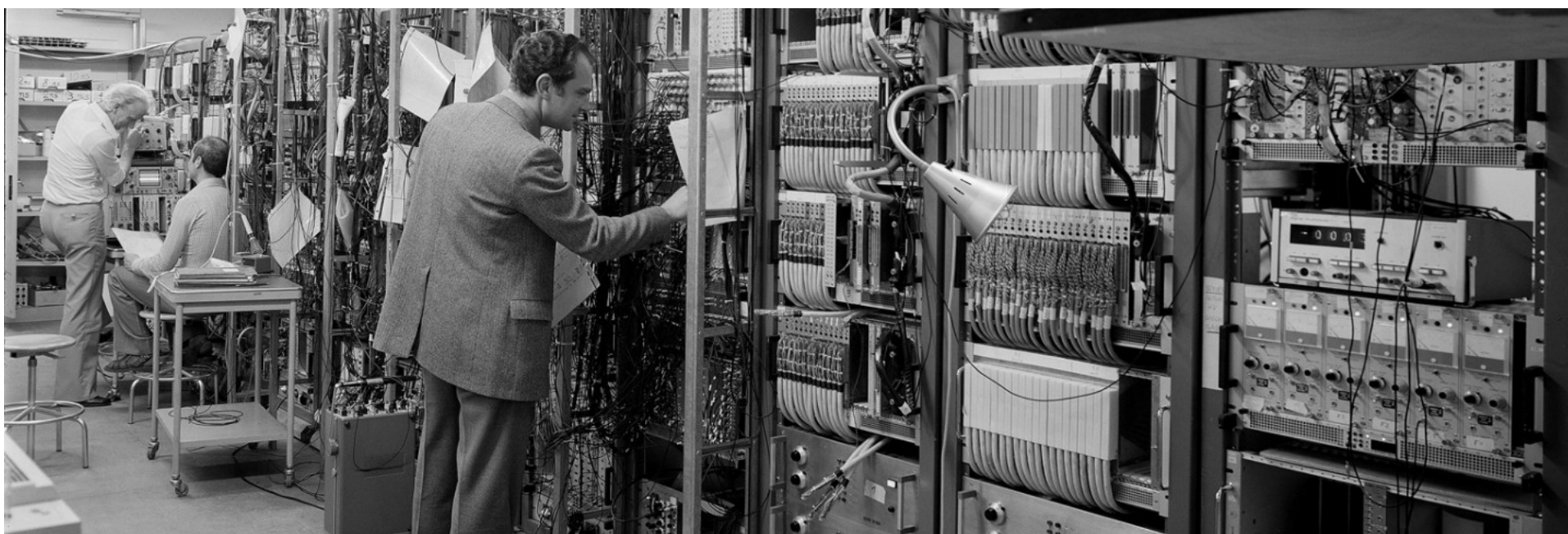




DAQ HW

Hands-on Approach



ISOTDAQ 2017: 8th International School of Trigger and Data Acquisition

Nikhef, 30 Jan 2017

Andrea.Negri@pv.infn.it

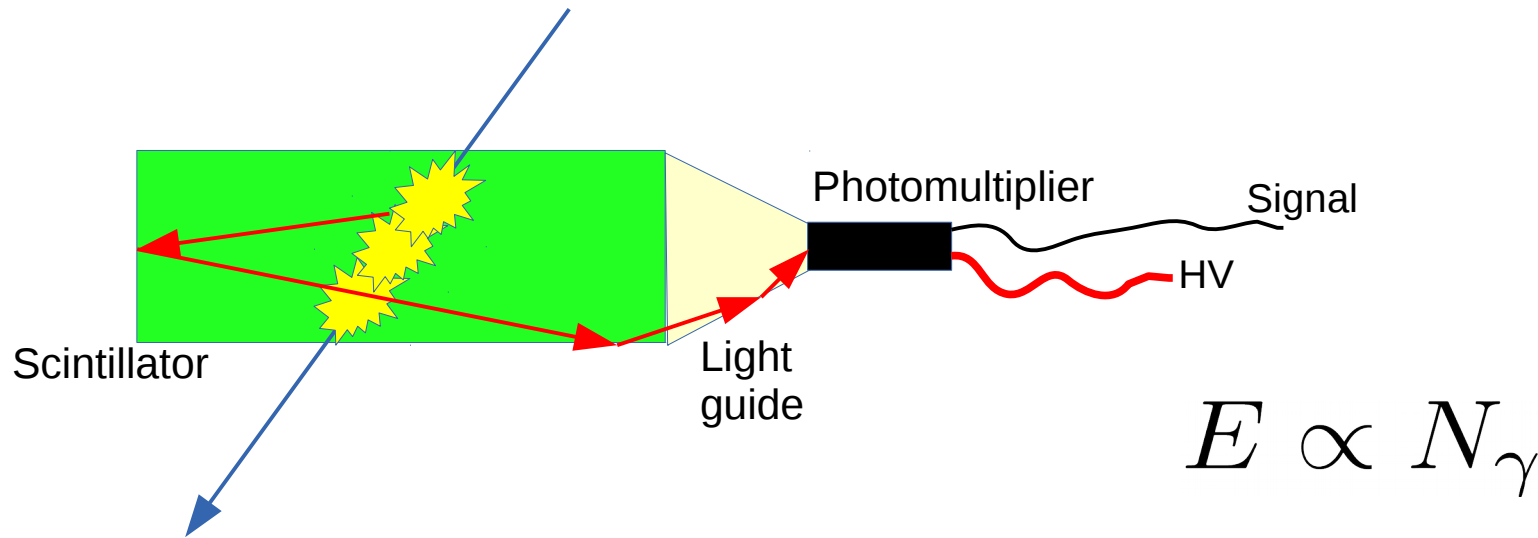
© Wainer Vandelli & Sergio Ballestrero

- 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

- 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

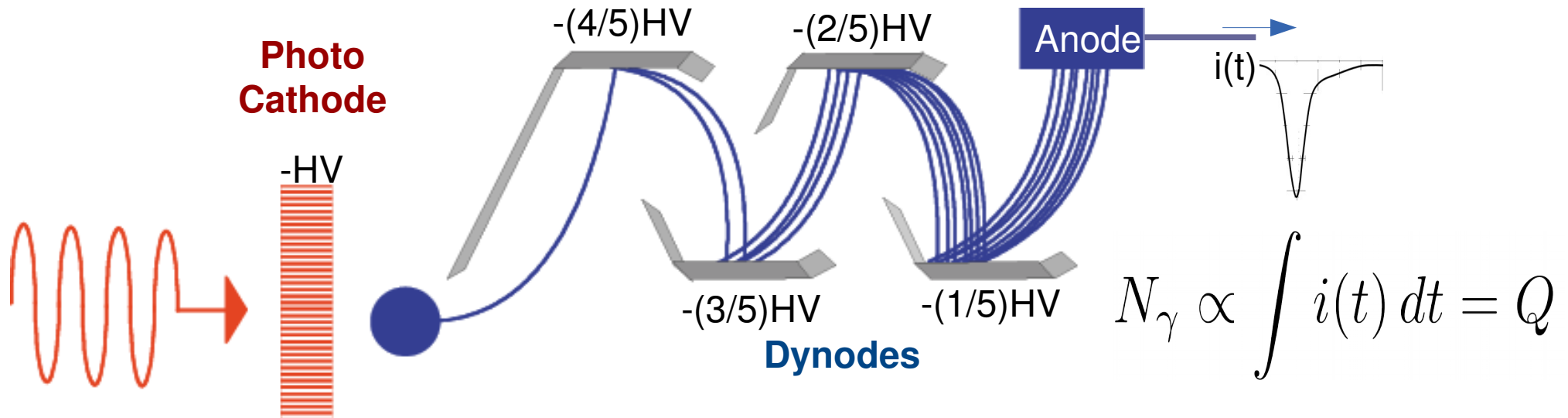


Energy measurement



- 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

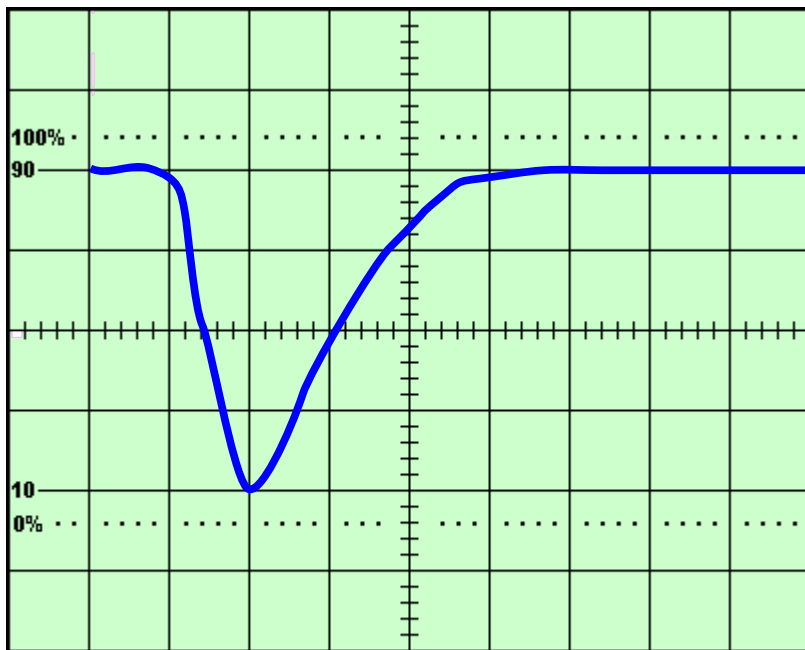


- **Photo cathode:** photon to electron conversion via photo-electric effect
 - typical quantum efficiency $\approx 1-10\%$ (max 30%), depends on material and wavelength
- **Dynodes:** electrodes that amplify number of electrons thanks to secondary emission
 - typical overall gain $\approx 10^6$
- **Dark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

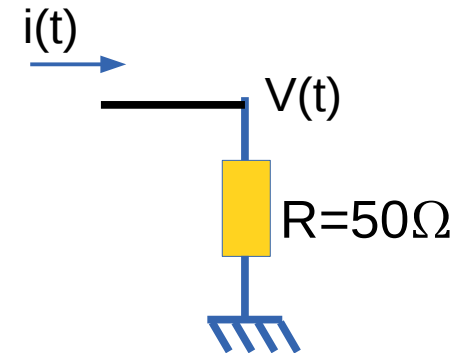
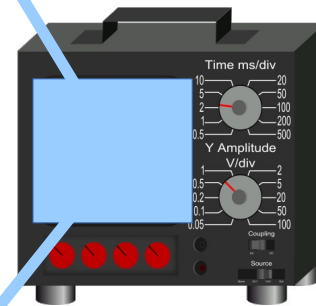


Start the measure

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



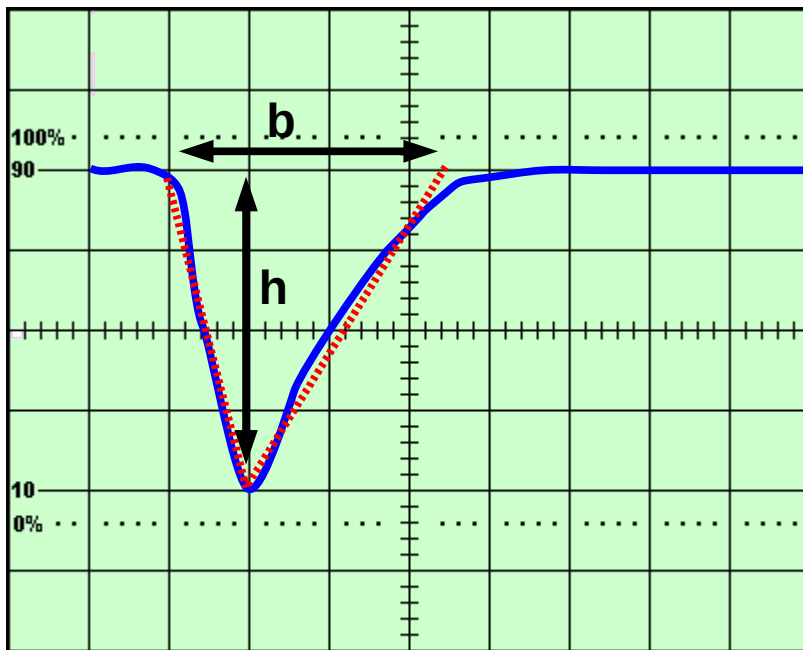
CH1: V/div 100mV Title:
CH2: V/div
Time/div: 20ns



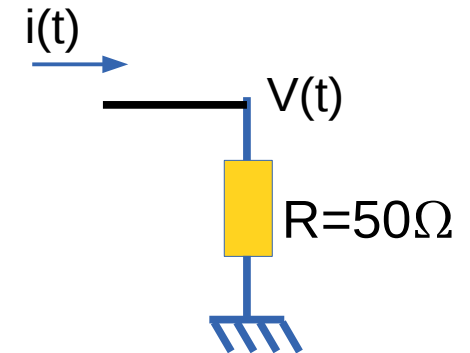
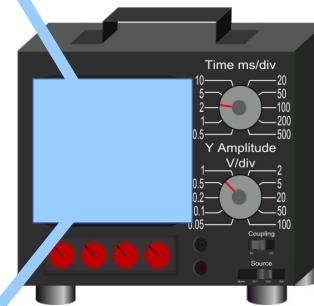
$$Q = \int i(t) dt = \frac{1}{R} \int V(t) dt$$

Good old oscilloscope

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



CH1: V/div 100mV Title:
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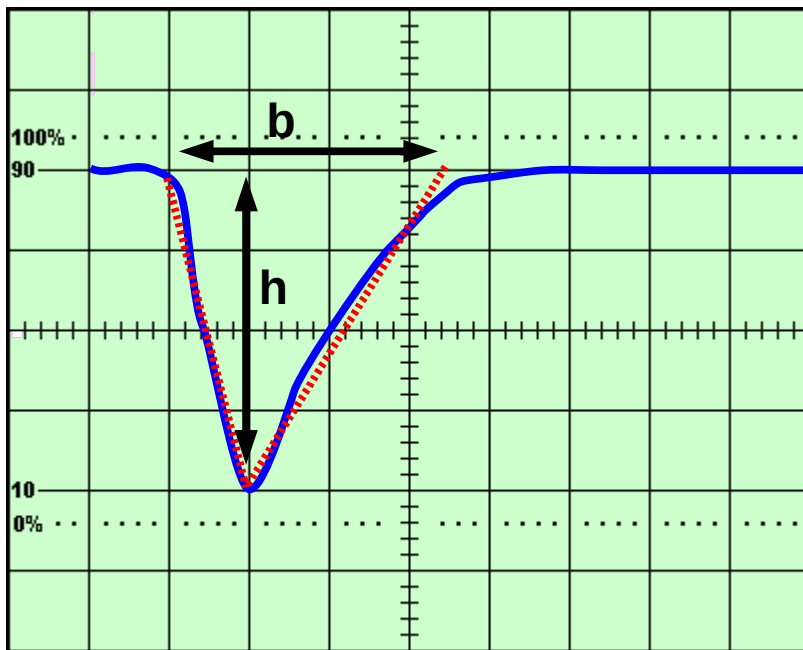


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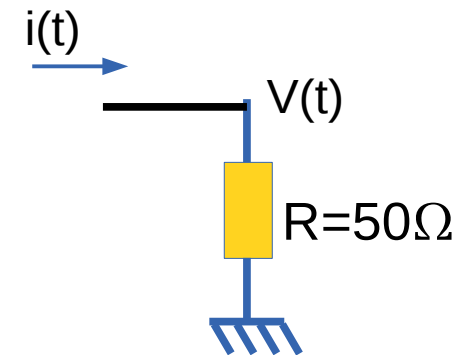
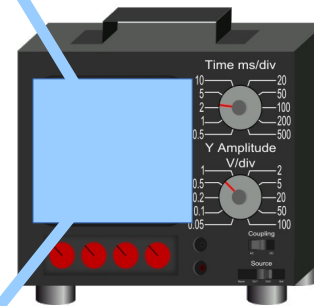
$$Q \approx \frac{1}{R} \frac{bh}{2} = \frac{1}{50\Omega} \frac{(3.5 \cdot (20\text{ns})) (4 \cdot (100\text{mV}))}{2} = 280\text{pC}$$

Good old oscilloscope

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



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Good old oscilloscope

- Approximate Q measurement using oscilloscope
 - Linear approximation of an exponential decay
- Easy, but
 - Deadtime 5 min, $\sim 3 \times 10^{-3}$ 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!

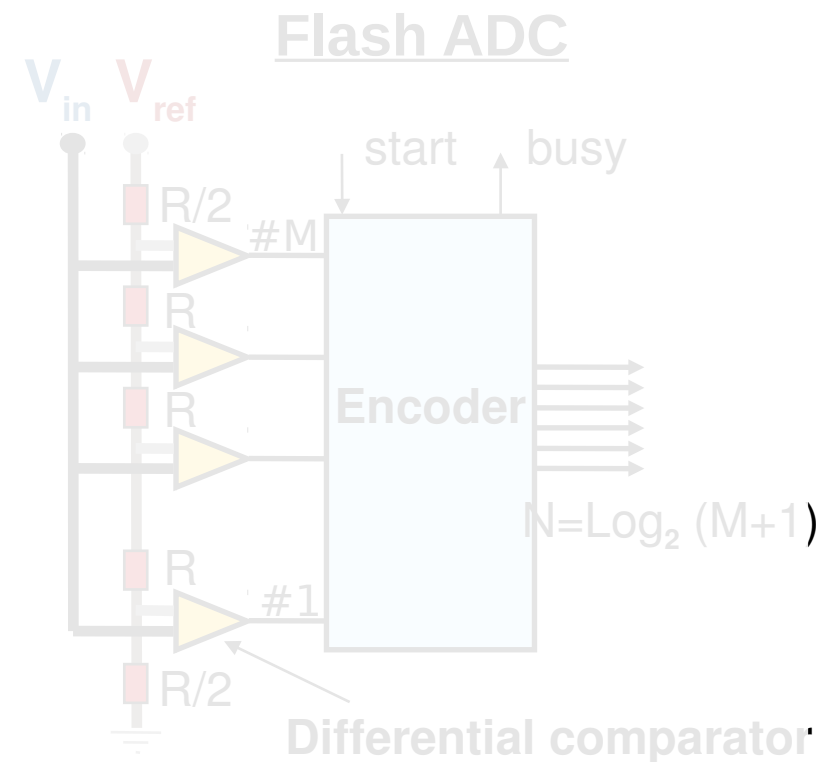
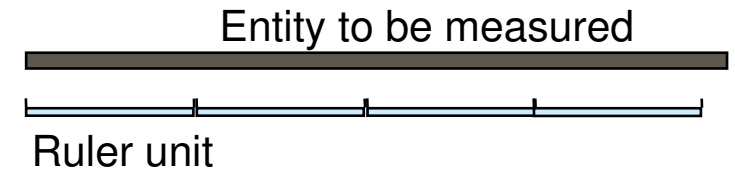


