Trigger and Data Acquisition (DAQ)

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Level-1 Trigger of the CMS experiment

LHC, CERN

contents

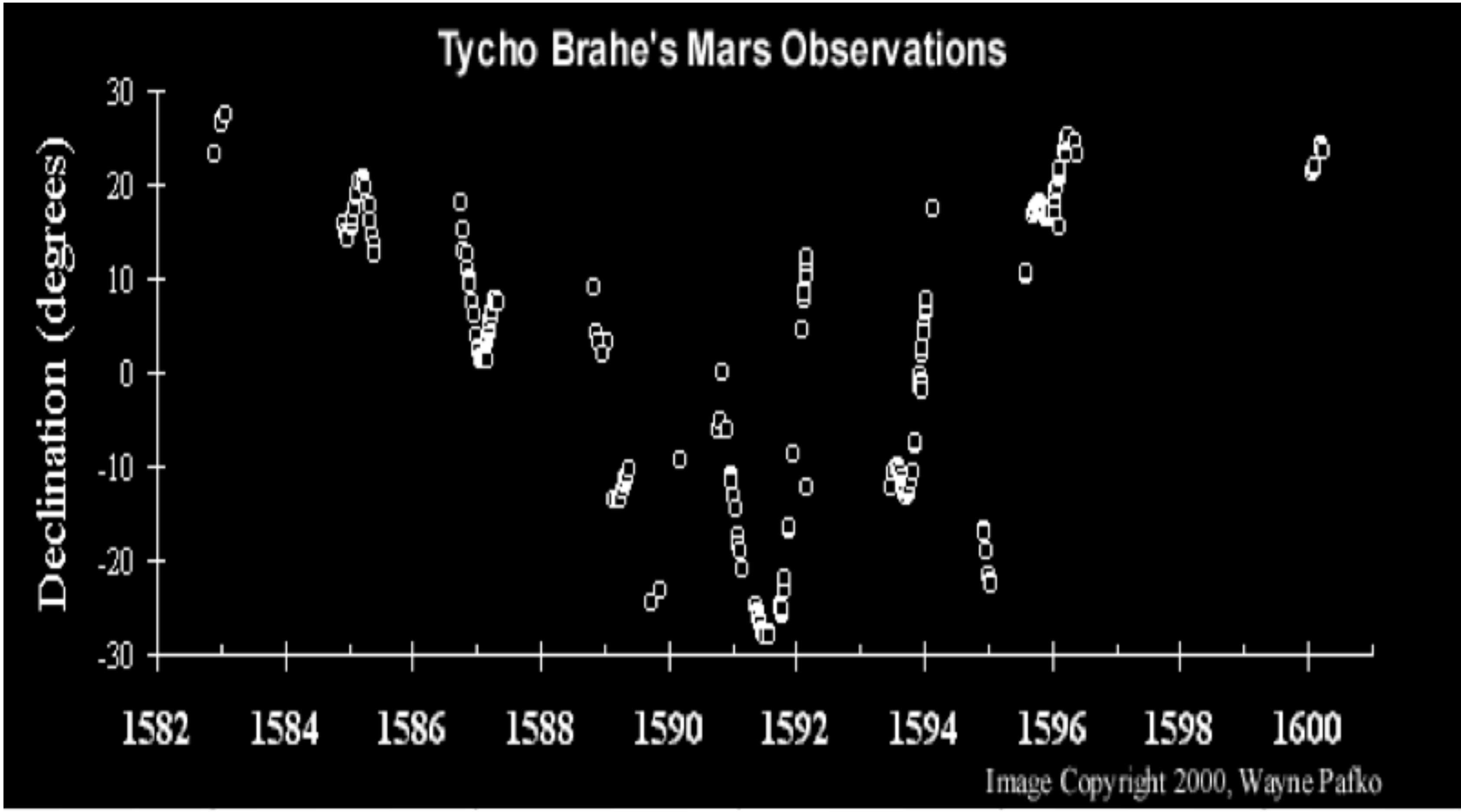
- **aiming at a general introduction**
- **obviously more examples from my own practical experience**
- **important to understand the concepts, not to memorize the details → interrupt and ask if something is not clear!**

- **you have the slides**
- **but sometimes you will try to arrive at answers to questions yourselves – don't cheat by looking at the following slides ☺!**

What is Data Acquisition?

- Old example: Tycho Brahe and the Orbit of Mars
  - "I've studied all available charts of the planets and stars and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What's needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years." *Tycho Brahe, 1563 (age 17)*
- First measurement campaign
- Systematic data acquisition
  - Controlled conditions (same time of the day and month)
  - Careful observation of boundary conditions
    - weather, light conditions
    - important for data quality, systematic uncertainties

First Systematic Data Acquisition



- data acquisition over 18 years, normally every month
- each measurement: 1 hour (with naked eye)

… in today's terminology

- bandwidth (bw): amount of data transferred per sampling time unit
  - data transfer: writing to logbook
  - about 100 bytes per hour
  - cf. LHC experiments: 100 000 000 000 bytes per second
- "trigger": when do you take your measurement?
  - once per day: rate = 1/86400 Hz
  - LHC experiments: ~ 100 000 Hz

today: most signals are electronic

- photographic emulsions and bubble chambers have largely disappeared
  - the few remaining such systems (e.g. OPERA) are usually also processed electronically
- most modern detectors yield electronic signals
  - wire (drift) chambers
  - silicon (semiconductor) devices
  - photo detectors (photomultipliers)
- *WHY ?*
- *GOOD ?*
- *BAD ?*

advantages of electronic signals

- digitize and write directly to “logbook” (data storage)
  - no human errors
  - much faster
- possible to use a trigger
  - automatic selection of events to be stored

gas detector (proportional chamber)

detector types

- today, we directly “see” in detectors only particles we know already
  - “messenger” particles
  - “new” particles are too short-lived to reach detectors

- which are these “messenger” particles?

detector types

- today, we directly “see” in detectors only particles we know already
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- which are these “messenger” particles?
  - electrons / positrons / photons
  - protons / charged pions / other charged hadrons
  - neutrons / other neutral hadrons
  - muons
  - missing (transverse) momentum

detector types

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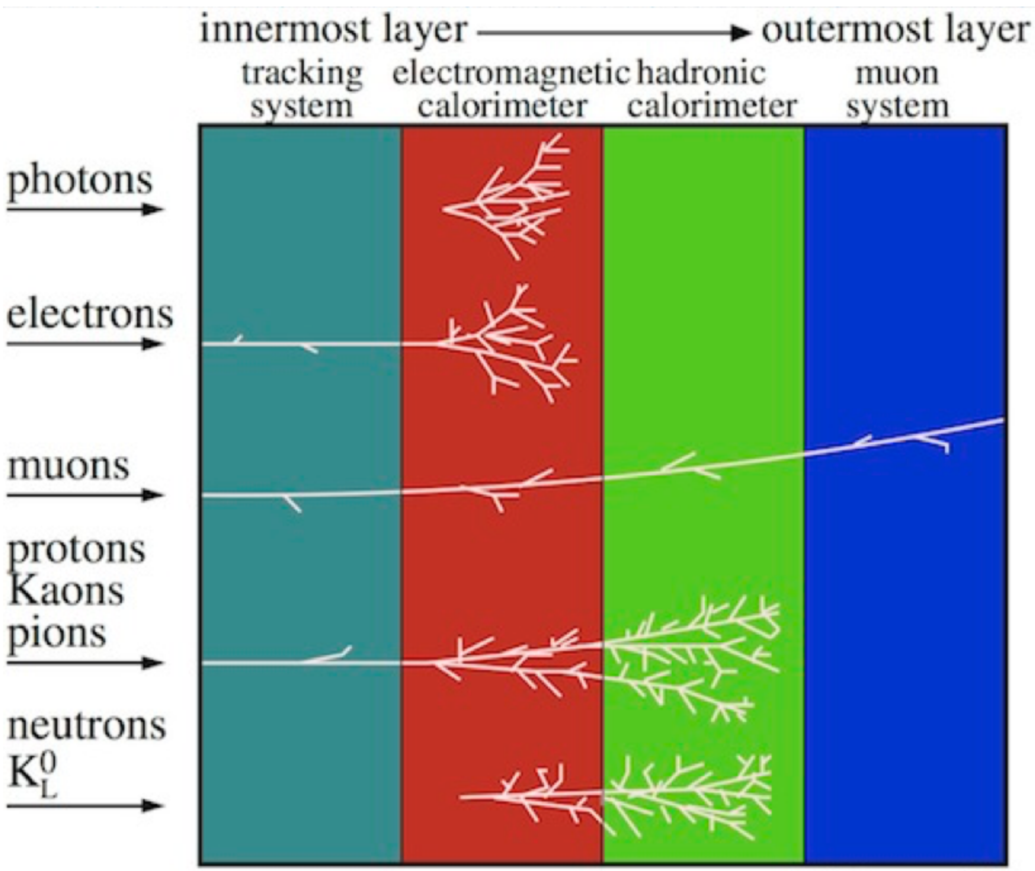
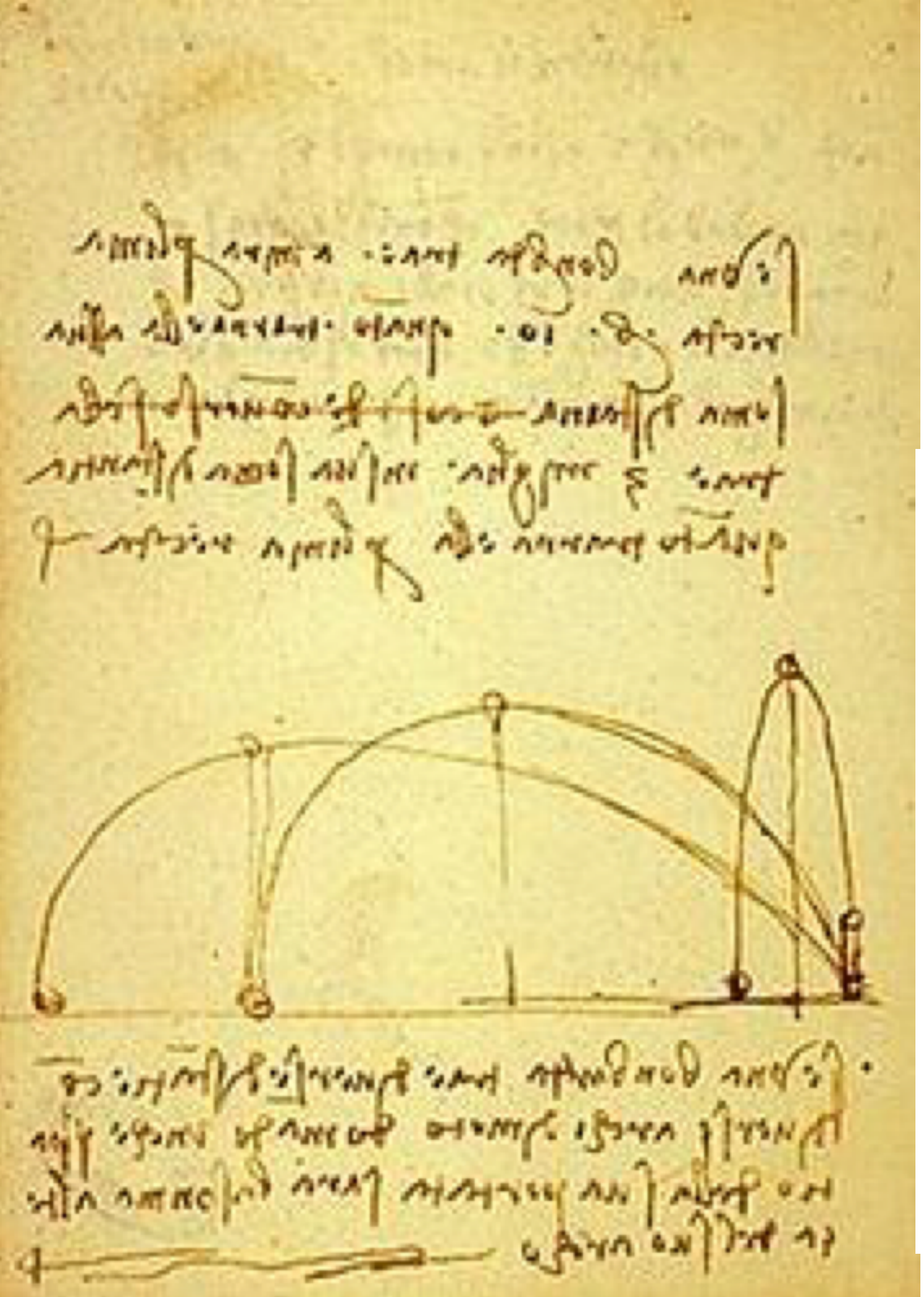


detector measurement observables

- particle presence
  - yes / no signal
  - e.g., for trigger
- position
  - for charged particles, in magnetic field: tracking → charge and momentum
- energy
  - calorimeters
  - not necessarily available from other detectors (such as ionization gas detectors, thin scintillators etc.): "minimum ionizing particles" ("MIP")
- time
  - select particles from same event
  - for slow particles: energy from time of flight ("TOF")
  - in slow detectors (gas ionization detectors): get position information from time: drift chambers, time projection chambers

