Trigger and DAQ

How to find and take your data

Thiago R. F. P. Tomei (SPRACE)

General Aspects of Trigger and DAQ

Trigger and DAQ: Definitions

Trigger: a system that selects **interesting interactions** and gives the signal to start the data acquisition.

- *Interesting:* defined by what kind of physics you want to do
  - High-energy physics, rare decays, neutrino physics, …
- *Interaction:* (or "event") defined by what experiment you're running
  - Collider detector, germanium calorimeter, neutrino experiment, …

Data AcQuisition (DAQ): a system that **collects the data** signaled by the trigger from the detectors.

- Transduces the physical signal to electric signal – "reads out" the data
  - Analog-to-digital conversion at some stage
- Synchronization, data formatting, data organization
- Data storage in permanent media

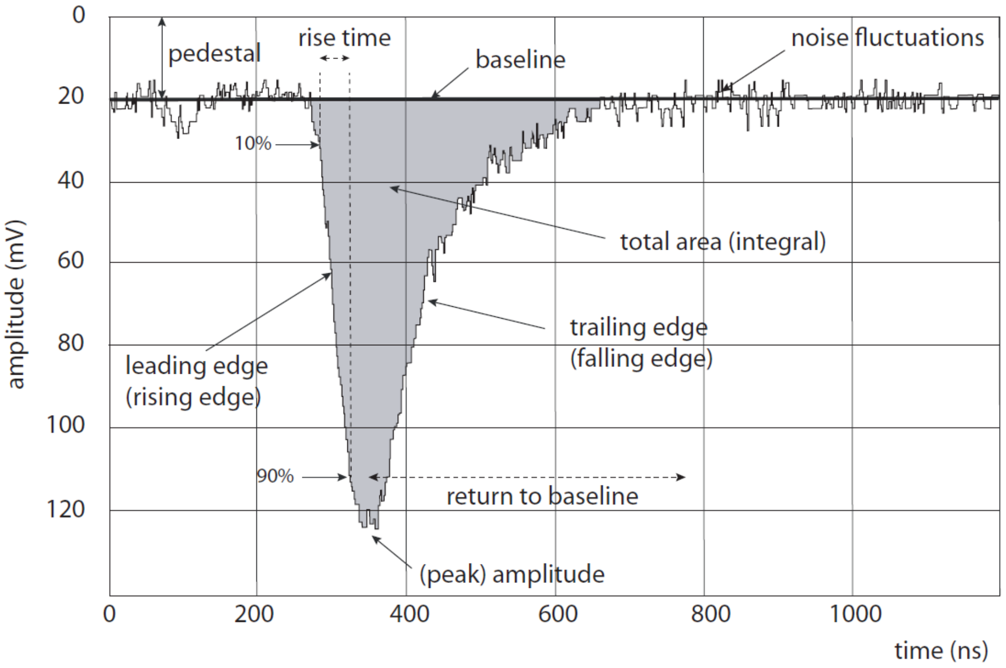
Electronic Readout

Electronic readout and processing of detector signals is
the most common form of data acquisition in (astro)particle physics.

Readout electronic tasks:

- Electronic coupling to the detector to receive its signal.
- Amplification of the input signal and electronic processing (pulse shaping. discrimination)
- Optimization of the output signal depending on the application.
  - Signal-to-noise ratio
  - Determination of the primary deposited energy in the detector (energy measurement)
  - Determination of a precision mark of the signal arrival time (time measurement)
  - Rate tolerance
- Digitization and storage (buffering – see later) of the output signal.

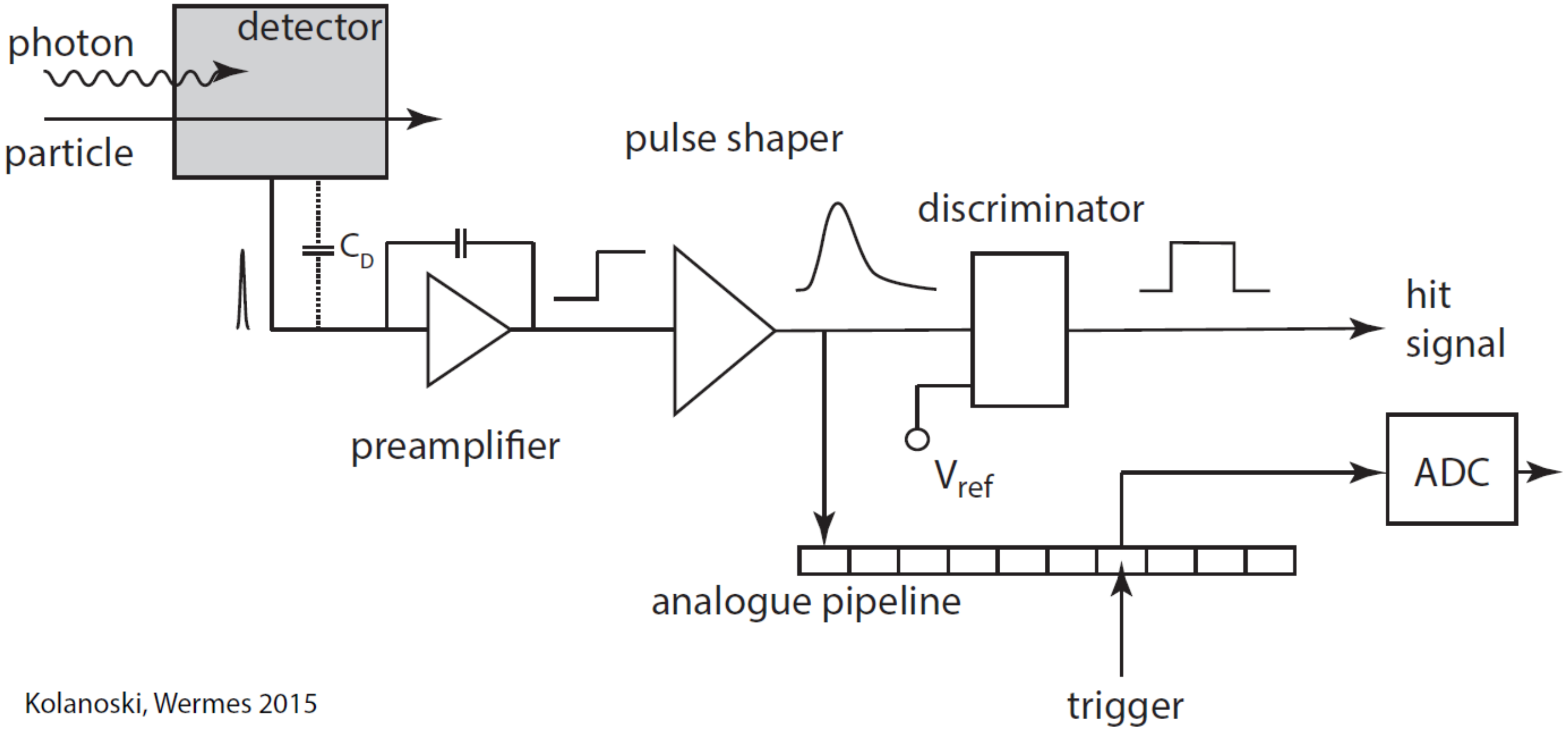
Example of a Signal Pulse



Kolanoski, Wermes 2017

- Drift chamber signal
- Output of a photomultiplier on oscilloscope
- Pulse from semiconductor detector (already preamplified)

Readout and Front End (1)



Kolanoski, Wermes 2015

Readout and Front End (2)

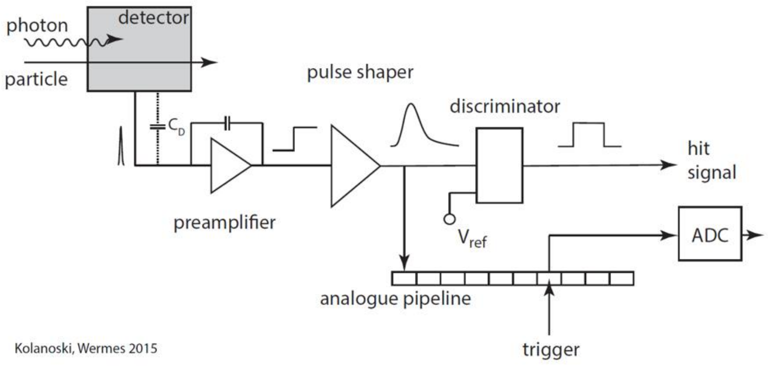
Detector reacts to particle delivering a short current signal.

Signal input to the preamplifier.

- First (often only) amplifier amplification stage of readout chain
- If a capacitive feedback loop is realized -→ integrate the input current
- Output: voltage step proportional to signal charge

Voltage step filtered by a shaper.

- Pulse that returns to baseline after finite time
- Bandwidth limitation of the signal (also reduces electronic noise)



Kolanoski, Wermes 2015

Output signal is proportional to energy deposited in the detector if the readout is linear

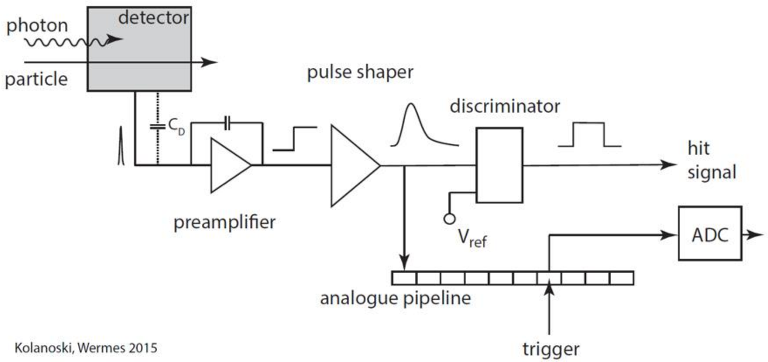
Discriminator: signal voltage compared to reference Vref

- Success → digital signal generated

Readout and Front End (3)

You may need a **trigger** system.