Analog to Digital Conversion

- Digitization

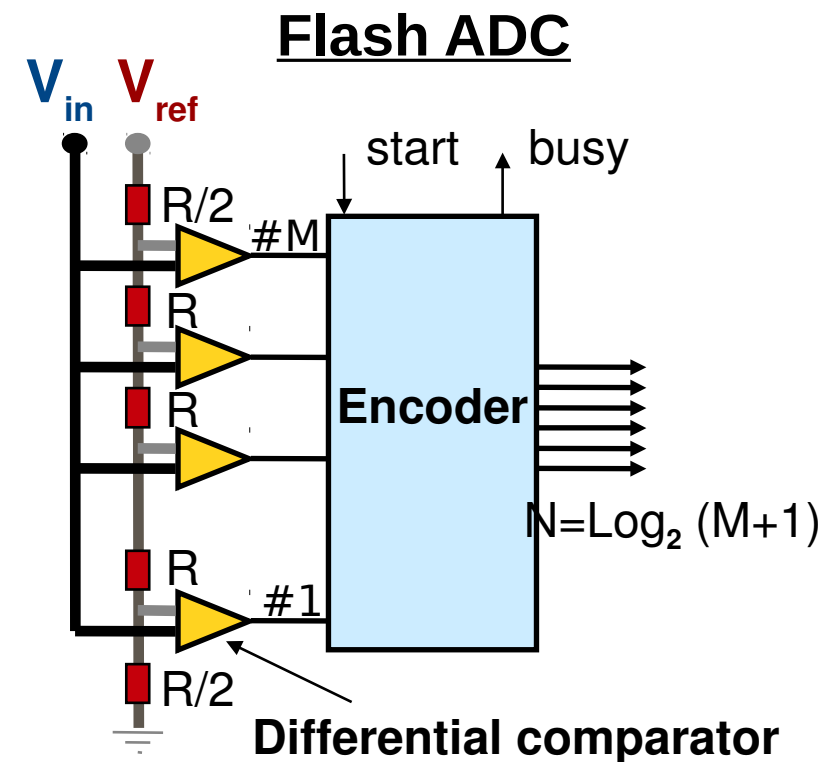
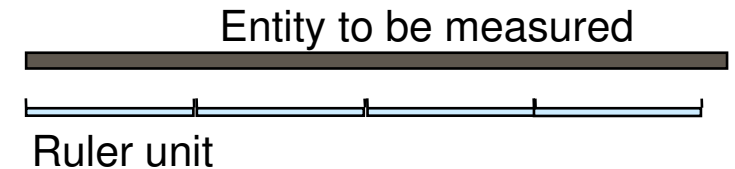
Lab 8

- 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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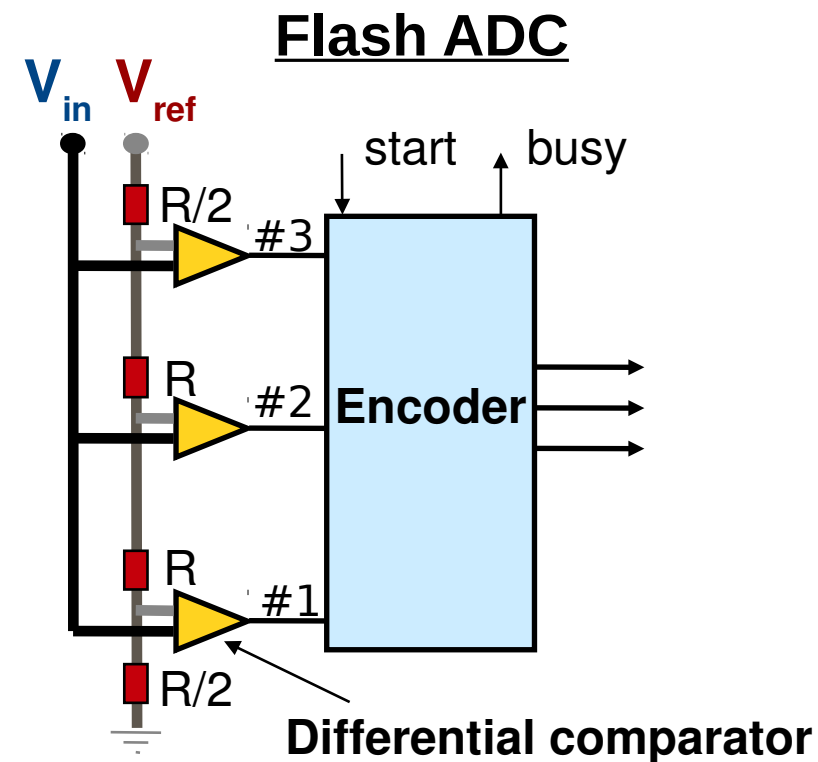


Analog to Digital Conversion

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 - Encoding an analog value into a binary representation
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- Flash ADC simplest and fastest implementation

$x = V_{in}/V_{ref}$	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

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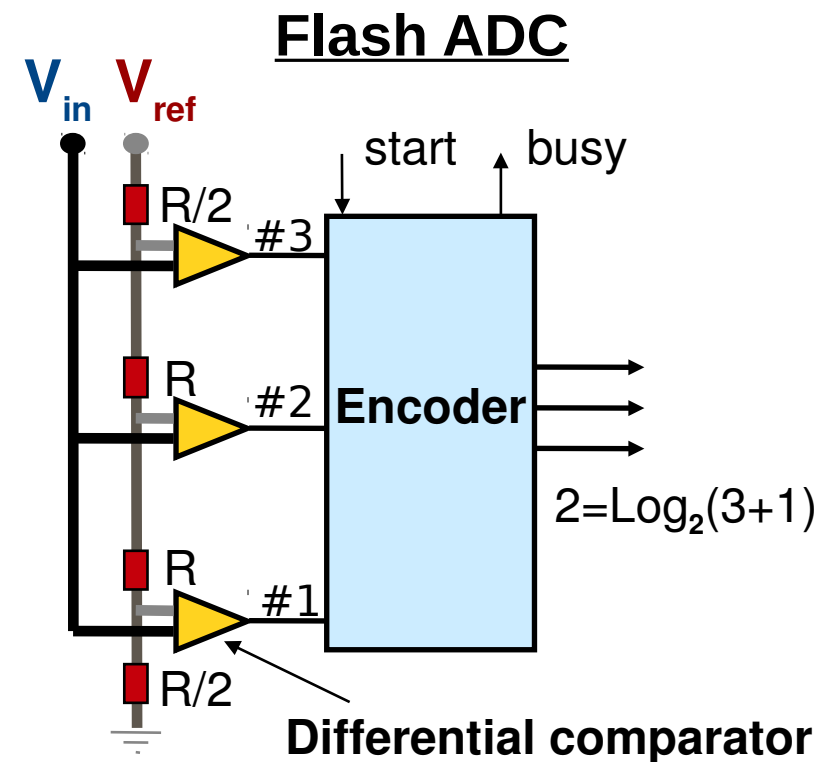
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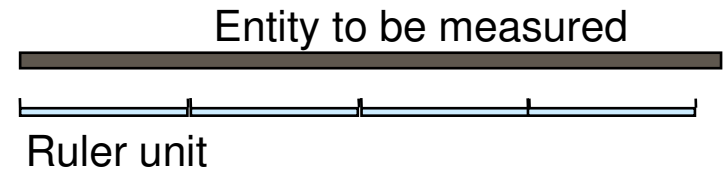
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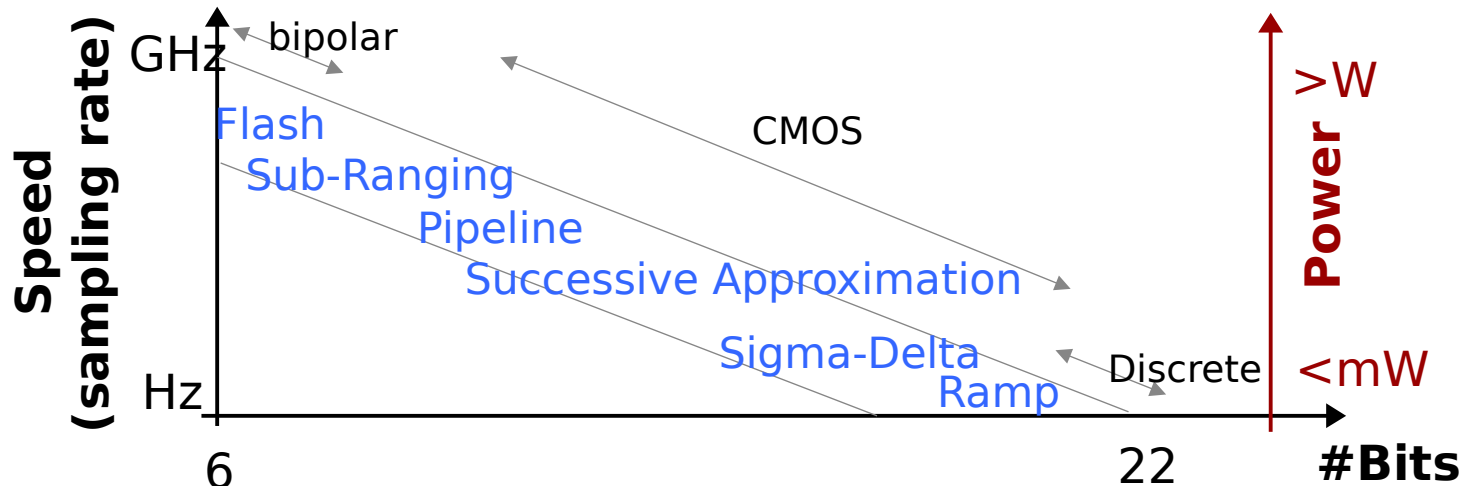
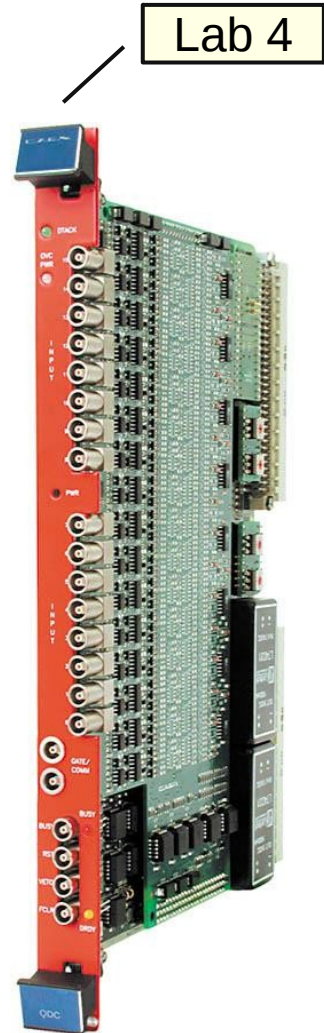


ADC Characteristics

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

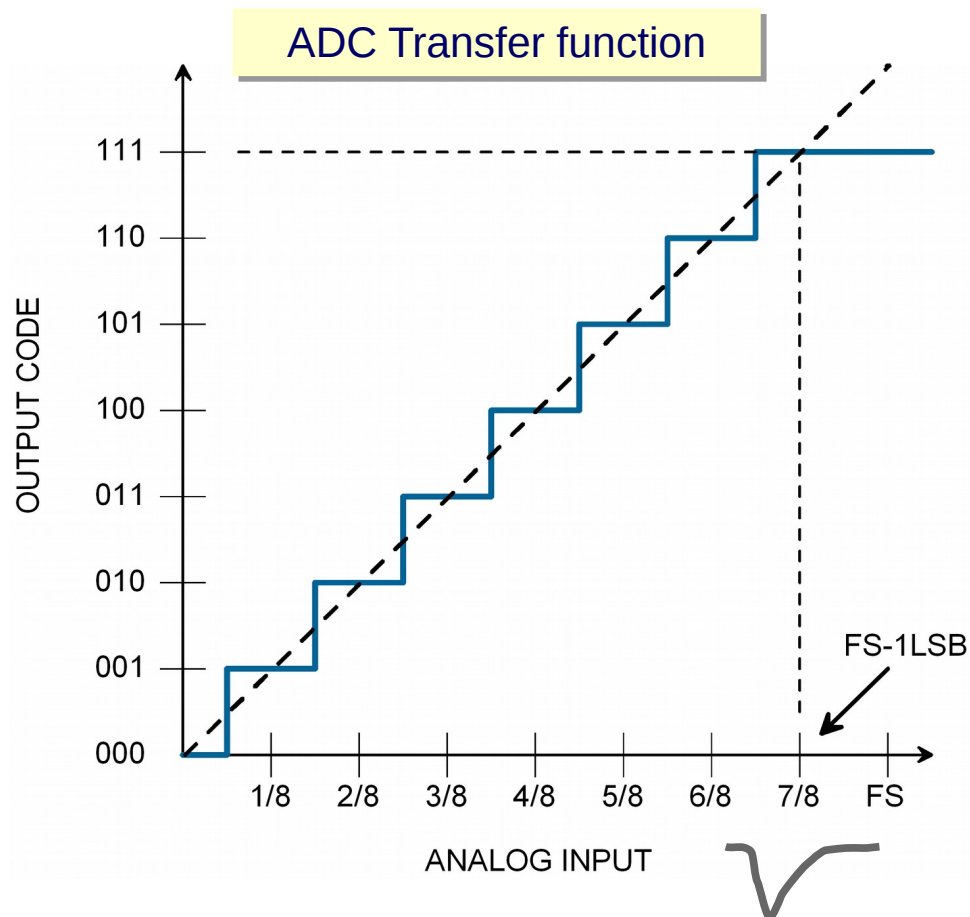


Lab 4



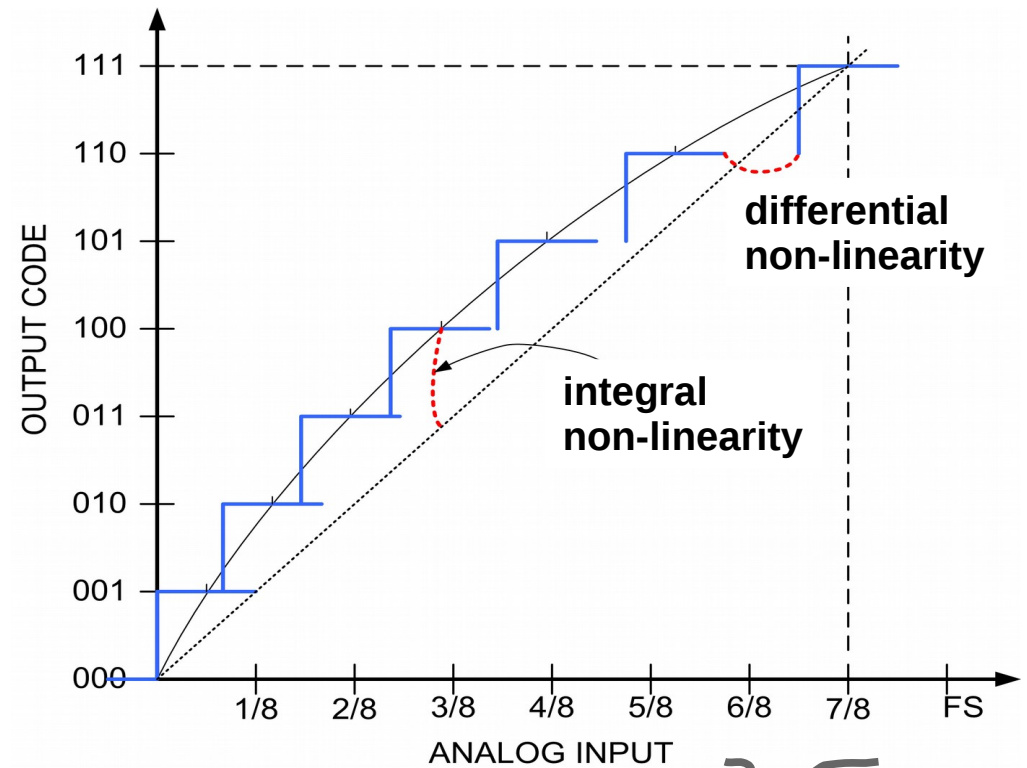
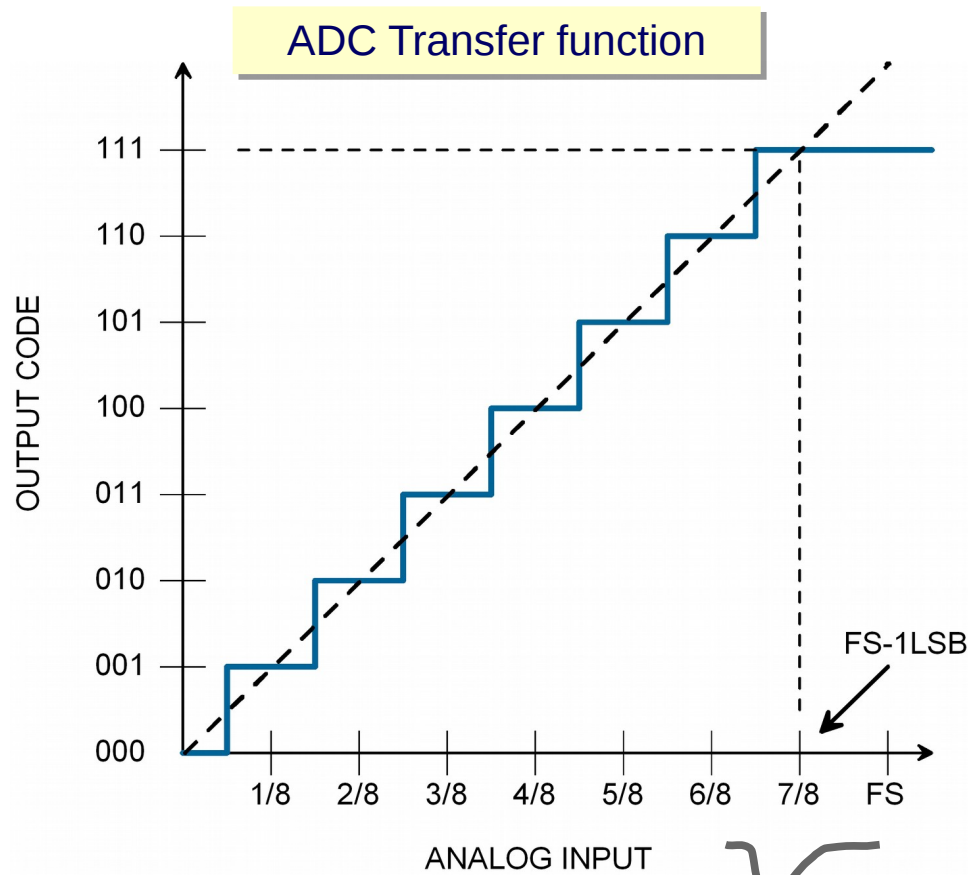
ADC Accuracies

