Introduction to Trigger and Data Acquisition

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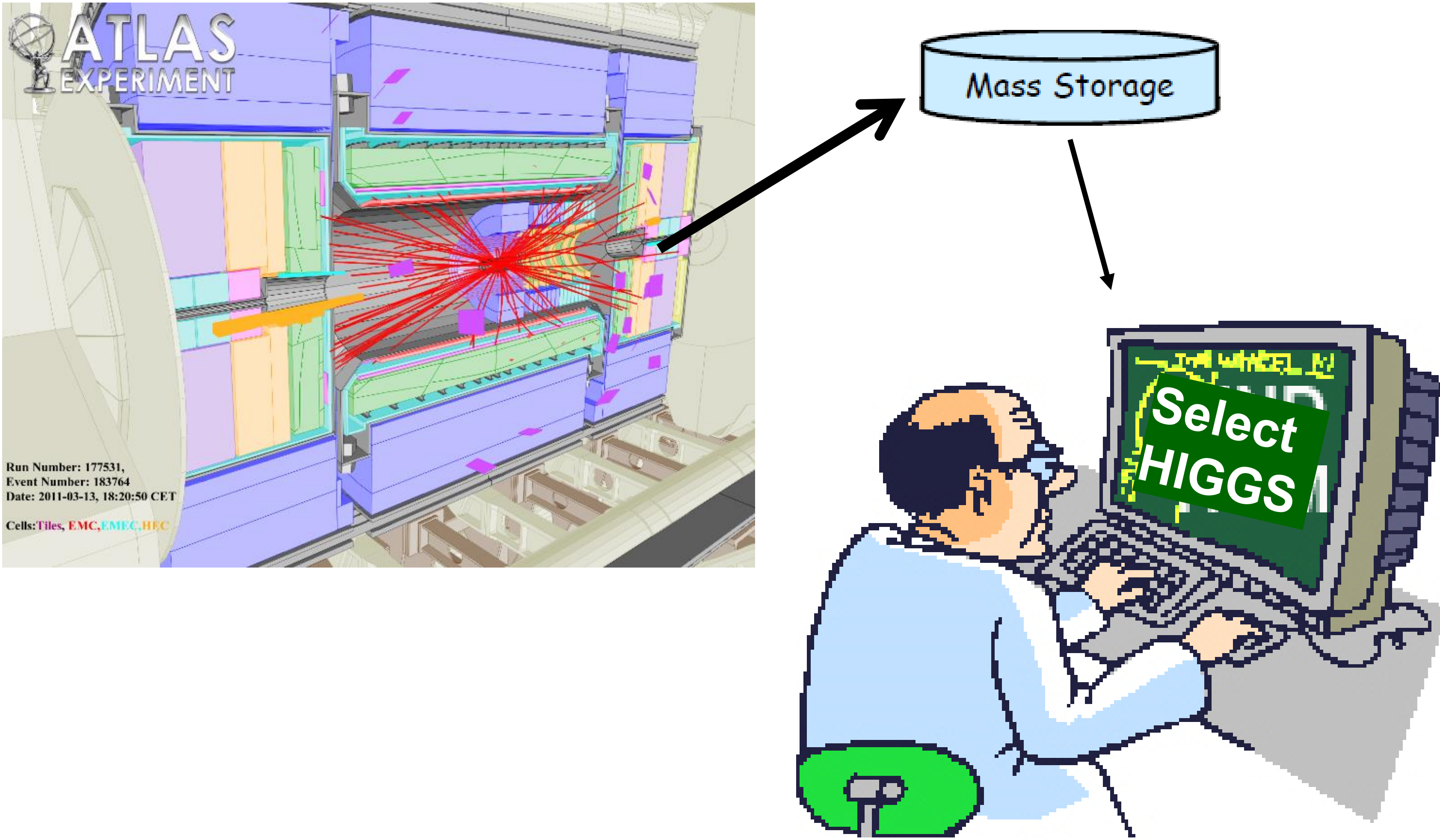
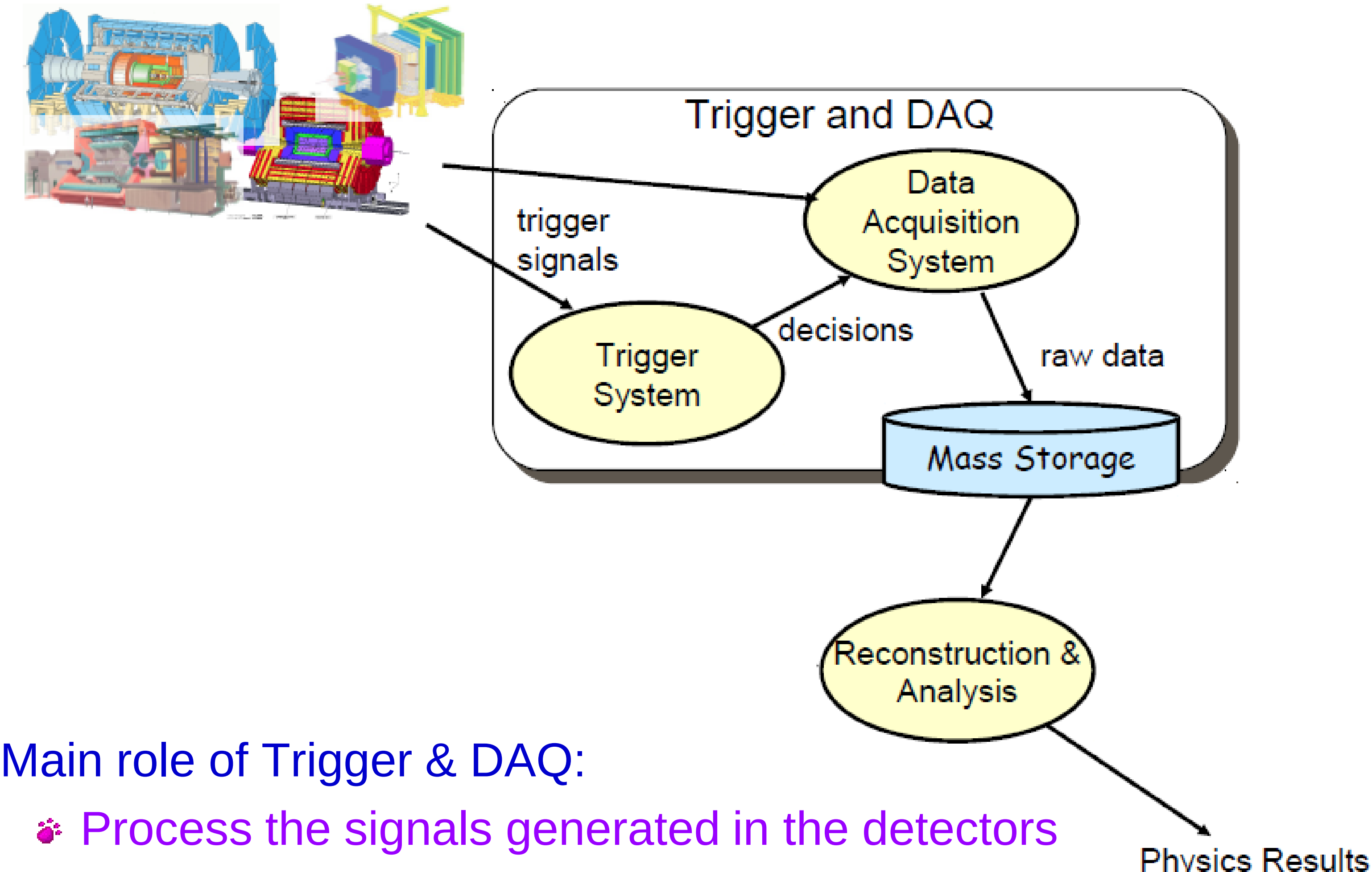
What is it about...

- How to get from   to



Or



- Main role of Trigger & DAQ:
  - Process the signals generated in the detectors
  - Select the ‘interesting’ events and reject the ‘boring’ ones
  - Save interesting ones on mass storage for physics analysis
- Heartbeat of the experiment!

DAQ

- Abbreviation for Data Acquisition System
- Wikipedia:
  - Process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer.
- In HEP it consists mainly of electronics, computer science, networking and quite some physics
- Tasks
  - Gathers the data produced by the detectors (Readout)
  - Forms complete events (Event Building)
  - Possibly feeds (several) levels of deciding to keep the collision (called typically event in the following)
  - Stores event data (Data logging)
  - Provides control, configuration and monitoring facilities

Trigger

- That's one

- But that's not what we want to discuss here
- Trigger = in general something which tells you when is the "right" moment to take your data
- Trigger = process to very rapidly decide if you want to keep the data if you can't keep all of them. The decision is based on some 'simple' criteria
- This can happen in several stages, if needed
- Note, DAQ and Trigger often are not two separate issues, but are 'interwoven'

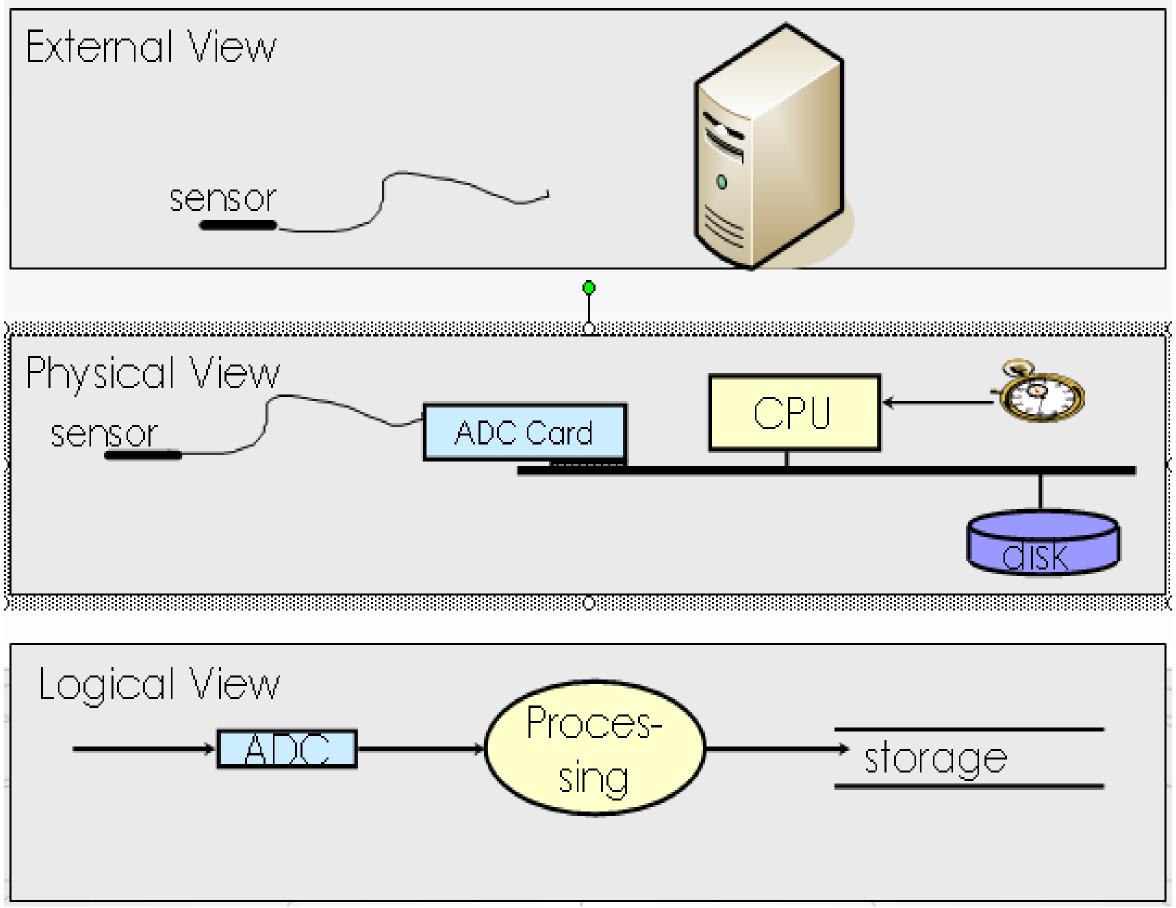
Goals of this lecture

- Understand how data acquisition is devised
  - Start with simple example and then get more complex

- Introduce the terms you will hear when you hear about data acquisition in a HEP experiment

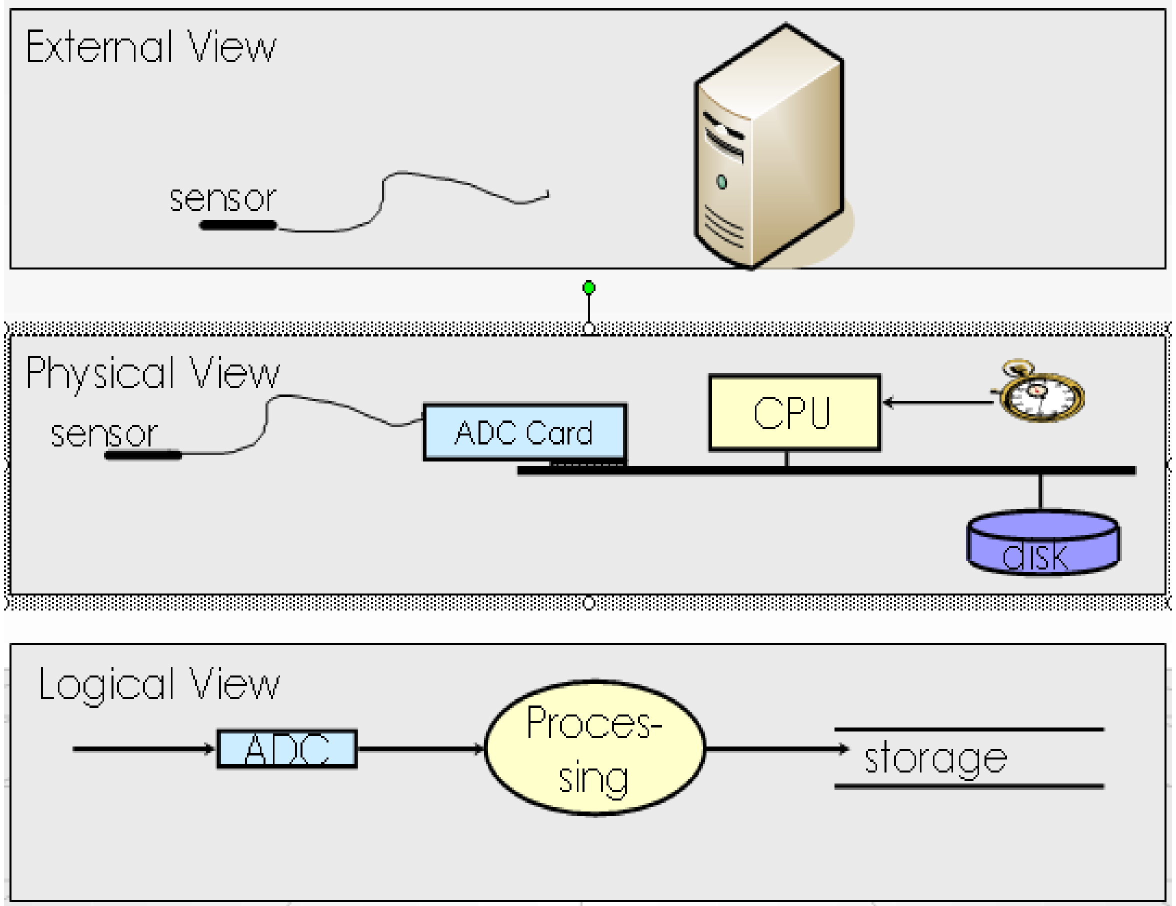
- All this might be a bit technical but might help you later during your Ph.D. and it is actually also quite some fun!

Trivial DAQ (periodic trigger)



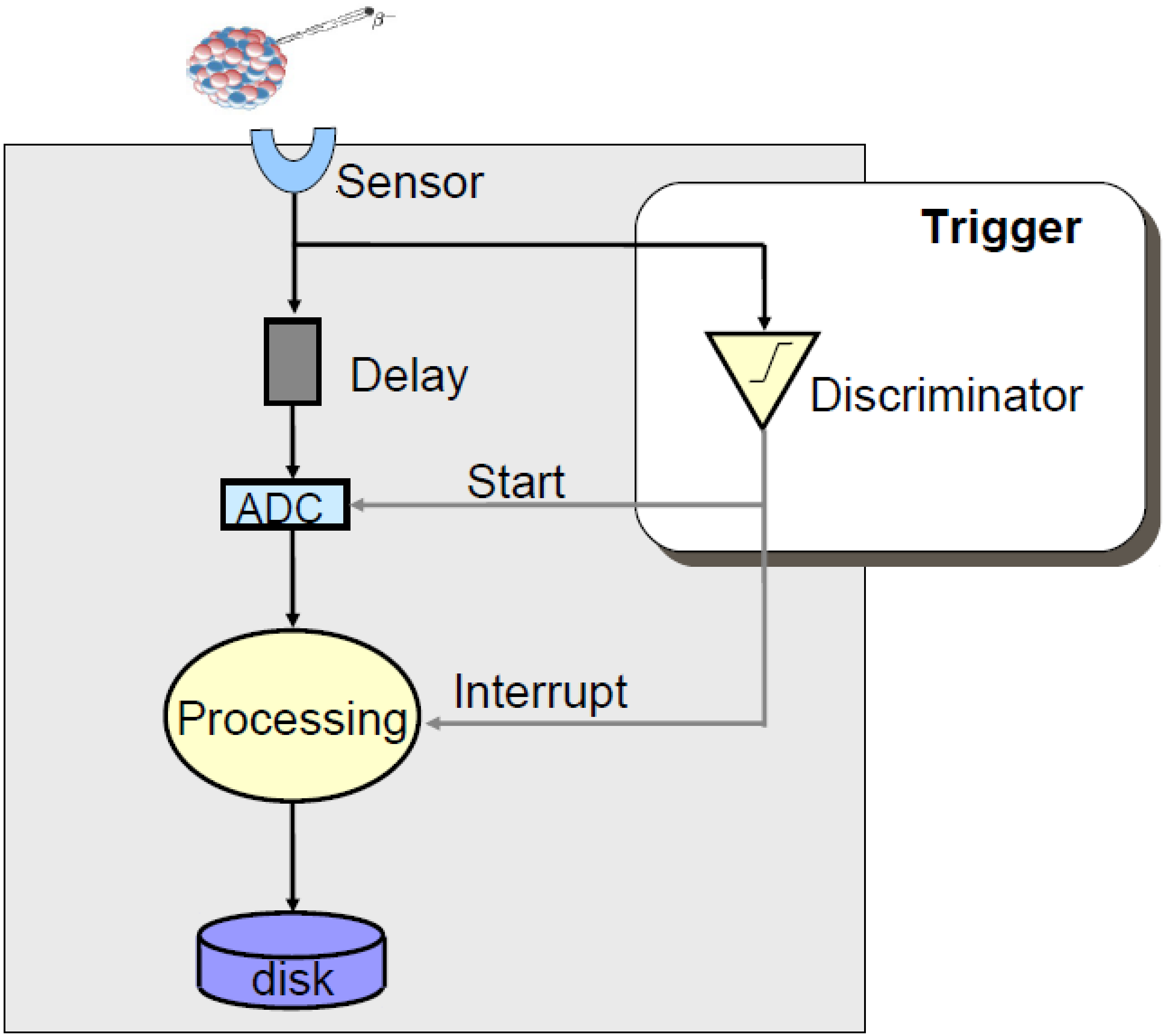
- Measure temperature at a fixed frequency
- ADC performs analog to digital conversion (digitisation)
  - Our frontend electronics
- CPU does readout and processing

Trivial DAQ (periodic trigger)



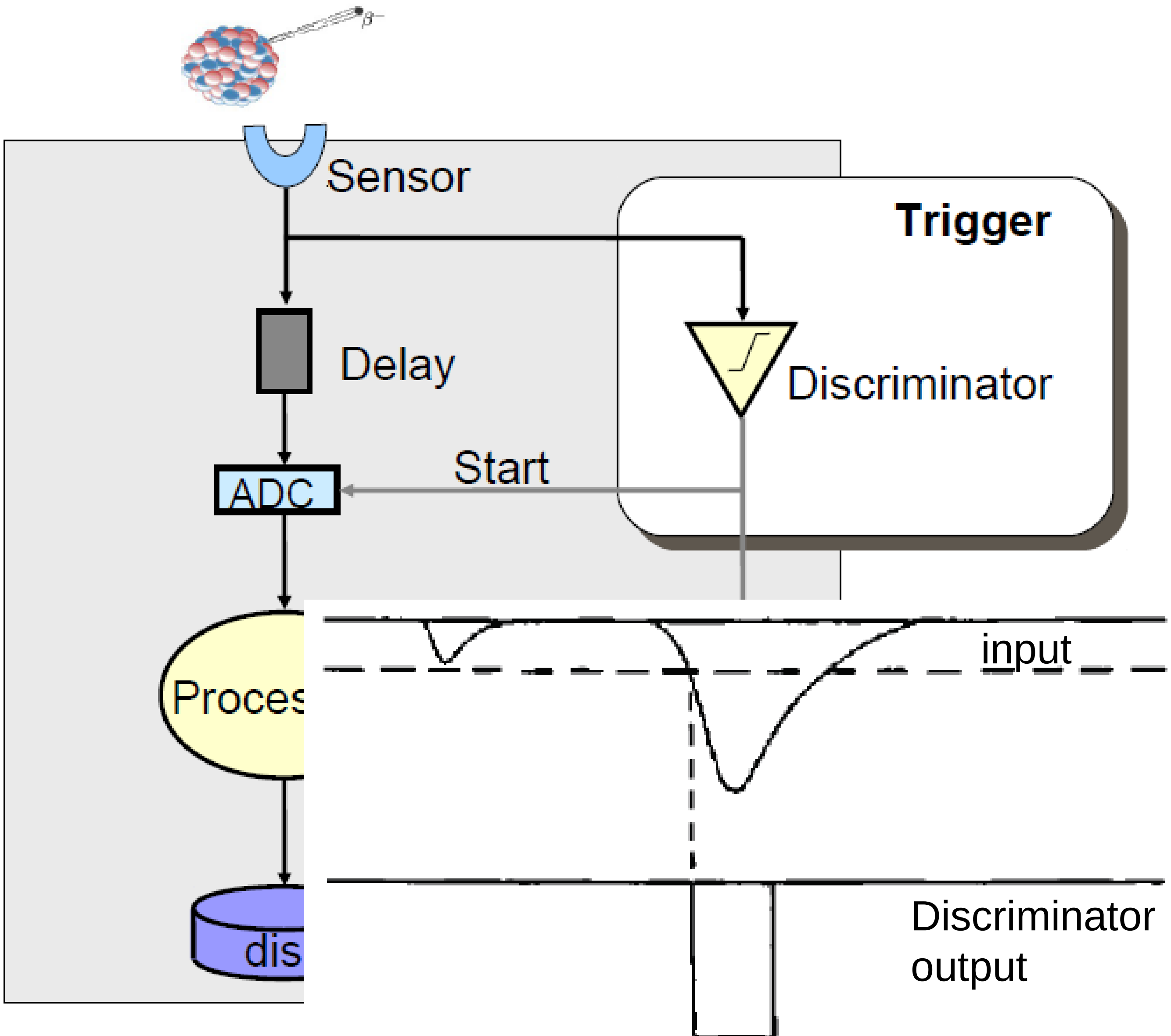
- Measure temperature at a fixed frequency
- The system is clearly limited by the time to process a measurement (or event)
- Example τ=1ms to
  - ADC conversion +CPU processing +Storage
- Sustain maximal ~1/1ms=1kHz ***periodic trigger*** rate

Trivial DAQ with a trigger



- Example: measure β decay properties
- Our events are asynchronous and unpredictable
  - Need a physics trigger
- Delay compensates for the trigger latency

