Data Acquisition Hardware (Hands-on Approach)

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Outline

- Introduction
- Measure energy deposition
  - Scintillator setup
  - Photomultiplier
  - Analog-to-Digital conversion
  - Charge-to-Digital conversion
  - QDC in real life
- Measure position
  - Wire chamber setup
  - Time-to-Digital conversion
  - TDC in real life
- Corollary

Introduction

➔This wants to be a hands-on approach to the basic DAQ hardware

➔We will discuss two different experiments, requiring different techniques and components

➔ We also have some good real data to discuss

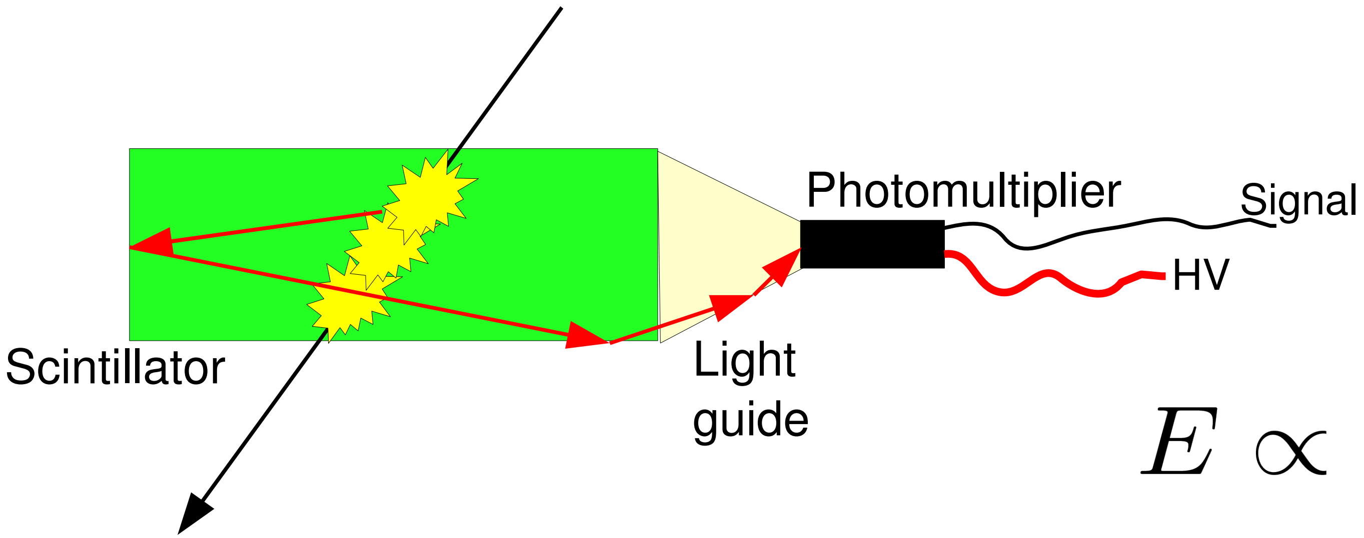
- You we will see, we are talking about real life here

➔Let's get started!

Material and ideas have been taken from CERN Summer Student lectures of P.Farthouat, C.Joram and O.Ullaland

1st experiment

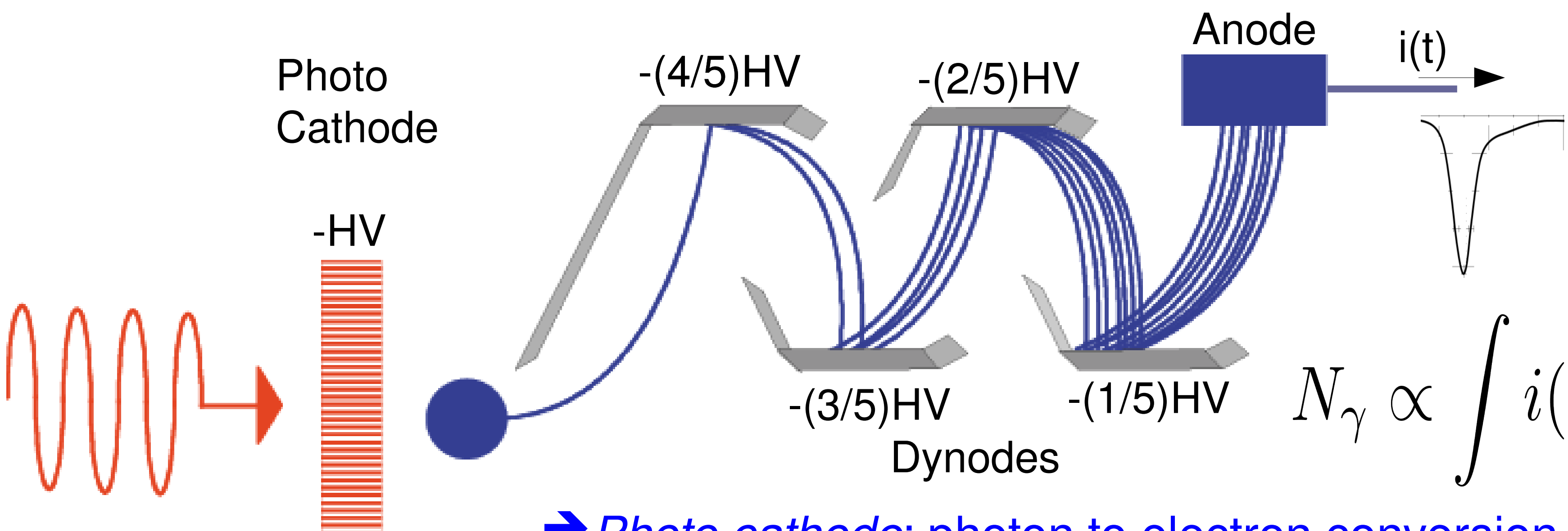
Energy measurement



$$E \propto N_\gamma$$

- ➔ Measure the energy deposited by a particle traversing a (special) medium
- ➔ The (detector) medium is a scintillator → The molecules, excited by the passing particle, relax emitting light
  - The amount of light is proportional to the deposited energy
- ➔ The light is then collected, using dedicated optical means (light guide), and fed into a photo-detector → photomultiplier

Photomultiplier



$$N_\gamma \propto \int i(t)\, dt = Q$$

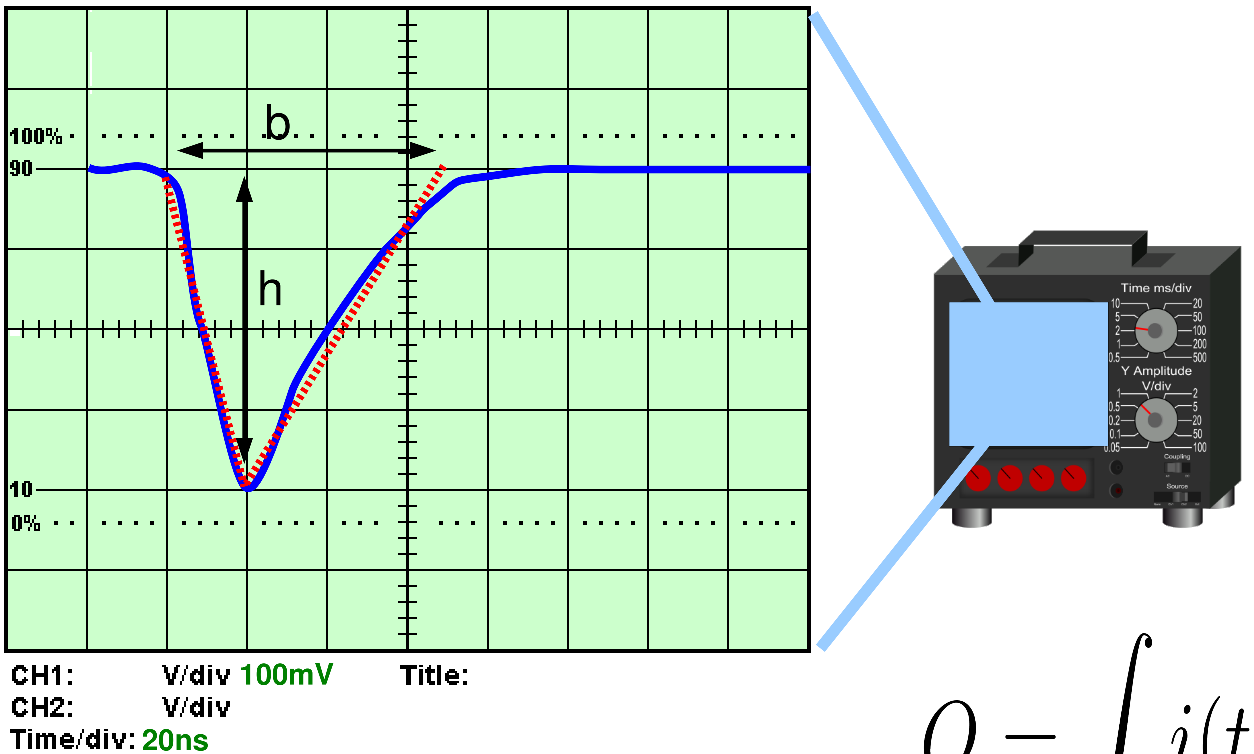
➔ *Photo cathode*: photon to electron conversion via photo-electric effect

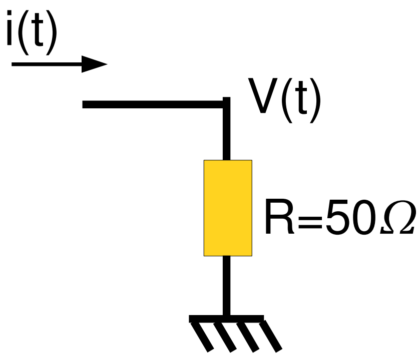
- Typical quantum efficiency ≈1-10% (depends on material and wavelength)

➔ *Dynodes*: electrodes that amplify the number of electrons thanks to secondary emission

- Typical overall gain $\approx 10^6$

➔ *Dark current*: current flowing in the PMT without light → noise



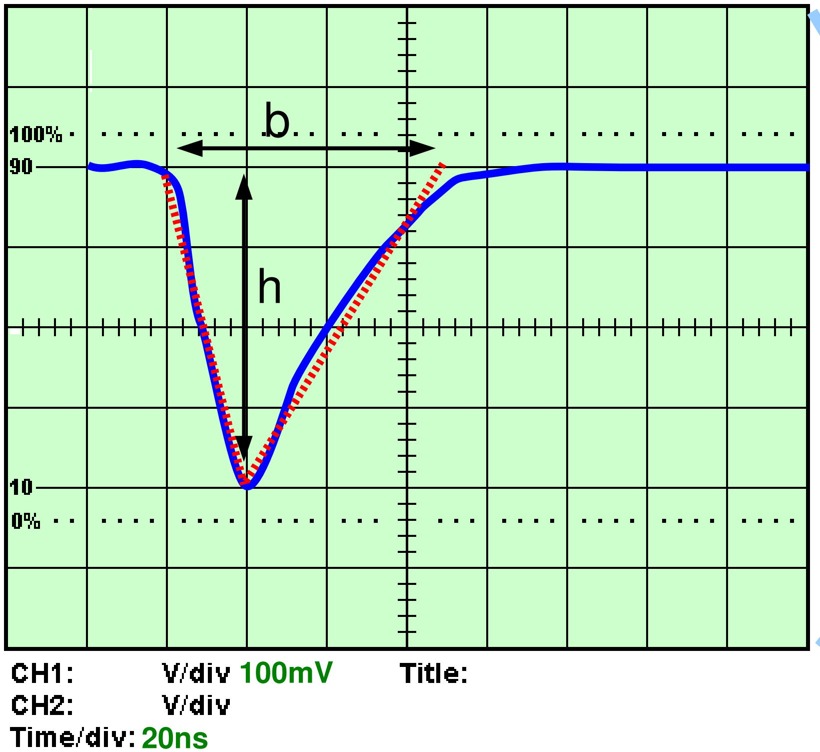


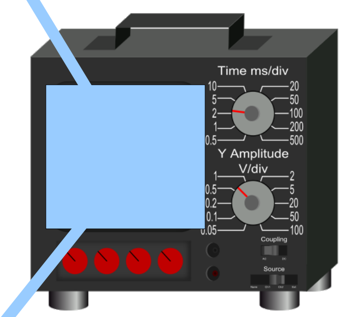
$$Q = \int i(t)\,dt = \frac{1}{R}\int V(t)\,dt$$

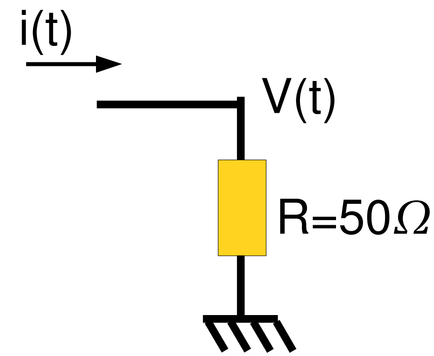
Good old scope

➔ Approximate Q measurement using oscilloscope

- Linear approximation of a exponential decay



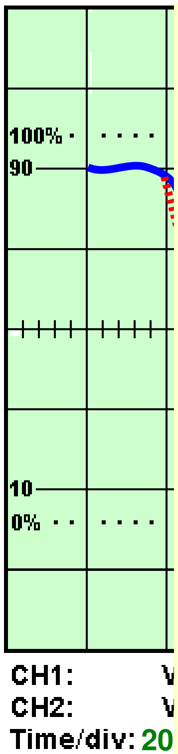




$$Q = \int i(t)\,dt = \frac{1}{R}\int V(t)\,dt$$

$$Q \approx \frac{1}{R}\frac{bh}{2} = \frac{1}{50\Omega}\frac{(3.5\cdot(20\text{ns}))(4\cdot(100\text{mV}))}{2} = 280\text{pC}$$

Getting started



Done! (In less than 5 slides)

- Approximate measurement
- Deadtime ~3000%/Hz (if you are good)
- Encode the data into some sort of electronic format by hand

Wouldn't be much more convenient to have a direct electronic measurement? It could save the data in some digital format and fill a histogram on-line. Wouldn't be cool?

The scope method is still fundamental: allows for the validation of your DAQ (and, yes, you should never thrust it a priori!)

