# DAQ HW

## Hands-on Approach

**ISOTDAQ 2020**
**11th** International School of Trigger and Data Acquisition
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School of Engineering (ETSE),
University of Valencia

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# 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


- Acknowledgements
  - © Andrea Negri (Univ. of Pavia, Italy)
  - © 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 yesterday's 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, …

➔DAQ is a wide and vast field

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

# Electronics: What is needed for?

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

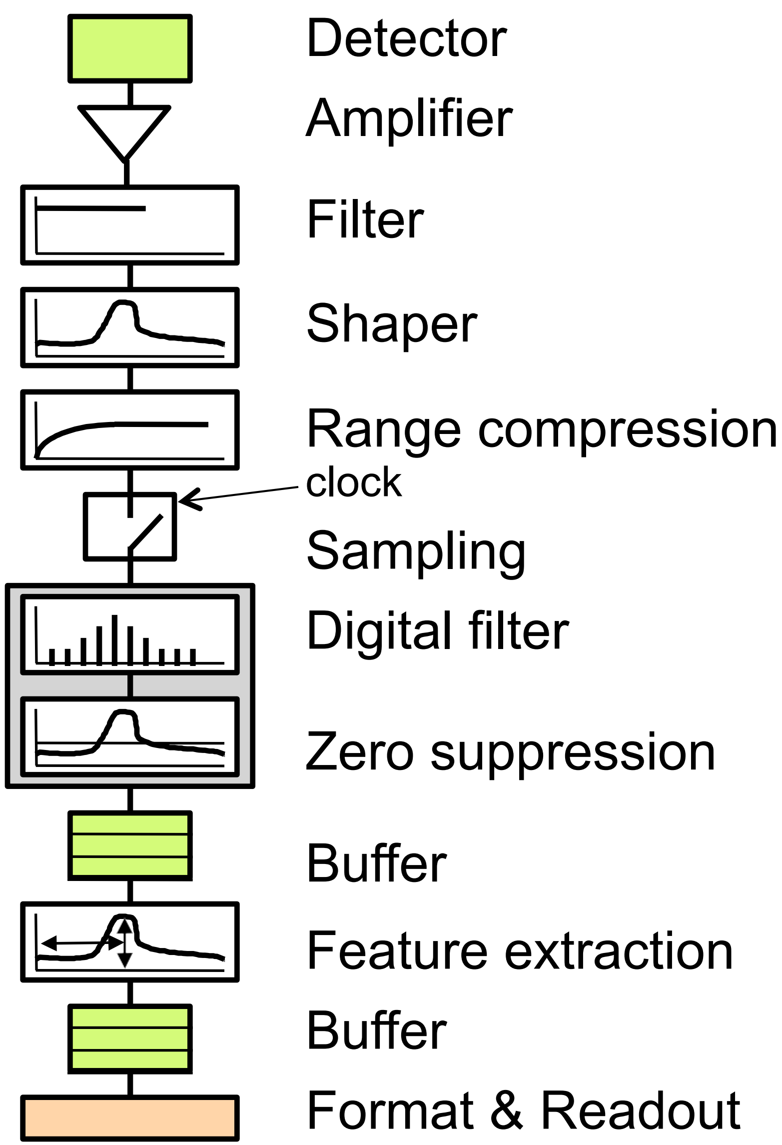
➔Adapt the signal to optimize different, **incompatible**, characteristics → Compromise

- Detect minimum detectable signal
- Precise energy measurement
- Fast signal rate
- Precise timing
- Insensitivity to pulse shape

➔Digitize the signal

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

# Readout chain




➔Front-end electronics very specialized

- 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

- Find yourself dealing or choosing commercial electronics

➔We just discuss selected functions and principles

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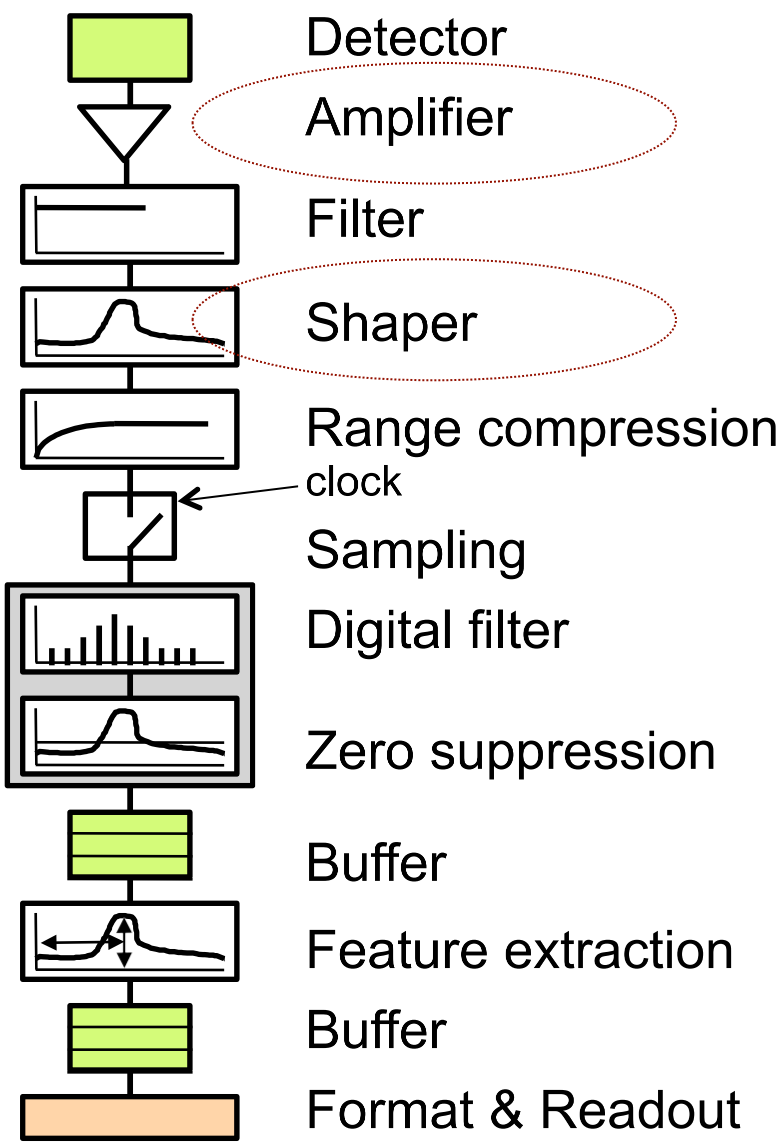

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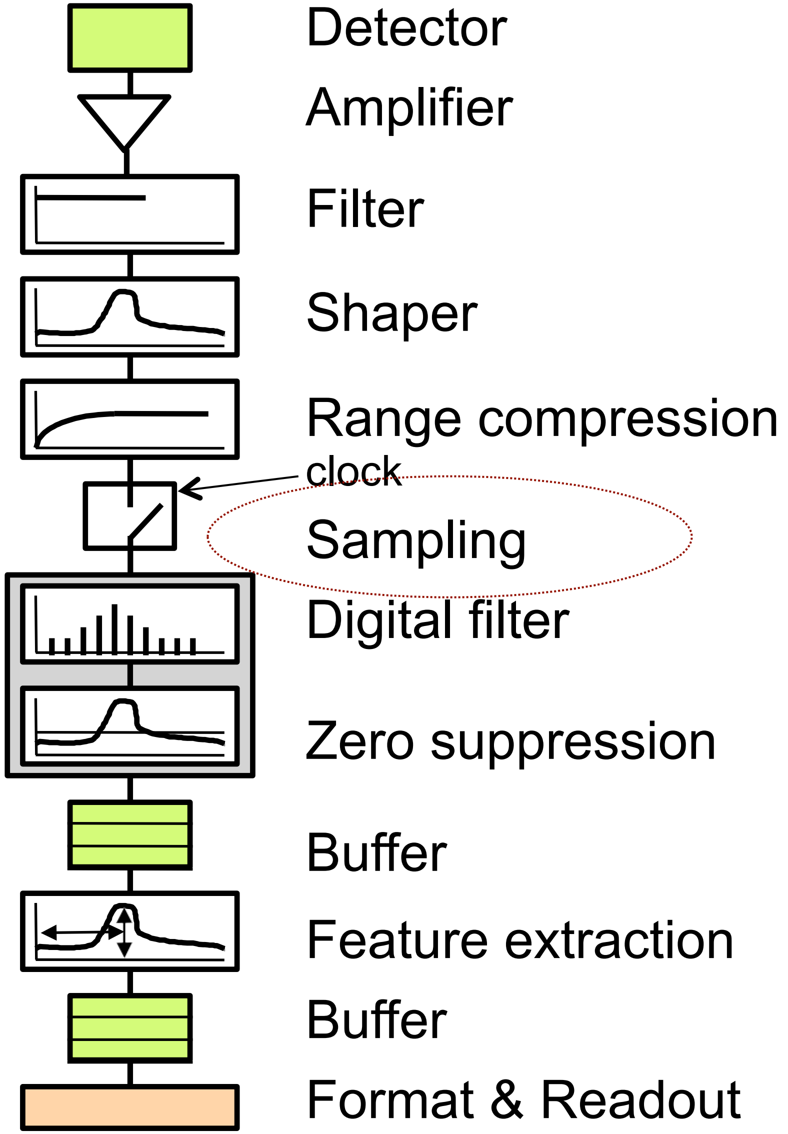
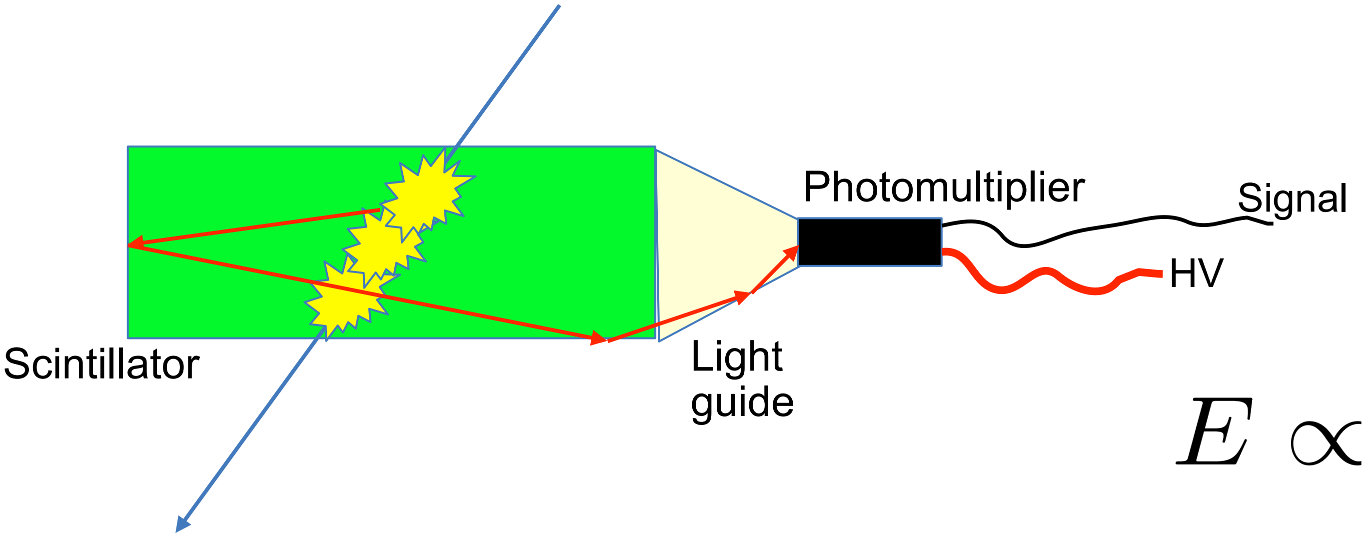


# Outline

- 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

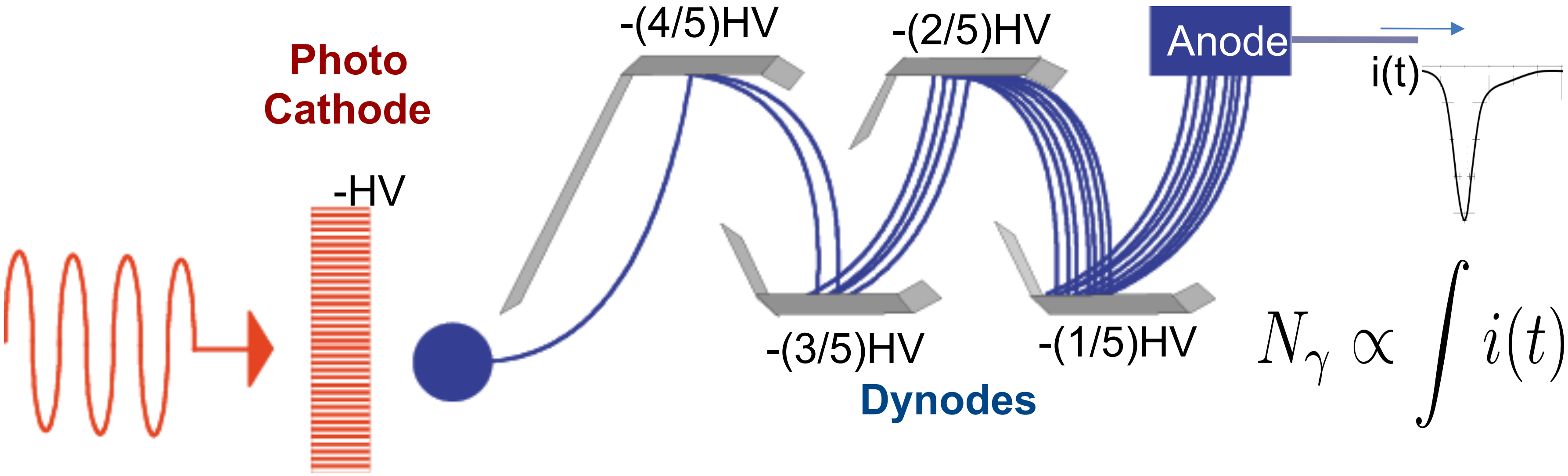
# Energy measurement




$$E \propto N_\gamma$$

- 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
- The light is then
  - collected, using dedicated optical means (**light guide**)
  - fed into a photo-detector: **photomultiplier**

# Photomultiplier

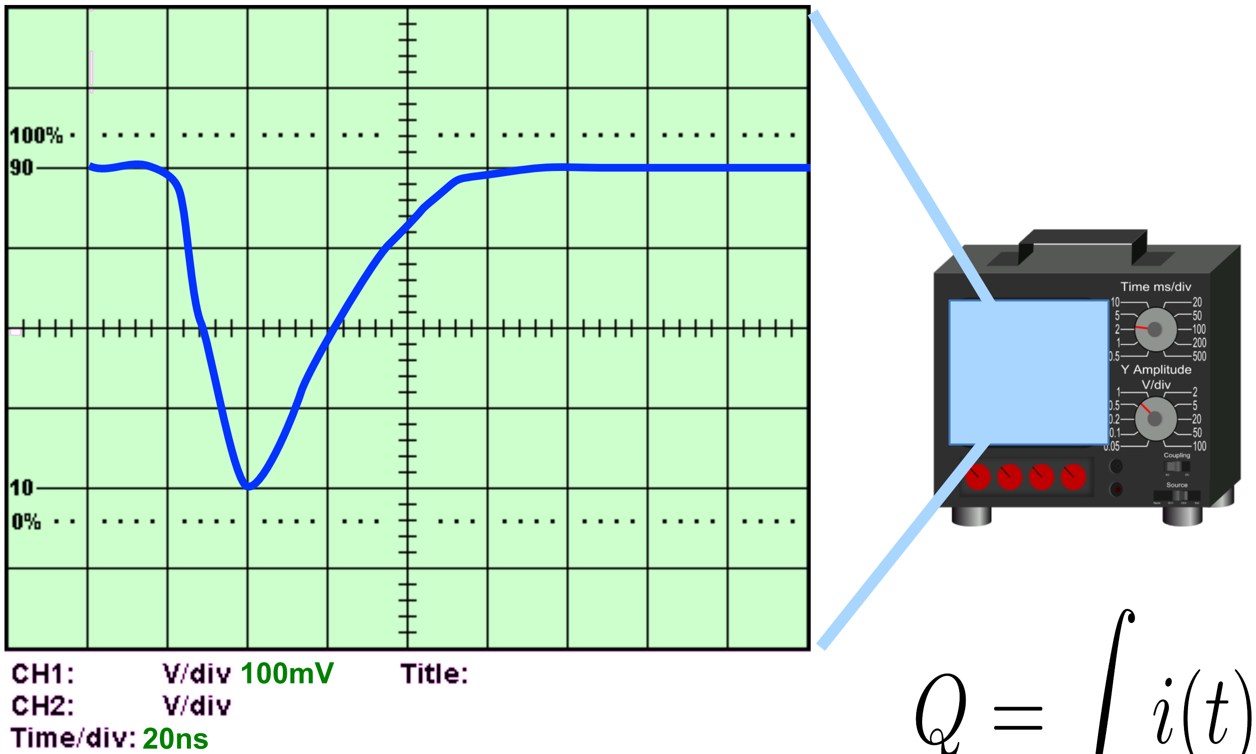


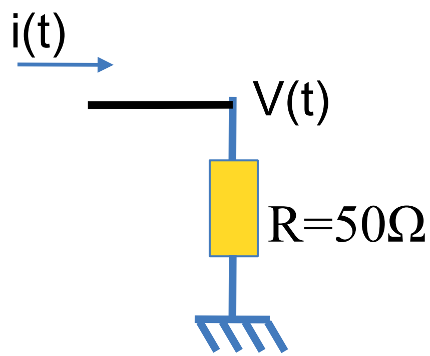

$$N_\gamma \propto \int i(t)\,dt = Q$$

- **Photo cathode**: photon to electron conversion via photo-electric effect
  - typical quantum efficiency ≈1-10% (max 30%), depends on material and wavelength
- **Dynodes**: electrodes that amplify number of electrons thanks to secondary emission
  - Photocathode to anode: typical overall gain $\approx 10^6$
- **Dark current**: noise
  - current flowing in PMT without light

# Start the measure

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




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

# Good old oscilloscope

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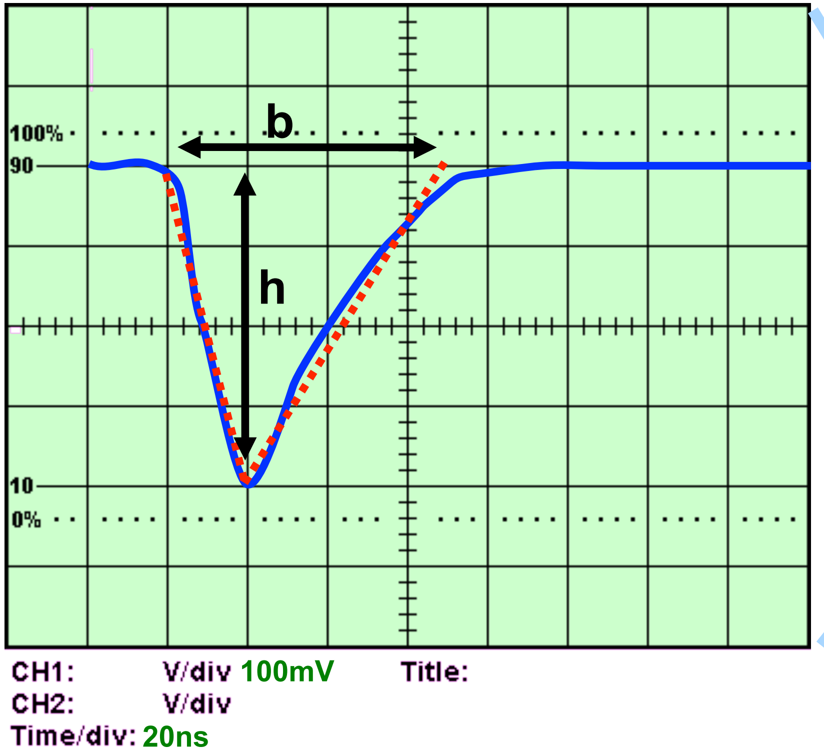


