DAQ HW

Hands-on Approach

ISOTDAQ 2022
12th International School of Trigger and Data Acquisition
13-23 June 2022
INFN Sez. Catania & Department of Physics and Astronomy "E.Majorana", Catania

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vincenzo.izzo@cern.ch

Introduction

- This wants to be a hands-on approach to the basic DAQ hardware
  - We will discuss different experiments, requiring different techniques and components
  - We also have some good real data to discuss
  - You will see, we are talking about real life here

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How does HW work?

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How does HW…

Where do physics data come from?

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…does HW…

Where…

How do physics events become bits and numbers?

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- Acknowledgements
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  - © Wainer Vandelli (CERN/PH-ATD)
  - © Sergio Ballestrero (Univ. Johannesburg & CERN)
    - Material and ideas have been taken from CERN Summer Student lectures of P.Farthouat, C.Joram and O.Ullaland; 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

Introduction on DAQ

From previous lecture (A. Negri)

➔"Data Acquisition" on Wikipedia: data acquisition (DAQ) is the process of **sampling signals** that measure real world physical conditions and **converting** the resulting samples into digital numeric values that....

➔Data acquisition is an **alchemy** of electronics, computer science, networking, physics

– …. resources and manpower matter as well, …

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  - ➔I will mostly refer to DAQ in High-Energy Physics

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➔ DAQ is a wide and vast field

- ➔ I will mostly refer to DAQ in High-Energy Physics
  - ➔ We'll discuss only the basic principles of DAQ
    - ➔ Some of these might be the starting points for your next experiments

Electronics: What is needed for?

Typically, electronics interfaces DAQ with the detector

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

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- Detect minimum detectable signal
- Precise energy measurement
- Fast signal rate
- Precise timing
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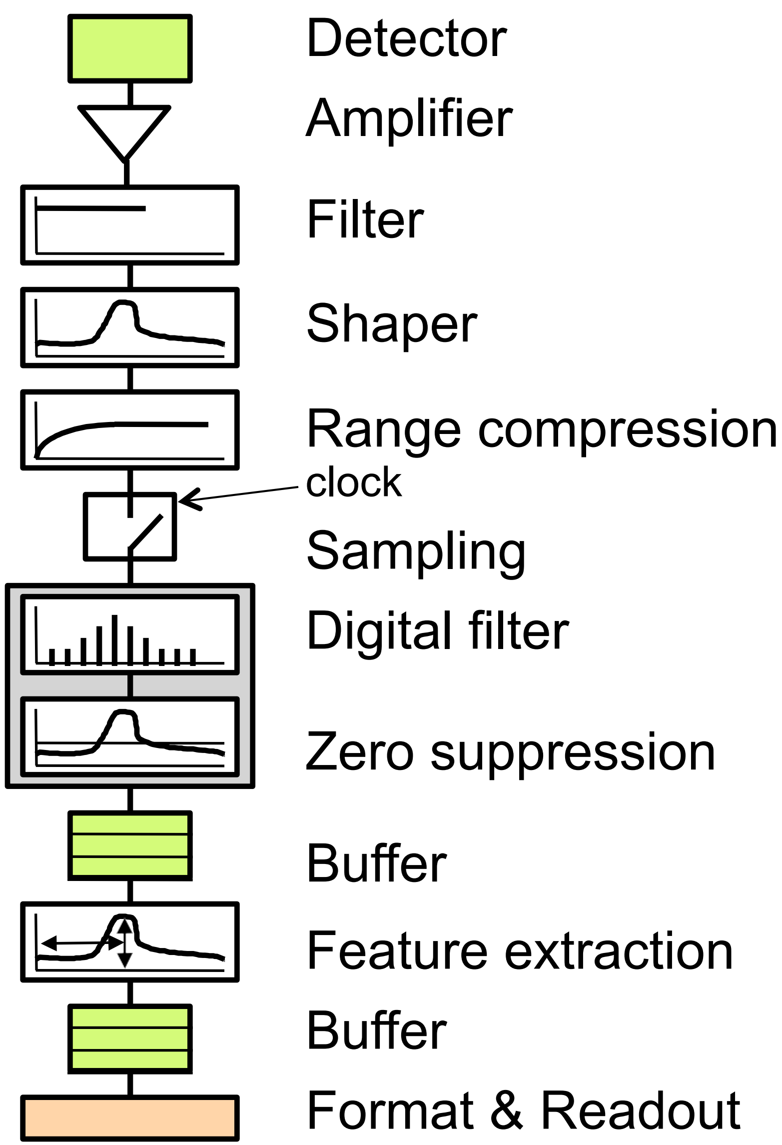
➔Digitize the signal

- provide a digital representation of the measurement
- allow for subsequent processing, transmission, storage using digital electronics → Computers, Fibres, Networks, …

Readout chain



➔Front-end electronics very specialized

- translates signals from a specific detector to a standard digital world
- custom build to match detector characteristics

➔We cannot discuss all design and architecture details

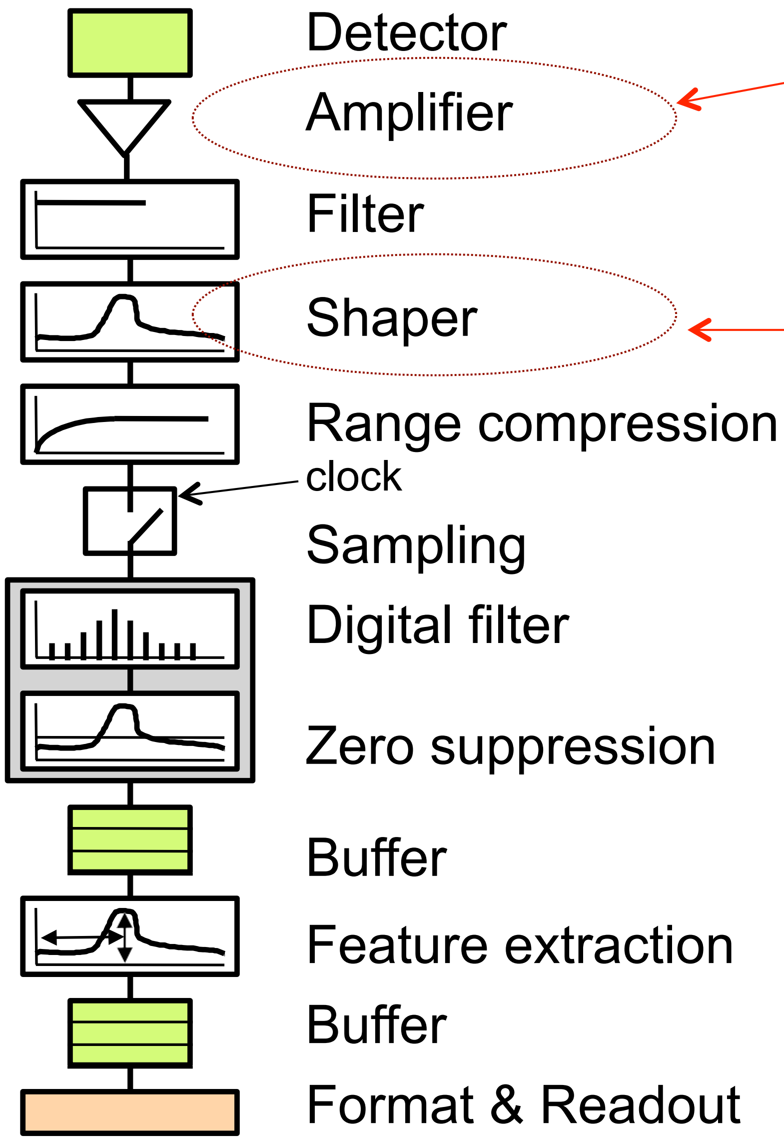
- if you are into electronic design you already know many topics

➔I want to provide you with basic guidelines

- This hopefully may help you when dealing or choosing commercial electronics

➔We only discuss selected functions and principles

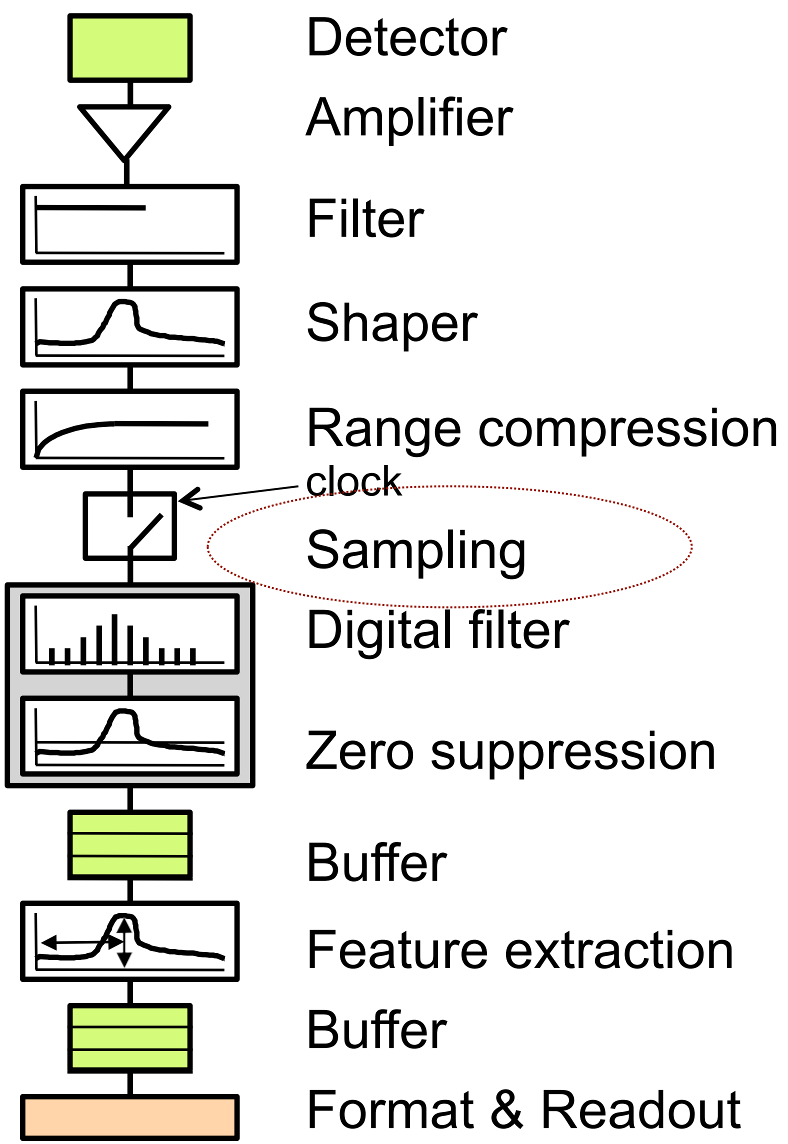
Readout chain



Main functionalities:

- Amplify the tiny signal produced by the detector
- Improve Signal-to-Noise ratio
- Receive the (amplified) signal and give it a specific shape

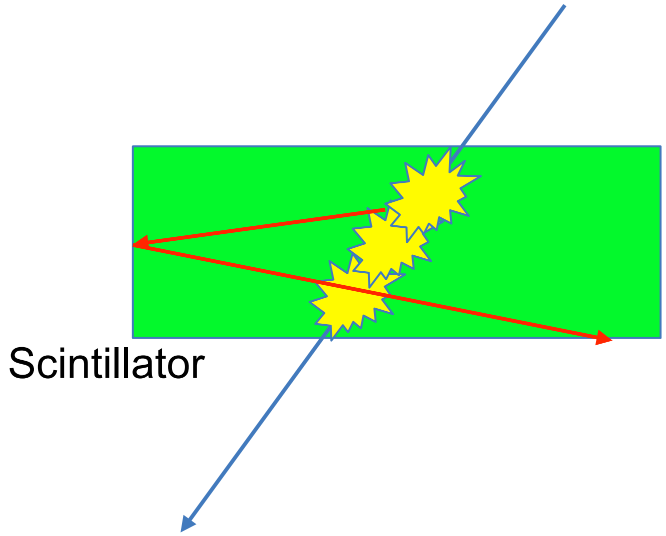
Readout chain



Outline

- Introduction
  - DAQ, Electronics & Readout Chain
- 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

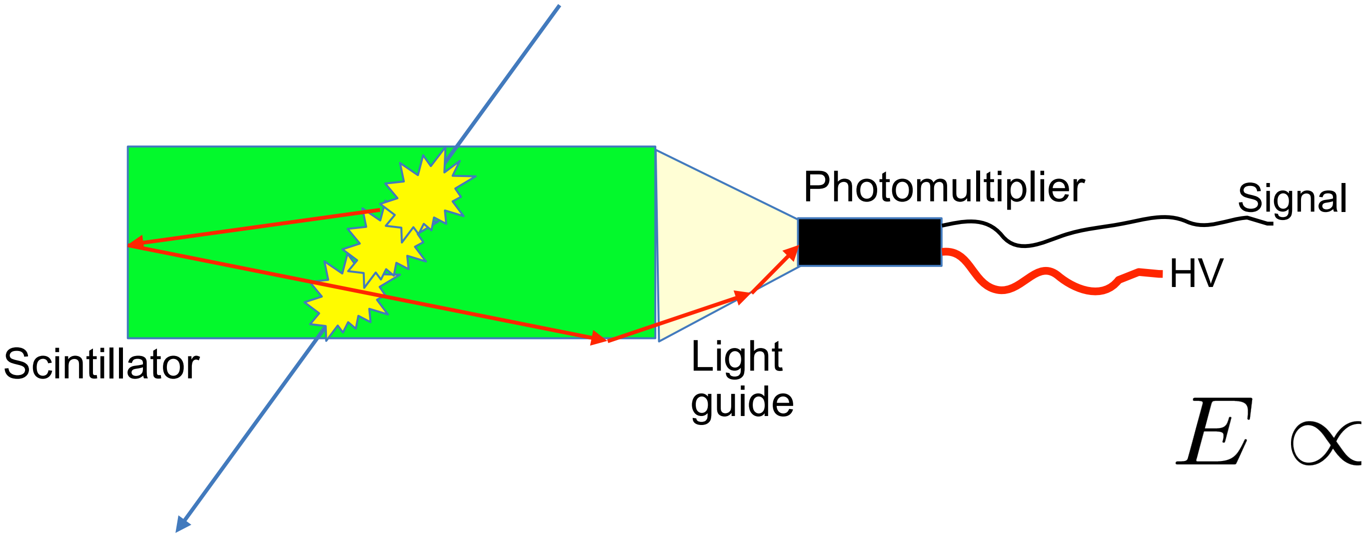
Energy measurement



$$E \propto N_\gamma$$

- Measure energy deposited by a particle traversing a medium
- The medium (detector) is a **scintillator**
  - Molecules, excited by the passing particle, relax emitting light
  - The amount of light is proportional to the deposited energy
  - We want to collect light with the highest possible collection efficiency

Energy measurement



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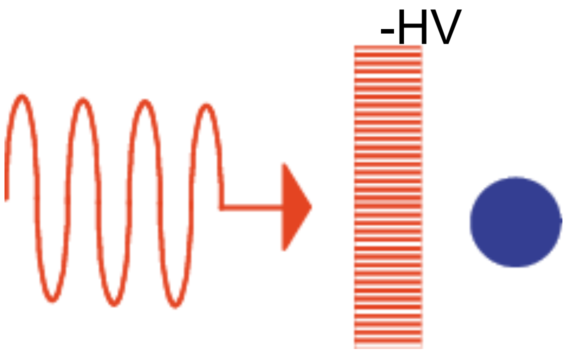
  - The amount of light is <u>proportional</u> to the deposited energy
  - We want to collect light with the highest possible collection efficiency
- The light is then
  - collected, using dedicated passive optical means (**light guide**)
  - fed into a photo-detector: **photomultiplier**

Photomultiplier

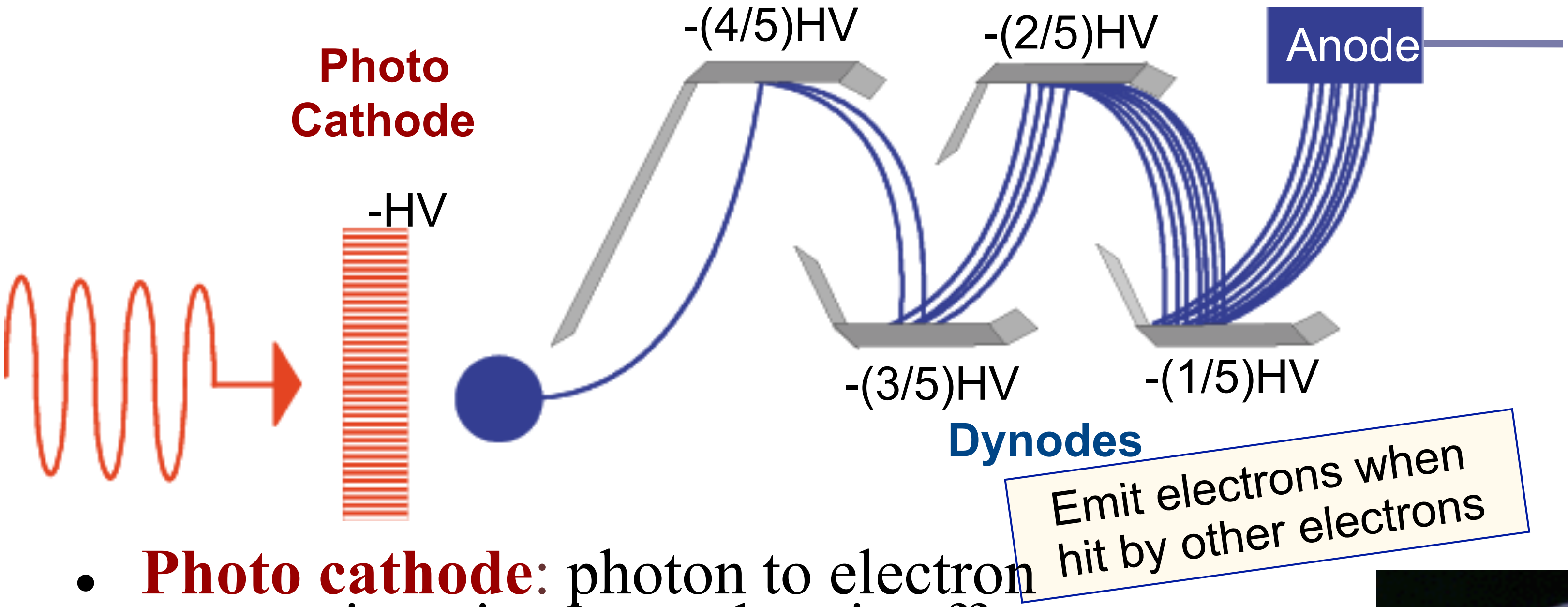
Photo Cathode

Easily emits electrons when hit by light



- **Photo cathode**: photon to electron conversion via photo-electric effect
  - typical quantum efficiency ≈1-10% (max 30%), depends on material and wavelength

Photomultiplier



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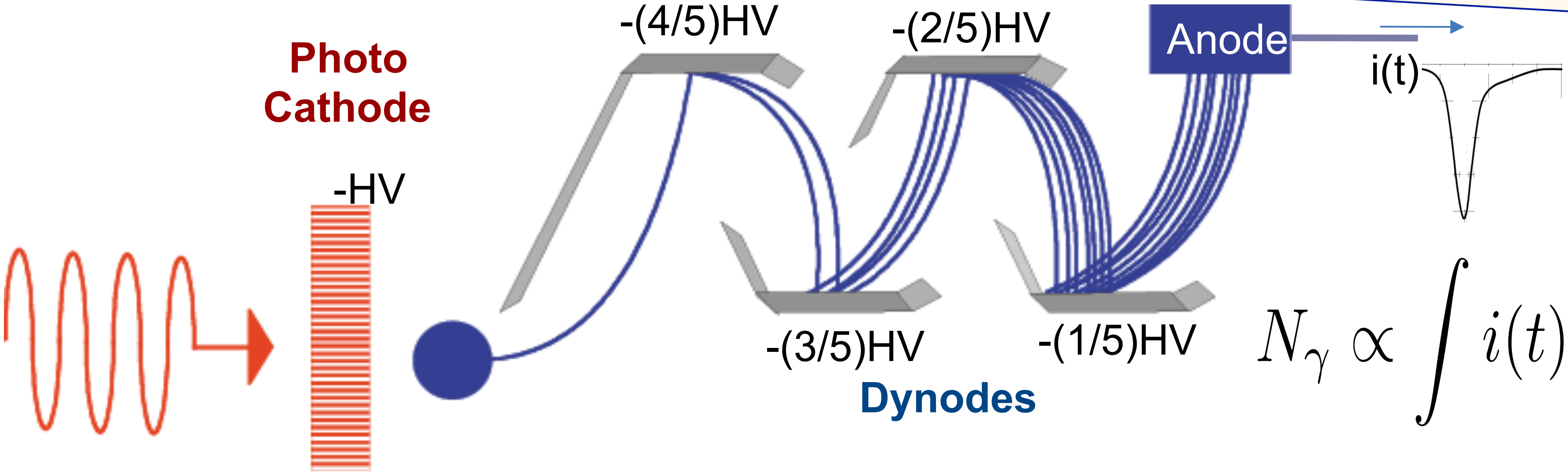
  - Photocathode to anode: typical overall gain $\approx 10^6$

Photomultiplier

Very few photons converted into an electrical signal



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

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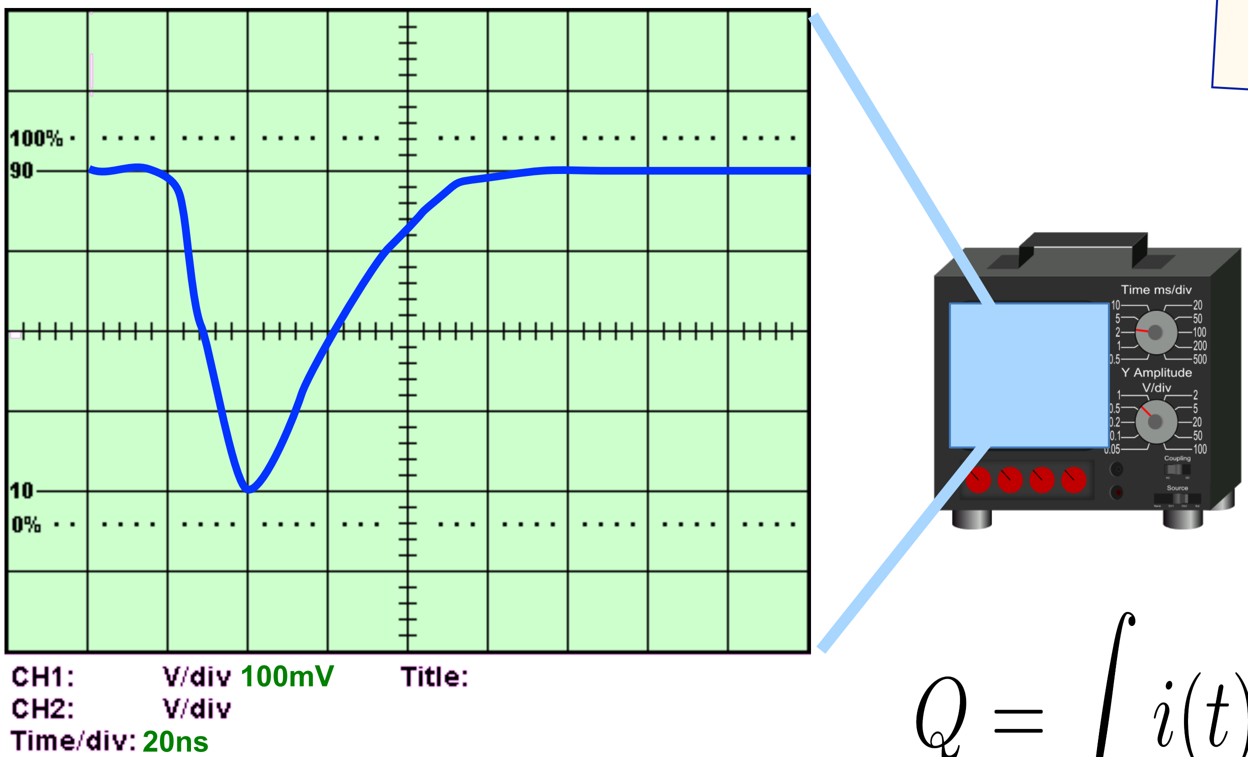
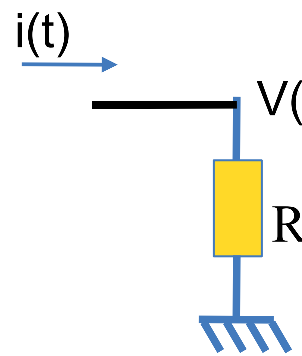
- **Dark current**: noise
  - current flowing in PMT without light, due to thermal fluctuations

