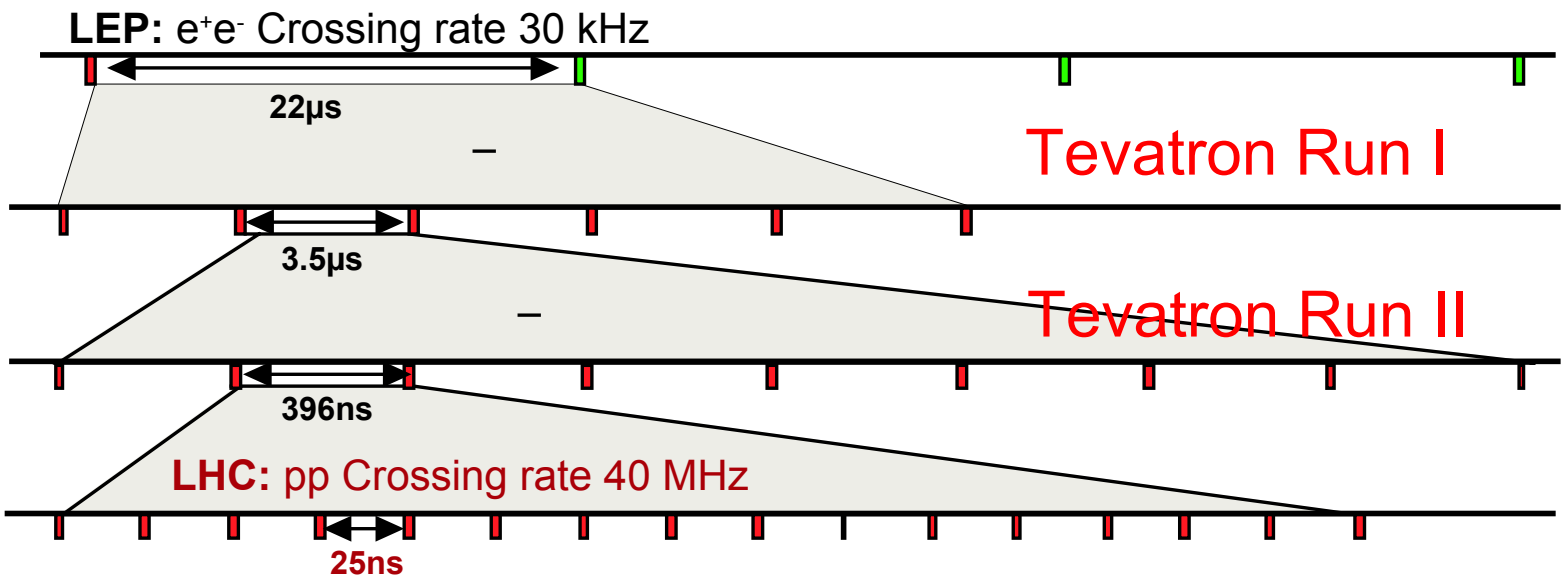
Physics selection at the LHC





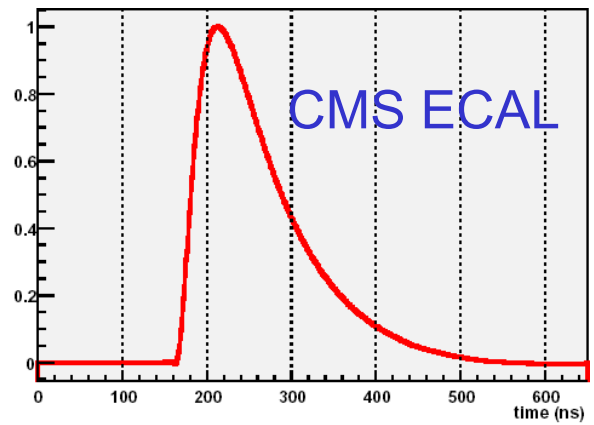
Beam crossings: LEP, Tevatron & LHC

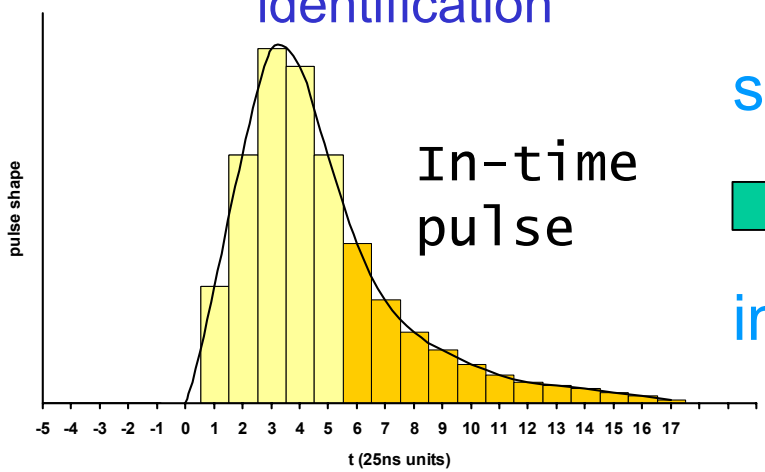
- LHC will have ~3600 bunches
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns



Pile-up

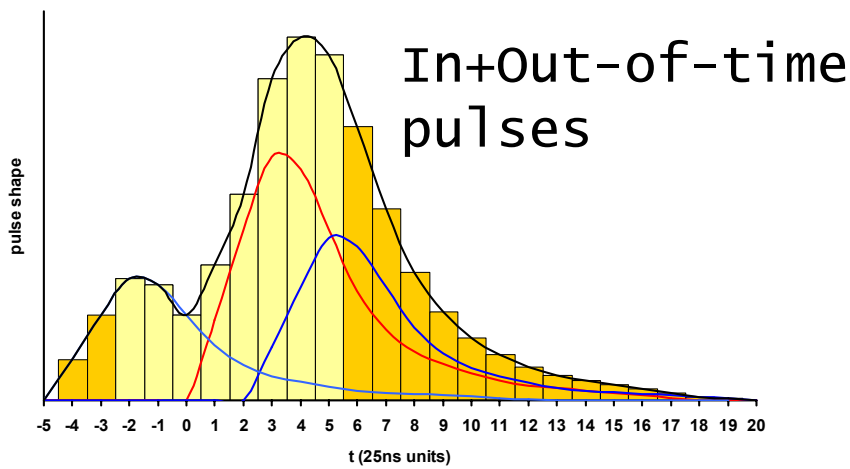
- "In-time" pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"





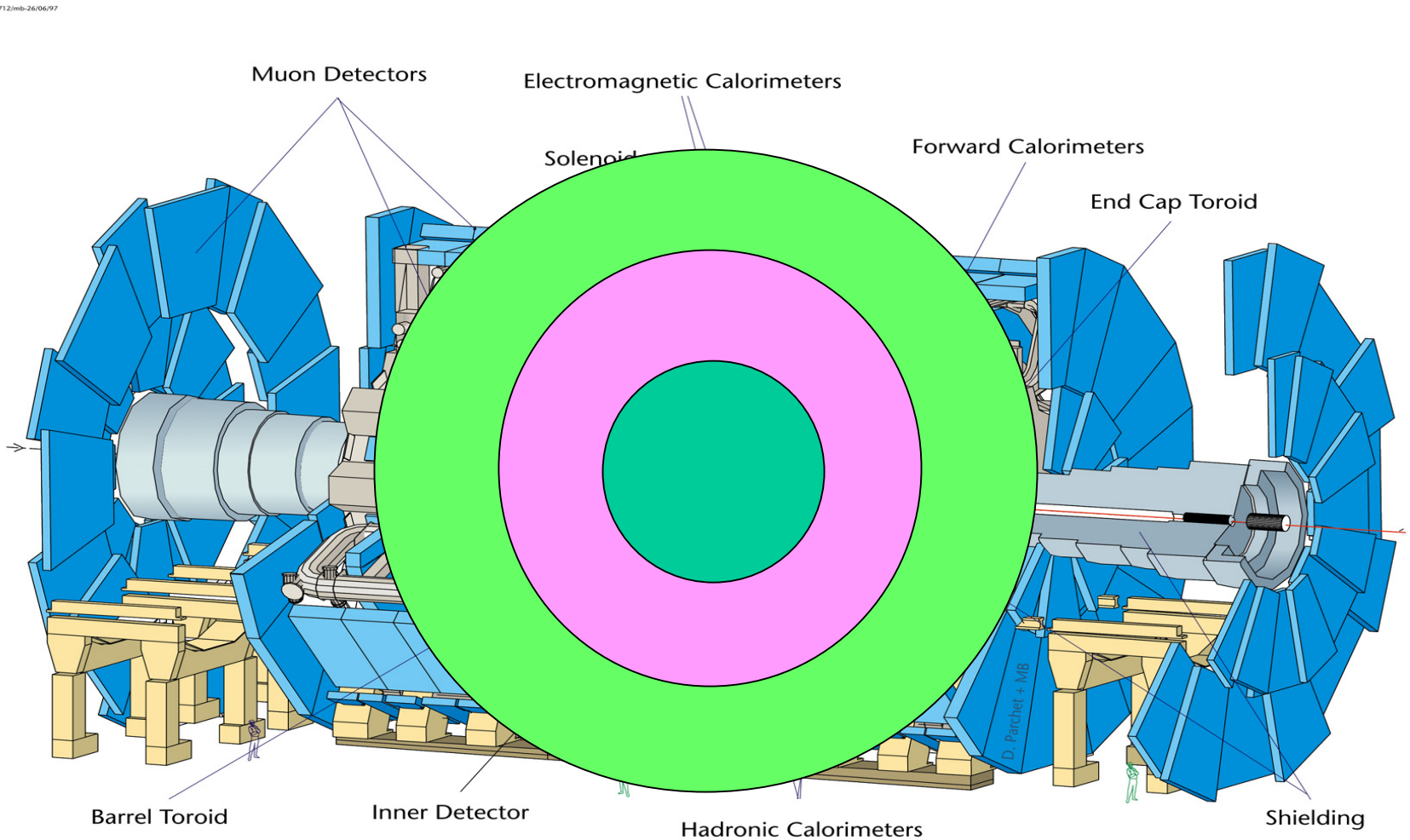
super–

impose



Time of Flight

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



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: architecture

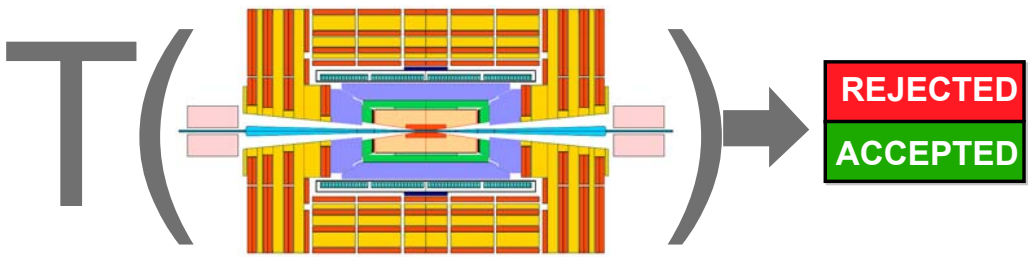
Triggering

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 CHF

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

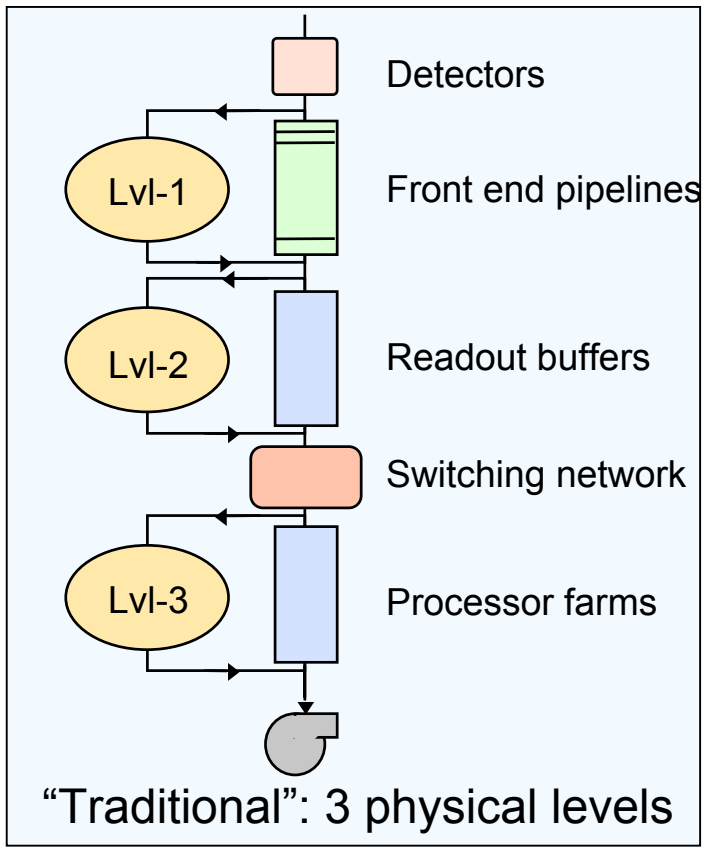
Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

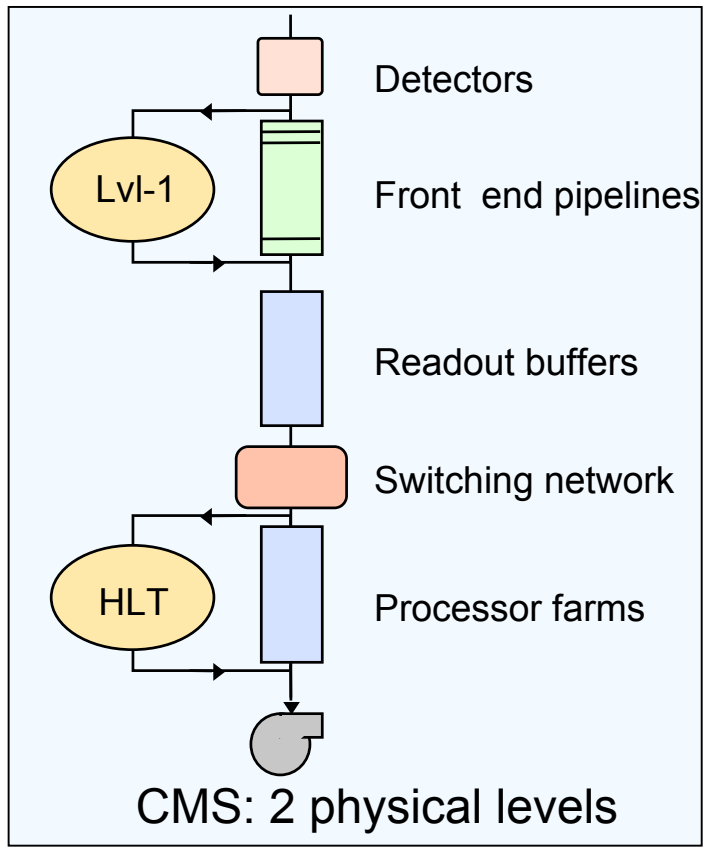
TRIGGER LEVELS

(possibly with zero dead time)

