Electronics, Trigger and Data Acquisition

Summer Student Programme 2015, CERN

Part 1

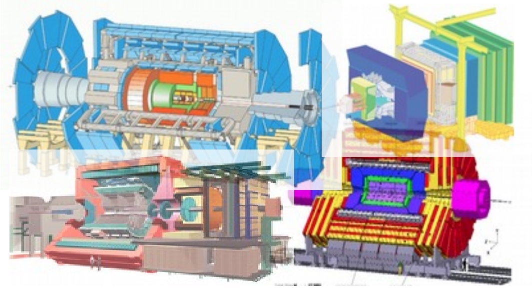
W.Vandelli CERN/PH-ADT
Wainer.Vandelli@cern.ch

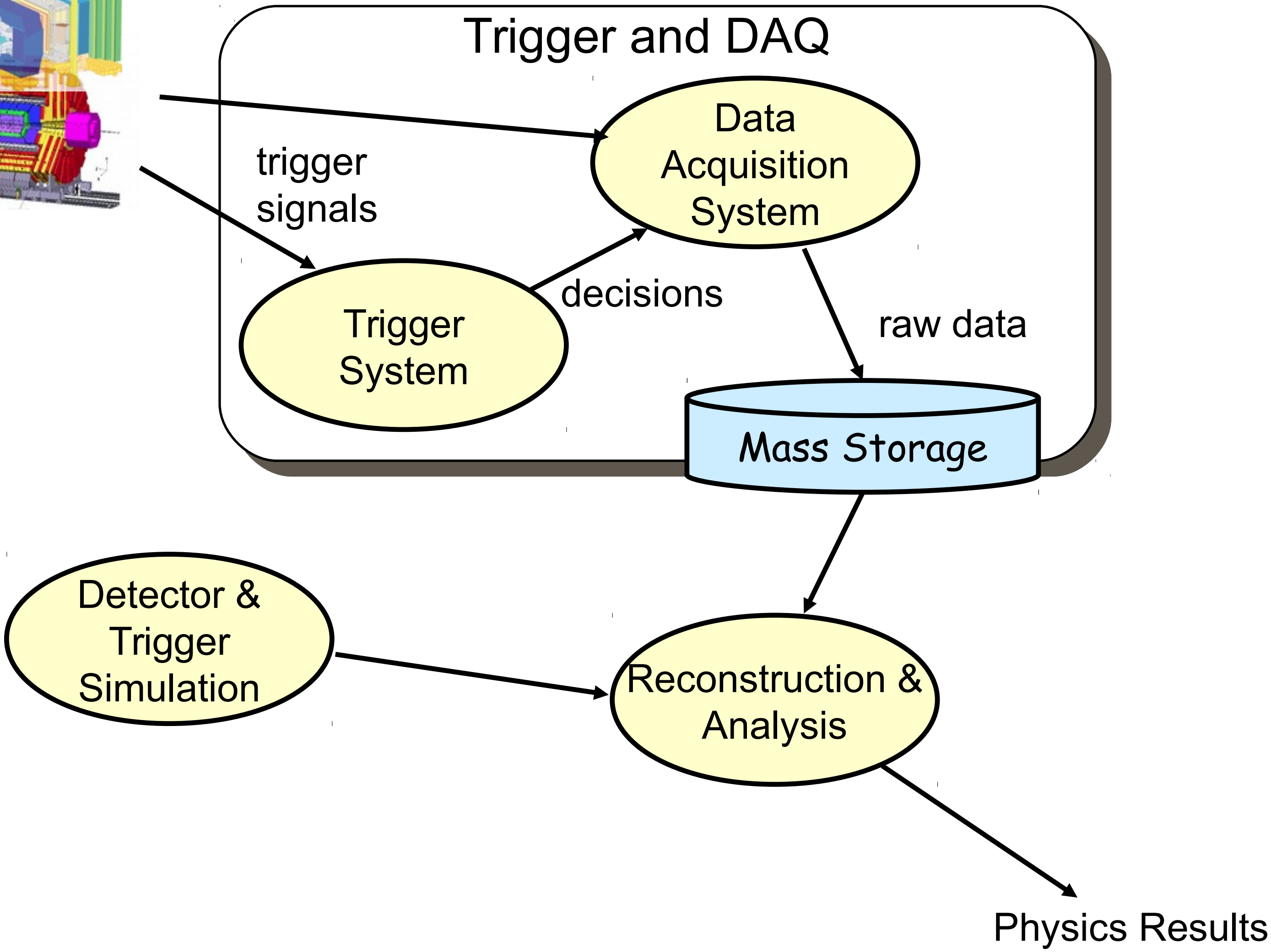
Introduction

- ➔ Data acquisition is an **alchemy** of electronics, computer science, networking, physics
  - …, resources and manpower matter as well, …
- ➔ I will mostly refer to DAQ in High-Energy Physics
- ➔ Topics are pretty much correlated → You will experience this through the lecture non-linearity

Material and ideas from my predecessors (N.Neufeld and C.Gaspar), the “Physics data acquisition and analysis” lessons given by R.Ferrari at the University of Parma, Italy, “Analog and Digital Electronics for Detectors” of H. Spieler and all lectures of ISOTDAQ schools, in particular M.Joos and C.Schwick

General Overview





➔Overall the main role of Electronics Trigger & DAQ is to process the signals generated in a detector, storing the interesting information on a permanent storage

Electronics

What is needed for?

➔ Collect electrical signals from the detector. Typically a short current pulse

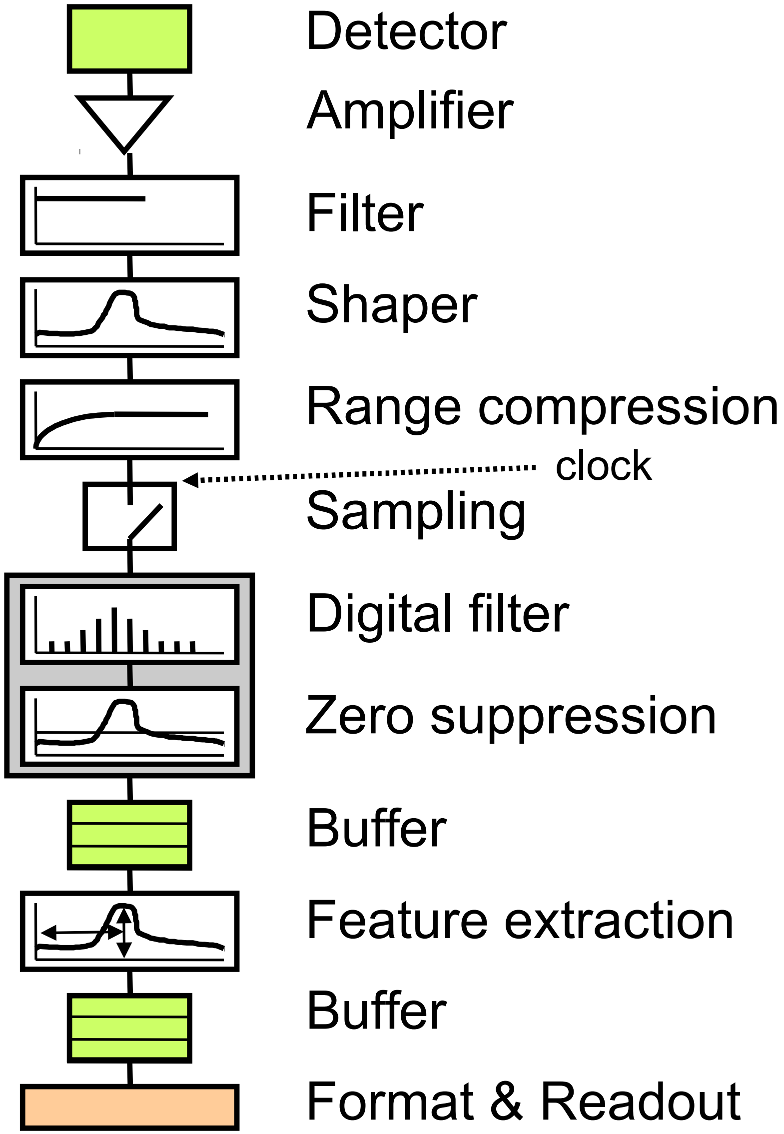
➔ Adapt the signal to optimize different, **incompatible**, characteristics → Compromise

- minimum detectable signal
- energy measurement
- signal rate
- timing
- insensitivity to pulse shape

➔ Digitize the signal

- allow for subsequent processing, transmission, storage using digital electronics → Computers, Networks, …

Read-out chain


Detector

Amplifier

Filter

Shaper

Range compression

clock

Sampling

Digital filter

Zero suppression

Buffer

Feature extraction

Buffer

Format & Readout

➔ Front-end electronics very specialized

- custom build to match detector characteristics

➔ Cannot discuss all design and architecture details

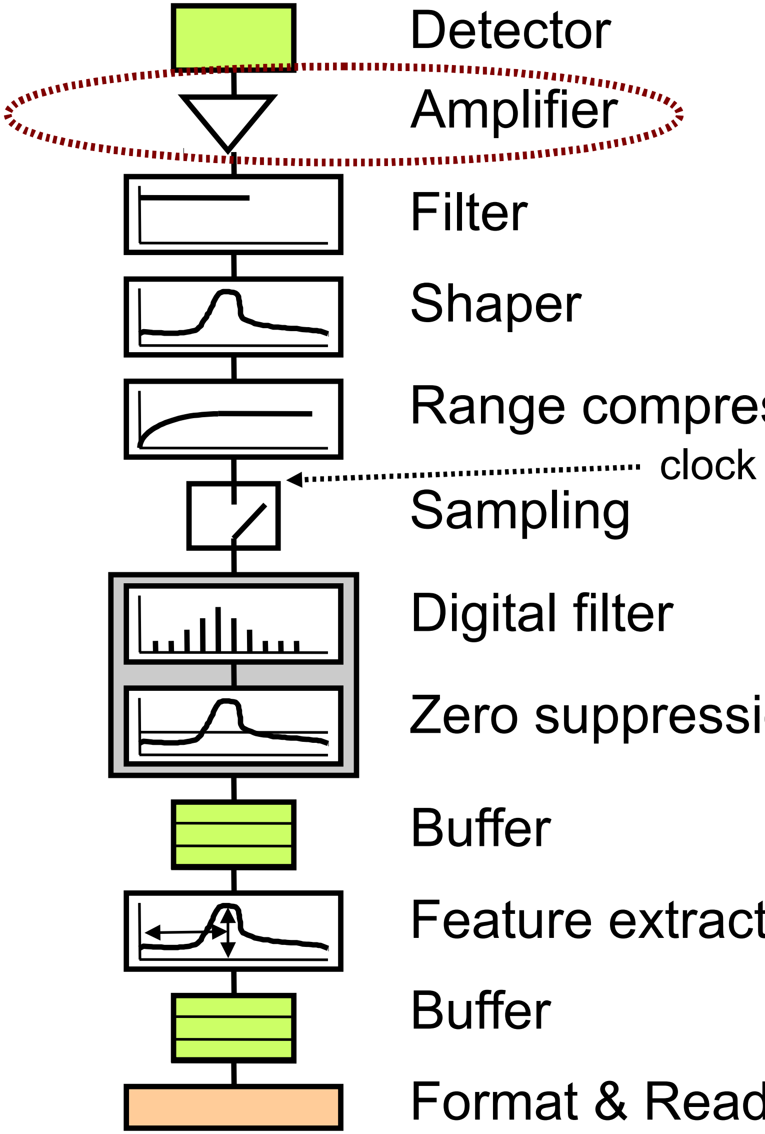
- if you are into electronic design you already know more than me

