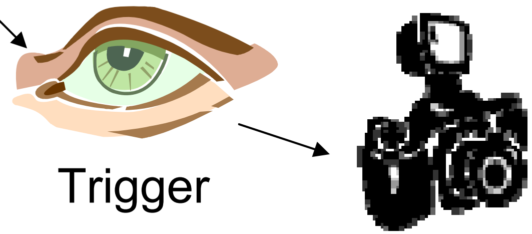
Triggering

<u>Example:</u> Suppose you'd like to take an exceptional photograph of the CN-tower.

Poor strategy: Take pictures continuously until your film is used up or camera memory is full

Better strategy: Watch and wait until something interesting happens (human trigger)...but this could take a long time

Best strategy: Build a trigger! (e.g. light sensor, camera records only the most interesting event)…



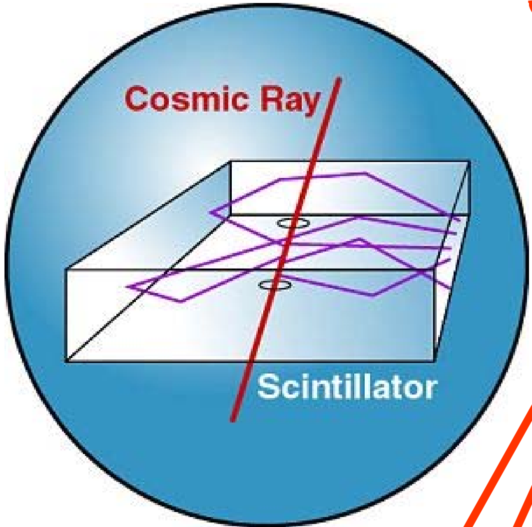
Lecture Outline

- Part 1: Introduction
  - General characteristics of triggers
  - Physics Motivation
  - LHC Triggers
  - ATLAS Level 1 Trigger
- Part 2: Advanced
  - Technology for triggers
  - Higher Level Triggers
    - ZEUS HLT
    - ATLAS HLT
  - Commissioning
    - ATLAS Triggers Today
    - Cosmic ray muon trigger
  - Problem set

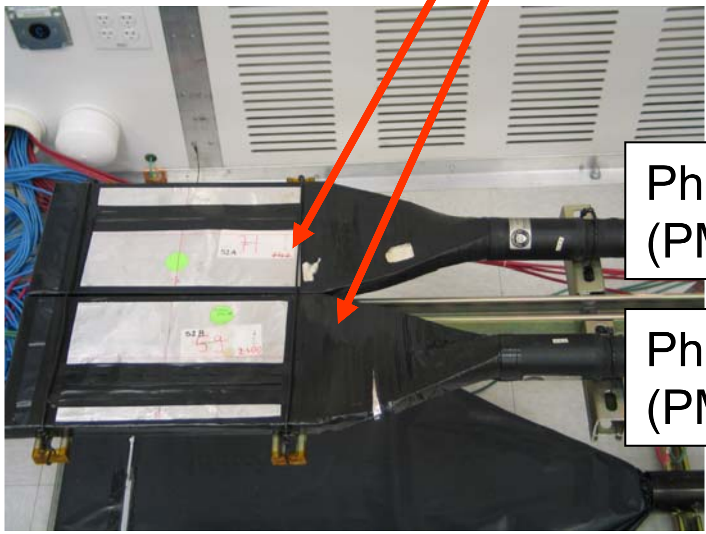
Basic Trigger: Photographer

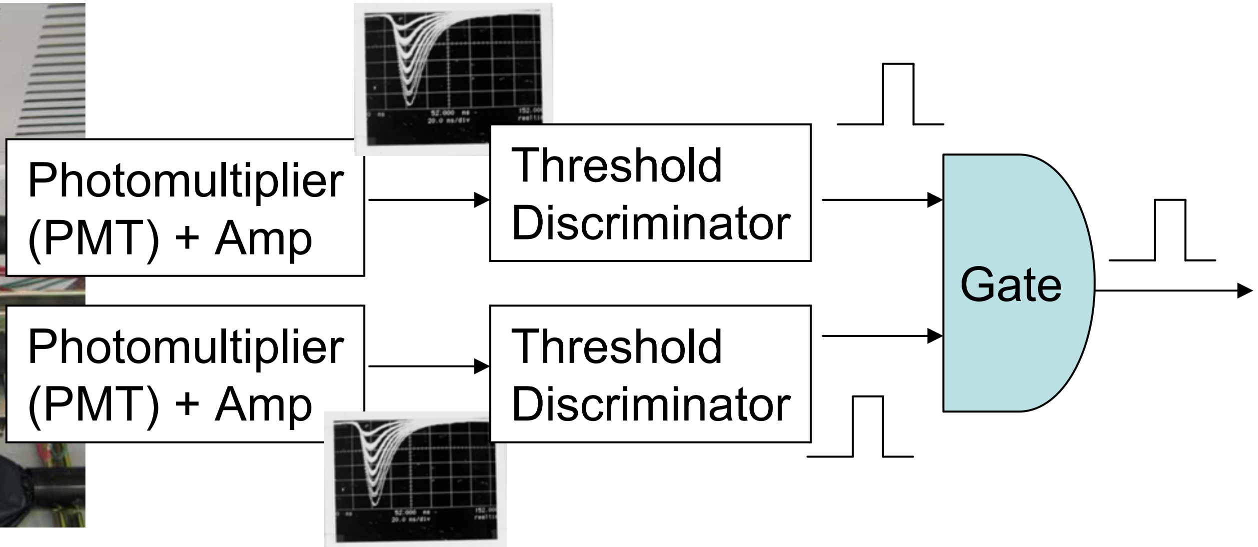
- Trigger Rate *R*: speed at which you can record images / event
- Event size: *S*
- Bandwidth: $B = S * R$
- Deadtime: time during which trigger is busy
  - Can't take two photos at the same time
  - Data acquisition is "dead" while one photo is being recorded.
  - Ideally deadtime << %
- Efficiency: $\varepsilon = N_{recorded} / N_{Total\_events}$
  - Events recorded / total interesting events
- Purity: $p = N_{good} / N_{recorded}$
  - Ratio of good events / total events
- Example: digital camera
  - Max trigger rate ~ 3 Hz
  - Event size ~ 3 MB
  - Data acquisition rate ~ 3 MB * 3Hz ~ 9 MB/s
  - Deadtime depends on camera
  - Efficiency/purity depend on photographer

Simple Trigger in High Energy Physics: Scintillator Paddles



- Testbeams
  (e.g. CERN, Fermilab, DESY, …)
- Cosmic ray setups, detector commissioning

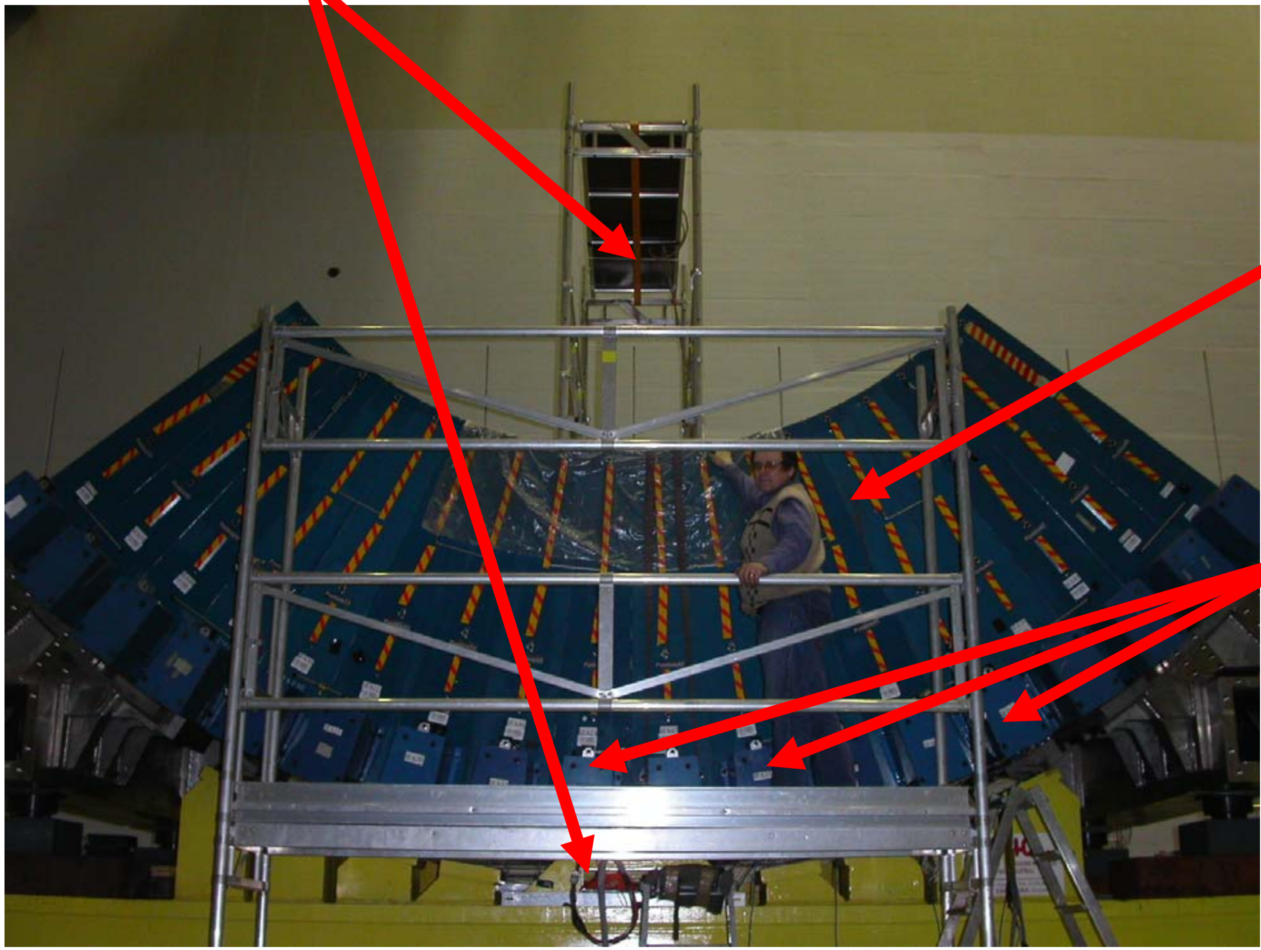




Testing a subdetector for the ATLAS experiment at CERN

Pair of scintillators for cosmic ray trigger.

Test setup in surface building Dec ’03.

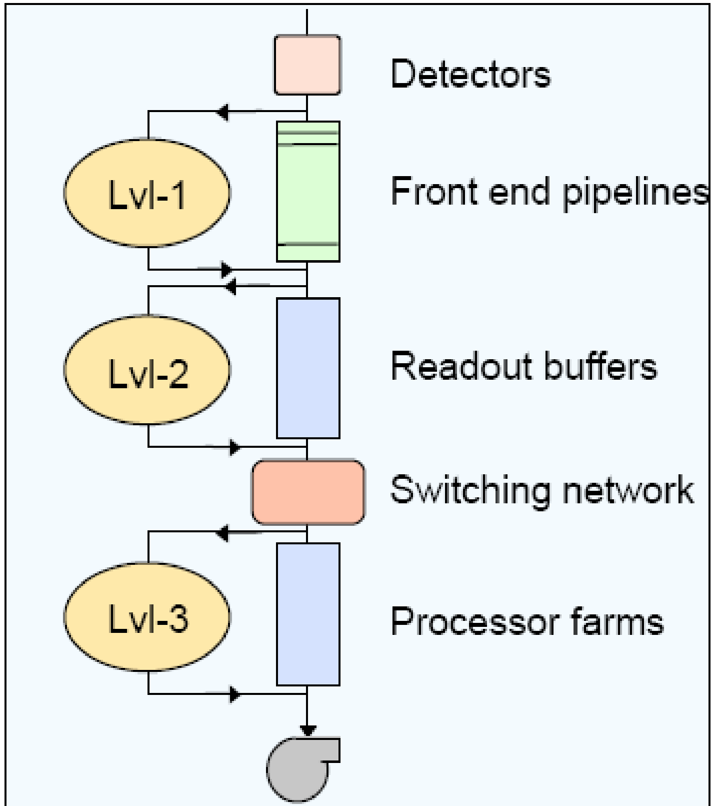


Physicist

Hadronic calorimeter modules equipped with final electronics and cables (trigger, fibre optic readout, control) to counting room 75 m distant

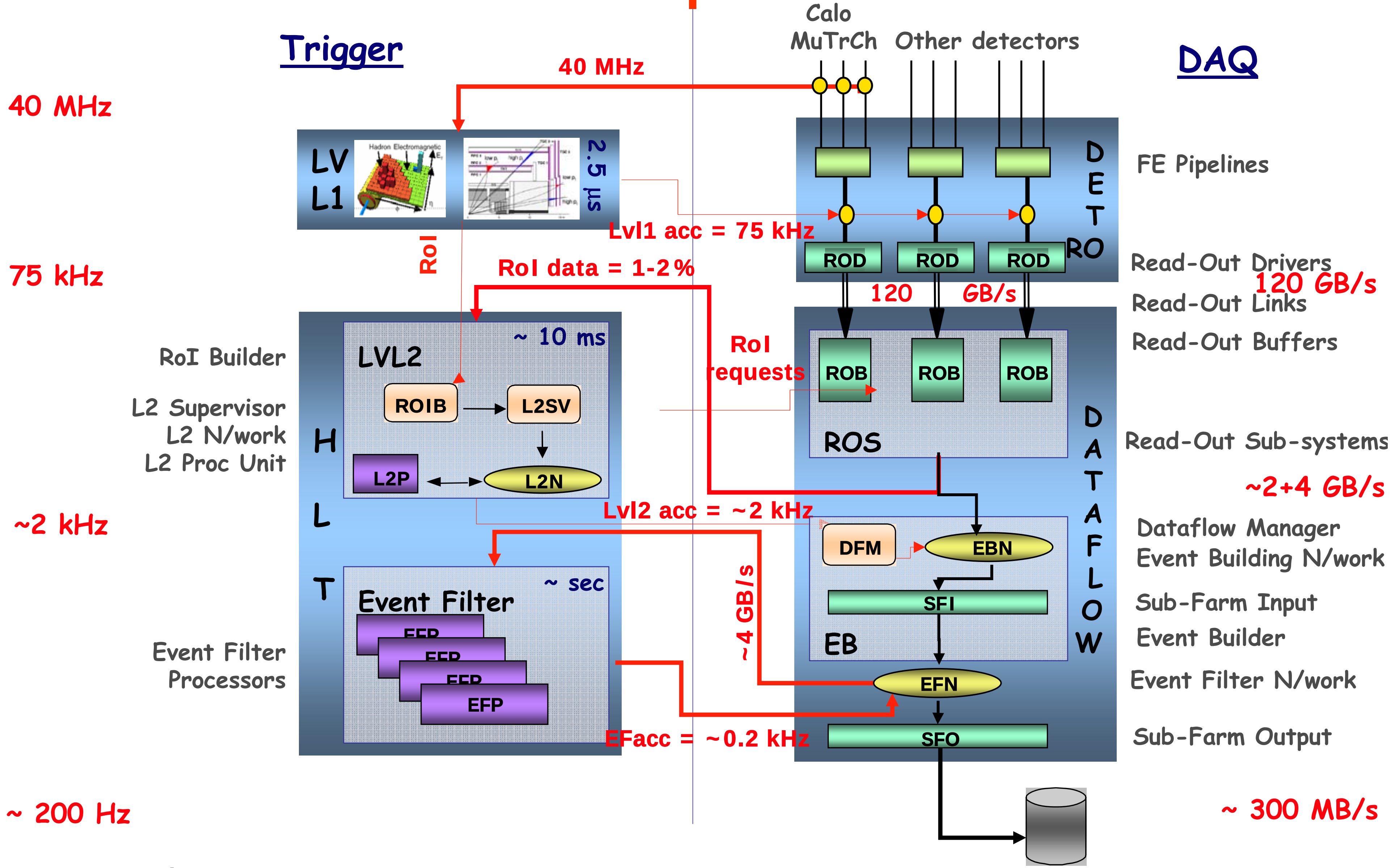
Basics of Triggers and Data Acquisition (DAQ) Systems

- Triggers divided into “levels”
  - Each level a successive approximation
- First Level Trigger (Level-1)
  - Fast decision times ~ ❍s
  - Typically specialized hardware
  - Data from detectors stored in pipeline until decision of accept/reject
  - Decision must be made before end of pipeline (latency time)
- Higher level(s) (HLT / L2 / L3)
  - Longer decision times ~ ms
  - Typically Farm of Linux PC’s, high-speed network
  - Partial or full event data now in memory
- DAQ:
  - Data flow from detector through buffers to storage on tape/disk



“Traditional”: 3 physical levels

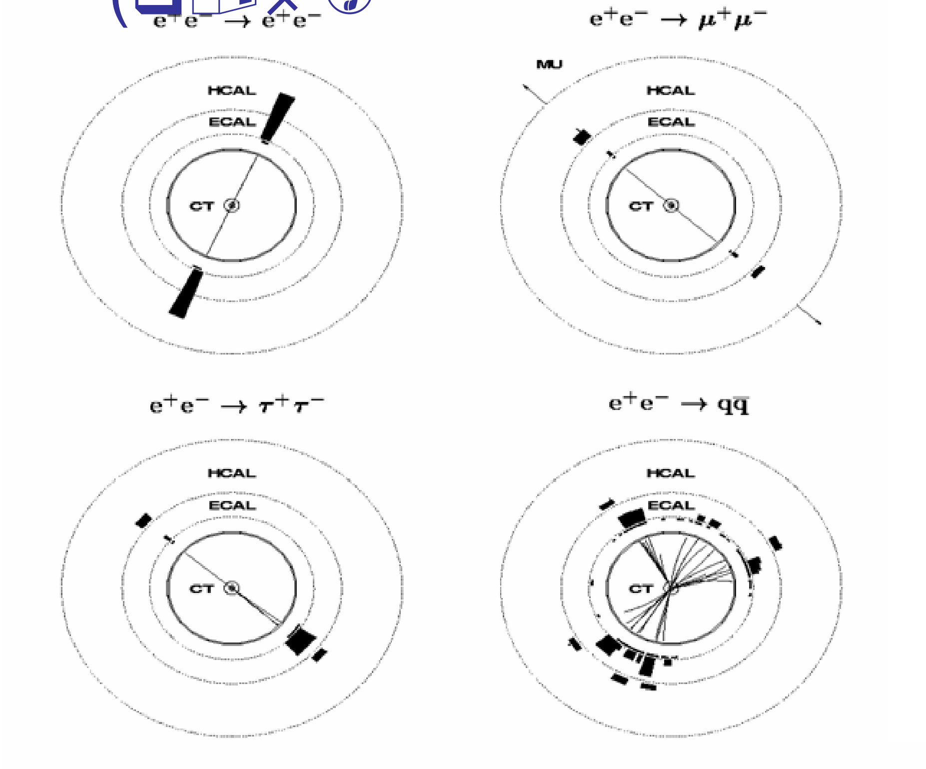
Complicated Example: Trigger / DAQ for the ATLAS Experiment at CERN