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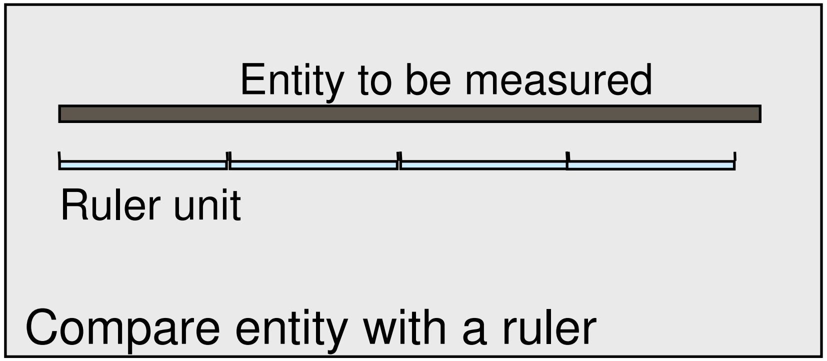
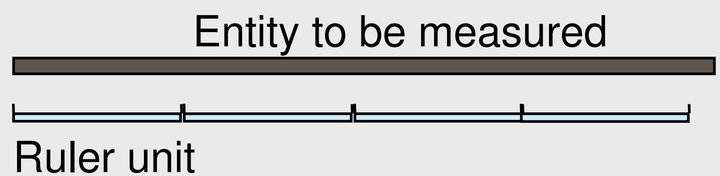
Analog to digital conversion: introduction

➔Digitization → Encode a analog value into a binary representation



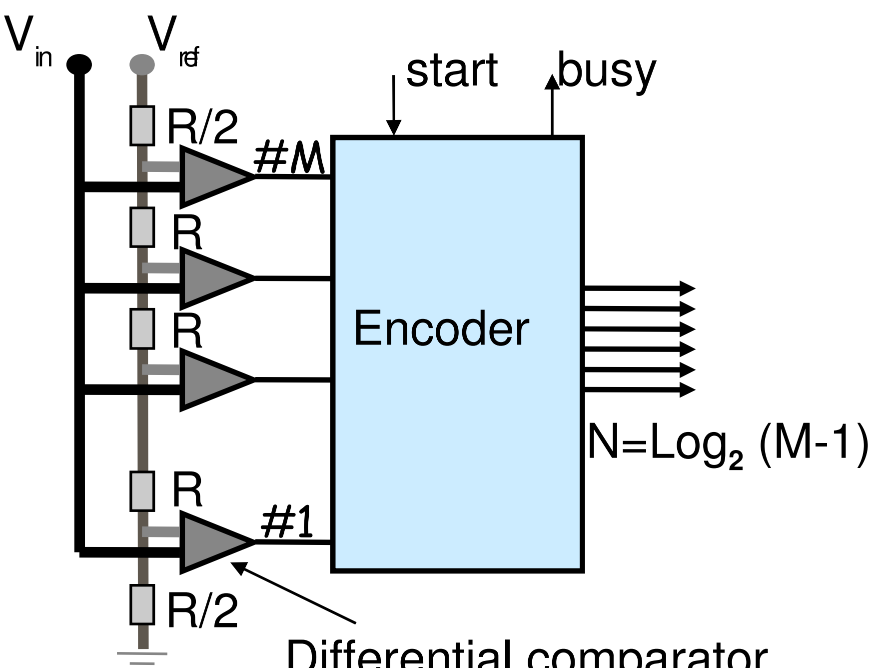
Analog to digital conversion: Flash ADC

➔Digitization → Encode a analog value into a binary representation



Compare entity with a ruler

Flash ADC



➔Flash ADC simplest and fastest implementation

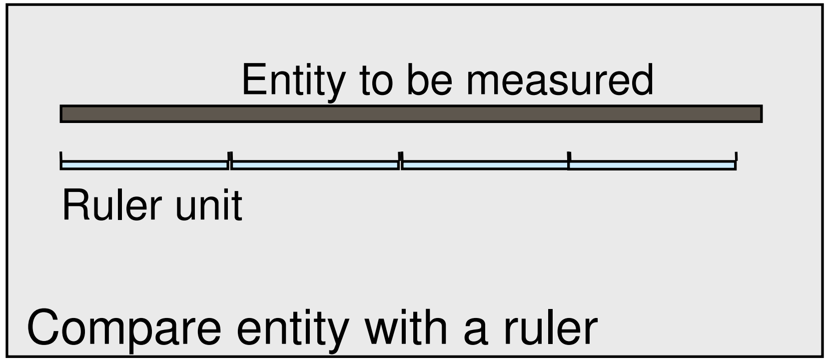
➔Performs M comparisons in parallel

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

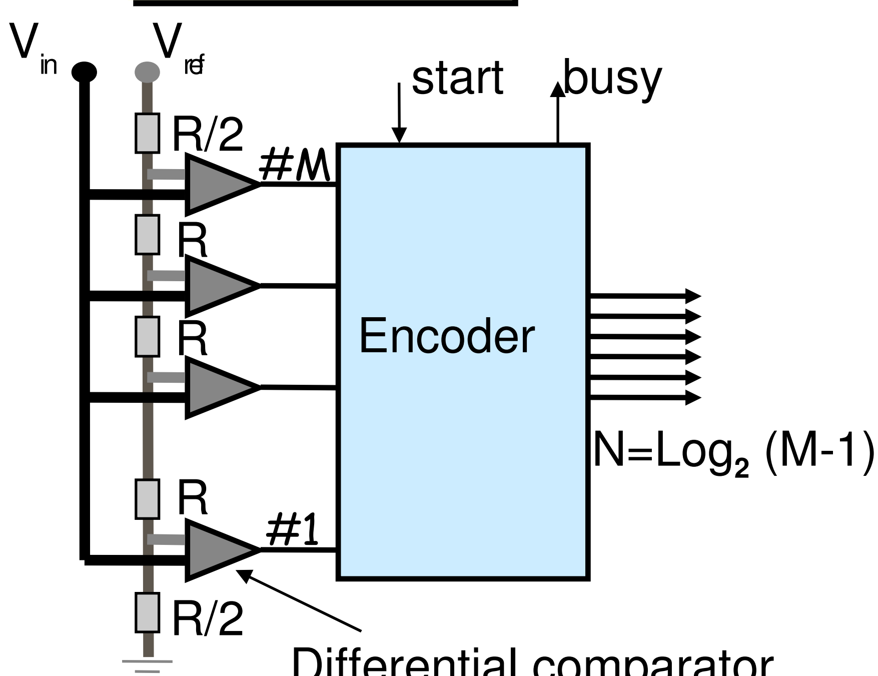
➔Result is encoded into a compact binary form of N bits

Analog to digital conversion: Flash ADC

➔Digitization → Encode a analog value into a binary representation



Flash ADC

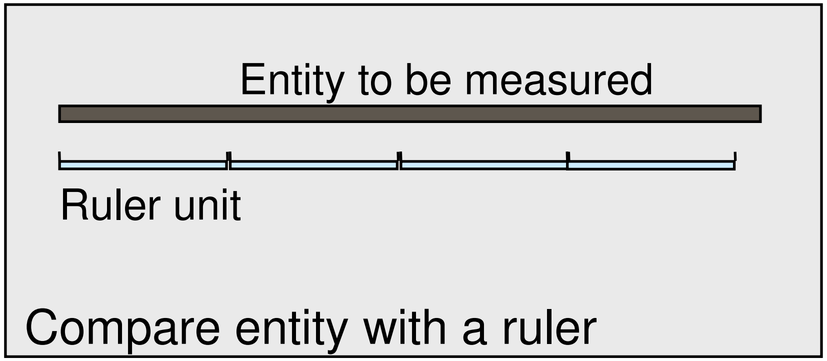


➔Example M=3 → N=2

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



➔ Resolution (LSB), the ruler unit: $V_{max}/2^N$

- 8bit, 1V → LSB=3.9mV

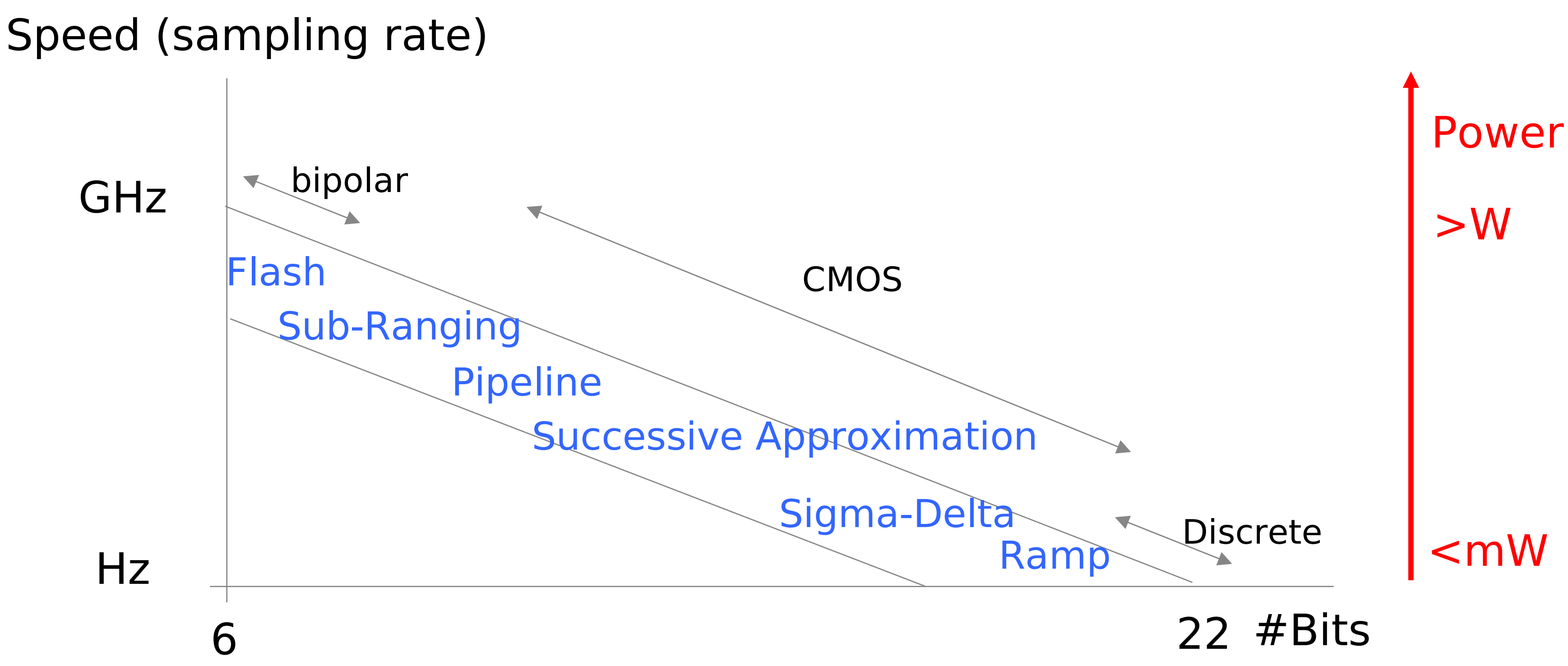
➔ Quantization error, because of finite size of the ruler unit: ±LSB/2

➔ Dynamic range: V_{max}/LSB

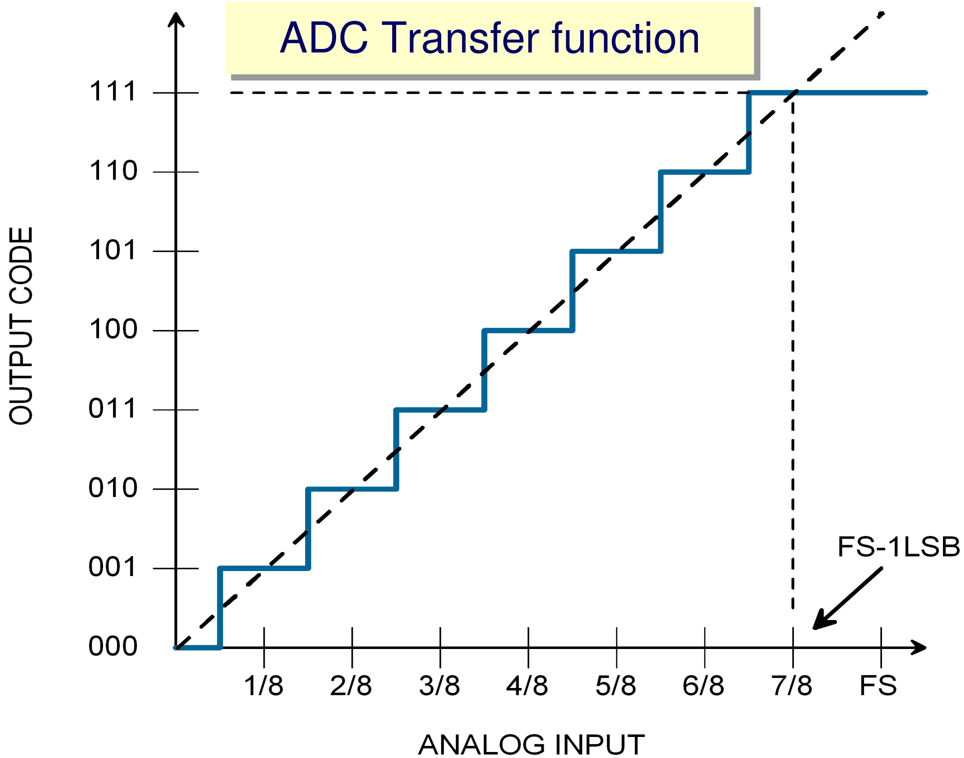
- N for linear ADC
- >N for non-linear ADC
  - Constant relative resolution on the valid input range

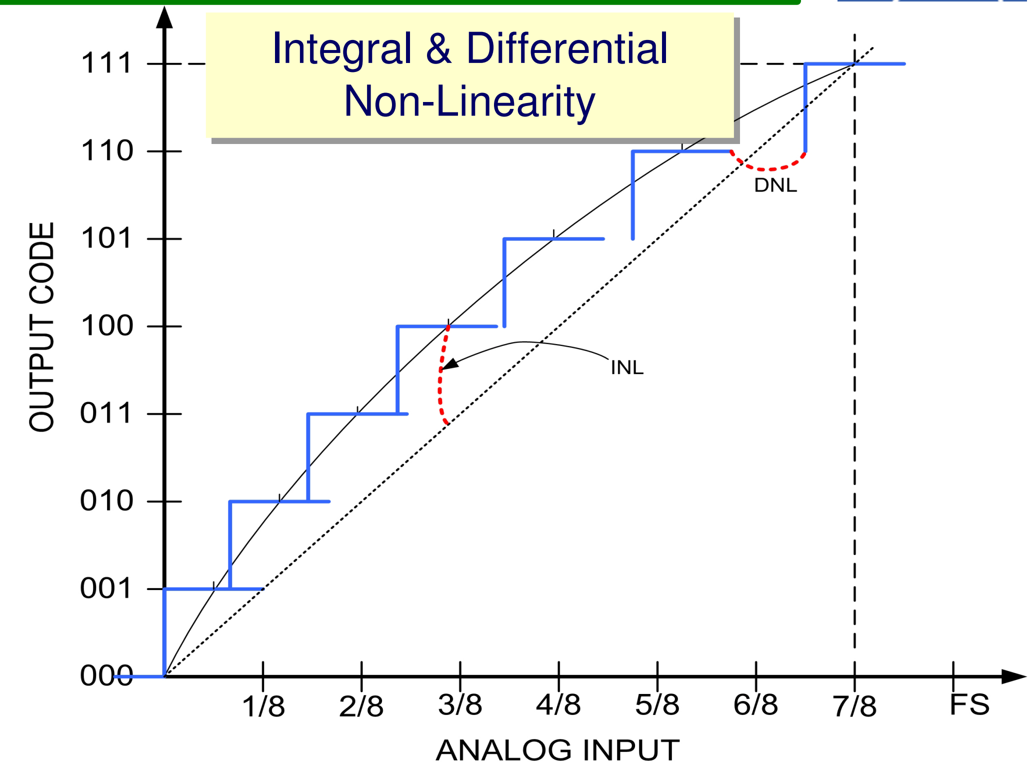
ADC phase-space

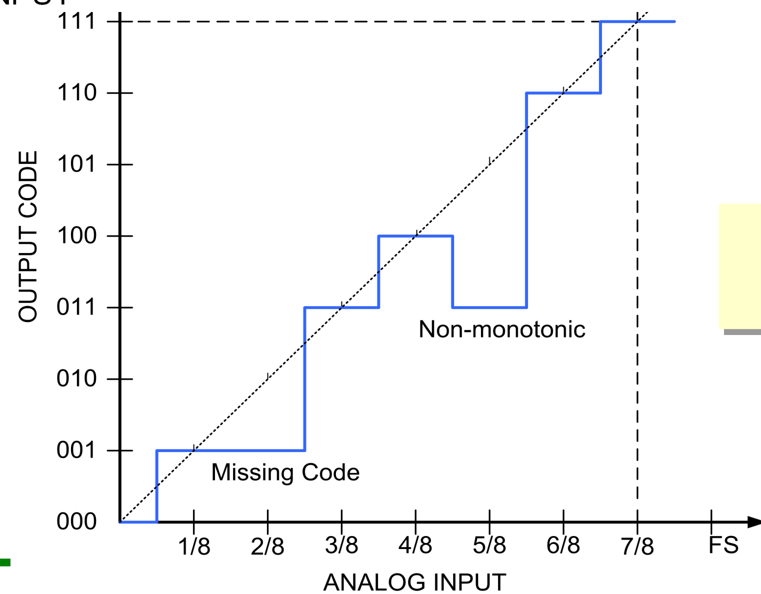
Many different ADC technique exists, mostly because of the trade-off between speed and resolution