➔ Find yourself dealing or choosing commercial electronics

- provide you with base guidelines

➔ Selected functions and principles

Read-out chain



Detector

Amplifier

Filter

Shaper

Range compression

clock

Sampling

Digital filter

Zero suppression

Buffer

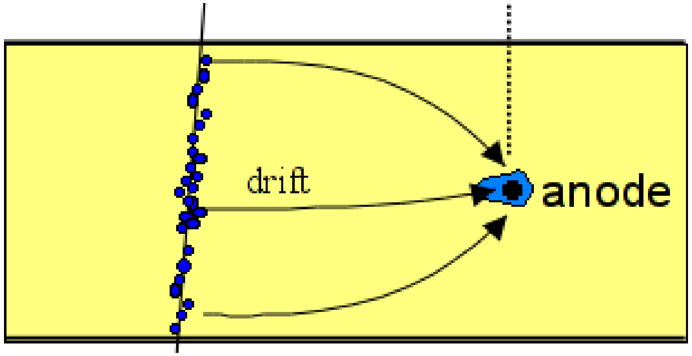
Feature extraction

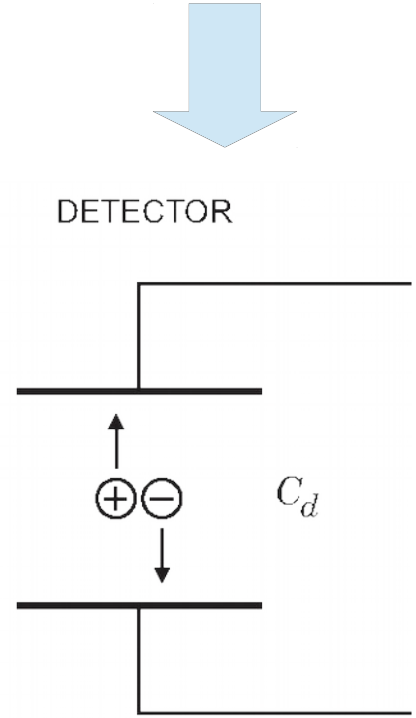
Buffer

Format & Readout

What is a signal?

- ➔ Detector electrically represented by a capacitor Cd
  - more realistic scheme will include other contributions
- ➔ The interaction with a passing particle generate a small current pulse i_s due to the release of energy E





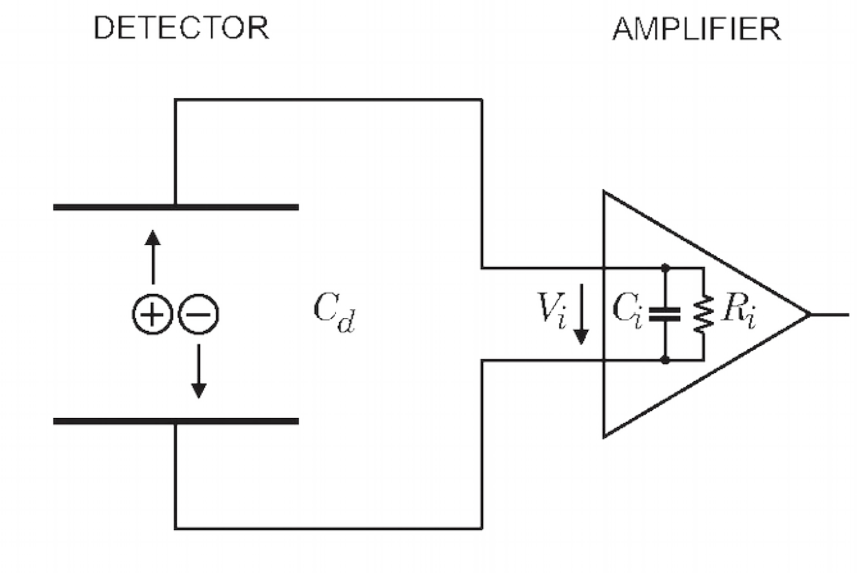
$$E \propto Q_s = \int i_s(t)dt$$

- ➔ Current pulse duration can range from 100 ps to O(10) μs

Amplification

➔ Signals are possibly very small

- improve signal resolution, adapt it to next stages
- improve signal-to-noise ratio …



Using a simple voltage amplifier, the sensed **input voltage V_i depends on the detector capacitance.**

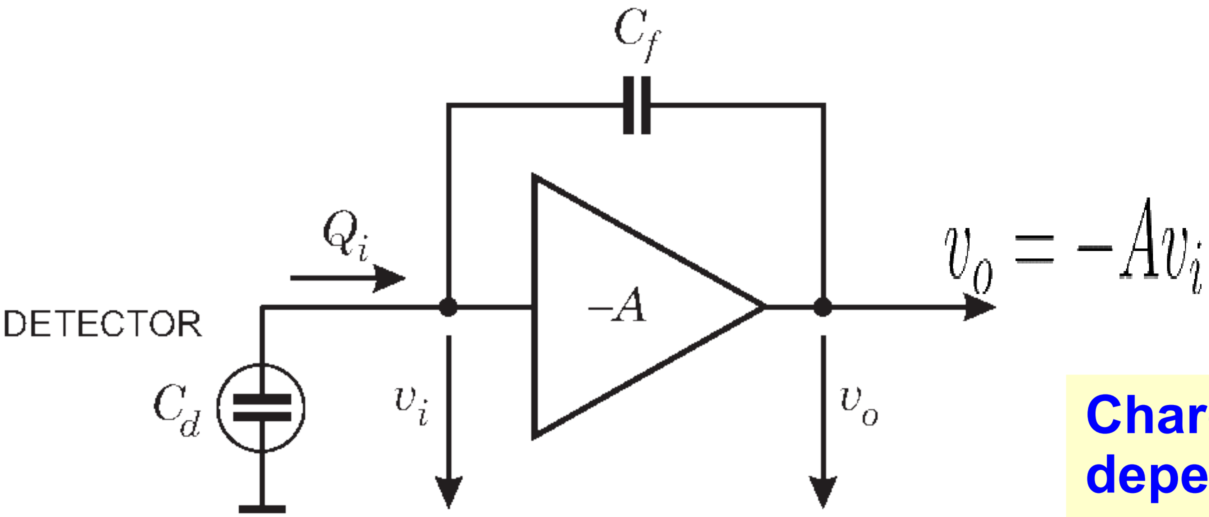
Detector capacitance could be a function of the operation point (e.g. high voltage) and/or detector dimension.

⇩

Additional **calibration** efforts

$$V_i = \frac{Q_S}{C_d + C_i}$$

Charge-Sensitive Amplification



Charge amplification only depends on a well-controlled component

$$A_Q = \frac{v_o}{Q_i} = \frac{Av_i}{C_f(A+1)v_i} = \frac{A}{A+1}\frac{1}{C_f} \approx \frac{1}{C_f} \quad (A \gg 1)$$

$$\frac{Q_i}{Q_s} = \frac{C_i}{1 + \frac{C_d}{C_i}}$$

Large input capacitance to improve charge sharing

Signal-to-Noise ratio

➔Improving signal-to-noise ratio improves the minimum detectable signal

➔Electronic noise does not necessarily dominate in every measurements

$$\Delta E = \sqrt{\Delta E^2{}_{fluc} + \Delta E^2{}_{noise}}$$

Fluctuations due to physical detection process (e.g. energy deposition) or detector readout (e.g. photomultiplier)

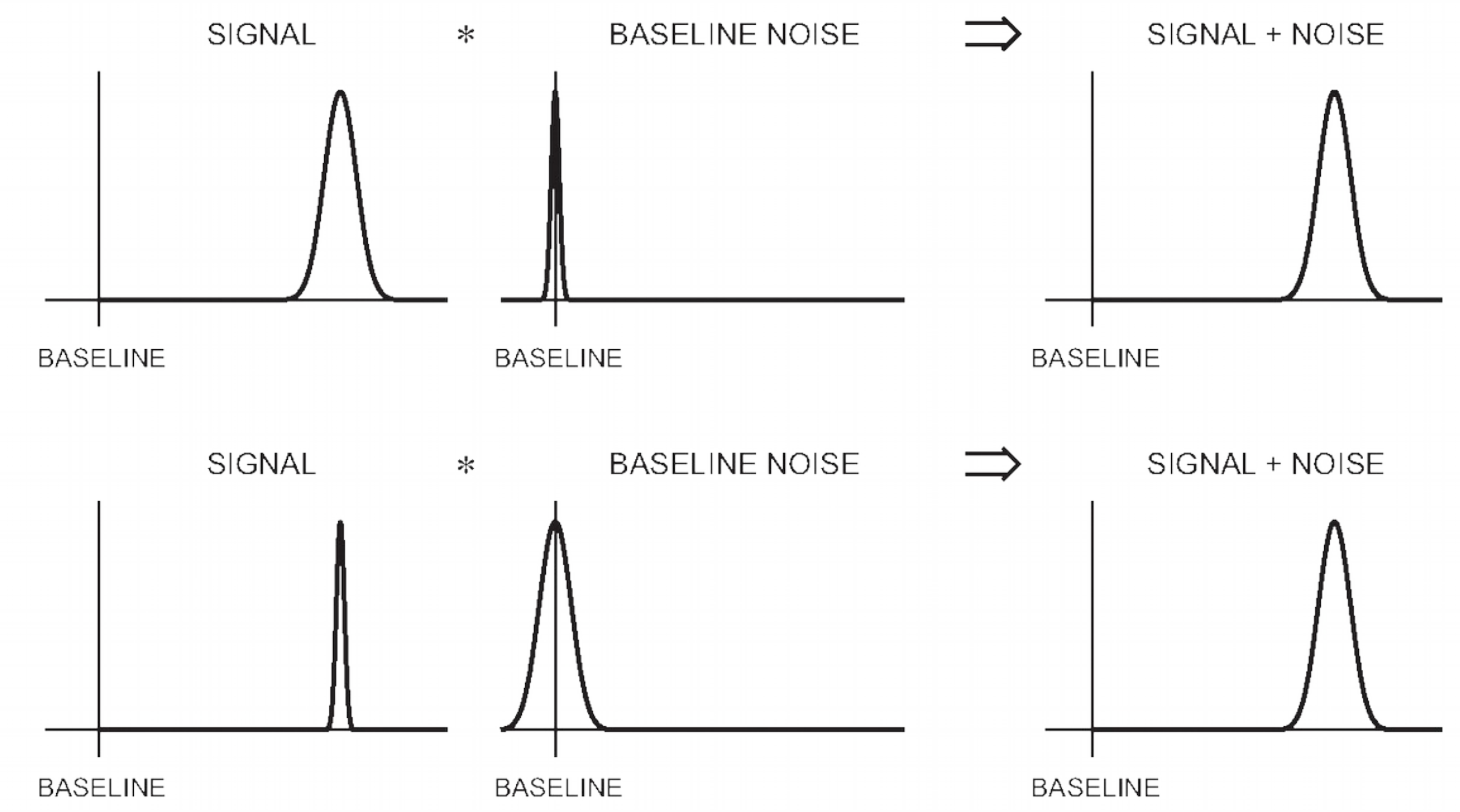
Electronic noise

- Thermal noise: velocity fluctuations in charge carriers
- Shot noise: fluctuations in carrier number (e.g. diode barrier crossing)