- ❑ Decision to keep/reject the signal for further processing
- ❑ Can involve the readout detector or formed by other detectors.
- ❑ Trigger delay – signal must be delayed/stored
  - ▪ Sequential buffers
  - ▪ Delay cables



Depending on the requirements:

- ❑ Buffer full analogue signal
- ❑ Buffer only digitized hit signal

Upon trigger:

- ❑ Signal digitization via analog-to-digital (ADC) converter
- ❑ Arrival time via time-to-digital (TDC) converter
- ❑ Signal passed to back-end electronics – further data acquisition and processing.

Why do you need a Trigger?

We need a system to tell us that something interesting is happening ☺

Can't we "take data" all the time…?

- Yes, in some experiments we can!

Usually, experimental constraints don't allow it.

- Ultra-rare events
- Excessive background and/or noise
- Experimental limitations
  - Detector electronics, DAQ, offline computing/storage

Tao of the trigger

Traditional way: the double path

- Trigger path: from dedicated detectors to the trigger logic
- Data path: from all detectors to the storage system

Modern way:

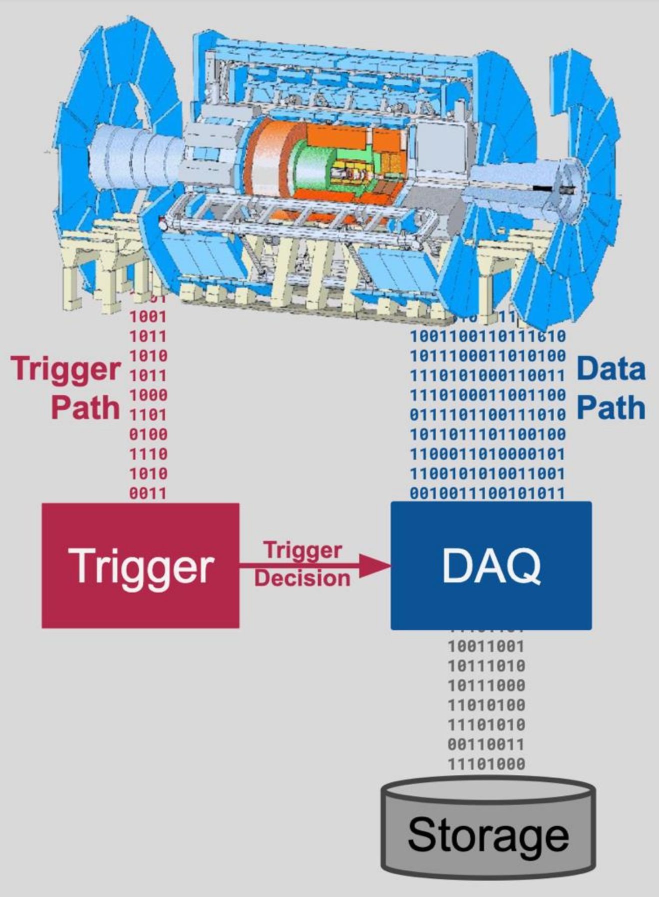
all detectors contribute to the trigger

- Example: silicon tracking detectors in ATLAS/CMS will contribute to the (hardware) trigger in the HL-LHC.
- Made possible by technology improvements

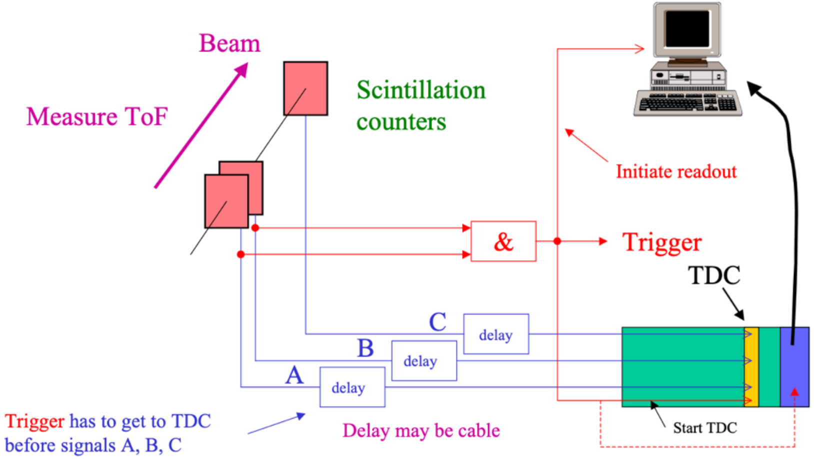
Triggerless way:

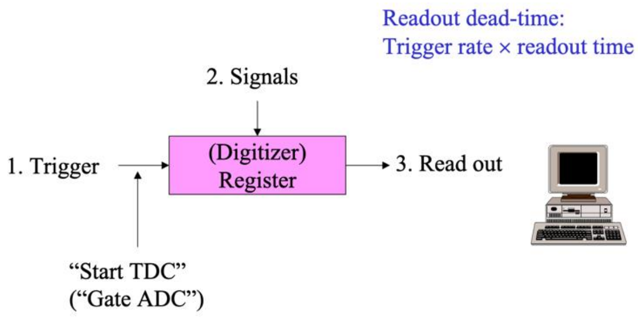
not all experiments need a trigger!

- LHCb manages to run without a hardware trigger, sending data continuously.
- The DAQ must keep up with the data rate.



Ex: Trigger in Time-of-flight experiment





Particle randomly arrives and crosses three detectors

- Signals A, B, C.

A AND B through the trigger path:

- Coincidence minimises fake signals
- Starts readout
- Starts TDC timing ("stopwatch")

A, B, C through the data path:

- Artificial delay to allow trigger to arrive first
- Readout by time-digital converters: measure t_A, t_B, t_C
- $t_A \approx t_B = t_C - \Delta_{TOF}$

Limitations

- Trigger must be fast (low latency)
- Readout time may be slow (deadtime – see later)
  - Worse for large number of channels!

Trigger Requirements

The trifold optimization:

- **High efficiency** for signal events
- **High rejection** (low efficiency) for background events
- **Low latency** for decision
  - Events are not recorded while the trigger doesn’t finish!

It must be possible to measure the efficiency precisely.

The trigger must be unbiased:

- With respect to aspects other than the one used for trigger
- Example: the efficiency of a trigger that detects an electron should not depend on the presence of another electron in the event.

Deadtime

Minimum time after registering a signal after which:

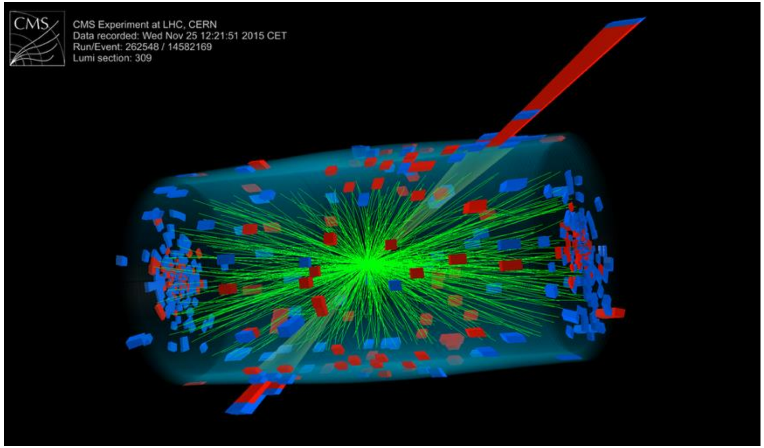
- Either the detector cannot register a further signal
- Or cannot distinguish a second or third signal from the first one
- Typical total of up to O(10%)

Deadtime sources include:

- Detector deadtime (e.g. recovery after electric discharge)
- Trigger and readout deadtime
  (e.g. time for signal registration and processing)

In complex detectors:

- Deadtime of an individual channel does not necessarily govern the dead time of the entire detector
- Experimental measurement consists of many individual signals combined
- Accounting for a channel's deadtime as an inefficiency



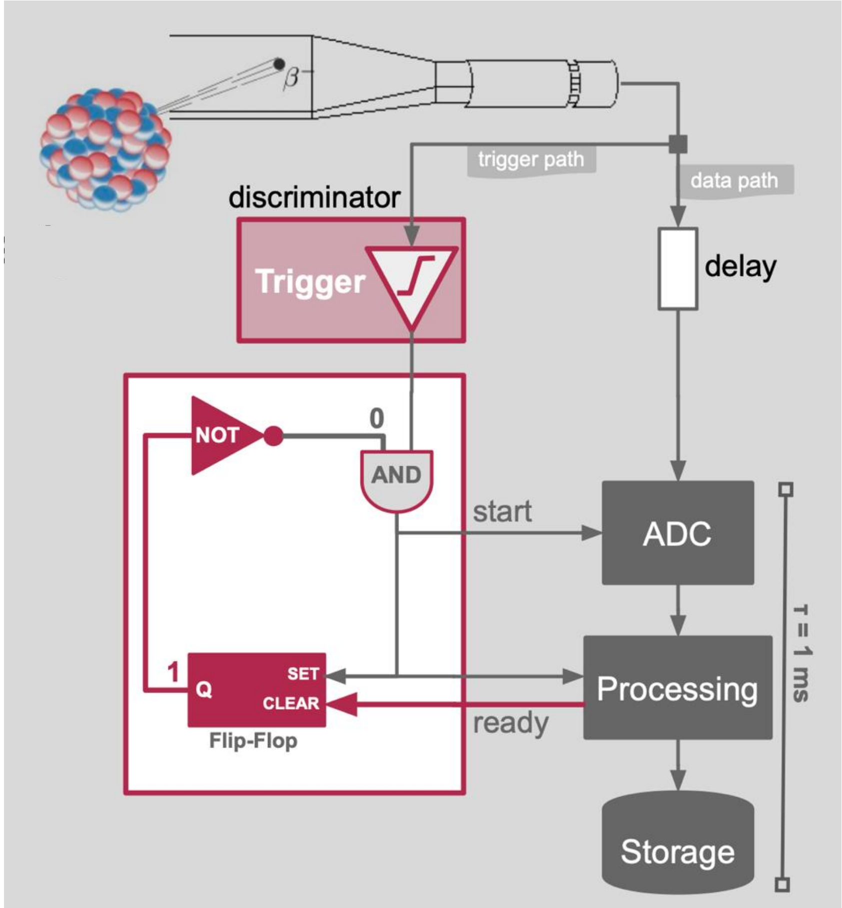
Busy logic

Our trigger and DAQ must be able to:

- ❑ Determine if there is an "event" (trigger)
- ❑ Process and store data from the event (DAQ)
- ❑ Without getting paralysed by new events

We need a feedback mechanism, to know if the data processing pipeline is free to process a new event: **busy logic**

- ❑ Minimal busy logic can be implemented with AND gate, NOT gate and flip-flop.