ADC (In)Accuracies







Extreme Differential Non-Linearity

Charge to Digital → QDC

- ADC converts a voltage into a digital representation. However, in our experiment, we have a current and we are interested in the total charge
- QDC → Charge to Digital Converter
  - Essentially an integration step followed by an ADC
- Integration requires limits → gate

$$I = \int_a^b f(x)\, dx$$

QDC and experiment 1

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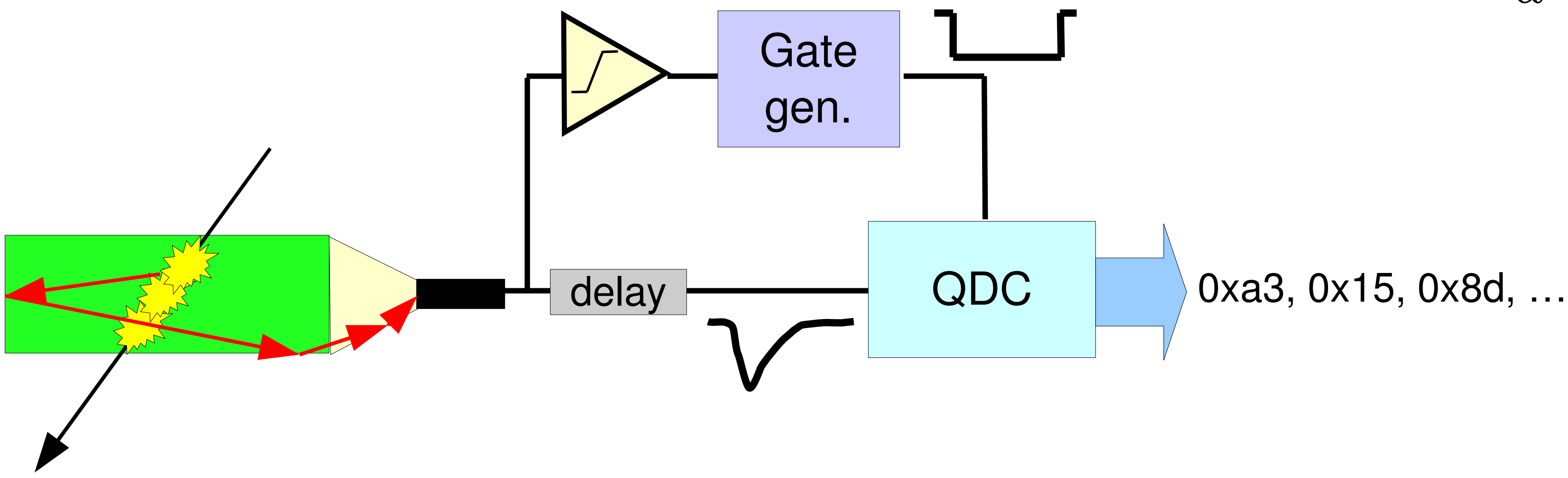
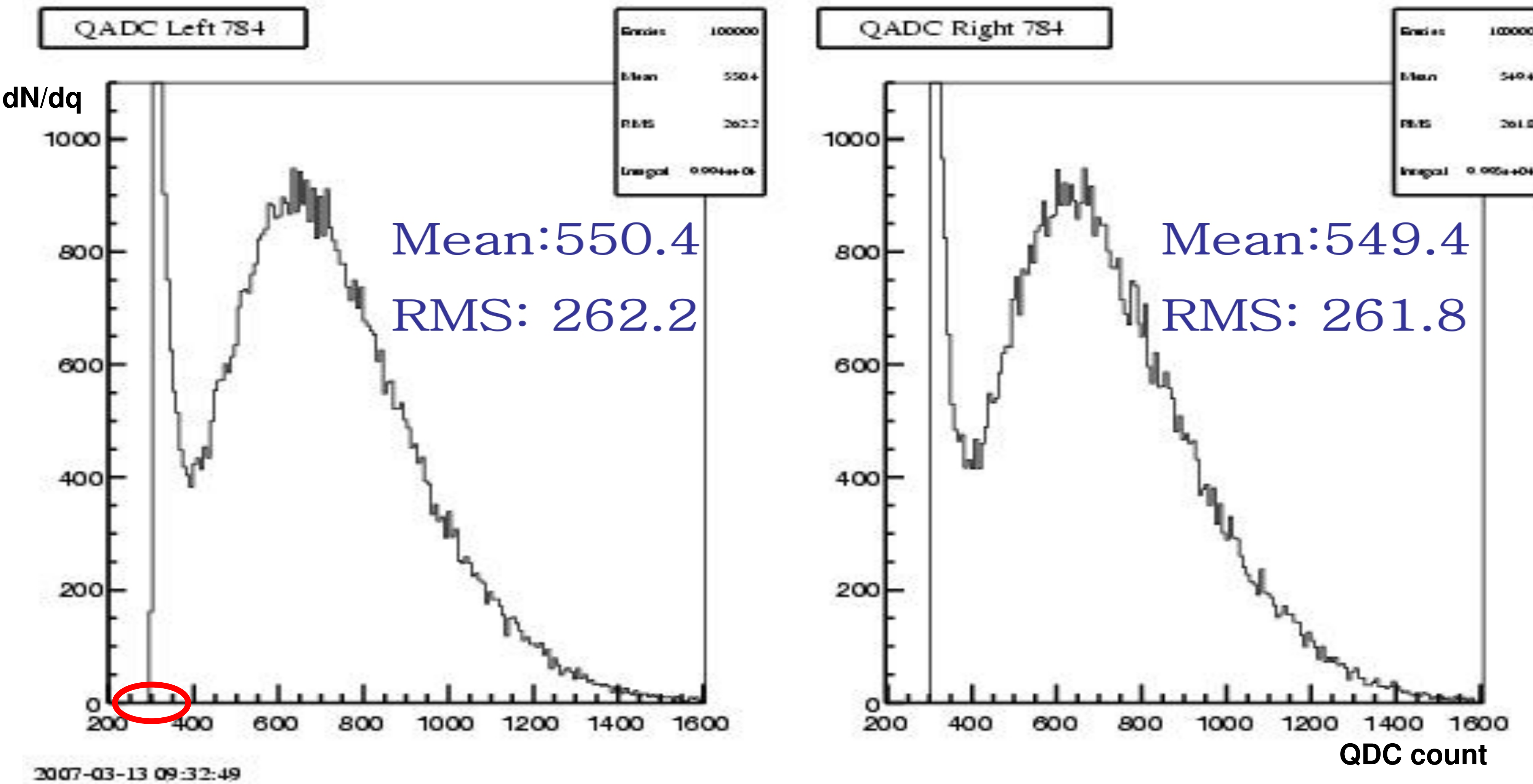


- ➔We are done: we have a digital representation of:

$$Q \propto N_\gamma \propto E$$

Question: what should follow the QDC? With which aim?

QDC and experiment 1



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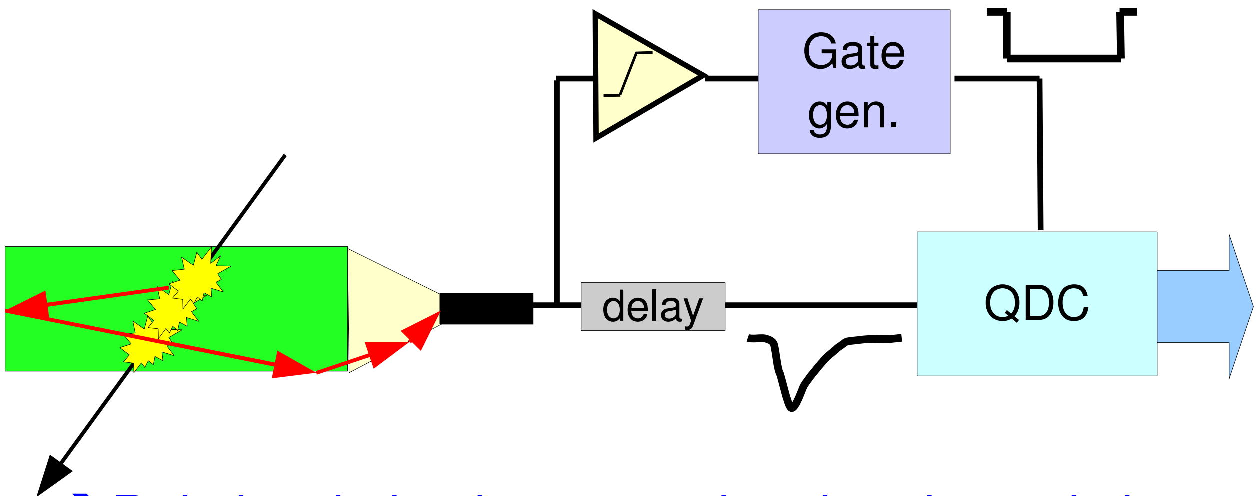
QDC: Timing



$$I = \int_a^b f(x)\,dx$$

➔ Relative timing between signal and gate is important

- Delay tuning

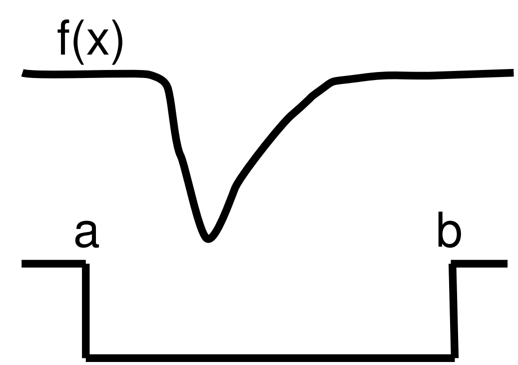
Q: the tail is exponential, how large is large enough?

➔ Gate should be large enough to contain the full pulse and to accommodate for the jitter

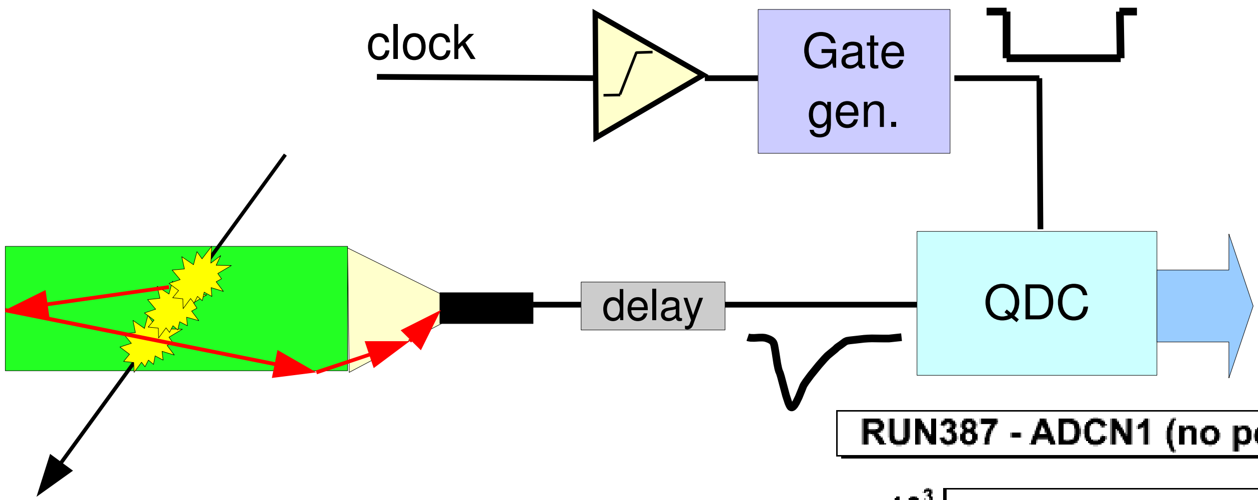
- Fluctuations are always with us!

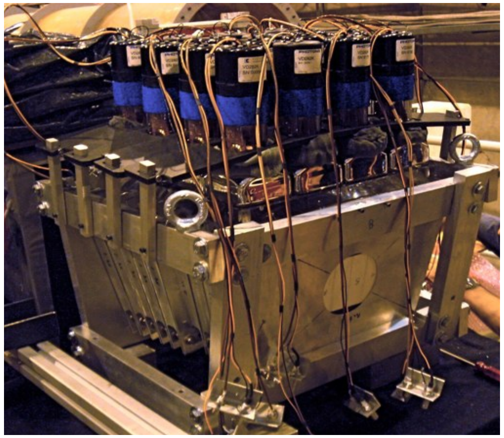
➔ Gate should not be too large → increases the noise level

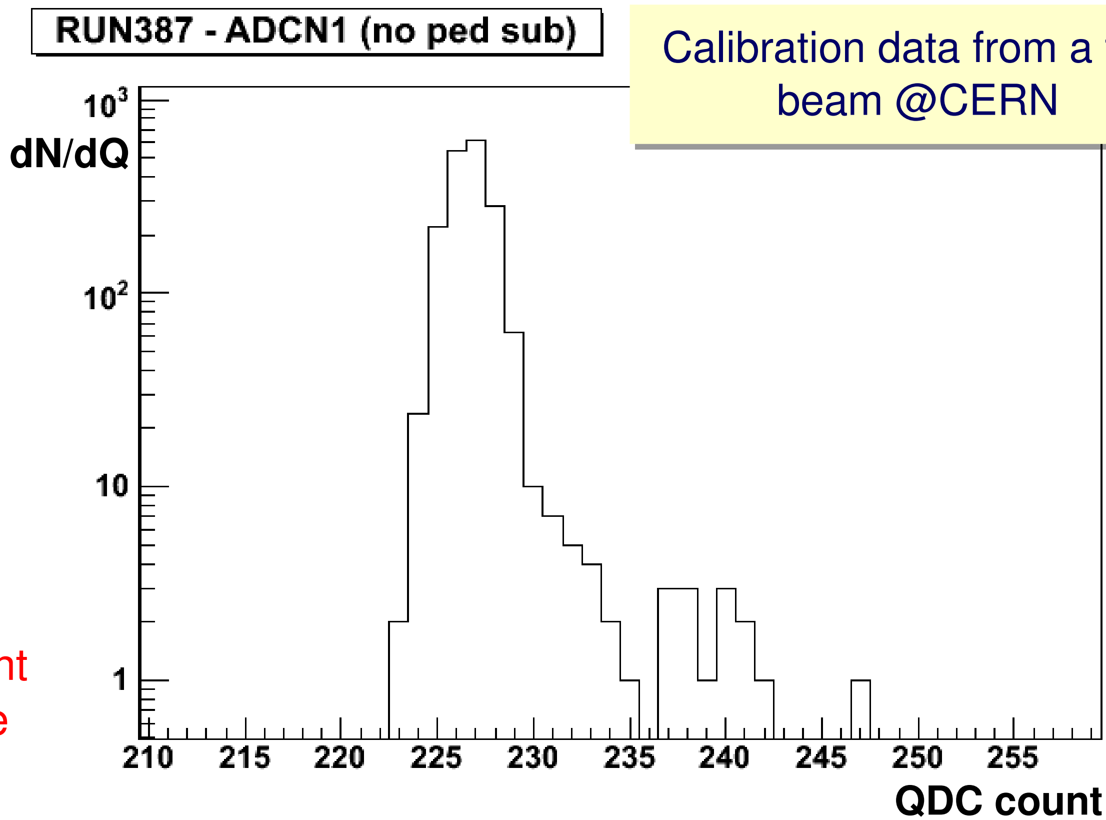
- By the way, which is the noise contribution to our charge measurement?



