Electronics, Trigger and Data Acquisition
part 1

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Roberto Ferrari
Instituto Nazionale di Fisica Nucleare

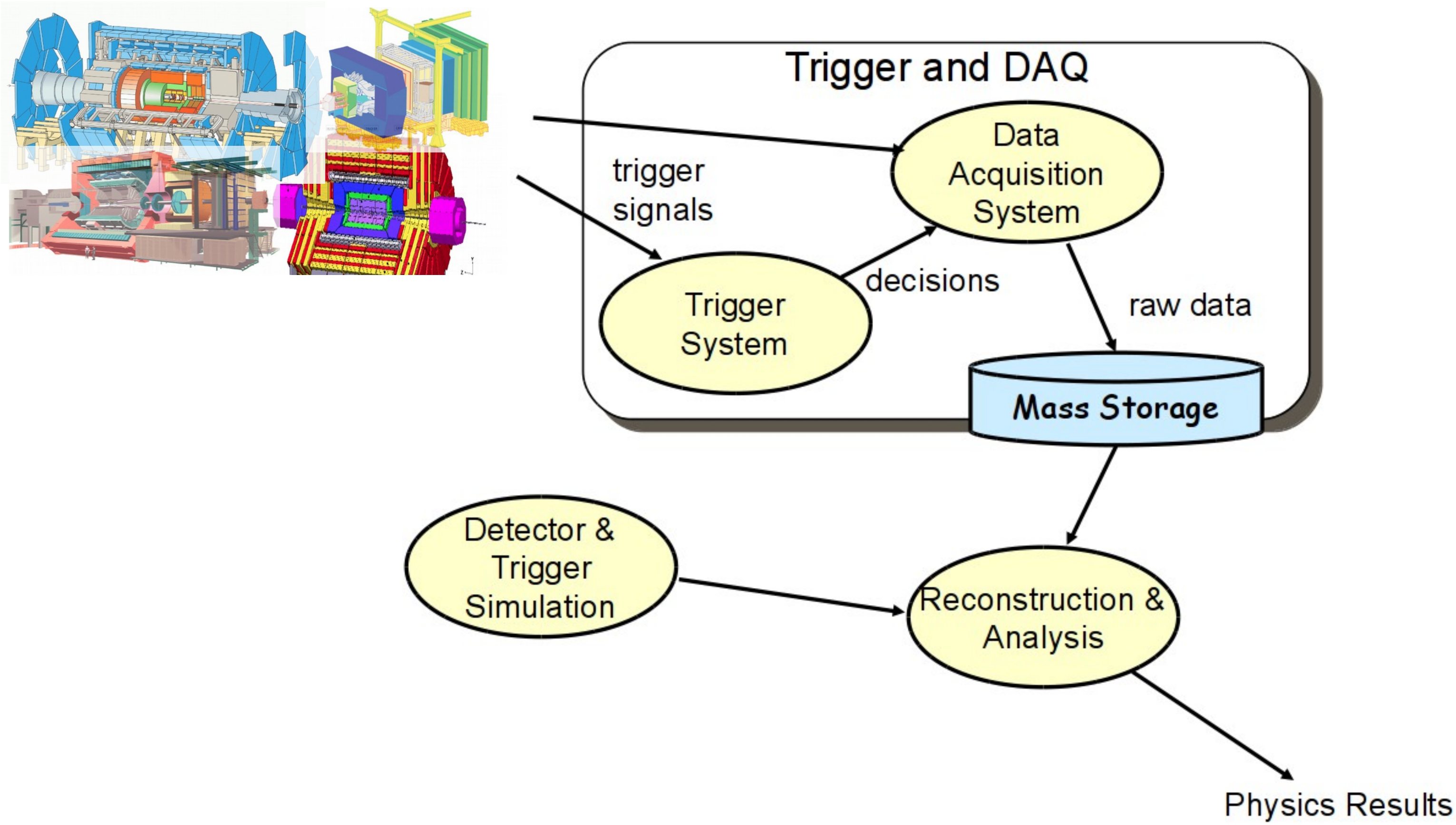
roberto.ferrari@pv.infn.it

Introduction

- Lectures will be concerned with Data Acquisition (DAQ) in High-Energy Physics …
- Data acquisition is an **alchemy** of electronics, computer science, networking, physics
  - …, resources and manpower matter as well, …
- Topics are pretty much correlated → you will realise this in the lecture non-linearity

Credits: material and ideas come largely from my predecessor (Wainer Vandelli) and from the lectures of ISOTDAQ schools (http://isotdaq.web.cern.ch/isotdaq/isotdaq/Home.html)

General Overview



- main role of Electronics, Trigger & DAQ is to process signals generated in “a detector”, likely storing all useful information in some safe place

Signals ?

- Sometimes, somewhere in our detector, something ("one event") happens, i.e. in some short time several particles interact within it.
- In High-Energy Physics, even a single event is composed by sequences of many different probabilistic (quantum-mechanics) processes → fluctuations are built-in
- At the end, "electrical" signals arrive at detector output terminals, different signals:

  a) have different characteristics (size, arrival time, duration, …)

  b) carry different, (likely) independent, information

  c) need quite some electronics in order to become "profitable"

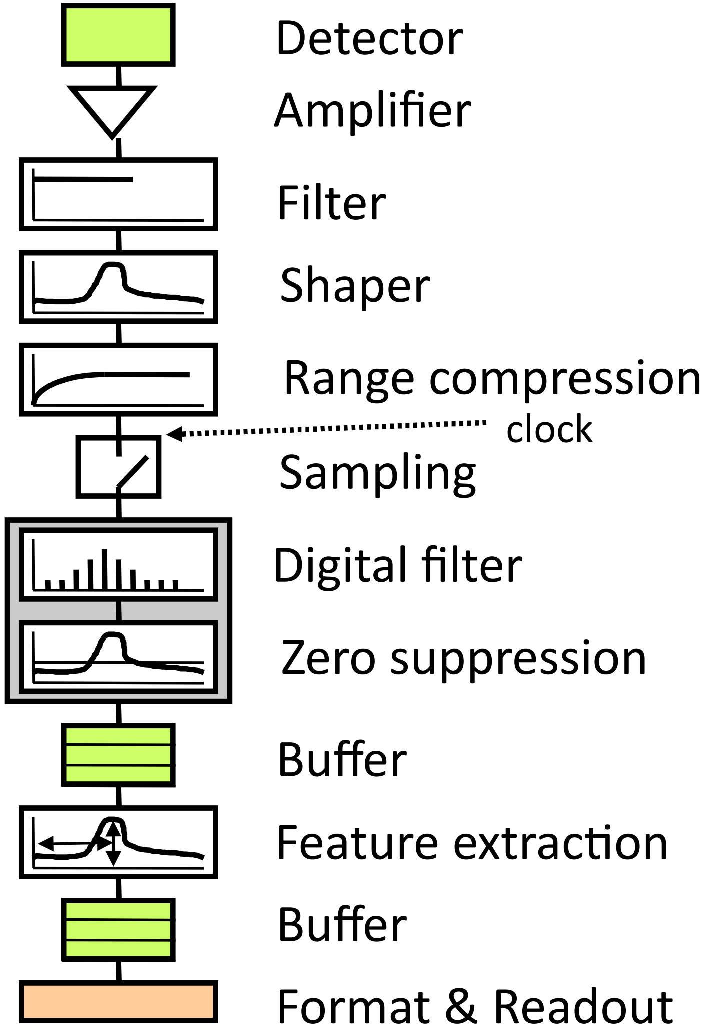
Electronics

[Horowitz & Hill, The Art of Electronics]

Role ?

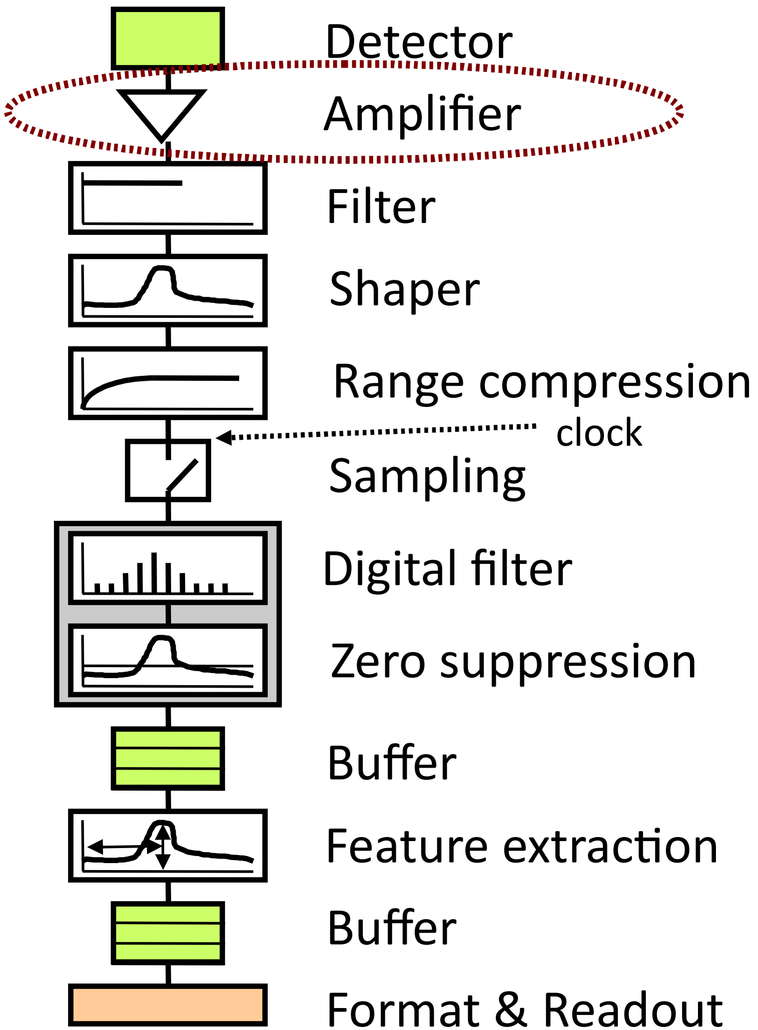
- Sense, transform and collect electrical signals from detector(s) – very often short current/light pulses (i.e. bunches of electrons or photons)
  - you may be interested in total charge or in signal time or in both
- Adapt signals to optimize different, **conflicting**, characteristics → balance:
  - minimum detectable signal (min. noise and max. signal-to-noise ratio)
  - maximum detectable signal (dynamic range)
  - speed (signal rate)
  - timing
  - pulse shape dependence
- Digitize and preserve information
  - allow for subsequent processing, transmission, storage using digital electronics → computers, networks, …

