DATA ACQUISITION
ELECTRONICS & TRIGGER

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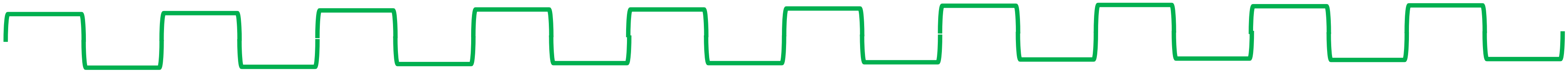
CERN

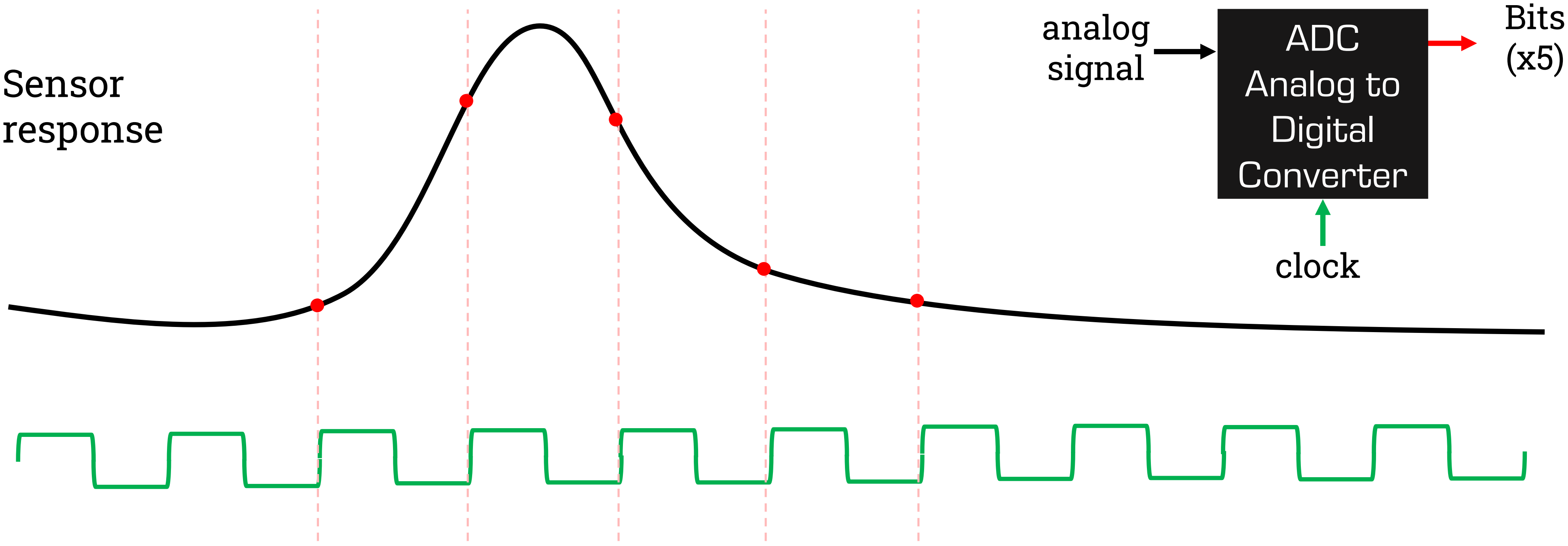
Summer Student Lectures Programme
CERN, 27 July 2023

SIGNAL PROCESSING
CLOCK

WHAT IS A CLOCK?



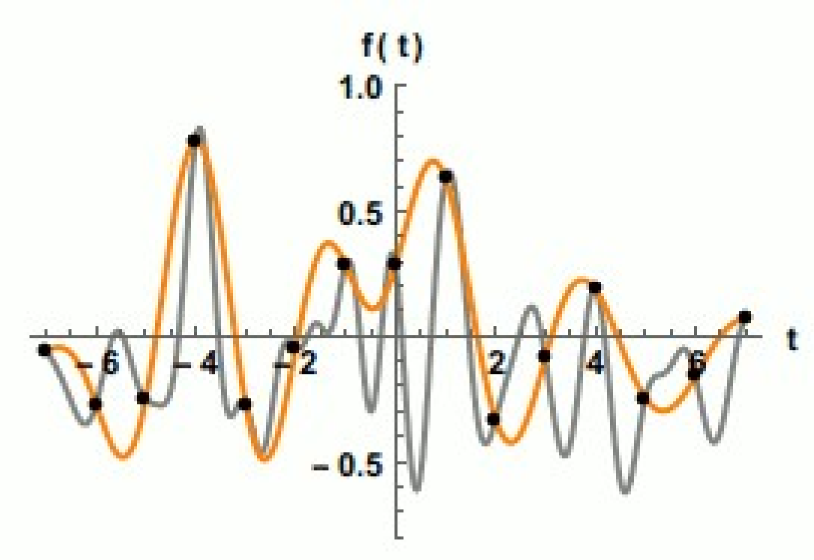
DIGITIZING A WHOLE PULSE

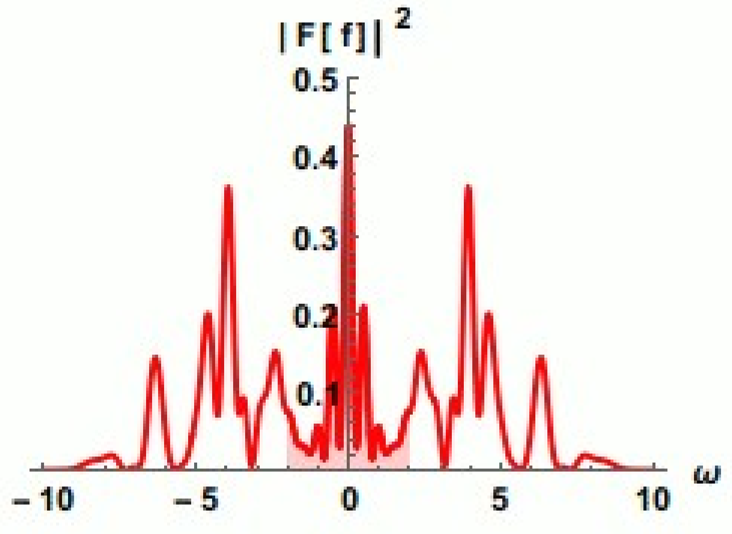


From E. Mendes, "Timing for DAQ" (ISOTDAQ 2022)

NYQUIST-SHANNON THEOREM

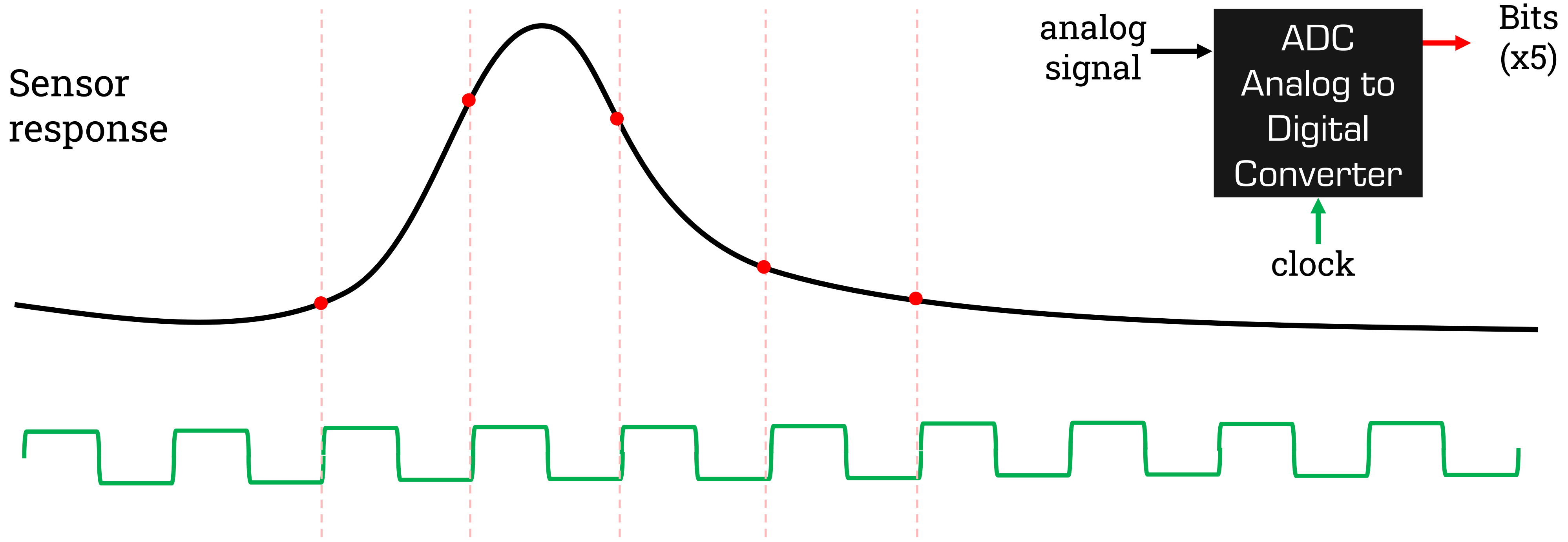
If a pulse contains no frequencies higher than f_{max} hertz, then it can be completely determined from its values at a sequence of points spaced less than $1/2f_{max}$ seconds apart.





