Metody eksperymentalne w fizyce wysokich energii

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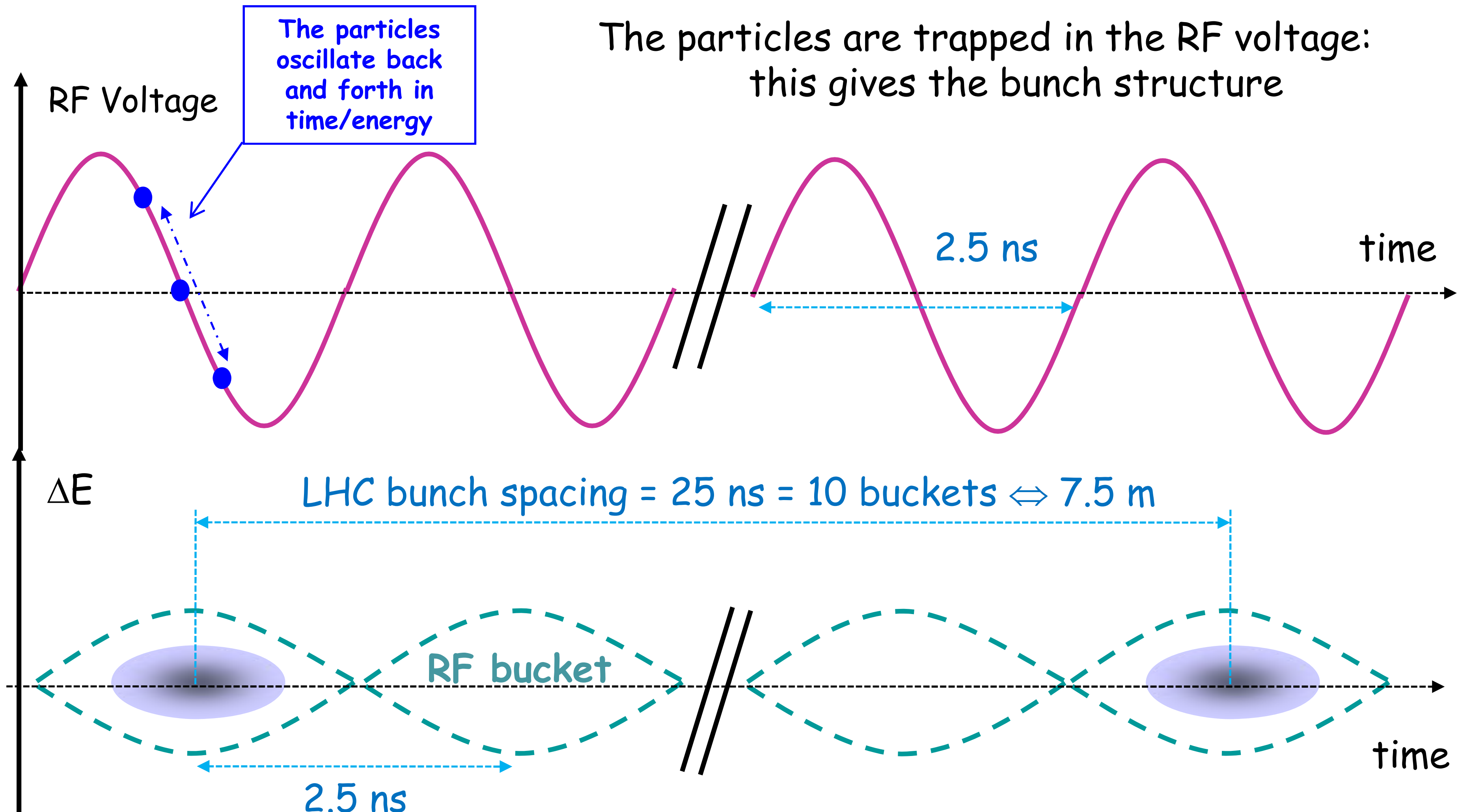
Wykład X

- Systemy wyzwalania zbierania danych

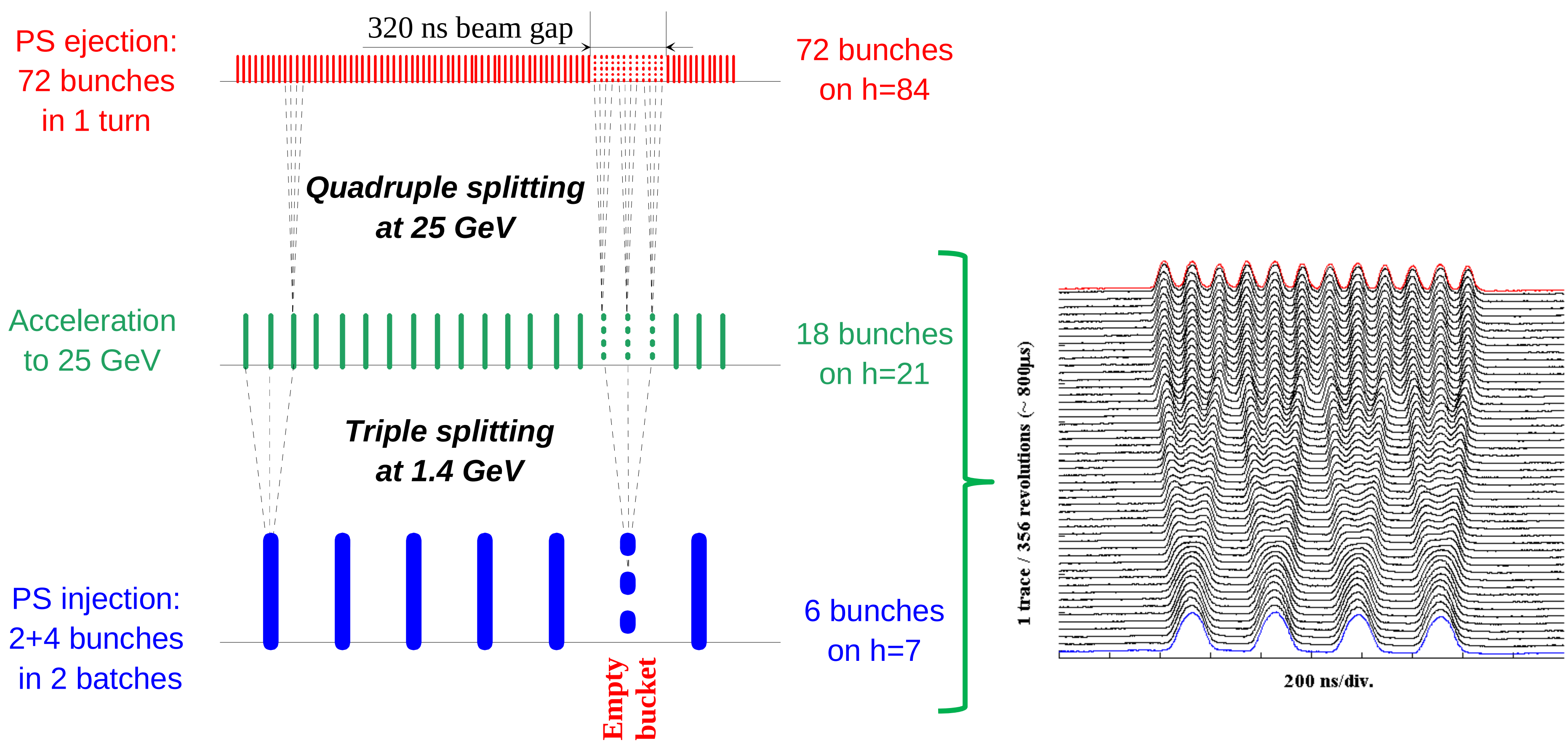
RF buckets and bunches



	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

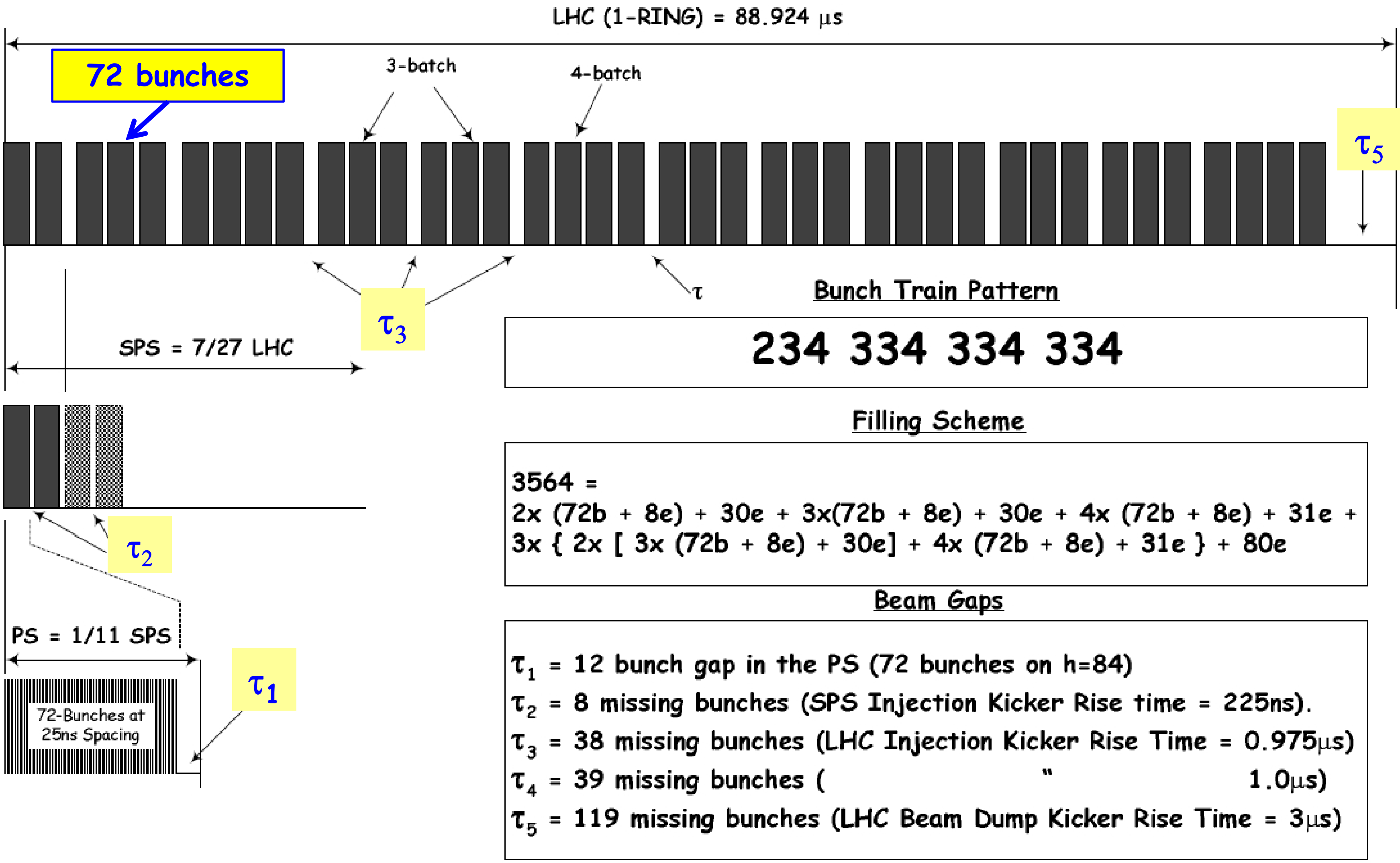
Bunch Splitting at the PS

- The bunch splitting in the PS machine is the most delicate operation that is performed in the injector chain.
- The quality of the splitting is critical for the LHC (uniform intensity in all bunches…).

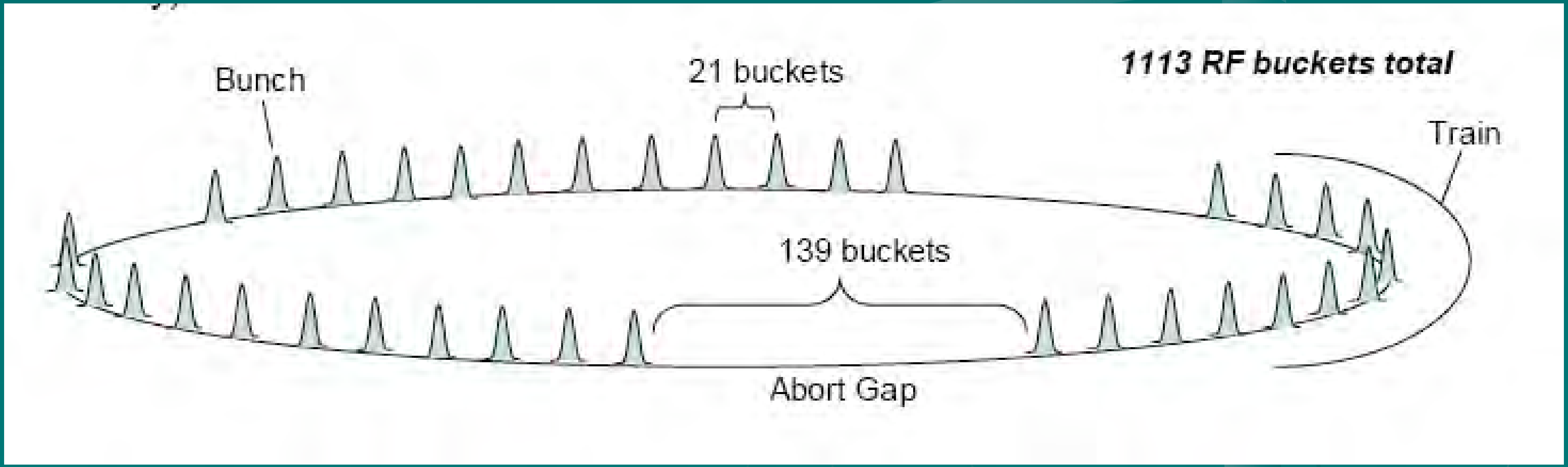


Bunch pattern details

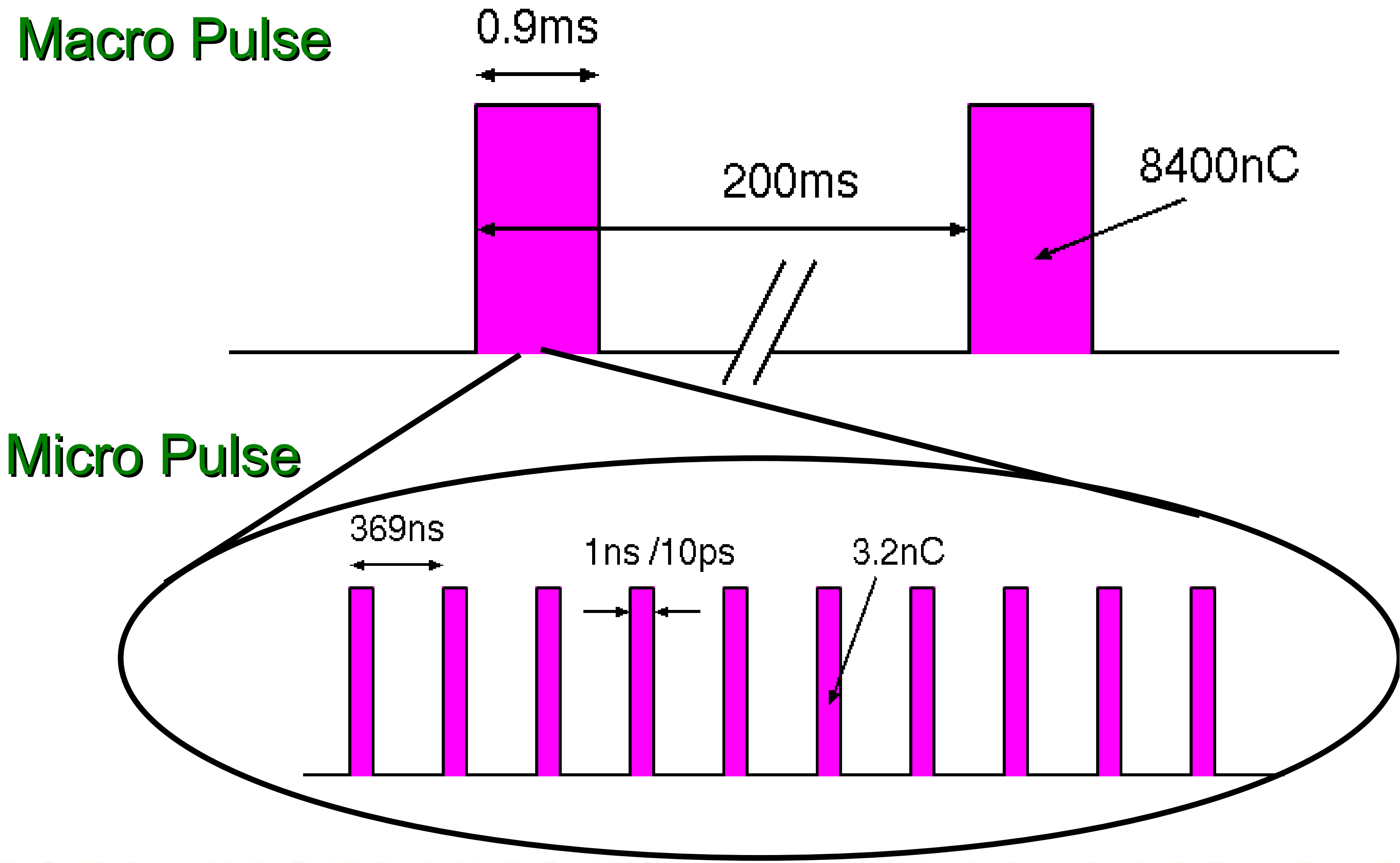
- The nominal LHC pattern consists of 39 groups of 72 bunches (spaced by 25 ns), with variable spacing between the groups to accommodate the rise times of the fast injection and extraction magnets ('kickers').
- There is a long 3 μs hole (τ_5)for the LHC dump kicker (see later).



