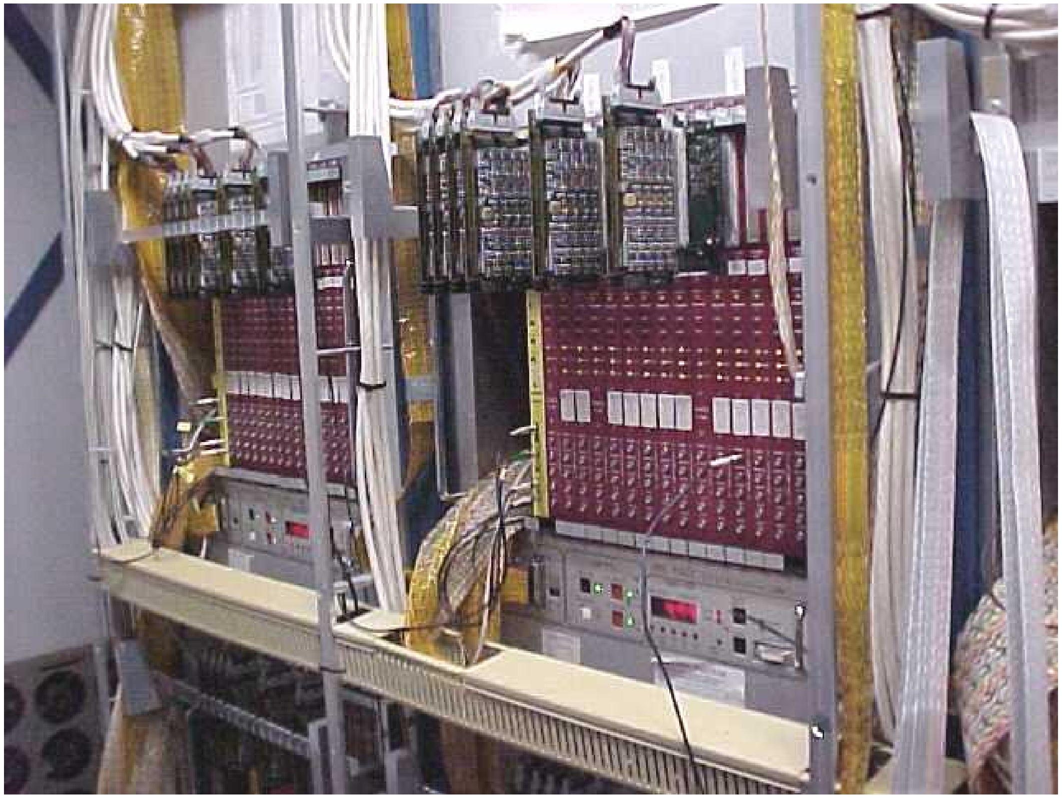
Last time: EM/HAD Showers and Calorimetry

Today's Lecture:

1) Calorimeter resolution
2) Triggering and Data Acquisition



Course Assessment

1. Exam in the Summer (60%)
2. Two sets of assessed problem sheets (15%) each
   - Facilities & Detection techniques (Distributed Fri 31 October, return Mon 24 November)
   - Treatment of experimental data (Distribute Fri 28 November, return Tues 13 January)
3. One presentation of a ‘case study’ (10%)
   - Approx 15 minutes + 5 minutes questions on an important particle physics result
   - Describe motivation, apparatus, method and results
   - ...use original papers and www as references
   - ...as if giving a seminar on your own work
   - Assessed by PRN and a couple of friendly postdocs / Ph.D. students
   - Provisionally three dates for the 7 talks (Mon 1 Dec, Fri 5 Dec, Mon 8 Dec)
   - Possible topics - see next slide
   - Topic and date allocations next Monday 10 November

Example topics for Case studies

1. Current limits on the Higgs mass and where they come from
2. Measurement of $\sin 2\beta$ at B factories
3. Discovery of the top quark at the Tevatron
4. Discovery of neutrino mass at Super Kamiokande and elsewhere
5. Measurement of the proton structure function $F_2(x, Q^2)$ at HERA
6. Evidence for the quark-gluon plasma from heavy ion collisions at CERN and Brookhaven
7. Determination of the Number of Neutrinos at LEP
8. How ATLAS or CMS will find the Higgs boson
9. Why do we want a future e^+e^- collider and what will it look like?
10. Prospects for discovering supersymmetry at the LHC
11. Black hole production at the LHC
12. Many many more possibilities [by agreement with PRN] . . . . . .

. . . Your talk should *not* be on the same topic as your C4 project

. . . We should not duplicate topics, so please have a first and second choice topic for Monday

Calorimter Resolution

Resolution of a Calorimter usually Considered in 3 parts:

