Metody eksperymentalne w fizyce wysokich energii

prof. dr hab. A.F.Żarnecki
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład X

- Systemy wyzwalania zbierania danych

Zegar wiązki

Gdy mówimy o elektronice odczytowej detektora i o układach wyzwalania zbierania danych kluczowe znaczenia ma czas.

Tym co narzuca wymagania dotyczące szybkości odczytu i zbierania danych jest częstość rejestrowanych zderzeń cząstek.

Częstość przecięć - "zegar" wiązki, wynika z konstrukcji maszyny.

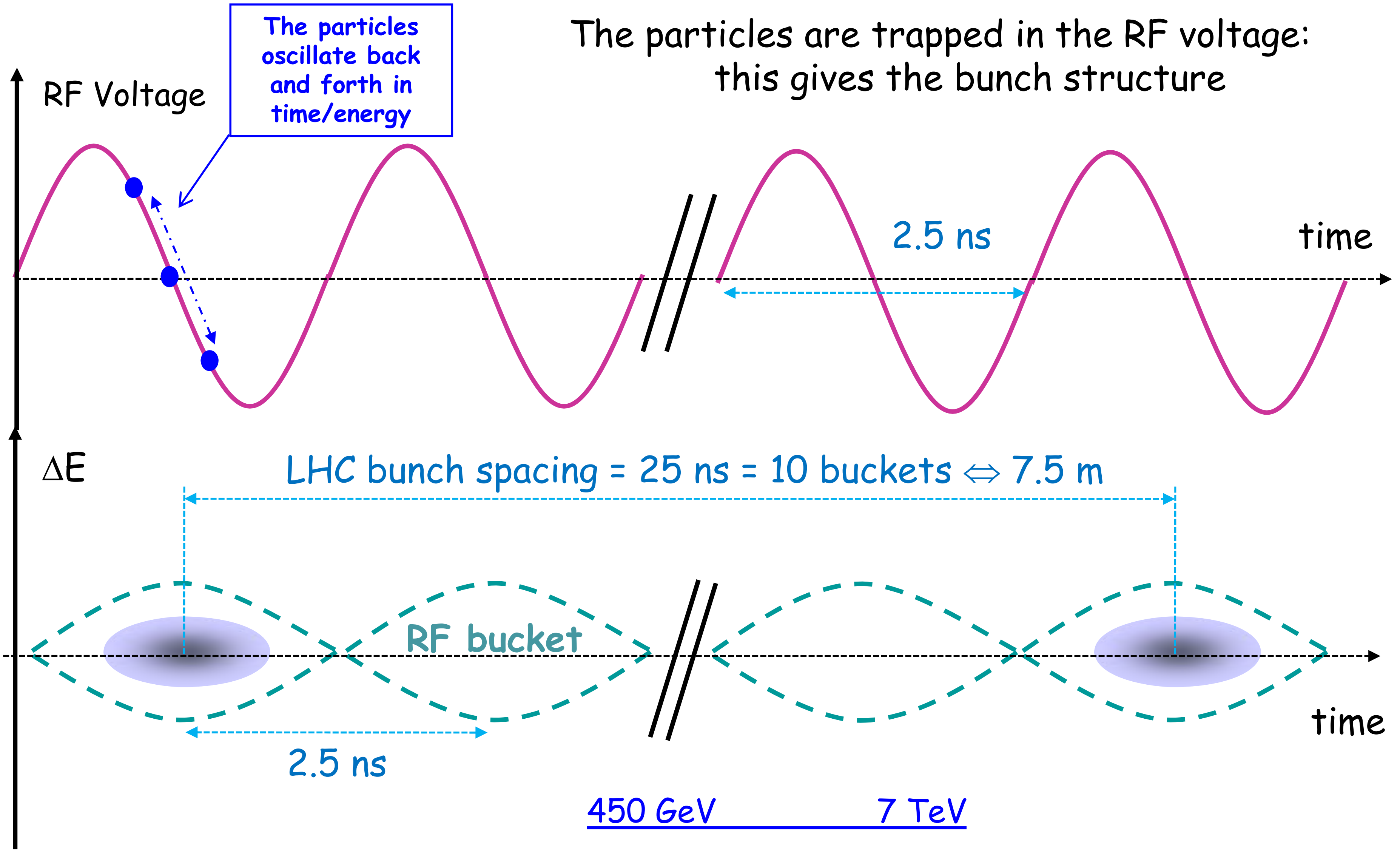
Częstość zdarzeń zależy także od świetlności i przekroju czynnego.

W eksperymentach przed LHC częstość zdarzeń << częstość przecięć.

Ale w każdym przecięciu może potencjalnie nastąpić zderzenie - musimy być na to przygotowani, elektronika i układ wyzwalania musi działać z zegarem wiązki...

RF buckets and bunches 400 MHz@LHC

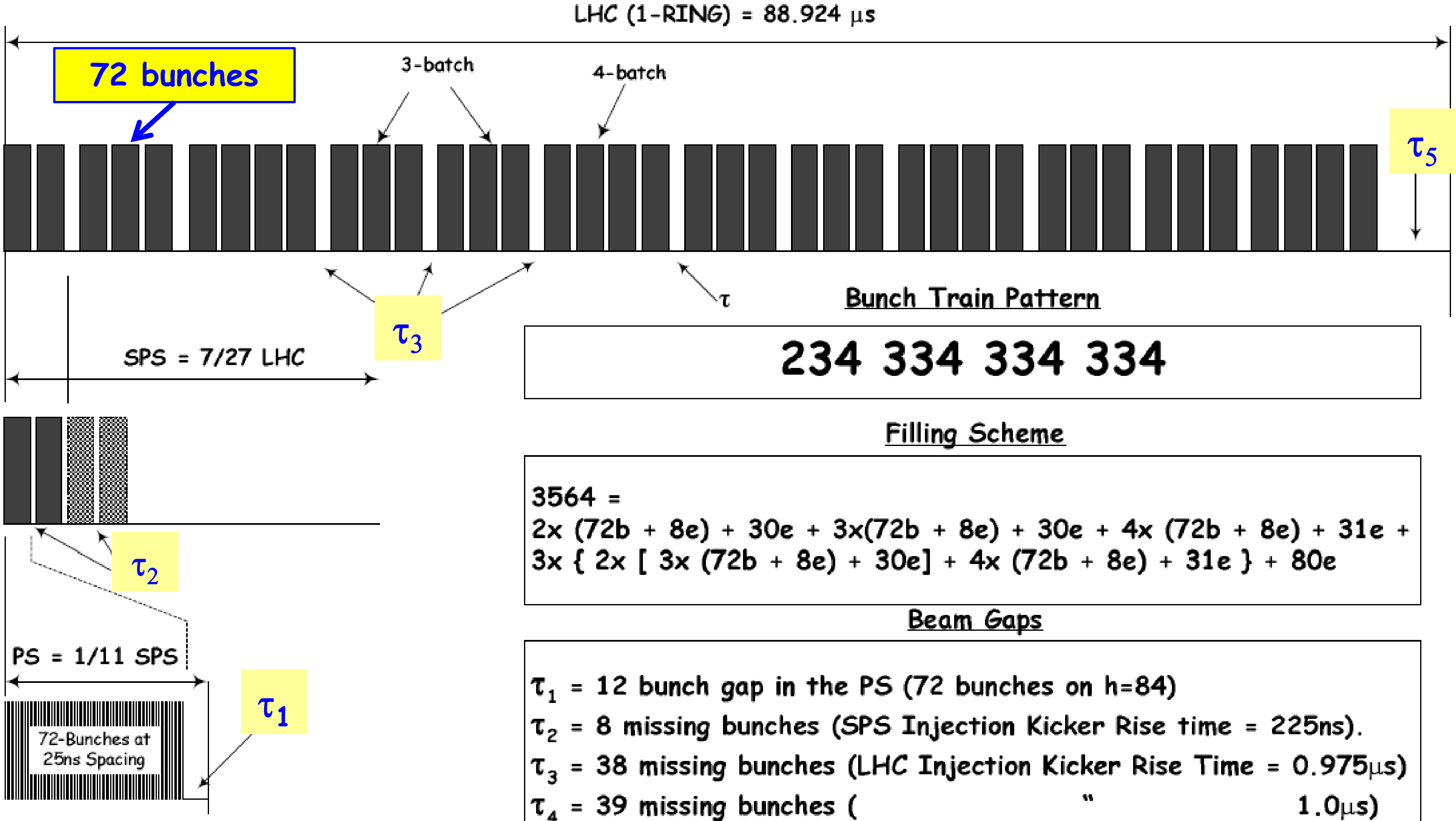
The particles are trapped in the RF voltage:
this gives the bunch structure



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

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).



Bunch Train Pattern

234 334 334 334

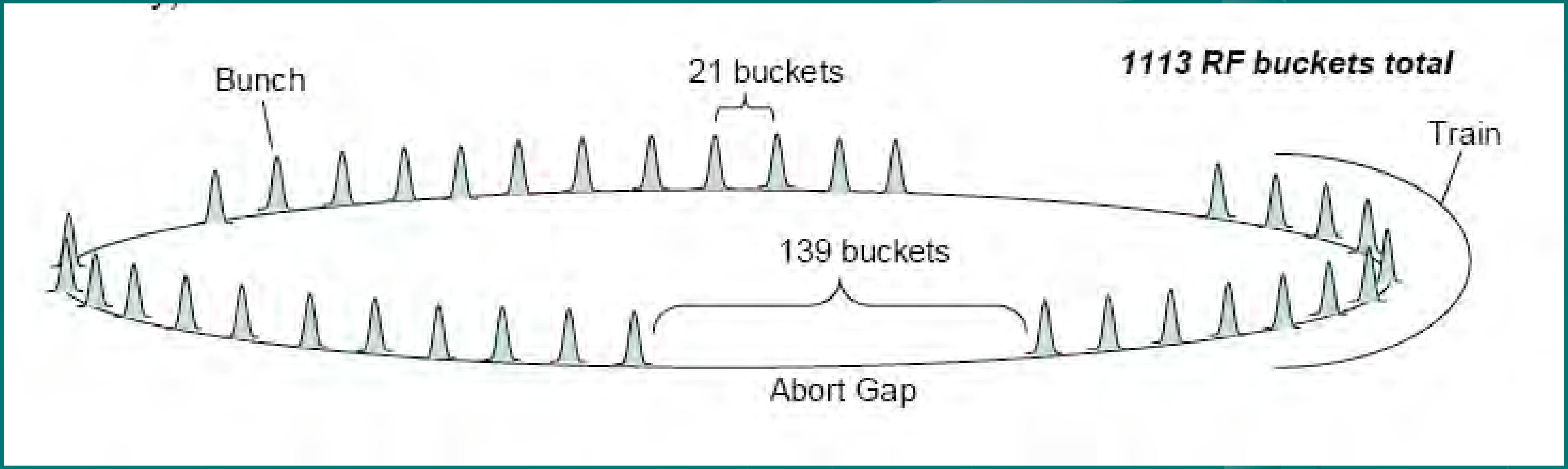
Filling Scheme

3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

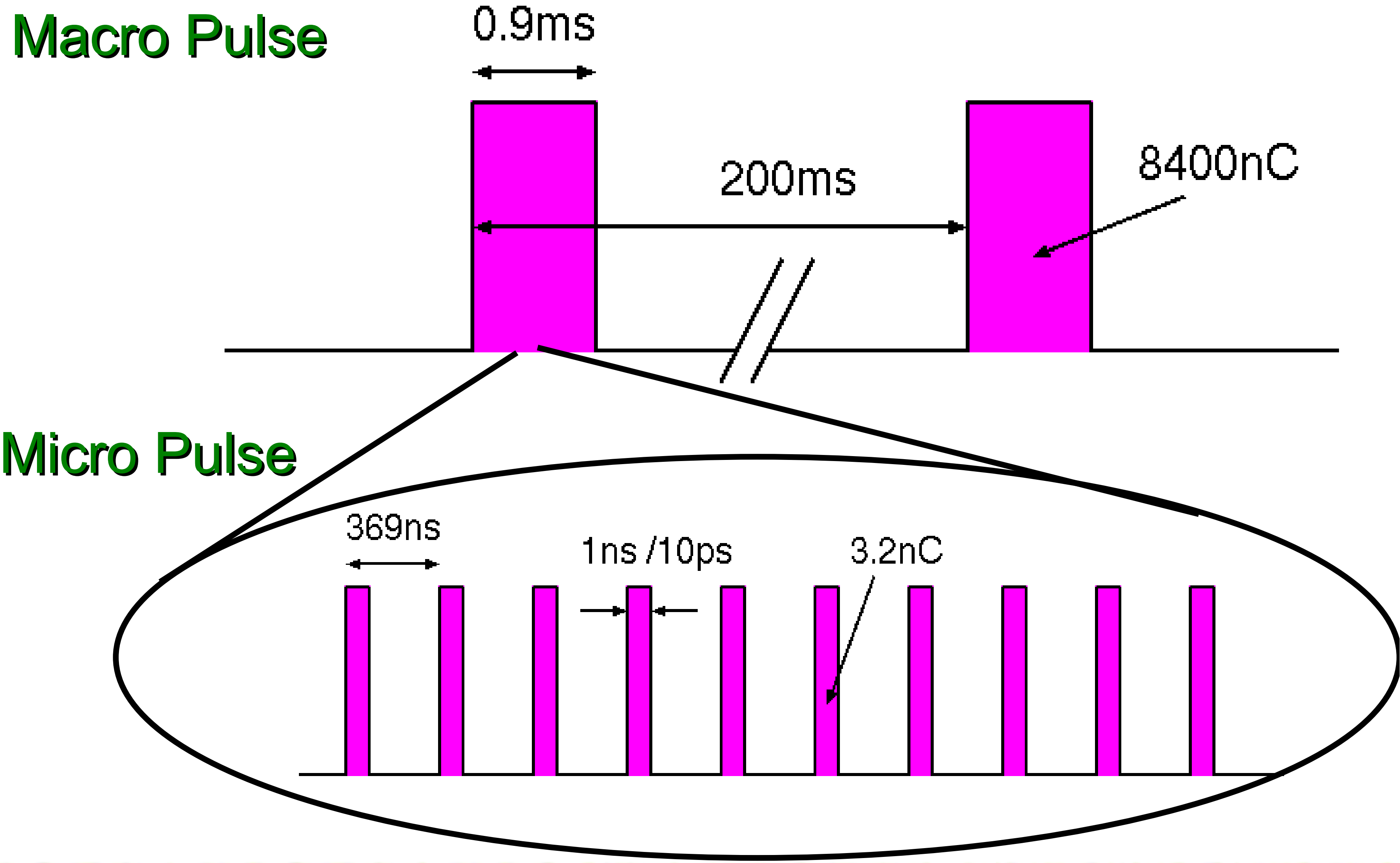
Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs)
τ_4 = 39 missing bunches (" 1.0μs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs)

Tevatron Bunch Structure



Pulse structure

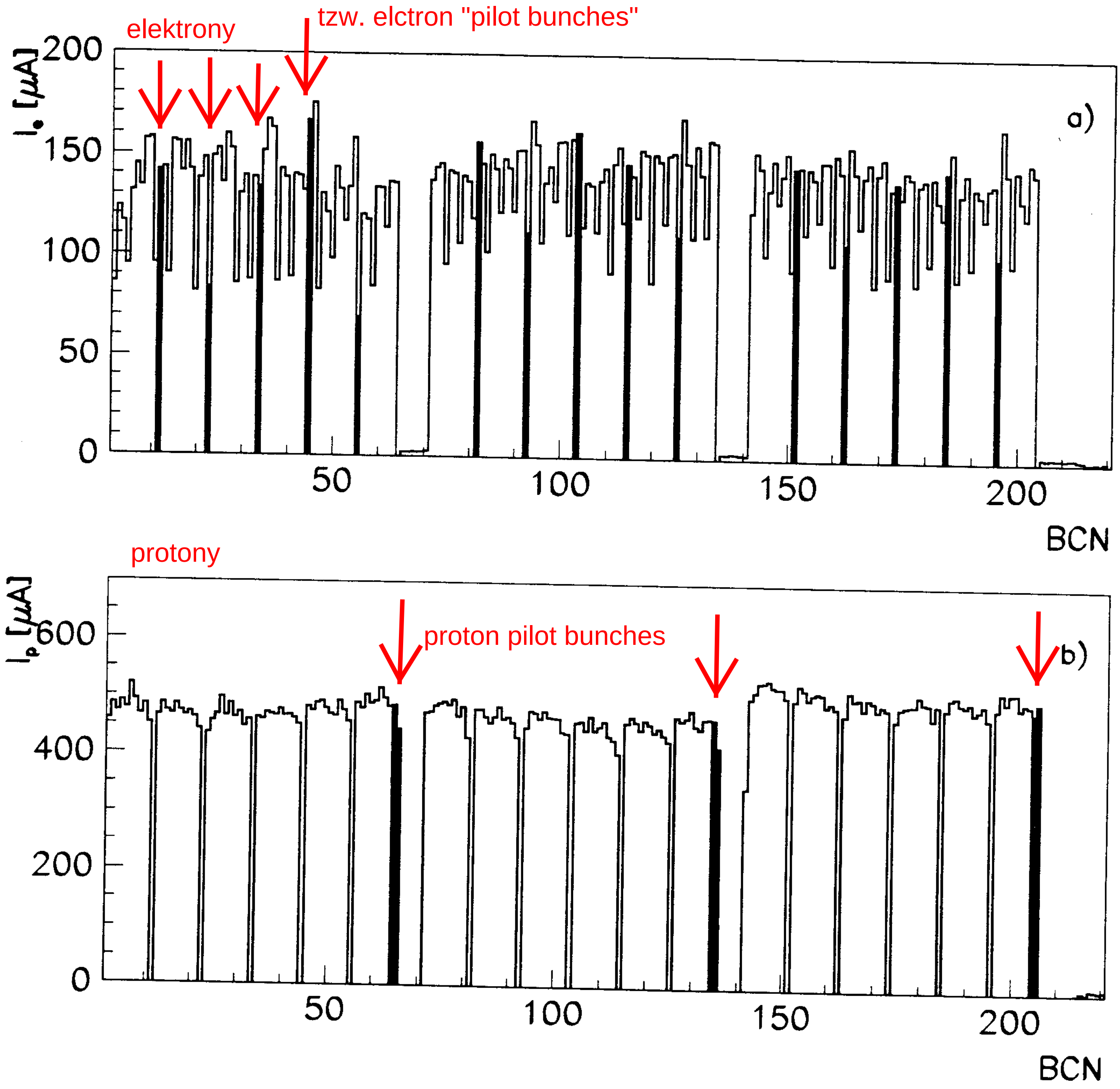


HERA: electron-proton collider at DESY (1992-2007)

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} mA^{-2}cm^{-2}s^{-1}	3.33			4.0	5.0	6.0
Luminosity $\mathcal{L}$/ 10^{31} cm^{-2} 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
50
100
150
200
BCN
a)
protony
I_p [μA]
600
400
200
0
proton pilot bunches
b)
50
100
150
200
BCN

Selekcja przypadków

W każdym eksperymencie (a zwłaszcza przy kolajderach) potrzebujemy jakiś narzędzi do selekcji przypadków.

Każdy pomiar fizyczny/odkrycie oparte jest na starannie wybranej próbce danych. Wiemy dokładnie jakiego typu przypadki badamy...

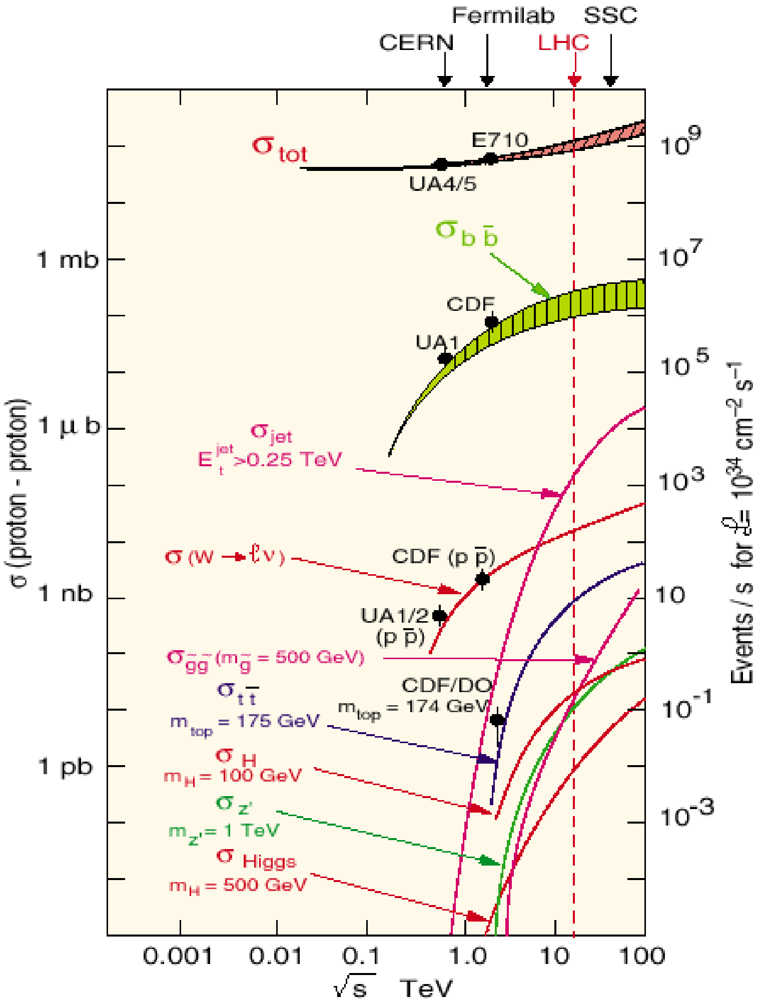
Ostateczna selekcja jest wielokrotnie zmieniana, optymalizowana. Aby nie zabierała zbyt dużo czasu trzeba wcześniej dokonać wstępnej selekcji, która odrzuci niepotrzebne przypadki.

Można sobie wyobrazić eksperyment, który zapisuje wszystkie rejestrowane przypadki i cała selekcja odbywa się off-line.

Jednak w wiekszości przypadków jest to niemożliwe, wstępnej selecji trzeba dokonać w trakcie zbierania danych: on-line.

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
  - $t\bar{t}$ 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...



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

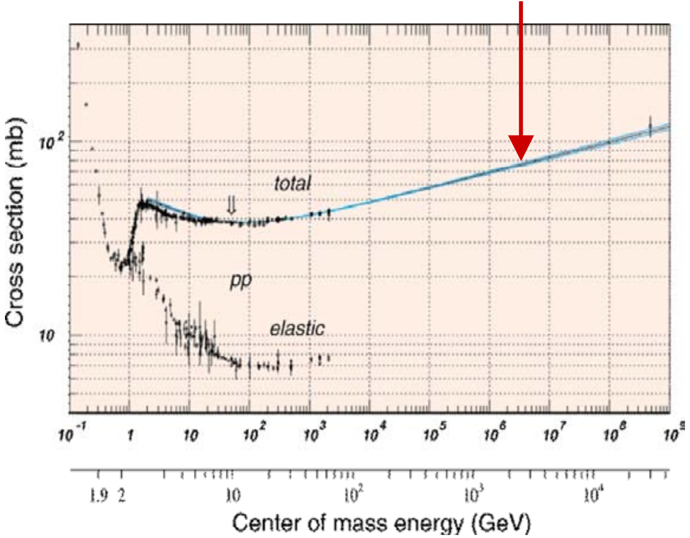
System wyzwalania

Basics

- 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)

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 = 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


σ(pp)≈70 mb

Operating conditions (summary):

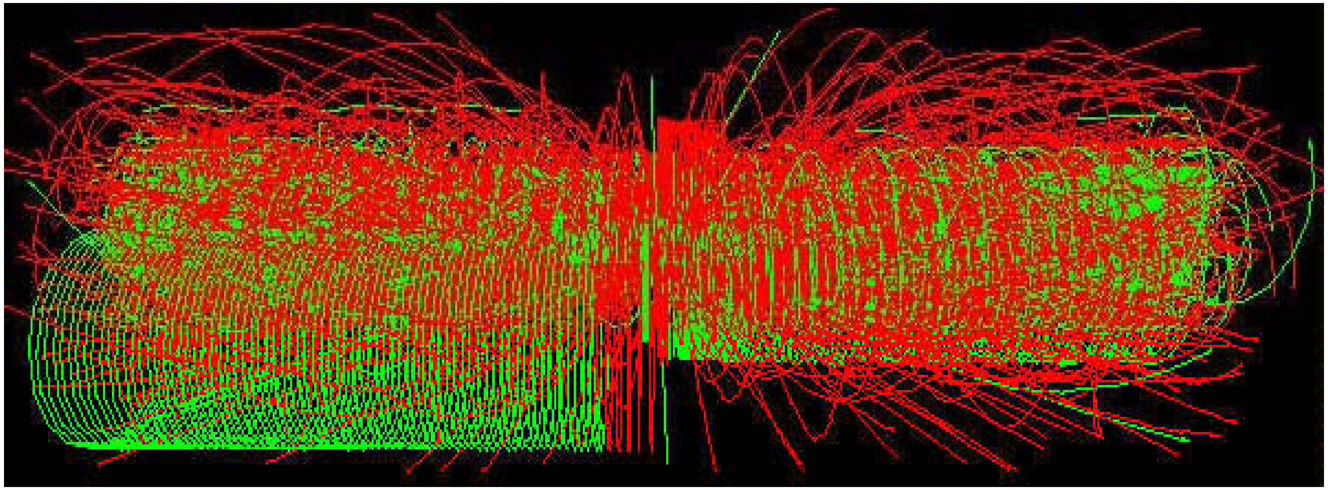
1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

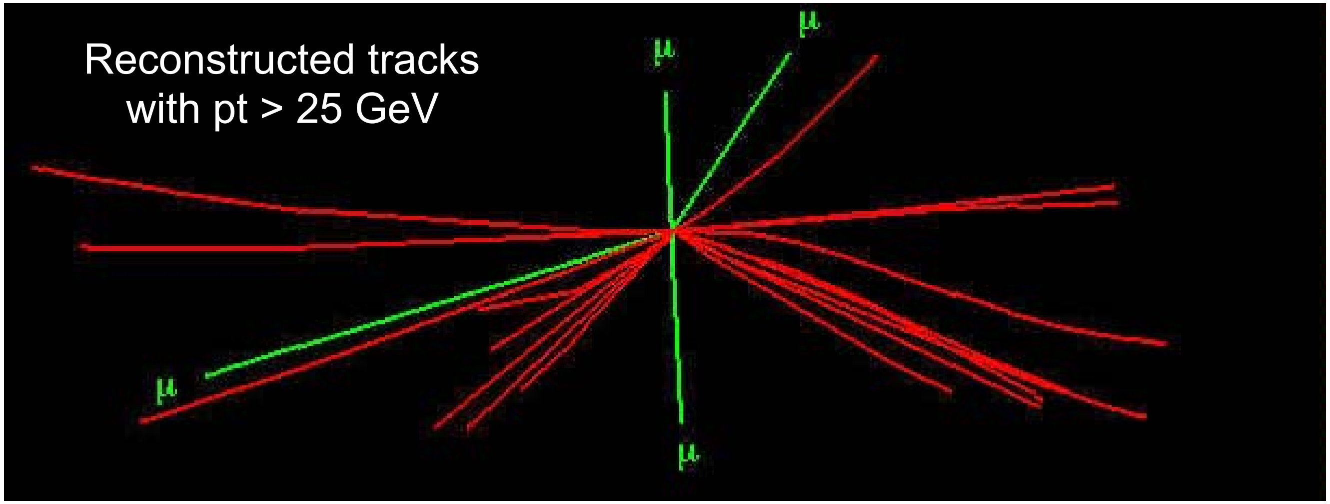
pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

- 20 min bias events overlap
- H→ZZ

Z →μμ

H→ 4 muons: the cleanest (“golden”) signature





Reconstructed tracks with pt > 25 GeV

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

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

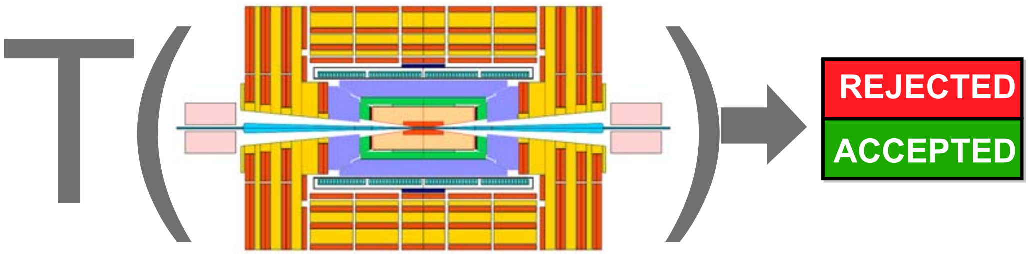
Triggering

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

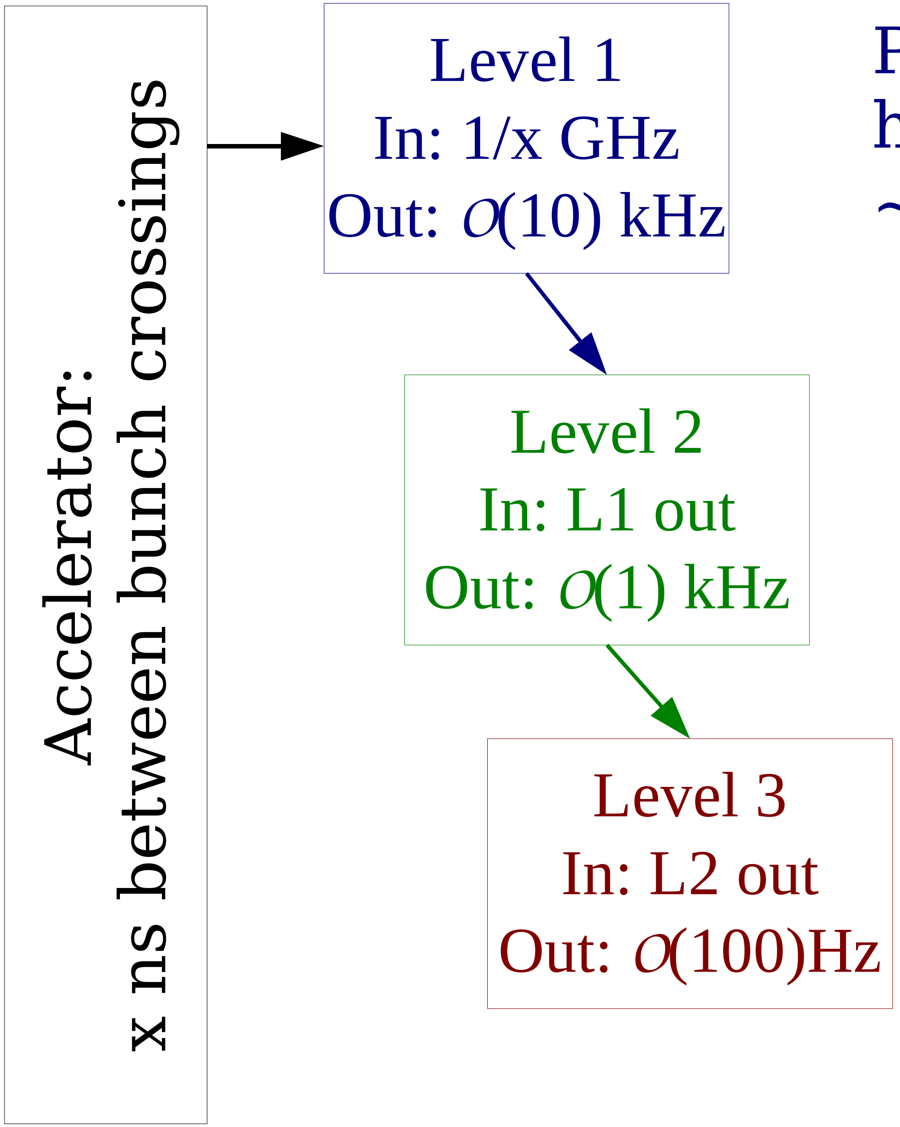
(possibly with zero dead time)