Tevatron Bunch Structure



Pulse structure

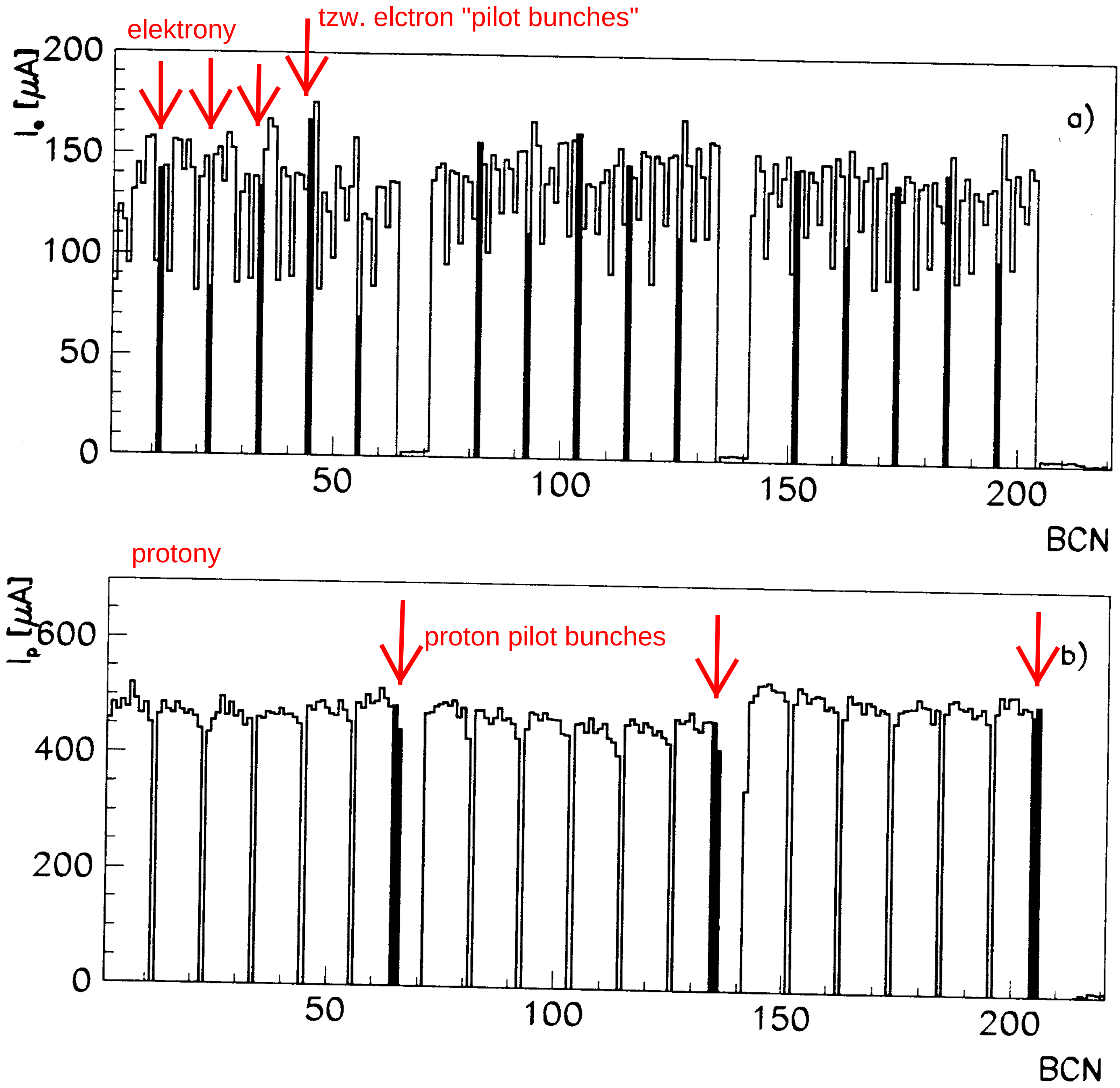


HERA: electron-proton collider at DESY (1992-2007)

Nie wszystkie "paczki" cząstek zderzały się z wiązką przeciwbieżną
=> niesłychanie pomocne w ocenie tła wiązki !

	Design	1992	1993	1994	1995	1996
Number of p bunches	210	10	90	170	180	180
Number of e bunches	210	12	94	168	189	189
Number of colliding bunches	210	10	84	153	174	174
p momentum p_0 / GeV / c	820	820	820	820	820	820
p current I_0 / mA	163	2		54	73	80
e momentum p_0 / GeV / c	30	26.67	26.67	27.52	27.52	27.52
e current I_0 / mA	58	3.4		36	37	40
Specific luminosity $\mathcal{L}_{sp} / 10^{29}\,\mathrm{mA}^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	3.33			4.0	5.0	6.0
Luminosity $\mathcal{L} / 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.5			0.4	0.7	0.8
Delivered integrated luminosity $\int \mathcal{L}\,dt$ / pbarn^{-1}	(50)	0.06	1.1	6.2	12.3	15
Long. polarization P_0 / %				65	70	70

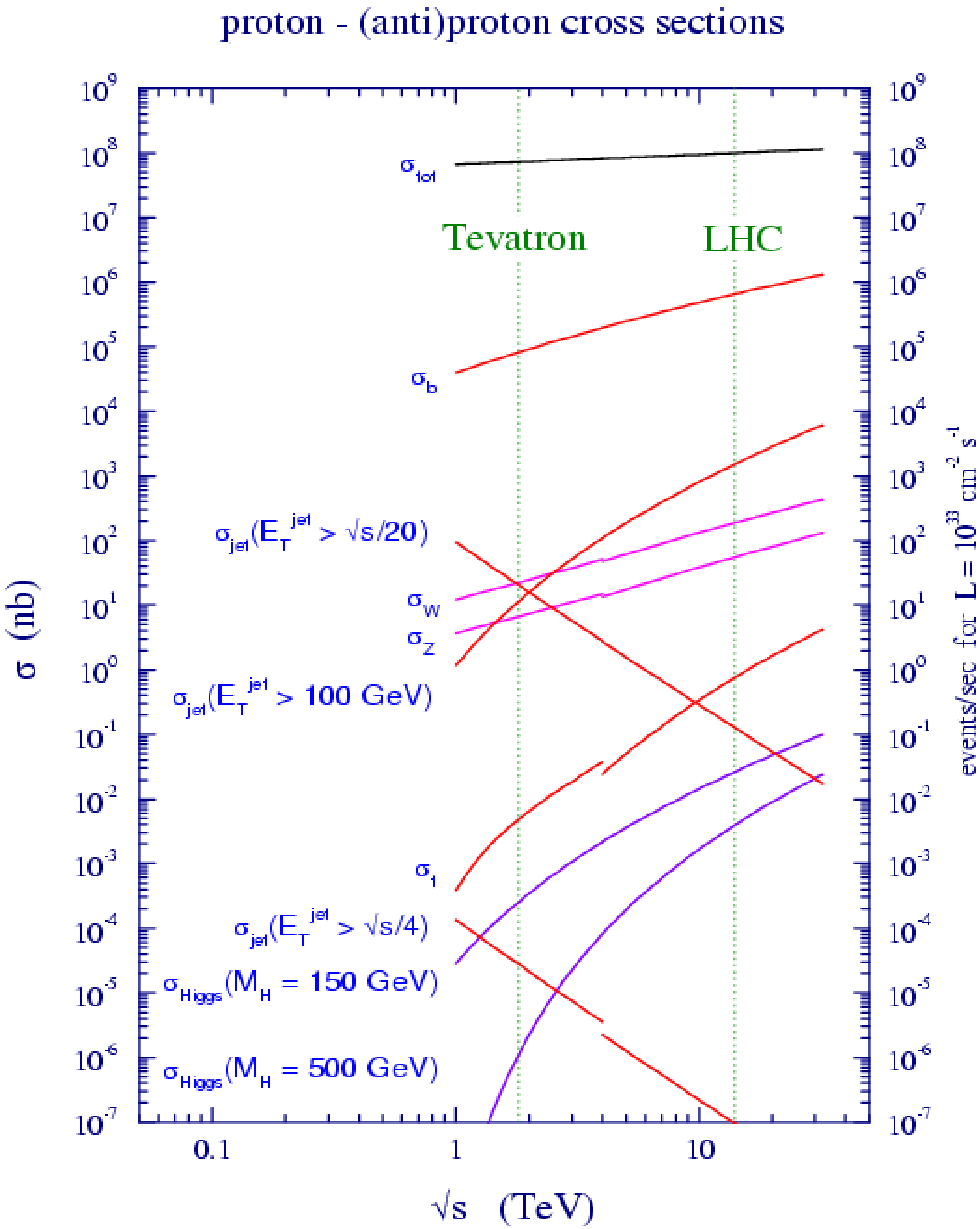
Table 3: Development of the main machine parameters since the first data taking in 1992.



elektrony
tzw. elctron "pilot bunches"
I_e [µA]
200
150
100
50
0
a)
50
100
150
200
BCN
protony
I_p [µA]
600
400
200
0
proton pilot bunches
b)
50
100
150
200
BCN

The Basics

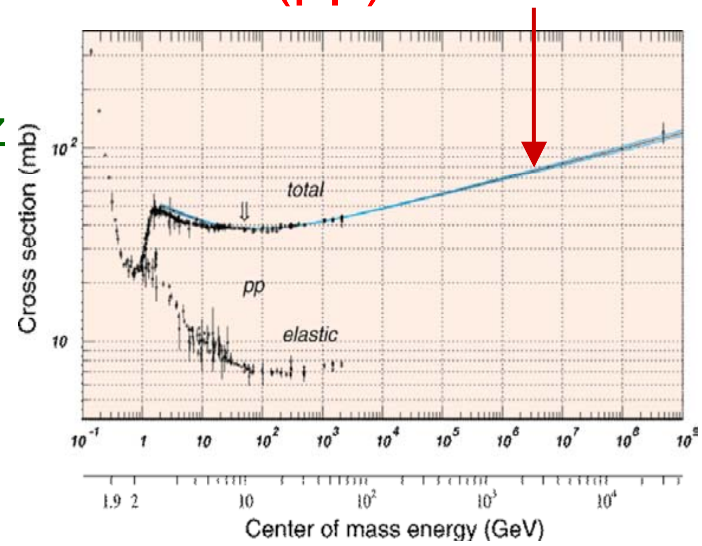
- Total cross-sections are large:
  - ~80 mb at $\sqrt{s}$ = 1.8 TeV
  - @10^{32}, that's 8 MHz!
- "Interesting" cross-sections (say W-> e) are much smaller:
  - $\mathcal{O}$(few nb)
  - @10^{32}, that's < 1 Hz
    - At 10^{34} at the LHC it becomes $\mathcal{O}$(10 Hz)!



pp cross section and min. bias

- **# of interactions/crossing:**
  - Interactions/s:
    - Lum = $10^{34}\ cm^{-2}s^{-1} = 10^{7} mb^{-1}Hz$
    - $\sigma(pp)$ = 70 mb
    - Interaction Rate, R = 7×10^{8} Hz
  - Events/beam crossing:
    - Δt = 25 ns = 2.5×10^{-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

$\sigma(pp) \approx 70$ mb



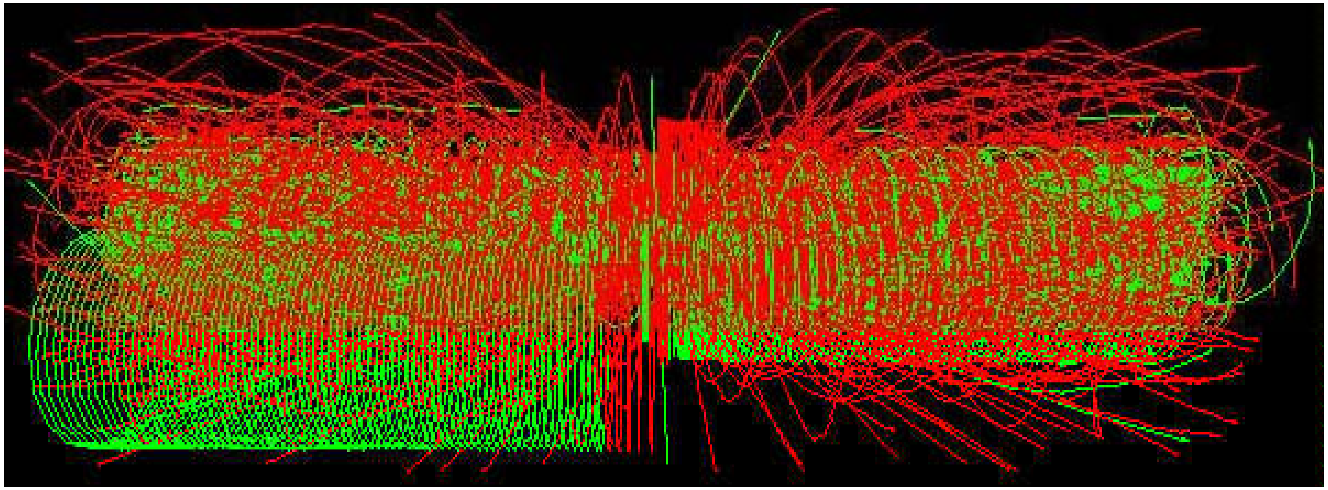
> Operating conditions (summary):
> 1) A "good" event containing a Higgs decay +
> 2) ≈ 20 extra "bad" (minimum bias) interactions

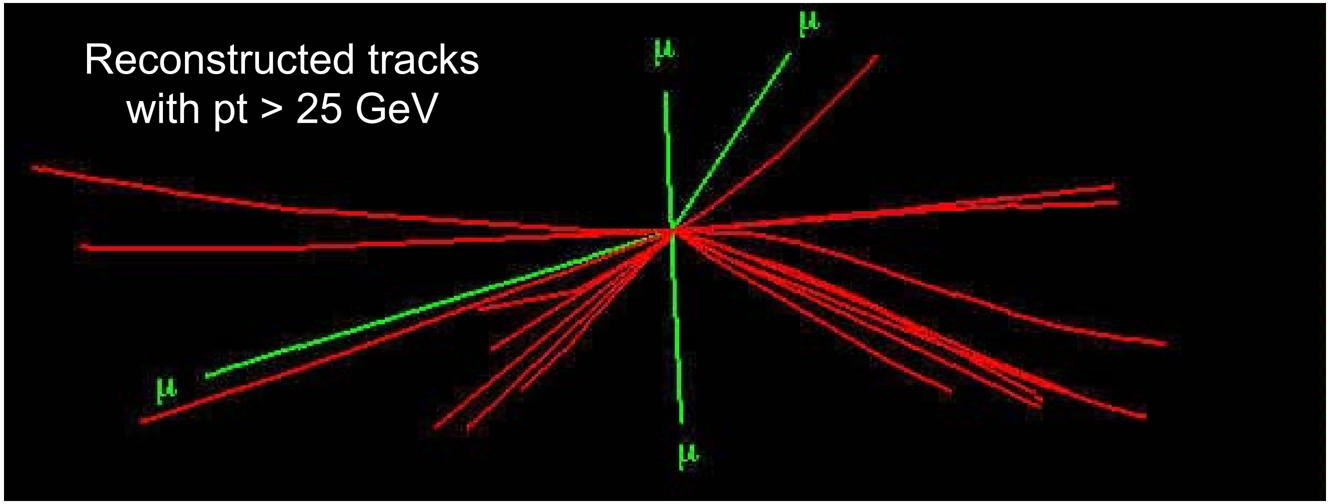
pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

- 20 min bias events overlap
- H→ZZ

Z →μμ

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

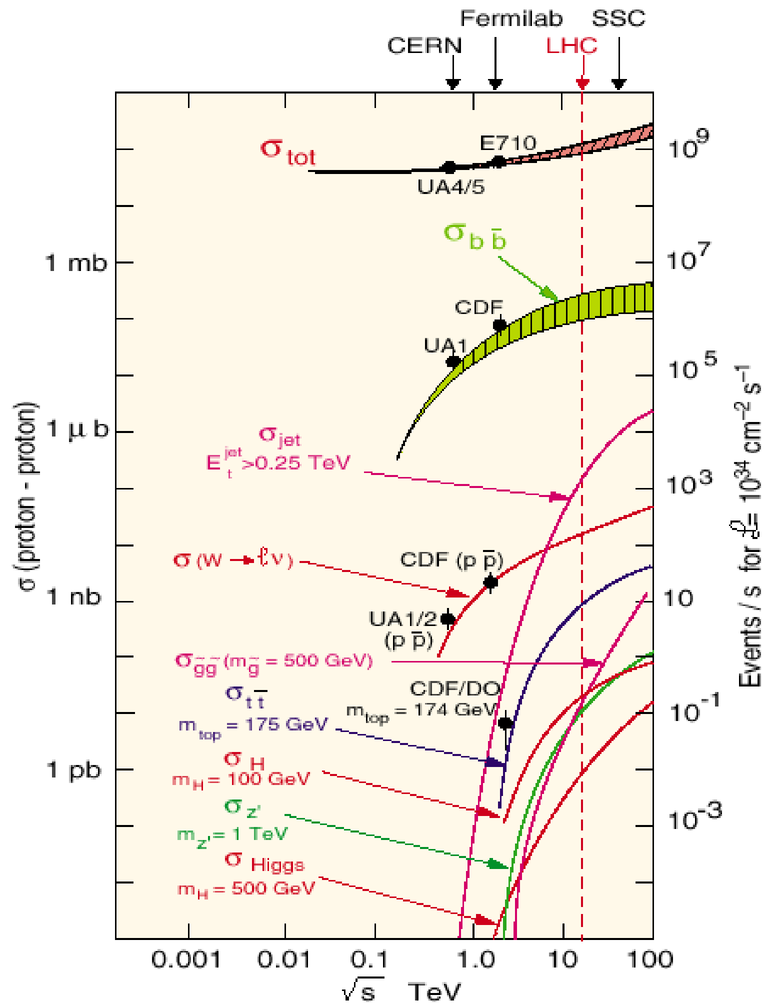




And this (not the H though…) repeats every 25 ns…

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...



Basics II

- Trigger goal:
  - "To select interesting events for offline analysis"...
  - ... while minimizing deadtime!
- "Interesting" is a relative concept:
  - Depends on physics priorities (need for compromise in multi-purpose experiments)
  - Only interesting if event passes offline cuts!
  - Includes events needed to validate analysis
    - Determination of efficiencies
    - Control samples
    - ... (more later)

Dataflow Arguments

- Tevatron: "precision" raw data ~200 kB/evt (zero suppressed and compressed)
  - L1 input if used that: > 3 Tbps
    - Need to slim and factorize for processing
    - But sometimes also duplicate....
  - To tape (100 Hz): ~20 MB/s
- LHC: ~1 MB/evts
  - L1 input if used that: > 300 Tbps
  - To tape (200 Hz): ~200 MB/s
- So, trigger is not just a physics argument

Basics III

- During decision-making process, data needs to be "stored"
  - Slower process ("latency") means "deeper memory"
  - There is a "traditional architecture" (CDF, DØ, ATLAS, CMS....)
  - Rapid evolution in technology opens door to new ideas however (BTeV, CKM, to a lesser extent LHCb?)
- But, all other things being equal, faster processing means less rejection and therefore more output bandwith (and storage and ...)