Online Selection Flow in pp

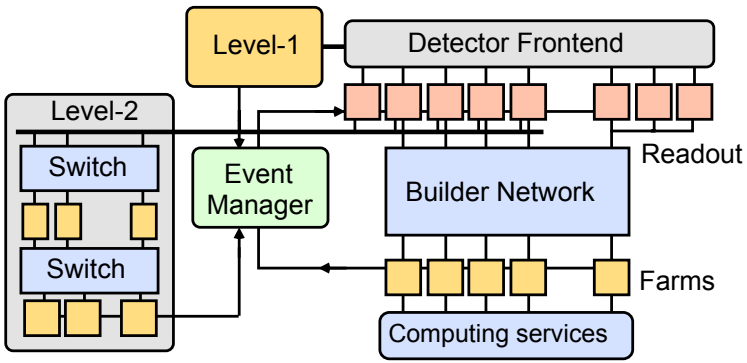
- Level-1 trigger: reduce 40 MHz to 10^5 Hz
  - This step is always there
  - Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps

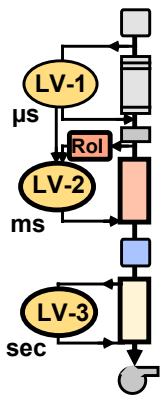




Three physical entities

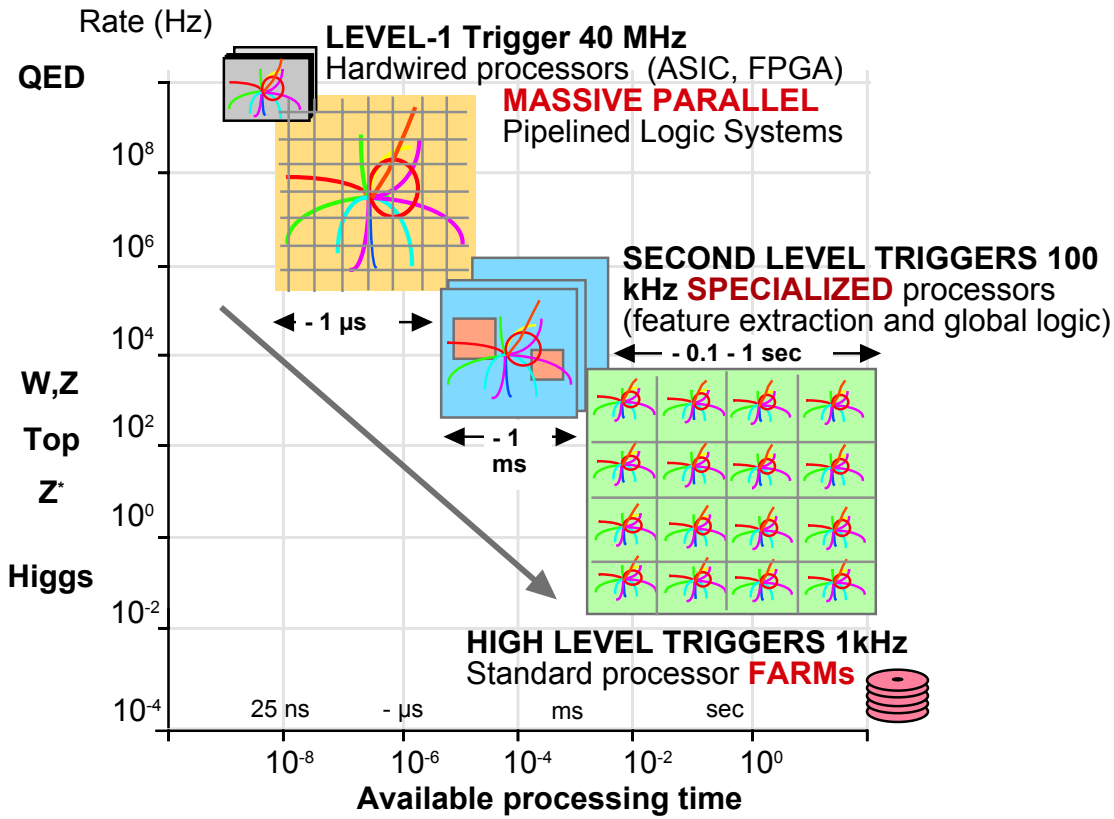
- Additional processing in LV-2: reduce network bandwidth requirements



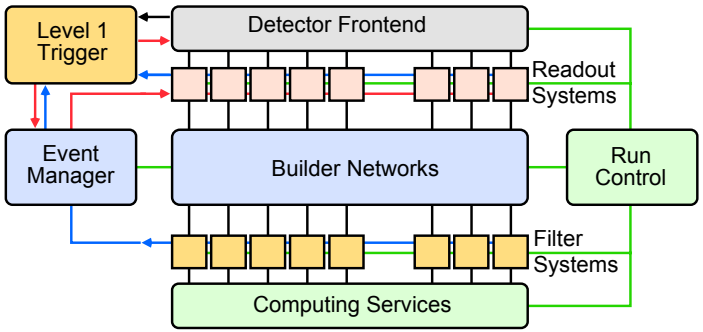


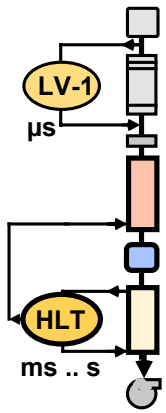
40 MHz
10^5 Hz
10^3 Hz
10 Gb/s

10^2 Hz



Two physical entities



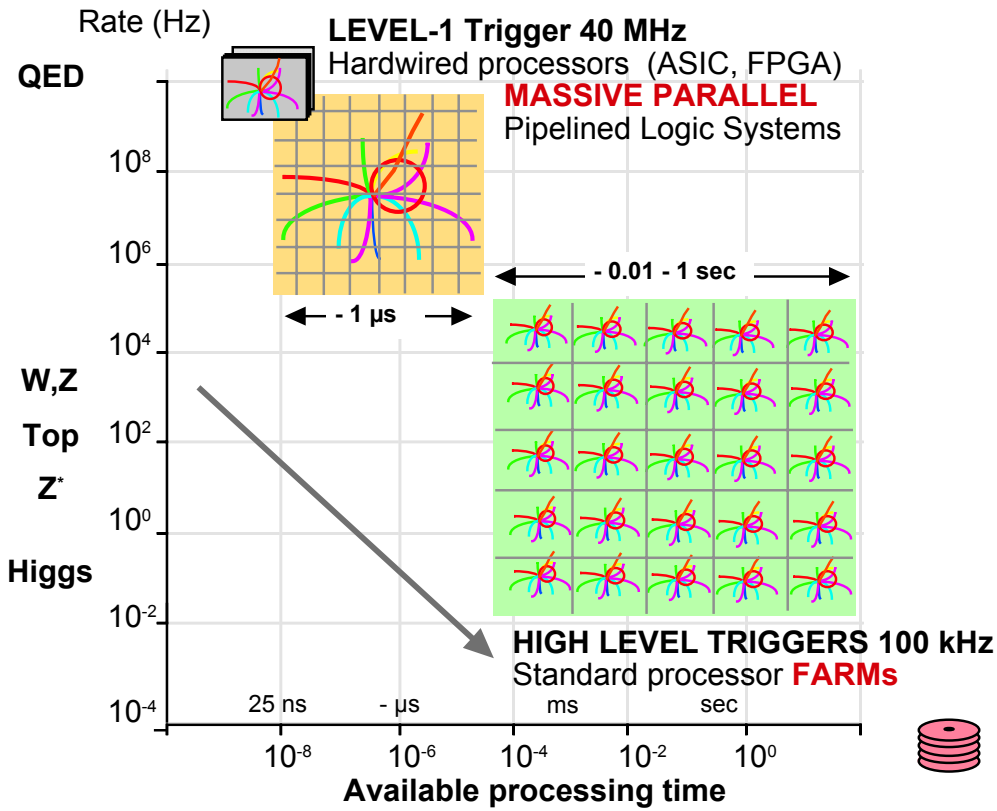


40 MHz

10^5 Hz

1000 Gb/s

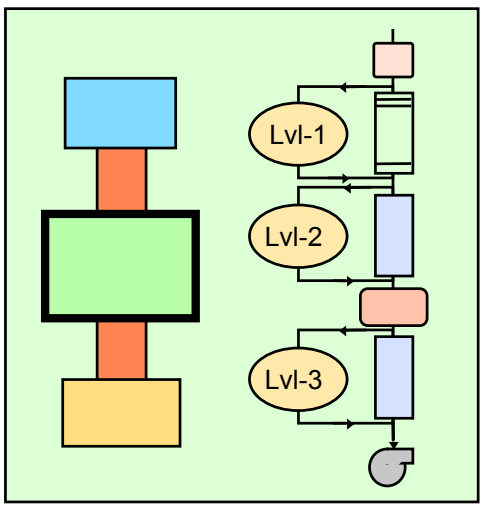
10^2 Hz



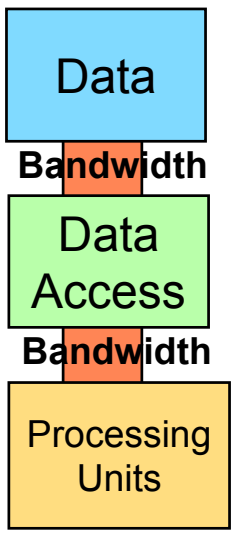
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Comparison of 2 vs 3 physical levels

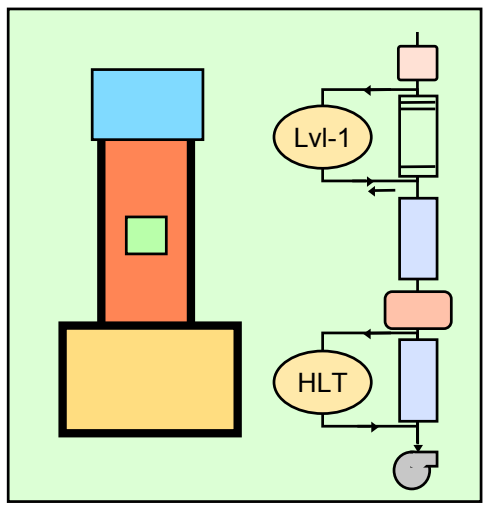
- Three Physical Levels
  - Investment in:
    - Control Logic
    - Specialized processors



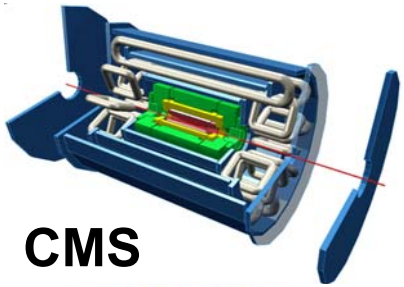
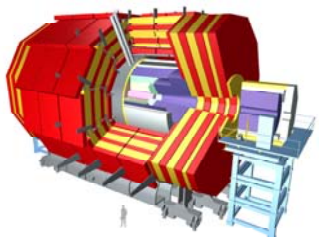
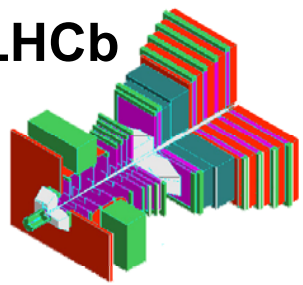
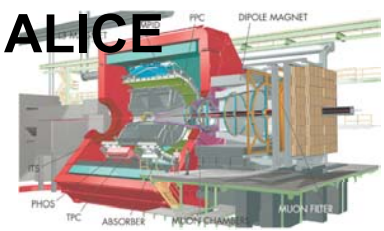
Model



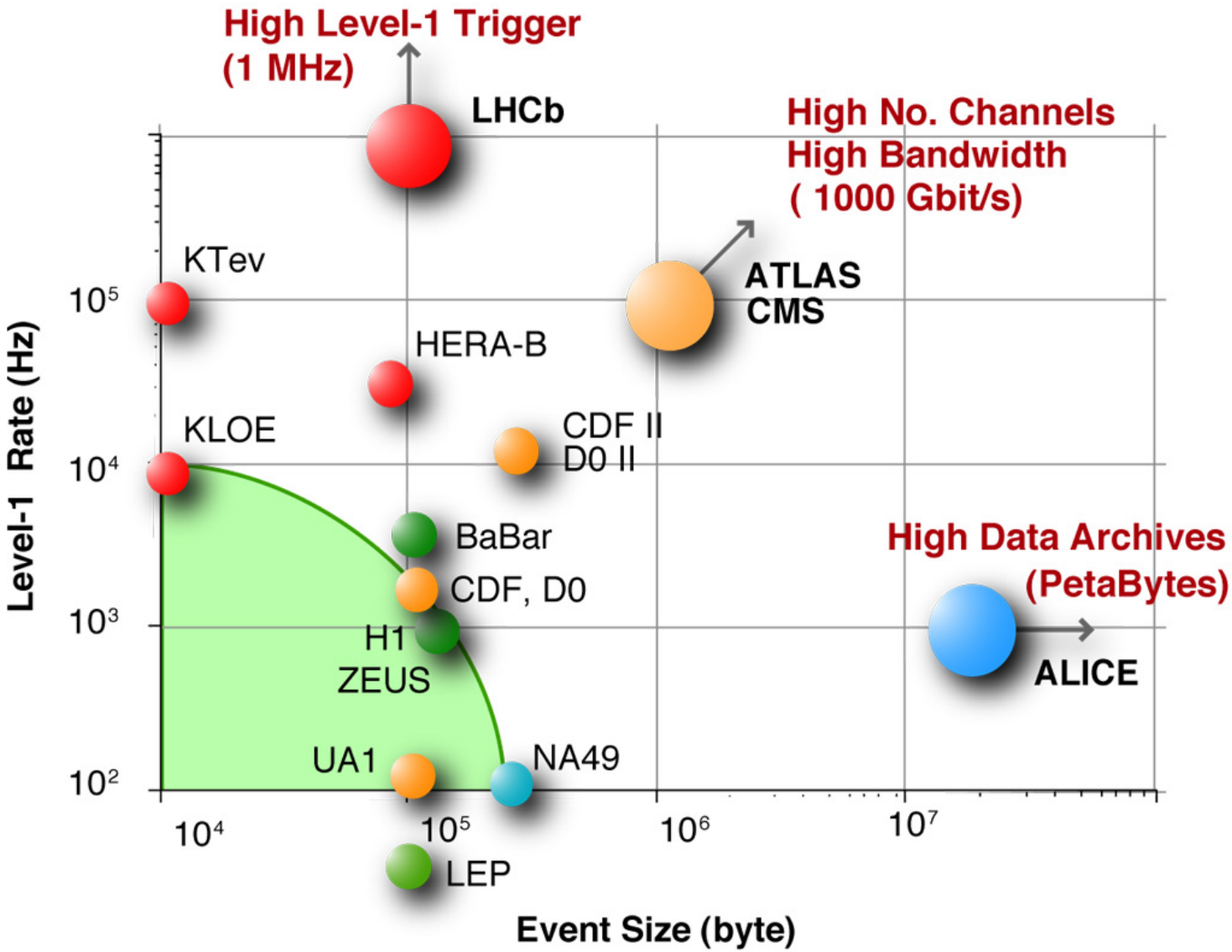
- Two Physical Levels
  - Investment in:
    - Bandwidth
    - Commercial Processors