System wyzwalania

Nie jest możliwe efektywne odrzucanie tła w jednym kroku

=> wielostopniowy system selekcji

“Traditional” Architecture



Accelerator:
x ns between bunch crossings

Level 1
In: 1/x GHz
Out: $\mathcal{O}(10)$ kHz

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

Level 2
In: L1 out
Out: $\mathcal{O}(1)$ kHz

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

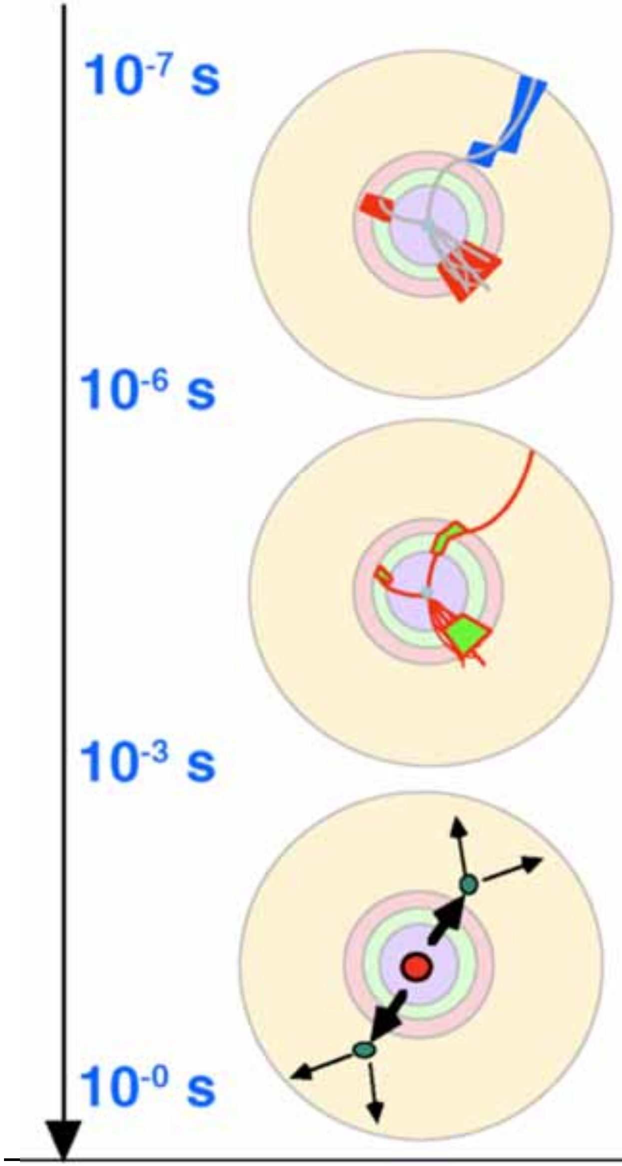
Level 3
In: L2 out
Out: $\mathcal{O}(100)$Hz

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”

LHC 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

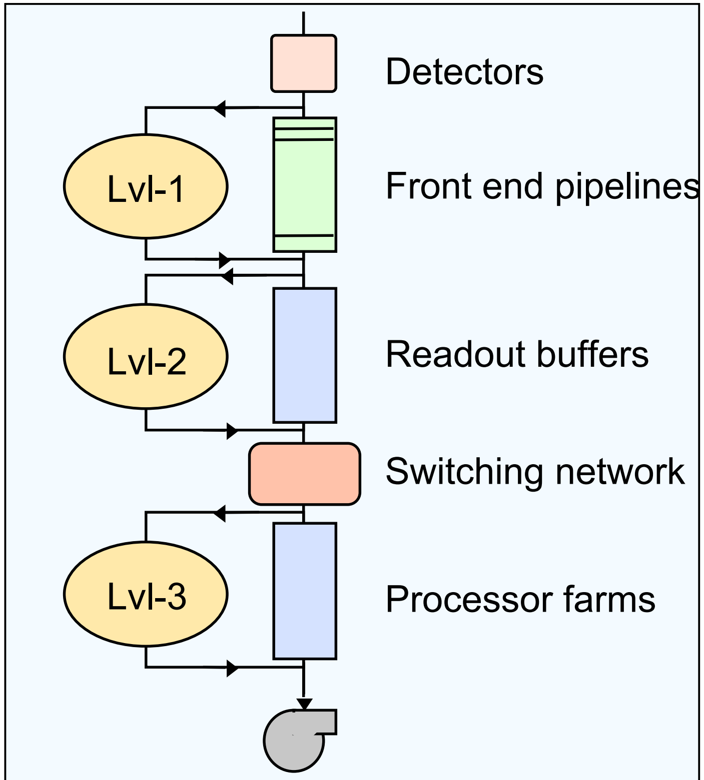
Level-3 events to tape 100- 300 Hz

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



Detectors

Lvl-1

Front end pipelines

Lvl-2

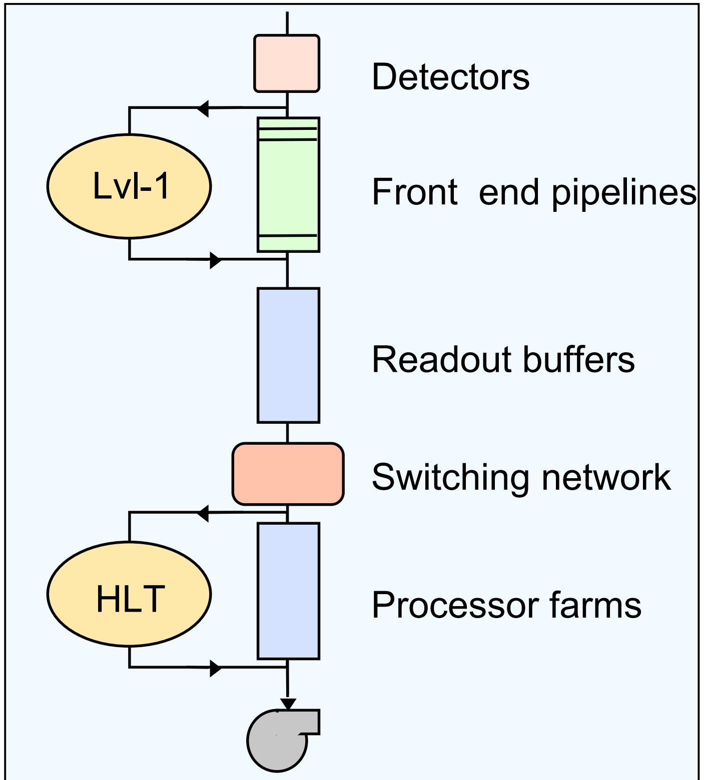
Readout buffers

Switching network

Lvl-3

Processor farms

“Traditional”: 3 physical levels



Detectors

Lvl-1

Front end pipelines

Readout buffers

Switching network

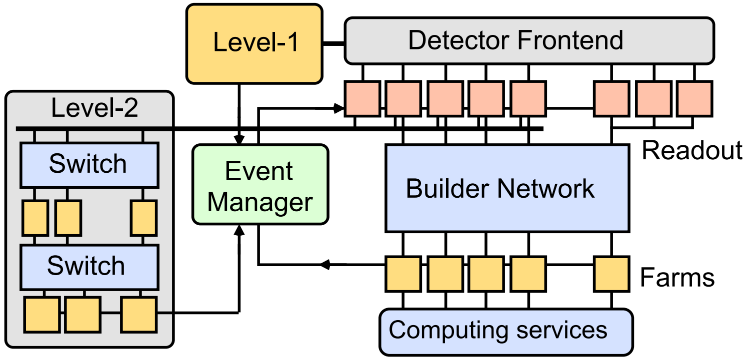
HLT

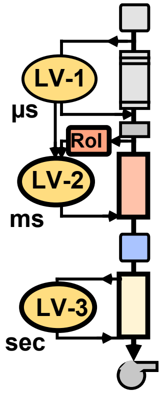
Processor farms

CMS: 2 physical levels

Three physical entities

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





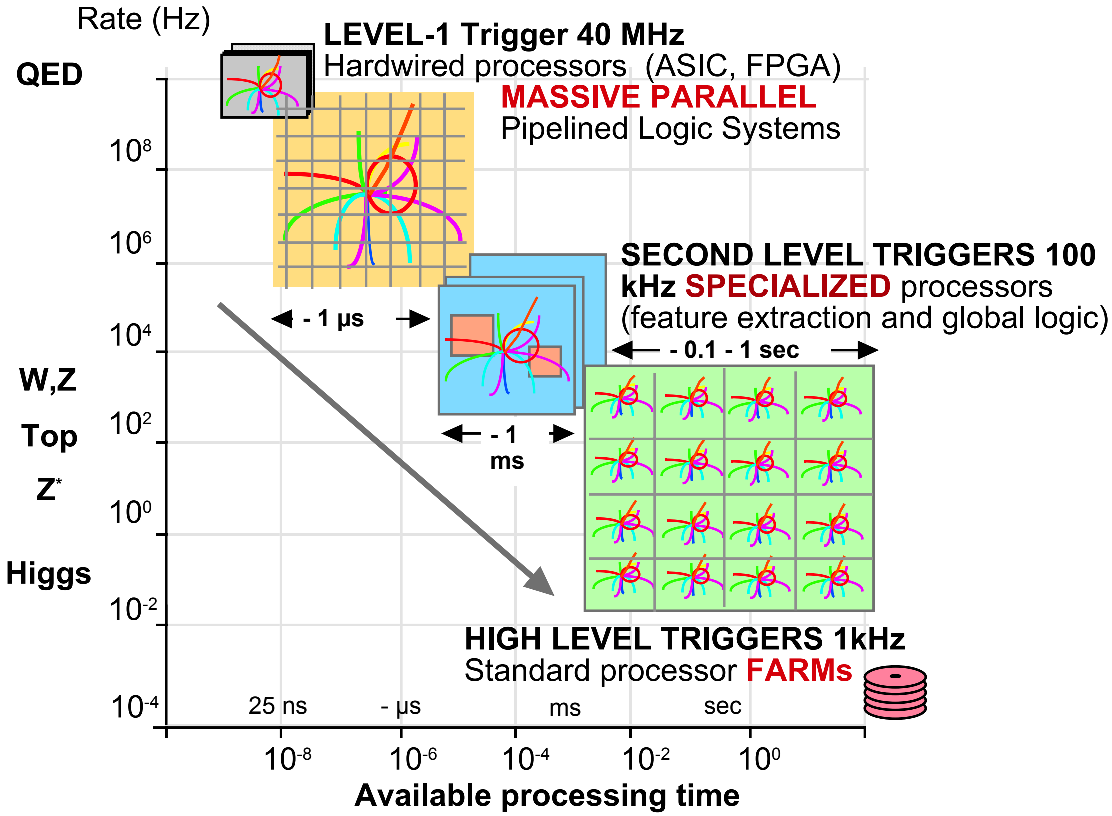
40 MHz

10^5 Hz

10^3 Hz

10 Gb/s

10^2 Hz

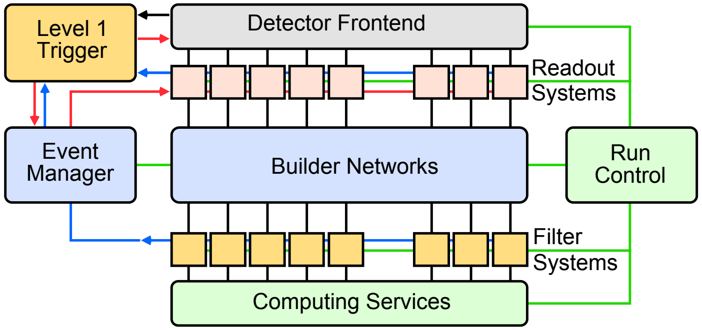


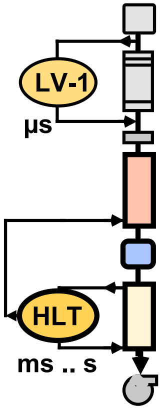
LEVEL-1 Trigger 40 MHz
Hardwired processors (ASIC, FPGA)
MASSIVE PARALLEL
Pipelined Logic Systems

SECOND LEVEL TRIGGERS 100 kHz SPECIALIZED processors
(feature extraction and global logic)

HIGH LEVEL TRIGGERS 1kHz
Standard processor **FARMs**

Two physical entities



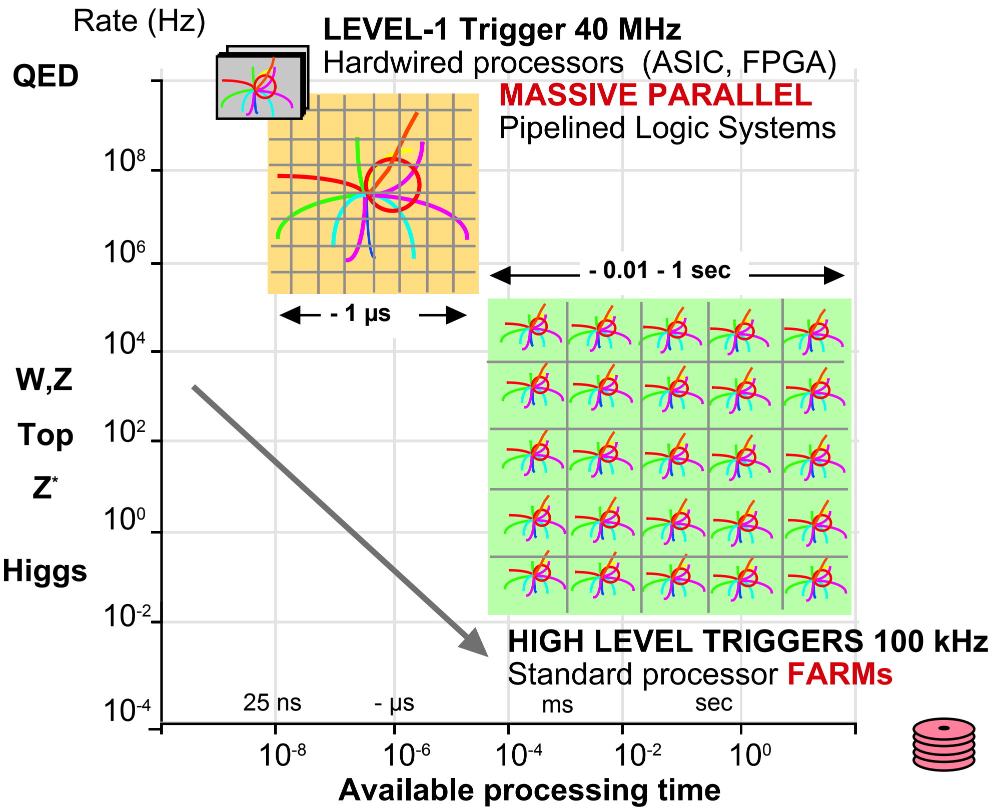


40 MHz

10^5 Hz

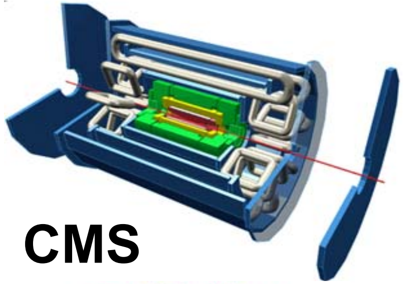
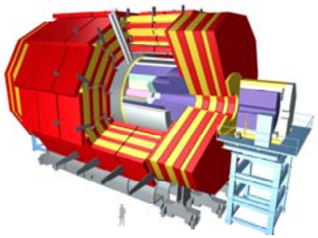
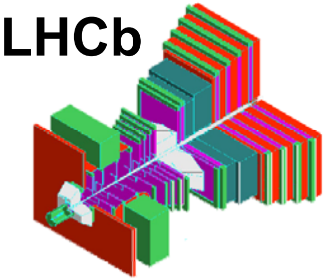
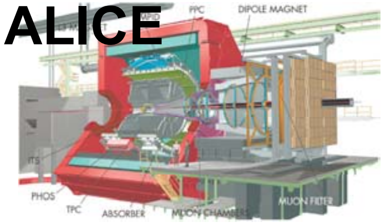
1000 Gb/s

10^2 Hz



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

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)

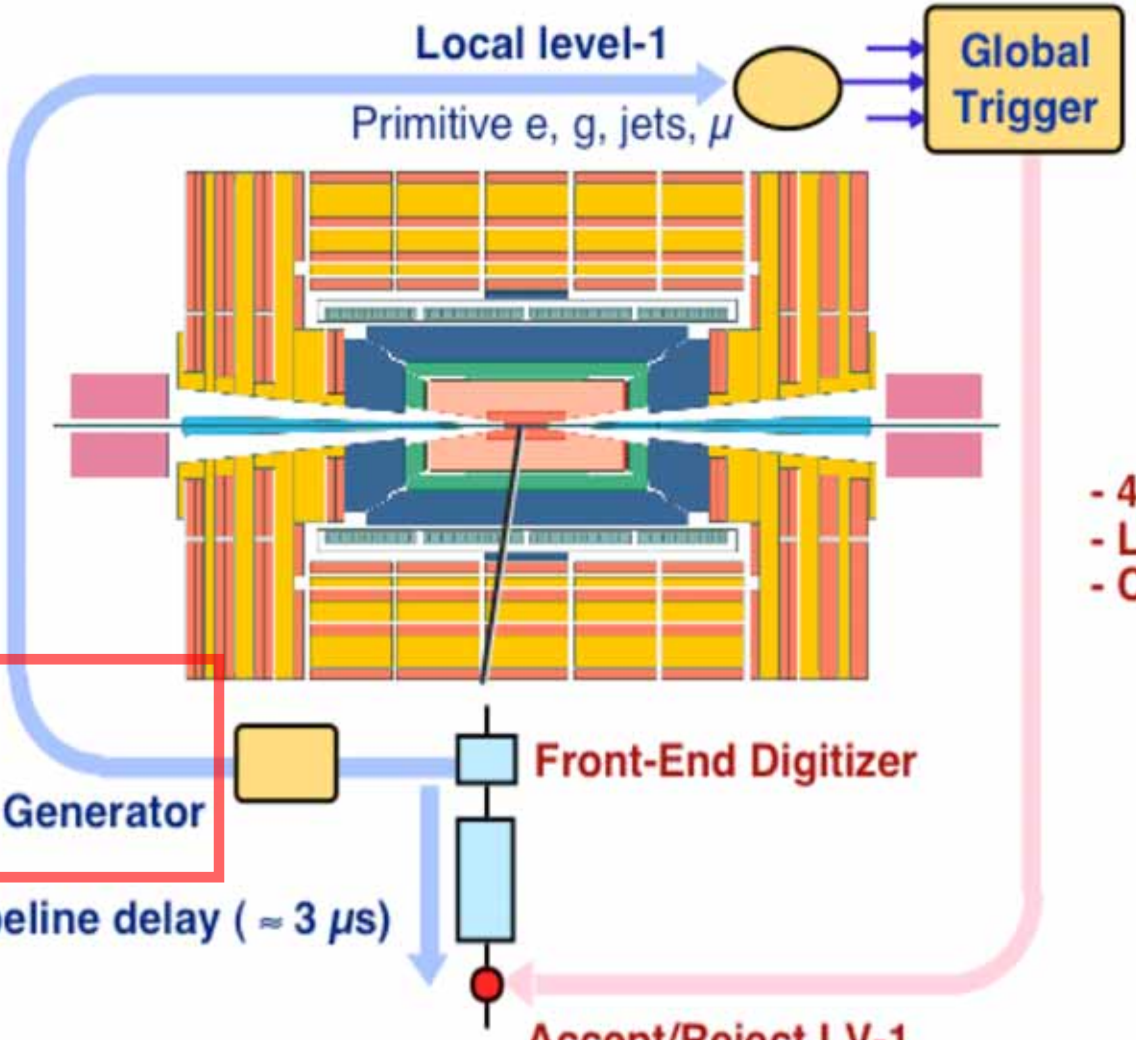
System wyzwalania

Nie jest możliwe efektywne odrzucanie tła w jednym kroku

=> wielostopniowy system selekcji

Kluczowy jest Poziom-1

Level 1 Trigger Operation



- 40 MHz Clock
- Level-1 Accept
- Controls

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)

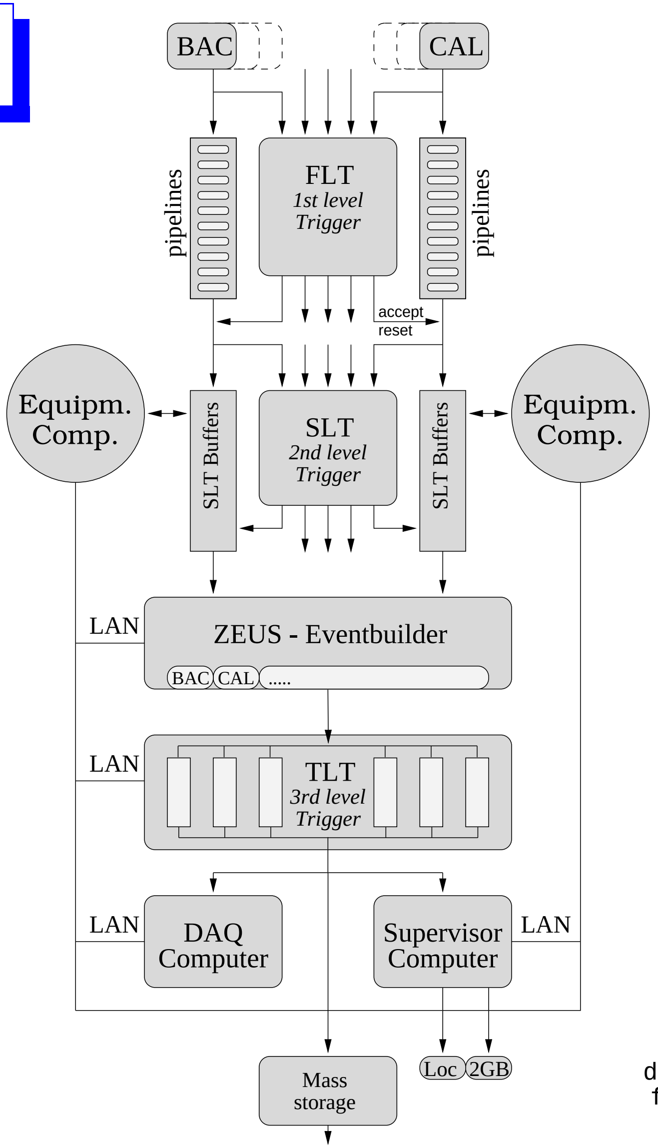
* musimy wprowadzać uproszczenia

(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

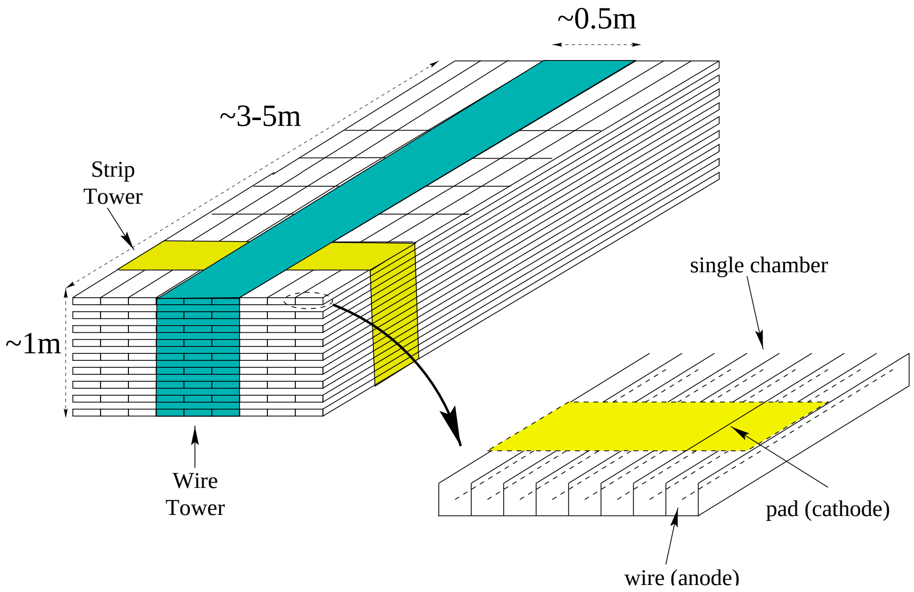
expert supervision
Run Control
Data Quality Monitoring

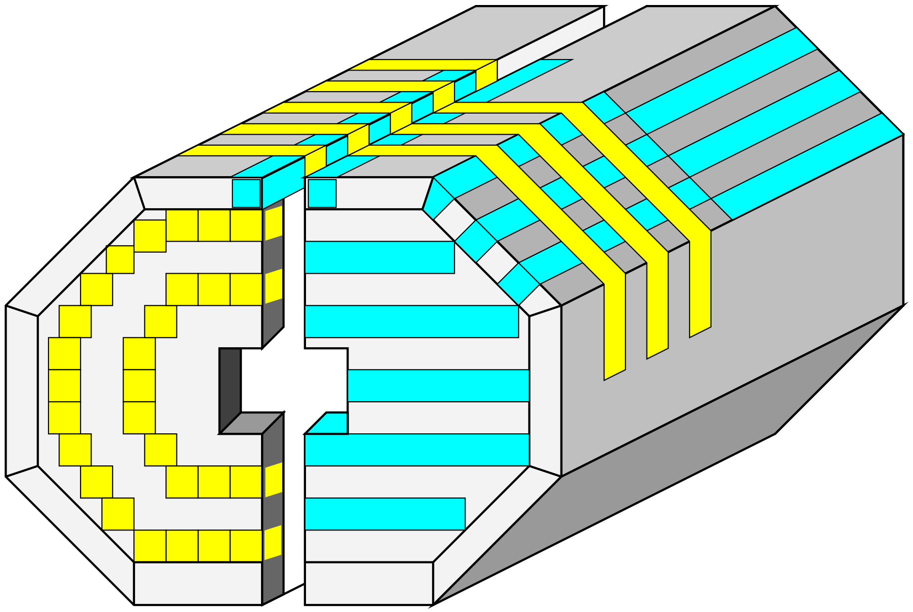
data transfer to main storage
facility (~0.5-1 MByte/sec.)