Start the measurement

- Approximate Q measurement using oscilloscope
  - Linear approximation of a exponential decay

We start from an electron pulse, i.e. a current signal





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

Remeber: the TOTAL charge is proportional to the light

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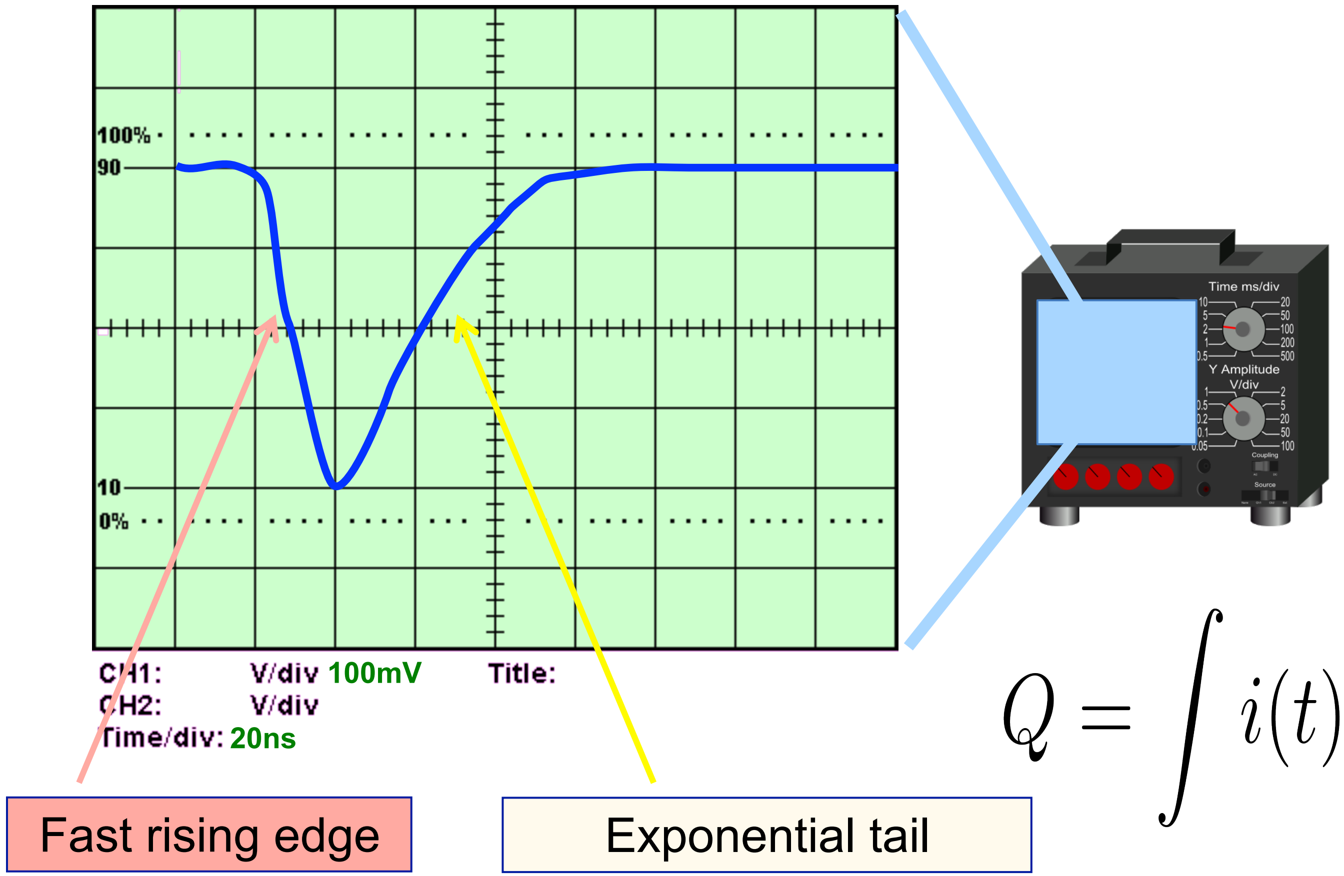

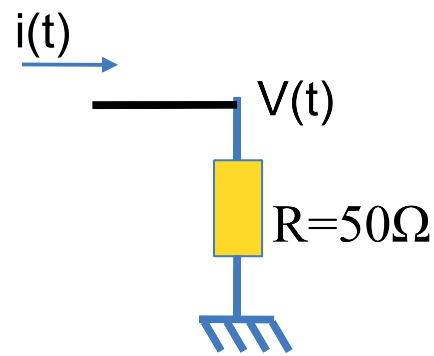

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Good old oscilloscope

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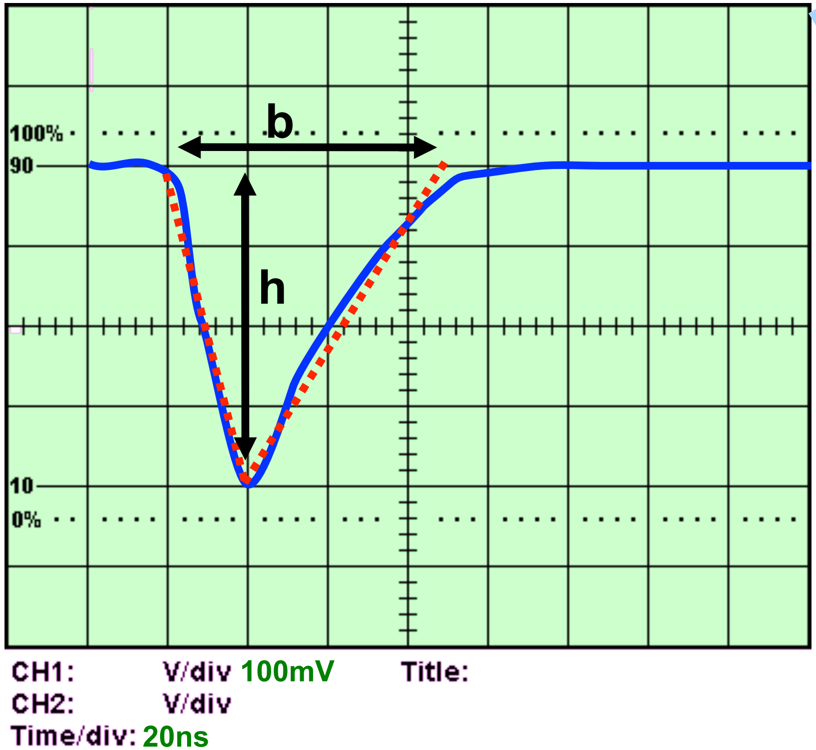
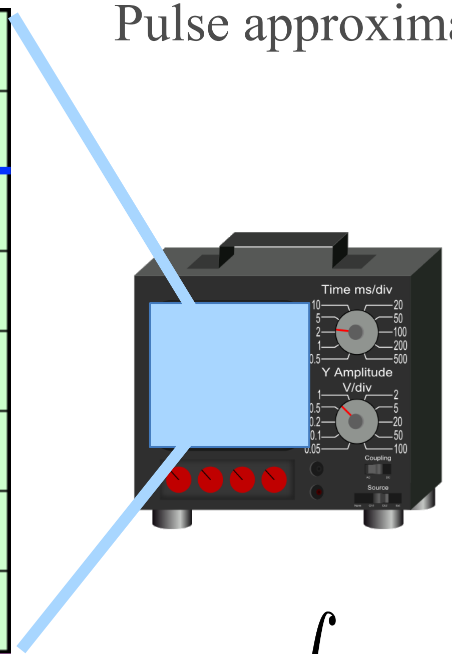
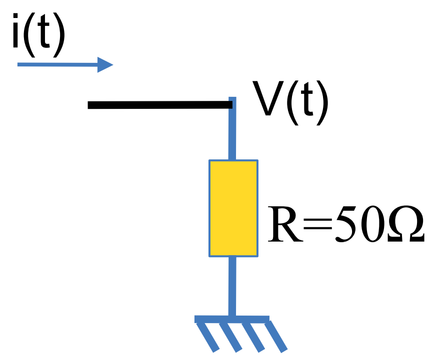


Pulse approximates a triangle





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

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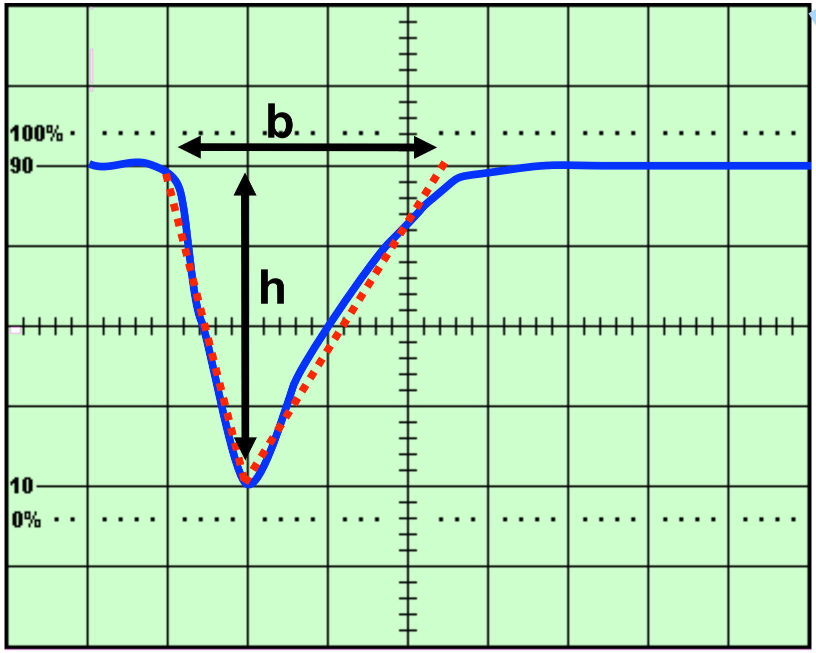

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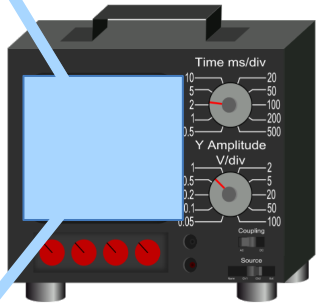

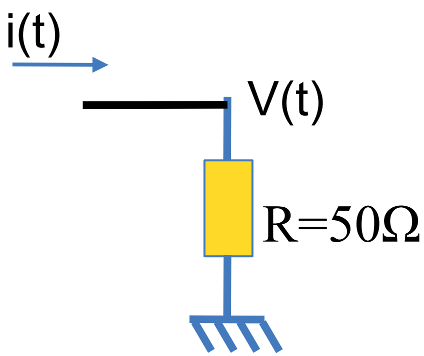

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- Approximate Q measurement using oscilloscope
  - Linear approximation of a exponential decay
- We have a number representing our event! It's easy, but
  - Deadtime 3 – 5 min, ~ 3×10^{-3} Hz (if you are good)
  - Necessary to encode data into some sort of electronic format by hand, in order to manipulate it, visualize it, etc..

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LHC experiments have millions of channels to be acquired @40 MHz

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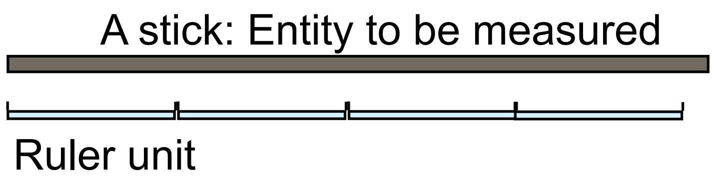
- N.B.: the oscilloscope method is still fundamental
  - it allows for the **validation** of your DAQ
  - yes, you should never thrust it a priori!

Analog to Digital Conversion

- Digitization

Lab 8

  - Encoding an analog value into a binary representation
  - By comparing entity with a ruler



We use this technique every day in our life

- Flash ADC simplest and fastest implementation
  - M comparisons in parallel
  - Input voltage V_{in} compared with M fractions of a reference voltage
    - $(1/2)\ V_{ref}/M \rightarrow (M-1/2)\ V_{ref}/M$
    - E.g.: M=3
  - Result is encoded into a compact binary form of N bits
    - $N=\log_2 (M+1)$

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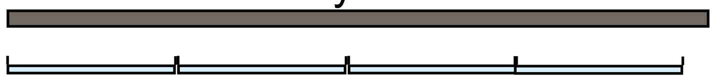

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Now our entity is a voltage, and we need one (or more) voltage as a reference

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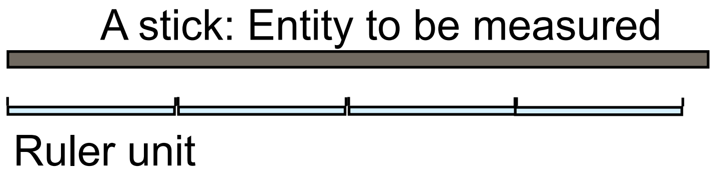

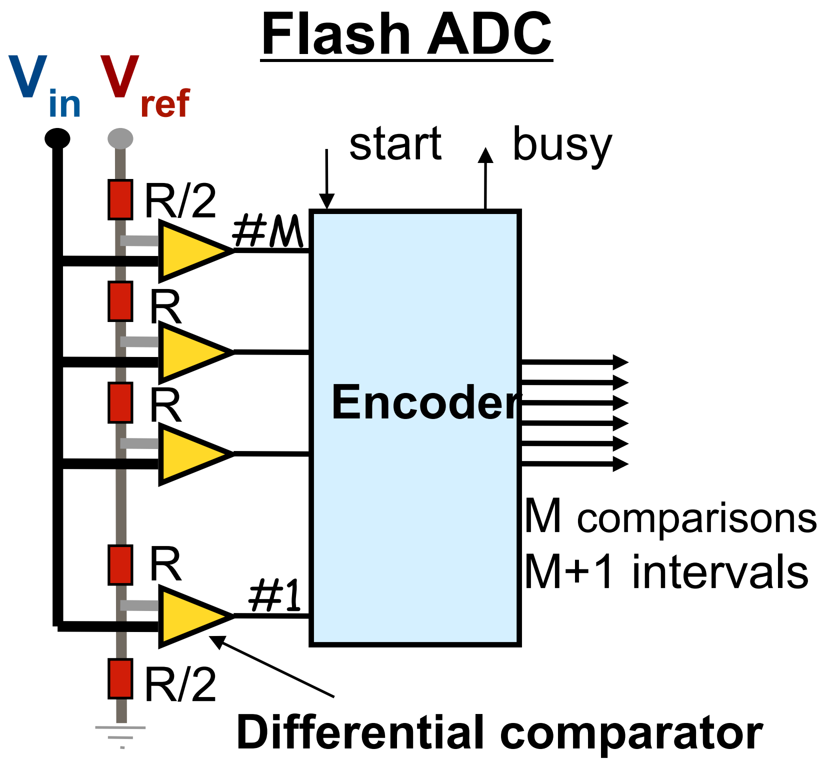

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    - Example: M=3 comparisons
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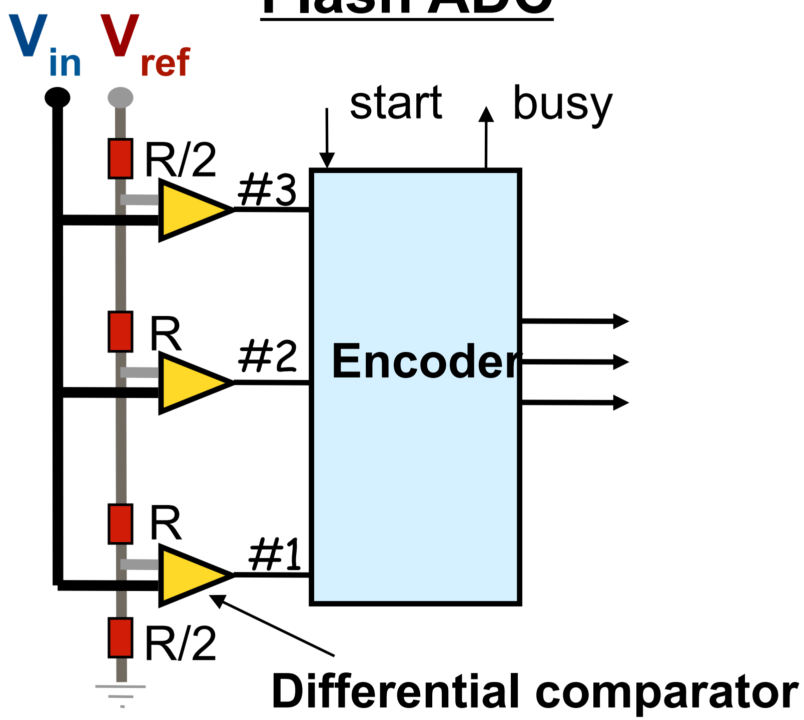
$x = V_{in}/V_{ref}$	Comparison results	Encoded form
x <1/6	000	00
1/6≤ x <3/6	001	01
3/6≤ x <5/6	011	10
5/6≤ x	111	11

Flash ADC



Analog to Digital Conversion

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  - Input voltage V_{in} compared with M fractions of a reference voltage
    - (1/2) V_{ref}/M → (M-1/2) V_{ref} /M
    - Example: M=3 comparisons
  - V_{in} / V_{ref} takes one of M+1 values.

N-bit ADC { Result is encoded in compact binary form of N bits, $N=\log_2 (M+1)$ bits

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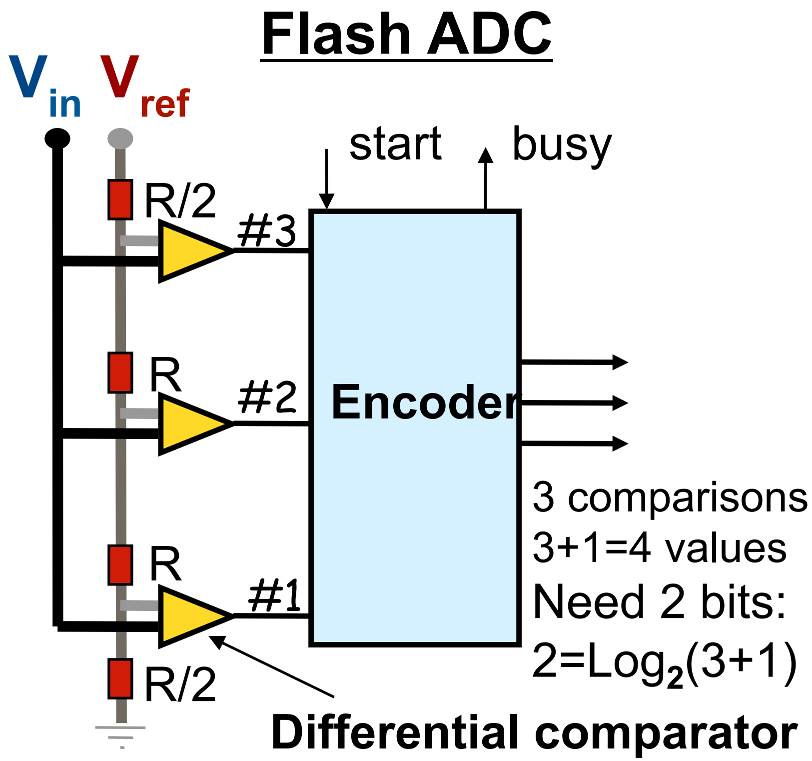
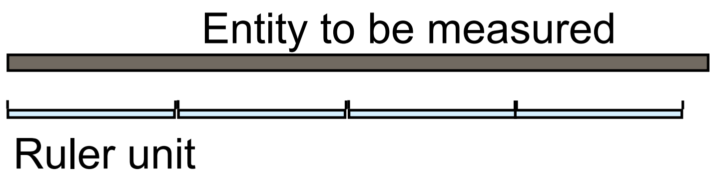
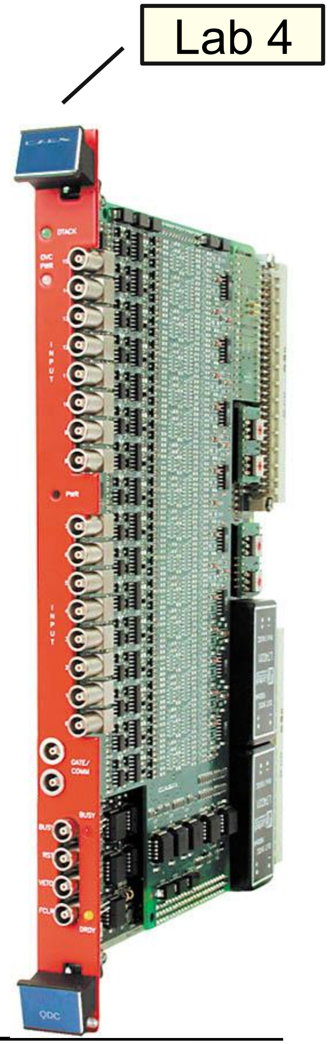


ADC Characteristics



- We want to buy the ADC that best fits with our needs:
- We want a very fast device, with very low power consumption, with less than 1 mV resolution, etc..



