Metody eksperymentalne w fizyce wysokich energii

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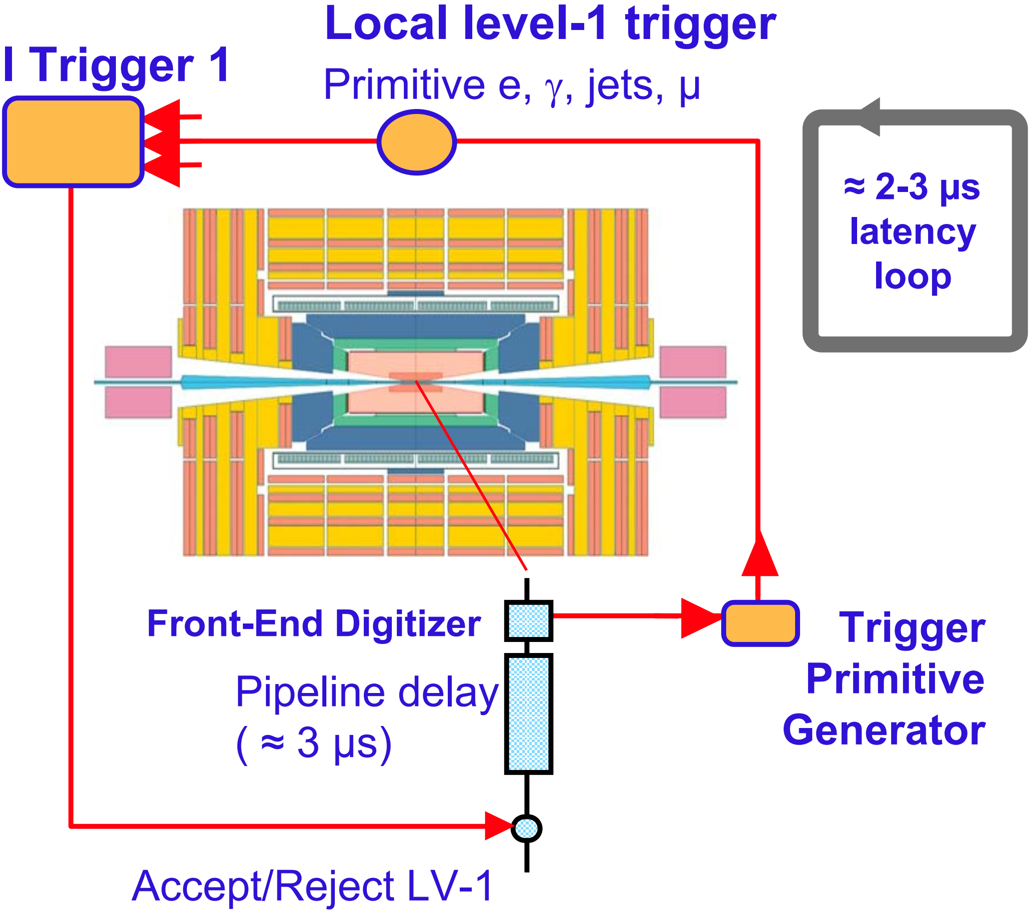
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład XI

- Systemy wyzwalania i zbierania danych

Level-1 Trigger: decision loop

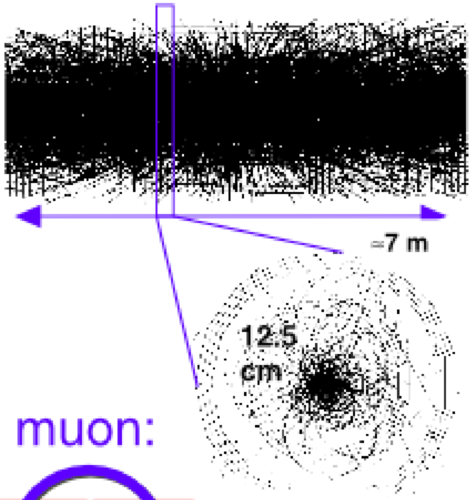
- Synchronous 40 MHz digital system
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- At Lvl-1: process only calo+μ info



ATLAS and CMS Strategy

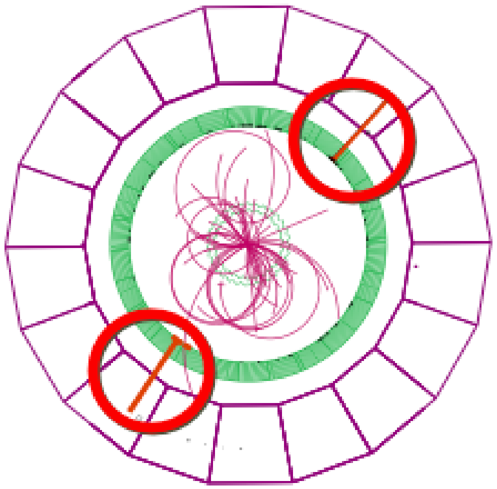
Level-1 : only calorimeters & muons ....

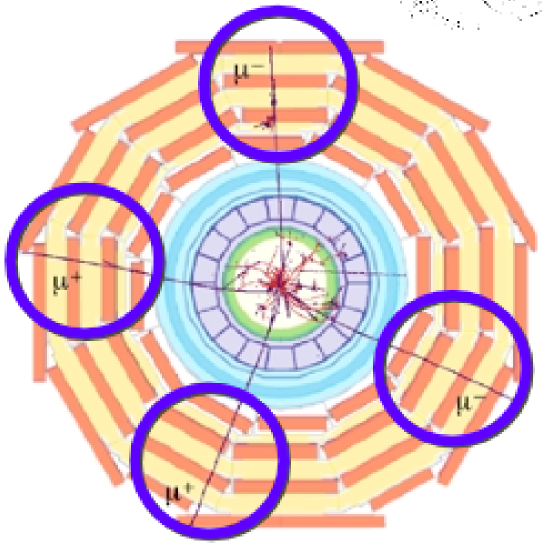
Compare to Central tracking at L = 10^{34}
(50 ns integration, ≈1000 tracks)



Algorithm Complexity
+
huge amount of data

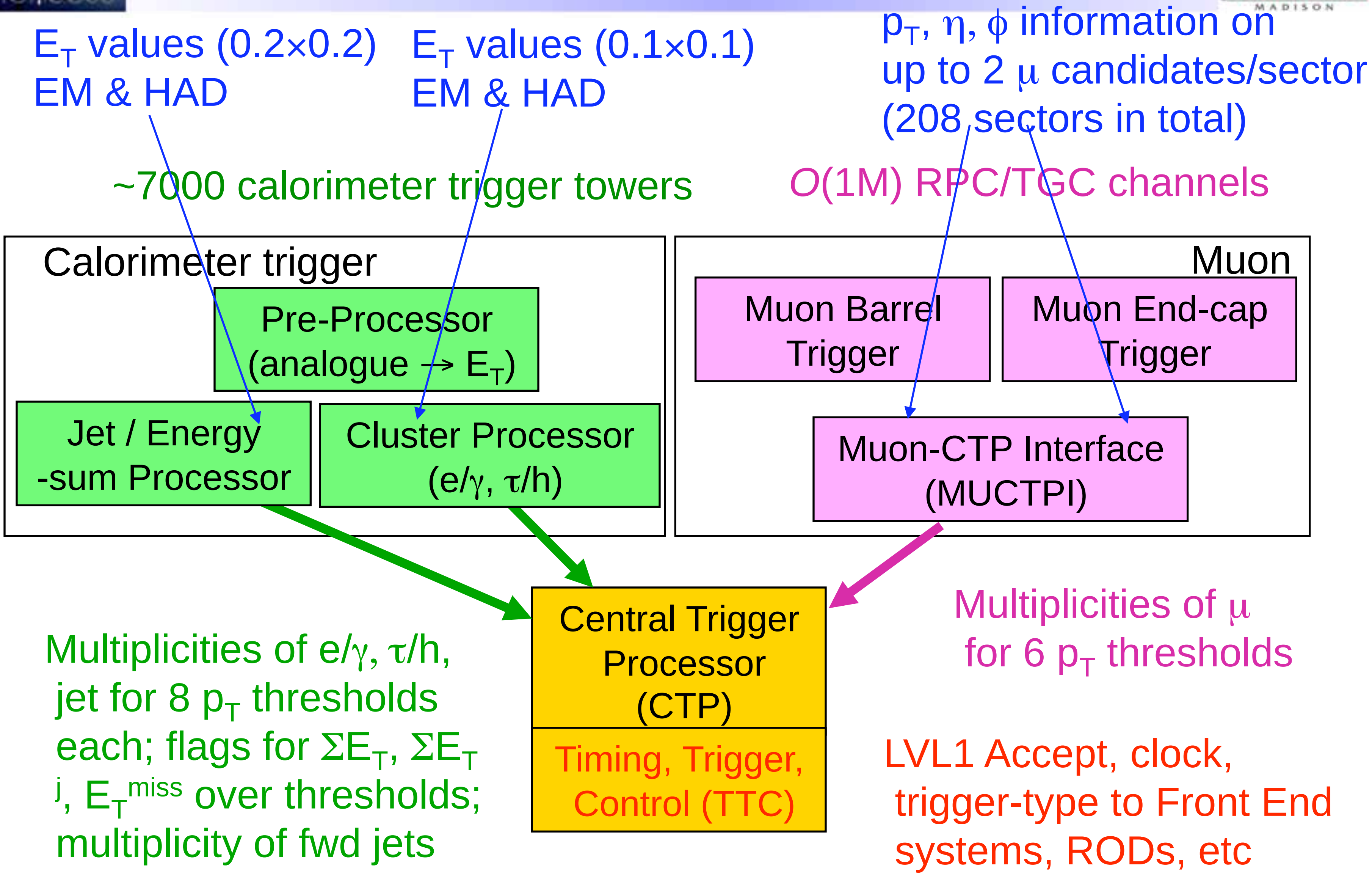
Pattern recognition much easier on calo & muon:





Complexity handled in software on CPUs

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)

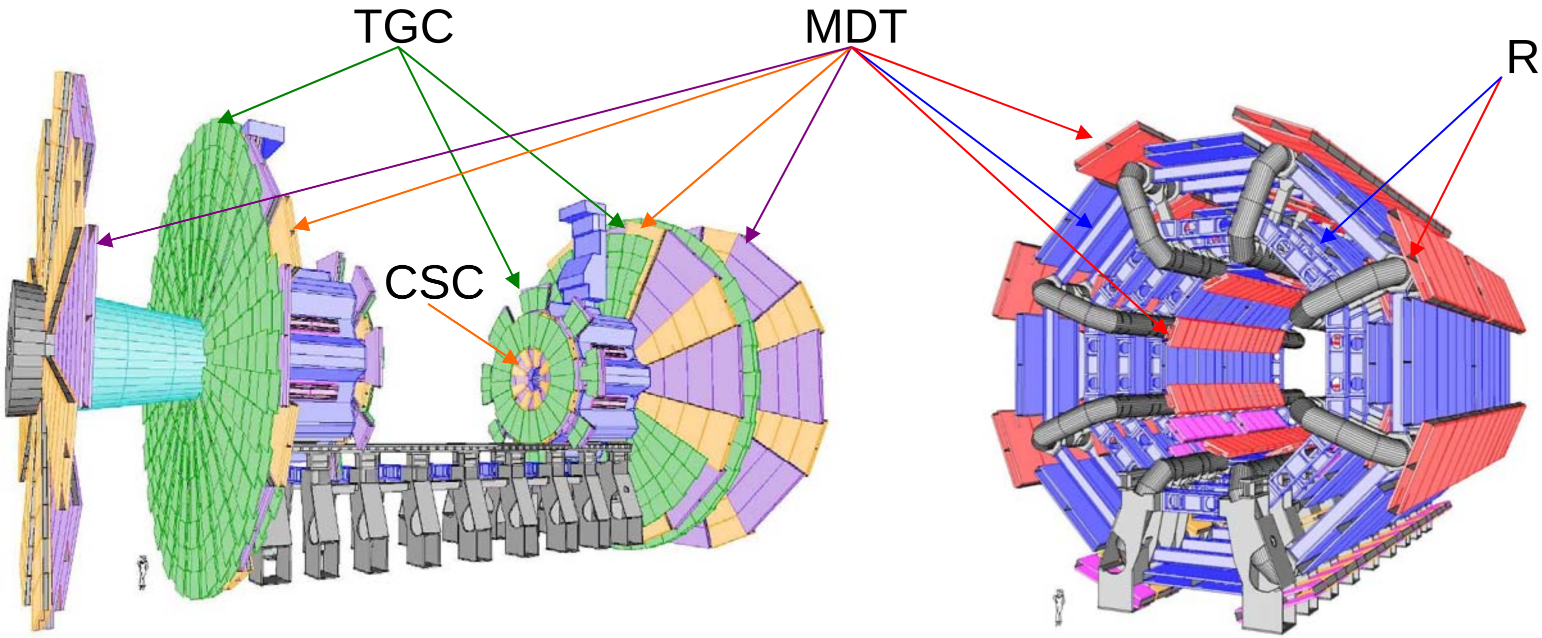
Multiplicities of e/γ, τ/h, jet for 8 p_T thresholds each; flags for ΣE_T, ΣE_T^j, E_T^{miss} over thresholds; multiplicity of fwd jets

Multiplicities of μ for 6 p_T thresholds

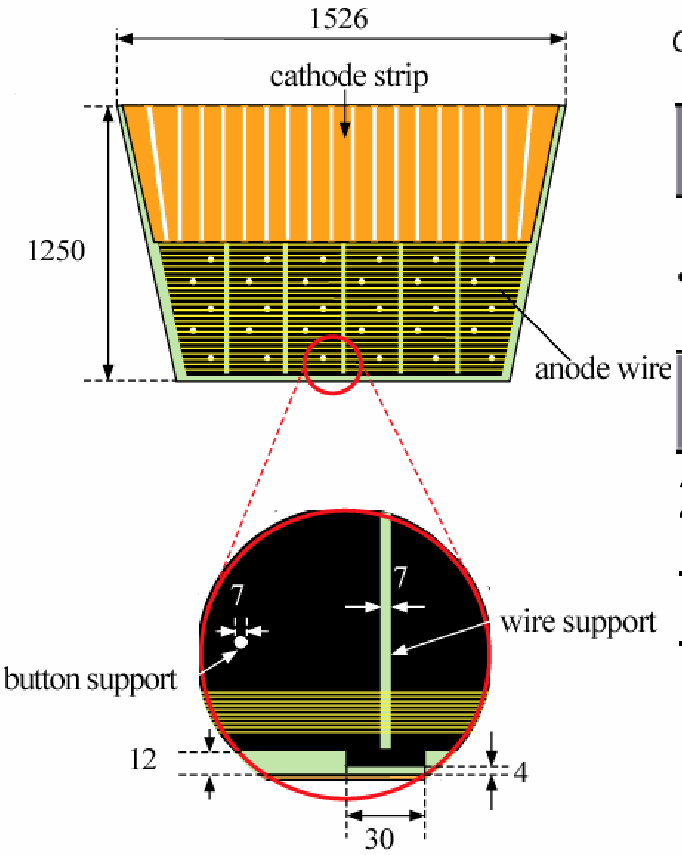
LVL1 Accept, clock, trigger-type to Front End systems, RODs, etc

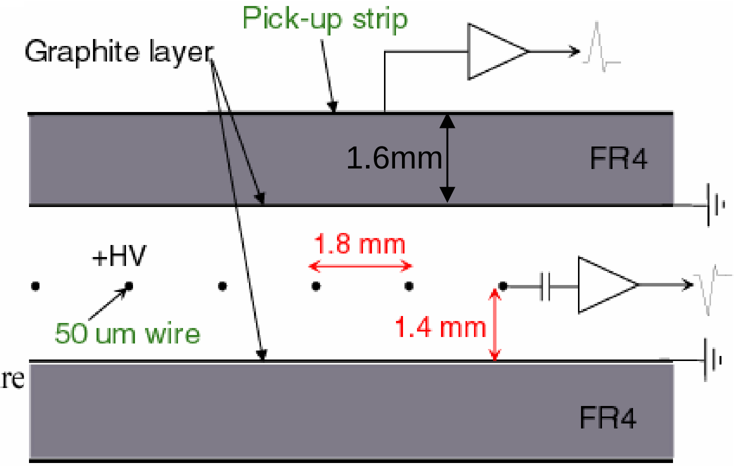
4 technologies of muon system

	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)



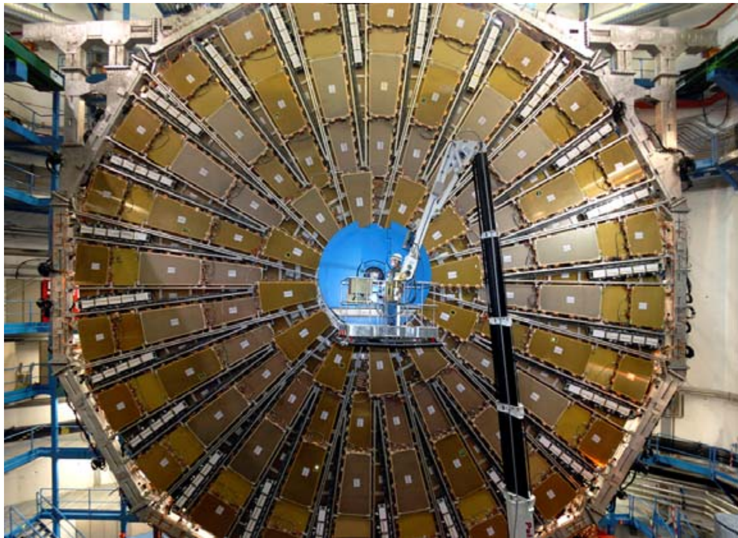


Gas mixture
CO_2/n-pentane
(55/45)

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

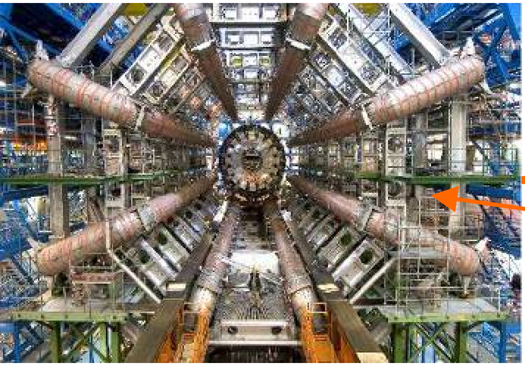


ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) muon system

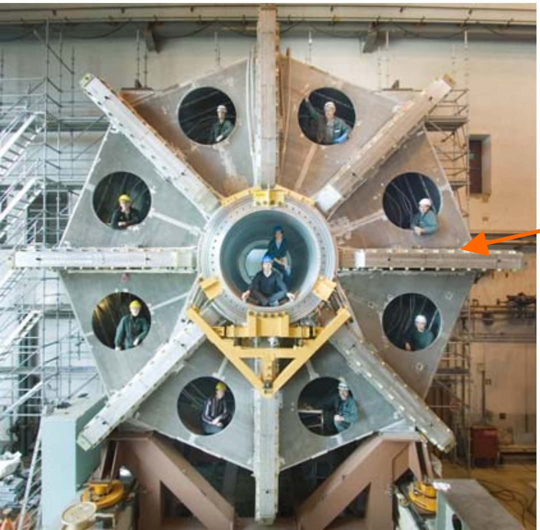
Toroidal magnets bend particles in η direction

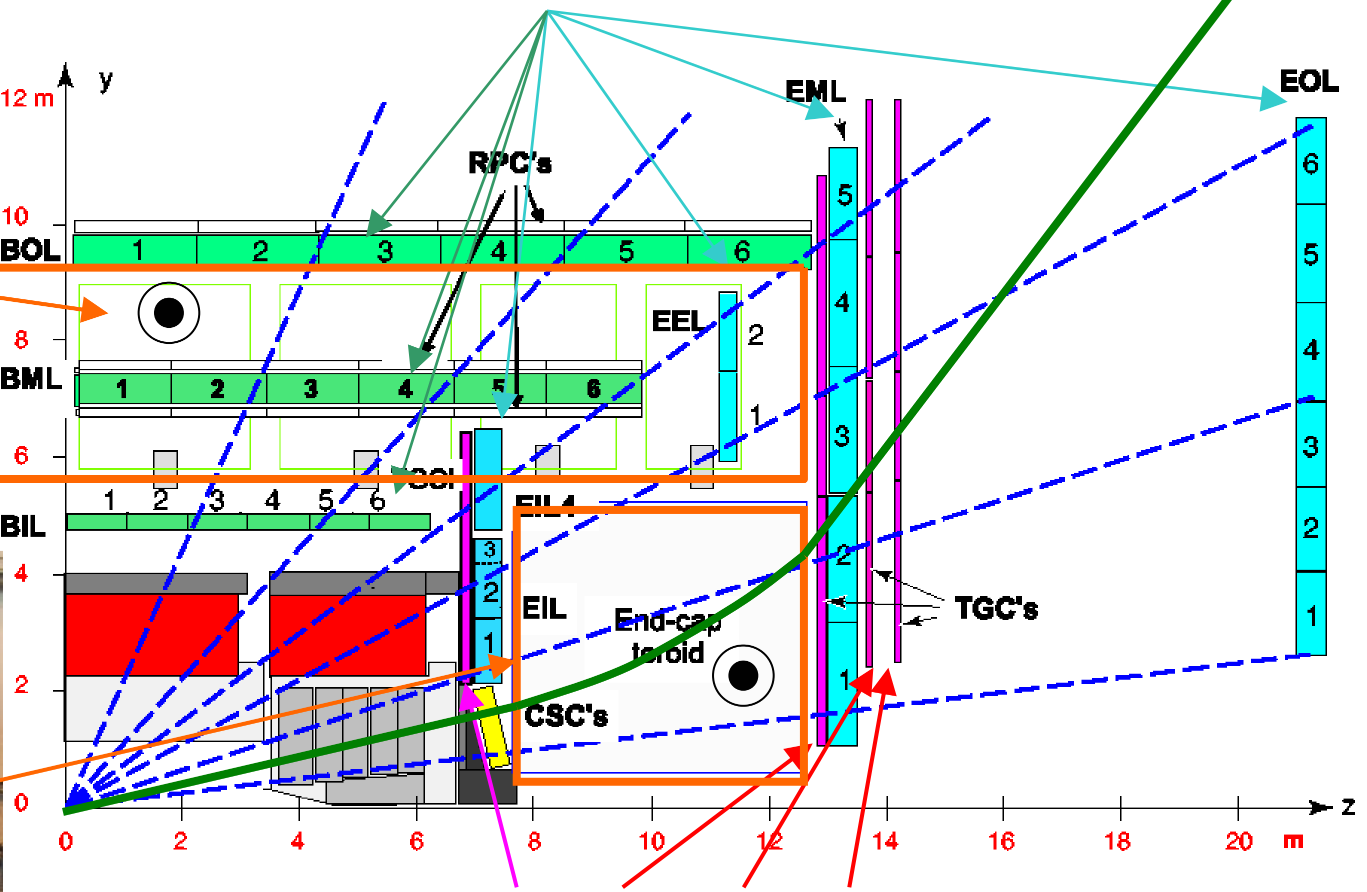
MDT

Barrel toroidal magnet



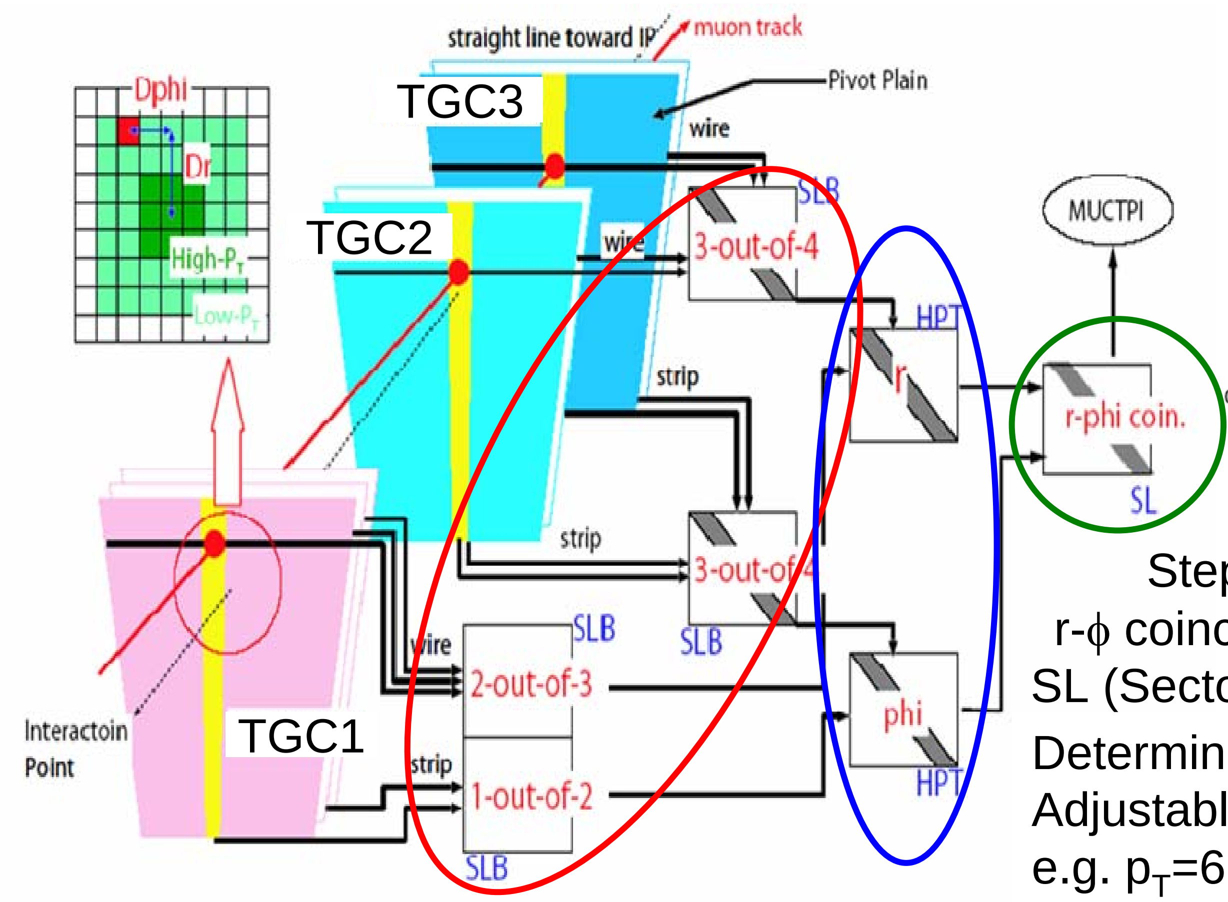
Endcap toroidal magnet

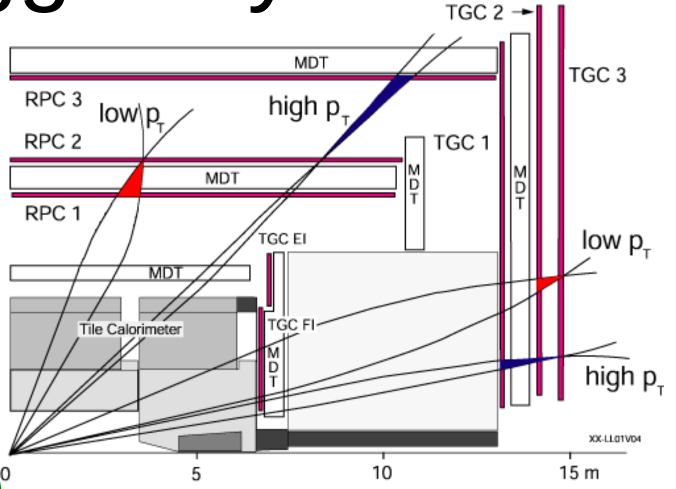




$\text{TGC} : 2 + \underbrace{3 + 2 + 2}_{\text{Triggering}} = 9$ layers

Level1 Endcap Muon Trigger System





Step 3
r-ϕ coincidence
SL (Sector Logic)