- ADC transfer function
 - Output code vs analog input



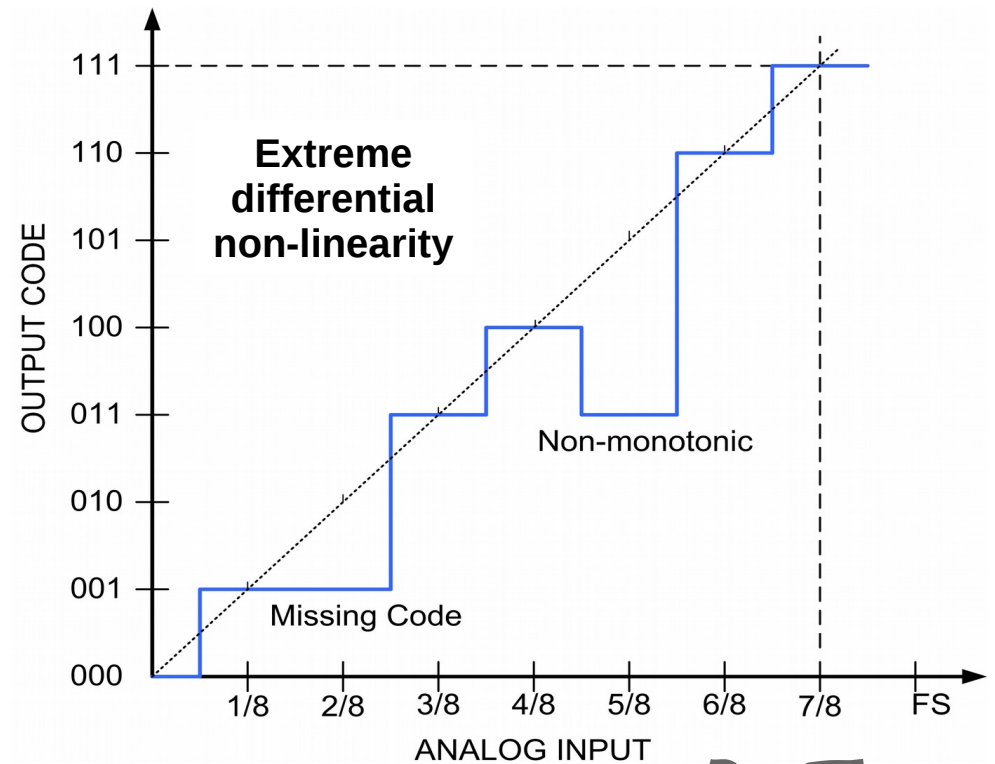
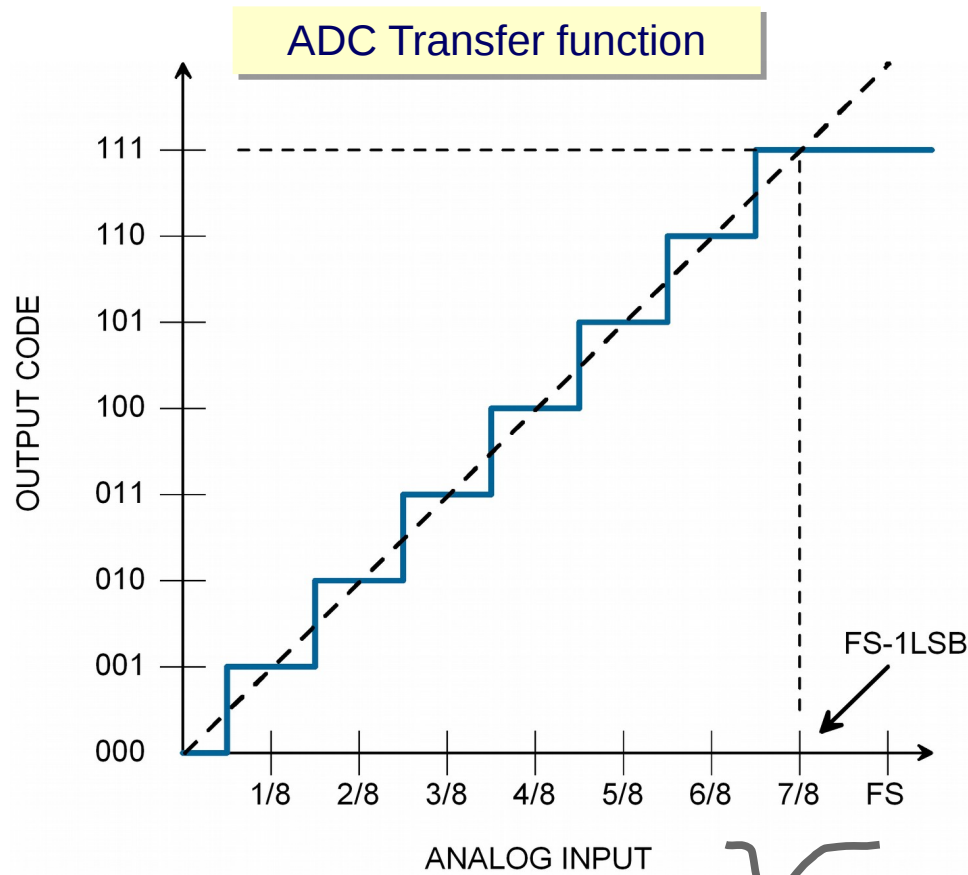
ADC (In)Accuracies

- ADC transfer function
 - Output code vs analog input



ADC (In)Accuracies

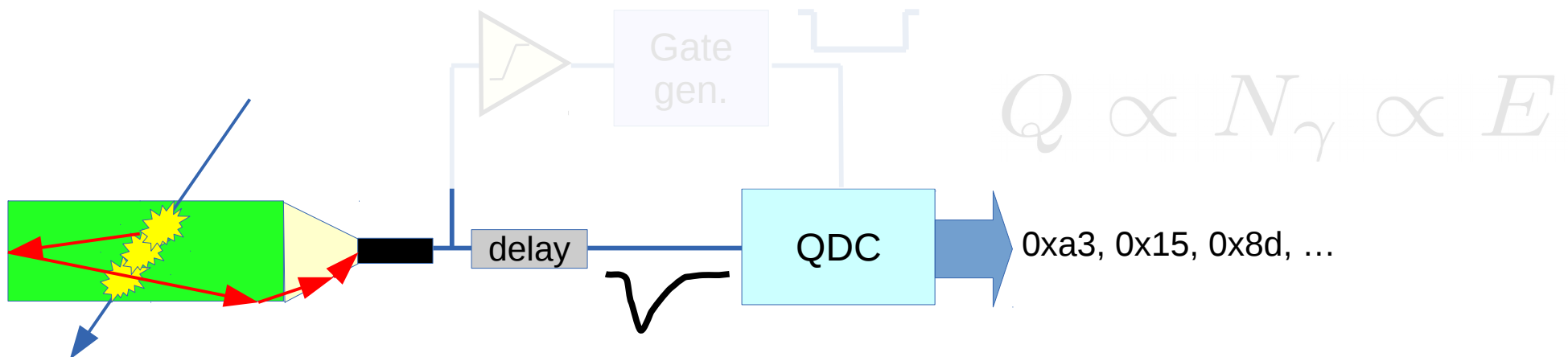
- ADC transfer function
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Charge to Digital

- 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

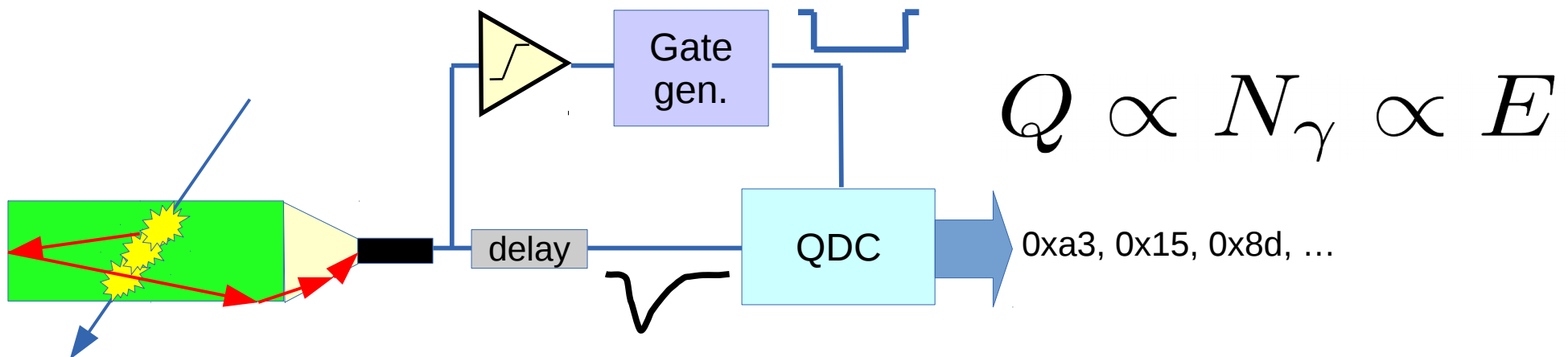
$$I = \int_a^b f(x) dx$$



Charge to Digital

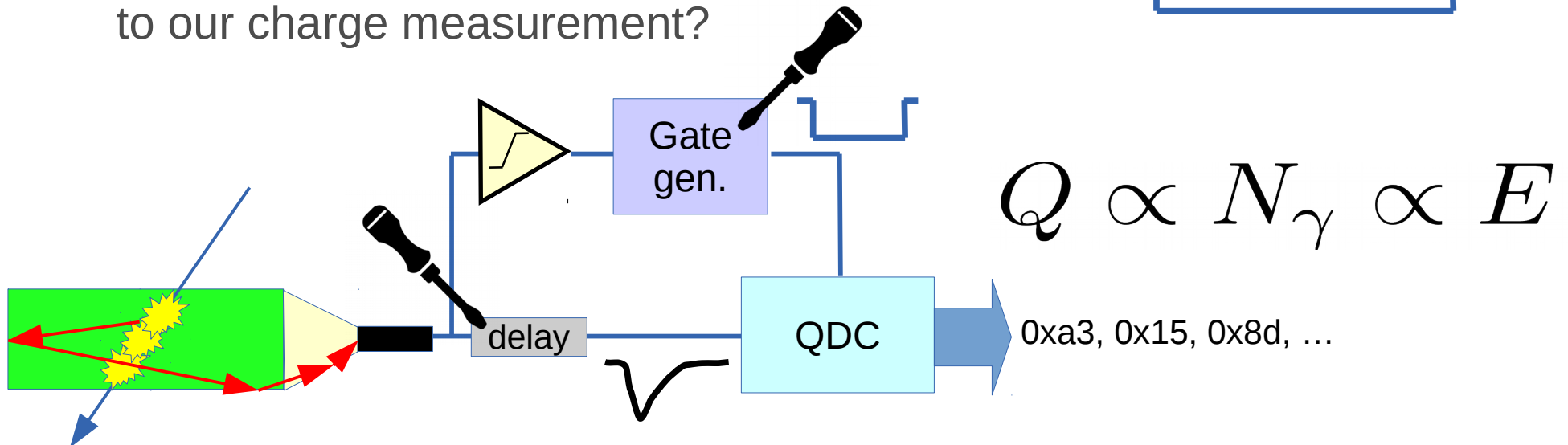
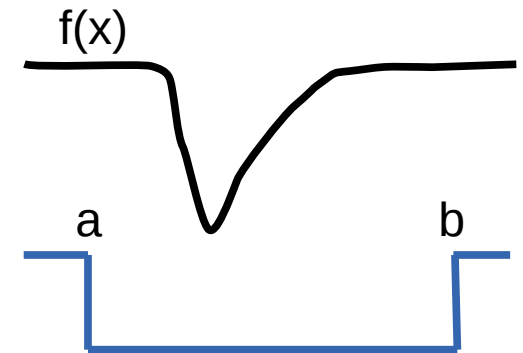
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QDC: timing

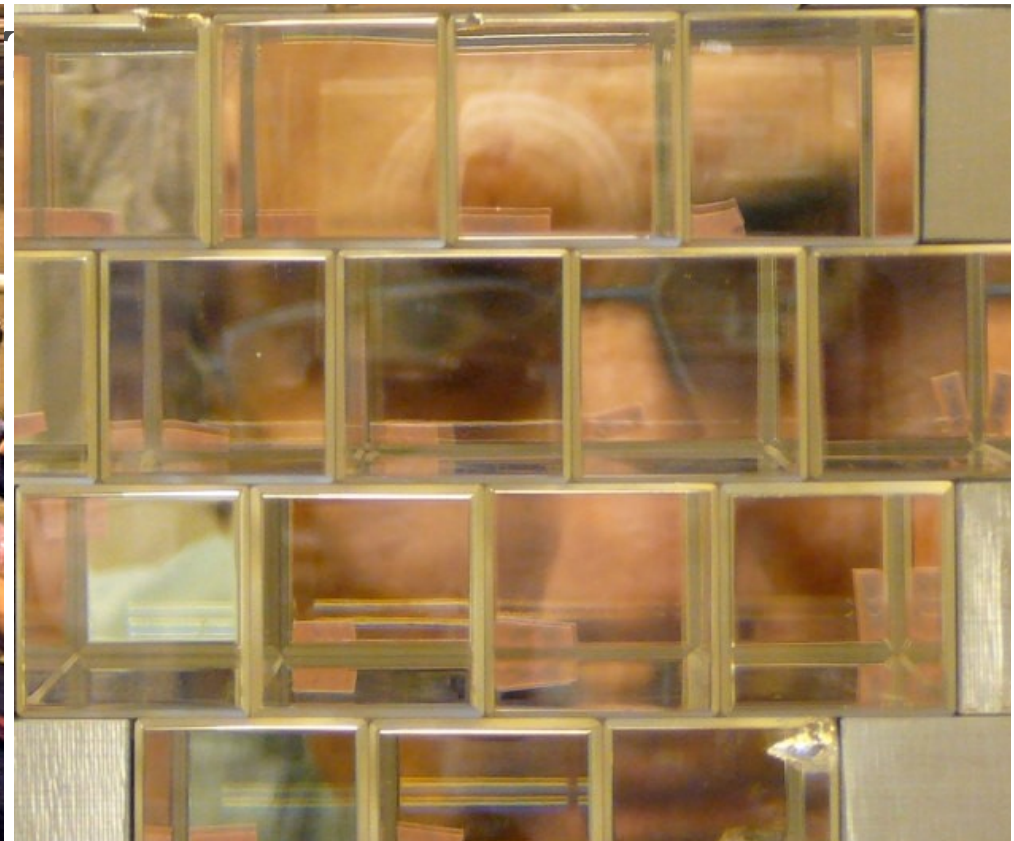
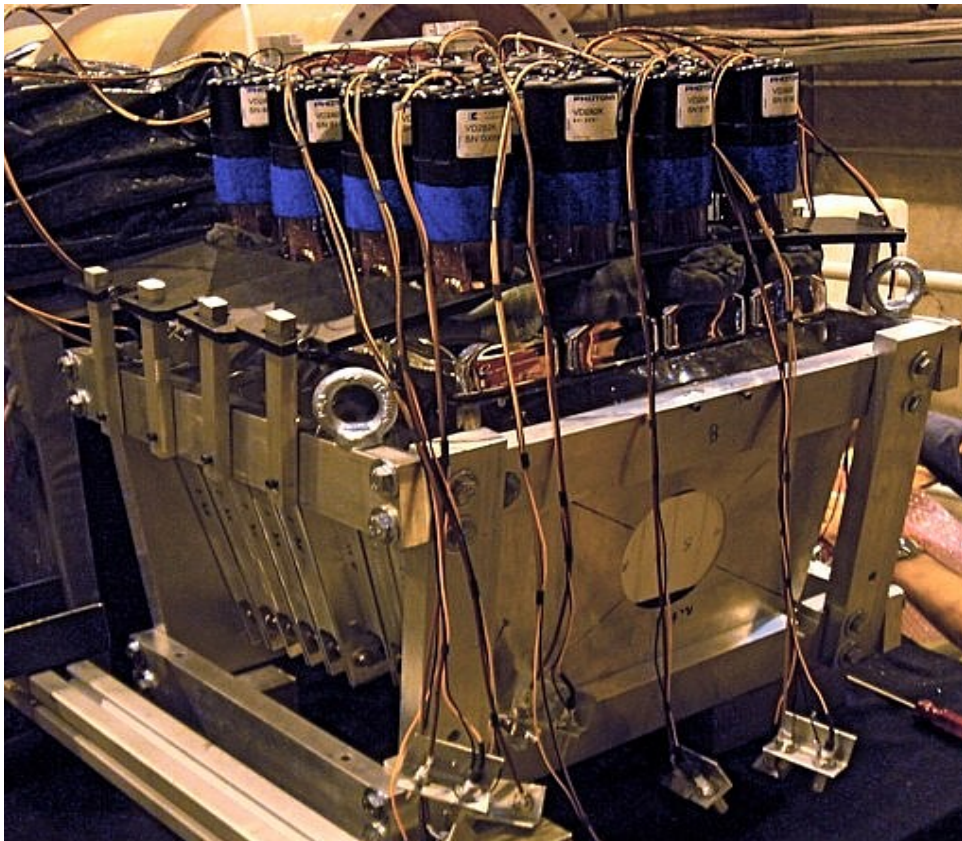
- Relative timing between signal and gate is important
 - Delay tuning Labs 2, 3, 4
- Gate should be **large enough** to contain the full pulse and to accommodate for the jitter
 - Fluctuations are always with us!
- Gate should **not be too large**
 - Increases the noise level
 - By the way, which is the noise contribution to our charge measurement?



Example of QDC data

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

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



QDC spectra

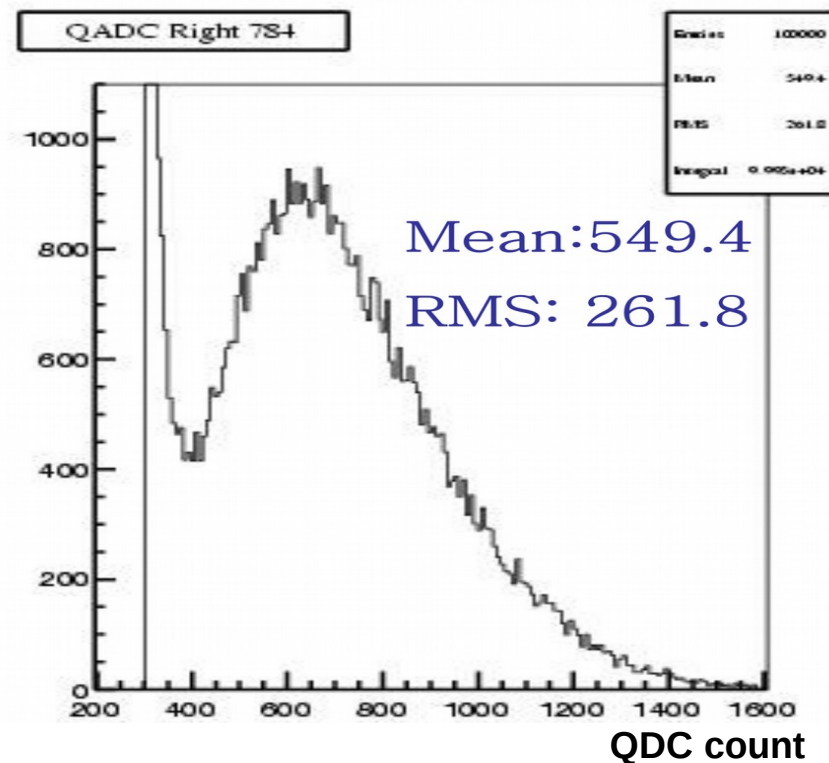
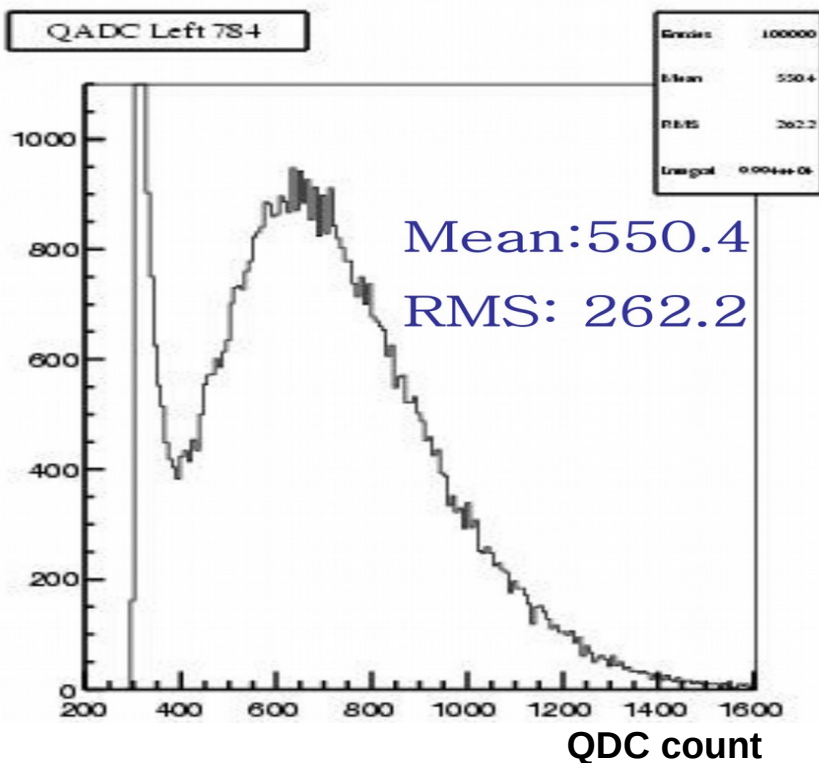
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$$Q \propto N_{\gamma} \propto E$$

- But, what is the 1st peak?

- How can we estimate it?



