16TH PISA MEETING ON ADVANCED DETECTORS La Biodola, Isola d'Elba, May 26-June 1, 2024

A novel detector for 4D tracking in particle therapy

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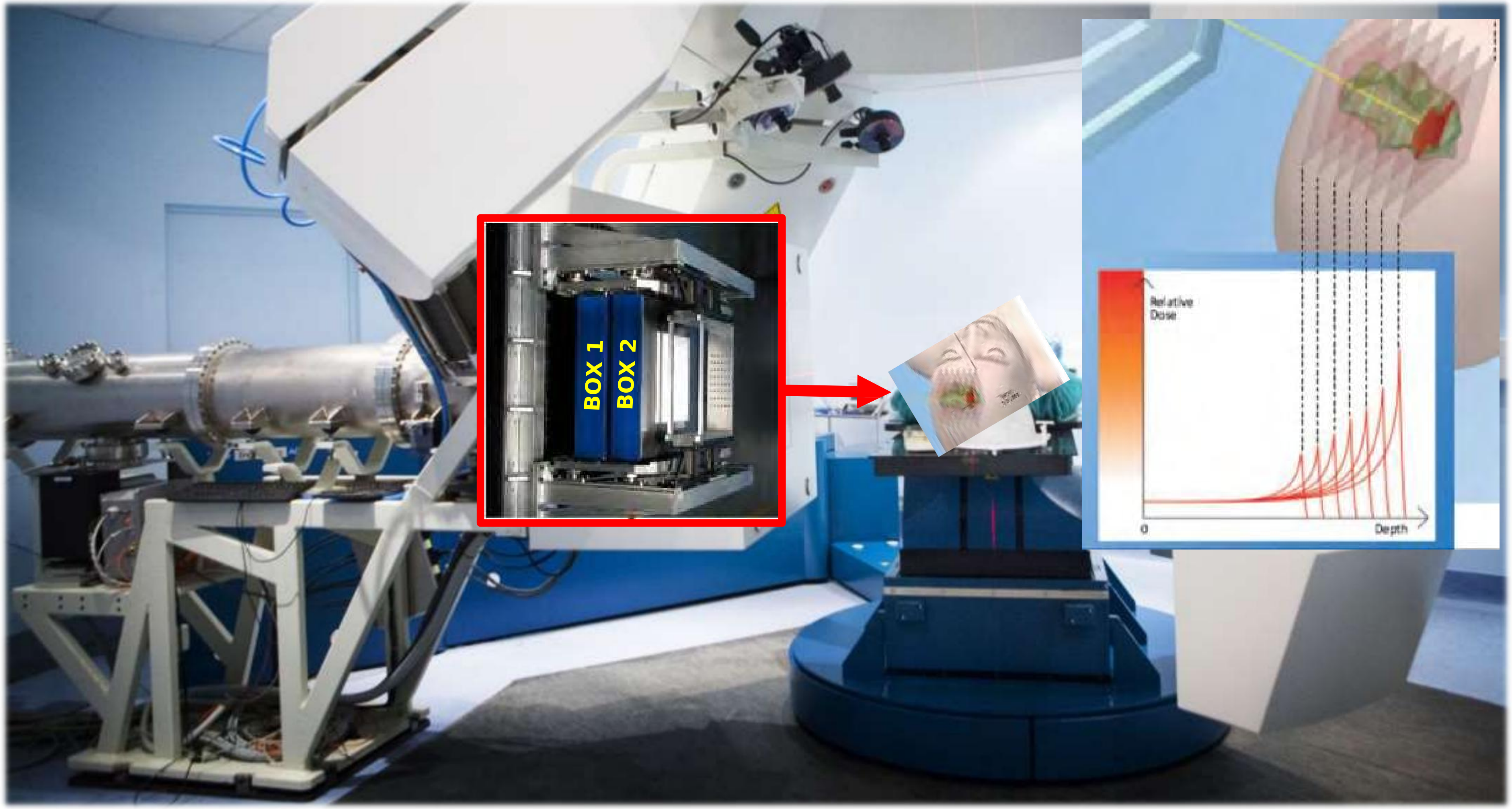
Superconducting Ion Gantry

Motivation



New technologies for:

- **Dose delivery System**
- **Range verification**

for particle therapy applications

- **Beam monitors**:
  - **Position and shape** measurement
  - **Particle flux** measurement

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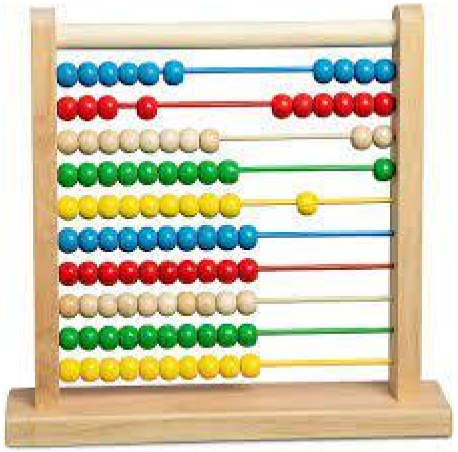
Superconducting Ion Gantry

Summary

1. Proton and carbon ion counter based on silicon sensors



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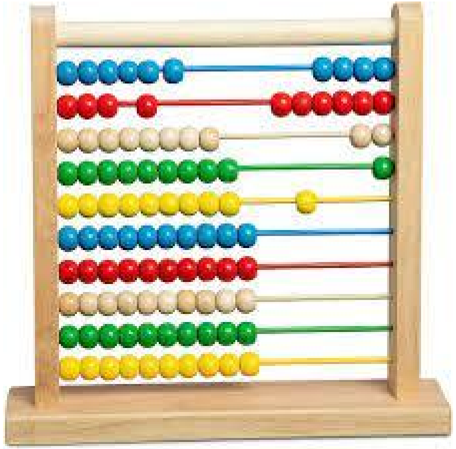

2. Integration of the counter with a TDC (Cern picoTDC) to measure the time of arrival of beam particles

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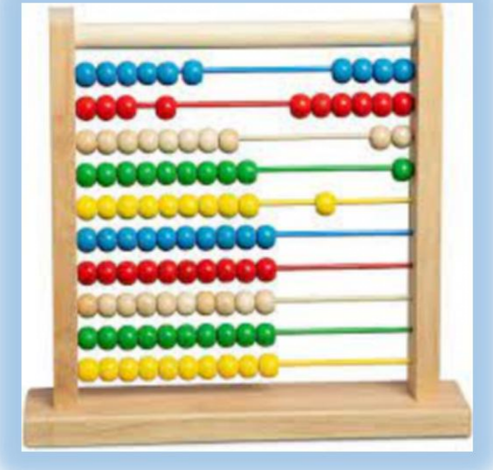
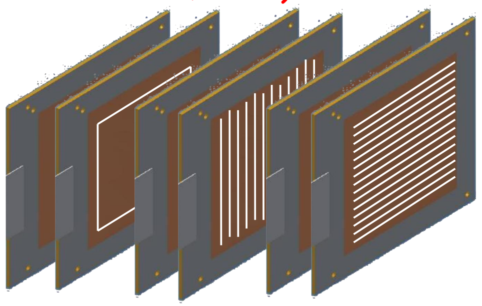


2. Integration of the counter with a TDC (Cern picoTDC) to measure the time of arrival of beam particles

- From **Integrated Charge** with Gas Ionization Chambers to **Number of Particles** with Silicon Detectors

Gas detector
(ionization chambers,
MWPC, ...)



- Sensitivity → 10^4 protons
- Collection times → ~ 100 µs
- Time resolution → poor

Not suitable for scanning modalities with timing of the order of tens of microseconds

New beam monitors based on single particle counting for Particle Therapy

- From **Integrated Charge** with Gas Ionization Chambers to **Number of Particles** with Silicon Detectors

Gas detector
(ionization chambers,
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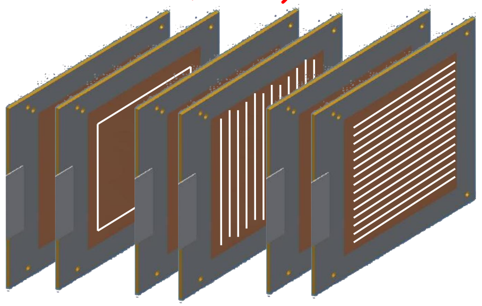
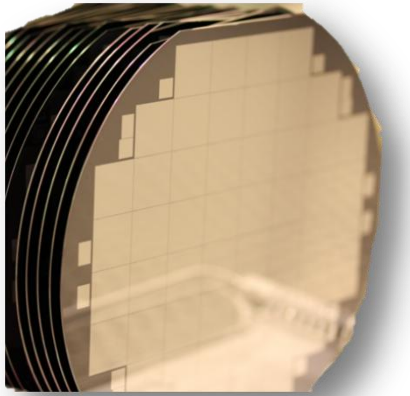


Thin Silicon Detectors
(Active Thickness ~ 50 μm)



- Sensitivity → 10^4 protons → Single particle
- Collection times → ~ 100 μs → ~ ns
- Time resolution → poor → ~ 50 ps

Not suitable for scanning modalities with timing of the order of tens of microseconds

Single particle discrimination
→ Direct counting # particles at clinical fluence rate (~10^9 cm^{-2} s^{-1})

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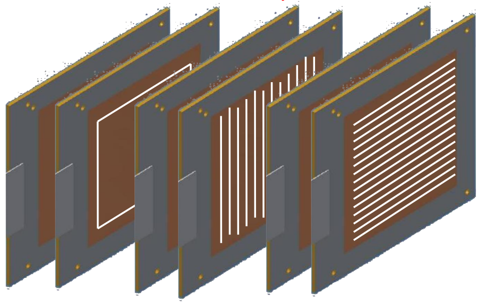

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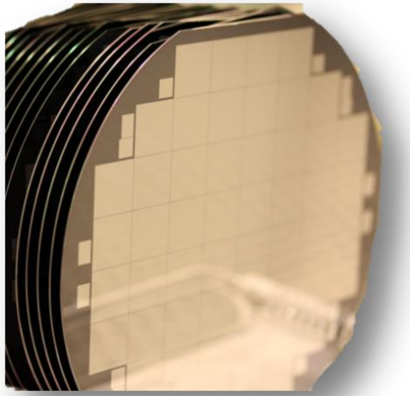


- Sensitivity → 10^4 protons → Single particle
- Collection times → ~ 100 µs → ~ ns
- Time resolution → poor → ~ 50 ps

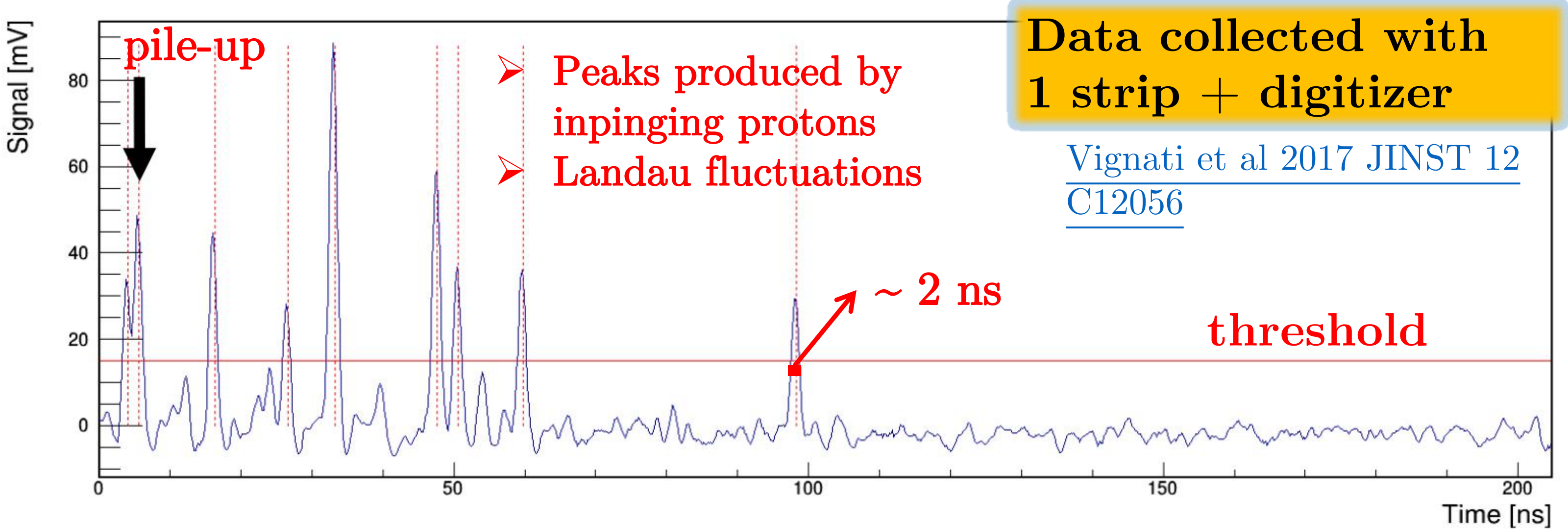
Main issue:
- Signal pile-up
  - ➢ fast sensors & segmentation
  - ➢ fast readout electronics

Not suitable for scanning modalities with timing of the order of tens of microseconds

Single particle discrimination
→ Direct counting # particles at clinical fluence rate (~10^9 cm^{-2} s^{-1})

Sensors and readout electronics

- Sensor for **protons**:
  - Low Gain Avalanche Detectors segmented in strips
  - Thickness ~ 50 μm
  - Internal gain ~ 10
- Sensor for **carbon ions**
  - Strip segmented diode sensors
  - Thickness ~ 60 μm



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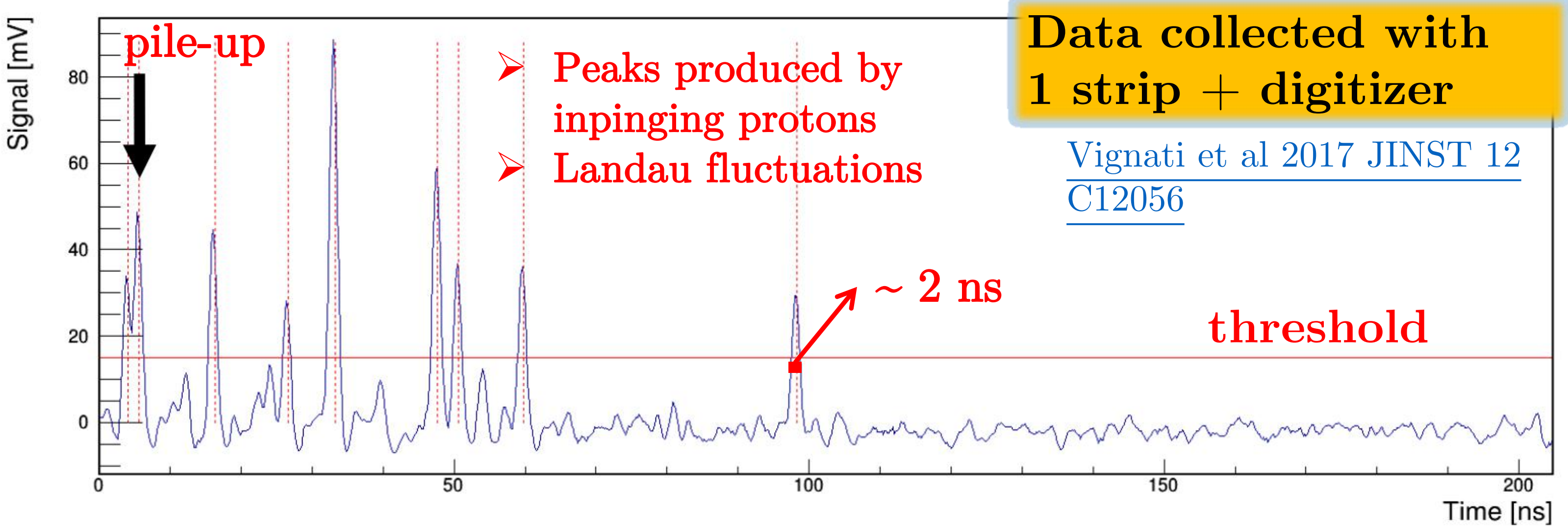
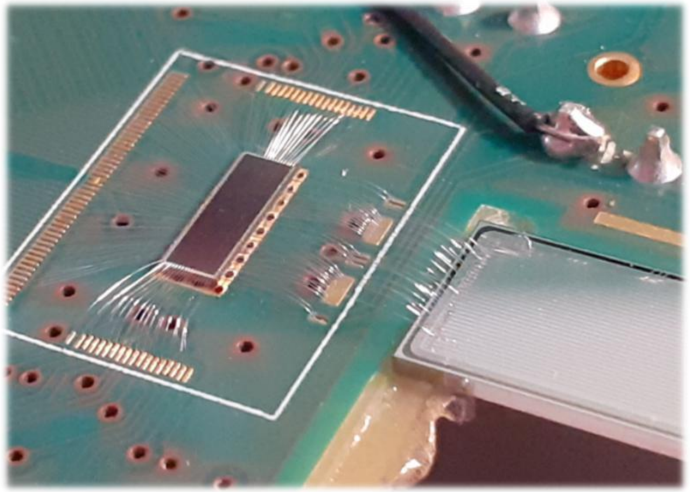


Data collected with 1 strip + digitizer

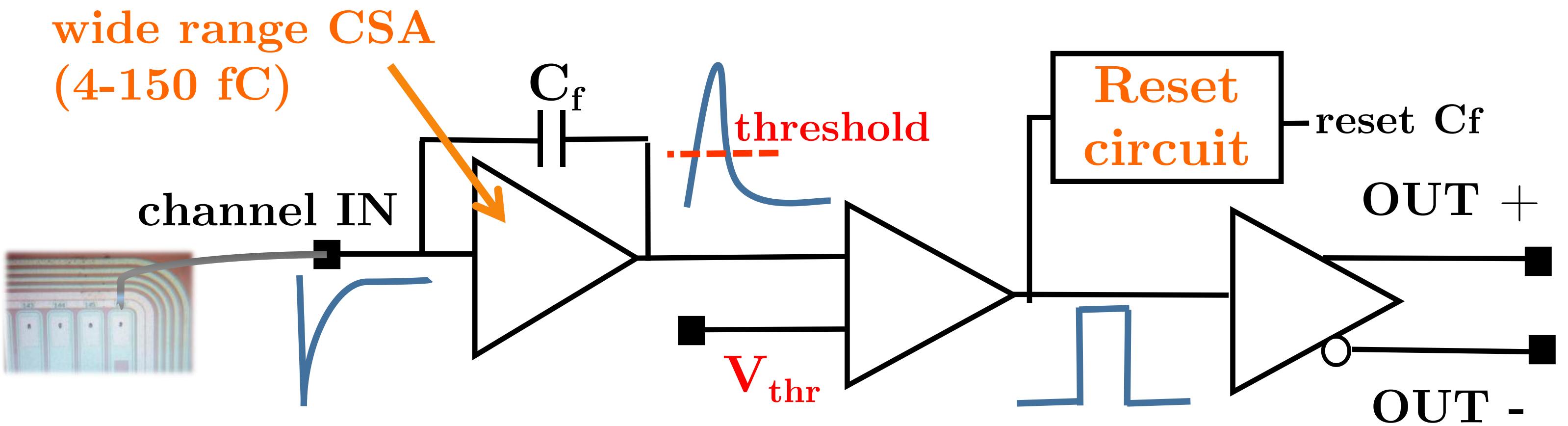
Vignati et al 2017 JINST 12 C12056

ABACUS chip



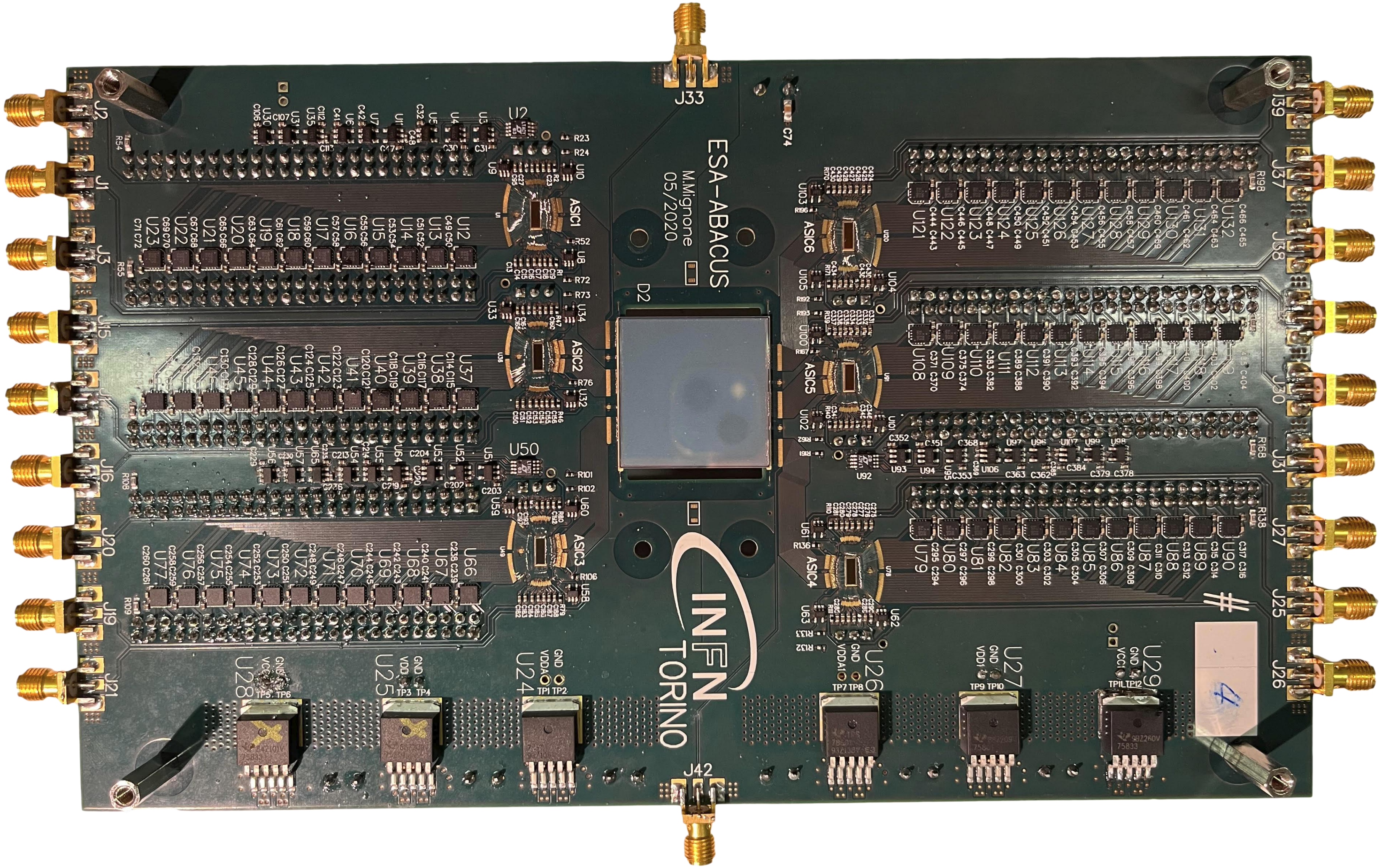
Fausti et Al, 10.1016/j.nima.2020.164666