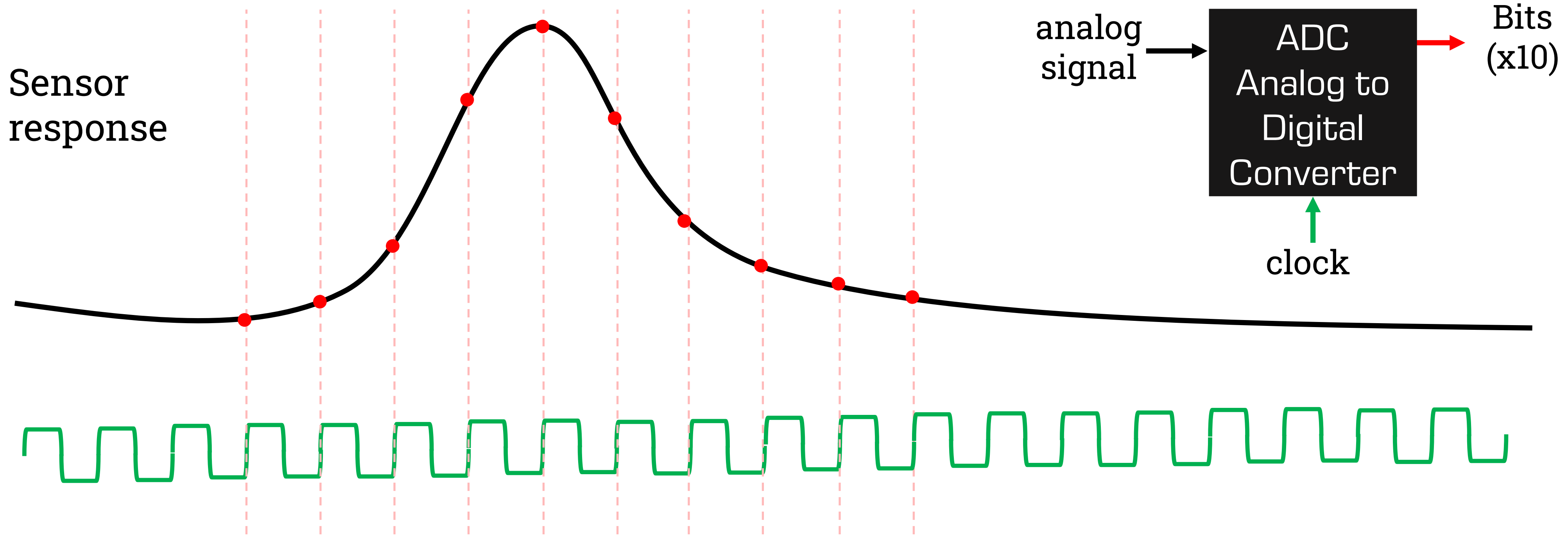
From J. Bertolotti, https://commons.wikimedia.org/wiki/File:Nyquist_sampling.gif

TRY AGAIN…



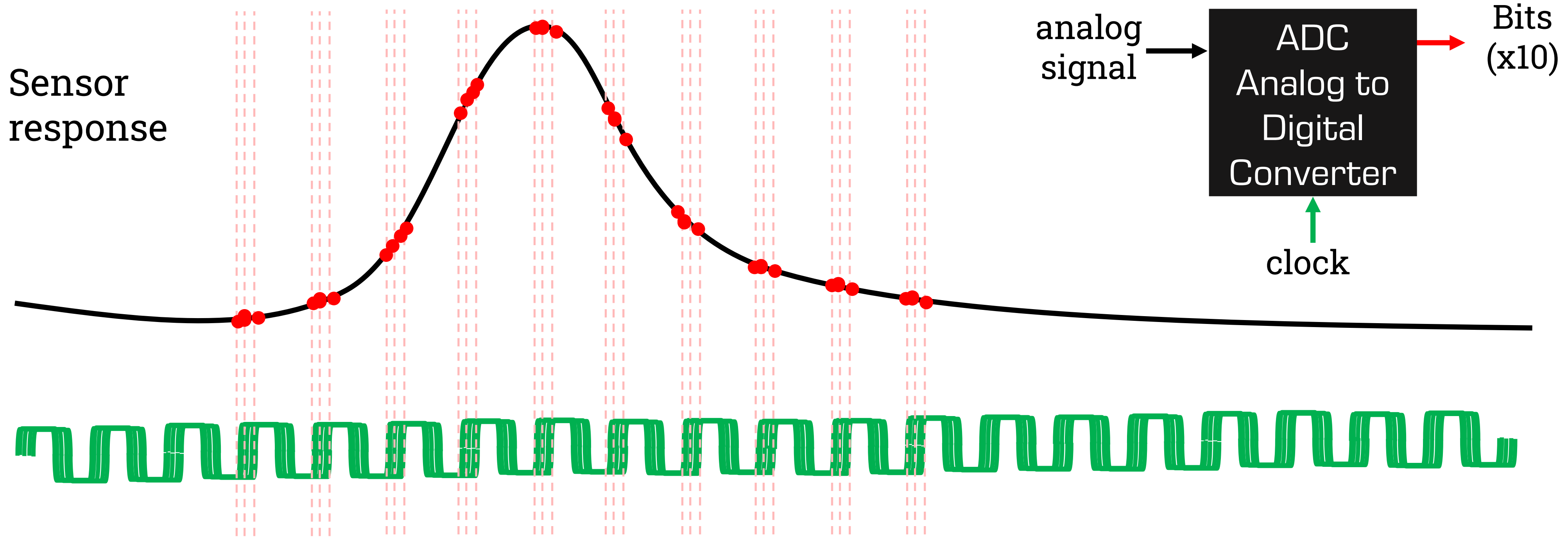
From E. Mendes, "Timing for DAQ" (ISOTDAQ 2022)

...WITH MORE SAMPLES



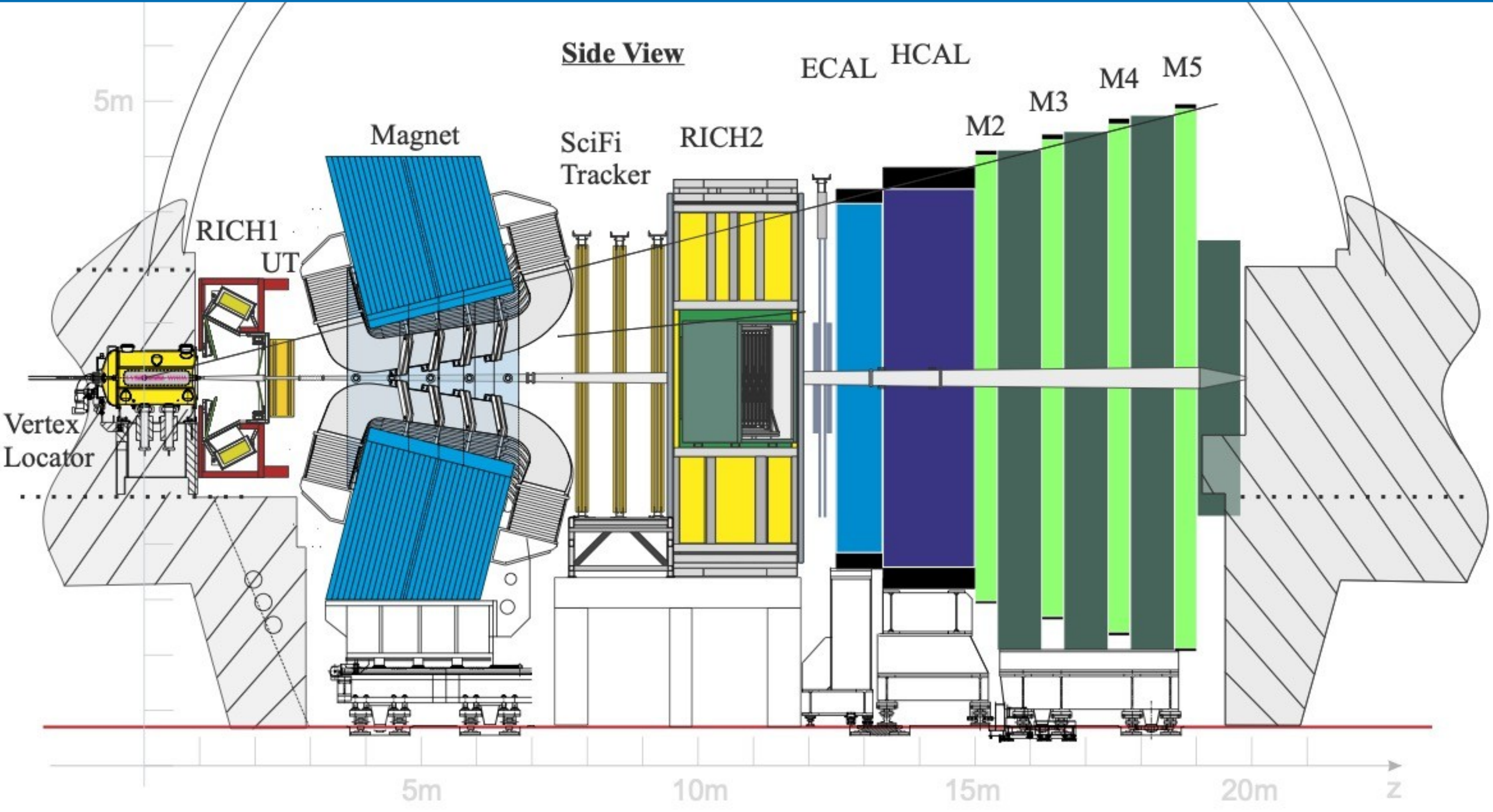
From E. Mendes, "Timing for DAQ" (ISOTDAQ 2022)

...AND CLOCK JITTER ☹



From E. Mendes, "Timing for DAQ" (ISOTDAQ 2022)

