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TRIGGER PRINCIPLES

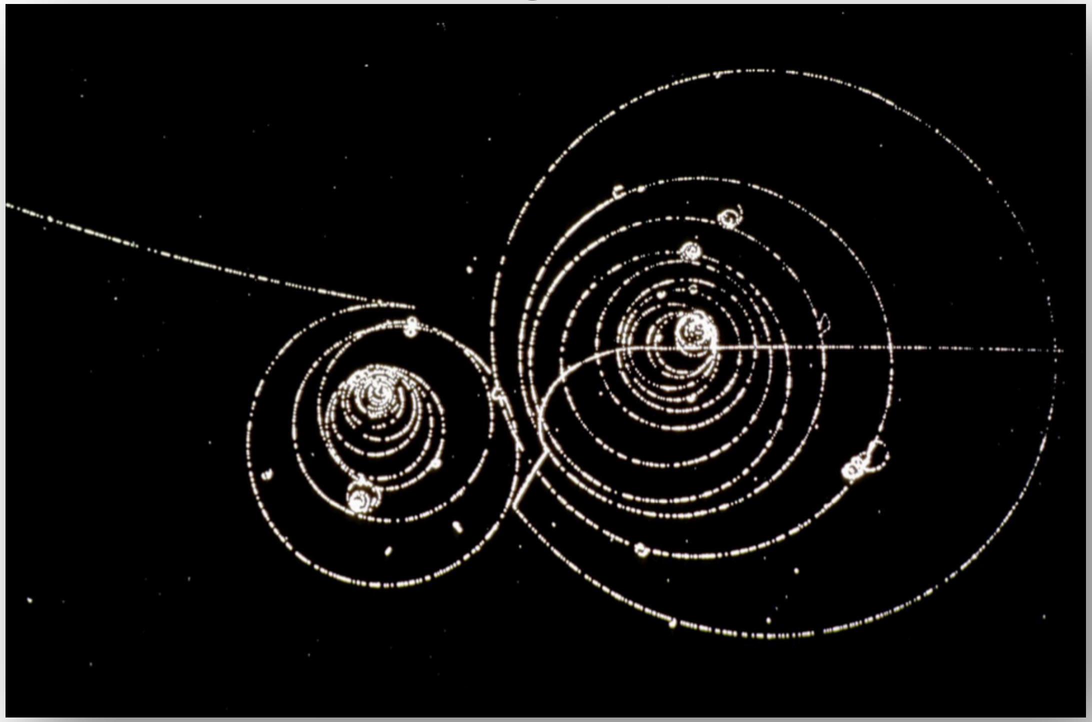
OUTLINE

- ➡ trigger selectivity and robustness with examples
- ➡ how to build a trigger system from first principles
- ➡ principles and examples of L1 triggers
- ➡ principles and examples of software triggers

THE TRIGGER CONCEPT

A very good photo during your holidays

Cloud-chamber images recorded on film



- **Take a photo: open the bolt and let the sensors operate**
  - are the **subjects** ready?
  - **focused** the image?
  - is enough **light** for your lenses (or add a flash light)?
  - only if your hand is not **shaking**

The trigger starts the photo process

→ **Identify the interesting event**

→ **Good sensitivity to parameters**

→ **Good synchronisation**

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  - The input rate is everything produced by nature or by the accelerator
  - The output rate is the interesting physics (ideal trigger)
- **In a real trigger system**
  - The trigger accepts events with features **similar** to the signal
  - The final rate is often dominated by not interesting physics

EXPECTED INPUT RATE

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

For a collider experiment: x Luminosity

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

An example?

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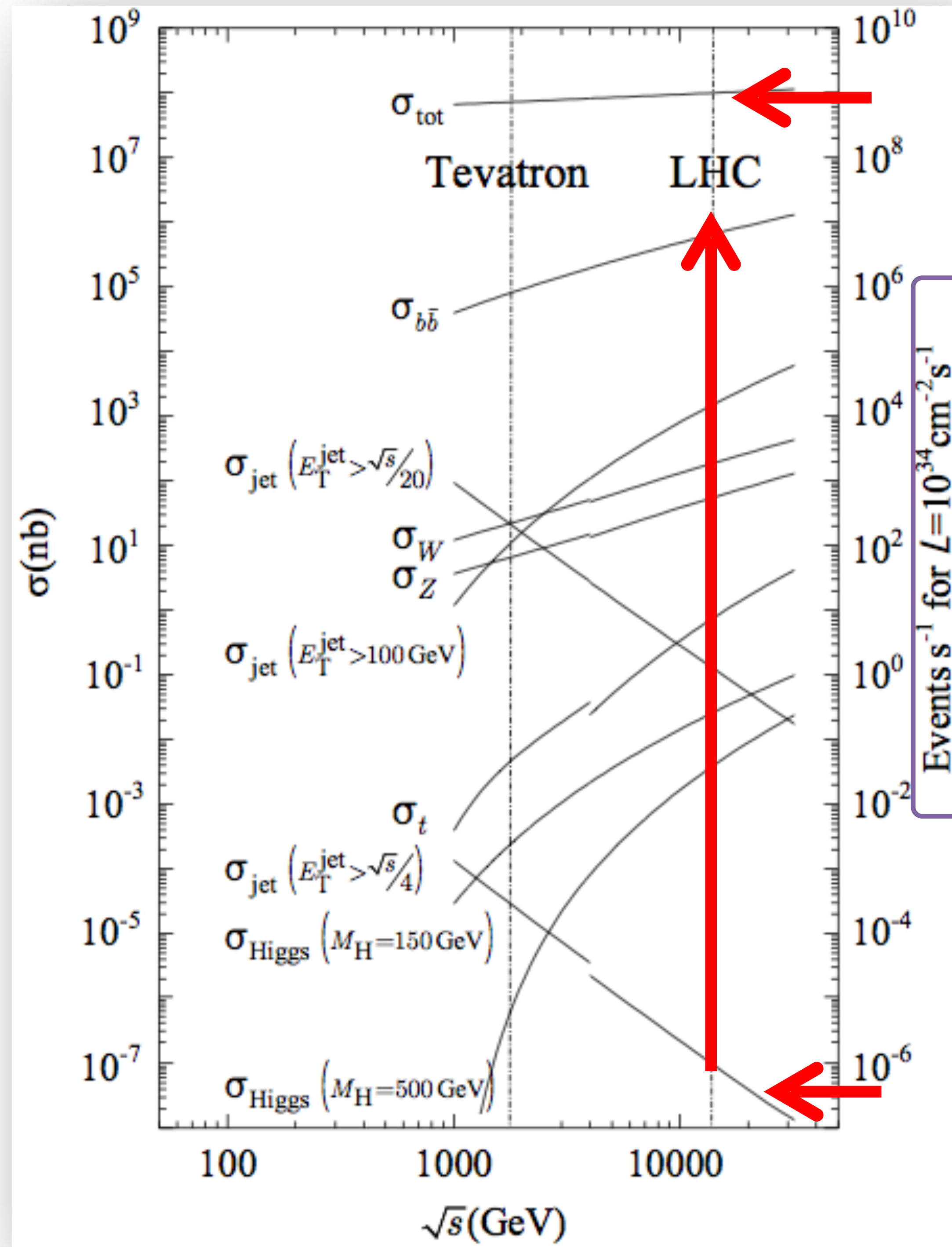
LHC: the trigger challenge!

Total non-diffractive p-p cross section is **70 mb**
Total expected rate is ~ GHz!!!

Huge range of cross-sections and production rates:

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

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



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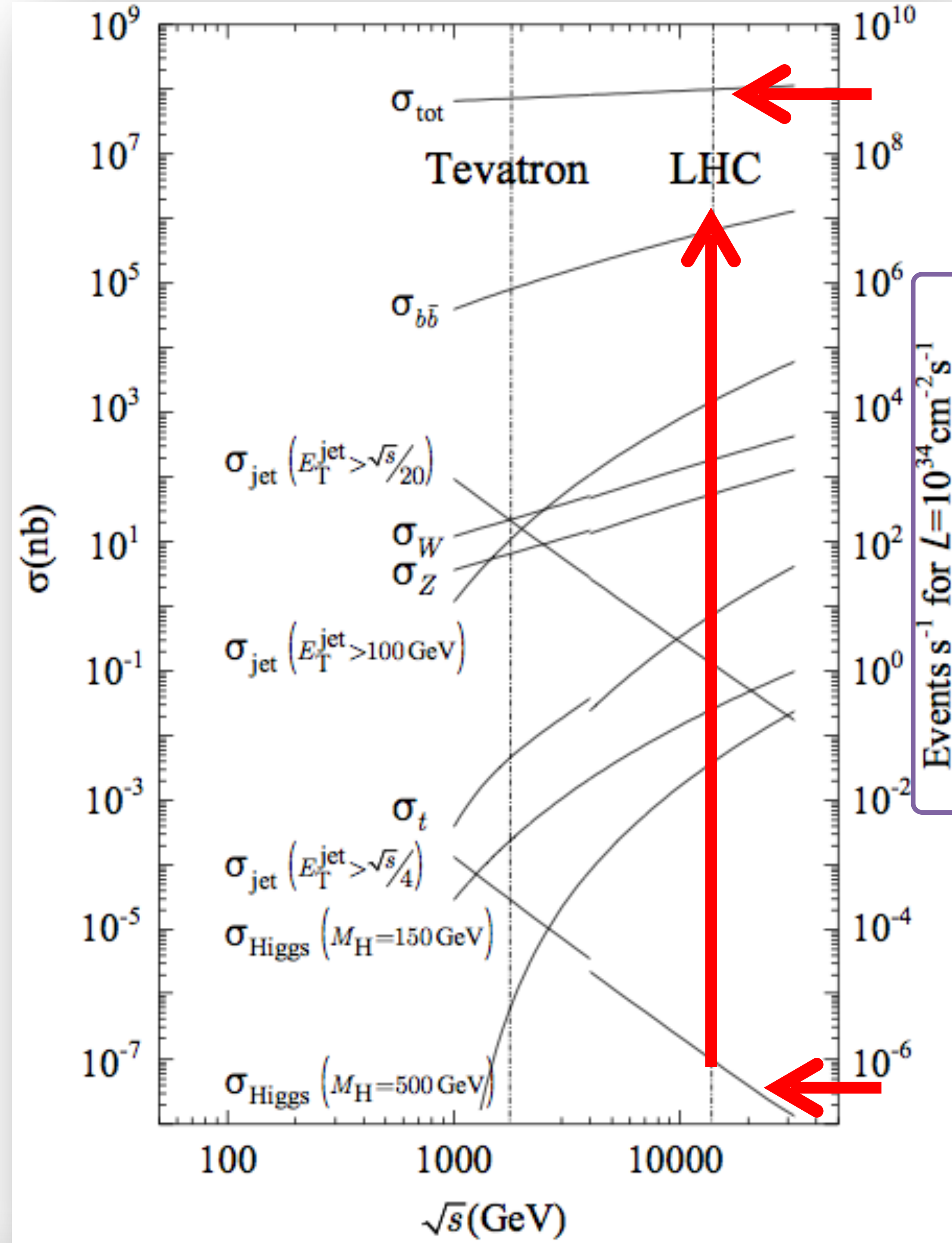
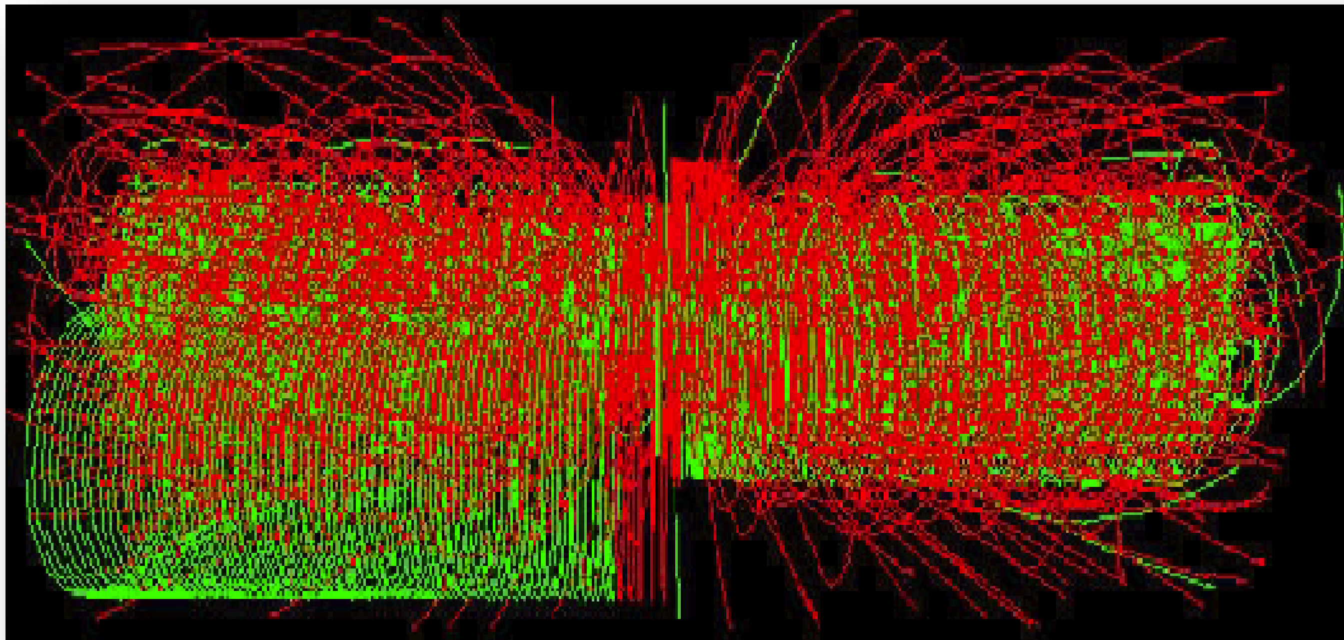


In hadronic colliders, trigger selection is crucial

WHICH IS A GOOD TRIGGER FOR THE HIGGS BOSON @LHC?

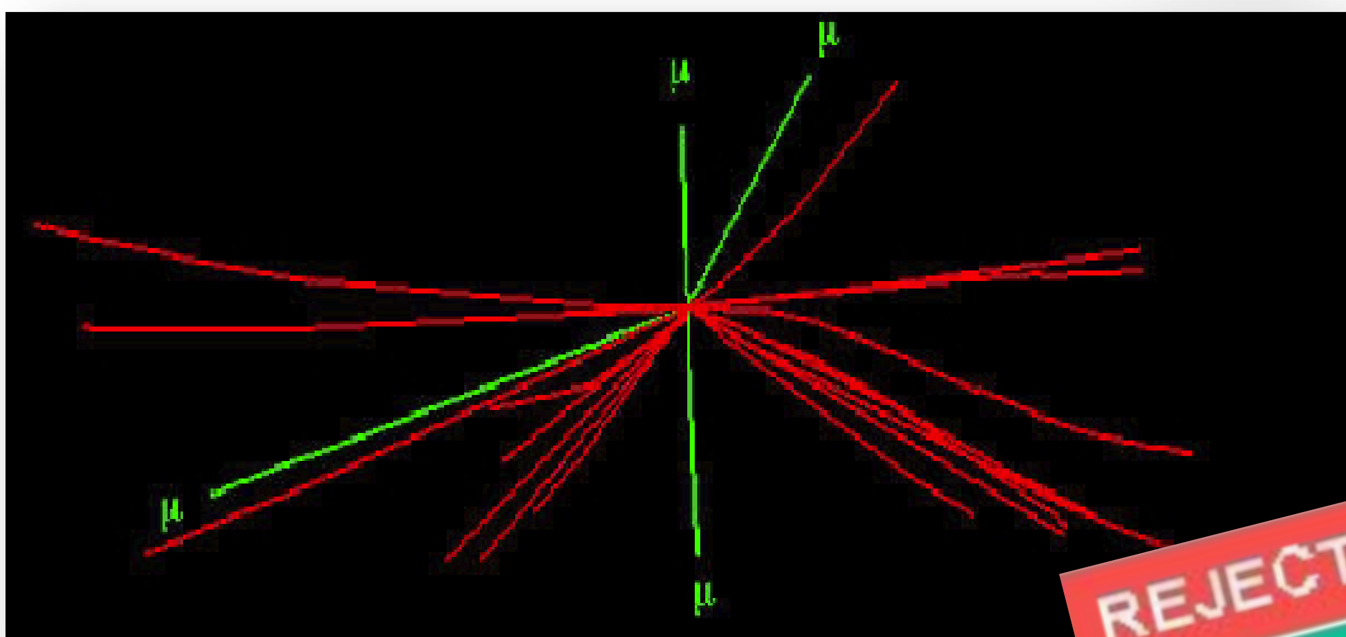
@LHC: proton-proton collider

All tracks



Only high-pT tracks

+30 MinBias



Higgs -> 4μ

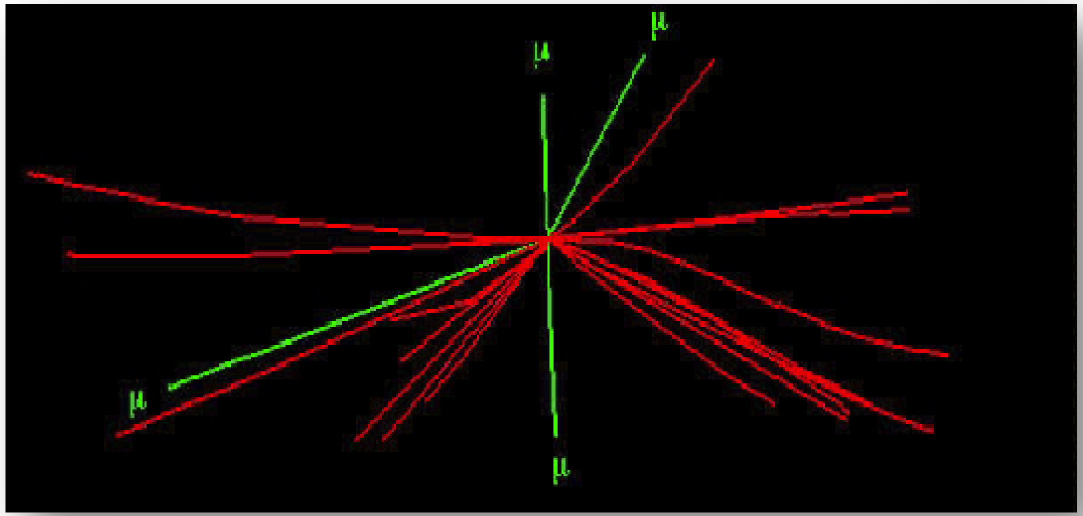
signal events **Higgs ➔ 4μ** as it appears at the LHC (concurrently with soft collisions from other p-p interactions)

↓

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

TRIGGER STRATEGY

- **For the Higgs discovery @LHC:**
  - high p_T muons are interesting (**signal**)
  - low p_T muons are not interesting (**background**)
- **Which is the best p_T threshold?**



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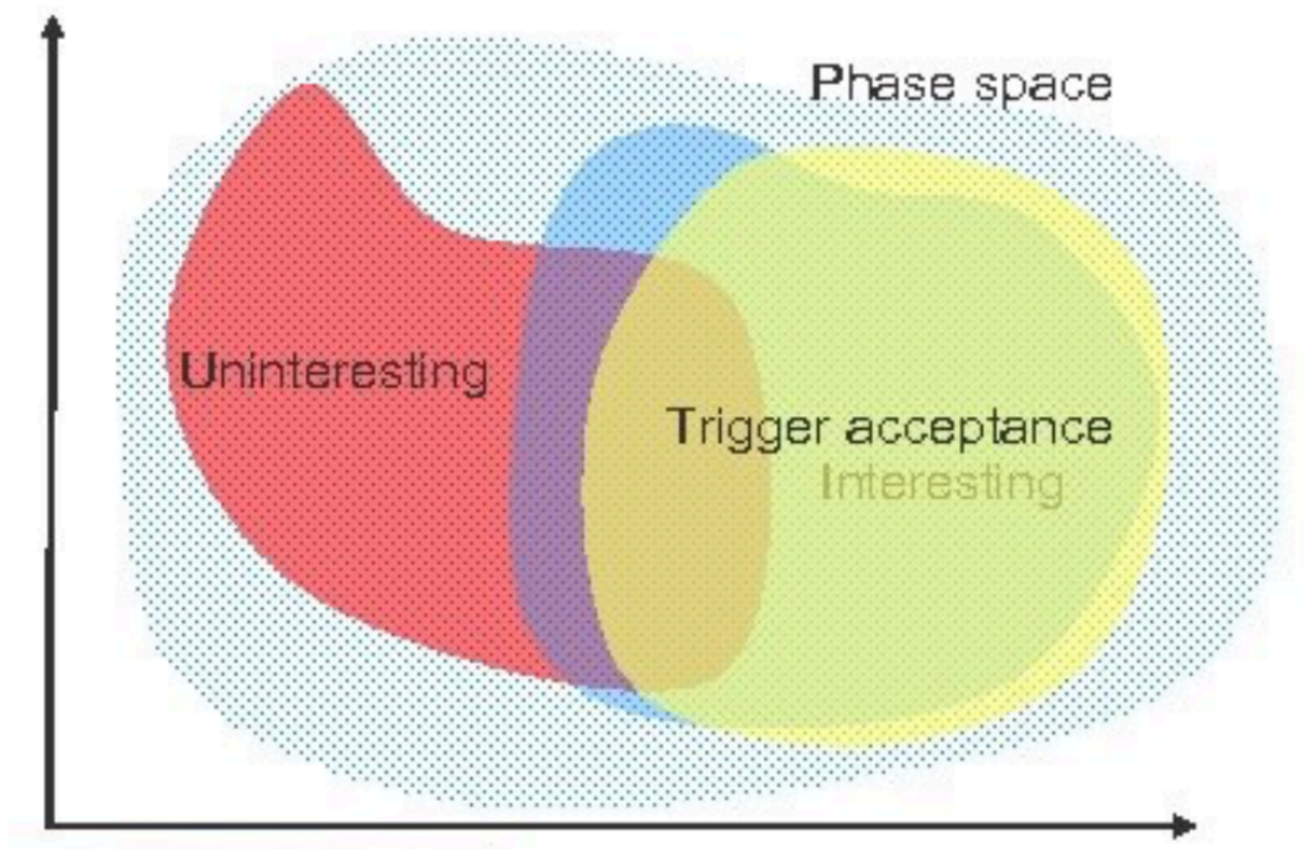

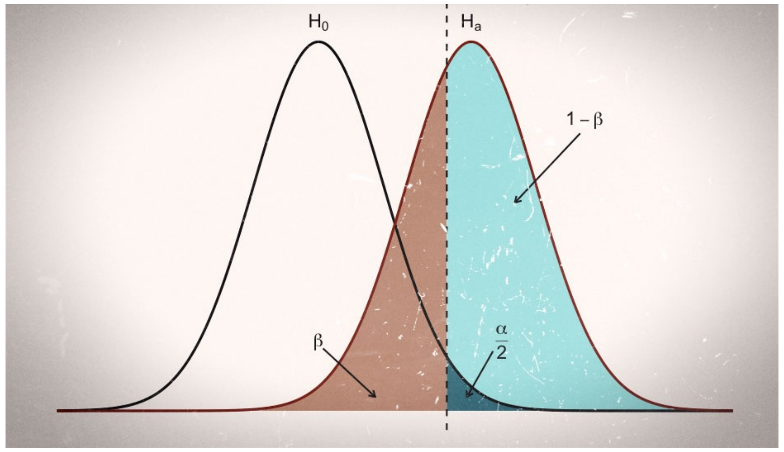

The strategy strongly depends on the source of physics events: cosmic rays? lepton colliders? hadron colliders?


which is the best filter?
MATTER
ANTIMATTER
DOESN'T MATTER

- **There is not unique answer**
  - depends on the signal and the background

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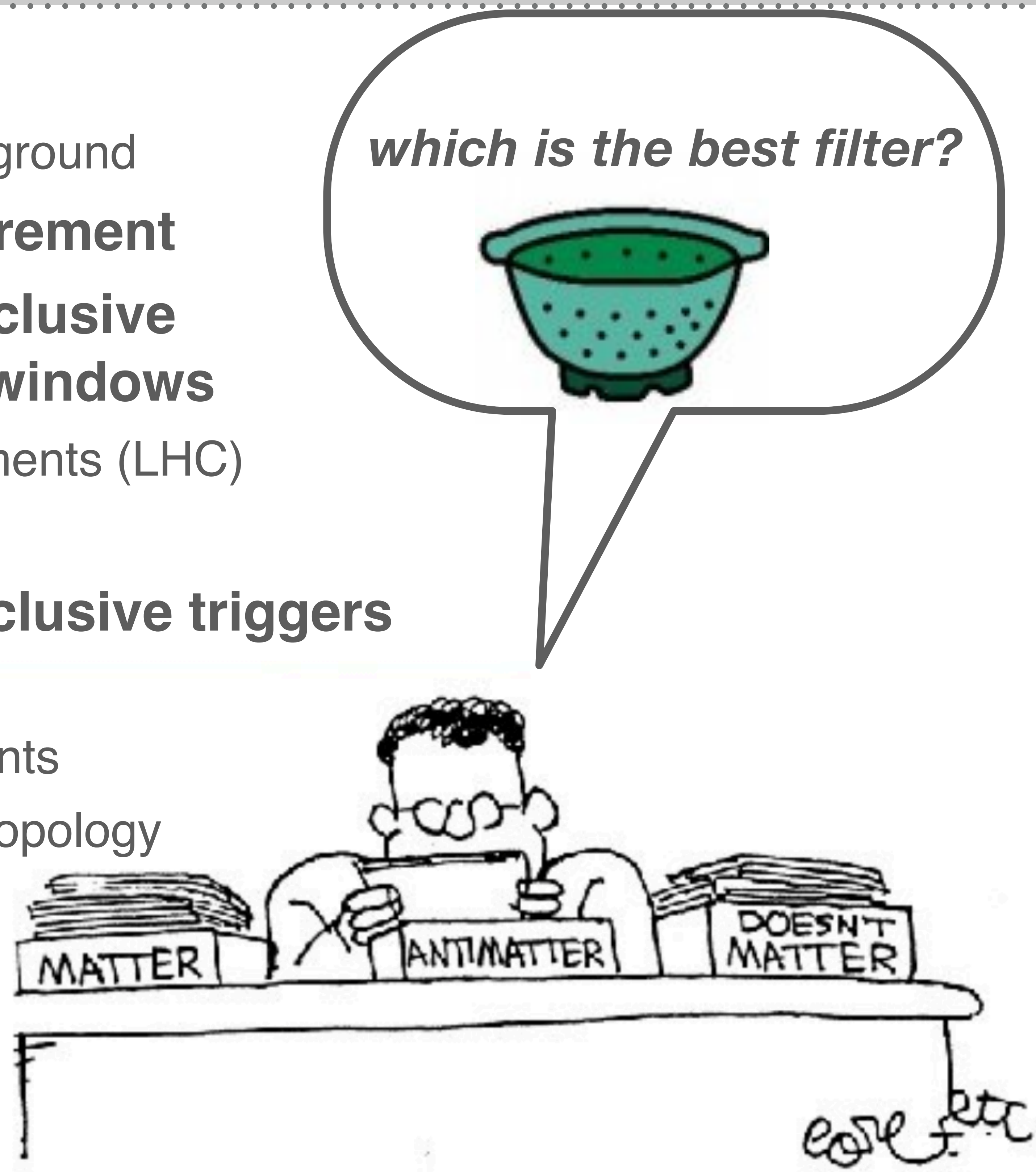

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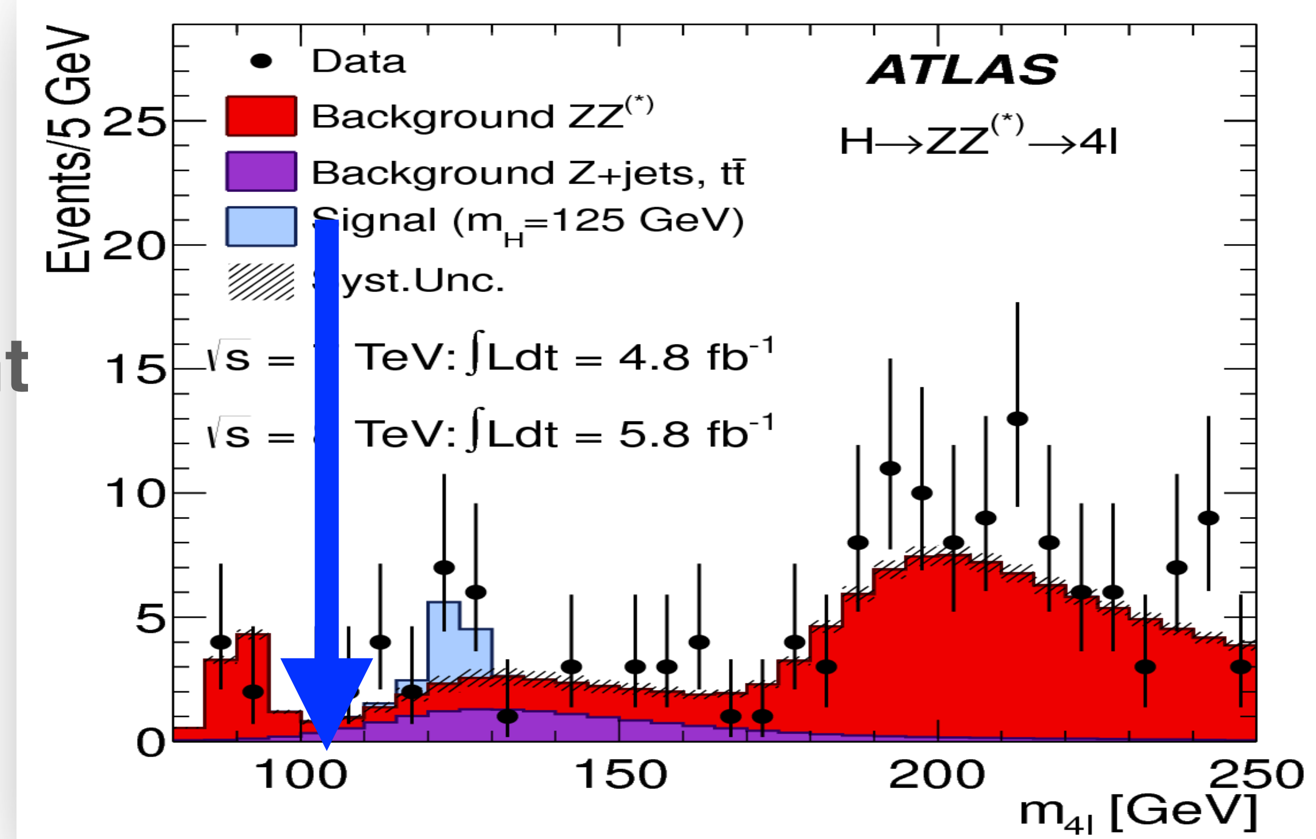
- **Precision experiments prefer exclusive triggers on well-known selections**
  - for example lepton-collider experiments
  - e.g. selections recreating the event topology
- **In addition, different independent trigger selections for cross-calibrations**
  - Background is unavoidable
  - Some events need to be stored to measure systematics

REQUIREMENT N.1: HIGH SIGNAL EFFICIENCY

$$\epsilon_{trigger} = \frac{N_{good}^{accepted}}{N_{good}^{expected}}$$

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



- **It drives the design of the experiment and of the T/DAQ architecture**
- **Depends on the acceptance**
  - of detectors, DAQ,…..
- **Depends on the selection**
  - tuned on Monte Carlo simulations

- **Which is an acceptable efficiency?**

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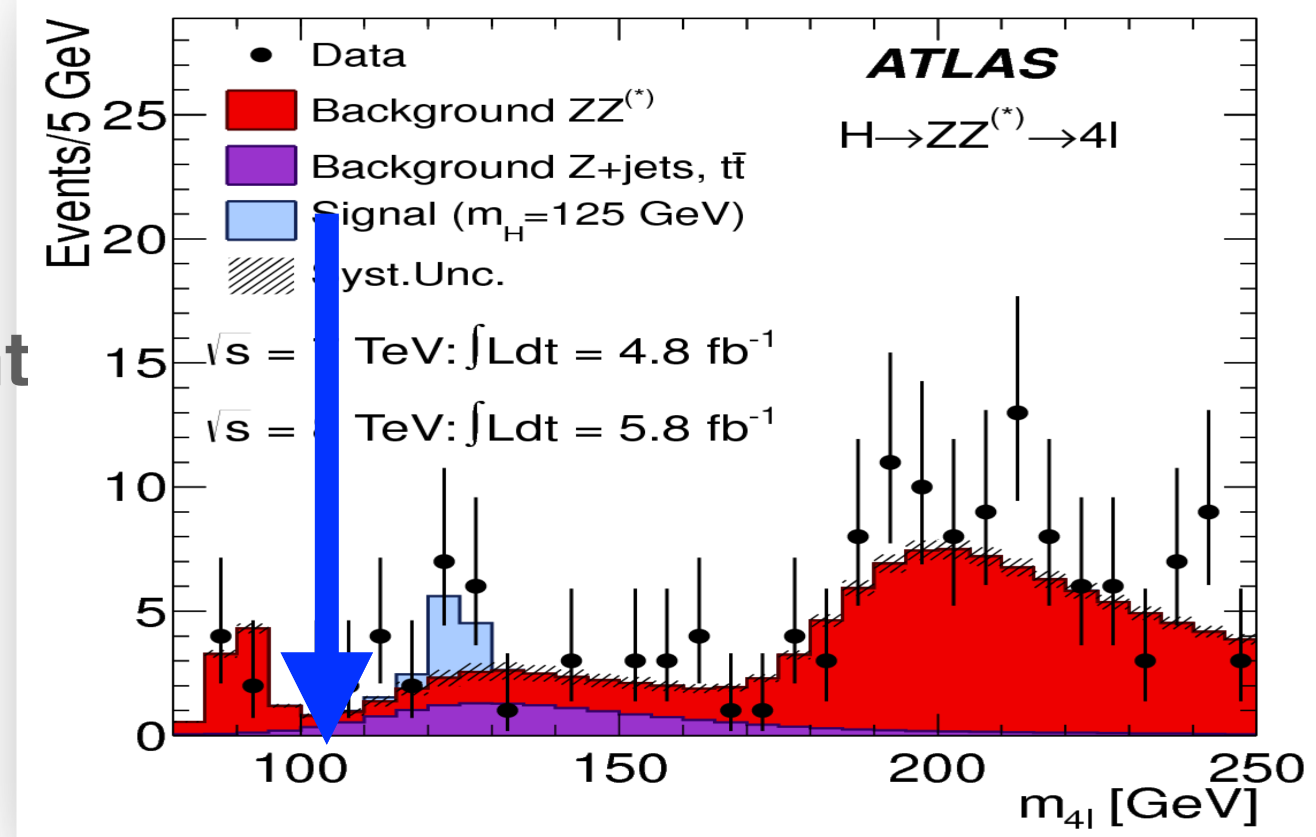

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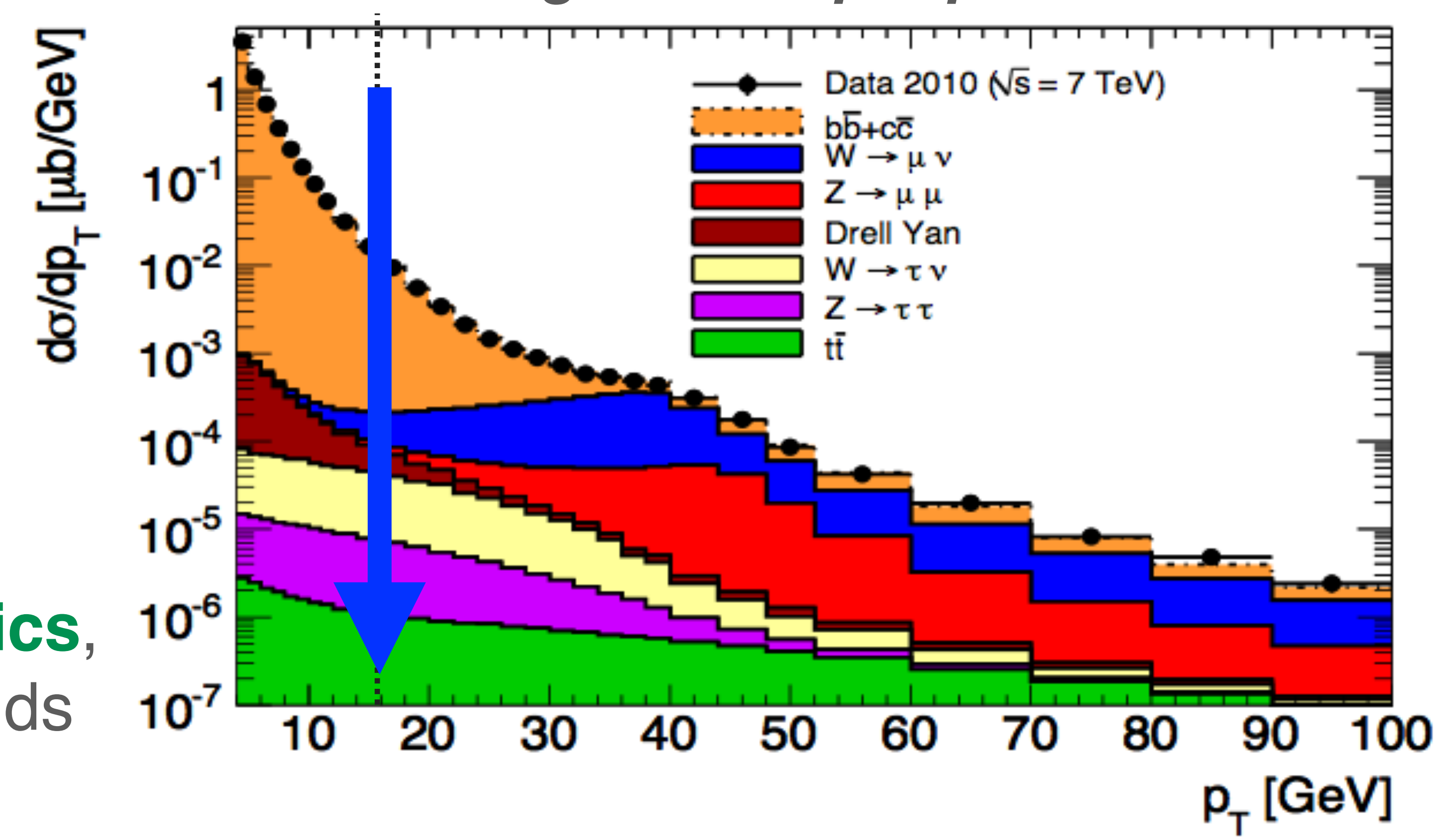
REQUIREMENT 2: GOOD BACKGROUND REJECTION

$$R_{trigger} = \frac{N_{bad}^{expected}}{N_{bad}^{accepted}}$$

- ➡ **Rate control is critical**
  - ➡ in particular on hadron colliders
- ➡ **Need solid understanding of background shapes**
  - ➡ Monte Carlo simulation of **all physics**, detector noise, machine backgrounds
- ➡ **Not easy!**
- ➡ **Backgrounds are often known with great uncertainties**
  - ➡ trigger must be **flexible and robust**

Inclusive single muon p_T spectrum @LHC



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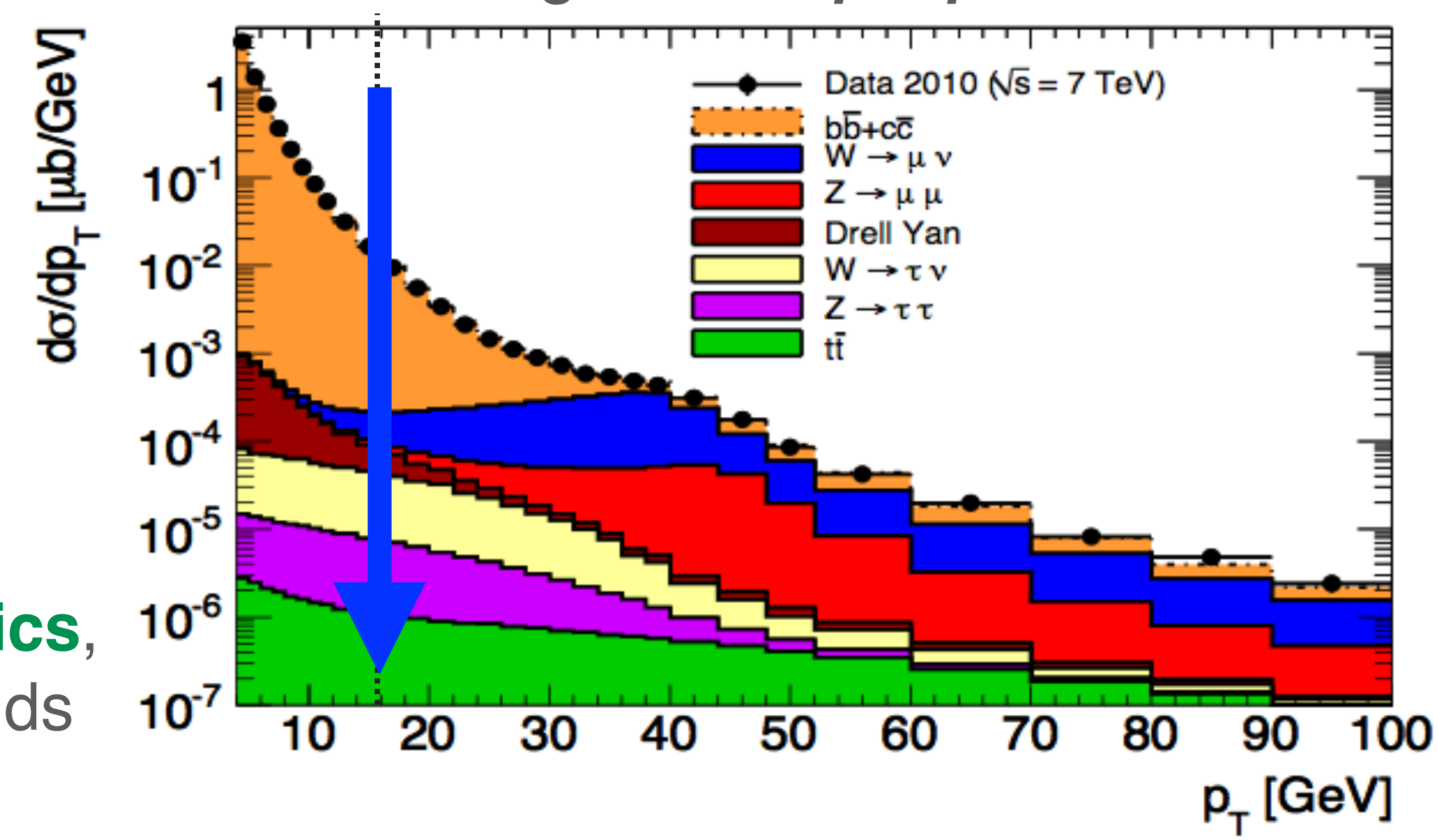

