Imperial College London

TRIGGER AND DATA-ACQUISITION: PART I

UK Advanced Instrumentation Course 2024

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CREDITS

- These slides draw heavily from a long and distinguished heritage of slides drawing heavily from other people's slides which drew heavily from other people's slides, who...
  - Some of these include Sioni Summers, Alessandro Thea, Alex Tapper, Dan Saunders, Georg Auzinger – thanks to them all!

A (SLIGHTLY UNAPOLOGETIC) APOLOGY

- My examples are heavily biased towards the LHC and CMS
  - It's where my experience is, it is what I know
- The boundary between Trigger and DAQ is blurry, and I tend to err to the Trigger side
  - It's where my experience is, it is what I know

SCIENCE: THE BASICS

- Science is the art of knowing what to record, and when

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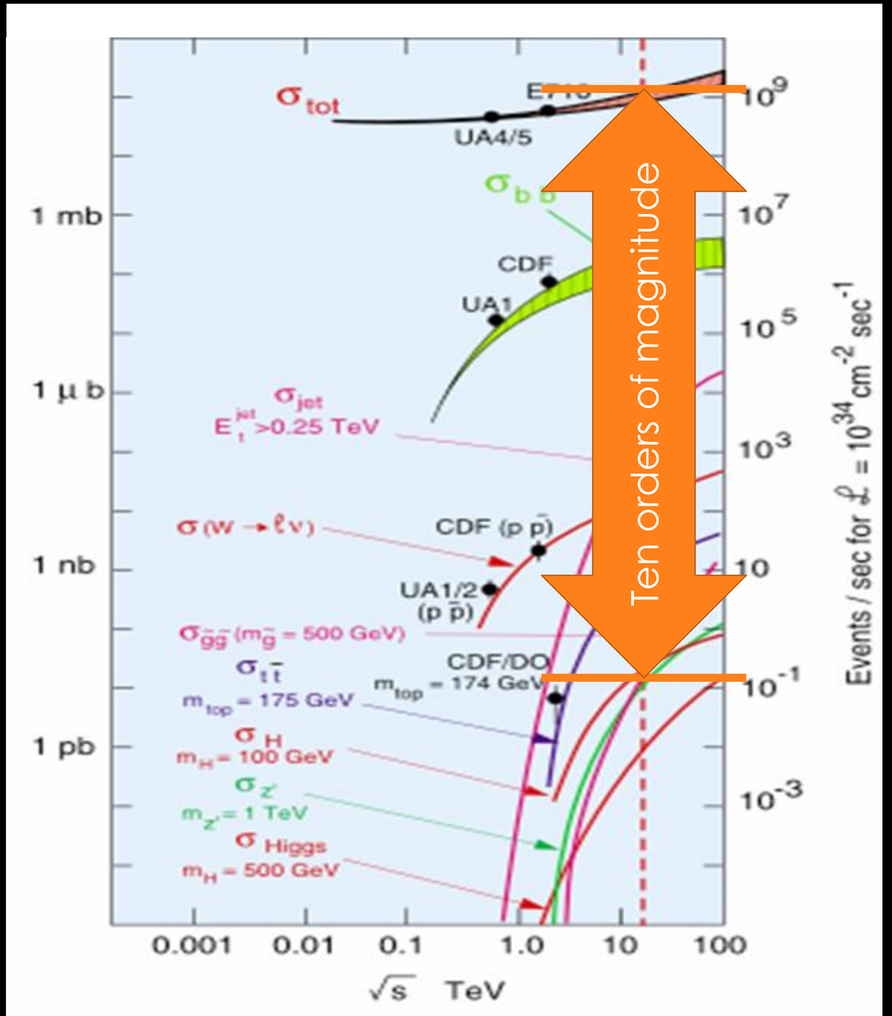
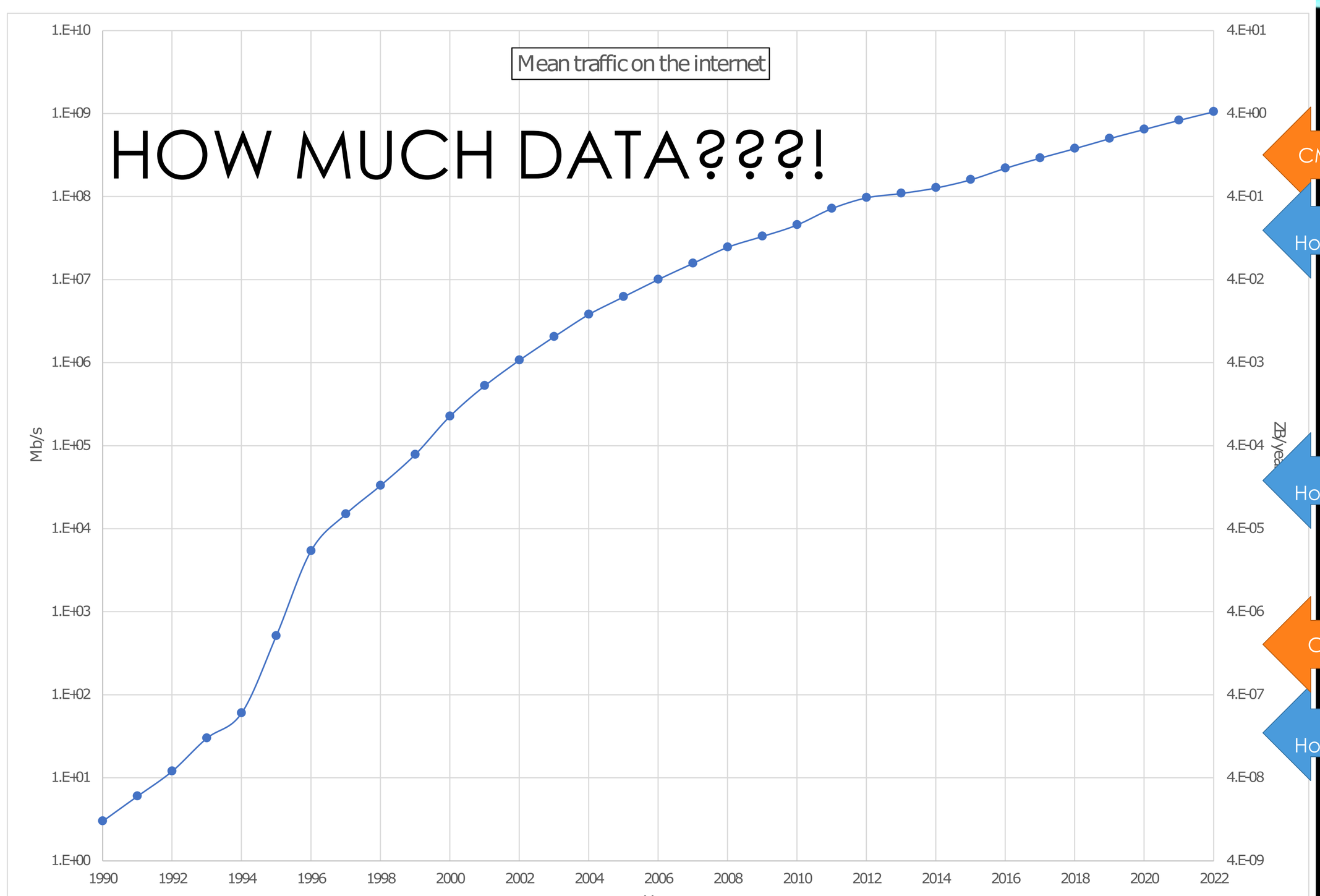
- Science is the art of knowing what to record, and when
- With CMS & ATLAS in "discovery mode", we care about the Higgs Boson or rarer
  - Higgs Boson production is ten orders of magnitude below the total interaction rate
  - That is a needle in a haystack the same mass as the Empire State Building
- And we want statistics, a lot of statistics



UNFORTUNATELY, STATISTICS REQUIRES DATA

- The LHC's 40MHz crossing rate and 2×10^{34} cm^{-2} s^{-1} luminosity was chosen to provide 2 billion interactions per second
- Unfortunately, 40MHz on a 70 million channel tracker produces the equivalent of 25Pbit/s of data

HOW MUCH DATA???!



CMS Raw

CMS compressed

1,000,000× Home broadband

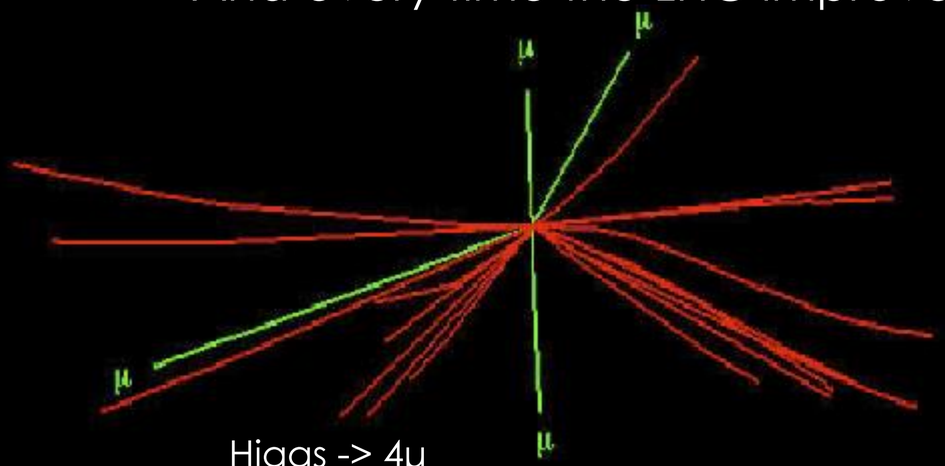
1,000× Home broadband

CMS tape-store

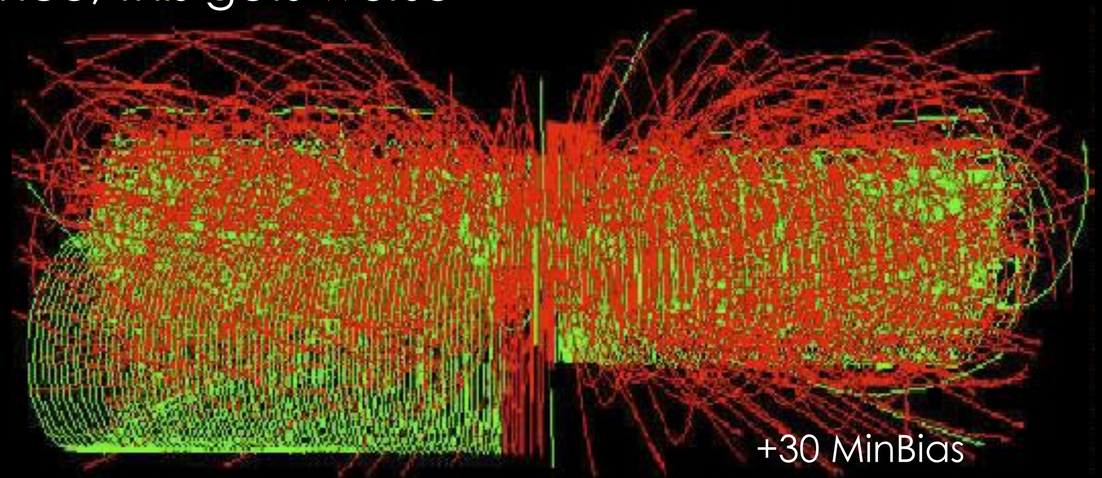
1× Home broadband

UNFORTUNATELY, STATISTICS REQUIRES DATA

- The LHC's 40MHz crossing rate and 2×10^{34} cm^{-2} s^{-1} luminosity was chosen to provide 2 billion interactions per second
- Unfortunately, 2×10^{34} cm^{-2} s^{-1} luminosity produces ~50 times more background in your detector than signal (if there is a signal at all), making selection tricky
  - And every time the LHC improves its performance, this gets worse



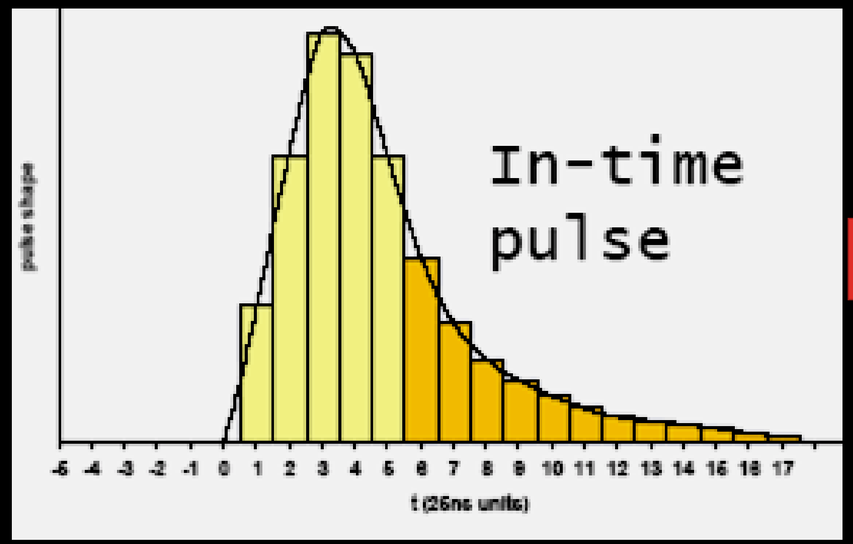
Higgs -> 4μ



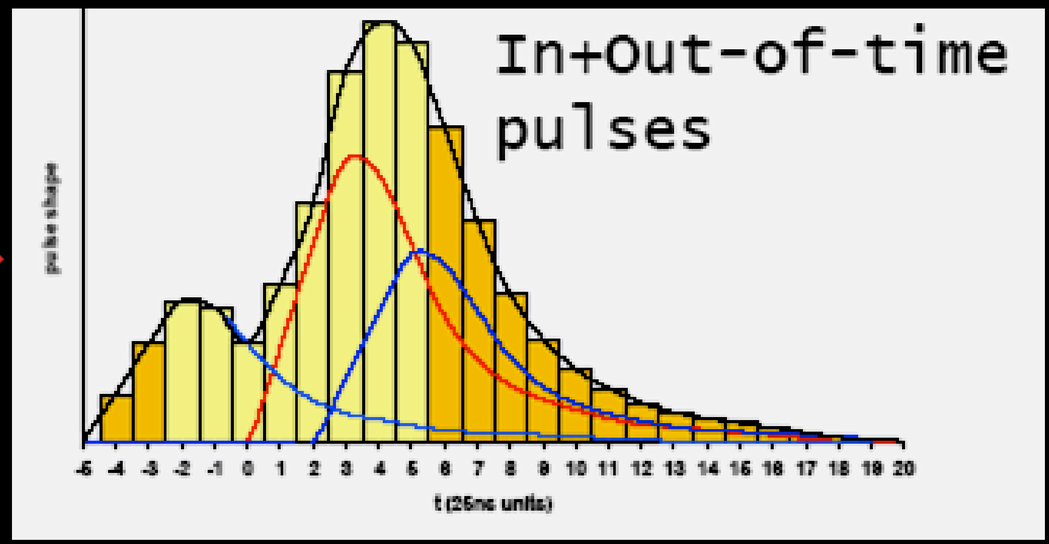
+30 MinBias

UNFORTUNATELY, STATISTICS REQUIRES DATA

- And it gets worse…
  - In-time pile up: Same crossing different interactions
  - At LHC, new events come every 25 ns
  - Out-of-time pile up: Due to events from different crossings
  - Need to identify the bunch crossing that a given event comes from

