An introduction to the trigger systems

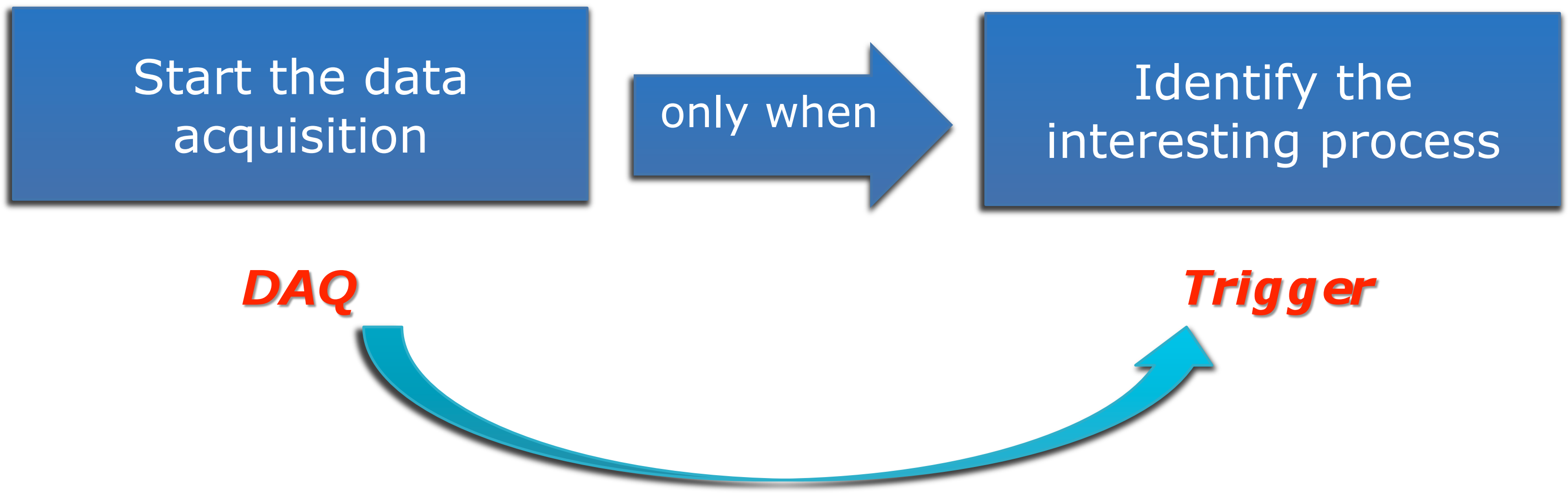
F.Pastore (RHUL)

Outline

- Trigger concept and requirements
  - The challenge of the hadron collider experiments
- Trigger architecture
  - Dead-time and the multilevel triggers
- Trigger selections and connections to physics
  - Measuring the trigger efficiency
  - Trigger menus

Most of the examples refer to LHC and ATLAS in particular, not by chance….

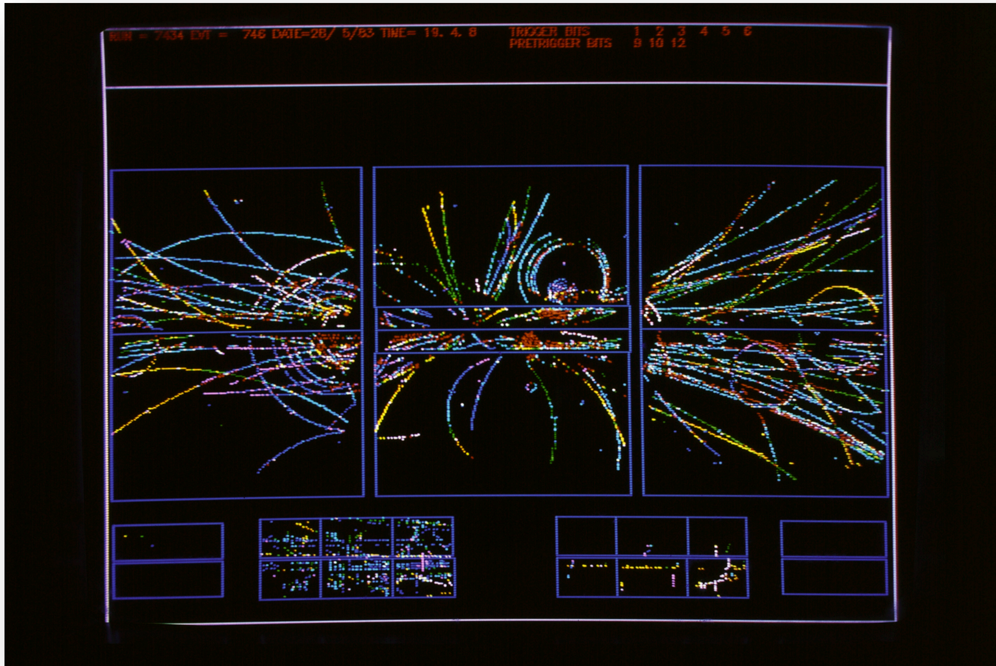
Trigger concept in HEP



- What is "interesting"?
  - Define what is signal and what is background
- Which is the final affordable rate of the DAQ system?
  - Define the maximum allowed rate
- How fast the selection must be?
  - Define the maximum allowed processing time

Trigger for collider experiments

- At the collider experiments, we have bunches of particles crossing at regular intervals and interactions occur during the bunch-crossings (BCs)
  - **Event**: the trigger selects the bunch crossing of interest for physics studies, and all the information from the detectors corresponding at that given BC are recorded



The role of the trigger is to make the **online selection** of particle collisions potentially containing interesting physics

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

L = Instant. luminosity
f_{BC} = Rate of bunch crossings
μ = Average (pp) interactions / BC

The problem of the rate

colliders	BC time	collision rate	Design luminosity (cm^{-2} s^{-1})
LEP	22 ms	45 kHz	7 x 10^{31}
Tevatron	396/132 ns	2.5/7.6 MHz	4 x 10^{32}
LHC	25 ns	40 MHz	10^{34} →

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

25 * 40 MHz ≈ 70 mb *10/nb
≈ **1GHz**

Maximum acceptable rate ~ O(100) Hz

- The crossing time defines an overall time constant for signal integration, DAQ and trigger
- Even at low luminosity colliders, the rate of the interactions is not affordable by any data taking system
  - The output rate is limited by the **offline computing budget and storage capacity**
  - Only a small fraction of production rate can be used in the analysis
- Don't worry, not any interaction is interesting for our studies, most of them can be rejected…..

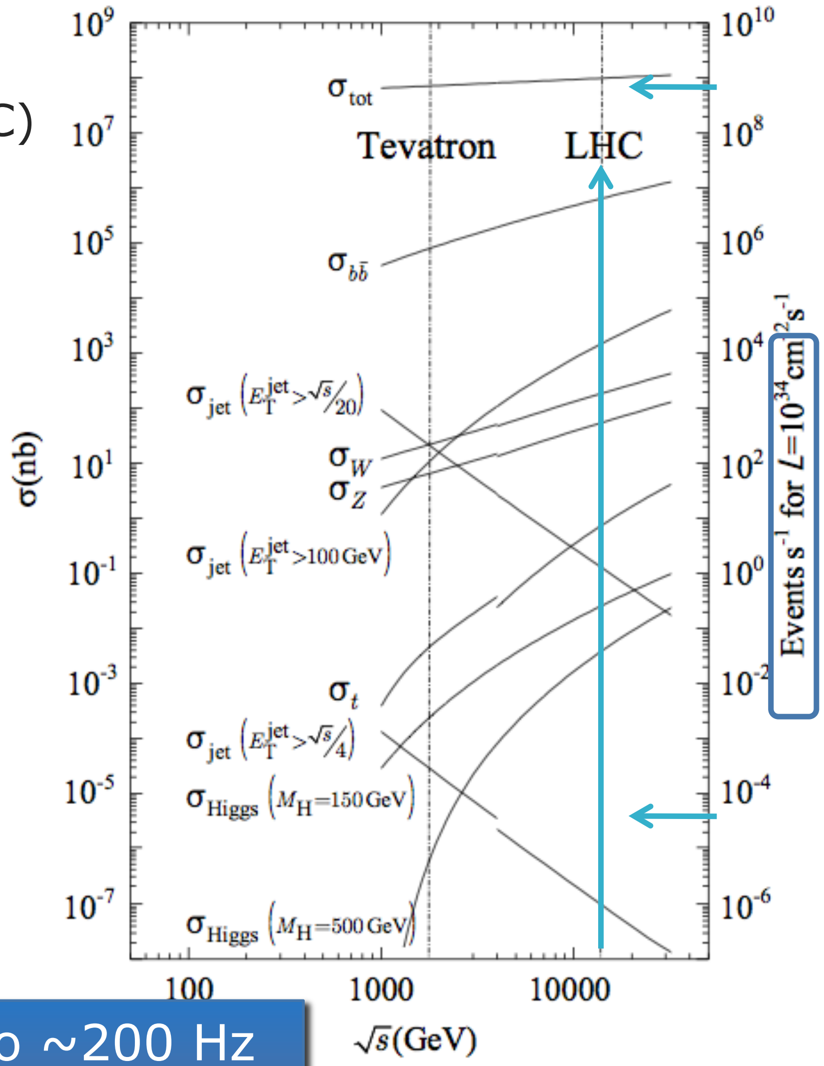
A trigger challenge: hadron colliders

- Production cross-sections span over many orders of magnitude (10 Tevatron, 12-13 LHC)
  - Collision rate is dominated by non interesting physics
  - Background discrimination is crucial

Total non-diffractive p-p cross section at LHC ($\sqrt{s}$=14 TeV) is ~ **70 mb**

Huge range of cross-sections and production rates (example with design Luminosity):

Beauty (0.7 mb)	– 10^3 Hz
W/Z (200/60 nb)	– 100 Hz
Top (0.8 nb)	– 10 Hz
Higgs - 150 GeV (30 pb)	– 0.1 Hz

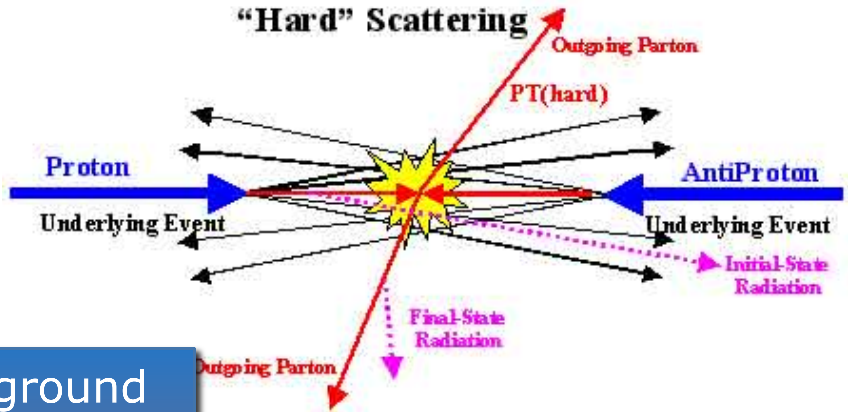


Trigger must reduce event rates from GHz to ~200 Hz

…and more requirements

Inclusive selection

- Multi-purpose experiments: the trigger must satisfy a broad physics program, with no bias
  - Main discovery channel (Higgs @LHC, top @Tevatron), with precision EW
  - Search for new phenomena
  - Tests of pert-QCD, B physics….



Flexible to cope changes in Luminosity and background

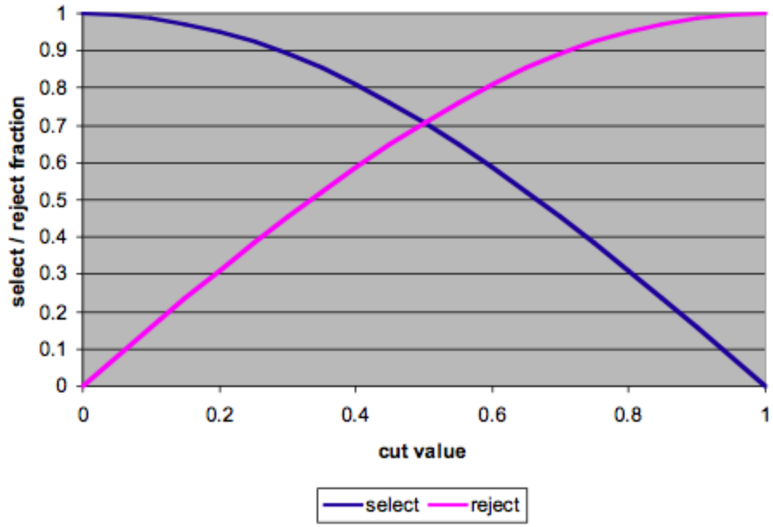
- Unlike e+e- colliders, each event contains more than one interaction, which add superimposed information on the detectors: pile-up
  - "underlying events" from other partons in the same collision and interactions from nearby bunch-crossings
    - Detectors requirements
    - The event characteristics vary with luminosity, not a simple events rescaling but events with different number of muons, clusters,... affecting:
      - the event-size, mainly with huge number of readout channels
      - the trigger selection

trigger requirements in HEP, i.e. what we want from the trigger?