QDC: pedestal subtraction



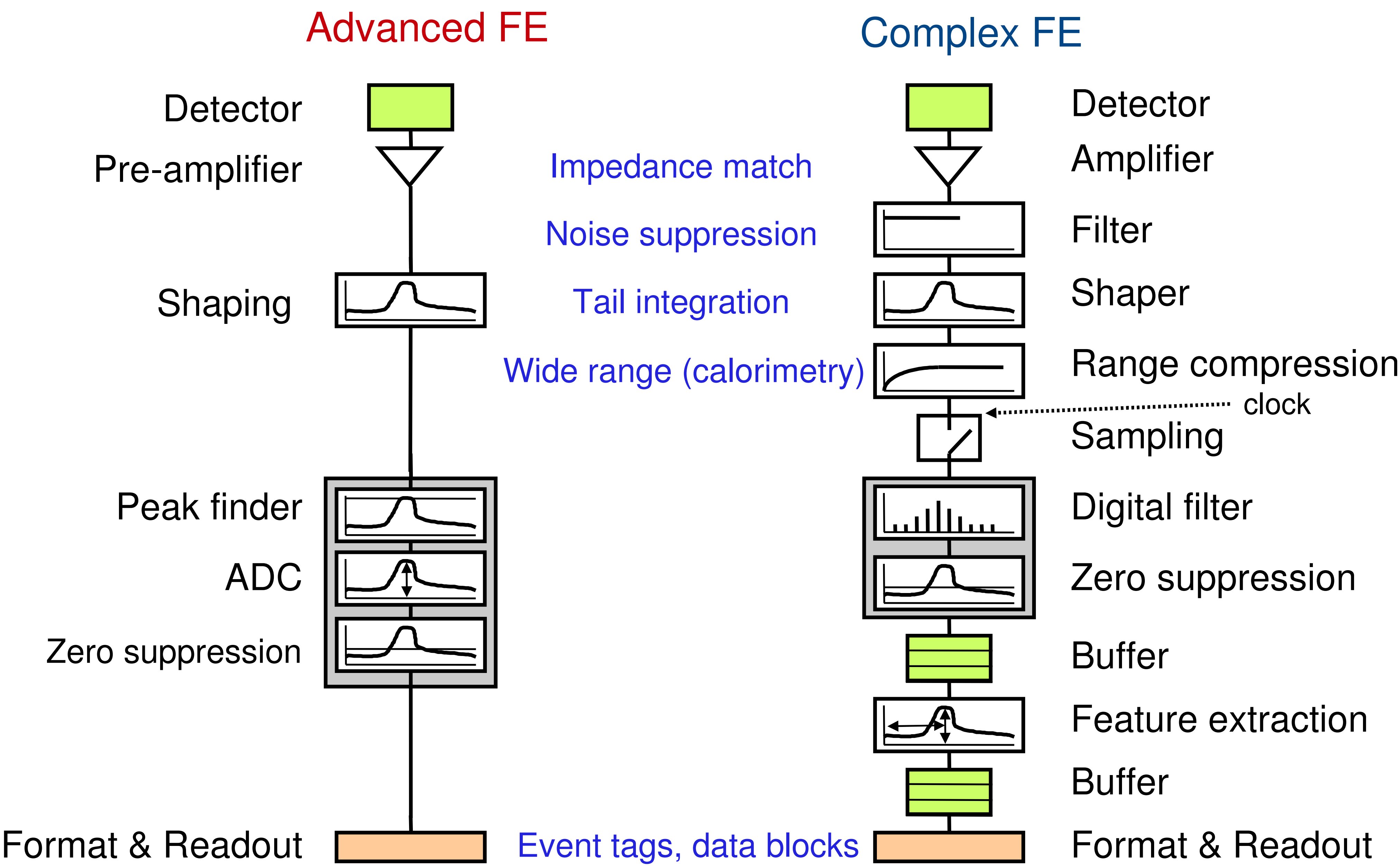




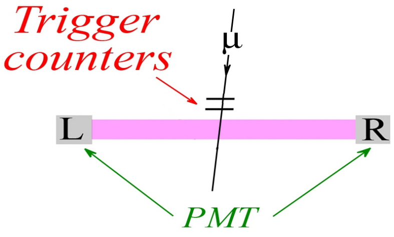
Calibration data from a test beam @CERN

- ➔ With an out-of-phase trigger we can measure the baseline (pedestal)
  - PMT dark current, thermal noise, …
  - Out-of-time particles
- ➔ The same noise enters our physics measurements and contributes with an offset to the distribution
- ➔ The result of a pedestal measurement has to be subtracted from our charge measurements

A word on front-end electronics

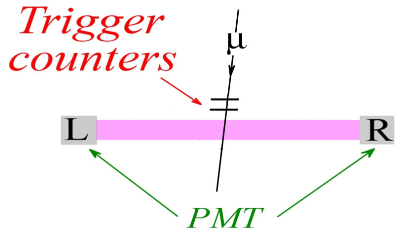


Real QDCs at work



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

Real QDCs at work



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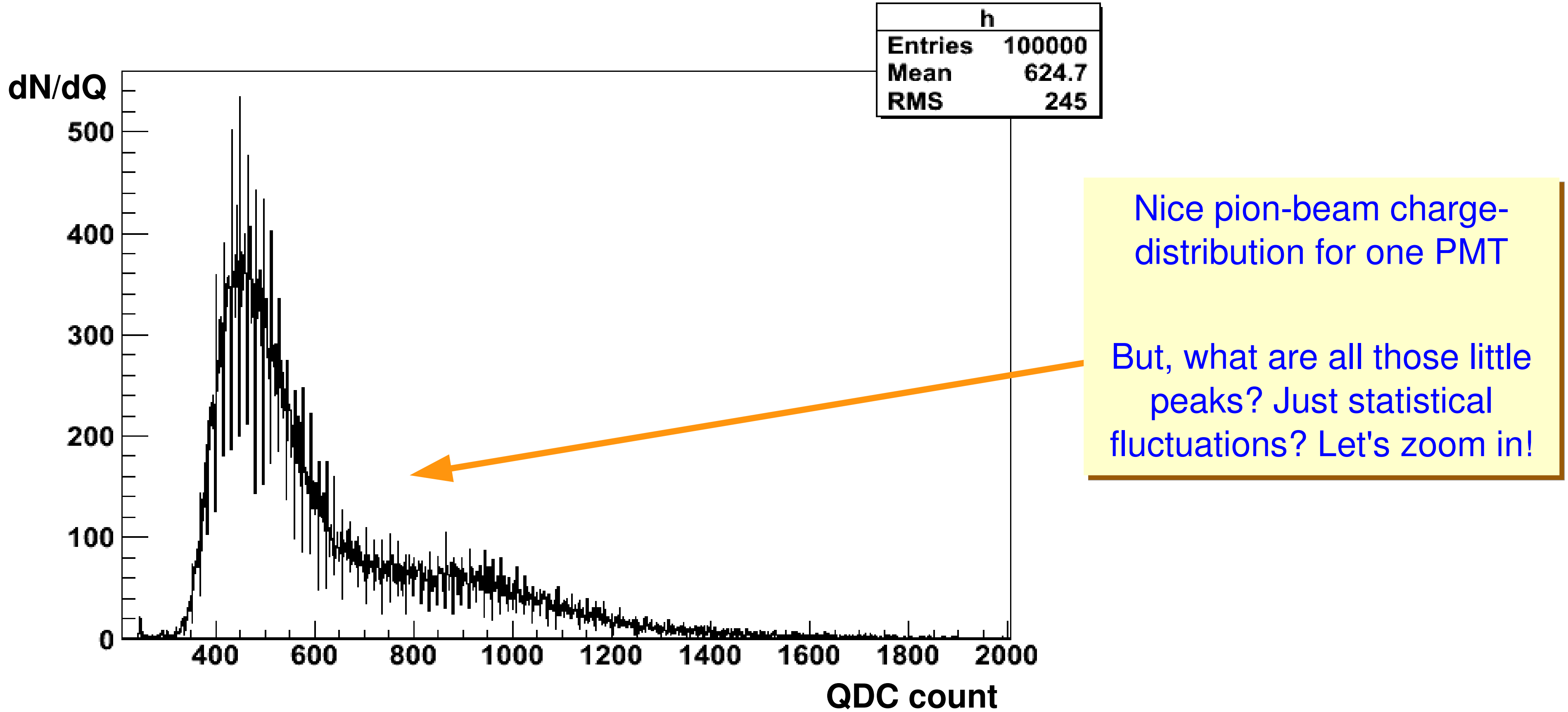

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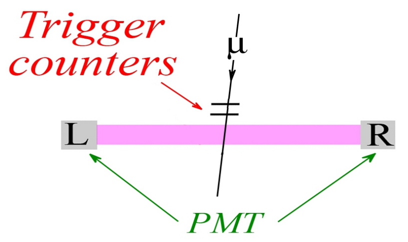
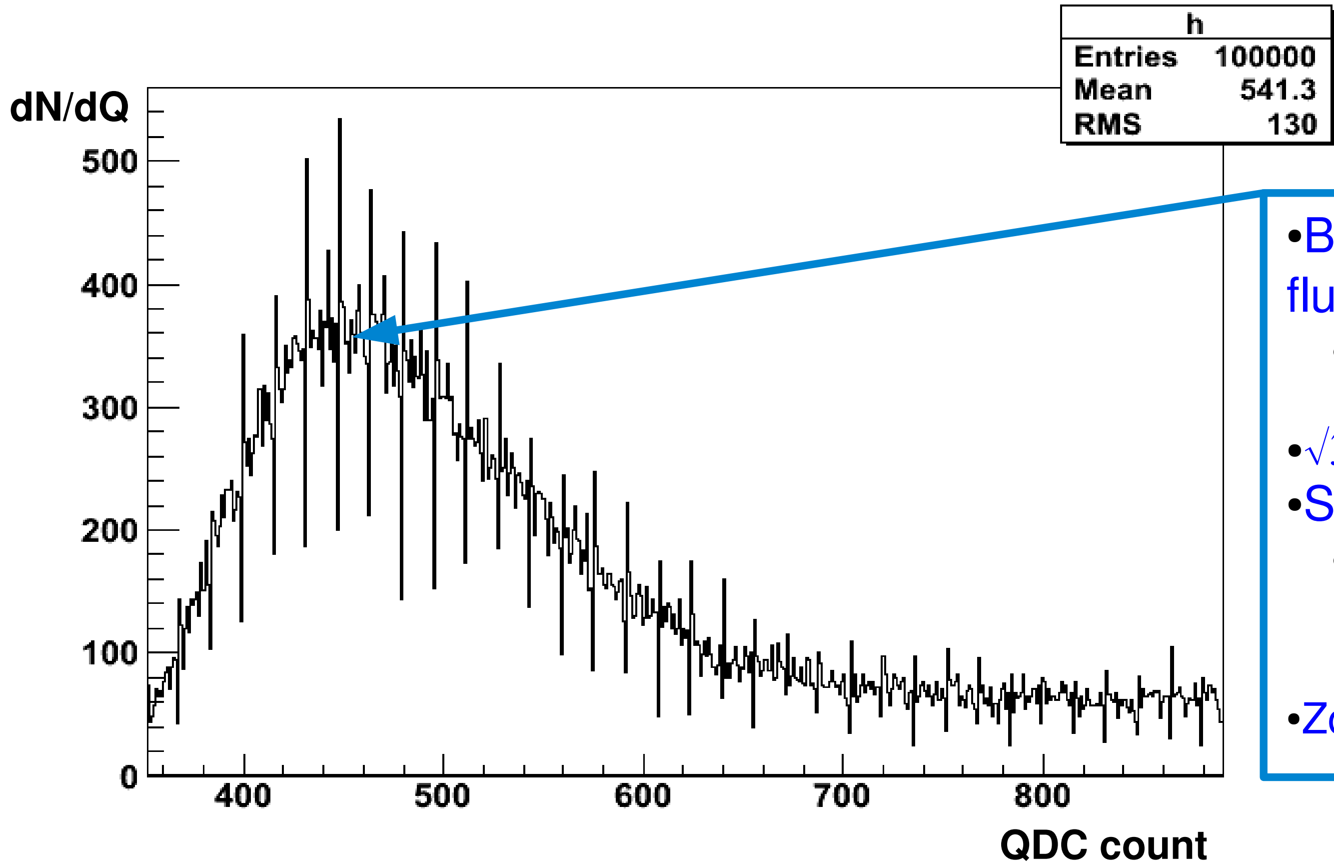
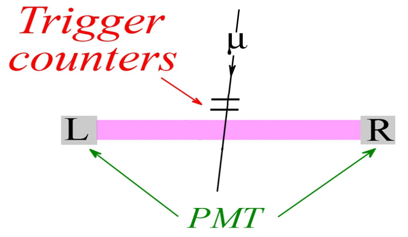


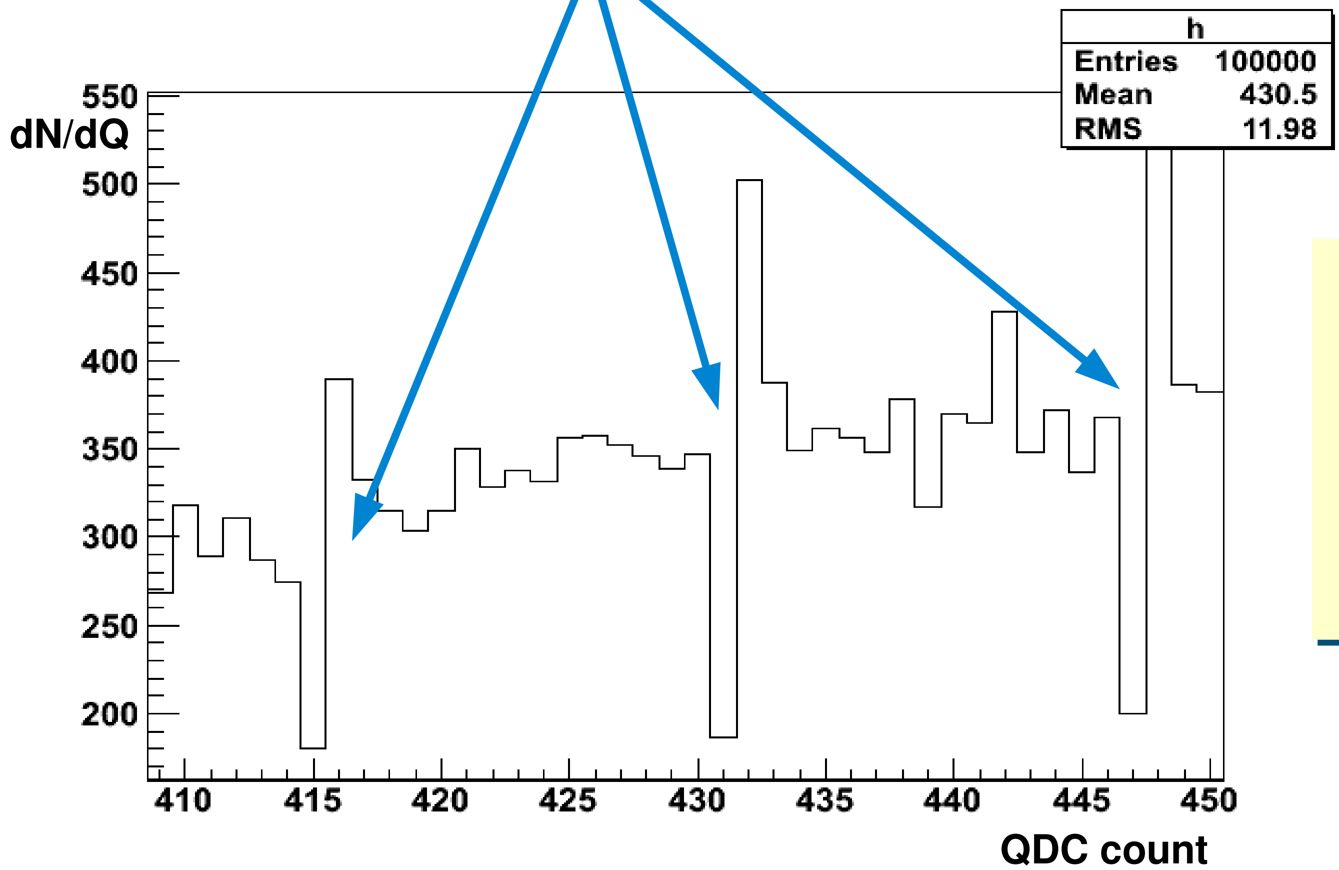


- Bin with N entries shall fluctuate with
  - $\sigma=\sqrt{N}$
- $\sqrt{360} \sim 18 \rightarrow (540\text{-}360)/18 = 10\sigma$
- Spikes are regularly distributed
  - Some systematic effect must be taking place
- Zoom in a bit more!