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

BAC Strip Towers

Transverse energy estimate for First Level Trigger (FLT)

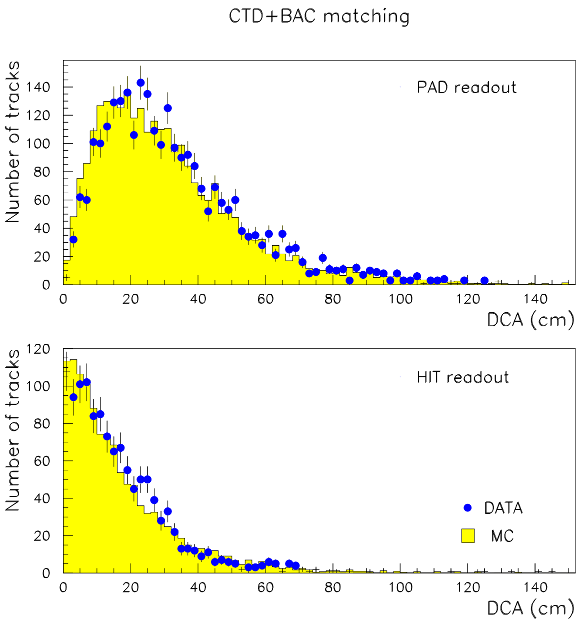


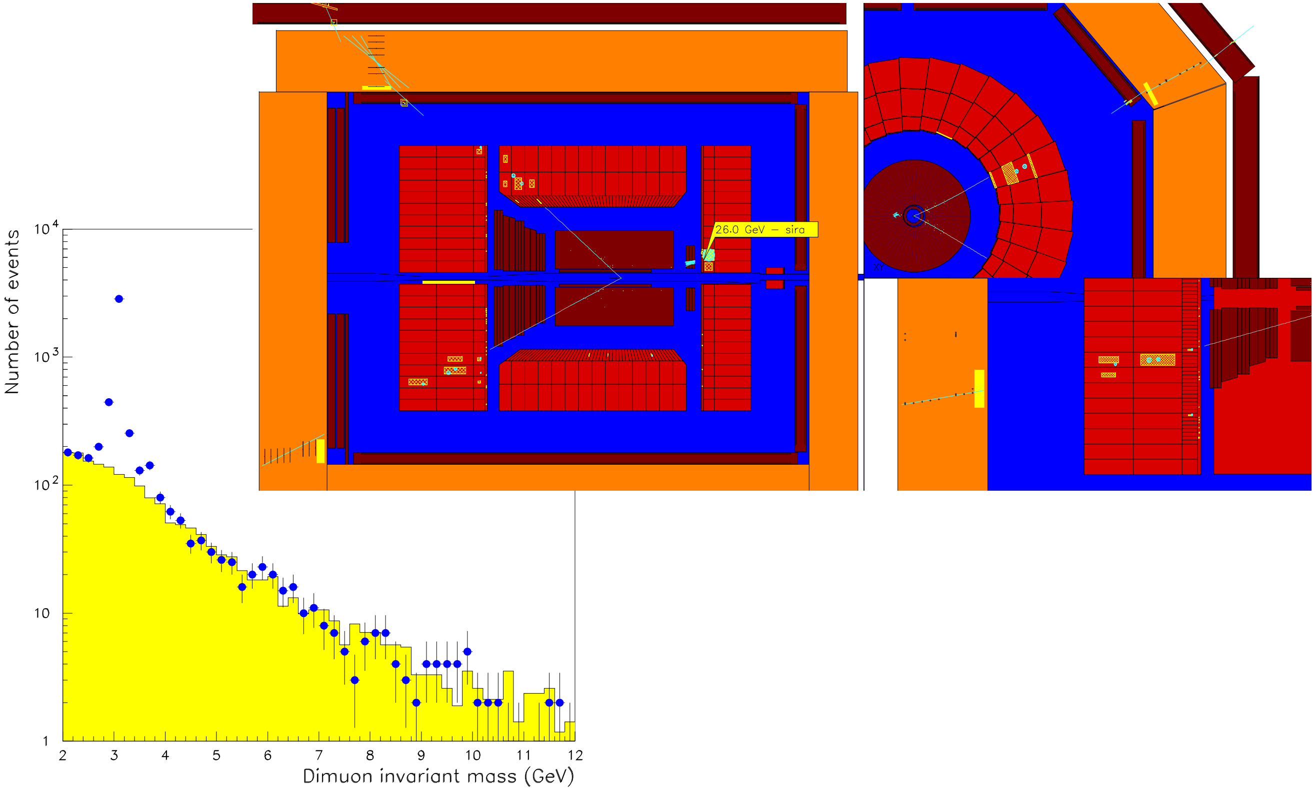


- Strips are constructed using neighbour pad towers
- In Barrel: Strip towers are perpendicular to wire towers
- In Endcaps: Strips are formed in semi-circles around beam-pipe

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

BAC as a muon detector

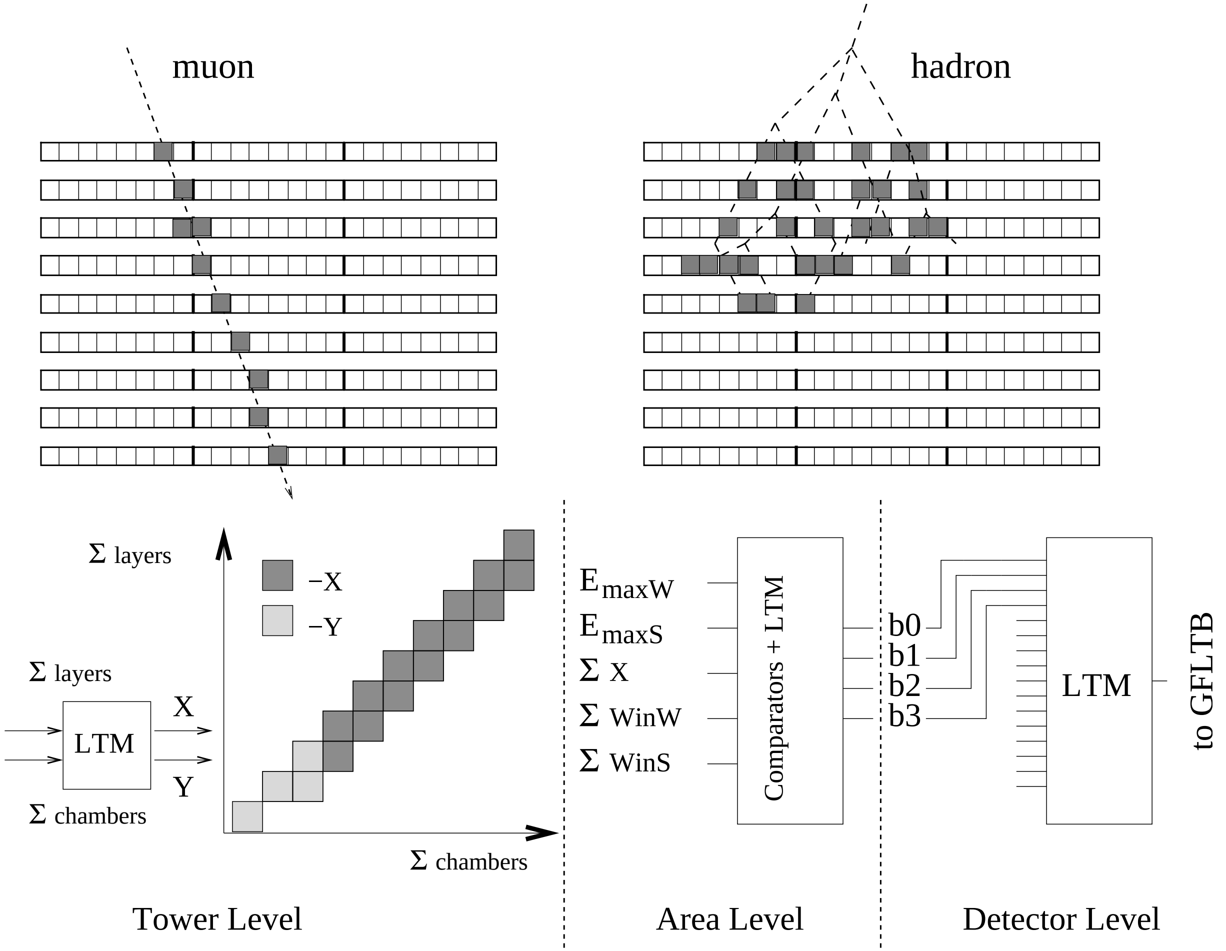




- Position (HIT) readout fully installed in 1997/98
- Di-muon analysis: J/ψ, ψ' and Bethe-Heitler

BAC Muon Trigger Algorithm: Basic Idea

Kluczowe odróżnienie mionu od wypływów



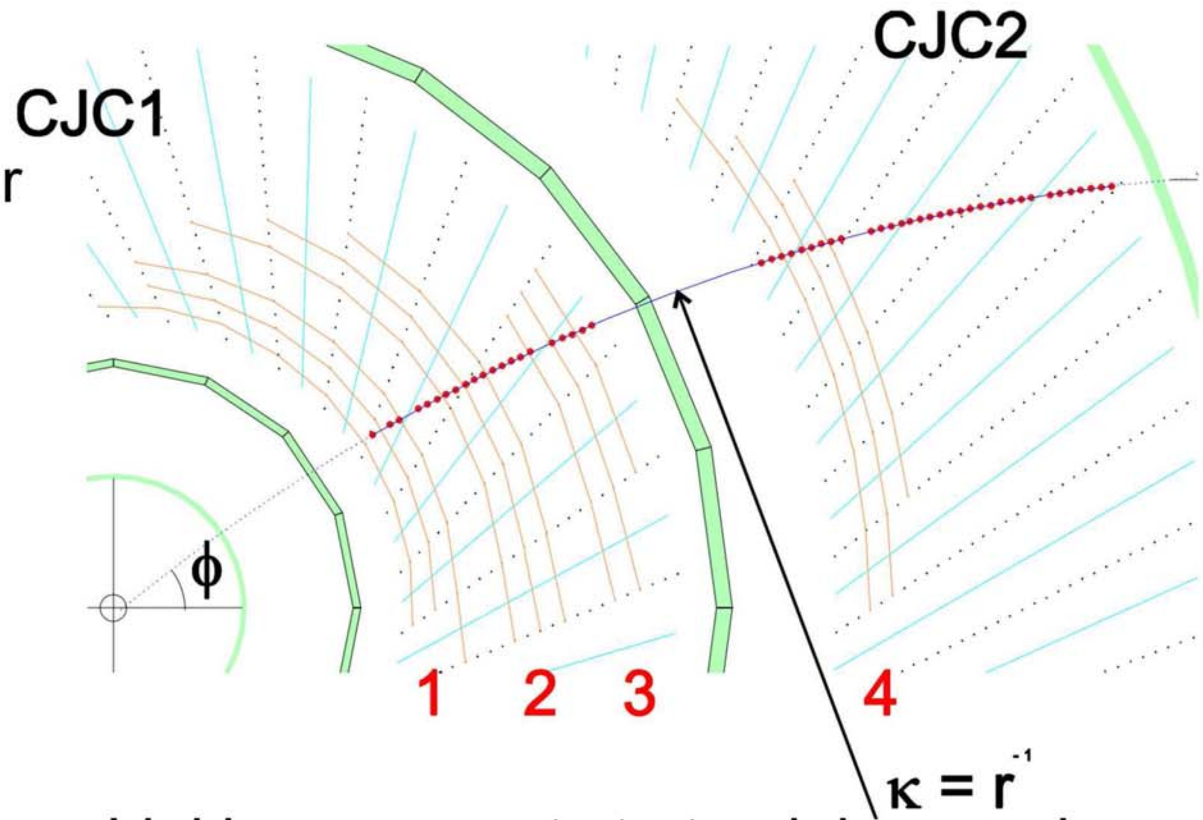
- fast pattern recognition in wire towers
- counting $\Sigma chambers$ and $\Sigma layers$
- LTM memory to classify events
- flexible fillings possible for each tower

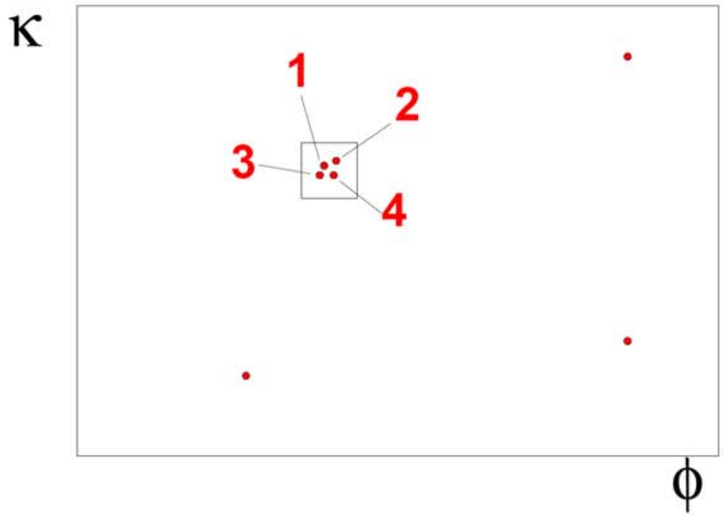
Dla każdej wieży:
bit X - mion
bit Y - wypływ hadronowy

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

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





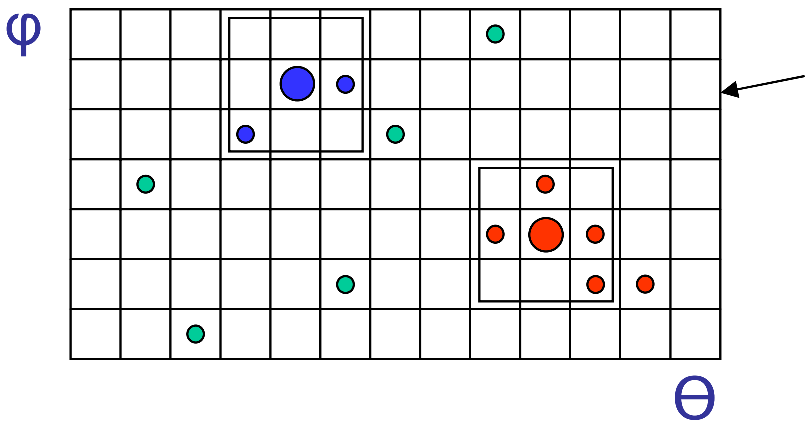
- Linking segments to track in κ–ϕ plane by searching clusters
- Fit track parameters =>
  - Search for particle resonances
  - Provide trigger decision for L1/L2/L3

Principle of the Jet Trigger

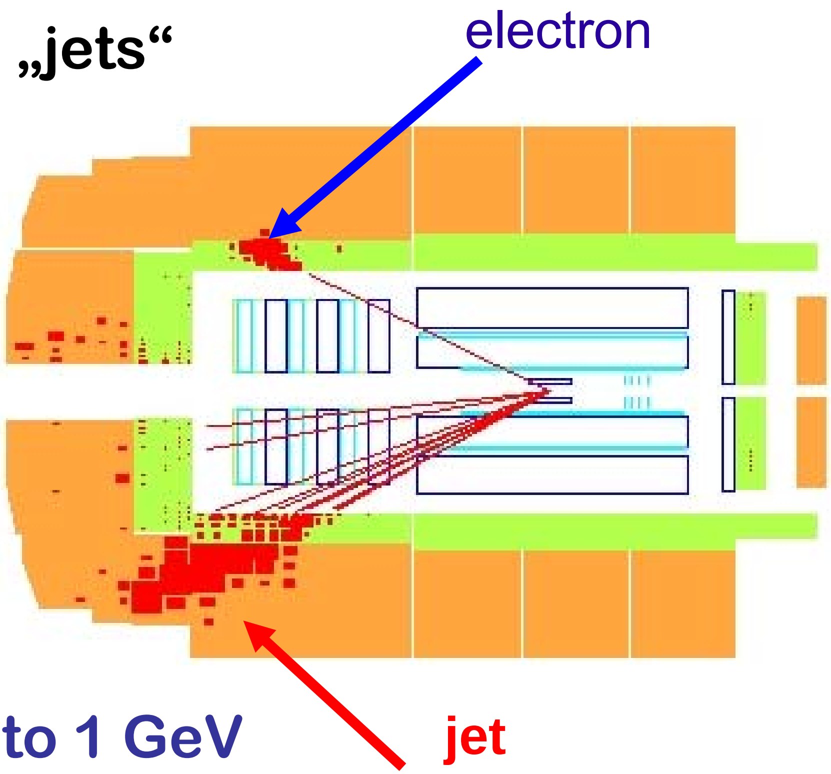
A calorimeter trigger implementing a real-time jet cluster algorithm within 800 ns (L1 latency 2.3 µs)

Why?

Avoid summing noise: trigger on low energy electrons and jets



here: 2 „jets“ found



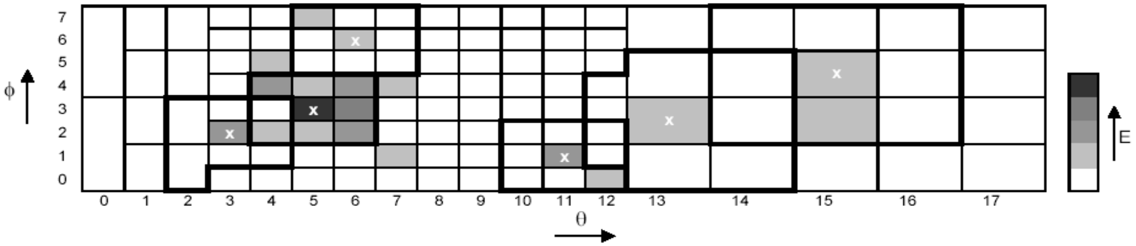
Jet variables extracted:
Energy, topology (Θ, φ)

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")

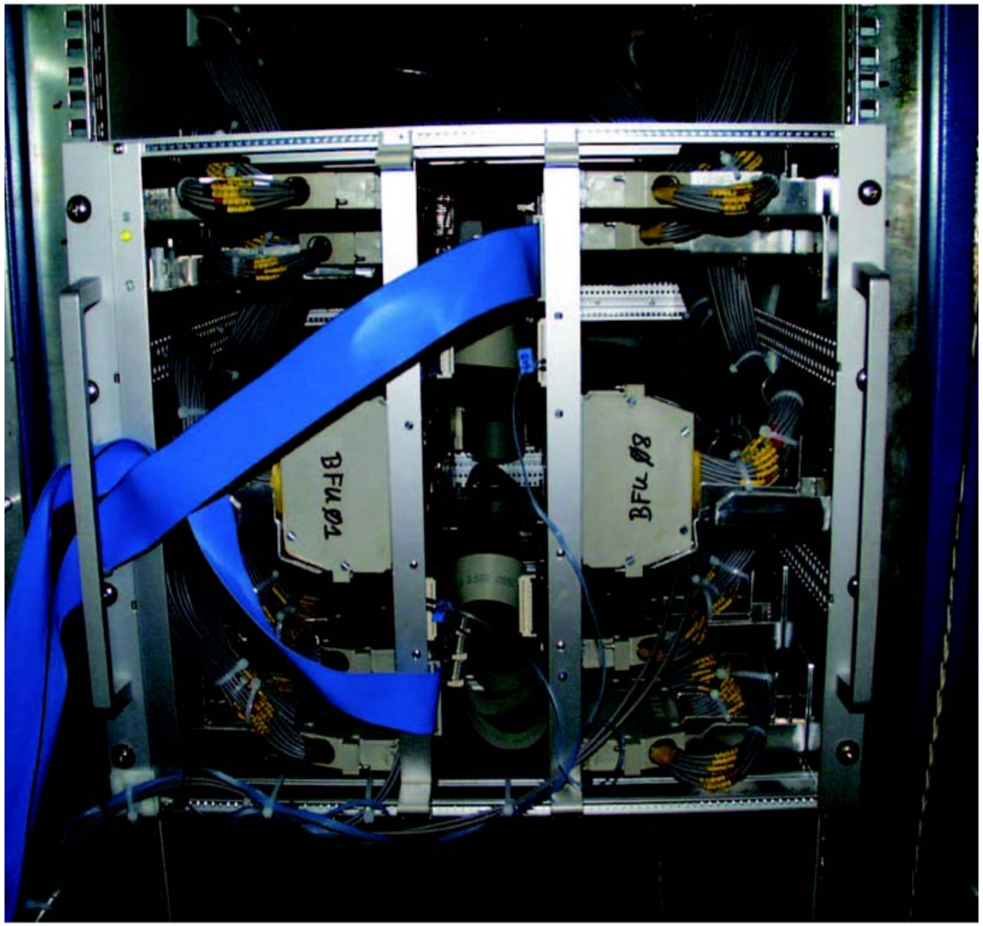


Hardware:

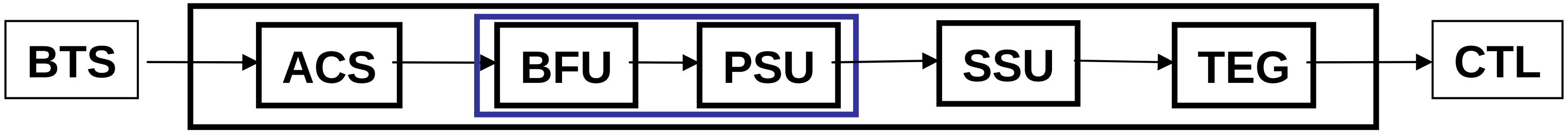
BFU – Bump Finder Unit:

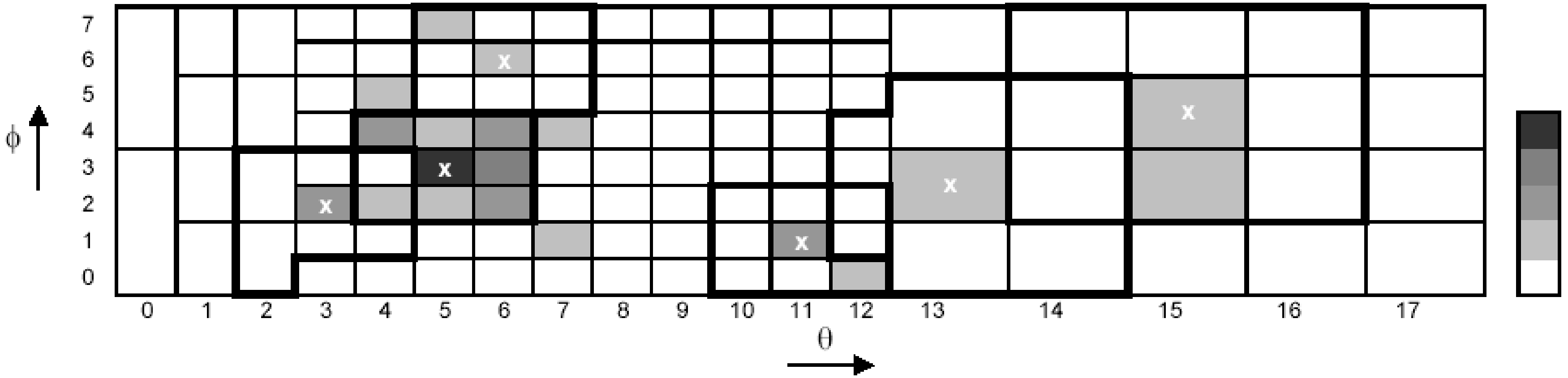
- **2 boards**
- **32 Altera FPGAs x 500k gates**
- **Input 440 towers, output 116 jets**
- **Output rate 1.2 GB/s**

- **Latency 100 ns**



Jet Finder Algorithm within 800 ns





Jets size:
R ~0.7

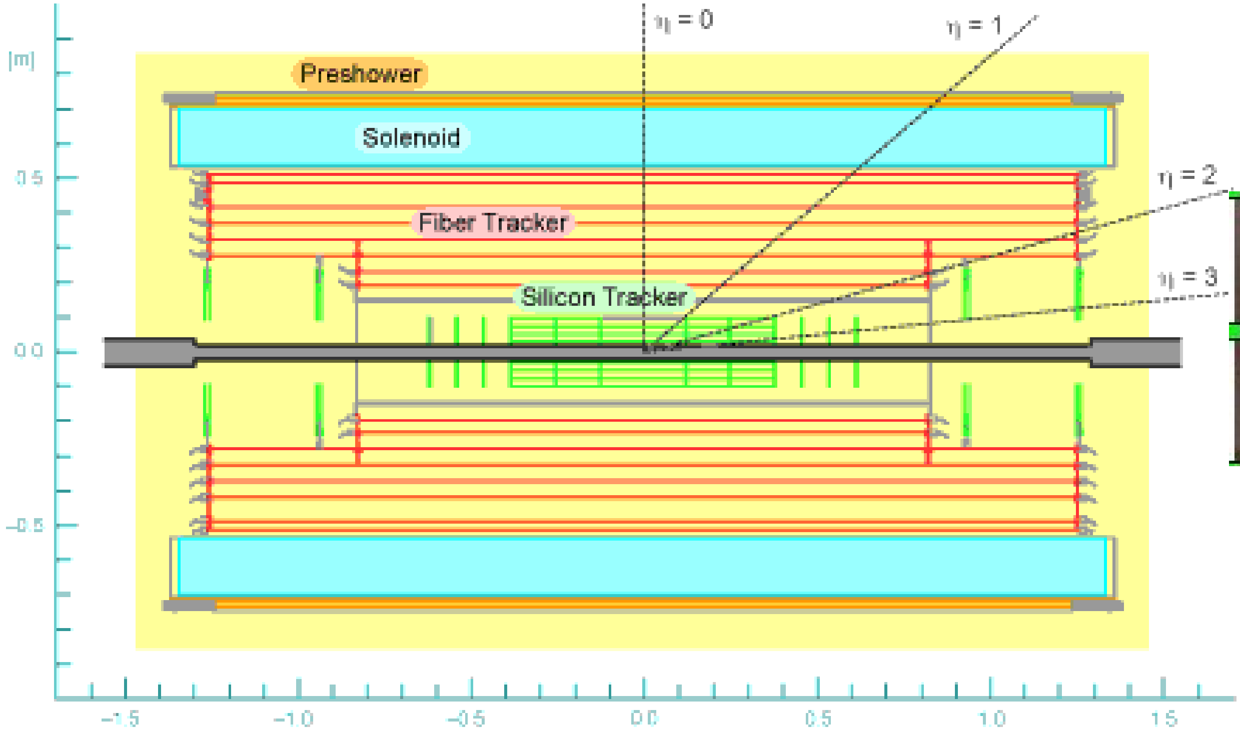
- **Adc Calculation Storage:** digitize and sum towers - cut coherent noise
- **Bump Finder Unit:** cluster algorithm (find jets) within 100ns!
- **Primary Sorting Unit:** sort 16 „jets“ in decreasing energy
- **Secondary Sorting Unit:**

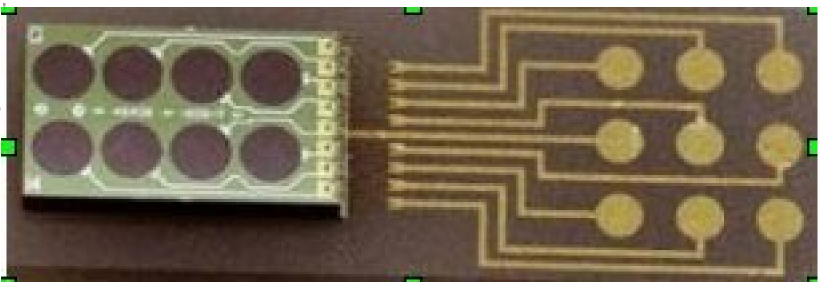
→ leading jets are physics, „lower“ jets are noise

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

Hardware Example: L1CTT (D0)

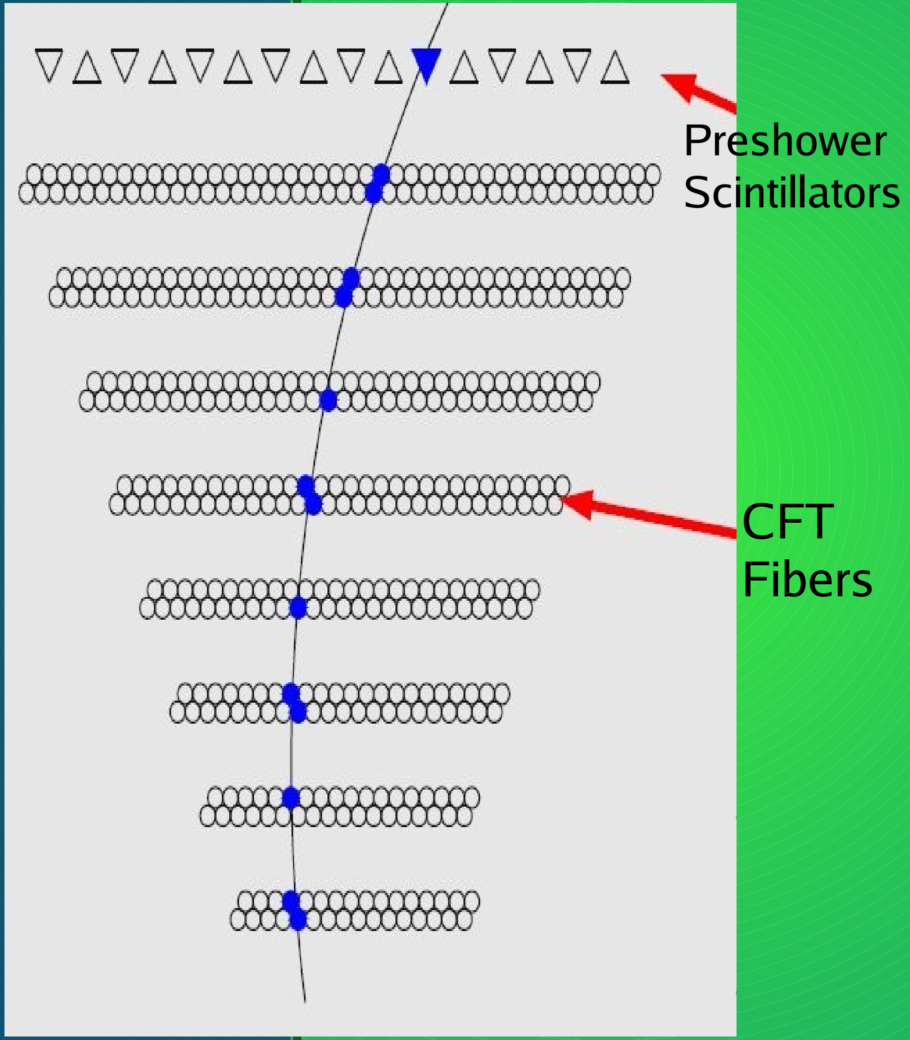
- Scintillating fiber tracker, read out using VLPCs