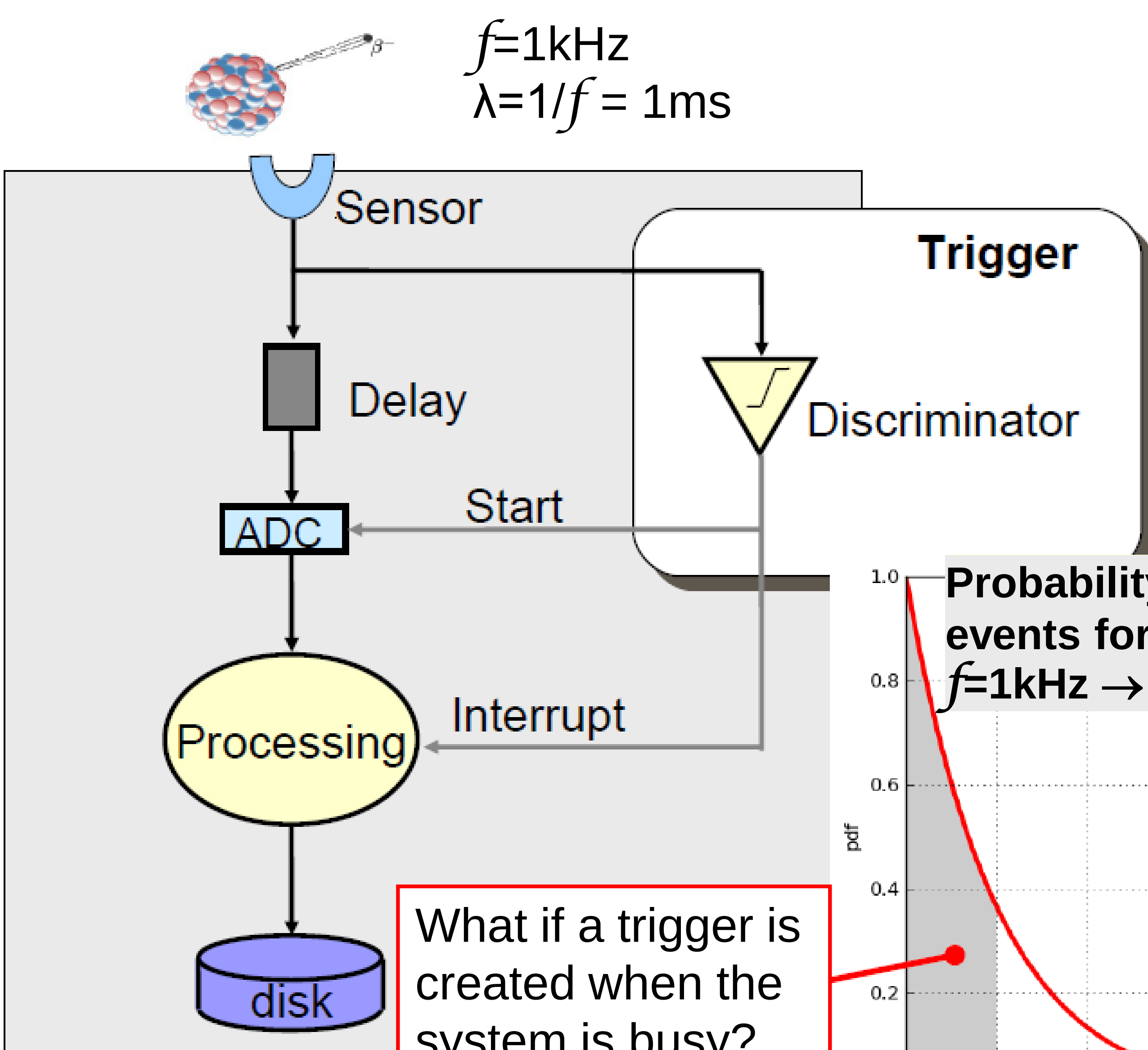
Trivial DAQ with a trigger



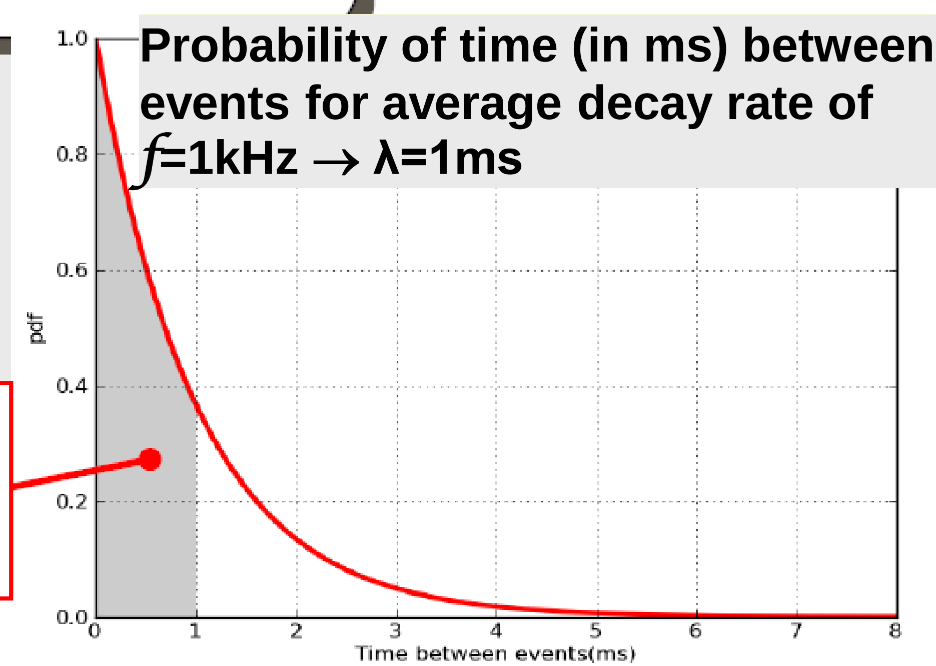
- Example: measure β decay properties
- Our events are asynchronous and unpredictable
  - Need a physics trigger
- Discriminator: generate an output signal only if amplitude of input pulse is greater than a certain threshold

Trivial DAQ with a trigger

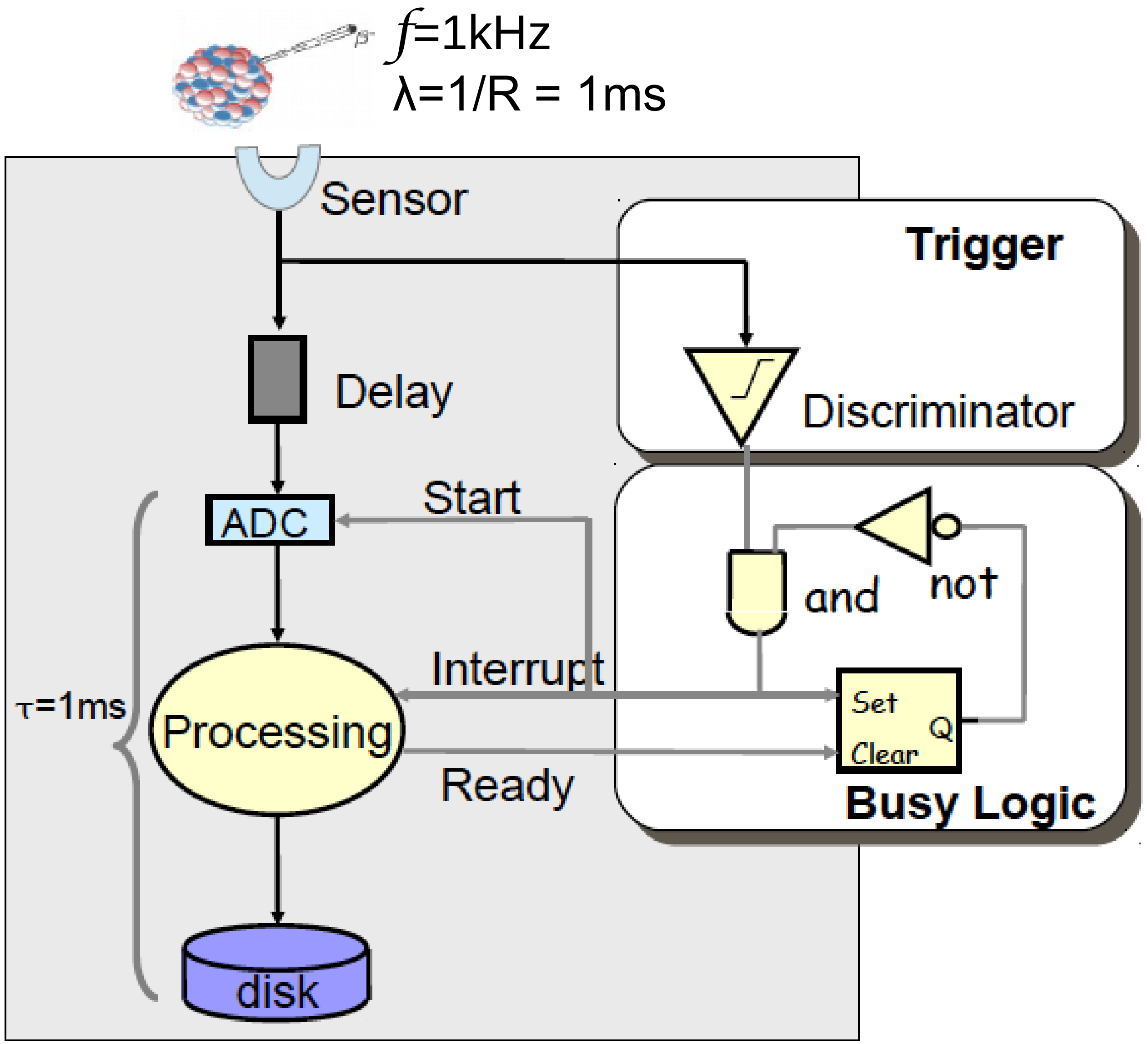
- Example: measure β decay properties
  - Stochastic process
  - Need a physics trigger



What if a trigger is created when the system is busy?



Trivial DAQ with a trigger



- Busy logic avoids triggers while processing
- Which (average) DAQ rate can we achieve now?
- Reminder: τ=1ms was sufficient to run at 1kHz with a clock trigger

Deadtime and Efficiency

- Definitions
  - Average rate of physics phenomenon (input): f
  - Process rate: $\lambda = 1/f$
  - Average rates of DAQ (output): □
  - Deadtime: □
    - Time the system requires to process an event, without being able to handle other triggers
  - Probability that DAQ is busy: P[busy] = □□□
  - Probability that DAQ is free: P[free] = 1 - □□□
- Therefore
  - $n = f \times P[\text{free}]$ Þ $n = f(1 - n \times t)$ Þ $n = \dfrac{f}{1 + f \times t} < f$
  - Efficiency: $e = \dfrac{N_{saved}}{N_{tot}} = \dfrac{1}{1 + f \times t} < 100\%$

Deadtime and Efficiency

- Due to stochastic fluctuations
  - DAQ rate < physics rate $n = \frac{f}{1+f\tau} < f$
  - Efficiency always < 100% $e = \frac{1}{1+f\tau} < 1$
- In our example: f=1kHz, $\tau=1$ms
  - ν = 1kHz / (1 + 1kHz · 1ms) = 500Hz
  - ε = 1 / (1 + 1kHz · 1ms) = 50%

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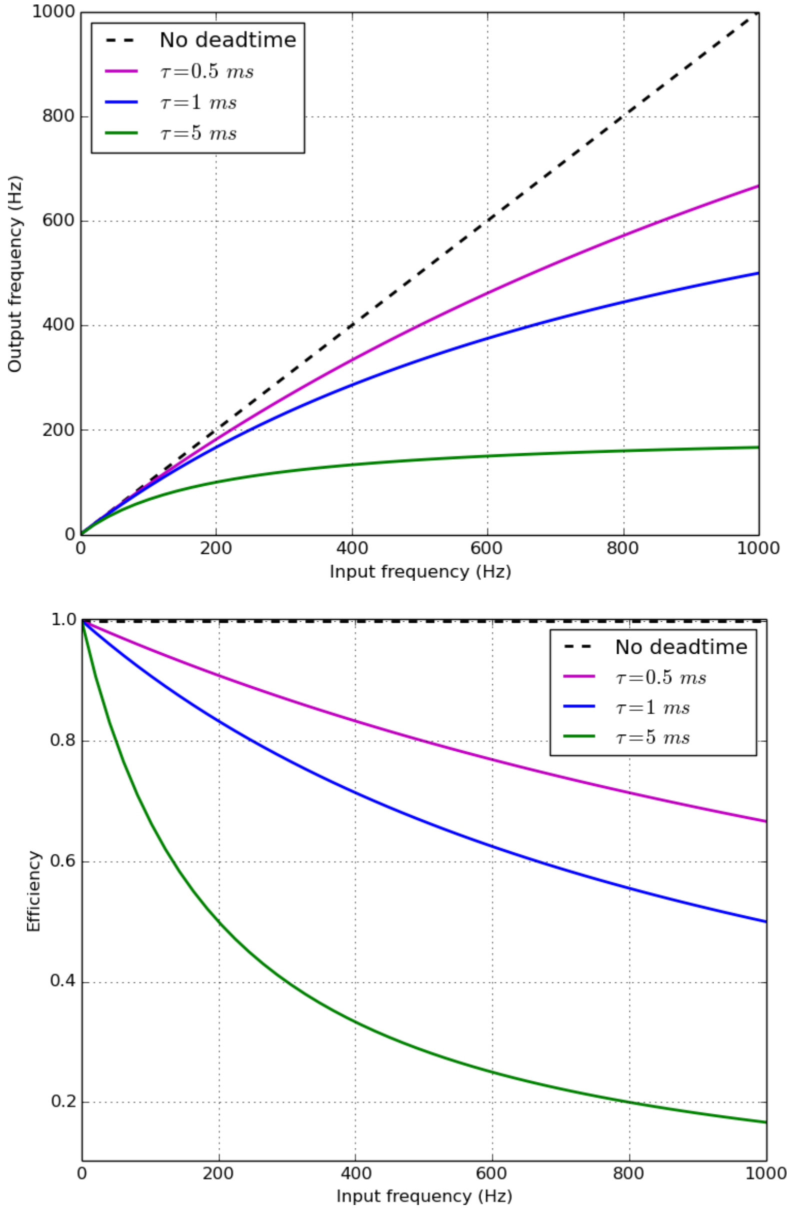
  - ε = 1 / (1 + 1kHz · 1ms) = 50%
- To have higher efficiency → $f \cdot \tau << 1$
- e.g. f=1kHz, ε>99%

  → τ = 1/f (1/ε - 1) = 0.1 ms

  → 1/τ>10kHz



Deadtime and Efficiency

- Due to stochastic fluctuations
  - DAQ rate < physics rate $n=\frac{f}{1+ft}<f$
  - Efficiency always < 100% $e=\frac{1}{1+ft}<1$
- In our example: f=1kHz, τ=1ms
  - ν = 1kHz / (1 + 1kHz · 1ms) = 500Hz
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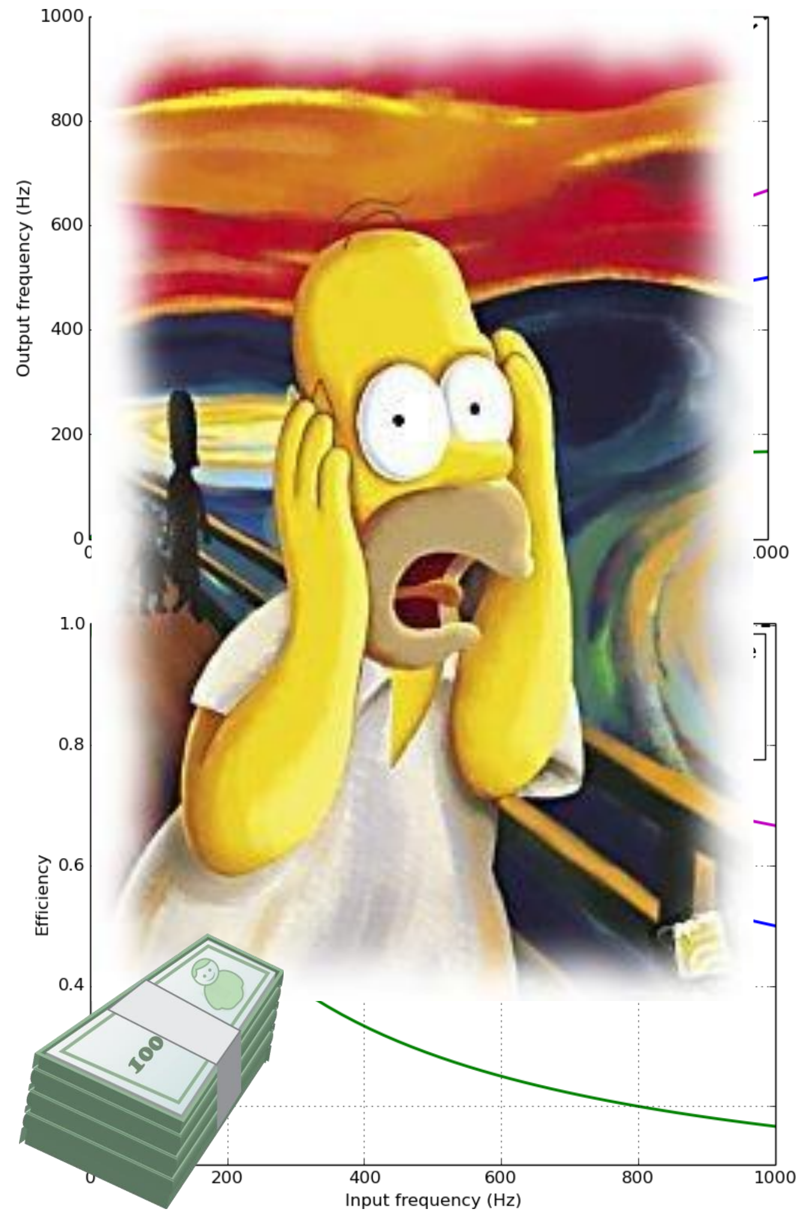
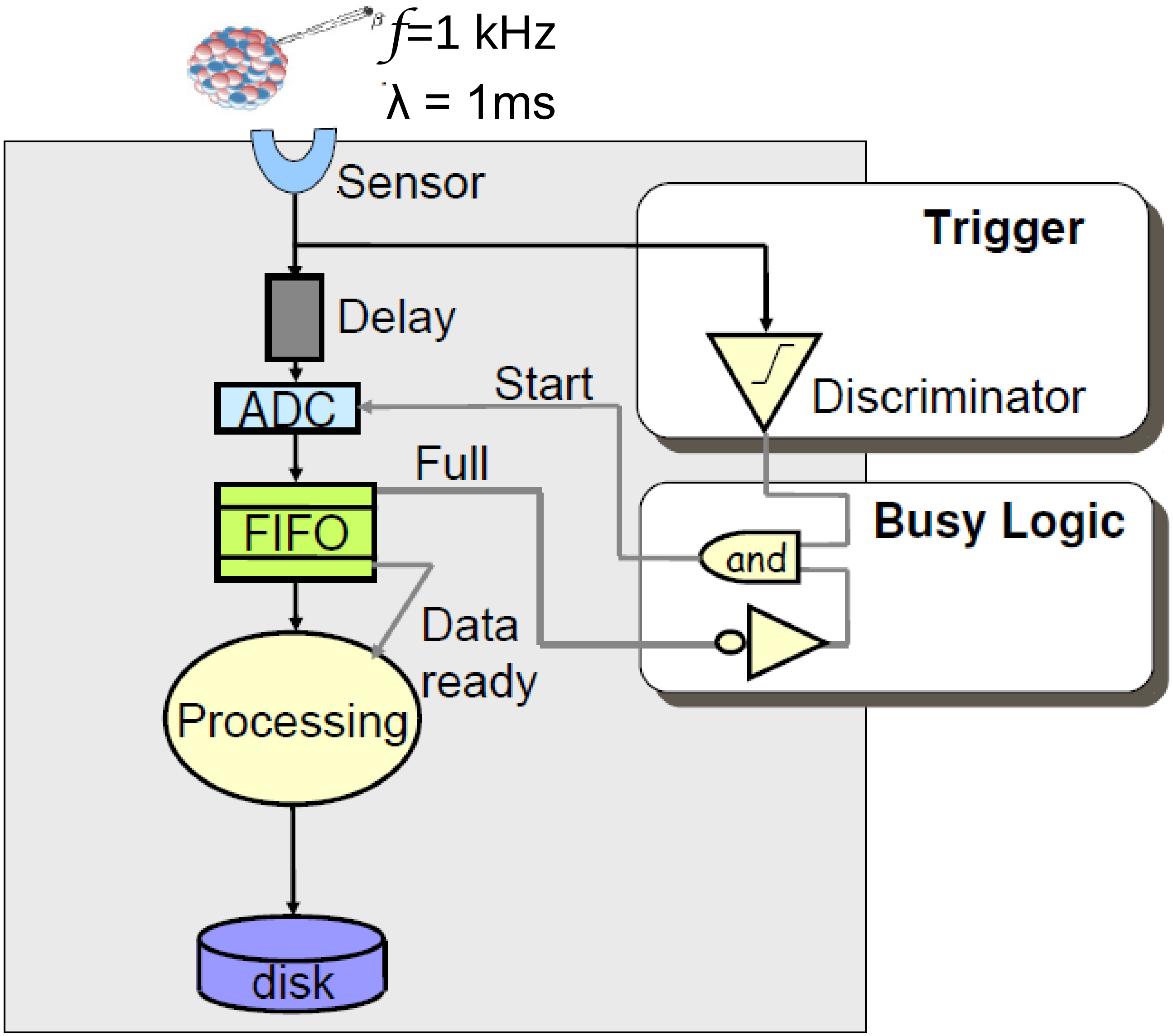
- To have higher efficiency → $f\cdot\tau$<<1
- e.g. f=1kHz, ε>99%

  → τ = 1/f (1/ε - 1) = 0.1 ms

  → 1/τ>10kHz
- In order to cope with the input signal fluctuations, we would need to overdesign our DAQ system by a factor 10. hmmmm…