Signal-to-Noise ratio

- ➔Improving signal-to-noise ratio improves the minimum detectable signal
- ➔Electronic noise does not necessarily dominate in every measurements

$$\Delta E = \sqrt{\Delta E^{2}{}_{fluc} + \Delta E^{2}{}_{noise}}$$

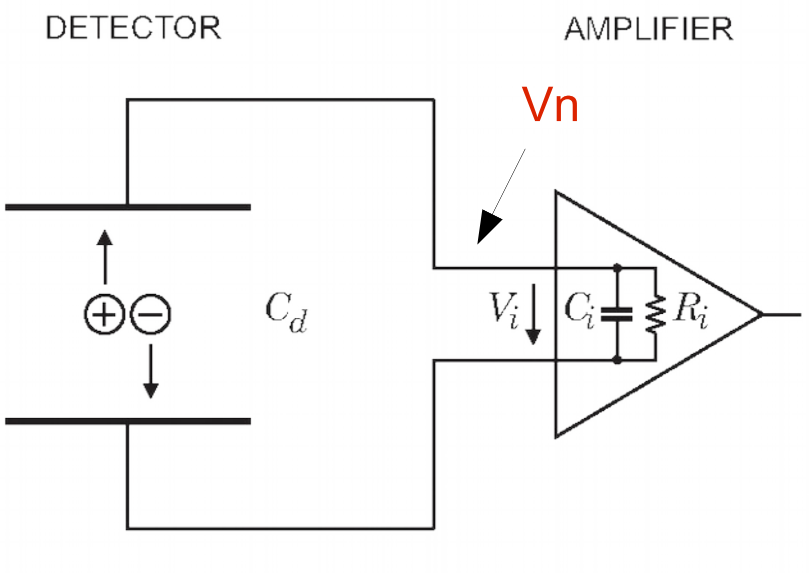


S/N needs optimization

SNR and capacitance

- Given a signal charge Qs

$$V_s = \frac{Qs}{C_d + C_i}$$



- Assuming an input noise Vn

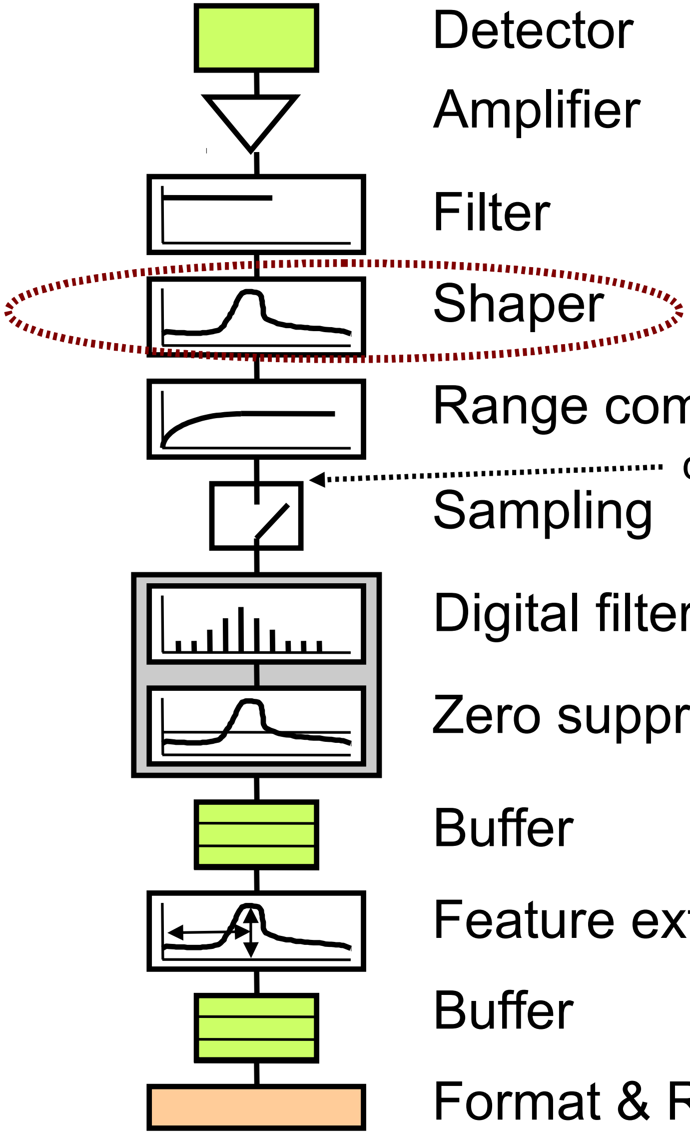
$$\frac{V_s}{V_n} = \frac{Q_s}{V_n \underbrace{(C_d + C_s)}}$$

SNR inversely proportional to input capacitance

→

Thick detectors normally provide larger signals **and noise**

Read-out chain



Detector

Amplifier

Filter

Shaper

Range compression

clock

Sampling

Digital filter

Zero suppression

Buffer

Feature extraction

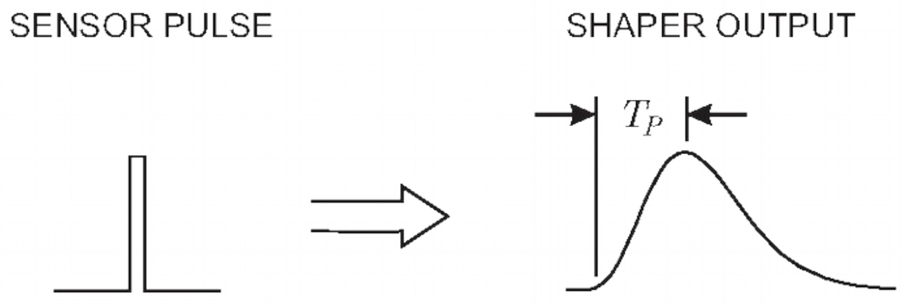
Buffer

Format & Readout

Pulse shaping

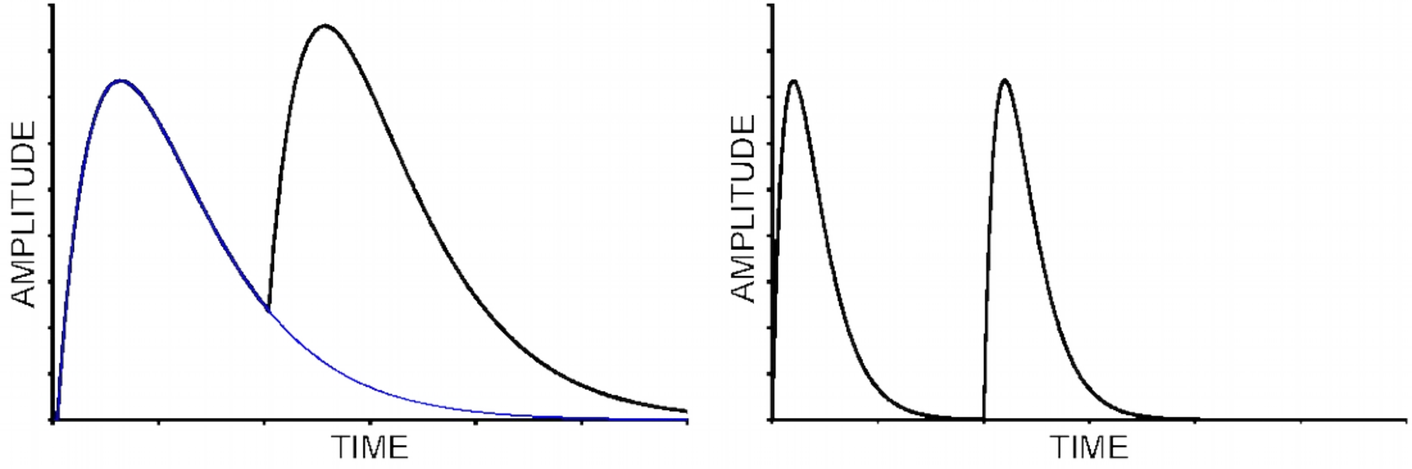
➔Reduce signal bandwidth → improve SNR

- fast rising signals have large bandwidth
- shaper broadens signals



➔Limit pulse width → avoid overlap of successive pulses

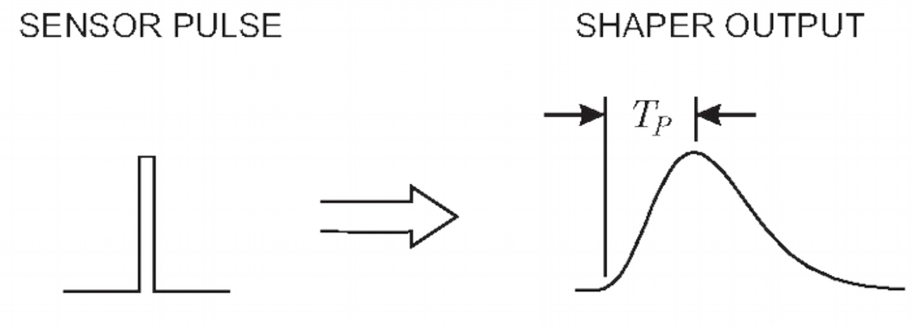
- increase maximum signal rate at the cost of more noise



Pulse shaping

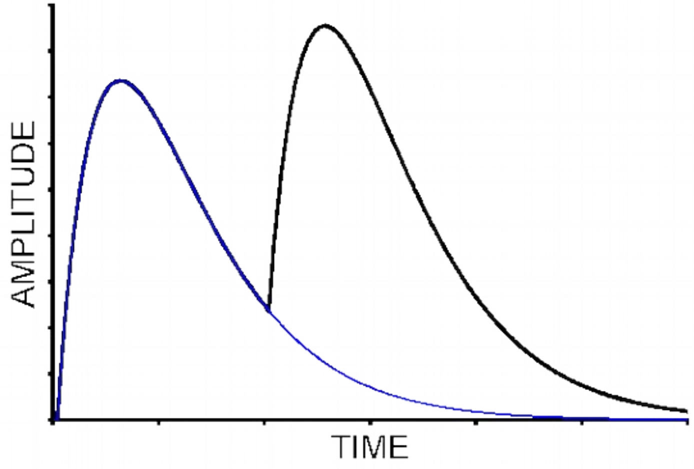
➔ Reduce signal bandwidth → improve SNR

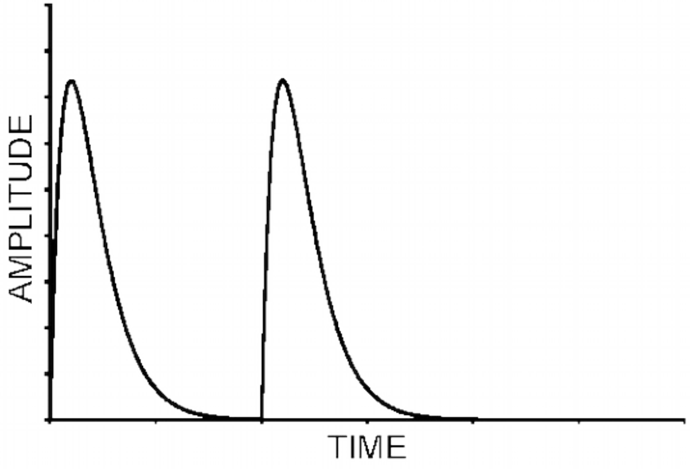
- fast rising signals have large bandwidth
- shaper broadens signals