- Rate control = strong **background rejection**
  - Instrumental or physics background
  - Sometimes backgrounds have rates much larger than the signal
    - Need to identify **characteristics** which can suppress the background
    - Need to demonstrate solid **understanding** of background rate and shapes

- Maximize the collection of data for physics process of interest = **high efficiency** for benchmark physics processes
  - $\varepsilon_{trigger} = \mathbf{N_{good}\ (accepted) / N_{good}\ (produced)}$

  - Not always both requirements can be realized: a compromise between number of processors working in parallel and fastness of the algorithms - to make it affordable
  - as selection criteria are tightened
    - background rejection improves
    - But selection efficiency decreases

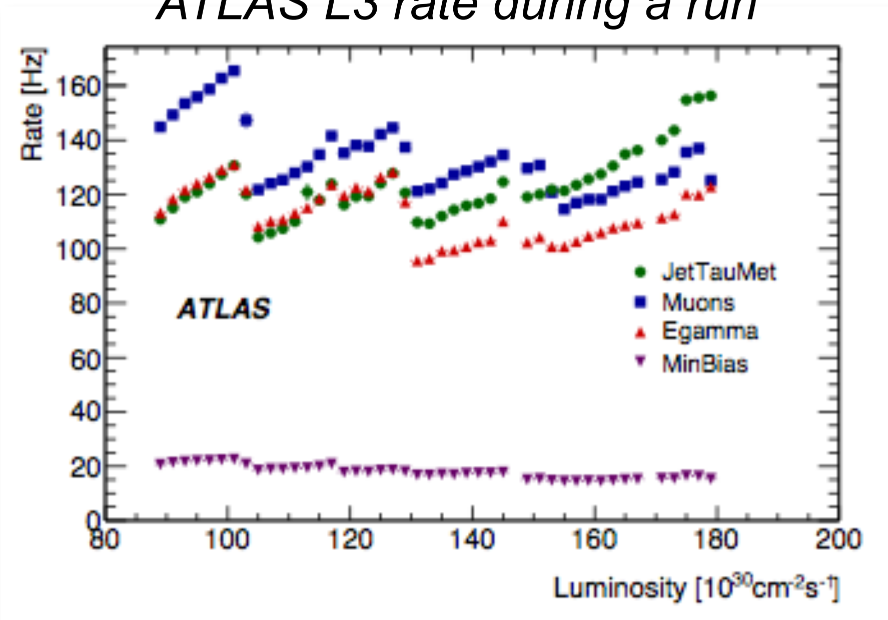


- **Robustness** of the selection is required, since discarded events are lost forever (reliable)

Different kind of triggers

- The bulk of the selected events are those useful for the physics analysis, but the trigger must also ensure rates for
  - Instrumental and physics background studies
  - Detector and trigger efficiency measurement from data
  - Calibrations, tagging, energy scales…..
- Back-up triggers
  - Back-up is misleading…. These triggers are mandatory for most of the analysis
  - Some large rate back-up triggers can be pre-scaled
- Pre-scaled triggers
  - Only a fraction N of the events satisfying the criteria is recorded. This is useful for collecting samples of high-rate triggers without swamping the DAQ system
  - Since trigger rate changes with Luminosity, **dynamic pre-scales** are sometimes used (reduce the pre-scales as Luminosity falls)

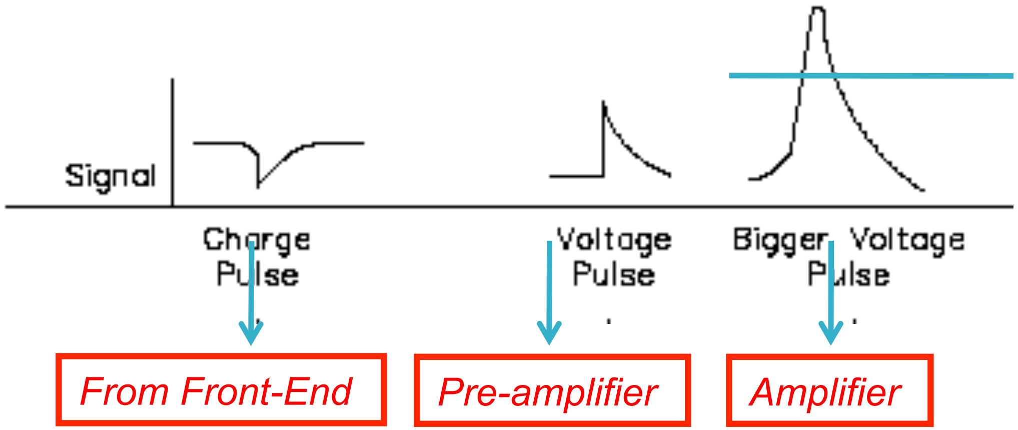
ATLAS L3 rate during a run

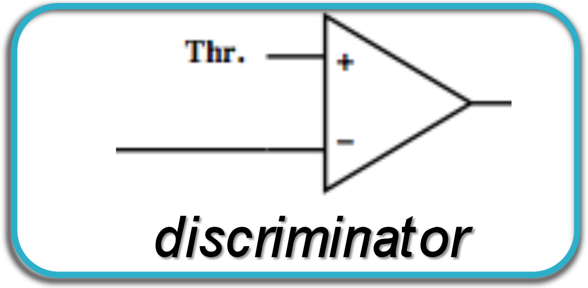


Minimum-bias triggers provide control triggers on the collision (soft QCD events), usually pre-scaled

The simplest trigger system

- Source: signals from Front-End electronics
  - Binary trackers (pixels, strips)
  - Analog signals from trackers, time of light

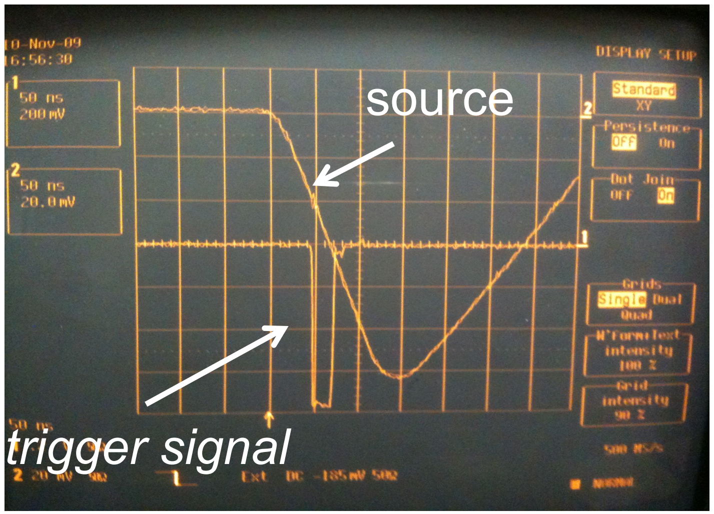




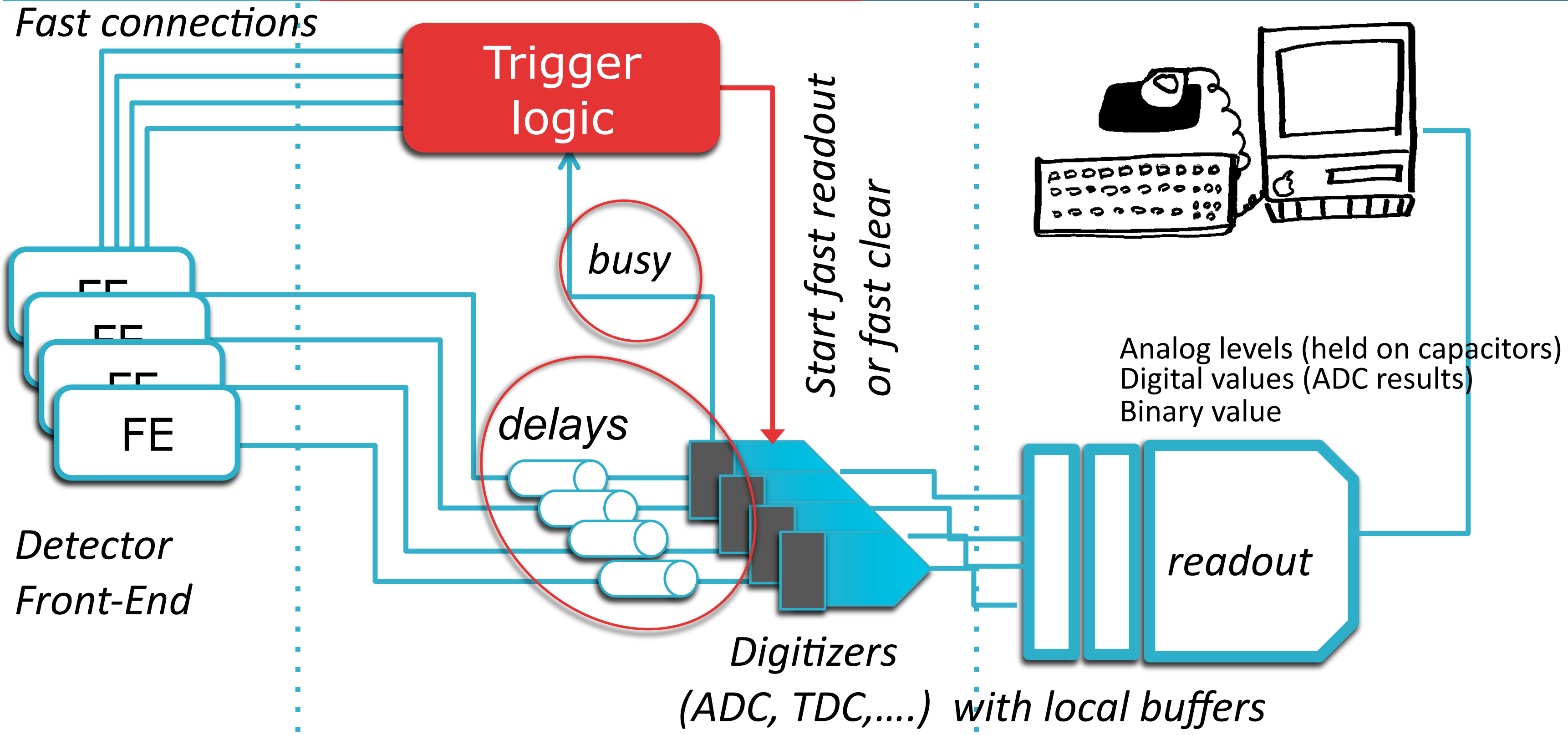
Yes

No

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



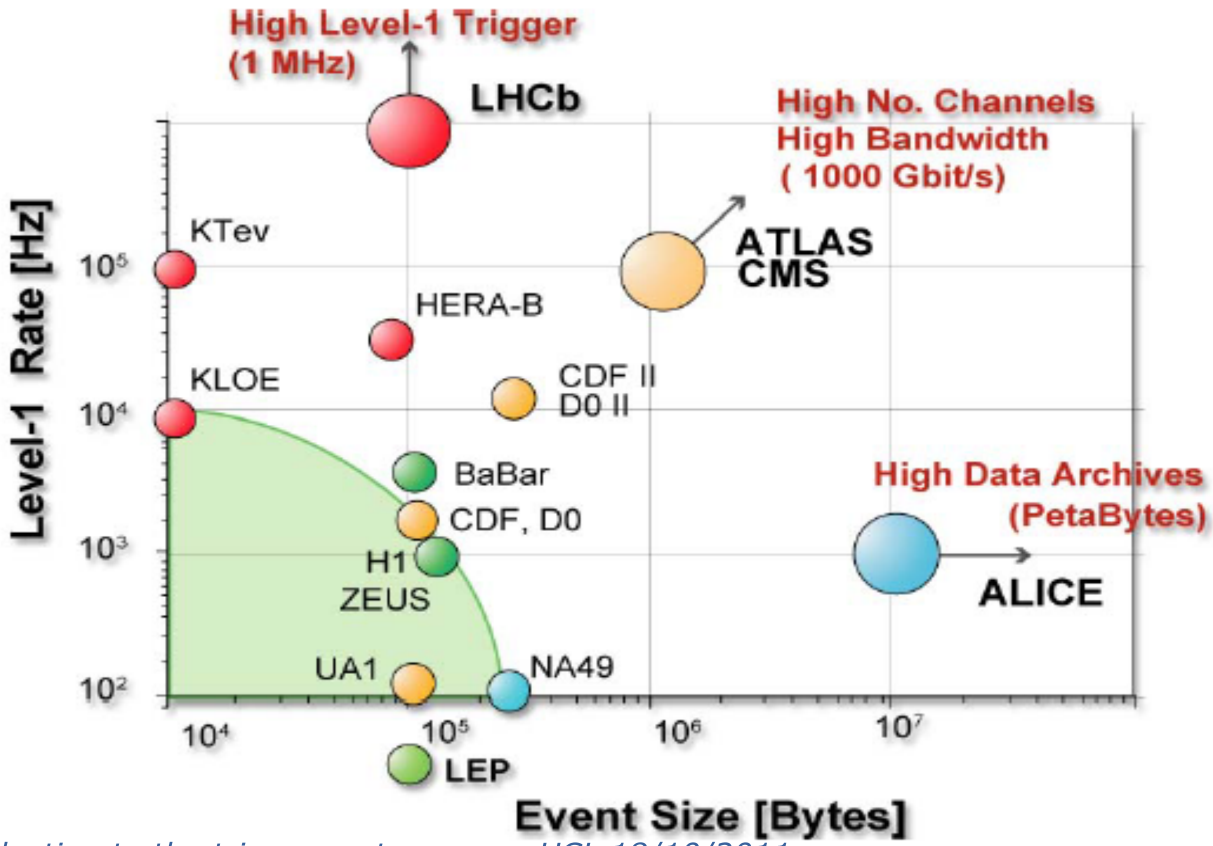
Trigger latency and readout BUSY



- **Trigger latency** = finite time to form the trigger decision and distribute it to the digitizers
  - More complex is the selection, longer the latency
  - Signals have to be delayed until the trigger decision is available at the digitizers
- Valid interactions are rejected due to **system busy** during digitization/readout
  - **Dead-time** is source of inefficiency

