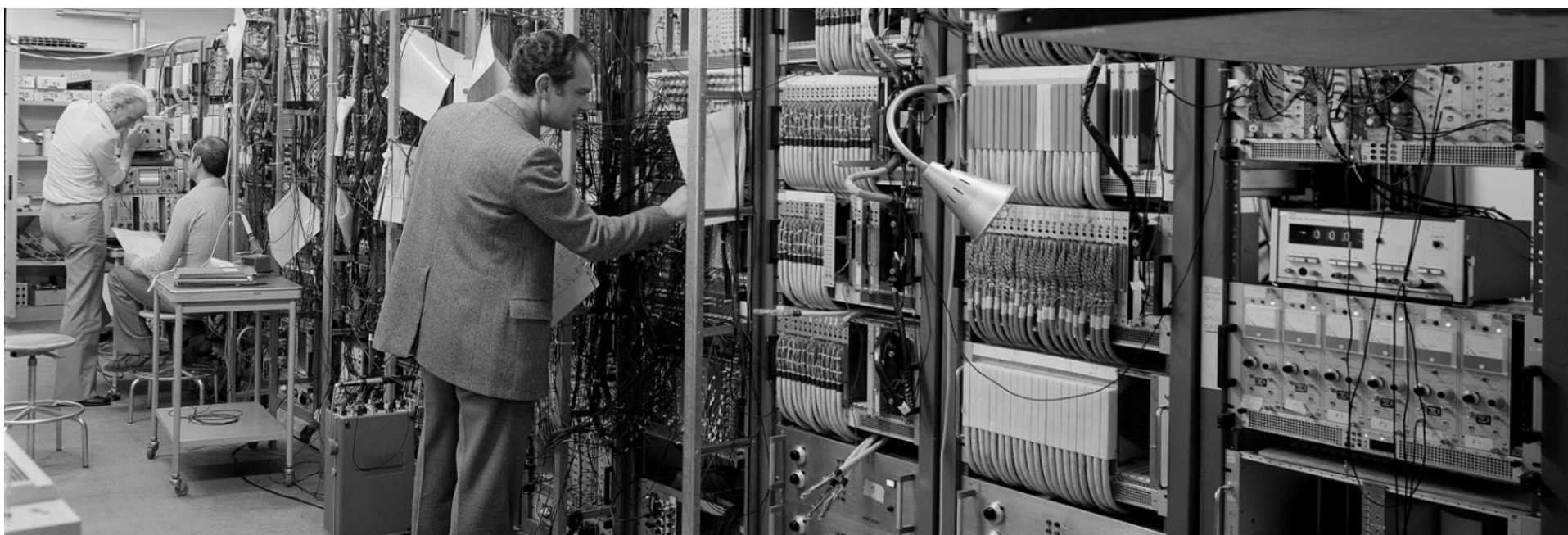# DAQ HW
Hands-on Approach

ISOTDAQ 2016: 7th International School of Trigger and Data Acquisition

Rehovot, 25 Jan 2016
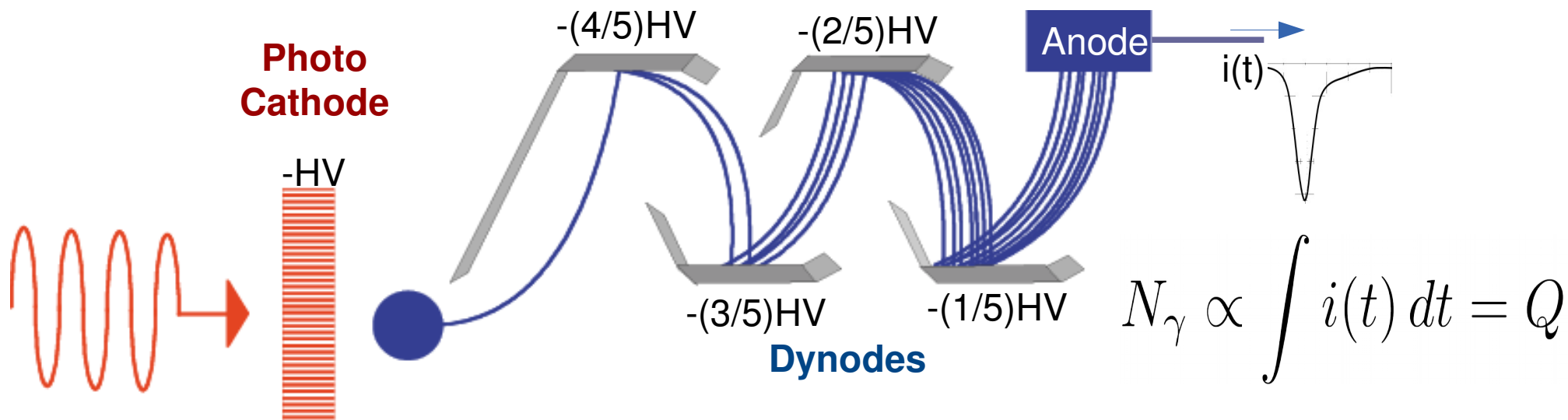
Andrea.Negri@pv.infn.it

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
    - © 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

1st experiment
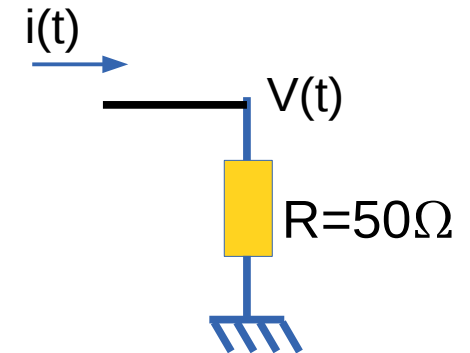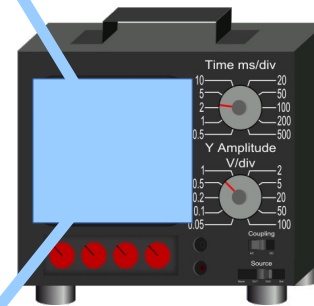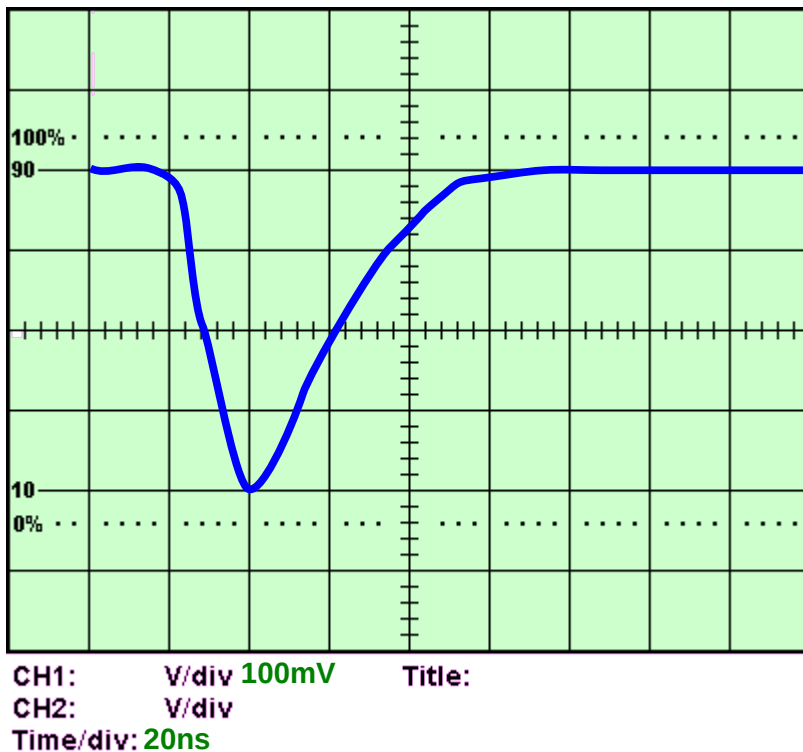NEXT EXIT

Energy measurement

$$E \propto N_\gamma$$
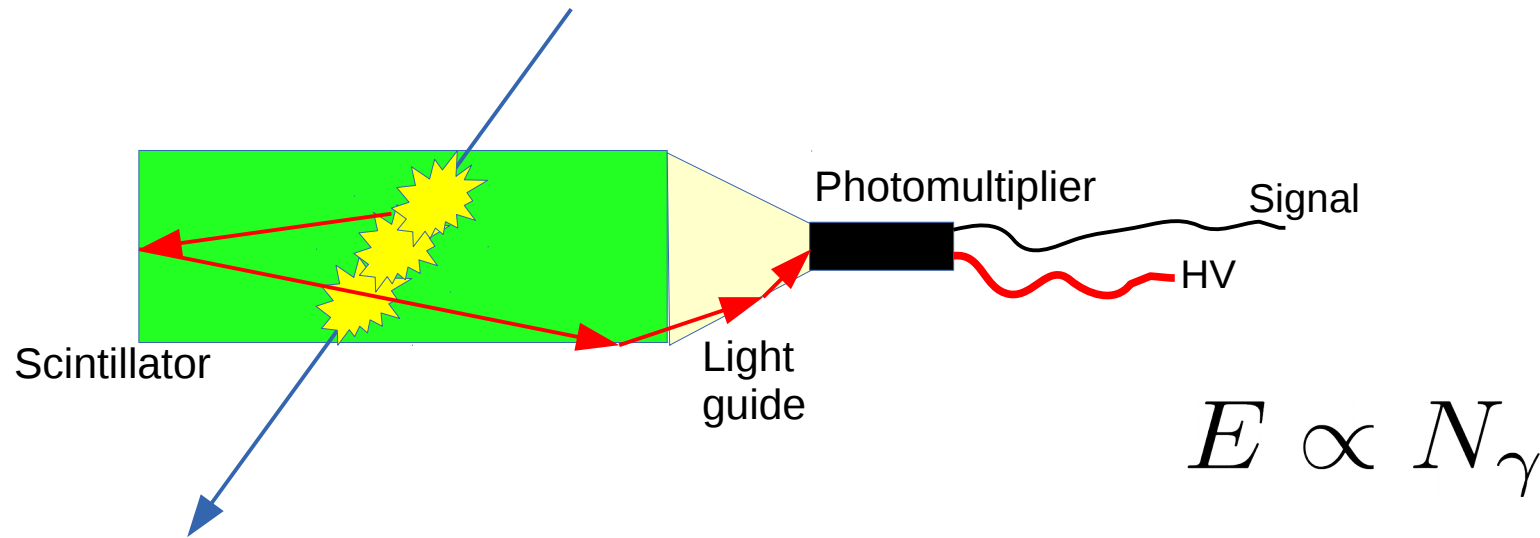
- Measure energy deposited by a particle traversing a medium
- The medium (detector) is a **scintillator**
  - Molecules, excited by the passing particle, relax emitting light
  - The amount of light is <u>proportional</u> to the deposited energy
- The light is then
  - collected, using dedicated optical means (**light guide)**
  - fed into a photo-detector: **photomultiplier**

Photomultiplier

Photo Cathode

-(4/5)HV   -(2/5)HV   Anode

i(t)

-HV

-(3/5)HV   -(1/5)HV

Dynodes

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

- **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
  - typical overall gain ≈10^6

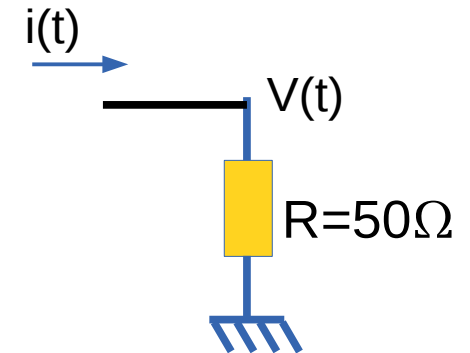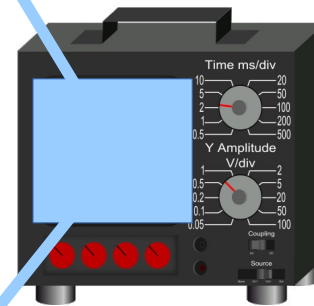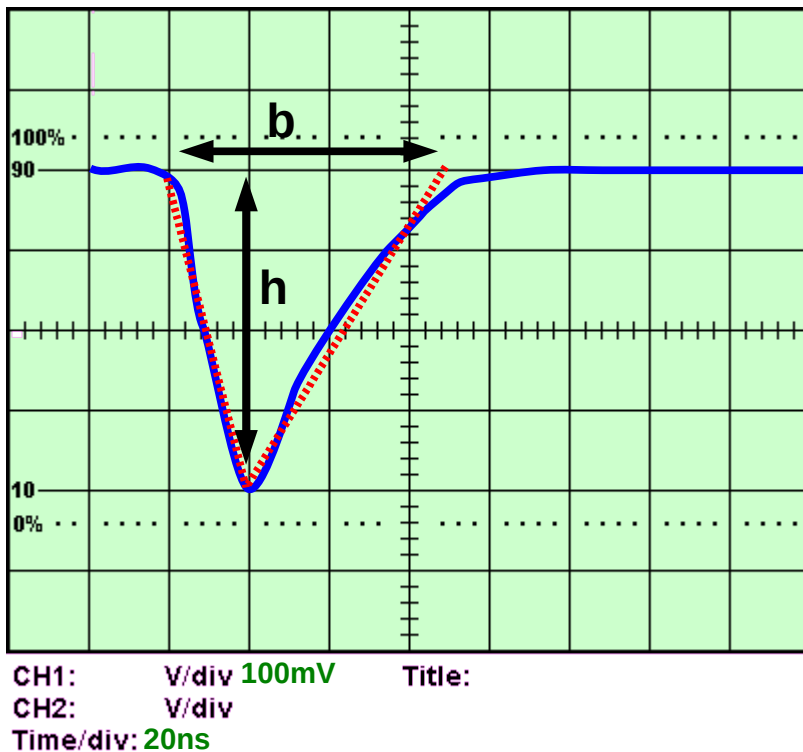- **Dark current**: noise
  - current flowing in PMT without light

Start the measure

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

CH1: V/div 100mV   Title:
CH2: V/div
Time/div: 20ns

i(t)

V(t)

R=50Ω

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

Good old oscilloscope

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

CH1:   V/div **100mV**   Title:
CH2:   V/div
Time/div: **20ns**

i(t)

V(t)

R=50Ω

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

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

Good old oscilloscope

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

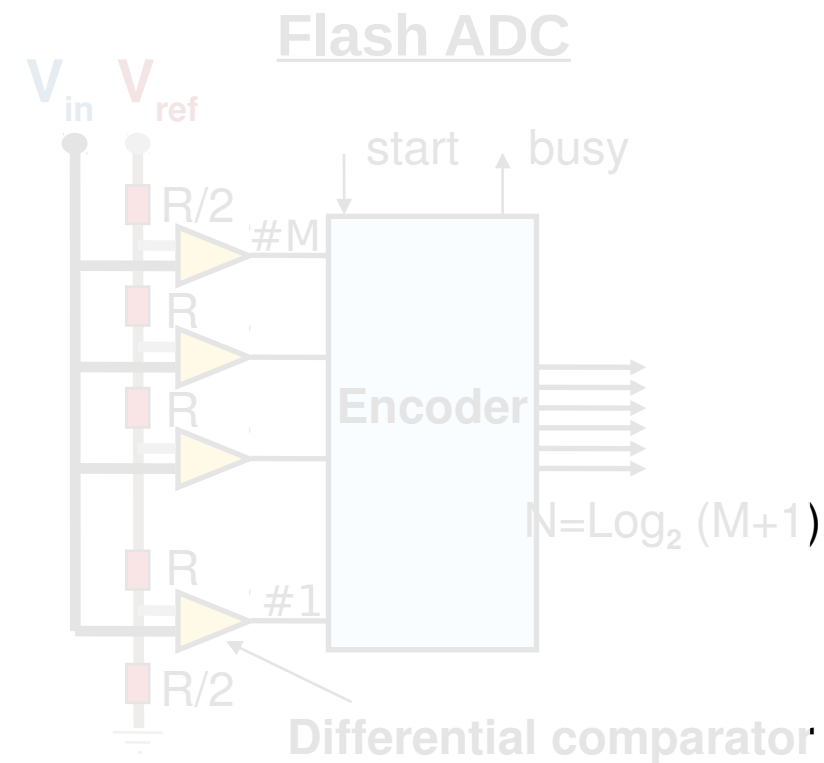CH1:   V/div 100mV   Title:
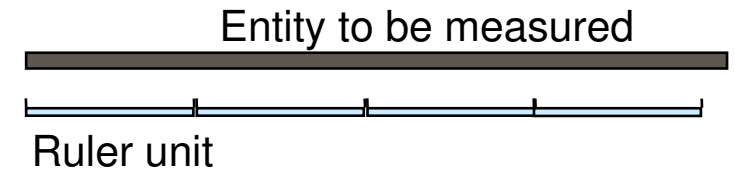CH2:   V/div
Time/div: 20ns