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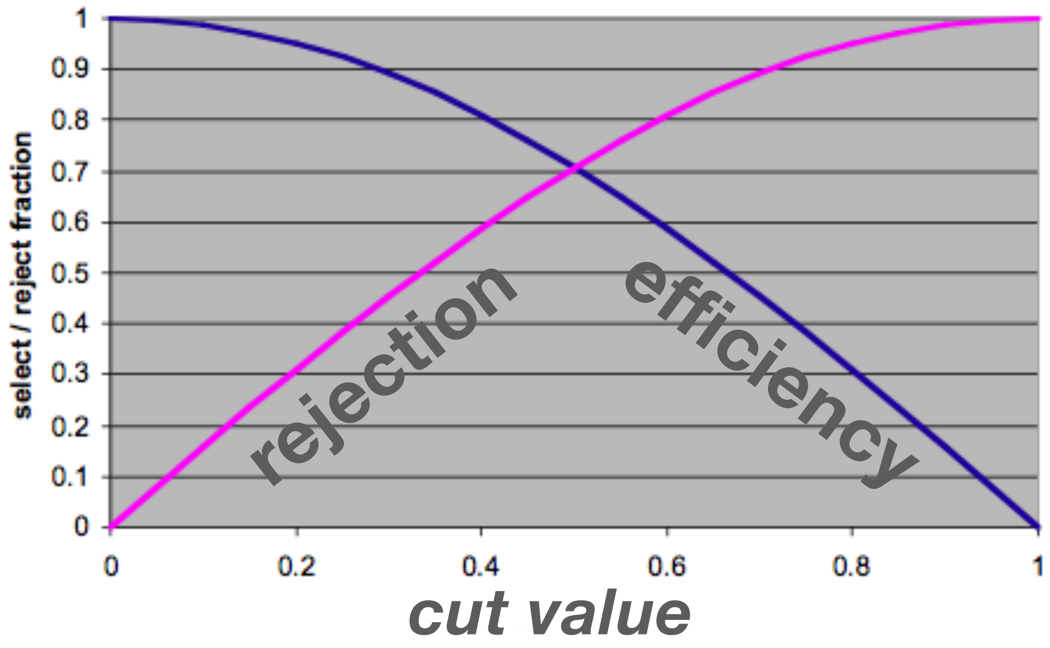

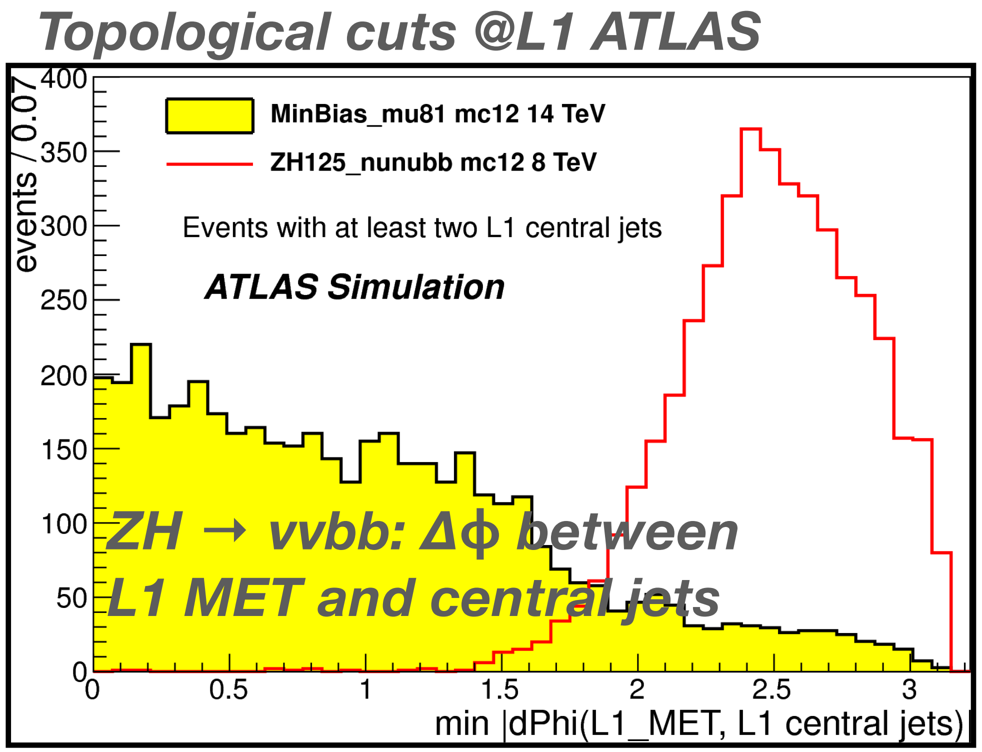

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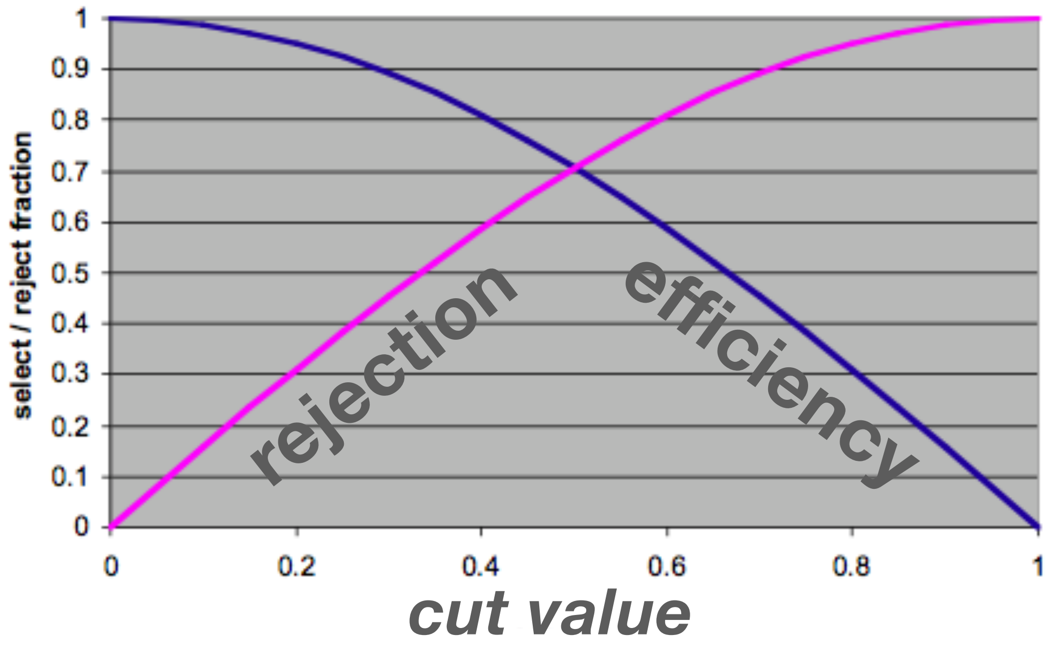
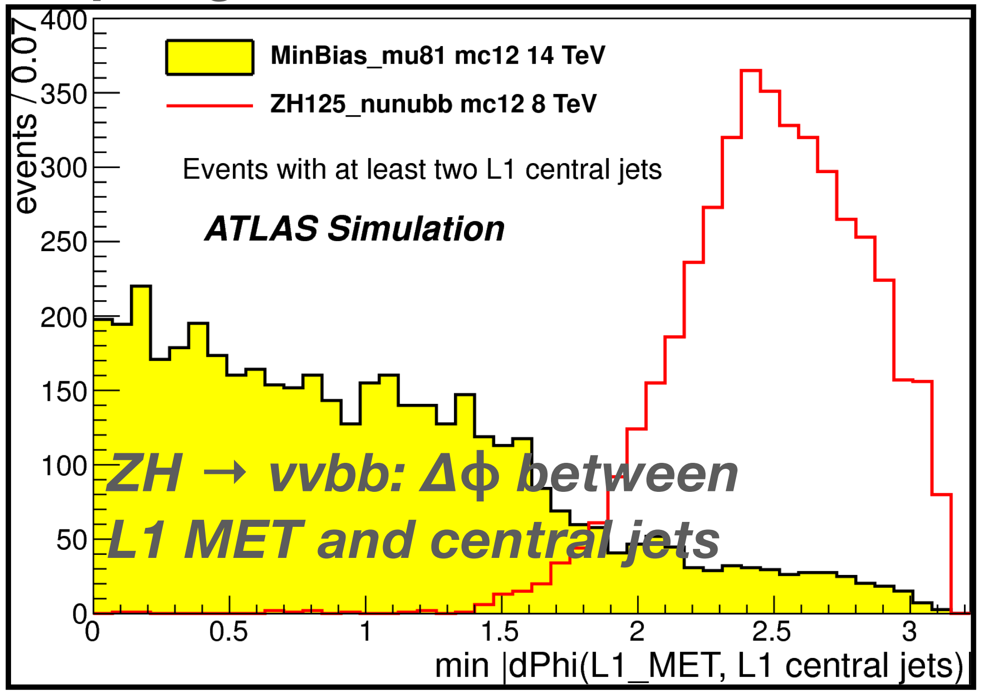


Topological cuts @L1 ATLAS



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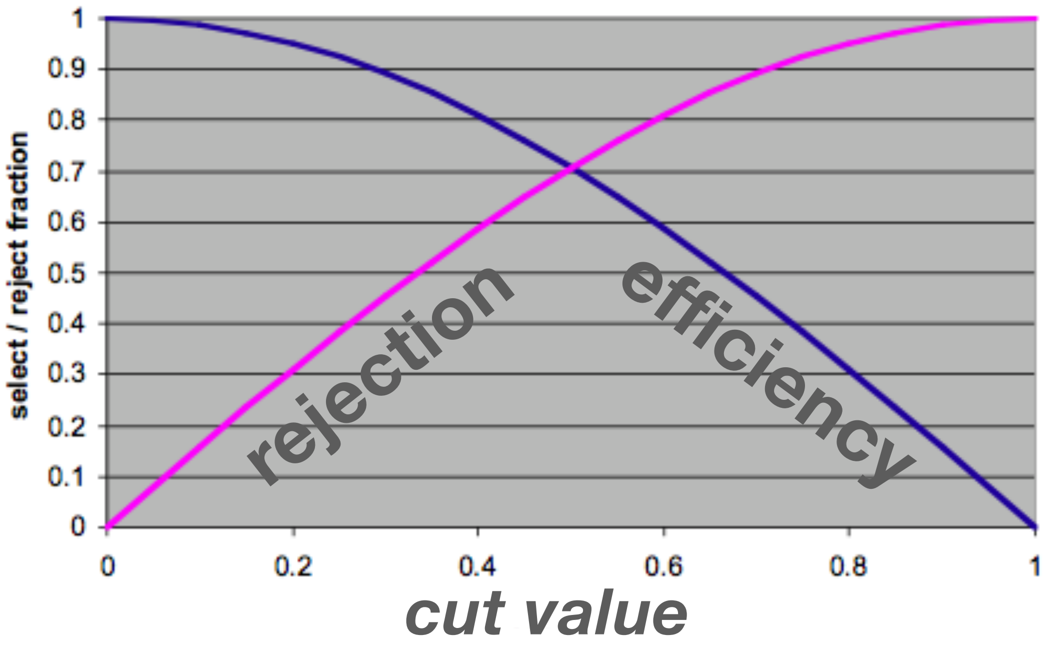

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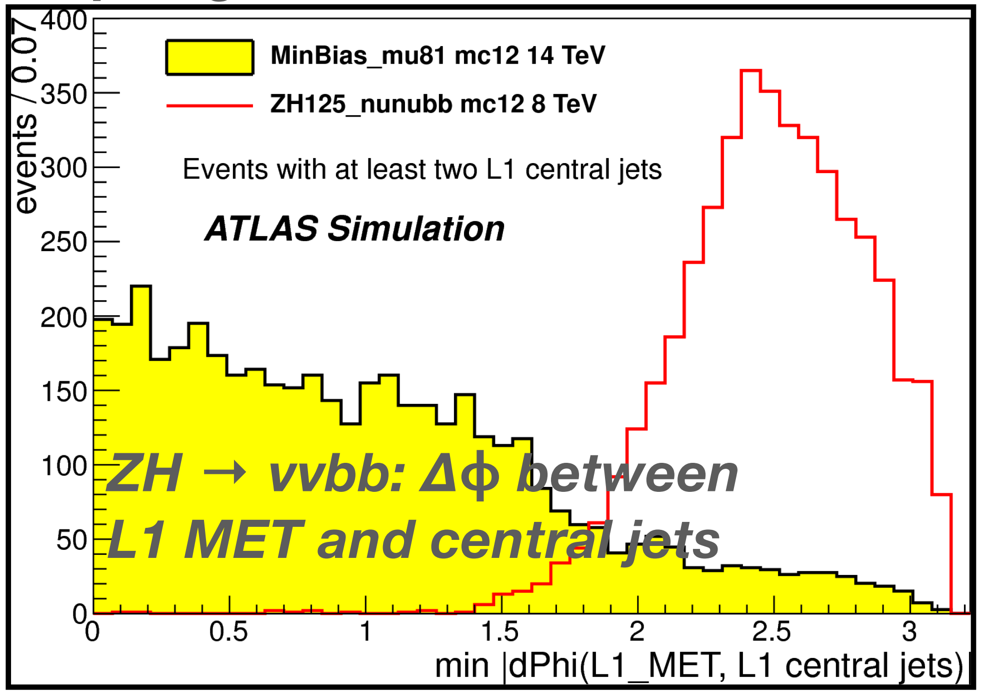

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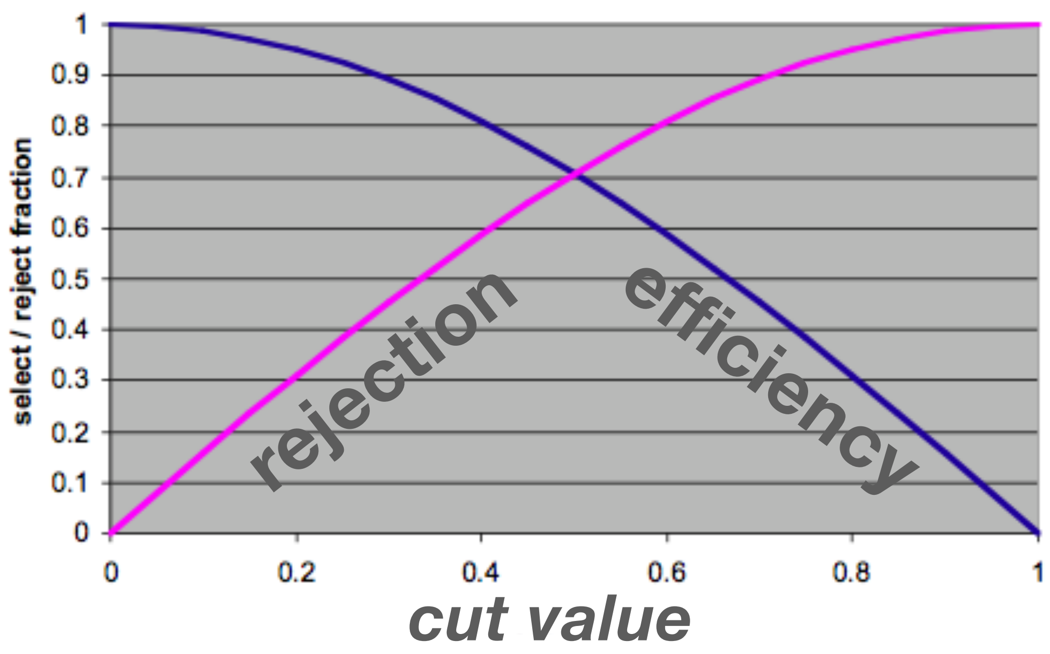
- ➡ Add new **parameters**
  - ➡ maybe need new detectors?



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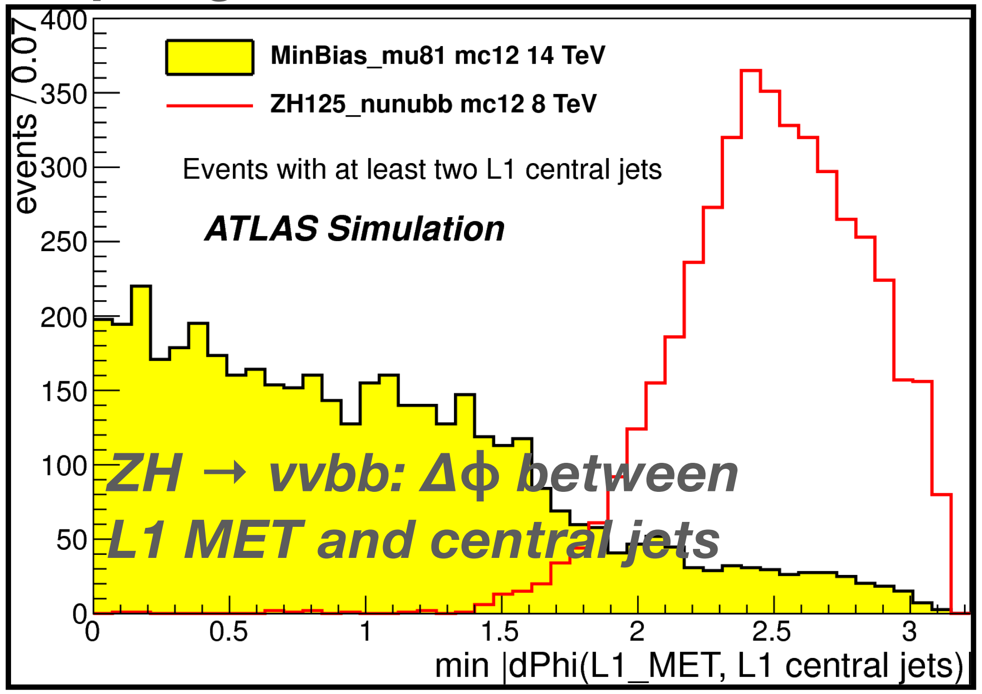

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- ➡ or run faster algorithms?
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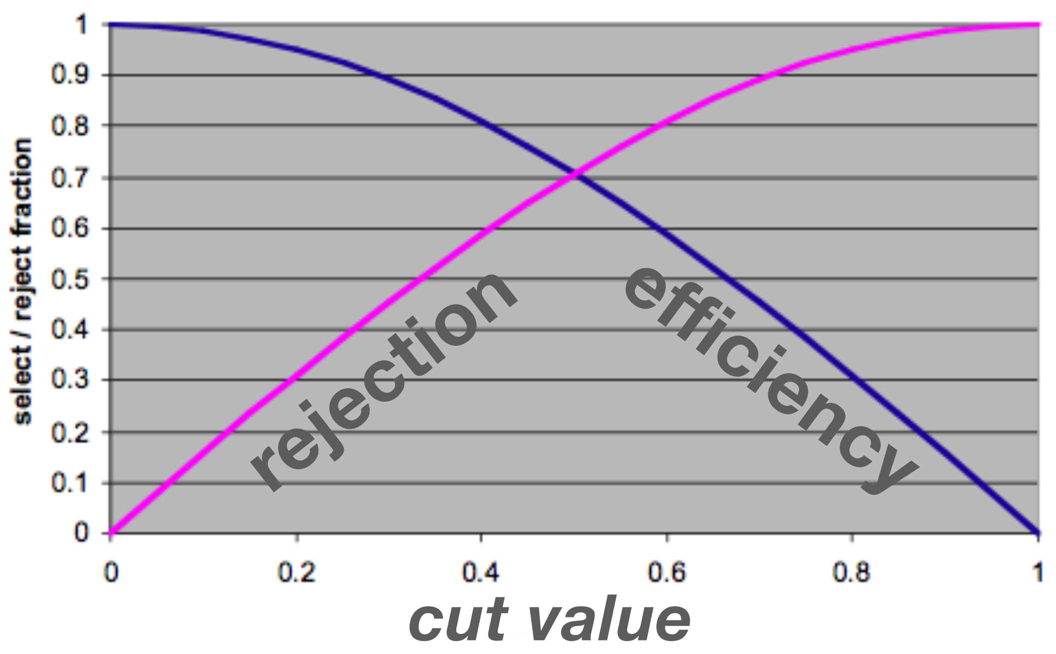

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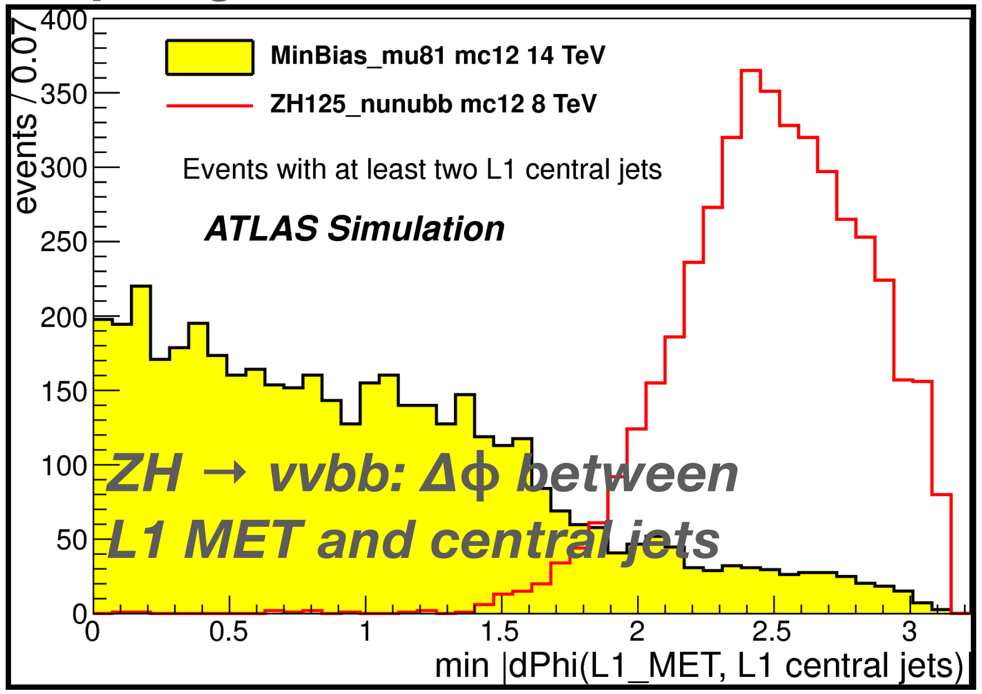

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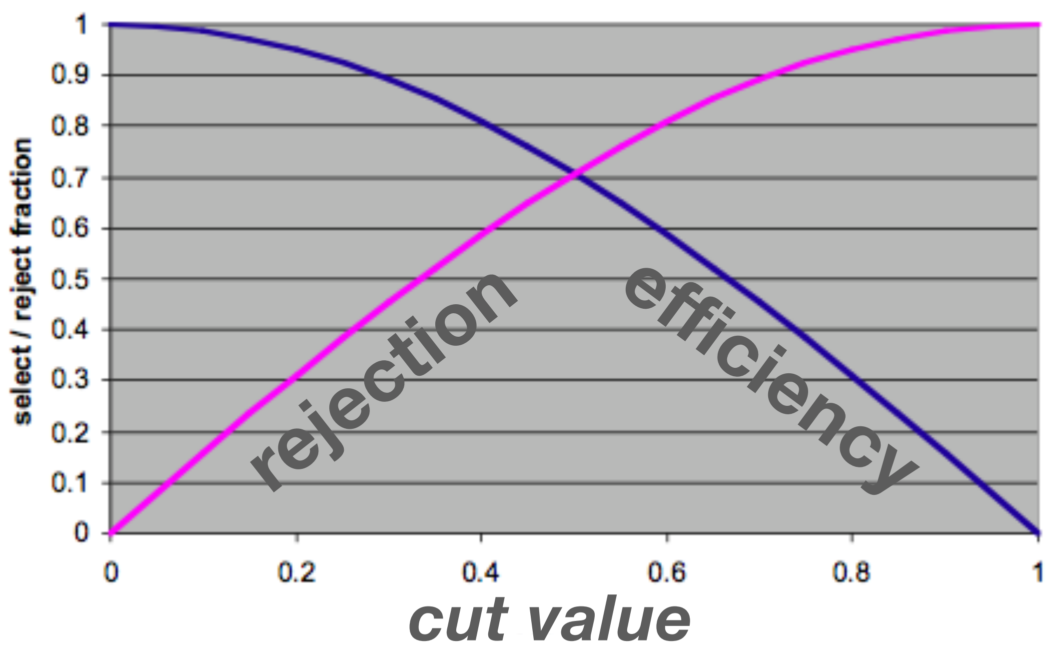

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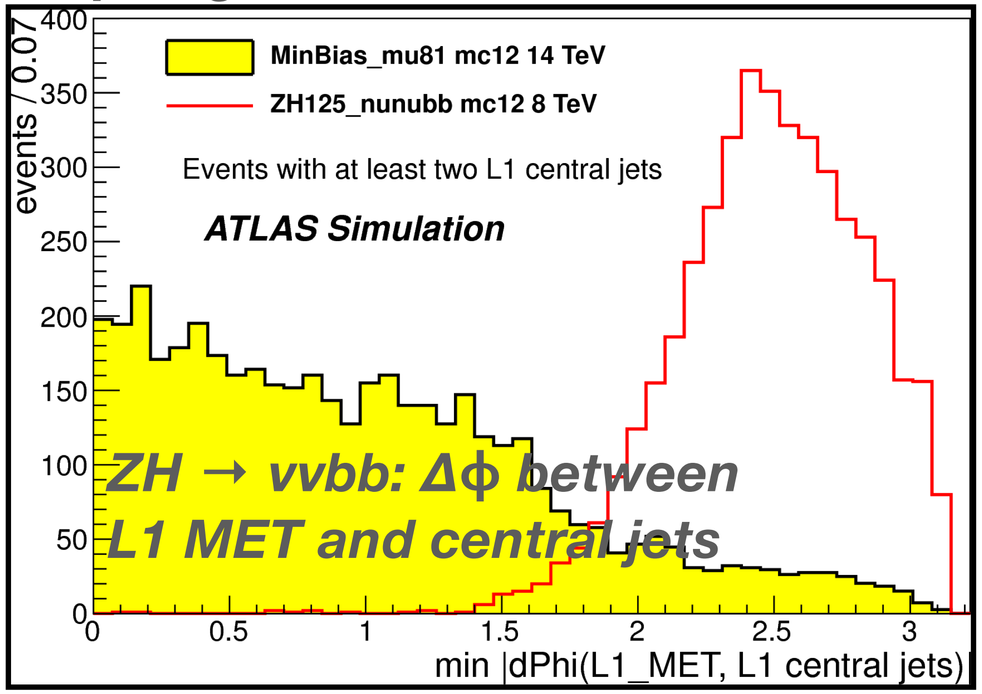

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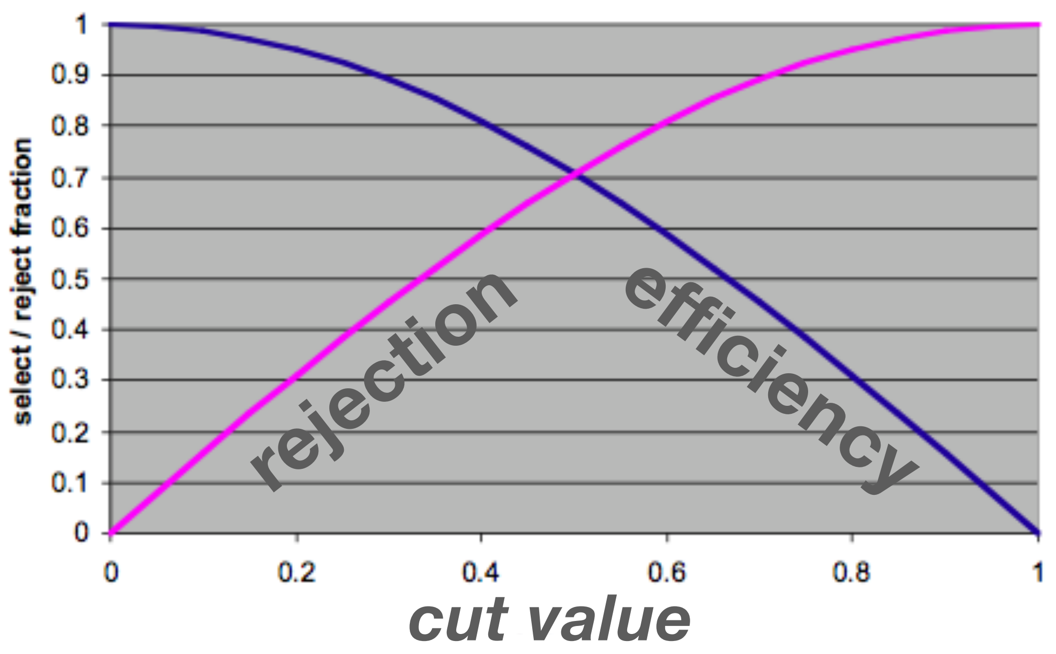

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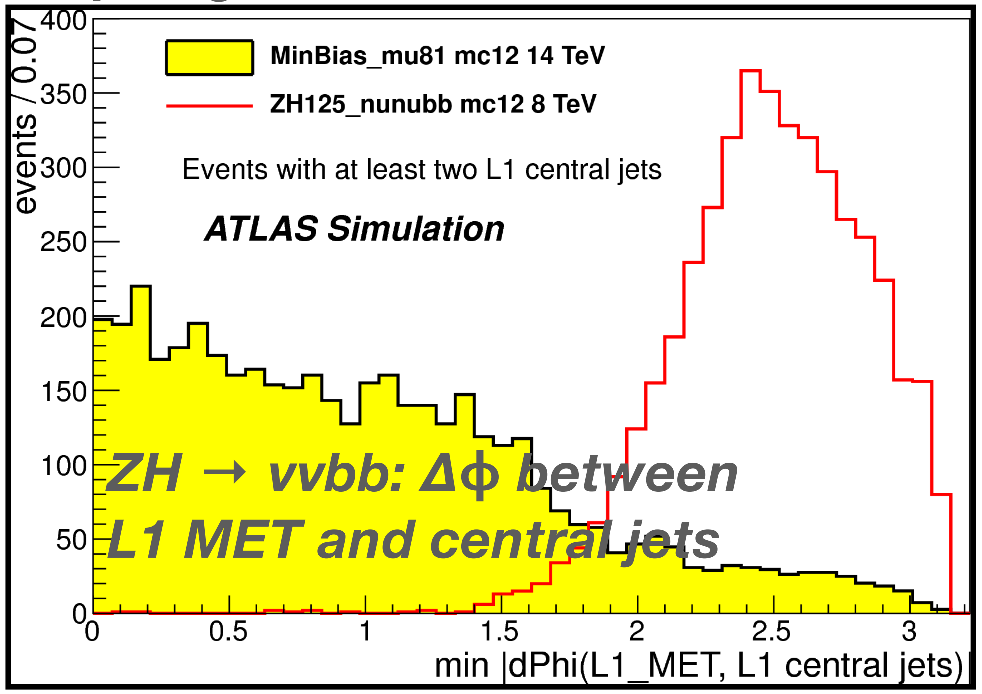

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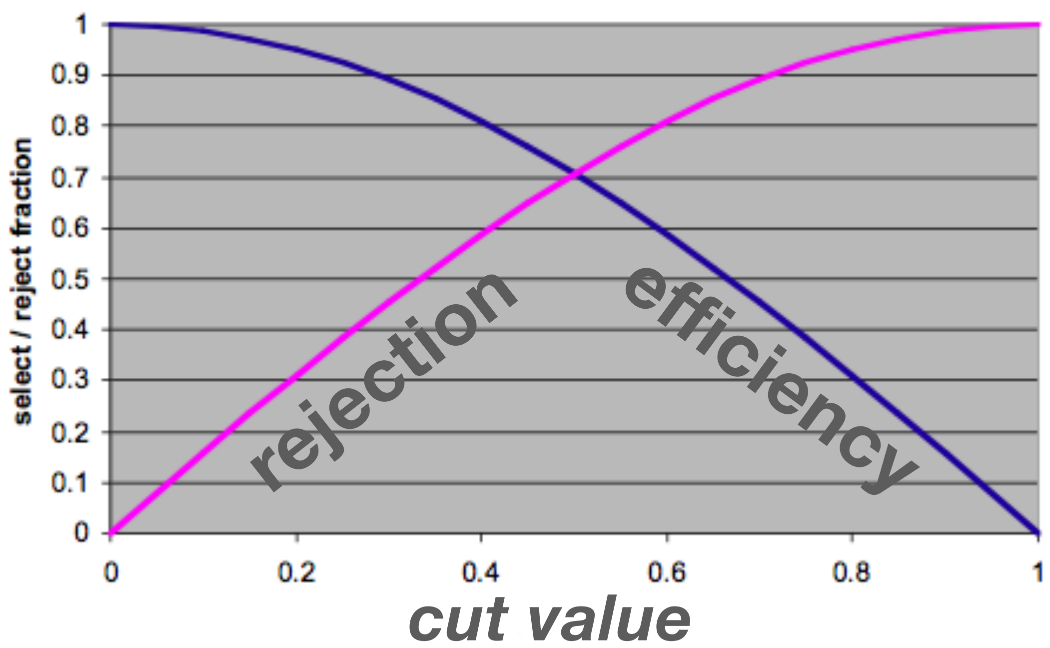
- ➡ **Scalability is always an advantage**
- ➡ **Whatever criteria you choose, discarded events are lost for ever!**
- ➡ **Always ask yourself: is the trigger reliable?**
  - ➡ If you don't trust your trigger, add control samples
  - ➡ and always **monitor** your trigger



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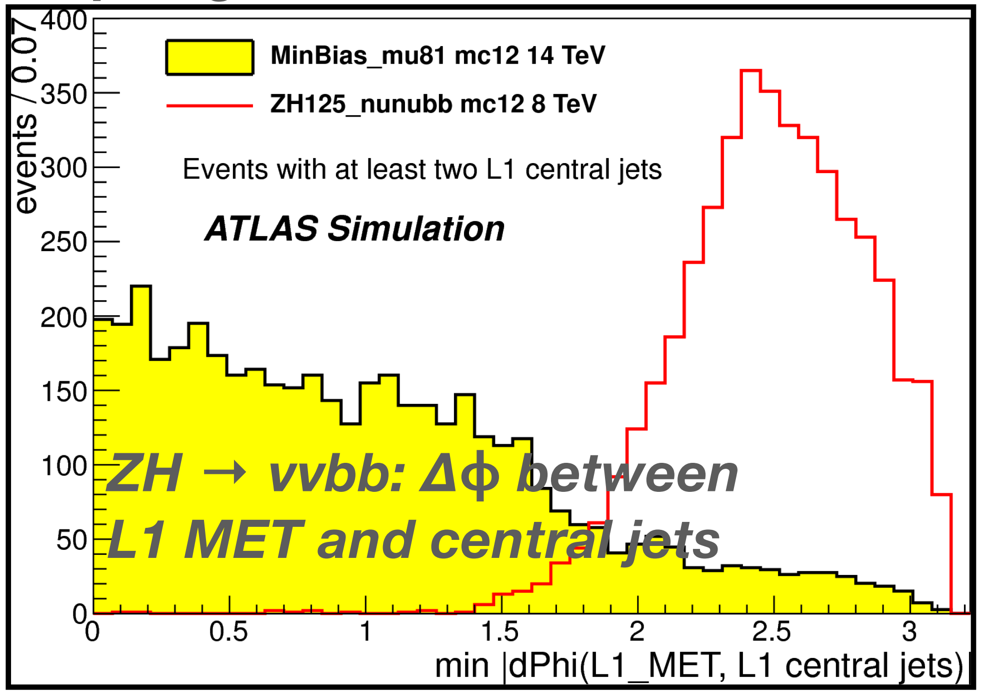

TRIGGER EFFICIENCY IS A PARAMETER OF YOUR MEASUREMENT

$$BR_{signal} = \frac{N_{candidate} - N_{bkg}}{\alpha \cdot \epsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

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

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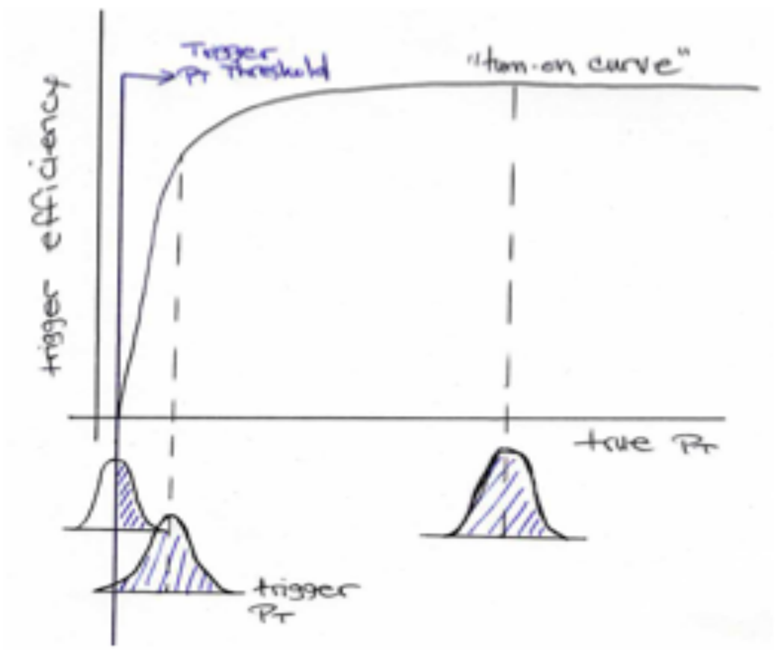
- ➡ Trigger efficiency must be precisely known, since it enters the cross-sections measurements
- ➡ For some precise measurements, the target performance is not the high efficiency, but the systematic error on determining it

TRIGGER PERFORMANCE MEASUREMENTS

- **The threshold is not applied as a step function, due to the finite resolution of the parameters**
  - It's an Error function, usually called **trigger turn-on**
- **The capability of controlling the rate depends on the resolution on the trigger parameter**



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  - If quick, better background suppression
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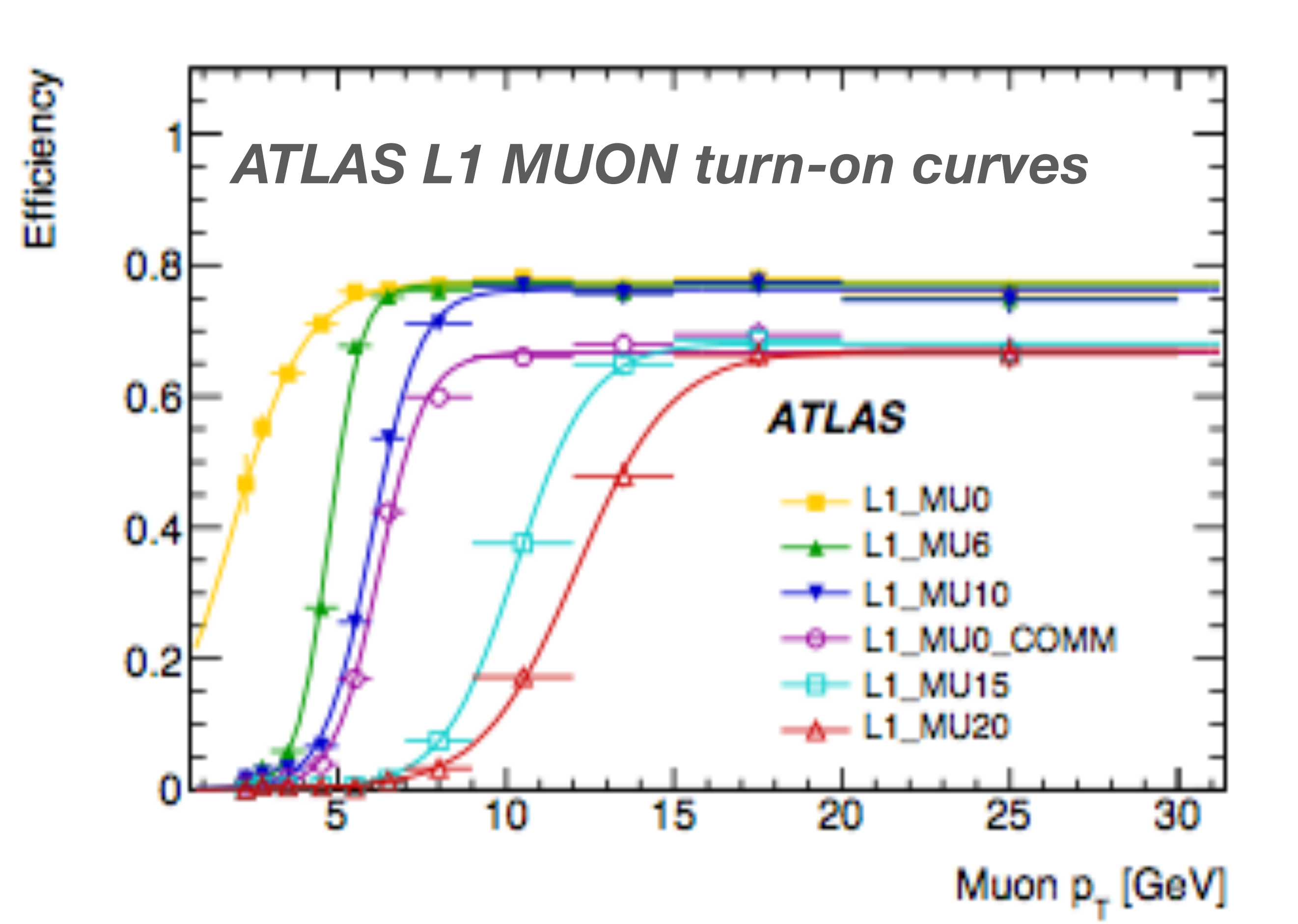

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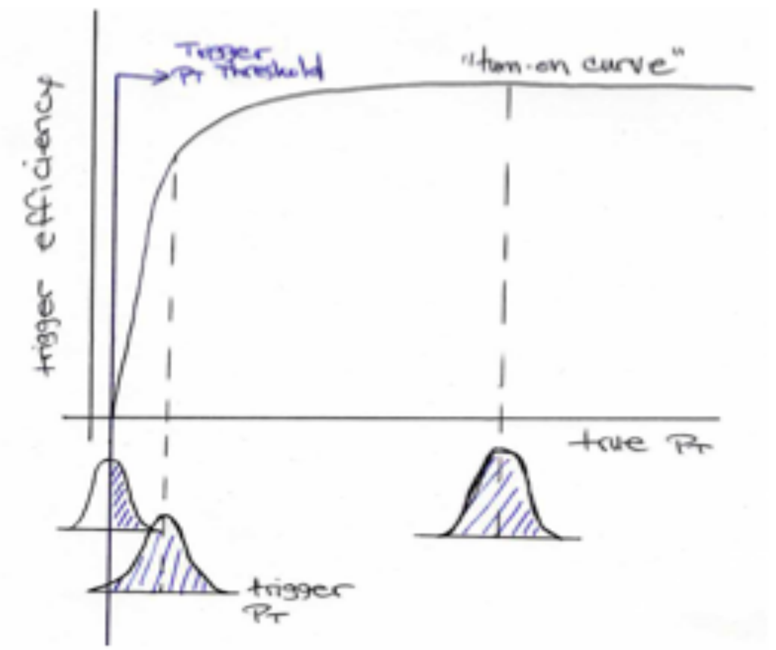

