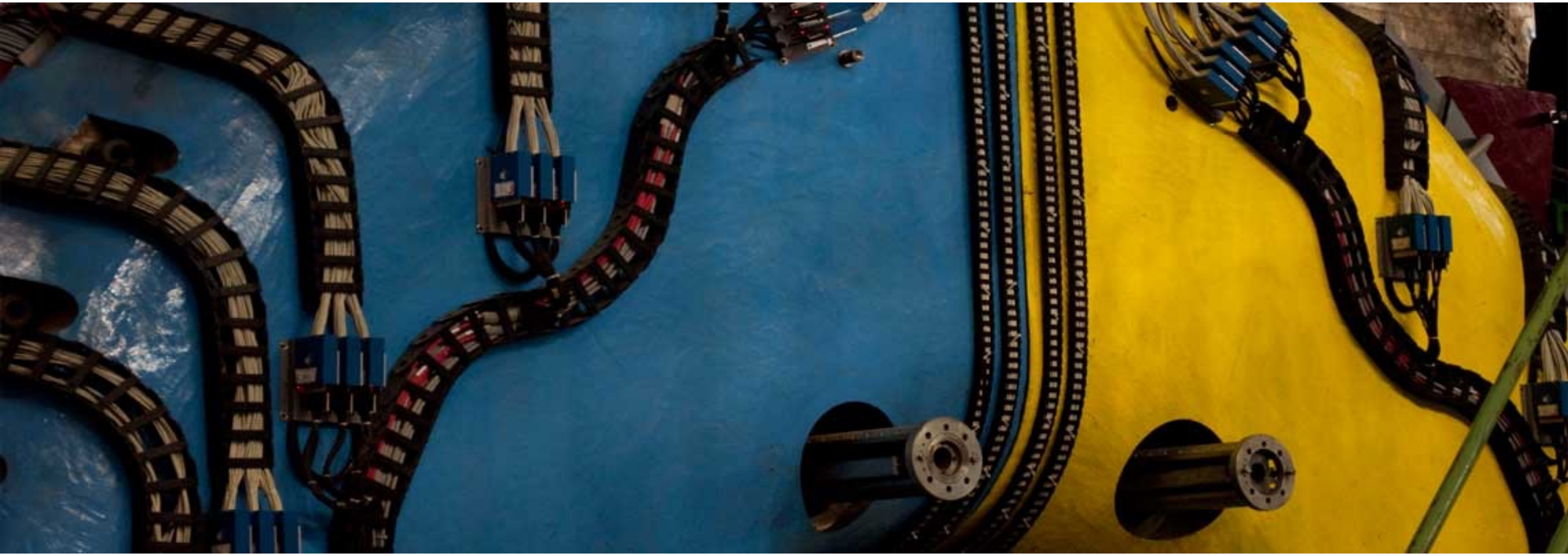
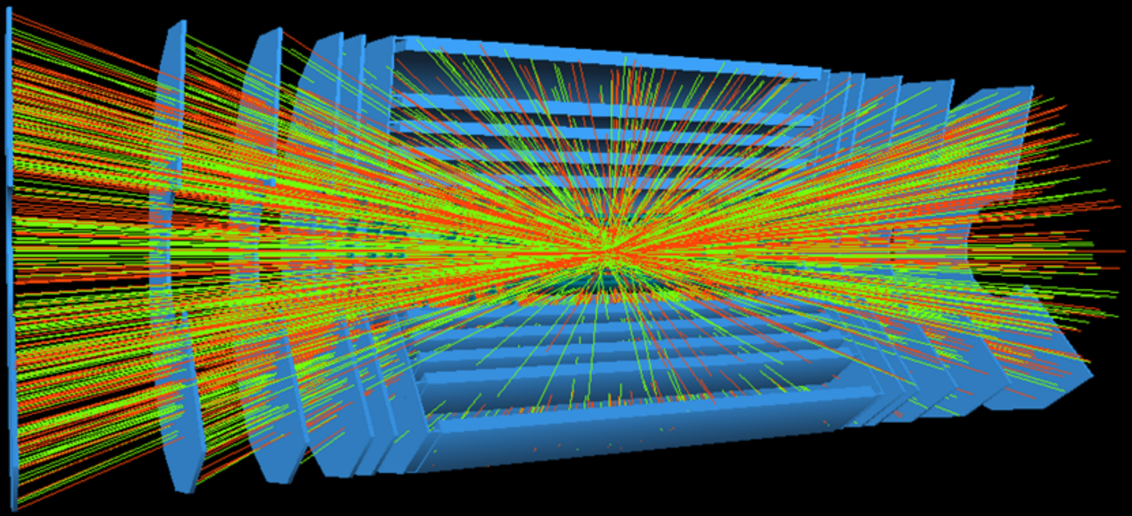


# Introduction to trigger concepts

**F.Pastore (Royal Holloway Univ. of London)**

francesca.pastore@cern.ch

# The data deluge



- In many systems, like particle physics or astronomy experiments, to store all the possibly relevant data provided by the sensors is UNREALISTIC and often becomes also UNDESIRABLE
- Three approaches are possible:
  - Reduced amount of data (packing and/or filtering) → ***Trigger!***
  - Faster data transmission and processing
  - Both!

# The trigger concept

Digital signal saying **YES** or **NO**

- It's like deciding to take a very good photo during your holidays:
  - **click the button** to open the bolt and let the sensors operate
    - take the photo only when you think the **subjects** are ready
    - **focus** the image
    - only if there is enough **light** for your lenses (or add a flash light)
    - only if your hand is not **shaking**

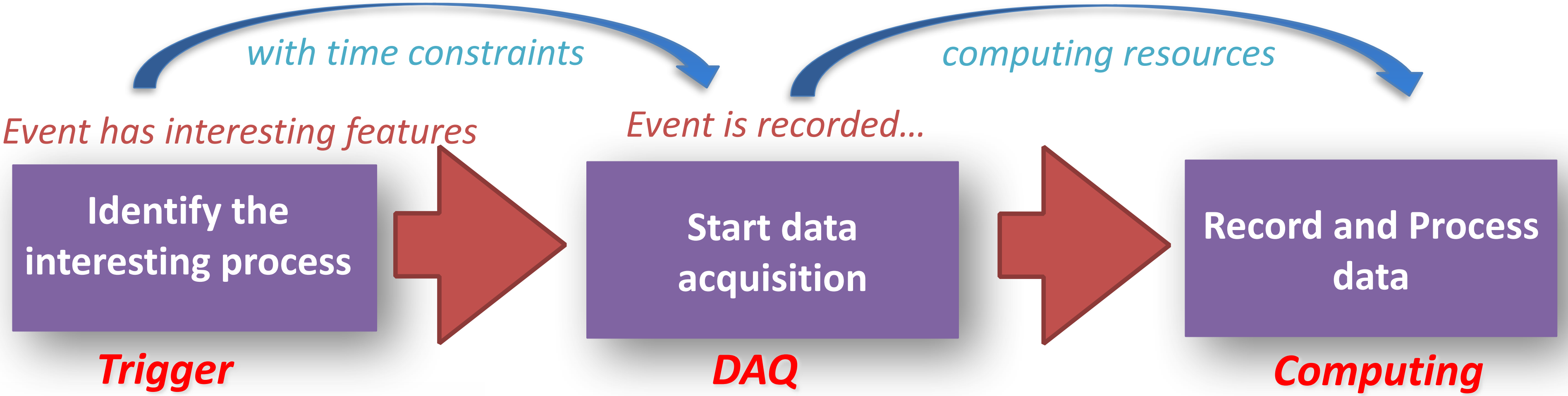
→ The trigger starts the photo process

→ First identify the interesting event

→ Ensure the sensitivity to parameters

→ Ensure a good synchronisation

# Trigger concept in HEP



with time constraints

computing resources

Event has interesting features

Event is recorded…

Identify the interesting process

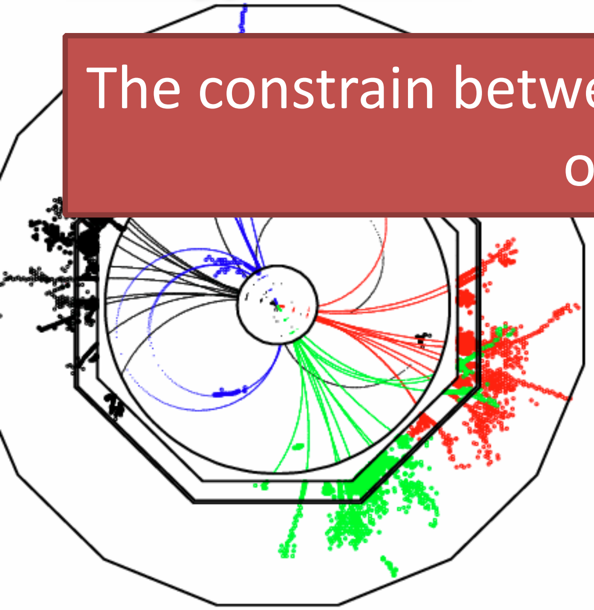
Start data acquisition

Record and Process data

**Trigger**

**DAQ**

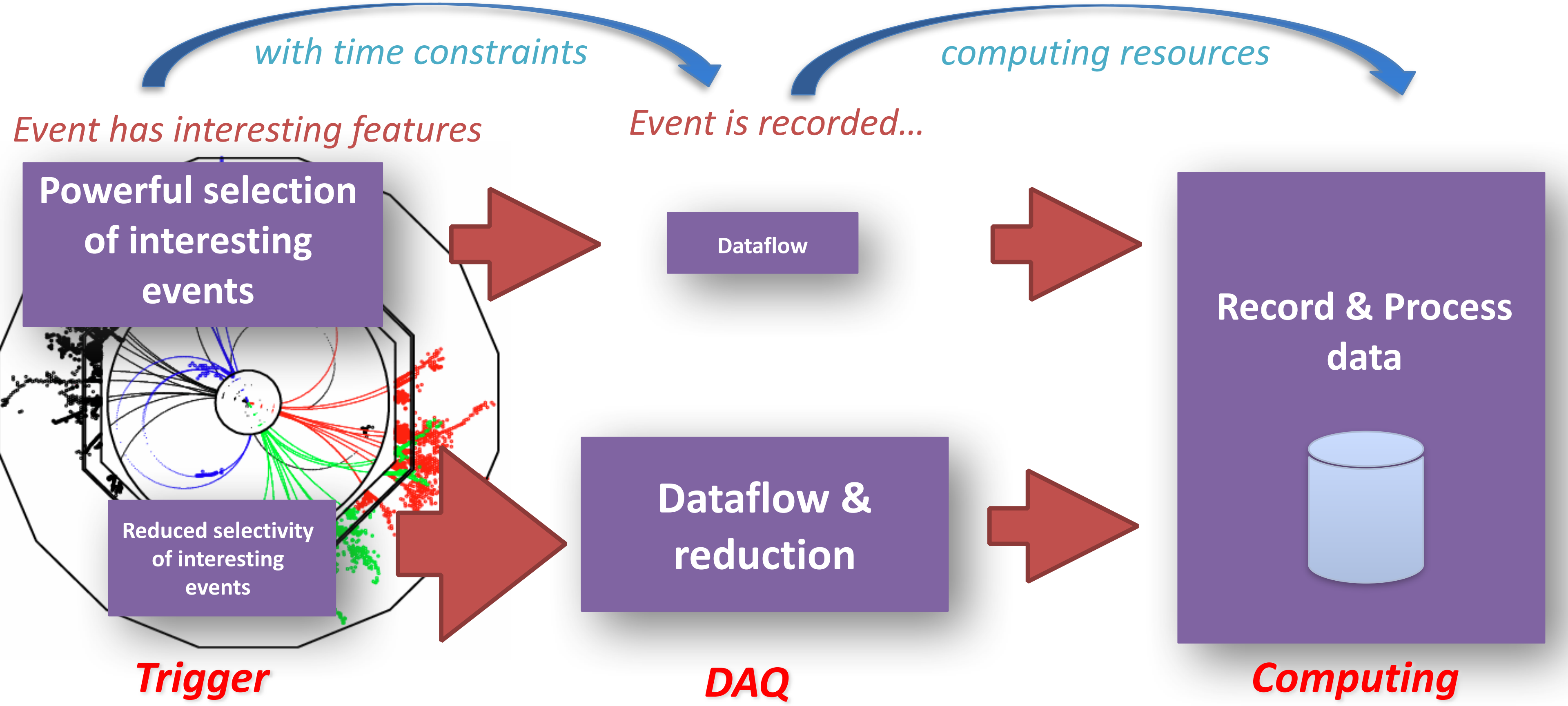
**Computing**



The constrain between trigger and DAQ rate is the storage and the offline computing capabilities

- What is “interesting”?
  - Define what is signal and what is background
- Which is the balance between Trigger and DAQ resources?
  - Define the maximum allowed rate
- How fast the selection must be?
  - Define the maximum allowed processing time

# Balance between trigger and DAQ



*with time constraints*

*computing resources*

*Event has interesting features*

*Event is recorded…*

**Powerful selection of interesting events**

Dataflow

**Record & Process data**

Reduced selectivity of interesting events

**Dataflow & reduction**

***Trigger***

***DAQ***

***Computing***

- If the trigger decision is highly selective, one can reduce the size of the dataflow
- If the selectivity of the trigger is not enough, due to the large irreducible background, a large data flow is needed

# 1: Which is the expected trigger rate?

***The expected event rate is derived from the physics process (x-section) and the detector sensitivity***

***For a collider experiment: x Luminosity***

$$R = \sigma_{in} \times L$$

## LHC: the trigger challenge!

Total non-diffractive p-p cross section is **70 mb**

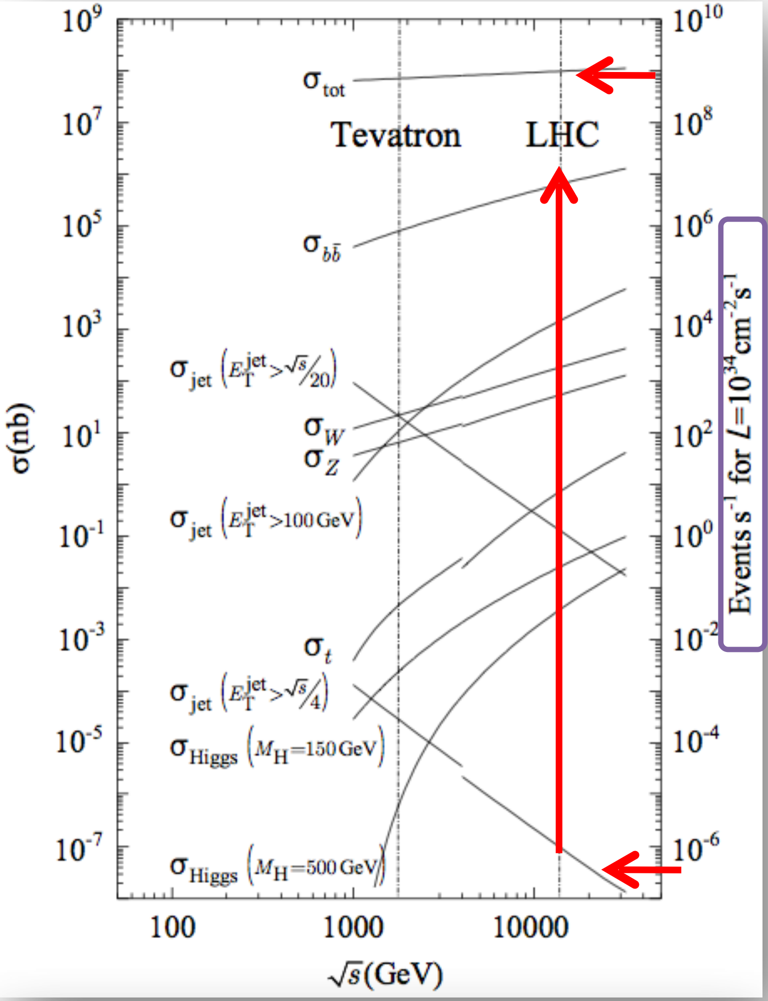
**Total trigger rate is ~ GHz!!!**

Huge range of cross-sections and production rates at design:

| | |
|---|---|
| Beauty (0.7 mb) | – 1000 Hz |
| W/Z (200/60 nb) | – 100 Hz |
| Top (0.8 nb) | – 10 Hz |
| Higgs - 125 GeV (30 pb) | – 0.1 Hz |

$$\frac{\sigma_{tot}}{\sigma_{H(500\,\mathrm{GeV})}} \approx \frac{100\,mb}{1\,pb} \approx 10^{11}$$

- The final rate is often dominated by not interesting physics
- The trigger accepts events with features **similar** to the signal



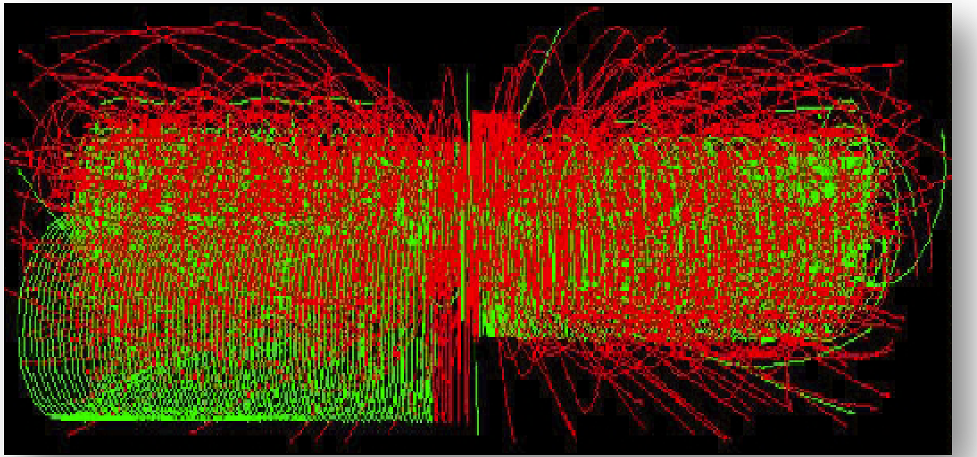
In hadronic colliders, background discrimination is crucial

# 2: which is an easy selection?

- *Looking for discriminating features within widely extended systems*
- *With limited amount of time*
- *With limited resources*

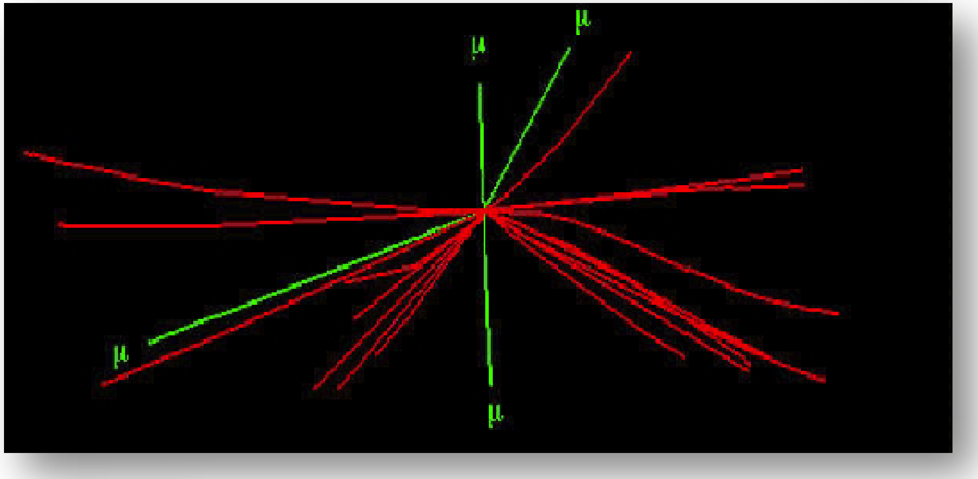
# Which is a good trigger for the Higgs Boson @LHC?

All tracks



Only high-pT tracks

+30 MinBias



Higgs -> 4μ

## @LHC: proton-proton collider

signal events **Higgs → 4μ** as it appears at the LHC (concurrently with soft collisions from other p-p interactions)

The trigger selection based on **high transverse momentum muons** (at least one)

REJECTED

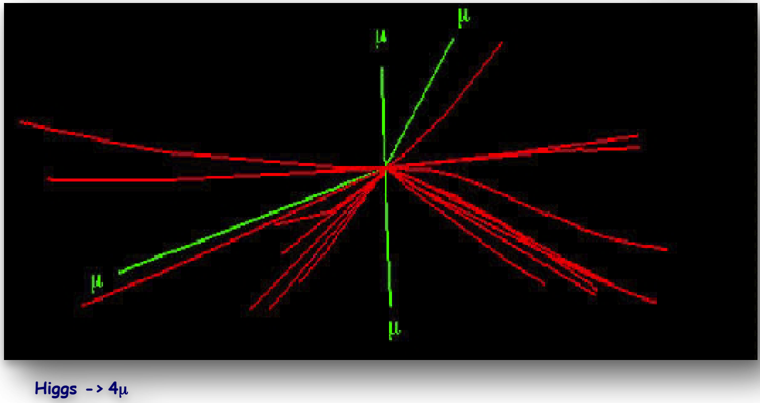
ACCEPTED

***Which is the best filter?***

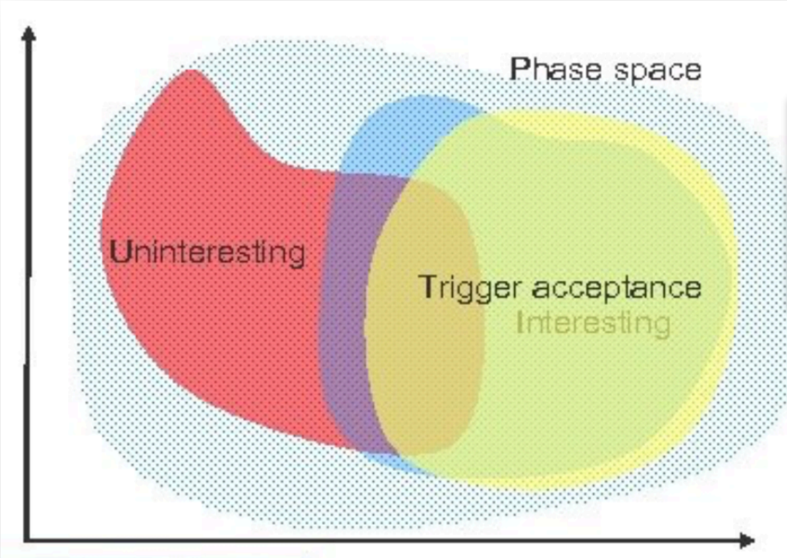
# Trigger requirements

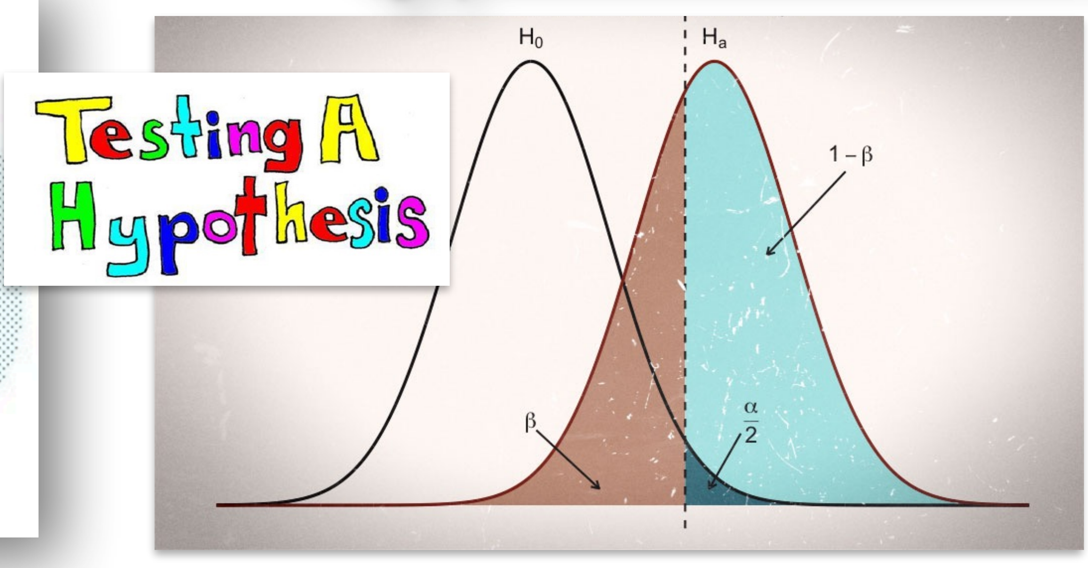
# Trigger parameters to easily distinguish

- Remember the Higgs discovery @LHC:
  - high $p_T$ muons are interesting (**signal**)
  - low $p_T$ muons are not interesting (**background**)
- Which $p_T$ threshold then?
  - background is unavoidable!



Higgs -> 4μ





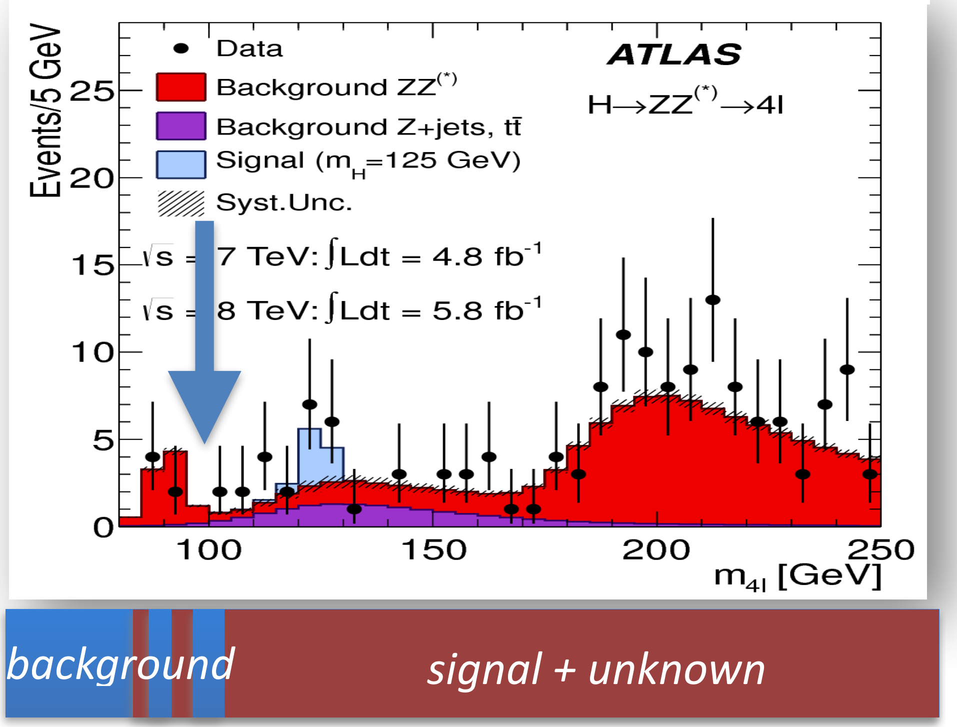
compromise strongly depends on the source of physics events: cosmic rays? lepton colliders? hadron colliders?