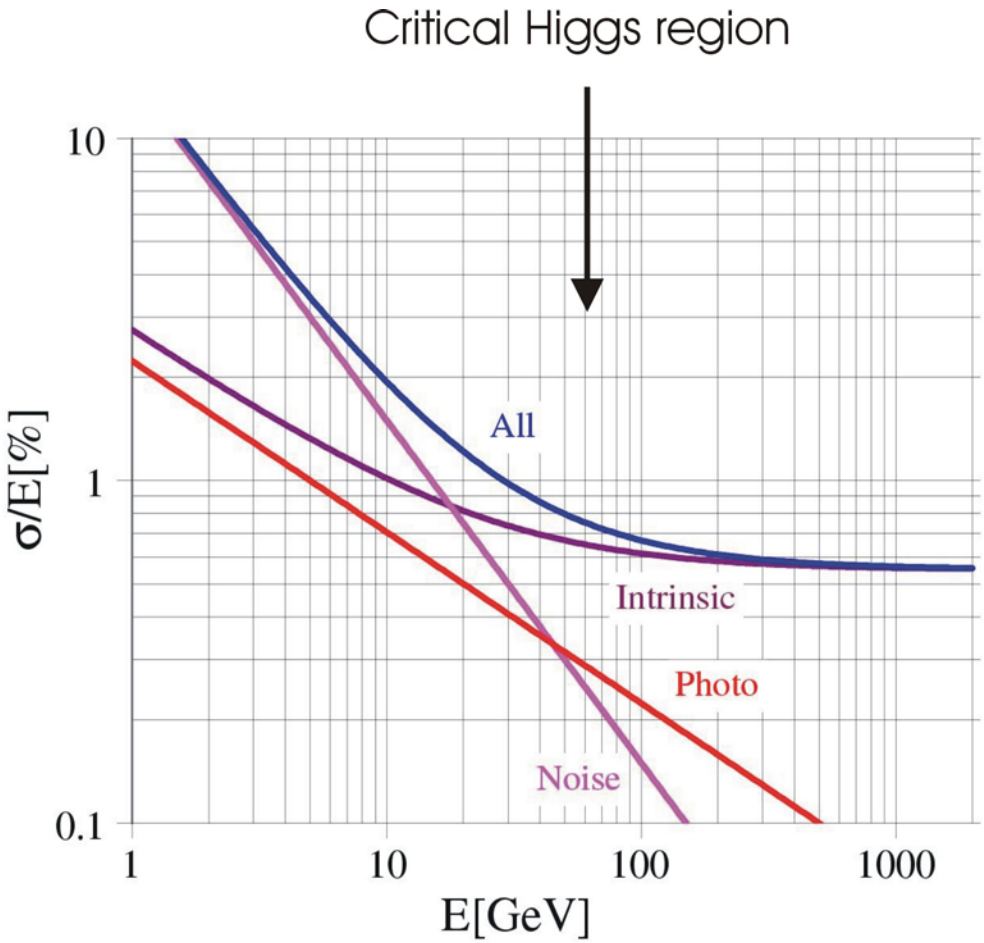
1. $\sigma(E) \propto \sqrt{E}$ 'counting error' due to statistical fluctuations in showering / sampling
2. $\sigma(E) \propto const$ Energy independent error due to electronic noise, pile-up of other events at LHC ...
3. $\sigma(E) \propto E$ Losses due to leakage or dead material, systematics such as miscalibration

Usually quoted as a fractional error ($\bigoplus$ means 'add in quadrature')

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

typically for em calo $a = 0.1, b = c = 0.01$ for had $a \sim 0.4$

Example: CMS



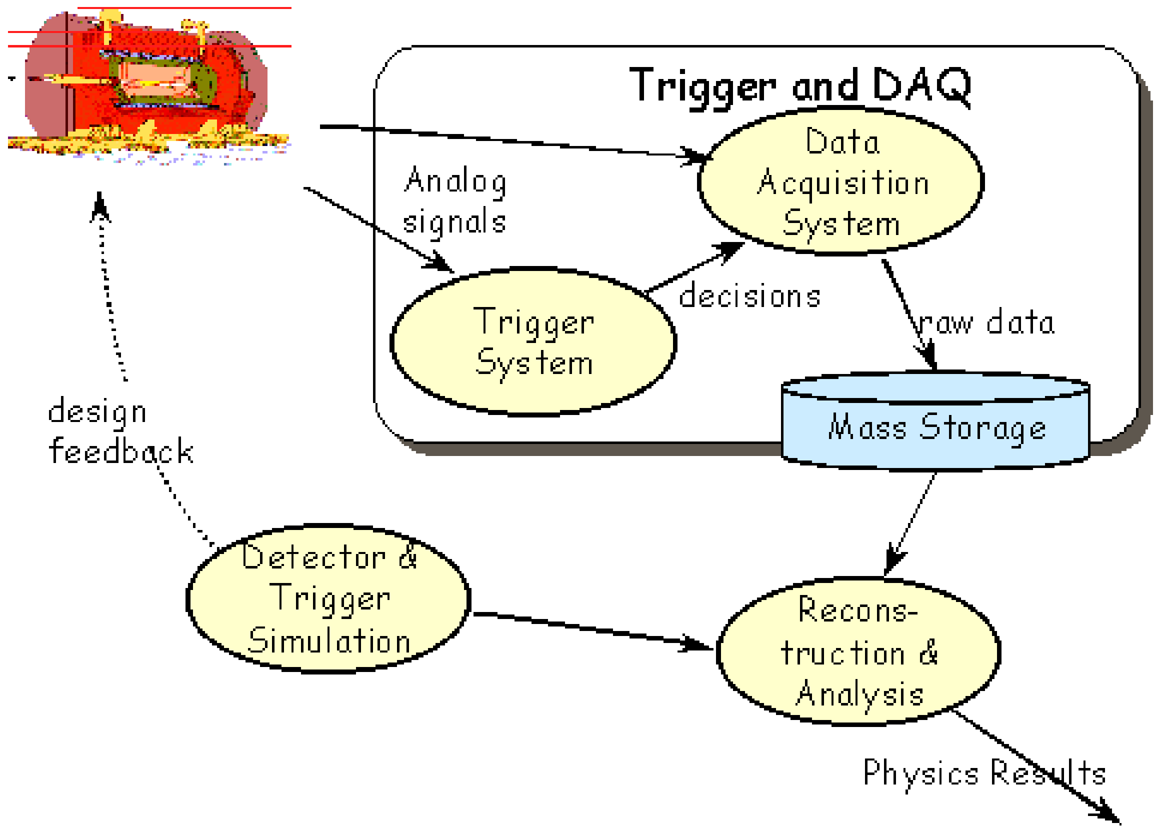
At low E, $\sigma(E)/E \sim 1/E$, dominated by noise, pile-up etc

At high E, $\sigma(E)/E \sim 1/E^{1/2}$, dominated by `intrinsic' statistical sampling error

c.f. trackers, $\sigma(p_t)/p_t \propto p_t$

NB! Calorimeter resolution improves with increasing energy
Tracking resolution deteriorates with increasing energy
… the two types of detector are often complementary!

