

TRIGGER AND DATA-ACQUISITION: PART I

UK Advanced Instrumentation Course 2022

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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

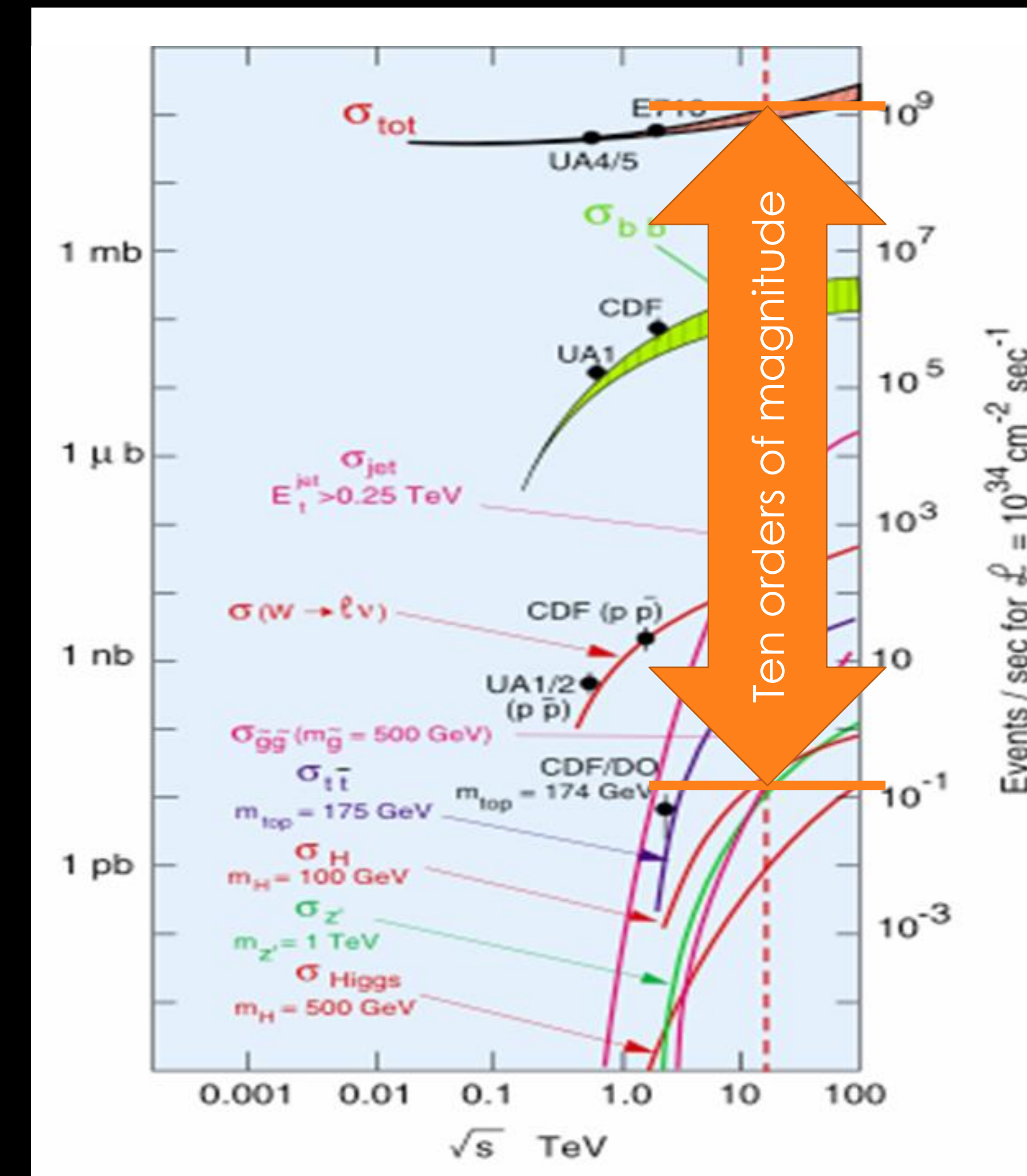
- My examples are heavily biased towards the LHC and CMS
 - It's where my experience is, it is what I know
- The boundary between Trigger and DAQ is blurry, and I tend to err to the Trigger side
 - It's where my experience is, it is what I know

SCIENCE: THE BASICS

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

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- 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

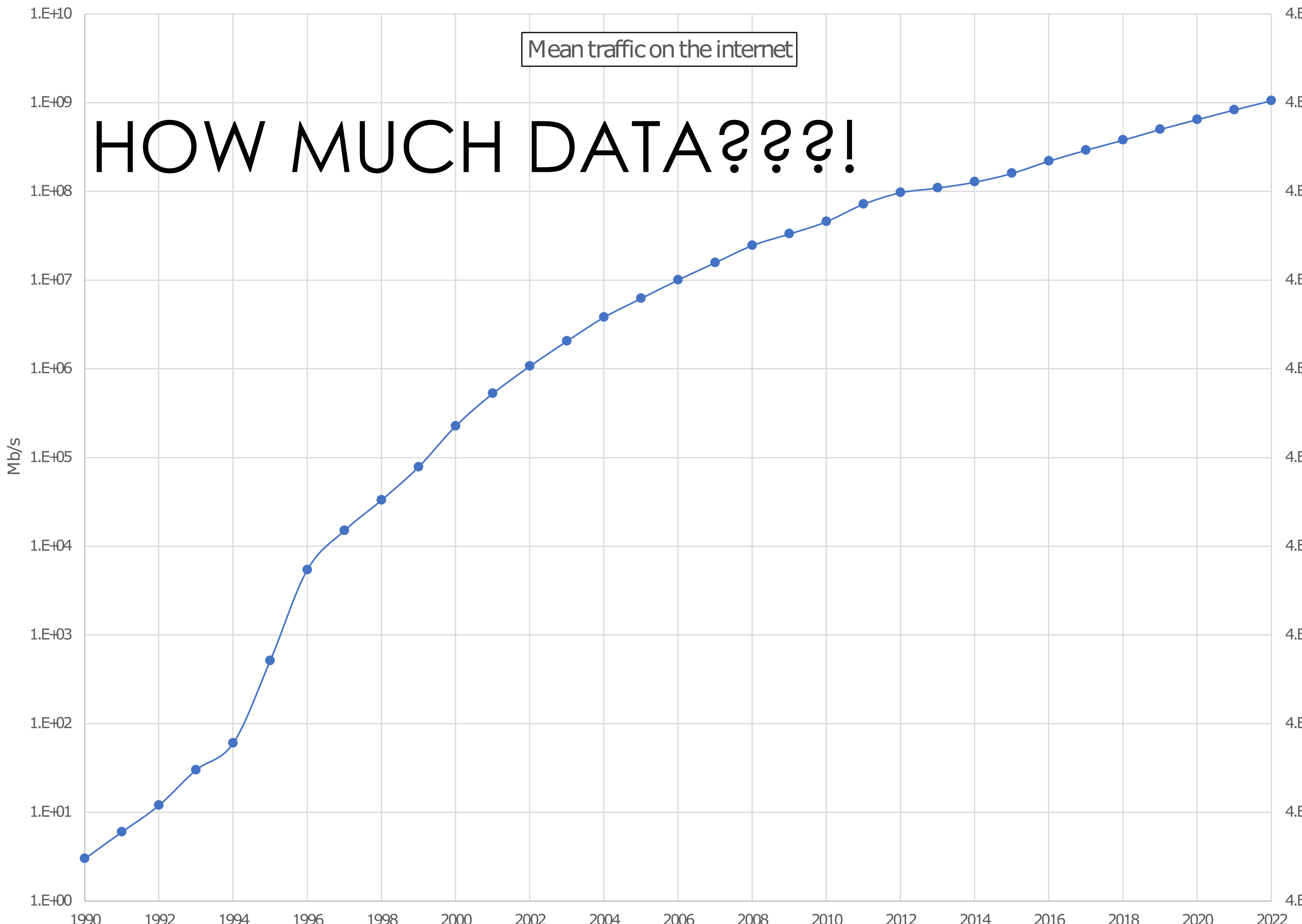


UNFORTUNATELY, STATISTICS REQUIRES DATA

- The LHC's **40MHz crossing rate** and **$2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ 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???

Mean traffic on the internet



CMS compressed

1,000,000×
Home broadband

1,000×
Home broadband

CMS tape-store

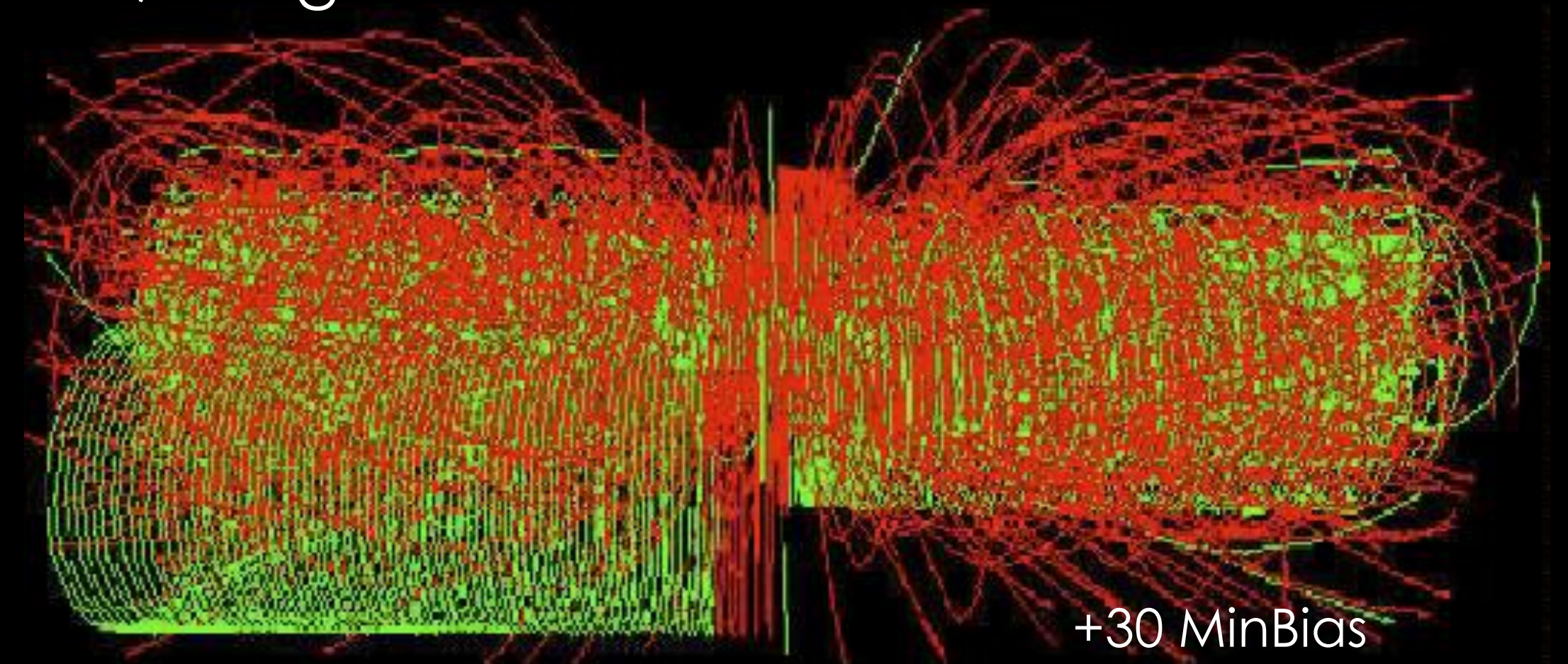
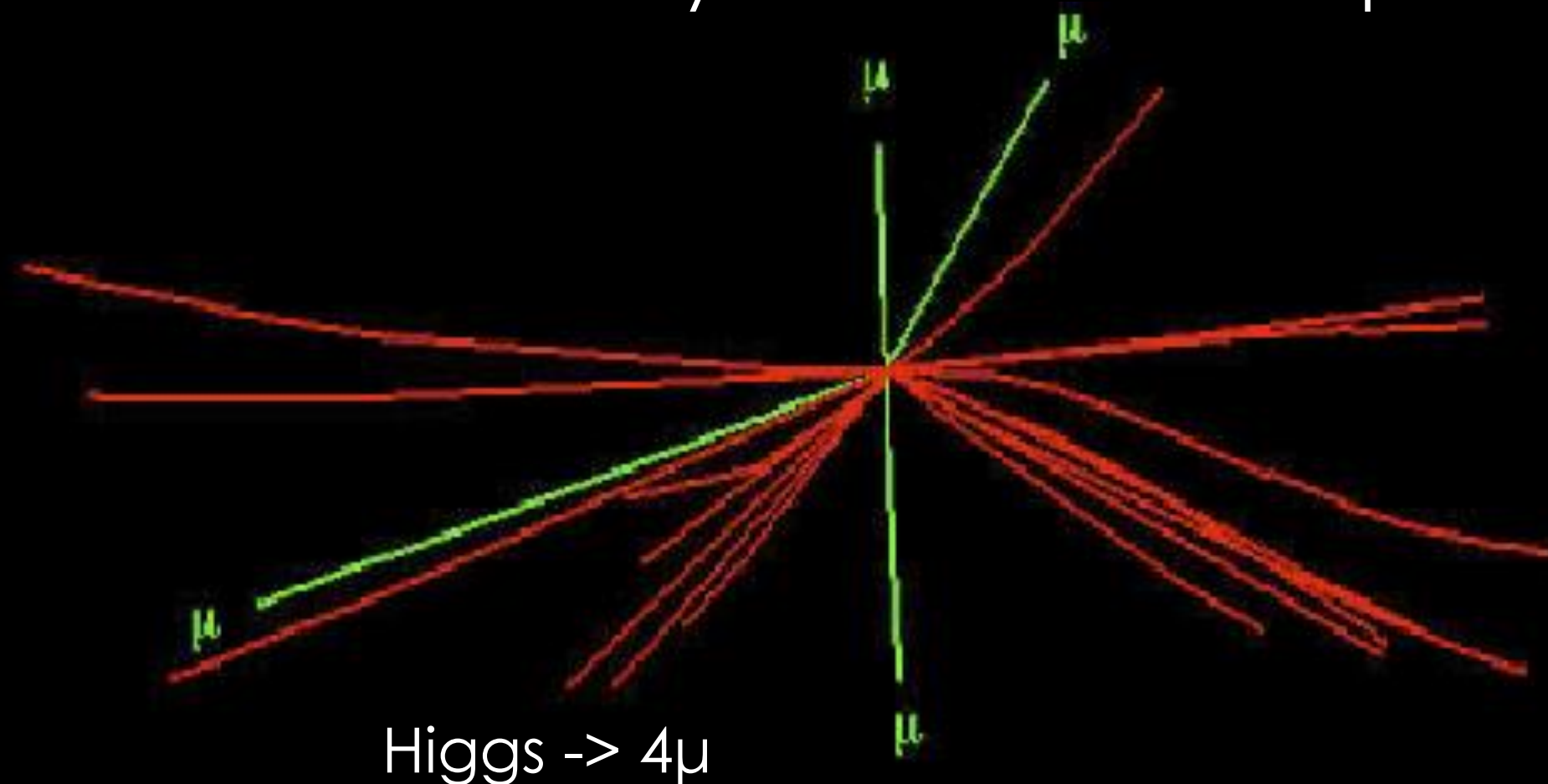
1×
Home broadband

7
CMS Raw

ZB/year

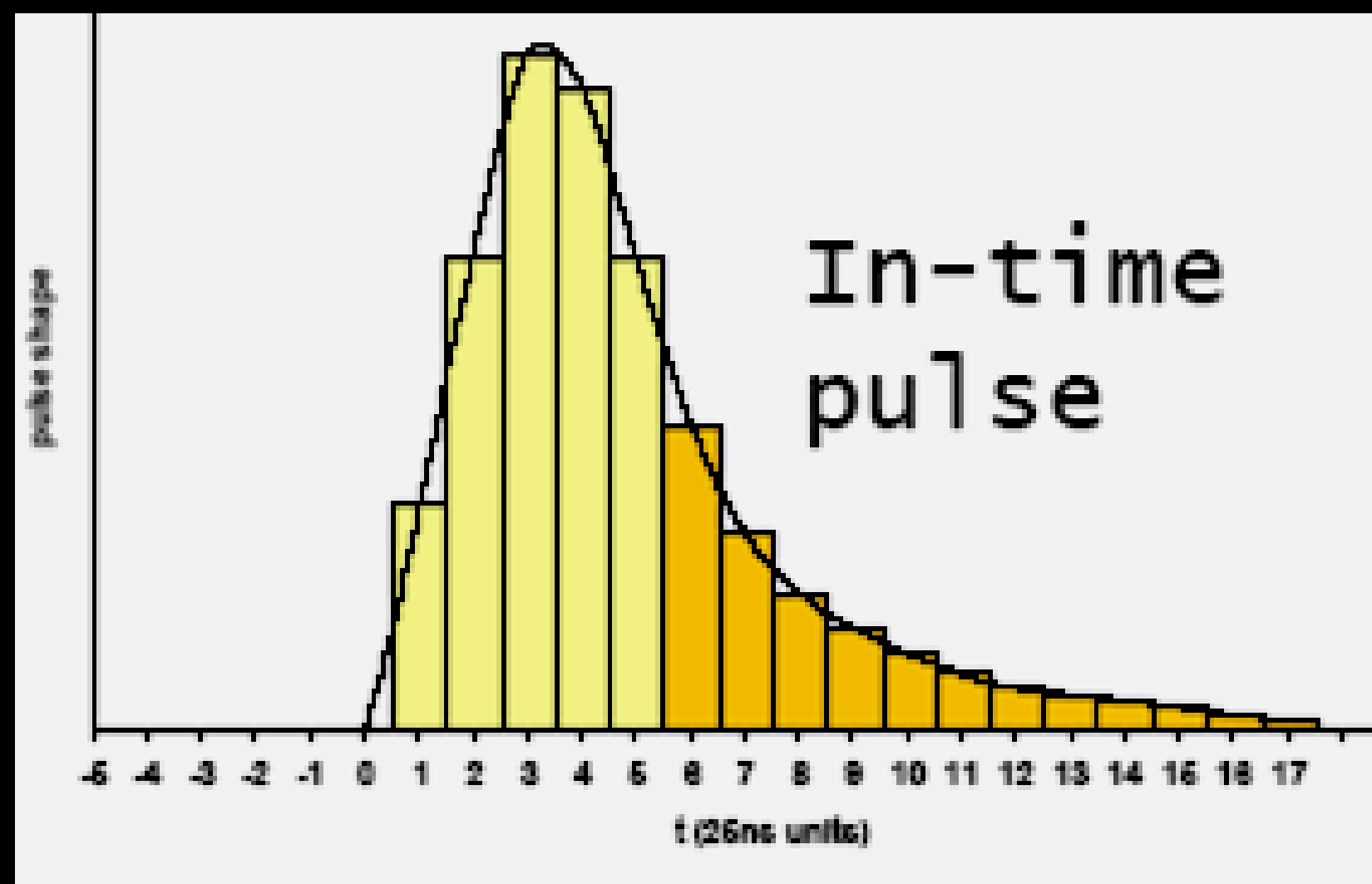
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- Unfortunately, $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity produces **~ 50 times more background in your detector than signal** (if there is a signal at all), making selection tricky
 - And every time the LHC improves its performance, this gets worse