Read-Out Chain



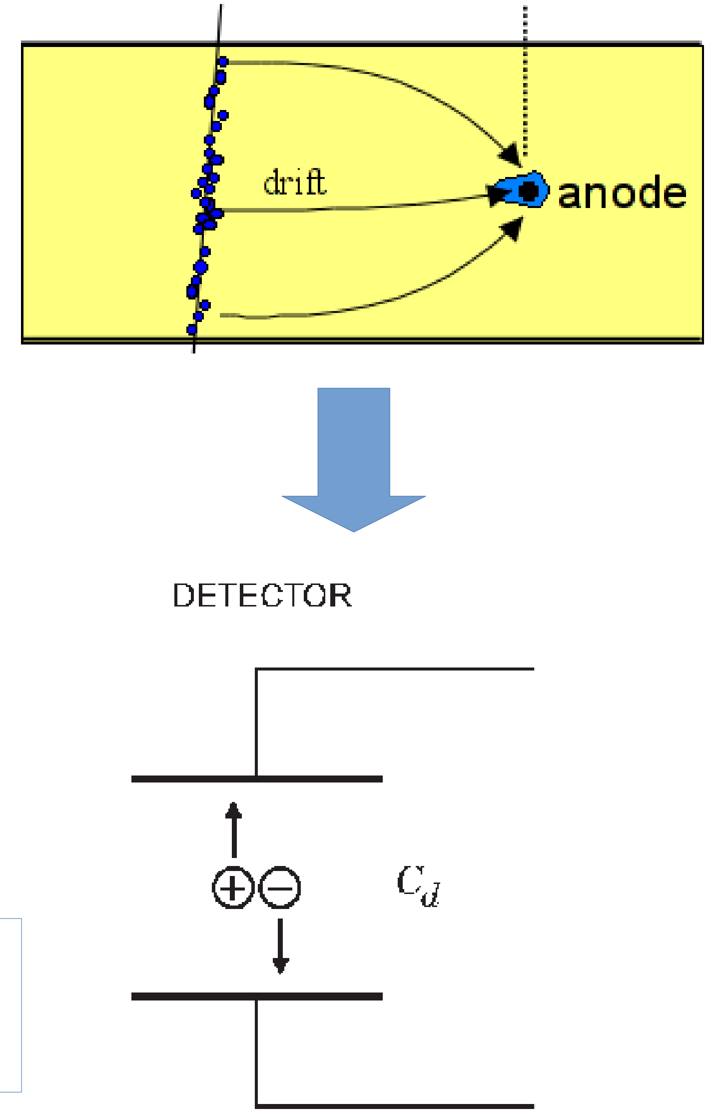
- Front-end electronics very specialized
  - custom-built to match detector characteristics
- Cannot discuss all design and architecture details
  - if you are into electronic design you already know more than me
- Find yourself dealing or choosing commercial electronics
  - provide you with base guidelines
- Selected functions and principles

Read-Out Chain



What can a Signal be ?

- Detectors may be electrically represented as a capacitor (Cd)
  - more realistic schemes will include other contributions
- Interactions of passing particle → energy release E → short current pulse i_s

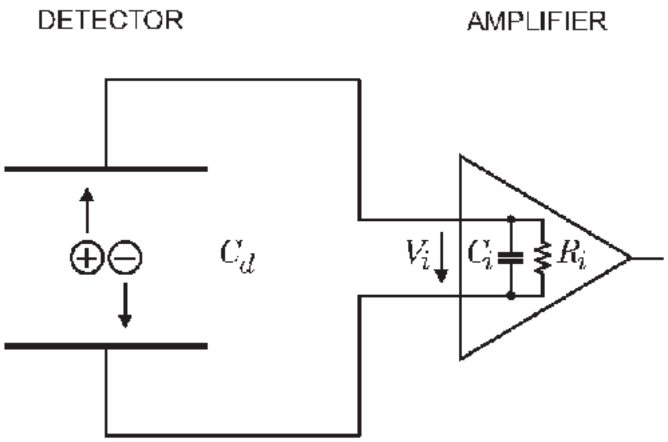


$$E \propto Q_s = \int i_s(t)\,dt$$

- Pulse duration may range from O(100 ps) up to O(10 µs)

Voltage-Sensitive Amplifier

- Signals are possibly very small, amplify to:
  - improve signal resolution, adapt it to next stages
  - avoid SNR degradation ...



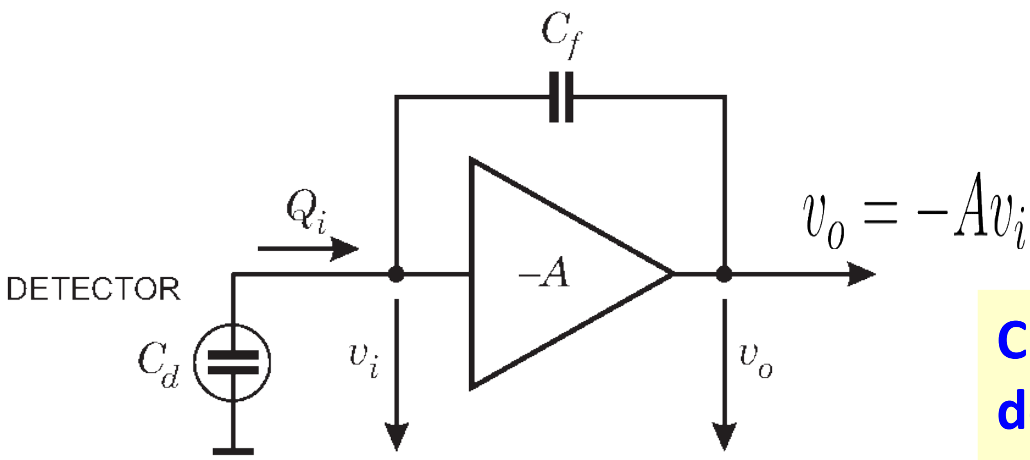
Using a simple voltage amplifier, the sensed **input voltage V_i depends on the detector capacitance.**

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 Amplifier



Charge amplification only depends on a well-controlled component

Effective (dynamic) input capacitance:

$$C_i = \frac{Q_i}{v_i} = C_f(A+1)$$

Gain:

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

Charge Transfer

$$C_i = \frac{Q_i}{v_i} = C_f(A+1)$$

What total-charge fraction is measured ?

$$\frac{Q_i}{Q_s} = \frac{C_i v_i}{Q_{det} + Q_i} = \frac{C_i}{Q_s} \cdot \frac{Q_s}{C_i + C_{det}} = \frac{1}{1 + \frac{C_{det}}{C_i}} \approx 1 \ \ (\text{if } C_i >> C_{det})$$

Need **large input capacitance** to maximize charge transfer

Signal-to-Noise Ratio (SNR)

- Improving SNR improves sensitivity (minimum detectable signal)
- Electronic noise does not necessarily dominate each measurement

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

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 (SNR)

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- Electronic noise does not necessarily dominate each measurement

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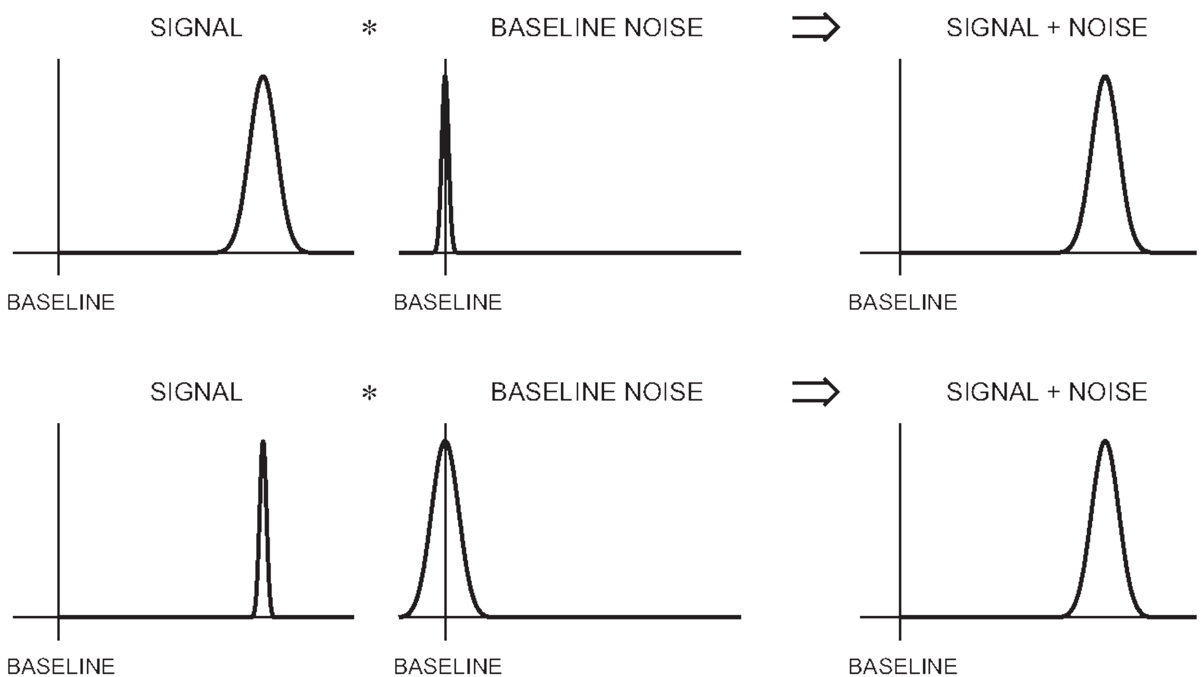