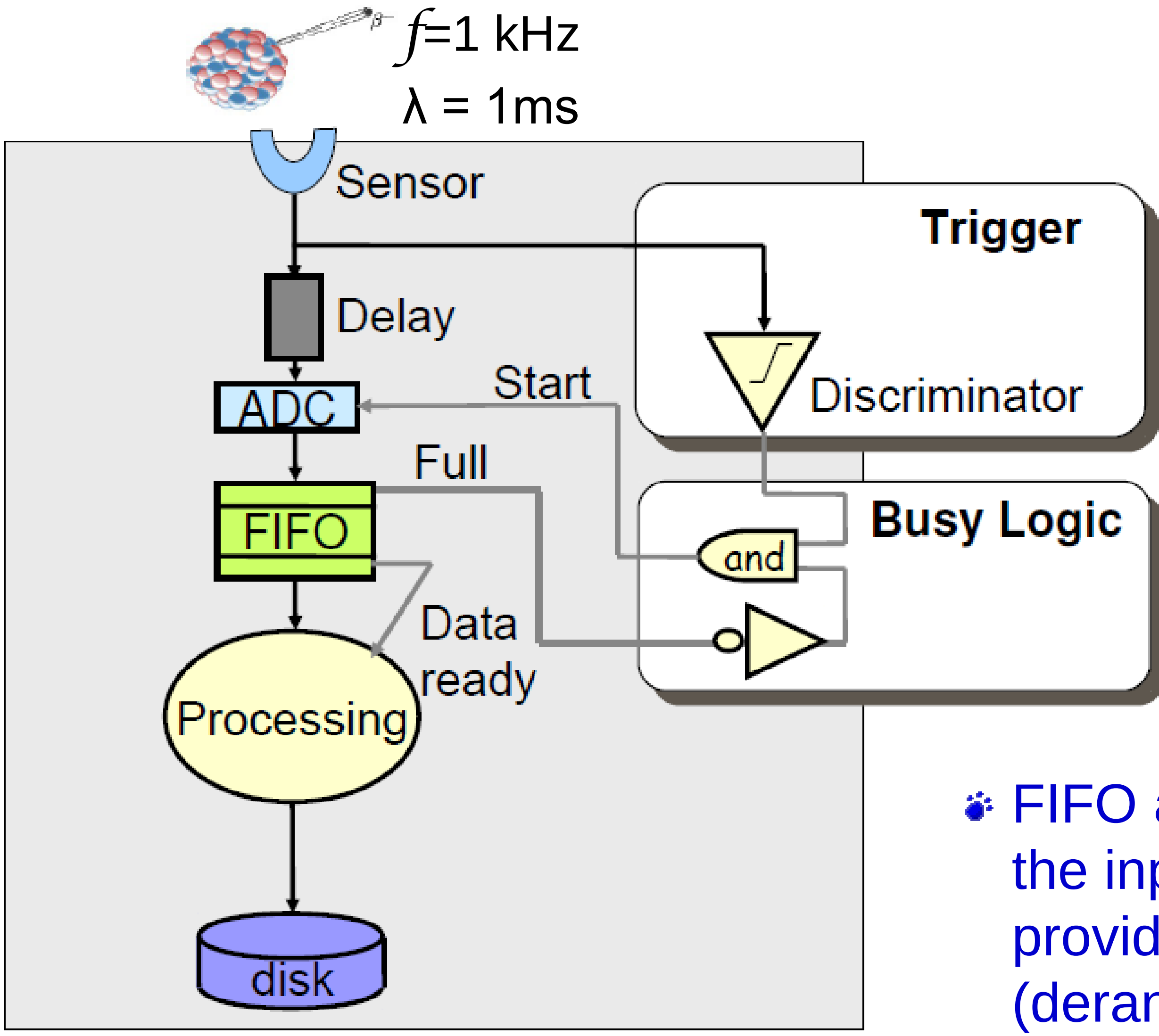


Trivial DAQ with Derandomisation

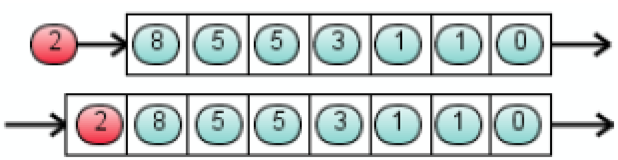


- Buffers are introduced which hold temporarily the data.
- They decouple the data production from the data processing
  ➔Better performance

Trivial DAQ with Derandomisation

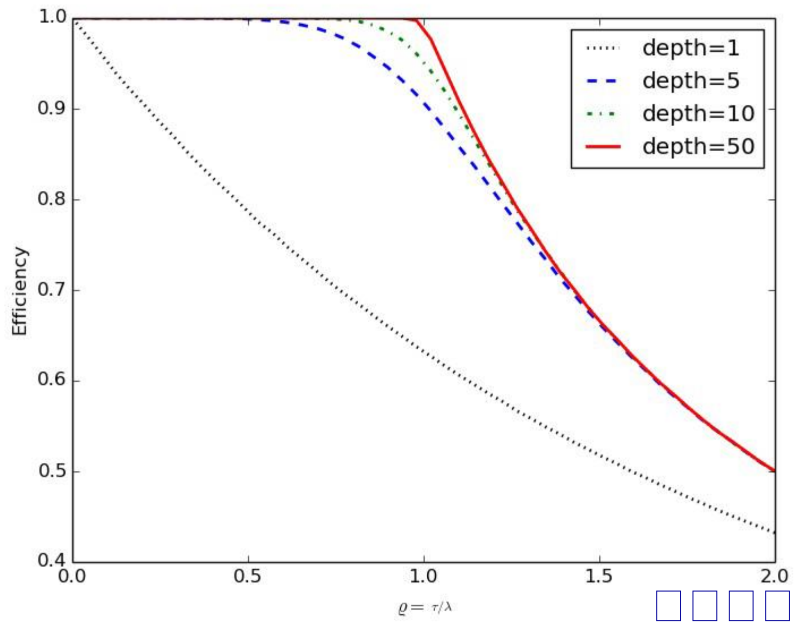


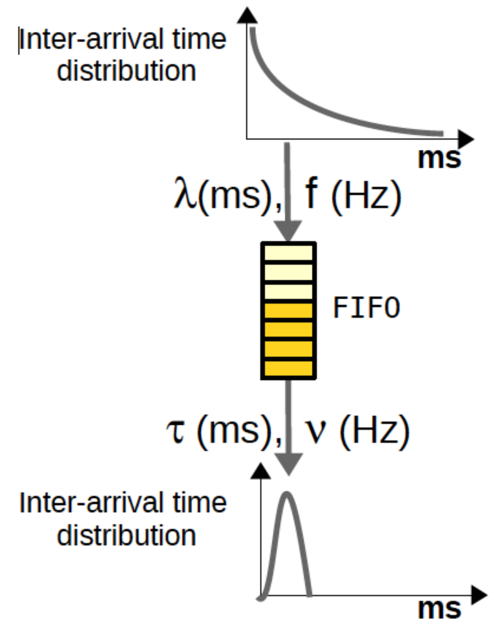
- First In First Out
  - Buffer area organized as a queue
  - Depth: number of cells
  - Implemented in HW and SW



- FIFO absorbs and smoothes the input fluctuations, providing a ~steady (derandomized) output rate
- introduces an additional latency on the data path

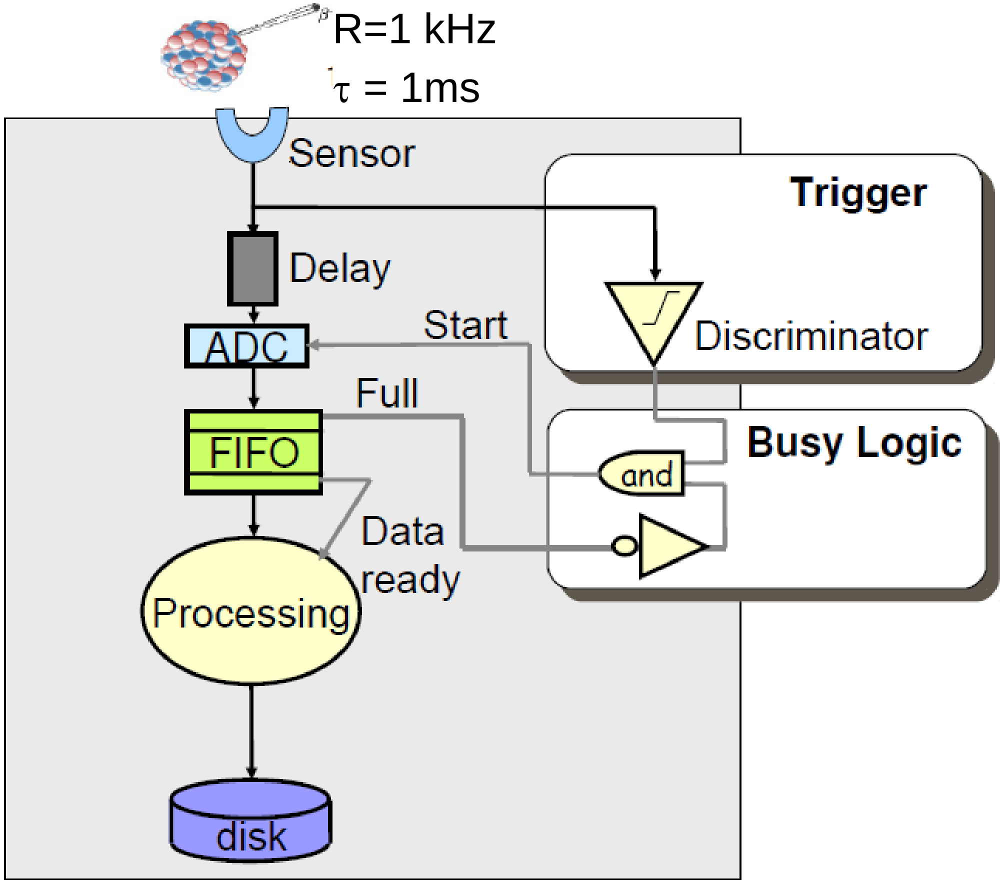
De-randomization: queuing theory





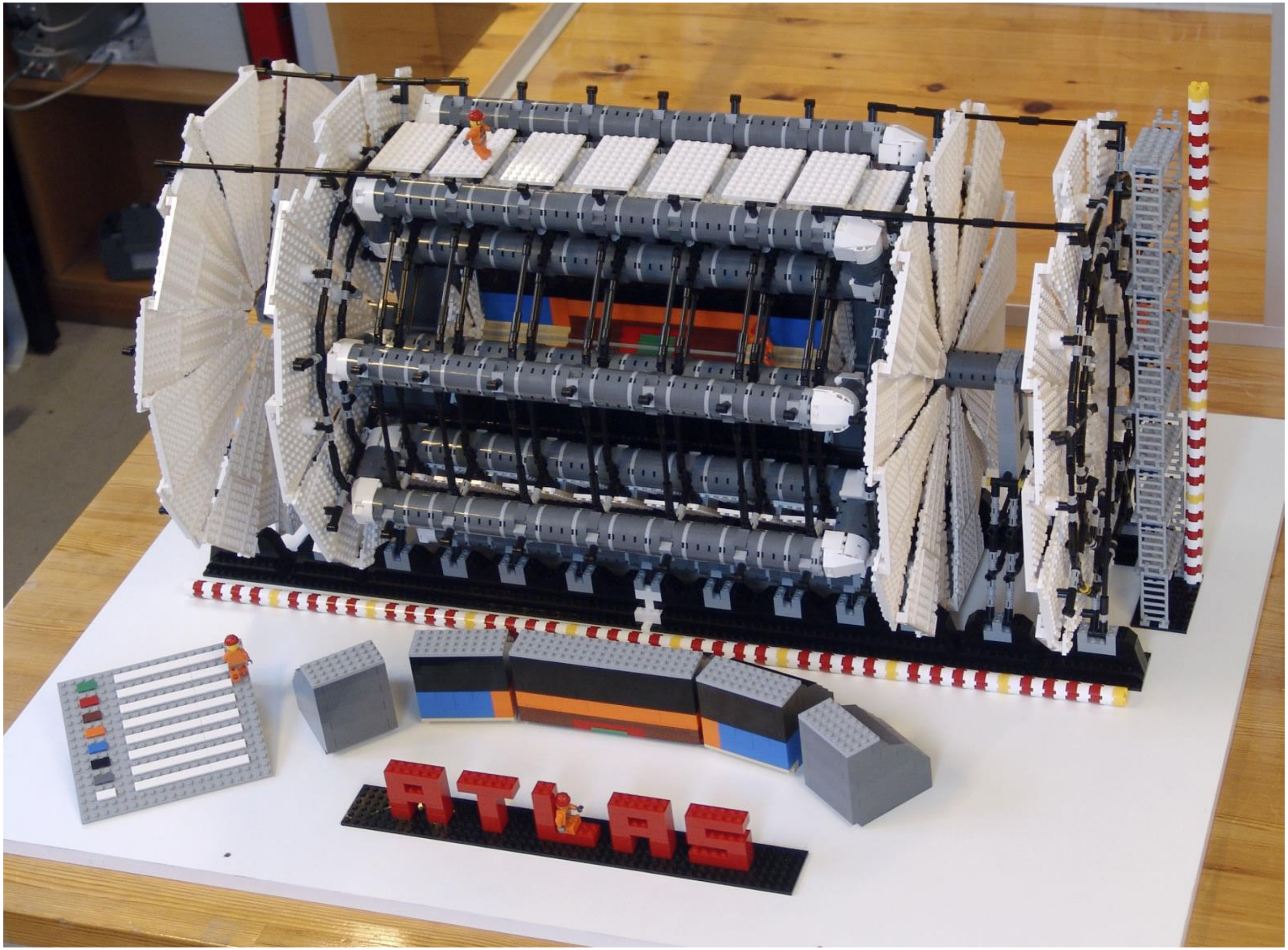
- Efficiency vs traffic intensity (□□□□□□□□□) for different queue depths
  - □ > 1, the system is overloaded
  - □ << 1, the output is over-designed
  - □ ~ 1, using a queue, high efficiency can be obtained with moderate depth
- Analytic calculation possible for very simple systems only
  - Otherwise Monte Carlo simulation is required

Trivial DAQ with Derandomisation

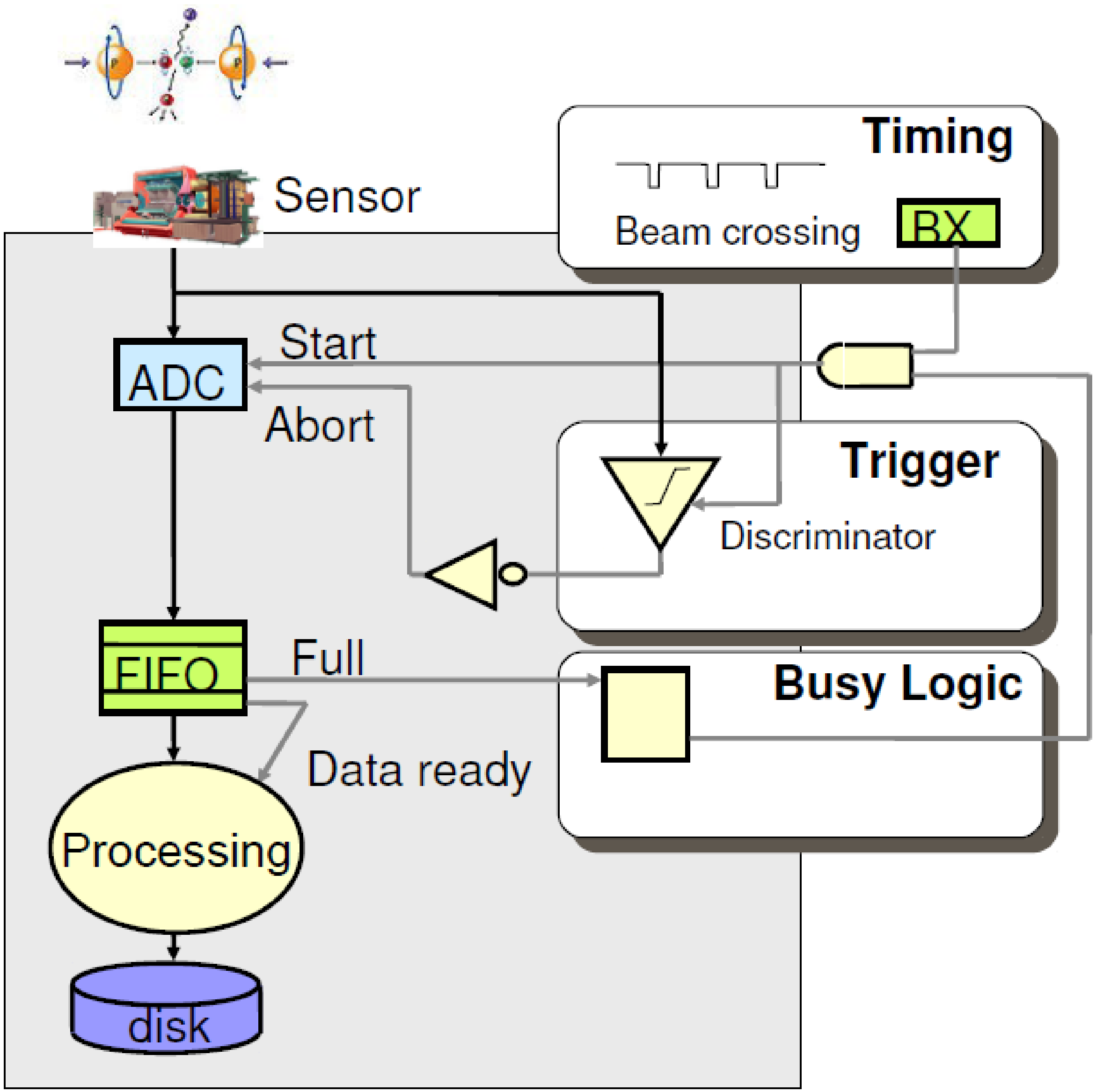


- Almost 100% efficiency and minimal deadtime if
  - ADC is able to operate at rate >>$\mathcal{R}$
  - Data processing and storing operates at ~$\mathcal{R}$
- Minimises the amount of "unnecessary" fast components
- Could the delay be replaced with a "FIFO"?
  - Analog pipelines → Heavily used in HEP DAQs

Let's have a closer look at DAQ at a collider

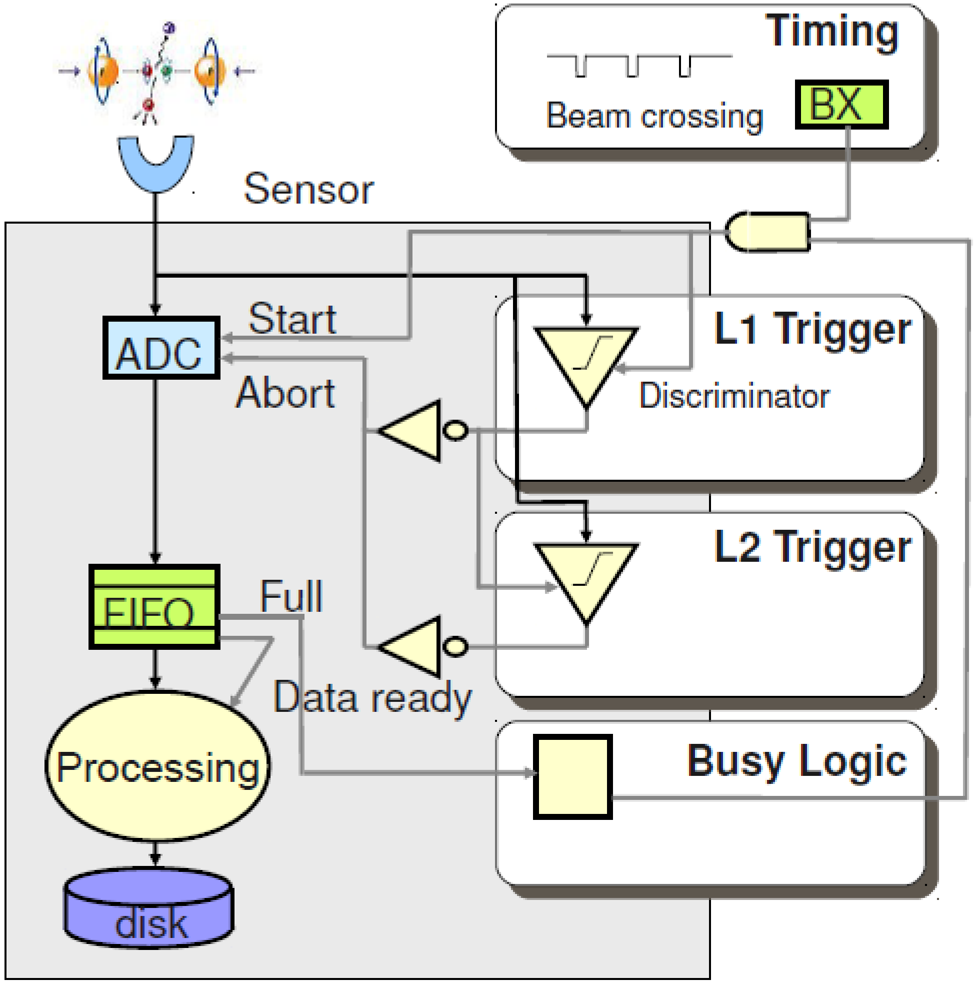


DAQ: Collider mode



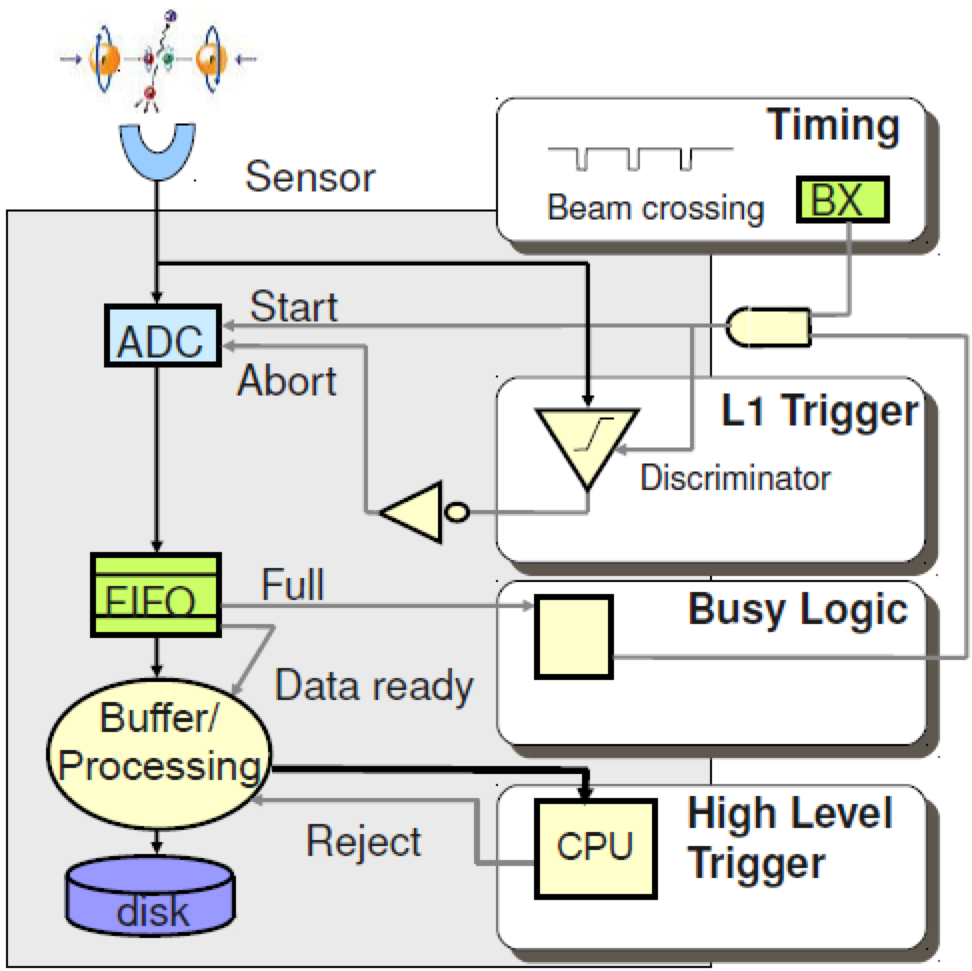
- Particle collisions are synchronous
- Trigger rejects uninteresting events
- Even if collisions are synchronous, the triggers (interesting events) are unpredictable
- Derandomisation is still needed
- No trigger deadtime if trigger latency below time between two beam crossings

Multi-Level Trigger



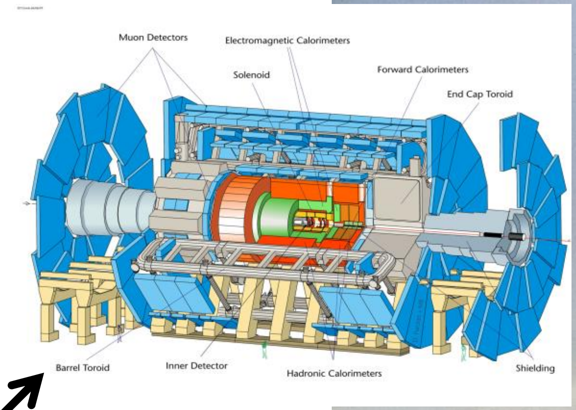
- For complicated triggers latency can be long
  - if $\tau_{trig} > \tau_{BX}$, deadtime>50%
- Split trigger in several levels with increasing complexity and latency
- All levels can reject events
  - with $\tau_{L1} < \tau_{BX}$, trigger deadtime only $\nu_{L1} \cdot \tau_{L2}$

Multi-Level Trigger



- For optimal data reduction can add trigger level between readout and storage (High-level trigger)
- Has access to some/all processed data

Scaling up

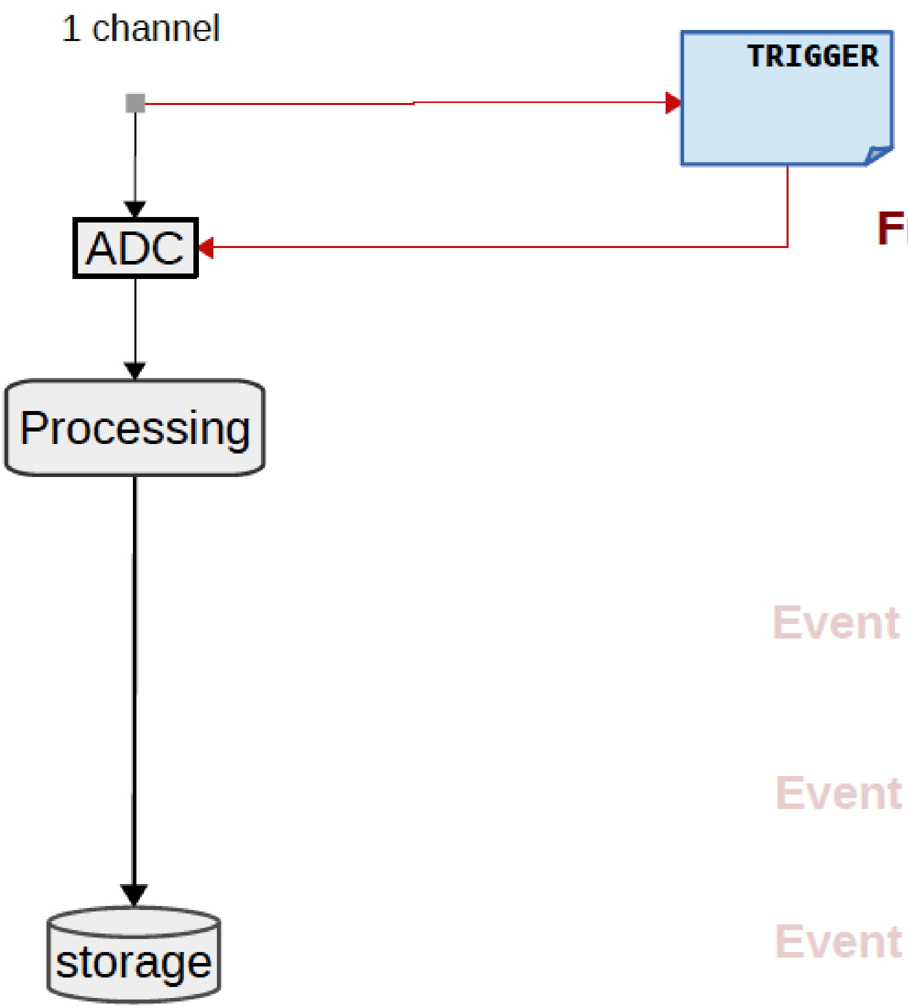


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

sensor

A bit more complicated….