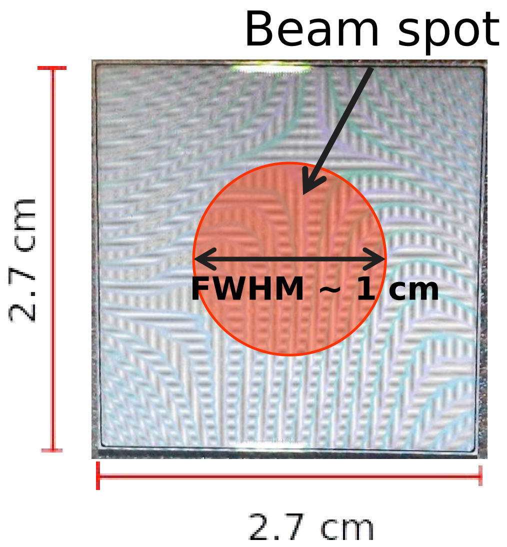
- 110 nm CMOS technology
- 24 channels
- Adjustable threshold voltage for each channel
- Dead time < 10 ns
- 100 % efficiency up to input f = 160 MHz



Particle counter prototype: ESA-ABACUS

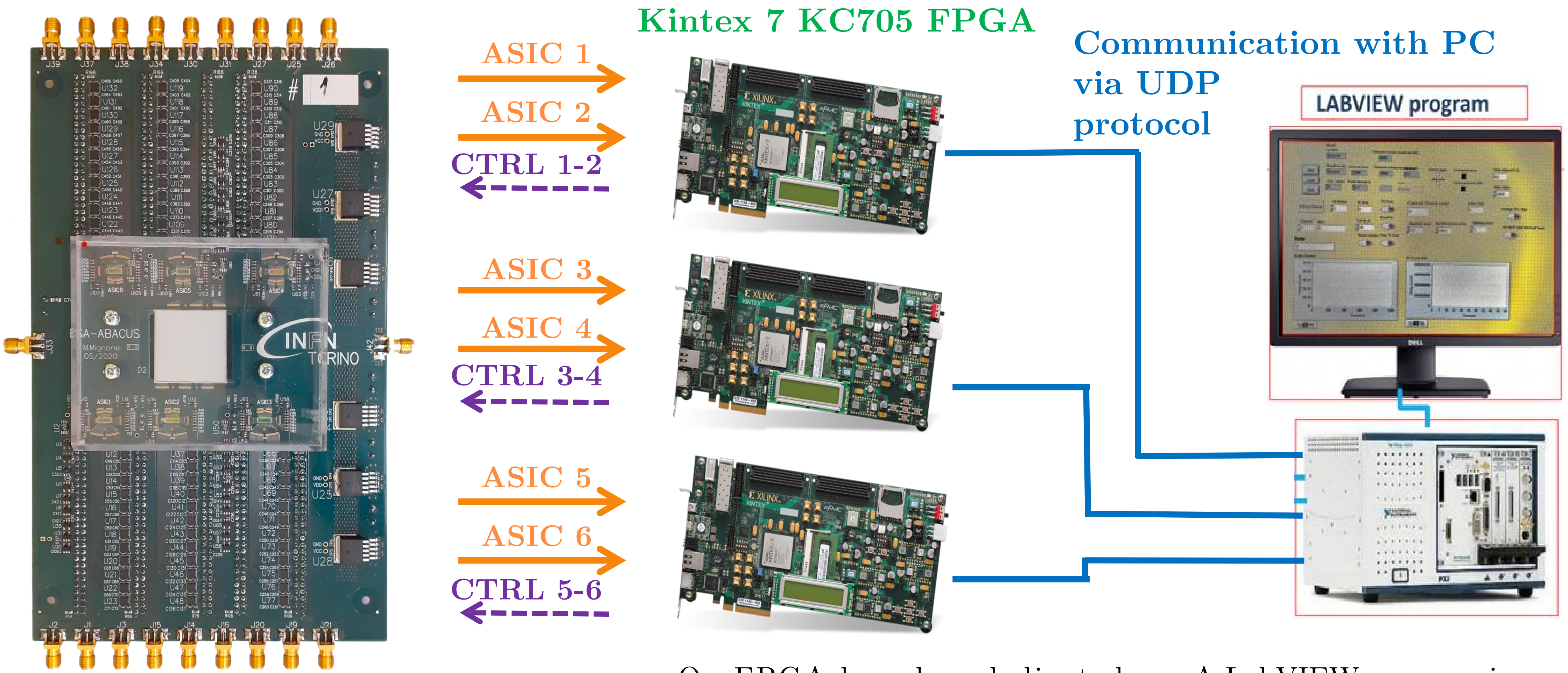
- 6 ABACUS chips reading out 144 strips of the sensor in the middle





Strips with:
Width → 114 µm
Length → 26214 µm
Pitch → 180 µm
Active thickness → ~50 µm
Capacitance → ~7 pF

Data acquisition system



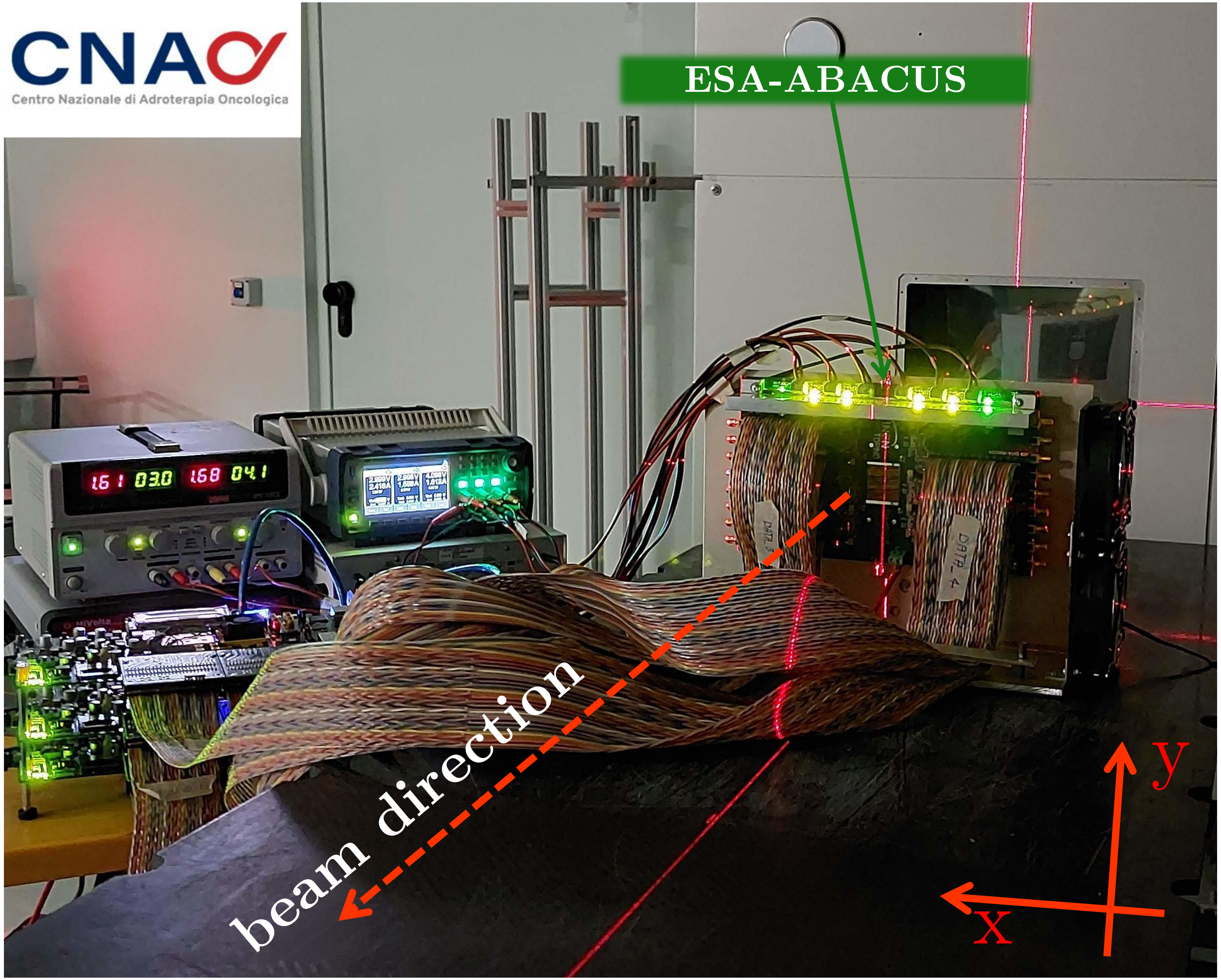
ABACUS digital outputs
Digital signals to set thresholds

On FPGA boards a dedicated firmware implements a counter for each of the 48 channels to store the number of 0-1 transitions.

A LabVIEW program is used for

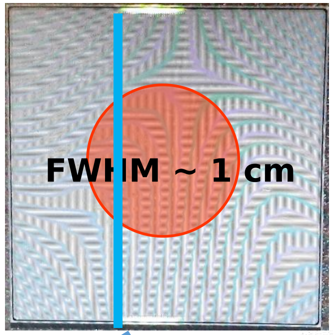
- reading counters and time stamps from FPGA boards
- saving data for offline analysis
- setting threshold voltages

Beam test in CNAO with protons and carbon ions



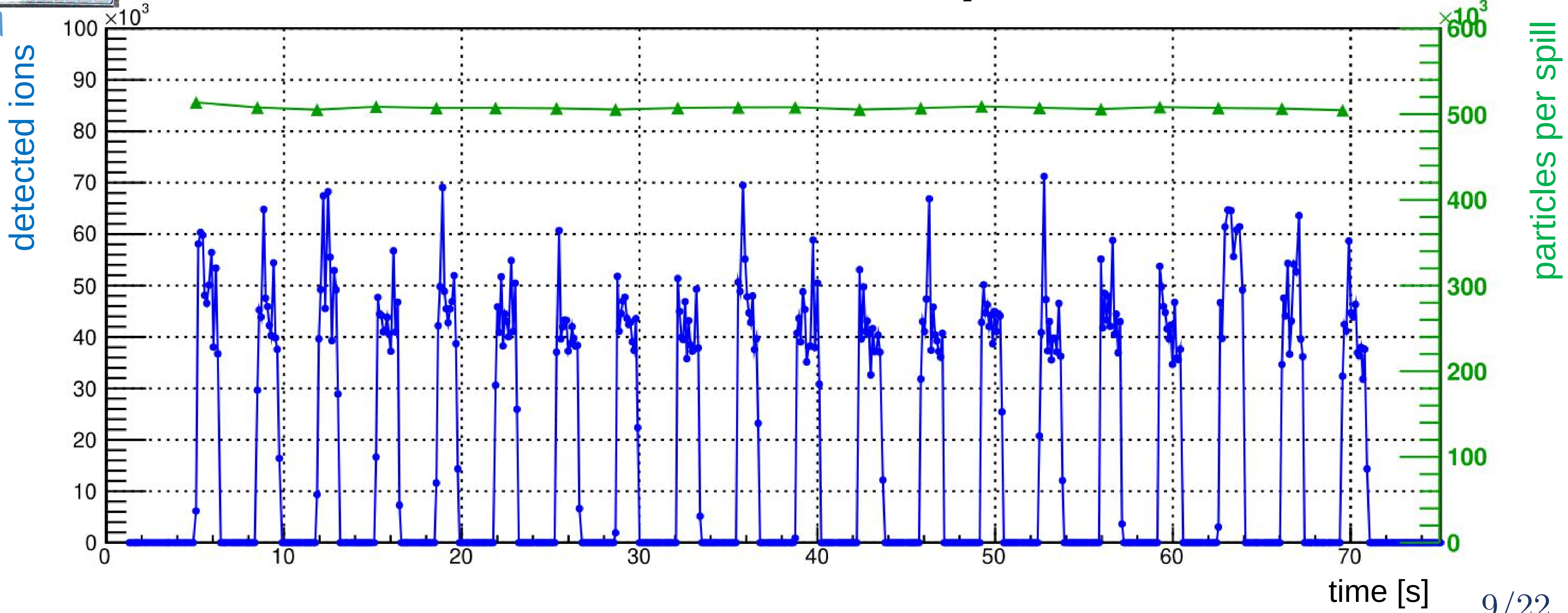
- Beam test in CNAO, Pavia (Italy)
  - ESA-ABACUS-1 for protons
  - ESA-ABACUS-2 for carbon ions
- Runs with different energies
  - 60 - 230 MeV (protons)
  - 115 - 400 MeV/u (carbon ions)
- Energies corresponding to 2-5 MIPs
- Different beam fluence rates:
  - 20, 50, 100 % of *clinical* fluence rate of $2x10^9$ protons/(cm^2s) and $5x10^7$ carbon ions/(cm^2s)

Detected carbon ions in one strip



- **Acceleration process in a synchrotron for particle therapy occurs in cycles costisting in acceleration + extraction**
- **Blue circles** → **# of detected ions** in strip number 56
- **Green triangles** → **Particles per spill (PPS)**, i.e. sum of all particles in one spill

E = 115.23 MeV - I = 100 % **Strip 56**



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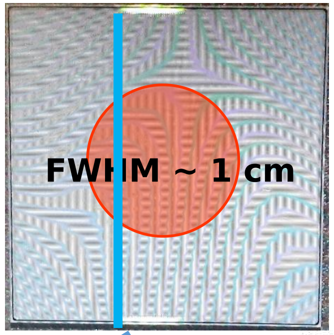

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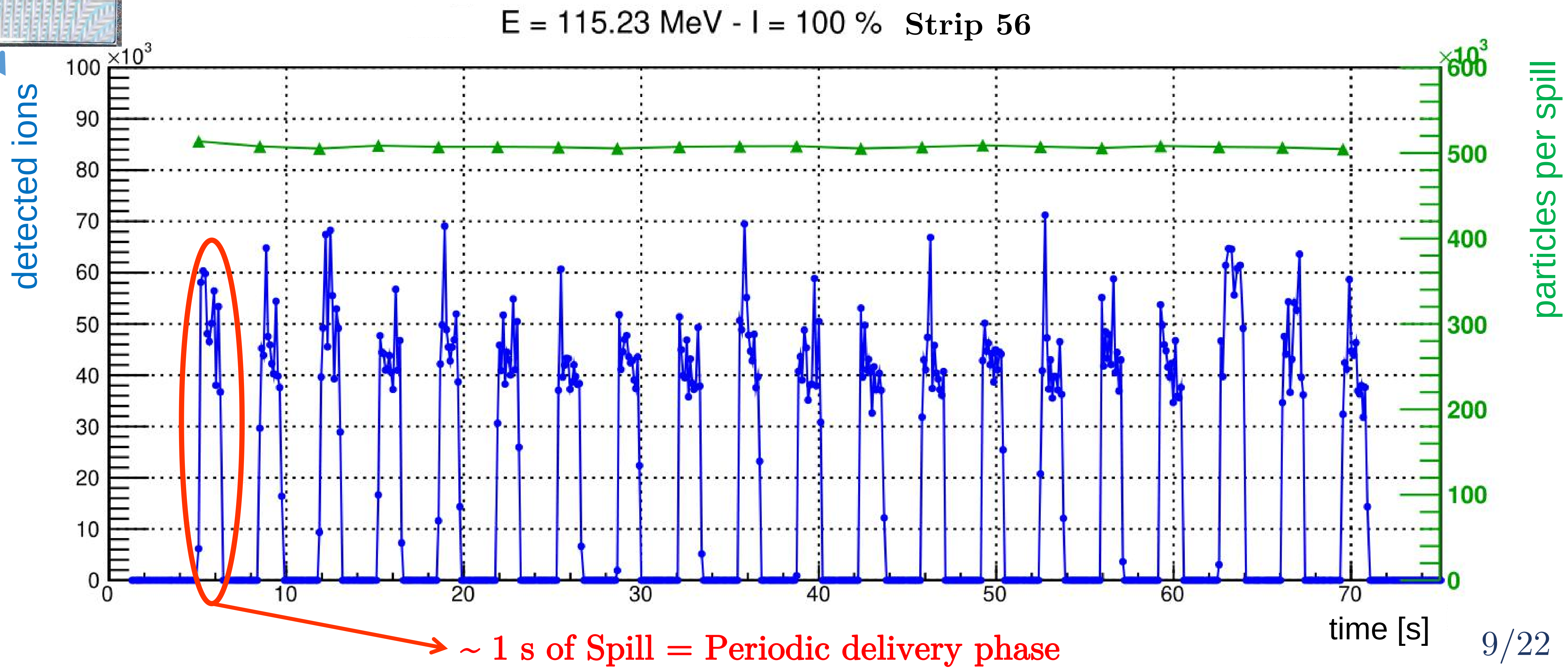
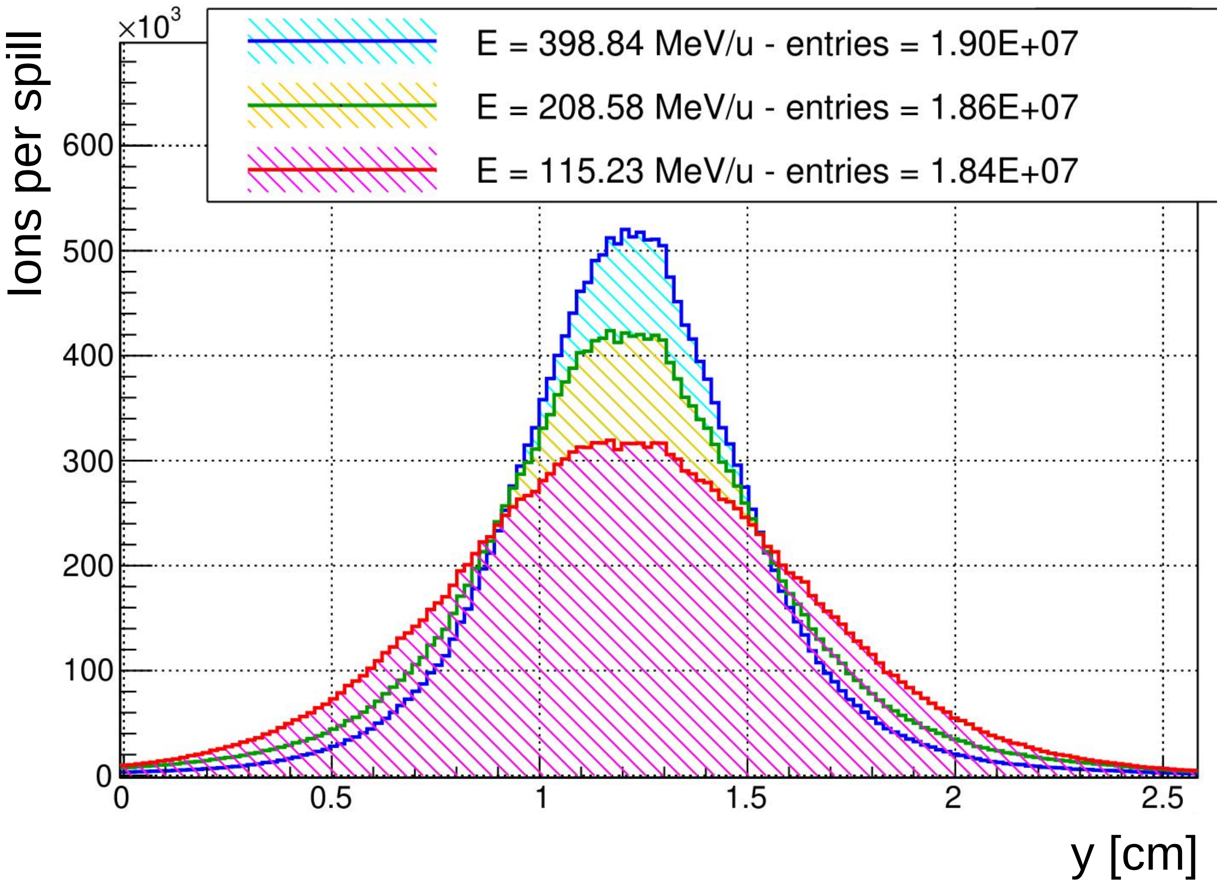


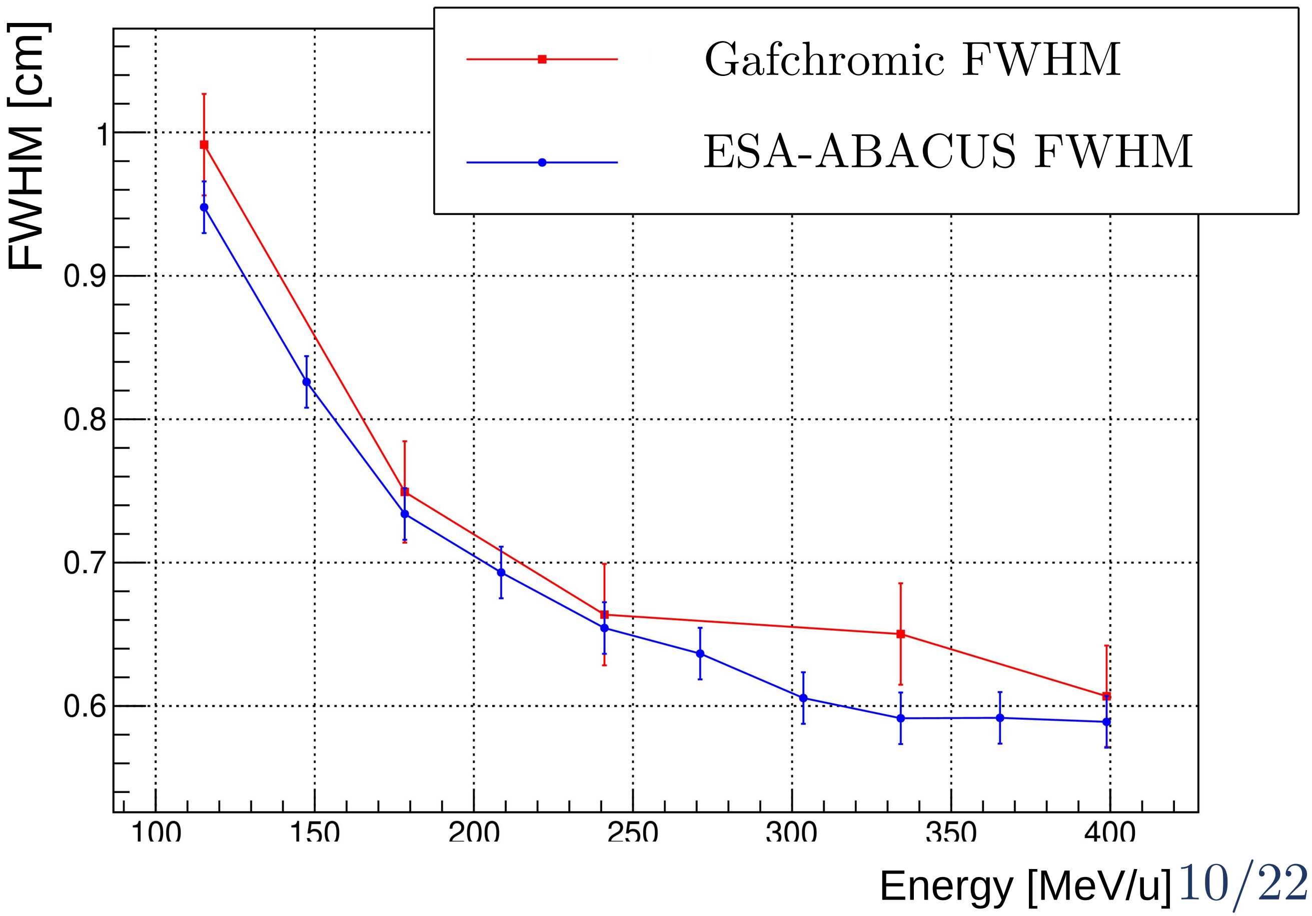
Carbon ions - beam projection on y axis

- 3 beam projections along the axis perpendicular to the strips for 3 different energies
- Non gaussian tails