S/N needs optimization

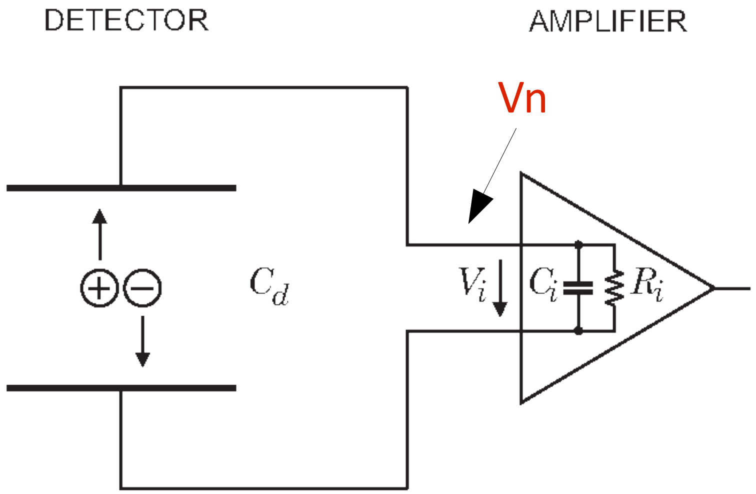
SNR .vs. Detector Capacitance

voltage-sensitive amplifier

→ given signal charge Qs

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

→ assuming input noise Vn

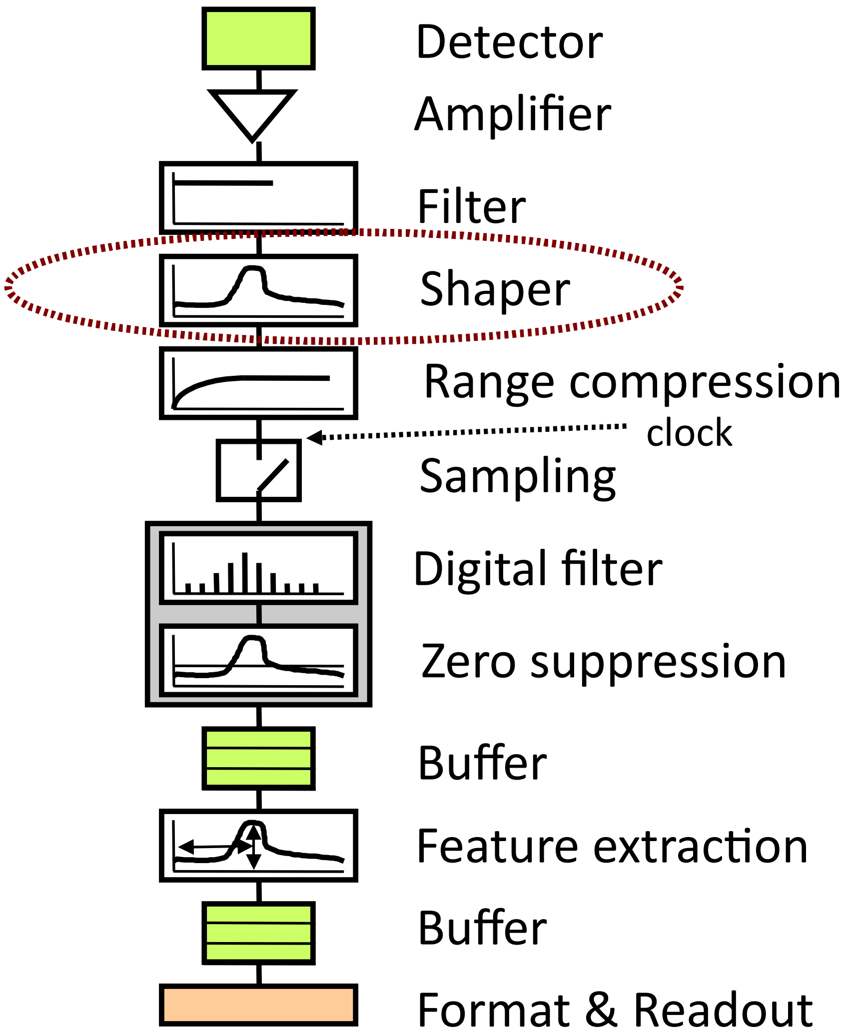


$$\frac{V_s}{V_n} = \frac{Q_s}{V_n(C_d + C_i)}$$

SNR inversely proportional to total input capacitance

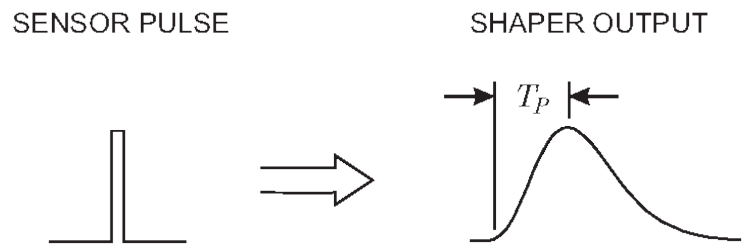
→ Thick detectors normally provide larger signals **and noise**

Read-Out Chain

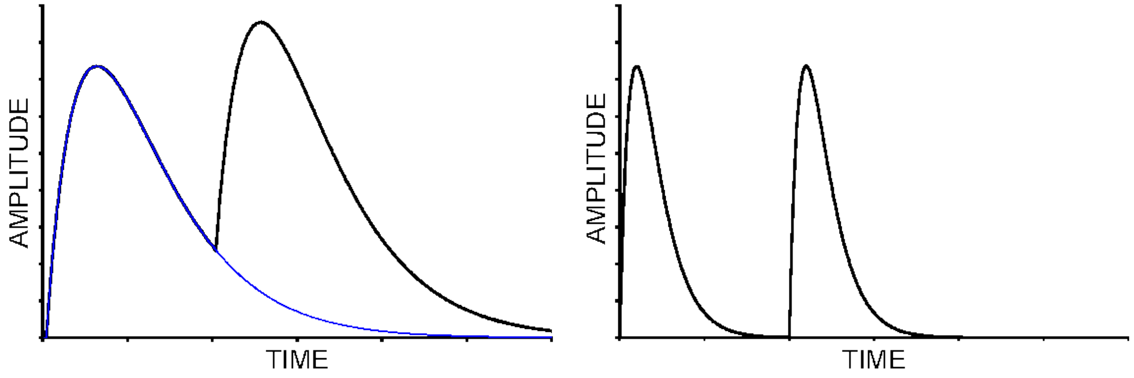


Pulse Shaping

- Reduce signal bandwidth (low-pass filter) → improve SNR
  - fast rising signals have large bandwidth
  - shaper broadens signals



- Limit pulse width (high-pass filter) → avoid overlap of successive pulses
  - increase maximum signal rate at the cost of more noise



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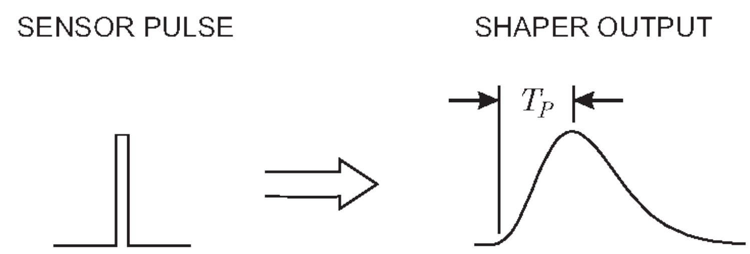