ADC Characteristics

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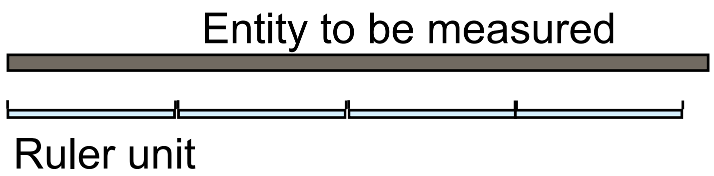

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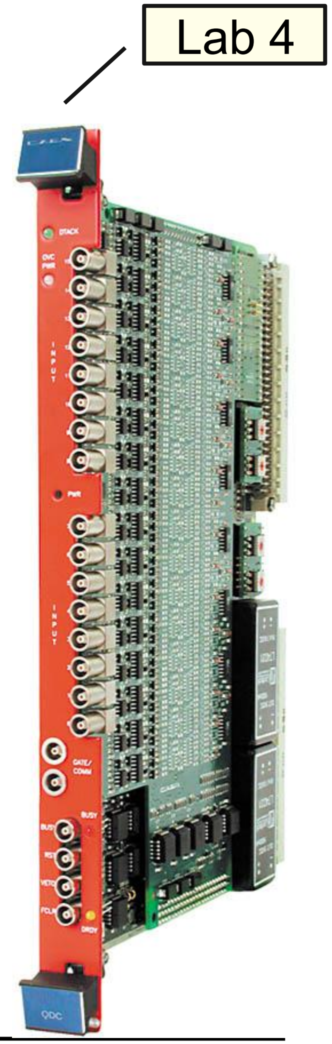

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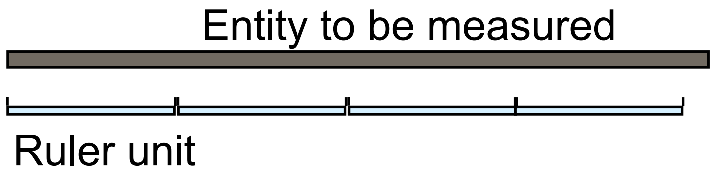

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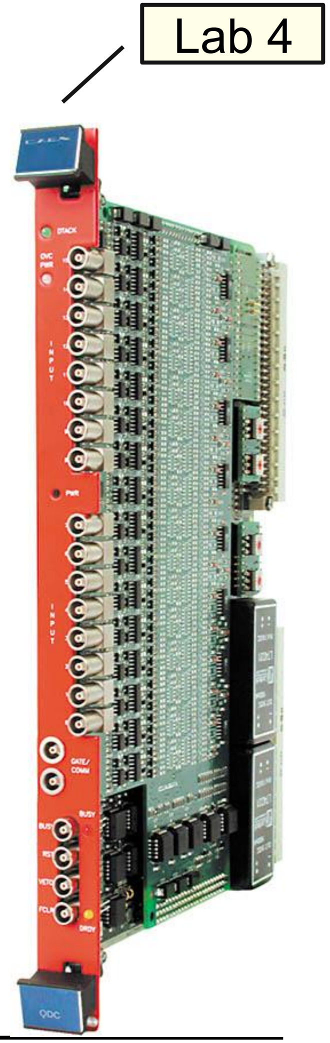
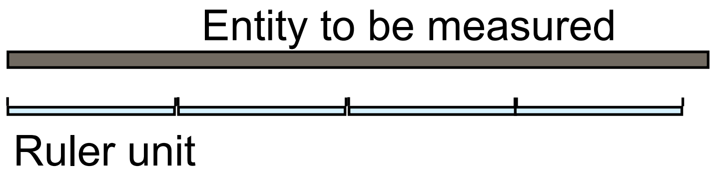
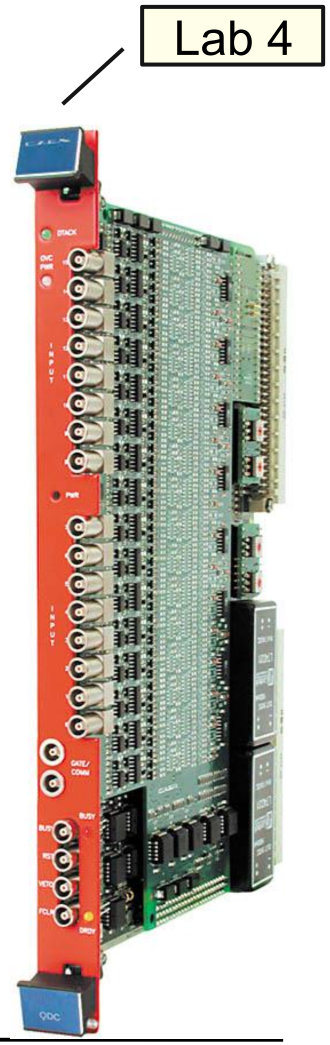


ADC Characteristics

- Resolution (LSB), the ruler unit: $V_{max}/2^N$
  - e.g.: 1V and 8bit (M=256) → LSB = 3.9 mV



- Quantization error: ±LSB/2



Resolution depends on the number of comparators in the ADC

The N (number of bits) essentially tells you how many steps you have in the ADC

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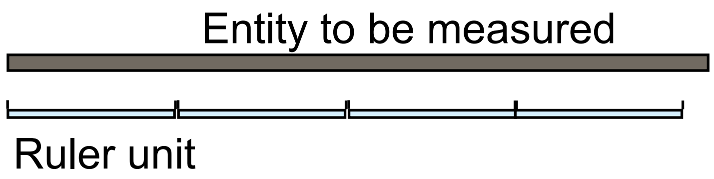
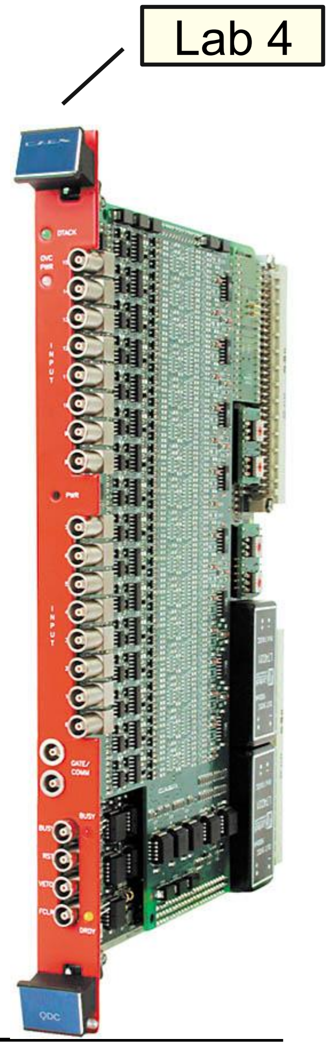
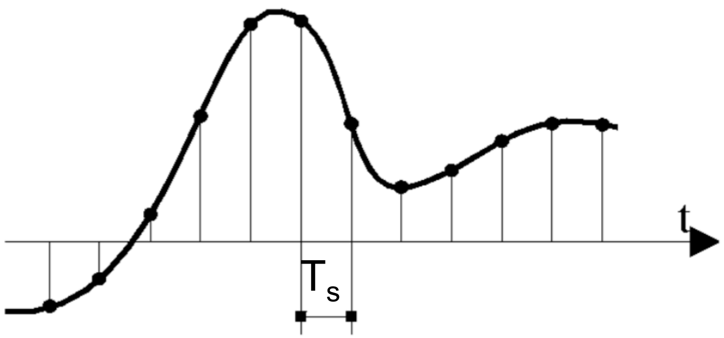
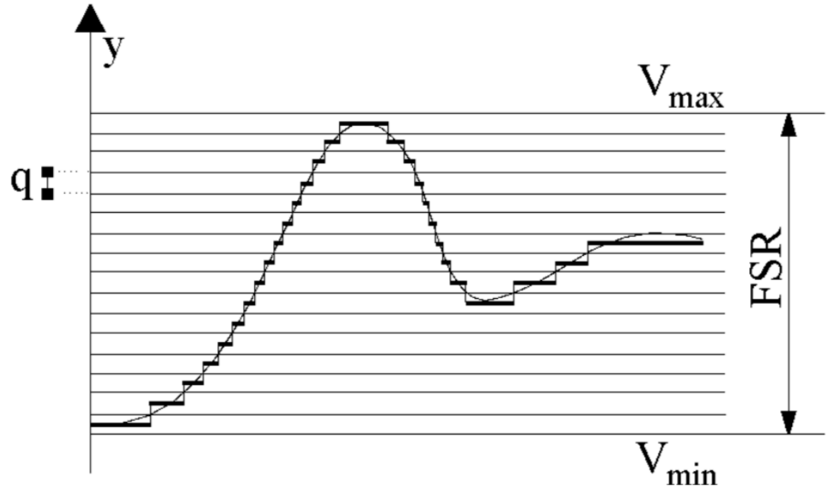




Sampled signal, S(t)



Sampling frequency, $f_s=1/T_s$



Amplitude coding with N=4
(16 different steps)

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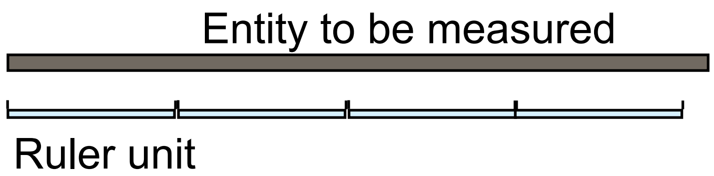
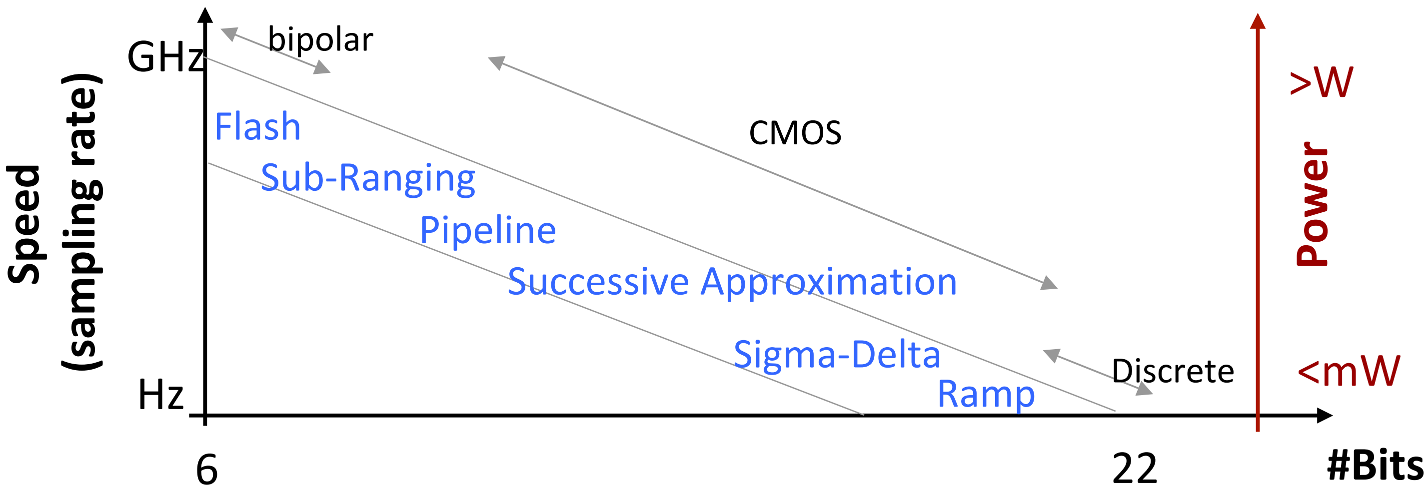
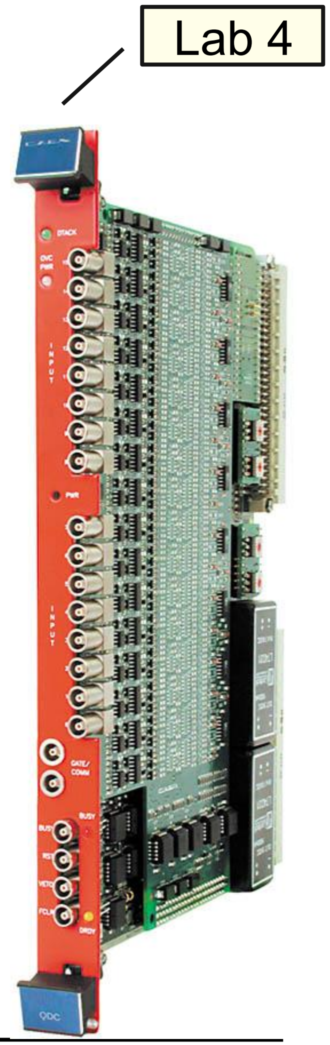


- Quantization error: ±LSB/2

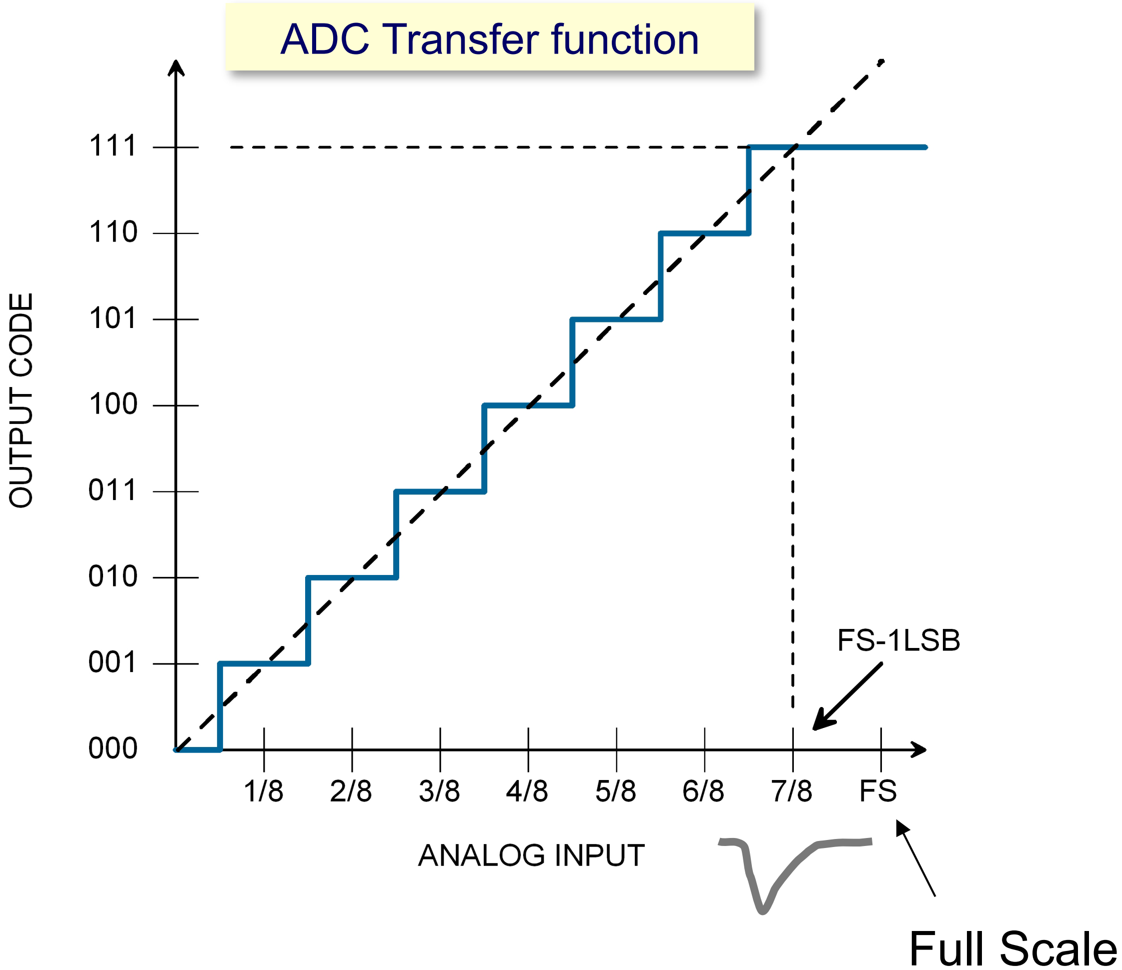
- Many different ADC architecture/technique exists
  - mostly because of the trade-off between speed and resolution





ADC Accuracies

- ADC transfer function
  - Output code vs analog input



ADC (In)Accuracies

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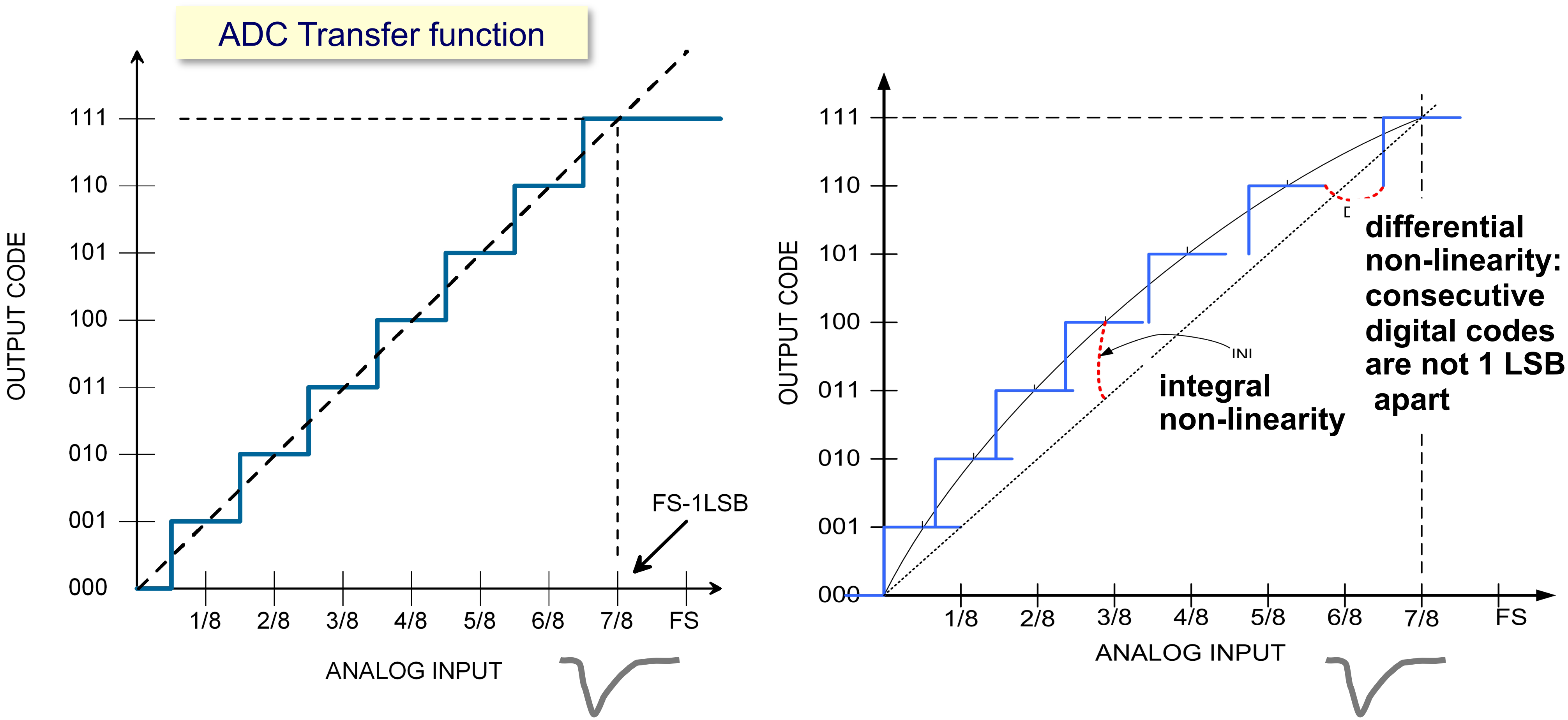

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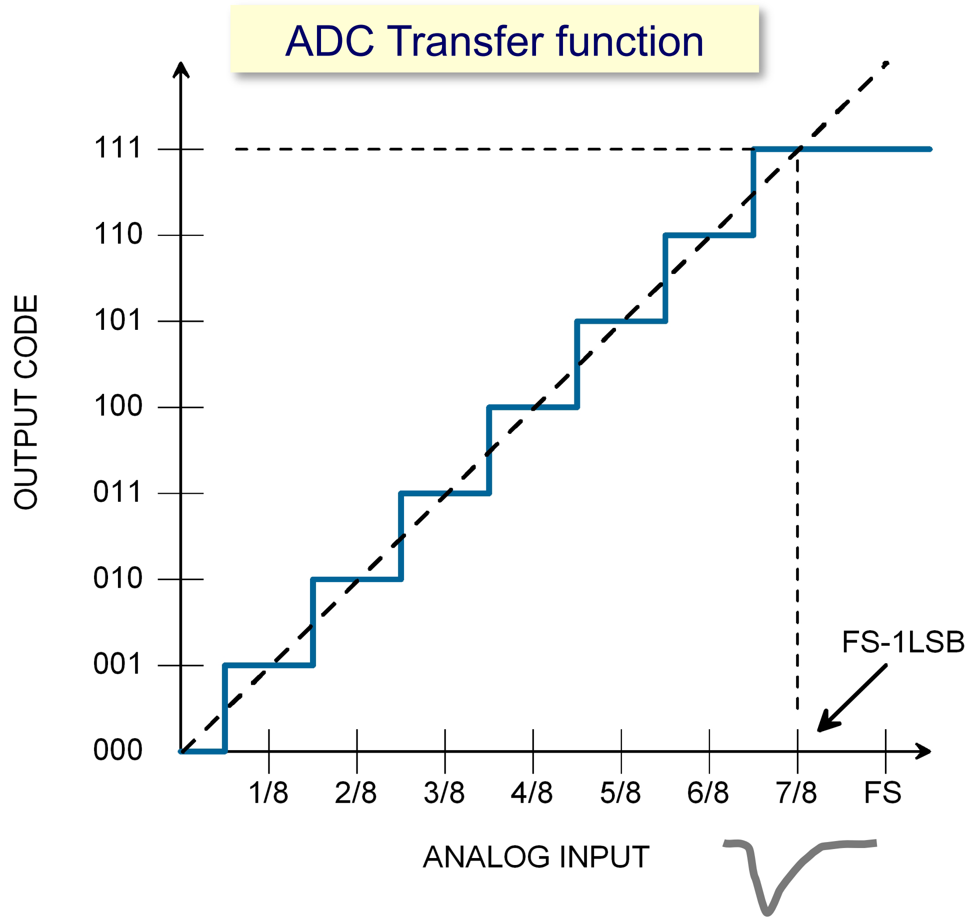
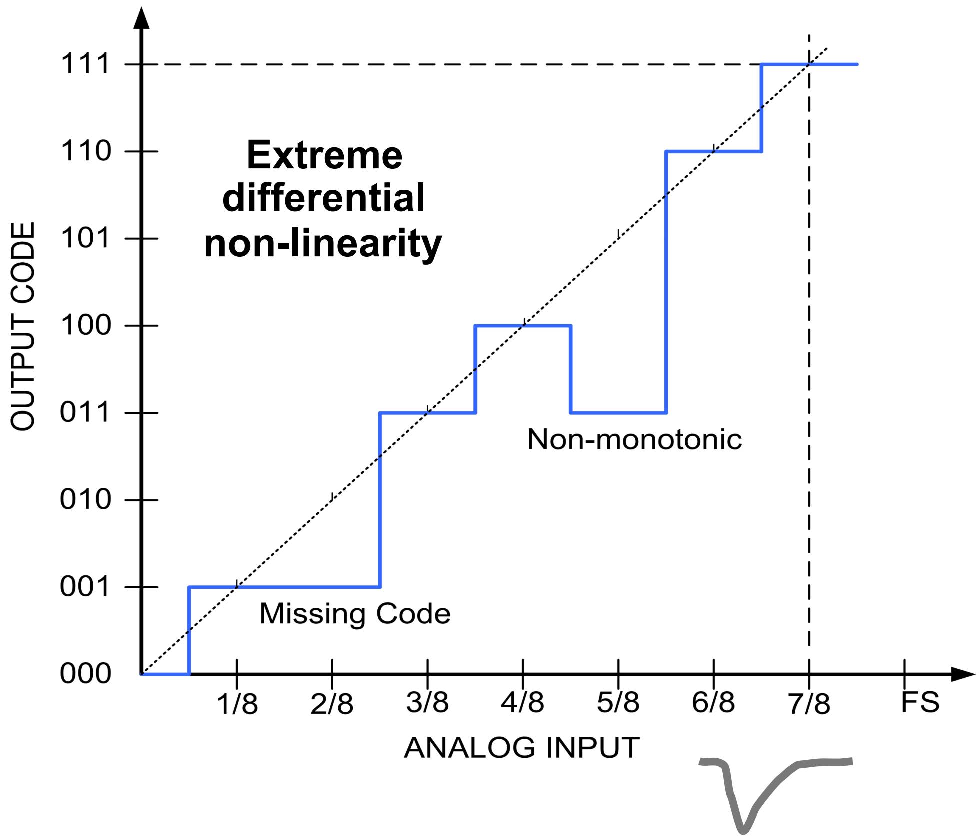
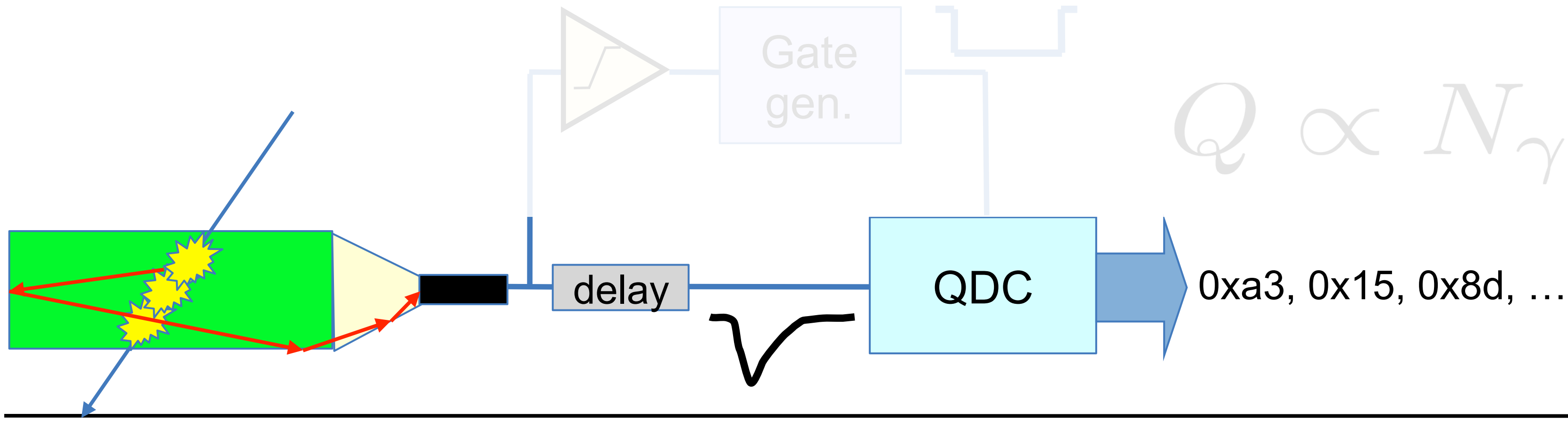




