ARISTOTLE UNIVERSITY OF THESSALONIKI

DAQ HW

Hands-on Approach

ISOTDAQ 2018

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Kostas.Kordas@cern.ch

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 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

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

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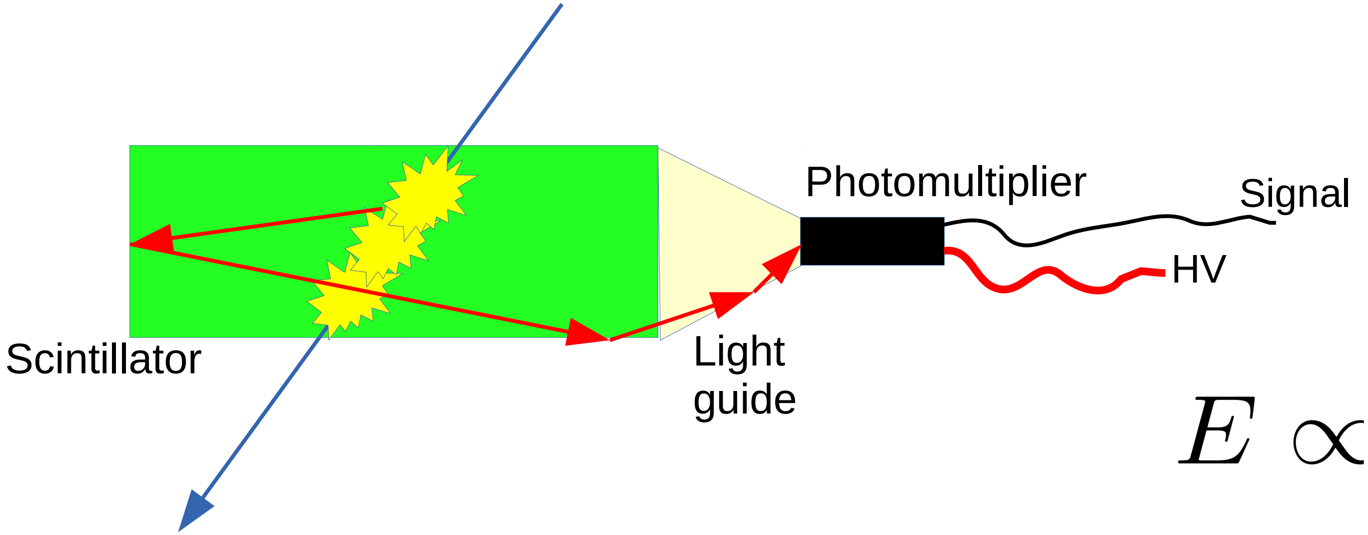
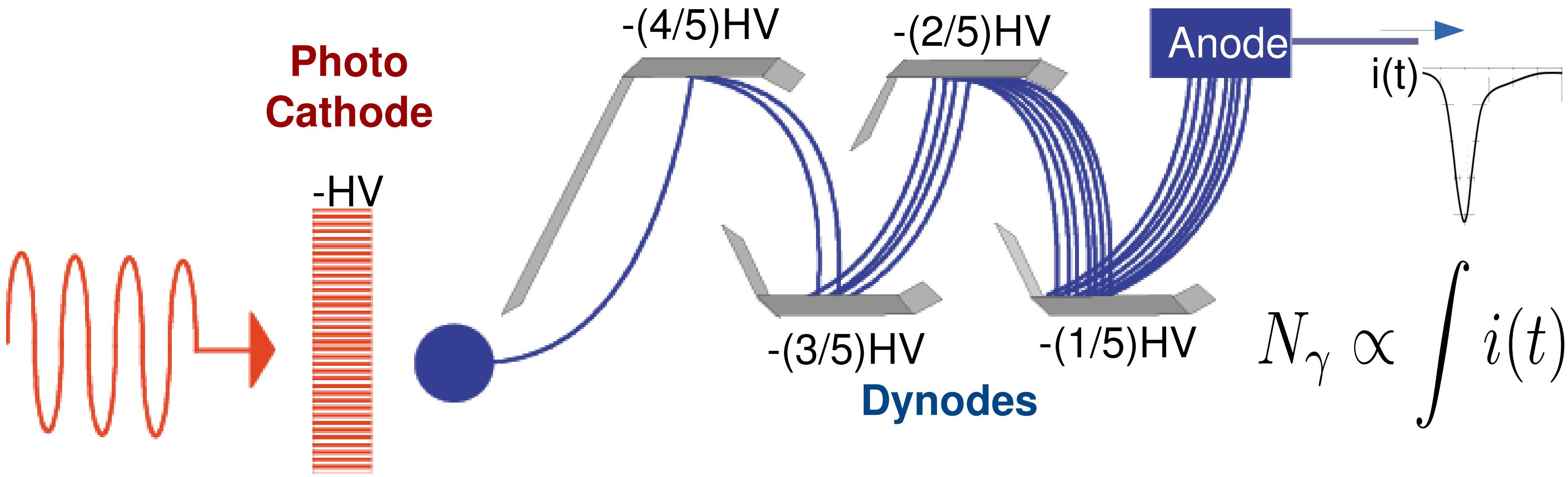
Energy measurement



$$E \propto N_\gamma$$

- 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

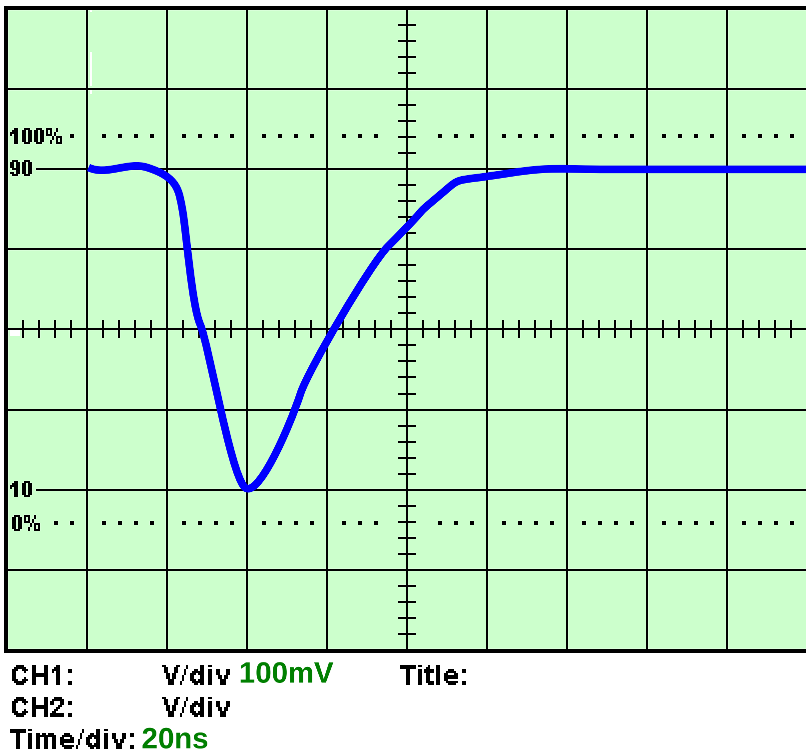


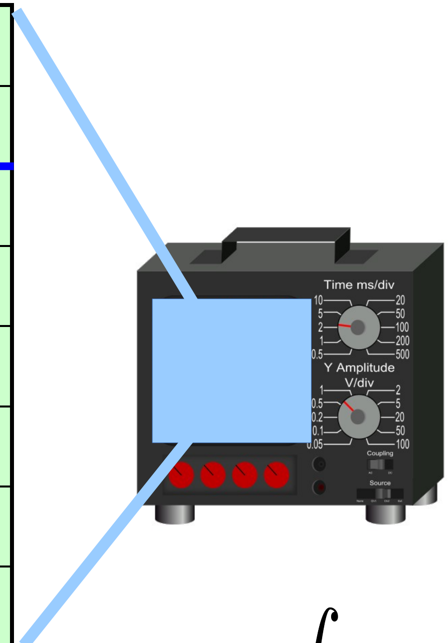
$$N_\gamma \propto \int i(t)\, dt = Q$$

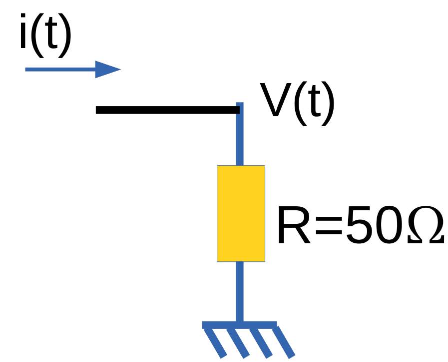
- **Photo cathode**: photon to electron conversion via photo-electric effect
  - typical quantum efficiency ≈1-10% (max 30%), depends on material and wavelength
- **Dynodes**: electrodes that amplify number of electrons thanks to secondary emission
  - Photocathode to anode: typical overall gain $\approx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

Start the measure

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



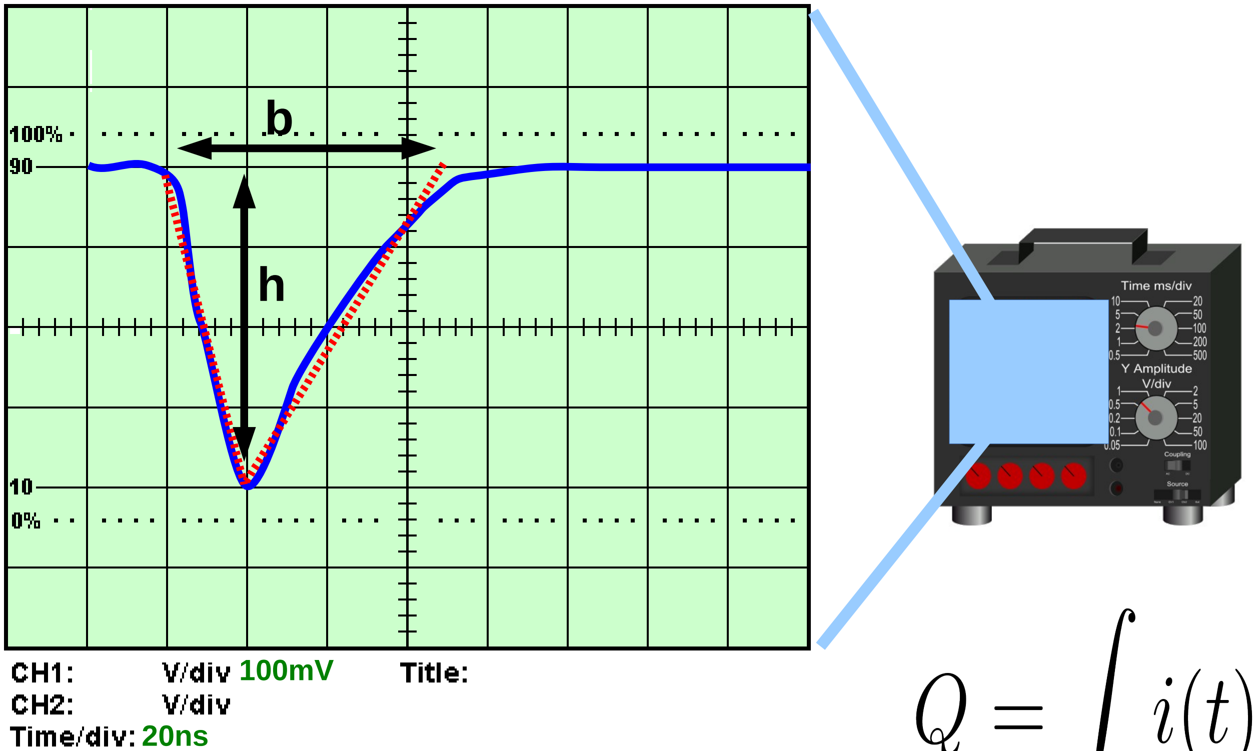


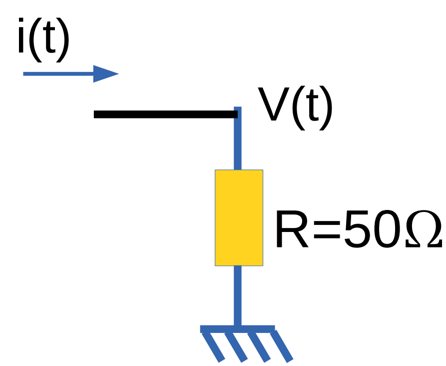


$$Q = \int i(t)\, dt = \frac{1}{R} \int V(t)\, dt$$

Good old oscilloscope

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





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

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

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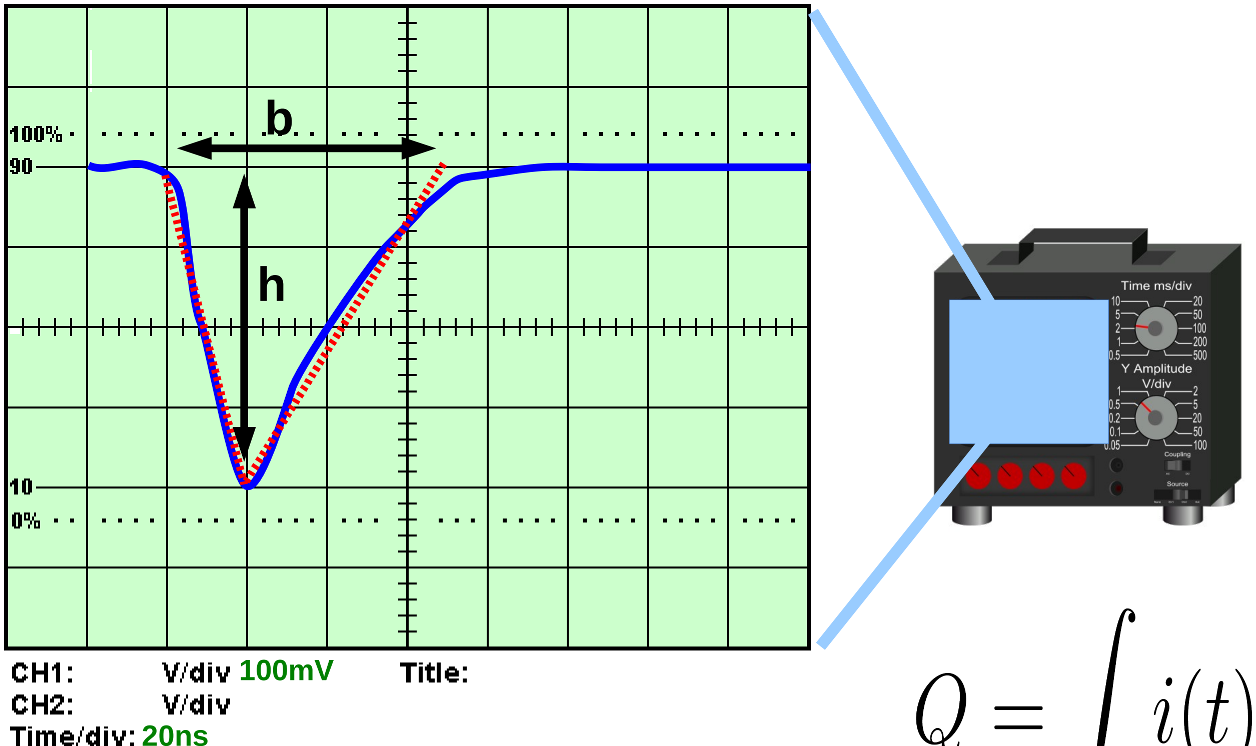

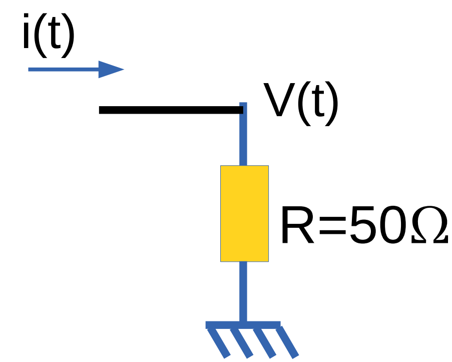

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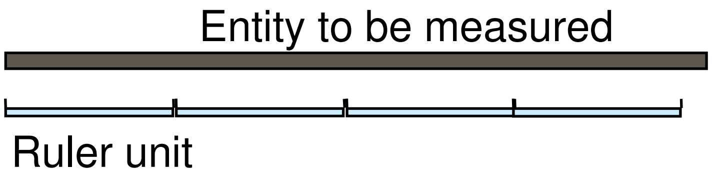
Good old oscilloscope

- 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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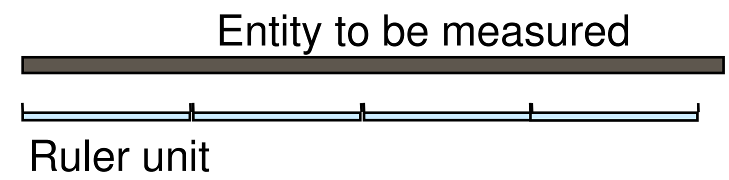

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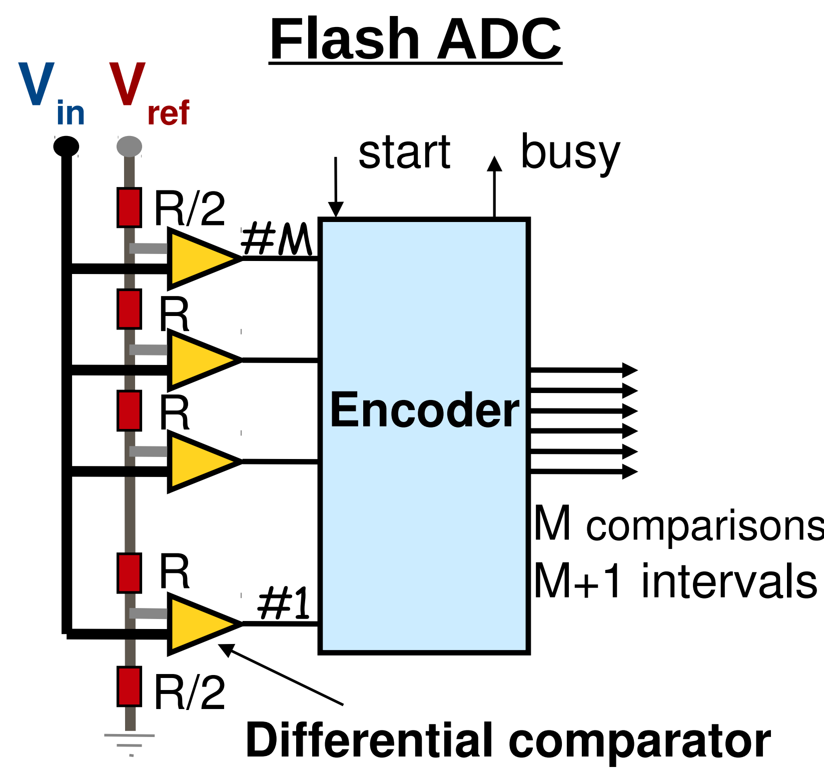

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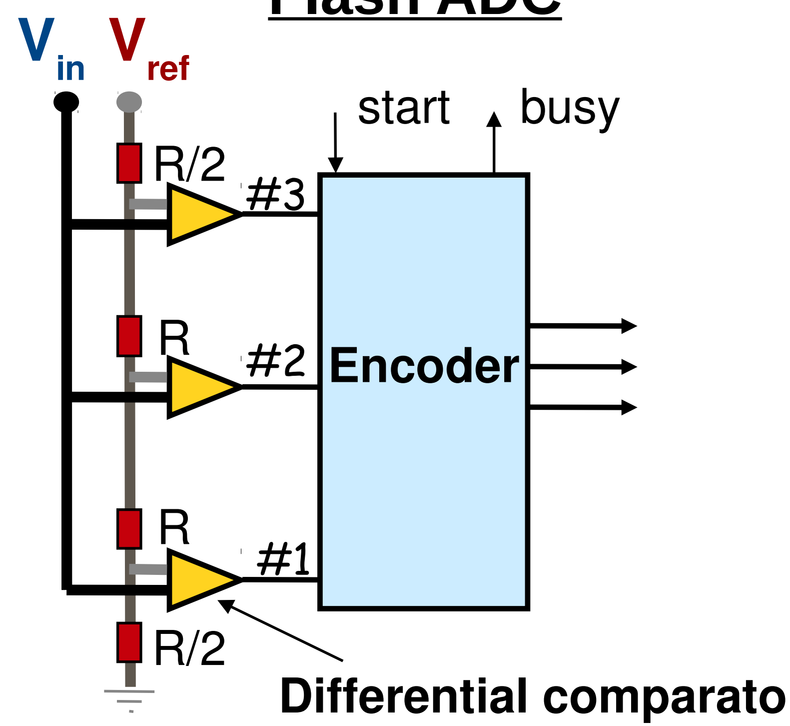
$x = V_{in}/V_{ref}$	Comparison results	Encoded form
$x < 1/6$	000	00
$1/6 \leq x < 3/6$	001	01
$3/6 \leq x < 5/6$	011	10
$5/6 \leq x$	111	11