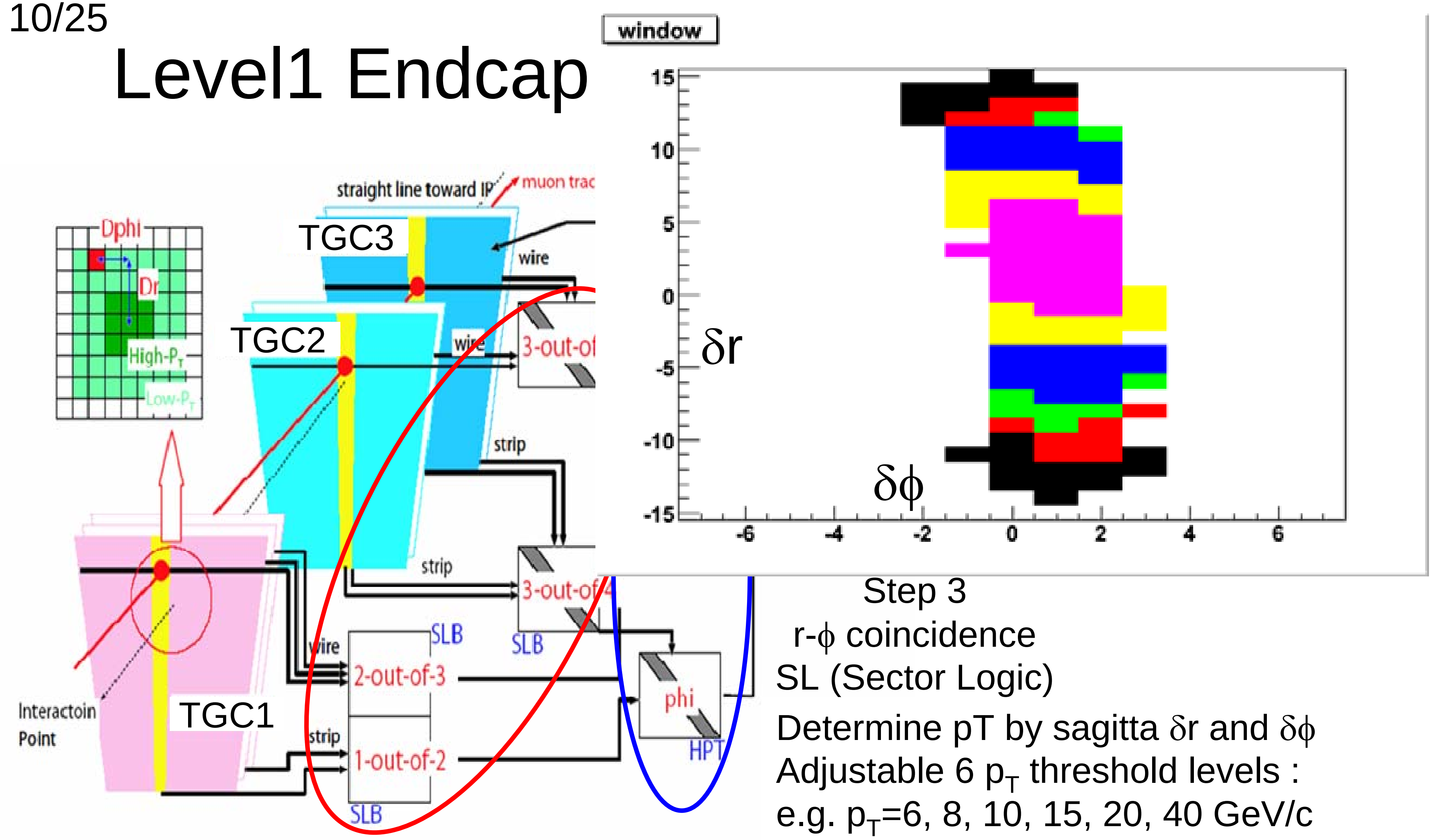
Determine pT by sagitta δr and $\delta\phi$
Adjustable 6 p_T threshold levels :
e.g. p_T=6, 8, 10, 15, 20, 40 GeV/c

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

Level1 Endcap



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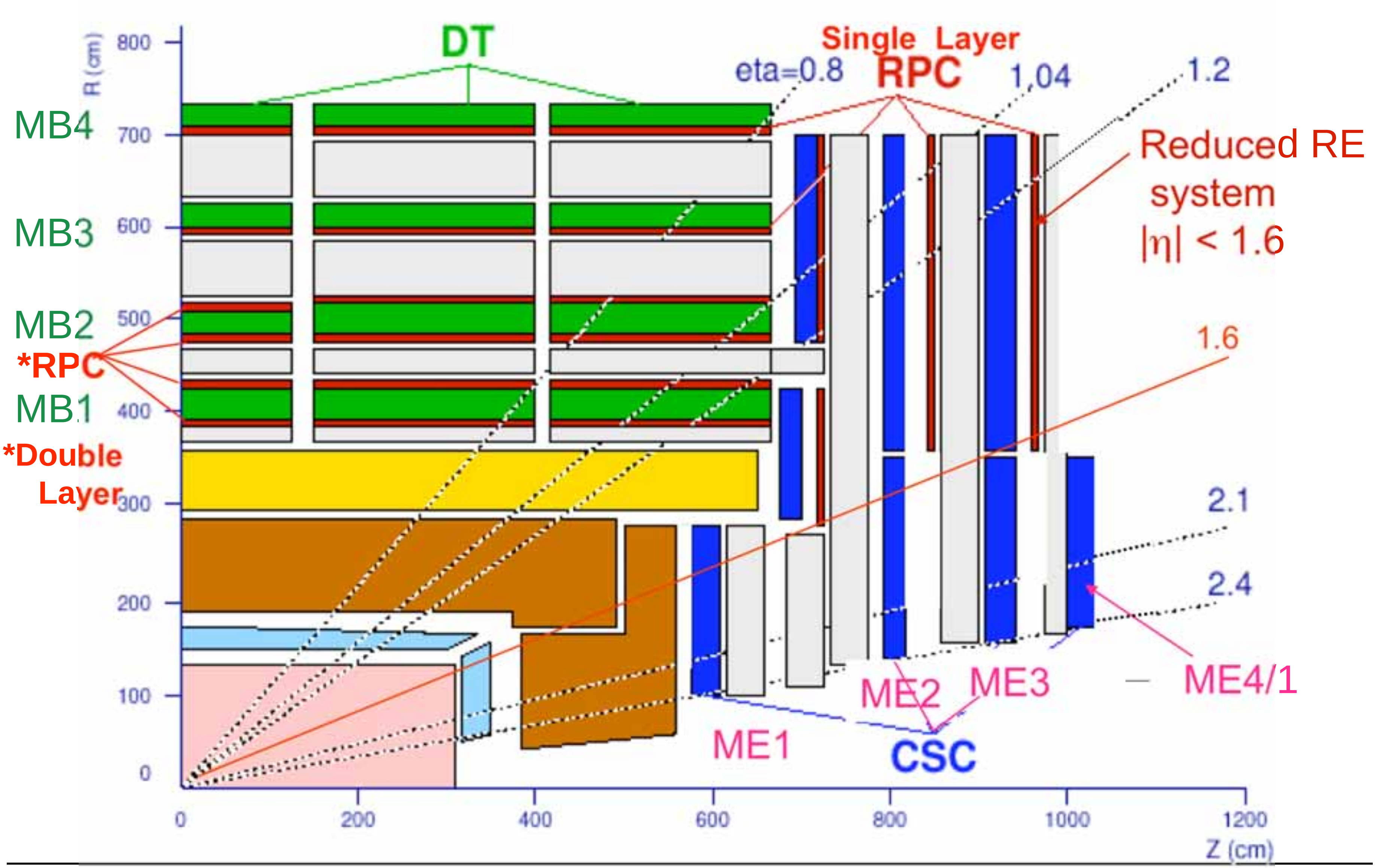
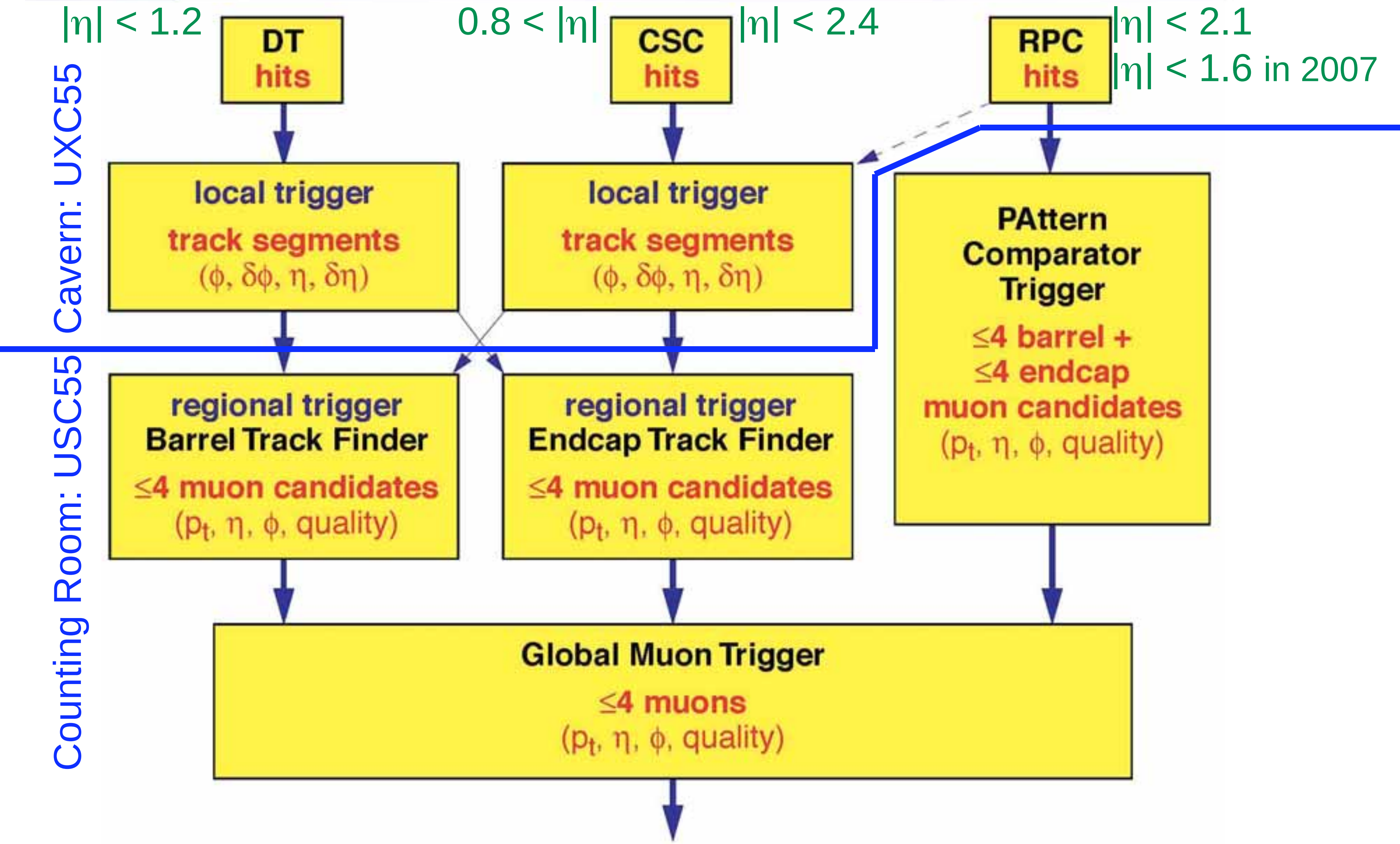
20 GeV/c threshold : 8.2 kHz

CMS Muon Chambers



Muon Trigger Overview



$|\eta| < 1.2$

DT hits

$0.8 < |\eta|$

CSC hits

$|\eta| < 2.4$

RPC hits

$|\eta| < 2.1$

$|\eta| < 1.6$ in 2007

Cavern: UXC55

Counting Room: USC55

local trigger

track segments

$(\phi, \delta\phi, \eta, \delta\eta)$

local trigger

track segments

$(\phi, \delta\phi, \eta, \delta\eta)$

PAttern Comparator Trigger

$\leq$4 barrel + $\leq$4 endcap muon candidates

$(p_t, \eta, \phi, \text{quality})$

regional trigger Barrel Track Finder

$\leq$4 muon candidates

$(p_t, \eta, \phi, \text{quality})$

regional trigger Endcap Track Finder

$\leq$4 muon candidates

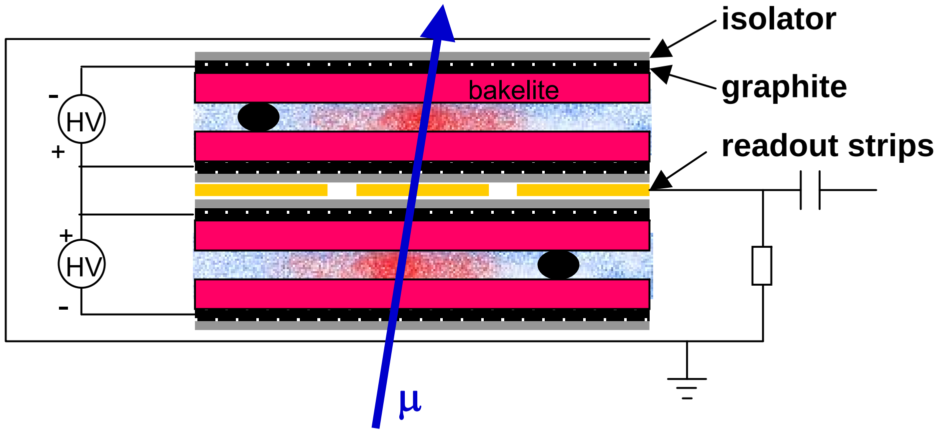
$(p_t, \eta, \phi, \text{quality})$

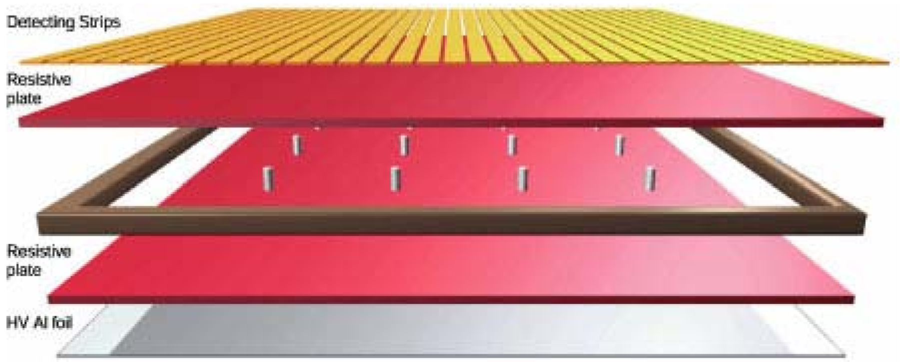
Global Muon Trigger

$\leq$4 muons

$(p_t, \eta, \phi, \text{quality})$

RPC - Resistive Plate Chambers

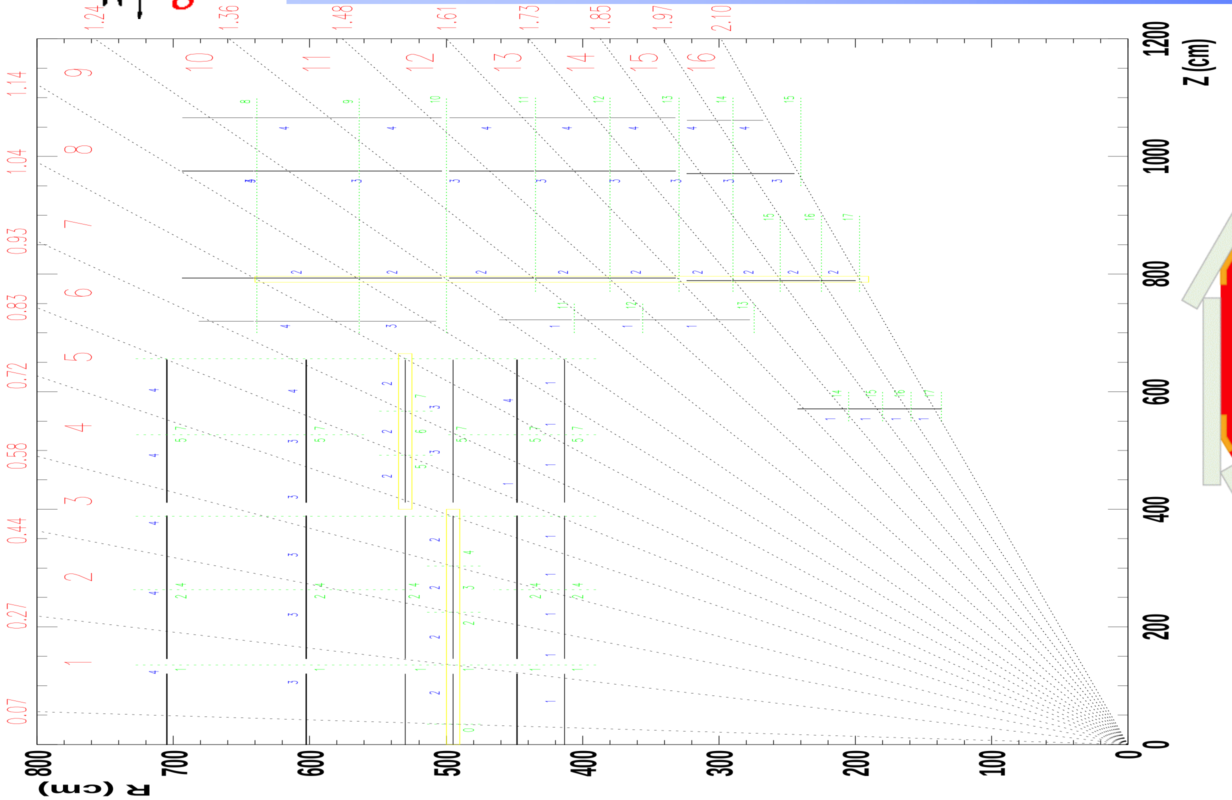


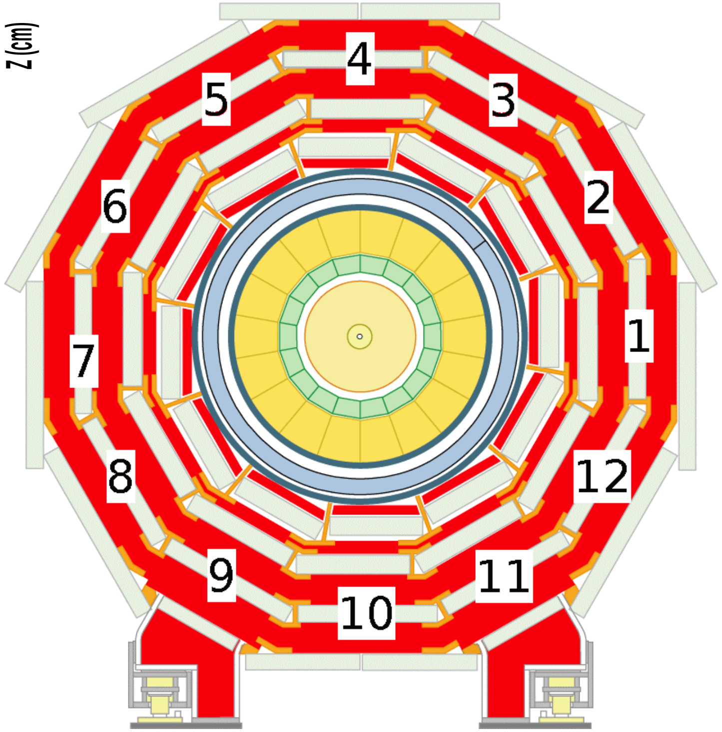


Gaseous, fast detectors, optimized for muons measurements

- Gas gap thickness: **2 mm**
- Readout Strips:
  pitch: 0.5 – 4 cm,
  length: 20 -130 cm
- High Voltage ~ **9.5 kV**
- Gas mixture: 96.2% $C_2H_2F_4$, 3.5% isoC_4H_{10}, 0.3% SF_6
- **Time resolution ~ 1 ns**
- **Efficiency > 95% @ 1kHz/cm^2**
- **Chamber noise < 5 Hz/cm^2**