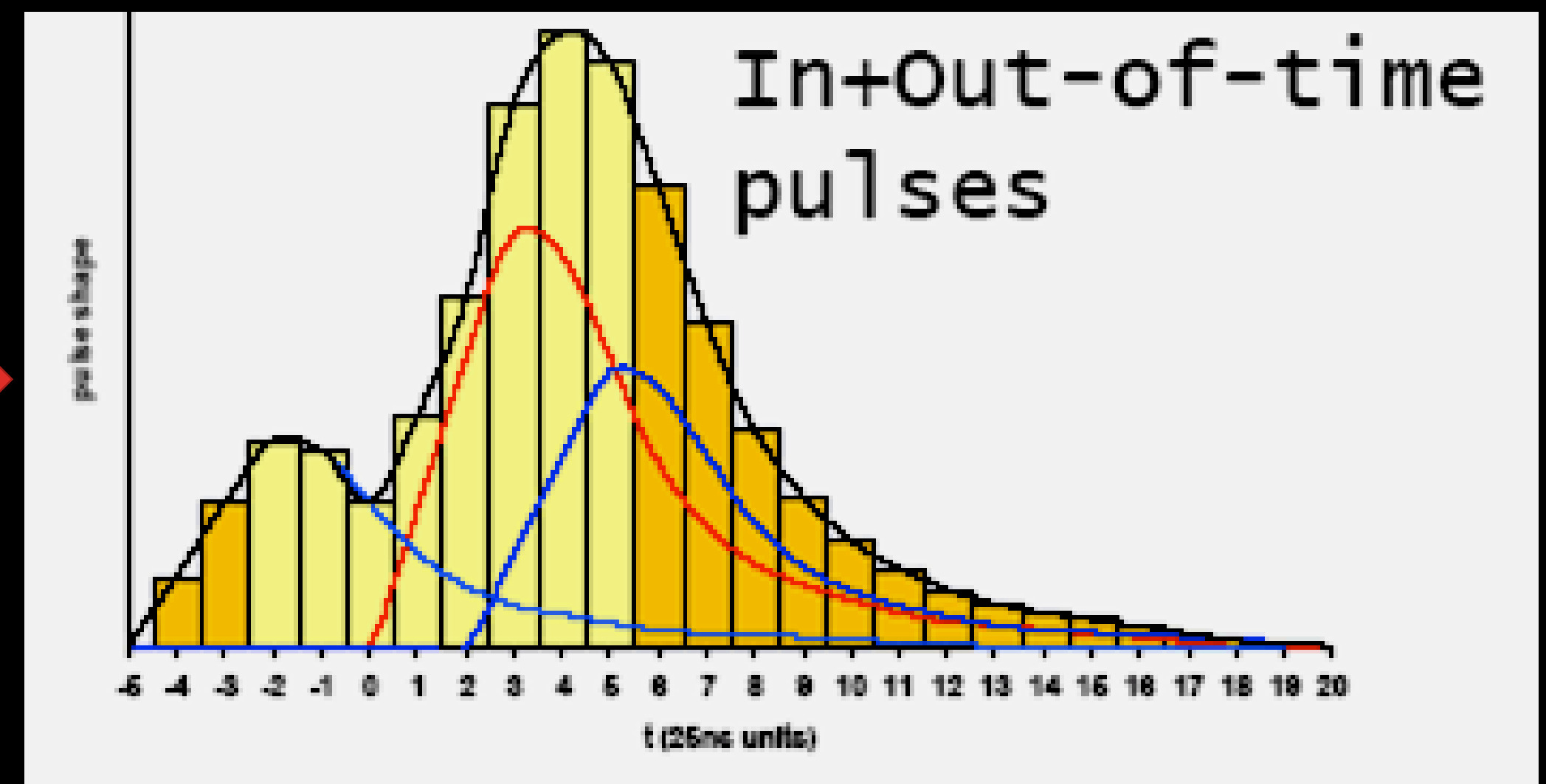


UNFORTUNATELY, STATISTICS REQUIRES DATA

- 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

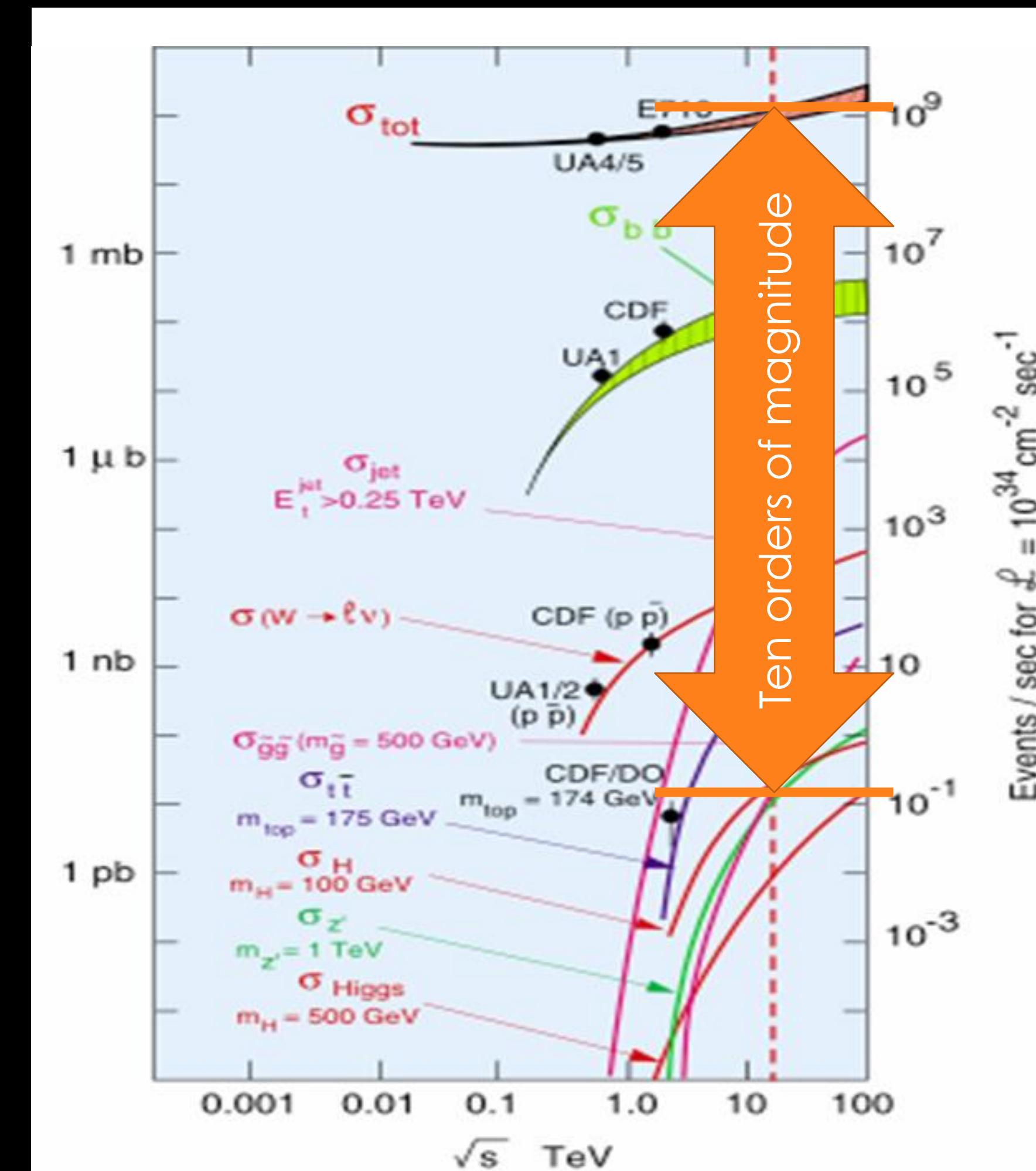


Superimpose



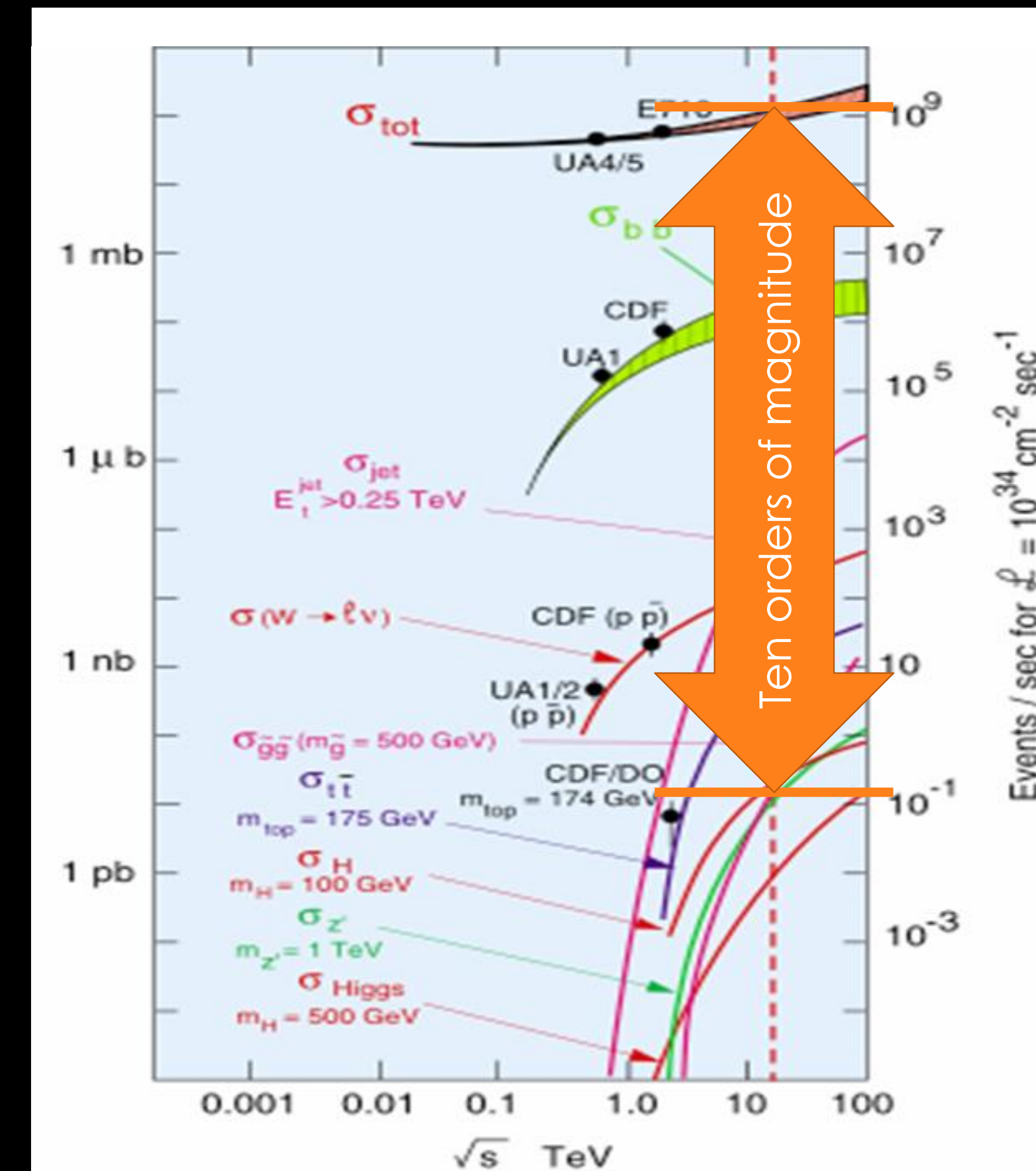
SCIENCE: THE BASICS

- 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



SCIENCE: THE BASICS

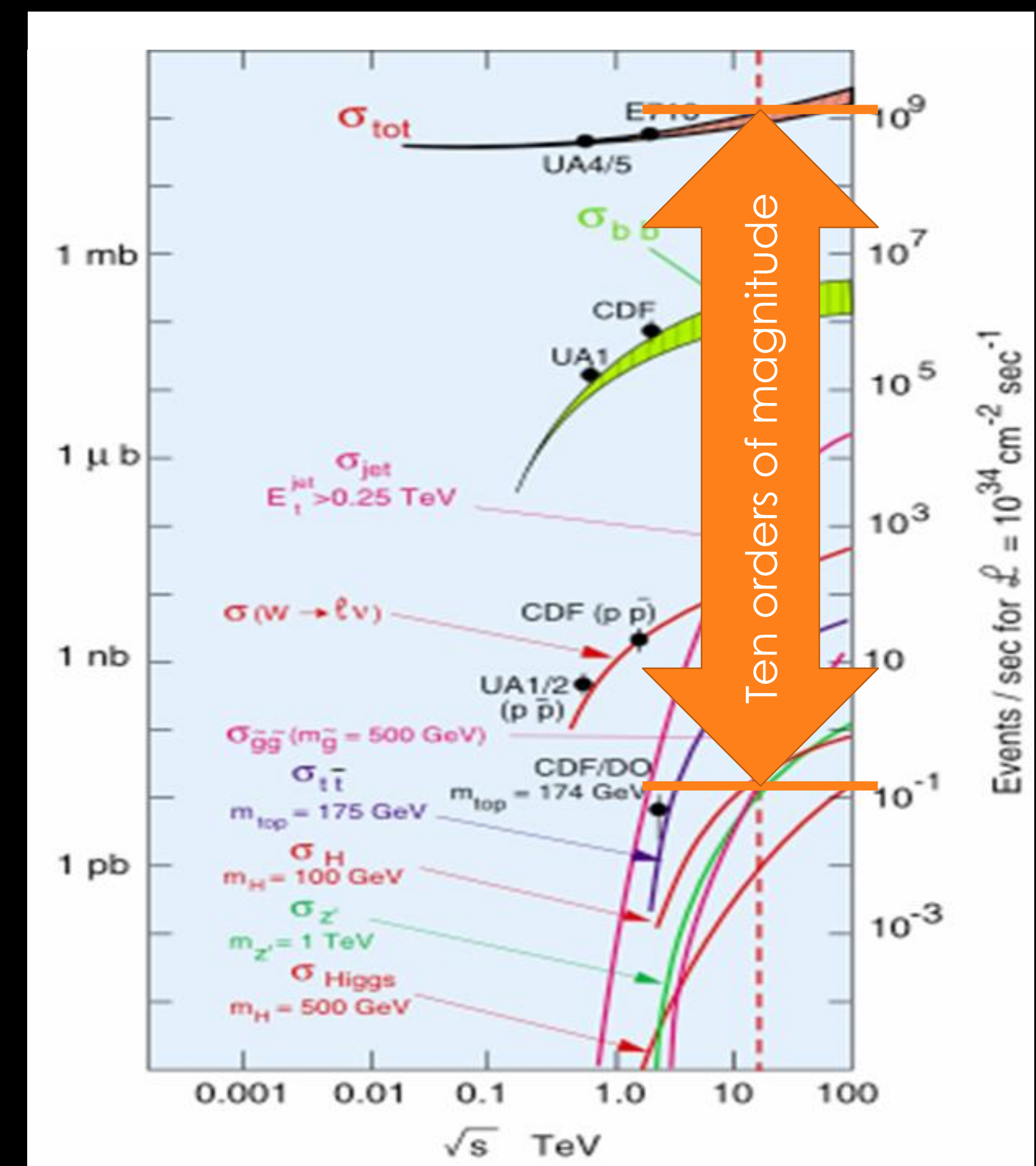
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 - Don't screw up!