Trigger and data acquisition trends

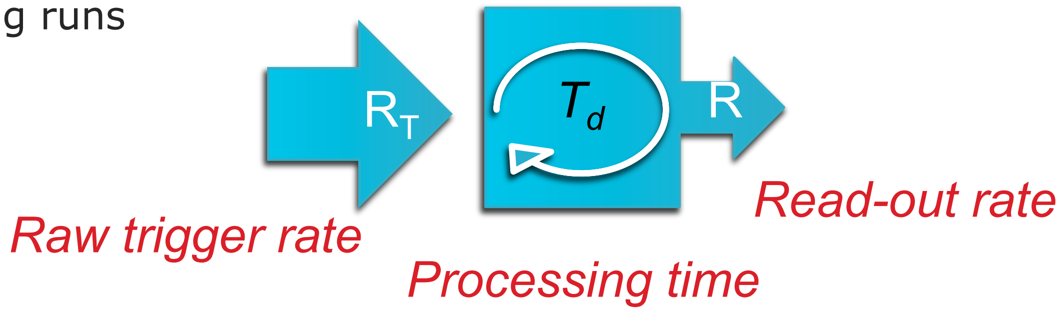
- As the data volumes and rates increase, new architectures need to be developed
  - Allowed data bandwidth = Rate x Event size



Dead-time

- The most important parameter controlling the design and performance of high speed **DAQ systems**
  - Occurs whenever a given step in the processing takes a **finite amount of time**
  - It's the fraction of the acquisition time in which no events can be recorded, typically of the order of **few %**

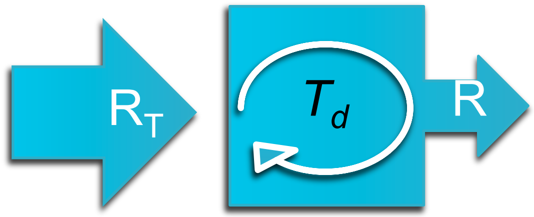
- Mainly three sources:
  - Readout dead-time:
    - before the complete event has been readout, no other events can be processed (during this time the DAQ asserts a BUSY)
  - Trigger dead-time:
    - trigger logic processing time, summed over all the components
  - Operational dead-time:
    - data-taking runs



Maximize event recording rate

R_T = raw trigger rate
R = number of events read per second (DAQ rate)
T_d = dead time interval per event

fractional dead-time = $R \times T_d$
live time = $(1 - R \times T_d)$
number of events read: $R = (1 - R \times T_d) \times R_T$

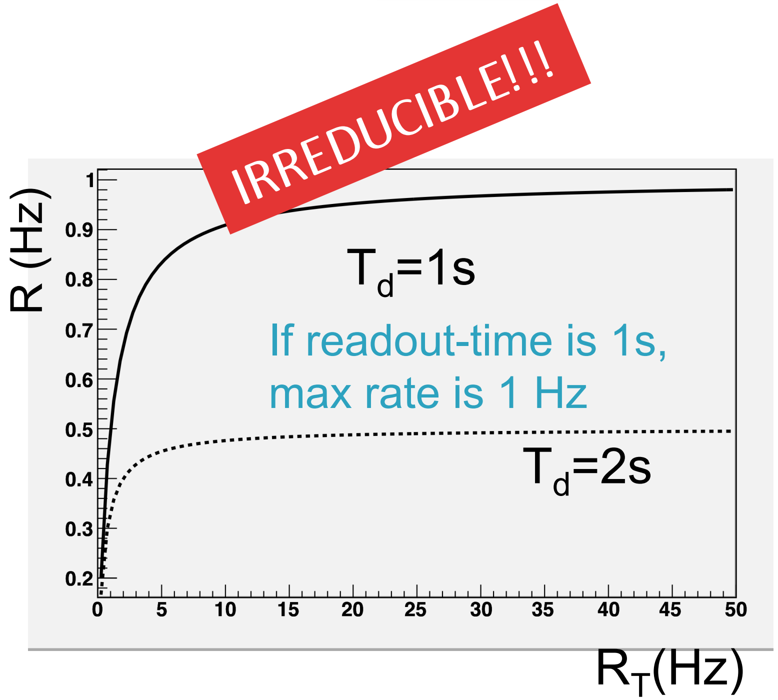


The fraction of surviving events (lifetime ratio) is:

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

T_d limits the maximum DAQ rate ($R=1/T_d$) regardless of the trigger rate :

- We always lose events if $R_T > 1/T_d$
- If exactly $R_T = 1/T_d$ -> dead-time is 50%
- Due to fluctuations, the incoming rate is higher than the processing one



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

FAST TRIGGER!
LOW DATA RATE!

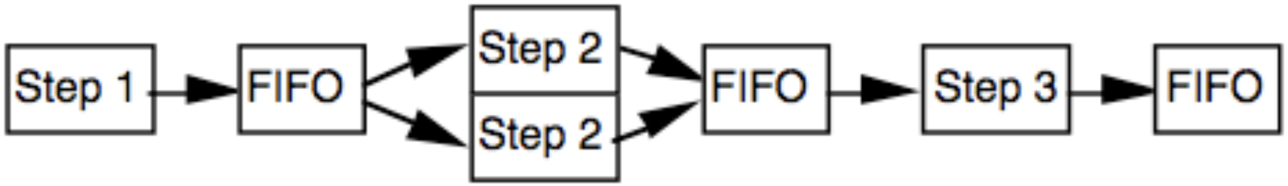
Features to minimize dead-time

- Two approaches are followed for large dataflow systems

  - Parallelism
    - Independent readout and trigger processing paths, one for each detector element
    - Digitization and DAQ processed in parallel (as many as affordable!)

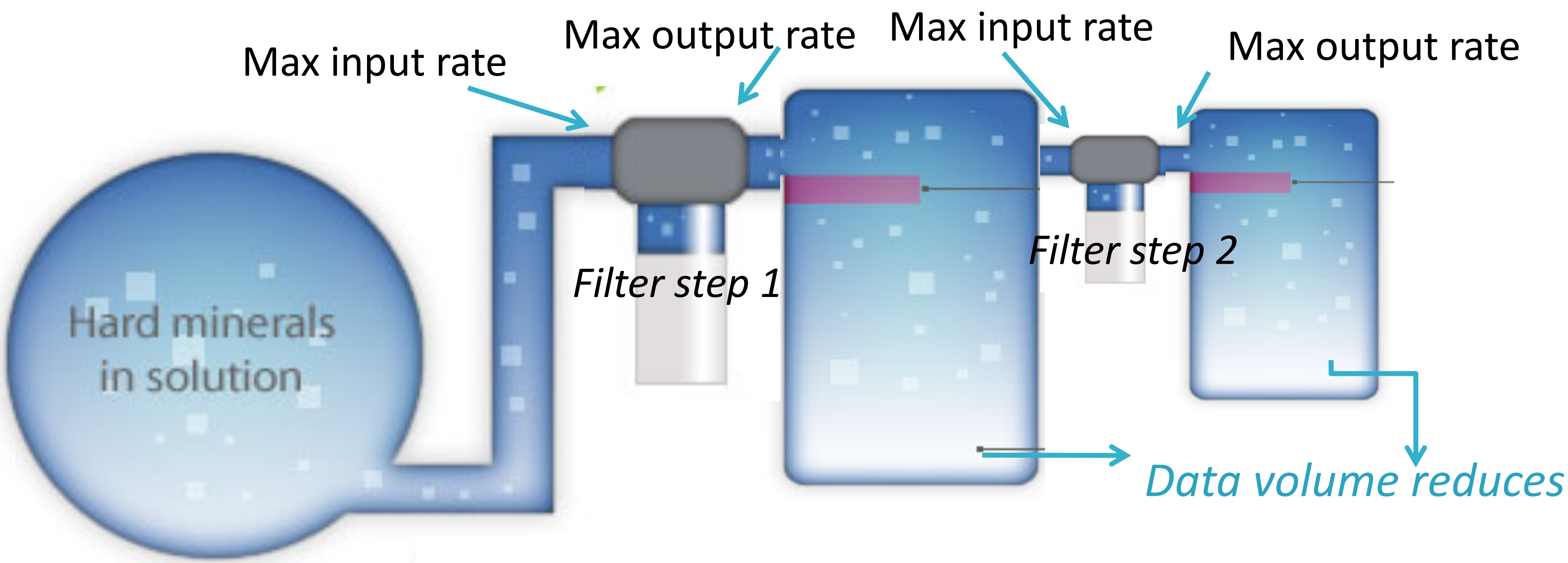
Segment as much as you can!

  - Pipeline processing to absorb fluctuations
    - Organize process in different steps
    - Use of local **buffers** (FIFOs) between steps allows steps with different timing (big events processed during short events).
    - The depth of local buffers limits the processing time of the subsequent step: better if step3 is faster than step2



Buffering and filtering

- At each step, data volume is reduced, more refined filtering to the next step
- At each step, data are held in buffers
  - The input rate defines the **processing time** of the filter 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

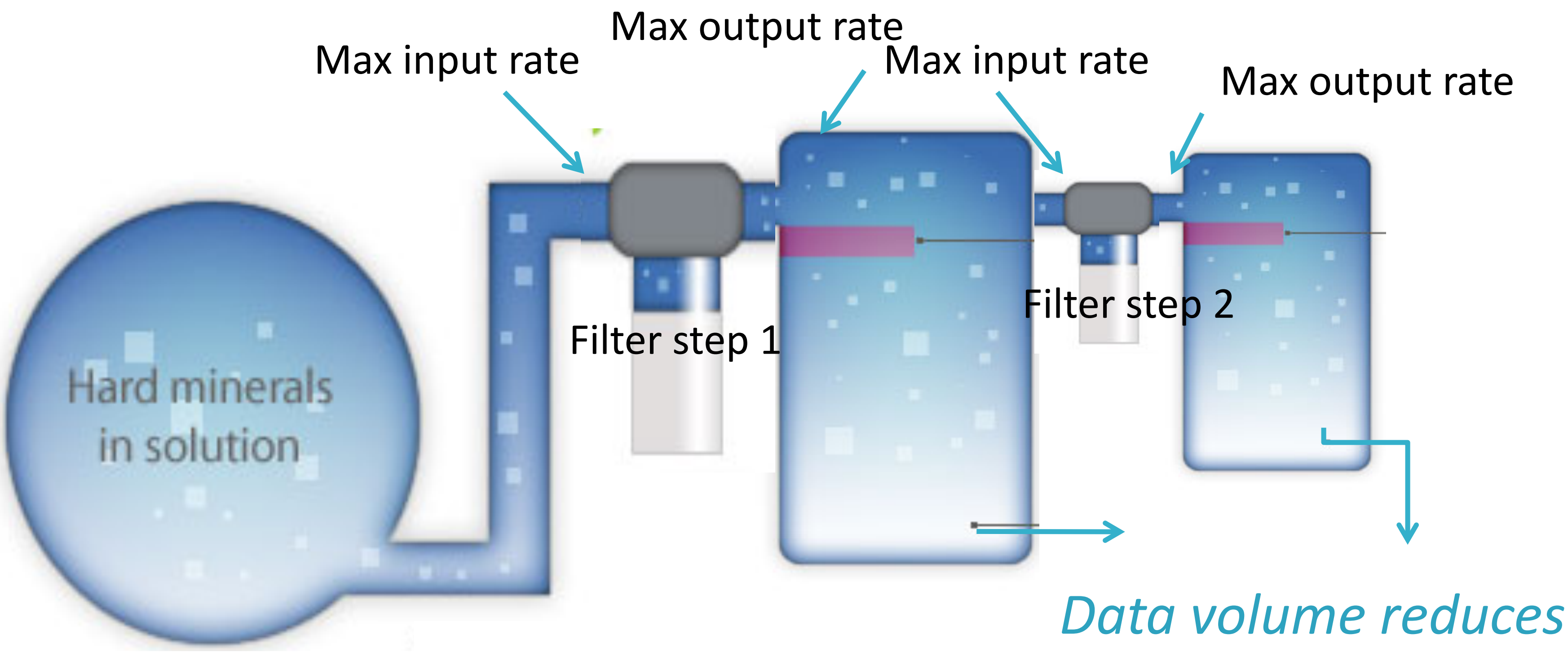


As long as the buffers do not fill up (overflow), no additional dead-time is introduced!