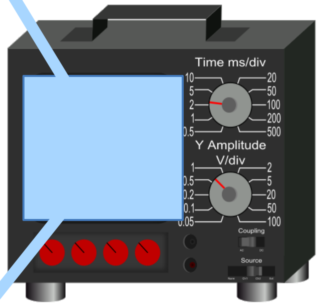


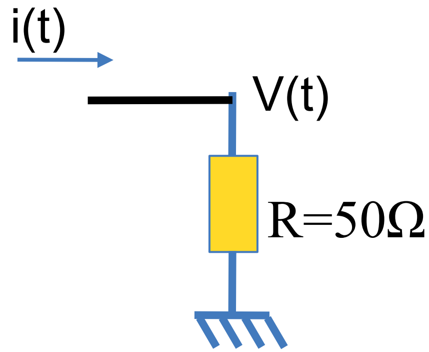


$$Q = \int i(t)\,dt = \frac{1}{R}\int V(t)\,dt$$

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

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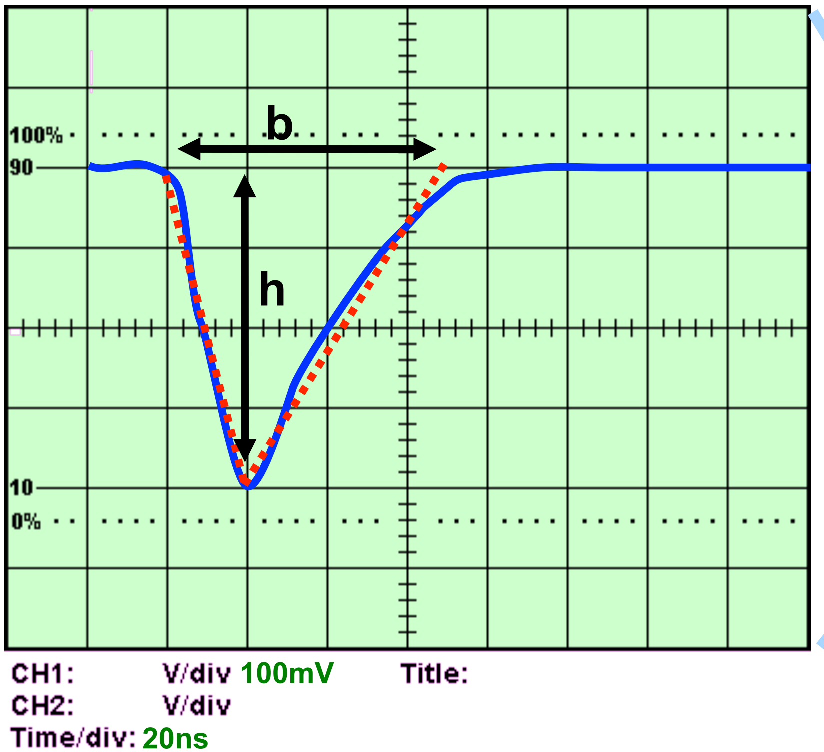


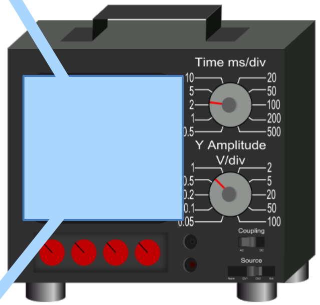


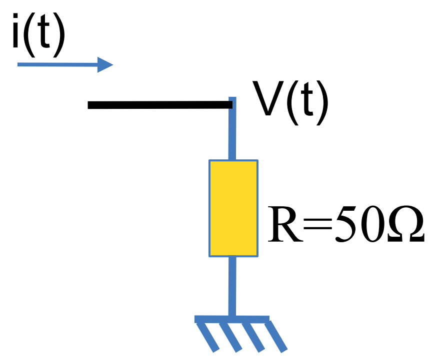


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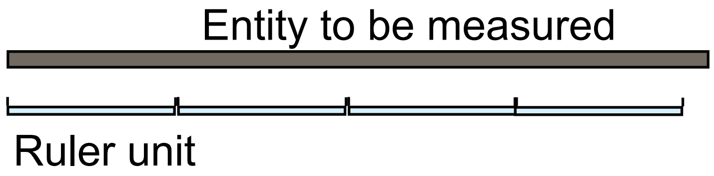
# Good old oscilloscope

- Approximate Q measurement using oscilloscope
  - Linear approximation of a exponential decay
- Easy, but
  - Deadtime 5 min, ~ $3 \times 10^{-3}$ Hz (if you are good)
  - Necessary to encode data into some sort of electronic format by hand
- Wouldn't be much more convenient to have a direct electronic measurement?
  - Save data in some digital format, fill a histogram on-line,etc ...
- 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




- 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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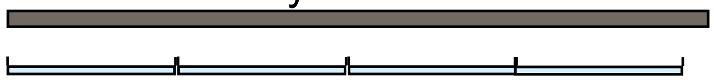


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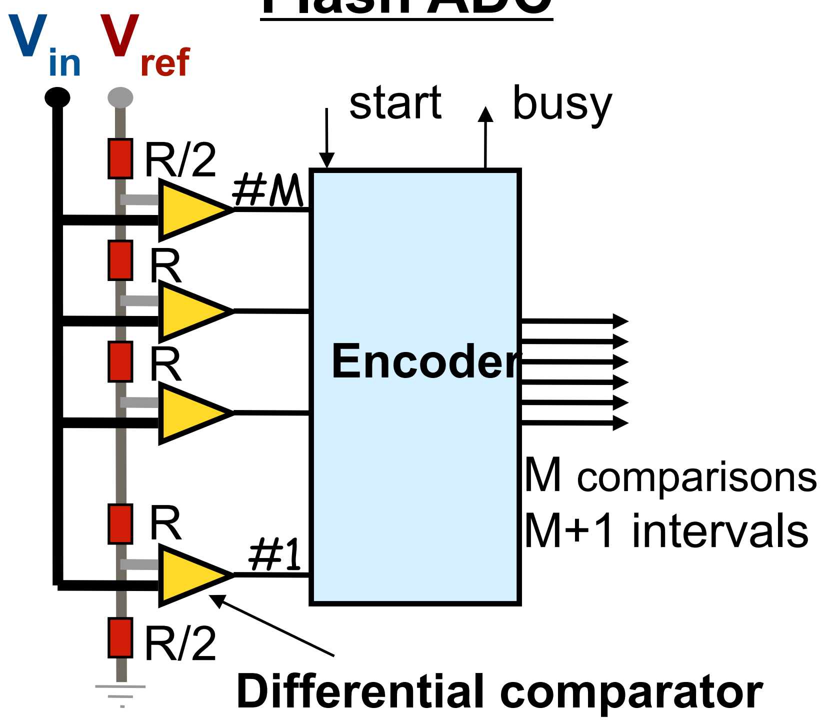

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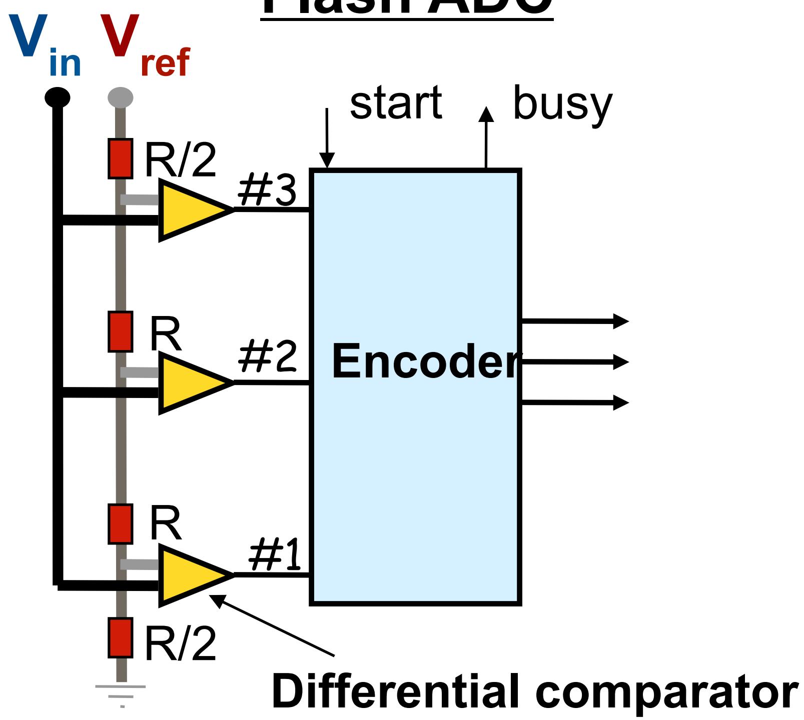
| $x = V_{in}/V_{ref}$ | Comparison results | Encoded form |
|---|---|---|
| x <1/6 | 000 | 00 |
| 1/6≤ x <3/6 | 001 | 01 |
| 3/6≤ x <5/6 | 011 | 10 |
| 5/6≤ x | 111 | 11 |

Flash ADC



# Analog to Digital Conversion

- Digitization
  - Encoding an analog value into a binary representation
  - By comparing entity with a ruler
- Flash ADC simplest and fastest implementation
  - M comparisons in parallel
  - Input voltage $V_{in}$ compared with M fractions of a reference voltage
    - $(1/2)\ V_{ref}/M \rightarrow (M-1/2)\ V_{ref}/M$
    - 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

| $x = V_{in}/V_{ref}$ | Comparison results | Encoded form |
|---|---|---|
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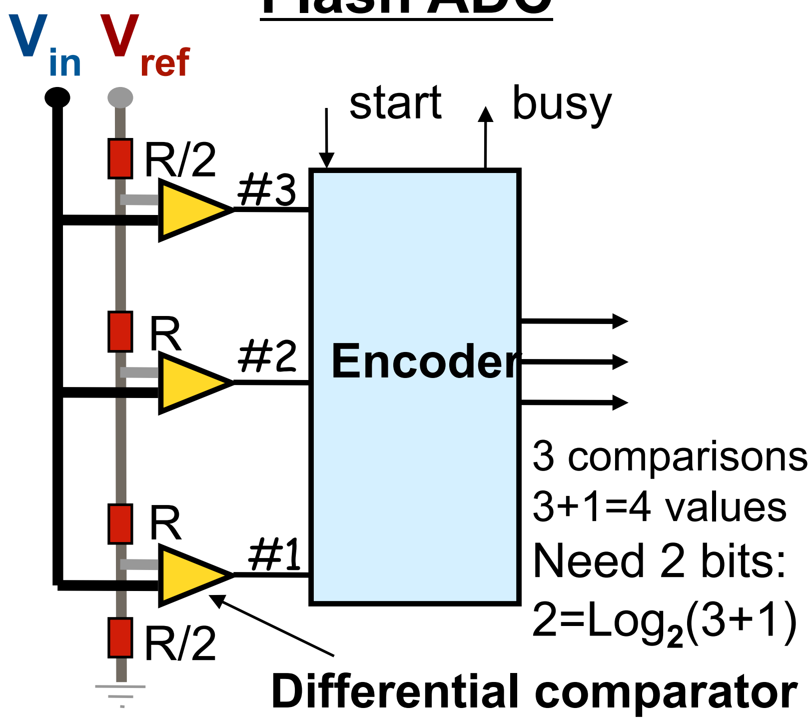
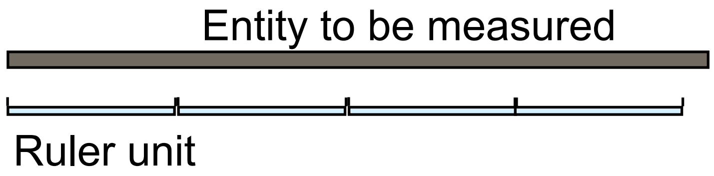
**Flash ADC**

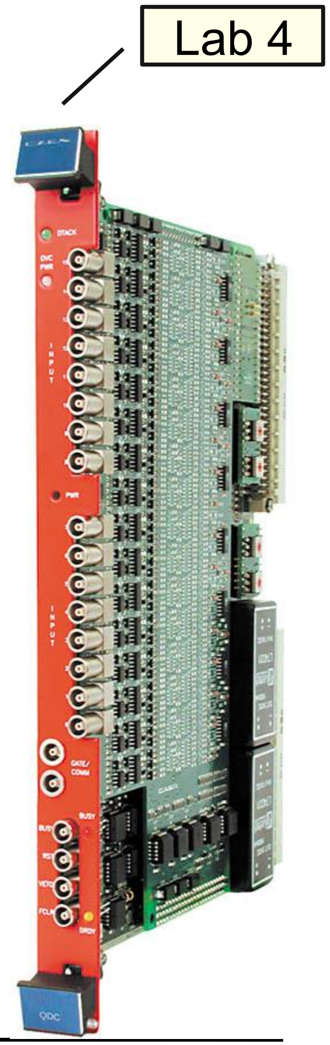


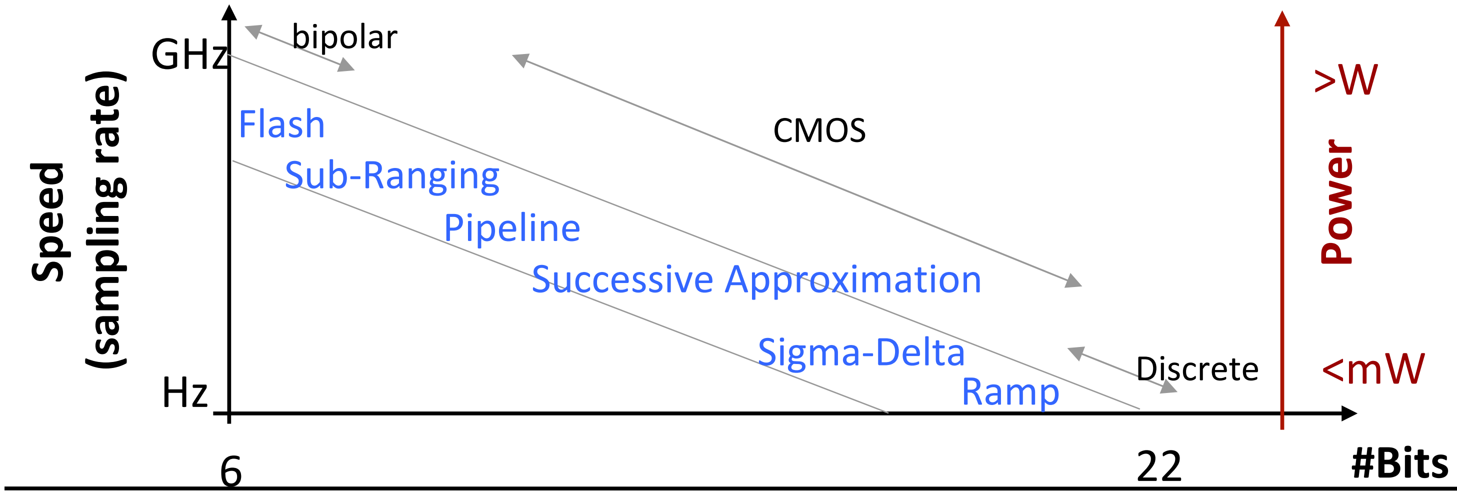
# ADC Characteristics

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



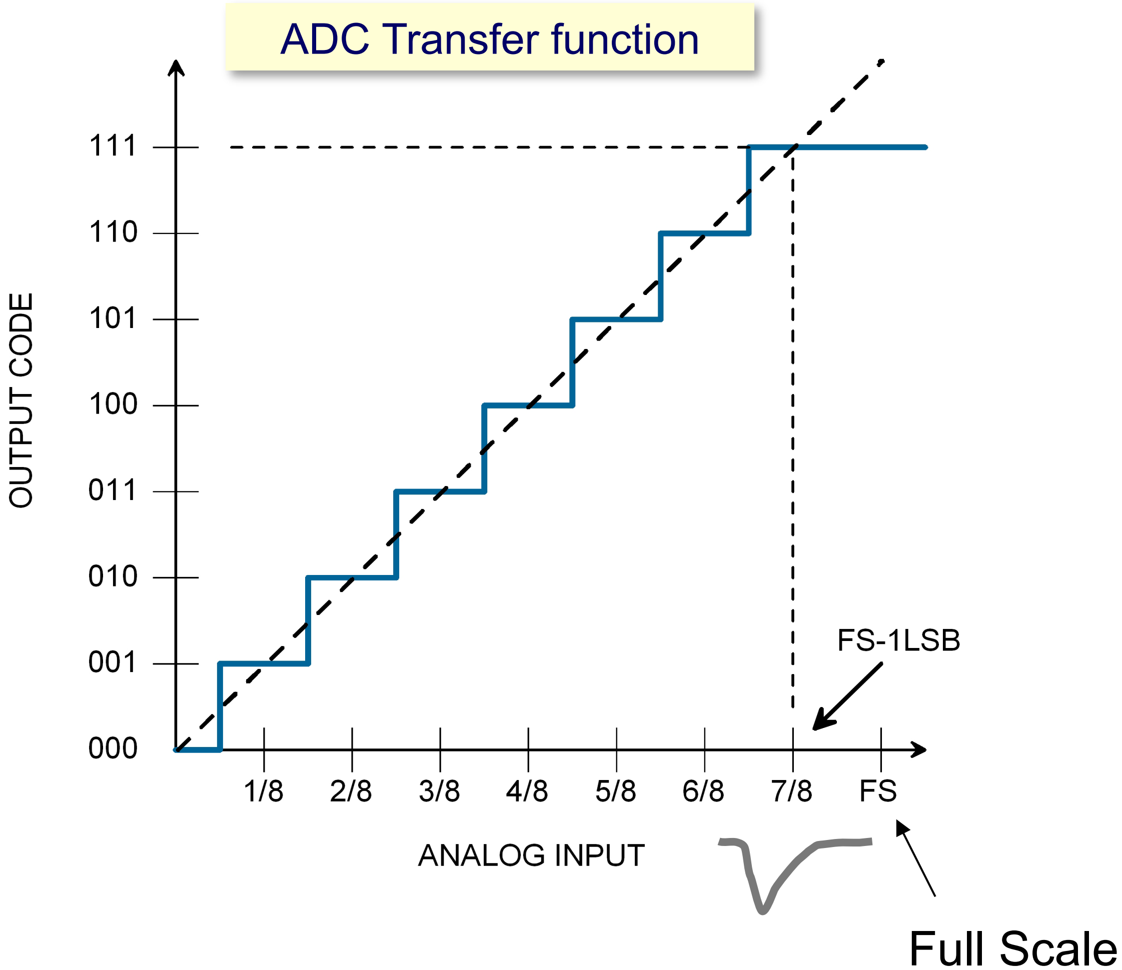

- Quantization error: ±LSB/2
- Accuracies
  - see next slide
- Many different ADC architecture/technique exists
  - mostly because of the trade-off between speed and resolution