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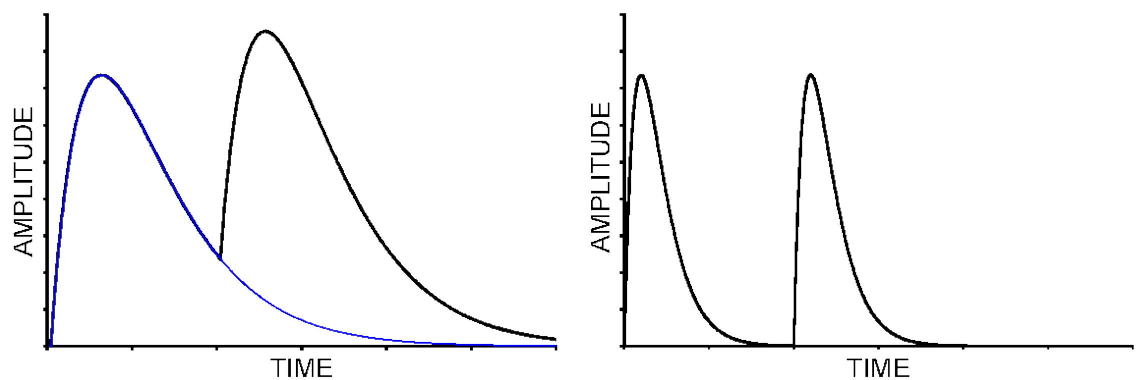
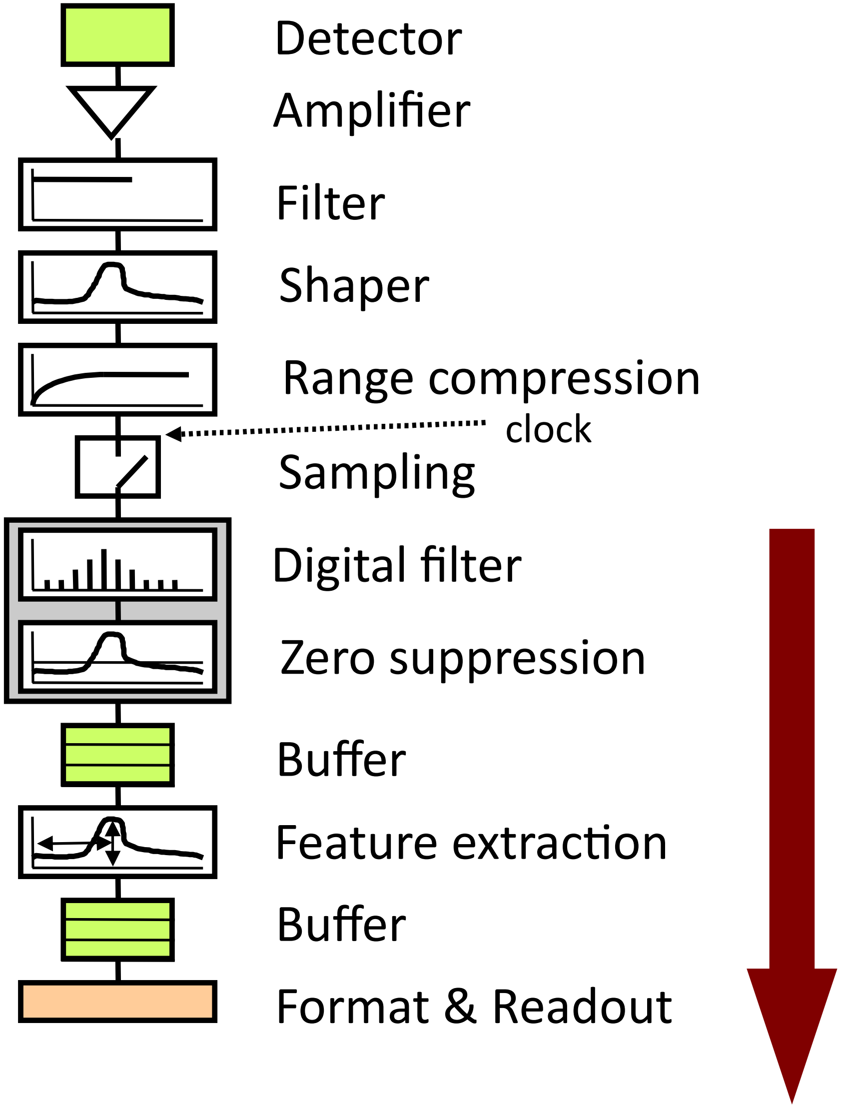


Shaping is often a compromise

$CR\text{-}(RC)^n$ shaping is often a good compromise

Read-Out Chain



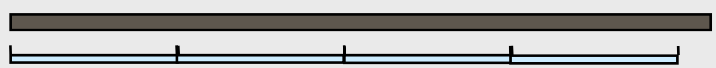
Analog-to-Digital Conversion Introduction

Digitization → encode analog information into a numerical (discrete) format

Why ? Much easier to handle and preserve

Which format ? Usually binary, sometimes BCD

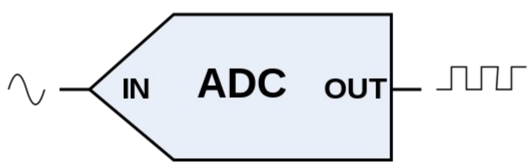
Entity to be measured



Ruler unit

Compare entity (→ count) with a ruler

Electrical Symbol:



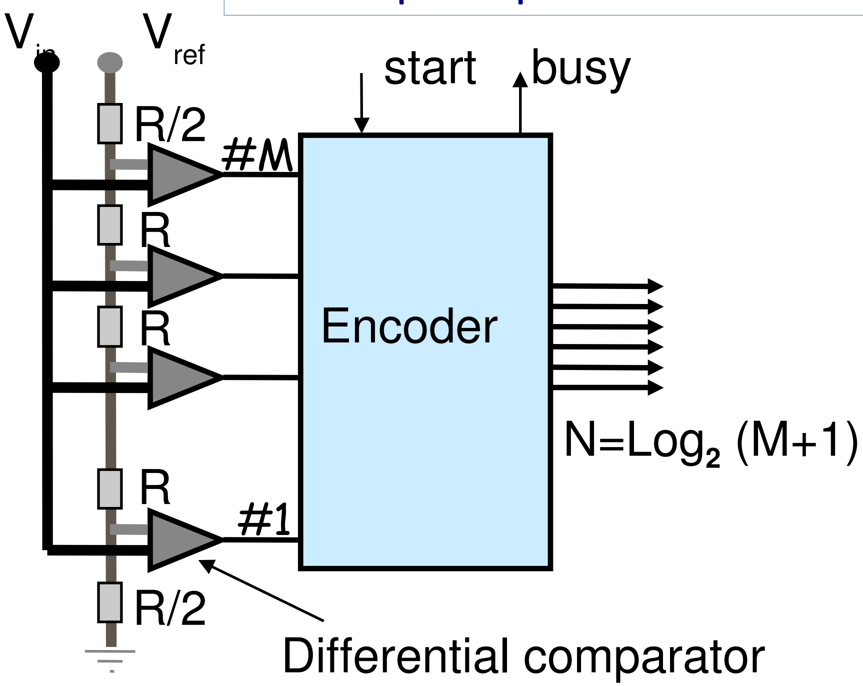
Allow further processing and storage in digital electronics and computers

Flash ADC

- Simplest and fastest implementation
- Performs M comparisons in parallel
  - input V compared with M fractions of a reference voltage:

    $0.5*V_{ref/}/M,\ 1.5*V_{ref/}/M,\ \dots\ (M-0.5)*V_{ref/}/M$

    in step of $V_{ref/}/M$
- Result encoded into compact N-bit binary value
- Sample input at fixed rate and fixed sample depth



- Simple ? Yes
- Fast ? Yes
- Could be non-linear ? Yes
- Cheap ? Oopss ...

Flash ADC

- Simplest and fastest implementation
- Performs M comparisons in parallel
  - input V compared with M fractions of a reference voltage:
    $0.5*V_{ref/}/M, 1.5*V_{ref/}/M, \ldots (M-0.5)*V_{ref/}/M$
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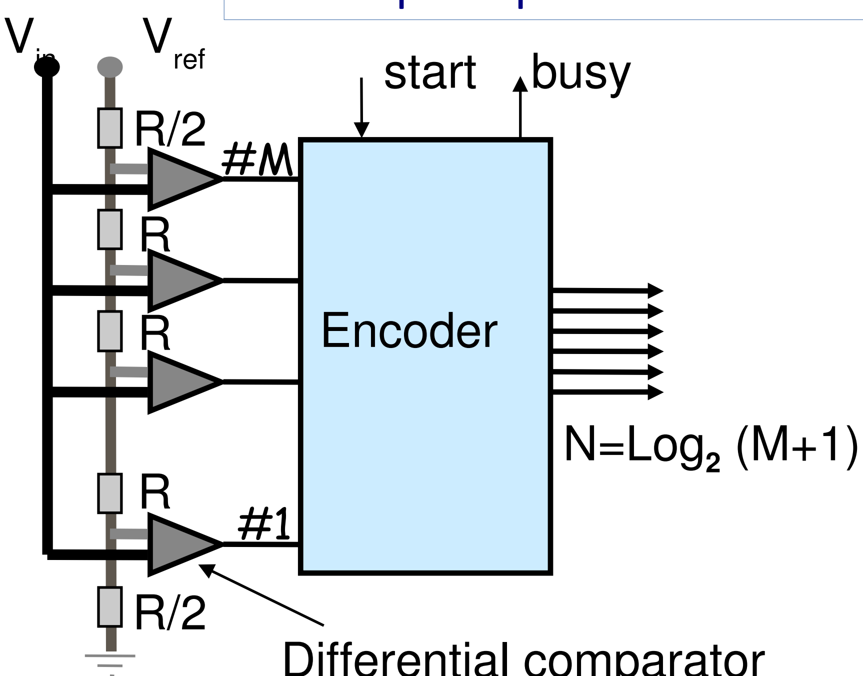
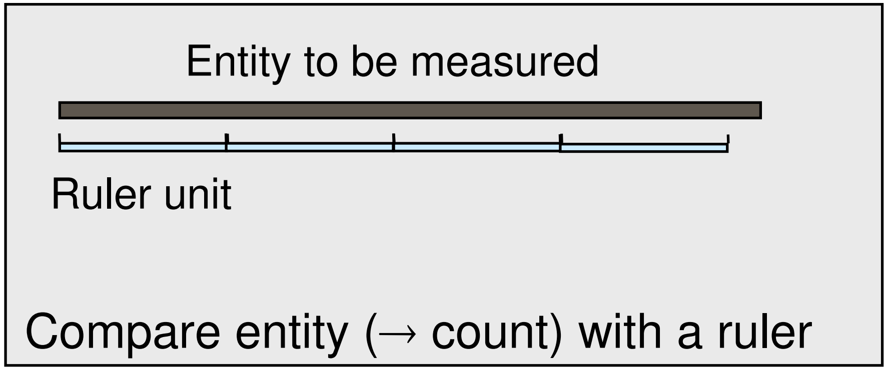