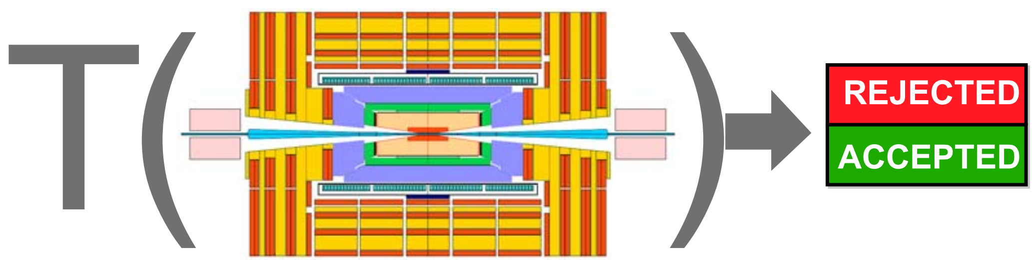
Triggering

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 :

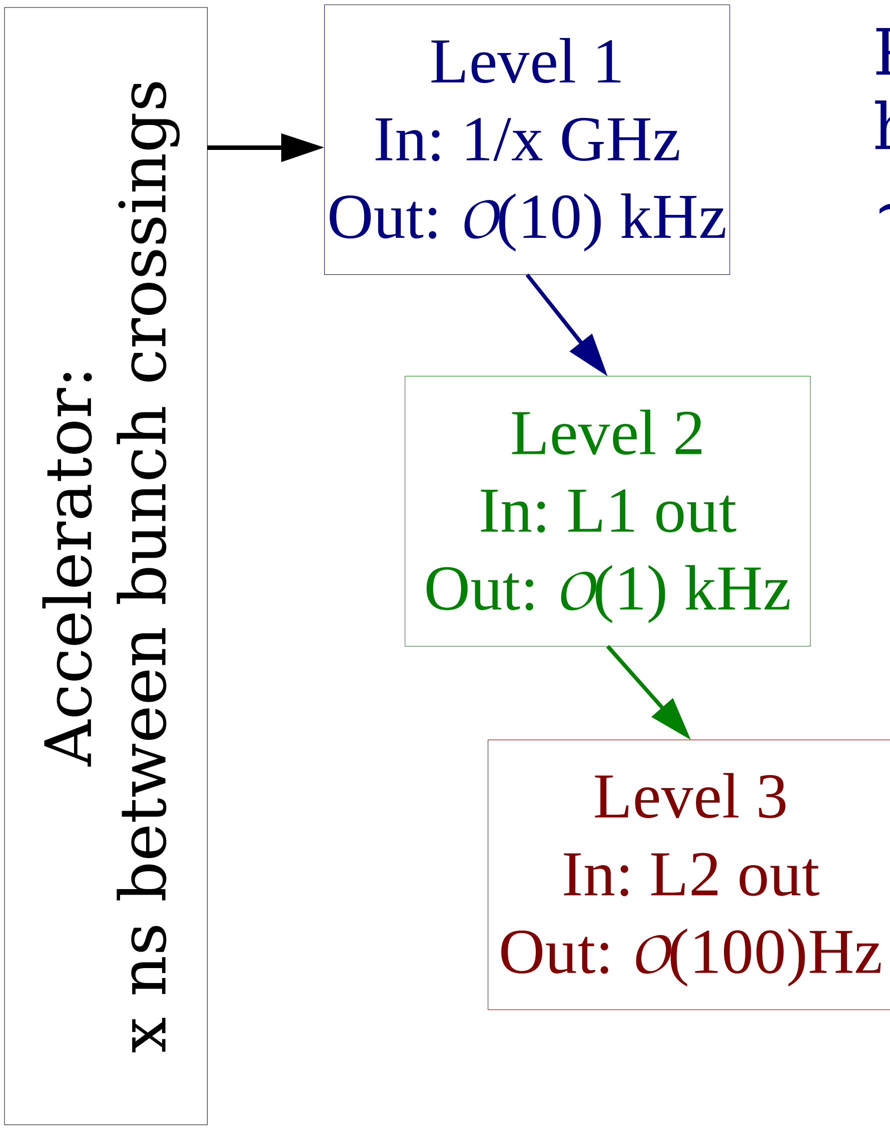
TRIGGER LEVELS

(possibly with zero dead time)

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

“Traditional” Architecture



Pipelined (often deadtimeless), hardware only, coarse readout, ~few μs latency

Hardware/Software mix, L1 inputs, ~100 μs latency

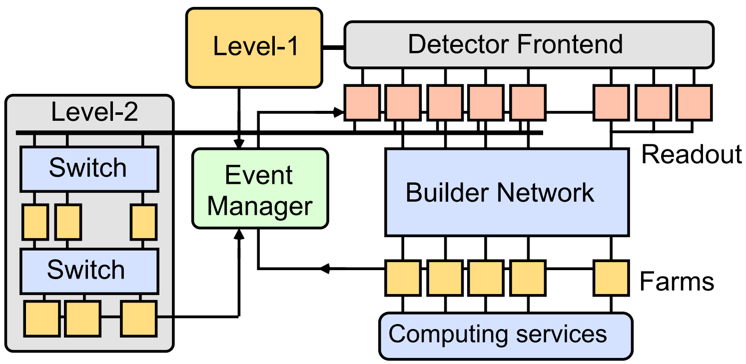
CPU farm, access to full event information, $\mathcal{O}$(1)s/event

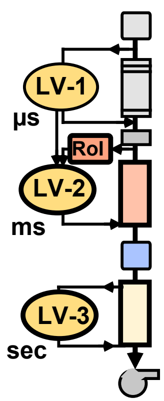
“Traditional” Elements

- Level 1 uses dedicated hardware, separate signals, per-subdetector “decision”
  - ASICs and FPGAs
- Level 2 uses dedicated hardware for “data preparation”, then CPUs for combination and decision
- Level 3 uses commercial CPUs
  - Difficulty is getting all of an event to a specific node, various approaches
    - “Concentrator(s)” -> bottleneck, single point of failure
    - “Fully distributed”

Three physical entities

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





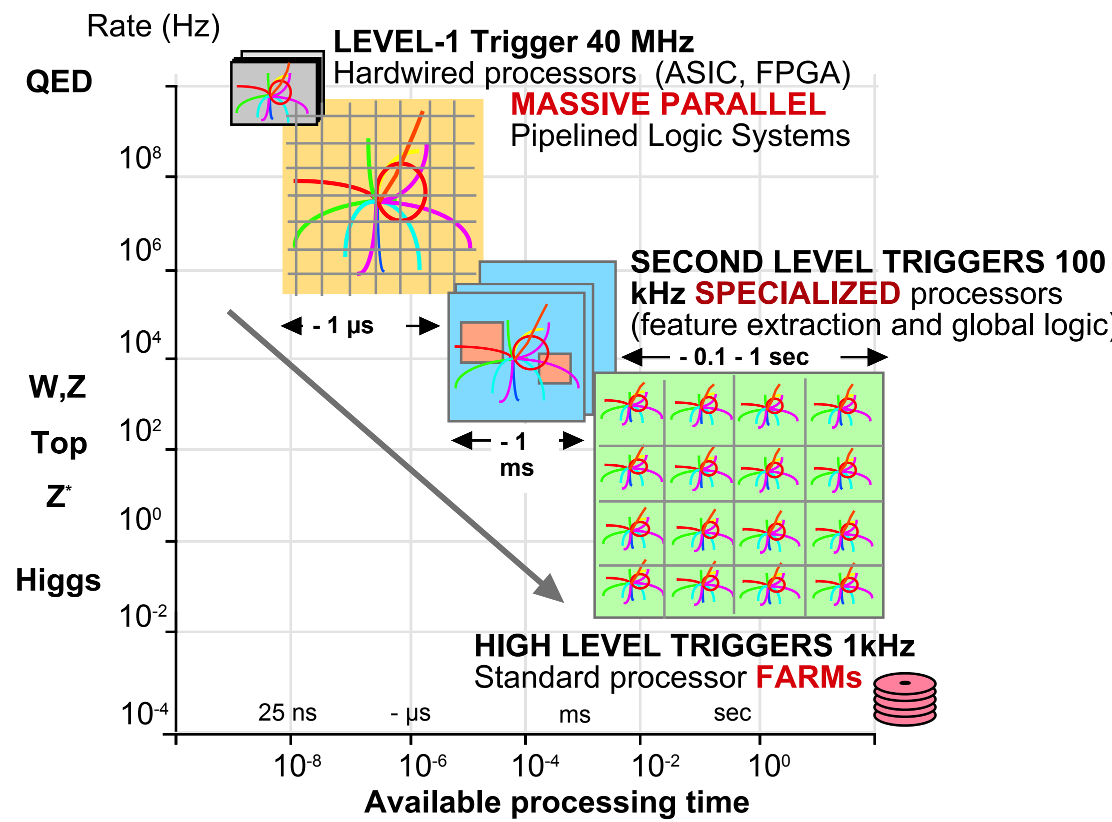
40 MHz

10^5 Hz

10^3 Hz

10 Gb/s

10^2 Hz



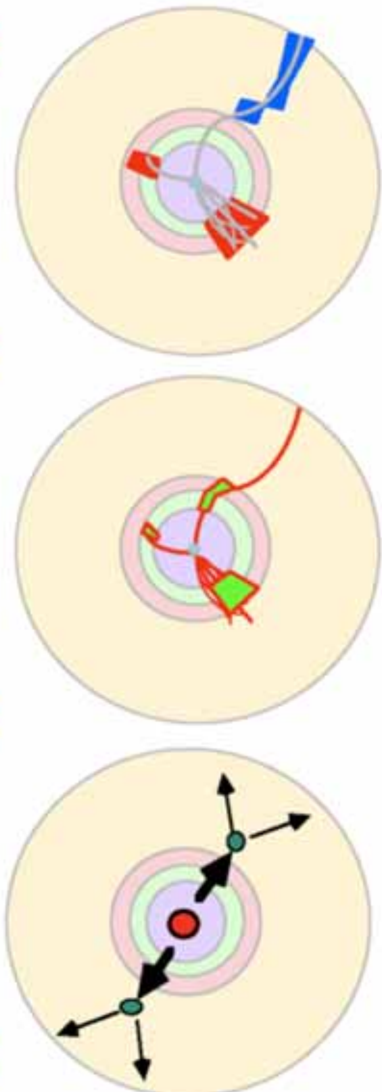
LHC Trigger Levels

10^{-7} s

10^{-6} s

10^{-3} s

10^{-0} s



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

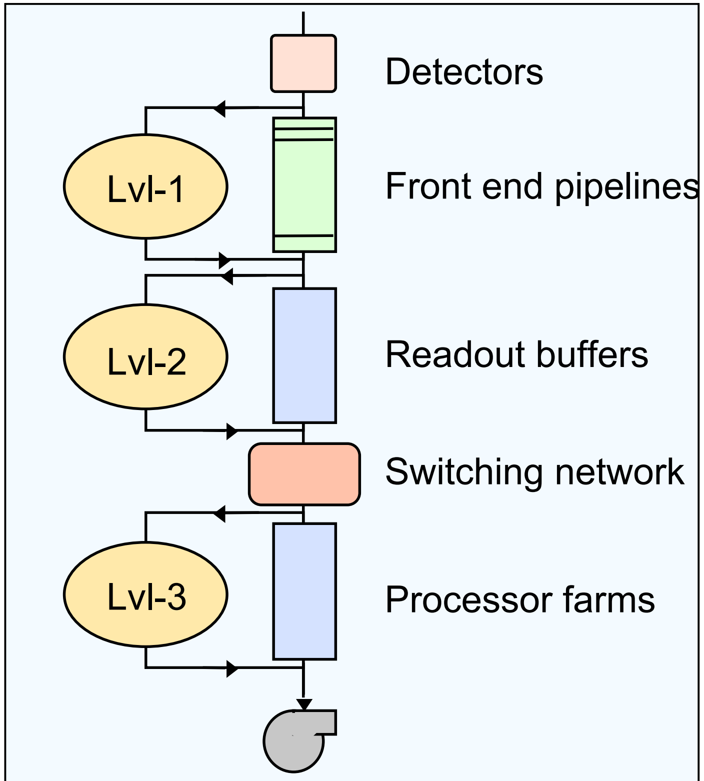
Level-3 events to tape 100- 300 Hz

Physics process identification

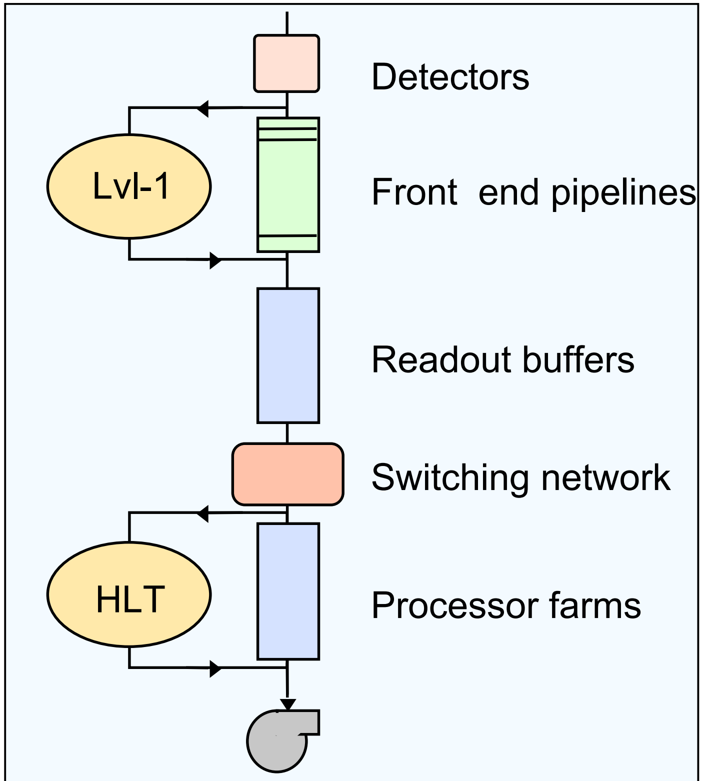
- Event reconstruction and analysis

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

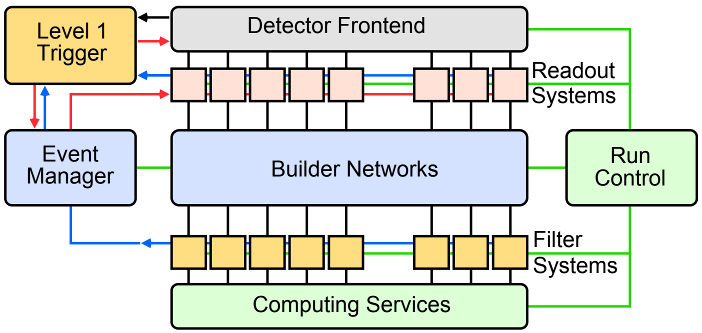


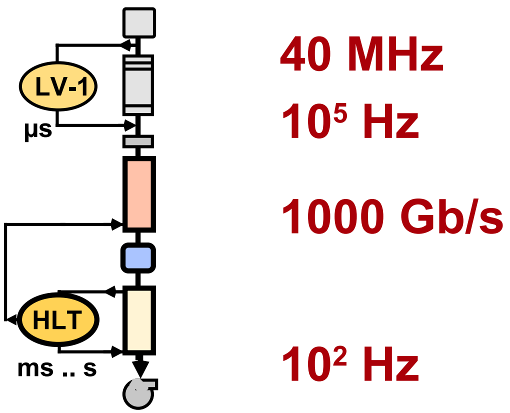
"Traditional": 3 physical levels

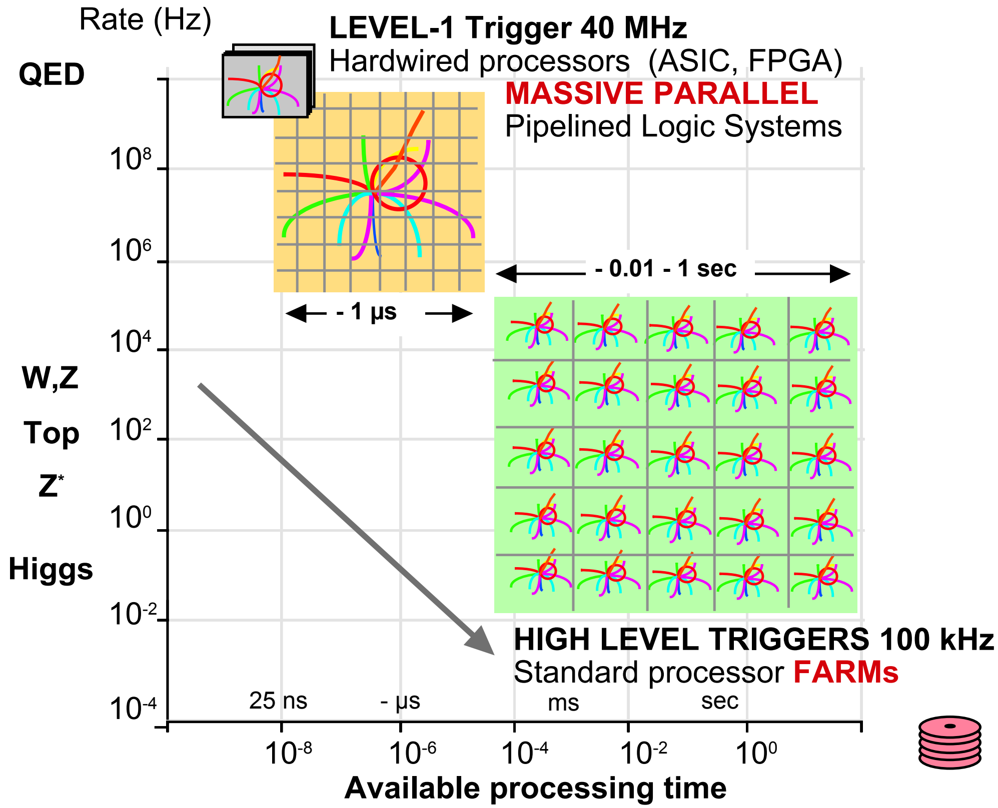


CMS: 2 physical levels

Two physical entities



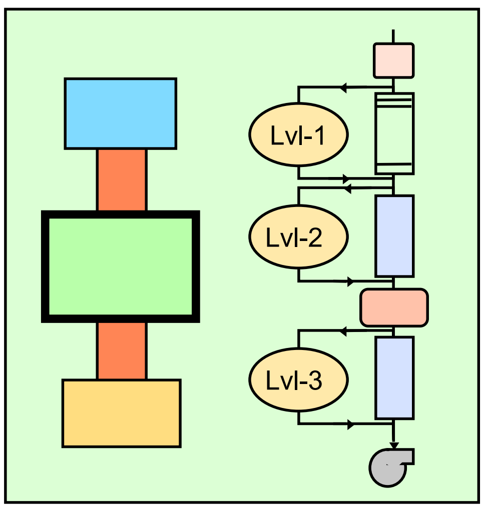




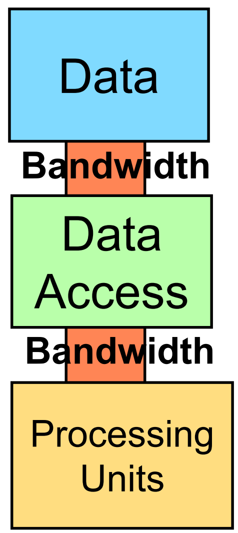
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Comparison of 2 vs 3 physical levels

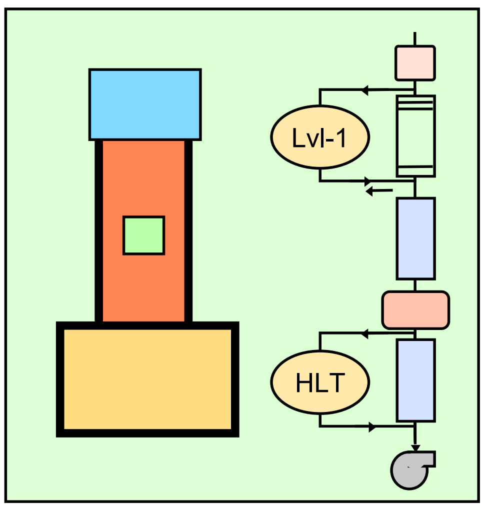
- Three Physical Levels
  - Investment in:
    - Control Logic
    - Specialized processors