Triggering and Data Acquisition
General Framework



DAQ = Data AcQuisition

From signals in detector, find interesting events and permanently store

Trigger & DAQ - Some Definitions

- **Trigger System:**
  - Selects in Real Time "interesting" events from the bulk of collisions. - Decides if YES or NO the event should be read out of the detector and stored
- **Data Acquisition System**
  - Gathers the data produced by the detector and stores it (for positive trigger decisions)
    - Front End Electronics:
      - Receive detector, trigger and timing signals and produce digitized information
    - Readout Network
      - Reads front end data and forms complete events (sometimes in stages) - Event building
    - Central DAQ
      - Stores event data, can do data processing or filtering
      - Overall Configuration Control and Monitoring

Trigger Requirements and Goals

LEP
σ_{tot}~30nb
Low bunch crossing rate
Low beam induced background
All physics events interesting
Take all physics (about 1 Hz)

LHC
σ_{tot}~30mb
High bunch crossing rate
High beam induced background
High p_t interactions interesting
Physics rate ~10^9 Hz
Take 1 physics event in 10^7

Triggers must …..

- Be as fast as possible - cf drift times in tracking detectors ~ms ☹
- Recognise good physics events with high efficiency
- Have well known efficiency (60 +/- 1 better than 90 +/- 5)
- Remove backgrounds, especially beam induced
- Select interesting from uninteresting physics (at hadron colliders)

LEP & LHC in Numbers

	LEP (1989)	LHC (2005)	Factor
Nr. Electronic Channels	≈ 100 000	≈ 10 000 000	× 10^2
Raw data rate	≈ 1 000 GB/s	≈ 1 000 TB/s	× 10^4
Data rate on Tape	≈ 1 MB/s	≈ 100 MB/s	× 10^2
Event size	≈ 100 KB	≈ 1 MB	× 10
Bunch Separation	22 μs	25 ns	× 10^3
Bunch Crossing Rate	45 KHz	40 MHz	× 10^3
Rate on Tape	10 Hz	100 Hz	× 10
Analysis	0.1 Hz (Z_0, W)	10^{-6} Hz (Higgs)	× 10^5

Trigger Levels

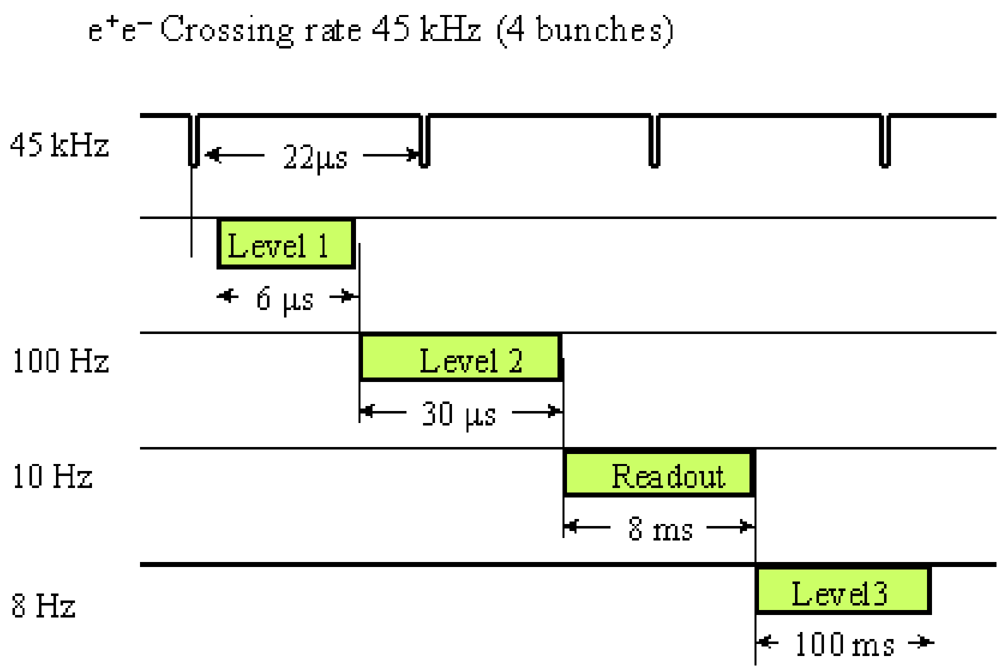
Most experiments adopt a multi-level approach to triggering, with decisions based on more and more information (so better and better rejection) at successive levels.

- Trigger levels
  - Hardware trigger: *Fast* trigger which uses crude data from few detectors and has normally a limited time budget and is usually implemented using hardwired logic.
    $\Rightarrow$ **Level-1** sometimes **Level-2**
  - Software triggers: Several trigger levels which refines the crude decisions of the hardware trigger by using more detailed data and more complex algorithms. It is usually implemented using processors running a program.
    $\Rightarrow$ **Level-2**, **Level-3**, **Level-4**, ...