- The increased number of channels require hierarchical structure with well defined interfaces between components



Front-End | data digitization, data buffering

Readout | data extraction, data formatting, data buffering

Event Building | event assembly, event buffering

Event Filtering | event rejection, event buffering

Event Logging | file storage, file buffering

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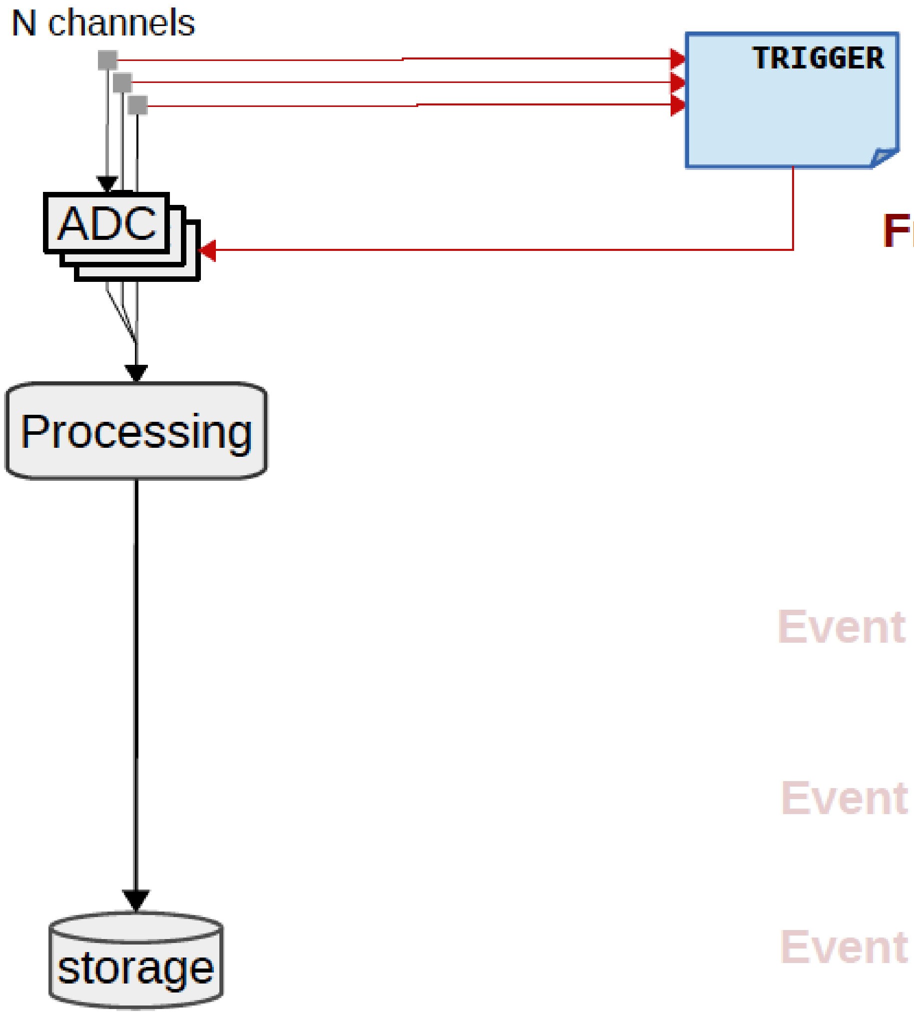

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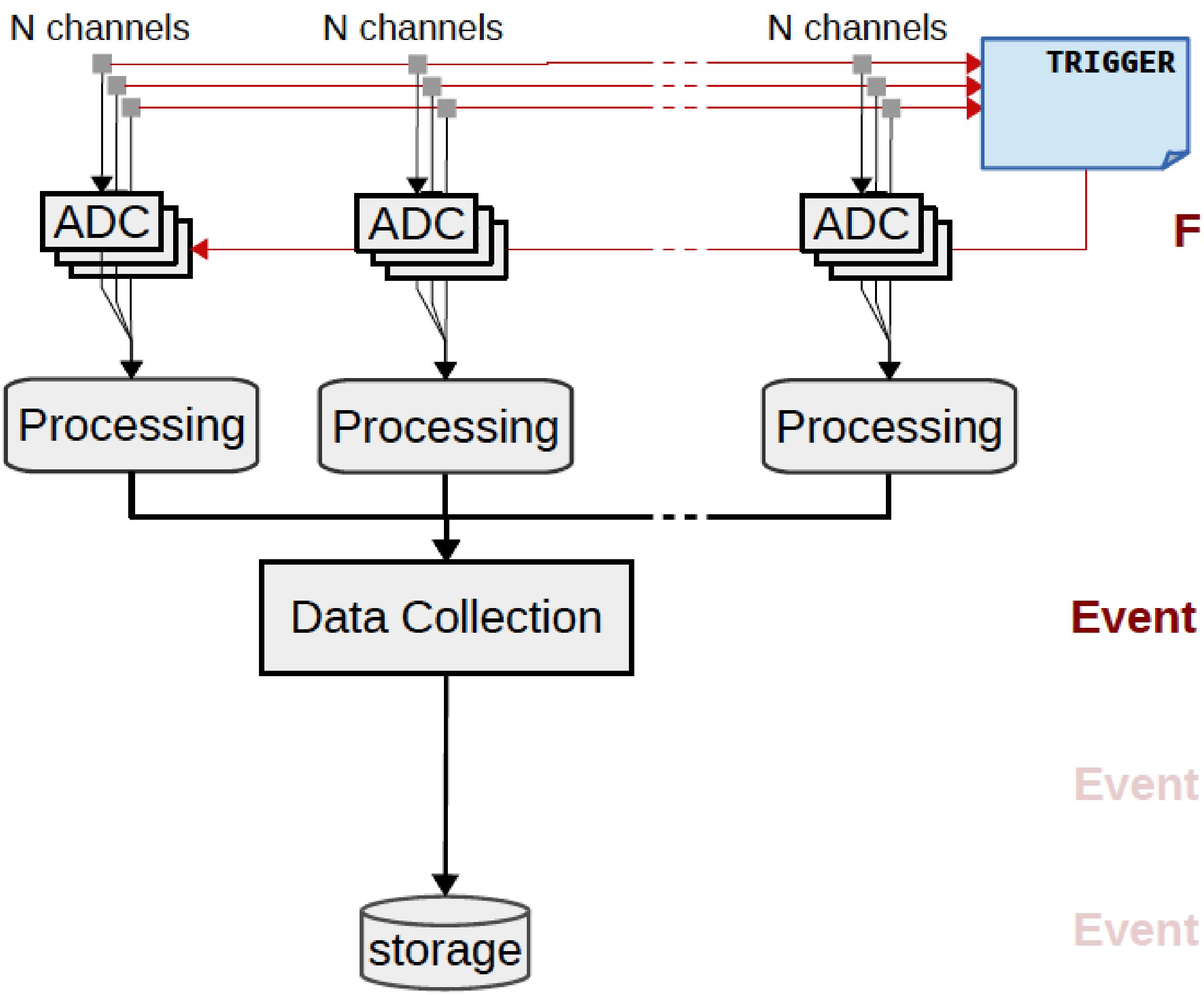

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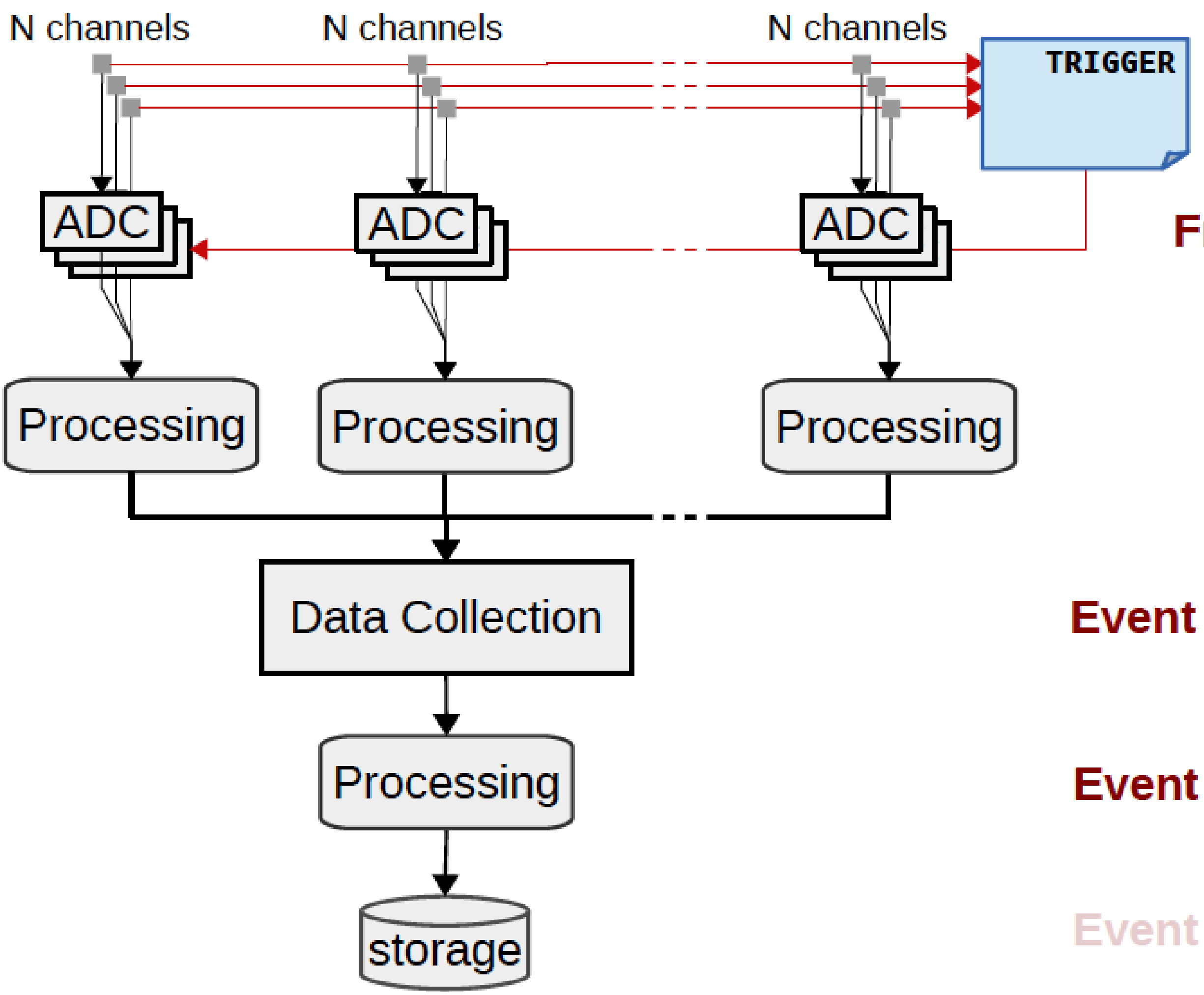

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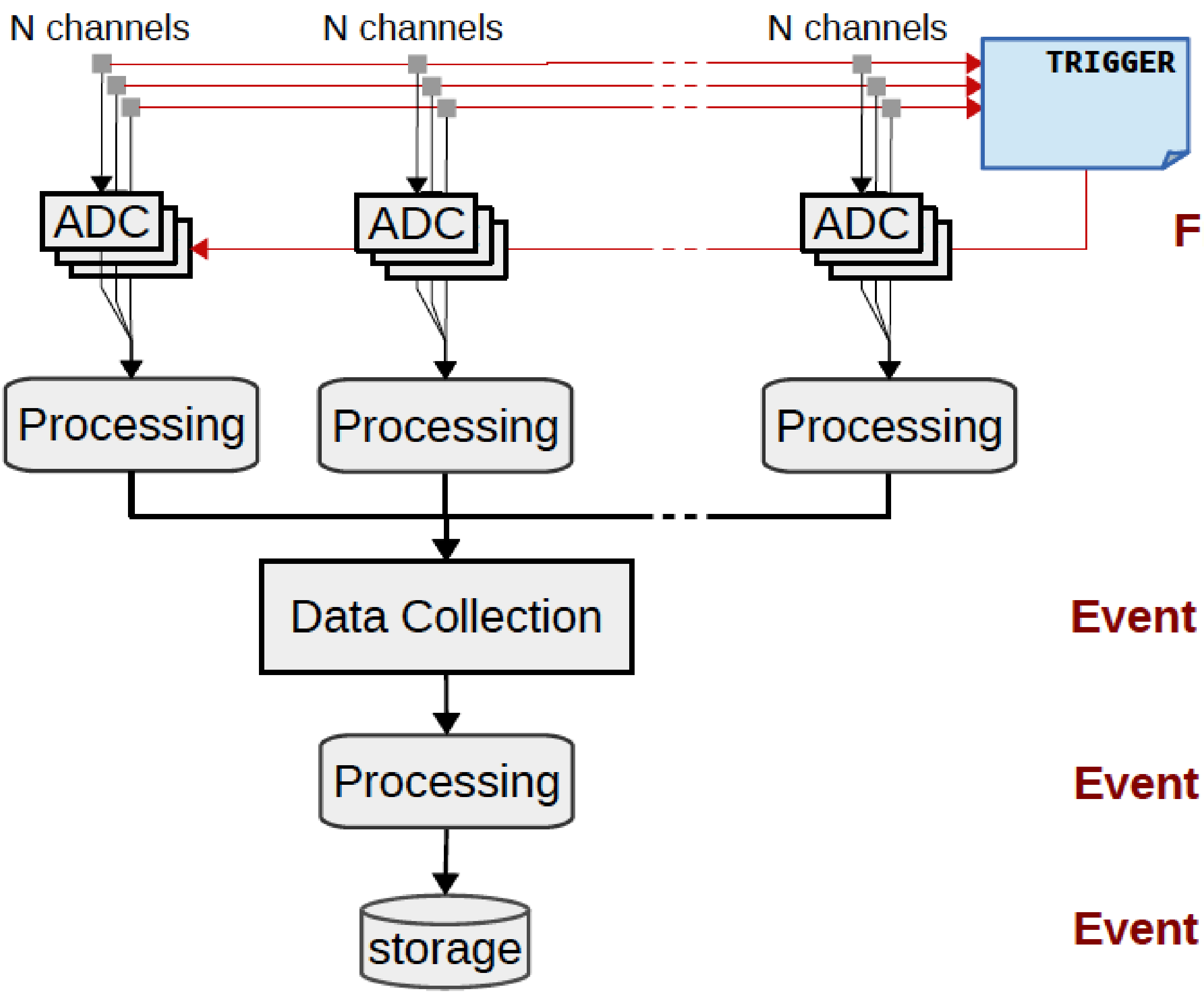

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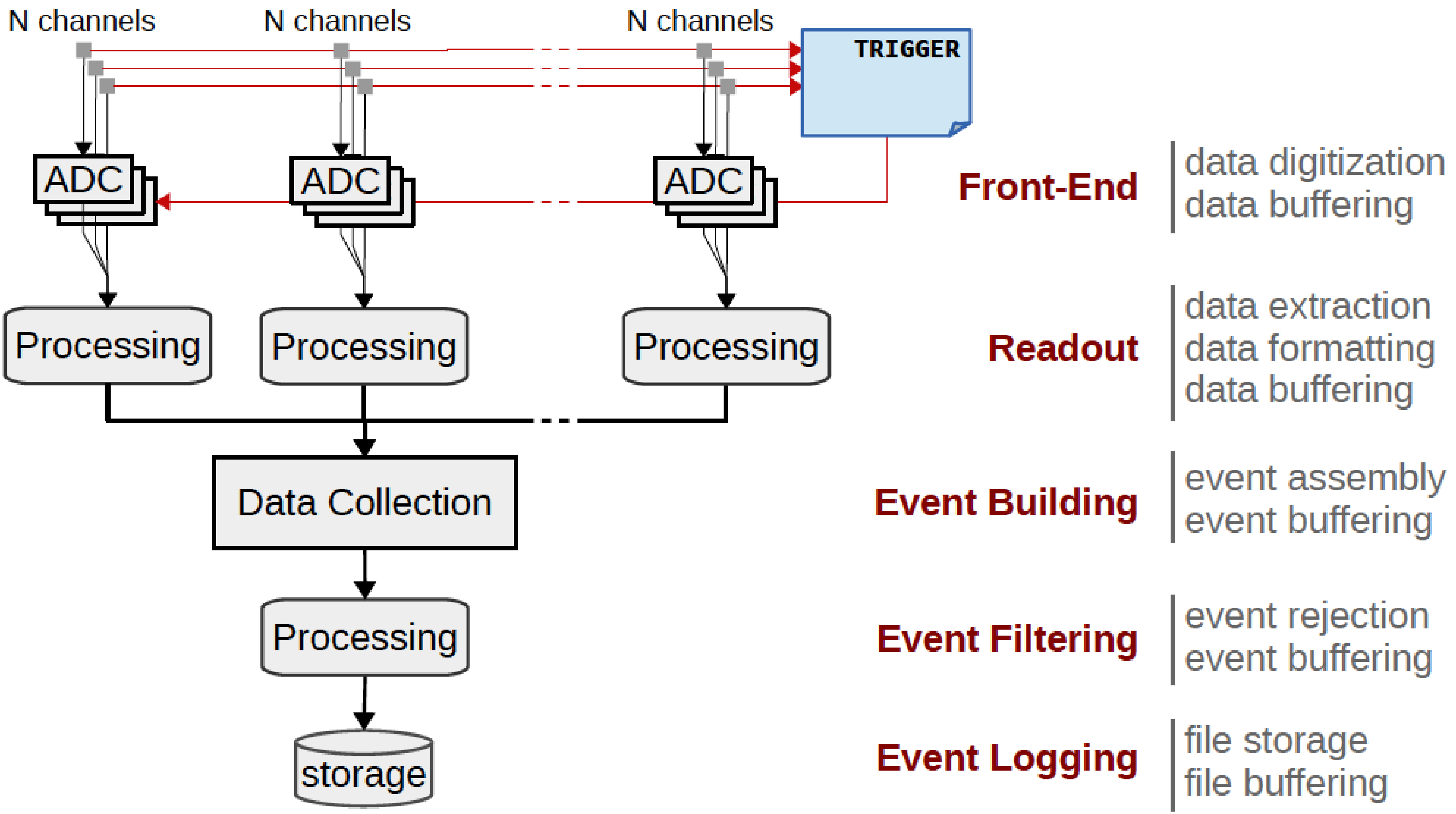
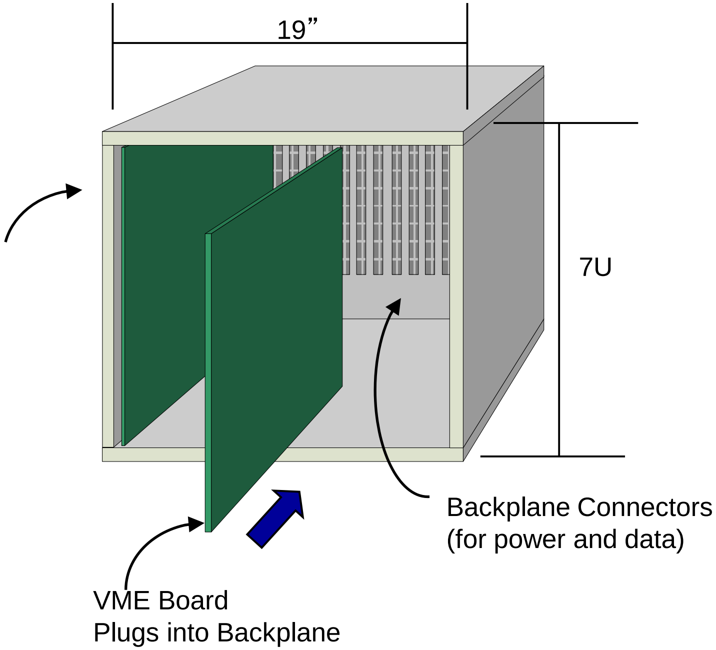
A bit more complicated….