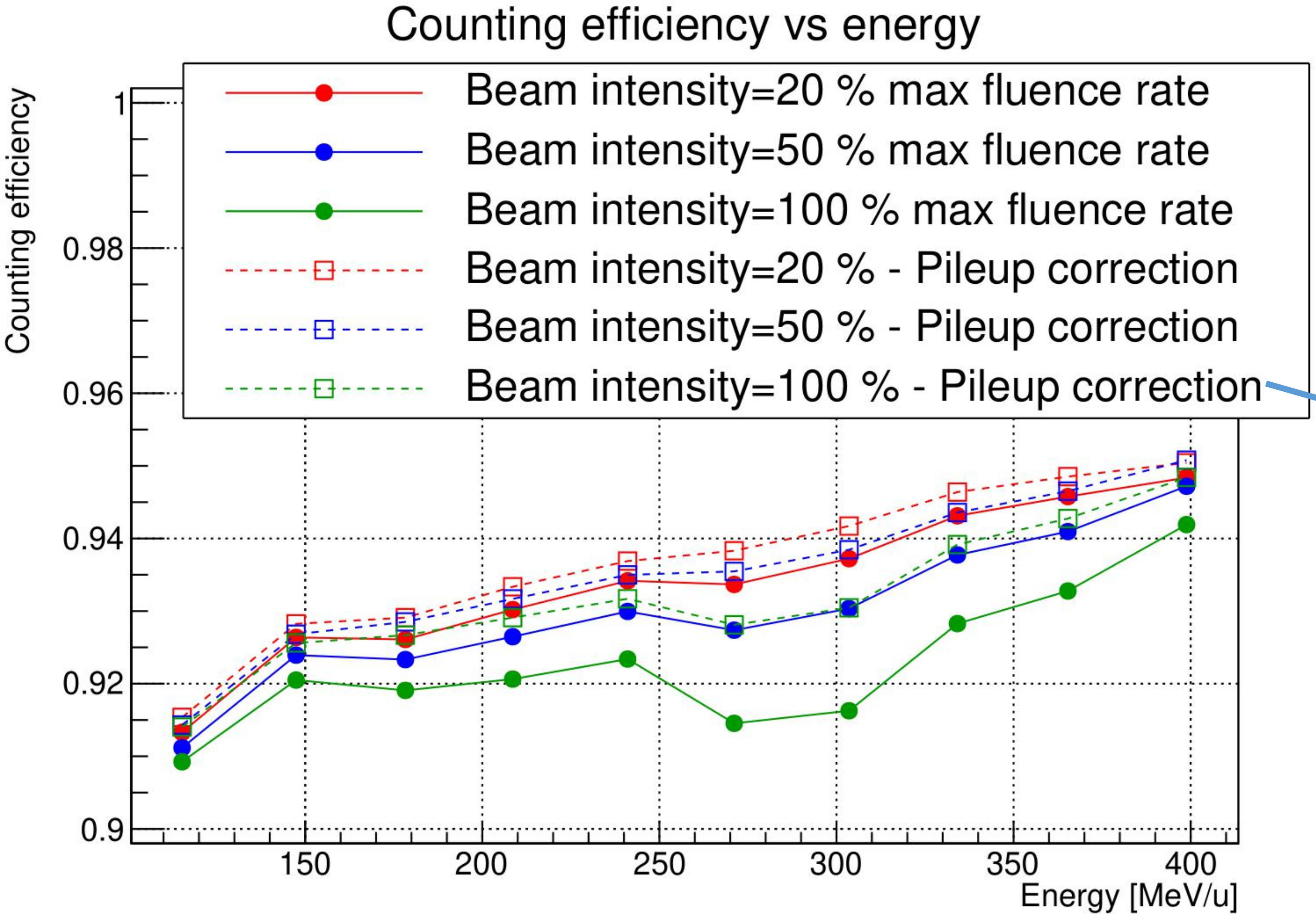
- Comparison with Gafchromic films
- Measured FWHM vs energy shows expected trend

FWHM vs energy



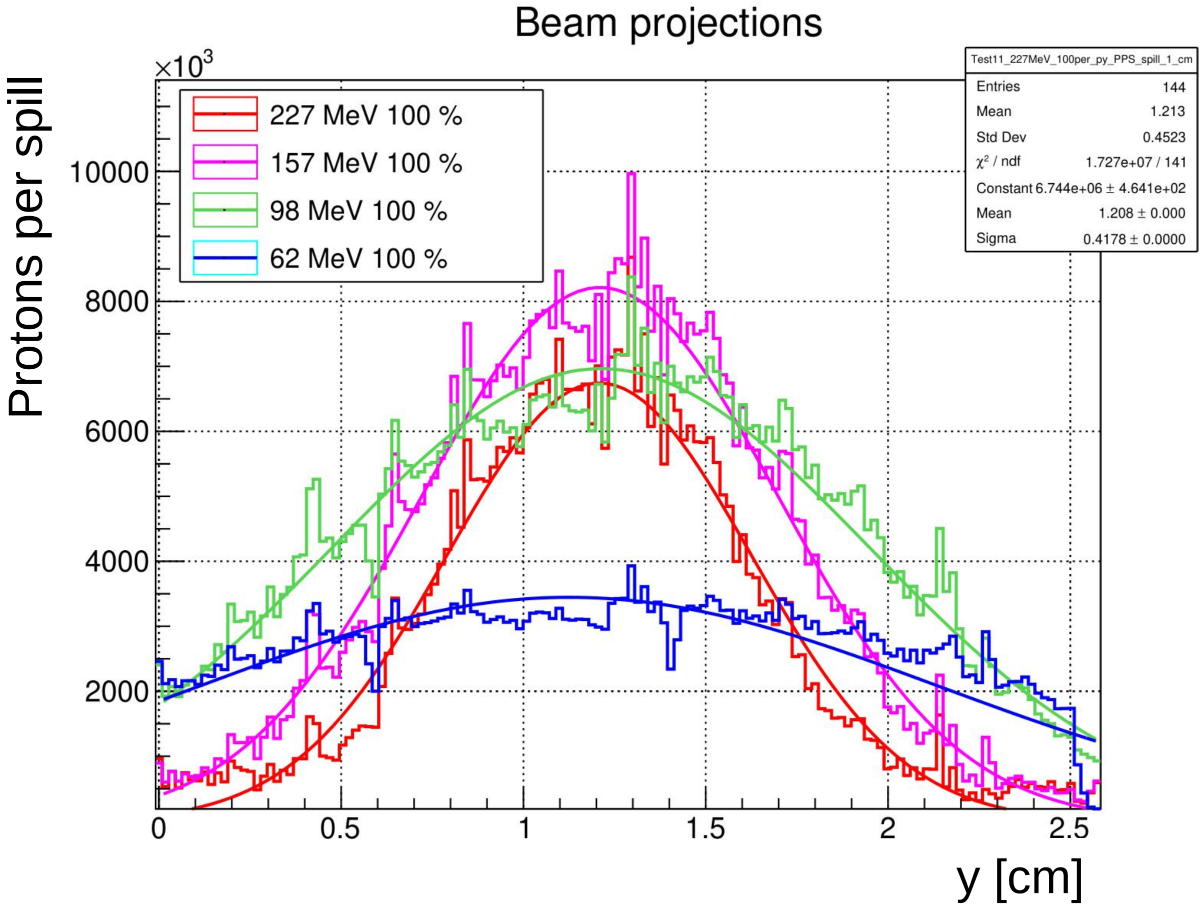
Carbon ions - Counting efficiency vs Energy

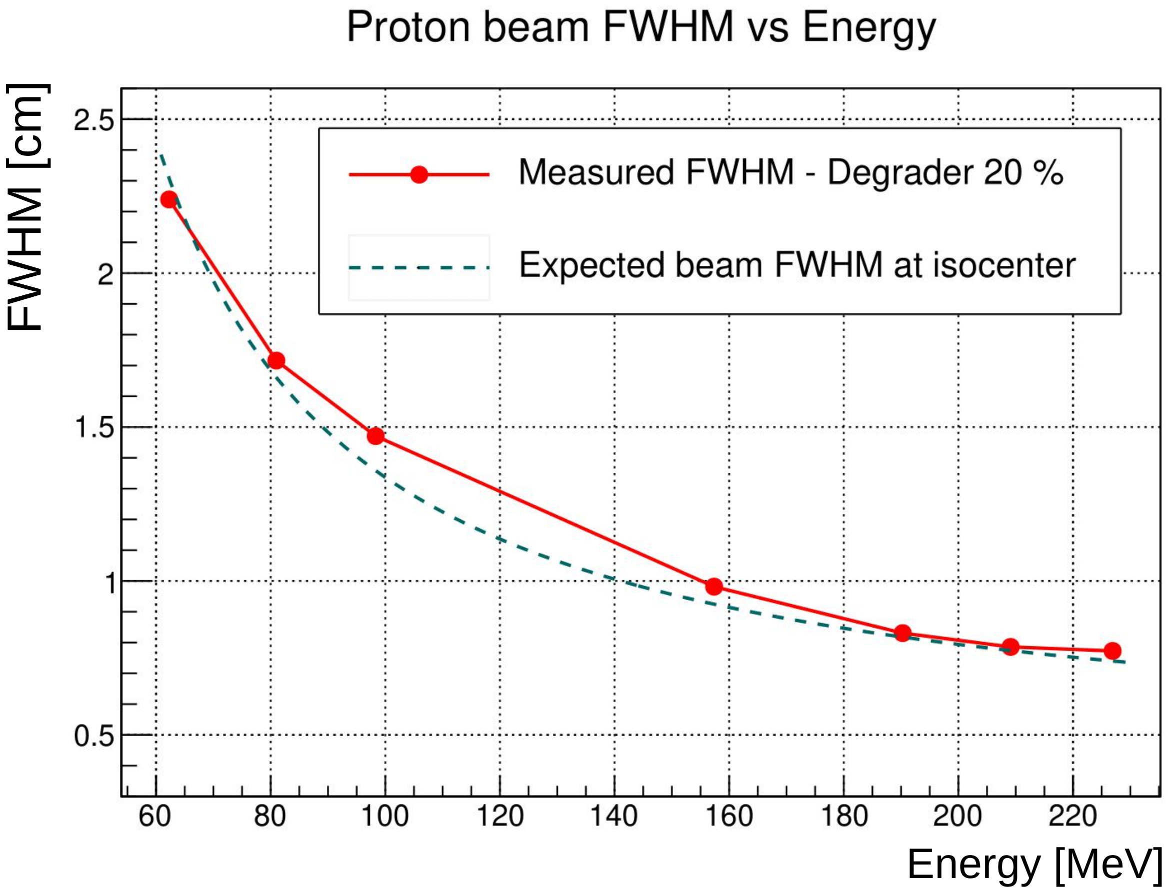
$$efficiency = \frac{counted\ PPS}{estimated\ PPS\ from\ ionization\ chamber\ readout}$$



- **Efficiency larger than 90 %**
- No dead region between strips
- Charge sharing between strips under study
- **Pile-up correction algorithm** (10.1016/j.nima.2022.167195) based on:
  - time duration of digital pulses
  - AND combinations between adjacent strips

Protons - beam projection on y axis





- Discrimination of the proton signals is still under study being the selection of the thresholds much more critical
- Curves → Gaussian fit

$$FWHM = 2\sqrt{2\ln(2)}\,\sigma_{Guaussian\ fit} \cdot p$$

Strip pitch = 180 μm

Expected FWHM at isocenter from Mirandola et Al 10.1118/1.4928397

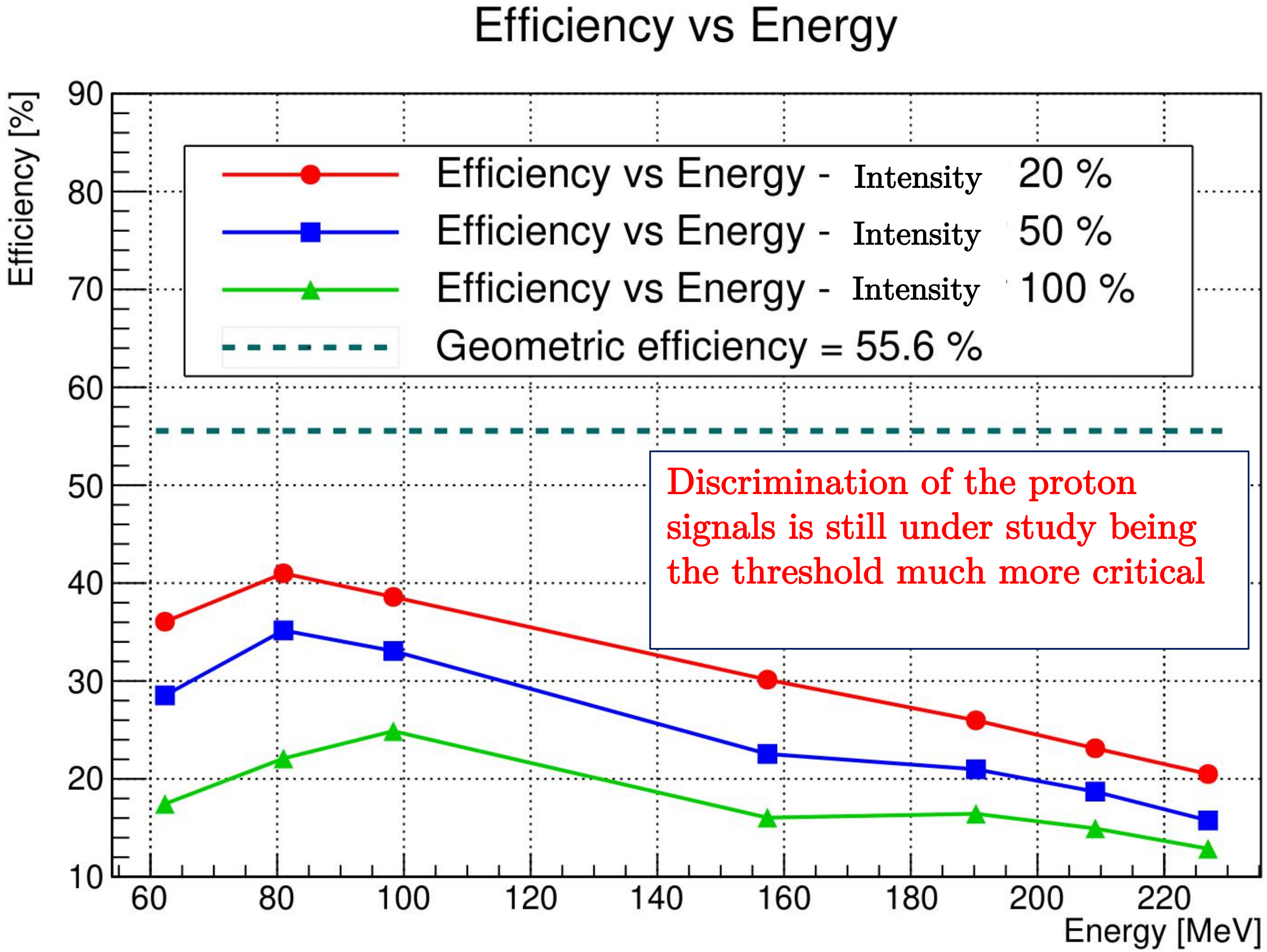
Protons - Counting efficiency vs Energy

$$efficiency = \frac{measured\ PPS}{requested\ PPS}$$

$$geometric\ efficiency = 1 - \frac{80\ \mu m}{180\ \mu m} = 0.556$$

strip pitch

Dead region between strips pitch



- **Energy effect**:
  - Broader beam at 62 MeV → loss of protons in the tails
  - Narrower beam at larger energy → superimposition on noise of amplitude distribution → increase of pile-up inefficiency in beam center
- **Intensity effect**:
  - The larger the fluence rate and the lower the efficiency because of pile-up

Summary

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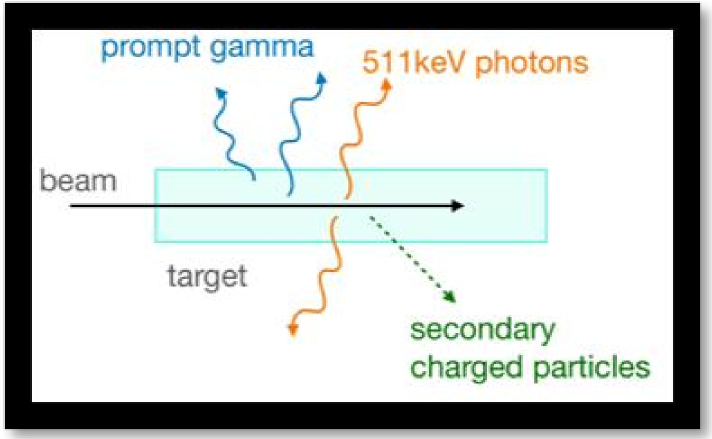
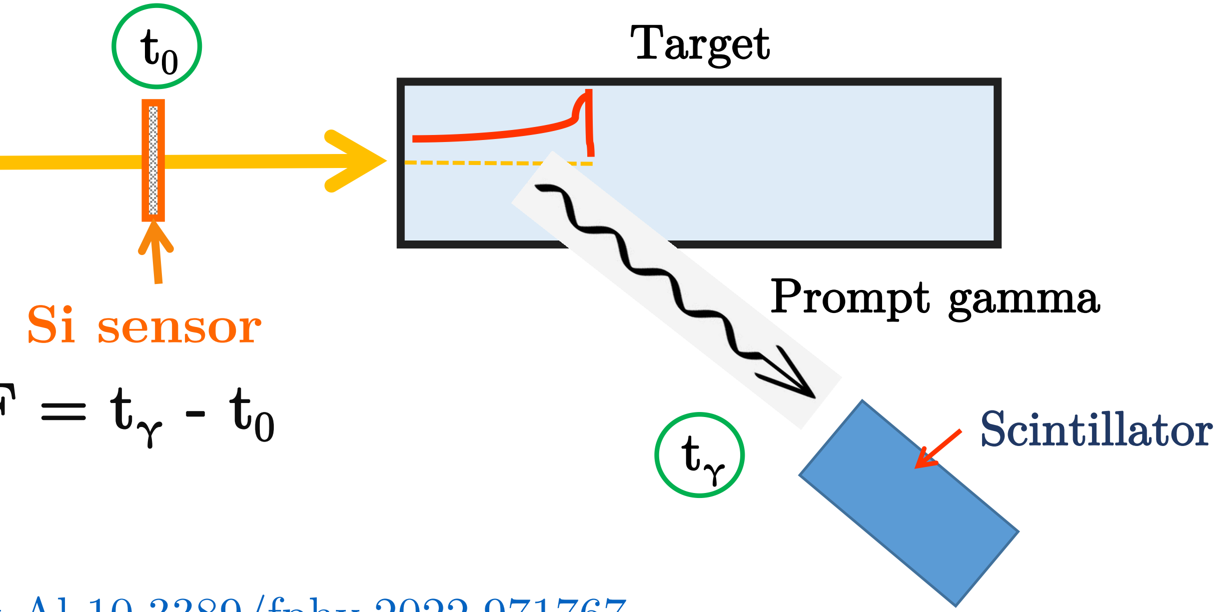
2. Integration of the counter with a TDC (CERN picoTDC) to measure the time of arrival of beam particles

- *Range verification* with prompt gamma timing



Primaries:
- protons
- carbon ions

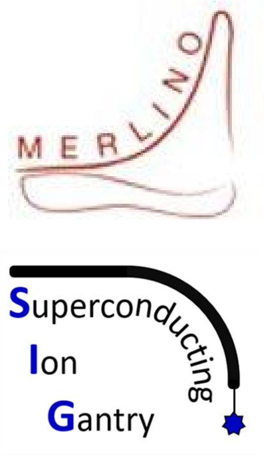


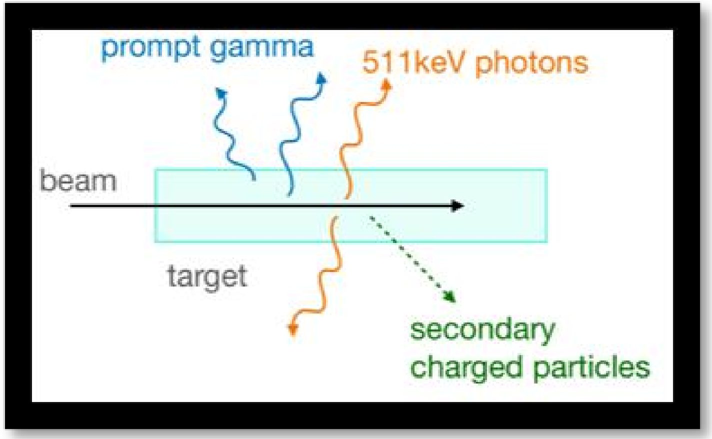
- $\mathrm{ToF} = t_\gamma - t_0$

Ferrero et Al 10.3389/fphy.2022.971767

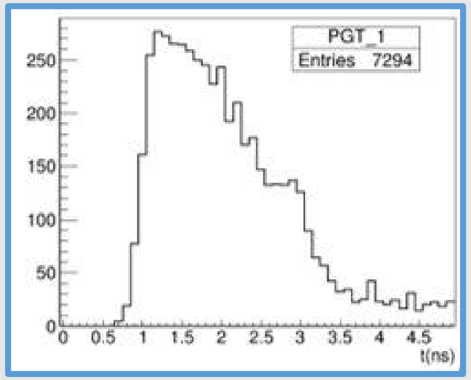
Why timing

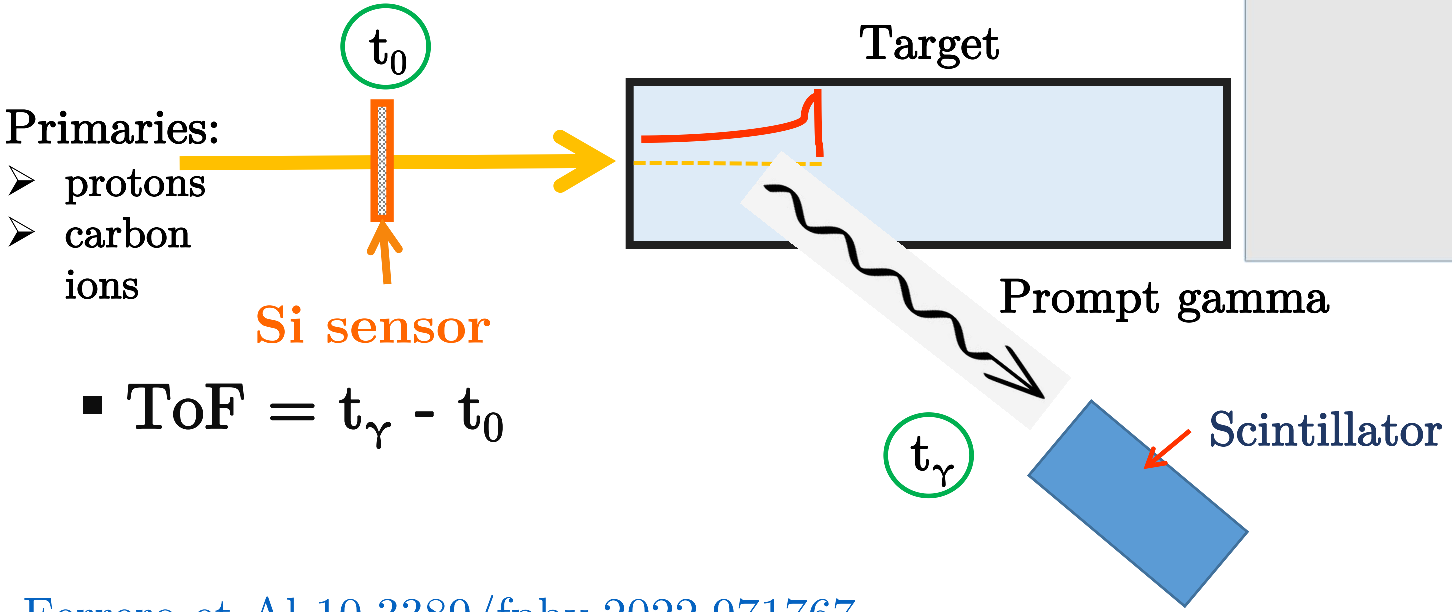
- *Range verification* with prompt gamma timing