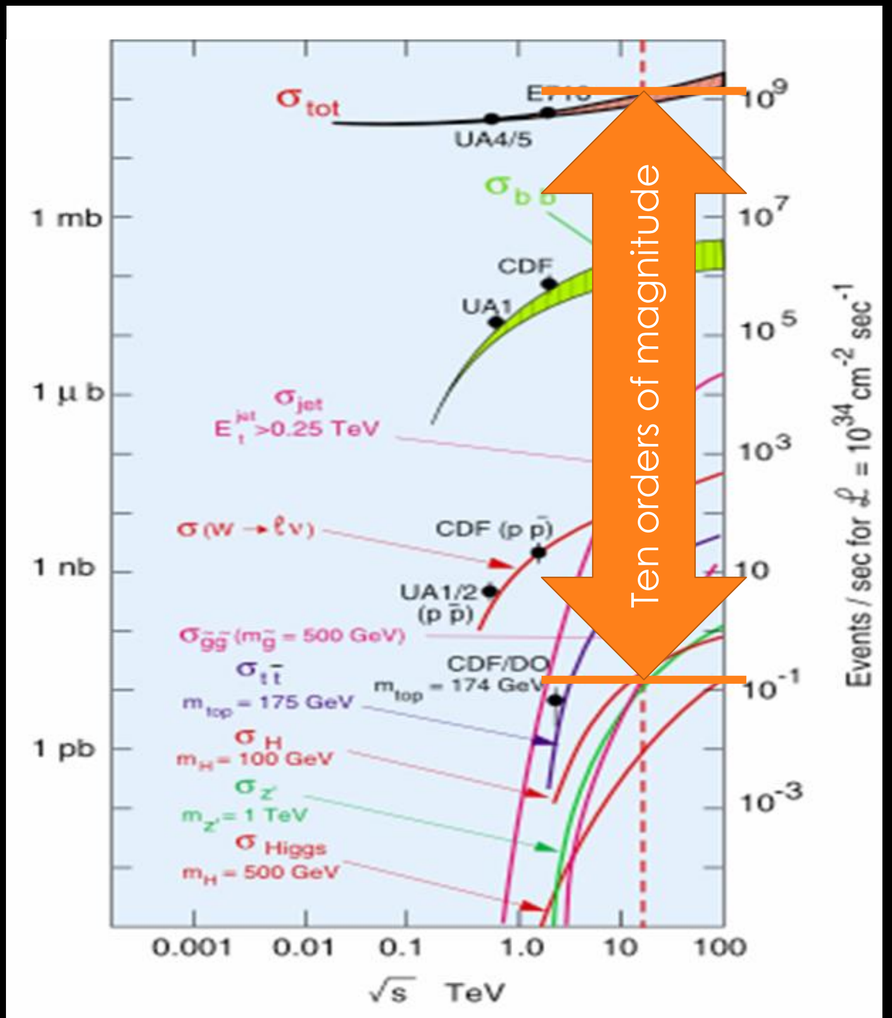


Superimpose



SCIENCE: THE BASICS

- Enormous data rate at e.g. CMS:
- 40 MHz collision rate x 1-2 MB event size > 60 TB/s
  - Can't write this to tape & process it later!
- Do we need to write it all to tape?
  - Tiny cross sections for Higgs and new physics
- Process each event, decide to accept/reject



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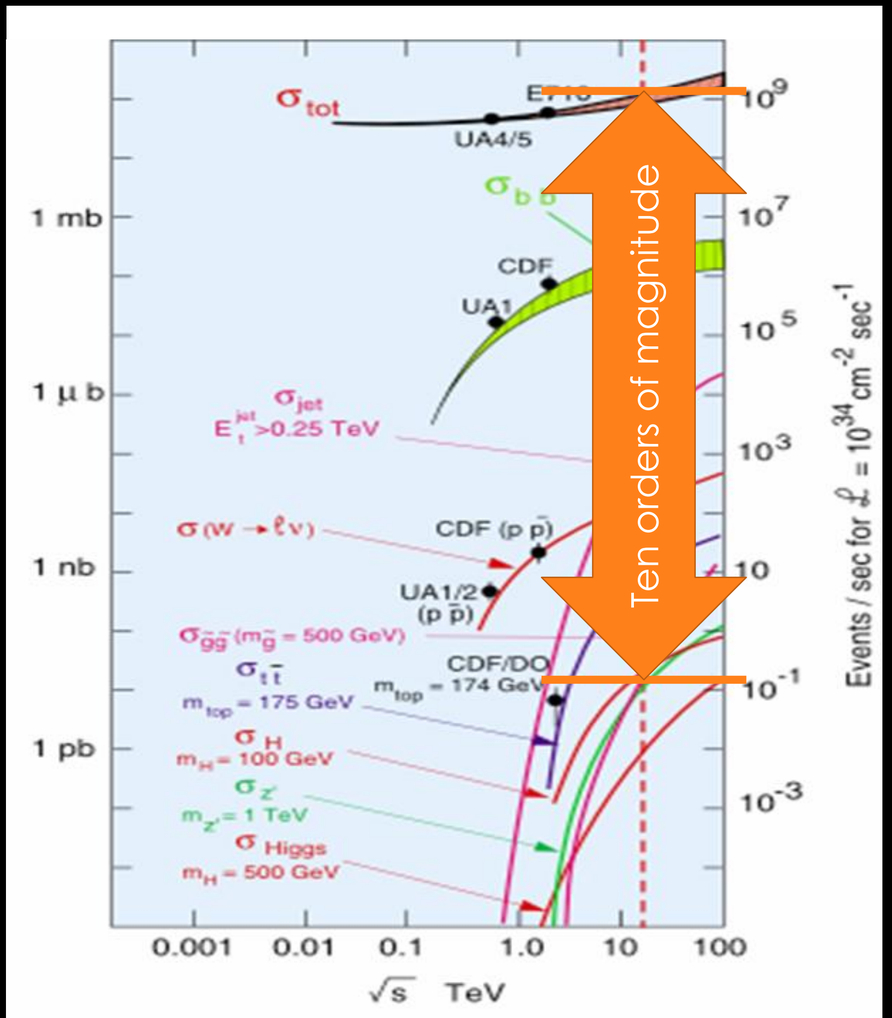
  - All online - can't go back and fix it
  - Don't screw up!



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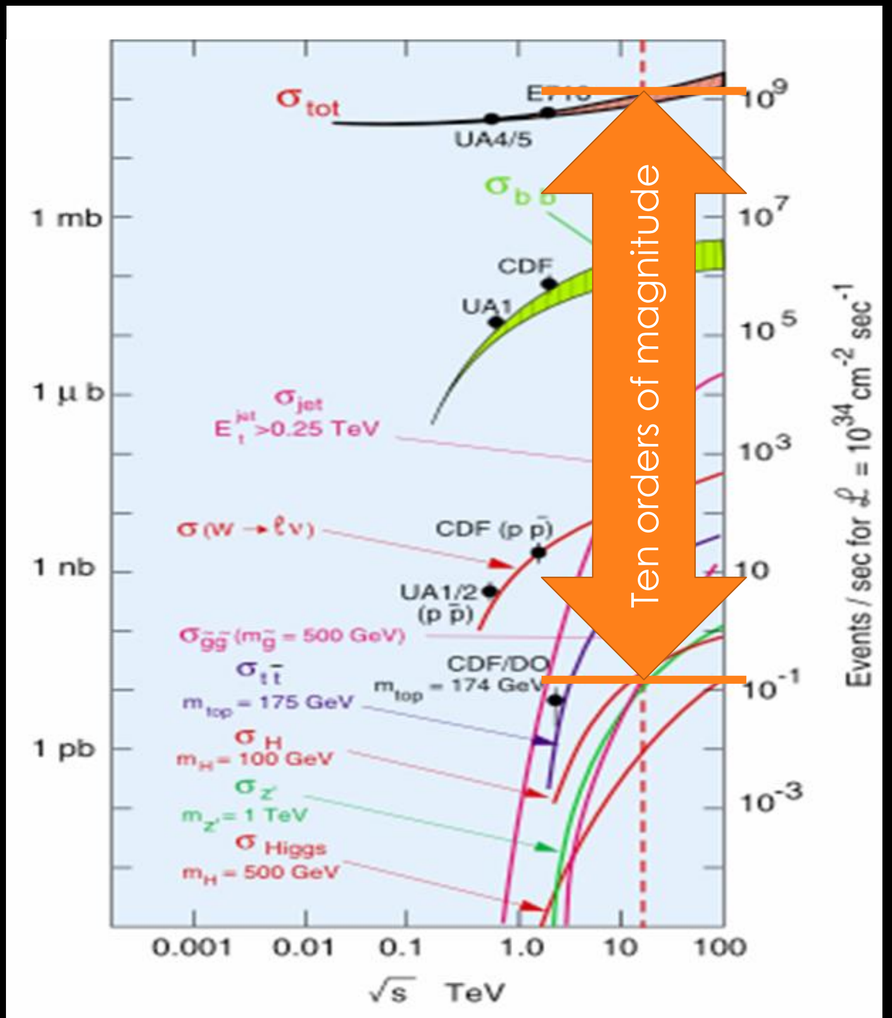
This is the art of Triggering



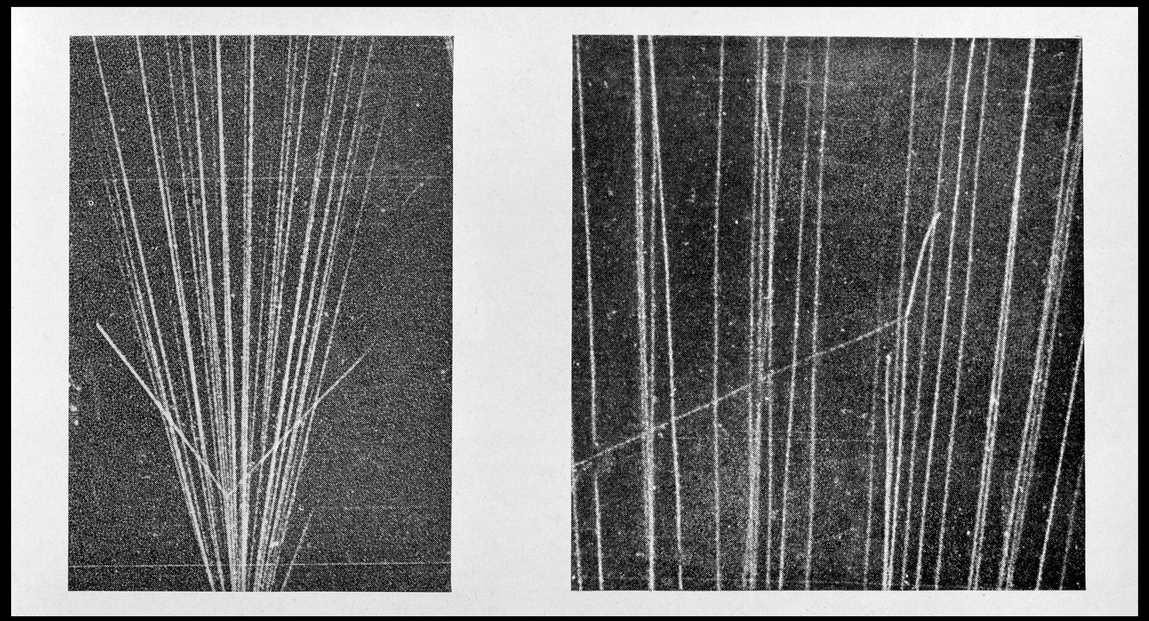
REMINDER

- Trigger basic requirements
  - Need high efficiency for selecting processes for physics analysis
  - Need large reduction of rate from unwanted high-rate processes
  - Robustness is essential
  - Highly flexible, to react to changing conditions
  - System must be affordable

WHAT'S ON THE (TRIGGER) MENU TODAY?