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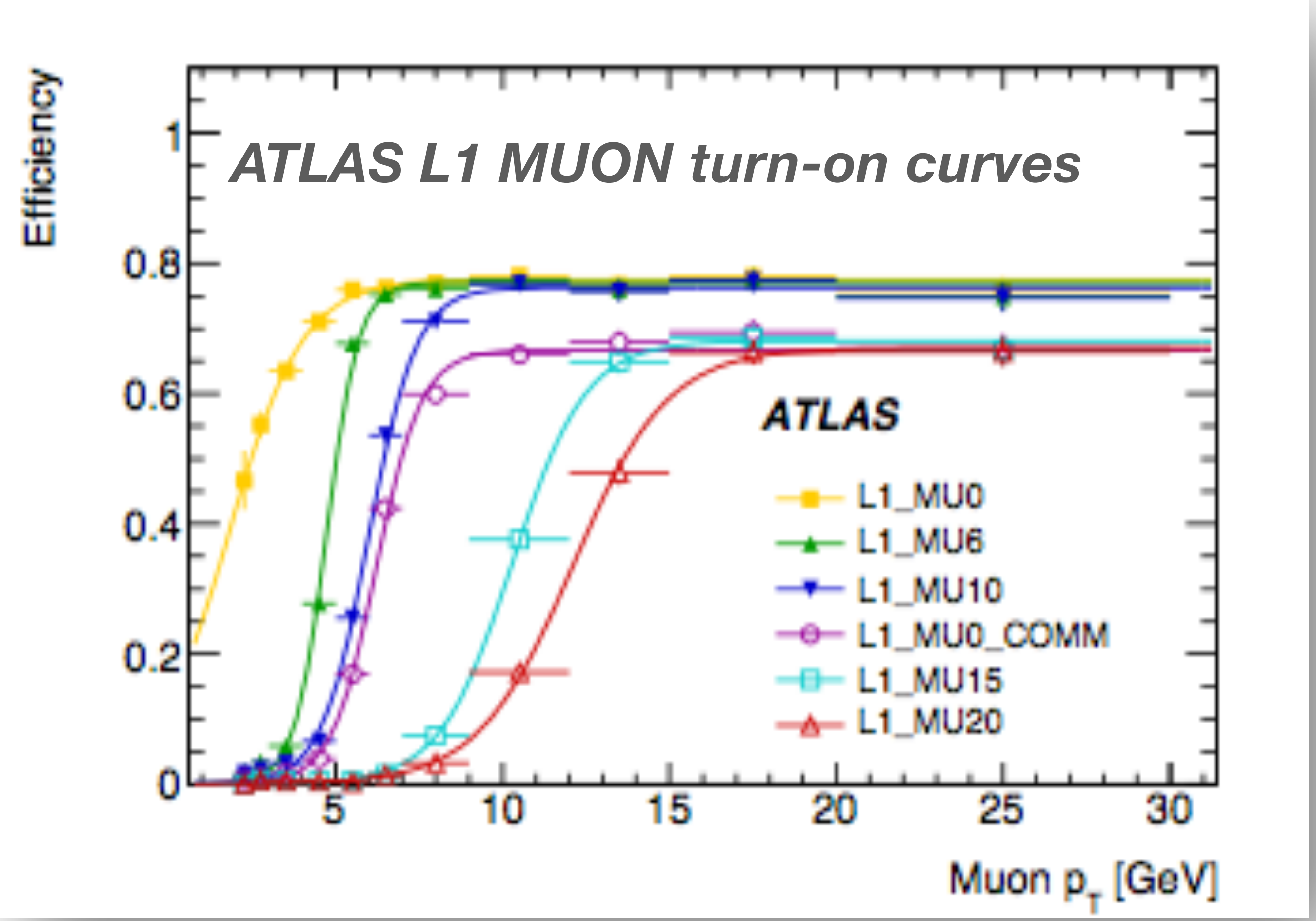


TRIGGER FOR PRECISION MEASUREMENTS: BABAR

Goal: precision measurement of CP violation

↓

Reduce systematic uncertainties

↓

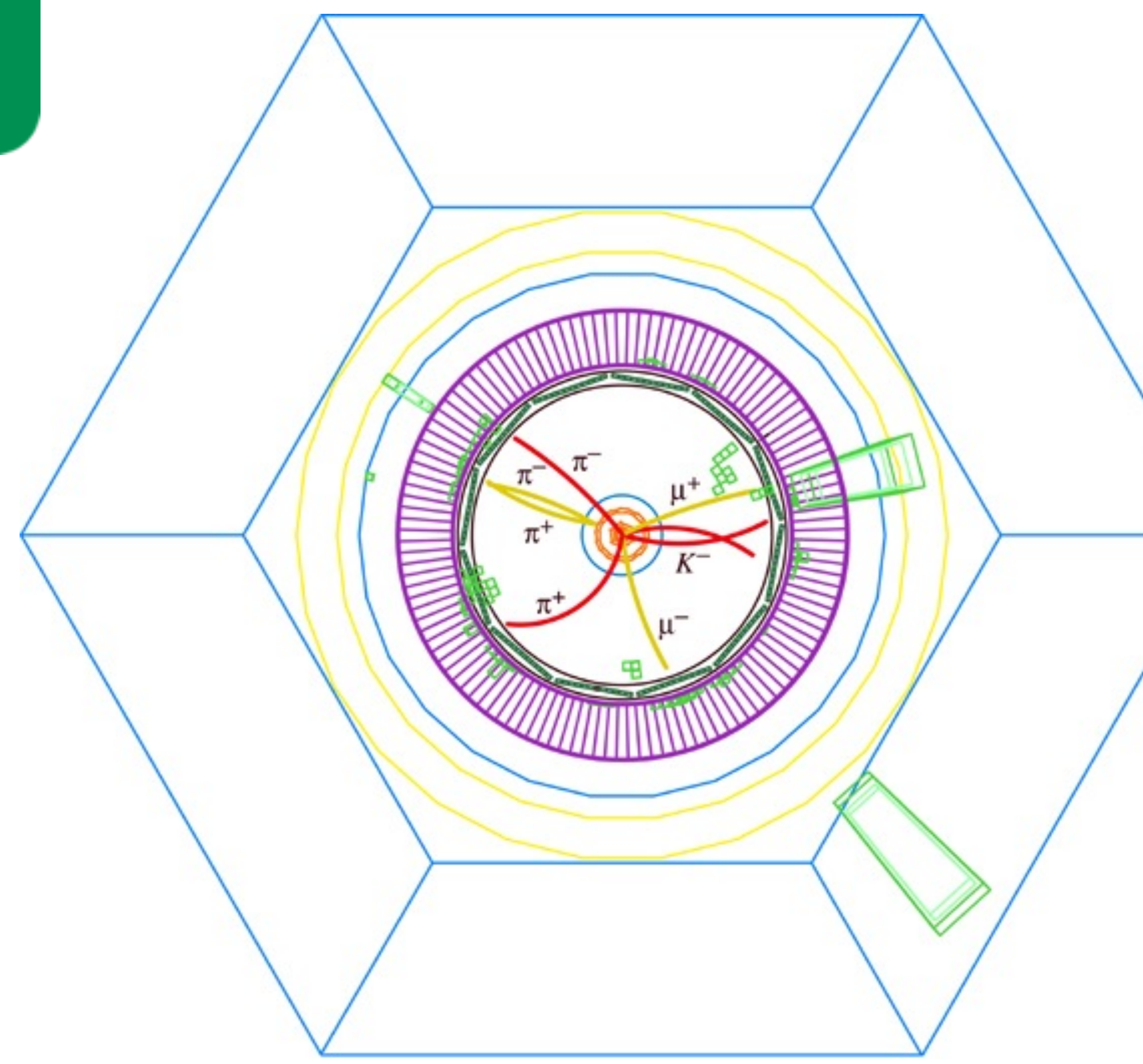
Know your detector (and trigger) very well!

Golden event in the BaBar Detector

e+e- collision producing a B and an anti-B

Golden B (for CP violation)

Tagging B



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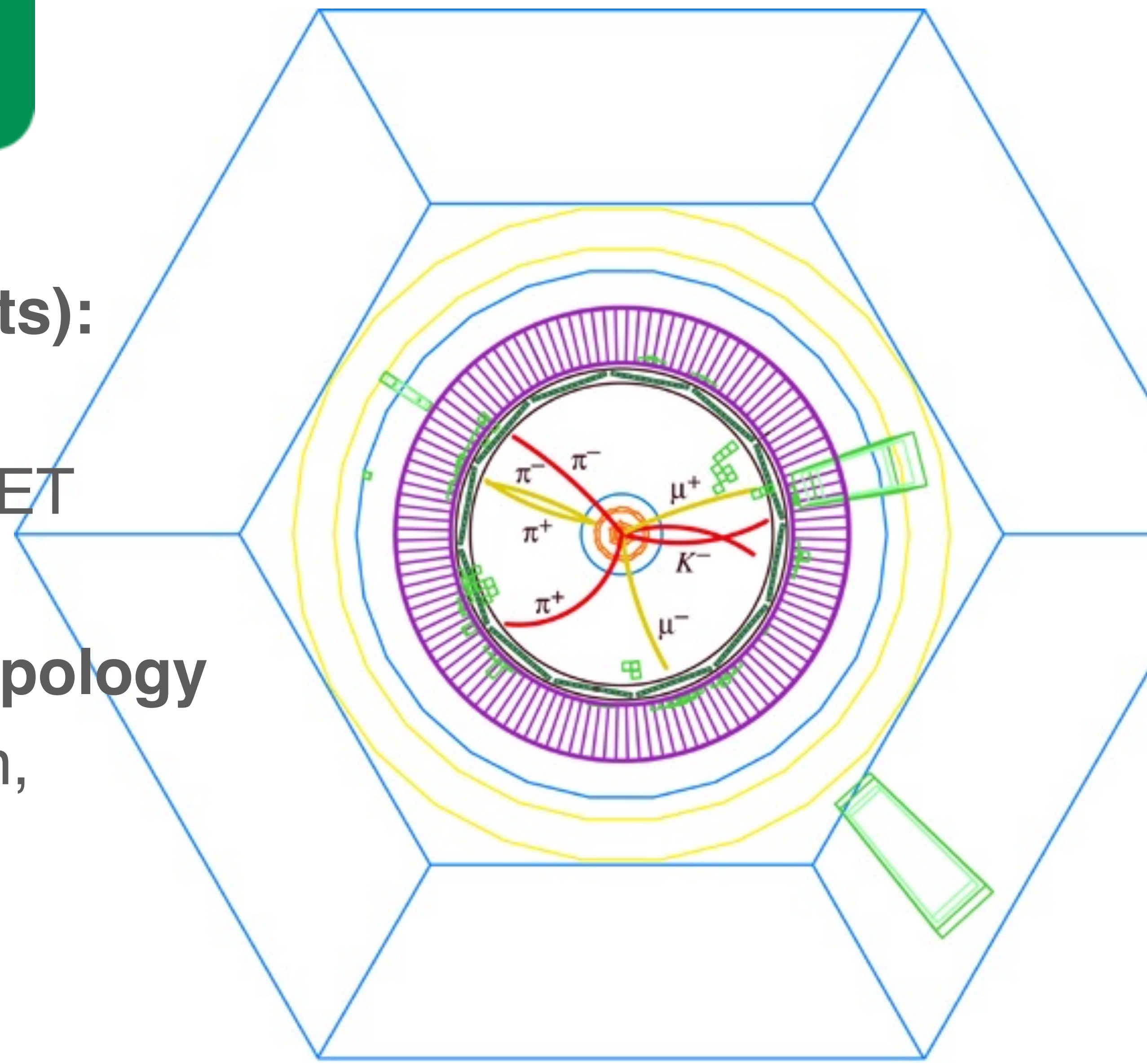
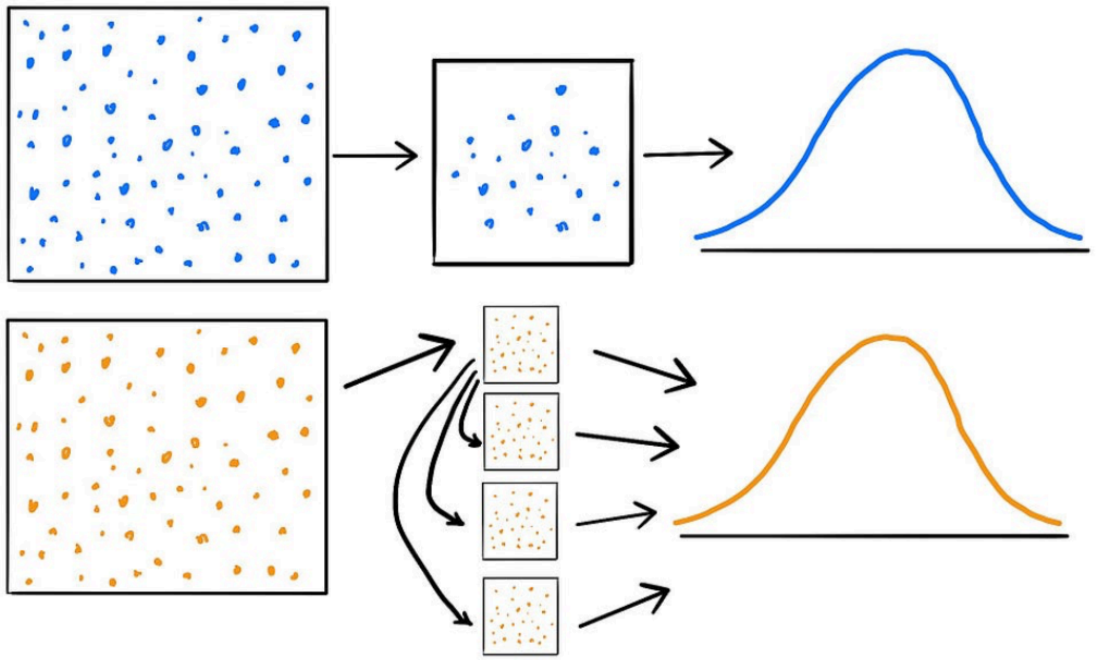


- **Multitude of trigger parameters (objects):**
  - Charged tracks in the drift chamber
  - EM calorimeter clusters with different ET
  - Particle identification capability
- **Exclusive selections for each event topology**
  - Number of objects, angular separation, matching tracks and clusters
- **Study both signal and background to minimise error on efficiency**
  - a lot of control samples

METHODS TO MEASURE TRIGGER EFFICIENCY

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

- **Relative measurement made on specific data samples**
  - **Boot-strap** method:
    - efficiency wrt looser (prescaled) threshold trigger
    - e.g. tracking efficiency wrt no tracking
  - **Orthogonal-trigger** method:
    - efficiency wrt an independent trigger
    - e.g. jet trigger wrt muon trigger



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METHODS TO MEASURE TRIGGER EFFICIENCY

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

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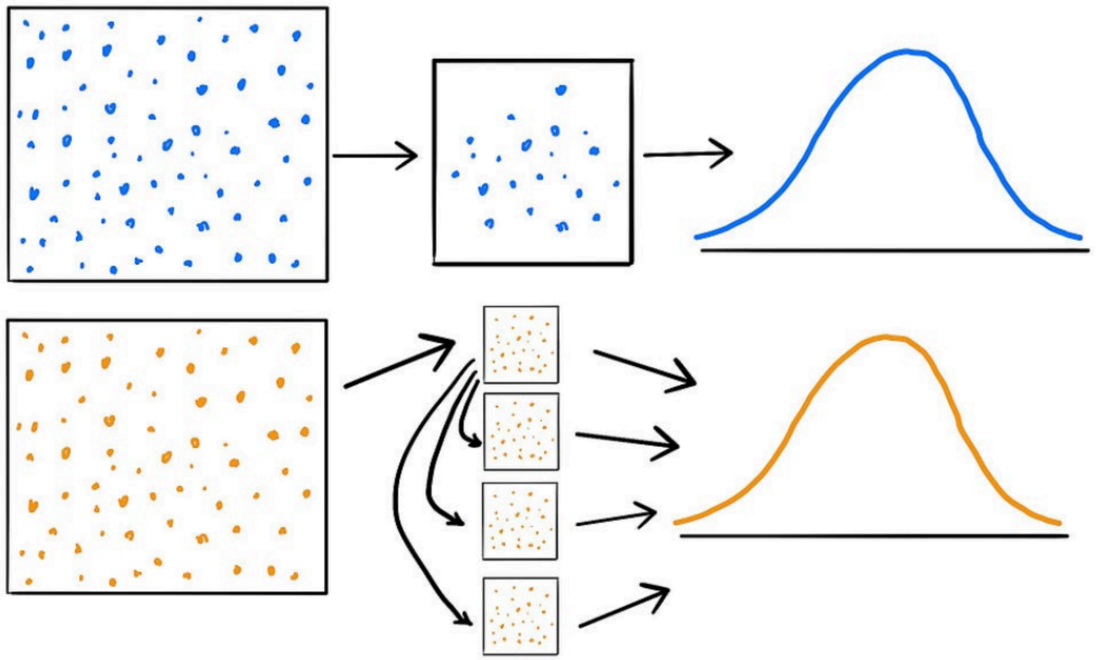

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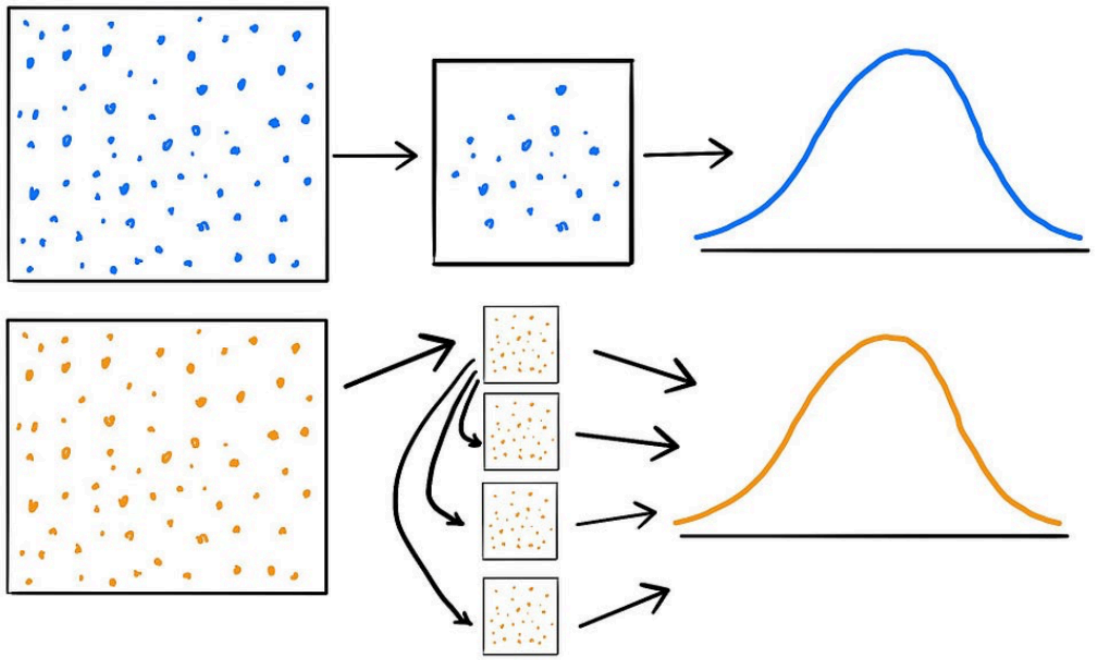

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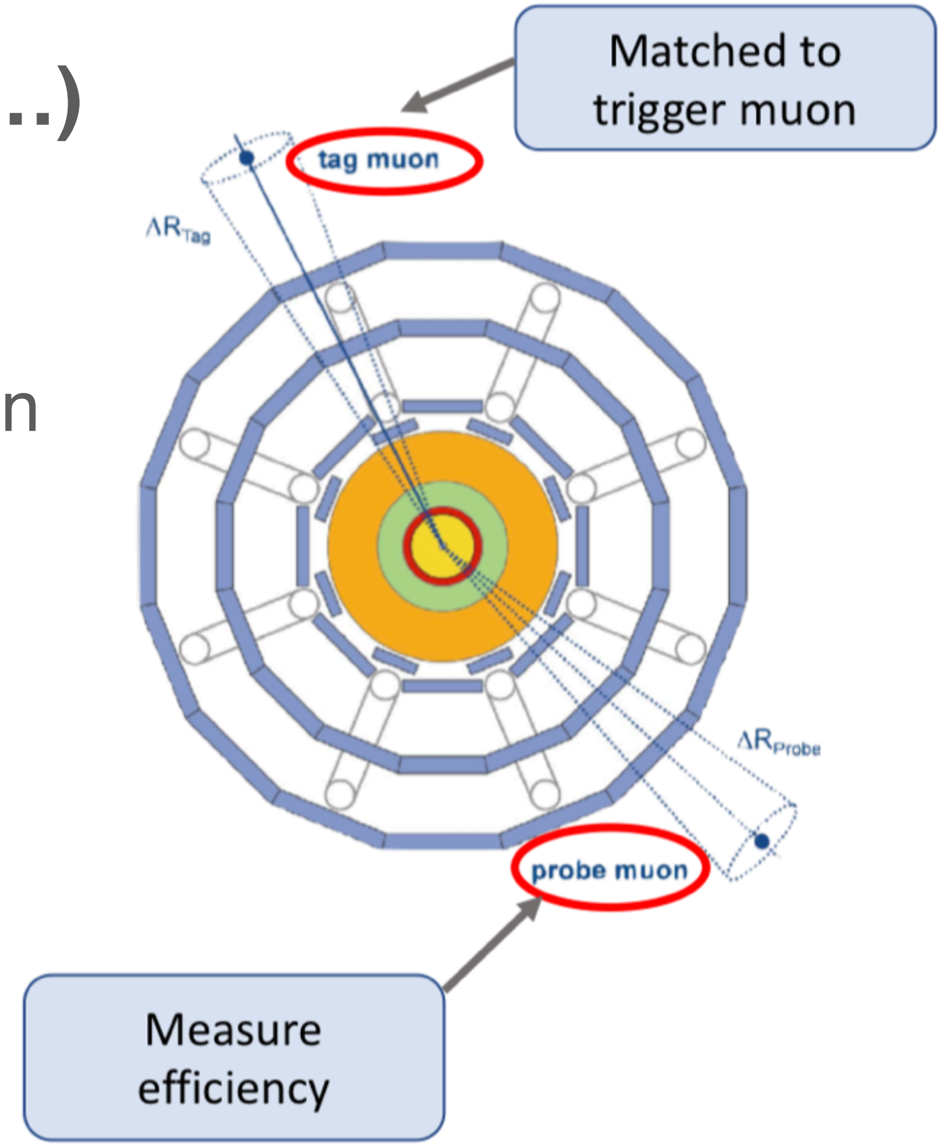
$$\text{Efficiency} = \frac{\text{number of events that passed the selection}}{\text{number of events without that selection}}$$

- **Experimental technique called Tag-and-Probe gives precise measurements for specific selections (for example electrons, muons,…)**
  - 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
- **How?**
  - Online: Trigger on independent selection (Tag)
  - Offline: Reconstruct the events that passed and apply a refined selection
    - For example Z mass selection
  - Offline: identify the Probe and measure efficiency



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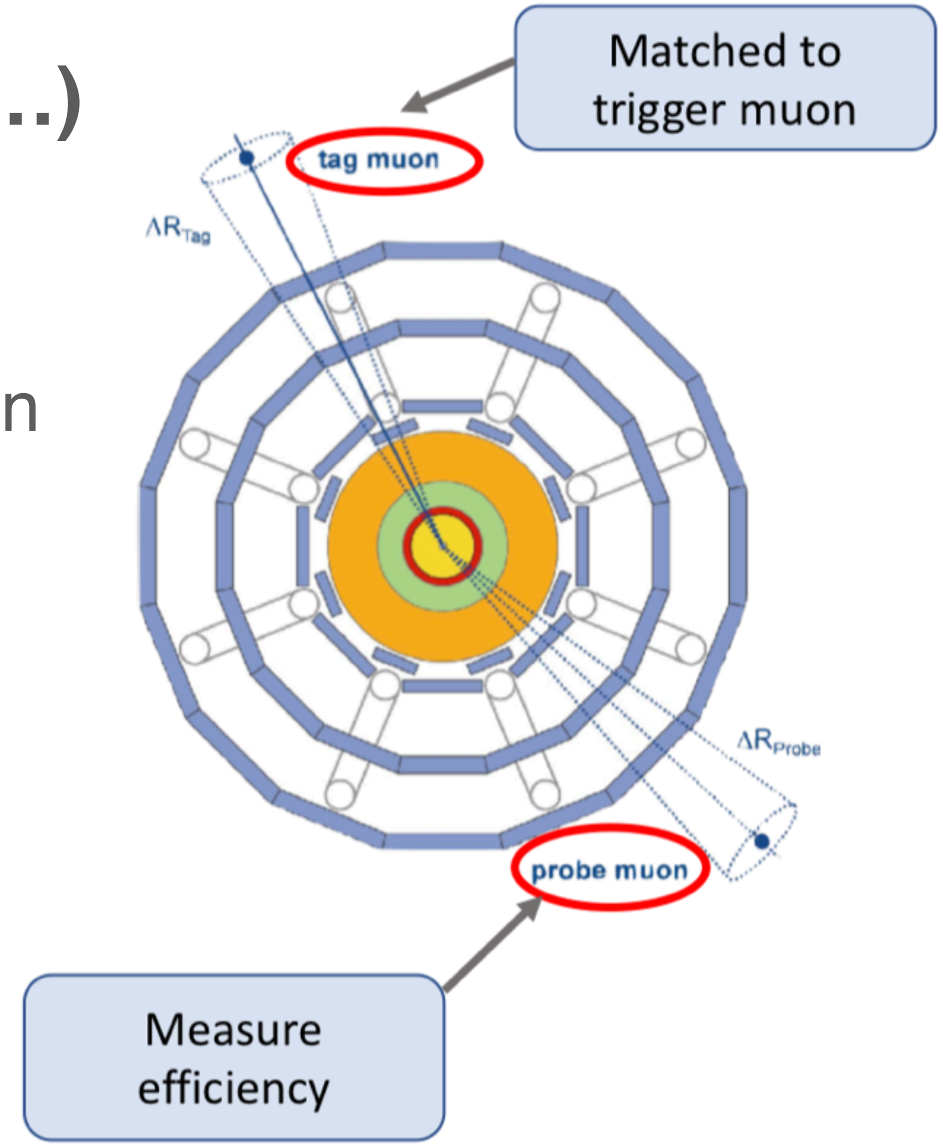
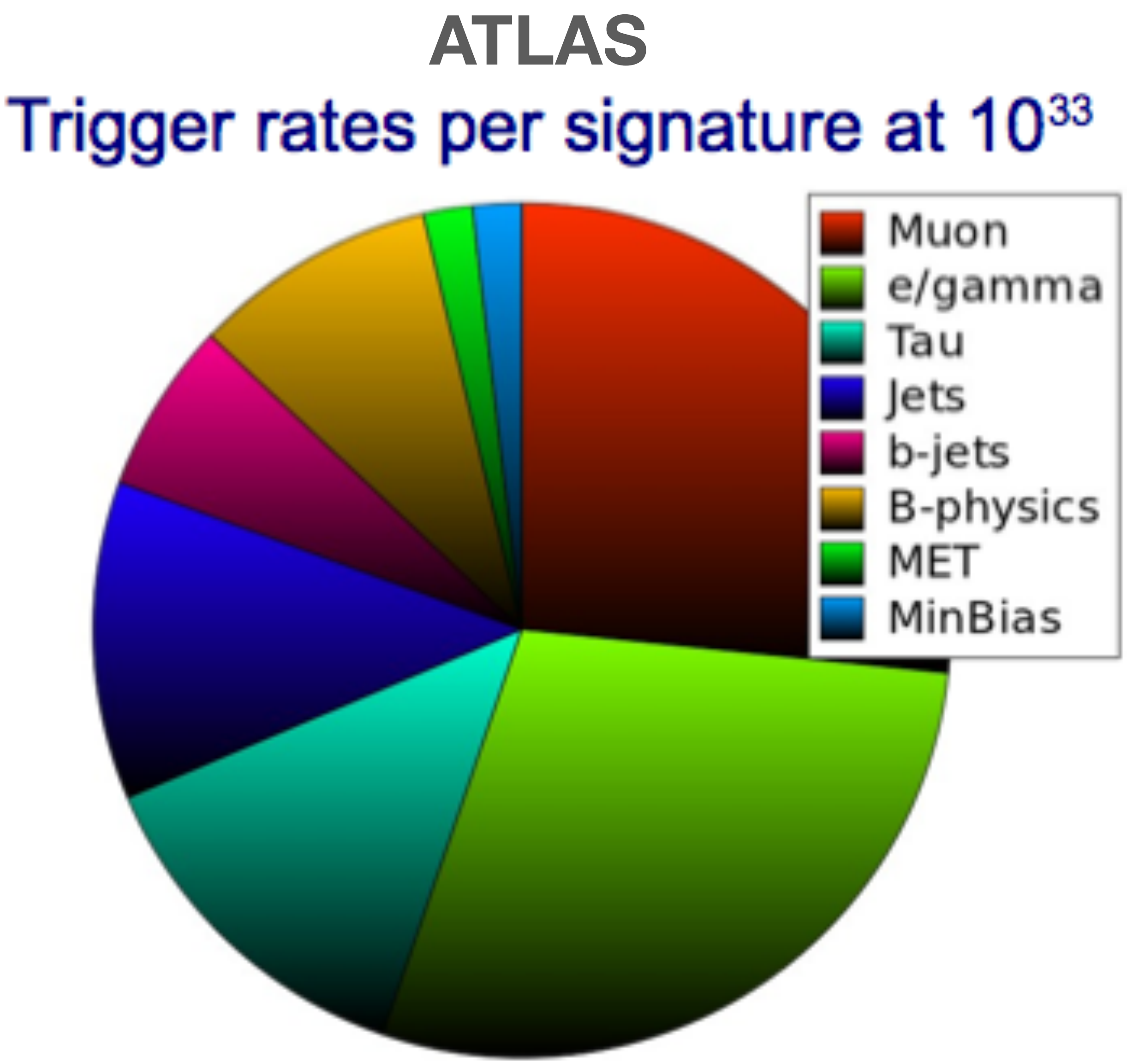


EXAMPLE OF TRIGGER STRATEGY (@ COLLIDERS)



- **Inclusive triggers for signal**
  - **Single high-p_T**
    - e/μ/γ: $p_T > 20$ GeV
    - jets: $p_T > 100$ GeV
  - **Multi-object combinations**
    - e-e, e-μ, μ-μ, e-τ, e-γ, μ-γ, etc…
    - to further reduce the rate
- **Back-up triggers to spot problems and provide control samples (often pre-scaled)**
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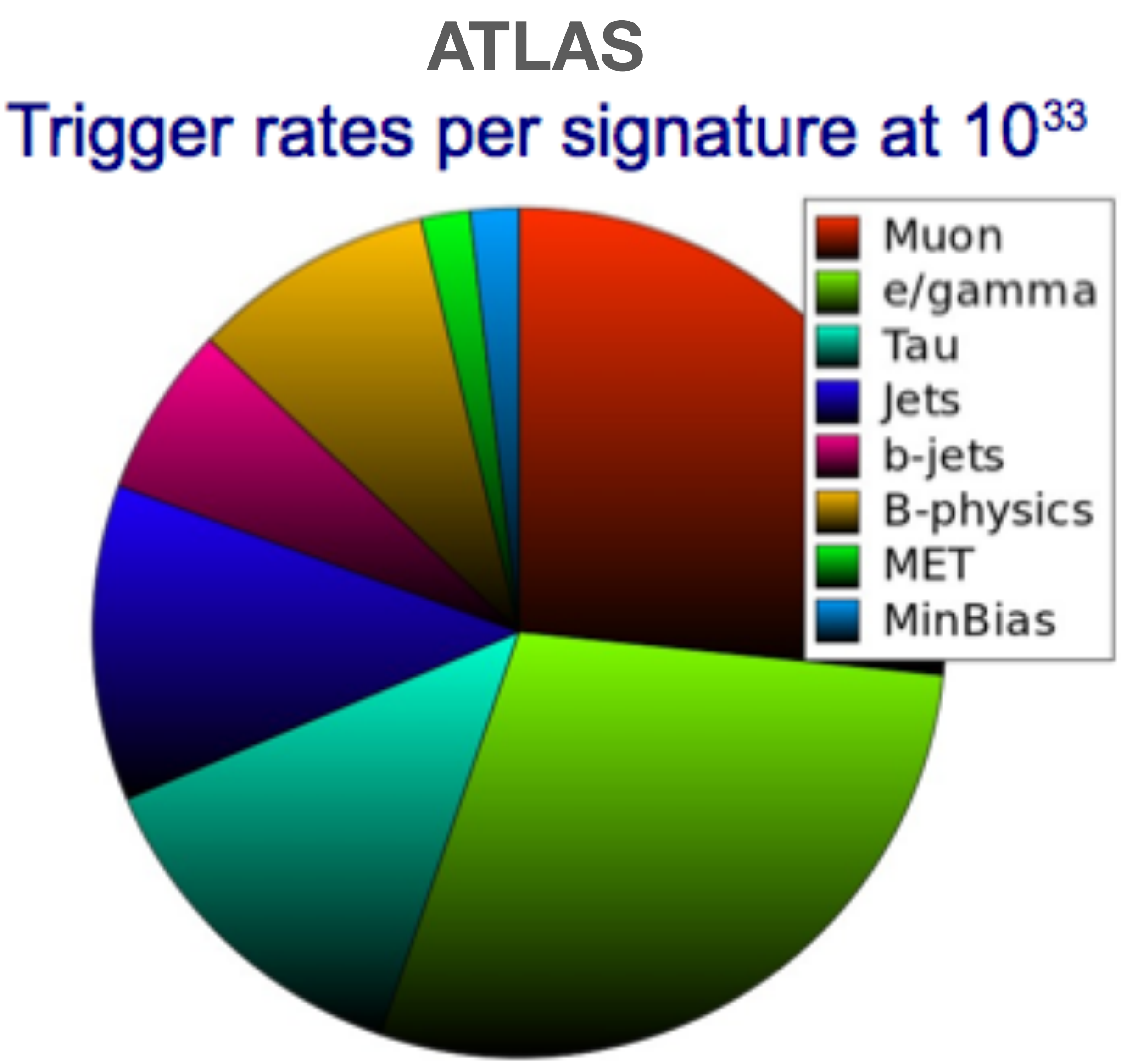

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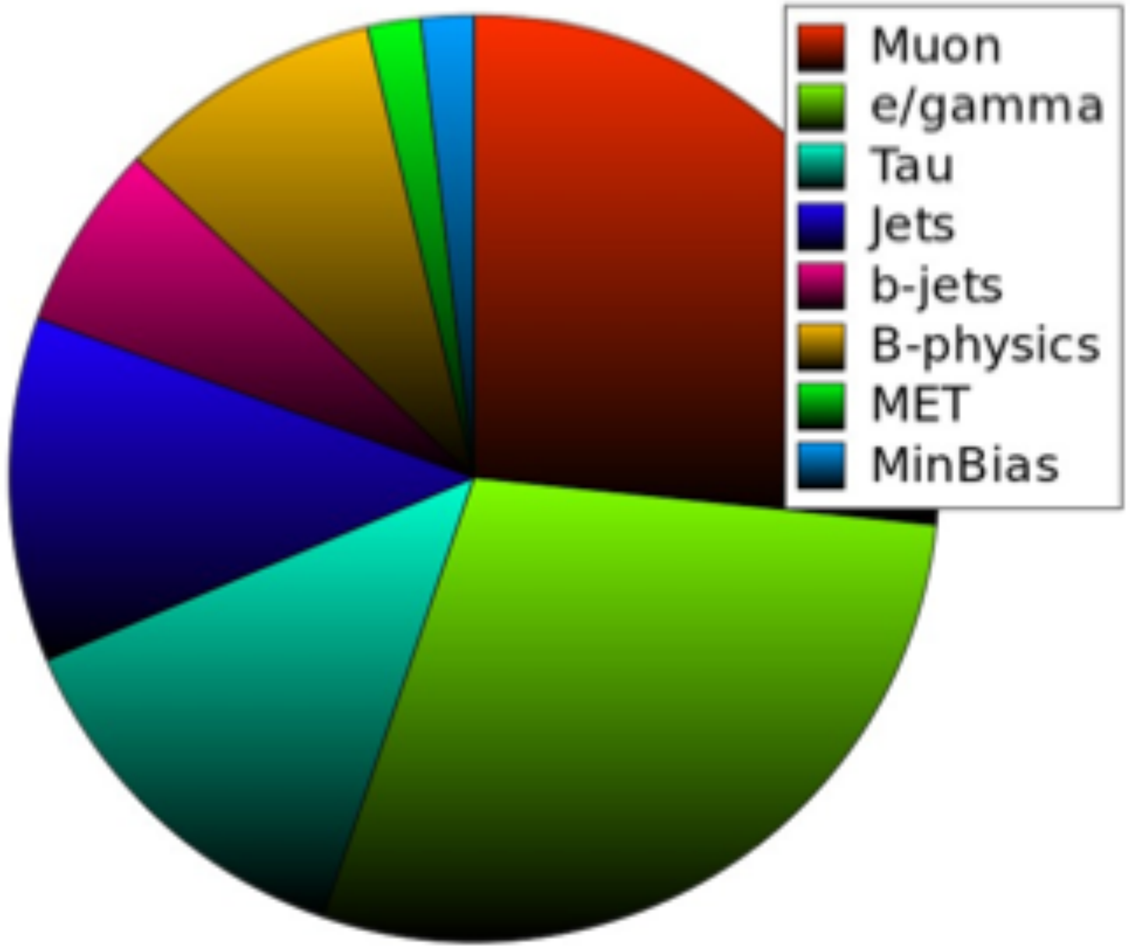
Isn’t it like a menu to chose in?

EXAMPLE OF TRIGGER STRATEGY (@ COLLIDERS)

ATLAS

Trigger rates per signature at 10^{33}



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Isn't it like a menu to chose in?

How much rate each?