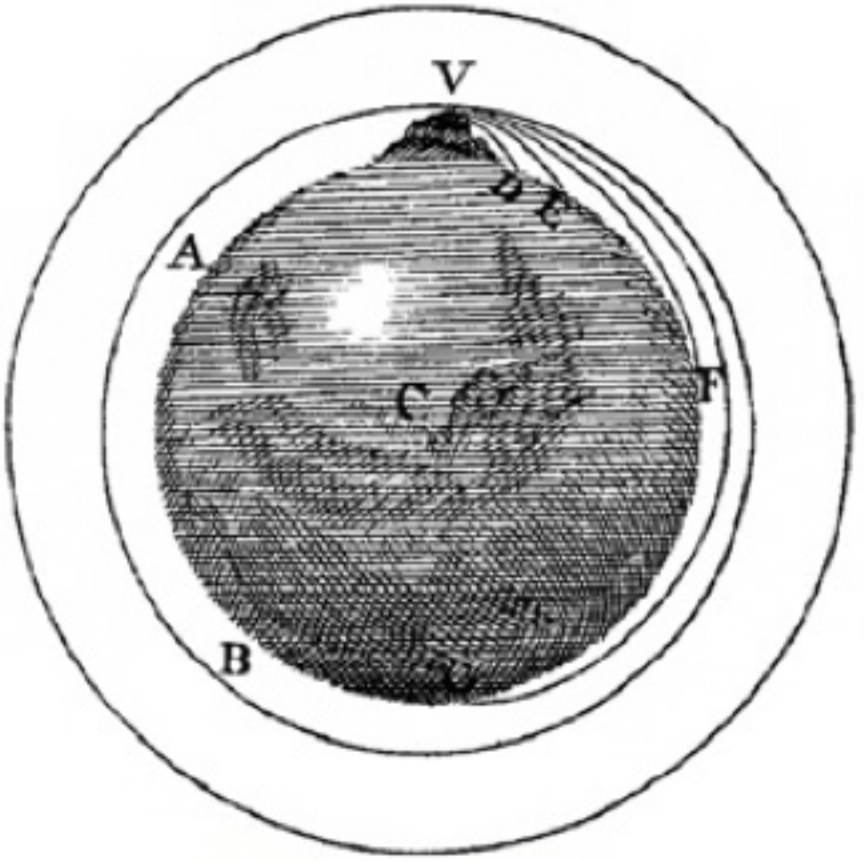
tracking

HEPHY Institute of High Energy Physics



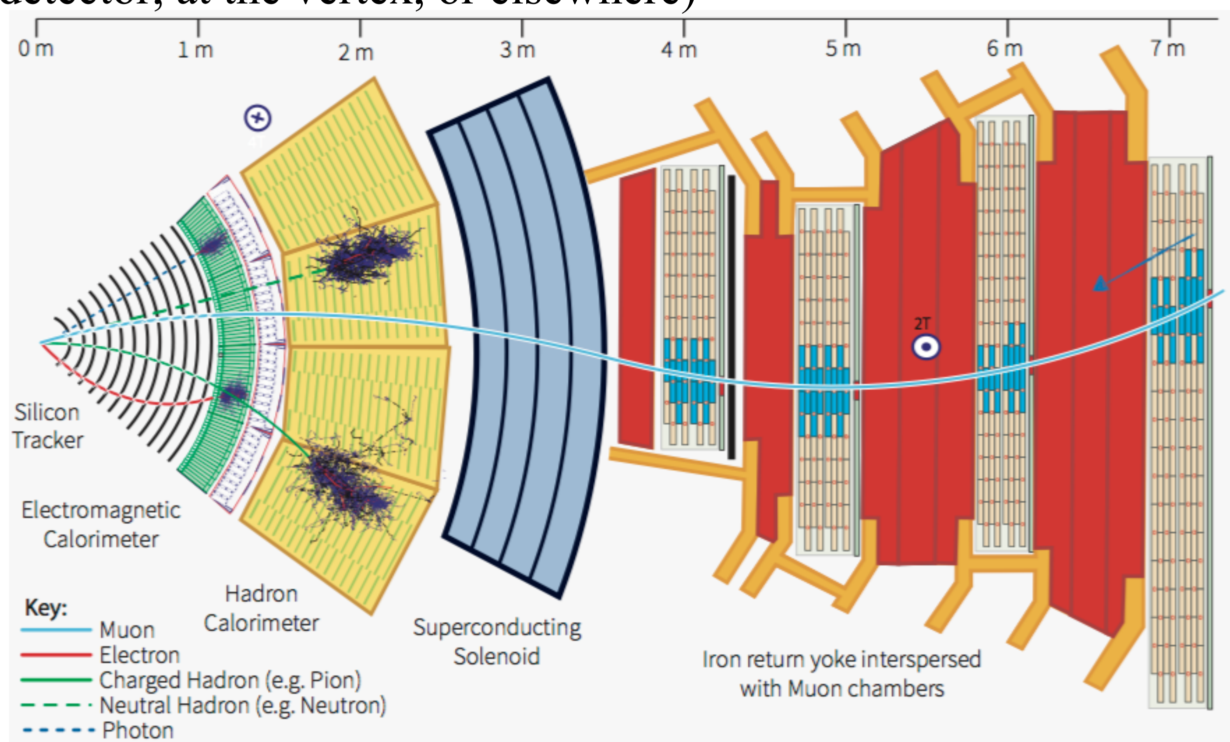
Leonardo da Vinci

Isaac Newton



tracking in data acquisition

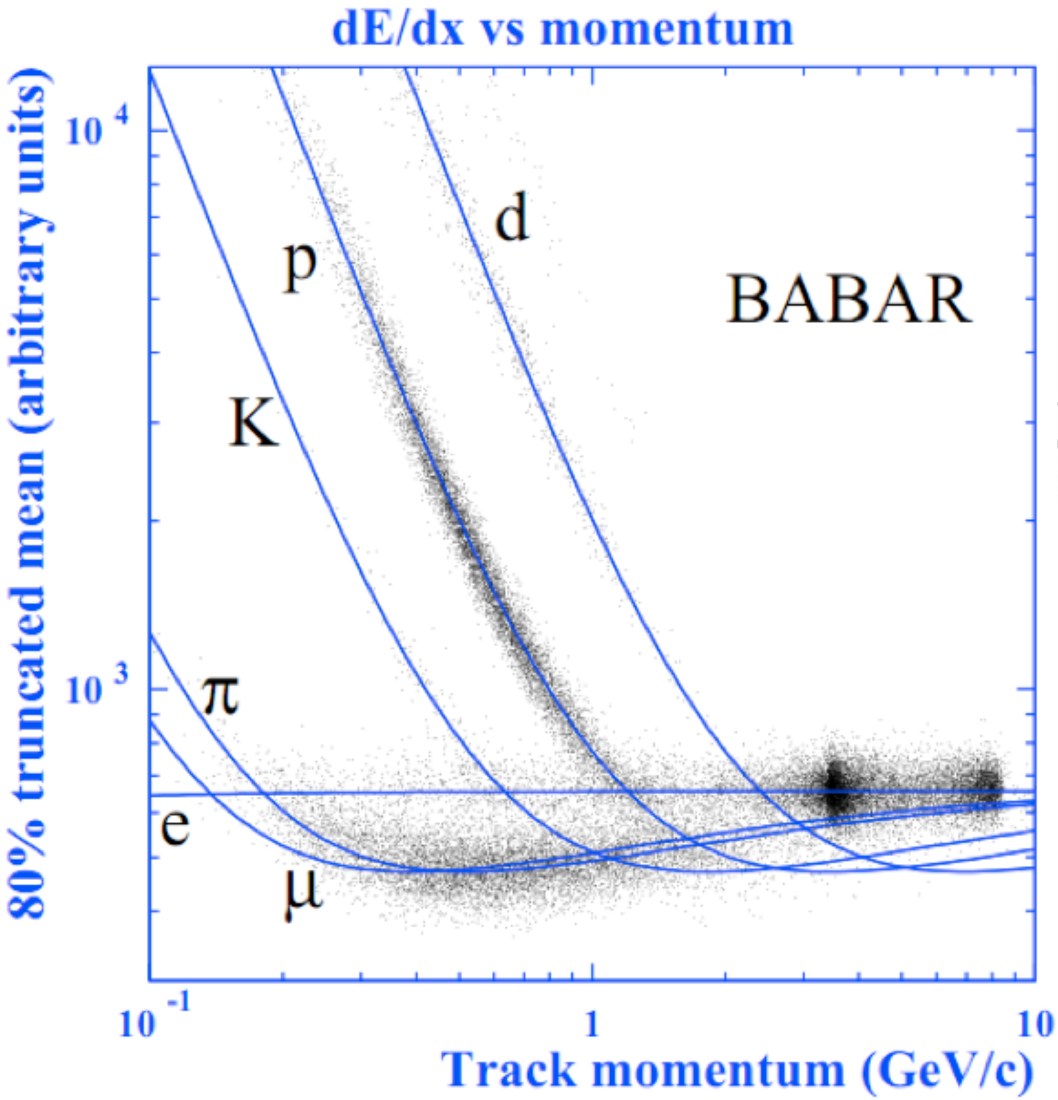
- position in magnetic field → charge and momentum
- many space point data (together with constant data of magnetic field) → one momentum vector
  - significant reduction in data volume
  - careful: with a trajectory bent in the magnetic field, it is important for which position you calculate the vector (somewhere in the tracking detector, at the vertex, or elsewhere)

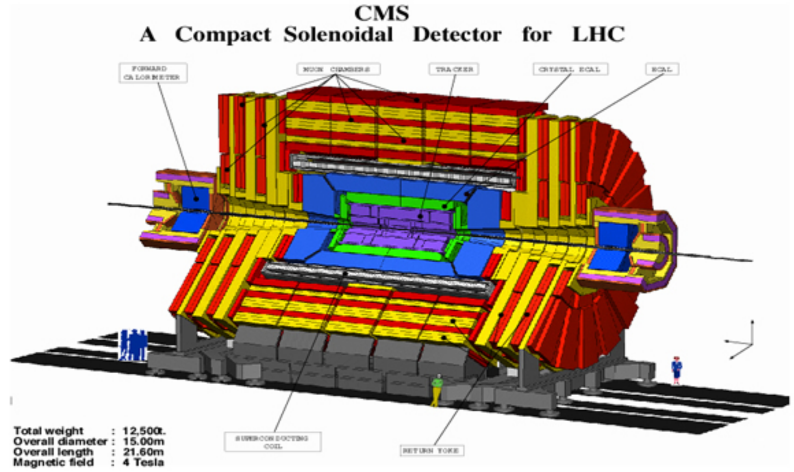


particle identification

- particles are uniquely defined by their mass
- for non-relativistic particles: measure momentum and energy → calculate mass
  - $E^2 = p^2 + m^2$
  - for relativistic particles: particle rest mass is negligible, momentum ~ energy
  - or: measure velocity (and energy) → calculate mass
  - velocity can be measured by Cherenkov detectors or Transition Radiation detectors
- another option: block all other particles
  - in particular, for muon detectors
  - all other particles blocked, muons are most penetrating (of all "visible" particles)

particle identification





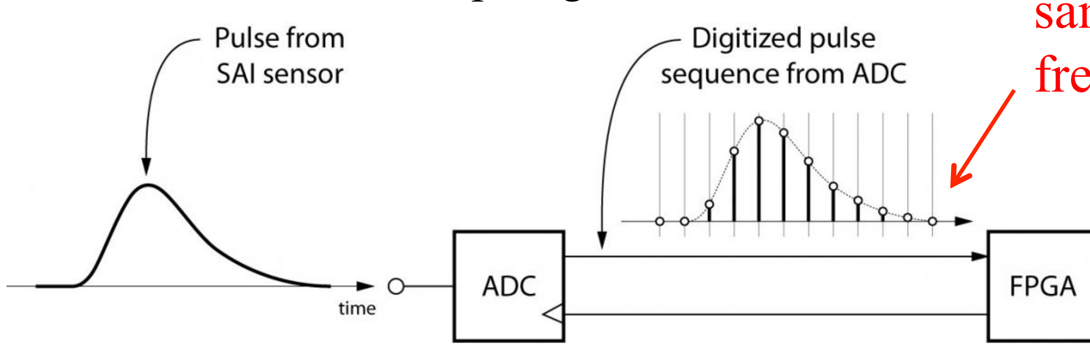
→ like momentum, particle ID can be established indirectly from other observables

digitization

- most modern particle detectors produce electrical signals → measure with a digital multimeter
  - voltage
  - current
  - resistance

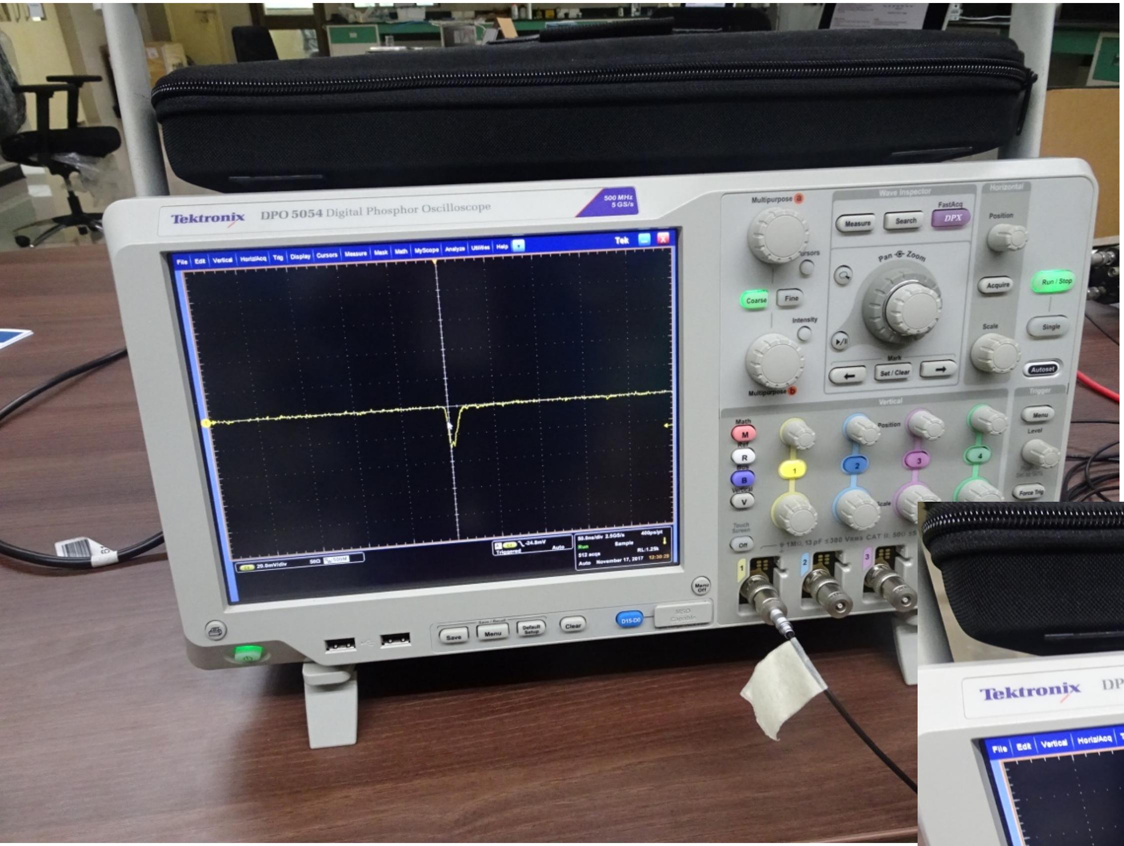
store automatically:

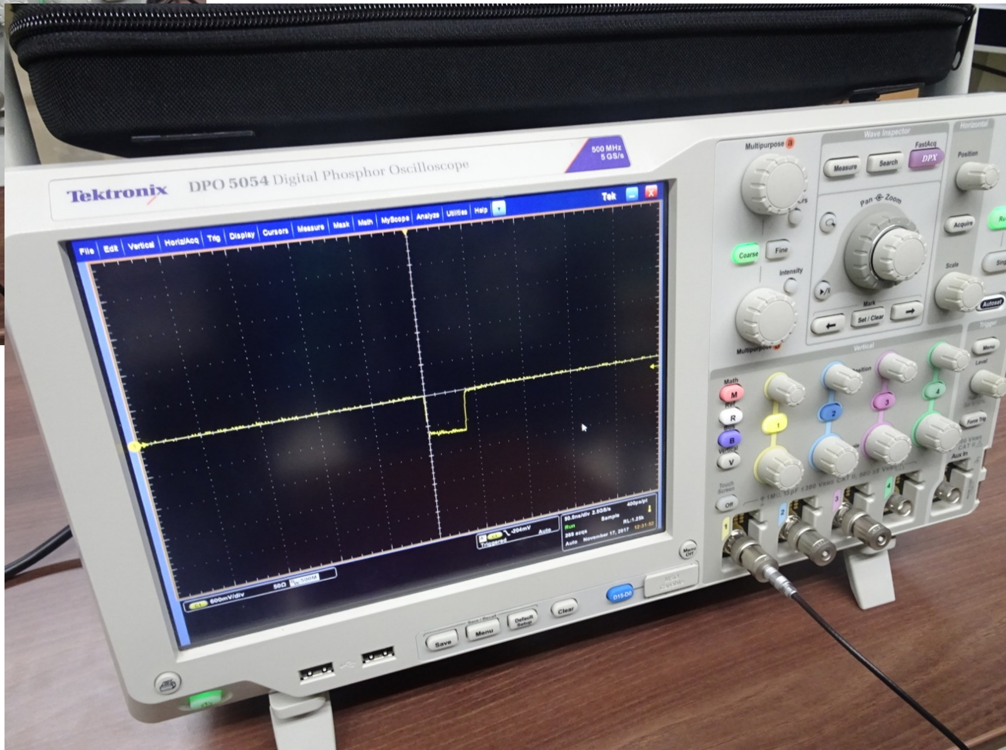
- ADC
  - analog-to-digital converter
- TDC
  - time-to-digital converter
  - measure delay between “start” and “stop” signal
- FADC
  - flash ADC



sampling frequency

digitization





digital raw data

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color coding

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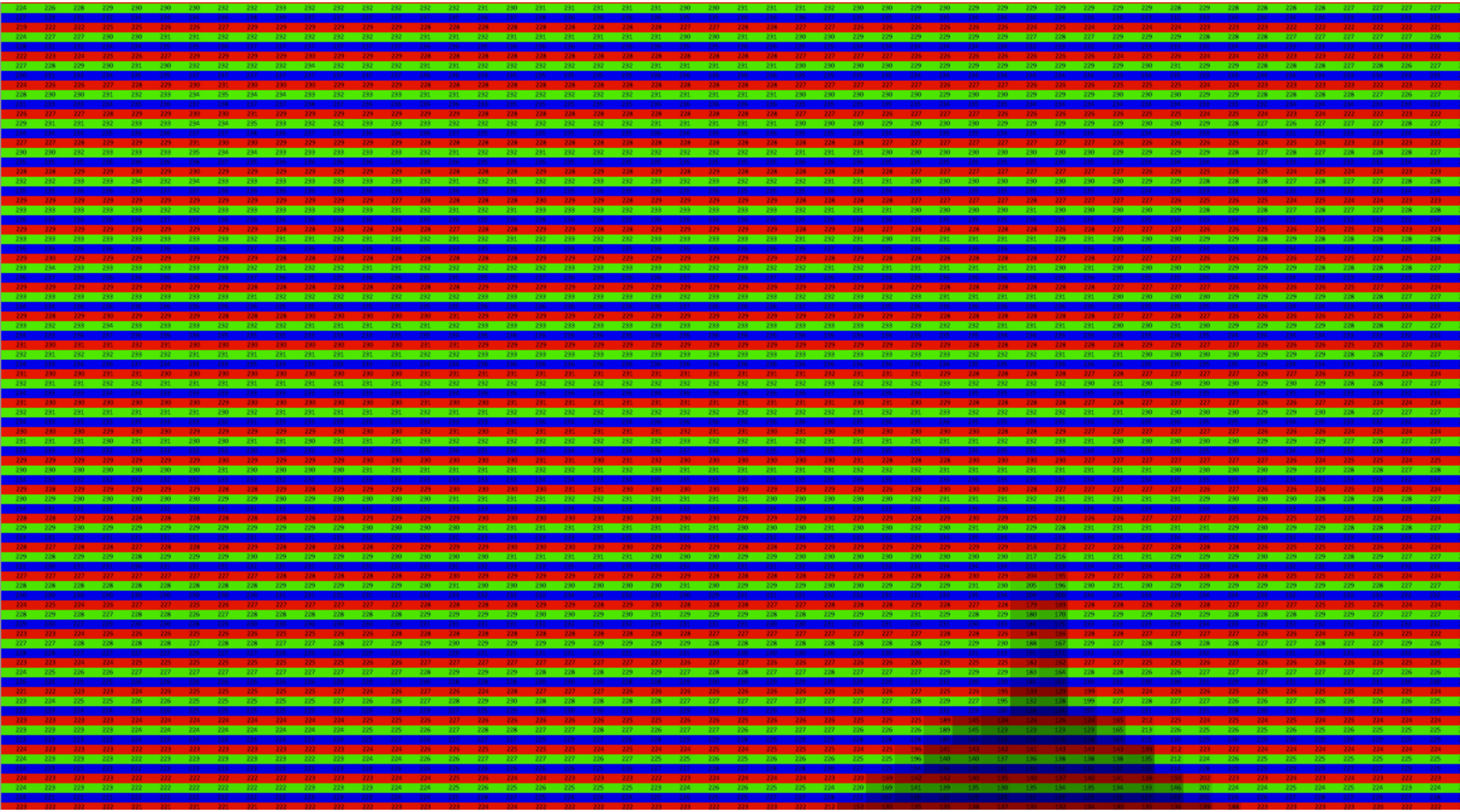
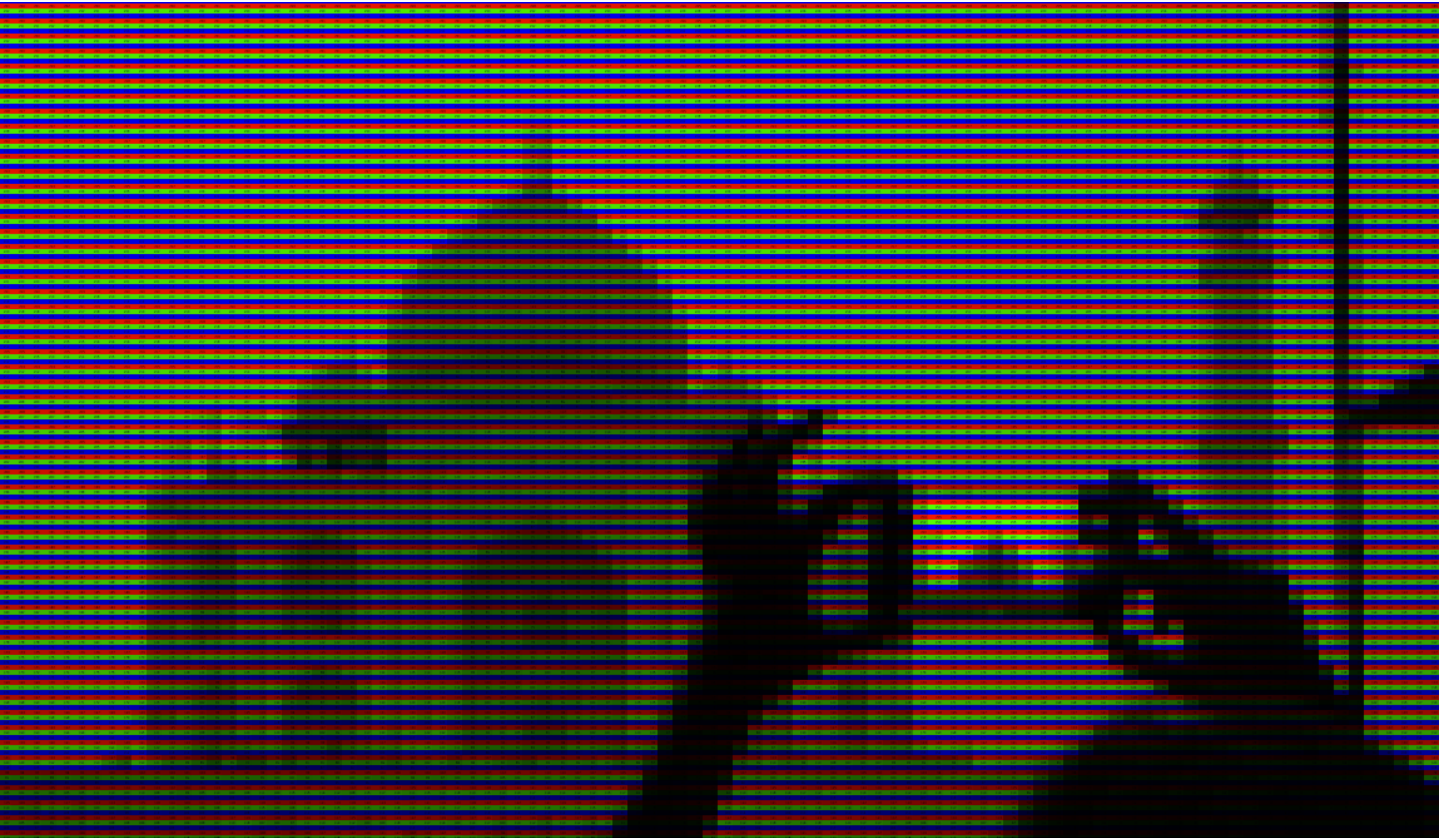
zoom out ...



aha!

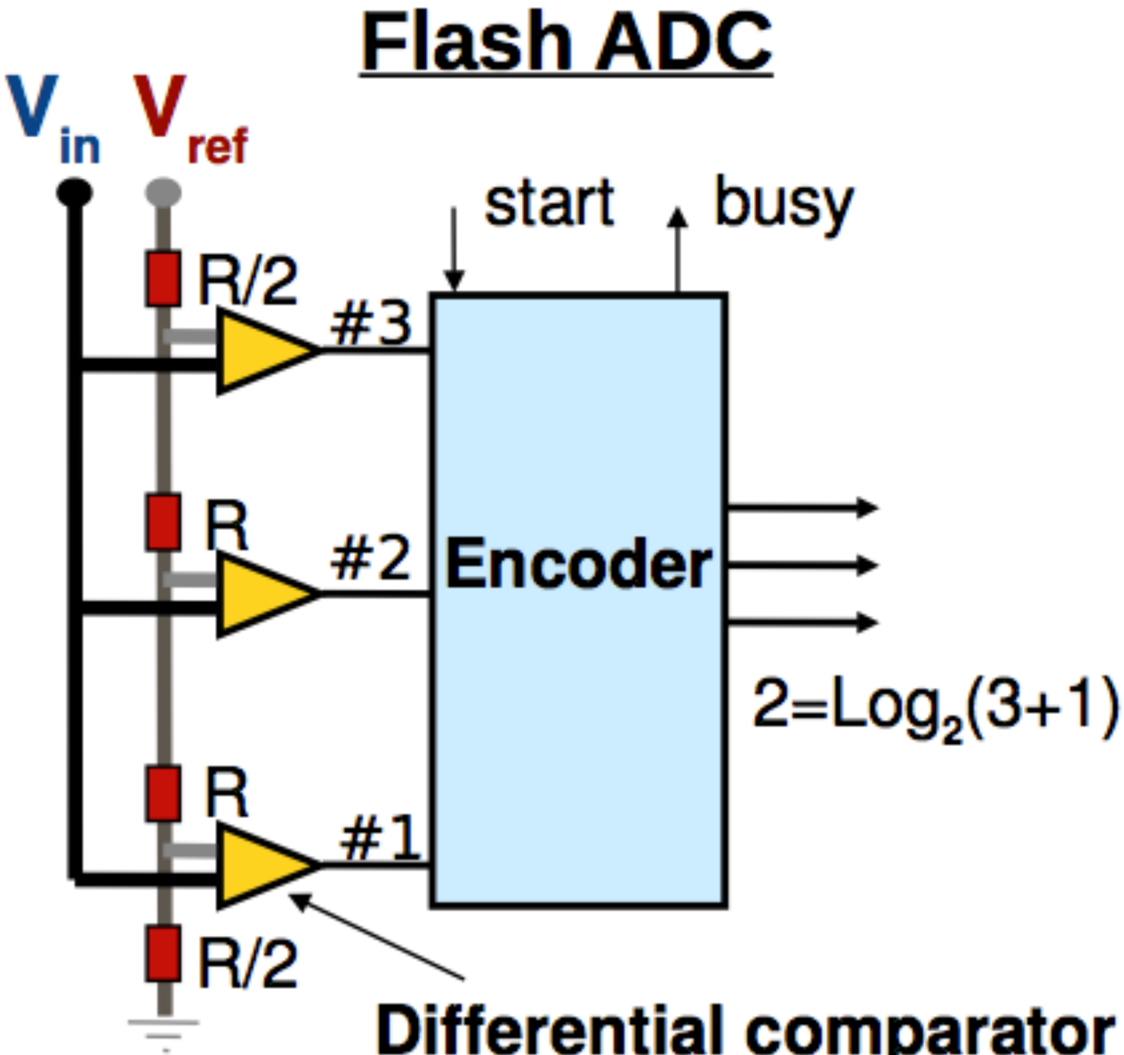


credits

- Matt Parker

- youtube/standupmaths
- matt@think-maths.co.uk
- http://www.think-maths.co.uk/spreadsheet

flash ADC implementation

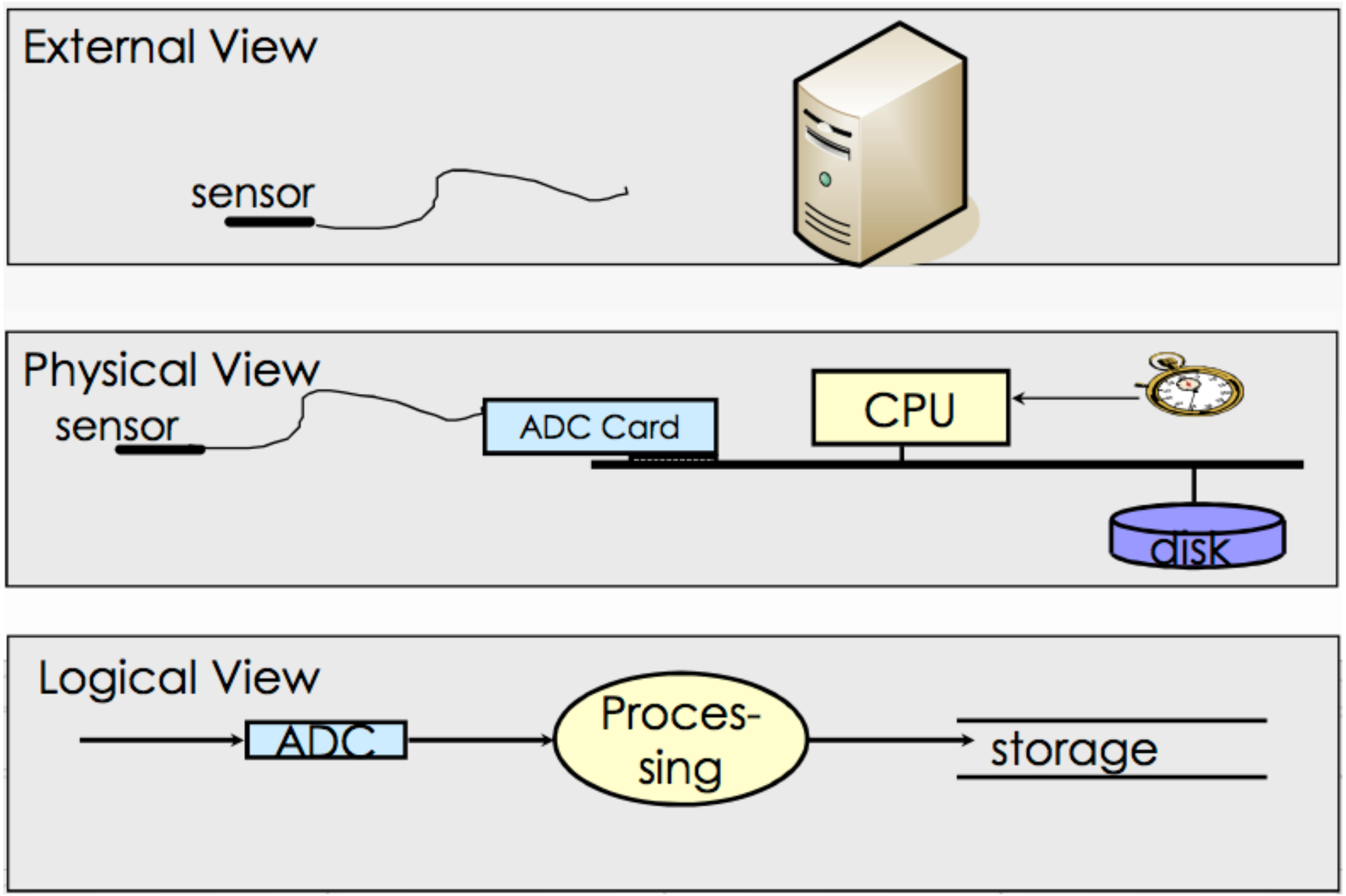


ADC characteristics

- sampling rate
- resolution
  - number of bits (N)