WHY YOU NEED A GLOBAL CLOCK

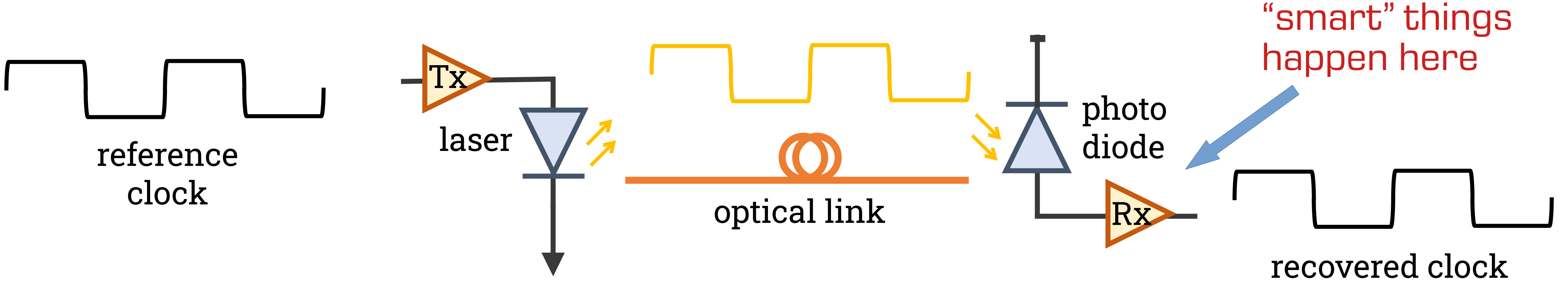


0 ns 17 ns 33 ns 40 ns 67 ns

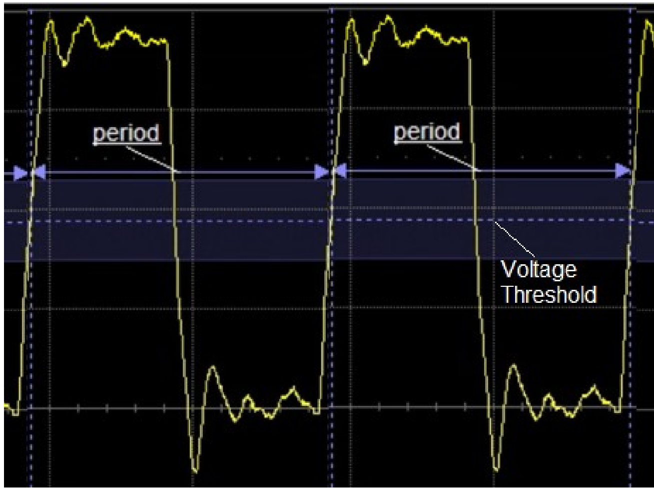
LHC collisions:
Every 25 ns

If a local clock is off by 1 ns (4%), the particle you wanted to measure is already gone!

CLOCK DISTRIBUTION



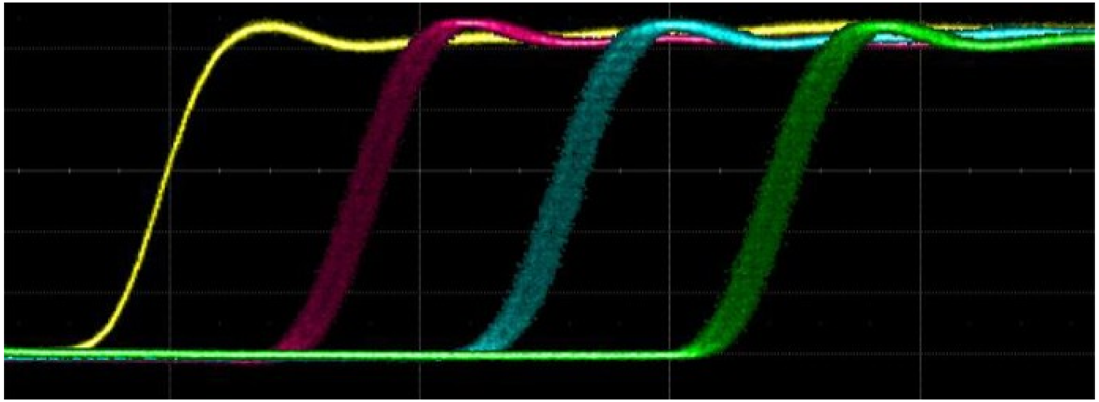
- Recovering clock frequency is easy: Rx could be a simple comparator:
input goes higher than threshold → clock tick
- Ok, not so easy:
If noise makes the signal a little higher or lower
→ clock ticks move → jitter



CLOCK RECOVERY

- Not just long distance optical links: clock transmission and recovery is needed within any sufficiently large circuit

  → that is where noise is picked up



Original First, second, third recovery

- Standard clock recovery:
  use the incoming clock to tune a local clock source (oscillator)
  → removes high-frequency jitter

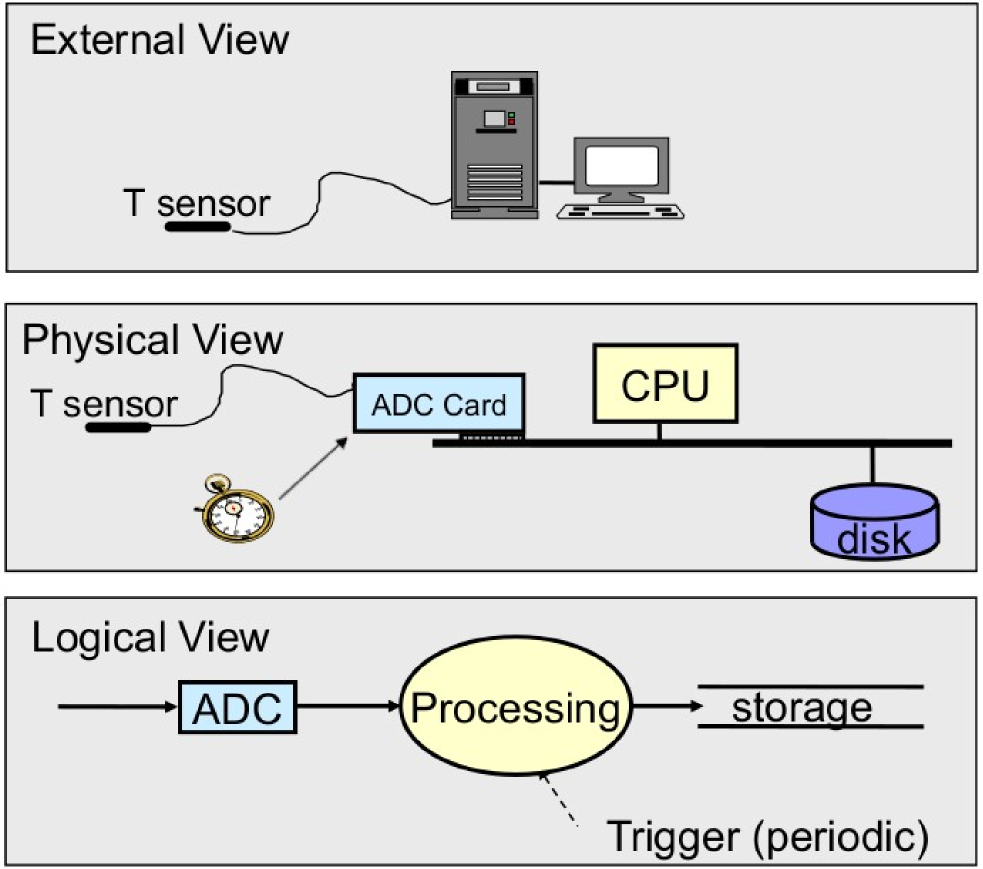
- Jitter cleaning:
  measure many clock periods and average them out
  → removes random jitter

TRIGGER **BASICS**

WHEN DO WE START?

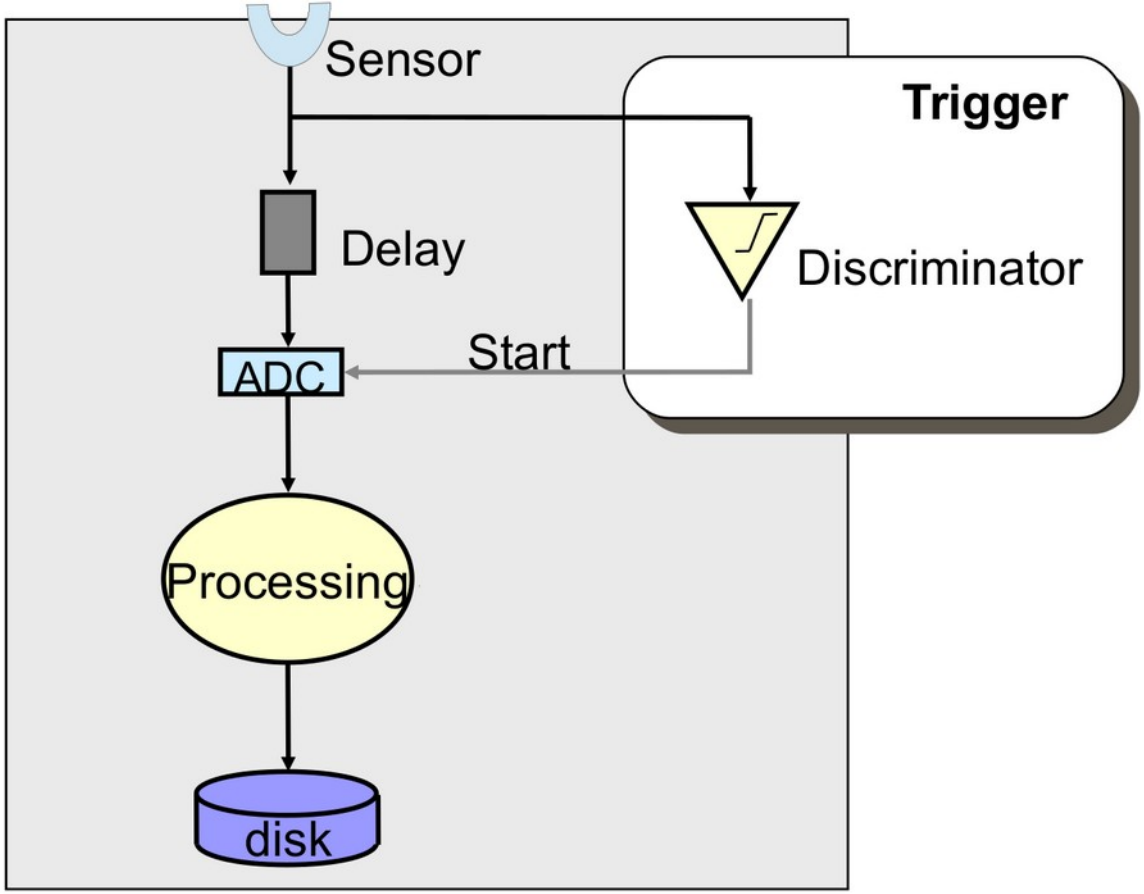
- A trigger is a prompt signal starting the data acquisition process
- When do you want to start? When something interesting happens!
- Who decides what "interesting" means?
  - The signal processing electronics itself. Examples:
    - Continuously sample the signal at a given frequency
    - Whenever a pulse is produced by the sensor, the ADC is started
  - An external entity. Examples:
    - A "particle spill" at a fixed-target beam line has started
    - The collider's clock, ticking with every collision
    - One or more "special" sensors in a detector have seen something interesting