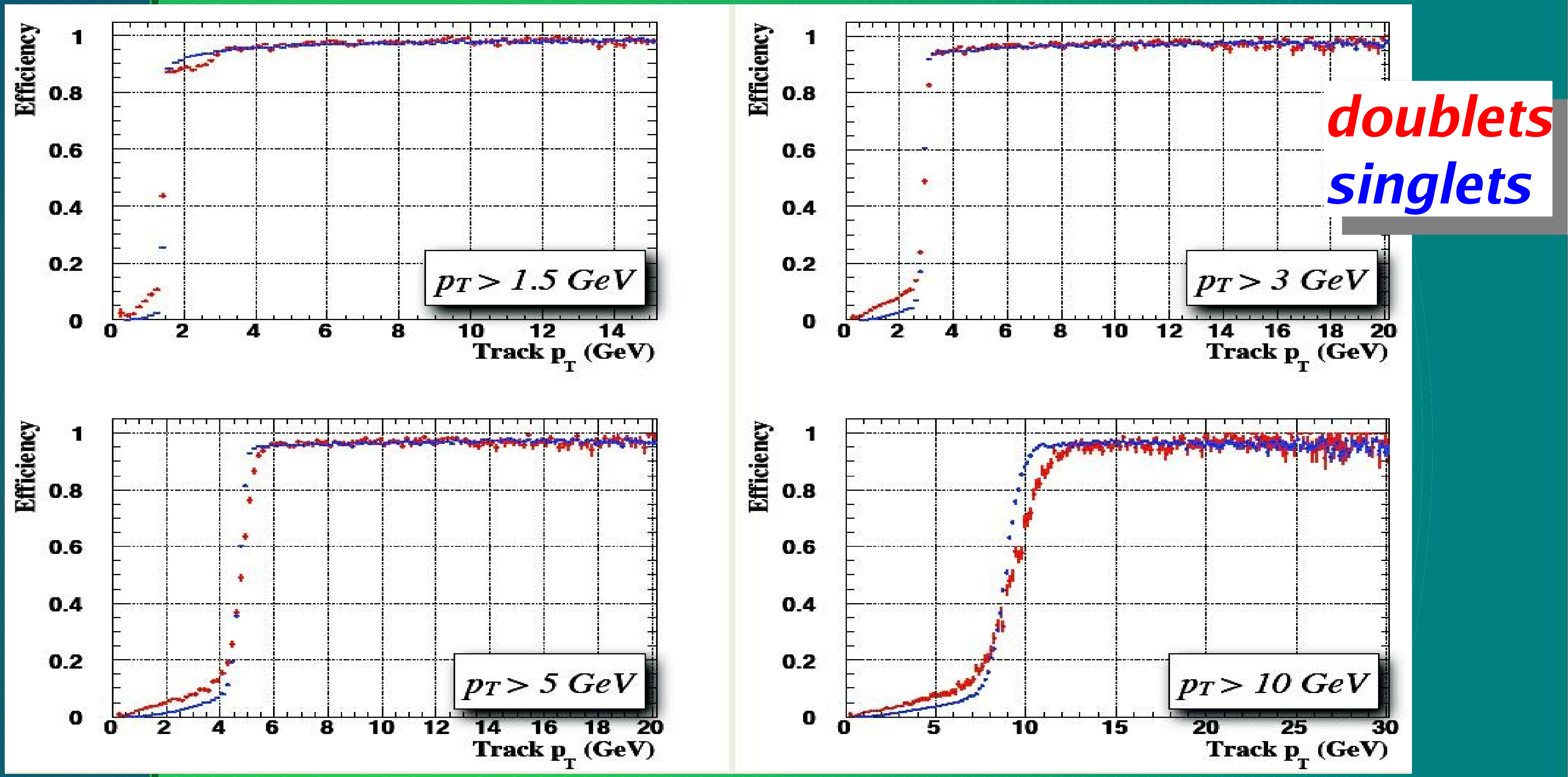
  - VPLC signals split, “trigger path” goes to discriminators
  - Compare hit pattern with pre-programmed track patterns for different p^T ranges

Central Track Trigger (CTT)



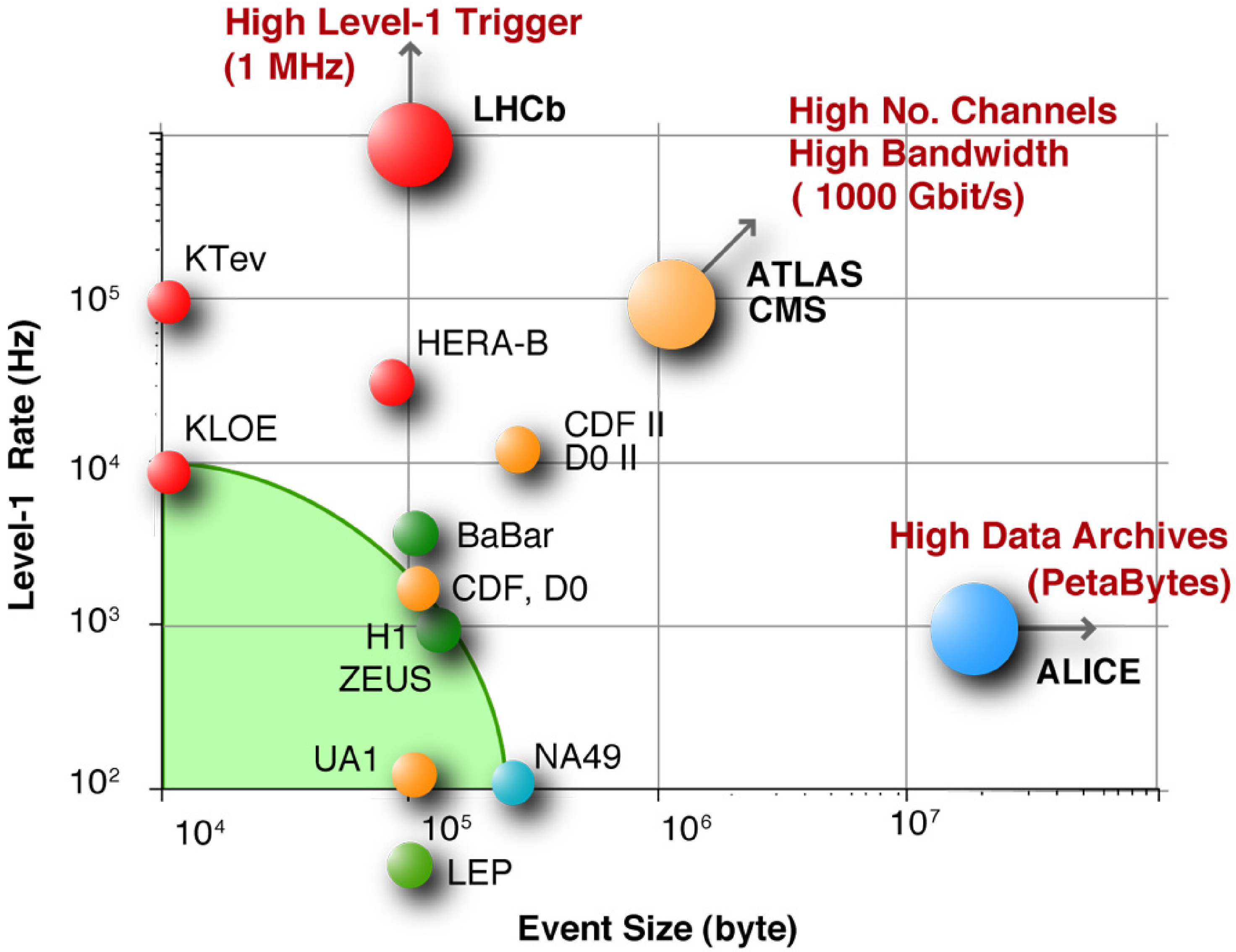
- Hardware trigger at level 1 (L1) running at 7.6MHz (132ns/decision)
- Uses hit patterns from CFT axial layers to find tracks in azimuthal plane with 4 different p_T thresholds: 1.5, 3, 5, 10 GeV
- All probable CFT hit patterns consistent with tracks (*track equations*) are stored in FPGAs
- For triggering purposes the azimuthal plane is segmented into 80 4.5°-wide *trigger sectors*
- Provides additional information on isolation and & pre-shower match
- Provides outputs to multiple downstream trigger components:
  - L1 Muon
  - L1 CalTrack
  - L2 silicon track trigger

CTT Performance: Turn-On Curves



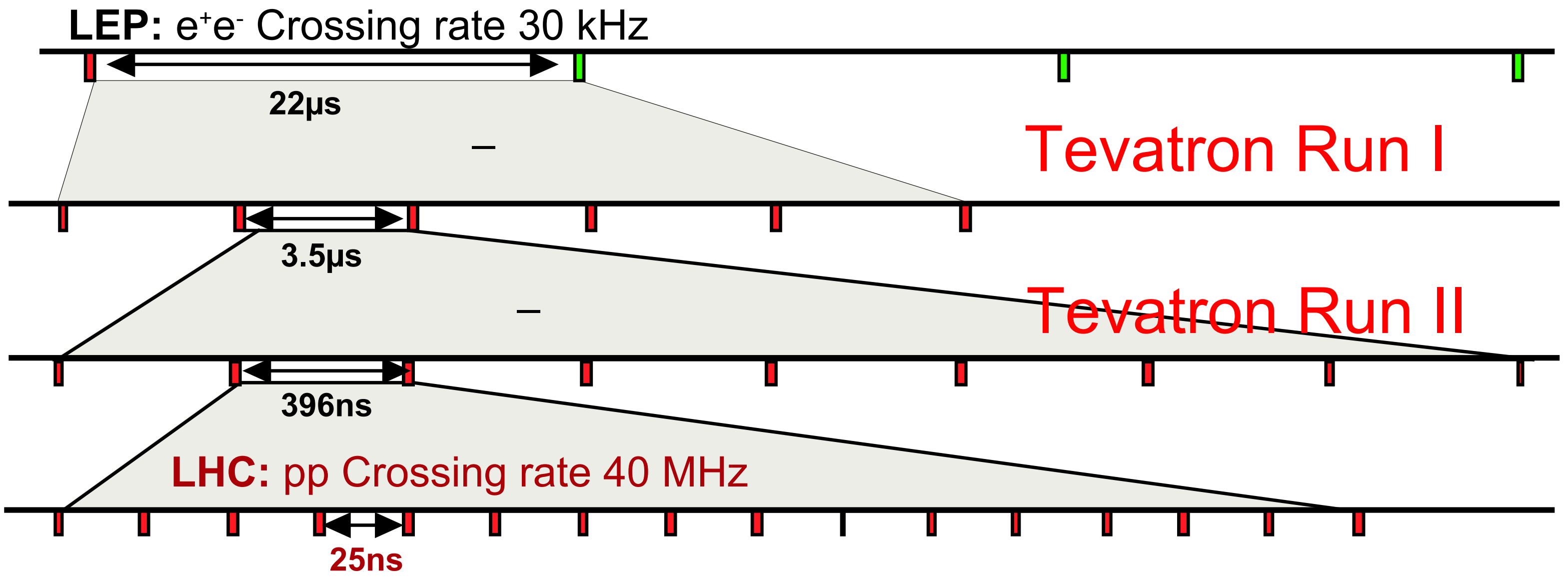
- Comparing CTT tracks with reconstructed tracks
- Sharper turn-ons with singlets

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



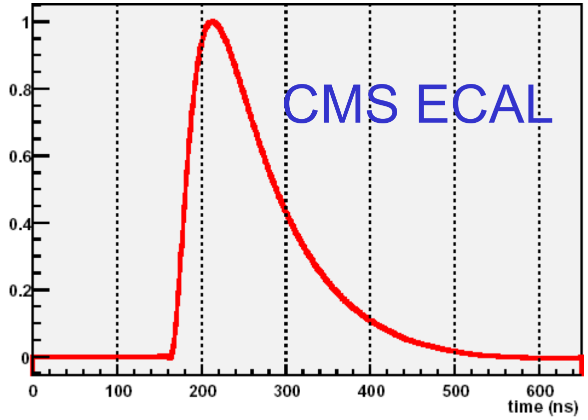
Kluczowy Poziom-1

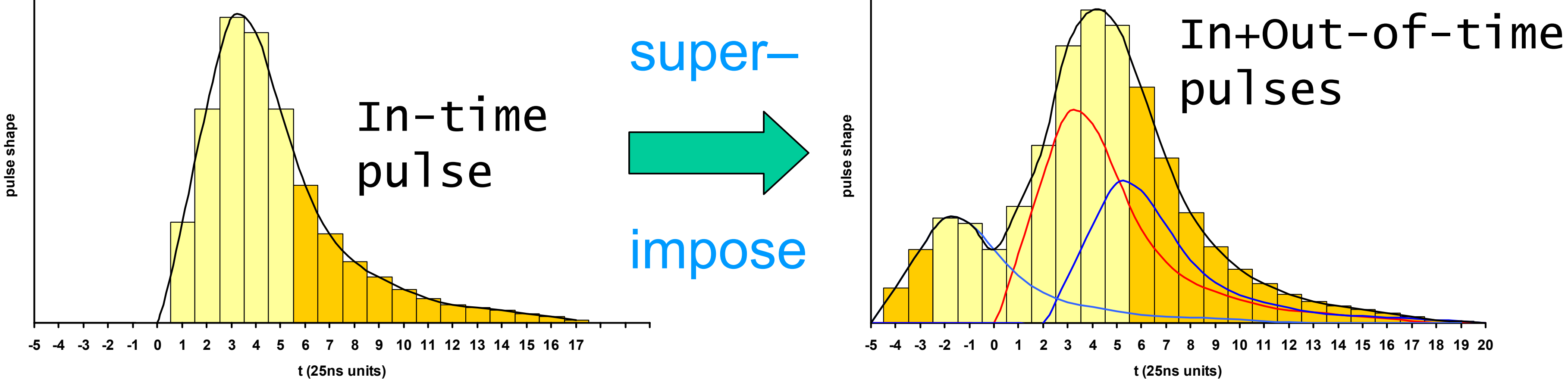
W LHC będzie dużo trudniej niż we wcześniejszych eksperymentach:

- mniej czasu na podjęcie decyzji
  nie wszystkie detektory mogą być użyte
- duże tło nakładających się przypadków
  nie możemy wyzwalać na globalne parametry przypadku
- duże tło QCD
  trzeba wykorzystywać żadkie sygnatury

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”





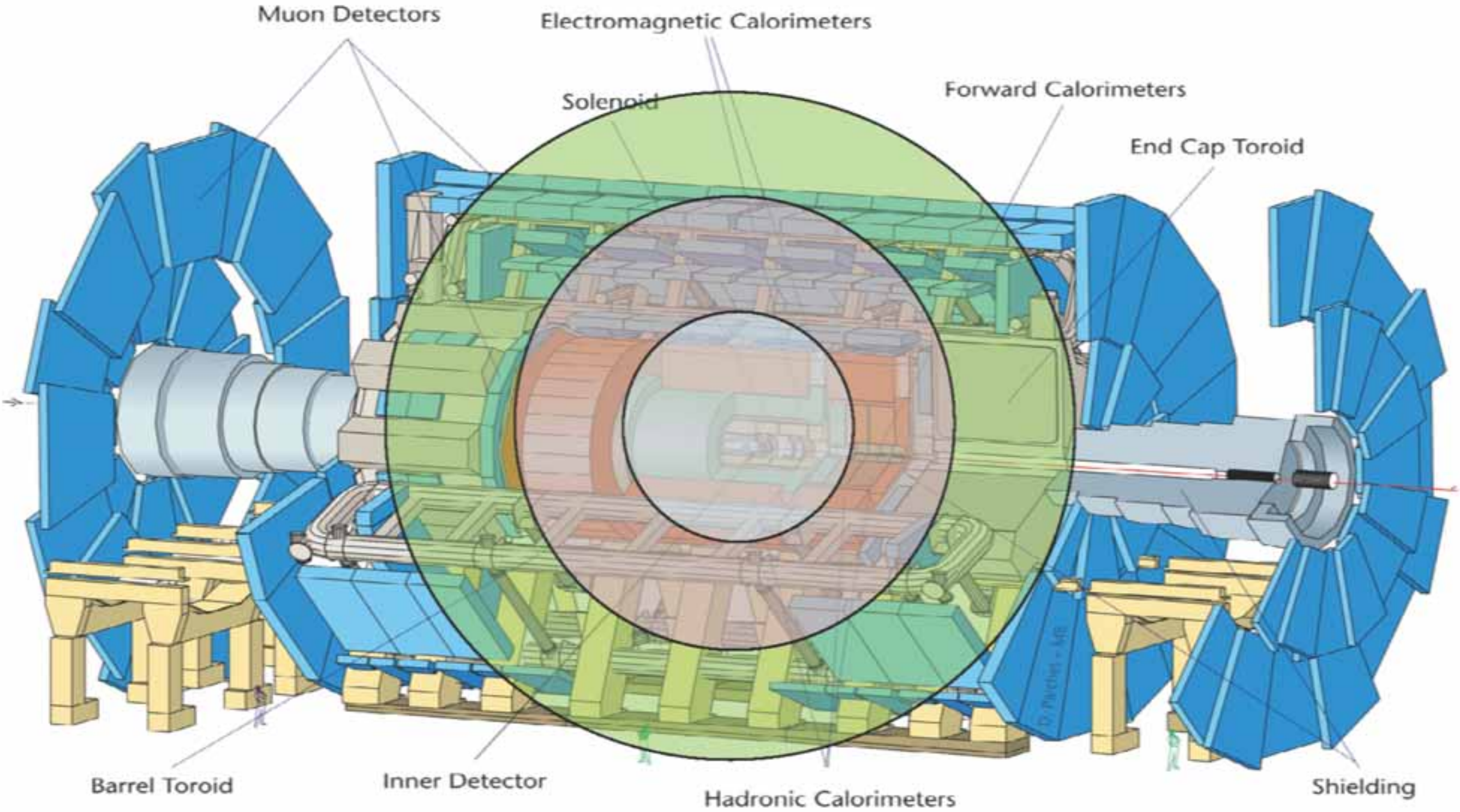
In-time pulse

super–impose

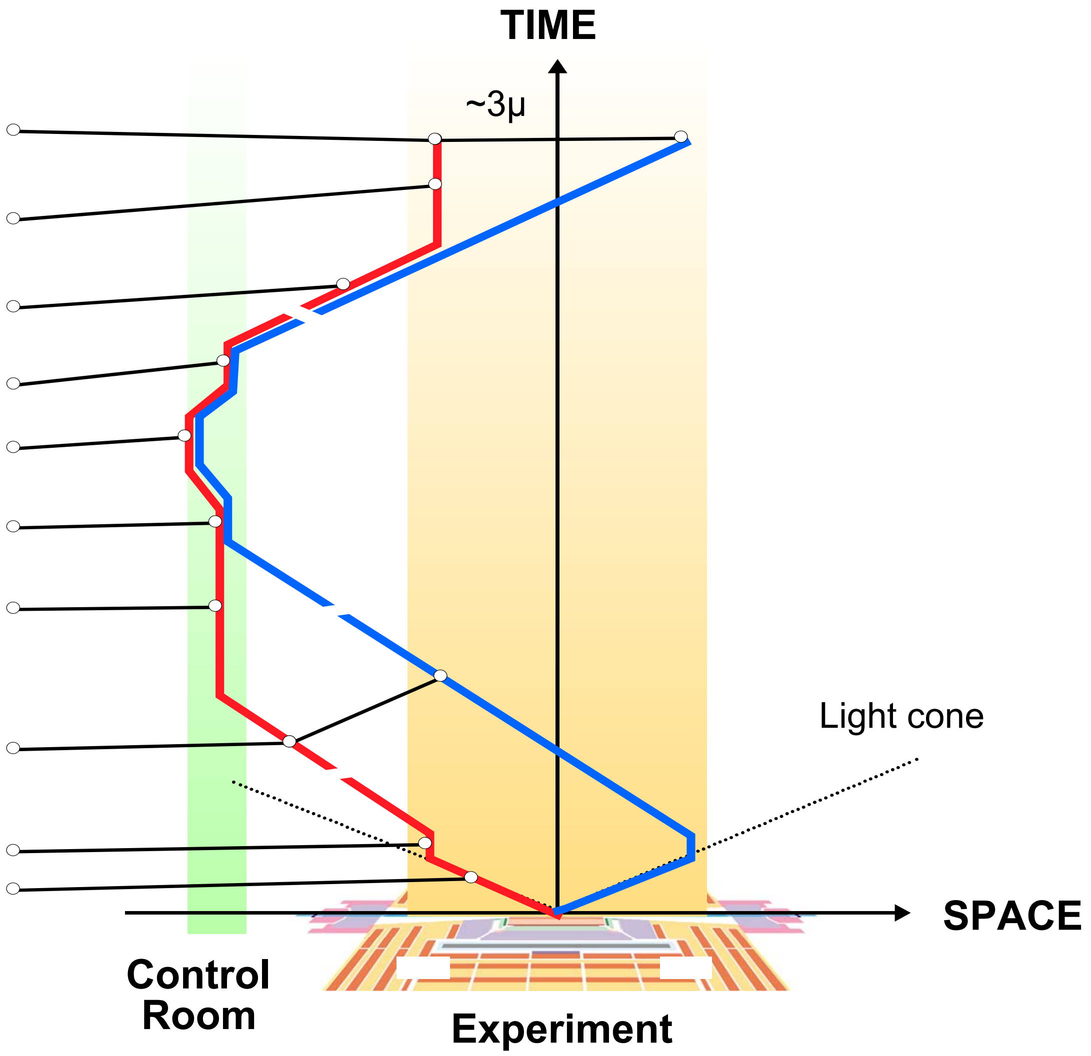
In+Out-of-time pulses

Challenges: Time of Flight

c = 30 cm/ns → in 25 ns, s = 7.5 m



Signaling and pipelining (II)



Level-1 Accept/Reject

Synchronization delay

Level-1 signal distribution

Global Trigger Processor

Regional Trigger Processors

Trigger Primitive Generation

Synchronization delay

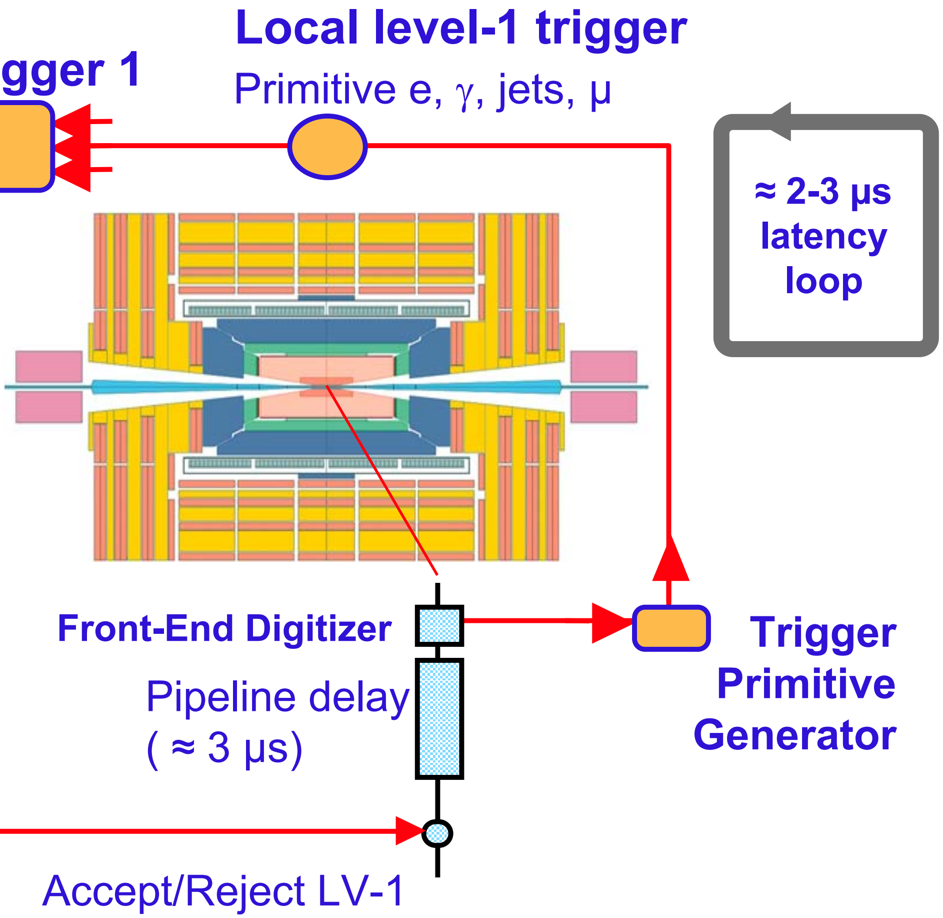
Data transportation to Control Room

Detector FrontEnd Digitizer

Particle Time of Fligth

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

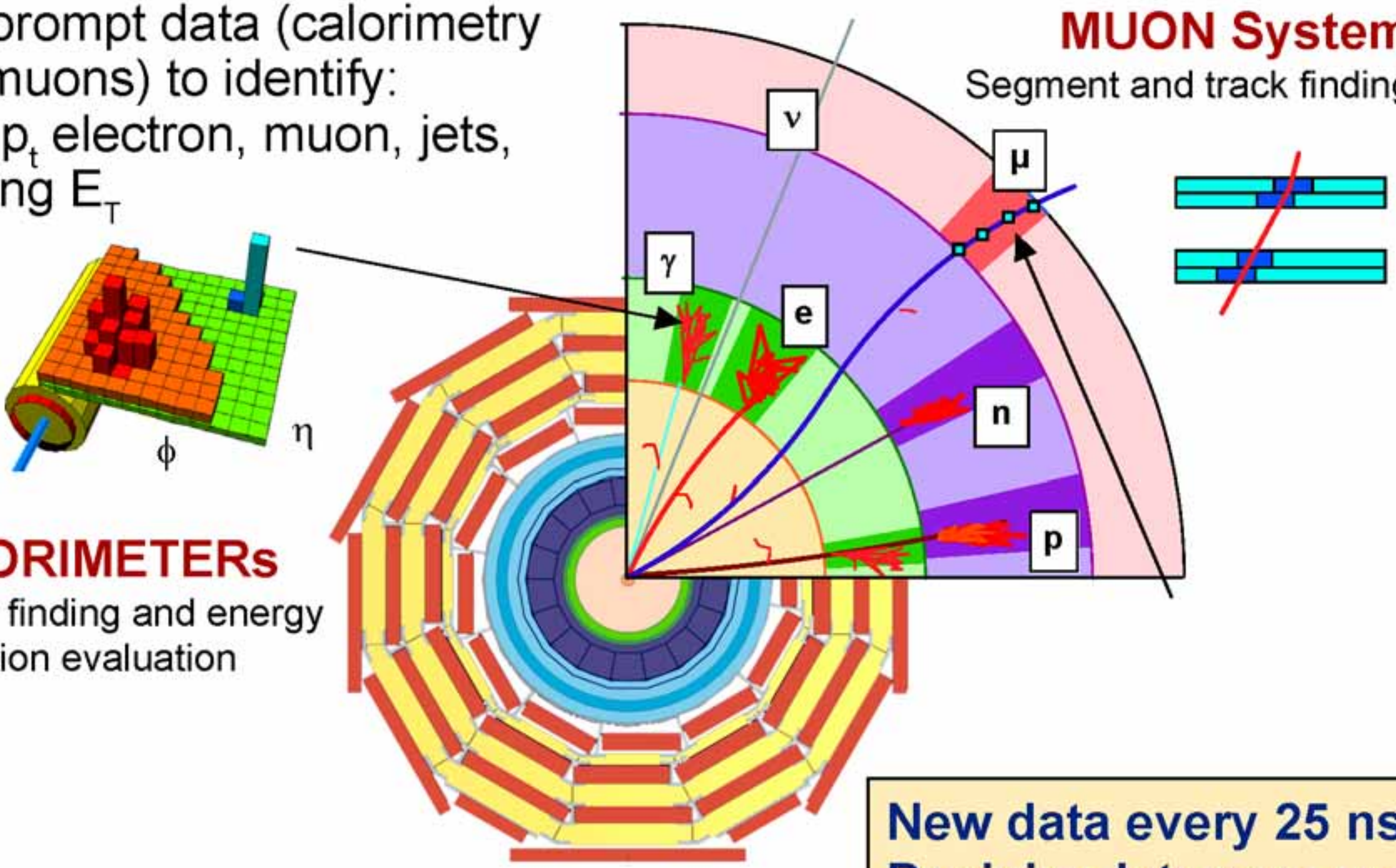


Level-1 trigger algorithms

- 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)

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

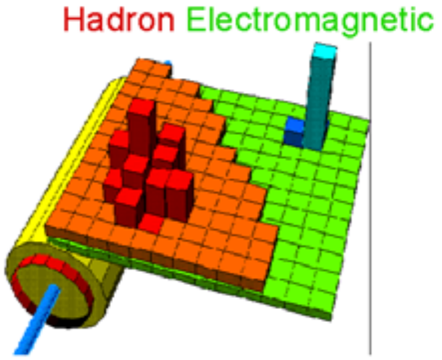
CALORIMETERs
Cluster finding and energy deposition evaluation

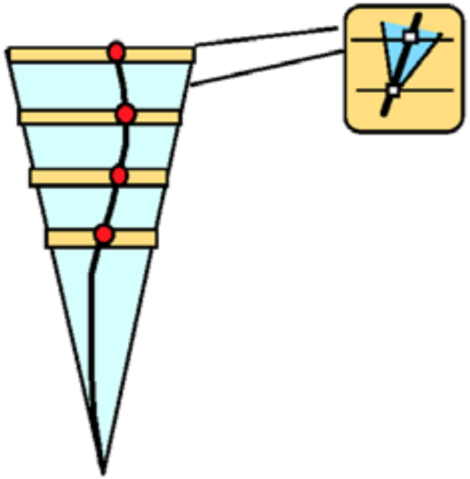
New data every 25 ns
Decision latency ~ µs