QDC spectra

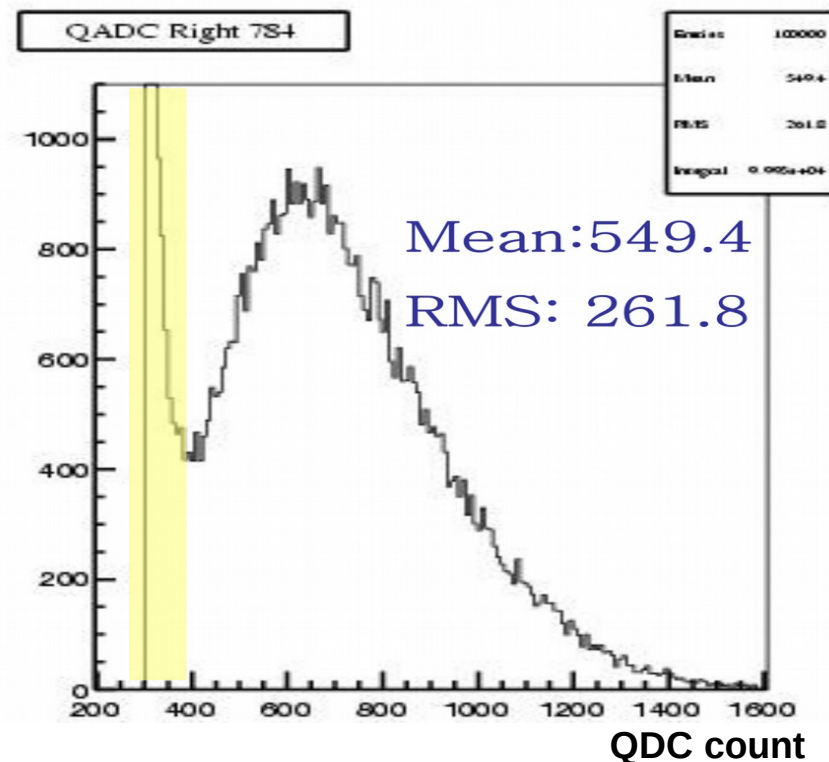
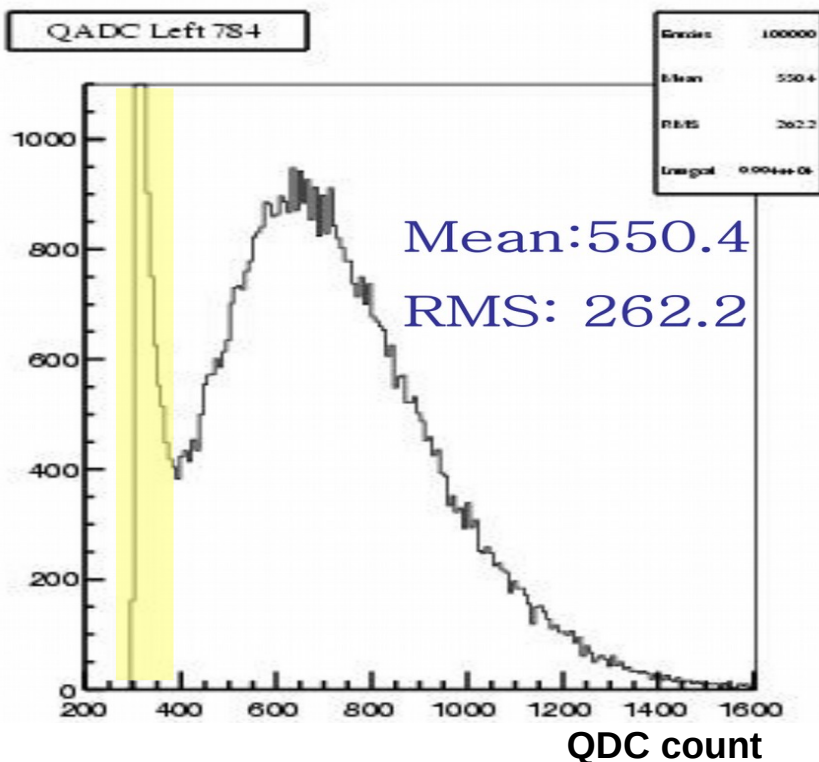
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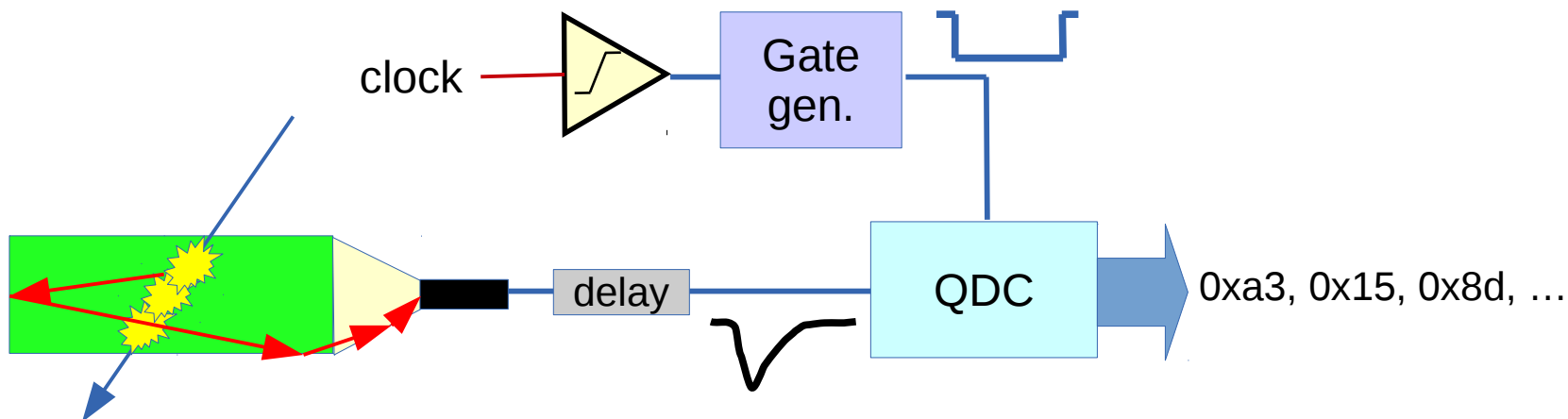
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QDC: pedestal subtraction

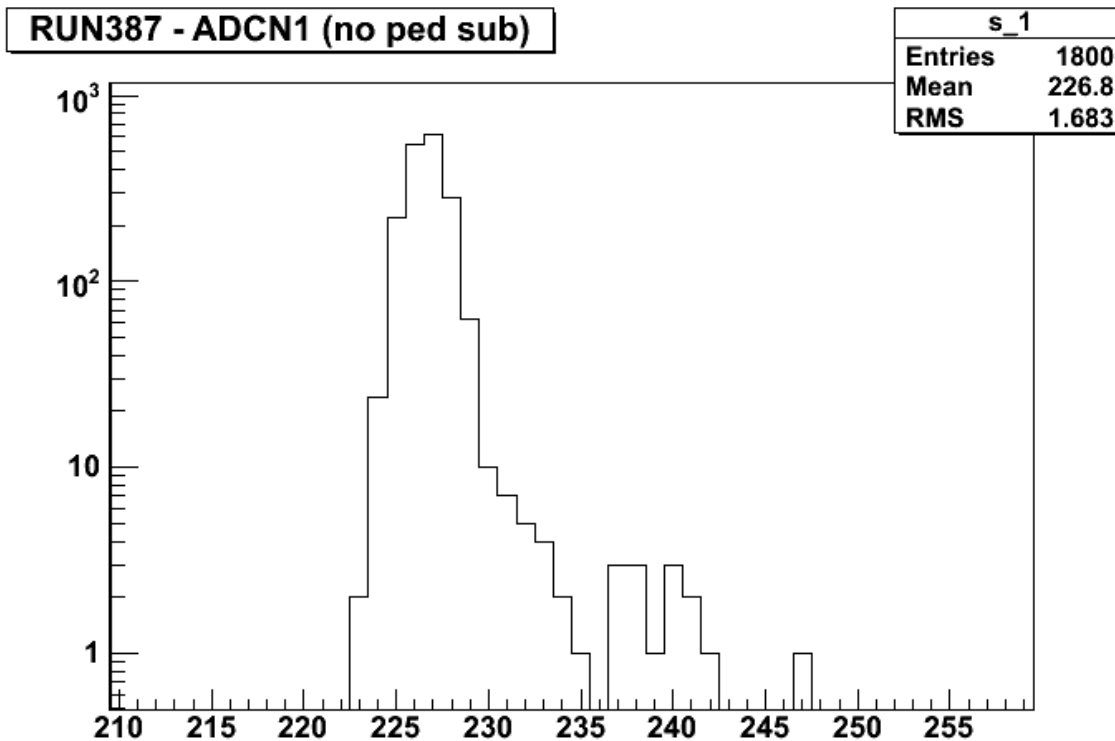
- The **pedestal** can be measured with an out-of-phase trigger
 - PMT dark current, thermal noise, ...
 - The same noise enters our physics measurements and contributes with an offset to the distribution
- The result of a pedestal measurement has to be subtracted from our charge measurements



QDC: pedestal subtraction



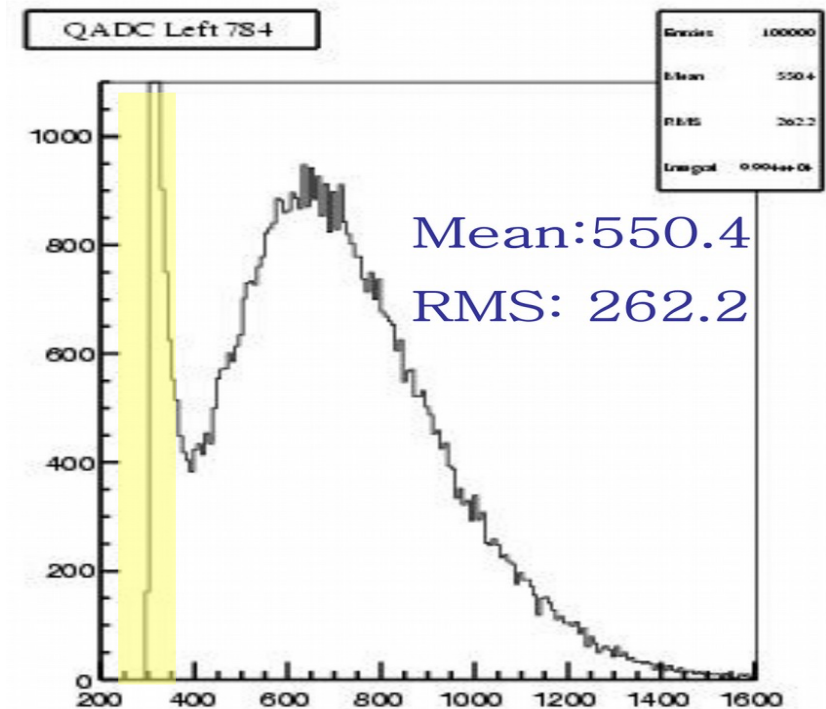
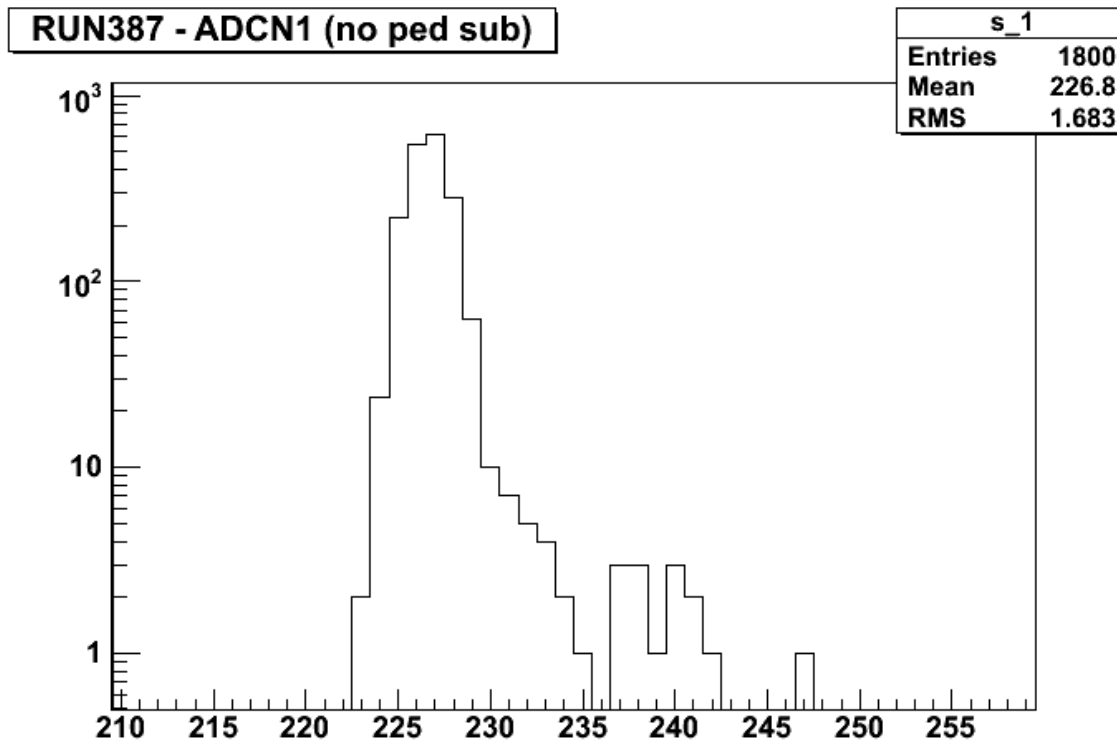
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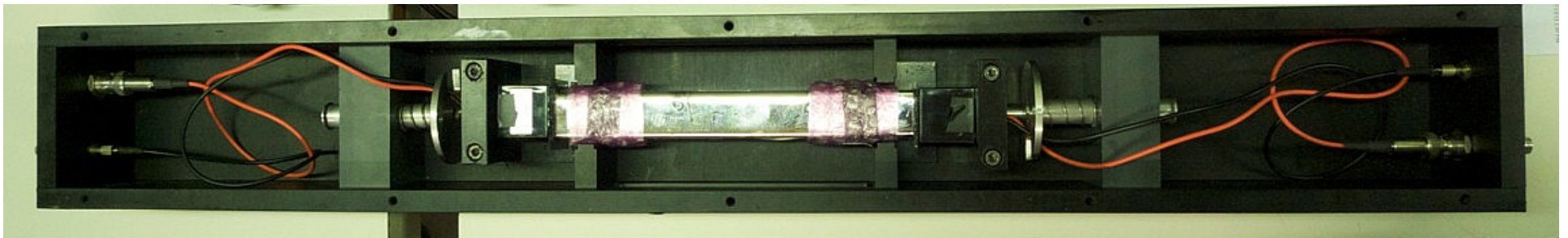
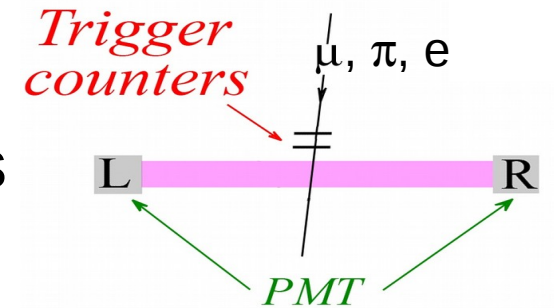


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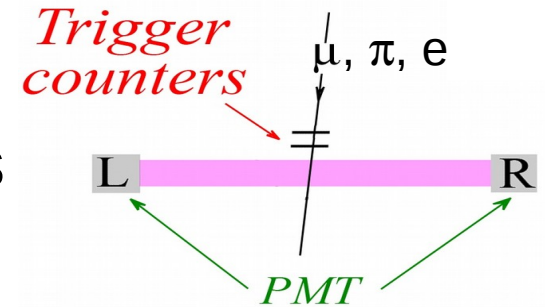
“Real” QDC at work

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

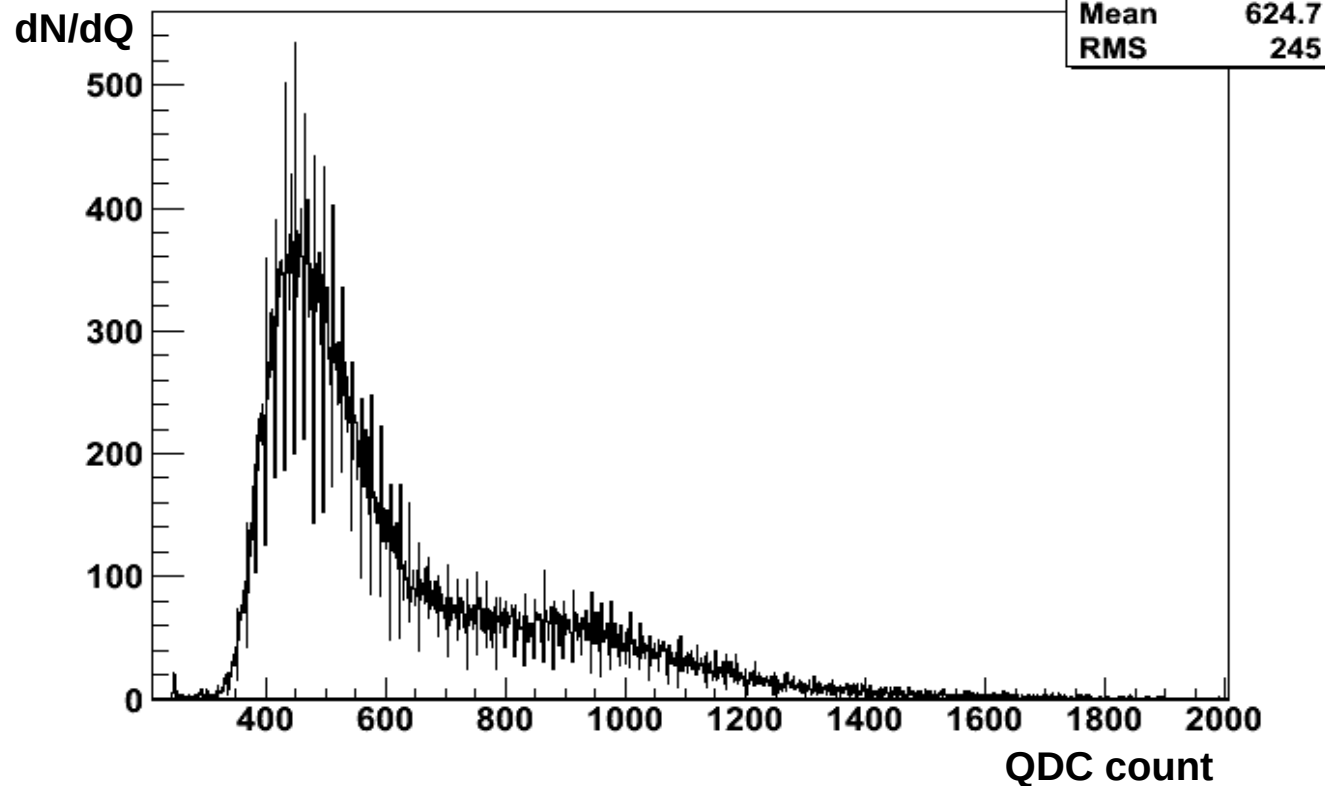


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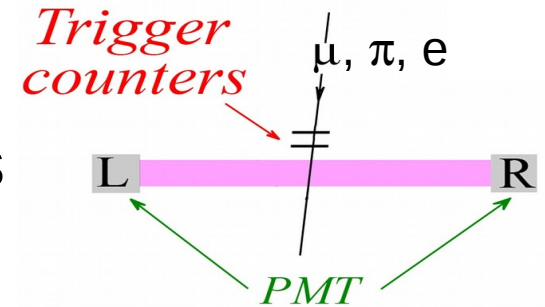