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

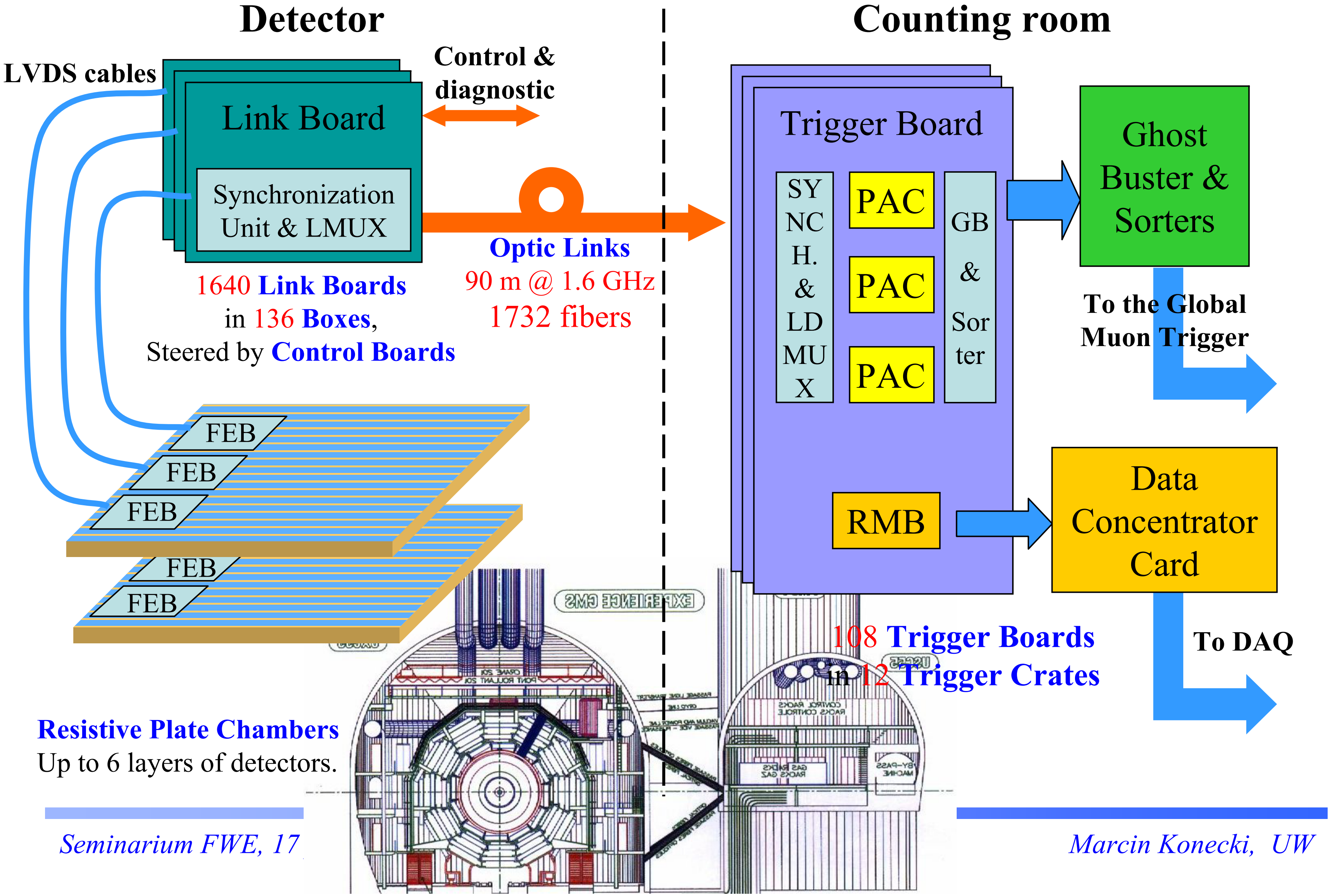
Synchronous system, working @ 40 MHz

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

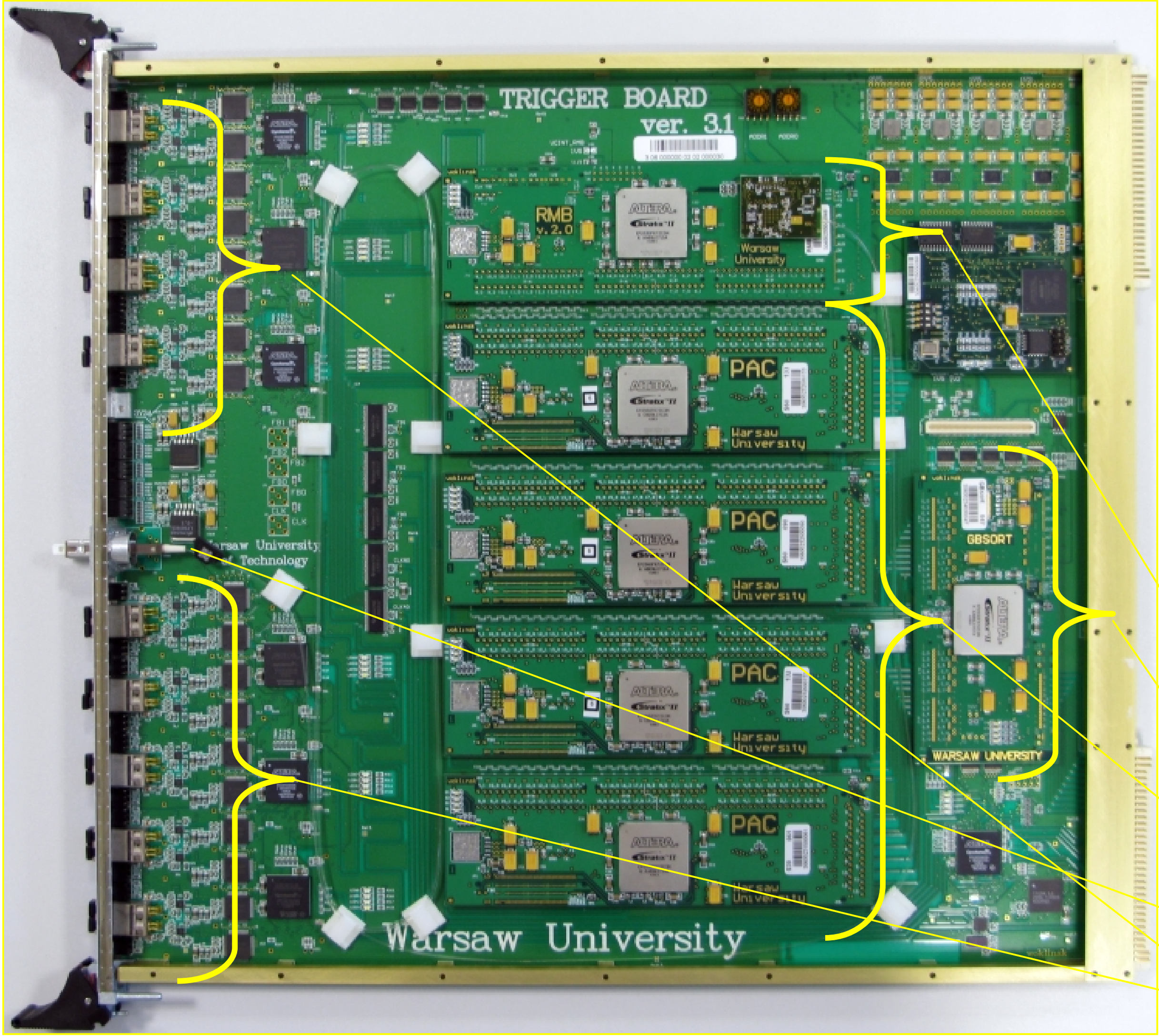
To the Global Muon Trigger

Data Concentrator Card

To DAQ

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

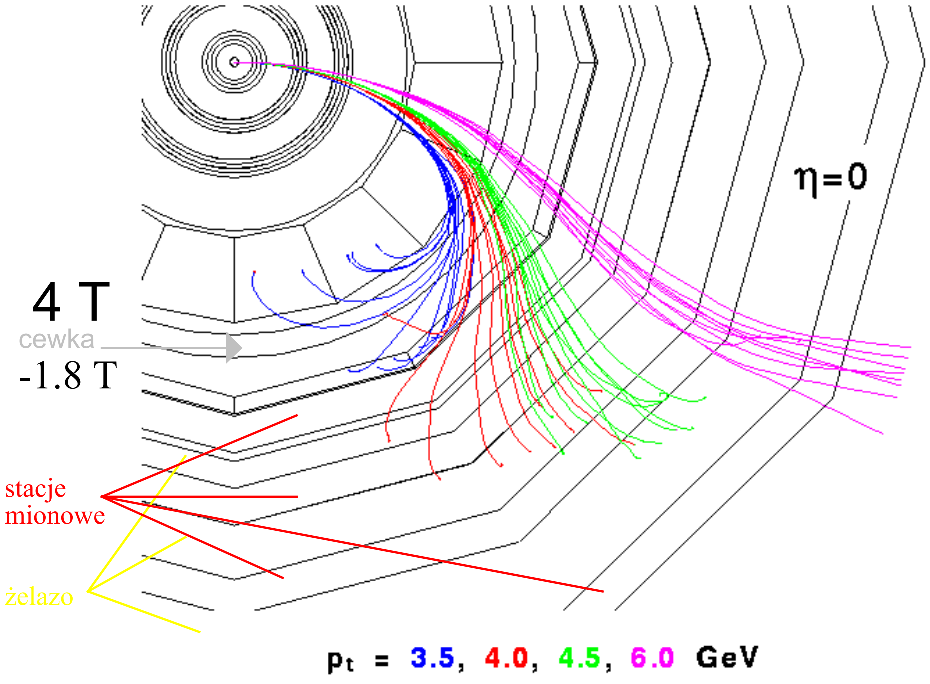
Serce systemu: Trigger Board




kasety trygera RPC

RMB
GB
PAC (tryger)
wyjście danych
wejscie danych

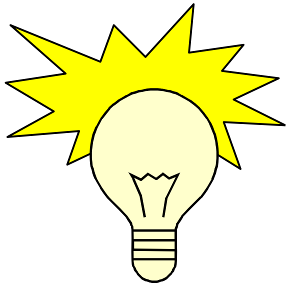
PAC Tryger – zasada działania (I)



Tor mionu w detektorze CMS

W obszarze wewnętrznym cewki panuje pole magnetyczne o indukcji 4 Tesle, powodujące zakrzywienie torów cząstek naładowanych. W obszarze zewnętrznym pole o wartości 1.8 Tesli jest skierowane przeciwnie powodując gięcie torów w przeciwną stronę.

- Promień krzywizny toru mionu zależny jest od jego pędu.
- Znaczny rozrzut torów o takim samym pędzie spowodowany jest przez proces rozpraszania wielokrotnego oraz fluktuacje strat energii. Miony o niskich pędach zatrzymywane są w żelazie.



PAC Tryger – zasada działania (II)

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

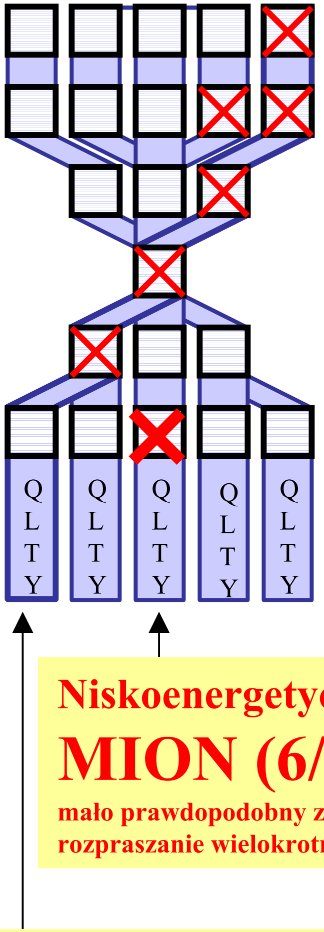
PACT – znajduje koincydencje zapalonych pasków w różnych płaszczyznach. Układ przestrzenny zapaleń porównywany jest ze wzorcem umożliwiając określenie pędu mionu.

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.

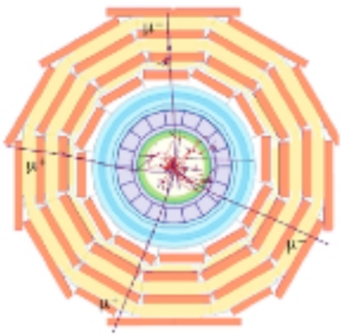


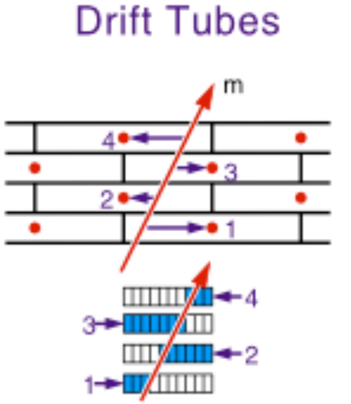
Niskoenergetyczny
MION (6/6),
mało prawdopodobny ze względu na rozpraszanie wielokrotne

Wysokoenergetyczny
MION (5/6)

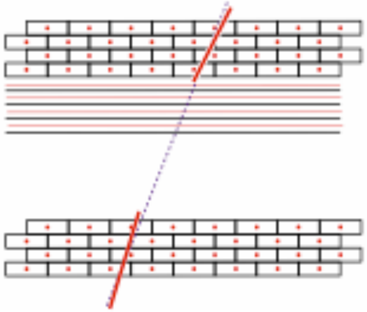
CMS Muon Trigger Track Finders

Drift Tubes (DT)



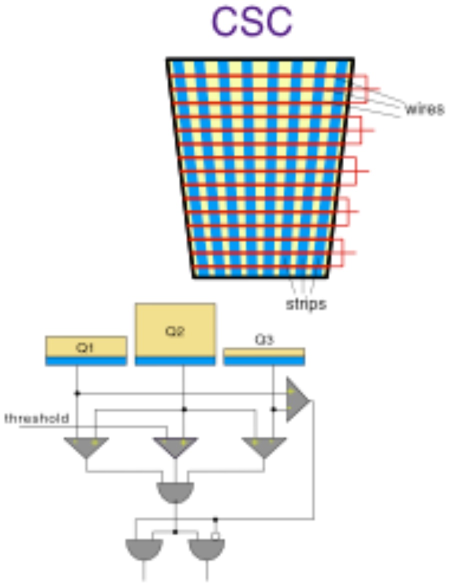


Meantimers recognize tracks and form vector / quartet.

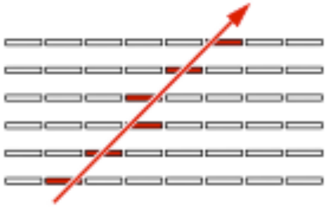


Correlator combines them into one vector / station.

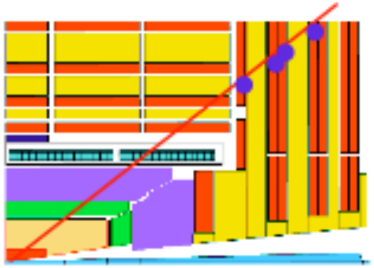
Cathod Strip Chambers (CSC)



Comparators give 1/2-strip resol.



Hit strips of 6 layers form a vector.



Sort based on P_T, Quality - keep loc.

Combine at next level - match

Sort again - Isolate?

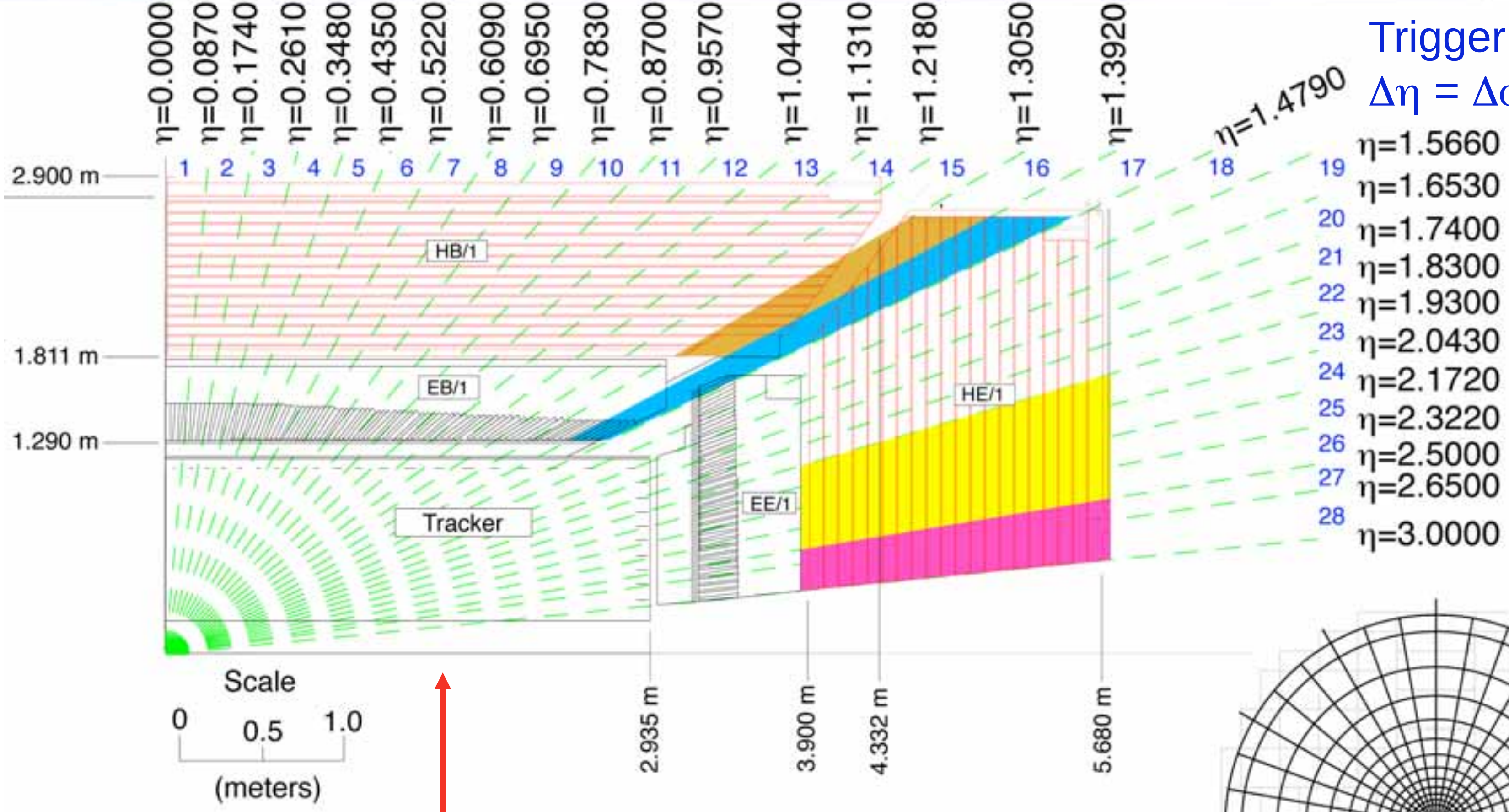
Top 4 highest P_T and quality muons with location coord.

Match with RPC

Improve efficiency and quality

CMS Calorimeter Geometry

Trigger towers:
$\Delta\eta = \Delta\phi = 0.087$



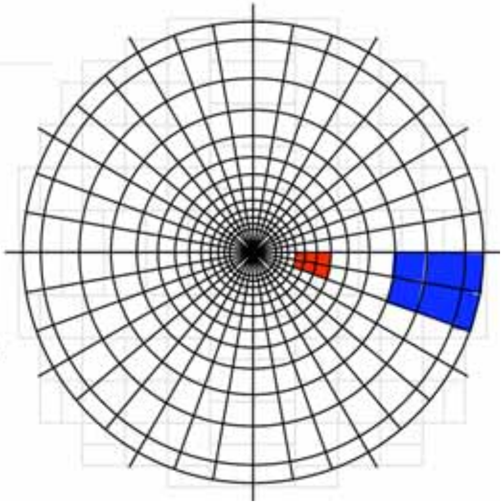
EB, EE, HB, HE map to 18 RCT crates

Provide e/γ and jet, τ, E_T triggers

2 HF calorimeters map on to 18 RCT crates

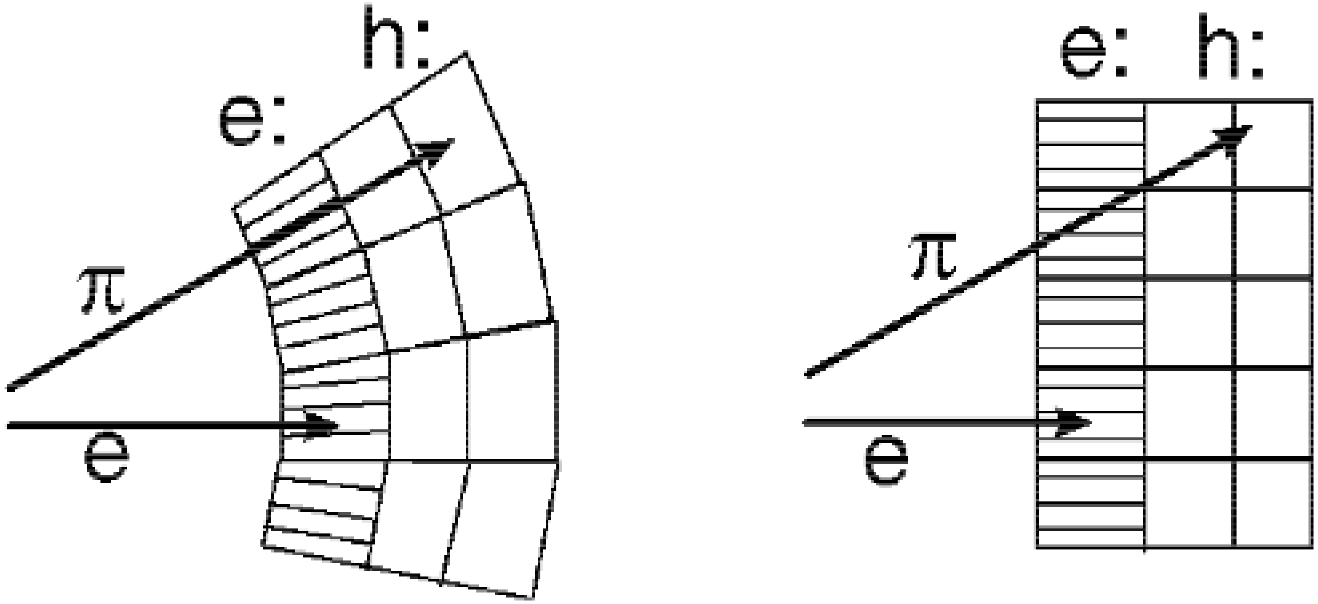
Readout segmentation: 36φ × 12η × 2z × 2F/B