Simulated ToF distribution





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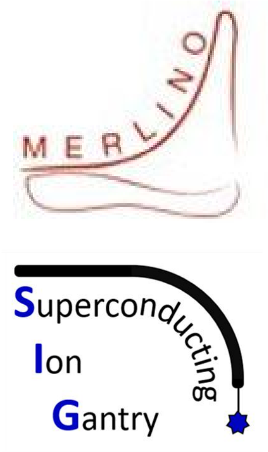

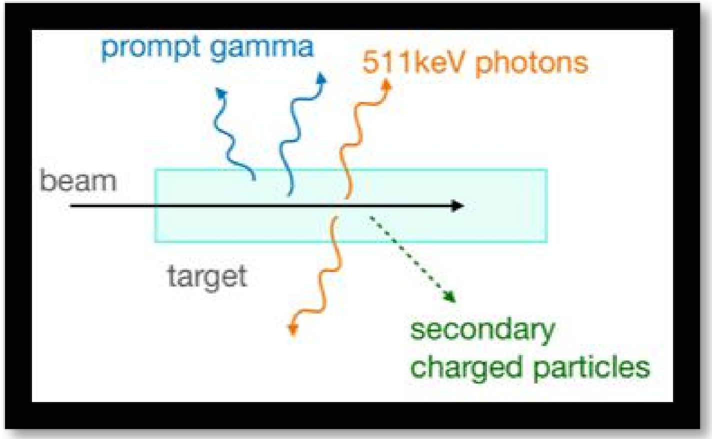

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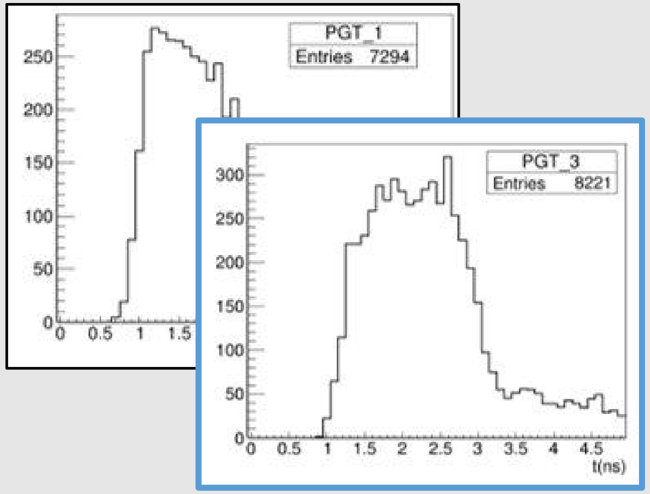

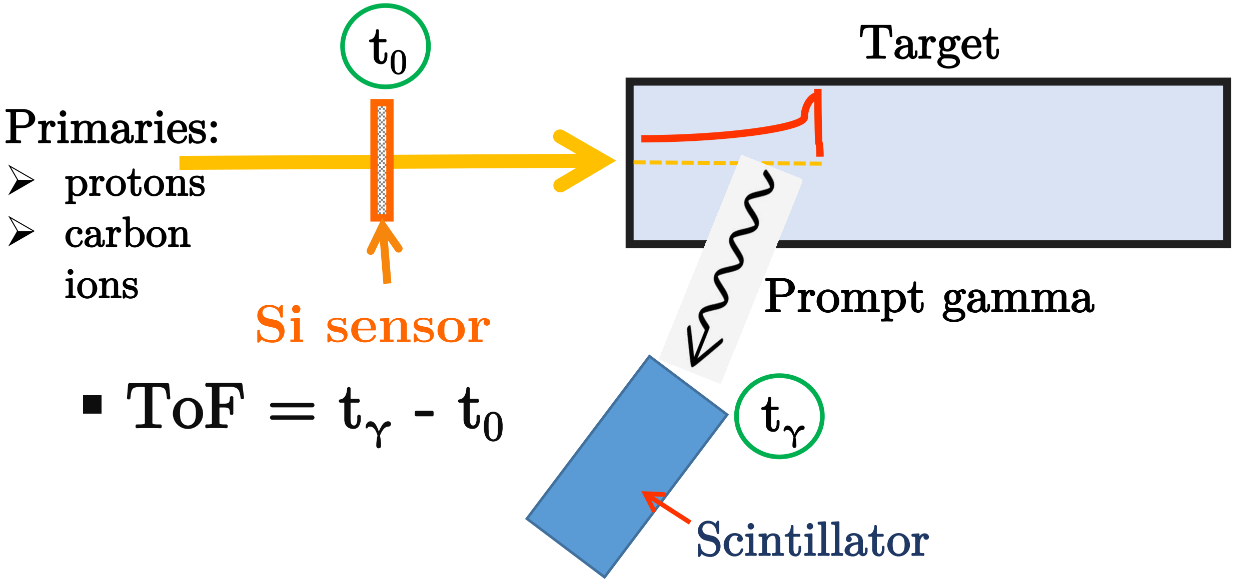

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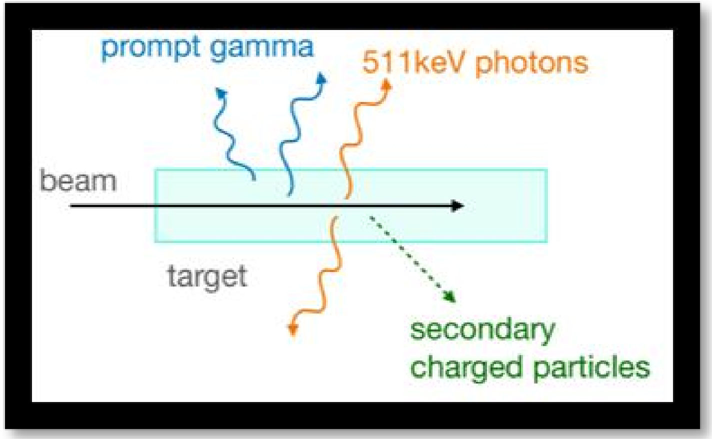
Ferrero et Al 10.3389/fphy.2022.971767

- *Range verification* with prompt gamma timing

Superconducting Ion Gantry (MERLINO)



Primaries:
- protons
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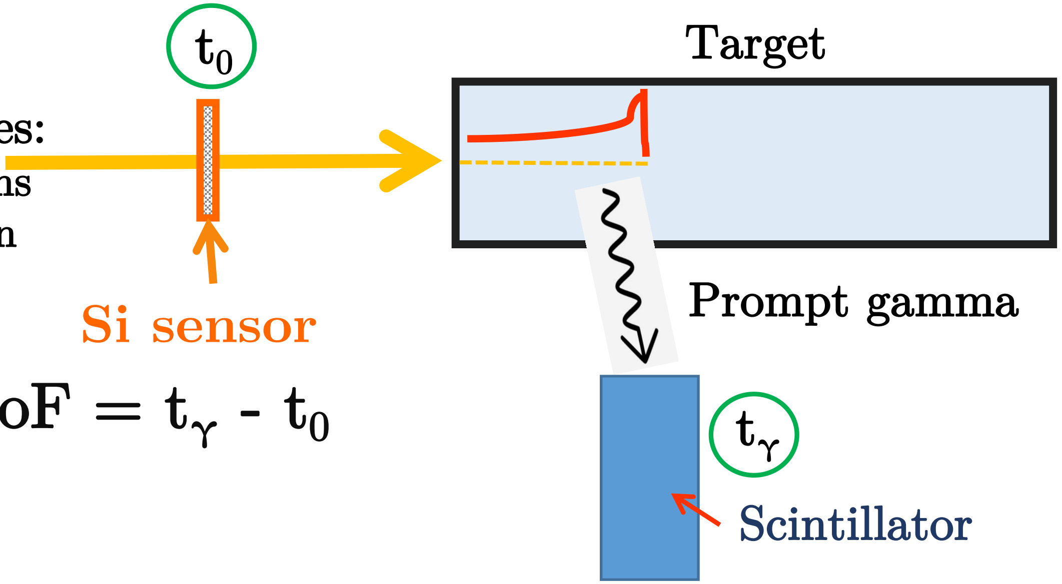

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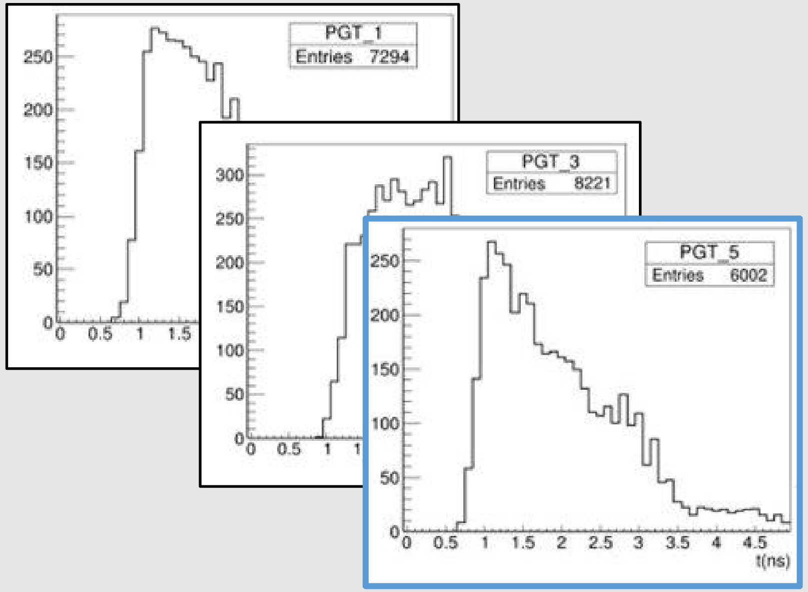
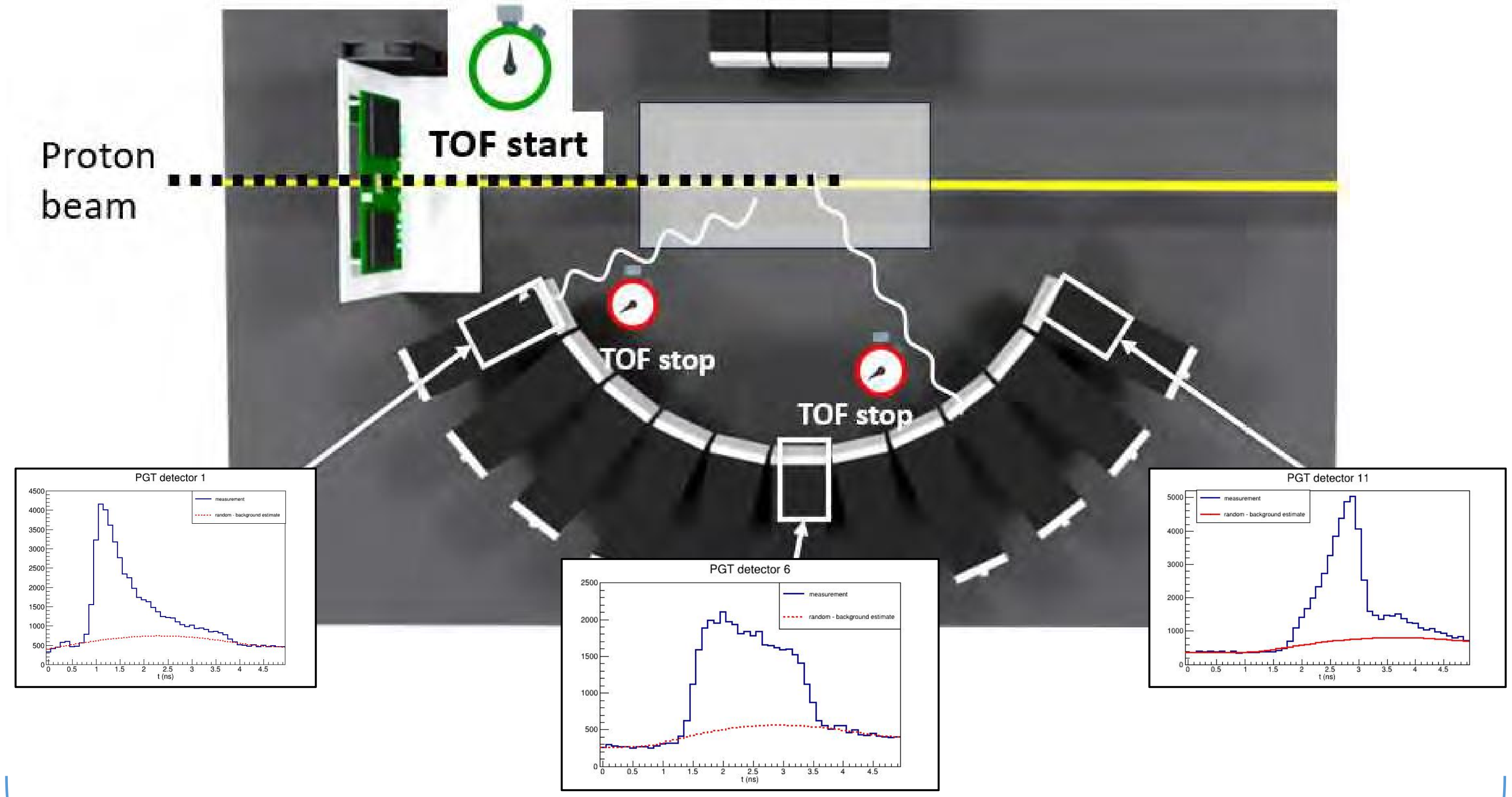


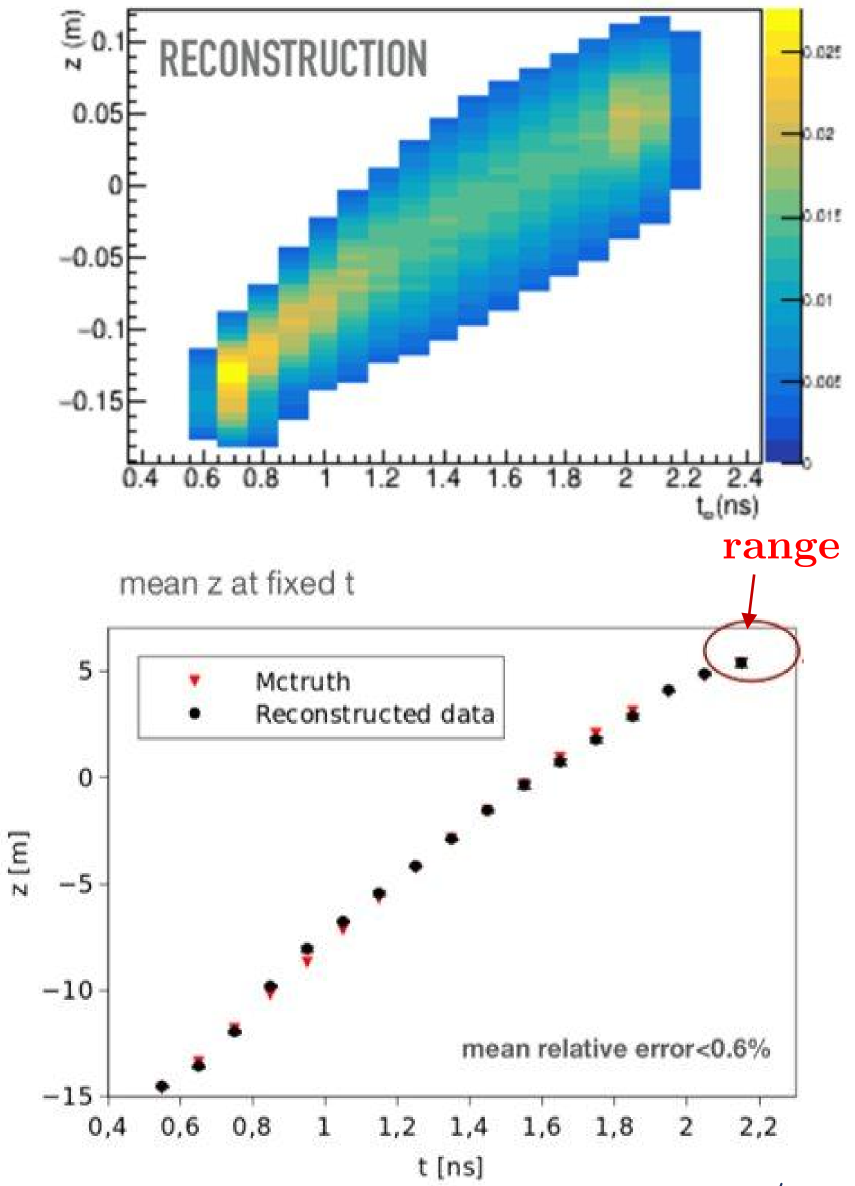
Ferrero et Al 10.3389/fphy.2022.971767

Recostruction of the particle range



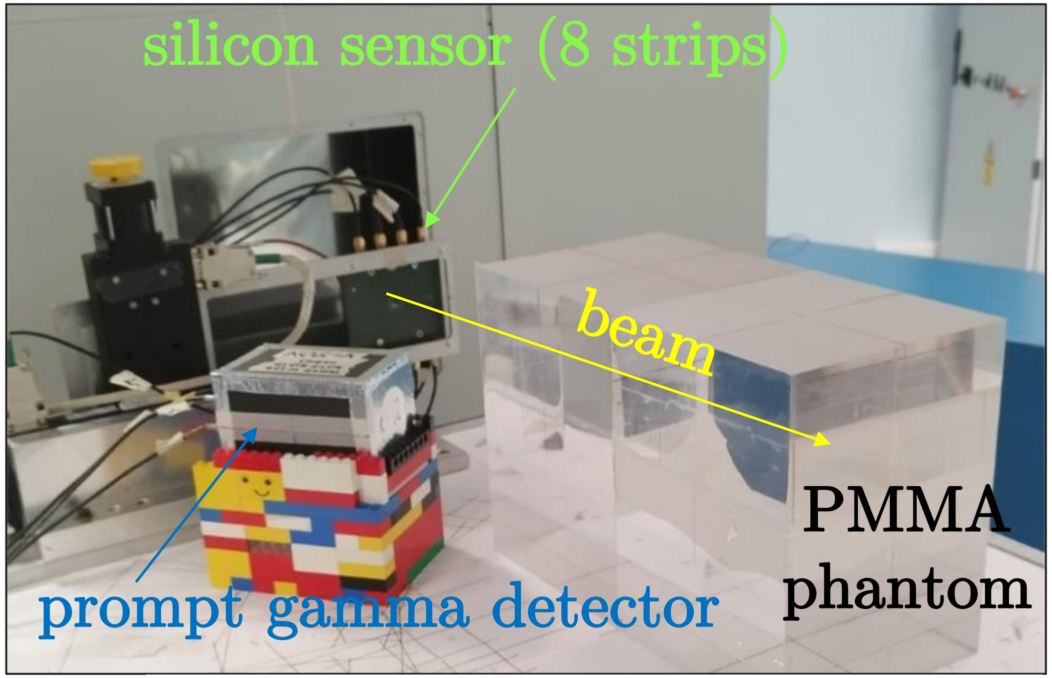
Spatiotemporal Emission Reconstruction MLEM-based solution

Pennazio, F, et al. "Proton therapy monitoring: Spatiotemporal emission reconstruction with prompt gamma timing and implementation with PET detectors." *PMB* 67.6 (2022): 065005.