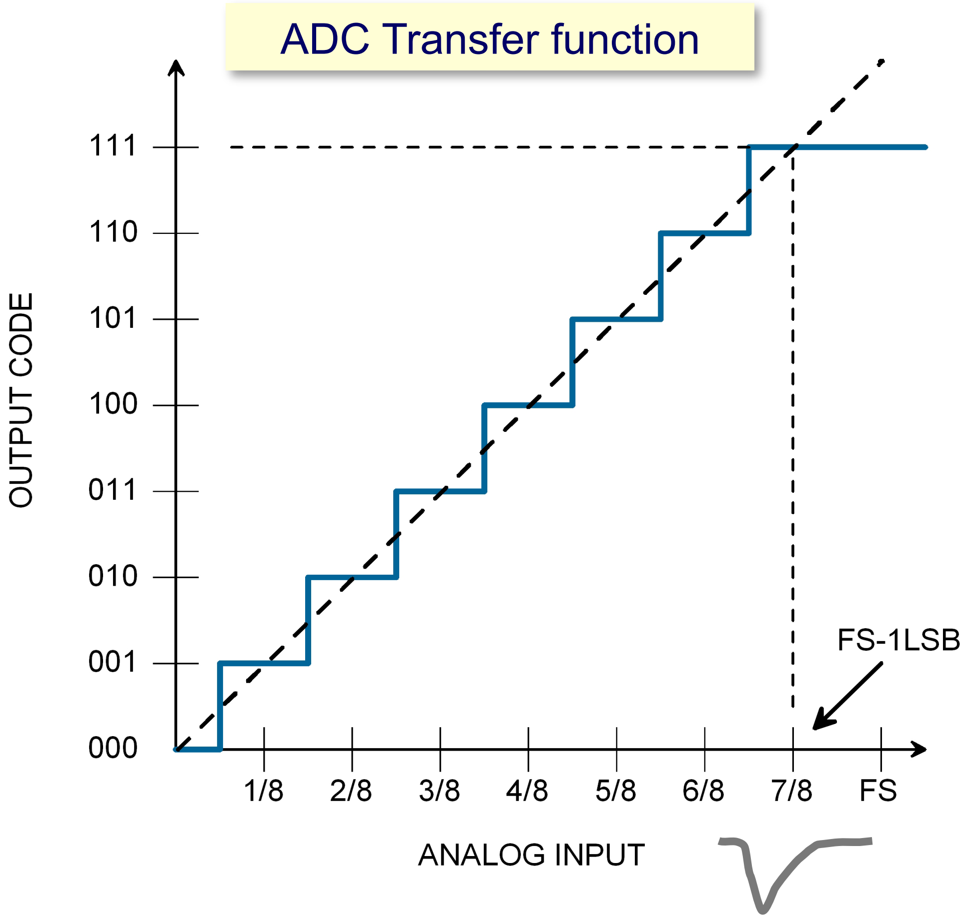
# ADC Accuracies

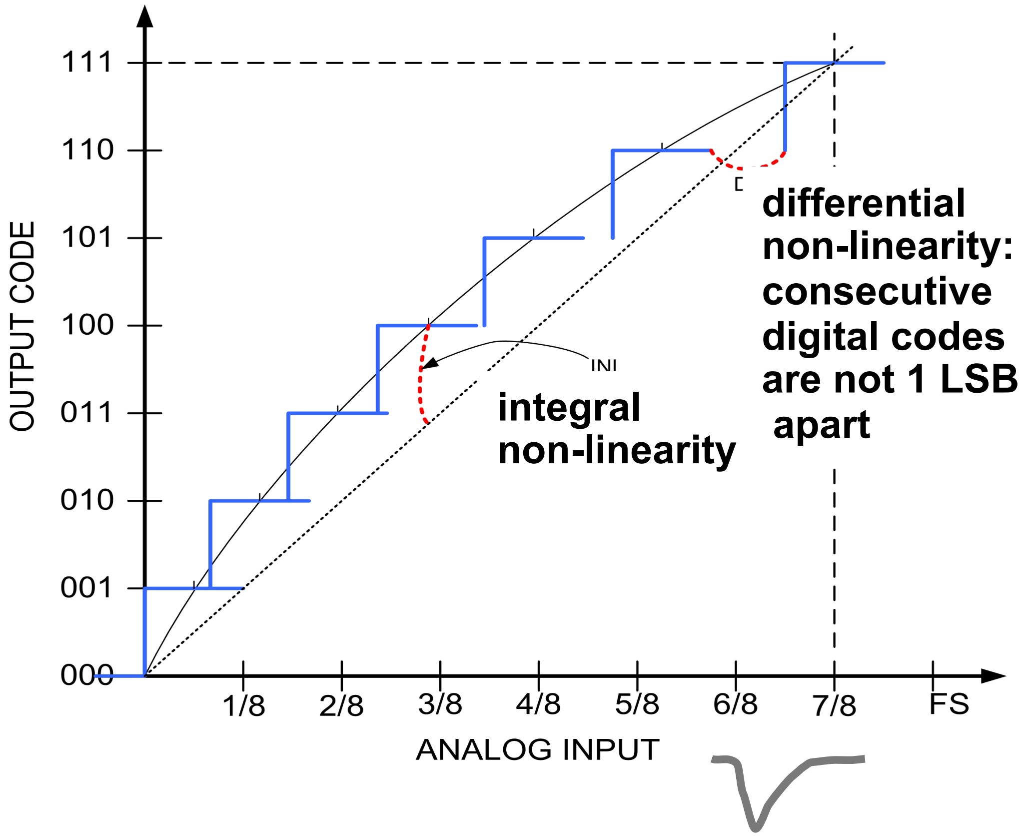
- ADC transfer function
  - Output code vs analog input



# ADC (In)Accuracies

- ADC transfer function
  - Output code vs analog input



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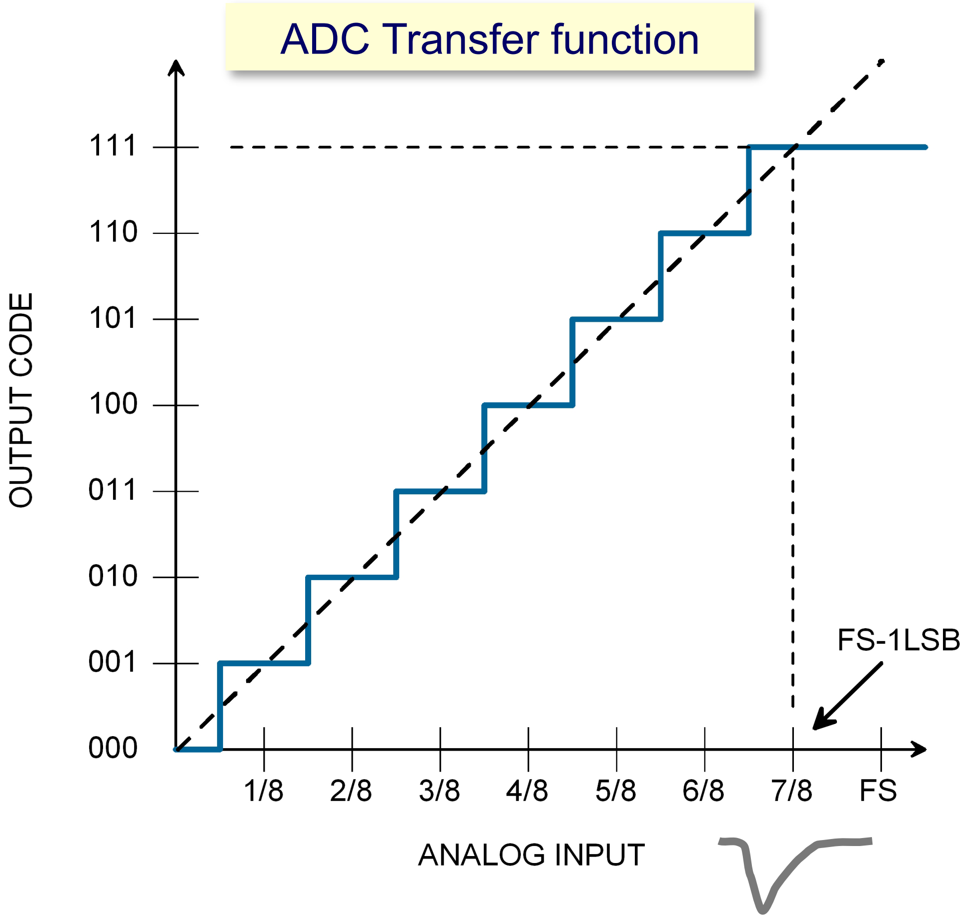
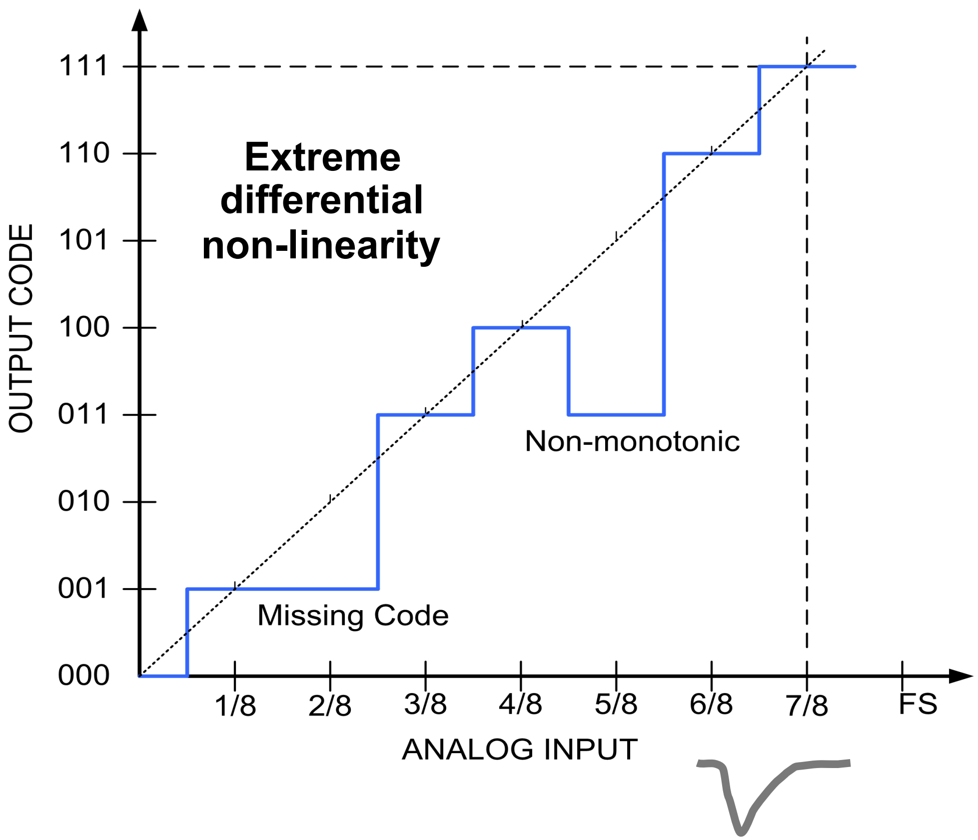


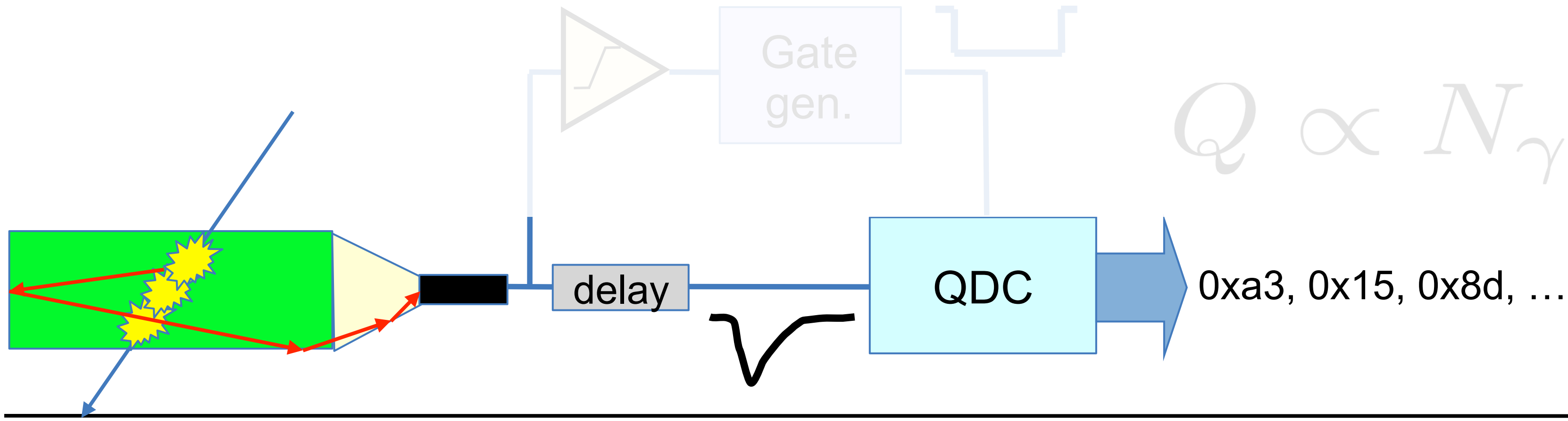



# Charge to Digital

- 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 $\rightarrow$ gate

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

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



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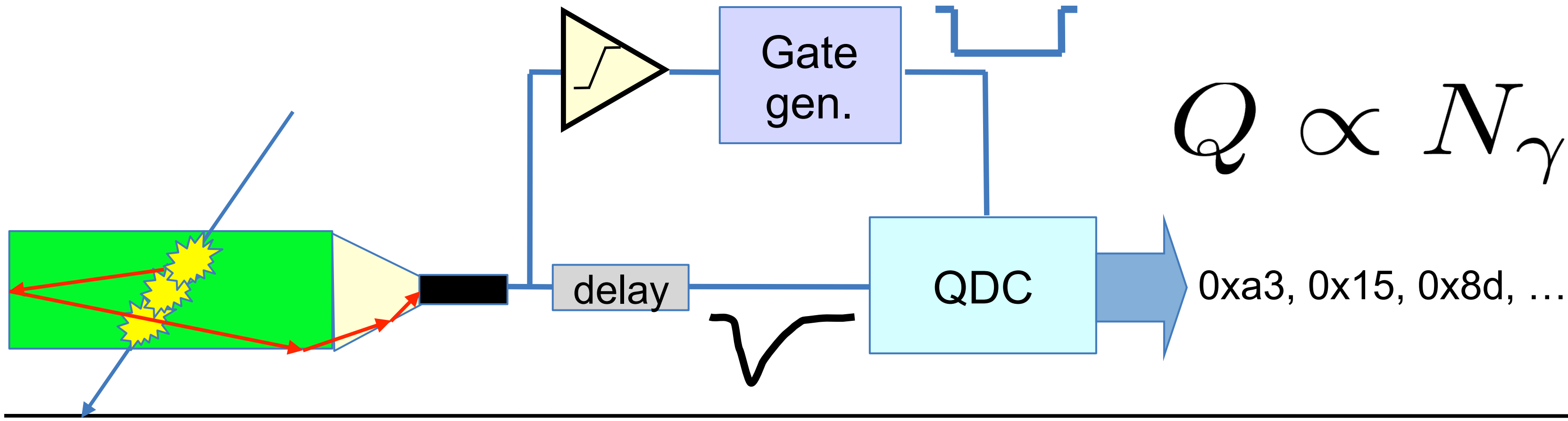


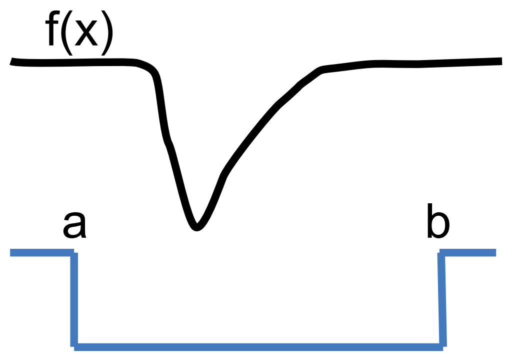

$$Q \propto N_\gamma \propto E$$

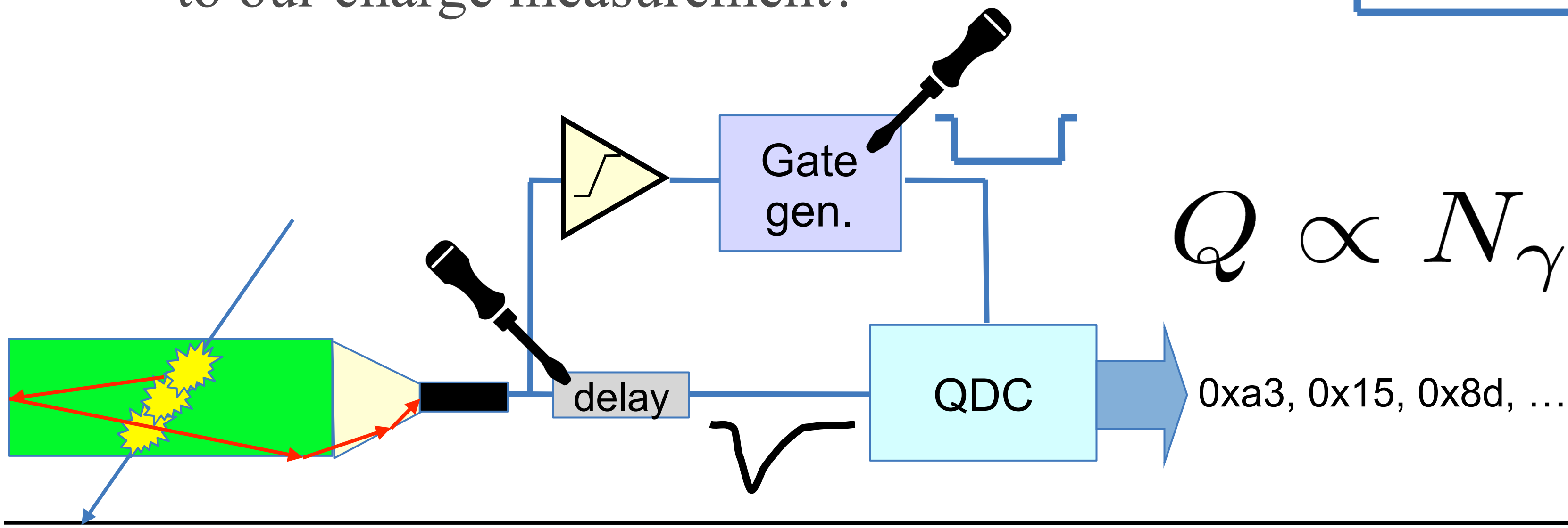
# QDC: timing

- 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?