TRIGGER STREAMERS

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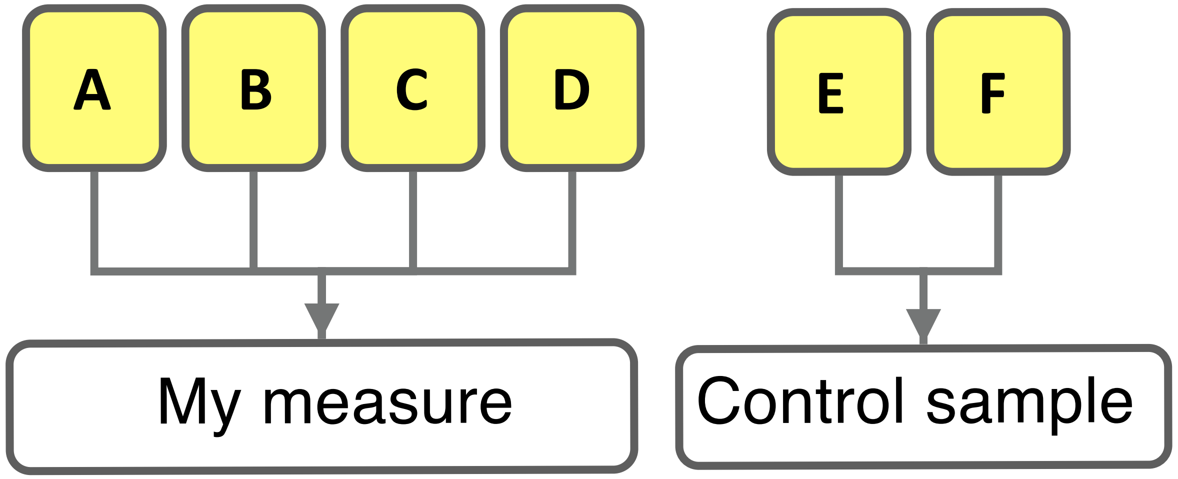

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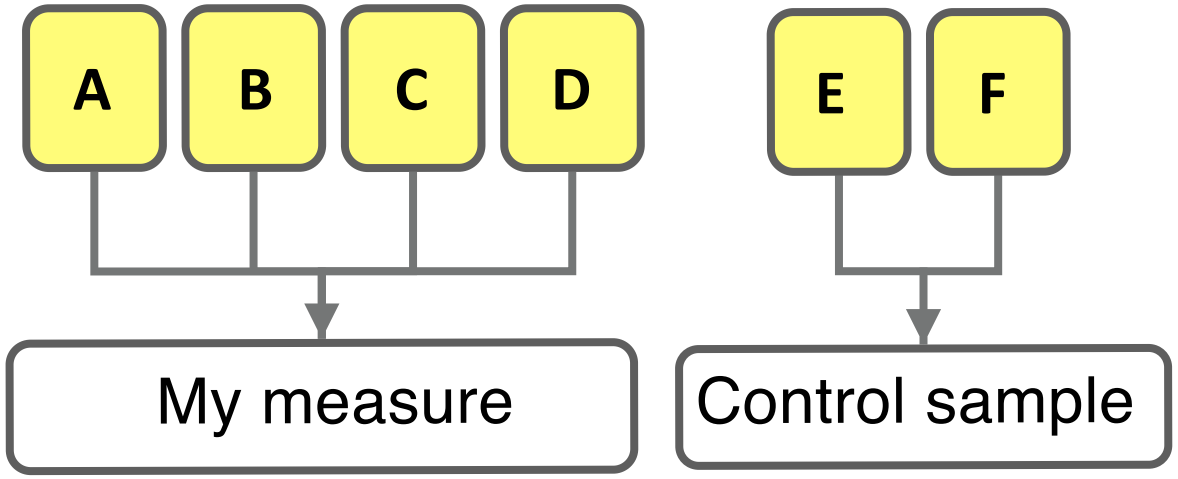

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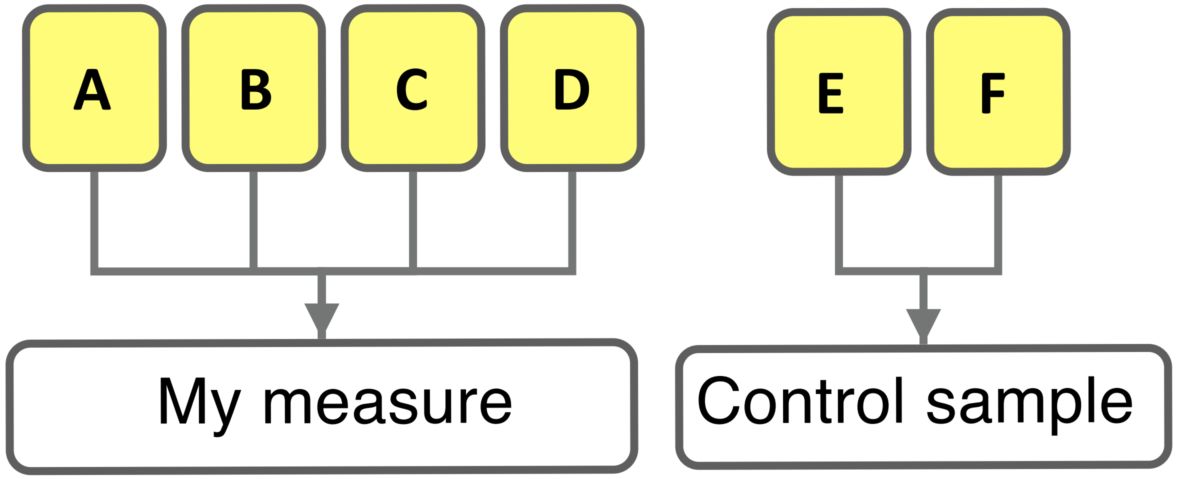

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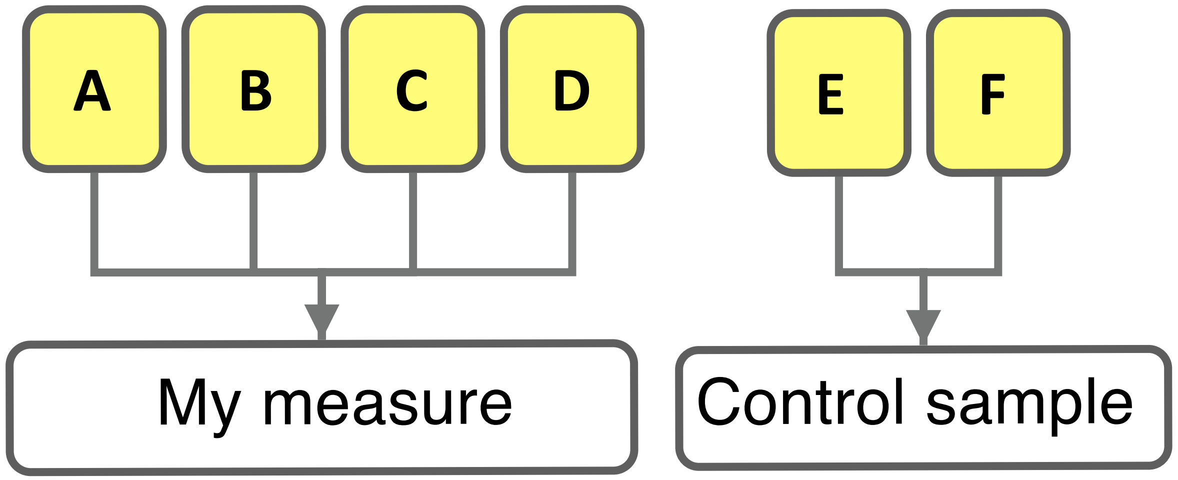

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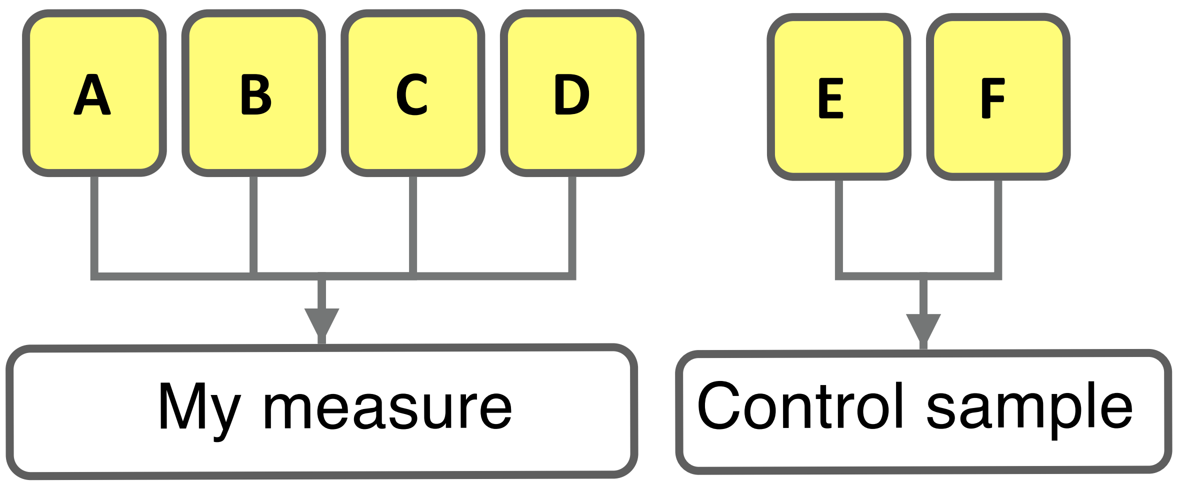
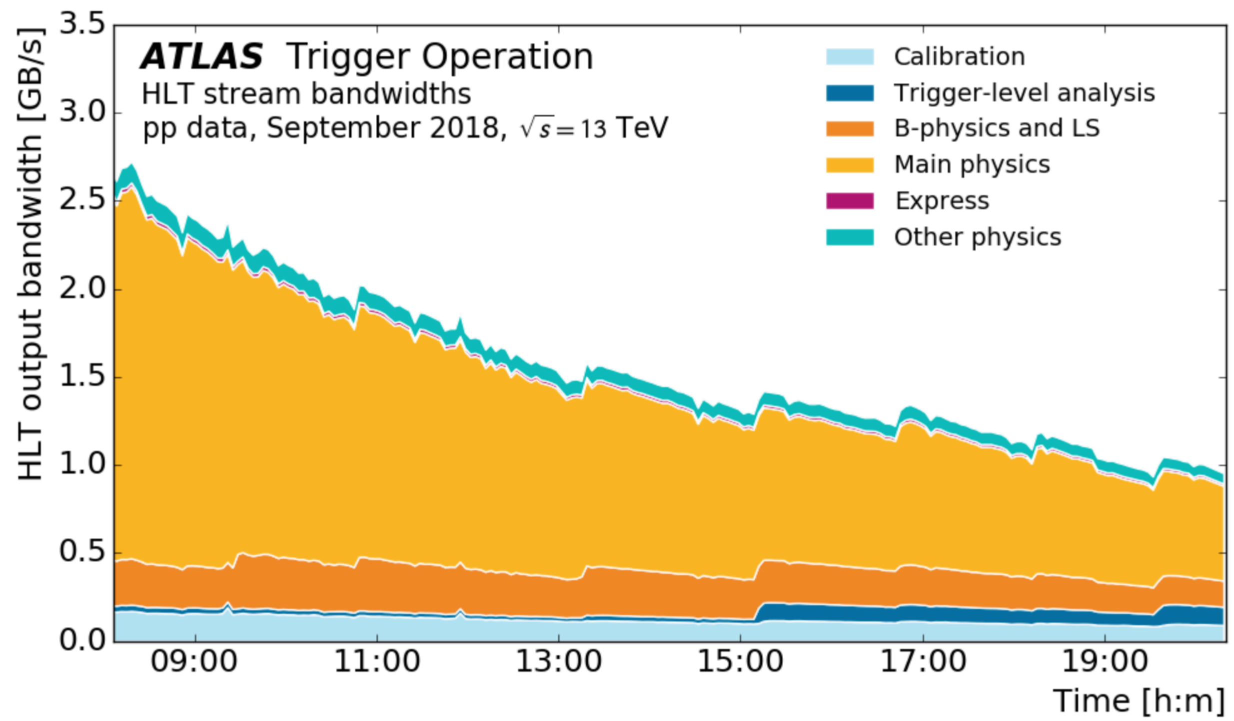


***Prescale**: record 1/N events. Useful for collecting samples of high-rate triggers without swamping the DAQ system*



often prescaled

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RATE ALLOCATION

- ✓The target is the final allowed DAQ bandwidth
- ✓The rate allocation on each trigger is based on
  - ✓Physics goals (+ calibration, monitoring…)
  - ✓Efficiency and background rejection
  - ✓Expected bandwidth consumed

How to extrapolate trigger rates ?

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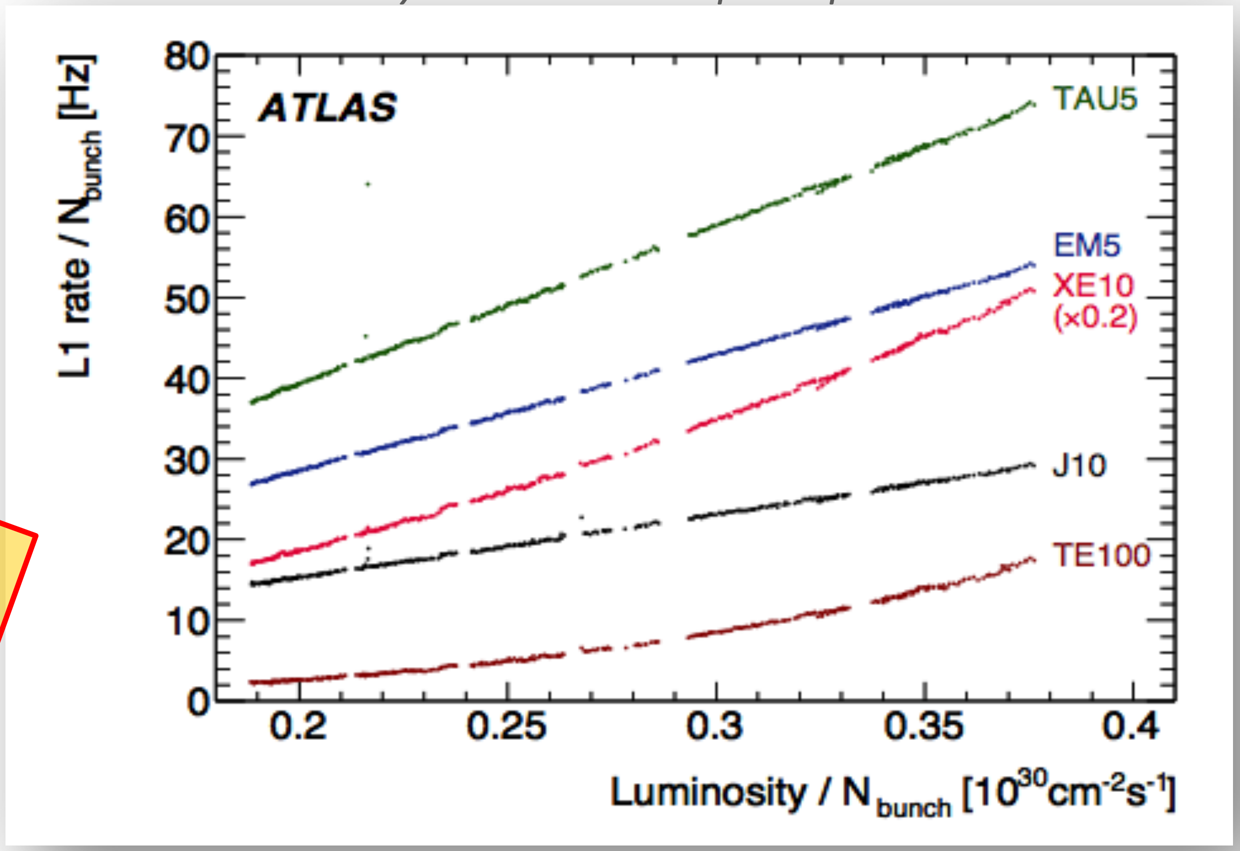
Rates scale linearly with luminosity, but linearity is smoothly broken due to pile-up



How to extrapolate trigger rates ?

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

Trigger Efficiency

- ➡ **During design and commissioning: use 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: scale with Luminosity**
  - ➡ but only some rates can be easily extrapolated to higher L

REDUNDANT AND FLEXIBLE TRIGGER MENUS

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}

OUTLINE

- ➡ trigger selectivity and robustness with examples
- ➡ **how to build a trigger system from first principles**
- ➡ principles and examples of L1 triggers
- ➡ principles and examples of software triggers

RECAP: ENSURE GOOD EFFICIENCY WITH...

Robustness!
Win against the unexpected!

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Win against the unexpected!

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  - 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

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- **Redundancy: to make trigger rates independent from the detector and the collider performance**
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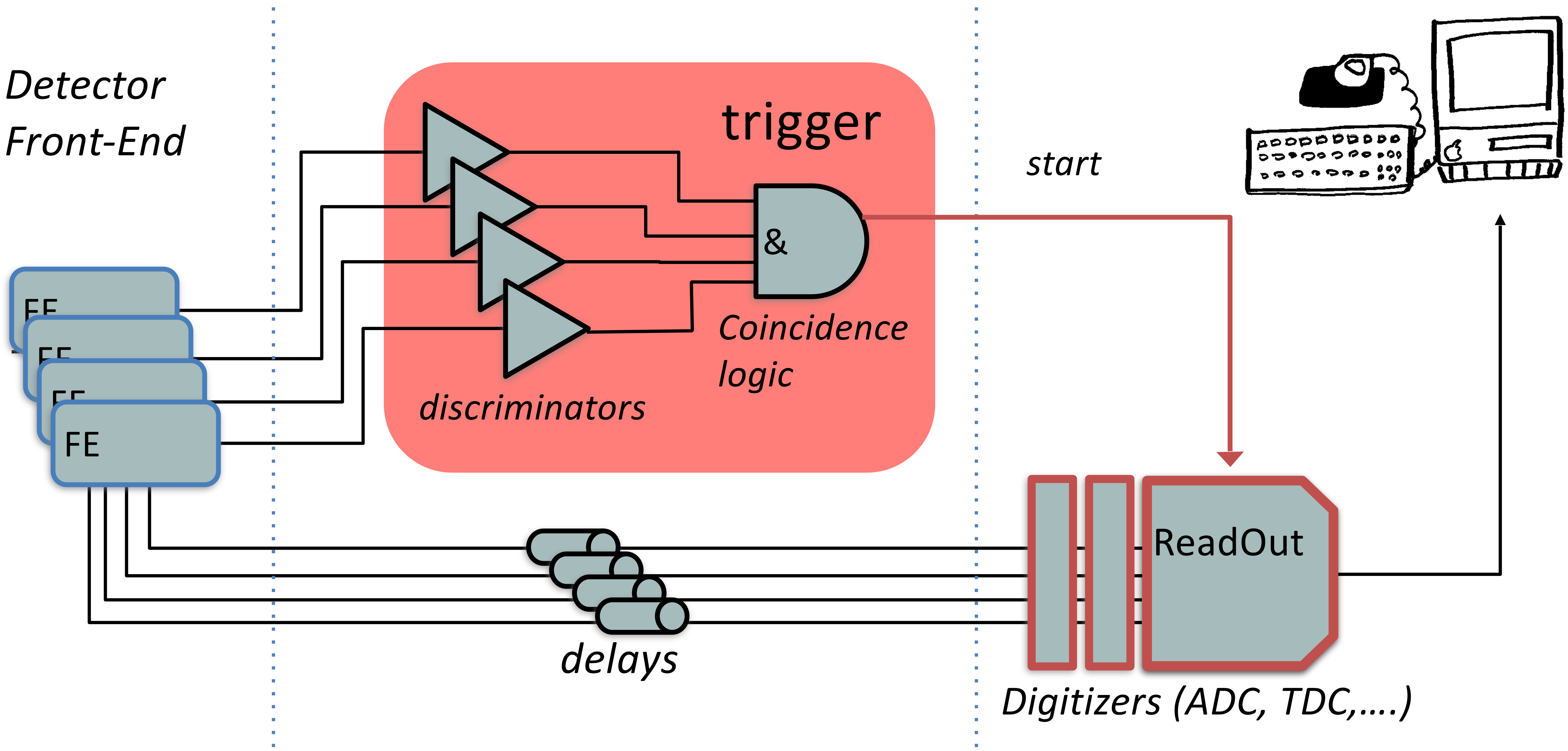
- **Selectivity**
  - Good granularity and good resolution of the parameters to ensure rejection of the unwanted background

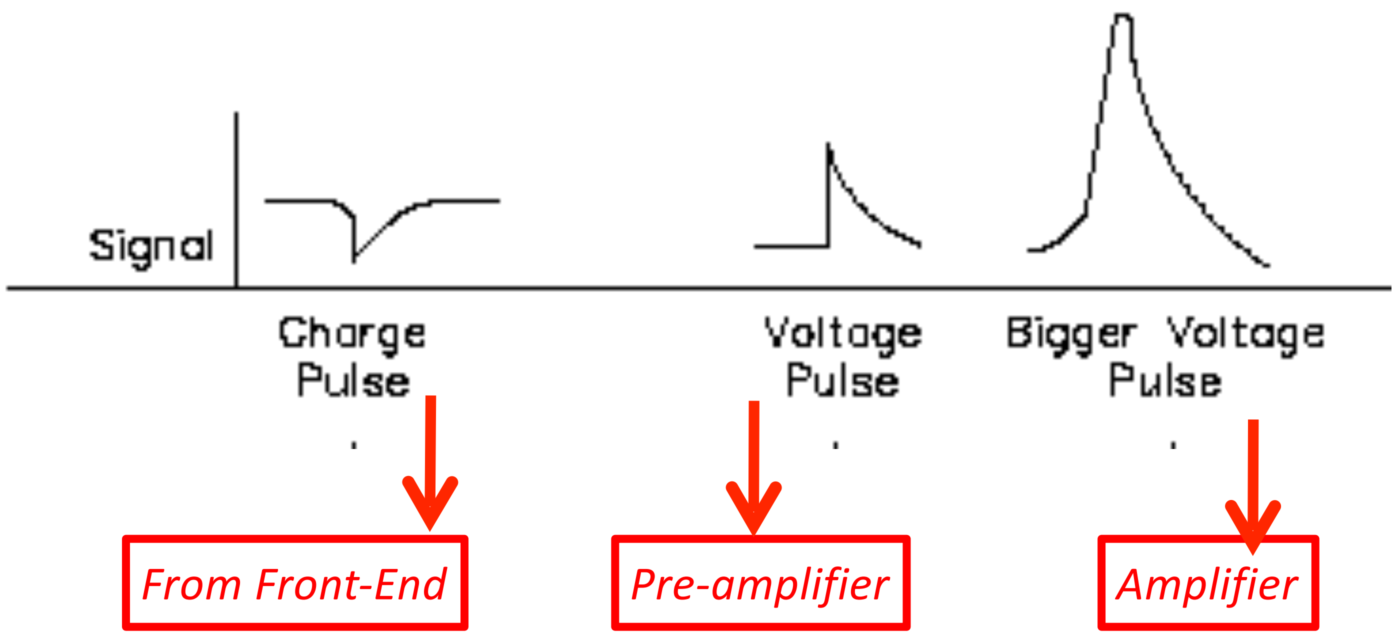
A SIMPLE TRIGGER SYSTEM

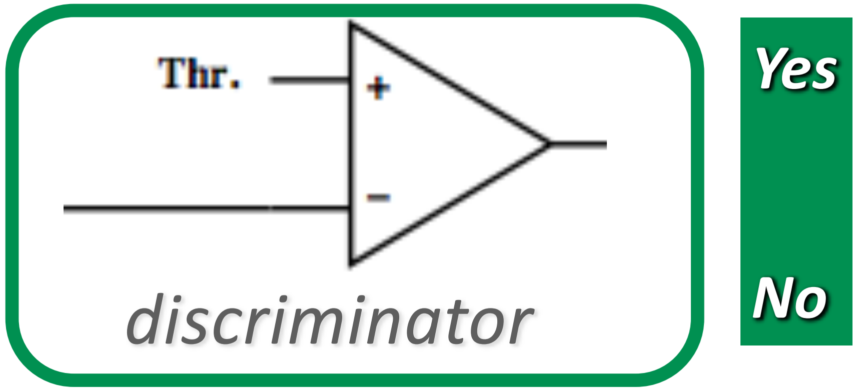


➡ **Chose a sensor/detector specific for your selection**
➡ **Dedicate Front-End electronics also used for trigger signals**

THE SIMPLEST TRIGGER SYSTEM

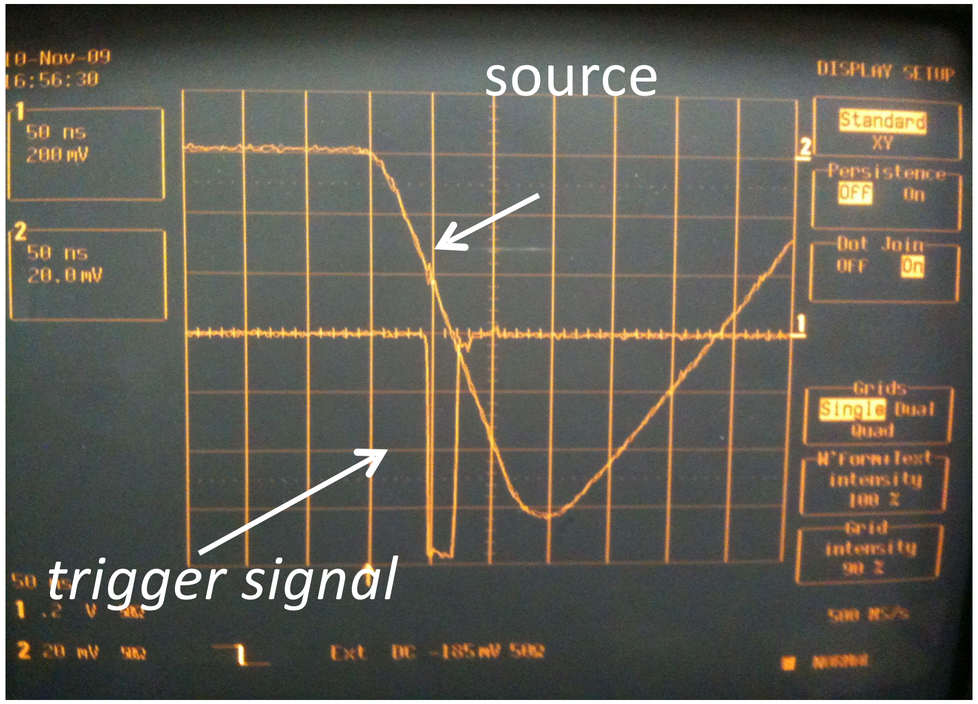
- **Source: signals from the Front-End of the detectors**
  - Binary trackers (pixels, strips)
  - Analog signals from trackers, time of light detectors, calorimeters,….





- **The simplest trigger is with a threshold**
  - Look at signal and noise
  - Apply a threshold as low as possible, since signals in HEP detectors have large amplitude variation

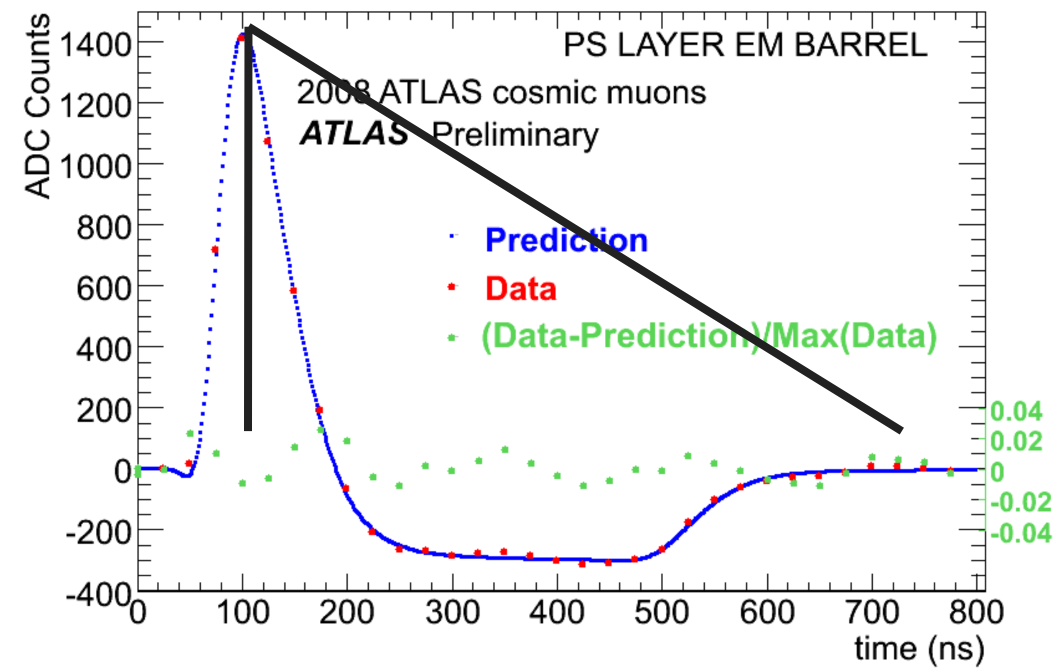
Compromise between hit efficiency and noise rate

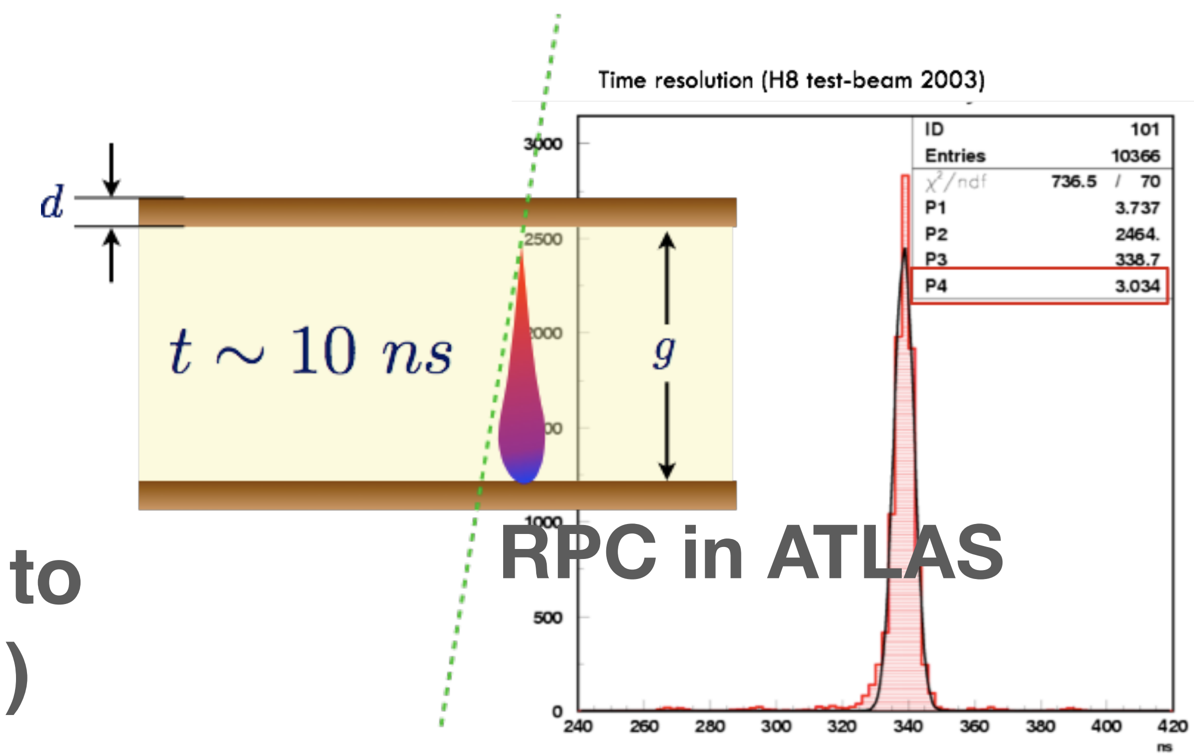


CHOSE YOUR TRIGGER DETECTOR

- **With these requirements**
  - **Fast signal**: good time resolution and low jittering
    - Signals from detectors are **shaped** and processed (e.g. peak-finder algorithms)
  - **High efficiency**
  - (**often) High rate capability**
- **Use either existing detectors or dedicated "trigger detectors"**
  - Organic scintillators
  - Electromagnetic calorimeters
  - Proportional chambers (short drift)
  - Cathode readout detectors (RPC,TGC,CSC)
- **Need optimal FE/trigger electronics to process the signal (common design)**

ATLAS Liquid Argon calorimeter

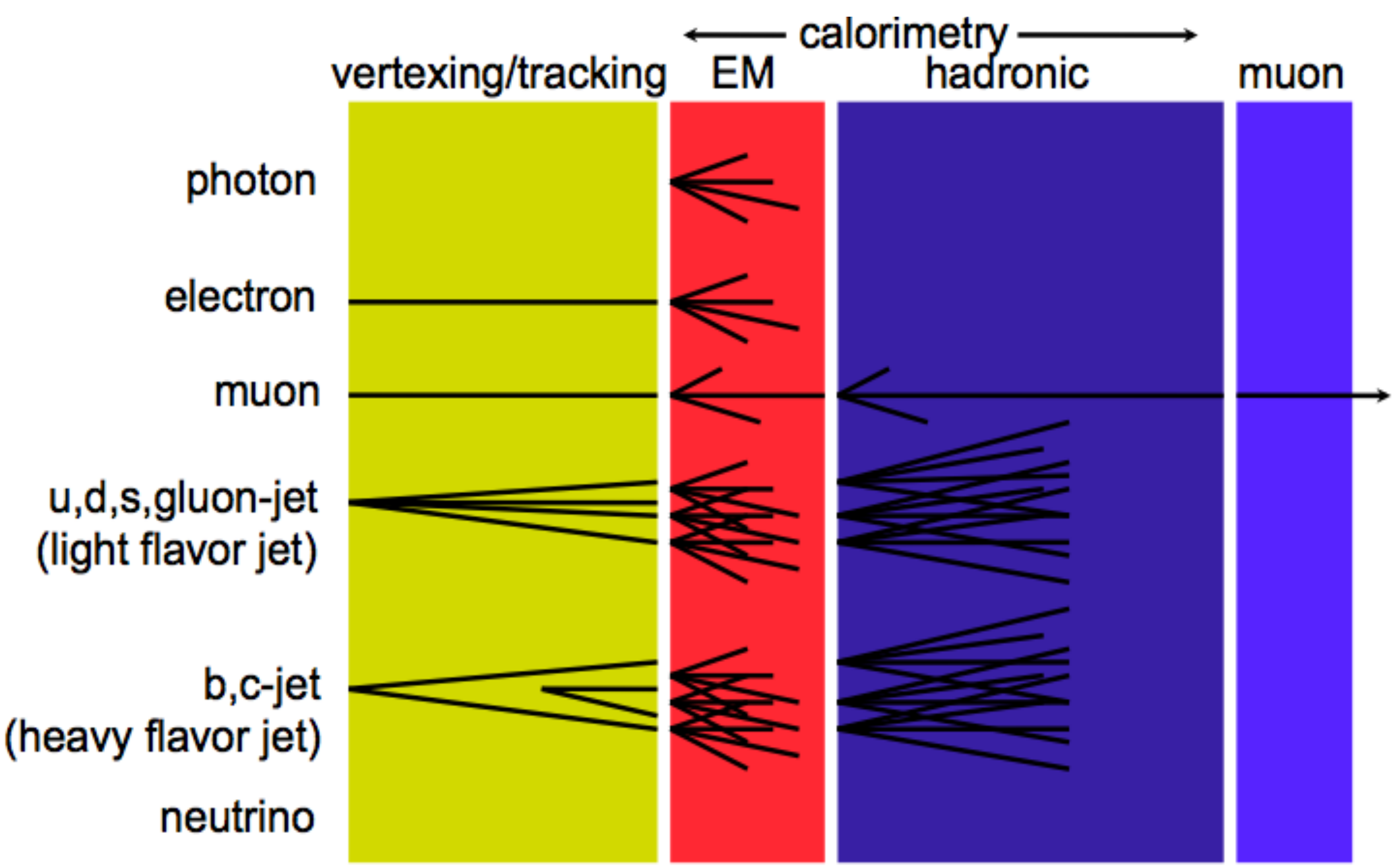




TRIGGER SELECTIONS

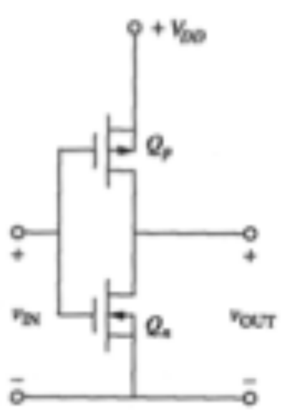
- **Can collect many parameters for discrimination**
  - Not only the amplitude of a signal
  - More complex quantities by software calculations (also MultiVariate Analysis)
- **At first, use intuitive criteria: be fast and reliable!**
  - Use clear/simple selections
  - i.e.: apply thresholds on: muon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

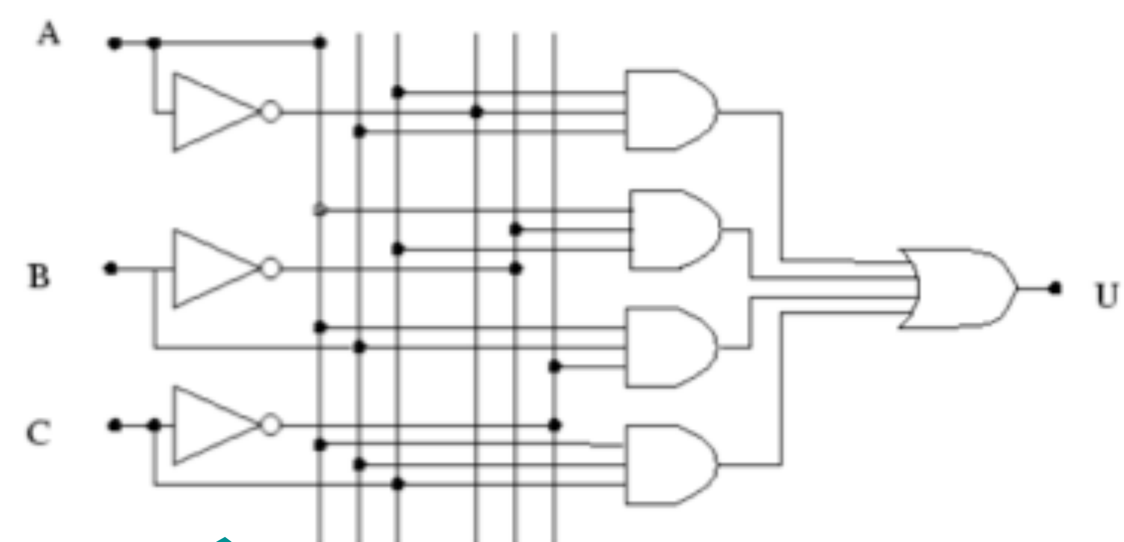
Eventually combine more signals together following a certain trigger logic (AND/OR), giving redundancy



HARDWARE TRIGGER LOGIC IMPLEMENTATION

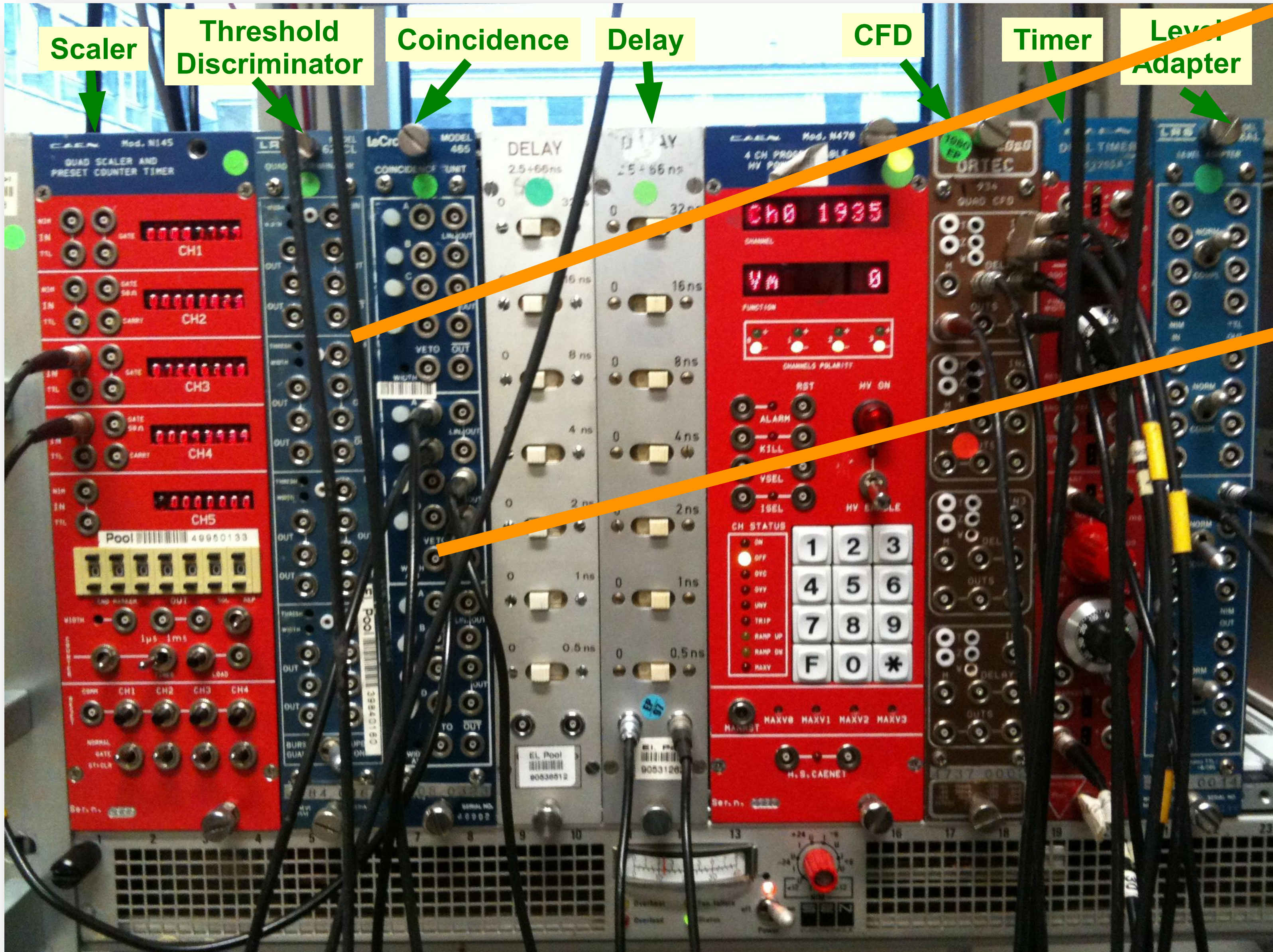
- **Analog systems: amplifiers, filters, comparators, ….**
- **Digital systems:**
  - Combinatorial: sum, decoders, multiplexers,….
  - Sequential: flip-flop, registers, counters,….
- **Converters: ADC, TDC, …..**



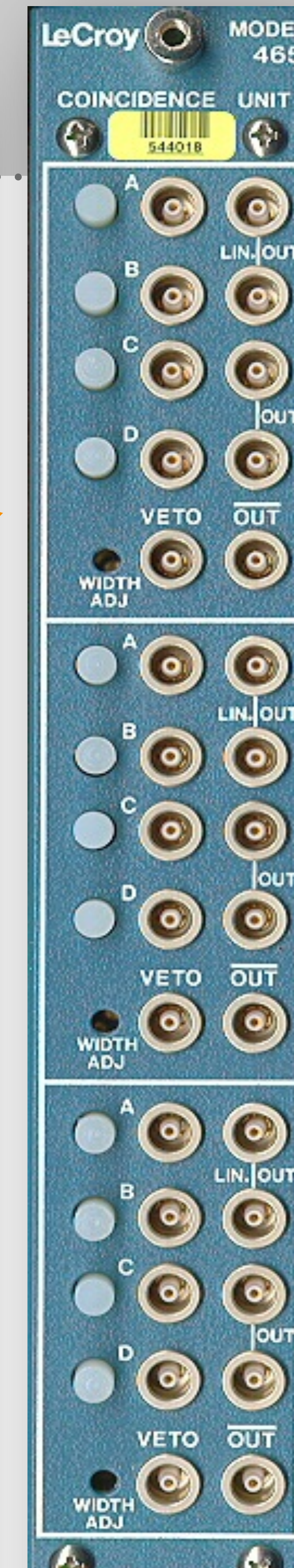


Any behaviour of our system can be described logically with a sequence of mathematical operators

OLDISH SIMPLE TRIGGER (NIM)

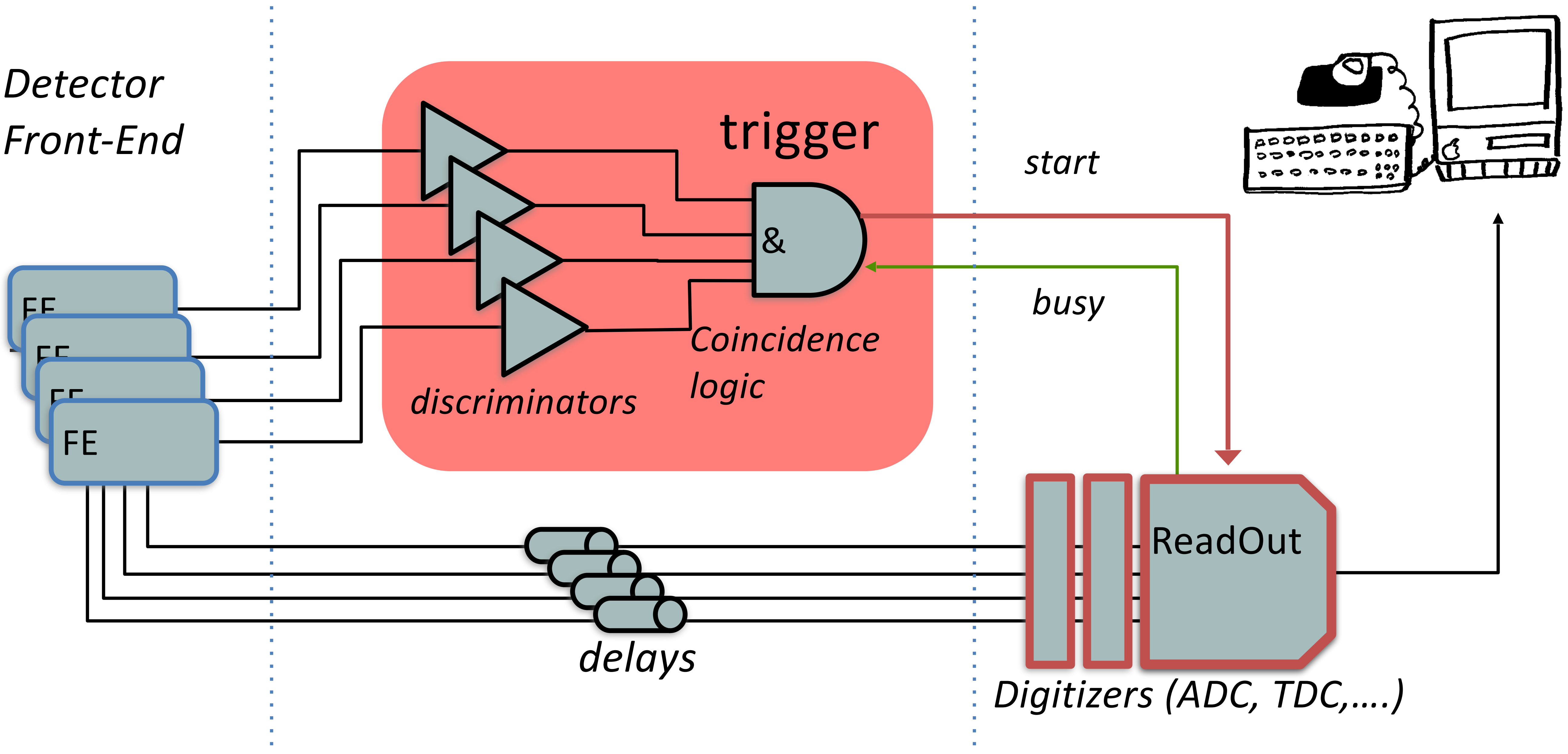


THRESHOLD DISCRIMINATOR



Coincidence Unit

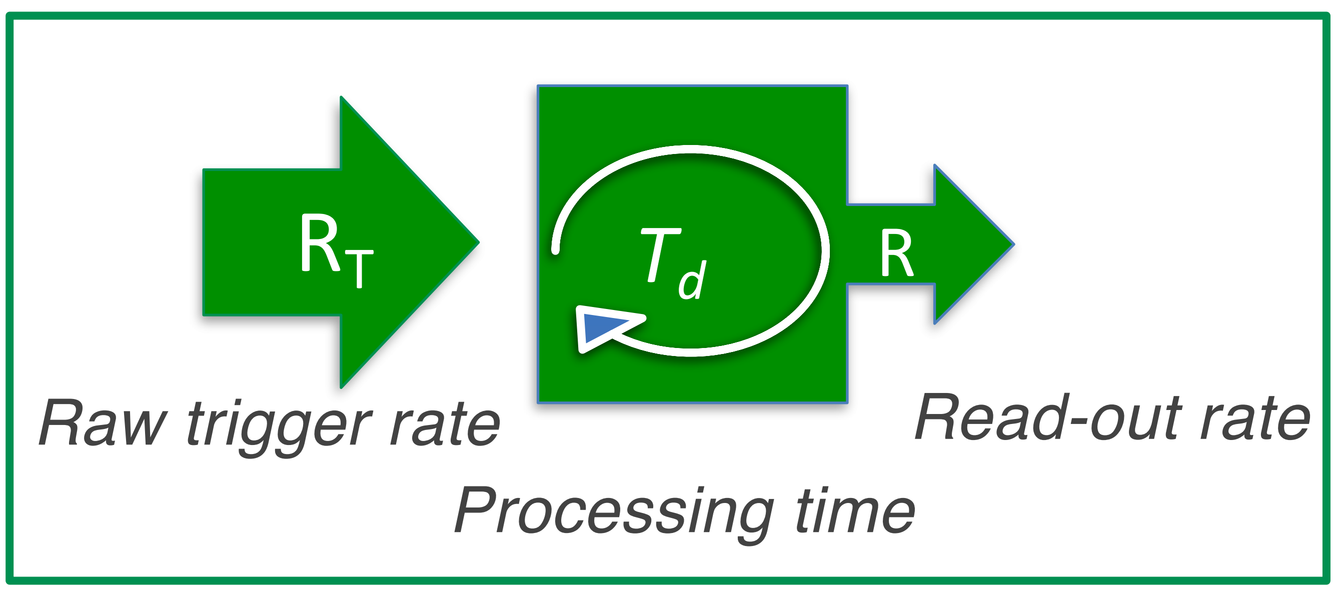
A SIMPLE TRIGGER SYSTEM



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

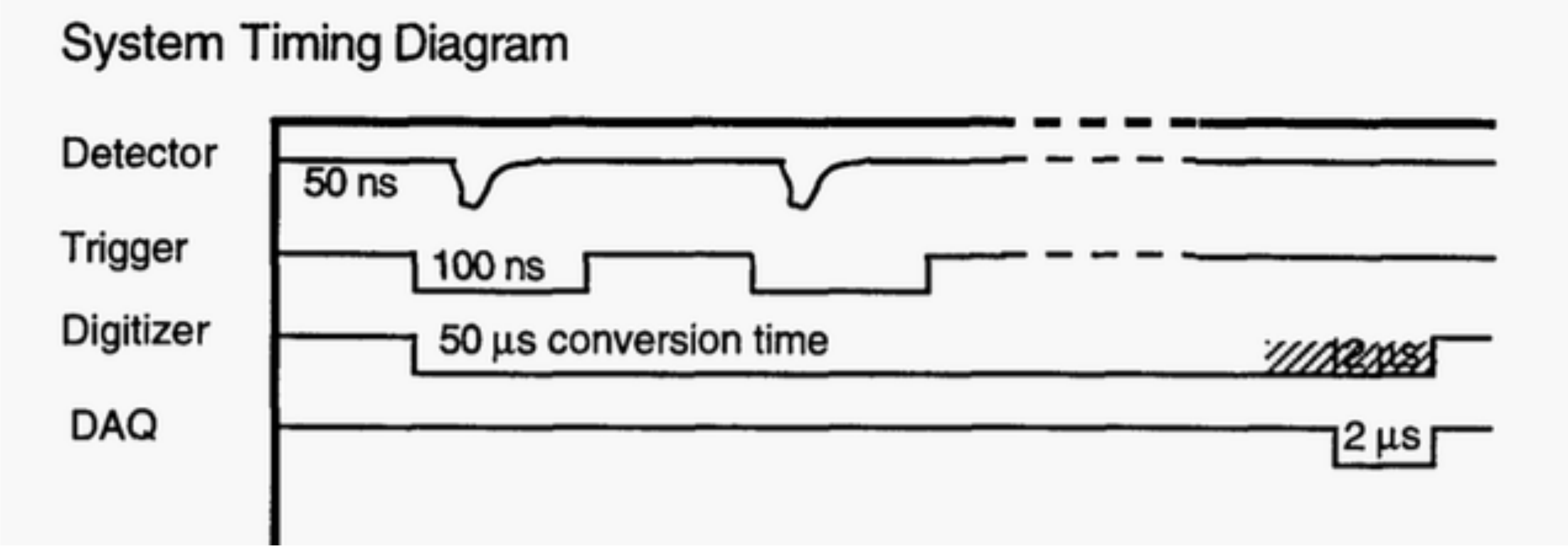
DEAD-TIME

- **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
- **And with input rate fluctuations!**



Affects efficiency!