Physics Rate, DAQ Rate, Deadtime

f: average physics rate (input)

ν: average DAQ rate (output)

τ: deadtime

- Needed to process an event, without being able to handle other triggers

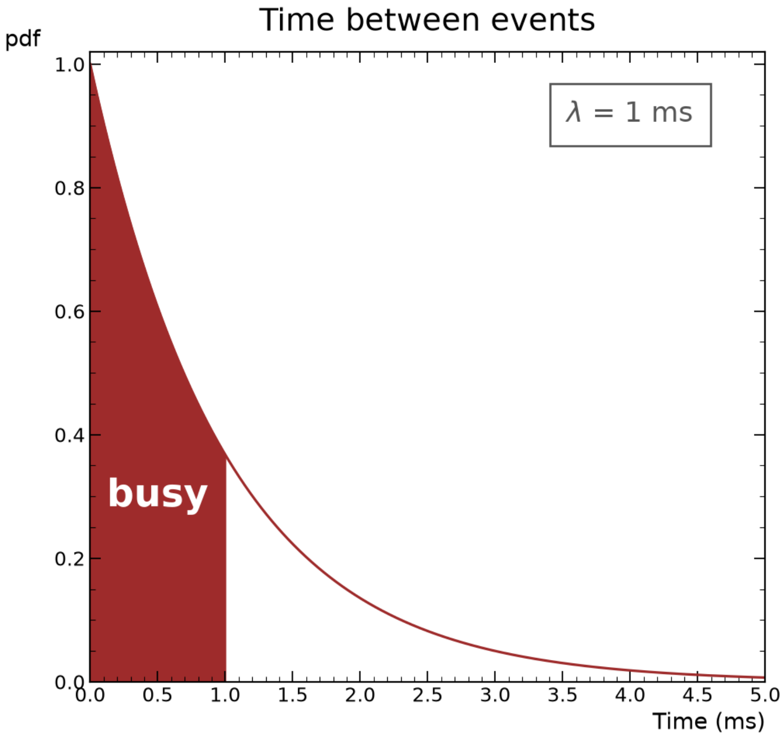
Probabilities:

- P[busy] = ντ, P[free] = 1 – ντ

Hence:

- ν = f P[free] = f (1 – ντ)

$$\nu = \frac{f}{1 + f\tau}$$



Deadtime and efficiency (1)

Due to stochastic fluctuations:

- DAQ rate always < physics rate

$$\nu = \frac{f}{1 + f\tau} < f$$

- Efficiency always < 100%

$$\varepsilon = \frac{N_{\text{rec}}}{N_{\text{tot}}} = \frac{1}{1 + f\tau} < 100\%$$

In our example:

- Physics rate: 1 kHz
- Deadtime: 1 ms

$$f = 1\,\text{kHz} \quad \nu = 500\,\text{Hz}$$

$$\tau = 1\,\text{ms} \quad \varepsilon = 50\%$$

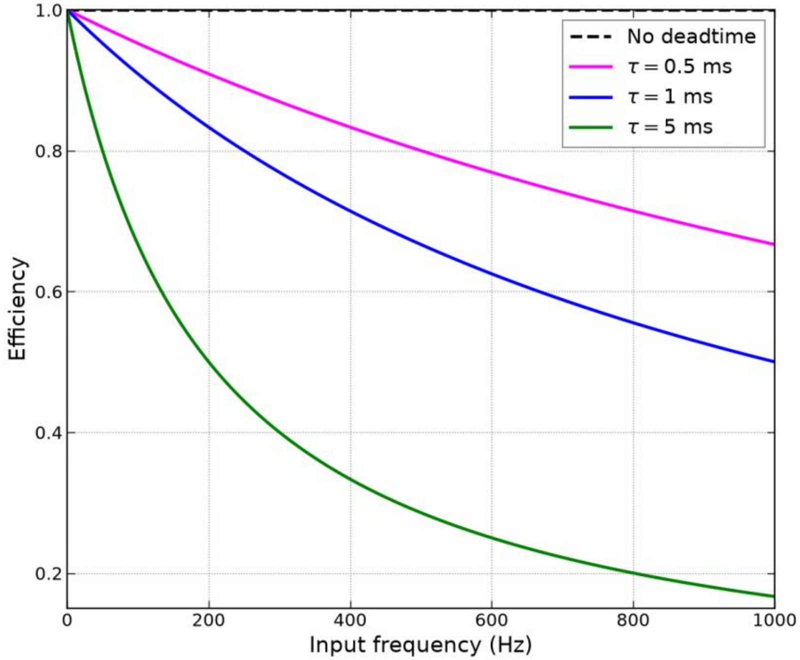
To obtain ν ~ τ, we need

$$f\tau \ll 1 \Rightarrow \tau \ll \lambda$$

Deadtime orders of magnitude smaller than
the characteristic time of the phenomenon

DAQ electronics able to work at a rate much higher than the physical rate

Deadtime and efficiency (2)



$$\varepsilon = \frac{N_{\mathrm{rec}}}{N_{\mathrm{tot}}} = \frac{1}{1 + f\tau}$$

To obtain 99% efficiency for f = 1 kHz

- $\tau < 0.01$ ms → $1/\tau > 100$ kHz

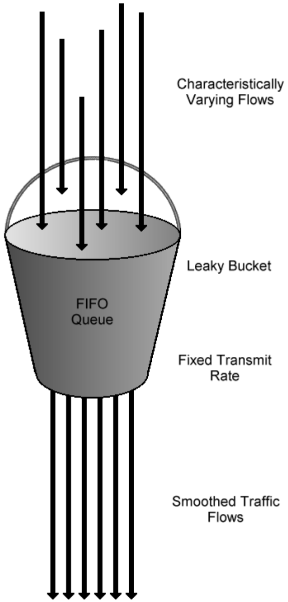
To cope with fluctuations,
we must overdesign the DAQ
by a factor of 100 (!)

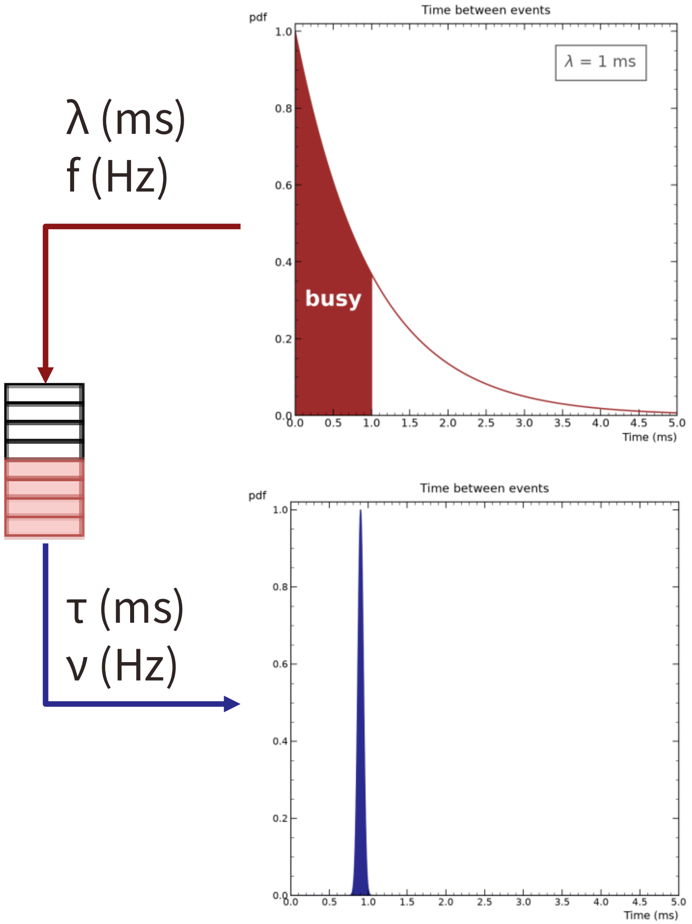
Is it possible to mitigate this effect?