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

# Example of QDC data

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

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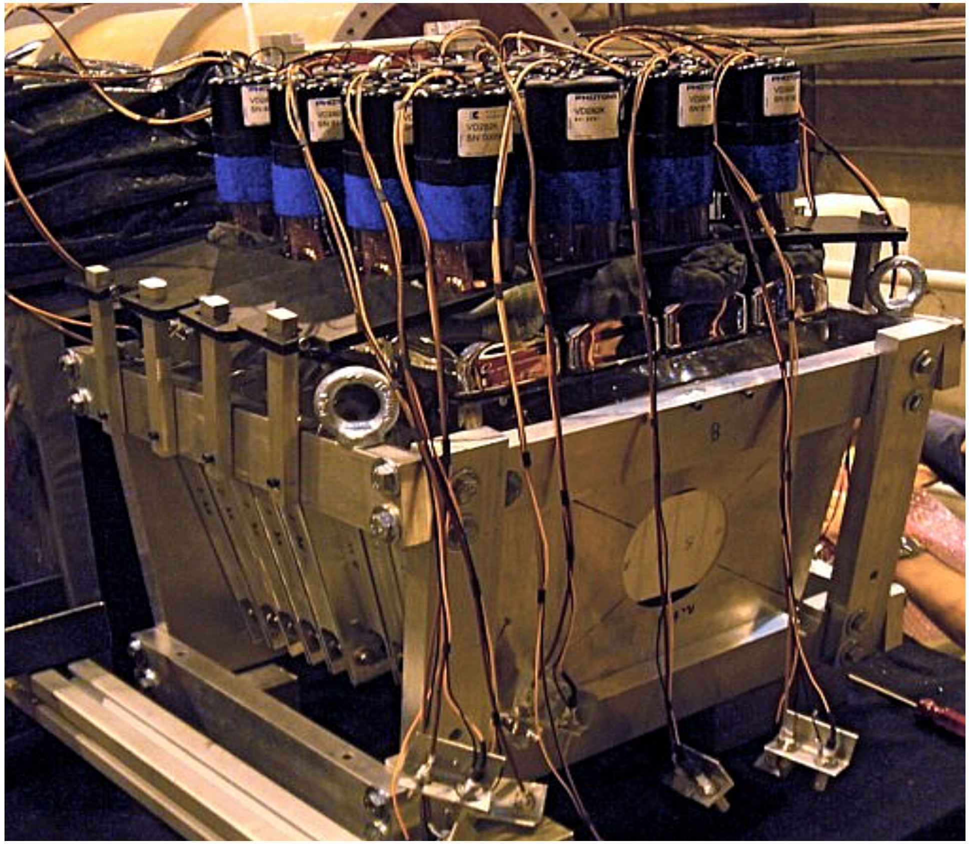

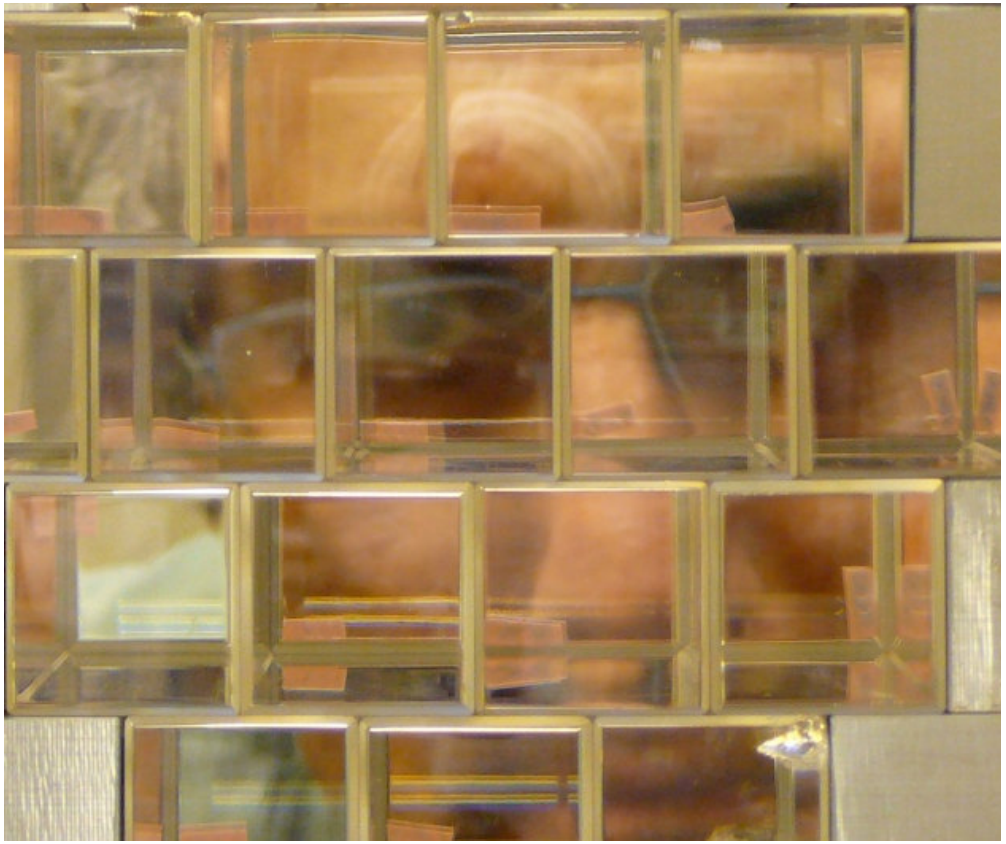

# QDC spectra

- Calorimetry R&D test beam @CERN
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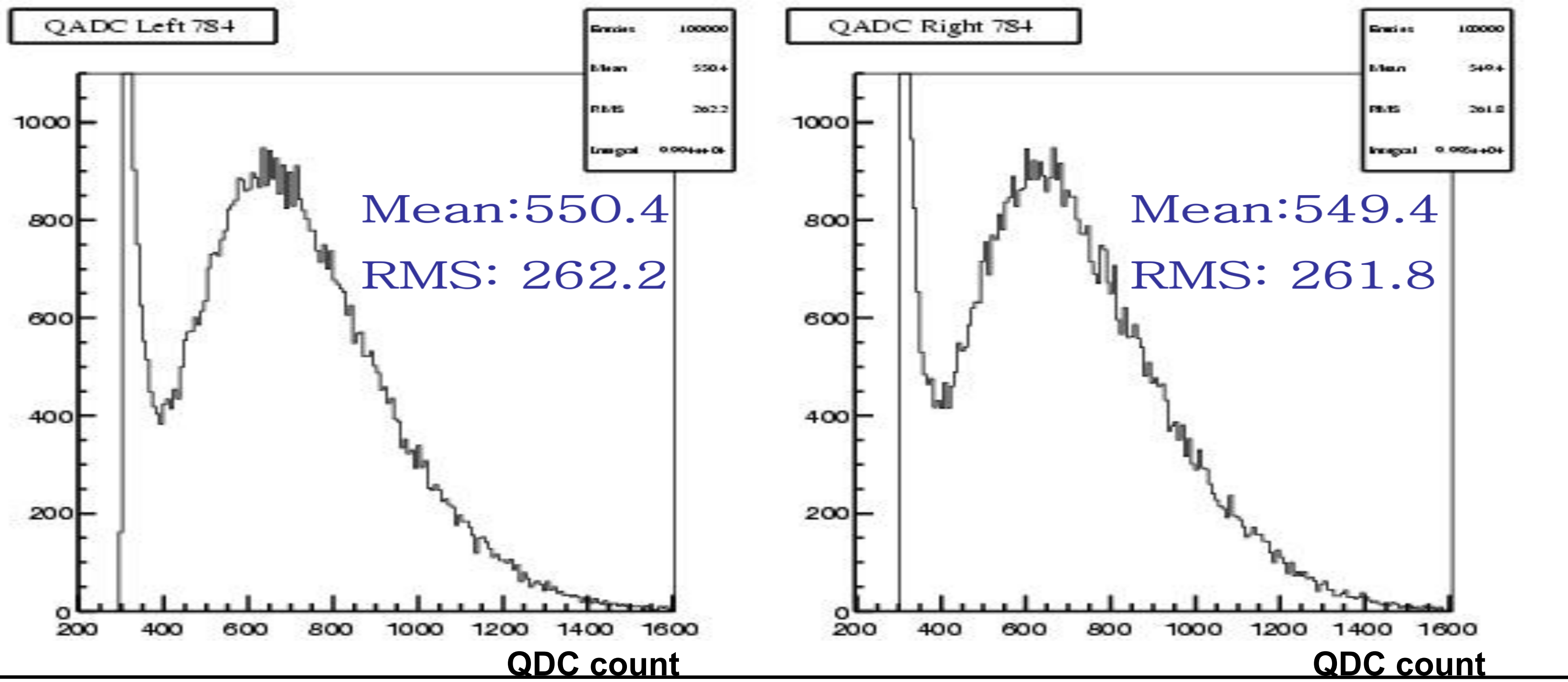
$$Q \propto N_\gamma \propto E$$

- But, what is the 1st peak?
  - How can we estimate it?



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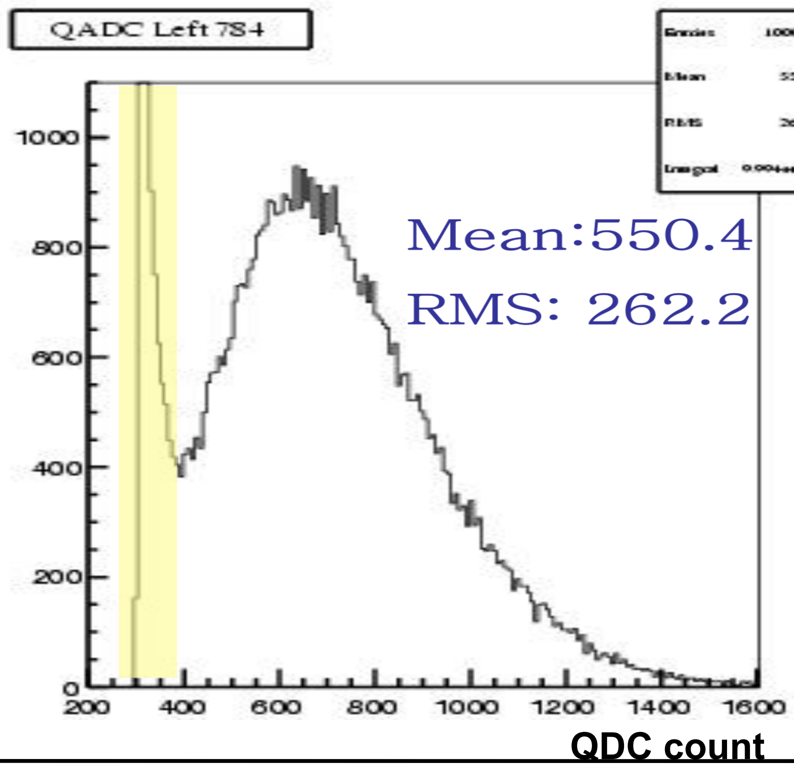
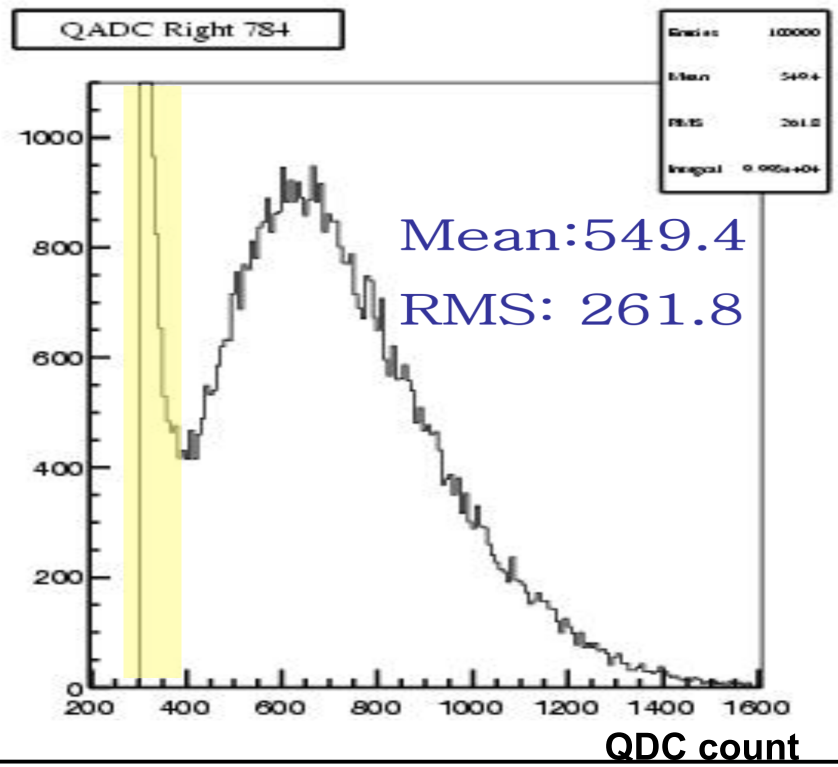
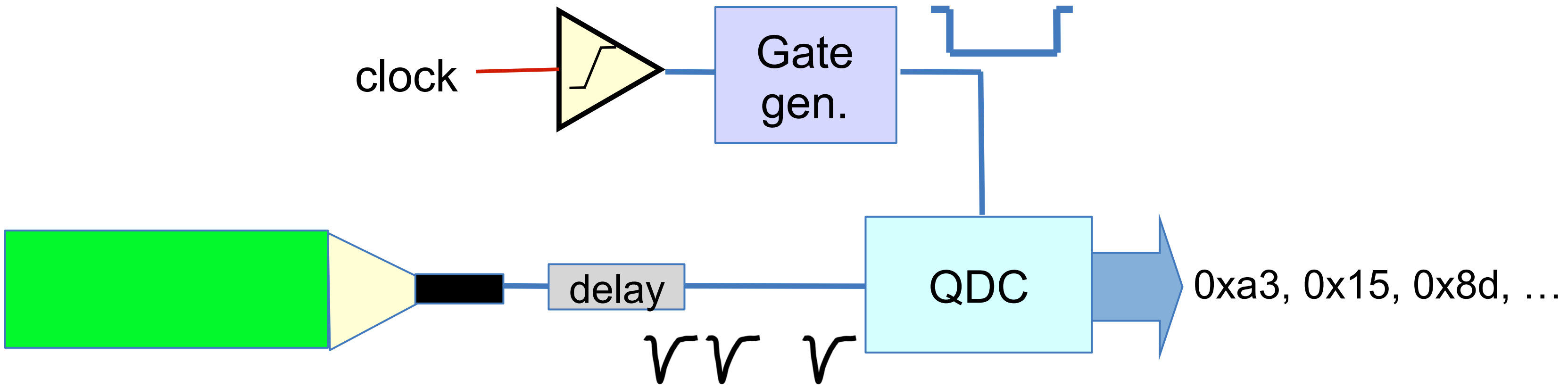


# QDC: pedestal subtraction

- The pedestal can be measured with an out-of-phase trigger
  - PMT dark current, thermal noise, …
  - 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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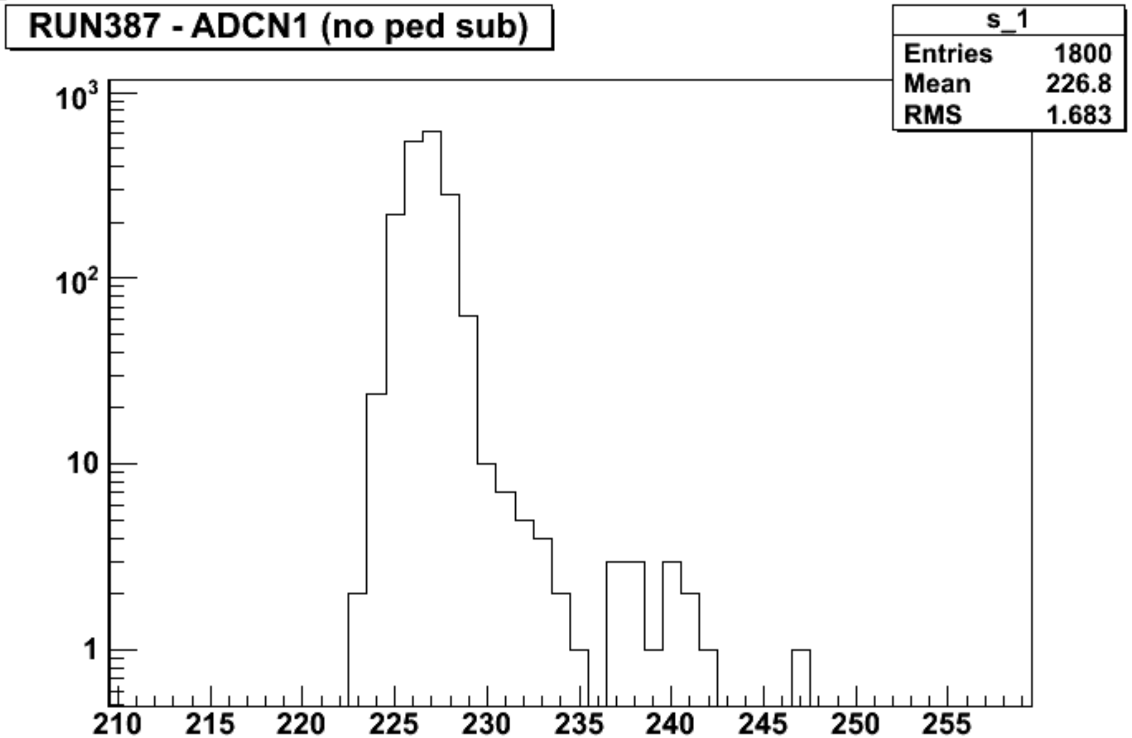

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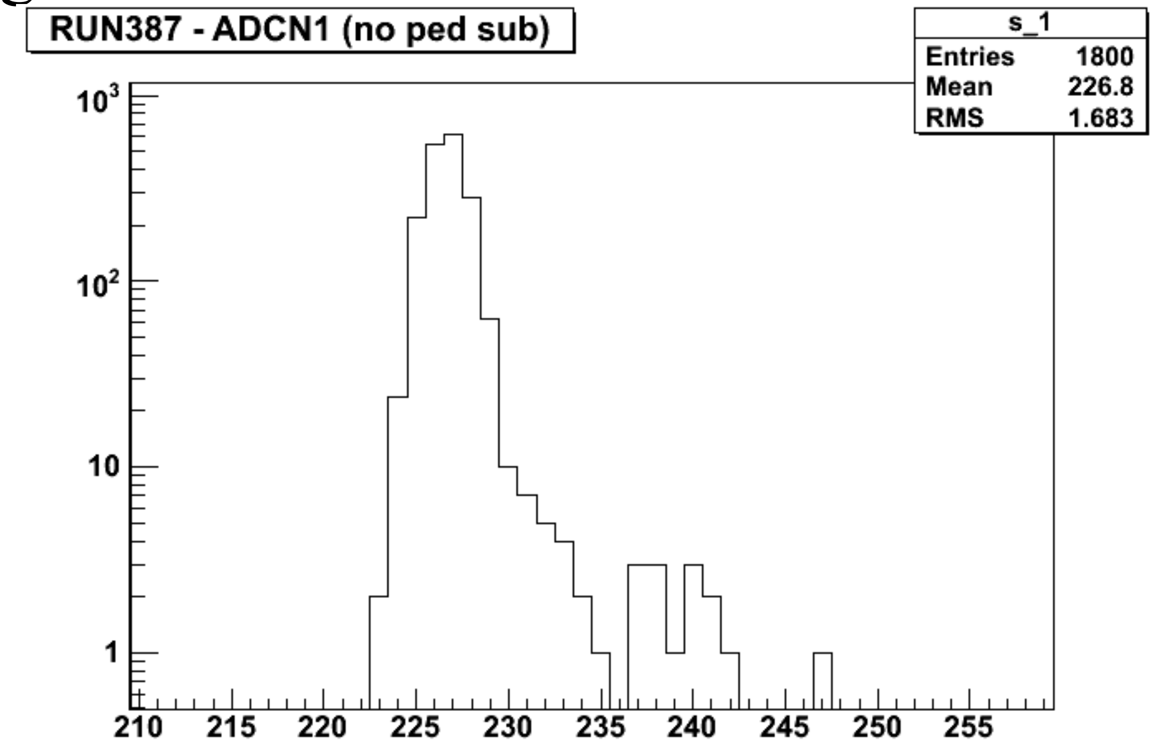
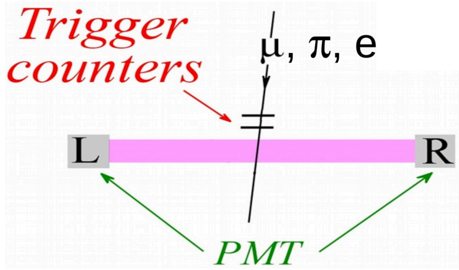
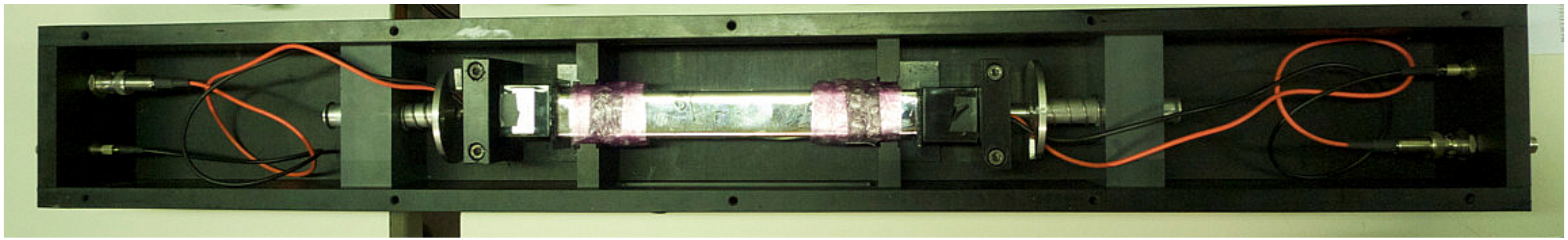