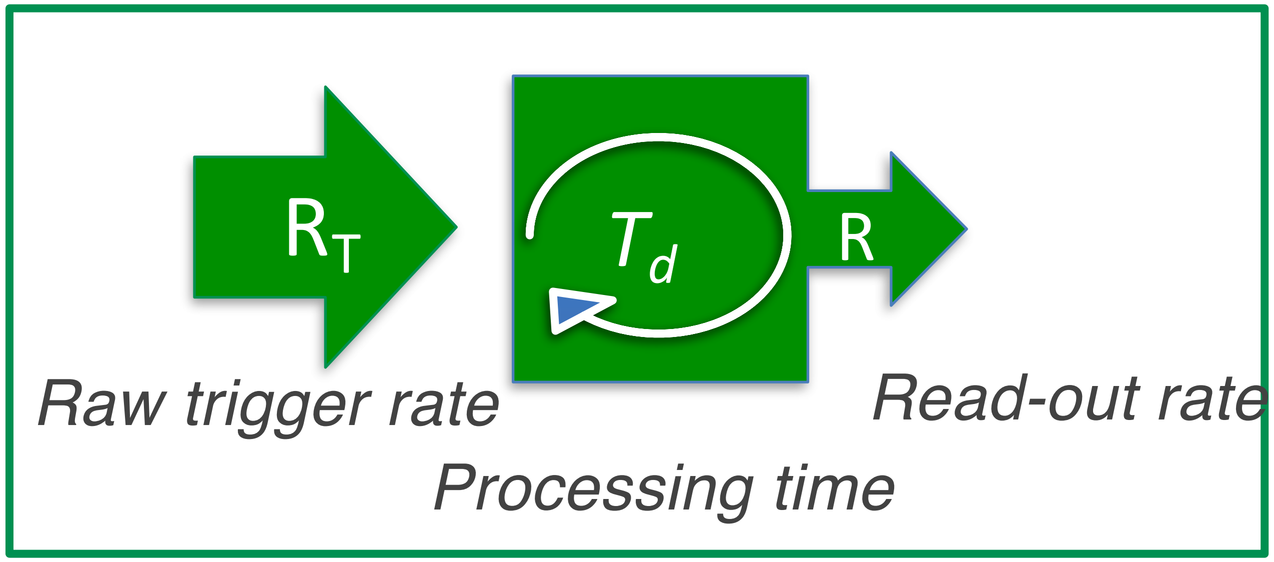
COMMON TIMING DIAGRAM



MAXIMISE RECORDING RATE

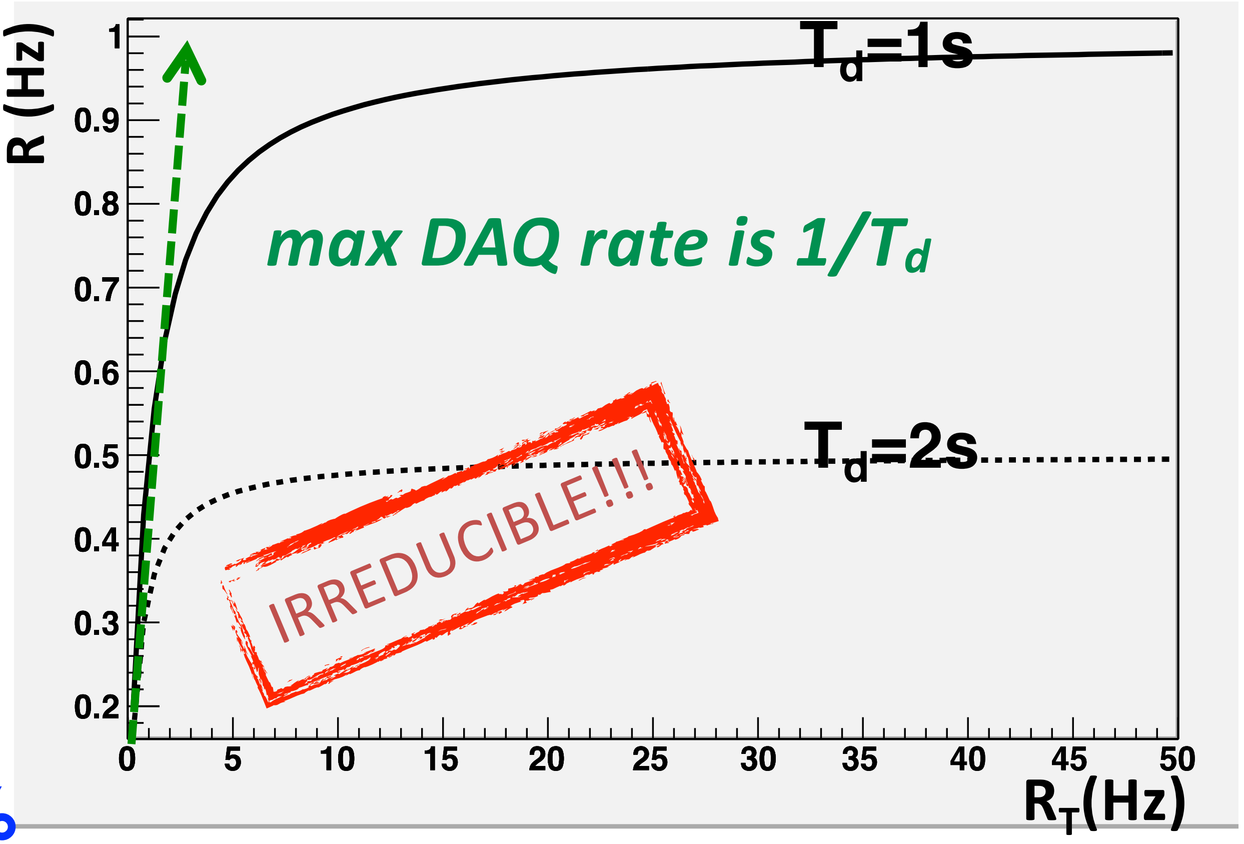
R_T = Trigger rate (average)
R = Readout rate
T_d = processing time of one event

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!

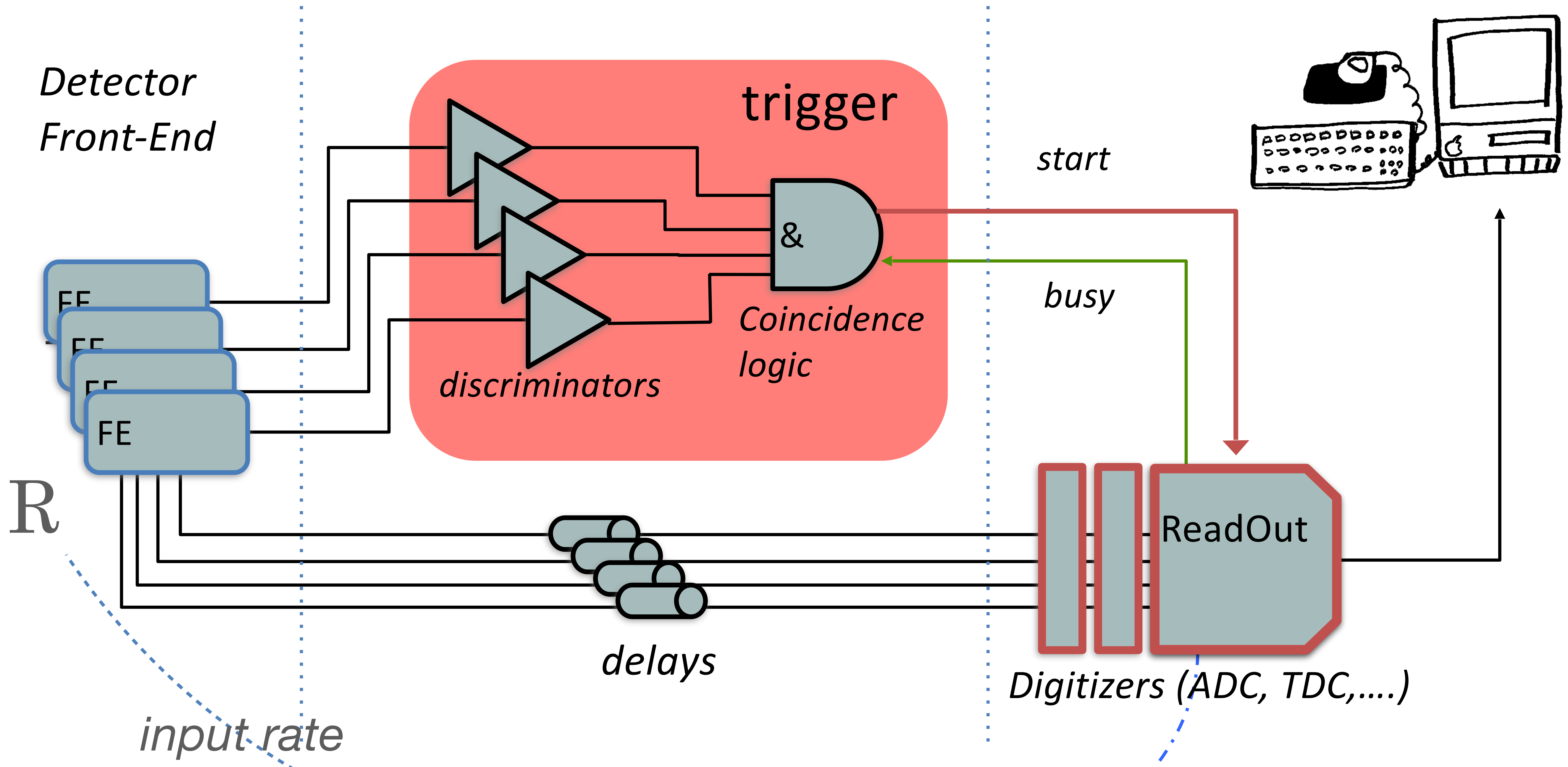


- **We always lose events if $R_T > 1/T_d$**
- **If exactly $R_T = 1/T_d$ -> dead-time is 50%**

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

FAST TRIGGER!
LOW INPUT RATE!

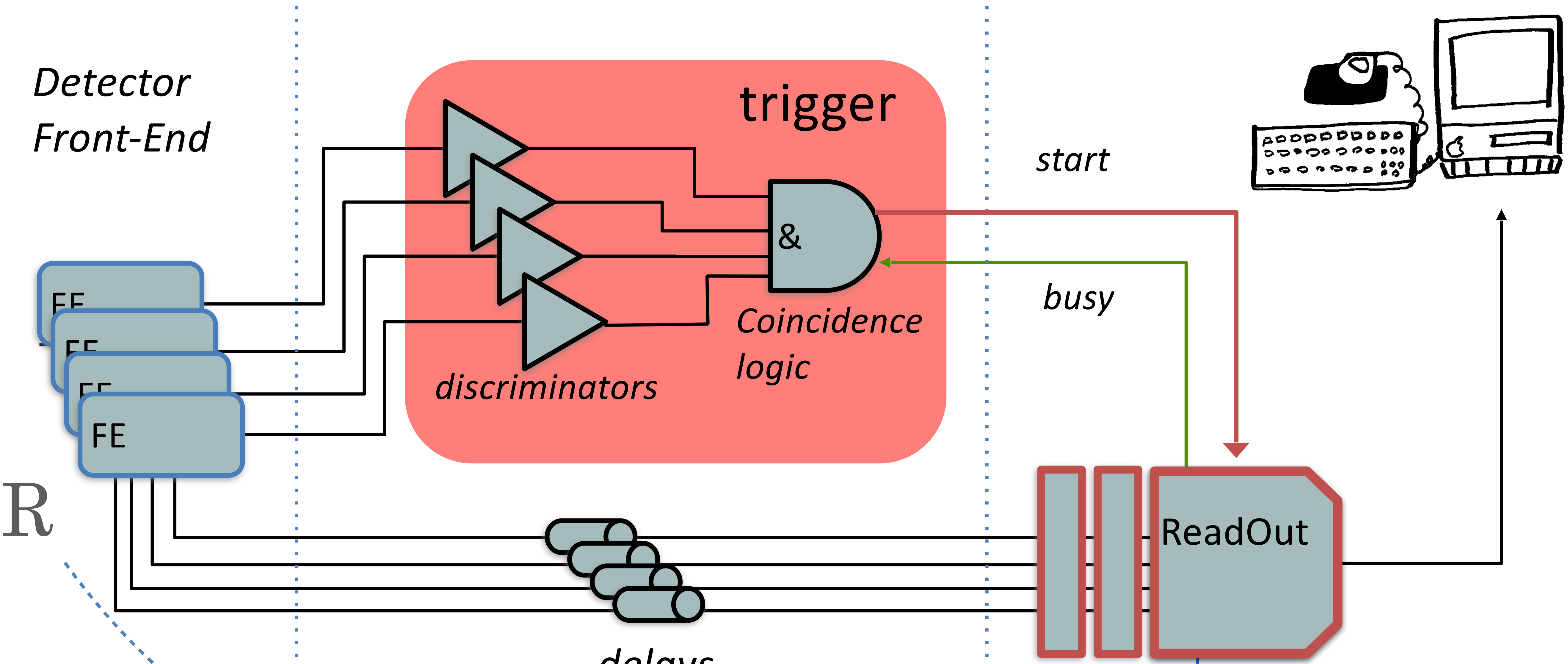
A SIMPLE TRIGGER SYSTEM



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

Fraction of lost events due to finite readout

A SIMPLE TRIGGER SYSTEM



How can we mitigate the dead-time?

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

Fraction of lost events due to finite readout

HOW TO MINIMISE DEAD-TIME….

HOW TO MINIMISE DEAD-TIME….

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

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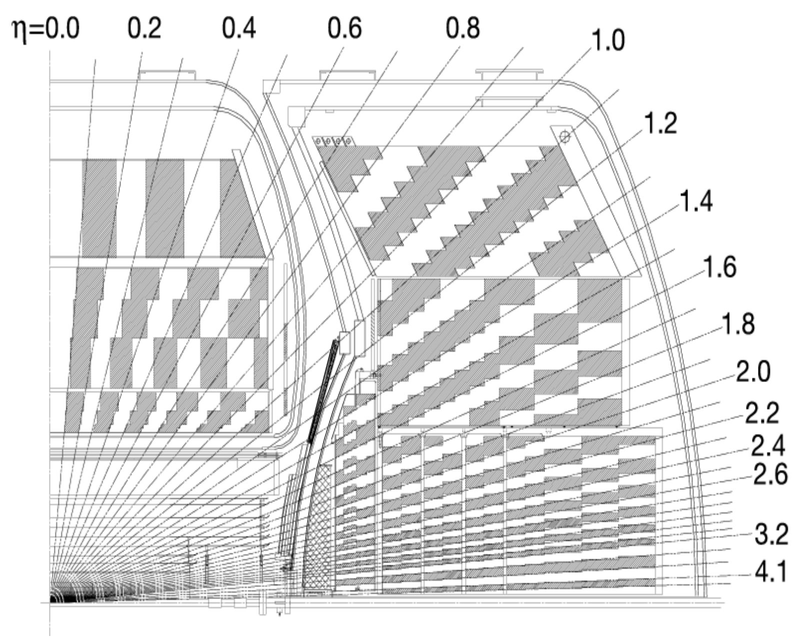

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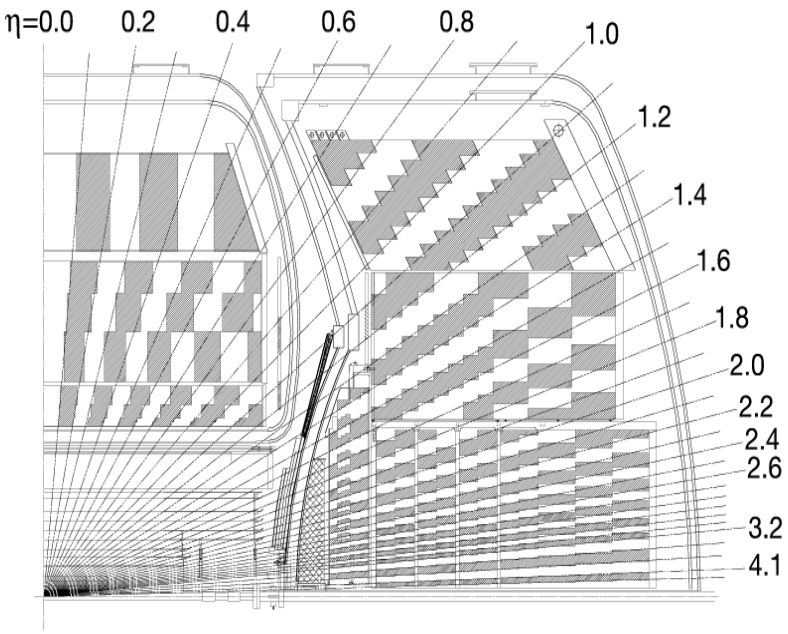

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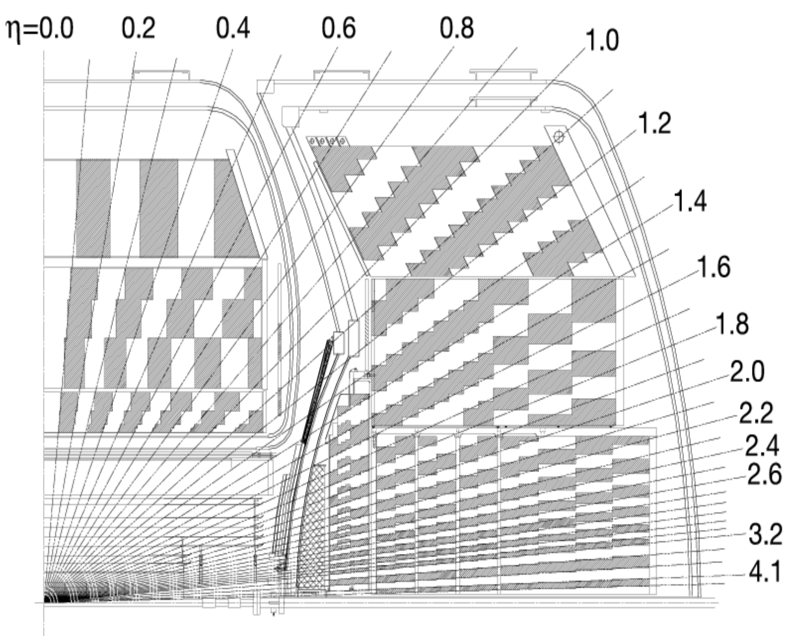

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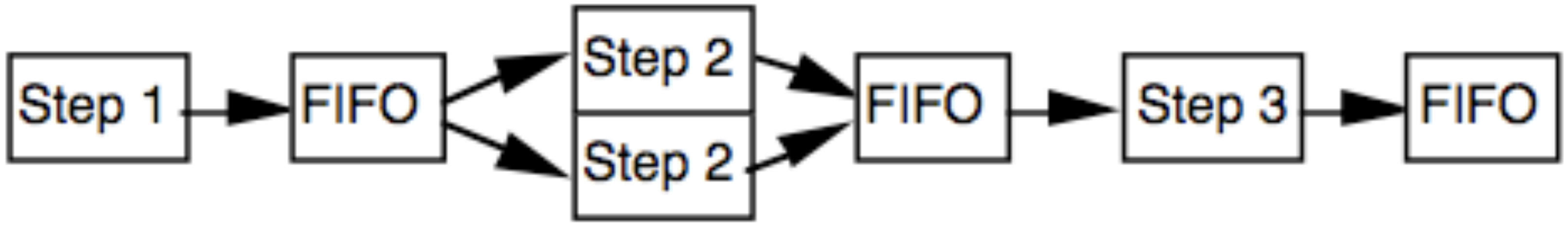
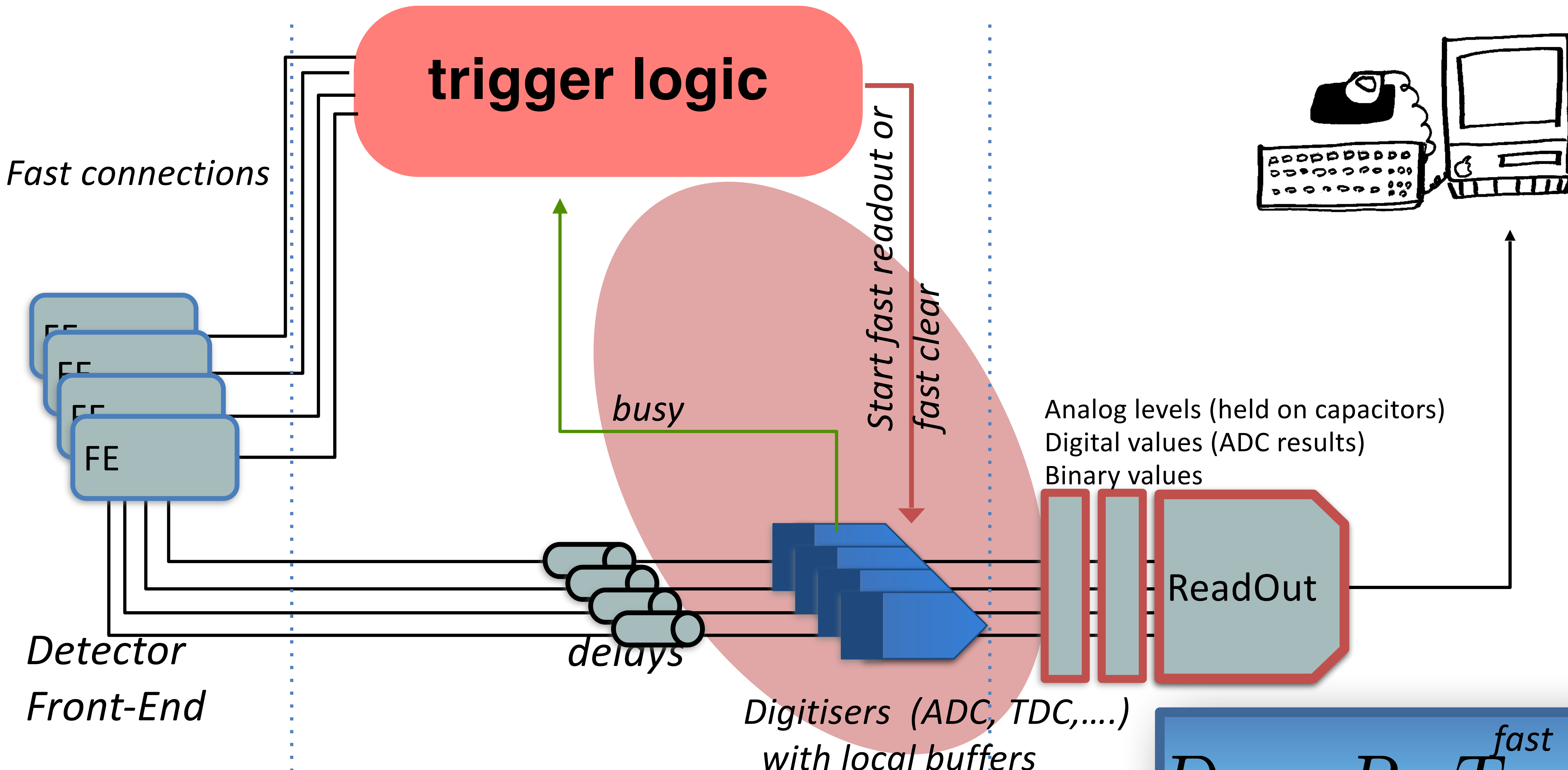


$$\frac{R}{R_T} = \frac{1}{1 + R_T T_d}$$

Try to absorb in capable buffers

MINIMISING READOUT DEAD-TIME...



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

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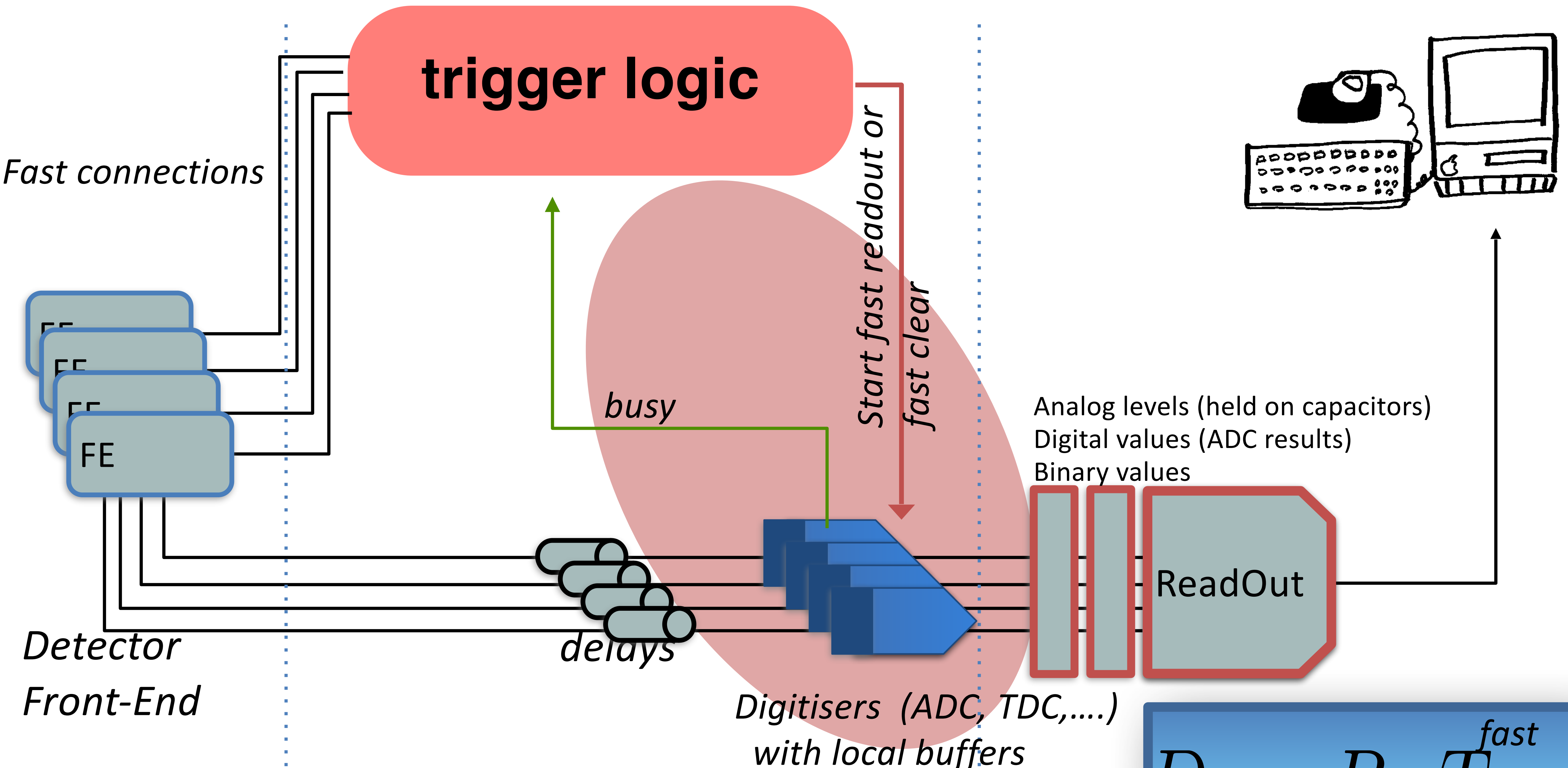
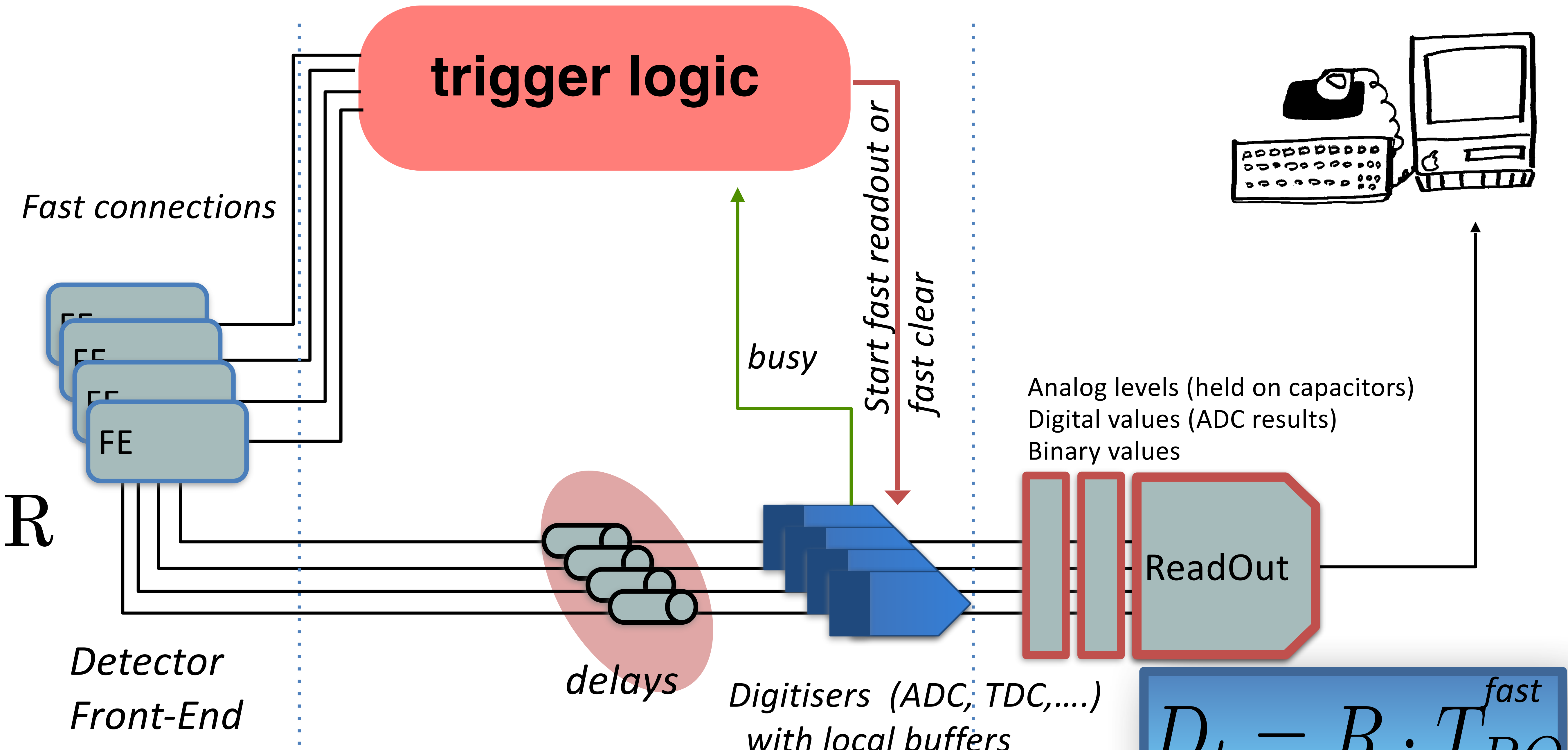


$$D_t = R \cdot T_{RO}^{fast}$$

- ➡ **Parallelism**: use multiple digitisers
- ➡ **Pipelining**: different stages of readout: fast local readout + global event readout (slow)

TRIGGER LATENCY



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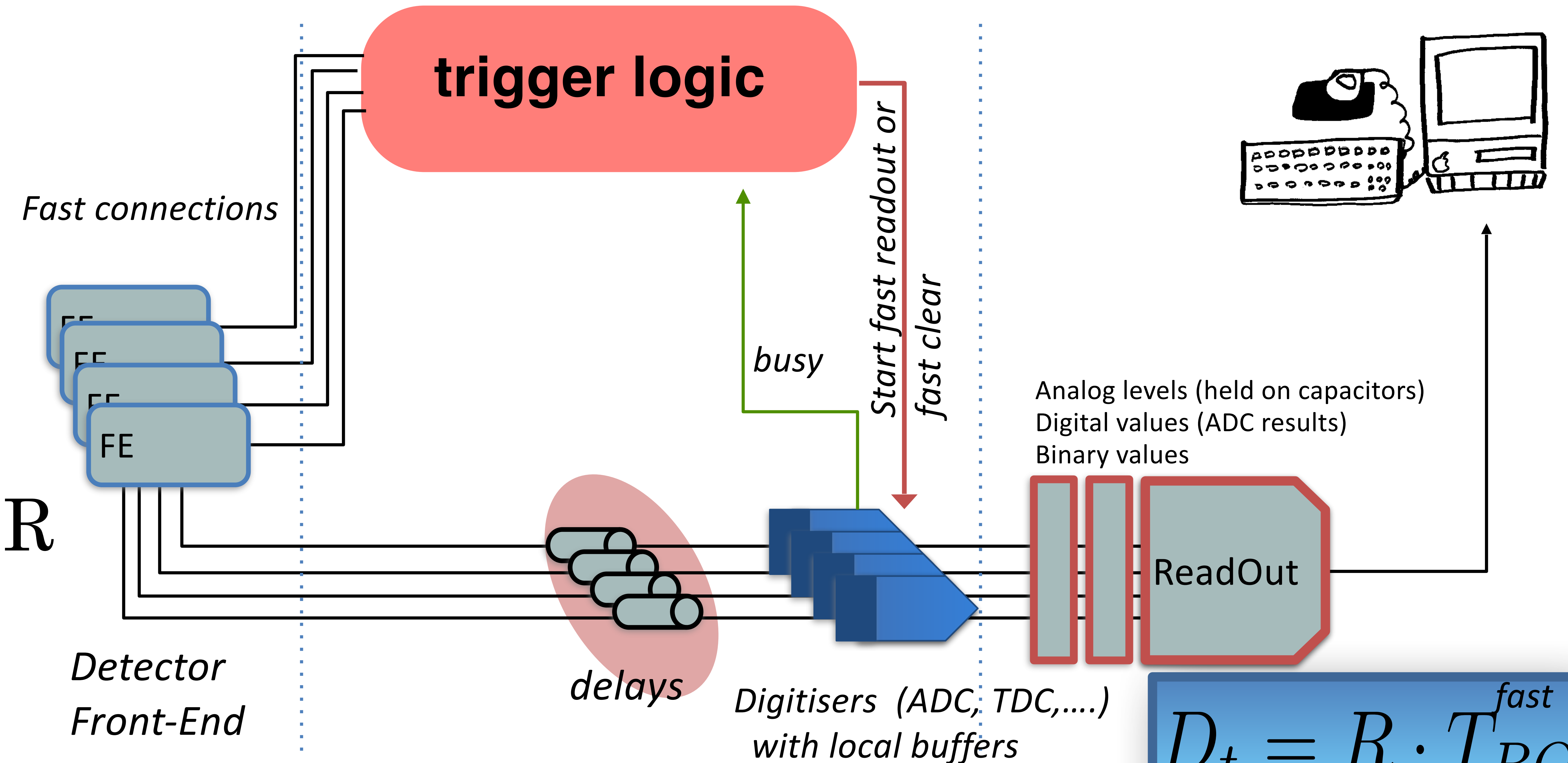
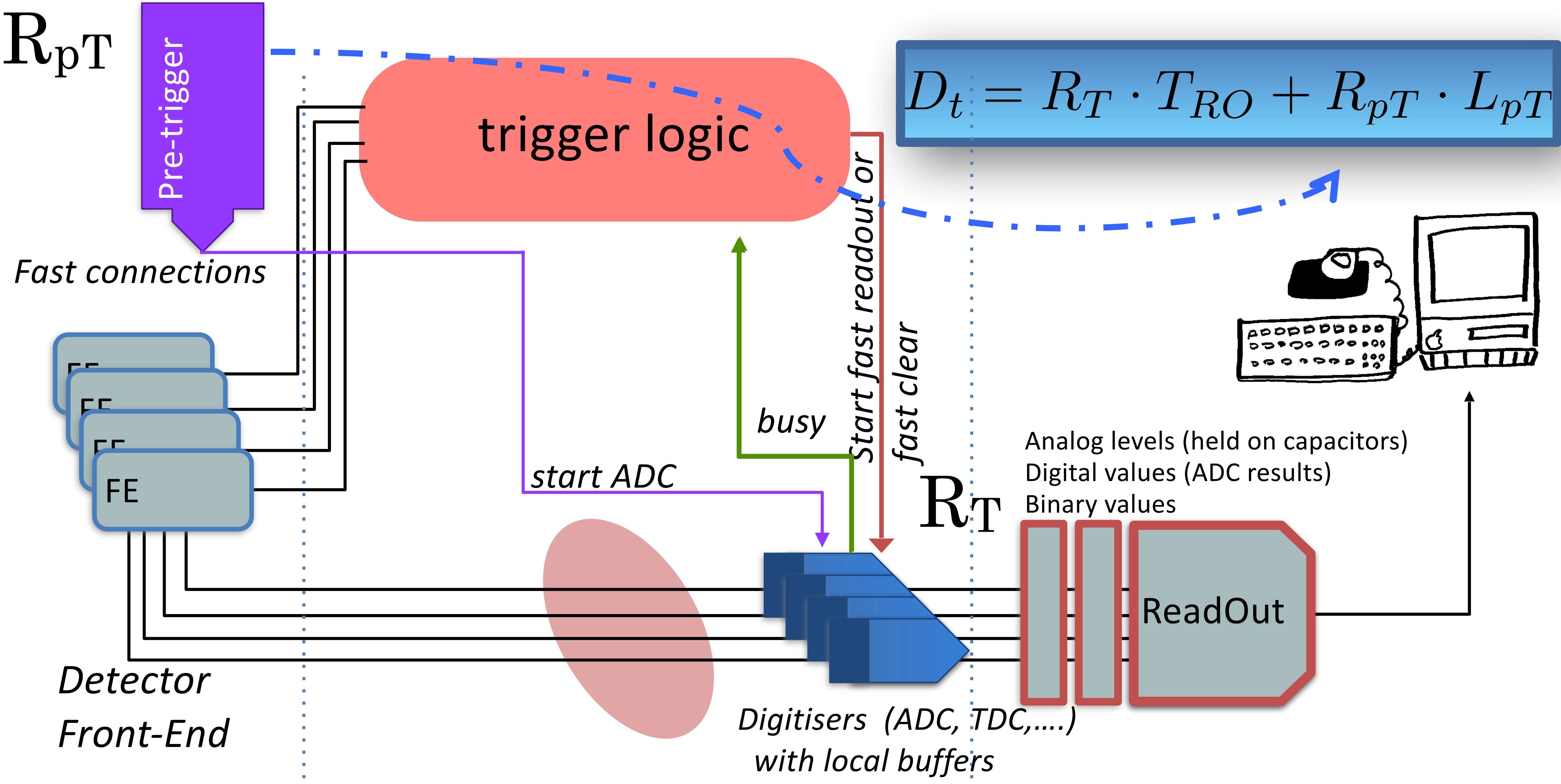


$$D_t = R \cdot T_{RO}^{fast}$$

- ➡ **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

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



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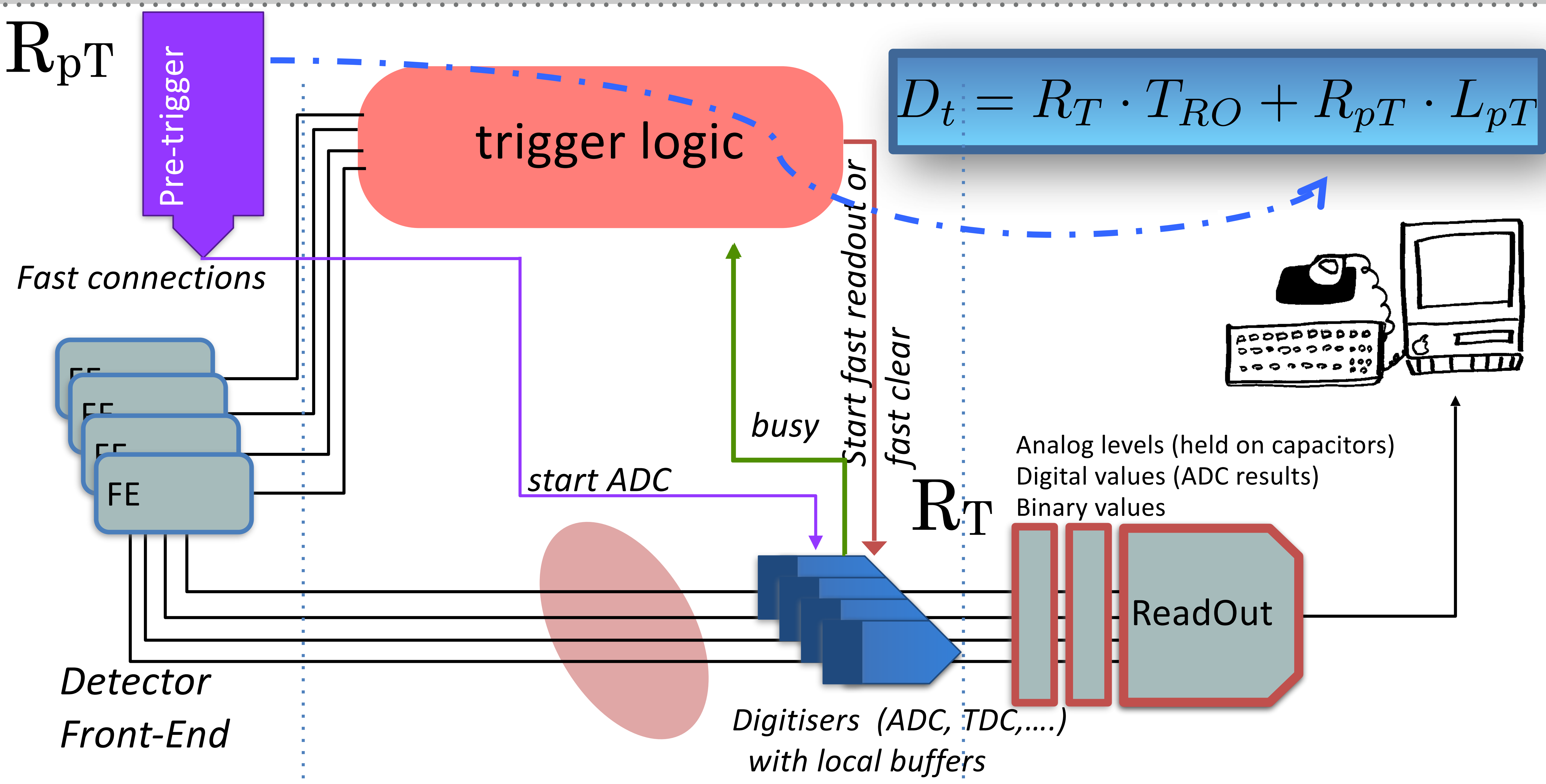