`Before' readout

`After' readout

LEP collider timing

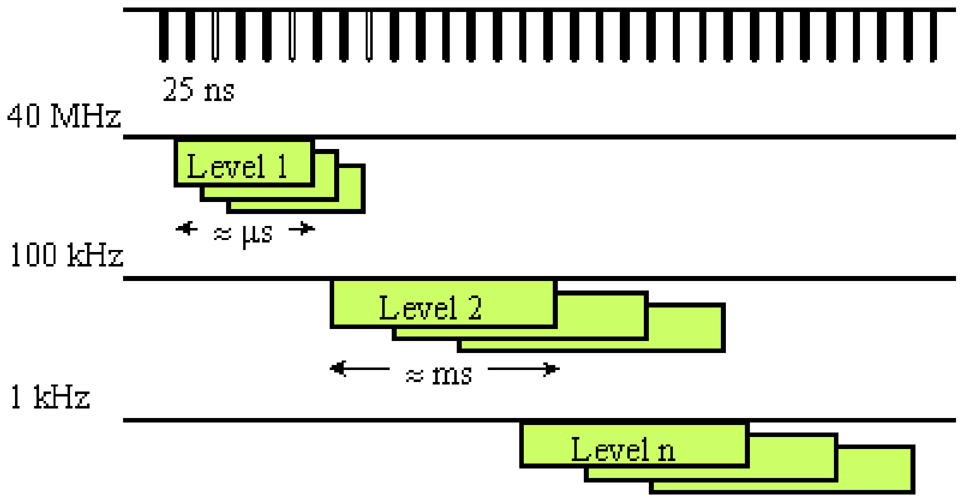


- Level 1 trigger latency < inter bunch crossings -> No deadtime
- No event overlapping
- Most of the electronics outside the detector

`Deadtime' is when detector is busy doing something like readout, so is insensitive to further collisions. At LEP, the (level 1) trigger is deadtime free – deadtime only when the detector is being read out.

LHC timing

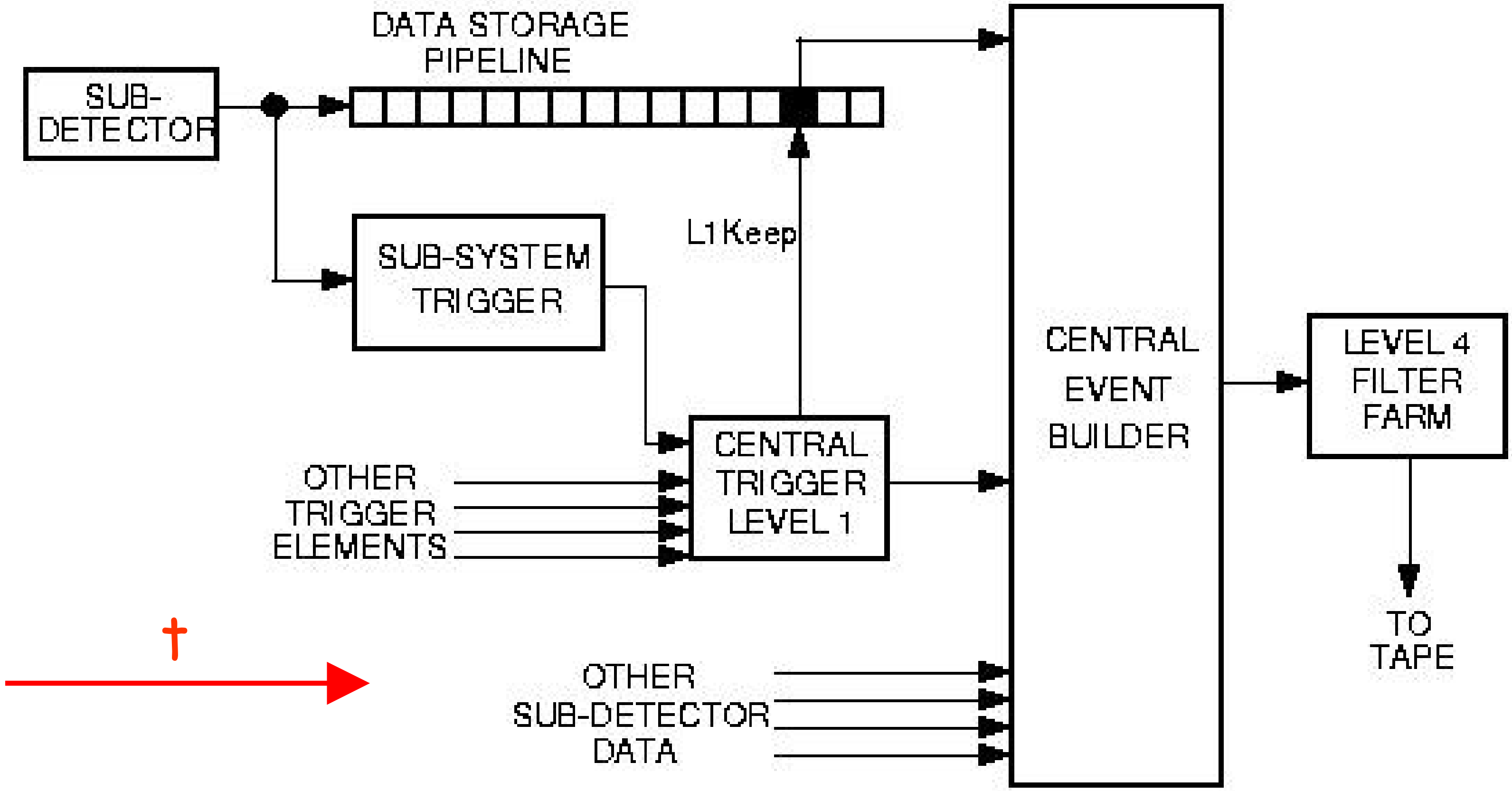
p p crossing rate 40 MHz ($L=10^{33}$ - $4 \cdot 10^{34} cm^{-2} s^{-1}$)



- Level 1 trigger time exceeds bunch interval
- Event overlap & signal pileup (multiple crossings since the detector cell memory greater than 25 ns)
- Very high number of channels

If (level 1) trigger is to stay deadtime free, need to cope with data from multiple bunch crossings simultaneously …… use `pipelining’

Principle of Pipelining



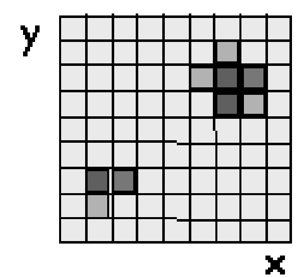
- Keep data from several bunch crossings while trigger has time to make decision. `Rewind’ to correct bunch crossing for readout.
- No deadtime until we decide to read out the full event.