Charge to Digital

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

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



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

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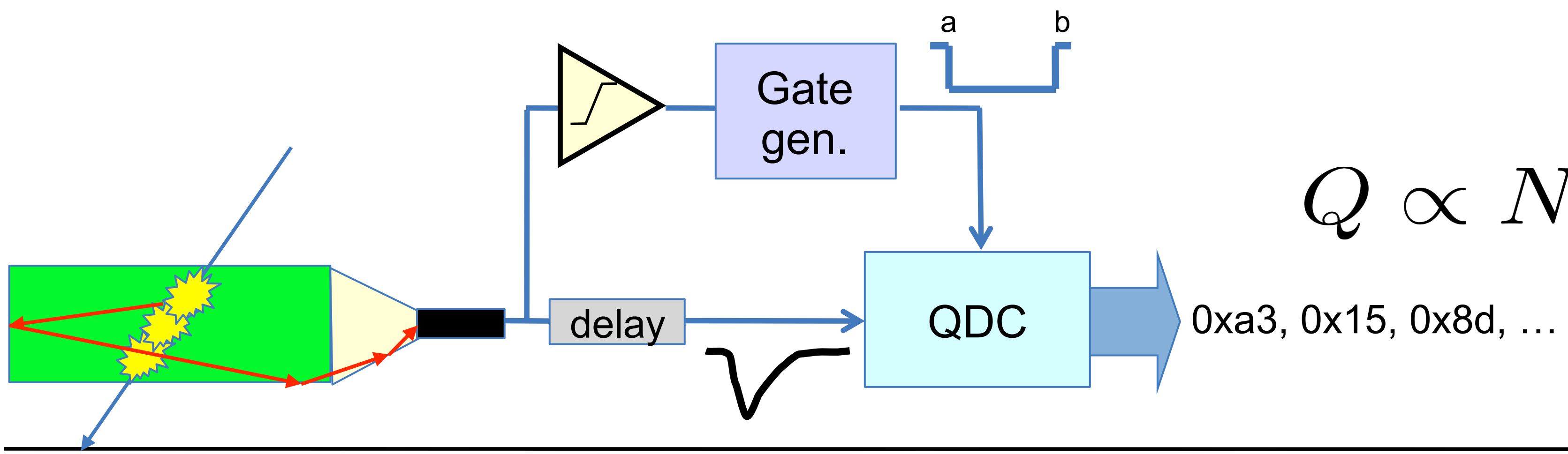


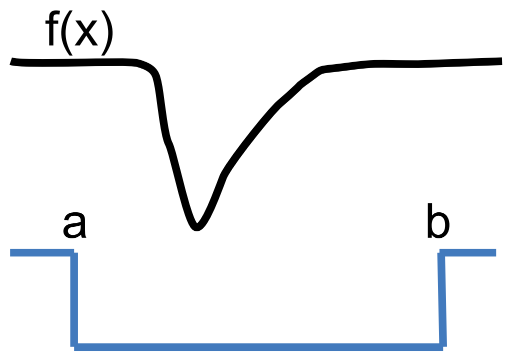
$$Q \propto N_\gamma \propto E$$

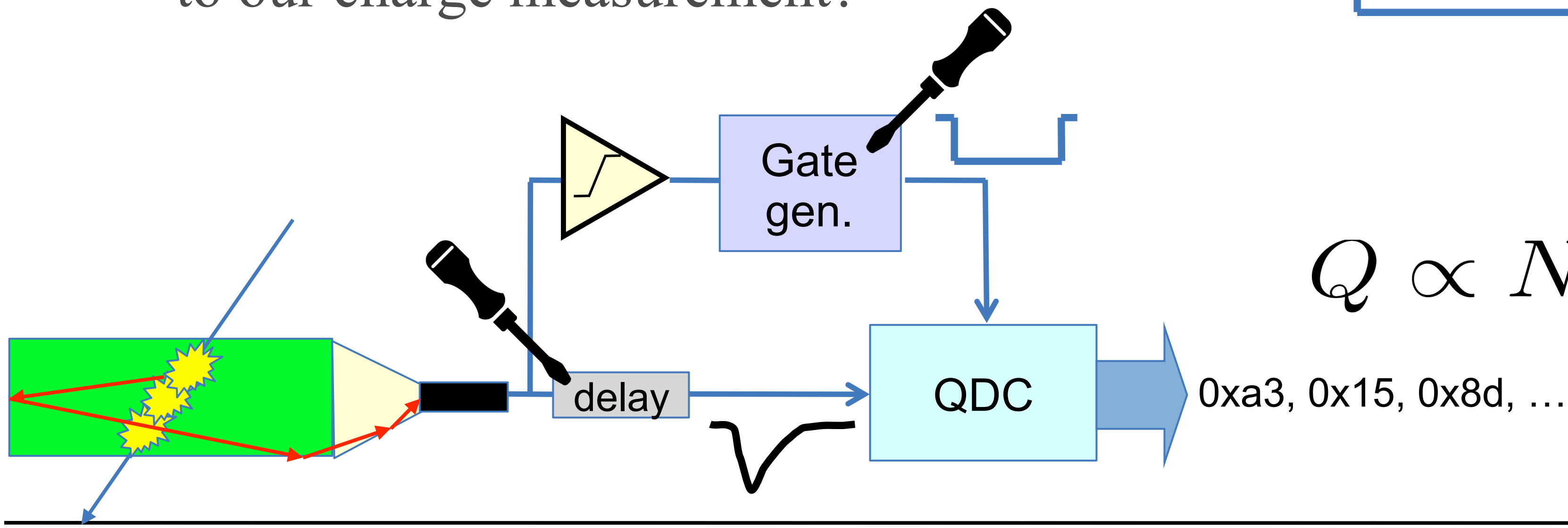
QDC: timing

- Relative timing between <u>signal</u> and <u>gate</u> is important
  - Delay tuning

Labs 2, 3, 4

- 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?





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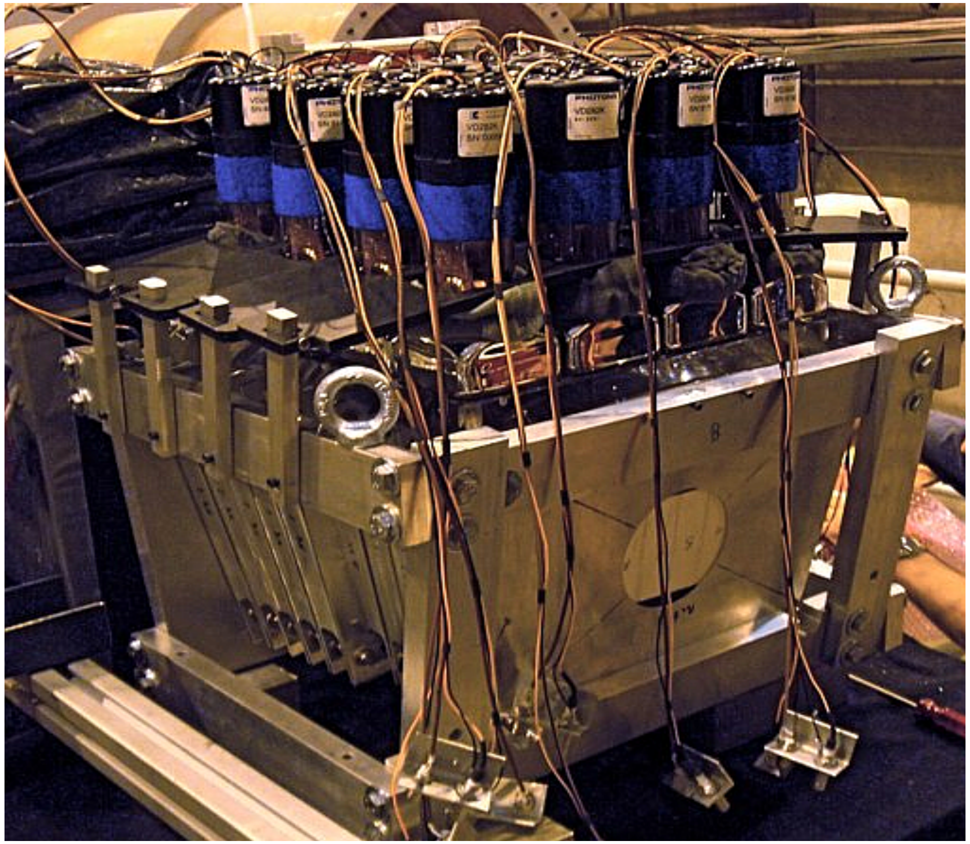
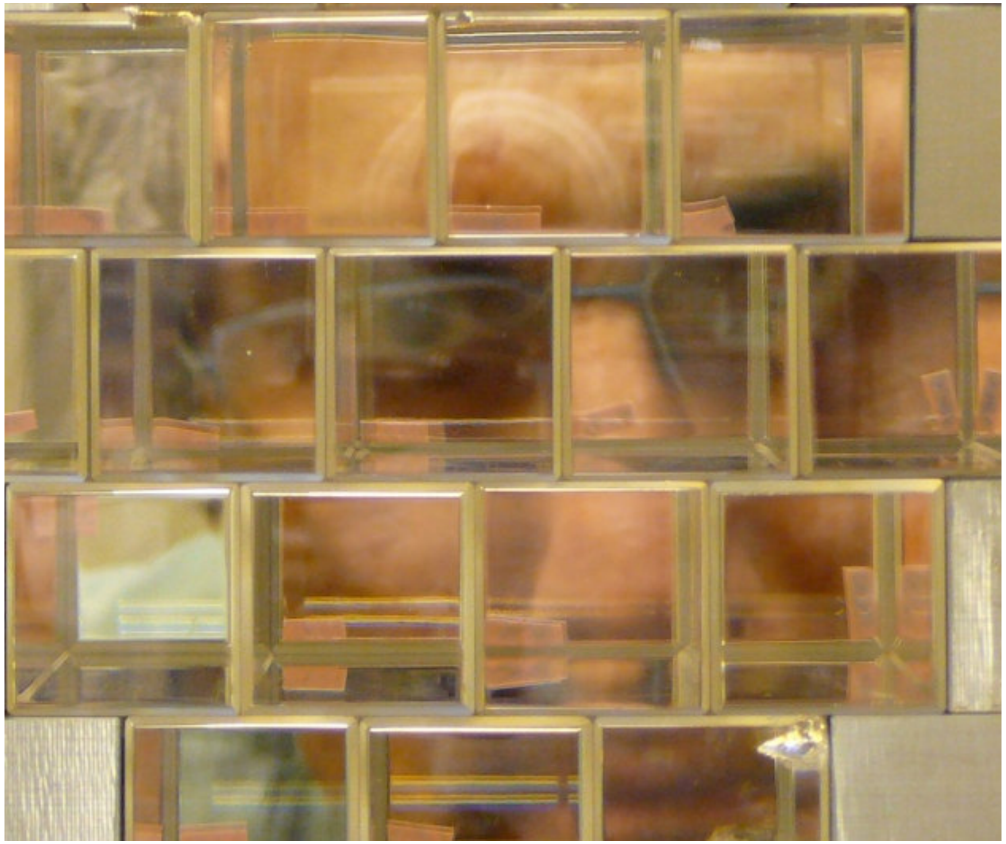
Example of QDC data

- Calorimetry R&D test beam @CERN
  - QDC spectra

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





QDC spectra

- Calorimetry R&D test beam @CERN
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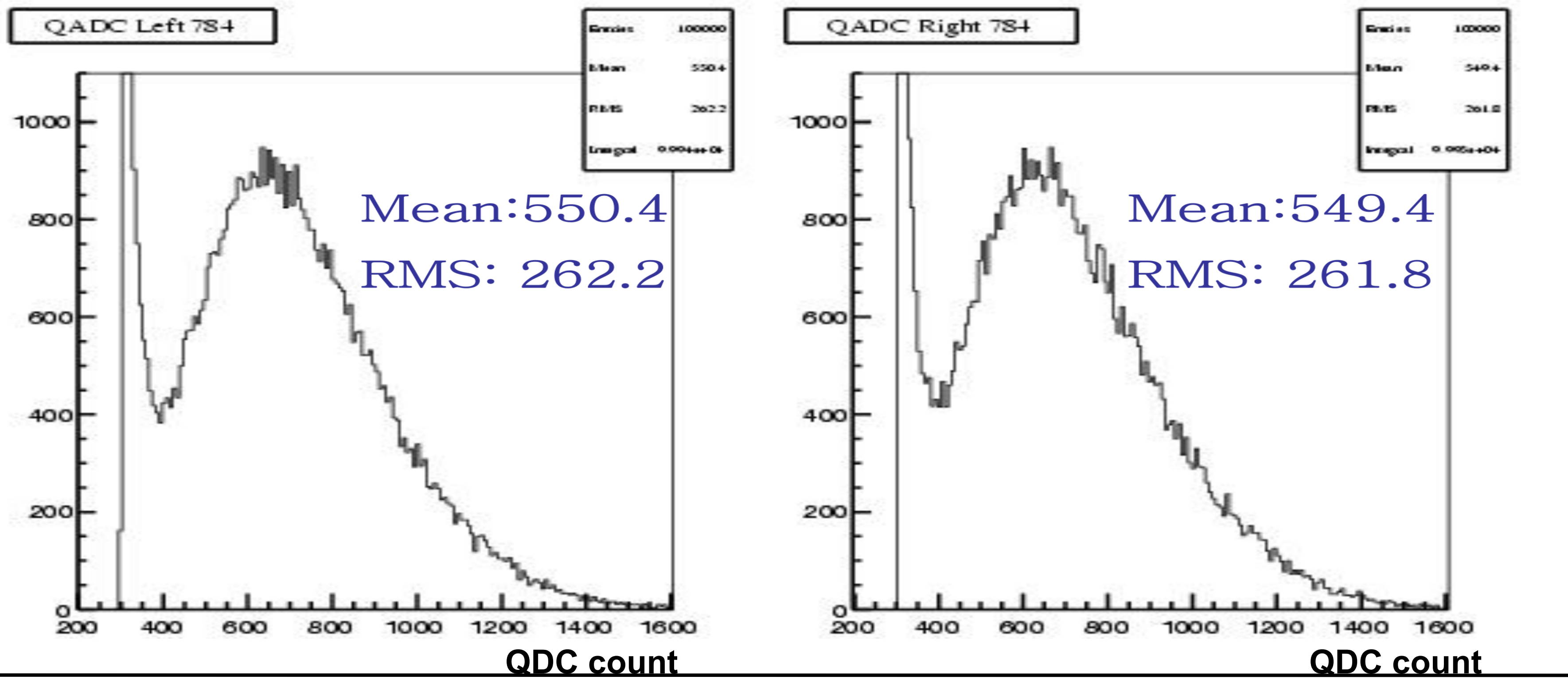
- But, what is the 1st peak?
  - How can we estimate it?



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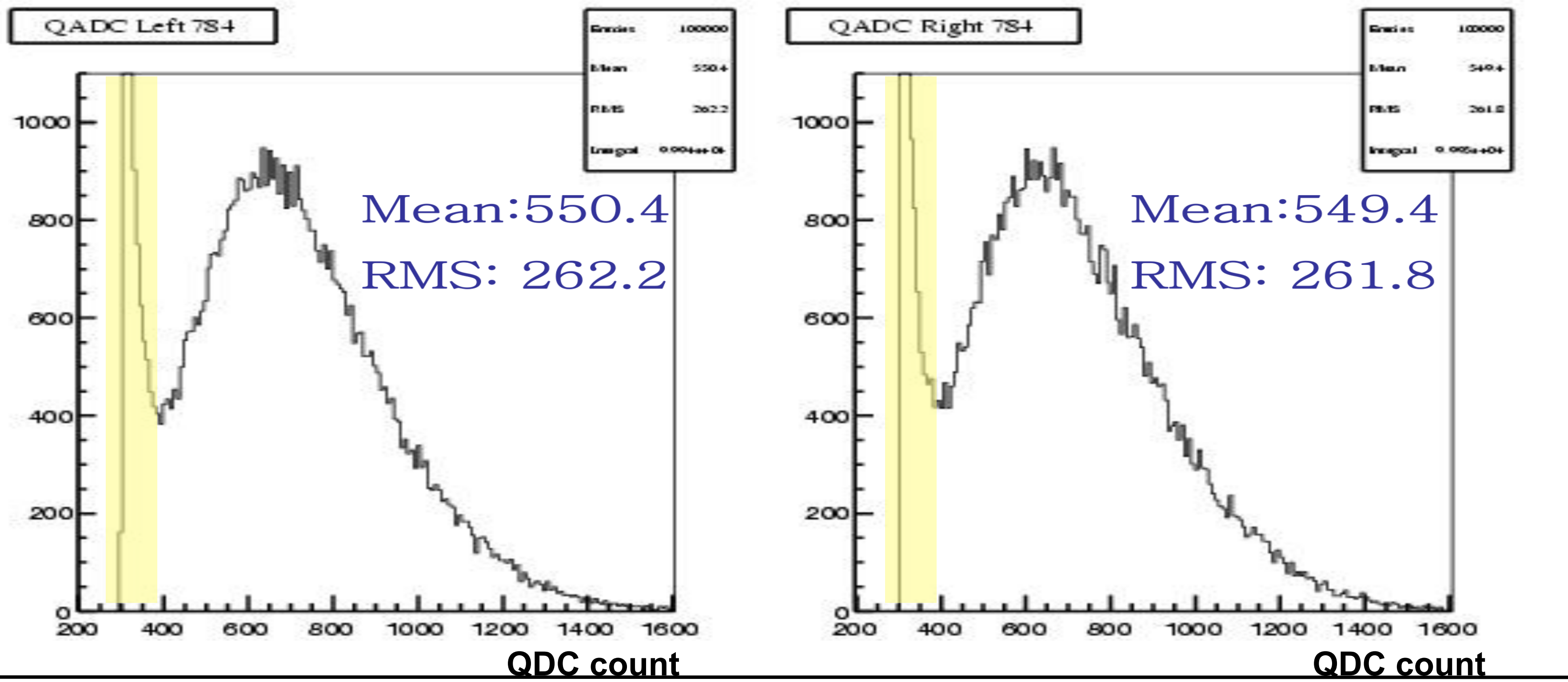
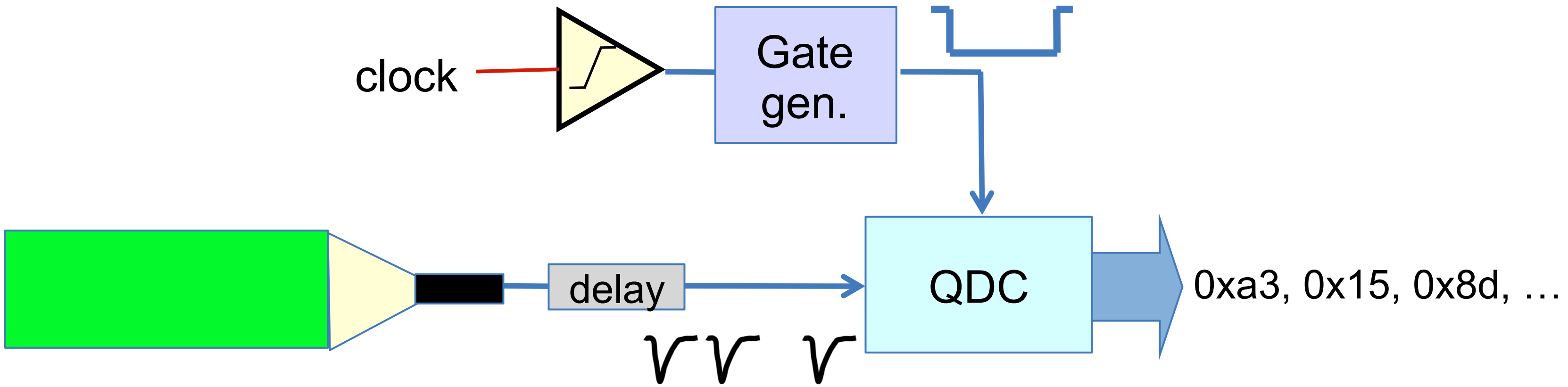


QDC: pedestal subtraction

- The pedestal can be measured with an out-of-phase trigger
  - PMT dark current, thermal noise, Jitter, fluctuations on power supply..
  - 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



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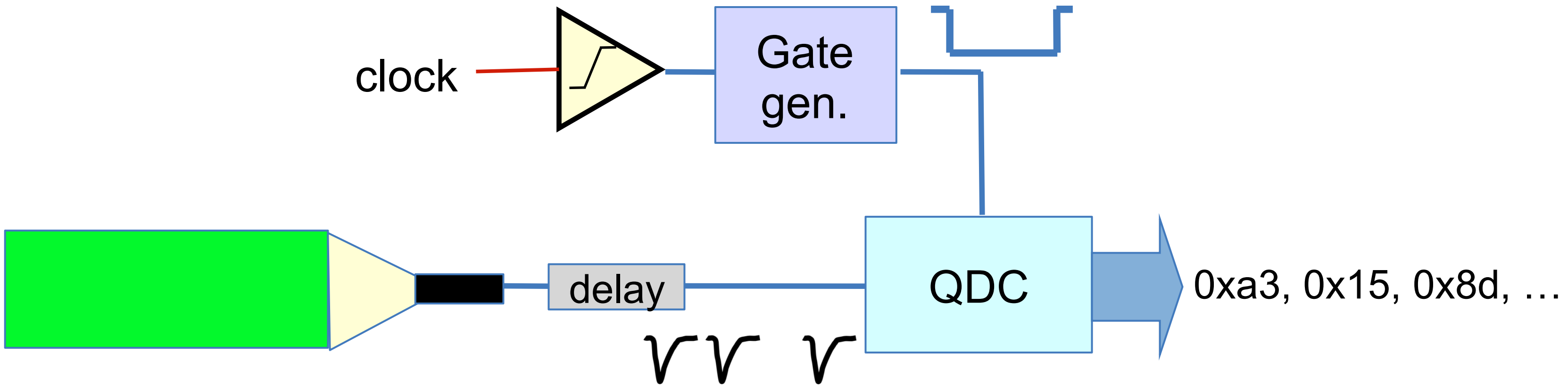
We essentially want to integrate the baseline of our setup



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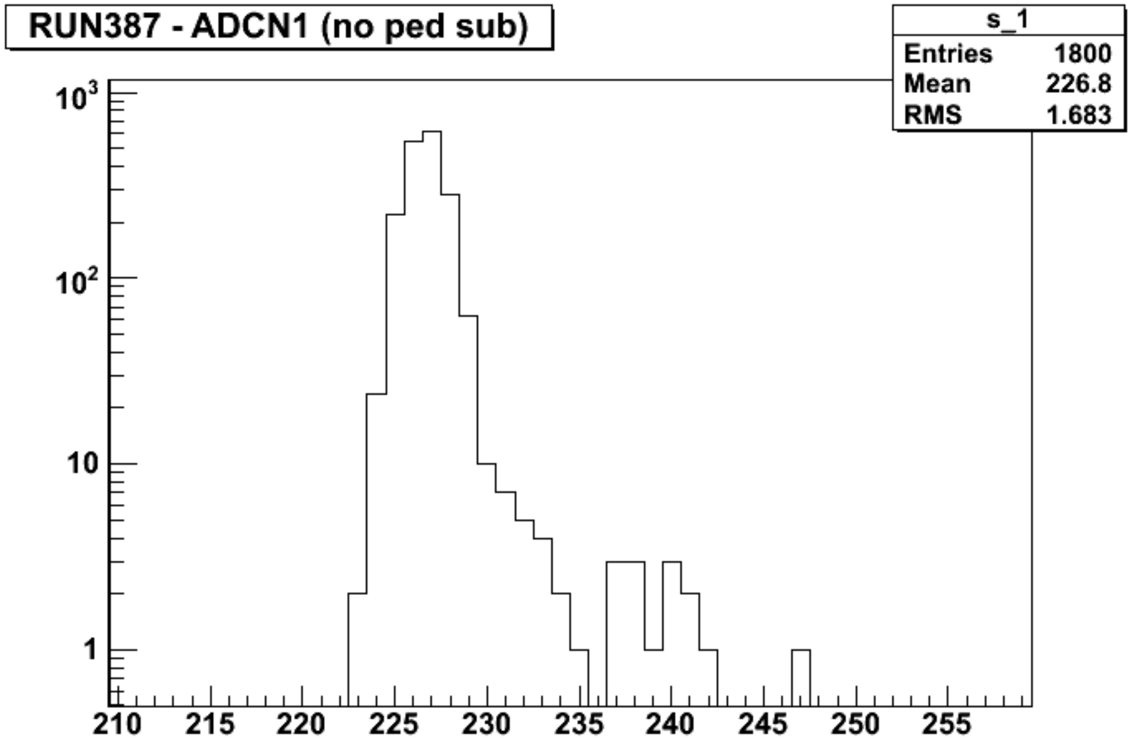