Trigger/DAQ parameters: summary

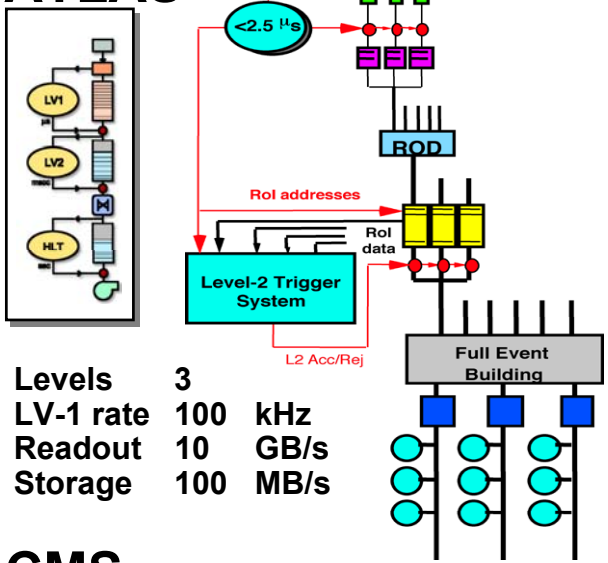
	No.Levels Trigger	Level-1 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS 	**3**	**10^5** LV-2 **10^3**	**10^6**	**10**	**100** (10^2)
CMS 	**2**	**10^5**	**10^6**	**100**	**100** (10^2)
LHCb 	**3**	LV-0 **10^6** LV-1 **4 10^4**	**2x10^5**	**4**	**40** (2x10^2)
ALICE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

Trigger/DAQ systems: present & future



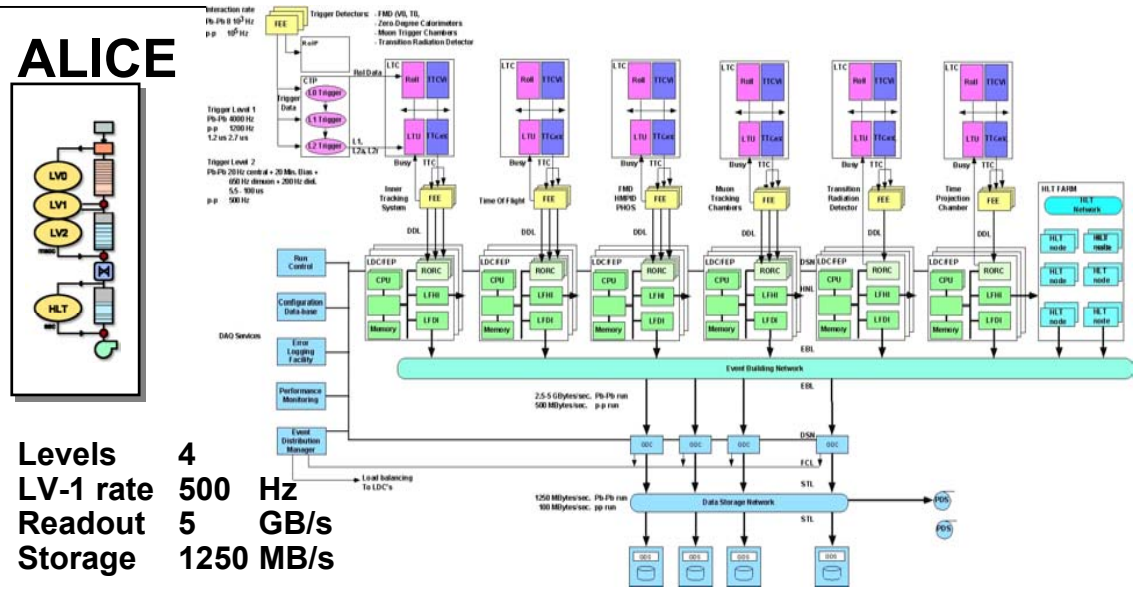
Trigger/DAQ systems: grand view

ATLAS



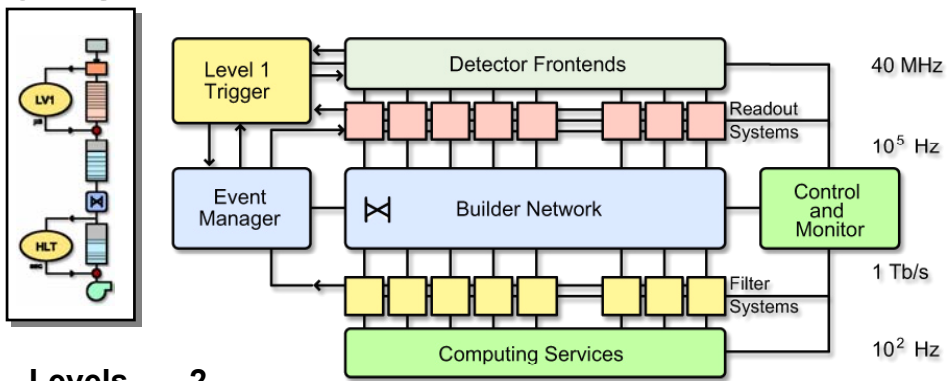
Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

ALICE



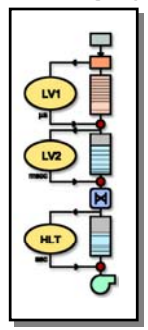
Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250	MB/s

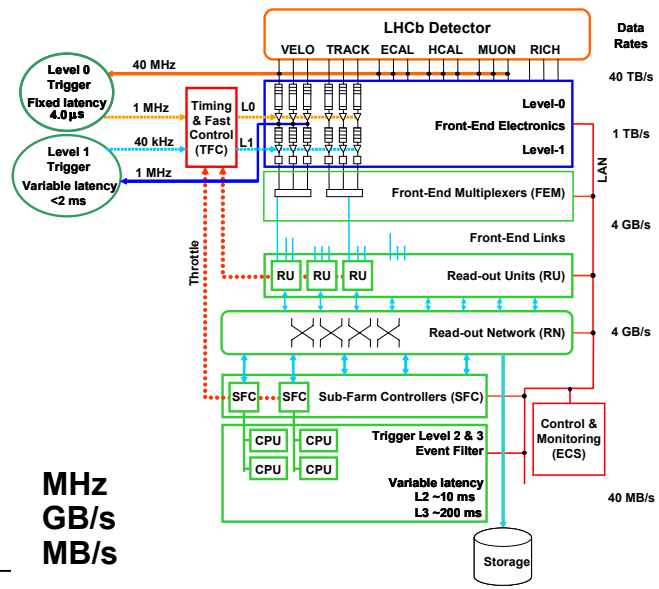
CMS



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

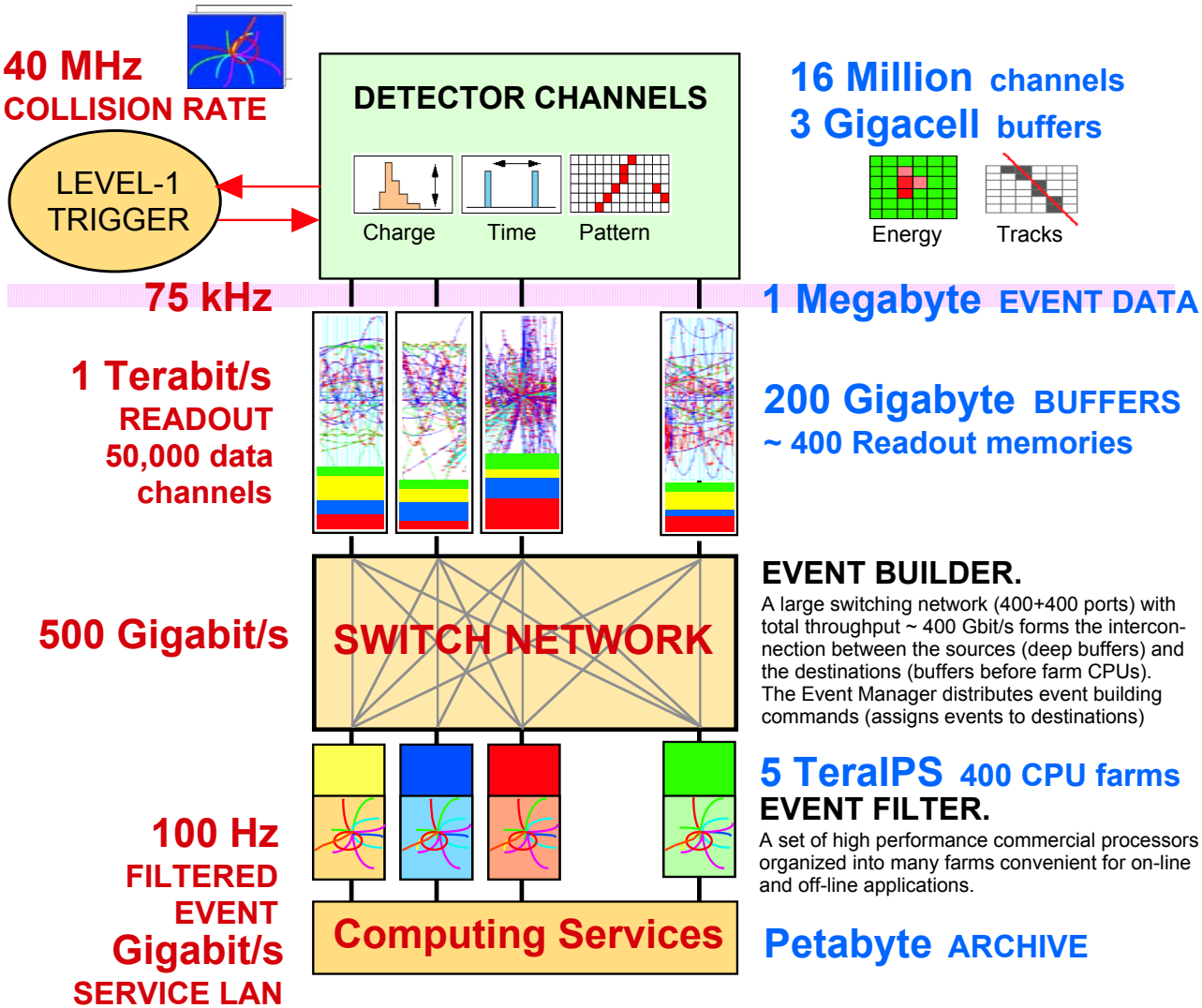
LHCb





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

Online Selection Flow in pp (II)



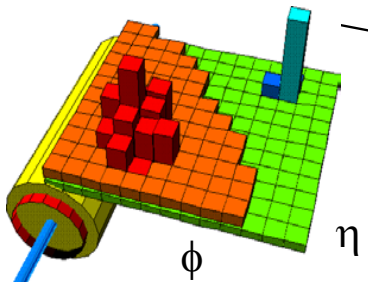
Level-1 Trigger

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; $P_T(e)$ ~ 30-40 GeV
    - $H(120\ \text{GeV}) \rightarrow \gamma\gamma$: $P_T(\gamma)$ ~ 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)
      - 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)