- **Very fast first stage of the trigger, signalling the presence of minimal activity in the detector**
  - Start the digitisers, when signals arrive
  - The main trigger decision comes later (after the digitisation) -> can be more complex

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**

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

i = 1 is the pre-trigger

R_i = Rate after the i-th level

L_i = Latency for the i-th level

T_{LRO} = Local readout time

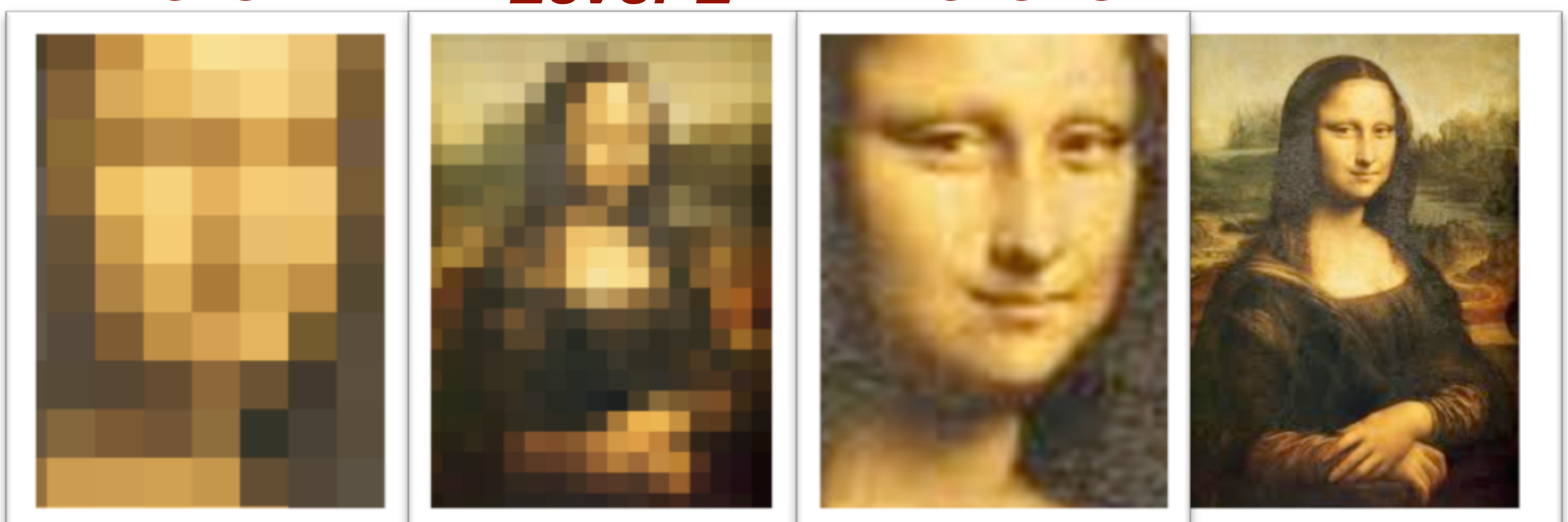
Readout dead-time is minimum if its input rate R_N is low!

Try to minimise each factor!

MULTI-LEVEL TRIGGERS

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

Level-1 ***Level-2*** ***Level-3***



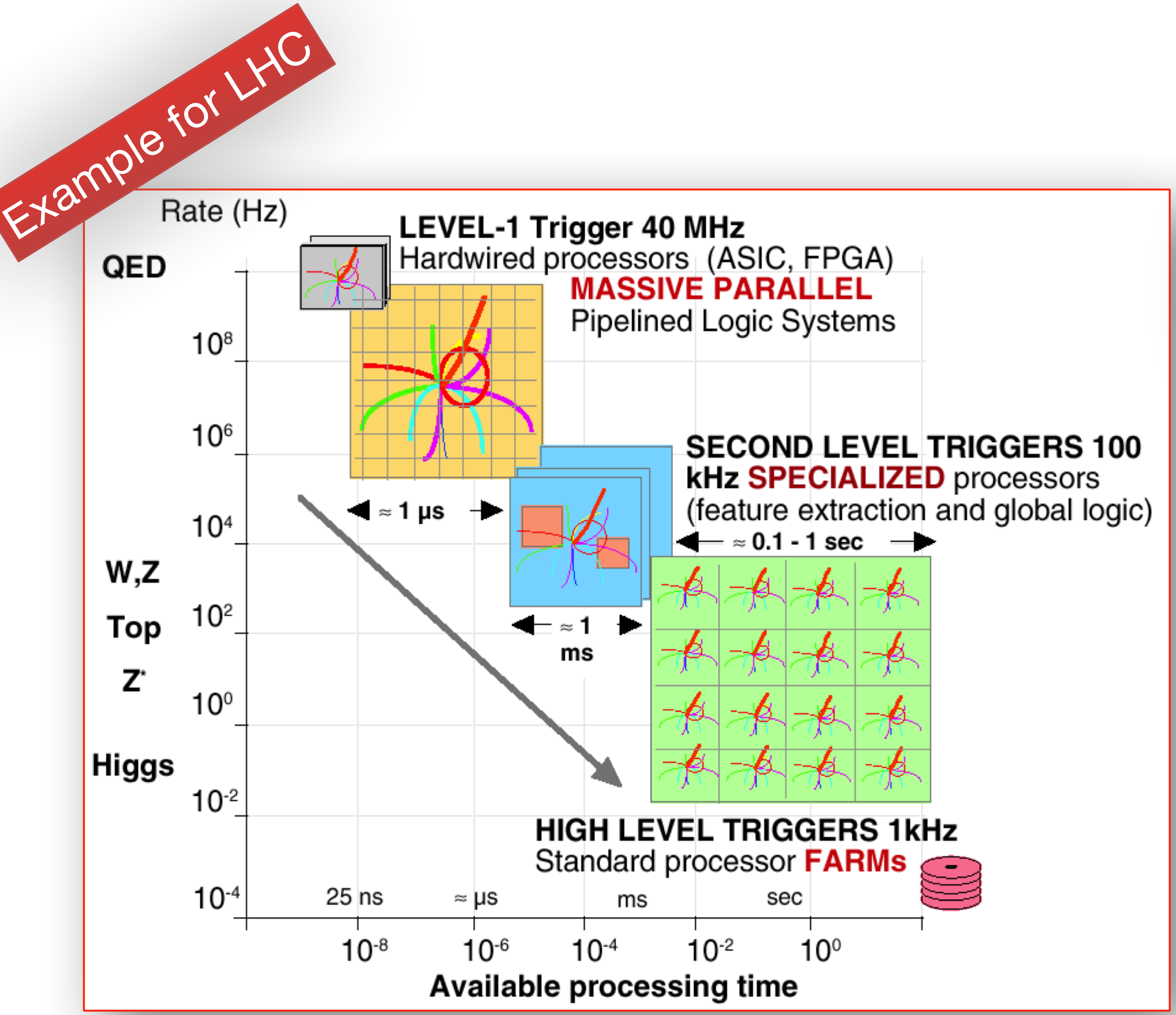
LHC experiments @ Run1

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

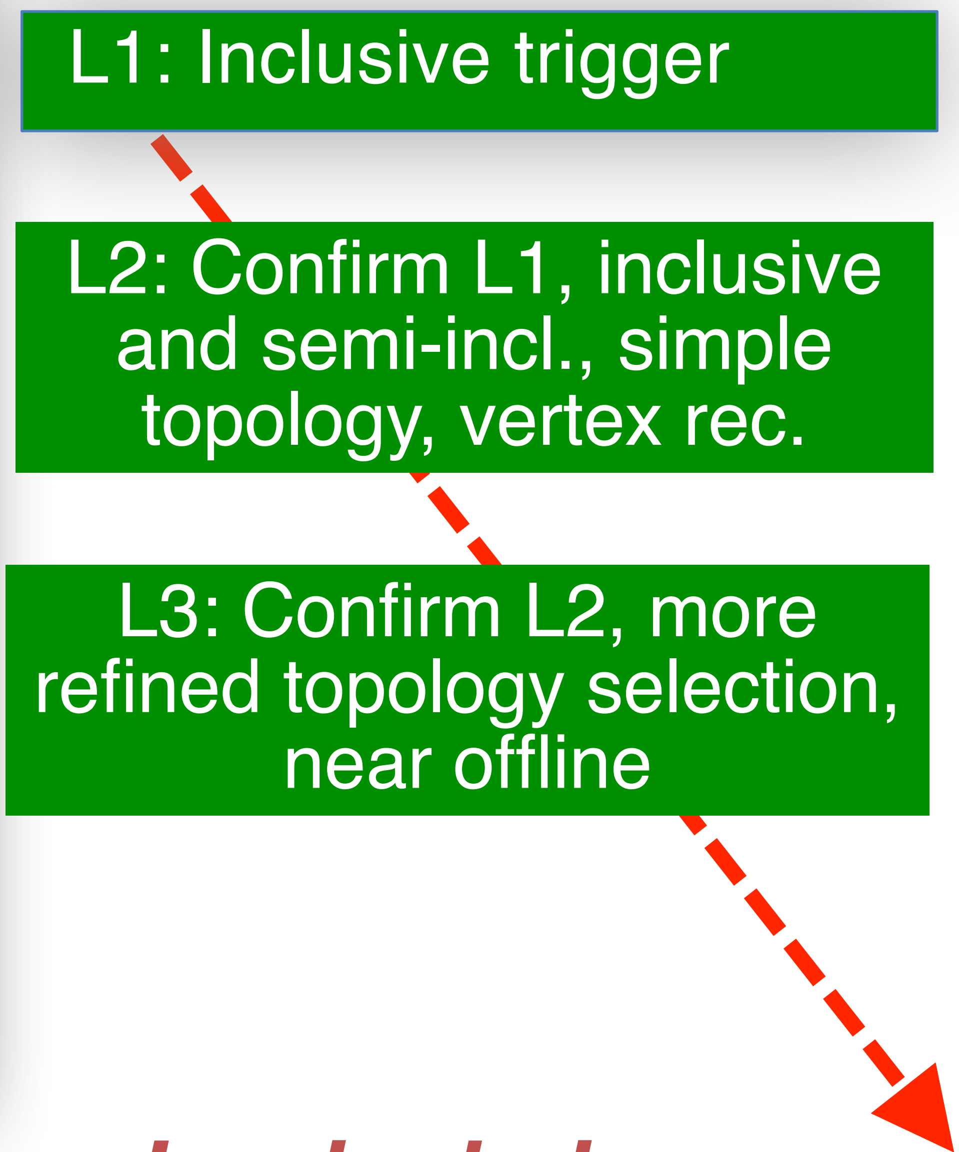
Lower event rate
Bigger event fragment size
More granularity information
More complexity
Longer latency
Bigger buffers

Efficiency for the desired physics must be kept high at all levels

USE OF MULTI-LEVEL TRIGGER

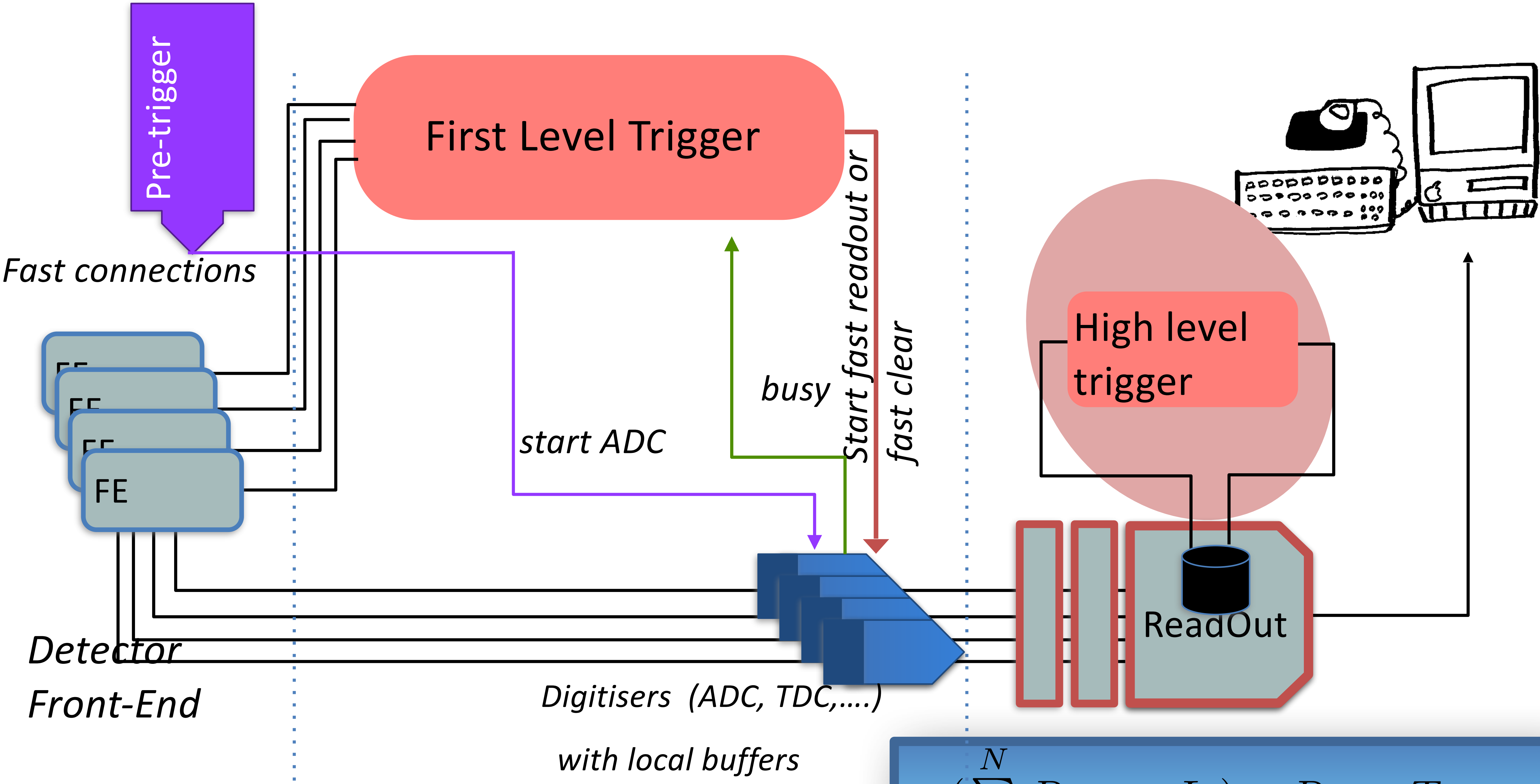


Architectural view



Logical view

SCHEMA OF A MULTI-LEVEL TRIGGER

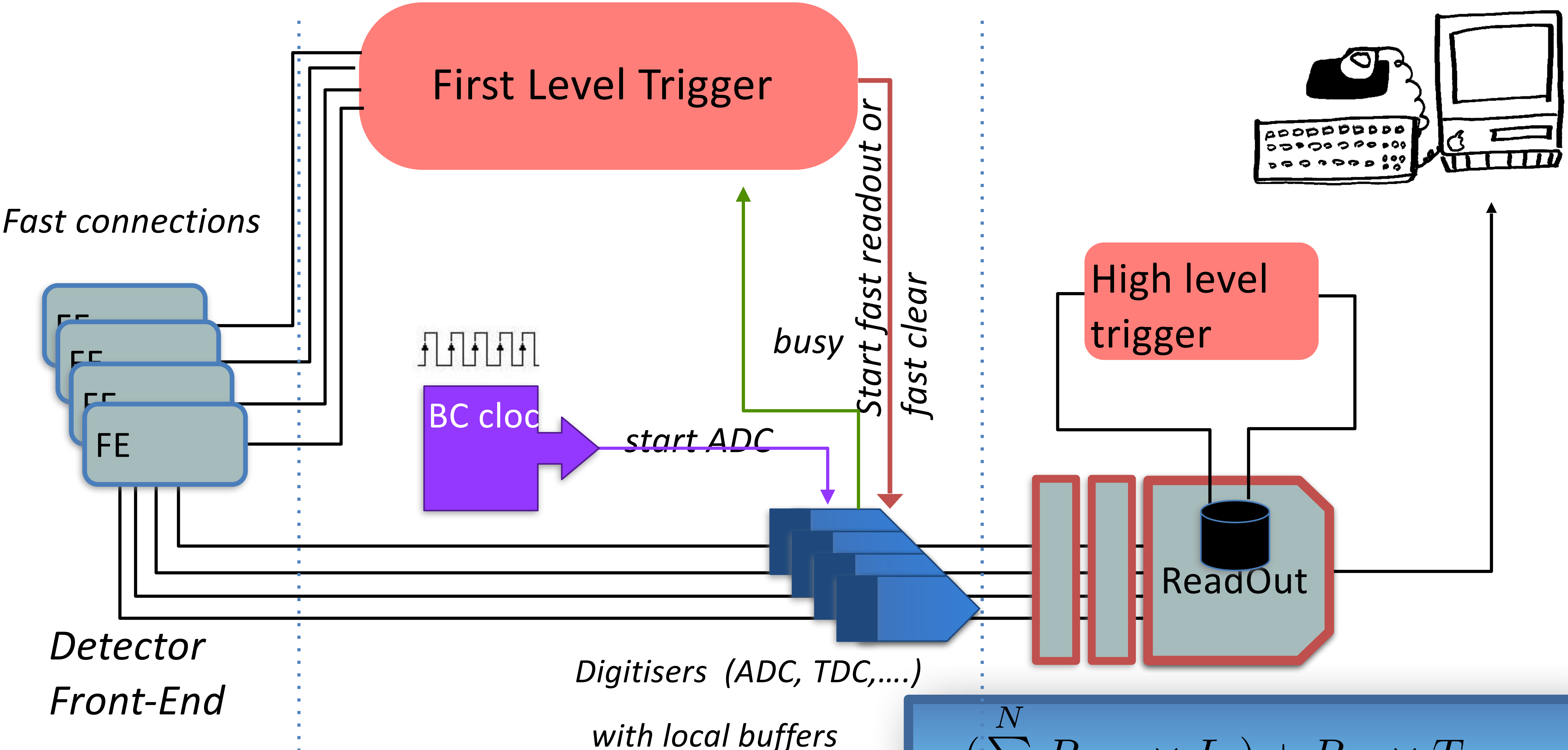


$$\left(\sum_{i=2}^{N} R_{i-1} \times L_i\right) + R_N \times T_{LRO}$$

➡ **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

THREE TYPES OF TRIGGER

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- **Global:**
  - an external system identifies the “interesting” event, all the readout data is collected for that **event identifier**

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THREE TYPES OF TRIGGER

- **Global:**
  - an external system identifies the “interesting” event, all the readout data is collected for that **event identifier**
- **Local:**
  - local trigger decision to readout data on the **local front-end modules**, readout collects fragments corresponding to that trigger
- **Continuous readout:**
  - front-end sends data continuously to the readout, at a fixed rate, regardless the data content. **Data size and rate are constant is size**. Readout cannot group fragments relative to an event

By Rick Harrison (license)

not really a photo, almost a movie

THREE TYPES OF TRIGGER

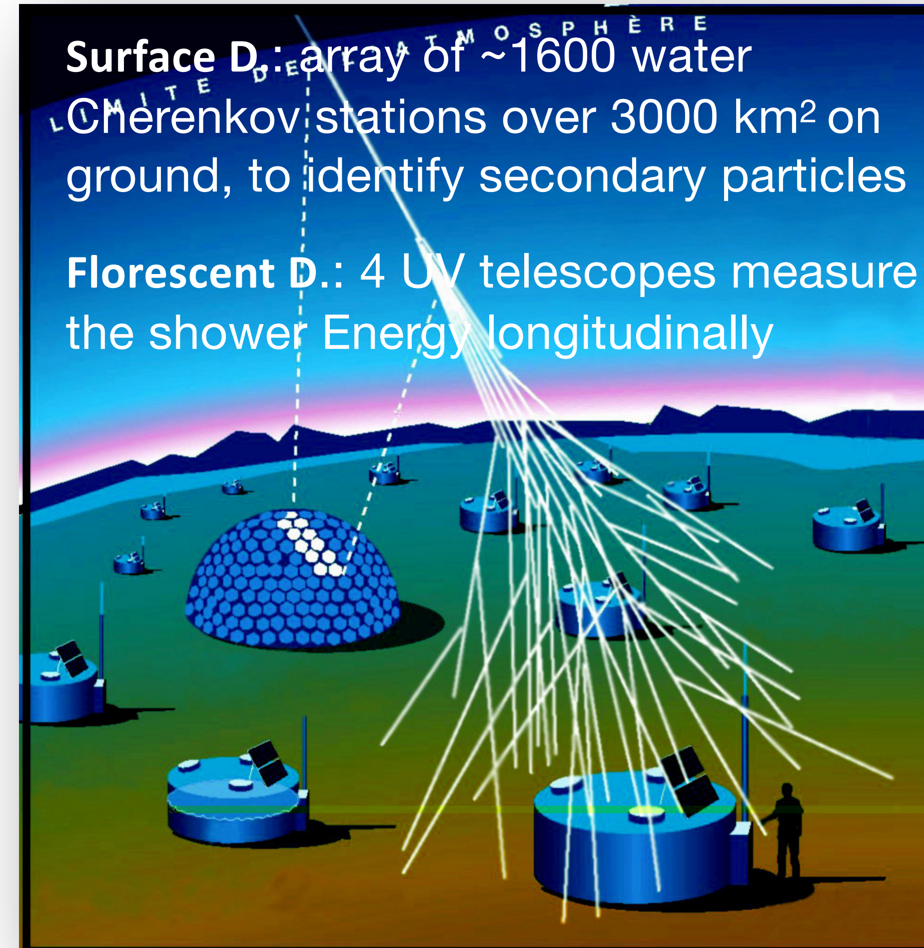
- **use cases:**
  - **Colliders**: normally use global trigger: if something interesting has been seen somewhere, take all the data corresponding to that bunch crossing
  - **Large distributed telescopes**: often use local trigger: readout data for the portions of the detector that have seen something
  - **Very slow detectors**: sometimes use continuous readout: sample the analogue signals at a fixed rate and let the downstream DAQ decide whether there were any interesting signals

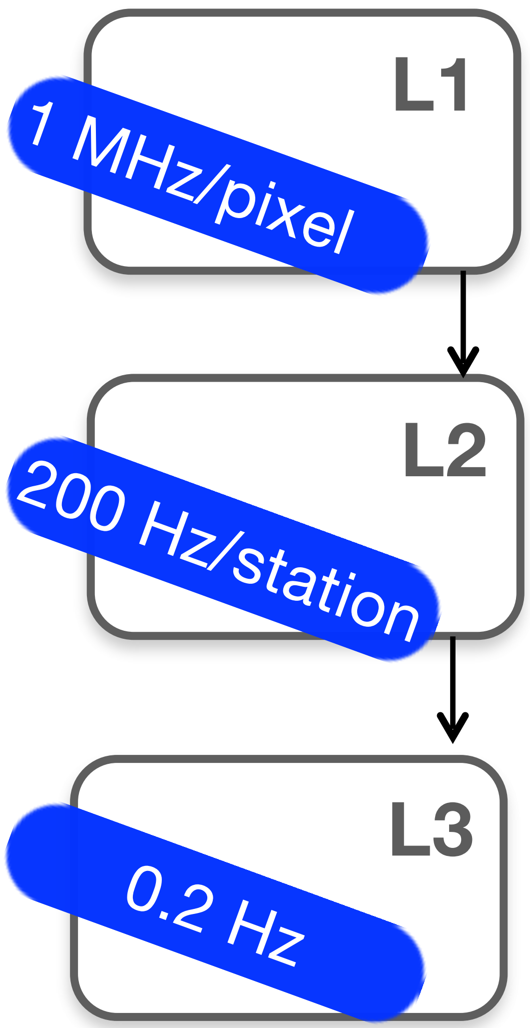
By Rick Harrison (license)

not really a photo, almost a movie

LOCAL SIGNATURES: AUGER OBSERVATORY

- **Two large area detectors detect showers generated by cosmic rays above 10^{17} eV**
  - Expected rate < $1/km^2$/century
- **On each detector, a 3-level trigger operates at a wide range of primary energies, for both vertical and very inclined showers**





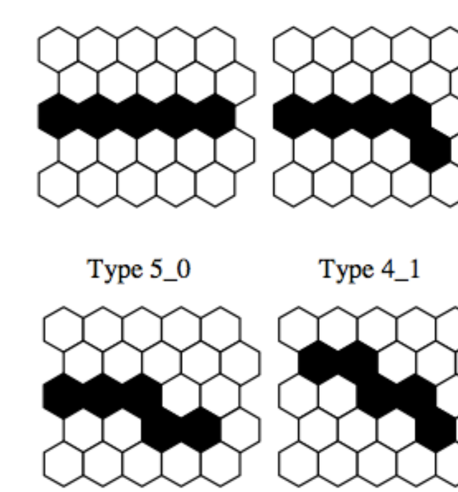
L1: (local) decides pixel status (on/off)

- 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

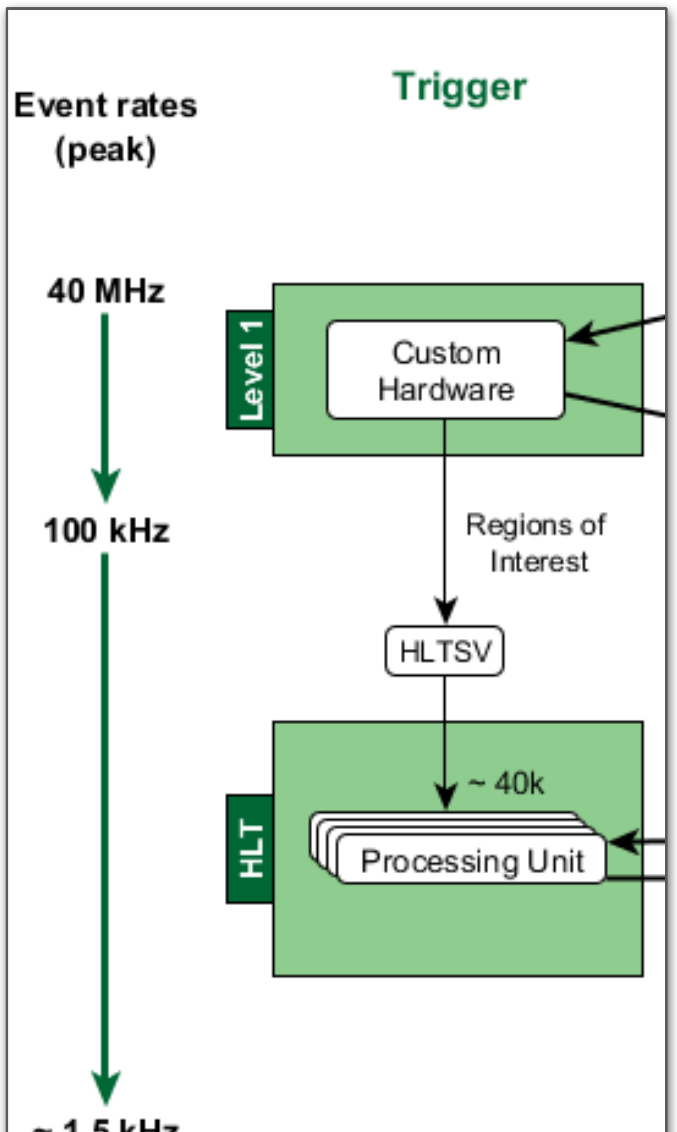


Example of L2 patterns

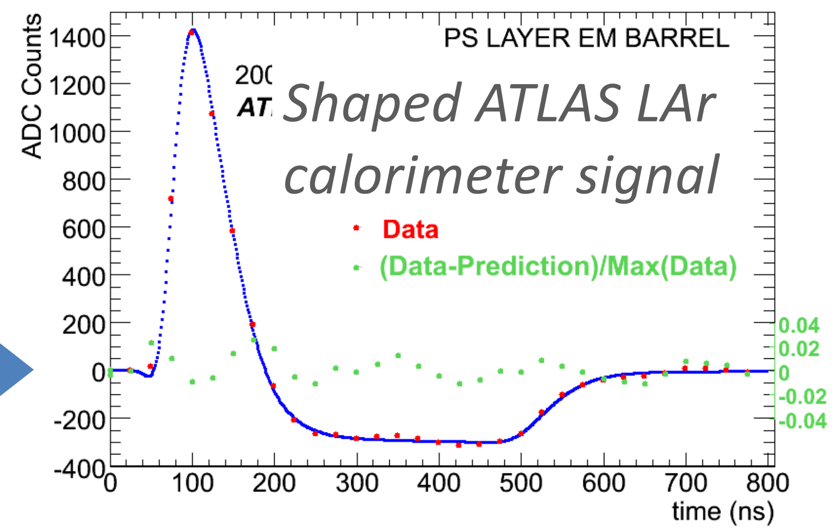
One event ~ 1MB → 0.2 MB/s bandwidth for the DAQ system

MULTIPLE SIGNATURES: ATLAS CALORIMETER TRIGGER

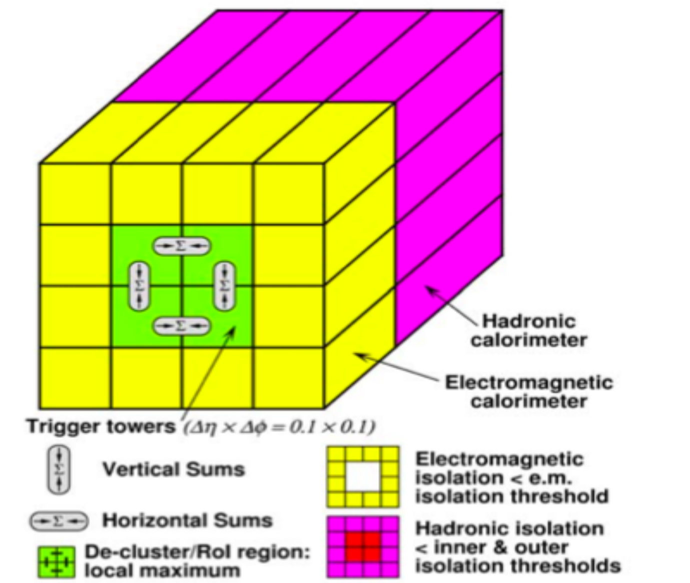
- Goal: identify high energy e, γ, τ, jets, missing E_T, ΣE_T

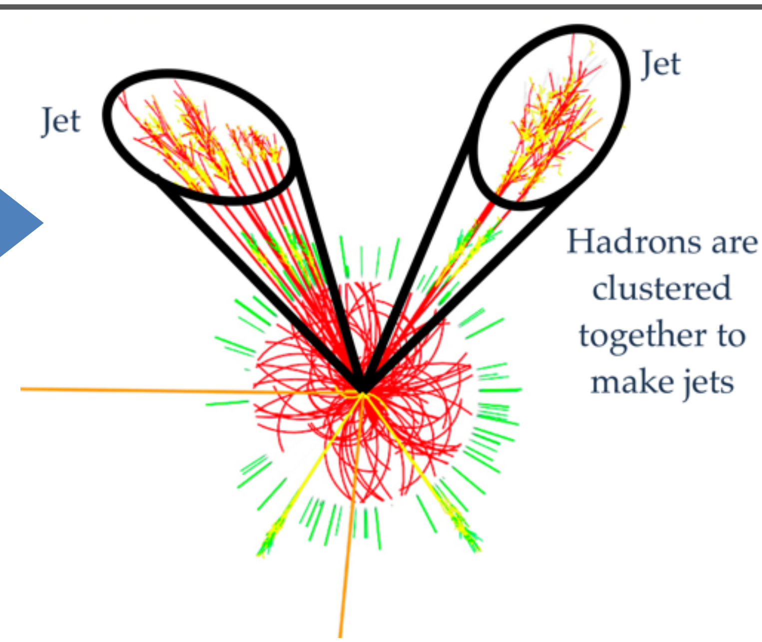


- **Dedicated Front-End electronics**
  - Each cell sends shaped analog signals



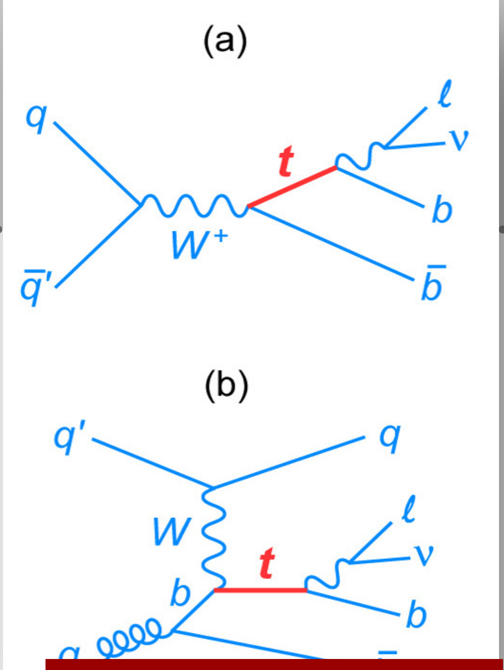
- **L1 hardware trigger (2.5 us)**
  - **ASICs** for simple cluster algorithms, with programmable E_T thresholds





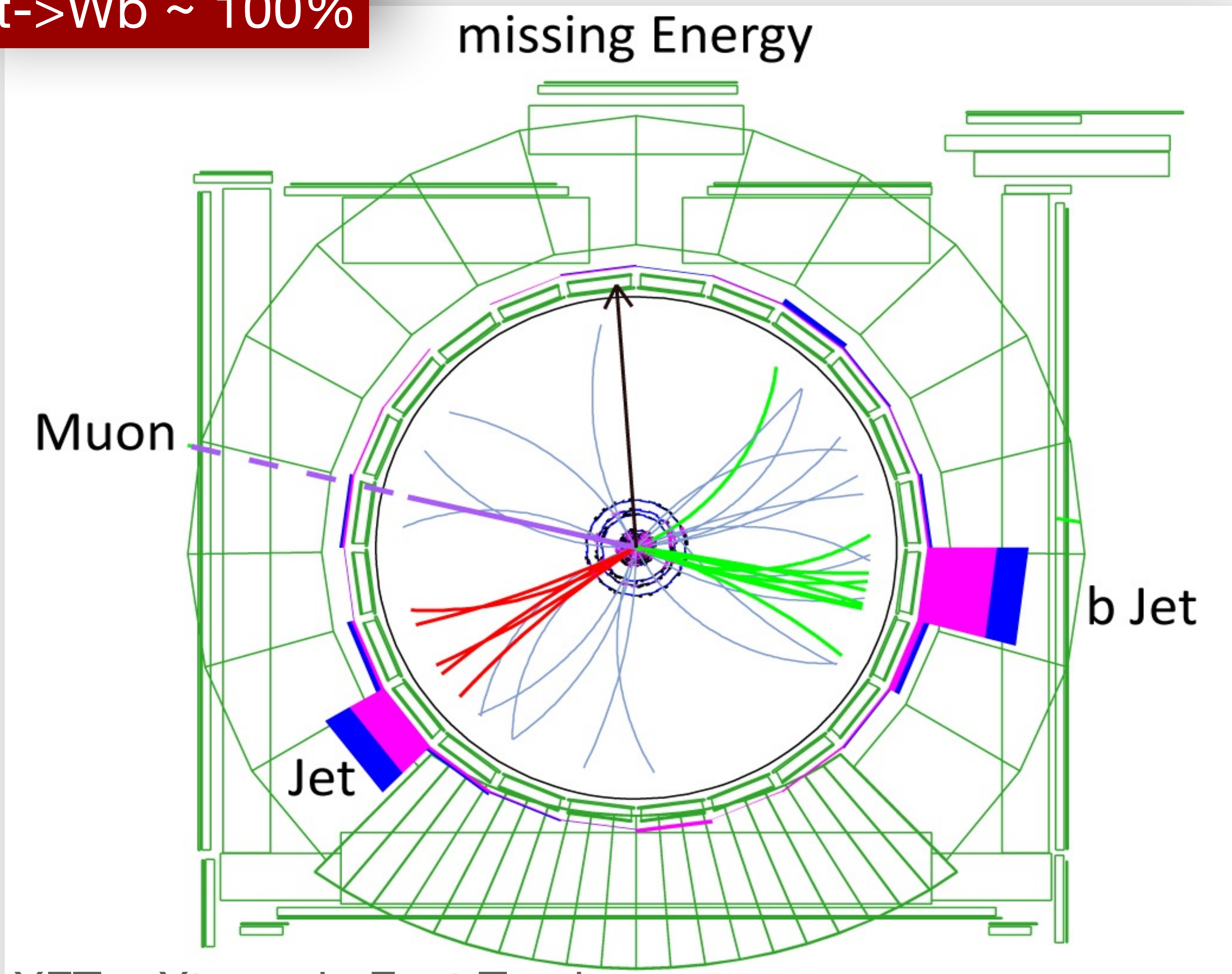
- **High-Level triggers software (~1s)**
  - **electron/jet separation using**
    - Cluster shapes
    - **Topological** variables, **tracking** information
    - **Isolation** criteria