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

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)
- Latest filter can have longer latency (more selective)

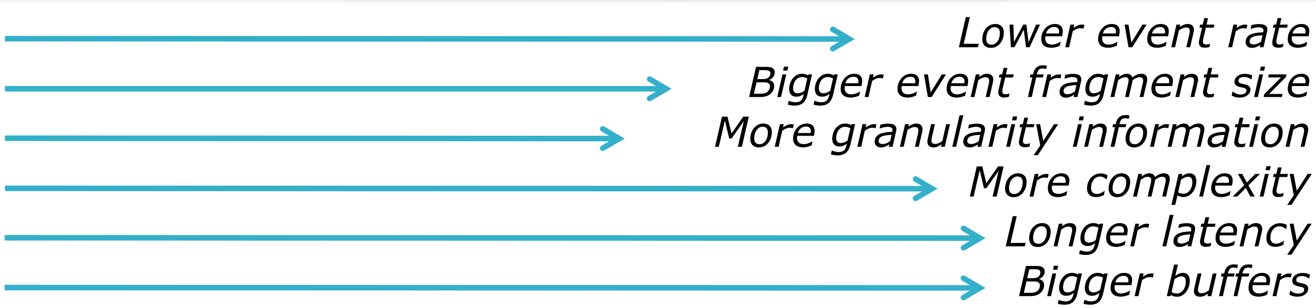


Multi-level triggers

- Adopted in large experiments, 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 power, with longer latency (more complex algorithms)

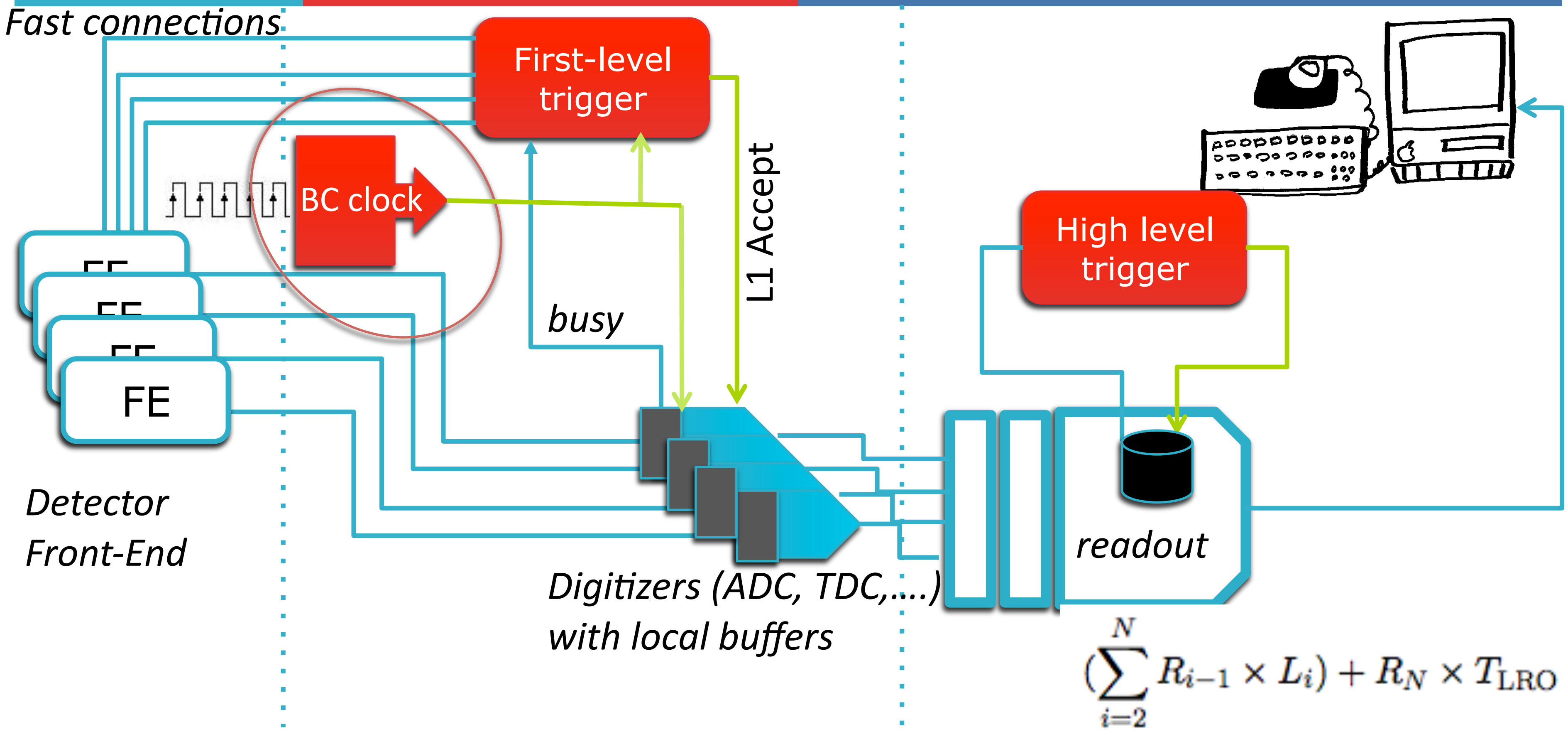
LHC experiments

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



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

Schema of a multi-level trigger @ colliders

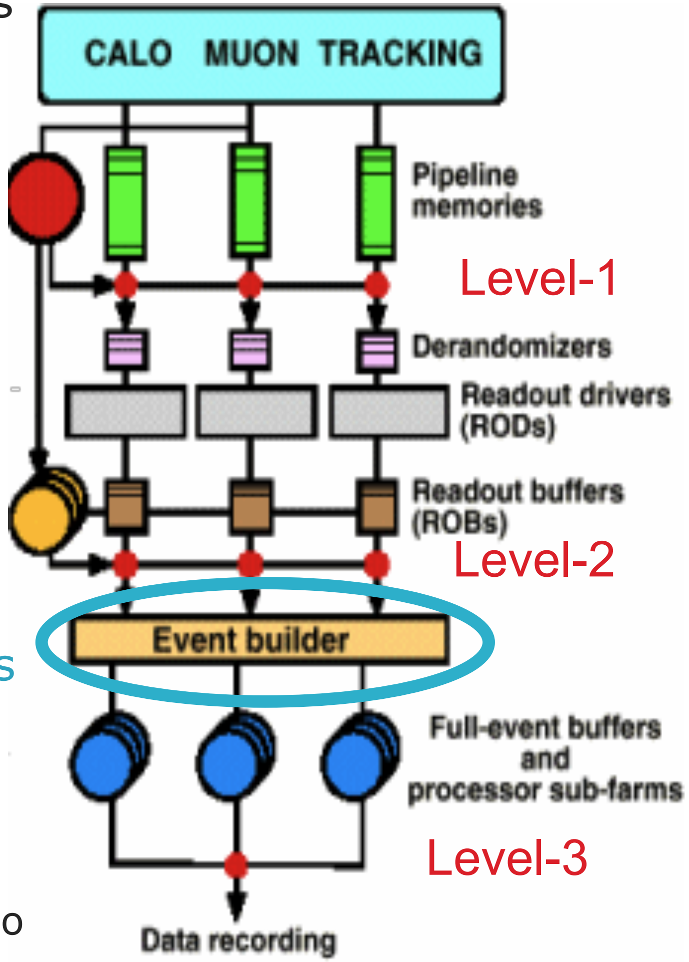


In the collider experiments, the BC clock can be used as a pre-trigger

- First-level trigger (synchronous) can use the time between two BCs to make its decision, **without dead-time**, if it's long enough
  - Fast electronics working at the BC frequency

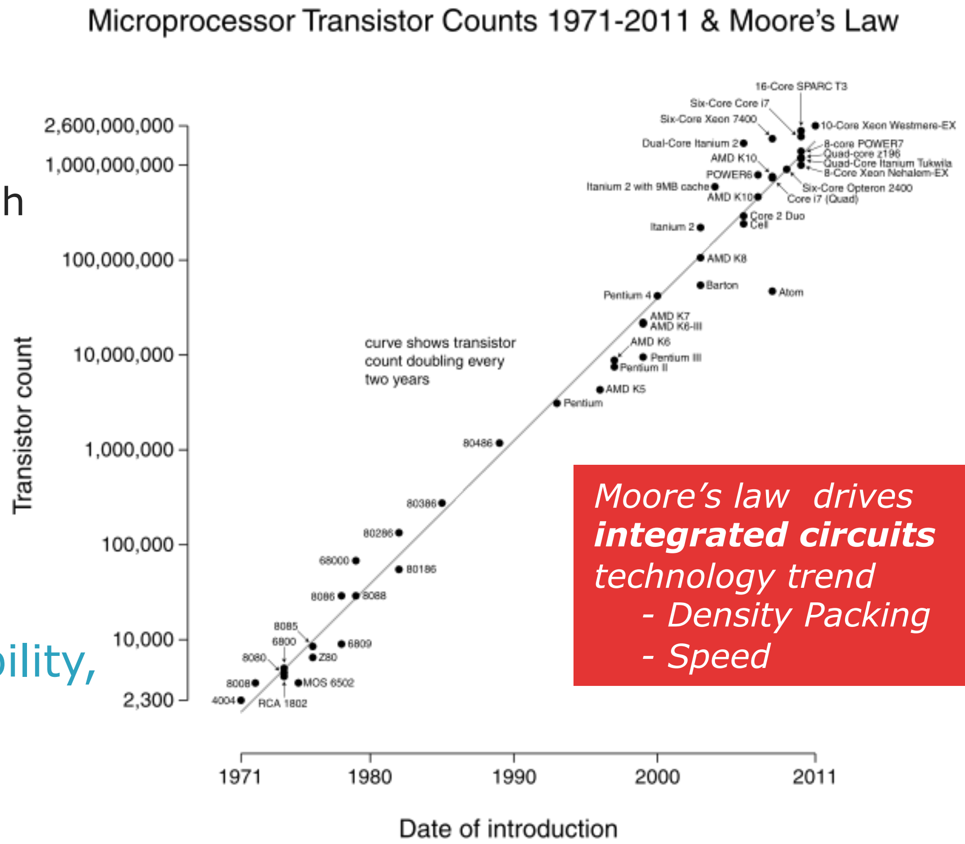
Logical division between levels

- **First-level**: Rapid rejection of high-rate backgrounds
  - **Fast custom electronics** processing fragments of data from FE
  - **Coarse granularity** data from detectors
    - Calorimeters for electrons/γ/jets, muon chambers
    - Usually does not need to access data from the tracking detectors (only if the rate can allow it)
  - **Needs high efficiency, but rejection power can be comparatively modest**
- **High-level**: rejection with more complex algorithms
  - **Software** selection, running on computer farms
  - Progressive reduction in rate after each stage allows use of more and more complex algorithms at affordable cost
  - Can access only part of the event or **the full event** (see next slides)
    - Full-precision and **full-granularity** information
    - **Fast tracking** in the inner detectors (for example to distinguish e/γ)



Level-1 trigger technologies

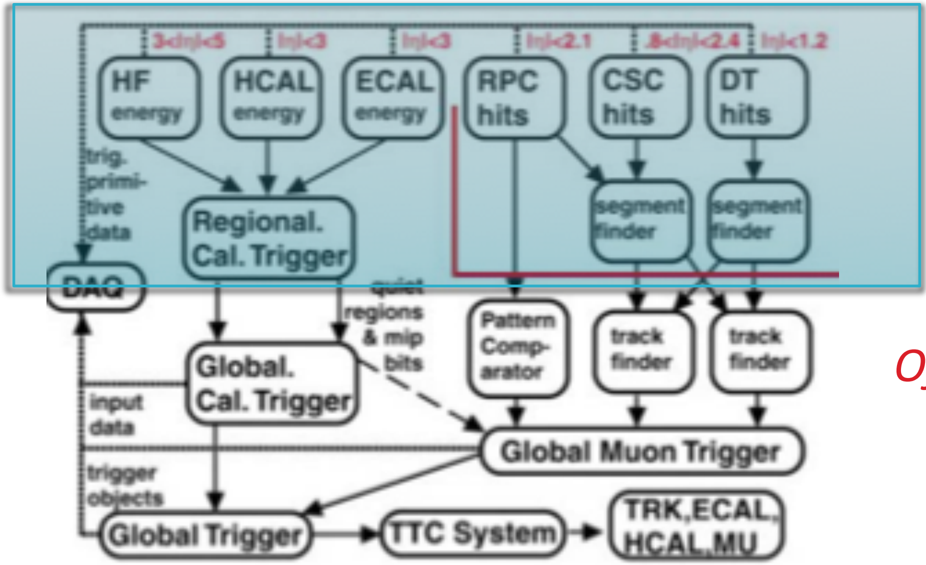
- Requirements for high rate systems
  - Complex and flexible algorithms
    - **Programmable** solutions with high level languages
  - Data compression and formatting
  - Monitor and automatic fault detection
- Integrated circuits
  - Offer advantage in terms of reliability, reduced power usage, reduced boards and better performance
- Microprocessors
  - A single chip with all essential functions of a complete computer: CPU, memory, I/O ports, interrupt logic, **connected on a single bus**
  - Could be **embedded in the readout system**: read, buffer and process data close to the front-end electronics



Moore's law drives ***integrated circuits*** *technology trend*
- *Density Packing*
- *Speed*

Data movement technologies

- A trigger system can be made of different components
  - Some elements have to be mounted on the detector (on-detector), some others can be placed into crates with bus connections (off-detector)