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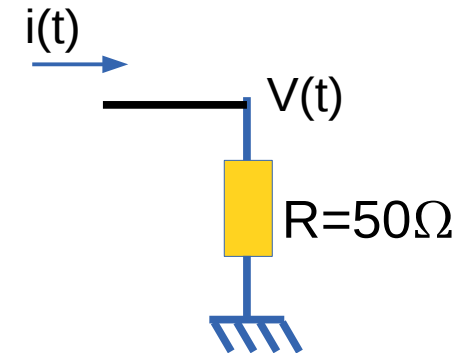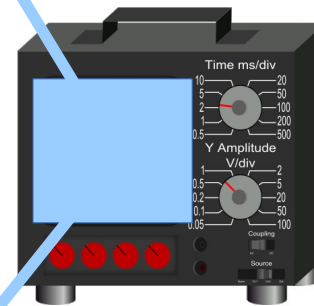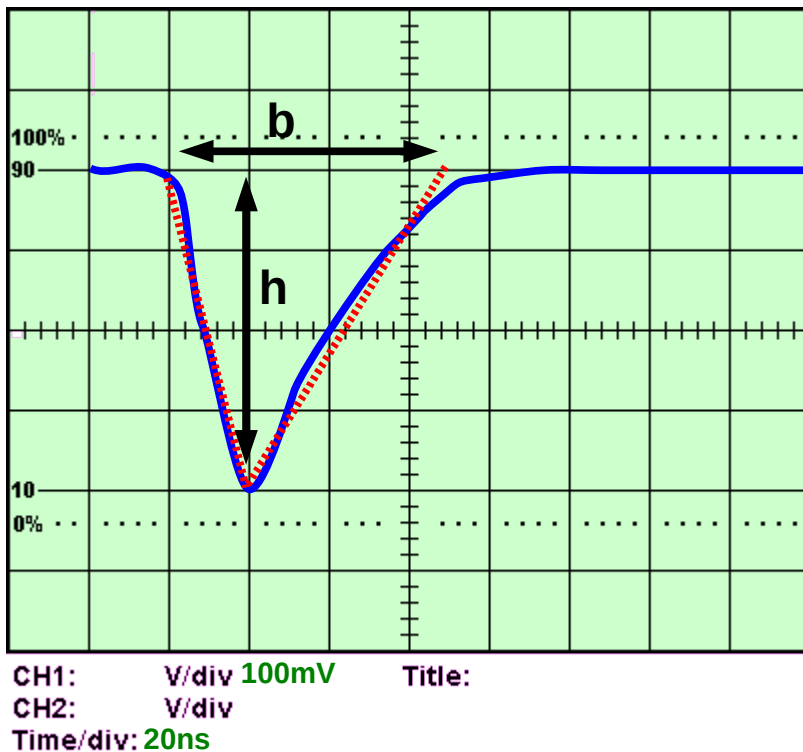
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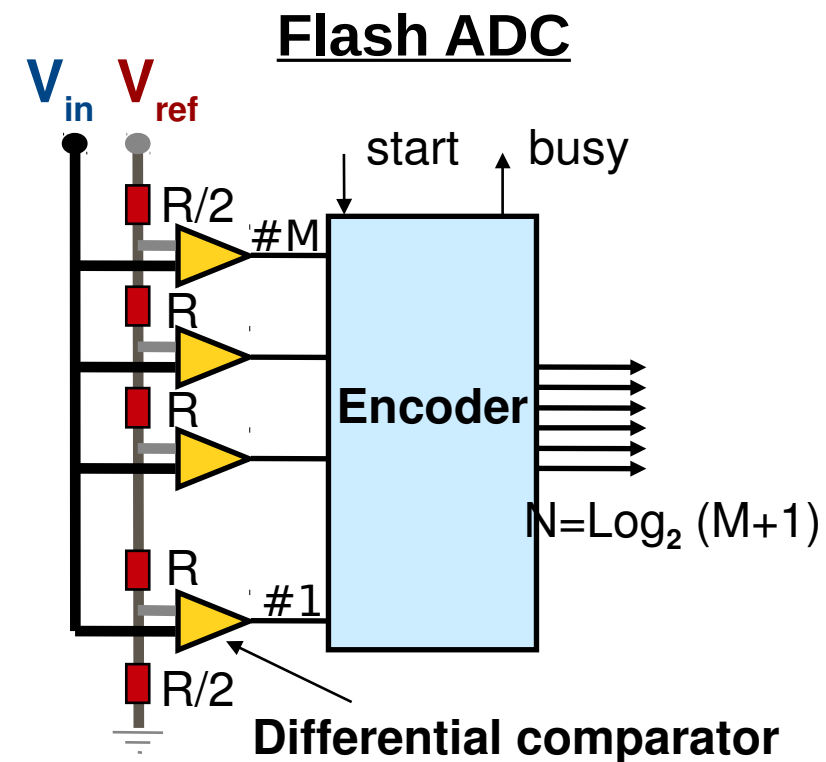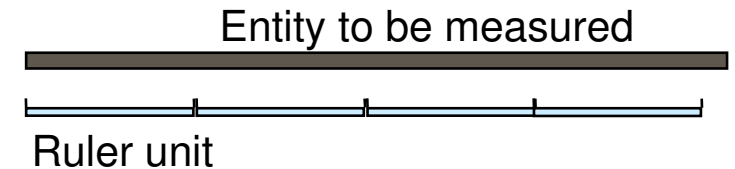
Good old oscilloscope

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

- Easy, but
  - Deadtime 5 min, ~3×10^{-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?
  - It could save the data in some digital format and fill a histogram on-line. Wouldn't be cool?

- 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 — Stefan' talk and lab 8

  - Encoding an analog value into a binary representation

  - By comparing entity with a ruler

  Entity to be measured

  Ruler unit

- 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

    - $N = Log_2 (M+1)$

Flash ADC

V_{in} V_{ref}

start   busy

R/2

#M

R

R

Encoder

$N = Log_2 (M+1)$

R

#1

R/2

Differential comparator
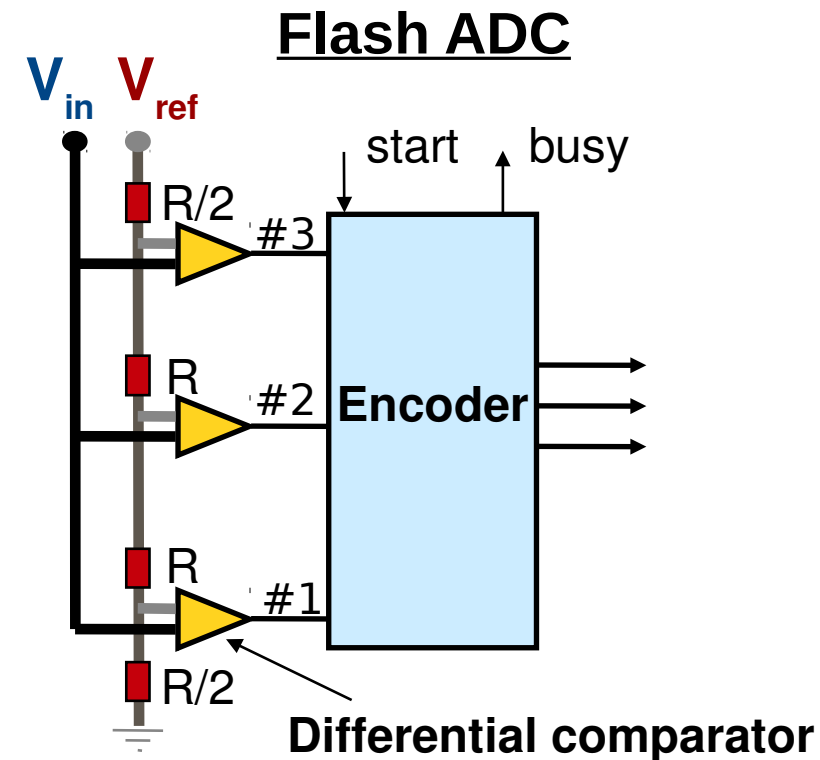
Analog to Digital Conversion

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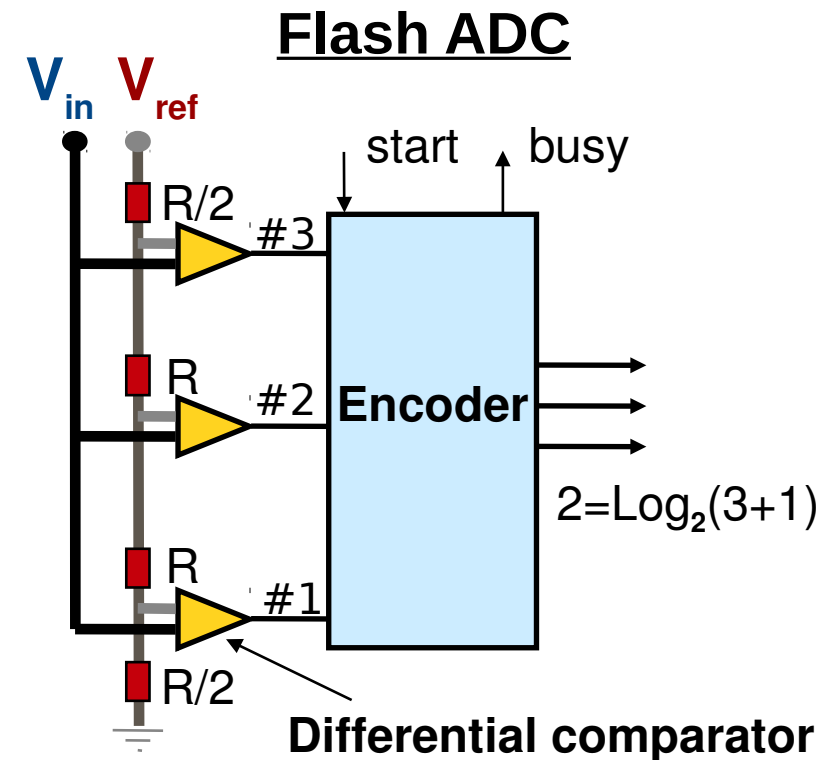
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Ruler unit

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R

R

Encoder

$N = Log_2 (M+1)$

R
#1

R/2

Differential comparator

Analog to Digital Conversion

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

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 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
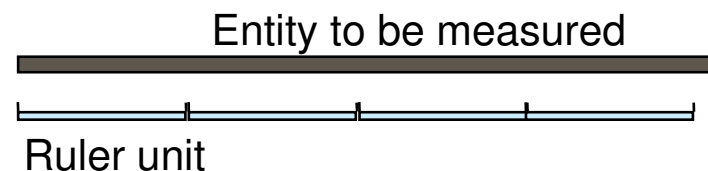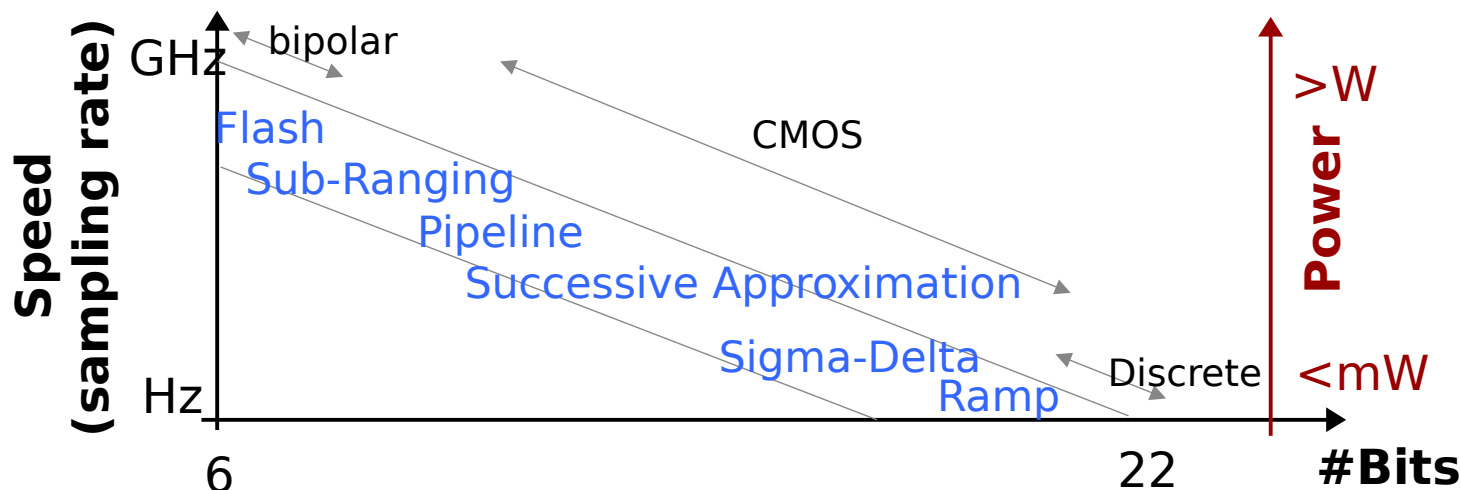   - $N = Log_2\,(M+1)$

Flash ADC

Differential comparator

Analog to Digital Conversion

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

$x = V_{in}/V_{ref}$	Comparison results	Encoded form
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- 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
    - $N = Log_2 (M+1)$

Flash ADC

$2 = Log_2(3+1)$

Differential comparator

ADC Characteristics

- ## Resolution (LSB), the ruler unit: V_{max}/N

  – e.g.: 1V and 8bit (N=256) → LSB = 3.9 mV

  Entity to be measured

  Ruler unit

- ## Quantization error: $\pm LSB/2$

  Lab 4

- ## 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
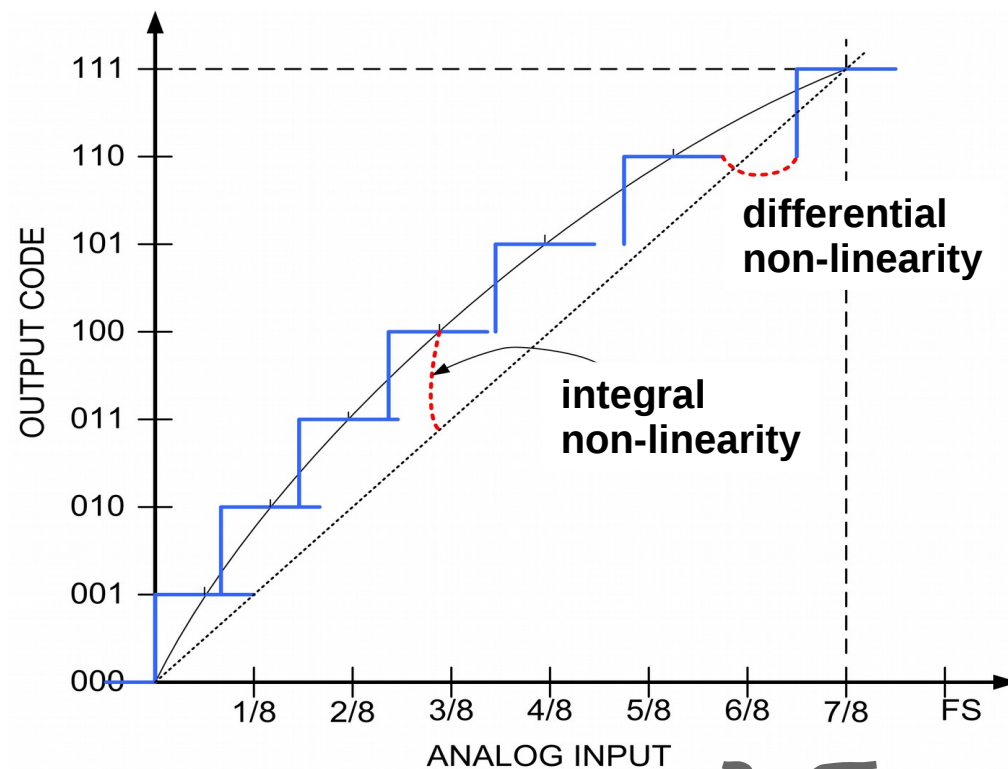
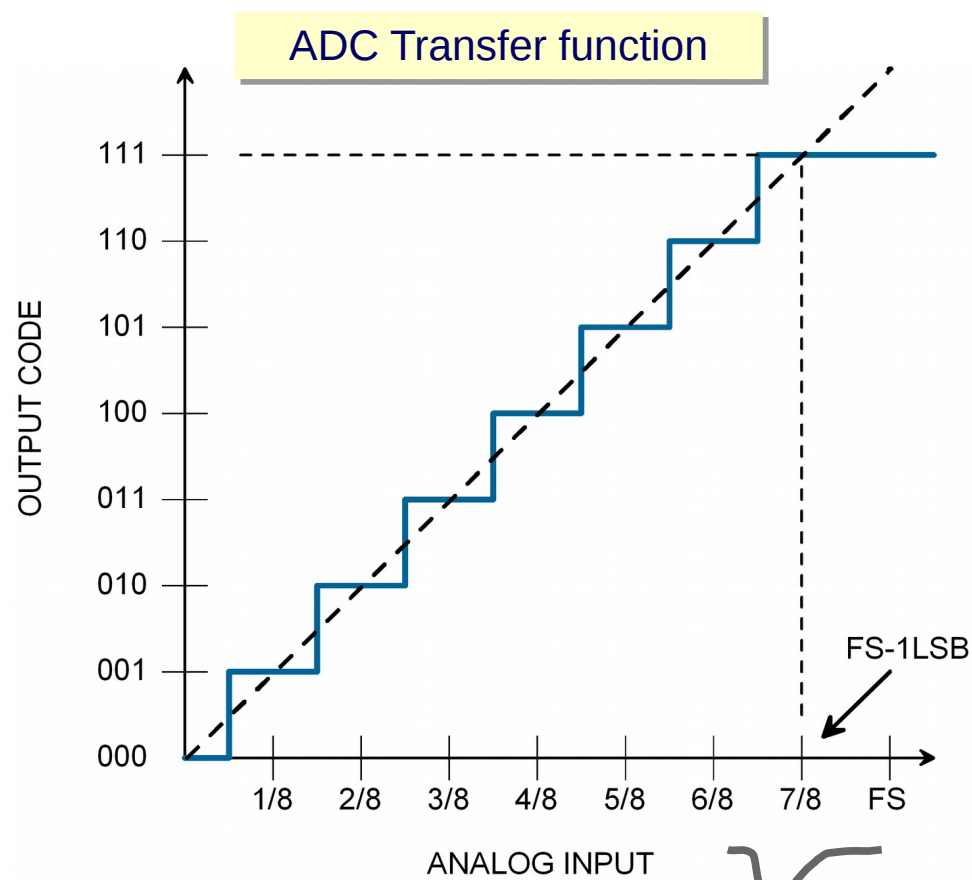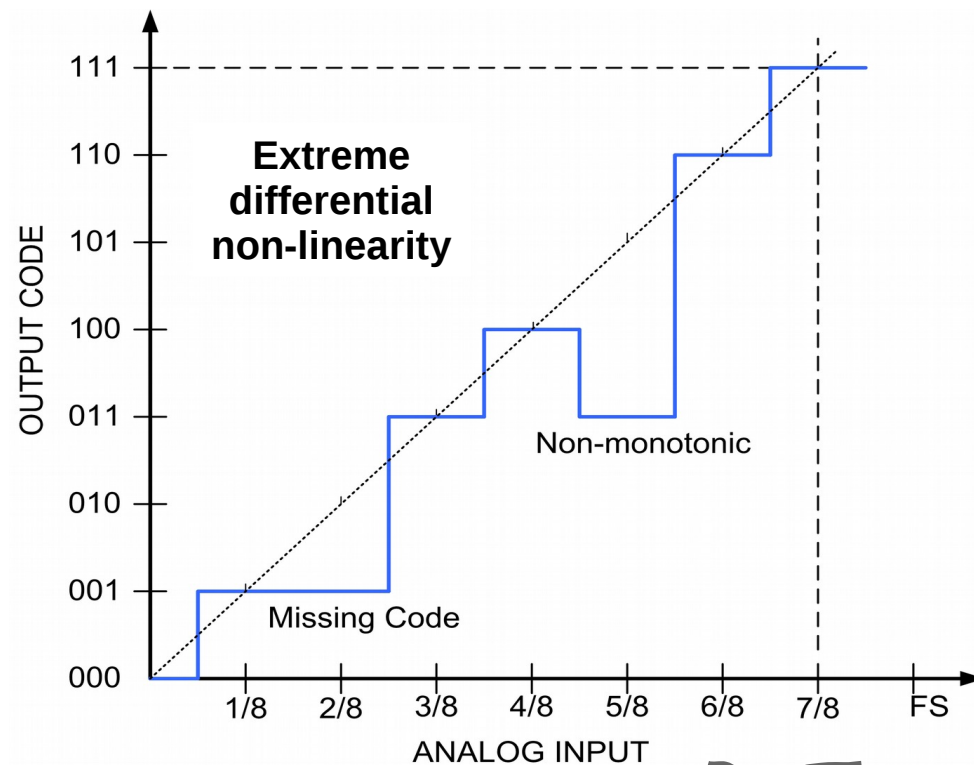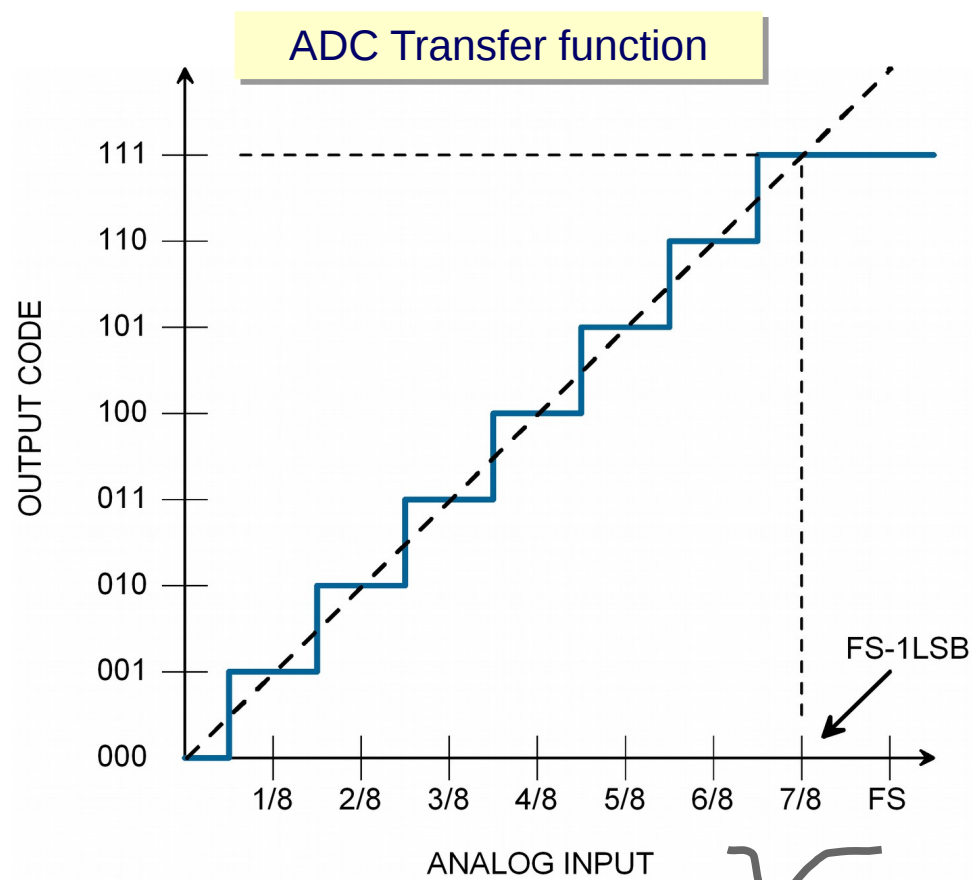 – mostly because of the trade-off between speed and resolution