INTERNAL SYNCHRONOUS TRIGGER



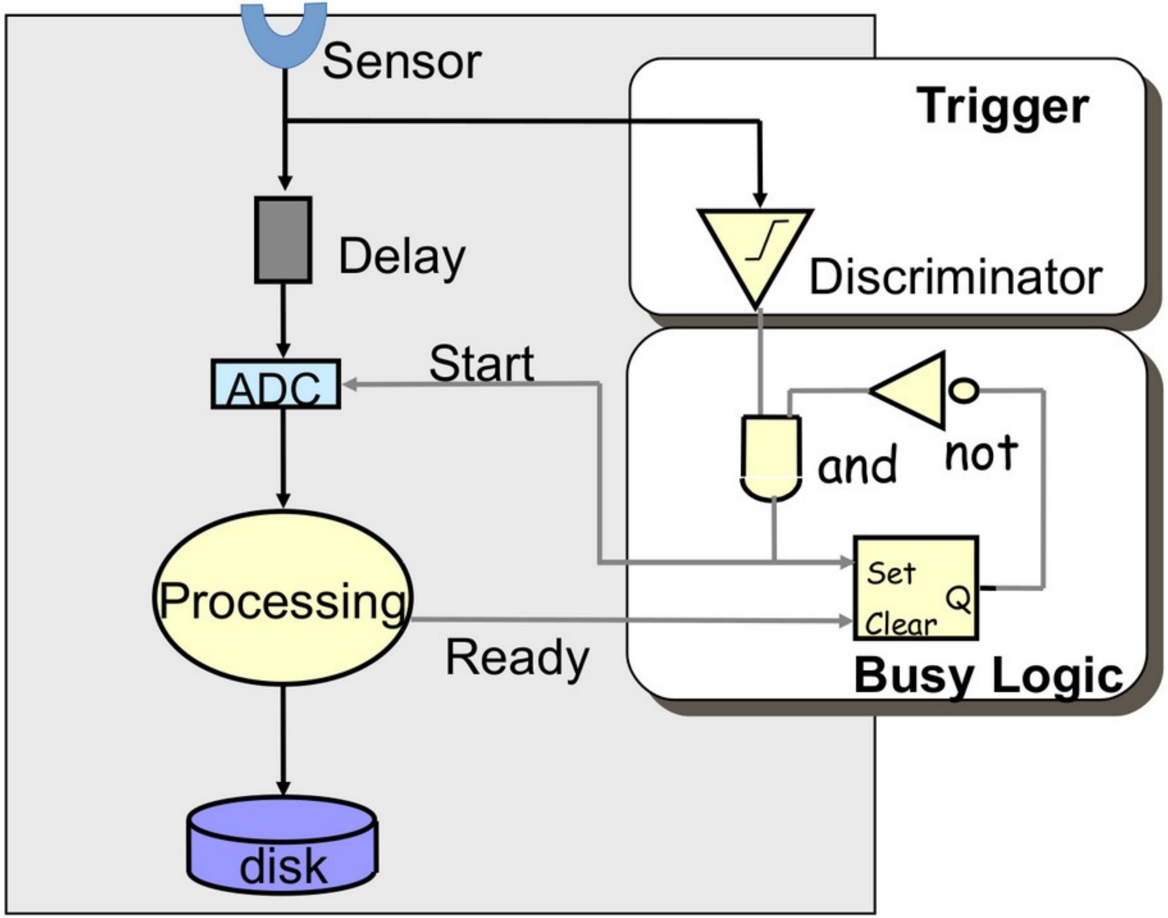
- Fully sequential system
- Limited by single-measurement processing time
- If the trigger clock is ticking at 1 kHz, ADC+Processing+Storage can take at most 1 ms per measurement

INTERNAL DATA-DRIVEN TRIGGER



- Trigger when signal goes over threshold
- Delay compensates for trigger latency,
  i.e.: time to reach decision
- What if a new signal arrives when the system is not done digitizing, processing, and storing the previous one?

BUSY

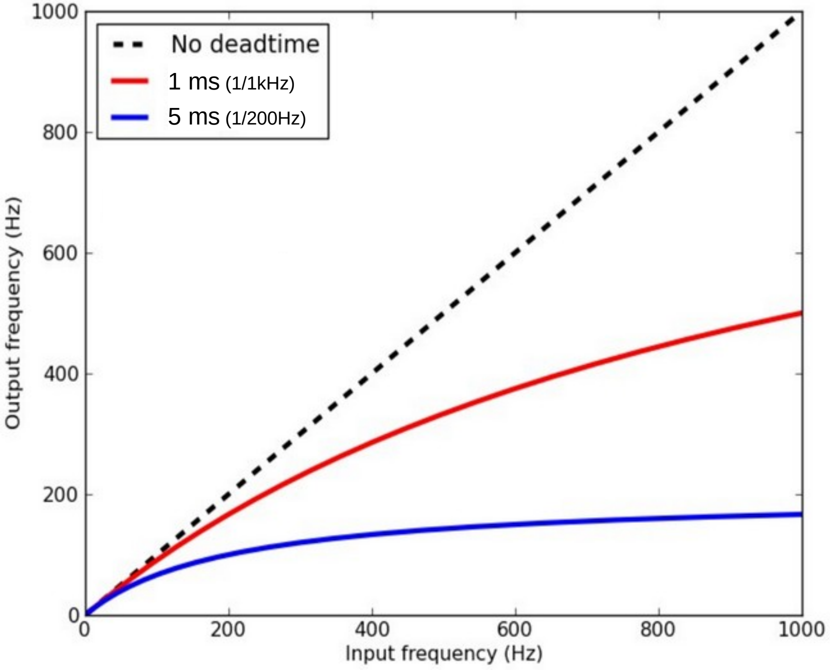


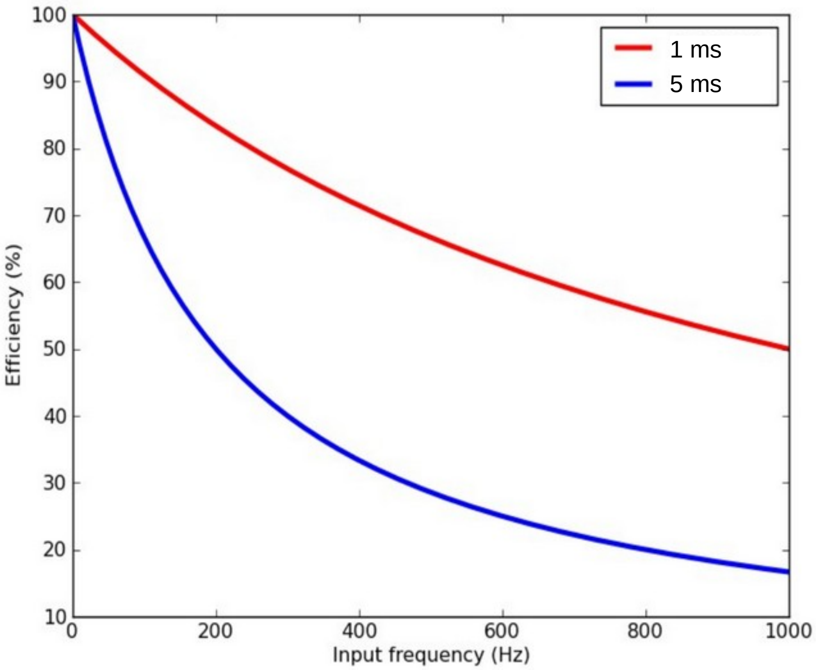
- Busy logic blocks triggers while processing
- While the DAQ is busy, no more data can be acquired → **dead time**

DEAD TIME AND EFFICIENCY

- Let's call the dead time per acquired signal T, average input signal rate f_{in}, and acquisition rate f_{out}
- If f_{in} is constant: $f_{out} = \min(f_{in}, 1/T) \rightarrow$ efficiency: $f_{out}/f_{in} = \min(1, 1/f_{in}T)$
- If the sensor observes a Poisson process, i.e. events occurring randomly with an average frequency of f_{in}:
  - Probability P_{out} of acquiring a signal after another arrived:
    $P_{out}(t) = 0$ for $t \leq T$ $\quad$ $P_{out}(t) = P_{in}(t-T)$ for $t > T$
  - Expected time between acquisitions:
    $1/f_{out} = \int_T^\infty tP_{in}(t-T)\mathrm{d}t = \int_0^\infty (t+T)P_{in}(t)\mathrm{d}t = 1/\mathrm{f}_{in}+\mathrm{T}$
  - **Efficiency:** $\boldsymbol{f_{out}/f_{in} = 1/(1+f_{in}T) < 100\%}$