# Requirement n.1: *high signal efficiency*

$$\varepsilon_{\text{trigger}} = N_{\text{signal (accepted)}} / N_{\text{signal (expected)}}$$

drives the design of the experiment, the Trigger and DAQ system

*4-leptons invariant mass, selected for H→ZZ→4l*



*background*

*signal + unknown*

- **Lepton colliders (precision machines)**
  - all is interesting (no physics background)
  - efficiency close to 100%
  - 99.9% accepted events, 0.1% rejected
- **Hadron colliders (discovery machines)**
  - large physics background, rejection is critical
  - good efficiency > 50%
  - 99.9% rejected events, 0,1% accepted

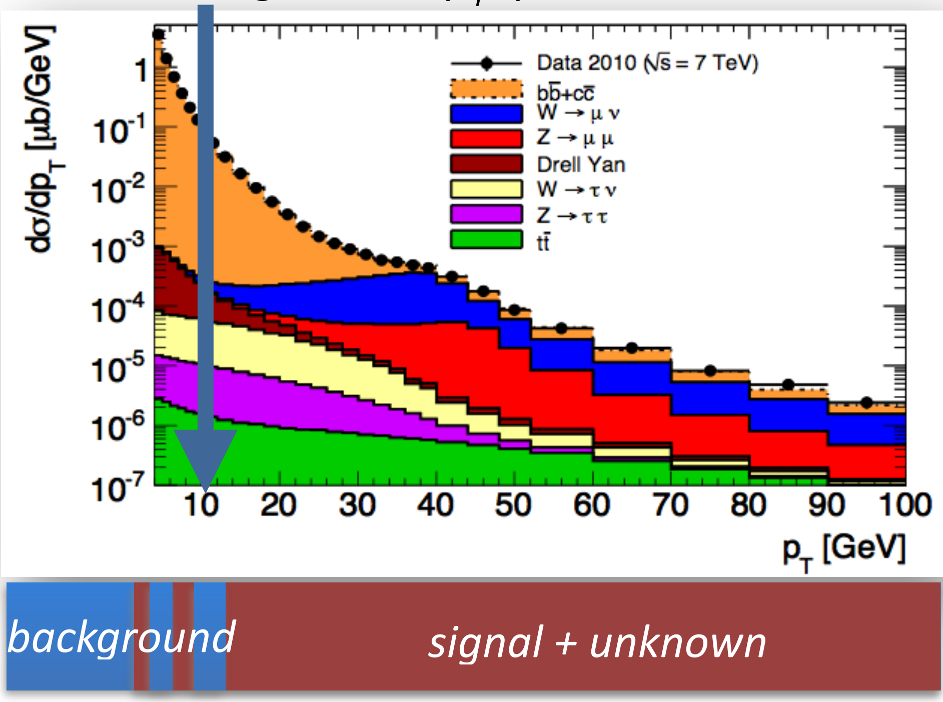
# Requirement 2: *good background rejection*

$$\mathrm{Rej}_{bkg} = 1 - N_{bad(accepted)}/N_{bad\ (produced/expected)}$$

- **Lepton colliders (precision machines)**
  - good background rejections ~10
- **Hadron colliders (discovery machines)**
  - good background rejections > ~$10^6$

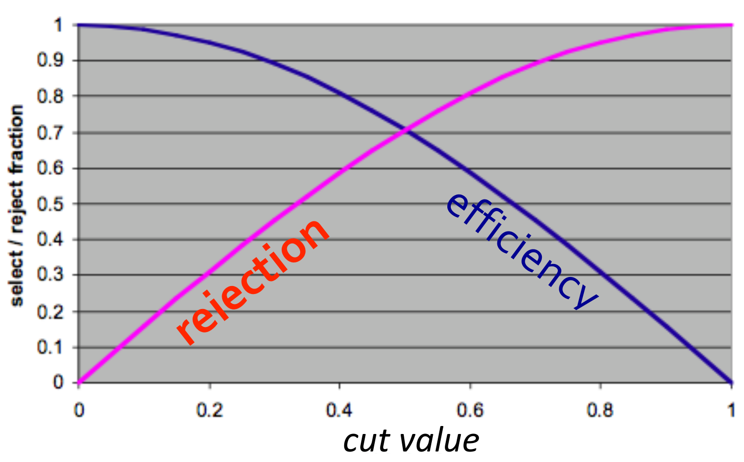
- **Rate control may be critical to run the full experiment (in particular for hadron colliders)**
  - Need solid understanding of background shapes during the design phase
    - Monte Carlo simulation of all physics, detector noise and machine backgrounds (not easy!)
  - Nevertheless, backgrounds are often known with great uncertainties
    - make your trigger **flexible and robust!**

*Inclusive single muon $p_T$ spectrum @LHC*

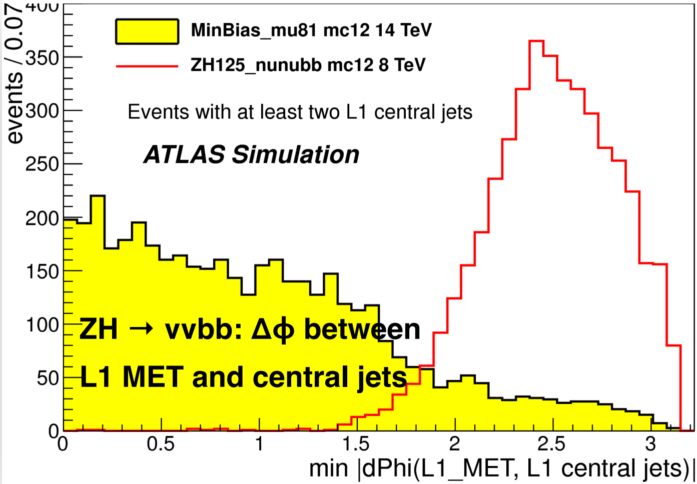


# ...with compromises?

- If any of the two requirements cannot be realised**, refine your selection**!
  - New parameters => add new detectors
  - More complex selections => new trigger architecture (buy more processors, faster algorithms)



*New topological cuts at L1 @ATLAS*



- Whatever criteria you choose, discarded events are lost for ever!
- So, check that your trigger system:
  - Is not biasing your measurement
    - Discovery experiments: use inclusive selections
    - Precision experiments: use well known selections
  - Is reliable
    - Do you trust your trigger? If not, add control samples!

and always monitor your trigger!

# Trigger efficiency is a parameter of your measurement

$$BR(Signal) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

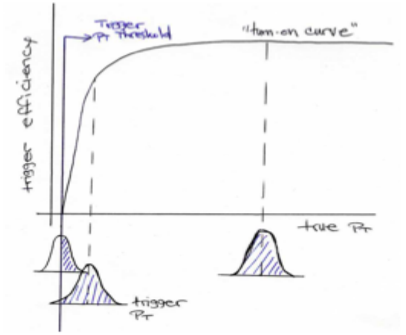
$$\alpha\cdot \varepsilon_{\mathrm{total}} = \alpha\cdot \varepsilon_{\mathrm{Tracking}} \cdot \varepsilon_{\mathrm{Reco}} \cdot \varepsilon_{\mathrm{L1\text{-}Trig}} \cdot \varepsilon_{\mathrm{L2\text{-}Trig}} \cdot \varepsilon_{\mathrm{L3\text{-}Trig}} \cdot \varepsilon_{\mathrm{vertex}} \cdot \varepsilon_{\mathrm{analysis}}$$

Trigger efficiency must be **precisely known**, since it enters in the calculation of the cross-sections

For some precise measurements, the crucial performance parameter is not the efficiency itself, but the **systematic** error on determining it

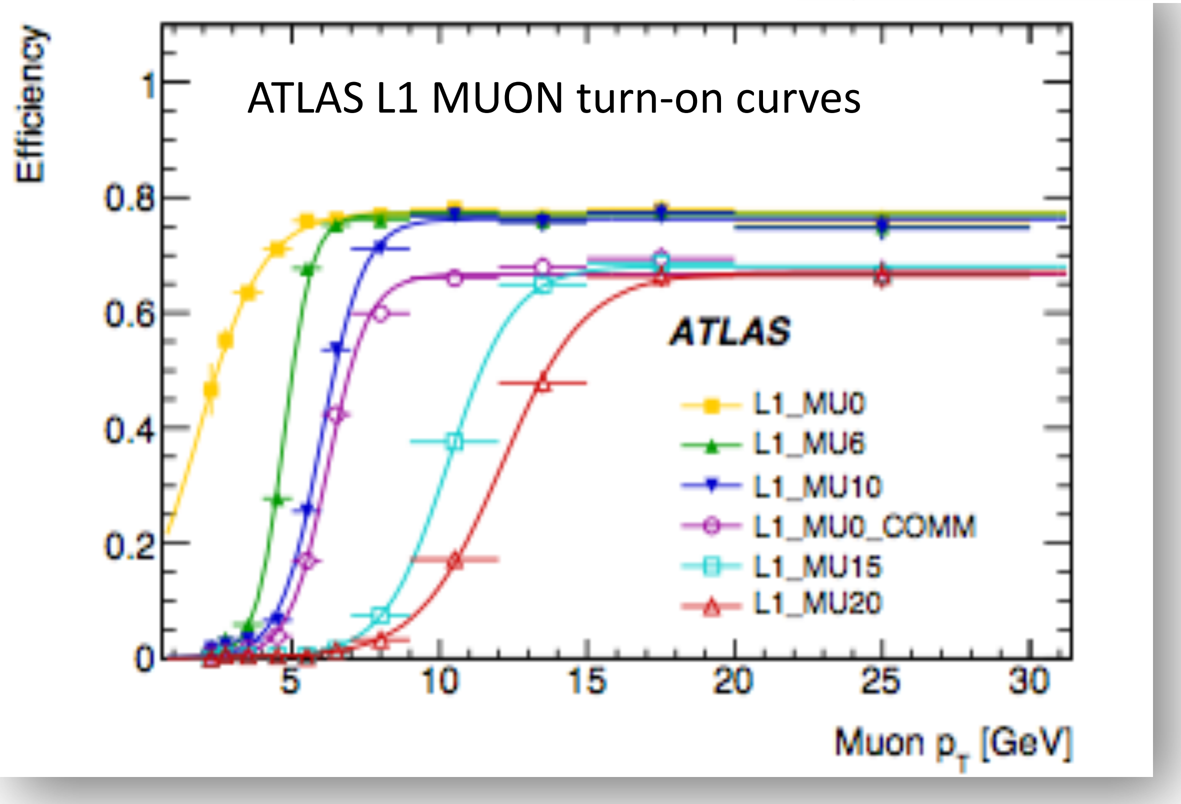
# Trigger efficiency measurement

The threshold is not exactly applied as a step function.
Better as an Error function, usually called **trigger turn-on**

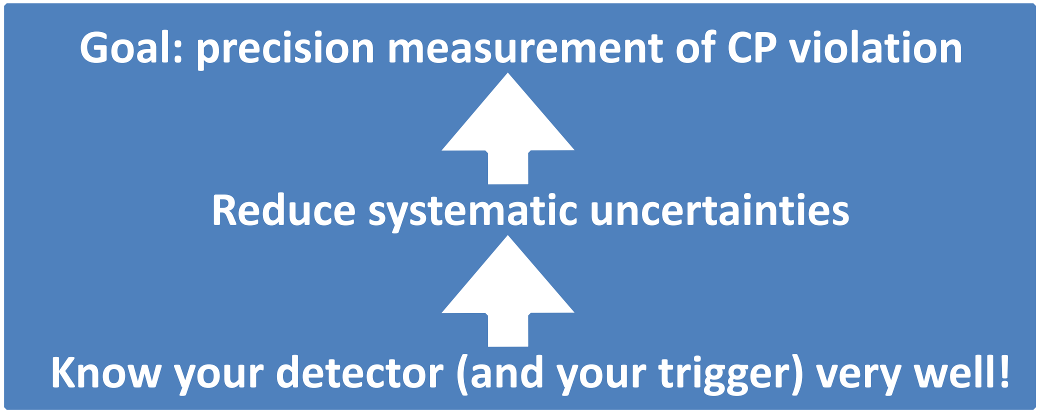


- The capability of controlling the rate depends on the **resolution** on the trigger parameter

- Measure efficiency on data after reconstruction
- Crucial is the **step region**, in which efficiency changes very quickly and contamination from background can be important (often abundant!)
  - If **quick**, better background suppression
  - If **slow**, can be better extrapolated and systematic error can be reduced


ATLAS L1 MUON turn-on curves

# Trigger for precision measurements: BaBar



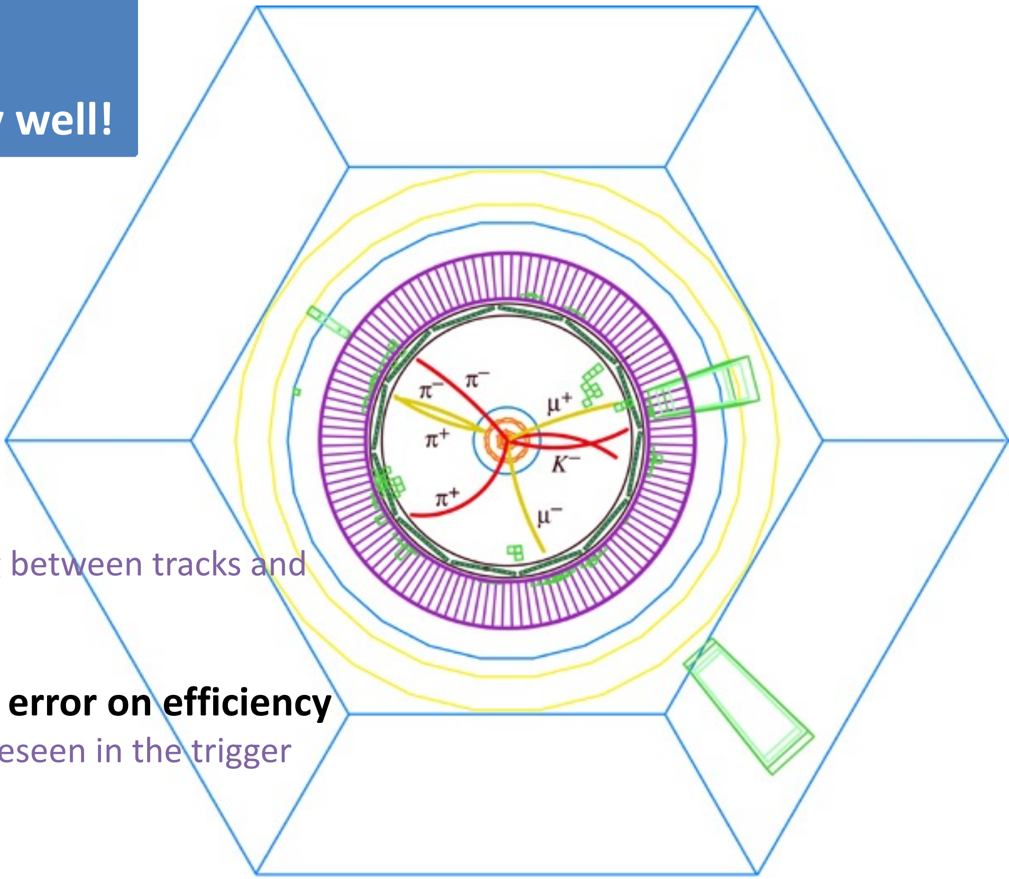
Goal: precision measurement of CP violation

Reduce systematic uncertainties

Know your detector (and your trigger) very well!

**Golden event in the BaBar Detector**
**e+e- collision producing a B and an anti-B**

🟨 *Golden B (for CP violation)*
🟥 *Tagging B*

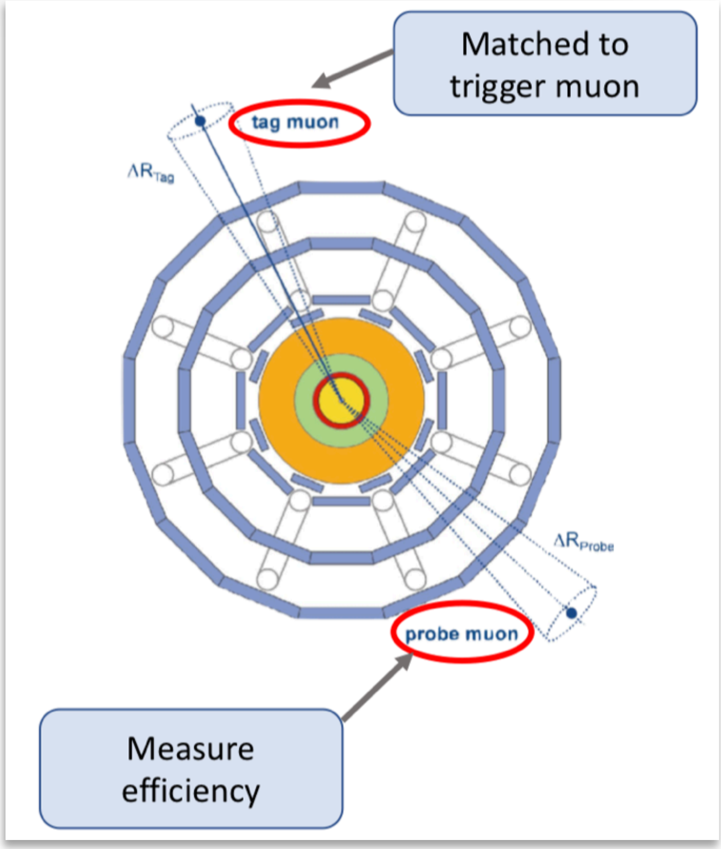


- **Multitude of trigger selections:**
  - **Charged tracks** in the drift chamber
  - **EM calorimeter clusters** with different $E_T$ cuts
  - Particle identification capability
- **Exclusive selections based on event topology**
  - **Number of objects**, angular separation, matching between tracks and clusters
- **Study both signal and background to minimise error on efficiency**
  - The selection of background samples must be foreseen in the trigger design

# Methods to measure trigger efficiency

$$\text{Efficiency} = \frac{\text{number of events that passed the selection}}{\text{number of events without that selection}}$$

- **Experimental technique called "Tag-and-probe"**: trigger on one particle (tag), measure how often another (probe) passes trigger
  - exploit a well-known physics process (like Z-boson decay into leptons) to select a clean sample
  - applicable on specific signals, usually with leptons
- **Boot-strap**: use sample triggered by looser (prescaled) trigger to measure efficiency of higher threshold trigger
- **Orthogonal trigger**: use sample triggered by one trigger (e.g. muon trigger) to measure efficiency of a different, independent trigger (e.g. jet trigger)
- **Simulation/emulation**: Monte Carlo simulation suffer from reduced knowledge of background, so used
  - to study acceptance on defined physics processes
  - to validate online selections

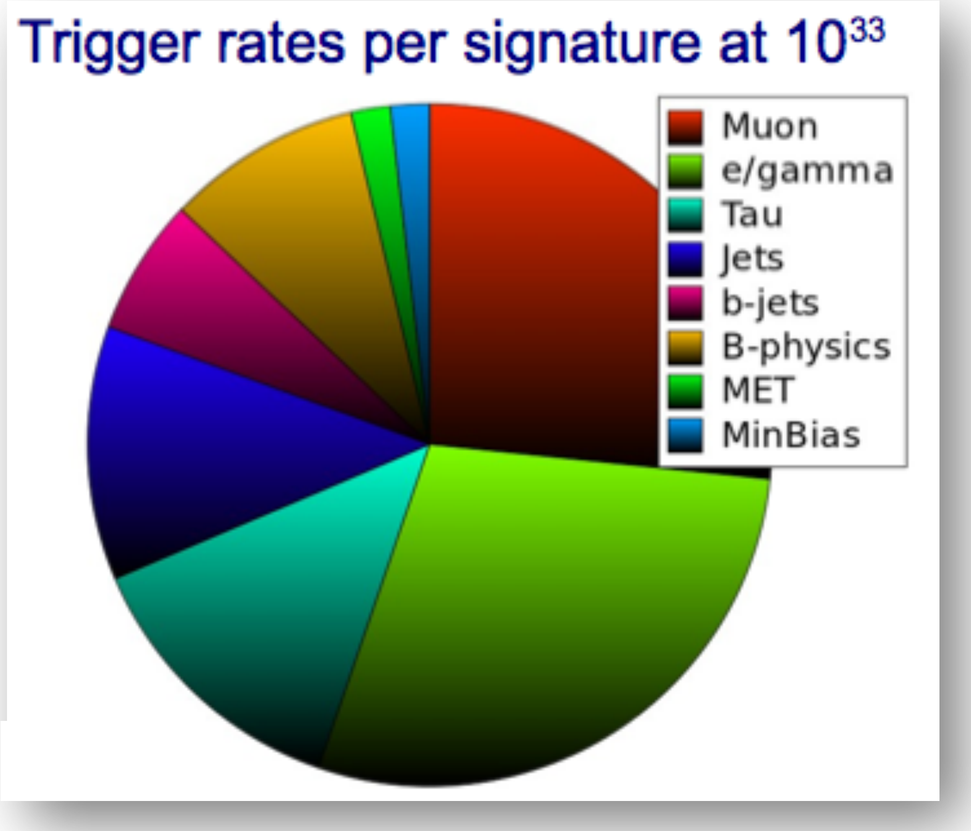


Matched to trigger muon

Measure efficiency

# Trigger strategy @ colliders: ATLAS menu

ATLAS



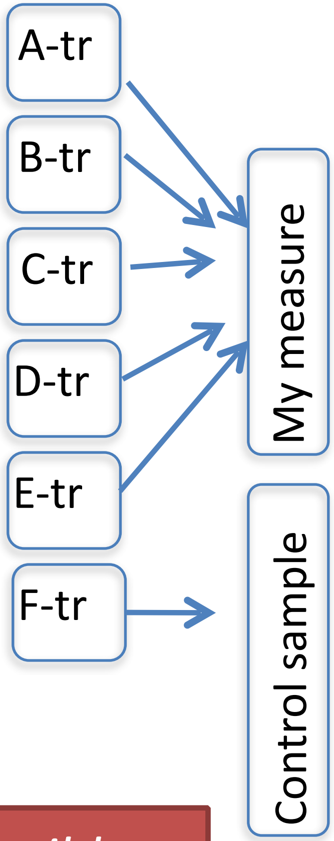
- Inclusive triggers to collect the **signal samples**
  - Single high-$p_T$
    - e/μ/γ ($p_T$>20 GeV)
    - jets ($p_T$>100 GeV)
  - Multi-object events
    - e-e, e-μ, μ-μ, e-τ, e-γ, μ-γ, etc… to further reduce the rate
- **Back-up triggers** designed to spot problems, provide control samples (often pre-scaled)
  - Jets ($p_T$>8, 20, 50, 70 GeV)
  - Inclusive leptons ($p_T$ > 4, 8 GeV)
  - Lepton + jet

# How many trigger selections?

Different **independent** trigger selections allows good cross-calibration of the efficiencies: so besides your “physics” triggers, foresee additional **back-up triggers**

- Physics triggers
  - **Discovery experiments**: inclusive selections ensure wide open windows
  - **Precision experiments**: exclusive triggers for multiple measurements
- Calibration triggers
  - Detectors calibrations
  - Detectors and trigger efficiency measurements
  - Tagging efficiency
  - Energy scale measurements
- Background triggers
  - Instrumental and physics background
  - Better description of the background can be extrapolated from data than from Monte Carlo
  - Understand resolutions, including the under-threshold population
- Monitor triggers
  - To monitor the trigger itself (remember, lost events are lost for ever!)

Bulk of the selected events!

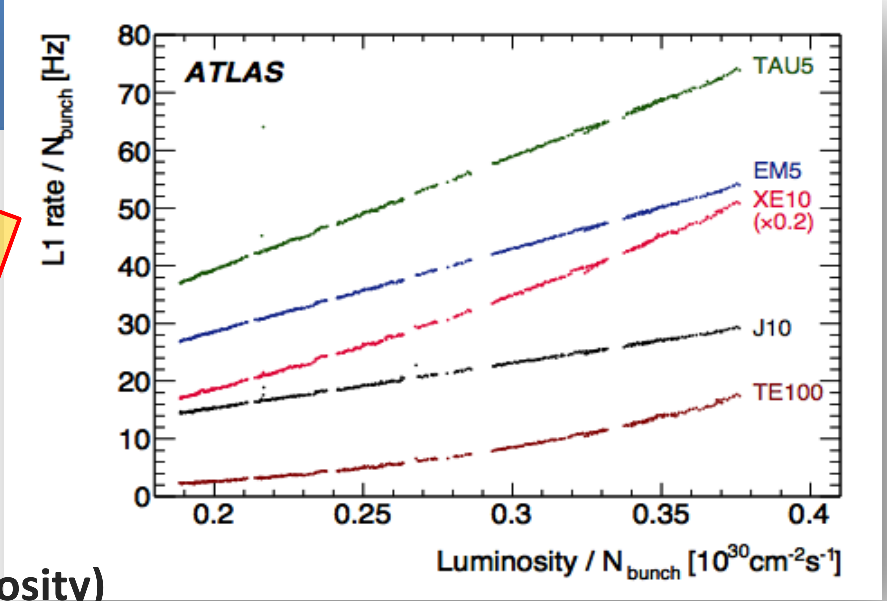


*Redundant and flexible trigger menus*

# Rate allocations of the trigger signatures

- ✓The target is the final allowed DAQ bandwidth
- ✓The rate allocation on each trigger based on
  - ✓Physics goals (plus calibration, monitoring samples)
  - ✓Required efficiency and background rejection
  - ✓Bandwidth consumed

*Rates scale linearly with luminosity, but linearity is smoothly broken due to pile-up*

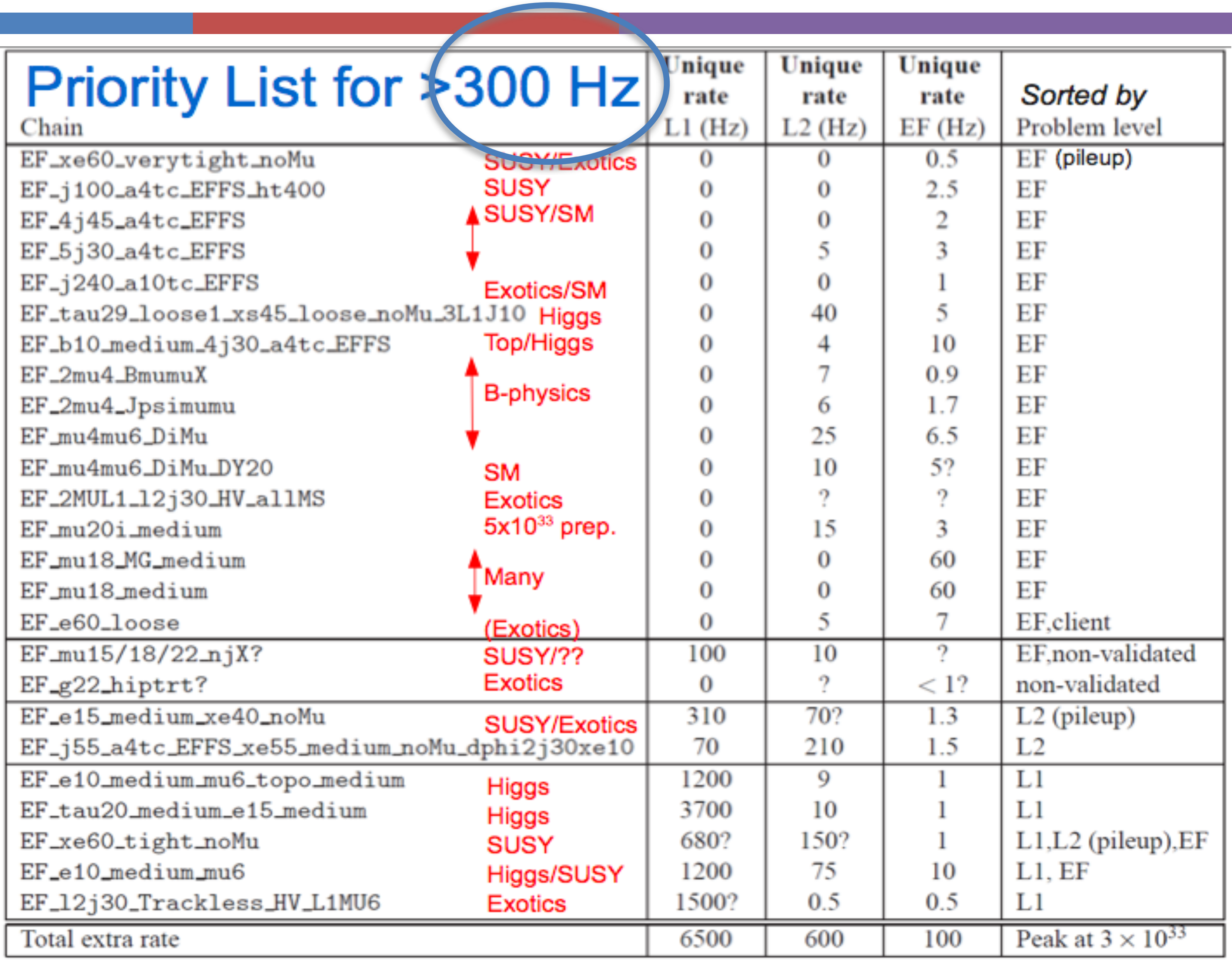


$$R_i = \mathrm{L} \int_{p_{T\_}\mathrm{inf}}^{p_{T\_}cutoff} \frac{d\sigma_i}{dp_T} \cdot \varepsilon(p_T)\, dp_T$$

Trigger Efficiency

**Need to extrapolate trigger rates (at given Luminosity)**

- For trigger design and commissioning: large samples of simulated data, including large cross-section backgrounds
  - 7 million of non-diffractive events used in the ATLAS trigger design
  - Large uncertainties due to detector response and background cross-sections: apply **safety factors**, then tuned with data
- During running (at colliders): but only some rates can be easily extrapolated to higher L



# Priority List for >300 Hz

| Chain | | Unique rate L1 (Hz) | Unique rate L2 (Hz) | Unique rate EF (Hz) | *Sorted by* Problem level |
|---|---|---|---|---|---|
| EF_xe60_verytight_noMu | SUSY/Exotics | 0 | 0 | 0.5 | EF (pileup) |
| EF_j100_a4tc_EFFS_ht400 | SUSY | 0 | 0 | 2.5 | EF |
| EF_4j45_a4tc_EFFS | ↕ SUSY/SM | 0 | 0 | 2 | EF |
| EF_5j30_a4tc_EFFS | | 0 | 5 | 3 | EF |
| EF_j240_a10tc_EFFS | Exotics/SM | 0 | 0 | 1 | EF |
| EF_tau29_loose1_xs45_loose_noMu_3L1J10 | Higgs | 0 | 40 | 5 | EF |
| EF_b10_medium_4j30_a4tc_EFFS | Top/Higgs | 0 | 4 | 10 | EF |
| EF_2mu4_BmumuX | ↕ B-physics | 0 | 7 | 0.9 | EF |
| EF_2mu4_Jpsimumu | | 0 | 6 | 1.7 | EF |
| EF_mu4mu6_DiMu | | 0 | 25 | 6.5 | EF |
| EF_mu4mu6_DiMu_DY20 | SM | 0 | 10 | 5? | EF |
| EF_2MUL1_l2j30_HV_allMS | Exotics | 0 | ? | ? | EF |
| EF_mu20i_medium | 5x10$^{33}$ prep. | 0 | 15 | 3 | EF |
| EF_mu18_MG_medium | ↕ Many | 0 | 0 | 60 | EF |
| EF_mu18_medium | | 0 | 0 | 60 | EF |
| EF_e60_loose | (Exotics) | 0 | 5 | 7 | EF,client |
| EF_mu15/18/22_njX? | SUSY/?? | 100 | 10 | ? | EF,non-validated |
| EF_g22_hiptrt? | Exotics | 0 | ? | < 1? | non-validated |
| EF_e15_medium_xe40_noMu | SUSY/Exotics | 310 | 70? | 1.3 | L2 (pileup) |
| EF_j55_a4tc_EFFS_xe55_medium_noMu_dphi2j30xe10 | | 70 | 210 | 1.5 | L2 |
| EF_e10_medium_mu6_topo_medium | Higgs | 1200 | 9 | 1 | L1 |
| EF_tau20_medium_e15_medium | Higgs | 3700 | 10 | 1 | L1 |
| EF_xe60_tight_noMu | SUSY | 680? | 150? | 1 | L1,L2 (pileup),EF |
| EF_e10_medium_mu6 | Higgs/SUSY | 1200 | 75 | 10 | L1, EF |
| EF_l2j30_Trackless_HV_L1MU6 | Exotics | 1500? | 0.5 | 0.5 | L1 |
| Total extra rate | | 6500 | 600 | 100 | Peak at 3 × 10$^{33}$ |

# Build up a trigger system

# Ensure good efficiency with…

Robustness! Win against the unexpected!