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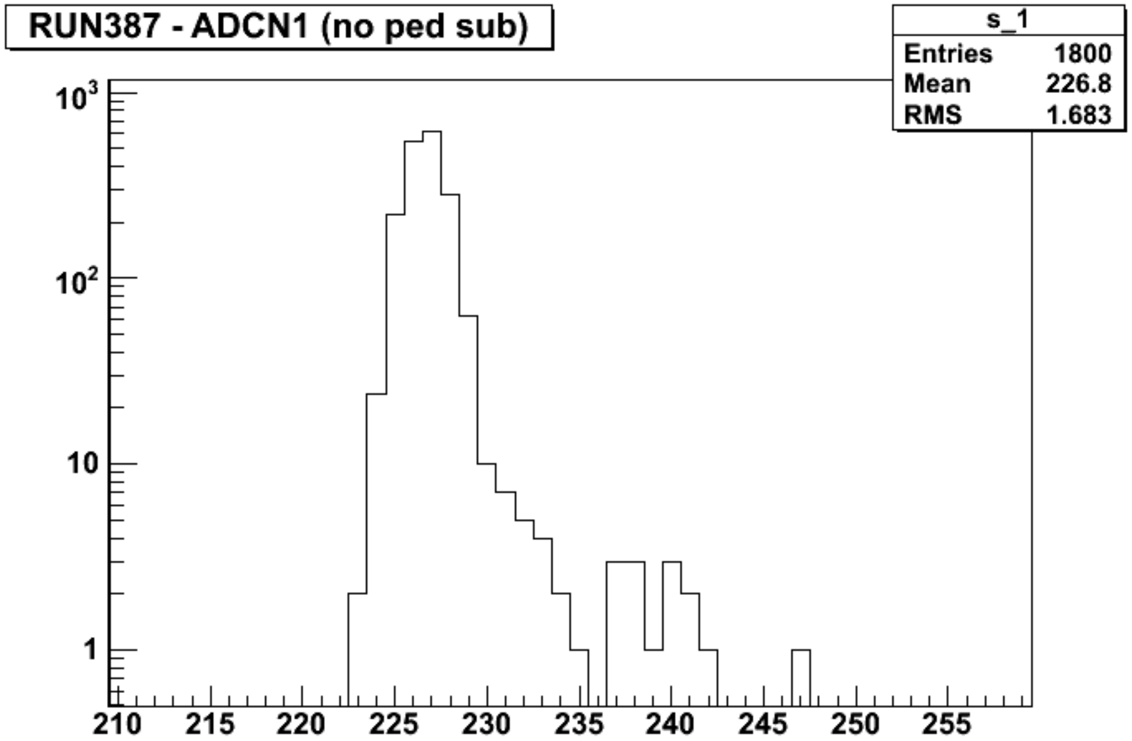
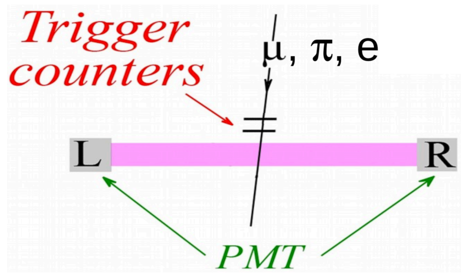
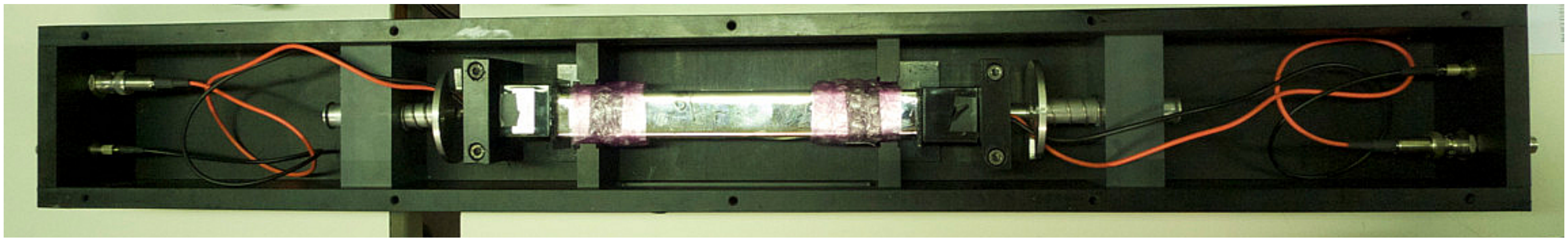


"Real" QDC at work

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





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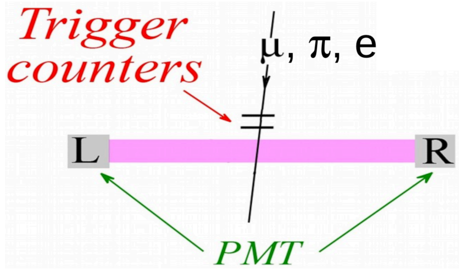
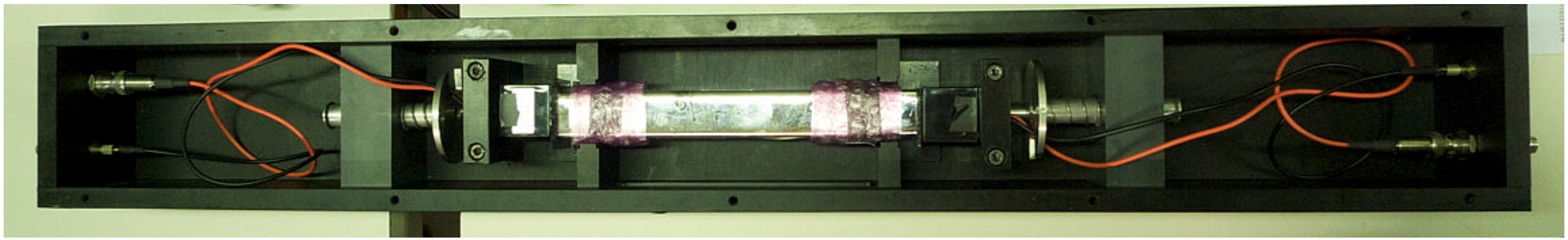


- $PbWO_4$ scintillating crystal equipped with two PMTs and exposed to e, μ and π beams
  - Real data from a test beam @CERN
- A lot of effects will sum-up in a realistic case, like a test-beam
  - We can’t feed our detector signal directly to the ADC (or QDC)
  - We have PMTs, transmission lines (with signal losses!), power supply fluctuations, impedance mismatches, reflections, distortions, etc..



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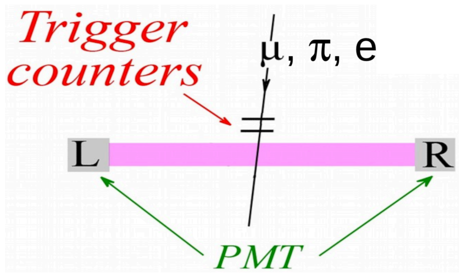
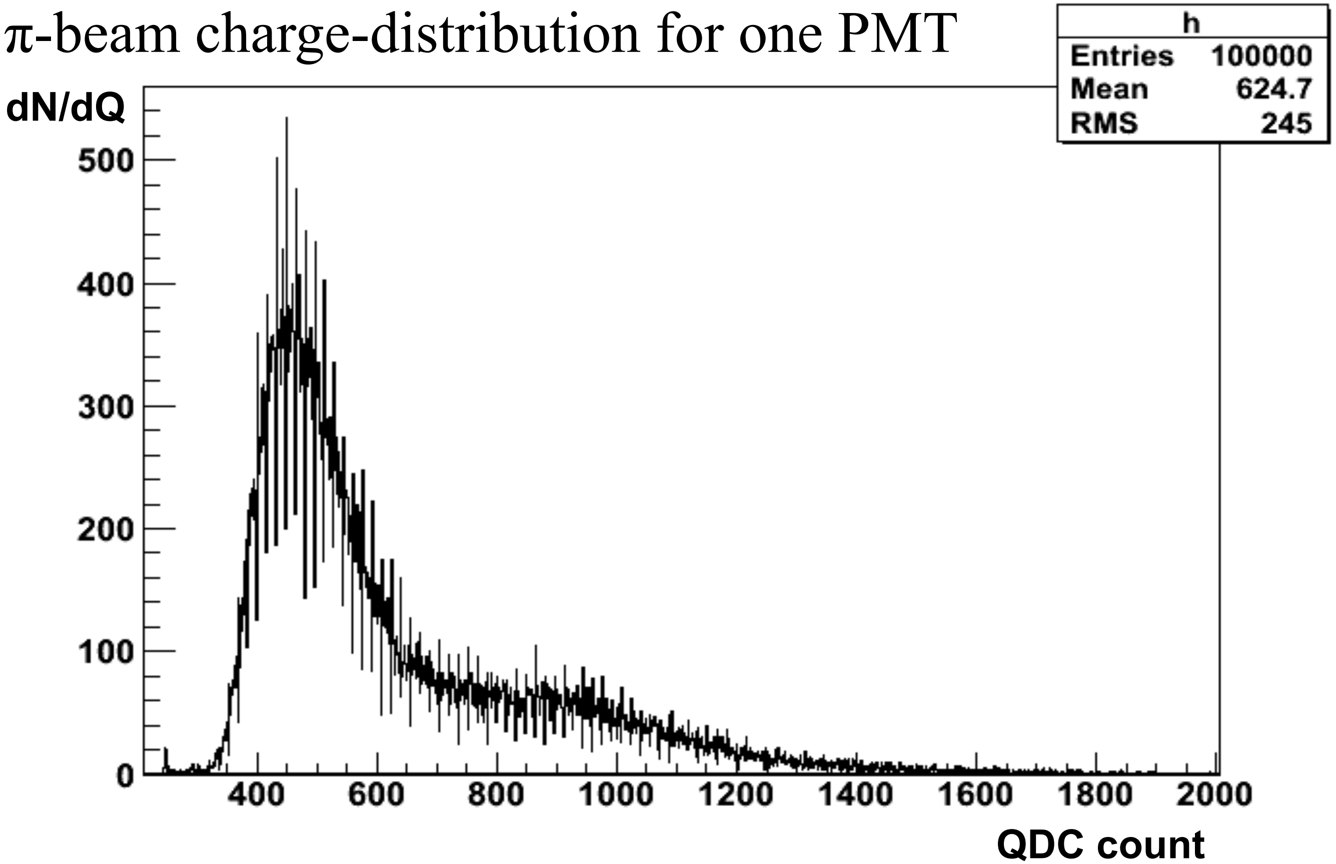


π-beam charge-distribution for one PMT



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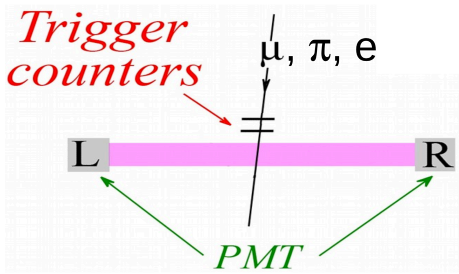

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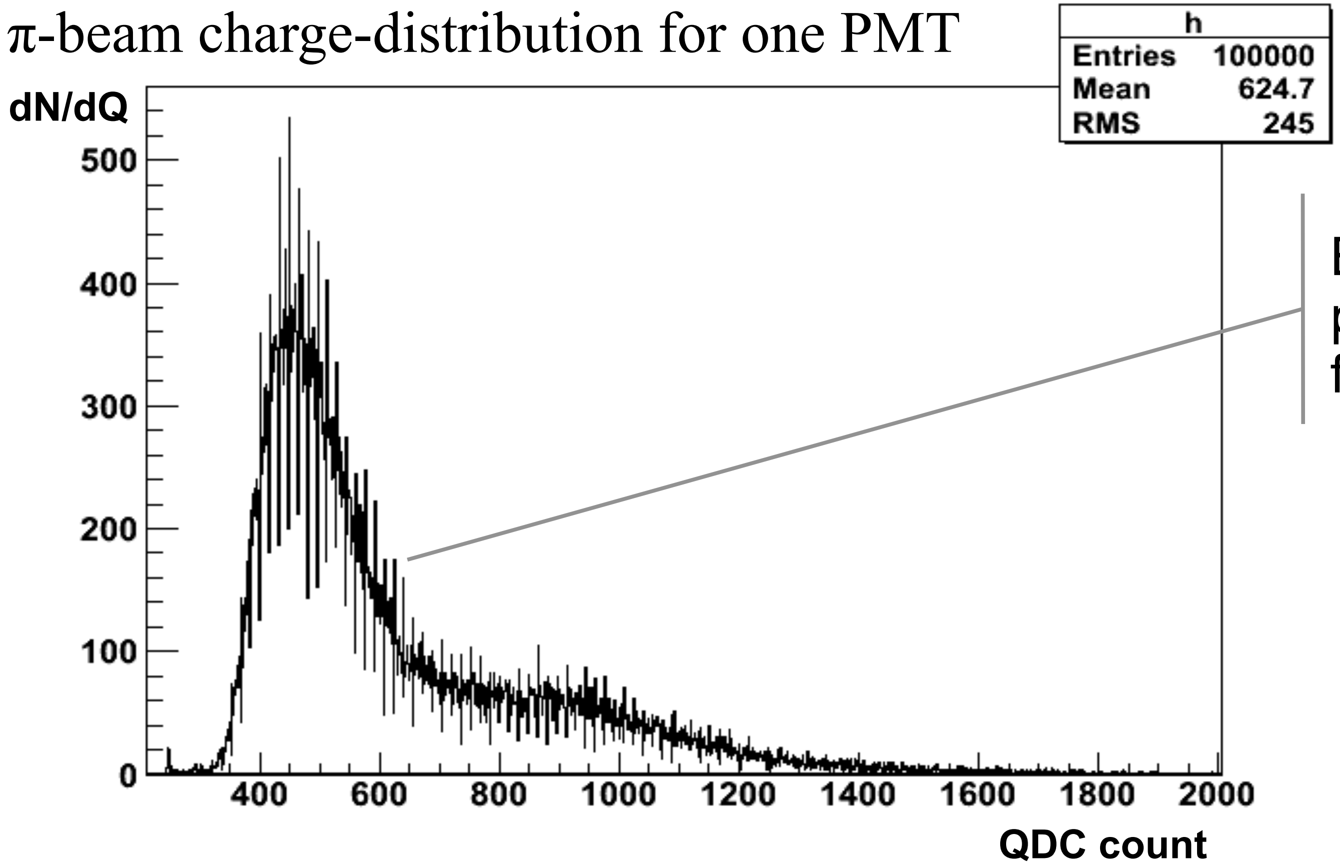

But, what are all those little peaks? Just statistical fluctuations?

Let's zoom in!

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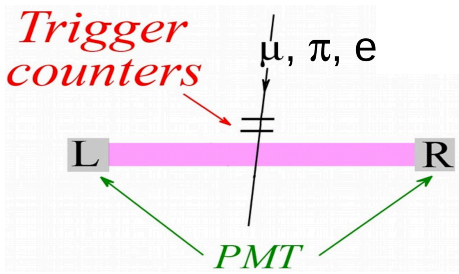

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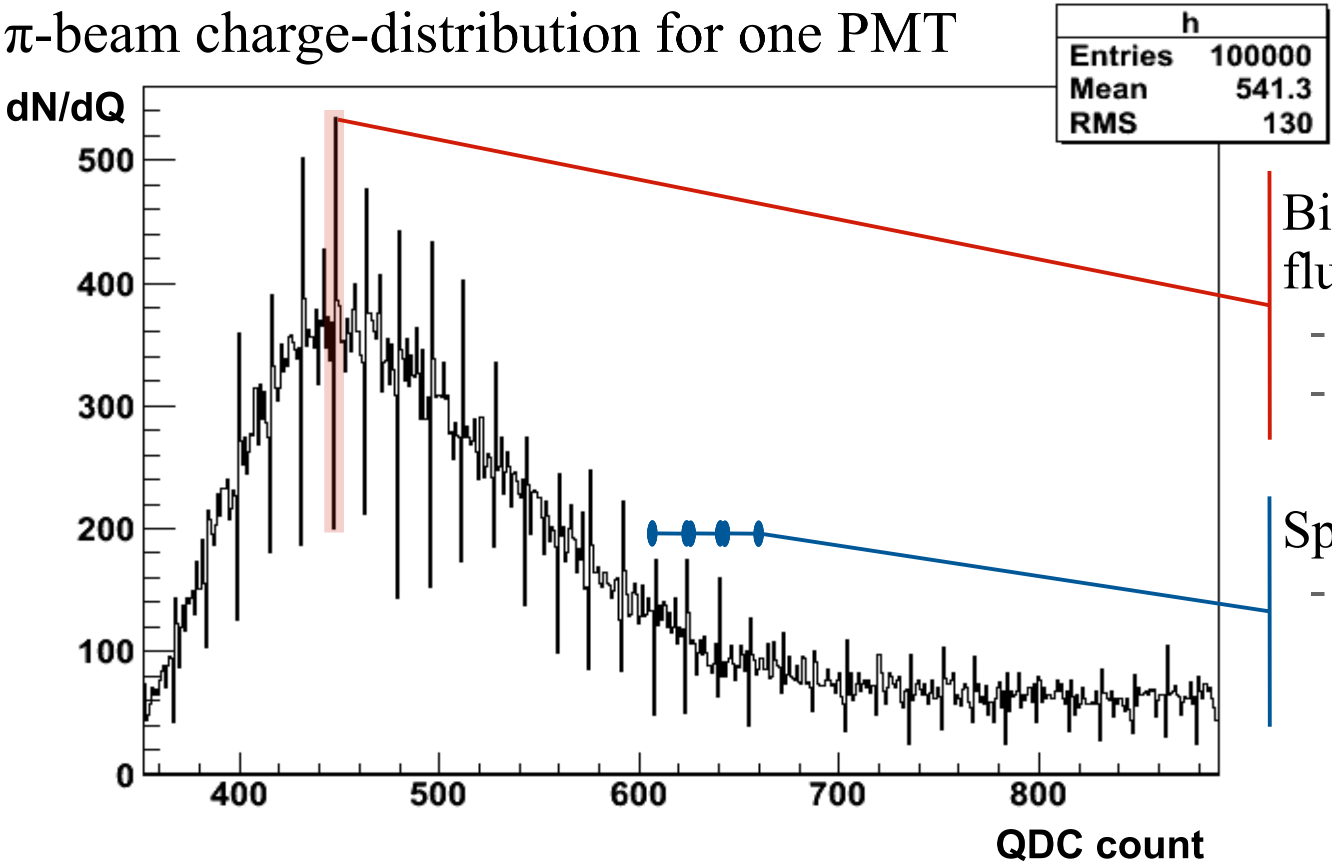

Bin with N entries can fluctuate with $\sigma = \sqrt{N}$
- expected $\sigma=\sqrt{360}\sim 19$
- observed ~200 (>10 σ)

Spikes are regularly distributed
- Some systematic effect must be taking place

Let's zoom in!

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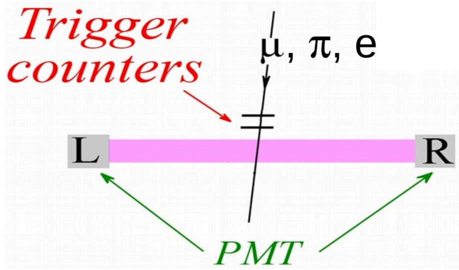

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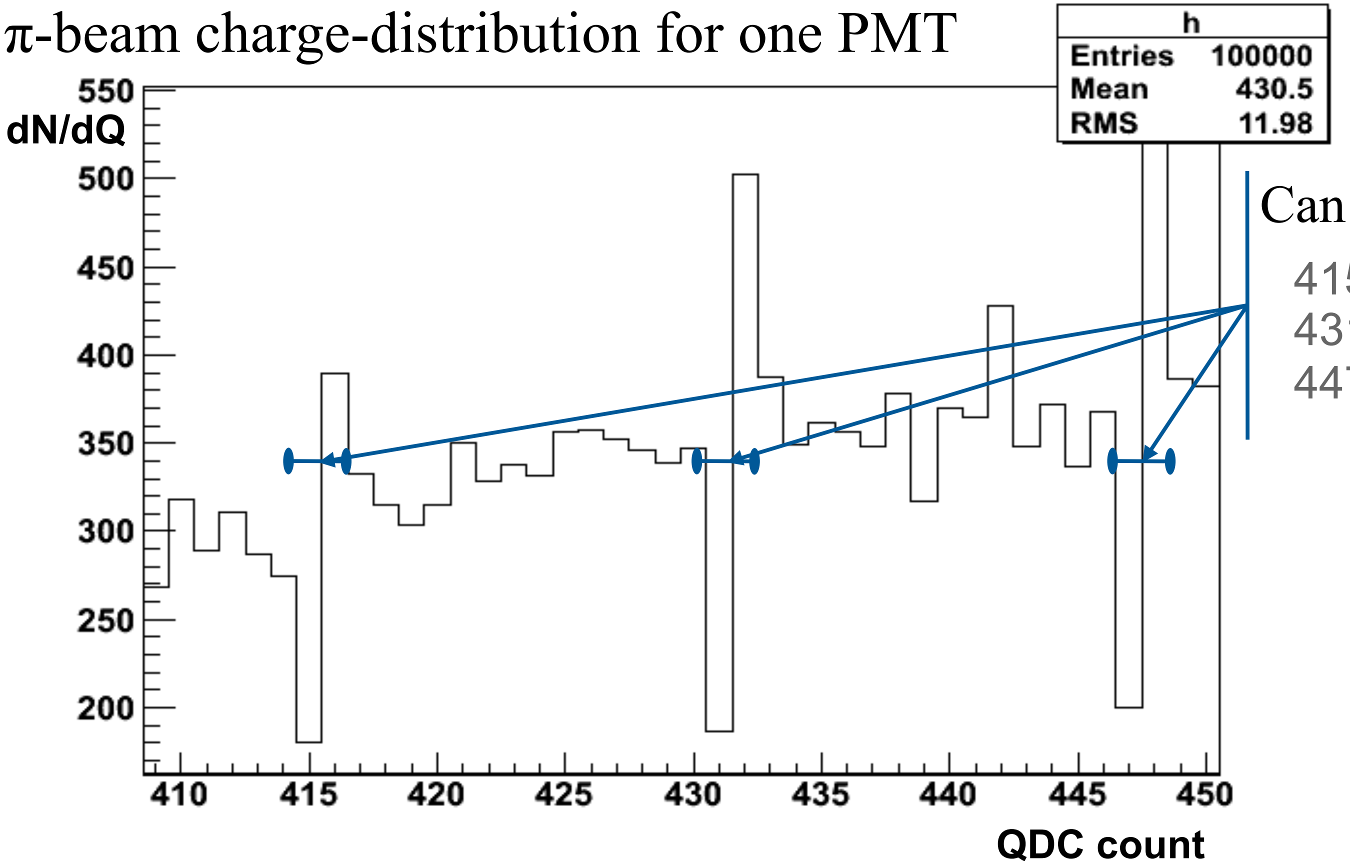

Can you see the effect?

415 & 416 →
431 & 432 →
447 & 448 →

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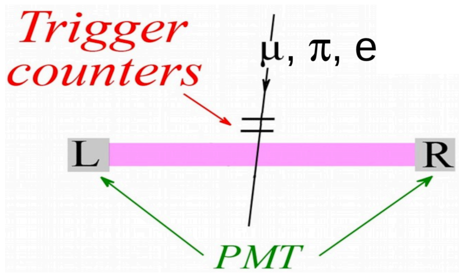

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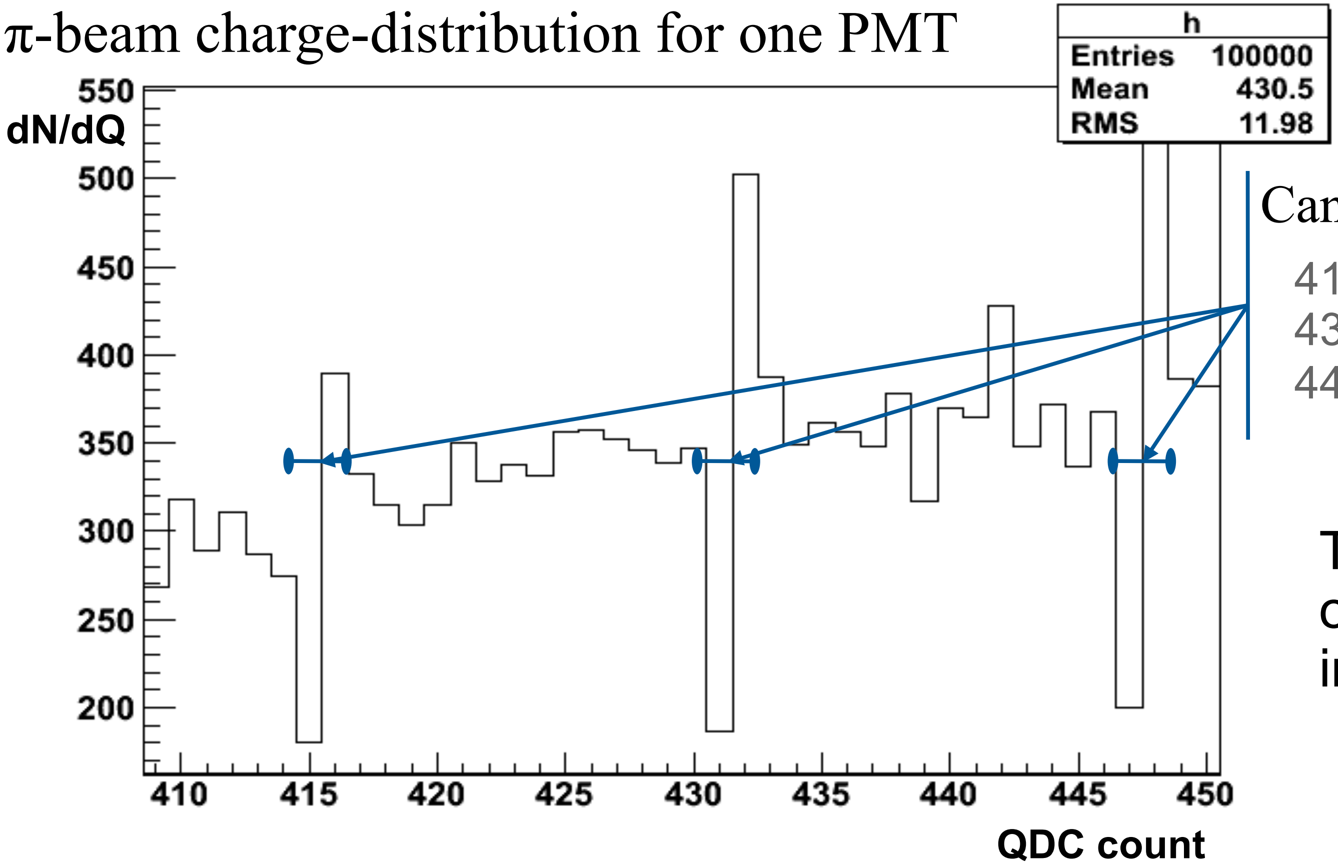


Can you see the effect?