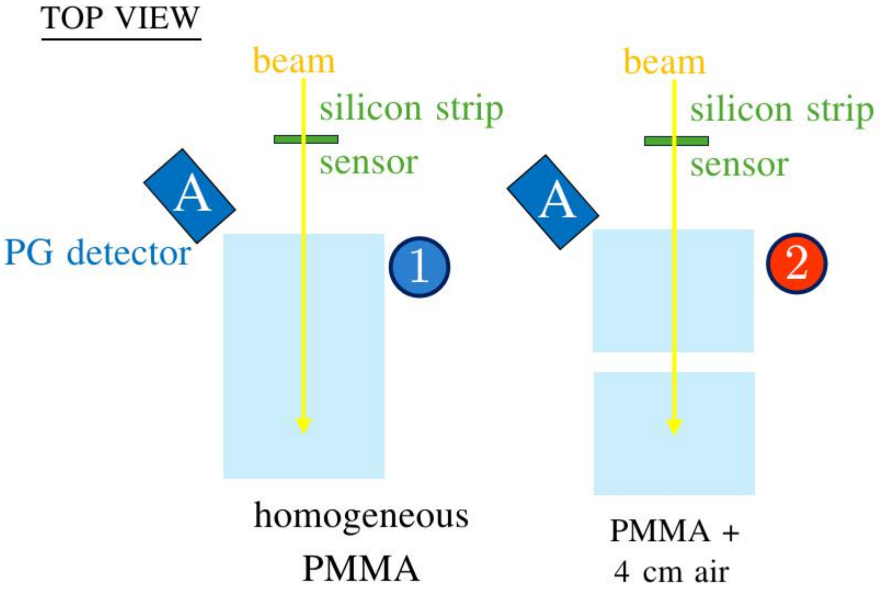


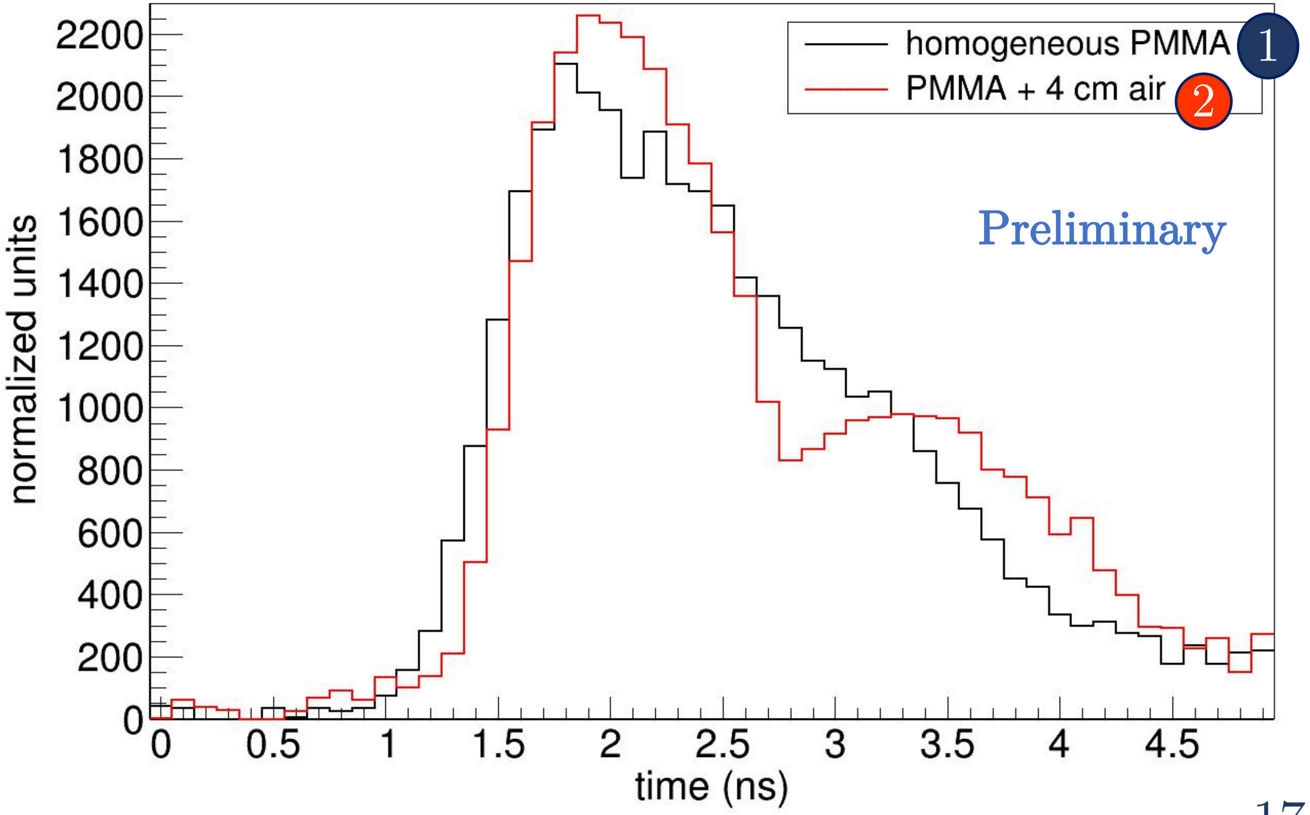
Ferrero et Al 10.3389/fphy.2022.971767

Prompt gamma timing measurement at subclinical rate with carbon ions

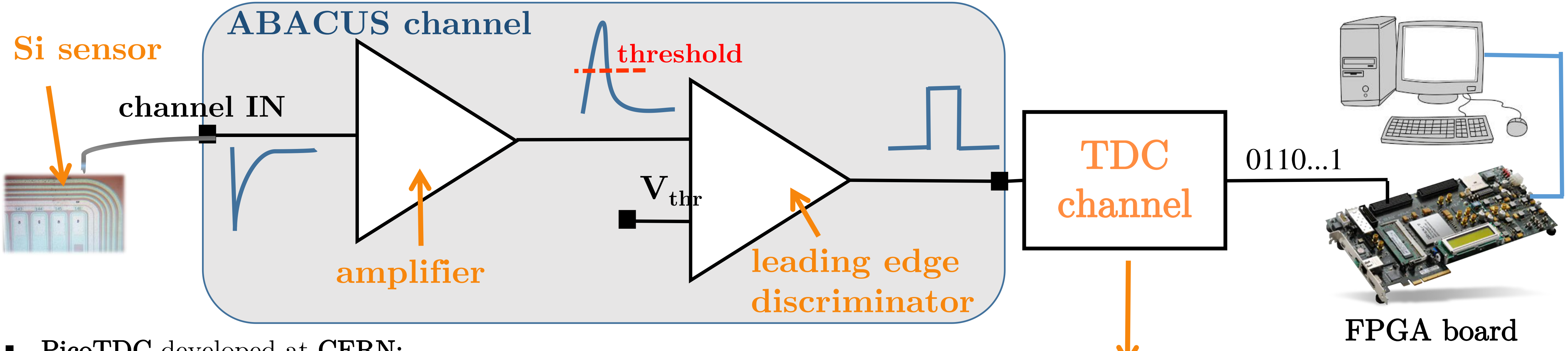


- Detector for primaries: **8-strip silicon sensor**
- Detector for promp gamma: **LaBr3(Ce) crystal (diameter = 3.81 cm, height = 3.81 cm) + SiPM matrix (2.4x2.4 cm^2)**
- Signal read-out made with **DT5742 digitizer** by CAEN
- Limitations of DAQ:
  - Dead time (efficiency 0.04 %)
  - Limited number of channels

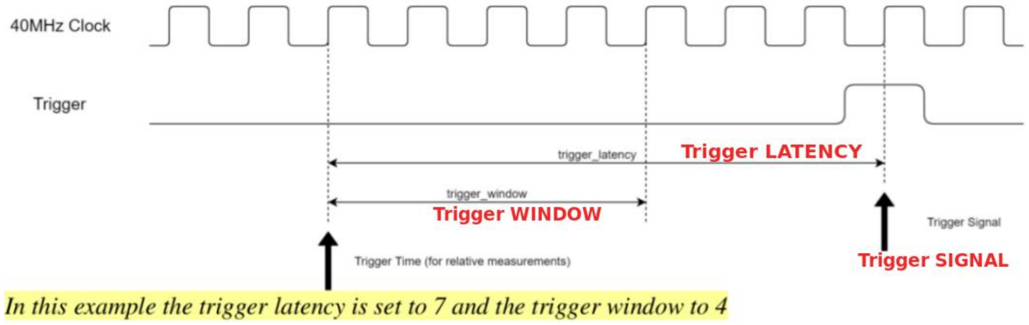




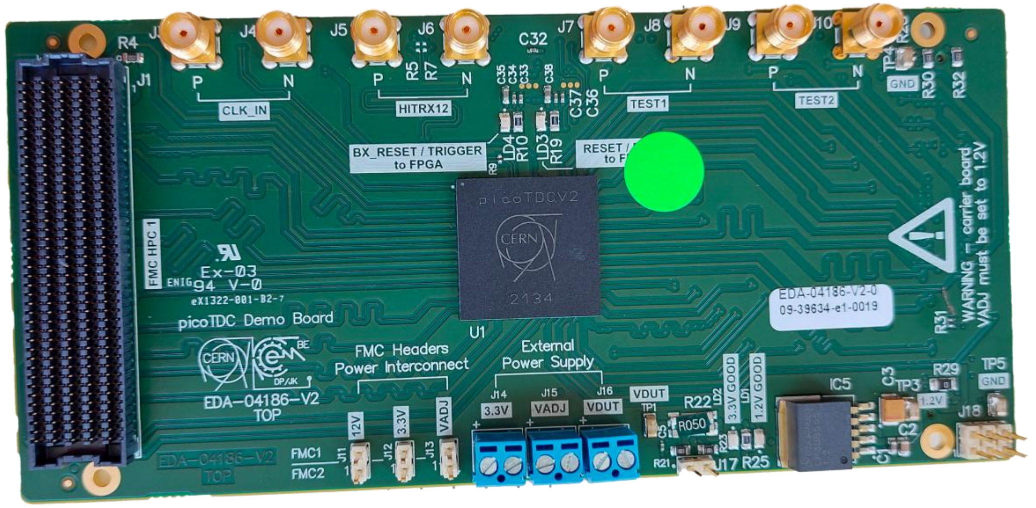
Integration ESA-ABACUS + picoTDC



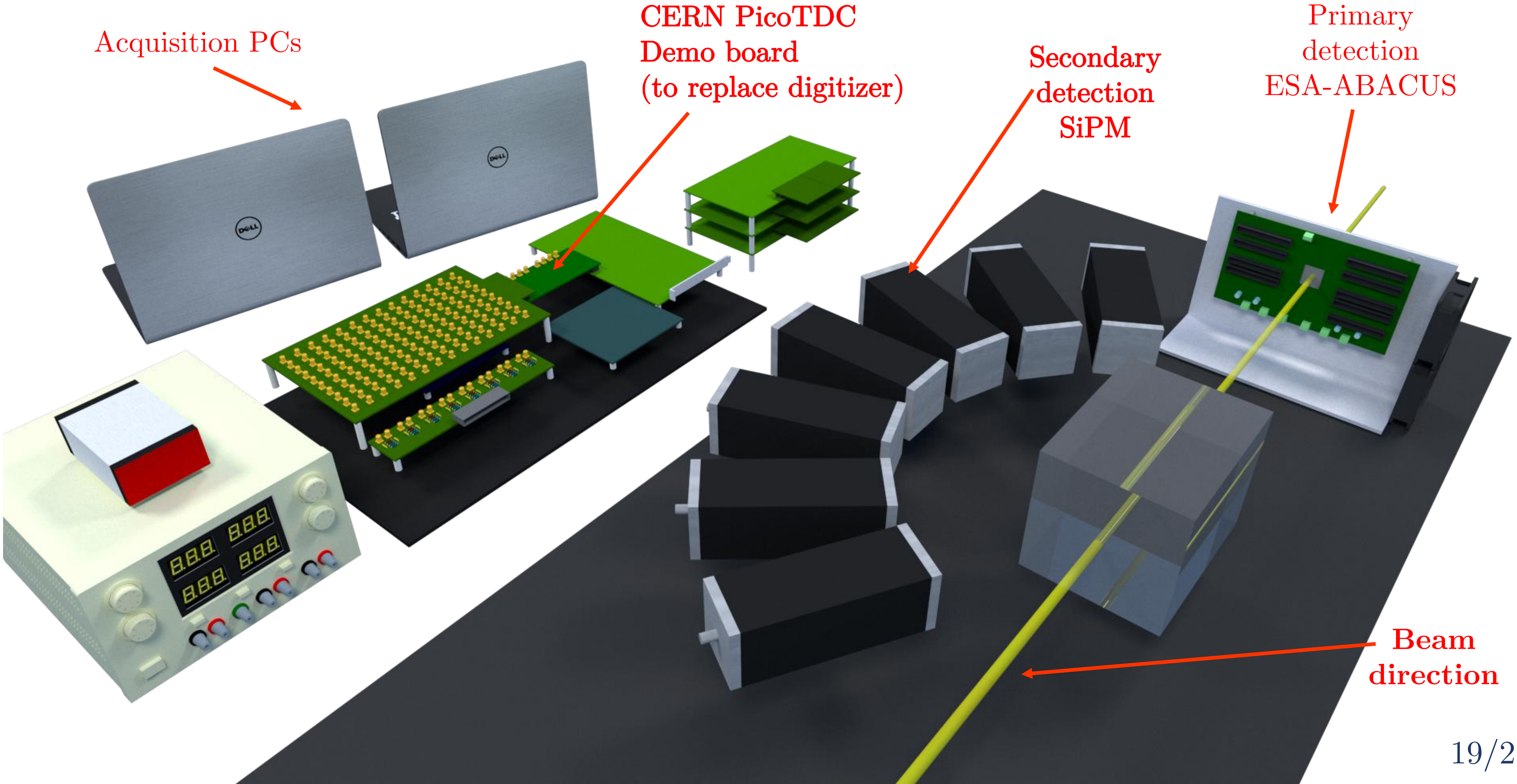
- **PicoTDC** developed at **CERN:**
  - based on **Delay Locked Loop** with **64 delay elements**
  - **Bin size = 3.05 ps**
  - **Dynamic range = 205 µs**
  - **64 channels**
  - **LVDS18 input signals**



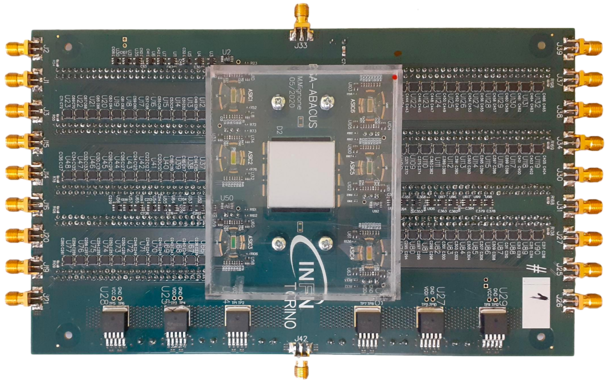
maximum trigger latency = 51 us = 2048 clock cycles



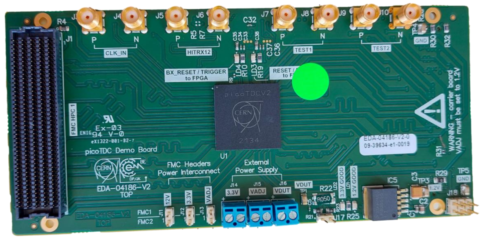
Particle tracking integration with range verification system



Measurements of crossing times of carbon ions

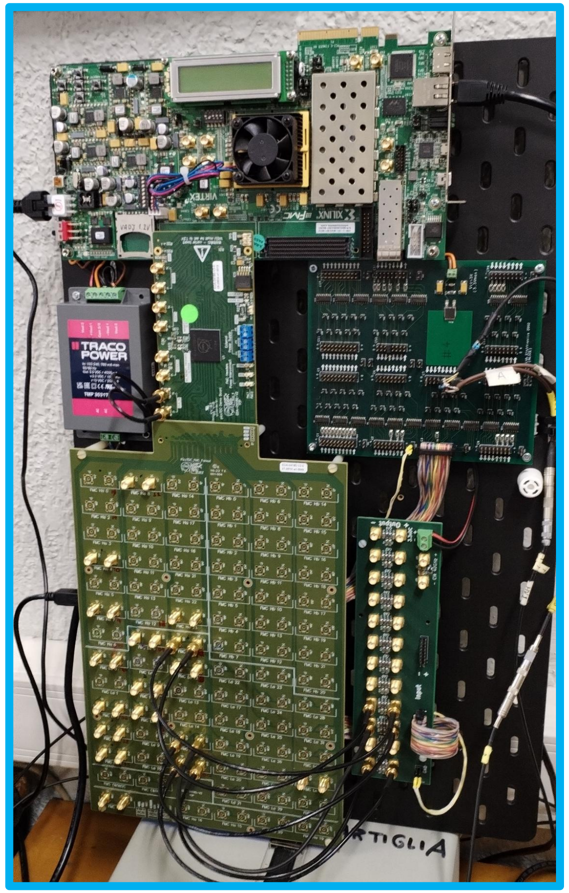


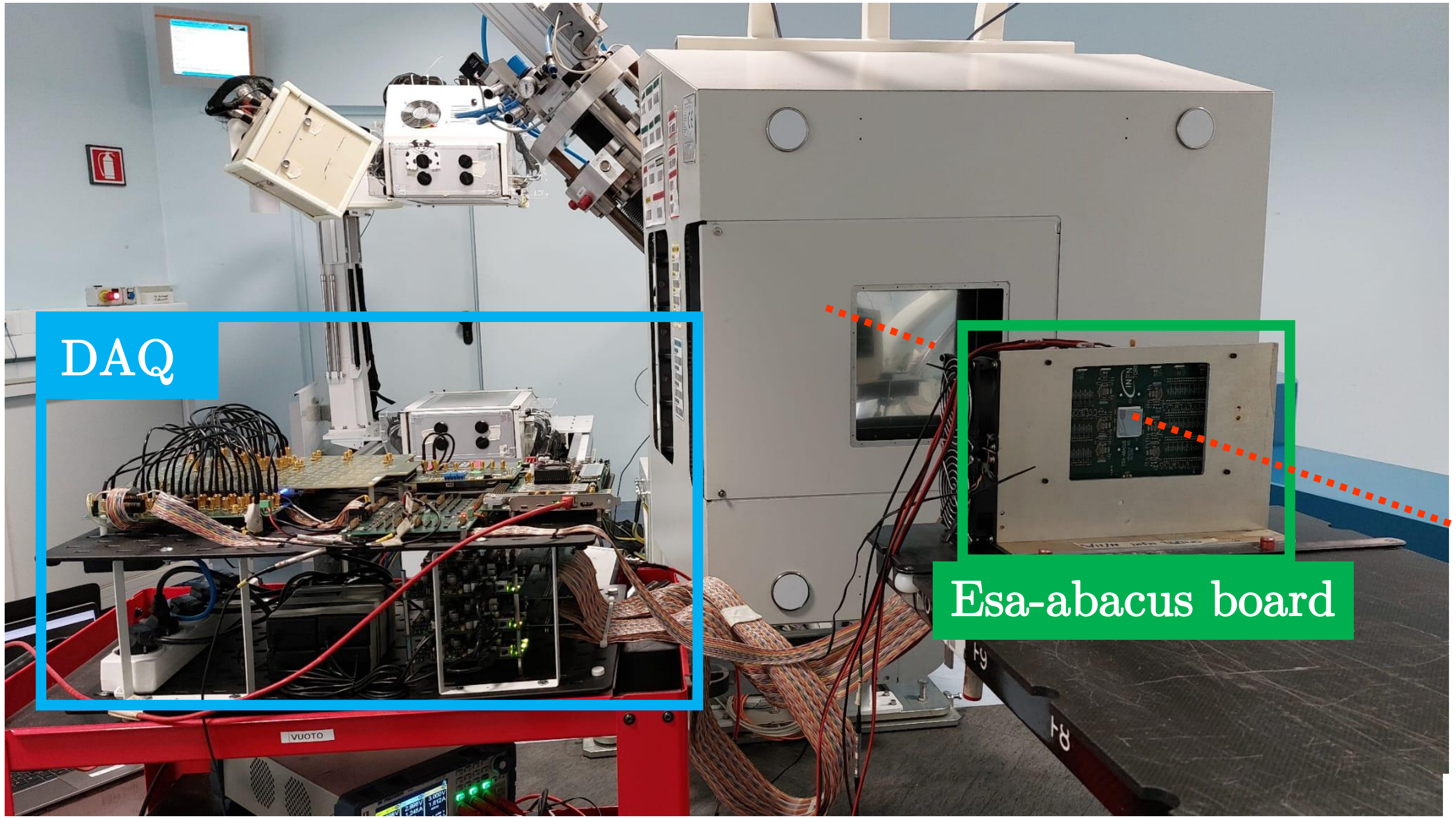
Now only 8 channels connected to the picoTDC
ASIC 1



Virtex 7 FPGA

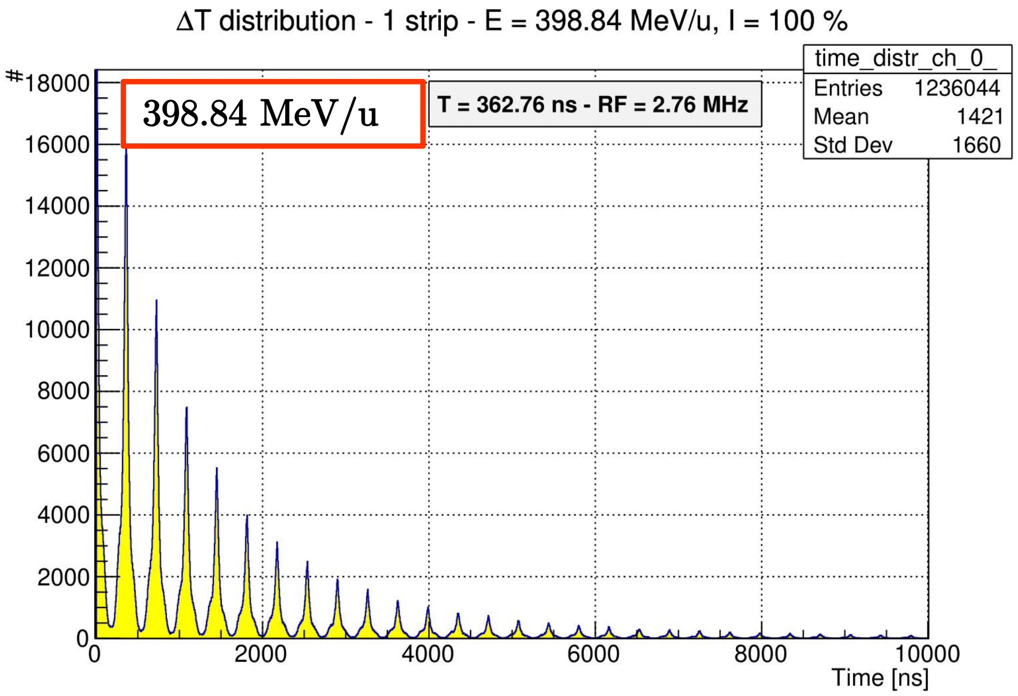
Acquisition PC

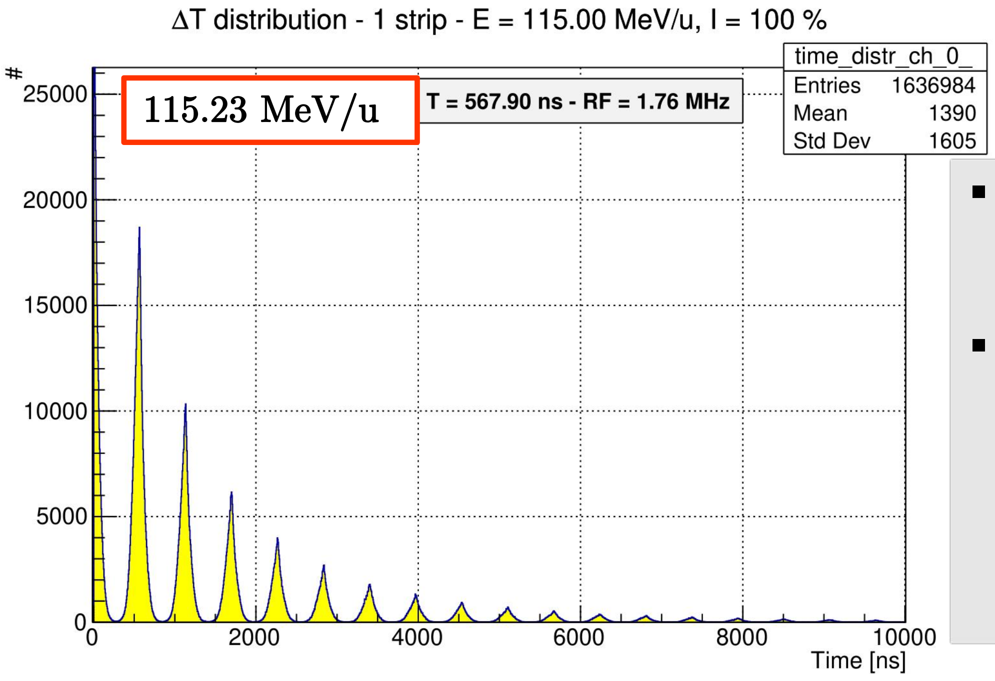




Carbon beam

Distributions of difference of crossing times - 1 strip (1)