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*

Real QDCs at work

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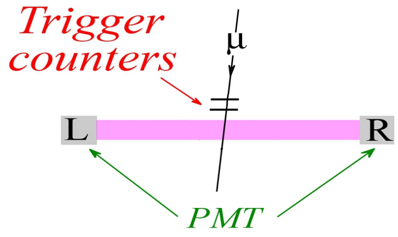
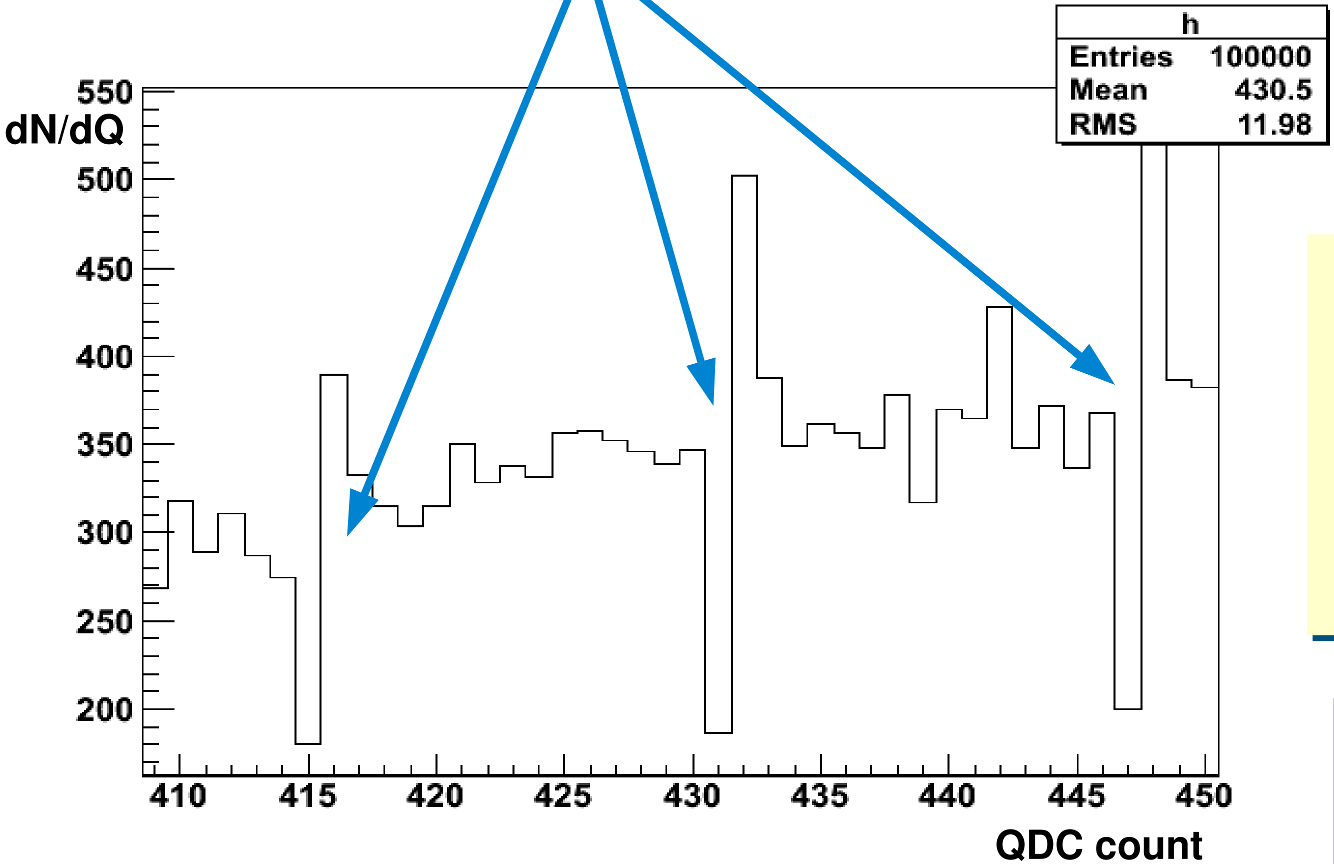




Can you see the effect?

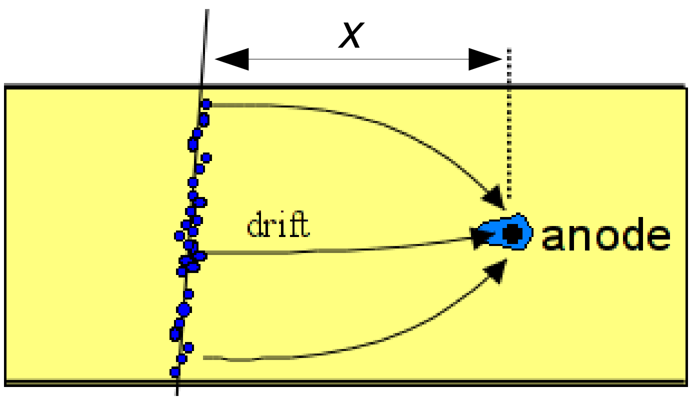
The QDC prefers output configurations of type *xxx*0 in respect of those like *xxxf*

Homework: which is the simplest way to fix this problem in the data? At which cost? Can you understand the module name?

Module: 4c6543726f79204c31313832

2nd experiment

Position measurement



➔ This time we want to measure the position of particle with a wire chamber

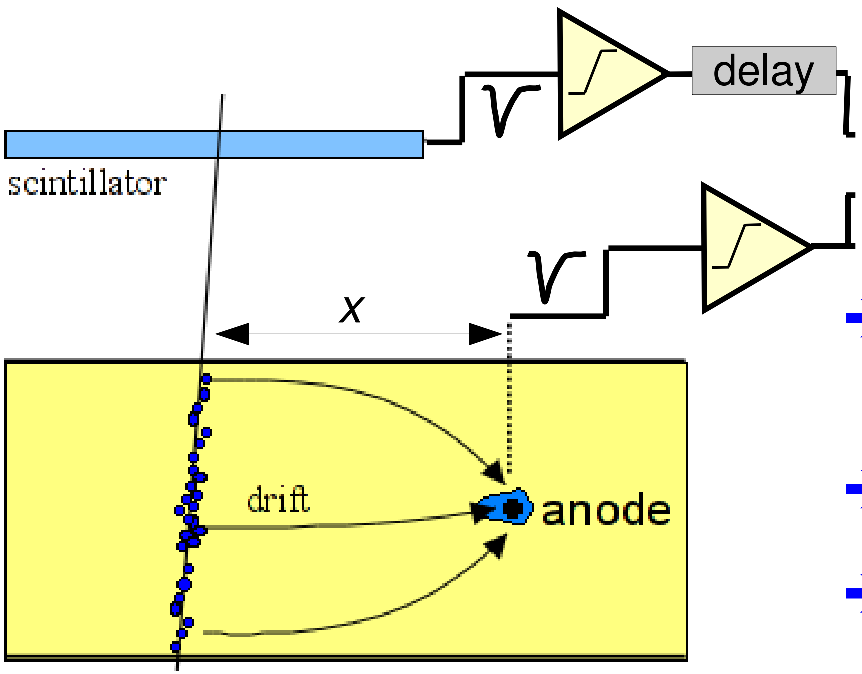
➔ The ionization electrons created by the passage of the particle will take a time Δt to reach the anode wire

➔ Transit time is normally negligible with respect to Δt

➔ If we consider a constant drift speed v_D (50μm/ns), then position is:

$$x = v_D \cdot \Delta t$$

Triggering



➔ The wire chamber alone is not sufficient however

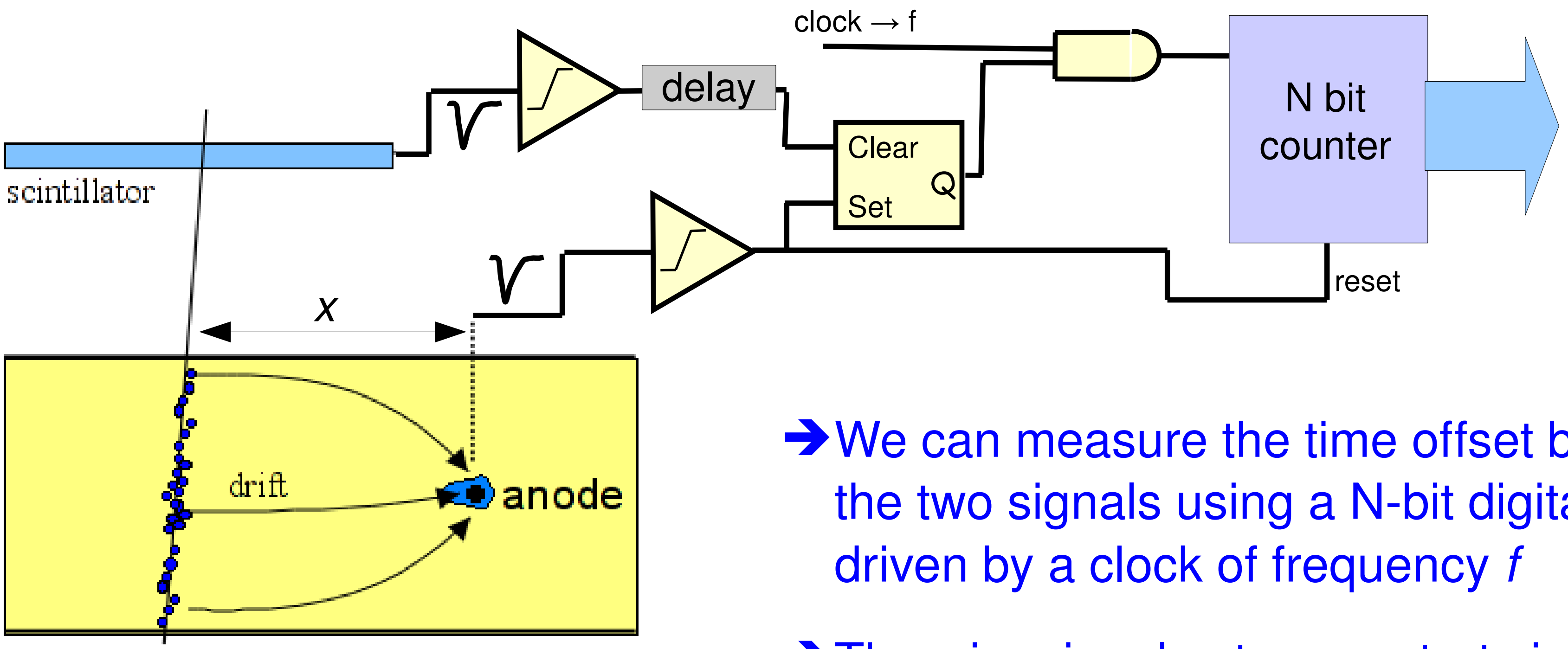
➔ We need a triggering system

➔ Therefore we will measure a relative time $\Delta t + t_0 = t^*$

- t_0 accounts for the time delays, offsets, … between the wire chamber and the triggering system

$$x = \alpha t^* + \beta$$

Time measurement

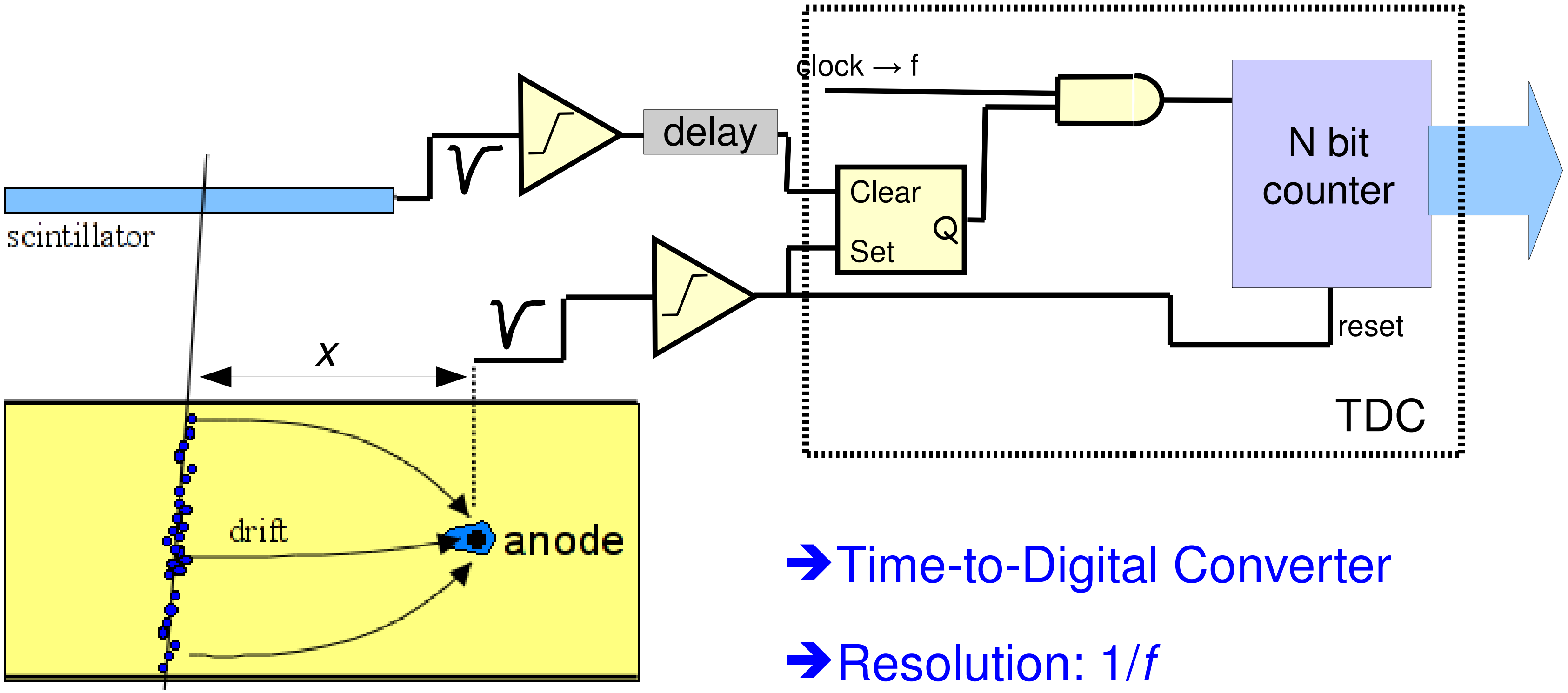


➔We can measure the time offset between the two signals using a N-bit digital counter driven by a clock of frequency *f*