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



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

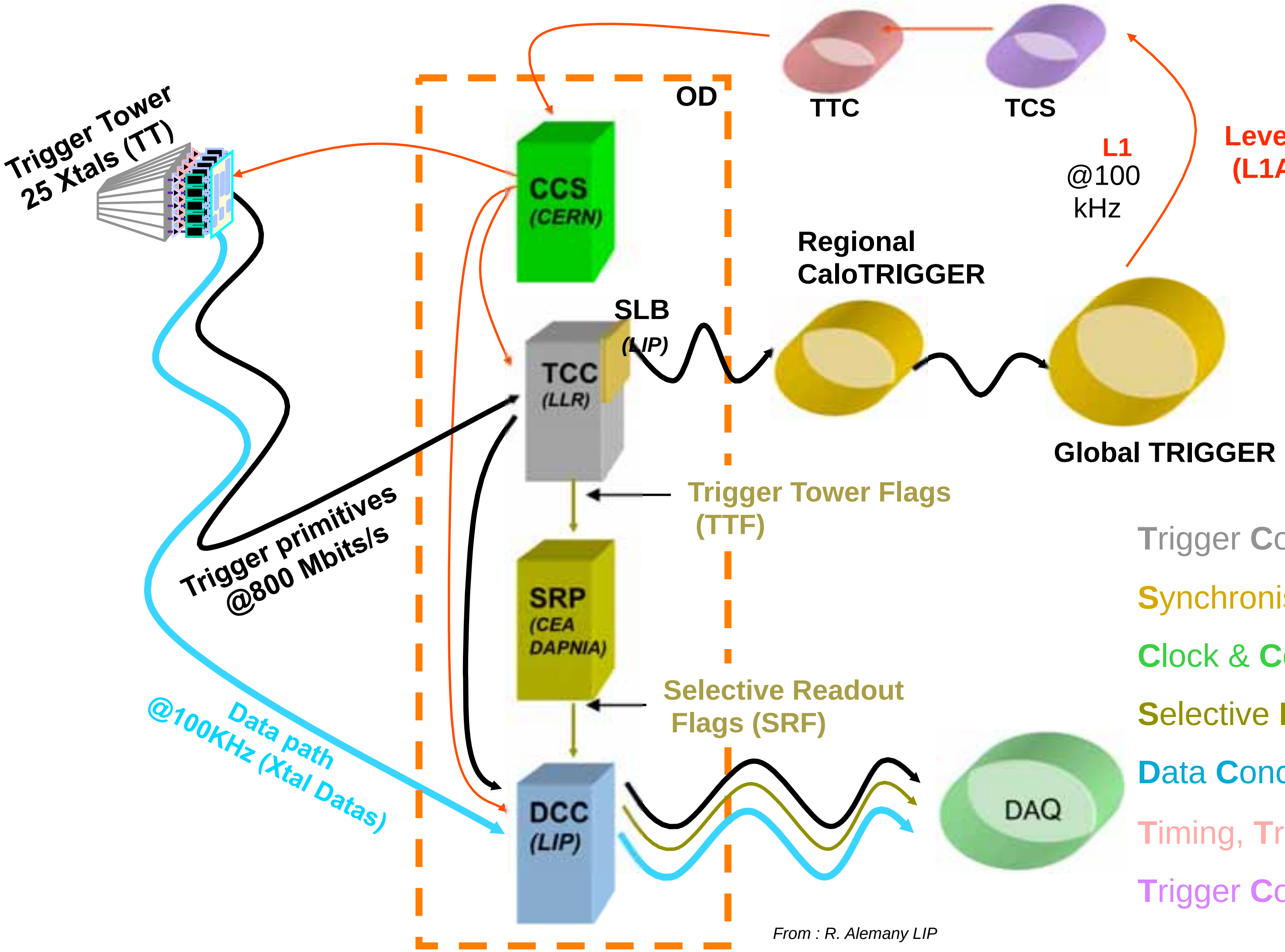
Projective Geometry



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

Calorimeter Trigger Processing



From : R. Alemany LIP

Trigger **C**oncentrator **C**ard

Synchronisation & **L**ink **B**oard

Clock & **C**ontrol **S**ystem

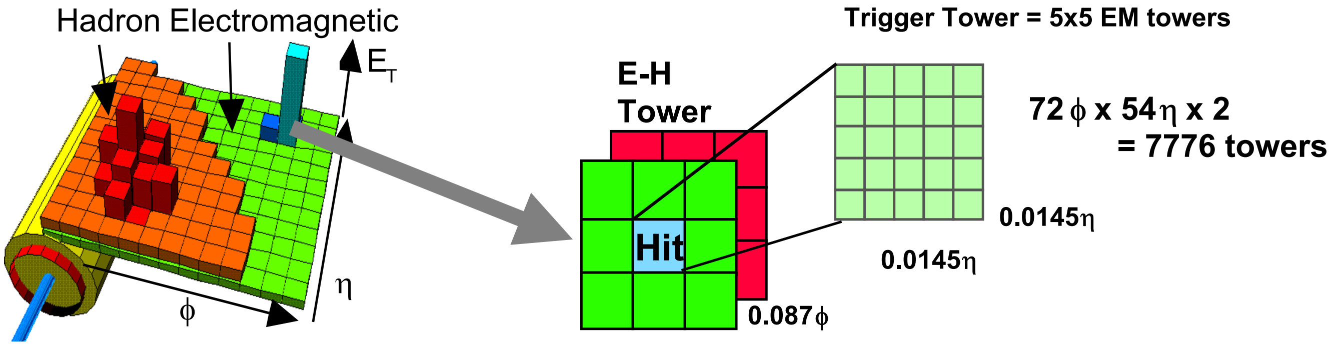
Selective **R**eadout **P**rocessor

Data **C**oncentrator **C**ard

Timing, **T**rigger & **C**ontrol

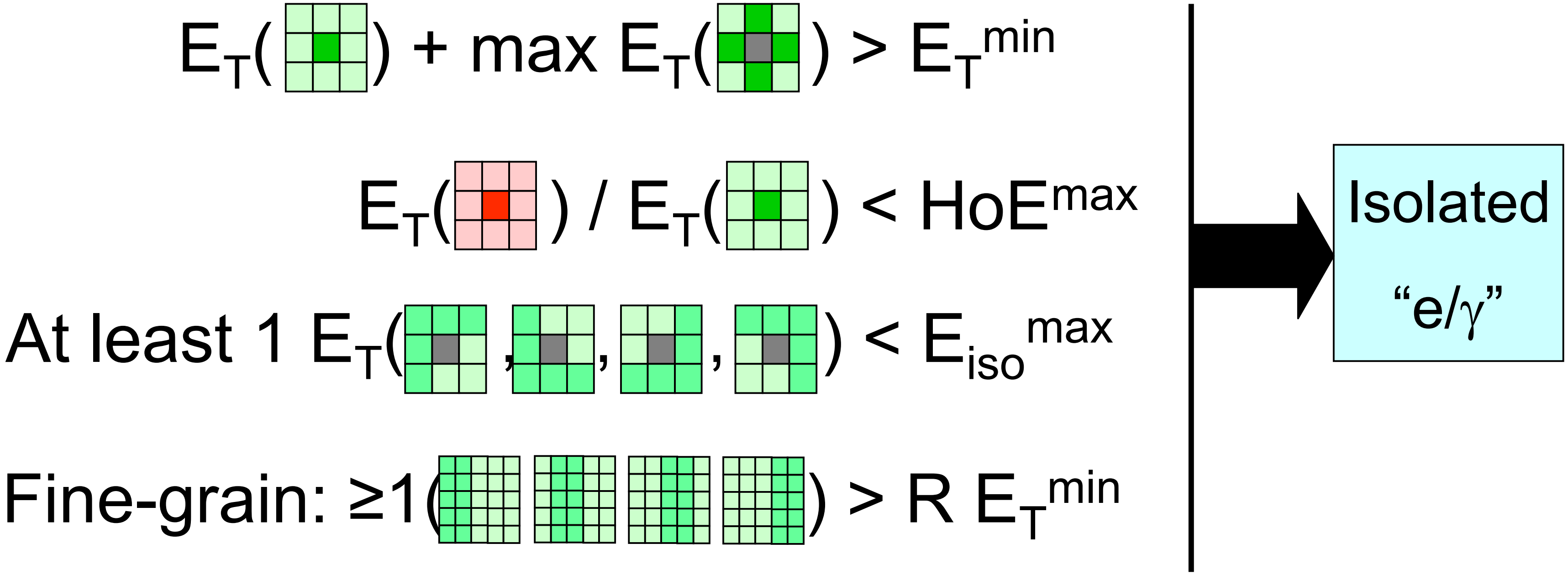
Trigger **C**ontrol **S**ystem

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



Trigger Tower = 5x5 EM towers

72 ϕ x 54 η x 2 = 7776 towers



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

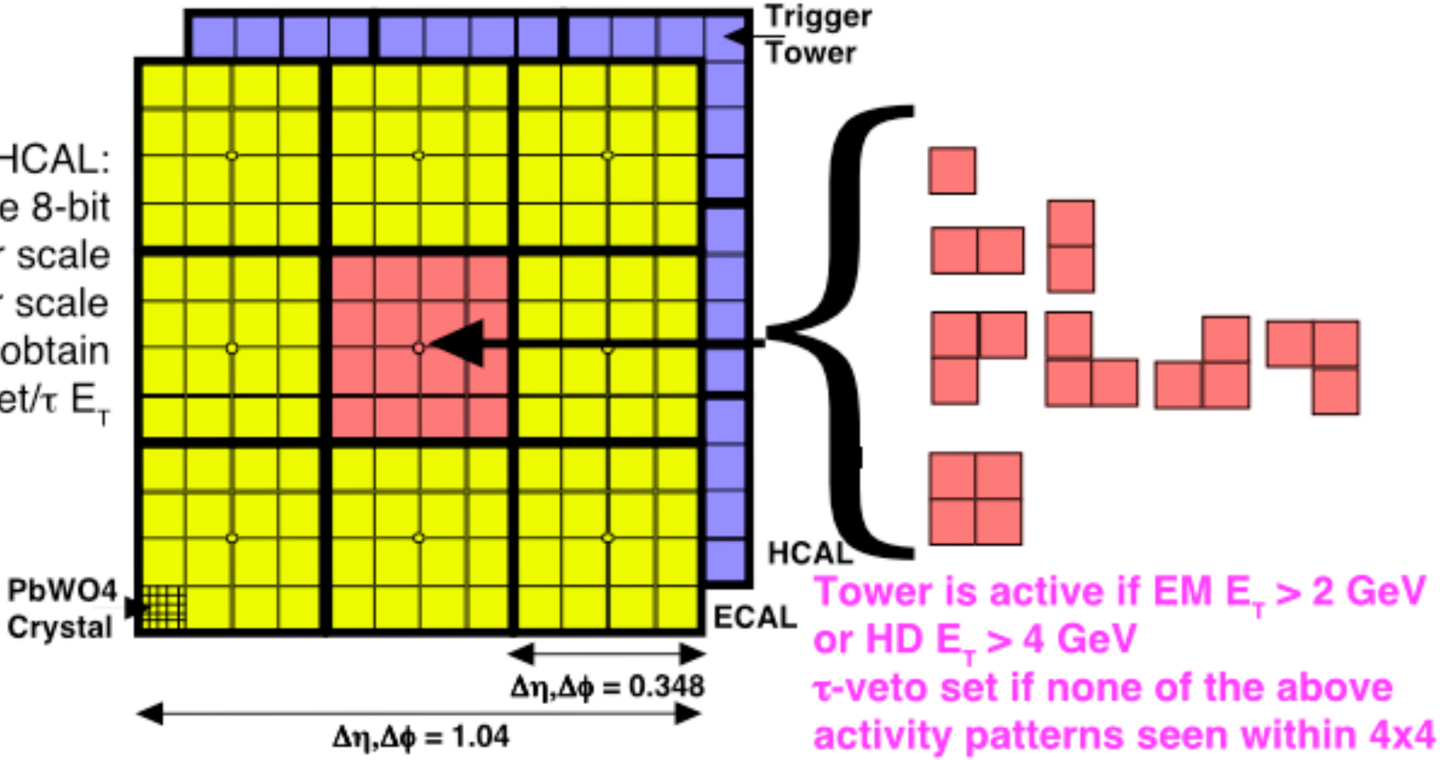
$E_T(\ ) / E_T(\ ) < HoE^{max}$

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

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

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

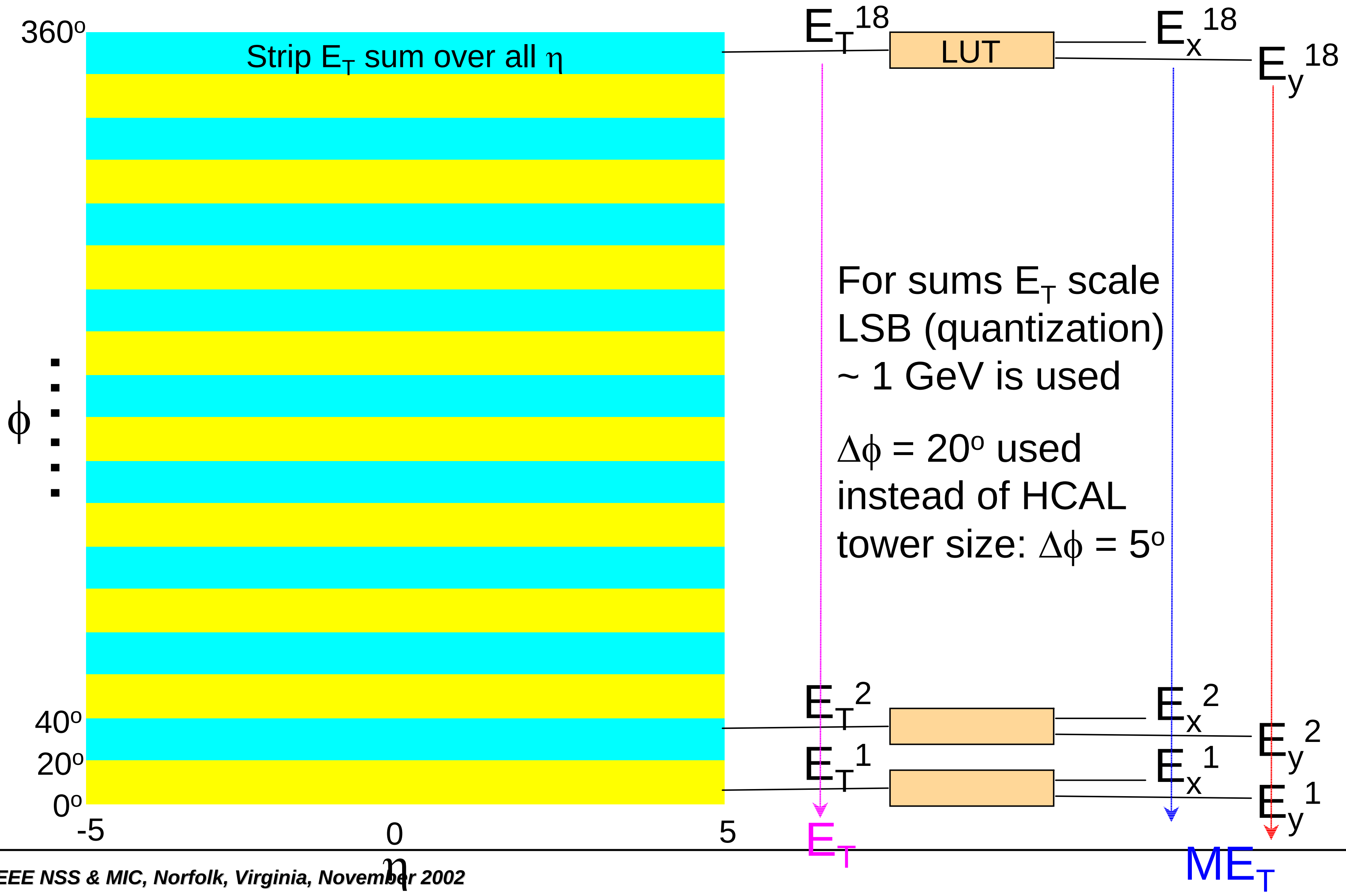
τ algorithm (isolated narrow energy deposits), within $-2.5 < \eta < 2.5$

- 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

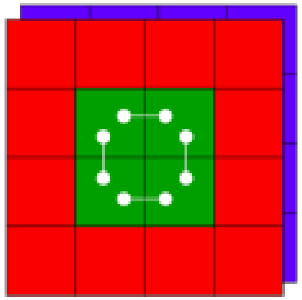


For sums E_T scale LSB (quantization) ~ 1 GeV is used

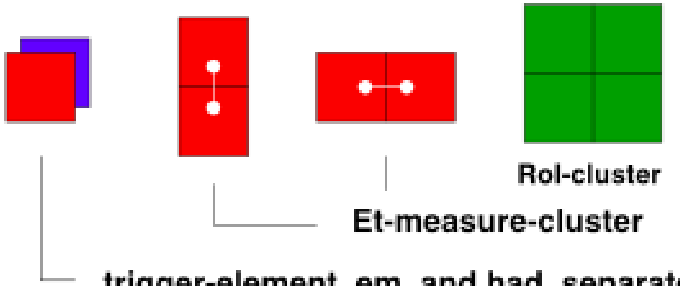
$\Delta\phi = 20^\circ$ used instead of HCAL tower size: $\Delta\phi = 5^\circ$

ATLAS Calorimeter Algorithms I

Electron/photon trigger



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

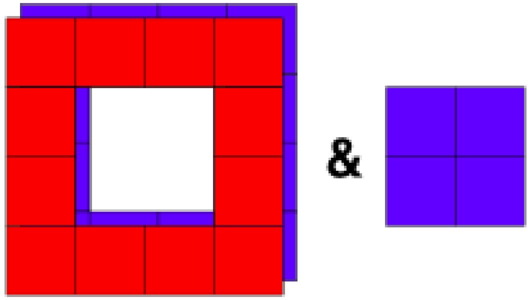


RoI-cluster

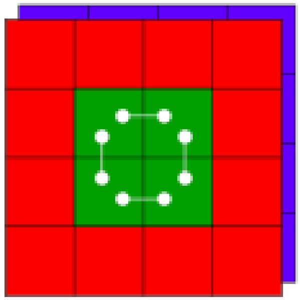
Et-measure-cluster

trigger-element, em. and had. separate

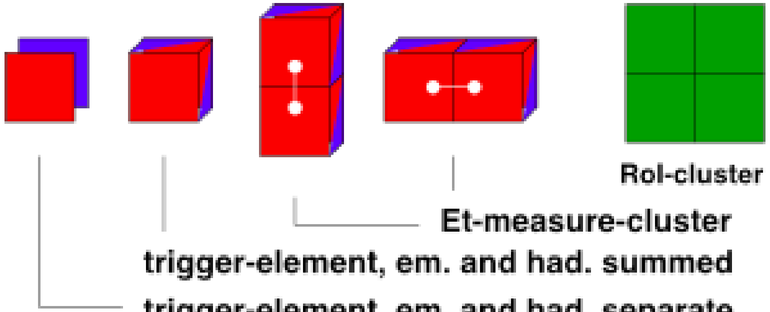
Isolation:



Hadron/tau trigger



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



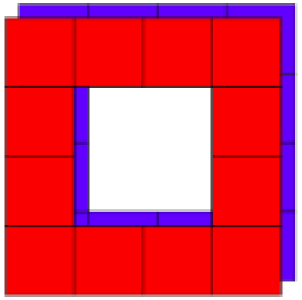
RoI-cluster

Et-measure-cluster

trigger-element, em. and had. summed

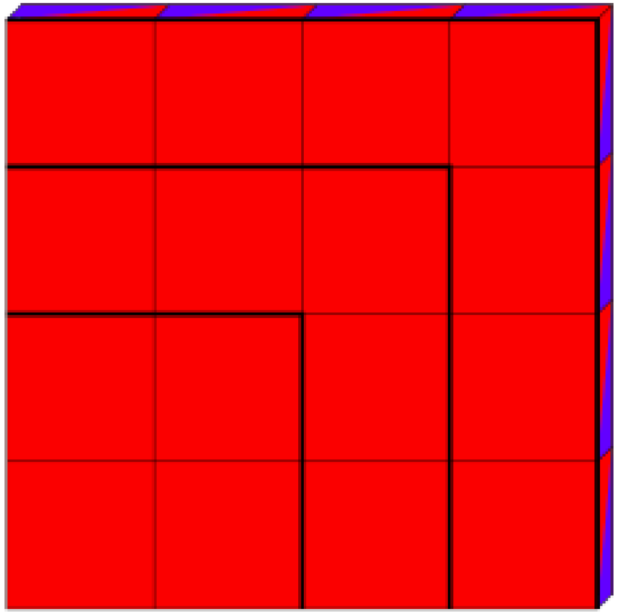
trigger-element, em. and had. separate

Isolation:

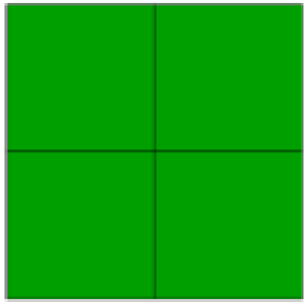


ATLAS Calorimeter Algorithms II

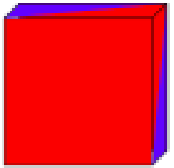
Jet trigger



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

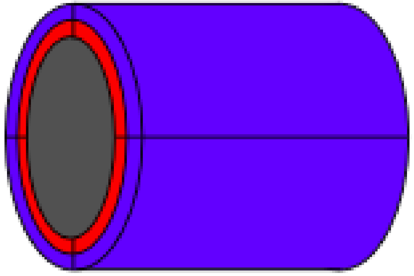


RoI-cluster



Jet-element, em. + had. summed

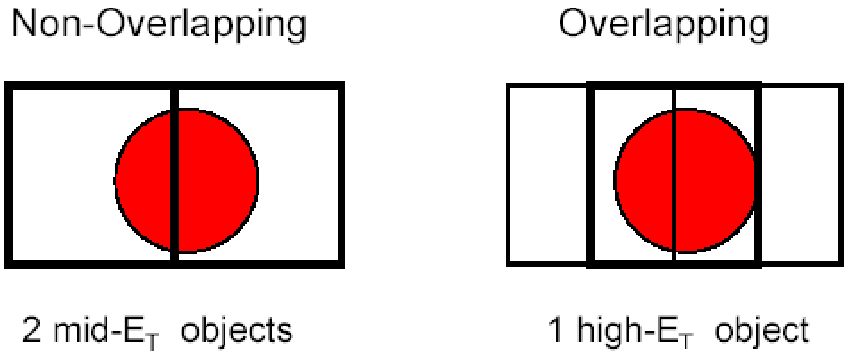
Et-miss / sum-Et trigger



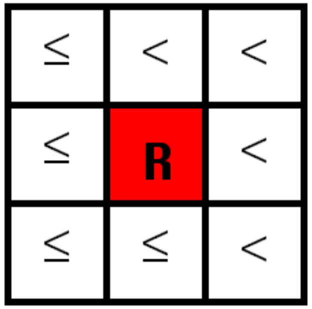
sum of Et
sum of Ex and Ey
|Eta| < 4.9

Jets

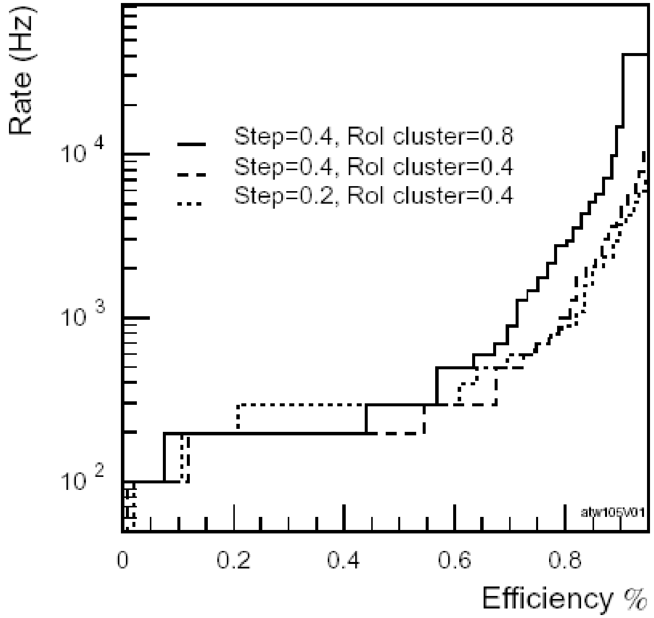
- Jets: very useful (compositeness, extra dimensions, SUSY decays) but also very abundant
  - Background to jets is jets; and QCD makes lots of them
  - Main issue is instrumental: don’t split jets, don’t overcount
    - Overlapping windows: efficient, but need additional “declustering” logic to remove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



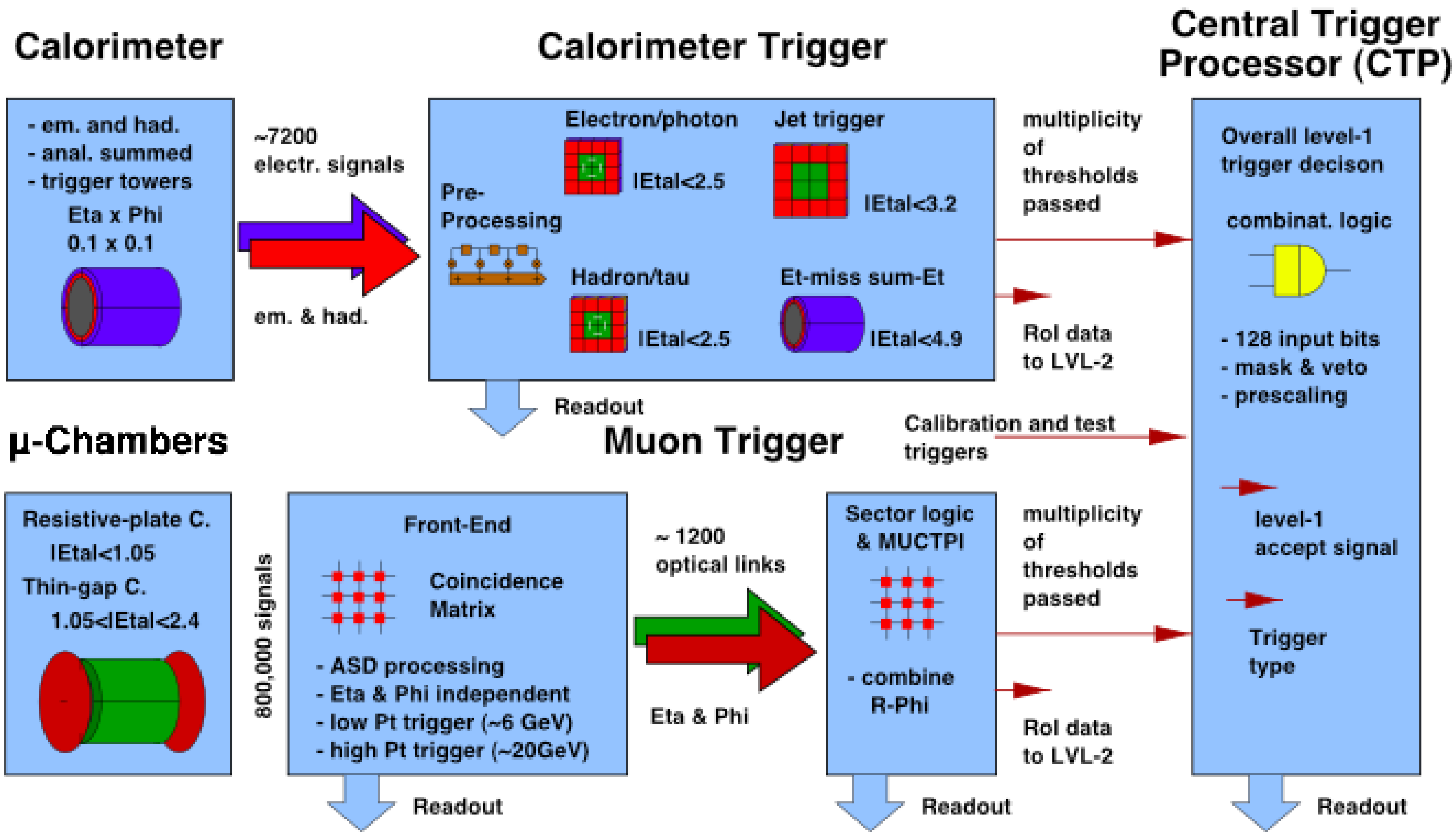
ATLAS: use ROI clusters, defined as maximum found in sliding window by half the jet window width



≤	<	<
≤	R	<
≤	≤	<



Trigger Flow : ATLAS Example



Calorimeter

- em. and had.
- anal. summed
- trigger towers

Eta x Phi
0.1 x 0.1

~7200
electr. signals

em. & had.

Calorimeter Trigger

Pre-
Processing

Electron/photon
lEtal<2.5

Jet trigger
lEtal<3.2

Hadron/tau
lEtal<2.5

Et-miss sum-Et
lEtal<4.9

Readout

multiplicity
of
thresholds
passed

RoI data
to LVL-2

Central Trigger Processor (CTP)

Overall level-1
trigger decison

combinat. logic

- 128 input bits
- mask & veto
- prescaling

level-1
accept signal

Trigger
type

Readout

Calibration and test
triggers

µ-Chambers

Resistive-plate C.
lEtal<1.05
Thin-gap C.
1.05<lEtal<2.4

800,000 signals

Muon Trigger

Front-End

Coincidence
Matrix

- ASD processing
- Eta & Phi independent
- low Pt trigger (~6 GeV)
- high Pt trigger (~20GeV)

Readout

~ 1200
optical links

Eta & Phi

Sector logic
& MUCTPI

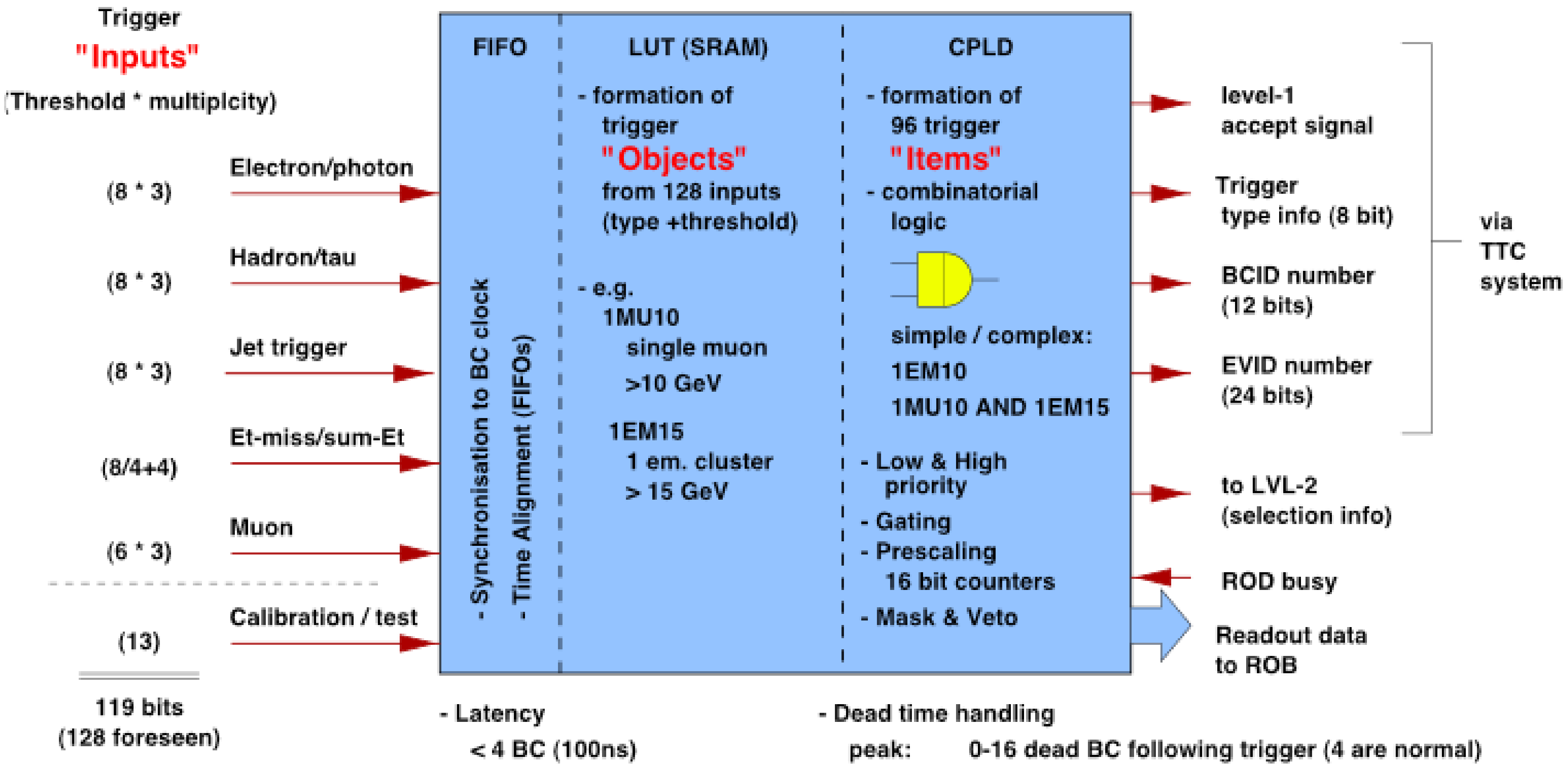
- combine
R-Phi

Readout

multiplicity
of
thresholds
passed

RoI data
to LVL-2

ATLAS Trigger Central Processor



Trigger
"Inputs"
(Threshold * multiplcity)

(8 * 3) Electron/photon

(8 * 3) Hadron/tau

(8 * 3) Jet trigger

(8/4+4) Et-miss/sum-Et

(6 * 3) Muon

(13) Calibration / test

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

level-1
accept signal

Trigger
type info (8 bit)

BCID number
(12 bits)

EVID number
(24 bits)

via
TTC
system

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)

CMS Calorimeter Trigger Rates: 2 x 10^{33} cm^{-2} s^{-1}

Mock

Trigger

Table

Trigger	Threshold (GeV)	95% Eff. (GeV)	Individual Rate (kHz)	Cumulative Rate (kHz)
e	20	27	4.9	4.9
ee	15	19	0.2	5.0
τ	89	~114	3.8	8.6
ττ	75	~100	0.7	8.8
j	130	152	1.5	9.5
jj	115	131	0.8	9.5
jjj	75	77	0.3	9.6
jjjj	55	62	0.2	9.6
e·j	10&100	15&125	0.4	9.8
e·τ	10&75	15&~100	0.8	10.0
Missing E_T	140	200	0.01	10.0
e·ME_T	10&75	15&140	0.4	10.3
j·ME_T	60&90	80&150	0.7	10.6
Total E_T	600	1200	0.04	10.6
H_T	400	470	0.6	10.7
e(NI)	45	51	0.2	10.8
ee(NI)	25	37	0.03	10.8
Total Rate				10.8

Selected Scenario: 5 kHz e/g, 5 kHz τ,jets, 1 kHz combined, rest μ

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

Scenario:

5 kHz e/γ,

5 kHz τ,jets,

1 kHz comb,

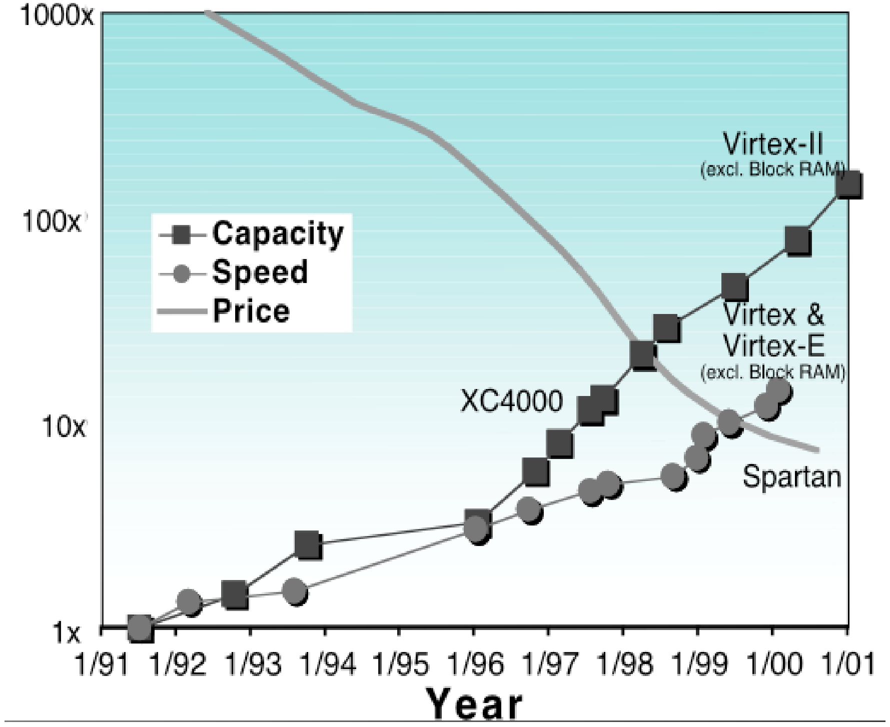
rest μ

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

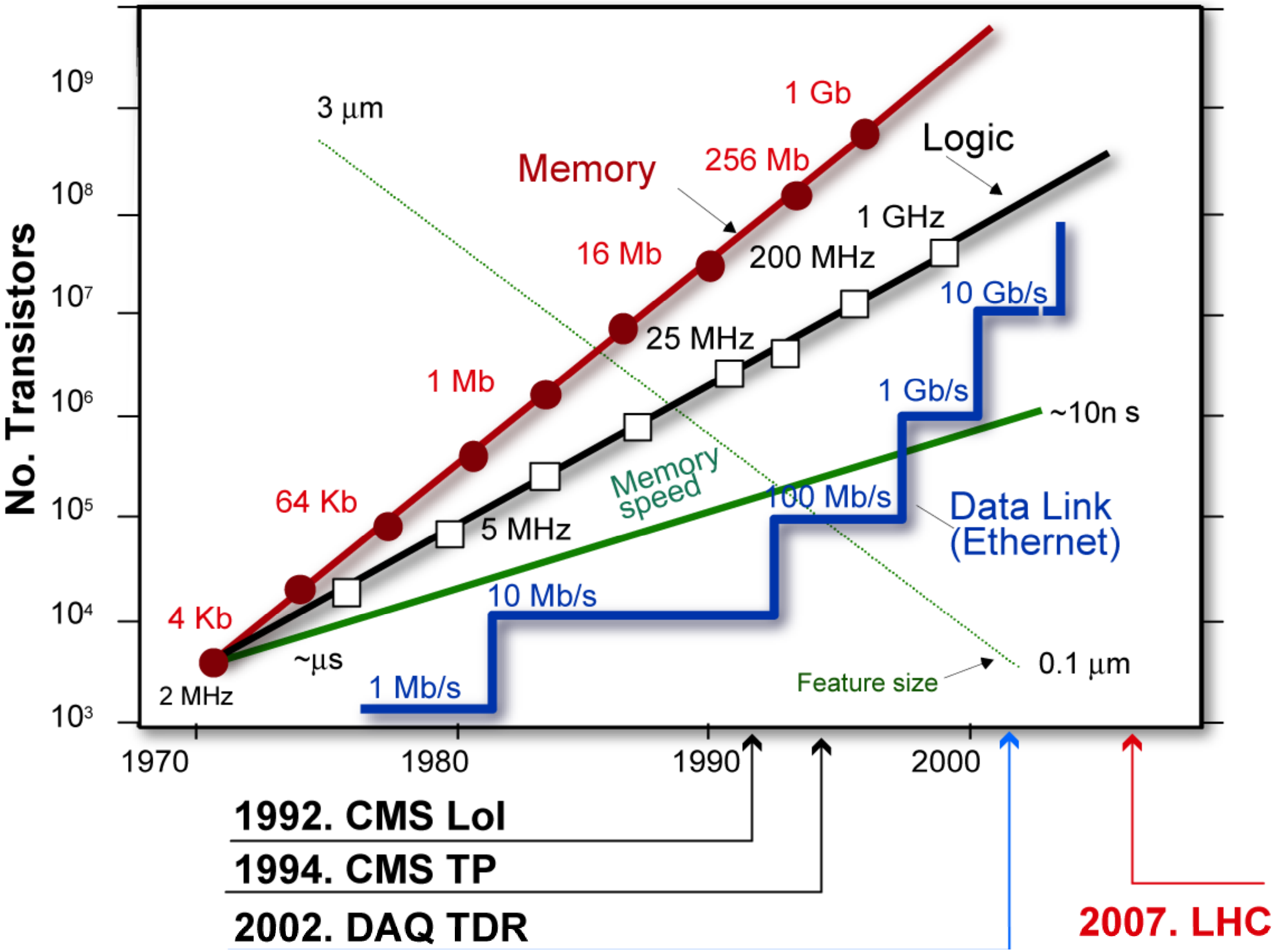
Channel	Total Efficiency	Trigger Efficiencies by trigger type (individual) cumulative				
$W\rightarrow e\nu$	70	e (70) 70				
$t\rightarrow eX$	91	e (82) 82	$e\cdot\tau$ (62) 86	τ (55) 89	jjj (24) 90	$e\cdot j$ (54) 91
$Z\rightarrow ee$	94	e (93) 93	ee (76) 94			
$H(115)\rightarrow\gamma\gamma$	99	e (99) 99	ee (82) 99			
$H(150)\rightarrow WW\rightarrow e\nu X$	87	e (78) 78	$e\cdot\tau$ (43) 81	τ (34) 83	$e\cdot j$ (39) 85	j (28) 87
$H(135)\rightarrow\tau\tau\rightarrow ej$	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		
$H(200)\rightarrow\tau\tau\rightarrow jj$	81	τ (75) 75	$\tau\tau$ (50) 79	j (24) 81	jj (9) 81	
$H(500)\rightarrow\tau\tau\rightarrow jj$	99	τ (94) 94	$\tau\tau$ (64) 94	j (94) 99	jj (73) 99	
$t\rightarrow$jets	53	H_T (39) 39	jjjj (26) 43	jjj (26) 46	jj (21) 47	j (35) 53
mSUGRA	99	j (99) 99				
$H(120)\rightarrow b\bar{b}$	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		

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



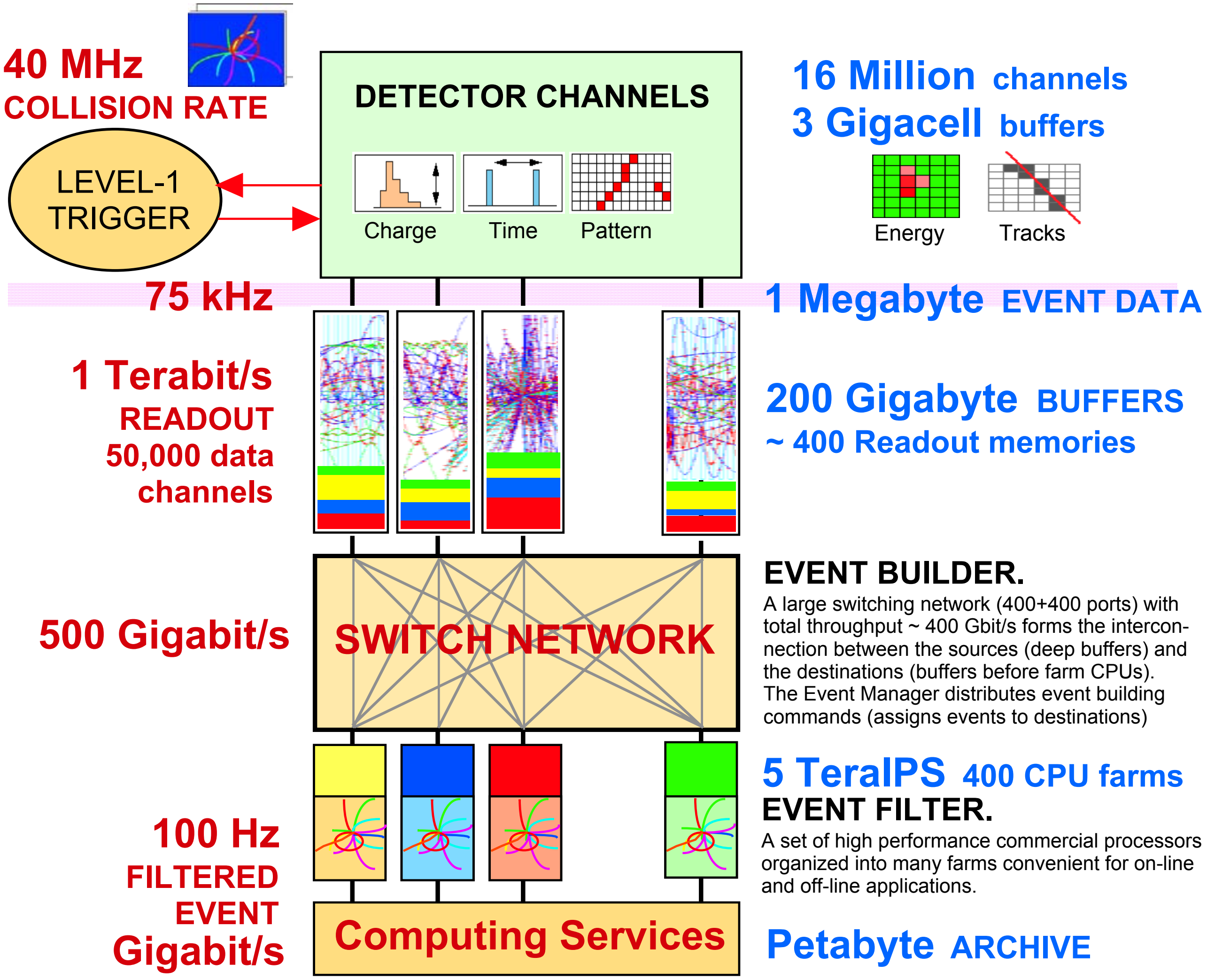
1992. CMS LoI

1994. CMS TP

2002. DAQ TDR

2007. LHC

Online Selection Flow in pp (II)



40 MHz
COLLISION RATE

16 Million channels
3 Gigacell buffers

75 kHz

1 Megabyte EVENT DATA

1 Terabit/s
READOUT
50,000 data channels

200 Gigabyte BUFFERS
~ 400 Readout memories

500 Gigabit/s

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

100 Hz
FILTERED EVENT

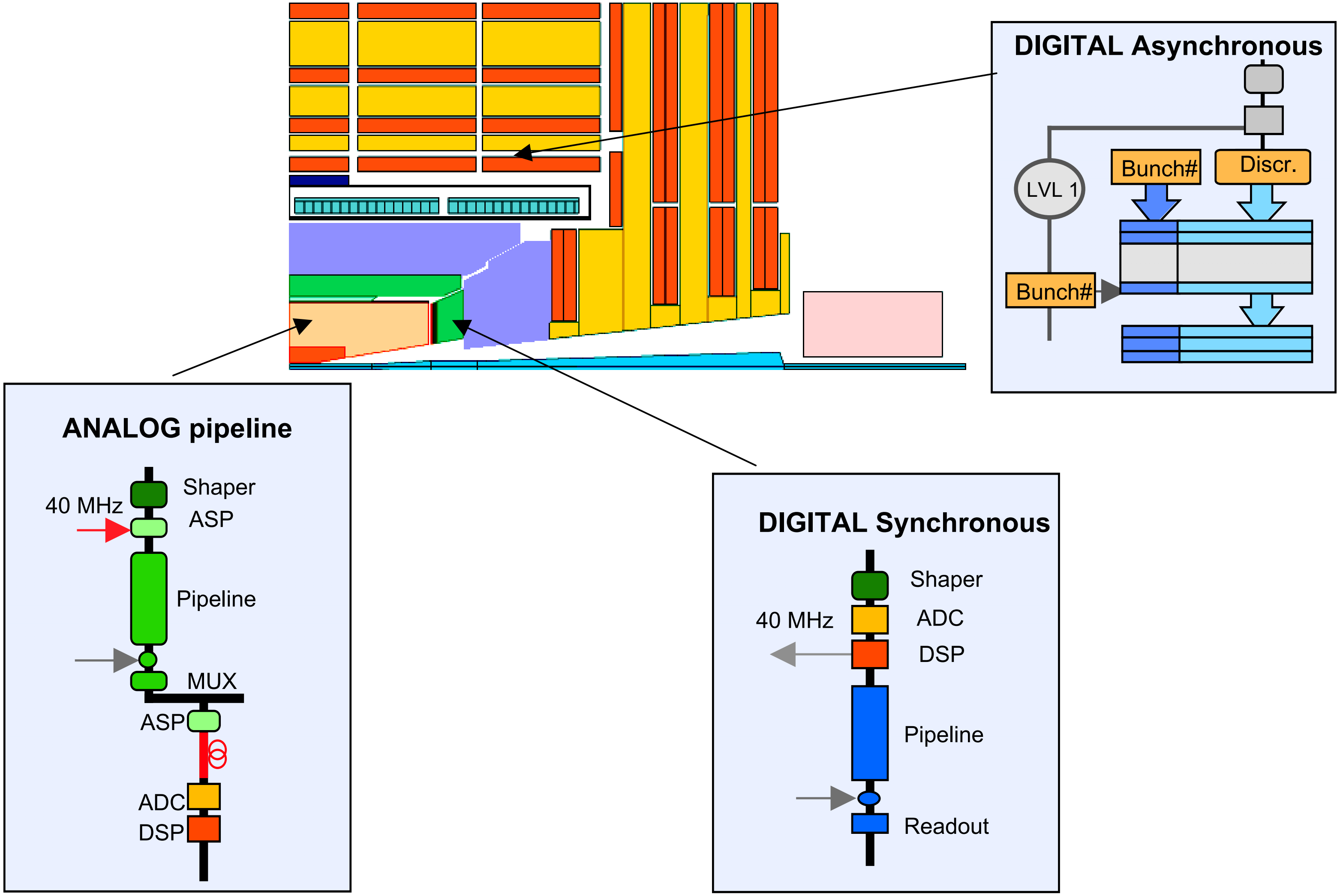
5 TeraIPS 400 CPU farms

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

Gigabit/s
SERVICE LAN

Petabyte ARCHIVE

Detector Readout: front-end types



DIGITAL Asynchronous

LVL 1

Bunch#

Discr.

Bunch#

ANALOG pipeline

Shaper

40 MHz

ASP

Pipeline

MUX

ASP

ADC

DSP

DIGITAL Synchronous

Shaper

40 MHz

ADC

DSP

Pipeline

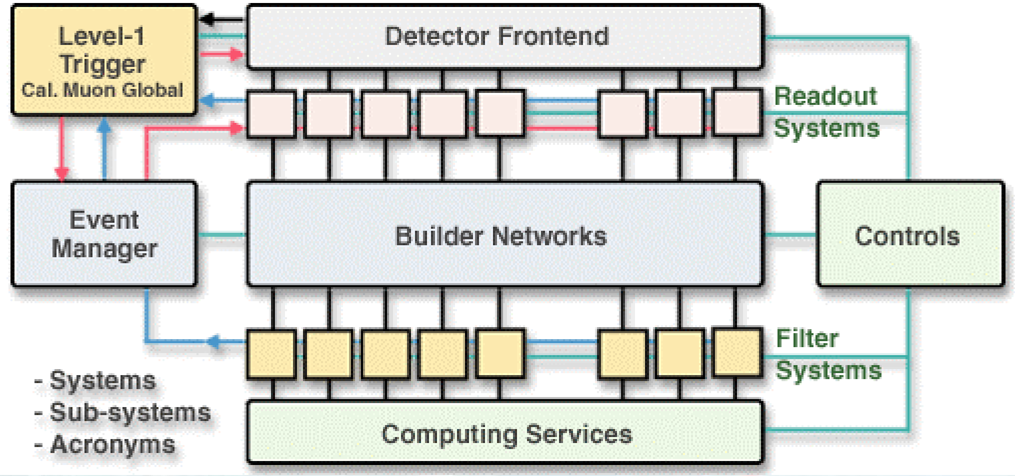
Readout

High-Level Triggers and DAQ at LHC

- In the LHC experiments, data are transferred to large buffer memories after a LVL1 accept
  - In normal operation, the subsequent stages should not introduce further dead-time
- The data rates at the HLT/DAQ input are still massive
  - ~1 MByte event size (after data compression) @ ~100 kHz event rate ⇒ ~ 100 GByte/s data rate
    (i.e ~800 Gbit/s)
- This is far beyond the capacity of the bus-based event building of, e.g., LEP
  - Use network-based event building to avoid bandwidth bottlenecks

e.g. CMS

CMS LVL1 Trigger TDR
CERN-LHCC-2000-038



Data are stored in Readout Systems until they have been transferred to the Filter Systems (associated with HLT processing), or until the event is rejected

No node in the system sees the full data rate — each Readout System covers only a part of the detector — each Filter System deals with only a fraction of the events

HLT and DAQ: Concepts

- The massive data rate after LVL1 poses problems even for network-based event building — different solutions are being adopted to address this, for example:
  - In CMS, the event building is factorized into a number of slices each of which sees only a fraction of the rate
    - Requires large total network bandwidth (⇒ cost), but avoids the need for a very large single network switch
  - In ATLAS, the Region-of-Interest (RoI) mechanism is used with sequential selection to access the data only as required – only move data needed for LVL2 processing
    - Reduces by a substantial factor the amount of data that need to be moved from the Readout Systems to the Processors
    - Implies relatively complicated mechanisms to serve the data selectively to the LVL2 trigger processors ⇒ more complex software

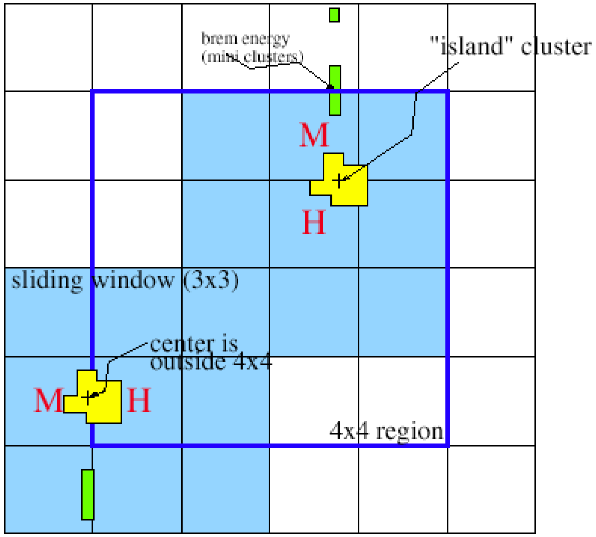
Example: electron selection (I)

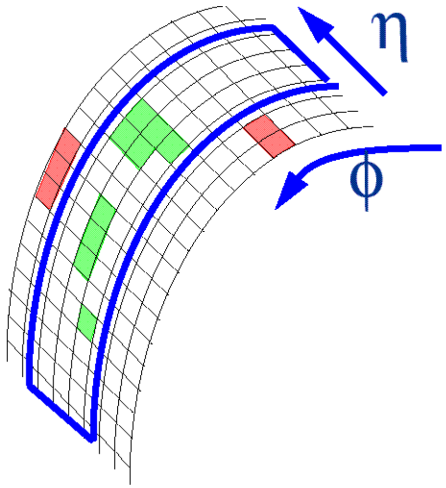
- “Level-2” electron:
  - 1-tower margin around 4x4 area found by Lvl-1 trigger
  - Apply “clustering”
  - Accept clusters if H/EM < 0.05
  - Select highest E_T cluster

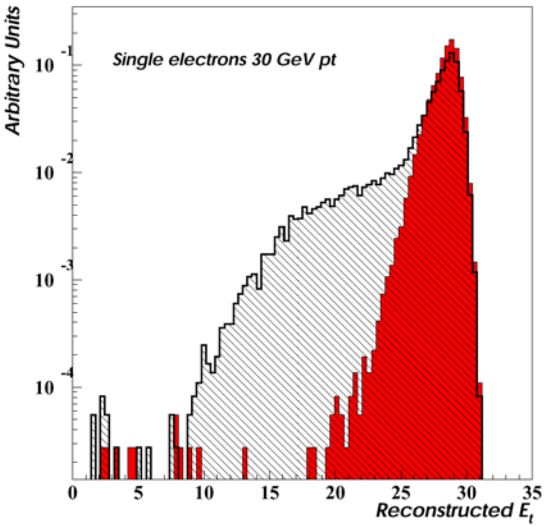
- Brem recovery:
  - Seed cluster with $E_T > E_T^{min}$
  - Road in ϕ around seed
  - Collect all clusters in road

  → “supercluster”

  and add all energy in road:

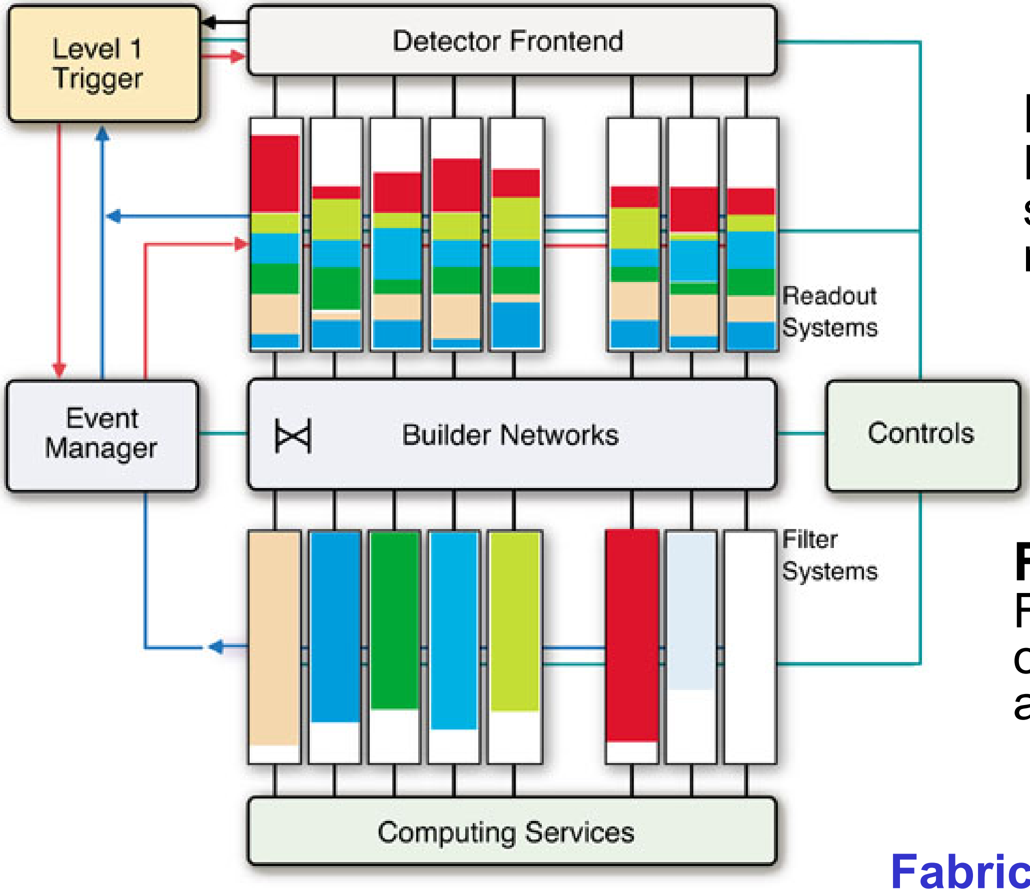






Event Building

- Form full-event-data buffers from fragments in the readout. Must interconnect data sources/destinations.