ATLAS & CMS Level 1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

- **Pattern recognition much faster/easier**

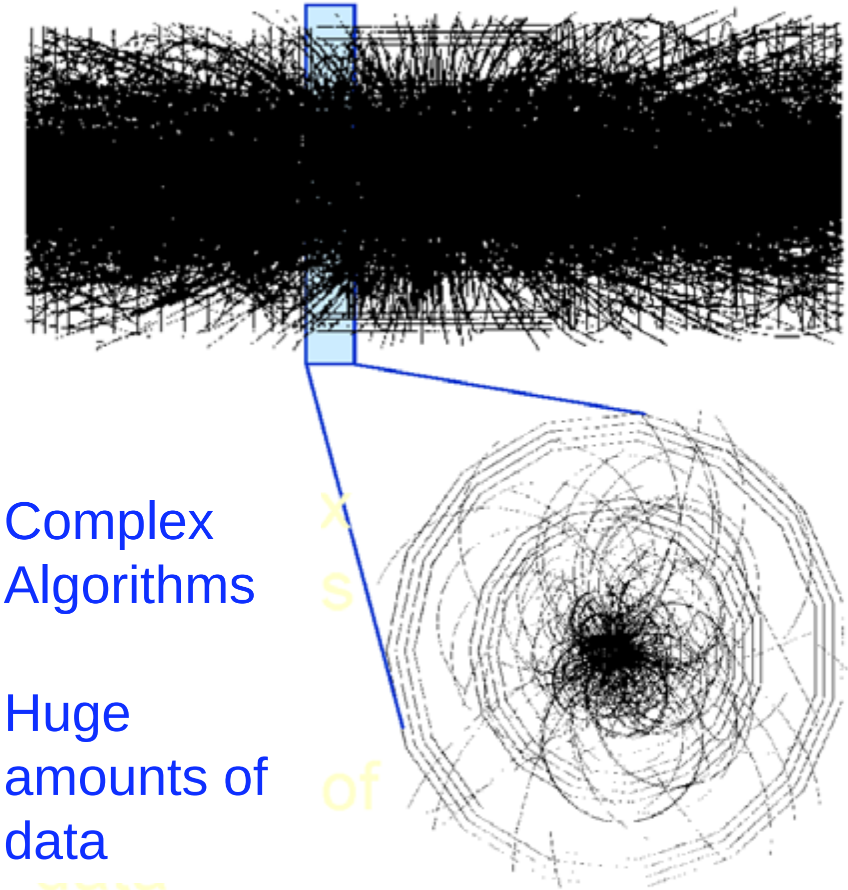




Simple Algorithms

Small amounts of data

- **Compare to tracker info**



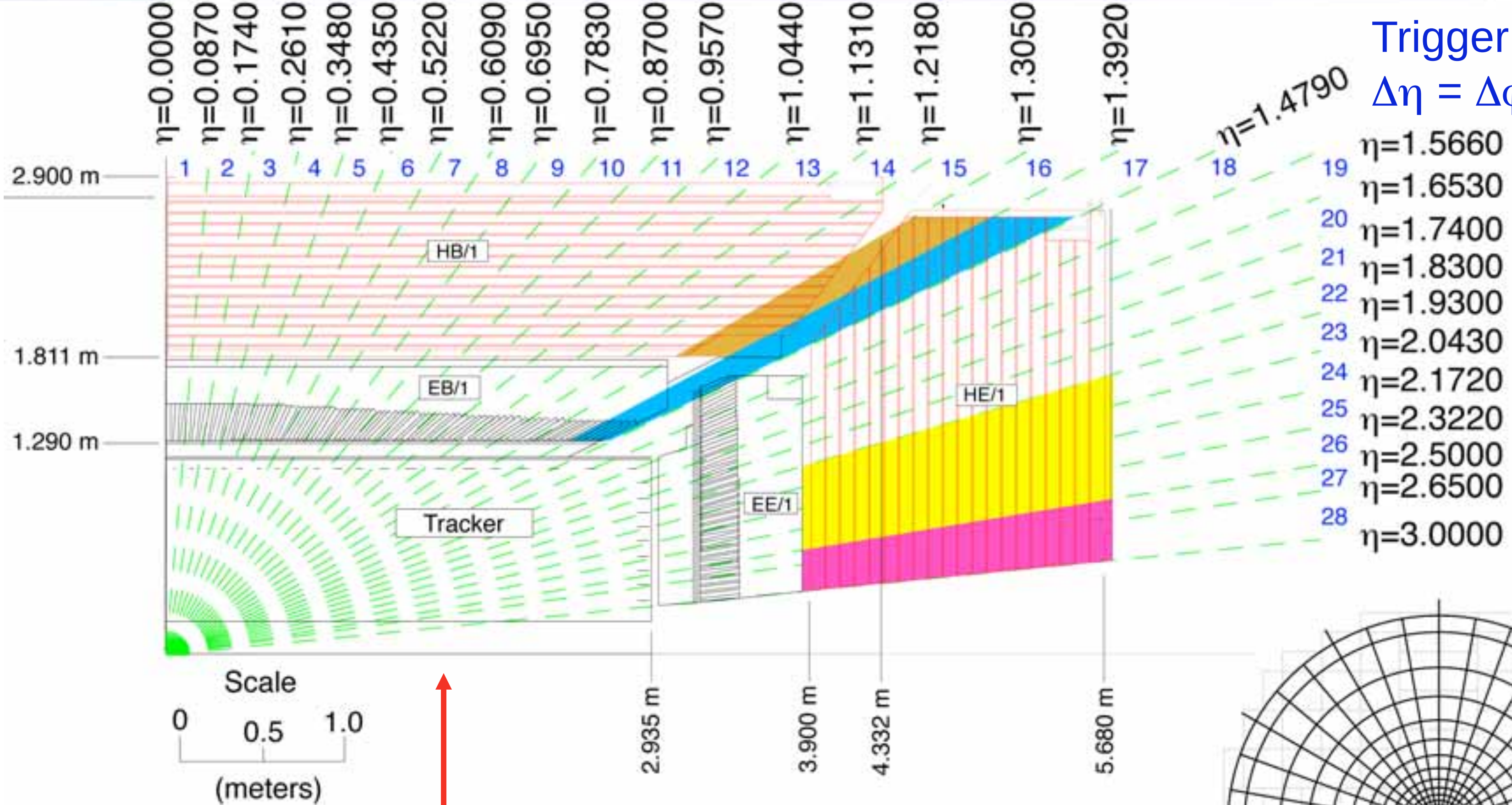
Complex Algorithms

Huge amounts of data

CMS Calorimeter Geometry

Trigger towers:

$\Delta\eta = \Delta\phi = 0.087$



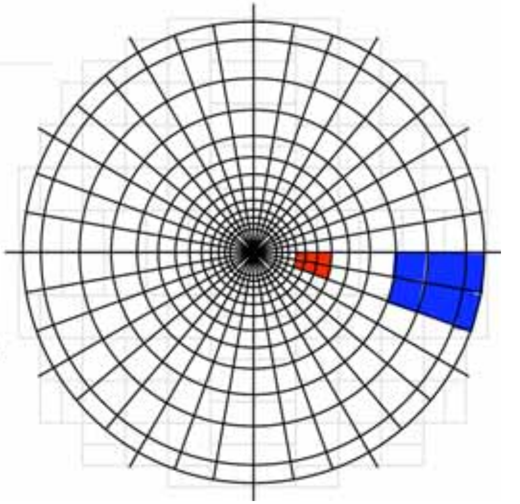
EB, EE, HB, HE map to 18 RCT crates

Provide e/γ and jet, τ, E_T triggers

2 HF calorimeters map on to 18 RCT crates

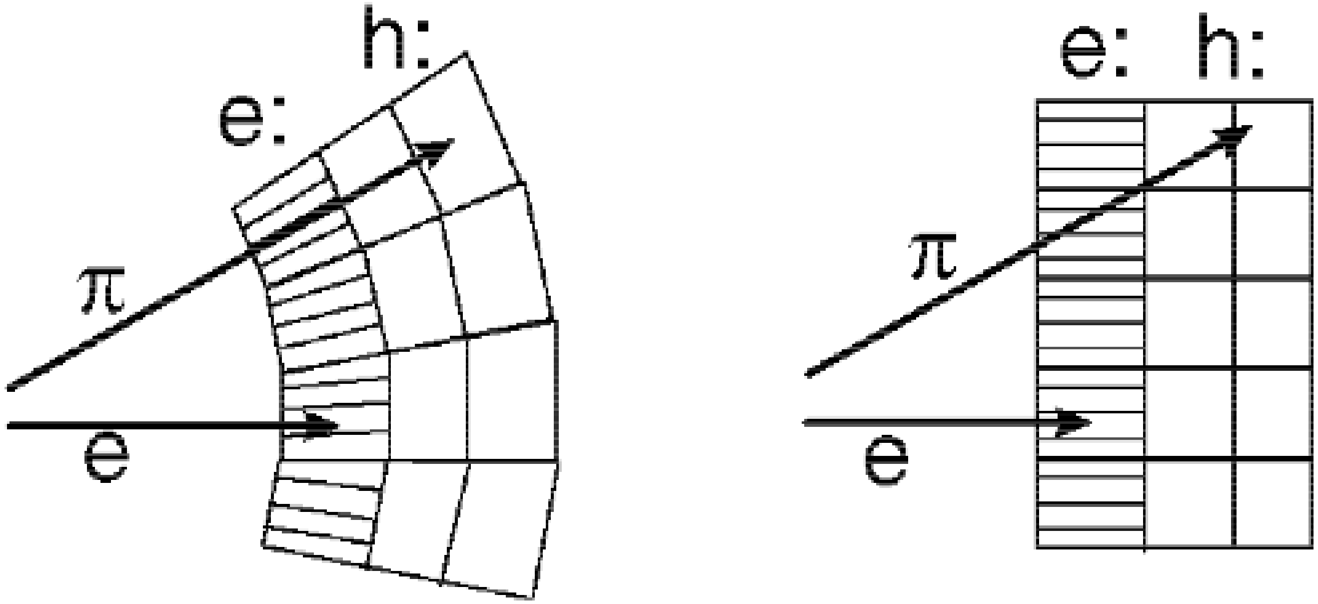
Readout segmentation: 36φ × 12η × 2z × 2F/B

Trigger Tower segmentation: 18φ × 4η × 2F/B



1 trigger tower (.087η x .087φ) = 5 x 5 ECAL xtals = 1 HCAL tower

Projective Geometry

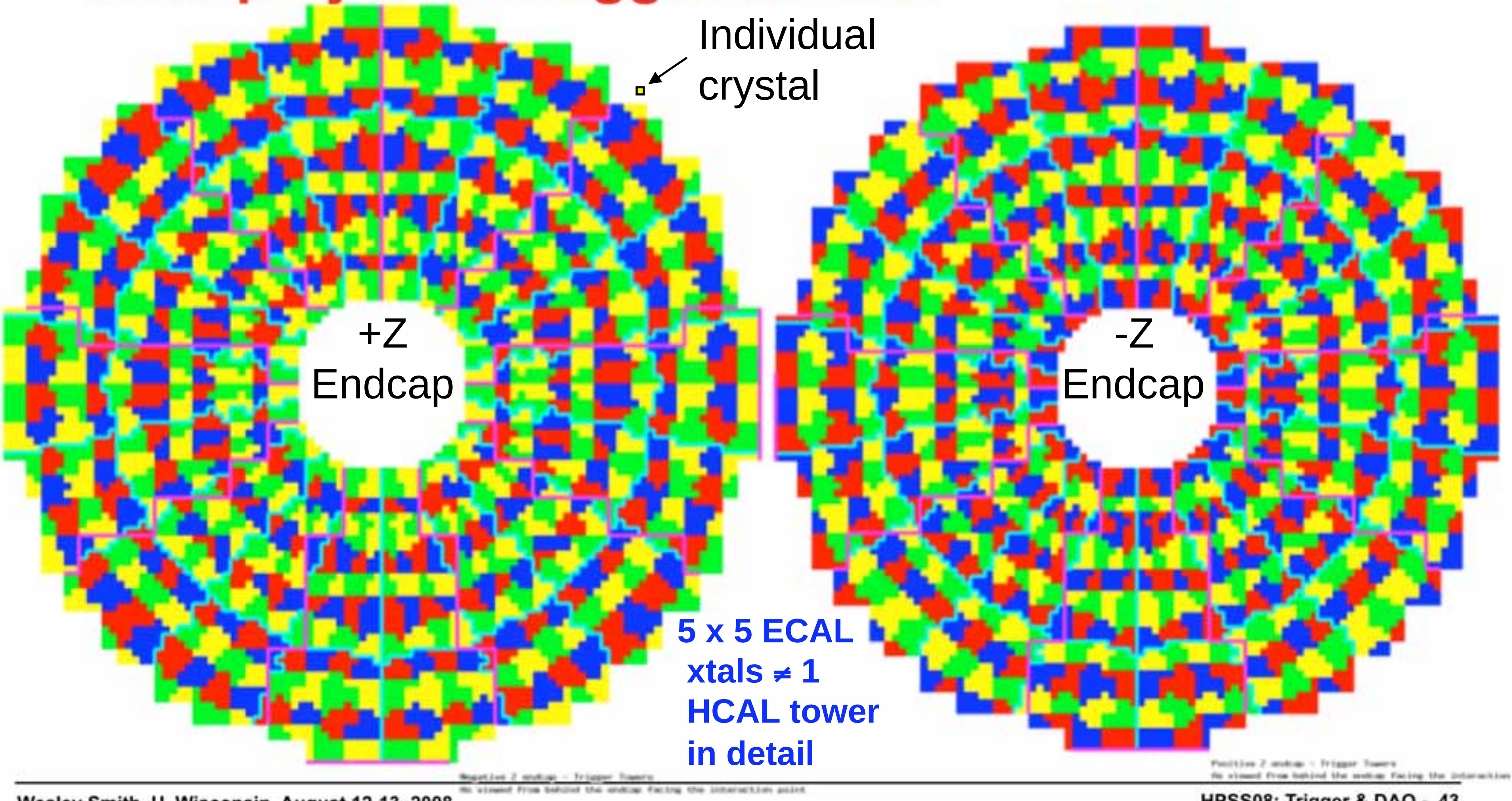


Projective geometry is important

- ZEUS: Used complicated cable mapping and pattern searches to reduce fake rate
- ATLAS, CMS: Calorimeters are built projective
- Mapping with muon system: Important for isolation

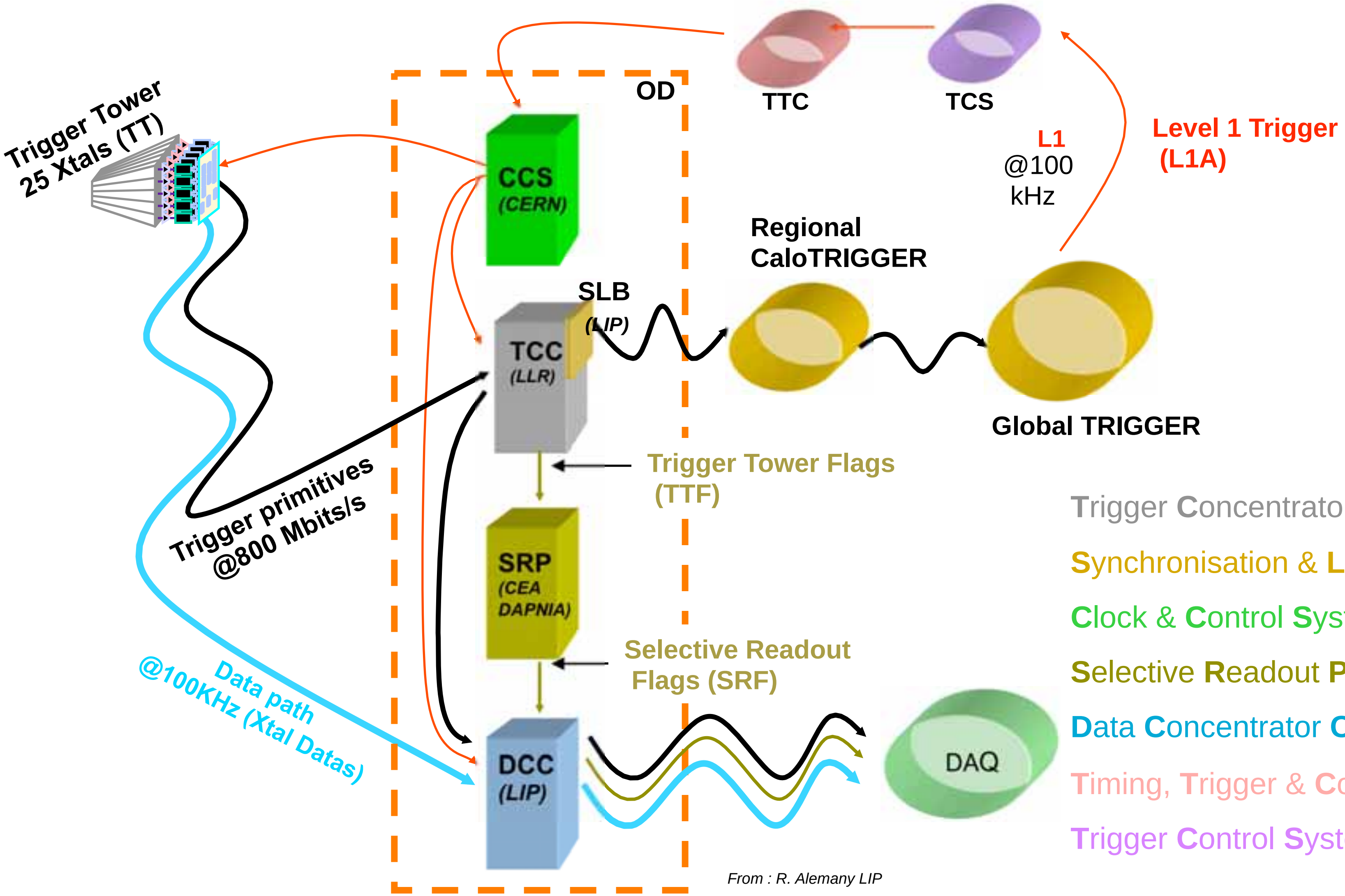
ECAL Endcap Geometry

Map non-projective x-y trigger crystal geometry onto projective trigger towers:



5 x 5 ECAL xtals ≠ 1 HCAL tower in detail

Calorimeter Trigger Processing



From : R. Alemany LIP

Trigger Concentrator Card

Synchronisation & Link Board

Clock & Control System

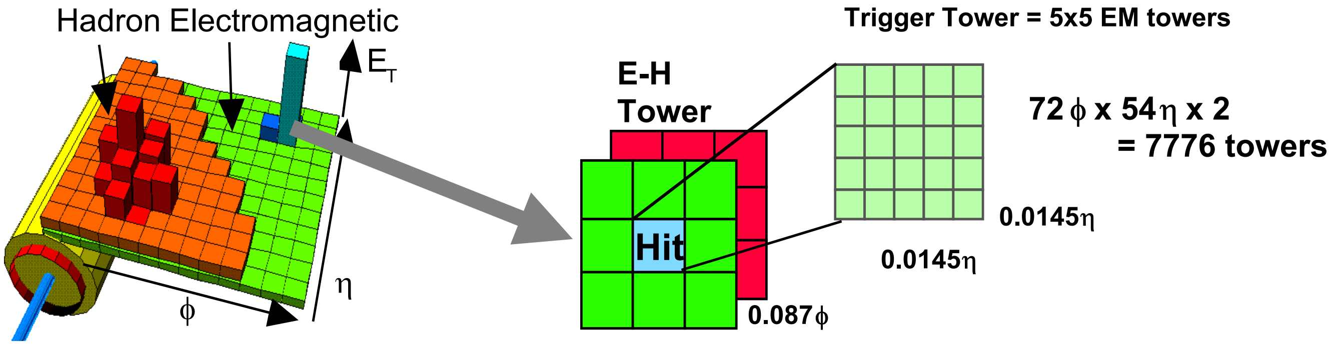
Selective Readout Processor

Data Concentrator Card

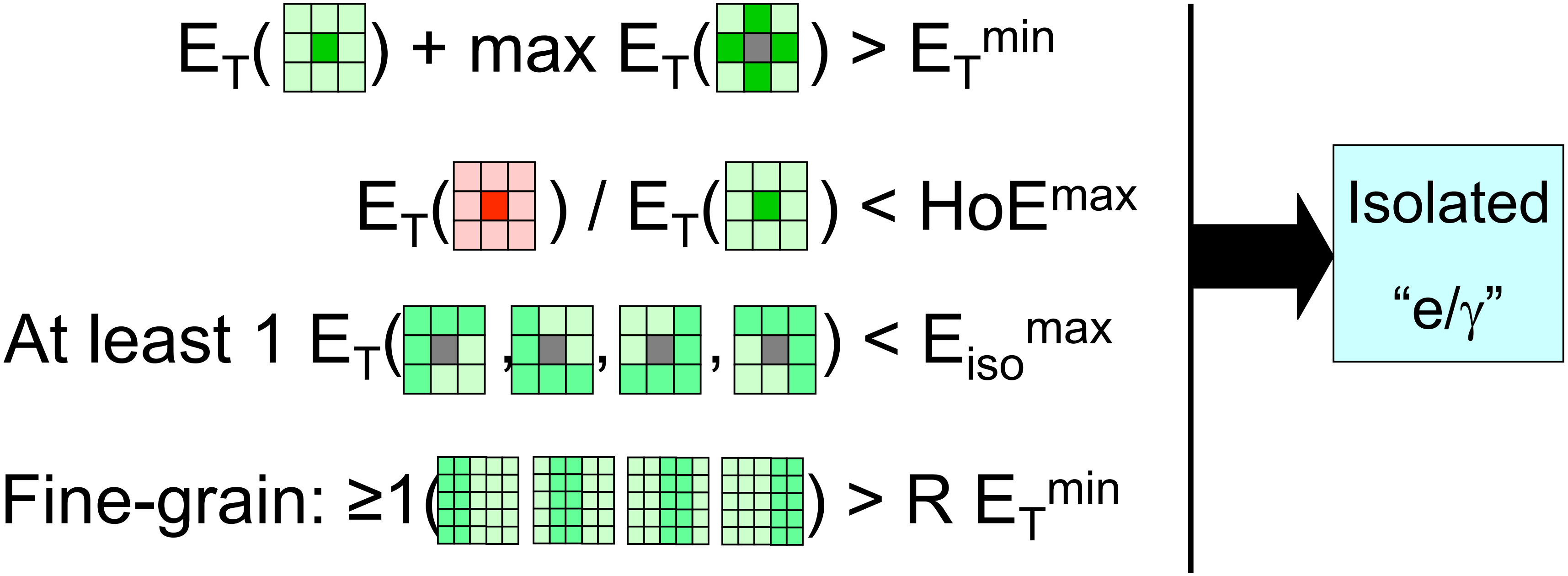
Timing, Trigger & Control

Trigger Control System

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



$72\,\phi \times 54\,\eta \times 2$ = 7776 towers



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

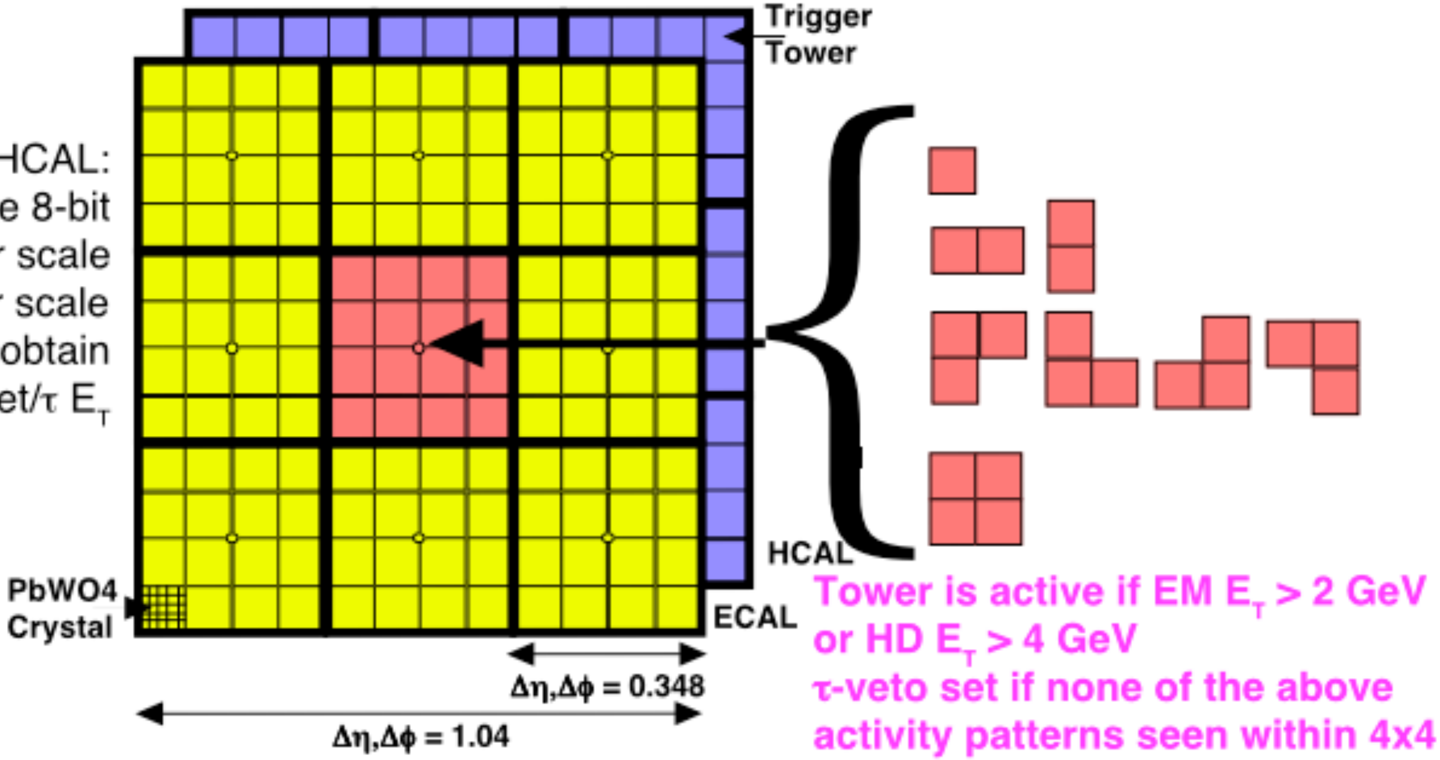
$E_T($▦$) / E_T($▦$) < HoE^{max}$

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

Fine-grain: ≥1(▦ ▦ ▦ ▦) $> R\, E_T^{min}$

Isolated "e/γ"

CMS τ / Jet Algorithm



Input from E/HCAL: Programmable 8-bit non-linear scale Converted to linear scale and summed to obtain 10-bit range jet/τ E_T

Tower is active if EM $E_T > 2$ GeV or HD $E_T > 4$ GeV

τ-veto set if none of the above activity patterns seen within 4x4

Jet or τ E_T

- 12x12 trigger tower E_T sums in 4x4 region steps with central region > others
- Larger trigger towers in HF but ~ same jet region size, 1.5 η x 1.0 φ

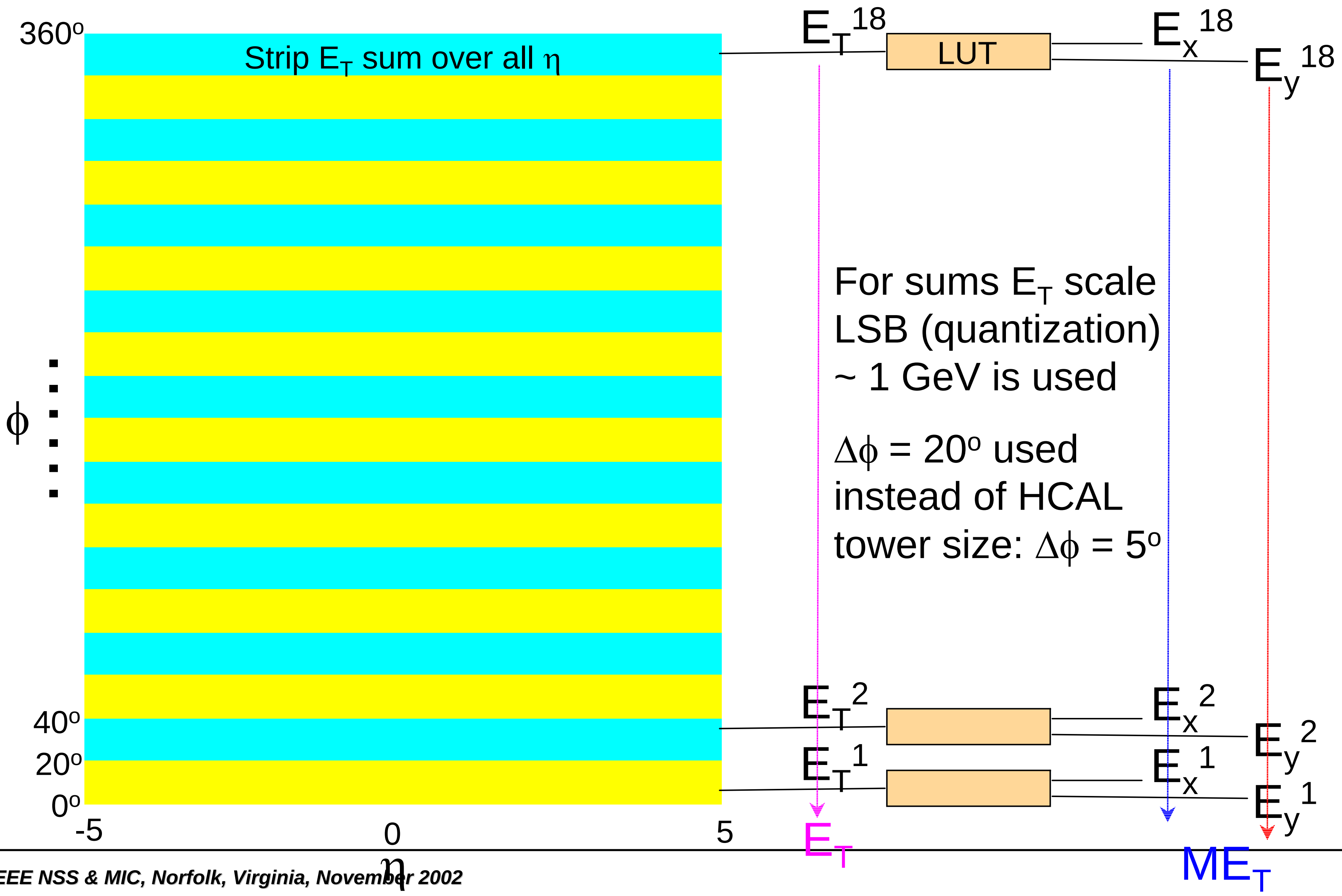
τ algorithm (isolated narrow energy deposits), within $-2.5 < \eta < 2.5$

- Redefine jet as τ jet if none of the nine 4x4 region τ-veto bits are on

Output

- Top 4 τ-jets and top 4 jets in central rapidity, and top 4 jets in forward rapidity