π -beam charge-distribution for one PMT

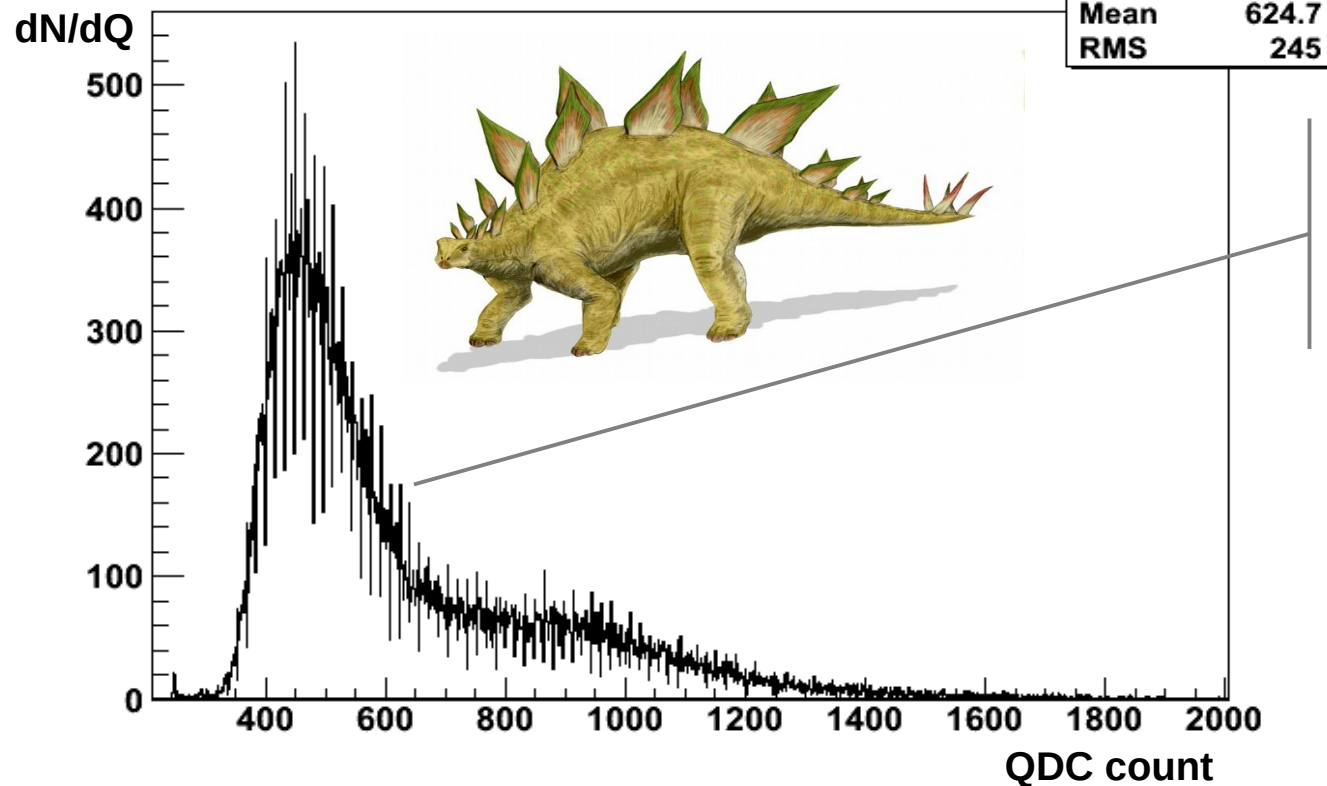


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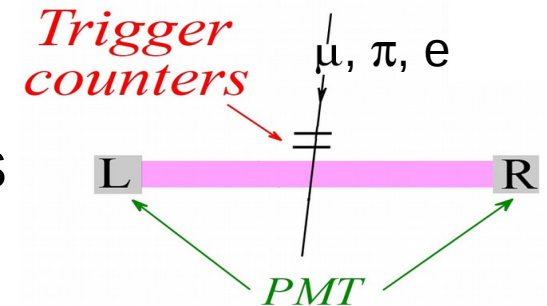


But, what are all those little peaks? Just statistical fluctuations?

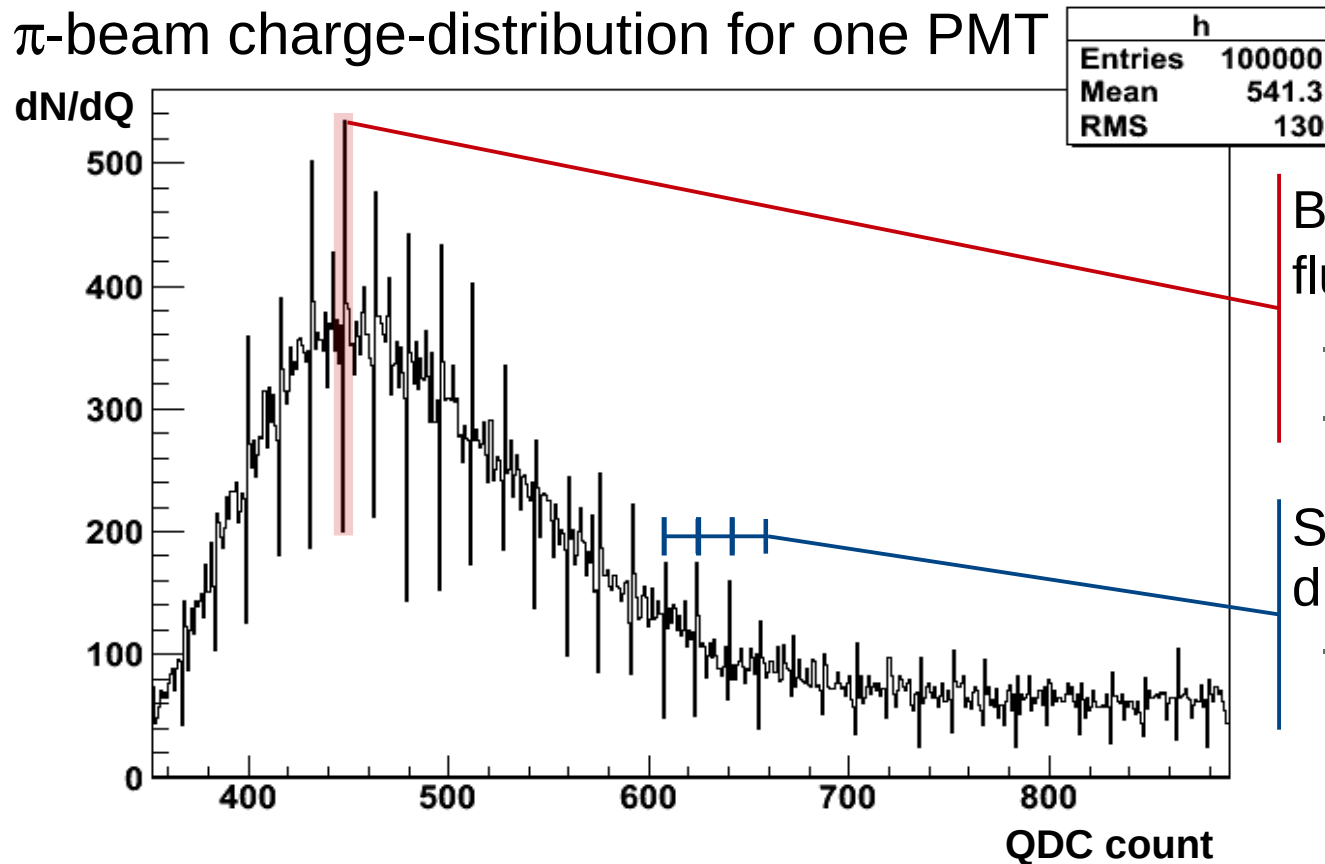
Let's zoom in!

“Real” QDC at work

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π -beam charge-distribution for one PMT



Bin with N entries can fluctuate with $\sigma = \sqrt{N}$

- expected $\sigma = \sqrt{360} \sim 19$
- observed ~ 200 (**10 σ**)

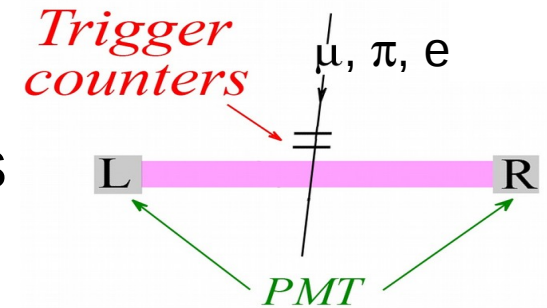
Spikes are regularly distributed

- Some systematic effect must be taking place

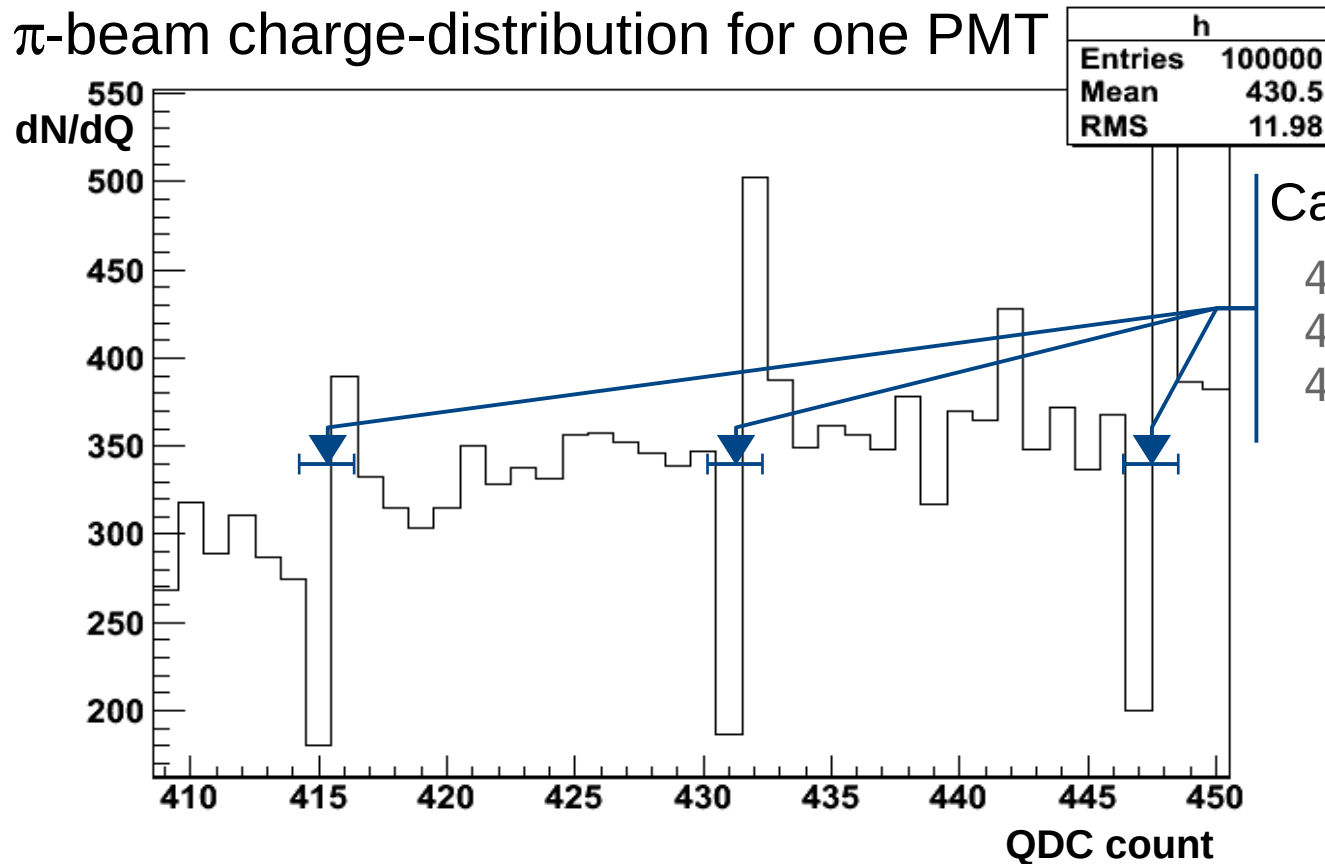
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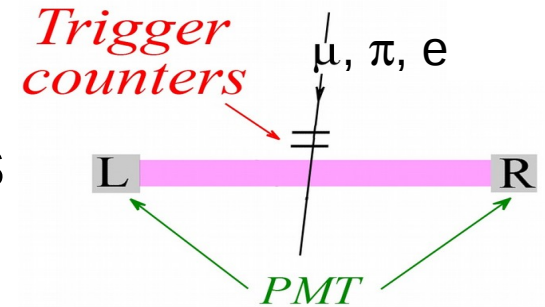


Can you see the effect?

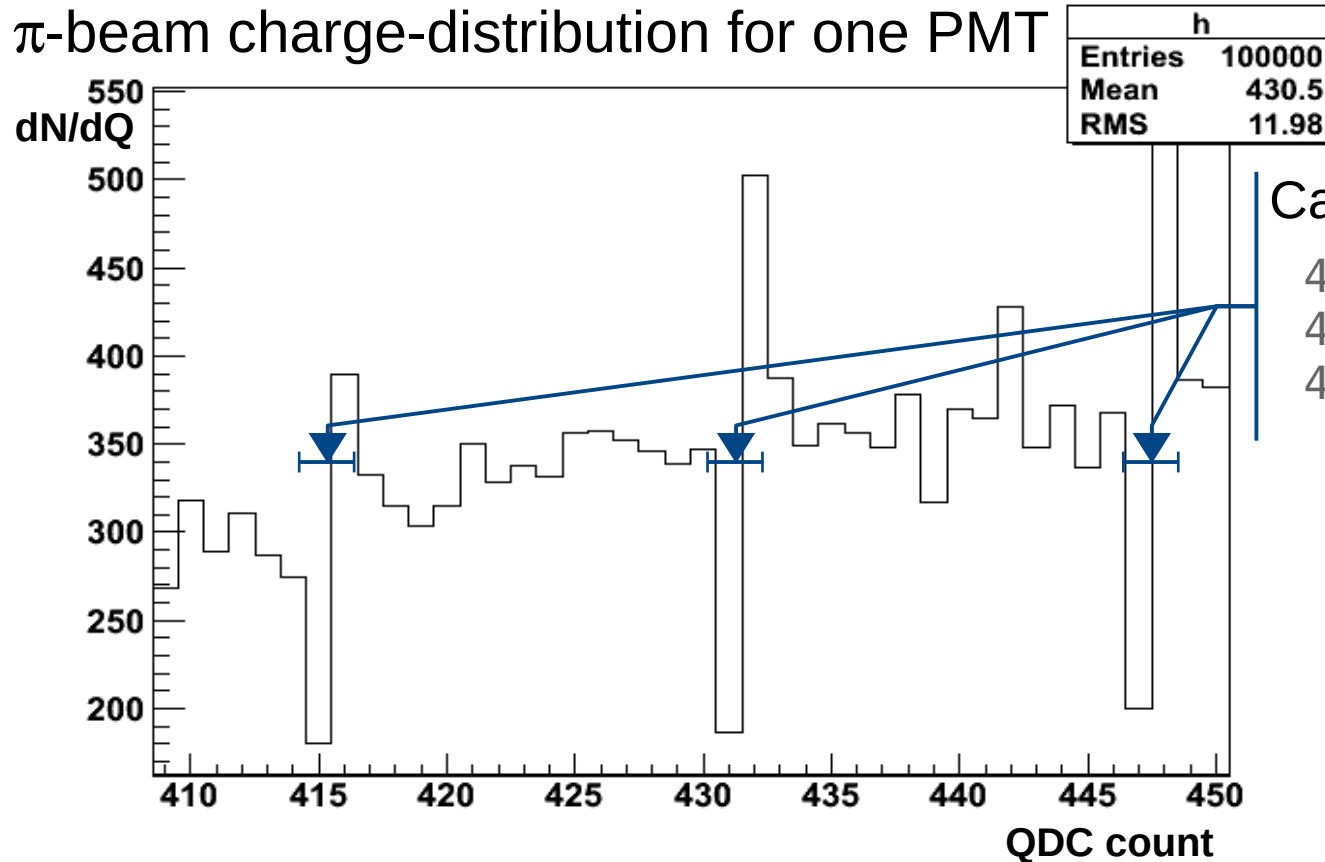
415 & 416
431 & 432
447 & 448

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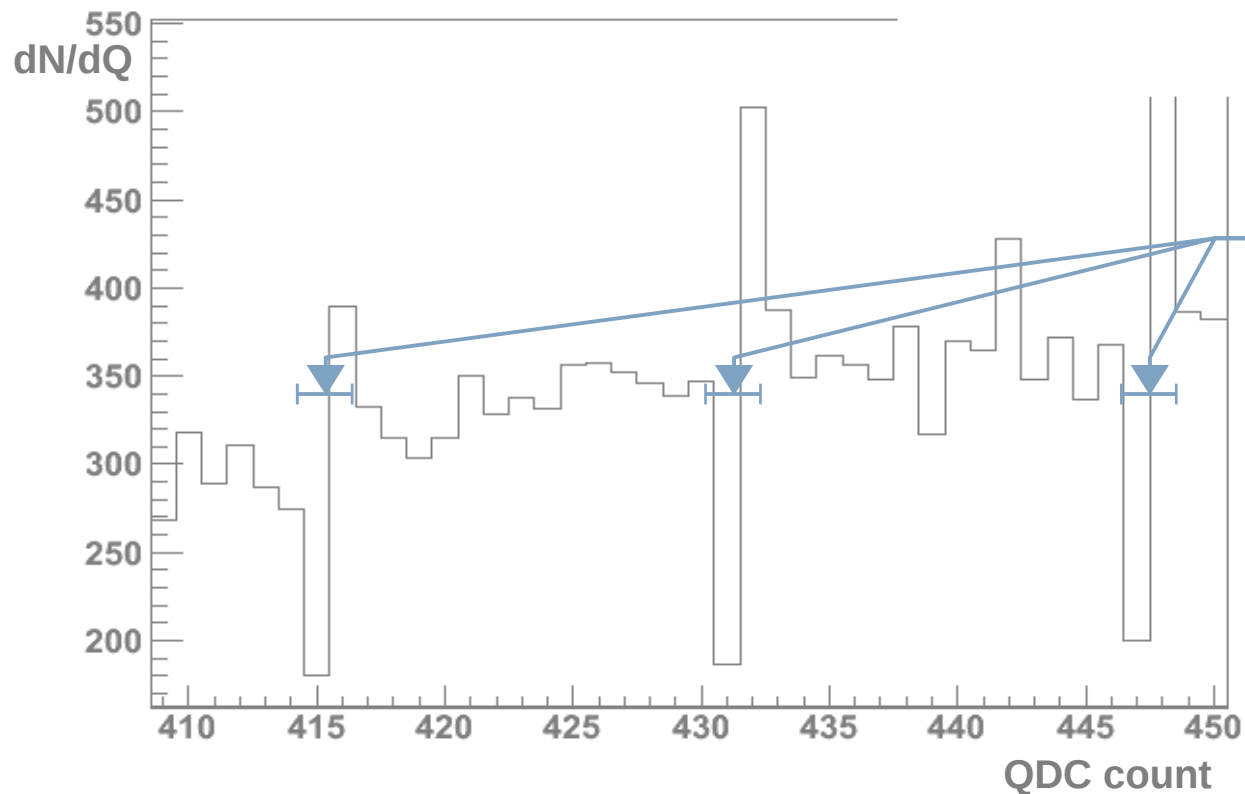
Can you see the effect?

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.. **β 0**
 in respect of 0x.. **α f**
 where $\beta = \alpha + 1$

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?