Example first level trigger – crude but fast reconstruction to look for regions of possible activity … LHCb calorimeter just looks for the highest pT particle using a sliding window and compares with a tunable threshold

LHCb L0 Calorimeter Trigger

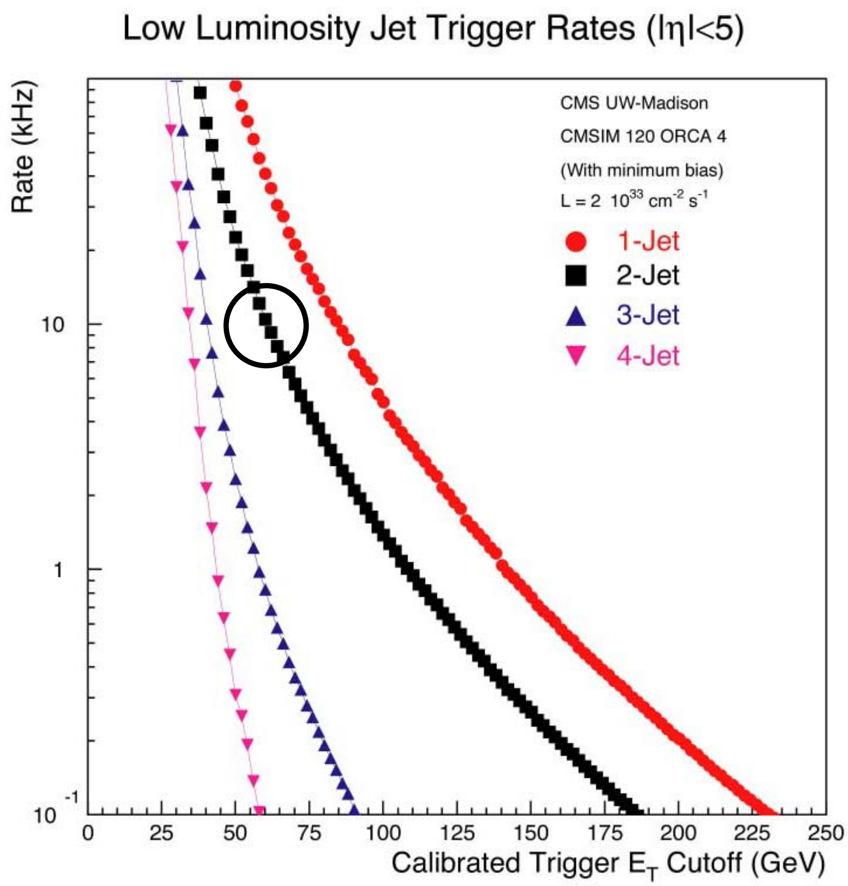
- Select the particles with the highest P_T
  - For the Level 0 decision, we need only the particle with the highest P_T
  - Check if above threshold

- Identify hot spots
  - Detect a high energy in a 'small' surface
  - Use a square of 2 x 2 cells area
    - 8 x 8 cm2 in the central region of ECAL
    - more than 50 x 50 cm2 in the outer region of HCAL



Trigger Thresholds

Usually triggering is a compromise between low thresholds (to optimise physics studies) and high thresholds (to keep background / physics rates under control)



e.g. suppose we want to trigger on a light Higgs (120 GeV) through decays →bbbar jets at 60 GeV each .....

... Huge rates! Very hard!

In fact level 1 jet thresholds >~ 100 GeV!

An example tracking trigger (H1 Fast Track Trigger):

Often only a subset of available information used for first level trigger to speed up the processing …

Principle of the FTT

Trigger Level 1: 2.3 μs

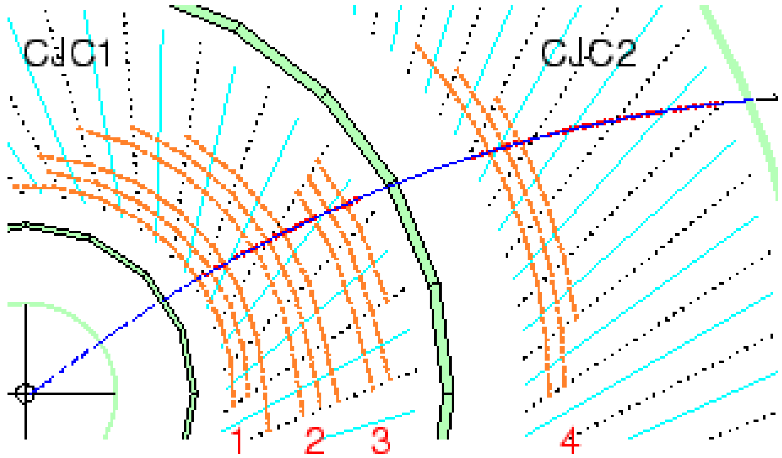
- Hit detection in 12 out of 56 drift chamber wires
- Finding track segments within a trigger group of 3 wires. (1-4)
- Coarse linking to trigger on multiplicity, topology

Trigger Level 2: 25 μs

- 3D linking with improved resolution
- Trigger decision based on full track information
- Track combinations for low multiplicity final states

Trigger Level 3: $\approx$ 100 μs

- Event reconstruction and particle identification (r esonances) using a processor farm.