# “Real” QDC at work

- $PbWO_4$ 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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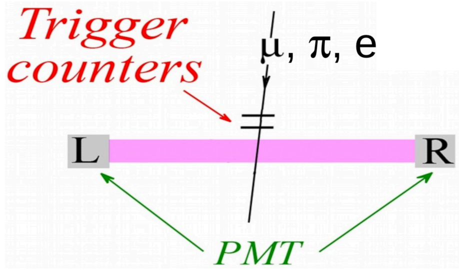
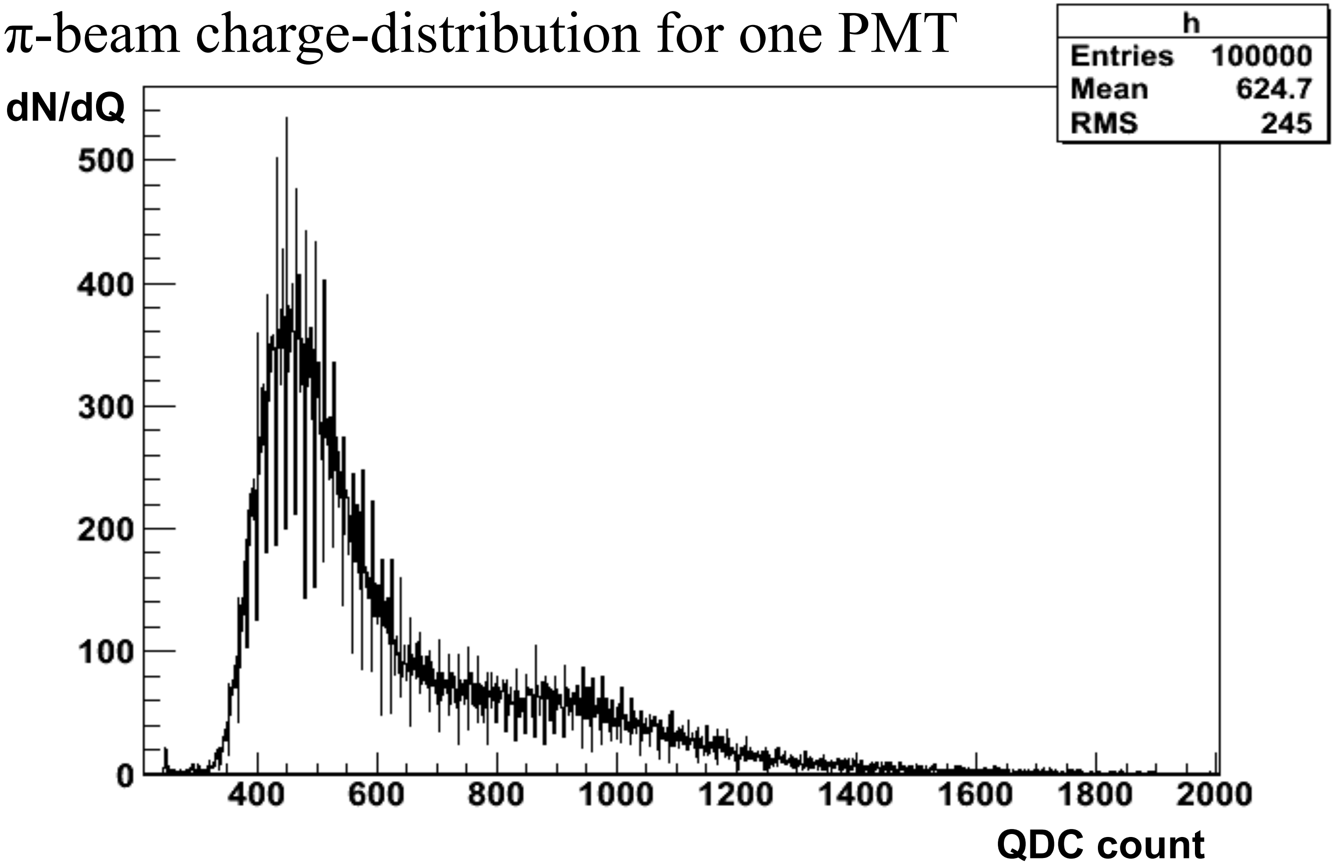



π-beam charge-distribution for one PMT



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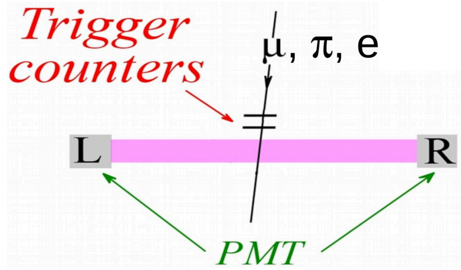


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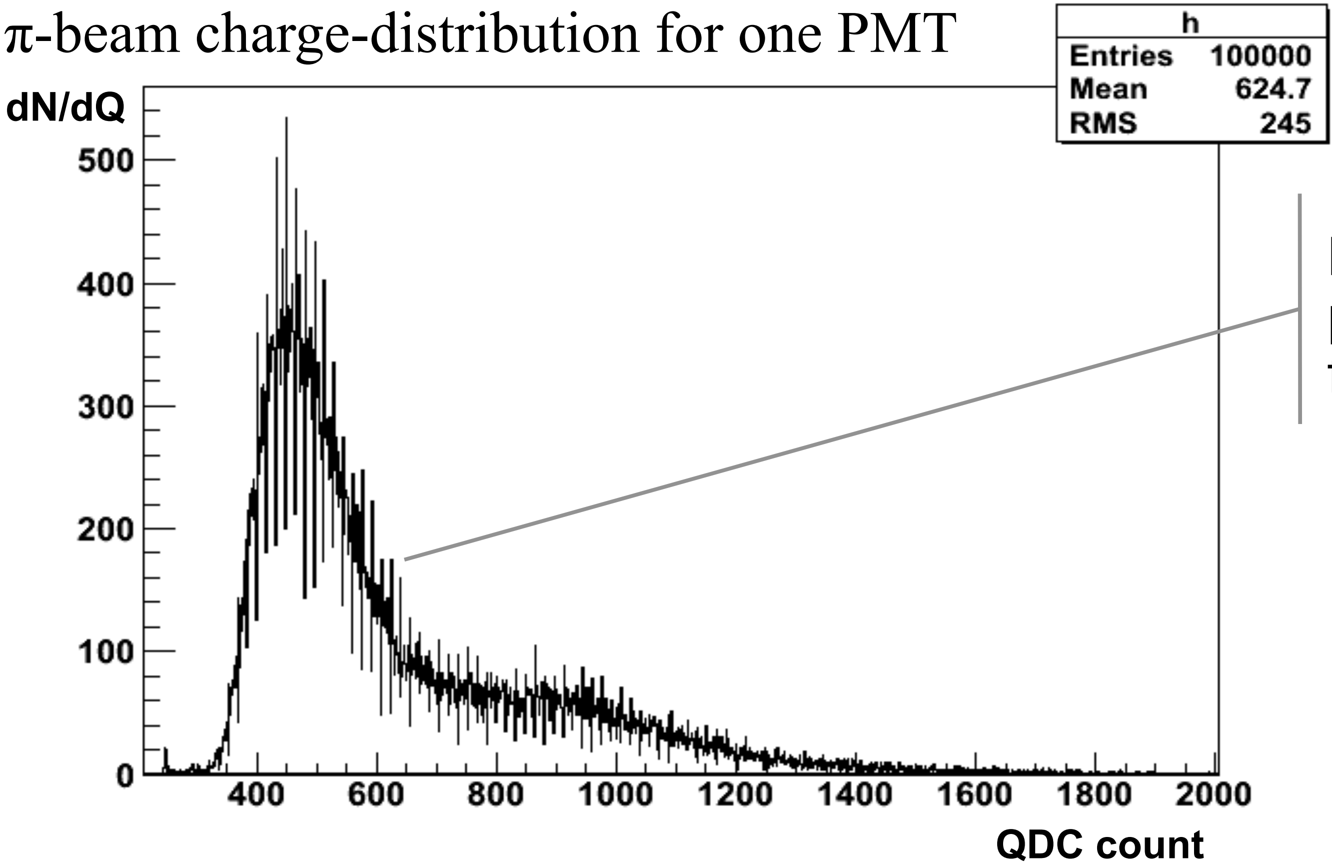


But, what are all those little peaks? Just statistical fluctuations?

**Let's zoom in!**

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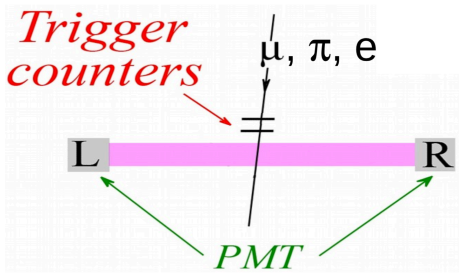


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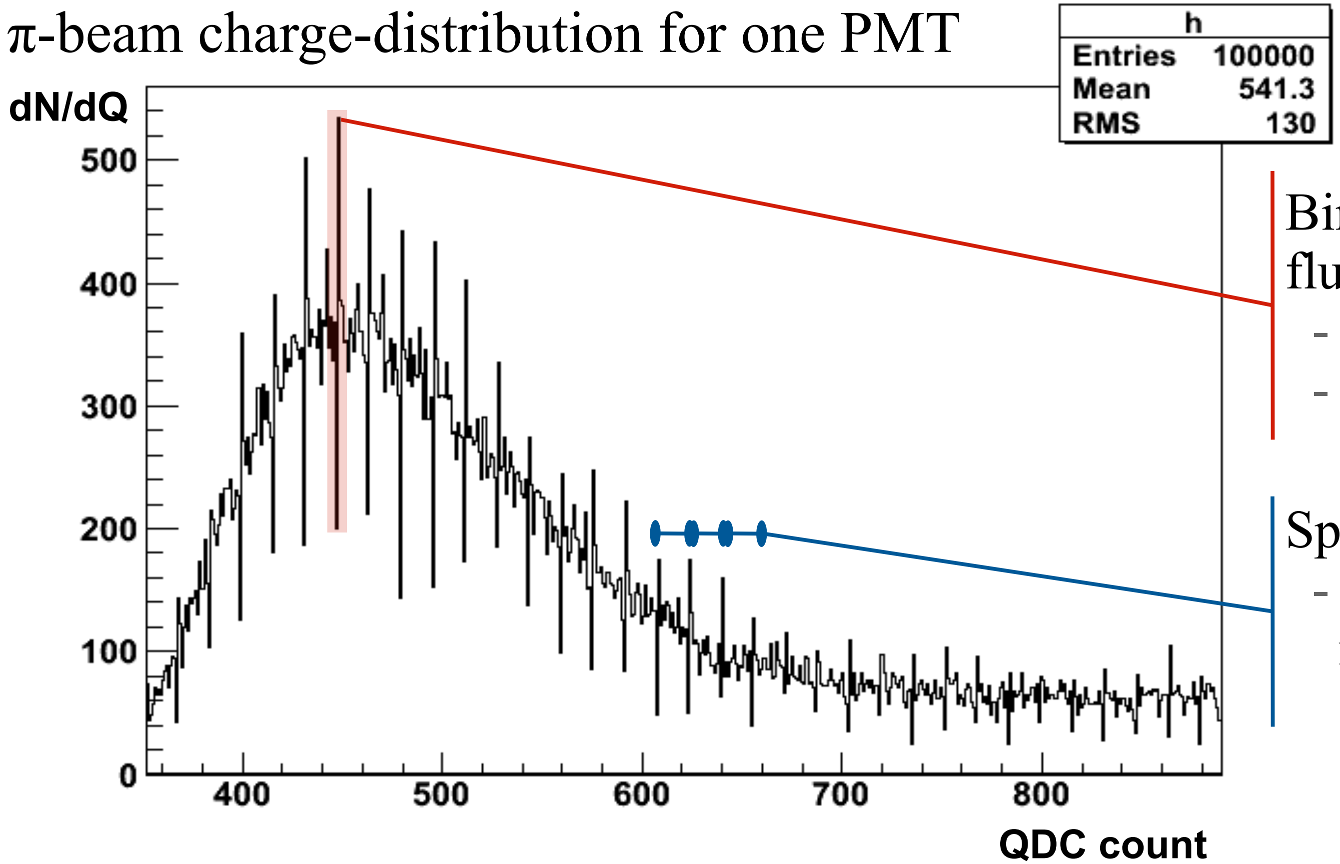


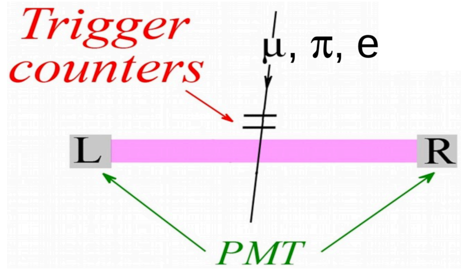

Bin with N entries can fluctuate with $\sigma = \sqrt{N}$
- expected $\sigma=\sqrt{360}\sim19$
- observed ~200 (10 σ)

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

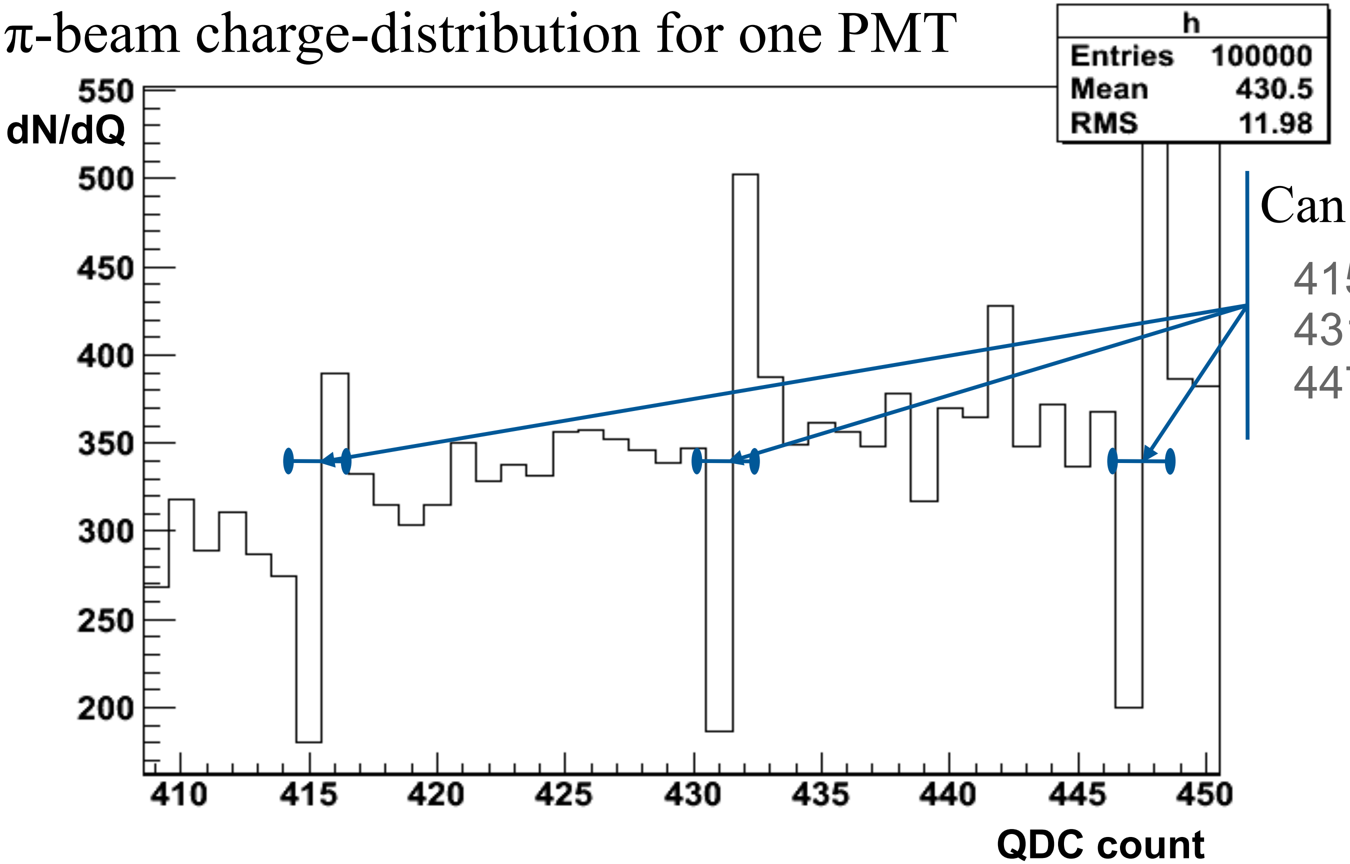
**Let's zoom in!**

# "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




π-beam charge-distribution for one PMT




Can you see the effect?