De-randomization (1)

Problem: system is very dependent on the signal arrival time

- Try to ensure events don't arrive when the system is busy
- Move from exponential arrival time distribution to steady data access time distribution





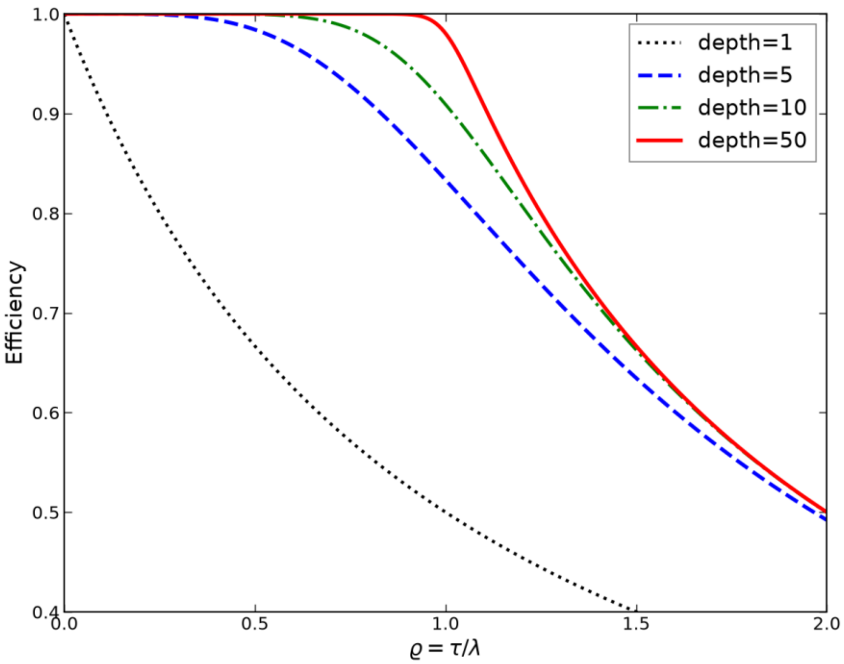
Solution: queue (buffer) to hold events "in transit" to be processed

- First-in, first-out (FIFO)
- A.k.a: "leaky bucket" algorithm

Queuing theory

Efficiency vs. traffic efficiency ($\rho = \tau / \lambda$) for different queue depths

- $\rho > 1$ ($\tau > \lambda$): system overloaded
- $\rho << 1$ ($\tau << \lambda$): system overdesigned
- $\rho \sim 1$ ($\tau \sim \lambda$): high efficiency even with moderated queue depths



De-randomization (2)

The FIFO buffer provides steady, de-randomized output rate

- ❑ Decouples the low-latency front-end from the data processing

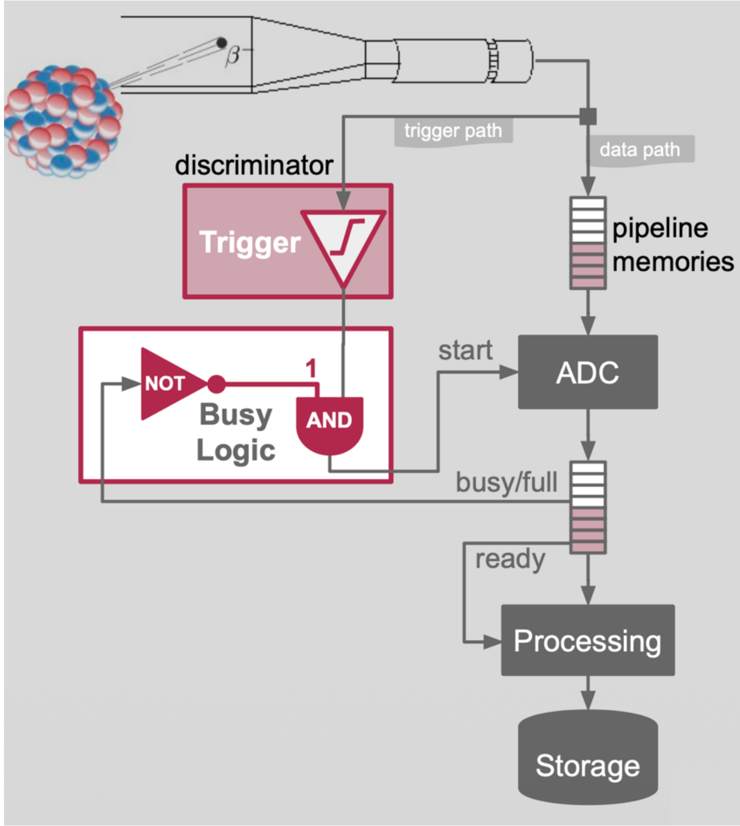
The processor is protected and pulls data from the buffer at a fixed rate

- ❑ "Busy" is now defined by the buffer occupancy

Efficiency close to 100% achievable if:

- ❑ ADC can operate at rate >> f
- ❑ Data processing and storing operate at a rate ~ f

Need for fast components minimized



De-randomization and Colliders

Buffers can be used also upstream in the digitization step

Analog pipelines are heavily used in Large Hadron Collider DAQs

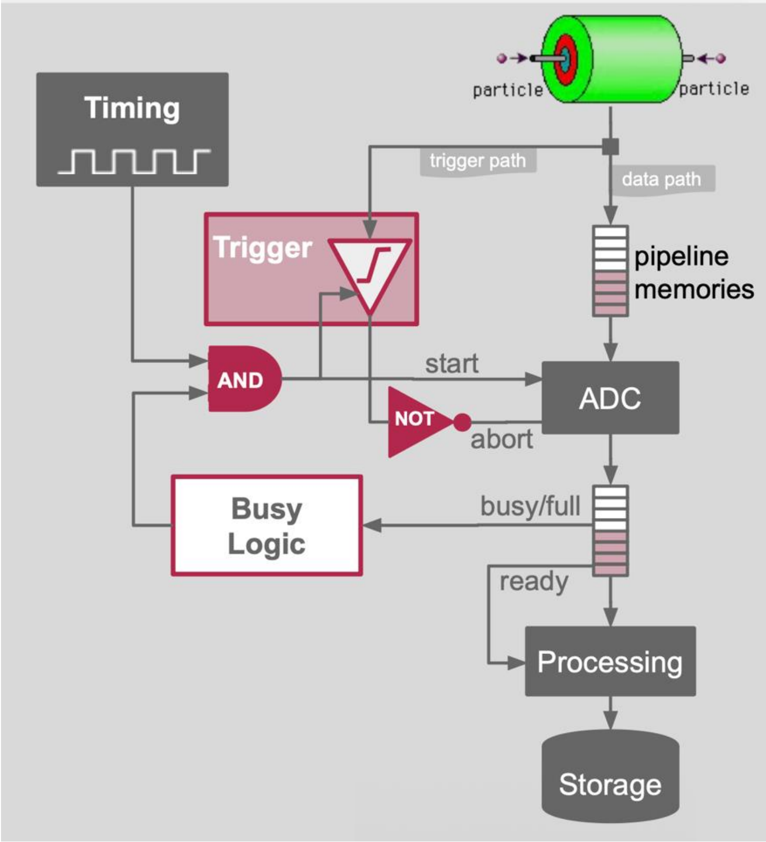
- Store analog signals while waiting for trigger
- Protecting ADC from fluctuations

Collider setups

- Collisions are synchronous
- Time distribution of triggers is random: good events are unpredictable

More complex busy logic to protect buffers and detectors

- Accept N events every bunch crossings
- Prevent dangerous trigger patterns



Multi-level Triggers

It is not always possible to meet both the physics requirements and achieve the needed trigger latency.

Multi-level triggers:

- First level (or “pre-trigger”): short latency, high efficiency, low rejection
- Further levels: increase latency, keep efficiency, increase rejection

HERA and Tevatron: collider experiments with three-level triggers

- Pure hardware (L1), mostly custom hardware (L2), computer farm (L3)

LHC: collider experiments with two (or less) triggers

- Thanks to technology improvements in the 90s and 00s

Scaling up (1)

Front End

- ❑ Data Digitization

Readout

- ❑ Data Extraction
- ❑ Data Formatting

Event Building

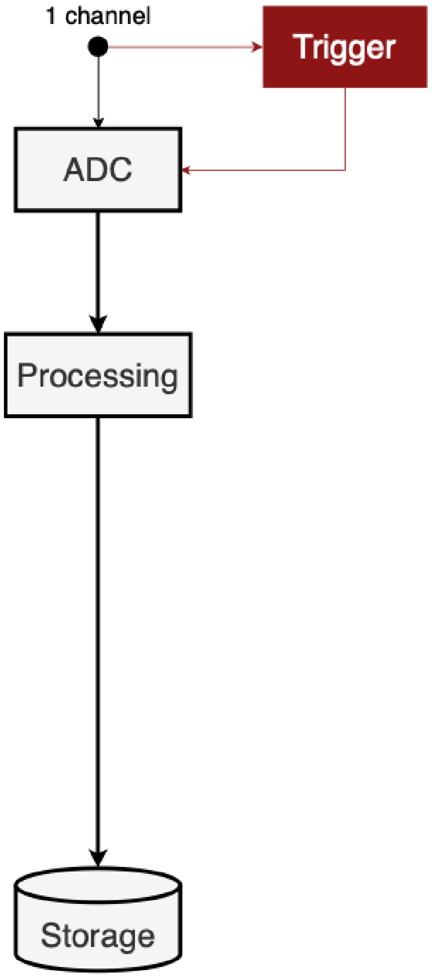
- ❑ Event Assembly

Event Filtering

- ❑ Event Rejection

Event Logging

- ❑ File Storage



Scaling up (2)

Front End

- ❑ Data Digitization

Readout

- ❑ Data Extraction
- ❑ Data Formatting

Event Building

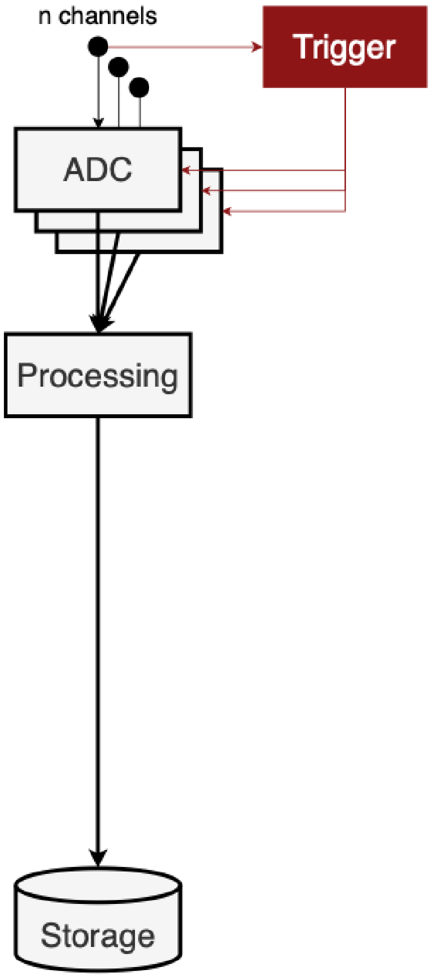
- ❑ Event Assembly

Event Filtering

- ❑ Event Rejection

Event Logging

- ❑ File Storage



Scaling up (3)