➔ Limit pulse width → avoid overlap of successive pulses

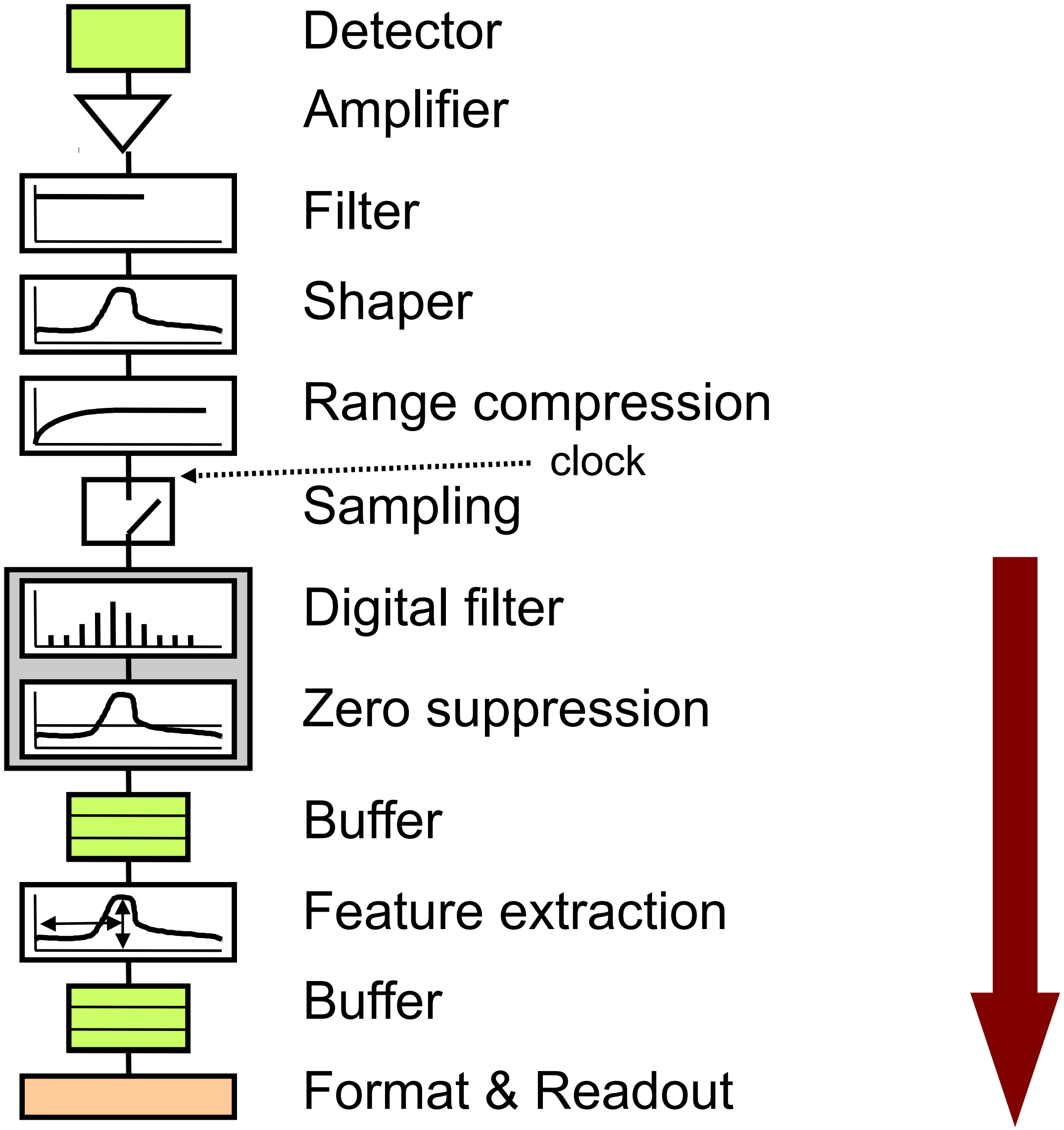
- increase maximum signal rate at the cost of more noise





Shaping is often a compromise

Read-out chain



Detector

Amplifier

Filter

Shaper

Range compression

clock

Sampling

Digital filter

Zero suppression

Buffer

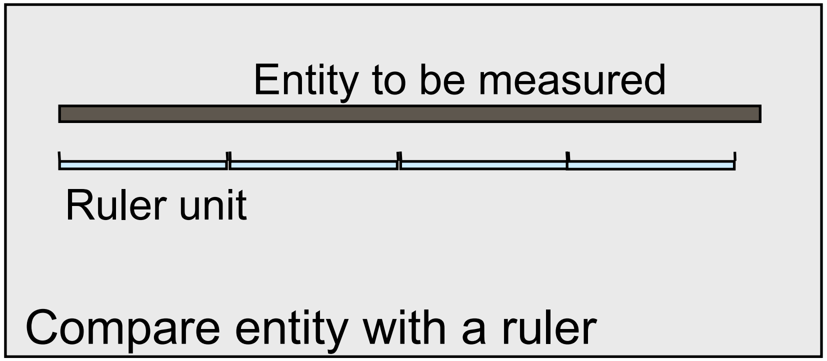
Feature extraction

Buffer

Format & Readout

Analog to digital conversion: introduction

➔Digitization → Encode a analog value into a binary representation

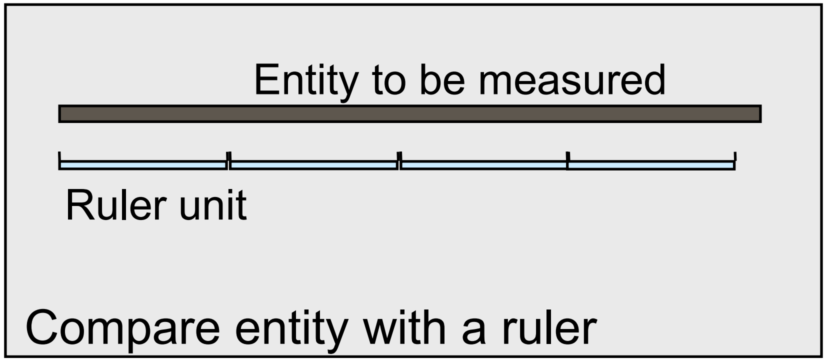


Compare entity with a ruler

Allow further processing and storage in digital electronics and computers

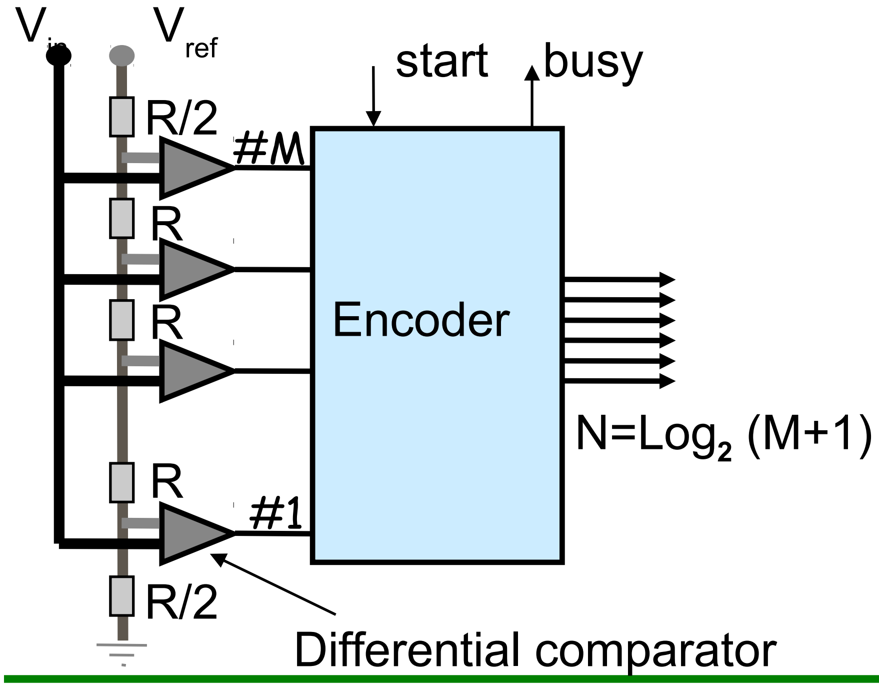
Analog to digital conversion: Flash ADC

➔Digitization → Encode a analog value into a binary representation



Compare entity with a ruler

Flash ADC



➔Flash ADC simplest and fastest implementation

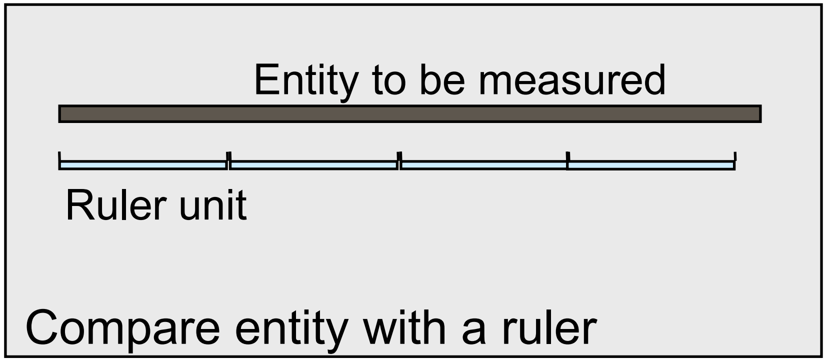
➔Performs M comparisons in parallel

- input voltage is compared with M fractions of a reference voltage: $V_{ref}/(2M) \rightarrow (M-1/2)V_{ref}/M$