Example M=3 → N=2

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

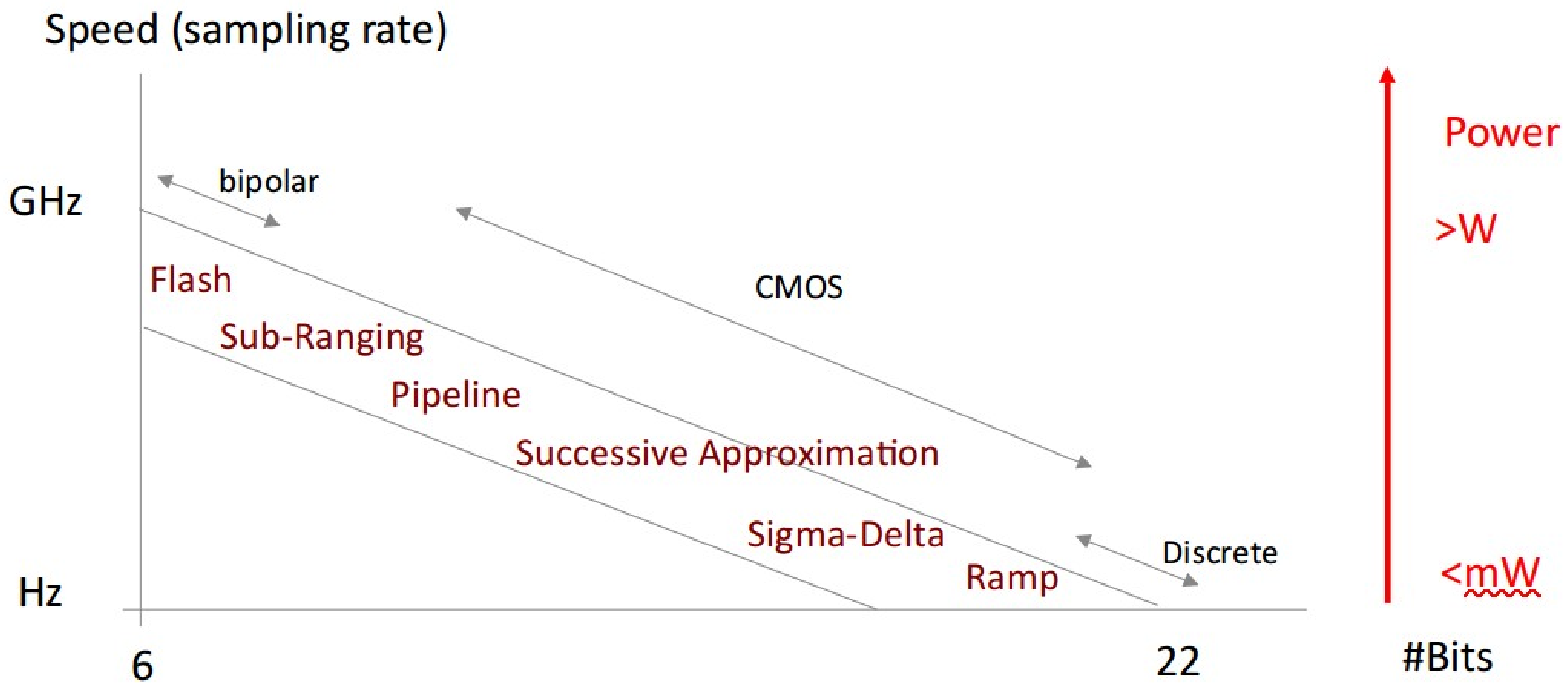
Digitization → encode analog information into a numerical (discrete) format



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

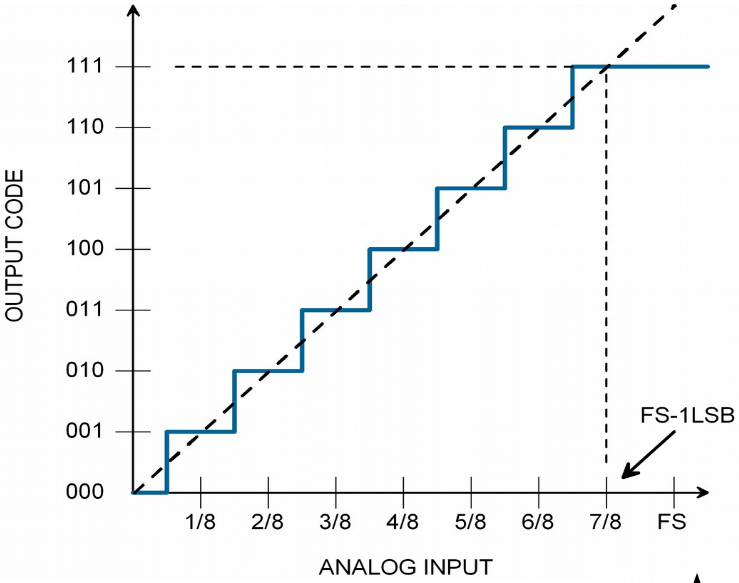
ADC Phase-Space

Many different ADC techniques exist, with different trade-offs between speed, resolution, power consumption, cost, ...