On-detector

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

Off-detector

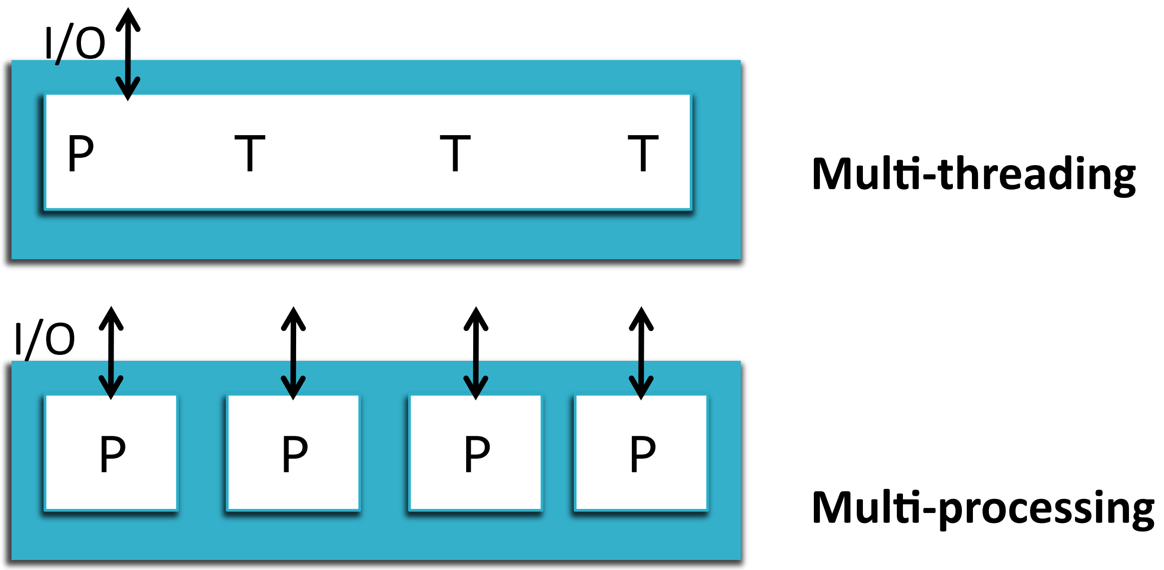
CMS first-level trigger

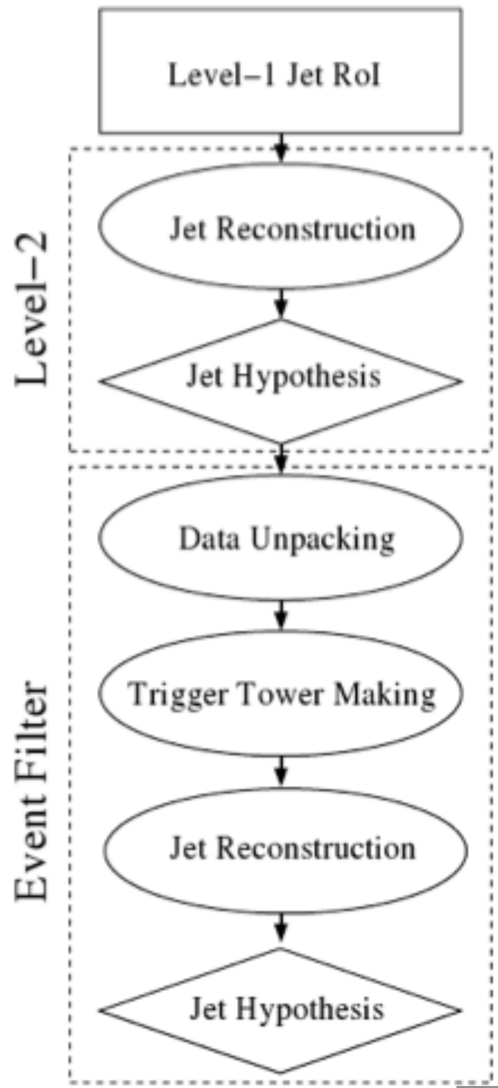
- High-speed serial **links**, electrical and optical, over a variety of distances
  - Low cost and low-power LVDS links, @400 Mbit/s (up to 10 m)
  - Optical **GHz-links** for longer distances (up to 100 m)

- High density **backplanes** for data exchanges within crates
  - High pin count, with point-to-point connections up to 160 Mbit/s
  - Large boards preferred

HLT design principles

- Early rejection
  - Alternate steps of feature extraction with hypothesis testing: events can be rejected at any step with a complex algorithm scheduling
- Event-level parallelism
  - Process more events in parallel, with multiple processors
  - Multi-processing or multi-threading
  - Queuing of the shared memory buffer within processors
- Algorithms are developed and optimized offline, often software is common to the offline reconstruction





High Level Trigger Architecture

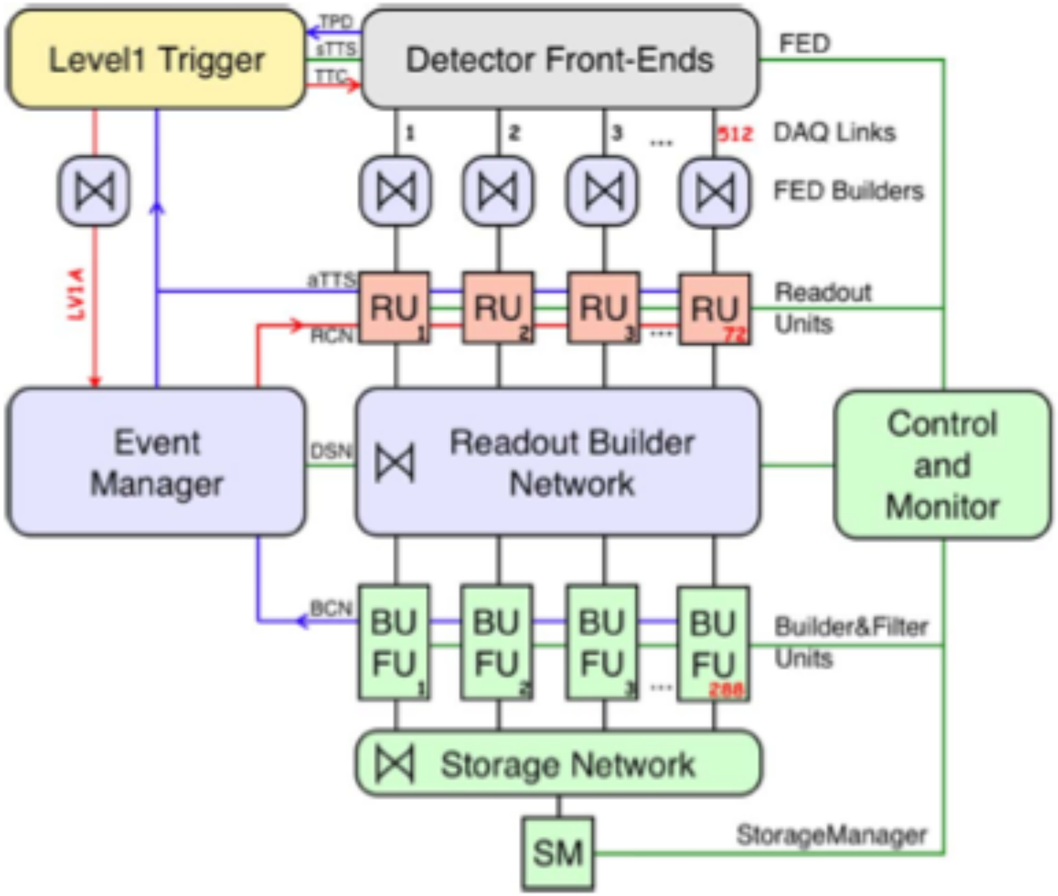
- After the L1 selection, data rates are reduced, but can be still massive
- Key parameter for the design is the **allowed bandwidth**, given by average event-size and trigger rate
  - LEP: 100 kByte event-size @ few Hz gives **few 100 kByte/s**
    - Supported by 40 Mbyte/s VME bus
  - ATLAS/CMS: 1 MByte event-size @100 kHz gives **~100 GByte/s**

	N.Levels	L1 rate (Hz)	Event size (Byte)	Readout bandw. (GB/s)	Filter out MB/s (Event/s)
ATLAS	3	L1: 10^5	10^6	10	~100 (10^2)
		L2: 10^3			
CMS	2	10^5	10^6	100	~100 (10^2)

- **Latest technologies** in processing power, high-speed network interfaces, optical data transmission are used
- High data rates are held by using
  - Network-based event building
  - Seeded reconstruction of data

Network-based HLT: CMS

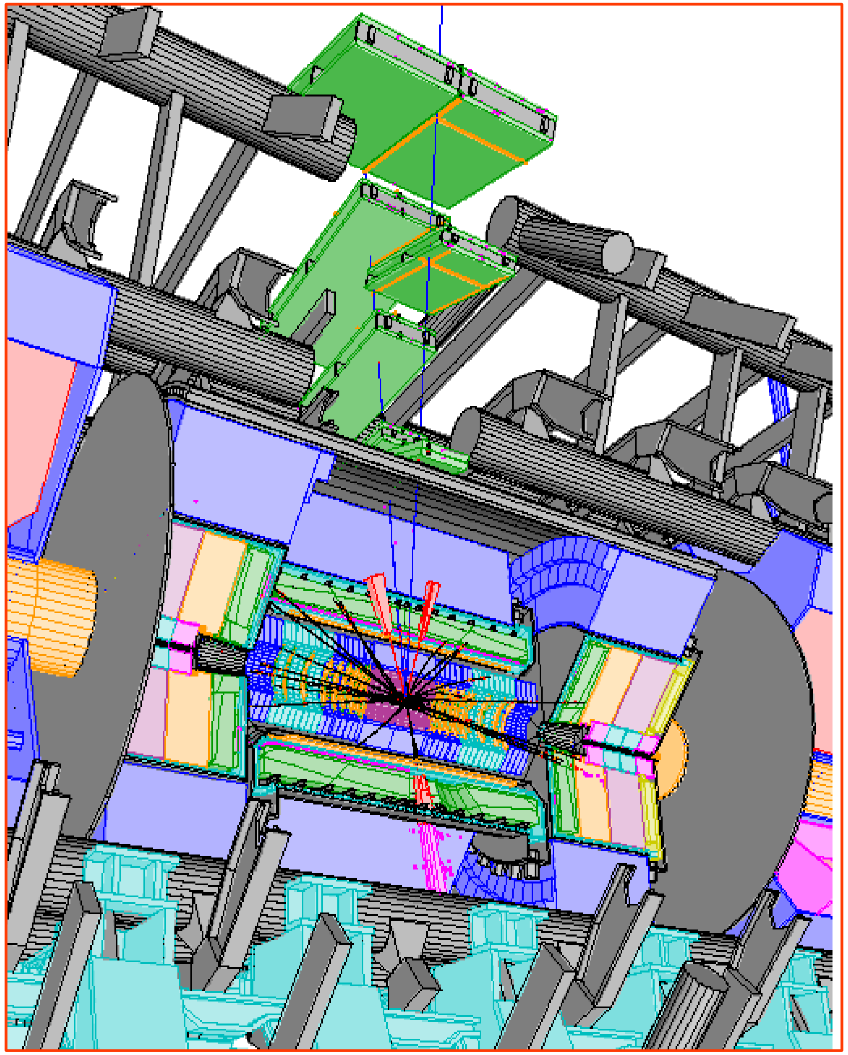
- Data from the readout system (RU) are transferred to the filters (FU) through a builder network
- Each filter unit processes only a fraction of the events
- Event-building is factorized into a **number of slices**, each one processing only 1/nth of the events
  - Large total bandwidth still required
  - No big central network switch
  - Scalable



FU = several CPU cores = several filtering processes executed in parallel

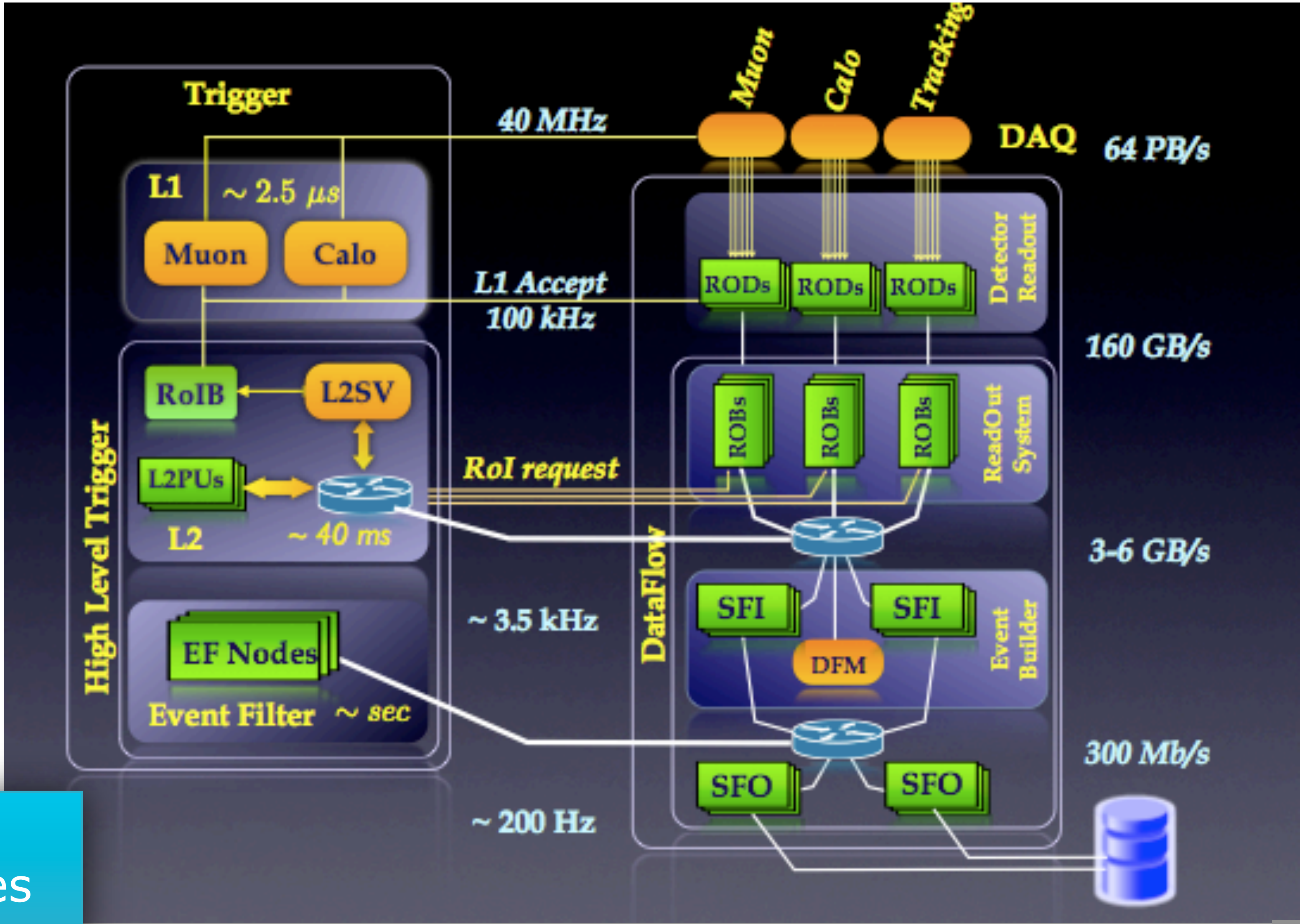
Seeded reconstruction HLT: ATLAS

- Level-2 uses the information seeded by Level-1 trigger
  - Only the data coming from the region indicated by the level-1 is processed, called **Region-of-Interest (RoI)**
  - The resulting total amount of RoI data is minimal: a few % of the Level-1 throughput
  - Level-2 can use the full granularity information of only a part of the detector
- No need for large bandwidth switches
- Complicate mechanism to serve the data selectively to the Level-2 processing