Speed (sampling rate)

GHz — bipolar

Flash

Sub-Ranging

Pipeline

Successive Approximation

Sigma-Delta
Ramp

CMOS

Discrete

Hz

6   22   **#Bits**

Power >W   <mW

ADC Accuracies

- ## ADC transfer function
  - ### Output code vs analog input

ADC Transfer function

- ## ADC transfer function
  - ### Output code vs analog input

ADC Transfer function

ADC (In)Accuracies
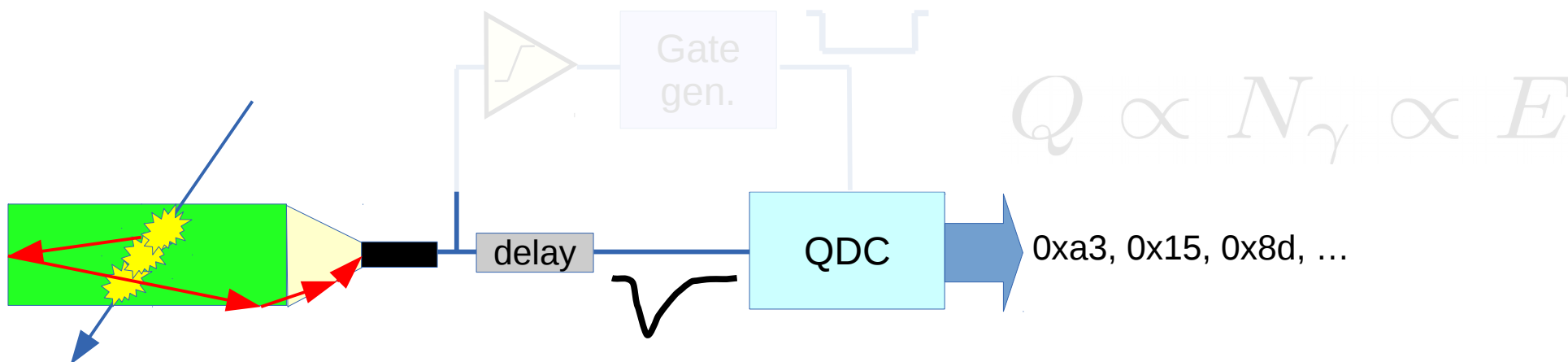
- ## ADC transfer function
  - ### Output code vs analog input
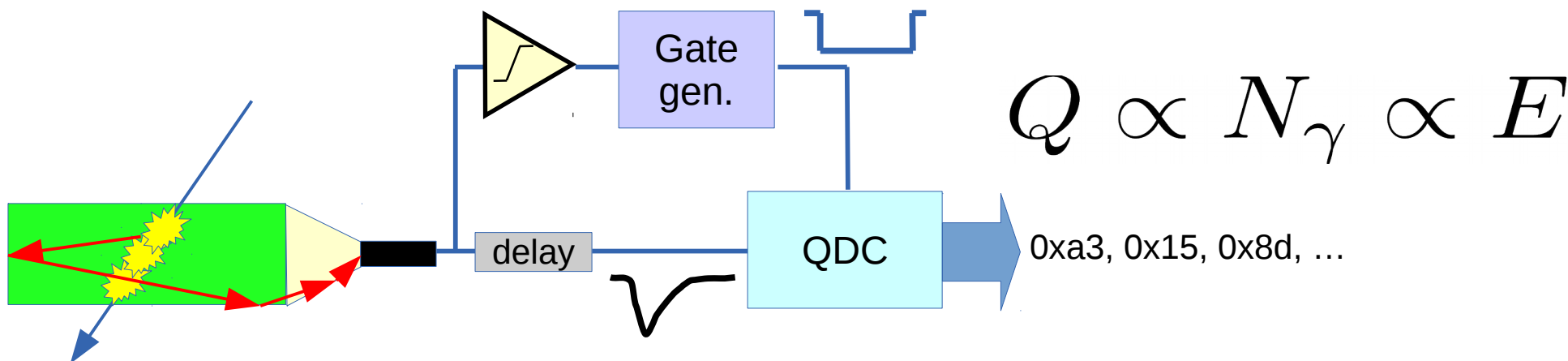

ADC Transfer function

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

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

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

delay   QDC   0xa3, 0x15, 0x8d, …

Charge to Digital

- ADC converts a voltage into a digital representation
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$$I = \int_a^b f(x)\, dx$$

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

delay

Gate gen.

QDC

0xa3, 0x15, 0x8d, …

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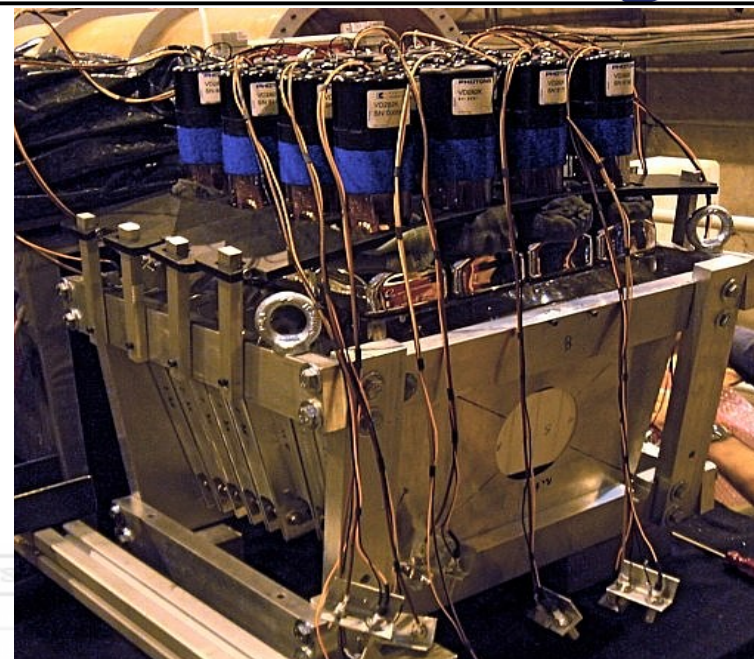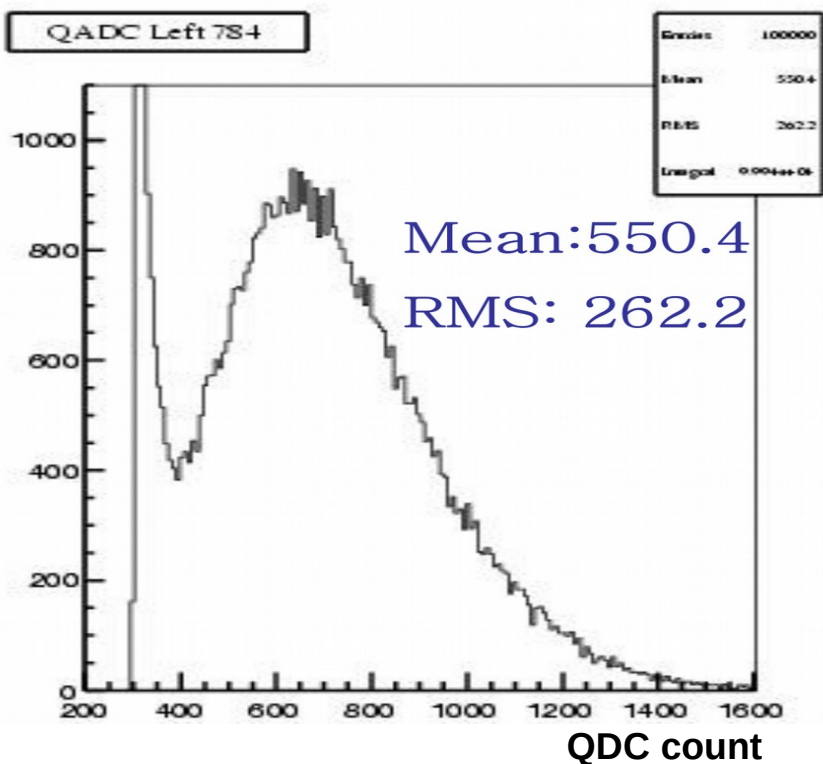 - By the way, which is the noise contribution to our charge measurement?

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

0xa3, 0x15, 0x8d, ...
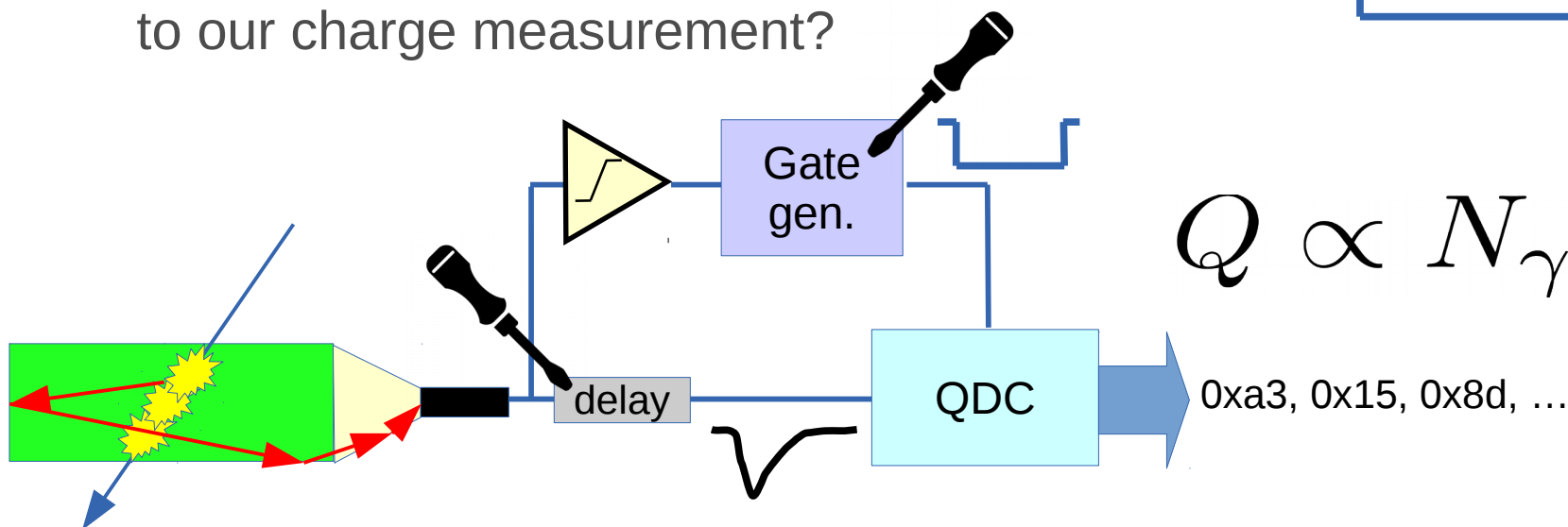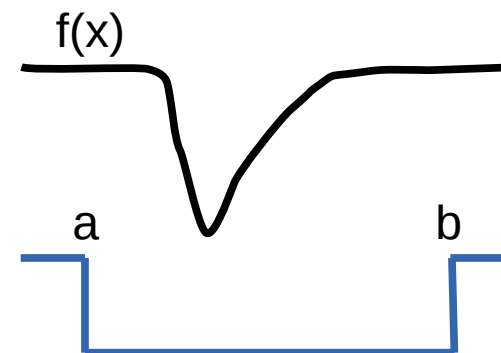
Example: QDC spectrum

- QDC spectra from data taken during a test beam @CERN (calorimetry R&D)
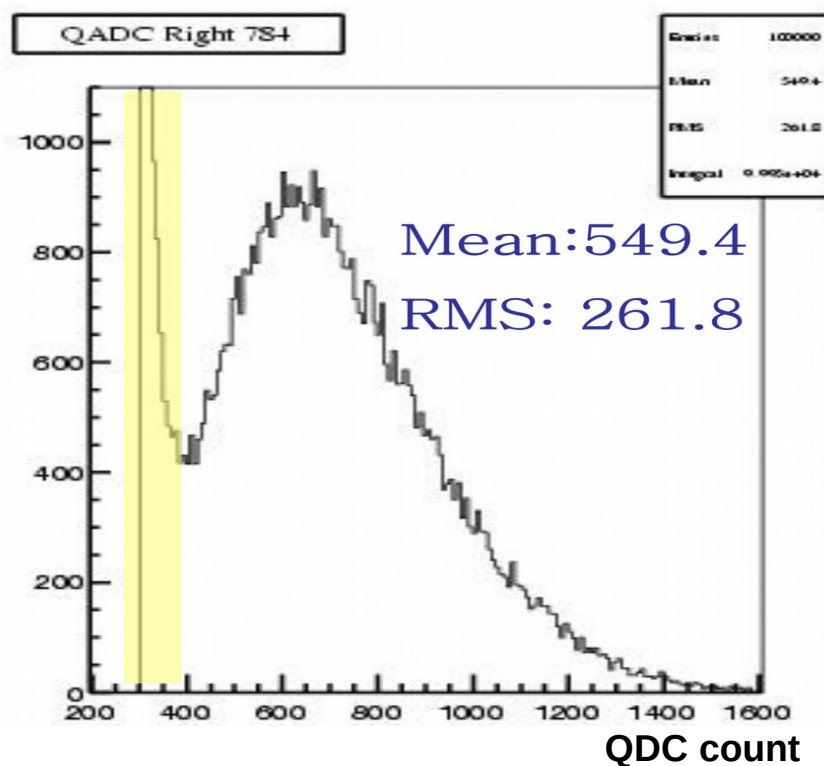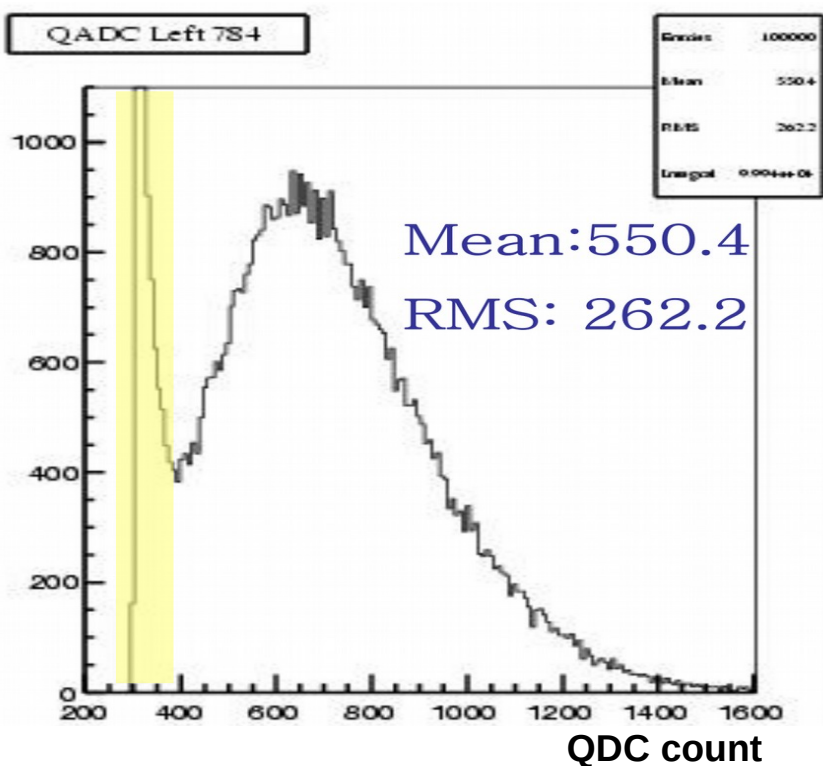
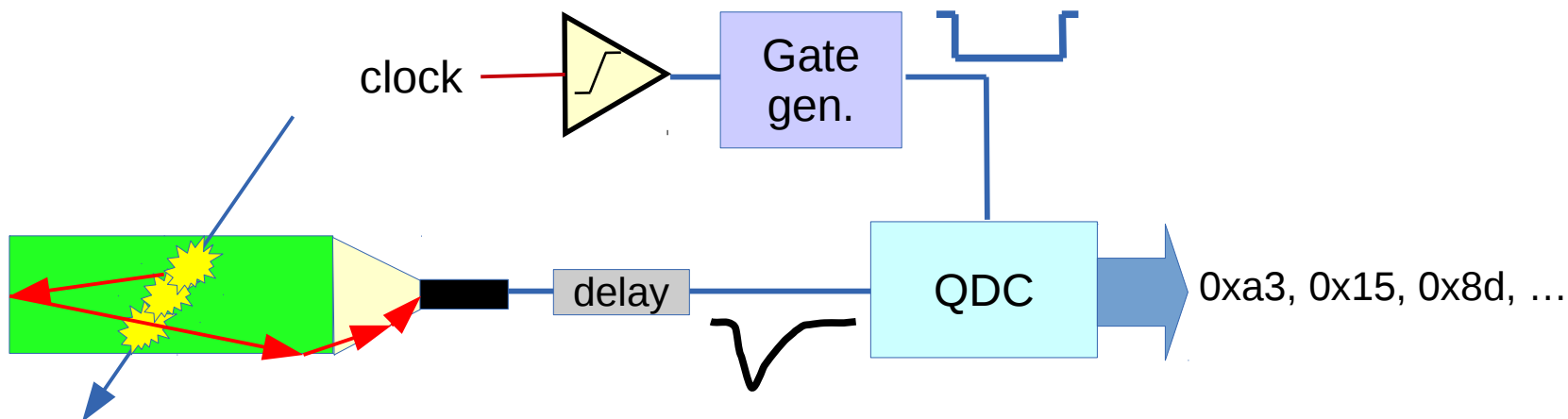$$Q \propto N_\gamma \propto E$$