- Measurement of time of arrival of carbon ions in 1 strip
- Acquisition in trigger mode:
  - window = 20 μs
  - Latency = 20 μs
  - Trigger frequency = 50 kHz

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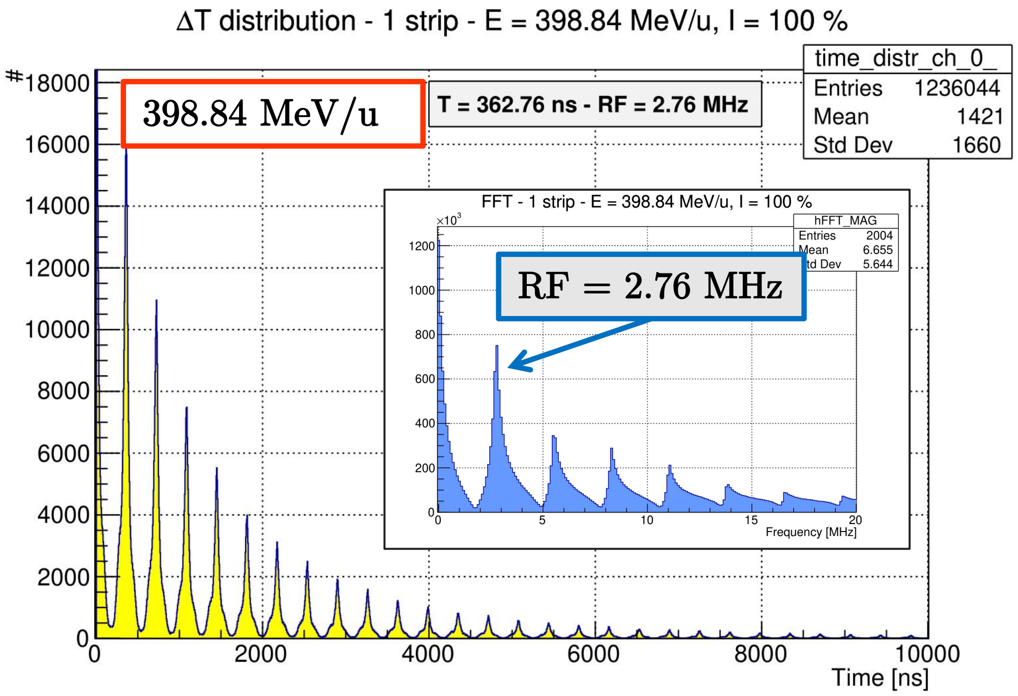

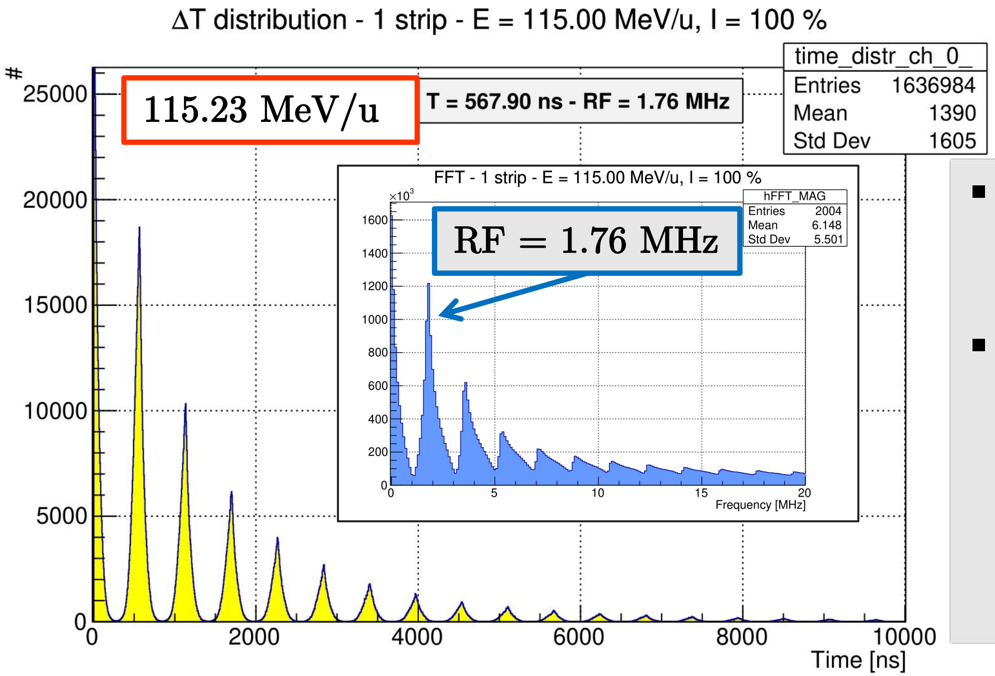

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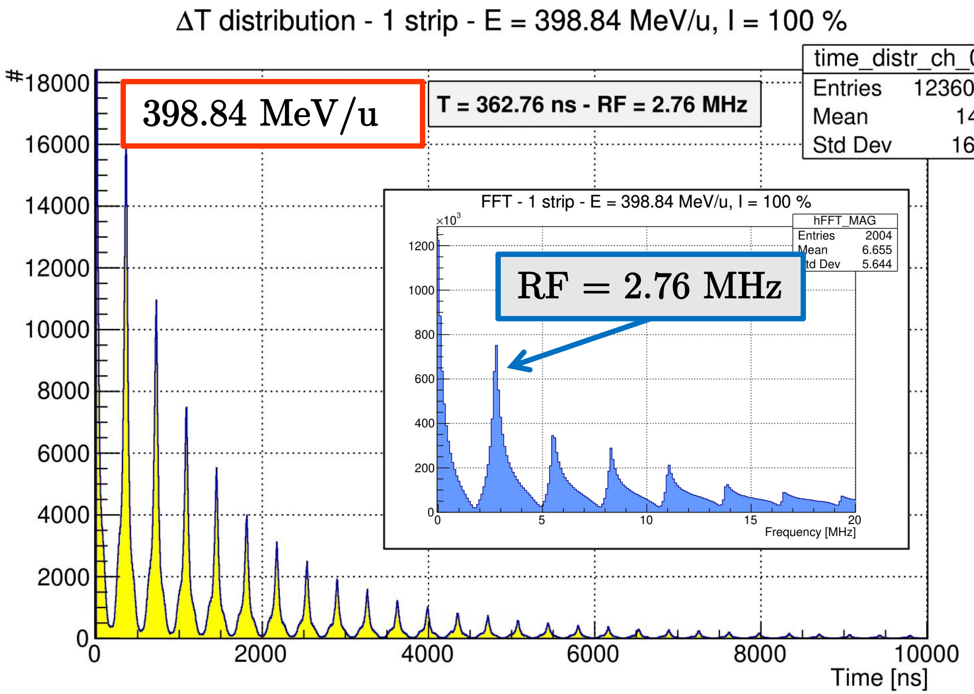

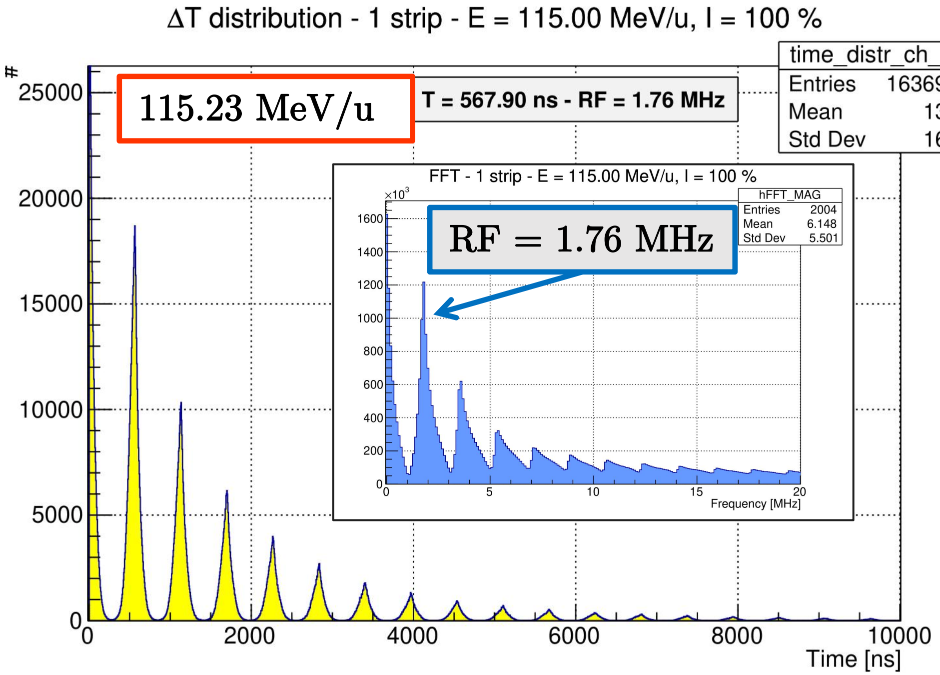

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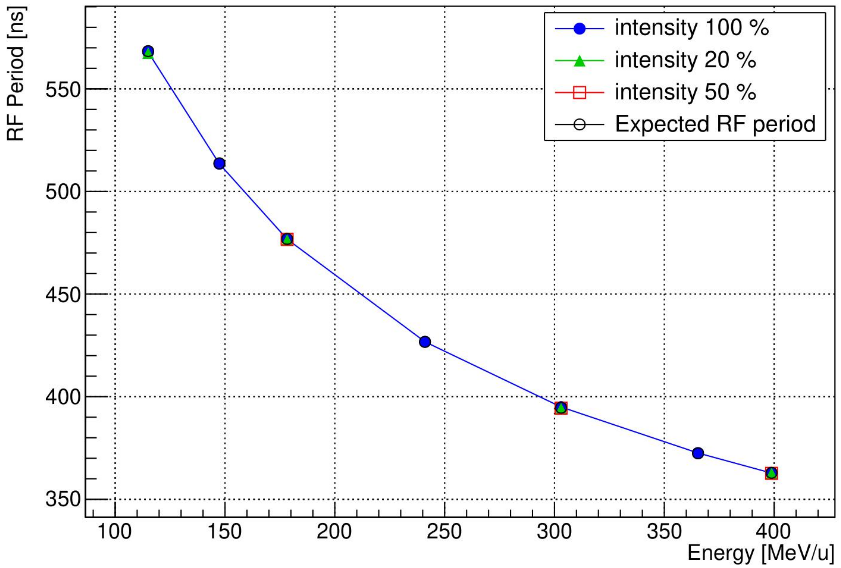


RF period vs energy

- Measured RF period compatible with expected values with *significance level of 5 %* ($Z_{gauss} \sim 0.3$)

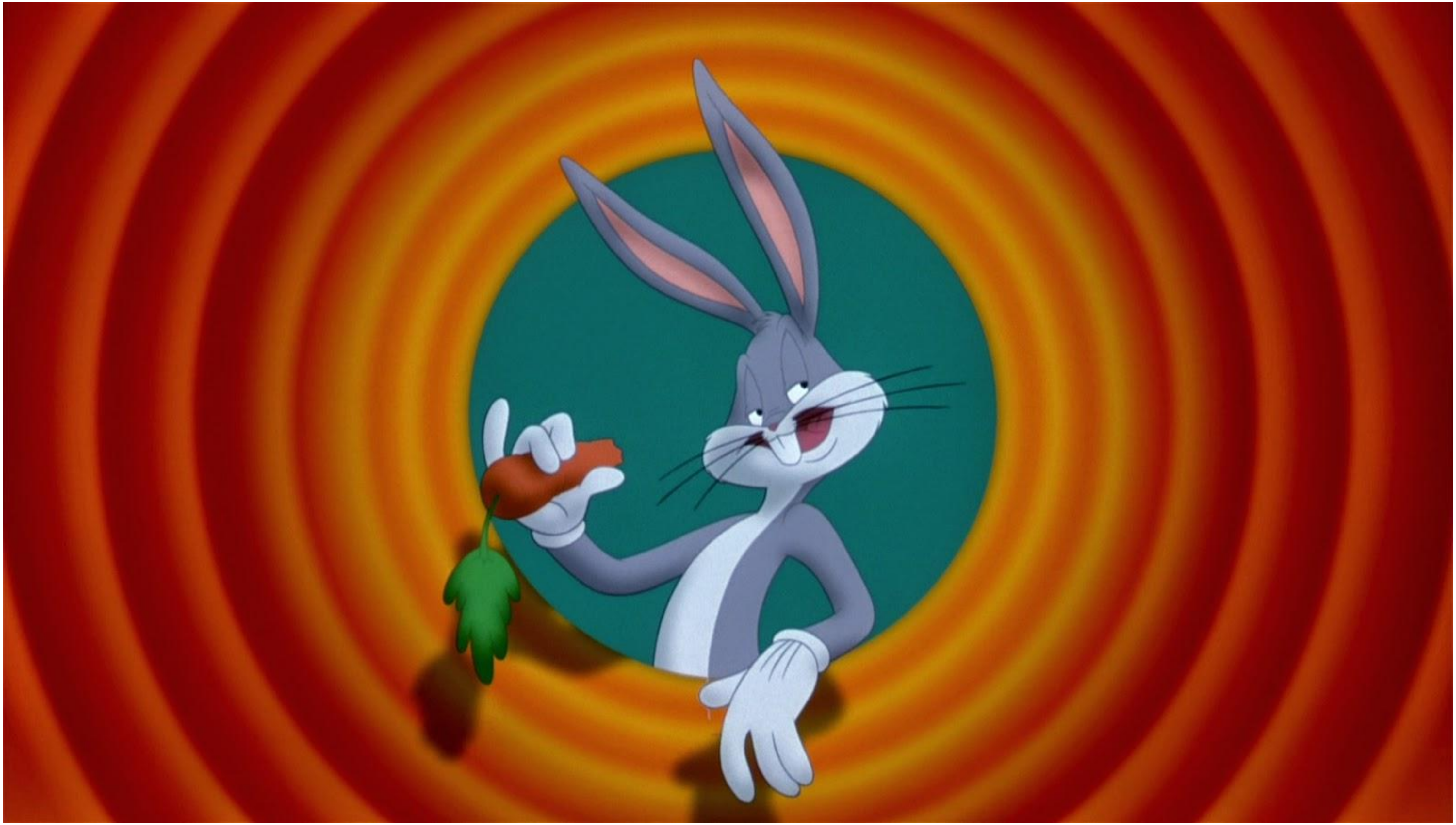
Conclusions and next steps

- **ESA-ABACUS board (counter)**
  - Tests of the **ESA-ABACUS** board with *clinical* **proton and carbon ion beams** prove
    - ➢feasibility of measuring the **particle rate** and **beam shape directly**
    - ➢good **stability in time**
  - Inefficiency due to pile-up was observed
  - The lower S/R ratio observed at the largest proton energies requires more investigation
  - Better uniformity expected in new ABACUS production

- **ESA-ABACUS board + picoTDC**
  - Measured beam frequency components in agreement with accelerator RF values
  - Results indicate that thin silicon detectors, custom readout electronics and the picoTDC allow for a full 4D tracking at the high rates of clinical beams

- First PGT measurements using the picoTDC were performed in April and the analysis is ongoing

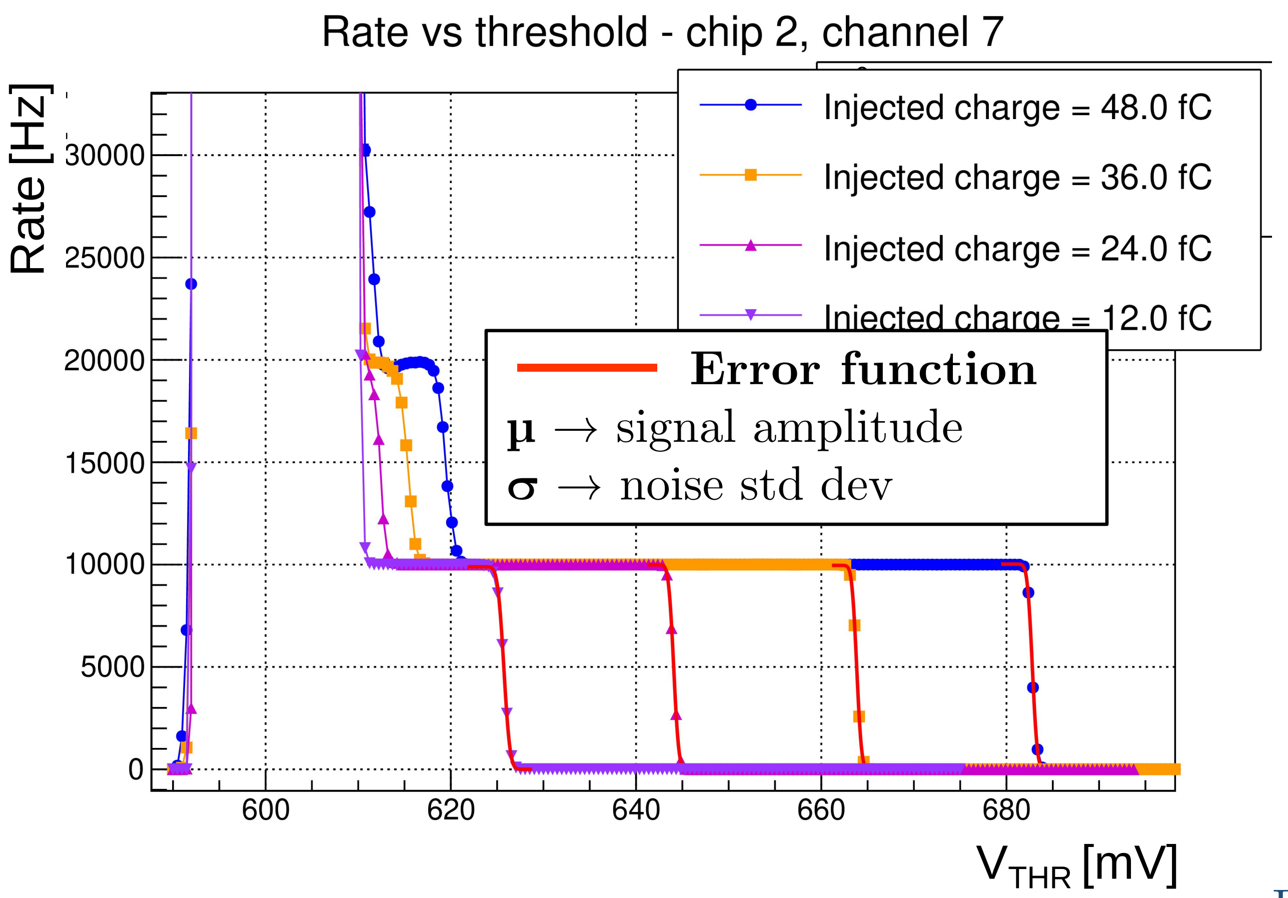
That's all Folks

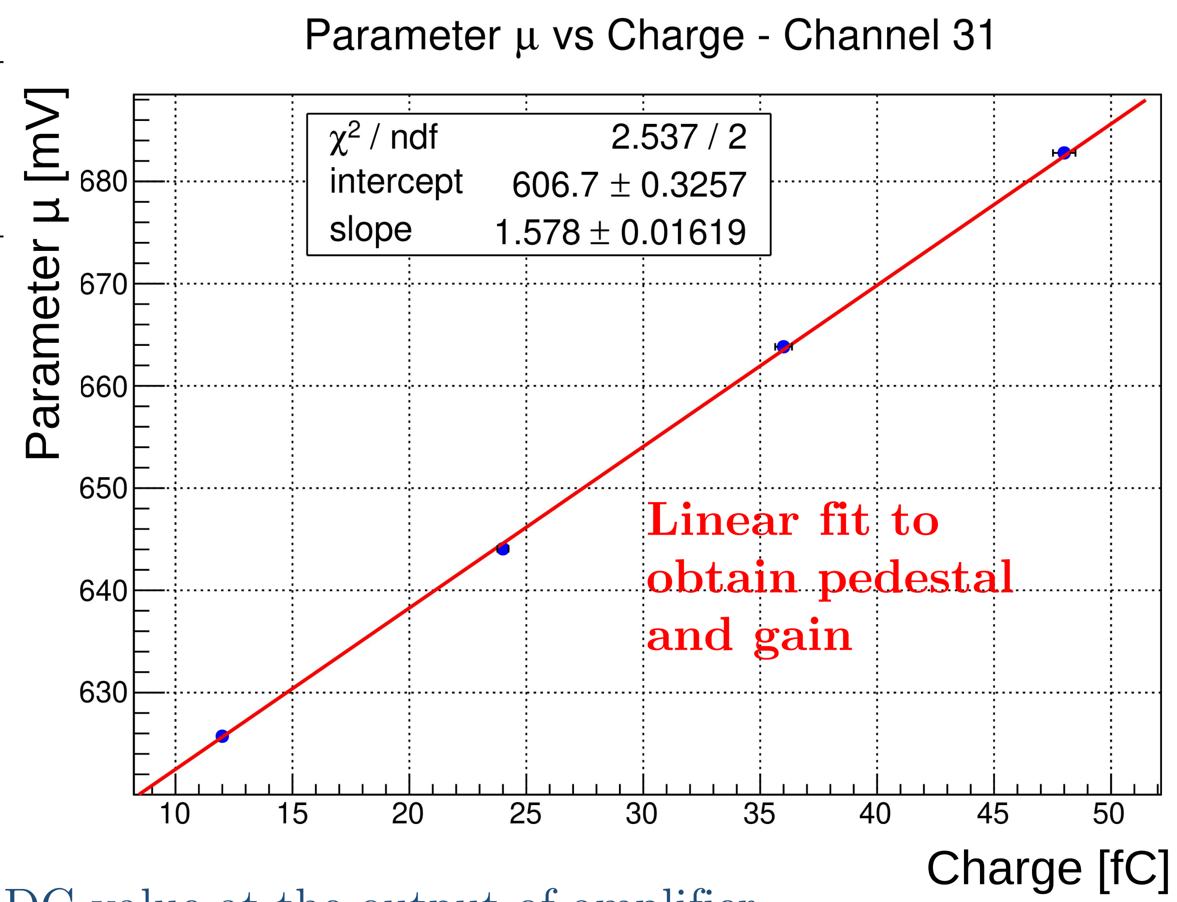


Backup

Characterization tests in laboratory

Different threshold scans injecting a constant charge into CSA with a pulse generator