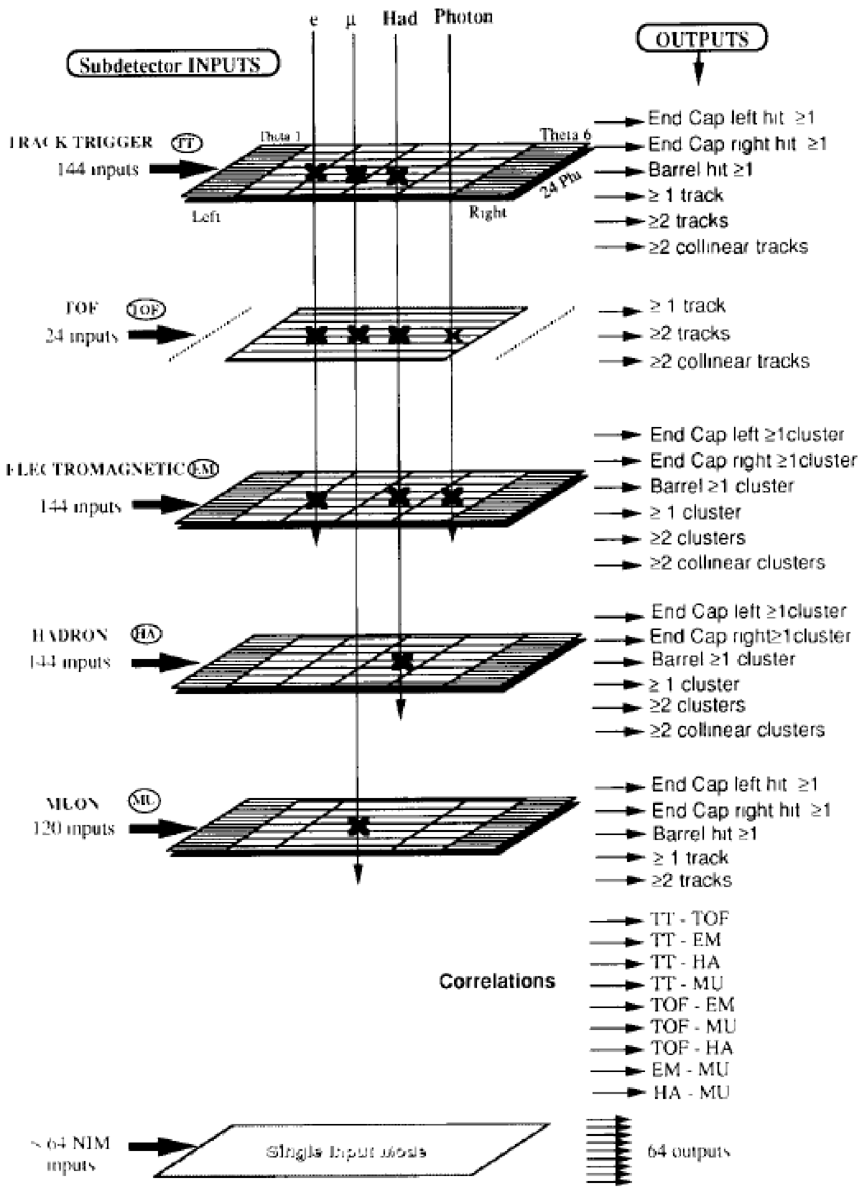


Note: Don't memorize details – understand basics, analyze

LEP Triggers much simpler

- Low rate Hz in e^+e^- collider at LEP from 1989-2000
- "Every event a good event"
- Example: OPAL trigger coincidence matrix of subdetectors in bins of (❑✉✗✆)

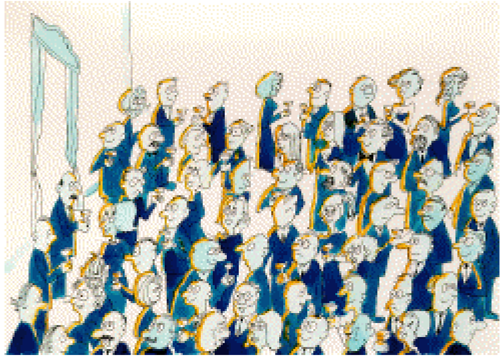




Trigger driven by Physics

Physics: What Gives Particles Mass?

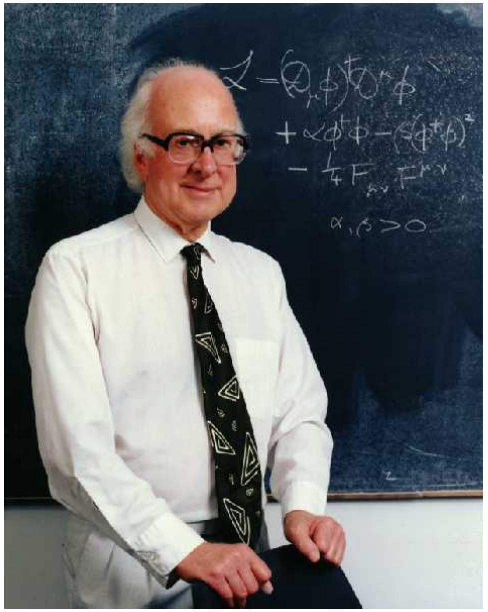
The Higgs Mechanism



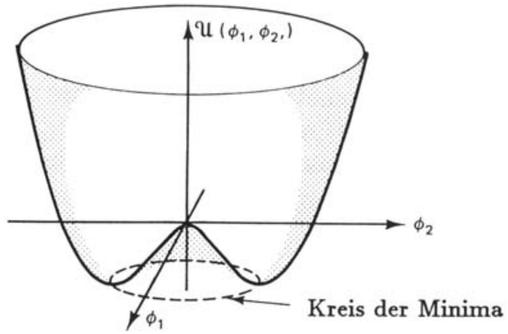
To understand the Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field ...

... a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step ...

... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs

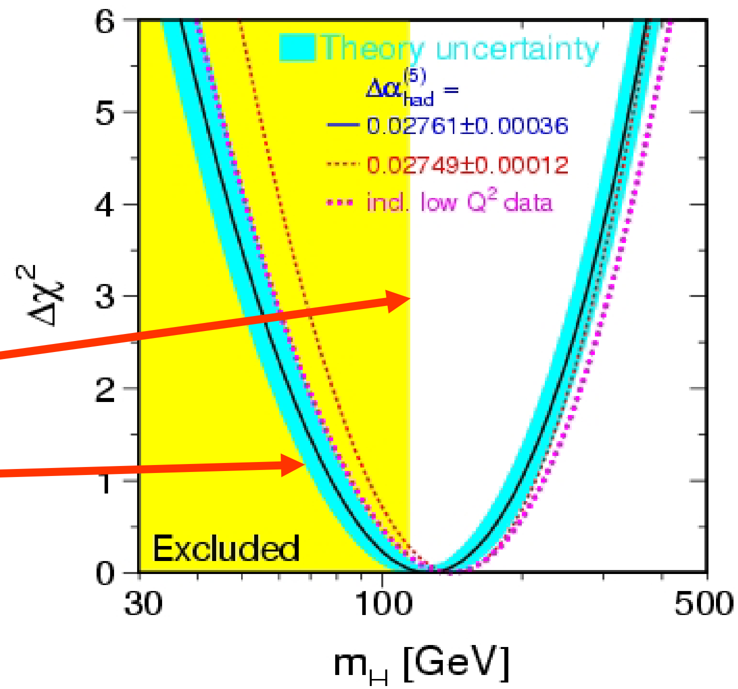


Professor Higgs

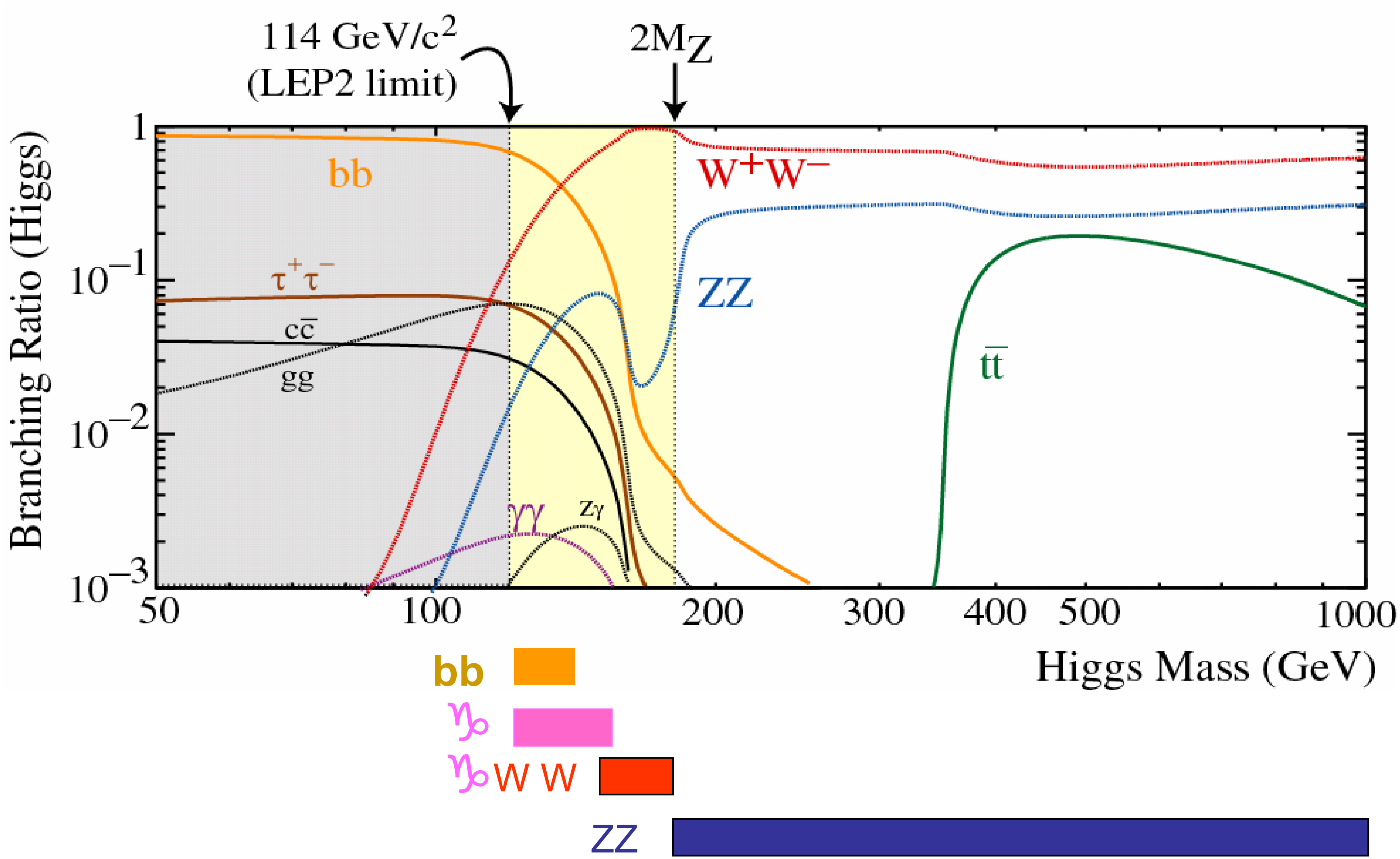


Higgs: What Gives Particles Mass?

- The missing piece of the Standard Model is the Higgs (H)
  - Spin-0 particle forming a scalar field everywhere in the universe
  - Example of a scalar field (temperature)
- Coupling of the Higgs field to a particle generates its mass
  - n.b. p/n mass from gluon fields, quark motion
  - Breaks electroweak symmetry: W,Z massive
- Higgs properties predicted – except its own exact mass
  - We know it must lie in the range 114 GeV < M_H< 1.2 TeV
  - Previous direct searches at CERN
  - Precision electroweak data (CERN, Fermilab)

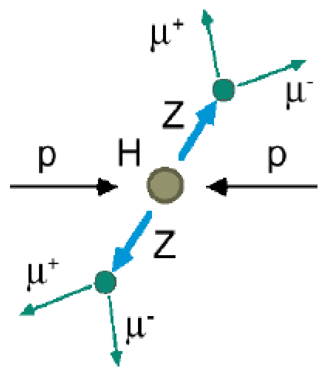


Search Channel Depends on M_H



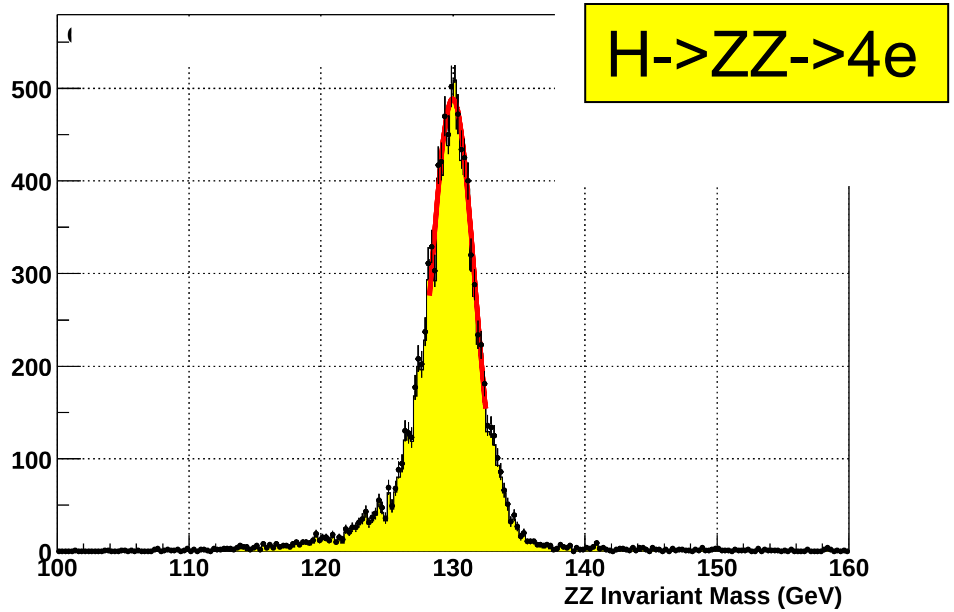
Intermediate Mass Higgs

$130 < M_H < 500$ GeV

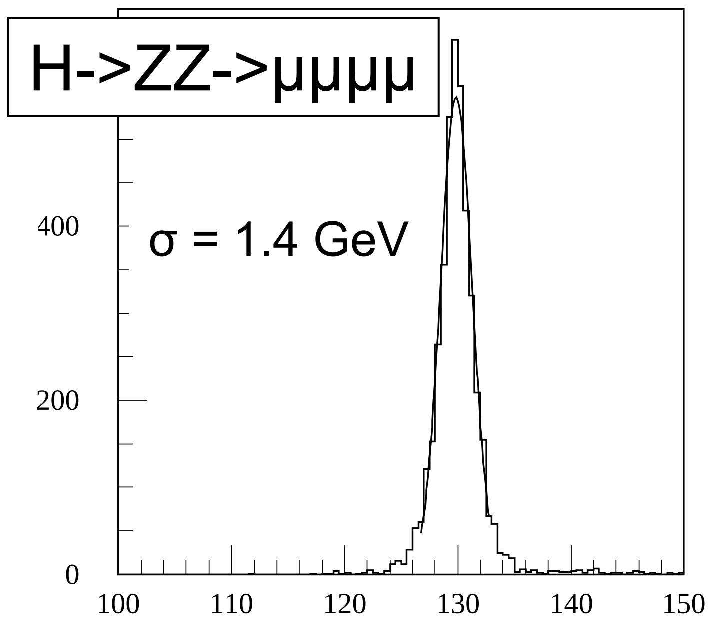


$$H \rightarrow ZZ \rightarrow l^+l^-l^+l^- \ \ (l = e, \mu)$$

- 4 high p_T leptons – “golden channel”
- Narrow mass peak, small background

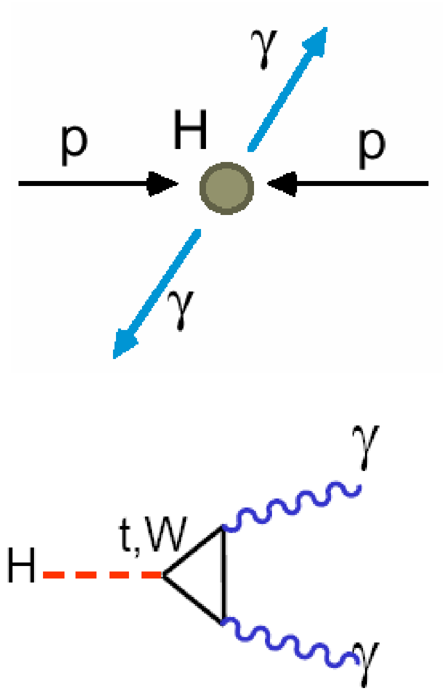


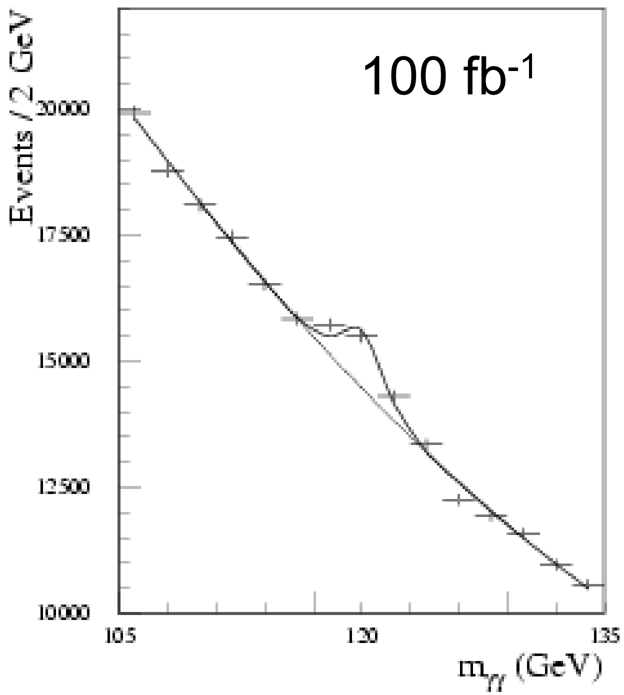
m_{ZZ} (GeV)