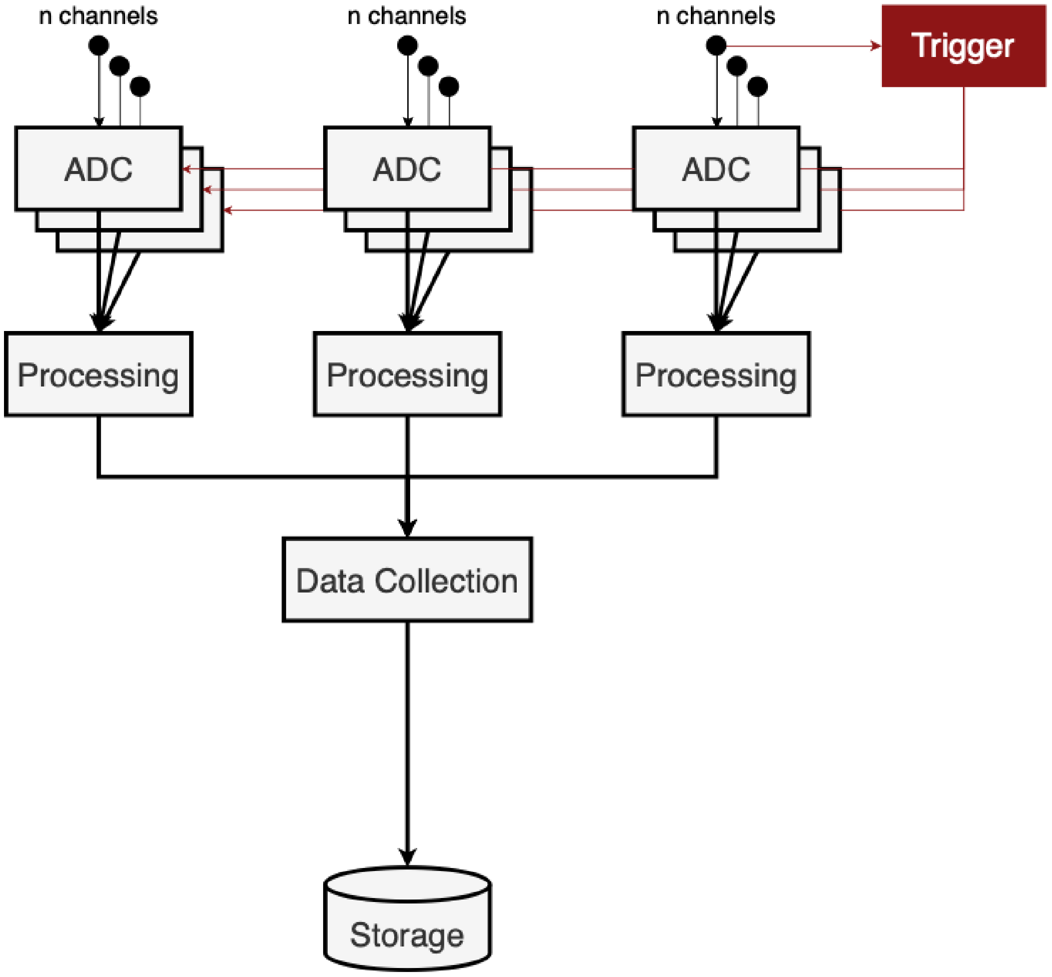
Front End
- ❑ Data Digitization

Readout
- ❑ Data Extraction
- ❑ Data Formatting

Event Building
- ❑ Event Assembly

Event Filtering
- ❑ Event Rejection

Event Logging
- ❑ File Storage



Scaling up (3)

Front End

- ❑ Data Digitization

Readout

- ❑ Data Extraction
- ❑ Data Formatting

Event Building

- ❑ Event Assembly

Event Filtering

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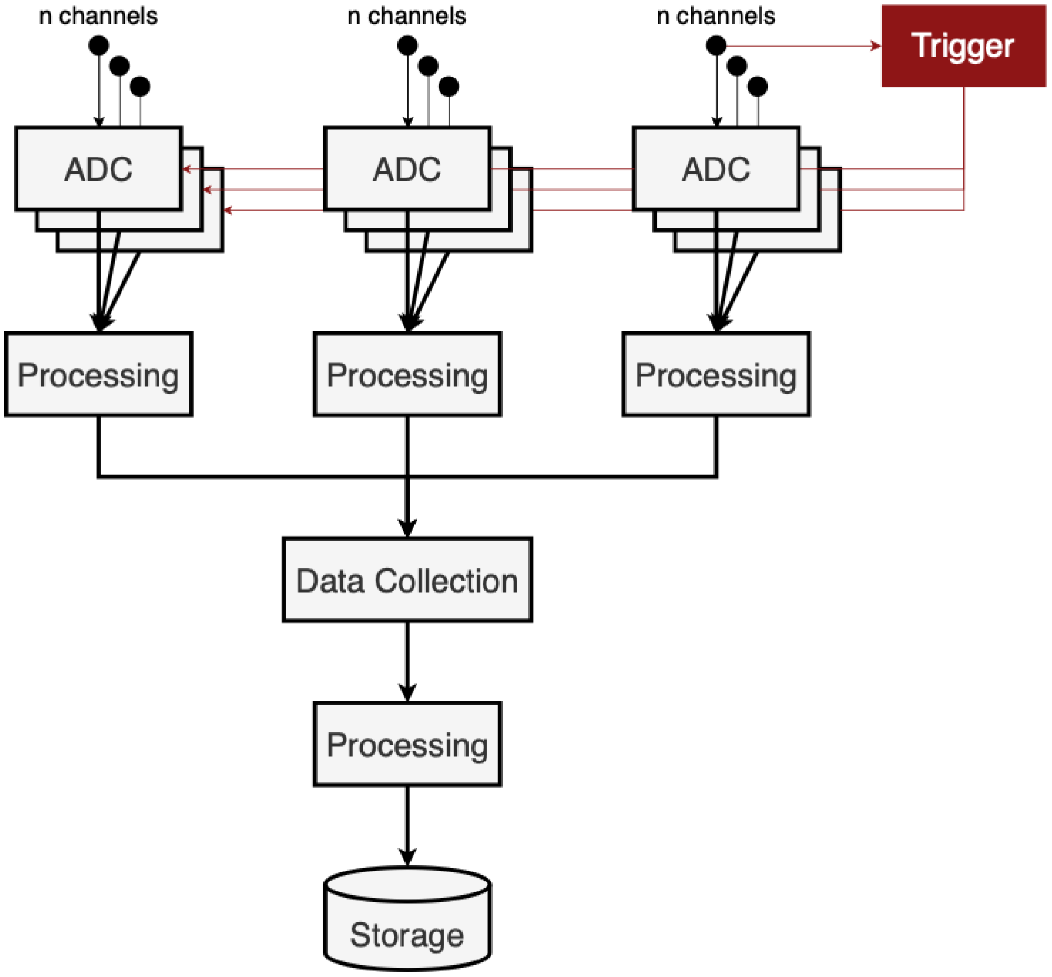
Event Logging

- ❑ File Storage



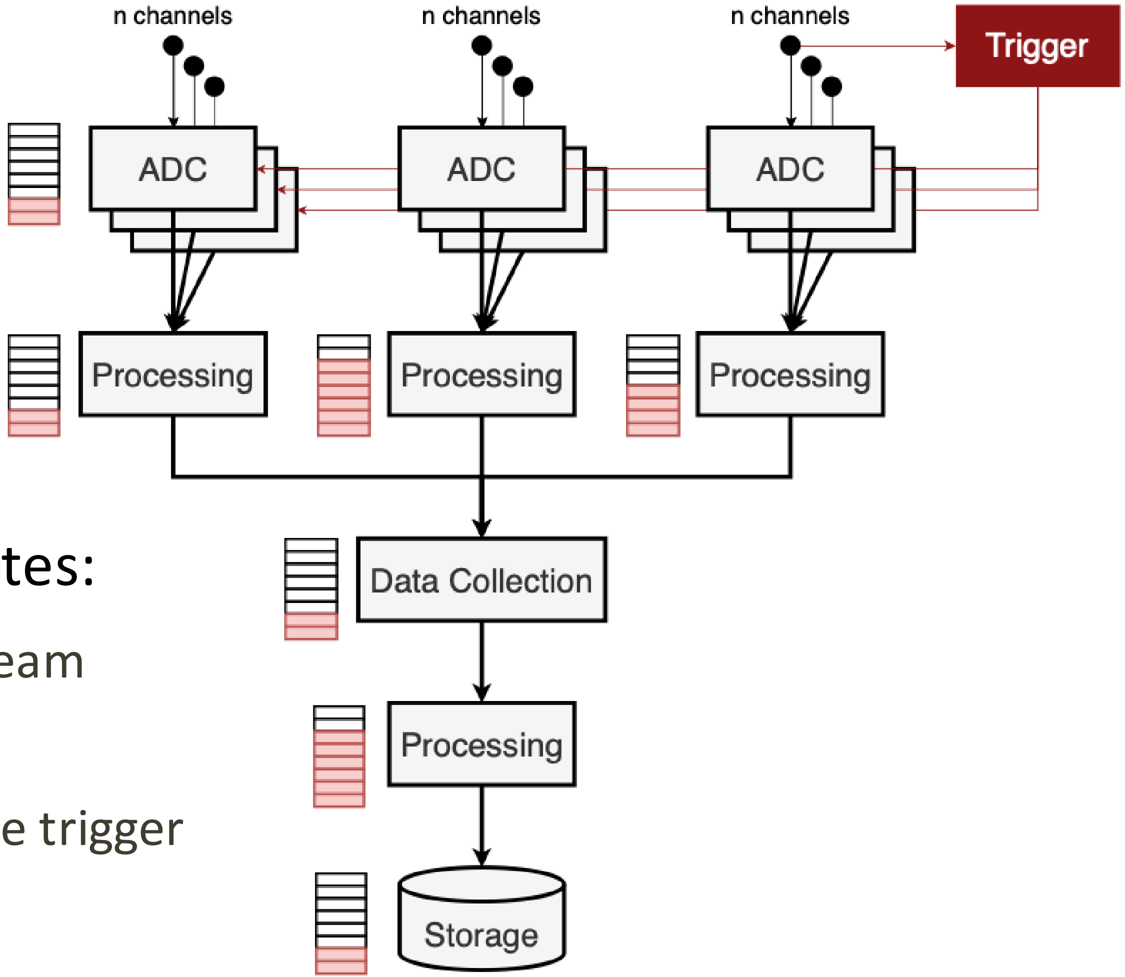
Scaling up (4)