THE EARLIEST TRIGGER

- Cloud-chamber images recorded on film
- Need some way to trigger the camera



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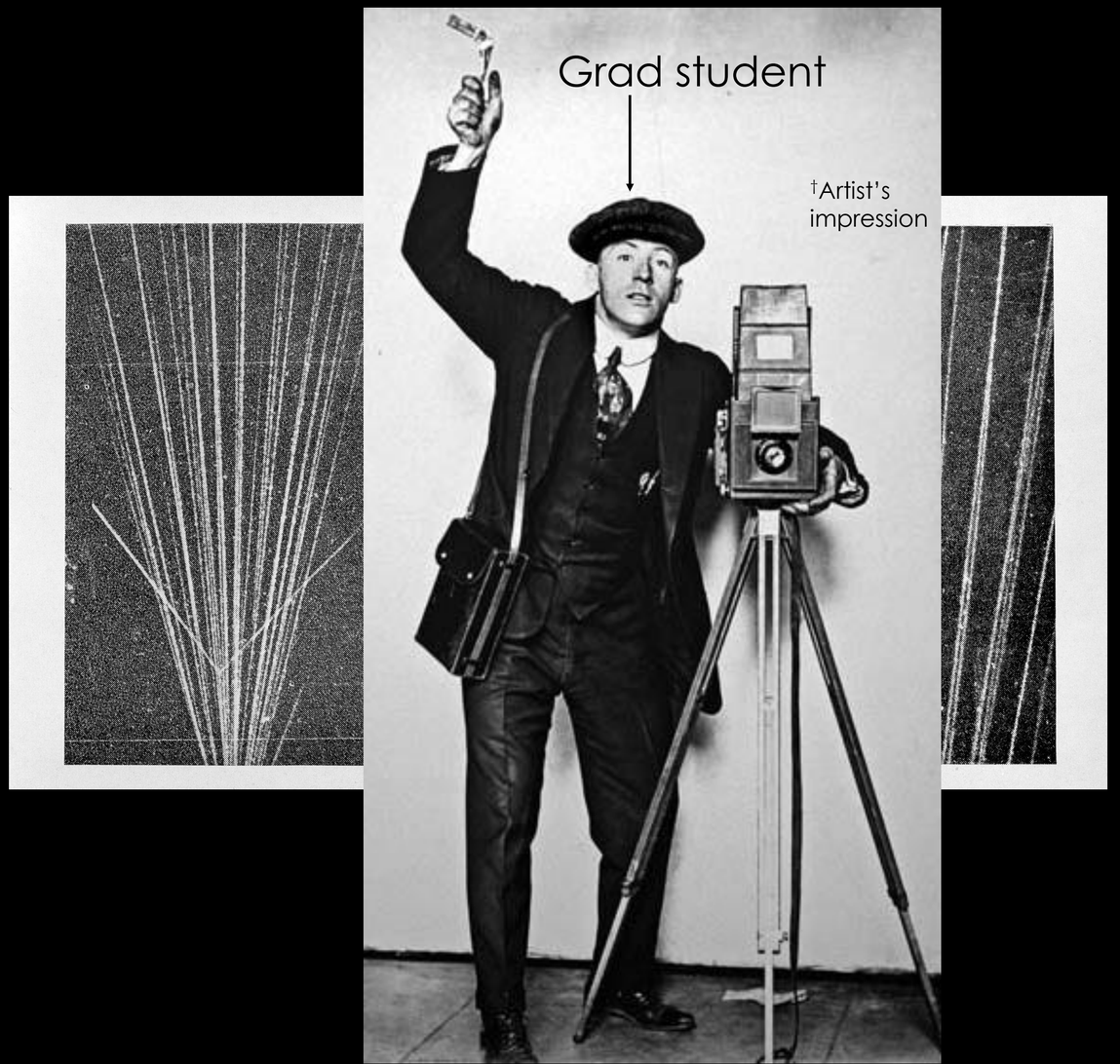
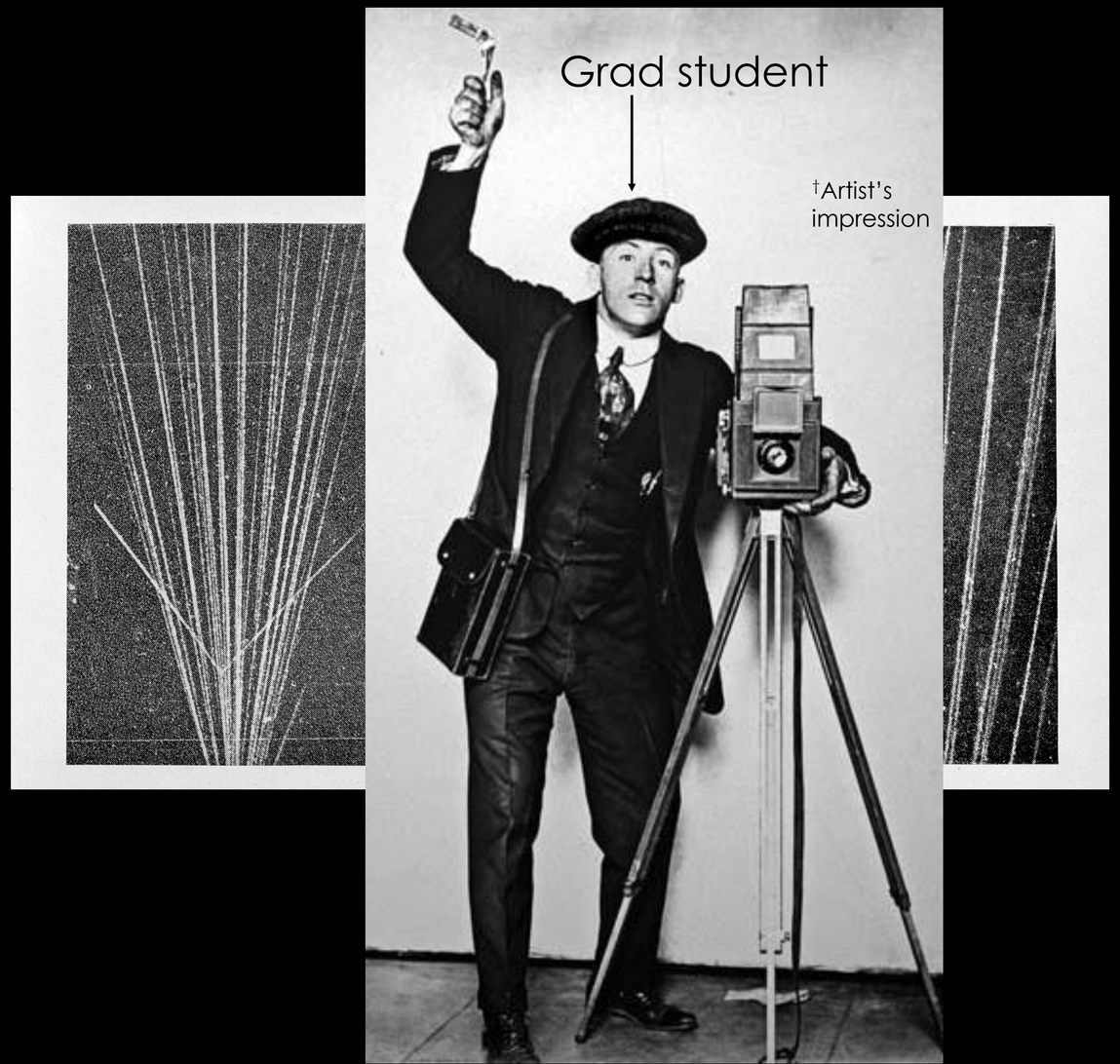


THE EARLIEST TRIGGER

- High efficiency? Nope – reflexes too slow
- Large rate reduction? Better than nothing
- Robustness? No – keep wanting sleep, coffee, toilet breaks, etc.
- Highly flexible? Depends on the student
- Affordable? Well that's one thing in your favour, I suppose



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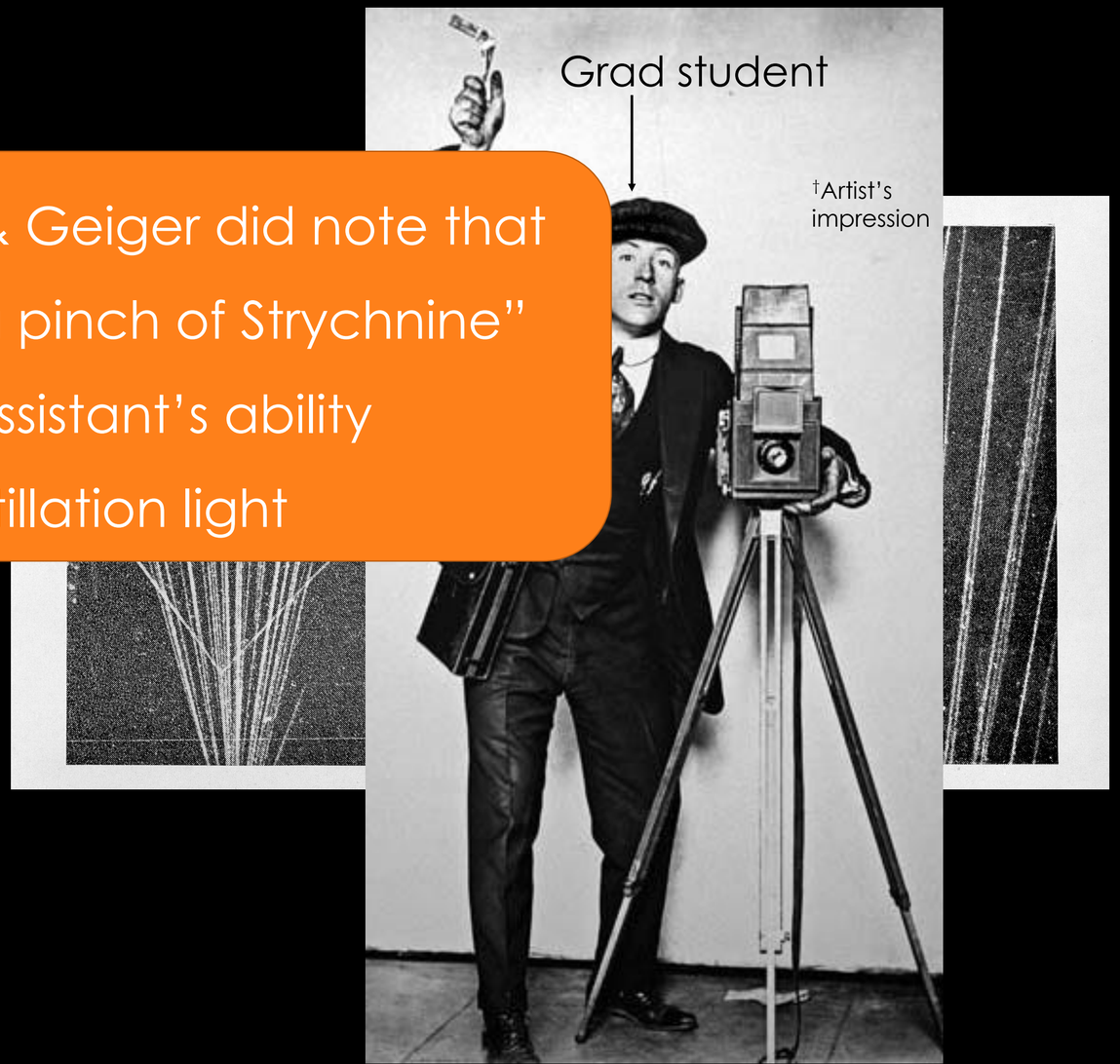


Although Rutherford & Geiger did note that "Strong coffee with a pinch of Strychnine" improved an assistant's ability to spot scintillation light

THE EARLIEST TRIGGER

- Blackett pioneered a technique to trigger the camera of cloud chambers (and got the Nobel prize for this and other work)
- Just missed out on discovering the positron in 1932
- Stevenson and Street used this to confirm the discovery of the muon in 1937

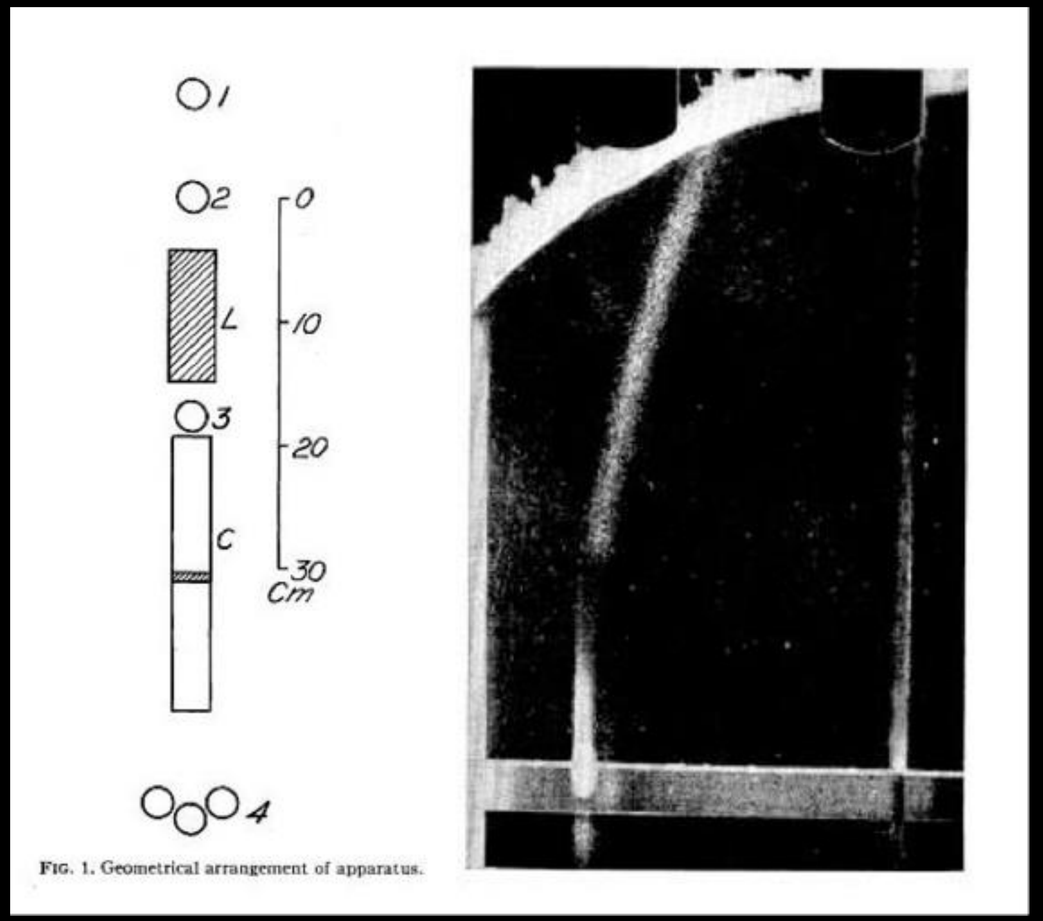
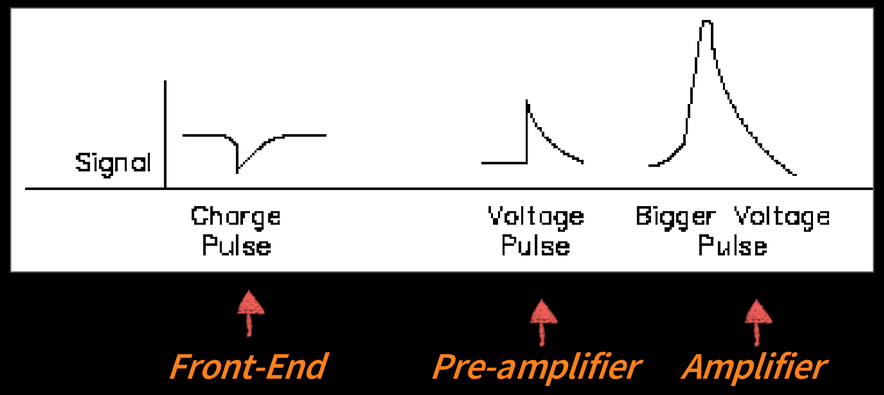


FIG. 1. Geometrical arrangement of apparatus.