MULTI OBJECTS TRIGGER: CDF



t->Wb ~ 100%

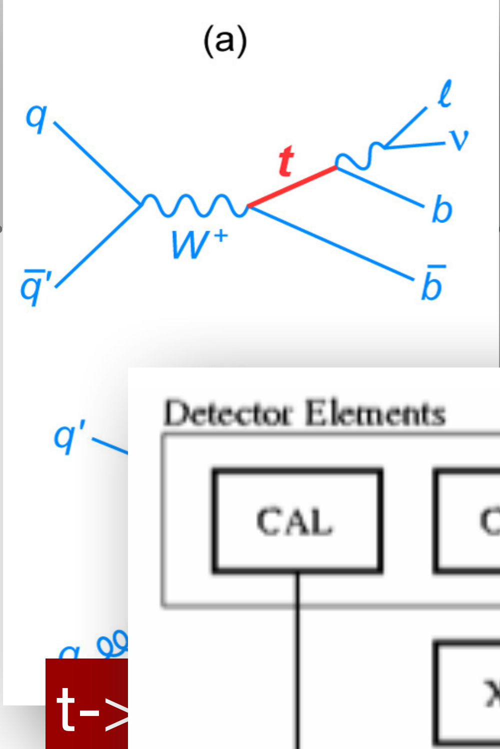
CDF single top event

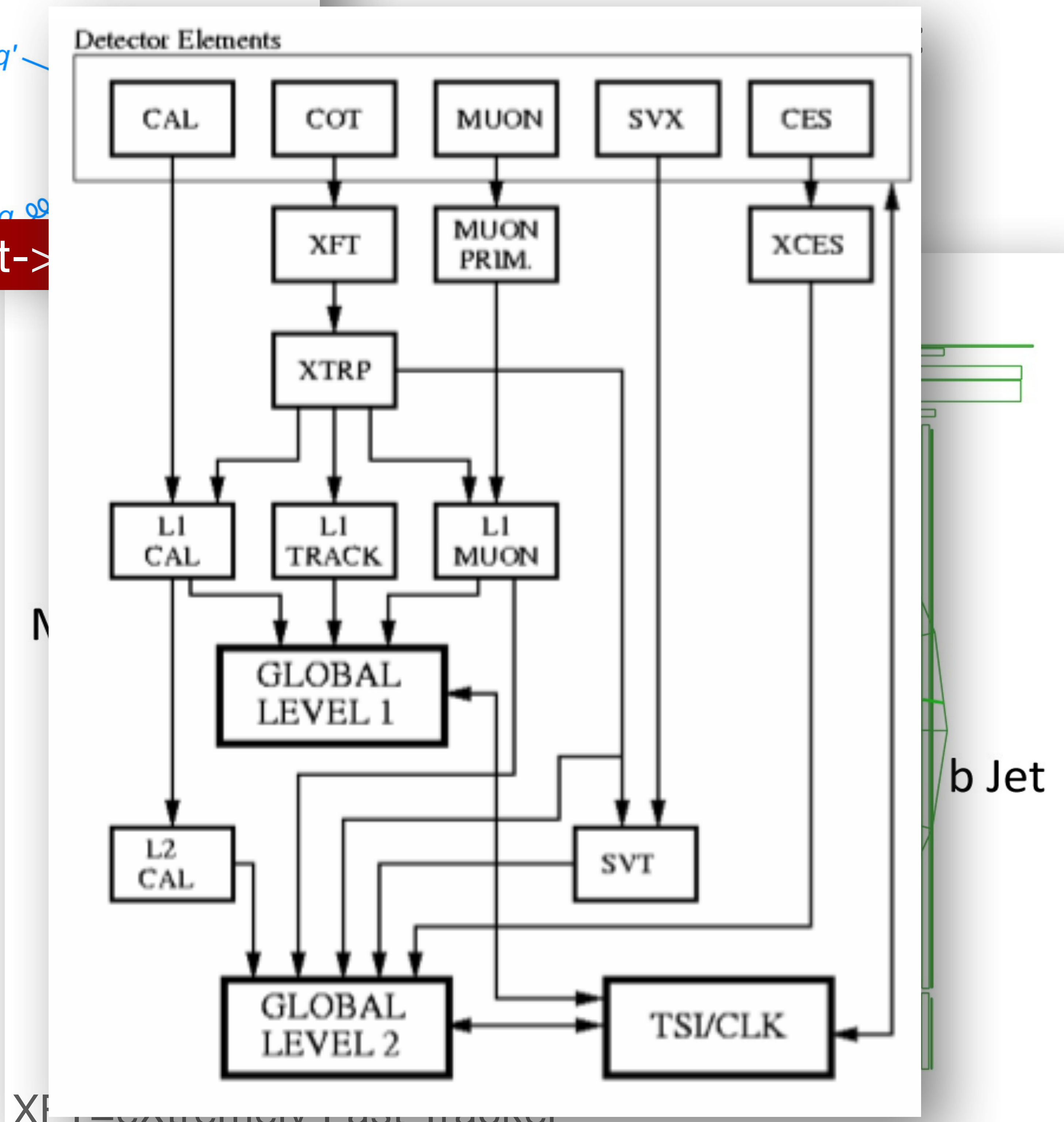


XFT=eXtremely Fast Tracker

- Signal characterization:
  - 1 high p_T lepton, in general isolated
  - Large MET from high energy neutrino
  - 2 jets, 1 of which is a b-jets
- Trigger objects at L1
  - Central tracking (XFT p_T>1.5GeV)
  - Calorimeter
    - Electron (Cal +XFT)
    - Photon (Cal)
    - Jet (Cal EM+HAD)
  - Missing E_T, SumE_T
  - Muon (Muon + XFT)
- Trigger objects at L2:
  - L1 information
  - SVT (displaced track, impact parameter)
  - Jet cluster
  - Isolated cluster
  - Calorimeter ShowerMax (CES)

MULTI OBJECTS TRIGGER: CDF





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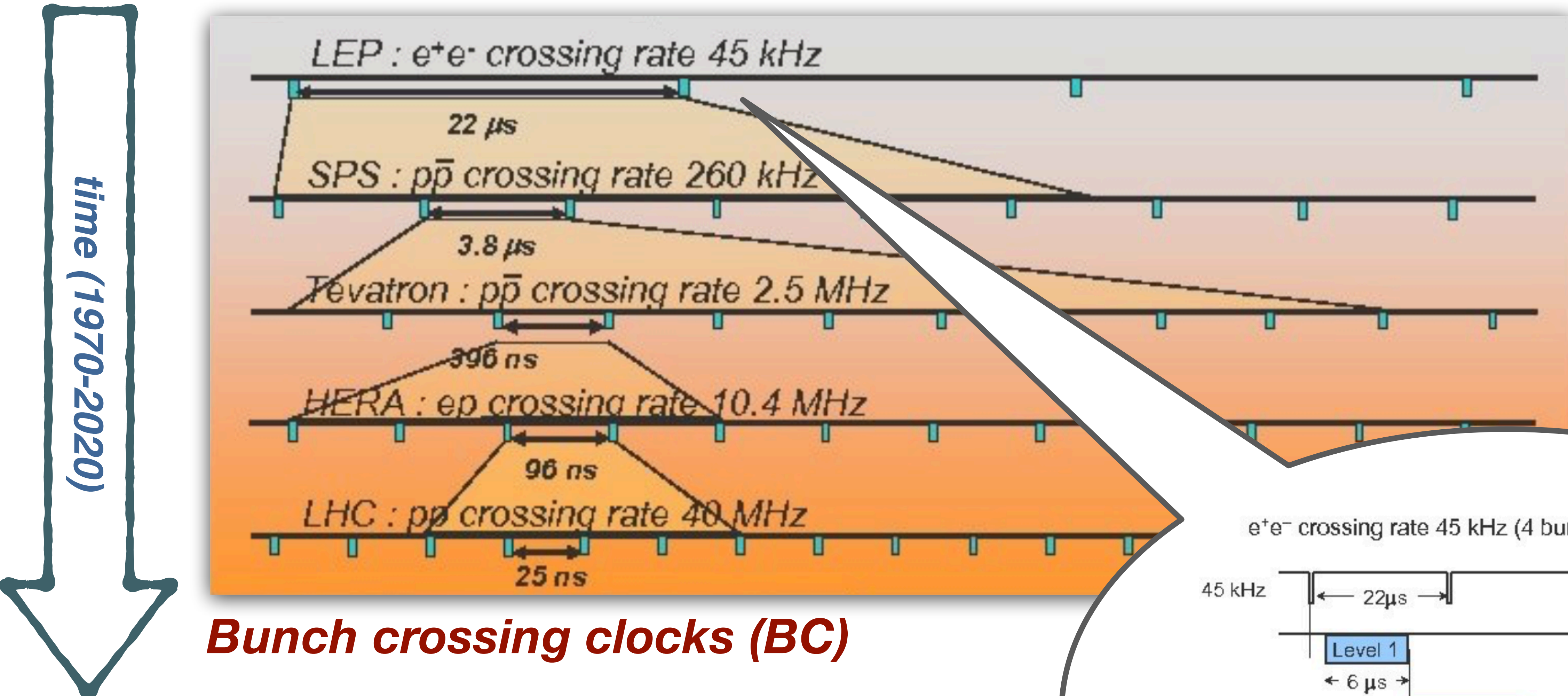
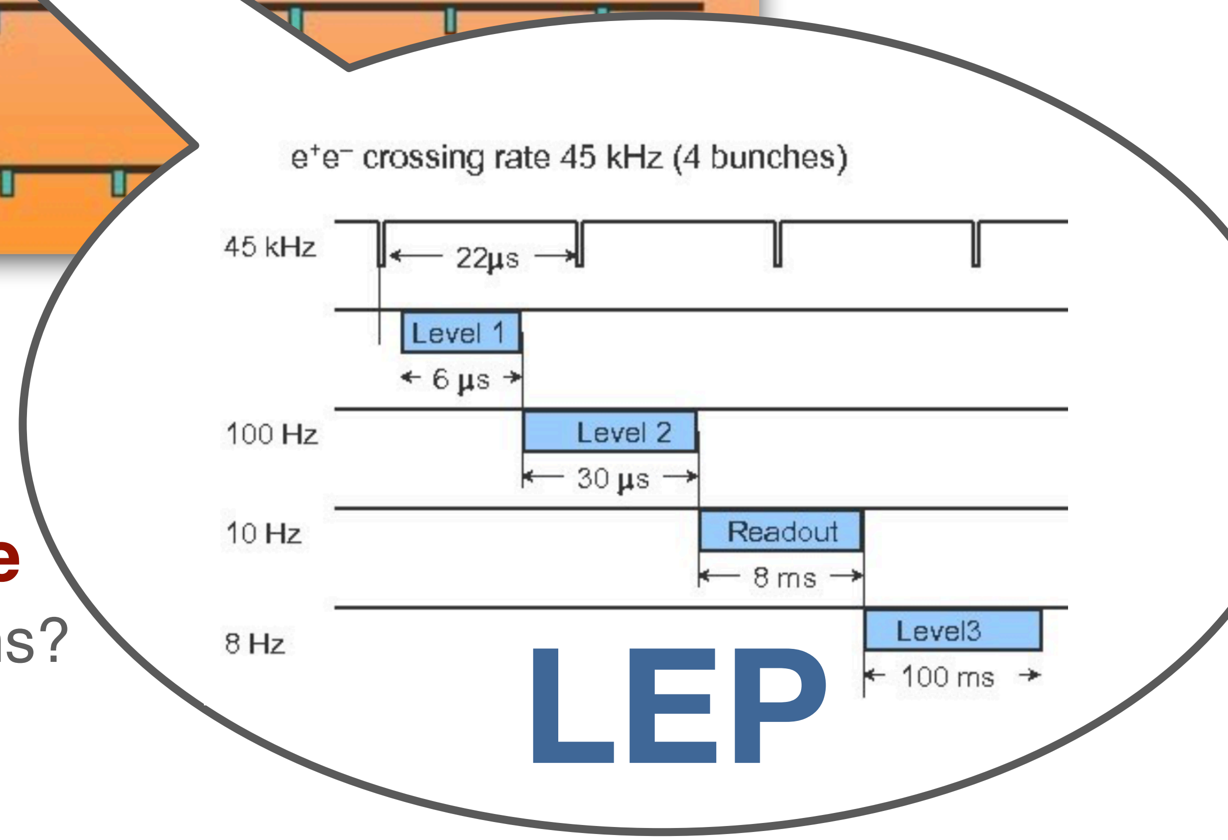
OUTLINE

- ➡ trigger selectivity and robustness with examples
- ➡ how to build a trigger system from first principles
- ➡ **principles and examples of L1 triggers**
- ➡ principles and examples of software triggers

IN A SYNCHRONOUS LEVEL-1 TRIGGER @ COLLIDERS



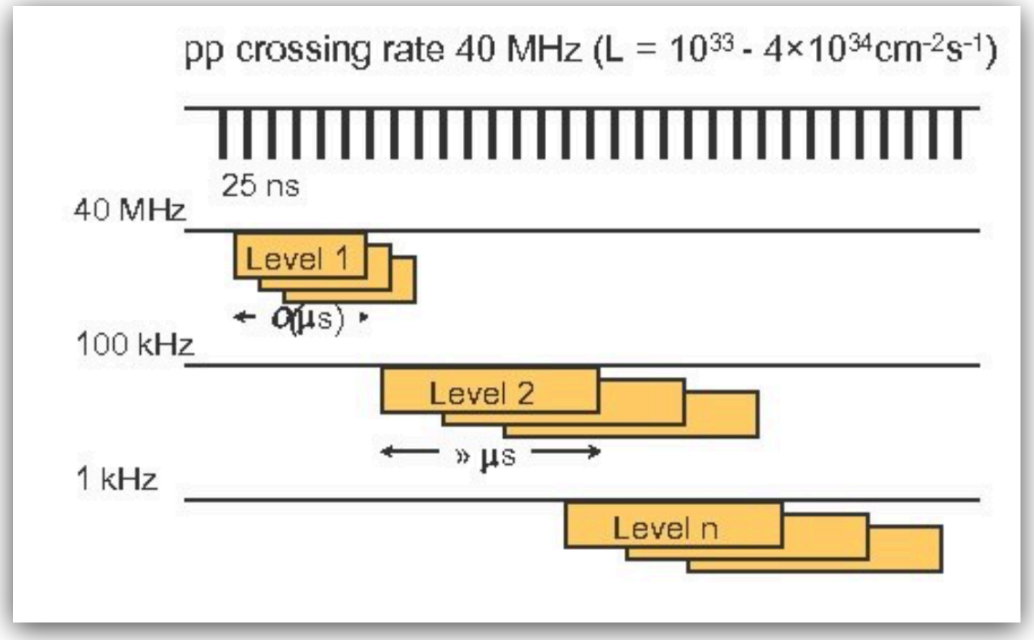
Bunch crossing clocks (BC)

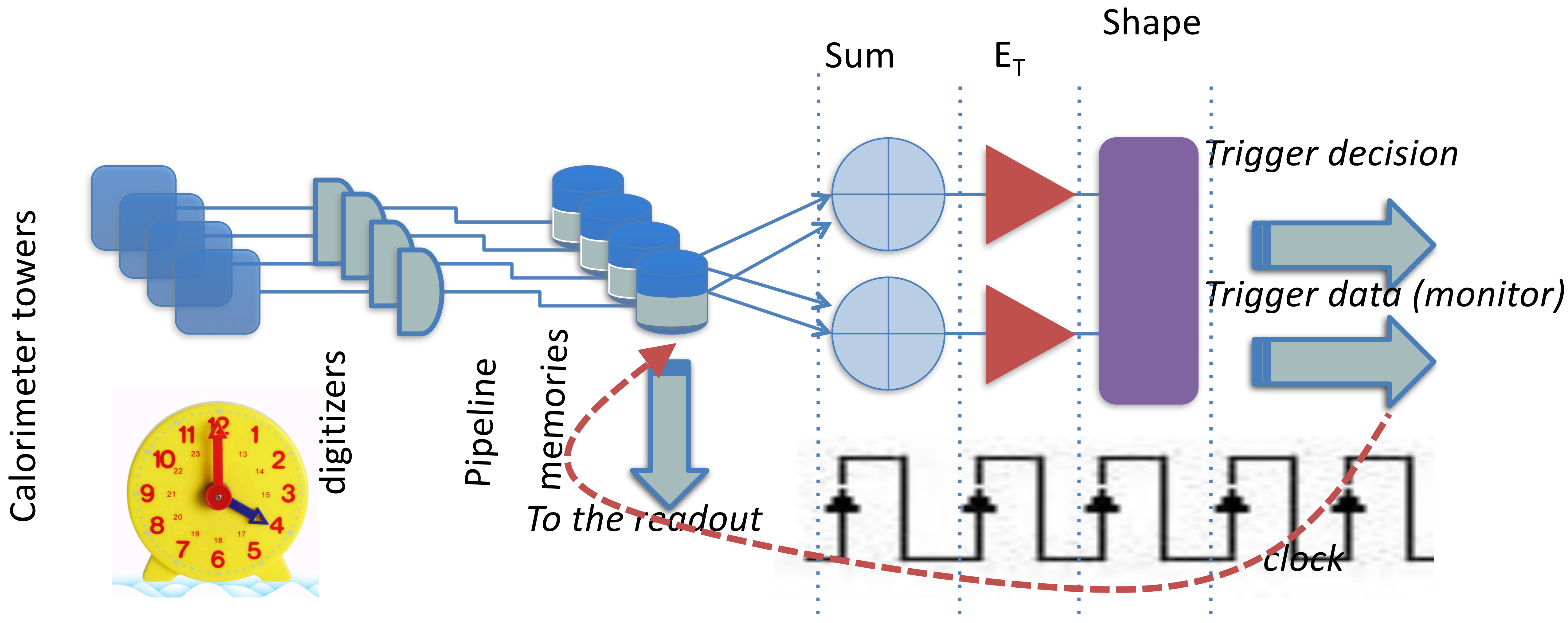


- **High luminosity driven by high clock rate**
  - can take trigger decision between two collisions?
- **@LEP (BC interval 22 μs):**
  - Level-1 trigger latency < bunch-interval
  - no event overlap
  - most electronics outside the detector

LEVEL-1 PIPELINE TRIGGER

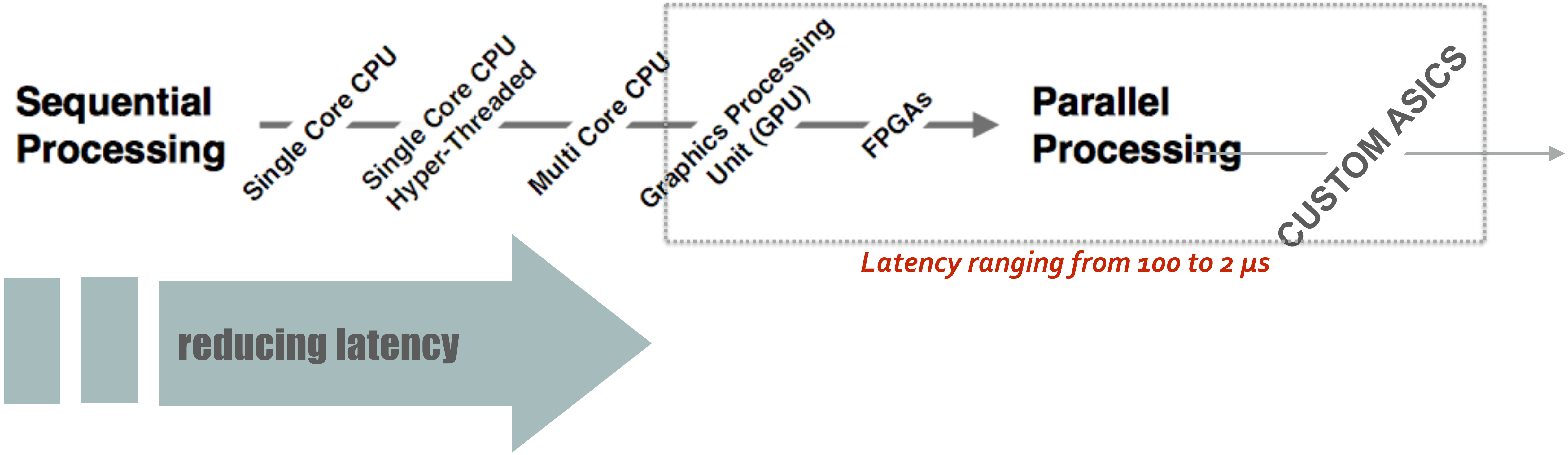
- **@LHC (25ns): L1 latency few μs > bunch interval**
  - events overlap
  - signals pileup (in the detectors)
  - mostly with large detectors (long distance -> latency)
- **Front-end buffer are pipelines @ fixed latency**
  - Each processor concurrently processes many events
  - Divide processing in steps, one per BC clock





TRIGGER (CO-)PROCESSORS

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



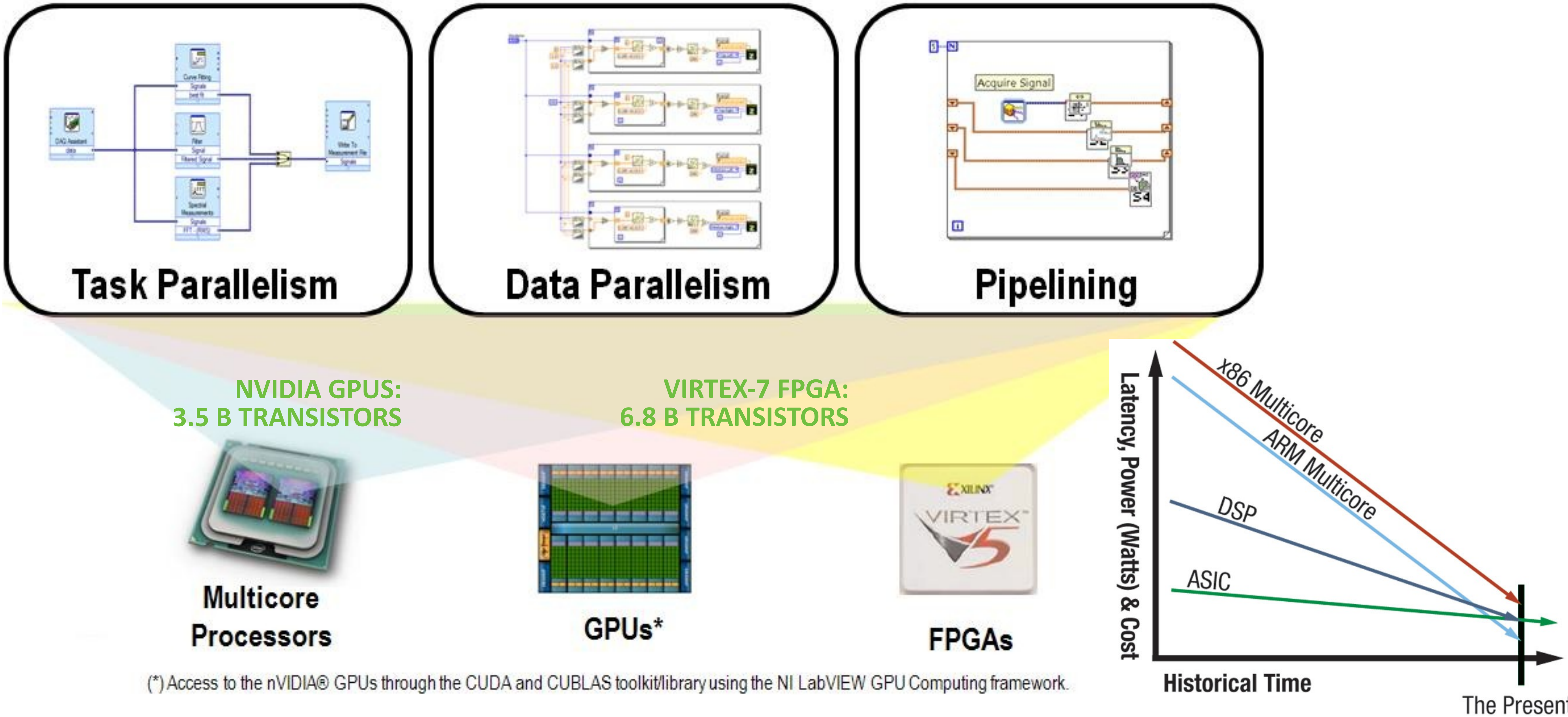
- **Microprocessors** (CPUs, GPGPUs, ARMs, DSP,…)
  - Available on the market or specific, programmed only once

need instructions

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

already learned the task

TRENDS: COMBINED TECHNOLOGY



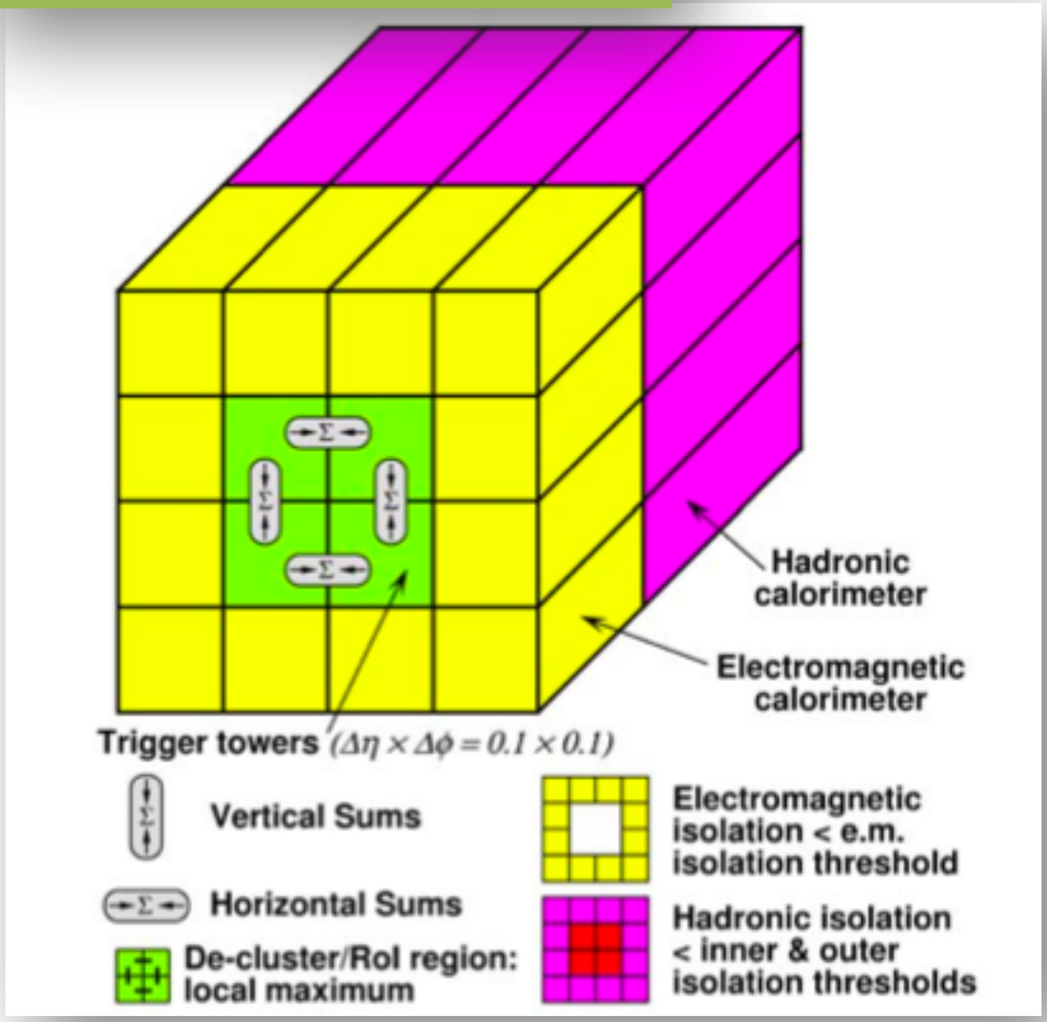
The right choice can be combining the best of both worlds by analysing which strengths of FPGA, GPU and CPU best fit the different demands of the application.

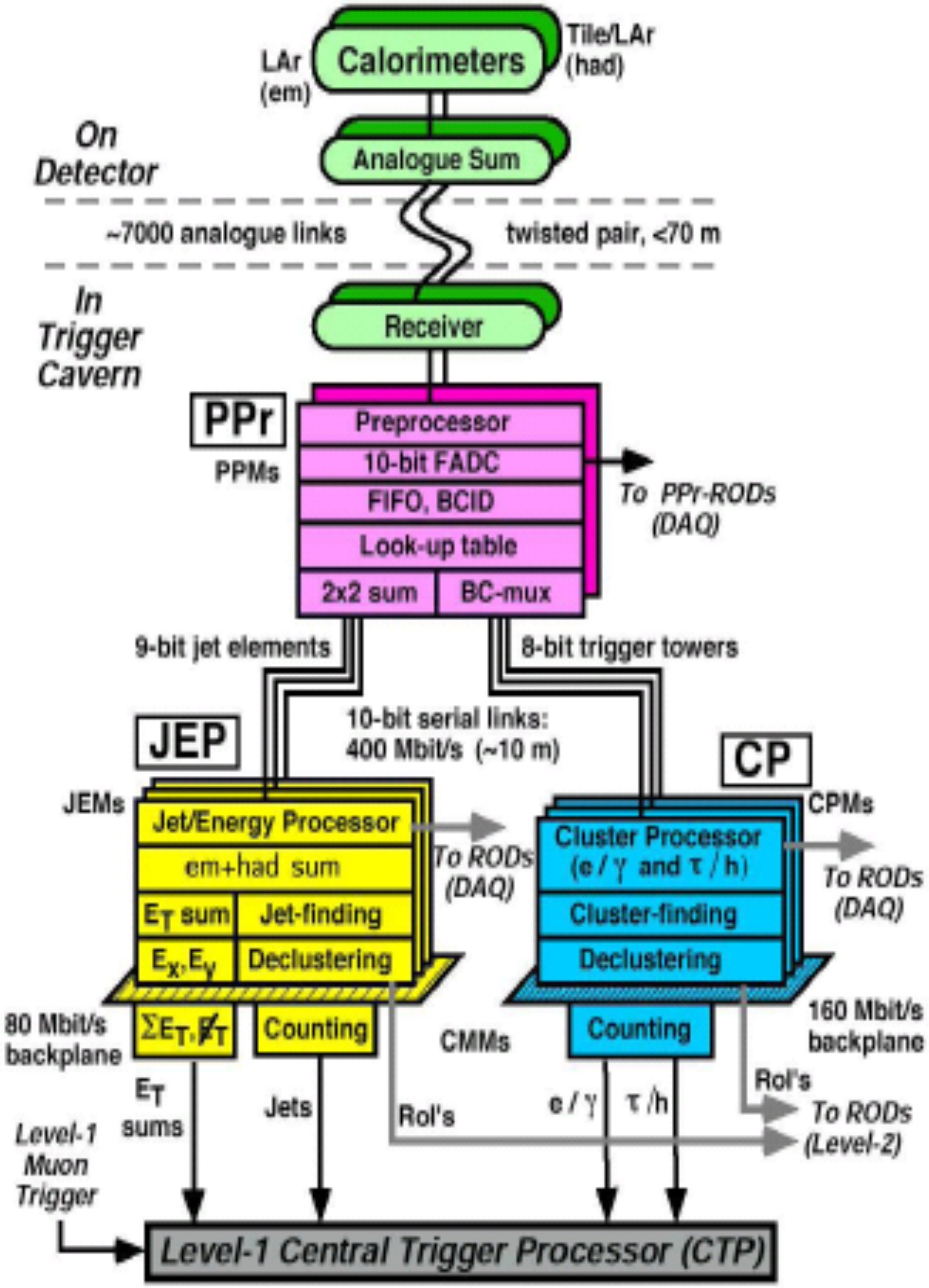
EXAMPLE: ATLAS CALORIMETER TRIGGER

- **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





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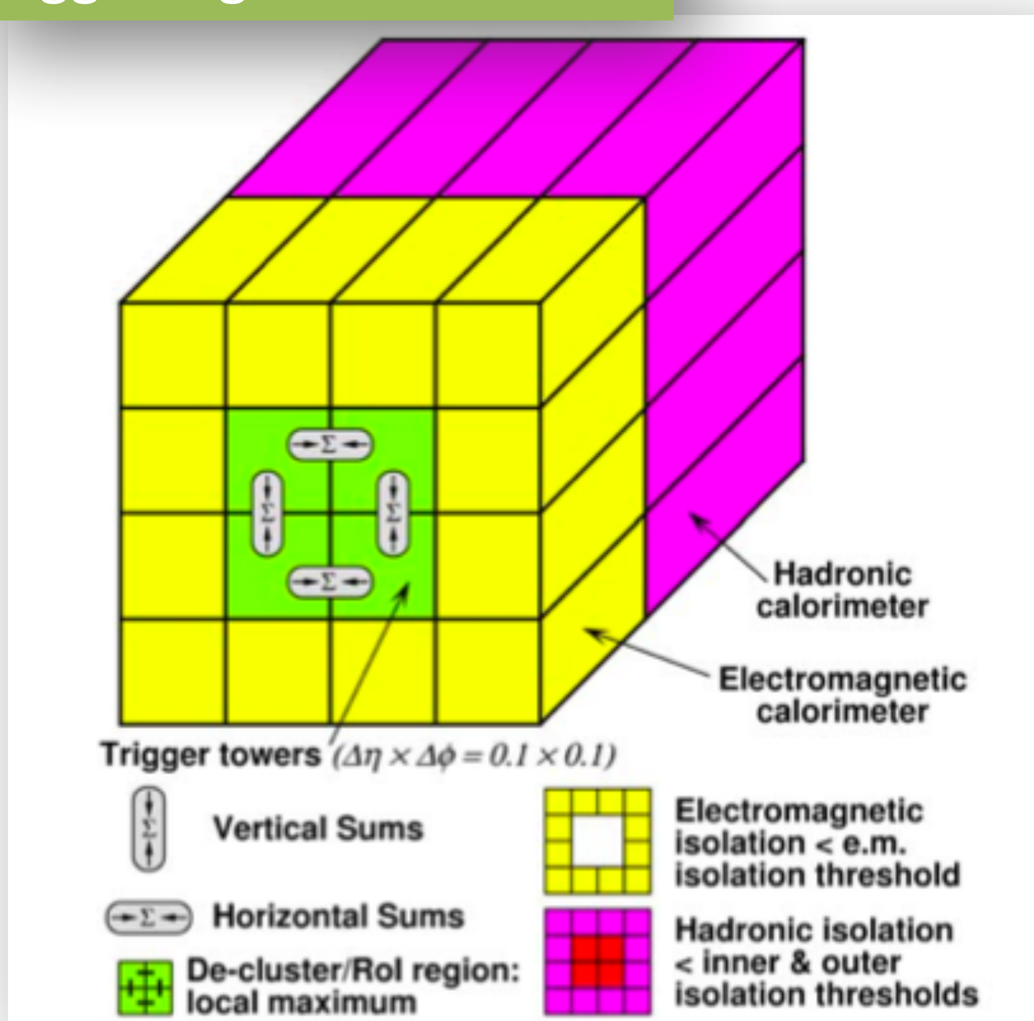
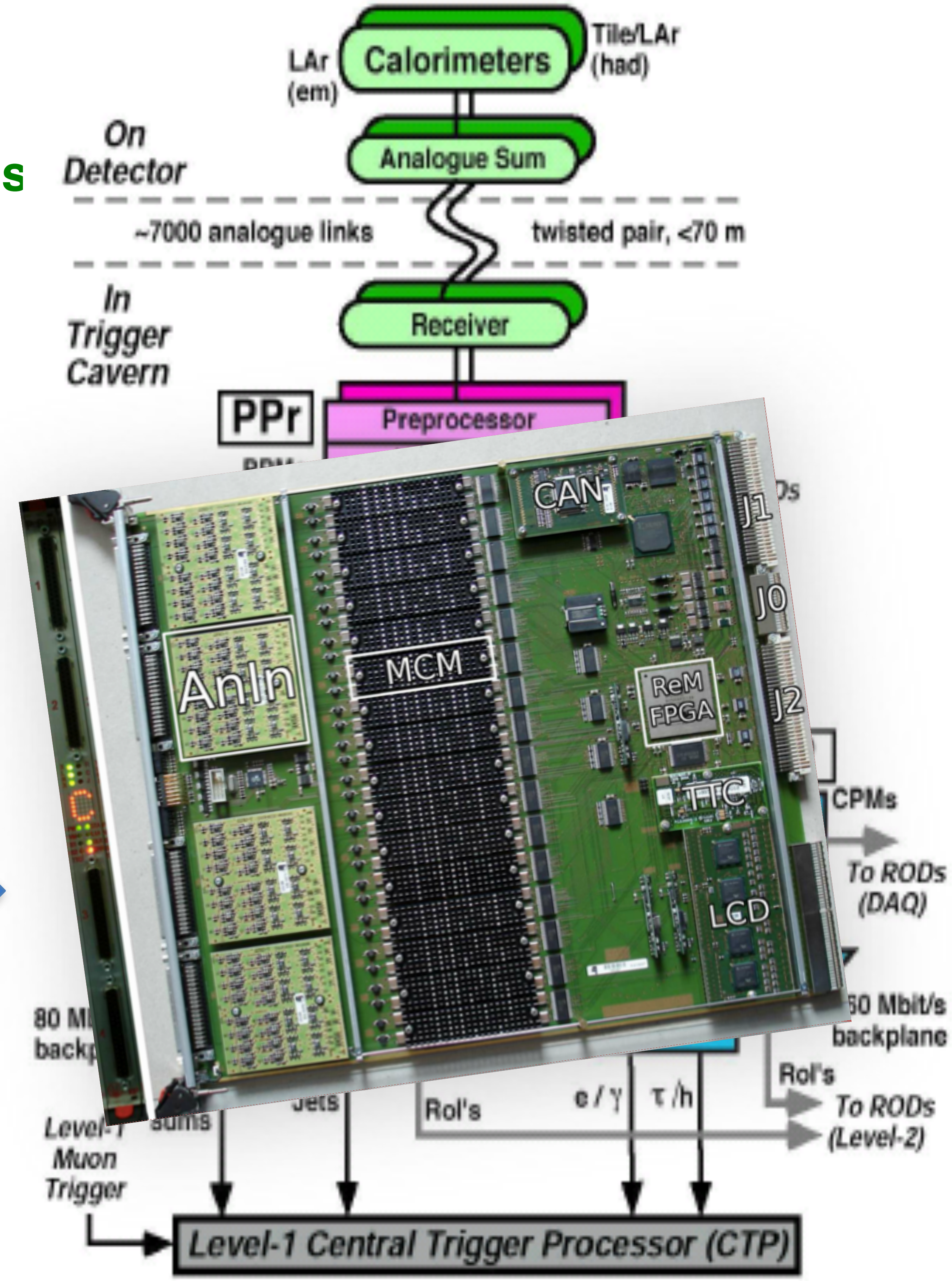
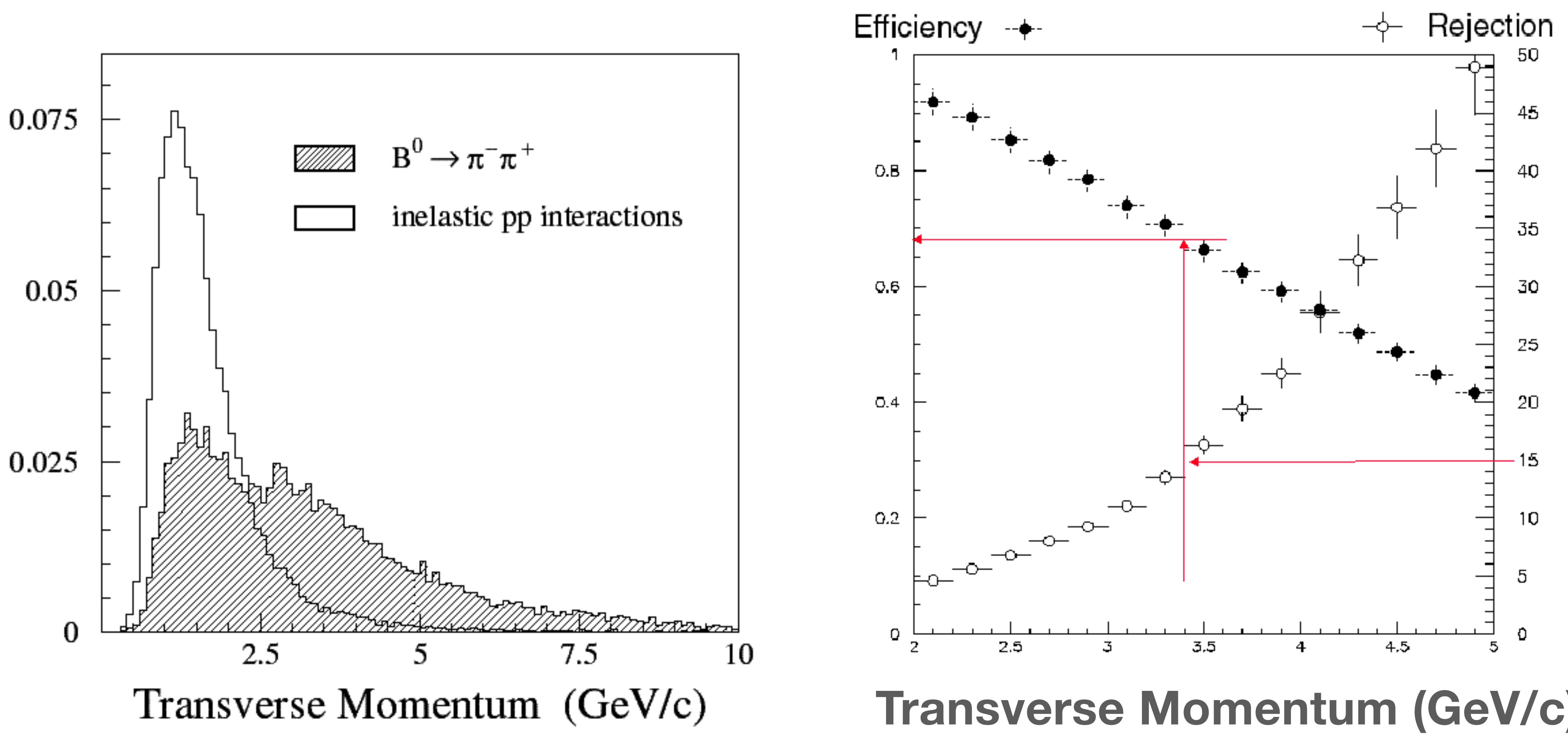