Buffering at all levels

- ❑ DAQ conceptualized as a multilevel buffering system

If system/buffer saturates:

- ❑ Exerts "pressure" upstream (backpressure)
- ❑ Up to exert "busy" in the trigger



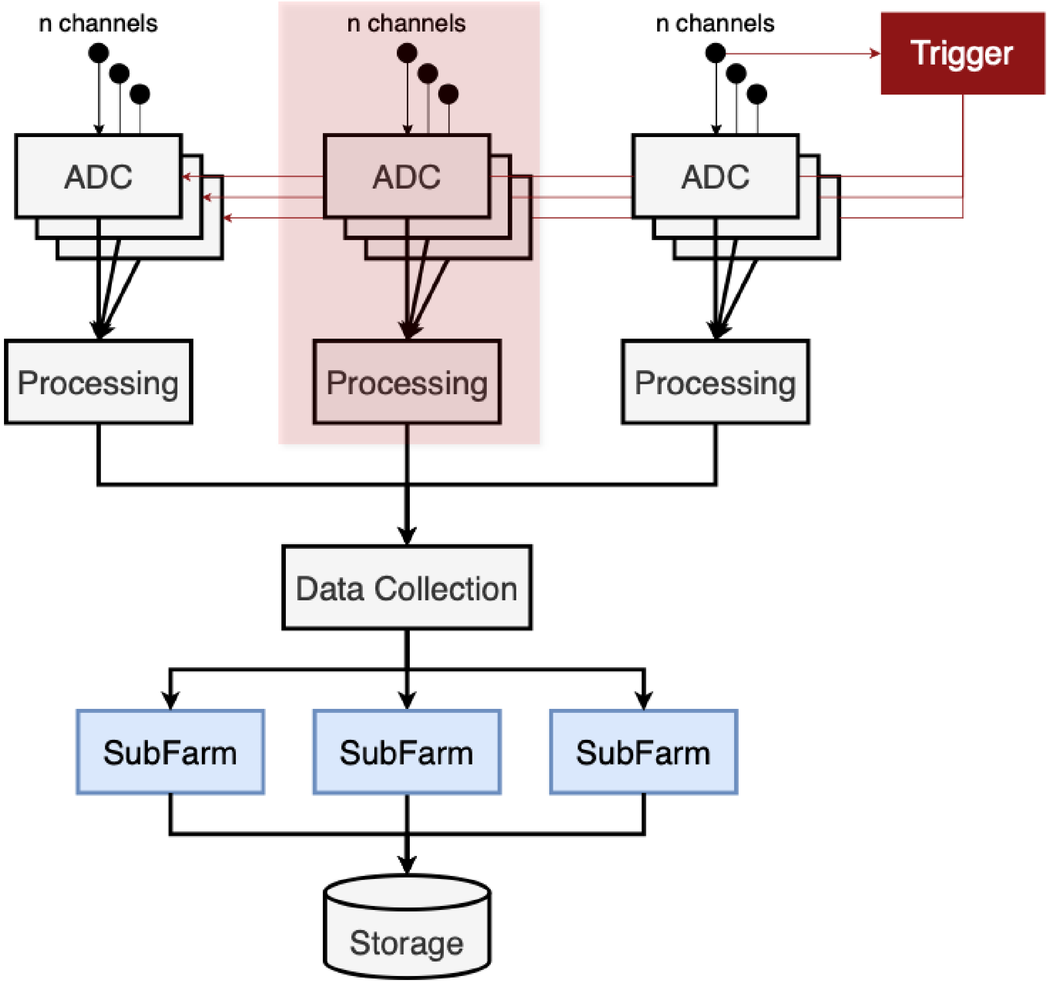
Scaling up (5)

DAQ building blocks

- ❑ Readout crates
- ❑ HLT filter units / racks
- ❑ Event builder units
- ❑ DAQ “slices”

This allows for easier DAQ reconfigurations

- ❑ Central DAQ for regular data taking
- ❑ Alternate DAQ for dedicated tests



Trigger and DAQ at the CMS LHC

Large Hadron Collider

Magnets

- 8.4 Tesla, superliquid He at 1.9K

Protons

- Speed: 0.999999991 c

Proton bunches

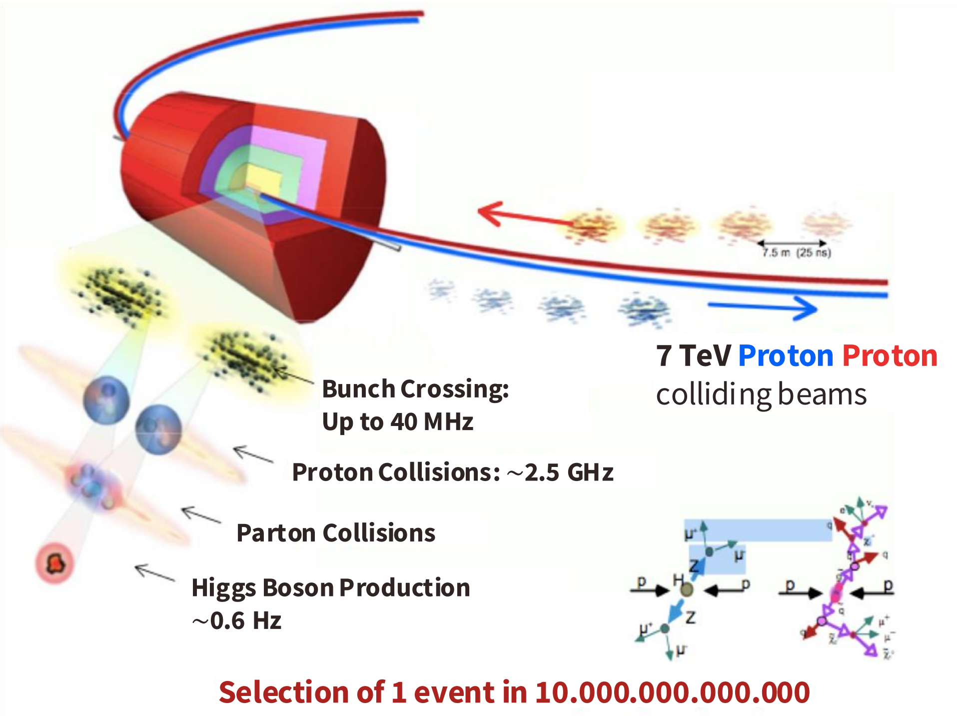
- 1.15 10^{11} protons
- 25 ns (7.5 m) distance

Proton beams

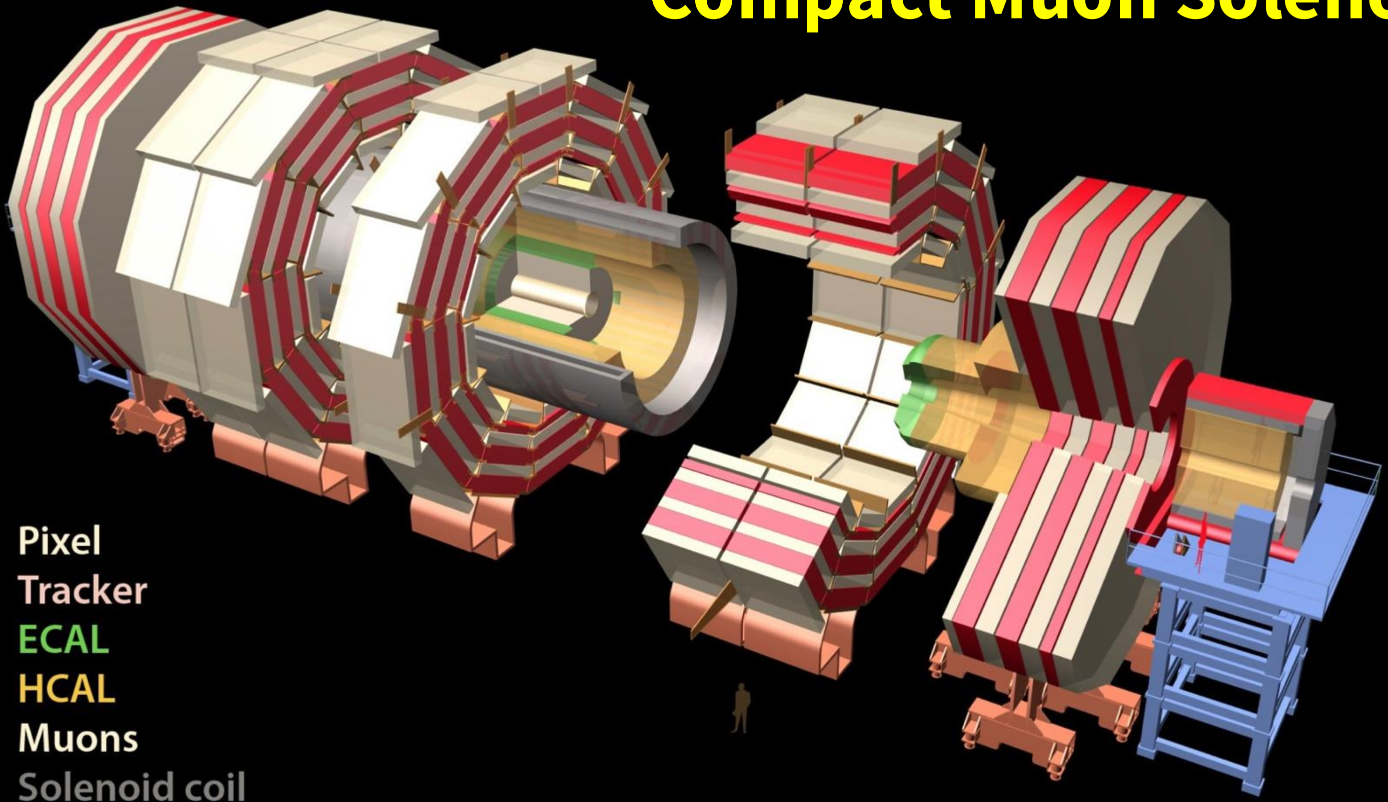
- Up to 2808 bunches (2448 bunches in 2025)
- 360 MJ / beam
  - Truck (36 t) at 500 km/h (!)