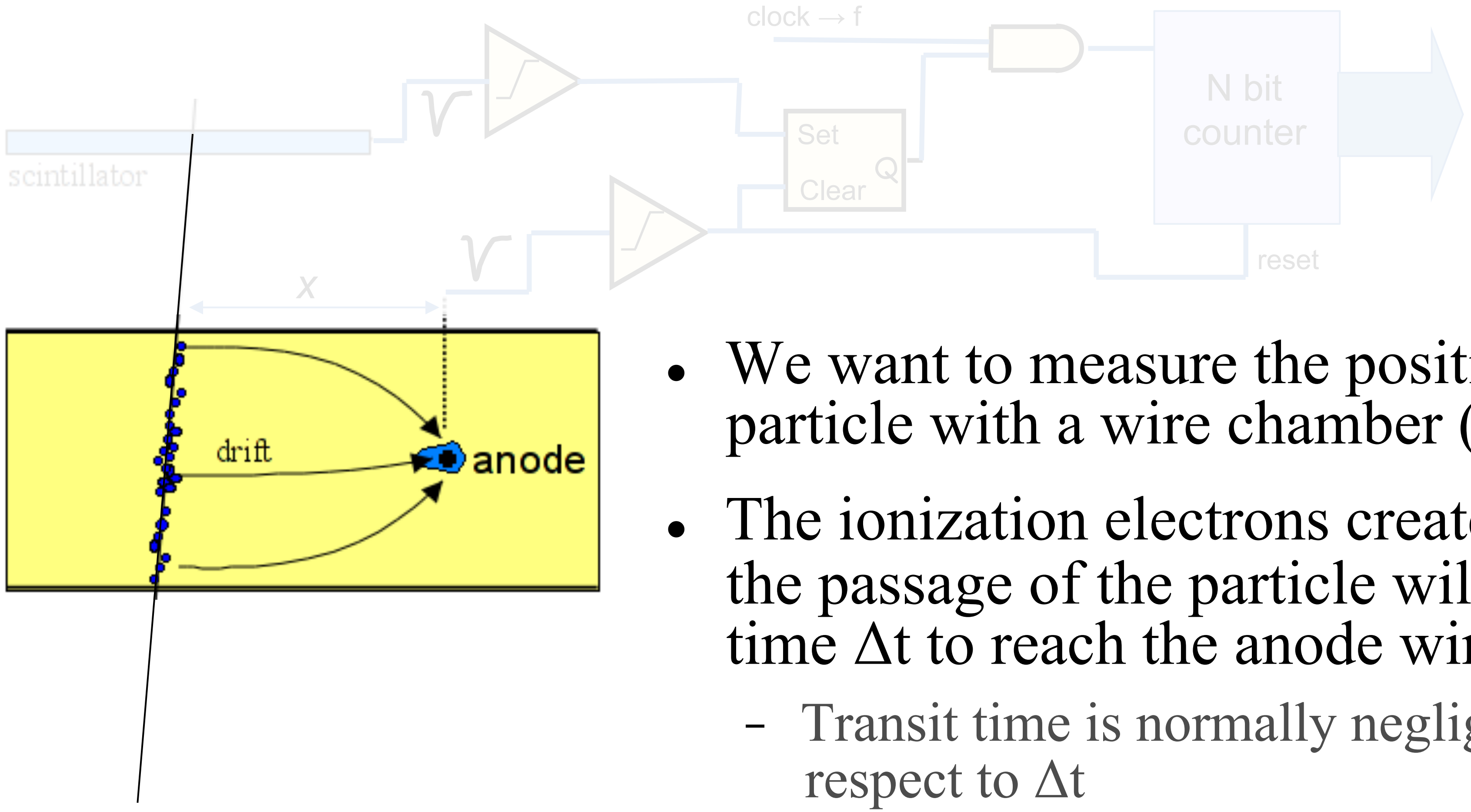
415 & 416 → 0x19**f** & 0x1A**0**
431 & 432 → 0x1A**f** & 0x1B**0**
447 & 448 → 0x1B**f** & 0x1C**0**

The QDC prefers output of type `0x...0` in respect of `0x...f`

Outline

- Introduction
  - DAQ, Electronics & Readout Chain
- 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

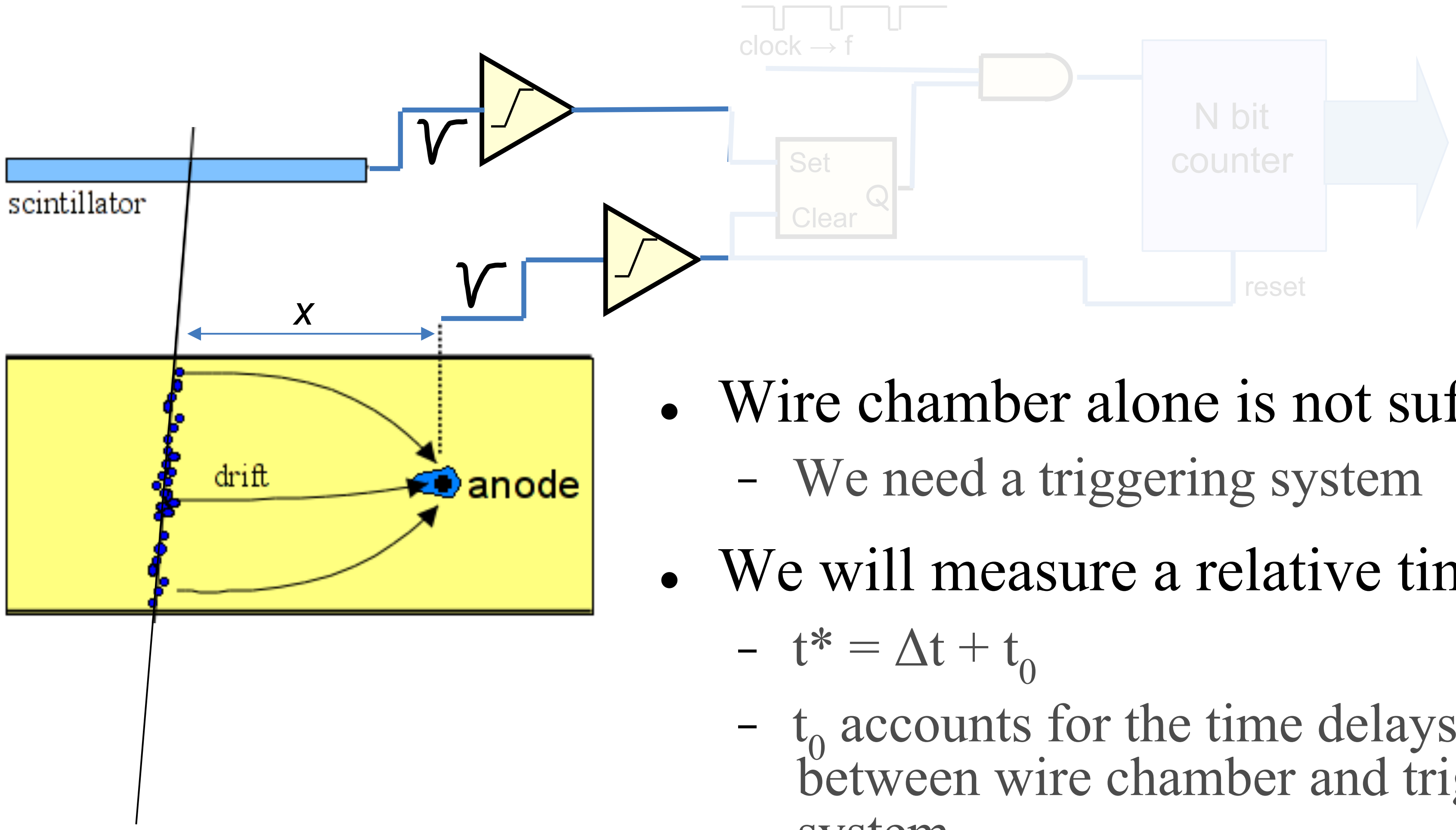
Position measurement



- We want to measure the position of particle with a wire chamber **(drift)**
- 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 (e.g.: 50 µm/ns), then position is:

$$\mathbf{x = v_D \cdot \Delta t}$$

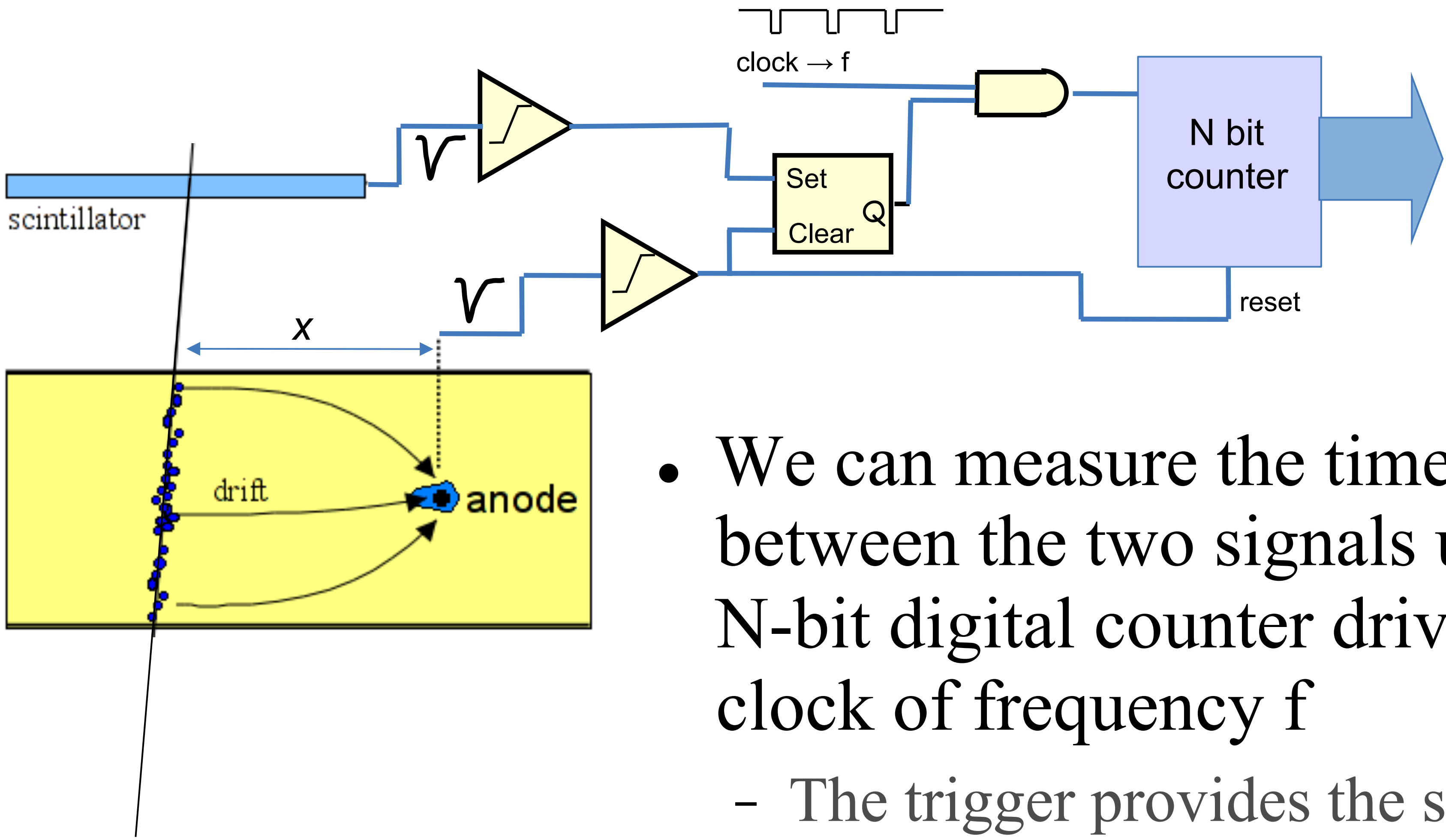
Triggering



- Wire chamber alone is not sufficient
  - We need a triggering system
- We will measure a relative time
  - $t^* = \Delta t + t_0$
  - t_0 accounts for the time delays, offsets, … between wire chamber and triggering system
- Assuming a constant drift

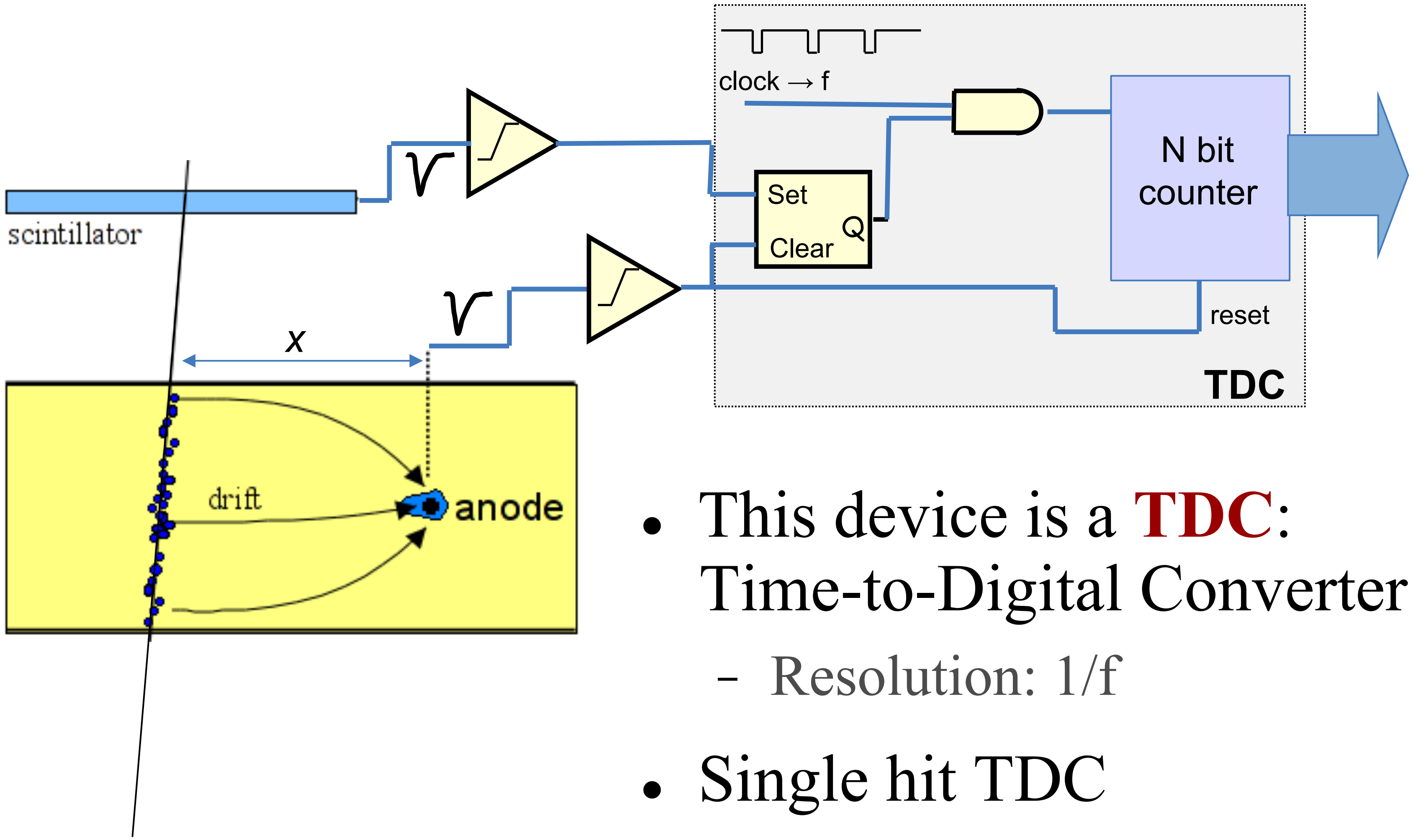
$$x = \alpha t^* + \beta$$

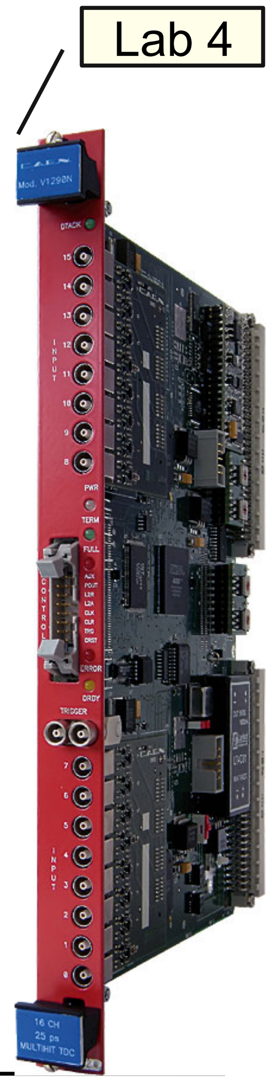
Time measurement



- We can measure the time offset between the two signals using a N-bit digital counter driven by a clock of frequency f
  - The trigger provides the start signal
  - Wire signal acts as a stop signal

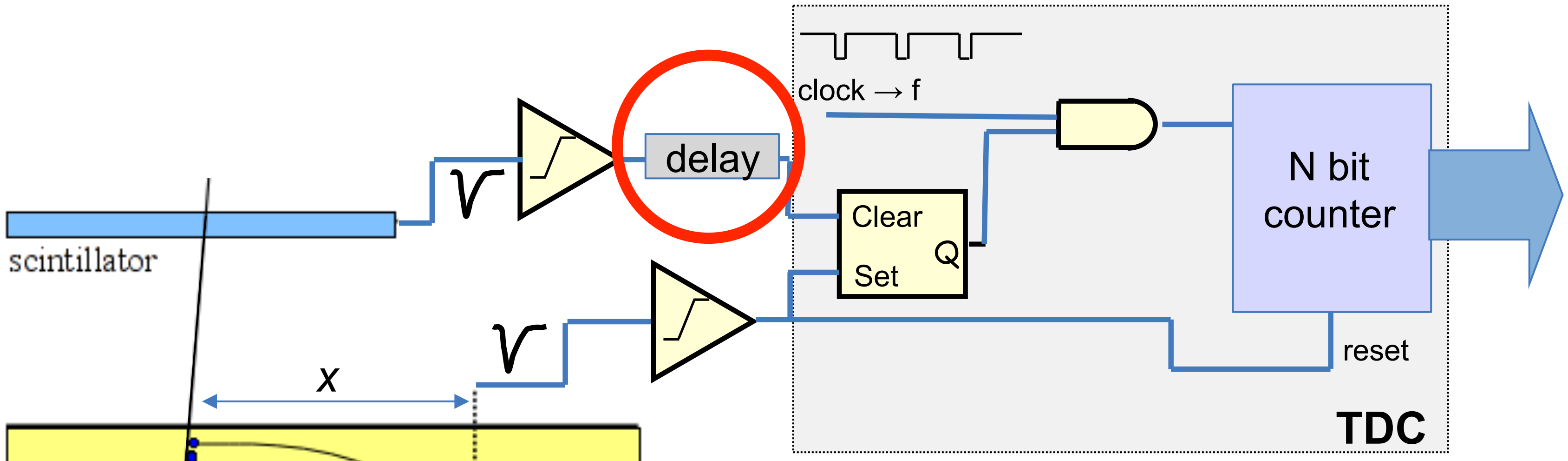
Time measurement: TDC

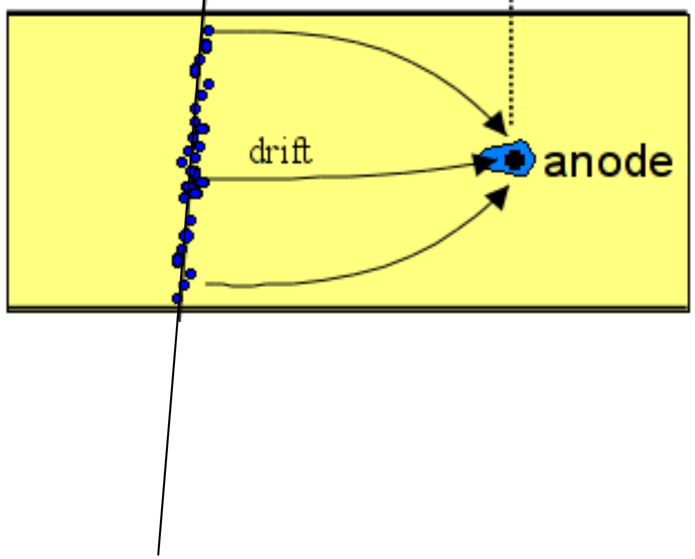




- This device is a **TDC**: Time-to-Digital Converter
  - Resolution: 1/f
- Single hit TDC
  - if a noise spike comes just before the signal, the measure is lost

Time measurement: TDC





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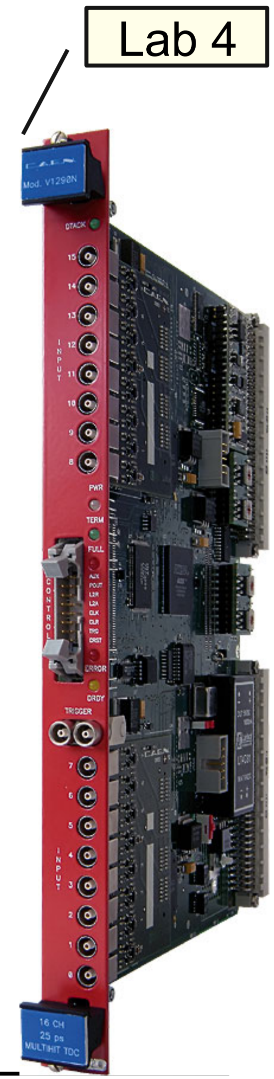
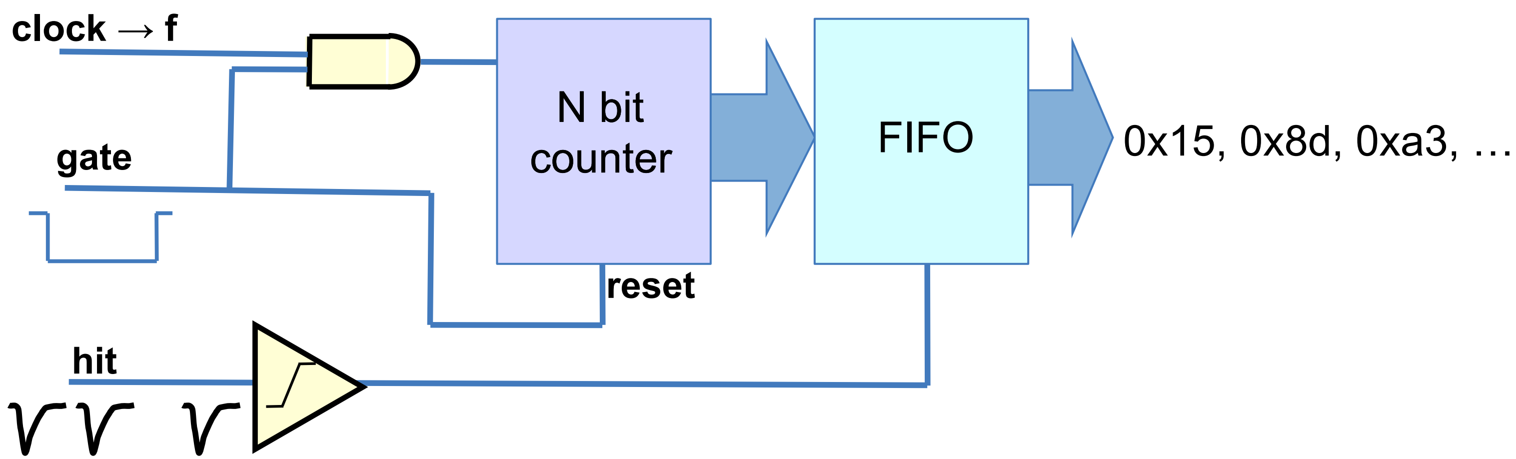