- But, what is the 1st peak?

Mean: 550.4
RMS: 262.2

QDC count

QDC spectra

- QDC spectra from data taken during a test beam @CERN (calorimetry R&D)

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

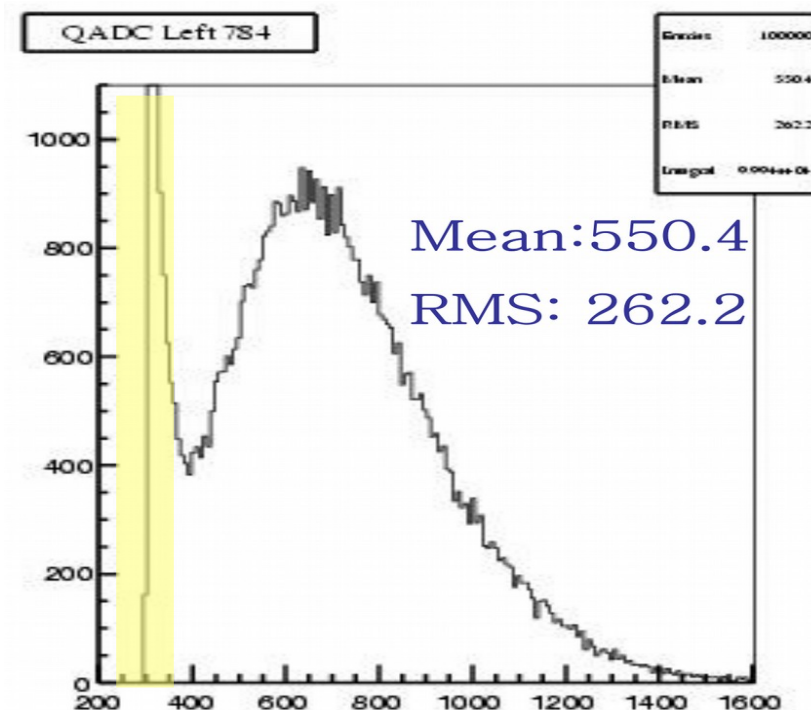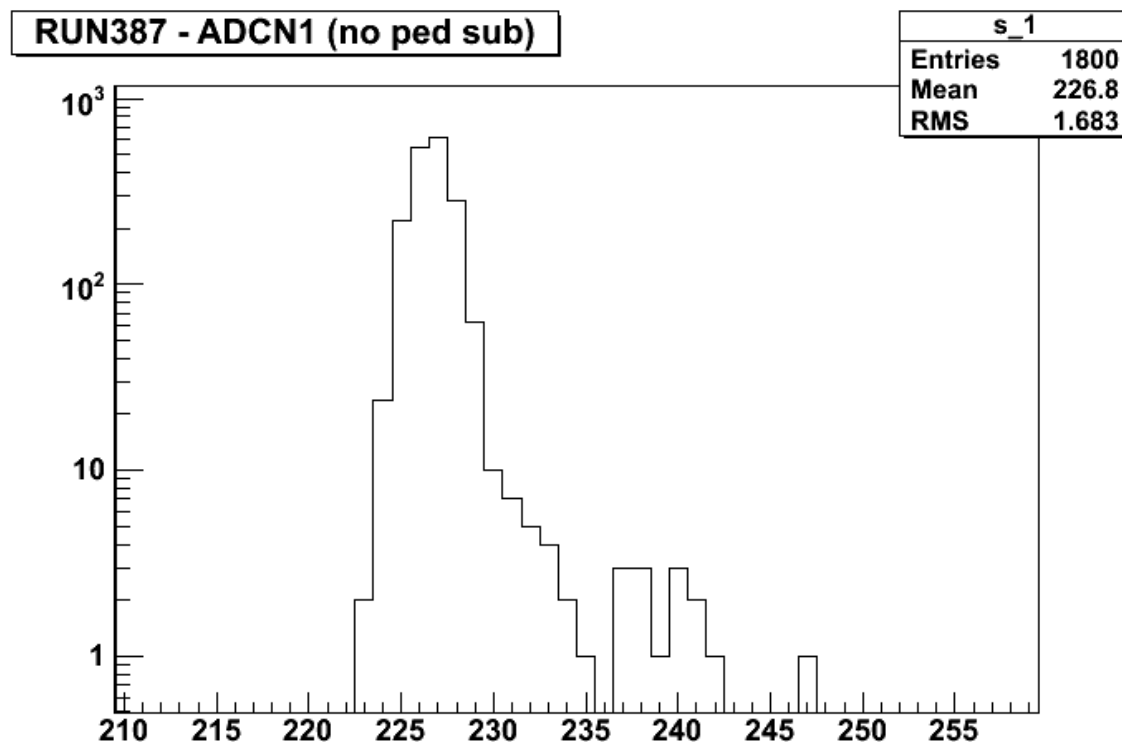- But, what is the 1st peak? How can we estimate it?

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

clock

Gate gen.

delay

QDC

0xa3, 0x15, 0x8d, …

QDC: pedestal subtraction

- The pedestal can be measured with an out-of-phase trigger
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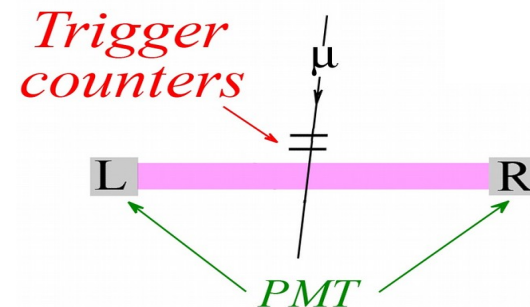- The result of a pedestal measurement has to be subtracted from our charge measurements

s_1	
Entries	1800
Mean	226.8
RMS	1.683

RUN387 - ADCN1 (no ped sub)

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
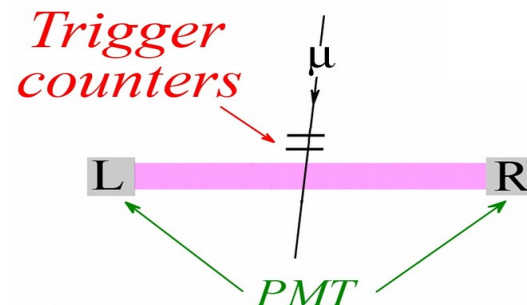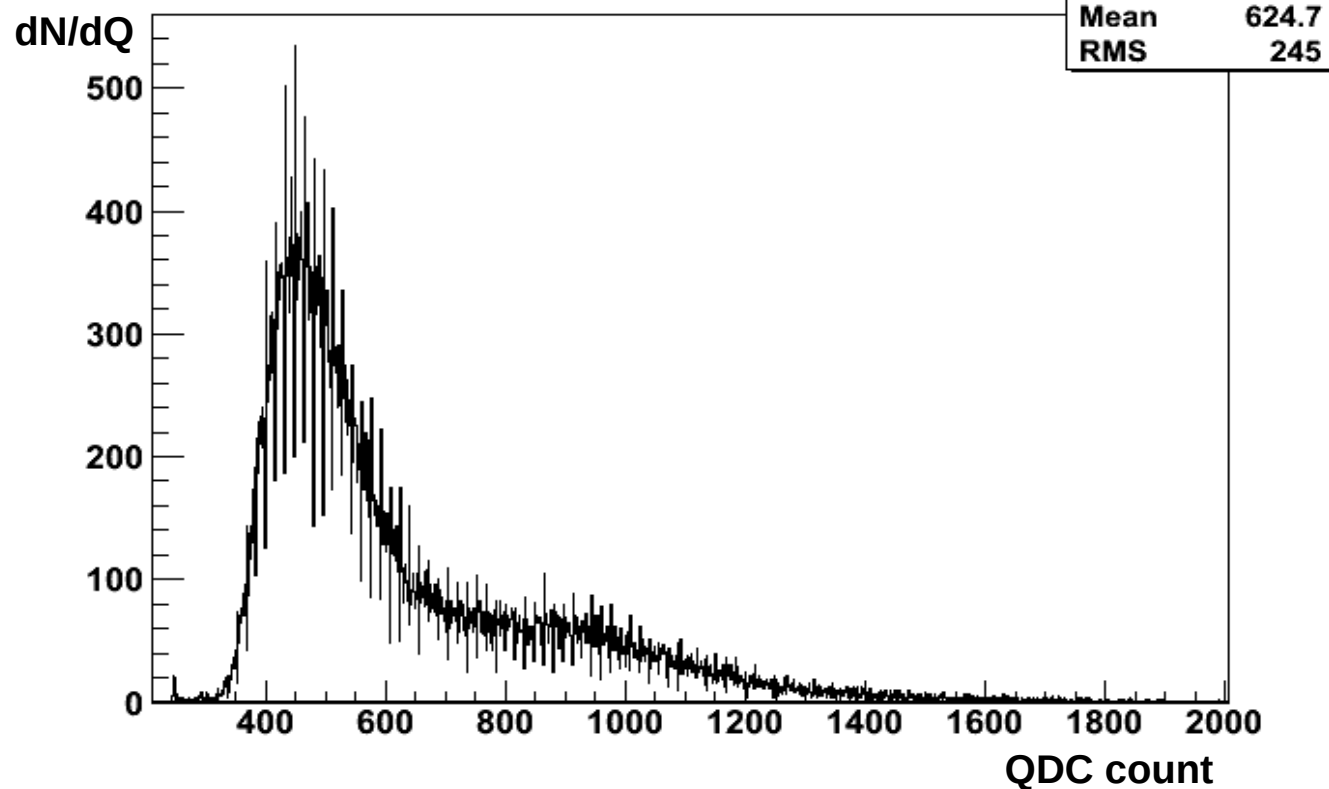
"Real" QDC at work

- PbWO$_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams
  - Real data from a test beam @CERN

"Real" QDC at work
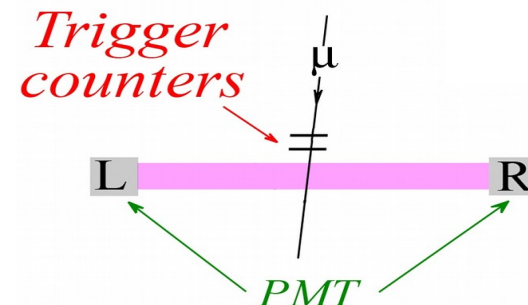
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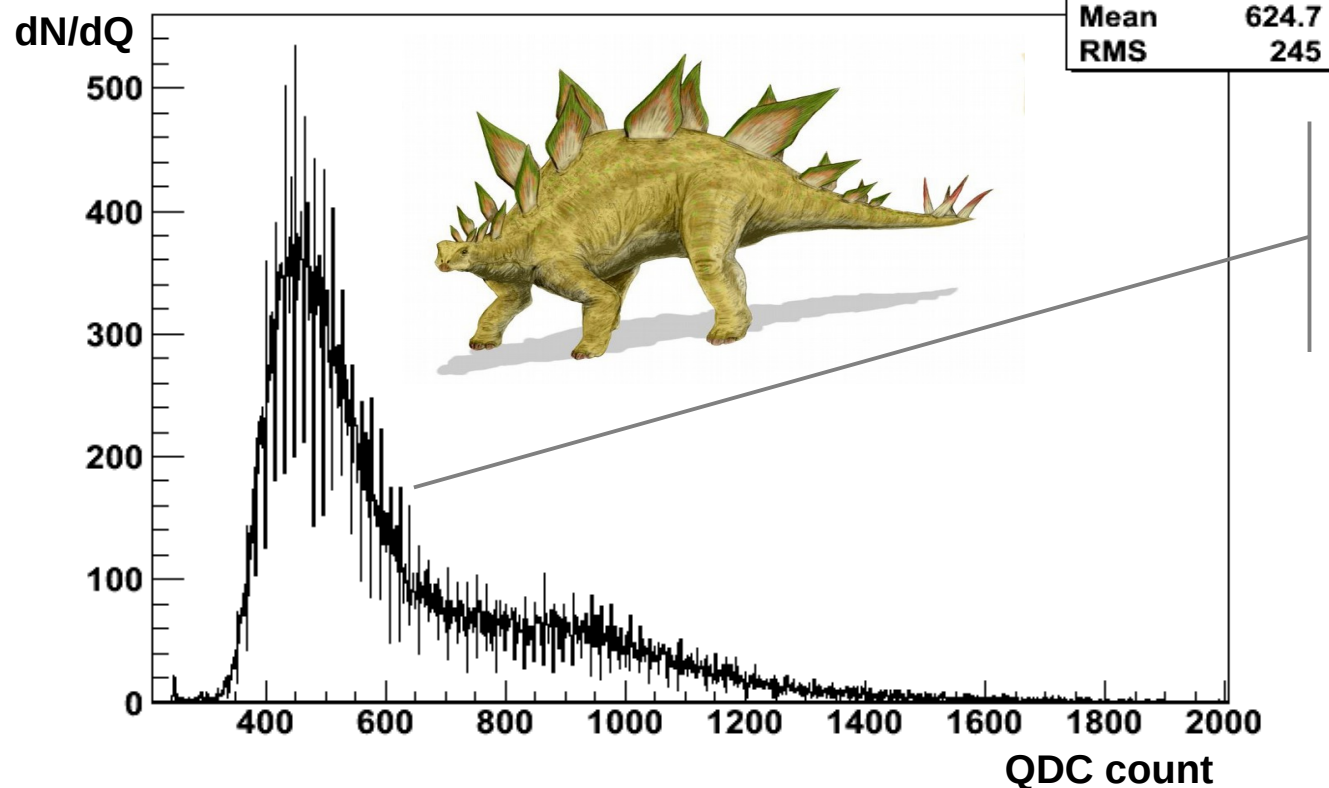π-beam charge-distribution for one PMT

h	
Entries	100000
Mean	624.7
RMS	245

"Real" QDC at work

- PbWO$_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams
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π-beam charge-distribution for one PMT

h	
Entries	100000
Mean	624.7
RMS	245

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

Let's zoom in!