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This is the art of Triggering



REMINDER

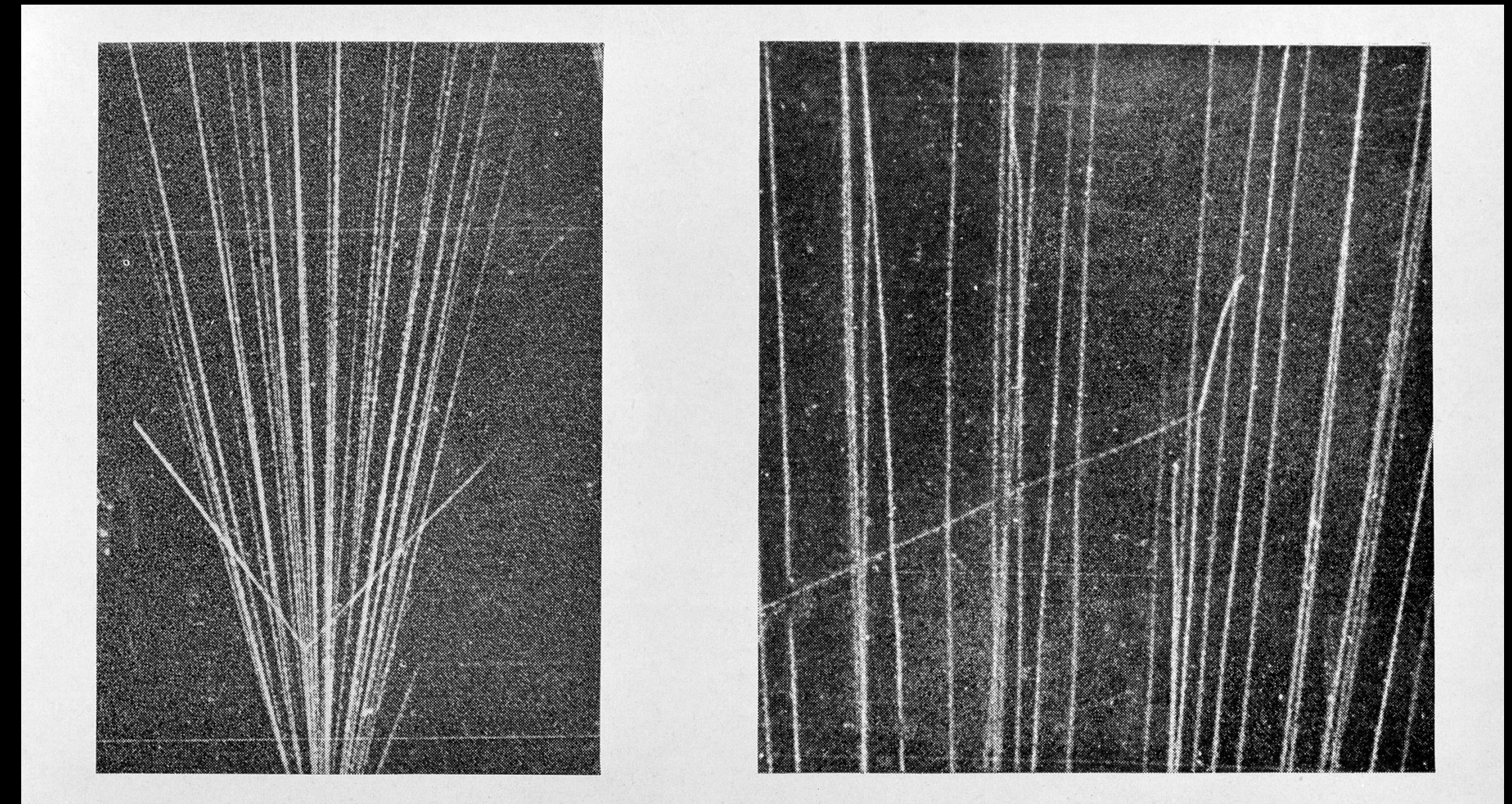
- Trigger basic requirements
 - Need **high efficiency** for selecting processes for physics analysis
 - Need **large reduction** of rate from unwanted high-rate processes
 - **Robustness** is essential
 - **Highly flexible**, to react to changing conditions
 - System must be **affordable**

WHAT'S ON THE (TRIGGER) MENU TODAY?



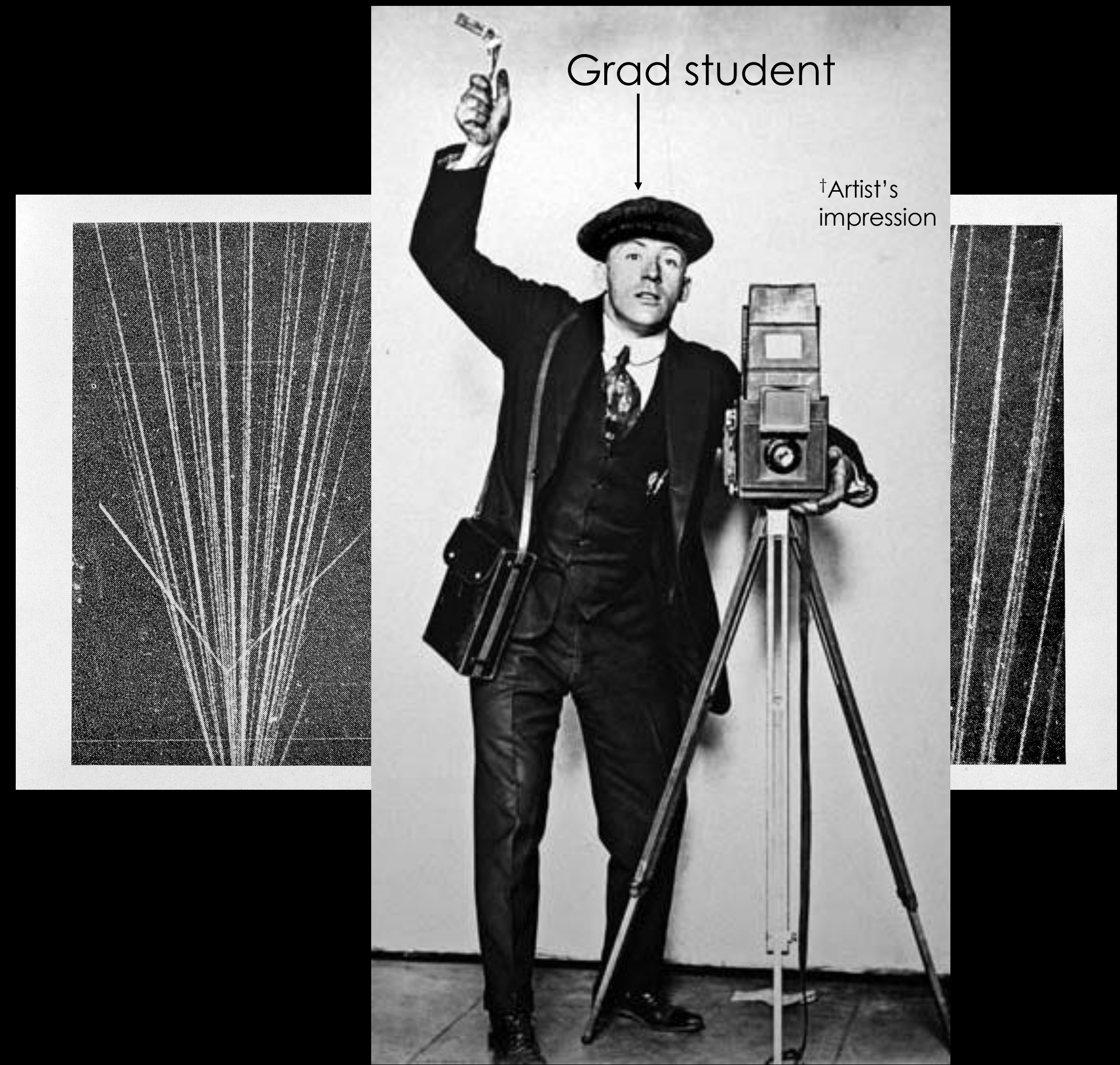
THE EARLIEST TRIGGER

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



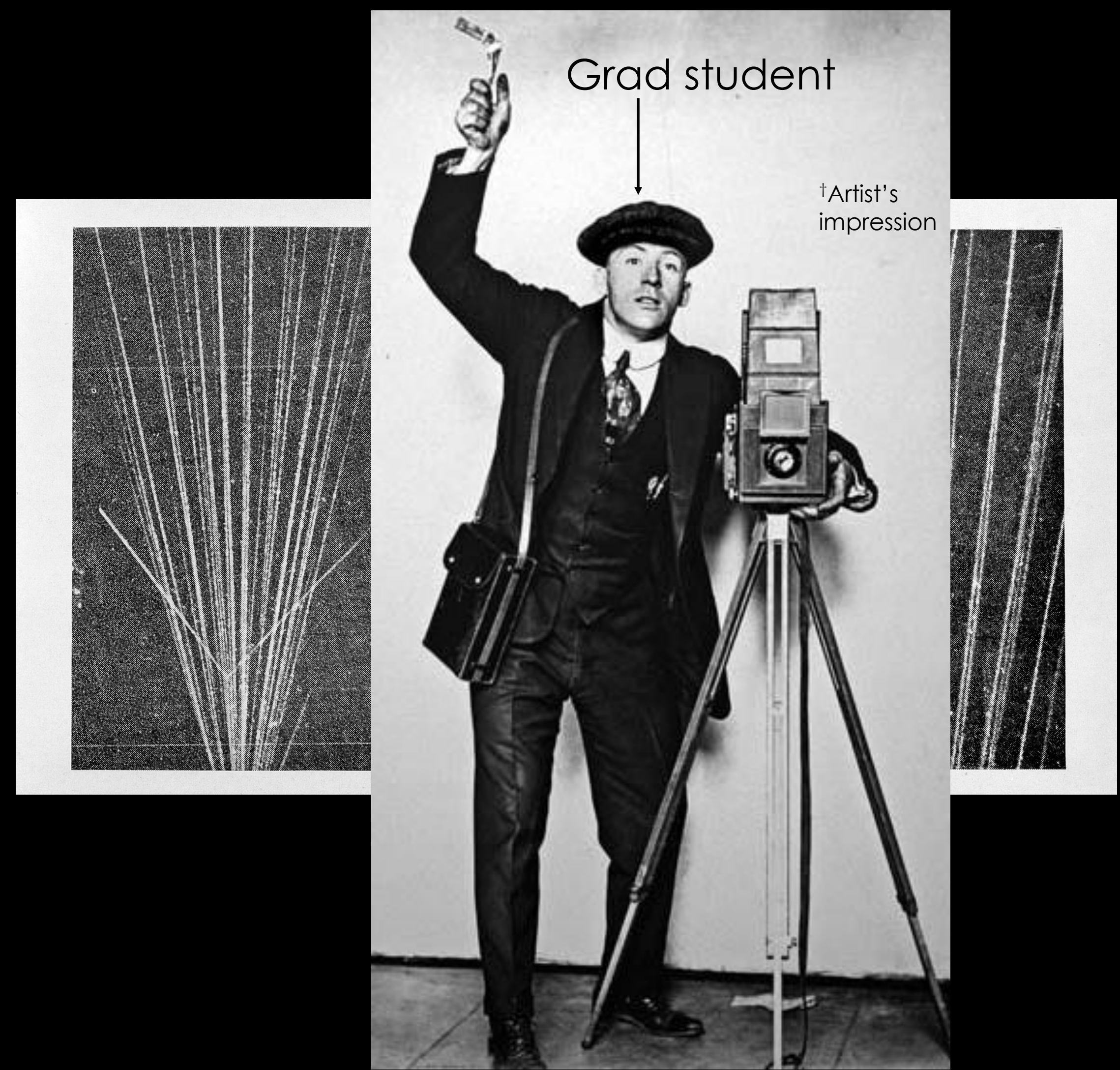
THE EARLIEST TRIGGER

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



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



THE EARLIEST TRIGGER

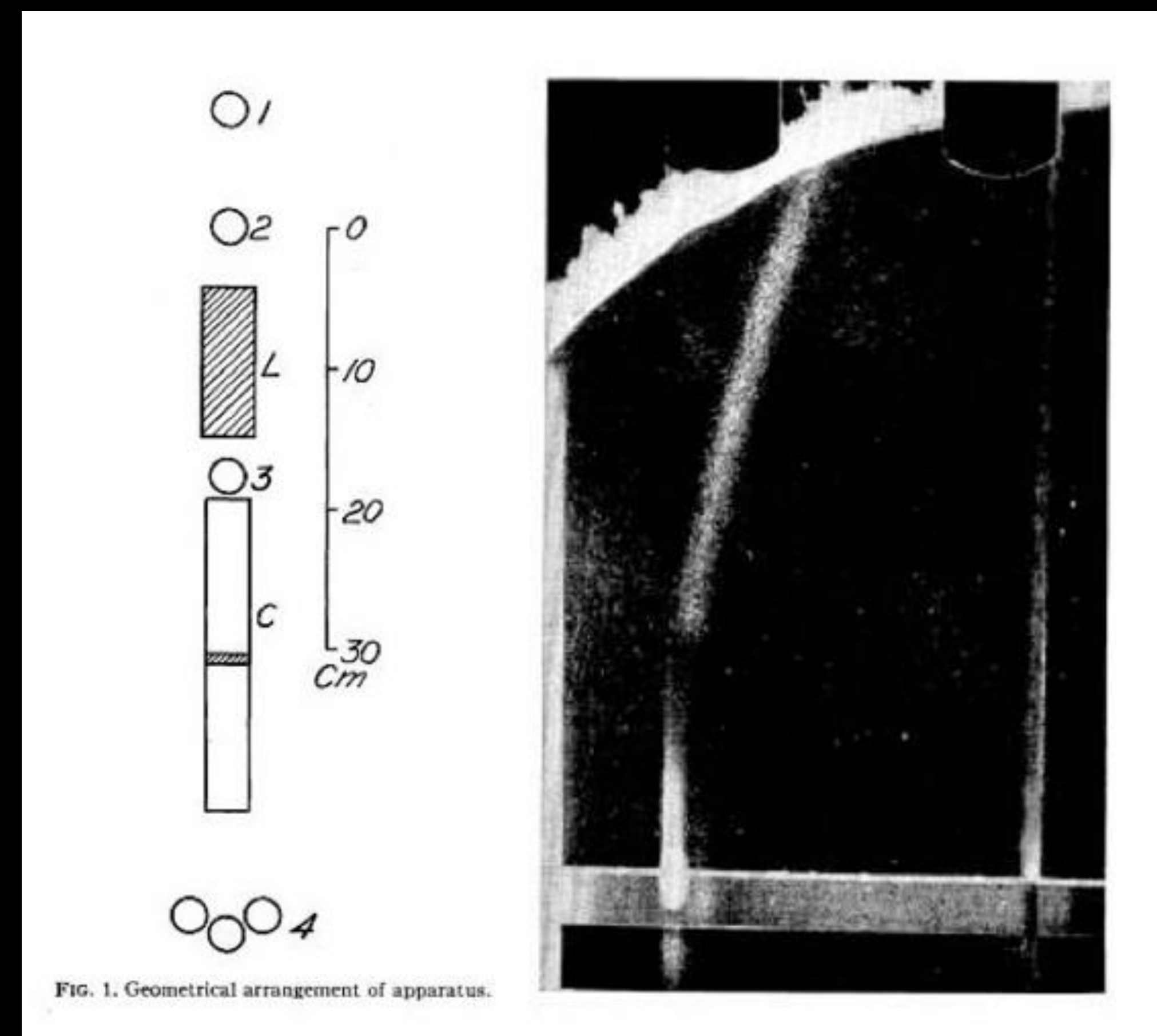
- High efficiency? No
- Large rate reduction
- Robustness? No – coffee, toilet break
- Highly flexible? Depends on the student
- Affordable? Well that's one thing in your favour, I suppose

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

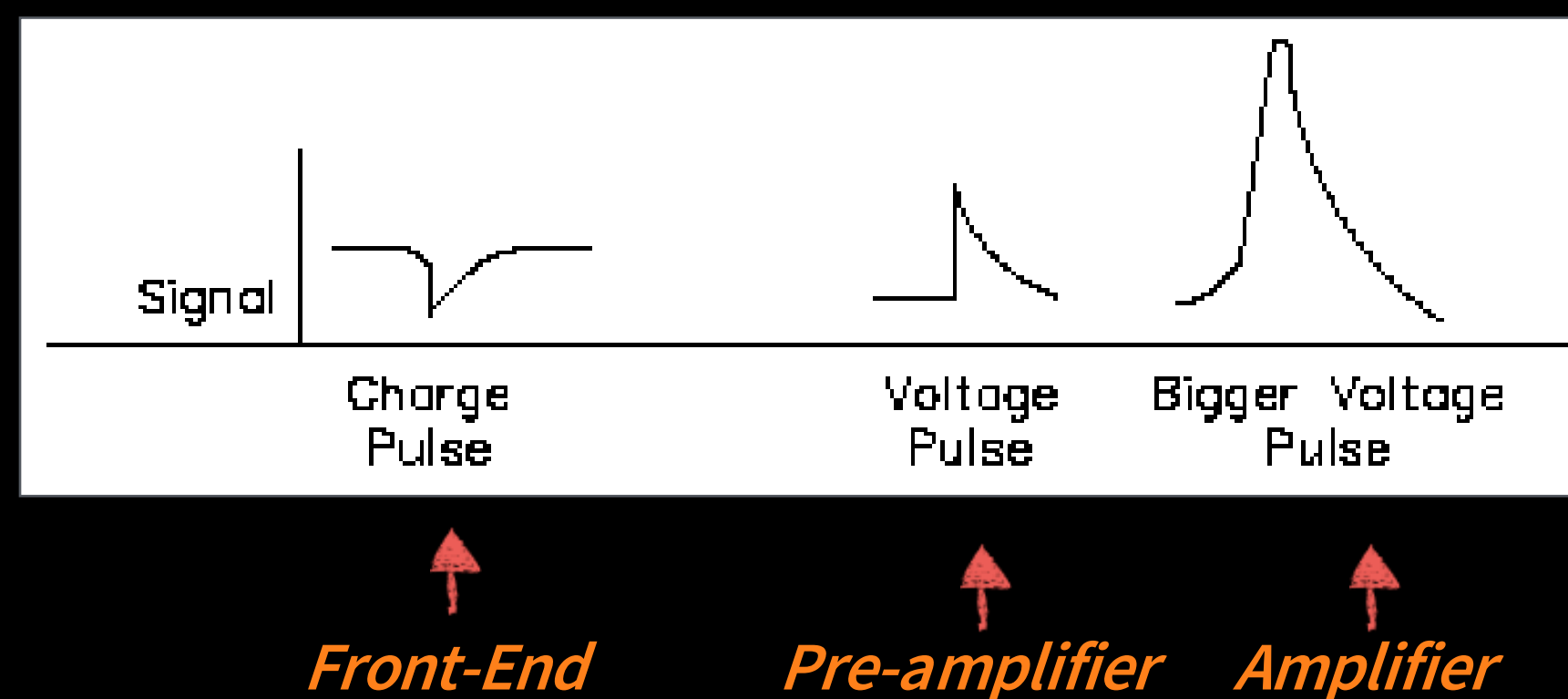
- Blackett pioneered a technique to trigger the camera of cloud chambers (and got the Nobel prize for this and other work)
- Just missed out on discovering the positron in 1932
- Stevenson and Street used this to confirm the discovery of the muon in 1937