- LSB: “least significant bit”
  - measurement unit
  - LSB = Vmax / N
- dynamic range: ratio largest/smallest value
  - N for linear ADC
  - >N for non-linear ADC

simple DAQ system



readout chain (for one channel)

- preamplifier
- discriminator
- analog buffer
- **ADC (digitization)**
- zero suppression
- digital buffer
- multiplexer
- network
- **storage**

Trigger

trig•ger | ˈtrigər |

noun

a small device that releases a spring or catch and so sets off a mechanism, esp. in order to fire a gun: *he pulled the trigger of the shotgun.*

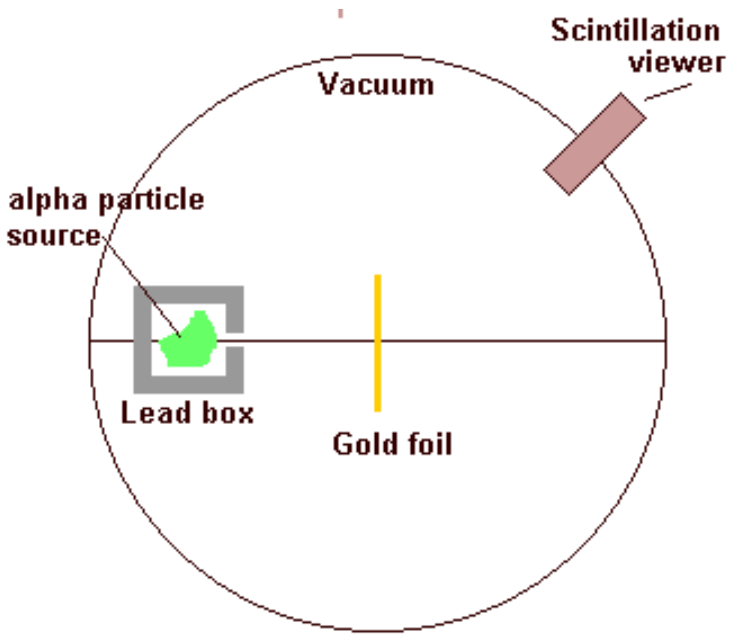
• an event or thing that causes something to happen: *the trigger for the strike was the closure of a mine.*

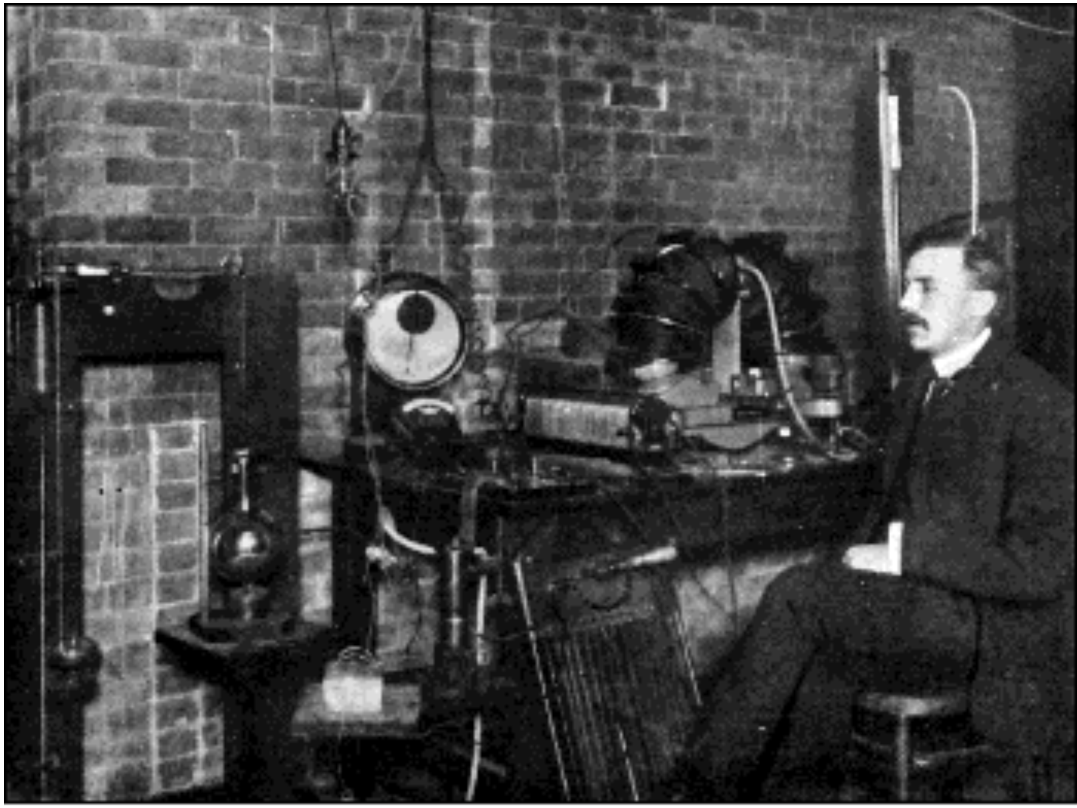
Wikipedia: “**A trigger is a system that uses simple criteria to rapidly decide which events in a particle detector to keep when only a small fraction of the total can be recorded. “**

trigger: features

- simple
- rapid
- selective
- needed when only a small fraction can be recorded

- first particle physics experiments needed no trigger
- were looking for most frequent events
- physicists observed all events



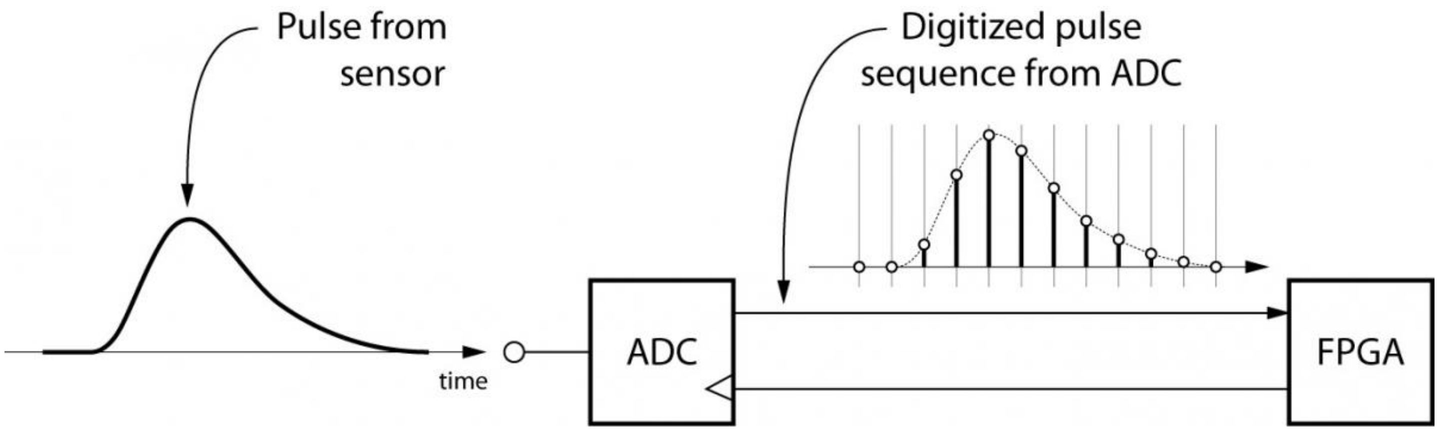


Ernest Rutherford with Gold Foil Experiment

- later physicists started to look for rare events
  - "frequent" events were known already
- searching "good" events among thousands of "background" events was partly done by auxiliary staff
  - "scanning girls" for bubble chamber photographs

periodic trigger - look all the time

- digitize at constant intervals
  - at each “clock cycle”
  - you might also say: “no trigger”, or “untriggered readout”



- select data afterwards
  - from digital information

- all you need ... or not?

periodic trigger - look all the time

- digitize at constant intervals
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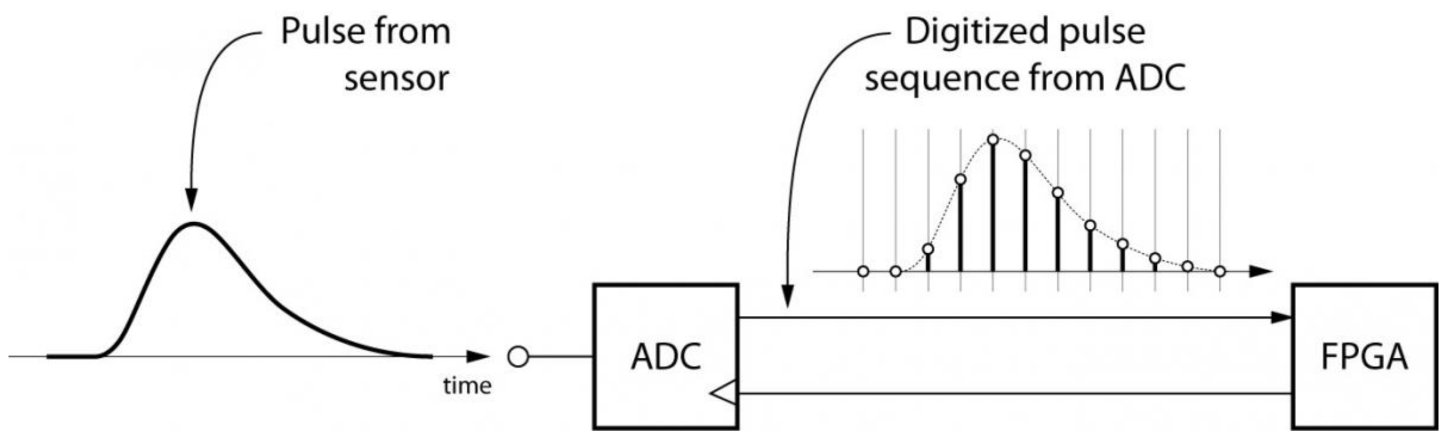
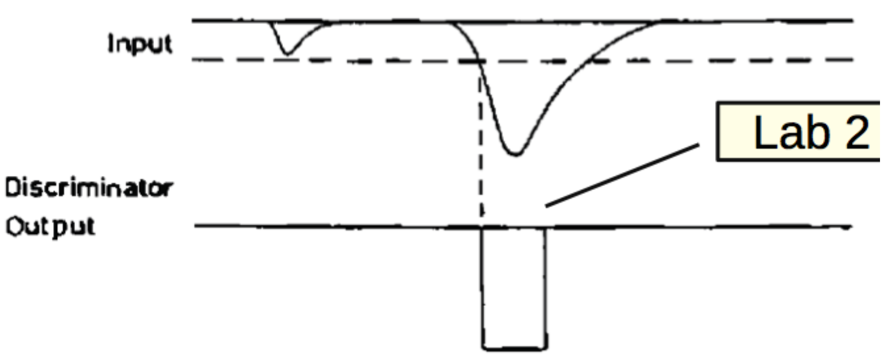


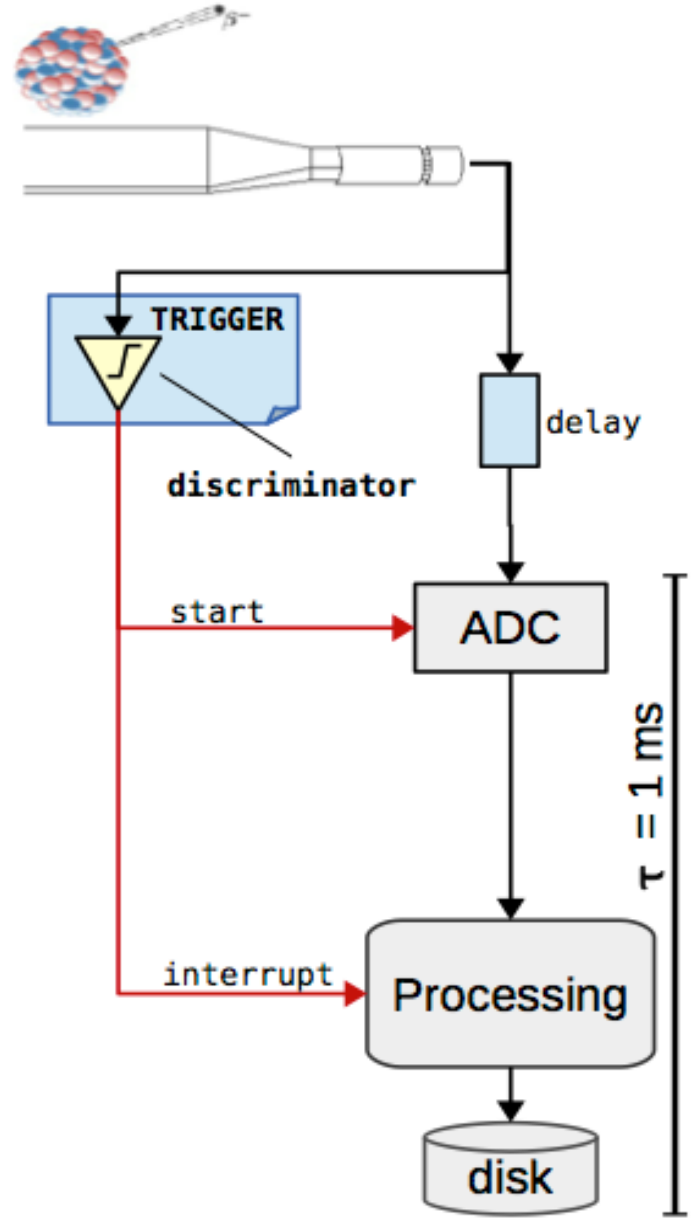
- may be not very efficient
  - needs fast "flash" ADC
  - big data volume to handle
  - mostly zeroes → have to remove using "zero suppression mechanism"
- e.g. digitization interval $\tau = 1$ ms → readout rate = 1 kHz

trigger: "tell me when to read out"!