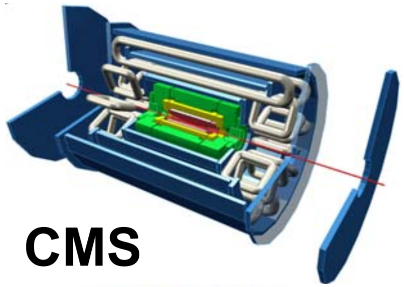
Model

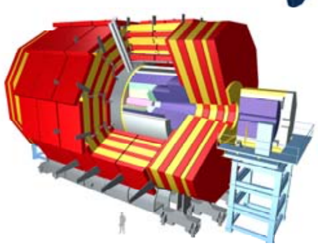


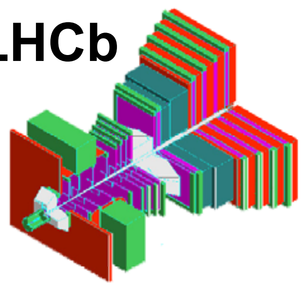
- Two Physical Levels
  - Investment in:
    - Bandwidth
    - Commercial Processors

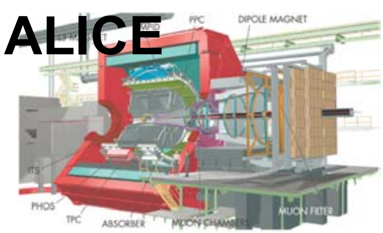


Trigger/DAQ parameters: summary



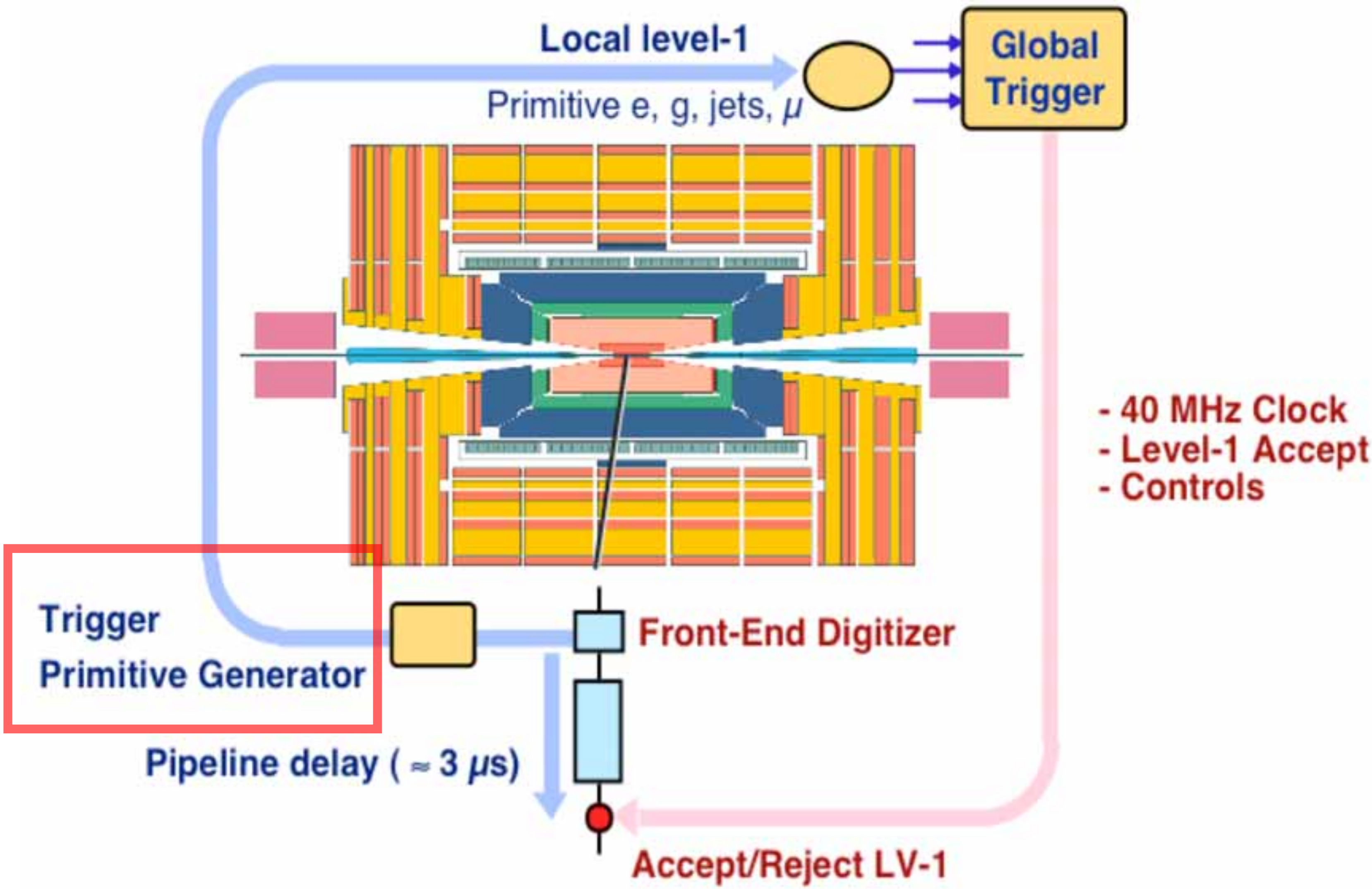






	No.Levels Trigger	Level-1 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS	**3**	**10^5** LV-2 **10^3**	**10^6**	**10**	**100** (10^2)
CMS	**2**	**10^5**	**10^6**	**100**	**100** (10^2)
LHCb	**3**	LV-0 **10^6** LV-1 **$4\ 10^4$**	**$2x10^5$**	**4**	**40** ($2x10^2$)
ALICE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

Level 1 Trigger Operation



Level-1 trigger

Najważniejsza i najtrudniejsza część układu wyzwalania

* bardzo mało czasu na podjęcie decyzji
* możliwe tylko najprostsze operacje na danych:
    - dodawanie
    - mnożenie
    - adresowanie pamięci (!)

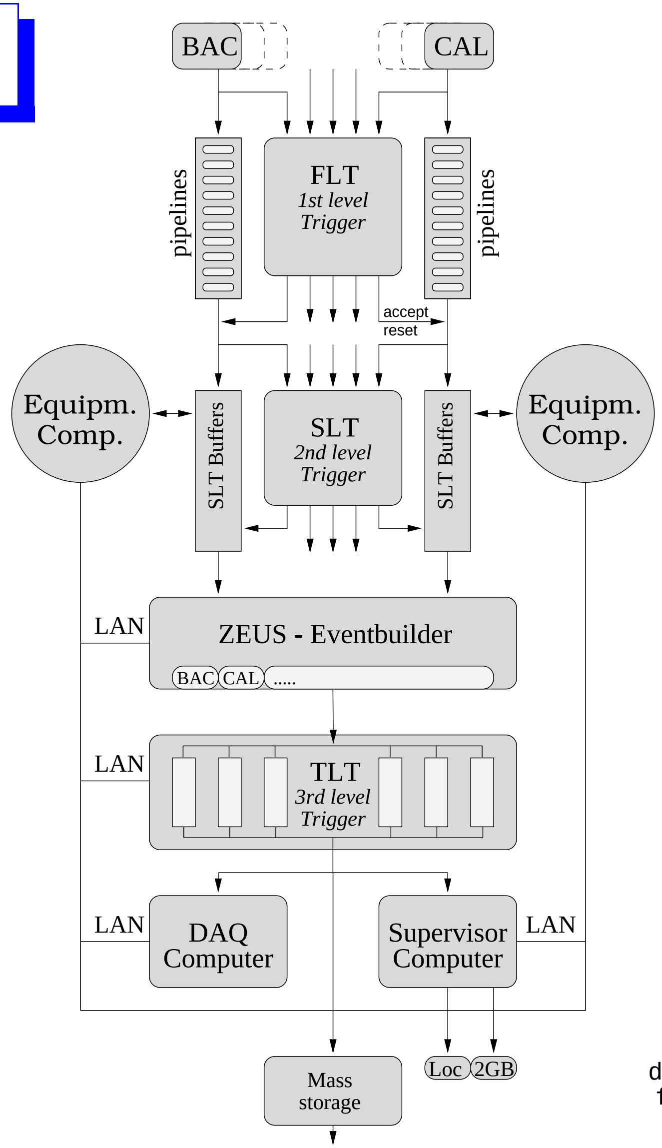
  => jedyny sposób na wykonanie bardziej złożonych operacji to policzyć wcześniej wszystkie możliwości i zapisac w LUT (Look-Up Table)

* musimy wprowadzać uproszczenia

  (ograniczenie strumienia danych => przestrzeni adresowej)
* musimy się pogodzić z dużymi błędami

* najważniejsza jest efektywność (czystość zapewnimy potem)

ZEUS Trigger Scheme

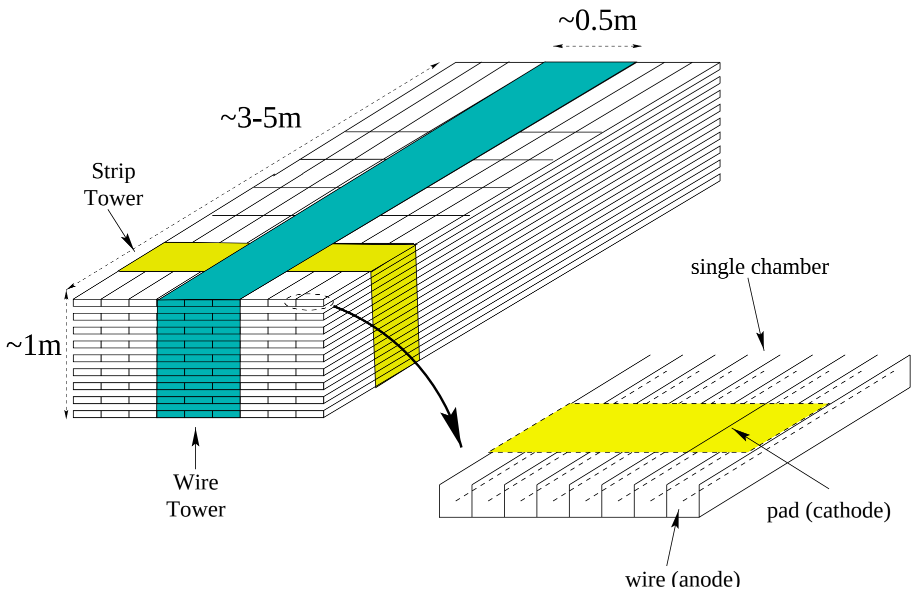


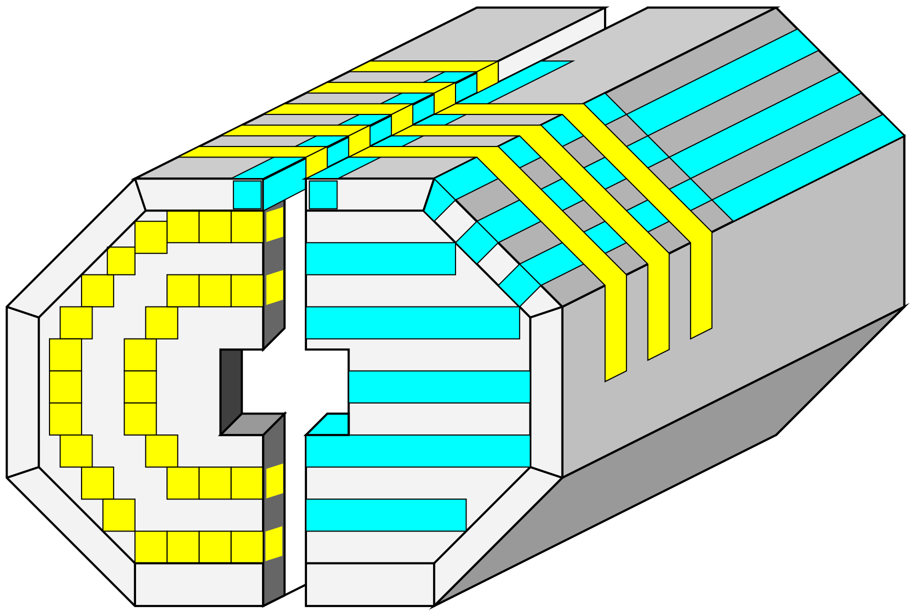

```
ZEUS readout components
data input rate 10 MHz

5 us pipelines
and local FLT

rate accepted by
Global FLT 1 kHz

pipelined local SLT
local equipment computers

rate accepted by
Global SLT 100 Hz

Event builder
collecting subevents
formatting

TLT
farm of Linux workstations

rate accepted by
TLT ~5 Hz

expert supervision
Run Control
Data Quality Monitoring

data transfer to main storage
facility (~0.5-1 MByte/sec.)
```

- 3 Level Trigger: FLT - fifo pipelines, SLT - DPM memory, TLT: software

BAC Strip Towers

Transverse energy estimate for First Level Trigger (FLT)

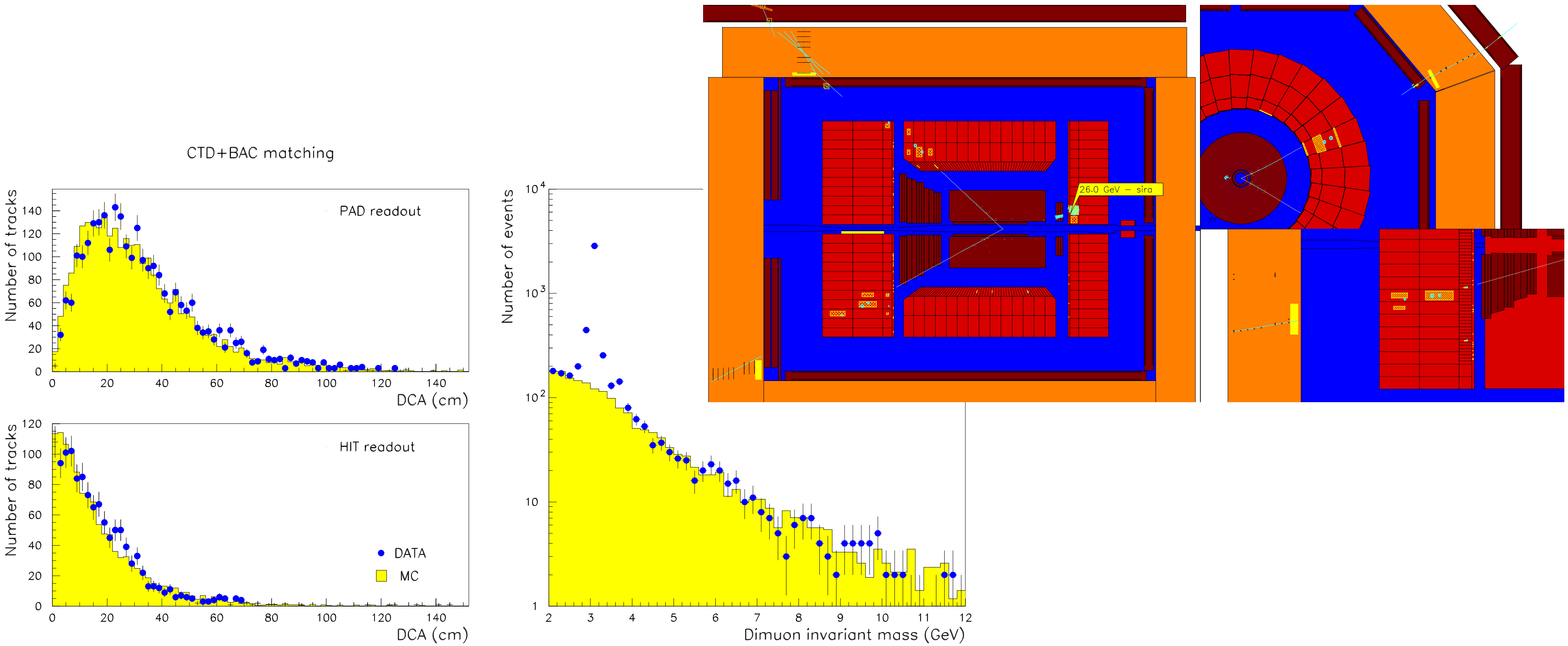




- Strips are constructed using neighbour pad towers
- In Barrel: Strip towers are perpendicular to wire towers
- In Endcaps: Strips are formed in semi-circles around beam-pipe

Energy in each strip tower scaled on hardware level by sin(angle)

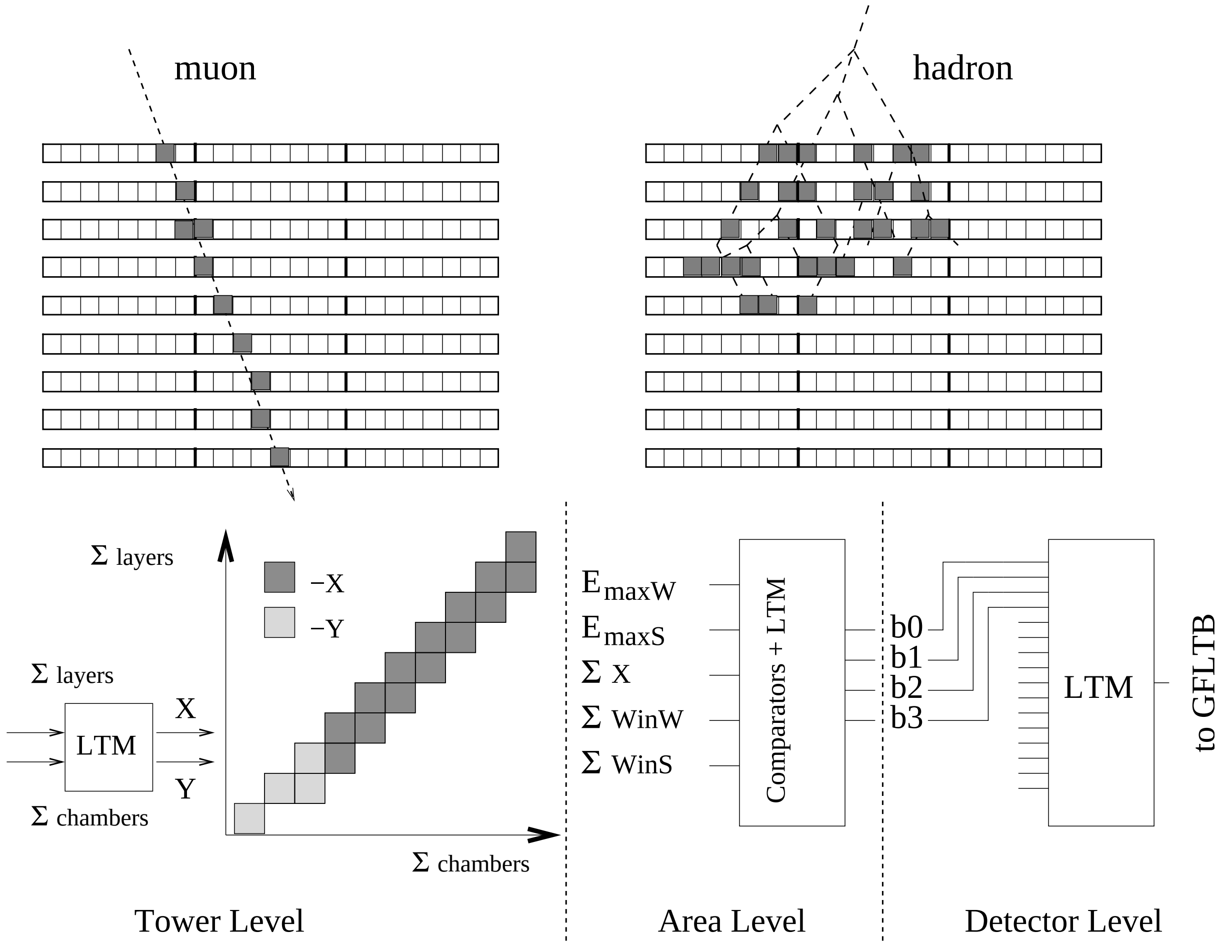
BAC as a muon detector



- Position (HIT) readout fully installed in 1997/98
- Di-muon analysis: J/ψ, ψ' and Bethe-Heitler