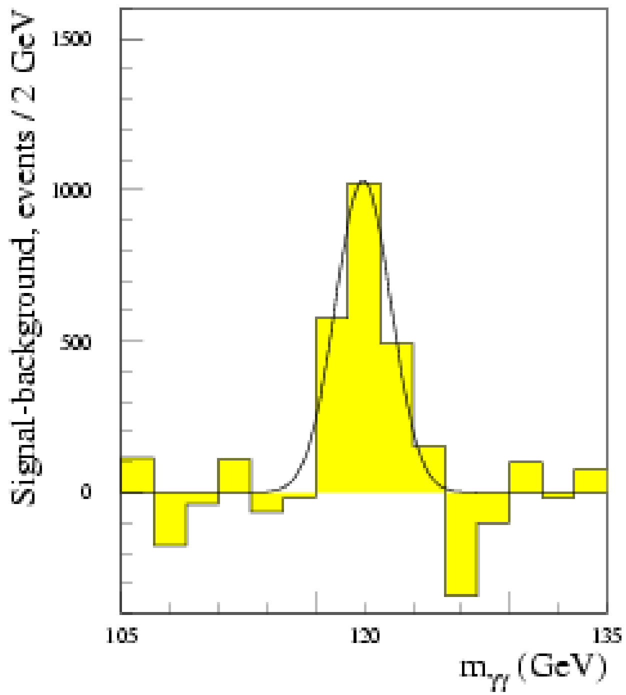


m_{ZZ} (GeV)

Low mass Higgs m_H<140 GeV : $H \rightarrow \gamma\gamma$

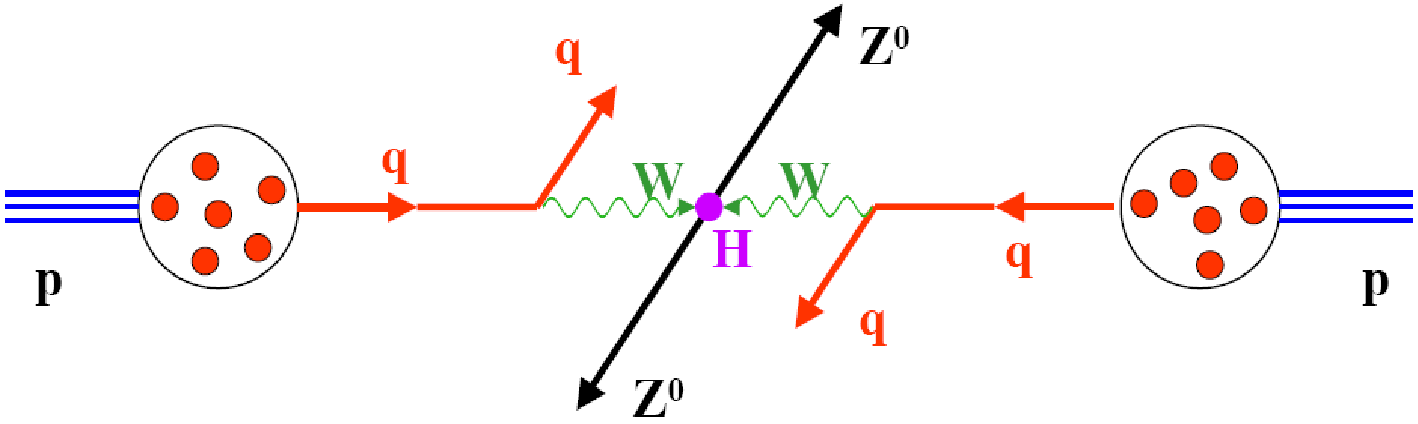




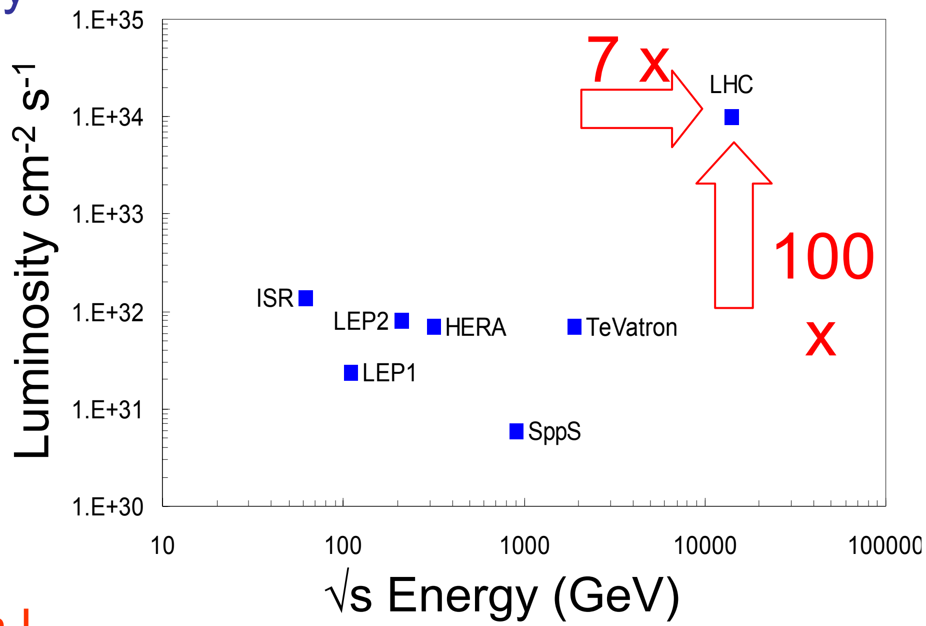


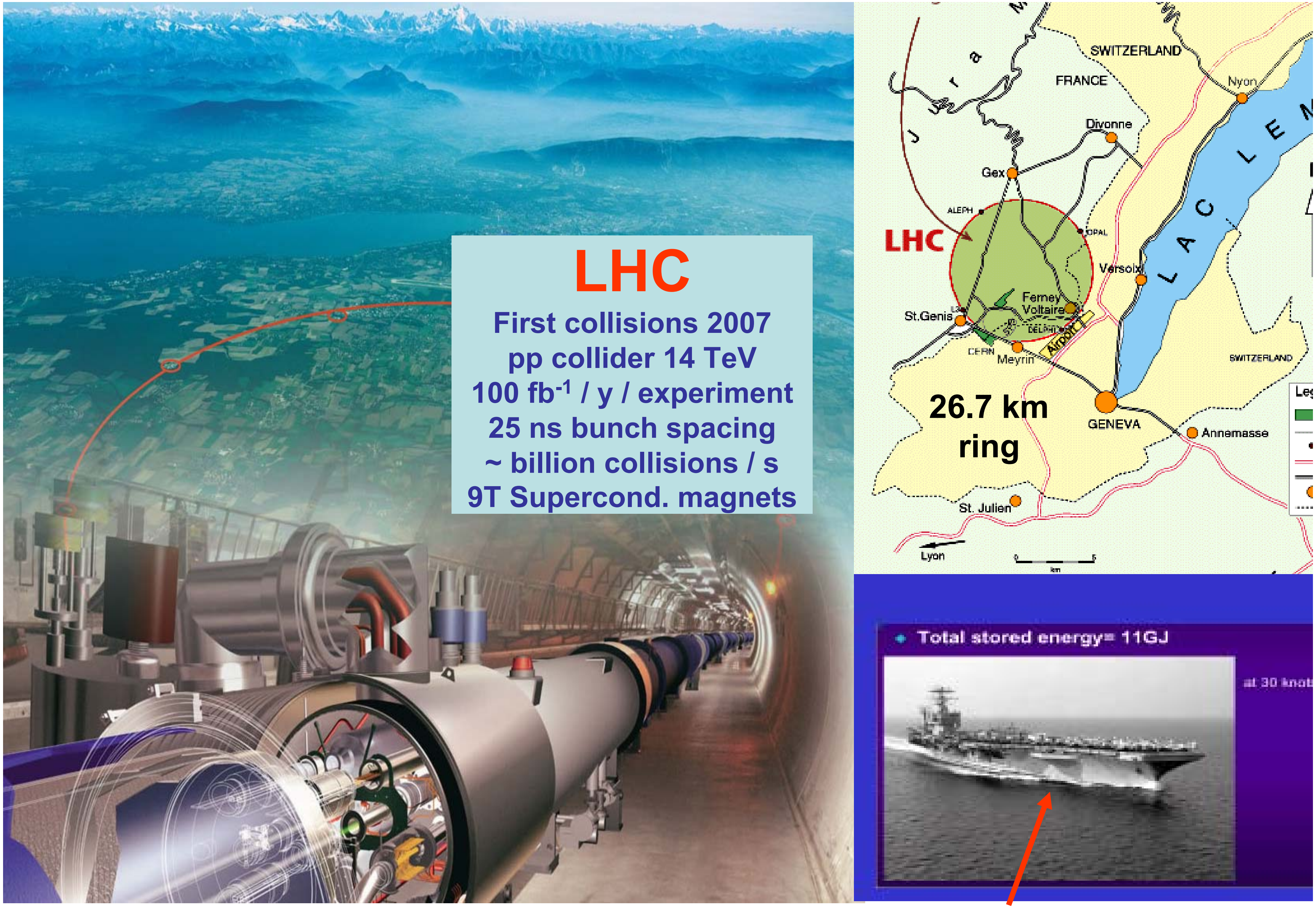
- $H \rightarrow \gamma\gamma$: decay is rare (BR ~ 10^{-3})
- Hardest region: small signal on large background
- <u>With good calorimeter resolution can observe a mass peak</u>
- Estimate background from sidebands

The Large Hadron Collider (LHC)



- Questions about the Higgs, unification, and dark matter should be answered by probing physics at the TeV scale
- To probe physics at ~ 1 TeV in p-p collisions, need:
  - E(quark) > 1 TeV
  - E(proton) > 6 TeV
- LHC p-p collider: 7 TeV x 7 TeV
- High luminosity:
  - Design luminosity of $L=10^{34}$ cm^{-2} s^{-1}
    - Physics Rate = L x ♦
  - nb. σ ~ 1/s -> 2*s requires factor 10 in L
  - Design 100 fb^{-1} / year per experiment

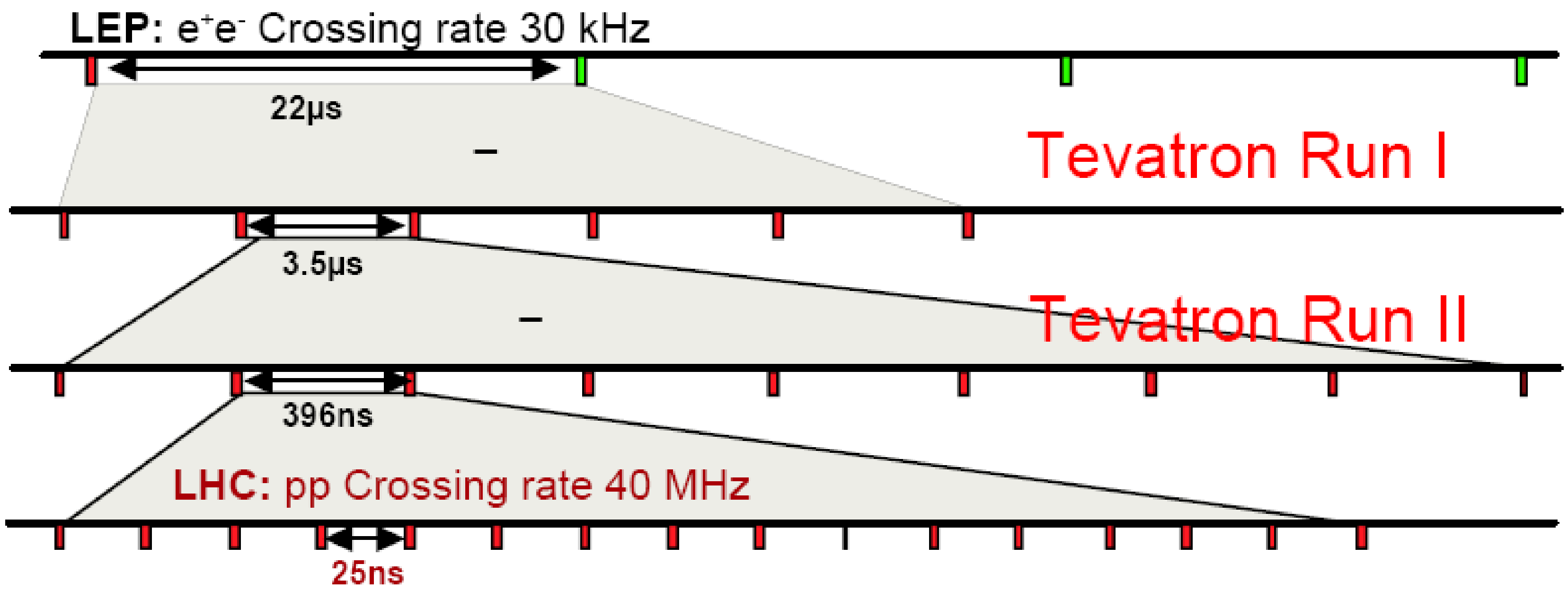




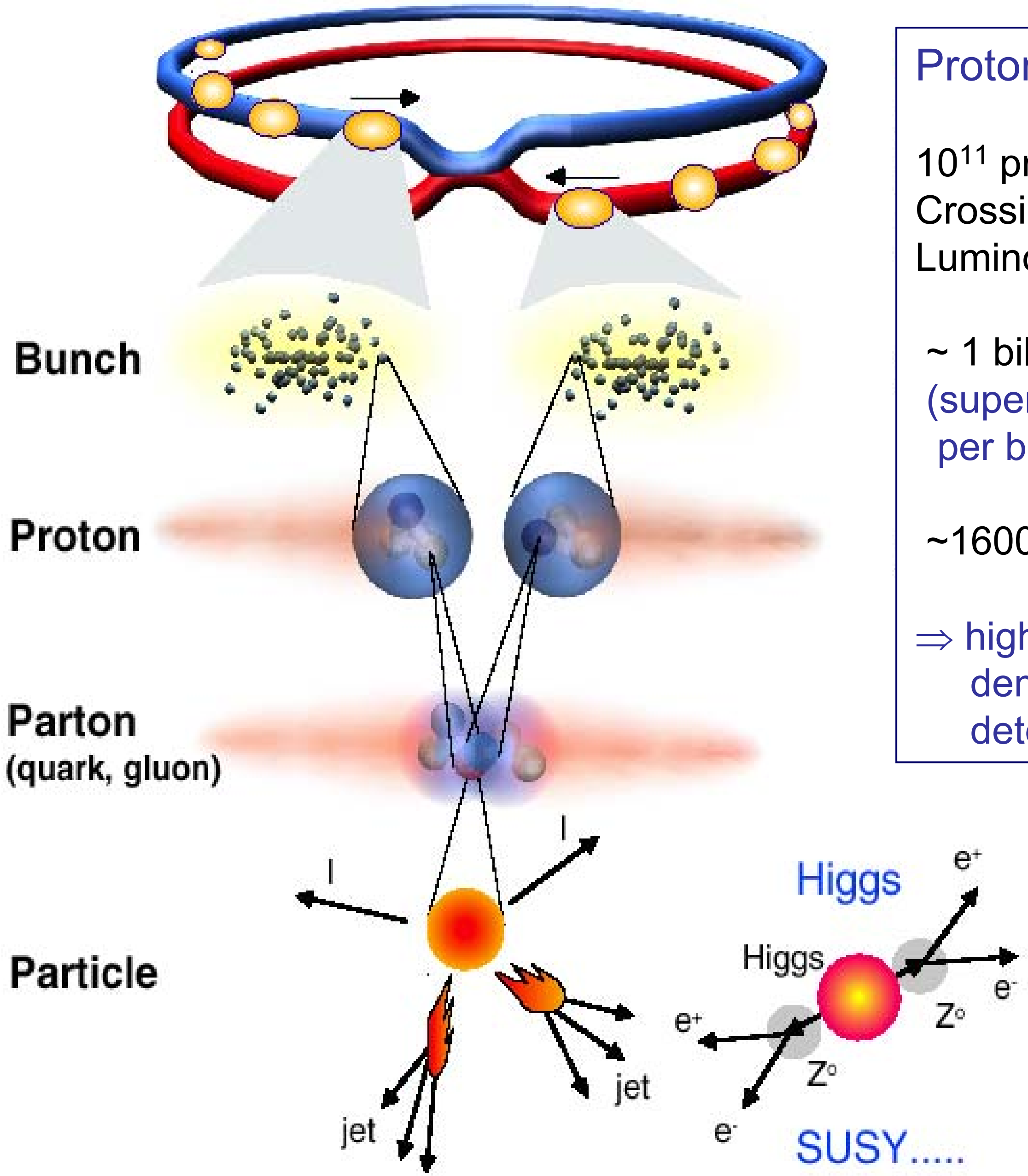
Energy (2 LHC beams) = 11 GJ = 7% of energy stored in an aircraft carrier at 30 knots

LHC Bunch Structure

- The LHC will have ~ 3600 bunches
- It is being built in the existing LEP tunnel (27 km)
- Distance between bunches = 27 km / 3600 = 7.5 m
- Time between bunches = 7.5 m / c = 25 ns



Collisions at the LHC



Proton – proton collisions:

10^{11} protons / bunch
Crossing rate of p-bunches: 40 Million / s
Luminosity: $L = 10^{34}\ cm^{-2}\ s^{-1}$