- **Flexibility: to cope changes in conditions and background**
  - Programmable thresholds, high granularity to maintain uniform performance, able to follow changes of luminosity, beam-size and vertex position, able to reach physics results also after 10 years of data taking

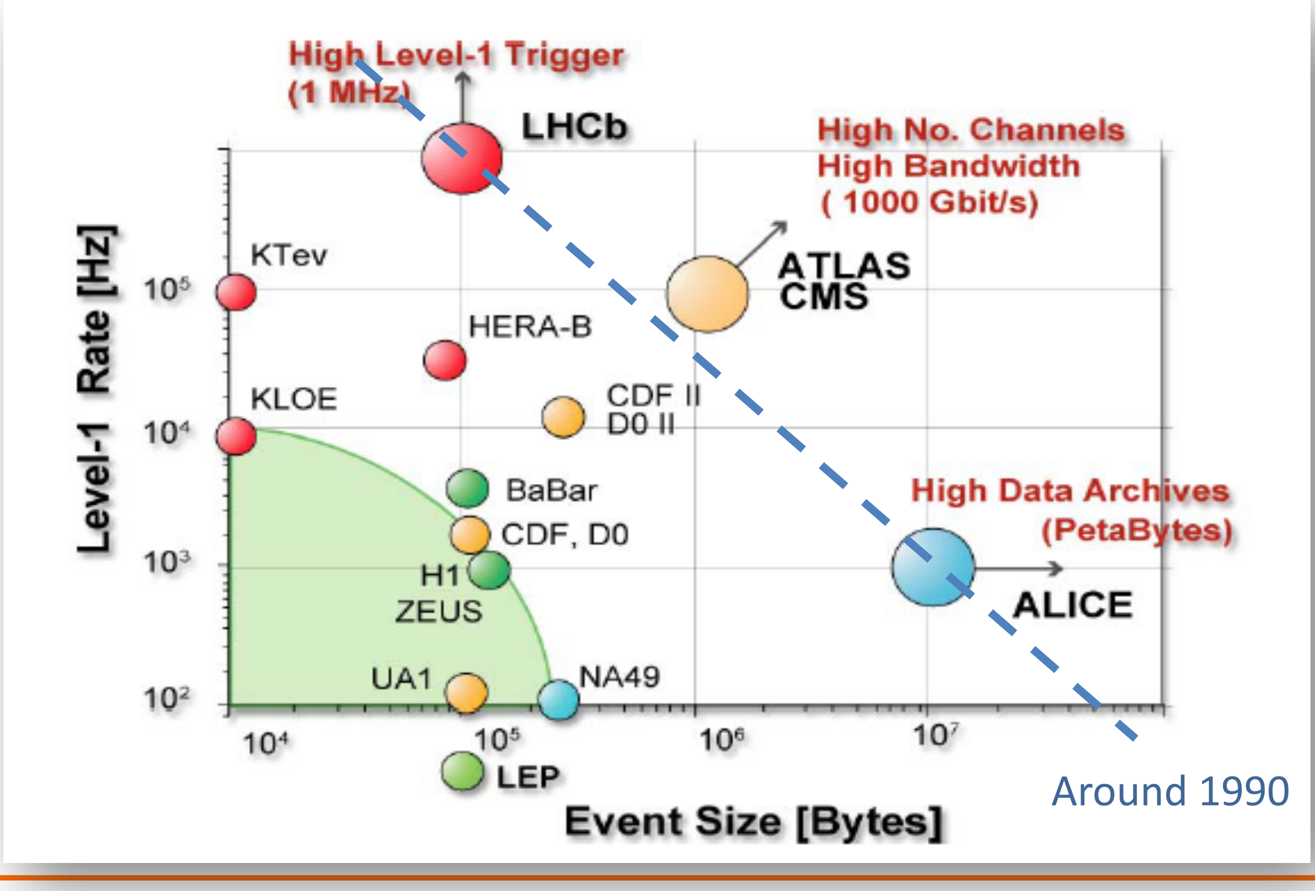
- **Redundancy: to make trigger rates independent from the detector and the collider performance**
  - Different backgrounds can change the event shape and dimension, so the result of your trigger selection

- **Selectivity**
  - Good granularity and good resolution of the parameters to ensure rejection of the unwanted background

# Trigger and data acquisition trends

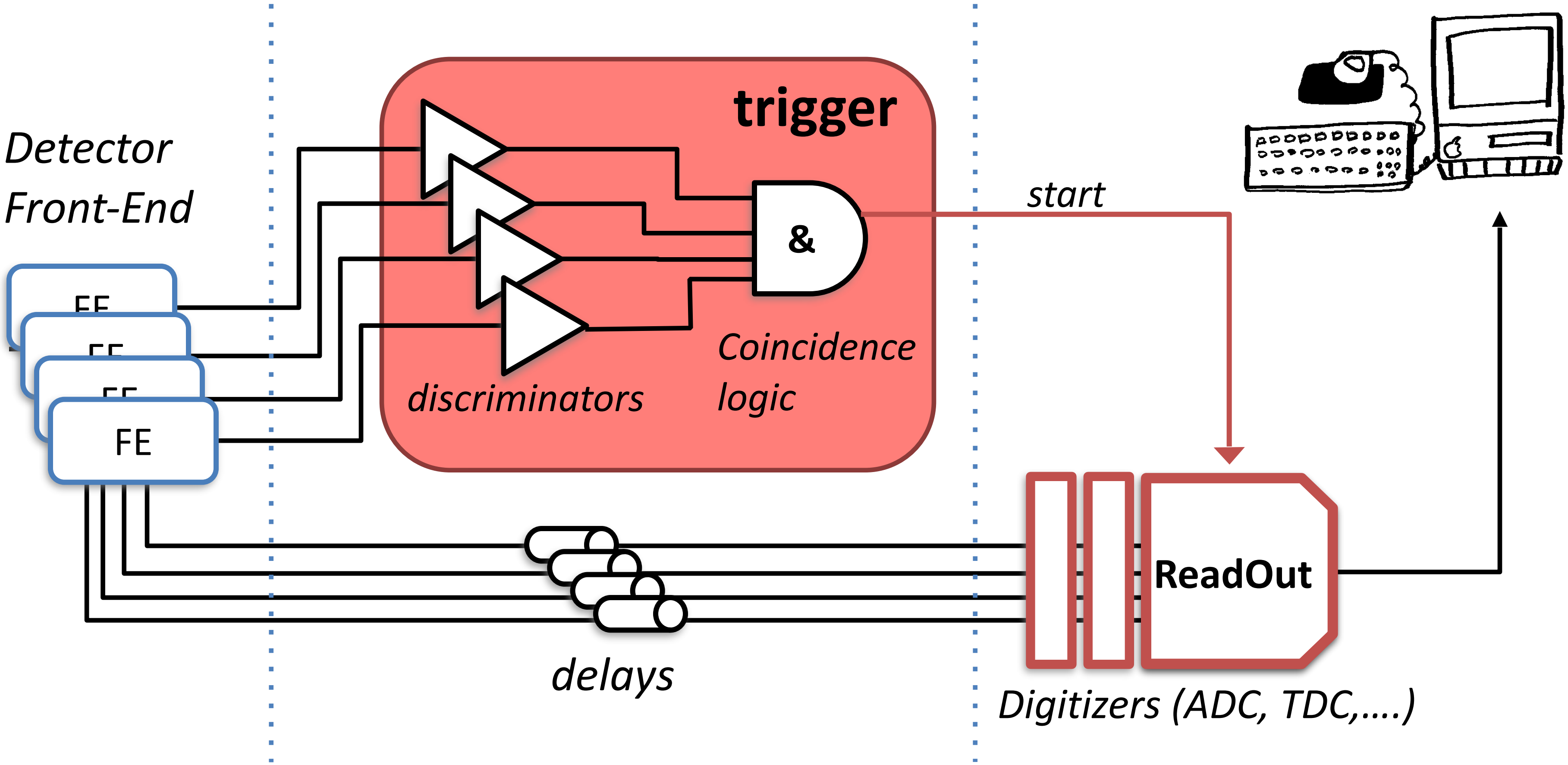
$$R_{DAQ} = R_T^{max} \times S_E$$

As the data volumes and rates increase, new architectures need to be developed



Around 1990

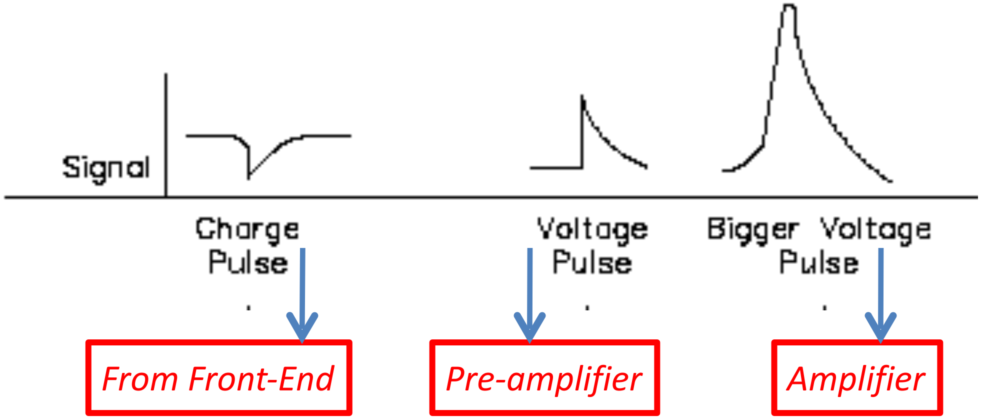
# A simple trigger system

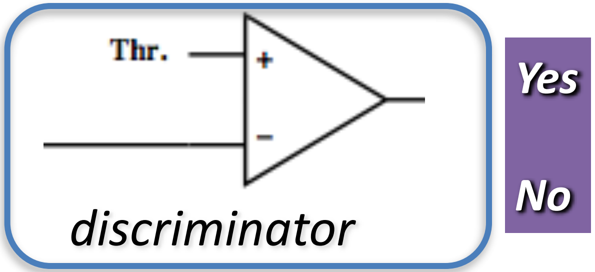


- Chose a sensor/detector specific for your selection
- Dedicate Front-End electronics also used for trigger signals

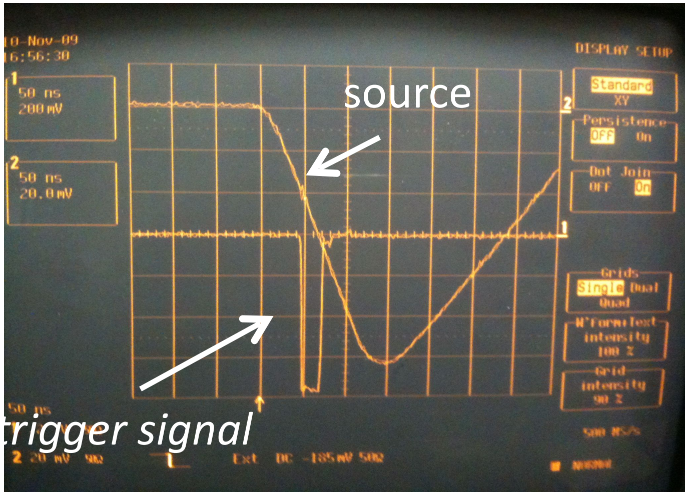
# The simplest trigger system

- **Source**: signals from the Front-End of the detectors
  - Binary trackers (pixels, strips)
  - Analog signals from trackers, time of light detectors, calorimeters,….



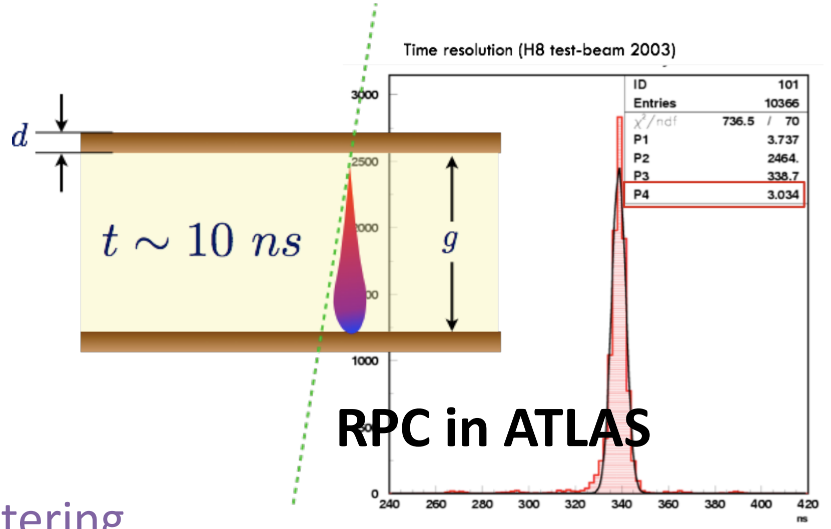


- The simplest trigger is: **apply a threshold**
  - Look at the signal
  - Apply a threshold as low as possible, since signals in HEP detectors have large amplitude variation
  - Compromise between hit efficiency and noise rate



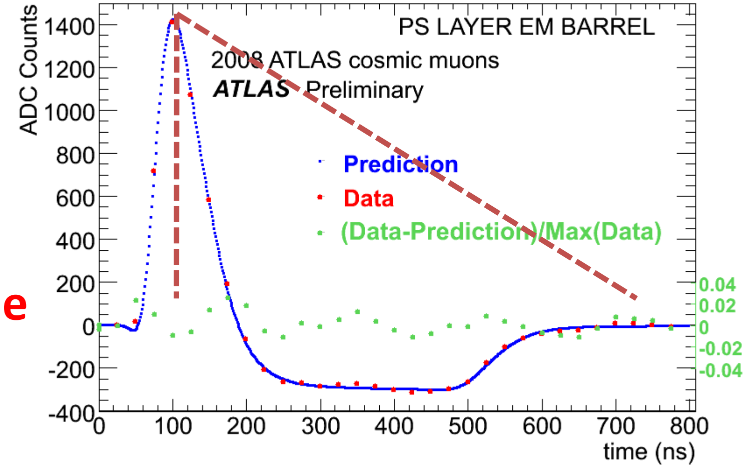
# Chose your trigger detector

- Use signals from either existing detectors or dedicated “trigger detectors”
  - Organic scintillators
  - Electromagnetic calorimeters
  - Proportional chambers (short drift)
  - Cathode readout detectors (RPC,TGC,CSC)



- With these requirements
  - **Fast signal**: good time resolution and low jittering
    - Signals from slower detectors are shaped and processed to find the unique peak (peak-finder algorithms)
  - **High efficiency**
  - **(often) High rate capability**

***ATLAS Liquid Argon calorimeter***

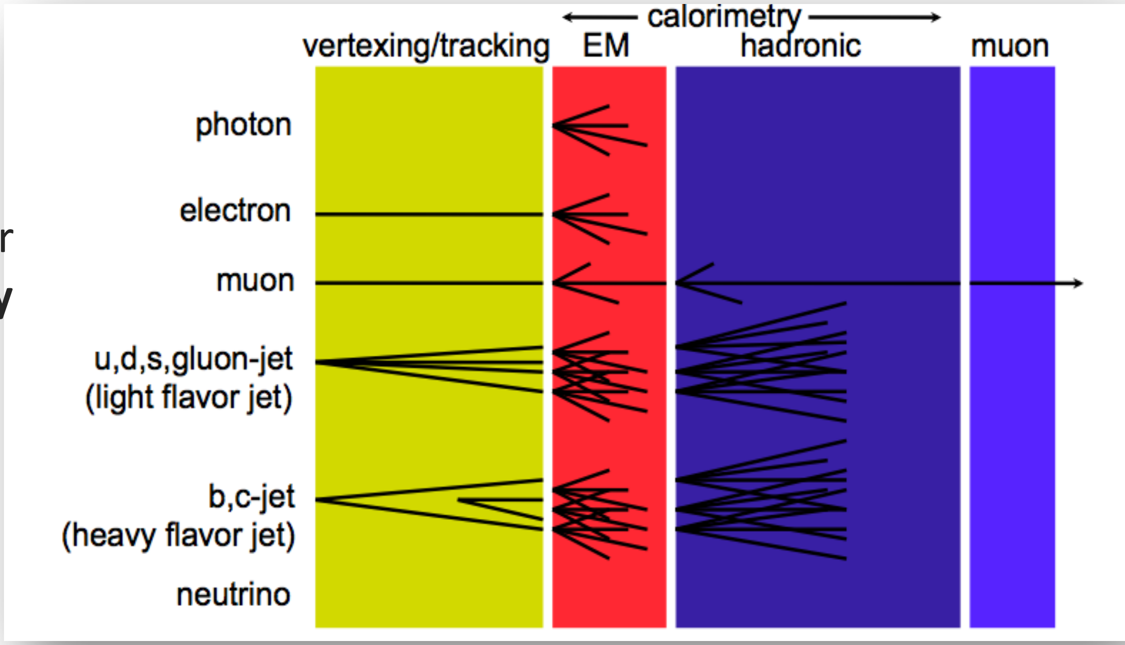


- **Need optimal FE/trigger electronics to process the signal (common design)**

# Trigger signatures

- Can collect **many** parameters for discrimination of a given topology
  - Not only the amplitude of a signal
  - More complex quantities by software calculations (also MultiVariate Analysis)
- At <u>first</u>, use intuitive criteria: **be fast and reliable!**
  - Use clear/simple signatures
    - i.e.: apply thresholds on: muon momenta, energy deposits in the calorimeters, good quality tracks in the tracker detectors....

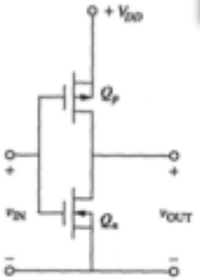
- Eventually combine more signals together following a certain trigger logic (AND/OR), giving **redundancy**

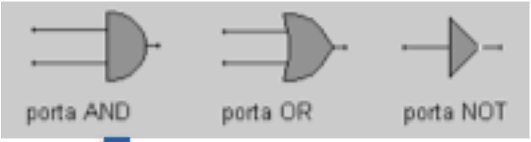


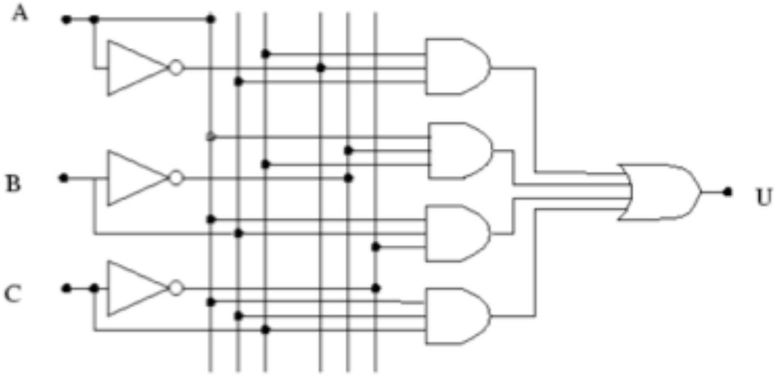
# Hardware trigger logic implementation

- Analog systems: amplifiers, filters, comparators, ….
- Digital systems:
  - Combinatorial: sum, decoders, multiplexers,….
  - Sequential: flip-flop, registers, counters,….
- Converters: ADC, TDC, …..

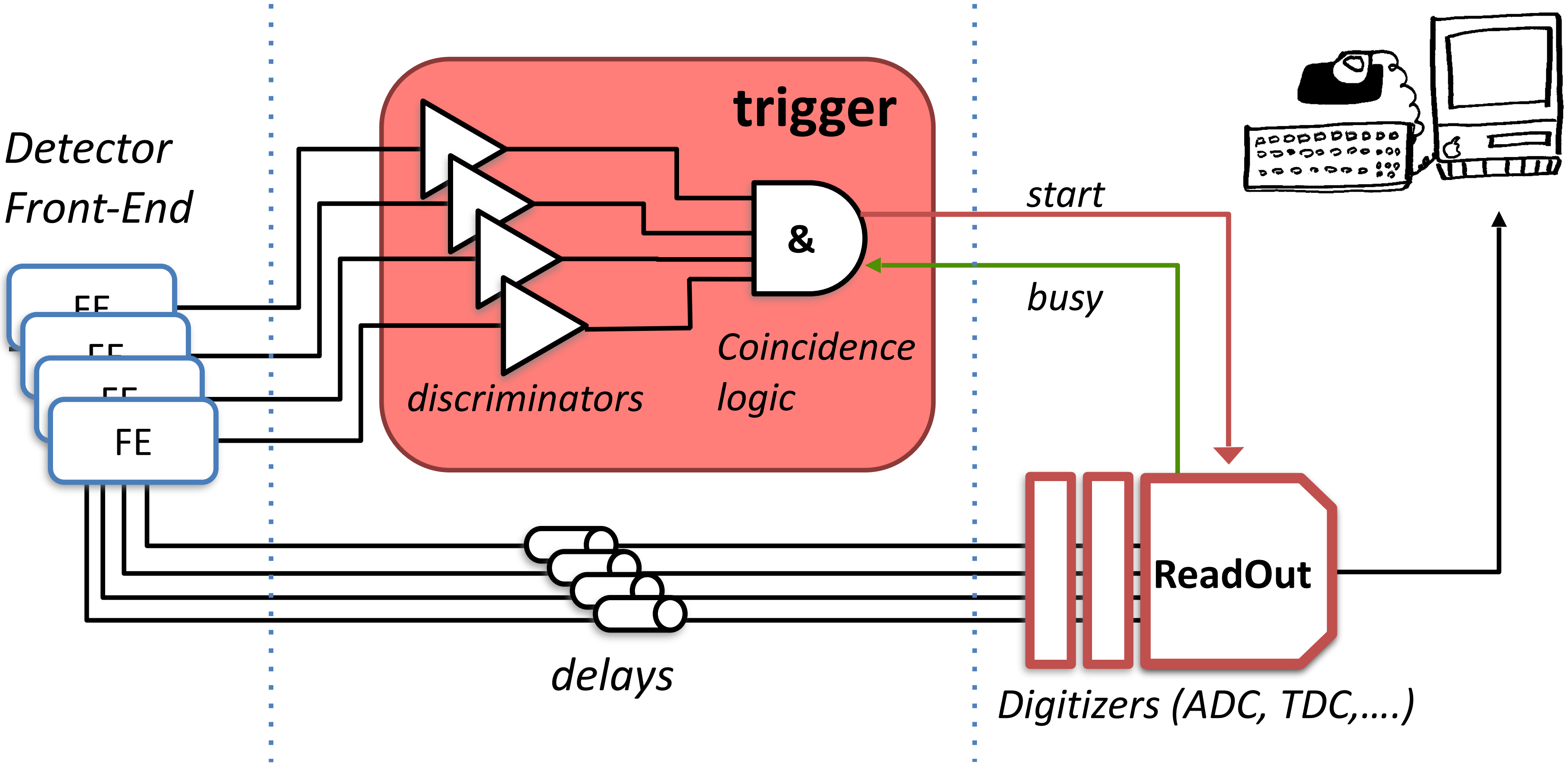
Any behaviour of our system can be described logically with a sequence of mathematical operators







# A simple trigger system



- Due to **fluctuations**, the incoming rate can be higher than the processing one
- Valid signals can be rejected due to system **busy**

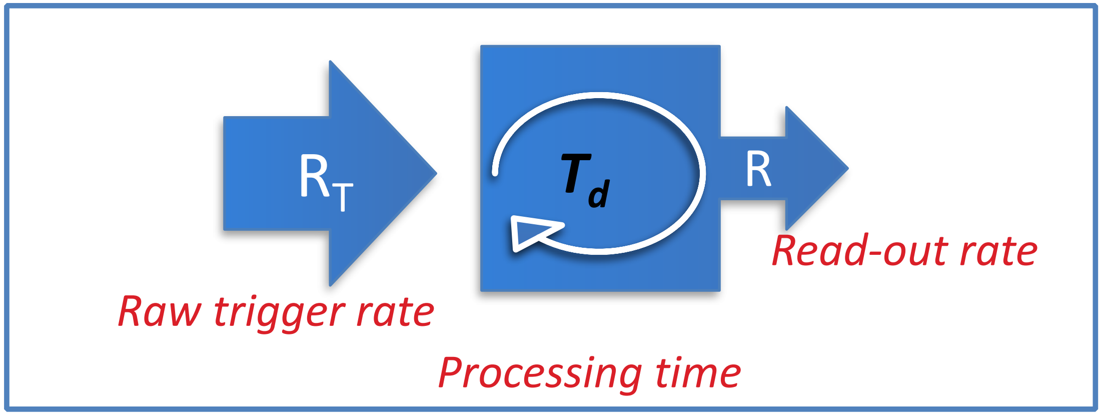
# Dead-time

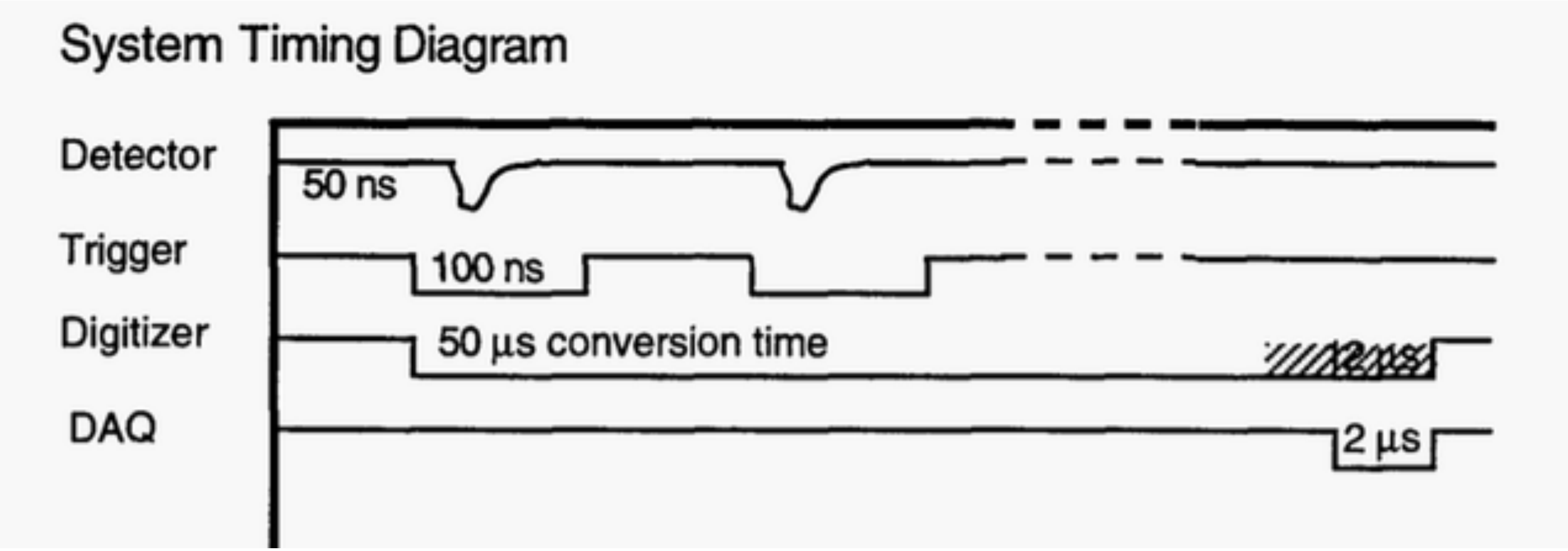
- The most important parameter in designing high speed **T/DAQ systems**
  - The fraction of the acquisition time in which no events can be recorded. It can be typically of the order of **few %**

- Occurs when a given step in the processing takes a **finite amount of time**
  - Readout dead-time
  - Trigger dead-time
  - Operational dead-time

Affects efficiency!