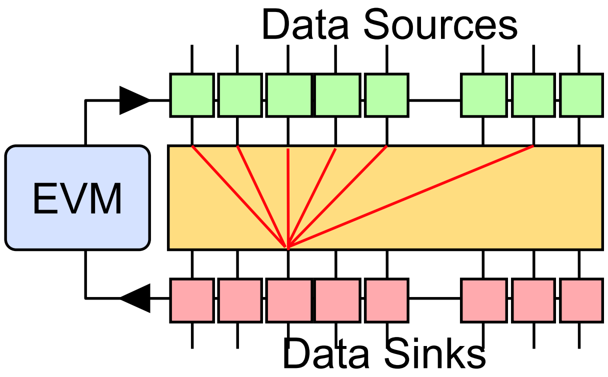
Event fragments :
Event data fragments are stored in separated physical memory systems

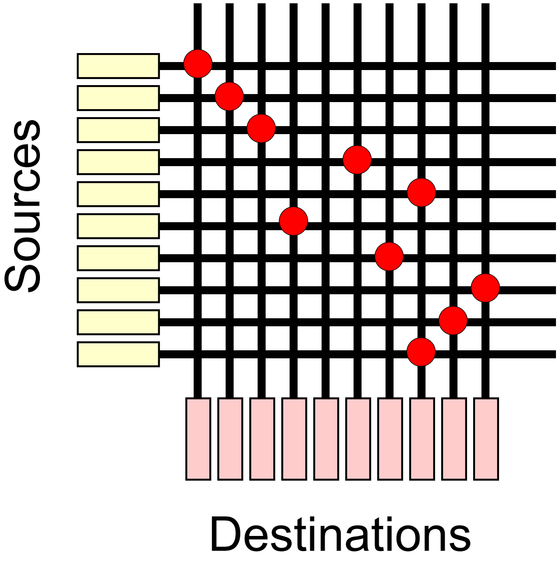
Full events :
Full event data are stored into one physical memory system associated to a processing unit

Hardware:
Fabric of switches for builder networks
PC motherboards for data Source/Destination nodes

Event Building via a Switch

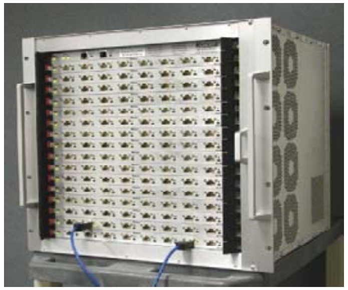
- Three major issues:
  - Link utilization
  - The bottleneck on the outputs
  - The large number of ports needed
- Space-division: crossbar
  - Simultaneous transfers between any arbitrary set of inputs and outputs
    - Can be both self-routing and arbiter-based (determine connectivity between S's and D's for each cycle); the faster the fabric, the smaller the arbitration complexity
    - Does not solve Output Contention issue
    - Need *Traffic Shaping*



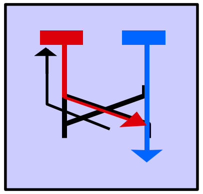


Switching technologies

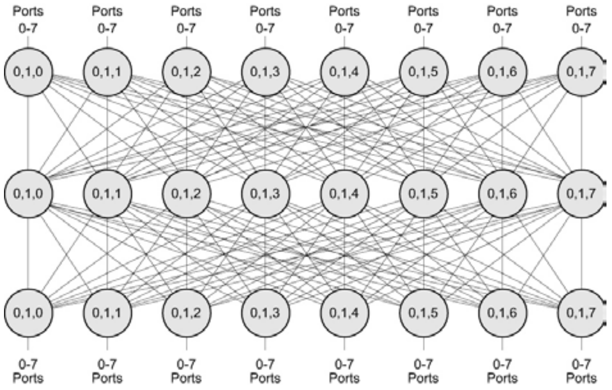
Myricom: Myrinet 2000



- Switch: **Clos-128 @ 2.5** Gb/s ports
- **NIC**: M3S-PCI64B-2 (**LANai9**)
- **Custom Firmware**

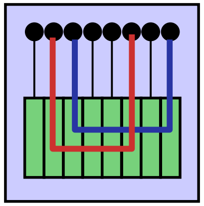


wormhole data
transport with flow
control at all stages

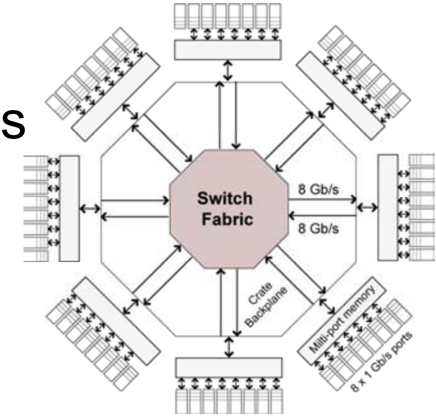


Gigabit Ethernet

- Switch: Foundry **FastIron64 @ 1.2** Gb/s ports
- **NIC**: **Alteon** (running standard firmware)



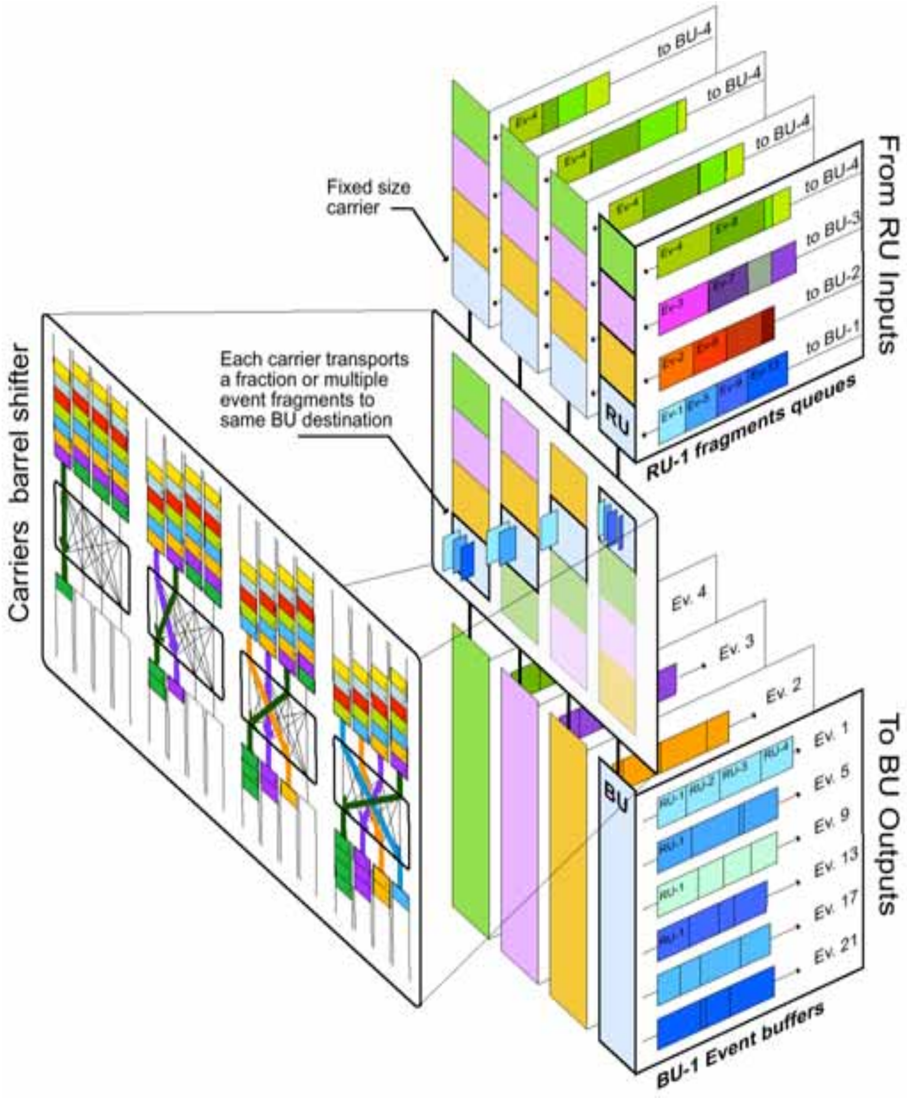
Implementation:
Multi-port memory system R/W bandwidth greater than sum of all port speeds
Packet switching
Contention resolved by Output buffer.
Packets can be lost.



Infiniband

- 2.5 Gb/s demo products. First tests completed recently.

Myrinet Barrel-Shifter



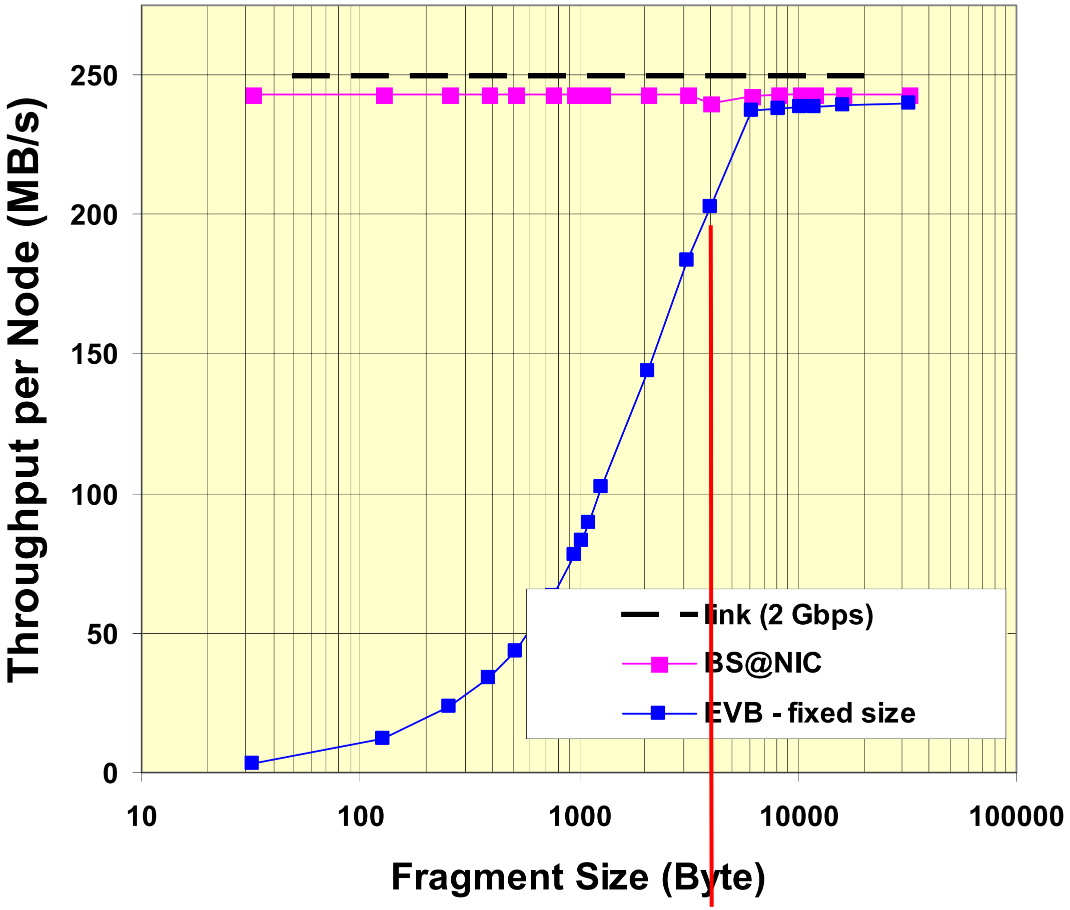
BS **implemented in firmware**

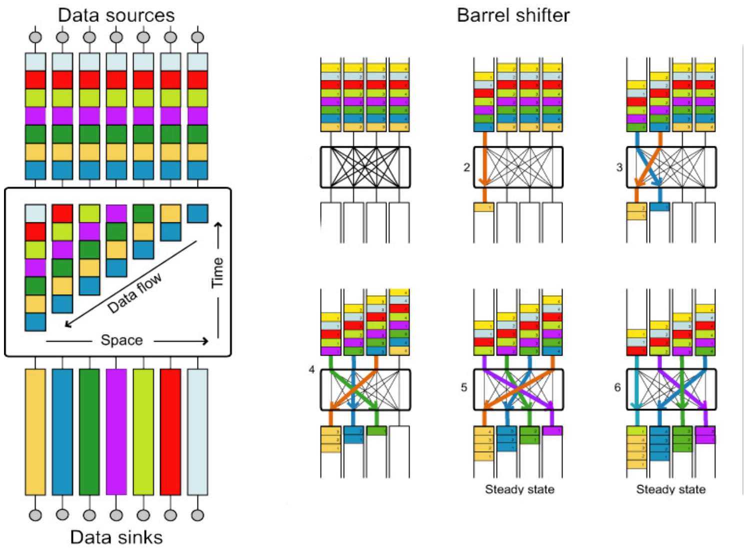
- Each source has message queue per destination
- Sources divide messages into fixed size packets (carriers) and cycle through all destinations
- Messages can span more than one packet and a packet can contain data of more than one message
- No external synchronization (relies on Myrinet back pressure by HW flow control)

zero-copy, **OS-bypass**

principle works for multi stage switches

A Myrinet-based 32x32 EVB





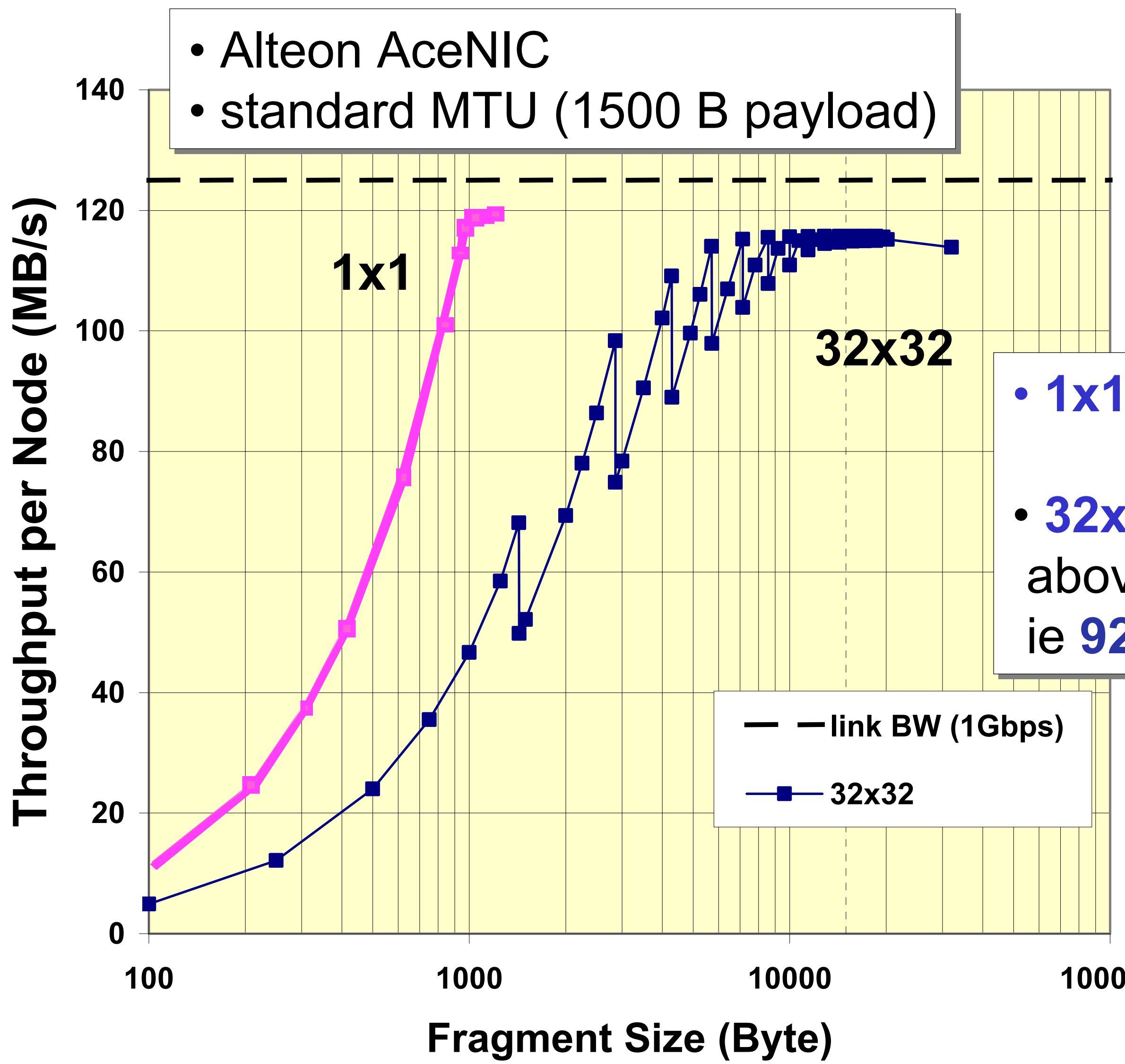
- Fixed-size event fragments

  below 4k: Fragment < BS carrier
  above 4k: Fragment > BS carrier

- Throughput at **234 MB/s**

  = **94% of link Bandwidth**

Gigabit Ethernet-based 32x32 EVB



- Alteon AceNIC
- standard MTU (1500 B payload)

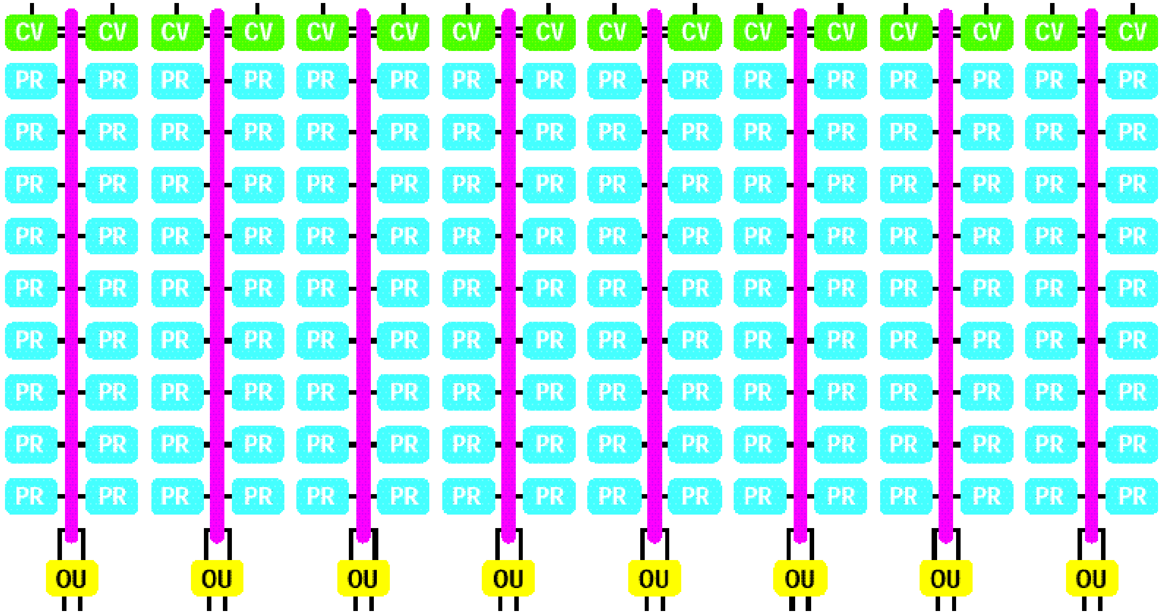
- **1x1** asymptotically to 125 MB/s

- **32x32** saw tooth due to MTU above **10k**: plateau of 115 MB/s ie **92%** of link speed (1Gbps)

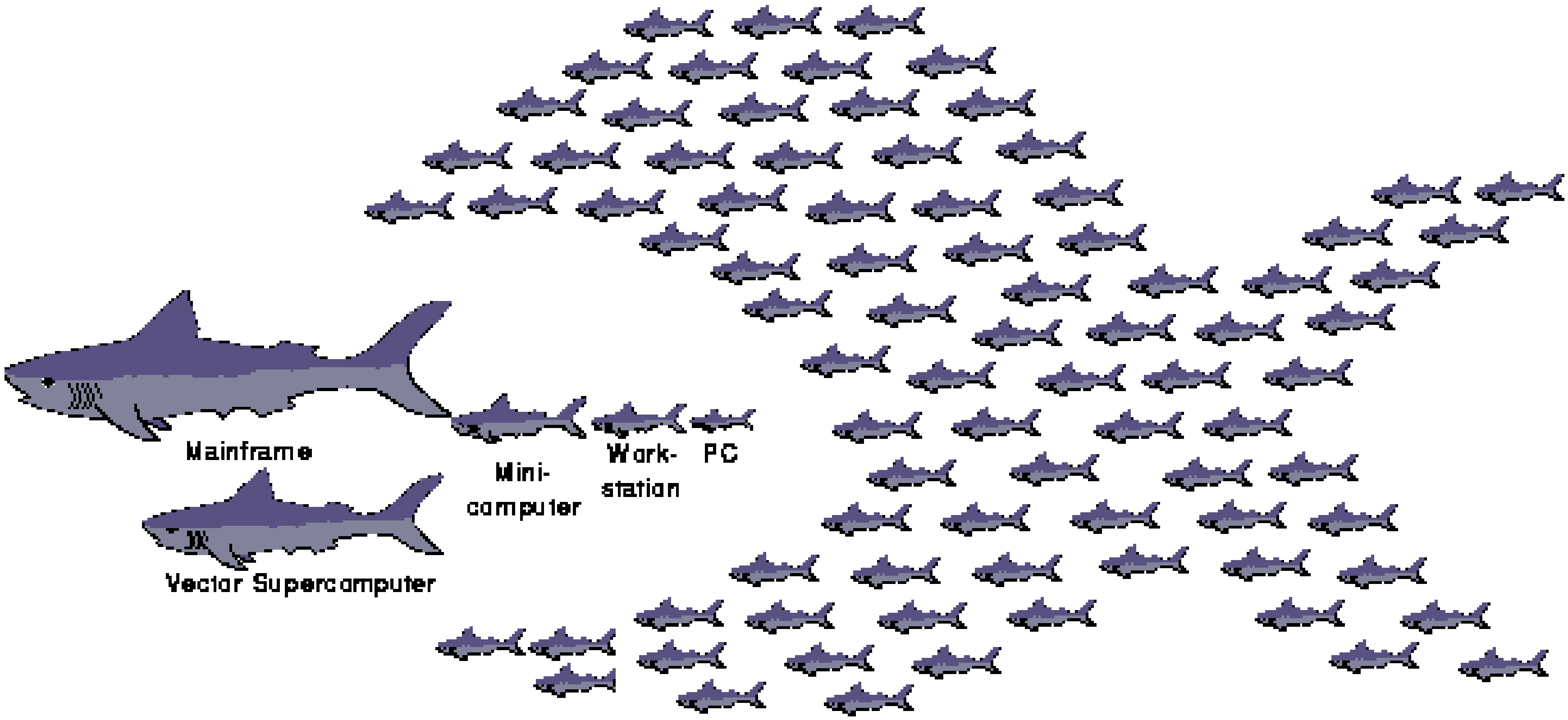
Processor Engines

- Final stage of the filtering process: almost an offline-quality reconstruction & selection
  - Need real programmable processors; and lots of them
  - (Almost) all experiments in HEP: using/will use a processor farm

CDF example: 16 sub-farms of 9 processors each



Processor Farm: the 90's super-computer; the 2000's large computer



NOW

Found at the NOW project (http://now.cs.berkeley.edu)

Processor Farms: conclusion

- Explosion of number of farms installed
  - Very cost-effective
    - Linux is free but also very stable, production-quality
    - Interconnect: Ethernet, Myrinet (if more demanding I/O); both technologies inexpensive and performant
  - Large number of message-passing packages, various API's on the market
    - Use of a standard (VIA?) could be the last remaining tool to be used on this front
  - Despite recent growth, it's a mature process: basic elements (PC, Linux, Network) are all mature technologies. Problem solved. What's left: Control & Monitor. A Standard (Web/Java-based?) could do lots here.
    - Lots of prototypes and ideas. Need real-life experience.
    - Problem is human interaction

HLT requirements and operation

- Strategy/design guidelines
  - Use offline software as much as possible
    - Ease of maintenance, but also understanding of the detector
- Boundary conditions:
  - Code runs in a single processor, which analyzes one event at a time
  - HLT (or Level-3) has access to full event data (full granularity and resolution)
  - Only limitations:
    - CPU time
    - Output selection rate (~10^2 Hz)
    - Precision of calibration constants
- Main requirements:
  - Satisfy physics program (see later): high efficiency
  - Selection must be inclusive (to discover the unpredicted as well)
  - Must not require precise knowledge of calibration/run conditions
  - Efficiency must be measurable from data alone
  - All algorithms/processors must be monitored closely

Physics, Signatures and Triggers

Some physics and their experimental signatures:

- Higgs
  - $\gamma\gamma$, bbar, WW, ZZ (peak)
- Supersymmetry
  - multi-leptons or same-sign lepton pairs
  - jets and Missing E_T
- Z'
  - di-electron, di-muon (peak)
- W'
  - electron or muon and Missing E_T
- Large Extra dimensions
  - jet + Missing E_T (mono-jet)
  - di-fermion, di-boson
- Compositeness
  - di-jet (hi mass tail)
  - lepton and jet (LeptoQuark)

Corresponding "primary" triggers:

- di-photon
- di-electron
- di-muon
- di-jet
  - with b-tagging

- Inclusive leptons, either:
  - higher threshold
  - Isolation cut
  - Pre-scale applied

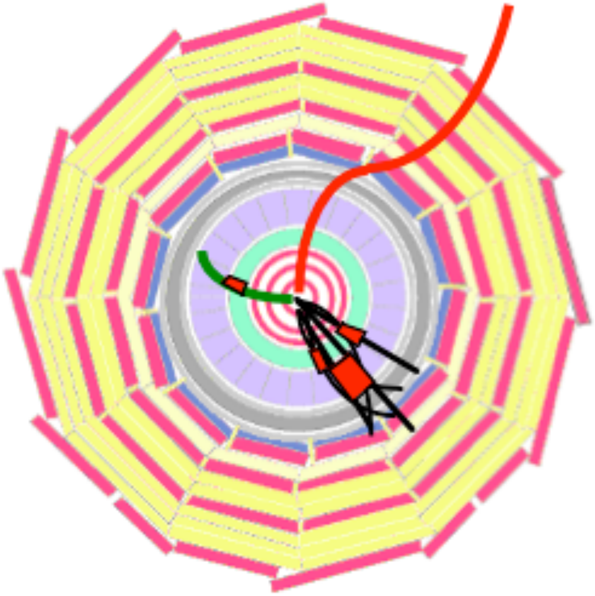
- Missing E_T .
  - Jet(s)
  - leptons

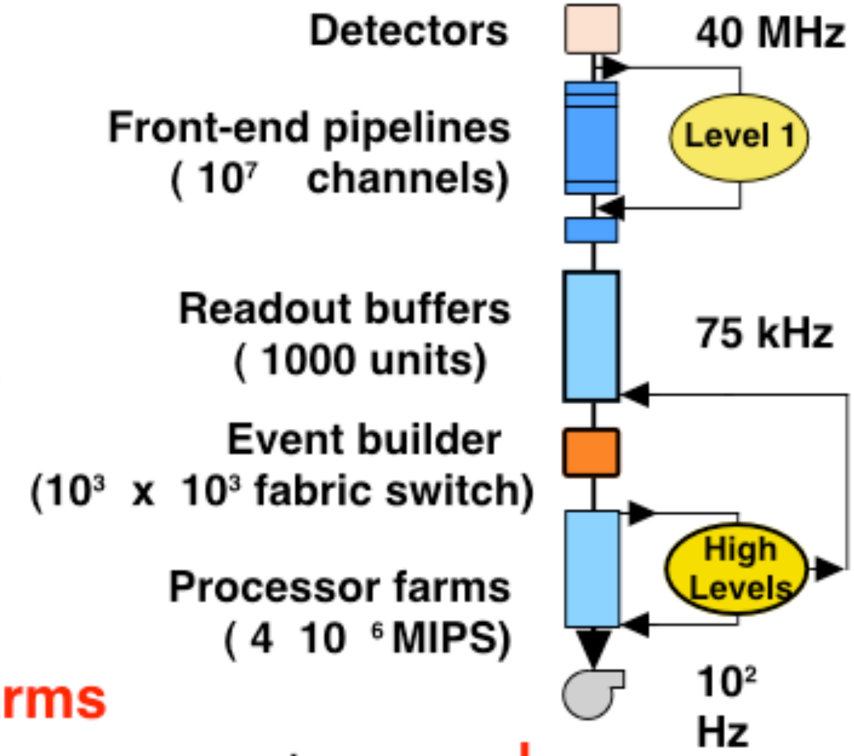
- "mixed" or "composite" triggers
  - …

HLT menu

- Illustrative menu for LHC at $2\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$ luminosity (CMS):
  - $p_T^e > 29$ GeV or 2 electrons $p_T^e > 17$ GeV
    - Rate ~ 34 Hz
  - $p_T^\gamma > 80$ GeV or 2 photons $p_T^\gamma > 40, 25$ GeV
    - Rate ~ 9 Hz
  - $p_T^\mu > 19$ GeV or 2 muons $p_T^\mu > 7$ GeV
    - Rate ~ 29 Hz
  - $p_T^\tau > 86$ GeV or 2 taus $p_T^\tau > 59$ GeV
    - Rate ~ 4 Hz
  - $p_T^{jet} > 180$ GeV and missing $E_T > 123$ GeV
    - Rate ~ 5 Hz
  - $p_T^{jet} > 657$ GeV or 3 jets $p_T^{jet} > 247$ GeV or 4 jets $p_T^{jet} > 113$ GeV
    - Rate ~ 9 Hz
  - Others (electron•jet; b-jets, etc.)
    - Rate ~ 7 Hz
  - Total ~ 100 Hz of which a large fraction is “physics” – large uncertainty on rates!
    - Need to balance physics coverage against offline computing cost