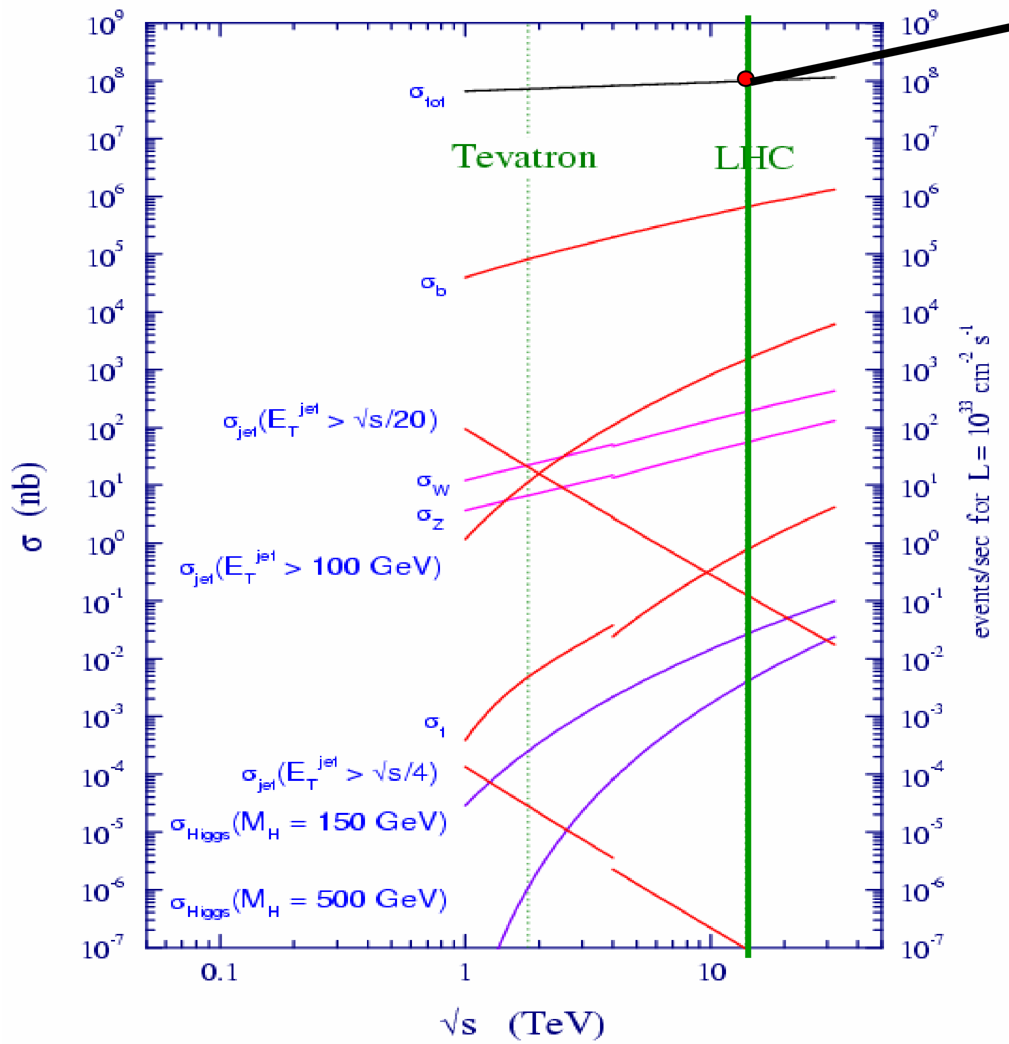
~ 1 billion pp collisions / s
(superposition of 25 pp-interactions per bunch crossing: **pile-up**)

~1600 charged particles in the detector

⇒ high particle densities
demanding requirements for the detectors and trigger

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

The Price of High Luminosity: Pileup



Total event rate:

$R = L \times \sigma_{inelastic}(pp)$

$\approx 10^{34}\ cm^{-2}\ s^{-1} \times 70\ mb$

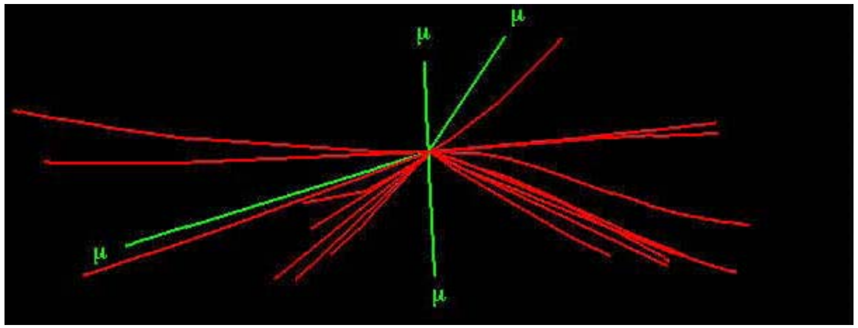
≈ 700 MHz

~ 25 inelastic “minimum bias” low-p_T events produced on average in each bunch crossing of 25 ns

→ pile-up

e.g. “Golden” Higgs channel:

$$H \rightarrow ZZ \rightarrow 4\mu$$



Reconstructed tracks p_T>25 GeV

Trigger challenge: billions and billions of min-bias events for every Higgs event !

Production Rates for LHC at L = 10^{33} cm^{-2} s^{-1}

(10% design Luminosity)

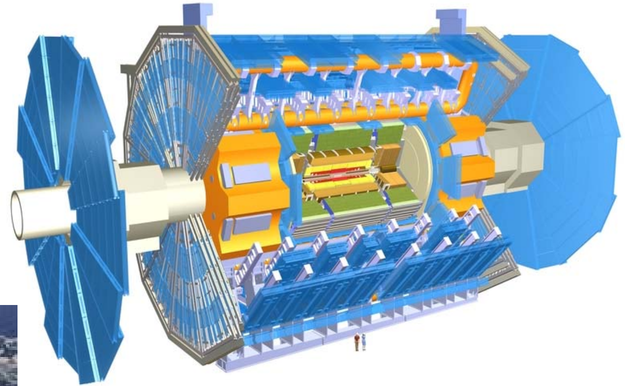
	Process	Events/s	Events / year ($10\ fb^{-1}$)
SM	$W \to e\nu$	15	10^8
	$Z \to ee$	1.5	10^7
	$t\bar{t}$	1	10^7
	$b\bar{b}$	10^6	$10^{12} - 10^{13}$
	QCD jets (p_T> 200 GeV)	10^2	10^9
Higgs	H (m =130 GeV)	0.02	10^5
SUSY	$\tilde{g}\tilde{g}$ (m = 1 TeV)	0.001	10^4
Exotics	"Black holes" m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3

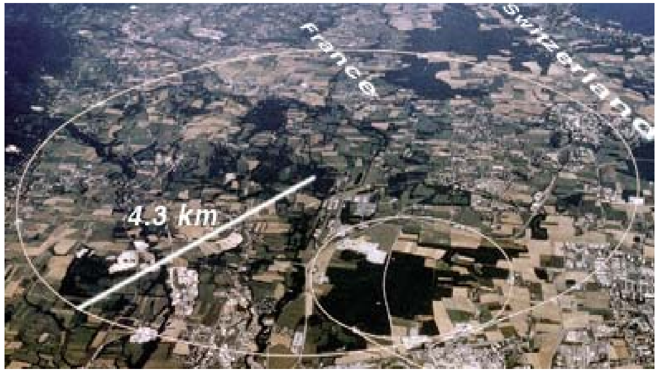
Wealth of physics: LHC is a b-factory, top factory, W/Z factory, Higgs factory, SUSY factory, …

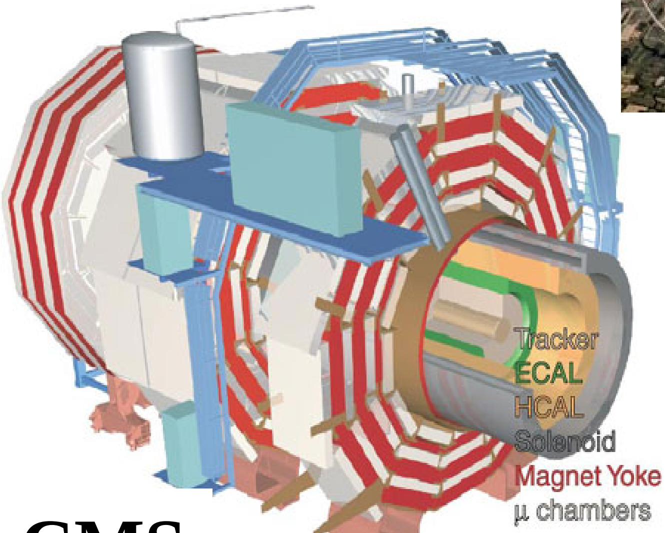
Alice Heavy-ion programme

4 LHC Experiments

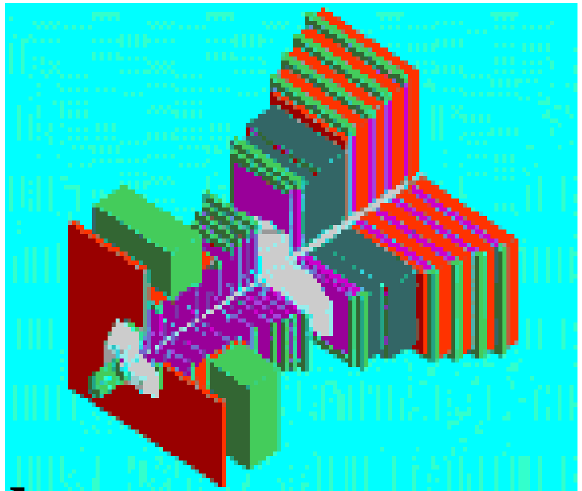
Atlas General-purpose detector







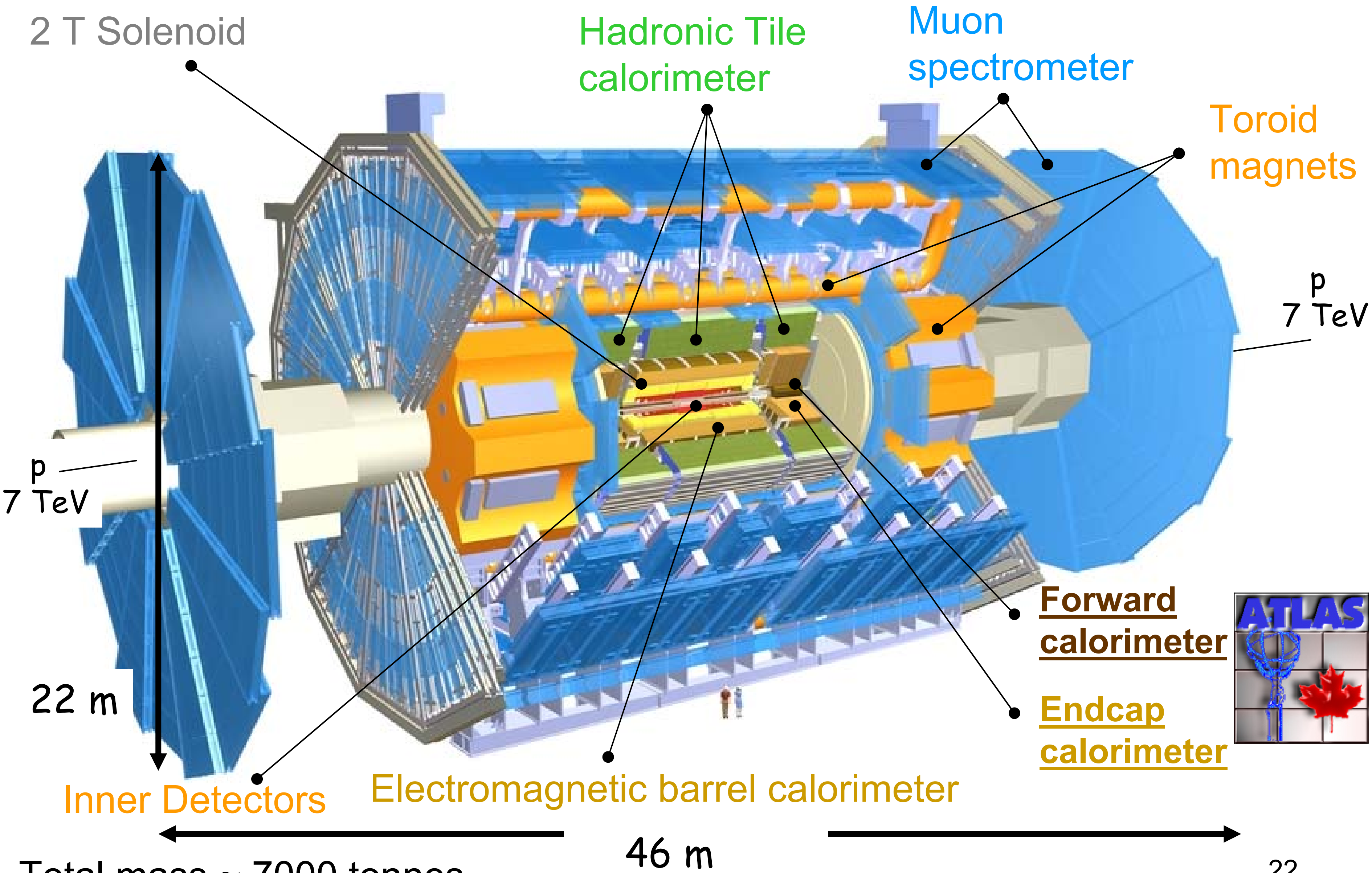
CMS General-purpose detector



LHCb

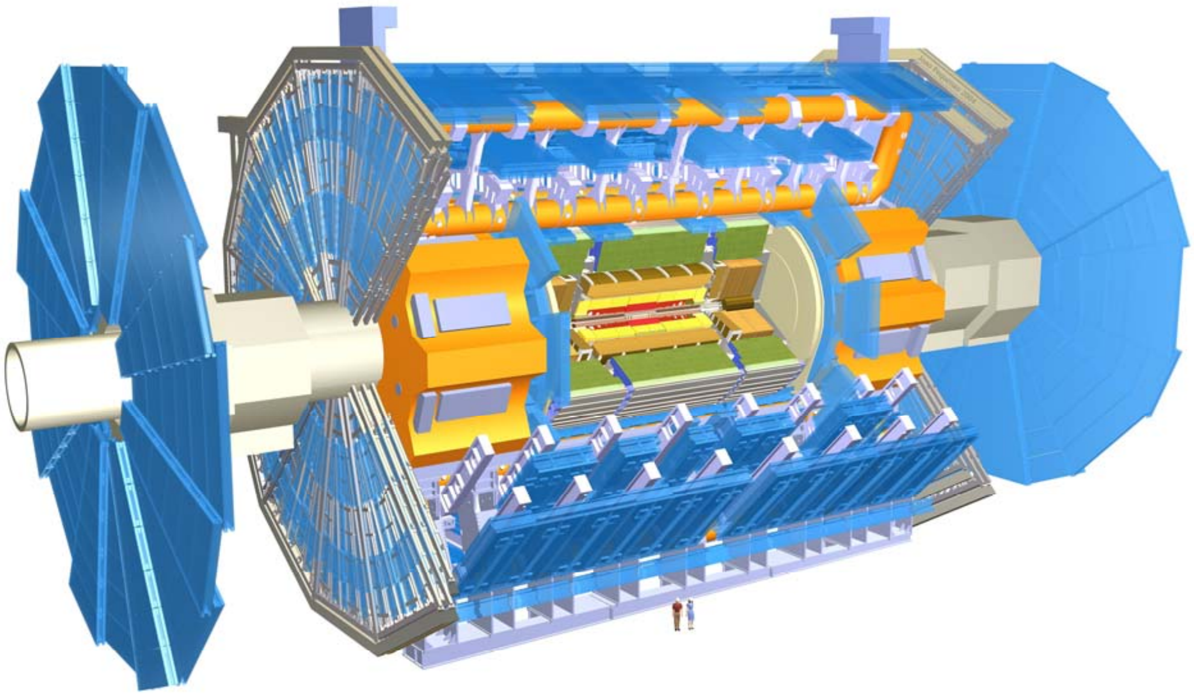
Dedicated b-physics

ATLAS (A Toroidal LHC ApparatuS)