Flash ADC



Analog to Digital Conversion

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- 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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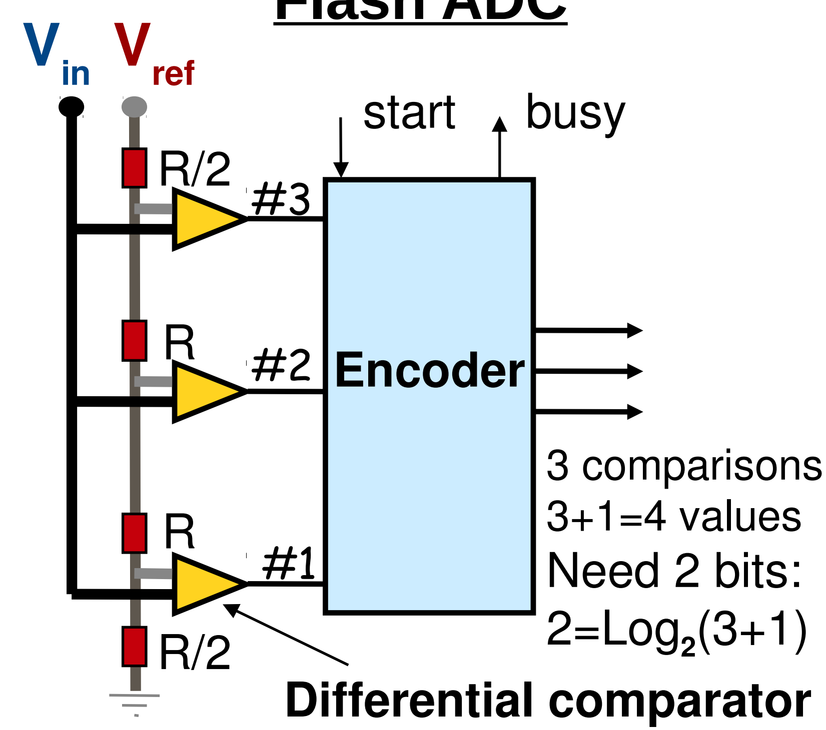
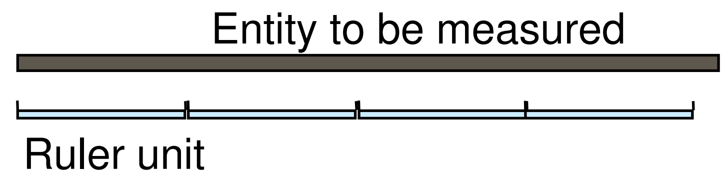
Flash ADC

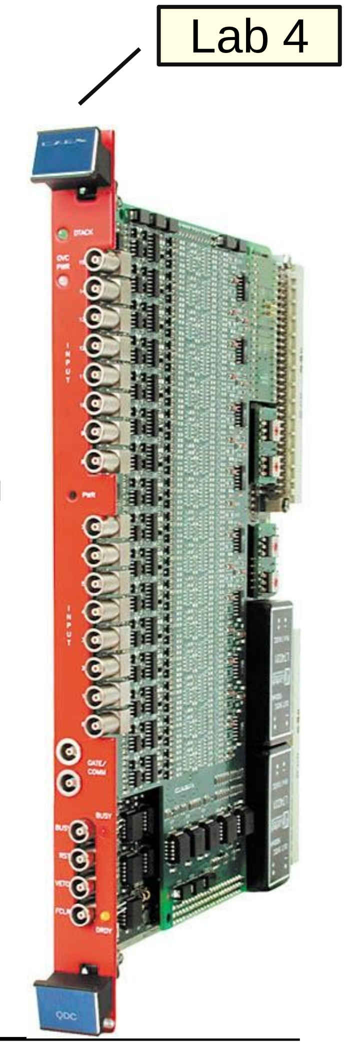


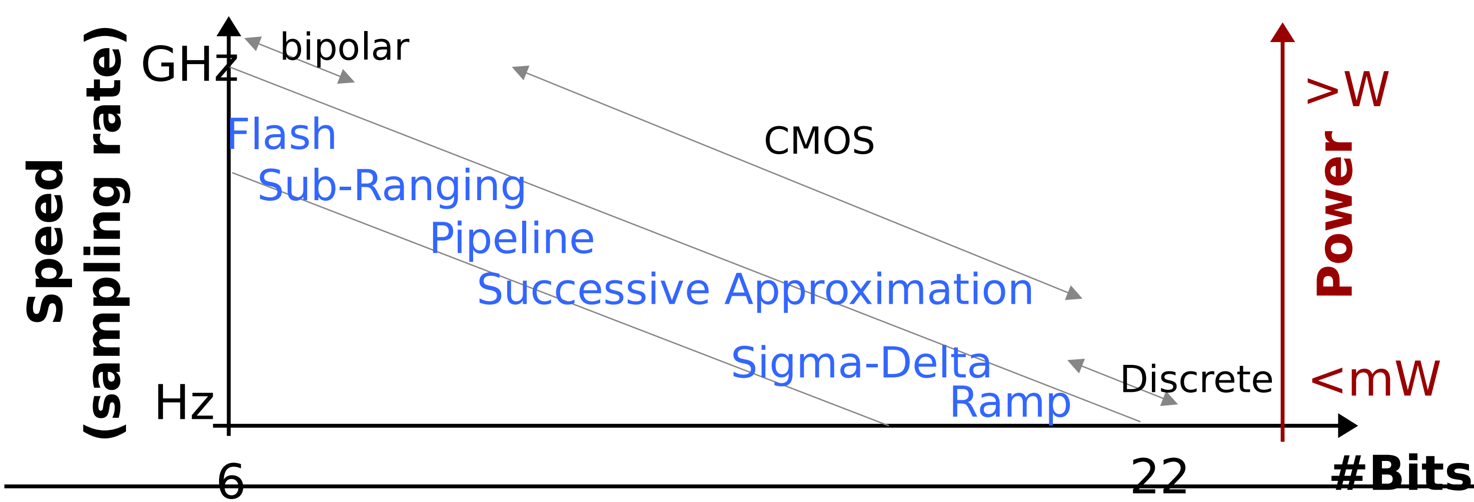
ADC Characteristics

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



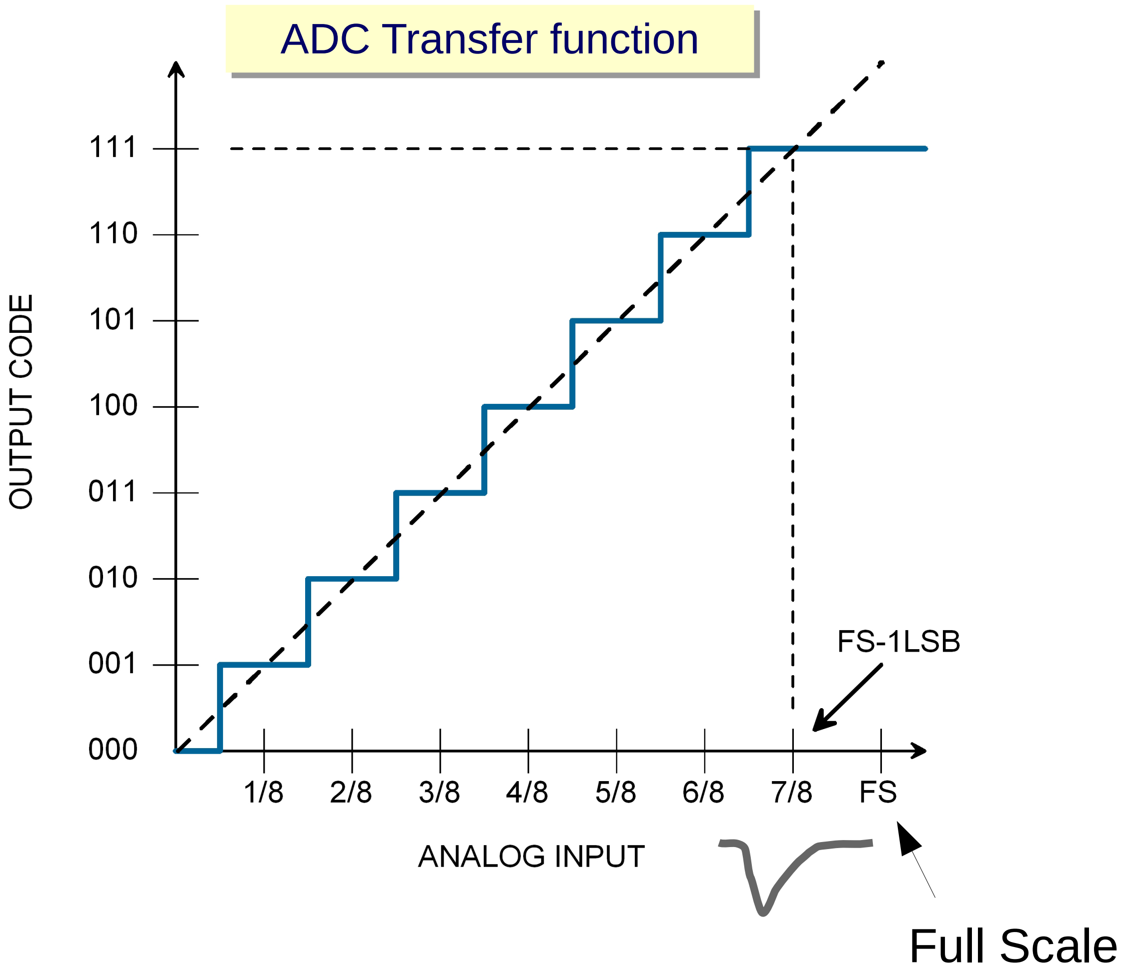
- Quantization error: ±LSB/2
- Dynamic range: ratio largest /smallest value (in $\log_2$)
  - N for linear ADC
  - >N for non-linear ADC
    (Constant relative resolution on the valid input range)
- Many different ADC technique exists
  - mostly because of the trade-off between speed and resolution





ADC Accuracies

- ADC transfer function
  - Output code vs analog input



ADC (In)Accuracies

- ADC transfer function
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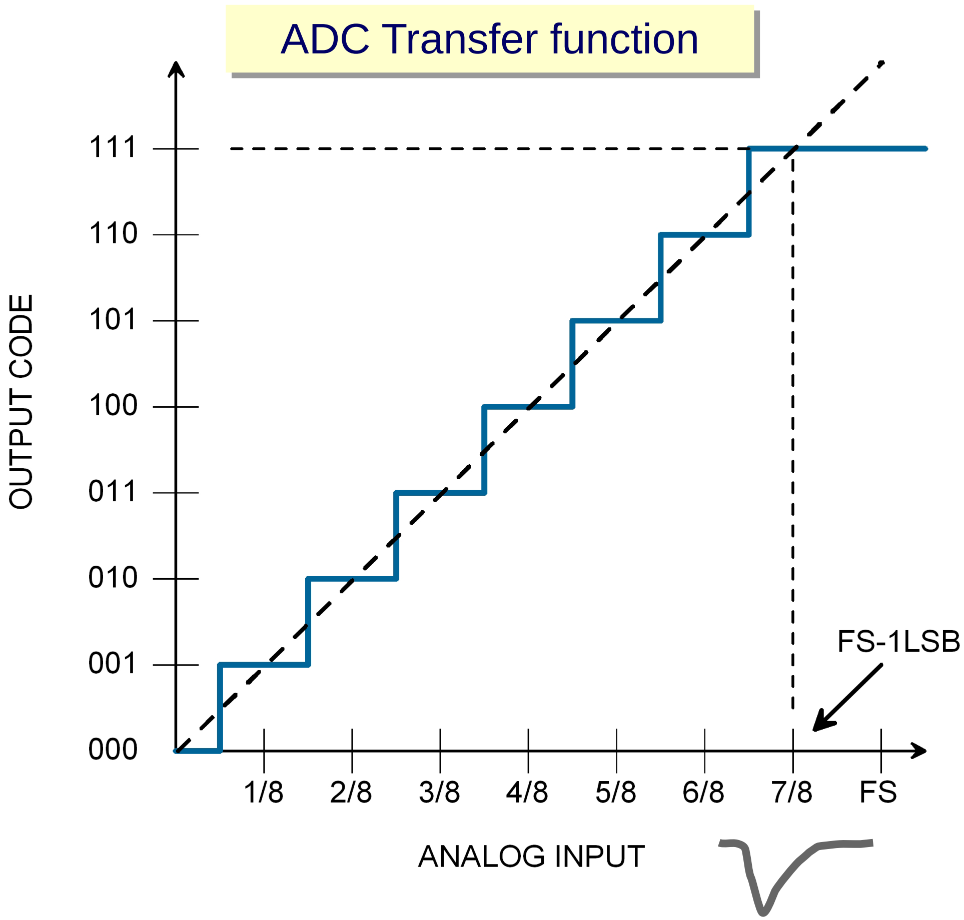

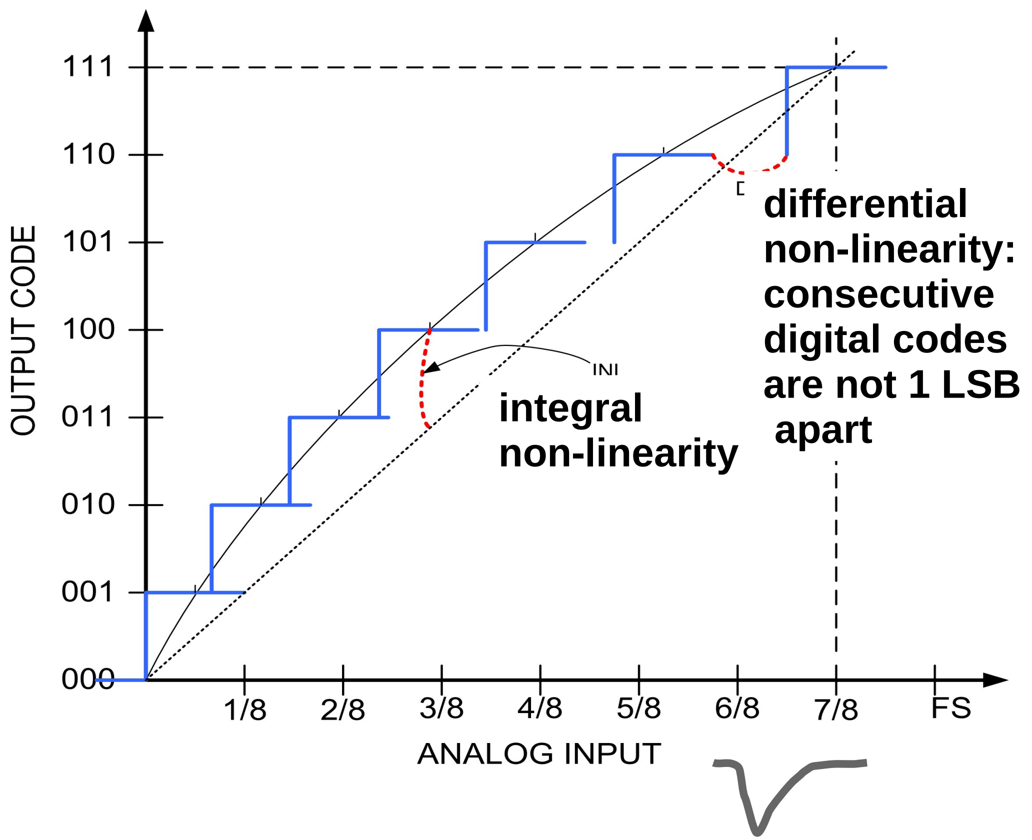

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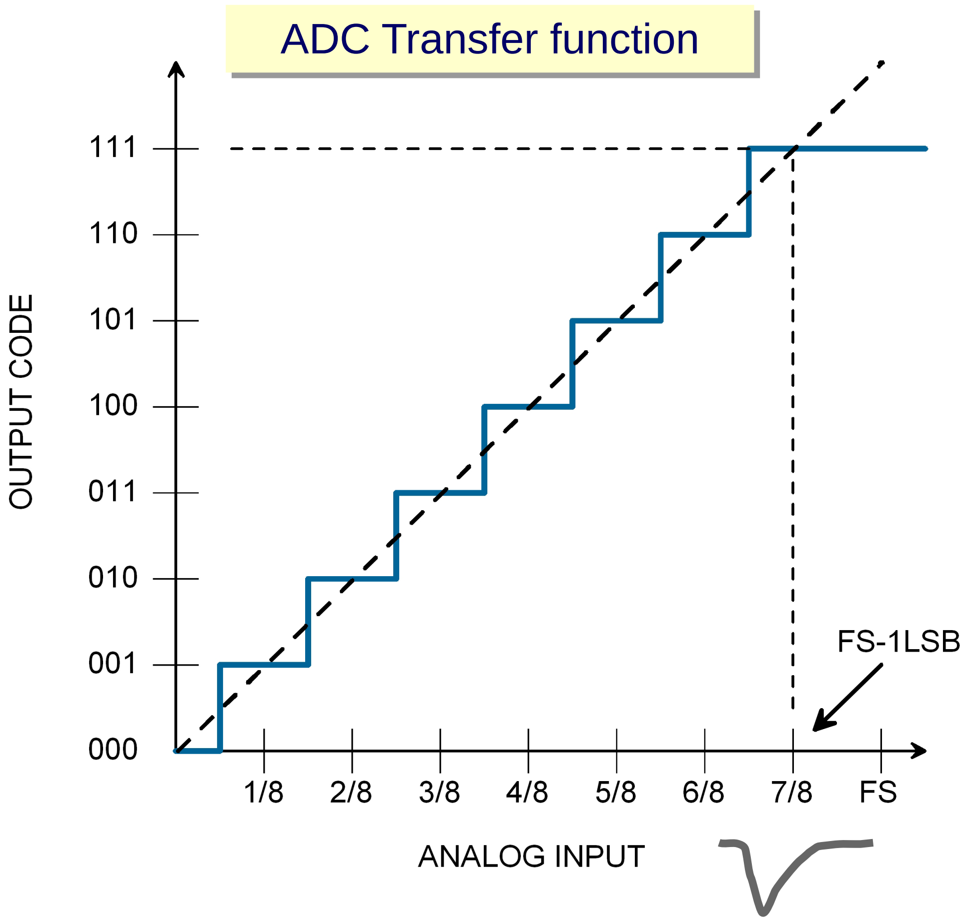
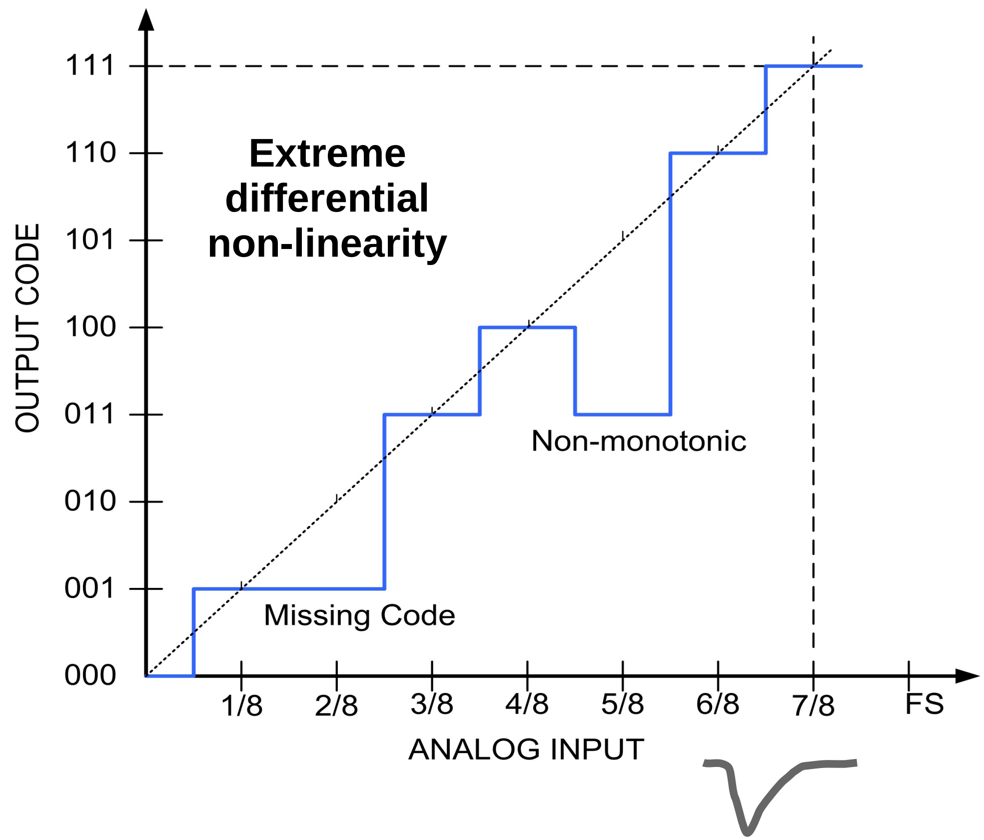
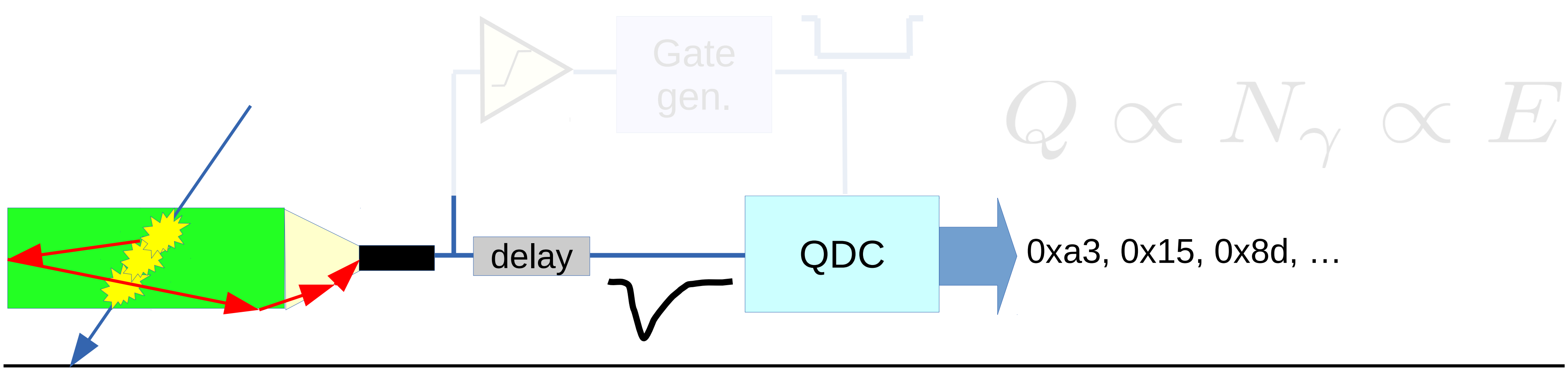