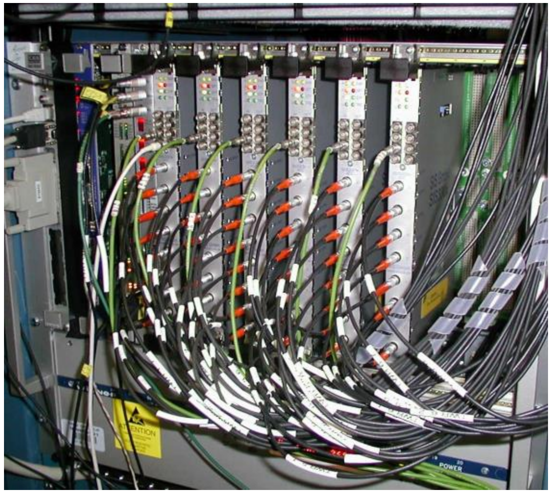
- Buffering usually needed at all levels



Read-out Topology

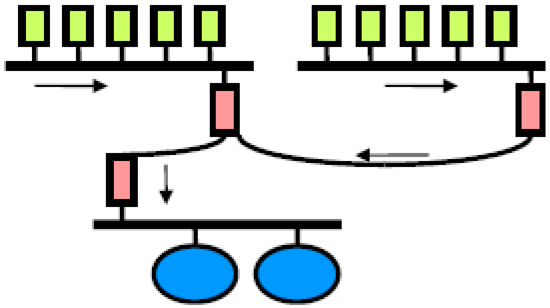
- Reading out = building events out of many detector channels
- We define “building blocks”
  - Example: readout crates, event building nodes, …
- Crate: many modules put in a common chassis which provides
  - Mechanical support
  - Power
  - A standardised way to access the data
  - Provides signal and protocol standard for communication
- All this is provided by standards for (readout) electronics such as NIM or VME (IEEE 1014)

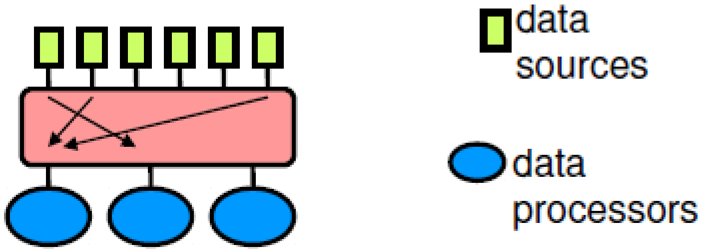




Read-out Topology

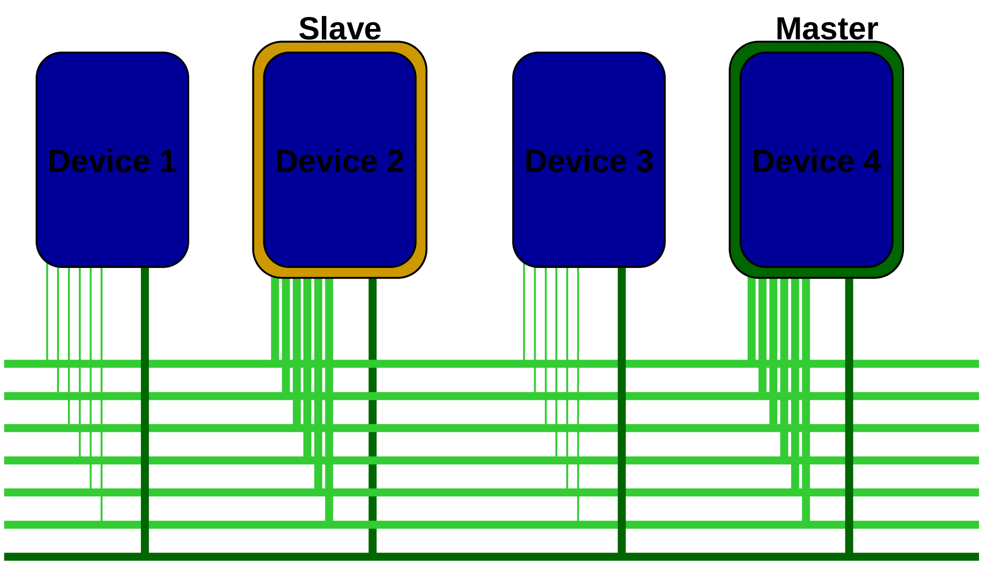
- How to organize the interconnections inside the building blocks and between building blocks?
- Two main classes: bus or network
  - Both of them are very generic concepts





Bus

- A bus connects two or more devices and allows them to communicate
  - Bus → group of electrical lines
- Examples: VME, PCI, SCSI, Parallel ATA, …
- The bus is shared between all devices on the bus → arbitration is required
- Devices can be masters or slaves (some can be both)
- Devices can be uniquely identified ("addressed") on the bus

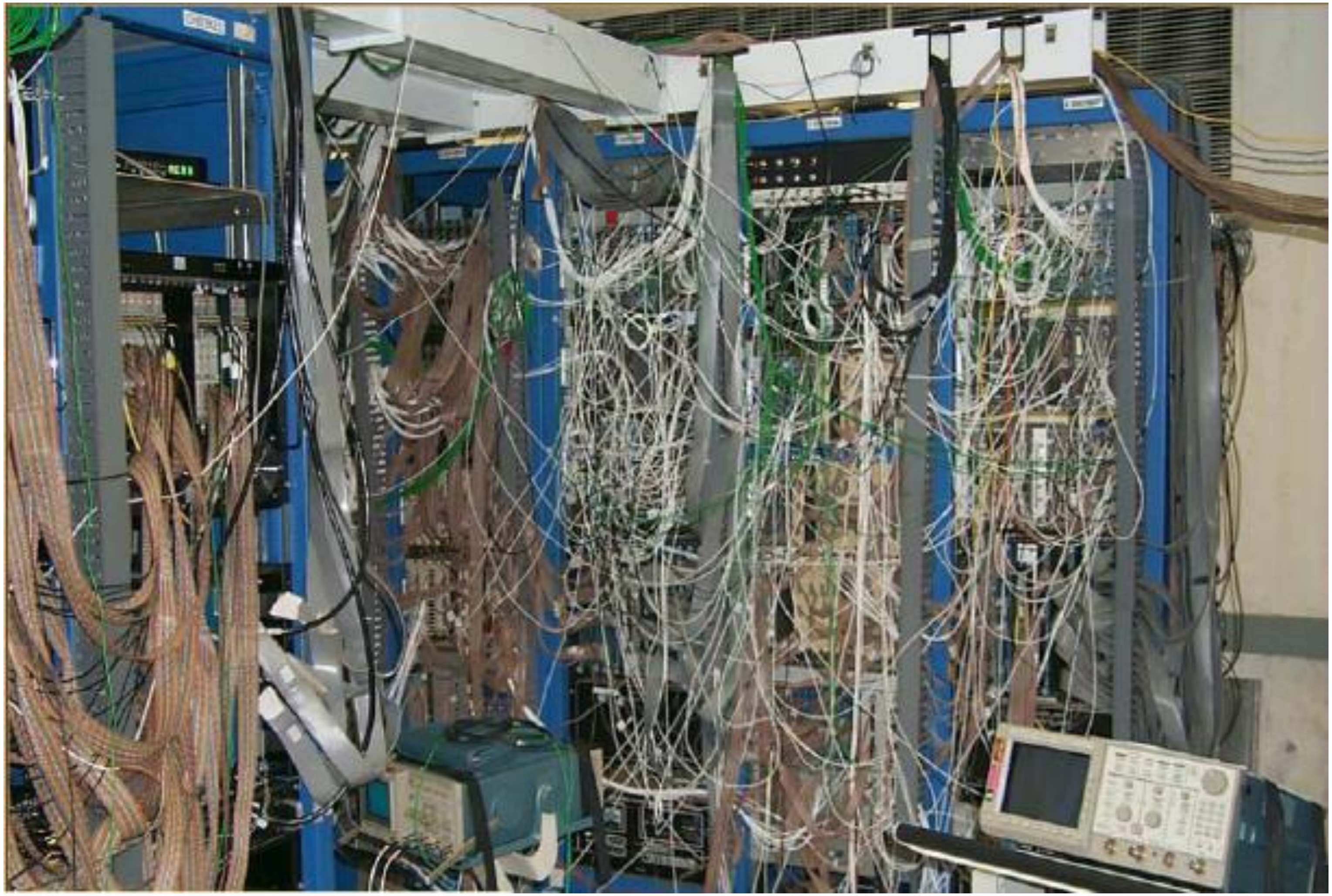


Bus

- Relatively simple to implement
  - Constant number of lines
  - Each device implements the same interface
  - ➔Easy to add new devices
- Scalability issues
  - Number of devices and physical bus-length is limited
  - Each new active device slows everybody down as bus bandwidth* shared among all the devices
  - Maximum bus size (bus width) is limited (128 bit for PC-system bus)
    - Determines how much data can be transmitted at one time
  - Maximum bus frequency (number of elementary operations per second) is inversely proportional to the bus length
- Typical buses have a lot of control, data and address lines (e.g. SCSI cable (Small Computer System Interface)
- Buses are typically useful for systems < 1 GB/s

Bandwidth = amount of data transferred / per unit of time (measured in Bytes/h)

Bus: another limitation

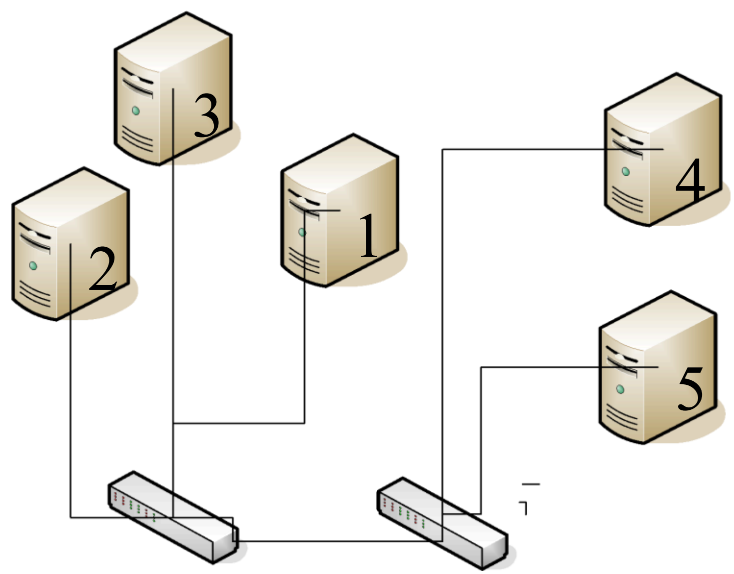


Network based DAQ

- In large (HEP) experiments we typically have thousands of devices to read, which are sometimes very far from each other → *buses can not do that*
- Network technology solves the scalability issues of buses
  - Examples: Ethernet, Telephone, Infiniband, …
  - Devices are equal ("peers")
  - They communicate directly with each other by sending messages
    - No arbitration necessary
    - Bandwidth guaranteed
  - Data and control use the same path
    - Much fewer lines (e.g. in traditional Ethernet only two)
  - On an network a device is identified by a network address
    - Eg: phone-number, MAC address
  - At the signaling level buses tend to use parallel copper lines. Network technologies can be also optical or wireless

Switched Networks

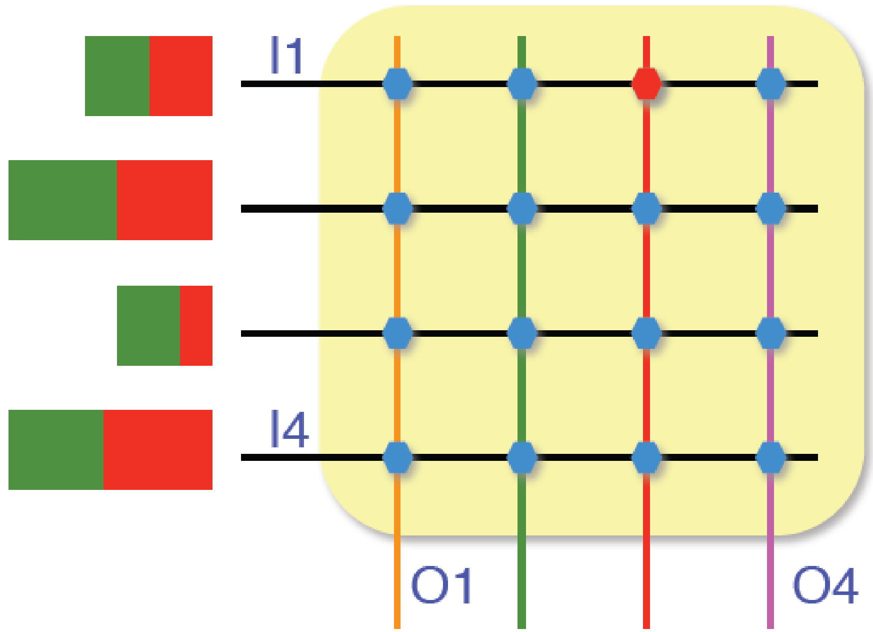
- Modern networks are *switched with point-to-point links*
- Each node is connected either to another node or to a switch
- Switches can be connected to other switches
- A path from one node to another leads through 1 or more switches
- Switches move messages between sources and destinations
  - Find the right path
  - Handle "congestion" (two messages with the same destination at the same time)



- Example
  - While 2 can send data to 1 and 4, 3 can send at full speed to 5
  - 2 can distribute the bandwidth between 1 and 4 as needed

Switched Network

- Challenge
  - Find the right path
  - Handle “congestion” (two messages with the same destination at the same time)



DAQ challenges at LHC

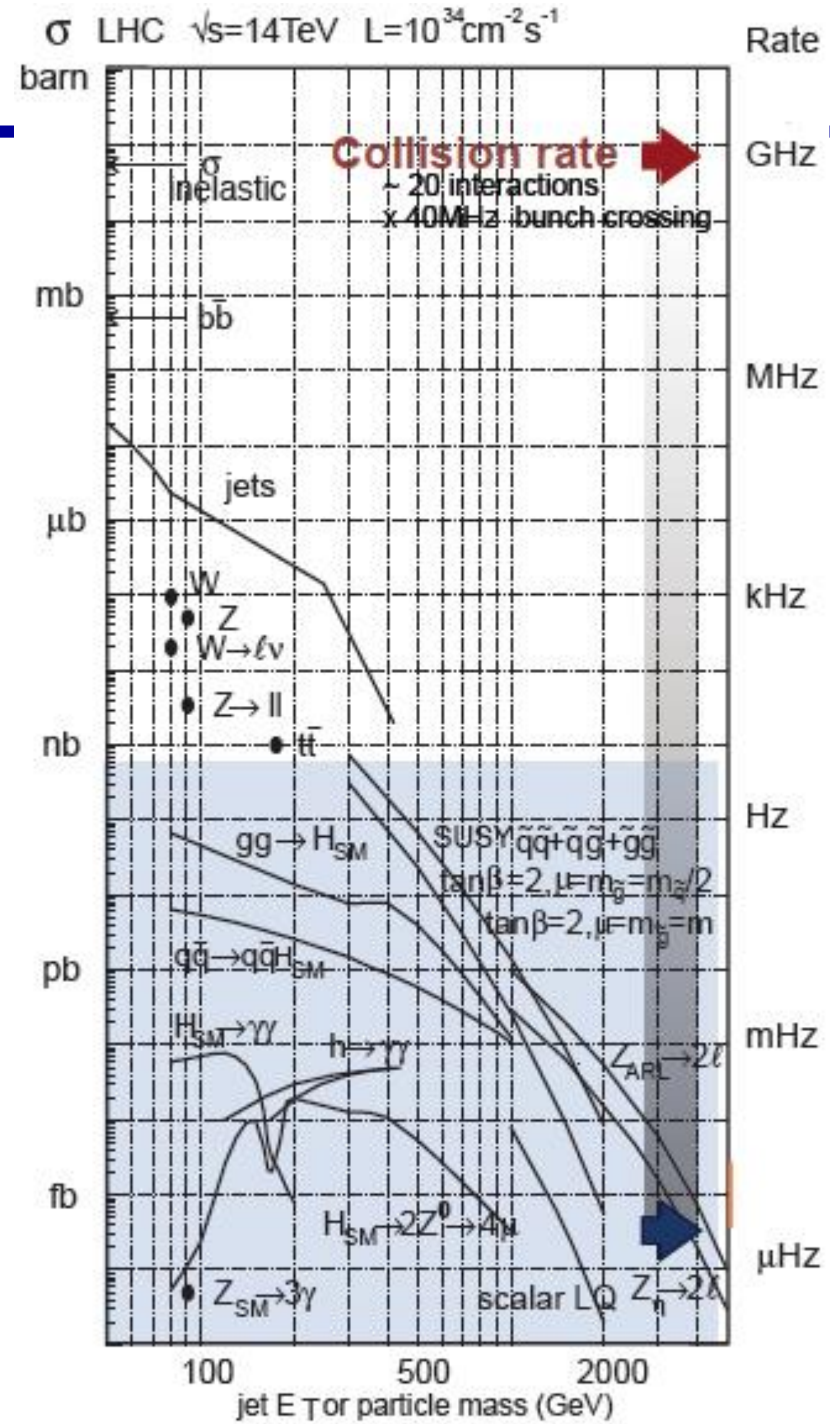
- Challenge 1
  - Physics – Rejection power
  - Requirements for TDAQ driven by rejection power required for the search of rare events
- Challenge 2
  - Accelerator – Bunch crossing frequency
  - Highest luminosity needed for the production of rare events in wide mass range
- Challenge 3
  - Detector – Size and data volume
    - Unprecedented data volumes from huge and complex detectors

Challenge 1: Physics

- Cross sections for most processes at the LHC span ~10 orders of magnitude
- LHC is a factory for almost everything: t, b, W, Z…
- But: some signatures have small branching ratios (e.g. $H \rightarrow \gamma\gamma$, BR $\sim 10^{-3}$)

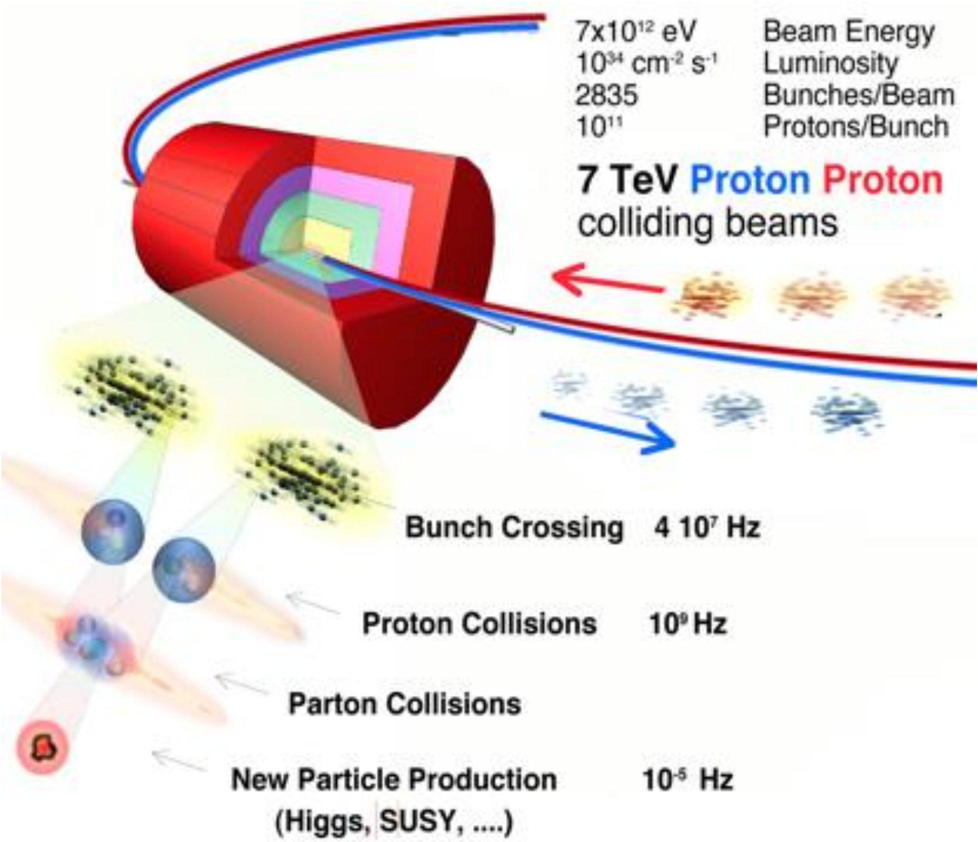
Process	**Production Rate** $\mathbf{10^{34}\ cm^{-2}s^{-1}}$
inelastic	**~1 GHz**
bbbar	**5 MHz**
$W \rightarrow l\nu$	**150 Hz**
$Z \rightarrow l\nu$	**15 Hz**
ttbar	**10 Hz**
Z'	**0.5 Hz**
H(125) SM	**0.4 Hz**

- $L=10^{34}\ cm^{-2}s^{-1}$: Collision rate: $\sim 10^9$ Hz. event selection: $\sim 1/10^{13}$ or 10^{-4}Hz !



Challenge 1: Physics

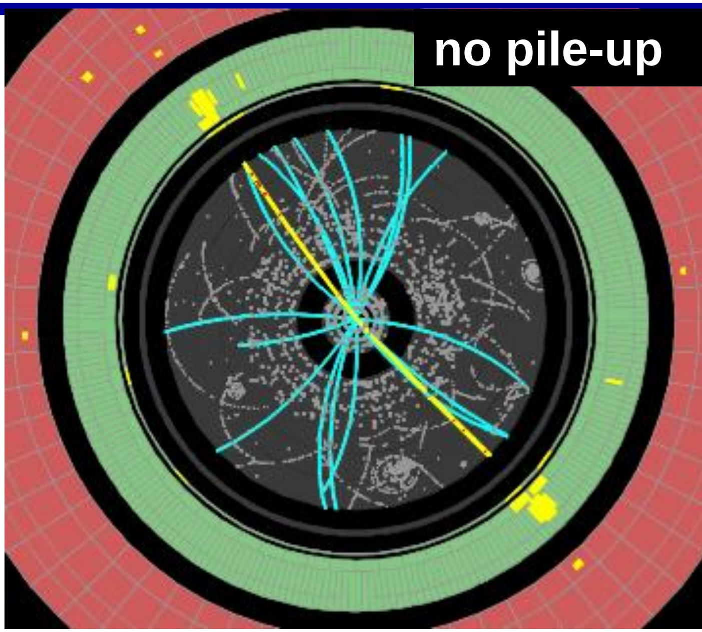
- Requirements for TDAQ driven by the search for rare events within the overwhelming amount of "uninteresting" collisions
- Main physics aim
  - Measure Higgs properties
  - Searches for new particles beyond the Standard Model
    - Susy, extra-dimensions, new gauge bosons, black holes etc.
  - Plus many interesting Standard Model studies to be done

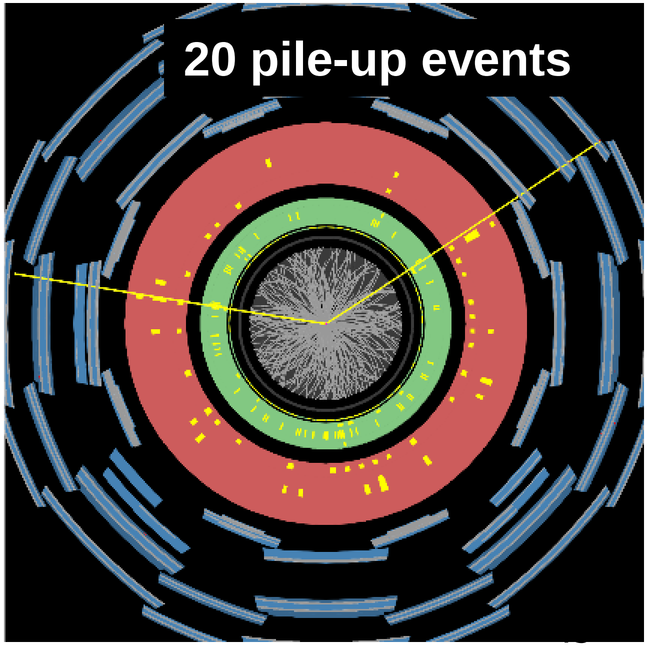


- All of this must fit in ~500-1000 Hz of data written out to storage
- Not trivial, $W \to l\nu$: 150 Hz @ 10^{34} $cm^{-2}s^{-1}$
  - "Good" physics can become your enemy!

Challenge 2: Accelerator

- Unlike e^+e^- colliders, proton colliders are more ‘messy’ due to proton remnants
- Multiple collisions per bunch crossing
  - At L=10^{34} $cm^{-2}s^{-1}$ expect ~25-50 overlapping p-p interactions on top of each collision (pile-up) in Run 2 (had up to 30 in Run 1) ➔ >1000 particles seen in the detector!