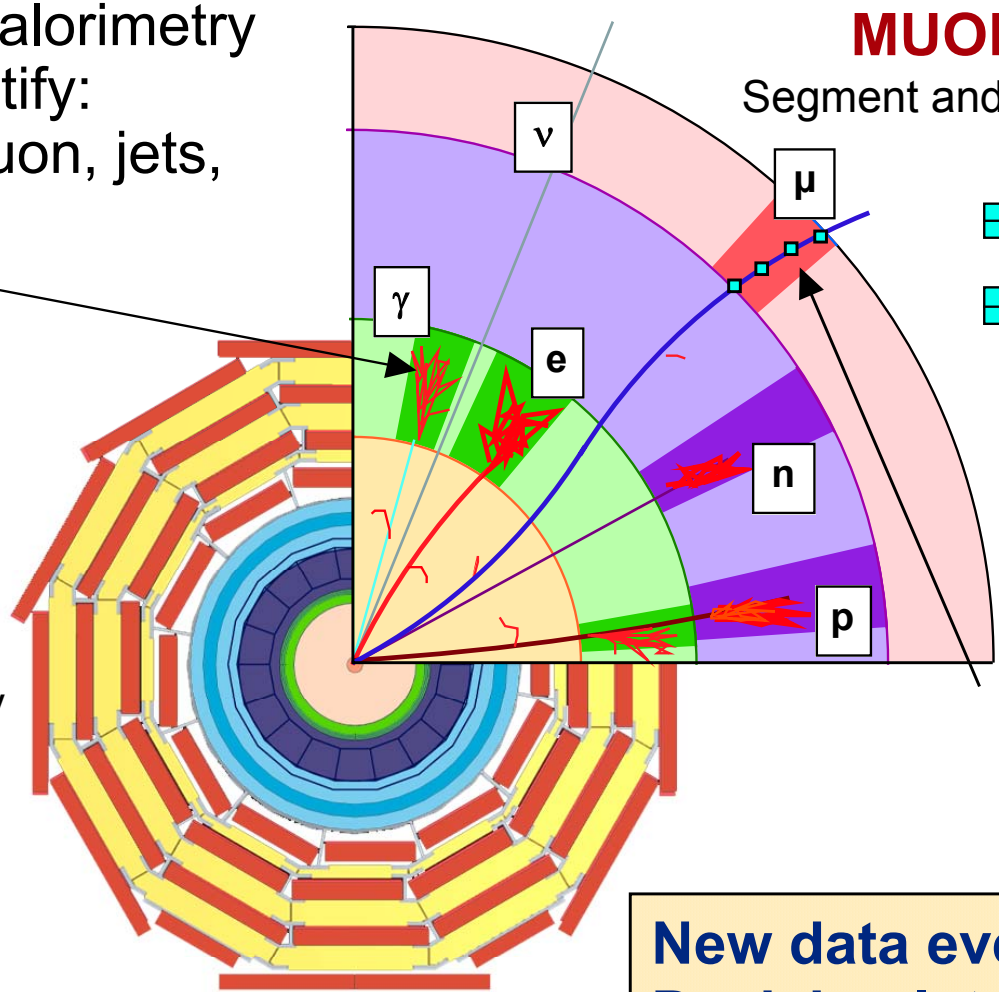
Particle signatures in the detector(s)

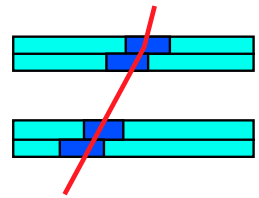
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



CALORIMETERs
Cluster finding and energy deposition evaluation

MUON System
Segment and track finding

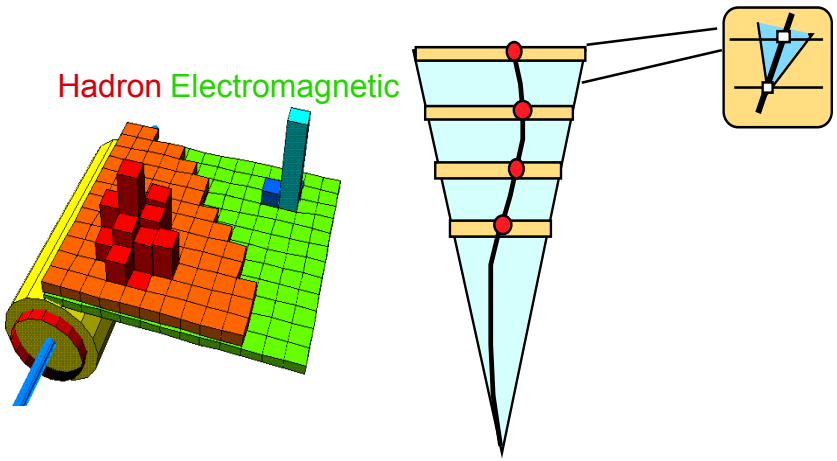




New data every 25 ns
Decision latency ~ μs

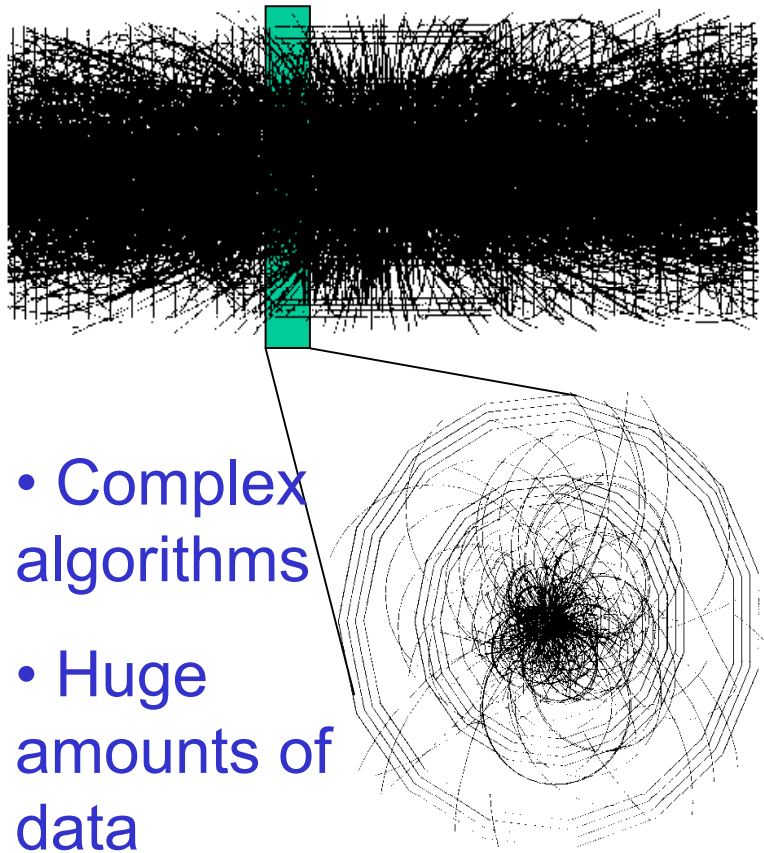
At Level-1: only calo and muon info

- Pattern recognition much faster/easier



- Simple algorithms
- Small amounts of data
- Local decisions

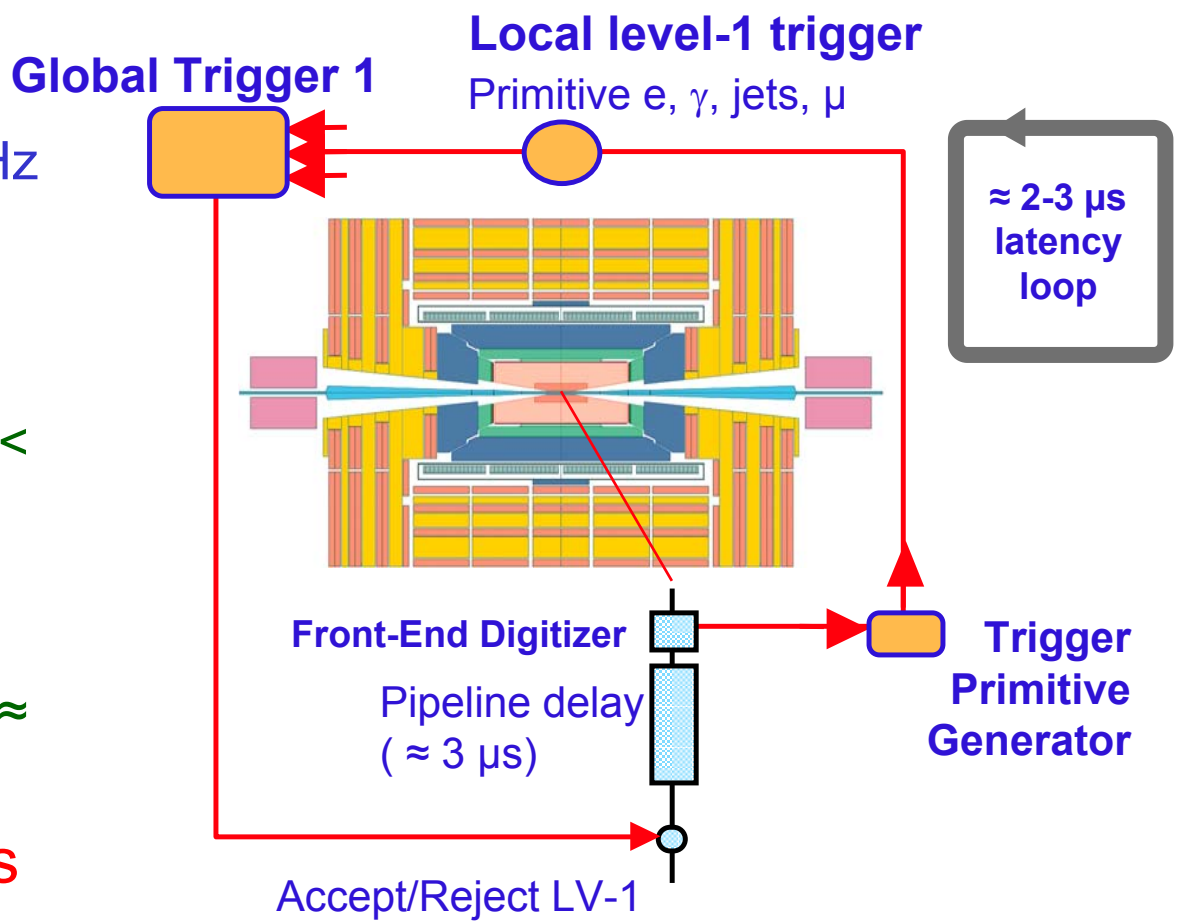
- Compare to tracker info



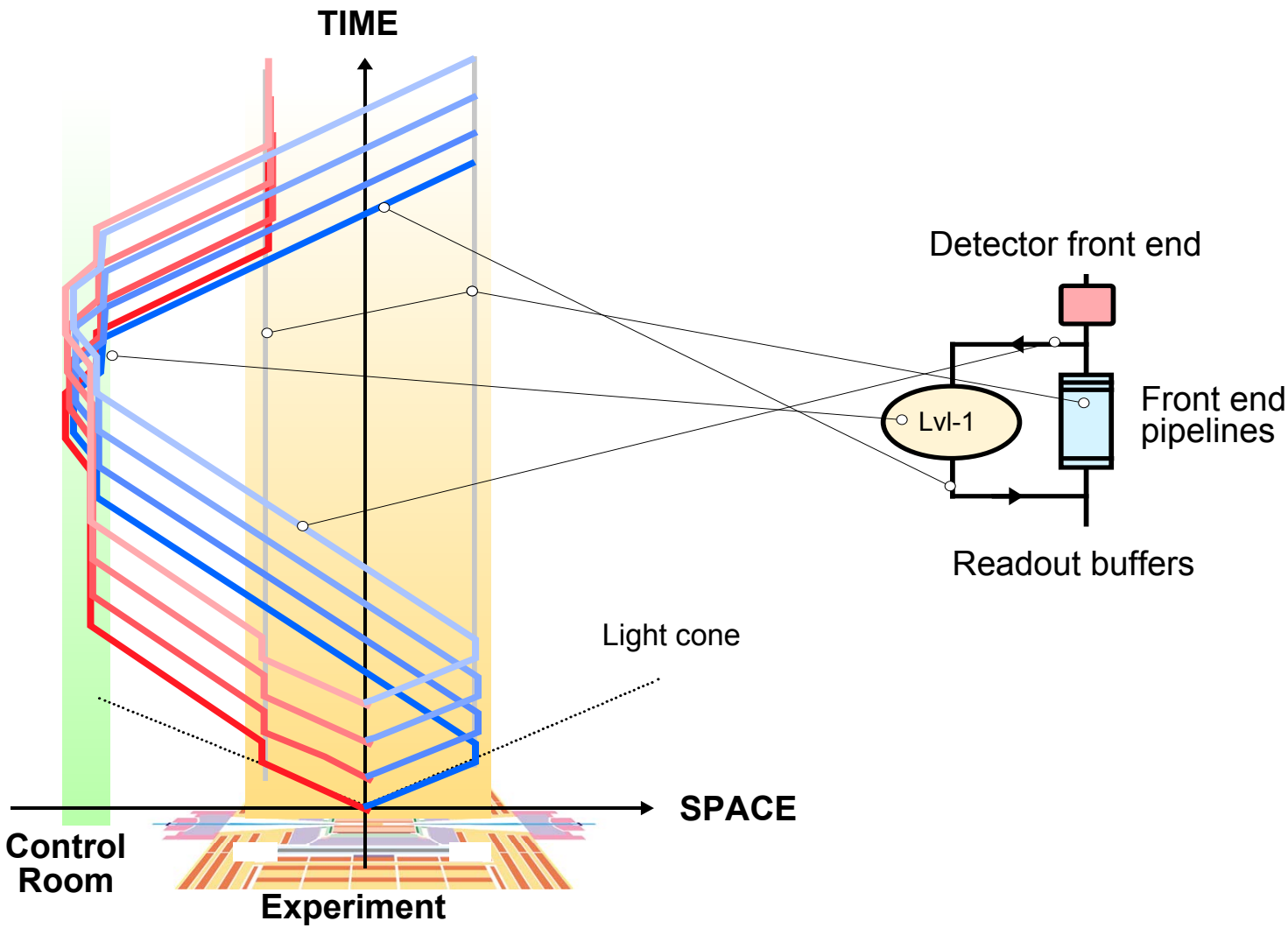
- Complex algorithms
- Huge amounts of data
- Need to link sub-detectors