Missing / Total E_T Algorithm



For sums E_T scale LSB (quantization) ~ 1 GeV is used

Δφ = 20° used instead of HCAL tower size: Δφ = 5°

H_T Trigger

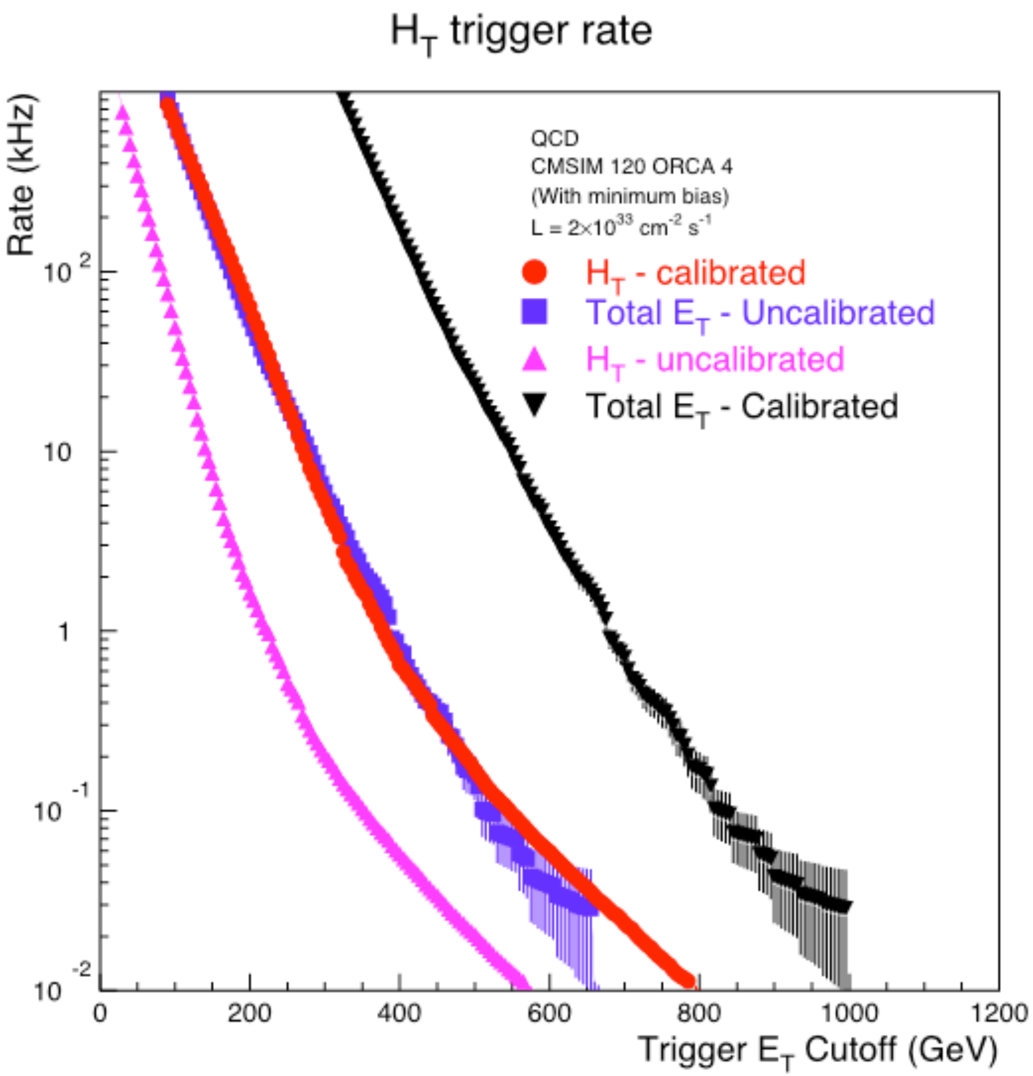
Total scalar E_T integrates too much noise and is not easily calibrated

- At L1 tower-by-tower E_T calibration is not available

However, jet calibration is available as function of (E_T, η, ϕ)

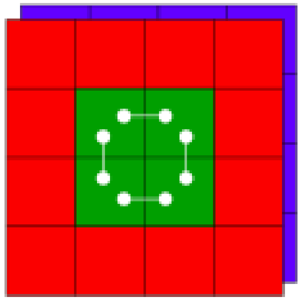
Therefore, H_T which is the sum of scalar E_T of all high E_T objects in the event is more useful for heavy particle discovery/study

- SUSY sparticles
- Top

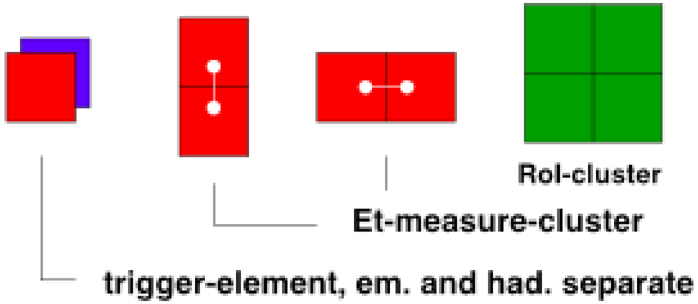


ATLAS Calorimeter Algorithms I

Electron/photon trigger

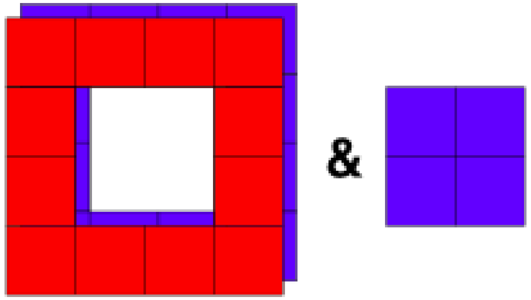


4 x 4 window
0.1 x 0.1 elements
step by 1 element
|Eta|<2.5

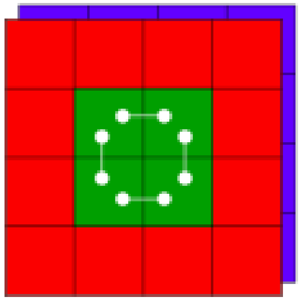


RoI-cluster
Et-measure-cluster
trigger-element, em. and had. separate

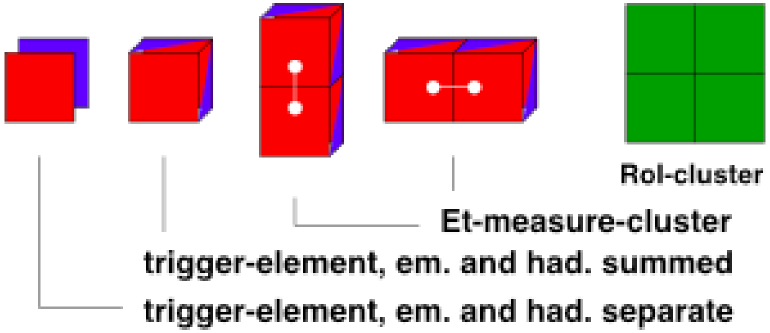
Isolation:



Hadron/tau trigger

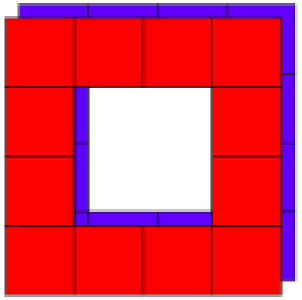


4 x 4 window
0.1 x 0.1 elements
step by 1 element
|Eta|<2.5



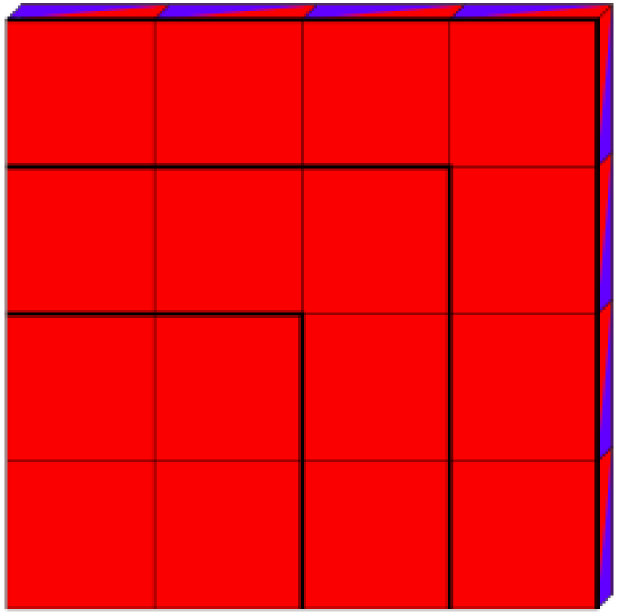
RoI-cluster
Et-measure-cluster
trigger-element, em. and had. summed
trigger-element, em. and had. separate

Isolation:

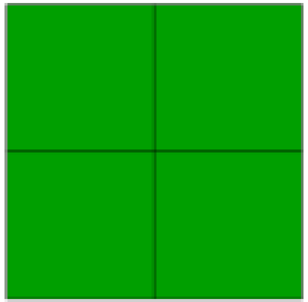


ATLAS Calorimeter Algorithms II

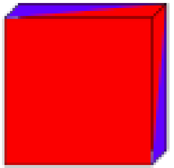
Jet trigger



programmable
4 x 4 or 3 x 3 or
2 x 2 window
0.2 x 0.2 jet-elements
step by 1 jet-element
|Eta| < 3.2

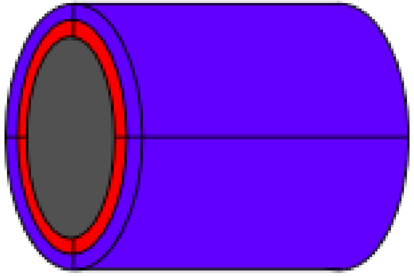


RoI-cluster



Jet-element, em. + had. summed

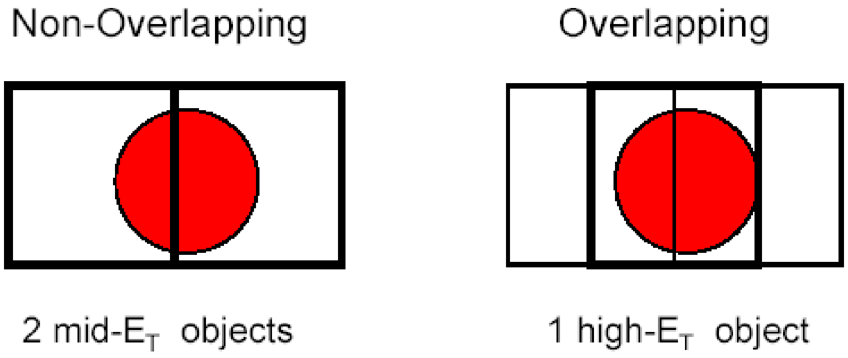
Et-miss / sum-Et trigger



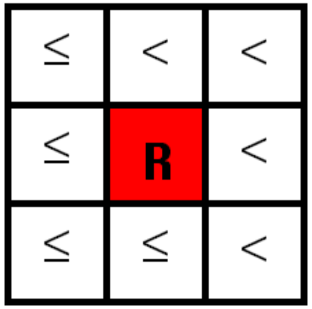
sum of Et
sum of Ex and Ey
|Eta| < 4.9

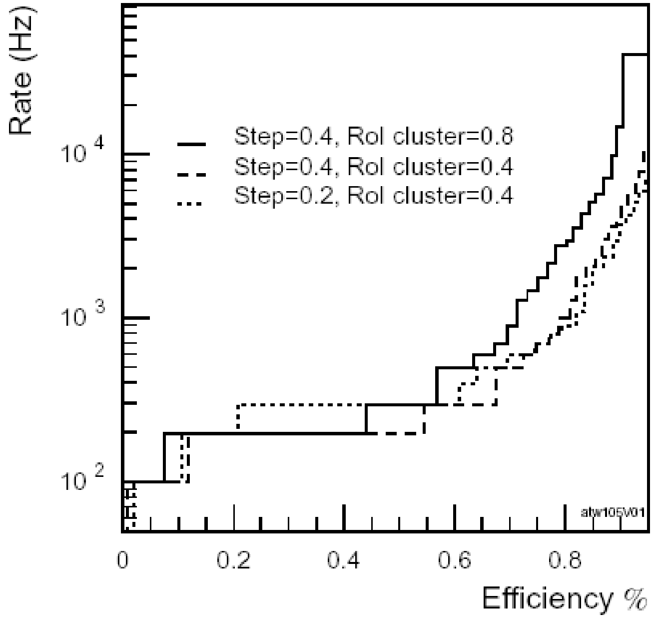
Jets

- 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



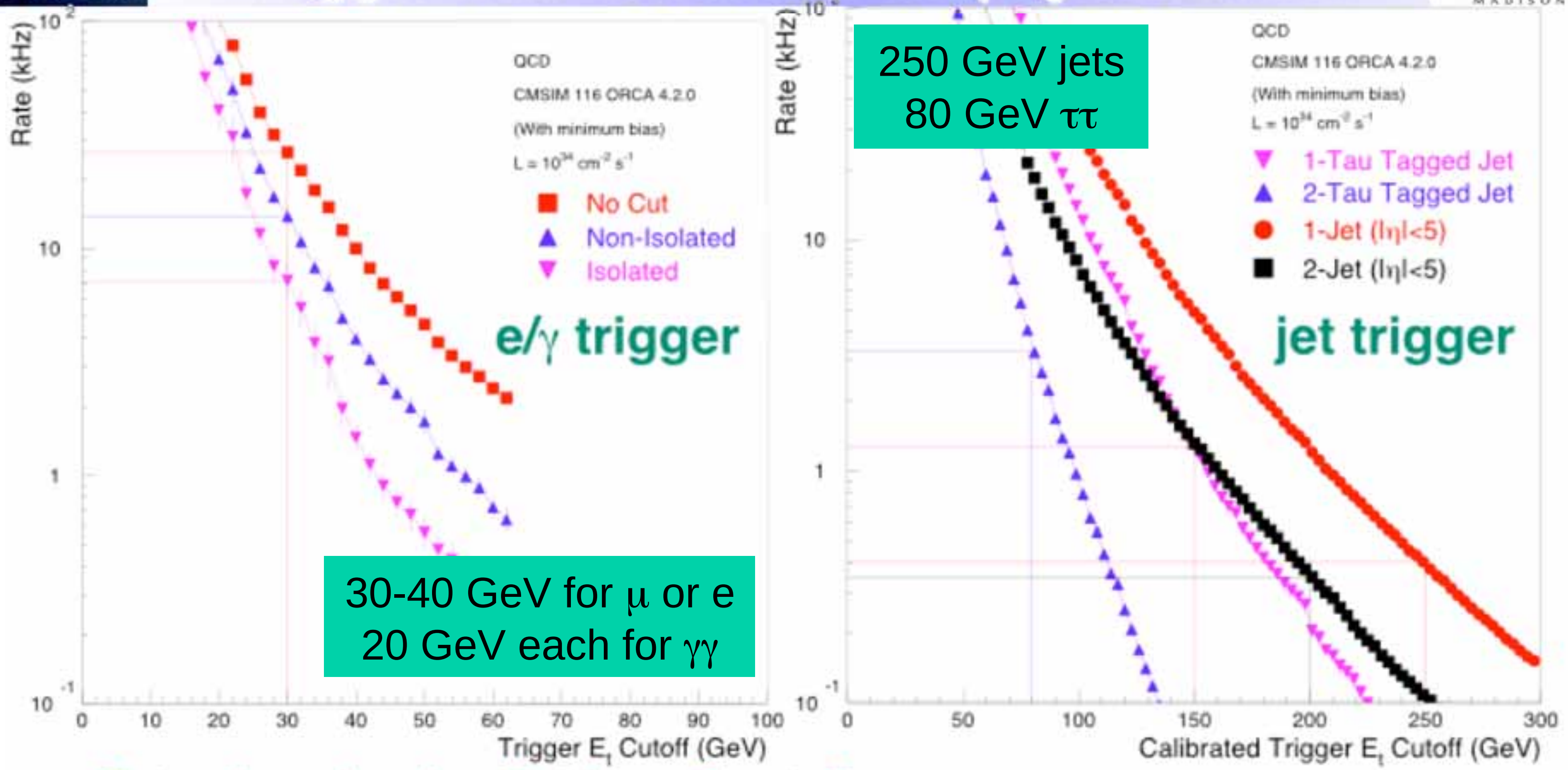
ATLAS: use ROI clusters, defined as maximum found in sliding window by half the jet window width





Level-1 Trigger Rates:

Trigger cuts determine the physics reach



250 GeV jets
80 GeV ττ

30-40 GeV for μ or e
20 GeV each for γγ

- **Efficiency for H→γγ and H→4 leptons = >90% (in fiducial volume of detector)**
- **Efficiency for WH and ttH production with W→lν = ~85%**
- **Efficiency for qqH with H→ττ (τ→1/3 prong hadronic) = ~75%**
- **Efficiency for qqH with H→invisible or H→bb = ~40-50%**

ATLAS LVL1 Trigger

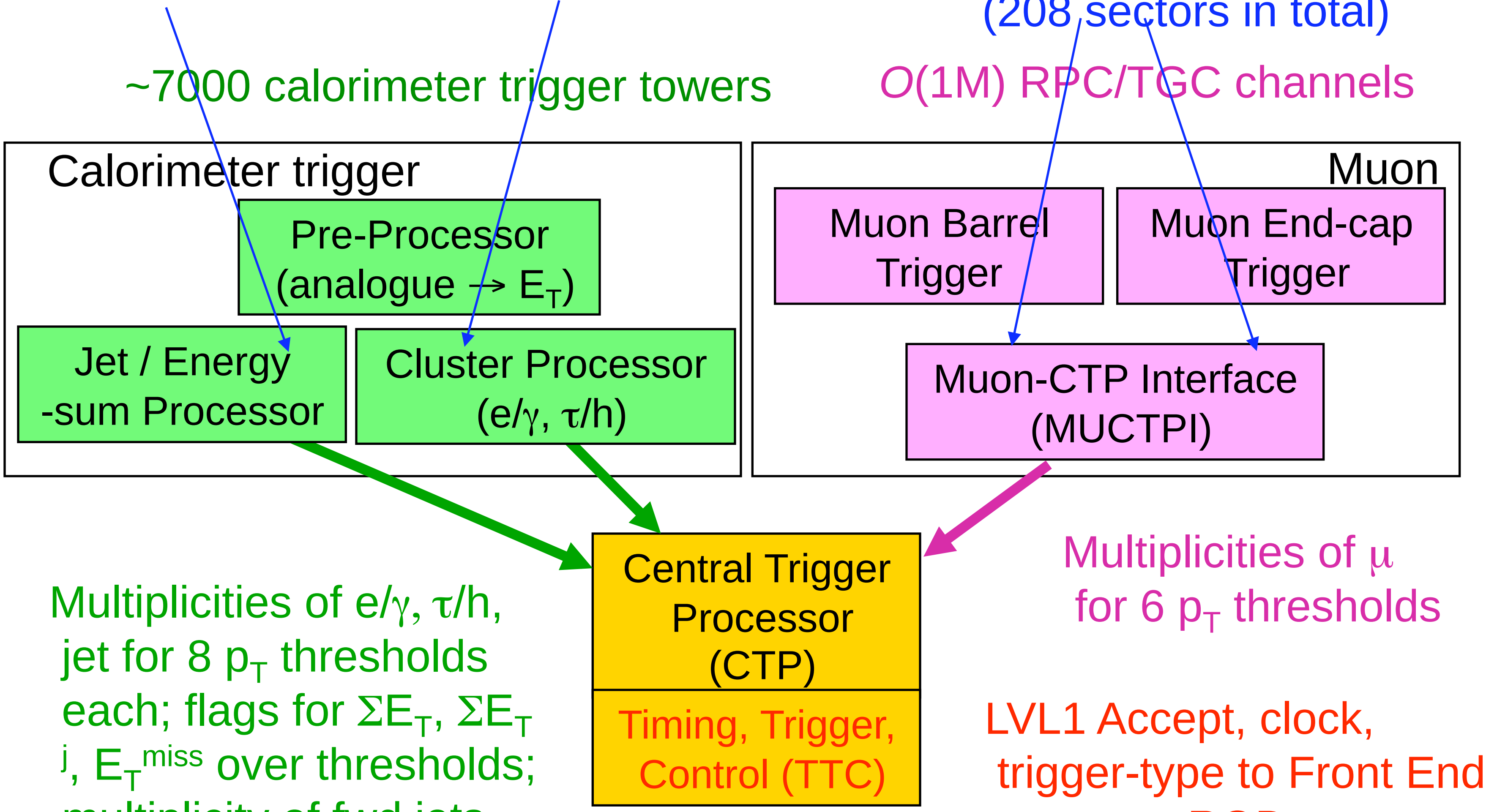
E_T values (0.2×0.2)
EM & HAD

E_T values (0.1×0.1)
EM & HAD

p_T, η, ϕ information on
up to 2 μ candidates/sector
(208 sectors in total)

~7000 calorimeter trigger towers

O(1M) RPC/TGC channels



Calorimeter trigger

Pre-Processor
(analogue → E_T)

Jet / Energy
-sum Processor

Cluster Processor
(e/γ, τ/h)

Muon

Muon Barrel
Trigger

Muon End-cap
Trigger

Muon-CTP Interface
(MUCTPI)

Central Trigger
Processor
(CTP)

Timing, Trigger,
Control (TTC)

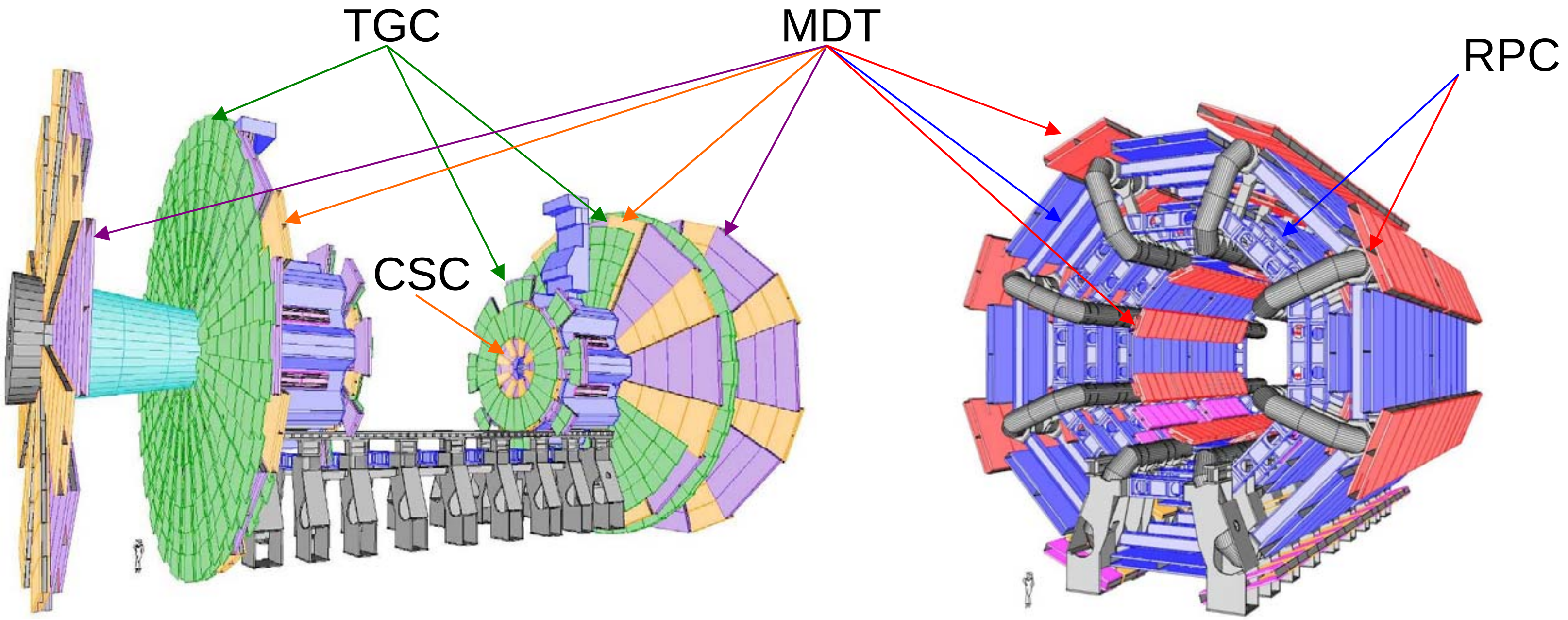
Multiplicities of e/γ, τ/h, jet for 8 p_T thresholds each; flags for ΣE_T, ΣE_T^j, E_T^{miss} over thresholds; multiplicity of fwd jets

Multiplicities of μ
for 6 p_T thresholds

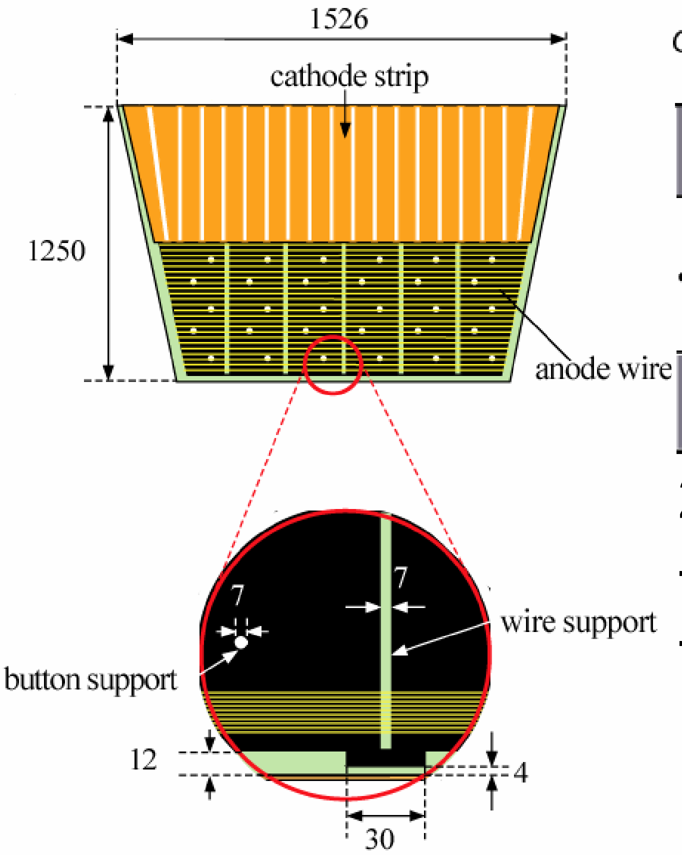
LVL1 Accept, clock,
trigger-type to Front End
systems, RODs, etc

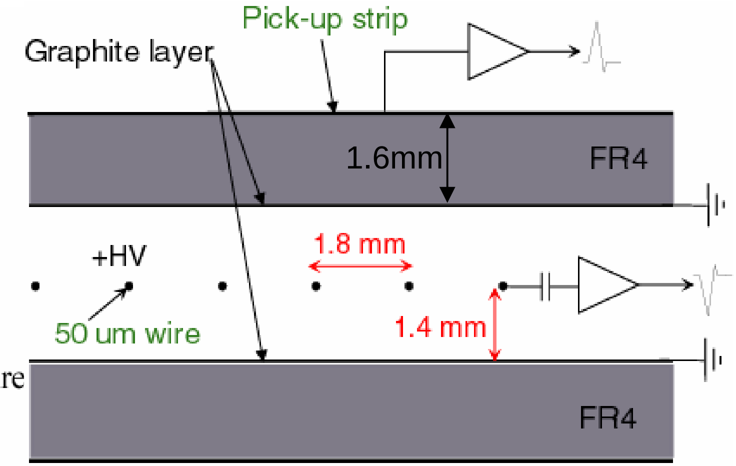
4 technologies of muon system

	Function	Coverage	No. of chambers	No. of channels
TGC Thin Gap Chamber	Triggering 2nd coordinate	$1.05<\|\eta\|<2.7$ (<2.4 for triggering)	3588	318000
RPC Resistive Plate Chamber	Triggering 2nd coordinate	$\|\eta\|<1.05$	606	373000
MDT Monitored Drift Tube	Precision tracking (η)	$\|\eta\|<2.7$ (innermost layer : $\|\eta\|< 2.0$)	1150	354000
CSC Cathode Strip Chamber	Precision tracking (η and ϕ)	$2.0<\|\eta\|<2.7$	32	31000



TGC (Thin Gap Chamber)



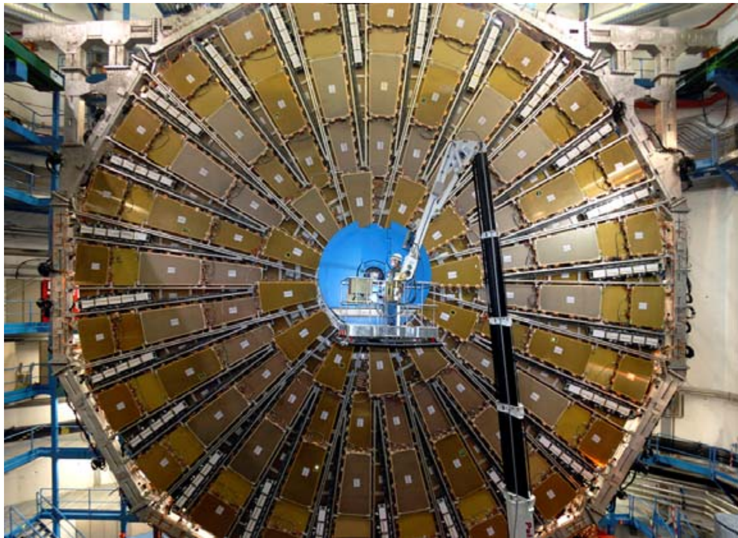


Gas mixture
CO_2/n-pentane
(55/45)

High Voltage
2900 V

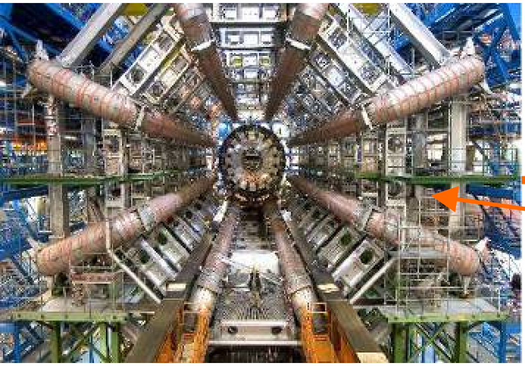
2D readout
- Anode wire readout in η direction
- Cathode strip readout in ϕ direction

Fast response : <25 ns
High efficiency : >98%
Radiation hard : ~0.6 C/cm
High rate capability : >1kHz/cm^2