➔Result is encoded into a compact binary form of N bits

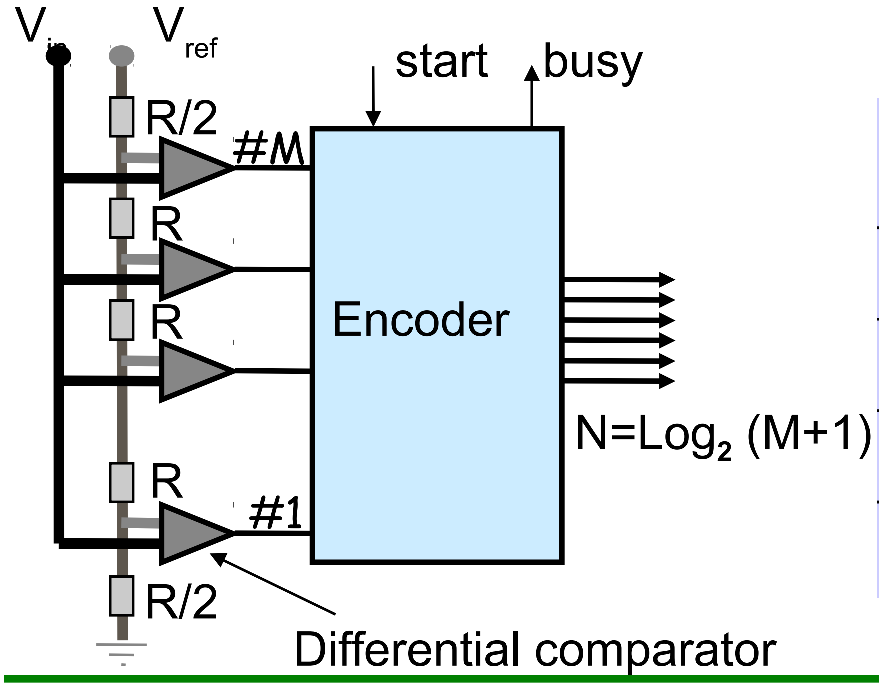
Analog to digital conversion: Flash ADC

- ➔Digitization → Encode a analog value into a binary representation



Compare entity with a ruler

Flash ADC



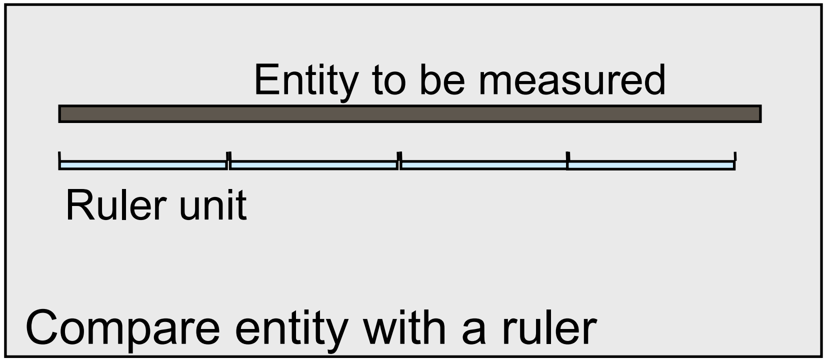
Differential comparator

- ➔Example M=3 → N=2

V_{in}/V_{ref}	Comparison results	Encoded form
<1/6	000	00
1/6≤ <3/6	001	01
3/6≤ <5/6	011	10
5/6≤	111	11

ADC Characteristics

- ➔Digitization → Encode a analog value into a binary representation

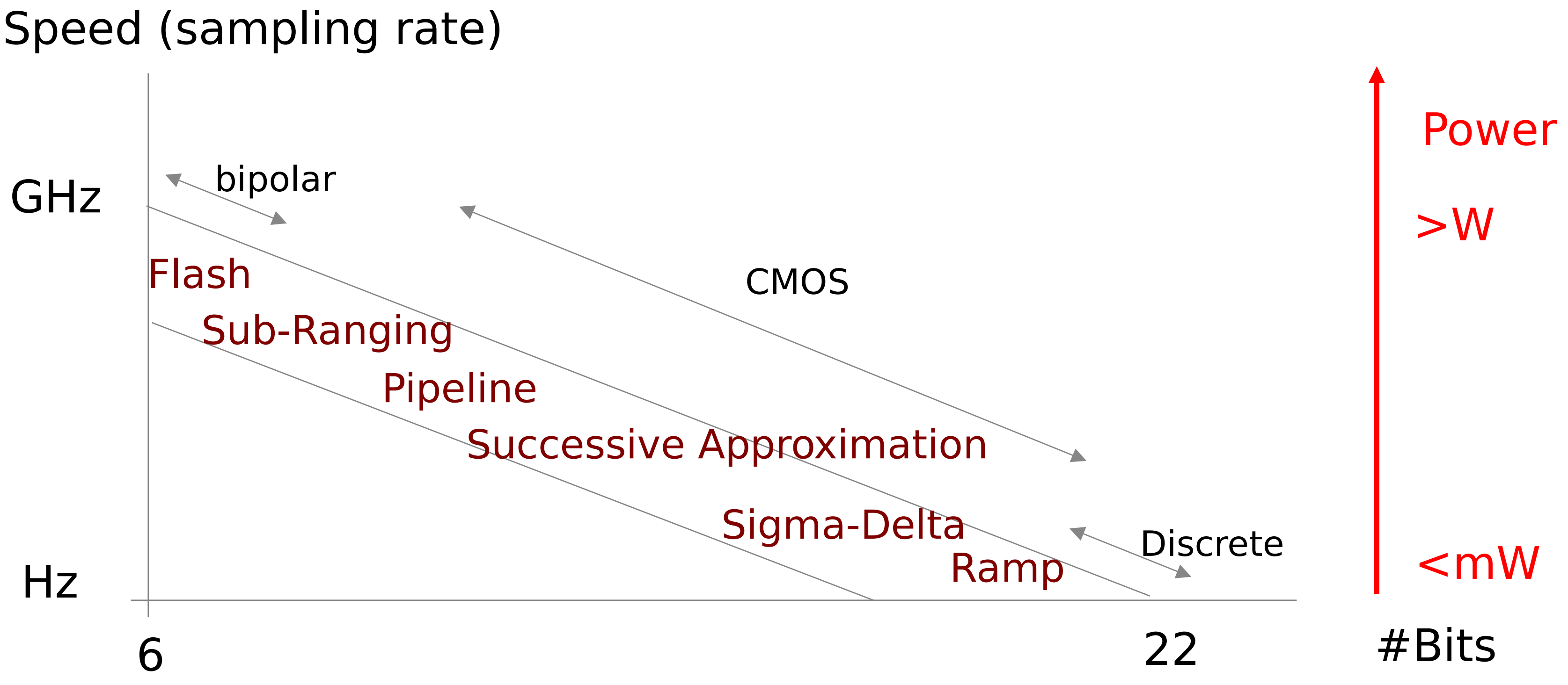


Compare entity with a ruler

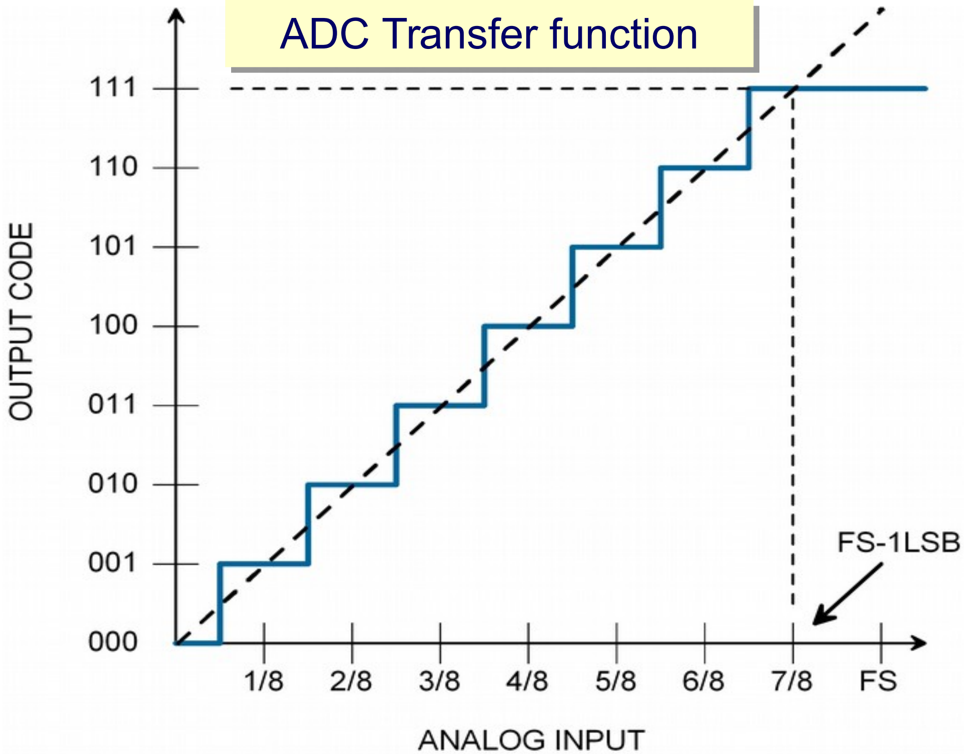
- ➔Resolution (LSB), the ruler unit: $V_{max}/2^N$
  - 8bit, 1V → LSB=3.9mV
- ➔Quantization error, because of finite size of the ruler unit: ±LSB/2
- ➔Dynamic range: V_{max}/LSB
  - N for linear ADC
  - >N for non-linear ADC
    - constant relative resolution on the valid input range

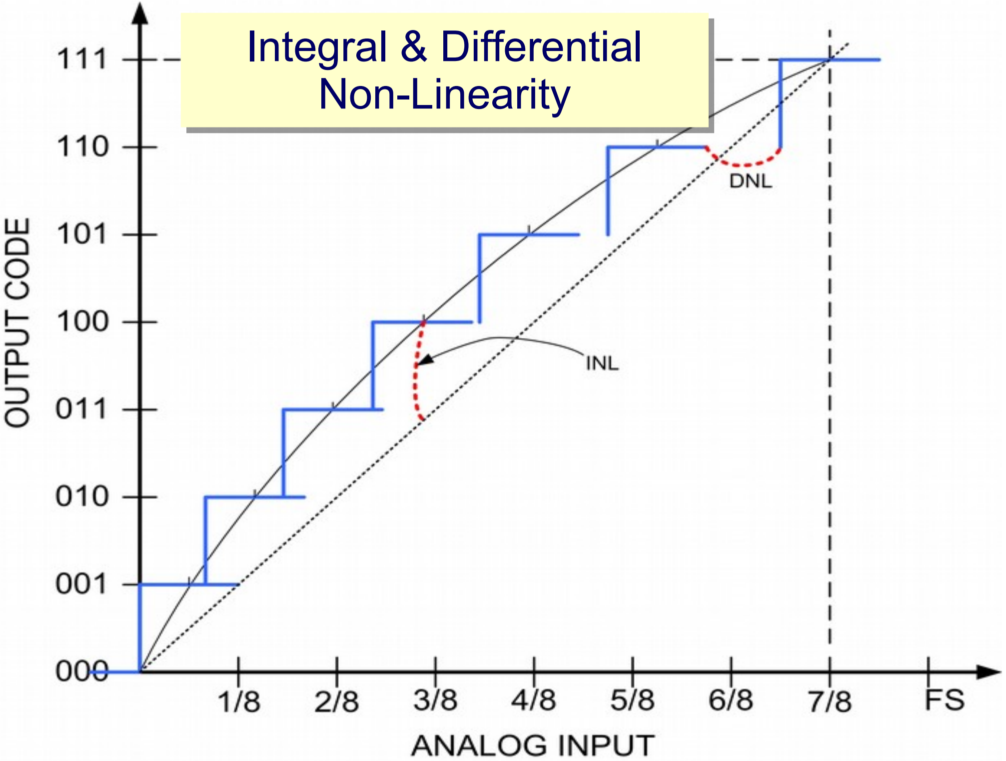
ADC phase-space

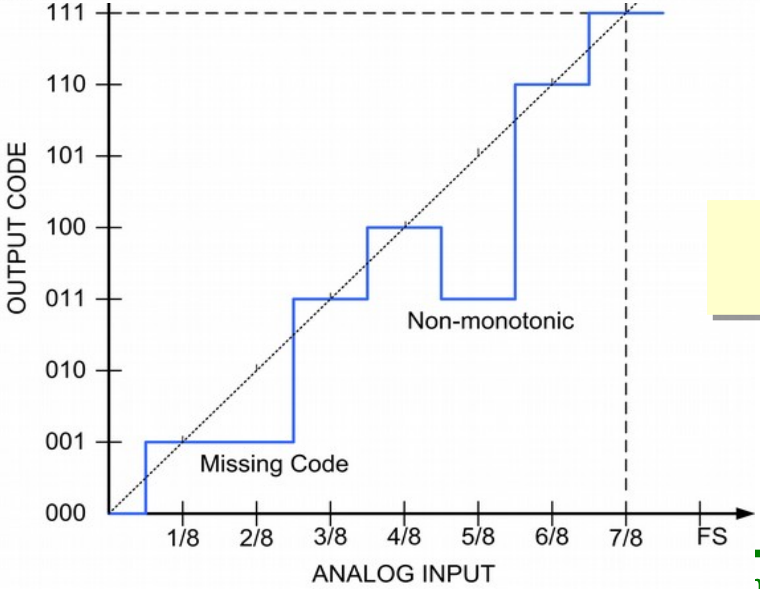
Many different ADC technique exists, mostly because of the trade-off between speed, resolution and power consumption (and cost)