415 & 416 →
431 & 432 →
447 & 448 →

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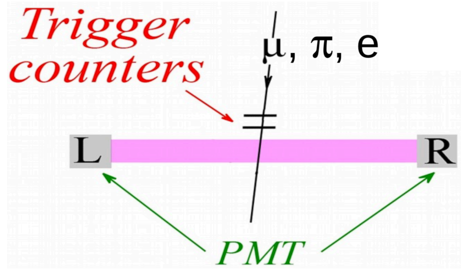


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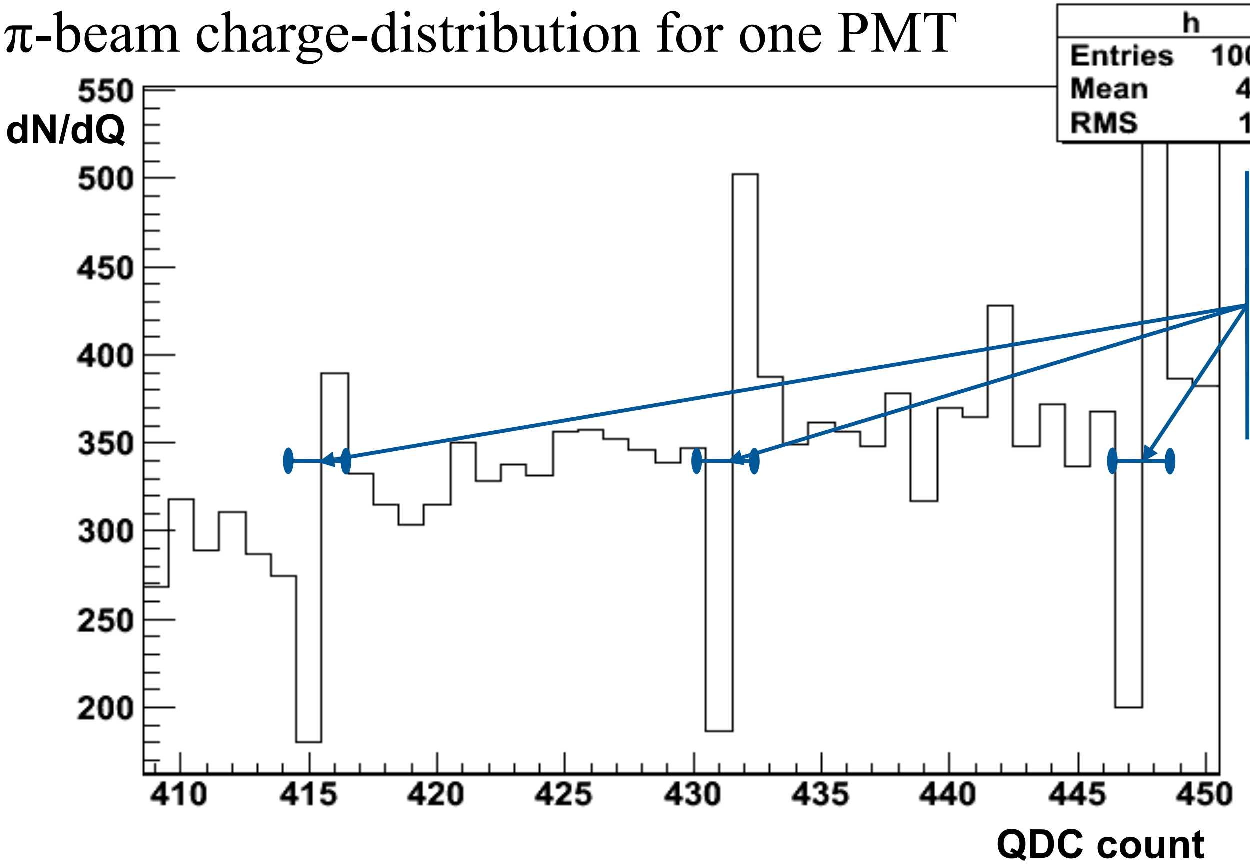



Can you see the effect?

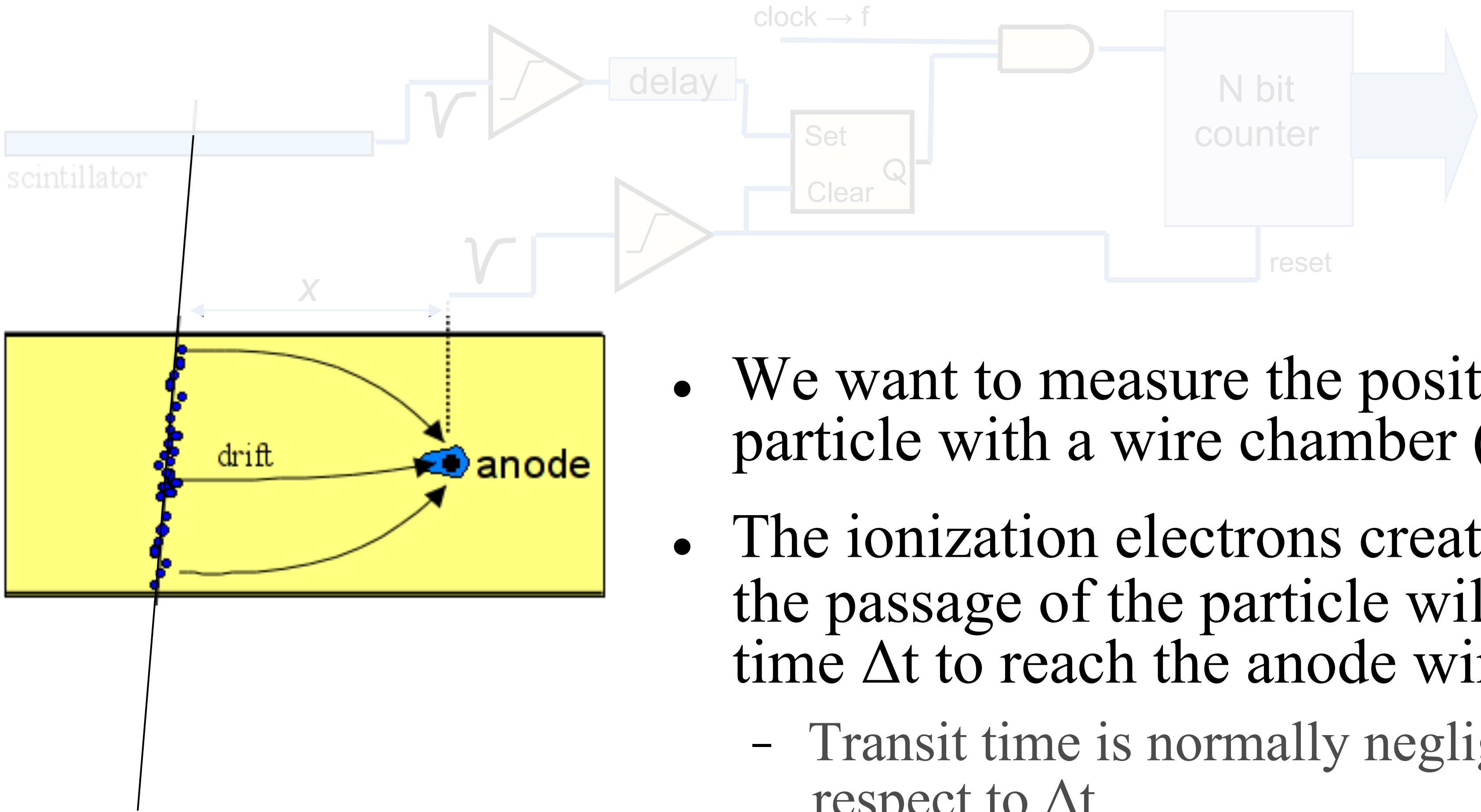
415 & 416 → 0x19**f** & 0x1A**0**
431 & 432 → 0x1A**f** & 0x1B**0**
447 & 448 → 0x1B**f** & 0x1C**0**

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

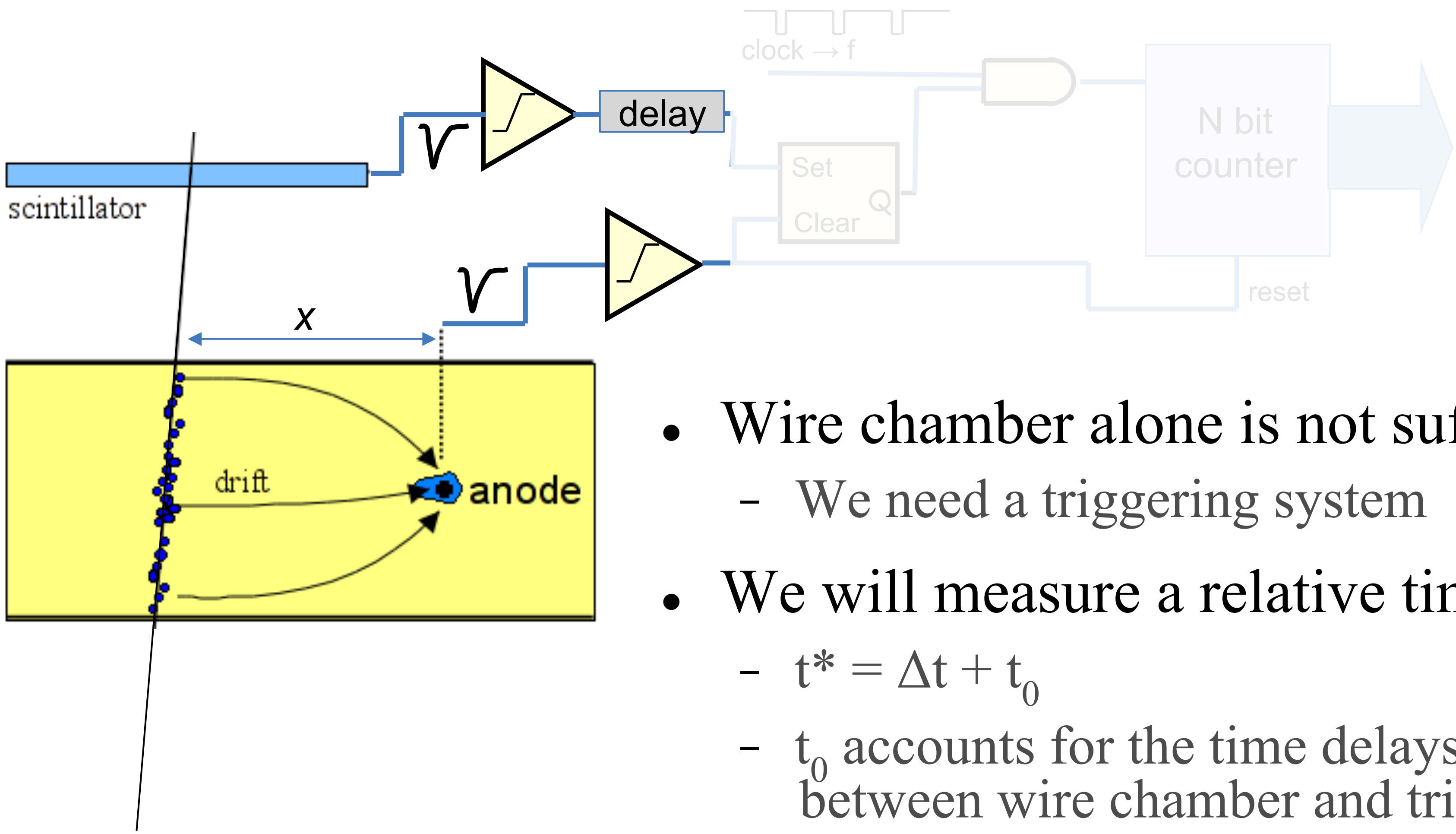
# Position measurement




- 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 $\Delta t$ to reach the anode wire
  - Transit time is normally negligible with respect to $\Delta t$
  - If we consider a constant drift speed $v_D$ (e.g.: 50 µm/ns), then position is:

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

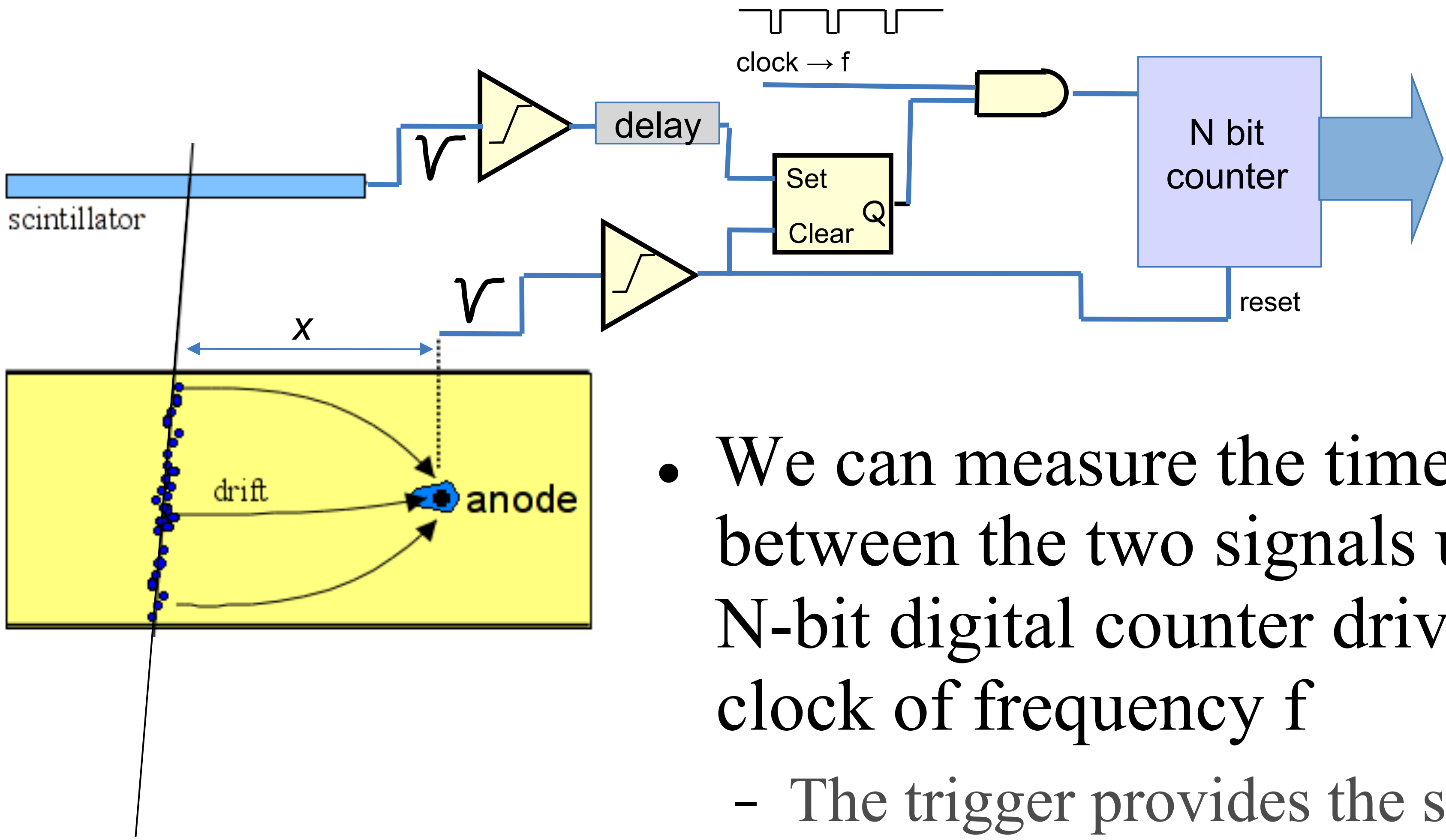
# Triggering




- 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

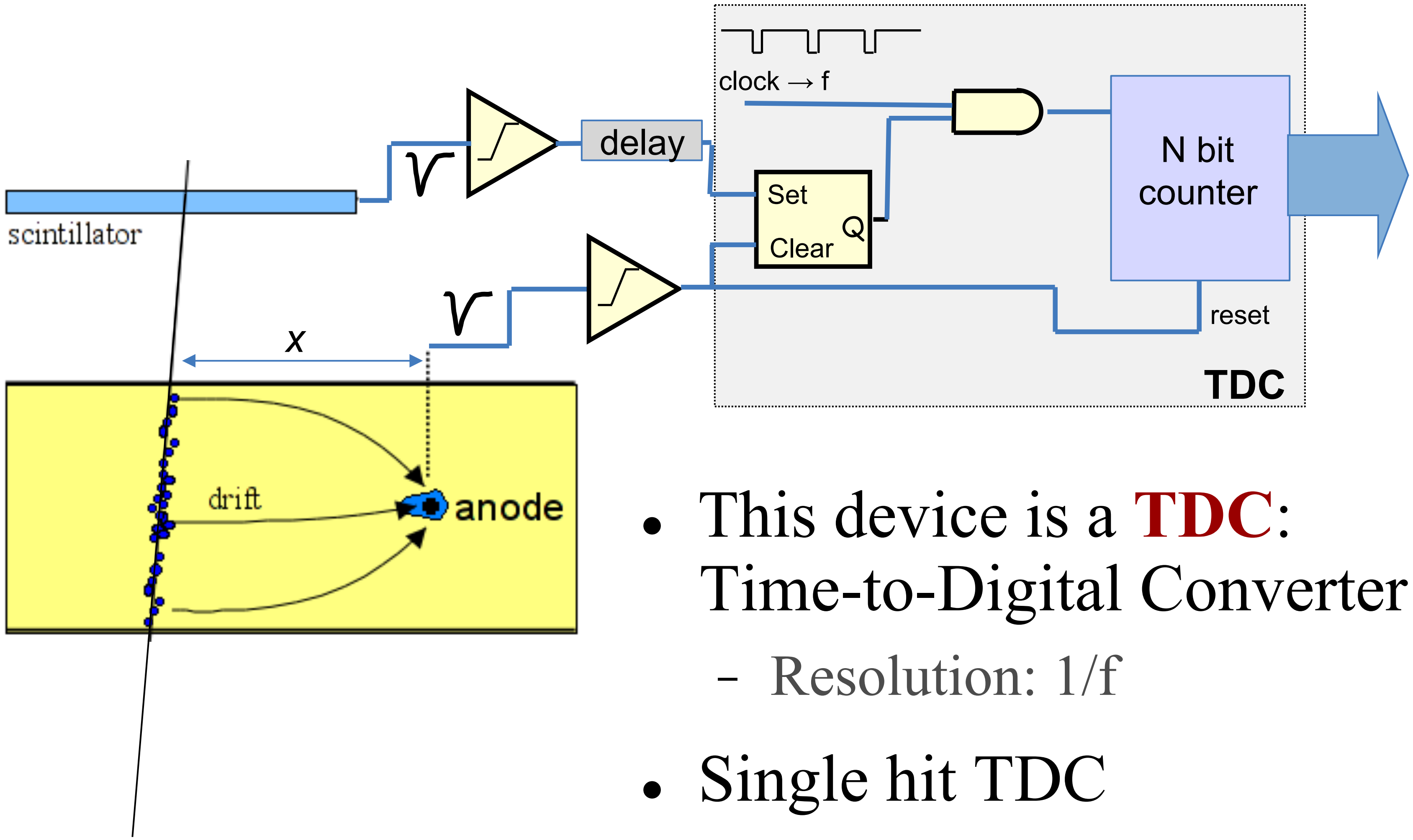
$$x = \alpha t^* + \beta$$

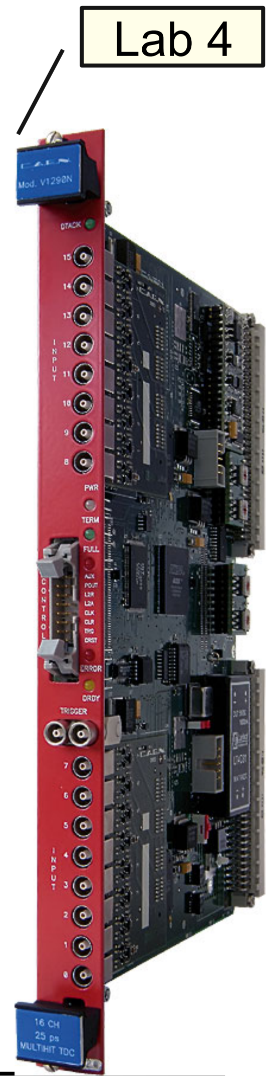
# Time measurement




- 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

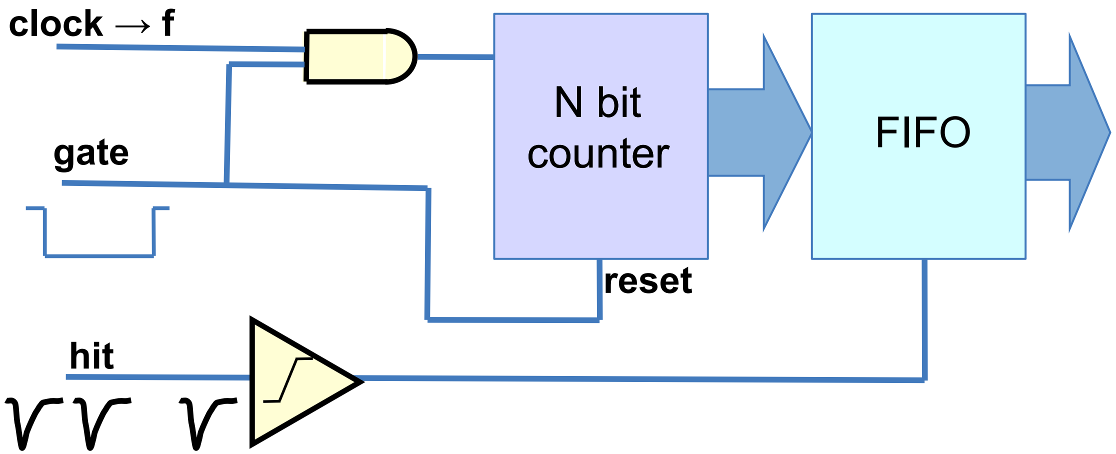



- This device is a **TDC**: Time-to-Digital Converter
  - Resolution: 1/f
- Single hit TDC
  - if a noise spike comes just before the signal, the measure is lost