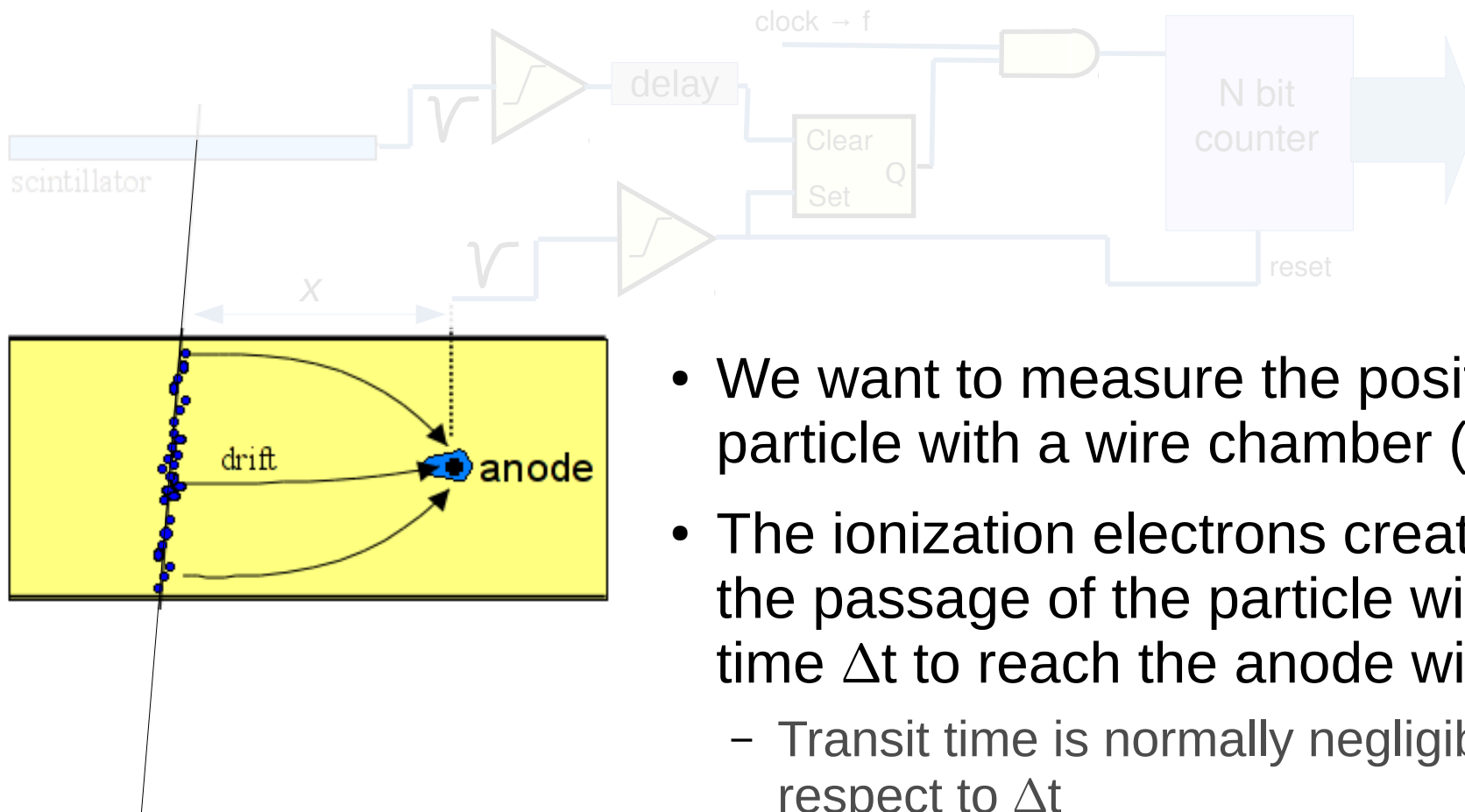
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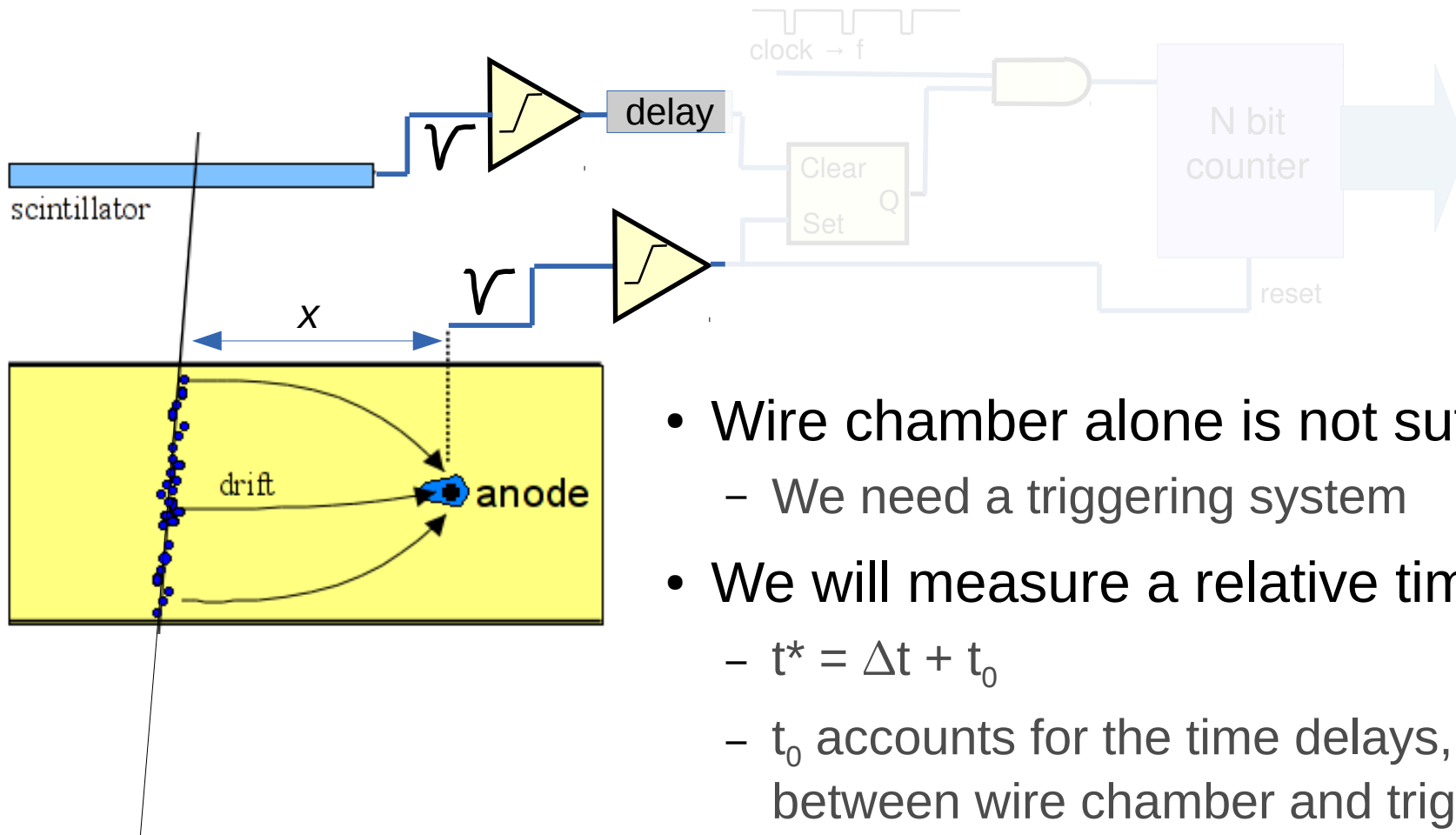
Position measurement



- 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.: $50 \mu\text{m/ns}$), then position is:

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

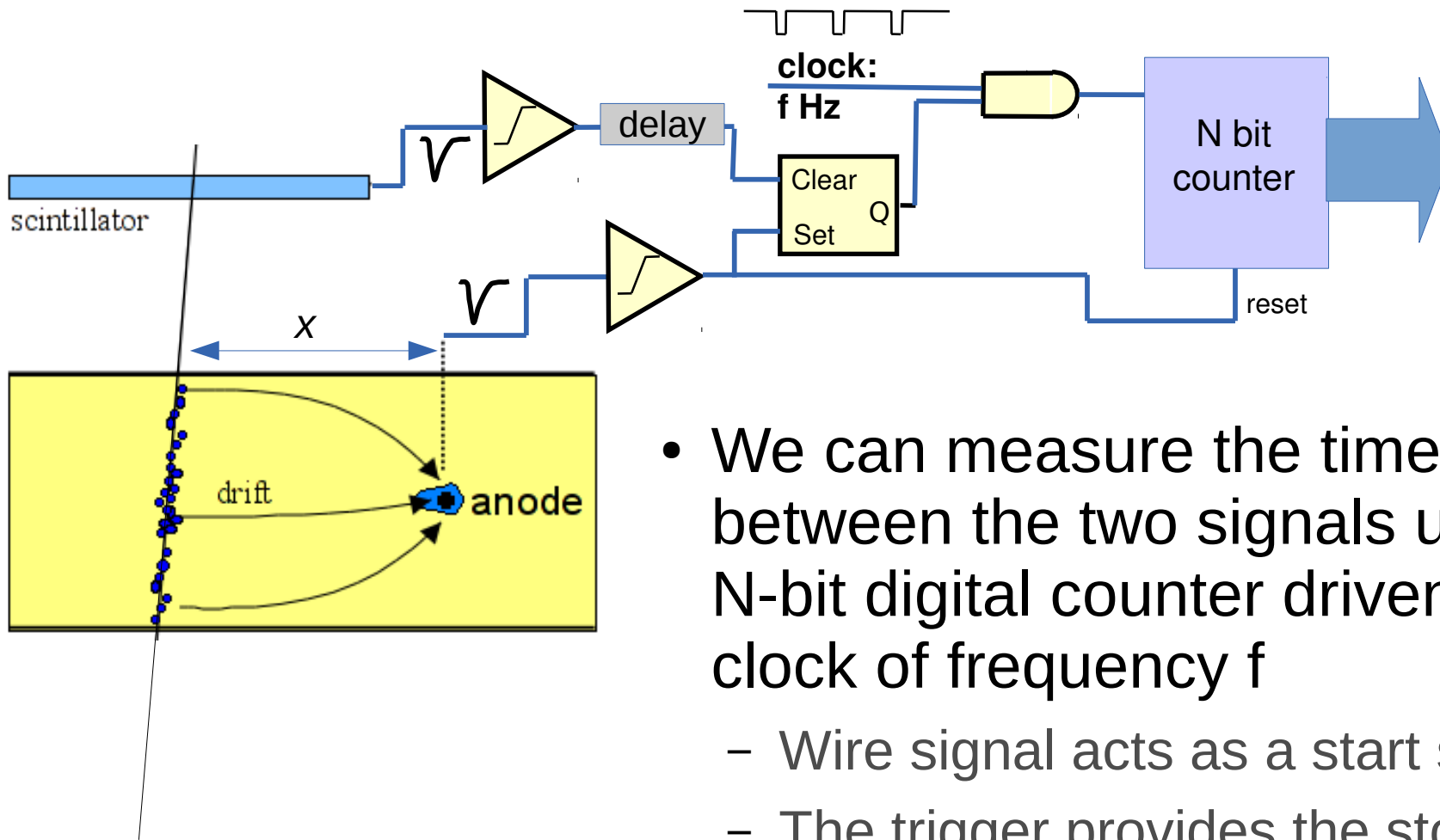
Triggering



- 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

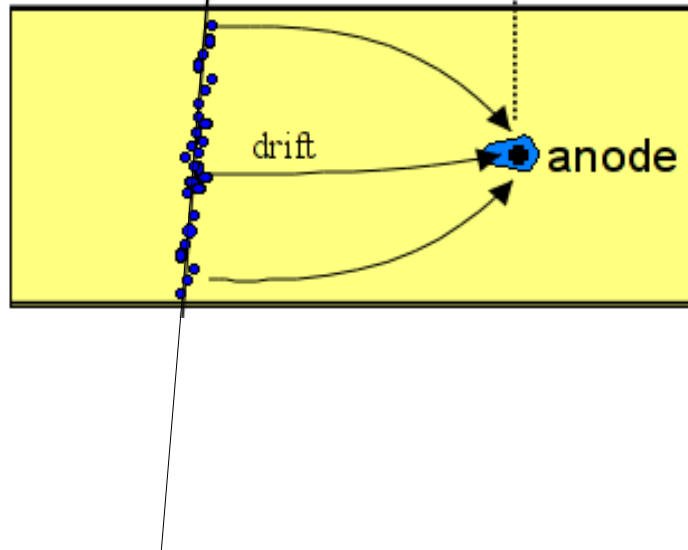
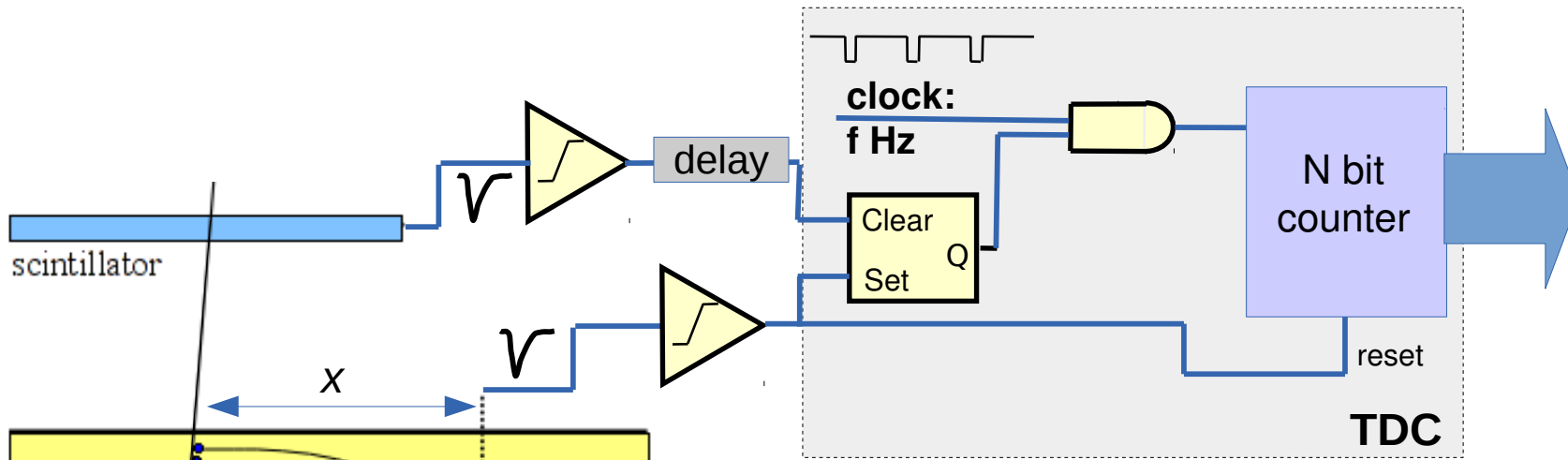
$$x = \alpha t^* + \beta$$

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



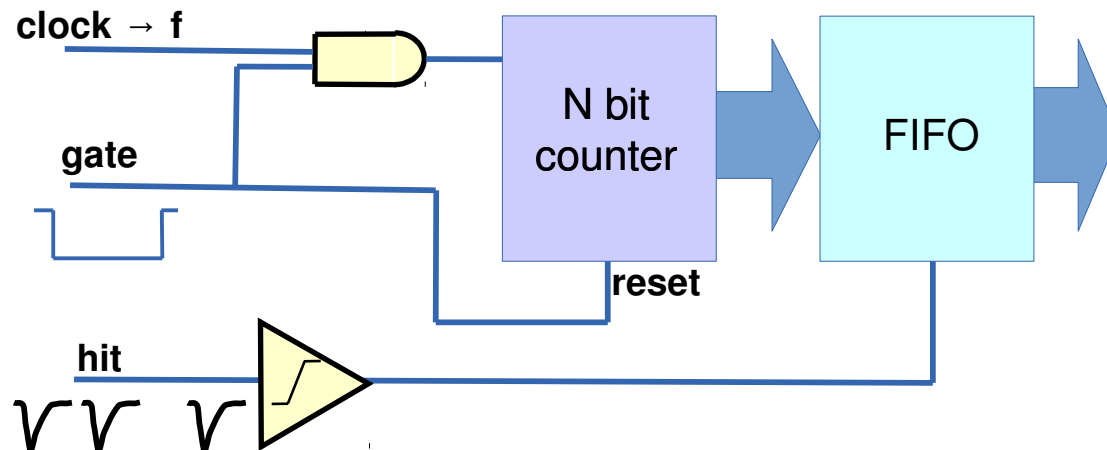
Lab 4



- 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

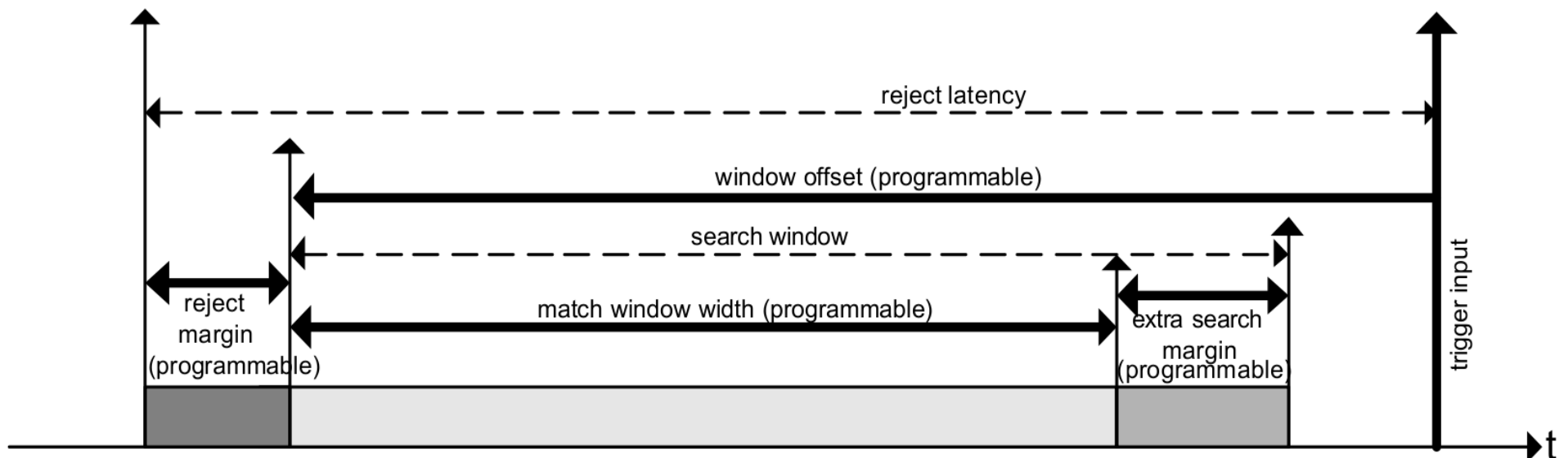
Multi-hit TDC

- 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 needed to tag the data



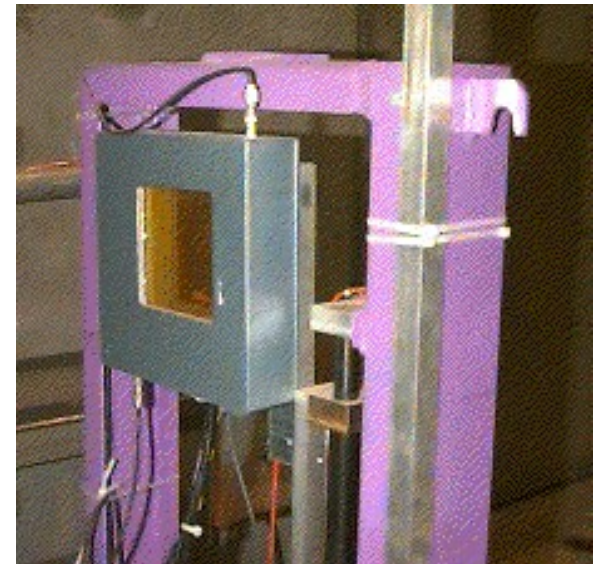
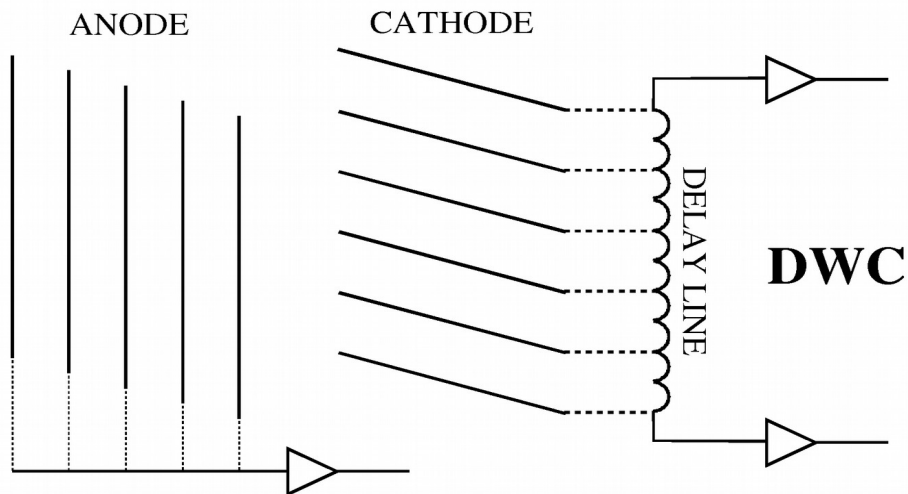
Actual TDCs