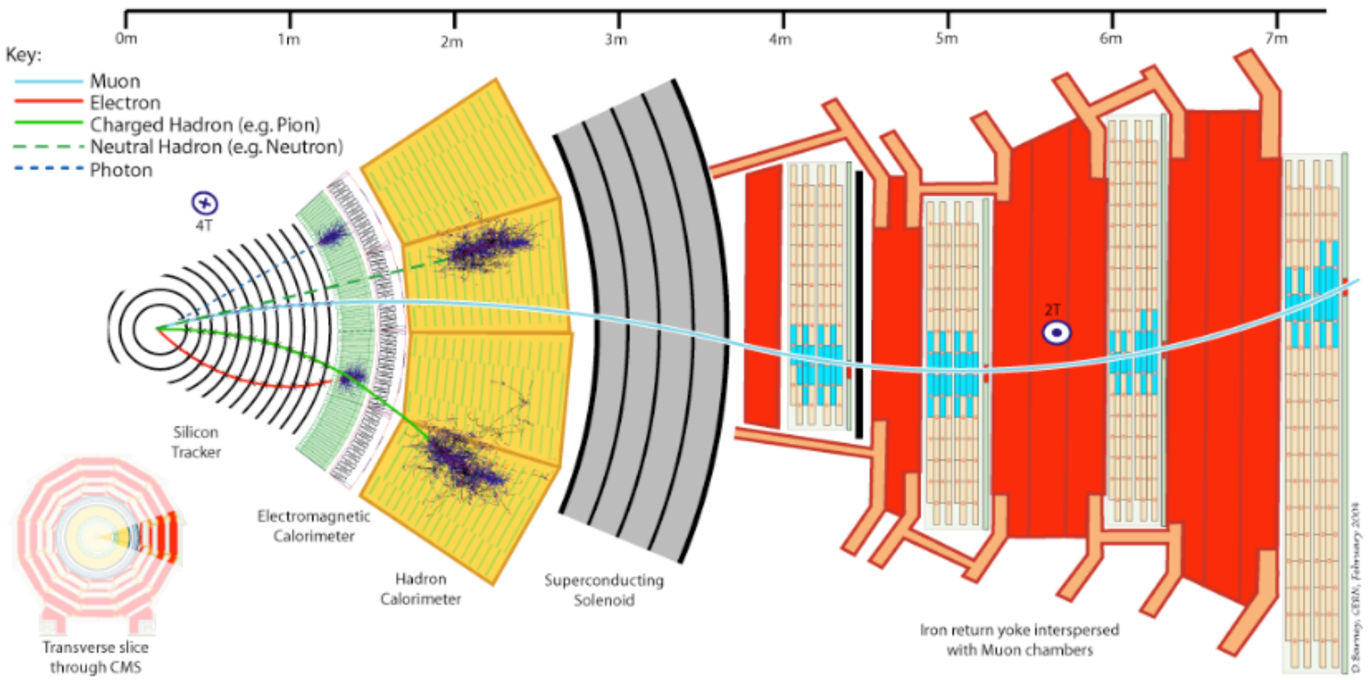
EXAMPLE: B MESON TRIGGER IN LHCB

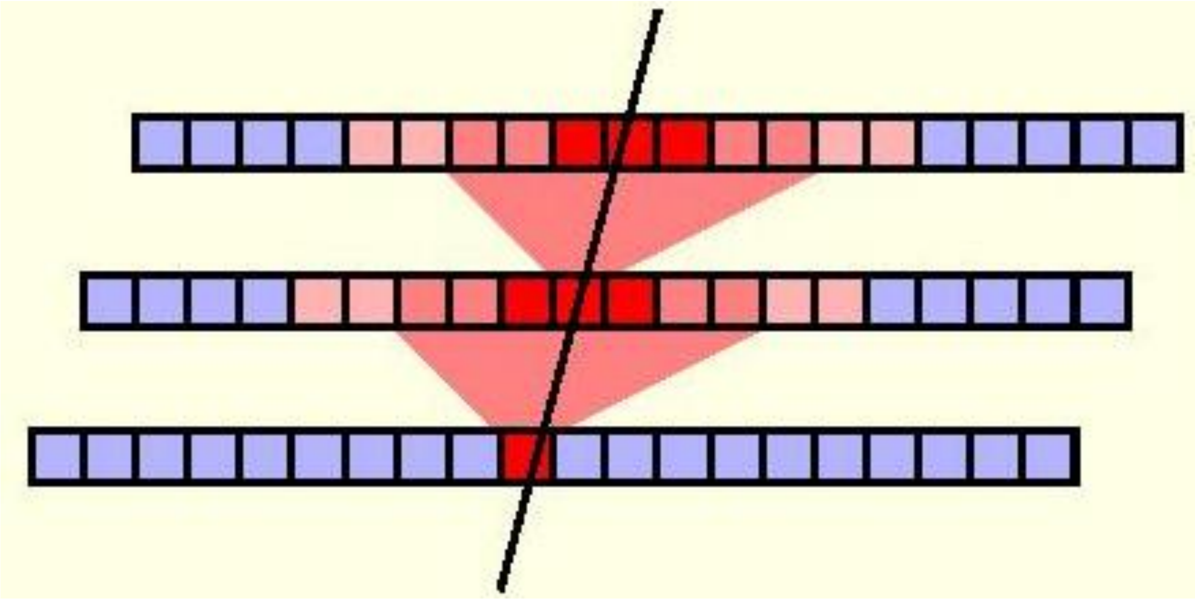
- **L0 trigger(~2 μs) : Calculates transverse momentum (p_T) of muons, electrons and hadrons**
  - Discriminating variable: highest p_T
- **Efficiency versus background rejection**

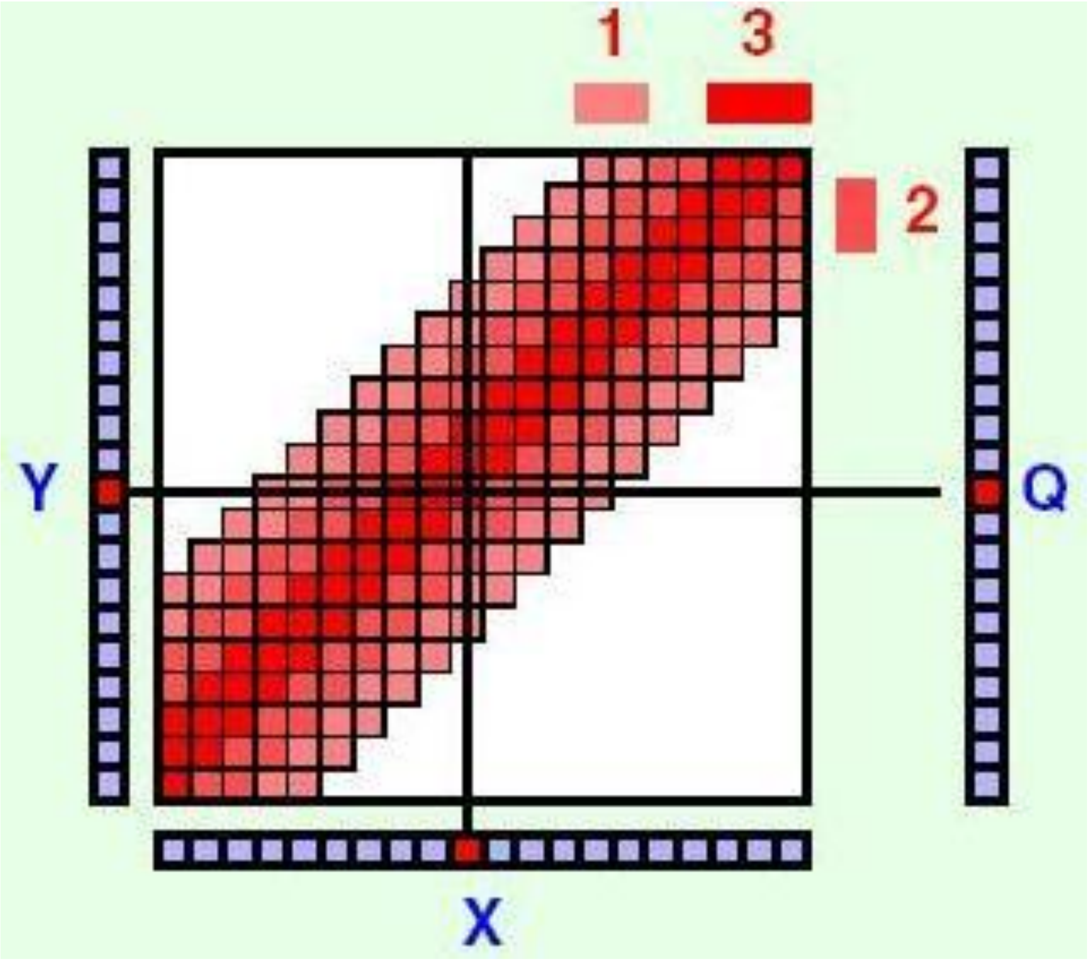


Transverse Momentum (GeV/c)

EXAMPLE: MUON TRIGGER (ATLAS/CMS)



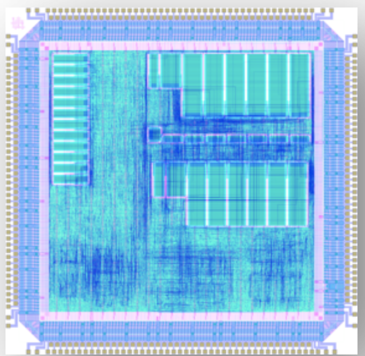




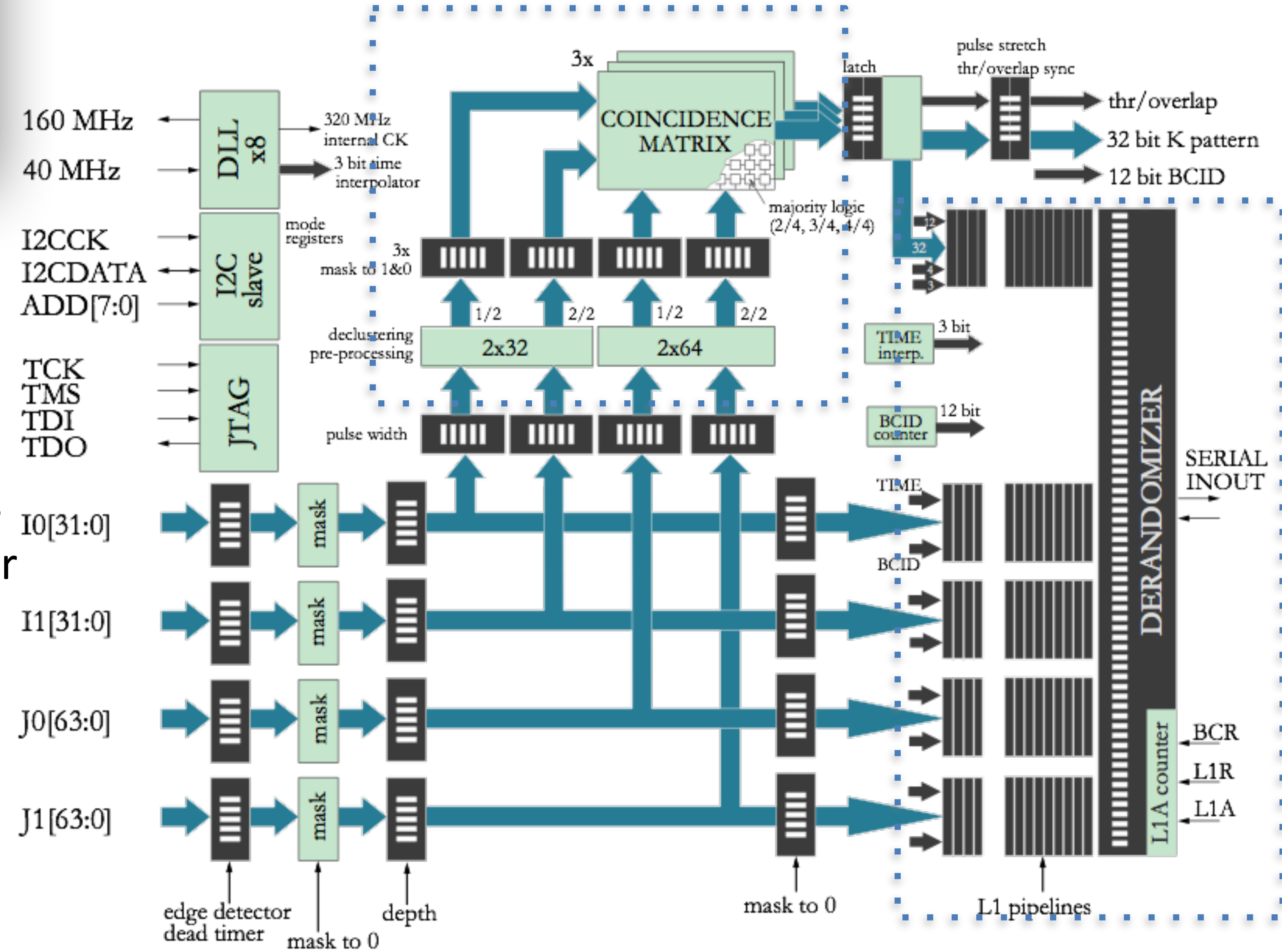
- ➡ **Several steps to evaluate muon transverse momentum above threshold**
- ➡ **First step of track finding**
  - ➡ Muons pointing to interaction region
  - ➡ Use multiple layers of muon chambers
  - ➡ Coincidence matrix or even simpler lookup table

EXAMPLE: LOGIC OF A TRIGGER ASIC

Coincidence Matrix ASIC for Muon Trigger in the Barrel of ATLAS



Trigger part



Trigger output

Readout output

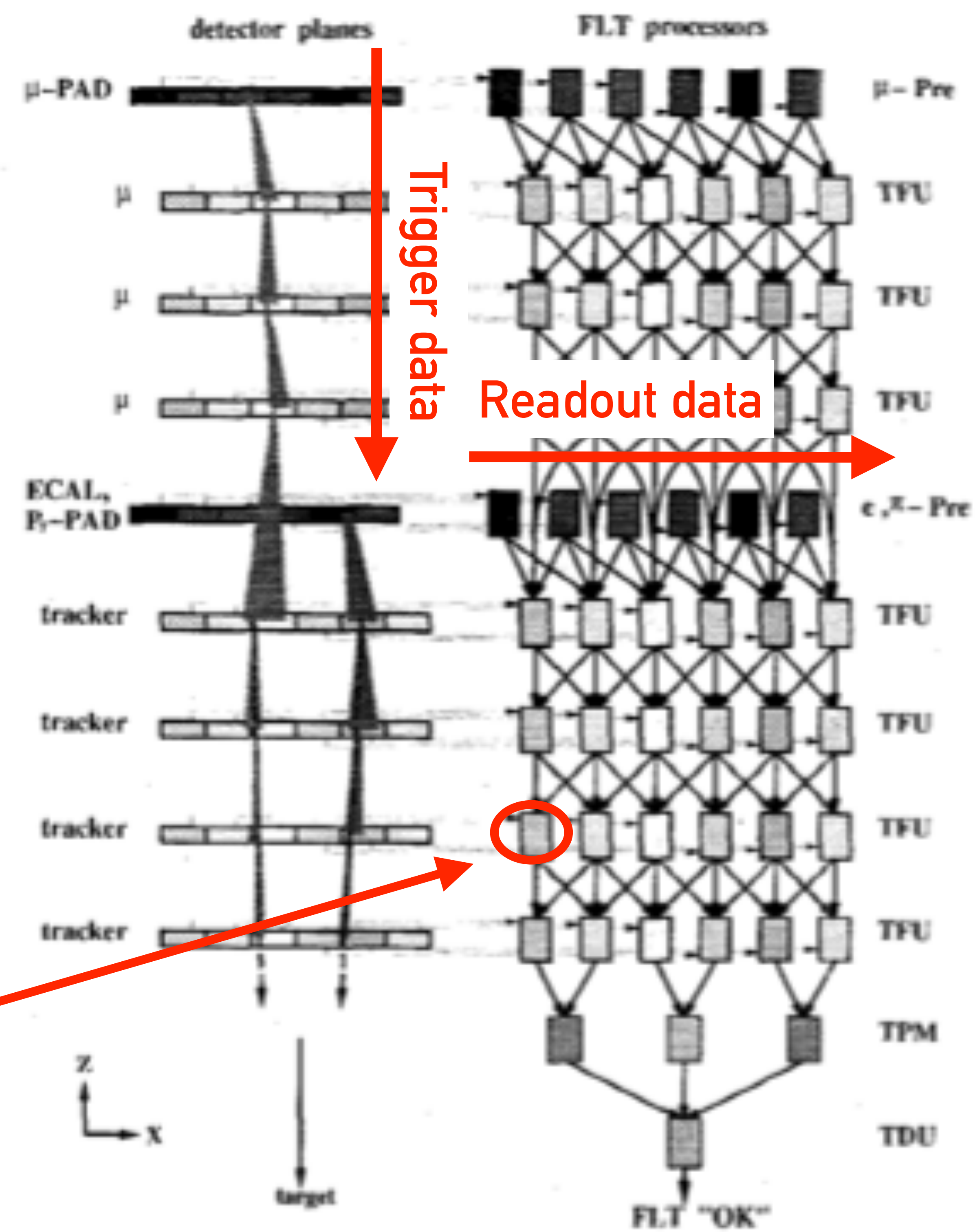
Digital inputs from detector

Input: synchronization signals

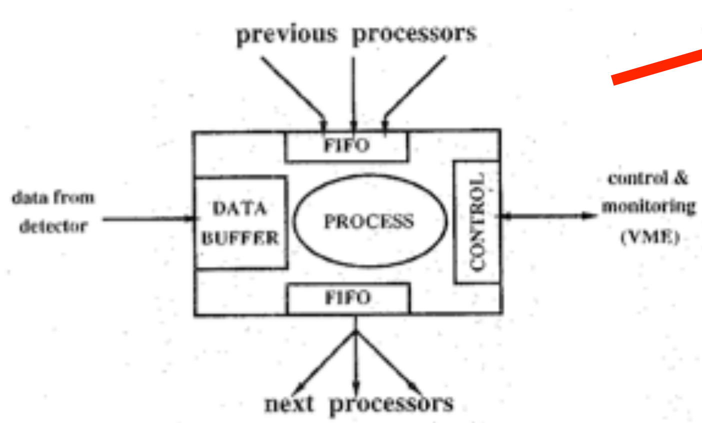
Readout part

EXAMPLE: HERA-B TRACK FINDER

- **Trigger goal: filter rare B decays out of p-nucleon interactions at 10 MHz**
  - Challenge: tracking with 7 layers < 10 µs
- **Iterative algorithm: each step processes only a Region of Interest (RoI) defined by the previous step**
  - Each unit handles only hits in a small part of the detector
- **Two data streams:**
  - **Detector data** transferred to on-board memory synchronously BC clock (left to right)
  - **RoI data** transferred asynchronously from unit to unit (top to bottom)

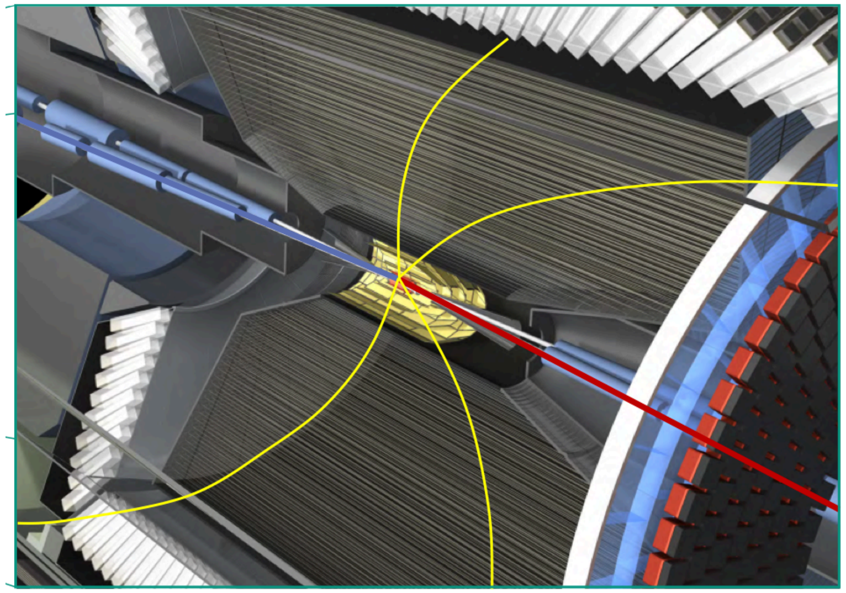


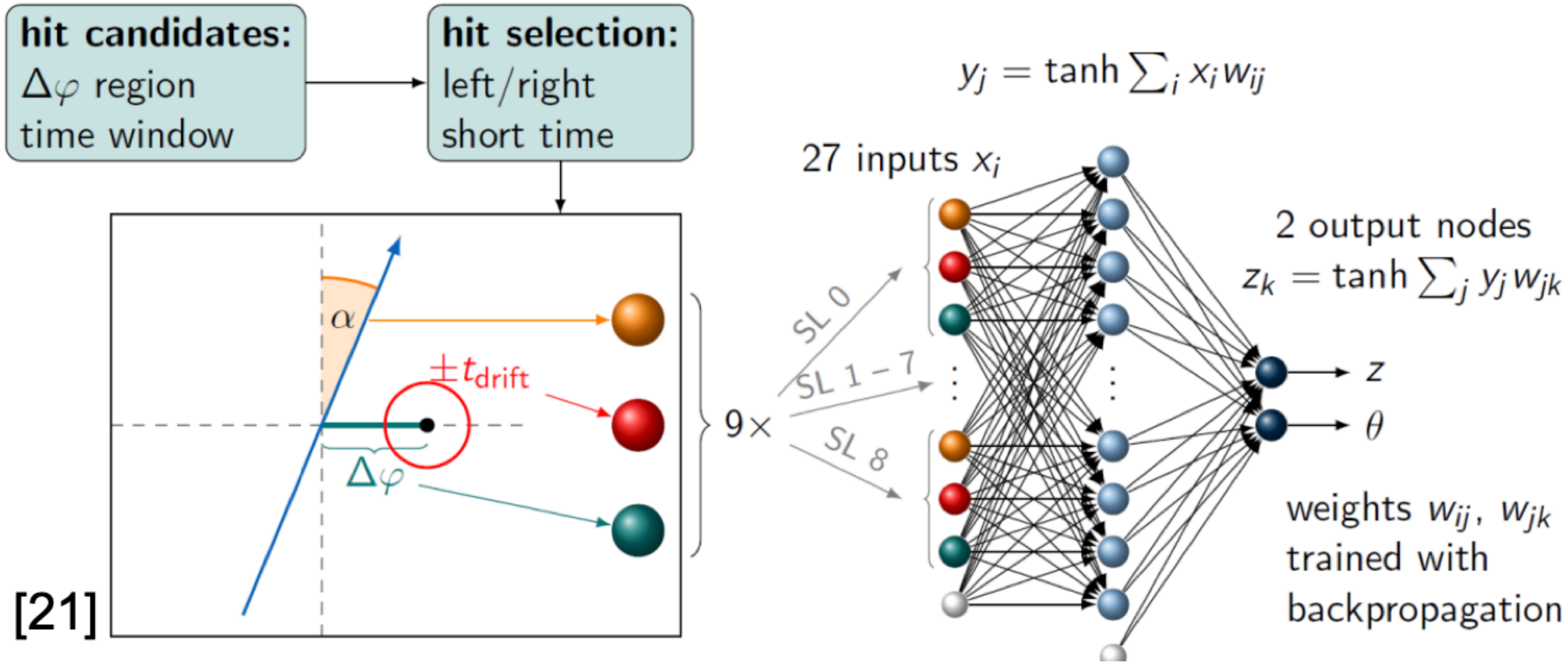
Track Finder Unit



forerunner of ATLAS RoI mechanism

NEW TRENDS: NEURAL NETWORKS ON ACCELERATORS





- **Bell-2 experiment on asymmetric e+e- collider SuperKEKB**
- **L1 z-vertex trigger (5 us L1 latency): suppress tracks outside the point of collision to reduce rate 130 -> 30 kHz**
  - reconstruct collision vertex on the z0 axis and the polar scattering angle θ for each track
  - **Multi-layer perceptron**, resulting 4.5 cm resolution
  - Estimation in 300 ns processing latency
  - 4 Virtex 6 FPGAs in parallel, one per quadrant of the drift chamber
  - running since 2020 [Ref]

OUTLINE

- ➡ trigger selectivity and robustness with examples
- ➡ how to build a trigger system from first principles
- ➡ principles and examples of L1 triggers
- ➡ **principles and examples of software triggers**

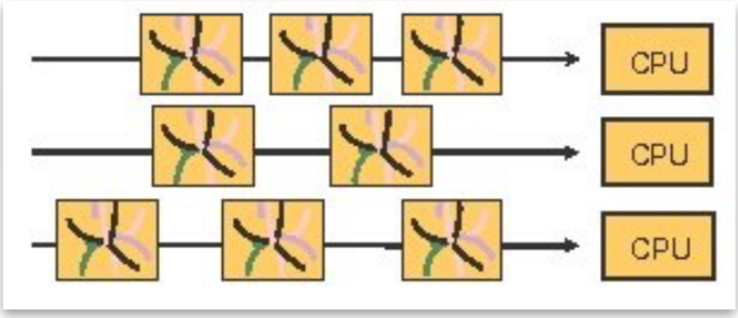
RECAP OF EVENT BUILDING AND FILTERING

	LEVELS	L1 RATE (HZ)	EVENT SIZE	READOUT BANDWIDTH
LEP	2/3	1 KHZ	100 KB	few 100 KB/S
ATLAS	2/3	100 KHZ (L2: 10 KHZ)	1.5 MB	30 GB/S
CMS	2	100 KHZ	1.5 MB	100 GB/S

cannot store on disk at this rate!

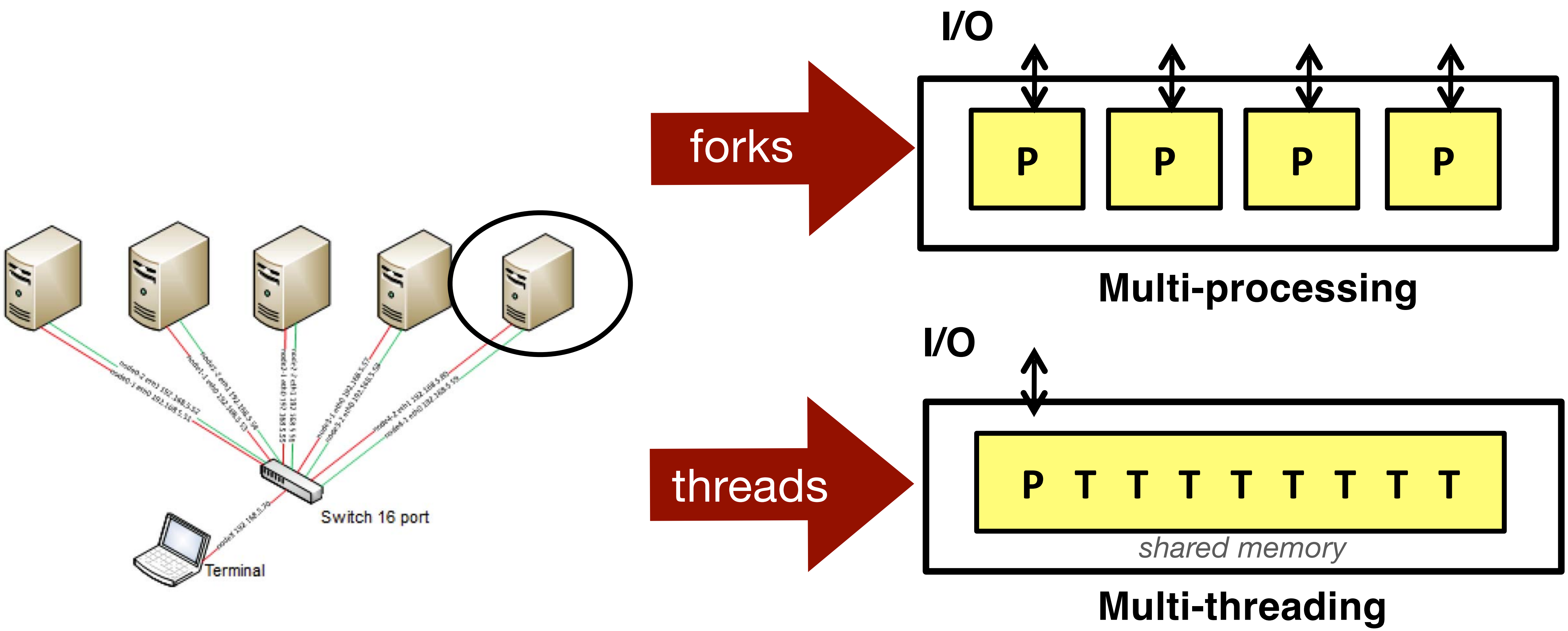
EVENT FILTER OUTPUT
~5 HZ
~1000 HZ
~1000 HZ

- **After the L1-trigger selection, data rates are reduced, but can be still massive**
  - **LEP**: 40 MB/s VME bus was able to support the bandwidth
  - **LHC**: need latest technologies in processing, high-speed network, optical data transmission
- **Event Building and Filter farms on networks**
  - farm processing: one event per processor
  - additional networks regulates the CPU assignment
  - commercial products: PCs (linux based), Ethernet protocols, standard LAN, configurable devices



ONLINE SOFTWARE: DESIGN PRINCIPLES

Increase parallelism to exploit all CPU resources (all cores!)

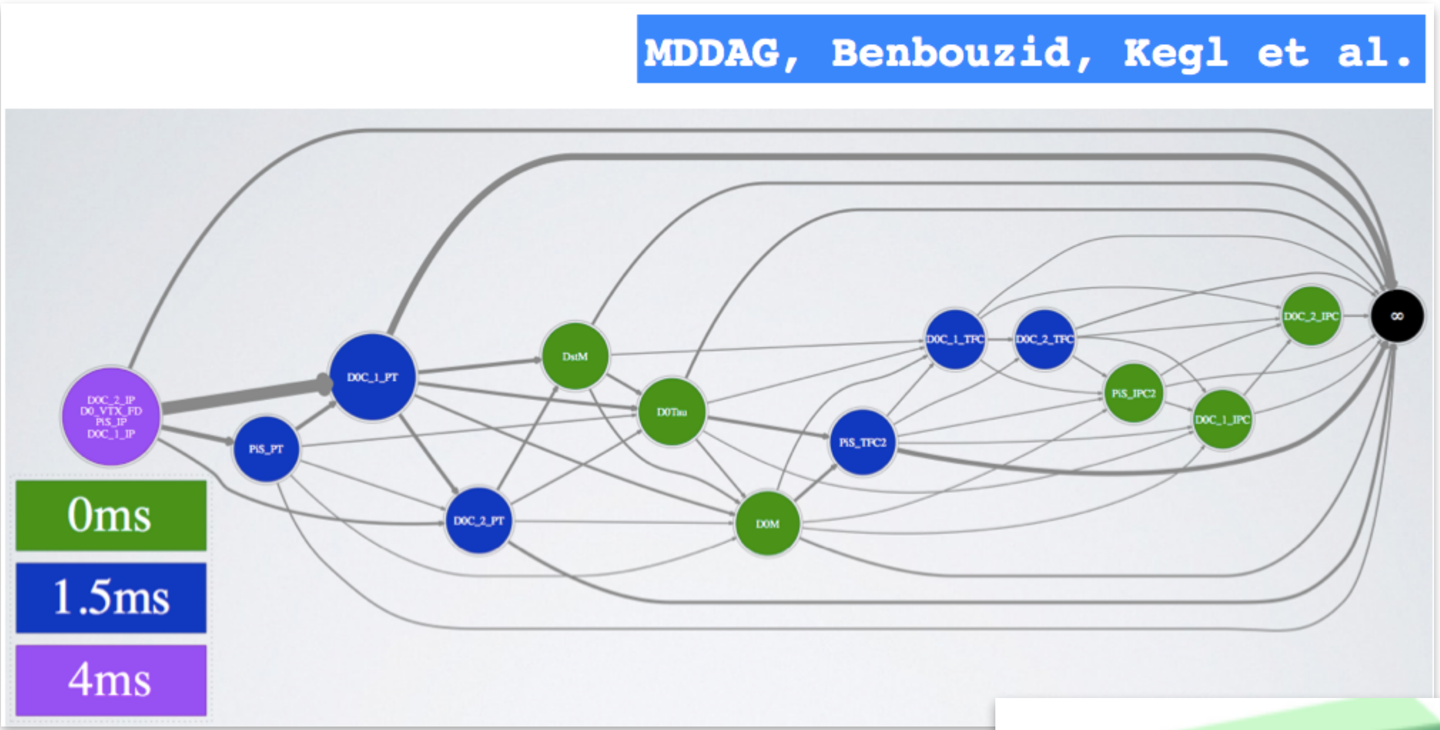


- ➡ Online software optimized for fast execution
- ➡ Early rejection: alternate feature extraction with hypothesis testing
- ➡ Partial event data processing
- ➡ Fast reconstruction: but close to offline, for easy maintenance and higher efficiency

CAN WE USE ANY ALGORITHMS ONLINE?

LATENCY IS THE CONSTRAINT!

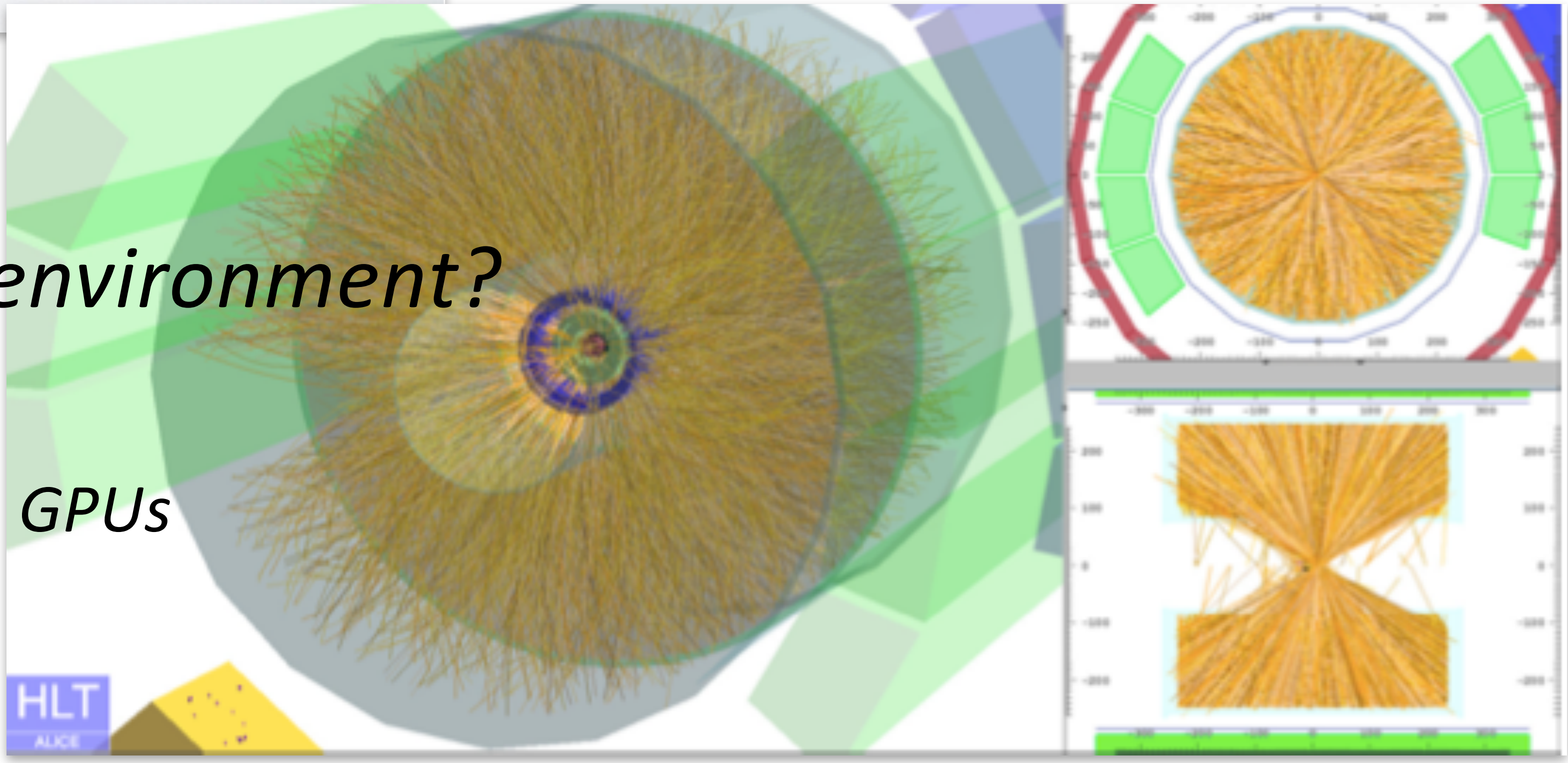
Multivariate analysis?



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

Pattern recognition in dense environment?

Yes, with the help of co-processors like GPUs



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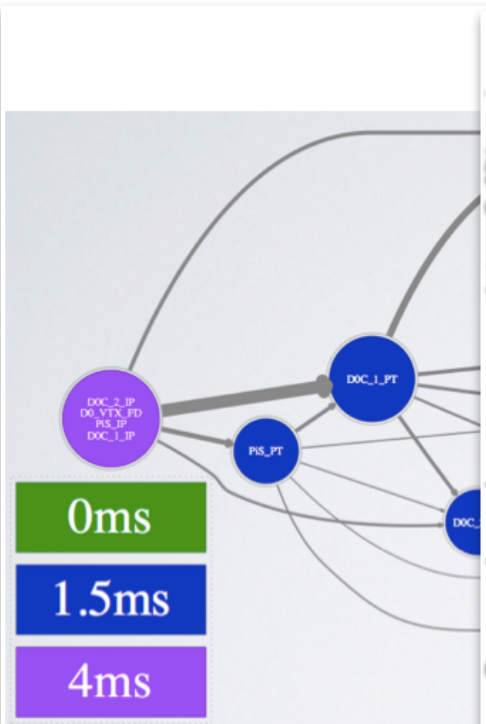

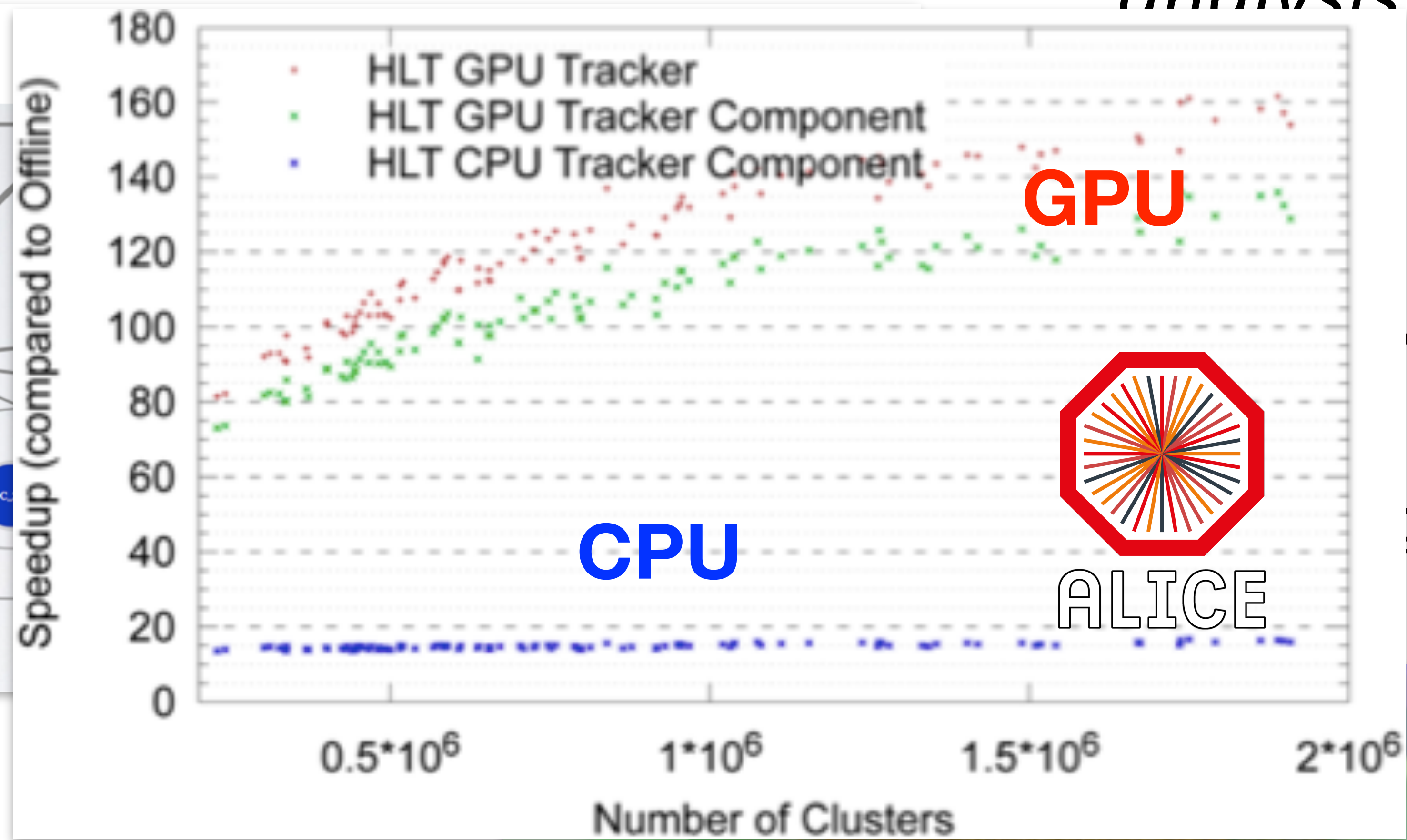

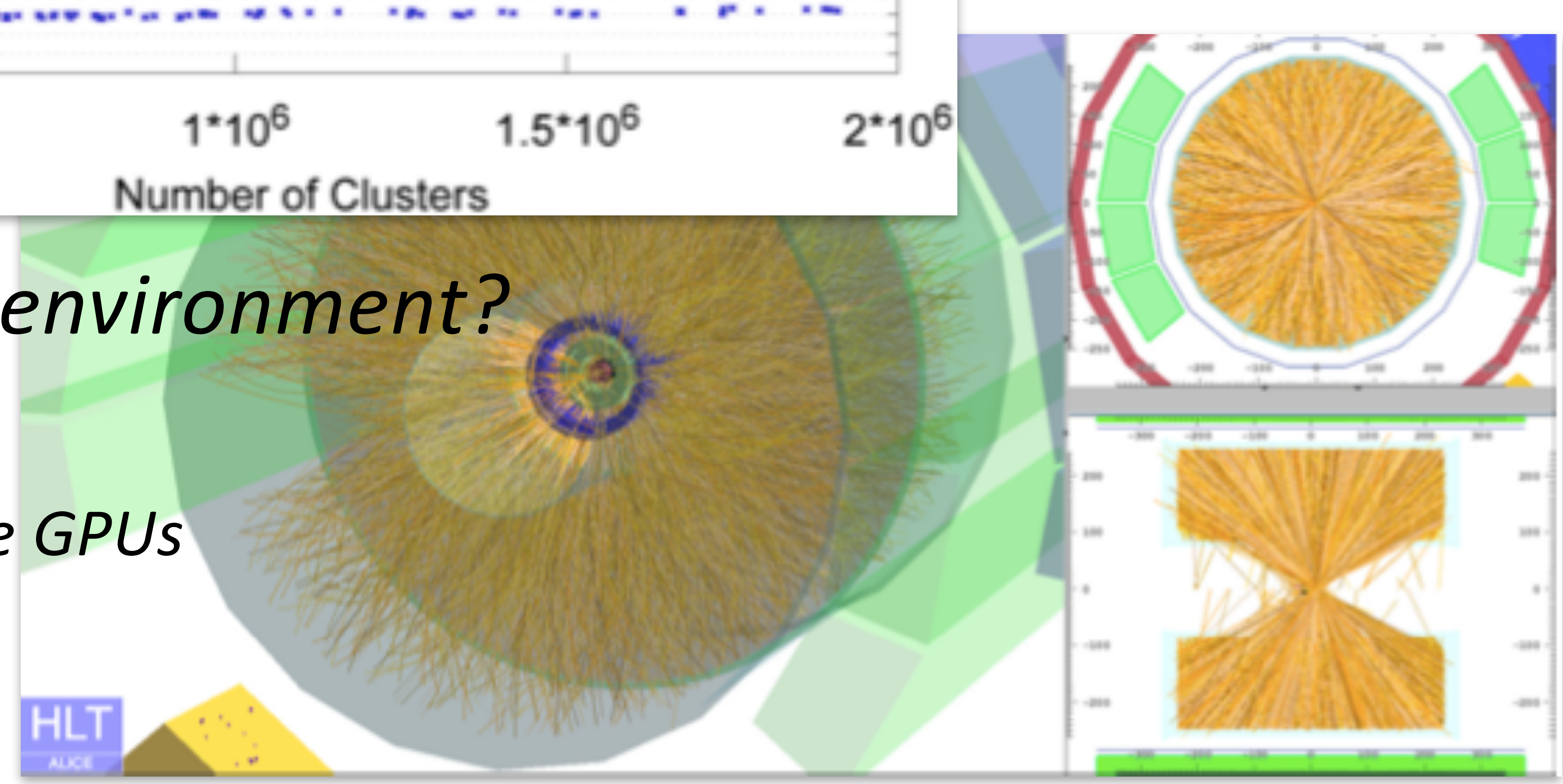

Pattern recognition in dense environment?

Yes, with the help of co-processors like GPUs

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 can be 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