Trigger photo capture when Geiger counters 1,2,3, but not 4 record coincidental measurements

THE SIMPLEST TRIGGER SYSTEMS

- Source: Use the signals from the Front-End of the detectors themselves
  - Binary: tracking detectors (pixels, strips)
  - Analog: tracking detectors, time of flight detectors, calorimeters, …



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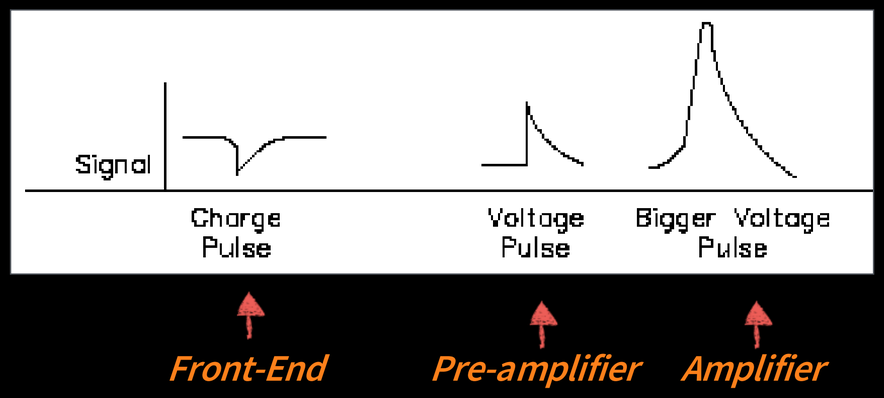
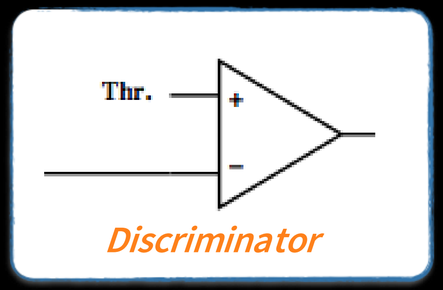
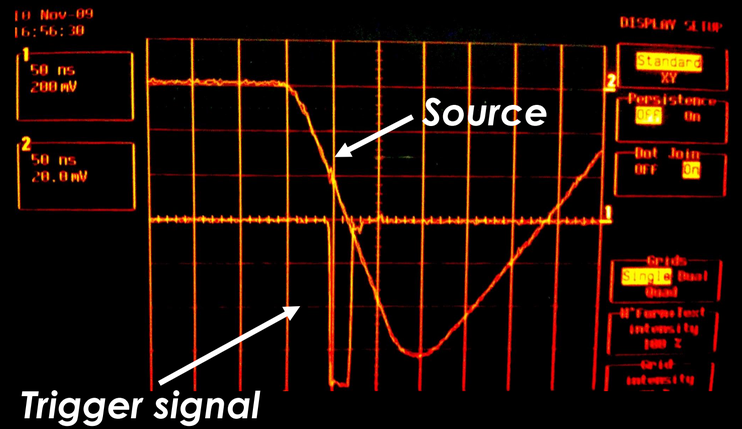




Accept

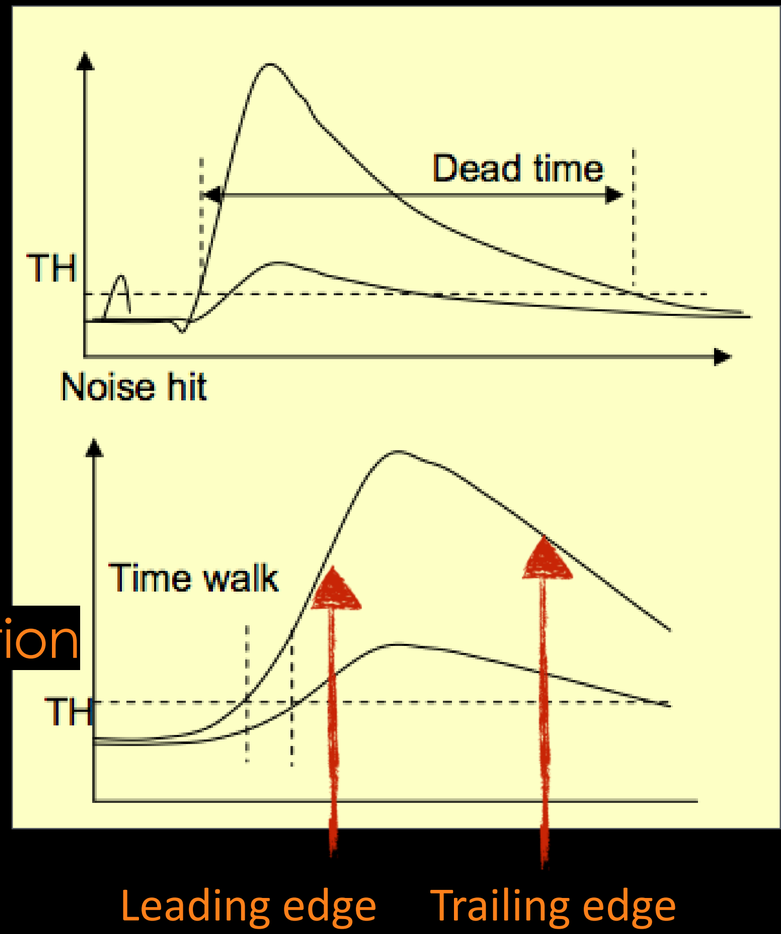
Reject



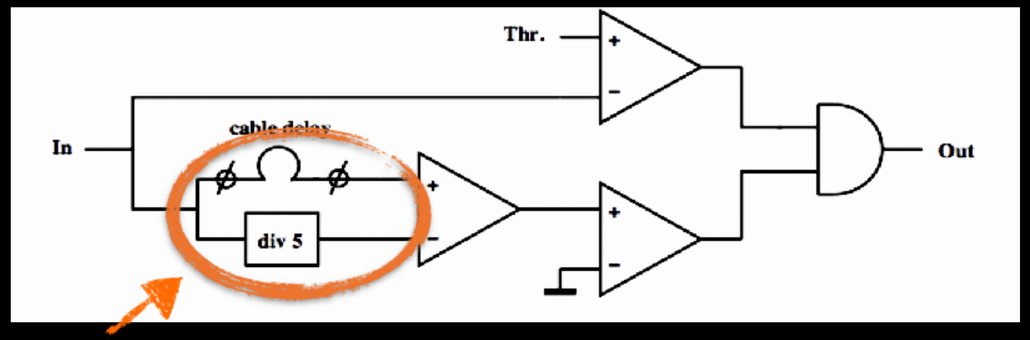
- The most trivial trigger algorithm: ***Signal > Threshold***
  - Apply the lowest possible threshold
  - Identify best compromise between hit efficiency and noise rate

DETECTOR SIGNALS CHARACTERISTICS

- Pulse width
  - Limits the effective hit rate
  - Must be adapted to the desired trigger rate
- Time walk
  - The threshold-crossing time depends on the signal amplitude
  - Must be minimal in good trigger systems
- Time walk can be suppressed by triggering on total signal fraction
  - Applicable on same-shape input signals with different amplitude
  - Useful for scintillator detectors and photomultipliers



THE CONSTANT FRACTION DISCRIMINATOR

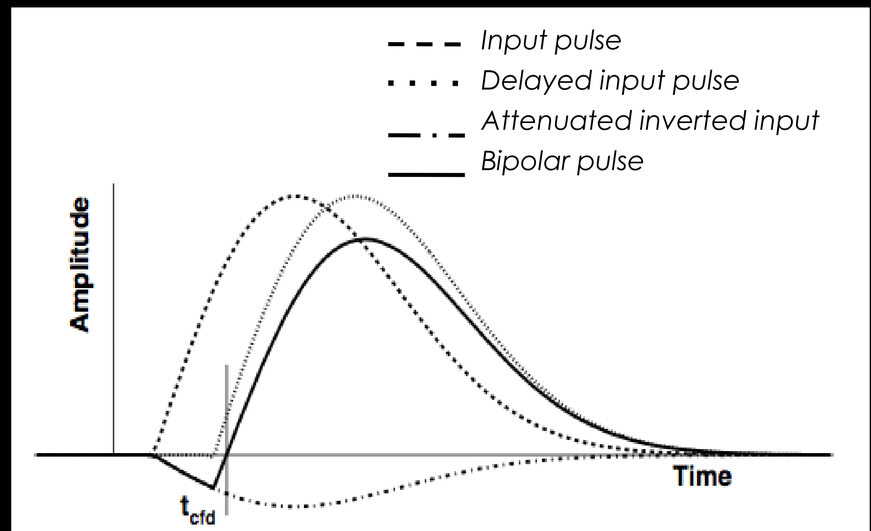


- Attenuation + configurable delay applied before the discrimination determines t_{CFD}
- If delay too short, the unit works as a normal discriminator since the output of the normal discriminator fires later than the CFD part

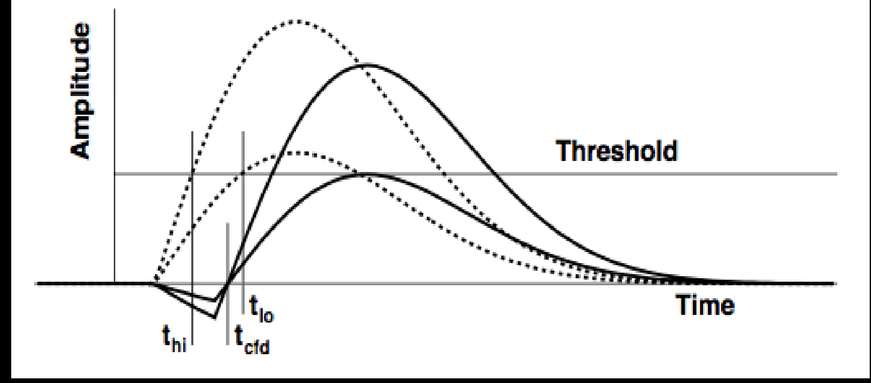
Signals with the same rising time, at a fraction f

$$\Delta t_f = t(f \cdot A_0) - t(A_0) = \text{const.}$$

$$A(t)/_f - \cdot A(t - \Delta t) = 0 \quad \text{at } t = t_{cfd}$$

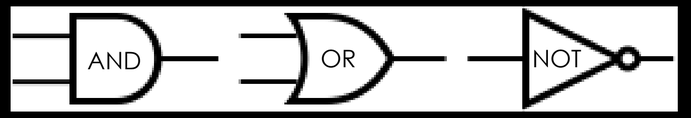


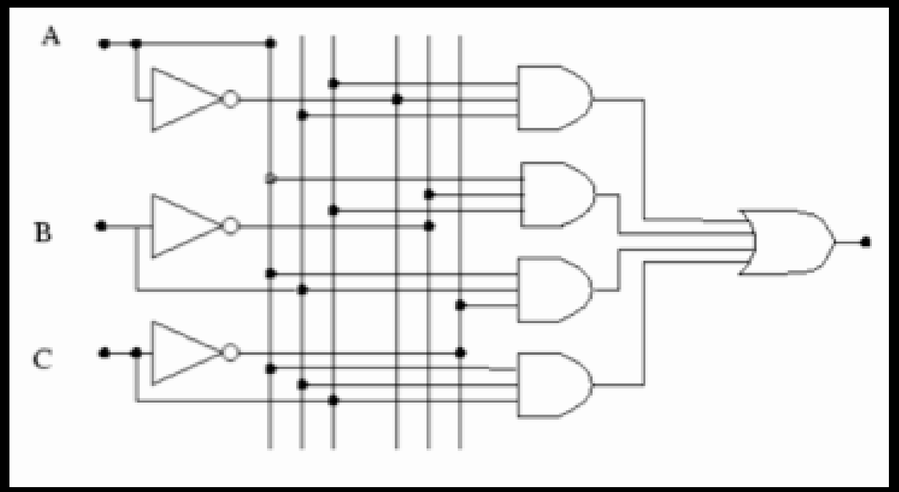
The output of the CFD fires when the bipolar pulse changes polarity



TRIGGER LOGIC IMPLEMENTATION

- Once we are in the digital domain, all manipulations can be broken down to a Boolean operations
- Combinatorial
  - Summing, Decoders, Multiplexers,…
- Sequential
  - Flip-flops, Registers, Counters,…





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- Combinatorial
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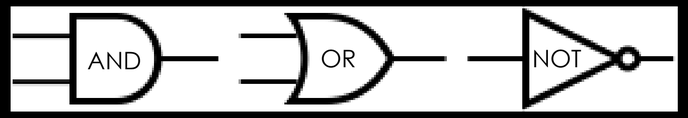
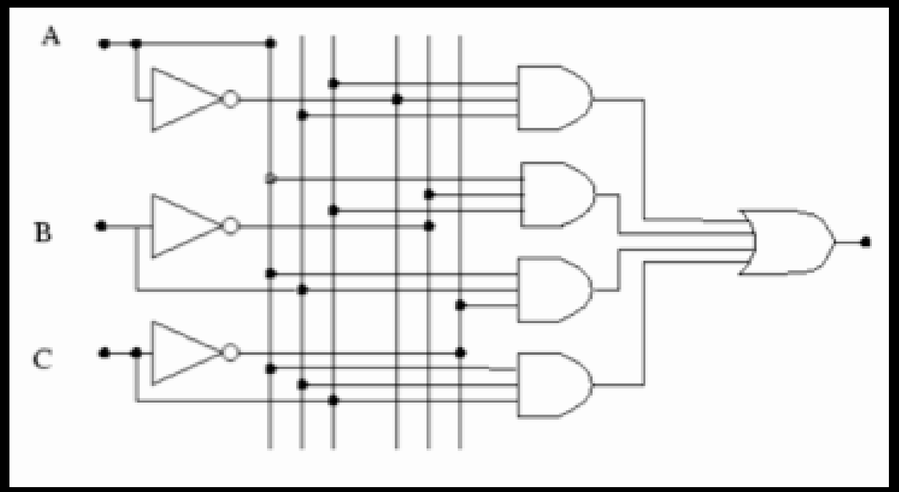
Data propagates as a wave through the logic