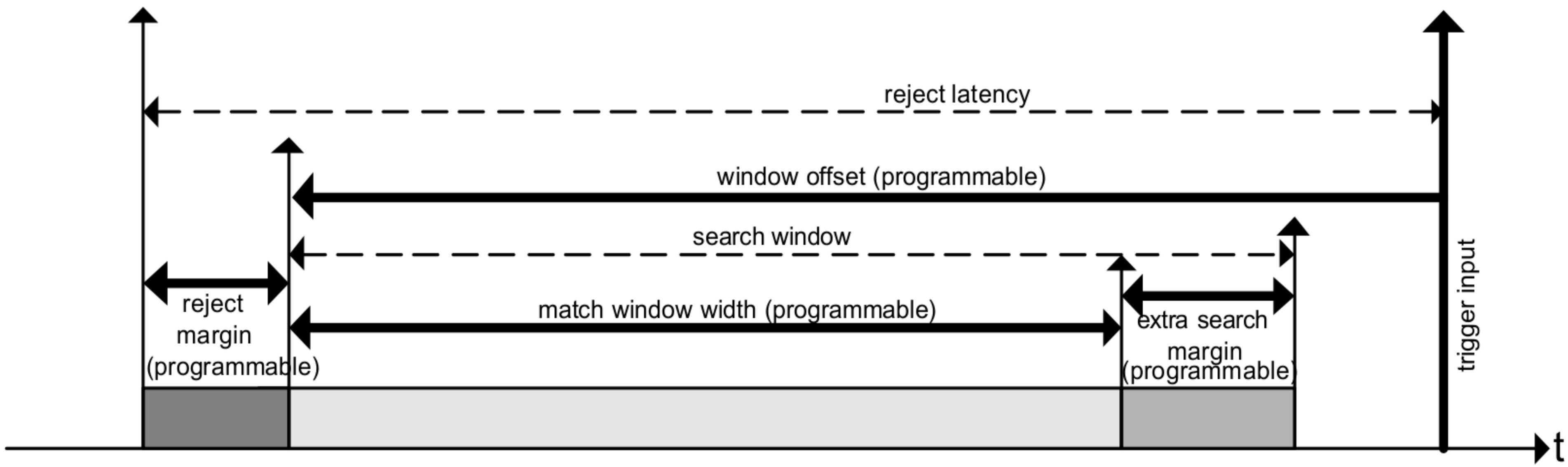
# Multi-hit TDC

- 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



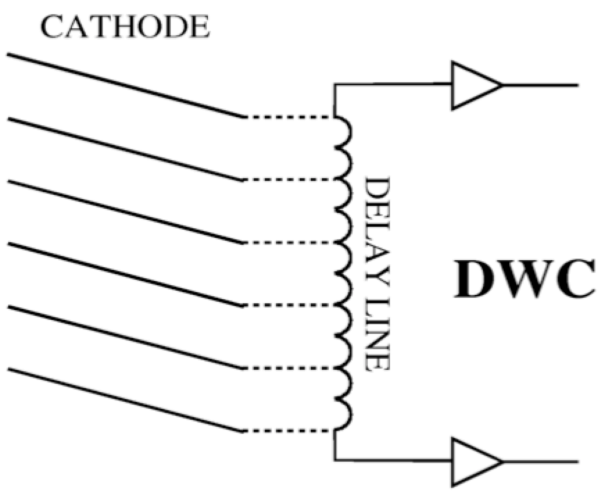
# Actual TDCs

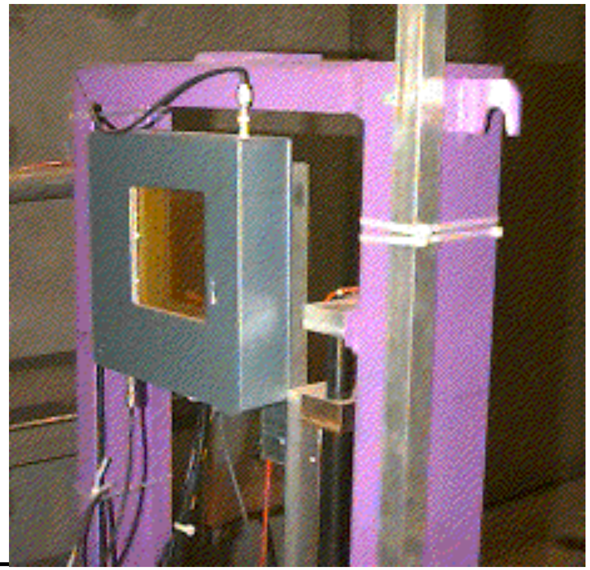
- Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching
  - Internal programmable delays
  - Internal generation of programmable gates
  - Programmable rejection frames
  - Usually via a dedicated C library/API



# 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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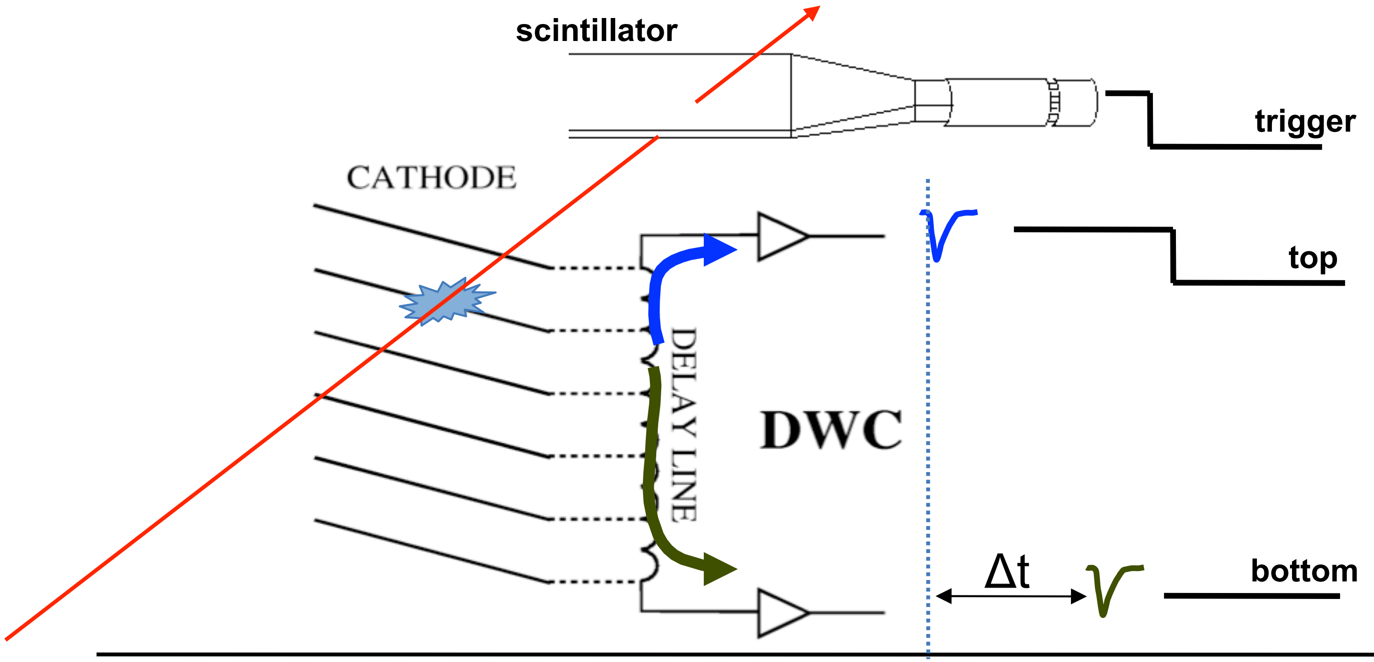
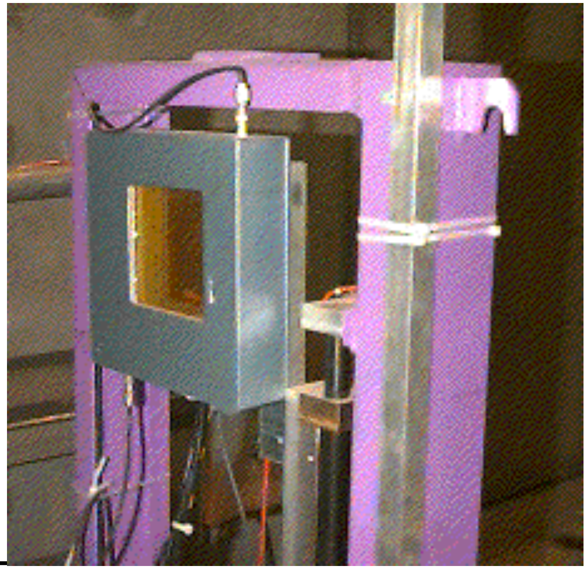
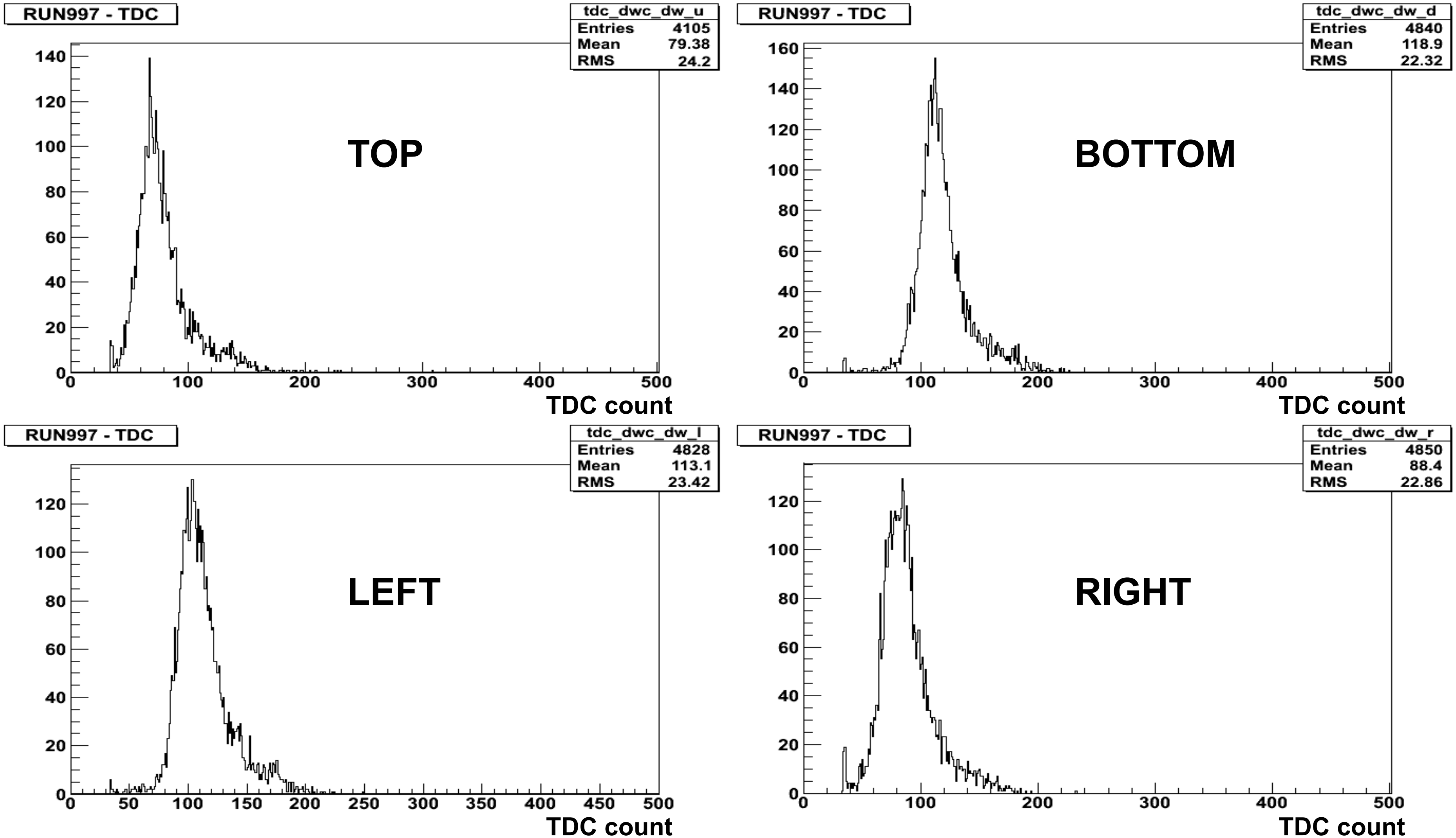


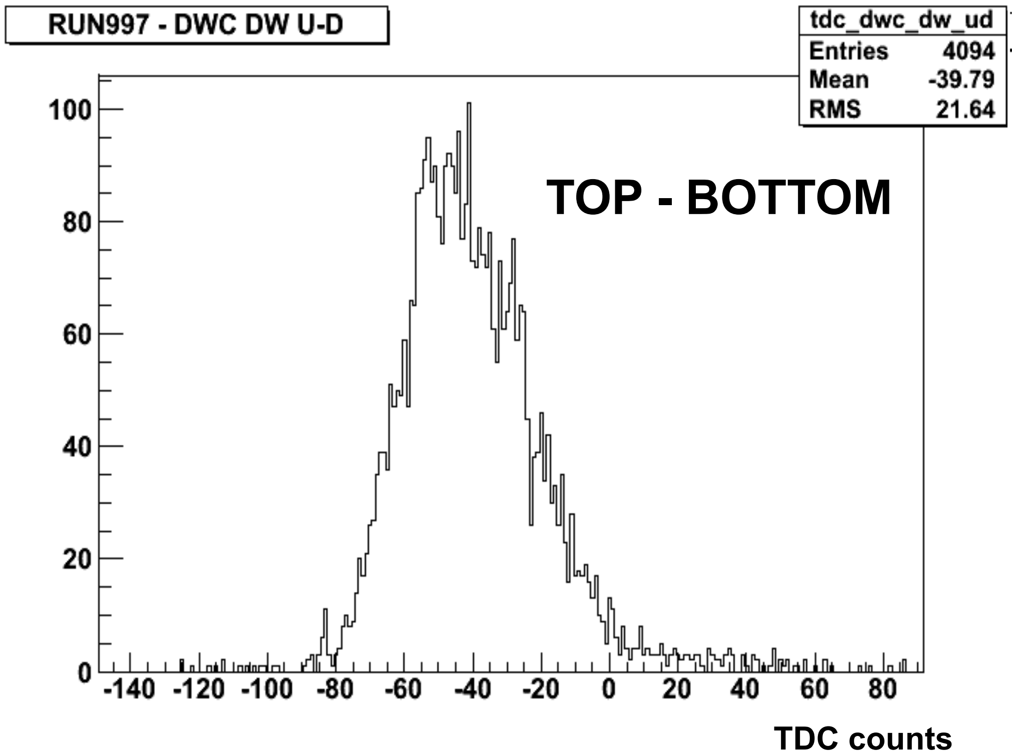
# Raw time data

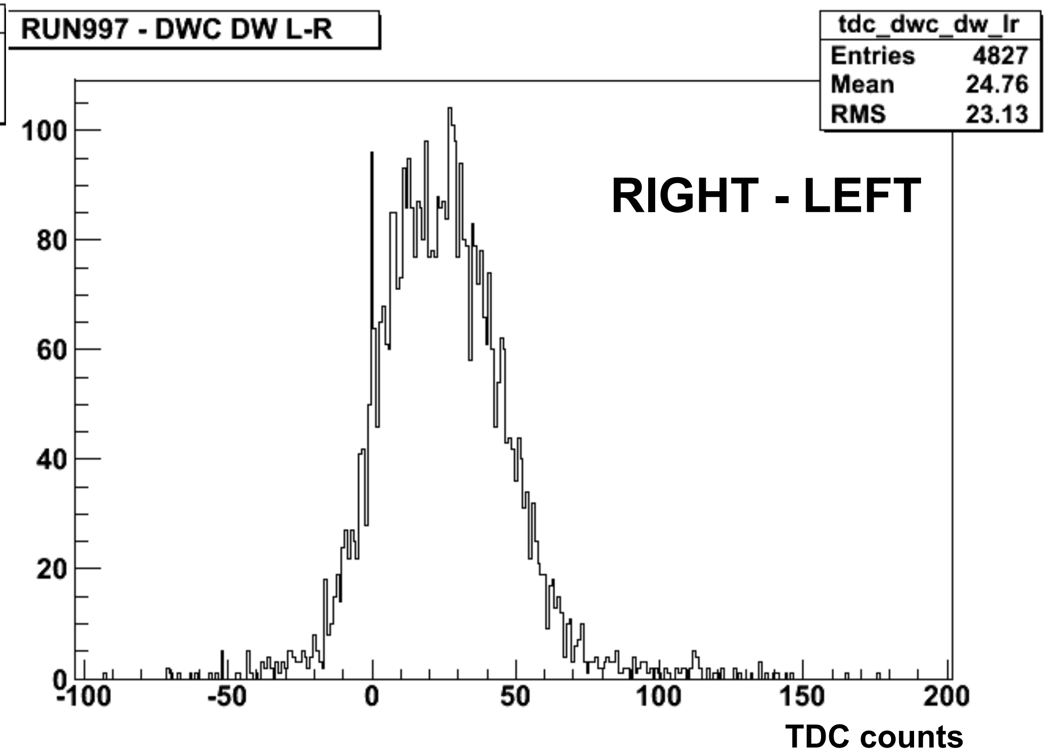
- Take a run (some thousands events)
  - Individual channel distribution