Multi-hit TDC

- Gate resets and starts the counter
  - It also provides the measurement period
- Each "hit" (i.e. signal) forces the FIFO to load the current value of the counter, that is the delay after the gate start
  - Common-start configuration
  - In order to distinguish between hits belonging to different gates, some additional logic is need to tag the data



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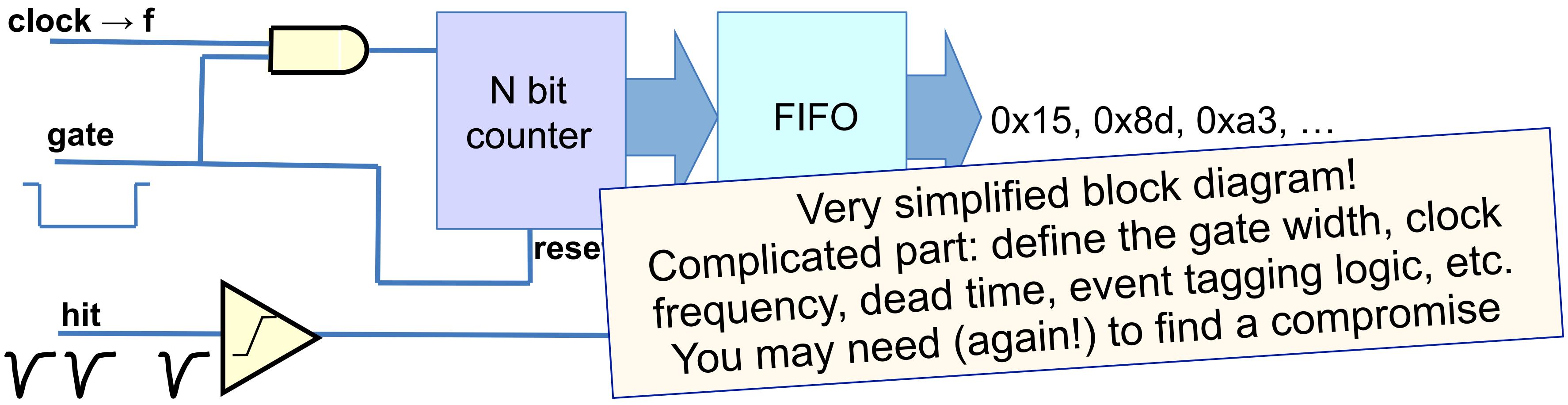
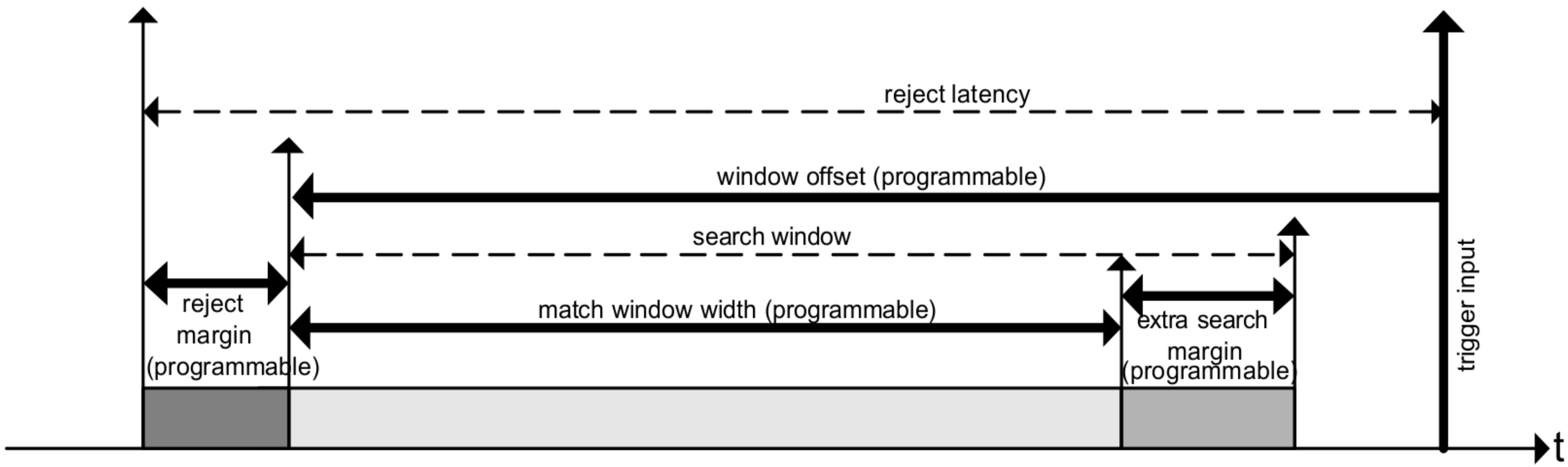


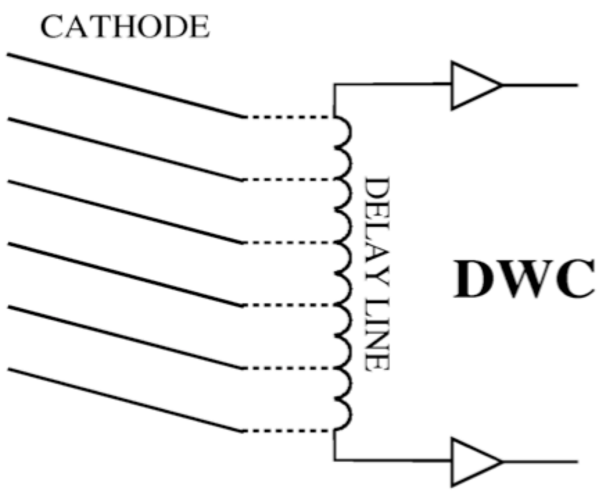
Actual TDCs

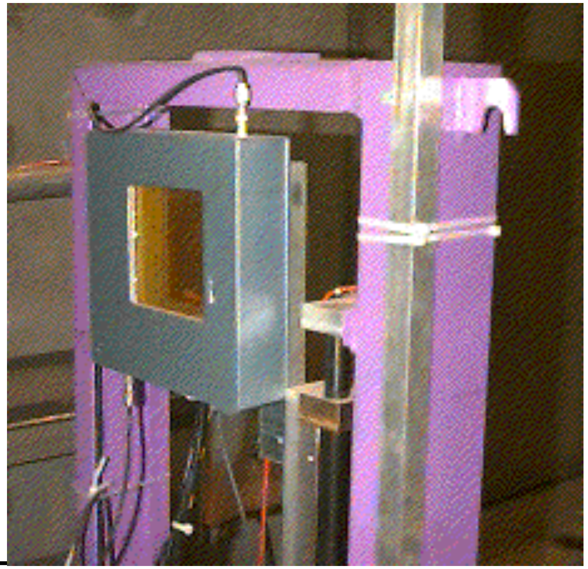
- Plenty of TDCs architectures available on the market
  - Common Start, Common Stop, Charging Capacitor, Vernier, etc.
- Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching
  - Internal programmable delays or generation of programmable gates
  - Programmable rejection frames
  - Usually via a dedicated C library/API



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 based on the delay gained along a delay line





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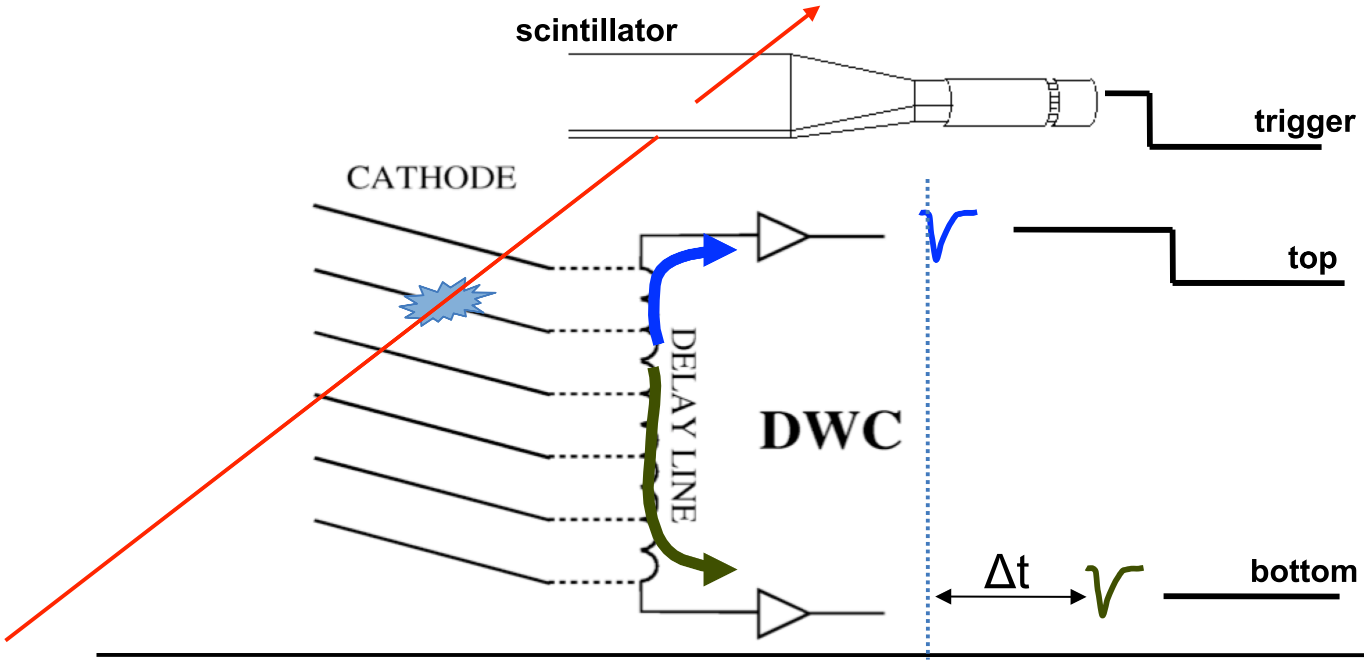

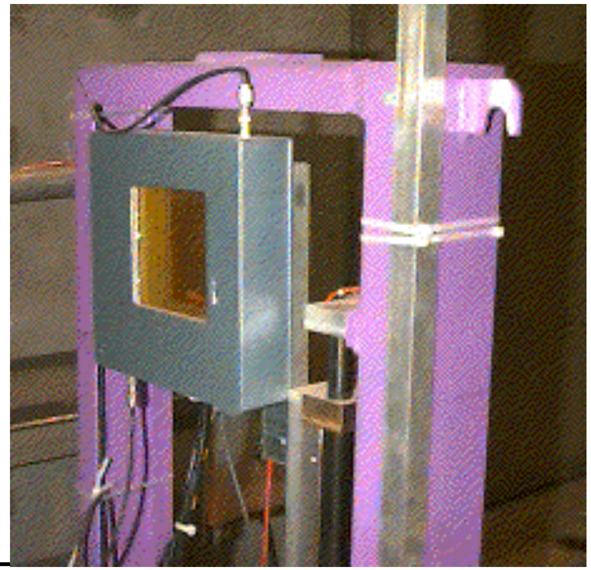

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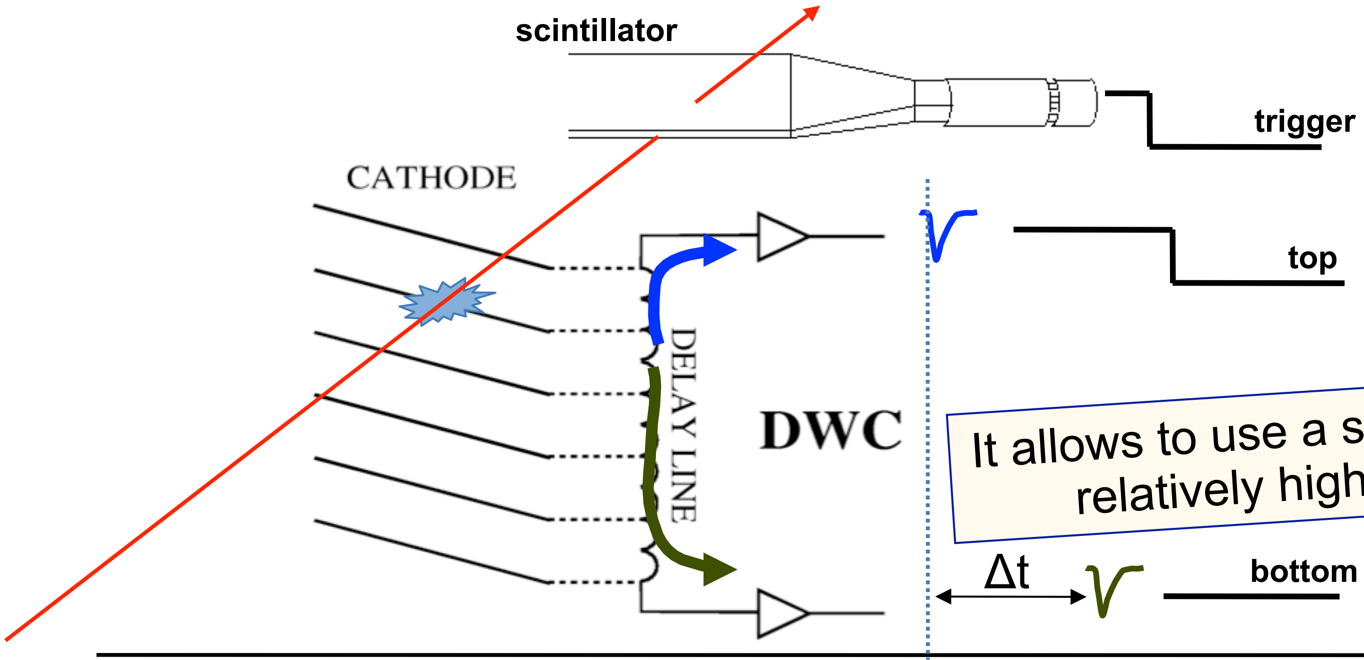
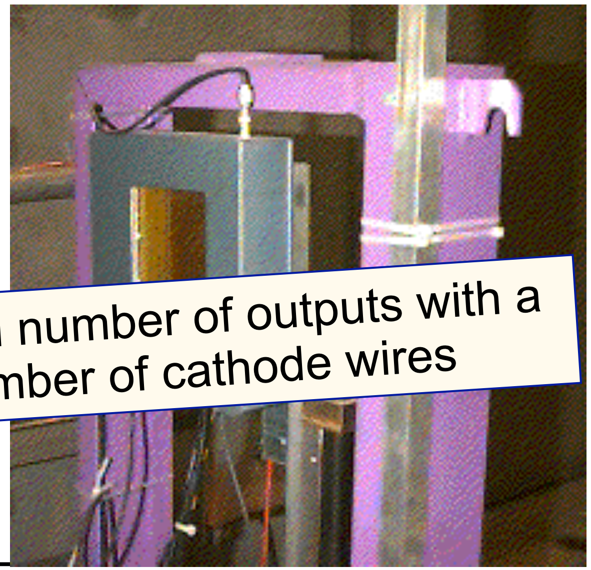
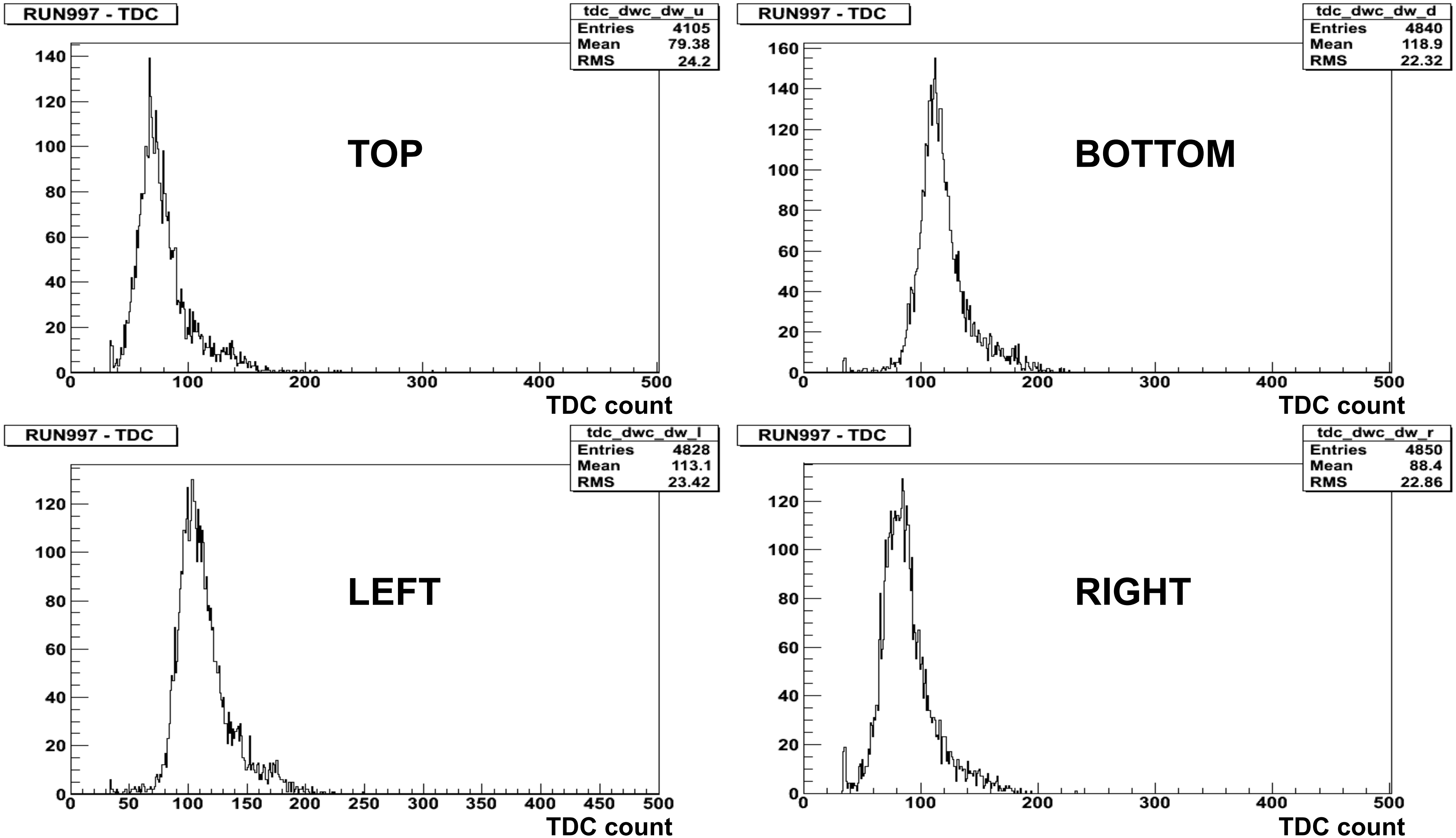




It allows to use a small number of outputs with a relatively high number of cathode wires

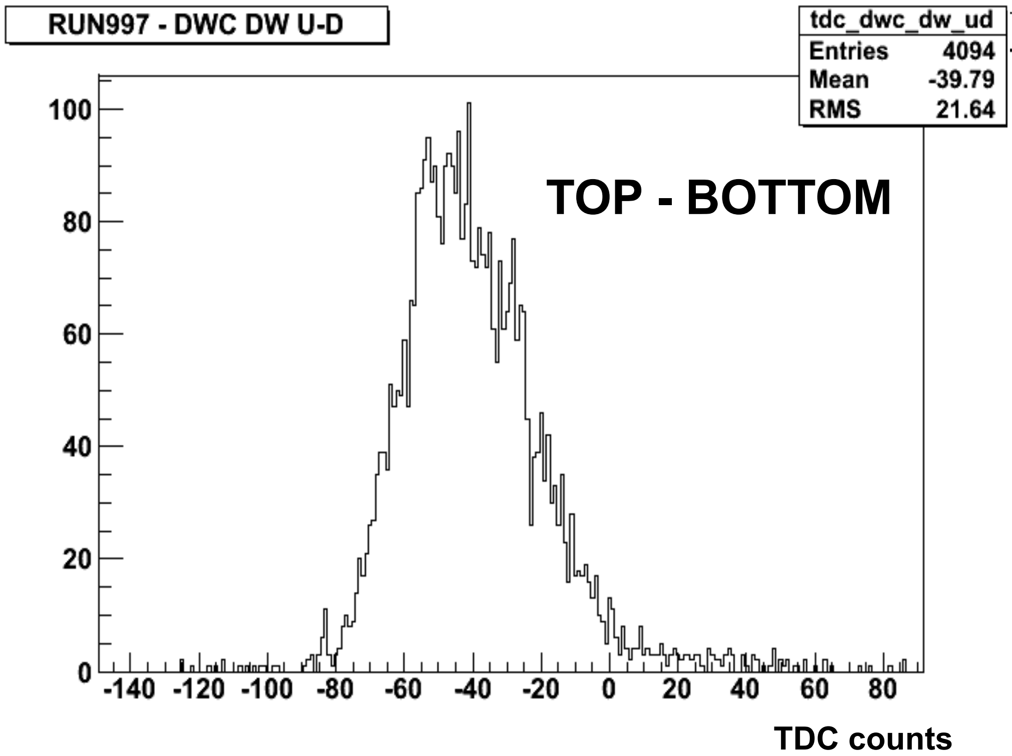
Raw time data

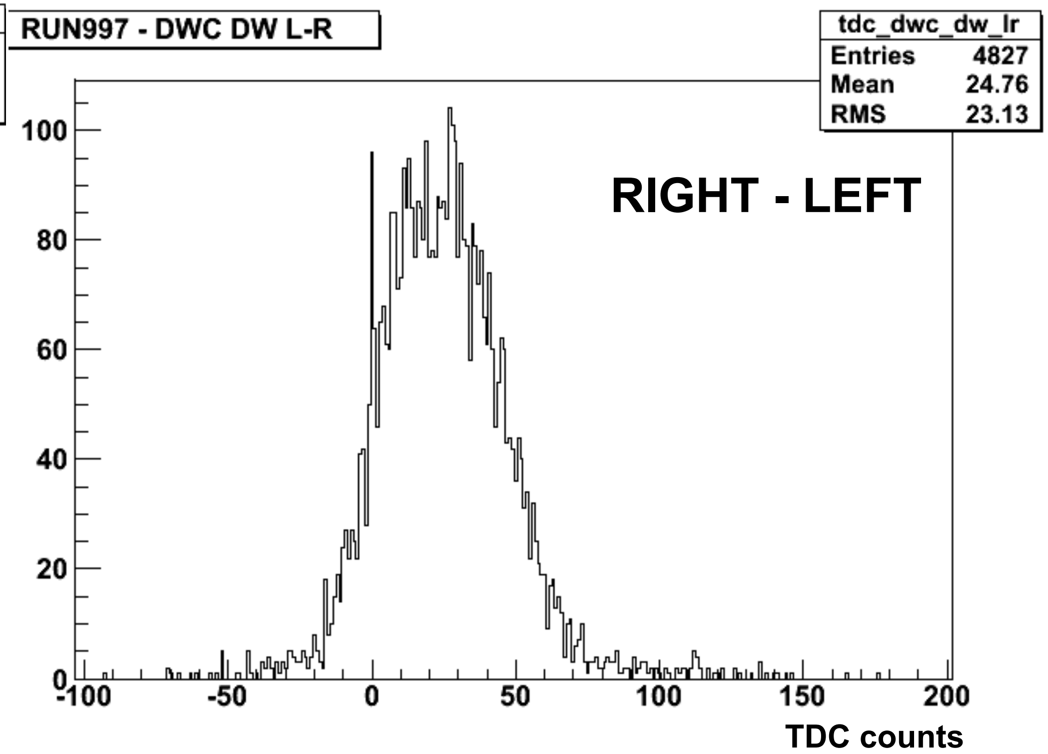
- Take a run (some thousands events)
  - Individual channel distribution



Un-calibrated beam profile

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





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  - DAQ, Electronics & Readout Chain
- 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: calibration