BAC Muon Trigger Algorithm: Basic Idea

Kluczowe odróżnienie mionu od wypływów

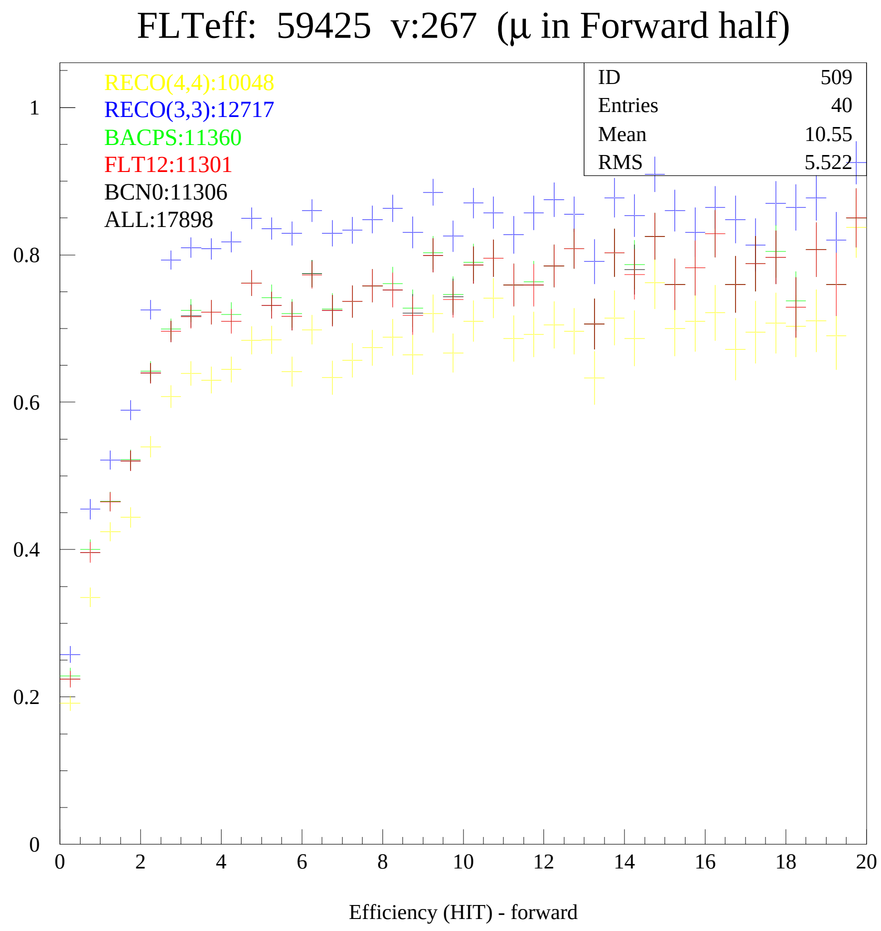


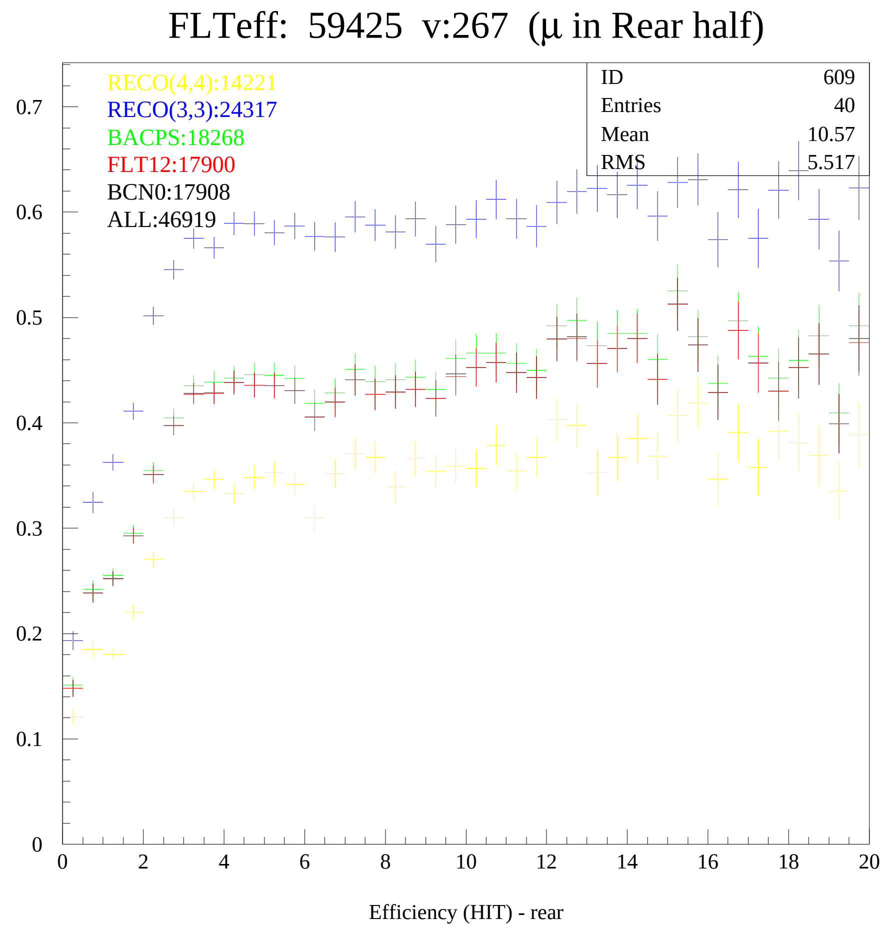
- fast pattern recognition in wire towers
- counting $\Sigma\, chambers$ and $\Sigma\, layers$
- LTM memory to classify events
- flexible fillings possible for each tower

Dla każdej wieży:
bit X - mion
bit Y - wypływ hadronowy

- BAC muon trigger logic on Tower, Area and Detector Level
- For "good"/quite towers: $(N_{layers} >= 3, N_{chambers} >= 3)$

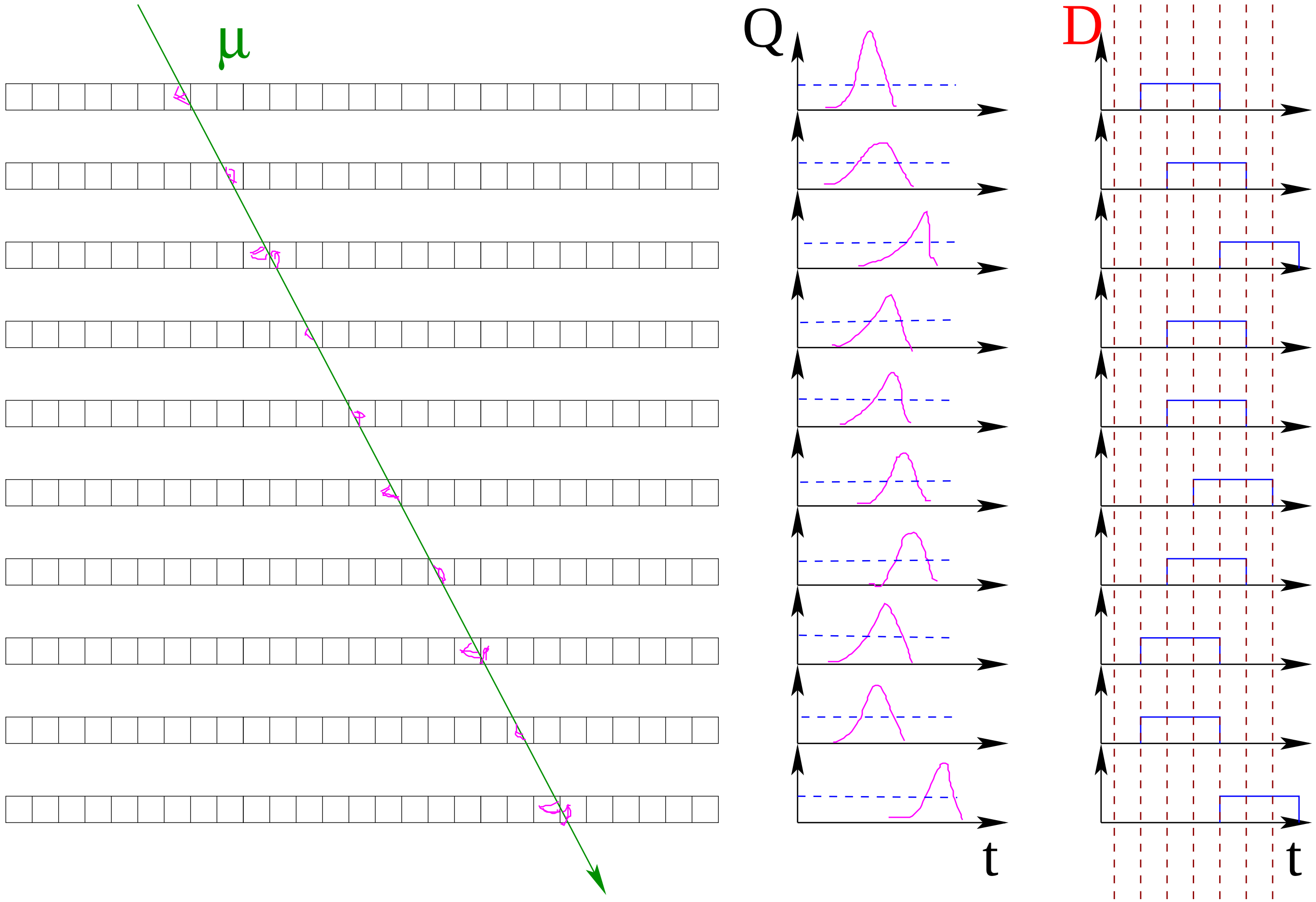
BAC FLT on-line efficiencies (from COSMIC run)





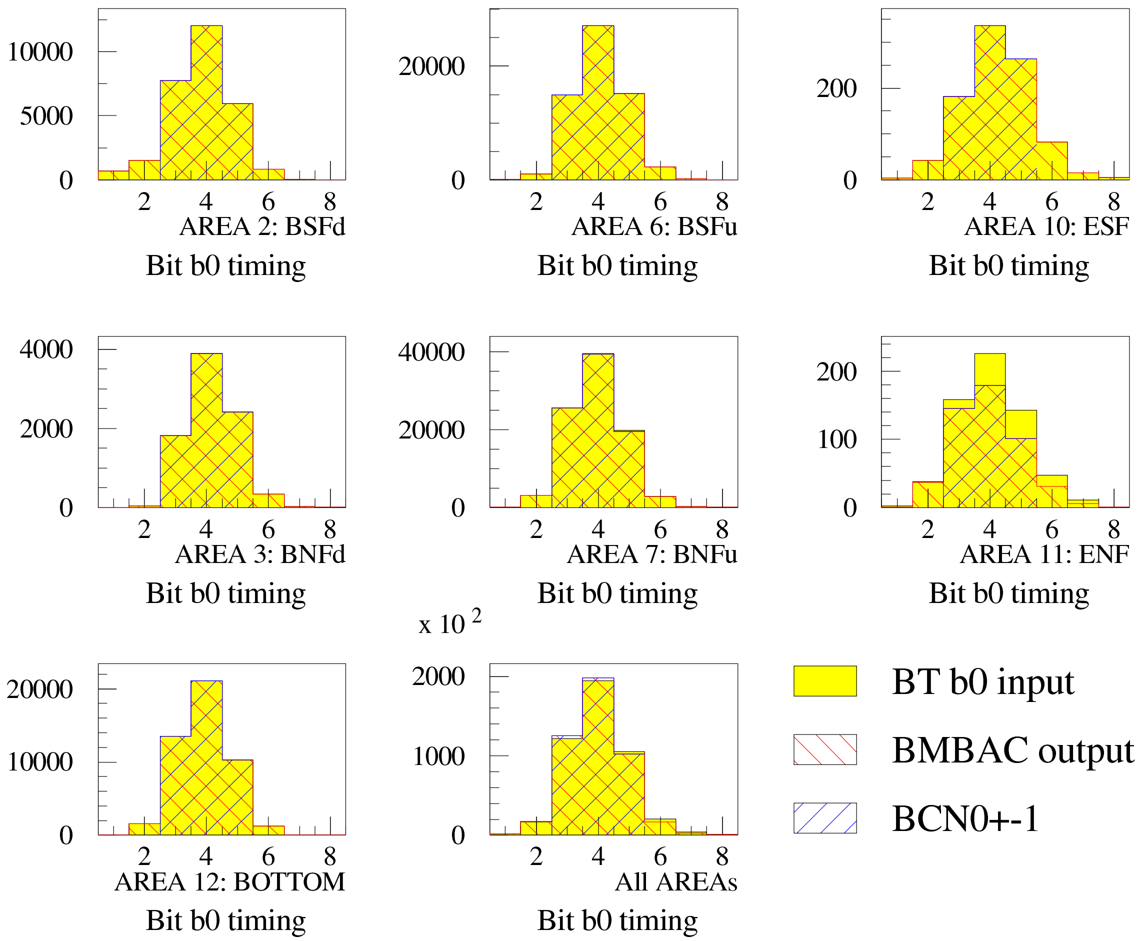
- calculated w.r.t. the FLT61 (BCAL-COSMIC-x*gTRK)
- trigger efficiency as a function of the muon momentum is plotted

Drift Time Problem: Wire Tower

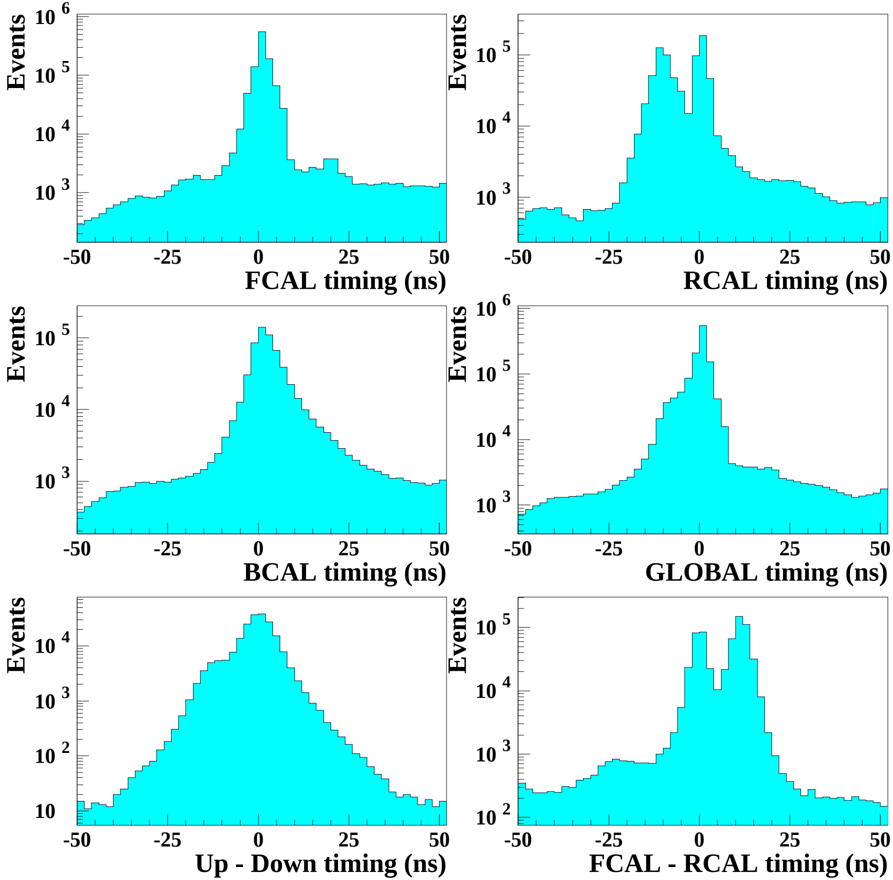


- amplitude discrimination in comparators (programmable threshold)
- digital signal is extended for 3 consecutive HERA clocks to reduce jitter effect
- $N_{layers}, N_{chambers}$ are calculated for each clock

BAC Trigger timings for selected Areas

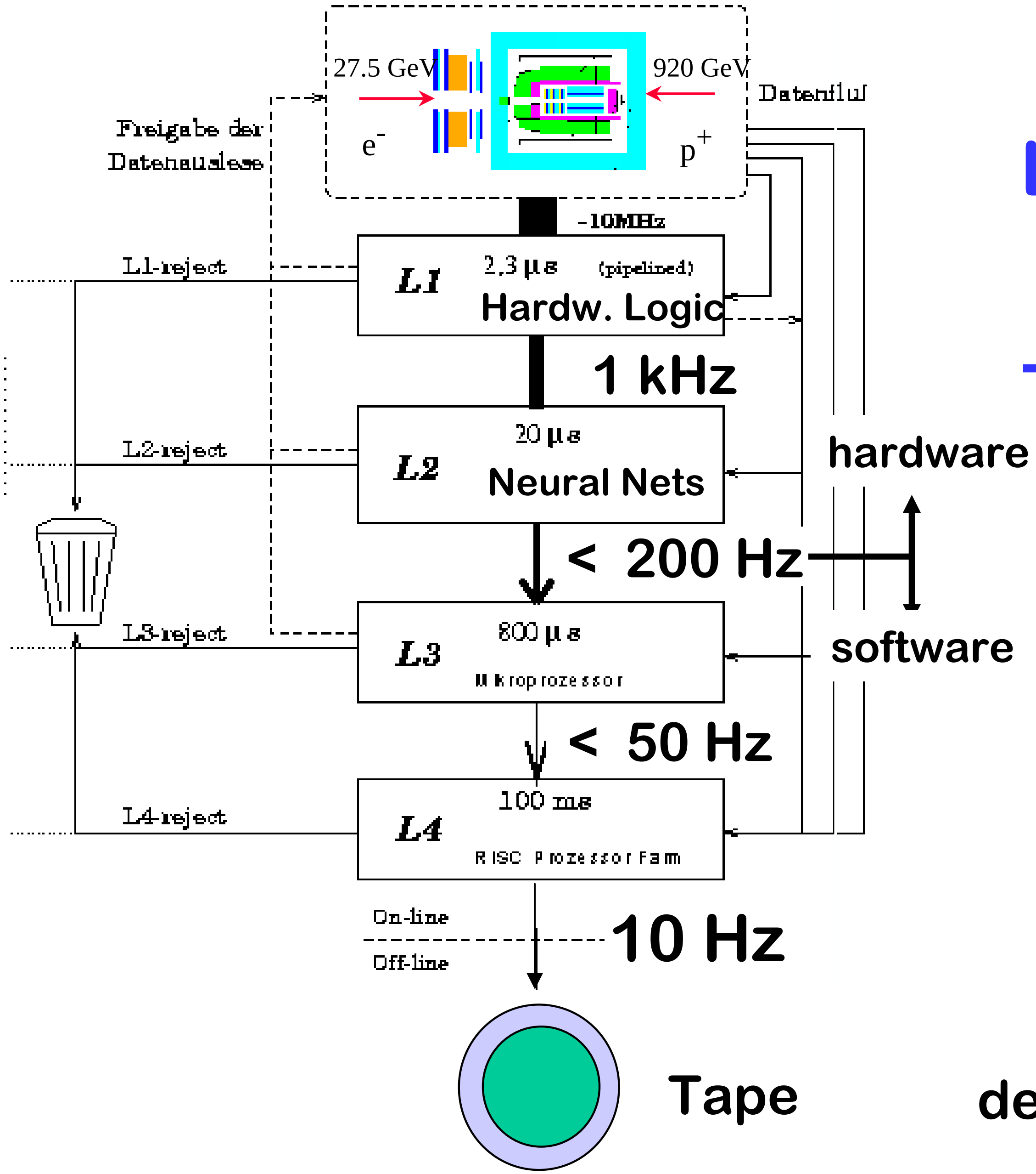


- Timing distribution of BAC muon trigger
- Each muon bit is extended for 2 consecutive HERA clocks
- Some irreducible jitter due to the drift time in gas ($\sim 100\,ns/1\,cm$)