Charge to Digital

- 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

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



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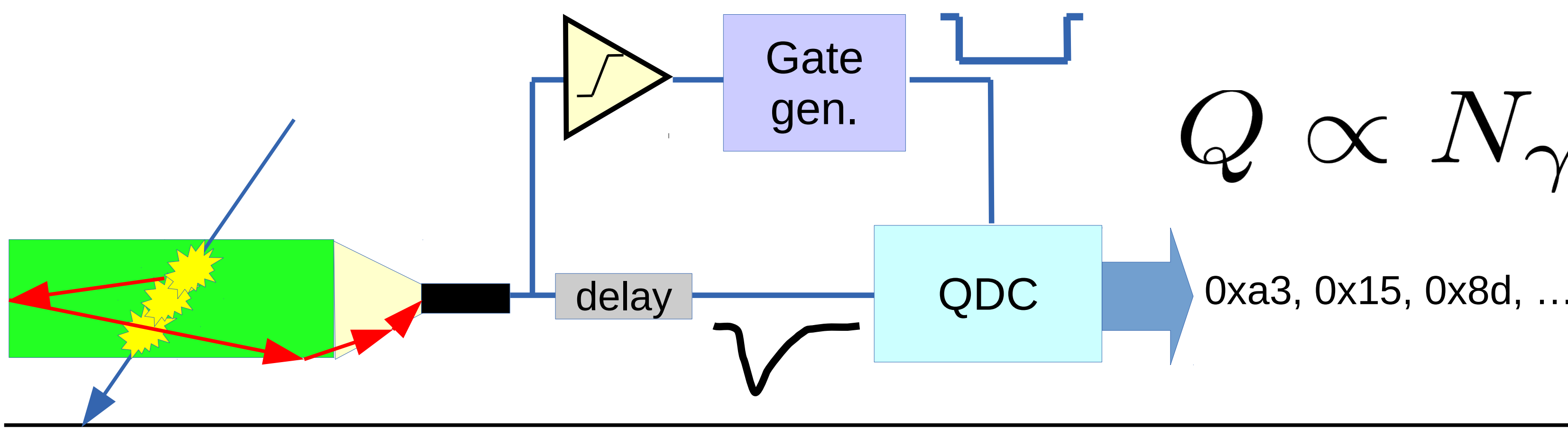


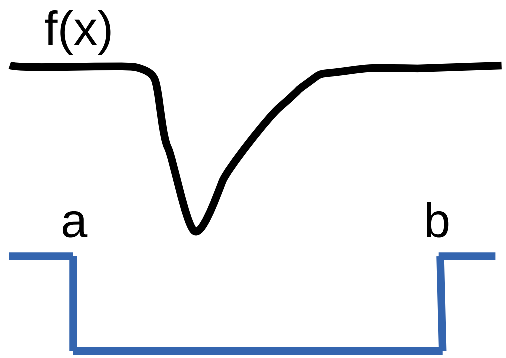
$$Q \propto N_\gamma \propto E$$

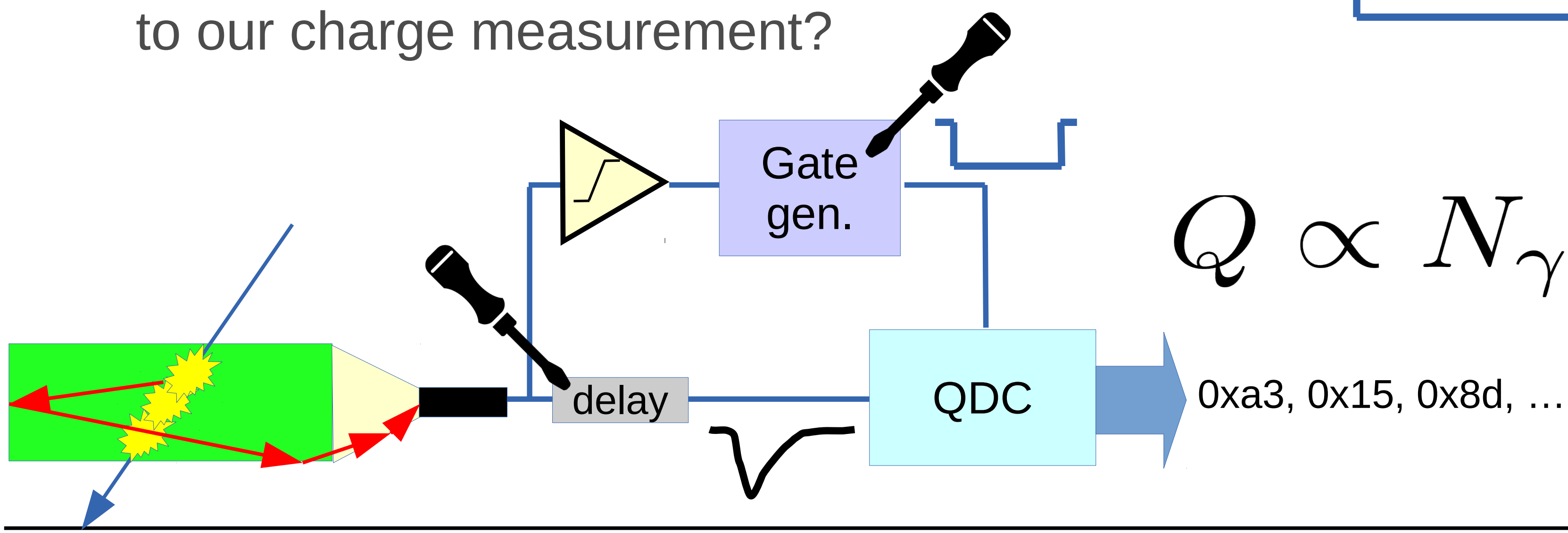
QDC: timing

- Relative timing between signal and gate 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

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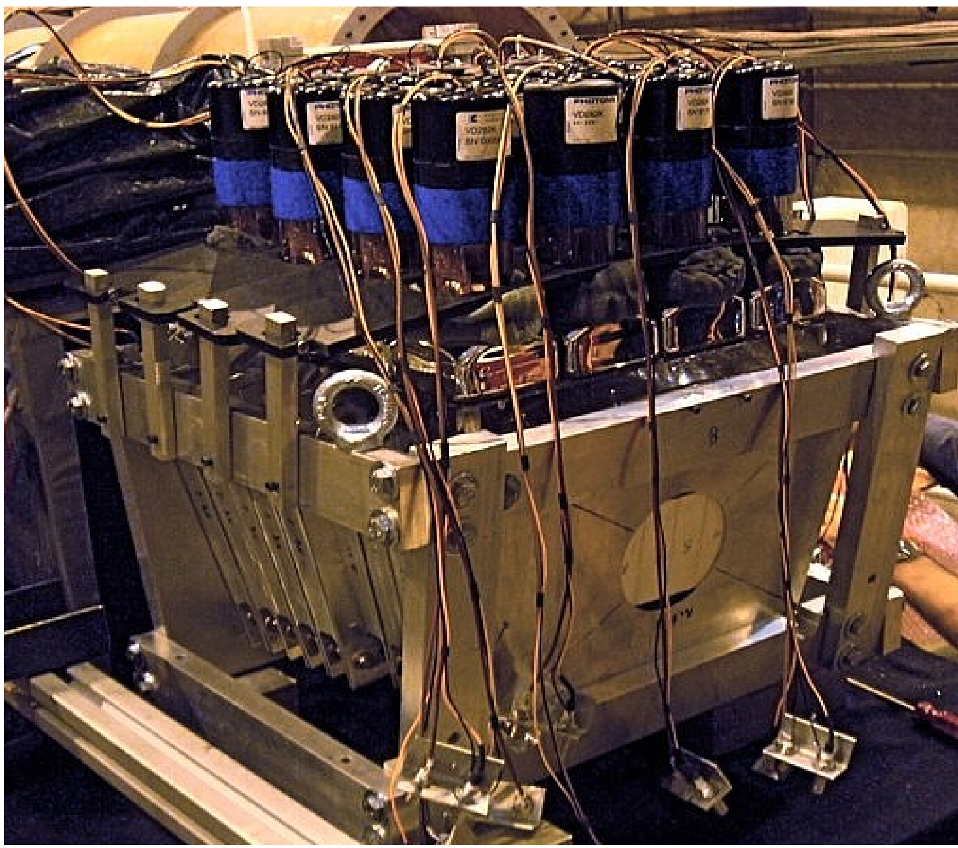

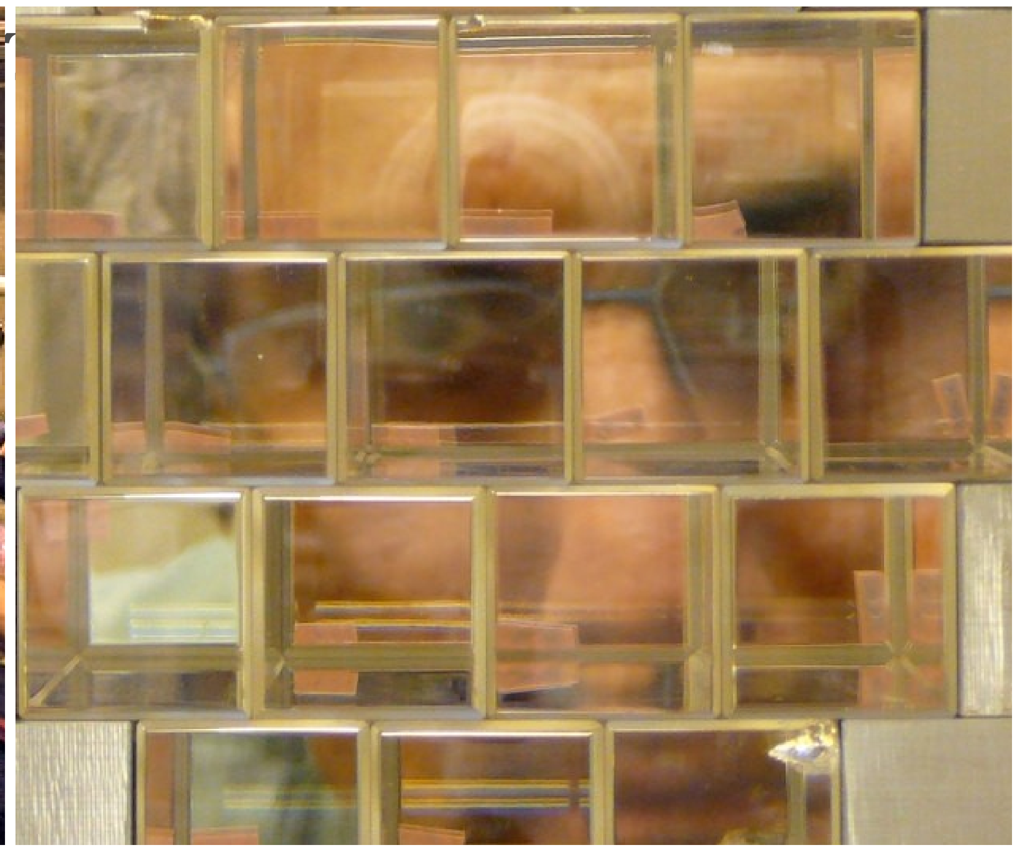

QDC spectra

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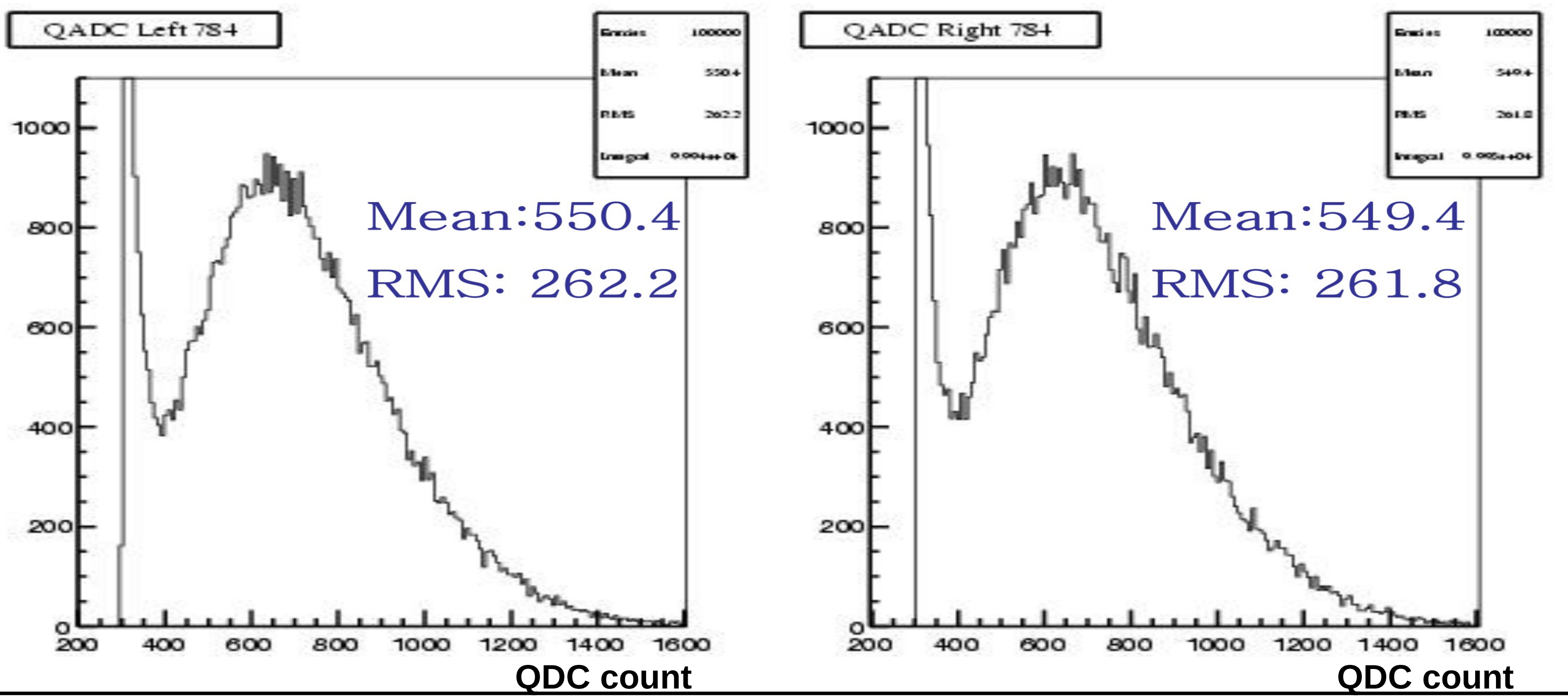
$$Q \propto N_\gamma \propto E$$