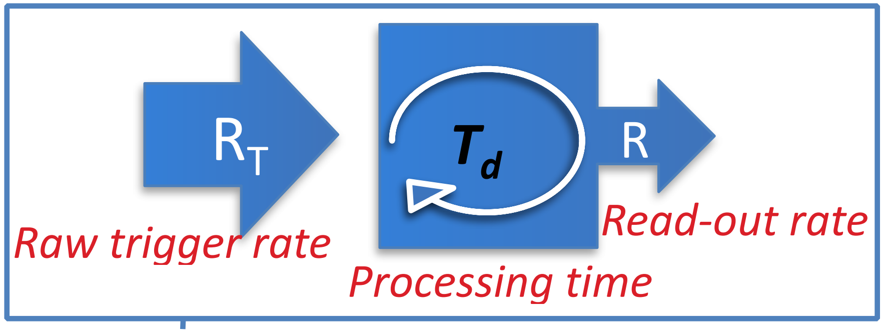
- **Fluctuations produce dead-time!**




System Timing Diagram
Detector
50 ns
Trigger
100 ns
Digitizer
50 µs conversion time
12 µs
DAQ
2 µs

# Maximise recording rate

*$R_T$ = Trigger rate (average)*
*$R$ = Readout rate*
*$T_d$ = processing time of one event*

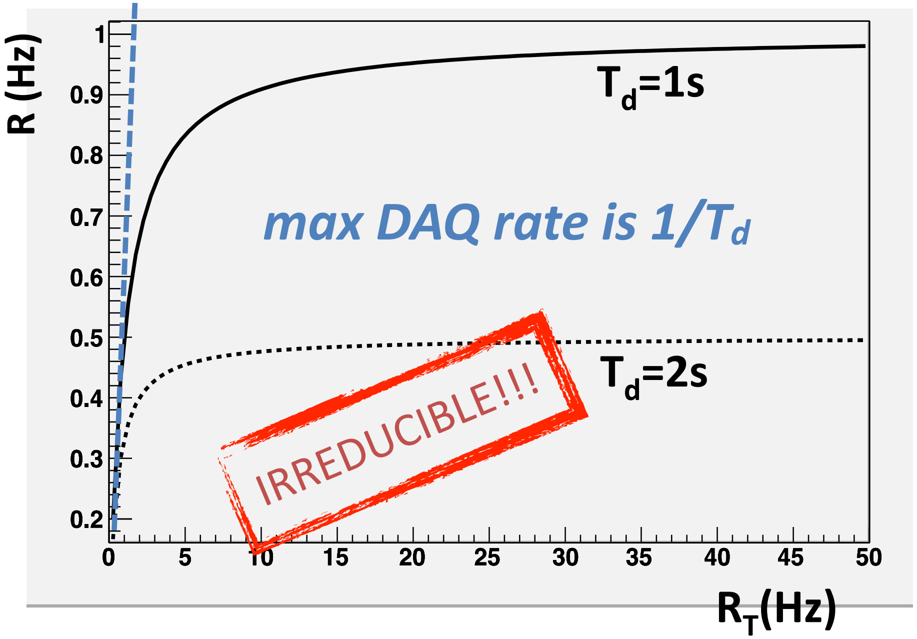


*fraction of lost events = $R \times T_d$*

*number of events read: $R = (1 - R \times T_d) \times R_T$*

$$\frac{R}{R_T} = \frac{1}{1 + R_T T_d}$$

***Fraction of surviving events!***



***max DAQ rate is 1/$T_d$***

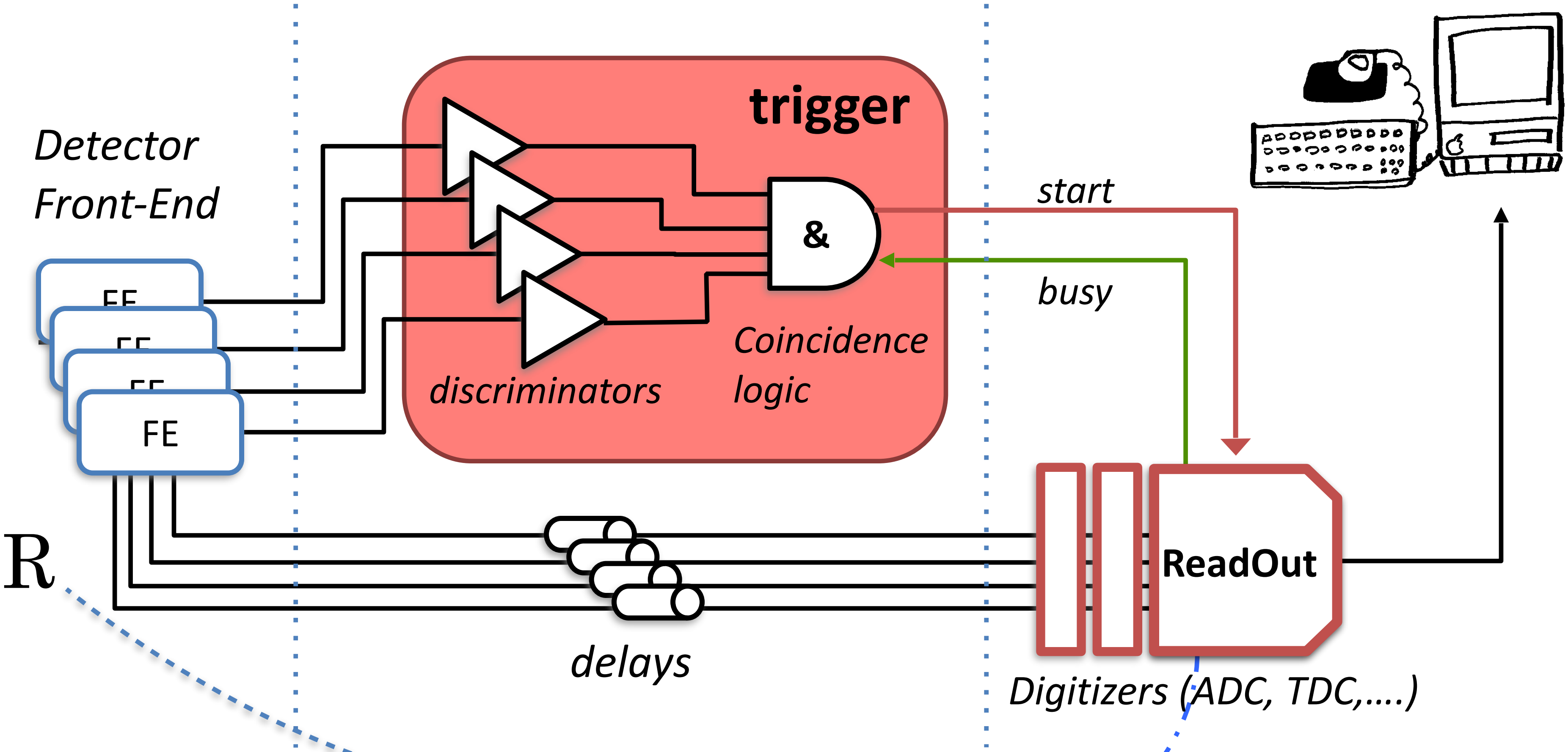
IRREDUCIBLE!!!

- We always lose events if $R_T > 1/T_d$
- If exactly $R_T = 1/T_d$ -> dead-time is 50%

The trick is to make both $R_T$ and $T_d$ as small as possible ($R \sim R_T$)

**FAST TRIGGER!**
**LOW INPUT RATE!**

# A simple trigger system

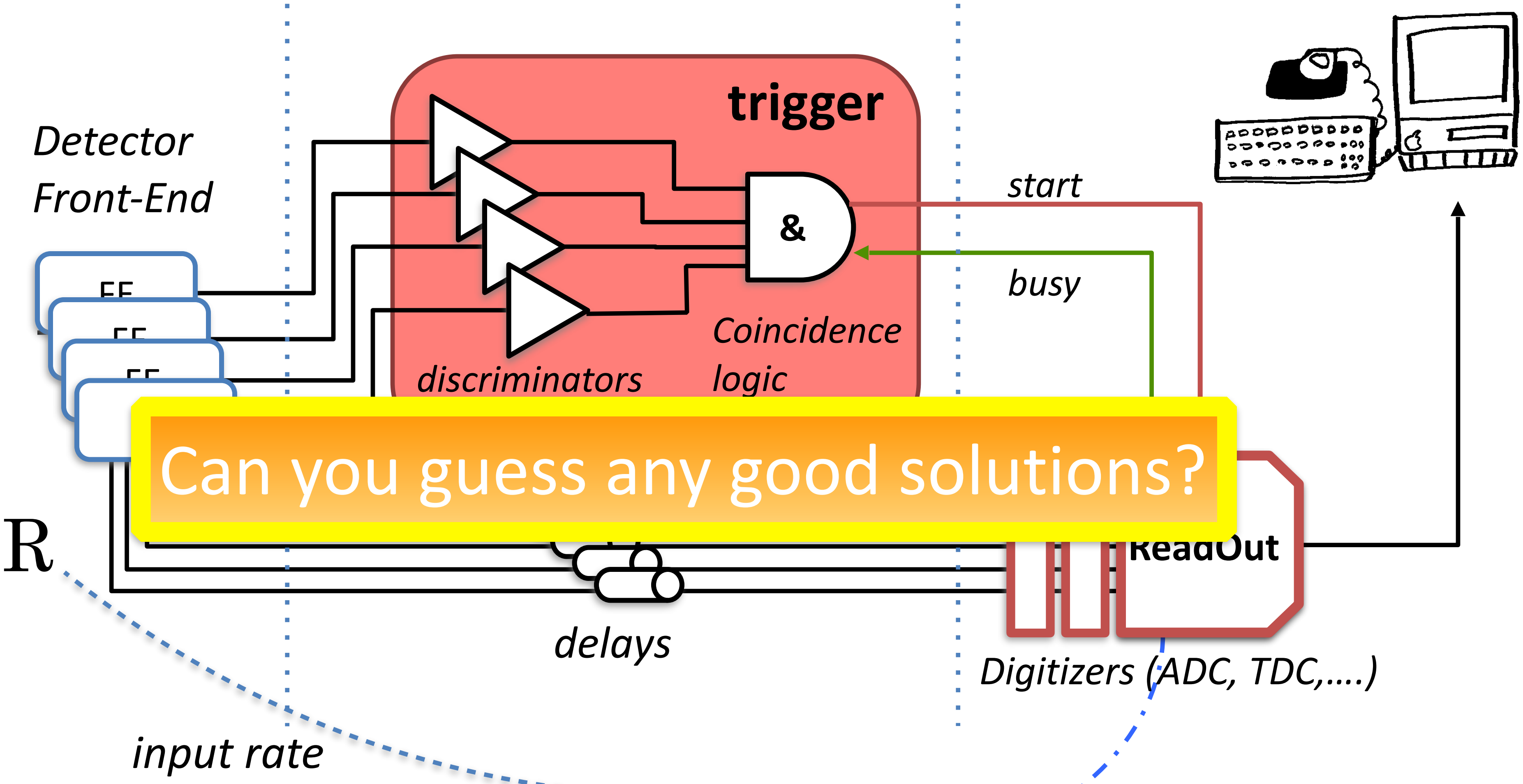


input rate

$$D_t = R \cdot T_{RO}$$

*Fraction of lost events due to finite readout*

# A simple trigger system



Can you guess any good solutions?

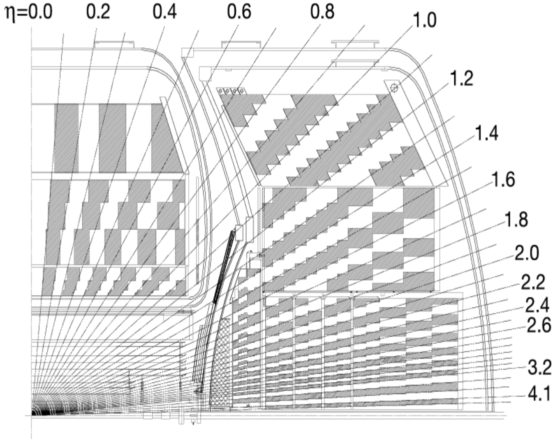
$$D_t = R \cdot T_{RO}$$

*Fraction of lost events due to finite readout*

# How to minimise dead-time….

- **1: Parallelism**
  - Independent readout and trigger processing paths, one for each sensor element
  - Digitisation and DAQ processed in parallel (as many as affordable!)

***Segment as much as you can!***

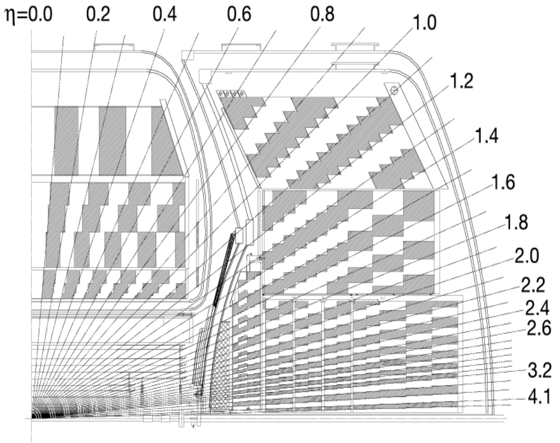


*DZero calorimeters showing the transverse and longitudinal segmentation pattern*

# How to minimise dead-time….

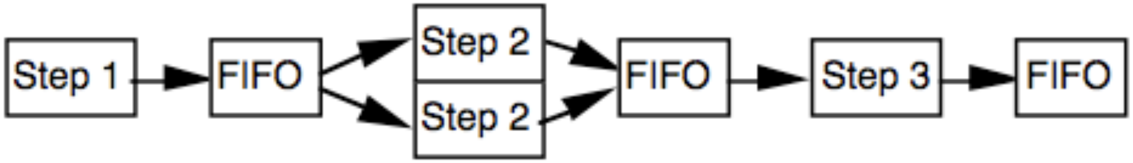
- **1: Parallelism**
  - Independent readout and trigger processing paths, one for each sensor element
  - Digitisation and DAQ processed in parallel (as many as affordable!)

***Segment as much as you can!***



*DZero calorimeters showing the transverse and longitudinal segmentation pattern*

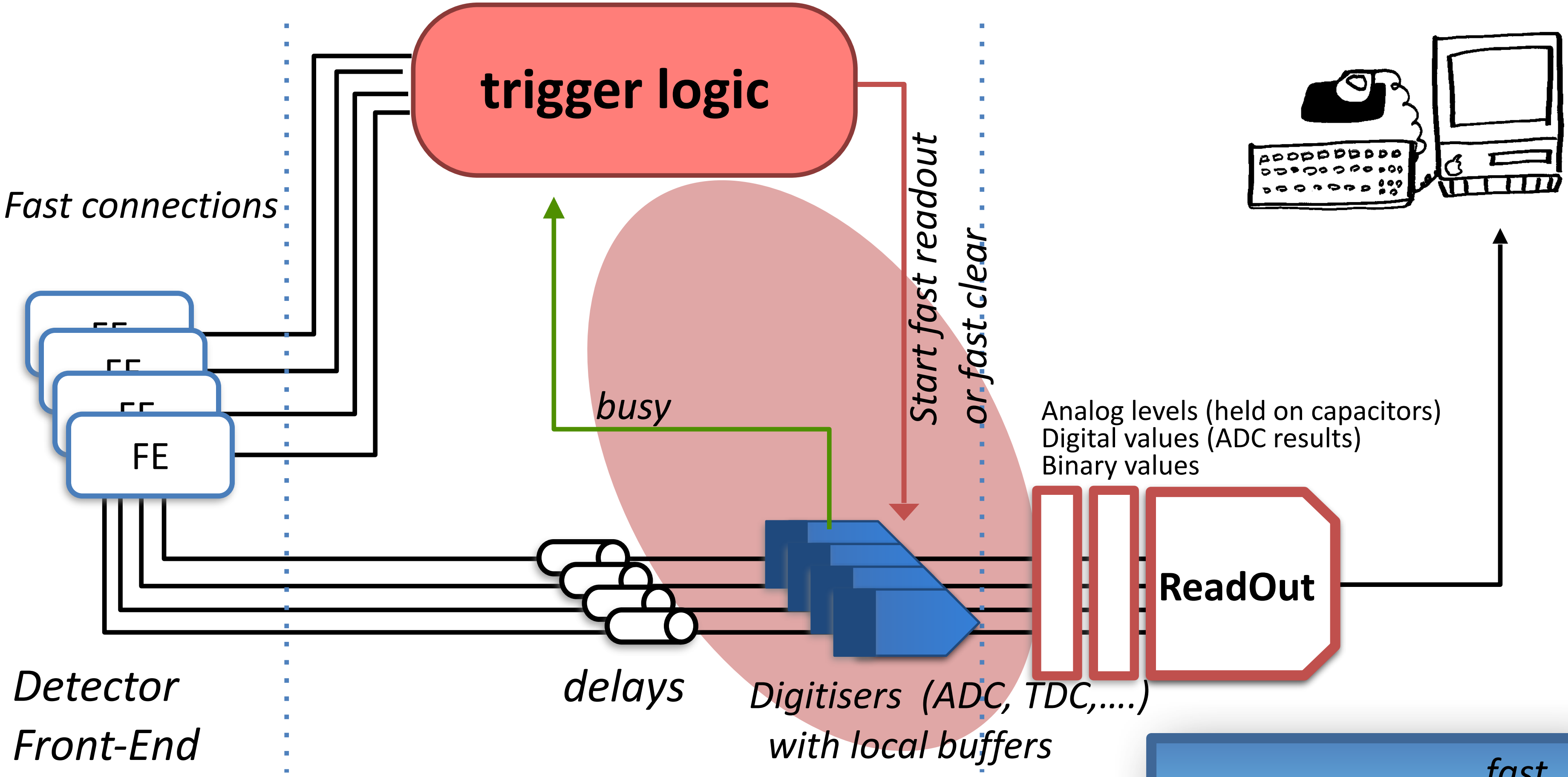
- **2: Pipeline processing with intermediate buffers,** to absorb fluctuations
  - Organise the process in different steps
  - Use local **buffers** between steps with different timing



$$\frac{R}{R_T} = \frac{1}{1 + R_T T_d}$$

*Try to absorb in capable buffers*

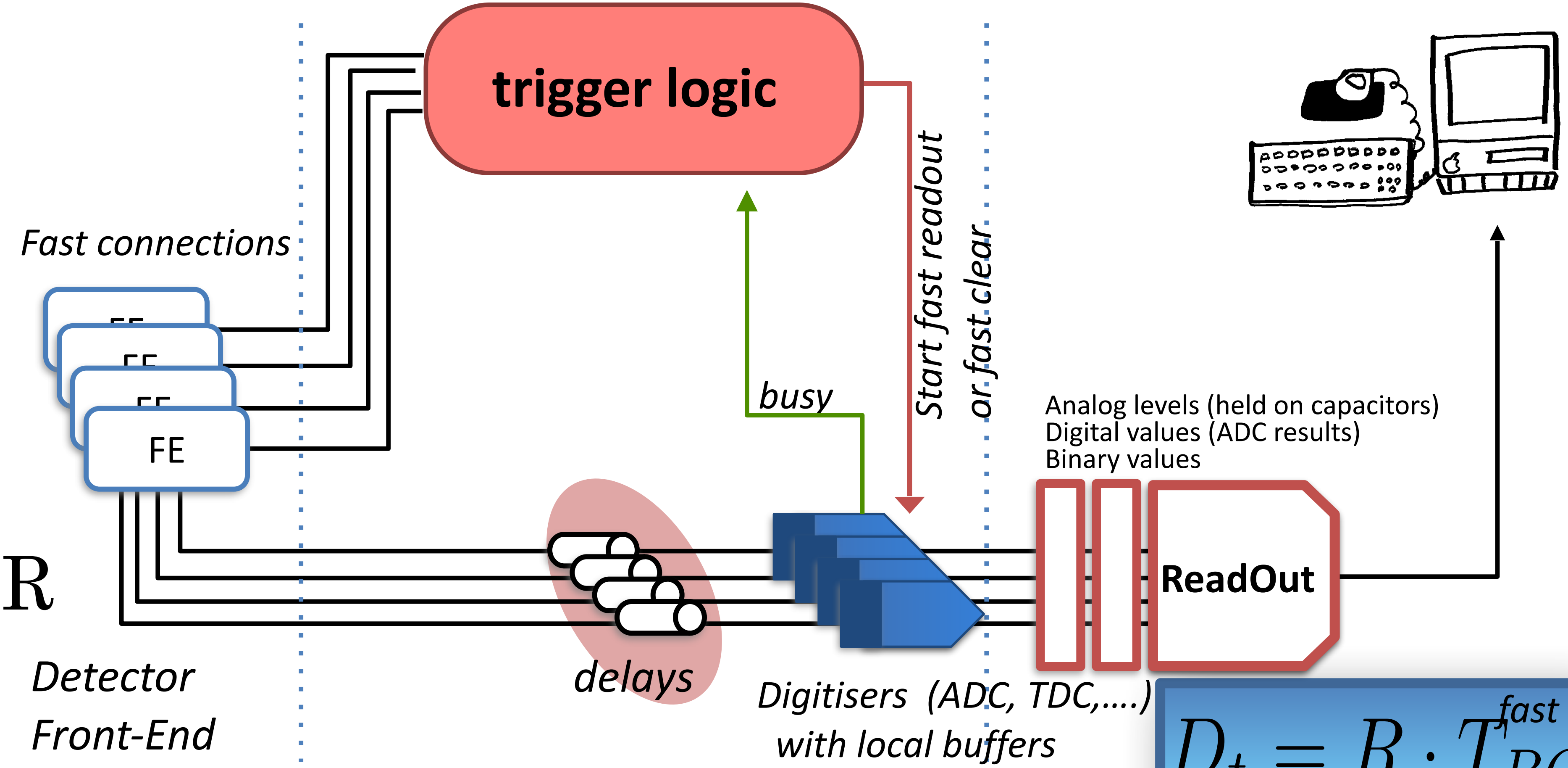
# Minimising readout dead-time…



$$D_t = R \cdot T_{RO}^{fast}$$

- **Parallelism**: Use multiple digitisers
- **Pipelining**: Different stages of readout: fast local readout + global event readout (slow)

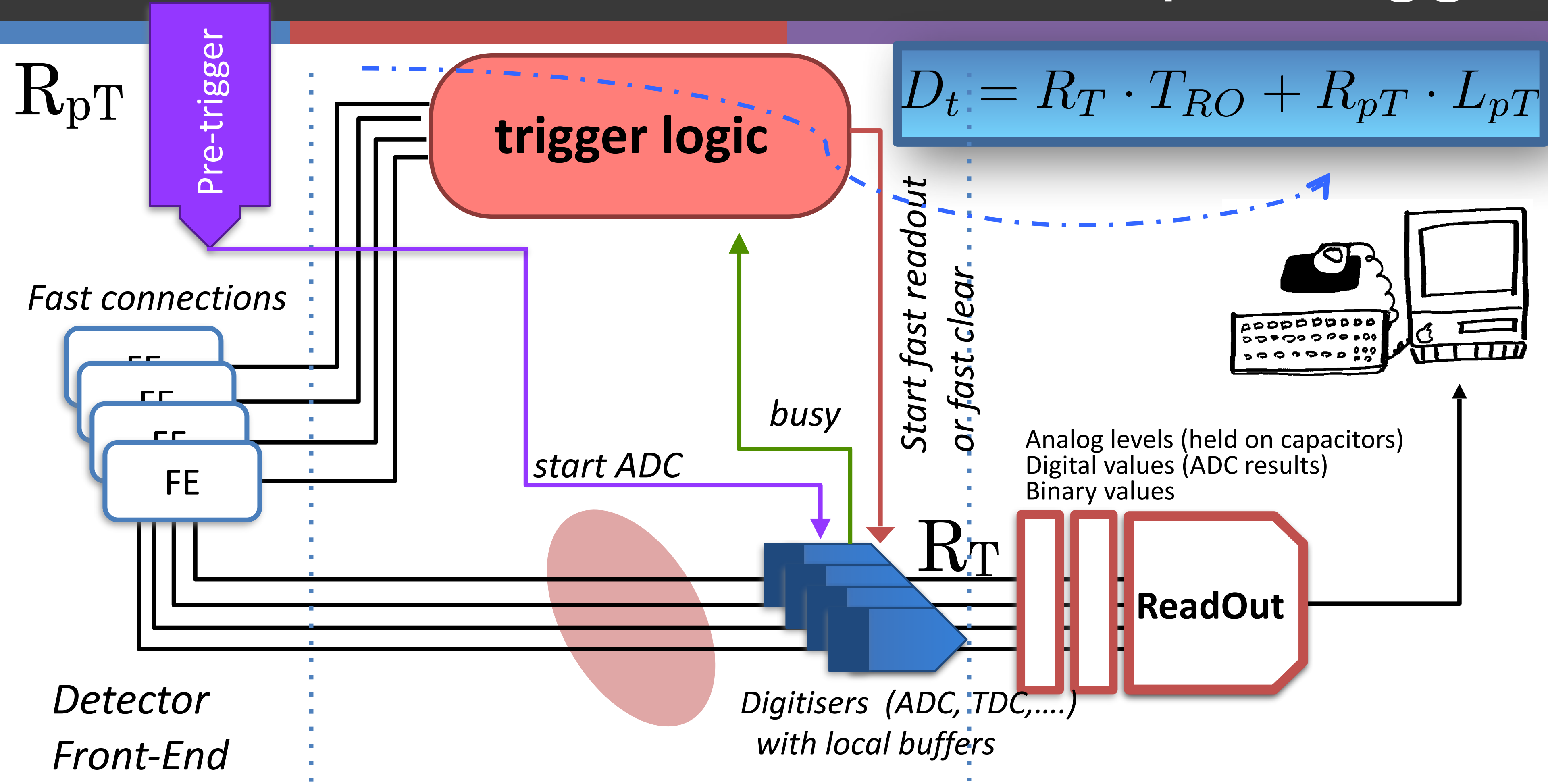
# Trigger latency



$$D_t = R \cdot T_{RO}^{fast}$$

- **Time to form the trigger decision and distribute to the digitisers**
- Signals are delayed until the trigger decision is available at the digitisers
  - But more complex is the selection, longer is the latency

# Add a pre-trigger



$$D_t = R_T \cdot T_{RO} + R_{pT} \cdot L_{pT}$$

- Add **a very fast** first stage of the trigger, signalling the presence of minimal activity in the detector
  - **START the digitisers**, when signals arrive
  - The main trigger decision comes later (after the digitisation) -> can be more complex

# Coupling rates and latencies

- Extend the idea… more levels of trigger, each one reducing the rate, even with longer latency

- Dead-time is the sum of the trigger dead-time, summed over the trigger levels, and the readout dead-time

$$\left(\sum_{i=2}^{N} R_{i-1} \times L_i\right) + R_N \times T_{\mathrm{LRO}}$$

i=1 is the pre-trigger

$R_i$ = Rate after the i-th level

$L_i$ = Latency for the i-th level

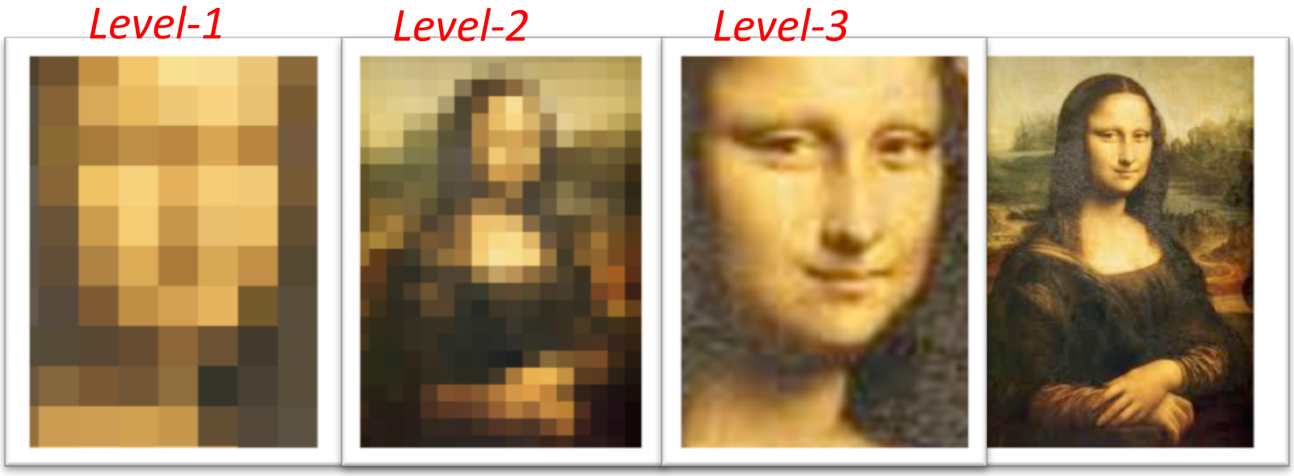
$T_{\mathrm{LRO}}$ = Local readout time

Readout dead-time is minimum if its input rate $R_N$ is low!