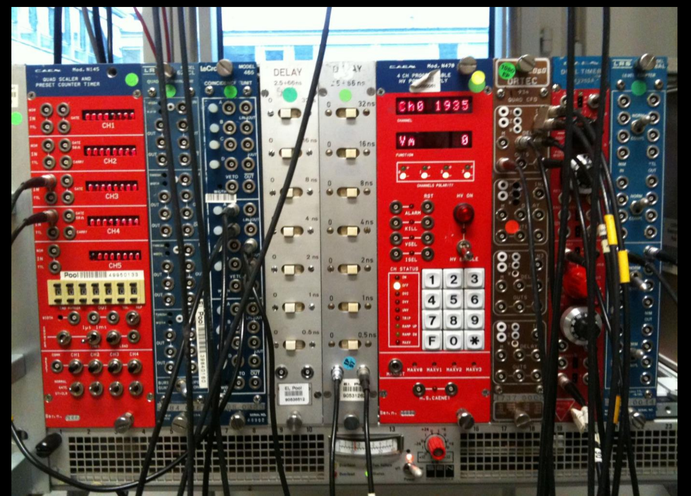
Operations happen at well defined times and in a well defined order





A SIMPLE TRIGGER WANTS A SIMPLE SYSTEM

- A simple trigger system can start with a NIM crate
- Common support for electronic modules
- Standard impedance, connections, logic levels
  - Watch out for negative voltage levels: Low = 0v, High = -0.8V



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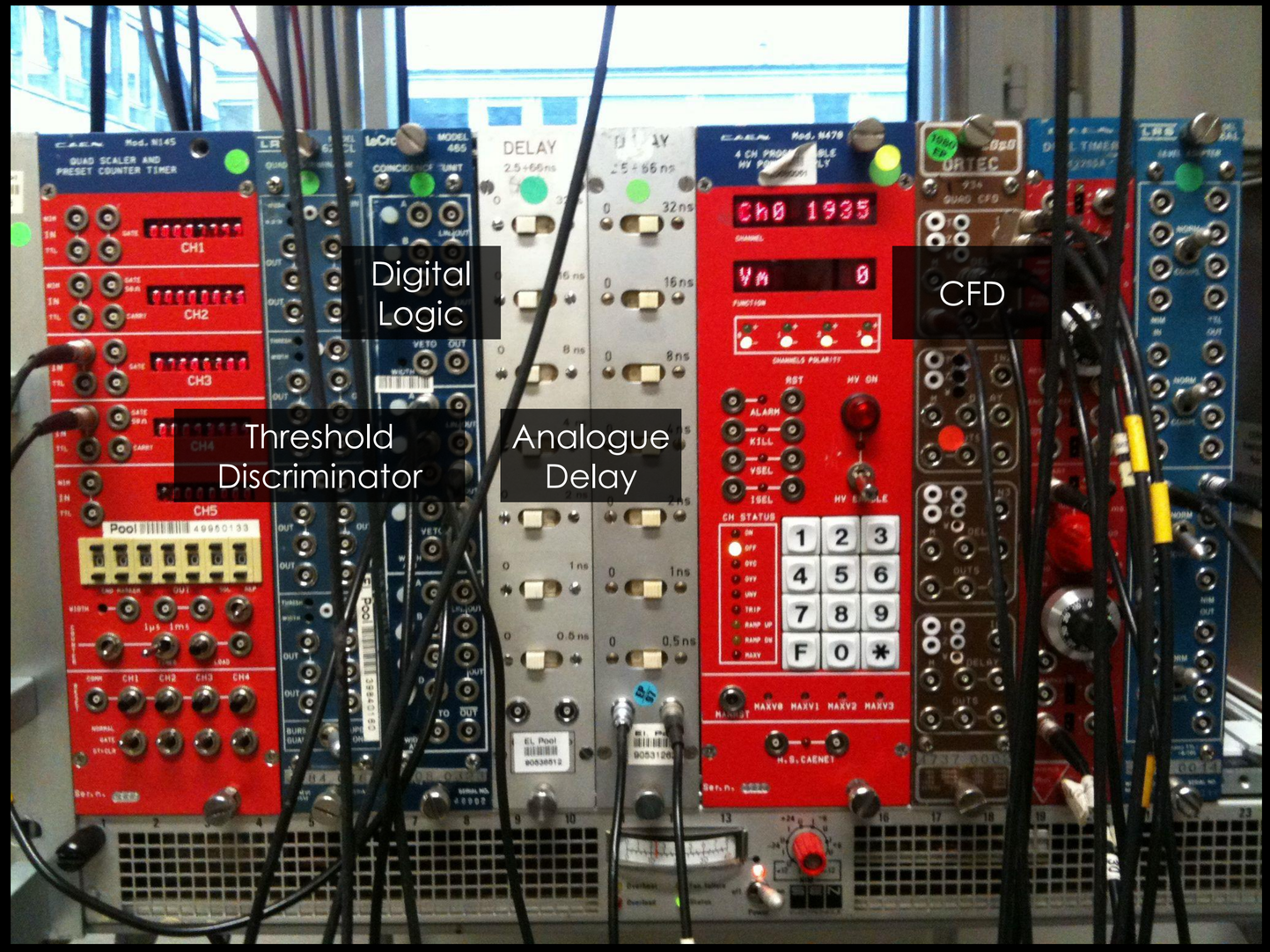
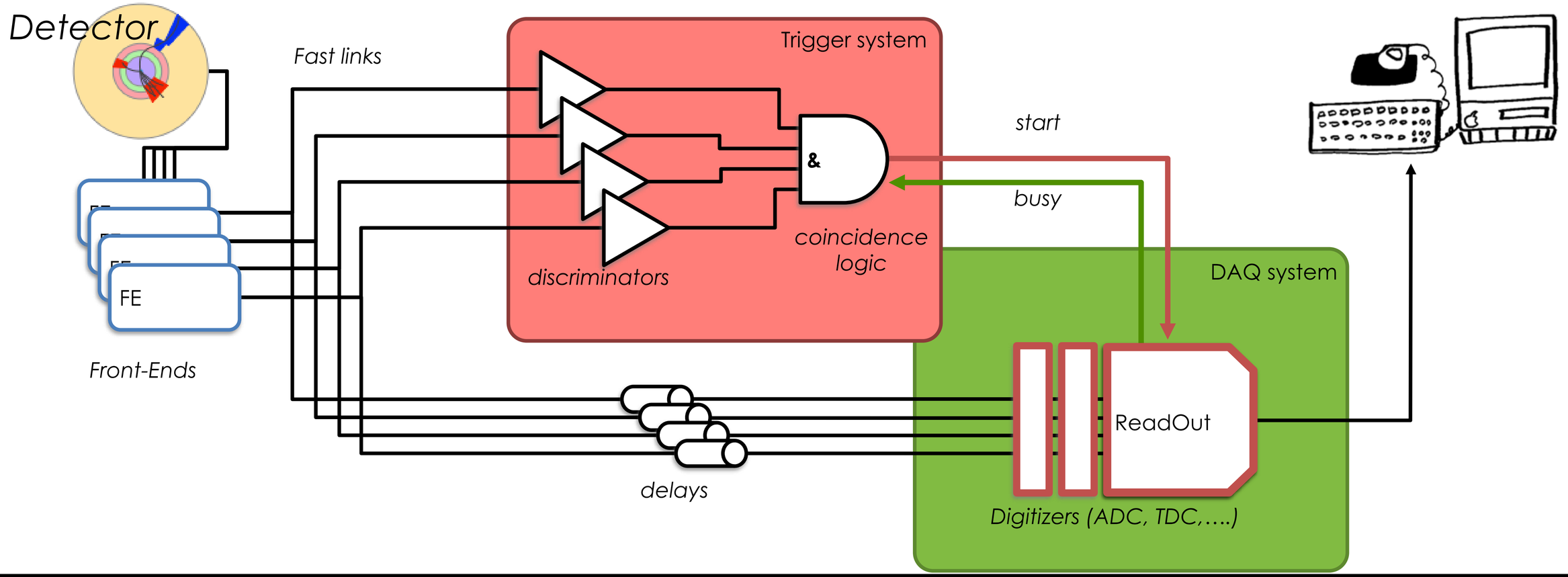
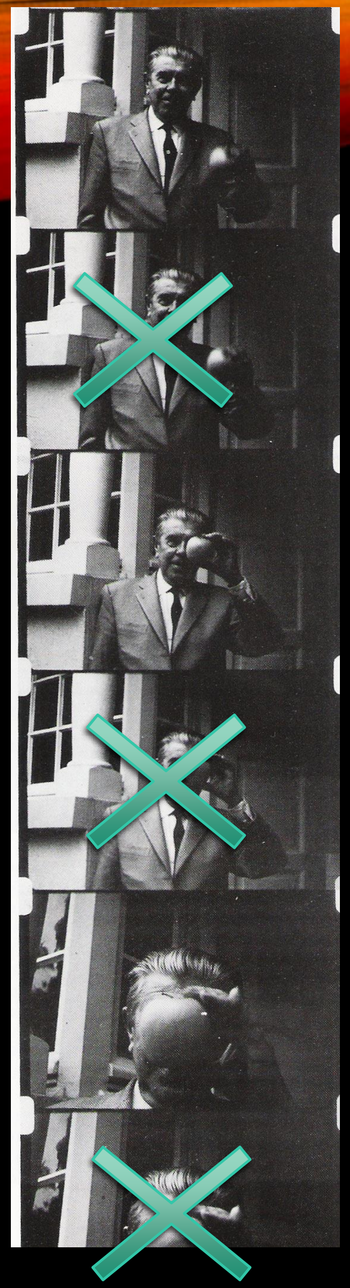


A SIMPLE TRIGGER AND DAQ SYSTEM



KEYWORD: DEADTIME



- The key parameter in high speed trigger systems design
  - The fraction of the acquisition time when no events can be recorded.
  - Typically of the order of **few %**
  - Reduces the overall system efficiency
- Arises when a given processing step takes a finite amount of time
  - Readout dead-time
  - Trigger dead-time
  - Operational dead-time

DEADTIME EXAMPLE

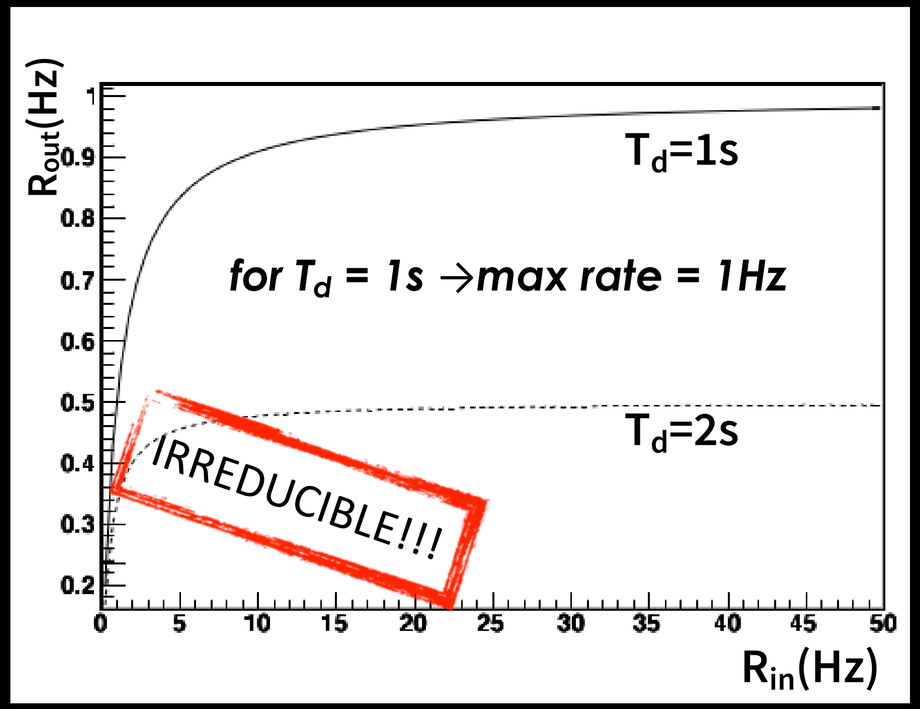
- Writing to disk or tape is much slow than accepting data into RAM
- If you select an event and start writing it to disk, you cannot accept any more events until you finish writing, even if they are interesting

DEADTIME EXAMPLE

- For input rate "R_{in}", Readout rate "R_{out}", and time taken to write to disk "T_d"
- Fraction of 1s "lost" to writing = $R_{out} \cdot T_d$
- Event output rate $R_{out} = (1-R_{out} \cdot T_d) \cdot R_{in}$

Fraction of surviving events

$$\frac{R_{out}}{R_{in}} = \frac{1}{1+R_{in}T_d}$$

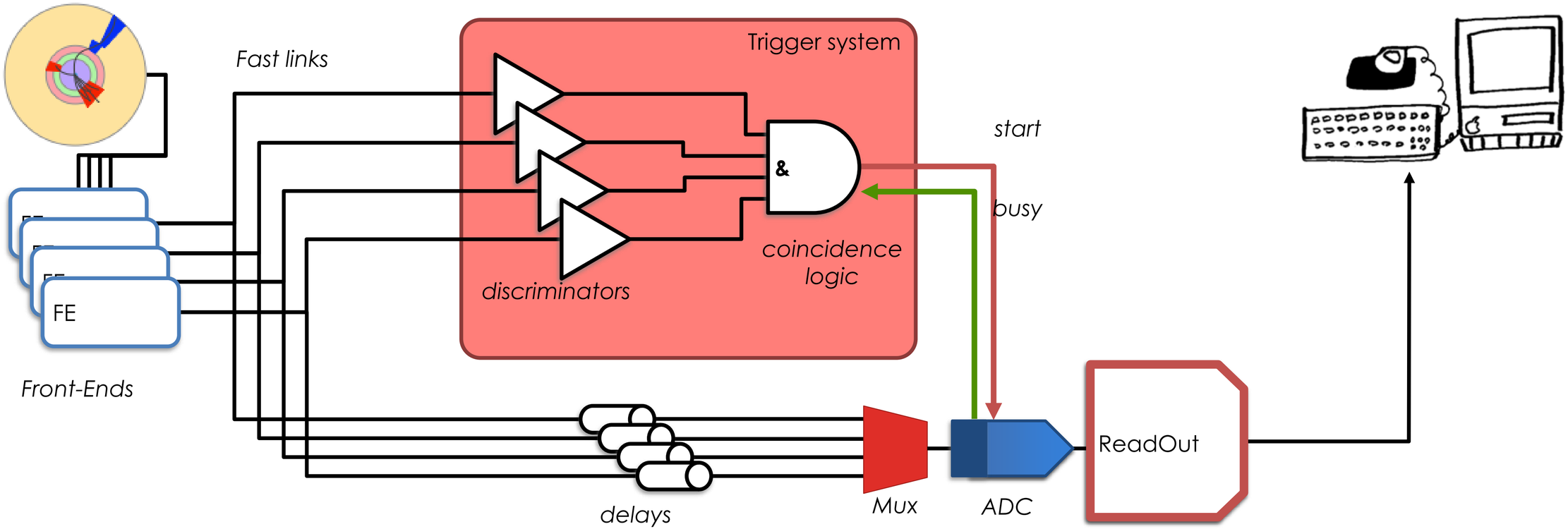


To achieve high efficiency $\Rightarrow R_{in} \cdot T_d \ll 1$

DEADTIME

- Writing to disk or tape is much slow than accepting data into RAM
- If you select an event and start writing it to disk, you cannot accept any more events until you finish writing, even if they are interesting
- Same principle applies to processing time
  - For example, ADCs