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

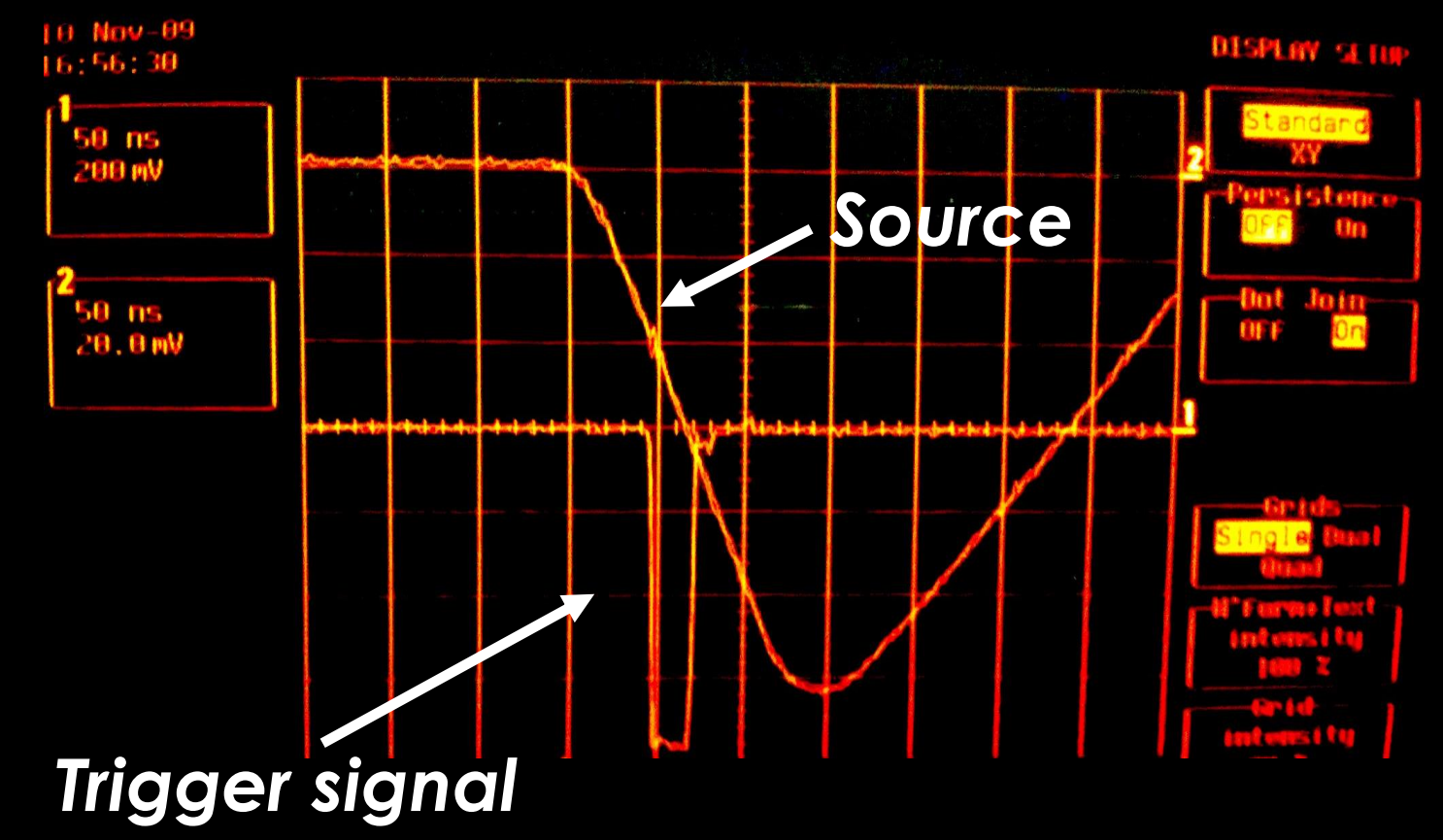
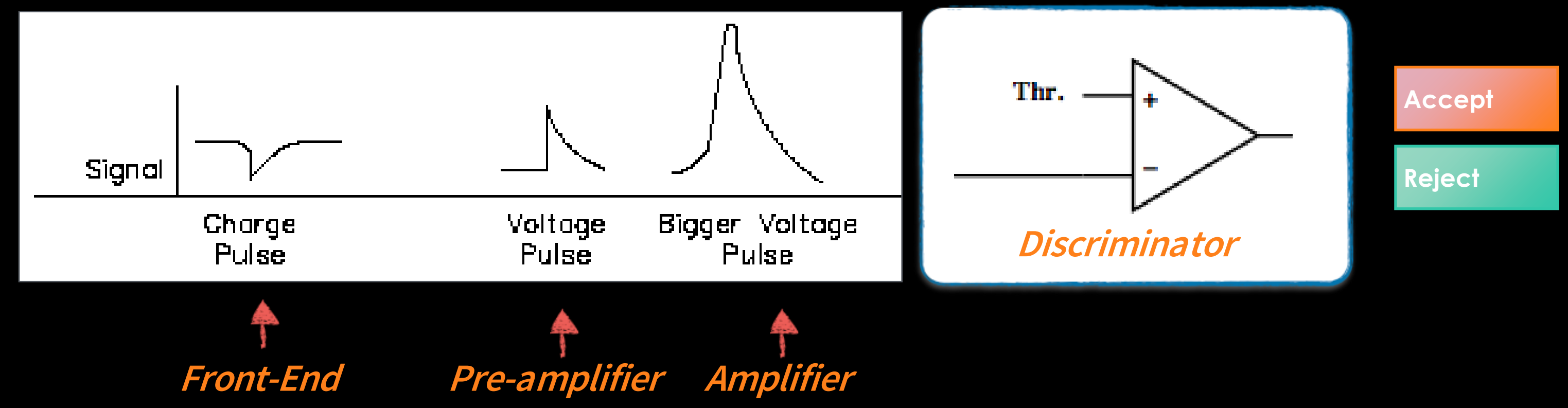
THE SIMPLEST TRIGGER SYSTEMS

- 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, ...



THE SIMPLEST TRIGGER SYSTEMS

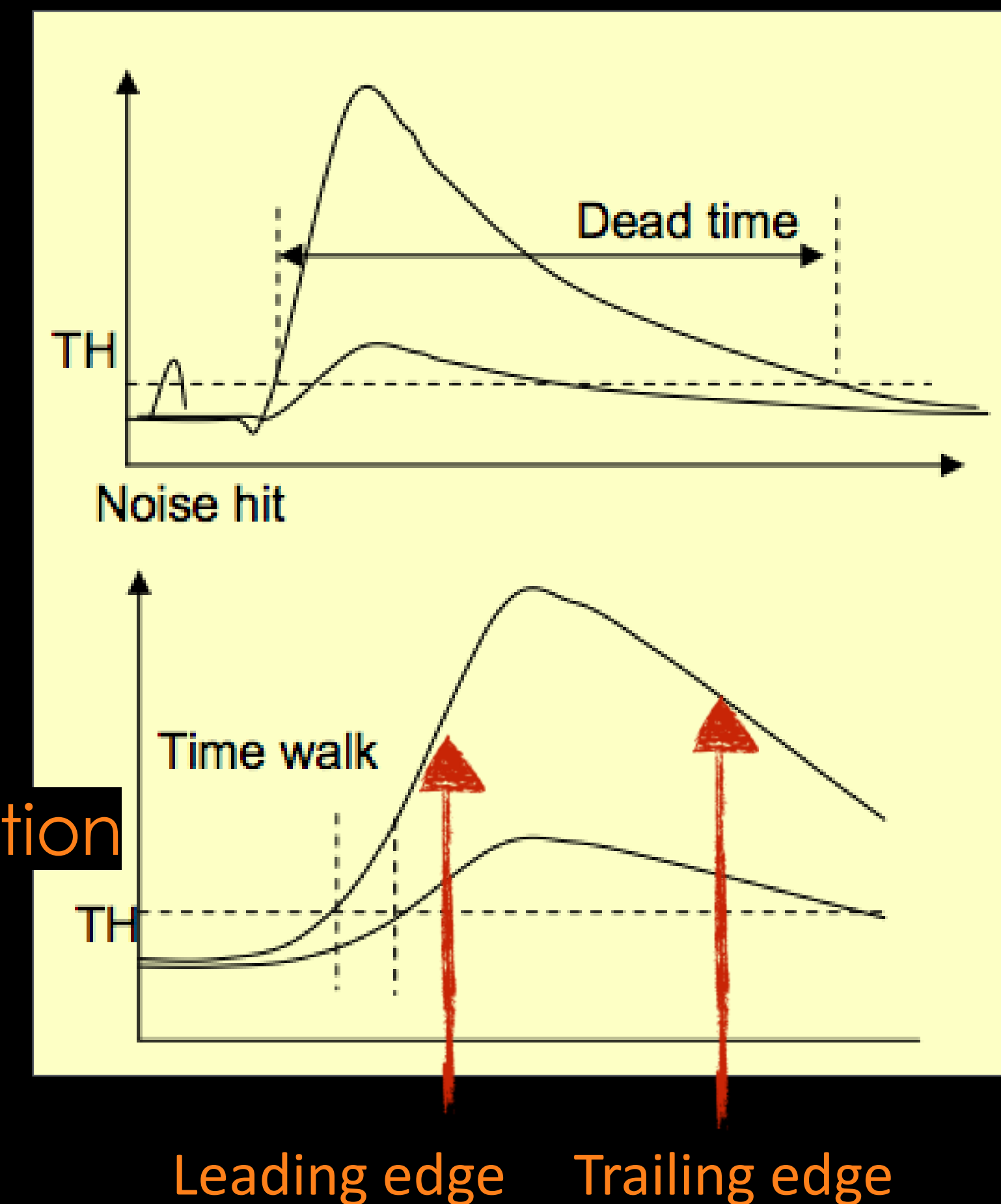
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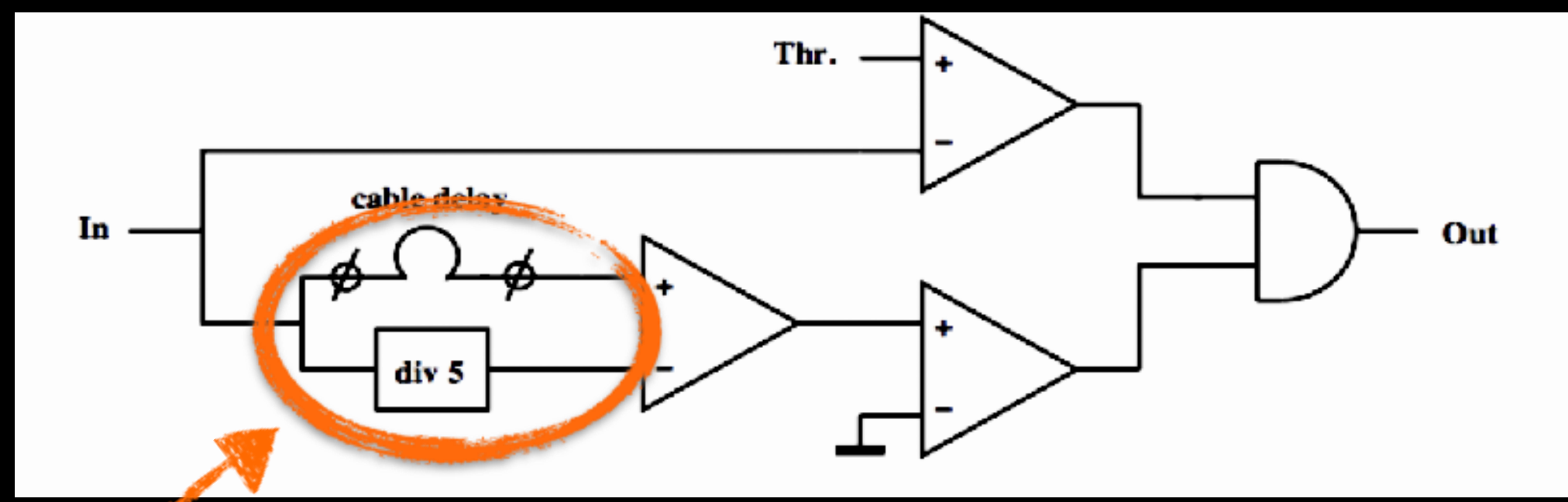
- The most trivial trigger algorithm: **Signal > Threshold**
 - Apply the lowest possible threshold
 - Identify best compromise between **hit efficiency** and **noise rate**

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

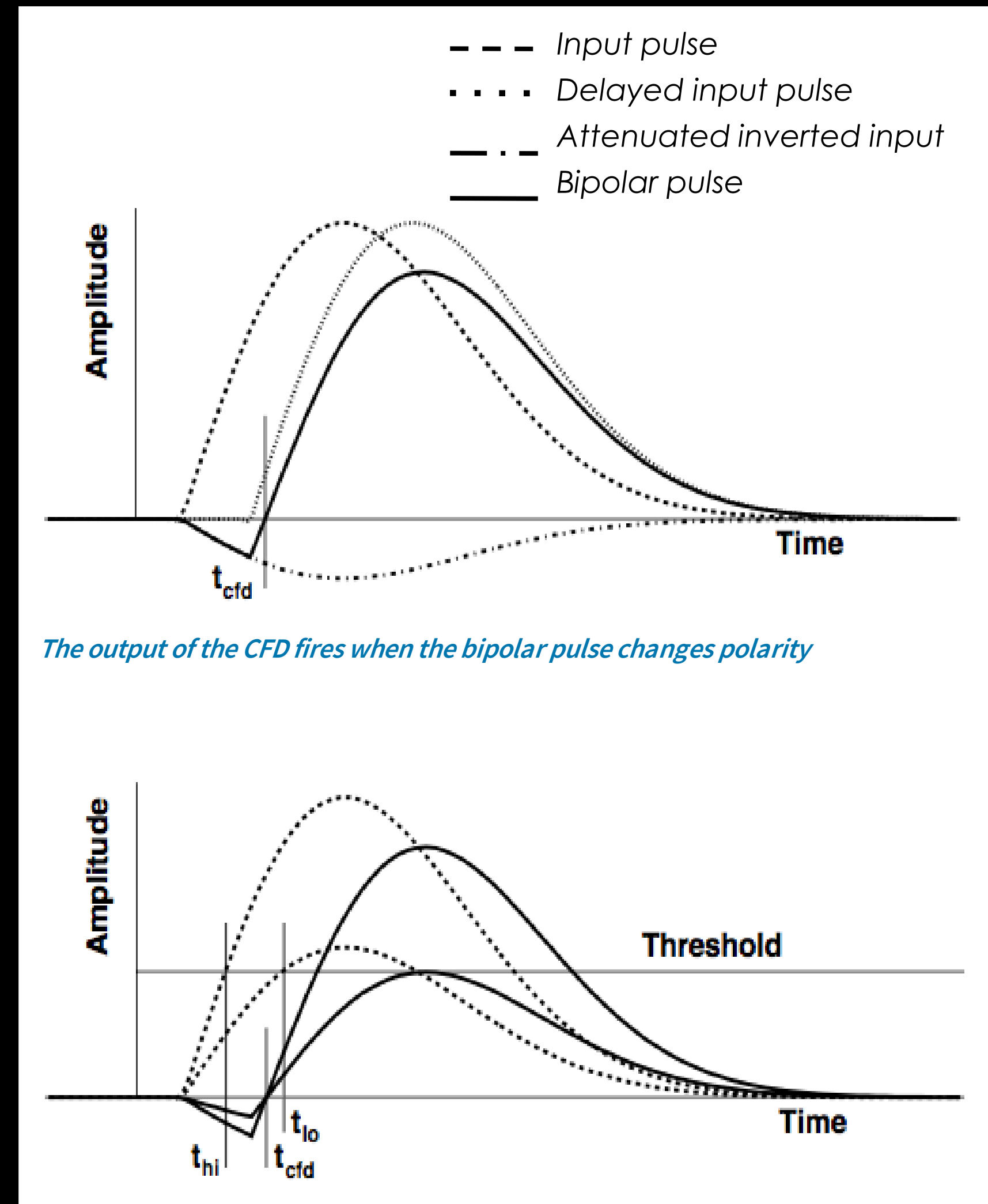


- Attenuation + configurable delay applied before the discrimination determines t_{CFD}
- If delay too short, the unit works as a normal discriminator since the output of the normal discriminator fires later than the CFD part