Level-1 Trigger: decision loop

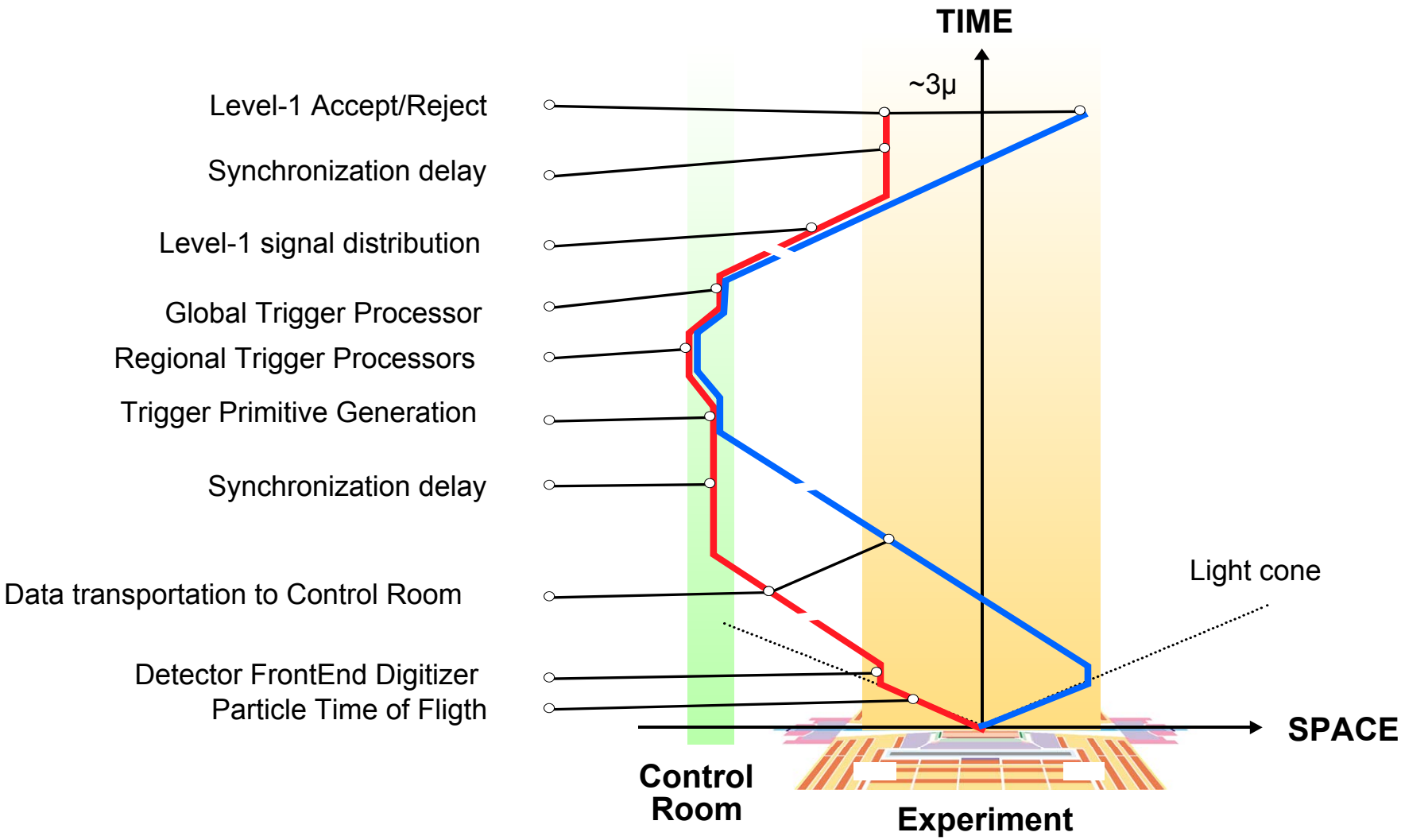
- Synchronous 40 MHz digital system
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- At Lvl-1: process only calo+μ info



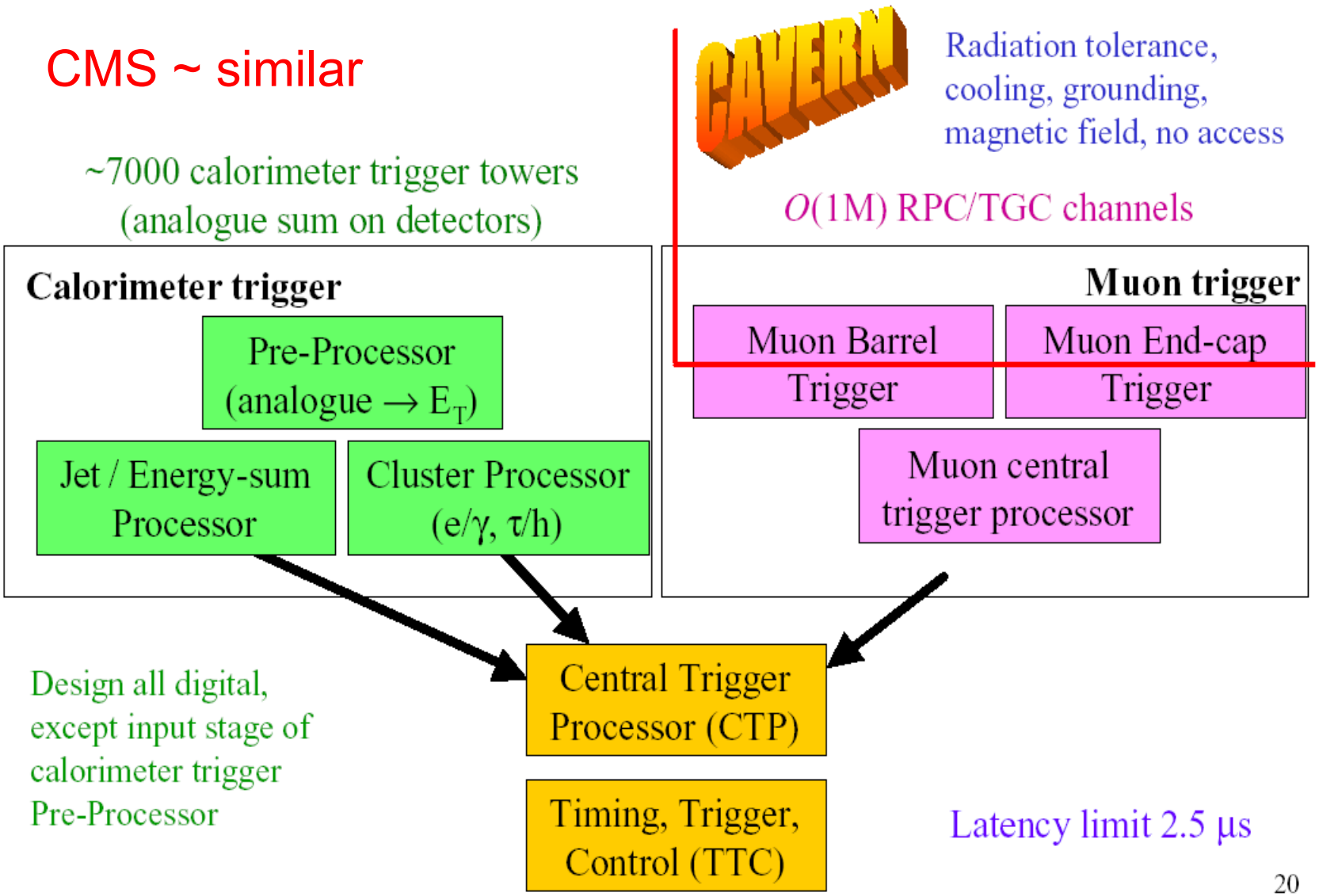
Signaling and pipelining



Signaling and pipelining (II)

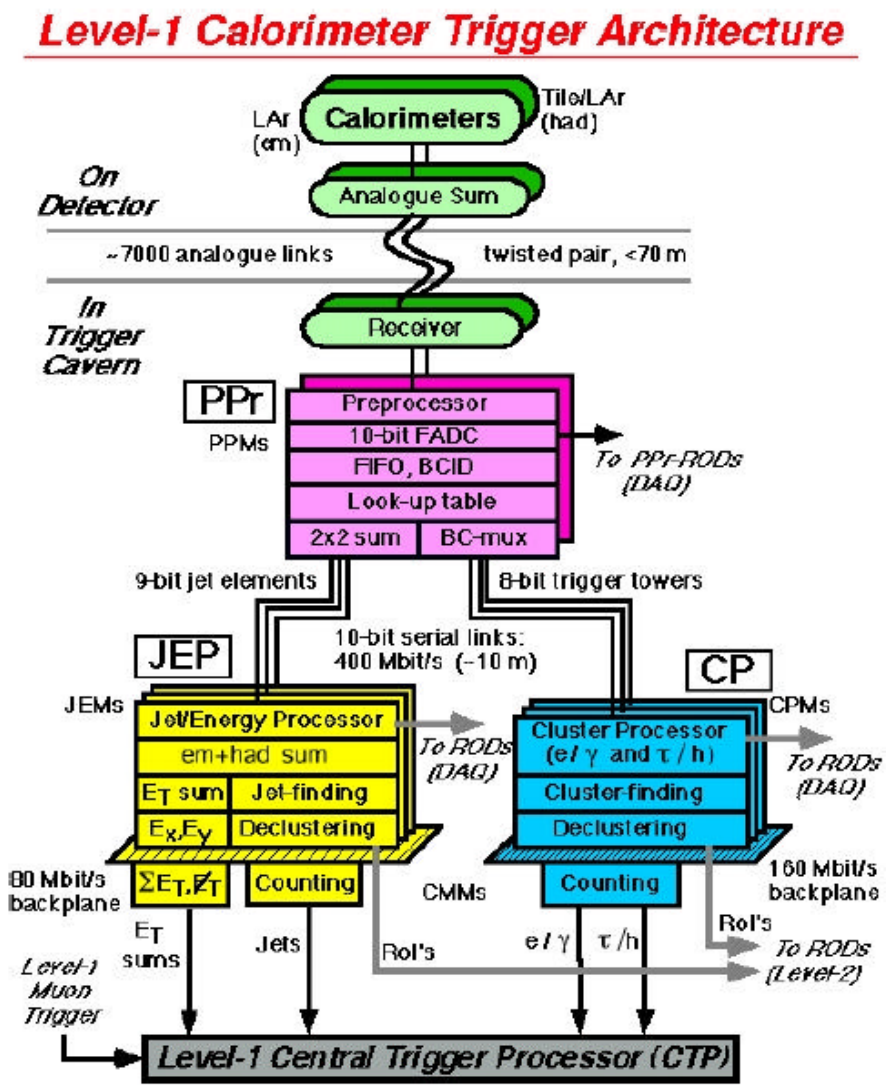


Lvl-1 trigger architecture: ATLAS

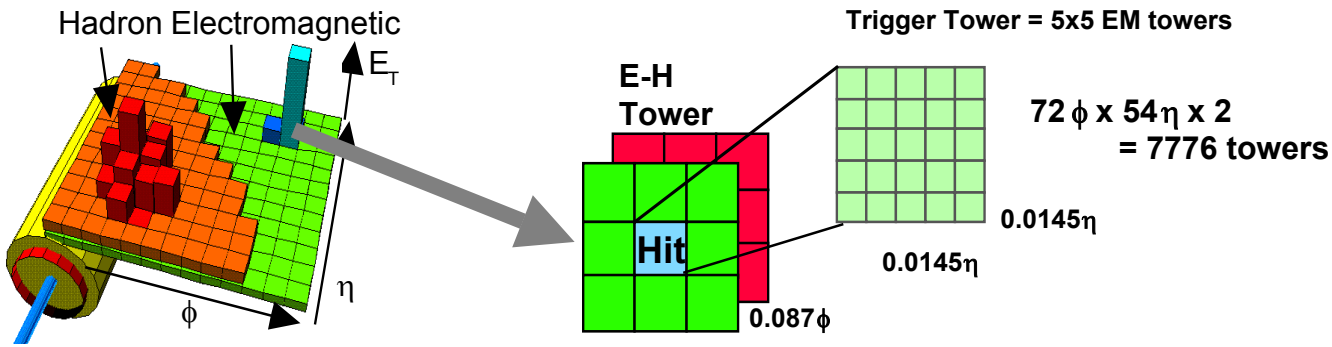


Level-1 trigger data flow: ATLAS

- 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)



E_T( ) + max E_T( ) > E_T^{min}

E_T( ) / E_T( ) < HoE^{max}

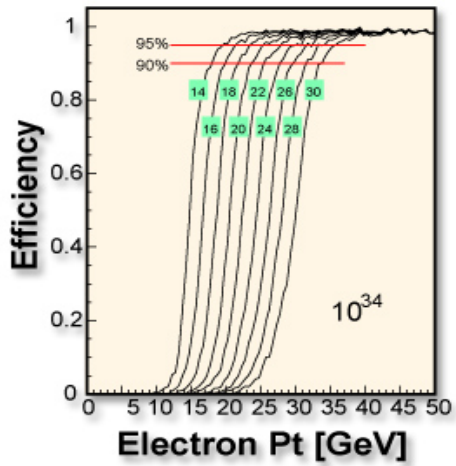
At least 1 E_T(, , ,) < E_{iso}^{max}

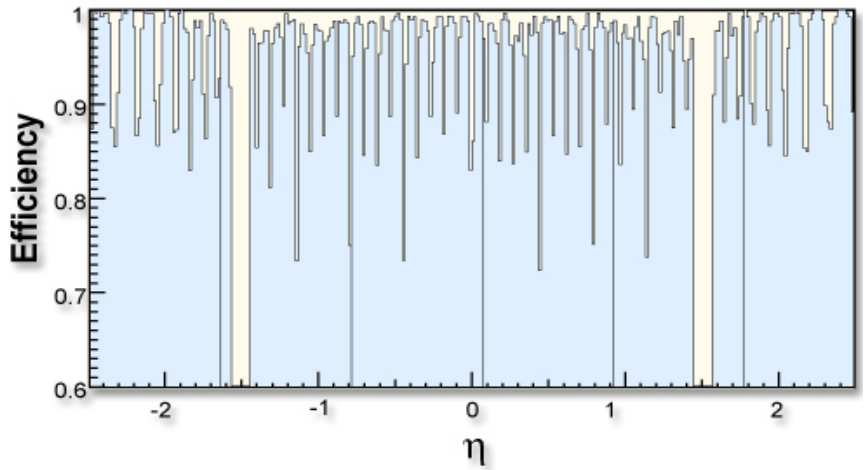
Fine-grain: ≥1( ) > R E_T^{min}

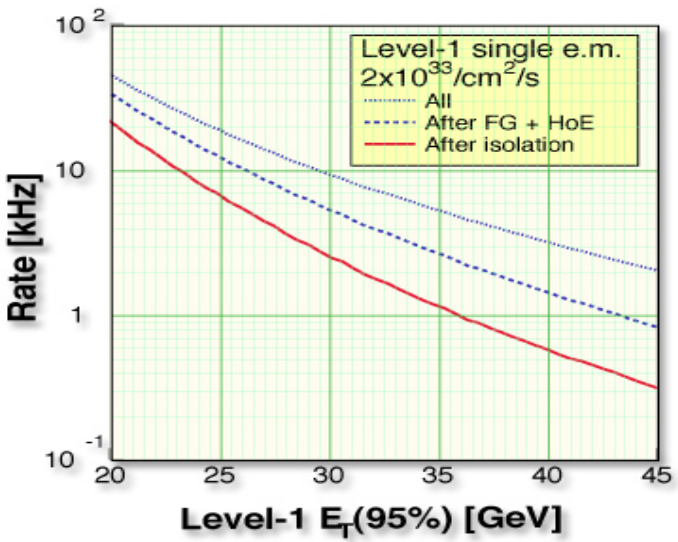
→ Isolated "e/γ"