A SIMPLE TRIGGER SYSTEM: DEADTIME



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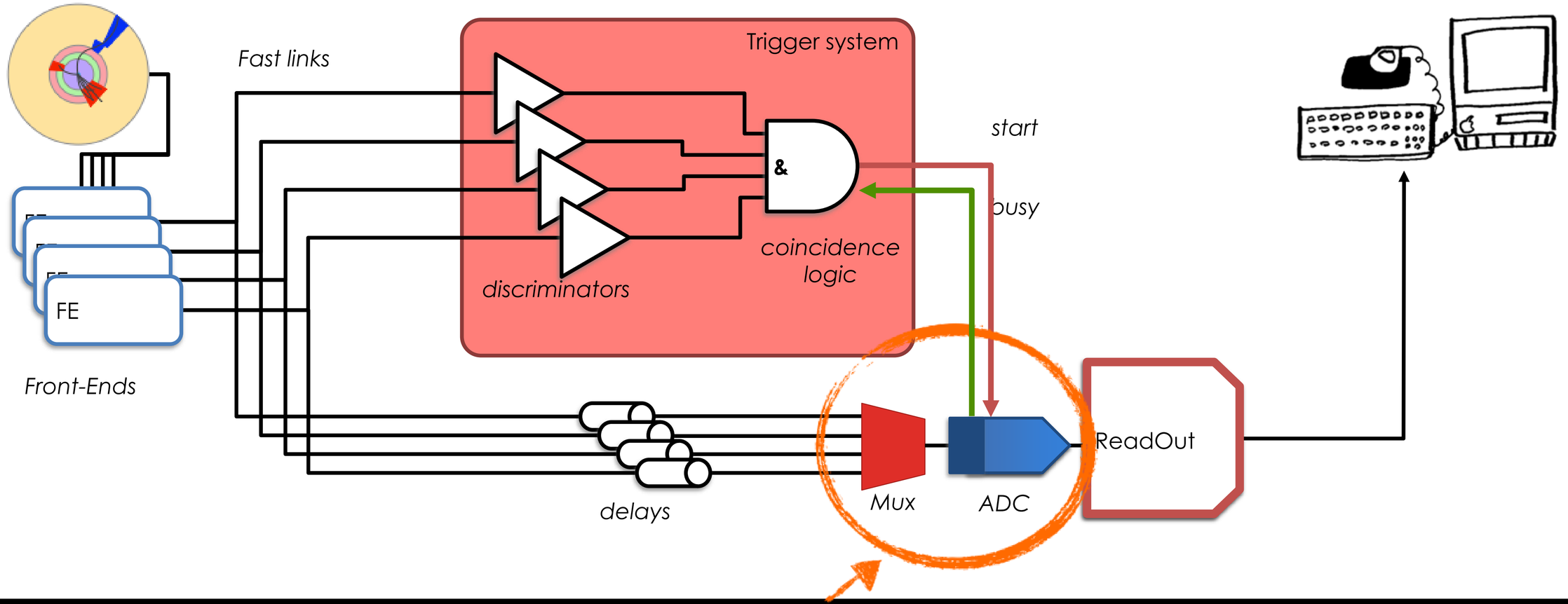
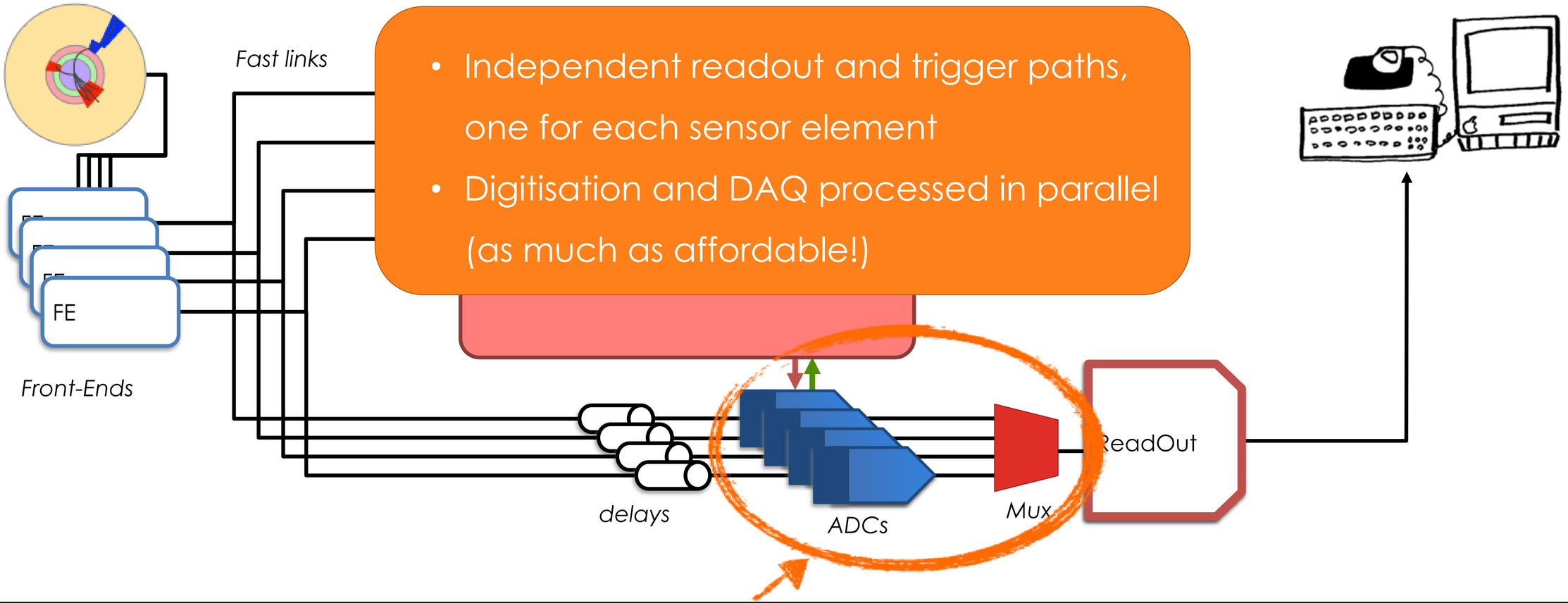


If ADC is the critical step for deadtime,
this is clearly a really bad plan

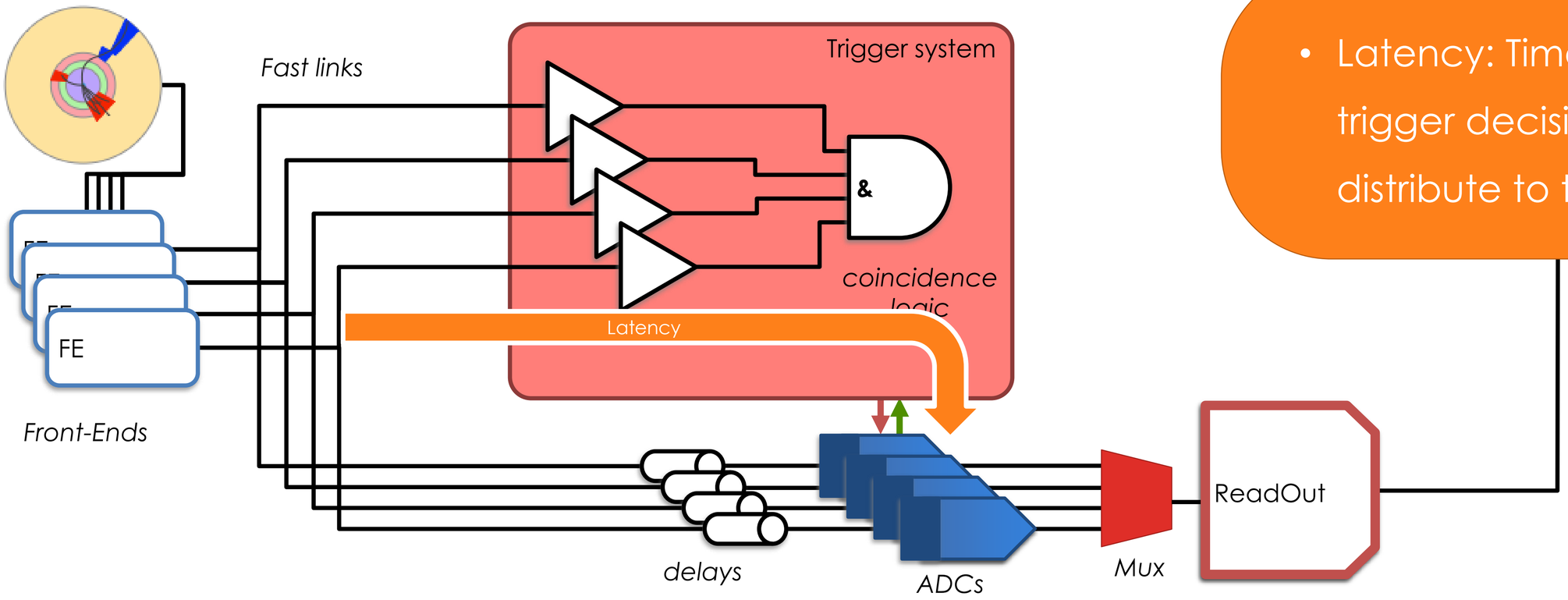
A SIMPLE TRIGGER SYSTEM: PARALLELISM



- Independent readout and trigger paths, one for each sensor element
- Digitisation and DAQ processed in parallel (as much as affordable!)

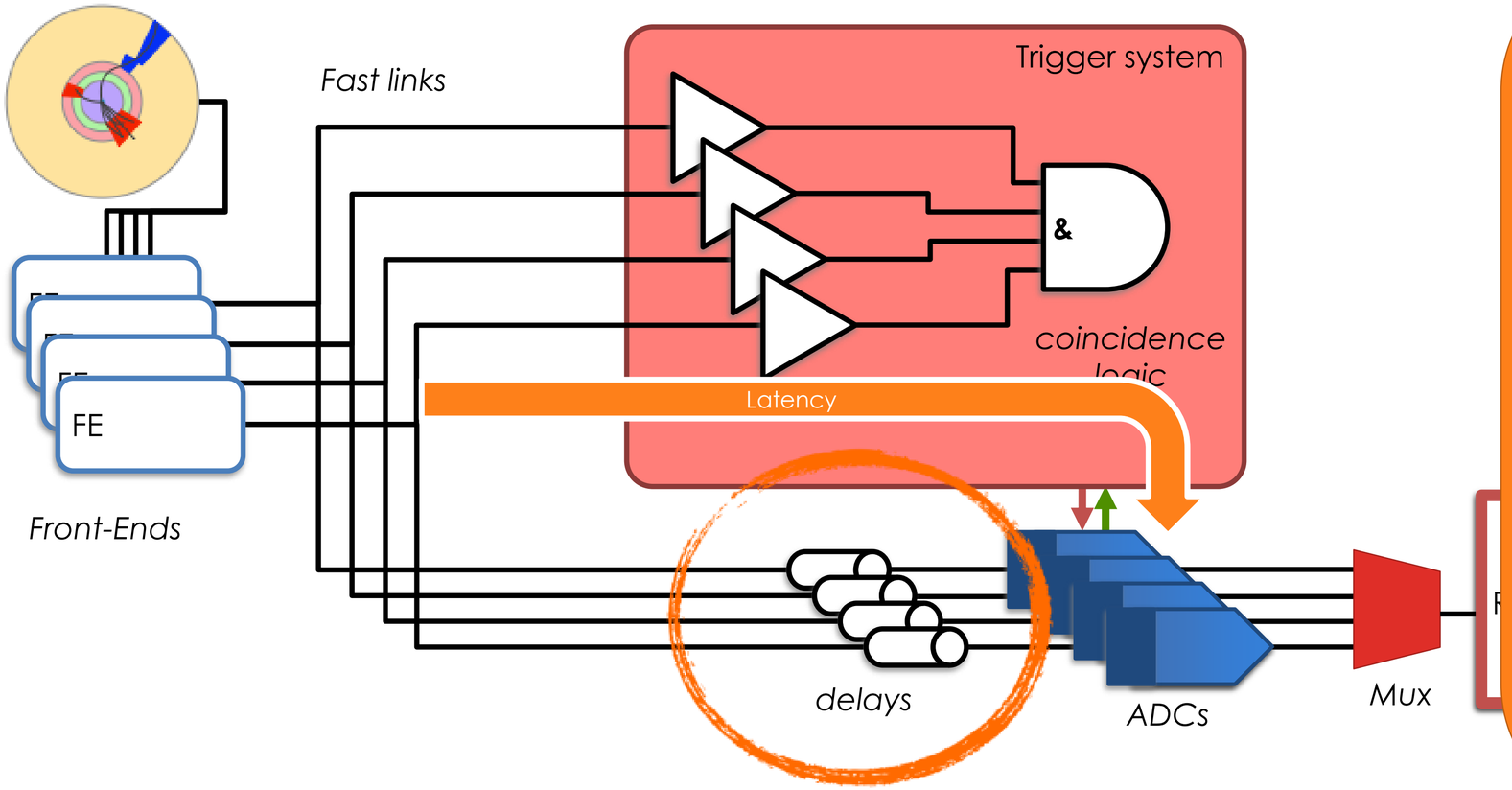
Much more sensible!
Potentially much more expensive!