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



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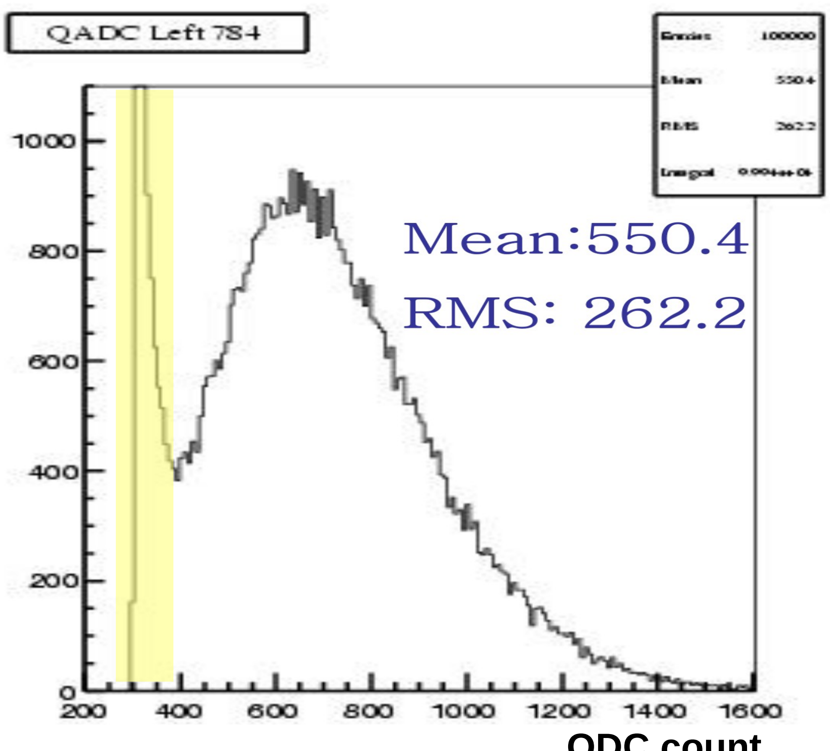
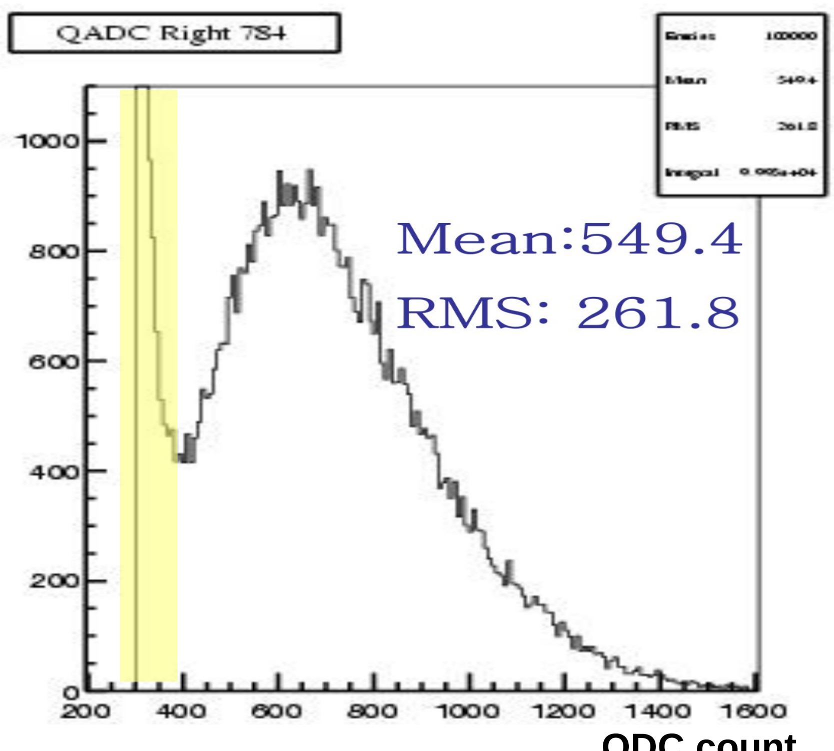
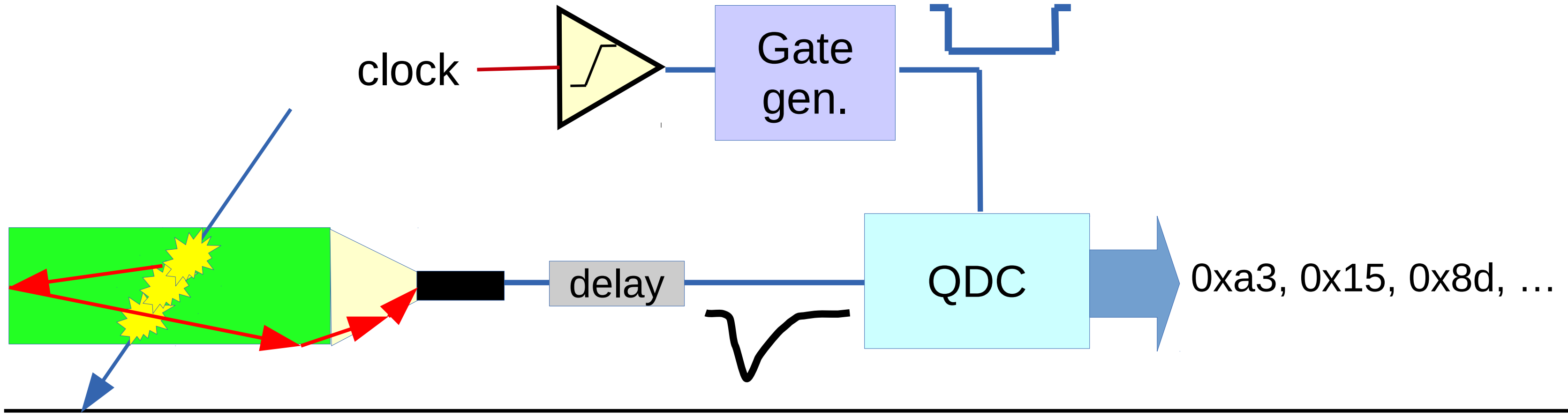




QDC: pedestal subtraction

- 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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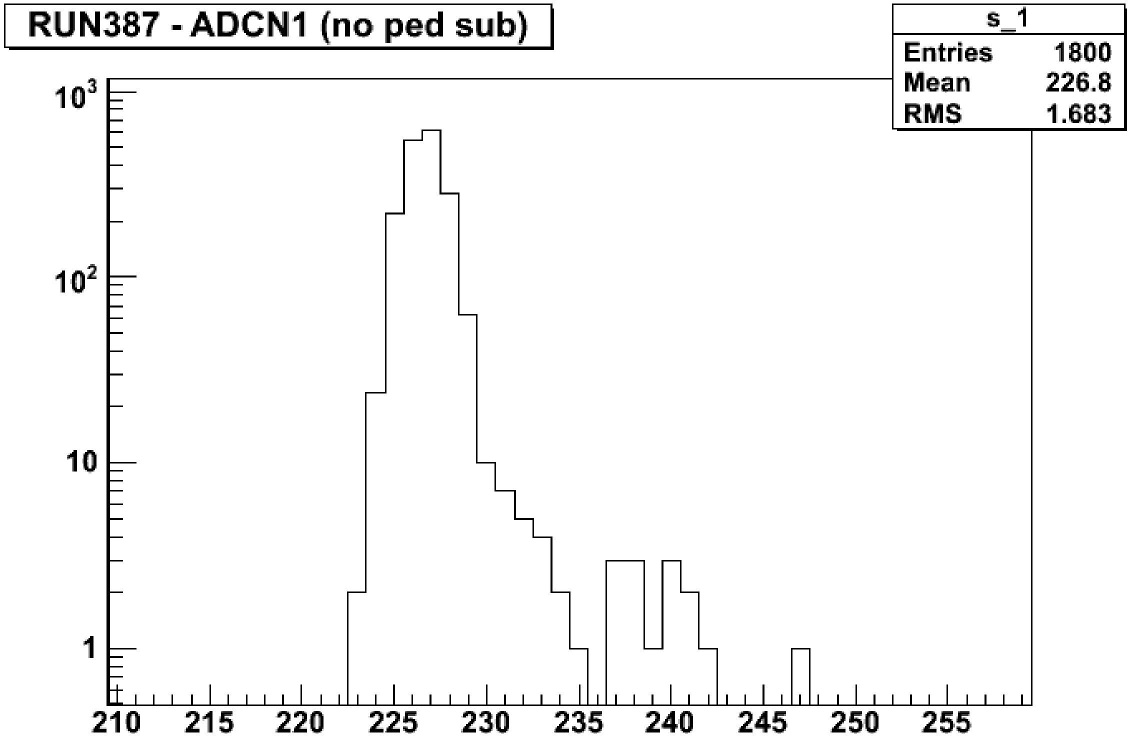

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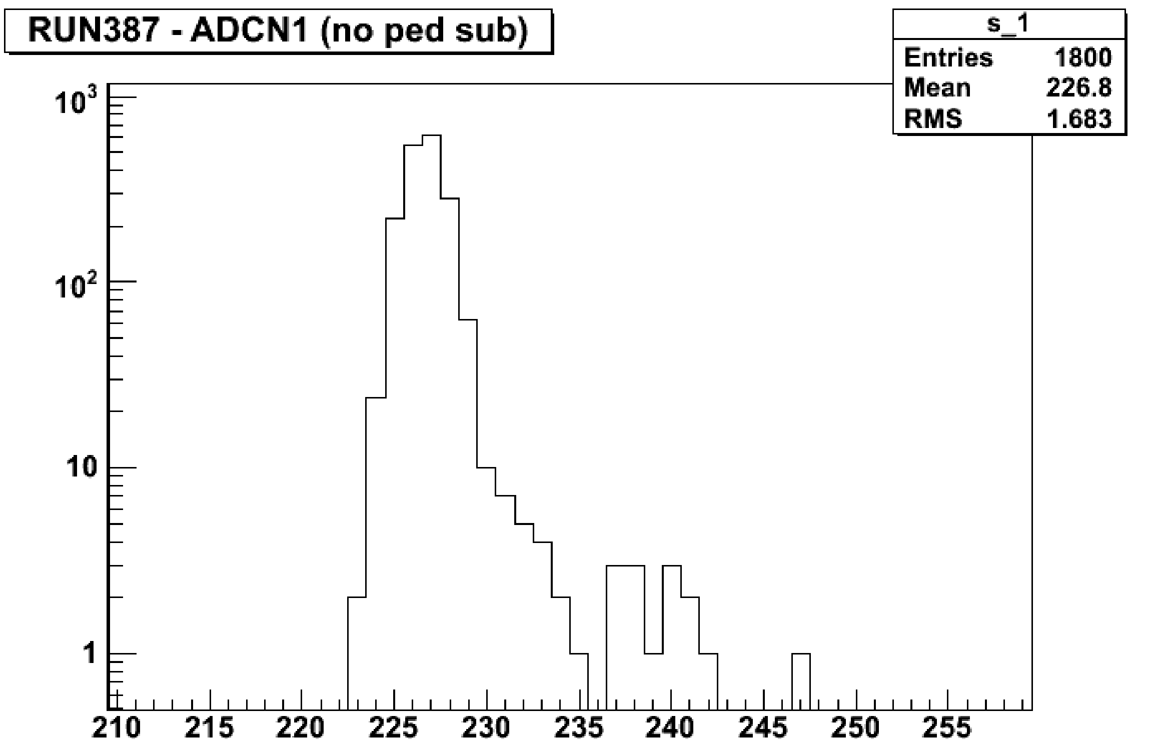
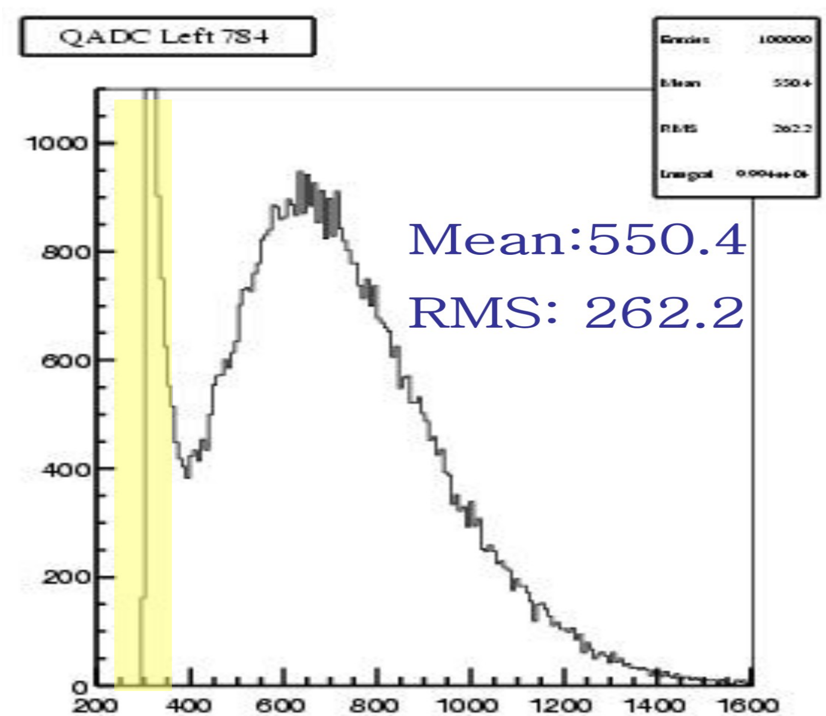
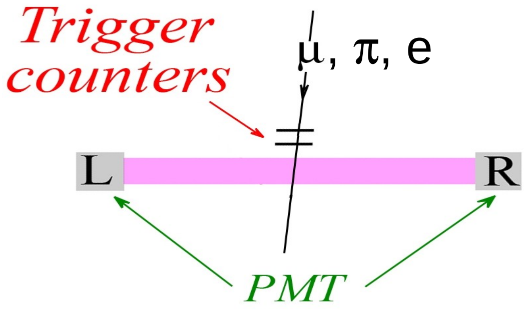
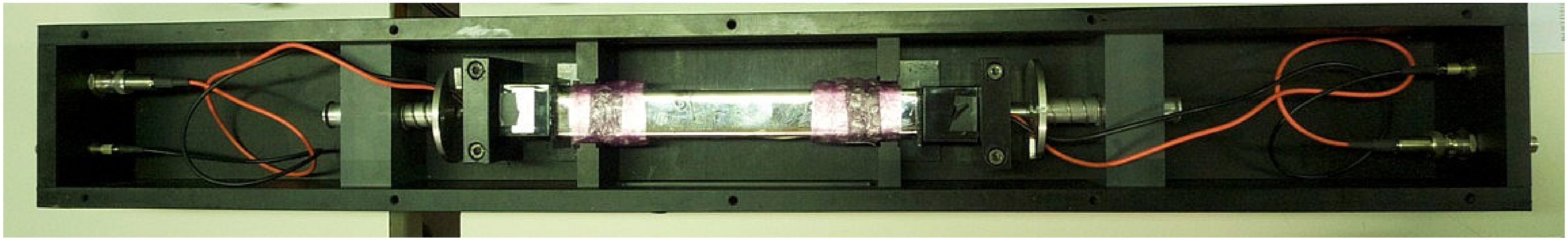




“Real” QDC at work



- $PbWO_4$ (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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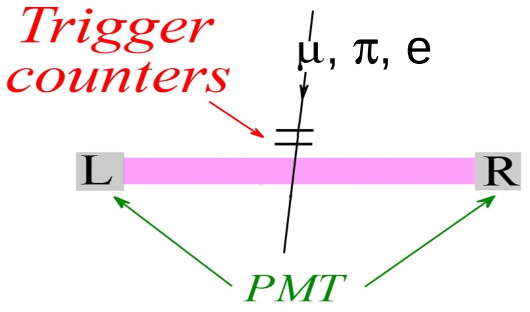
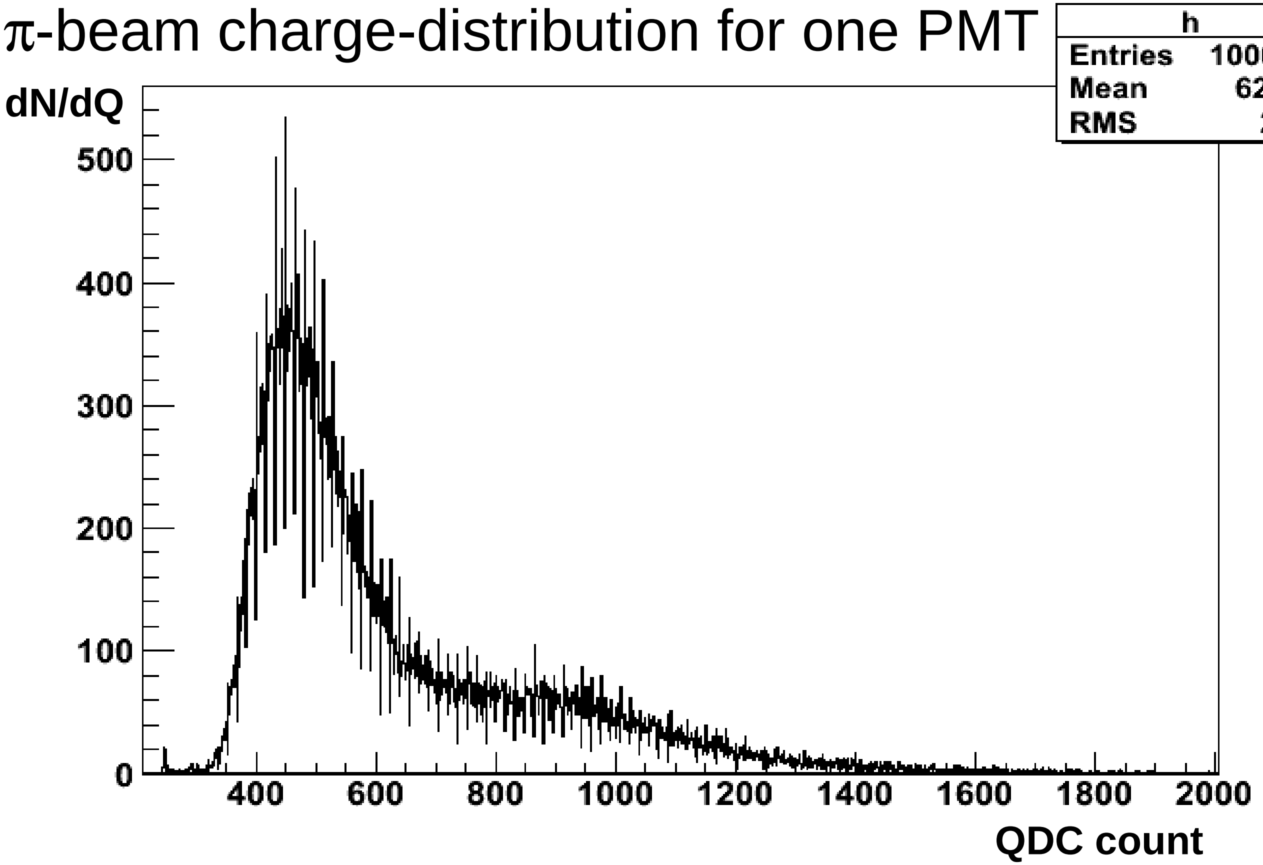


π-beam charge-distribution for one PMT



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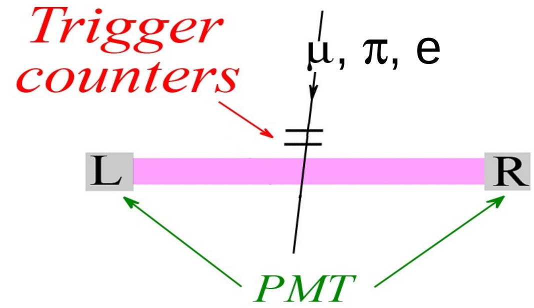

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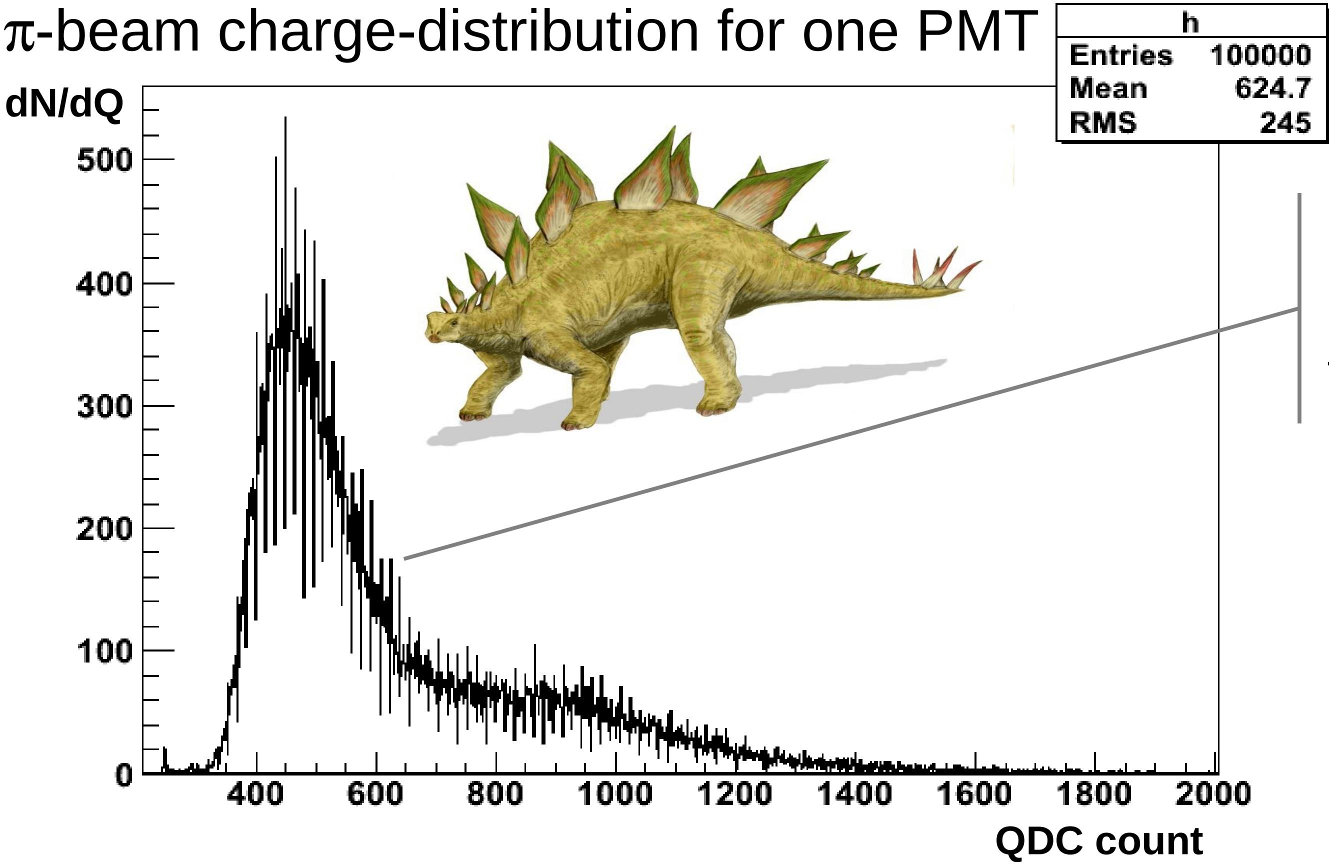

But, what are all those little peaks? Just statistical fluctuations?