- 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

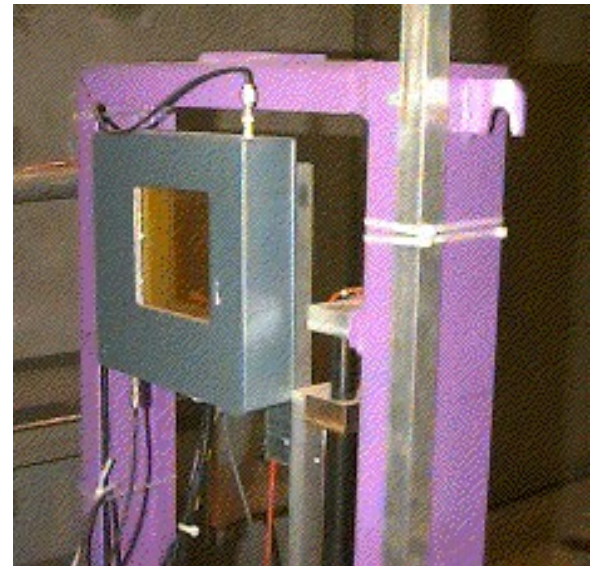
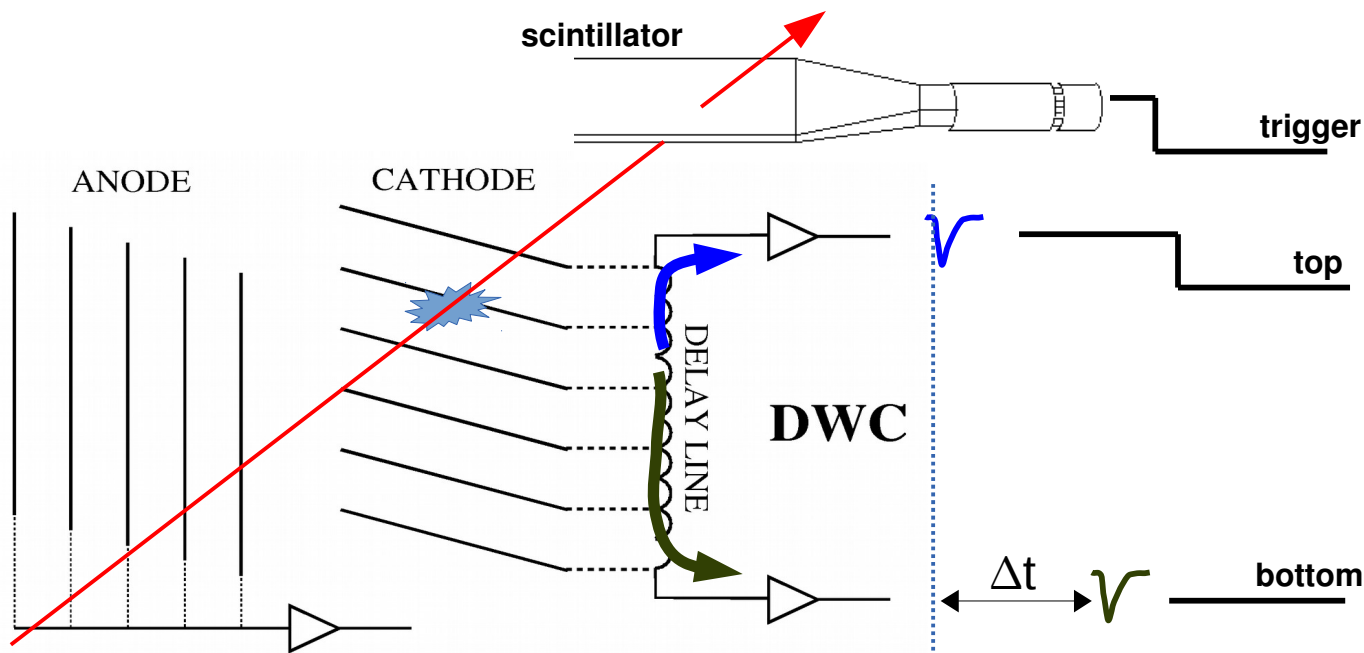
- XDWC: delay wire chambers
 - used on the SPS extracted lines to measure beam profiles
- Two cathode planes provide X and Y positions
 - Measurement based on the delay gained along a delay line



Real life wire chamber & TDC

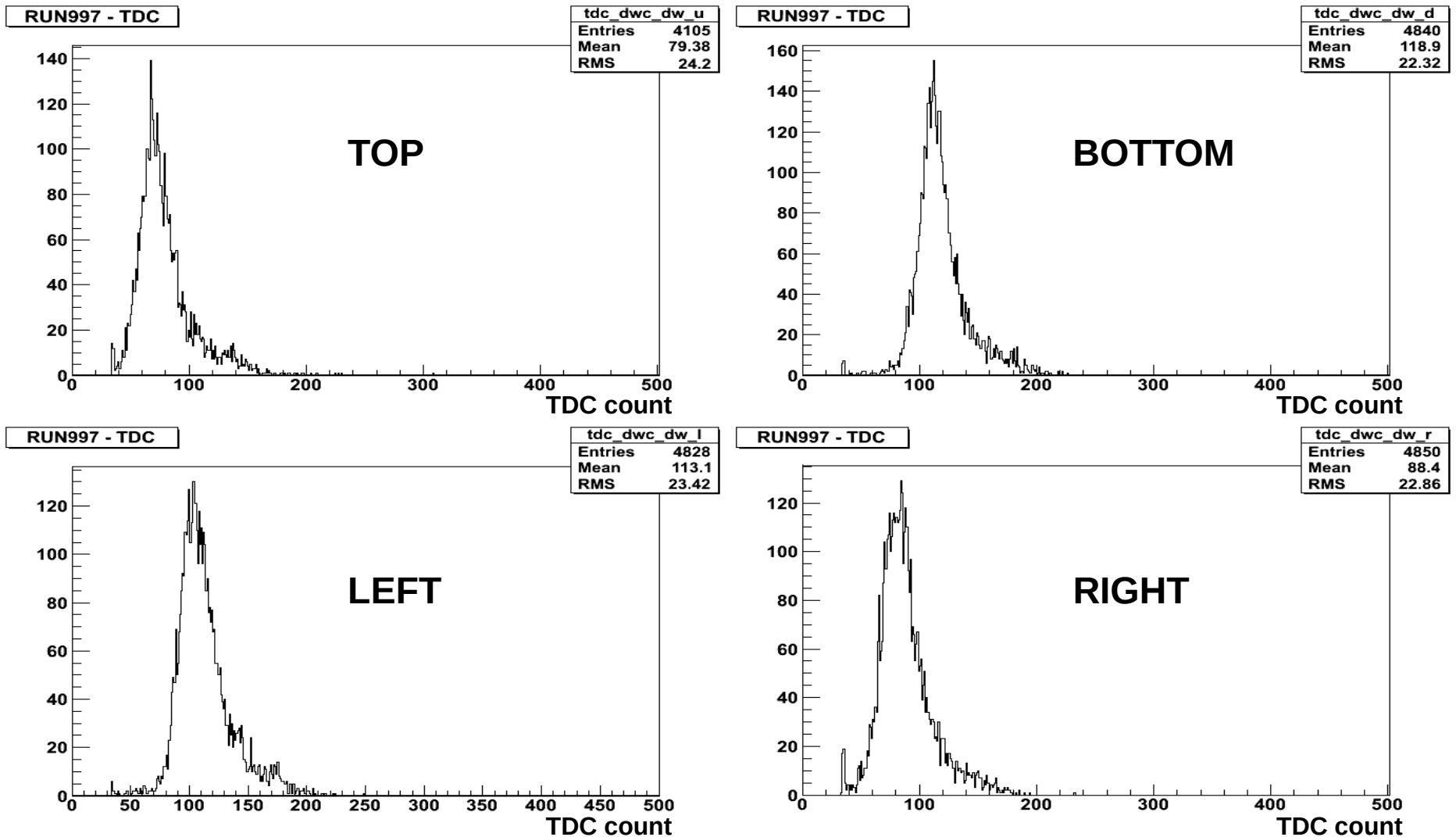
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$$y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$$



Raw time data

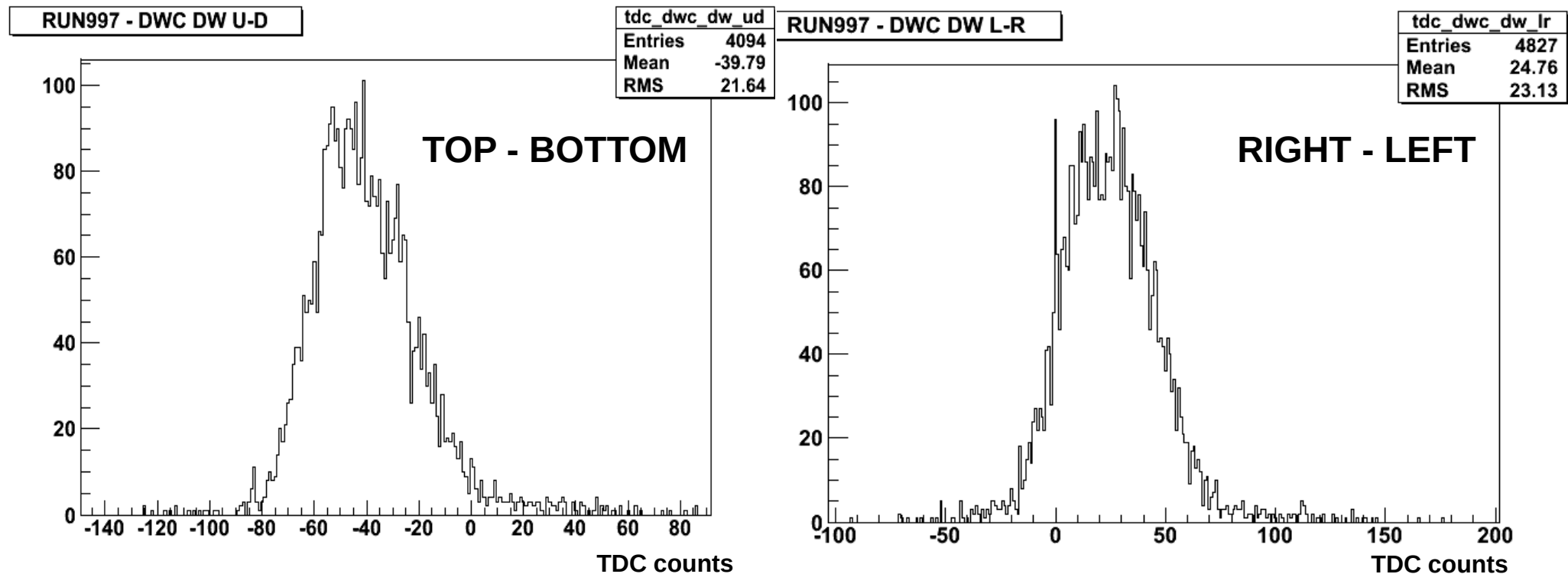
- Take a run (some thousands events)
 - Individual channel distribution



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)?



- 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**

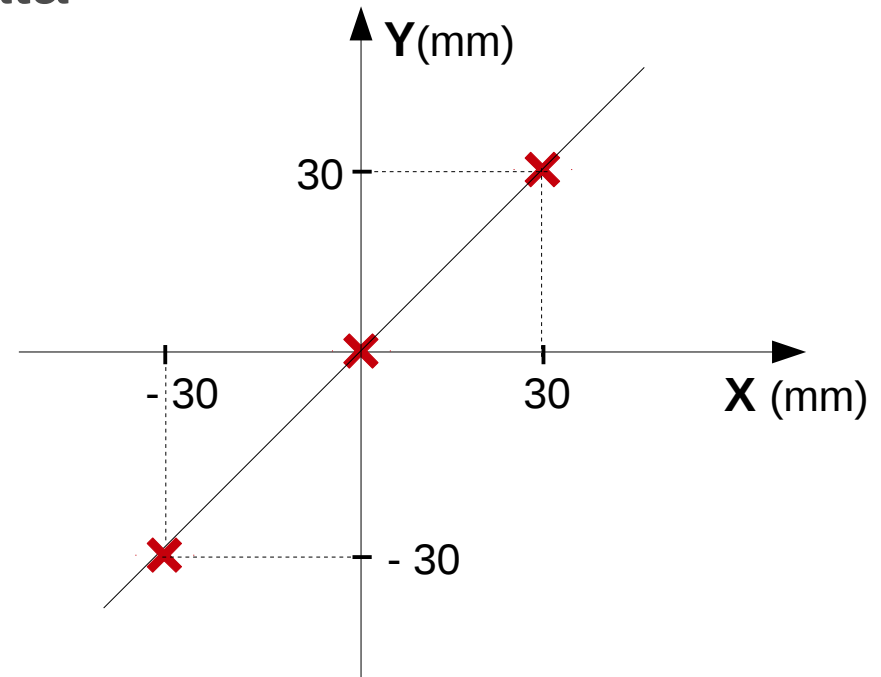


- Both experiments provide relative measurements
 - Values obtained via our systems are in some (known) relation with the interesting quantities
 - Scintillator $Q \propto N_\gamma \propto E$
 - MDWC $y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$
- Our instruments need 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 ($X=Y=30\text{mm}$)
 - Center ($X=Y=0\text{mm}$)
 - Left-bottom ($X=Y=-30\text{mm}$)
 - Interpolating the three points in t-x space, the parameters of the calibration equation can be measured

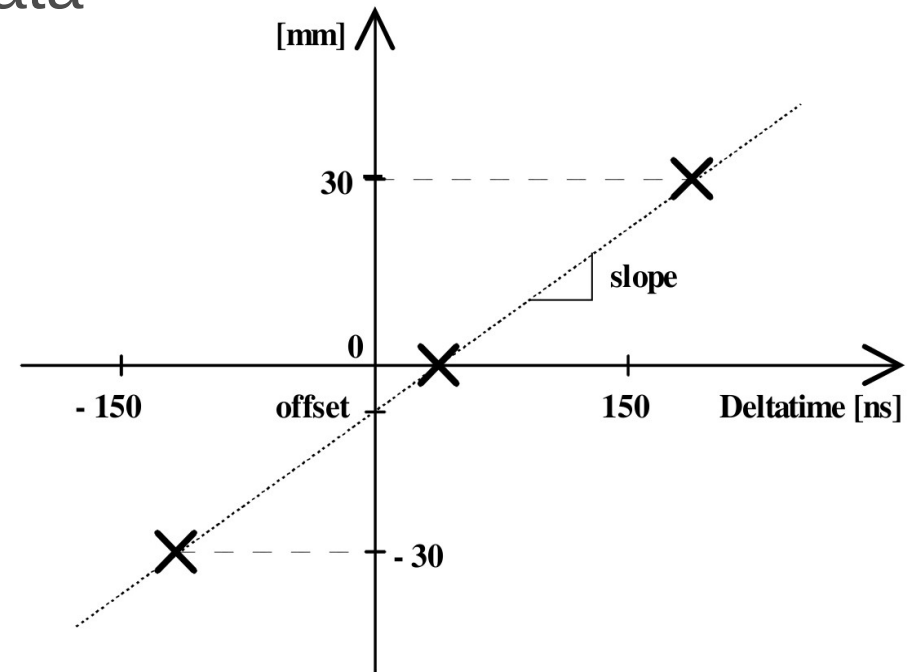


$$x = \alpha t^* + \beta$$

- Calibration shall be done with final setup and TDC

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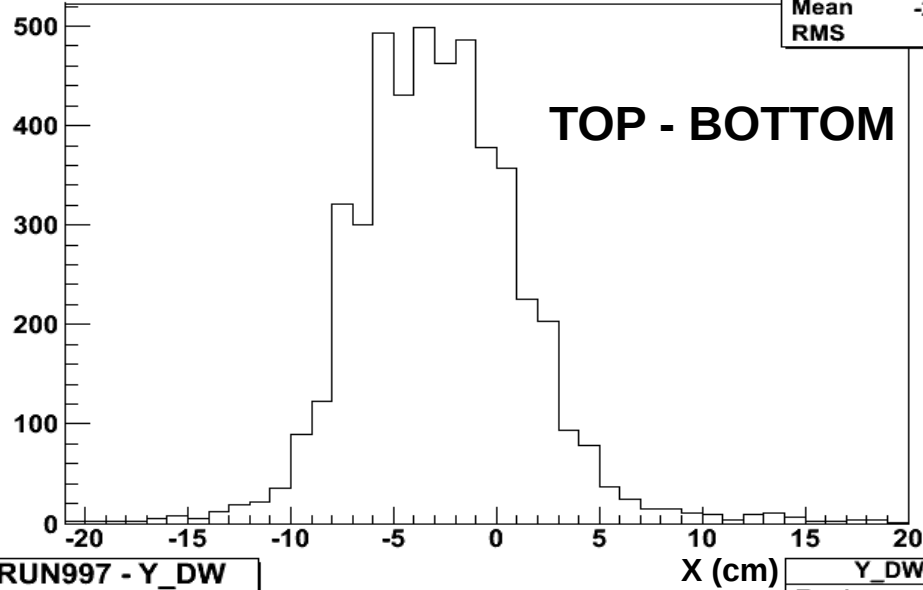
$$x = \alpha t^* + \beta$$