- events often arrive in asynchronous and unpredictable way
  - e.g. radioactive decay
- "trigger" needed to know when to digitize
  - **discriminator** generates an output signal only if amplitude of input pulse is greater than a certain threshold



  - ADC: analog-to-digital converter



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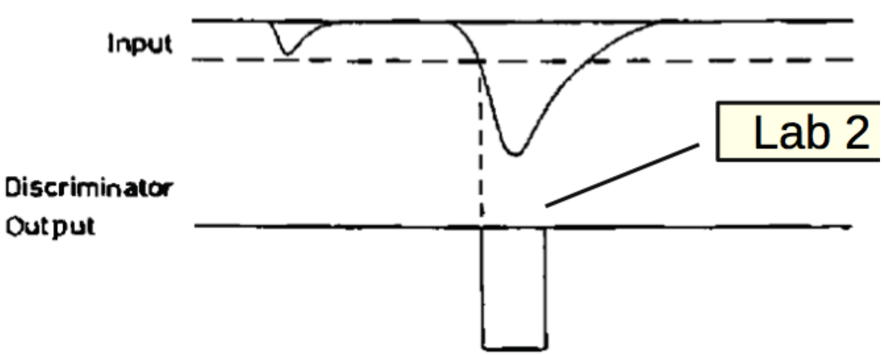
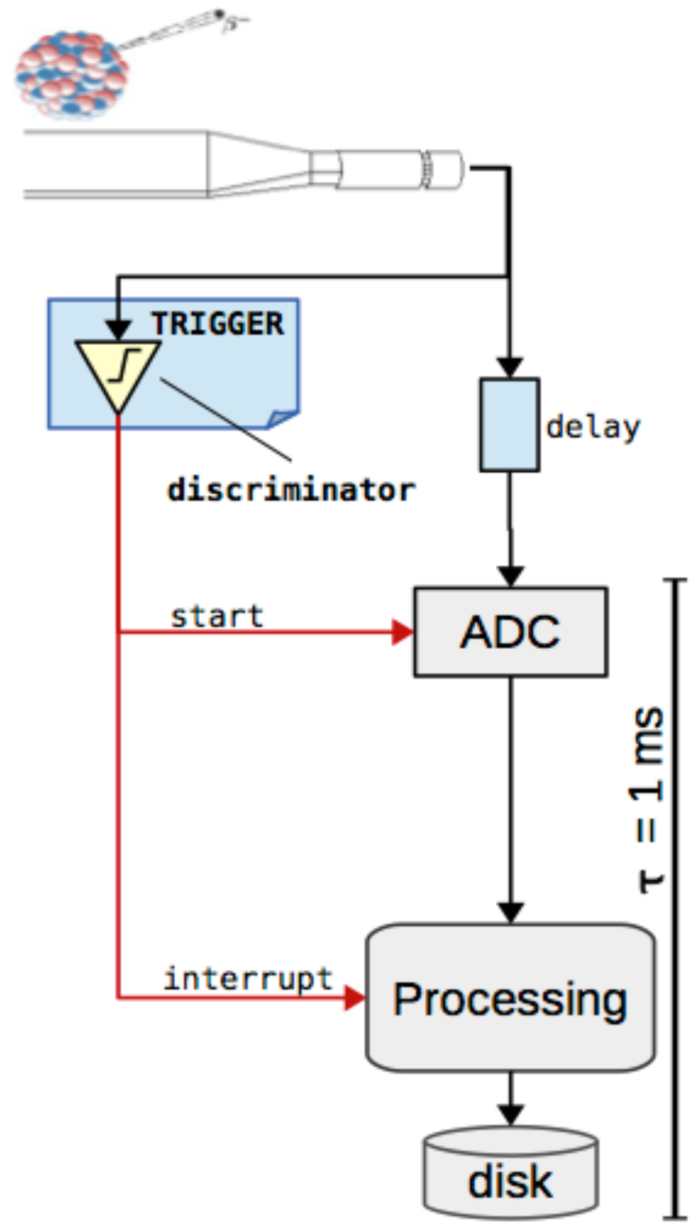
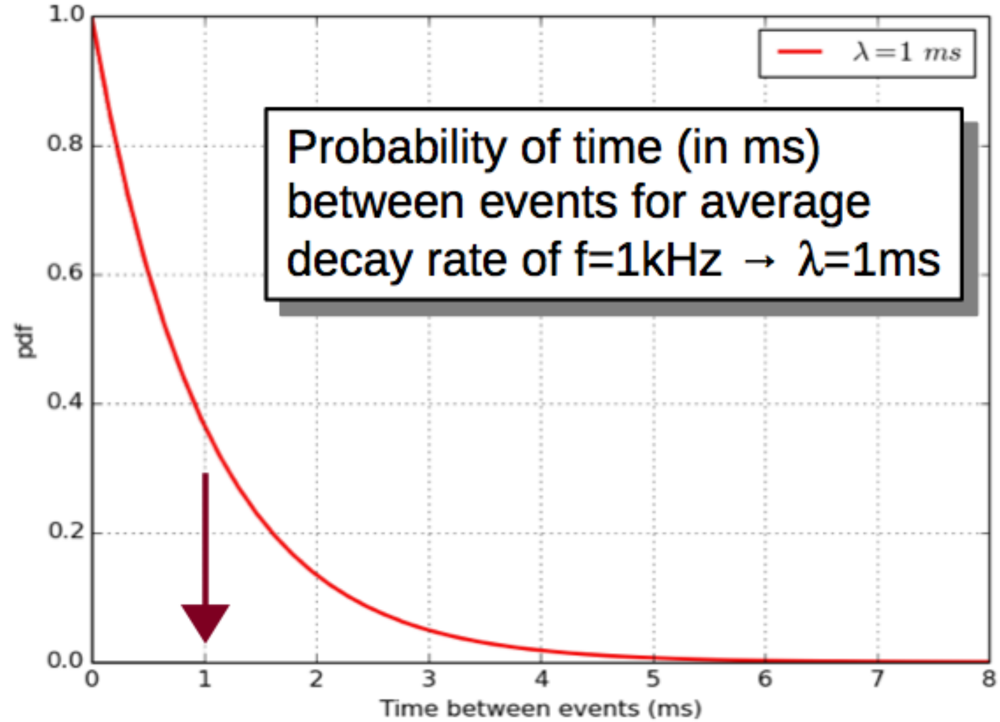




- *much cleverer – isn't it?*

using a trigger - what may happen?

- events arriving in random way:
- waiting time: exponential
- mean rate: 1 kHz
  - 1 event per millisecond on average
  - → average time between events: 1 ms
  - → we have to process one event per ms, on average

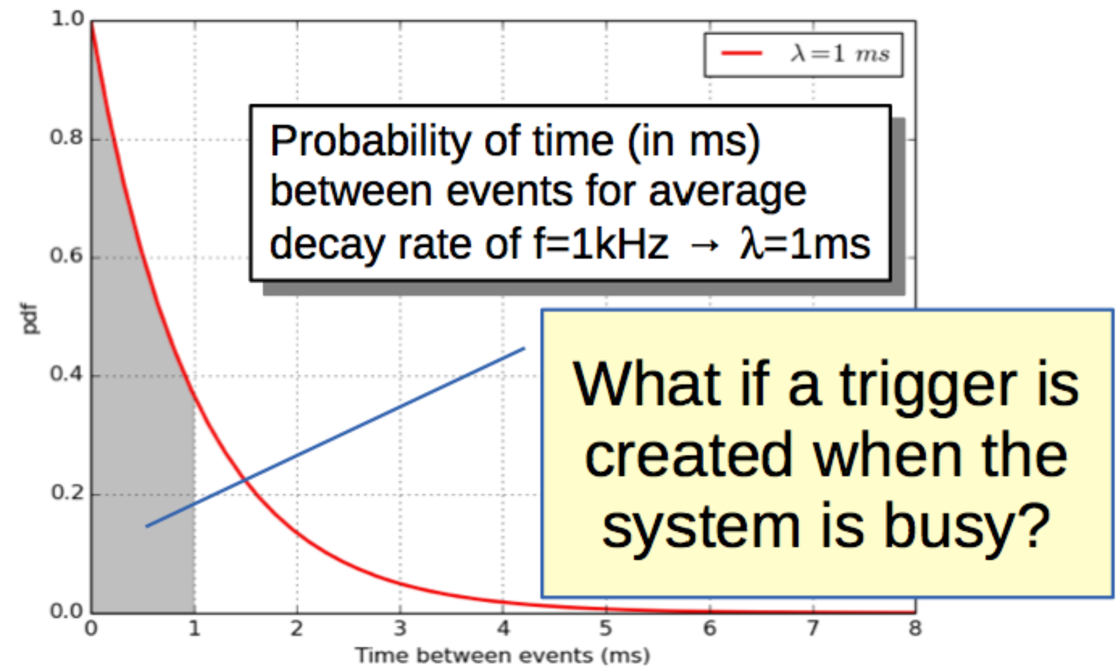


- but waiting time can be much longer or shorter!

→ *can this be a problem?*

using a trigger - what may happen?

- events arriving in random way:
- waiting time: exponential
- mean rate: 1 kHz
  - 1 event per millisecond on average
  - → average time between events: 1 ms
  - → we have to process one event per ms, on average
- but waiting time can be much longer or shorter!

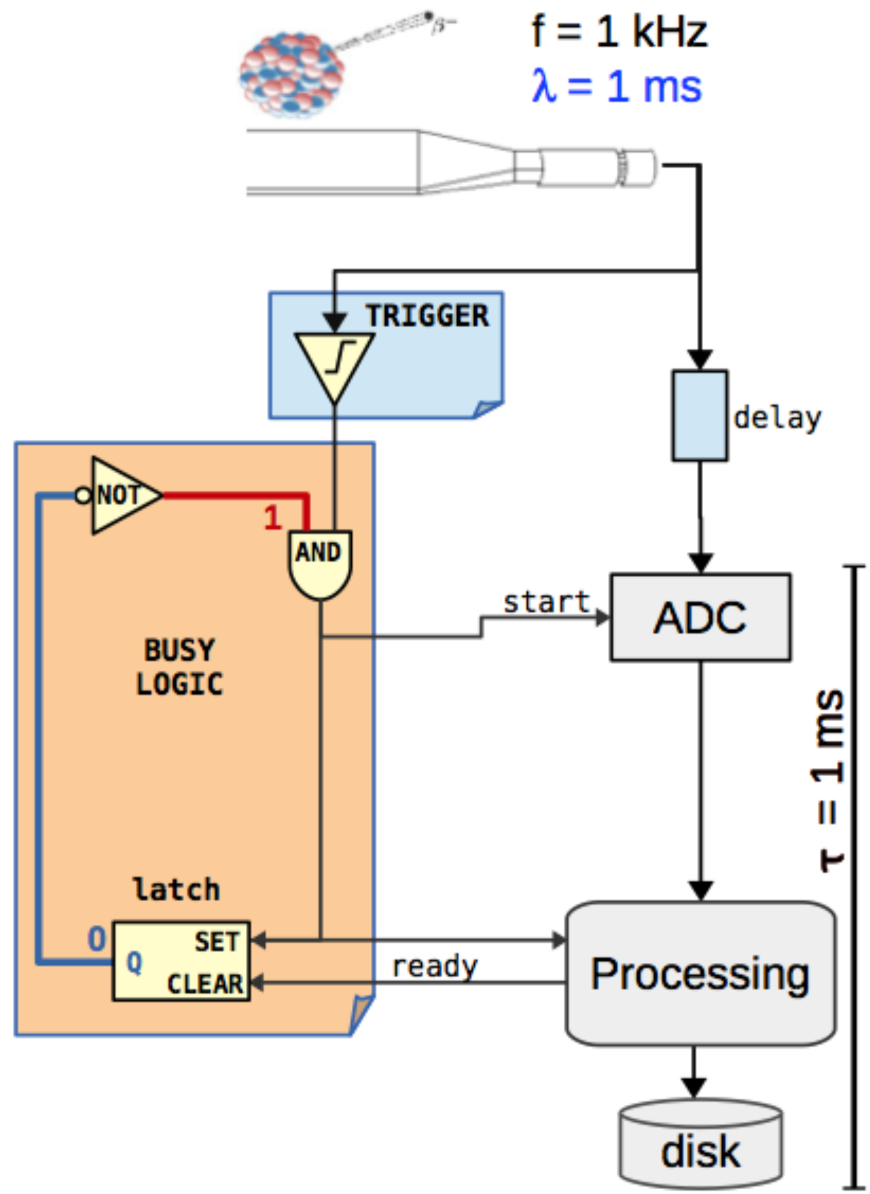


lose the preceding event?

crash the system?

leave me alone – I’m BUSY !

- **BUSY logic** avoids triggers while the system is busy in processing
  - e.g., AND port and latch
- latch (**flip-flop**):
  - a bistable circuit that changes state (Q) by signals applied to the control inputs (SET, CLEAR)
  - at first flip-flop state is “low” (zero) and so its negated input to the AND is “high” (one)



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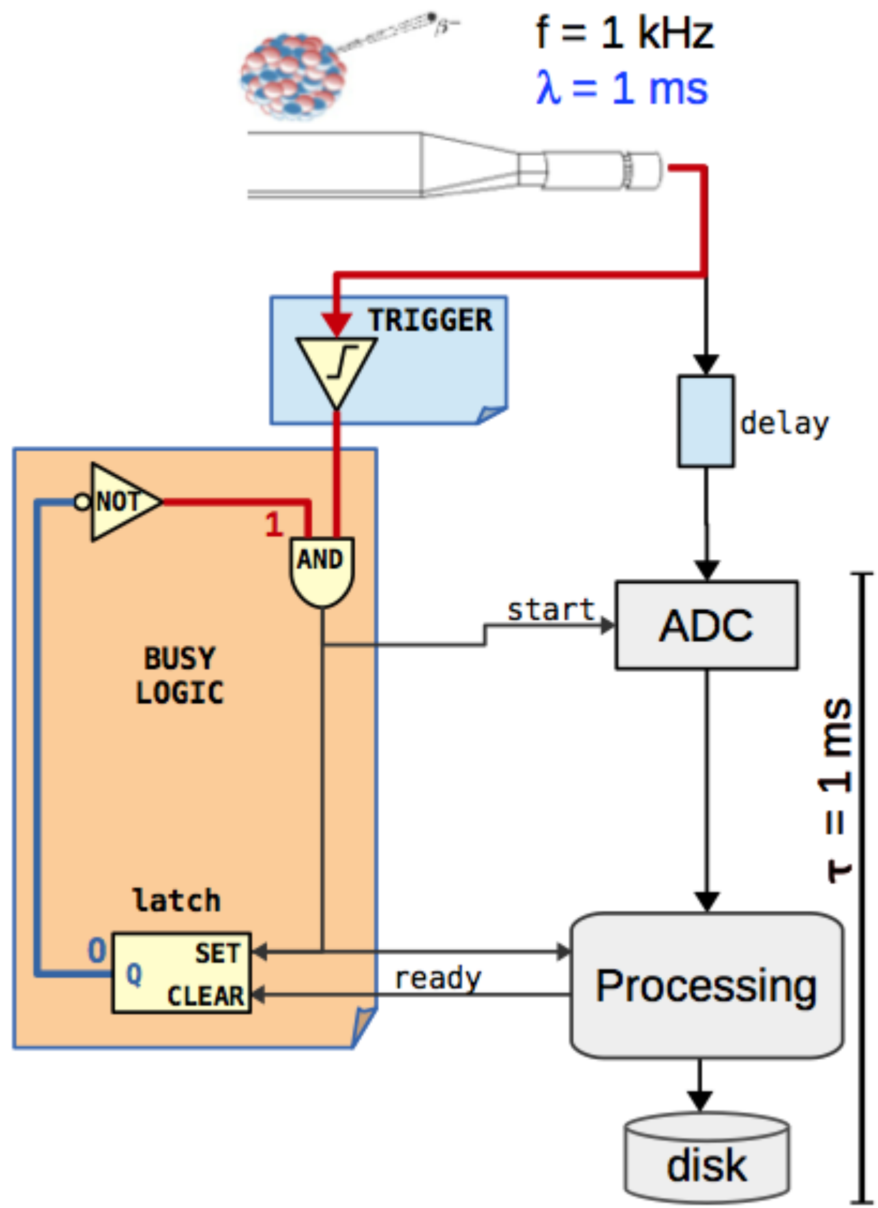