Let's zoom in!

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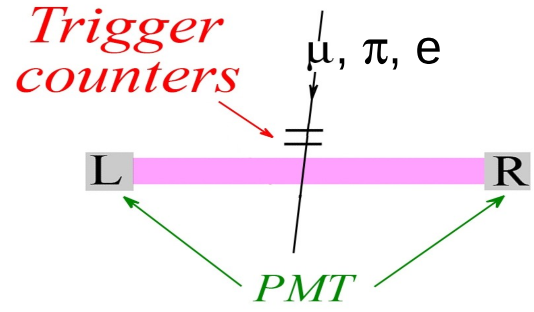

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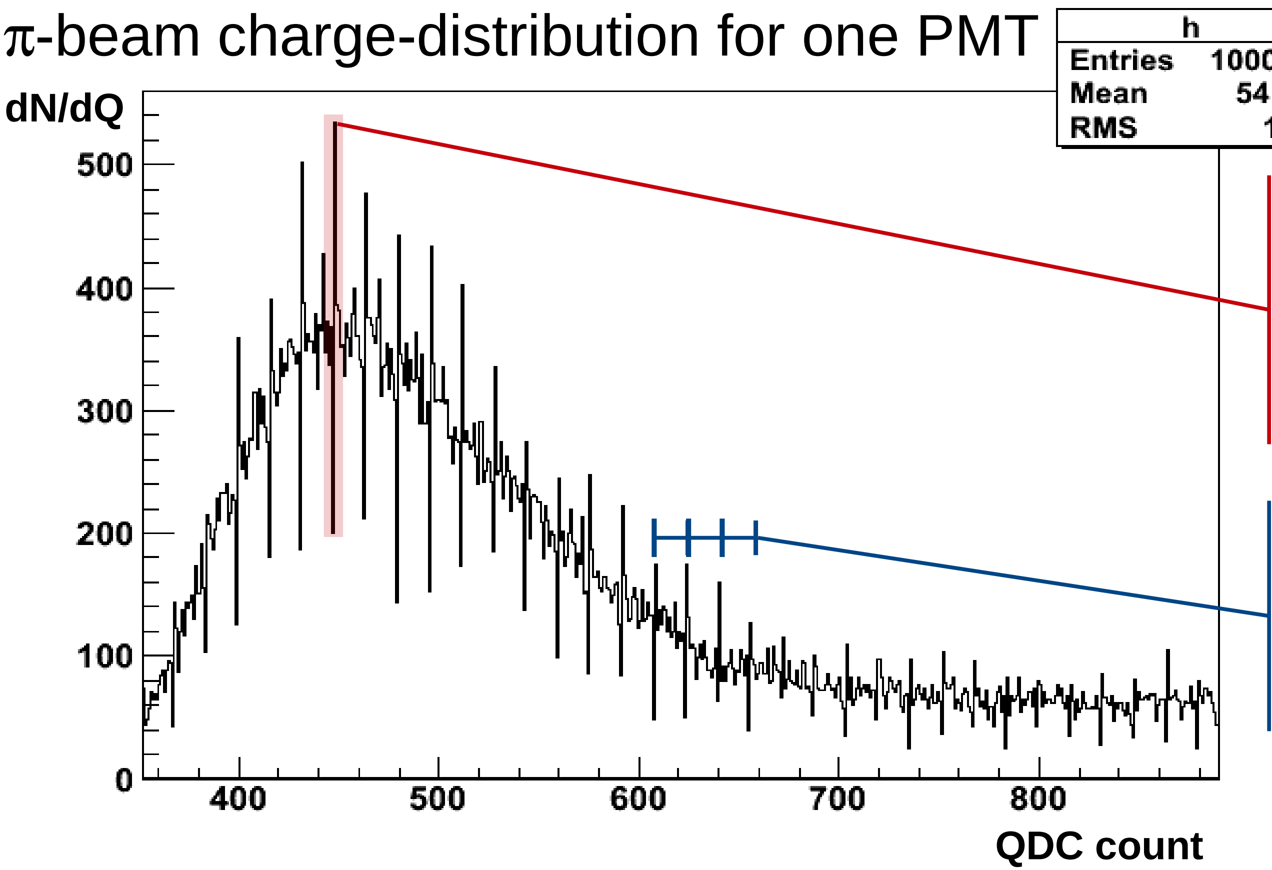

Bin with N entries can fluctuate with σ = √N
- expected σ=√360~19
- observed ~200 (10 σ)

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

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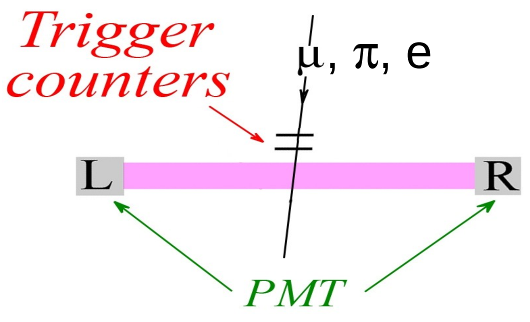

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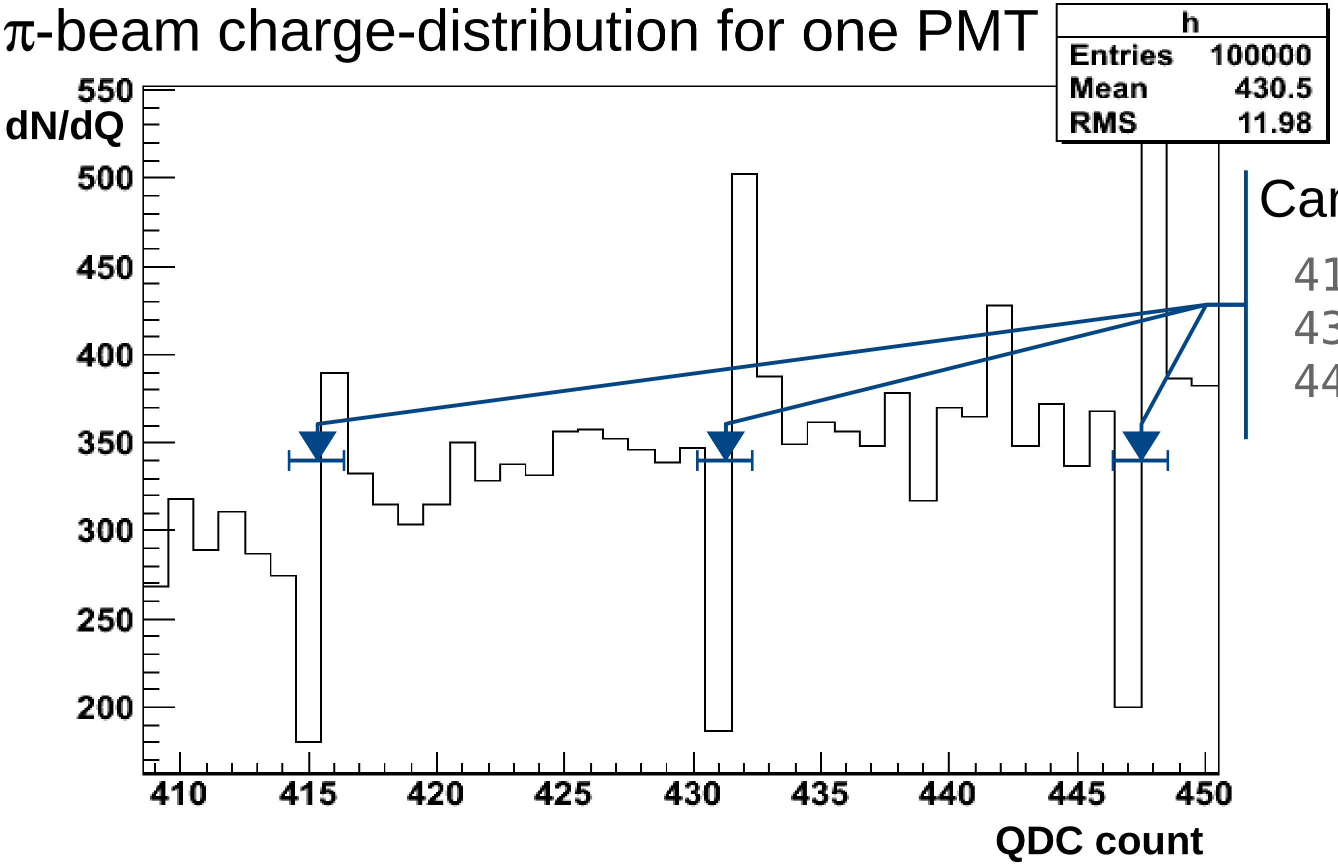

Can you see the effect?

415 & 416
431 & 432
447 & 448

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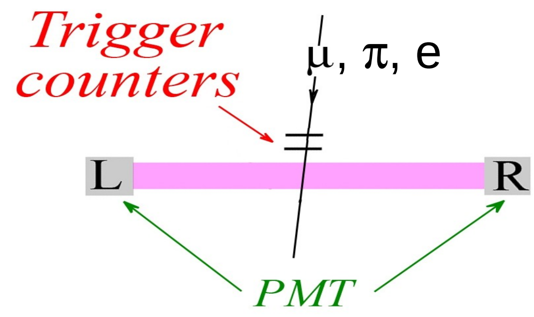

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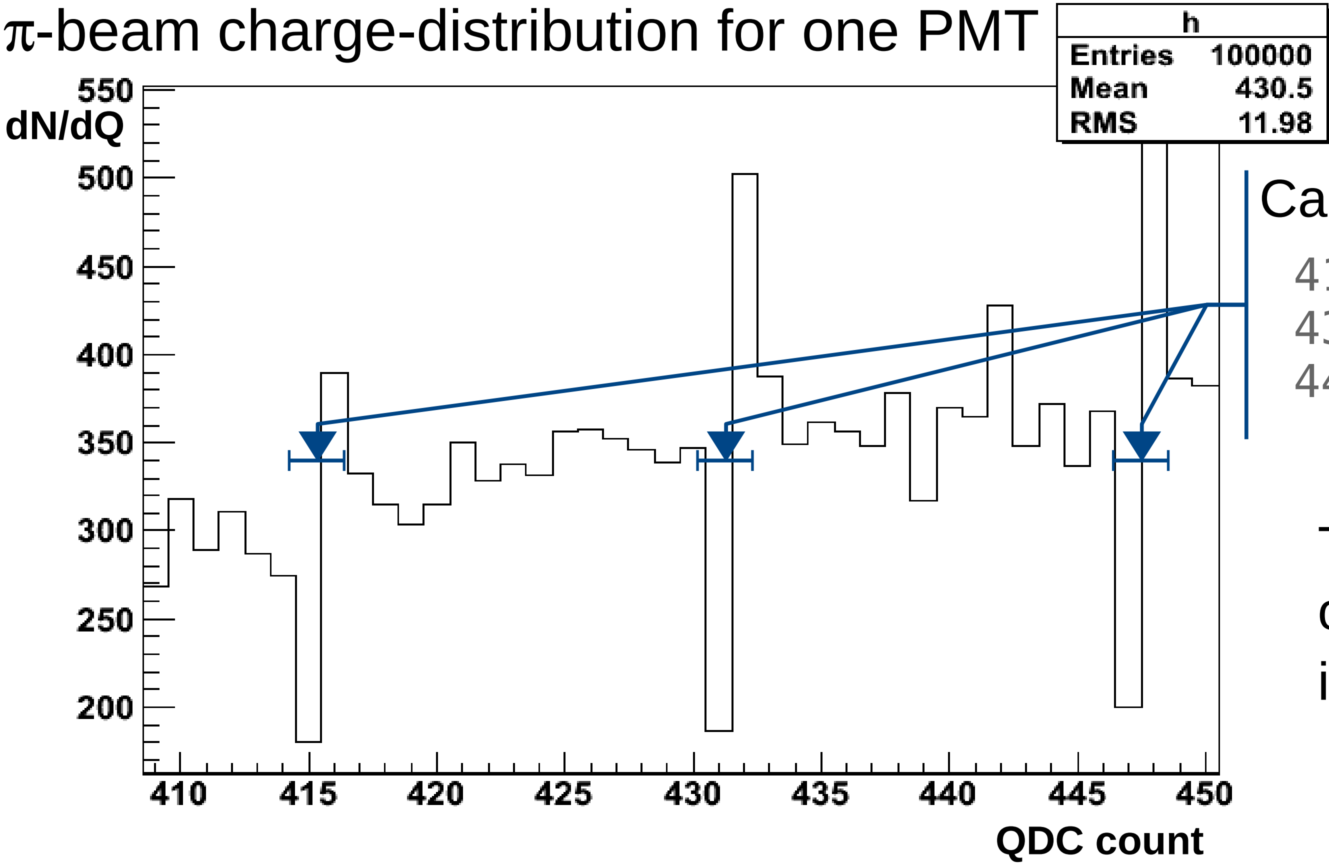


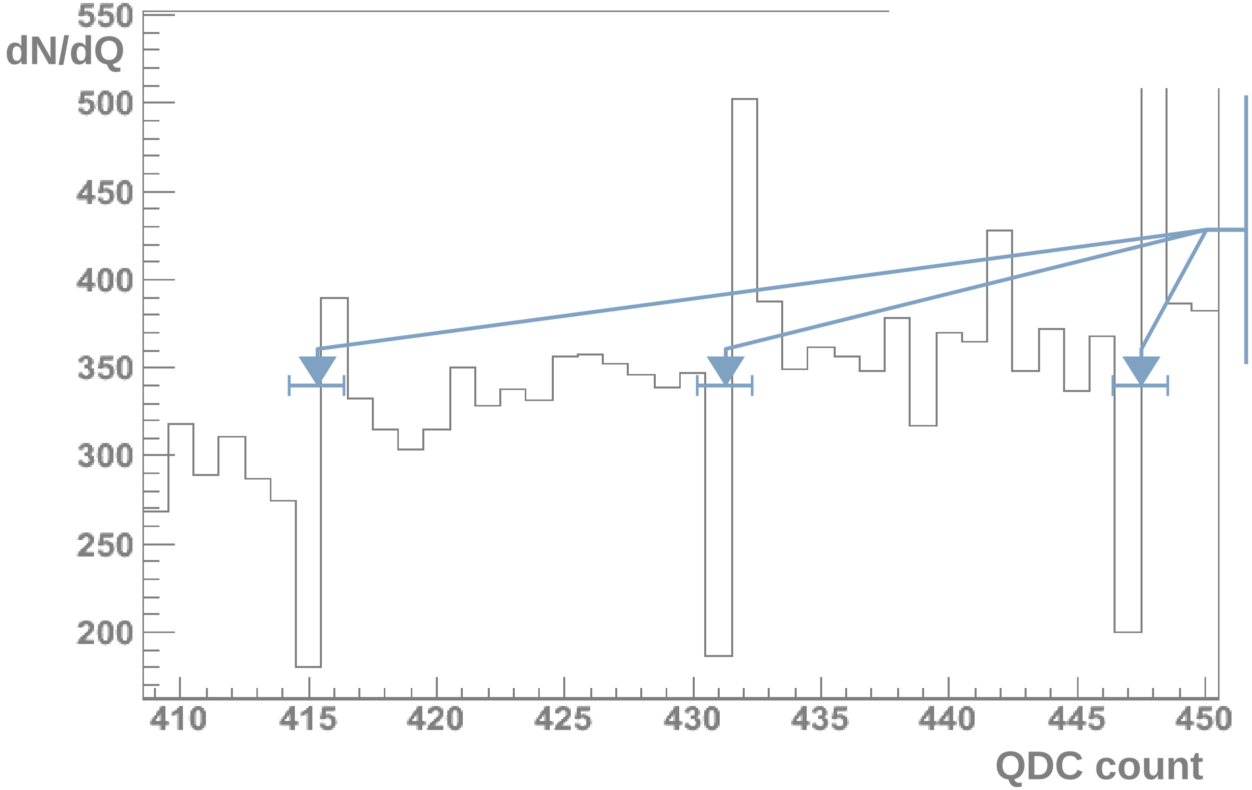
Can you see the effect?

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..β0 in respect of 0x..αf
where β = α + 1

Homework

- Which is the simplest way to fix this problem in the data?
  - At which cost?
- Can you understand the module name?
  - Module: 4c6543726f79204c31313832



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Outline

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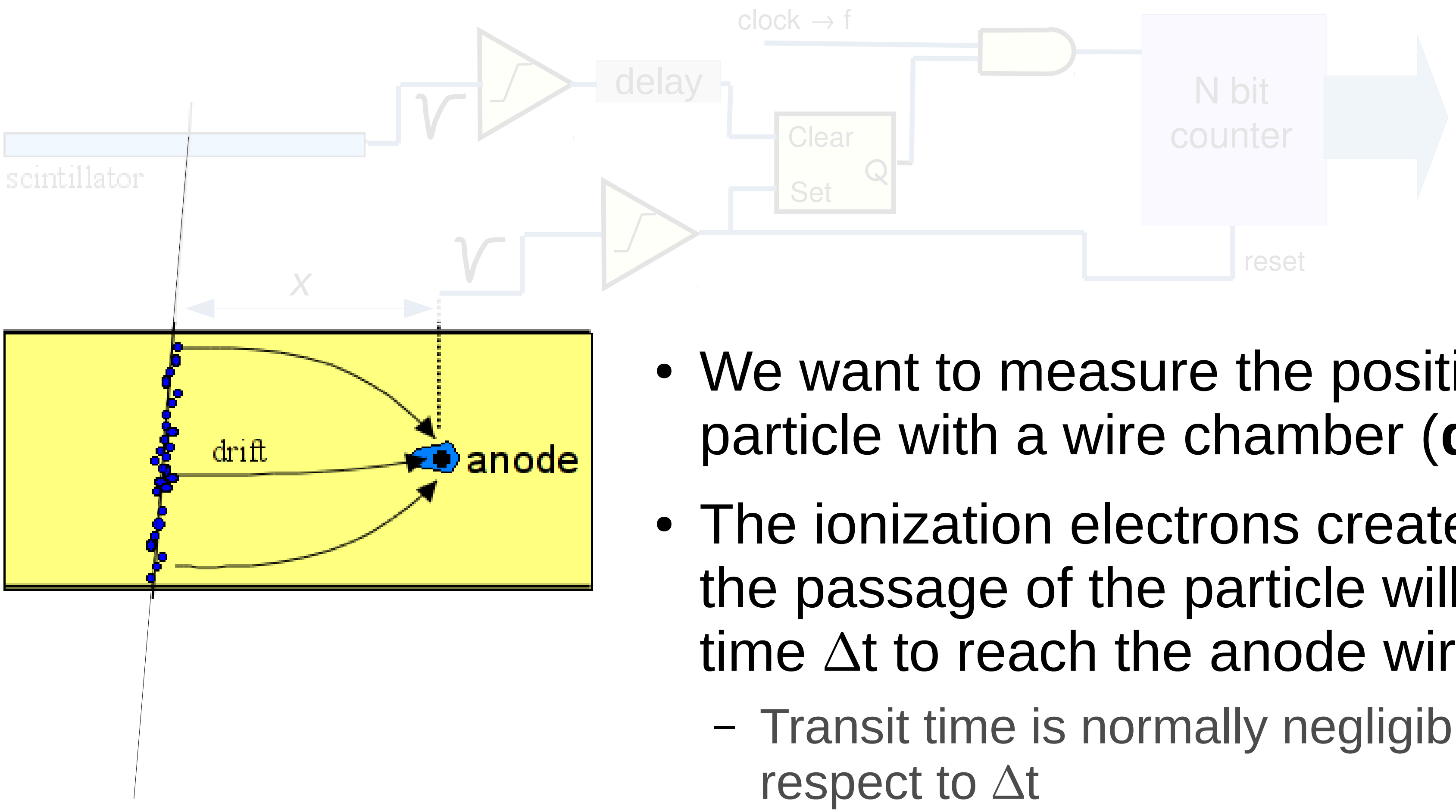
  - QDC in real life
- Measure position
  - Wire chamber setup
  - Time-to-Digital conversion
  - TDC in real life
- Corollary