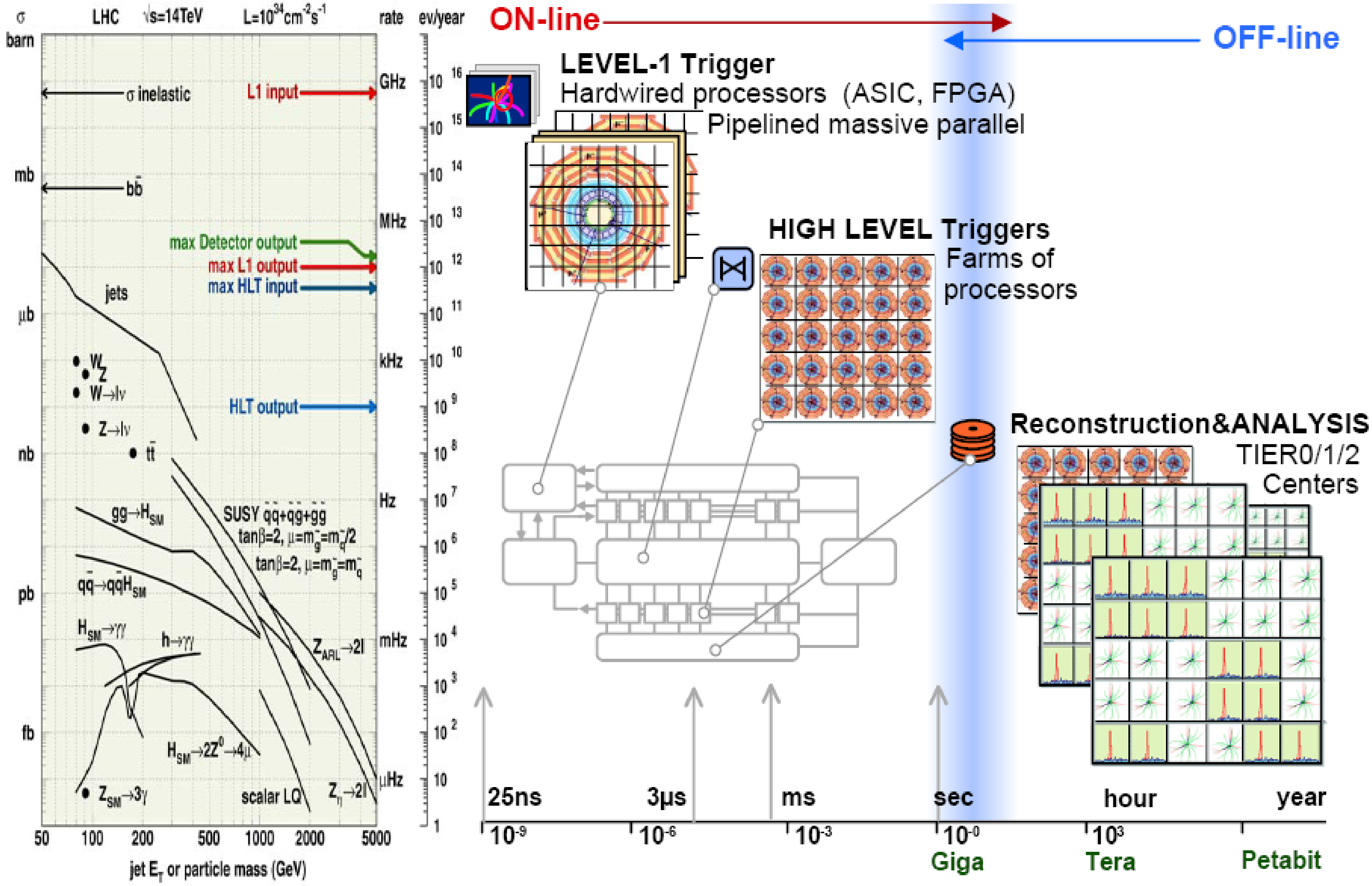


Total mass ~ 7000 tonnes

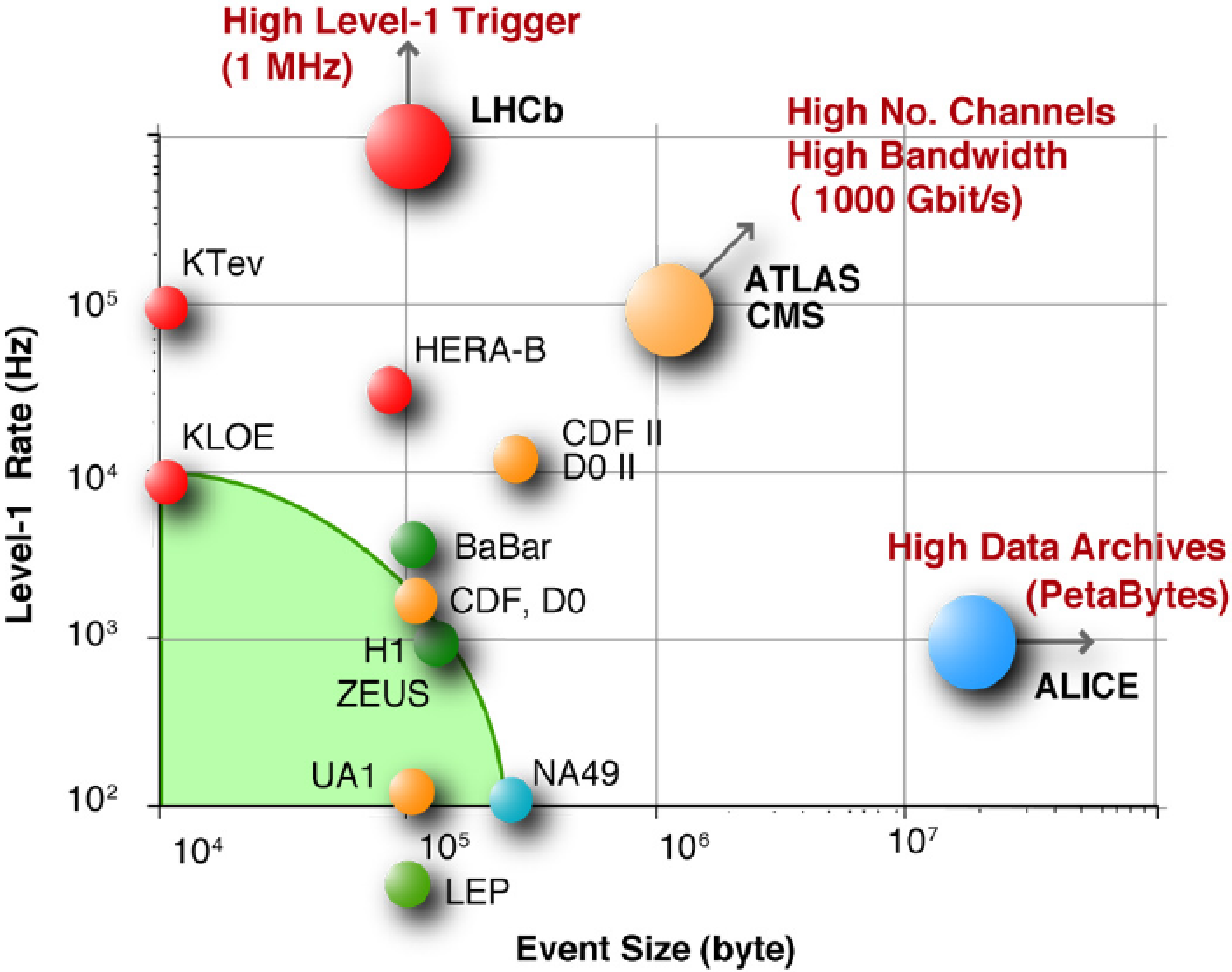
Scale of ATLAS



LHC Trigger Overview



Comparison of Triggers



Trigger / DAQ of the ATLAS Experiment at CERN

Trigger

40 MHz

Three logical levels

~2.5 μs	LVL1 - Fastest: Only Calo and Mu Hardwired
~ ms	LVL2 - Local: LVL1 refinement + track association
~ sec.	LVL3 - Full event: "Offline" analysis

~ 200 Hz

DAQ

Hierarchical data-flow

10's PB/s
(equivalent)
23 overlap ev/25ns
1400 particles/25ns

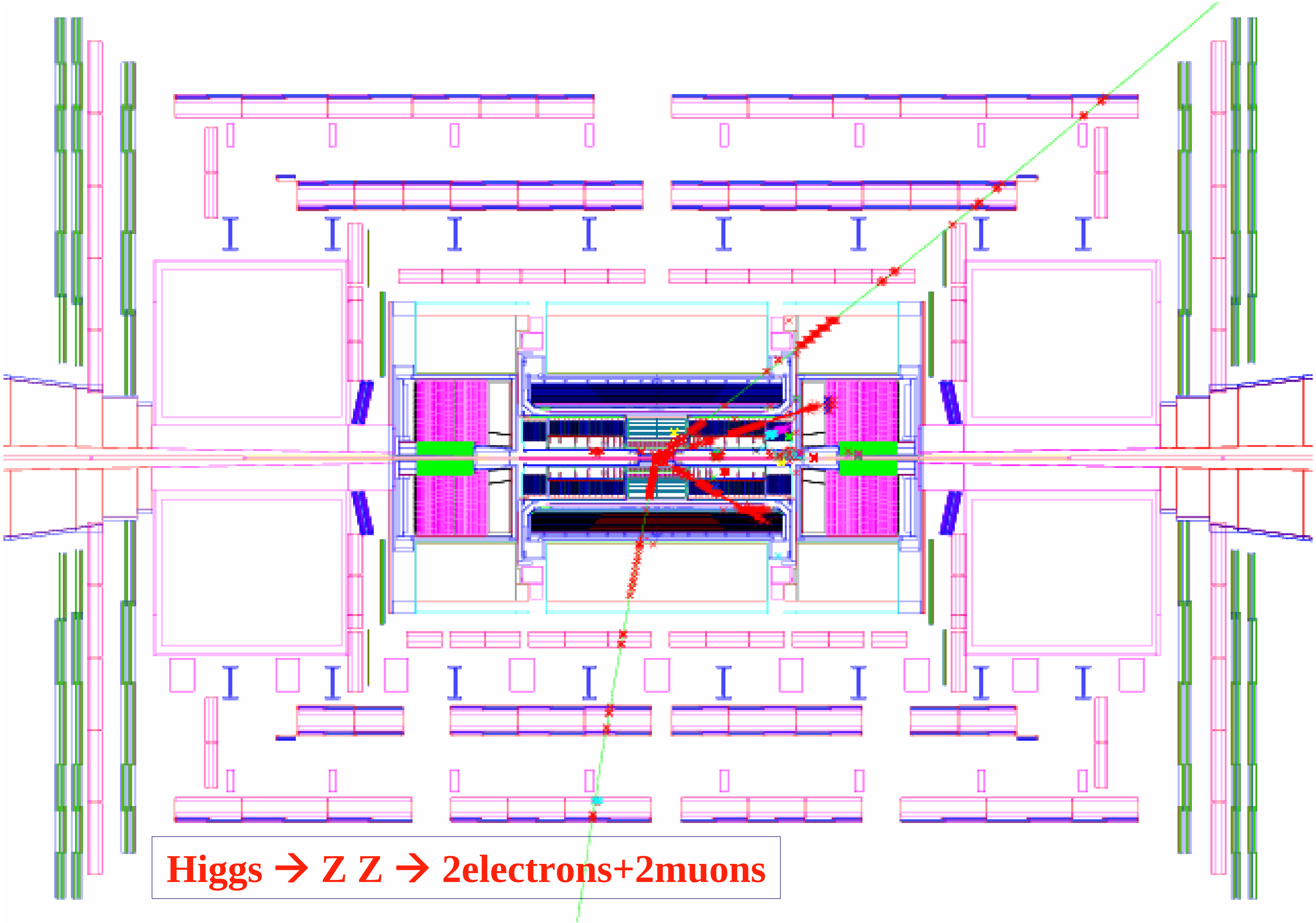
- On-detector electronics: Pipelines
- Event fragments buffered in parallel
- Full event in processor farm

~ 300 MB/s
-> 1 CD / 2 sec

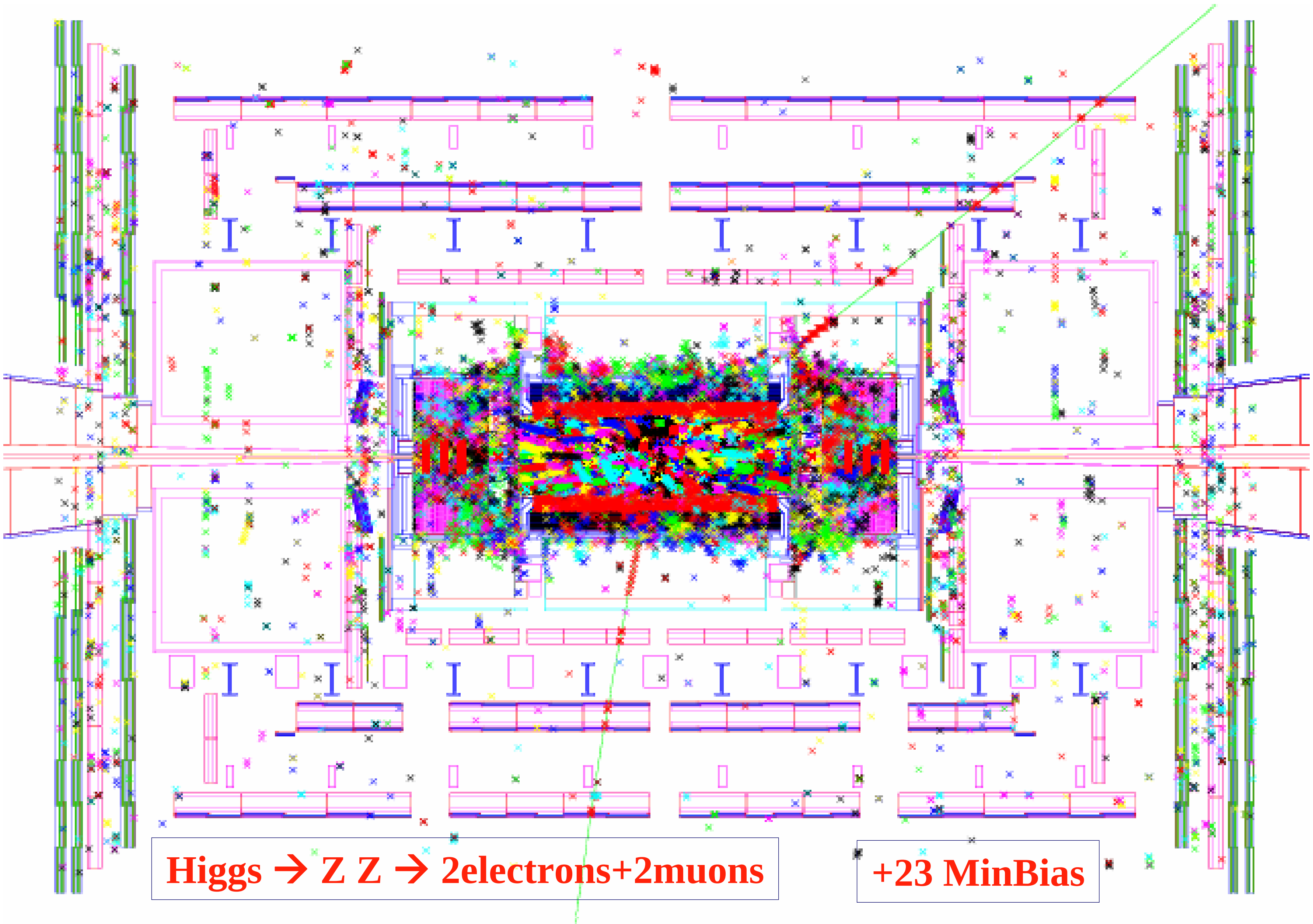
Physics

ATLAS Level 1

We want to extract this…

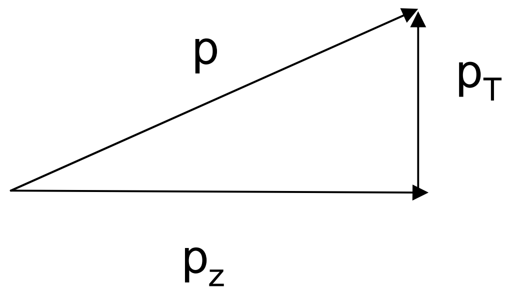


…from this…

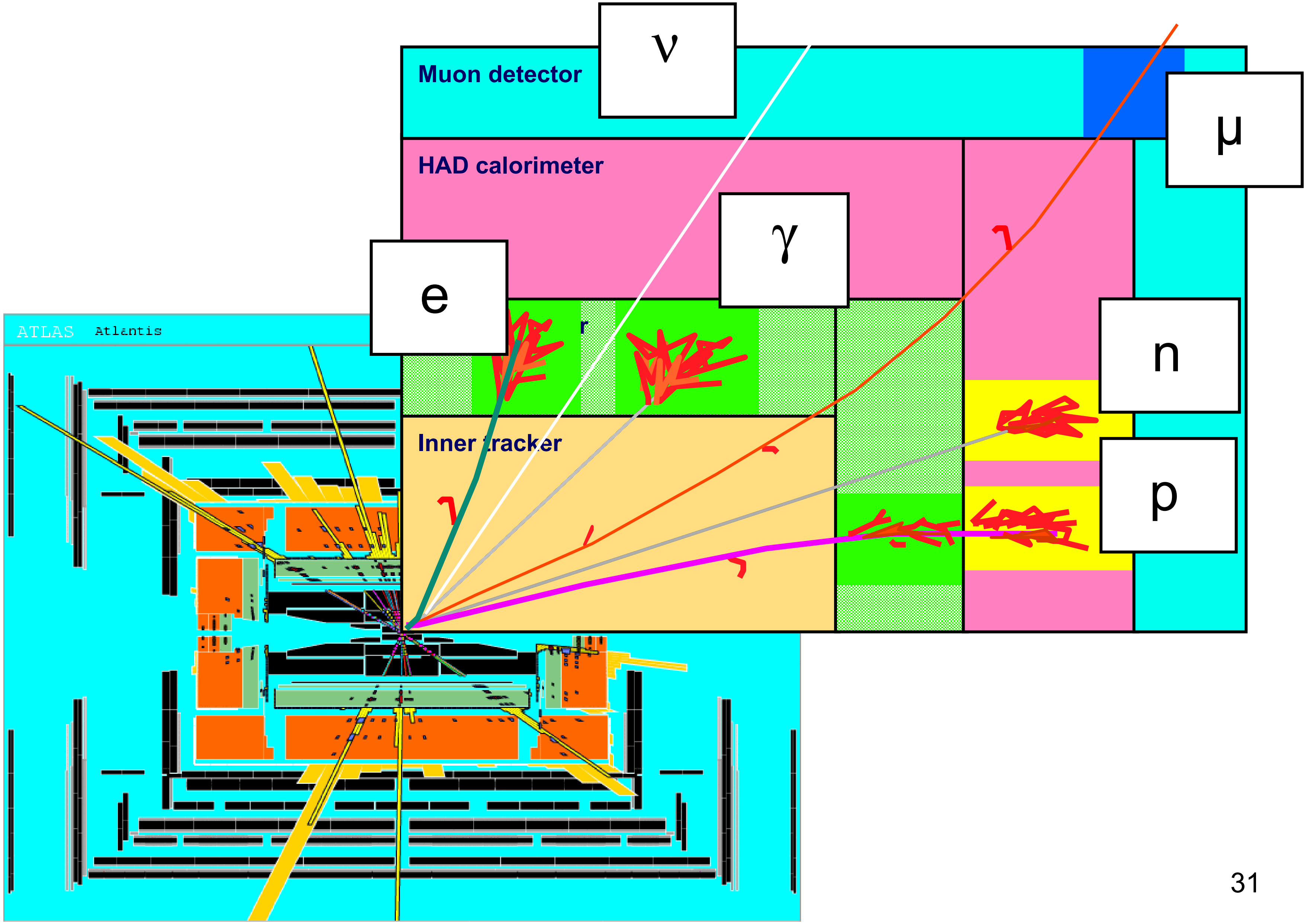


Level-1 Trigger

- Physics motivation:
  - pp collisions produce mainly hadrons with low transverse momenta p_T ~ 1 GeV
  - Most interesting physics includes particles (hadrons and leptons) with high p_T
    - H(120 GeV)→ $\gamma\gamma$: $p_T(\gamma)$ ~ 50 – 60 GeV
    - W→$e\nu$ M(W) = 80 GeV, $p_T(e)$ ~ 30 - 40 GeV
- Strategy:
  - Select signal with high thresholds
    - Electrons, muons, jets
  - Typical thresholds:
    - Single muons with $p_T > 20$ GeV
      - Dimuons $p_T > 6$ GeV
    - Single e/g with $p_T > 30$ GeV
      - Di-electrons with $p_T > 20$ GeV
    - Single jet with $p_T > 300$ GeV