KEYWORD: LATENCY



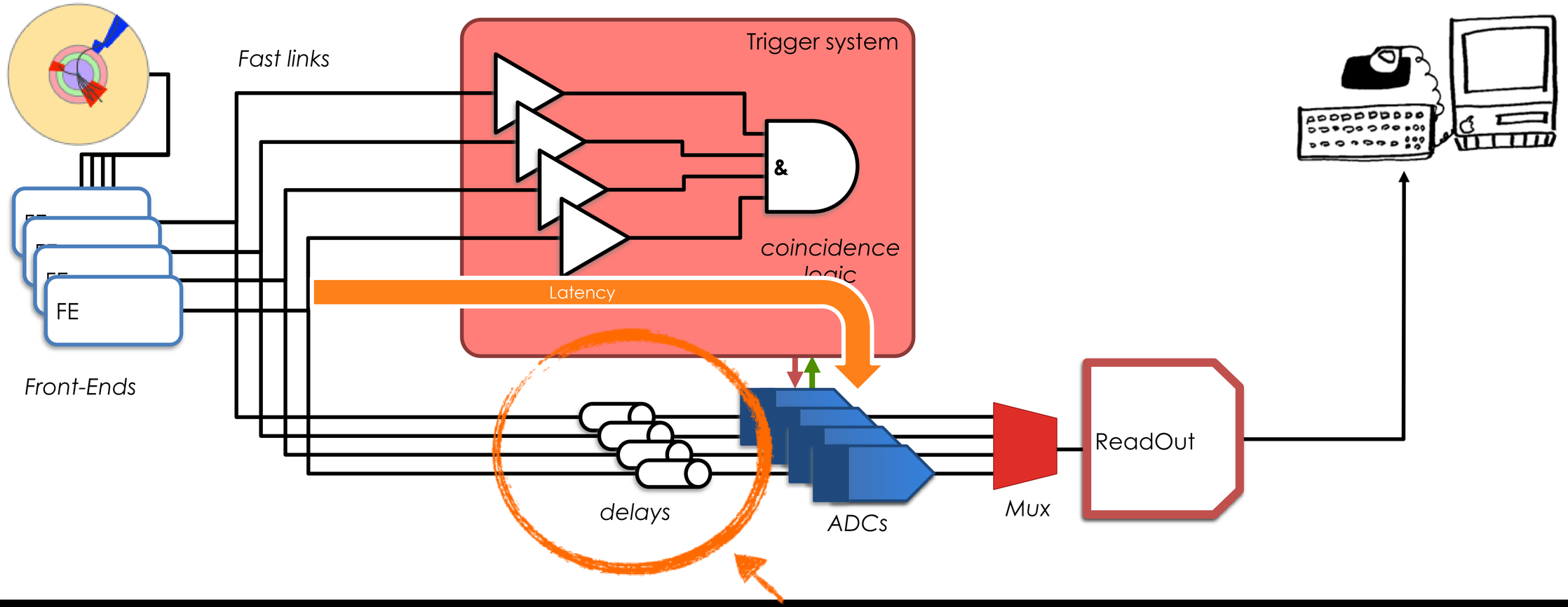
- Latency: Time to form the trigger decision and distribute to the digitisers

A SIMPLE TRIGGER SYSTEM: LATENCY



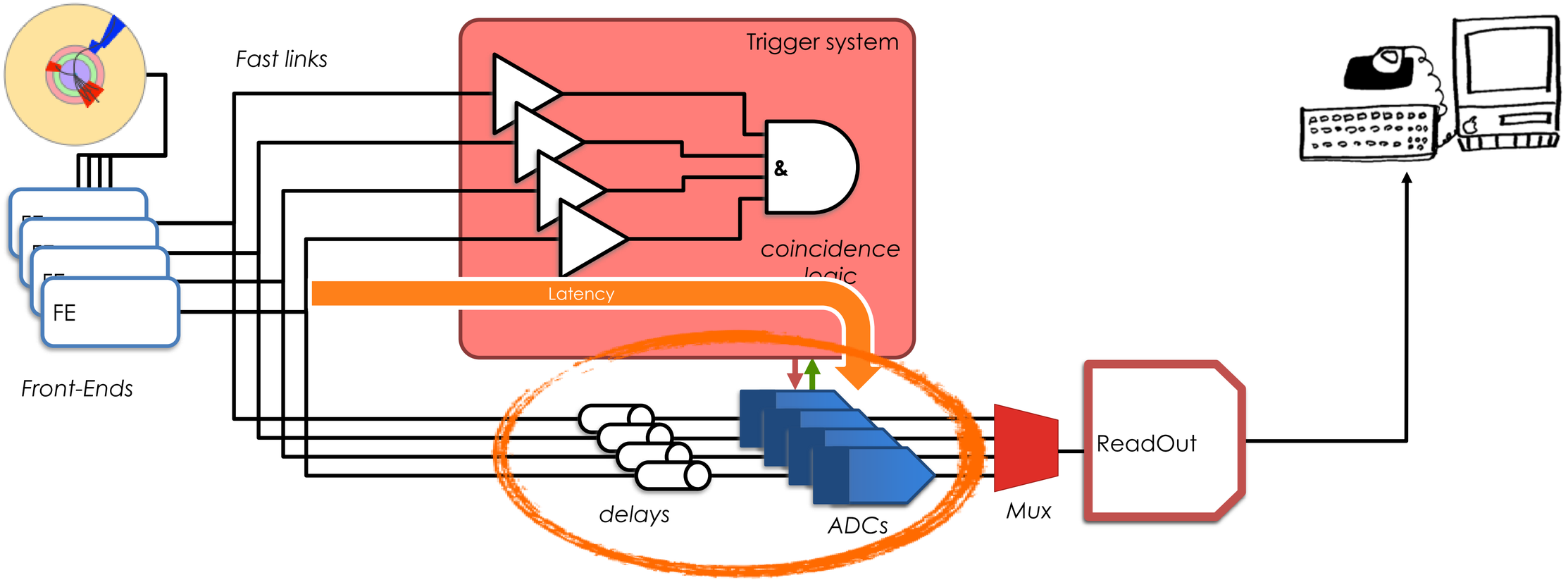
- Latency: Time to form the trigger decision and distribute to the digitisers
- Signals must be delayed until the trigger decision is available
- The more complex is the selection, the longer is the latency

A SIMPLE TRIGGER SYSTEM: LATENCY



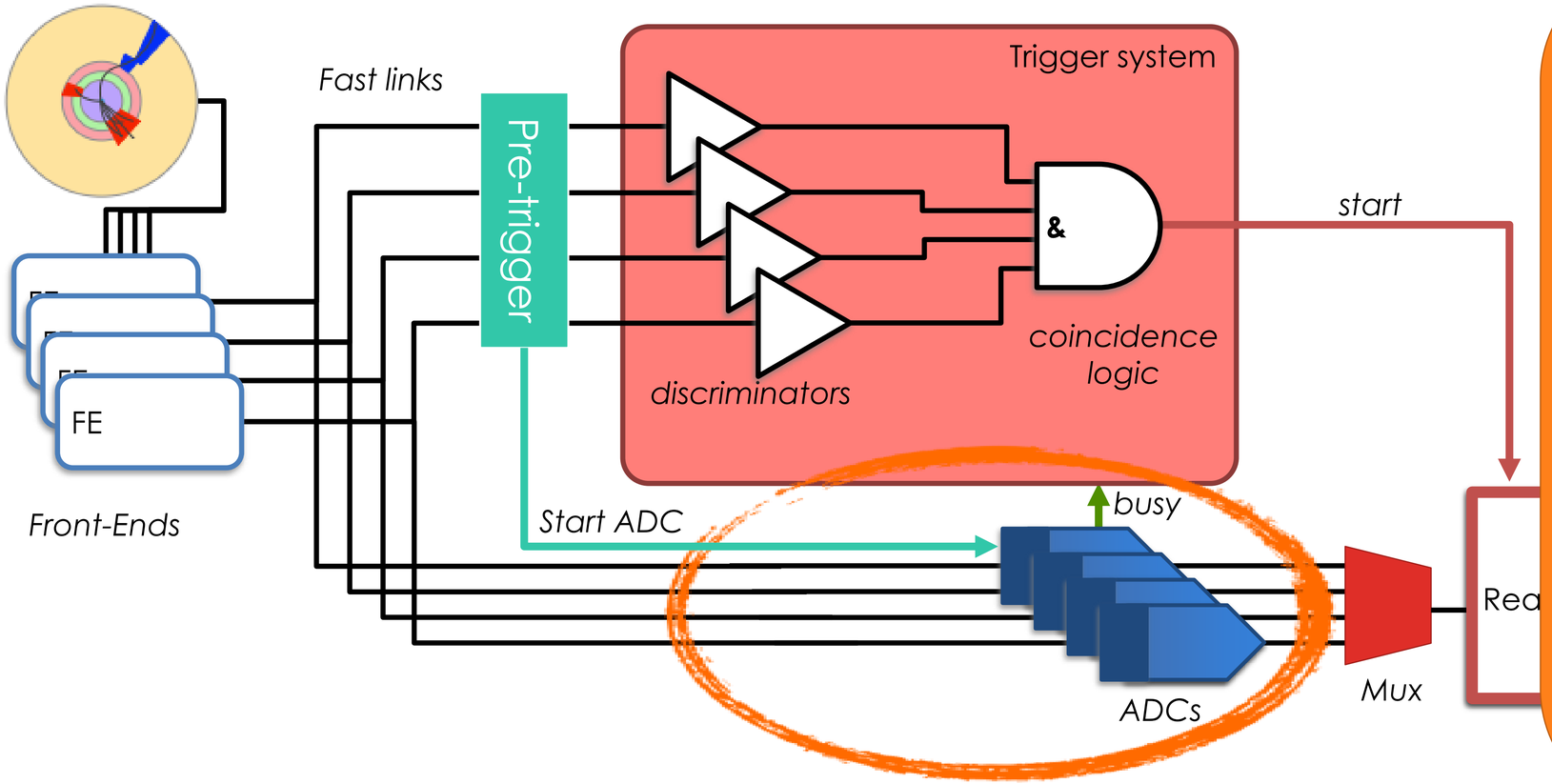
Analogue delay-lines are a bit risky, don't you think?
Especially for more than one channel

A SIMPLE TRIGGER SYSTEM



If the ADCs are the slow part,
can we use the time more profitably?

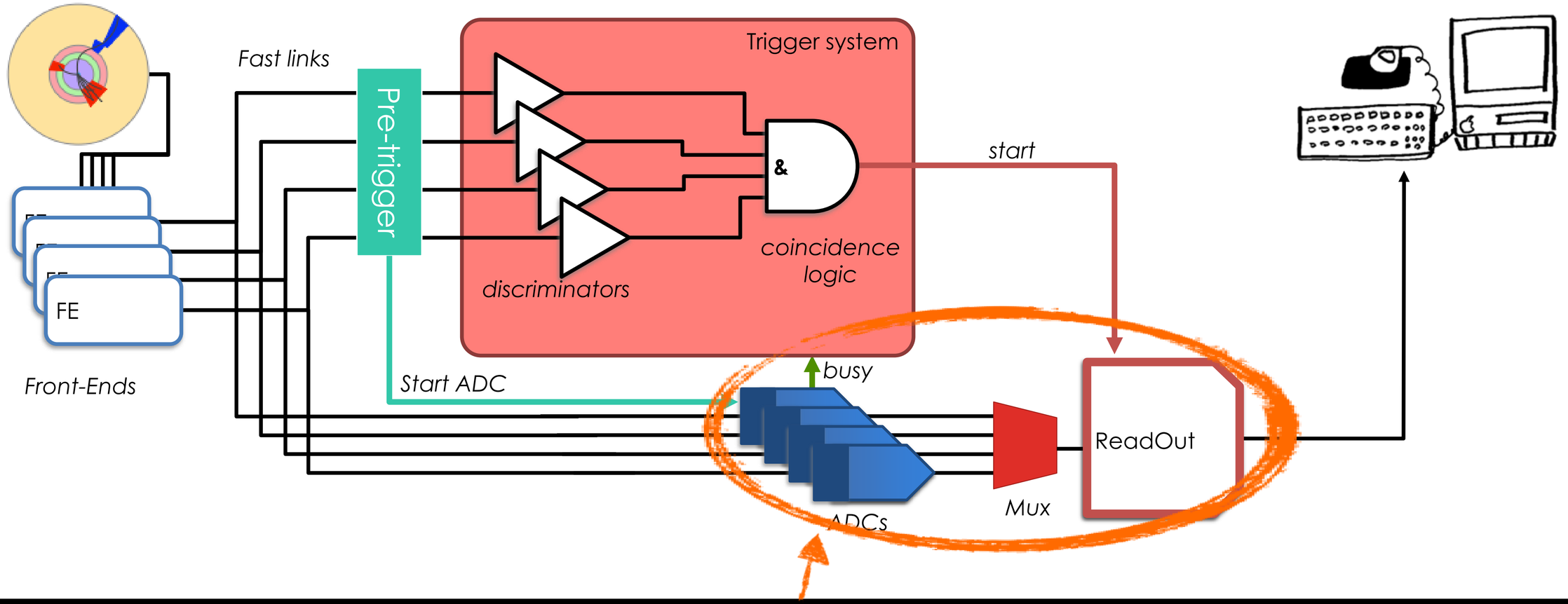
A SIMPLE TRIGGER SYSTEM: PRE-TRIGGER



- Pre-Trigger stage: very fast indicator of some minimal activity in the detector
- Used to START the digitisers, with no delay
- The complex trigger decision comes later