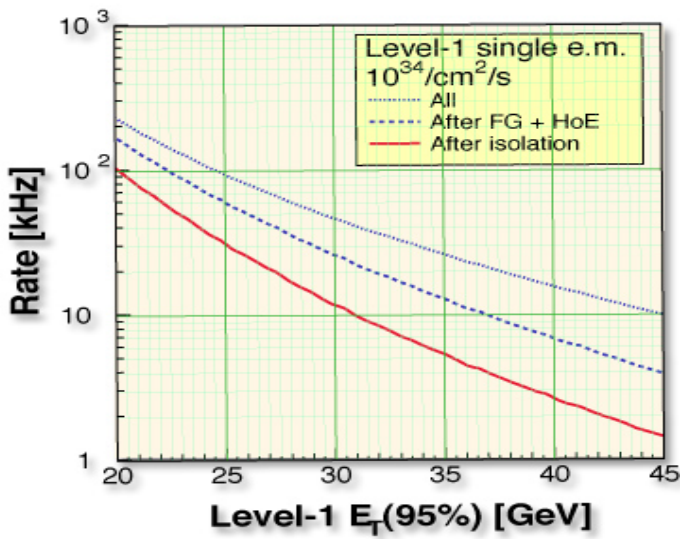
Lvl-1 Calo e/γ trigger: performance

- Efficiencies and Trigger Rates







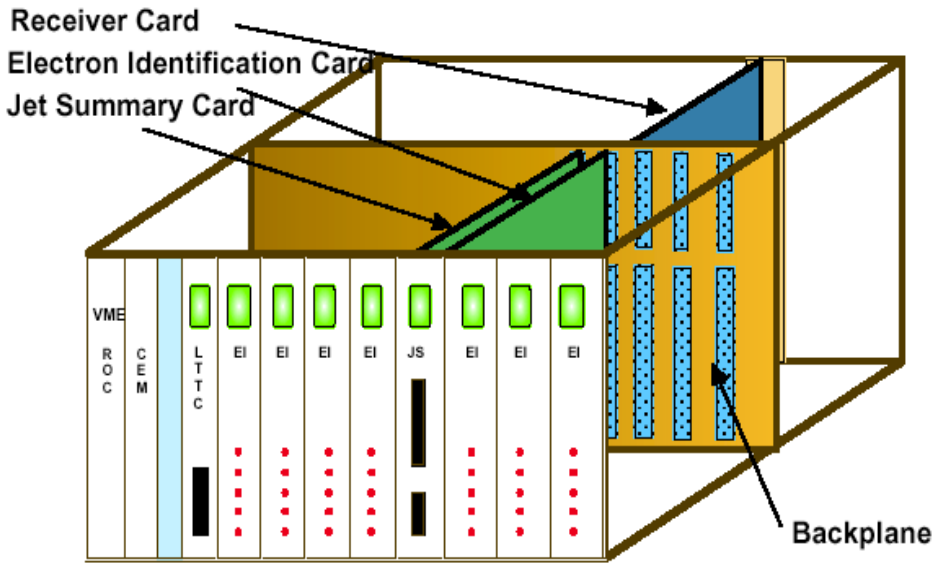


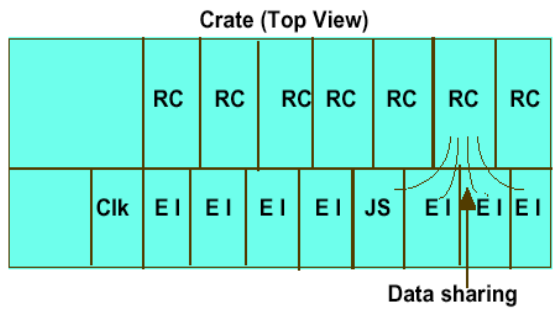
Technologies in Level-1 systems

- ASICs (Applicatio-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: implementation

- Calo trigger crates: 18
  - Operation:
    - ≈ 4000 Gb/s serial links
    - 224 inputs/crate
    - 18 bits/(trigger tower)
  - Cards: 32 towers/card
    - Receiver Card
    - Electron Isolation Card
    - Jet Summary Card
    - Lookup tables, ECL and ASIC chips
    - ASICs: process 8 or 16 towers (addition, e/γ algo)





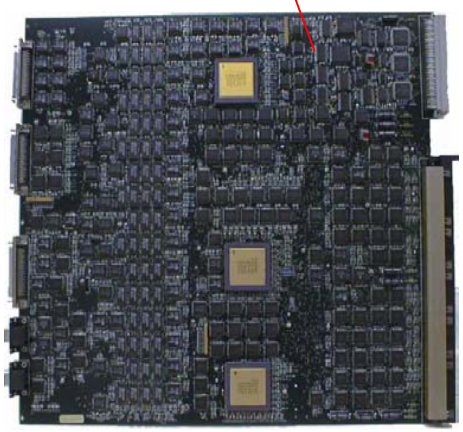
Lvl-1 Calo Trigger: prototypes

Trigger Crate
(160 MHz backplane)

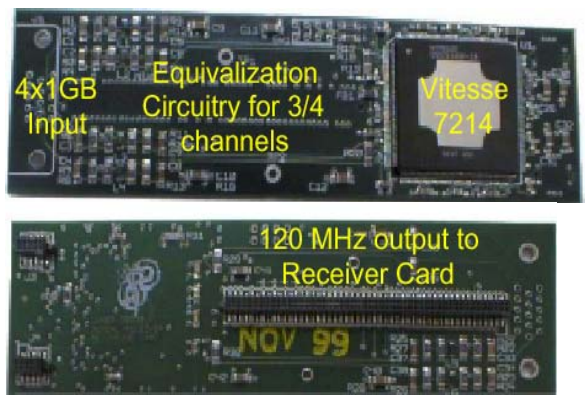
Back

Front

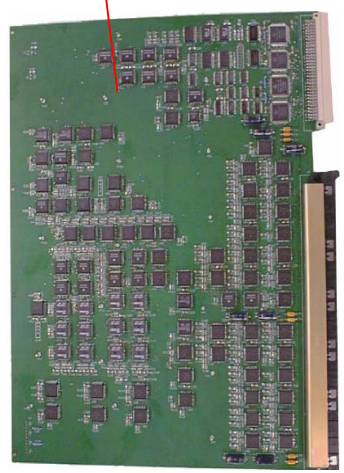
Receiver Card



Links

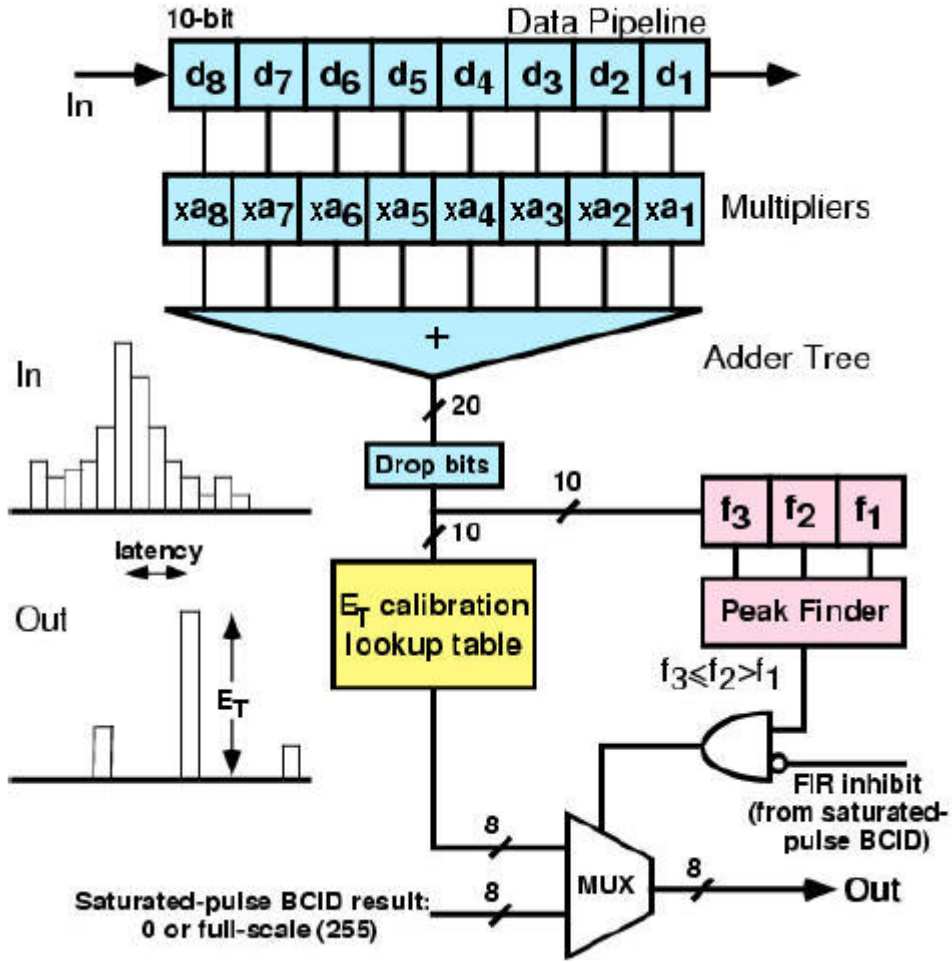


Electron
(isolation)
Card



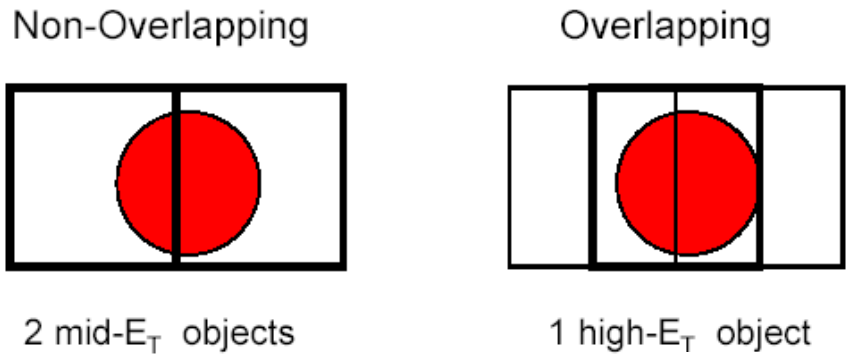
Bunch-crossing identification

- 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)

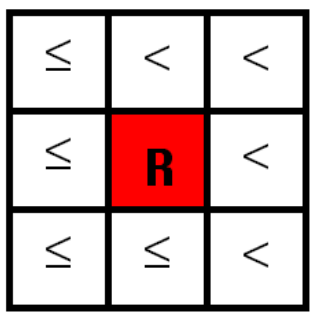


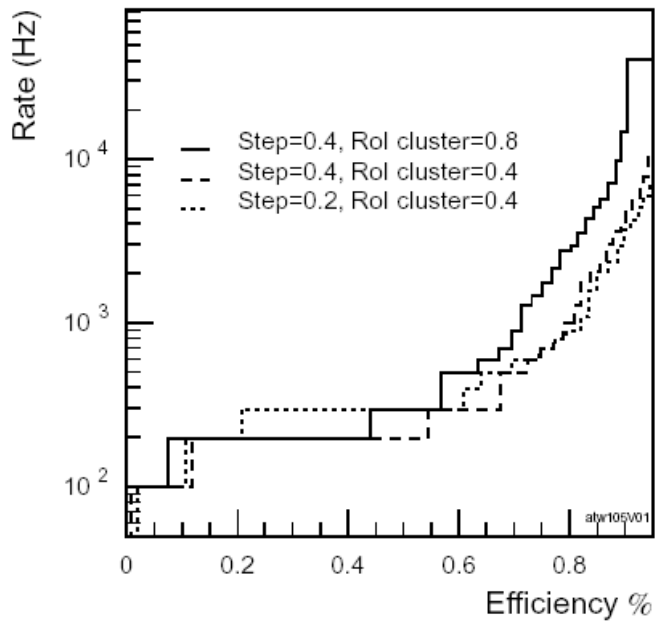
Jets

- Jets: very useful (compositeness, extra dimensions, SUSY decays) but also very abundant
  - Background to jets is jets; and QCD makes lots of them
  - Main issue is instrumental: don't split jets, don't overcount
    - Overlapping windows: efficient, but need additional "declustering" logic to remove multiple counts



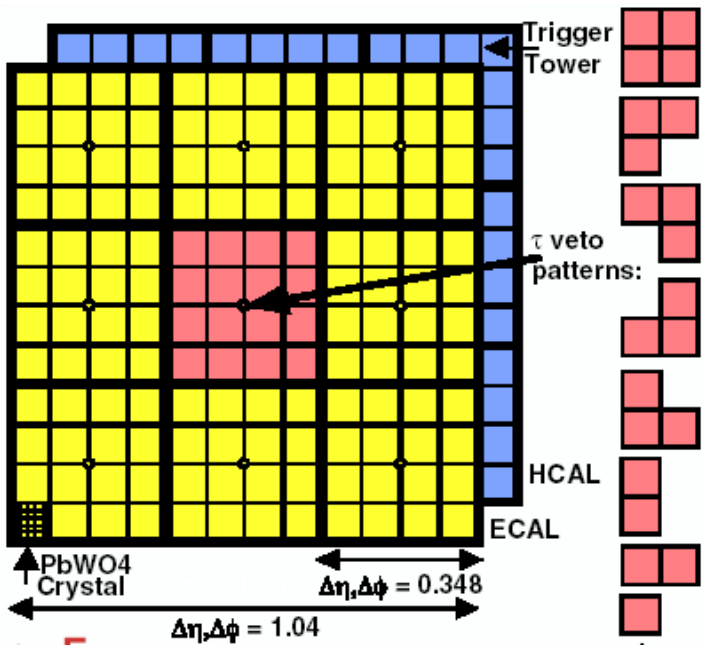
ATLAS: use ROI clusters, defined as maximum found in sliding window by half the jet window width