**Try to minimise each factor!**

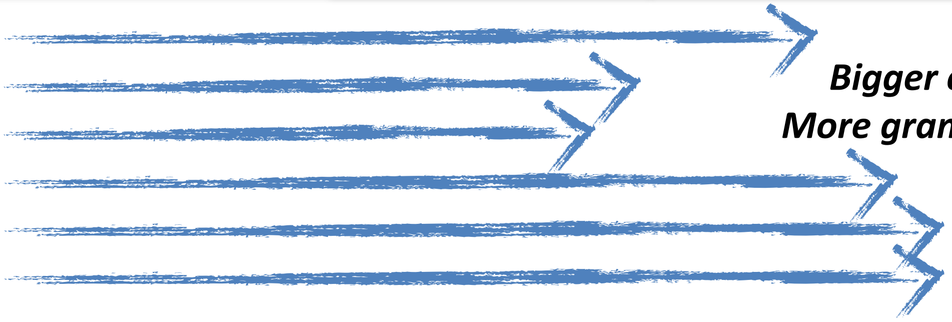
# Multi-level triggers

- Adopted in large experiments with large data volume
- Successively more complex decisions are made on successively lower data rates
  - First level with short latency, working at higher rates
  - Higher levels apply further rejection, with longer latency (more complex algorithms)



*LHC experiments @ Run1*

| Exp. | N.of Levels |
|---|---|
| ATLAS | 3 |
| CMS | 2 |
| LHCb | 3 |
| ALICE | 4 |

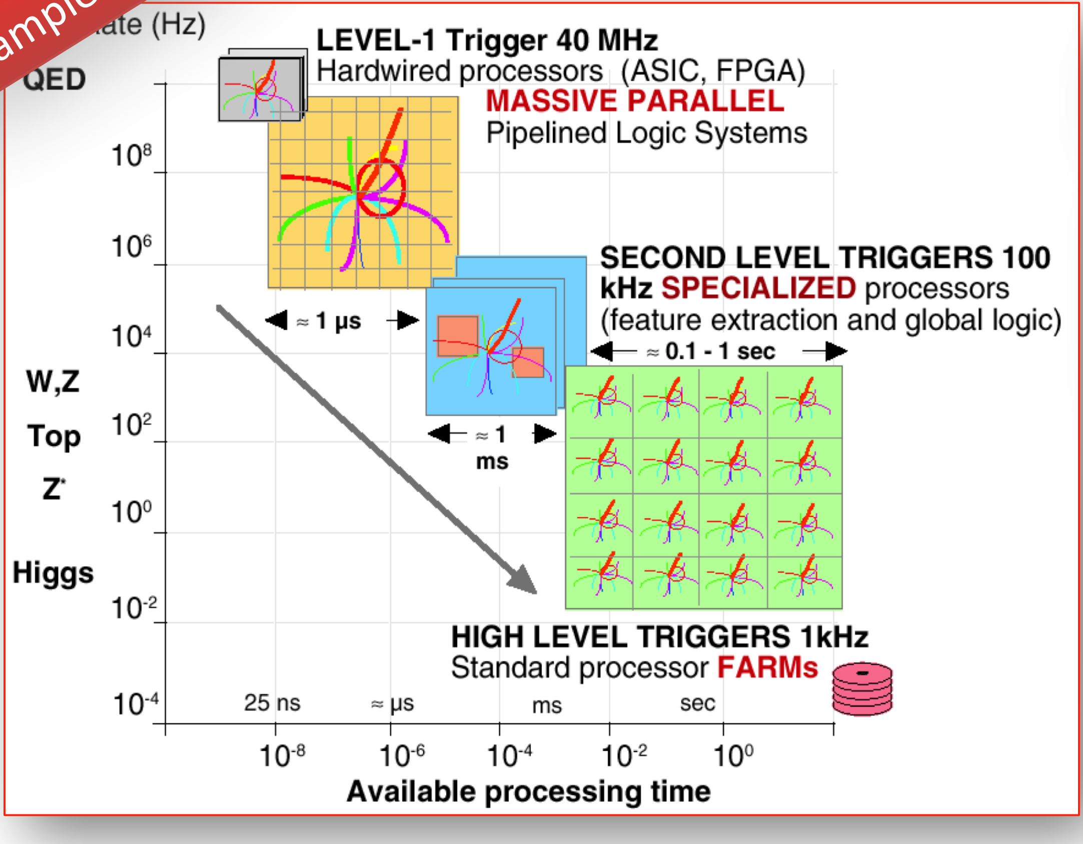


***Lower event rate***
***Bigger event fragment size***
***More granularity information***
***More complexity***
***Longer latency***
***Bigger buffers***

**Efficiency for the desired physics must be kept high at all levels, since rejected events are lost for ever**

# Use of multi-level trigger

Example for LHC



L1: Inclusive trigger

L2: Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

L3: Confirm L2, more refined topology selection, near offline

***Architectural view***

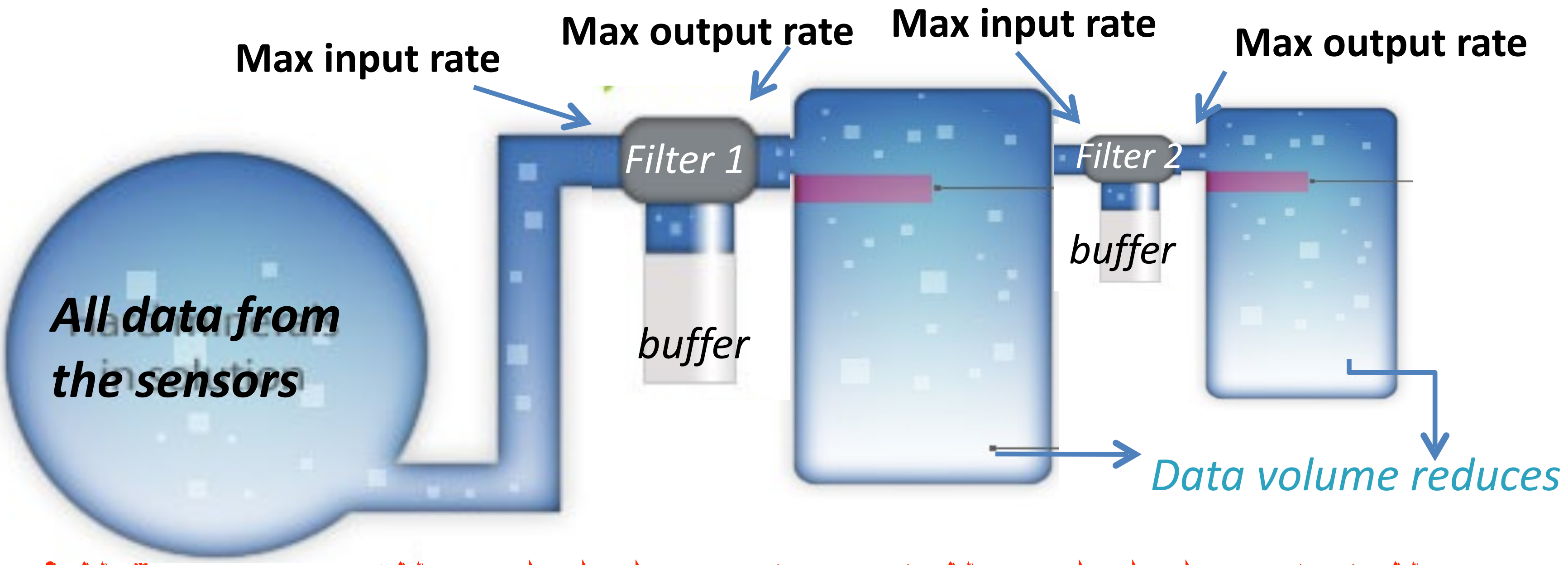
***Logical view***

# Buffering and filtering

- **At each step**, data volume is reduced, more refined filtering to the next step
  - The input rate defines the filter **processing time** and its **buffer size**
  - The output rate limits the maximum latency allowed in the **next step**
  - Filter power is limited by the capacity of the next step

**As long as the buffers do not fill up (overflow), no additional dead-time is introduced!**

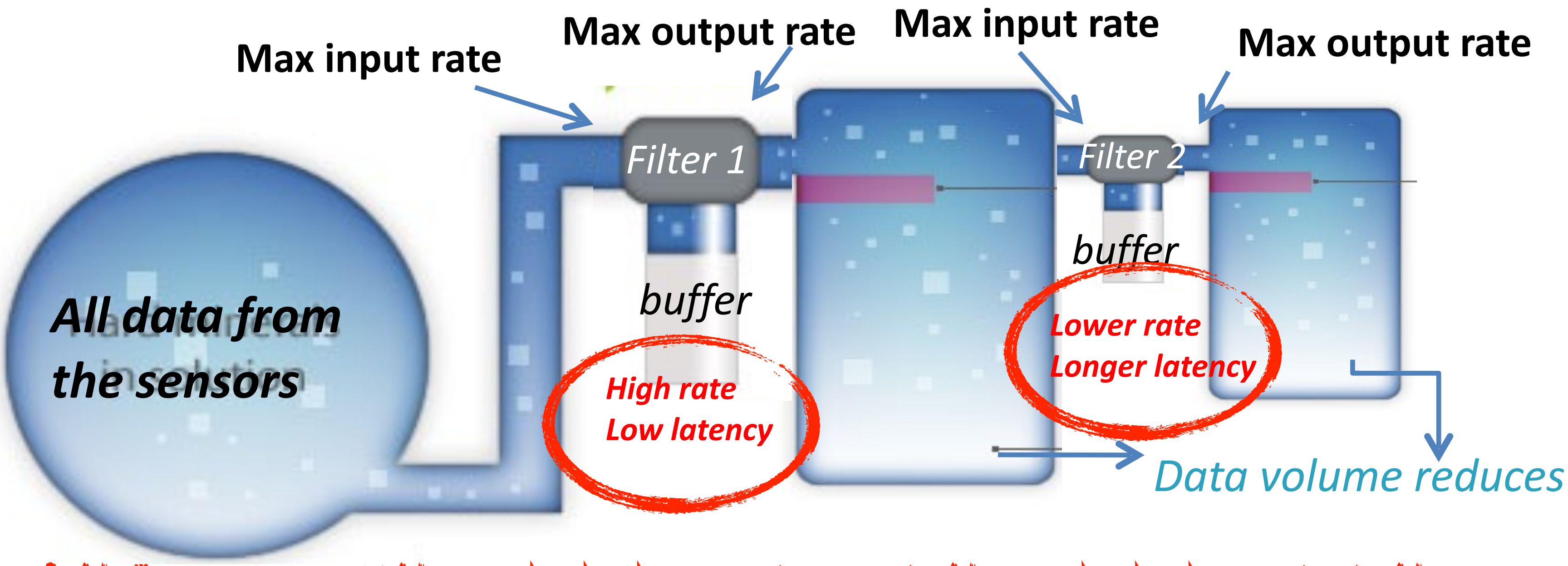
→ *BUSY signal is still needed*



LHC: 40 MHz ▶▶▶ 100 kHz ▶▶▶ 1 kHz

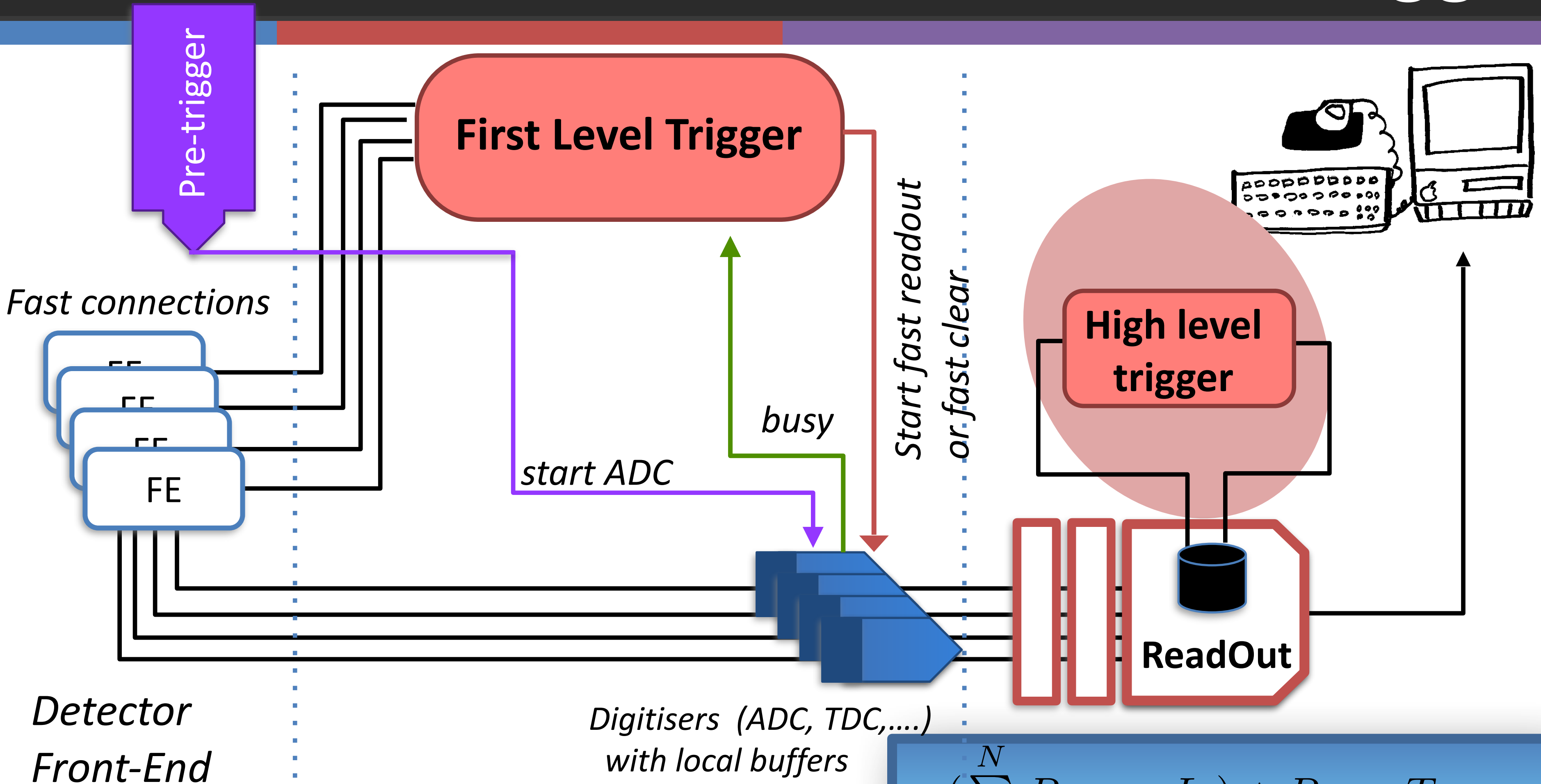
# Rates and latencies are strongly connected

- If the rate after filtering is higher than the capacity of the next step
  - Add filters (tighten the selection)
  - Add better filters (more complex selections)
  - Discard randomly (pre-scales)



LHC: 40 MHz ▶▶▶ 100 kHz ▶▶▶ 1 kHz

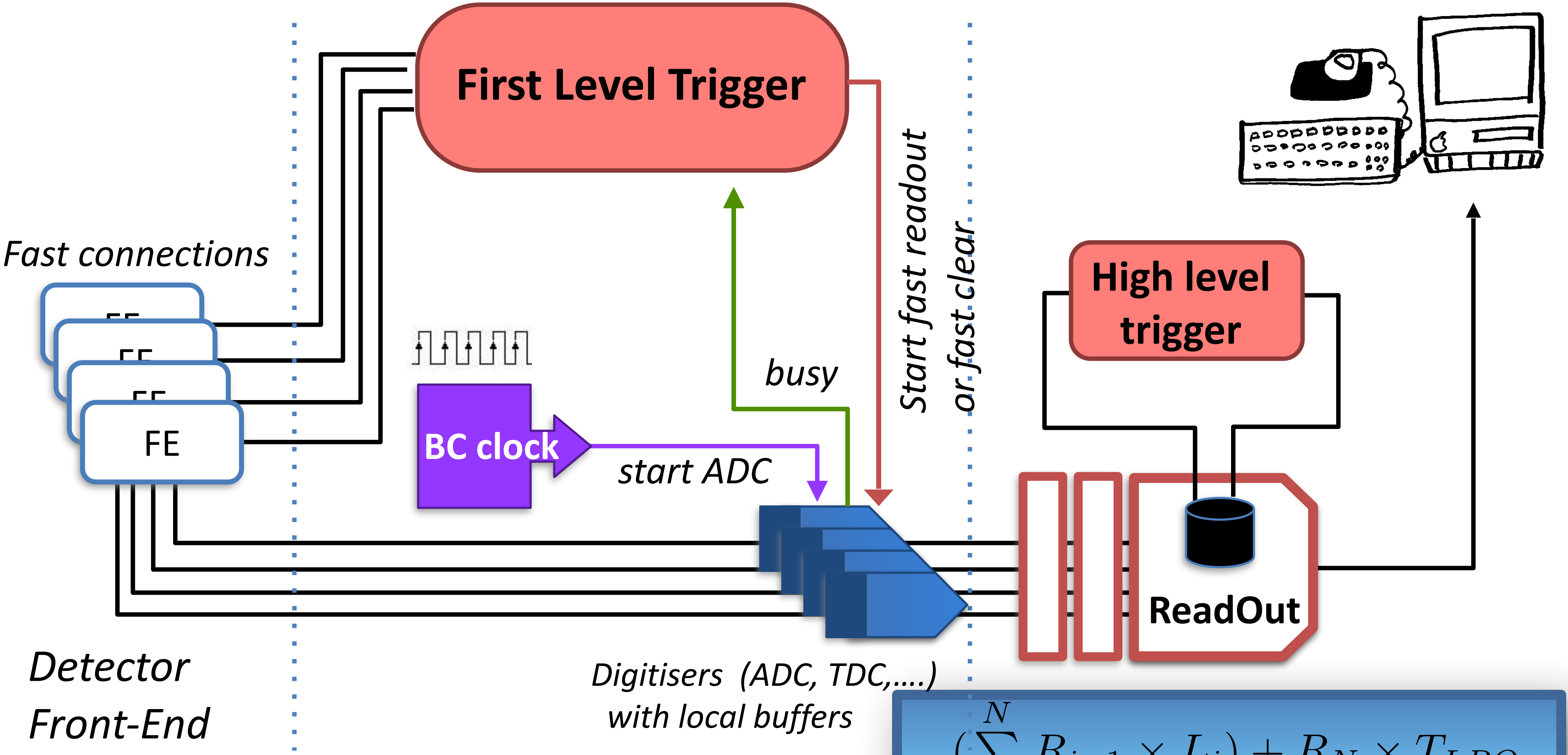
# Schema of a multi-level trigger



$$(\sum_{i=2}^{N} R_{i-1} \times L_i) + R_N \times T_{LRO}$$

- Different levels of trigger, accessing different buffers
- The pre-trigger starts the digitisation

# Schema of a multi-level trigger @ colliders

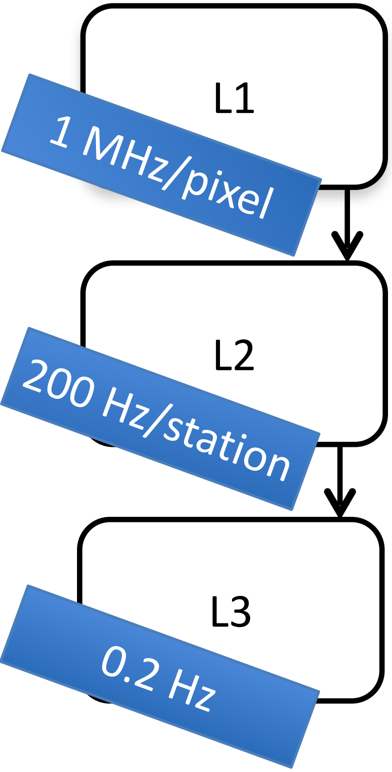


$$(\sum_{i=2}^{N} R_{i-1} \times L_i) + R_N \times T_{LRO}$$

- The BC clock can be used as a pre-trigger
  - First-level trigger is **synchronous** to the collision clock: can use the time between two collisions to make its decision, without dead-time

# Simple signatures: Auger observatory

- **Detect air showers generated by cosmic rays above $10^{17}$ eV**
  - Expected rate < 1/km²/century. Two large area detectors
- On each detector, a 3-level trigger operates at a wide range of primary energies, for both vertical and very inclined showers



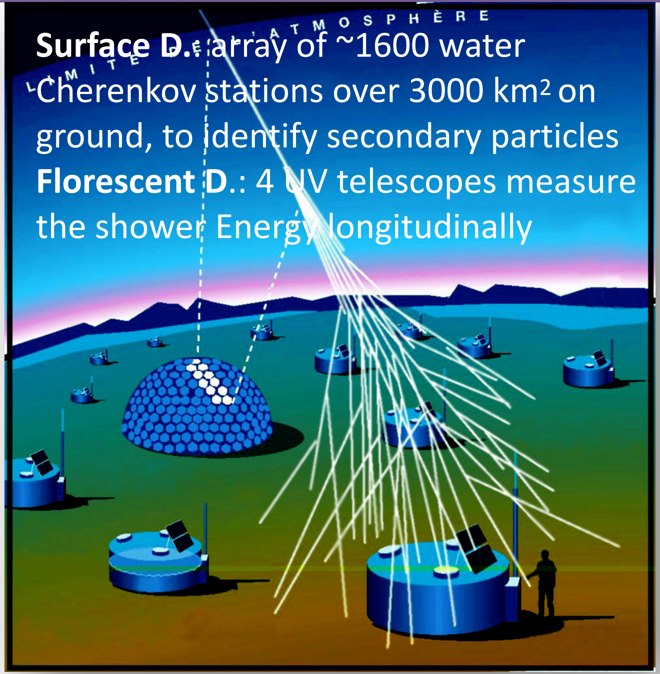
**L1: (local)** decides the pixel status (on/off)

- ADC counts > **threshold**
- ADC with 100 ns (**time** resolution)
- ADC values stored for **100 μs in buffers**
- **Synchronised** with a signal from a GPS clock

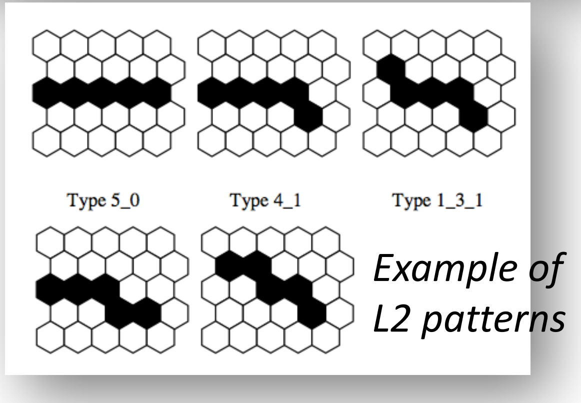
**L2: (local)** identifies track segments

- Geometrical criteria with recognition algorithms on programmable patterns

**L3: (central)** makes spatial and temporal correlation between L2 triggers



**Surface D.:** array of ~1600 water Cherenkov stations over 3000 km² on ground, to identify secondary particles
**Florescent D.**: 4 UV telescopes measure the shower Energy longitudinally

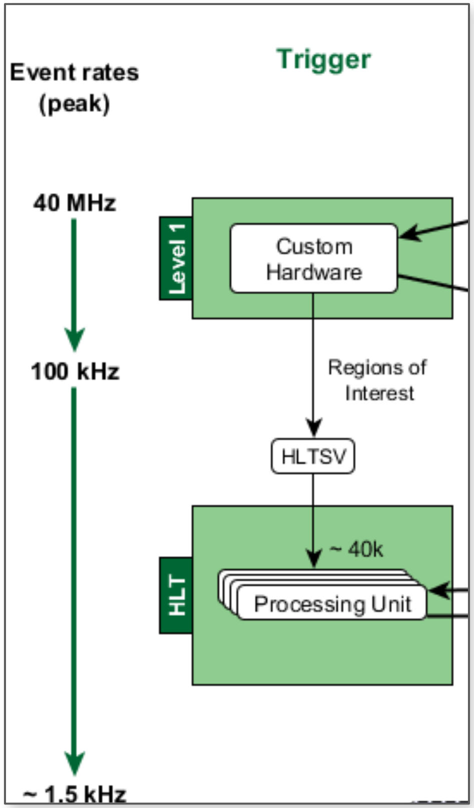


*Example of L2 patterns*

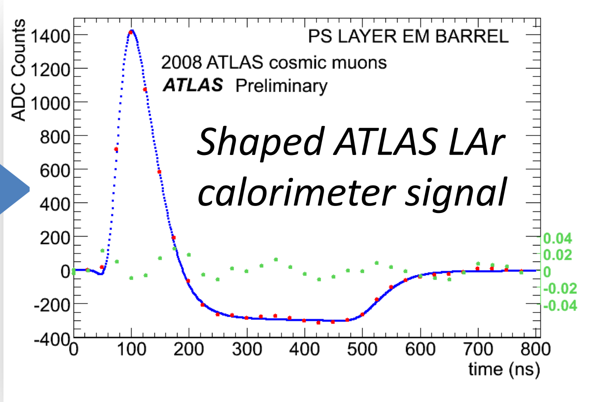
**One event ~ 1MB → 0.2 MB/s bandwidth for the DAQ system**

# Multiple signatures: ATLAS calorimeter trigger

- **Identify high energy e, γ, τ, jets, missing $E_T$, $\Sigma E_T$**

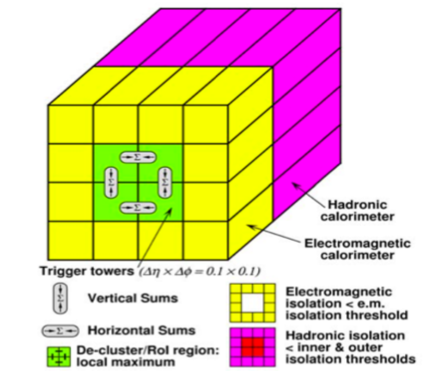


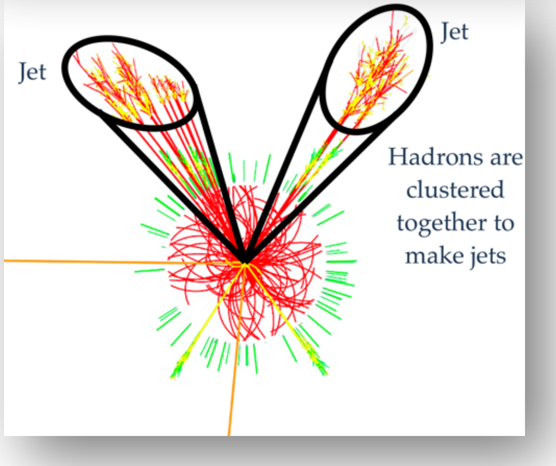
- Dedicated Front-End electronics
  - Each cell sends shaped analog signals



*Shaped ATLAS LAr calorimeter signal*

- Level-1 hardware trigger (2.5 us)
  - Dedicated **ASICs** apply simple cluster algorithms over cells and programmable $E_T$ thresholds