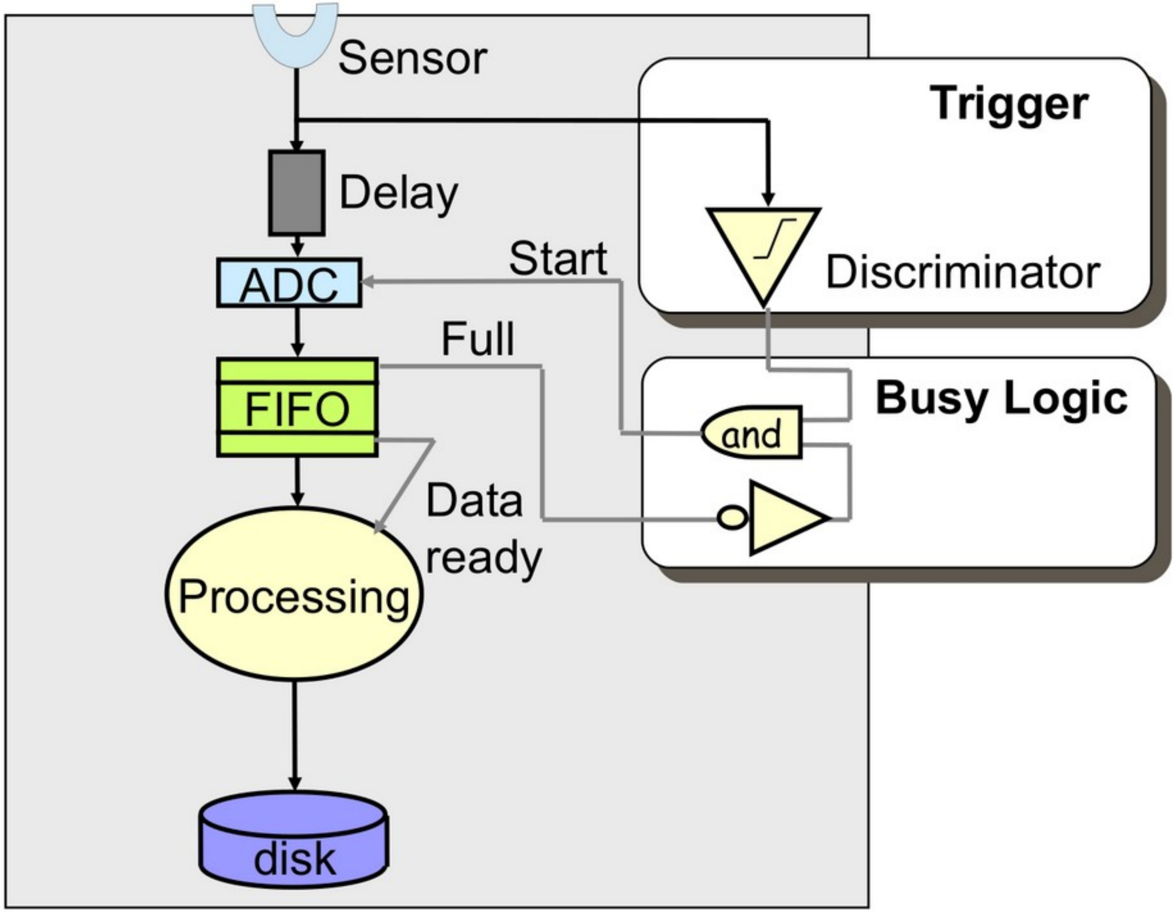
DEAD TIME AND EFFICIENCY





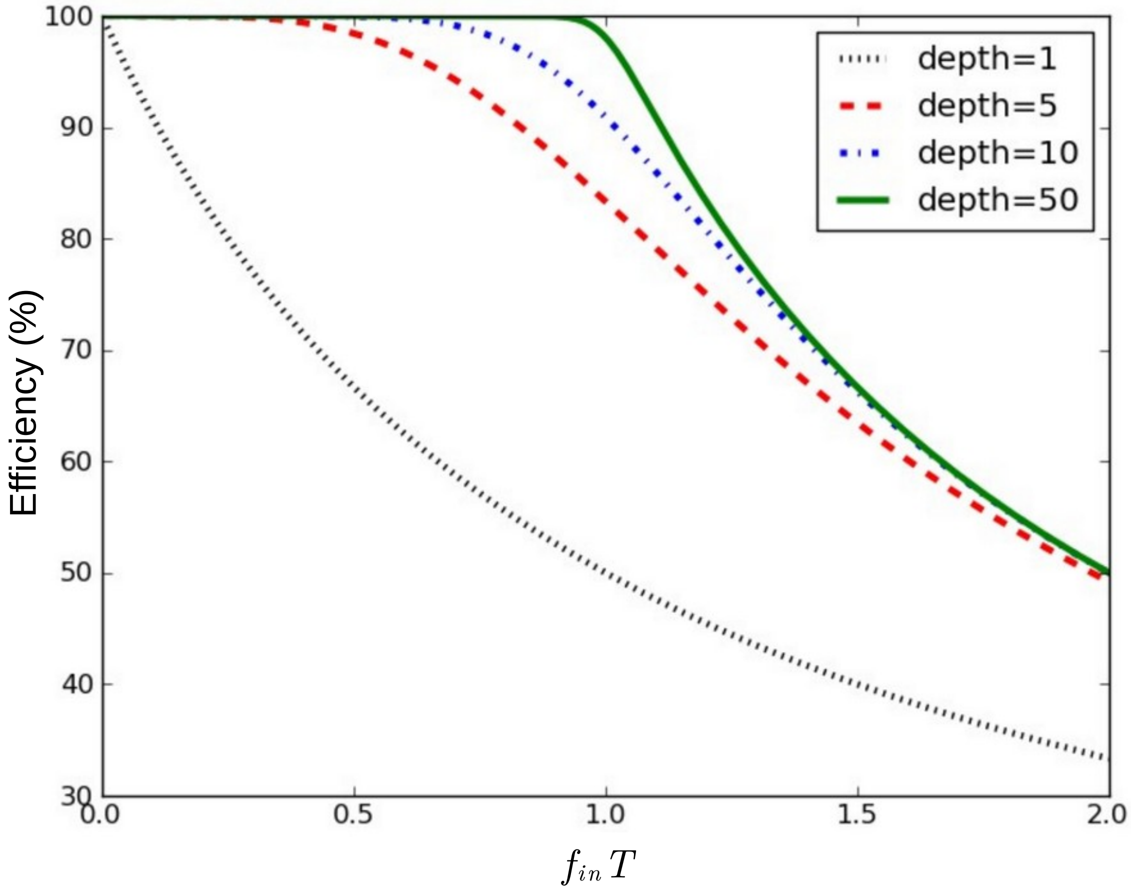
- 95% efficiency → $1/T = 19 f_{in}$
- 99% efficiency → $1/T = 99 f_{in}$
- High DAQ efficiency → low system usage

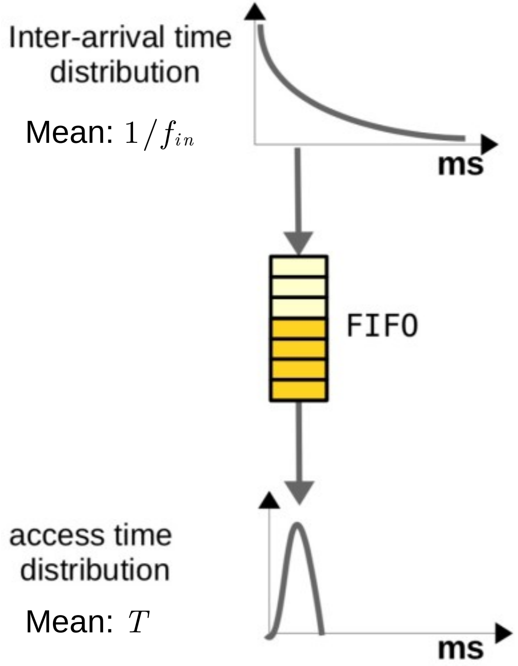
DERANDOMIZATION



- Add a buffer to absorb the input frequency peaks
- A first-in first-out (FIFO) buffer smooths the input fluctuations, providing a steady output stream (De-randomized)