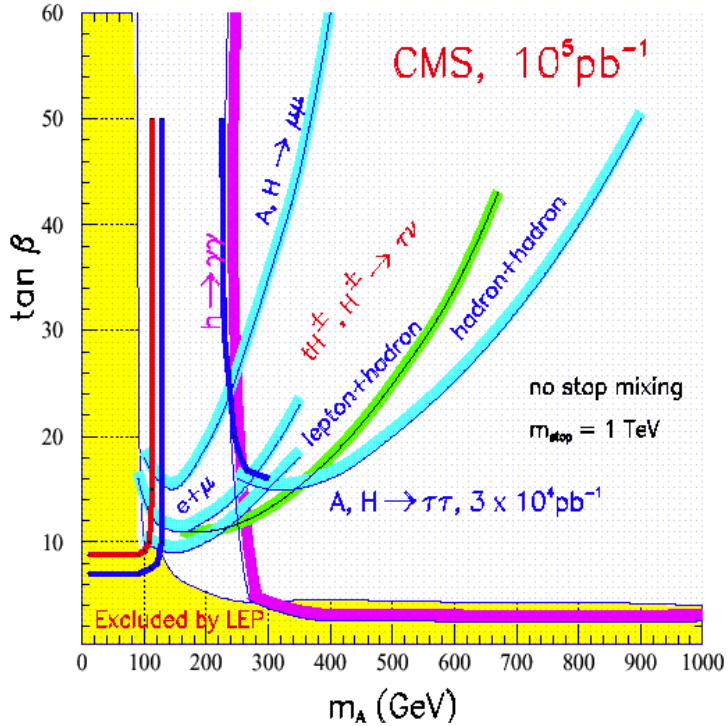




Tau jets

- The tau may turn out to be “the LHC lepton”
  - Important signatures in SUSY
- Tau trigger – CMS example
  - Start with a jet
  - Require isolation
    - Actually tau-veto

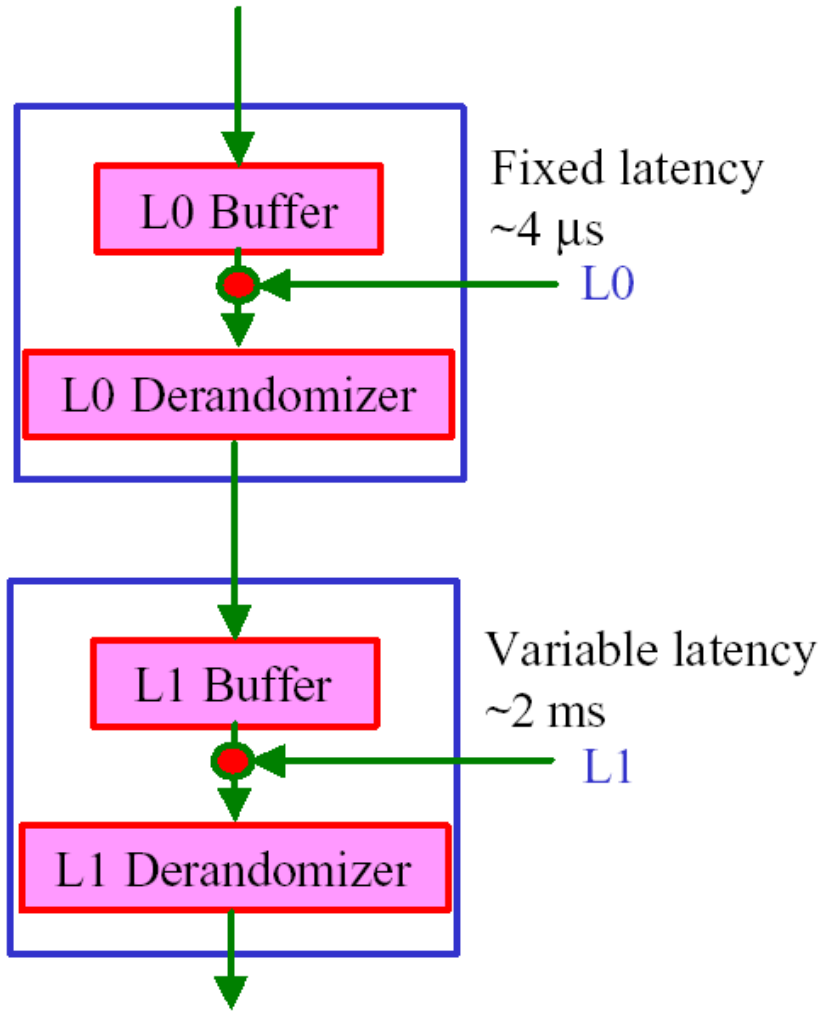




Jet = tau if all veto patterns in 4x4 are off

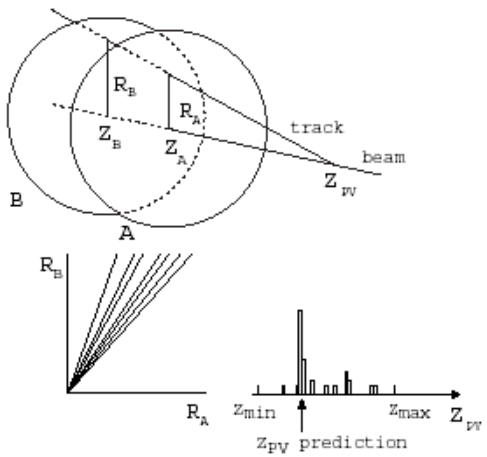
LvI-0/1 trigger in LHCb

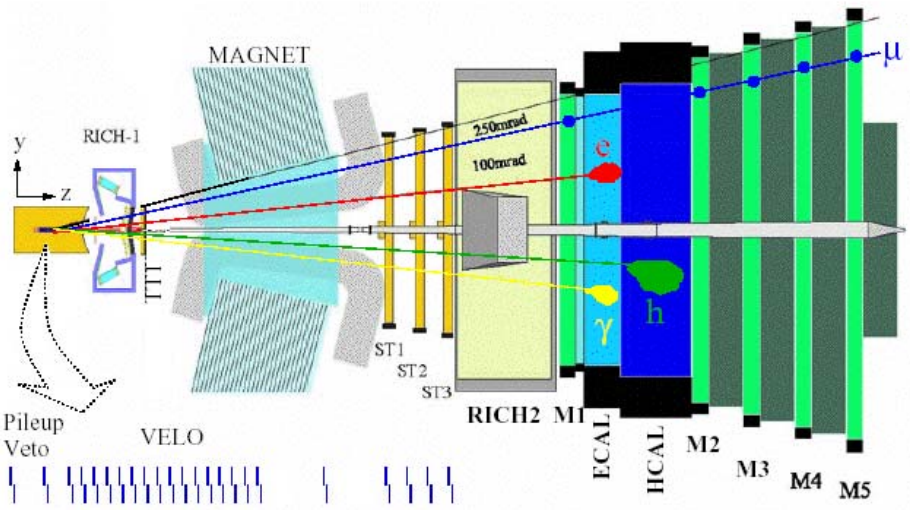
- First-Level (L0):
  - Pile-up veto (to select single-interaction crossings)
  - High-P_T muons
  - High-E_T EM particle or hadron
  - Input: 40 MHz; Output: 1MHz
- Second-Level (L1):
  - Track reconstruction in Si Vertex Locator
  - Match tracks with leptons/hadrons from L0
  - Estimate momentum of tracks
  - Input: 1 MHz; Output: 40 kHz

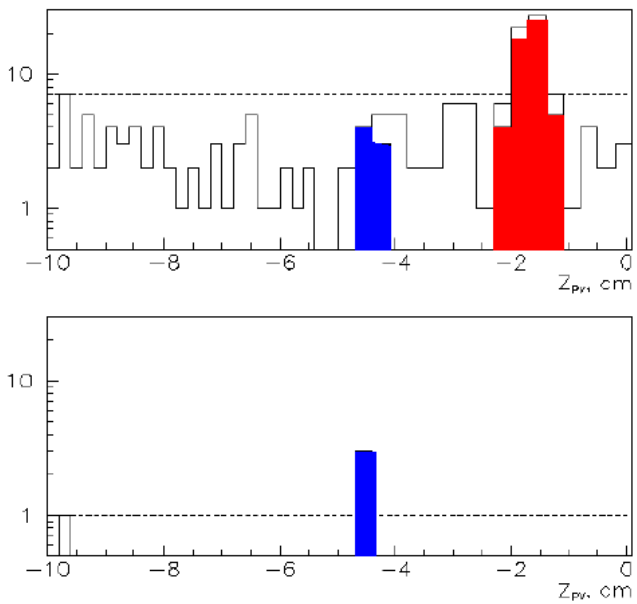


LHCb pileup veto

$$\frac{R_B}{R_A} = \frac{z_B - z_{PV}}{z_A - z_{PV}}$$

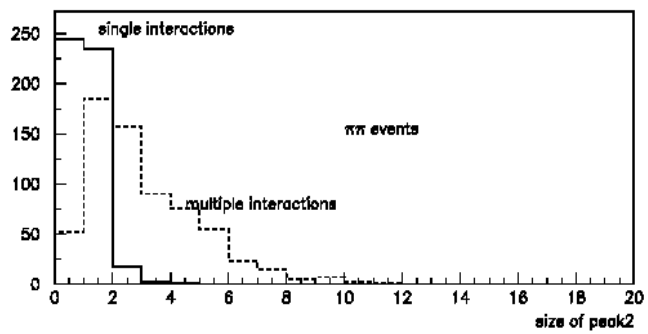






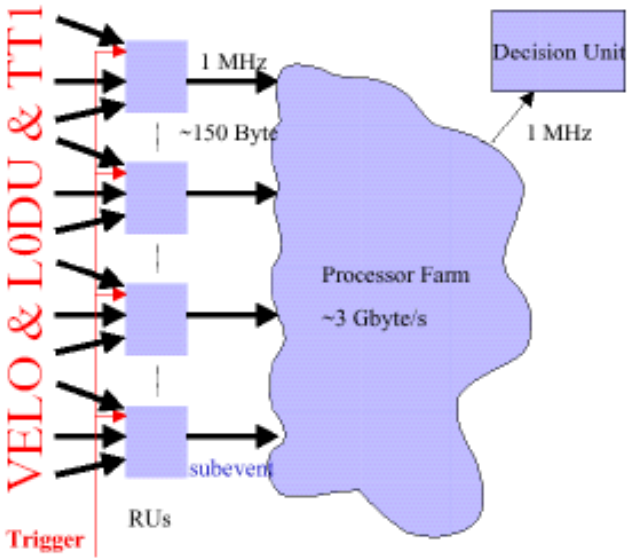
- Project tracks
- Find peak (above threshold), remove all hits belonging to it;
- Repeat, look for peak above threshold

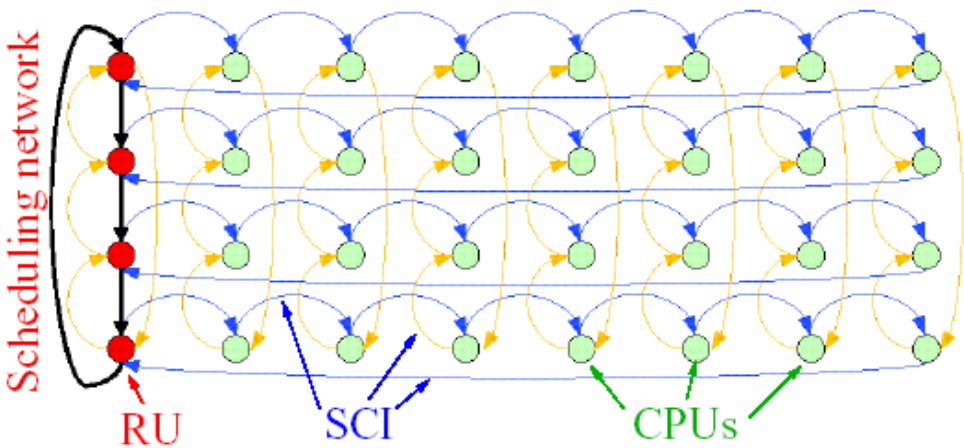
Accepts ~95% of single-interaction events; rejects ~60% of doubles



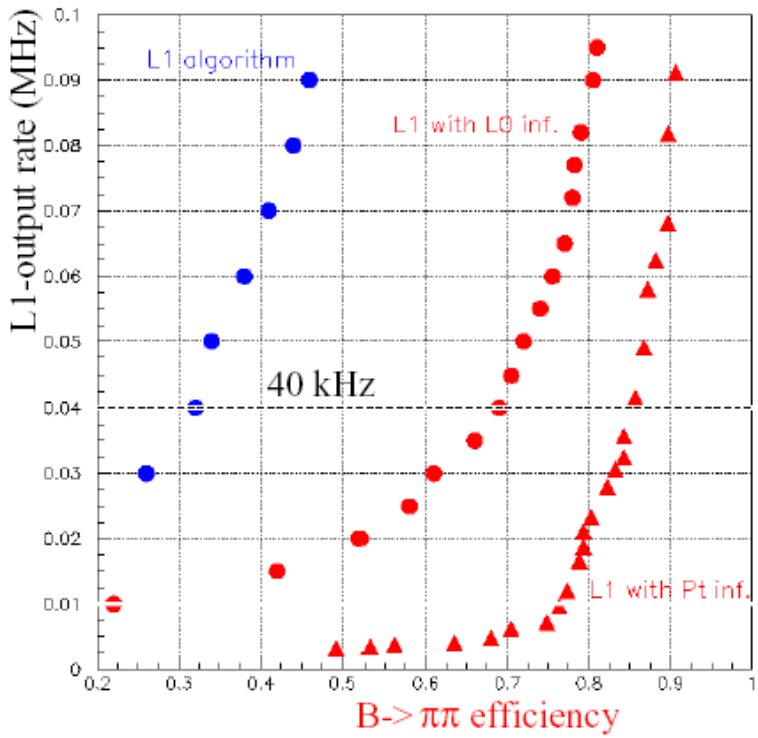
LHCb: Level-1 trigger

- Processor farm connected via SCI ring(s)