Signals with the same rising time, at a fraction f

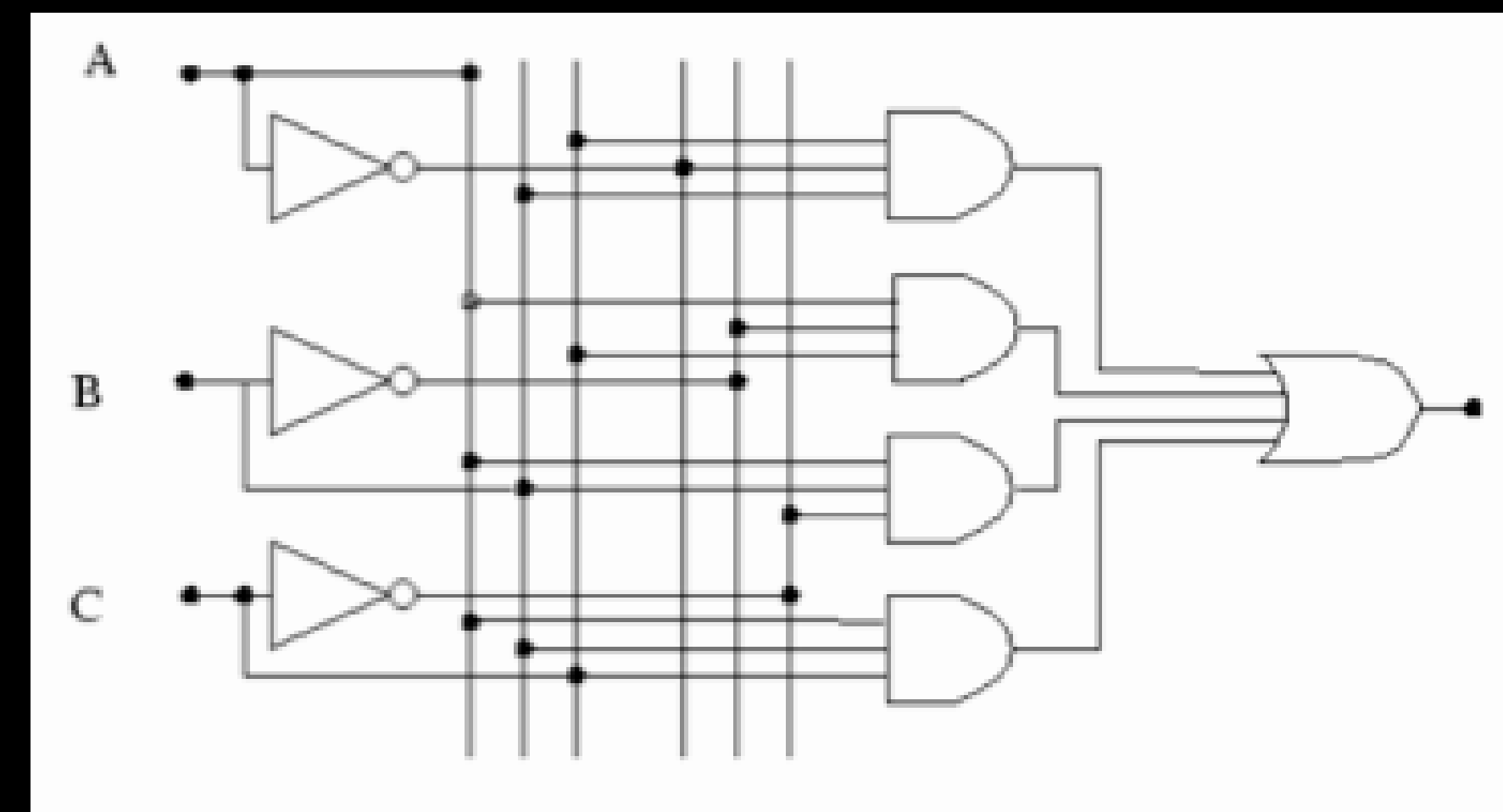
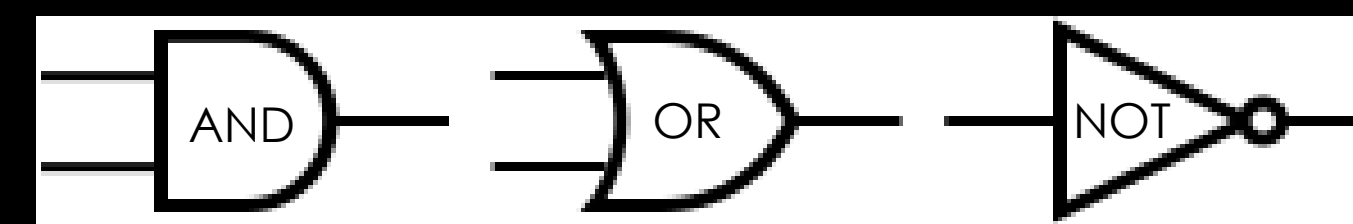
$$\Delta t_f = t(f \cdot A_0) - t(A_0) = \text{const.}$$

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



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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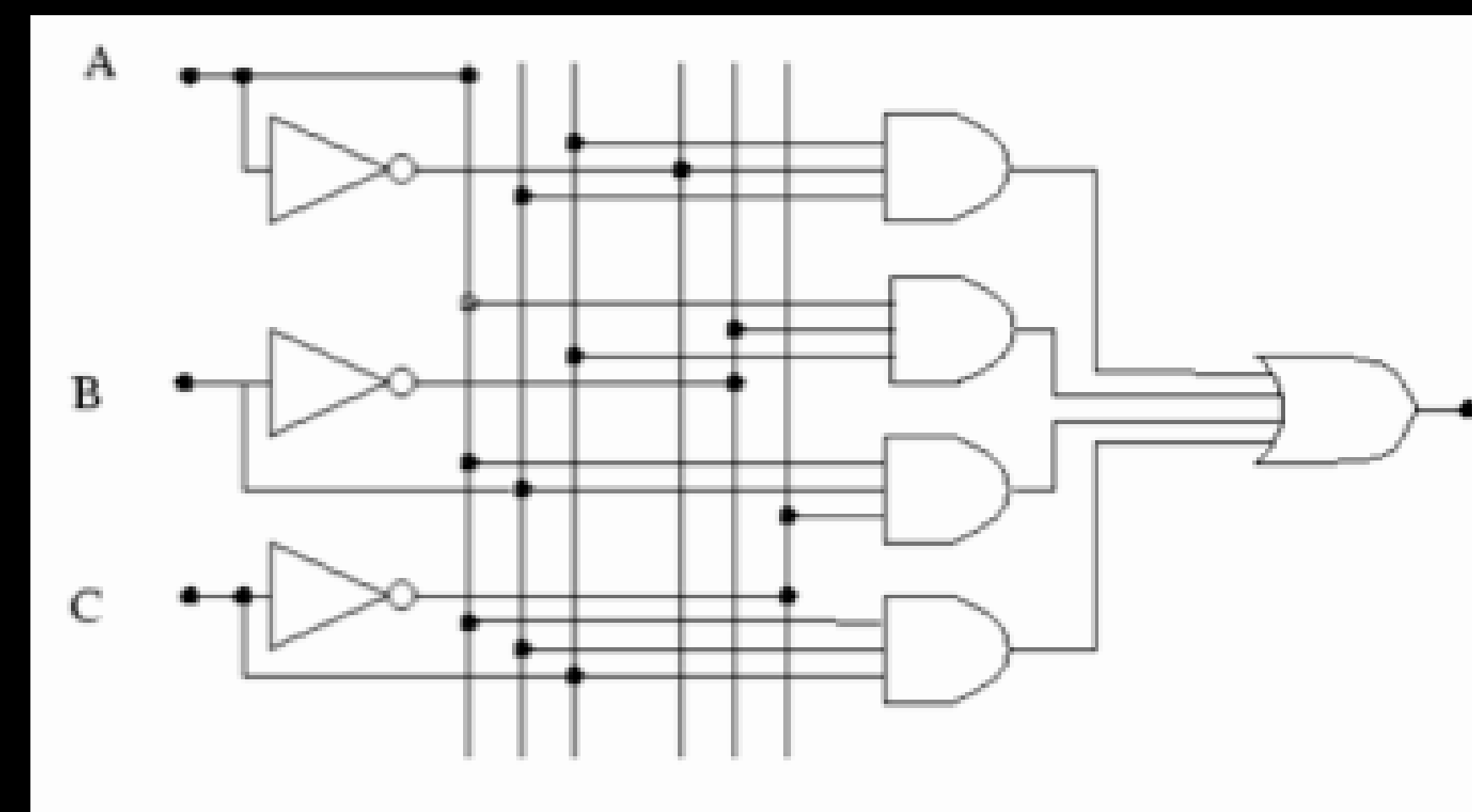
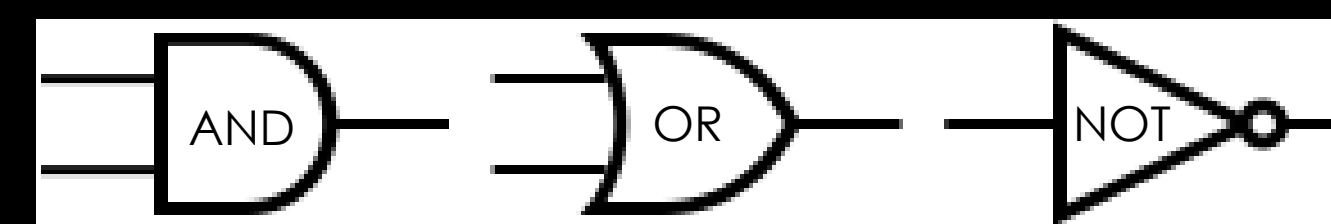
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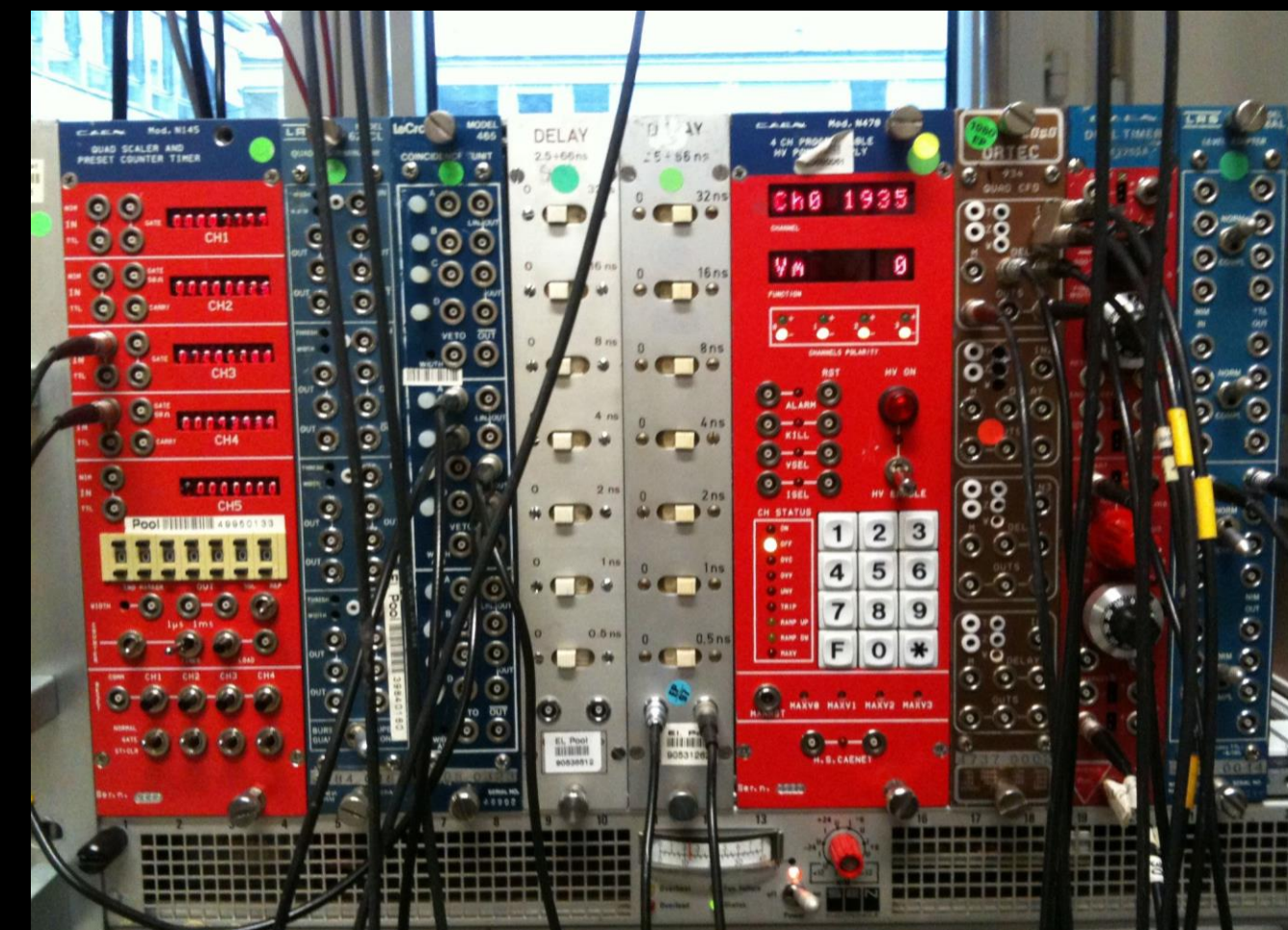
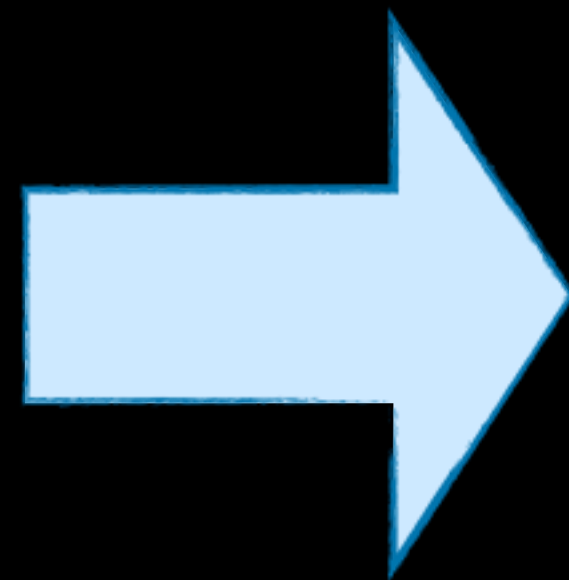
Data propagates
as a wave
through the logic