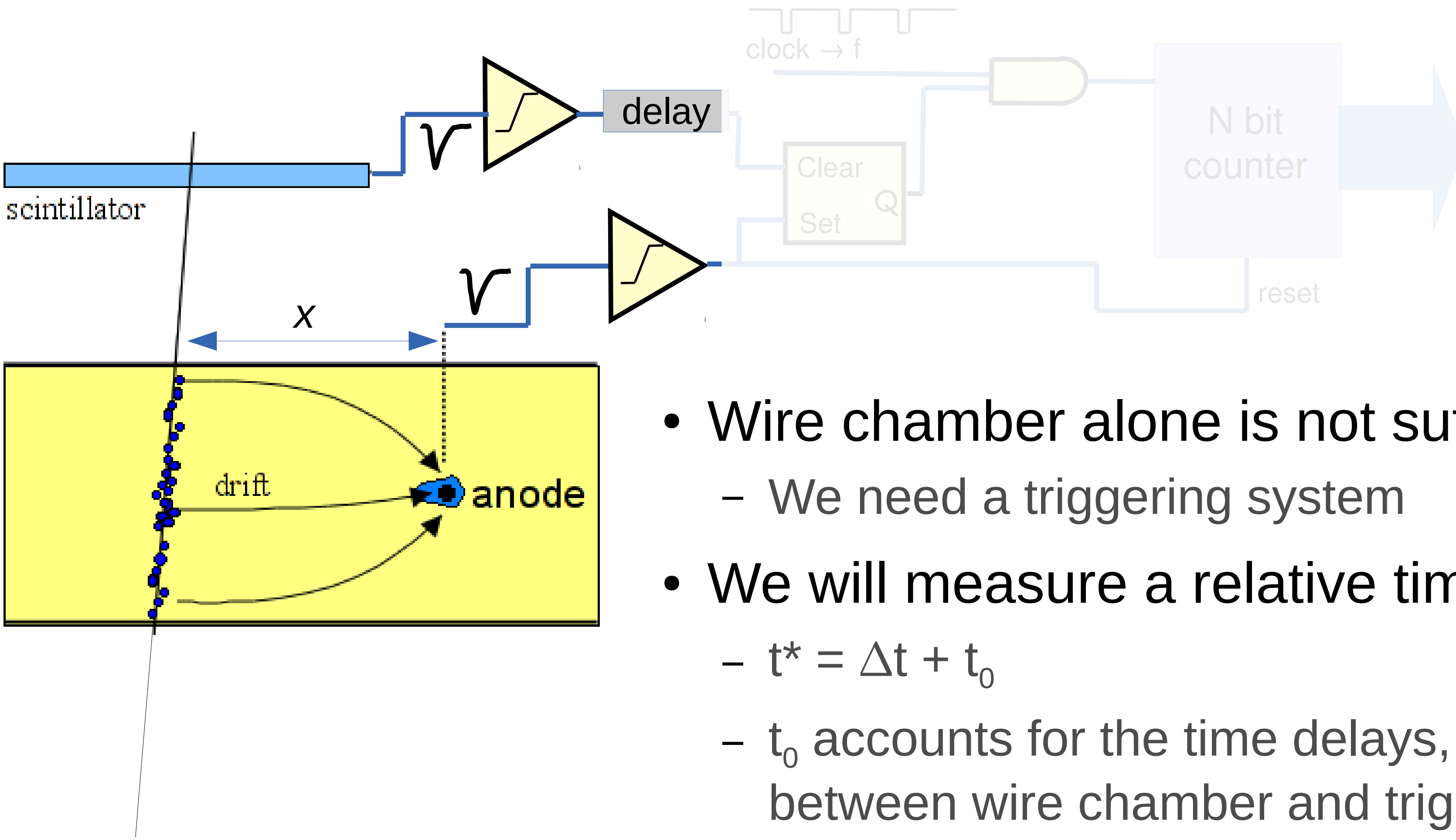
Position measurement



- 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:

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

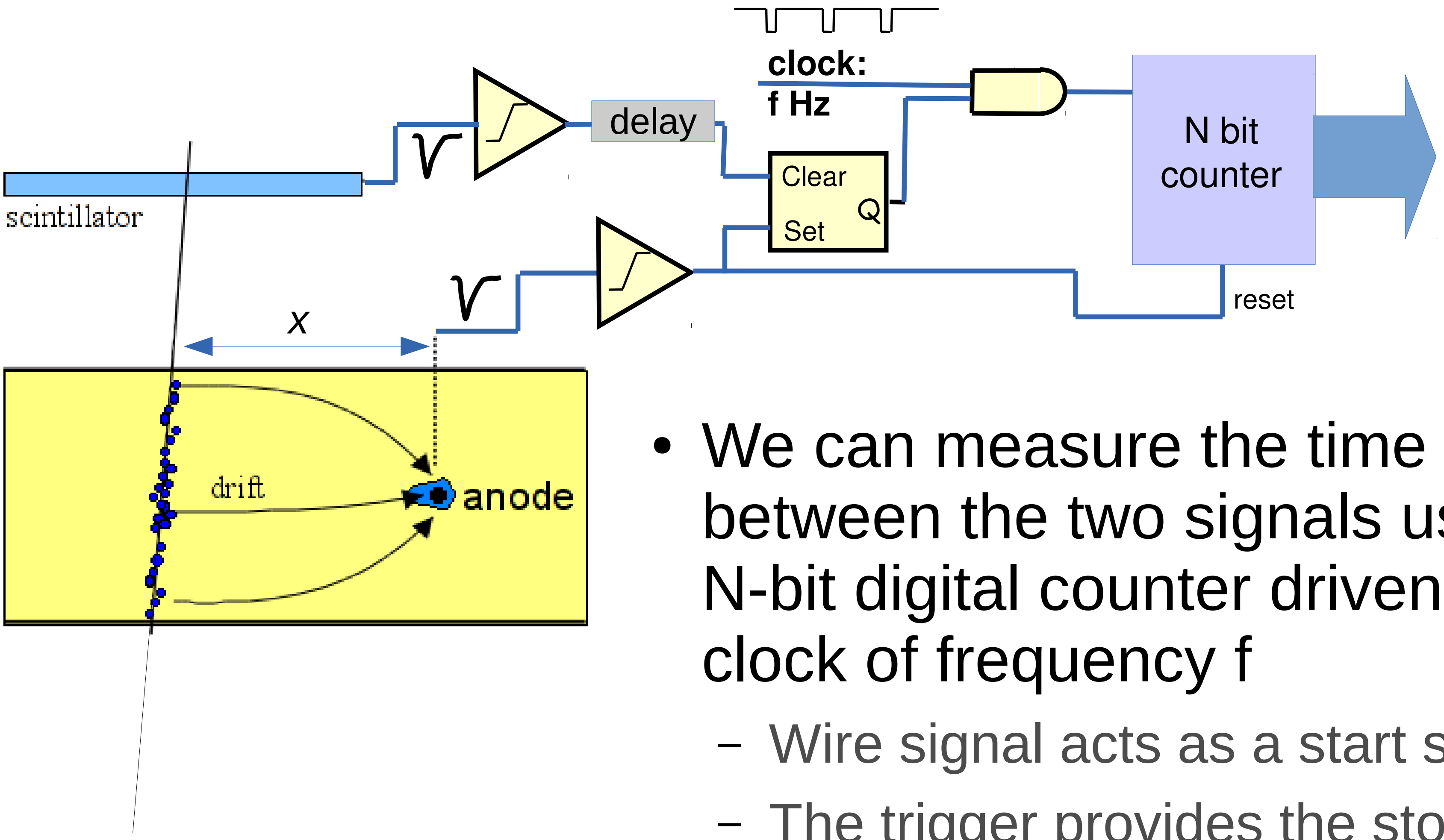
Triggering



- 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

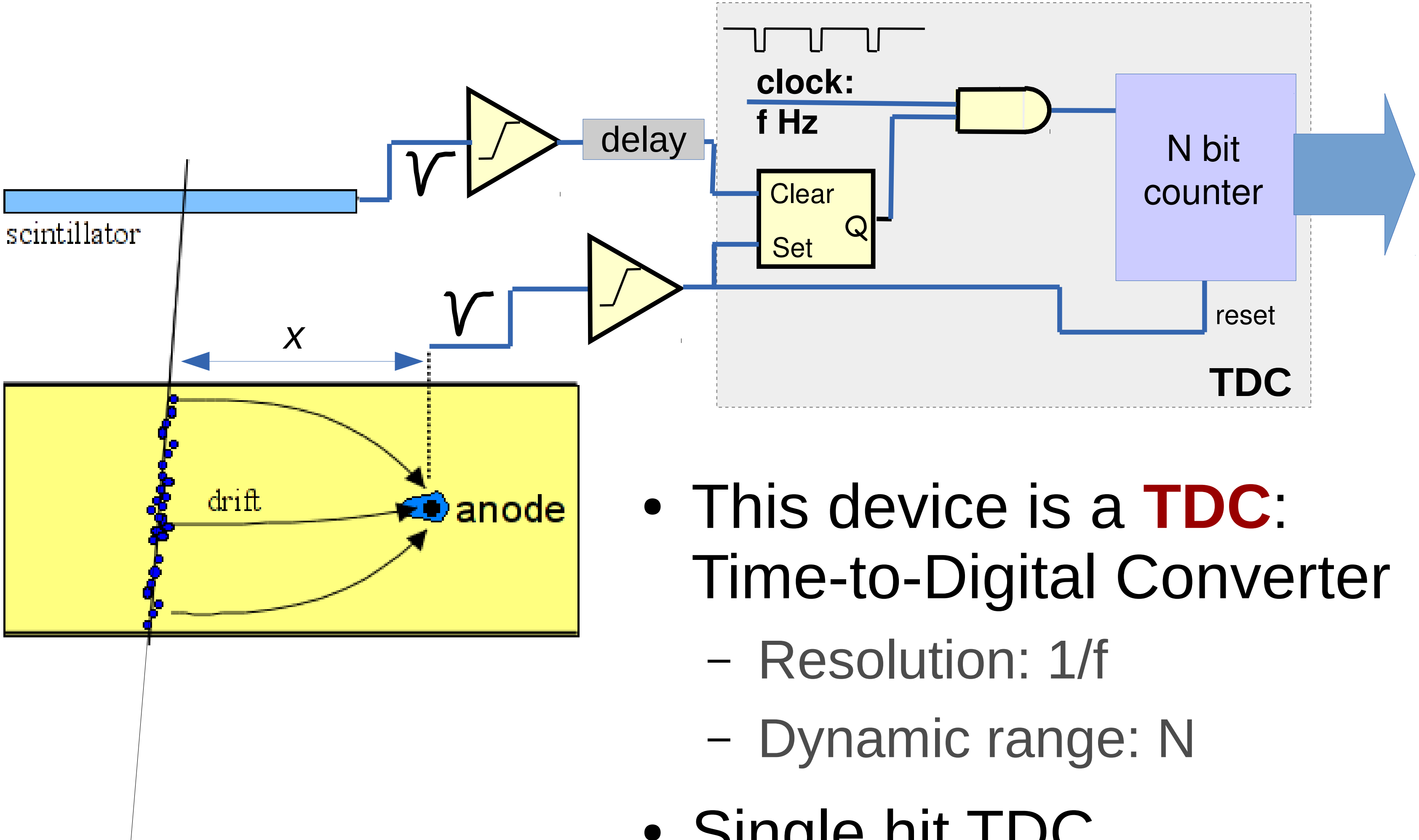
$$x = \alpha t^* + \beta$$

Time measurement

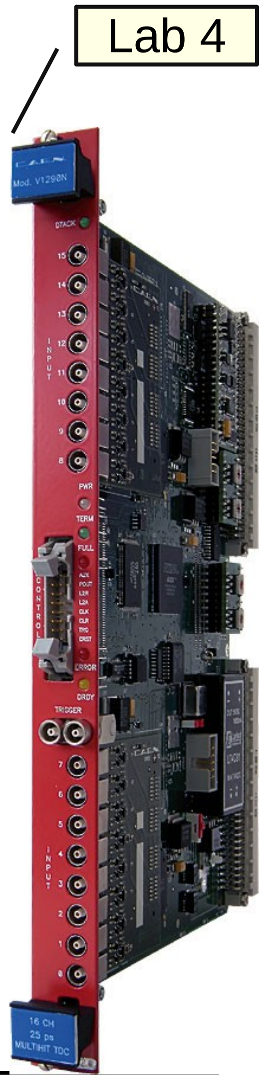


- We can measure the time offset between the two signals using a N-bit digital counter driven by a clock of frequency f
  - Wire signal acts as a start signal
  - The trigger provides the stop signal

Time measurement: TDC

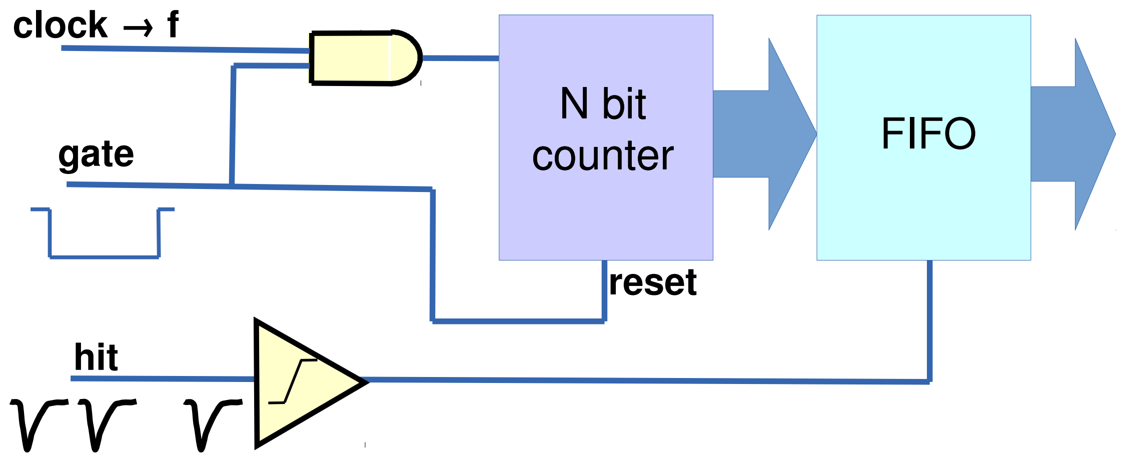


- This device is a **TDC**: Time-to-Digital Converter
  - Resolution: 1/f
  - Dynamic range: N
- Single hit TDC
  - if a noise spike comes just before the signal, the measure is lost



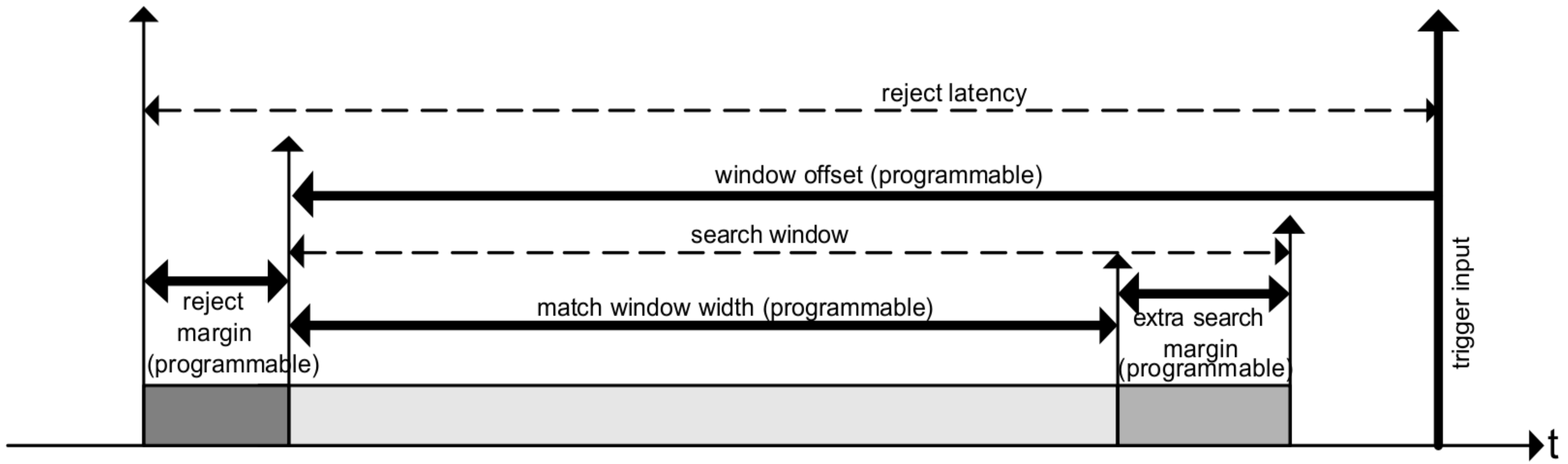
Multi-hit TDC

- 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



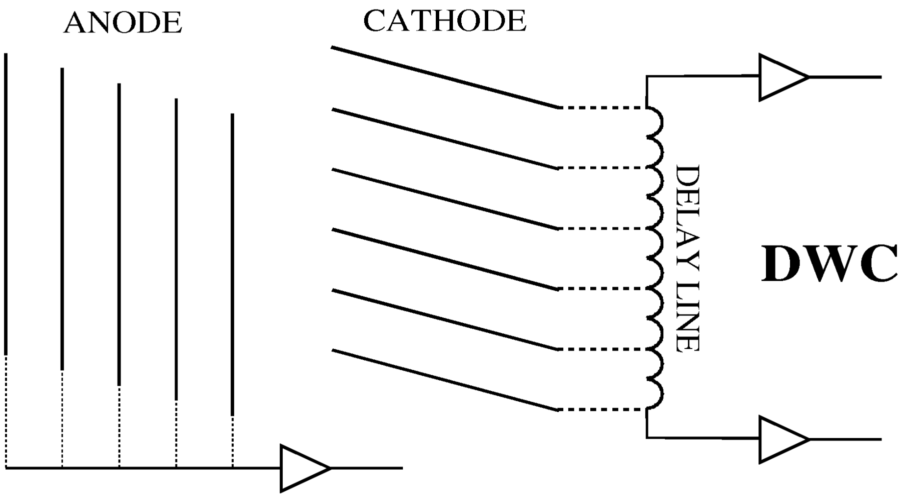
Actual TDCs

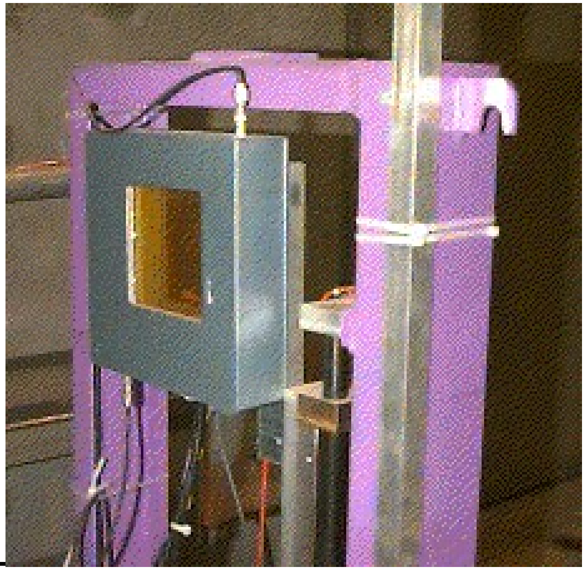
- Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching
  - Internal programmable delays
  - Internal generation of programmable gates
  - Programmable rejection frames
  - Usually via a dedicated C library/API