Events
FCAL timing (ns)
RCAL timing (ns)
BCAL timing (ns)
GLOBAL timing (ns)
Up - Down timing (ns)
FCAL - RCAL timing (ns)
-50
-25
0
25
50

The H1 Trigger System



L1 Calorimeter, Tracker, Muon Chamb. (all pipelined)

Global Trigger
Track refinement

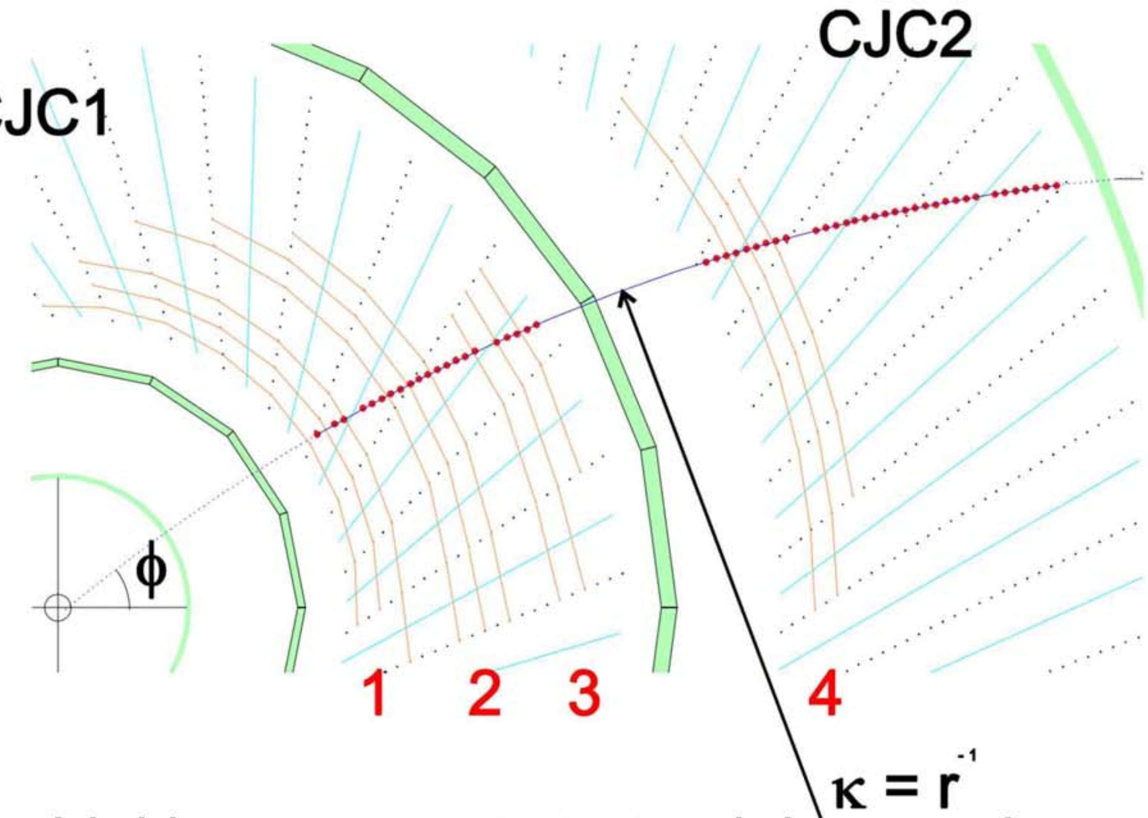
Matching Tracker/Calo

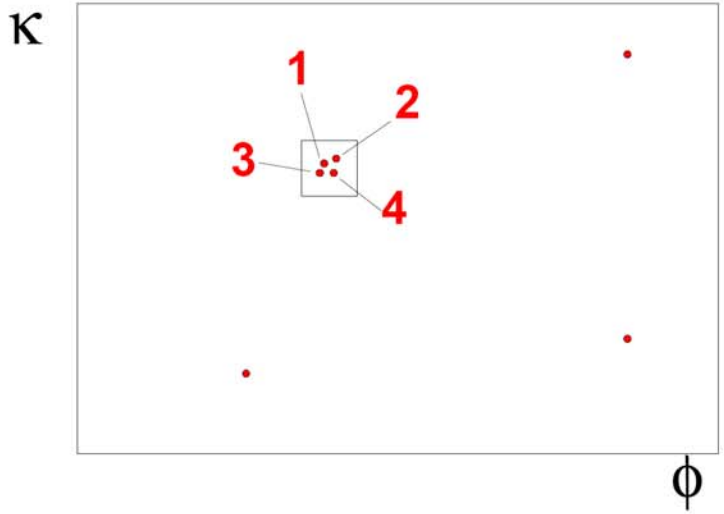
PC farm,
full reconstruction

dead time

The Fast Track Trigger (FTT) of H1

- FTT is based on selected wires of central jet chamber
- 4 groups of 3 wire layer each
- Each group provides a vertex constrained track segment, characterized by κ and ϕ





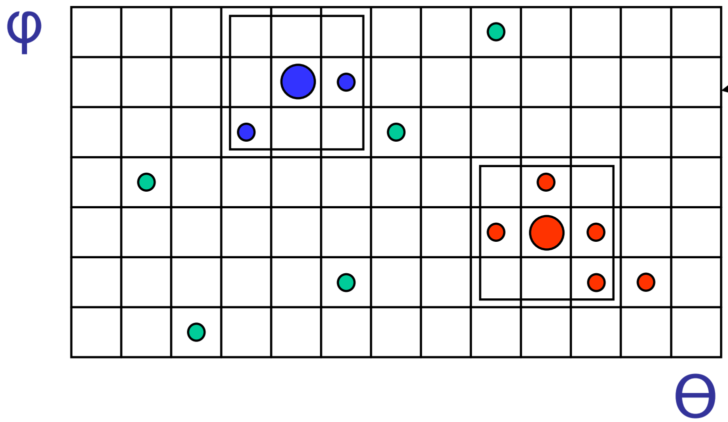
- Linking segments to track in κ–ϕ plane by searching clusters
- Fit track parameters =>
  - Search for particle resonances
  - Provide trigger decision for L1/L2/L3

Principle of the Jet Trigger

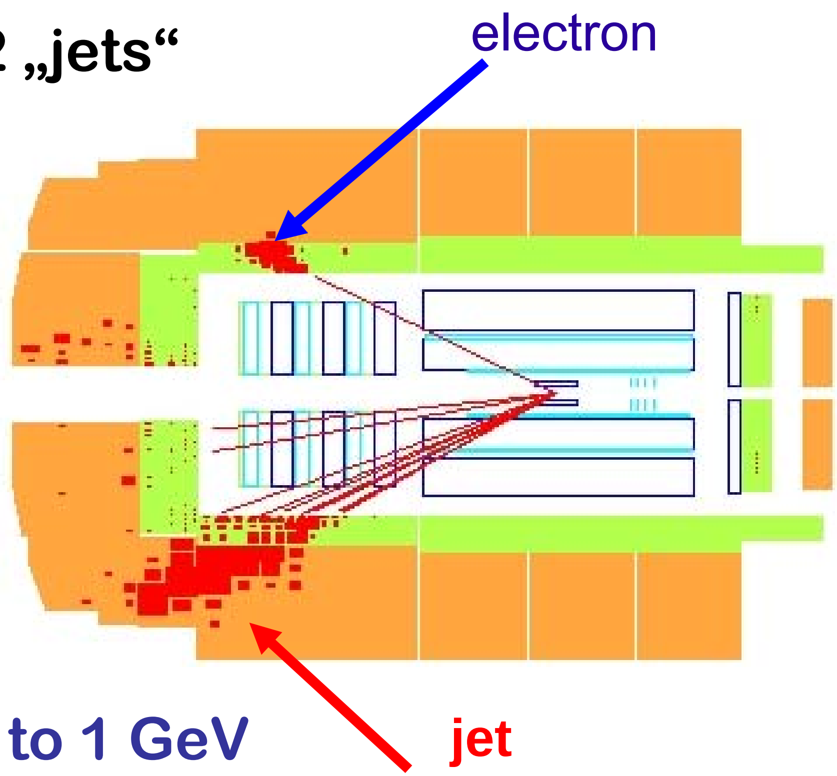
A calorimeter trigger implementing a real-time jet cluster algorithm within 800 ns (L1 latency 2.3 μs)

Why?

Avoid summing noise: trigger on low energy electrons and jets



here: 2 „jets" found

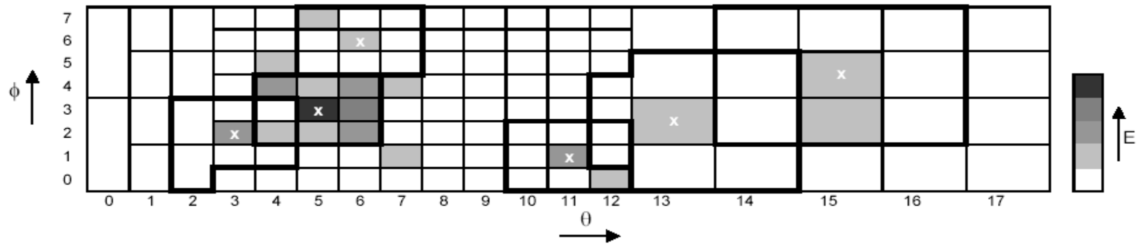


Jet variables extracted:
Energy, topology (θ, φ)

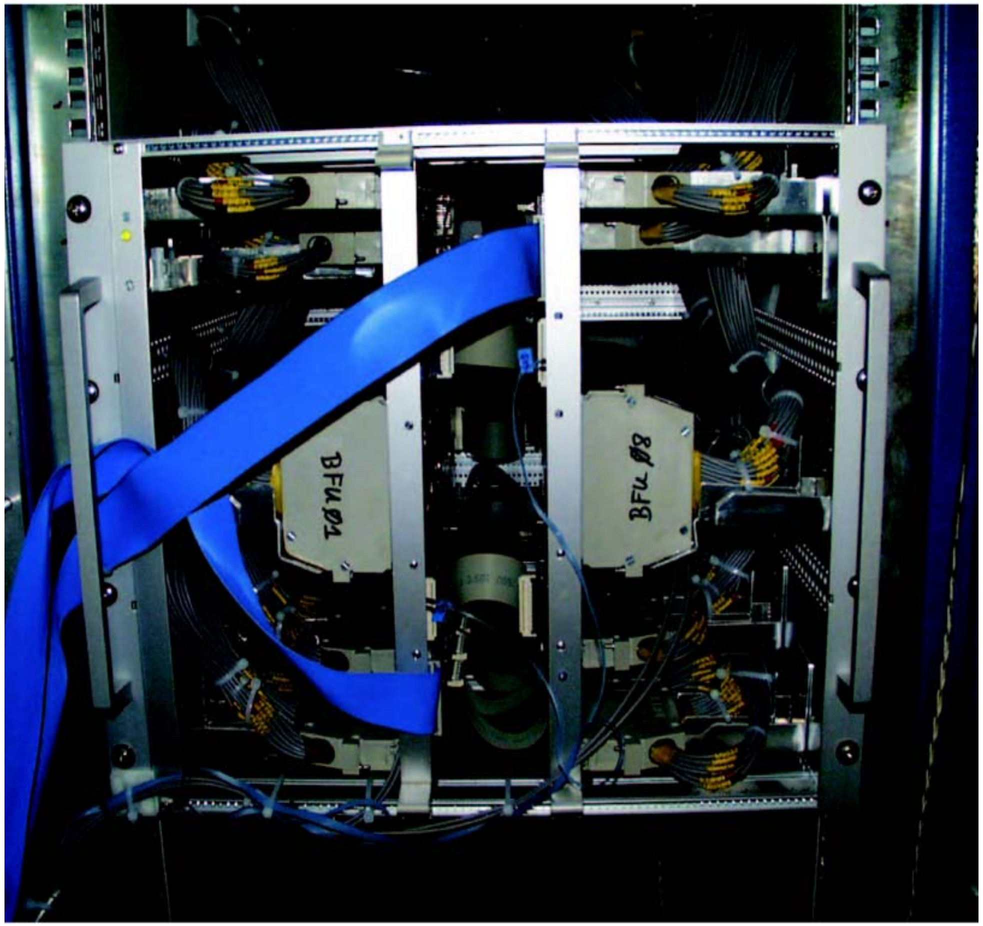
Major achievement
Reduce trigger thresholds from 5 GeV to 1 GeV

Parallel Cluster Algorithm (Jet Finder)

- Find local energy maxima:
  each tower compares its energy with all its neighbors ("jet centers")



- For each jet center:
  sum immediate neighbors ("jet energy")



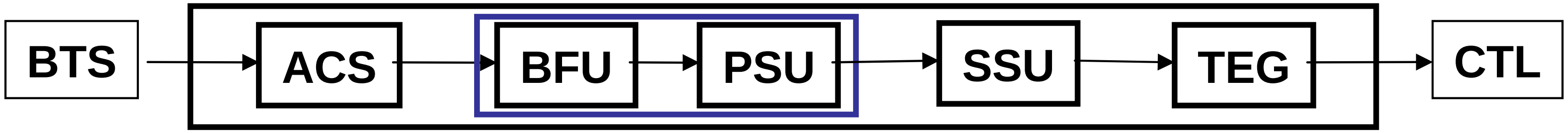
Hardware:

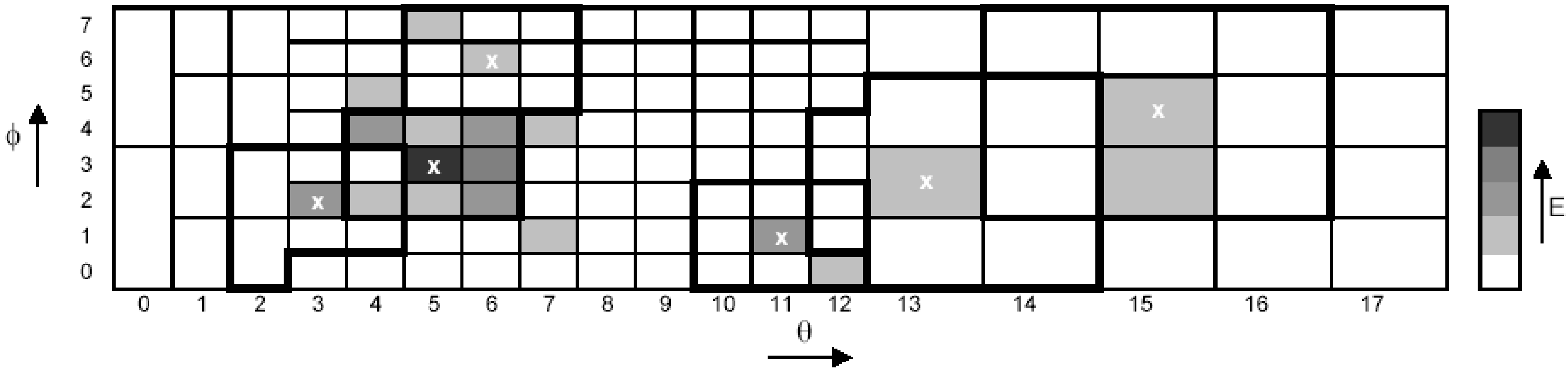
BFU – Bump Finder Unit:

- 2 boards
- 32 Altera FPGAs x 500k gates
- Input 440 towers, output 116 jets
- Output rate 1.2 GB/s

- Latency 100 ns

Jet Finder Algorithm within 800 ns



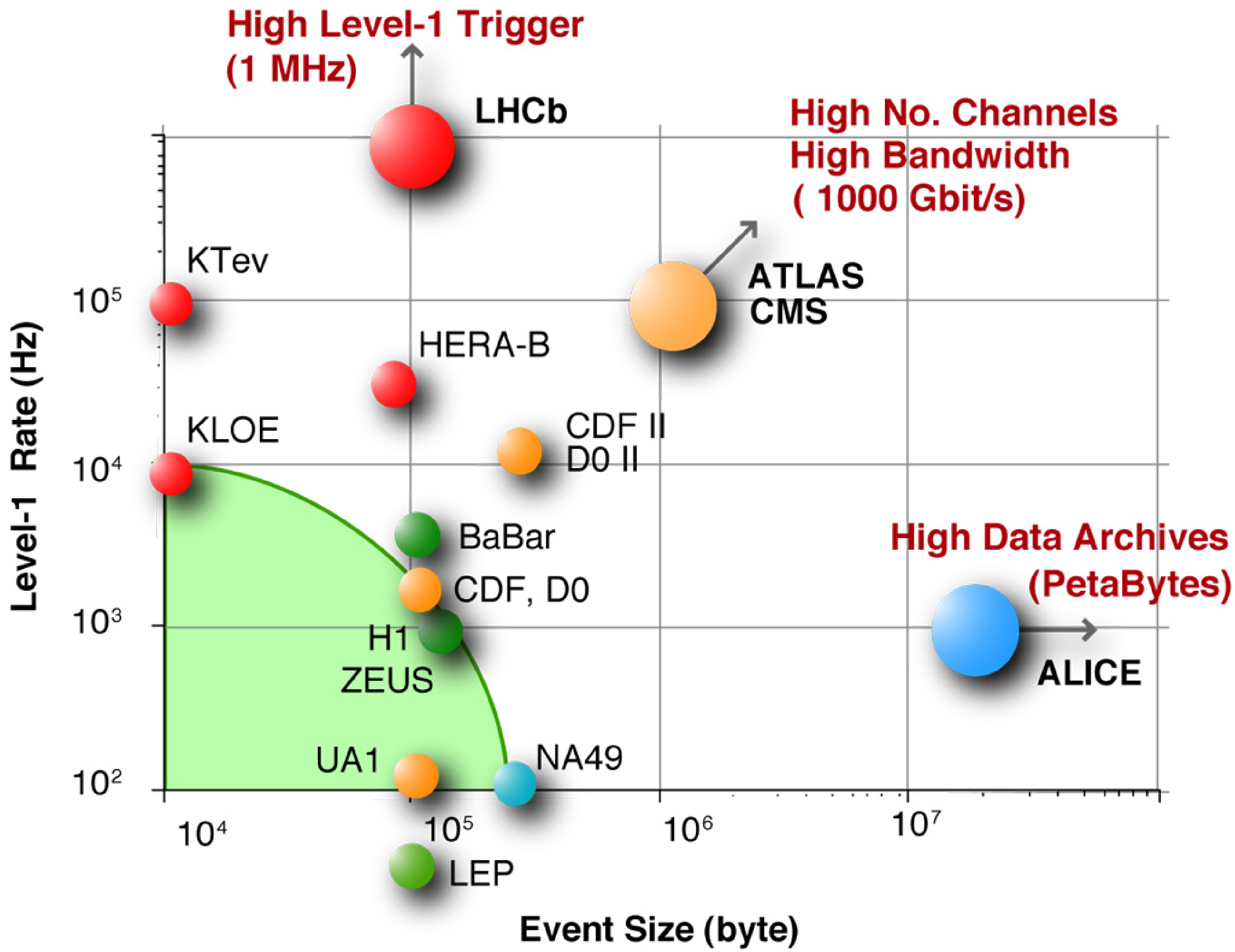


- **Adc Calculation Storage:** digitize and sum towers - cut coherent noise
- **Bump Finder Unit:** cluster algorithm (find jets) within 100ns!
- **Primary Sorting Unit:** sort 16 „jets“ in decreasing energy
- **Secondary Sorting Unit:**