➔The wire signal acts as a start signal

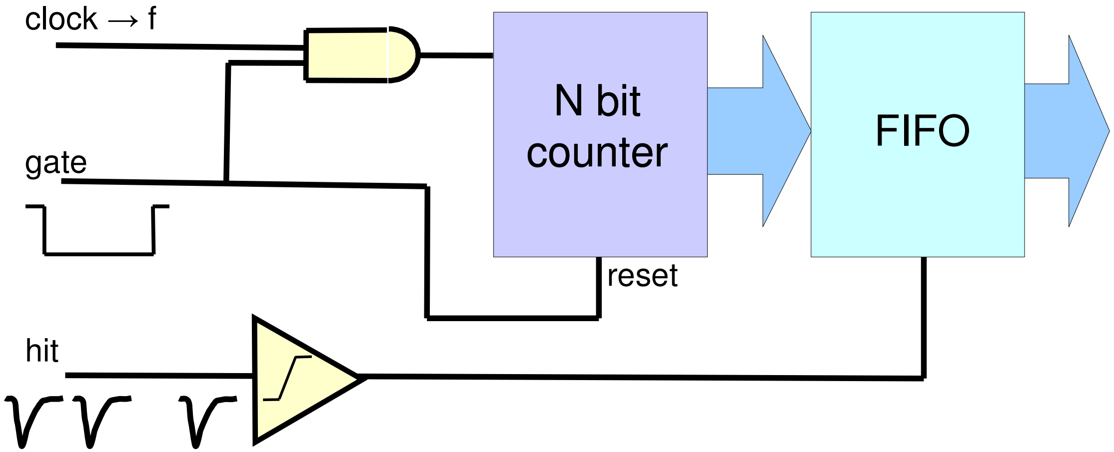
➔The trigger provides the stop signal

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



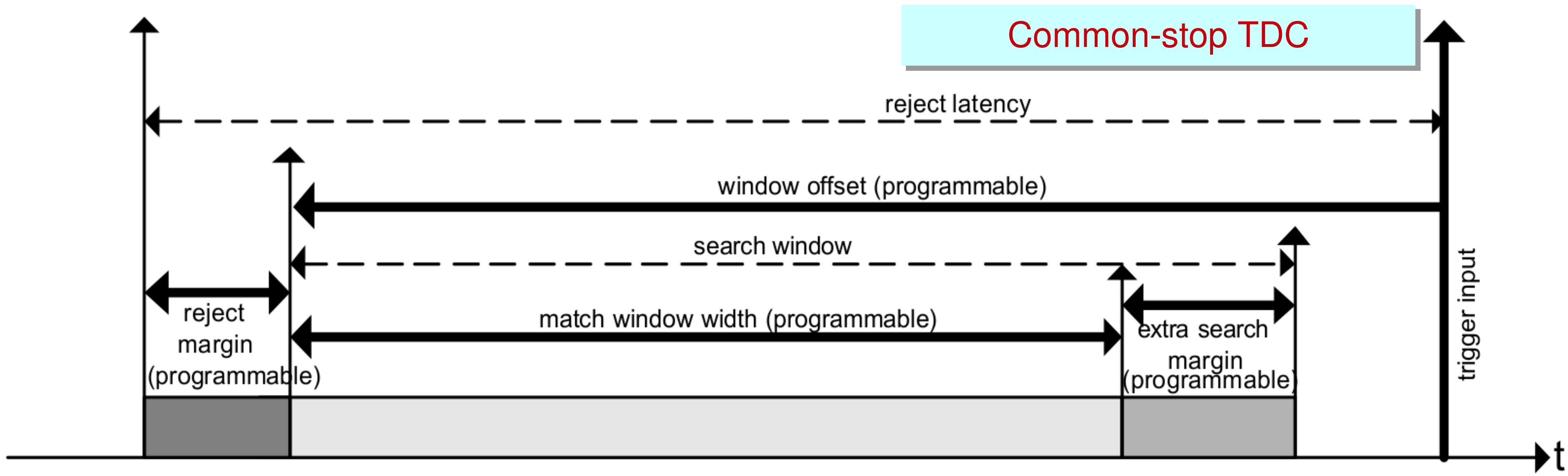
➔Gate resets and starts the counter. It also provides the measurement period. It must be smaller than $2^N/f$

➔Each "hit" (i.e. signal) forces the 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

➔Common-start configuration

Actual TDCs

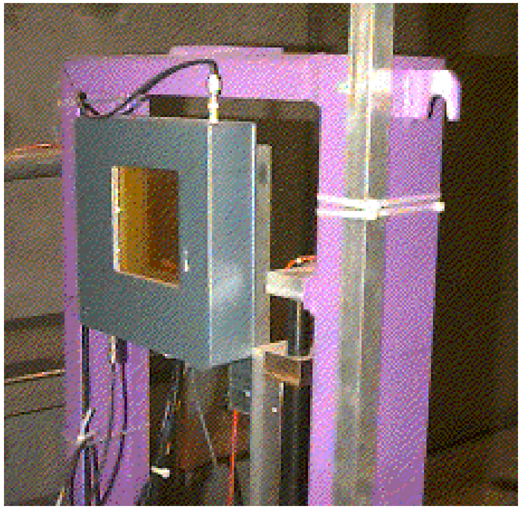


➔ Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching

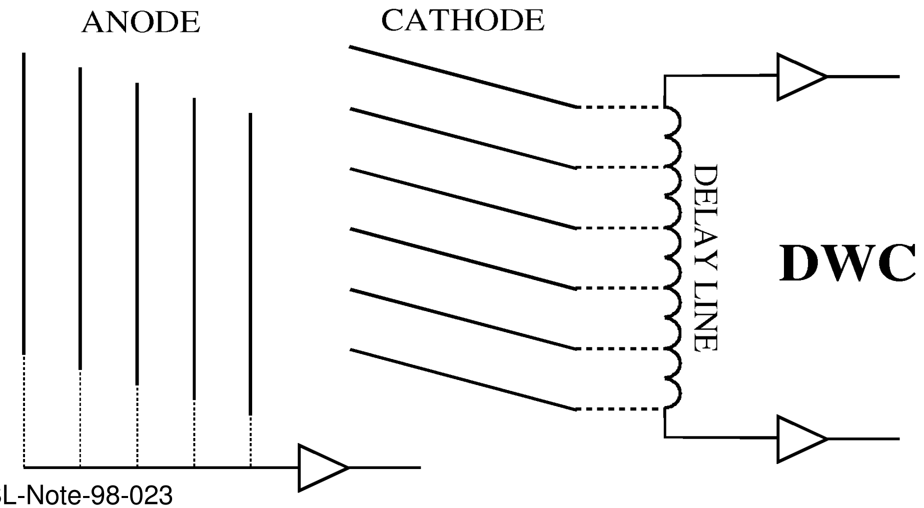
- Internal programmable delays
- Internal generation of programmable gates
- Programmable rejection frames

Can you imagine/sketch a common stop setup?

Real life wire chamber & TDC



- ➔XDWC: delay wire chambers used on the SPS extracted lines to measure beam profiles
- ➔Two cathode planes provide X and Y positions
- ➔Measurement is based on the delay gained along a delay line



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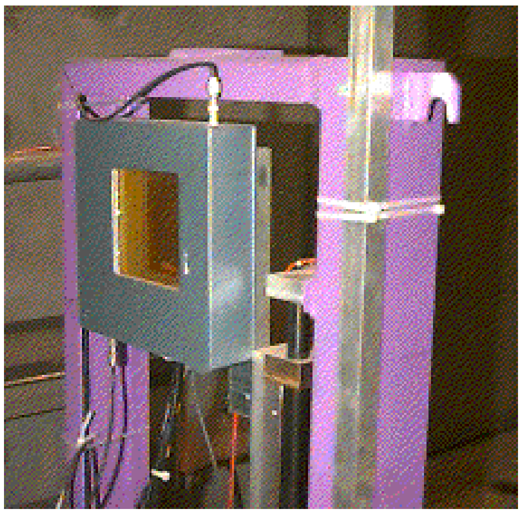
Principle



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- ➔ Two cathode planes provide X and Y positions
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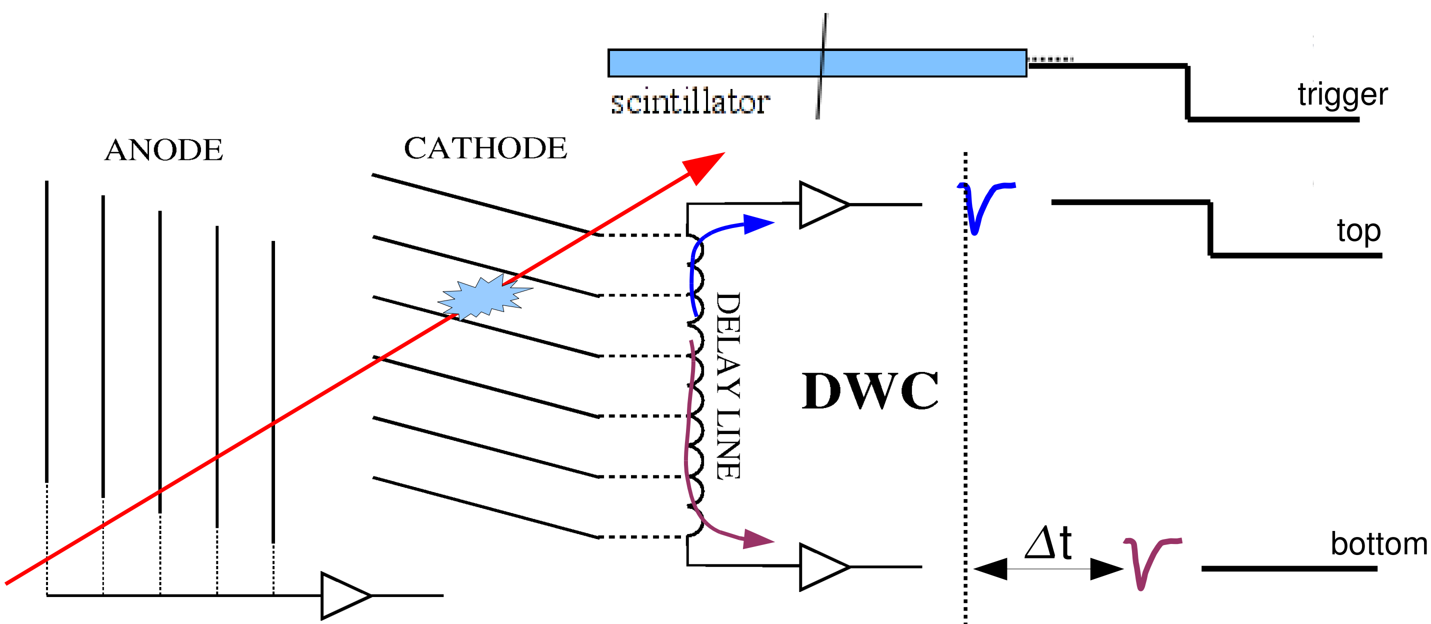
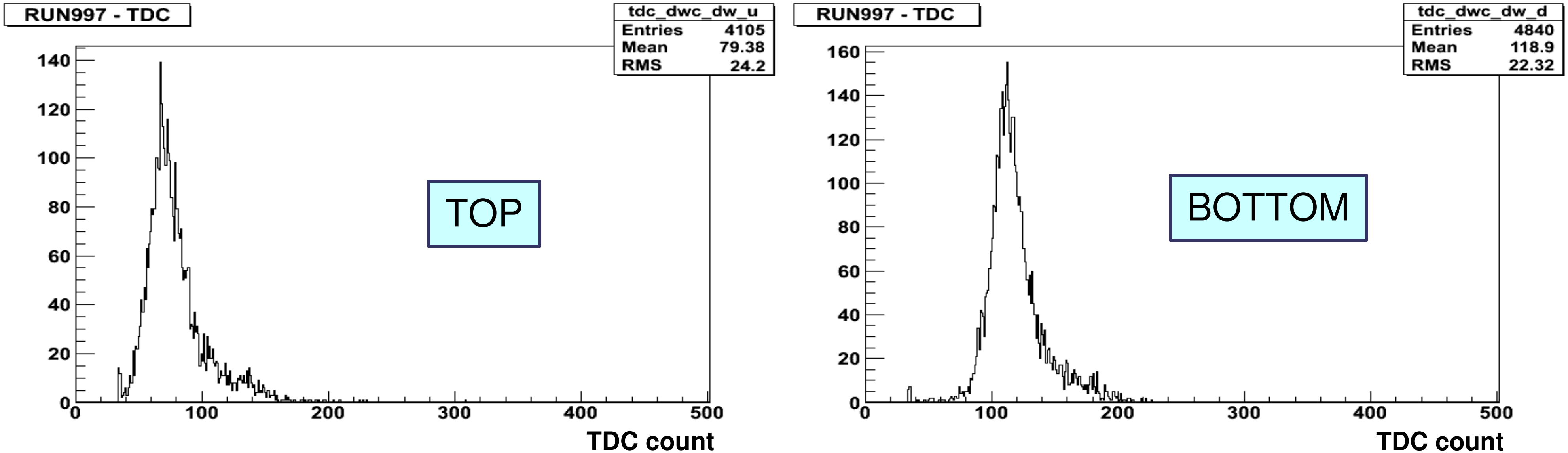
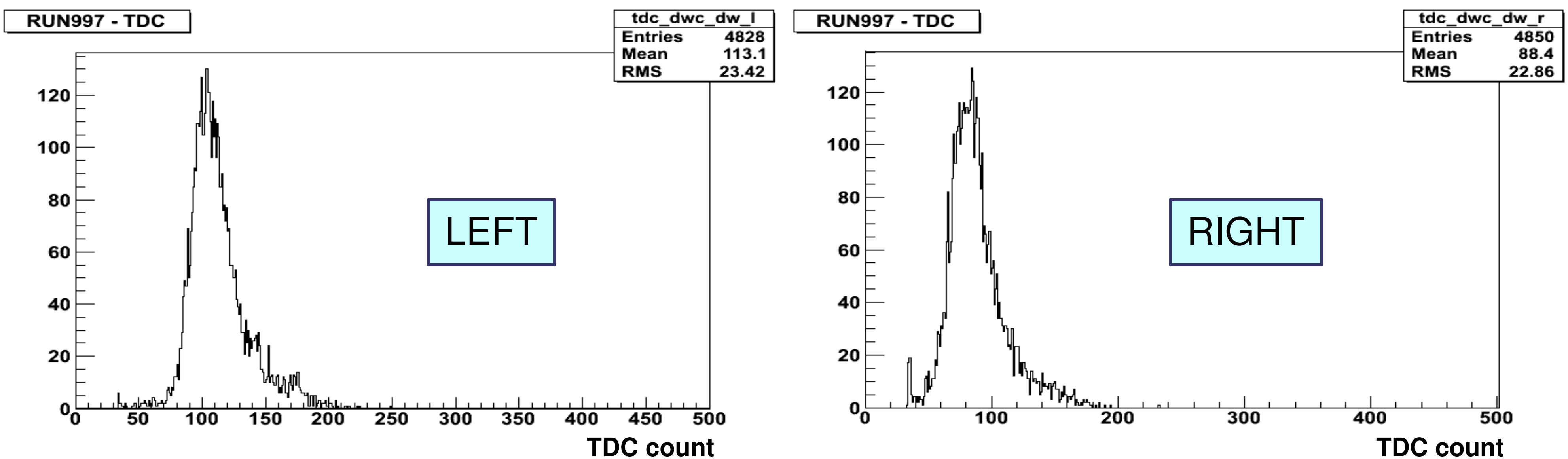
$$y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$$