$r - \phi$ view of the central drift chamber

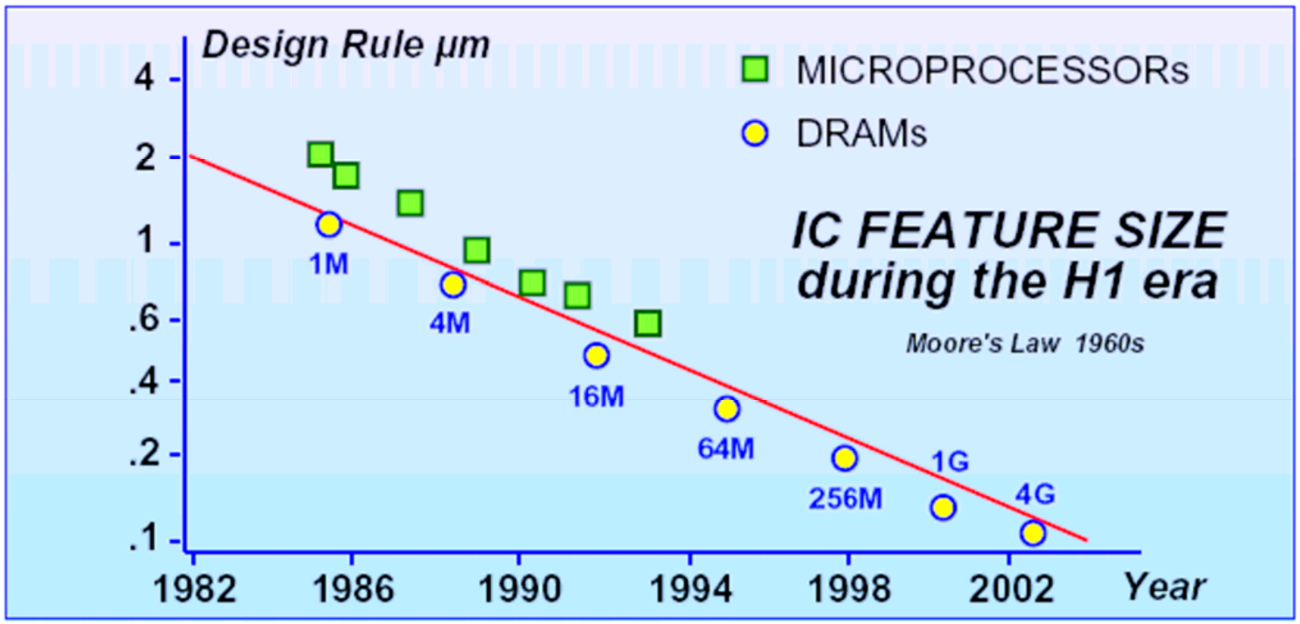
… nonetheless, only possible with very powerful electronics!

Fast Electronics - ASICs and FPGAs

"Application Specific Integrated Curcuit (ASIC)" and
"Field Programmable Gate Arrays" (FPGA)" technology
Development partly (but not only) driven by particle physics.

Hardware Technology Trends ...

(Bill Haynes)



Flash-MP3

2004 : 1 GB
2005 : 4 GB

2007 : 16 GB
2015 : 128 GB

	1995	1998	2000	2002	2004	2008	2015	2025
Minimum feature µm	0.35	0.25	0.18	0.13	0.10	0.07	*10 nm*	*< 1 nm*
DRAM bits/chip	64M	256M	1G	4G	16G	64G		
Logic transistors/cm2 M	4	7	13	25	50	90	*practical*	*spintronic*
SRAM cache bits/cm2 M	2	6	20	50	100	300	*limit ???*	*???*
Chip frequency MHz	150	225	300	400	500	700		
DRAM chip size mm2	190	280	420	640	960	1400		
Microproc. chip size mm2	250	300	360	430	520	620		
Max. Heatsink Power W	15	20	30	40	60	80		
Max. Battery Power W	2.5	2.5	3.0	3.5	4.0	4.5		

Slide shown at an H1 meeting Circa 1995(!)

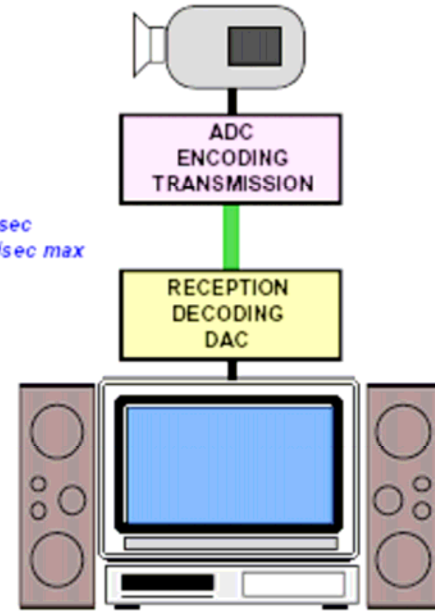
HDTV : High-Definition Television

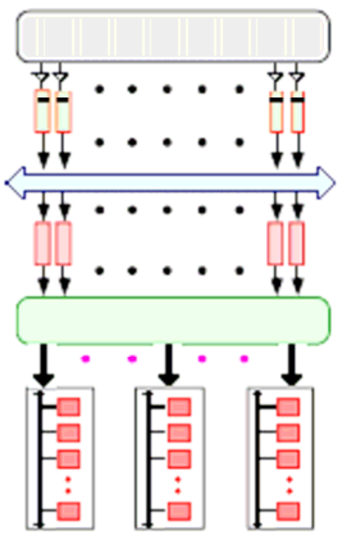
(Bill Haynes)

HDTV REQUIREMENTS

- DIGITAL (144 MHz, 10 bits)
- DIGITAL SIGNAL PROCESSING
- PIPELINING & MEMORY DELAYS
- DATA FILTERING & COMPRESSION
- HIGH SPEED SIGNAL TRANSMISSION
  1.3 GBit/s OPTICAL LINKS
- DATA DRIVEN ARCHITECTURES
- HIGH RATE MASS STORAGE RECORDING