→ leading jets are physics, „lower“ jets are noise

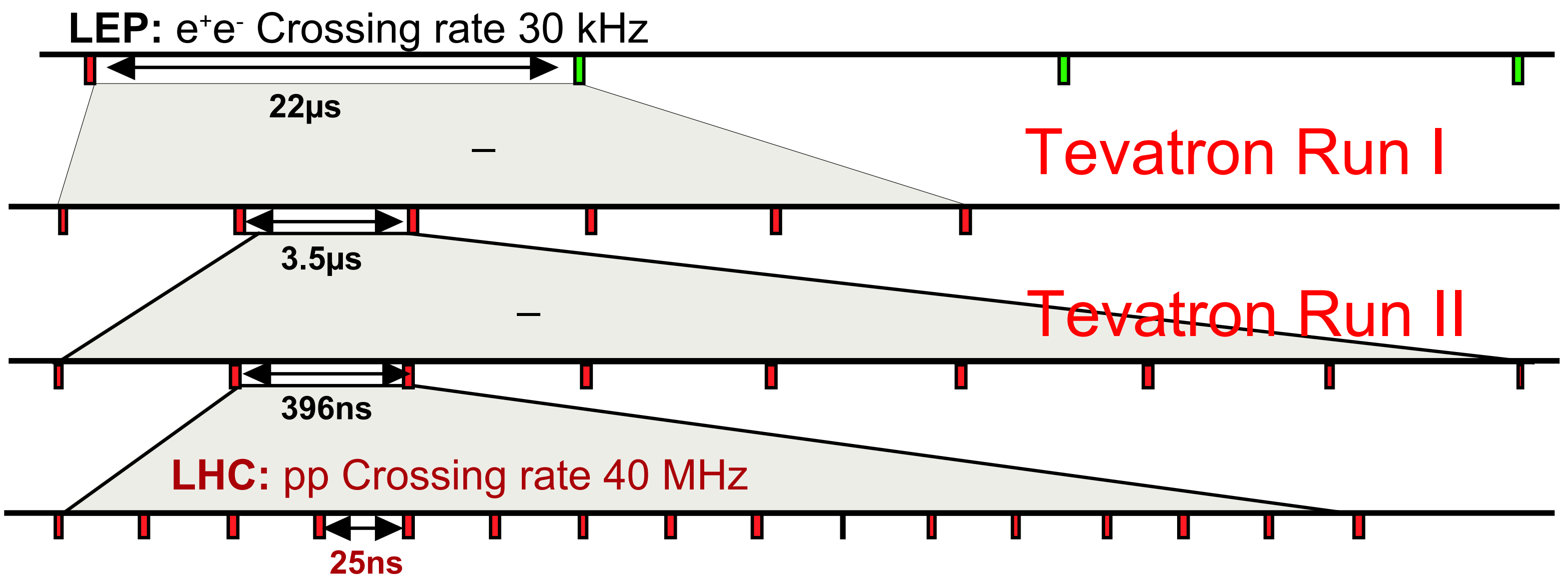
- **Trigger Element Generator:** apply topological conditions on individual jets, using energy and location in Θ and φ

Trigger/DAQ systems: present & future



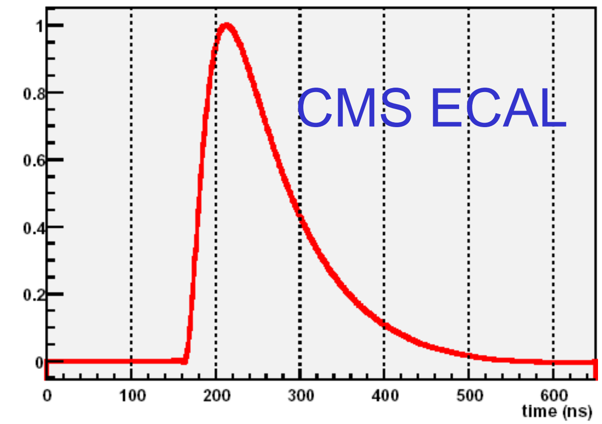
Beam crossings: LEP, Tevatron & LHC

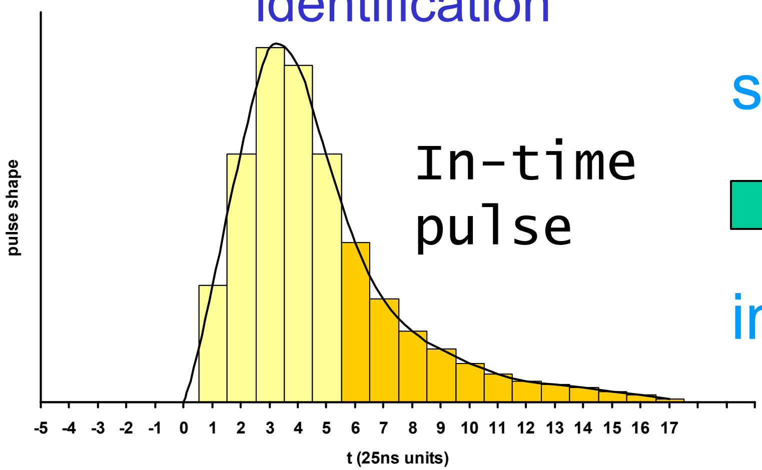
- LHC will have ~3600 bunches
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns



Pile-up

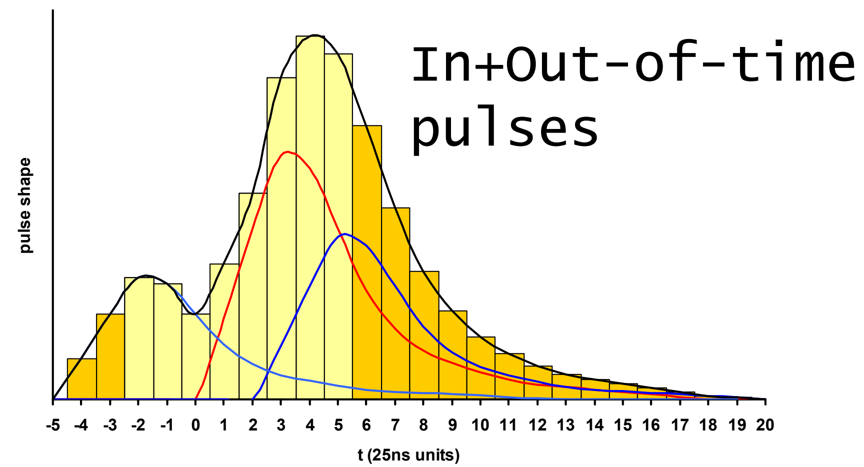
- “In-time” pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - “Out-of-time” pile-up: left-over signals from interactions in previous crossings
  - Need “bunch-crossing identification”





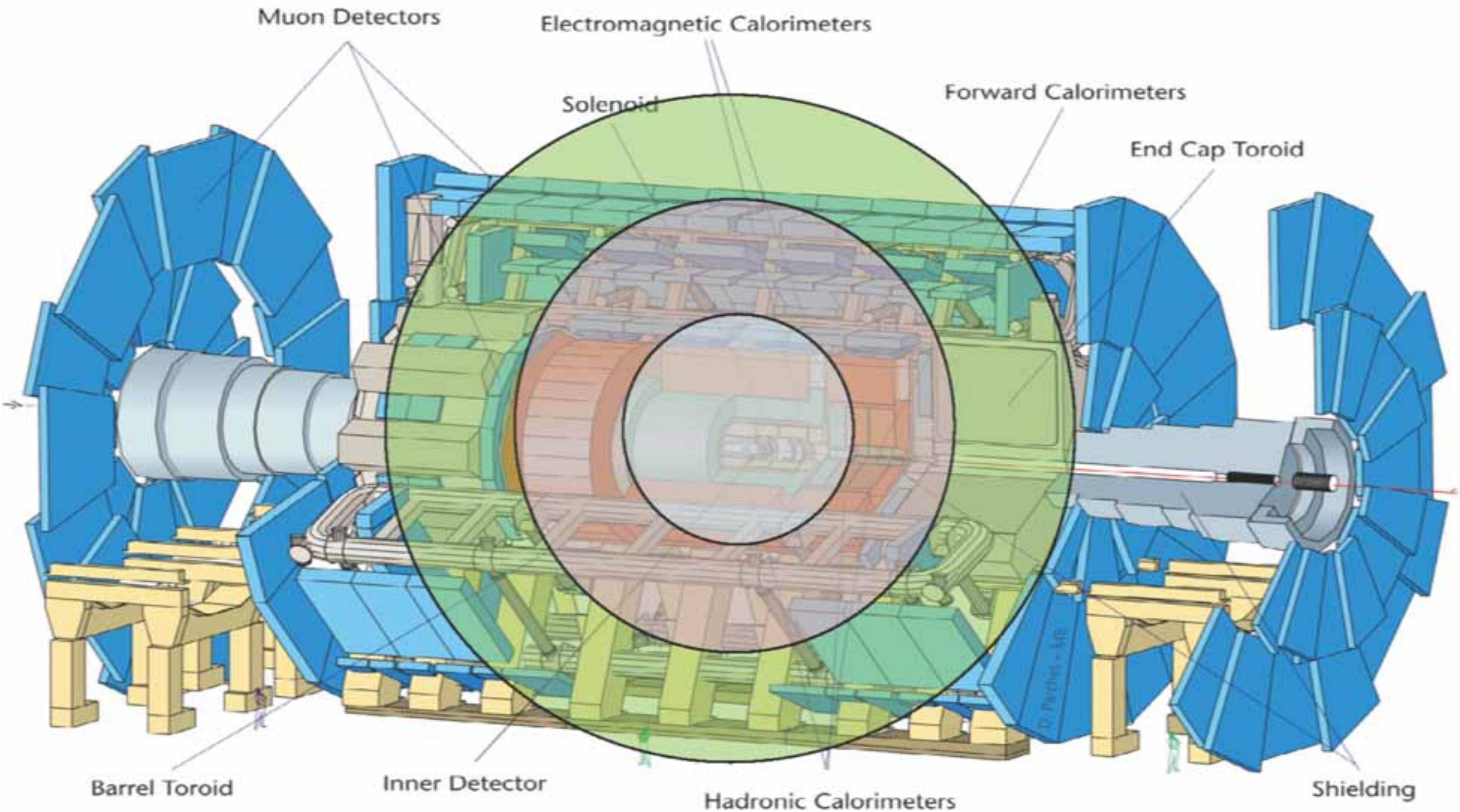
super–

impose



Challenges: Time of Flight

c = 30 cm/ns → in 25 ns, s = 7.5 m

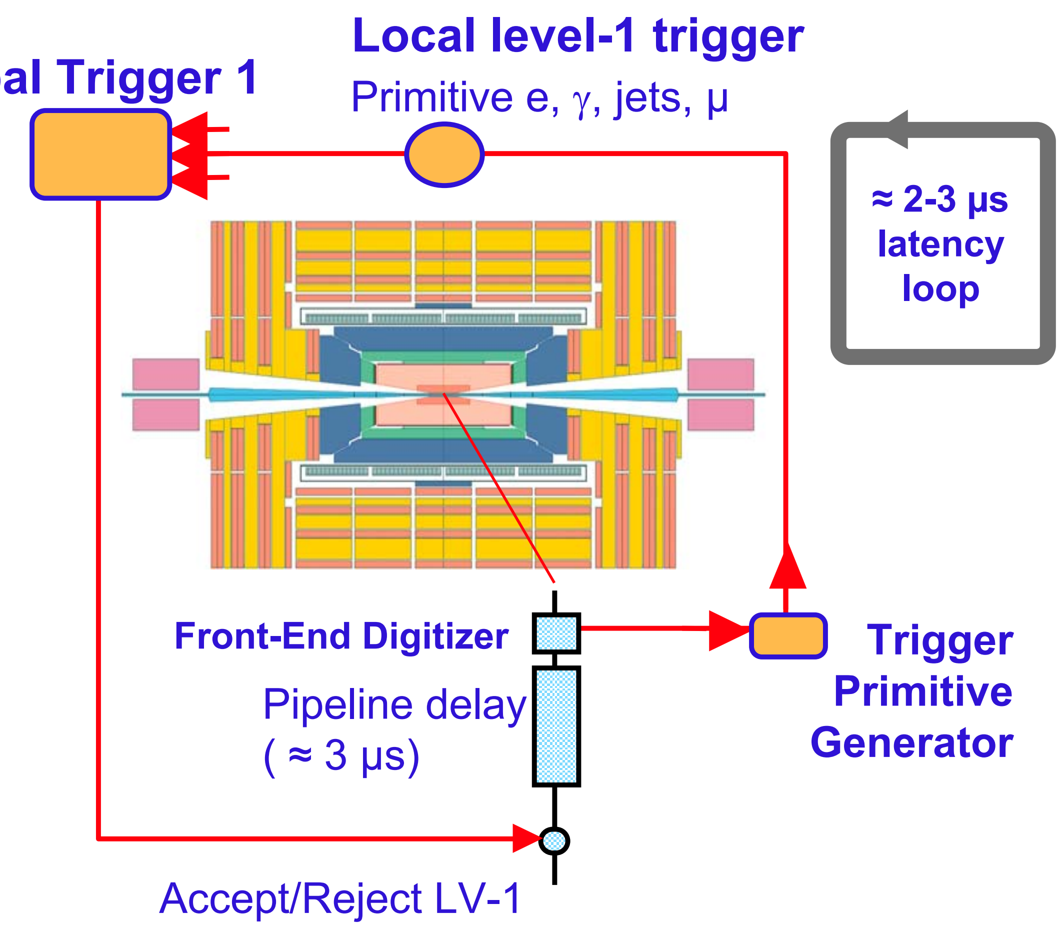


Level-1 trigger algorithms

- 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
    - $H(120\ GeV) \rightarrow \gamma\gamma$: $P_T(\gamma)$ ~ 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)

Level-1 Trigger: decision loop

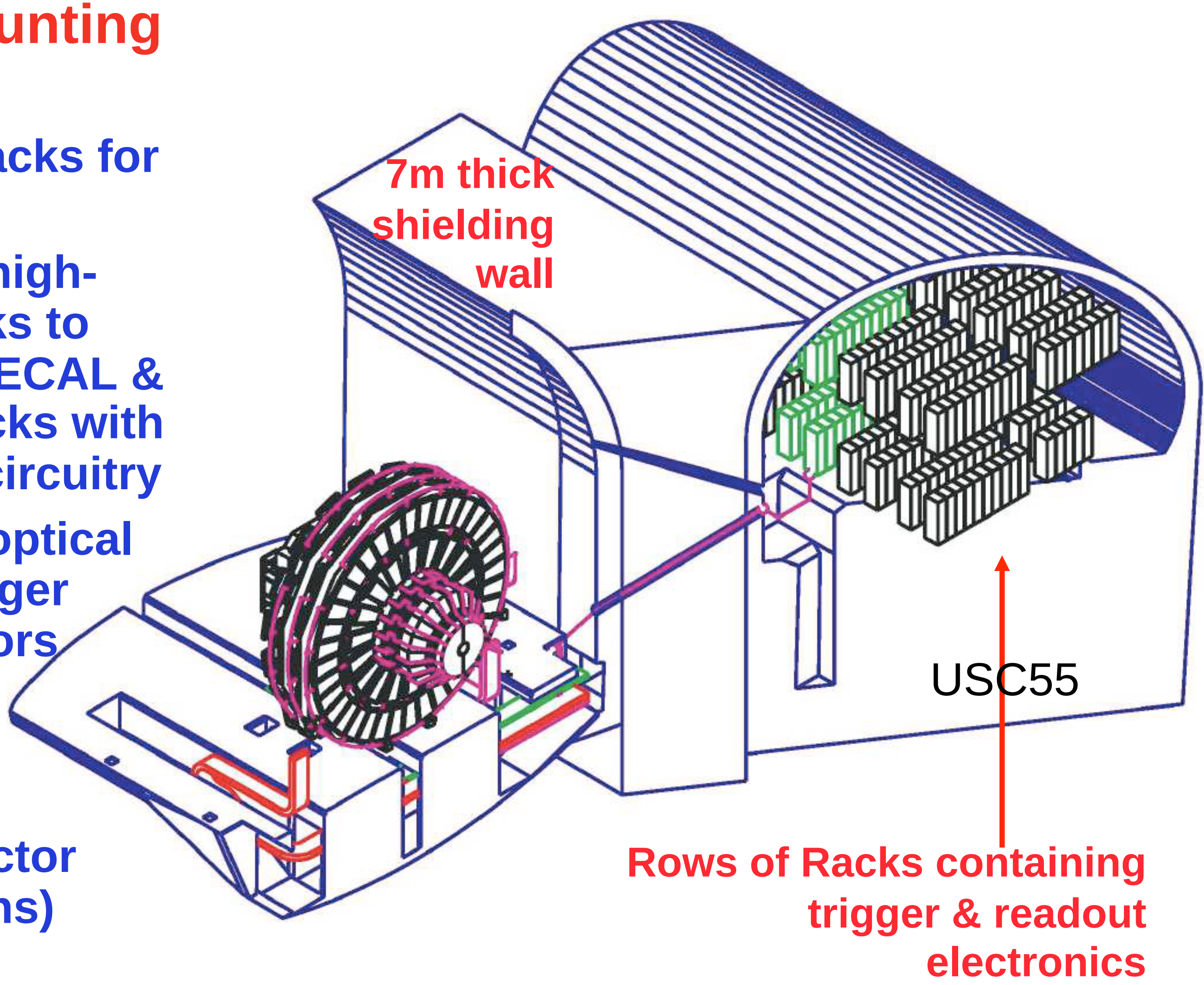
- Synchronous 40 MHz digital system
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- At Lvl-1: process only calo+μ info