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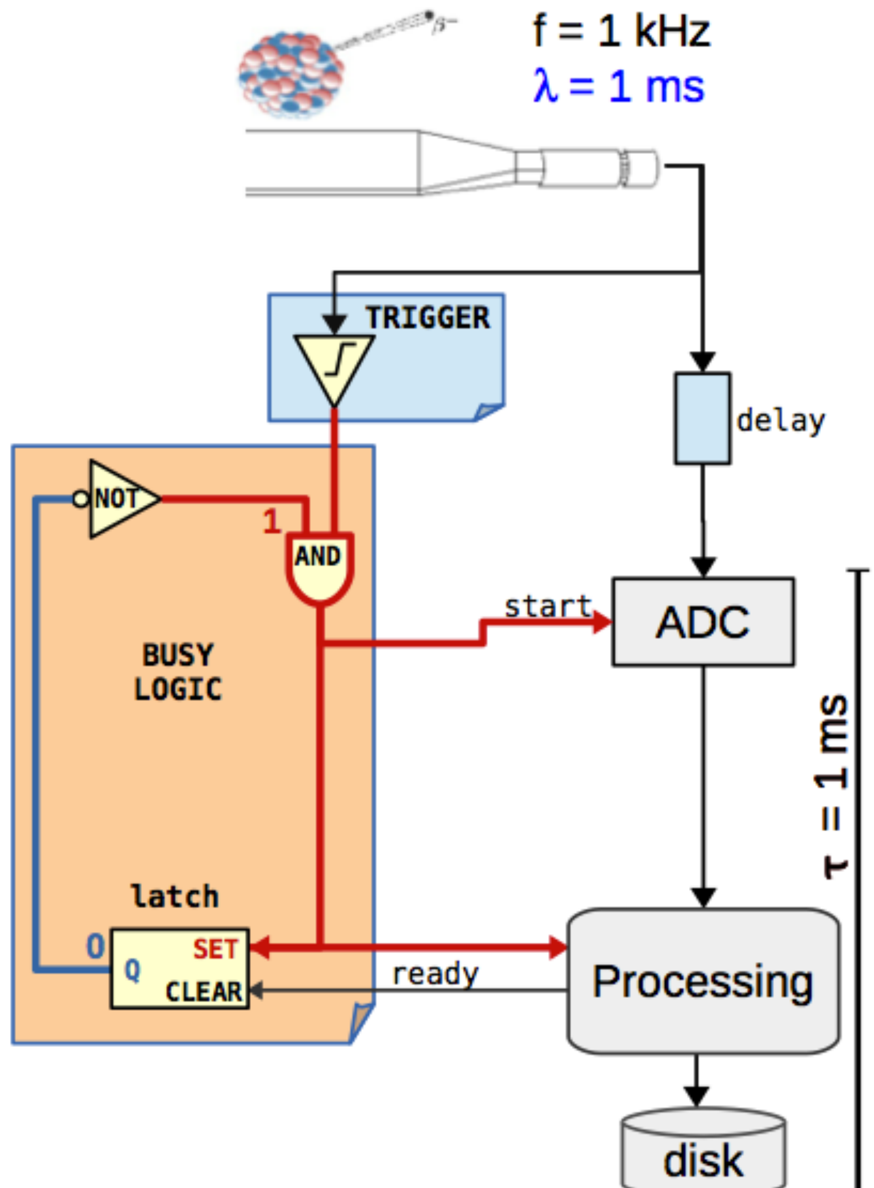
  - when a trigger arrives, it can pass the "AND"
  - → ADC and processing start, flip-flop is switched



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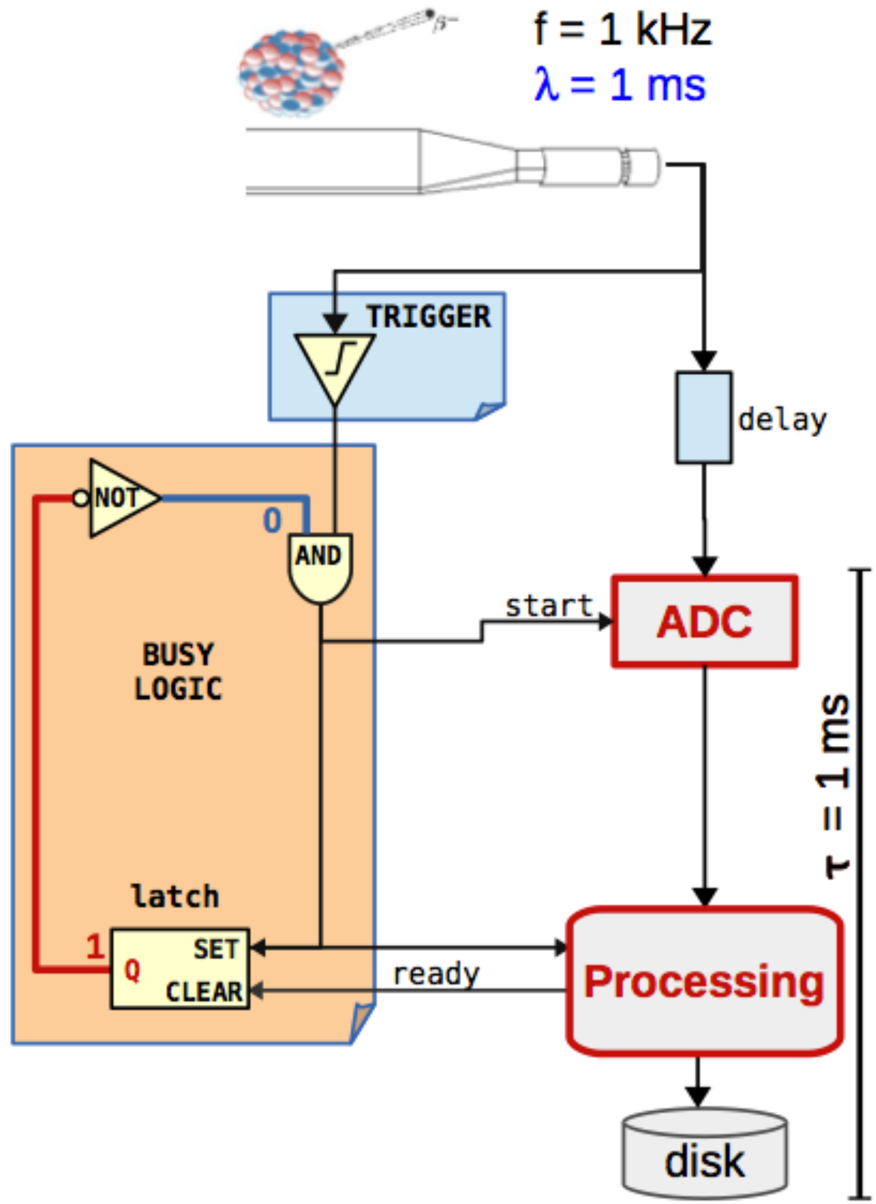
  - negated flip-flop signal at AND is "low", no new triggers can pass



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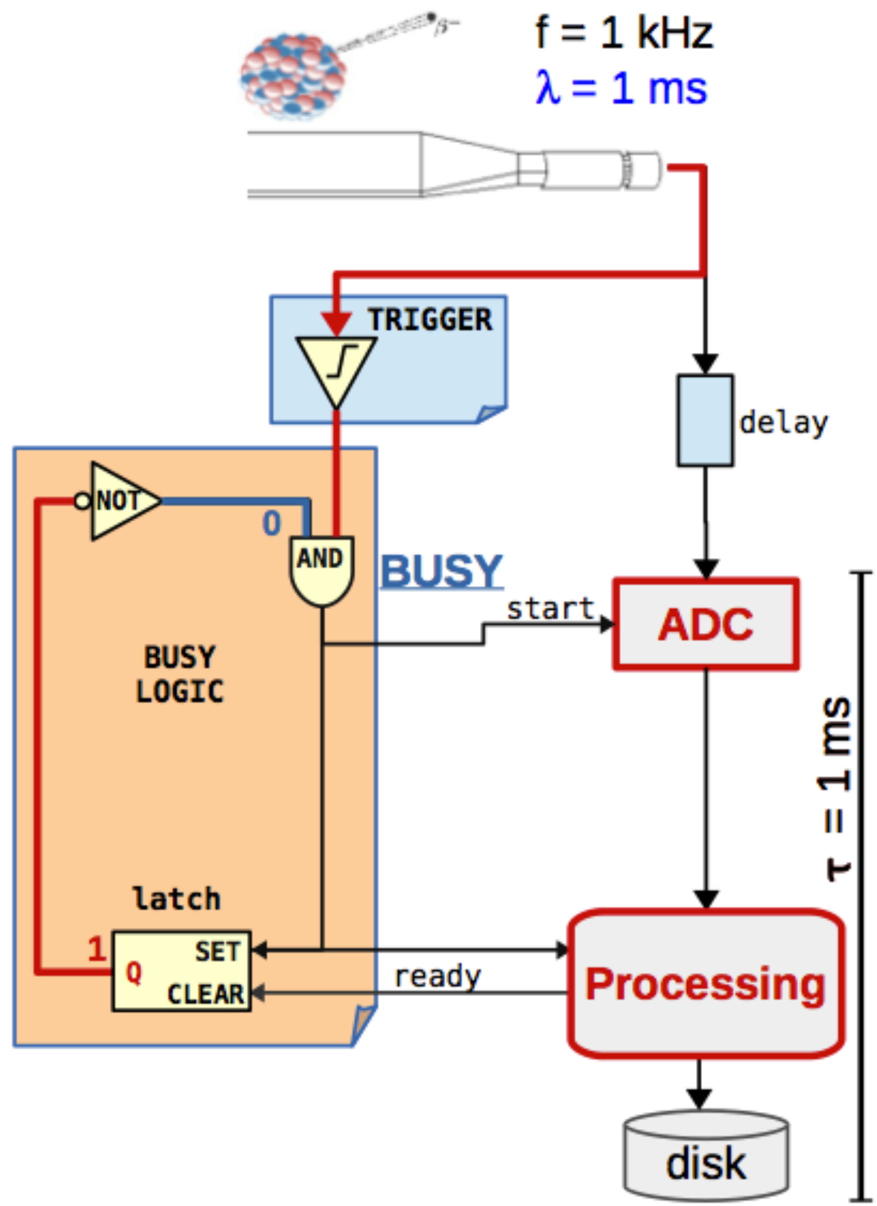
  - negated flip-flop signal at AND is "low", no new triggers can pass: in other words, the system asserts "BUSY"



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  - e.g., AND port and latch
- latch (**flip-flop**):
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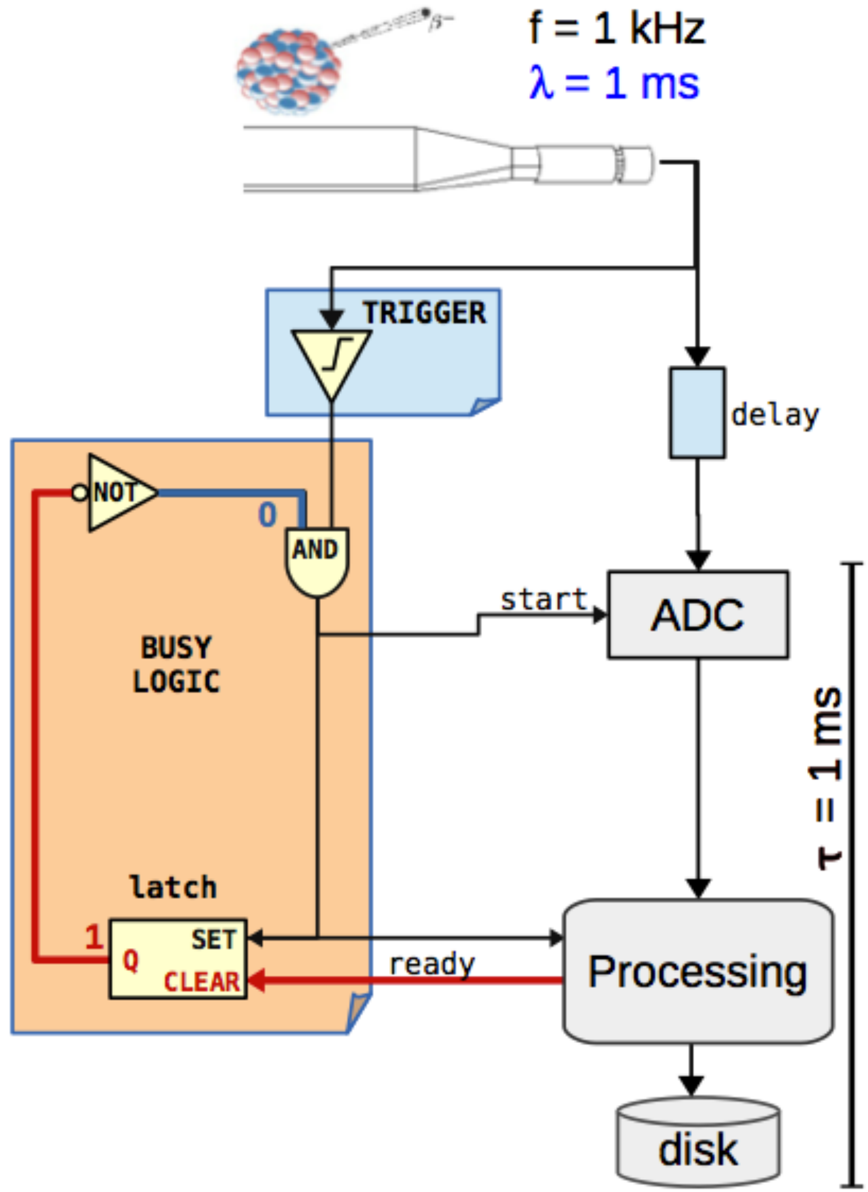
  - when processing is done, the flip-flop is reset