ADC (In)Accuracies


ADC Transfer function

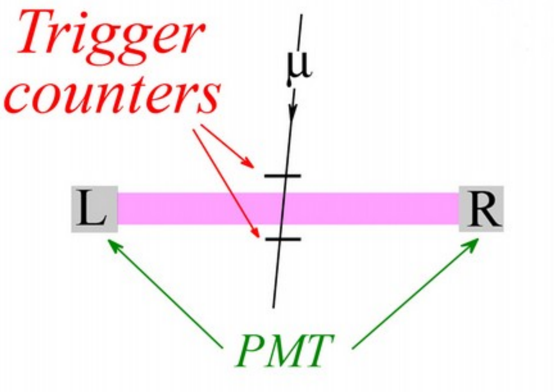

Integral & Differential Non-Linearity

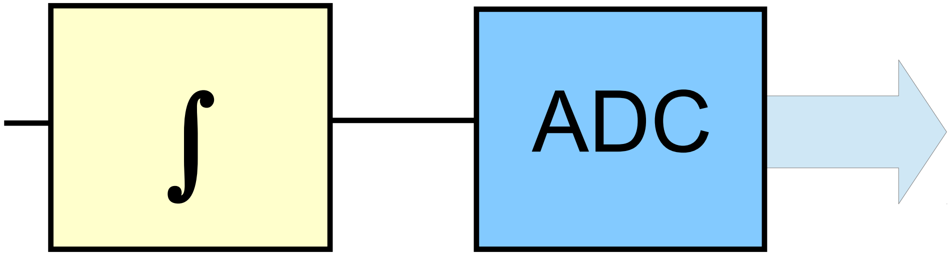


Extreme Differential Non-Linearity

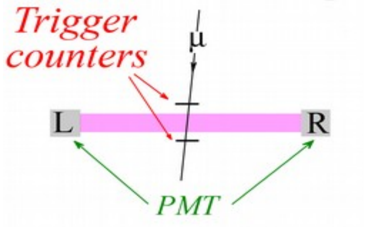
Real ADC at work

- ➔Real data from a beam test @CERN
- ➔$PbWO_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams
- ➔QDC → charge integrator followed by ADC

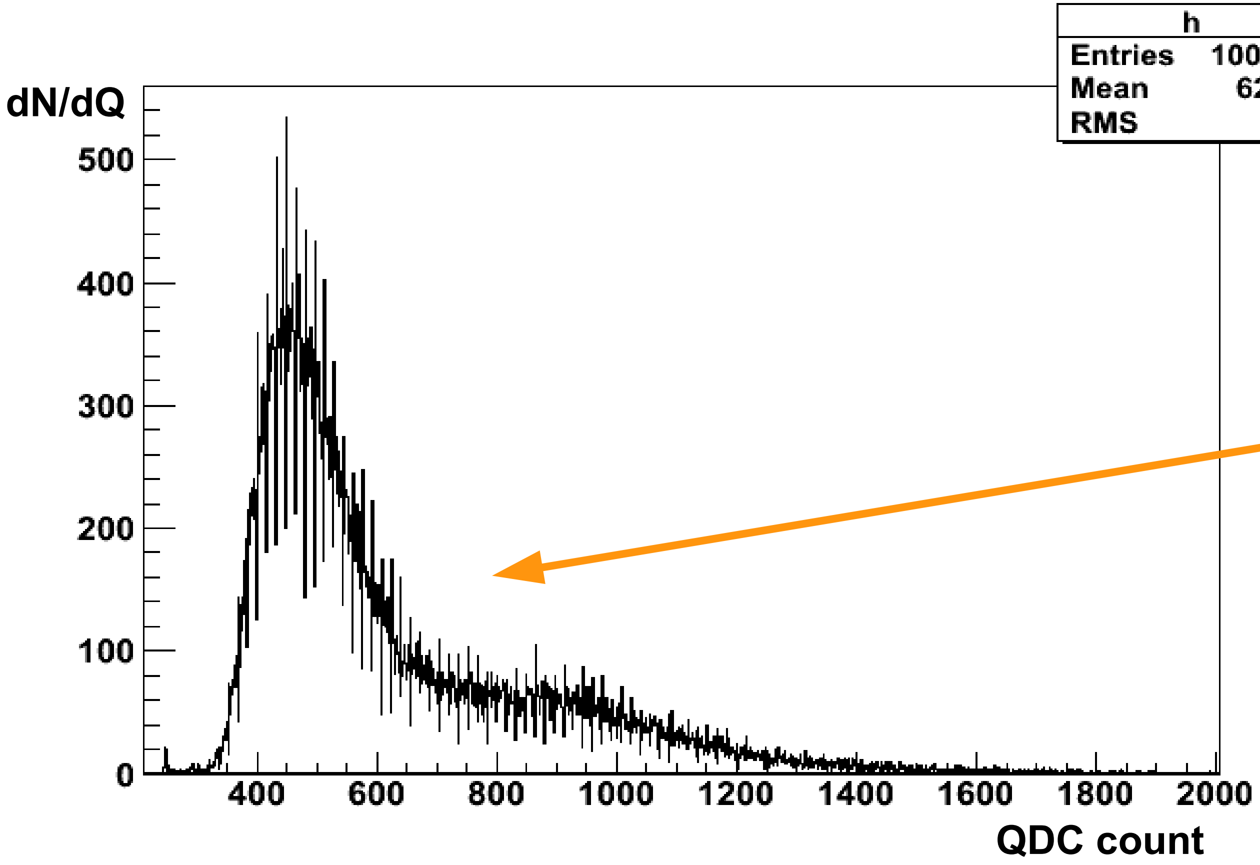




Real QDCs at work

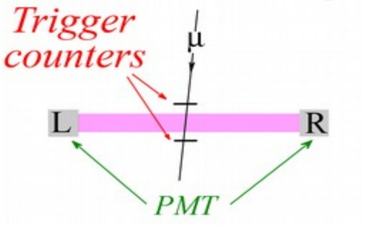


- ➔Real data from a beam test @CERN
- ➔PbWO$_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams

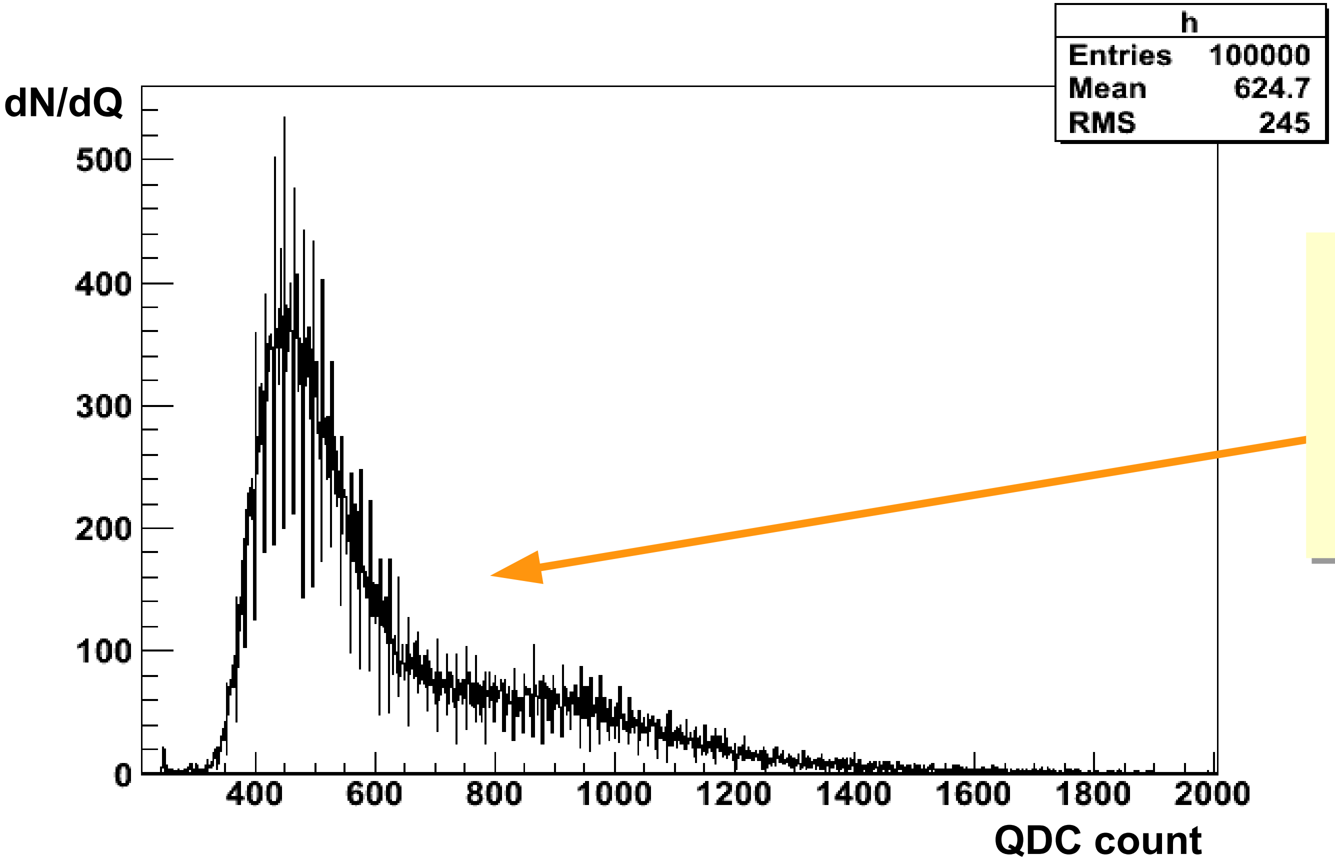


Nice pion-beam charge-distribution for one PMT

Real QDCs at work



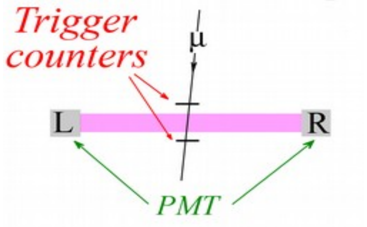
- ➔Real data from a beam test @CERN
- ➔$PbWO_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams