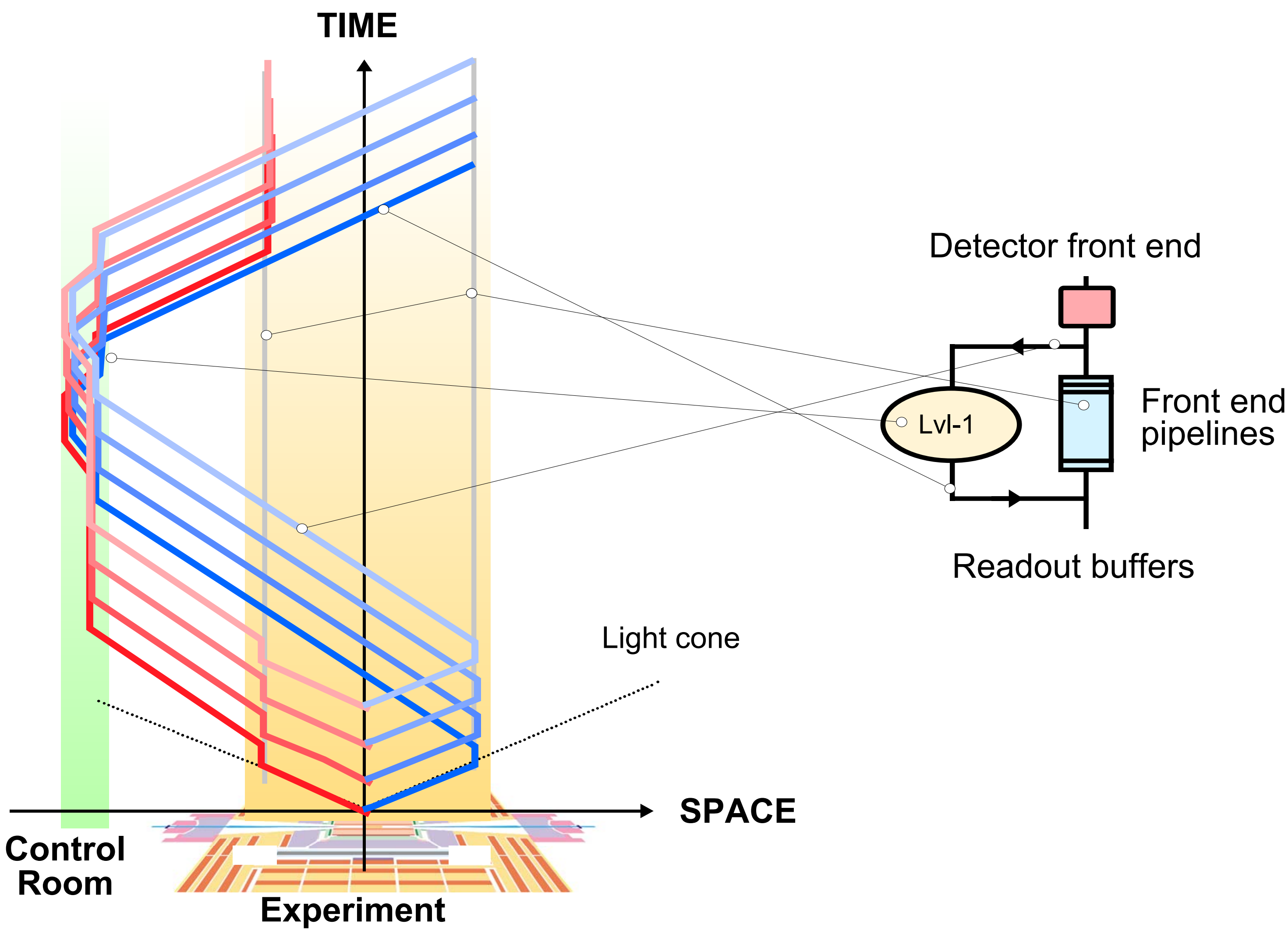
L1 Trigger Locations

Underground Counting Room

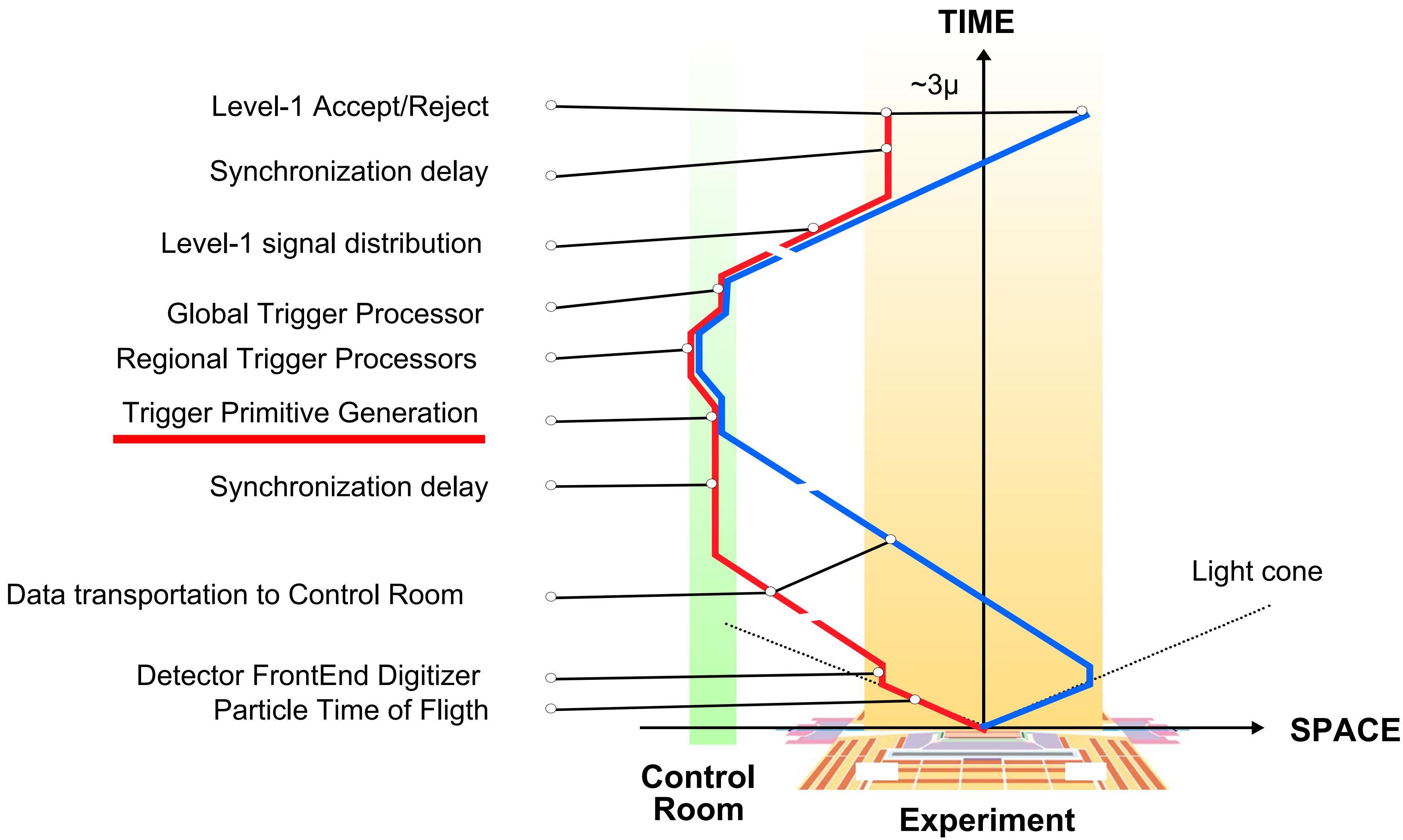
- Central rows of racks for trigger
- Connections via high-speed copper links to adjacent rows of ECAL & HCAL readout racks with trigger primitive circuitry
- Connections via optical fiber to muon trigger primitive generators on the detector
- Optical fibers connected via "tunnels" to detector (~90m fiber lengths)



Signaling and pipelining

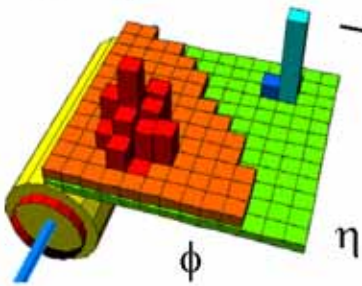


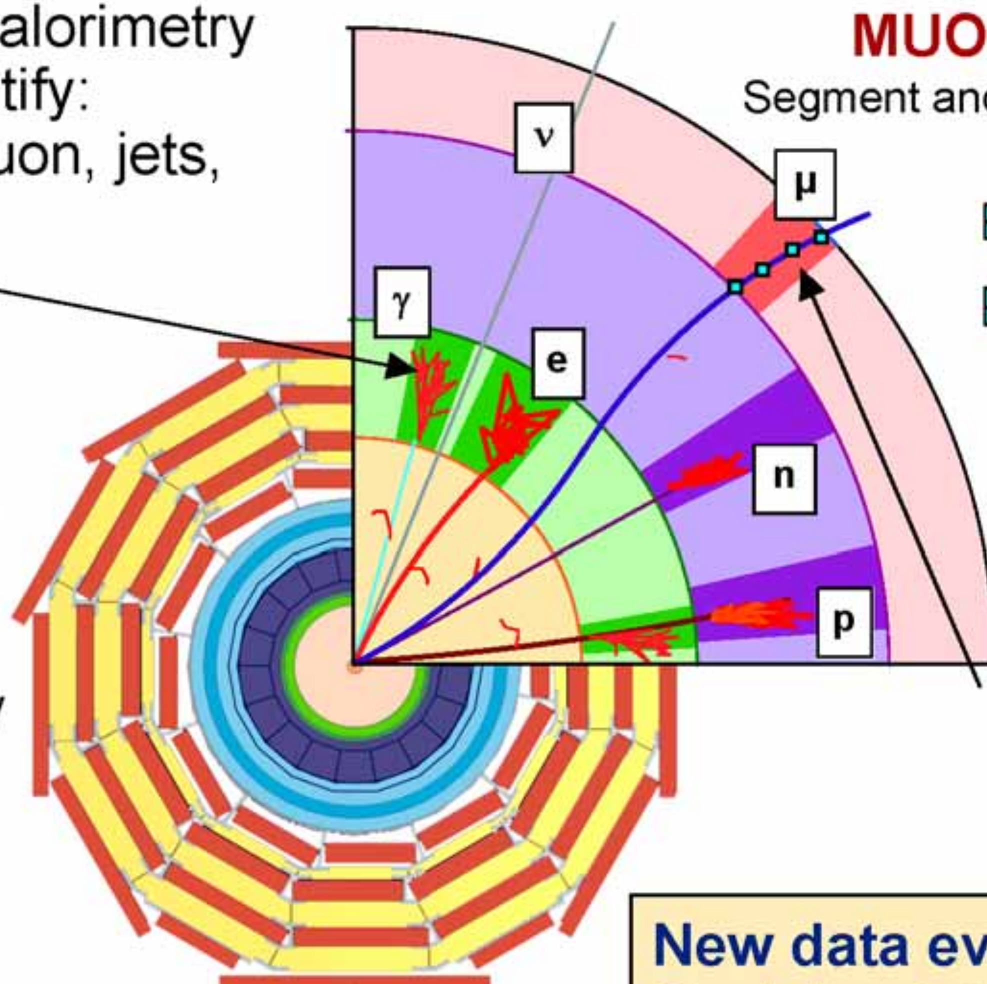
Signaling and pipelining (II)



ATLAS & CMS Trigger Data

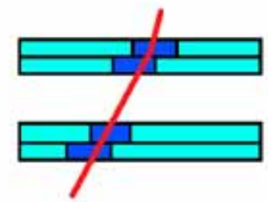
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T





MUON System

Segment and track finding



CALORIMETERs

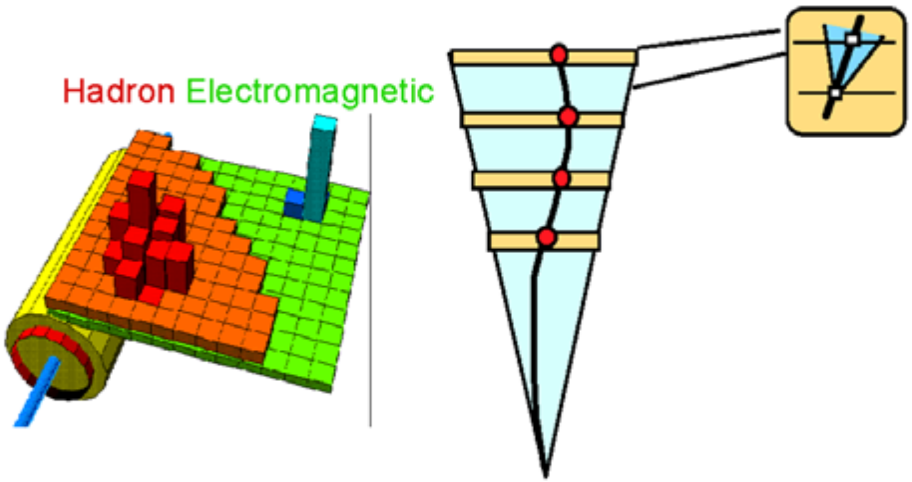
Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ μs

ATLAS & CMS Level 1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

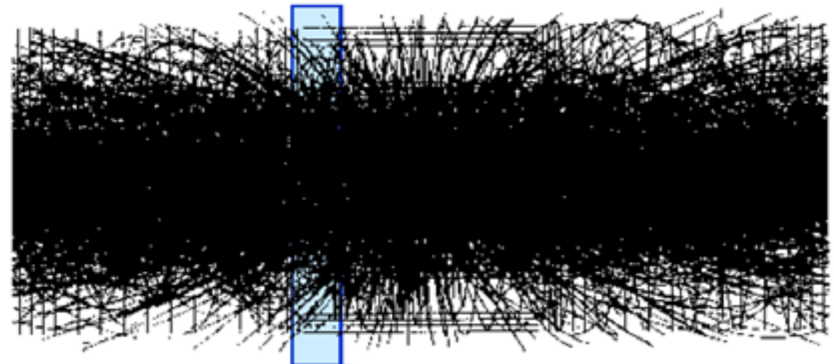
- **Pattern recognition much faster/easier**



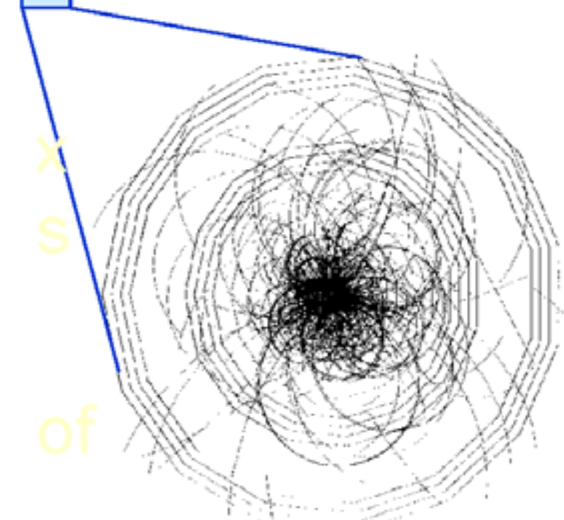
Simple Algorithms

Small amounts of data

- **Compare to tracker info**



Complex Algorithms



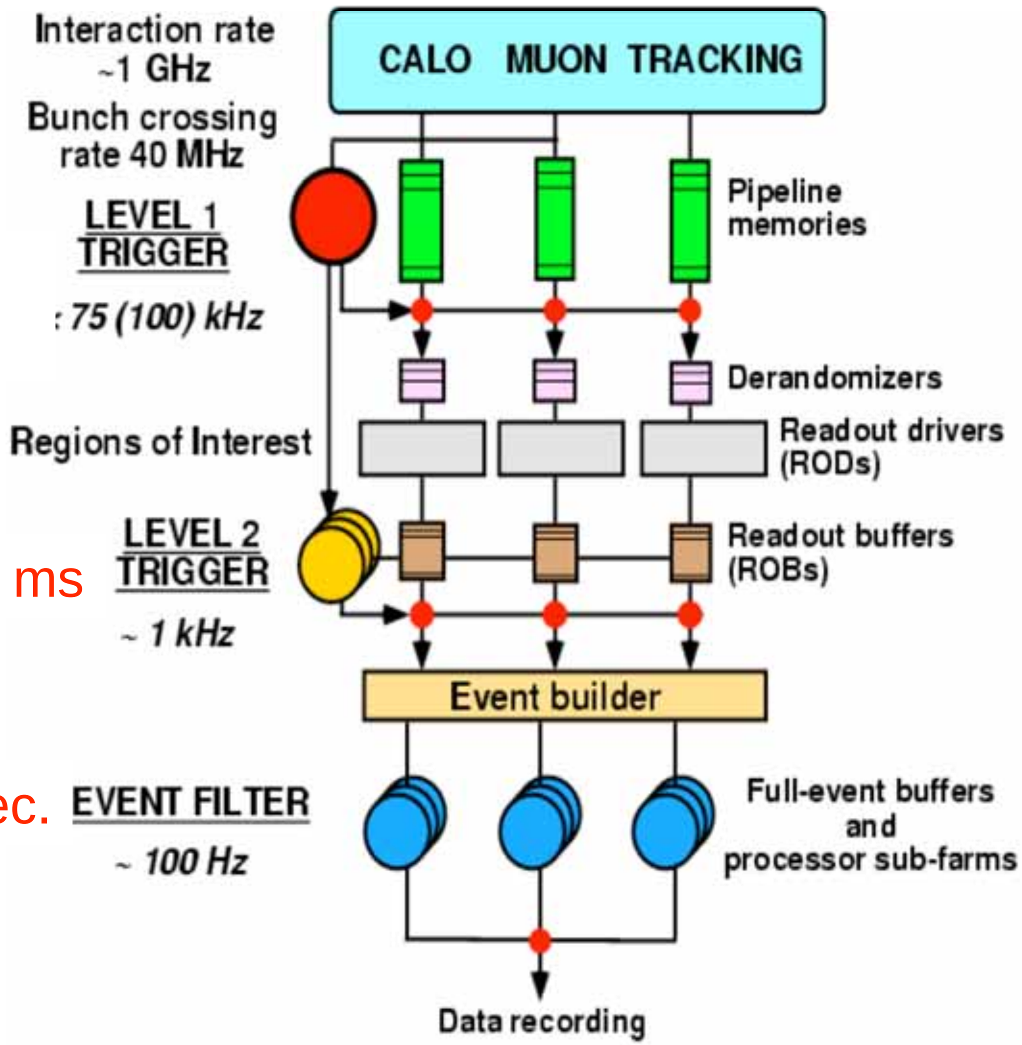
Huge amounts of data

ATLAS Three Level Trigger Architecture

2.5 µs

~10 ms

~ sec.



- **LVL1 decision** made with **calorimeter** data with coarse granularity and **muon trigger chambers** data.
  - Buffering on detector
- **LVL2 uses Region of Interest data** (ca. 2%) with full granularity and combines information from all detectors; performs fast rejection.
  - Buffering in ROBs
- **EventFilter** refines the selection, can perform **event reconstruction** at full granularity using latest alignment and calibration data.
  - Buffering in EB & EF

RoI Mechanism

LVL1 triggers on high p_T objects

- **Calorimeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

LVL2 uses Regions of Interest as identified by Level-1

- Local data reconstruction, analysis, and sub-detector matching of RoI data

The total amount of RoI data is minimal

- ~2% of the Level-1 throughput but it has to be extracted from the rest at 75 kHz