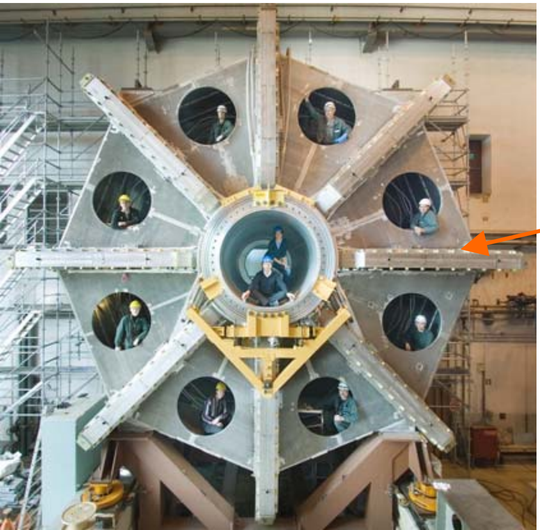


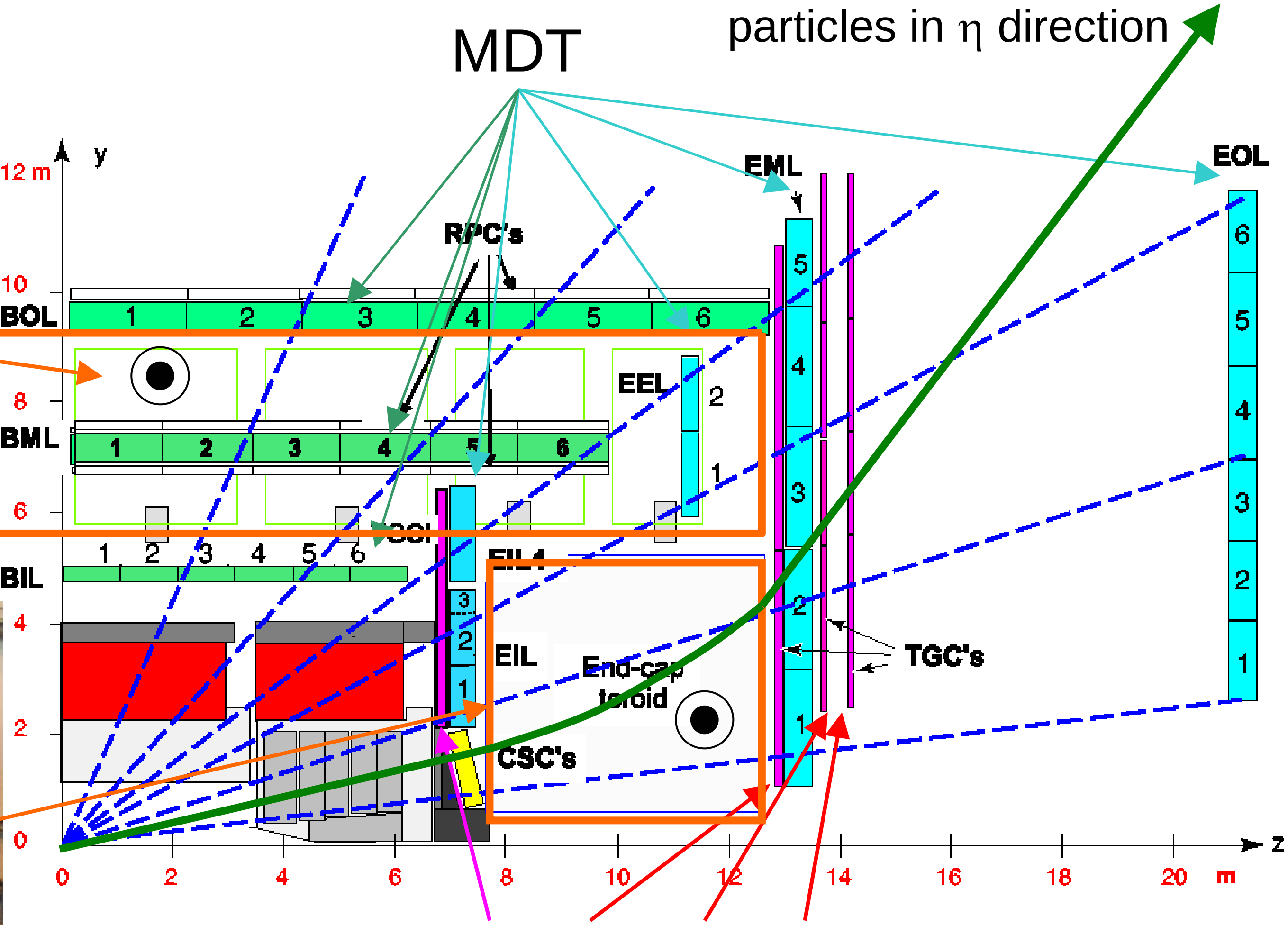
ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) muon system

Barrel toroidal magnet



Endcap toroidal magnet



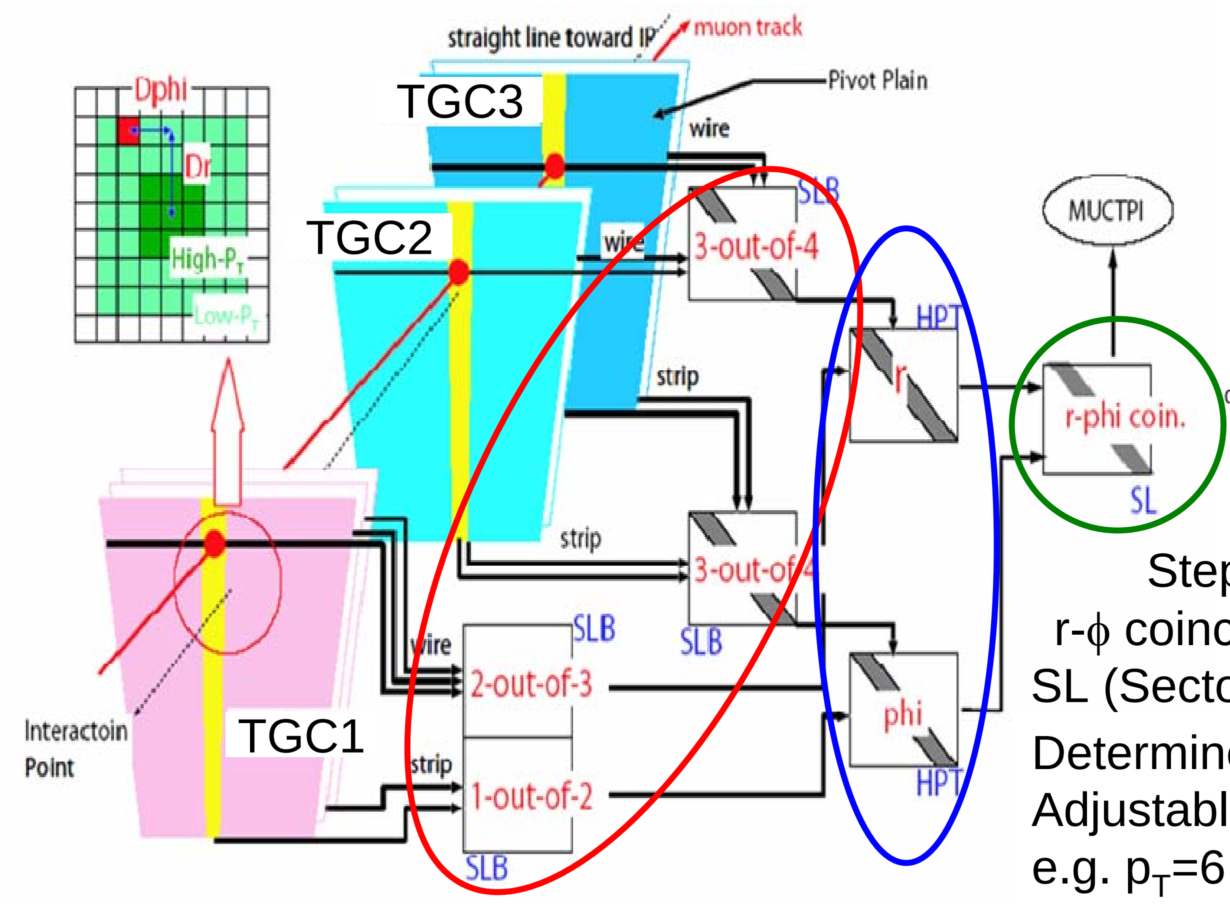


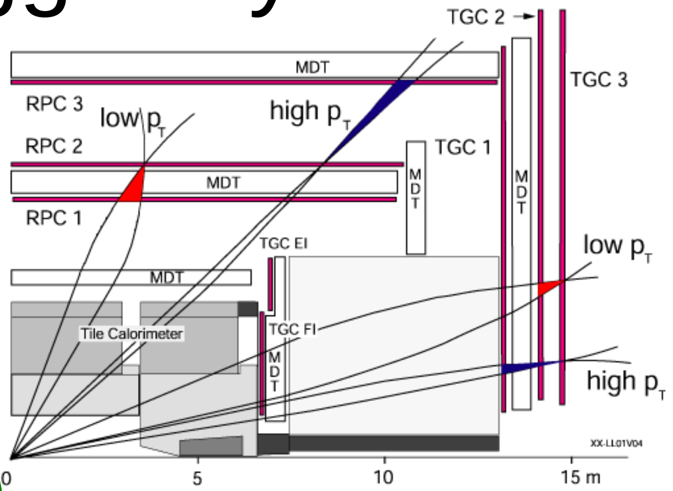
MDT

Toroidal magnets bend particles in η direction

TGC : 2 + $\underbrace{3 + 2 + 2}_{\text{Triggering}}$ = 9 layers

Level1 Endcap Muon Trigger System





Step 1
1 or 2-station coincidence
for low p_T muons
SLB (SLave Board)

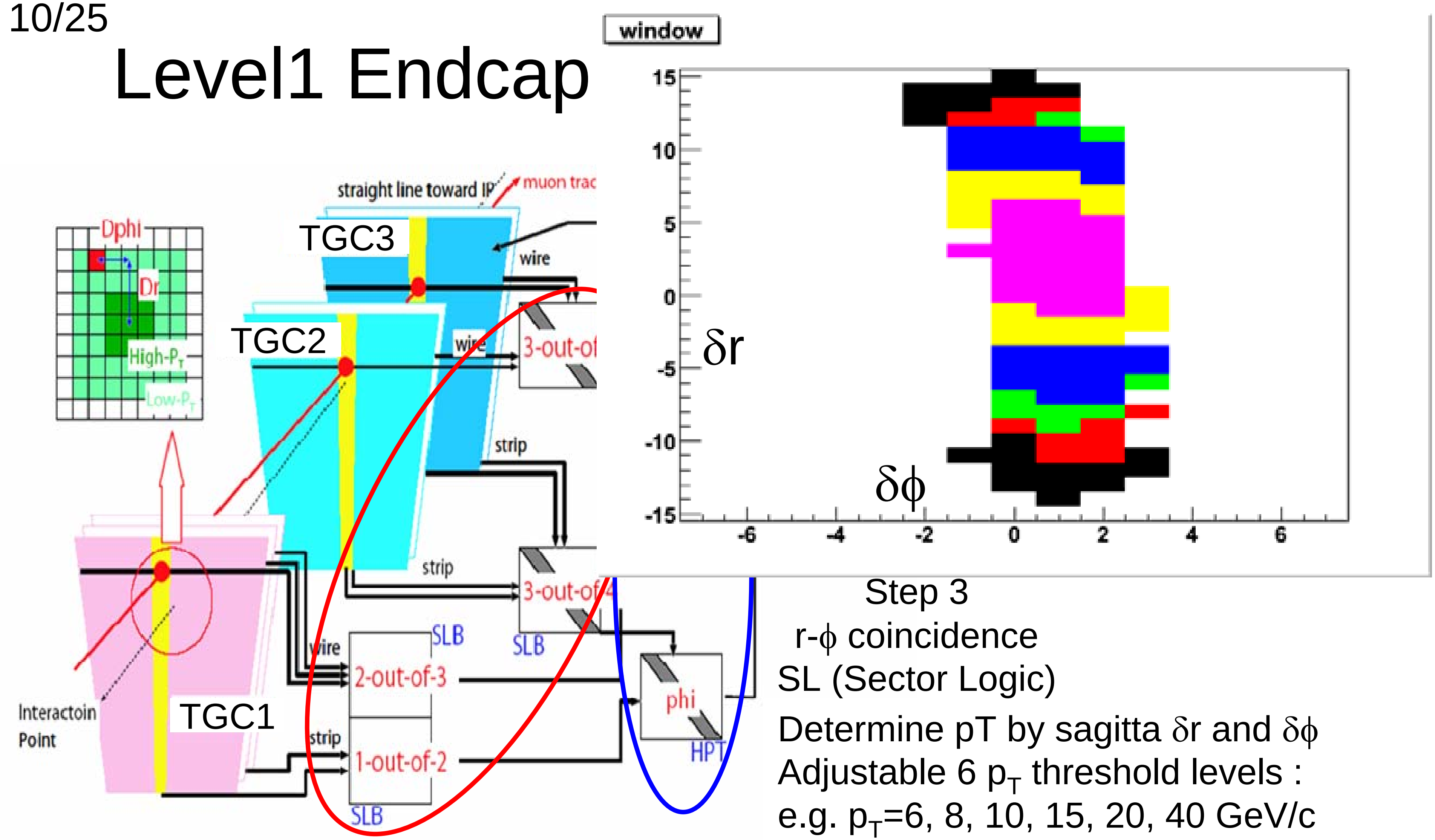
Step 2
3-station coincidence
for high p_T muons
HPT (High PT board)

Step 3
r-ϕ coincidence
SL (Sector Logic)

Determine pT by sagitta δr and $\delta\phi$
Adjustable 6 p_T threshold levels :
e.g. p_T=6, 8, 10, 15, 20, 40 GeV/c

Expected rate at 10^{34} $cm^{-2}s^{-1}$
6 GeV/c threshold : 87 kHz
20 GeV/c threshold : 8.2 kHz

Level1 Endcap



Step 3
r-ϕ coincidence
SL (Sector Logic)

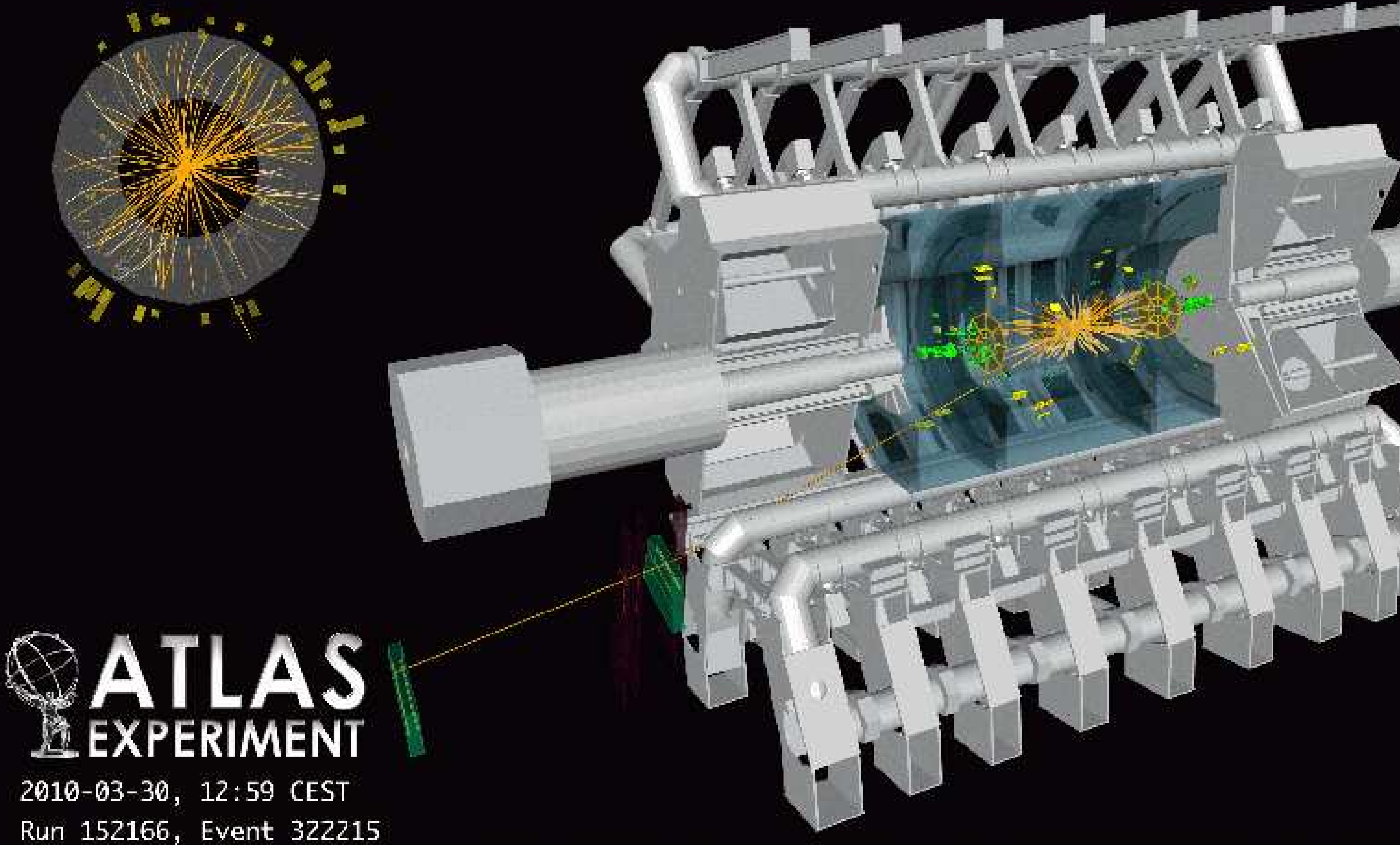
Determine pT by sagitta δr and δϕ
Adjustable 6 p_T threshold levels :
e.g. p_T=6, 8, 10, 15, 20, 40 GeV/c

Step 1
1 or 2-station coincidence
for low p_T muons
SLB (SLave Board)

Step 2
3-station coincidence
for high p_T muons
HPT (High PT board)

Expected rate at 10^{34} $cm^{-2}s^{-1}$
6 GeV/c threshold : 87 kHz
20 GeV/c threshold : 8.2 kHz

Collision Event at 7 TeV with Muon Candidate

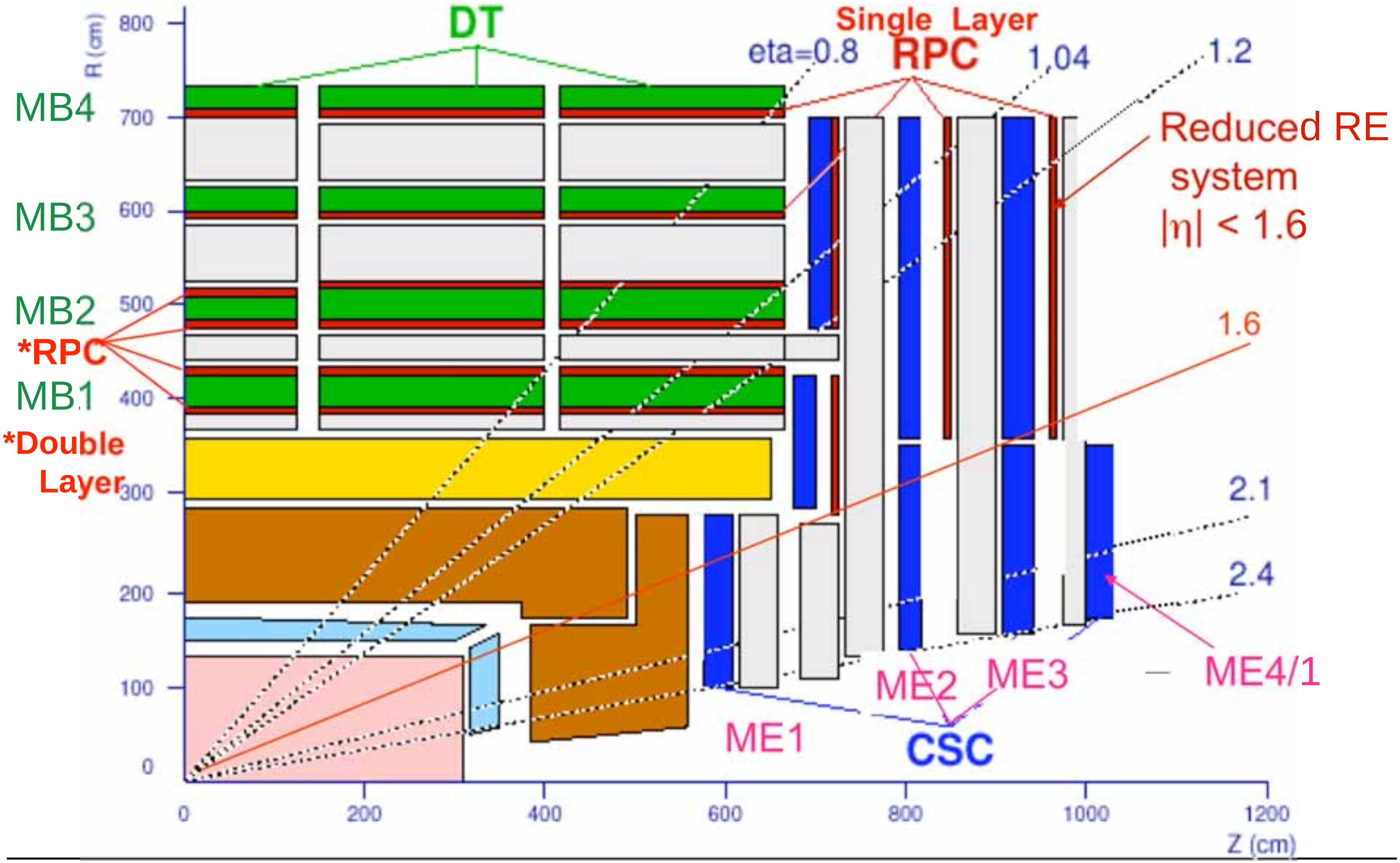


ATLAS
EXPERIMENT

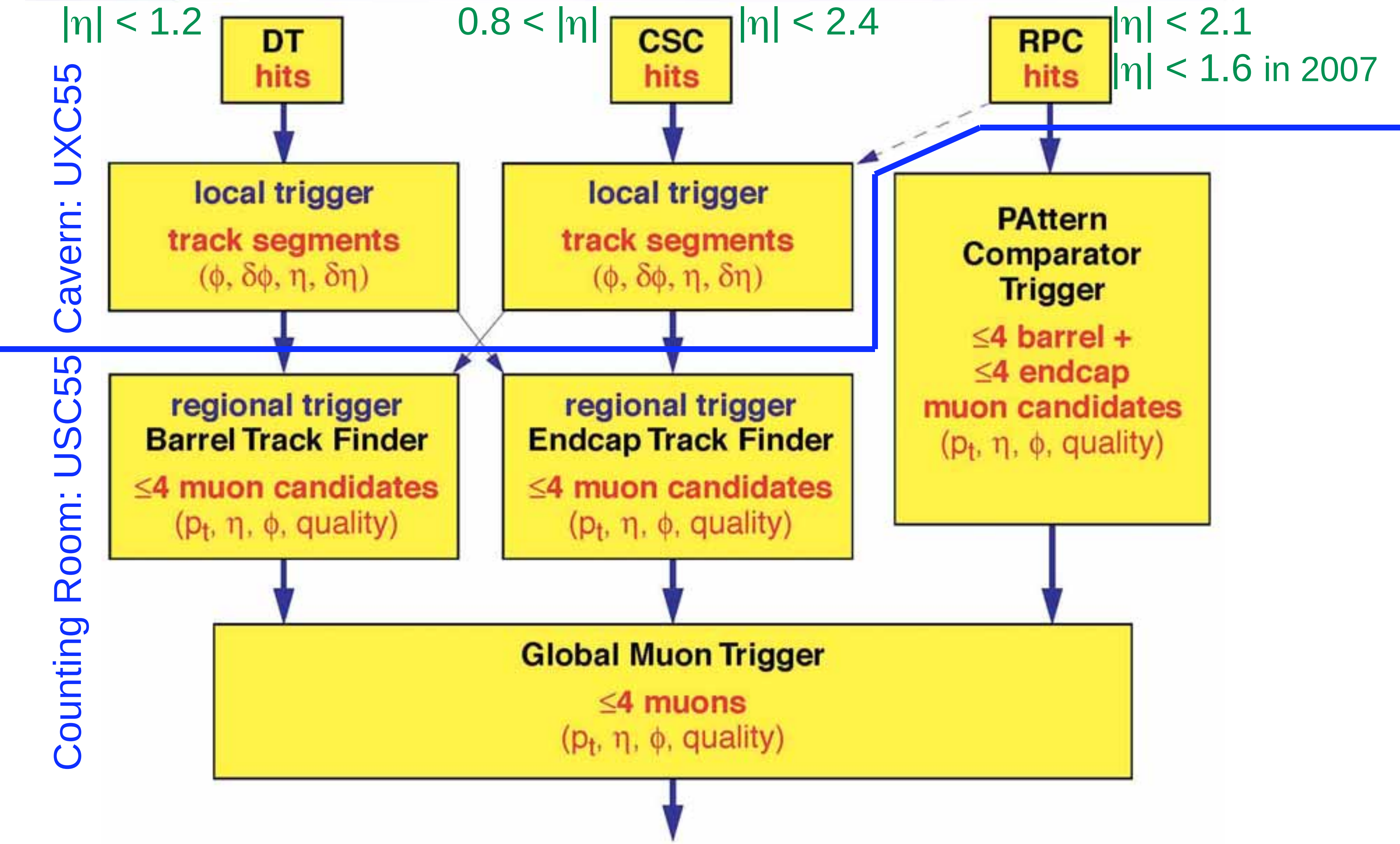
2010-03-30, 12:59 CEST
Run 152166, Event 322215

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

CMS Muon Chambers



Muon Trigger Overview



$|\eta| < 1.2$

$0.8 < |\eta|$

$|\eta| < 2.4$

$|\eta| < 2.1$

$|\eta| < 1.6$ in 2007

Cavern: UXC55

Counting Room: USC55

DT
hits

CSC
hits

RPC
hits

local trigger
track segments
$(\phi, \delta\phi, \eta, \delta\eta)$

local trigger
track segments
$(\phi, \delta\phi, \eta, \delta\eta)$

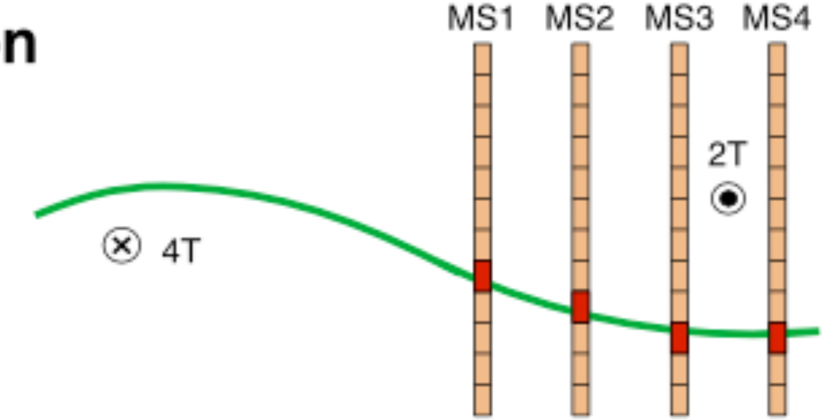
PAttern Comparator Trigger
≤4 barrel +
≤4 endcap
muon candidates
$(p_t, \eta, \phi$, quality)

regional trigger
Barrel Track Finder
≤4 muon candidates
$(p_t, \eta, \phi$, quality)

regional trigger
Endcap Track Finder
≤4 muon candidates
$(p_t, \eta, \phi$, quality)

Global Muon Trigger
≤4 muons
$(p_t, \eta, \phi$, quality)

CMS Muon Trigger Primitives



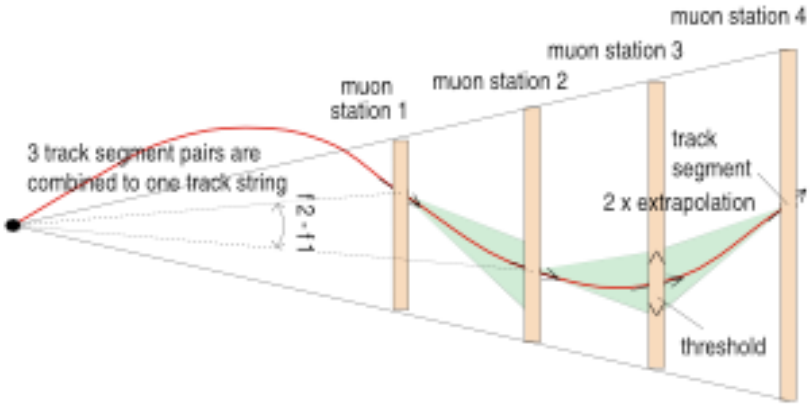
RPC pattern recognition
- Pattern catalog
- Fast logic