"Real" QDC at work

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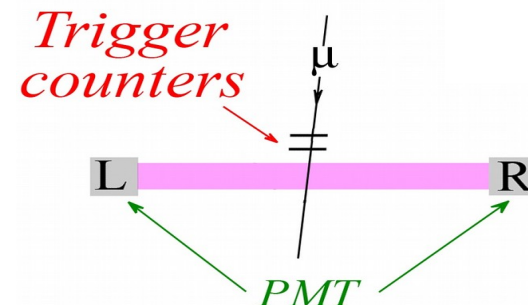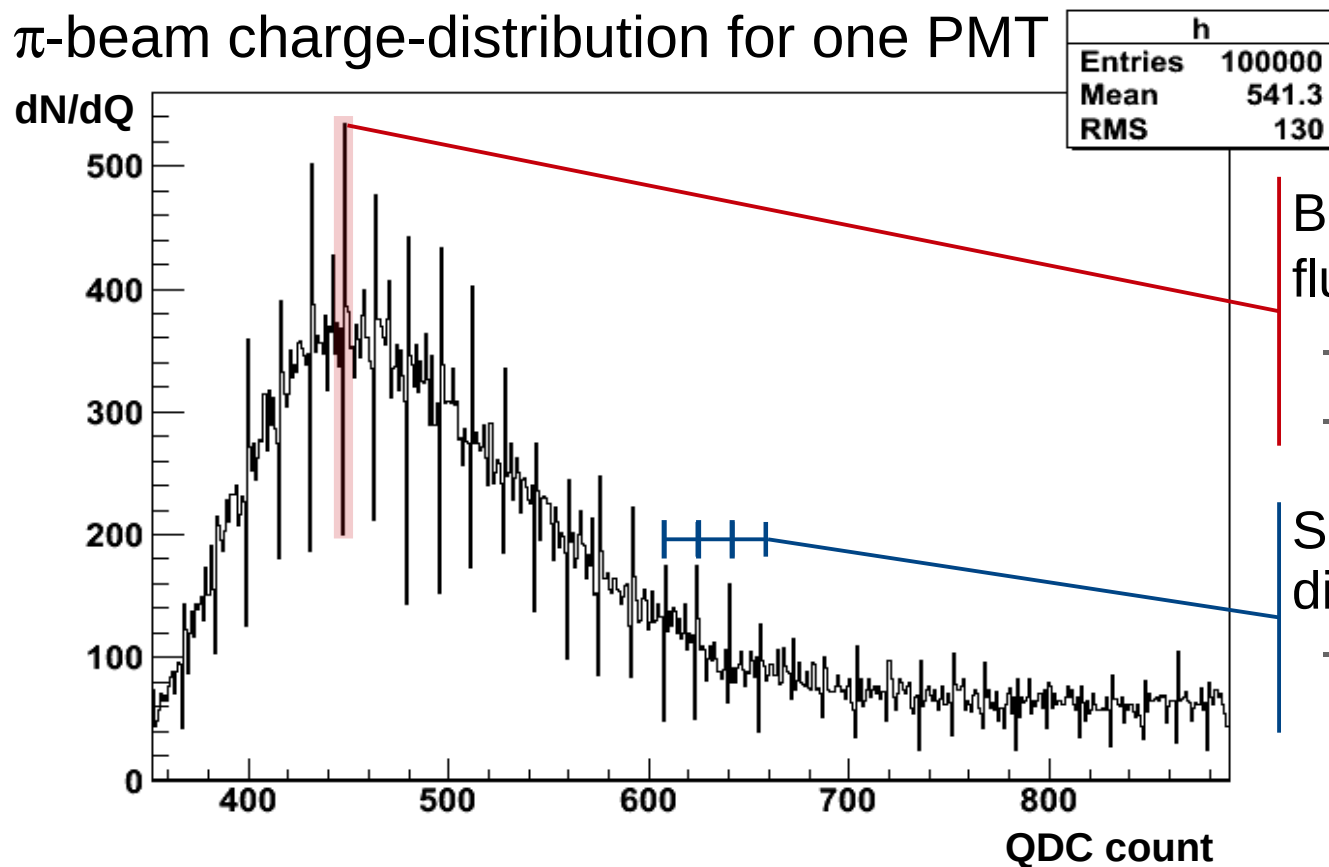   - Real data from a test beam @CERN

Trigger counters

L R

PMT

π-beam charge-distribution for one PMT

h	
Entries	100000
Mean	541.3
RMS	130

Bin with N entries can fluctuate with σ = √N
- expected σ=√N360~19
- observed ~200 (**10 σ**)

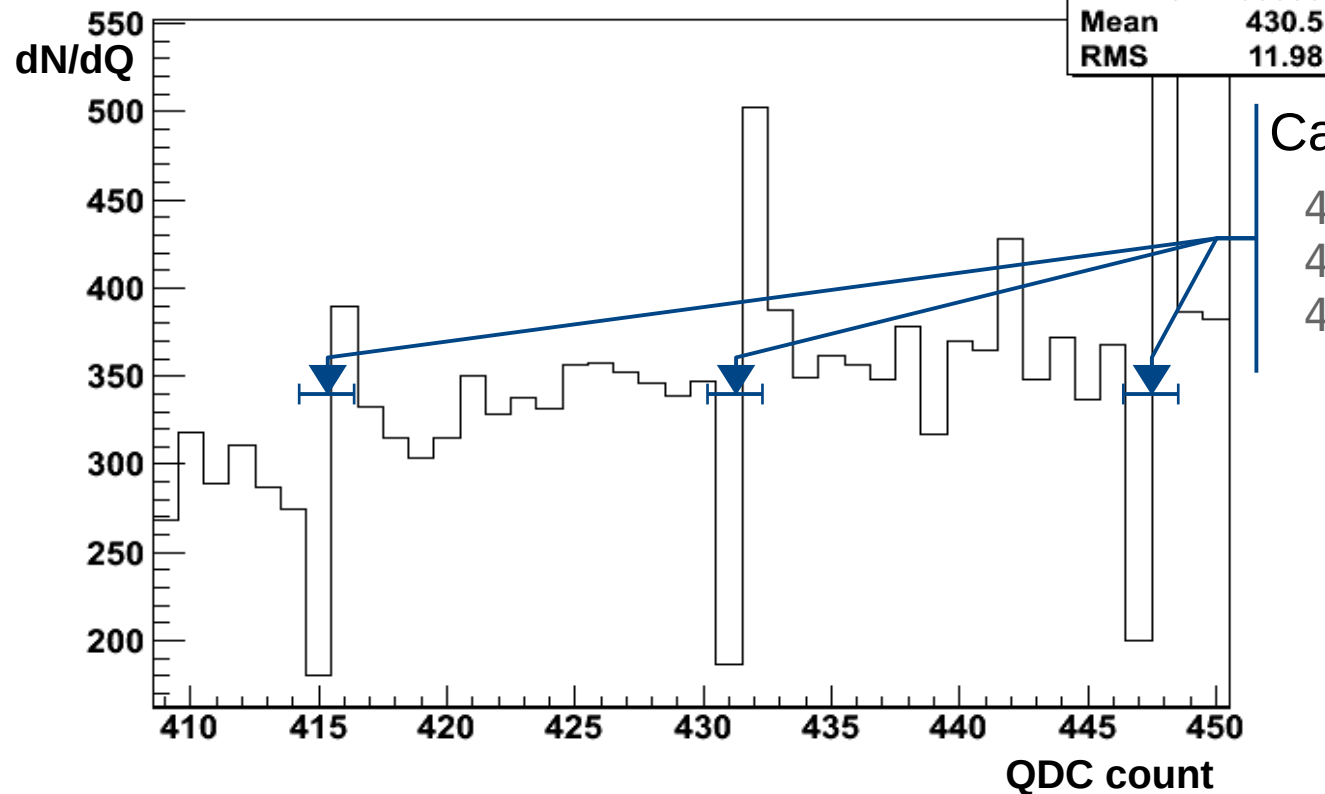**Spikes are regularly distributed**
- Some systematic effect must be taking place

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

Trigger counters
PMT

π-beam charge-distribution for one PMT

h	
Entries	100000
Mean	430.5
RMS	11.98

Can you see the effect?

415 & 416
431 & 432
447 & 448

"Real" QDC at work

- PbWO$_4$ (scintillating) crystal equipped with two PMTs and exposed to e,μ and π beams
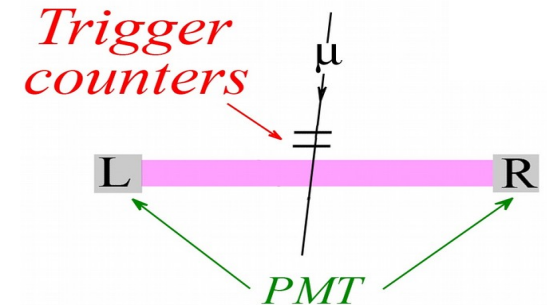 - Real data from a test beam @CERN

π-beam charge-distribution for one PMT

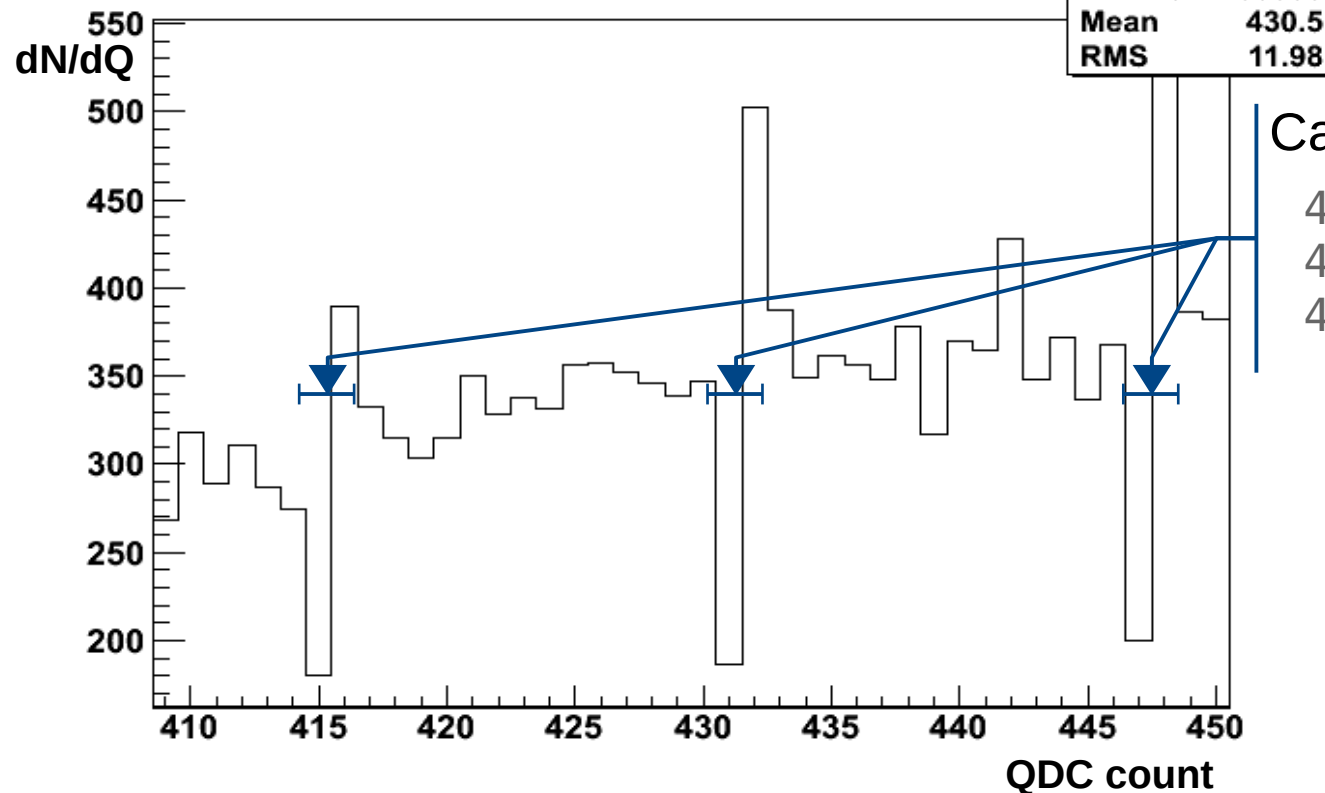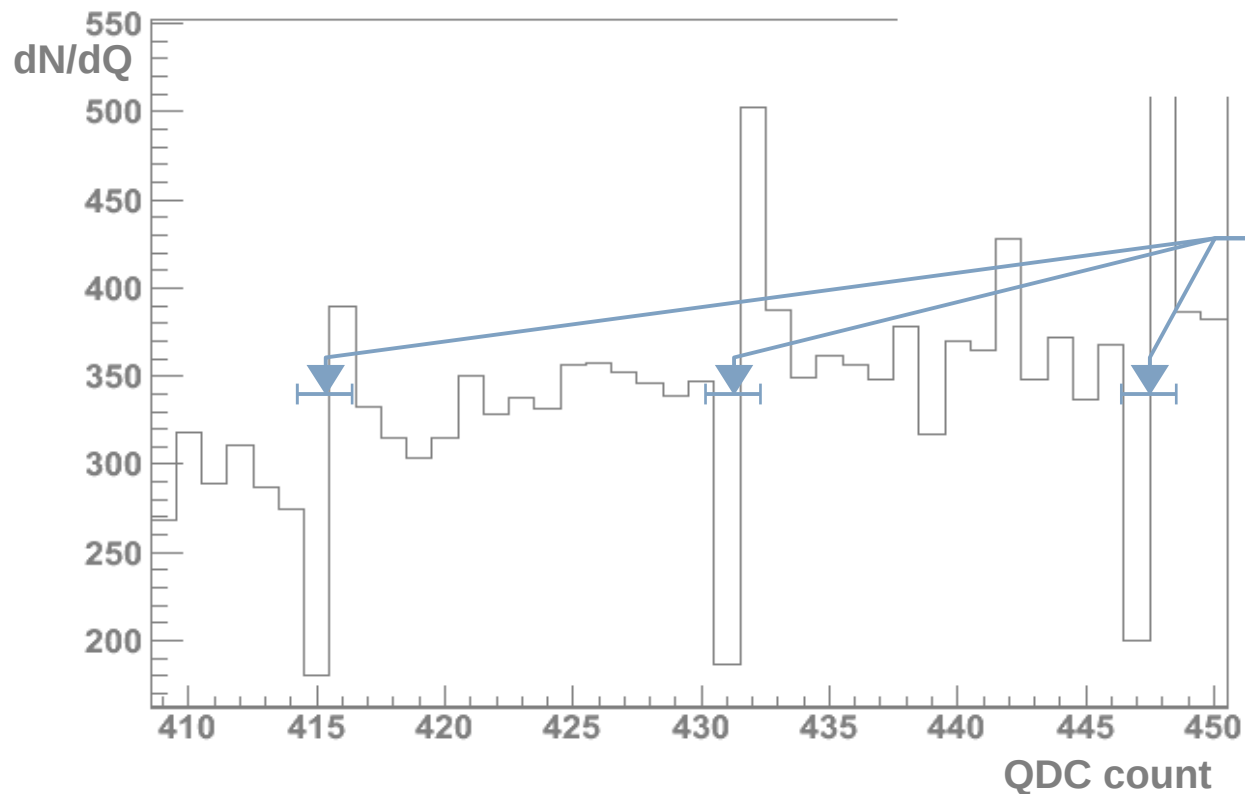Can you see the effect?

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

The QDC prefers output of type   0x..β**0** in respect of   0x..α**f**

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

Can you see the effect?

415 & 416 → 0x19**f** & 0x1A**0**
431 & 432 → 0x1A**f** & 0x1B**0**
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The QDC prefers
output of type   0x..β**0**
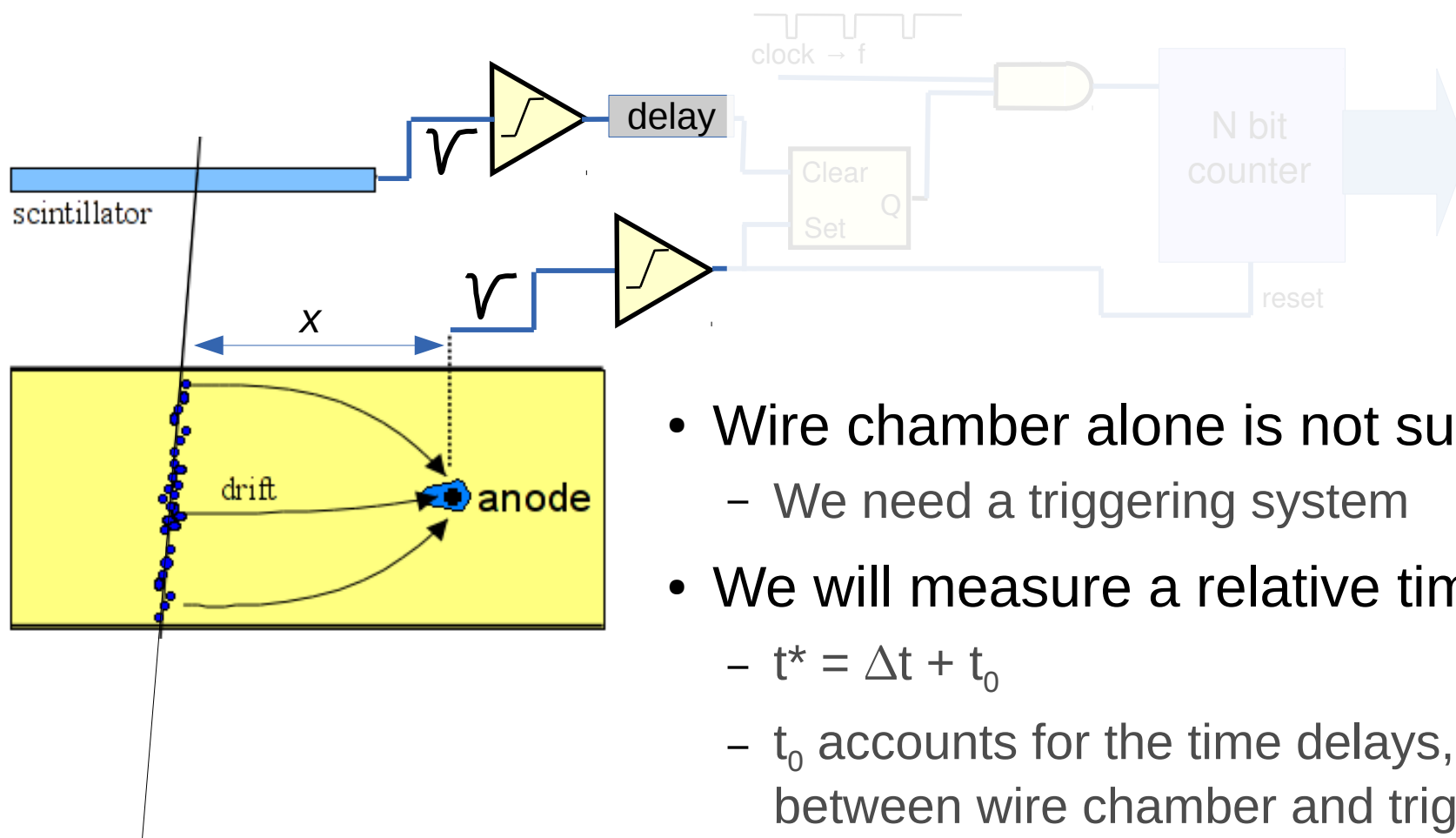in respect of   0x..α**f**
   where β = α + 1

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- 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