Challenge 3: Detector

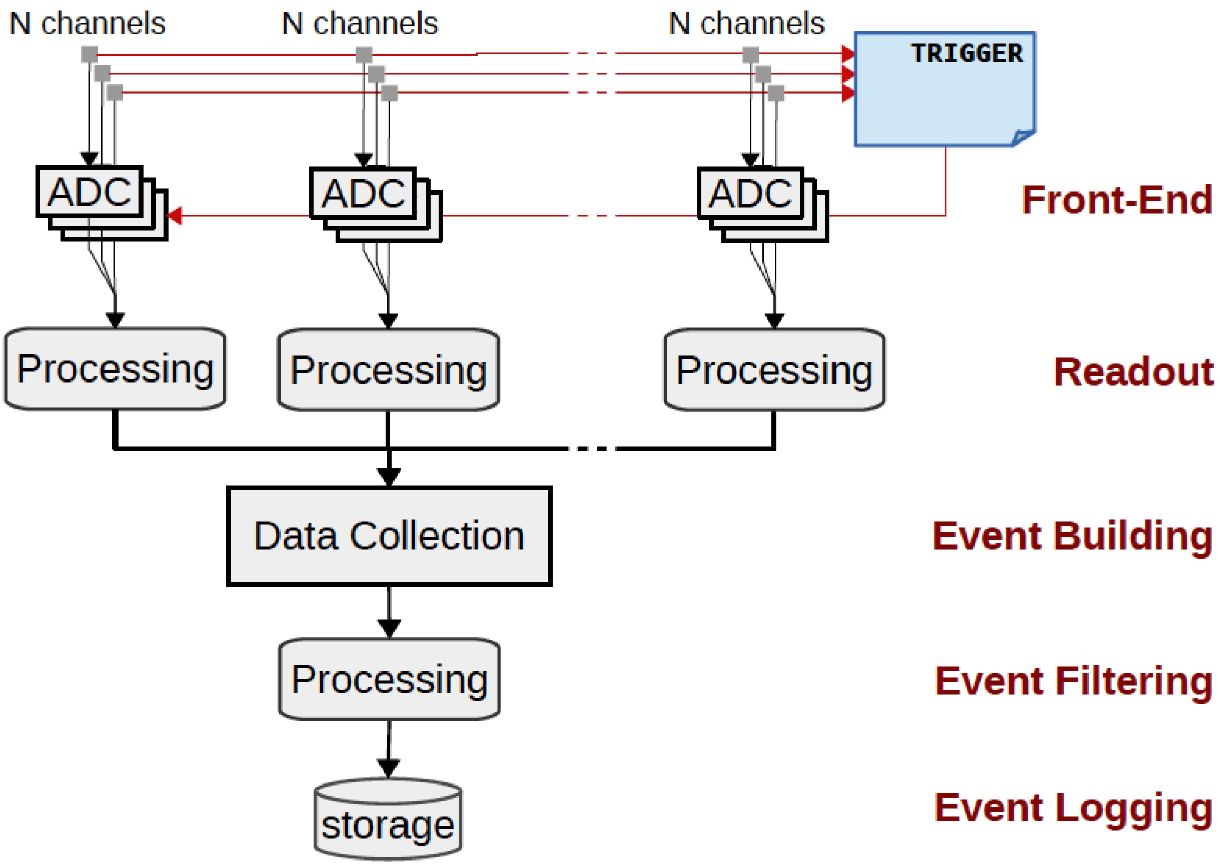
- Besides being huge: number of channels are O(10^6-10^8) at LHC, event sizes ~1 MB for pp collisions, 50 MB for pb-pb collisions in Alice
  - Need huge number of connections
- Some detectors need > 25ns to readout their channels and integrate more than one bunch crossing's worth of information (e.g. ATLAS LArg readout takes ~400ns)
- It's On-Line (cannot go back and recover events)
  - Need to monitor selection - need very good control over all conditions

Let's build a Trigger and DAQ for this

- What do we need?

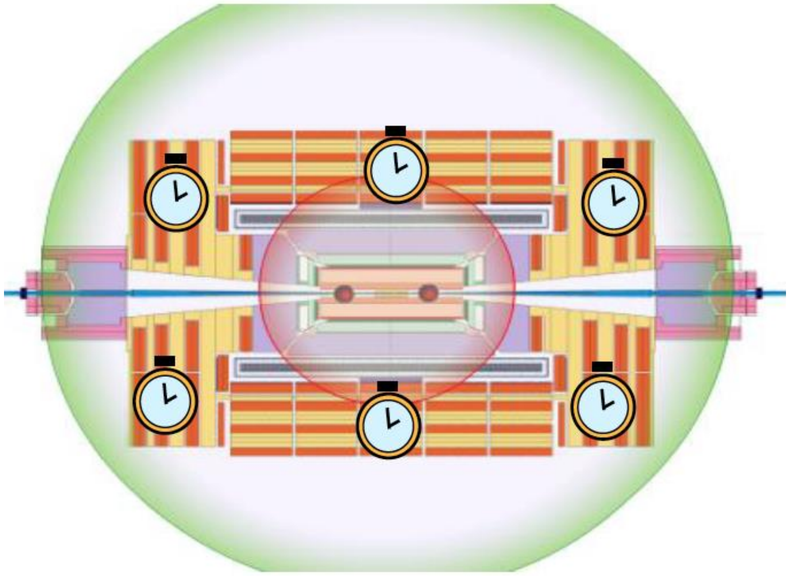
Let's build a Trigger and DAQ for this

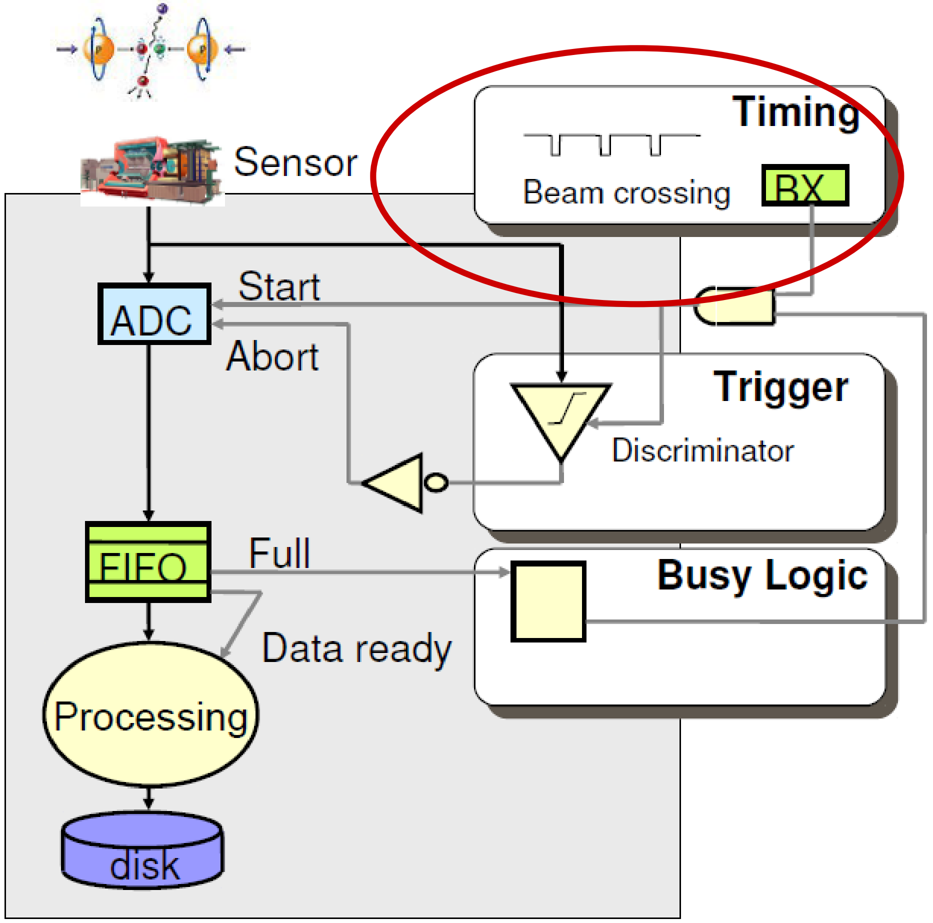
- What do we need?
  - Electronic readout of the sensors of the detectors ("front-end electronics")
  - A system to collect the selected data ("DAQ")



Let's build a Trigger and DAQ for this

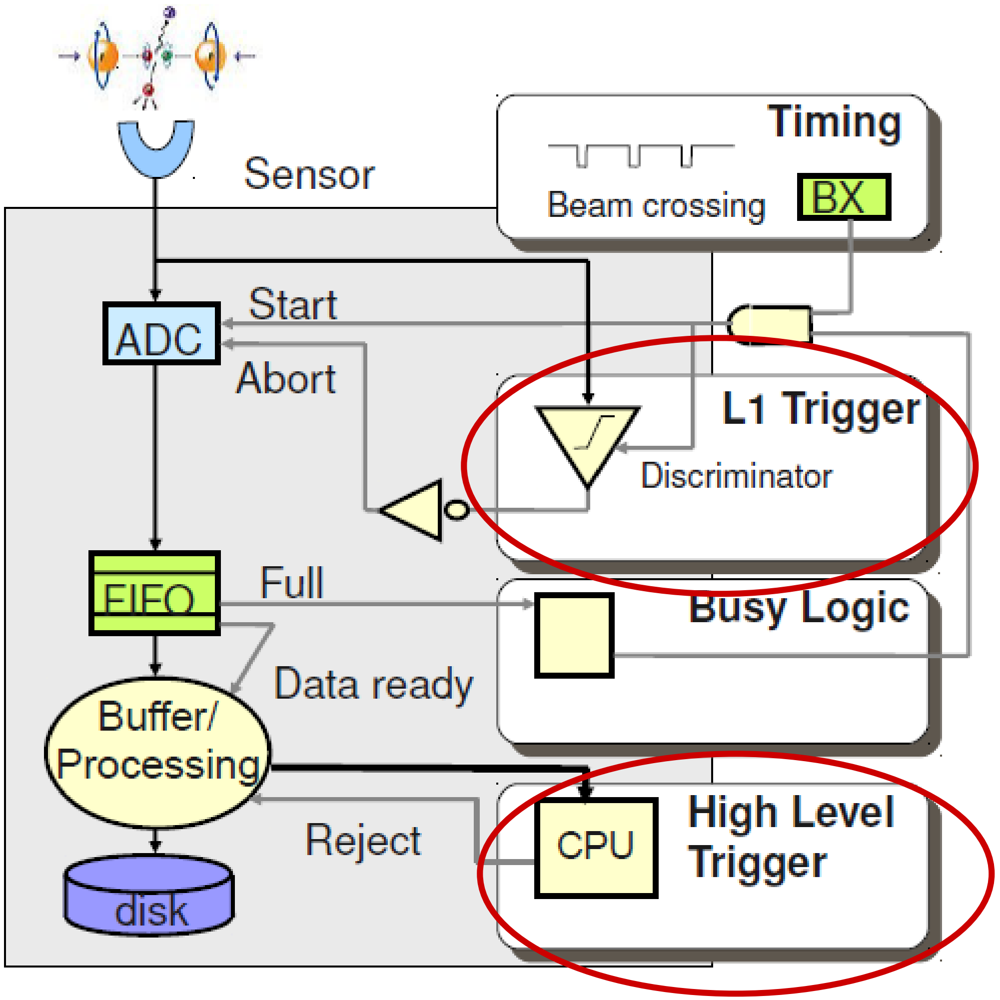
- What else do we need?
  - A system to keep all those things in sync ("clock")
  - Data belonging to the same bunch crossing must be processed together
  - Particle time of flight, cable delays, electronic delays all





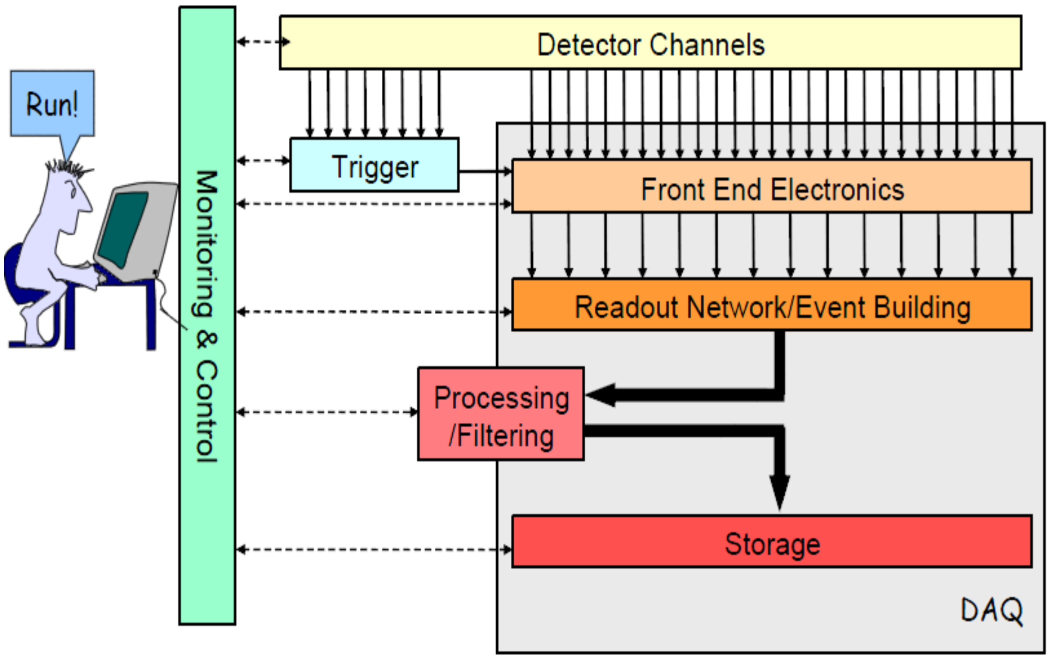
Let's build a Trigger and DAQ for this

- What do we need?
  - Electronic readout of the sensors of the detectors ("front-end electronics")
  - A system to collect the selected data ("DAQ")
  - A system to keep all those things in sync ("clock")
  - A trigger – multi-level due to complexity



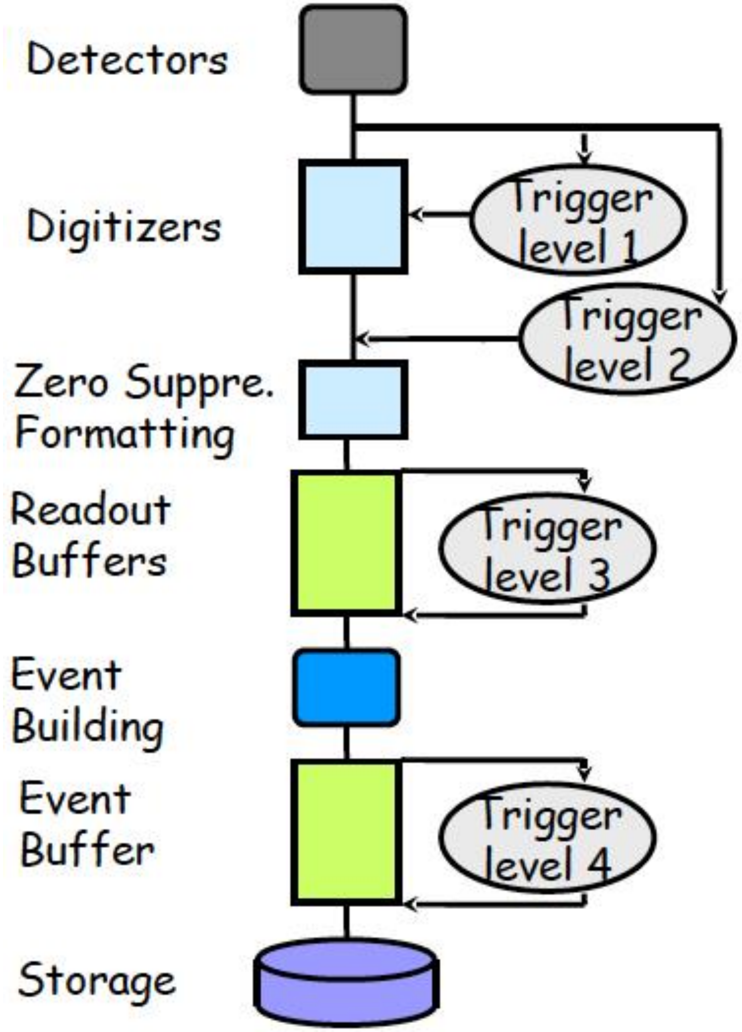
Let's build a Trigger and DAQ for this

- What do we need?
  - Electronic readout of the sensors of the detectors ("front-end electronics")
  - A system to collect the selected data ("DAQ")
  - A system to keep all those things in sync ("clock")
  - A trigger – multi-level due to complexity
  - A Control System to configure, control and monitor the entire DAQ



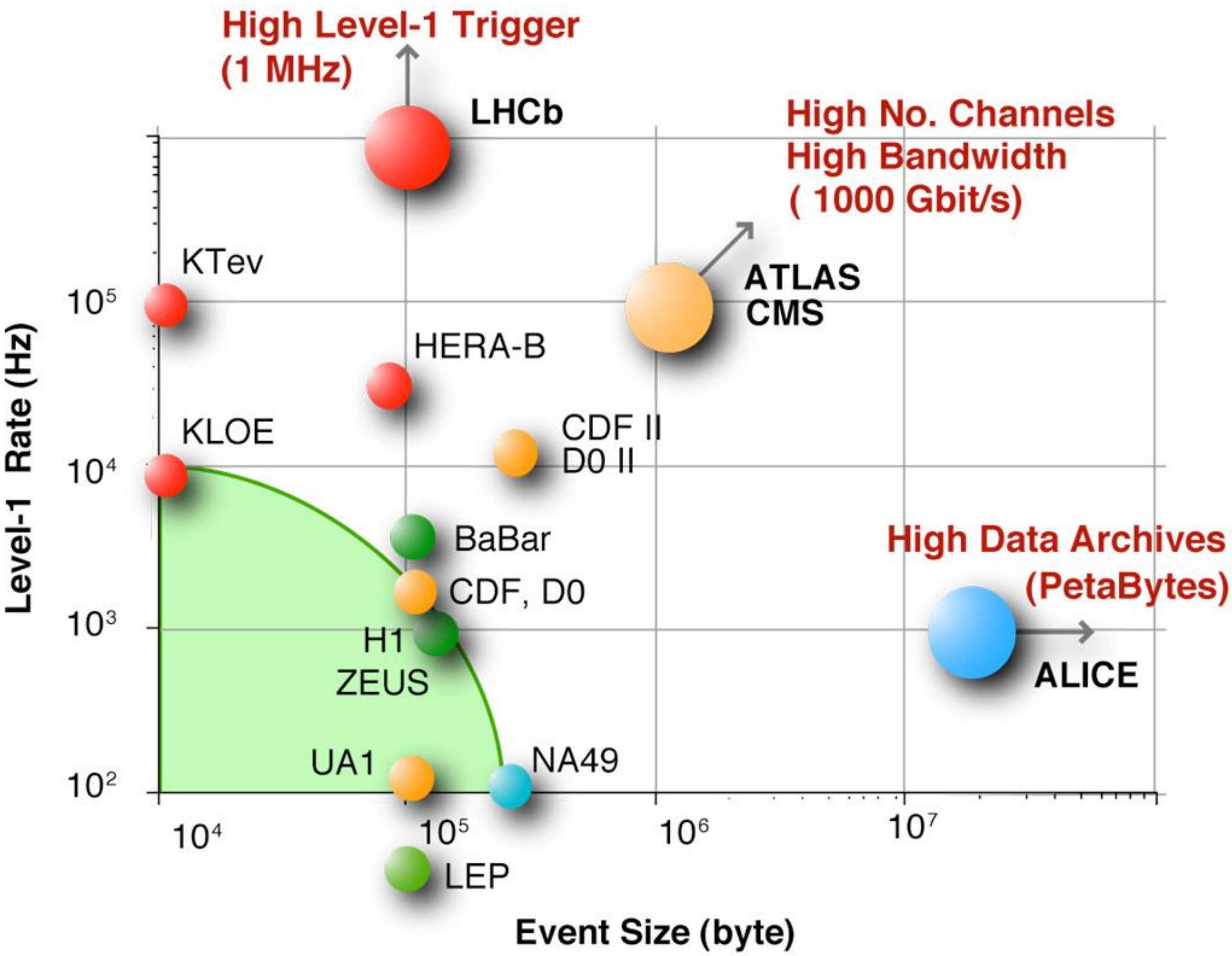
Multi-level trigger system

- Sometime impossible to take a proper decision in a single place
  - too long decision time
  - too far
  - too many inputs
- Distribute the decision burden in a hierarchical structure
  - Usually $\tau_{N+1} >> \tau_N$, $f_{N+1} << f_N$
- At the DAQ level, proper buffering must be provided for every trigger level
  - absorb latency
  - De-randomize

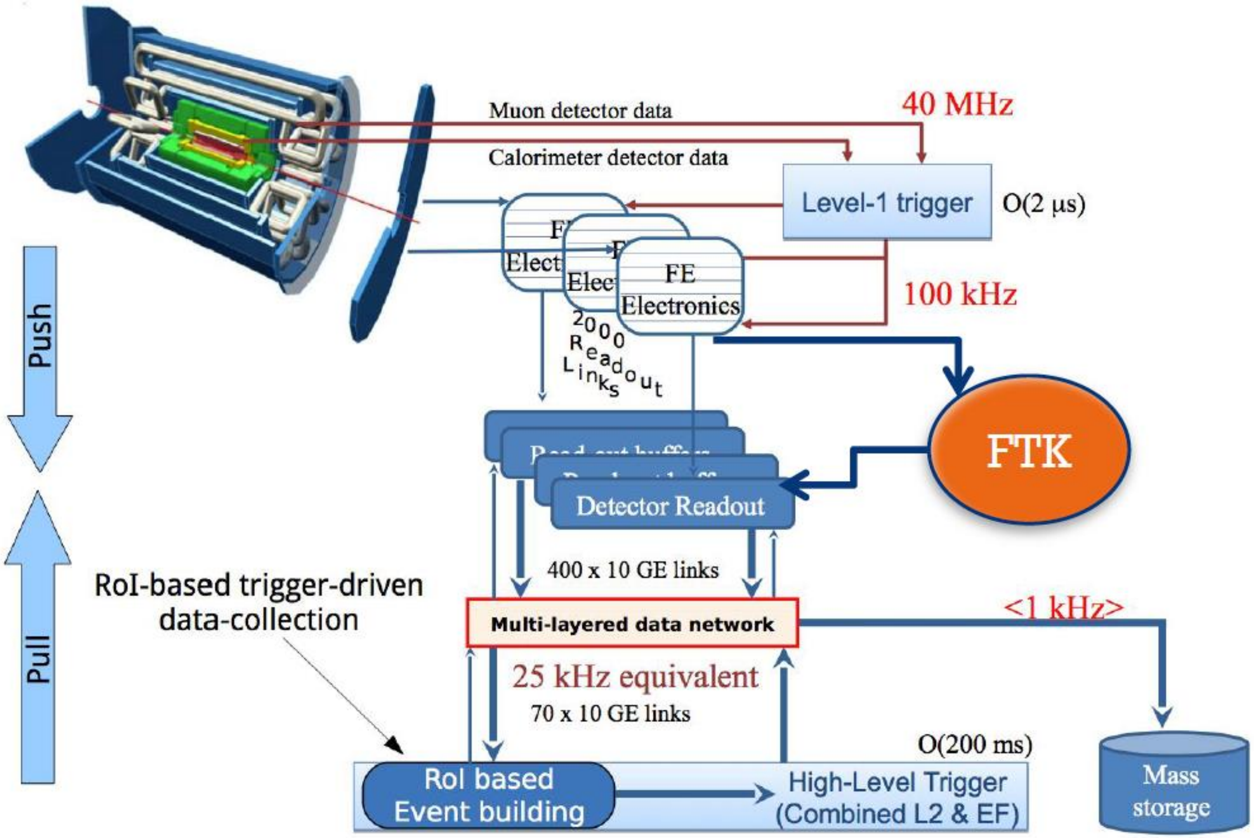


LHC DAQ phase-space

- When LHC experiments were designed back in the 90’
  - Raw data storage capped at ~ 1 PB / year per experiment