DC value at the output of amplifier

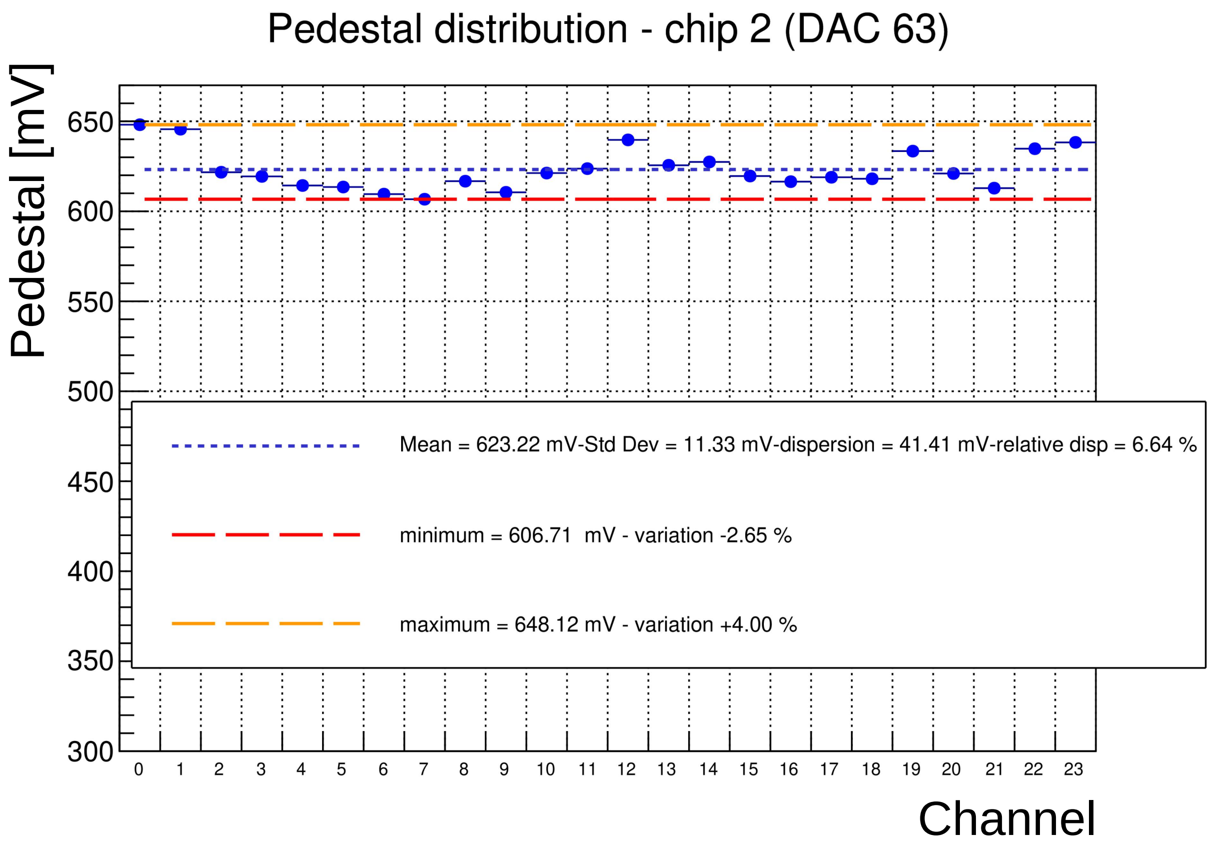
Chip 2 Channel 7

- **Intercept → Pedestal →** $\mathbf{(606.7 \pm 0.3)\ mV}$
- **Slope → Gain of the amplifier →** $\mathbf{(1.58 \pm 0.02)\ mV/fC}$

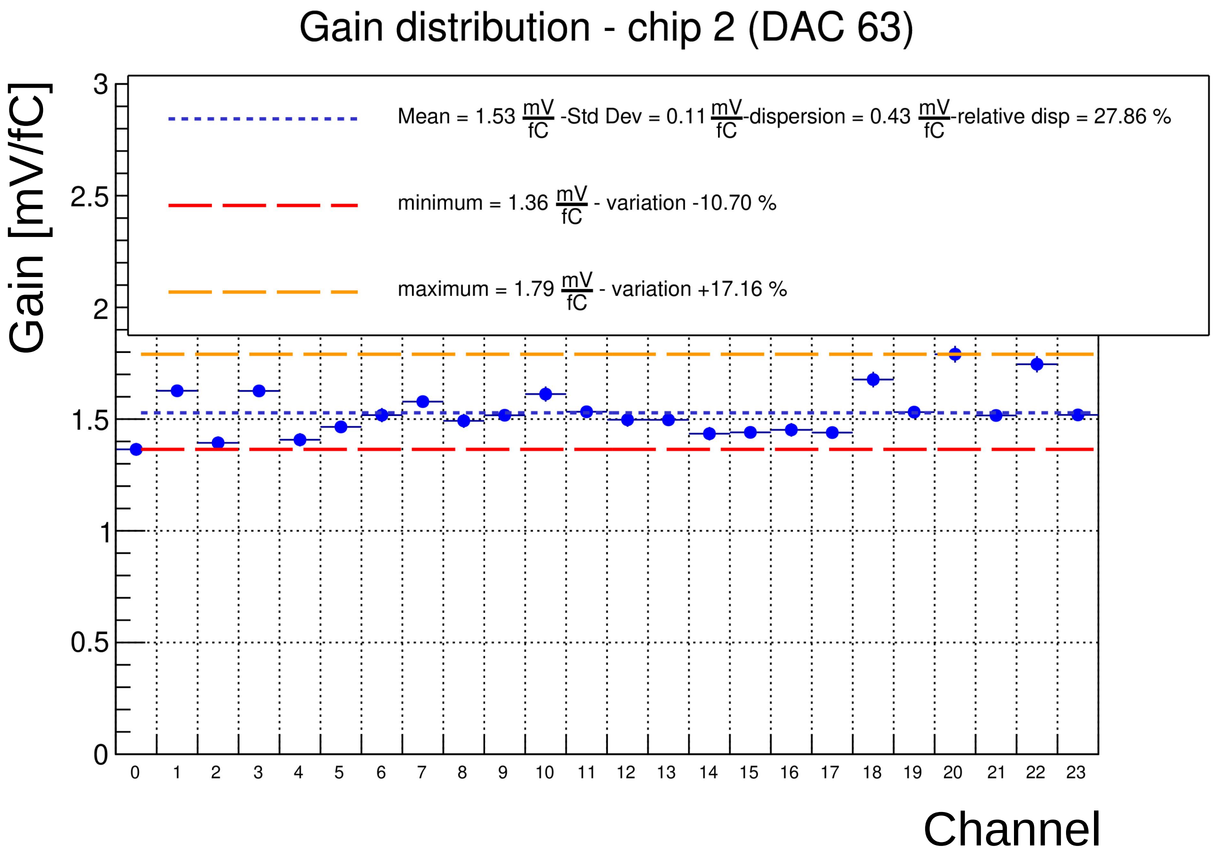
Example of pedestal and gain distributions: A

Iterating the same procedure for all channels. the following histograms are filled

ESA-ABACUS N4



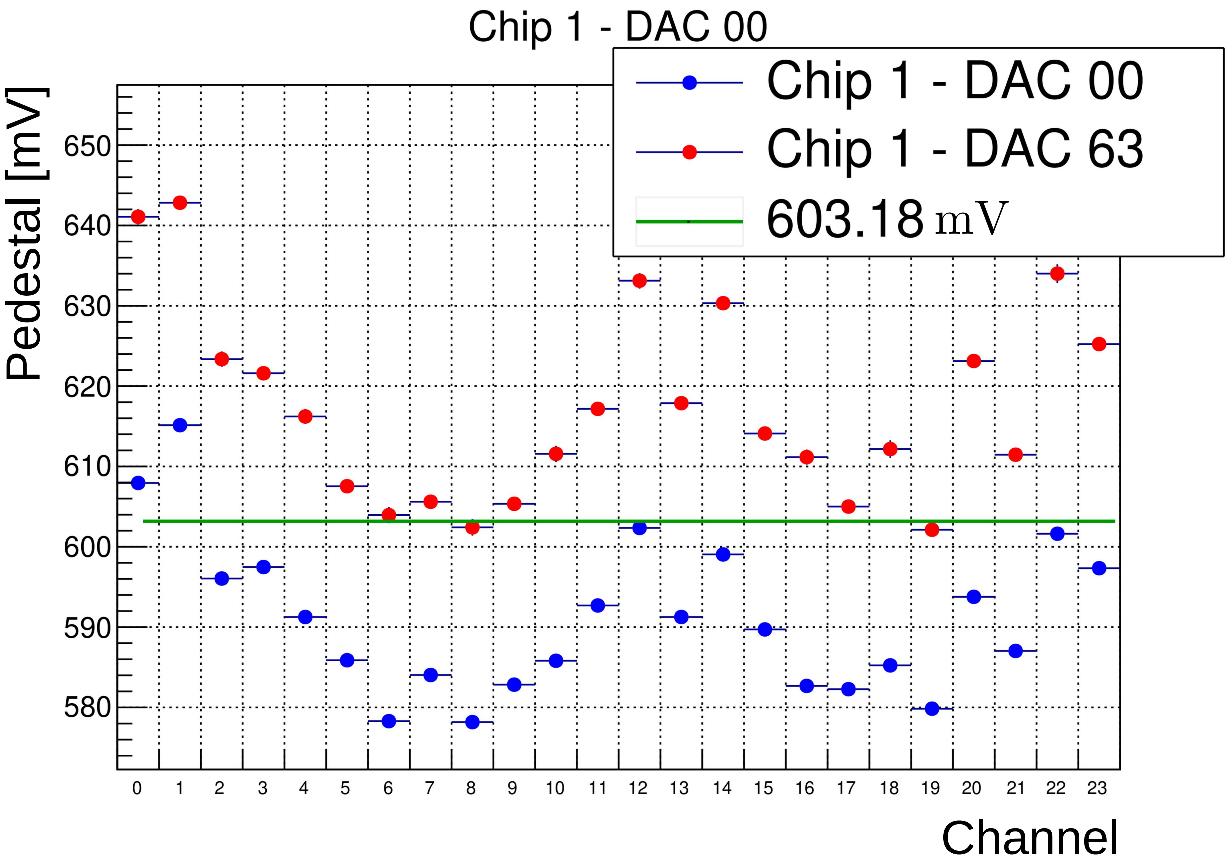
- Mean value $\rightarrow \sim 623$ mV
- Standard deviation $\rightarrow \sim 11$ mV
- Relative dispersion $\rightarrow \sim 2$ %

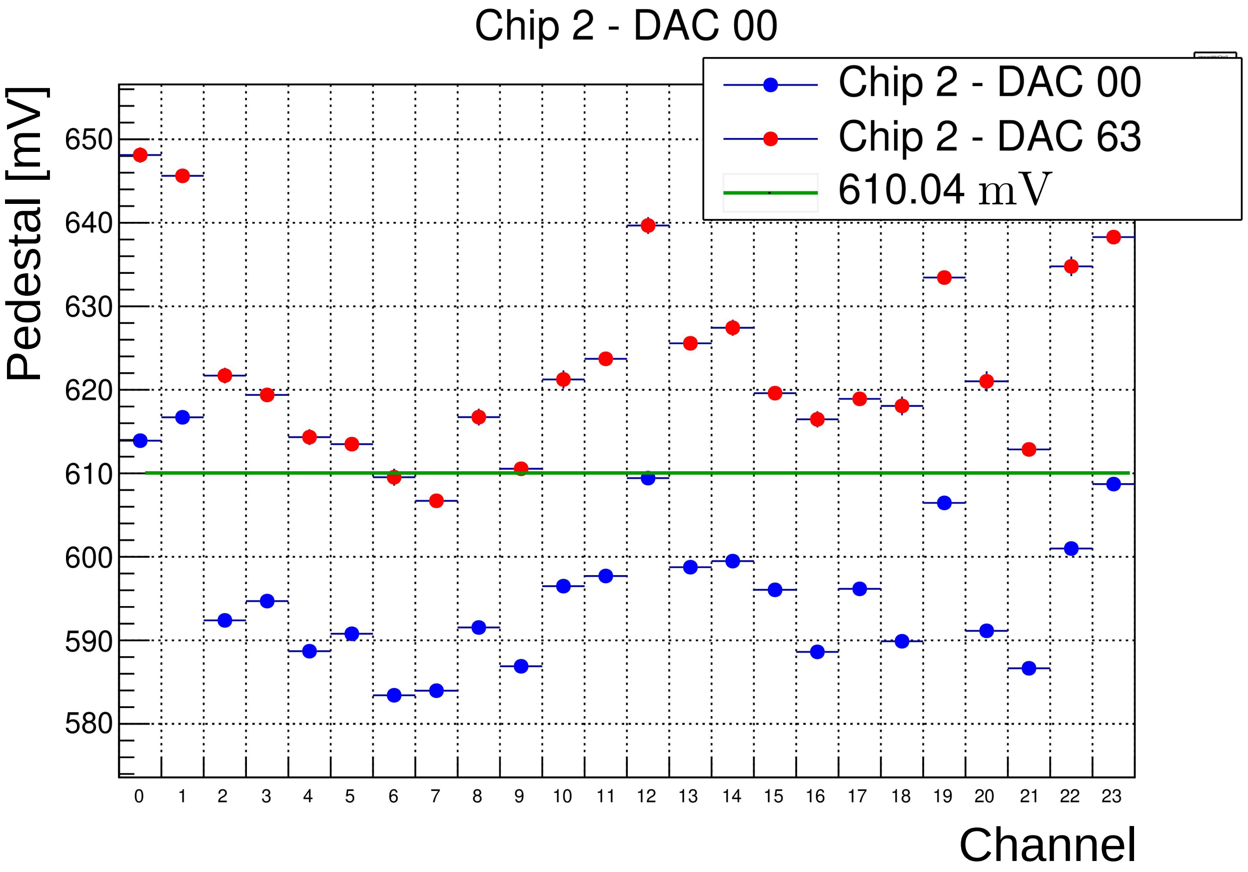


- Mean value $\rightarrow \sim 1.53$ mV/fC
- Standard deviation $\rightarrow \sim 0.11$ mV/fC
- Relative dispersion $\rightarrow \sim 7$ %

Optimization of pedestals with internal DACs

Example for 2 chips

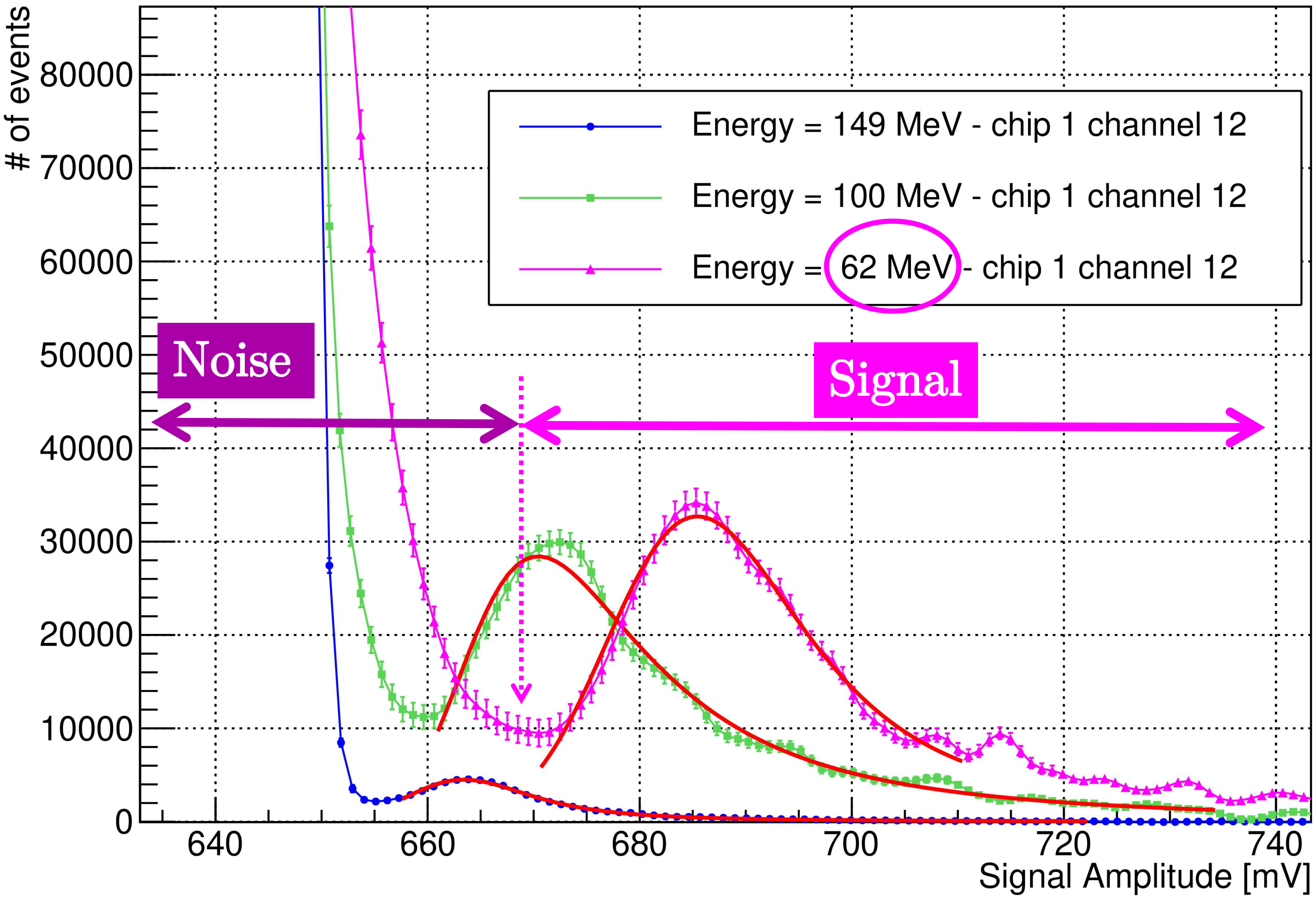




- Pedestal distributions measured for each chip for both internal **DAC = 63** and internal **DAC = 0** to make the *pedestal equalization*
- The **green line** is the median of the pedestals

Signal amplitude distributions

Signal amplitude distributions for 3 proton energies in 1 strip



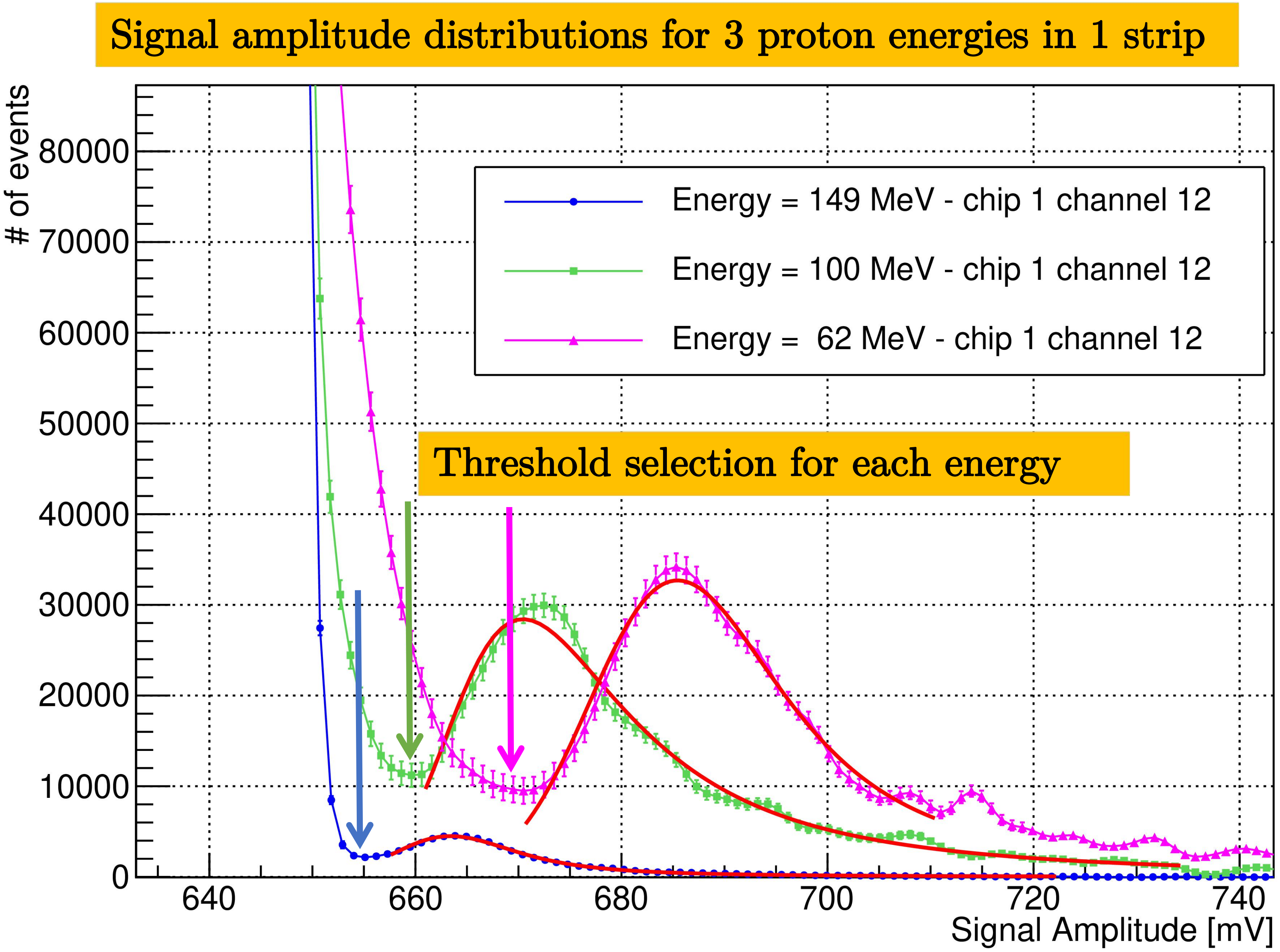
- Discriminating signal from noise
- Threshold scans with different beam energies
- Signal Amplitude distribution → Landau ∗ Gaussian

Convolution fit funtion* (red curves):