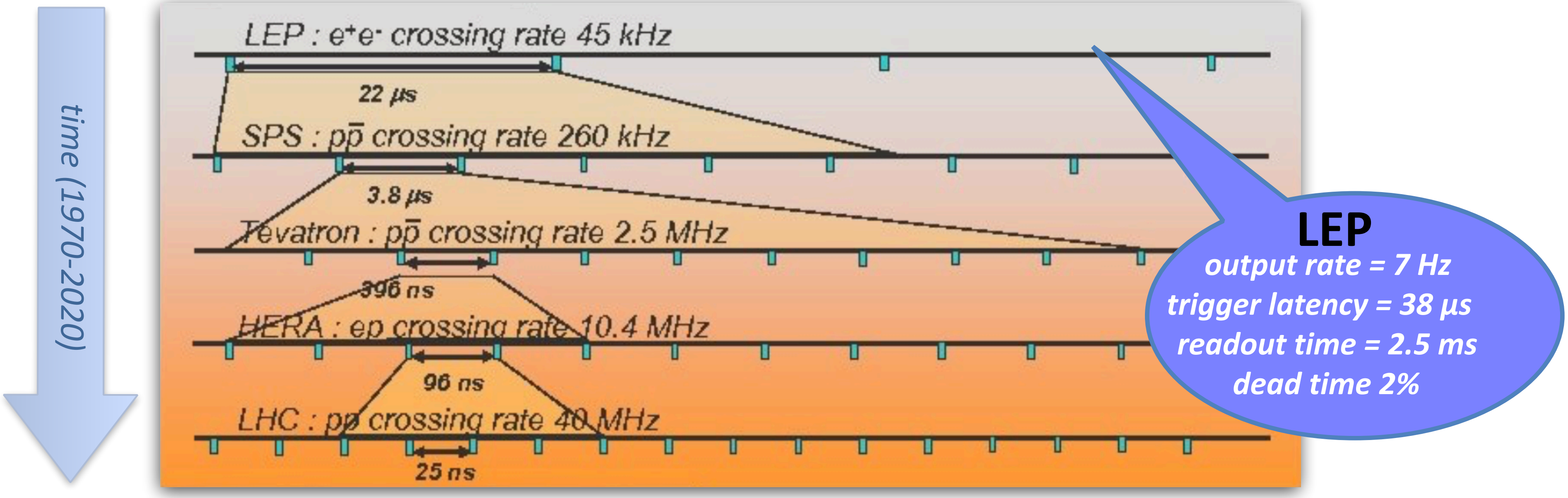




- High-Level triggers in software (~1 s)
  - electron/jet separation using
    - Cluster shapes
    - **Topological** variables, **tracking** information
    - **Isolation** criteria

# Trigger processing

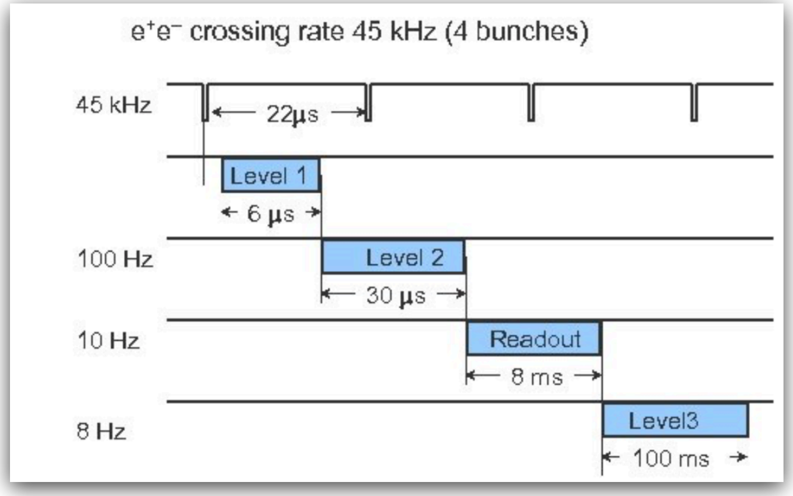
# In a Synchronous level-1 trigger @ colliders


time (1970-2020)
LEP : e+e- crossing rate 45 kHz
22 µs
SPS : pp̄ crossing rate 260 kHz
3.8 µs
Tevatron : pp̄ crossing rate 2.5 MHz
396 ns
HERA : ep crossing rate 10.4 MHz
96 ns
LHC : pp crossing rate 40 MHz
25 ns

**LEP**

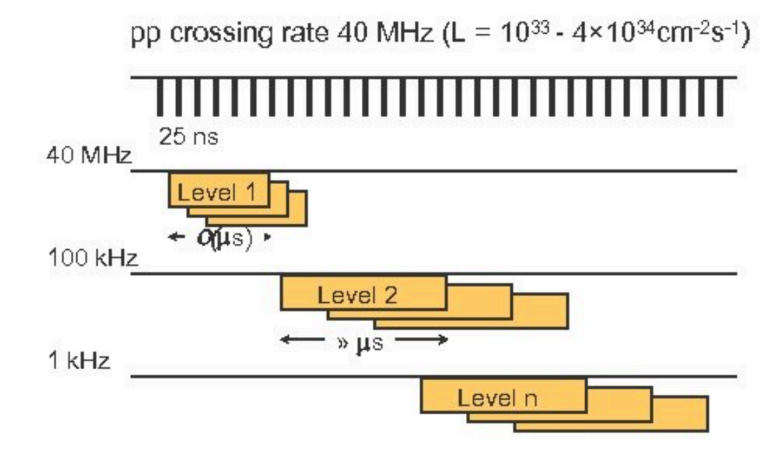
*output rate = 7 Hz*
*trigger latency = 38 µs*
*readout time = 2.5 ms*
*dead time 2%*

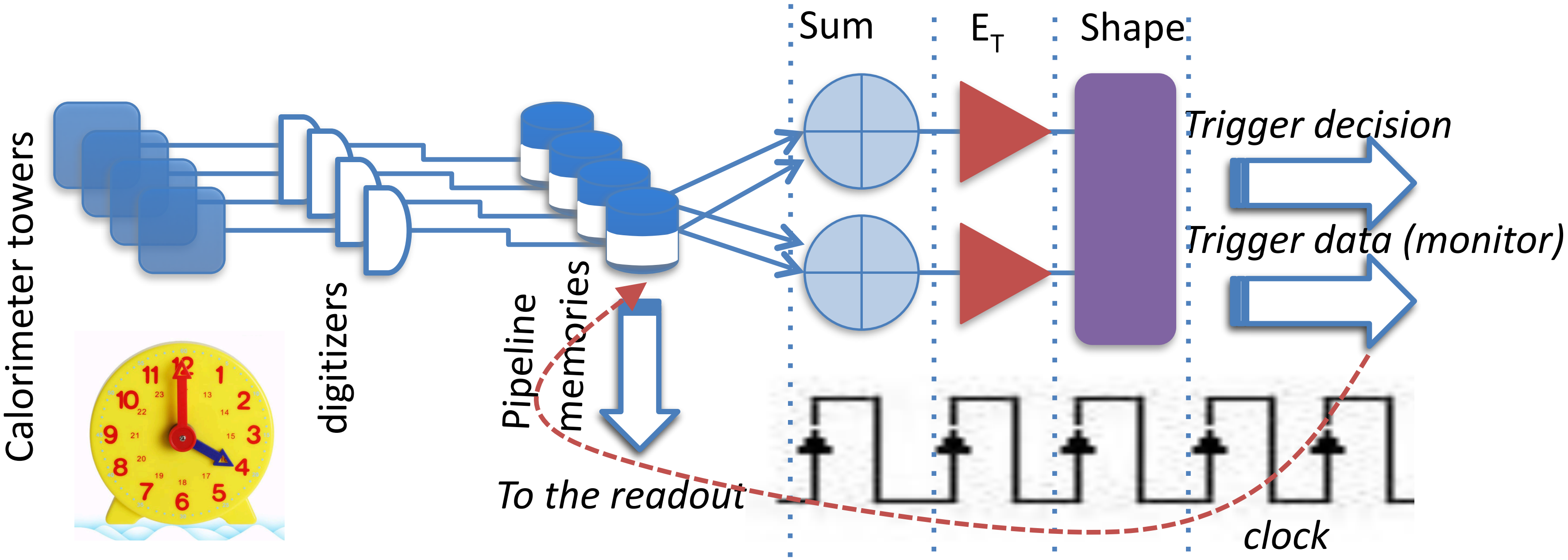
- In colliders high luminosity is driven by high clock rate
  - **can take trigger decision between two collisions?**
- **@LEP (BC interval 22 µs):**
  - Level-1 trigger latency < bunch-interval
  - no event overlap
  - most electronics outside the detector



# Level-1 pipeline trigger

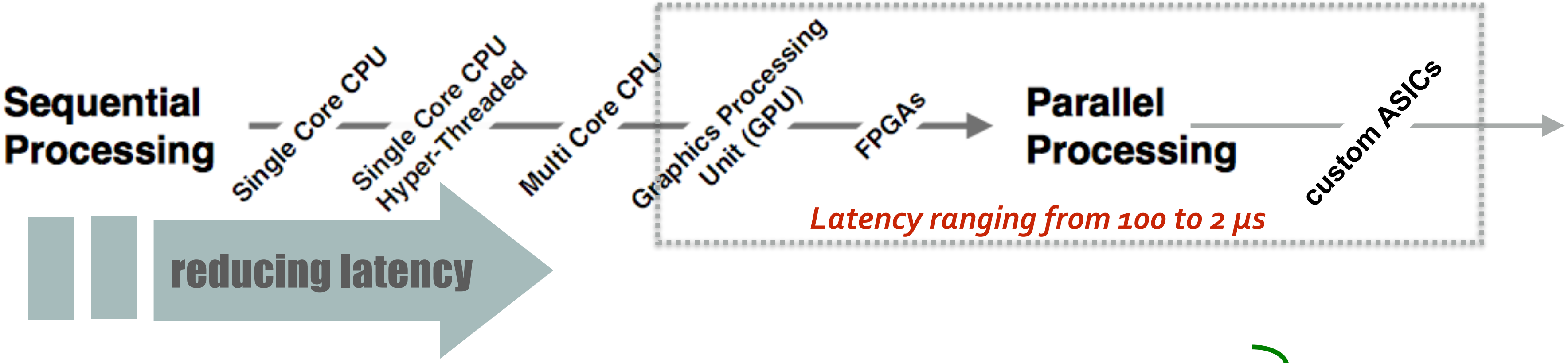
- @LHC (25ns): **L1 latency (few µs) exceeds bunch interval**
  - events overlap
  - signal pileup (in the detectors)
  - large detectors (large distance)
    - Latency = processing + data transmission time
- Front-end buffer pipelines @ **fixed trigger latency**
  - Each processor **concurrently** processes many events
  - Divide processing in steps, one per BC clock


pp crossing rate 40 MHz (L = $10^{33}$ - $4\times10^{34}$cm$^{-2}$s$^{-1}$)
25 ns
40 MHz
Level 1
O(µs)
100 kHz
Level 2
» µs
1 kHz
Level n



# Trigger (co-)processors

- General requirements
  - Fast processing
  - Flexible/programmable algorithms
  - Data compression and formatting
  - Monitor and automatic fault detection



Sequential Processing

Single Core CPU

Single Core CPU Hyper-Threaded

Multi Core CPU

Graphics Processing Unit (GPU)

FPGAs

Parallel Processing

custom ASICs

*Latency ranging from 100 to 2 μs*

reducing latency

- **Microprocessors** (CPUs, GPGPUs, ARMs, DSP=digital signal processors..)
  - Available on the market or specific, programmed only once

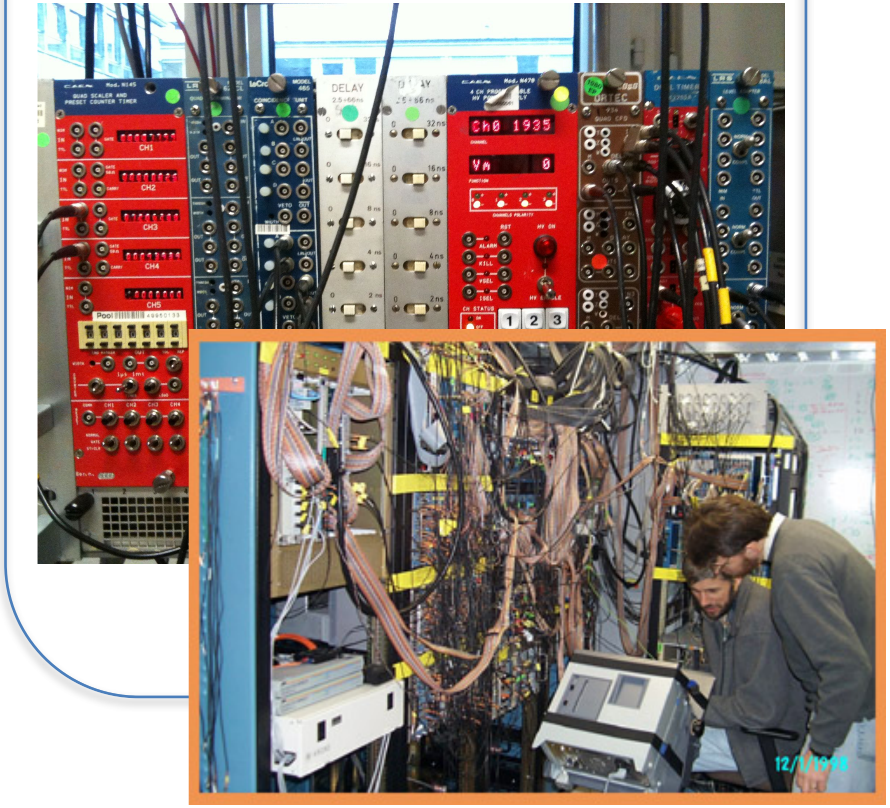
***need instructions***

- **Programmable logic devices** (FPGAs, CAMs,…)
  - More operations/clock cycle, but costly and difficult software developing

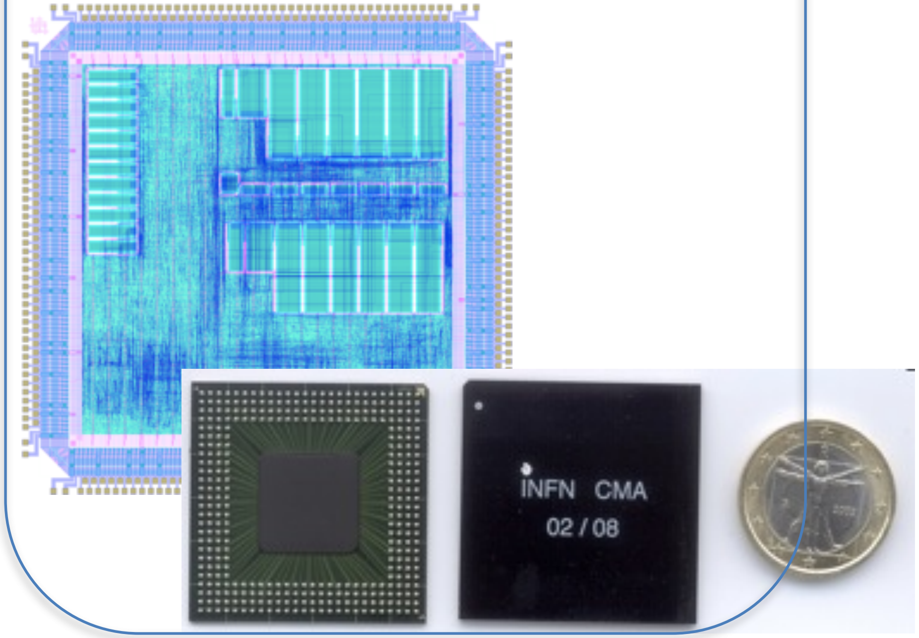
***already learned the task***

# Choose your L1 trigger system

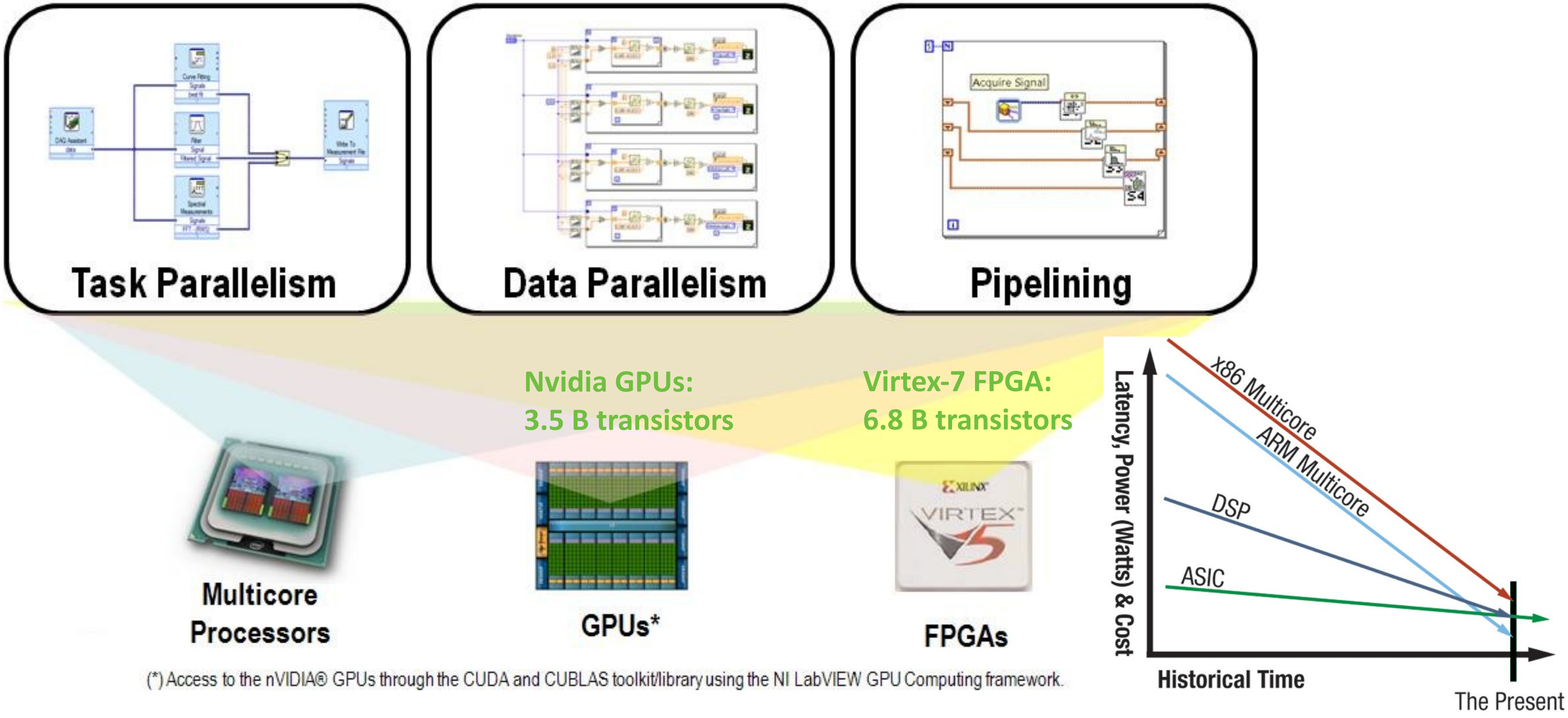
- Modular electronics
  - Simple algorithms
  - Low-cost
  - Intuitive and fast use



- Digital integrated systems
  - Highly complex algorithms
  - Fast signals processing
  - Specific knowledge of digital systems



# Trends: combined technology



Nvidia GPUs:
3.5 B transistors

Virtex-7 FPGA:
6.8 B transistors

(*) Access to the nVIDIA® GPUs through the CUDA and CUBLAS toolkit/library using the NI LabVIEW GPU Computing framework.

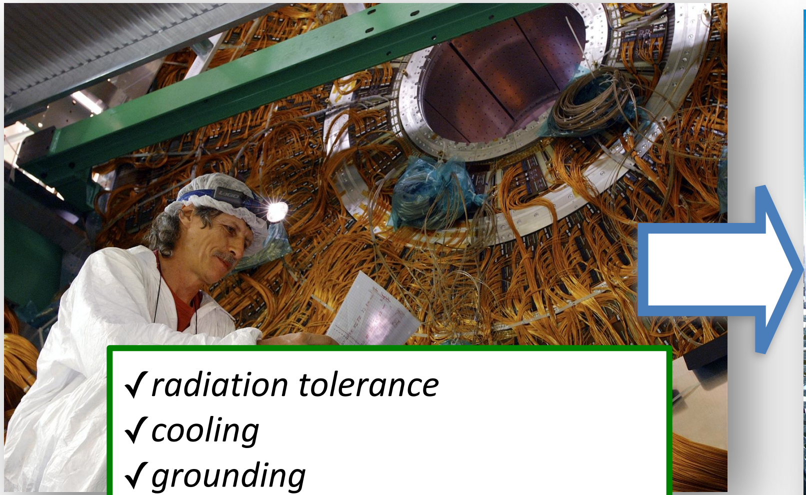
**The right choice can be combining the best of both worlds by analysing which strengths of FPGA, GPU and CPU best fit the different demands of the application.**

- Using standard interface (ethernet), can profit of standard tools and development time is reduced

# Fast data movement

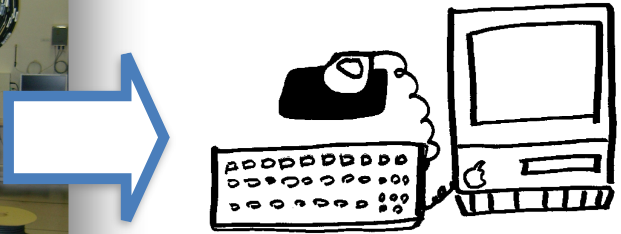
- Faster data processing are placed on-detector (close or joined to the FE)
- **Intermediate crates are good separation between FE (long duration) and PCs**

***On-detector***



- ✓ *radiation tolerance*
- ✓ *cooling*
- ✓ *grounding*
- ✓ *operation in magnetic field*
- ✓ *very restricted access*

***Off-detector***



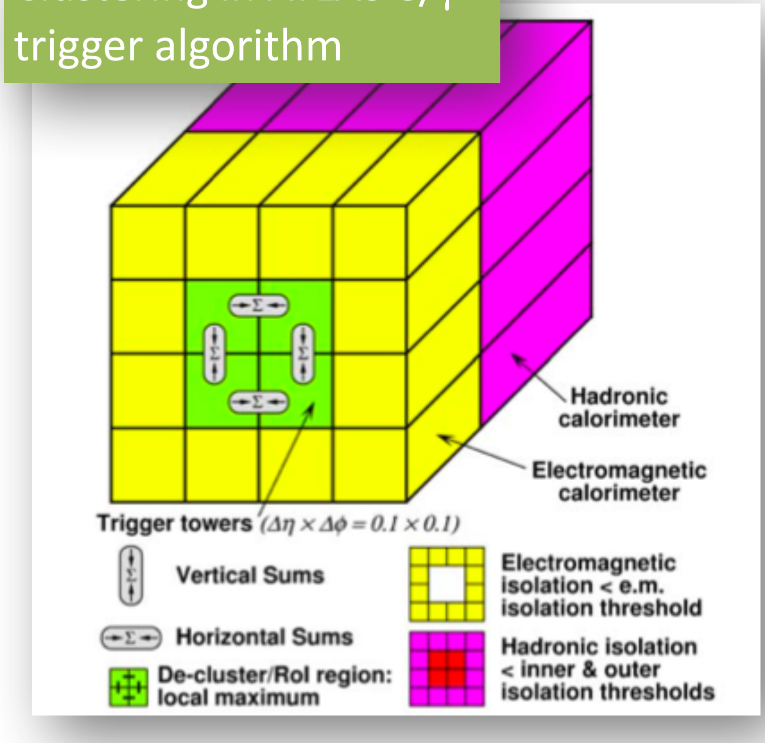
- **High-speed serial links**, electrical and optical, over a variety of distances
  - Low cost, low-power LVDS links, @400 Mbit/s (up to 10 m)
  - Optical GHz-links for longer distances (up to 100 m)
- **High density backplanes** for data exchanges within crates
  - High pin count, with point-to-point connections up to 160 Mbit/s
  - Large boards preferred

# Example: ATLAS calorimeter trigger

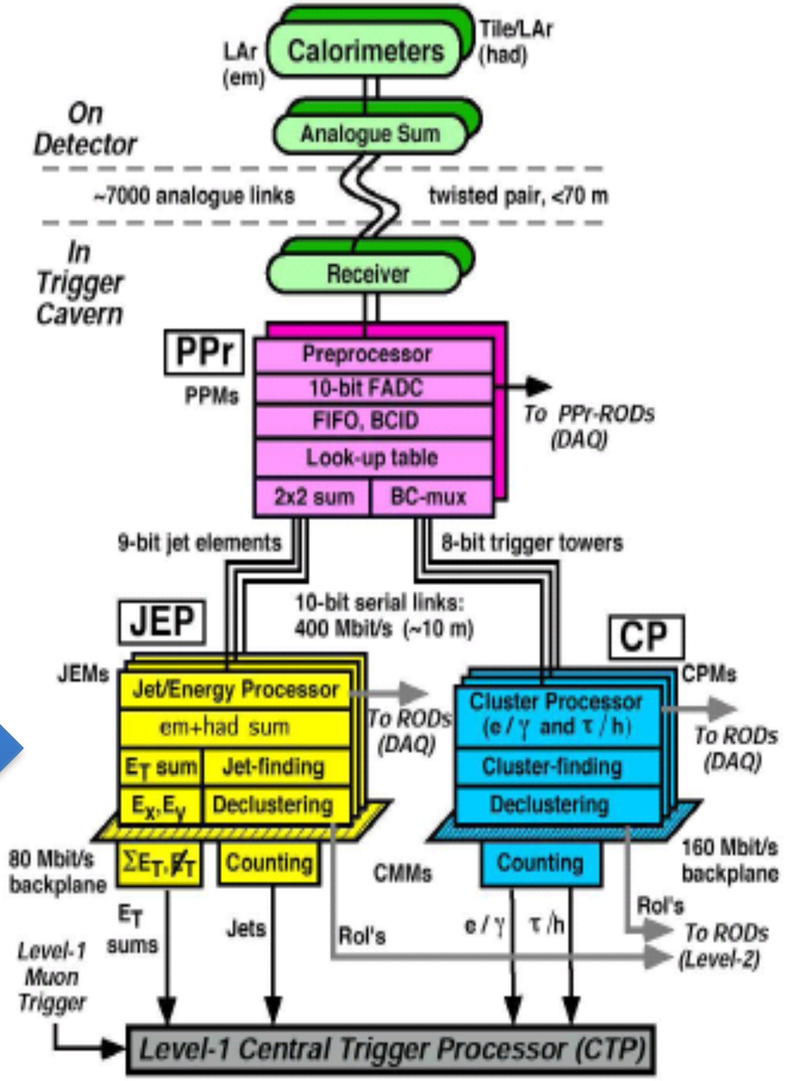
- Cluster Processor (CP)
- Jet/Energy Processor (JEP)

- Programmable FPGAs and ASICs on custom boards
- Total of 5000 digital links @ 400 Mb/s

Clustering in ATLAS e/γ trigger algorithm



Hadronic calorimeter
Electromagnetic calorimeter
Trigger towers $(\Delta\eta \times \Delta\phi = 0.1 \times 0.1)$
Vertical Sums
Horizontal Sums
De-cluster/RoI region: local maximum
Electromagnetic isolation < e.m. isolation threshold
Hadronic isolation < inner & outer isolation thresholds