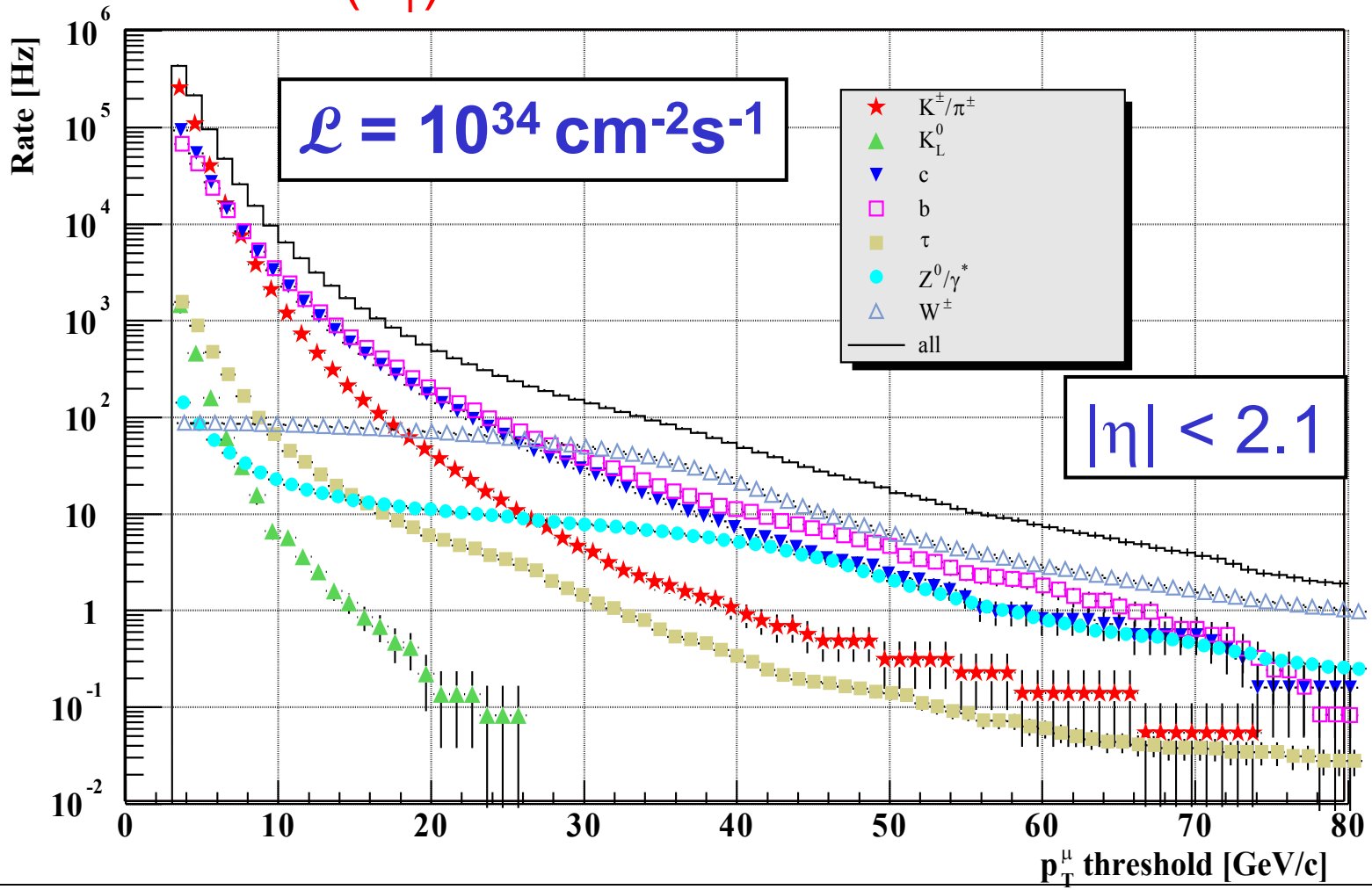


Basic task: find tracks, match to e/μ and estimate PT



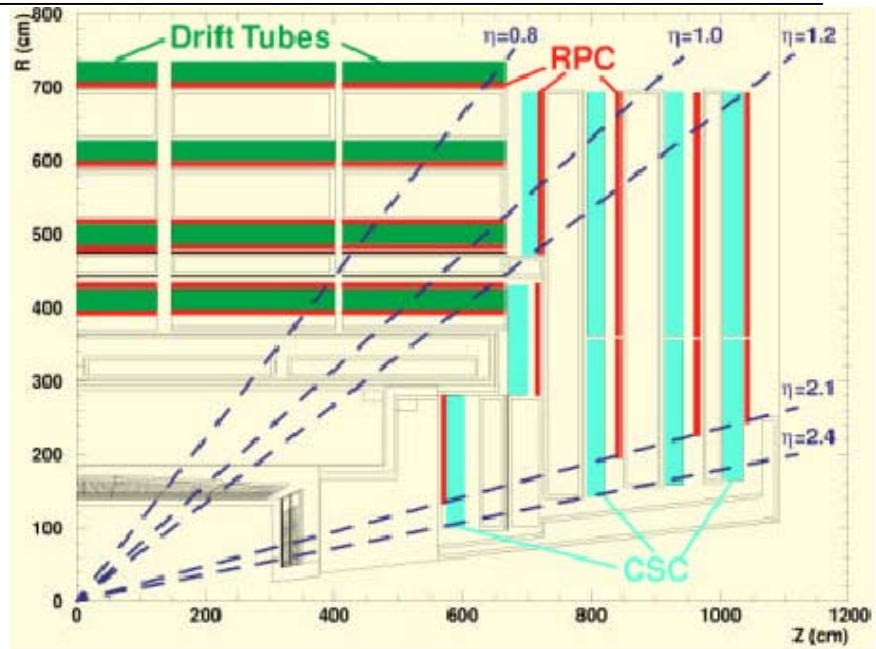
Triggering on Muons

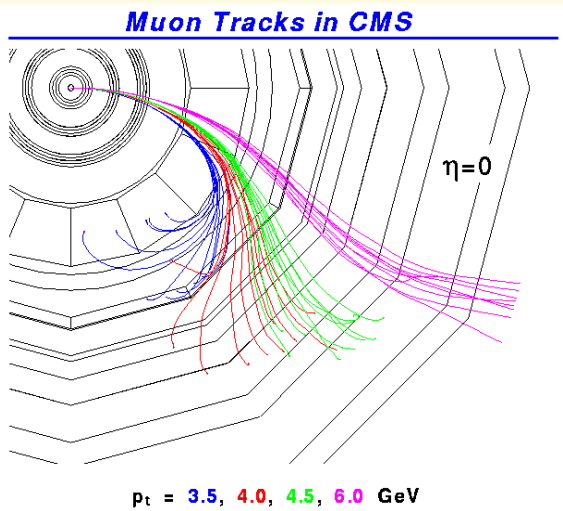
- A priori: rate is not too high is one can measure the momentum (P_T)



Lvl-1 Muon Trigger: CMS example

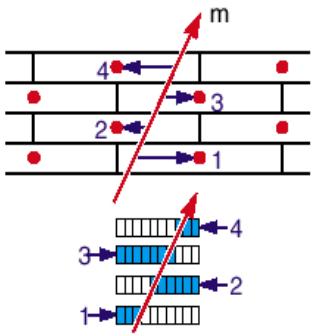
- Lvl-1 μ-trigger info from:
  - Dedicated trigger detector (Resistive parallel plate chambers RPC)
    - Excellent time resolution
  - Muon chambers with accurate position resolution
    - Drift Tubes (DT) in barrel
    - Cathode Strip Chambers (CSC) in endcaps
  - Bending in magnetic field → determine P_T
    - And cut on it



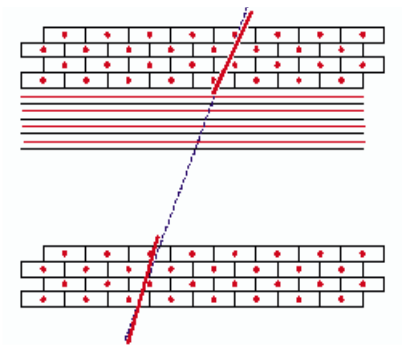


Lvl-1 muon trigger algorithms

Drift Tubes

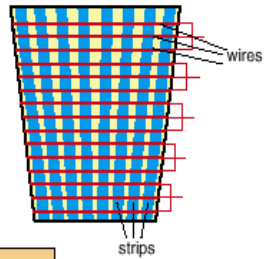


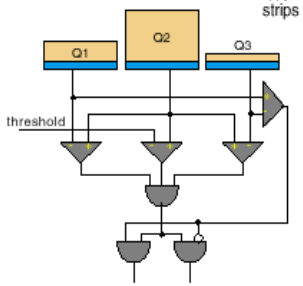
Meantimers recognize tracks and form vector / quartet.



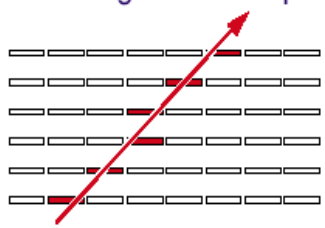
Correlator combines them into one vector / station.

CSC

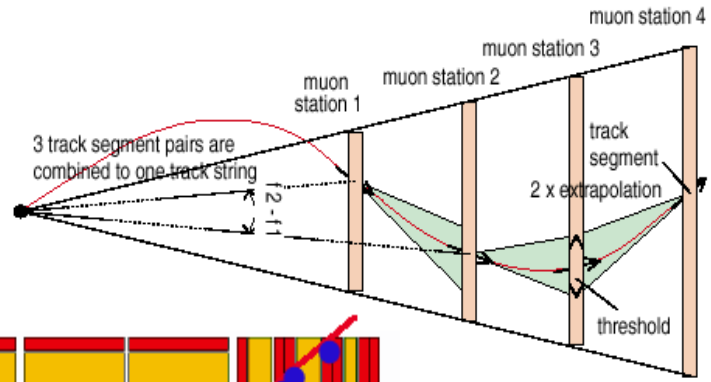


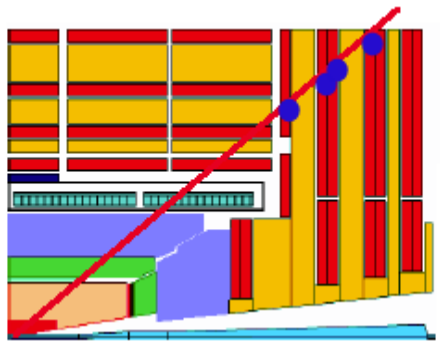


Comparators give 1/2-strip resol.



Hit strips of 6 layers form a vector.





- Extrapolation: using look-up tables
- Track Assembler: link track segment-pairs to tracks, cancel fakes
- Assignment: pt (5 bits), charge, η (6 bits) , φ(8 bits), quality (3 bits)

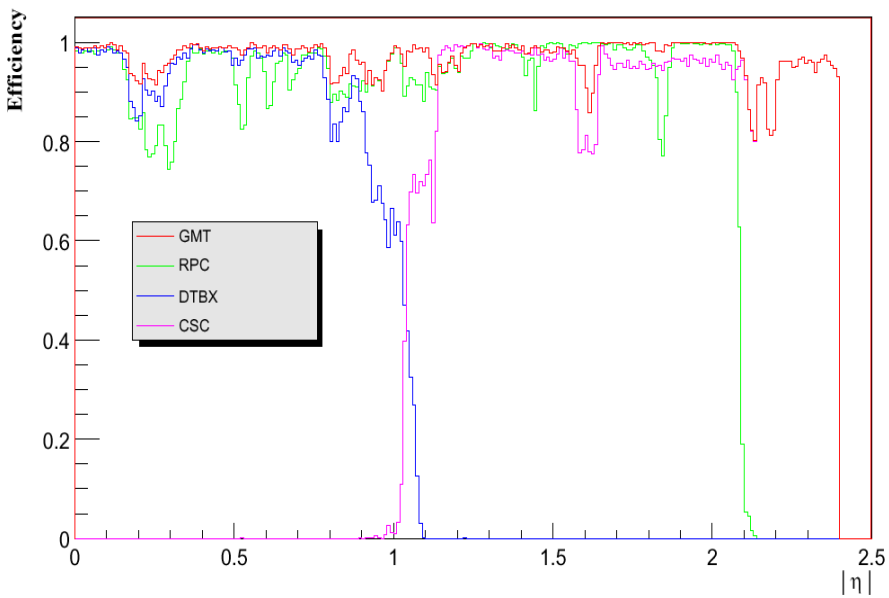
Hardware implementation:

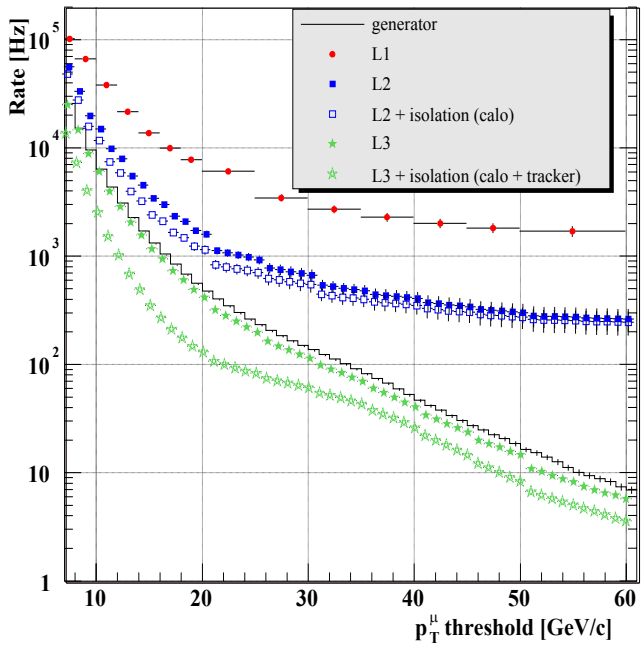
ASICs for Trigger Primitive Generators

FPGAs for Track Finder processors

Lvl-1 muon global trigger

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





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)

Lvl-1 Trigger: Summary

- Not an easy job
- Synchronous, pipelined system
  - Time needed for decision (+its propagation) ≈ 3 μs
  - Bunch crossing time = 25 ns
- Algorithms run on local, coarse data
  - Only calorimeter and muon information
  - Special-purpose hardware (ASICs), but also wide use of FPGAs
- Backgrounds are huge
  - Rejection factor is 400x20 ≈ 8,000
  - Rates: steep functions of thresholds
- Ultimately, determines physics reach of the experiments
  - Ongoing work