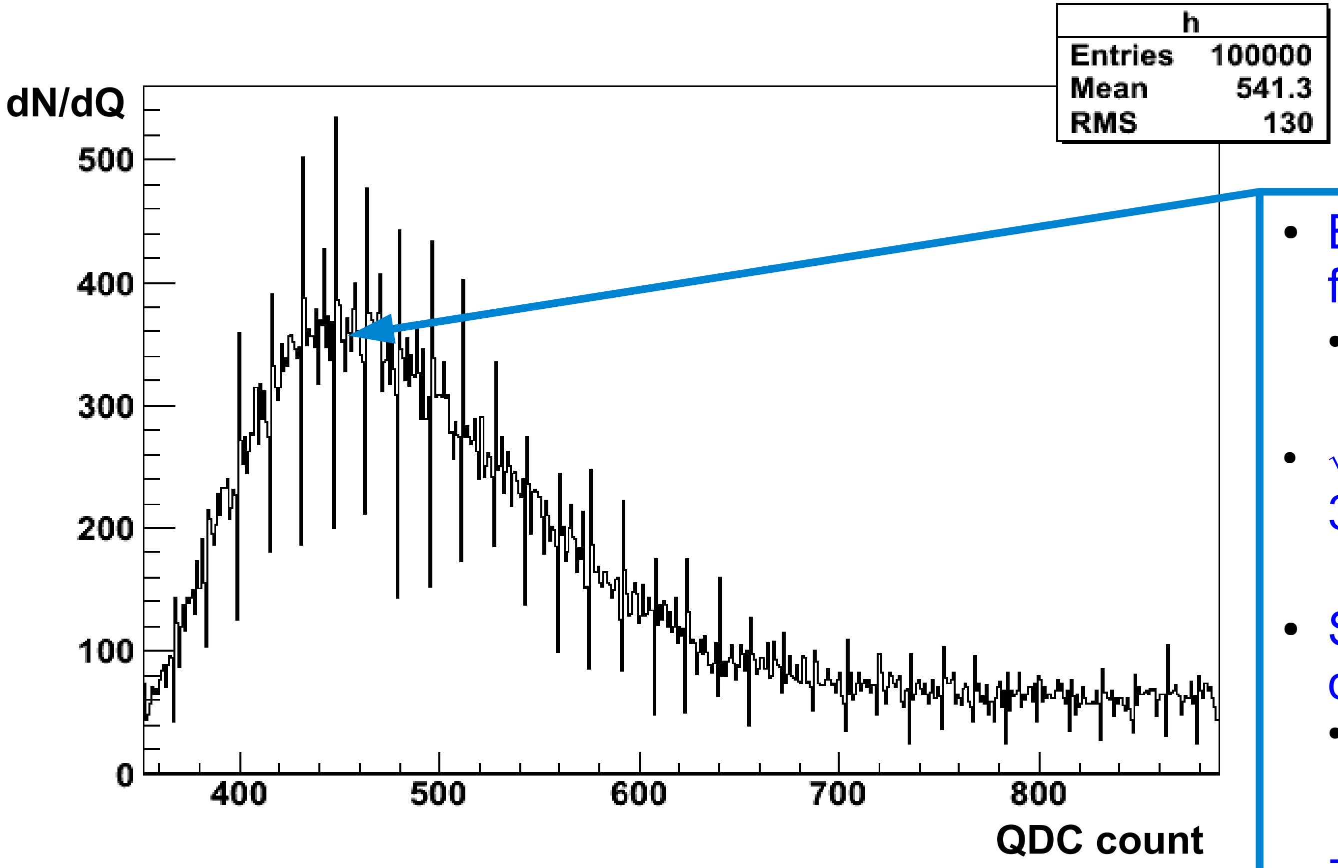


Nice pion-beam charge-distribution for one PMT

But, what are all those little peaks? Just statistical fluctuations? Let's zoom in!

Real QDCs at work

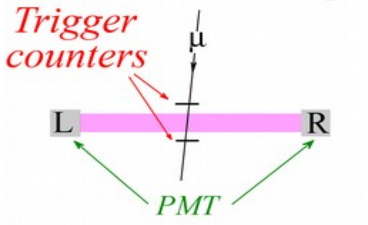


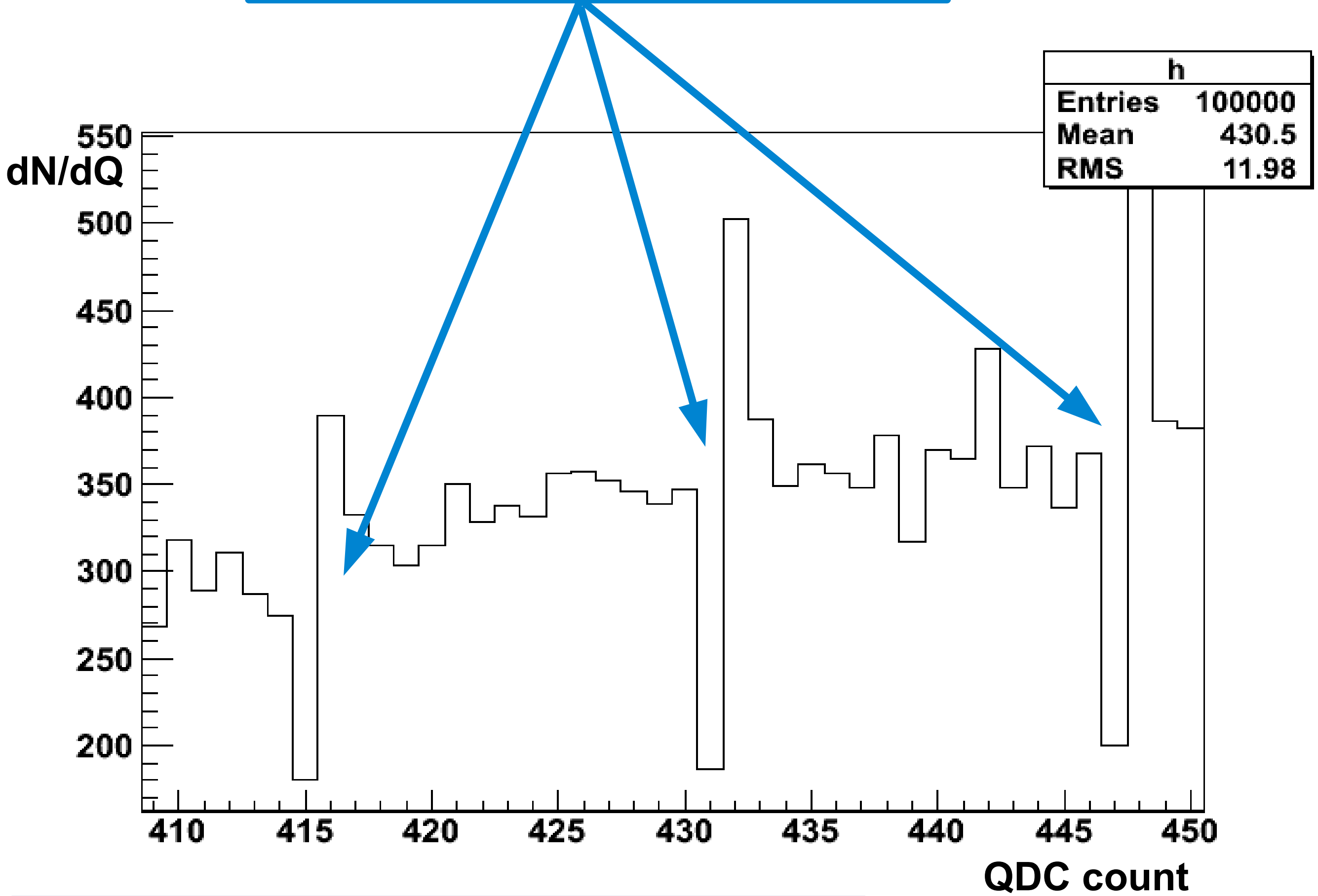


- Bin with N entries shall fluctuate with
  - $\sigma=\sqrt{N}$
- $\sqrt{360}\sim19 \rightarrow (540-360)/19\sim10\sigma$
- Spikes are regularly distributed
  - Some systematic effect must be taking place
- Zoom in a bit more!

Real QDCs at work

- 415 & 416 → 0x19f & 0x1a0
- 431 & 432 → 0x1af & 0x1b0
- 447 & 448 → 0x1bf & 0x1c0





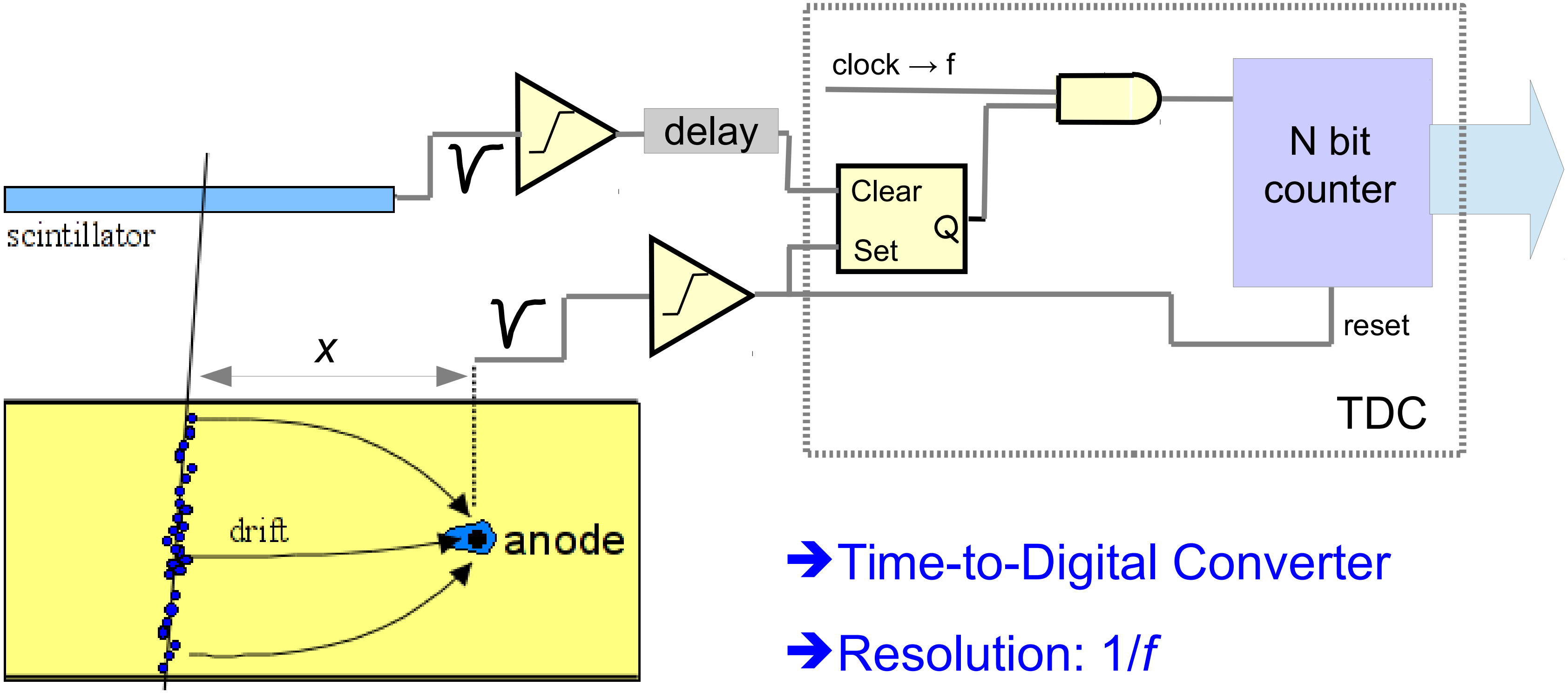
Can you see the effect?