2nd **experiment**
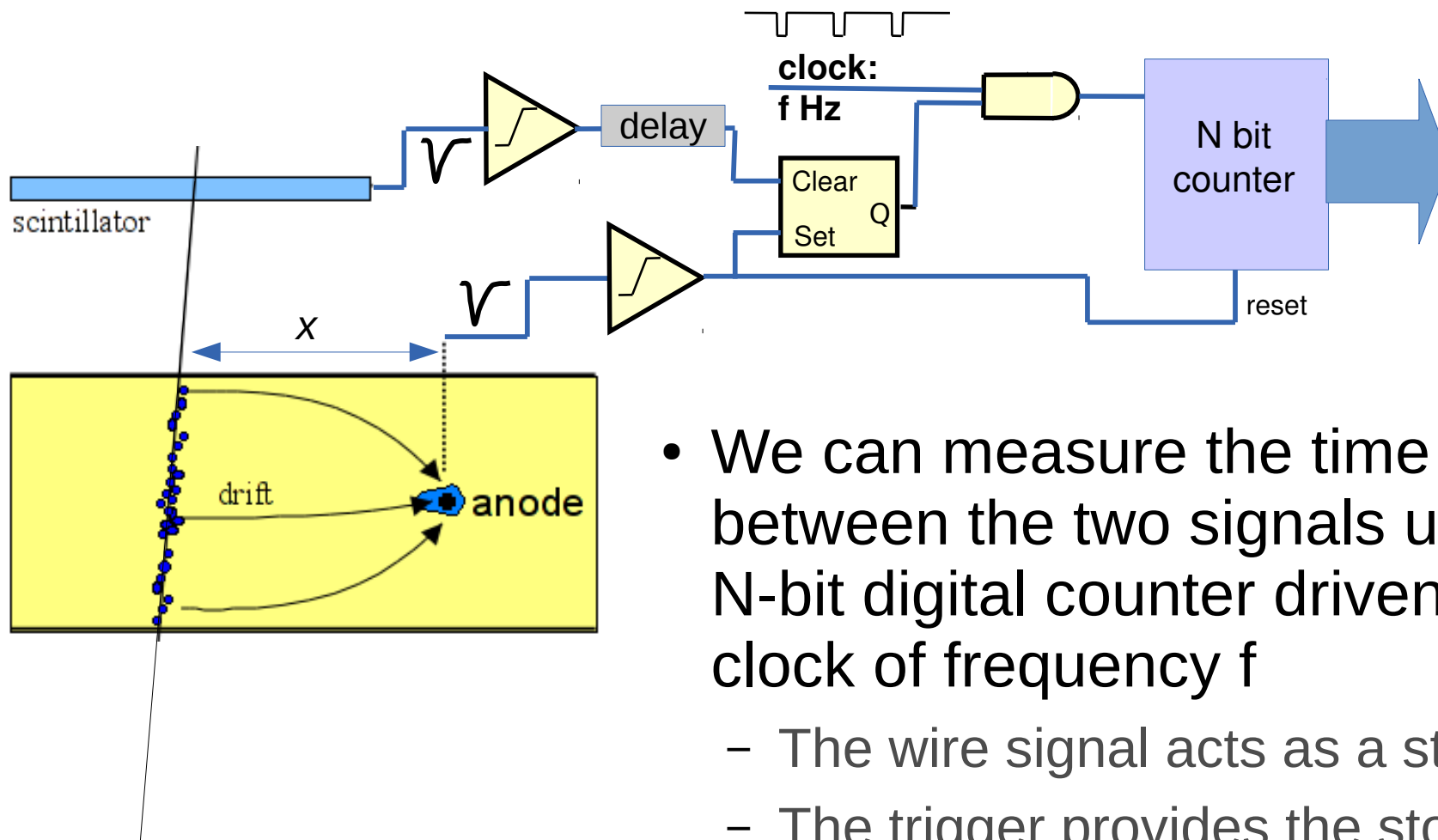NEXT EXIT

Position measurement
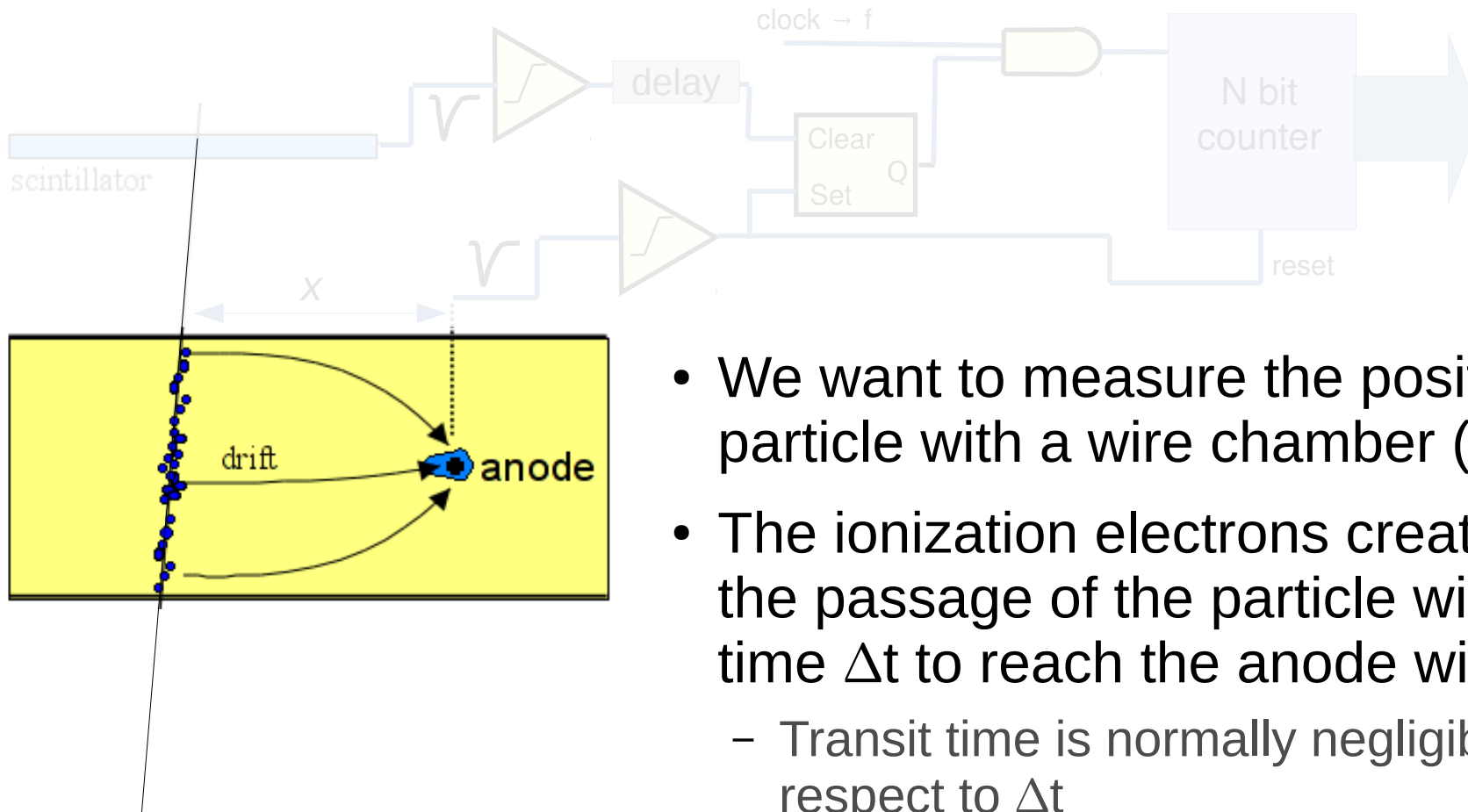
- We want to measure the position of particle with a wire chamber (**drift**)

- 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

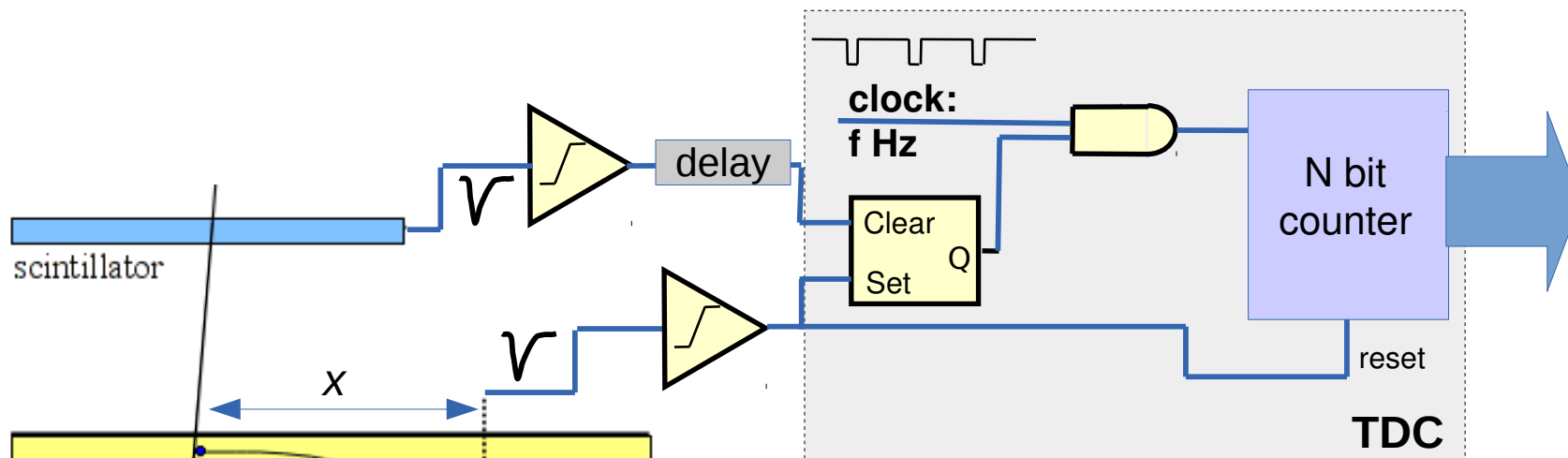 - If we consider a constant drift speed v_D (e.g.: 50μm/ns), then position is:

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

Triggering

clock → f

delay

v

scintillator

Clear

Set

Q

N bit
counter

v

reset

x

drift

anode

- 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

delay

**clock:
f Hz**

Clear

Set

Q

N bit
counter

reset

scintillator

x

drift

anode

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

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

Lab 4

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

clock → f

gate

N bit counter

FIFO

reset

hit

Actual TDCs
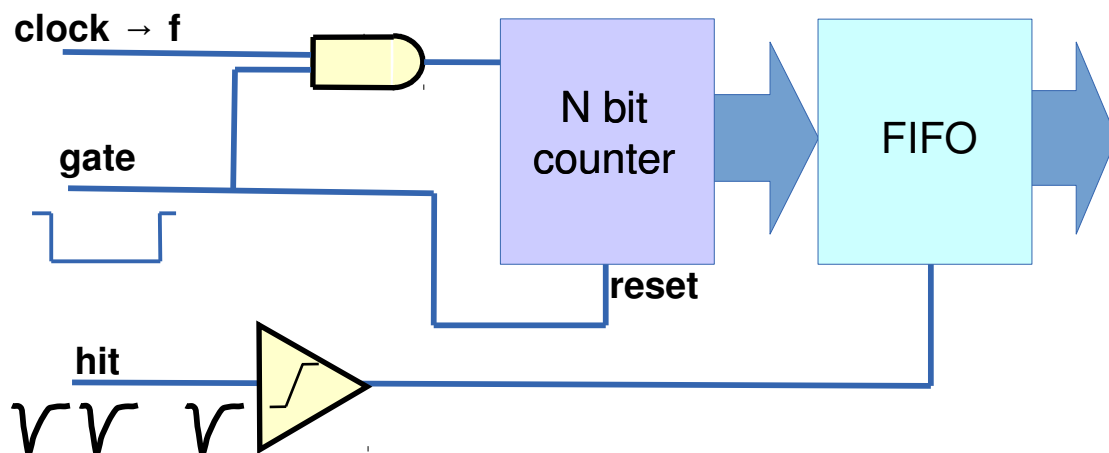
- Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching
  - Internal programmable delays
  - Internal generation of programmable gates
  - Programmable rejection frames
 - Usually via a dedicated C library/API
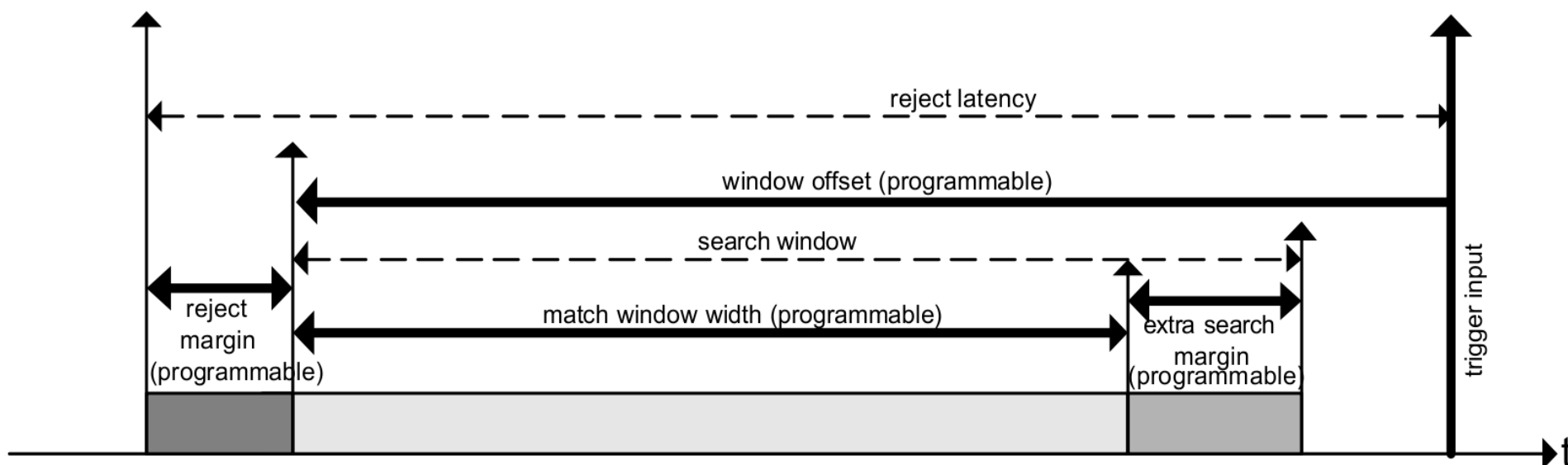
- XDWC: delay wire chambers
  - used on the SPS extracted lines to measure beam profiles