Memory to store patterns

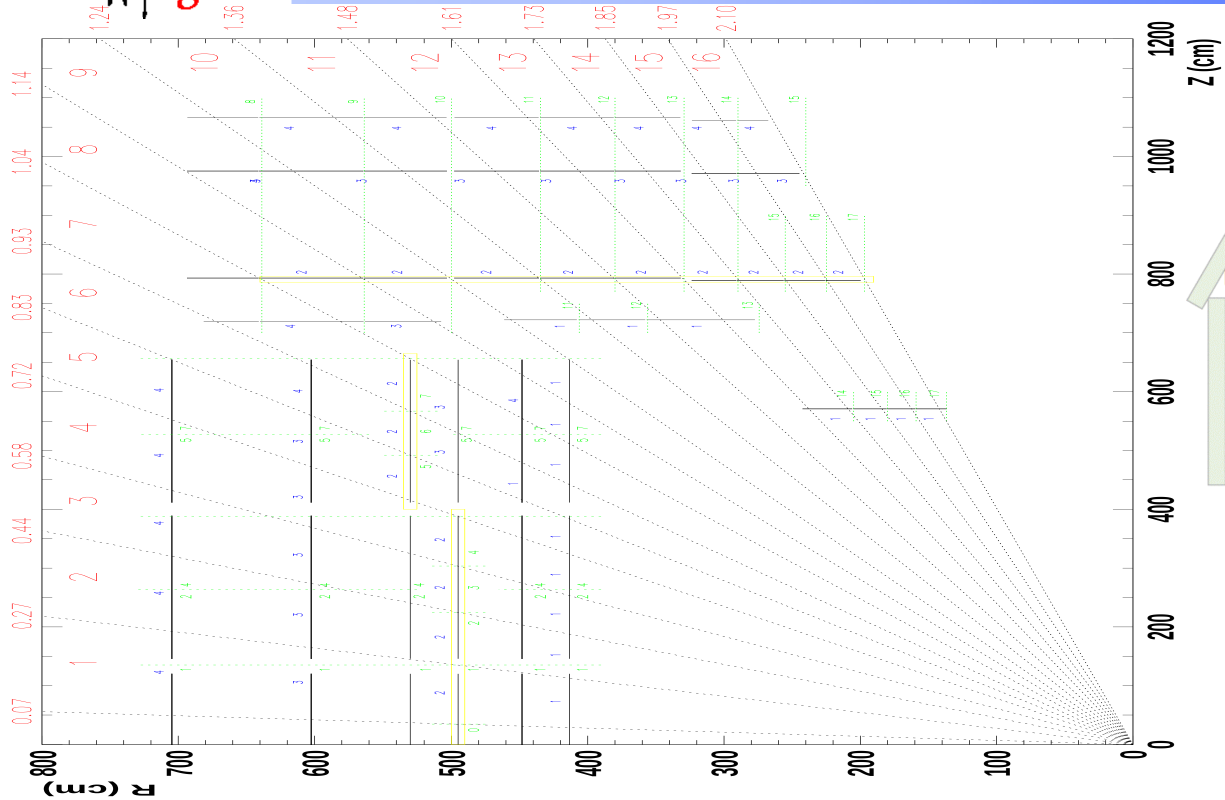
Fast logic for matching

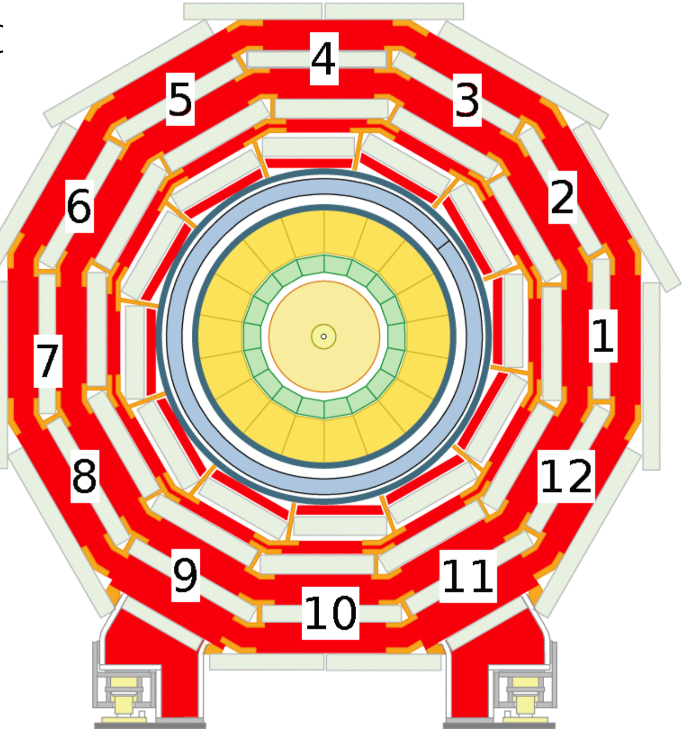
FPGAs are ideal

DT and CSC track finding:
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



System complexity





2 000 chambers of different shapes

165 000 strips – 1 bit electronic channels

~15 types of electronic boards

~2 000 pieces of electronic boards

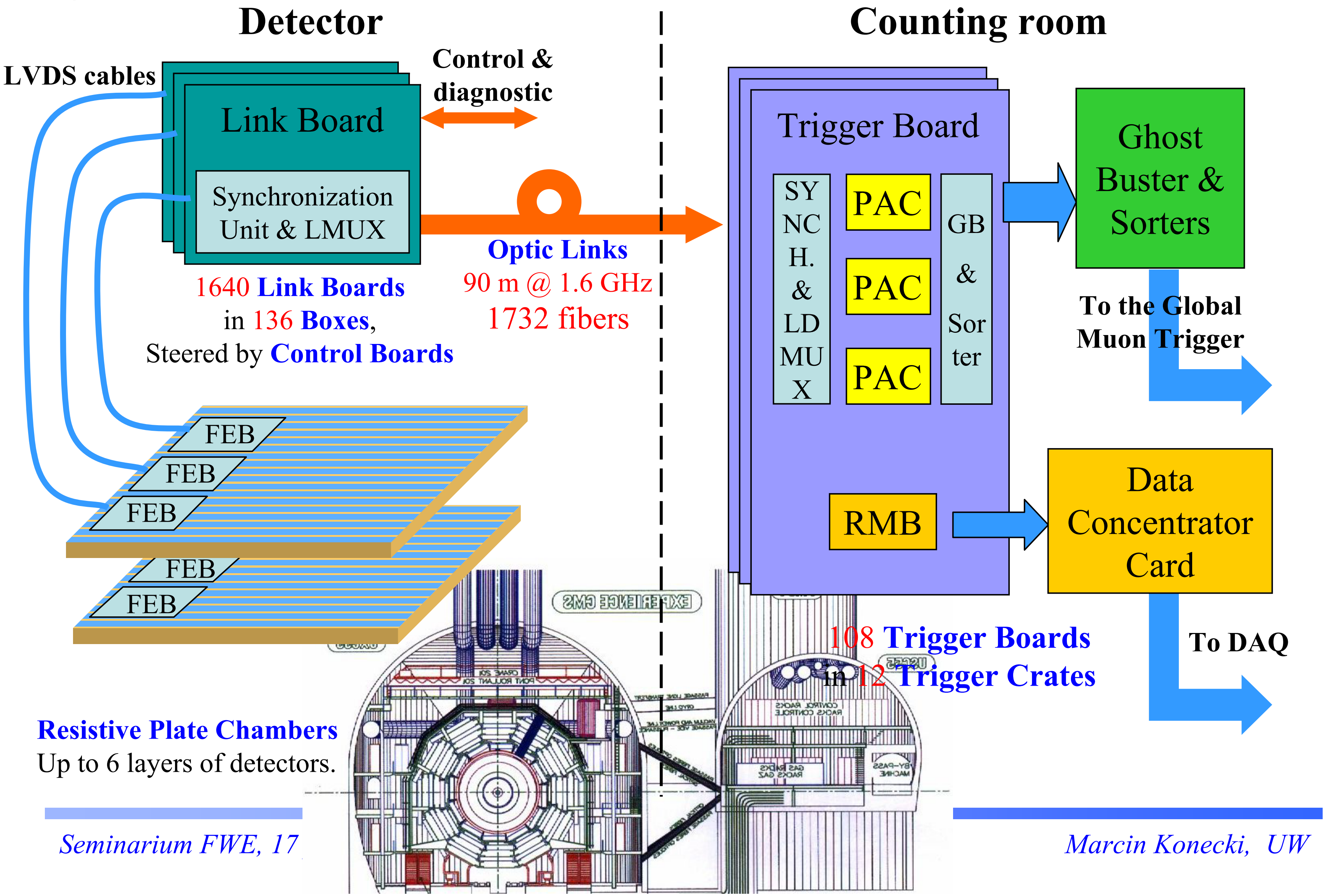
Synchronous system, working @ 40 MHz

Most boards programmable

Most boards controlled by computers

Kilometers of cables (electrical and optical)

RPC PAC Muon Trigger overview



Detector

Counting room

LVDS cables

Link Board

Synchronization Unit & LMUX

Control & diagnostic

Optic Links

90 m @ 1.6 GHz

1732 fibers

1640 **Link Boards** in 136 **Boxes**, Steered by **Control Boards**

FEB

FEB

FEB

FEB

FEB

Resistive Plate Chambers

Up to 6 layers of detectors.

Trigger Board

SYNCH. & LDMUX

PAC

PAC

PAC

GB & Sorter

RMB

Ghost Buster & Sorters

To the Global Muon Trigger

Data Concentrator Card

To DAQ

108 **Trigger Boards** in 12 **Trigger Crates**

PAC Tryger – zasada działania (II)

Mion przechodząc przez komory RPC znajdujące się w stacjach mionowych powoduje zapalenie pasków (stripów) komory.

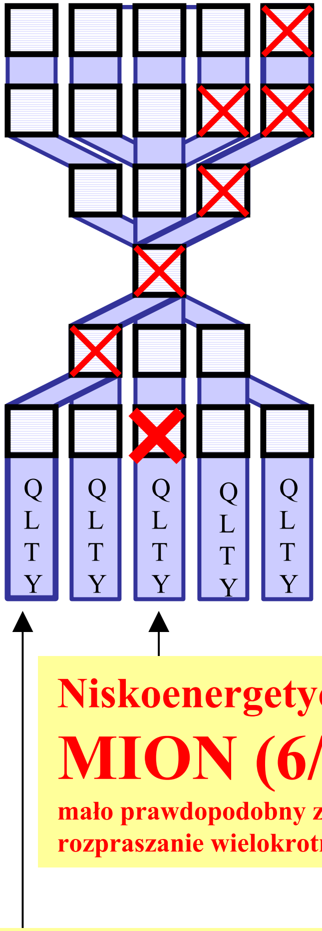
PACT – znajduje koincydencje zapalonych pasków w różnych płaszczyznach. Układ przestrzenny zapaleń porównywany jest ze wzorcem umożliwiając określenie pędu mionu.

Pożądane cechy trygera:

Czystość:
np. wymaganie zapaleń pasków we wszystkich możliwych płaszczyznach

Maksymalna efektywność
akceptacja przypadków z brakiem zapalonych pasków; niskoenergetyczne „nietypowe” miony często rozpoznawane jako wysokoenergetyczne.

Opracowano różne algorytmy dla trygera PAC (baseline, memory improved) oraz różne wzorce. Ich użycie uwarunkowane wymaganiami doświadczalnymi i parametrami komór.



Niskoenergetyczny MION (6/6),
mało prawdopodobny ze względu na rozpraszanie wielokrotne

Wysokoenergetyczny MION (5/6)

CMS Global Trigger

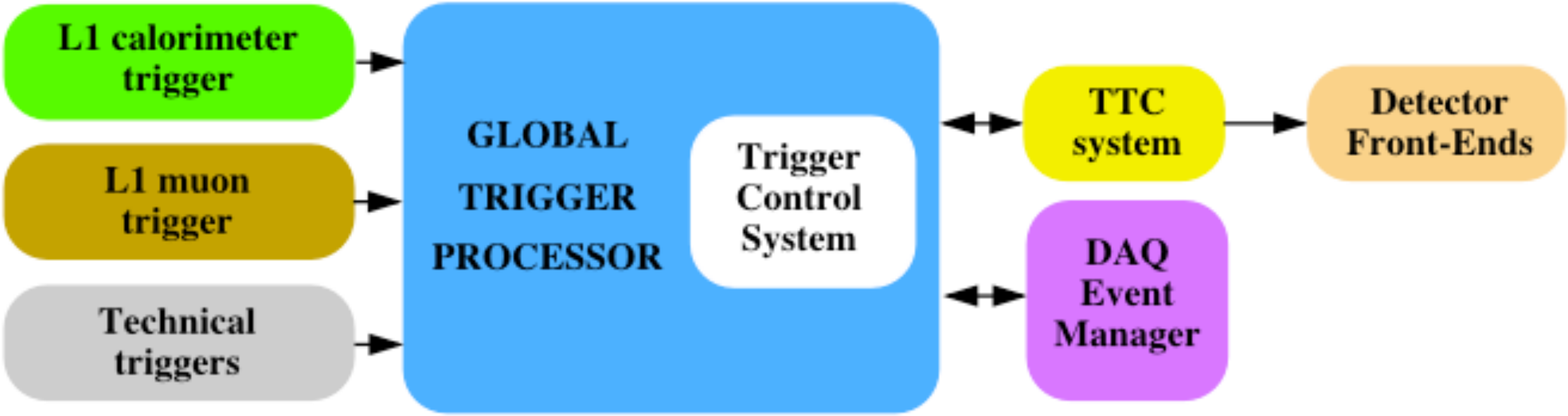
- Vienna

Input:

- Jets: 4 Central, 4 Forward, 4 Tau-tagged, & Multiplicities
- Electrons: 4 Isolated, 4 Non-isolated
- 4 Muons (from 8 RPC, 4 DT & 4 CSC w/P_t & quality)
  - All above include location in η and ϕ
- Missing E_T & Total E_T

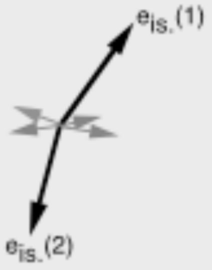
Output

- L1 Accept from combinations & proximity of above



Global L1 Trigger Algorithms

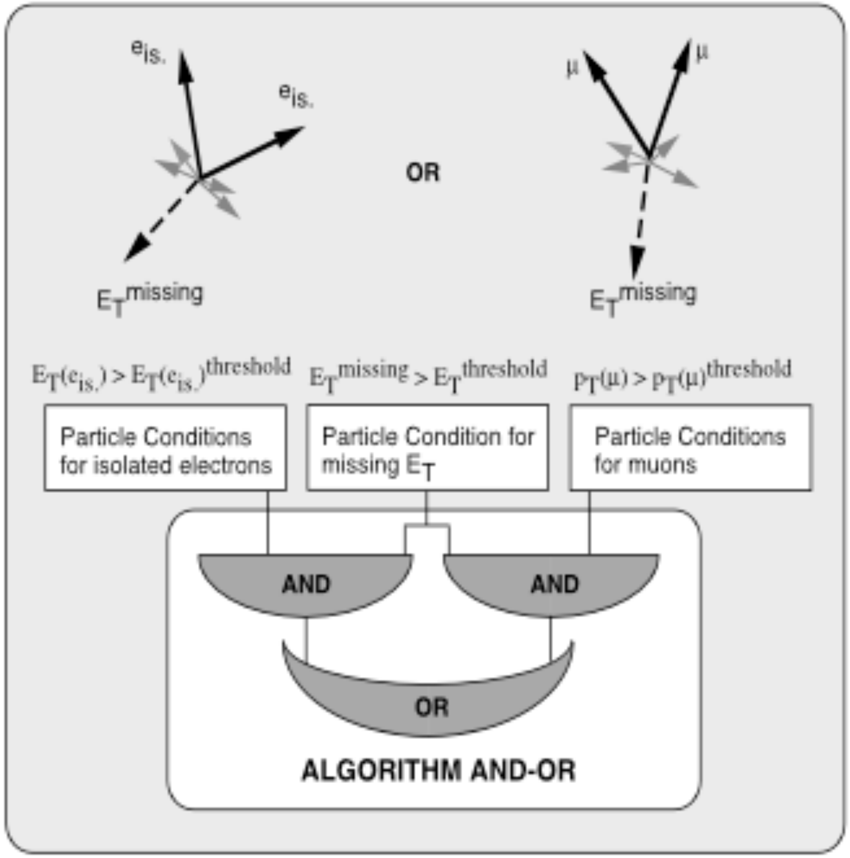
Particle Conditions



$E_T(1) > E_T(1)^{threshold}$
$E_T(2) > E_T(2)^{threshold}$
$0^o \leq \phi(1) < 360^o$
$0^o \leq \phi(2) < 360^o$
$170^o \leq |\phi(1) - \phi(2)| < 190^o$

$p_T(1) > p_T(1)^{threshold}$
$p_T(2) > p_T(2)^{threshold}$
$0^o \leq \phi(1) < 360^o$
$0^o \leq \phi(2) < 360^o$
$170^o \leq |\phi(1) - \phi(2)| < 190^o$
ISO(1) = 1, ISO(2) = 1
MIP(1) = 1, MIP(2) = 1
SGN (1) = 1, SGN(2) = -1

Logical Combinations



$E_T(e_{is.}) > E_T(e_{is.})^{threshold}$ — Particle Conditions for isolated electrons

$E_T^{missing} > E_T^{threshold}$ — Particle Condition for missing E_T

$p_T(\mu) > p_T(\mu)^{threshold}$ — Particle Conditions for muons

ALGORITHM AND-OR

Flexible algorithms implemented in FPGAs
100s of possible algorithms can be reprogrammed

Example Level-1 Trigger Table

(DAQ TDR: $L=2 \times 10^{33}$)

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			**16.0**

× 3 safety factor ⇒ 50 kHz (expected start-up DAQ bandwidth)

Only muon trigger has low enough threshold for B-physics (aka $B_s \rightarrow \mu\mu$)

CMS Calorimeter Physics Efficiency: 2 x 10^{33} cm^{-2} s^{-1}

Scenario:

5 kHz e/γ,

5 kHz τ,jets,

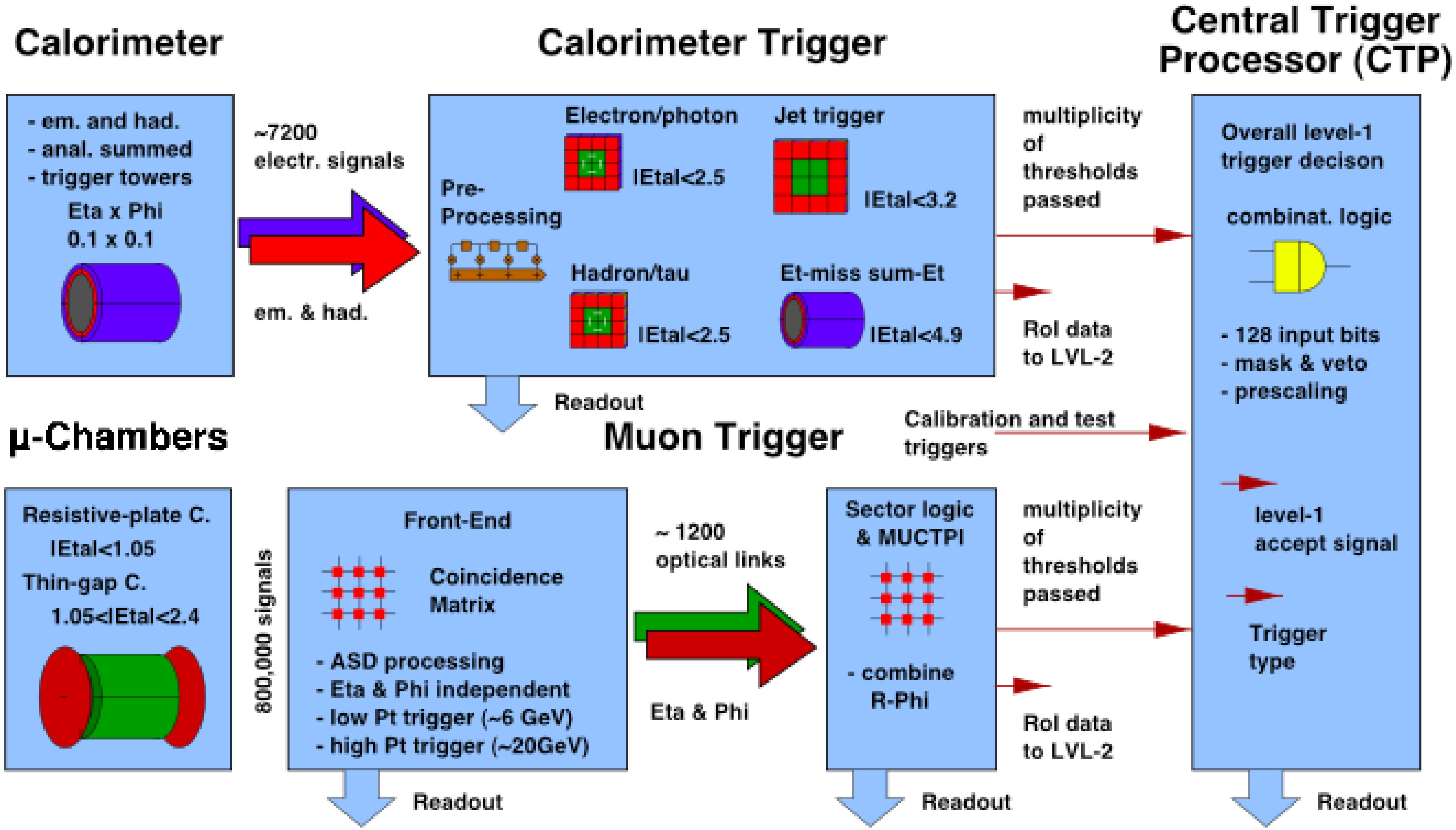
1 kHz comb,

rest μ

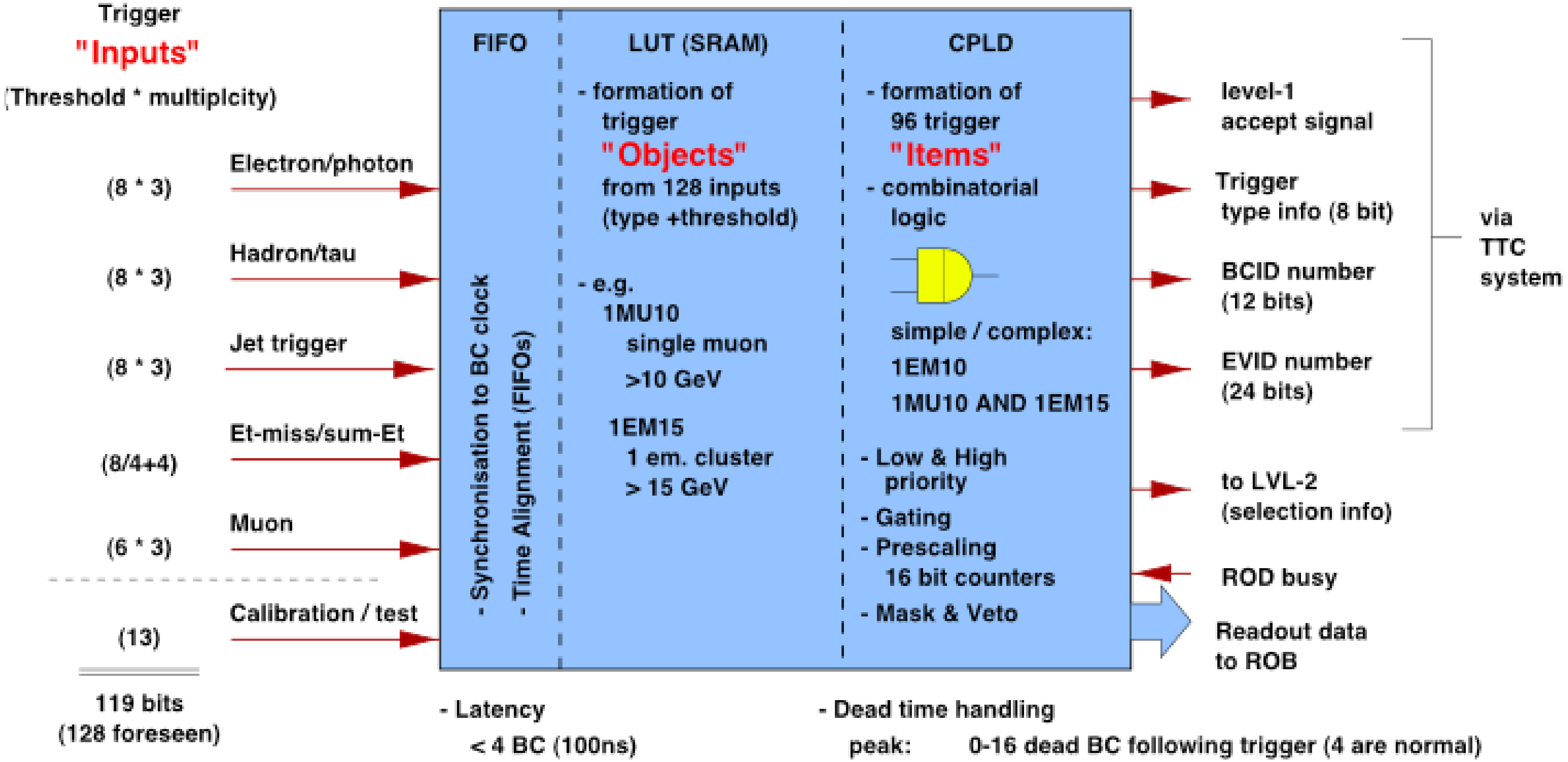
No generator level cuts other than requiring trigger objects within calo. (η<5) or tracker (e,γ,τ) acceptance

Channel	Total Efficiency	Trigger Efficiencies by trigger type (individual) cumulative				
$W\to e\nu$	70	e (70) 70				
$t\to eX$	91	e (82) 82	$e\cdot\tau$ (62) 86	τ (55) 89	jjj (24) 90	$e\cdot j$ (54) 91
$Z\to ee$	94	e (93) 93	ee (76) 94			
$H(115)\to\gamma\gamma$	99	e (99) 99	ee (82) 99			
$H(150)\to WW\to e\nu X$	87	e (78) 78	$e\cdot\tau$ (43) 81	τ (34) 83	$e\cdot j$ (39) 85	j (28) 87
$H(135)\to\tau\tau\to ej$	84	e (70) 70	$e\cdot\tau$ (46) 79	$e\cdot j$ (46) 82	τ (38) 84	j (34) 84
Charged higgs (200 GeV)	98	τ (85) 85	j (77) 96	$j\cdot mE_T$ (60) 98		
$H(200)\to\tau\tau\to jj$	81	τ (75) 75	$\tau\tau$ (50) 79	j (24) 81	jj (9) 81	
$H(500)\to\tau\tau\to jj$	99	τ (94) 94	$\tau\tau$ (64) 94	j (94) 99	jj (73) 99	
$t\to$jets	53	H_T (39) 39	jjjj (26) 43	jjj (26) 46	jj (21) 47	j (35) 53
mSUGRA	99	j (99) 99				
$H(120)\to bb$	41	jjj (12) 12	j (27) 30	τ (26) 41	jj (16) 41	
Invisible higgs (120 GeV)	44	$j\cdot mE_T$ (39) 39	j (22) 41	τ (13) 44		

Trigger Flow : ATLAS Example



ATLAS Trigger Central Processor



Trigger
"Inputs"
(Threshold * multiplcity)

Electron/photon	(8 * 3)
Hadron/tau	(8 * 3)
Jet trigger	(8 * 3)
Et-miss/sum-Et	(8/4+4)
Muon	(6 * 3)
Calibration / test	(13)

119 bits
(128 foreseen)

FIFO

- Synchronisation to BC clock
- Time Alignment (FIFOs)

LUT (SRAM)

- formation of trigger **"Objects"** from 128 inputs (type +threshold)
- e.g.
  1MU10
  single muon
  >10 GeV

  1EM15
  1 em. cluster
  > 15 GeV

CPLD

- formation of 96 trigger **"Items"**
- combinatorial logic

simple / complex:
1EM10
1MU10 AND 1EM15

- Low & High priority
- Gating
- Prescaling
  16 bit counters
- Mask & Veto

Outputs via TTC system:

- level-1 accept signal
- Trigger type info (8 bit)
- BCID number (12 bits)
- EVID number (24 bits)

to LVL-2 (selection info)

ROD busy

Readout data to ROB

- Latency
  < 4 BC (100ns)
- 1 printed circuit board

- Dead time handling

peak: 0-16 dead BC following trigger (4 are normal)
average: 1-32 triggers in 0-1.7 ms (8 in 80 us are normal)

Evolution of Level-1 Triggers

Discrete Logic

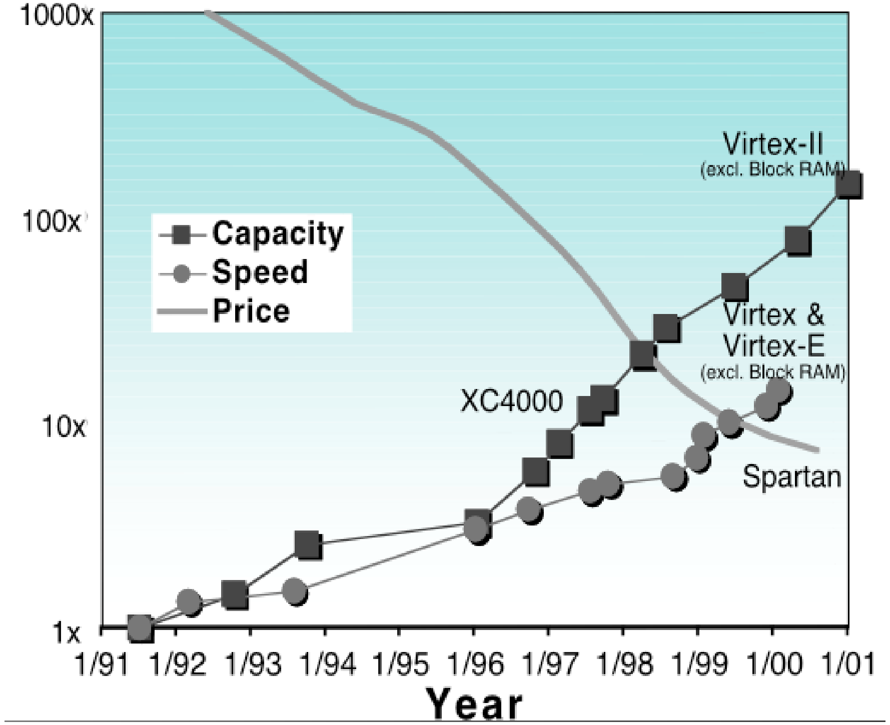
- D0,CDF
  - towers over thresholds + sums
- ZEUS
  - sums + pattern logic for object ID

ASICs

- CMS RCT -
  - object identification isolation, sorting, fast adders

FPGAs

- Almost everywhere -
  - Generic processors



Technology evolution