THE MAGIC OF QUEUING



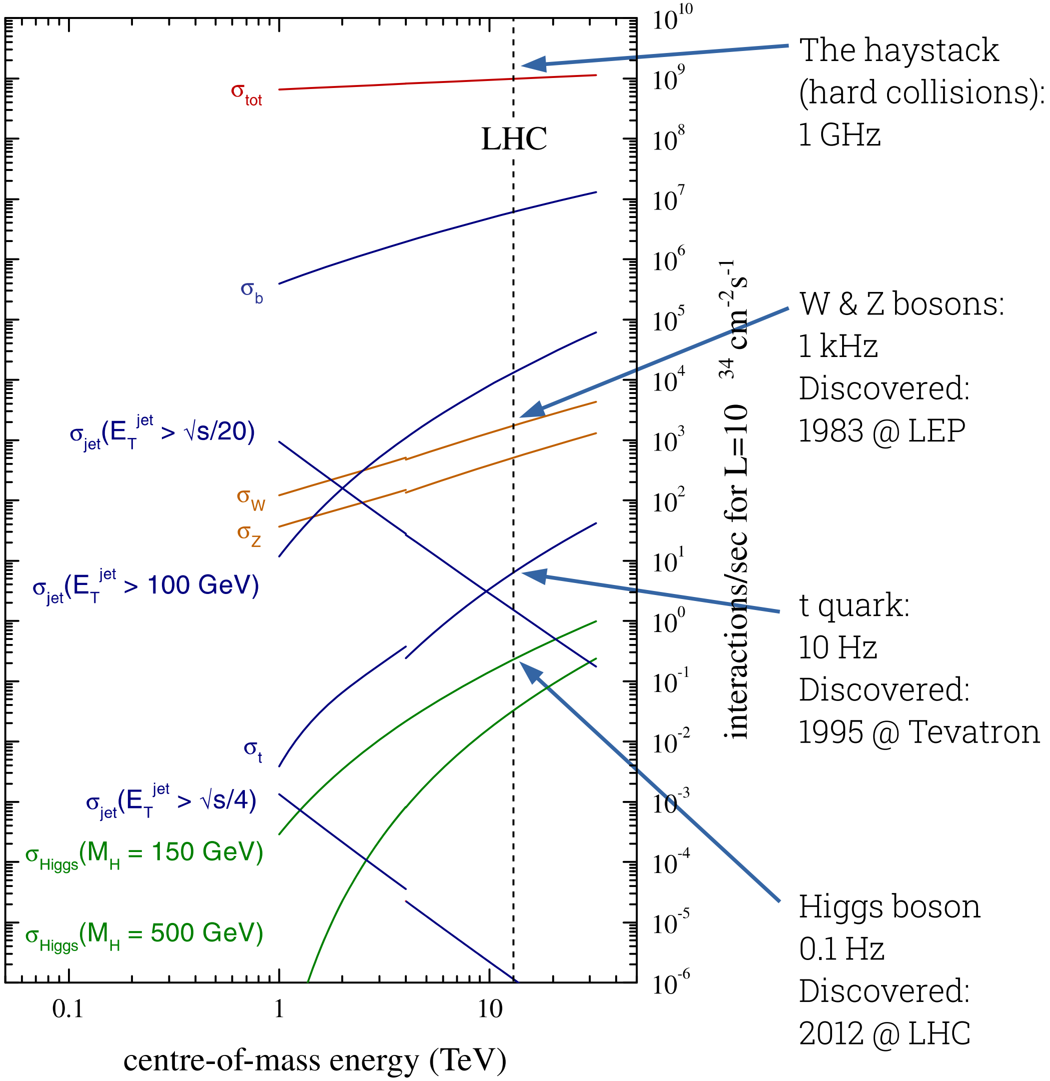


- With reasonable FIFO depth, we can now get 99% DAQ efficiency at $1/T = f_{in}$

Reminder: no FIFO → $1/T = 99 f_{in}$

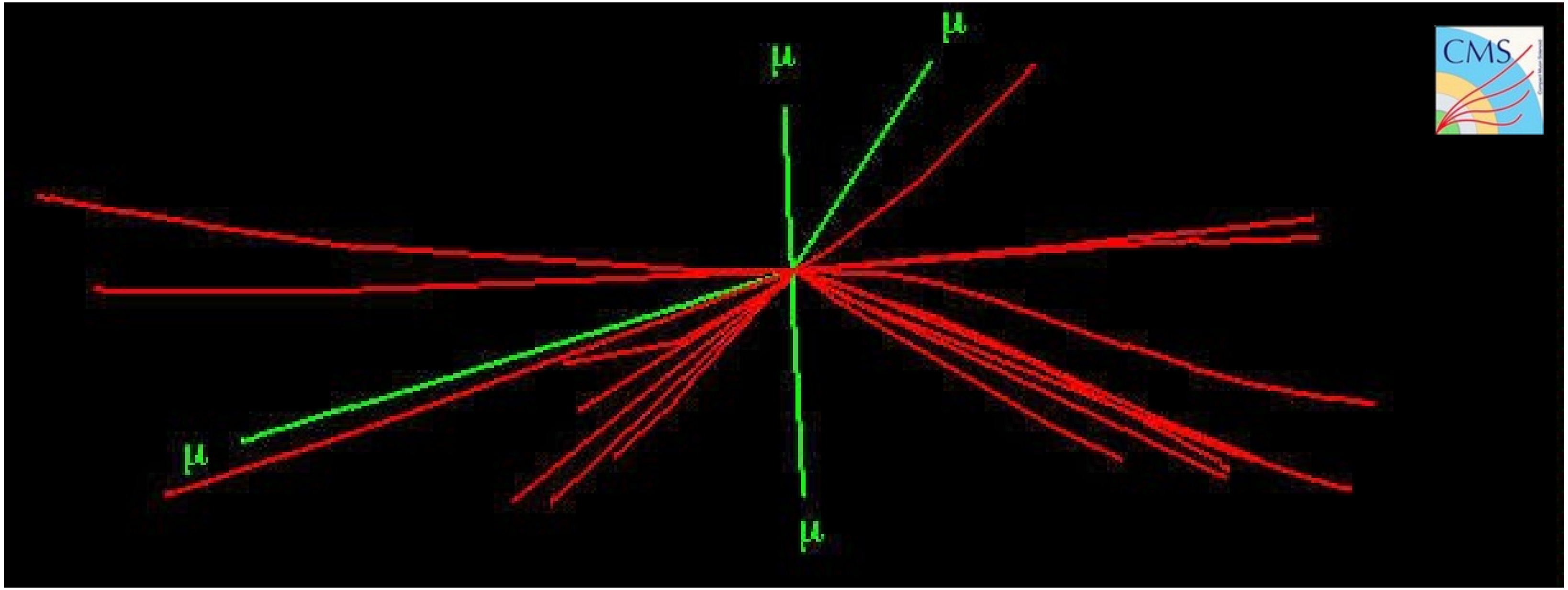
TRIGGER
DETECTORS

FINDING NEEDLES IN **HAYSTACKS**



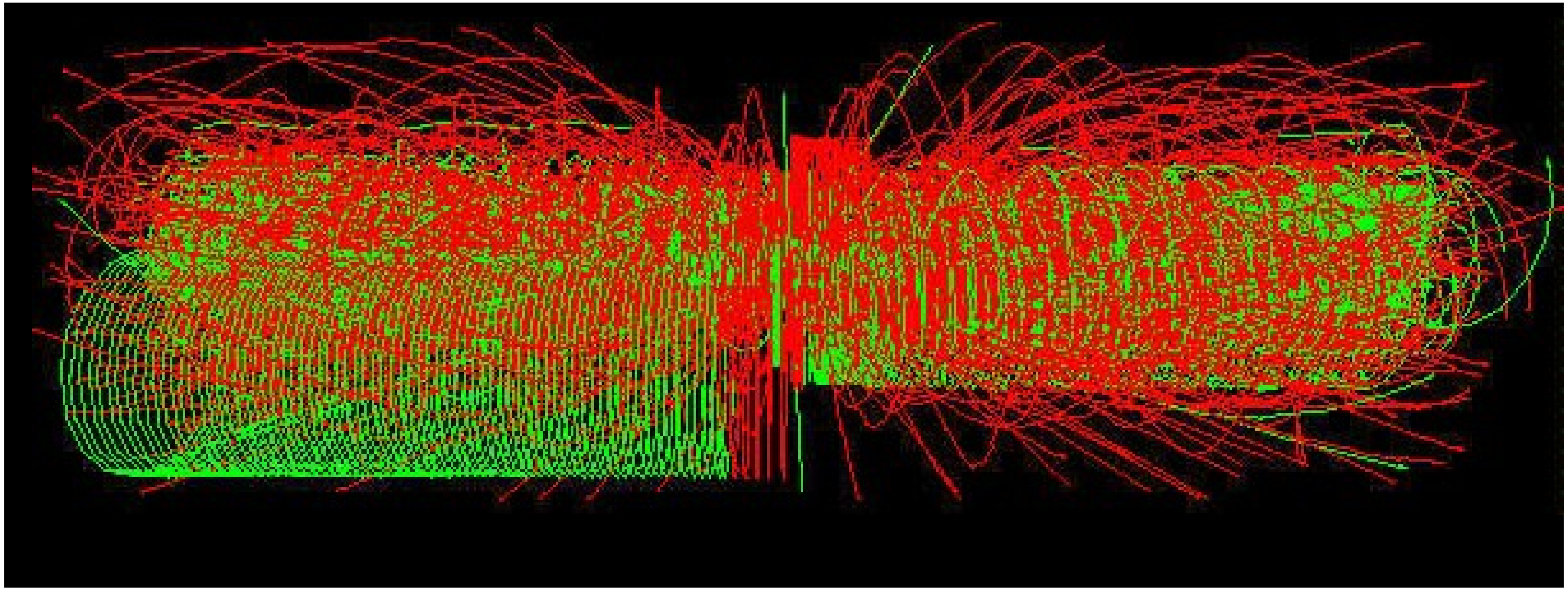
- Contemporary HEP focuses or rare processes
- The vast majority of the collisions is “boring”:
  - They only result in particles and processes that were studied to death decades ago
  - Interesting physics is ≥ 9 orders of magnitude rarer: ≥ one in a billion

THE NEEDLE



- This is what we're looking for:
  a Higgs boson decaying in four easily identifiable muons
- The LHC produces a few of these **per day**

THE HAYSTACK

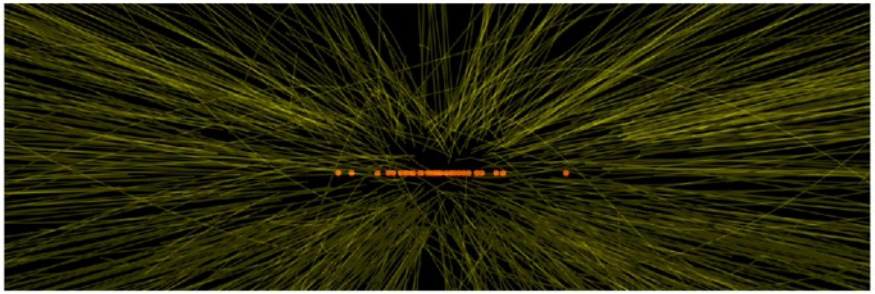


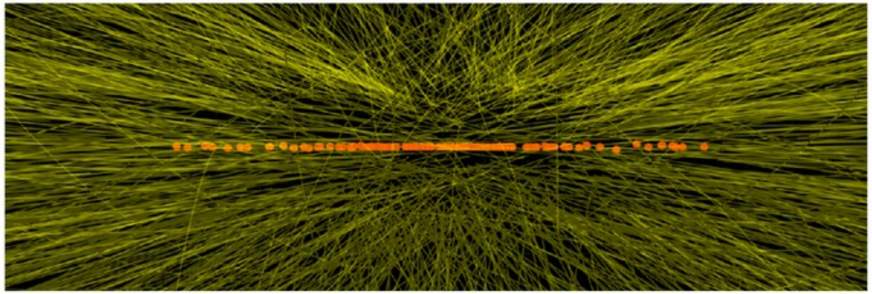
- This is where it hides:
  tens of other hard collisions producing 1000s of particles
- The LHC makes 40 million of these per second!