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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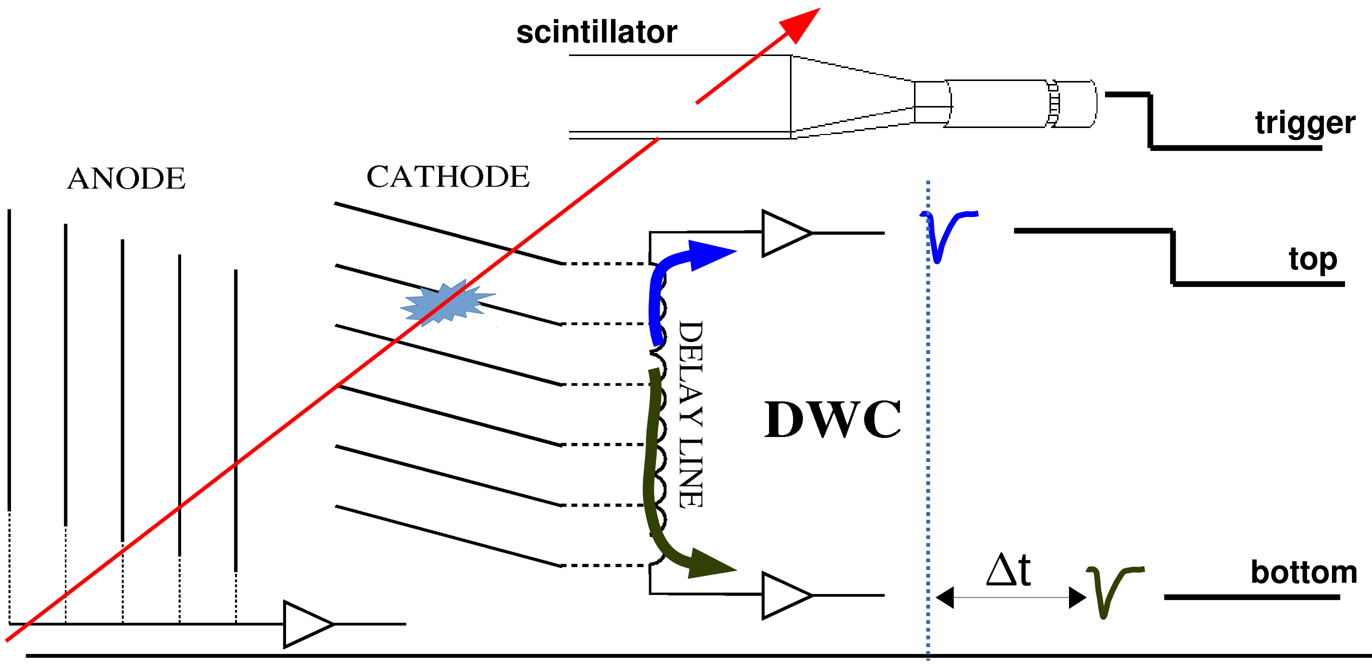
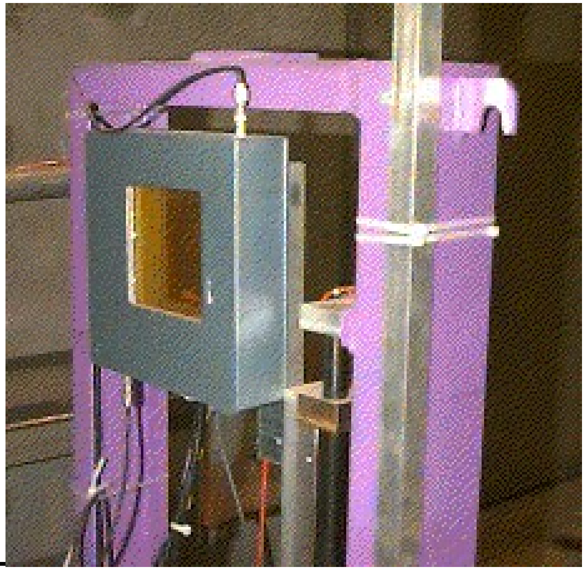
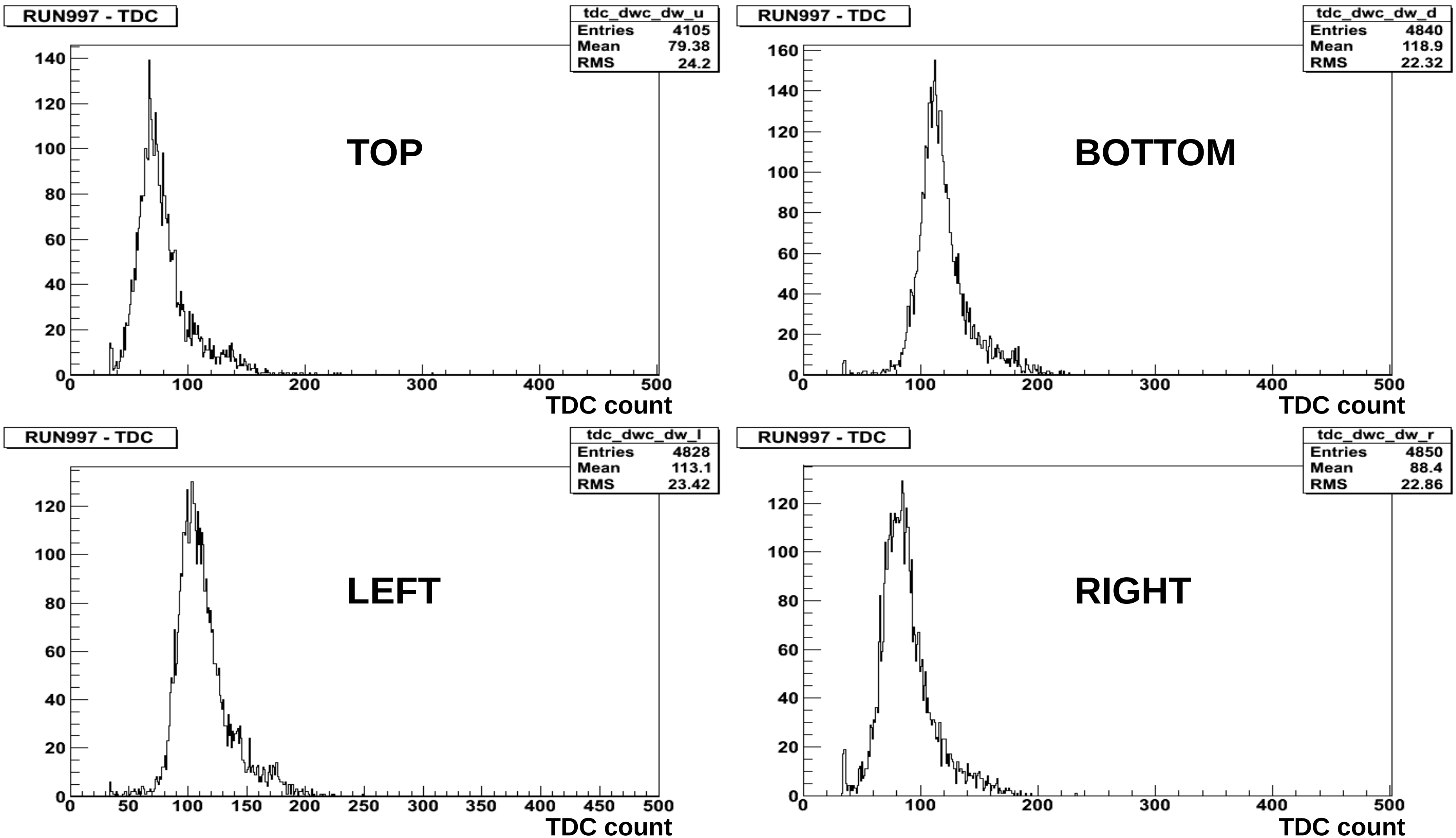




Raw time data

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



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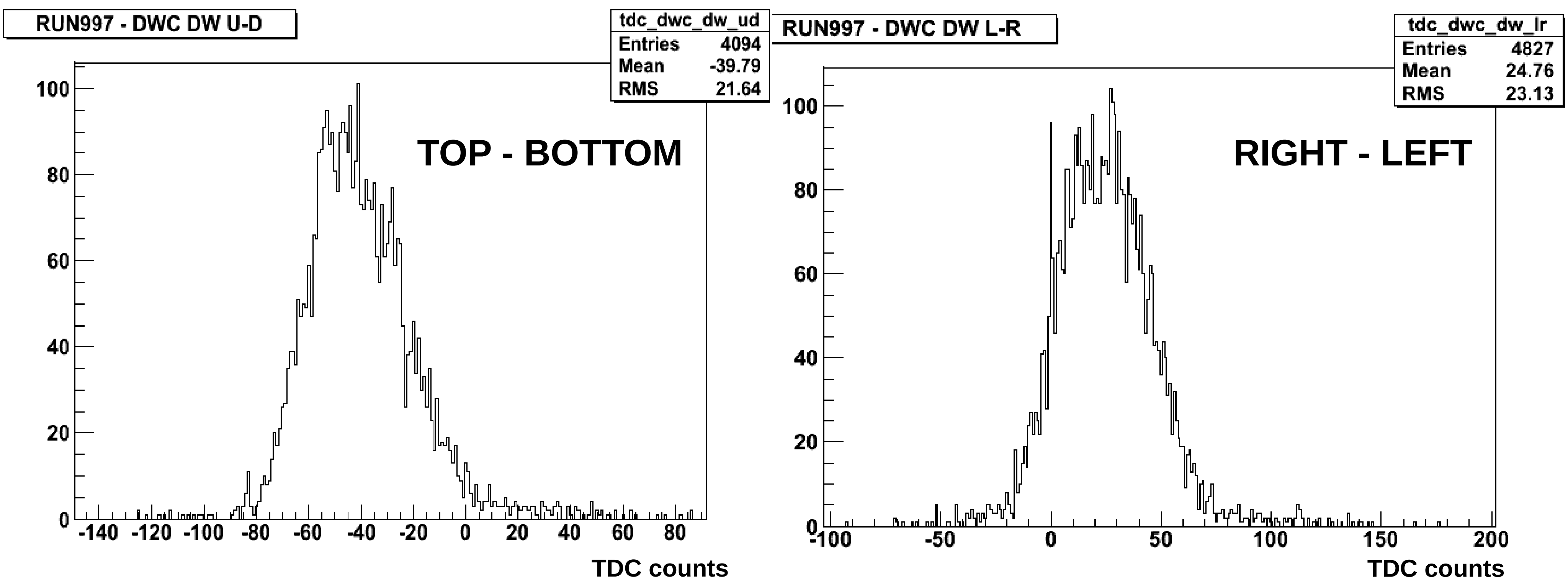
Un-calibrated beam profile

- 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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- Corollary: calibration

Calibration

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- Both experiments provide relative measurements
  - Values obtained via our systems are in some (known) relation with the interesting quantities
    - Scintillator $Q \propto N_\gamma \propto E$
    - MDWC $y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$
- 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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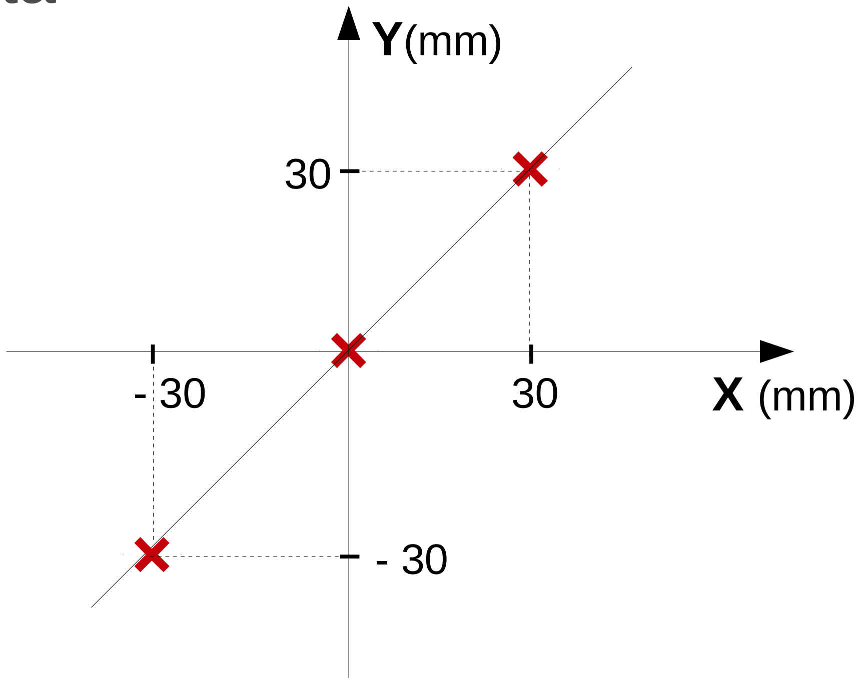
Back to XDWC: calibration

- 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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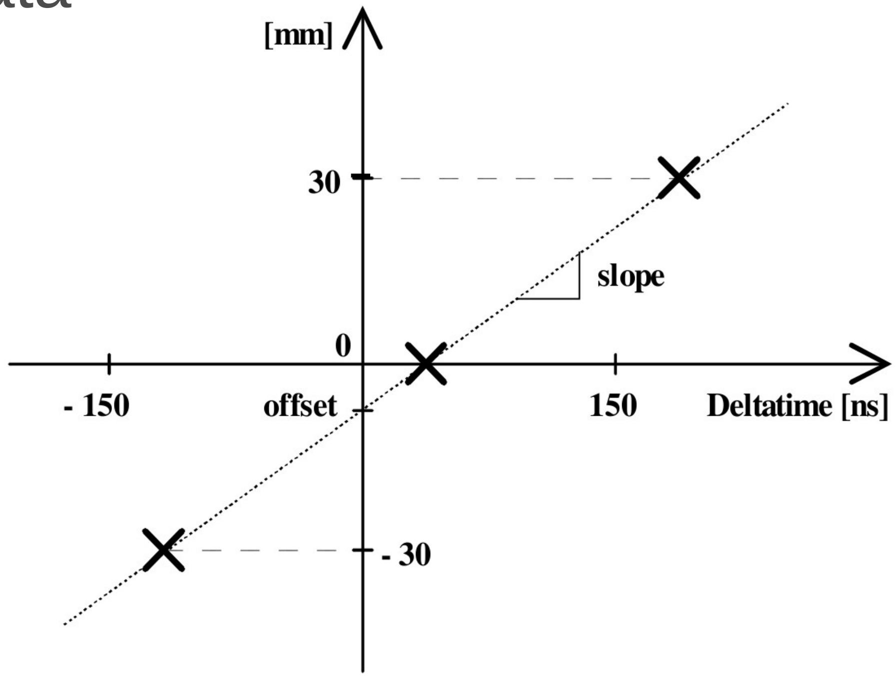

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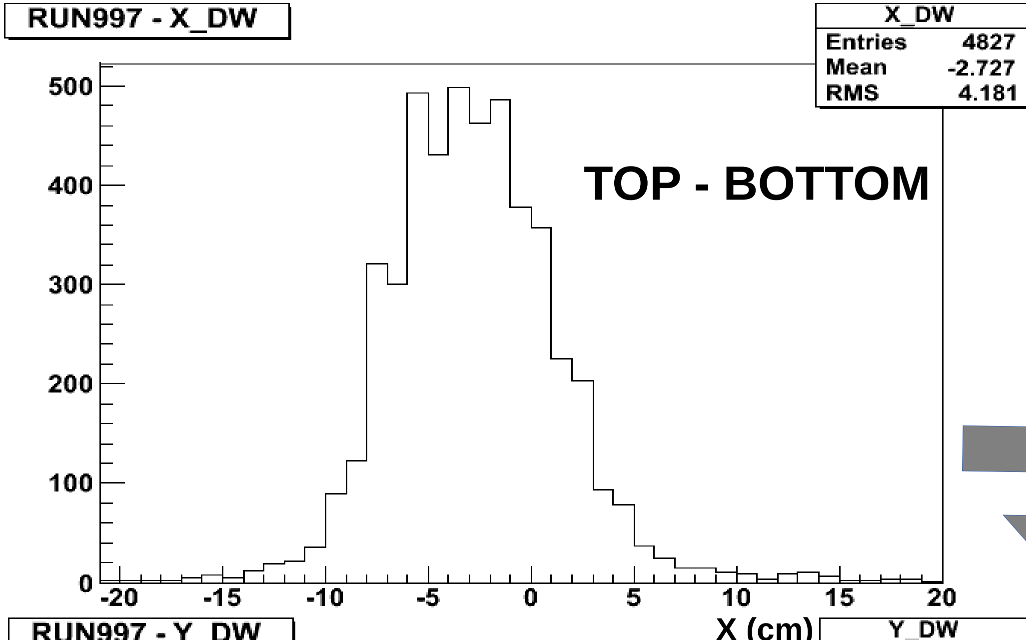
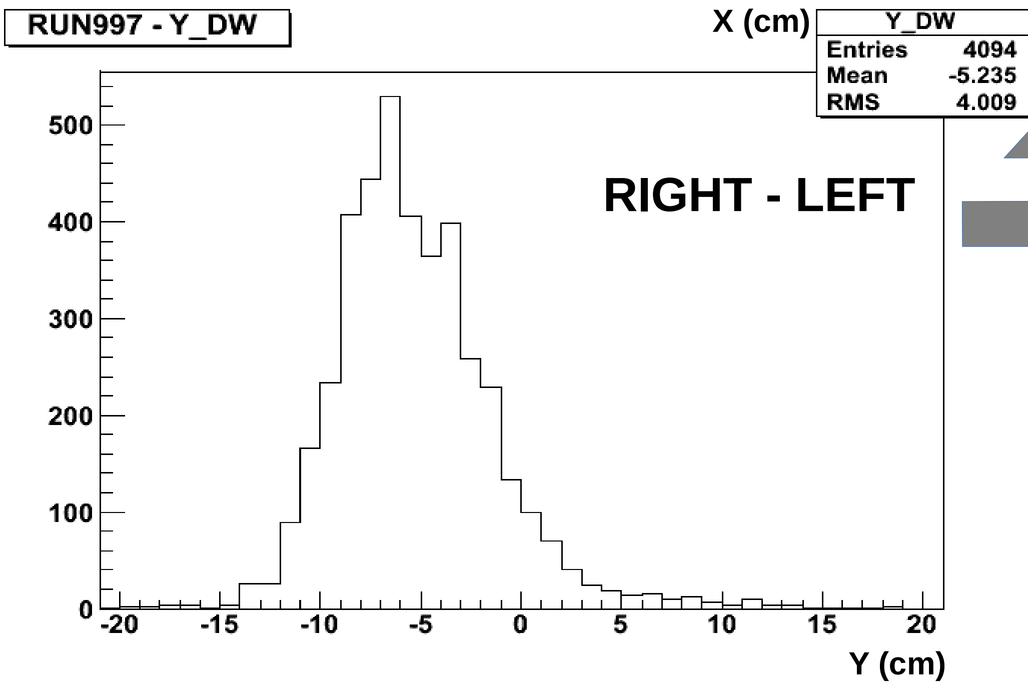
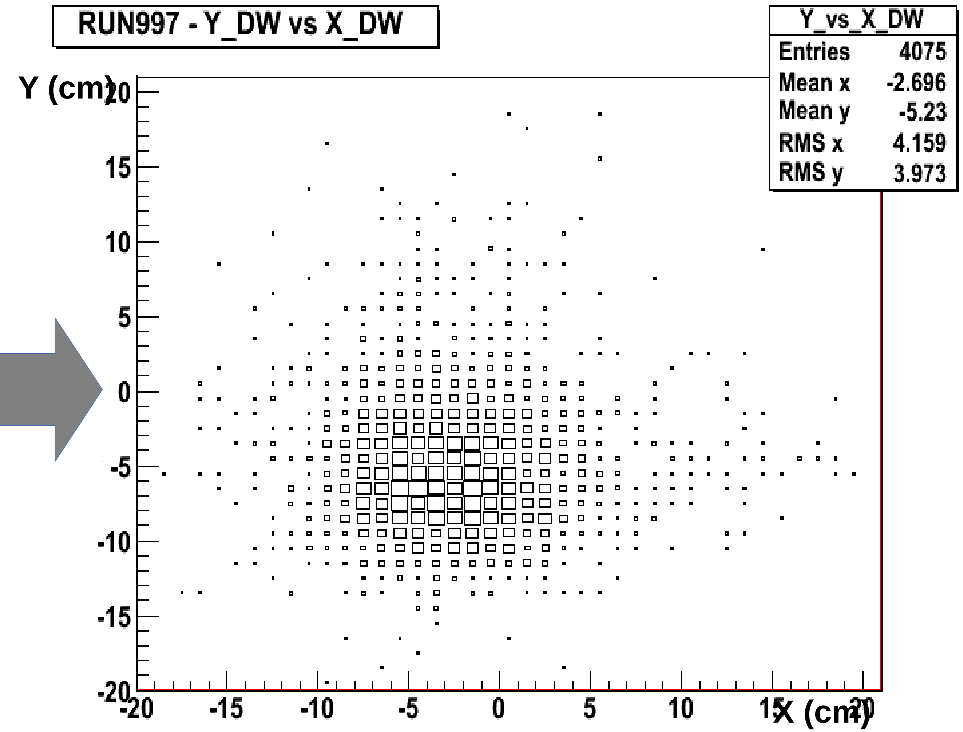
Calibrated XDWC