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

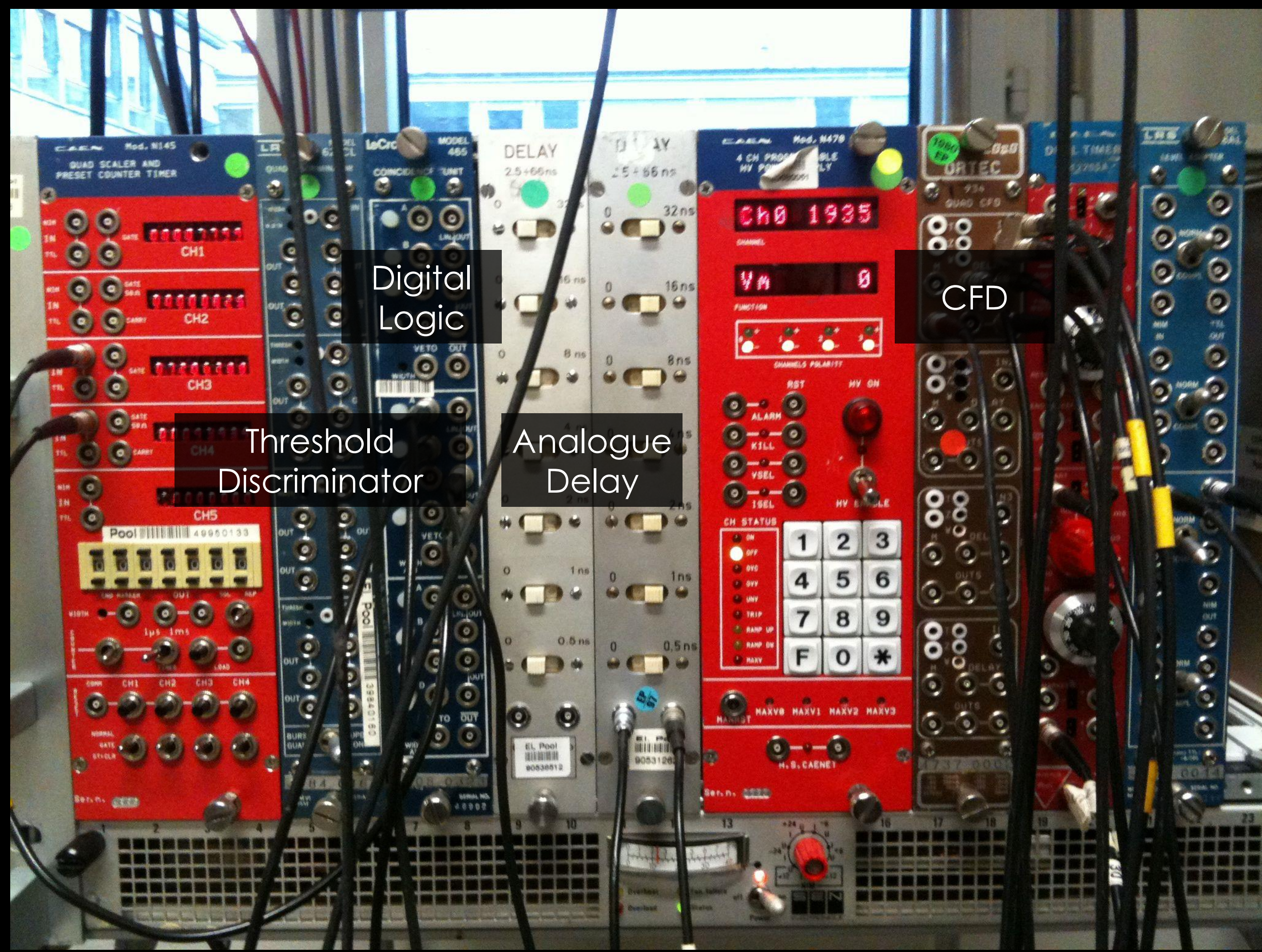


A SIMPLE TRIGGER WANTS A SIMPLE SYSTEM

- 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



A SIMPLE TRIGGER WANTS A SIMPLE SYSTEM



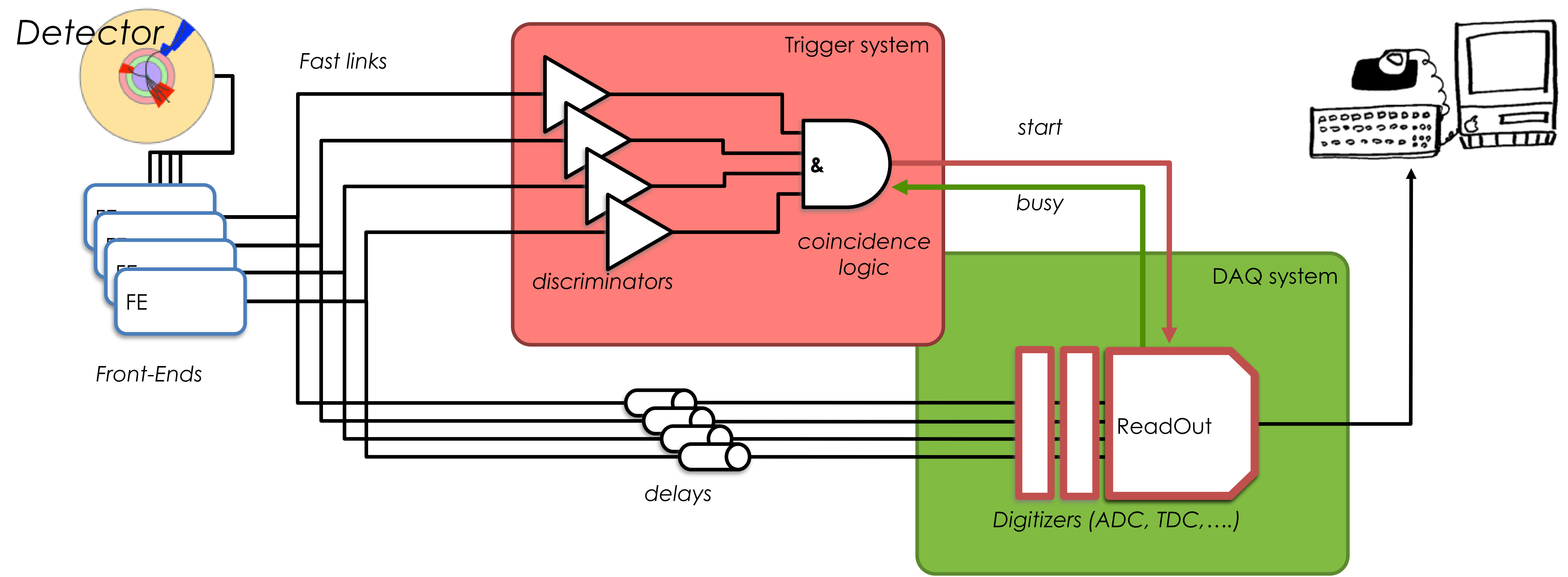
Digital Logic

CFD

Threshold Discriminator

Analogue Delay

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

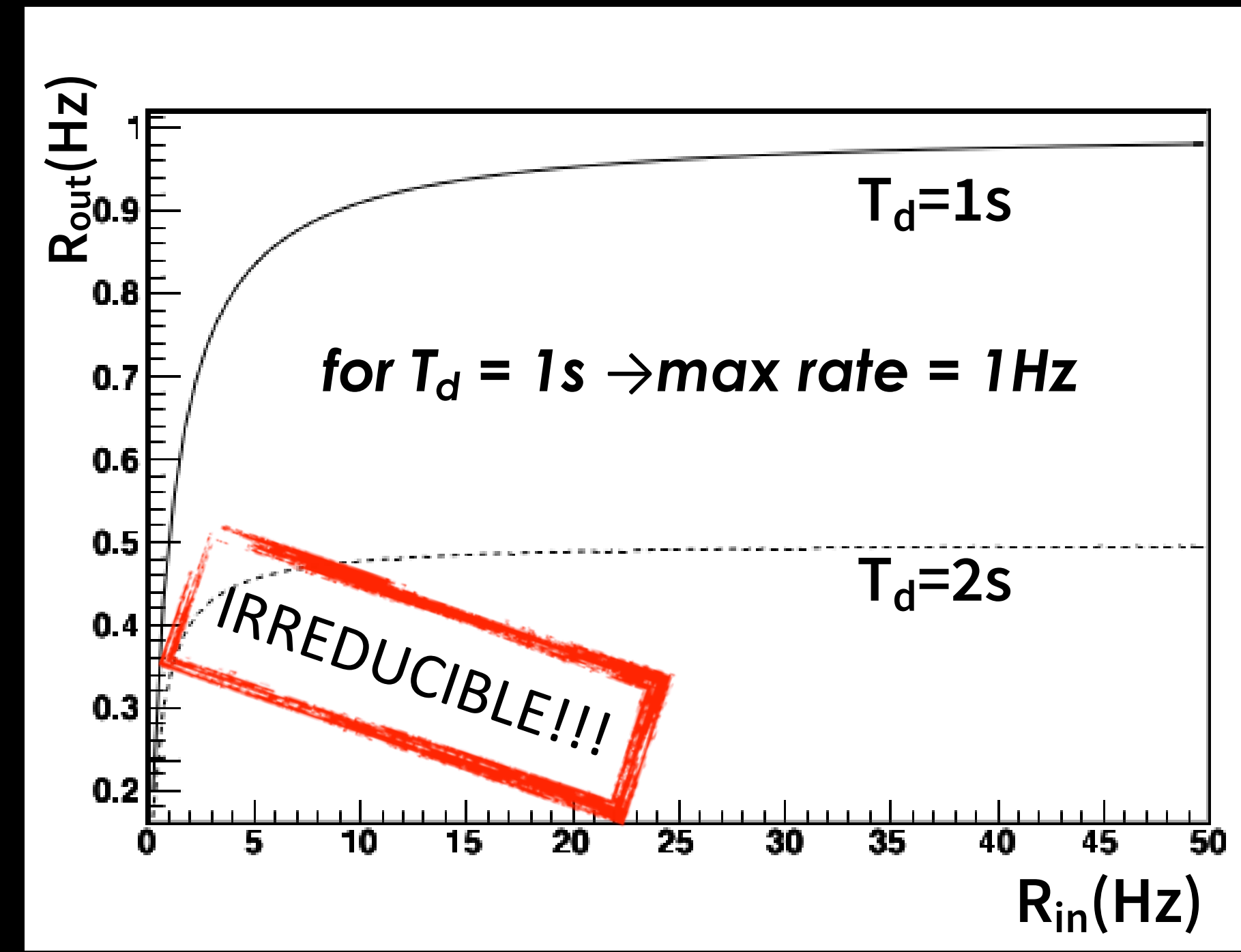
- Writing to disk or tape is much slower than accepting data into RAM
- If you select an event and start writing it to disk, you cannot accept any more events until you finish writing, even if they are interesting

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

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

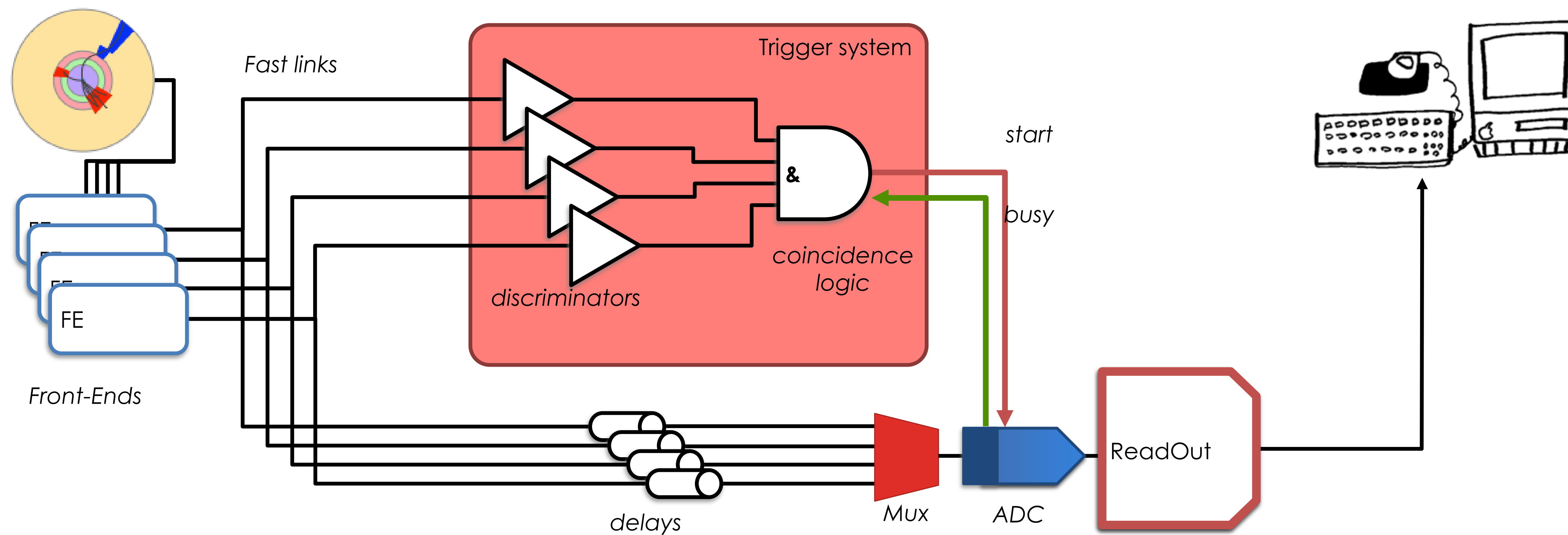


To achieve high efficiency $\Rightarrow R_{in} \cdot T_d \ll 1$

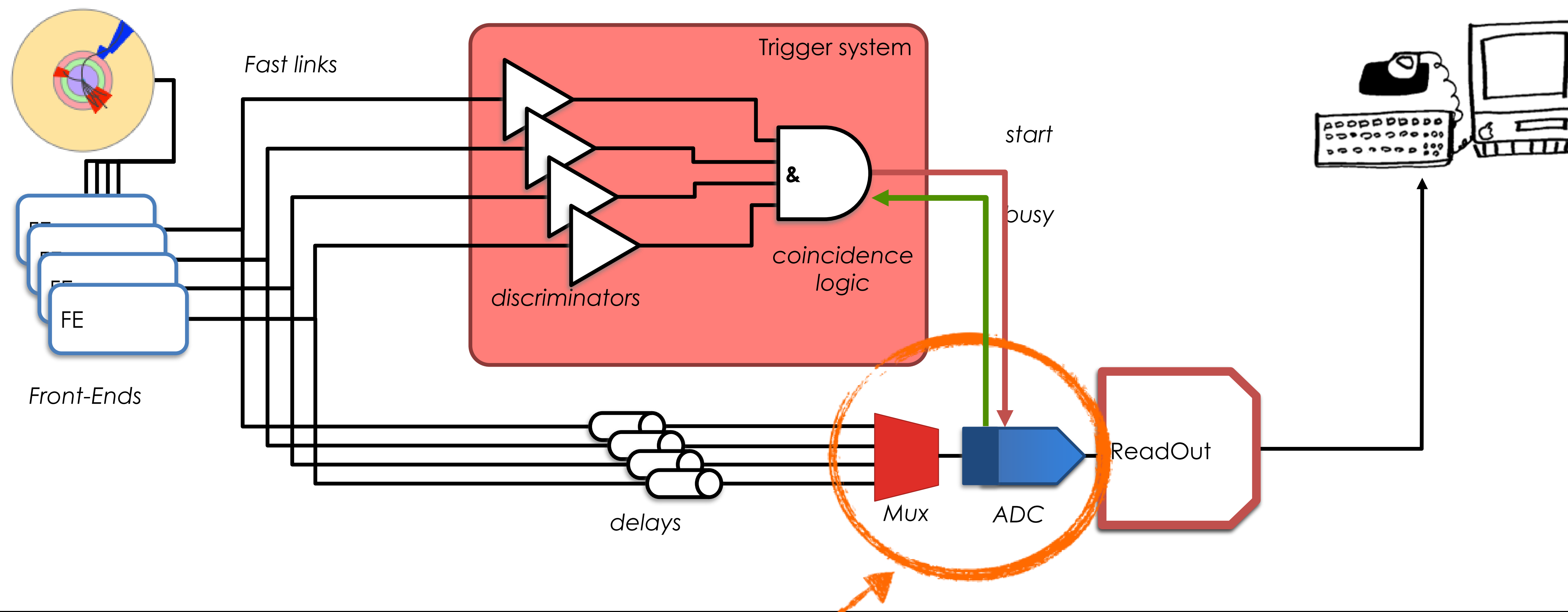
DEADTIME

- Writing to disk or tape is much slower 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