Data taking

- 1.6 Tb/s (~7 GB/s saved in disk)

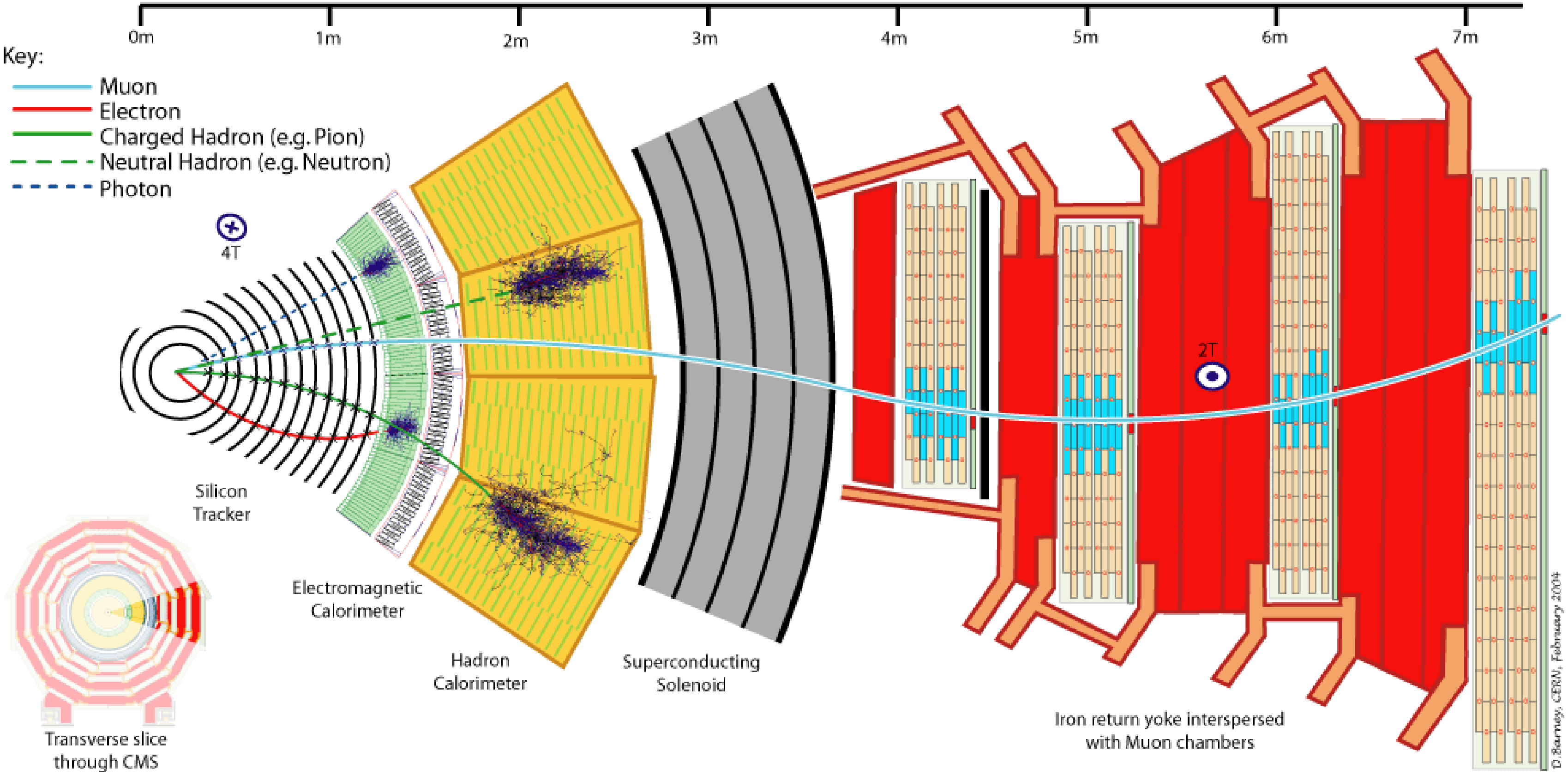


Compact Muon Solenoid (CMS)



Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

Particles in the CMS detector



CMS Trigger and DAQ

CMS cannot readout the full raw detector data (RAW) in all bunch crossings (~27 MHz)

Level-1 Trigger (L1T)

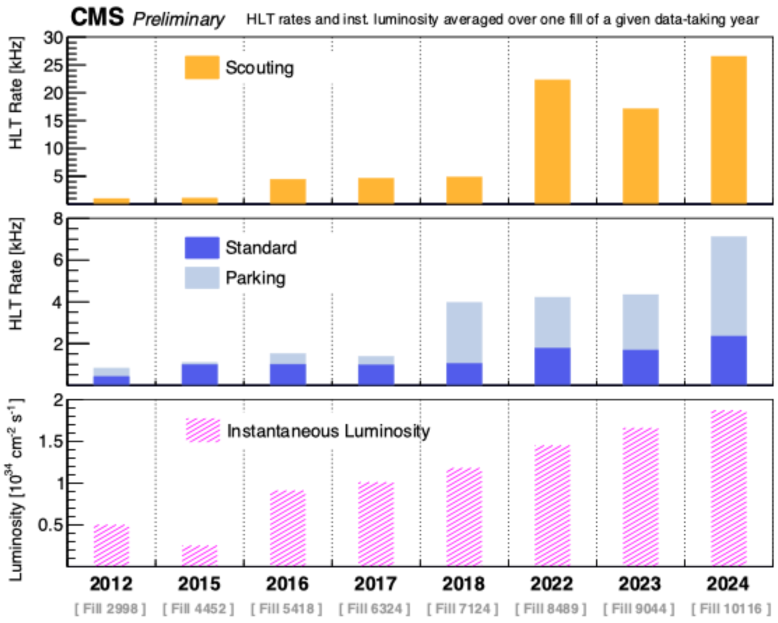
- Reduces rate from ZeroBias rate (~27 MHz) to ~110 kHz
- Select events already using physics criteria (e.g. "single high-p_T isolated muon")

At ~110 kHz the DAQ reads out the full RAW event (~1MB) [~100 GB/s]

- CMS cannot store all these data (disk/tape limit) nor reconstruct them (~20 s/event single CPU)

High Level Trigger (HLT)

- Performs a simplified event reconstruction using the full RAW event
- Reduces the rate from ~110 kHz to ~7 kHz
- "Standard" streams + Data Parking + Data Scouting



The Level-1 Trigger at CMS

Data from all the detectors is buffered locally for < 4μs

- Events are pipelined and each event is examined in a fixed time
- Use custom electronics to perform simple analysis

Level-1 Trigger

- Reduces rate from ~27 MHz → ~110 kHz
- Receives data from Calorimeters and Muon systems only

Implemented in custom optical hardware processors

- Uses field programmable gate arrays (FPGAs)
- Operates synchronously to the LHC clock (40 MHz)

Read-out decision based on programmable algorithms

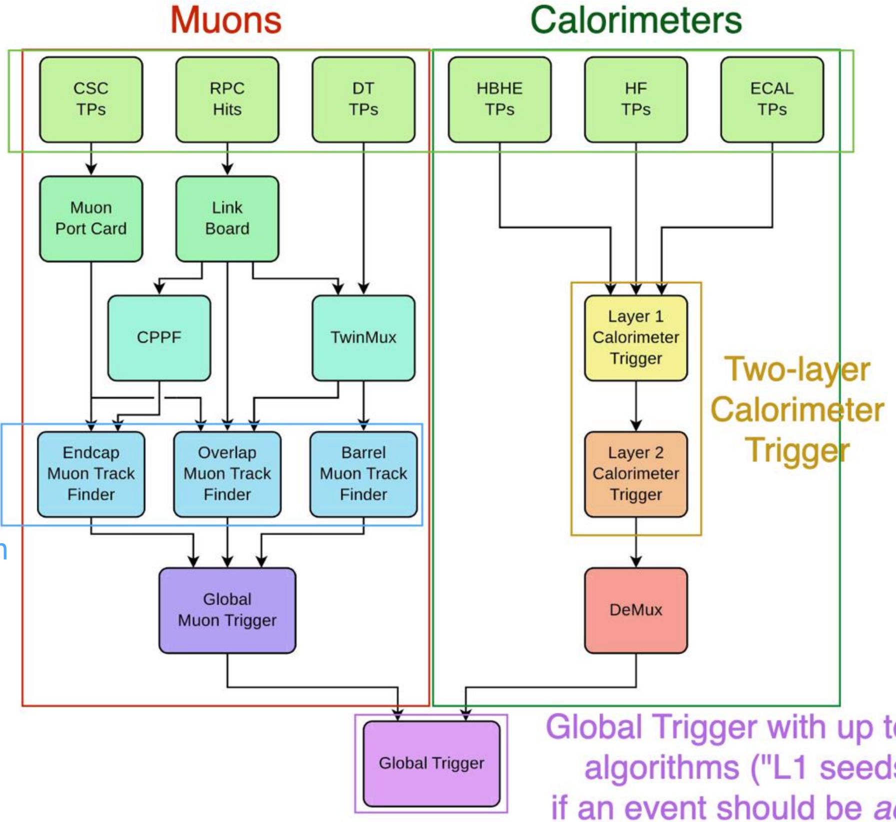
- Up to 512 L1T algorithms ("seeds")