EXCURSUS: CLOCK, AGAIN

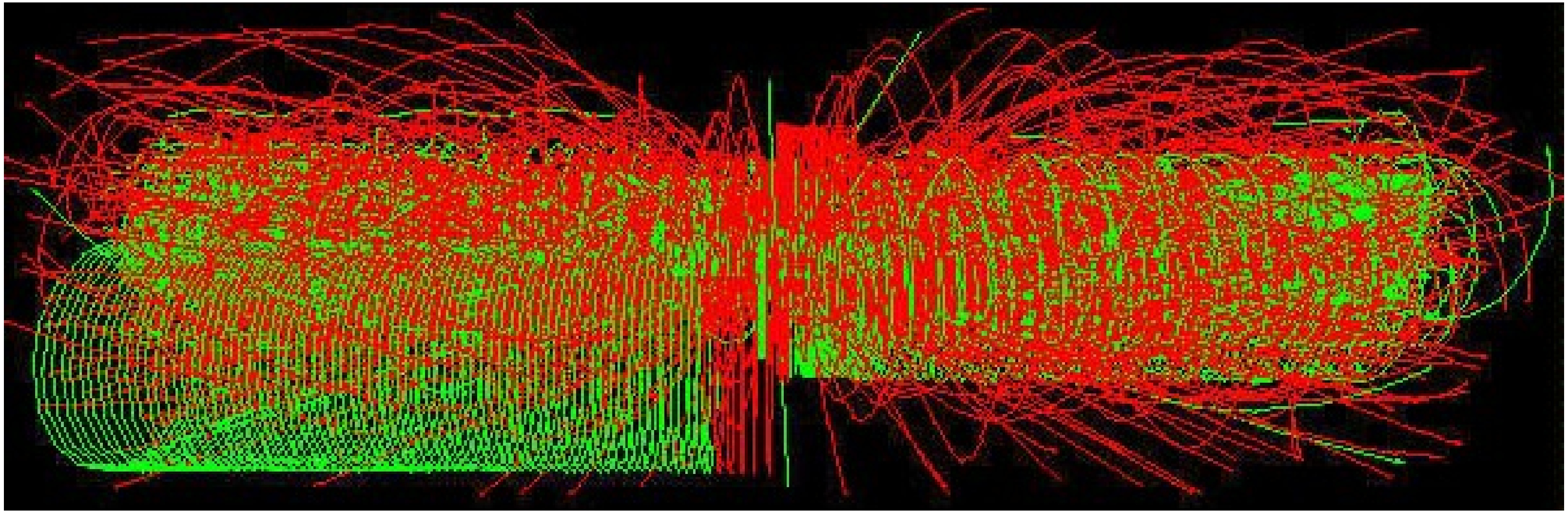
- Even though the tens of collisions are all produced by a single bunch crossing, the particles coming out of them won't produce signals in detectors at precisely at the same time

- If you had a sufficiently precise clock, you could use time as a "fourth dimension" to separate these superimposed signals
- All LHC experiments are working on this, in anticipation of the LHC increasing luminosity in 2028



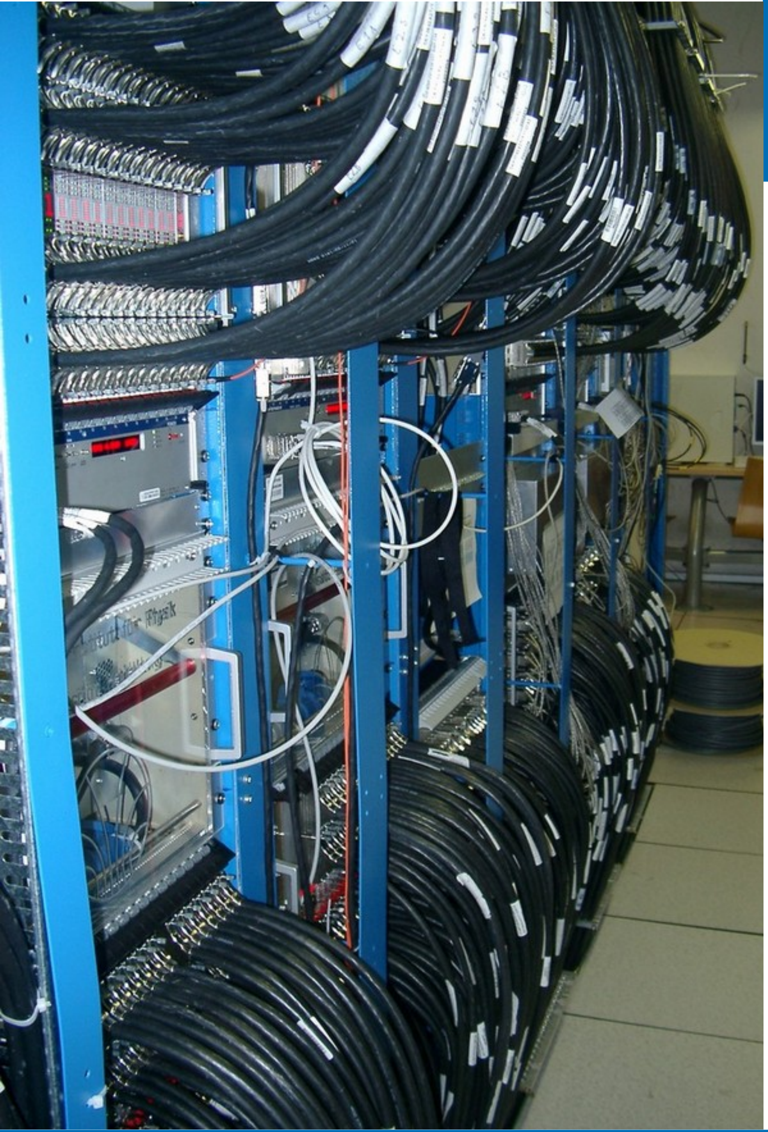


BACK TO THE HAYSTACK



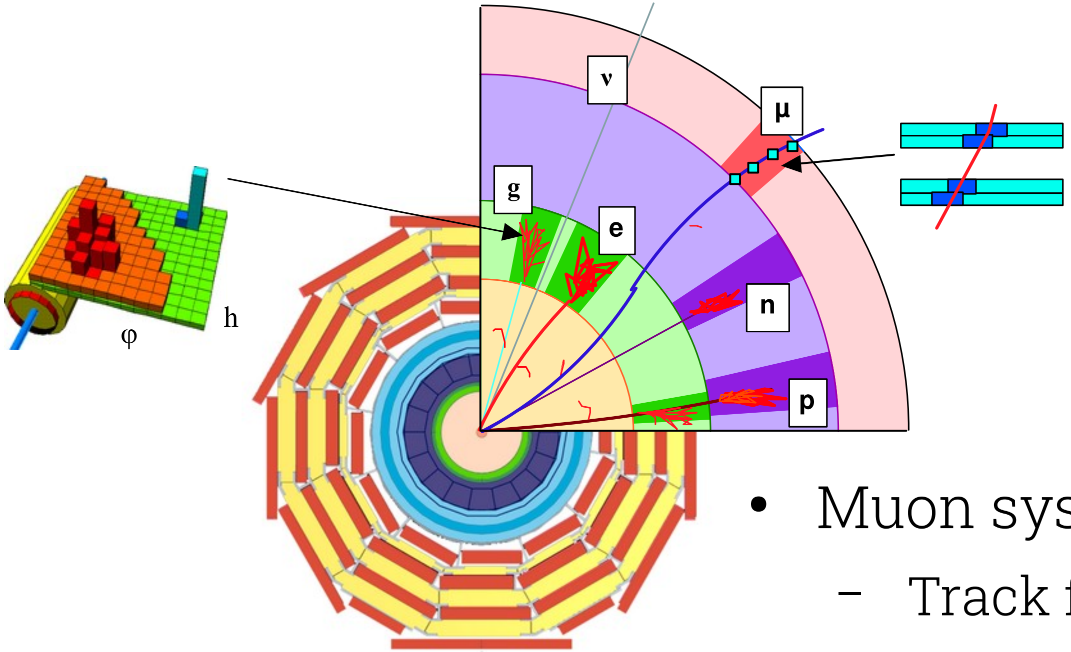
- Can we get all of these signals out of the detector?
- Yes, at a price: we have to route many (100k) of optical fibers into the bowels of our detector
  → might “steal” valuable sensitive volume from the detector itself

IF YOU MUST...