High Level Trigger Strategy





Detectors

40 MHz

Front-end pipelines
(10^7 channels)

Level 1

Readout buffers
(1000 units)

75 kHz

Event builder
(10^3 x 10^3 fabric switch)

Processor farms
(4 10^6 MIPS)

High Levels

10^2 Hz

High level triggers. CPU farms

- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,τ-jet tagging
- Full event reconstruction and analysis

Successive improvements : background event filtering, physics selection

Start with L1 Trigger Objects

Electrons, Photons, τ-jets, Jets, Missing E_T, Muons

- **HLT refines L1 objects (no volunteers)**

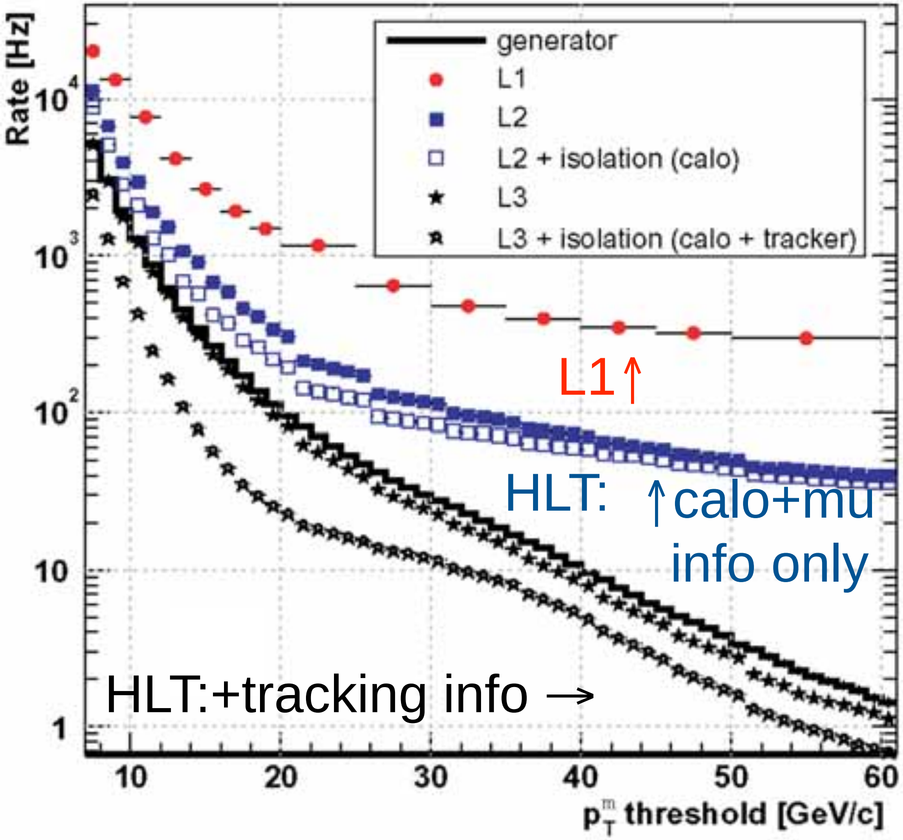
Goal

- **Keep L1T thresholds for electro-weak symmetry breaking physics**
- **However, reduce the dominant QCD background**
  - From 100 kHz down to 100 Hz nominally

QCD background reduction

- **Fake reduction: e±, γ, τ**
- **Improved resolution and isolation: μ**
- **Exploit event topology: Jets**
- **Association with other objects: Missing E_T**
- **Sophisticated algorithms necessary**
  - Full reconstruction of the objects
  - Due to time constraints we avoid full reconstruction of the event - L1 seeded reconstruction of the objects only
  - Full reconstruction only for the HLT passed events

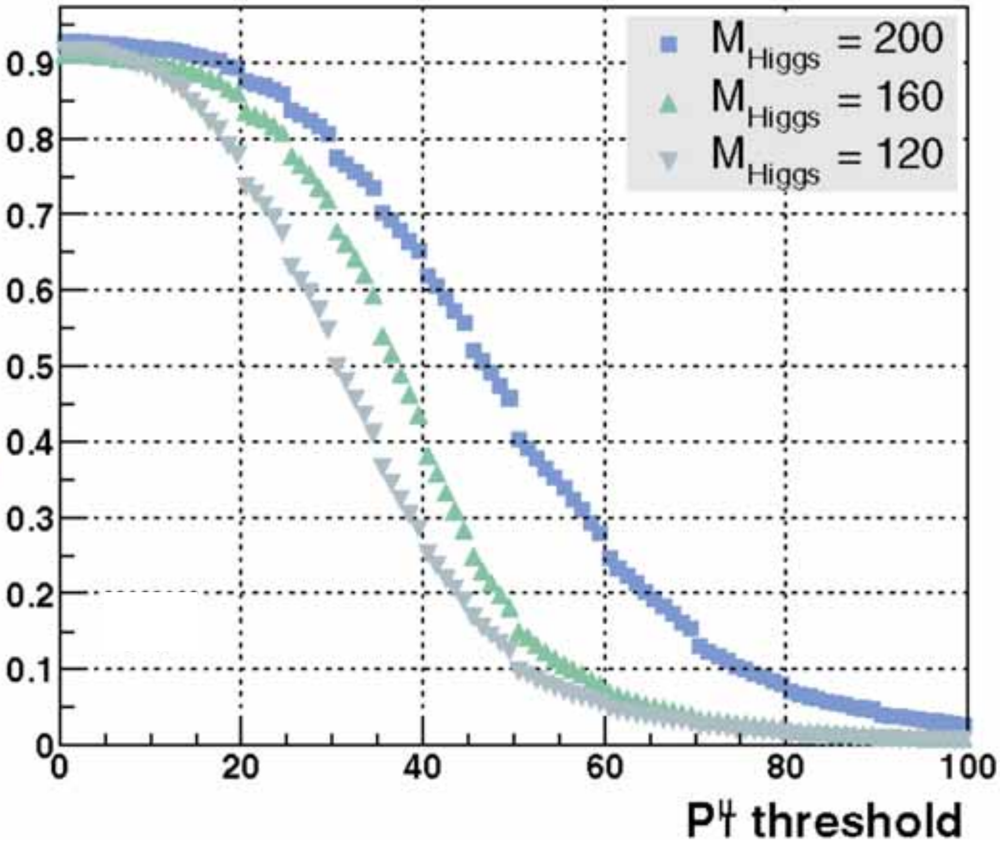
Muon Higher Level Trigger



L1↑

HLT: ↑calo+mu info only

HLT:+tracking info →

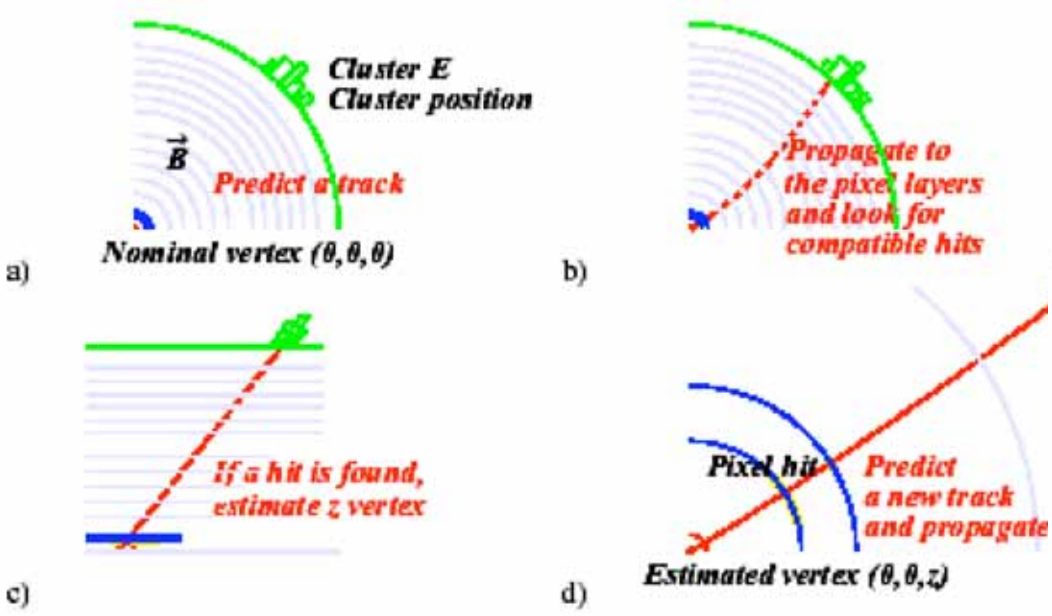


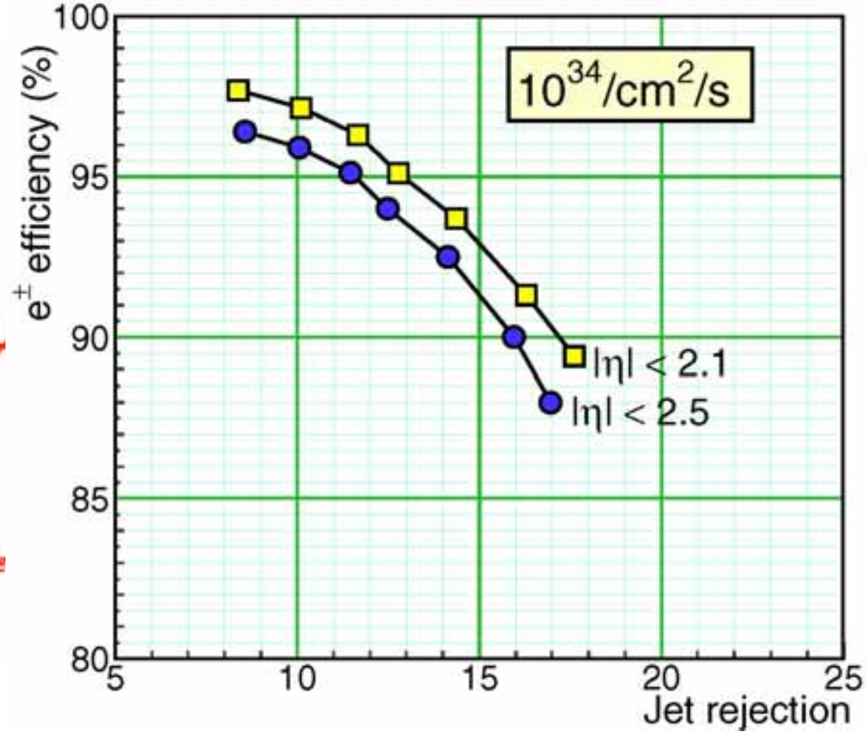
Trigger rates vs. muon p_T threshold through levels of HLT processing at $L = 2 \times 10^{33}$

Efficiency for Higgs selection vs. muon p_T threshold for different Higgs masses

CMS tracking for electron trigger

Present CMS electron HLT

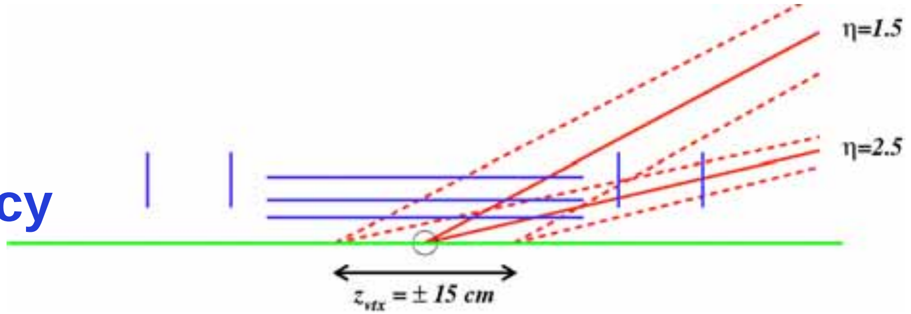




Factor of 10 rate reduction

γ: only tracker handle: isolation

- Need knowledge of vertex location to avoid loss of efficiency



Układ wyzwalania

Powinien zapewnić zebranie/zapisanie

* możliwie największej liczby przypadków "sygnału",
np. poszukiwanych procesów "nowej fizyki", produkcji bozonu Higgsa

* możliwie różnorodnych topologii tych przypadków
różne kanały produkcji i/lub rozpadu, różne zakresy kinematyczne
=> konieczne dla weryfikcji modeli, dopasowania parametrów

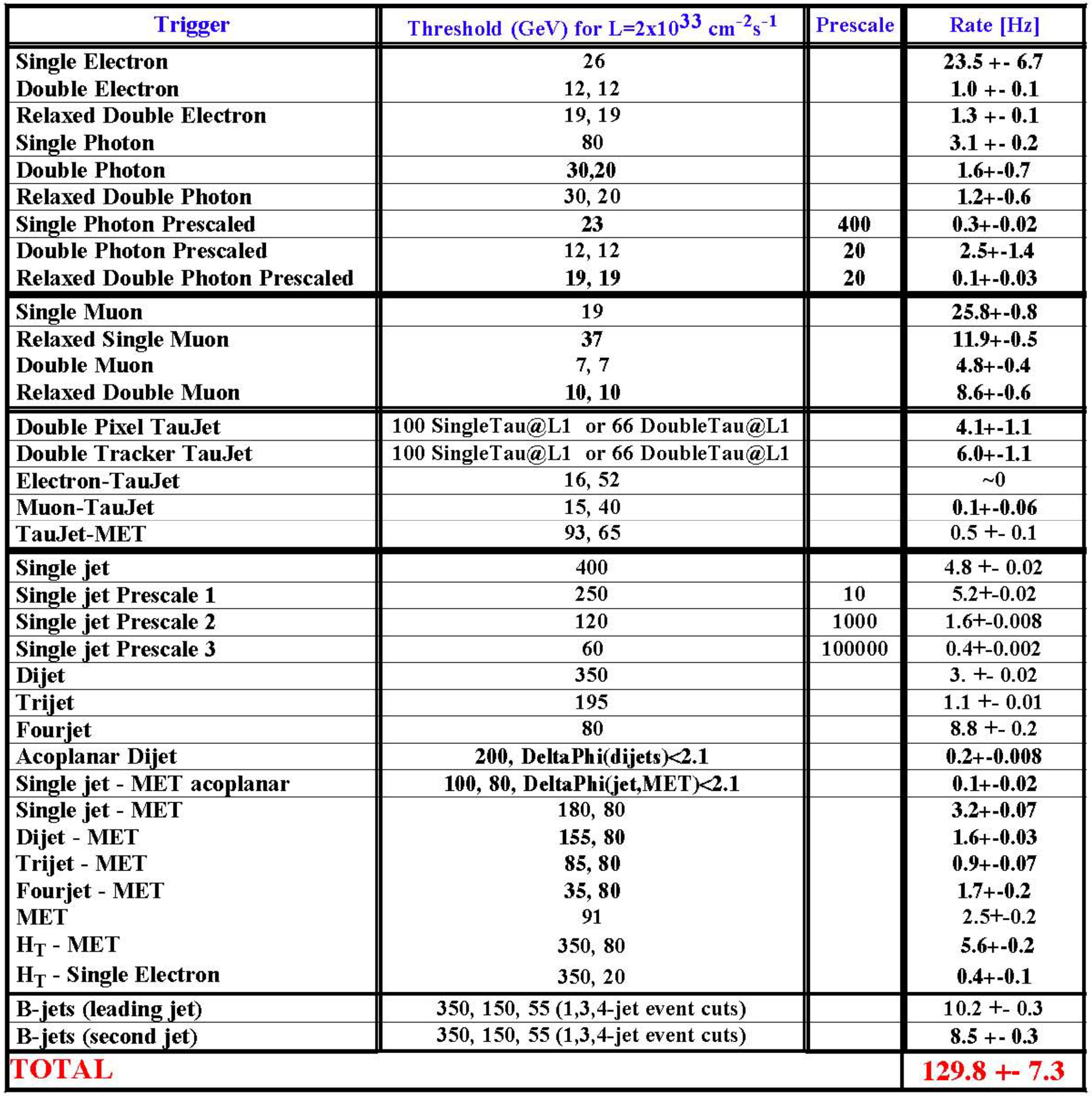
* odpowiedniej (minimalizacja błędów) liczby przypadków dla:
- synchronizacji detektora
- kalibracji detektora
- pozycjonowania detektora
- pomiaru procesów tła
- pomiaru procesów dających wkład do modeli (np. PDF)
- pomiaru procesów pozwalających na wyznaczenie świetlności

Układ wyzwalania

Aby zgromadzić wszystkie potrzebne informacje wykorzytujemy całą gamę wmożliwych triggerów:

- przypadki fizyczne (wybrane na podstawie kryteriów LV1/HLT)
- przypadki "minimum bias" ("cokolwiek w detektorze")
  - weryfikacja algorytmów selekcji
- przypadki losowe: przypadkowe przecięcie z wiązką
  - ocena tła wiązki
  - przypadkowe przecięcie bez wiązki
  - ocena poziomu szumów, pile-up
- przypadki kalibracyjne (różnego typu)
  - w zależności od typu detektora może to być impuls lasera, impuls ładunku, pomiar sygnału przy wydłużonej bramce...
- przypadki "środowiskowe"
  - każdy detektor odsyła istotne informacje o swoim działaniu
- przypadki testowe (różnego rodzaju)
  - każdy detektor wykonuje zadaną procedurę (np. generacja pseudo danych)

HLT Trigger Table - Example (CMS)



Trigger	Threshold (GeV) for L=2x10^{33} cm^{-2}s^{-1}	Prescale	Rate [Hz]
Single Electron	26		23.5 +- 6.7
Double Electron	12, 12		1.0 +- 0.1
Relaxed Double Electron	19, 19		1.3 +- 0.1
Single Photon	80		3.1 +- 0.2
Double Photon	30,20		1.6+-0.7
Relaxed Double Photon	30, 20		1.2+-0.6
Single Photon Prescaled	23	400	0.3+-0.02
Double Photon Prescaled	12, 12	20	2.5+-1.4
Relaxed Double Photon Prescaled	19, 19	20	0.1+-0.03
Single Muon	19		25.8+-0.8
Relaxed Single Muon	37		11.9+-0.5
Double Muon	7, 7		4.8+-0.4
Relaxed Double Muon	10, 10		8.6+-0.6
Double Pixel TauJet	100 SingleTau@L1 or 66 DoubleTau@L1		4.1+-1.1
Double Tracker TauJet	100 SingleTau@L1 or 66 DoubleTau@L1		6.0+-1.1
Electron-TauJet	16, 52		~0
Muon-TauJet	15, 40		0.1+-0.06
TauJet-MET	93, 65		0.5 +- 0.1
Single jet	400		4.8 +- 0.02
Single jet Prescale 1	250	10	5.2+-0.02
Single jet Prescale 2	120	1000	1.6+-0.008
Single jet Prescale 3	60	100000	0.4+-0.002
Dijet	350		3. +- 0.02
Trijet	195		1.1 +- 0.01
Fourjet	80		8.8 +- 0.2
Acoplanar Dijet	200, DeltaPhi(dijets)<2.1		0.2+-0.008
Single jet - MET acoplanar	100, 80, DeltaPhi(jet,MET)<2.1		0.1+-0.02
Single jet - MET	180, 80		3.2+-0.07
Dijet - MET	155, 80		1.6+-0.03
Trijet - MET	85, 80		0.9+-0.07
Fourjet - MET	35, 80		1.7+-0.2
MET	91		2.5+-0.2
H_T - MET	350, 80		5.6+-0.2
H_T - Single Electron	350, 20		0.4+-0.1
B-jets (leading jet)	350, 150, 55 (1,3,4-jet event cuts)		10.2 +- 0.3
B-jets (second jet)	350, 150, 55 (1,3,4-jet event cuts)		8.5 +- 0.3
TOTAL			129.8 +- 7.3

Electron, photon

muon

~60%

tau

jets

jets,met, HT

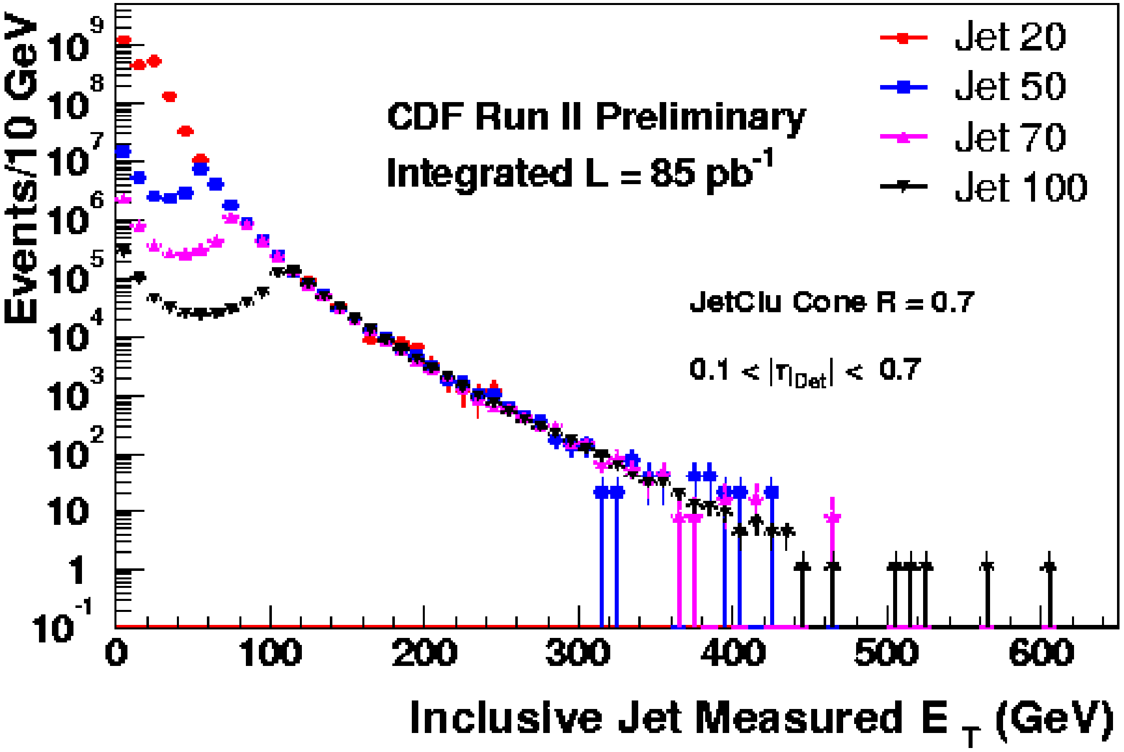
Pre-scales

- Inclusive jet triggers - rate too high to take them all

Sample

- Lower threshold -- higher pre-scale
- Lower threshold at lower trigger level
  - "sharp" cut at HLT
- "assemble" spectrum
- Fancy:

  dynamic prescales



Pre-requisites, Volunteers

- Pre-Requisite:
  - Only muons that have a L1 accept are pursued in the HLT.
  - Moreover, only that region may be even looked-at (reconstructed).

- Volunteer:
  - A muon “found” in the HLT, without a corresponding L1 accept
    - Possible Convention: such cannot be the cause of a trigger decision (CDF/CMS)
  - Cannot happen if only “seeded” (on L1 muon track) reconstruction is pursued in HLT
  - Can happen if global reconstruction is performed.

  - Very useful in understanding trigger efficiencies (more later).