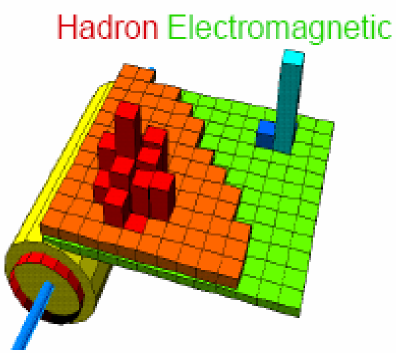


Particle identification

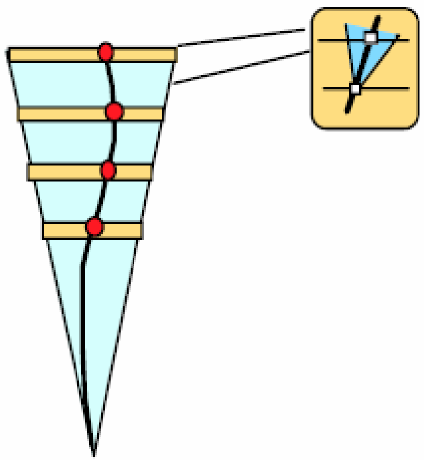


ATLAS L1: Calorimeter + Muon systems

- **Pattern recognition much faster/easier**



Calorimeter



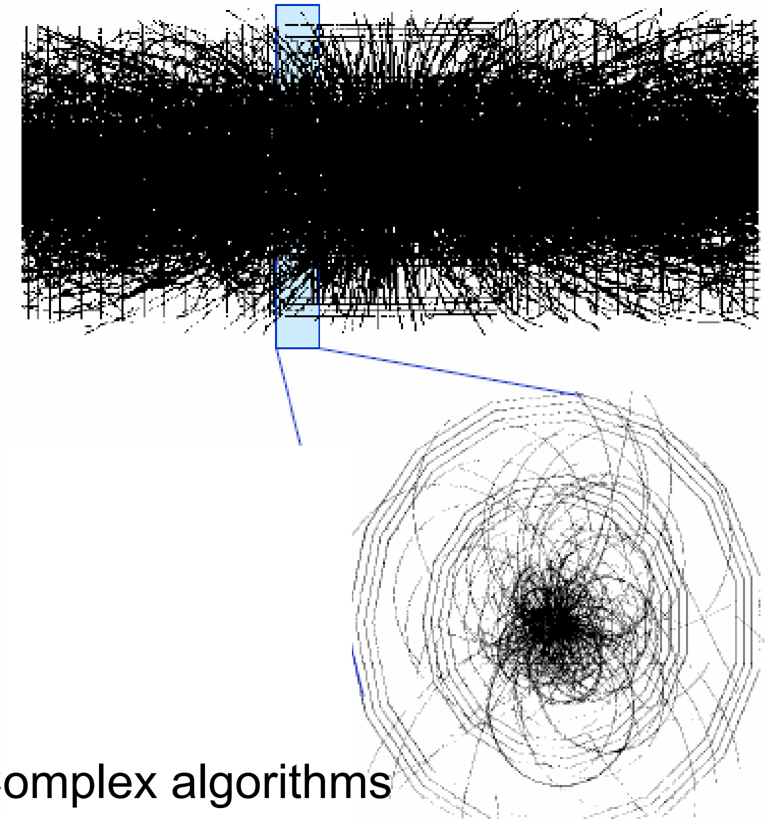
Muon system

Simple algorithms

Small amount of data

Localized decisions

- **Compare to tracker info**

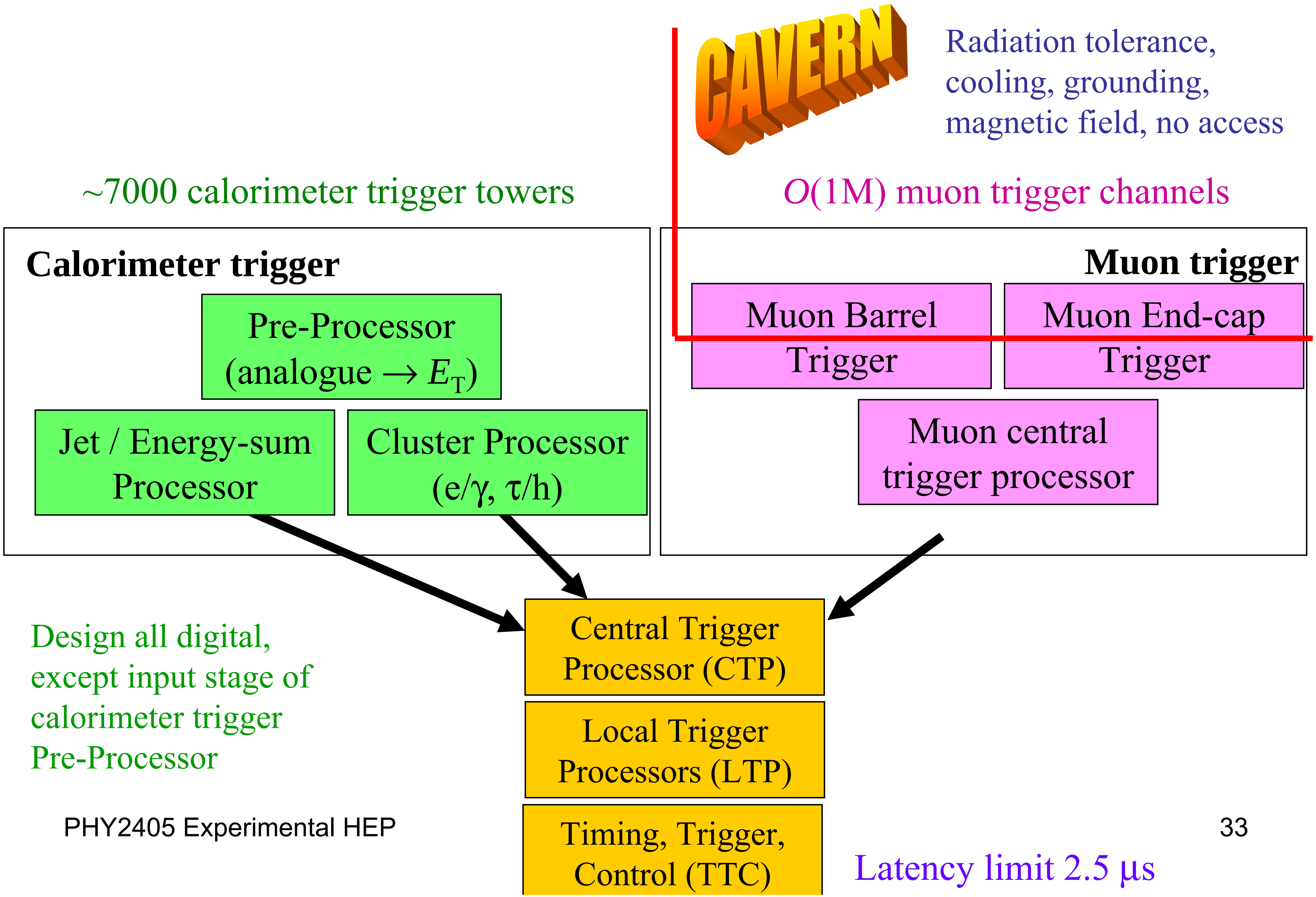


Complex algorithms

Large amount of data

Need to link data from sub-detectors

Overview of ATLAS LVL1 trigger

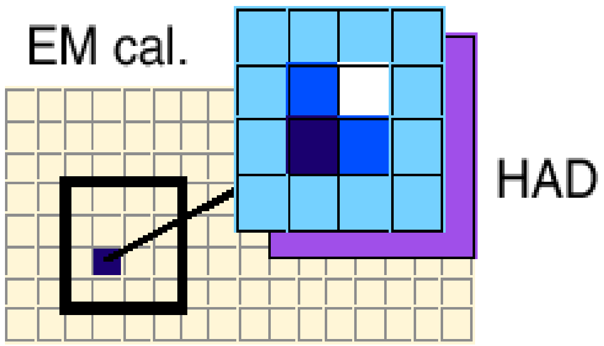


Design all digital, except input stage of calorimeter trigger Pre-Processor

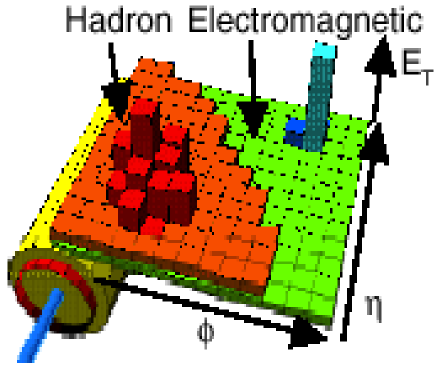
Latency limit 2.5 μs

ATLAS Isolated Electron Algorithm

4•4 cells $\Delta\phi \bullet \Delta\eta = .2 \bullet .2$



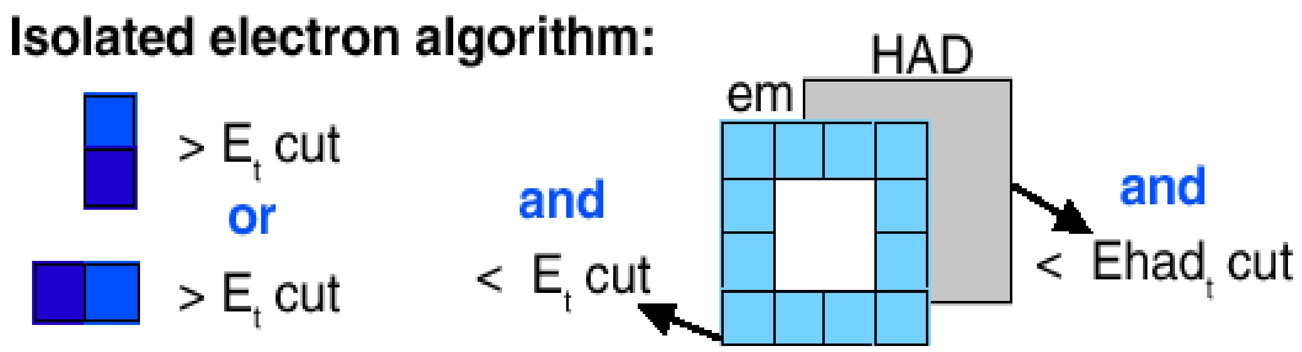
$\Delta\phi \bullet \Delta\eta = .1 \bullet .1$



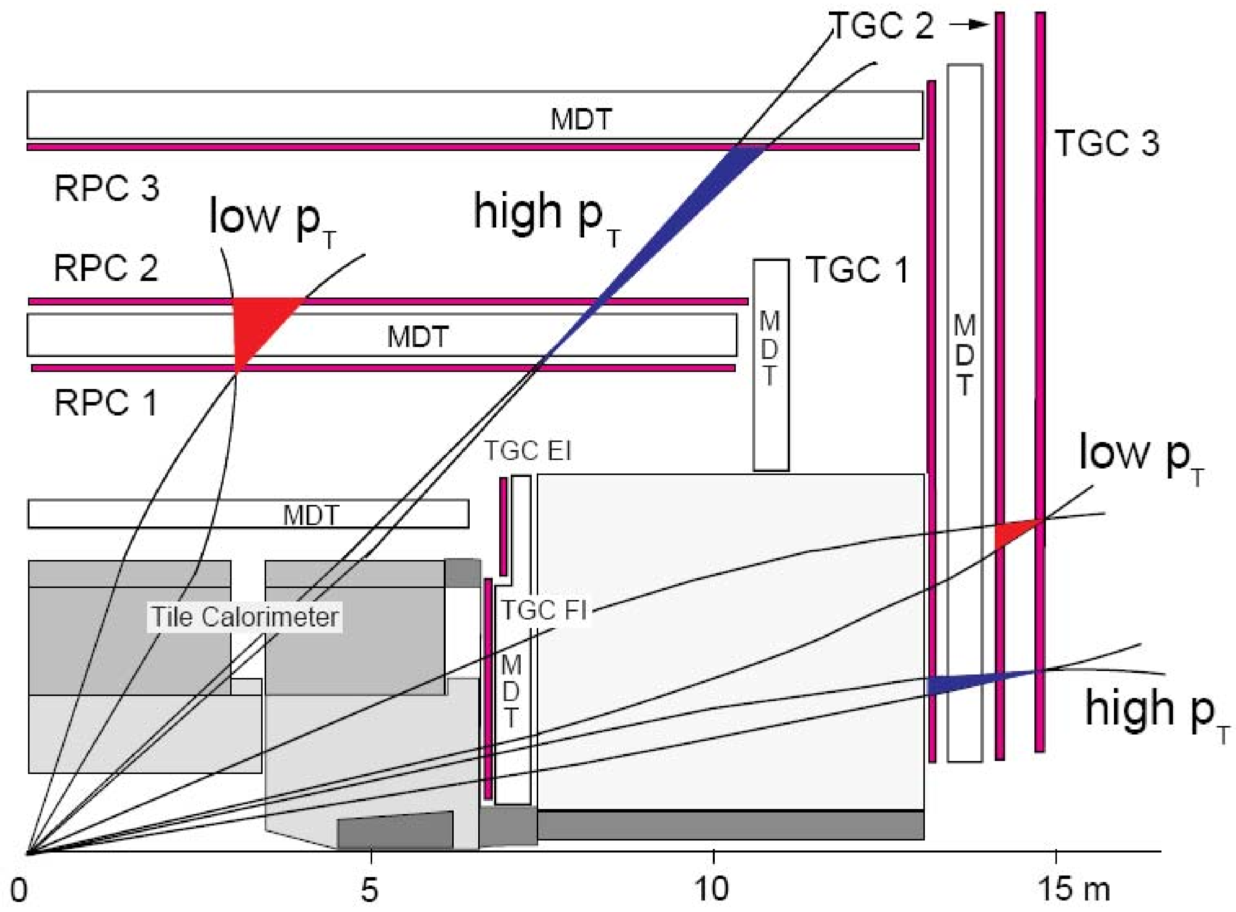
$\eta = -\log(\tan(\theta/2))$

Pseudorapidity

Pixel Processor

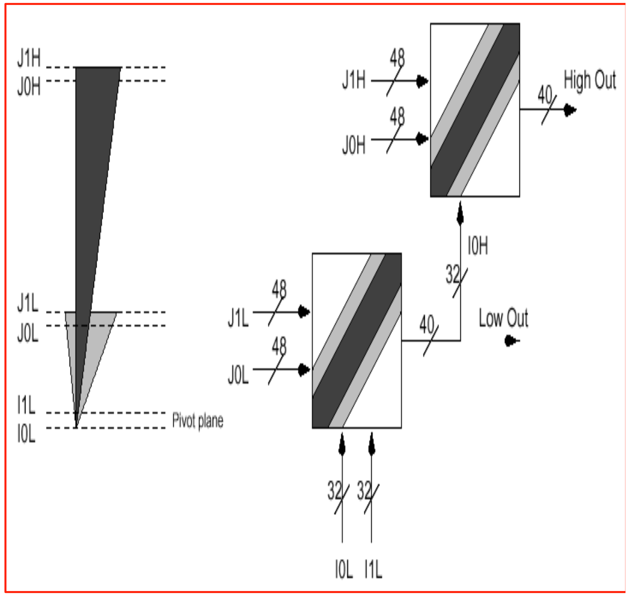


Level-1 Muon Trigger



1) Extrapolate tracks along windows defined by p_T threshold

2) Form coincidences between layers



RPC = resistive plate chambers
TGC = thin gap chambers
MDT = monitored drift tubes

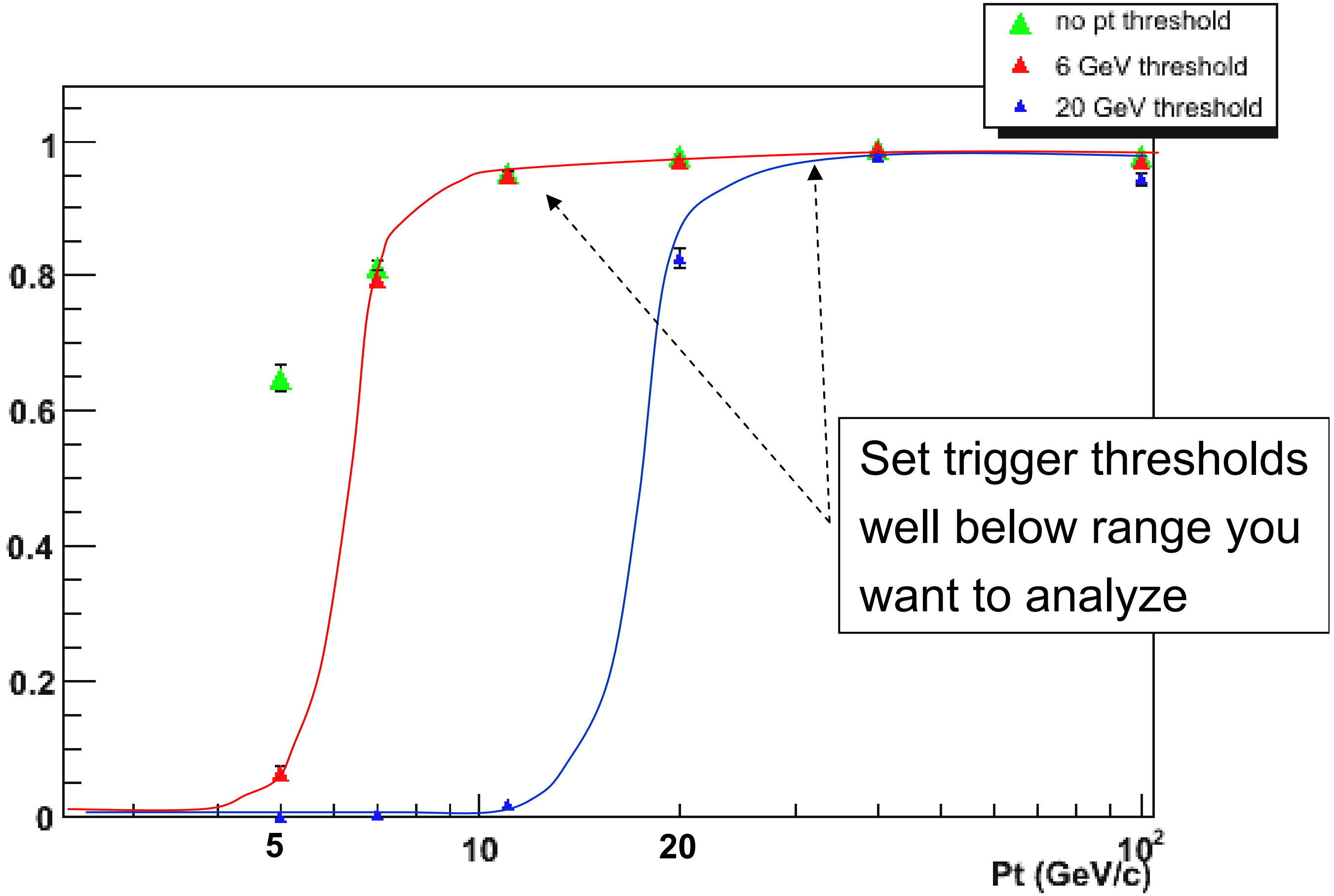
L1 Muon Trigger Efficiency curves @ L=10^{33}