CMS Level-1 Trigger Diagram

Trigger Primitives or Hits

Regional Track Finders

- Reconstruct muon tracks from hits or trigger primitives
- Assign η, φ, p_T and quality to each candidate

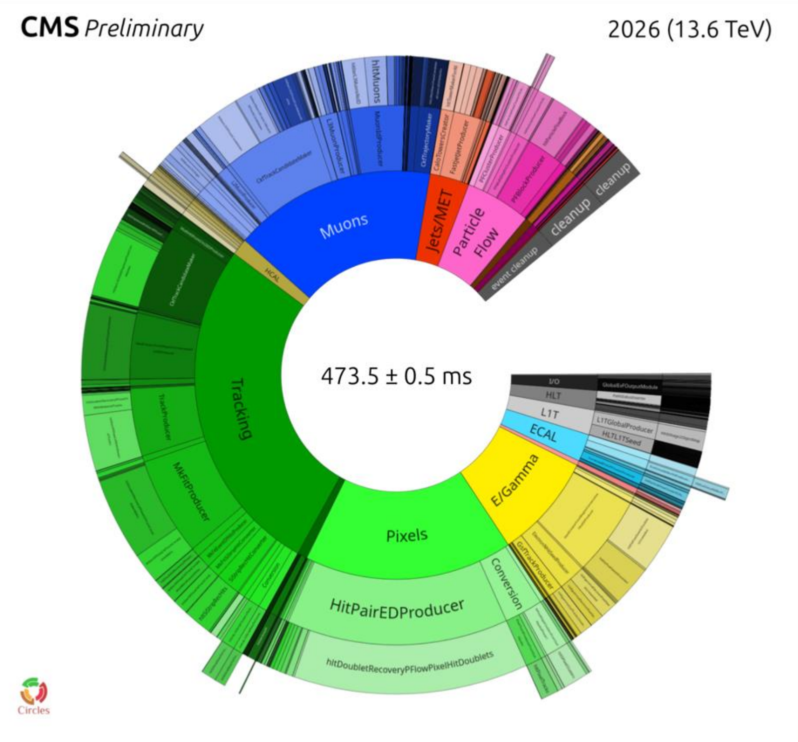


Calo Layer 1:
- Combines ECAL and HCAL inputs
- Position- & energy-dependent calibrations

Calo Layer 2
- Find jets, taus, and e/gamma candidates, computes energy sums
- Object-based pileup subtraction, isolation, calibrations

Global Trigger with up to 512 possible algorithms ("L1 seeds") to define if an event should be *accepted* or not

The High-Level Trigger at CMS



Full detector readout, full granularity

- ~110 kHz input rate (from Level-1 Trigger)

Implementation

- C++ software: CMSSW
  - Same as used for simulation and offline analyses
- Running on a cluster of GPU-equipped commercial PCs
- ~700 HLT algorithms ("paths")
- Quasi-online, input buffer 1-2 minutes

Performance

- ~470 ms average processing time to take a decision
- Peak throughput of ~9 GB/s aggregated over all streams
- ~2.5 kHz average output rate in "Standard" streams
  - Limited by offline storage & processing resources

The Data Acquisition at CMS

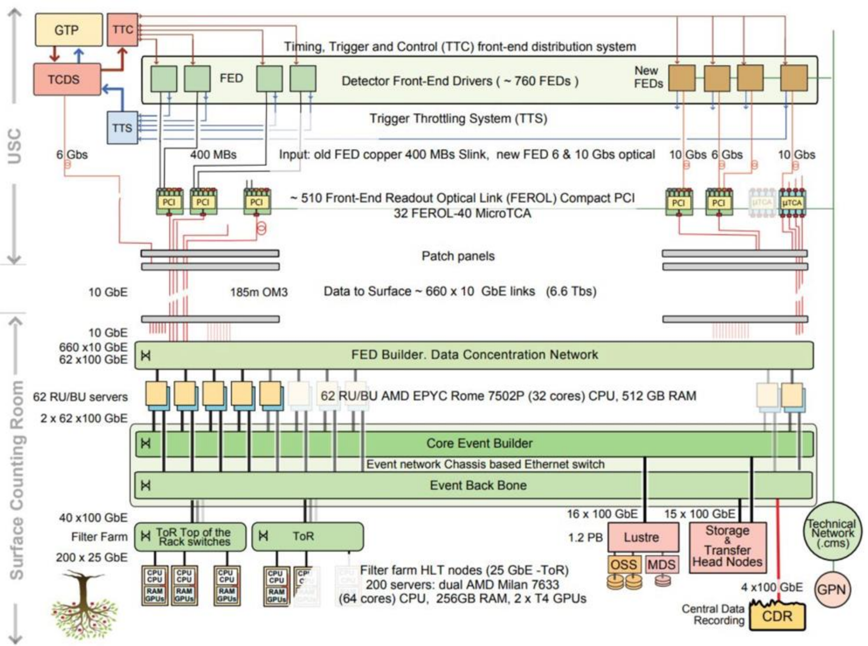
Readout in underground cavern

- Controlled by ~ 760 detector Front-End Drivers (FEDs)
- Linked to ~ 540 Front-End Readout Optical Links (FEROLs)

Data to surface: 6.6 Tb/s

Folded event building

- Readout and builder unit appliances housed in the same physical machine
- Advantage: bidirectional use of network links
- More demanding on individual PC CPU and I/O performance



A Trigger Example: Single Muon Trigger

L1 muon

- Direct copy from the L1T object

L2 muon

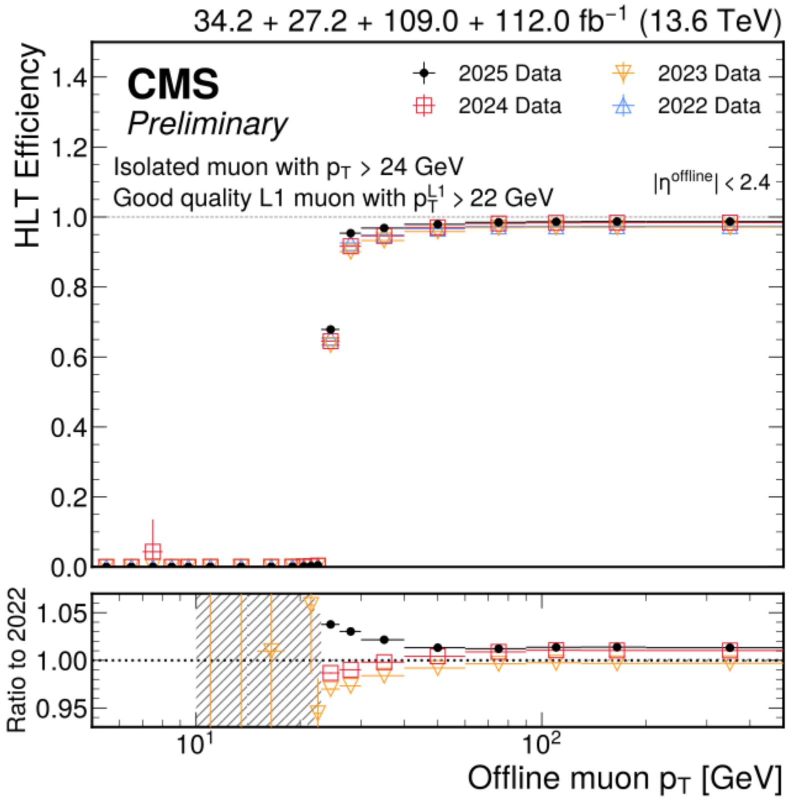
- HLT object reconstructed exclusively from hits in the muon system

L3 muon

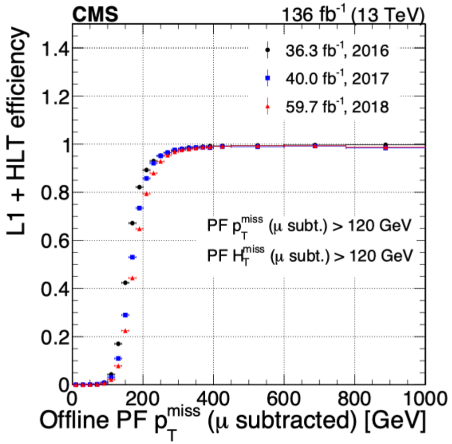
- HLT object reconstructed from hits both from the muon system and the silicon tracker
- Two flavours:
  - Inside out: seeded by tracks in the pixel detector
  - Outside in: seeded by L2 muons
- IO + OI combination, cleaning

Isolated muon

- Set of criteria that require muons to not have particles reconstructed near them
- Useful for muons from W and Z boson decays



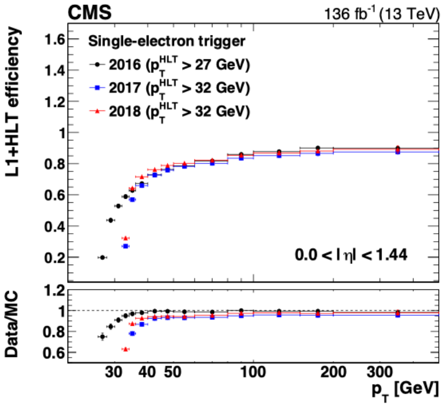
Measuring the Trigger Efficiency



Need to get an unbiased data sample.

Two main methods:

- Orthogonal trigger method
  - Select events with a trigger that is essentially independent of the one you want to measure
  - Example: select events with collected with a muon trigger, ask for a well-reconstructed muon, and check how many events pass missing p_T trigger
- Tag-and-probe
  - Profit from the presence of leptonic resonances (Z boson, J/ψ)
  - Identify with high certainty one lepton (tag) and check how many times the other lepton (probe) triggers



Conclusion

This is but the smallest introduction to the world of trigger and DAQ systems for High Energy Physics experiments.

Challenges in all areas

- Physics, electronics and computing

Important to follow technology development

- 10 years between system design and implementation

Always try new approaches and be bold

- Triggerless systems, data analysis with trigger objects, …

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