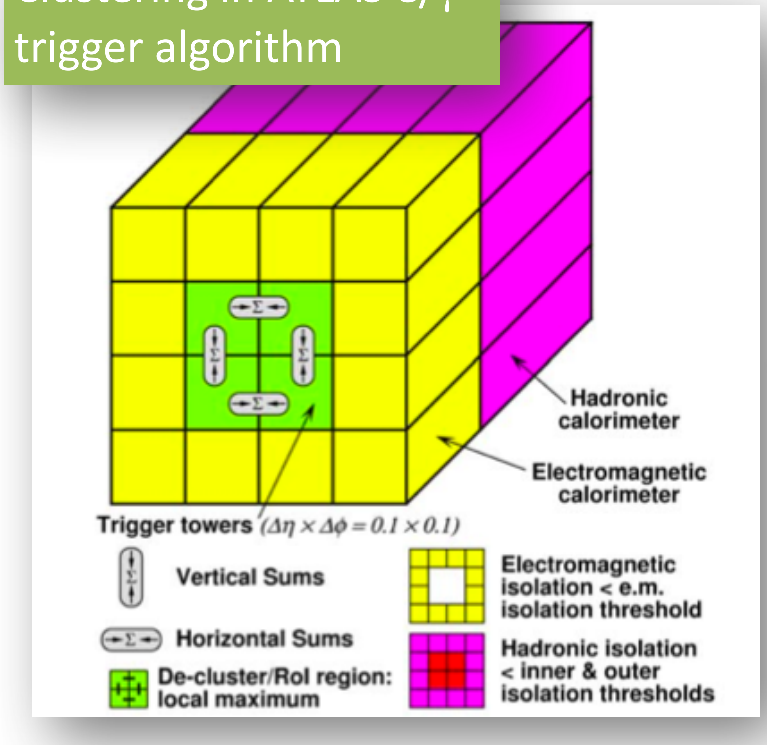


# Example: ATLAS L1 calorimeter trigger

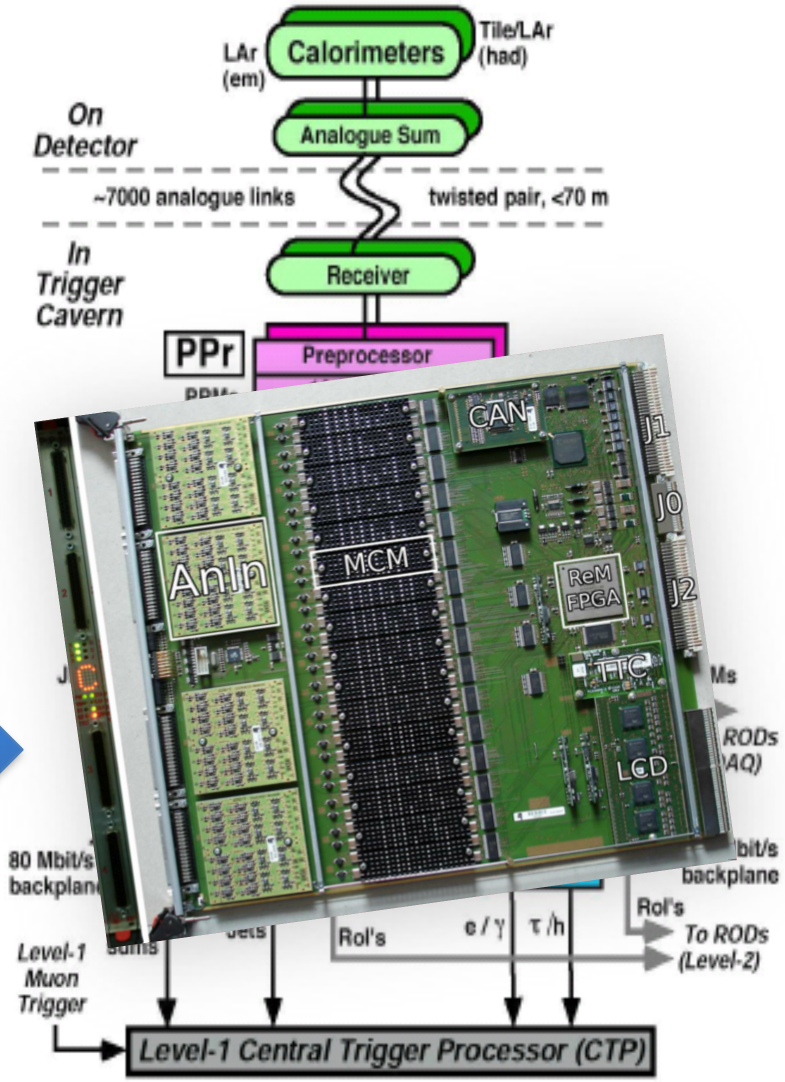
- Cluster Processor (CP)
- Jet/Energy Processor (JEP)

- Programmable FPGAs and ASICs on custom boards
- Total of 5000 digital links @ 400 Mb/s

Clustering in ATLAS e/γ trigger algorithm



Σ
Hadronic calorimeter
Electromagnetic calorimeter
Trigger towers $(\Delta\eta \times \Delta\phi = 0.1 \times 0.1)$
Vertical Sums
Horizontal Sums
De-cluster/RoI region: local maximum
Electromagnetic isolation < e.m. isolation threshold
Hadronic isolation < inner & outer isolation thresholds

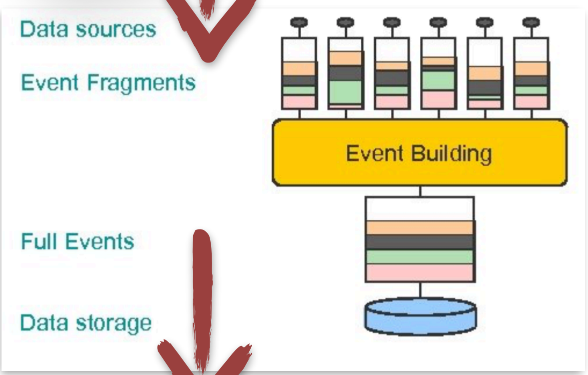


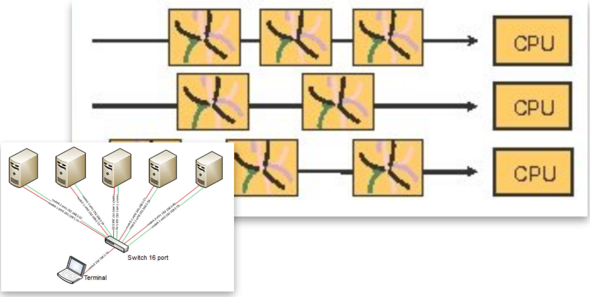
# High Level Trigger and DAQ components

|  | Levels | L1 rate (Hz) | Event size | Readout bandwidth | Event filter output |
|---|---|---|---|---|---|
| **LEP** | 2/3 | 1 kHz | 100 kB | few 100 kB/s | ~5 Hz |
| **ATLAS** | 2/3 | 100 kHz<br>(L2: 10 kHz) | 1.5 MB | 30 GB/s<br>(incremental Event Building) | ~1000 Hz |
| **CMS** | 2 | 100 kHz | 1.5 MB | 100 GB/s | ~1000 Hz |

*cannot store on disk at this rate!*

**Event Builder and Filter**

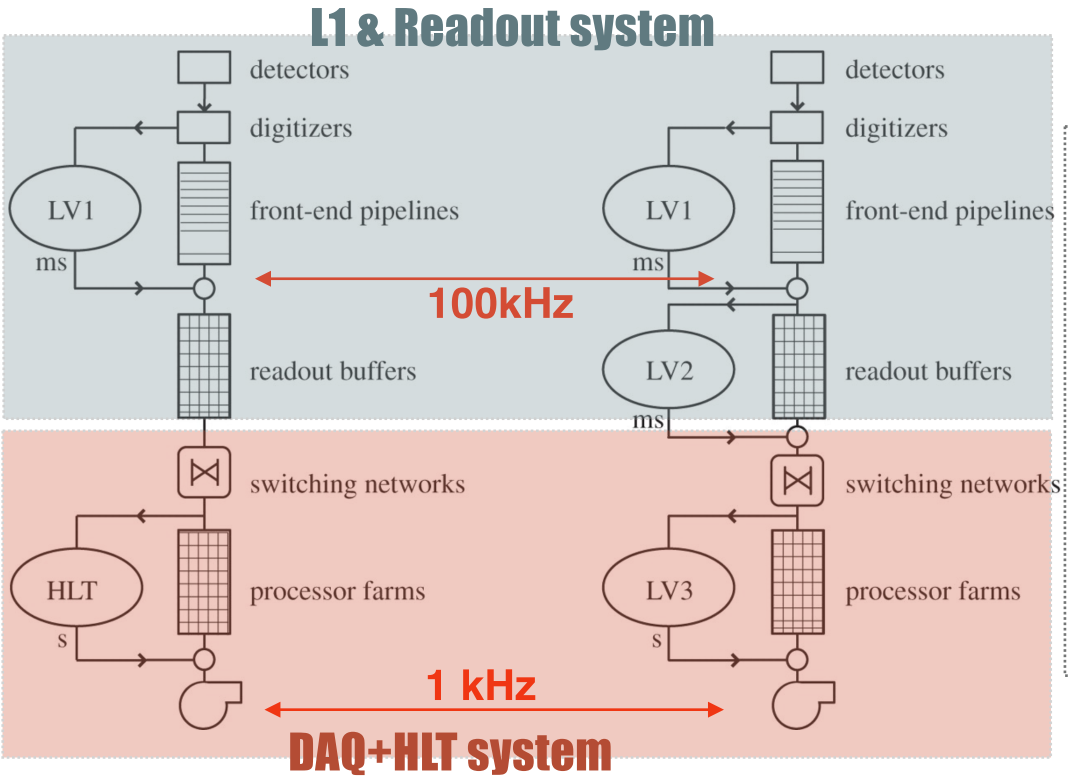




After the L1-trigger selection, data rates are reduced, but can be still massive!

- **Readout Network**: data are collected from Front-End buffers
  - LEP: 40 MB/s VME bus was able to support the bandwidth
  - LHC: use **latest technologies** in processing power, high-speed network interfaces, optical data transmission
- **Event Building and Filter farms**: events reconstructed and filtered
  - **farm processing**: one event per processor (larger latency, but scalable)
  - additional networks regulates the CPU assignment
  - prefer commercial products: PCs (linux based), Ethernet protocols, standard LAN, configurable devices

# Choosing the DAQ+HLT architecture



### ATLAS/CMS Example

- 1 MB/event at 100 kHz for O(100 ms) HLT latency
  - Network: 1 MB*100 kHz = **100 GB/s**
  - HLT farm: 100 kHz*100 ms = **O($10^4$) CPU cores**
- Can add intermediate steps (level-2) to reduce resources, at cost of complexity (at ms scale)

*See S.Cittolin, DOI: 10.1098/rsta.2011.0464*

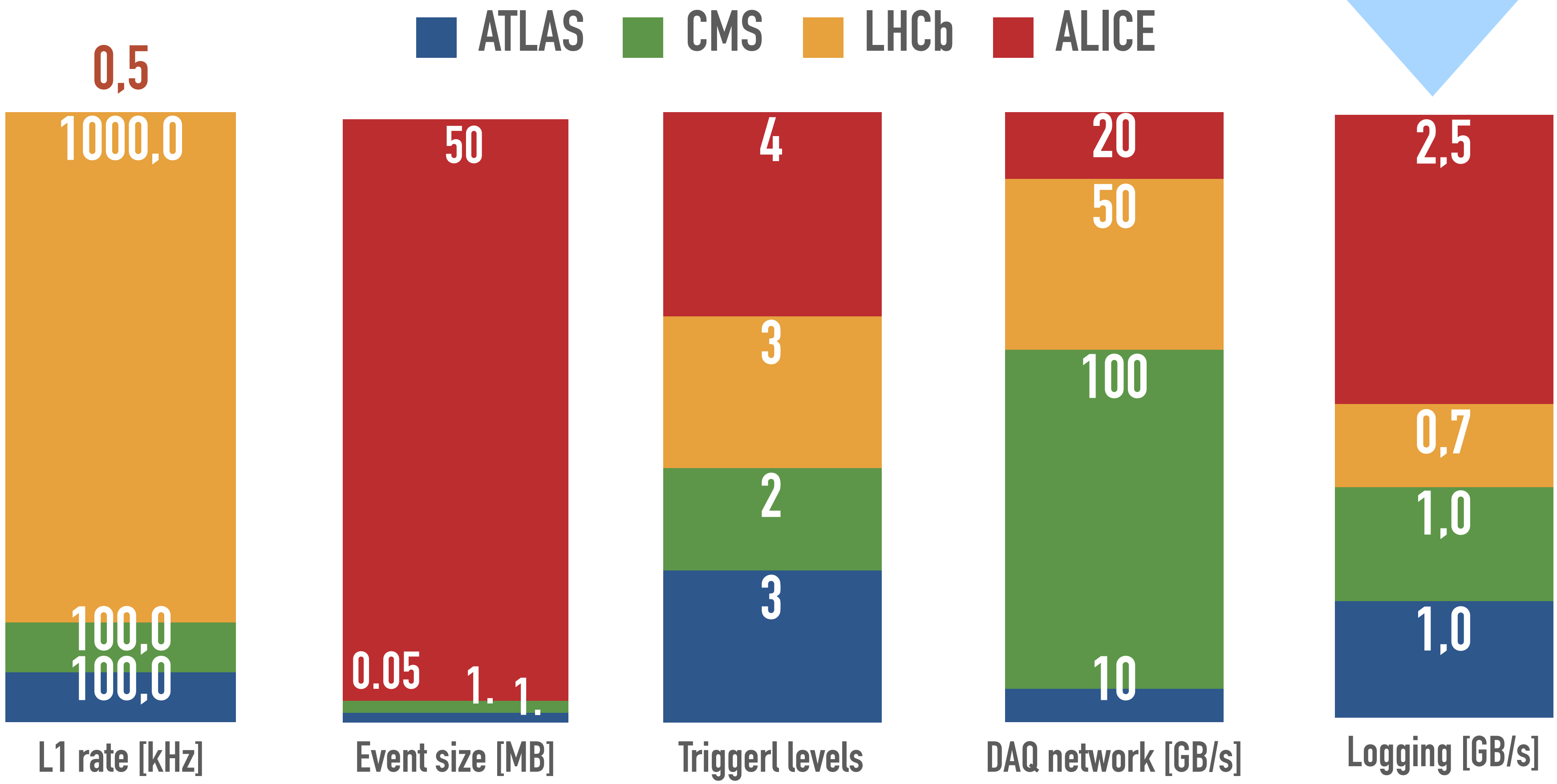
- High data rates can be held with different approaches
  - Network-based event building (LHC example: CMS)
  - Seeded reconstruction of partial data (LHC example: ATLAS)

# Comparing LHC experiments design

The 4 LHC experiments share the CERN budget for computing resources, which is the constrain between trigger and DAQ rate

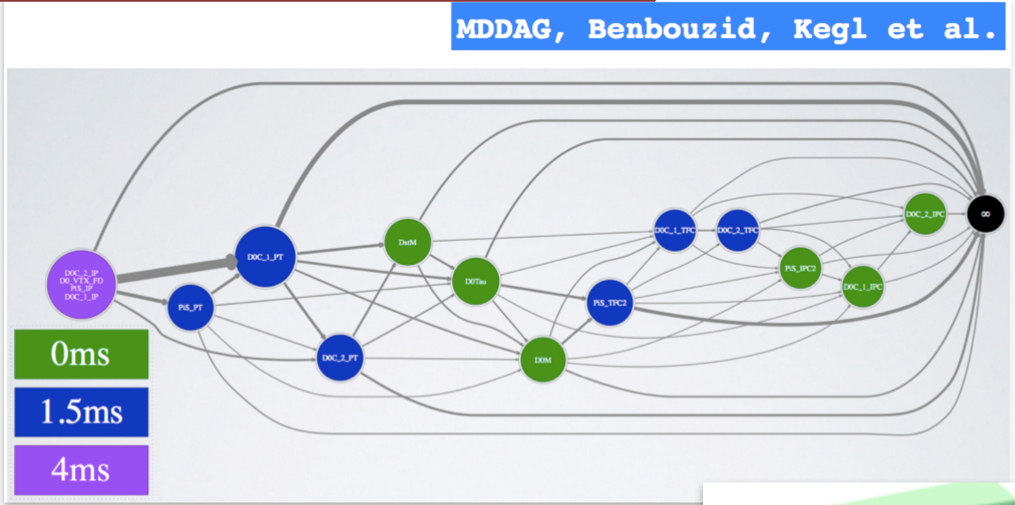
Design in 2009:

allowed storage and processing resources: ~1GB/s



# Can we use any algorithms online?

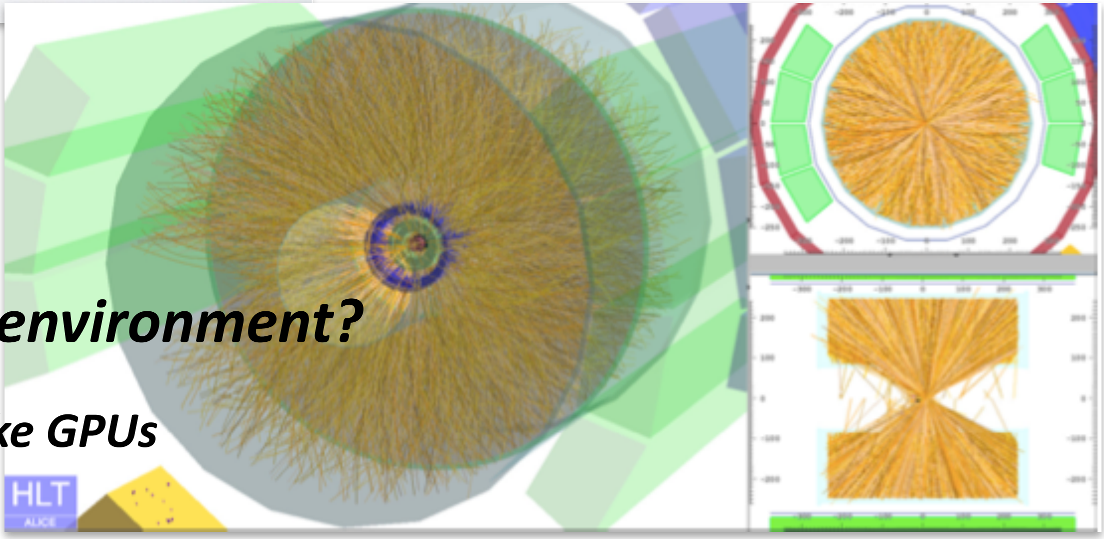
**Latency is the constraint!**



MDDAG, Benbouzid, Kegl et al.

***Multivariate analysis?***

*Yes, recently included in both software and hardware (FPGA) processing*

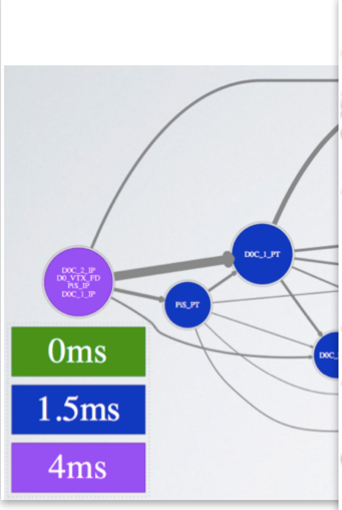


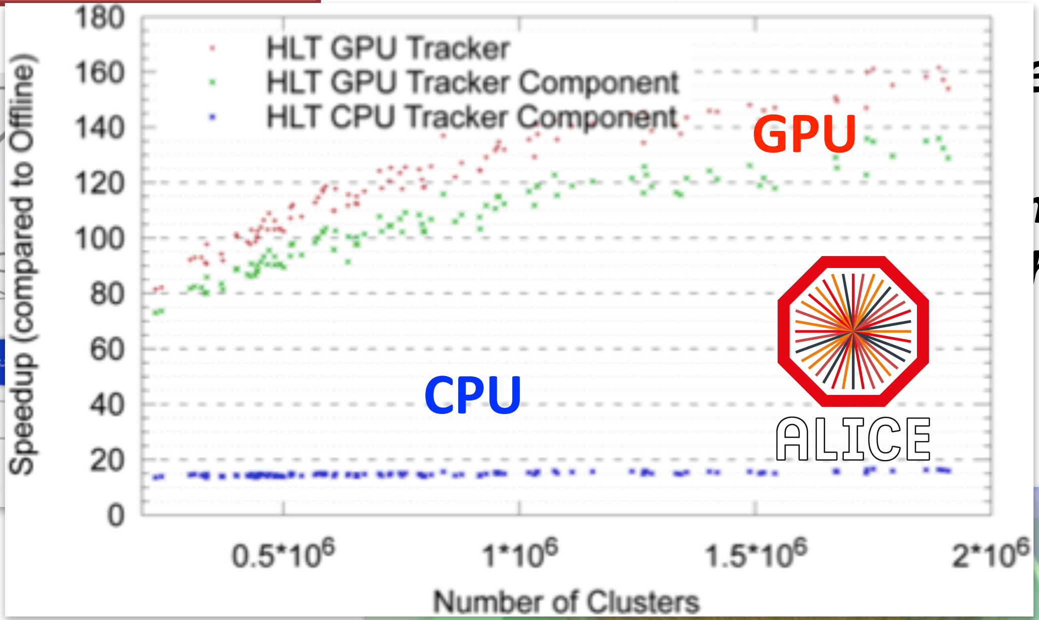
***Pattern recognition in dense environment?***

*Yes, with the help of co-processors like GPUs*

# Can we use any algorithms online?

**Latency is the constraint!**

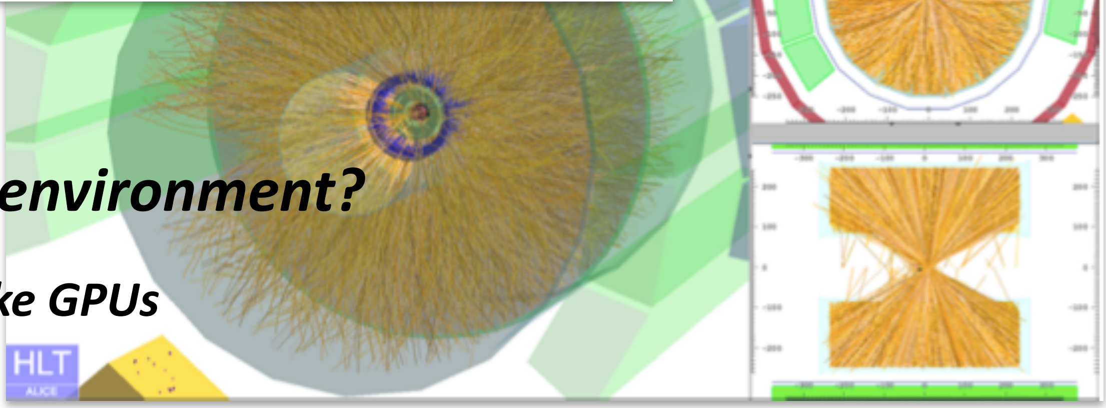




***e analysis?***

***ncluded in both***

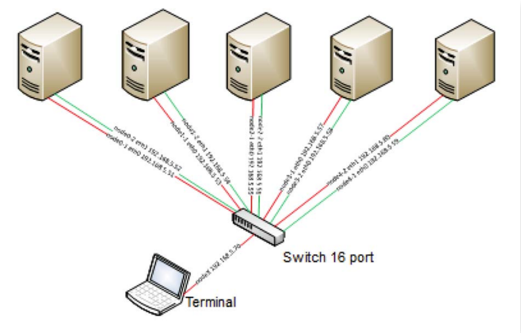
***hardware (FPGA)***



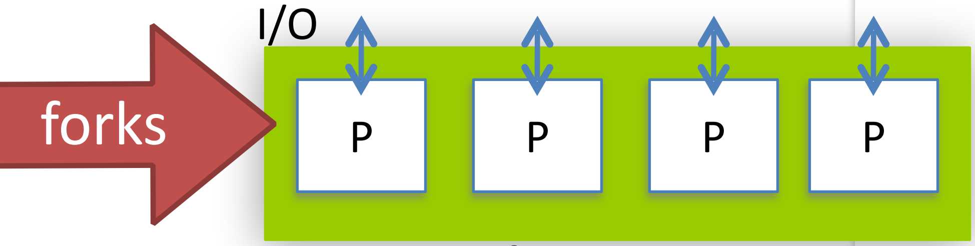
***Pattern recognition in dense environment?***

***Yes, with the help of co-processors like GPUs***

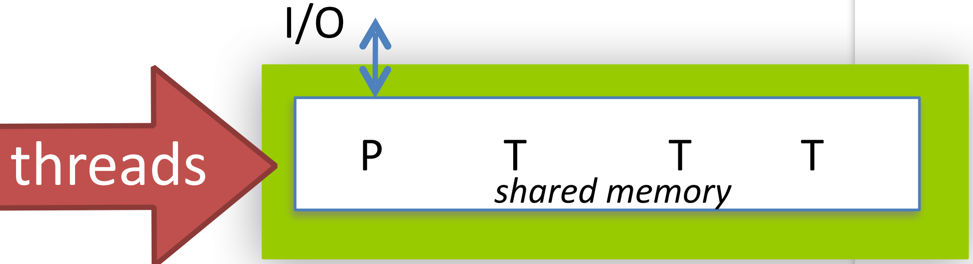
# HLT software design principles



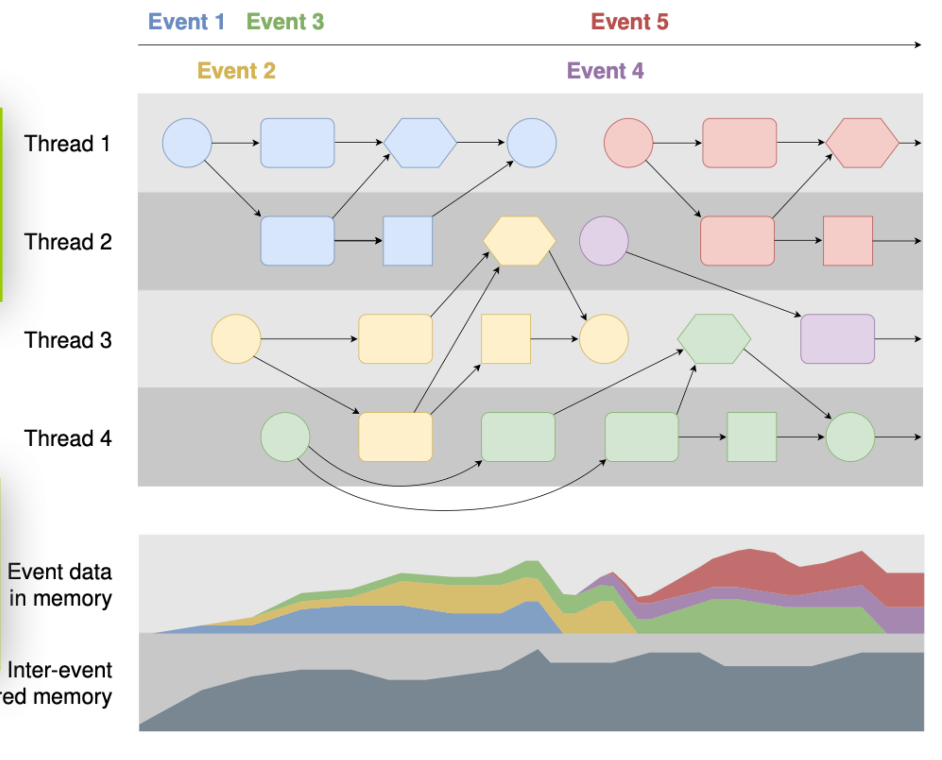
- **Early rejection:** alternate feature extraction with hypothesis testing
- **Partial event data processing**
- **Fast reconstruction:** but try to reuse offline software, for easy maintenance and higher efficiency
- **Increase parallelism to exploit all CPU resources (all cores!)**
  - event-level
  - algorithm-level



**Multi-processing**



**Multi-threading**



# What’s up for the future of software trigger?

what we want

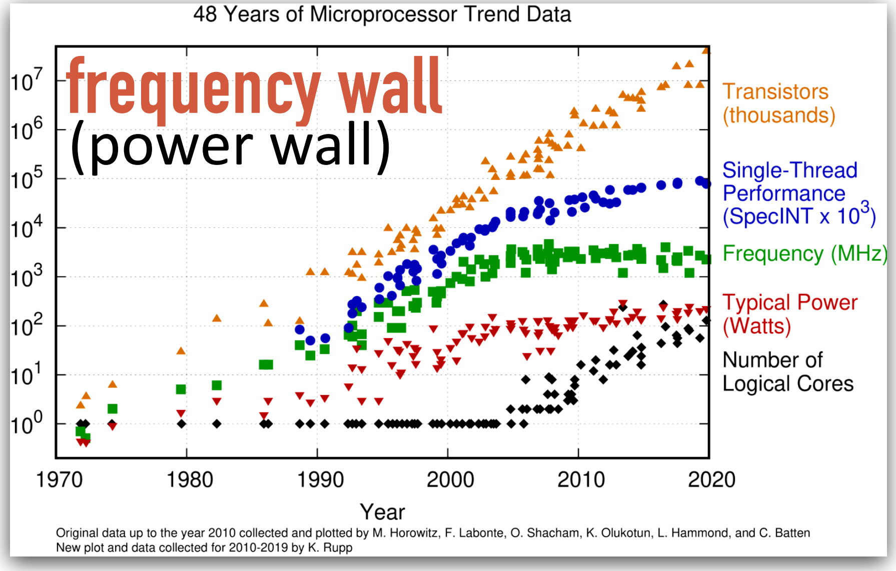
$$R = \mu \cdot f_{BC} = \sigma_{in} \cdot L$$

- ➡ Linear increase of digitisation time
- ➡ Factorial increase of reconstruction time
- ➡ Larger events, lots of more memory

Higher rates requires more processing/memory

what we have

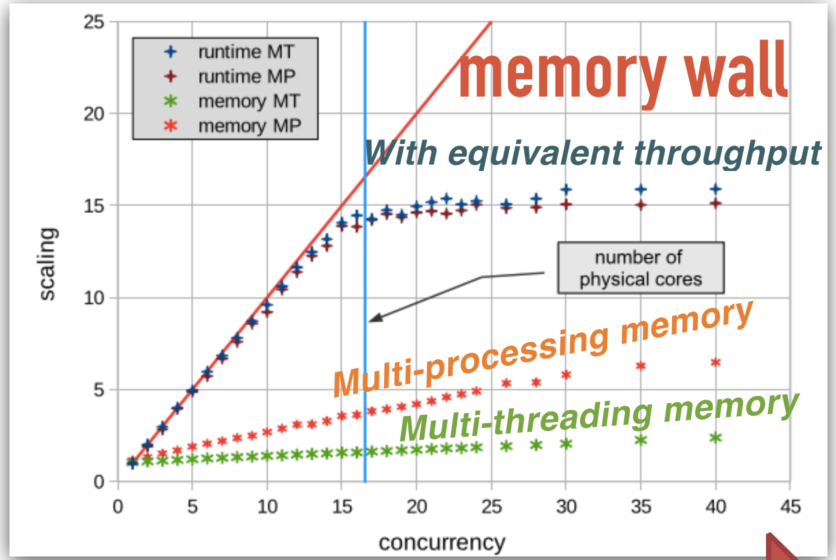
## Technology evolution



frequency wall (power wall)

Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2019 by K. Rupp

## Throughput/memory scaling for a tracking demonstrator



memory wall

With equivalent throughput

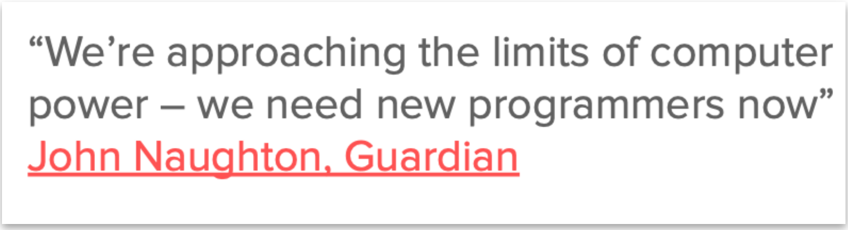
Multi-processing memory

Multi-threading memory

Exploit more efficiently instruction level parallelism (ILP)

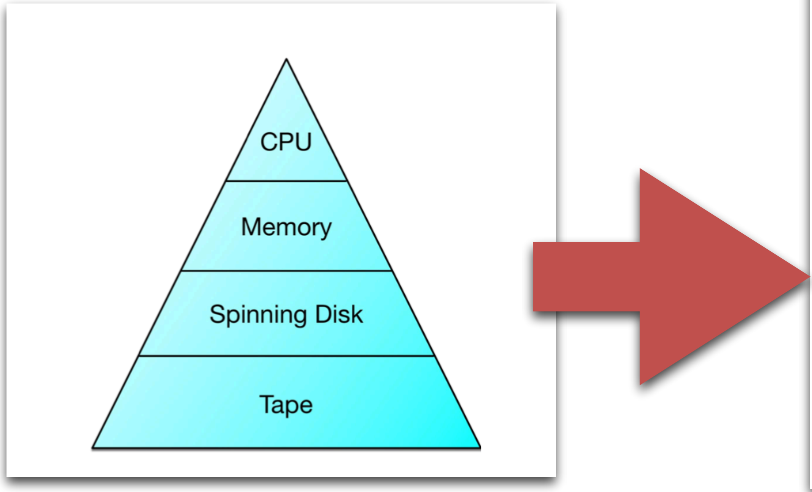
Limits on the capabilities of serial processing

# (Trigger) software evolution to break walls

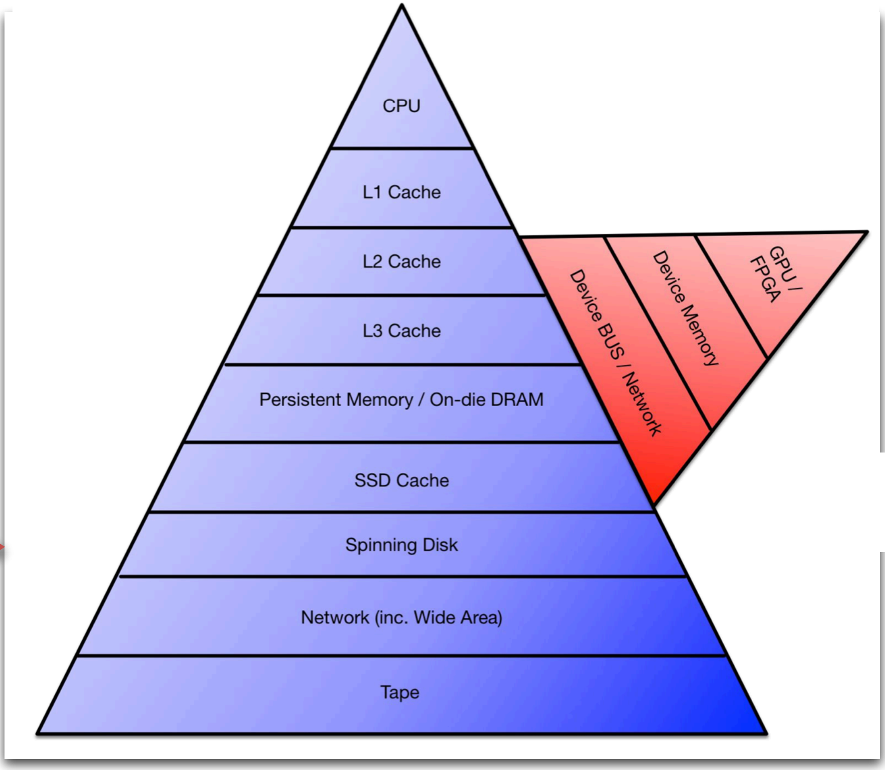


"We're approaching the limits of computer power – we need new programmers now"
John Naughton, Guardian

With explosion of novel computer architectures



See LP-2022 slides from Graeme Stewart



**==> Exploiting CPU hardware in new architectures**

- more complicated programming (vectorisation, memory sharing…)

**==> Move towards concurrent processing**

- multiple events in flight, sub-event parallelism
- delegate accelerators for specific tasks

# Concluding remarks

- The trigger strategy is a trade-off between physics requirements and affordable systems and technologies
  - A good design is crucial – then the work to maintain optimal performance is easy

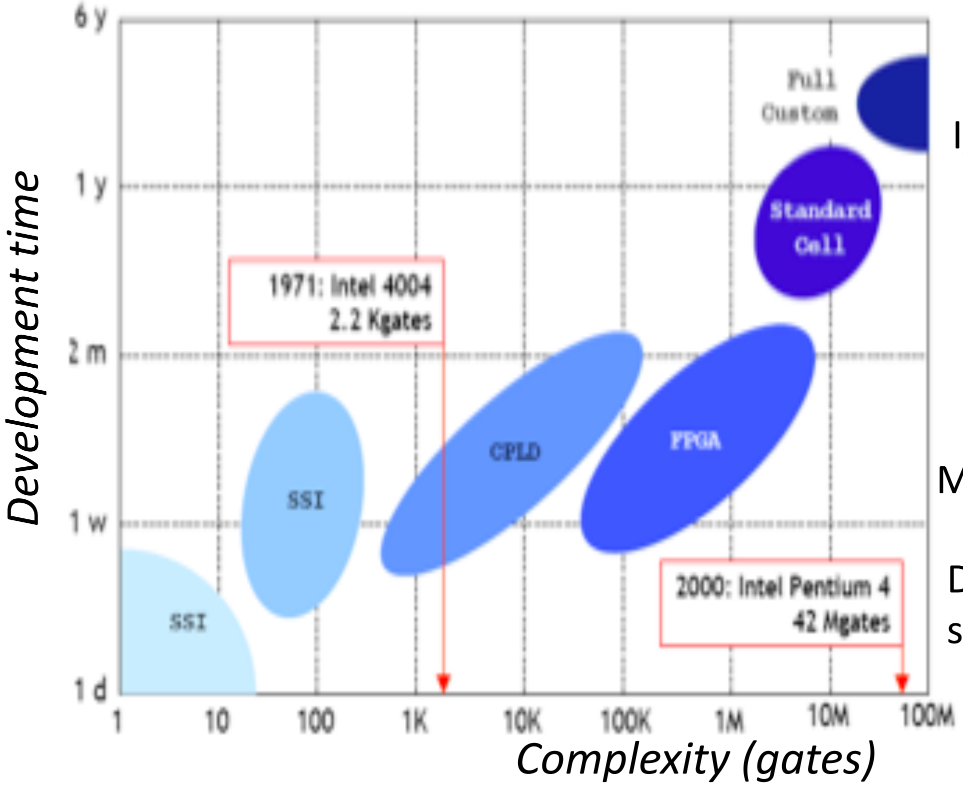
- Here we just reviewed the main trigger requirements coming from physics
  - High efficiency – rate control
  - Perfect knowledge of the trigger selection on signal and background
  - Flexibility and redundancy

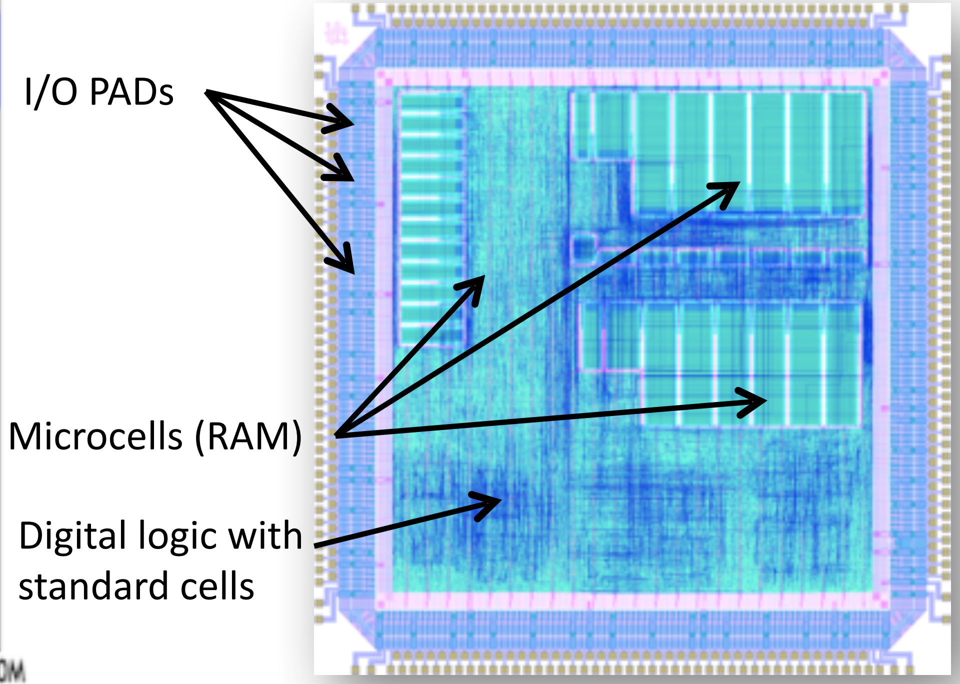
- Microelectronics, networking, computing expertise are required to build an efficient trigger system
  - But being always in close contact with the physics measurements we want to study

# Back-up slides

# Custom trigger processors?

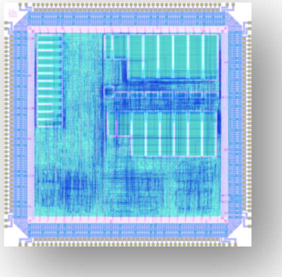
- Application-specific integrated circuits (**ASICs**): optimized for fast processing (Standard Cells, full custom)
  - Intel processors, ~ GHz
- Programmable ASICS (like Field-programmable gate arrays, **FPGAs**)
  - Easily find processors @ 100 MHz on the market (1/10 speed of full custom ASICs)





Layout of the CM ASIC

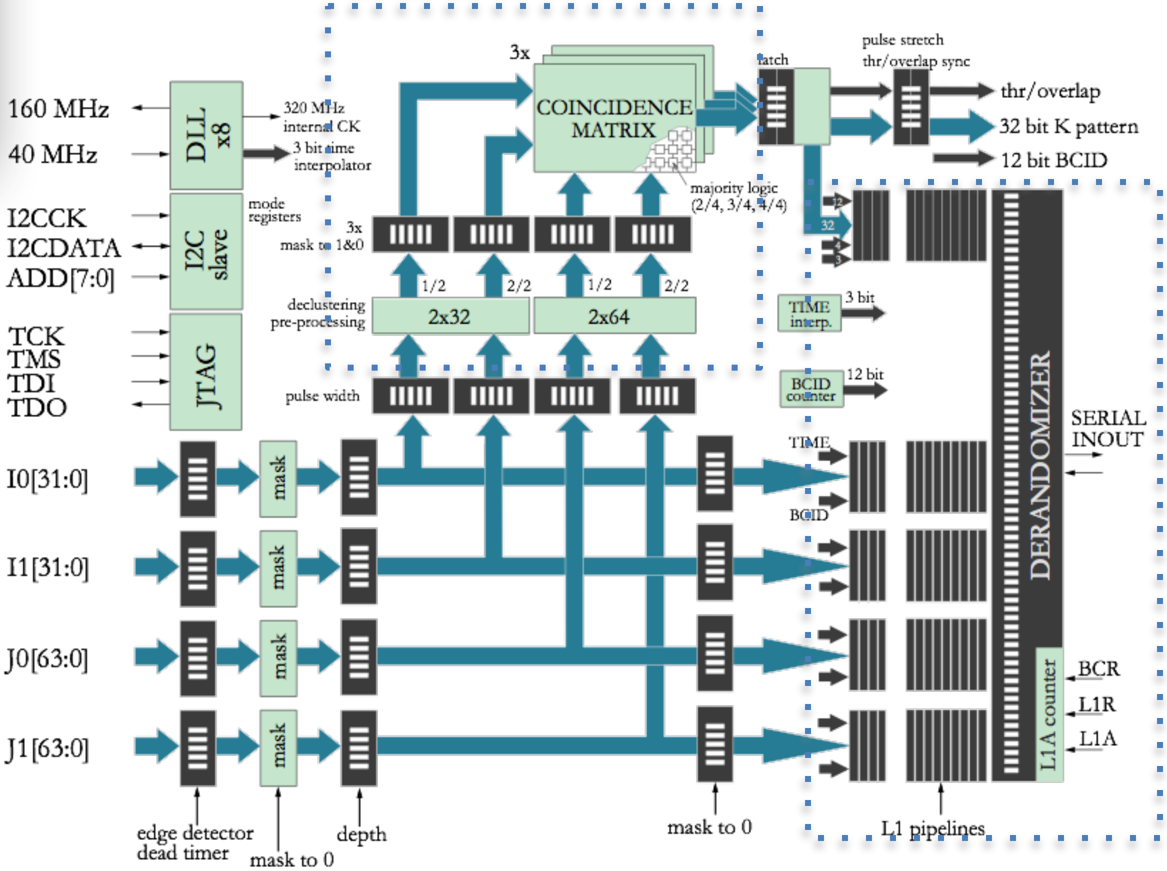
# Example: logic of a trigger ASIC



Trigger part

Trigger output

Digital inputs from detector



Readout output

Input: synchronization signals

Readout part

***Coincidence Matrix ASIC for Muon Trigger in the Barrel of ATLAS***

# Trends in processing technology

- Request of higher complexity → higher chip density → **smaller structure size** (for transistors and memory size): **32 nm → 10 nm**
  - Nvidia GPUs: 3.5 B transistors
  - Virtex-7 FPGA: 6.8 B transistors
  - 14 nm CPUs/FPGAs in 2014

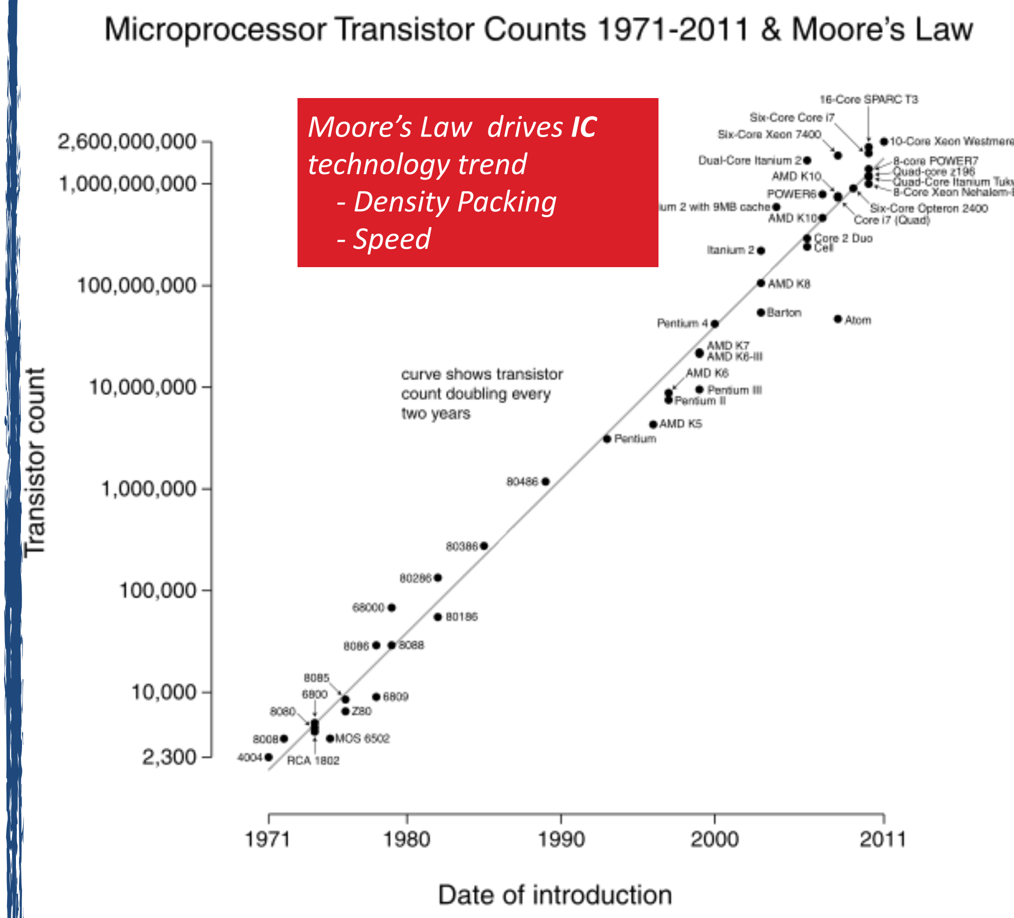
- For FPGAs, smaller feature size means higher-speed and/or less power consumption

- Multi-core evolution
  - Accelerated processing GPU+CPU
  - Needs increased I/O capability

- Moore's law will hold at least until 2020, for FPGAs and co-processors as well

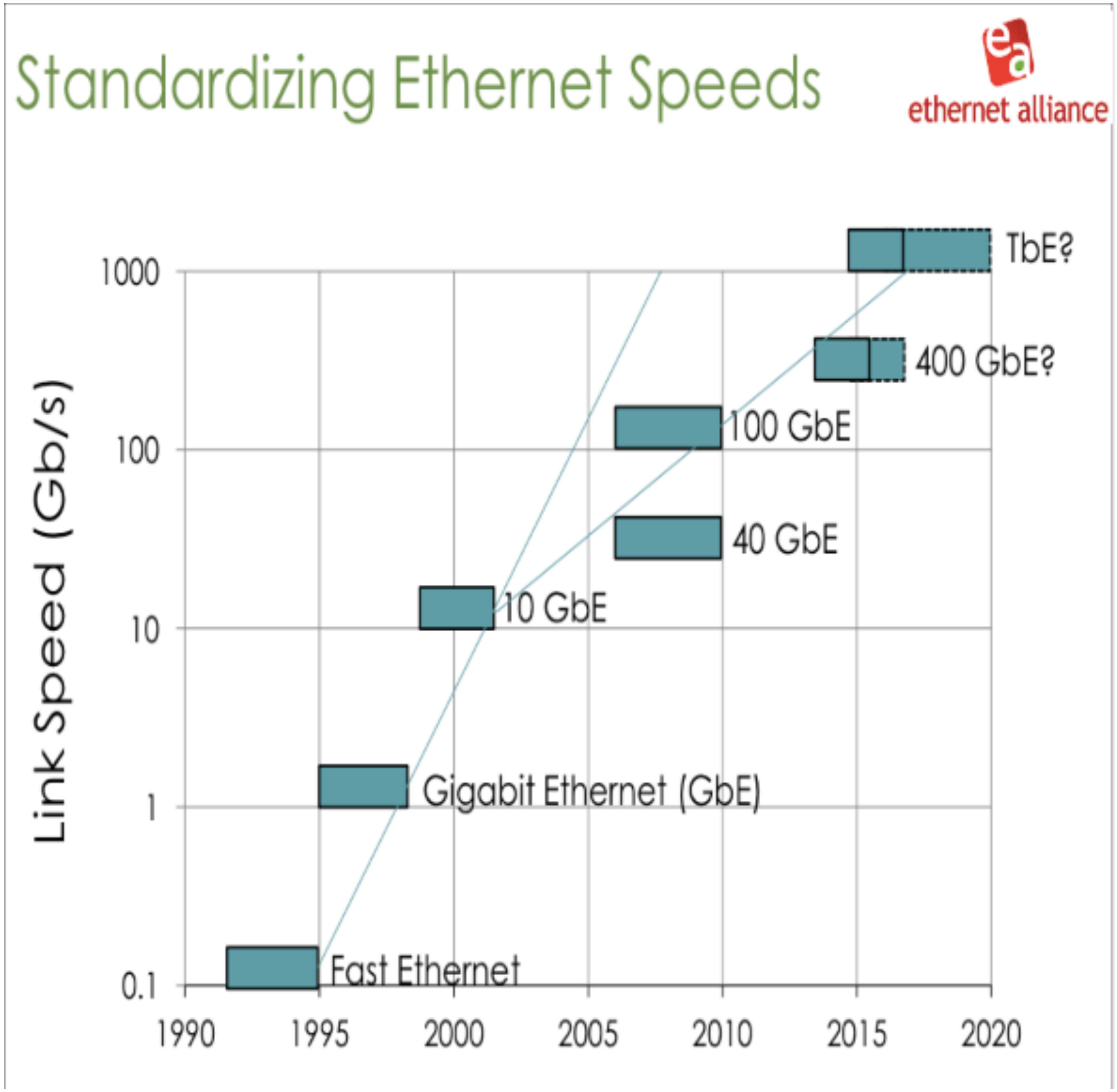
- Market driven by cost effective components for Smartphones, Phablets, Tablets, Ultrabooks, Notebooks ….

- Read also: http://cern.ch/go/DFG7



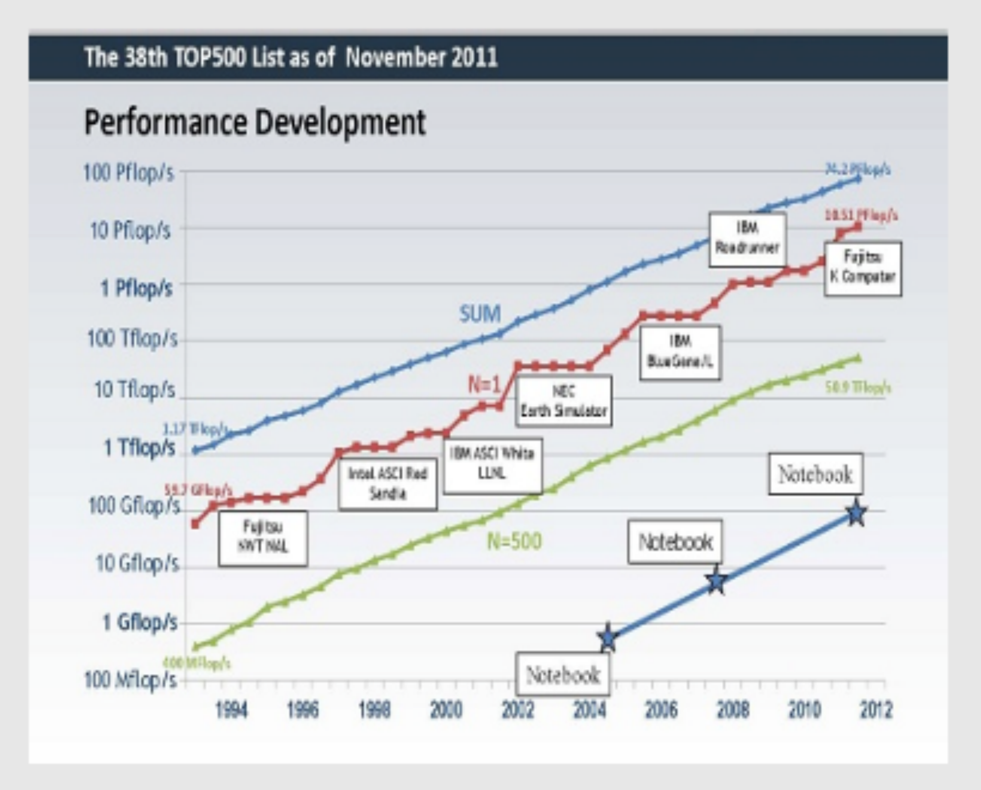
*Moore's Law drives **IC** technology trend*
- *Density Packing*
- *Speed*

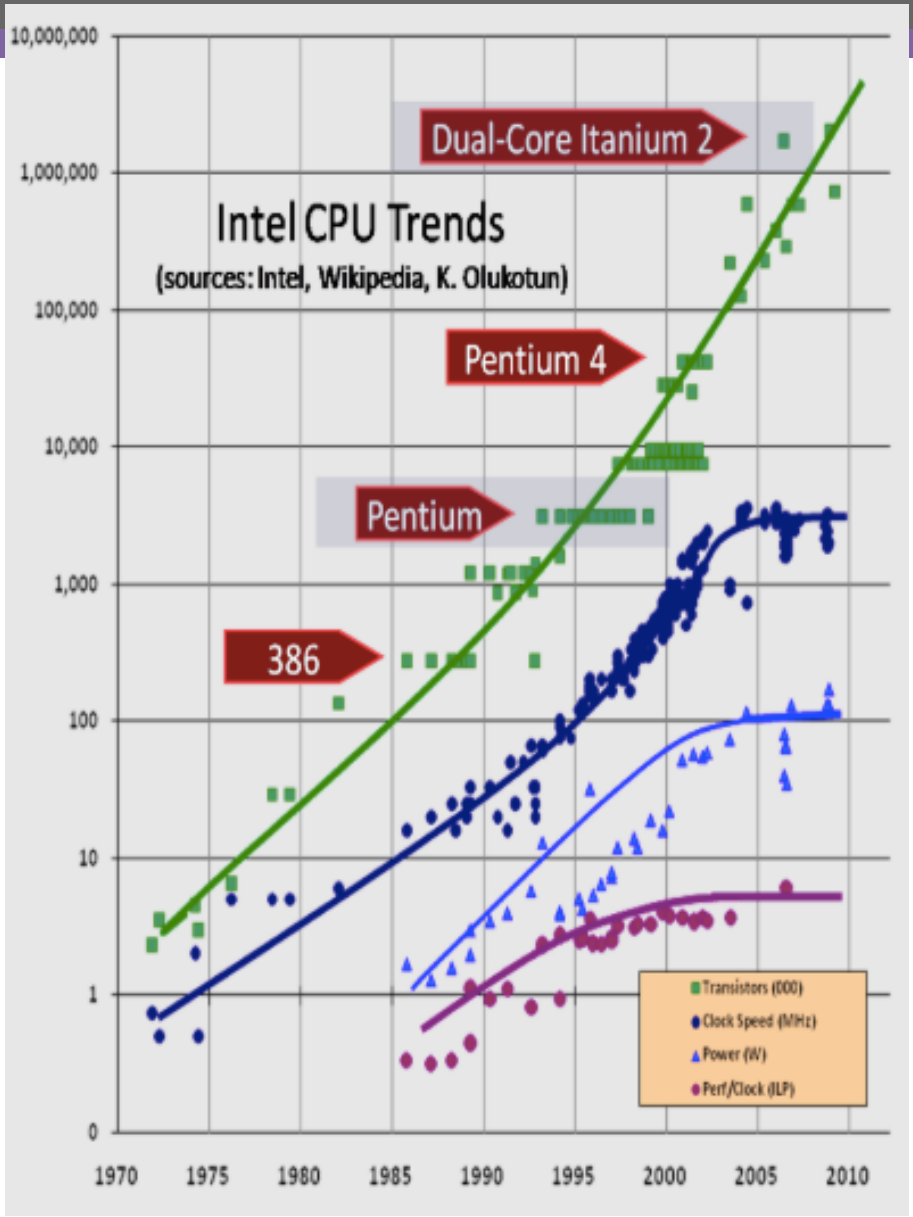
*Moore's Law: the number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years (Wikipedia)*



# Standardizing Ethernet Speeds

ethernet alliance


The 38th TOP500 List as of November 2011
Performance Development
100 Pflop/s
10 Pflop/s
1 Pflop/s
100 Tflop/s
10 Tflop/s
1 Tflop/s
100 Gflop/s
10 Gflop/s
1 Gflop/s
100 Mflop/s
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
74.2 Pflop/s
10.51 Pflop/s
50.9 Tflop/s
1.17 Tflop/s
59.7 Gflop/s
400 Mflop/s
SUM
N=1
N=500
IBM Roadrunner
Fujitsu K Computer
IBM BlueGene/L
NEC Earth Simulator
IBM ASCI White LLNL
Intel ASCI Red Sandia
Fujitsu NWT NAL
Notebook
Notebook
Notebook


Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)
Dual-Core Itanium 2
Pentium 4
Pentium
386
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
Transistors (000)
Clock Speed (MHz)
Power (W)
Perf/Clock (ILP)