Efficiencies have been computed for startup luminosity (**10^{33}**) and a nominal safety factor (x1):

track χ^2 > 3

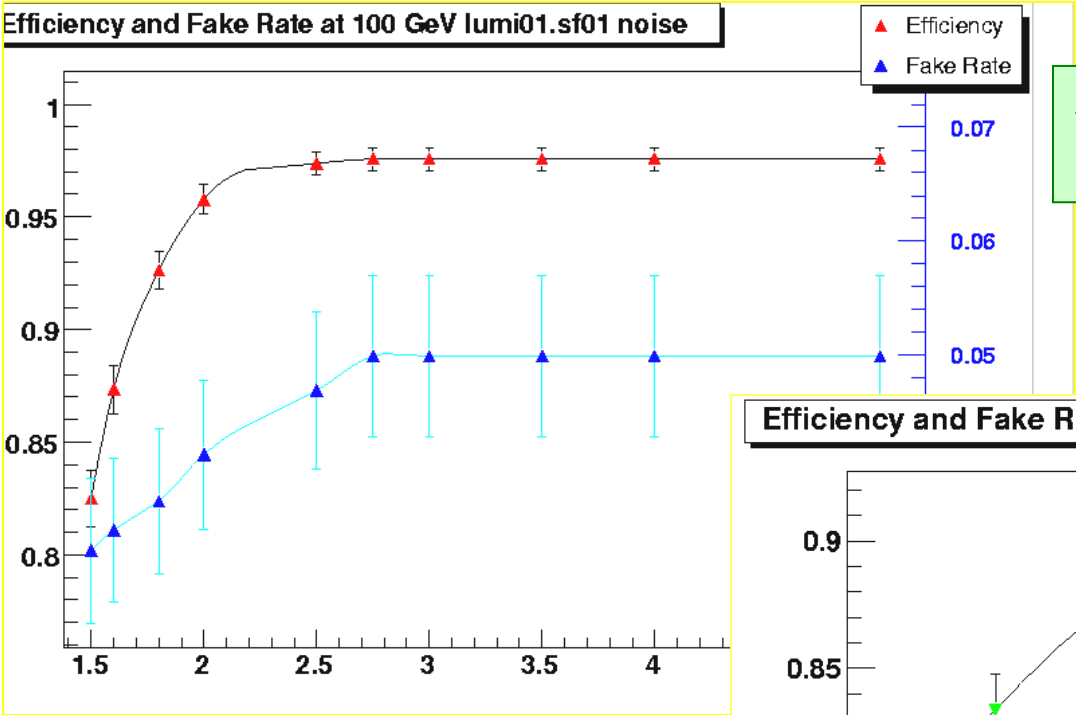
Single muon efficiency curves have been obtained for two different p_T thresholds:

- p_T = 6 GeV/c
- p_T = 20 GeV/c

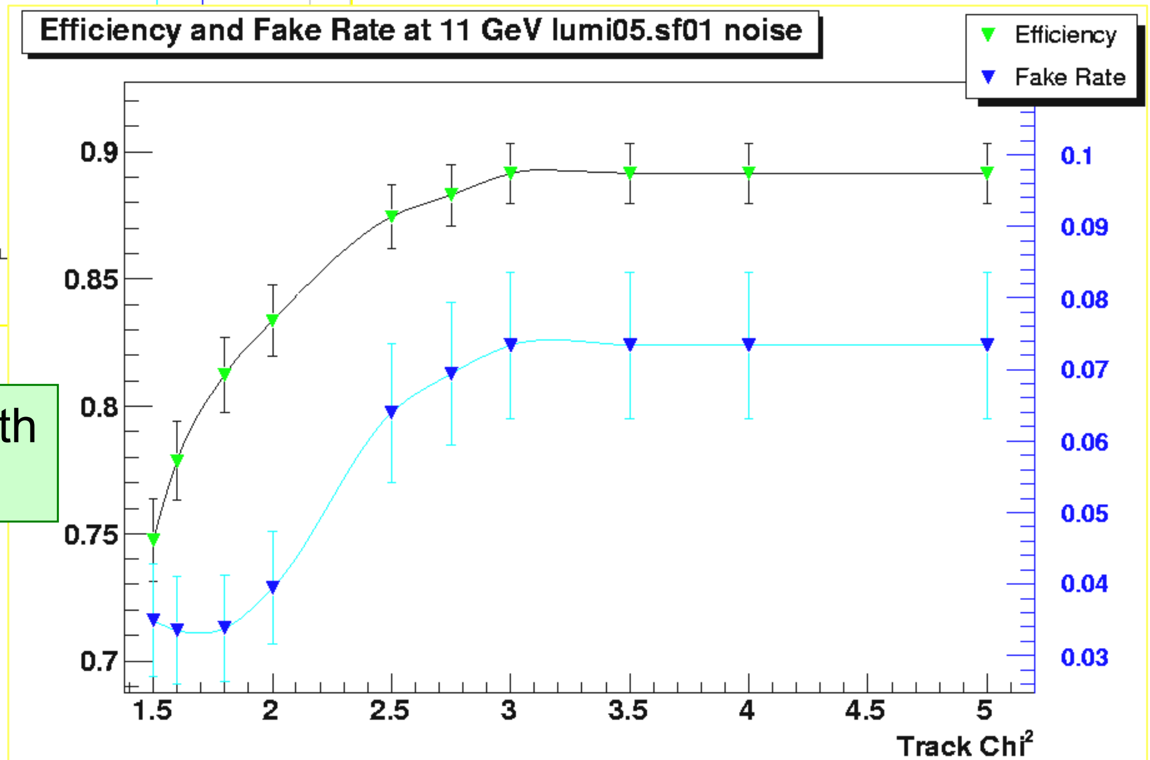


From CERN Trigger Meeting Jan '06

Efficiency & fakes **vs.** track χ^2 cut



Single muons with p_T = **100** GeV



Single muons with p_T = **11** GeV

ATLAS L1 Trigger Rates (kHz)

Selection (Trigger Menu)	$2*10^{33}$ $cm^{-2}s^{-1}$ (20% design Lumi)	10^{34} $cm^{-2}s^{-1}$ (full Lumi)
MU20 (muon p_T>20 GeV)	0.8	4.0
2MU6	0.2	1.0
EM25I (isolated electron p_T > 25 GeV)	12.0	22.0
2EM15I	4.0	5.0
J200 (jet p_T > 200 GeV)	0.2	0.2
3J90	0.2	0.2
4J65	0.2	0.2
J60 + xE60	0.4	0.5
TAU25I + xE30	2.0	1.0
MU10 + EM15I	0.1	0.4
Others (pre-scales, calib, …)	5.0	5.0
Total	**~ 25**	**~ 40**

LVL1 trigger rate (high lum) = 40 kHz
Total event size = 1.5 MB
Total # Readout Links (ROL) = 1600

Design system for <u>75 kHz --> 120 GB/s</u>

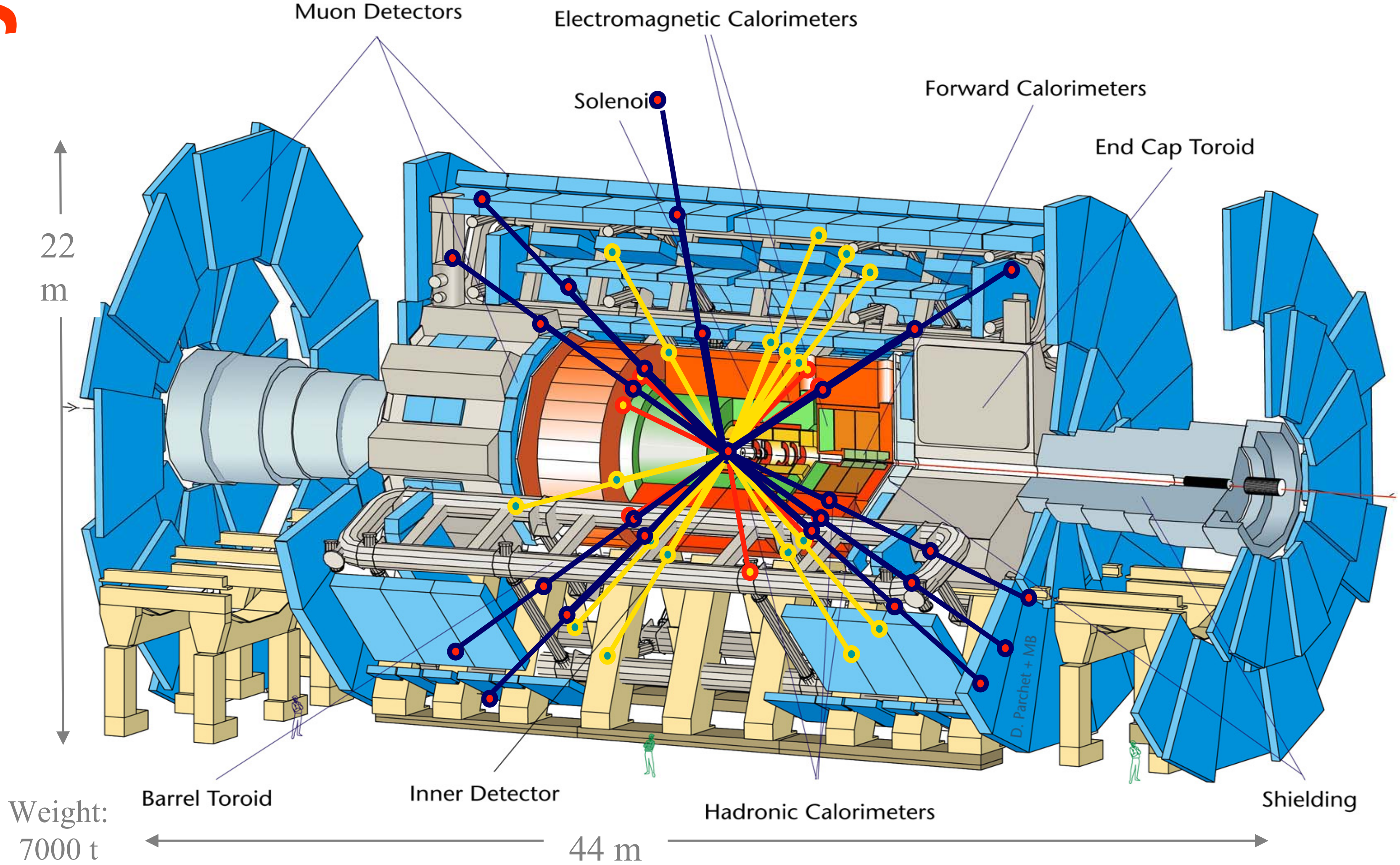
<u>(upgradeable to 100 kHz, 150 GB/s)</u>

Uncertainty ~ factor 2
Design system for 100 kHz

Level-1 latency

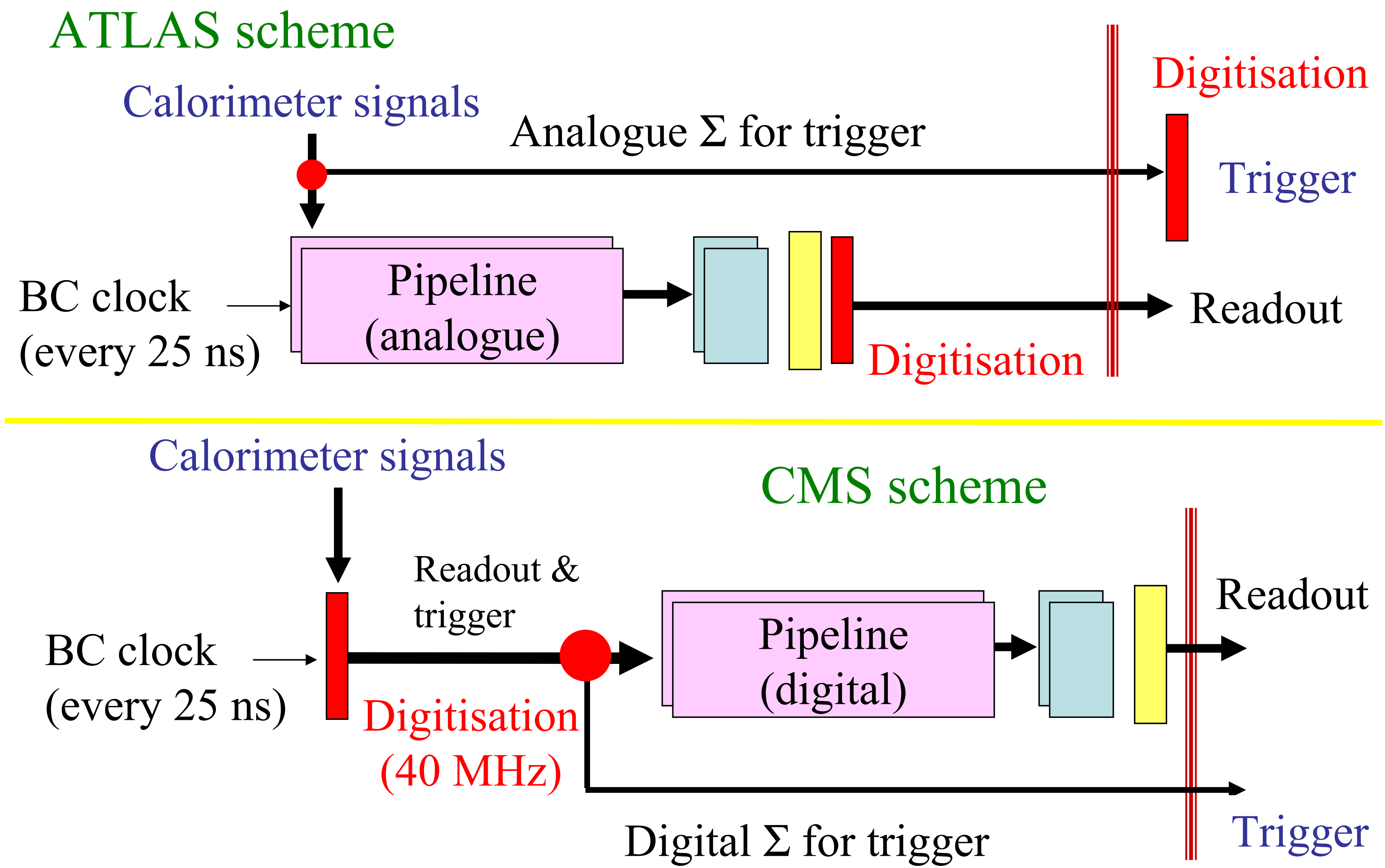
- Interactions every 25 ns …
- In 25 ns particles travel 7.5 m

- Cable length ~100 meters …
- In 25 ns signals travel 5 m



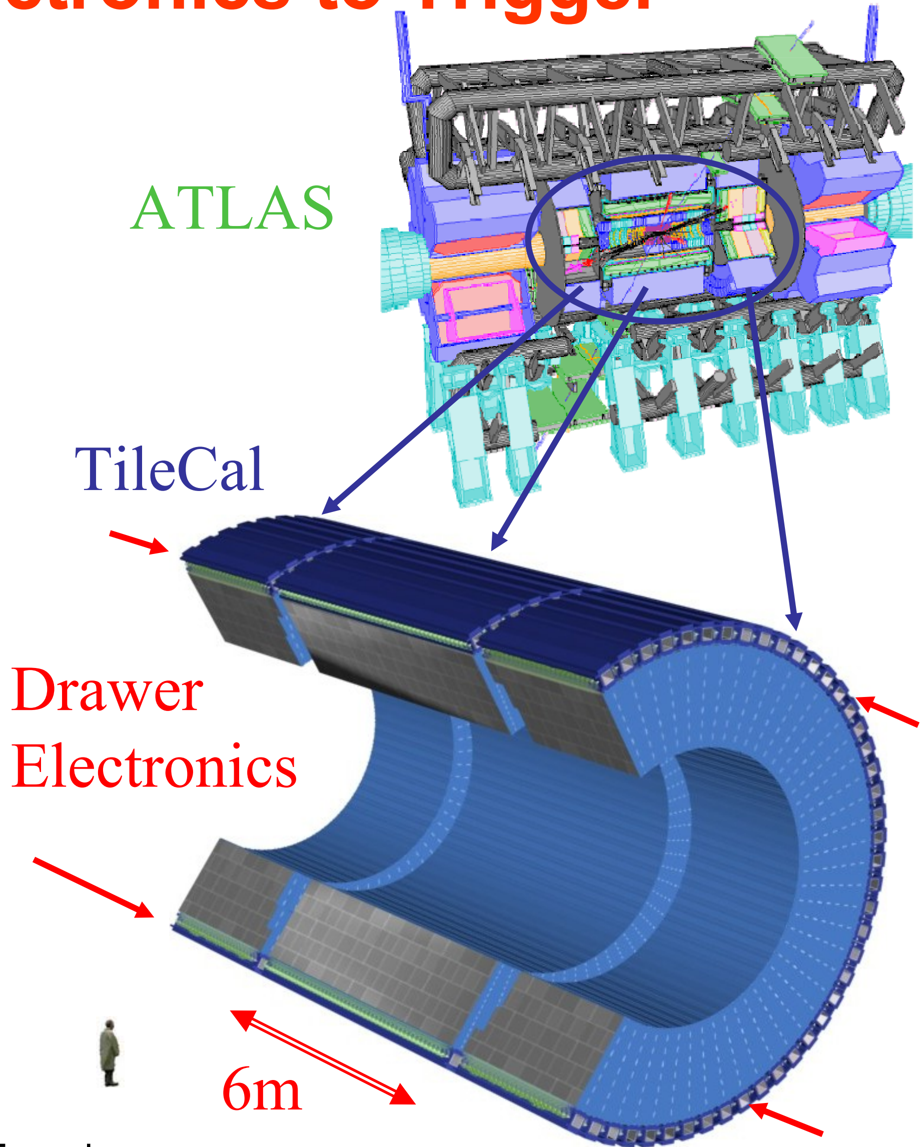
Total Level-1 latency = *(TOF+cables+processing+distribution)* = **2.5 μsec**	**For 2.5 μsec,** all signals must be stored **in electronics pipelines**

Digitisation options (ATLAS c.f. CMS)



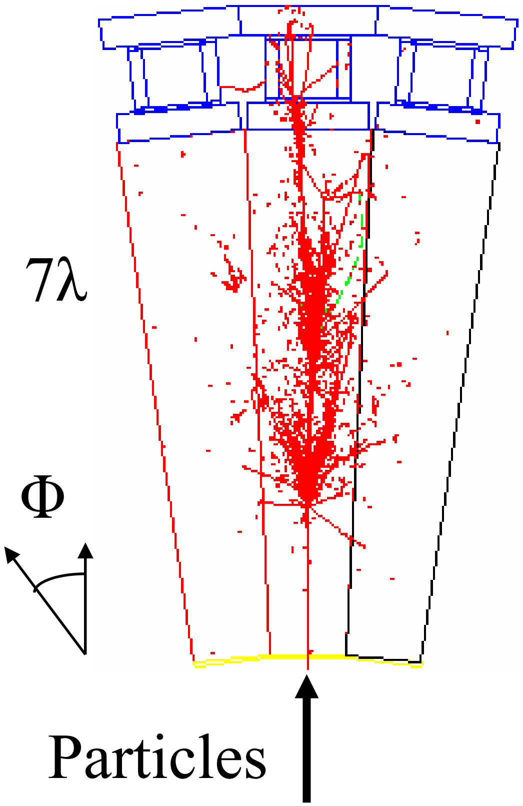
Example of Chain: From Front End Electronics to Trigger