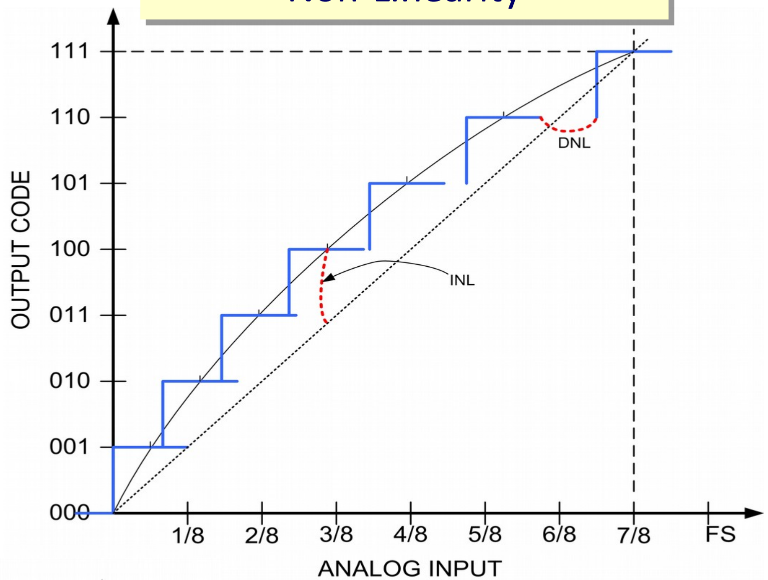


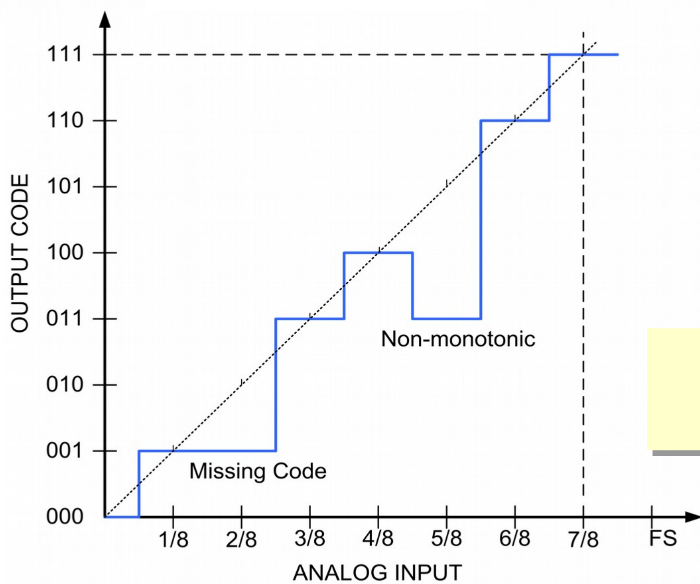
ADC (In)Accuracies

ADC Transfer function



Integral & Differential Non-Linearity

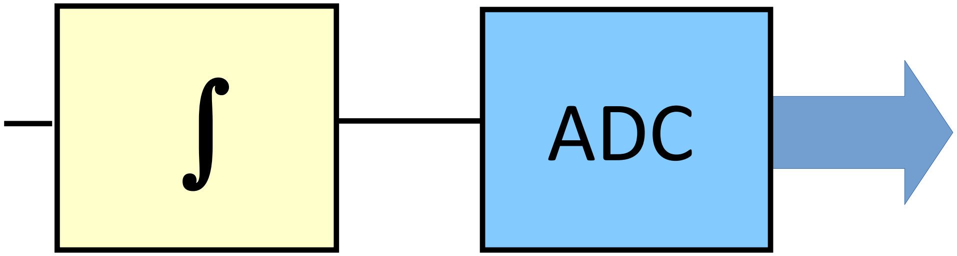


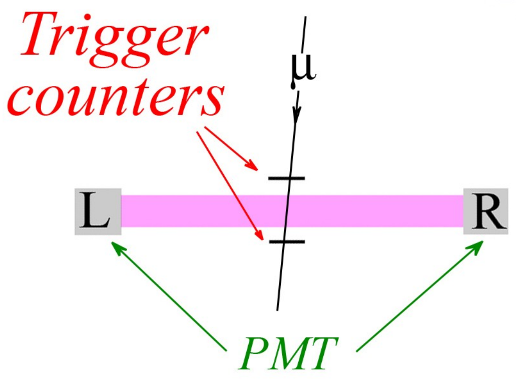


Extreme Differential Non-Linearity

Real ADC.s at Work

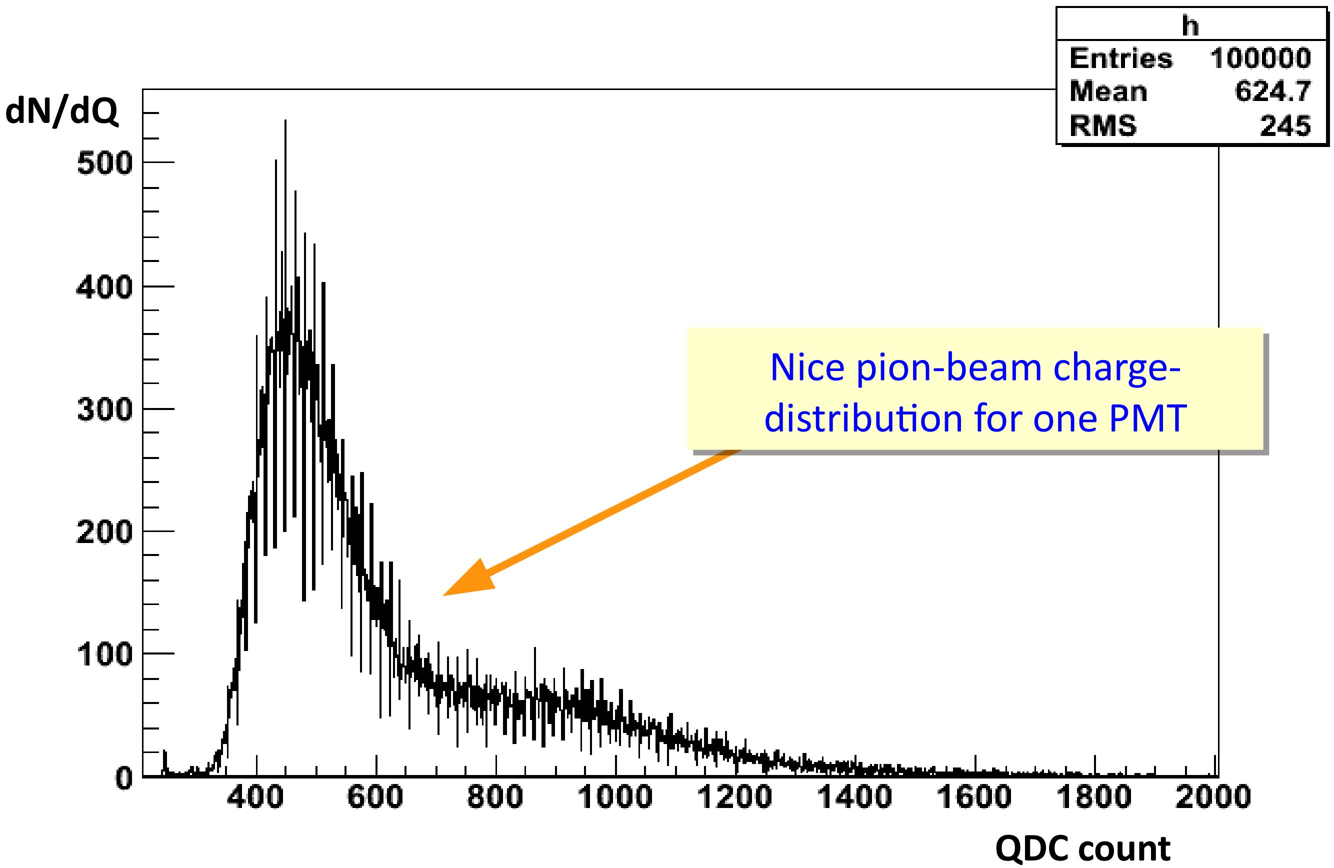
- Real data from a beam test @CERN
- $PbWO_4$ (scintillating) crystal equipped with two PMTs and exposed to e, μ and π beams
- QDC → (gated) charge integrator followed by ADC
  - → (fixed-duration) gate opened after trigger
  - → digital conversion started after gate closing
  - → integrator discharged after conversion

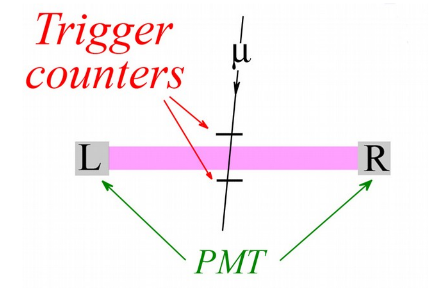




Real QDC.s at Work

$PbWO_4$ crystal equipped with two PMTs and exposed to e, μ and π beams





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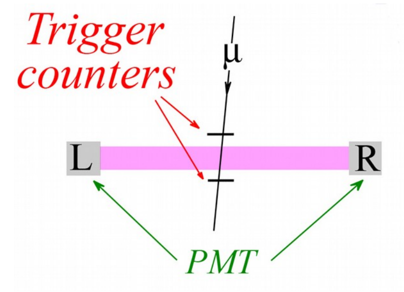
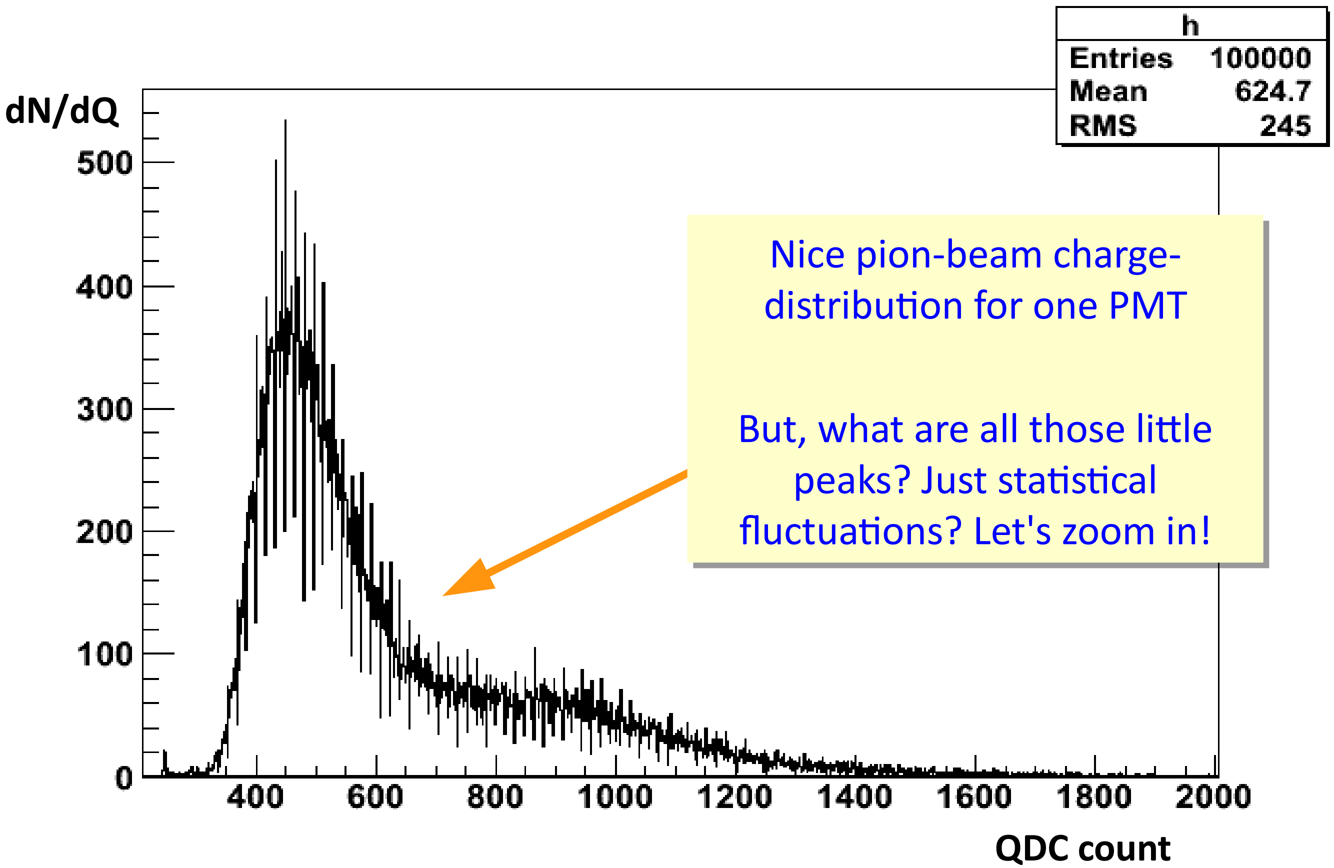
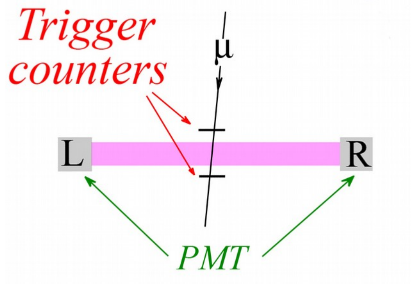