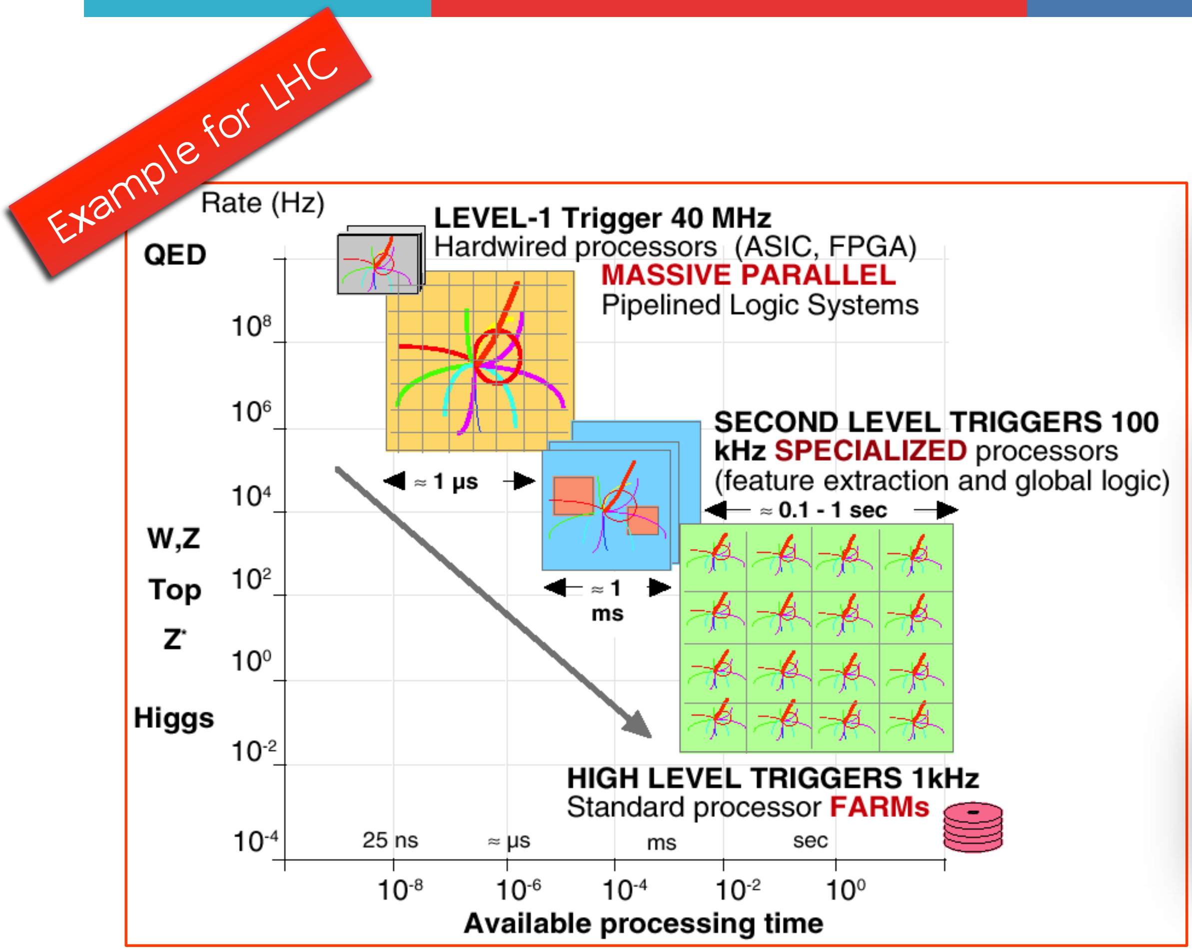
Typically, there are less than 2 RoIs per event accepted by Level-1

ATLAS trigger-DAQ system



Note rates and latencies

Trigger selections



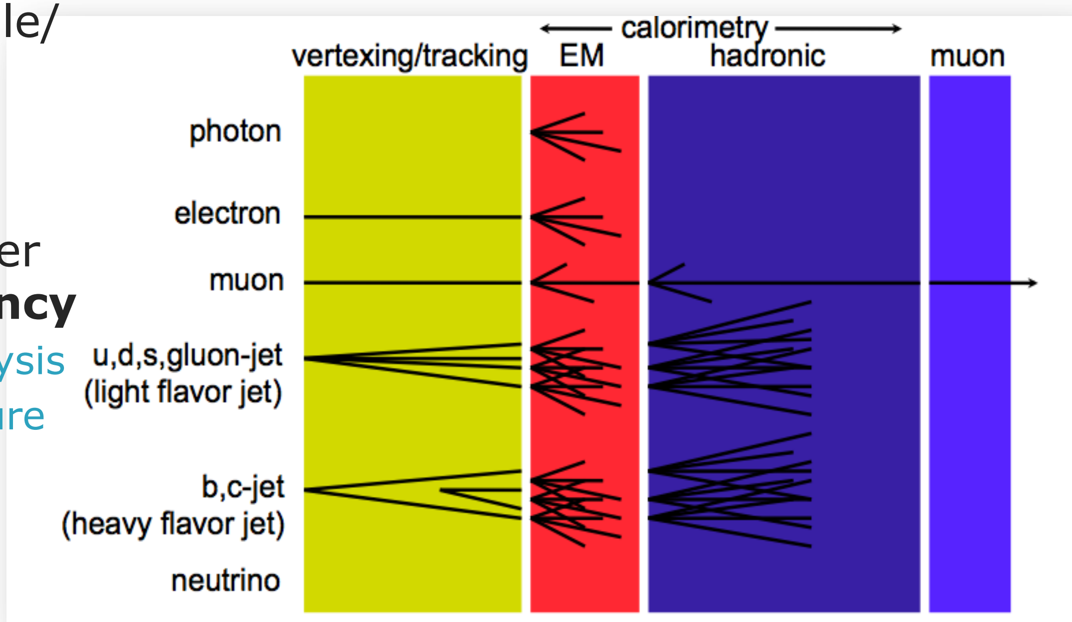
Inclusive trigger

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

Confirm L2, more refined topology selection, near offline

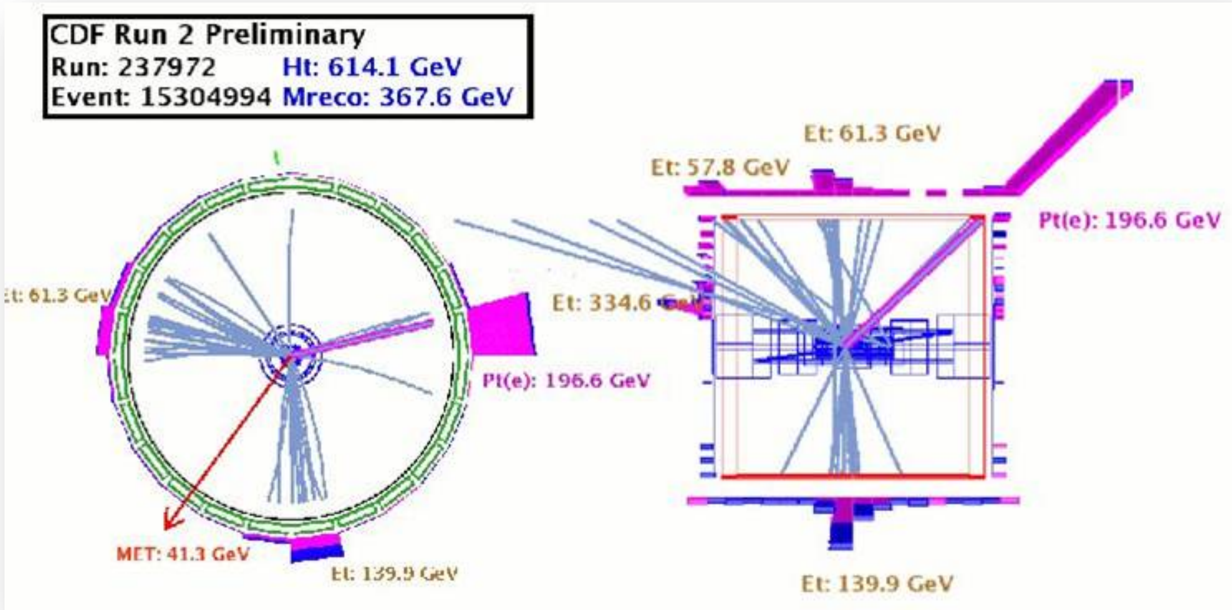
Trigger signatures

- **Signature**=one or more parameters used for discrimination
- Can be the amplitude of a signal passing a given **threshold** or a more complex quantity given by software calculation
  - We first use intuitive criteria: fast and reliable
  - Muon tracks, energy deposits in the calorimeters, tracks in the silicon detectors….
- Trigger selection is based on single/ double particle signatures
- Eventually combine more signals together following a certain trigger logic (AND/OR), giving **redundancy**
  - Different signatures -> one analysis
  - Different analysis -> one signature



Trigger criteria at colliders

- Apply thresholds on energy/momentum of the identified particles: most used are **electrons and muons** which have clear signature
- **Shower shapes and isolation criteria** are also used to separate single leptons from jets

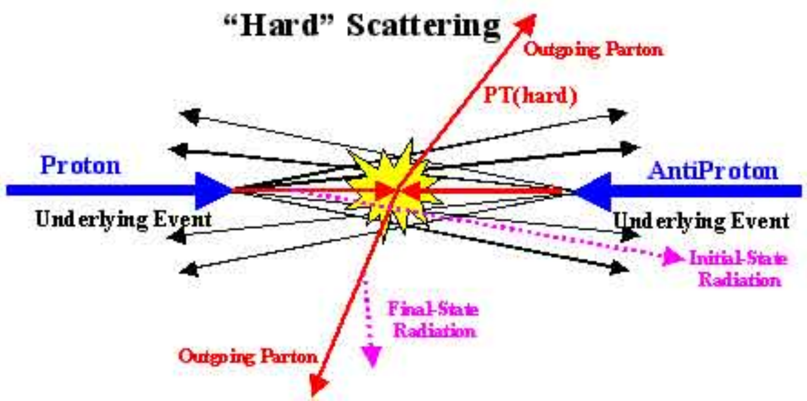


$$\not{E}_T = -\left| \sum_{i=towers} E_i \cdot \hat{n}_T^i \right|$$

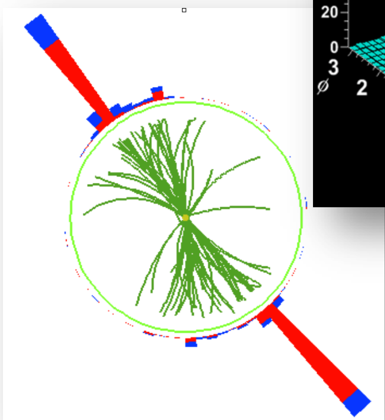
- In addition, global variables such **as total energy, missing energy** (for neutrino identification), **back-to-back tracks**, etc…

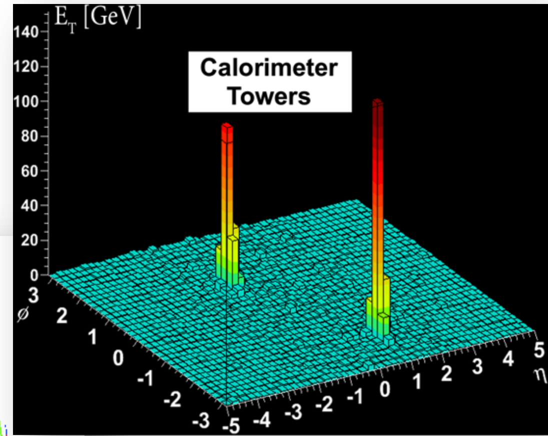
..and at hadron colliders

- Apply thresholds on **transverse** Energy (**E_T**) or transverse momentum (**p_T**): component of energy or momentum orthogonal to the beam axis
  - Initial p_T = 0 and $E_{total} < E_{2\ beams} = E_{cm}$