The ATLAS Trigger/DAQ System

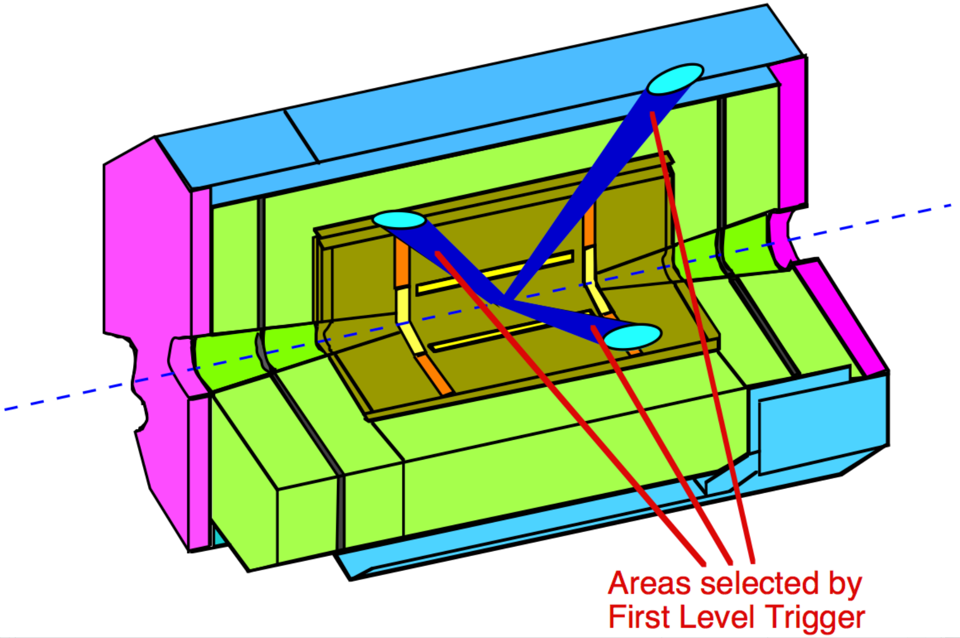


DAQ/HLT

- Overall Trigger & DAQ architecture: 3 trigger levels
- Level-1:
  - 2.5 μs latency
  - 100 kHz
- HLT: run L2 and EF in one farm
- Average output rate: 600 Hz, up 1kHz at peak luminosity
- Processing time: 0.2s on average
- Average event size 1.5 - 2 MB

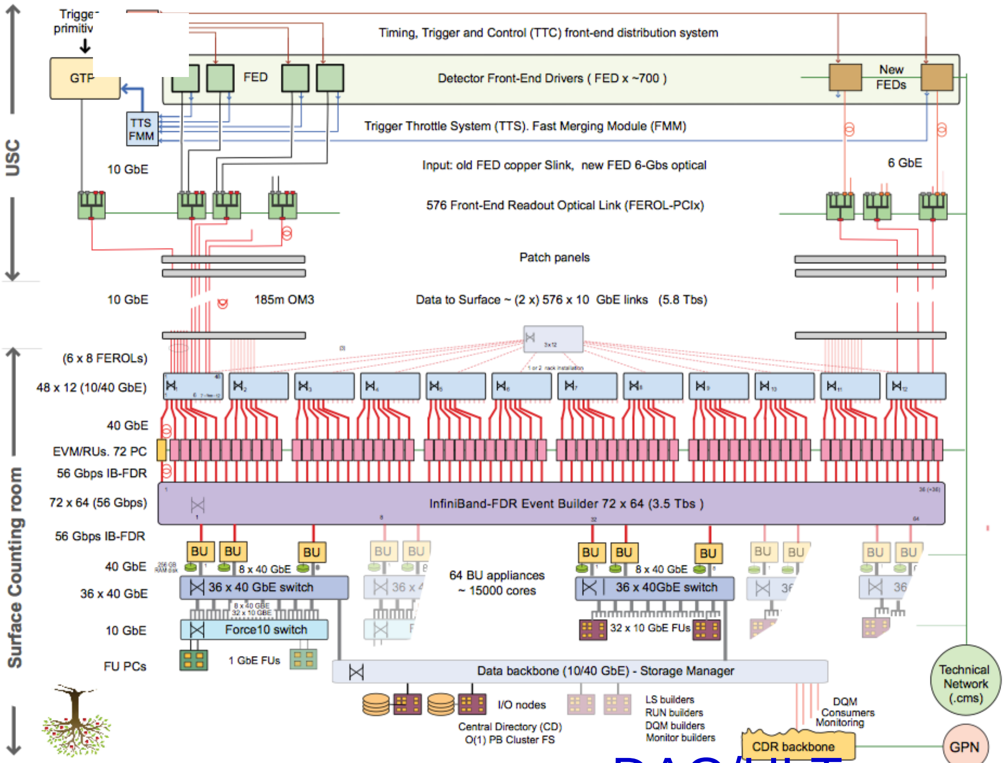
The ATLAS Special Features

- On-demand event building seeded by Region of Interests
  - No need to analyse the whole event in HLT, just look at regions flagged at L1 (e.g. regions with e/γ, μ, τ, jet candidates
  - On average look only at ~5% of the data



- L2 and EF run on same CPU within one farm (new in 2015)
  - Provides efficient coupling between subsequent selection steps, reducing duplication of CPU usage and network transfer
  - Allows flexible combination of fast and detailed processing

The CMS Trigger/DAQ System



- Overall Trigger & DAQ architechture: 2 trigger levels
- DAQ & HLT decoupled via inter-mediate shared temp. storage
- Level-1:
  - 3.2 μs latency
  - 100 kHz output
- DAQ/HLT
  - Event building at full L1 rate
  - Average output rate: ~1 kHz
  - Average event size 1.5 Mb
  - Max. Average CPU time: ~160 ms/event

The CMS Special Features

- 2 stage event building!
- 1st stage:
  - Combine fragments into super-fragment in RU (Reodout Unit) builder
  - Event building in builder units which then write events to transient files on RAM disk
- 2nd stage:
  - serve complete events to trigger farm.
- DAQ and HLT decoupled via intermediate shared temporary storage (new in 2015)

Detector front-end

Front-End Readout Optical Link

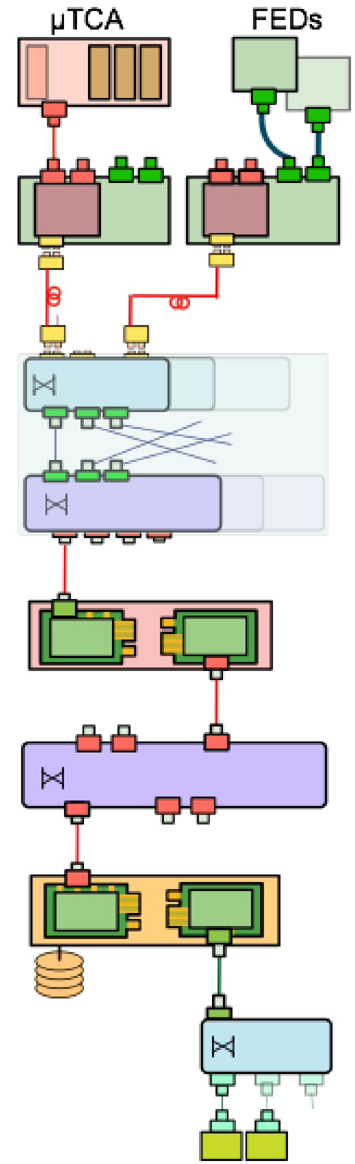
Data Concentrator switches

Readout Units

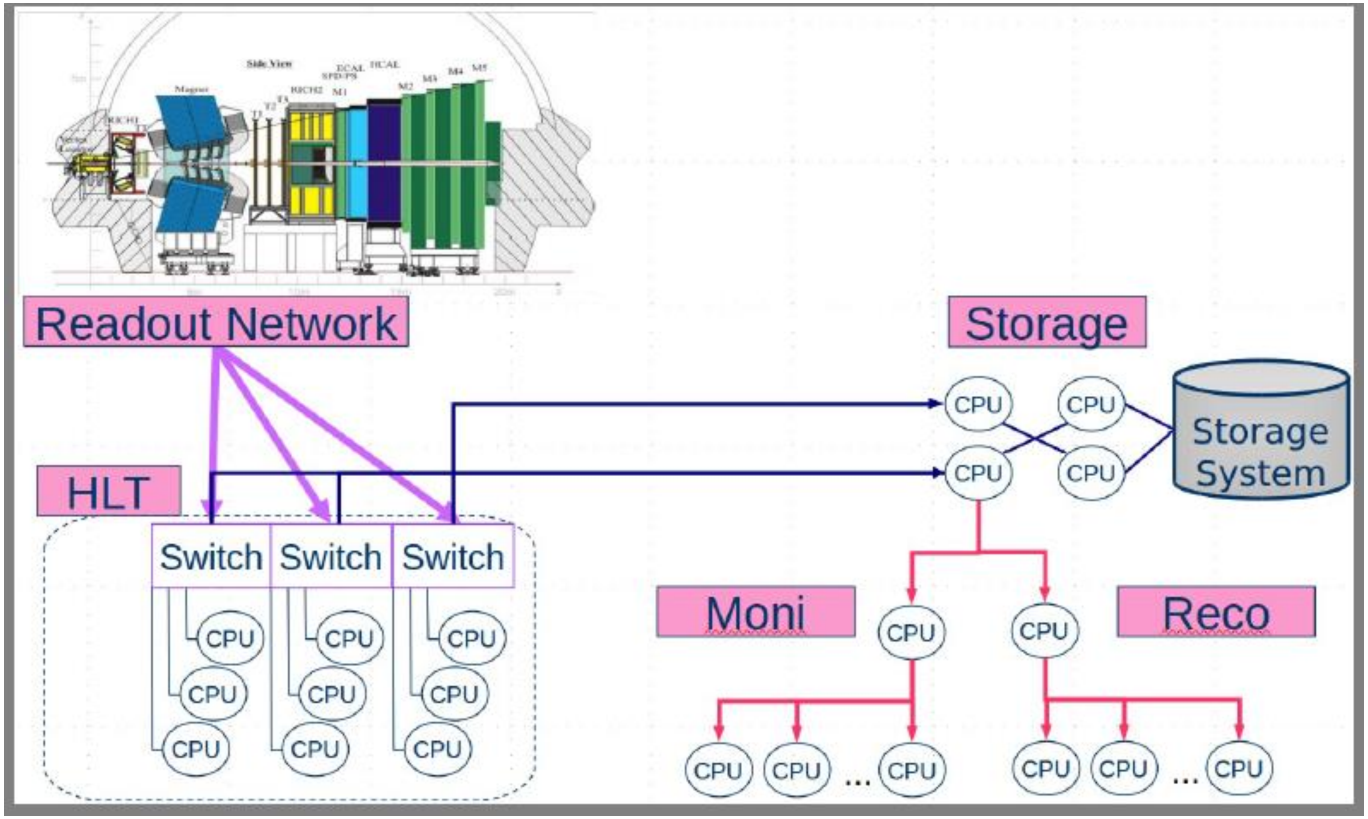
Event Builder switch

Builder Units

Filter Units (HLT)



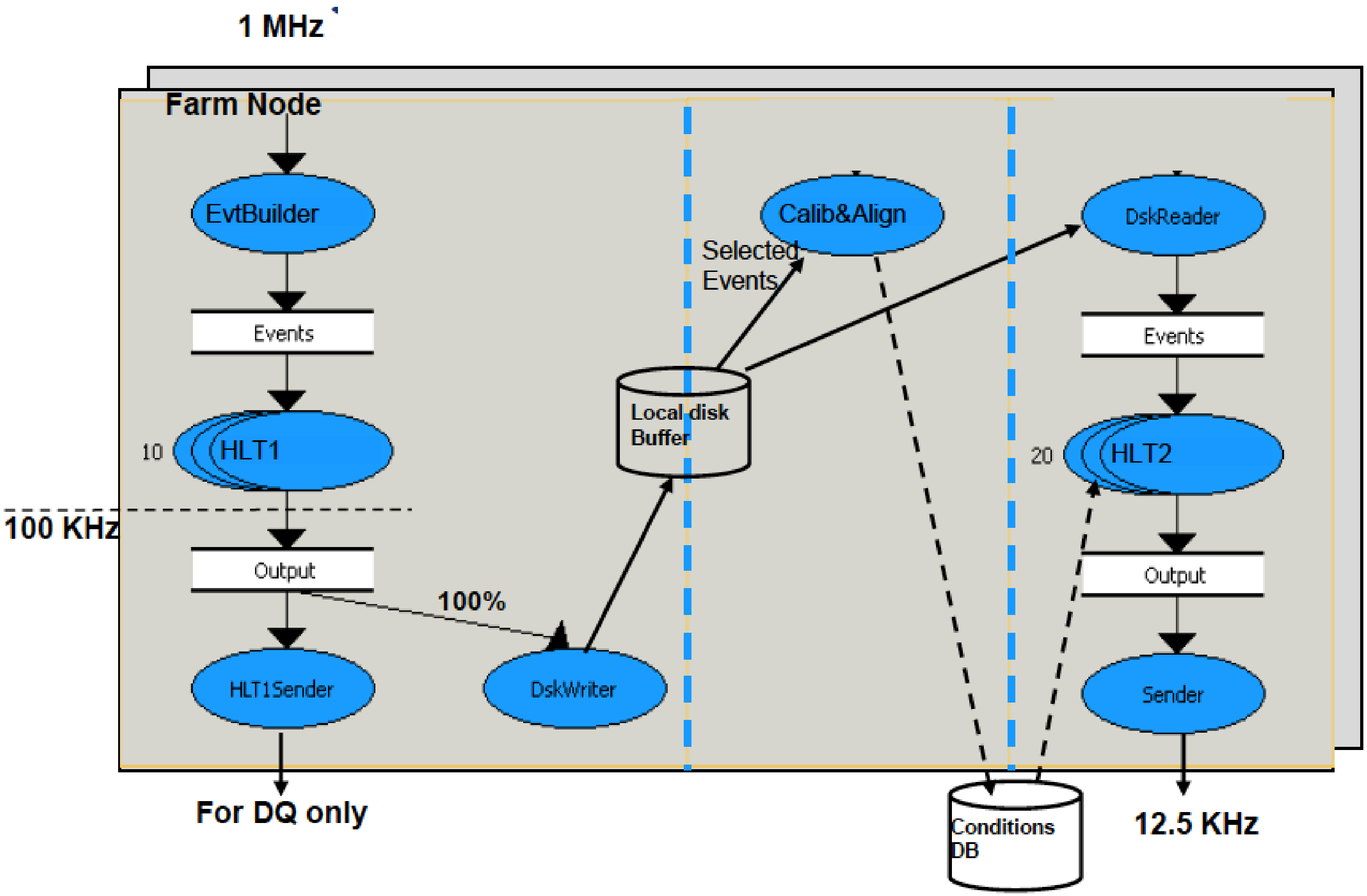
The LHCb Trigger/DAQ System



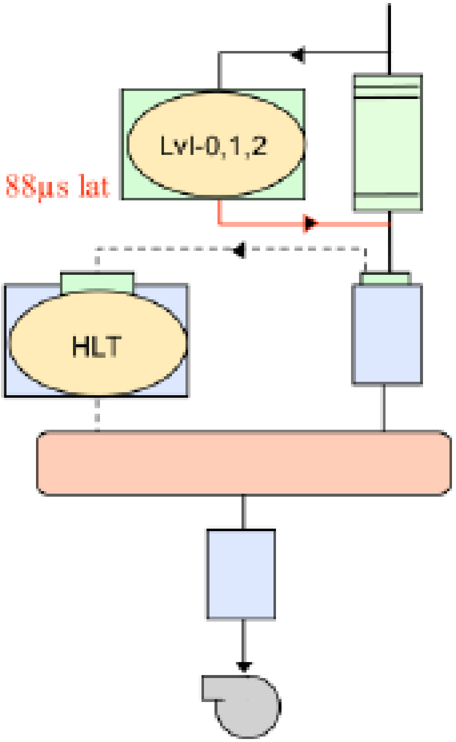
- Overall Trigger & DAQ architechture: 3 trigger levels
- Level-0:
  - 4 μs latency
  - 1 MHz output
- DAQ/HLT
  - L1: look displaced high p_T tracks, output 100-200 kHz
  - L2: full event reconstruction
  - Average output rate: 10 kHz,
  - Average event size 70 kB

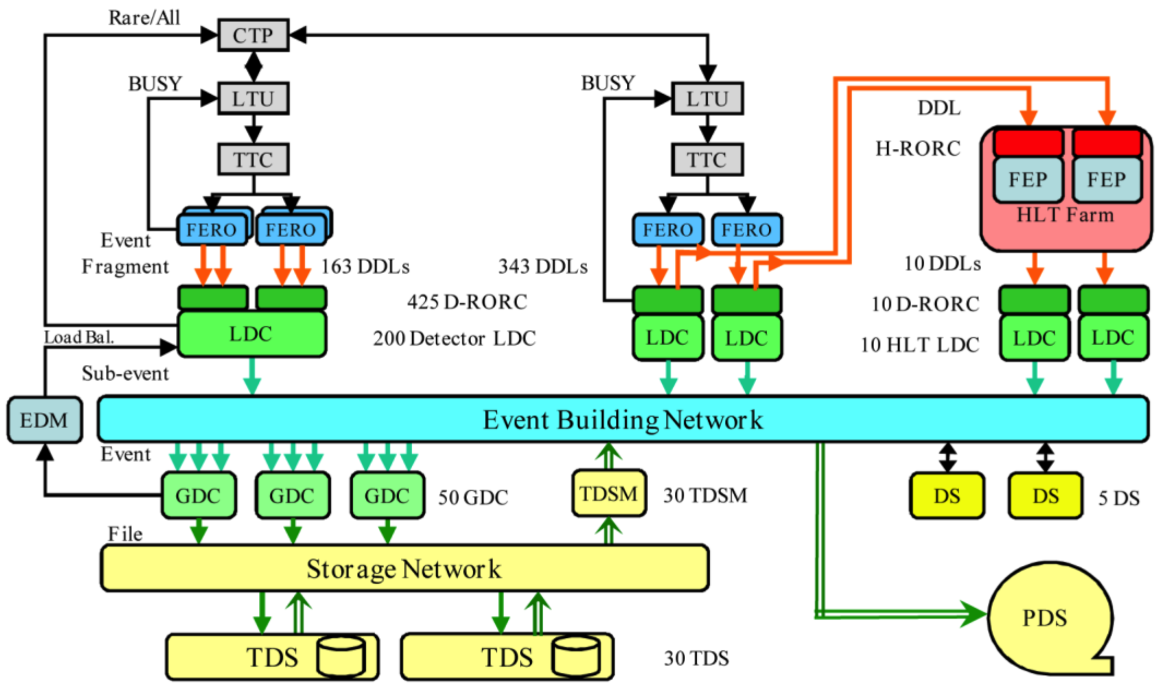
The LHCb Special Features

- HLT decoupled from data flow via local temporary storage!
  - Using periods without beam boost CPU usage by 200 %



The ALICE Trigger/DAQ System





- Alice has different constraints
  - Low rate: max 8 kHz pb+pb
  - Very large events: > 40MB
  - Slow detector (TPC ~ 100 μs)
- Overall Trigger & DAQ architecture: 4 trigger levels
- 3 hardware-based trigger, 1 software-based:
  - L0 – L2: 1.2, 6.5, 88 μs latency
  - L3: further rejection and data compression

The Alice Special Features

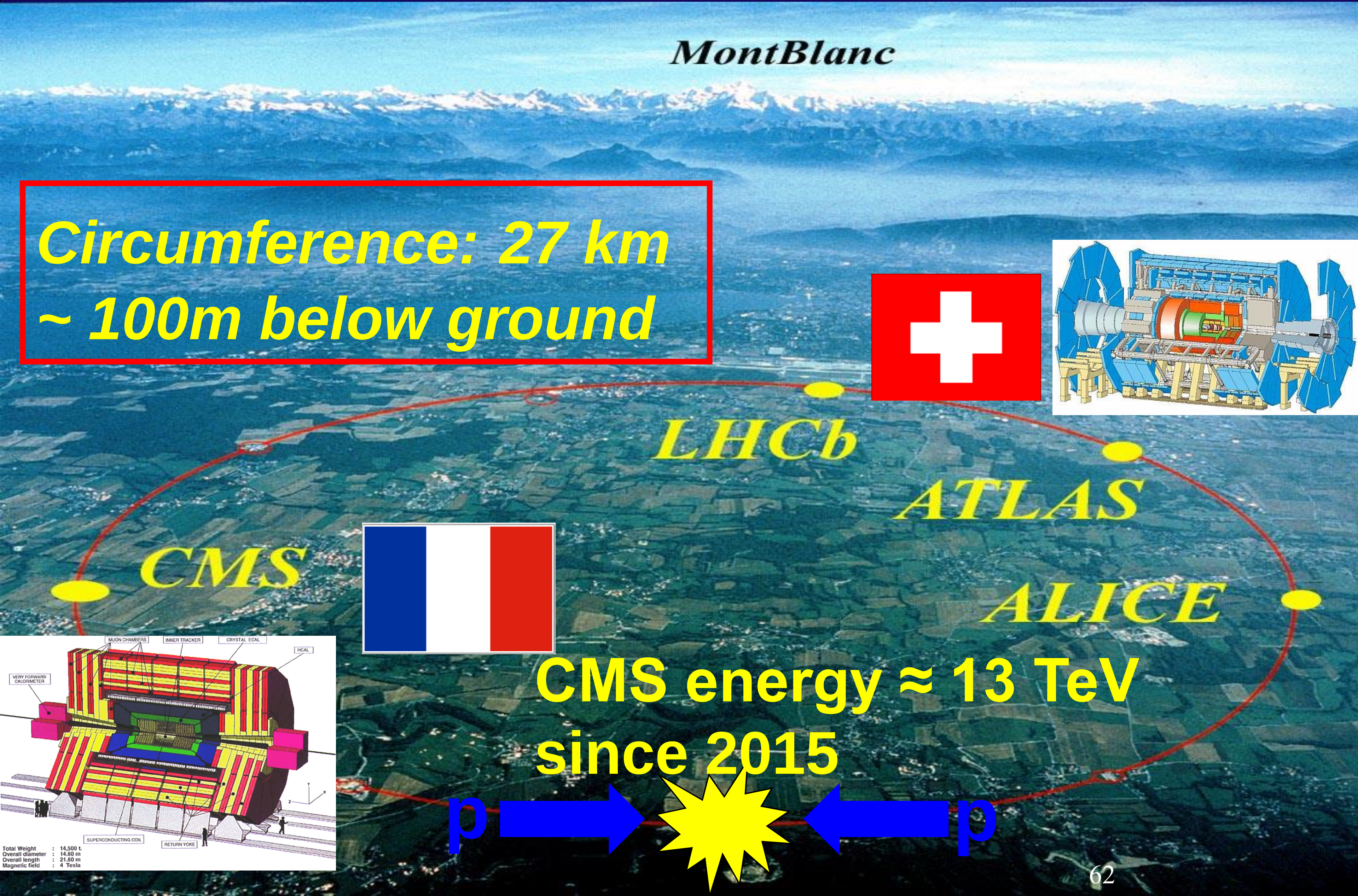
- Deal with huge events
  - 3 hardware level triggers
  - Heavy utilisation of hardware acceleration: FPGA + GPU
  - Use of data compression in trigger