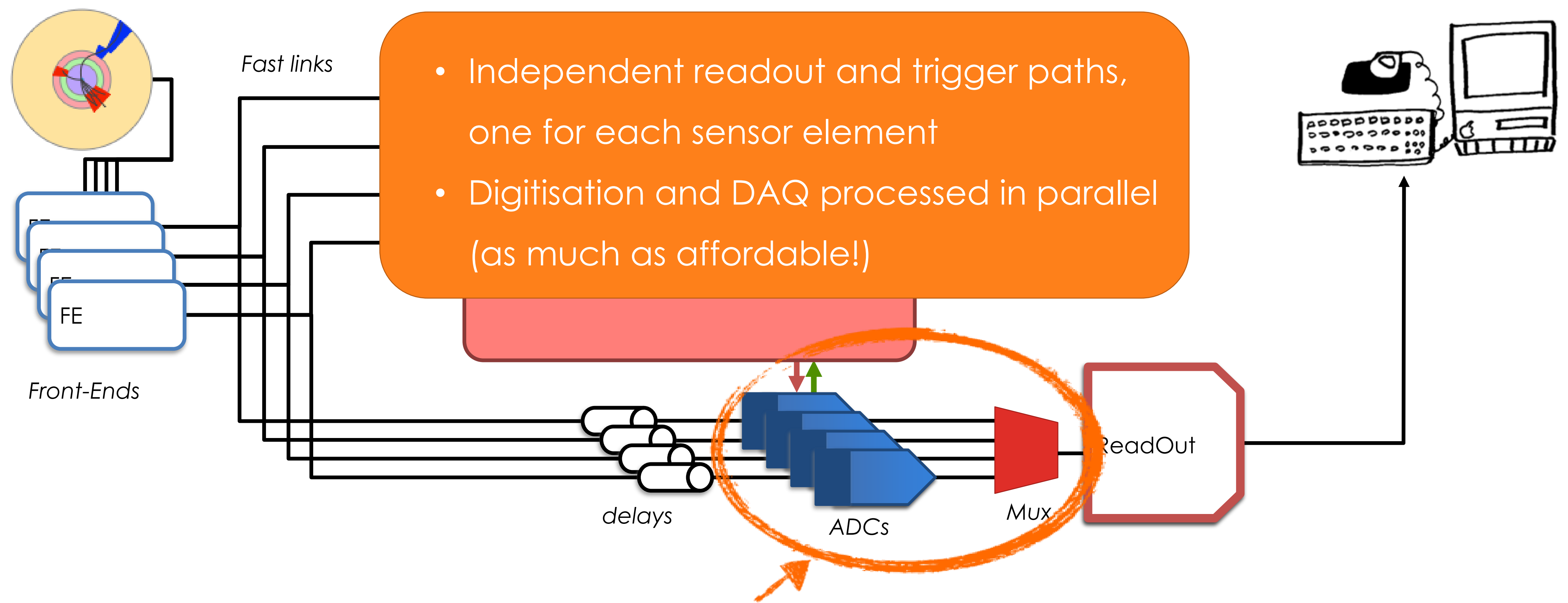


A SIMPLE TRIGGER SYSTEM: DEADTIME



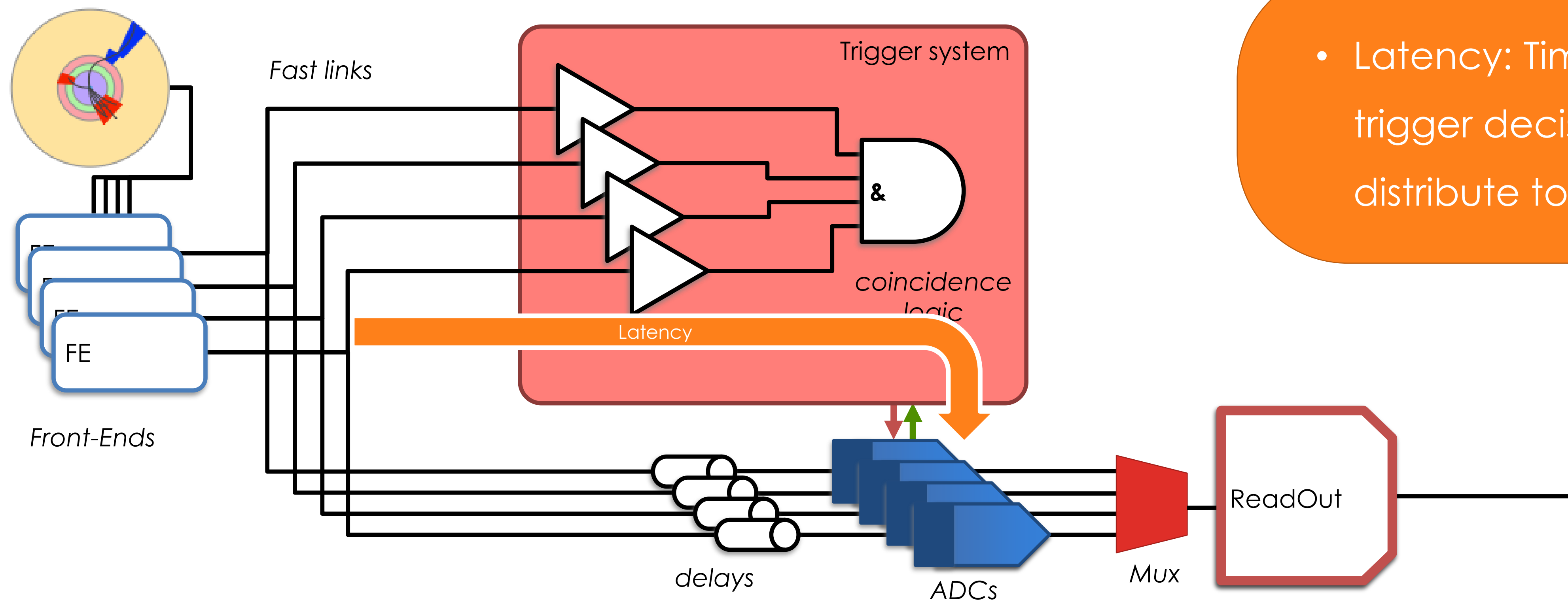
If ADC is the critical step for deadtime,
this is clearly a really bad plan

A SIMPLE TRIGGER SYSTEM: PARALLELISM



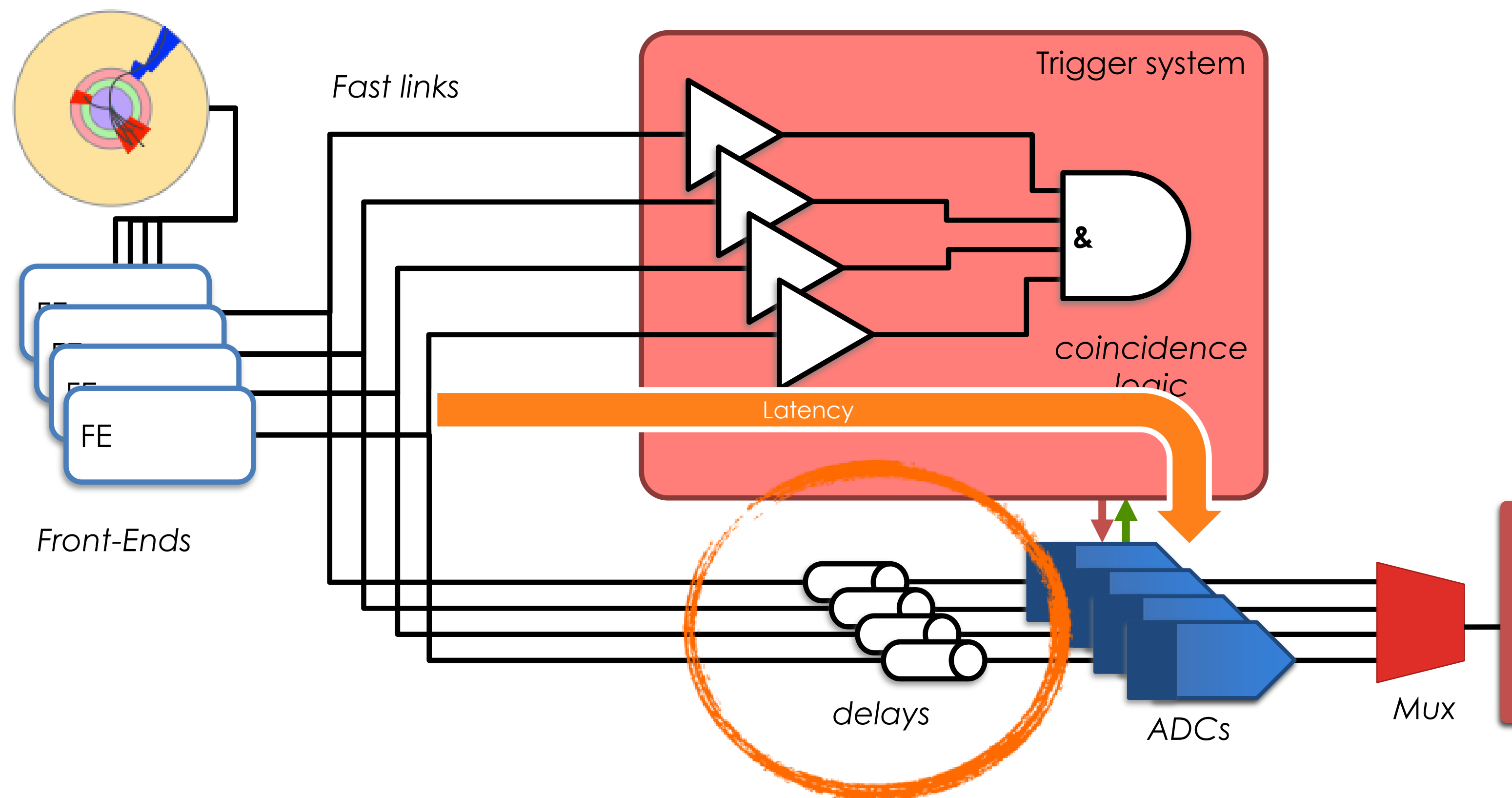
Much more sensible!
Potentially much more expensive!

KEYWORD: LATENCY



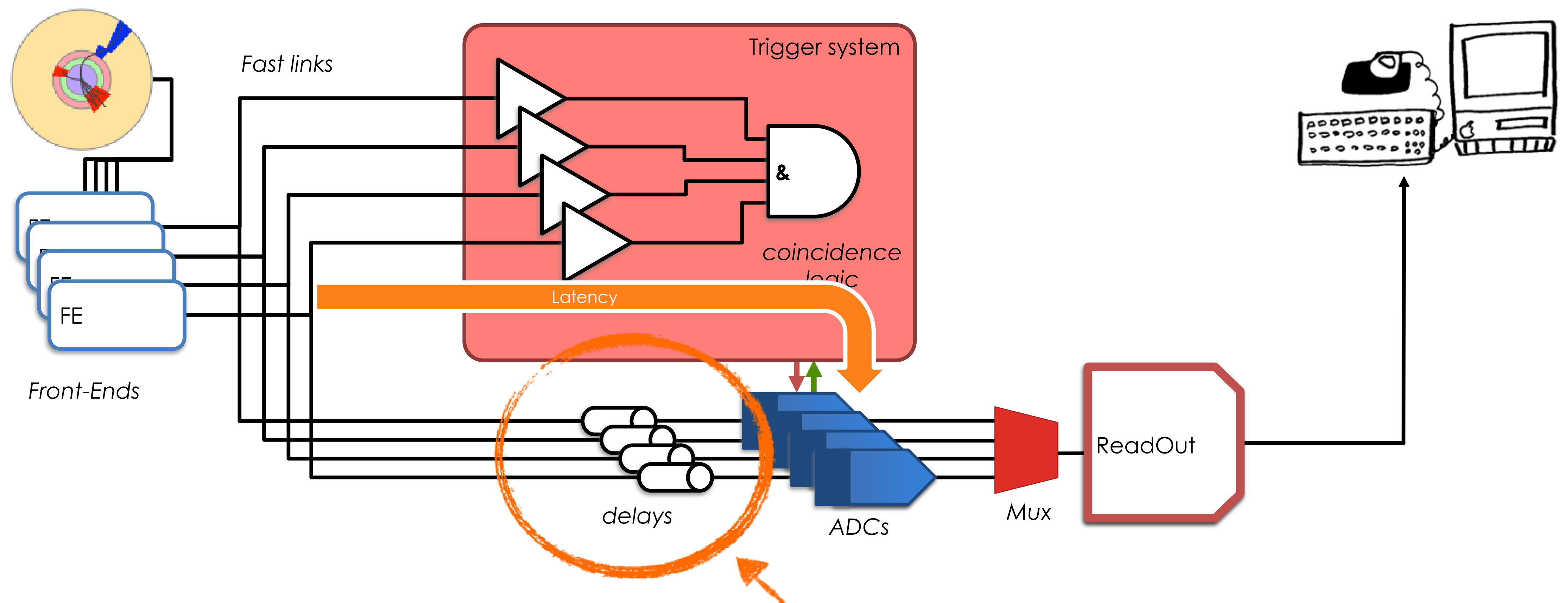
- Latency: Time to form the trigger decision and distribute to the digitisers

A SIMPLE TRIGGER SYSTEM: LATENCY



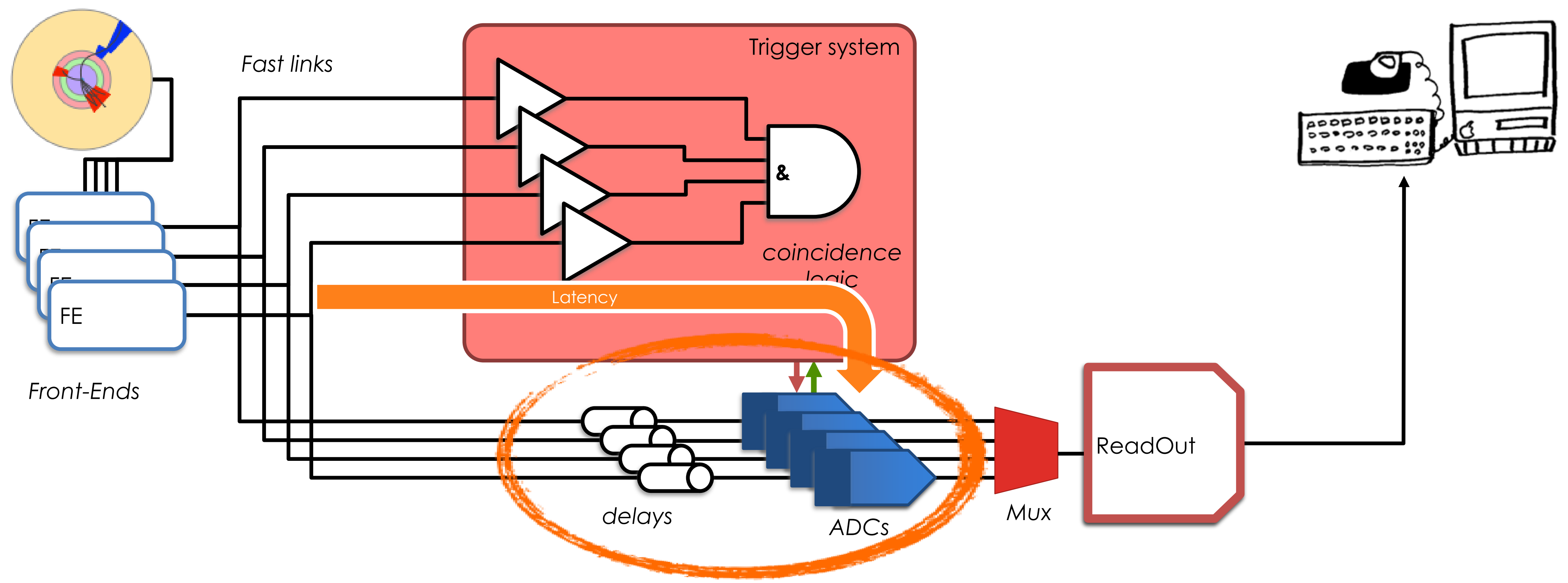
- Latency: Time to form the trigger decision and distribute to the digitisers
- Signals must be delayed until the trigger decision is available
- The more complex is the selection, the longer is the latency

A SIMPLE TRIGGER SYSTEM: LATENCY



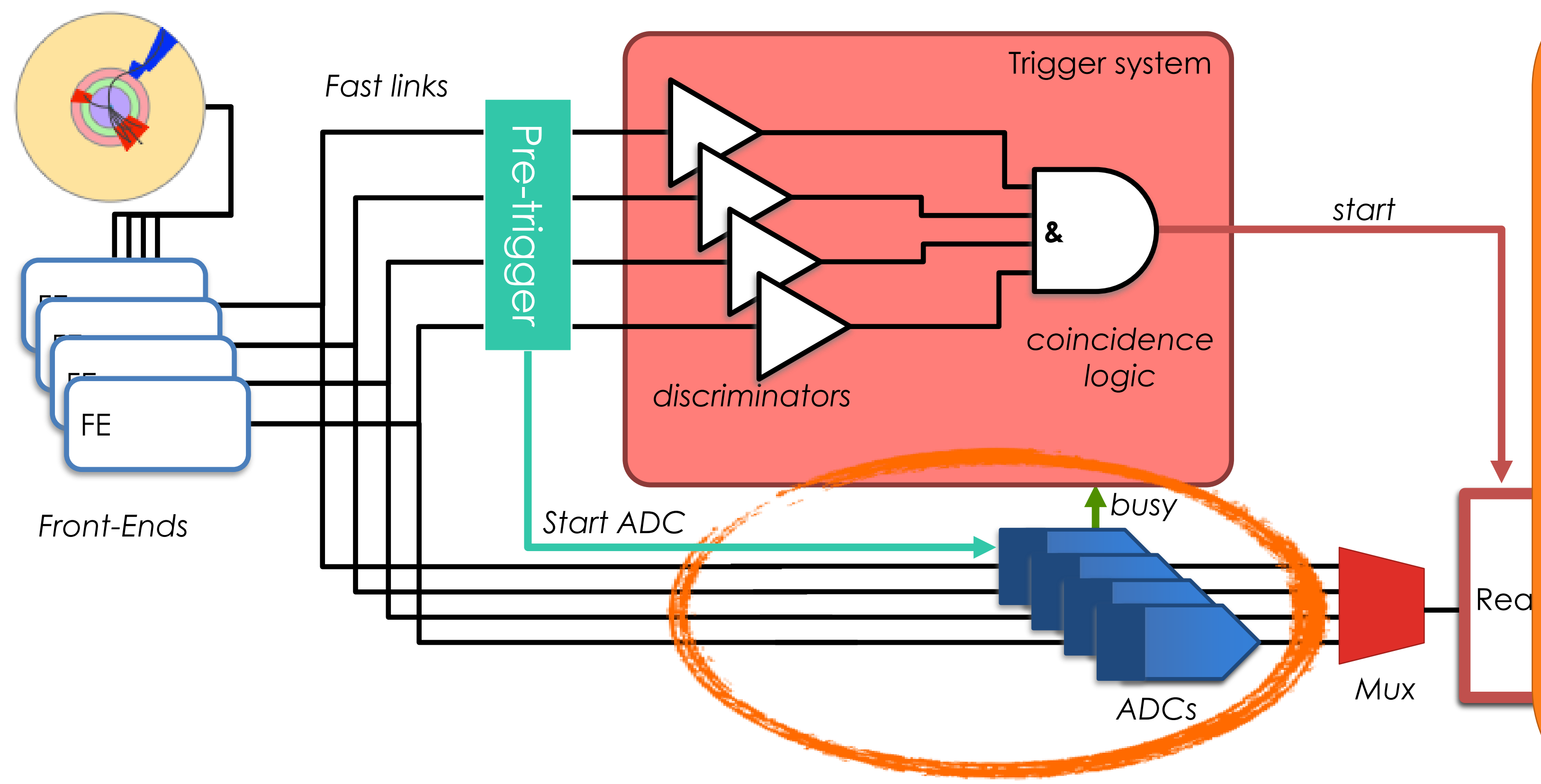
Analogue delay-lines are a bit risky, don't you think?
Especially for more than one channel