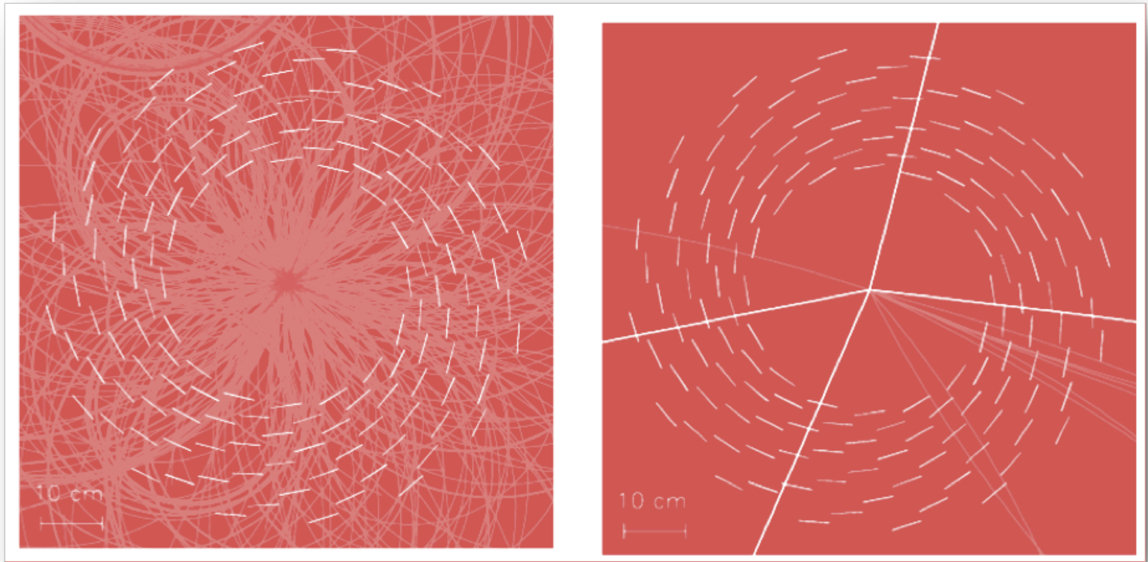


- The bulk of the cross-sections from Standard Model processes are the presence of **high-p_T** particles (**hard processes**)
  - In contrast most of the particles producing (minimum-bias) interactions are soft (p_T ~ 1 GeV)
  - Large missing E_T can be sign of new physics



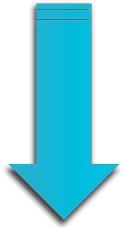


A simple trigger for the Higgs Boson



All tracks — Only high-pt tracks

Simulated **H→ 4μ** event at LHC with and without soft collisions

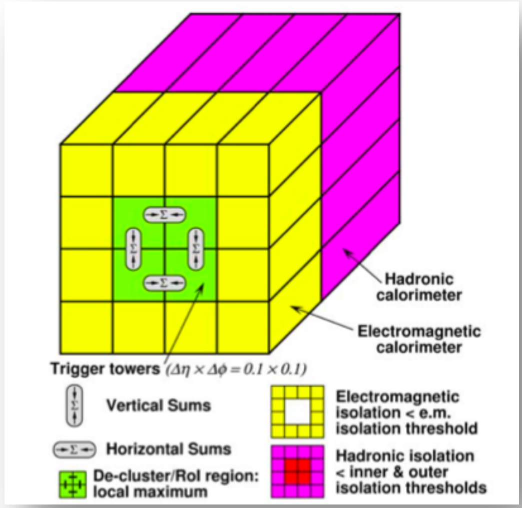


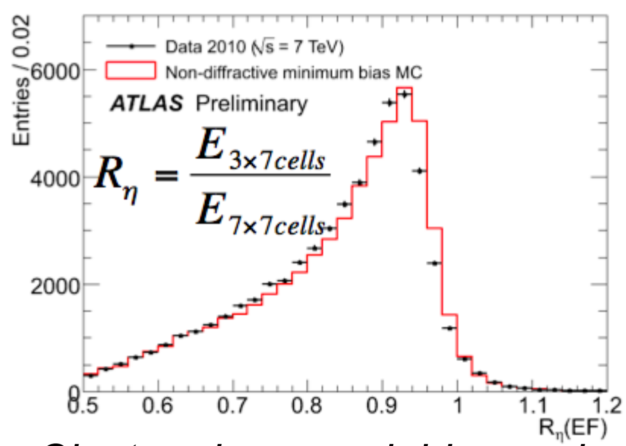
Trigger signature given by **high momentum muons**

Example of multilevel trigger: ATLAS calorimeter trigger

- e, γ, τ, jets, $E_T$miss, ΣE_T
  - Various combinations of cluster sums and isolation criteria
- Level-1
  - Dedicated **processors** apply the algorithms, using programmable E_T thresholds
  - Peak finder for BC identification (signal is larger than 1 BC)
- High-Level trigger
  - **Topological** variables and **tracking** information for electrons from Inner Detectors
    - Cluster shape at L2
    - Jet algorithms at L3 (Event Filter)
  - **Isolation** criteria can be imposed to control the rate (reducing jet background at low energies thresholds)

Level-1 clustering algorithm





Cluster shape variable used in HLT for e/γ selection

Trigger efficiency as a parameter of your measurement

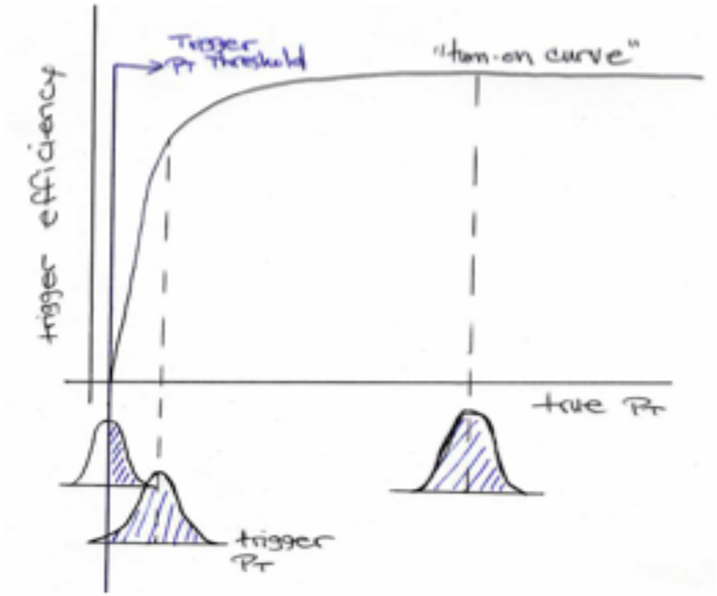
- Efficiency should be precisely known, since it enters in the calculation of the cross-sections
  - For some precise measurements, the crucial performance parameter can be not the efficiency, but the **systematic** error in determining it
  - The orthogonality of the trigger requirements allows good cross-calibration of the efficiency

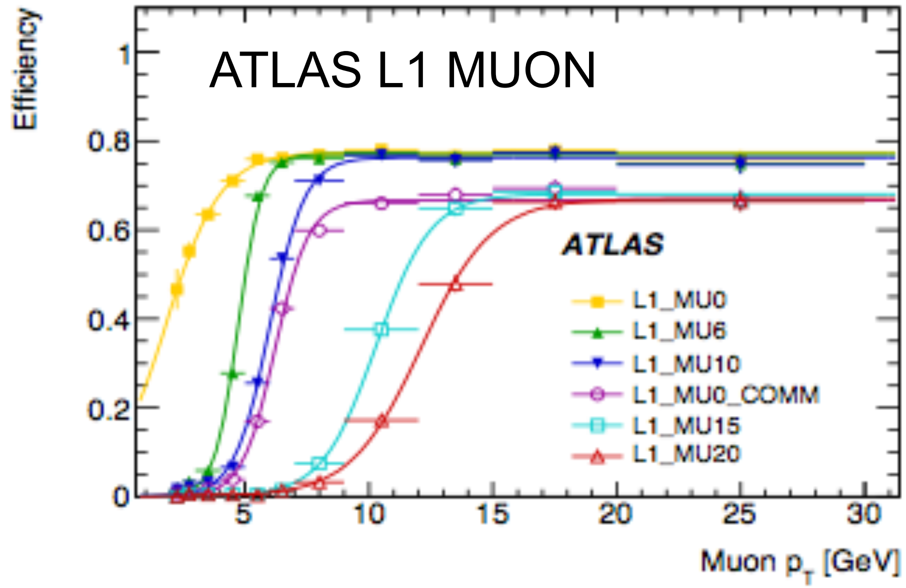
$$BR(\quad Signal \quad) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

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

The trigger turn-on curves

- The capability of rate control (and bkg suppression) depends on the **p_T (or E_T) resolution**
  - Worst at level-1 (coarse granularity, $\delta p_T/p_T$ up to 30%)
    - For example some particles can be under threshold, failing the trigger, because their p_T is underestimated
  - Crucial is the study of the step region, in which efficiency changes very quickly and contamination from background is important (soft particles)





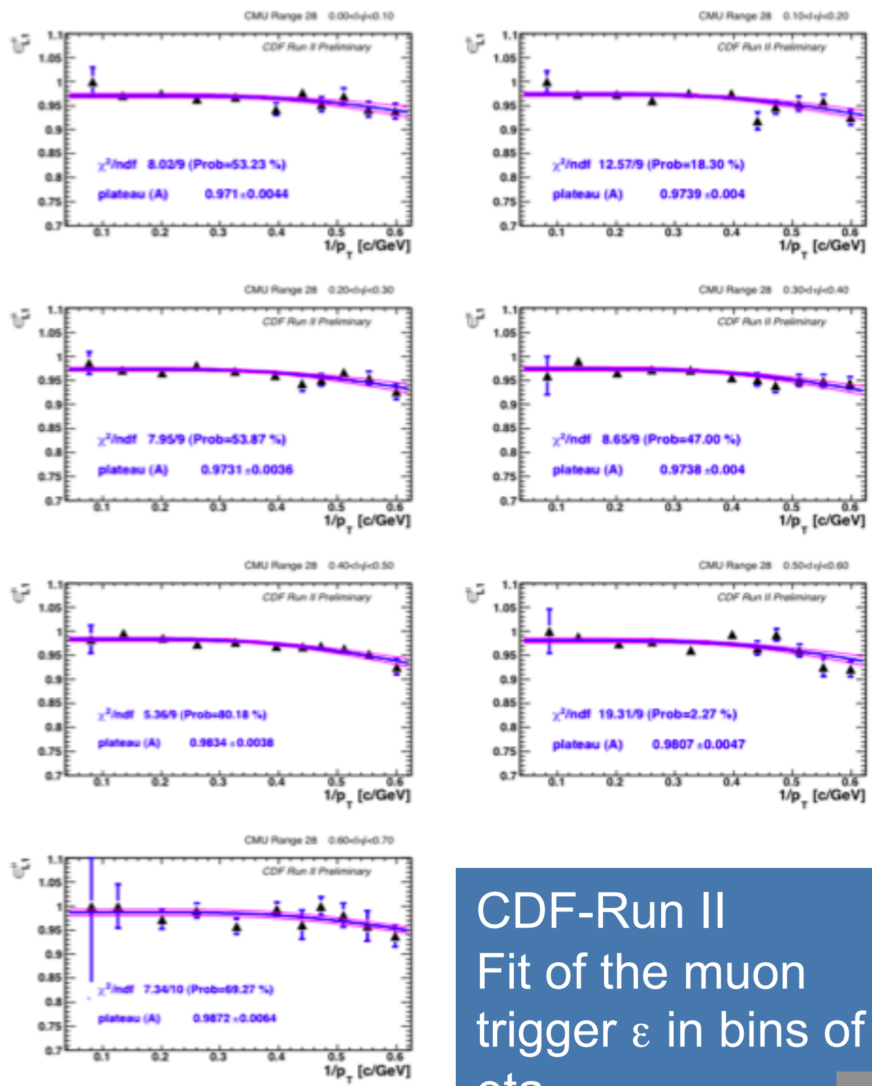
The dependency of ε on the true p_T/E_T, measured offline (with a resolution of order 0.1%) is described by the **turn-on curves**

Parametrizing the trigger efficiency

- The trigger behavior, and thus the analysis sample, can change quickly due to important changes in
  - Detector
  - Trigger hardware
  - Trigger algorithms
  - Trigger definition

- The analysis must keep track of all these changes

- Multi-dimensional study of the efficiency: ε(p_T, η, φ, run#)
  - Fit the turn-on curves for different bins of η, φ,
  - Actually fit the 1/p_T dependency since the resolution is gaussian in 1/p_T



CDF-Run II
Fit of the muon trigger ε in bins of eta

Trigger efficiency measurement (1)

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

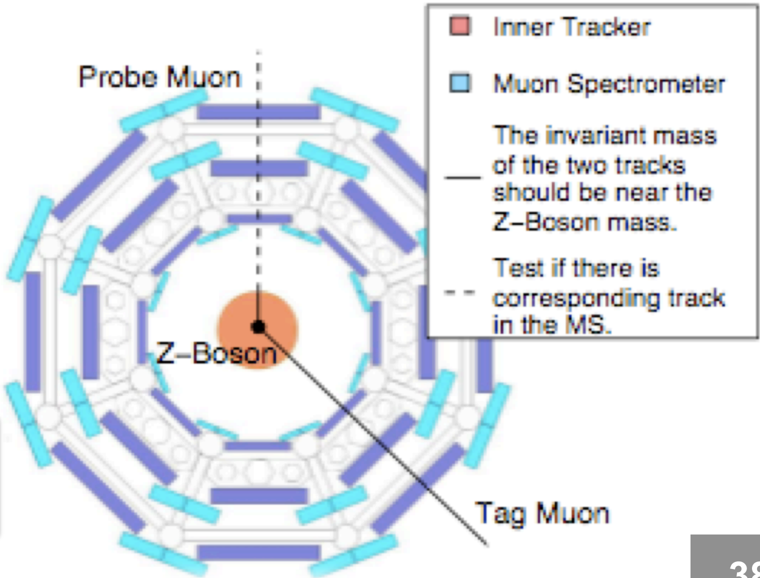
- Basic idea: compare two cases in which the trigger selection is and is not applied
  - It's crucial to select the correct **sample without biases**
- For HLT it's easily done using back-up triggers called pass-through
  - Do not apply the selection and calculate the denominator

$$\text{Eff(L2MU10)} = \frac{\text{events passing L2MU10}}{\text{events passing L2MU10\_PASSTHROUGH}}$$

Trigger efficiency measurement (2)

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

- For Level-1, we don't know the absolute denominator
- Different methods can be used:
  - Compare independent (orthogonal) triggers (not correlated, min-bias)
  - At the collider experiments can be measured with an experimental technique called "Tag-and-Probe" (mainly lepton triggers)
    - Clean signal sample (Z, J/Ψ to leptons)
    - Select track that triggered the event (Tag)
    - Find the other offline track (Probe)
    - Apply trigger selection on Probe
    - Helps in defining an unbiased sample (no background included)