Summary

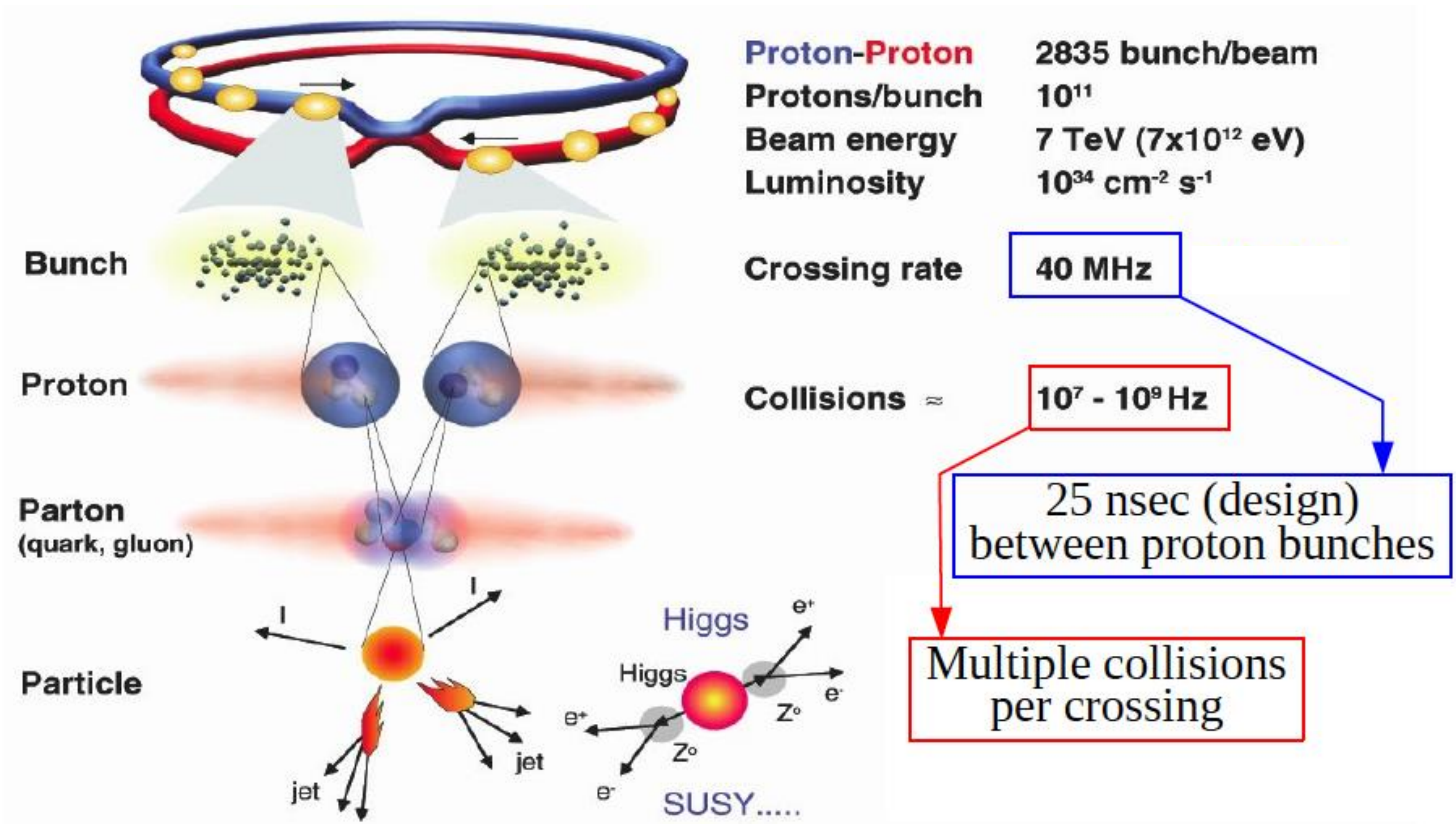
- The principle of a simple data acquisition system
- Introduction to some basic elements: trigger, derandomiser, FIFO, busy logic
- How data is transported
  - Bus versus network
- Challenge to design efficient trigger/DAQ for LHC
  - Very large collision rates (up to 40 MHz)
  - Very large data volumes (tens of MBytes per collision)
  - Very large rejection factors needed ($>10^5$)
- Showed data acquisition used in LHC experiments
  - Now everyone has upgraded their infrastructure for 2015

In case of time

Current biggest TDAQ systems used at CERN



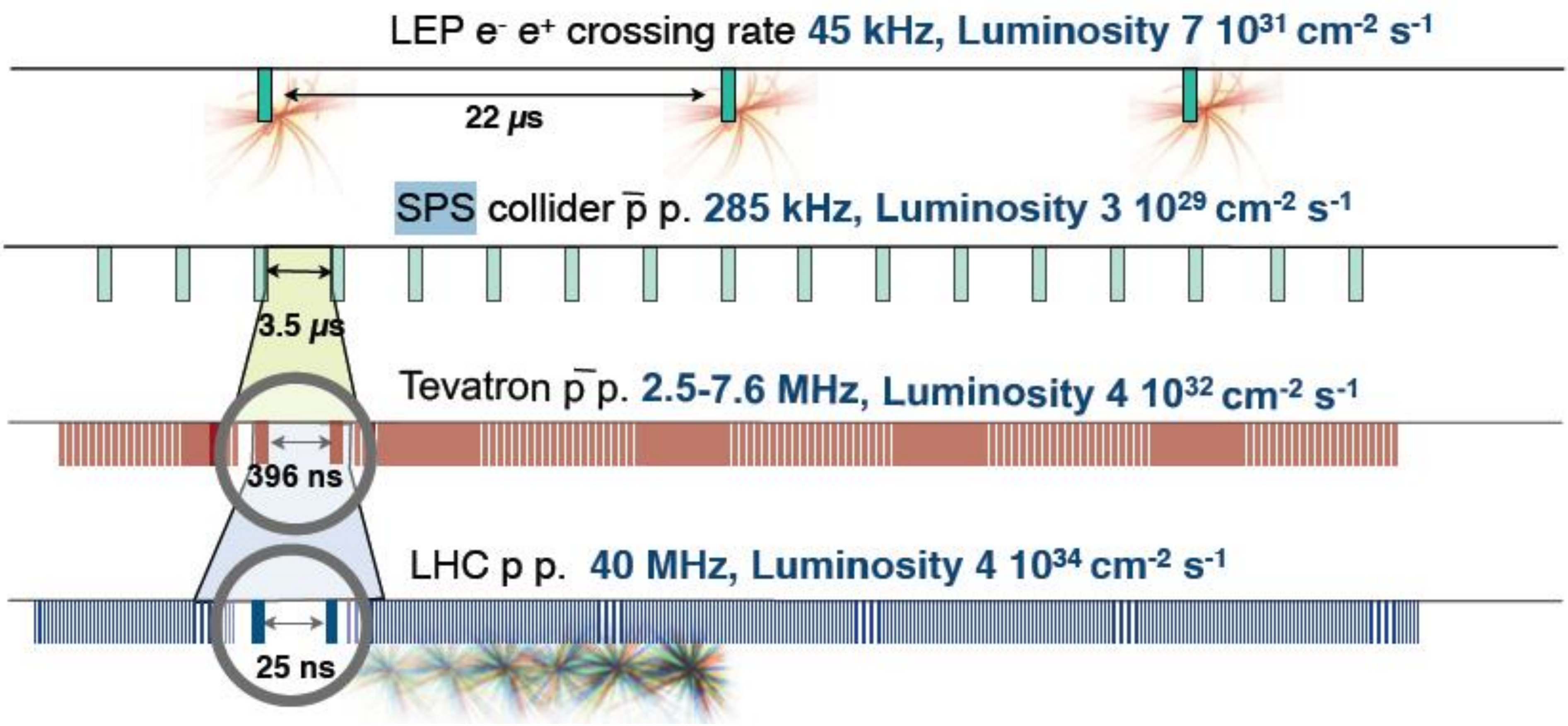
A Few LHC Facts



Luminosity

- Definition of luminosity
  - Number of collisions that can be produced per cm^2 and per second.
  - $R = dN/dt = L\ \sigma_p$

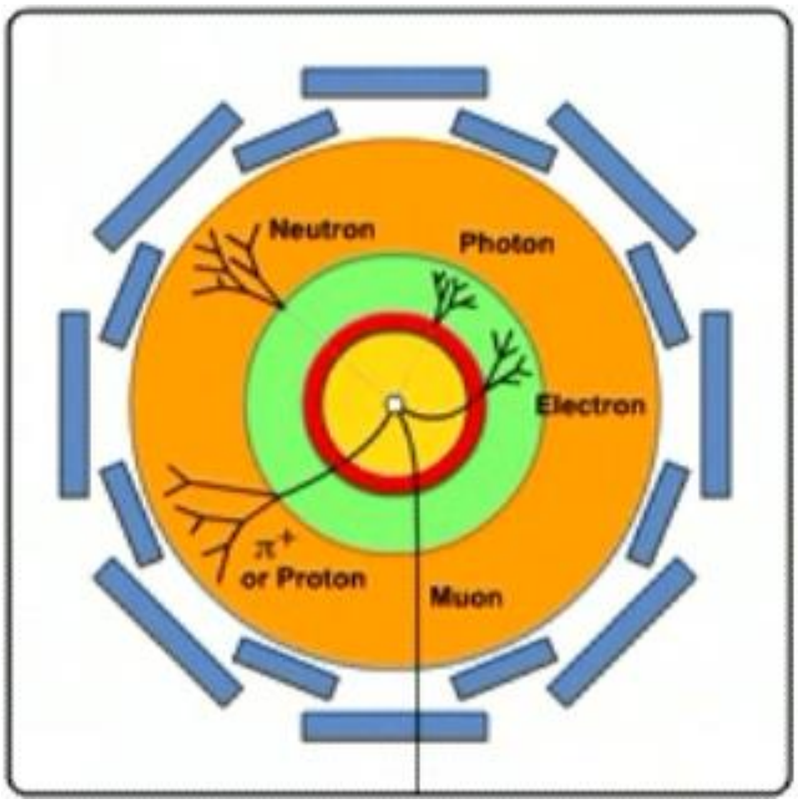
Colliders bunch crossing frequencies

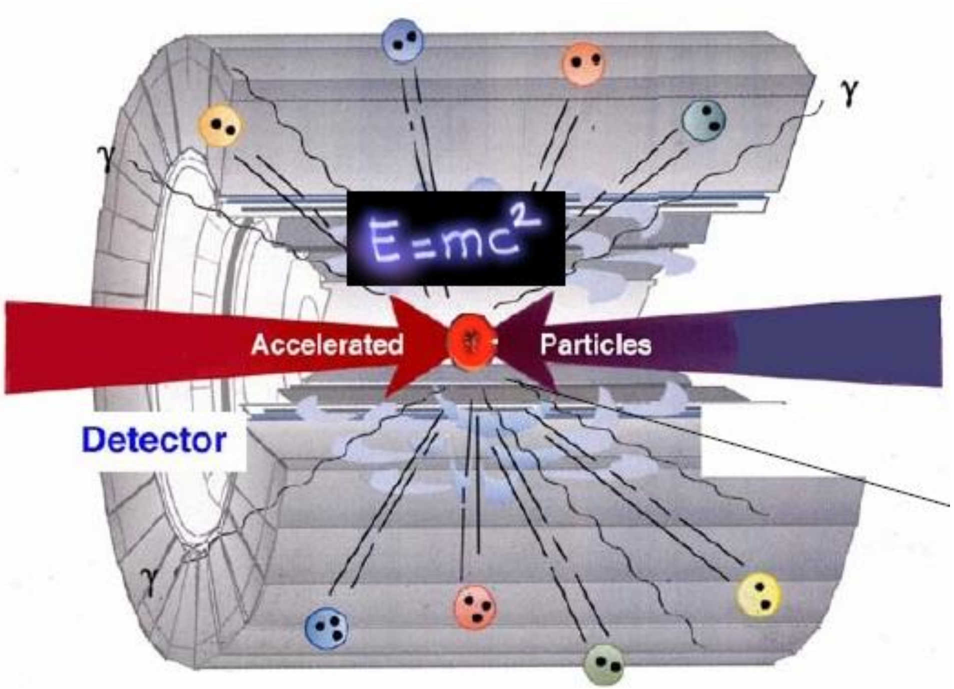


- 25 ns defines an overall time constant for signal integration, DAQ and trigger.

Principle of multi-purpose detector

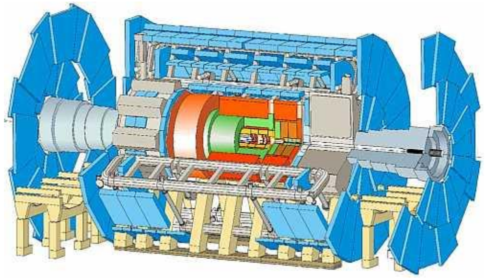
- Detectors built around collision point



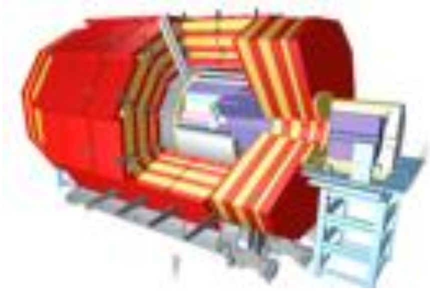


- Several layers of different detectors
  - Separate particle types
  - Measure their energies and direction

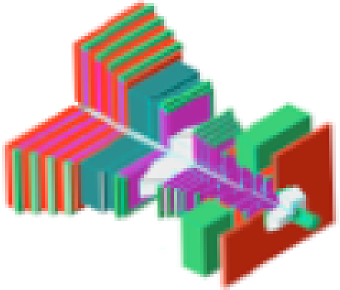
The LHC Experiments



- ATLAS
  - Study of pp and heavy ion collisions
  - Length: 40m, height: 22m, weight: 7000t
  - 10^8 readout channels, event size: 1.5MB



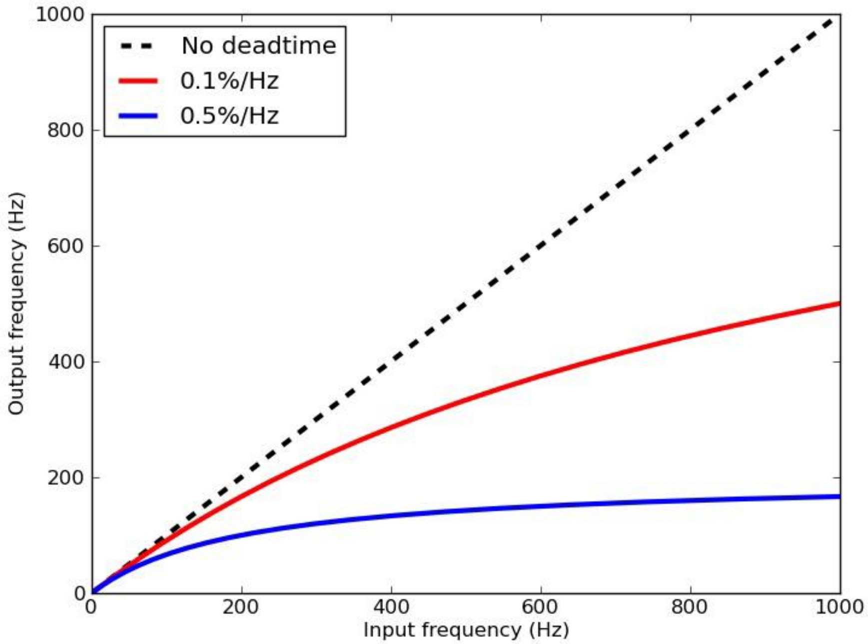
- CMS
  - Study of pp and heavy ion collisions
  - Length: 21m, height: 15m, weight: 12500t
  - 10^7 readout channels, event size 1MB

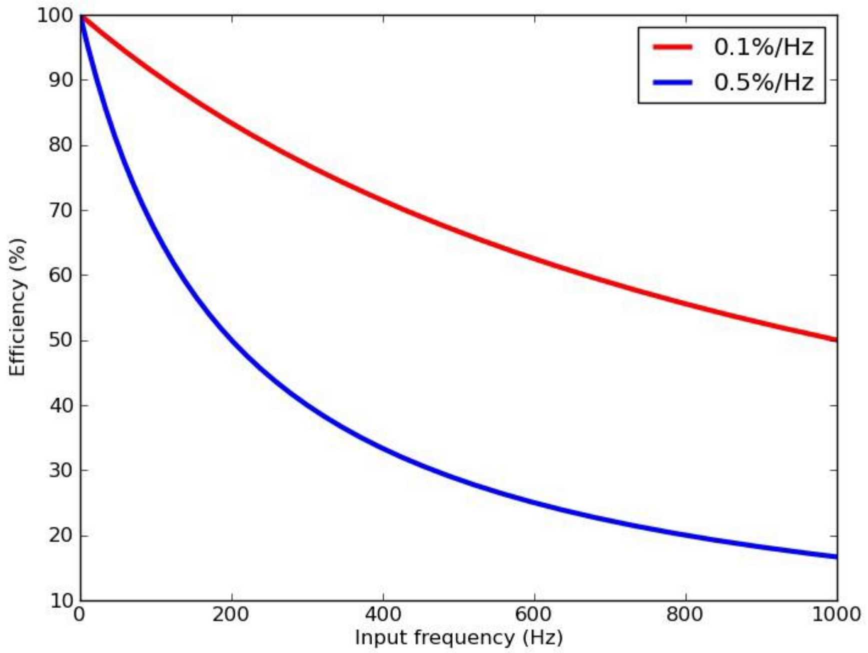


- LHCb
  - Study of CP violation in B decays
  - Length: 21m, height: 10m, weight: 5600t
  - 10^6 readout channels, event size: 35kB

- ALICE
  - Study of heavy ion collisions
  - Length: 21m, height: 16m, weight: 10000t
  - 10^6 readout channels, event size: 50MB

DAQ deadtime and efficiency

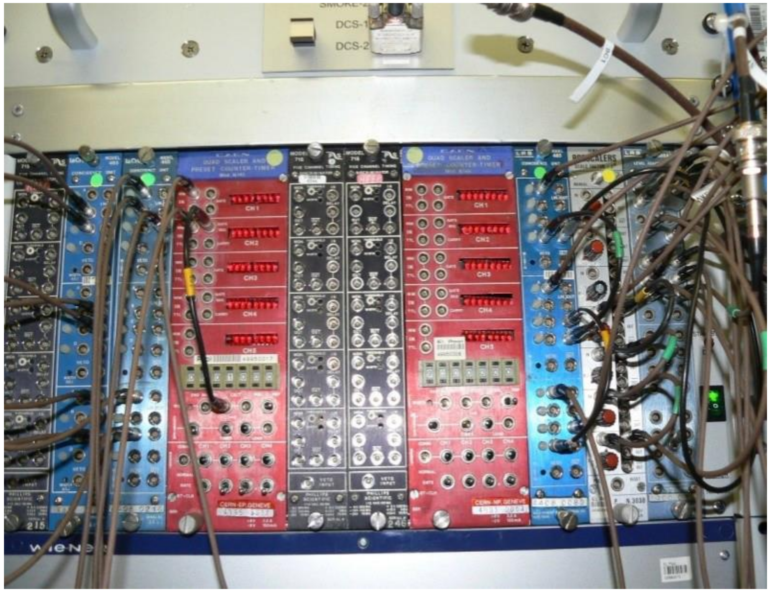


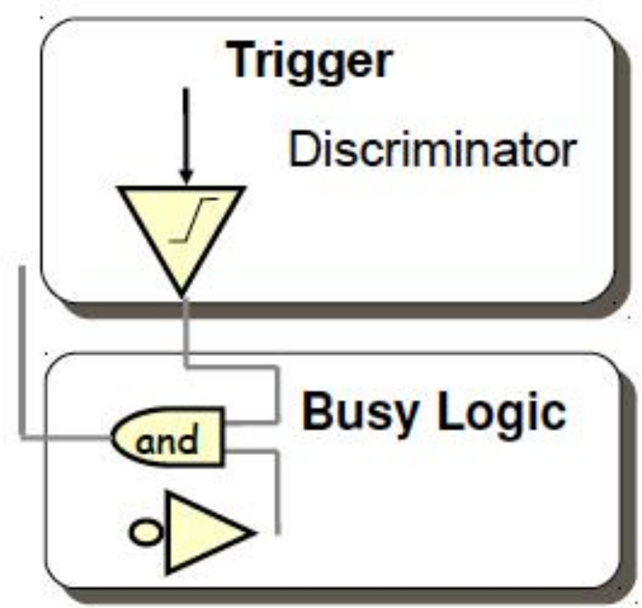


- If we want to obtain $\nu \sim f$ ($\varepsilon \sim 100\%$) $\rightarrow f\tau << 1 \rightarrow \tau << 1/f = \lambda$
  - f=1kHz, ε=99% $\rightarrow \tau <$0.1ms $\rightarrow 1/\tau >$10kHz
- In order to cope with the input signal fluctuations, need to overdesign DAQ system by a factor 10. Can this be mitigated?

NIM

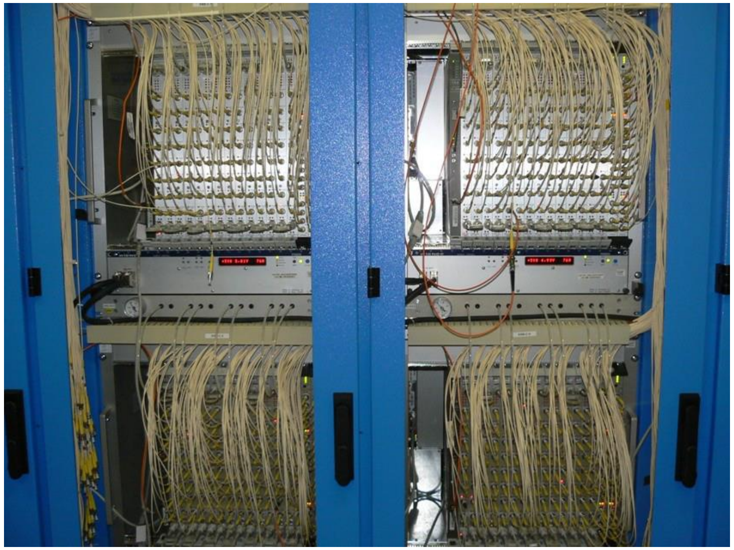
- NIM (1964)
  - “Nuclear Instrumentation Modules”
- NIM modules usually
  - Do not need software, are not connected to PCs
  - Implement logic and signal processing functions
    - Discriminators, Coincidences, Amplifiers, Logic gates, …
- Typically implement basic Trigger and Busy system
- New modules still appear on the market
  - Very diffused in medium-sized HEP experiments
  - Found in counting rooms of LHC exp.

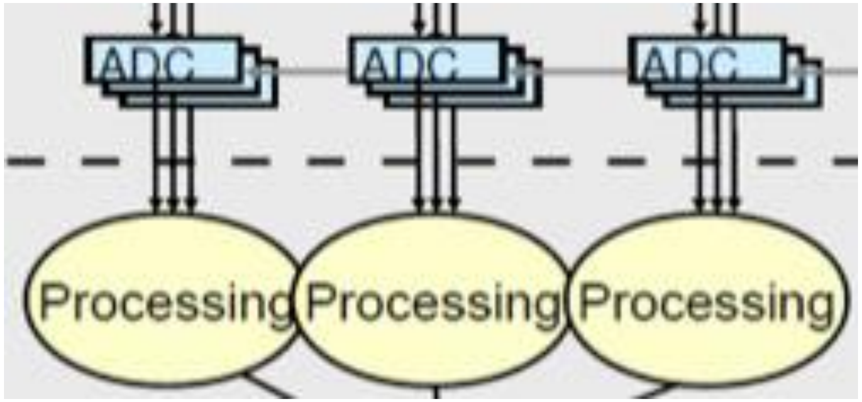




VME

- VMEbus: modules communicate via a "backplane"
  - Standardised way to access data
- Choice of many HEP experiments
  - Relatively simple protocol
  - A lot of commercially available functions
- More than 1000 VMEbus crates at CERN





Other (arising) standards

- PCI-based

- We know buses have limited scalability. Can we have “network-based” modular electronics?
- VXS → essentially VME plus switched interconnectivity
- ATCA and derivatives
  - standard designed for telecom companies
  - High-redundancy, data-throughput, high power density
  - being used for LHC upgrade programs

Deadtime and Efficiency

- System busy from trigger to end of processing
  - Trigger rate with no deadtime = input rate f per sec.
  - Dead time / trigger = τ sec.
    - Ratio between the time the DAQ is busy and the total time
  - For 1 second of live time = $1 + f\tau$ seconds
  - Live time fraction = $1 / (1 + f\tau)$
  - Real trigger (output) rate ν = $f / (1 + f\tau)$ per sec.
  - **Efficiency:** $N_{saved}/N_{tot} = \nu/f = 1/(1 + f \cdot \tau)$
    - Note, due to the fluctuations introduced by the stochastic process the efficiency will always be less 100%