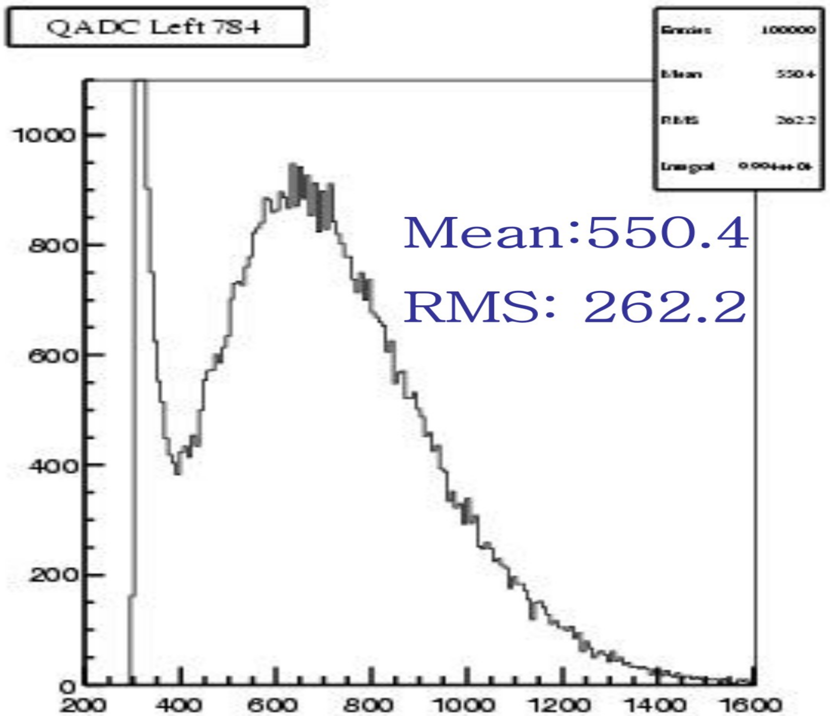


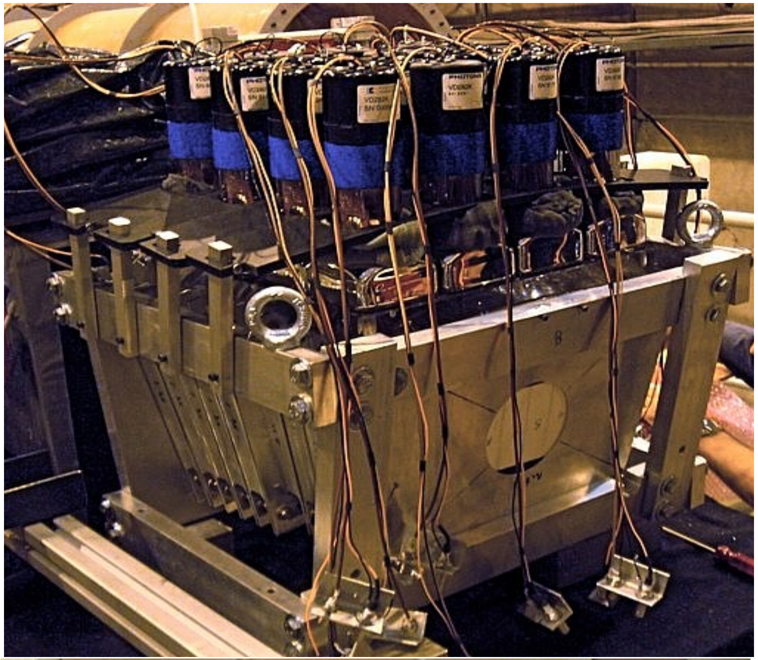
Beam profile

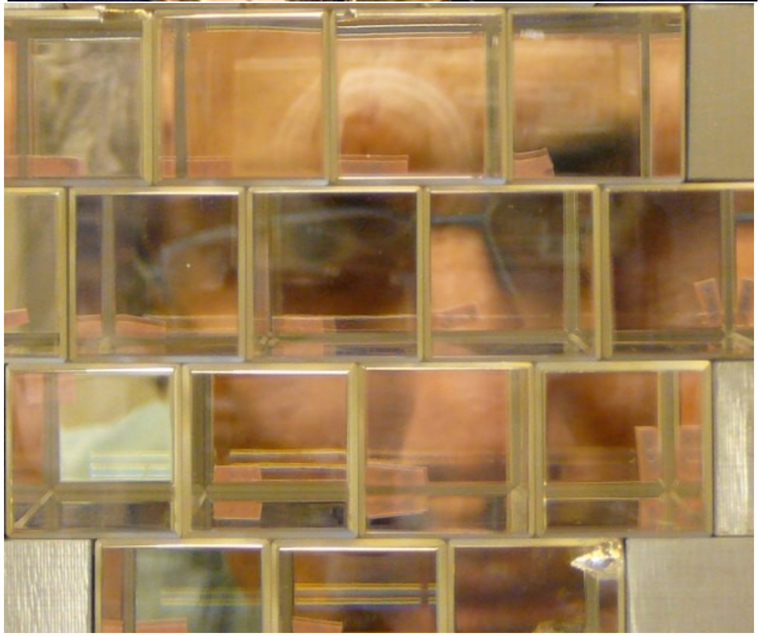


R&D calorimetry calibration

- It is more complicated
  - The beam energy is known
  - But MC is needed to take in account geometry, acceptance, beam profile, etc







E.g.: Crystal for isotope id

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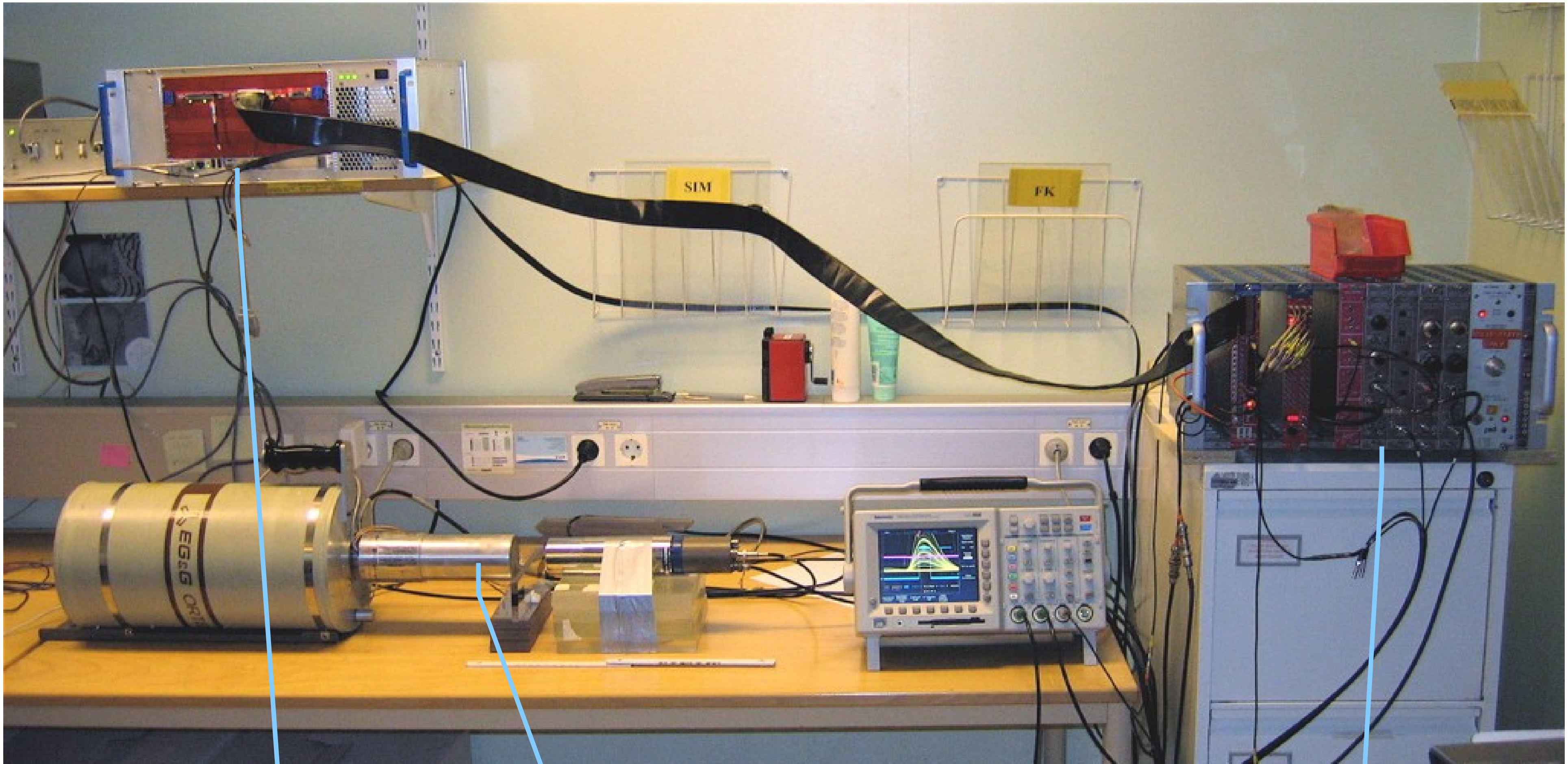


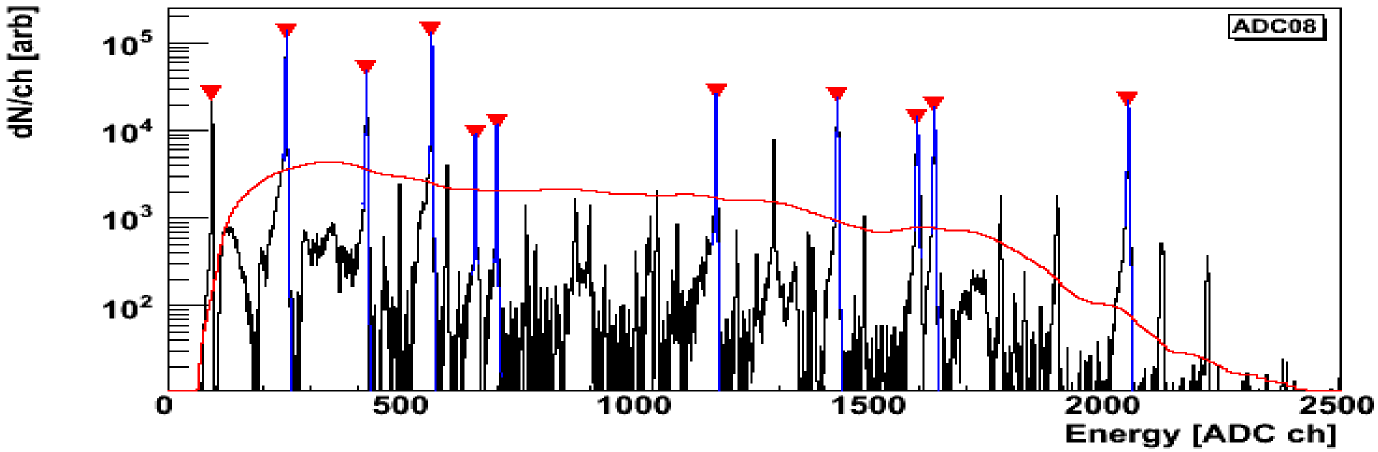
by Sergio Ballestrero

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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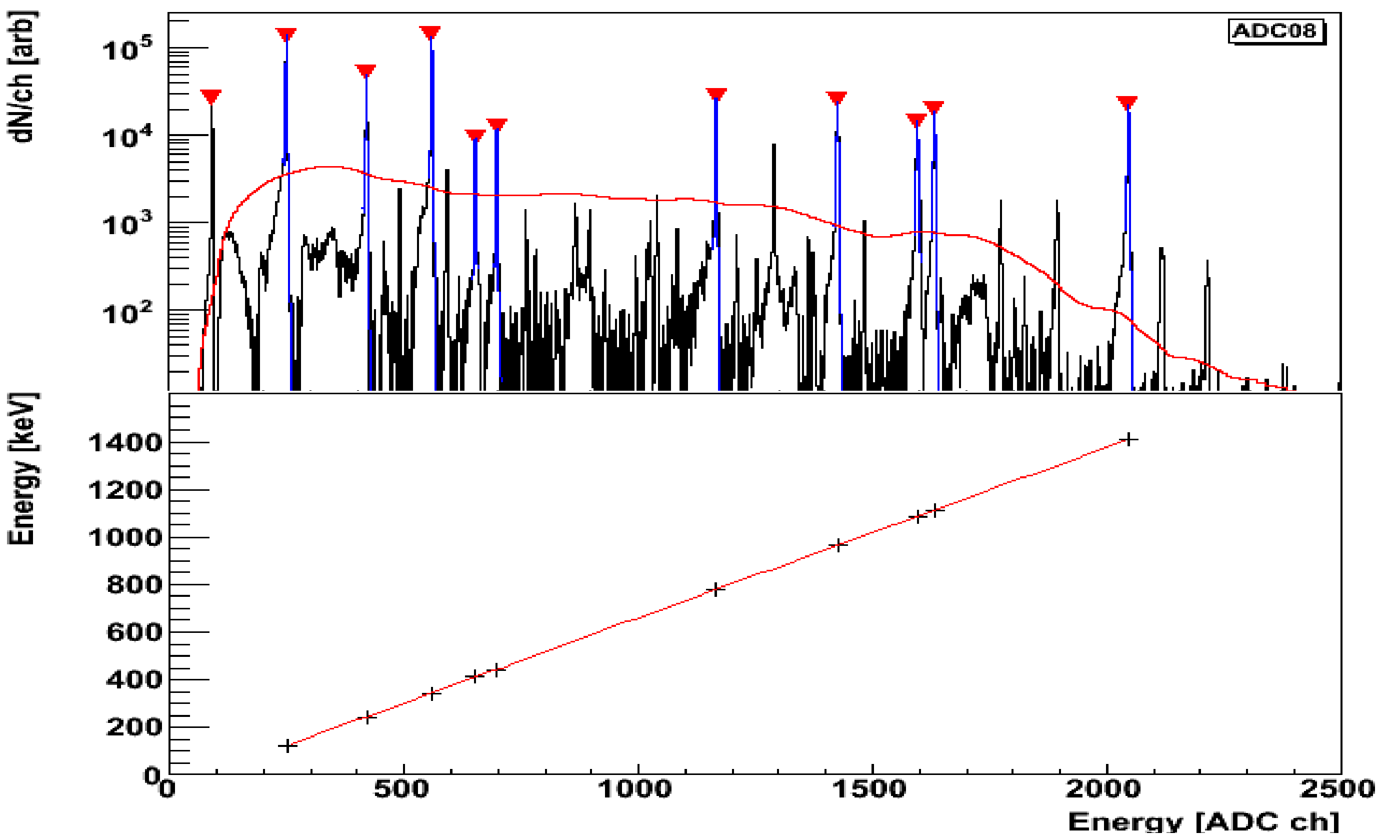
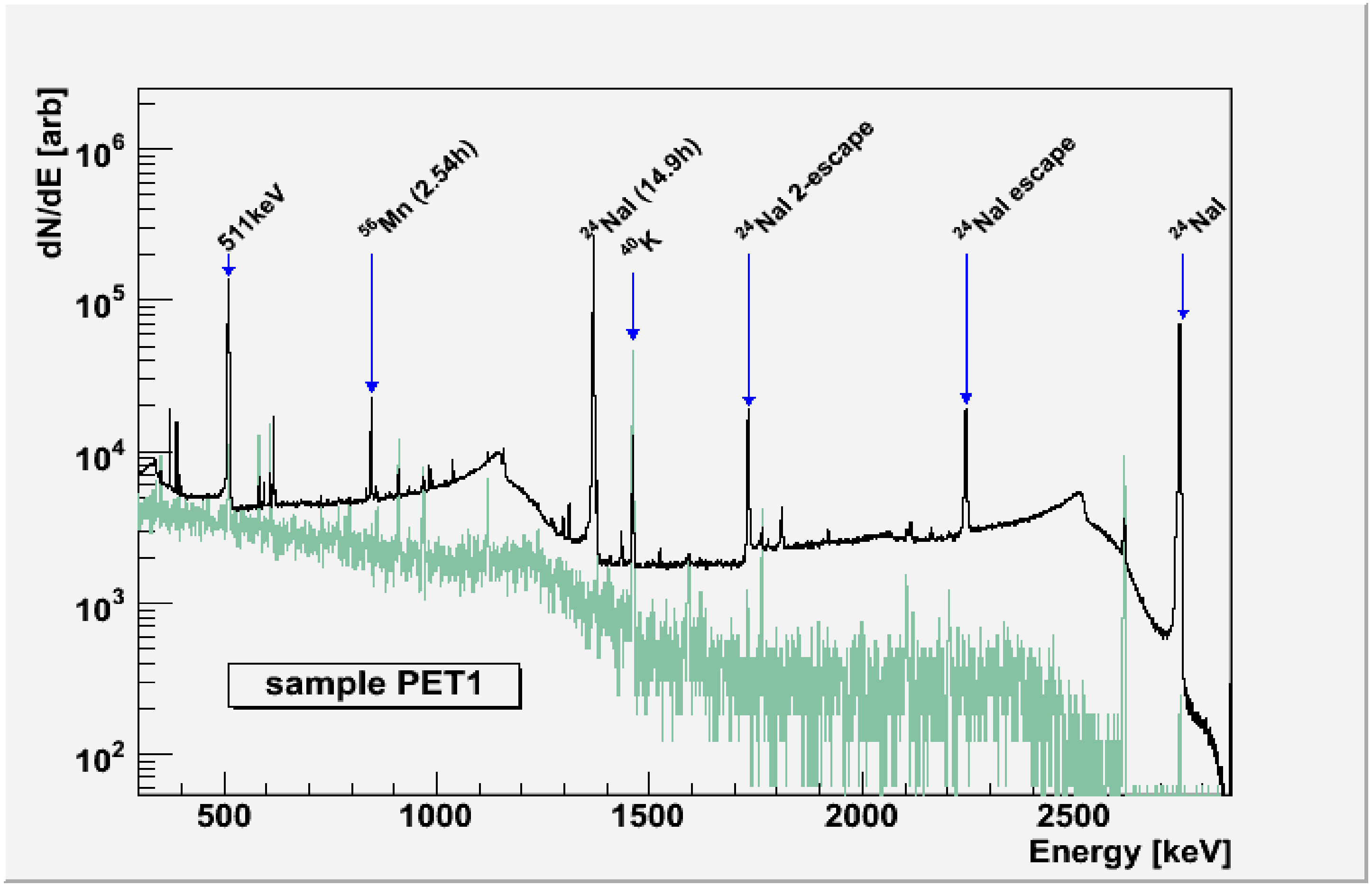


Isotope identification

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



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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