Use back-up triggers:
L1_LOWEST_THRESHOLD

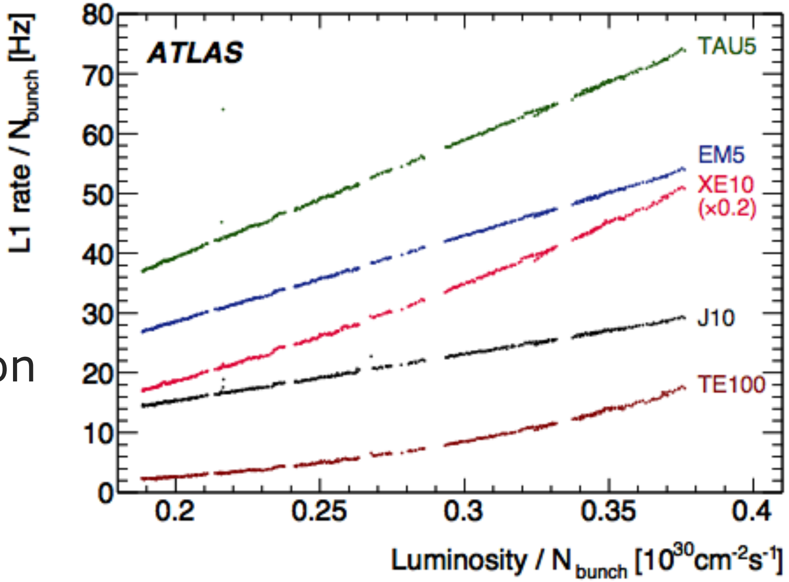
Rates allocation of the trigger signatures

✓Target is the final allowed bandwidth (~200 Hz @ LHC)
✓Trigger rate allocation on each trigger item is based on
- ✓Physics goals (plus calibration, monitoring samples)
- ✓Required efficiency and background rejection
- ✓Bandwidth consumed

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

Trigger Efficiency

- For design and commissioning, the trigger rates are calculated from large samples of simulated data, including large cross-section backgrounds
  - 7 million of non-diffractive events @70mb used for 10^{31} cm^{-2} s^{-1} in ALTAS
    - Large uncertainties due to detector response and jet cross-sections: apply safety factors, then tuned with data
- During running, extrapolation from data to higher Luminosity



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

A balance between physics interest and system bandwidth…

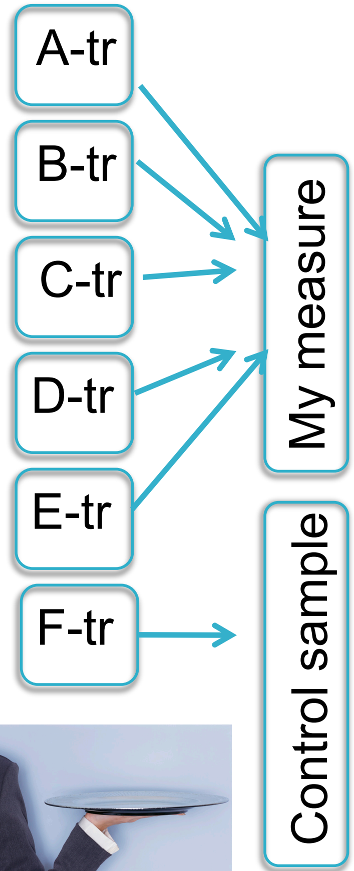
Lower thresholds would be desirable, but the physics coverage must be balanced against considerations of the offline computing cost

- How accommodate broad physics program?
- And cope with increasing luminosity?

Organize trigger menus!

Design a trigger menu

- A trigger menu is the list of our selection criteria
- Each item on the menu is a **trigger chain**
  - A trigger chain includes a set of cut-parameters or instructions from each trigger level (L1+L2+L3..)
  - Each chain has its own bandwidth allocation
  - An event is stored if one or more trigger chain criteria are met
- A well done trigger menu is crucial for the physics program
  - Multiple triggers serve the **same analysis** with different samples (going from the most inclusive to the most exclusive)
  - Ideally, will keep **some events from all processes** (to provide physics breadth and control samples)

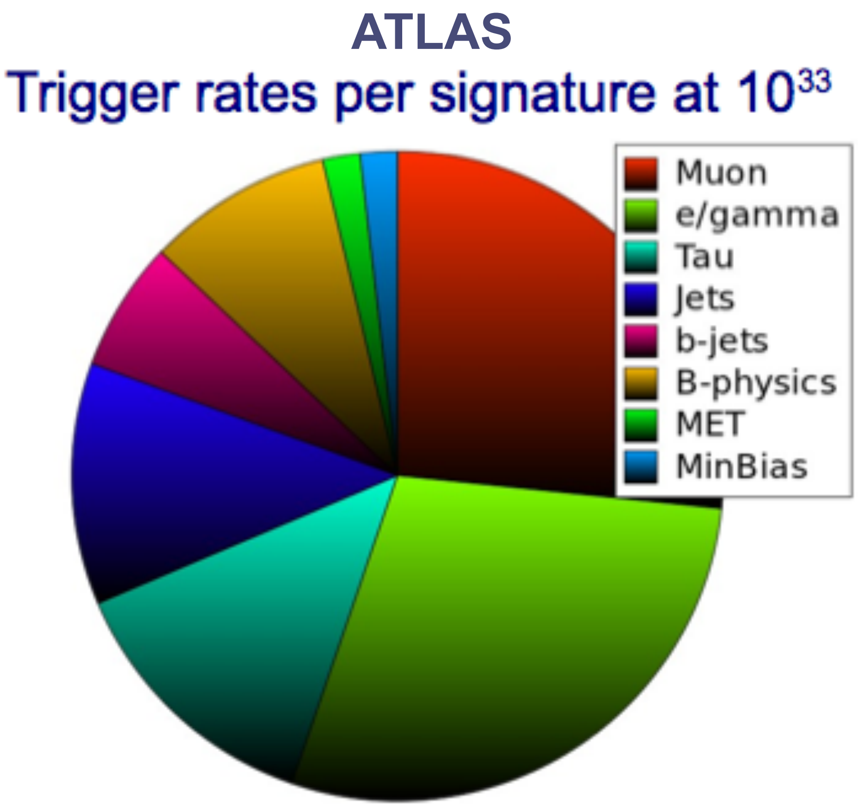


- The list must be
  - **Redundant** to ensure the efficiency measurement
  - Sufficiently **flexible** to face possible variations of the environment (detectors, machine luminosity) and the physics program

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}

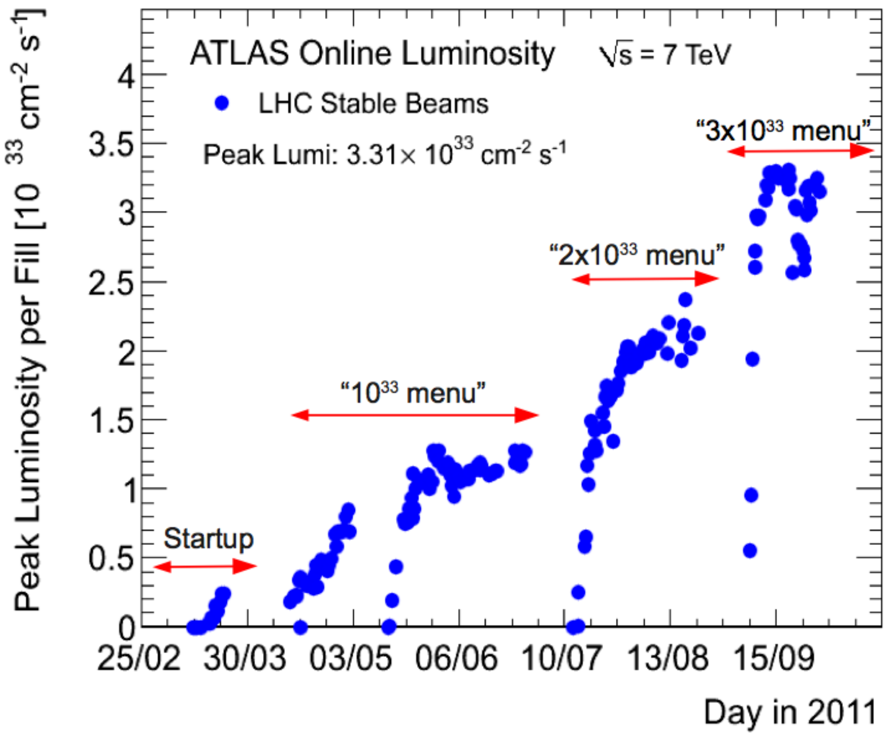
Trigger strategy @ colliders

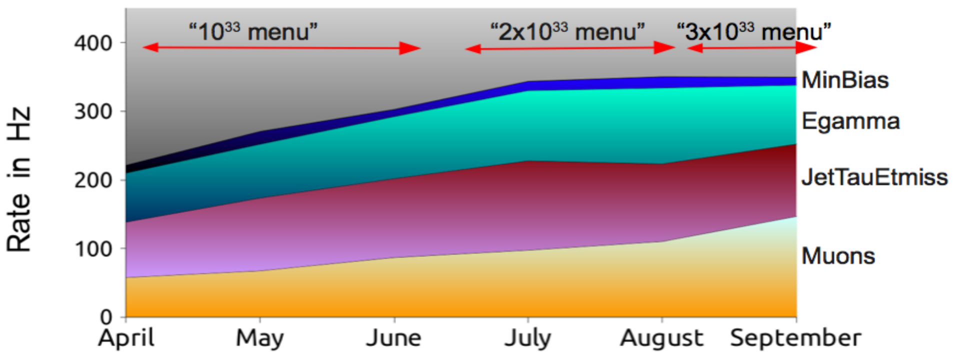


- Inclusive triggers designed to collect the signal samples (mostly un-prescaled)
  - Single high-p_T
    - $e/\mu/\gamma$ (p_T>20 GeV)
    - jets (p_T>100 GeV)
  - Multi-object events
    - e-e, e-μ, μ-μ, e-τ, e-γ, μ-γ, etc… to further reduce the rate

- 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

Example of trigger menu flexibility





- ATLAS start-up $L=10^{31}$ cm^{-2} s^{-1}
  - Level-1: Low p_T thresholds and loose selection criteria
    - In the meanwhile, deploy high thresholds and multi-objects triggers for validation (to be used as back-up triggers)
  - HLT: running in pass-through mode for offline validation or with low thresholds
- Trigger menu evolved in several steps with LHC peak luminosity
  - Complex signatures and higher p_T thresholds are added to reach the physics goals
  - Stable condition for important physics results (summer or winter conferences)
  - Mostly kept same balance between physics streams

Inclusive trigger example: from CDF

Trigger Chain: Inclusive High-p_T Central Electron

- Level 1
  - EM Cluster E_T > 8 GeV
  - Rφ Track p_T > 8 GeV
- Level 2
  - EM Cluster E_T > 16 GeV
  - Matched Track p_T > 8 GeV
  - Hadronic / EM energy < 0.125
- Level 3
  - EM Cluster E_T > 18 GeV
  - Matched Track p_T > 9 GeV
  - Shower profile consistent with e-

To efficiently collect W, Z, tt, tb, WW, WZ, ZZ, Wγ, Zγ, W', Z', etc…

Only one of these analysis needs to measure trigger efficiency, the others can benefit from one (use Standard Model Z,W)

Back-up trigger example: from CDF

Back-up Triggers for central Electron 18 GeV:

- W_NOTRACK
  - L1: EMET > 8 GeV && MET > 15 GeV
  - L2: EMET > 16 GeV && MET > 15 GeV
  - L3: EMET > 25 GeV && MET > 25 GeV
- NO_L2
  - L1: EMET > 8 GeV && rφ Track pT > 8 GeV
  - L2**: AUTO_ACCEPT**
  - L3: EMET > 18 GeV && Track pT > 9 GeV && shower profile consistent with e-
- NO_L3
  - L1: EMET > 8 GeV && rφ Track pT > 8 GeV
  - L2: EMET > 8 GeV && Track pT > 8 GeV && Energy at Shower Max > 3 GeV
  - L3: **AUTO_ACCEPT**

✓ **Factorize efficiency into all the components:**
- ✓ efficiency for track and EM inputs determined separately
- ✓ separate contributions from all the trigger levels

✓ **Use resolution at L2/L3 to improve purity**
- ✓only really care about L1 efficiency near L2 threshold

Redundant trigger Example: from CDF

- Inclusive, Redundant Inputs are helpful
- L1_EM8_PT8 feeds
  - Inclusive high-p_T central electron chains
  - Di-lepton chains (ee, eμ, eτ)
  - Several back-up triggers
  - 15 separate L3 trigger chains in total
- A ttbar cross section analysis uses
  - Inclusive high-p_T central e chains
  - Inclusive high-p_T forward e chains
  - MET + jet chains
  - Muon chains

Trigger menus must be

Inclusive:
Reduce the overhead for the program analysis

Redundant:
if there is a problem in one detector or in one trigger input, the physics is not affected (less efficiently, but still the measurement is possible)

Summarizing….

- The trigger strategy is a trade-off between physics requirements and affordable system power 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
  - Design an architecture with low dead-time, in which each step of the selection must accomplish requirements on speed and rate suppression
  - Perfect knowledge of the trigger selection on both signal and background
  - Flexibility and redundancy ensure a reliable system

- In particular, for hadron colliders, like LHC, the trigger performance is crucial for discovery or not discovery new physics that can be easily lost if we don’t think of it in advance!