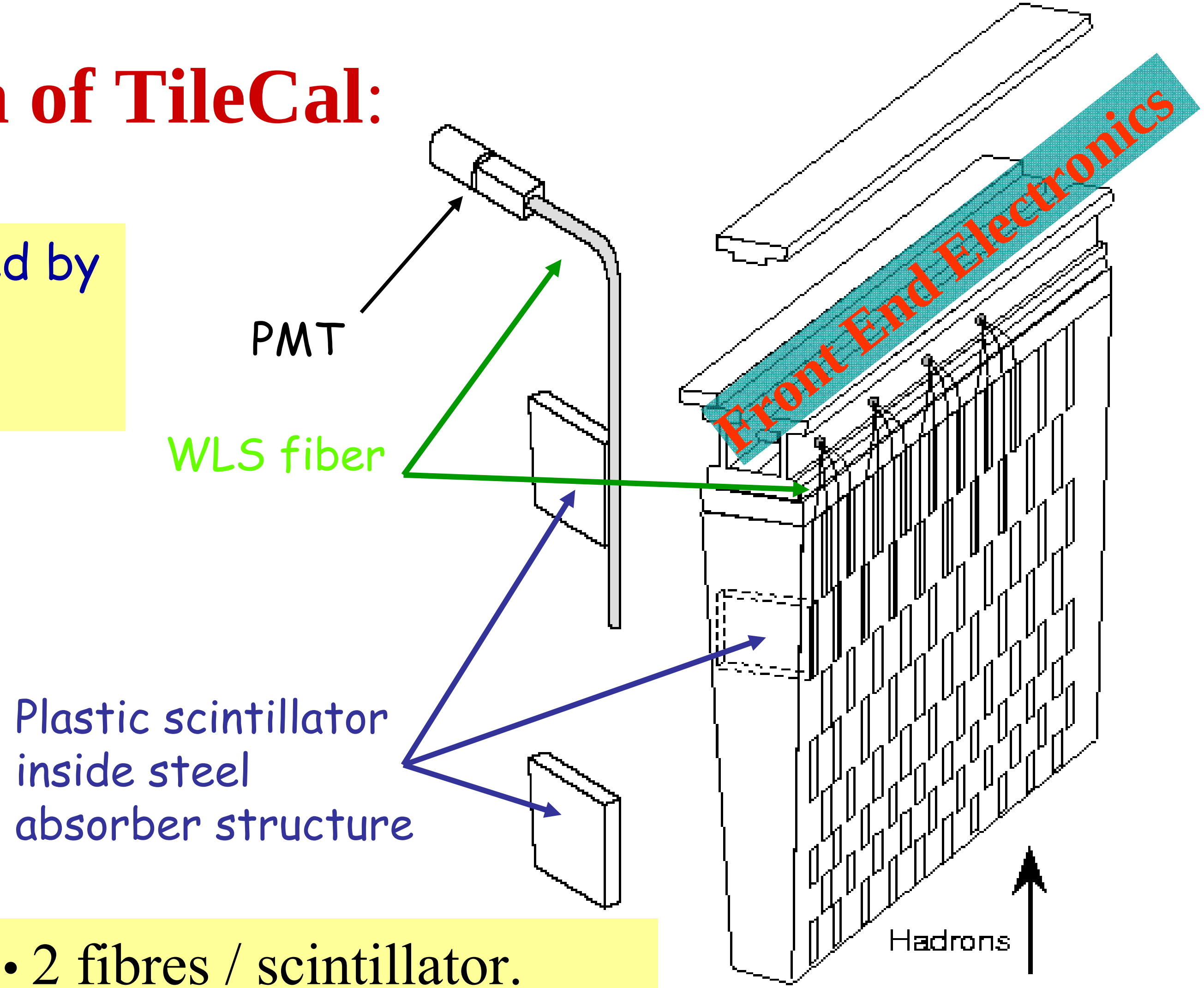
- Process 10000 PMT signals from ATLAS Hadronic Tile Calorimeter (TileCal)
- Electronics located in 256 “drawers”
  - Up to 45 PMT’s/drawer
- 16 bit dynamic range
  - Up to 2 TeV in a single cell
  - Down to 30 MeV per cell
    - Must see muons @ 350 MeV/cell for Calibration, monitoring, e^- ID
- Readout should not degrade calorimeter energy resolution
  - Electronics noise low when merging cells into jets
- Radiation tolerant
- LVL1 Trigger tower sums



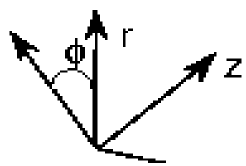
Operation of TileCal:

Measure light produced by charged particles in plastic scintillator.

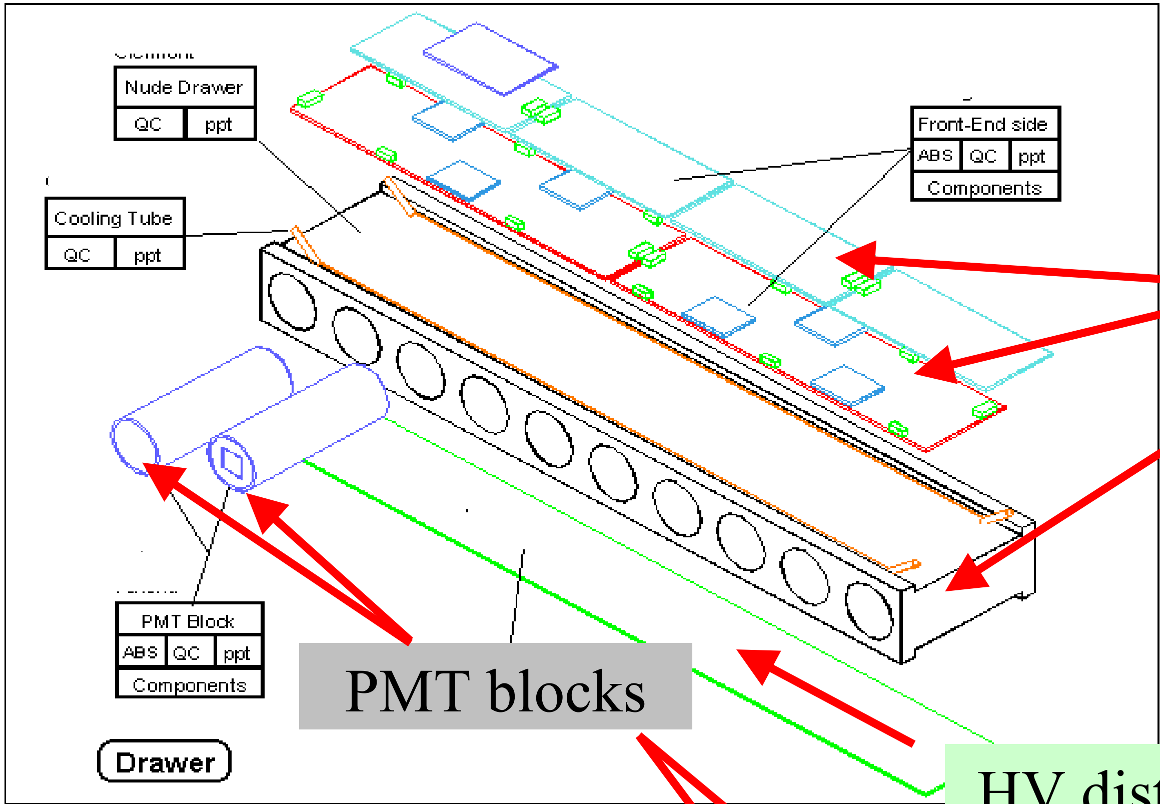




- 2 fibres / scintillator.
- Bundle fibres to form cells of 0.1 x 0.1 (η,φ)
- 2 PMT's per cell



TileCal Electronics Drawers



Readout electronics

Drawer mechanics

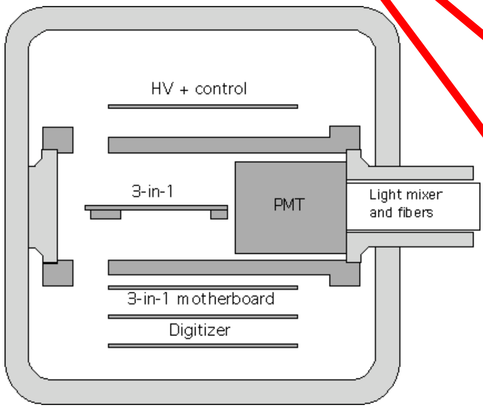
2 sections, each

ℓ=1.5 m m=50 kg

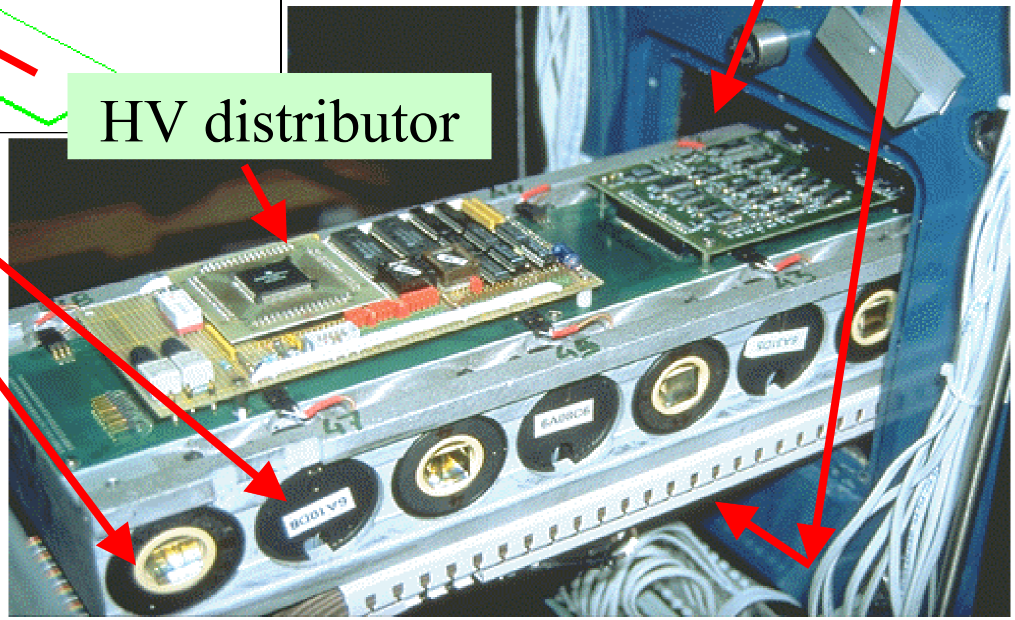
PMT blocks

HV distributor

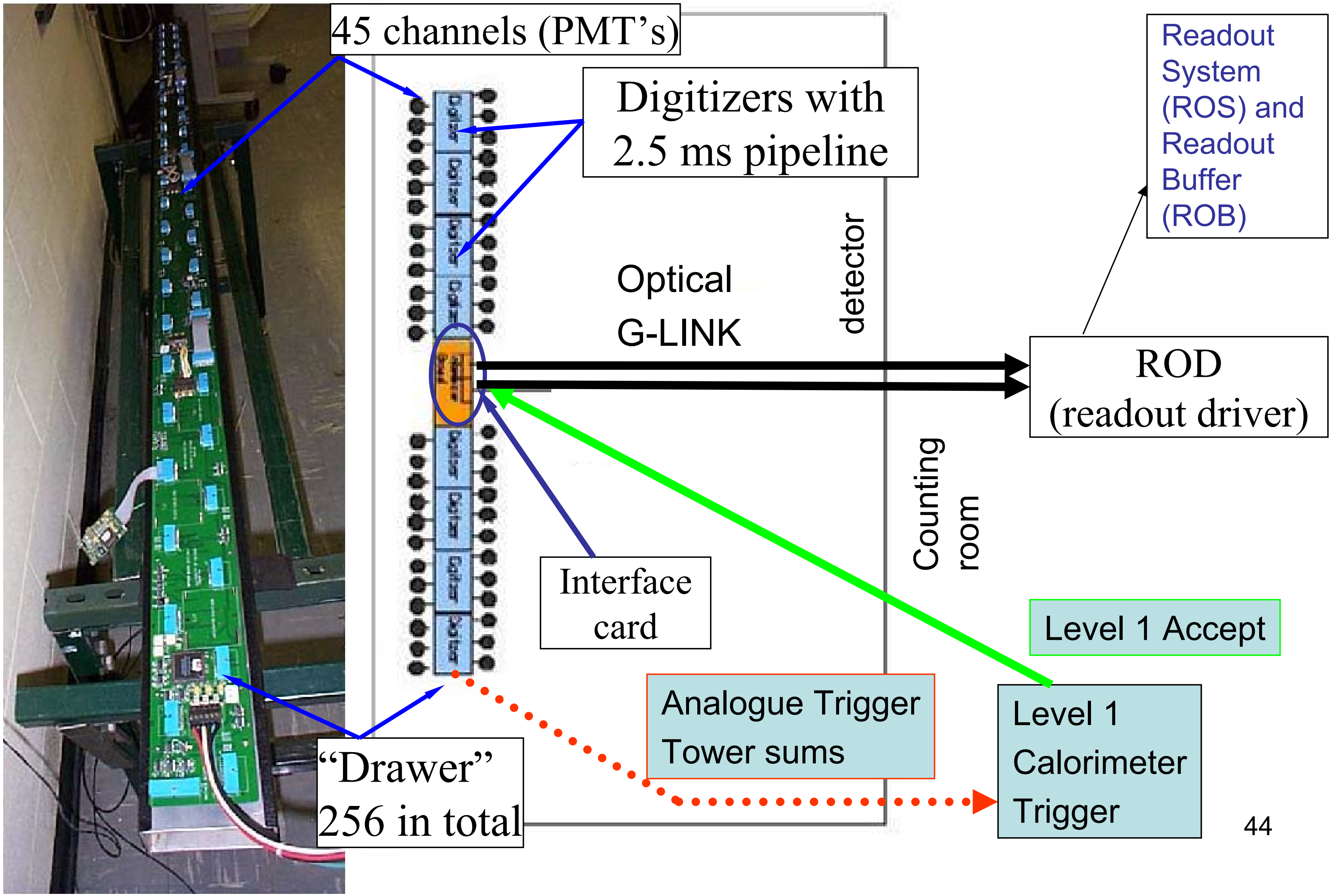
Drawer Cross section



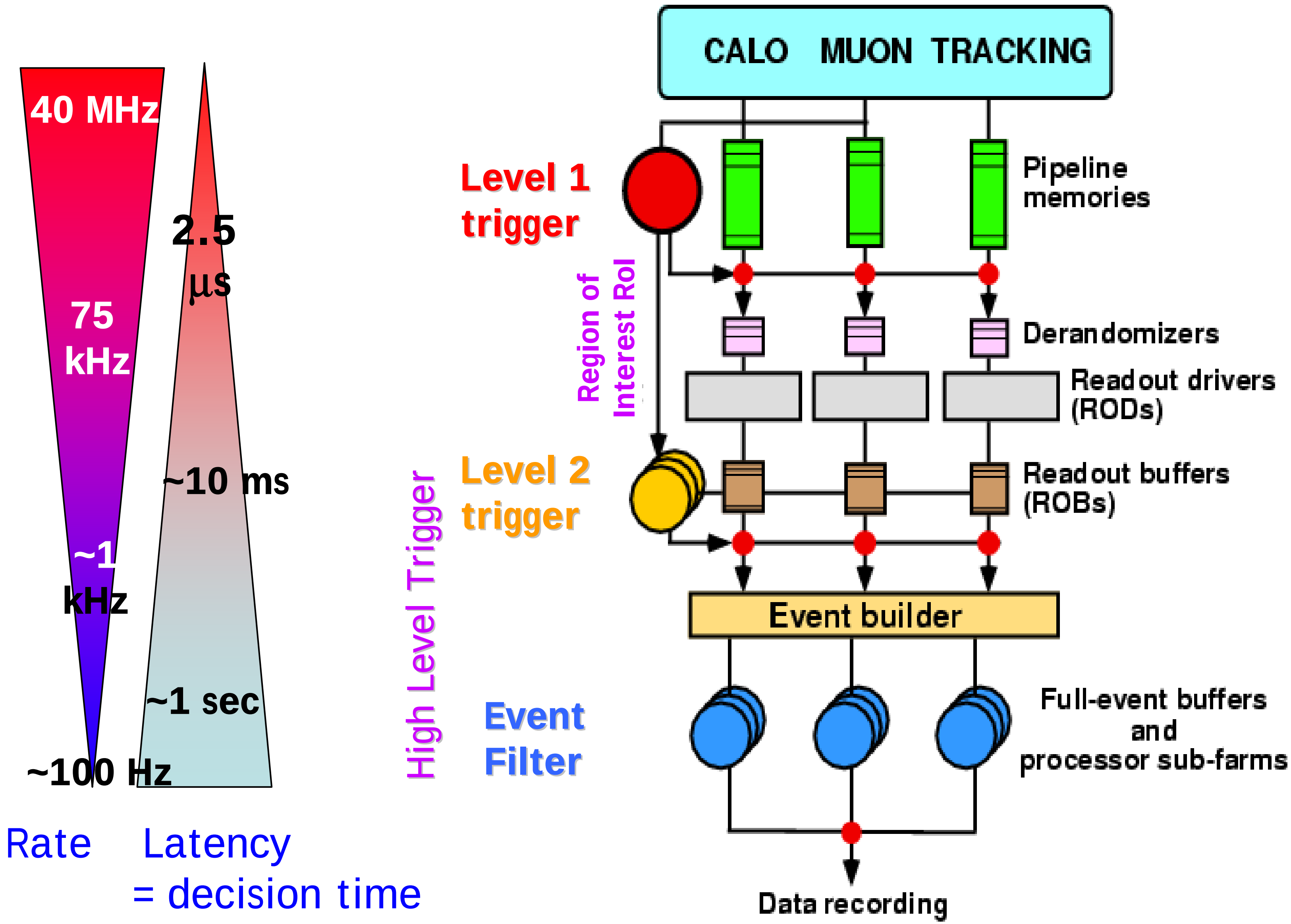
10 cm



TileCal Front End Electronics



Summary: The Trigger Architecture for the ATLAS Experiment at CERN



ATLAS Event