Human Eye DAQ ≈ 1 GByte/sec
Human Speech Output ≈ 100 bits/sec max





PP REQUIREMENTS

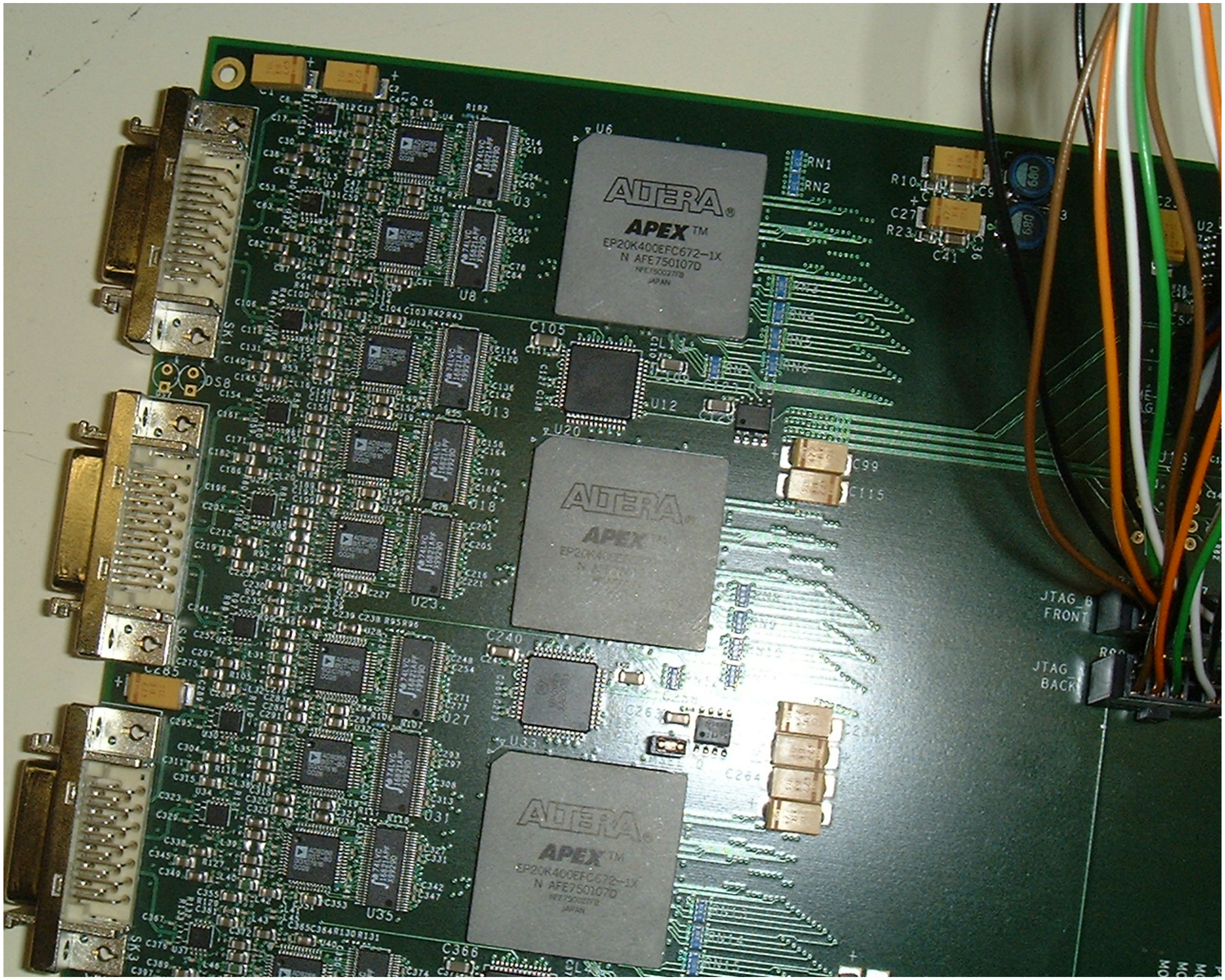
- DIGITAL (> 100 MHz, 8 - 12 bits)
- DIGITAL SIGNAL PROCESSING
- PIPELINING & MEMORY DELAYS
- DATA FILTERING & COMPRESSION
- HIGH SPEED DATA THROUGHPUT
- DATA DRIVEN ARCHITECTURES
- HIGH RATE MASS STORAGE RECORDING

ONE HDTV CHAIN
≈
ONE PP CHANNEL

With sophisticated and specific Program Selection !

cf 'Data Sink'

H1 Fast Track Trigger First Level



Front end Module of H1 Fast Track Trigger …. operates with a mixture of hard-wired electronics and programmable chips (FPGAs).

Trigger Performance

- Efficiency monitoring
  - Key point: REDUNDANCY

Need >1 trigger to be sensitive to the same physics:

Combination removes sensitivity to noise in a single trigger

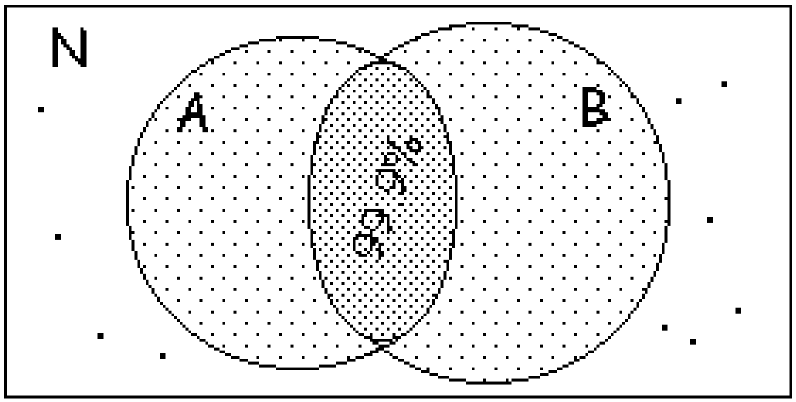
Use one trigger to evaluate efficiency of the other