The QDC prefers output configurations of type *xxx*0 in respect of those like *xxxf*

Typical differential non-linearity of successive approximation ADCs

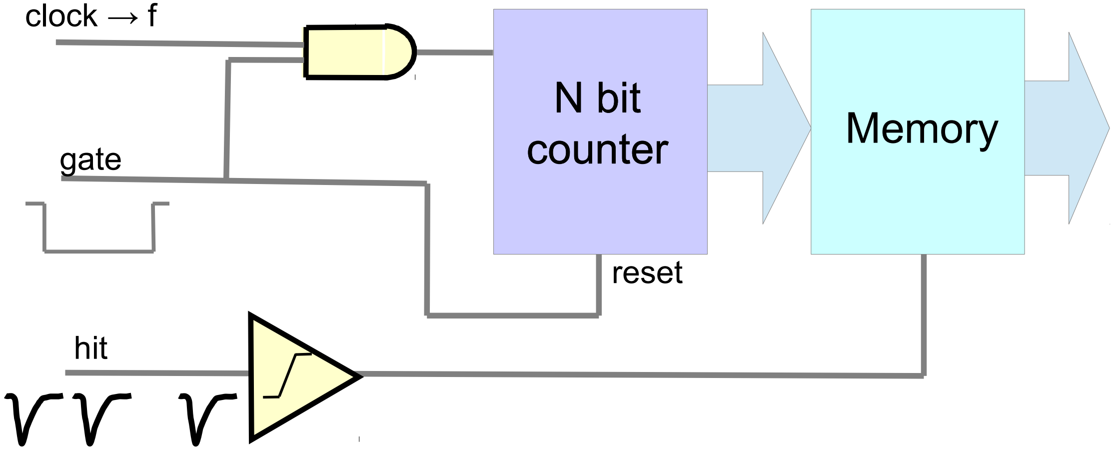
Homework: which is the simplest way to fix this problem in the data? At which cost?

Time measurement → TDC



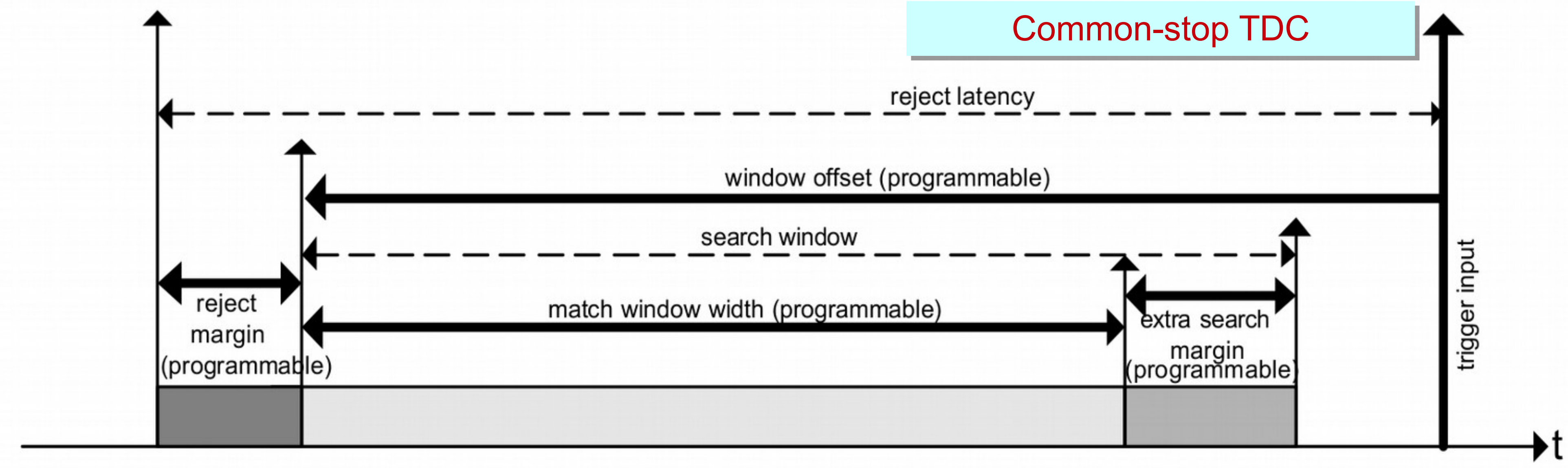
- ➔Time-to-Digital Converter
- ➔Resolution: 1/*f*
- ➔Dynamic range: N
- ➔Single hit TDC
  - e.g. a noise spikes comes just before the signal → measure is lost

Multi-hit TDC



- ➔Gate resets and starts the counter. It also provides the measurement period. It must be smaller than $2^N/f$
- ➔Each "hit" (i.e. signal) forces a memory (FIFO) to load the current value of the counter, that is the delay after the gate start
  - in order to distinguish between hits belonging to different gates, some additional logic is need to tag the data
- ➔<u>Common-start configuration</u>

Real TDCs



➔Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching

- internal programmable delays
- internal generation of programmable gates
- programmable rejection frames

Calibration

Calibration

➔Often our experiments provide relative measurements. The values obtained via our system are in some (known) relation with the interesting quantity

- due to physical detection mechanism
- due to signal processing

$$E \propto Q_s = \int i_s(t)dt$$

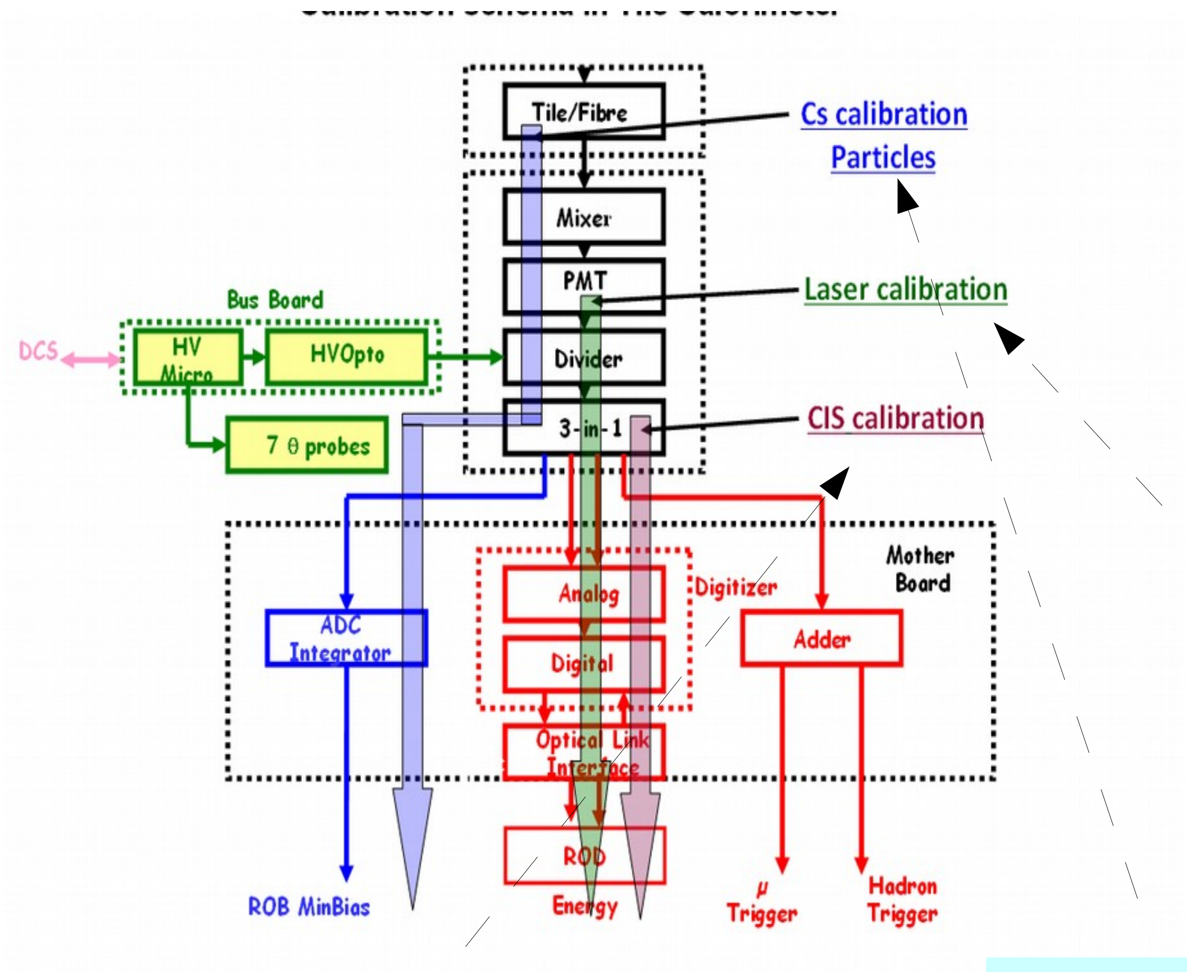
➔Detectors need to be calibrated in order to give us the answer we are looking for

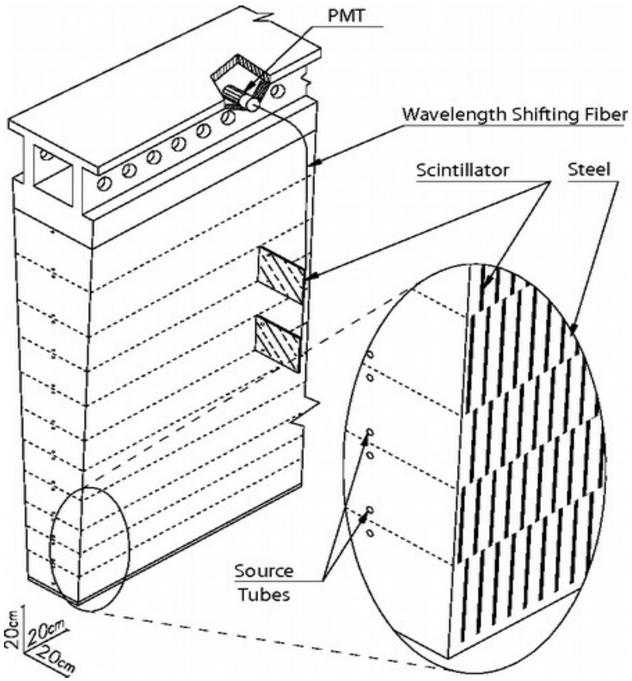
- determine the parameters that transform the raw data into a physics quantities
- normally depend on the experimental setup (e.g. cable length, delay settings, HV settings, …)
- parameters might change with aging (radiation) and beam conditions

➔The design of our detector and DAQ have to foreseen calibration mechanisms/procedures

- injection of known signals
- dedicated calibration *triggers* and data streams

ATLAS Tile Calorimeter Calibration





PMT non-linearities
Laser System

ADC count to charge
Charge Injection System

Detector non-uniformities
Cesium System

$$E_{channel} = A \cdot \overbrace{C_{ADC\rightarrow pC}} \cdot C_{pC\rightarrow GeV} \cdot \overbrace{C_{Cs}} \cdot \overbrace{C_{laser}}$$