Raw time data

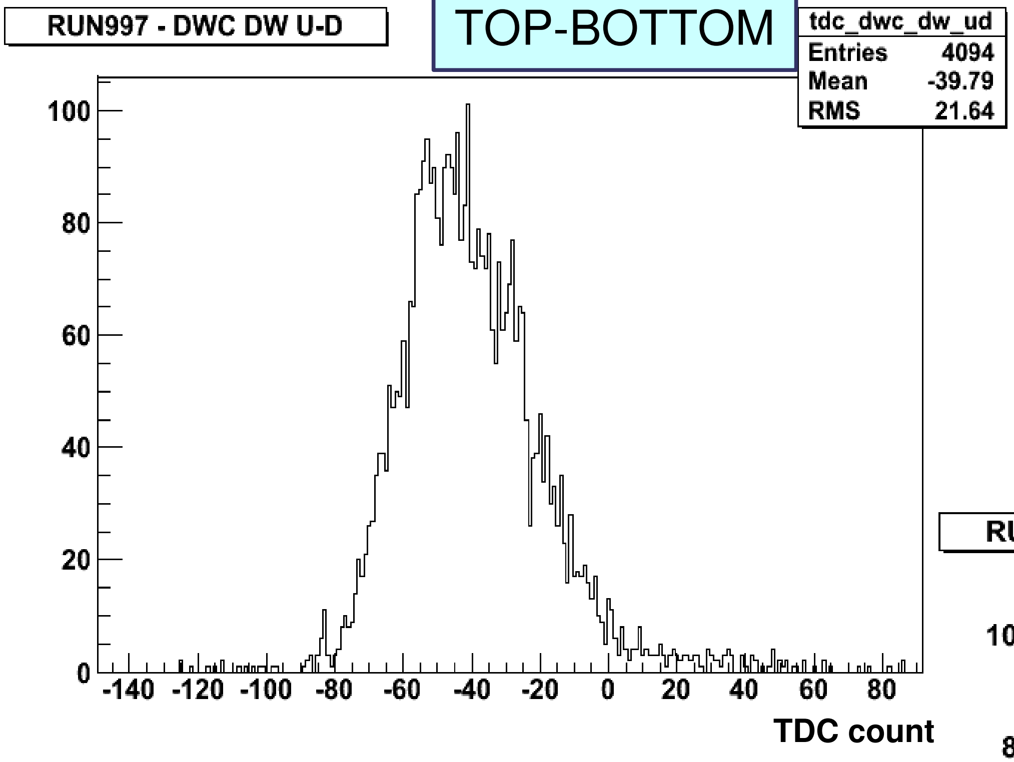


Individual channel distributions

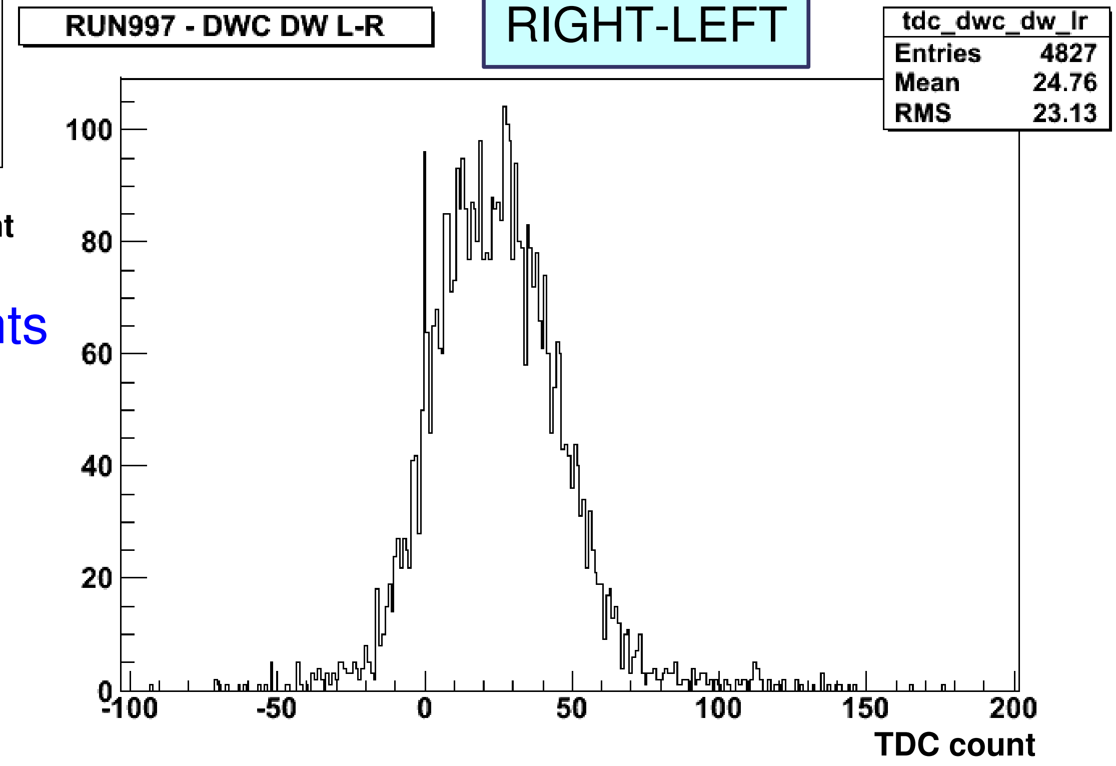


(Uncalibrated) Beam Profile

TOP-BOTTOM



RIGHT-LEFT



- ➔ Beam sizes are still in TDC counts
  - Not very useful, though
- ➔ How do we convert this into a known scale (e.g. cm)?

Corollary: calibration

Calibration

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

- Scintillator

$$Q \propto N_\gamma \propto E$$

- XDWC

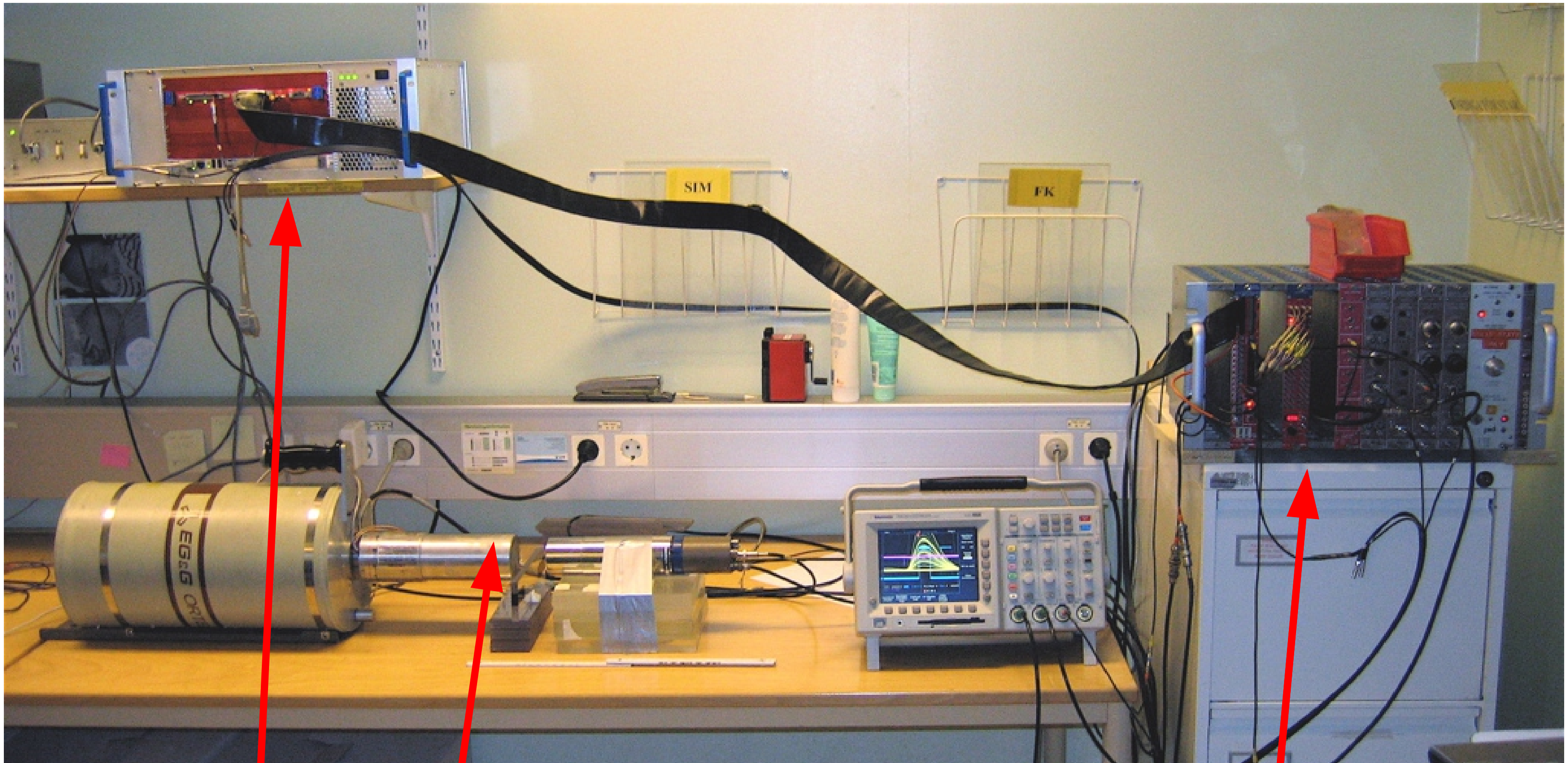
$$y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$$

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

- We have to determine the parameters that transform the raw data into a physics quantity
- The parameters normally depend on the experimental setup (e.g. cable length, delay settings, HV settings, …)

➔ In the design of our detector and DAQ we have to foreseen calibration mechanisms/procedures

Ge crystal for isotope identification

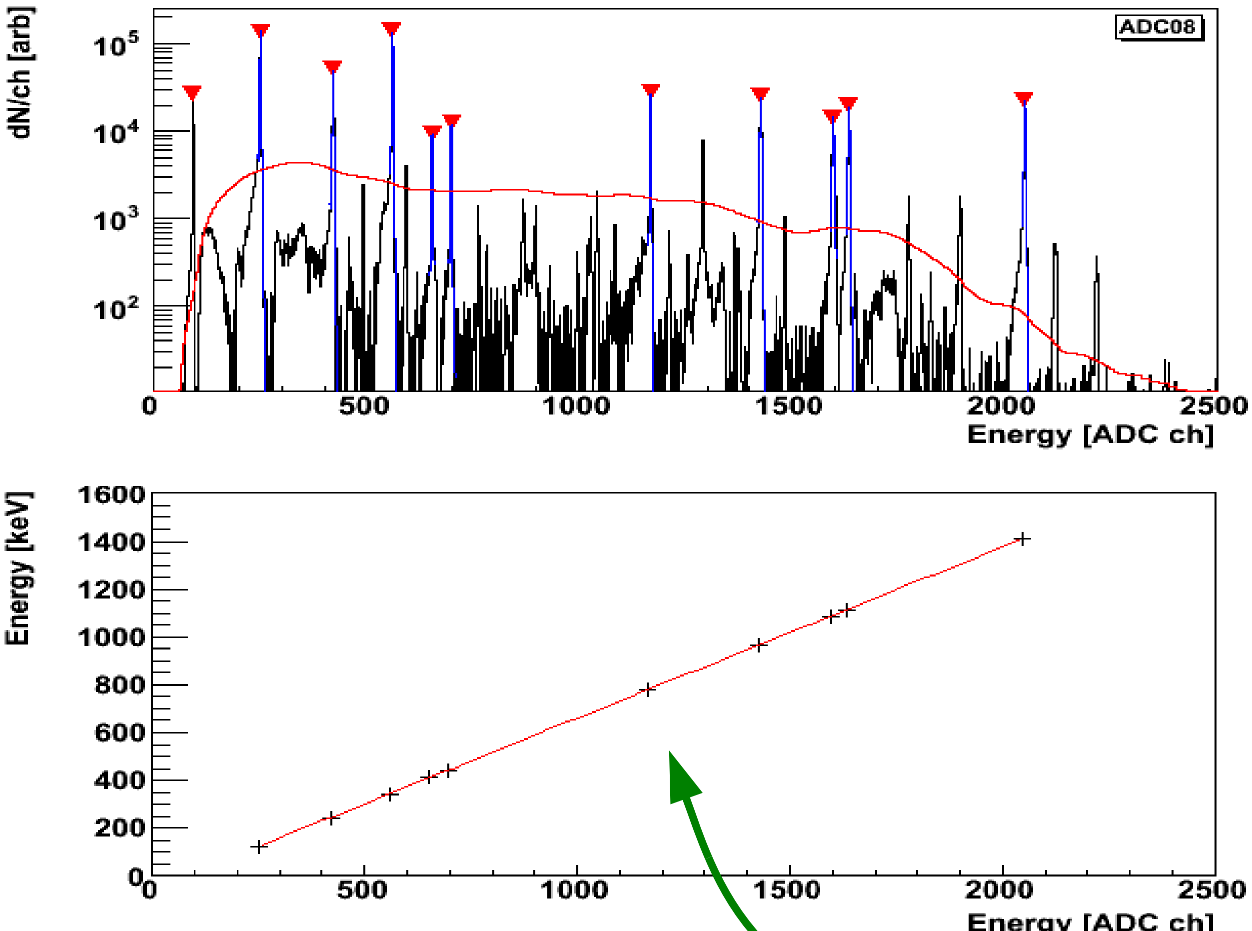


Crystal HPGe

Trigger & front-end

Readout (ADC)

Crystal calibration

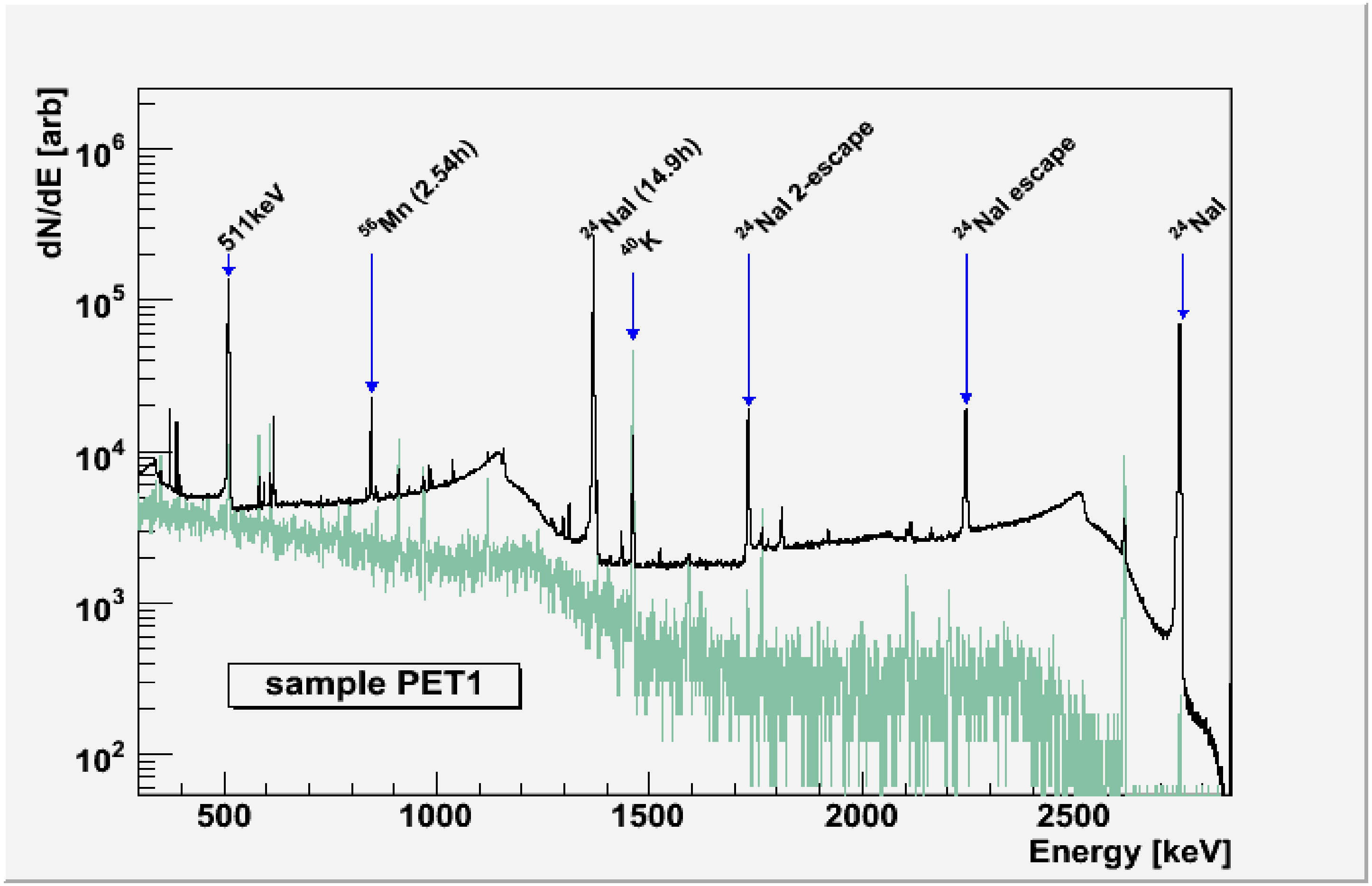


- ➔ ^{152}Europium reference source
  - Known γ emission lines
  - Peak find & fit
- ➔ Allow for definition of the parameters describing functional relation between ADC count and E