- Two cathode planes provide X and Y positions
  - Measurement based on the delay gained along a delay line
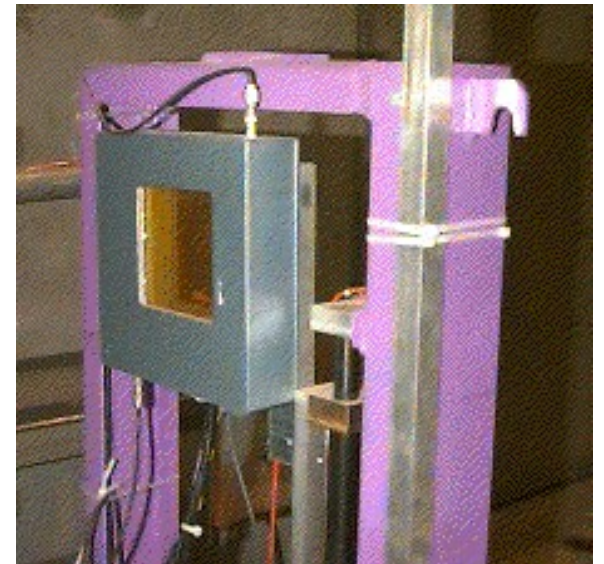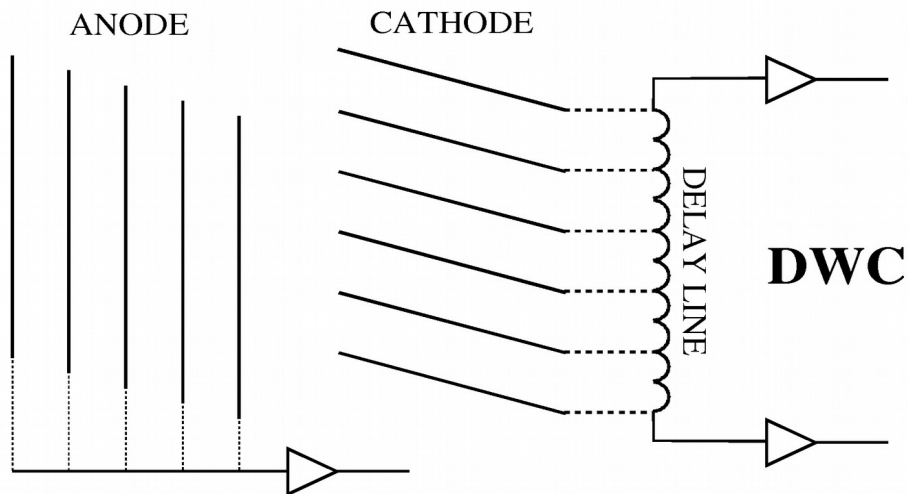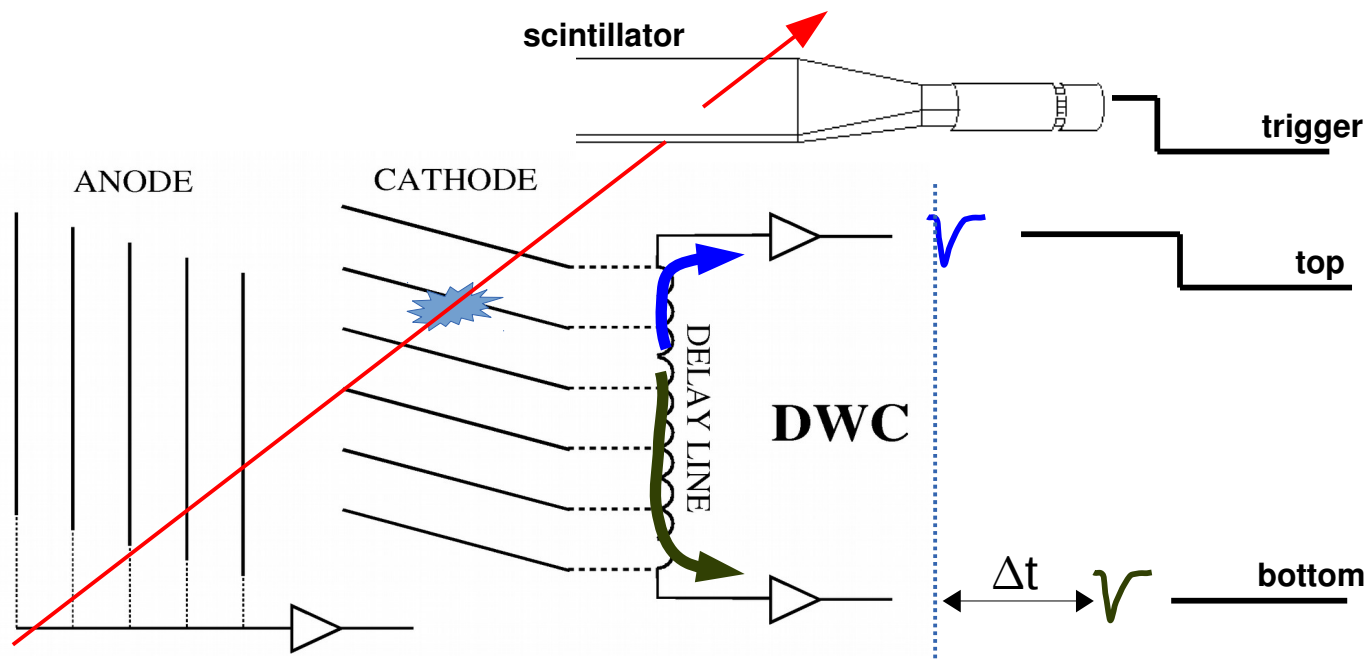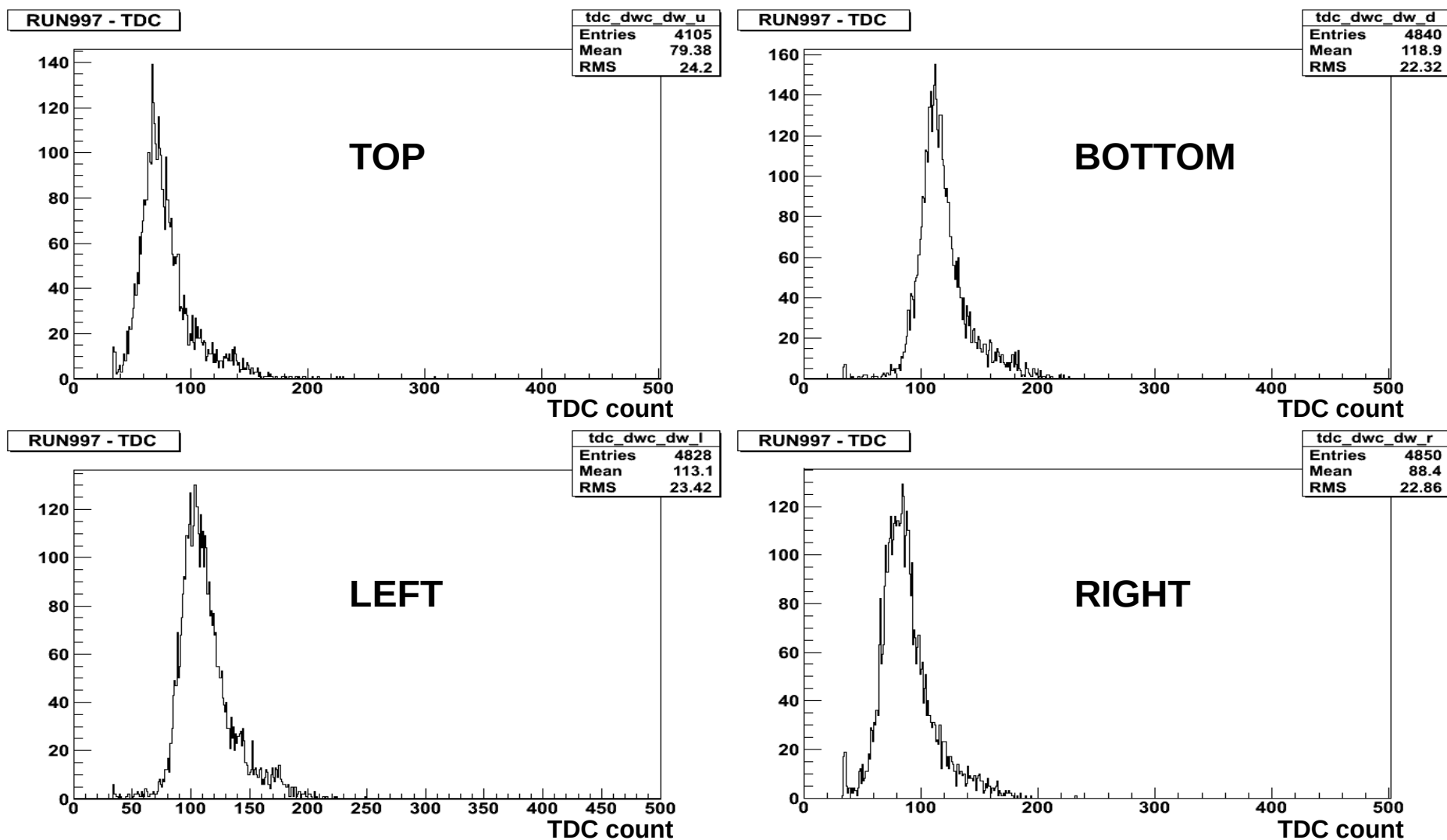
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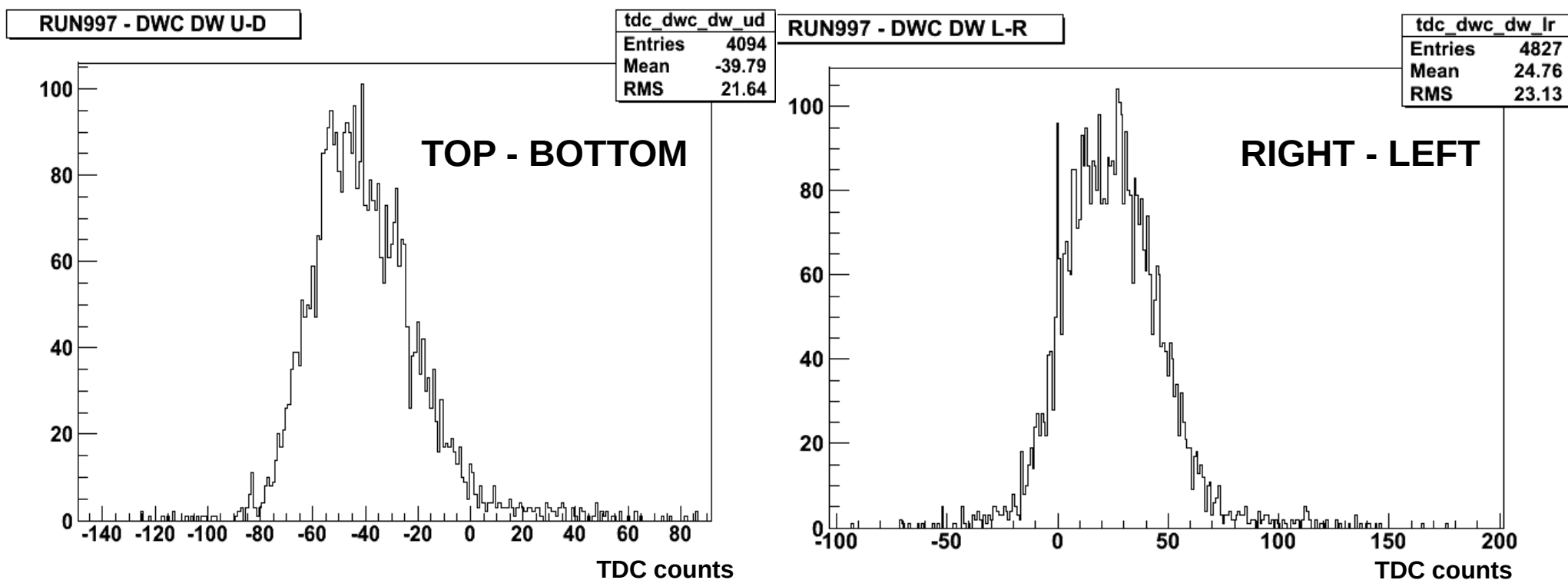 - Measurement based on the delay gained along a delay line

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

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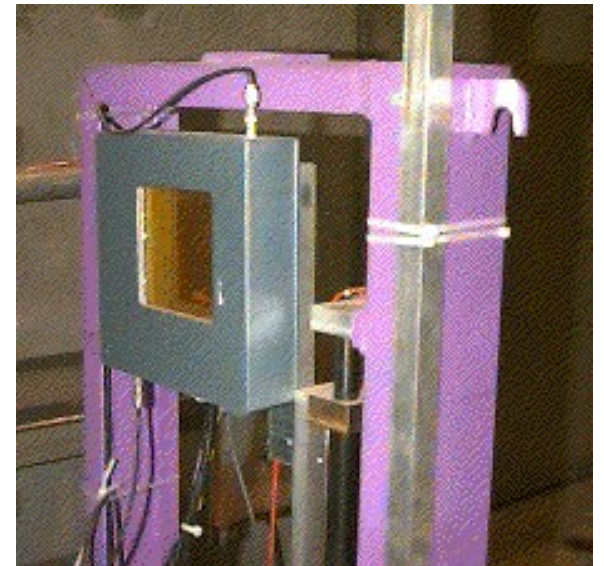
- Take a run (some thousands events)
  - Individual channel distribution

Un-calibrated beam profile

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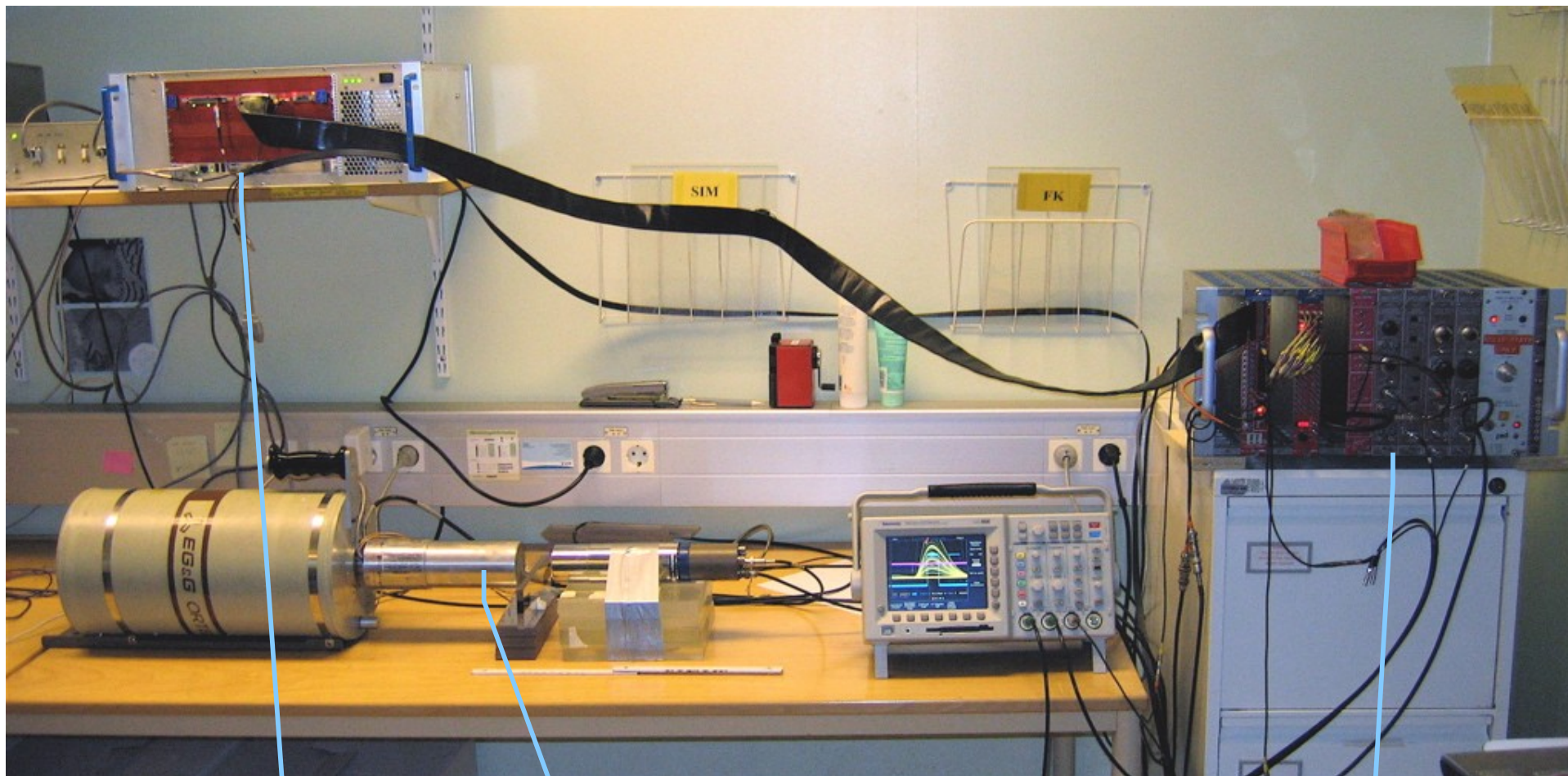 - How do we convert this into a known scale (e.g. cm)?

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: calibration**

Calibration

- Both experiments provide relative measurements
  - Values obtained via our systems are in some (known) relation with the interesting quantities
    - Scintillator $\quad Q \propto N_\gamma \propto E$
    - MDWC $\quad y = \alpha \cdot \Delta t + \beta = \alpha \cdot \left(t_{top} - t_{bottom} \right) + \beta$
- 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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Trigger and front-end
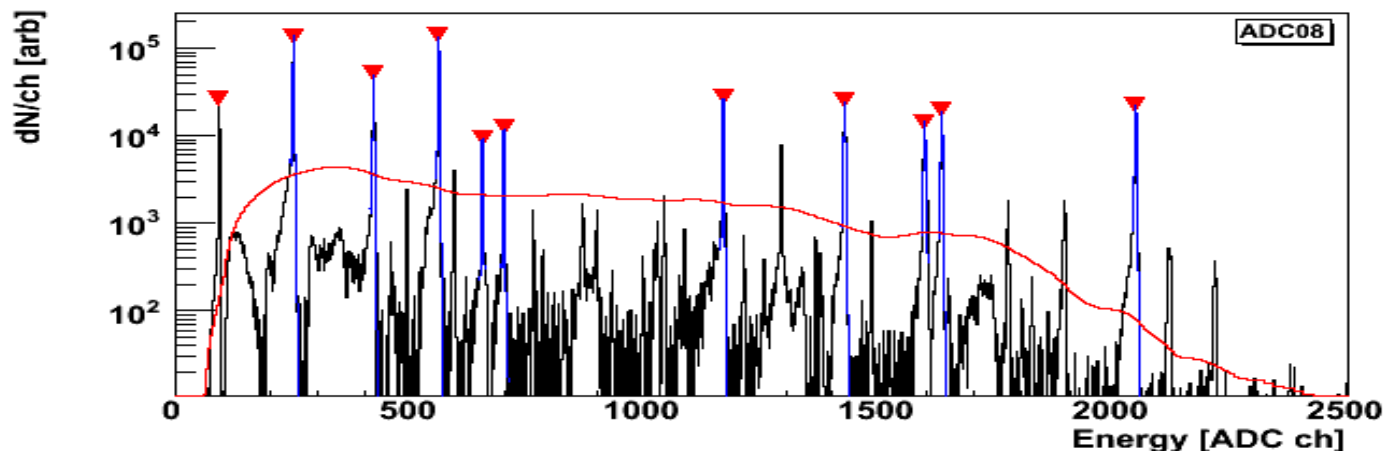
Crystal HPGe

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

$$Q \propto N_\gamma \propto E$$
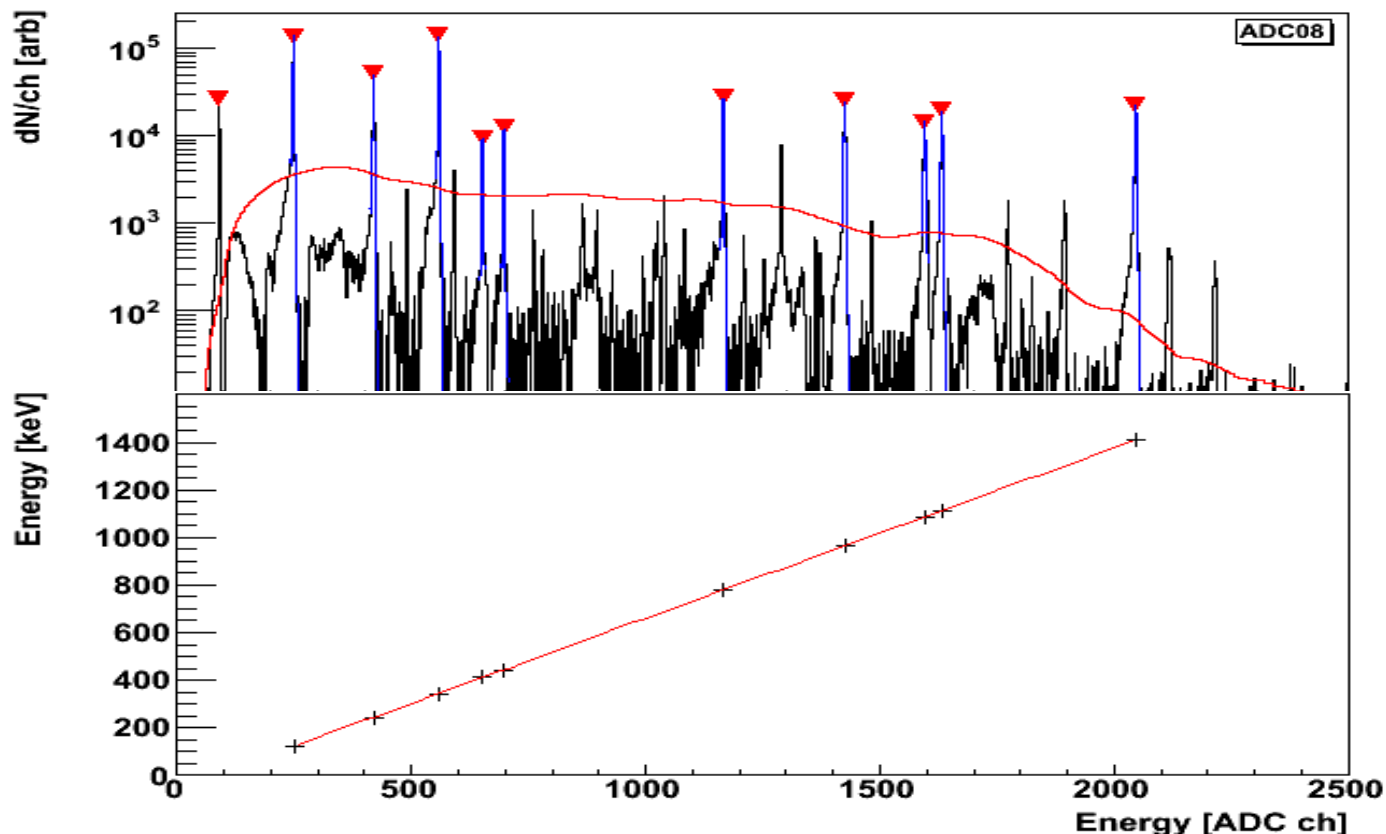
- Find the peaks and fit