- Use fast sensors as triggers
  - In HEP: try to identify high-momentum and high-energy particles
- The remaining sensors have to buffer the data in their pipelines until a decision is made
  - The trigger has hard latency constraints
  - This usually requires custom (expensive, inflexible) electronics

FAST, LOCAL ALGORITHMS



- Calorimeters:
  - Cluster finding
  - Energy deposition evaluation
  - Coarse grained wrt. real calorimeter resolution
- Muon systems:
  - Track finding
  - Momentum evaluation
  - Dedicated fast sensors

SUMMARY

- Trigger starts the data acquisition process
- Depending on requirements, it can be:
  - A local clock
  - A global clock (collision clock / spill start)
  - The signal itself
  - Signals from dedicated sensors

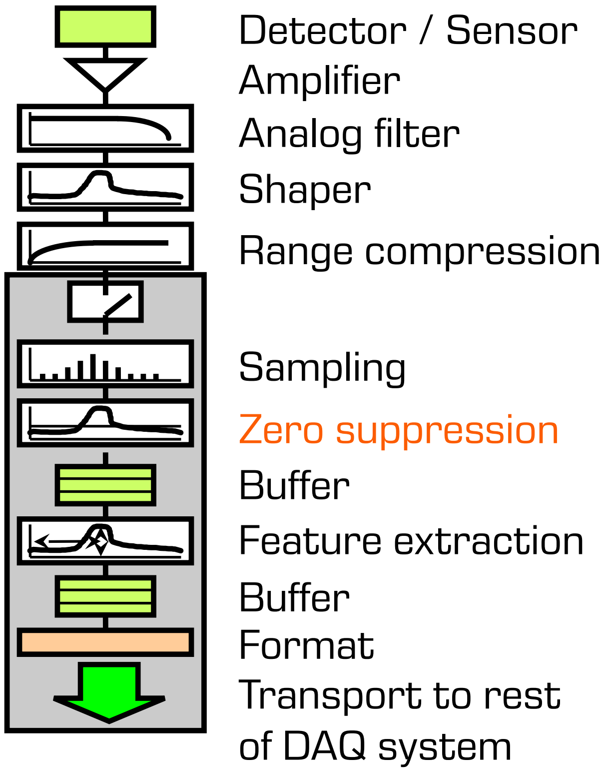
Complexity

- While the trigger decides, signals must be delayed/buffered
  → hard real-time constraints on the trigger system or data is lost
- If the trigger rate depends on a physical quantity,
  derandomising buffers are necessary to maintain good DAQ efficiency

BACKUP

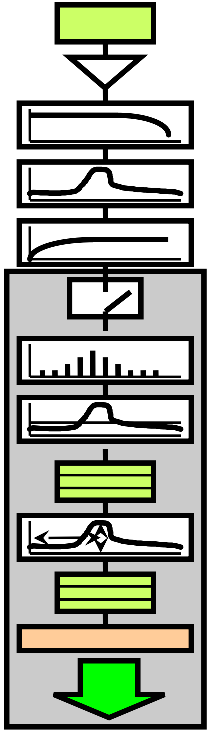
ZERO SUPPRESSION

- Without a physics-based trigger, why spend bandwidth sending data that is "zero" for the majority of the time?
- Perform "zero-suppression": only send data with non-zero content
  - Identify the data with a channel number and/or a time-stamp
  - We do not want to lose information of interest so this must be done with great care taking into account pedestals, baseline variations, common mode, noise, etc.
  - Not worth it for occupancies above ~10%

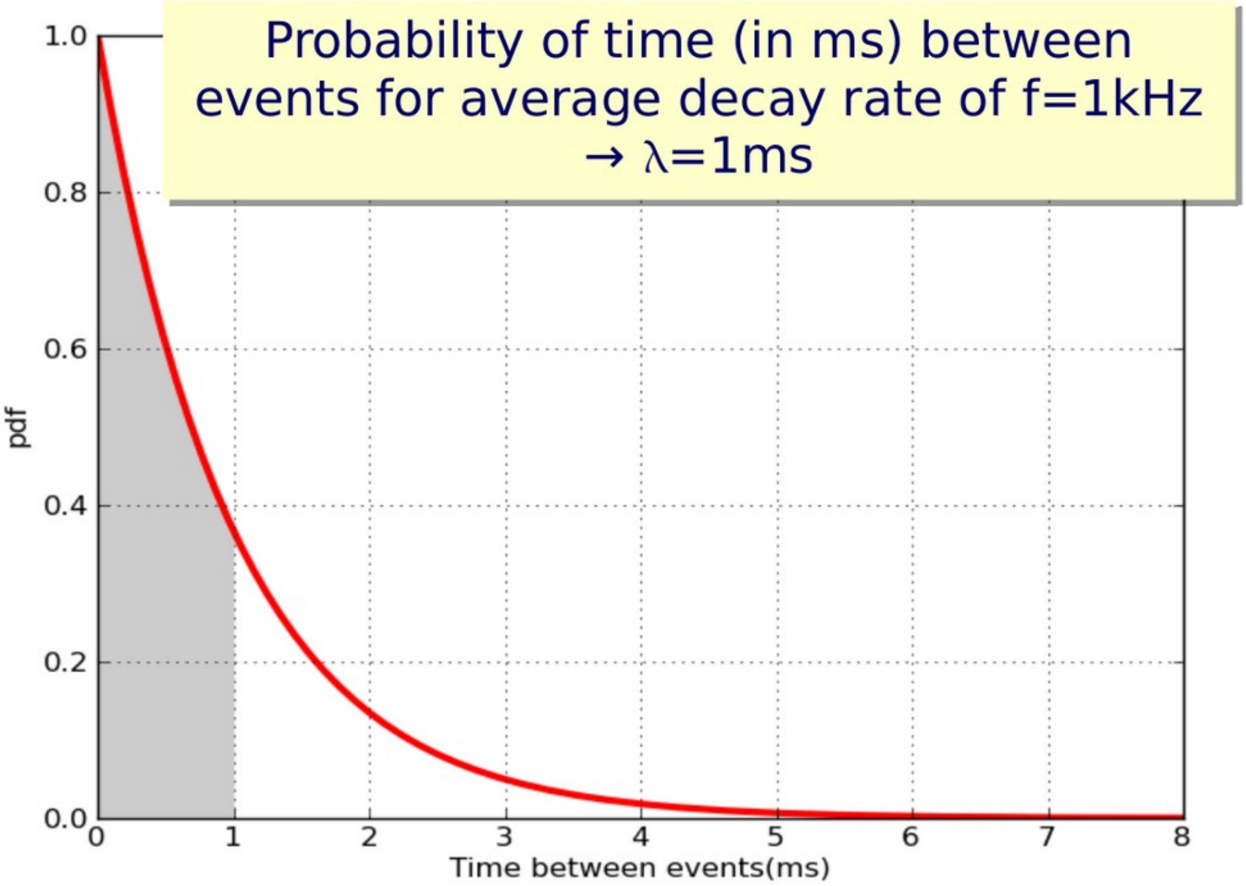


ZERO SUPPRESSION

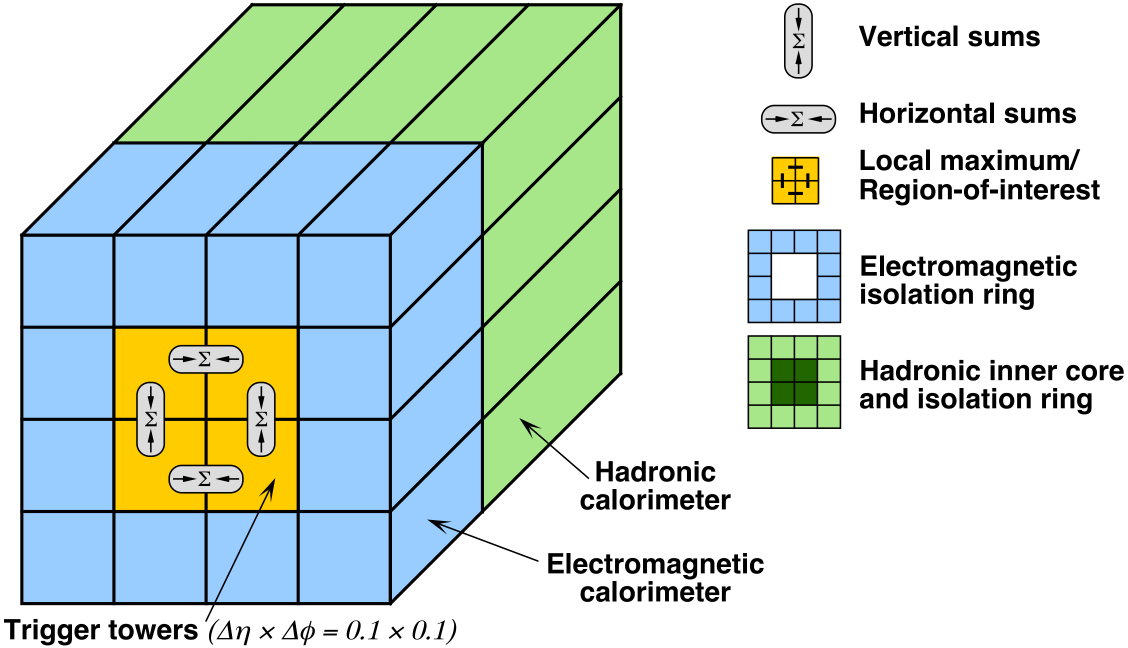
- Alternative: data compression
  - Huffman encoding and co.
  - Needs power, silicon…
- TANSTAFL
  (There Aint No Such Thing As A Free Lunch)
  - Data rates fluctuate all the time and we have to fit this into links with a given bandwidth
  - Not any more event synchronous
  - Complicated buffer handling (overflows)
  - Before an experiment is built and running it is very difficult to give reliable estimates of data rates needed (background, new physics, etc.)



POISSON PROCESS ARRIVAL TIMES



CALORIMETER TRIGGER ALGORITHMS



MUON TRIGGER ALGORITHMS