A SIMPLE TRIGGER SYSTEM



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

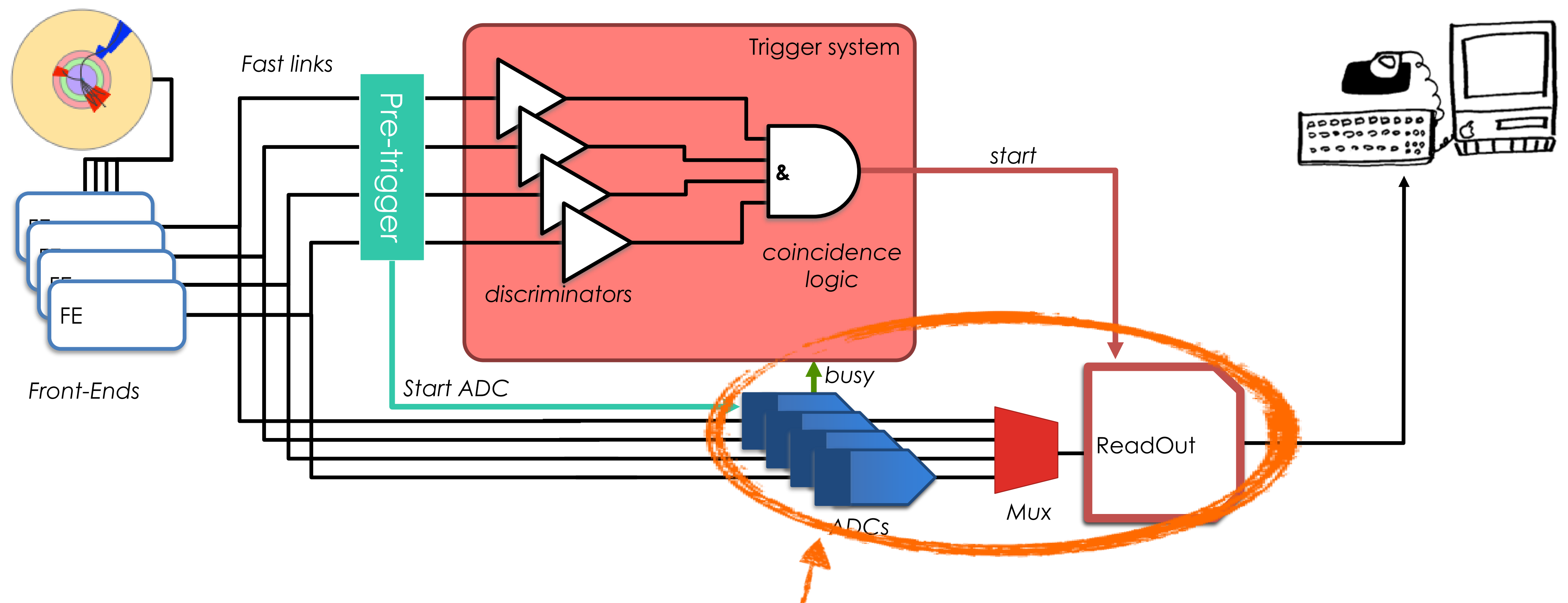
A SIMPLE TRIGGER SYSTEM: PRE-TRIGGER



- 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

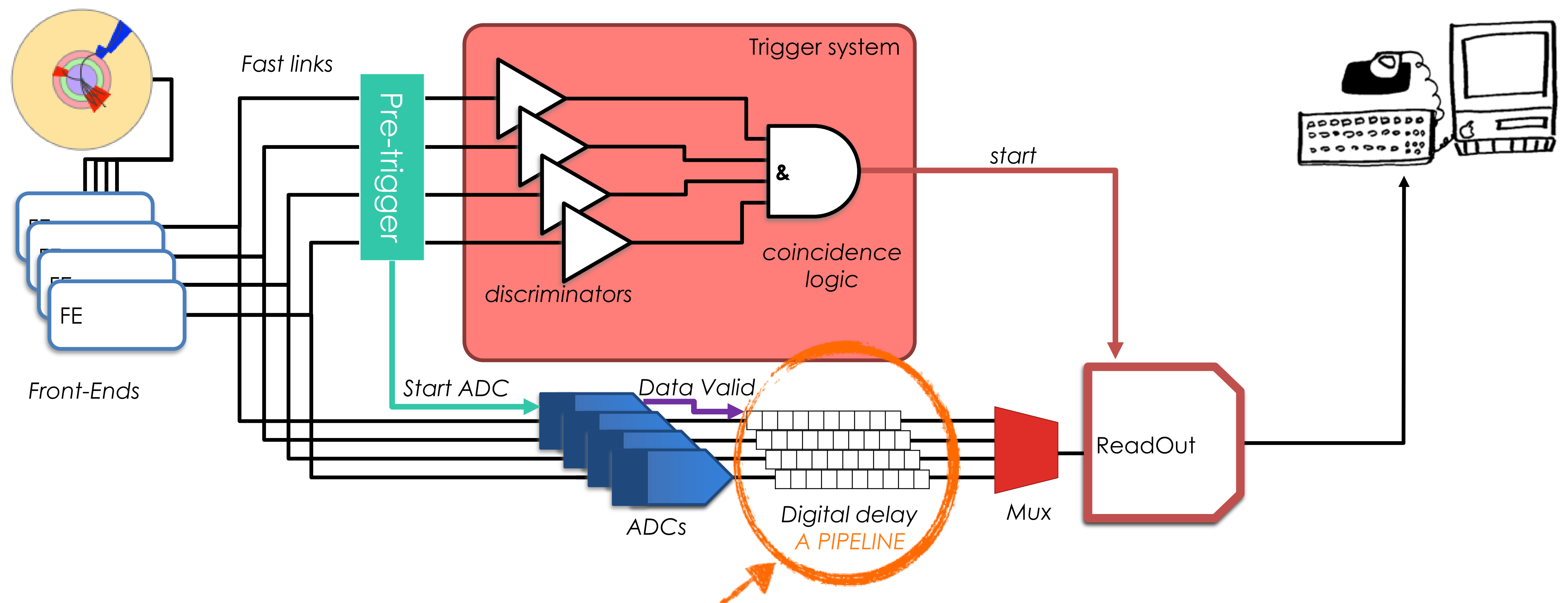
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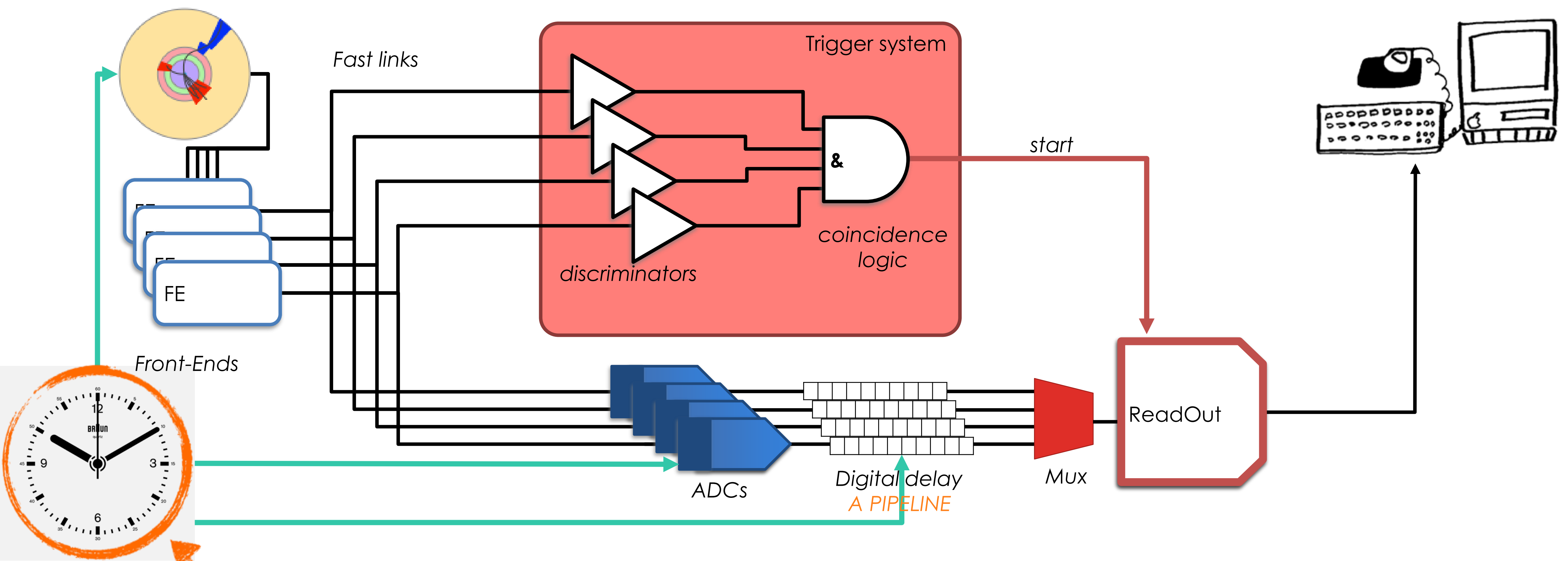
Assumes the digitization time is longer than the latency of the trigger system!
What if that is not true?

A SIMPLE TRIGGER SYSTEM: PRE-TRIGGER



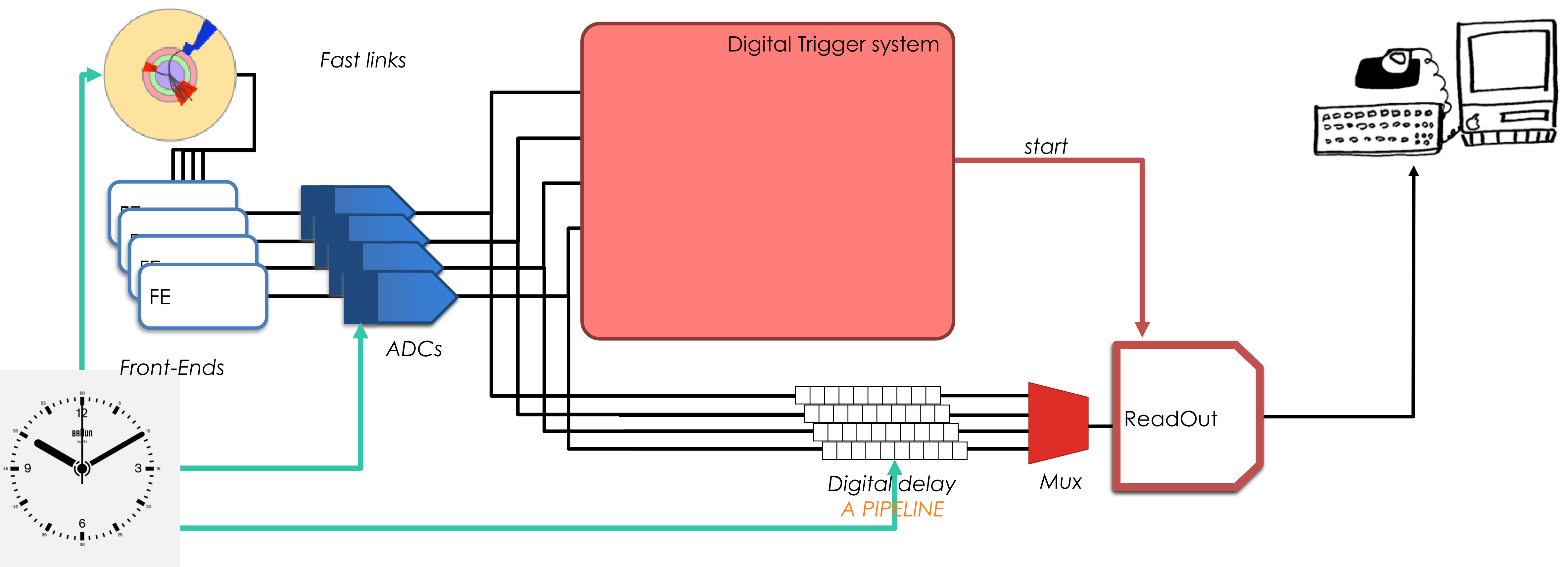
Since each digitization takes a finite time
Can store the result of each digitization in RAM until trigger decision is made

SIMPLE TRIGGER SYSTEM: BUNCHED COLLIDERS

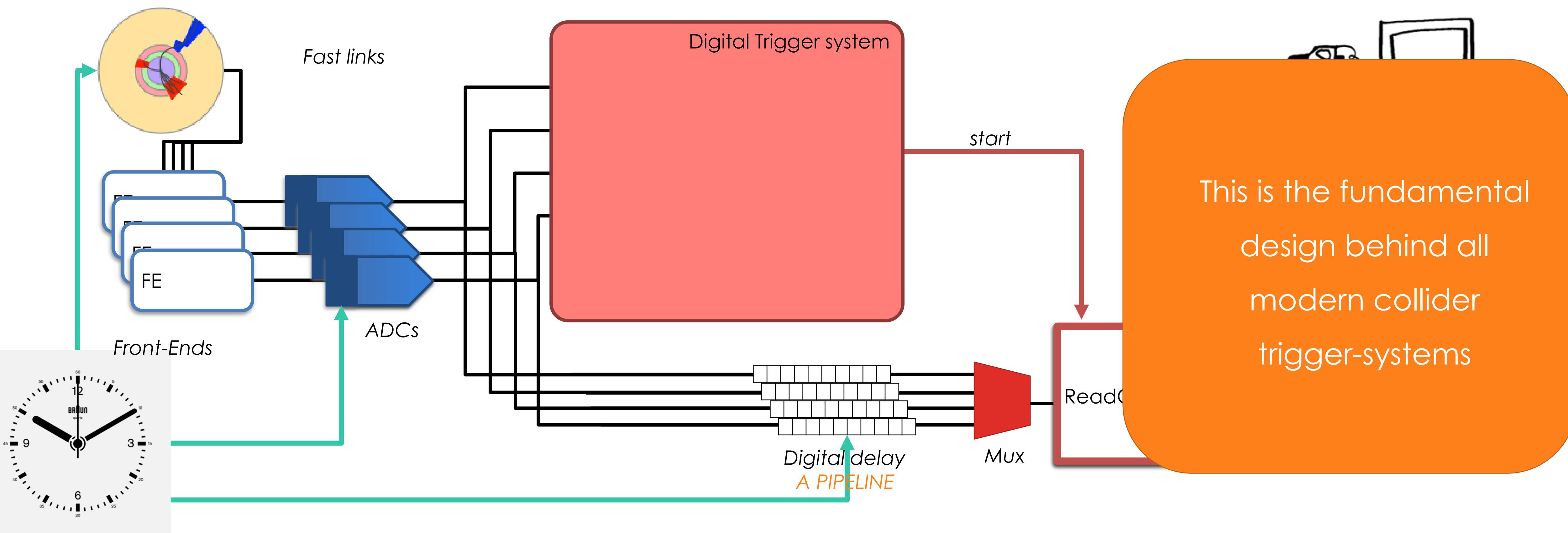


We have a master-clock – the bunch-crossings themselves!
No need for a pre-trigger

A SIMPLE TRIGGER SYSTEM: DIGITAL TRIGGERS



A SIMPLE TRIGGER SYSTEM: DIGITAL TRIGGERS



AND FINALLY: A PHILOSOPHICAL QUESTION

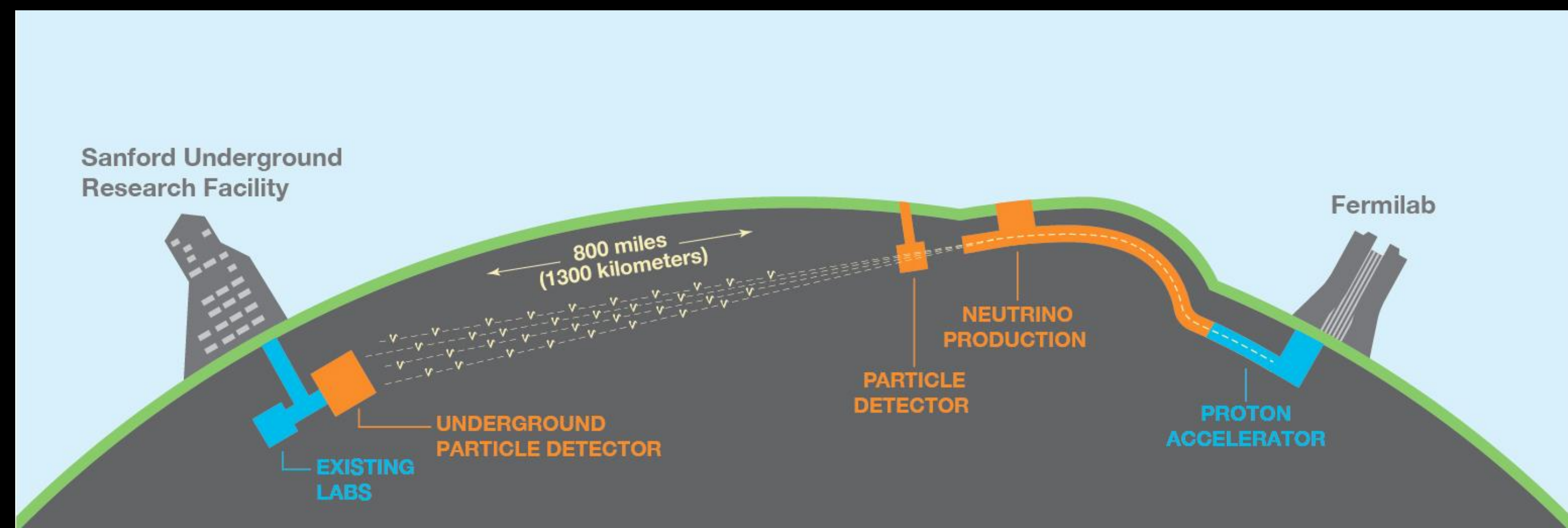
- If you only see what the trigger accepts, how do you know what you have thrown away?

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?