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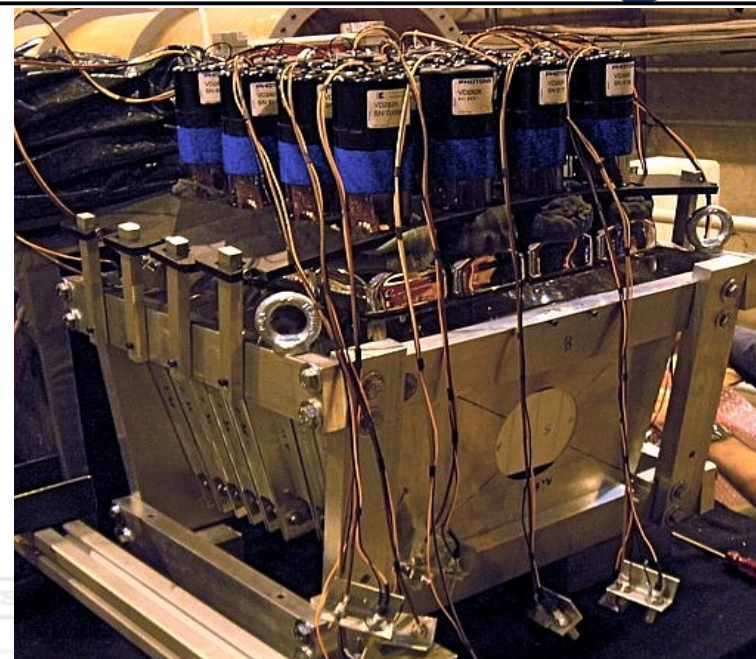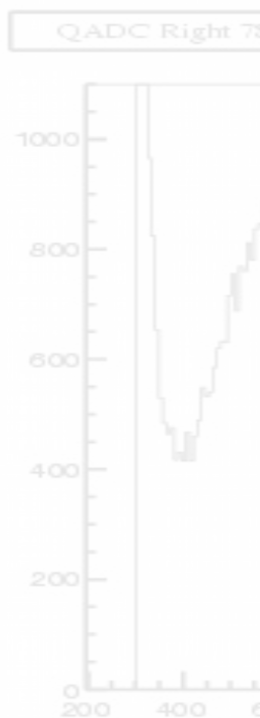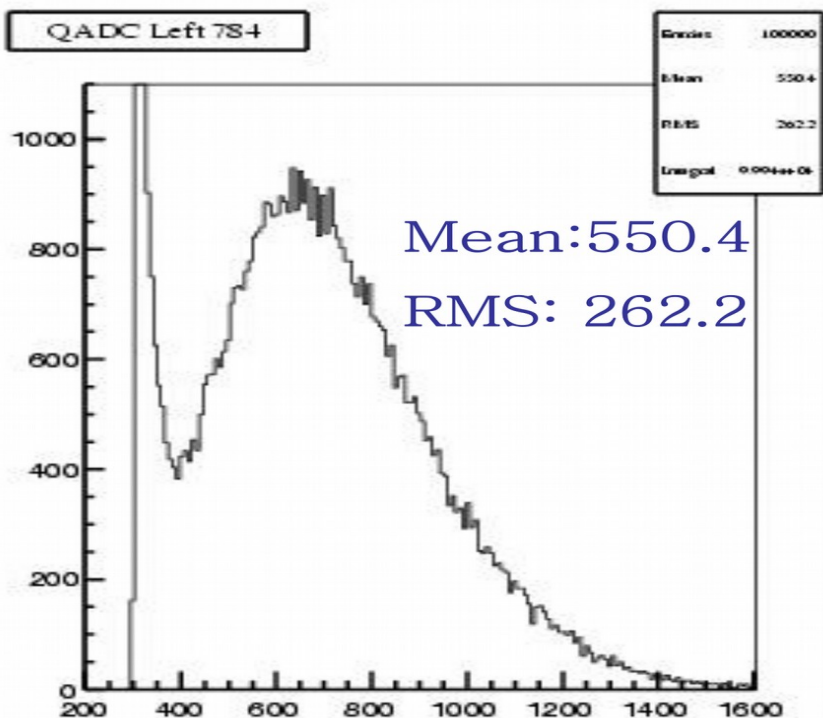
- Find the peaks and fit

Isotope identification

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

**by Sergio Ballestrero**

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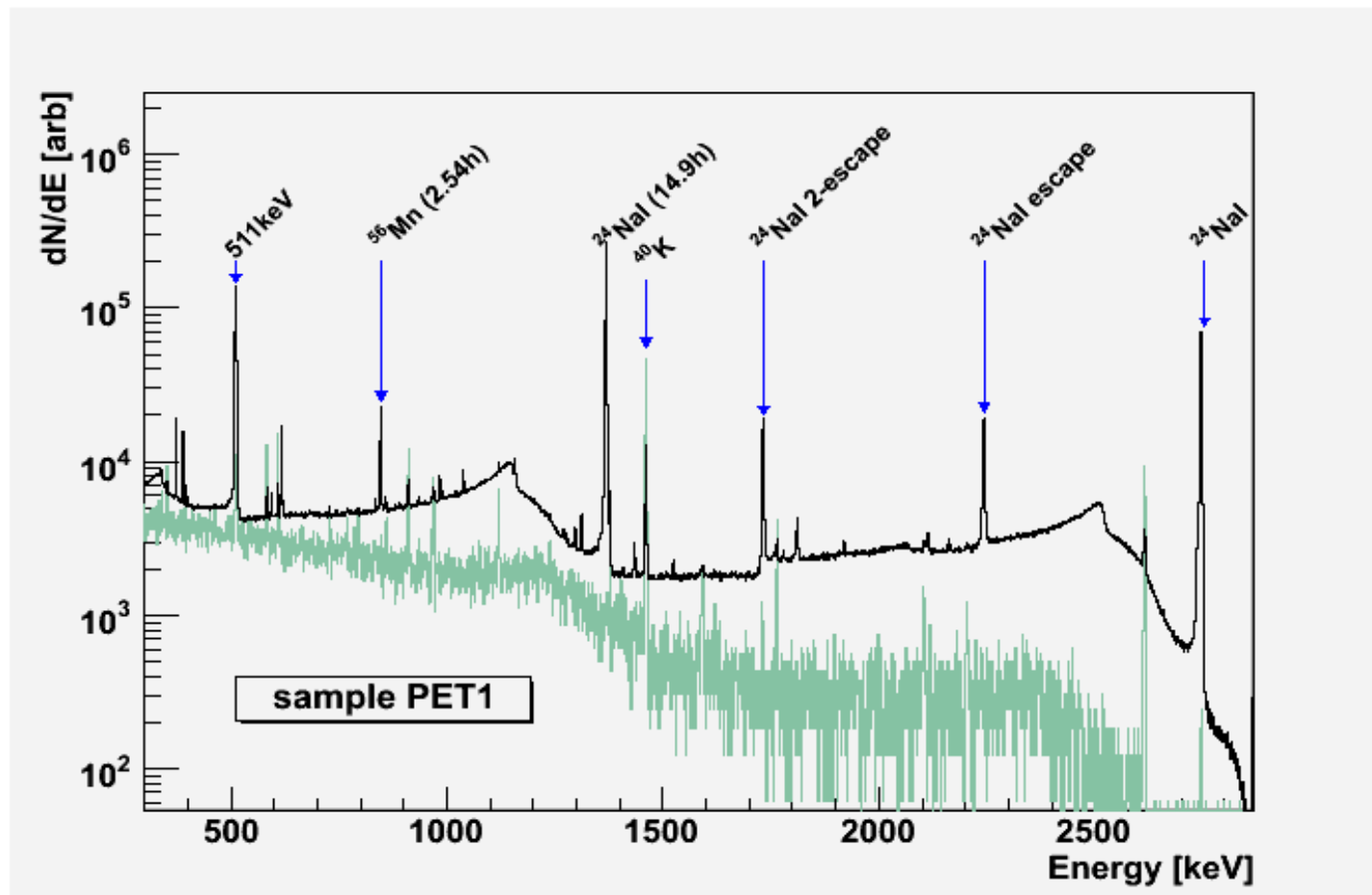
- ## It is more complicated
  - ### The beam energy is known
  - ### But MC is needed to take in account geometry, acceptance, beam profile, etc

QADC Left 7S4

Entries	100000
Mean	550.4
RMS	262.2
Integral	0.994e+06

Mean:550.4
RMS: 262.2

QADC Right 7S

- 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

$$x = \alpha t^* + \beta$$
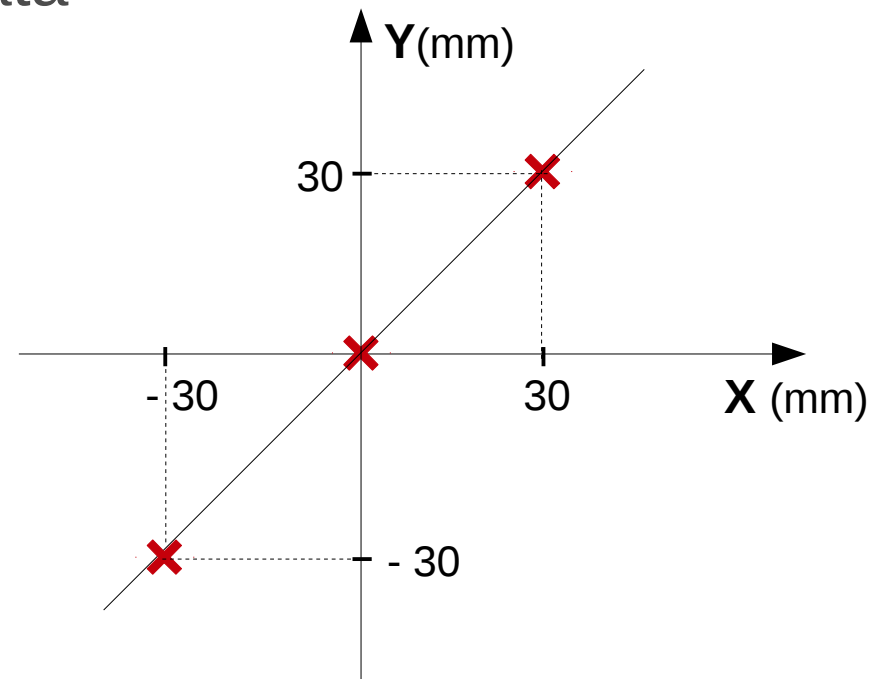
- Calibration shall be done with final setup and TDC

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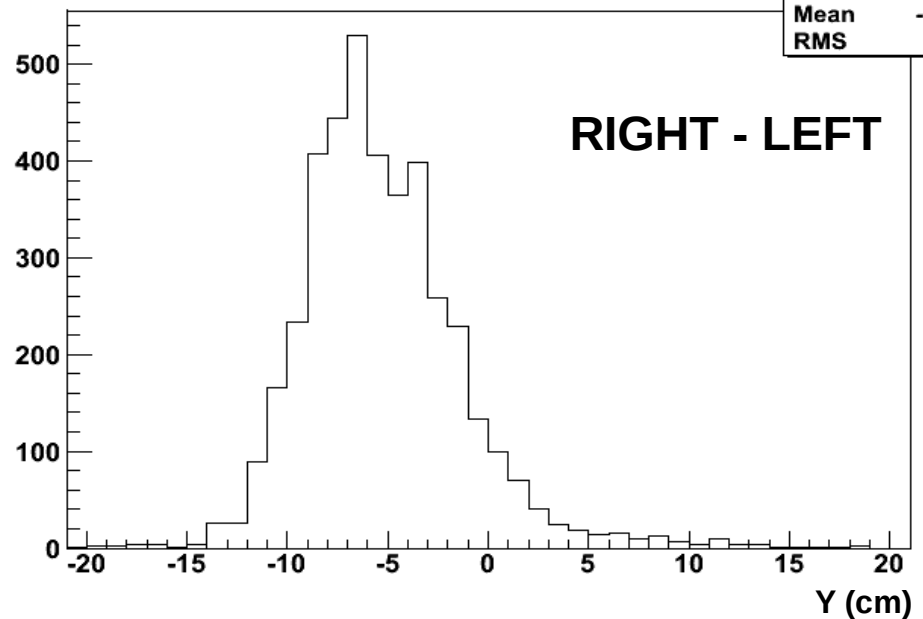
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Calibrated XDWC
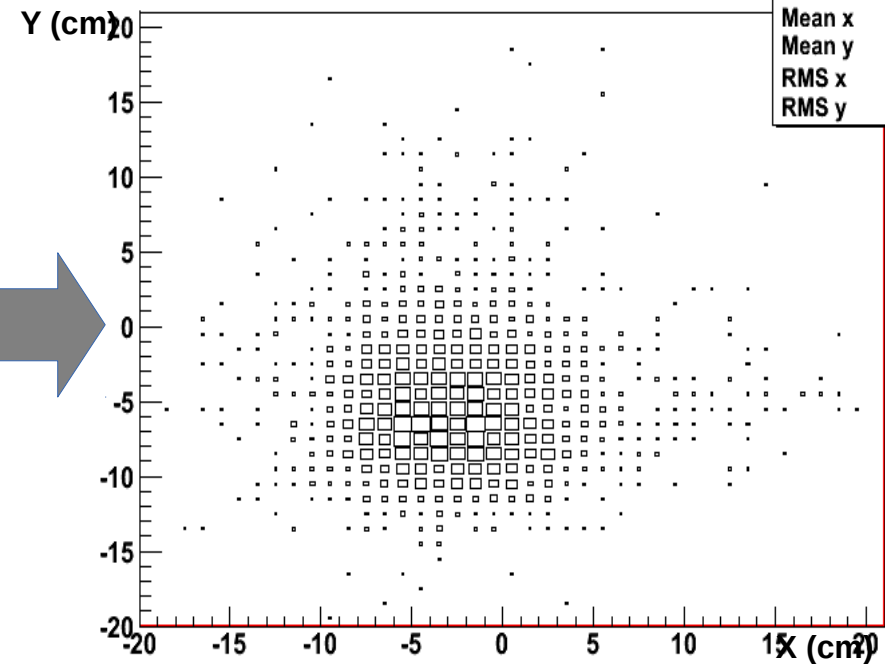
Wrap-up
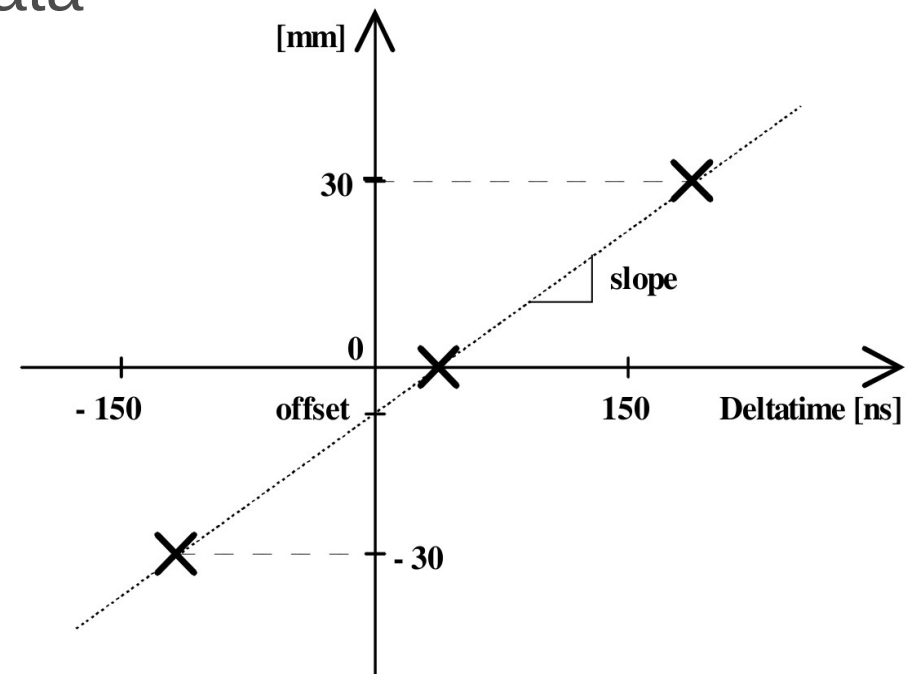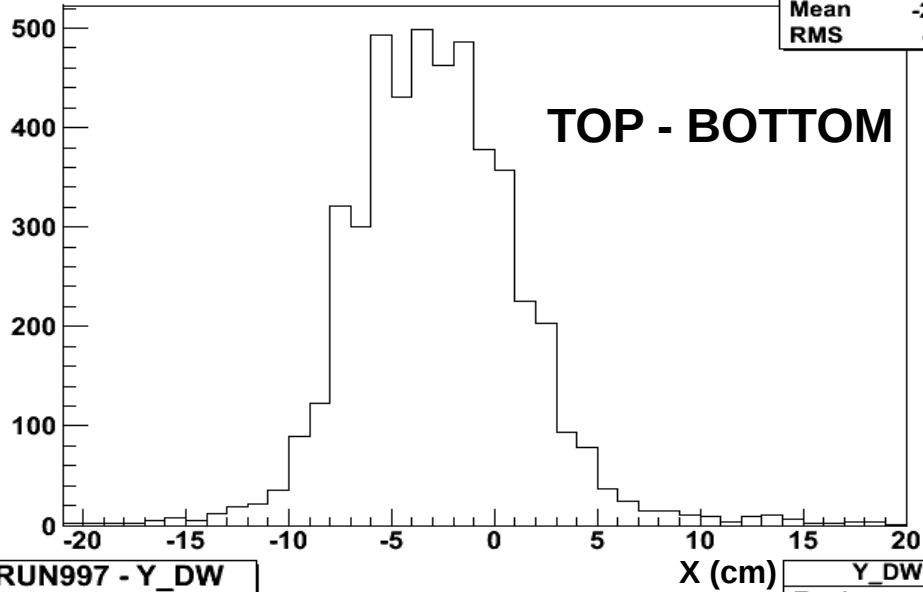
- Digitization techniques produce data directly manageable by digital systems (e.g. a computer)
  - Greatly simplifies the down-stream data-handling
  - Available on a variety of platforms: VME, ATCA, PCI, USB, …
  - Root of every modern DAQ system

- 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