- Ex: Electrons Efficiency

A = TPC (tracking)

B = Calorimeter

$$\varepsilon_A = \frac{N(A \cap B)}{N(B)}$$



Typically, events are only triggered if more than 1 subdetector sees them. This hugely suppressed `random' background such as noise in the detector or electronics of a single detector

Central Decision Logic

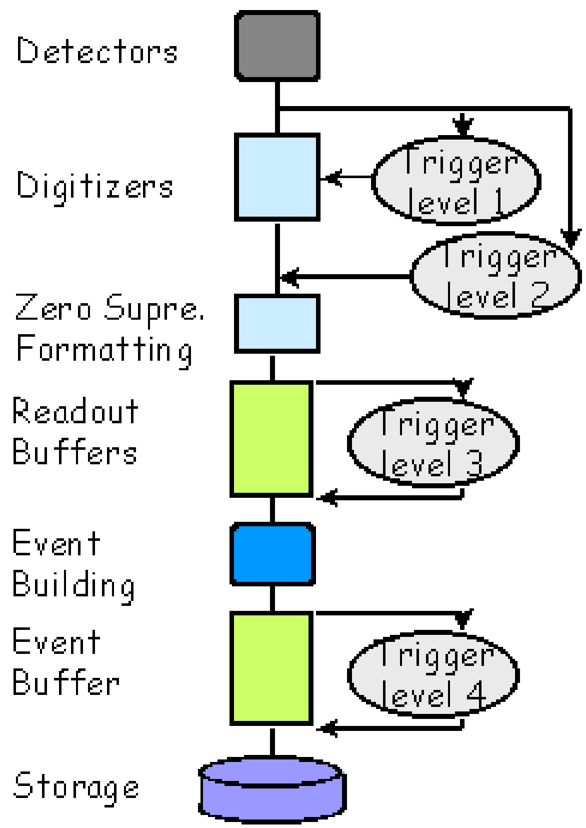
- Look Up Tables
  - Use N Boolean informations to make a single decision: YES / NO
  - Use a RAM of 2^N bits
  - Example: N=3

RAM Address

EM	μ	TR	RAM	
0	0	0		No track, no EM
0	0	1		Track, no μ
0	1	0		μ, track inefficient
0	1	1		μ, track
1	0	0		EM, no track
1	0	1		EM, track, no μ
1	1	0		EM, μ, track ineffic.
1	1	1		EM, μ, track

- To Trigger On:
  - "Single Photons"
  - ➡ 0,0,0,0,1,0,0,0
  - "At least one μ"
  - ➡ 0,0,1,1,0,0,1,1

Trigger Levels in DELPHI (LEP)



- **Level-1 (3 μs) (hardware proc.)**
  - **Single detector Information:**
    - Energy: calorimeter (EM and Had.)
    - Tracks: counting, coincidences
    - Muons: Had. Cal. and Muon Chambers
    - Luminosity: analog sums

45 kHz

- **Level-2 (36 μs) (hardware proc.)**
  - **Detector Coincidences:**
    - Accept only tracks coming from the IP.
    - Beam-gas rejection. Uses the TPC

100 Hz

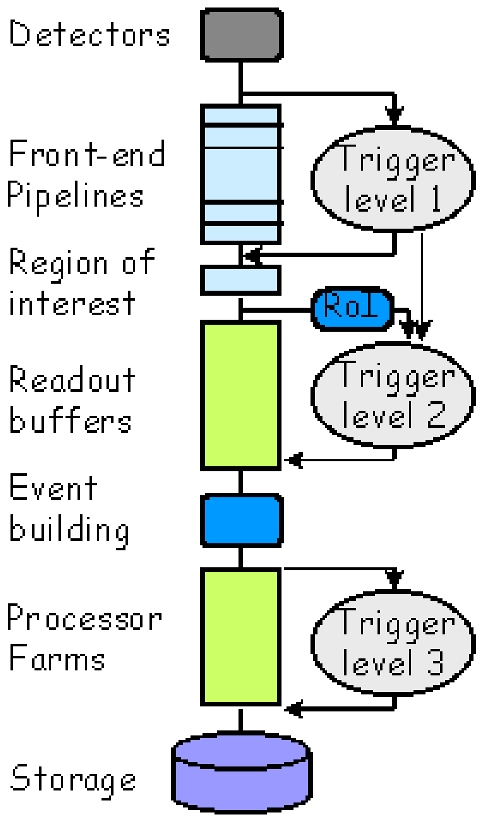
- **Level-3 (~ms) (In parallel for each sub-detector: OS9 processors)**
  - Verifies L2 triggers with digitized data

10 Hz

- **Level-4 (~ms) (a small farm: 3 alpha CPU)**
  - Reconstructs the event using all data
  - Rejects Empty Events
  - Tagging of interesting physics channels

8 Hz

Trigger Levels in ATLAS (LHC)



- **Level-1 (3.5 μs) (custom processors)**
  - Energy clusters in calorimeters
  - Muon trigger: tracking coincidence matrix.
- **Level-2 (100 μs) (specialized processors)**
  - Few Regions Of Interest relevant to trigger decisions
  - Selected information (ROI) by routers and switches
  - Feature extractors (DSP or specialized)
  - Staged local and global processors
- **Level-3 (~ms) (commercial processors)**
  - Reconstructs the event using all data
  - Selection of interesting physics channels

40 MHz

1 kHz

100 Hz