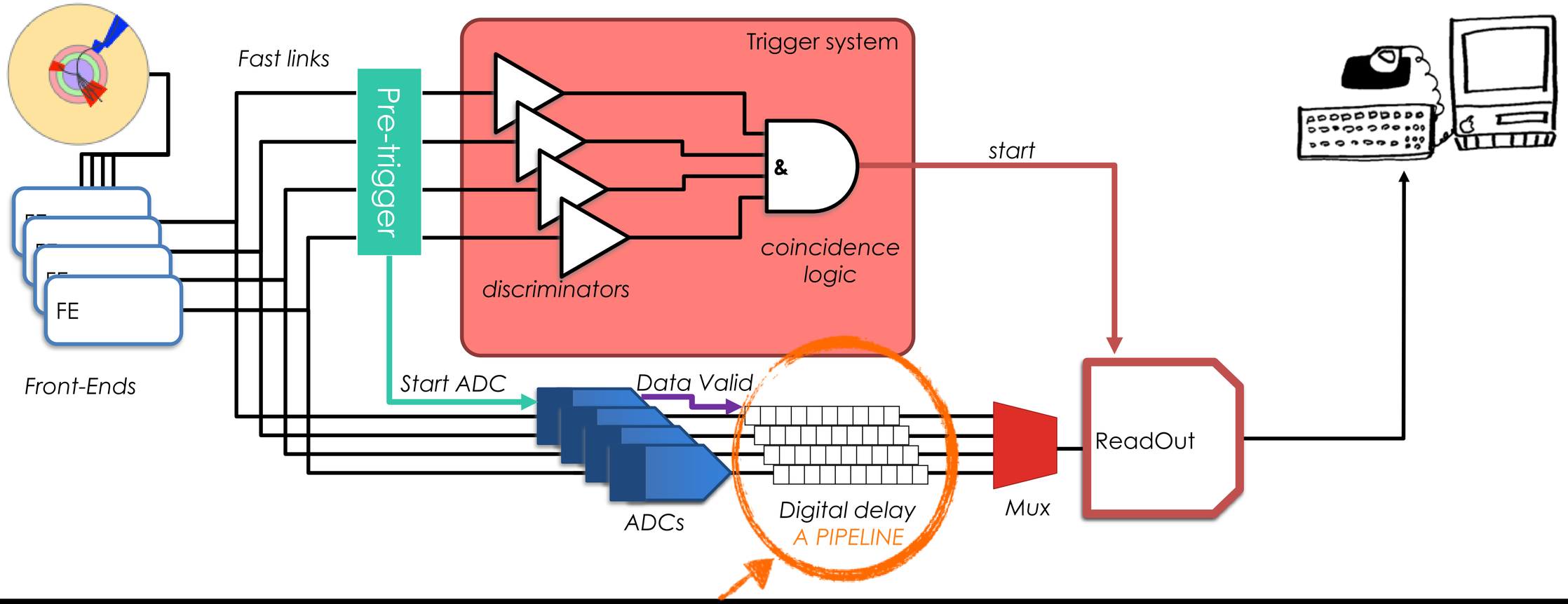
If the ADCs are the slow part,
can we use the time more profitably?

A SIMPLE TRIGGER SYSTEM: PRE-TRIGGER



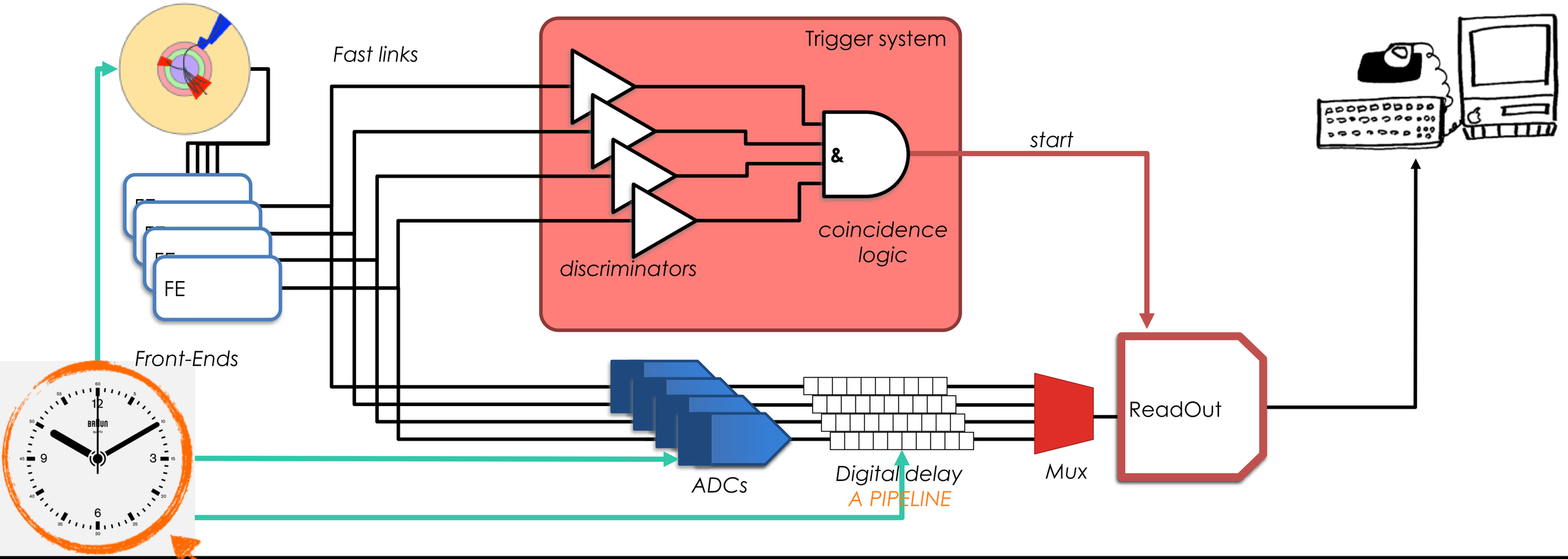
Assumes the digitization time is longer than the latency of the trigger system!
What if that is not true?

A SIMPLE TRIGGER SYSTEM: PRE-TRIGGER



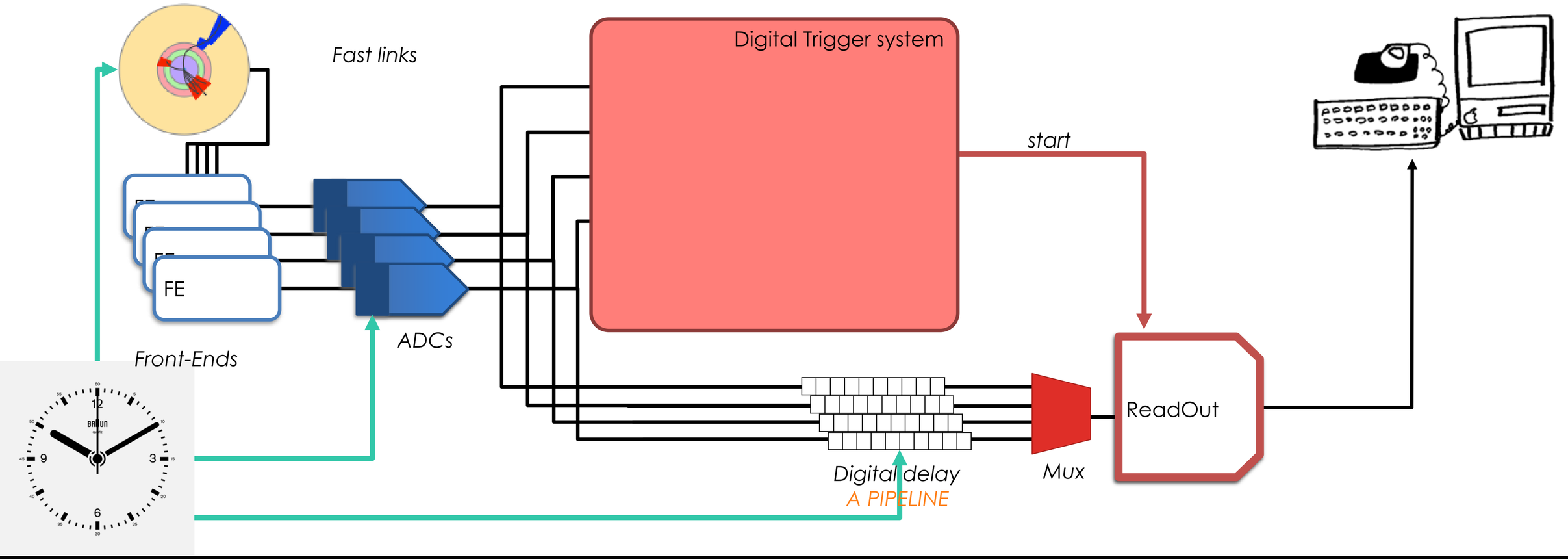
Since each digitization takes a finite time
Can store the result of each digitization in RAM until trigger decision is made

SIMPLE TRIGGER SYSTEM: BUNCHED COLLIDERS

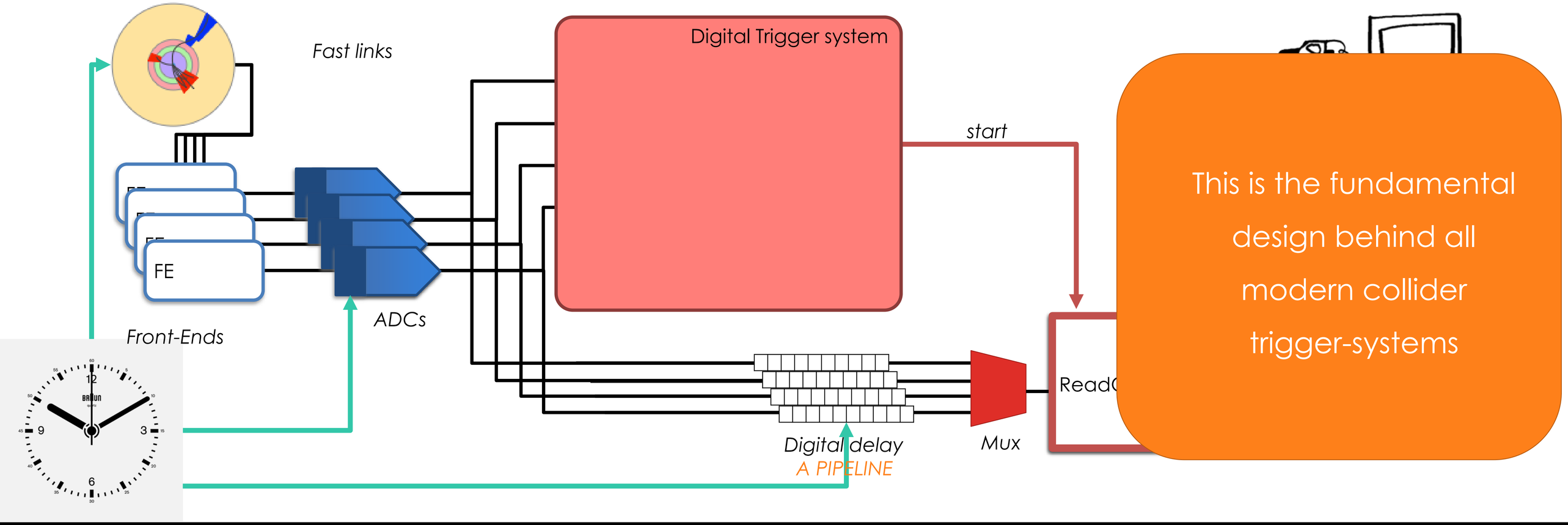


We have a master-clock – the bunch-crossings themselves!
No need for a pre-trigger

A SIMPLE TRIGGER SYSTEM: DIGITAL TRIGGERS



A SIMPLE TRIGGER SYSTEM: DIGITAL TRIGGERS



AND FINALLY: A PHILOSOPHICAL QUESTION

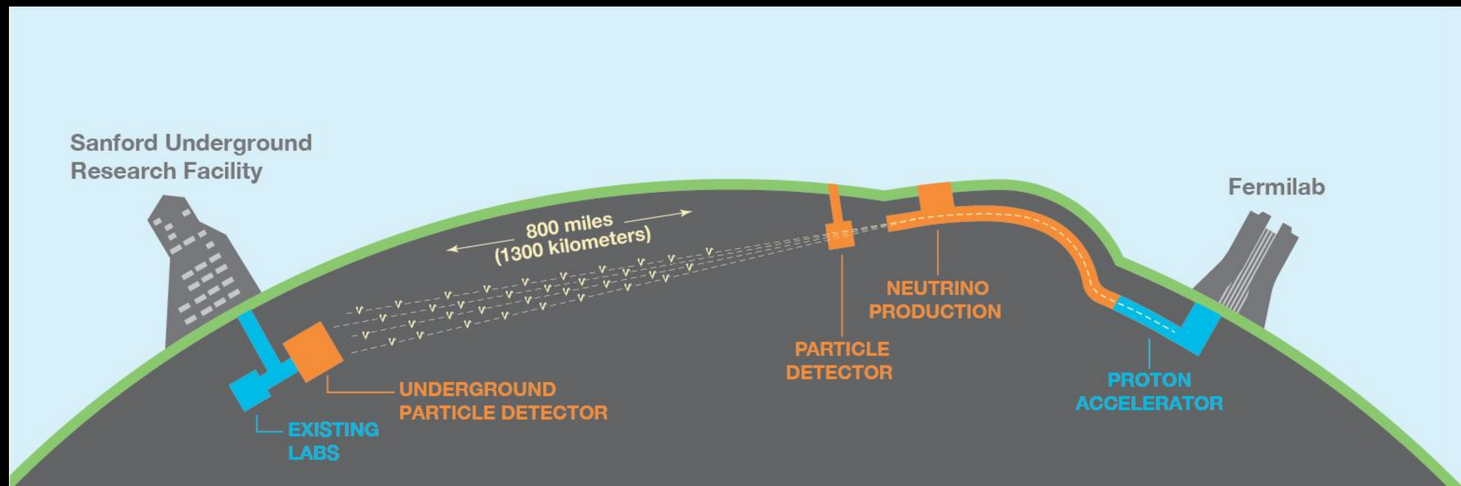
- If you only see what the trigger accepts, how do you know what you have thrown away?

AND FINALLY: A PHILOSOPHICAL QUESTION

- If you only see what the trigger accepts, how do you know what you have thrown away?
- A good trigger will also have so-called Minimum-bias or Zero-bias paths
  - Zero-bias – accept a truly random sample of events (even “empty”)
  - Minimum-bias – accept a random sample of crossings with collisions
- Allows you to look at what your trigger tells you not to

WHAT ABOUT NON-COLLIDER EXPERIMENTS?

- "Always on" detectors – "events" could occur at any time - continuous read out
  - But most of the time, nothing is happening
- Signals may be localised to one portion of the detector - local read out
- "Events" may have very different durations - few ms to 100s seconds (e.g. supernova)
- "Video" data compared to LHC experiments' "Photo" data
- Want to capture data when something 'interesting' does happen, and suppress the rest
- Everything I have said about deadtime, latency, min-bias paths, etc. still applies!



SEE YOU ON TUESDAY FOR PART II!

Any questions?