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Calibrated XDWC

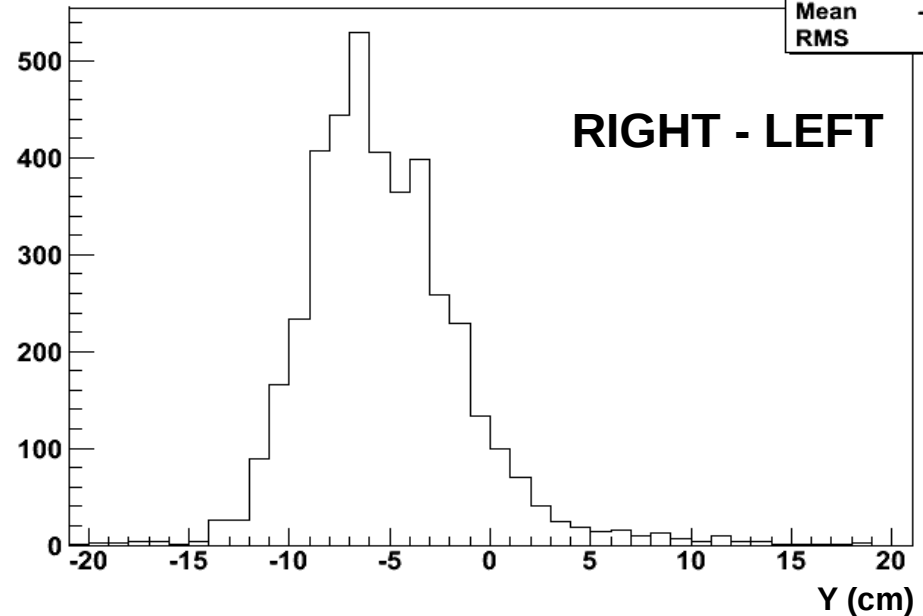
RUN997 - X_DW

X_DW	
Entries	4827
Mean	-2.727
RMS	4.181



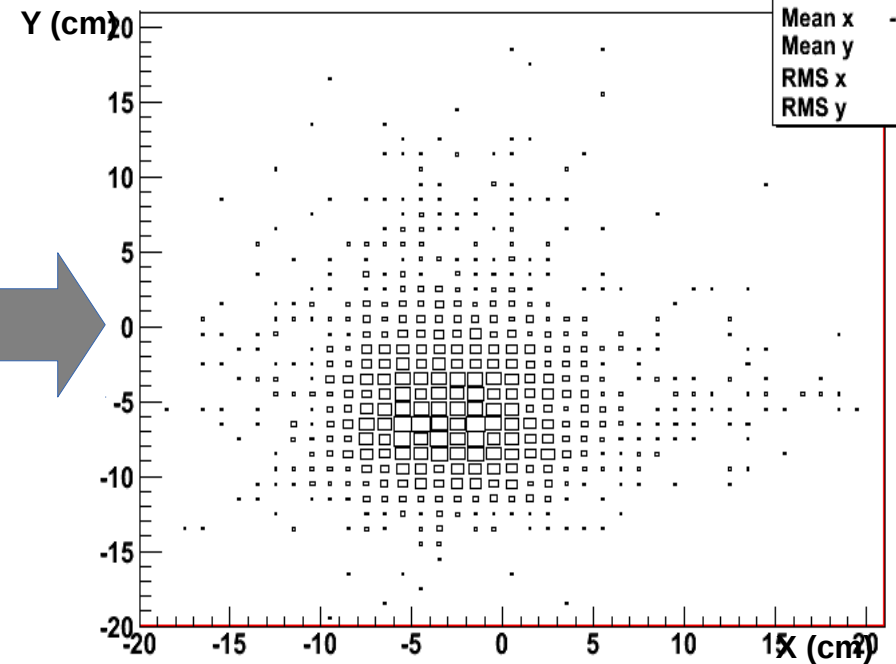
RUN997 - Y_DW

Y_DW	
Entries	4094
Mean	-5.235
RMS	4.009



Beam profile

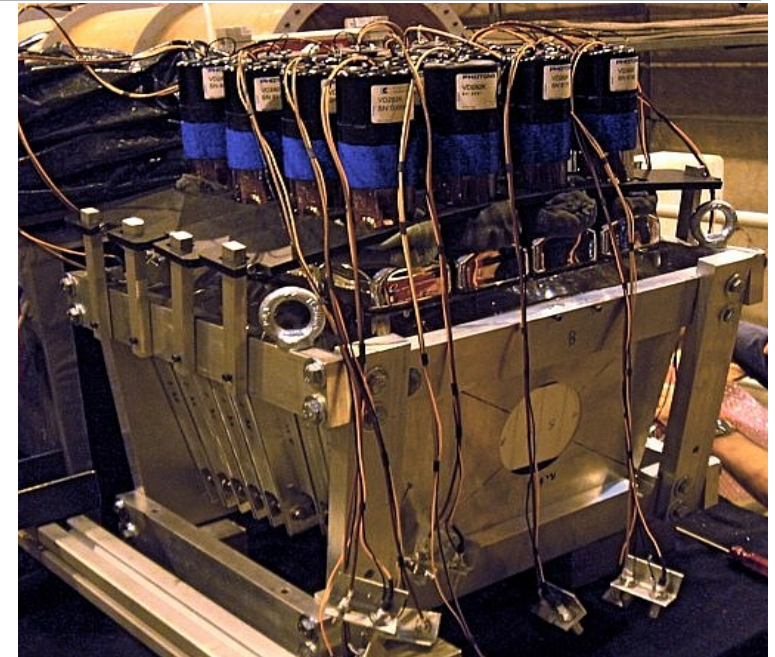
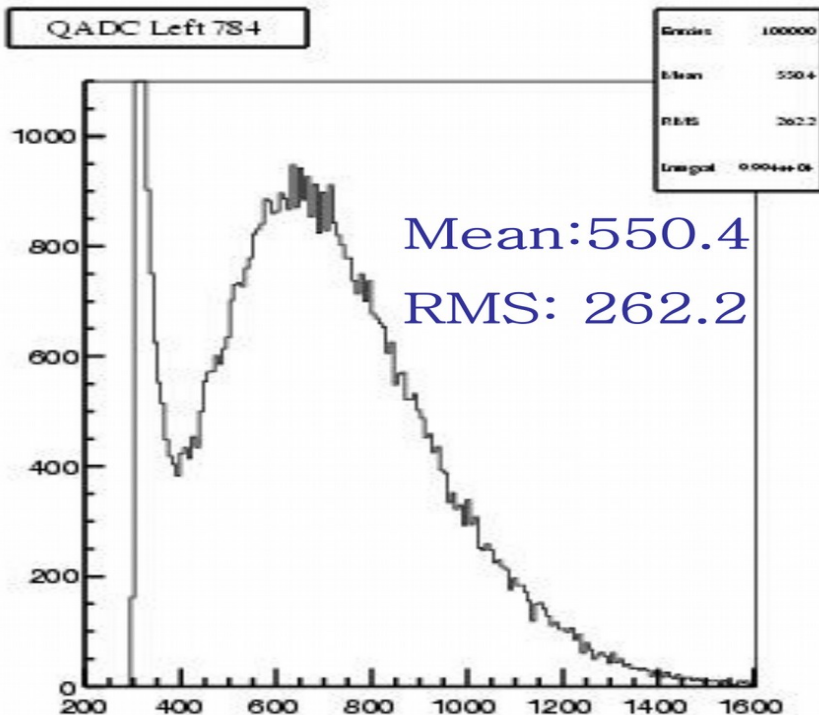
RUN997 - Y_DW vs X_DW



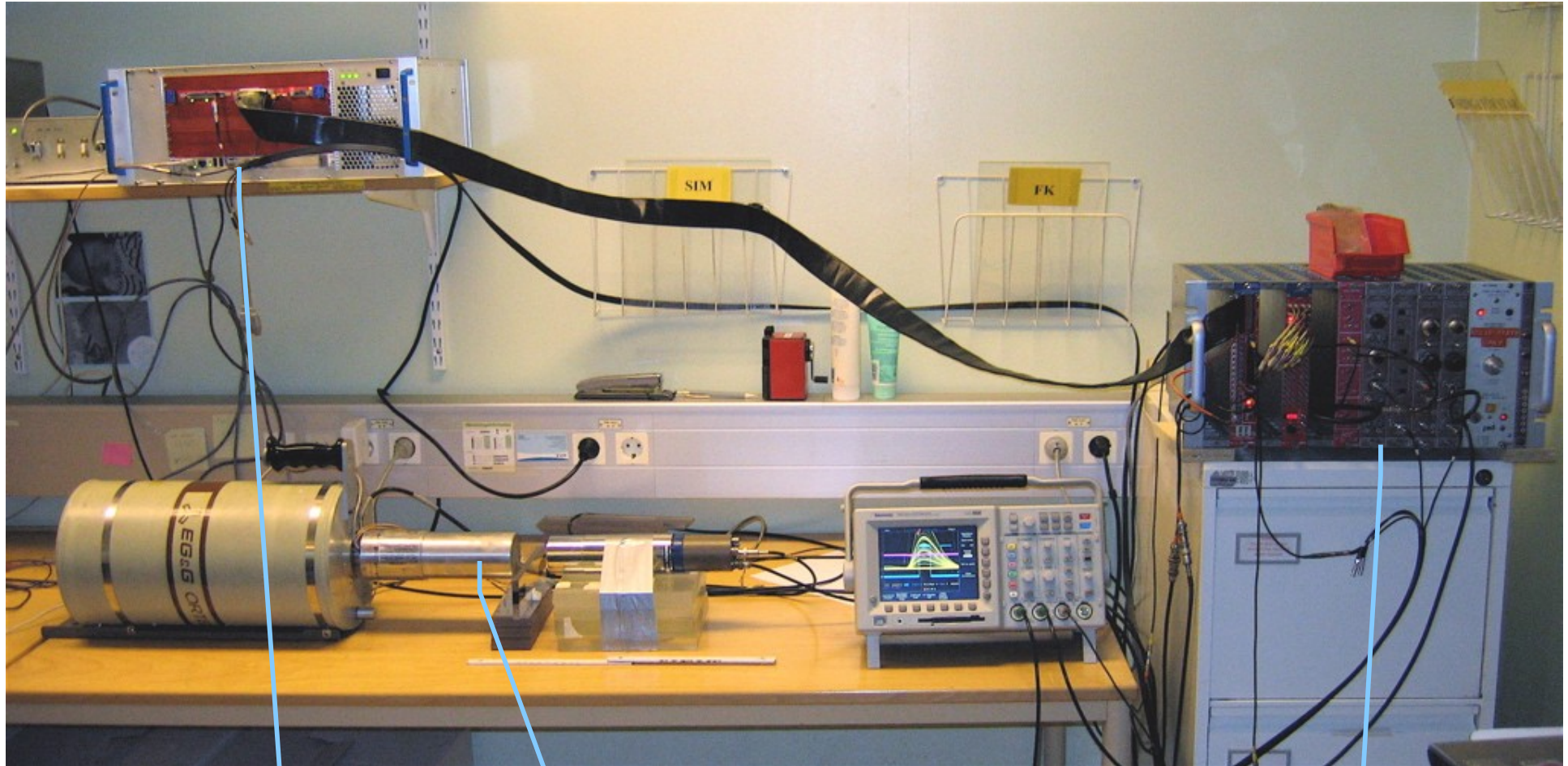
Y_vs_X_DW	
Entries	4075
Mean x	-2.696
Mean y	-5.23
RMS x	4.159
RMS y	3.973

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



Readout (ADC)

Crystal HPGe

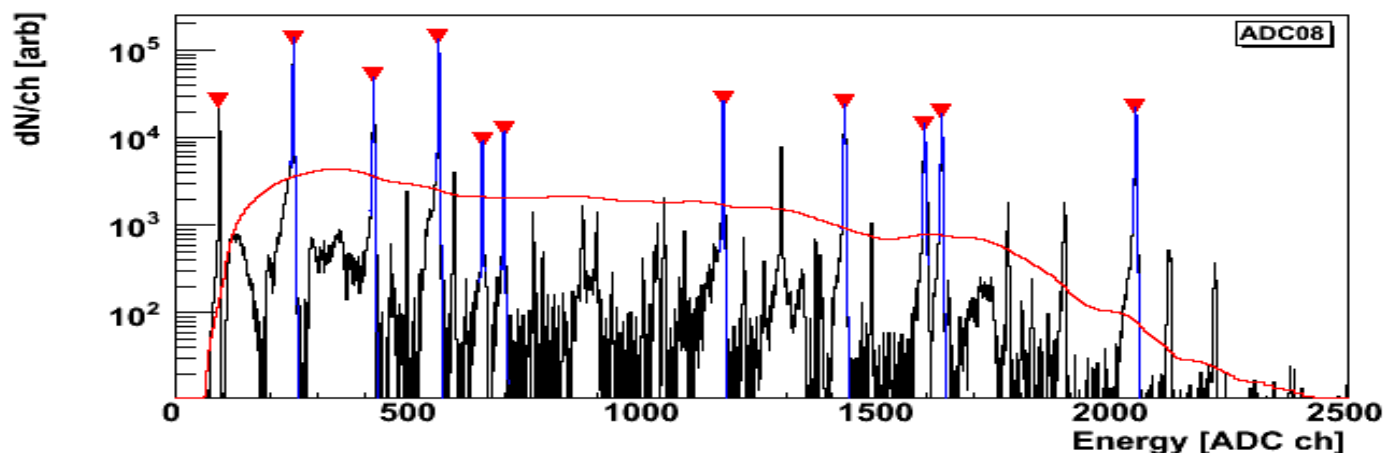
Trigger and front-end

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
- Find the peaks and fit

$$Q \propto N_{\gamma} \propto E$$

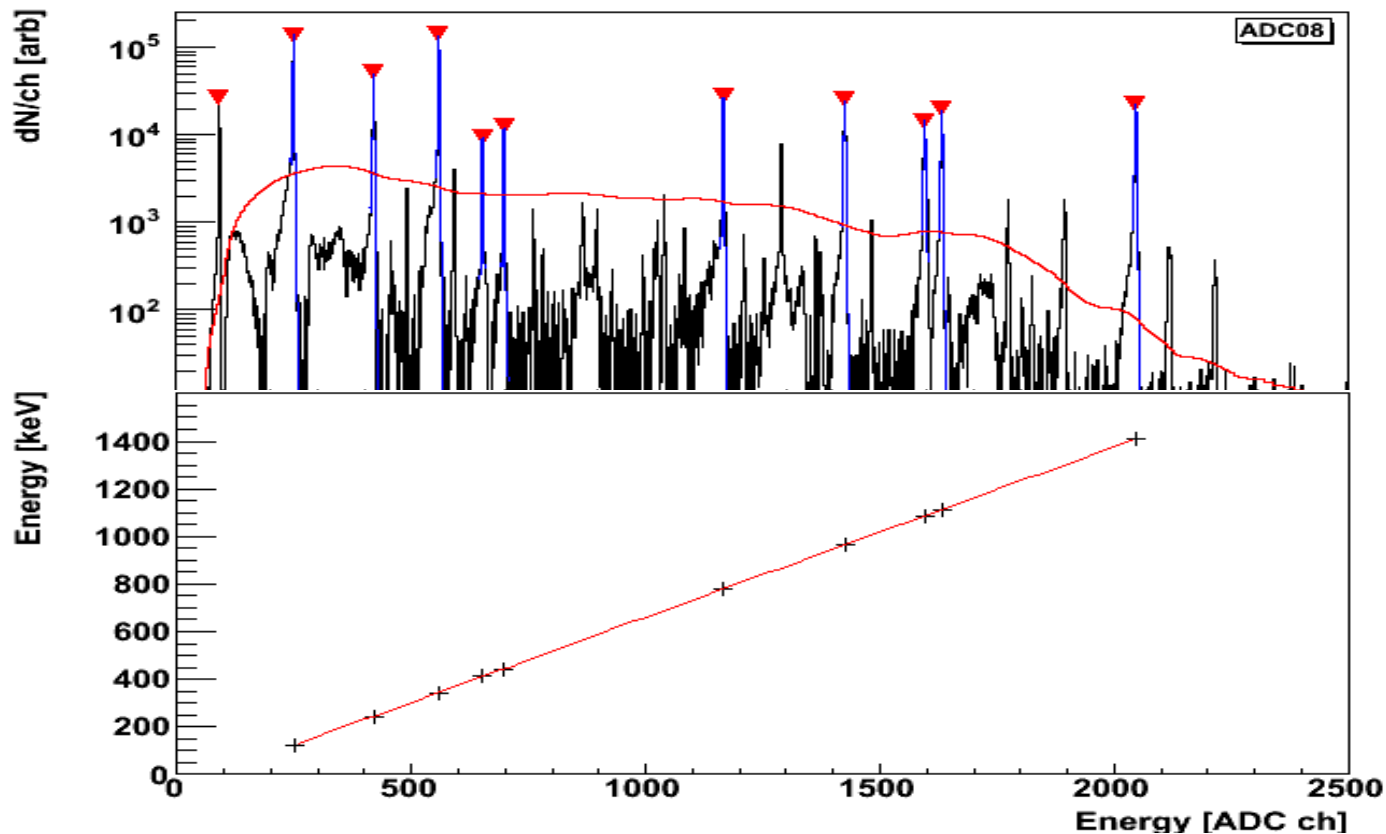


by Sergio Ballestrero

Ge crystal calibration

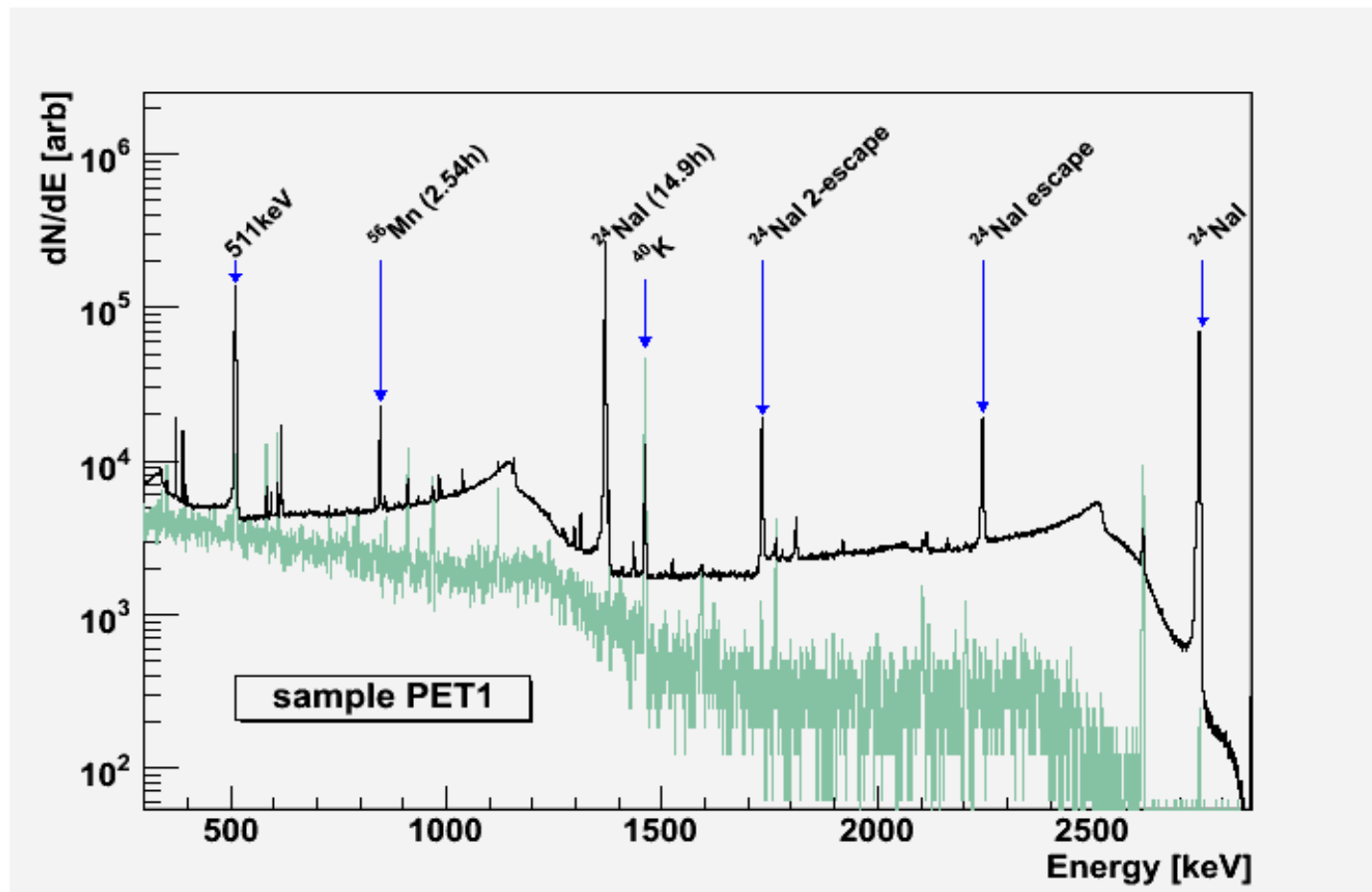
- ^{152}Eu reference source allows for definition of the parameters describing functional relation between ADC count and E
 - Known γ emission lines
- Find the peaks and fit

$$Q \propto N_{\gamma} \propto E$$



Isotope identification

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



by Sergio Ballestrero

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