$$Q \propto N_\gamma \propto E$$

- ➔ Reality is not perfectly linear
  - Polynomial fits
  - Physical models

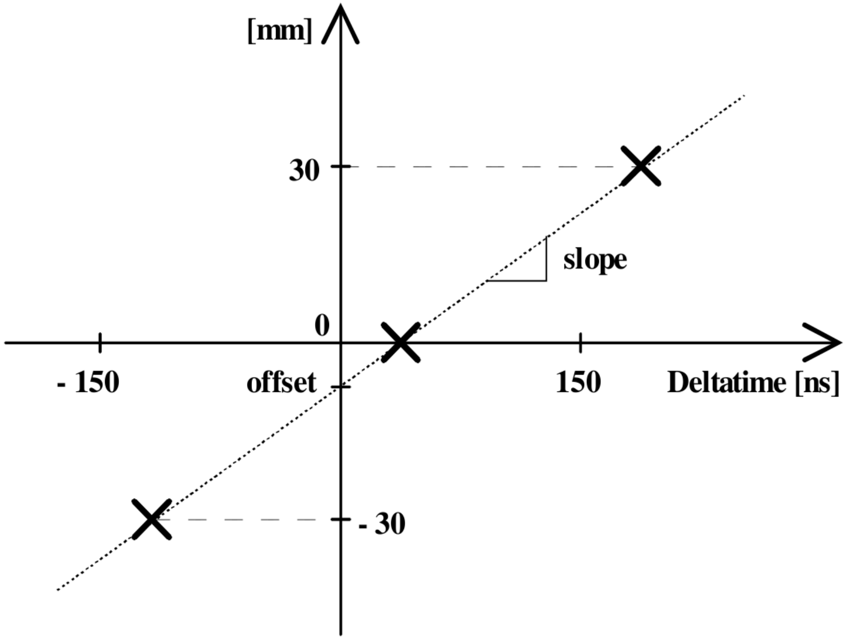
Isotope identification



Calibrate crystal setup can be used to identify isotopes generated in γ-irradiated samples

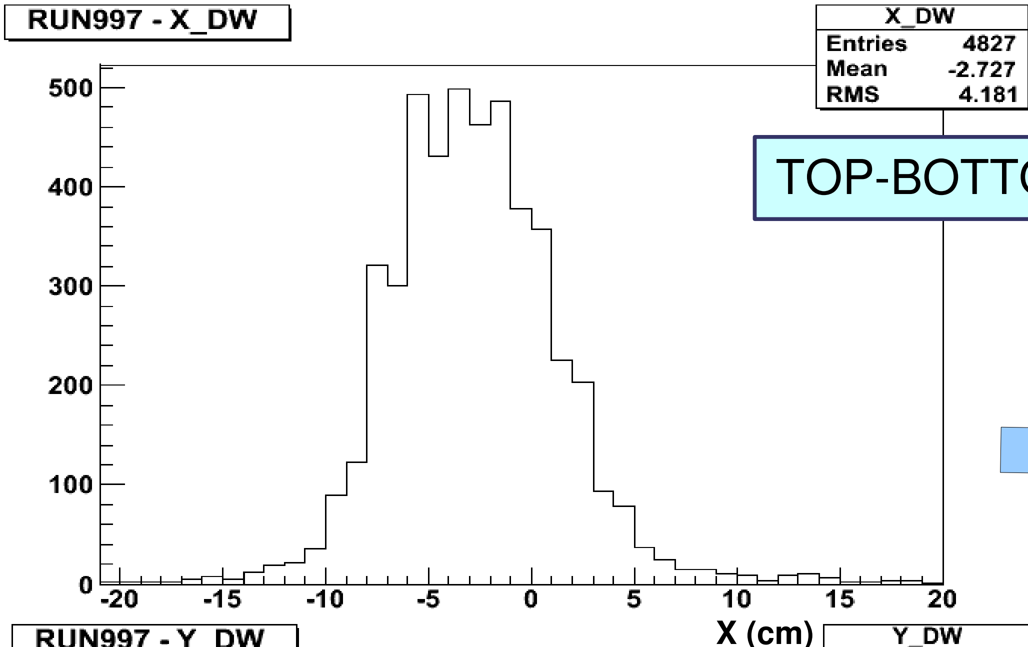
XDWC Calibration

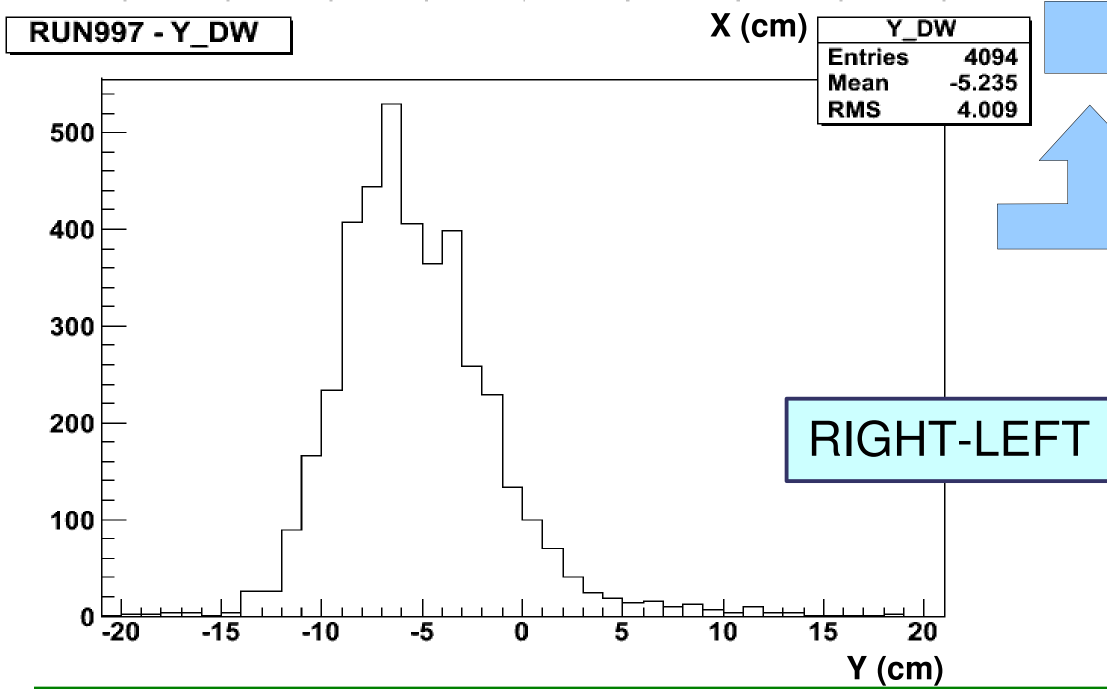
- XDWC chamber have 3 calibration inputs that allow for independent calibrations of X and Y axis with only 3 different sets of data
- The calibration input simulate signals from particles respectively hitting
  - Right-top corner (X=Y=30mm)
  - Center (X=Y=0mm)
  - Left-bottom corner (X=Y=-30mm)
- The calibration data sets shall be taken with final setup and TDC
- Interpolating the three points in the *t-x* space, the parameters of the calibration equation can be measured



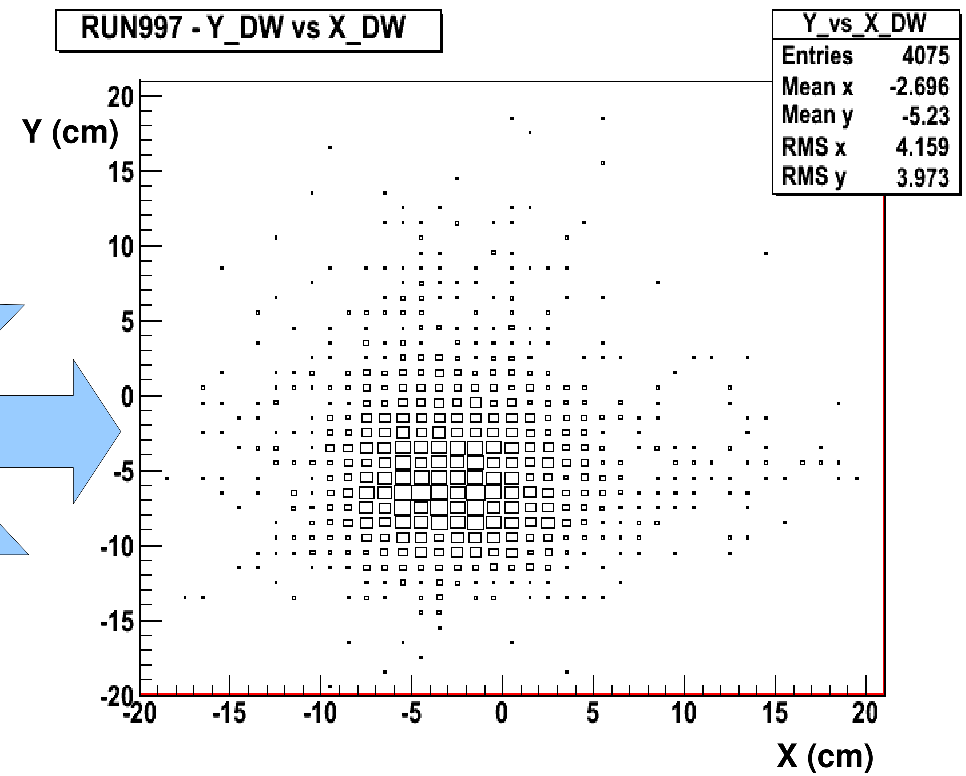
$$x = \alpha t^* + \beta$$

Calibrated XDWC





Beam profile



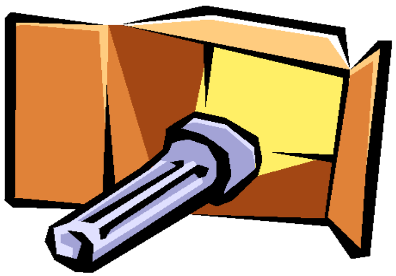
Wrap-up

➔ Digitization techniques produce data directly manageable by digital systems (e.g. a computer)

- Greatly simplifies the down-stream data-handling
- Root of every modern DAQ system
- Available on a variety of platforms: VME, PCI, USB, …

➔ Open the "black box" and see where the numbers come from

- Real electronics does not behave as the ideal one



➔ Trade-offs between speed/precision/cost exist

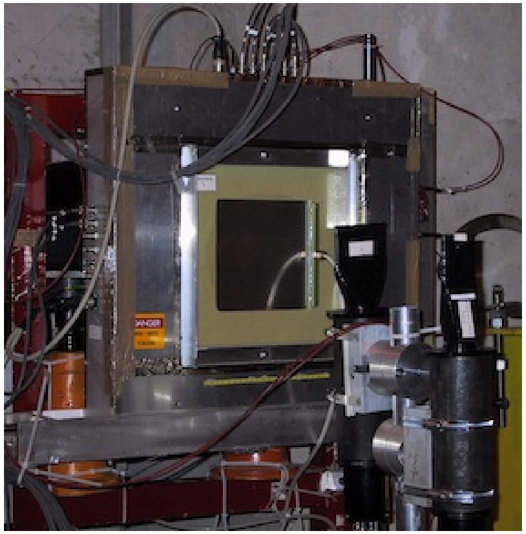
- You have to choose the solution that best suits you

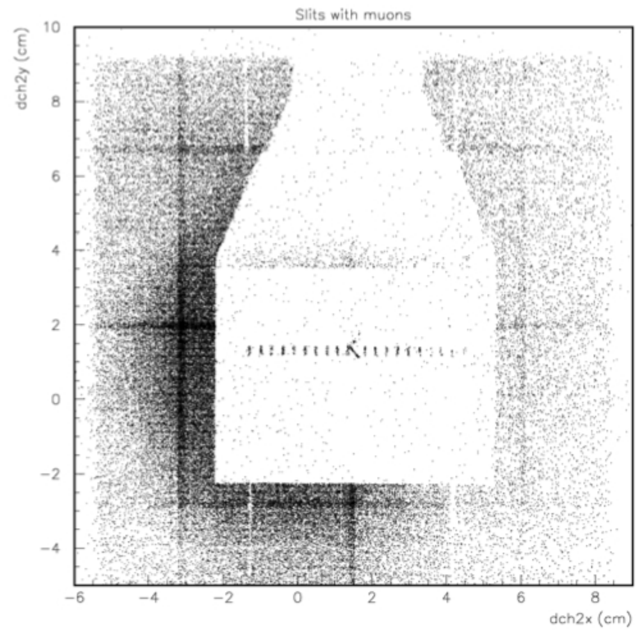
➔ Physics quantities are derived from the raw data via calibration

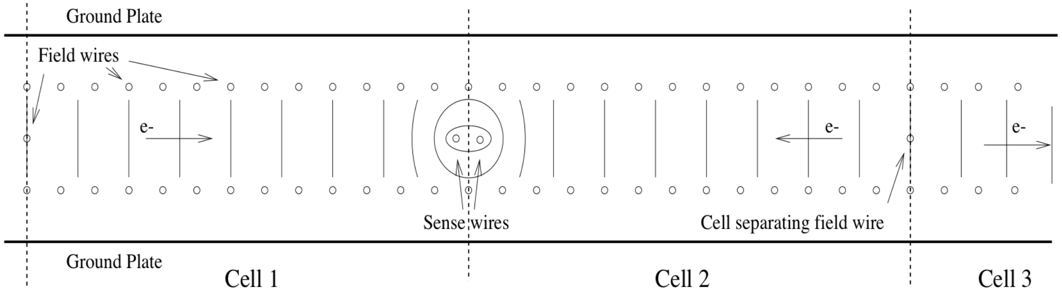
- Calibration procedures have to be foreseen for your detector and DAQ

Example – NA59 Drift Chambers

- ➔More complex, precise detectors need more sophisticated calibration
- ➔Calibrate both “detector behavior” and “DAQ behavior” (eg TDC), sometimes at once.







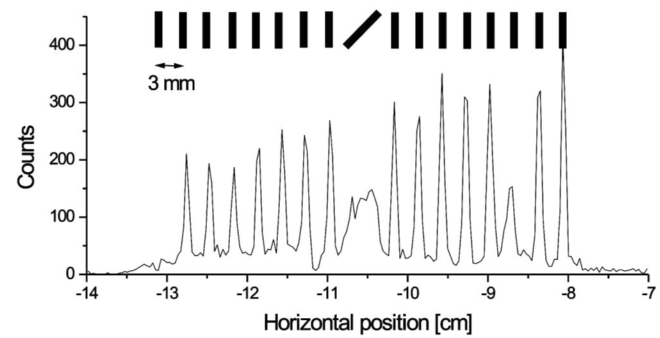


FIG. 4. Calibration data for drift chamber 4. The “comb” is due to slits in the veto (Slit1) combined with hits in the corresponding counter (Hit1) as indicated in the upper part of the figure.