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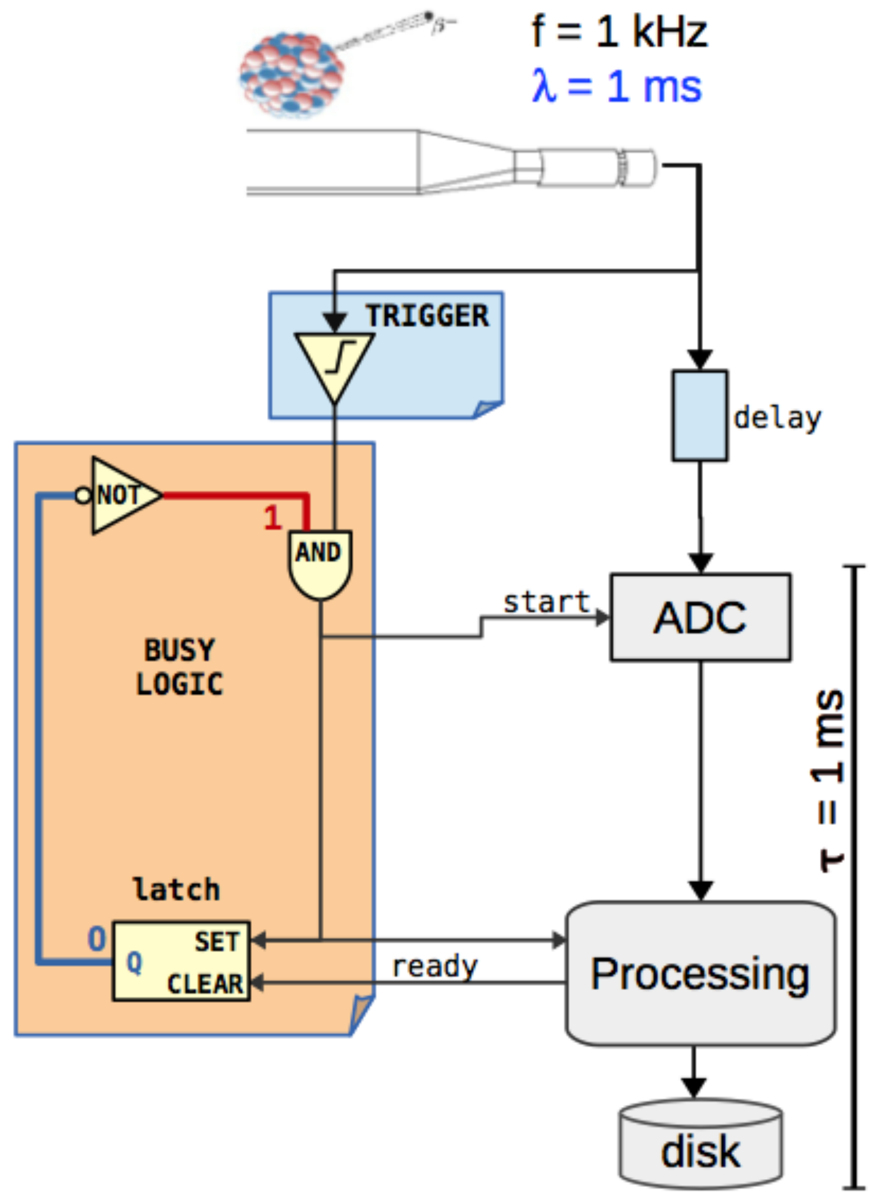
- **BUSY logic** avoids triggers while the system is busy in processing
  - e.g., AND port and latch
- latch (**flip-flop**):
  - a bistable circuit that changes state (Q) by signals applied to the control inputs (SET, CLEAR)
  - when processing is done, the flip-flop is reset to zero, and its negated output ("1") opens the AND-gate again for the next trigger



deadtime and trigger efficiency

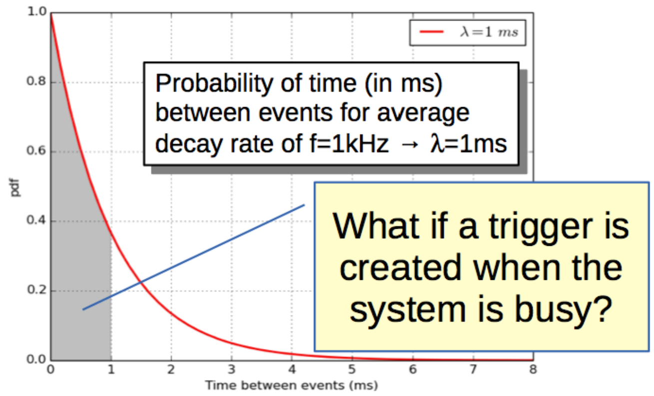
- with "clock trigger" (= untriggered readout):
- e.g. digitization interval τ = 1 ms → readout rate = 1 kHz
  - readout rate = sampling rate

- using a "real" trigger:

  definitions:
  - f: average input rate (physics events)
  - ν: average output rate (DAQ)
  - τ: deadtime (time needed to process an event)
  - probability for "BUSY": P(busy) = $\nu\tau$
  - probability for "not BUSY": P(ready) = $1 - \nu\tau$
- $\nu = f\,P(\text{ready})$
- $\nu = f\,(1 - \nu\tau)$
- $\nu = f\ /\ (1+f\tau)$

deadtime and trigger efficiency

- events come at irregular intervals (stochastic fluctuations)
  → DAQ rate < event rate : $\nu = f \;/\; (1+f\tau) \;<\; f$
  → efficiency due to DAQ : $\varepsilon = \nu/f = 1 \;/\; (1+f\tau) \;<\; 100\%$
  - e.g. $f = 1$ kHz, $\tau = 1$ ms → $\nu = 0.5$ kHz, $\varepsilon = 50\%$



definitions:

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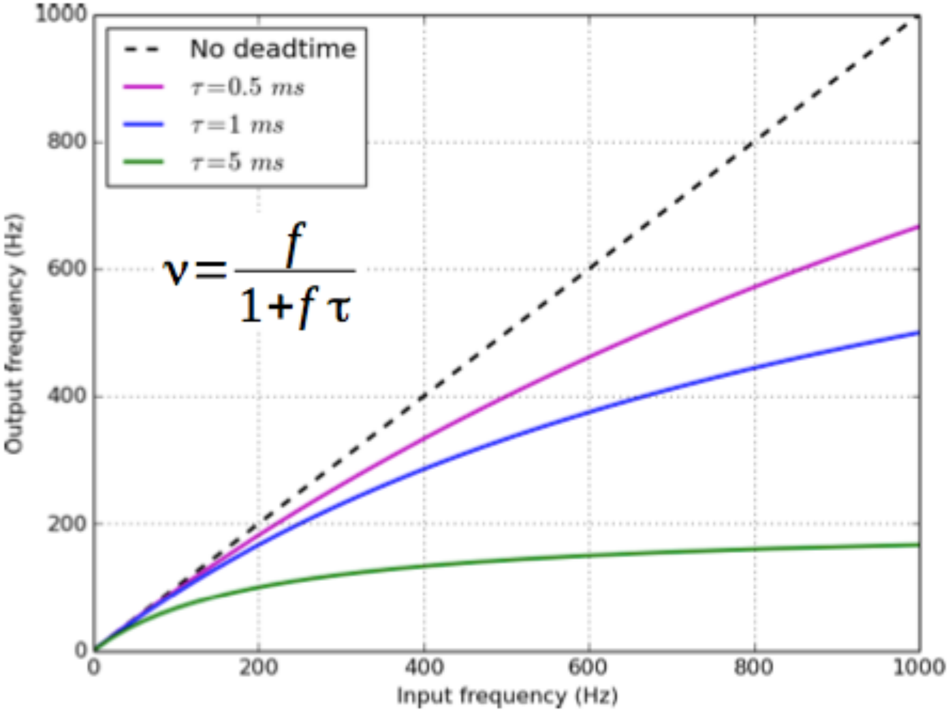
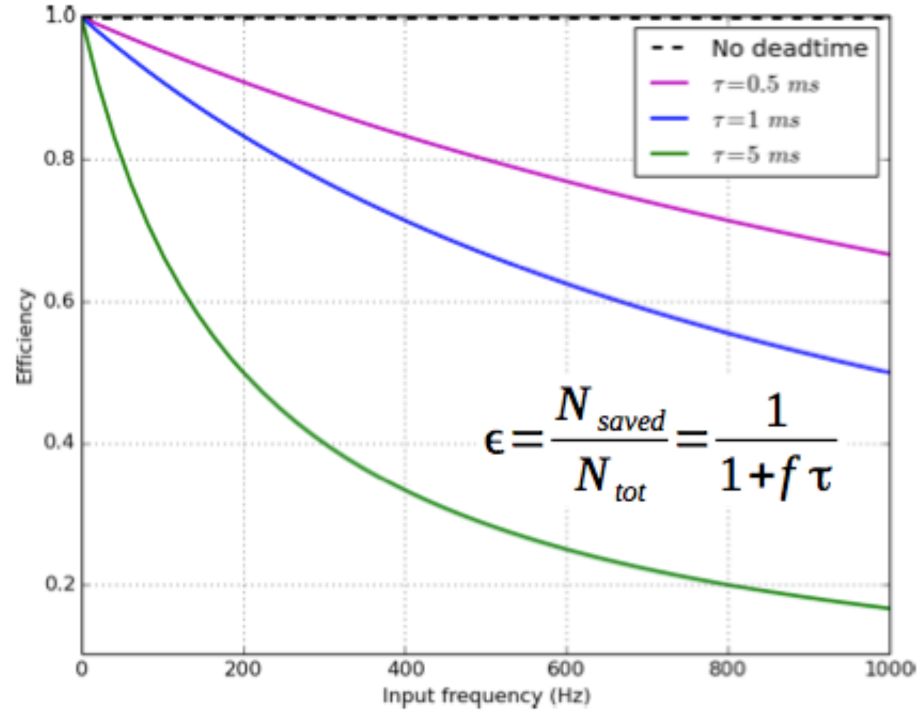
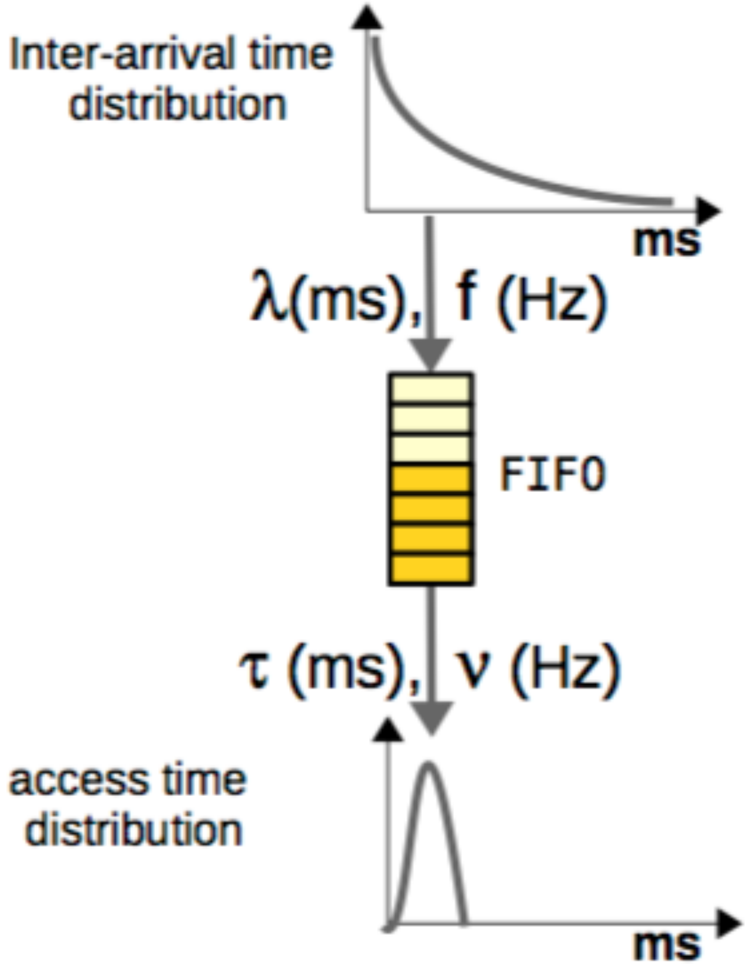
deadtime and trigger efficiency





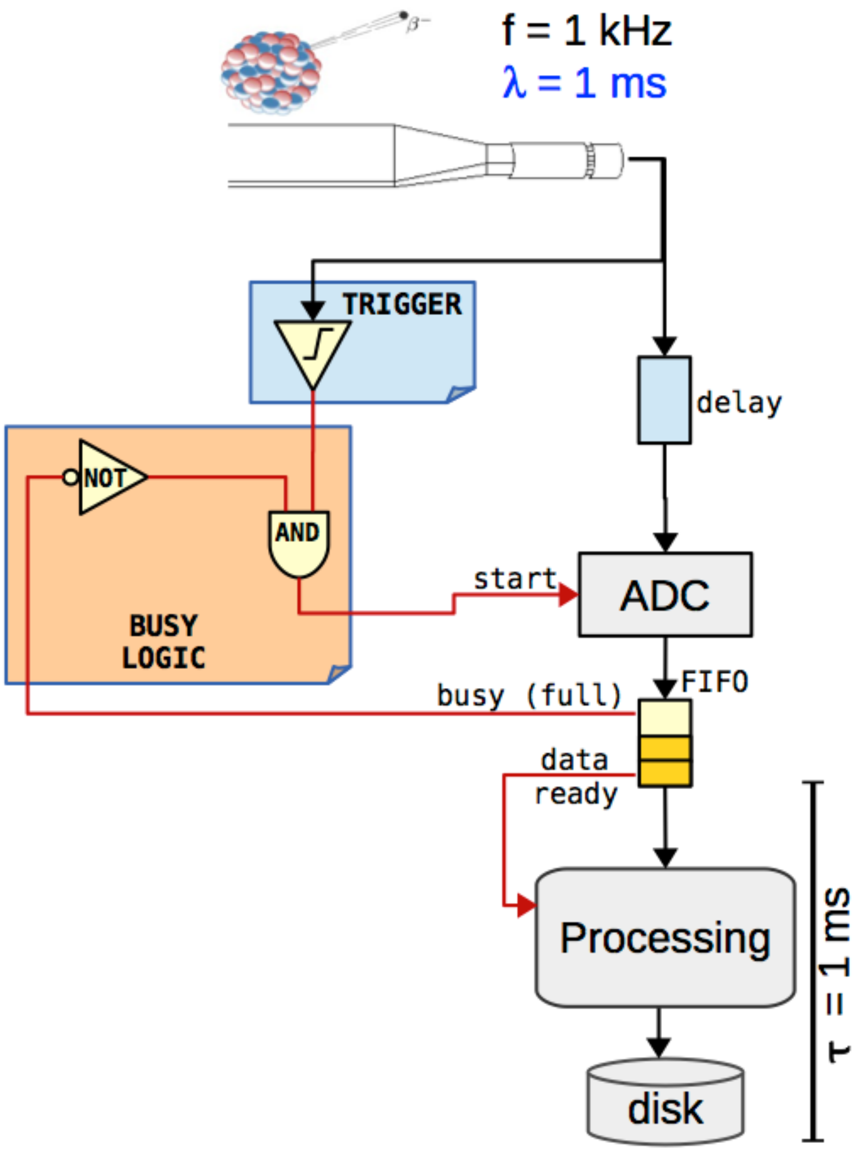
- in order to obtain $\varepsilon \sim 100\%$ ($\nu \sim f$) $\rightarrow$ $f\tau \ll 1$ $\rightarrow$ $\tau \ll 1/f$
  - $\varepsilon \sim 99\%$ for $f = 1$ kHz $\rightarrow$ $\tau < 0.01$ ms $\rightarrow$ $1/\tau > 100$ kHz
- to cope with the input signal fluctuations, we have to over-design our DAQ system by a factor of 100 ! ☹
- any clever ideas?