Calibration

- Previous experiments provide relative measurements
  - Values obtained via our systems are in some (known) relation with the interesting quantities
    - 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, …)
- NB: calibration mechanisms/procedures shall be foreseen in the design of our detector and DAQ

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However, we still don't know the proportionality factor between charge and energy, or between time and position

- Our inst… order to give us the ans…
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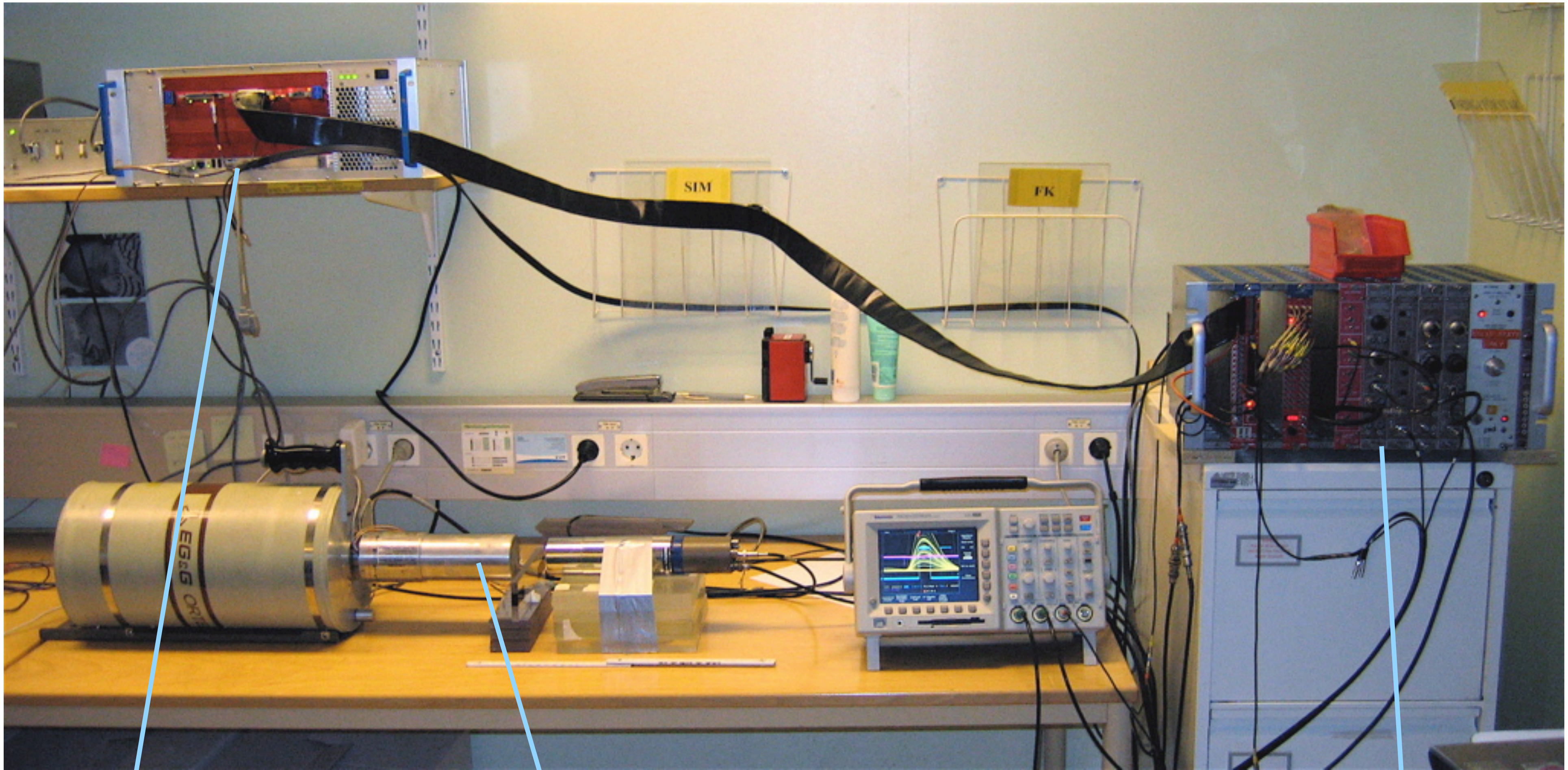
E.g.: Ge Crystal for isotope ID



Trigger and front-end

Crystal HPGe
Radiation detector

Readout (ADC)

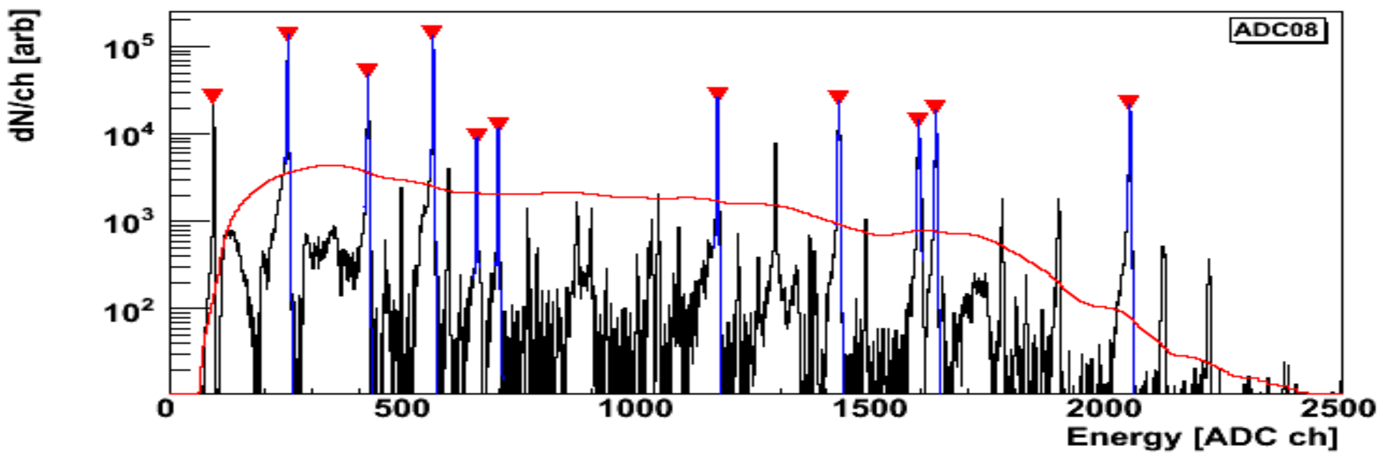
by Sergio Ballestrero

Ge crystal calibration

- ^{152}Eu reference source allows for definition of the parameters describing functional relation between ADC count and E
  - Known γ emission lines

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

- Find the peaks and fit



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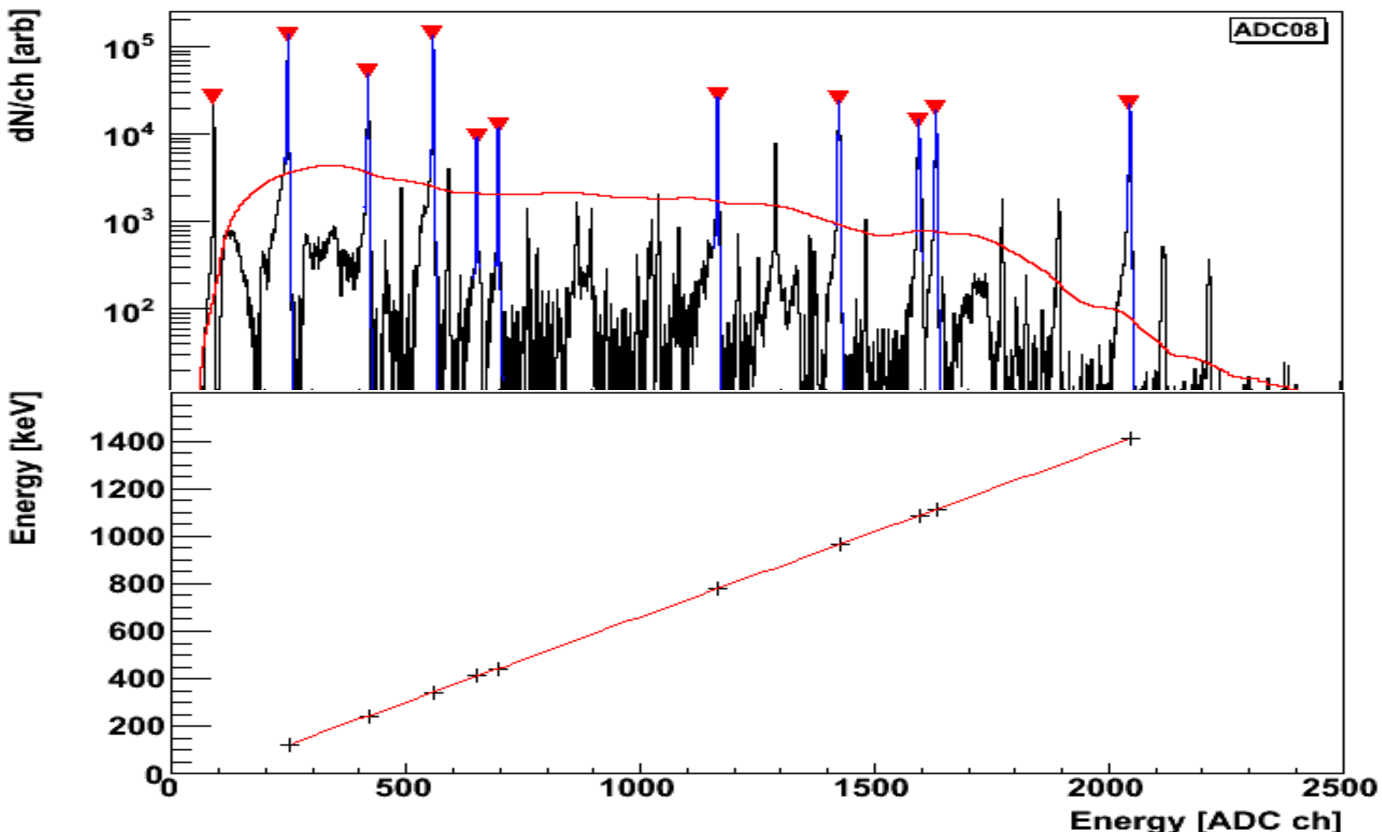

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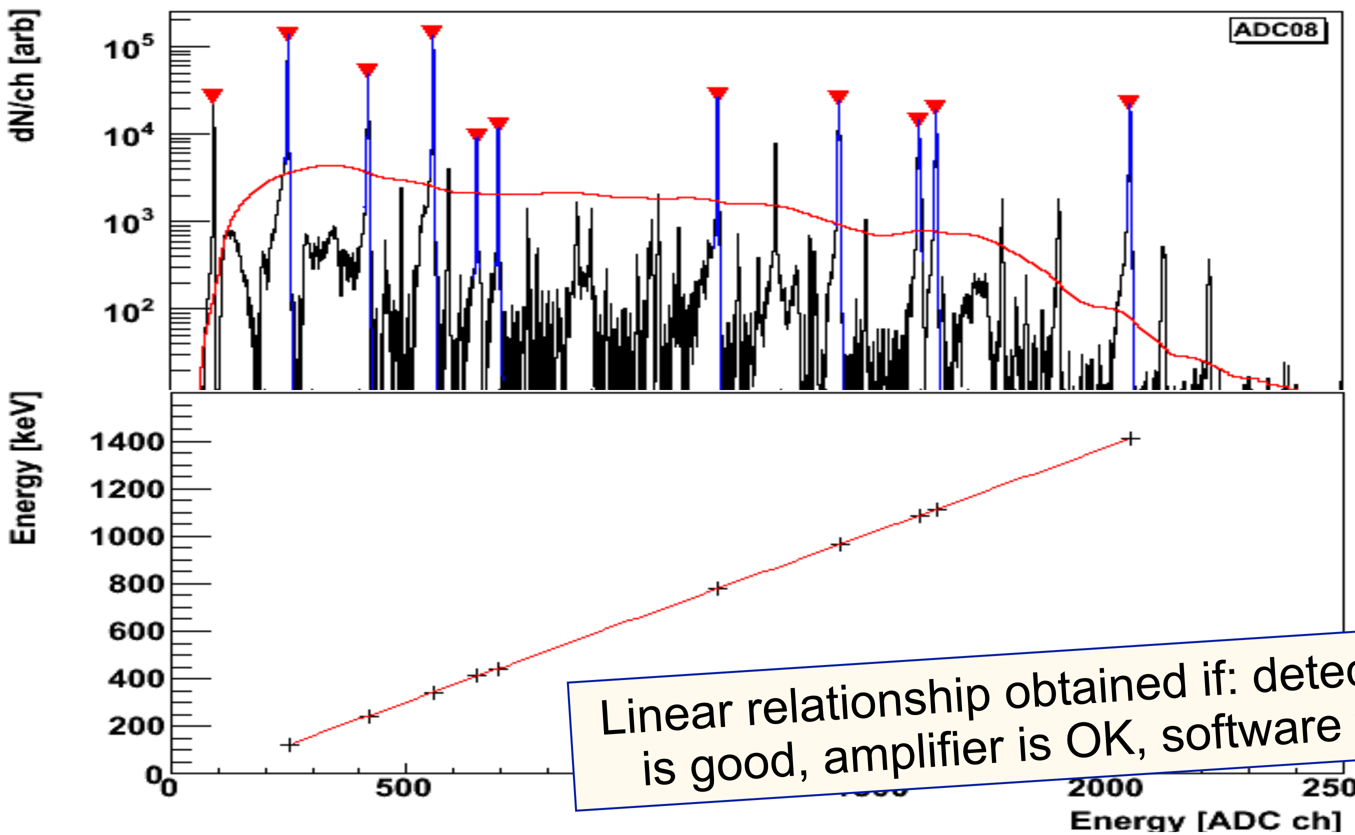
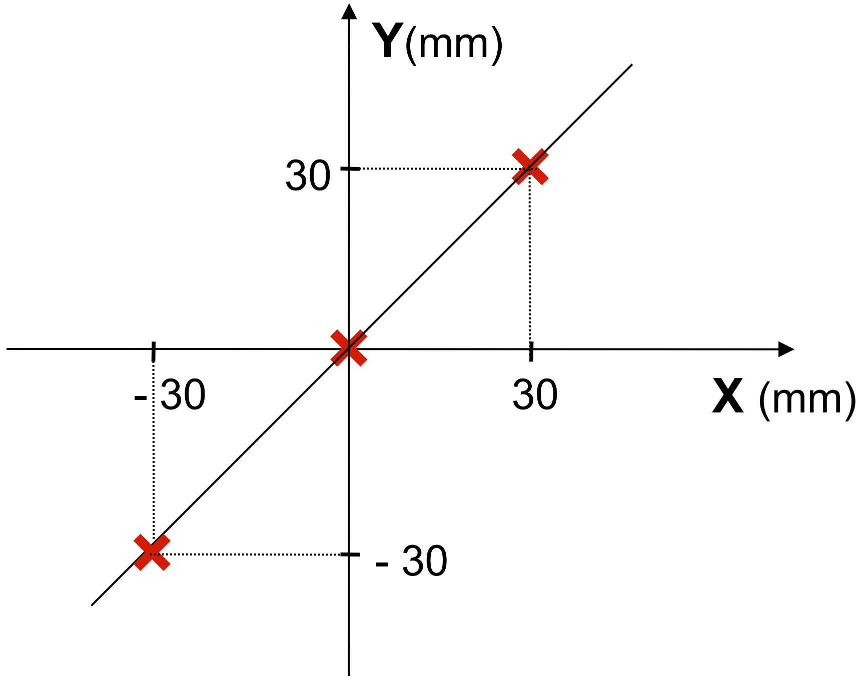


Linear relationship obtained if: detector is good, ADC is good, amplifier is OK, software well written, etc.

Back to XDWC: calibration

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



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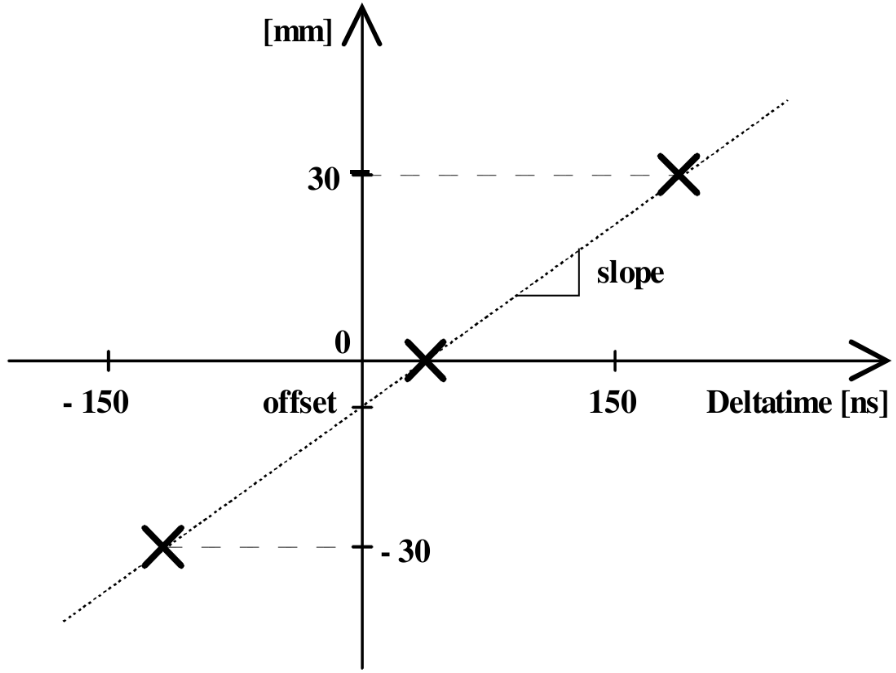

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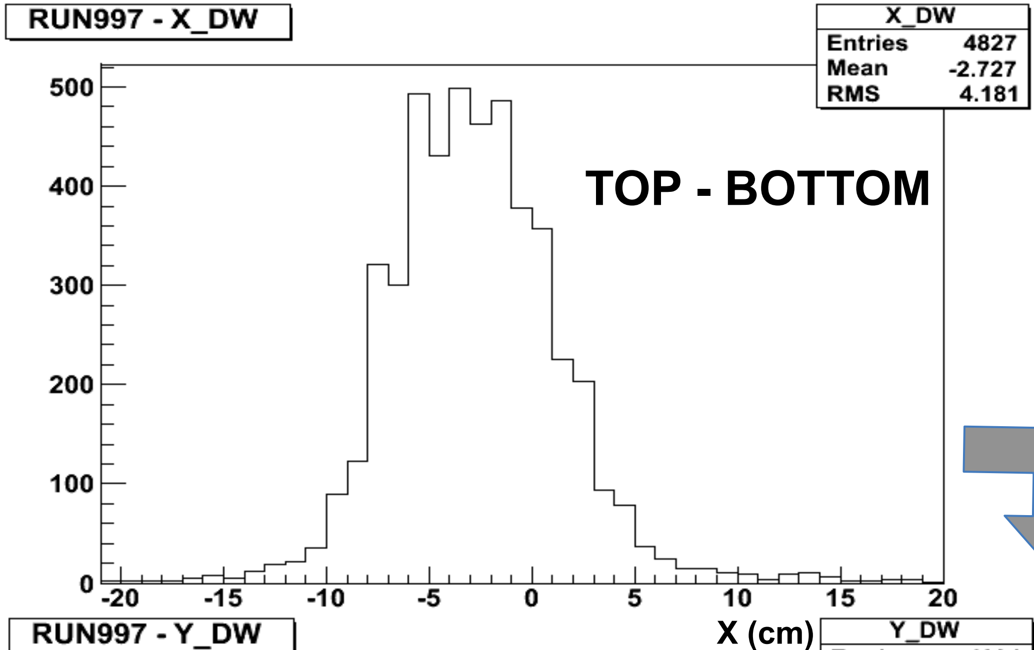
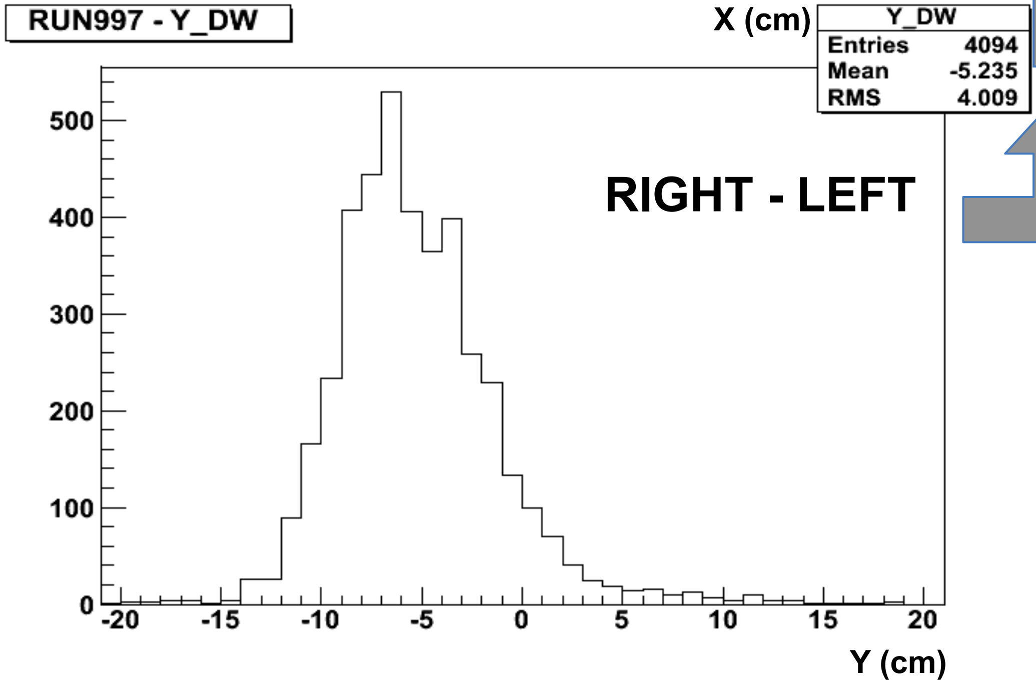
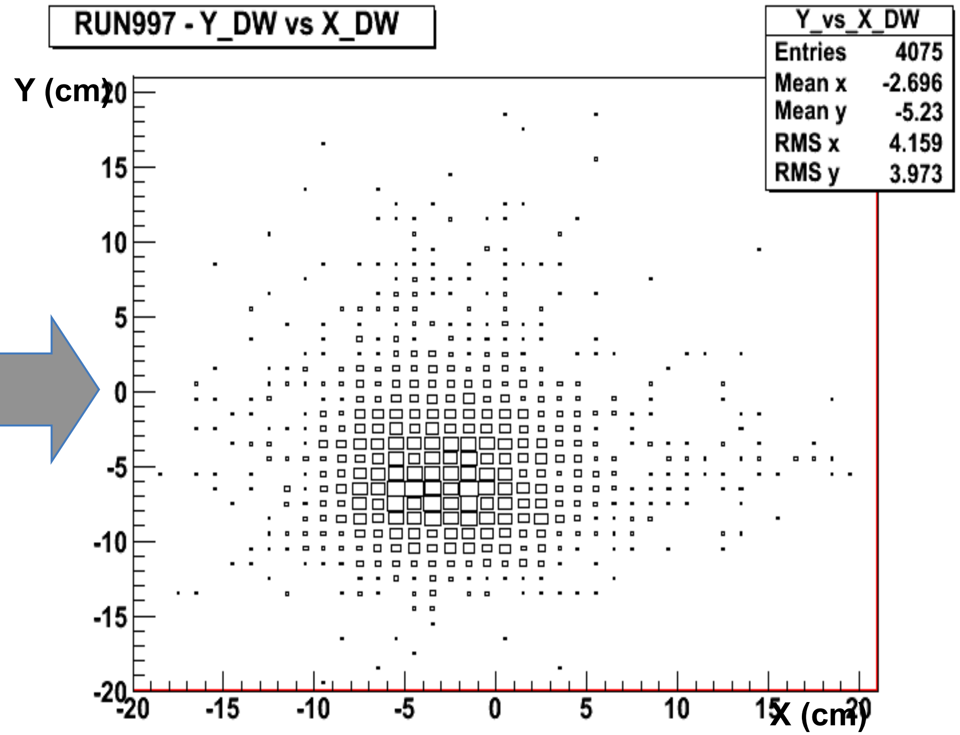
Calibrated XDWC





Beam profile



Wrap-up

- Digitization techniques produce data directly manageable by digital systems (e.g. a computer)
  - Greatly simplifies the down-stream data-handling
  - Available on a variety of platforms: VME, ATCA, PCI, USB, …
  - Root of every modern DAQ system
- Frequently you have to open the "black box" and see where 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 raw data via calibration
  - Calibration procedures to be foreseen for your detector/DAQ

Thank you!