ECAL Calibration and Alignment

- Goal: approximately 0.5% constant term

$$E = G \times F \times \sum C_i A_i$$

- G = overall gain
- F = correction function depending on type of particle, position, energy and cluster algorithm used
- C_i = intercalibration constant
- A_i = signal amplitude (ADC) in channel i

ECAL Calibration and Alignment

- **During construction, often possible to calibrate with radioactive sources (e.g. ^{60}Co), pulsers and so on.**
  - Design mechanical tolerances for resolution goal.
- **Test beams used to get overall gain factor.**
  - Test beam conditions (material in front of calorimeter often different, electronics used may not be final, cables almost certainly not final.
  - Understand response as function of position
- **Cosmic ray muons can be useful.**

CMS ECAL Calibration & Monitoring

➢ECAL Calibration (Resolution : ‘Constant Term of the Resolution Formula’) :

Raw (uncalibrated) Supermodule : 6%-10% ‘Resolution’
Spread among channels before calibration

Beam Test Precalibration : 2 % ‘Resolution’
With a ‘fast’ calibration
‘Lab Precalibration’ : 4 % ‘Resolution’

In-Situ Physics Calibration : 0.5 % ‘Resolution’
Timescale for calibration : Weeks

➢ECAL Monitoring (Monitor Stability and Measure Radiation Effects) :

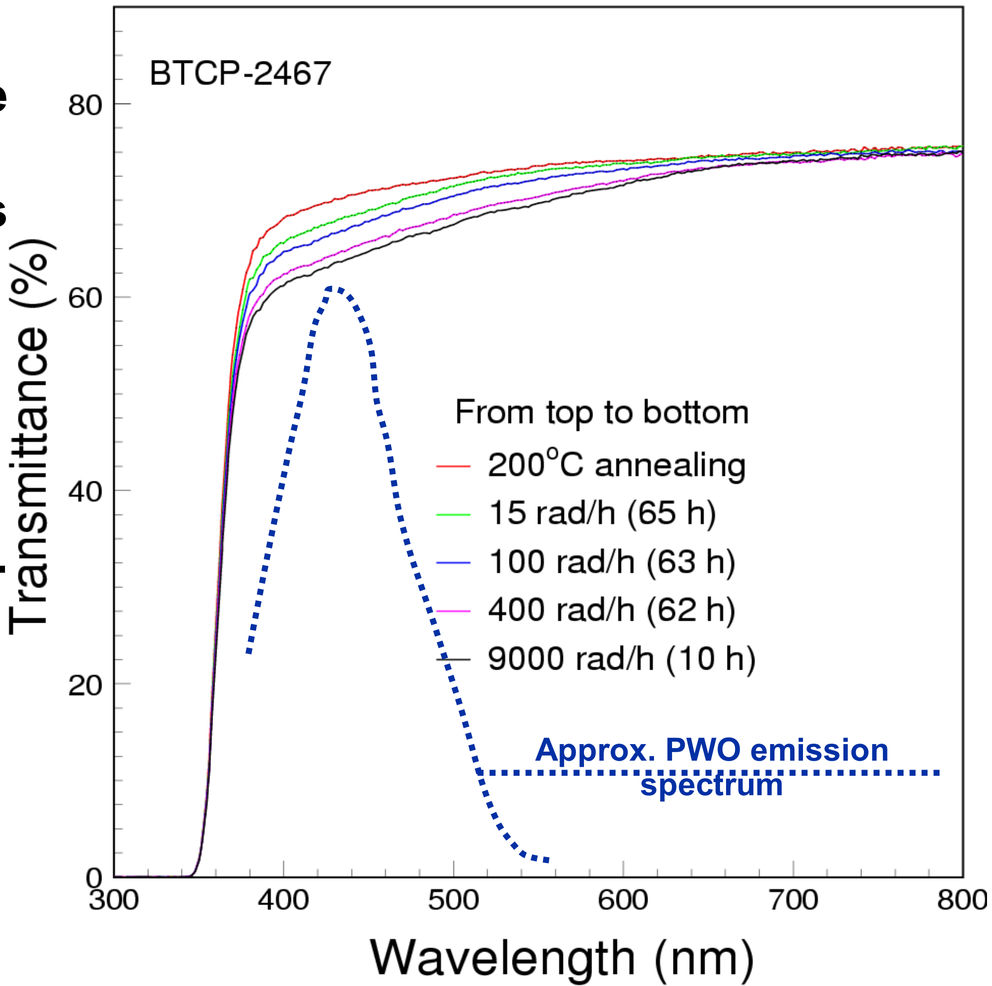
ECAL Stability (<< 0.5%) , Monitored with Laser Monitoring System

Transparency Loss Correction, Signal Change under Irradiation ~5% Measured with Laser Monitoring System

CMS: Radiation Effects PWO Transparency

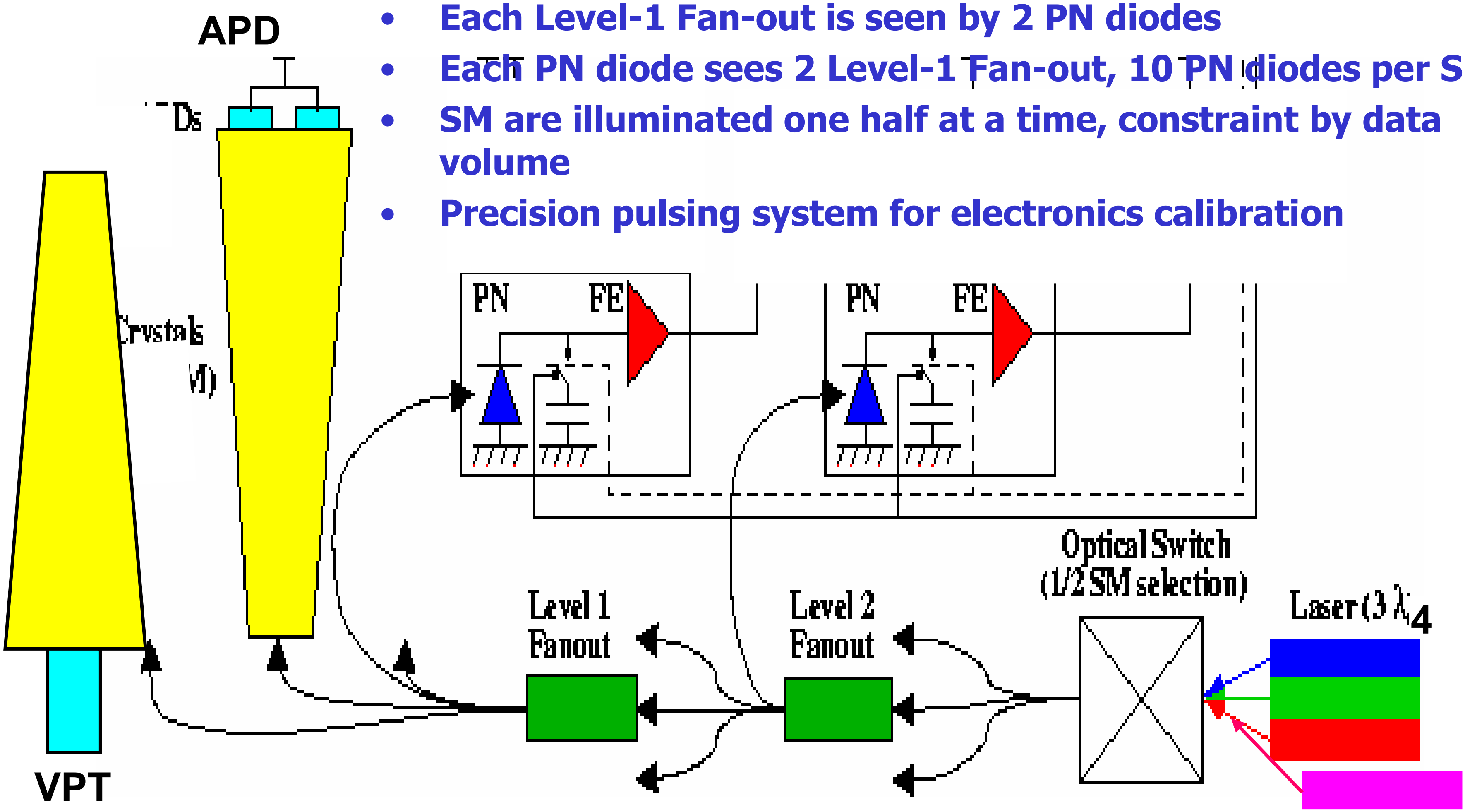
- Radiation reduces transparency in the blue, where PWO emission spectrum peaks
- Effect is dose rate dependent.
- Monitoring relative change of PWO transparency with pulsed laser light.

For CMS barrel (15 rad/hour) :
Transparency change at a level of ~5%.



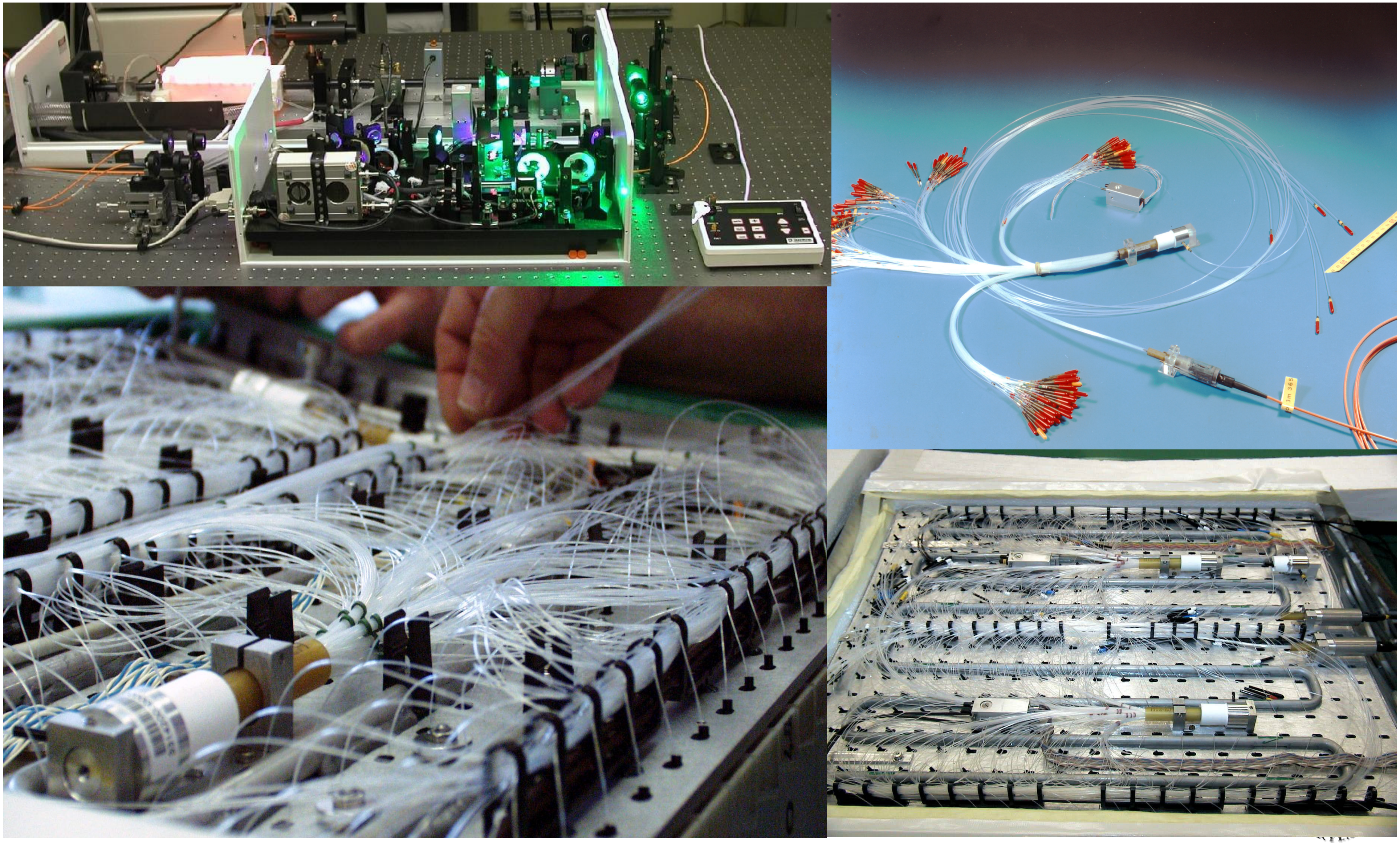
ECAL Laser Monitoring System

- Very stable PN-diodes used as reference system
- Each Level-1 Fan-out is seen by 2 PN diodes
- Each PN diode sees 2 Level-1 Fan-out, 10 PN diodes per SM
- SM are illuminated one half at a time, constraint by data volume
- Precision pulsing system for electronics calibration



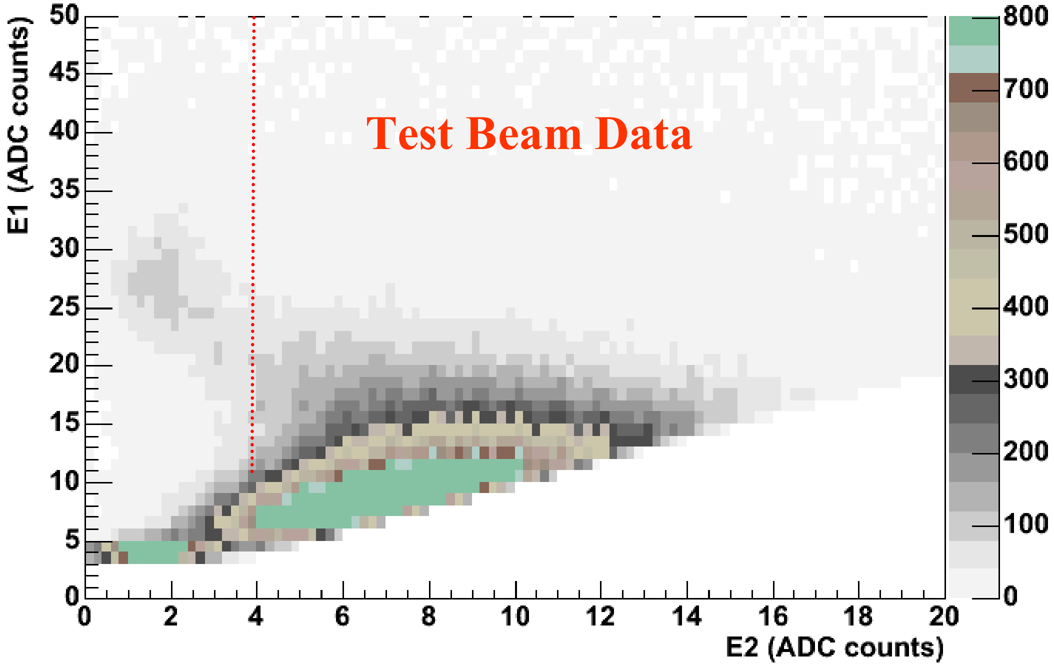
⇒Transparency of each crystal is measured with a precision of <0.1% every 20 minutes

ECAL Laser Monitoring System



Cosmic Muon Calibration

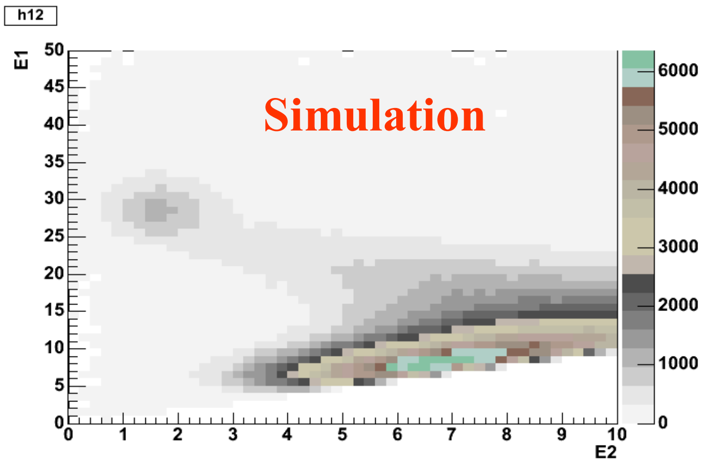
For APD gain (50) cosmic muons are hidden in the noise.
Run at higher gain (200).

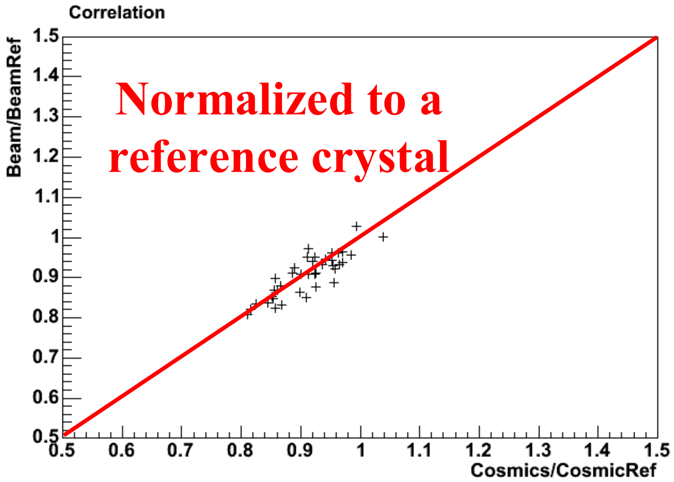


E1 is the highest energy deposit (maximum sample)

E2 is the second highest energy deposit in the 3x3 matrix (evaluated at the same sample as E1)

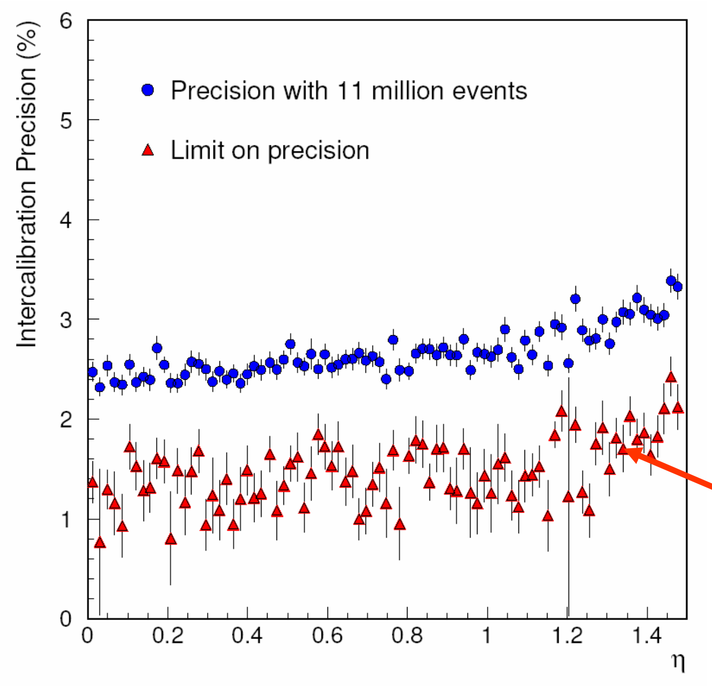
Relative calibration ~ 2% achievable.


Simulation


Normalized to a reference crystal

CMS In-situ : φ-uniformity method

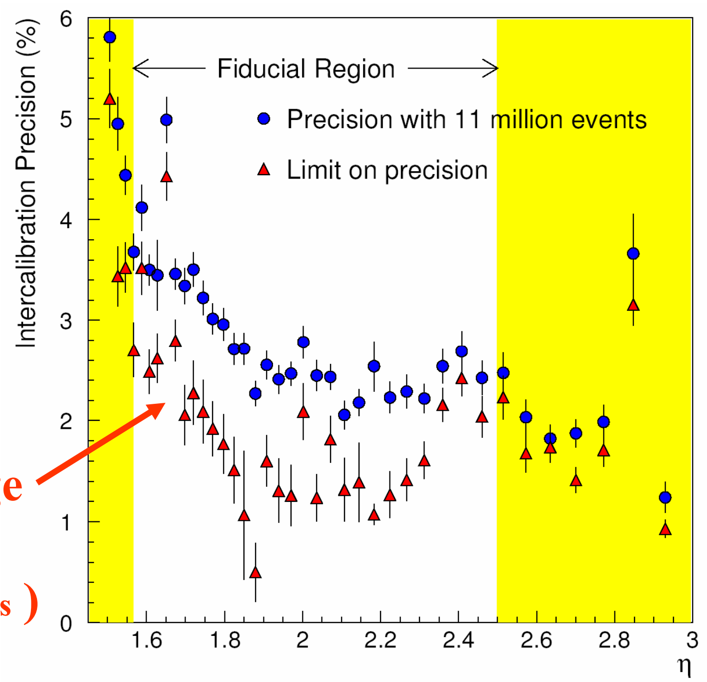
BARREL



11 million

Level-1 jet trigger events

ENDCAPS



Precision limits assuming no knowledge of tracker material

(~10h , 1kHz L-1 single jet triggers)

Idea: φ-uniformity of deposited energy in crystals at constant η

Limitations : non-uniformities in φ

- in-homogeneity of tracker material
- geometrical asymmetries

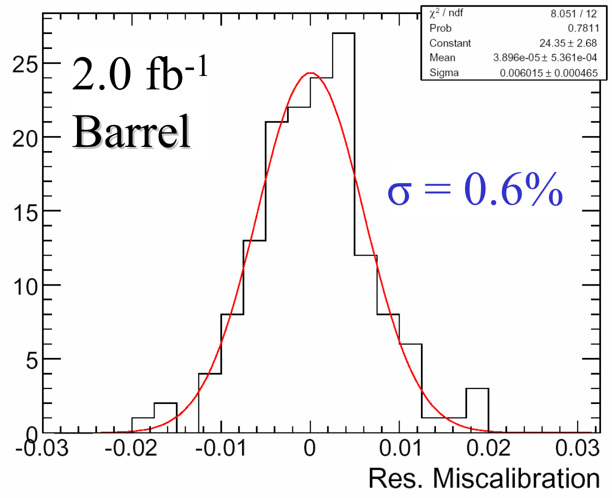
Used: Min-bias / Level-1 jet trigger events

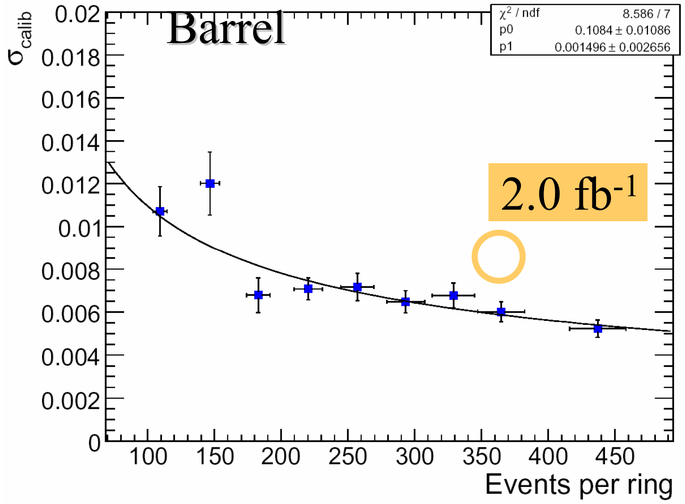
Method: Compare $<E_T>_{CRYSTAL}$ with $<E_T>_{RING}$.

Inter-calibration of η rings:

$Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-\gamma$, isolated electrons

CMS In-situ: using $Z \to e^+e^-$





Method:

Z mass constraint

Use cases:

- Inter-calibrate crystals in ECAL regions
- Inter-calibrate ECAL regions (i.e.rings in φ-symmetry method)
- Set the absolute energy scale
- Tune algorithmic corrections for electron reconstruction

Events Selection: Low brem electrons.

Algorithm:

Iterative (~10-15), constants are obtained from the peak of ε^i distribution.

$$\bar{\epsilon}^i = \frac{1}{2} \cdot \left[\left(\frac{M^i_{inv}}{M_Z} \right)^2 - 1 \right]$$

Results:

Assuming 5% mis-calibration between the rings and 2% mis-calibration between the crystals within a ring

⇩ *Statistics: **2.0 fb^{-1}***

0.6% ring inter-calibration precision

CMS In-situ: using isolated electrons

Target: 0.5% calibration precession

Sources: W→eν (10Hz HLT @ $2\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$),
$Z \rightarrow e^+e^-$ (2Hz HLT @ $2\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$),
$J/\Psi \rightarrow e^+e^-$, b/c→e, …

Method: E / P <width minimization>

ECAL

$$E = \sum^{5x5} c_i E_i$$

TRACKER

electron momentum

Event Selection:

We need a narrow E/P ⇒ Low brem $e^\pm$

Variables related to electron bremsstrahlung :

ECAL (S_{3x3}/S_{5x5})

TRACKER (track valid hits, χ^2/n.d.f., P_{out}/P_{in})

Efficiency after HLT: 20-40% Barrel ,
10-30% Endcaps

Background: S/B~8
(isol. electrons from W/QCD)
Part of it might be useful (b/c→e).

Calibration Constants extraction Techniques:

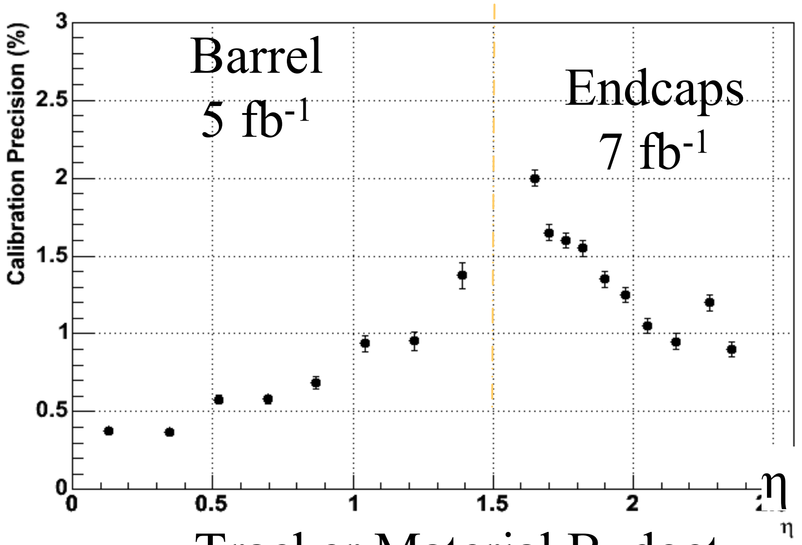
- L3/LEP iterative (~20 iterations),
- matrix inversion

Calibration Steps

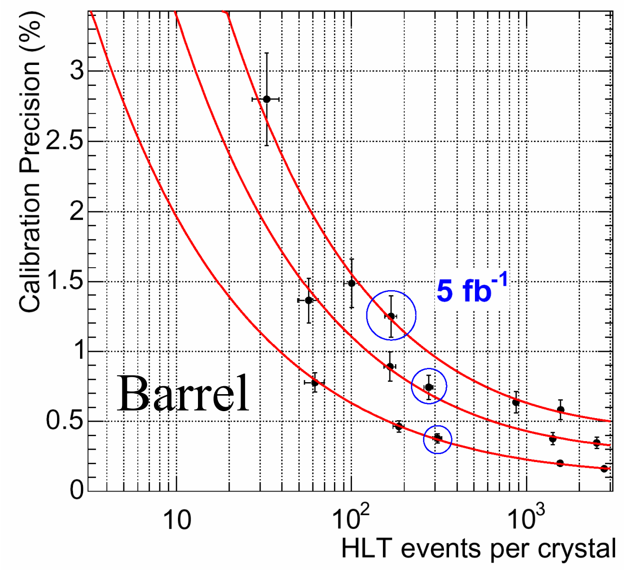
- Calibrate crystals in small η-φ regions
- Calibrate regions between themselves using tighter electron selection, $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-\gamma$

In-situ: using isolated electrons

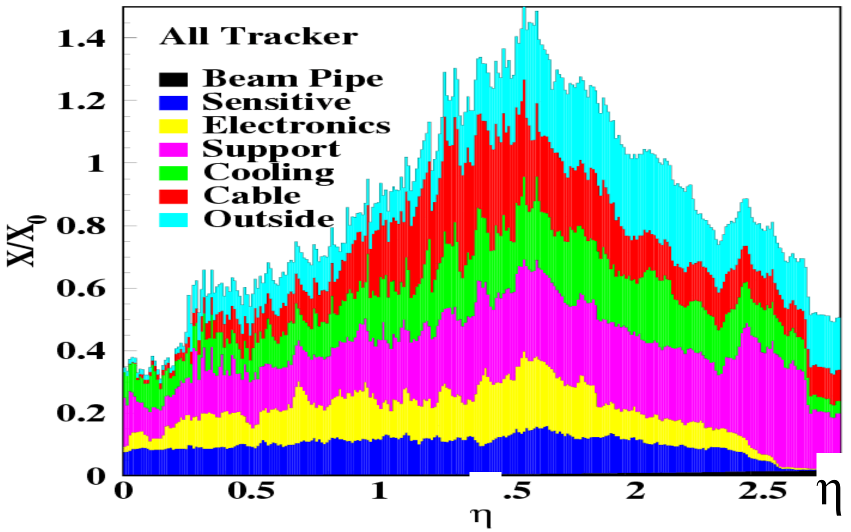
Calibration Precision versus η



Precision versus Statistics



Tracker Material Budget



ck Hadley

Higgs Boson Mass Resolution