“de-randomization”



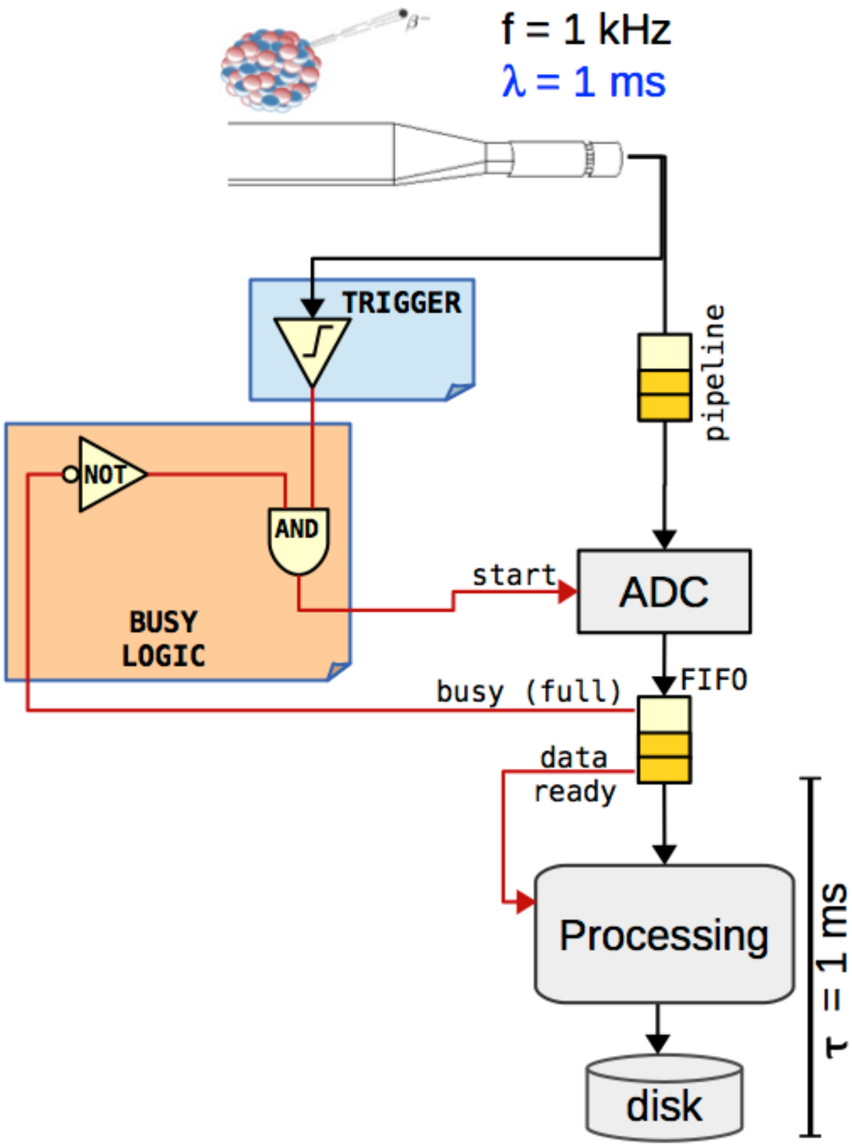
- fluctuations in arrival time absorbed by queue
- FIFO
  - first in, first out
  - “de-randomized” output rate
- additional latency

de-randomized DAQ with FIFO



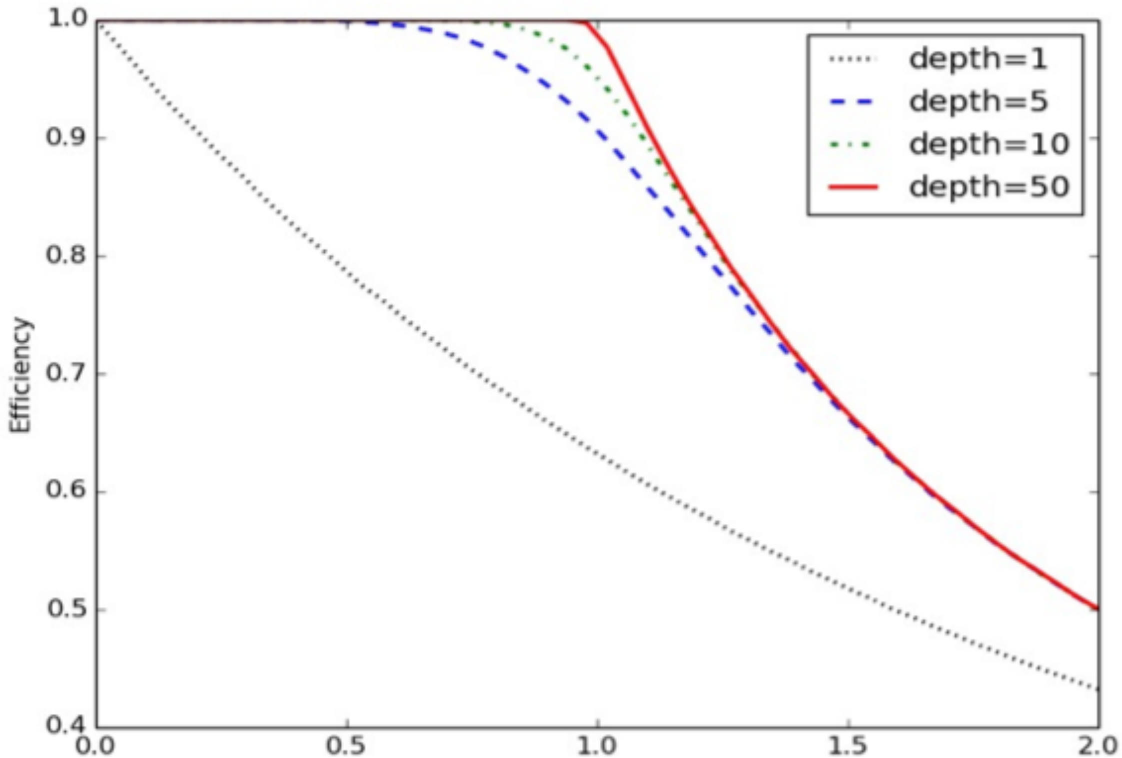
- can achieve high efficiency
  - small deadtime
  - ADC much faster than input rate
  - data processing at input rate
- ... and what if the ADC is challenged by the data rate?
  - could we put a buffer somewhat like a FIFO *before* the ADC?

analog pipeline



- analog pipeline before ADC
  - de-randomizing also the digitization step

queuing theory

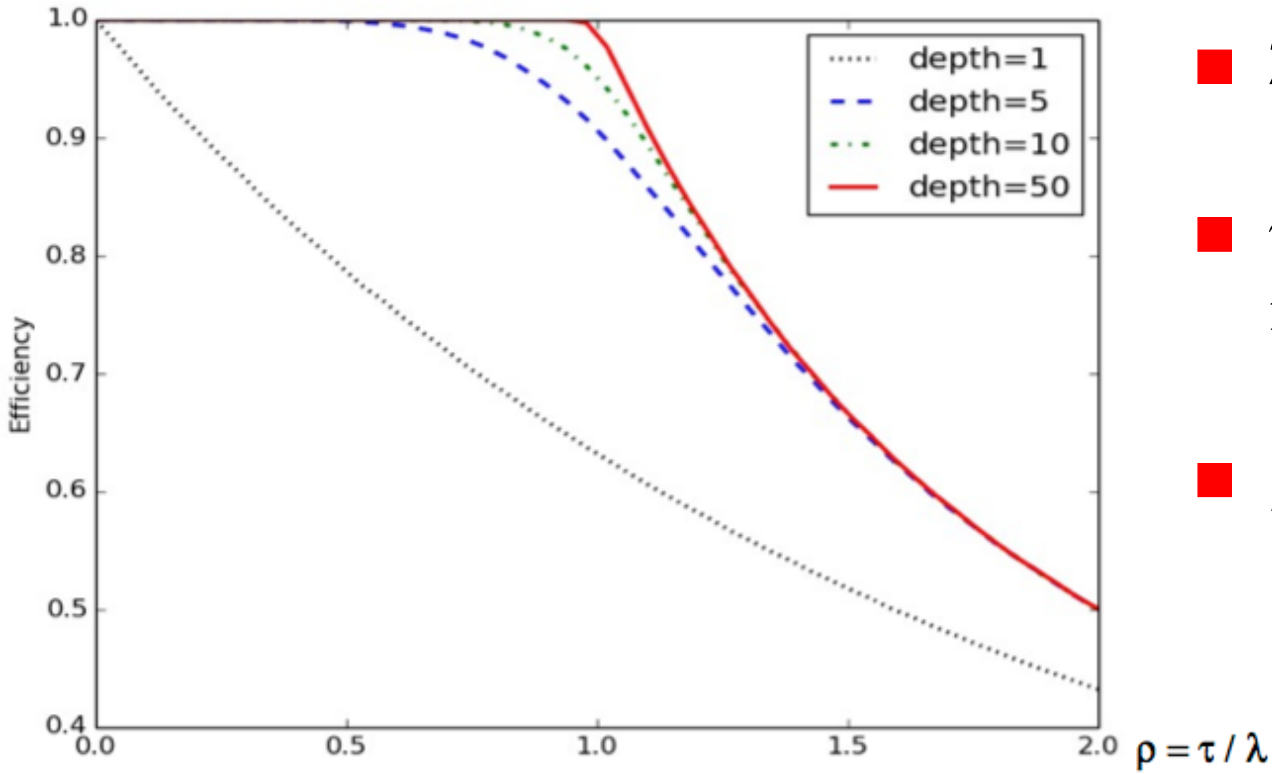


$\rho = \tau / \lambda$

- λ ... event interval
  - at input
- τ ... processing interval
  - at output
- $\rho = \tau / \lambda$

- which value of ρ is best?

queuing theory

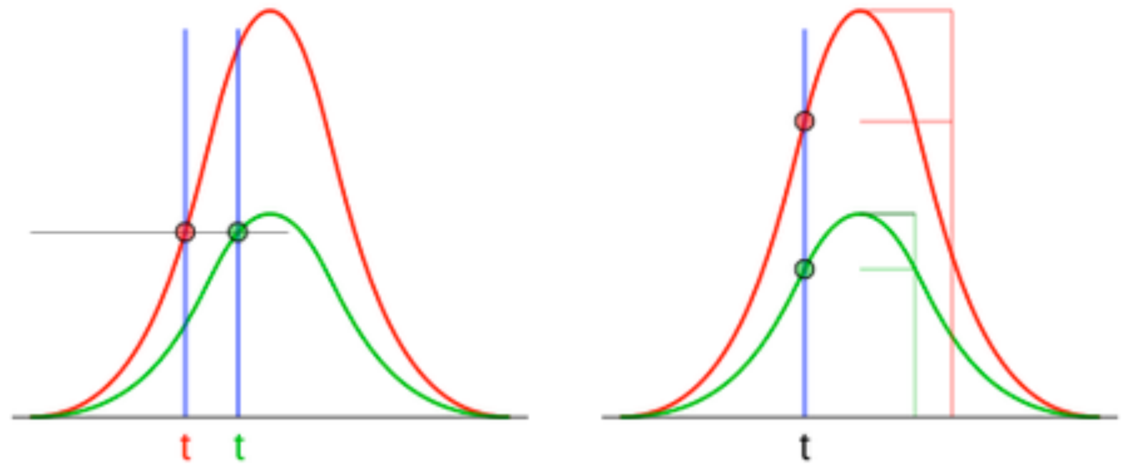


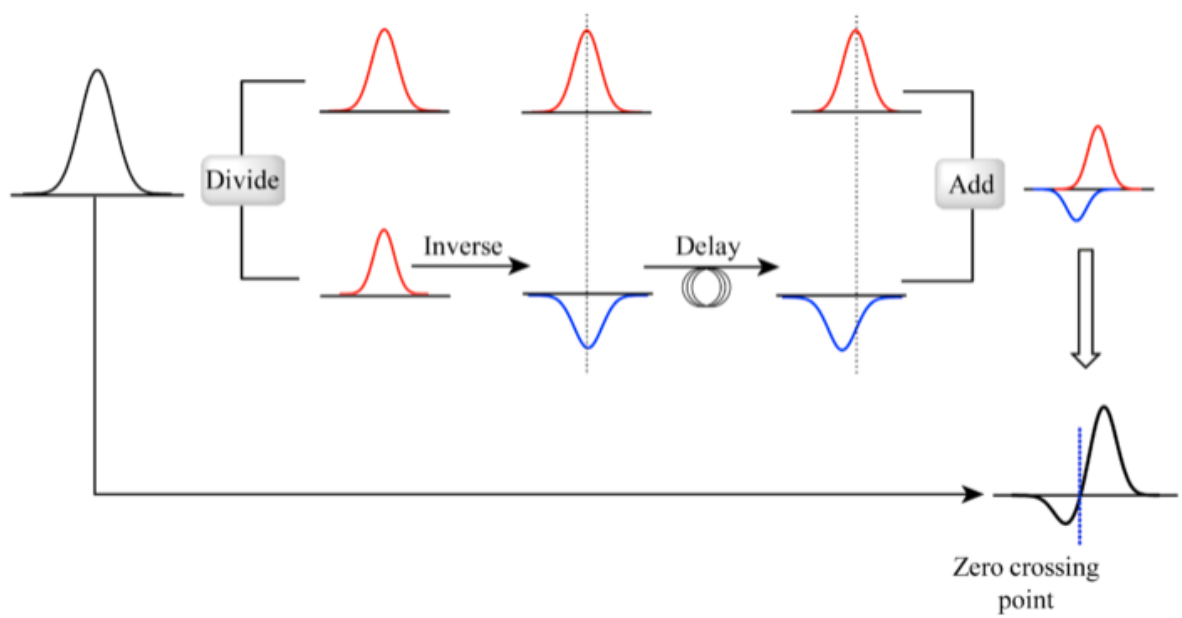
- λ ... event interval
  - at input
- τ ... processing interval
  - at output
- $\rho = \tau / \lambda$

- $\rho > 1$: system is overloaded (cannot cope with input rate)
- $\rho \ll 1$: system faster than needed (over-design, waste of money)
- $\rho \sim 1$: optimum design

time walk: constant fraction discriminator

- fixed threshold: dependence of the trigger time on the signal's peak height
- constant fraction of total height → independent of signal size
- achieved in electronics by dividing, inverting, delaying the signal
- measure time at zero-crossing





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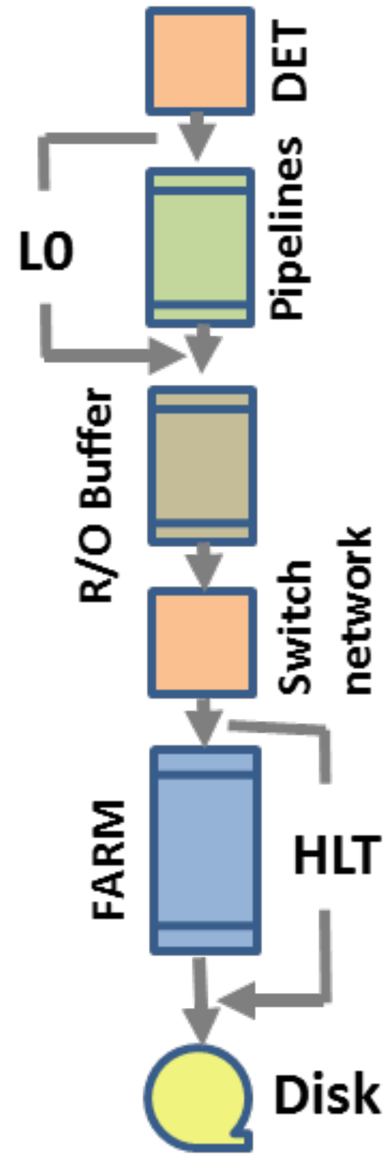
multi-level trigger

- first triggering criteria may be very simple
  - e.g., just wait for ADC (digitizer) to be ready
  - or simple selection criteria (such as minimum signal strength)
- additional triggering criteria may involve complicated calculations
- → benefit from multi-level trigger
  - first levels easy and quick
  - later levels complicated and more time-consuming
- first levels already remove many events → later, more complex levels face a smaller event frequency to cope with



further reading

- W. R. Leo, “Techniques For Nuclear And Particle Physics Experiments”, Springer, 1994
- CERN Summer Student Lectures
  - every year
  - https://indico.cern.ch/category/345/
- ISOTDAQ lectures
  - “International School of Trigger and Data AcQuisition”, various years
  - 2017: https://indico.cern.ch/event/557251/timetable/
- Technical Design Reports (TDR)
  - of big experiments such as ATLAS, CMS, BaBar, LHCb, D0
  - baselines, upgrades
  - different publication dates