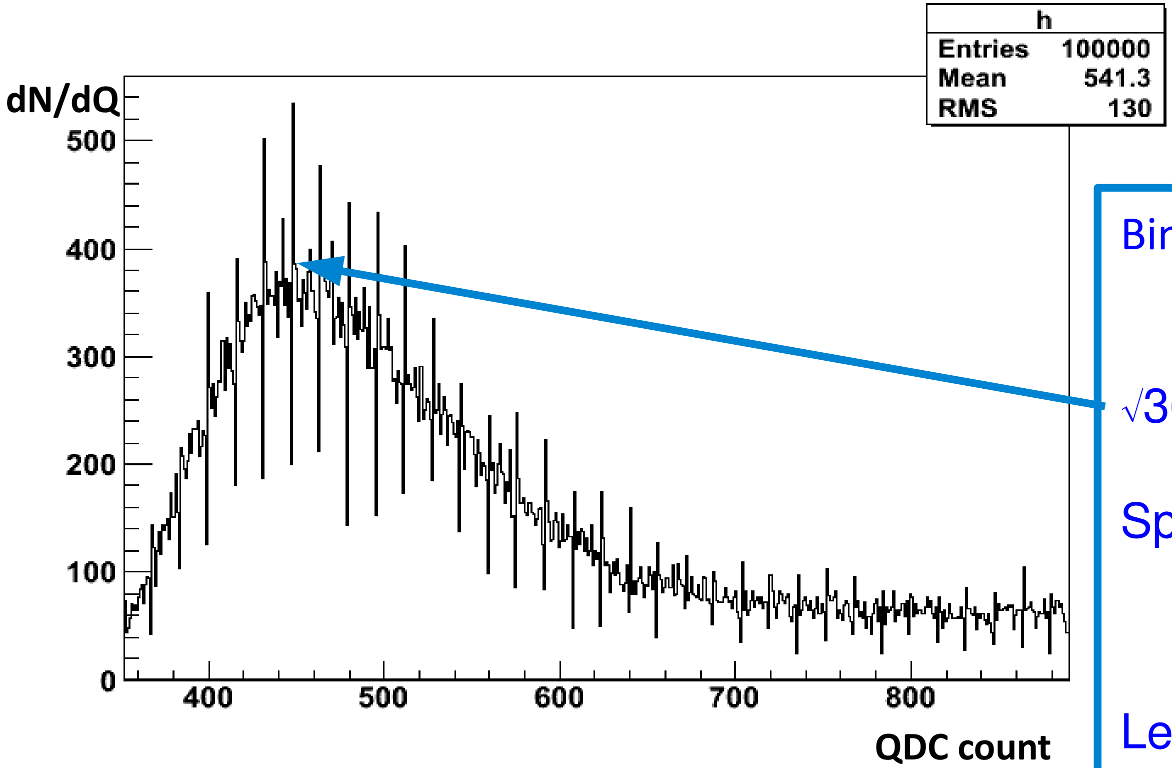


Nice pion-beam charge-distribution for one PMT

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

Real QDC.s at Work





Bin with N entries shall fluctuate with:

- σ=√N

√360~19 → (540-360)/19~10

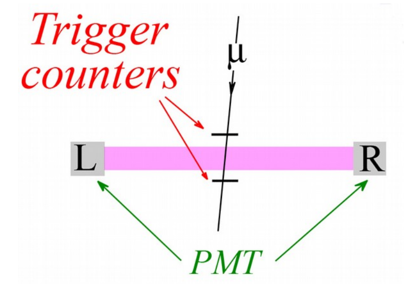
Spikes are regularly distributed

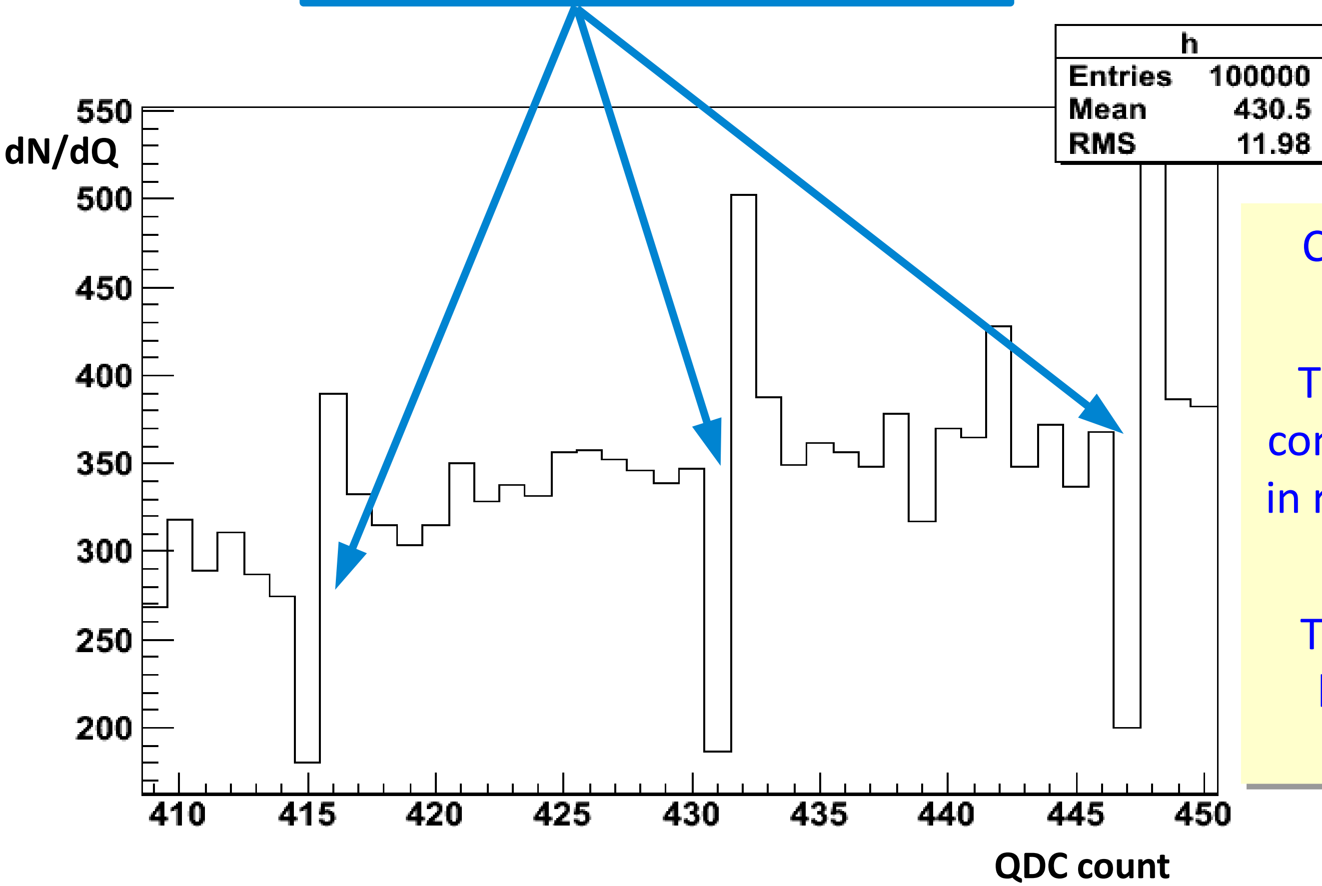
- some systematic effect is taking place

Let zoom in a bit more!

Real QDC.s 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: can you find a simple way to fix this problem in the data? What the cost?

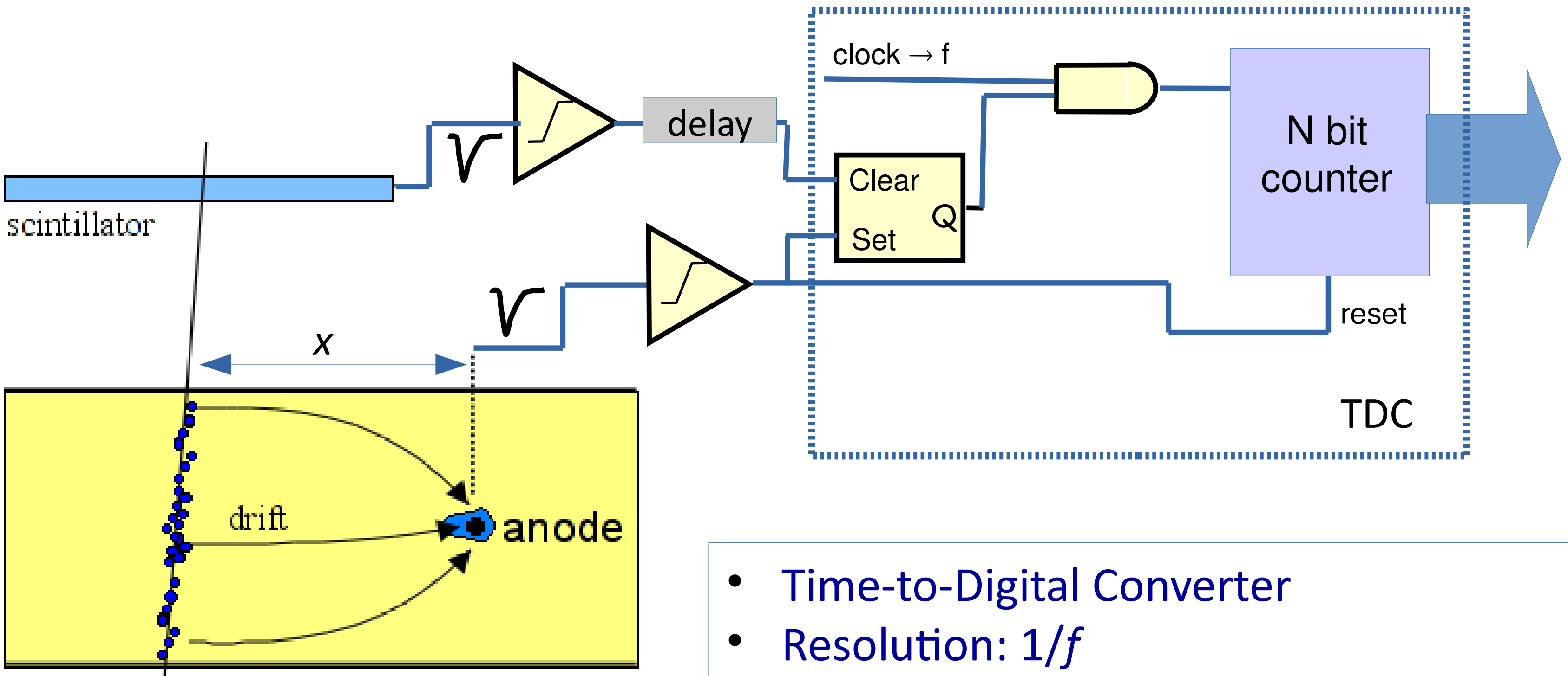
Some more … Peak-Sensing ADC

- QDC signals need to be fully integrated, gate need not to be too long
  → need precise and stable timing .vs. gate:
- high-rate unipolar pulses may suffer of baseline drift

→ to overcome such problems:

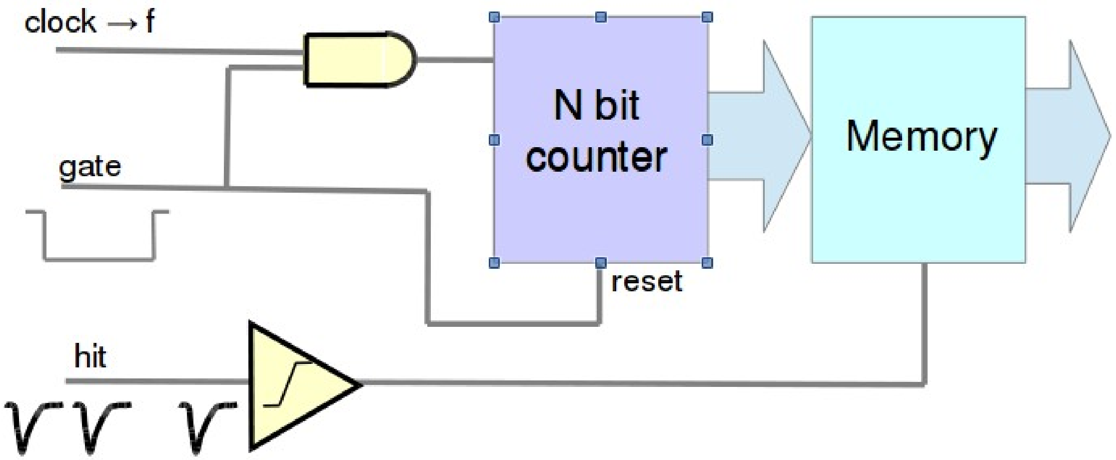
1) charge amplifier + shaper:
   - signal shape stable
   - peak value proportional to Q
2) peak-sensing ADC:
   - find Vmax within a gate (rise-time shouldn't be too fast)
   - at end-of-gate, convert

Time Measurements → TDC



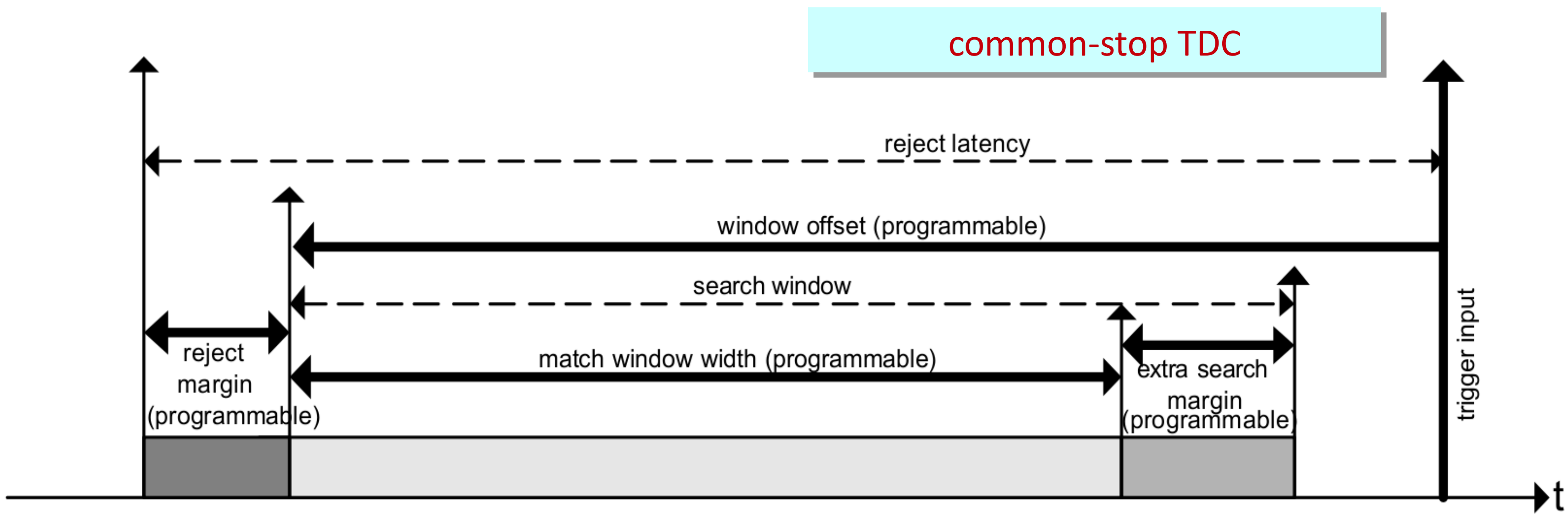
- Time-to-Digital Converter
- Resolution: $1/f$
- Dynamic range: N
- Single-hit TDC:
  - e.g. noise spike arriving just before the signal → measure lost

Multi-Hit TDC



- Gate resets and starts counter. Also provides measurement period
- Gate duration <~ $2^N/f$
- Each "hit" (i.e. signal) forces memory (FIFO) to load current counter value, that's delay wrt. gate opening
  - in order to distinguish hits belonging to different gates, some additional logic needed to tag data (end/start-of-gate marker)
- Common-start configuration

Real TDC.s



- Real TDCs provide advanced functionalities for fine-tuning hit-trigger matching
  - internal programmable delays
  - internal generation of programmable gates
  - programmable rejection frames

Digital Converters – Summary

Speaking about measuring fast (short) pulses ...

- Flash ADC: high-speed sampling, measure V
- QDC: pulse integration, measure Q, pedestal* proportional to gate length
- Peak Sensing ADC: measure V(peak)
- TDC: measure time intervals

- conversion (dead) time of commercial VME boards ~ few us

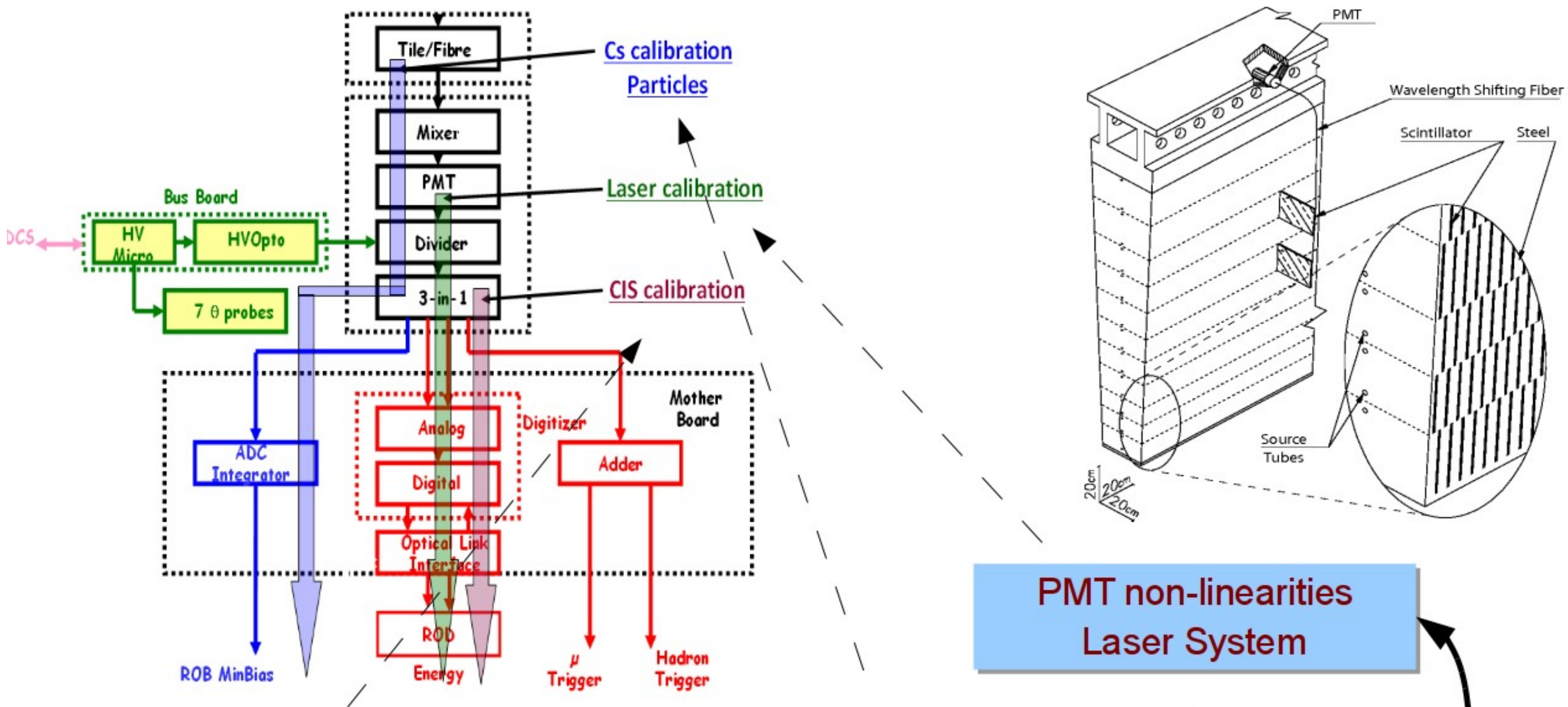
*pedestal = measurement of input noise (absence of signal)

Calibration

Calibration

- Our elx chain provides us with numbers (raw data) but … what do they really mean ?
- Likely related with physics quantities but with relations (transfer functions) affected by several uncertainties:
  - due to physical detection mechanisms
  - due to signal processing
- Transfer functions usually parametrized, sometimes based on (look-up) numeric tables
- All system elements need to be calibrated to keep optimal knowledge of all parameters → calibration procedures → calibration constants
- Calibration constants change with ageing (mainly due to radiation), beam conditions (electronics may have baseline drifting with pile-up), time … HV, LV, ...
- The design of our detector and DAQ has to foresee 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

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

to be continued...