# 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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# 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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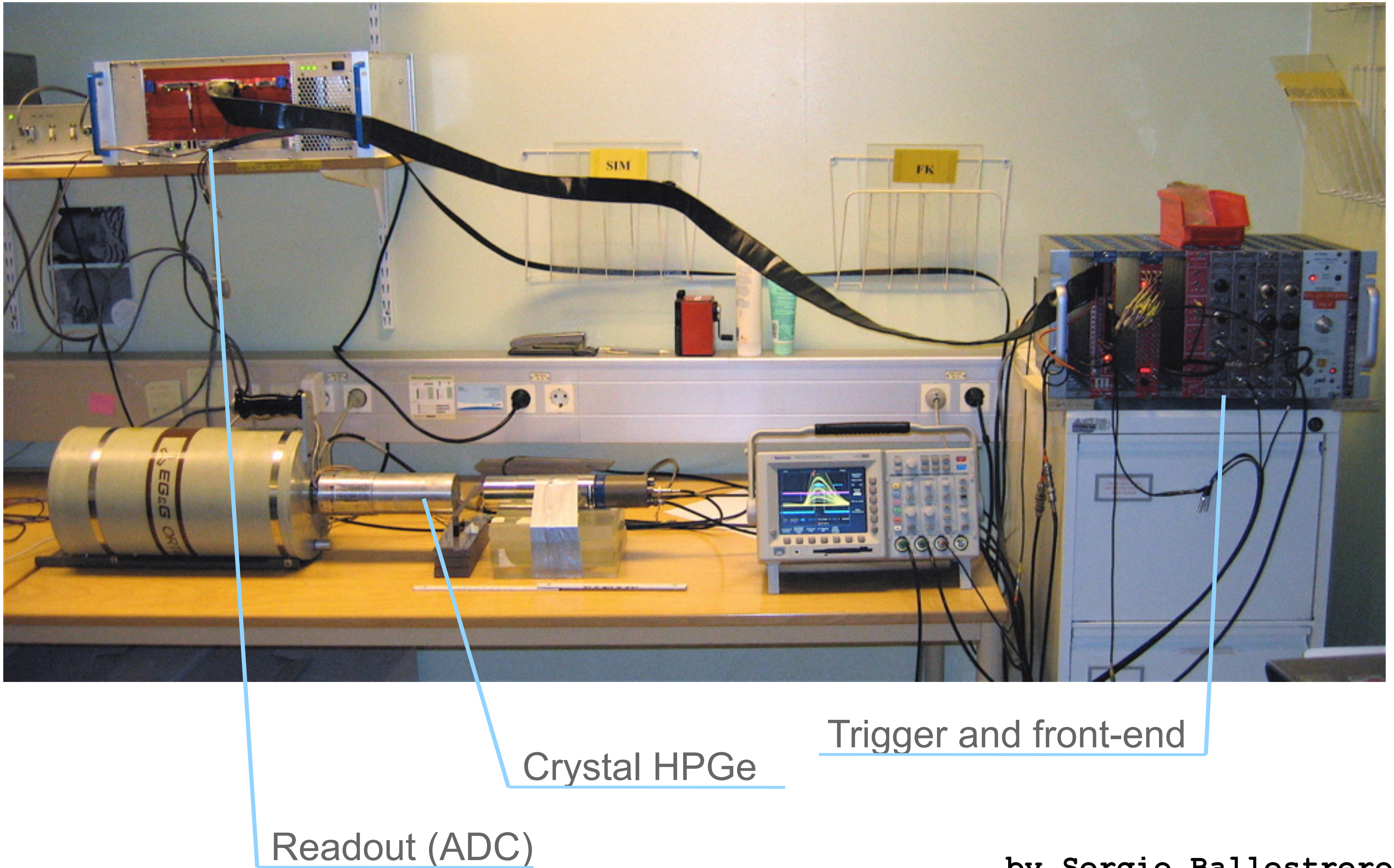
# E.g.: Ge Crystal for isotope ID



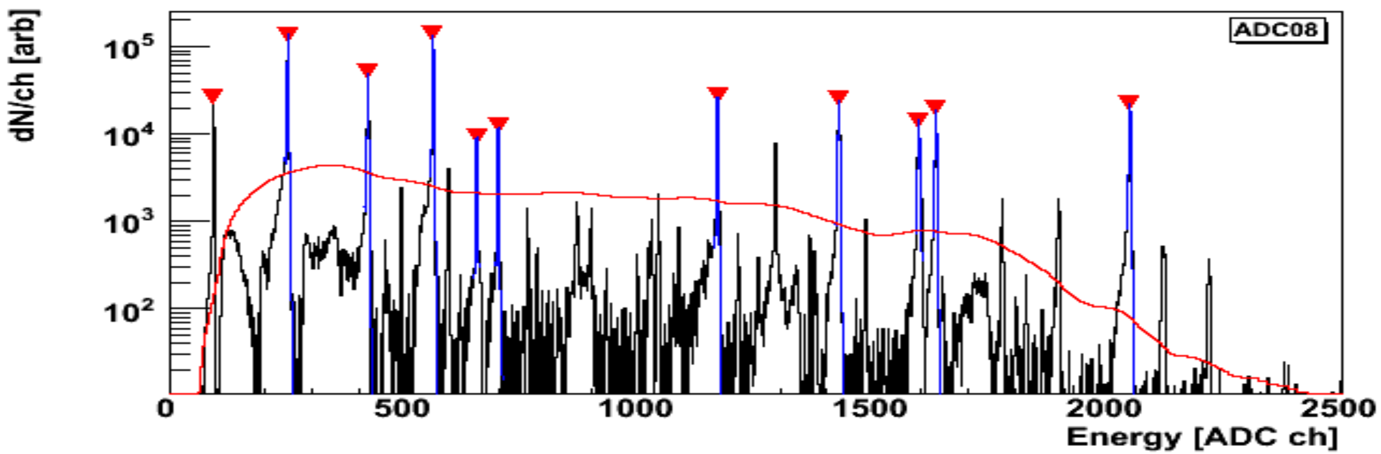

**by Sergio Ballestrero**

# 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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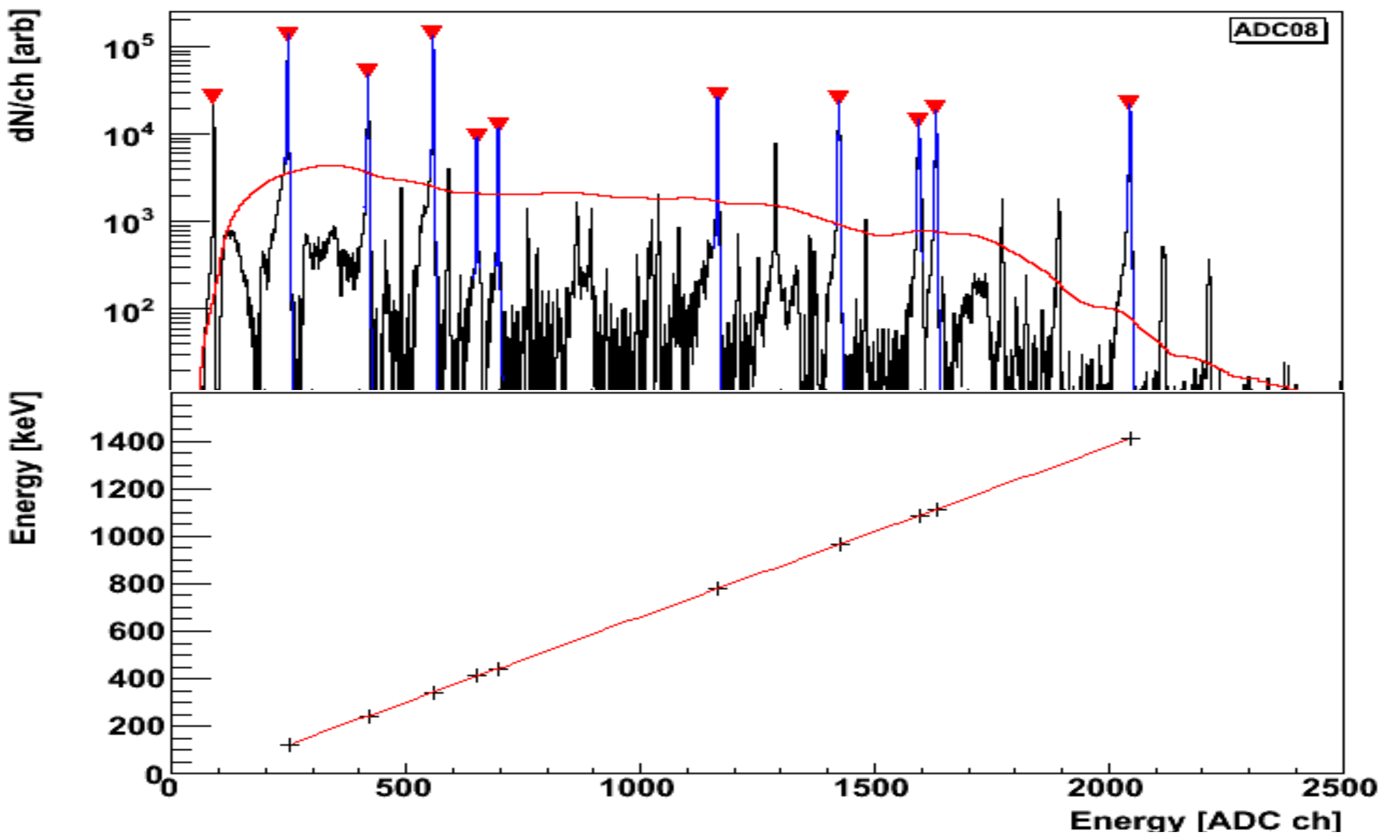
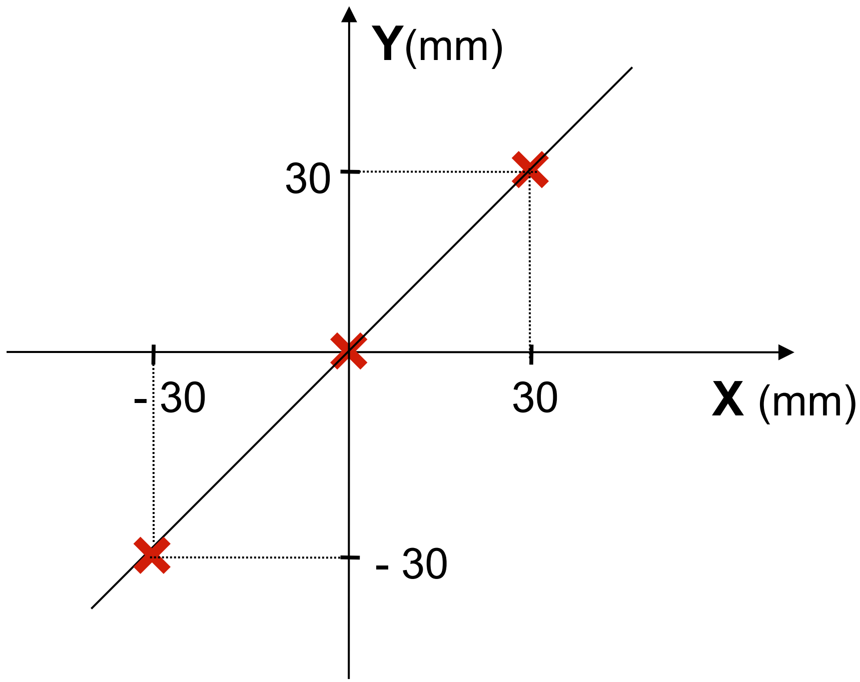


# Back to XDWC: calibration

- 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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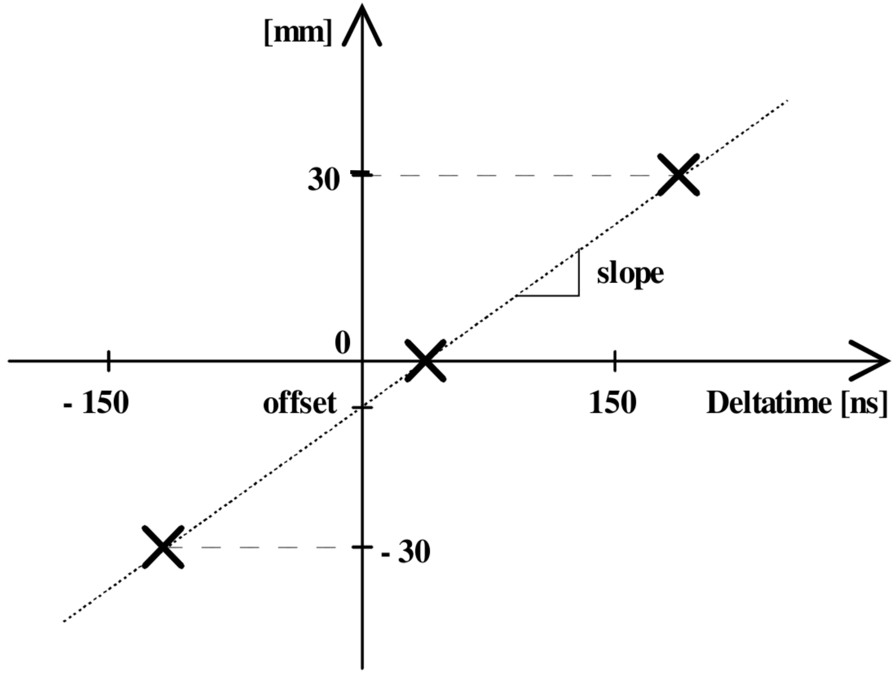


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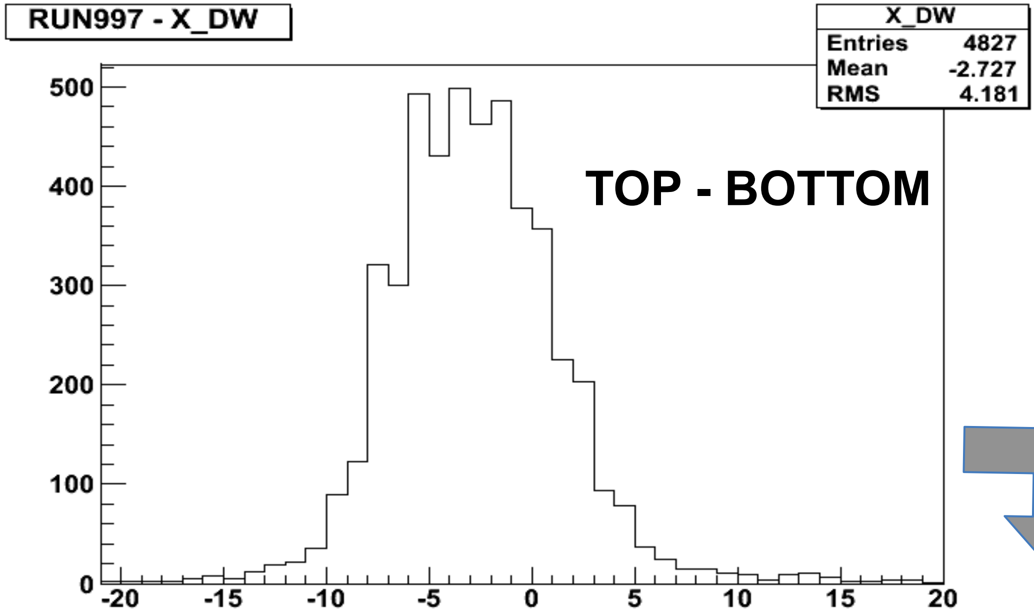
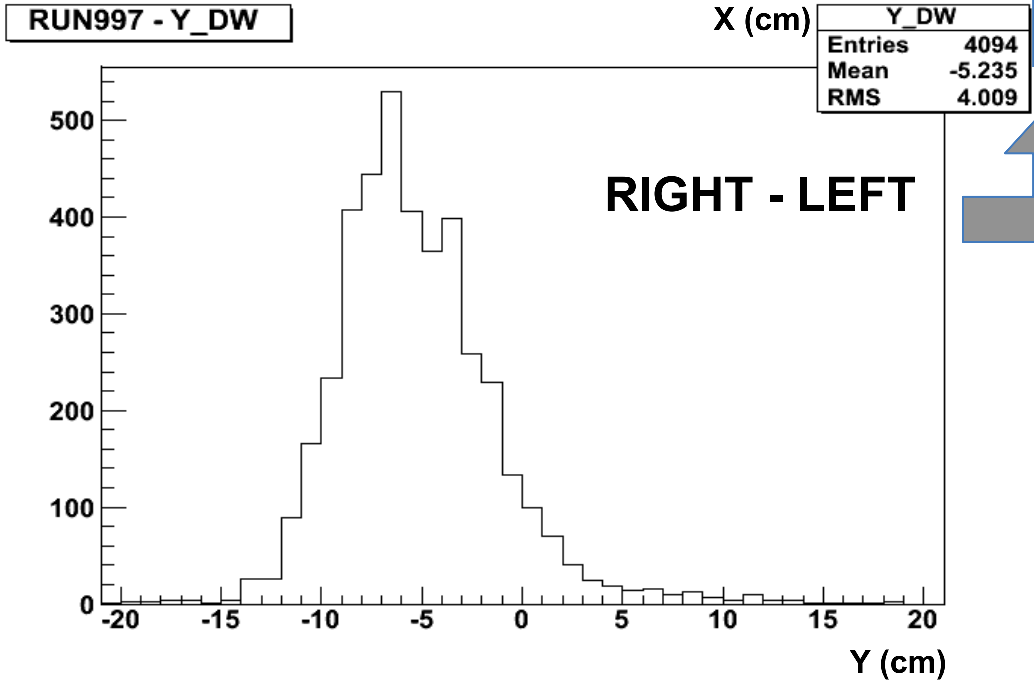
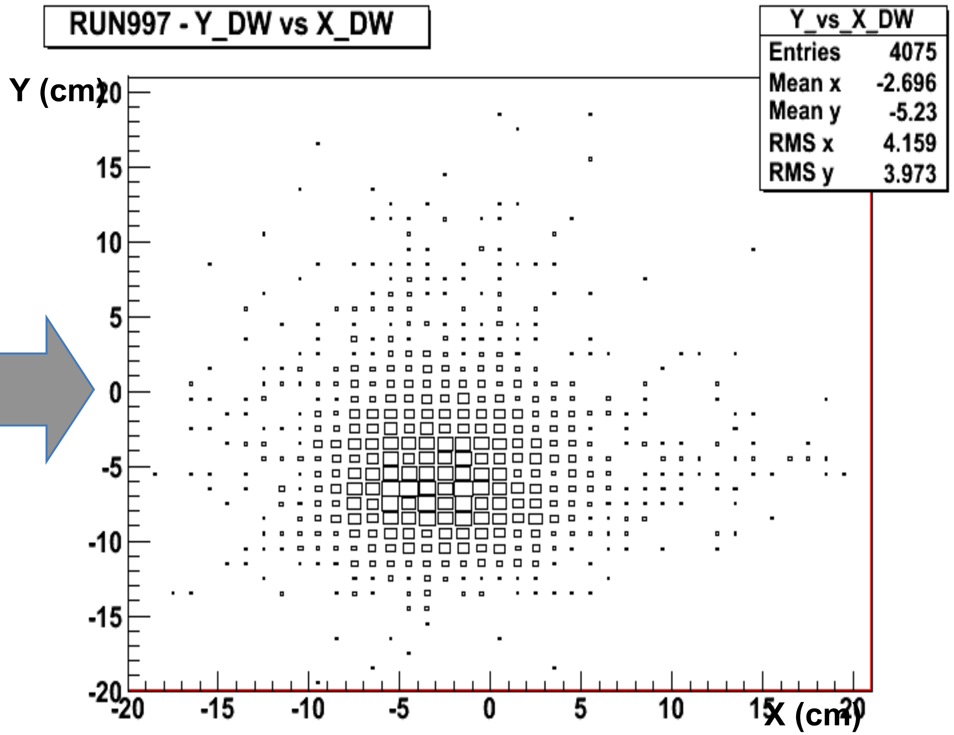
# Calibrated XDWC




## 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!