- MPV
- Width (scale parameter for the Landau)
- Area
- Gaussian Sigma

*Cartiglia et Al

Signal amplitude distributions



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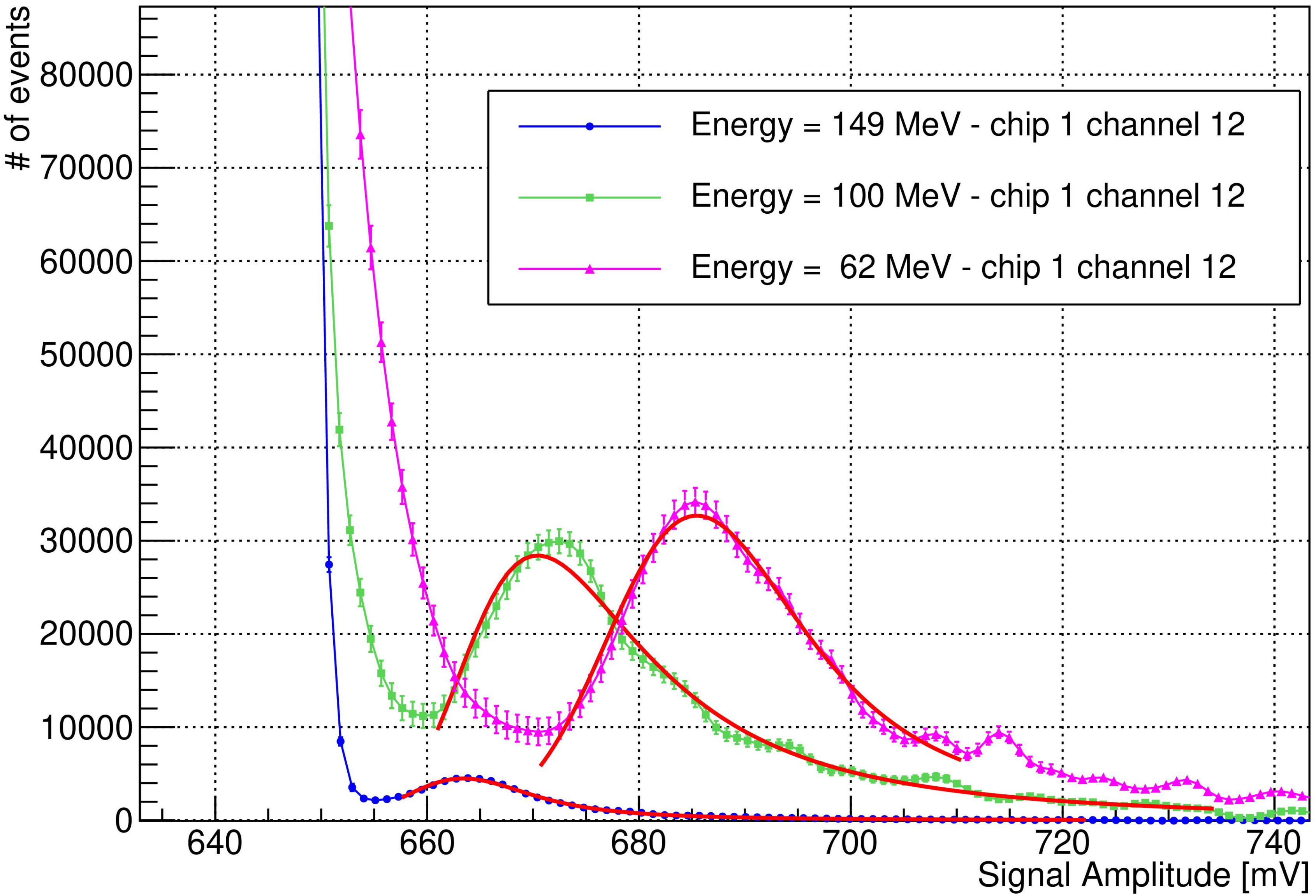

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*Cartiglia et Al

Selection of the thresholds

- How to select the threshold to discriminate signal from noise?
- Threshold scans with different beam energies
- Signal Amplitude distribution → Landau ∗ Gaussian

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*Cartiglia et Al

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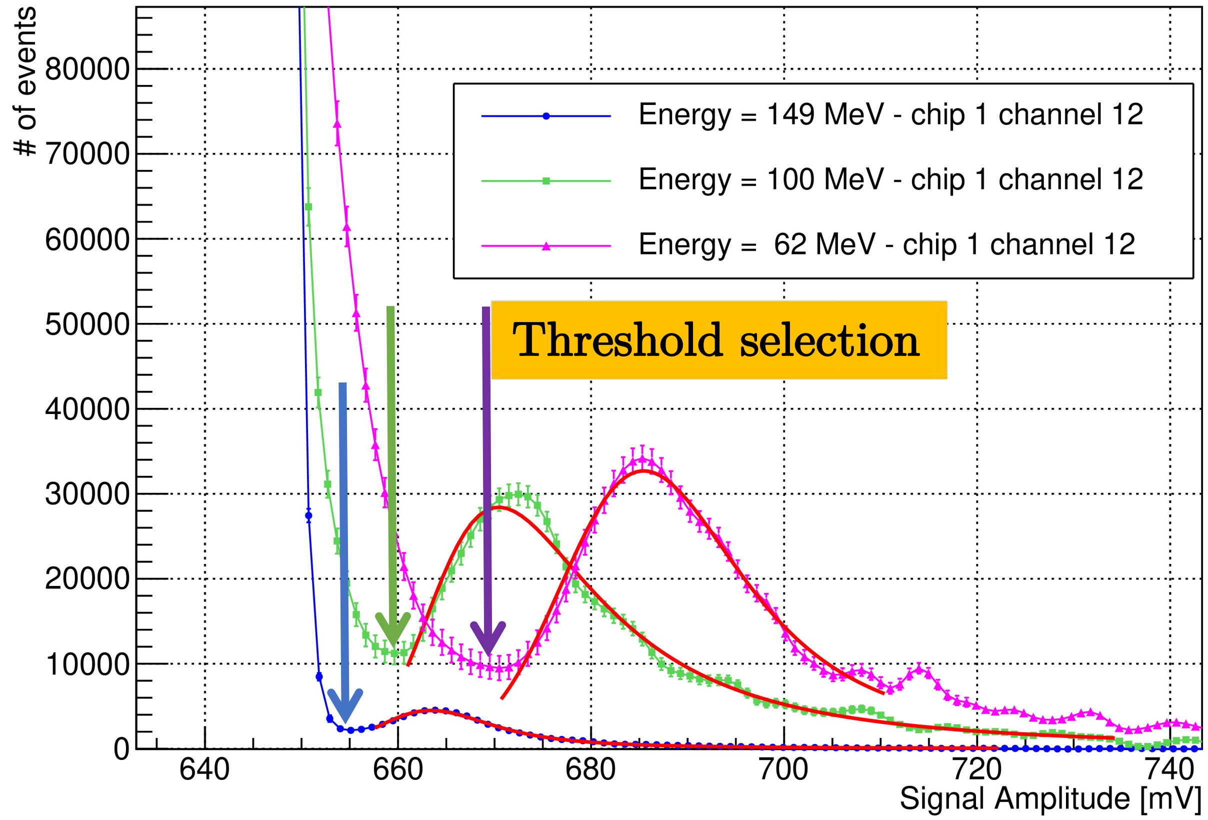
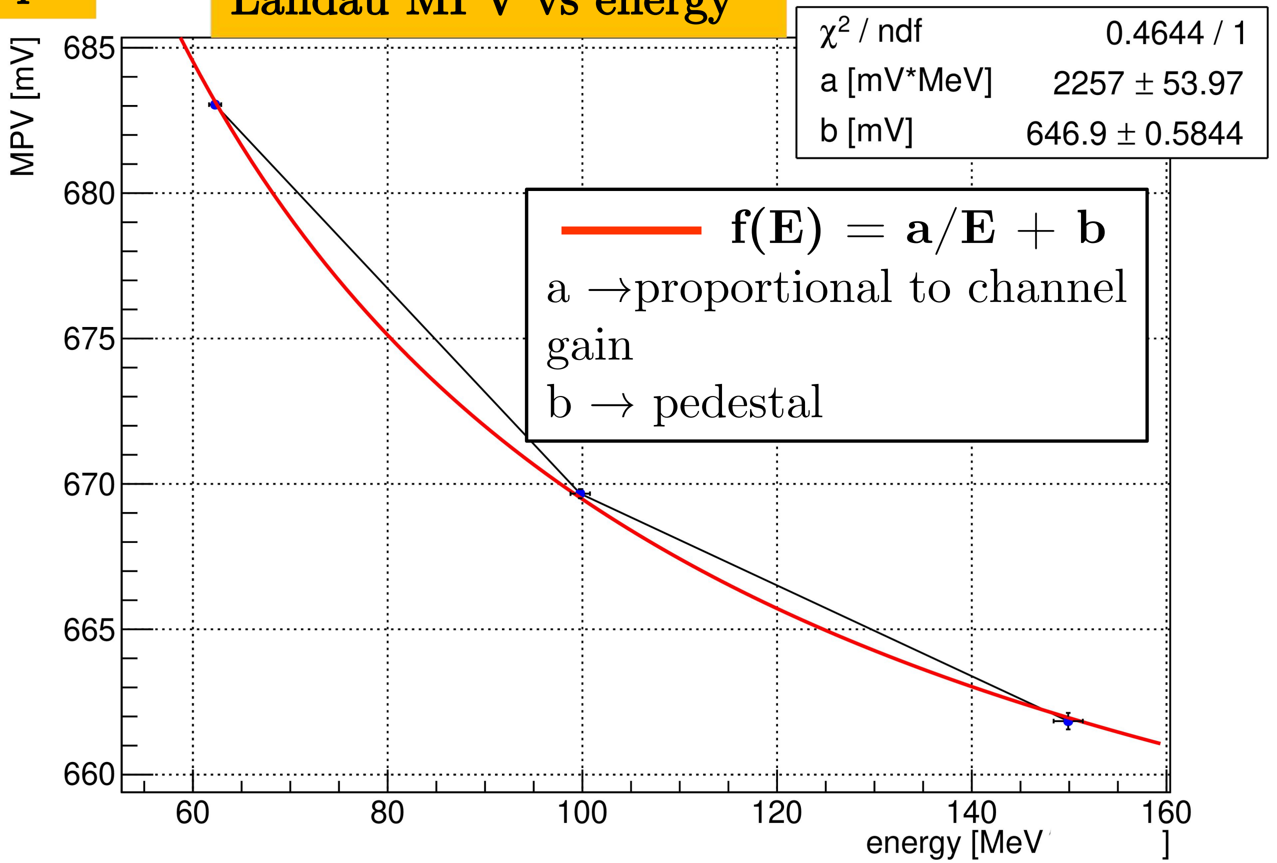
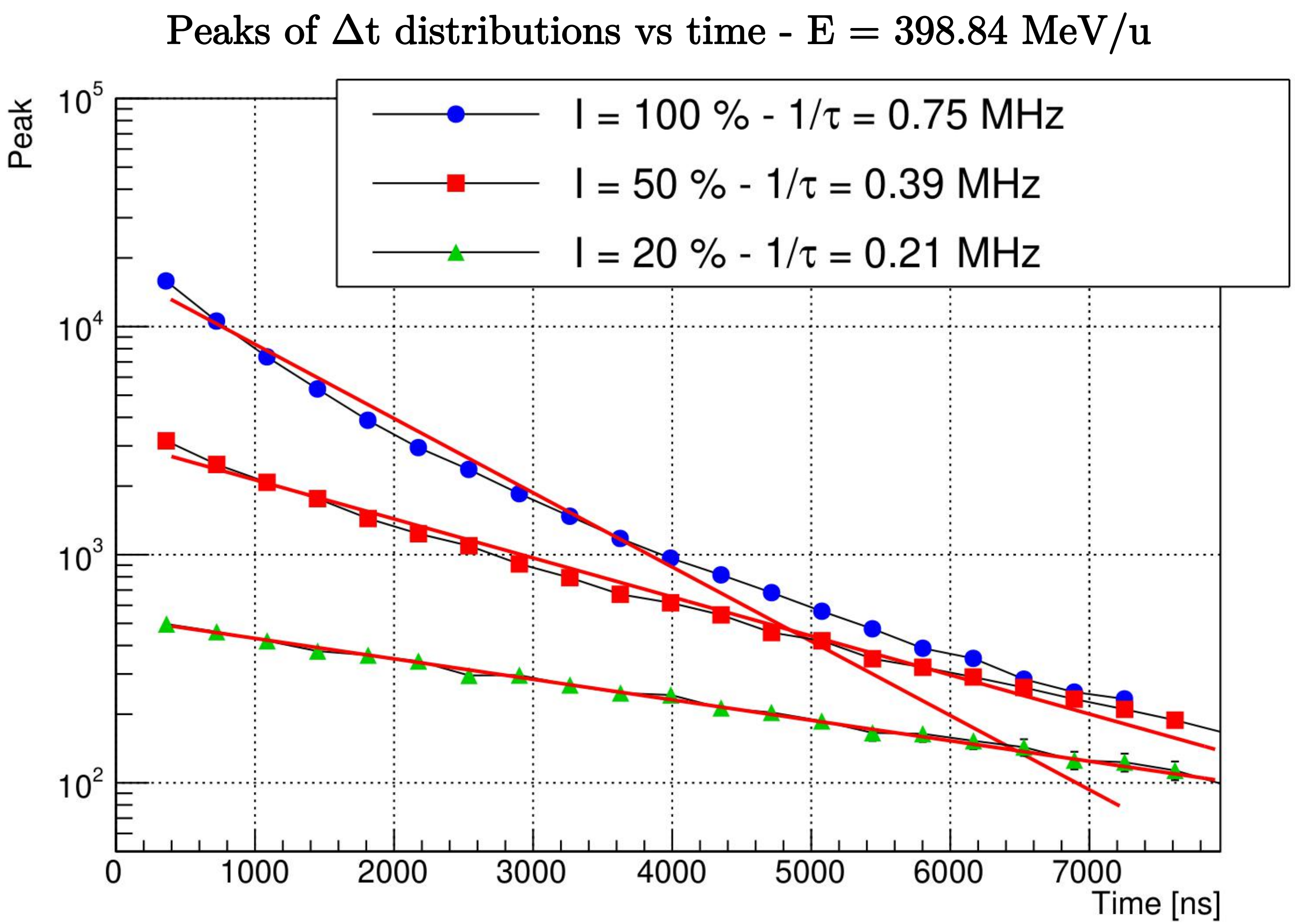


Landau MPV vs energy



Distributions of difference of crossing times - 1 strip (2)

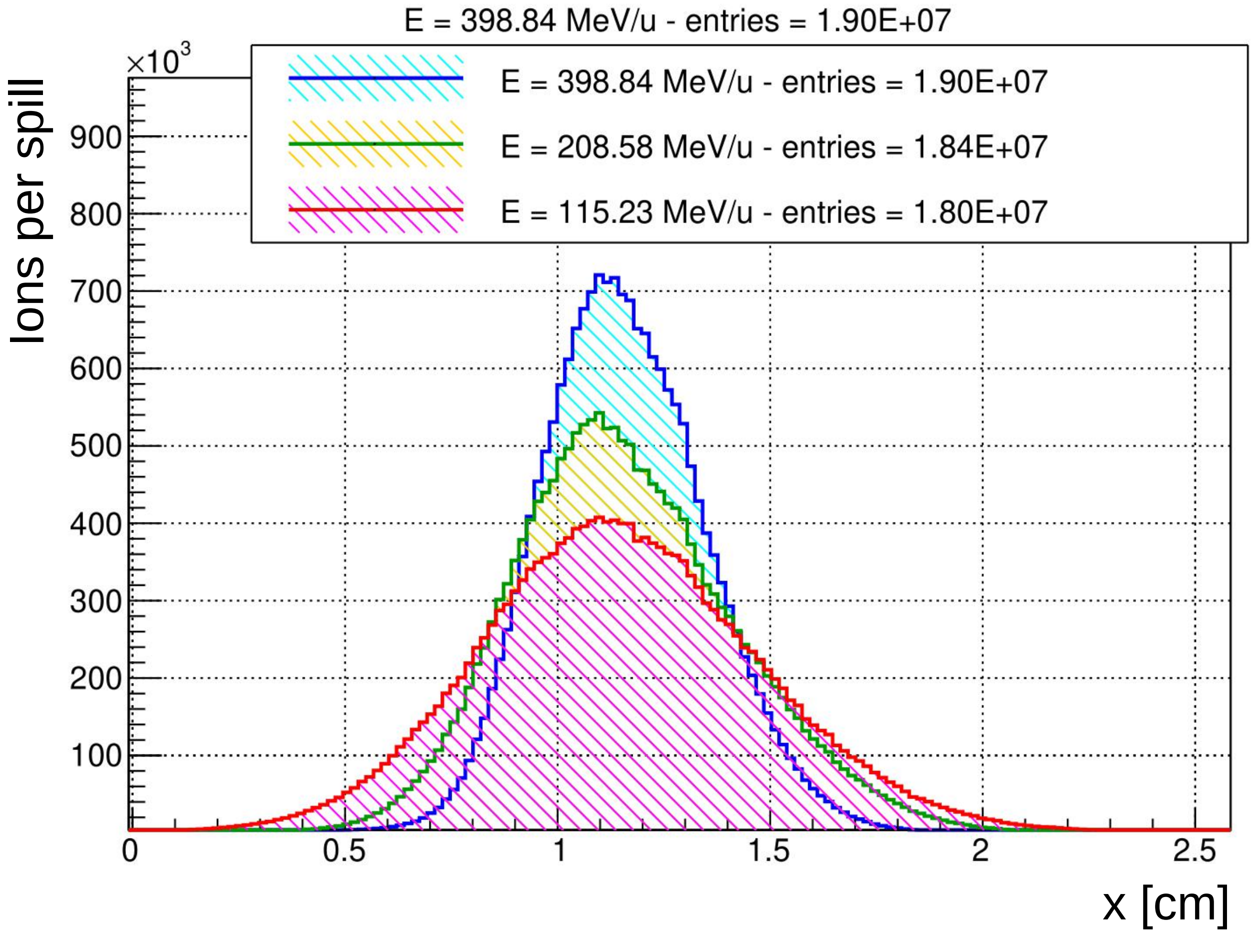


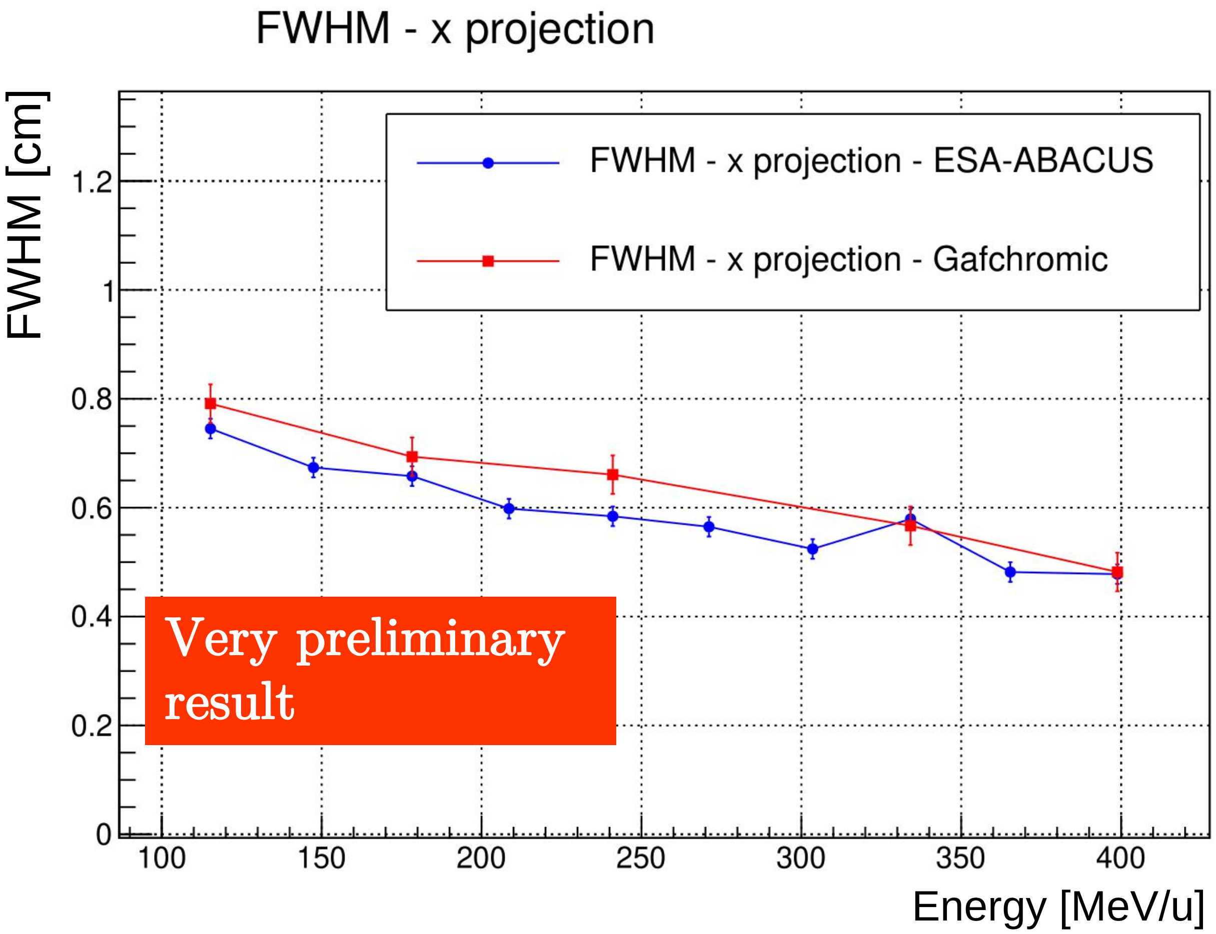
$$f(t) = Ae^{-\frac{t}{\tau}}$$

- *A = constant*
- *1/τ = mean frequency of particle on the strip*

- If the number of particles in each bunch is Possonian distributed, the peaks in Δt distributions are expected to decrease exponentially

Carbon ions - beam projection on x axis





Calculation of the charge produced in a strip for carbon ions

- Protons @ 62 MeV → expected charge in **60 µm = 3.629 fC → with gain = 10 → 36.29 fC**
- Protons @ 226 MeV → expected charge in **60 µm = 1.461 fC → with gain = 10 → 14.61 fC**

- Let's compute the charge produced by one **120 MeV/u carbon ion** in one strip

- Thickness **Δx = 60 µm**, silicon density **ρ = 2.329 g/cm³**, mean ionization energy in silicon **w = 3.6 eV/pair**

with the **same β** of the carbon

- $$\left.\frac{dE}{\rho dx}\right|_{el}^{(carbon)} = 36 \cdot \left.\frac{dE}{\rho dx}\right|_{el}^{(proton)} = 36 \cdot 5.118 \frac{MeV\ cm^2}{g} = 184.2 \frac{MeV\ cm^2}{g}$$

compatible with Hiraoka et al

@ 120 MeV (NIST PSTAR)

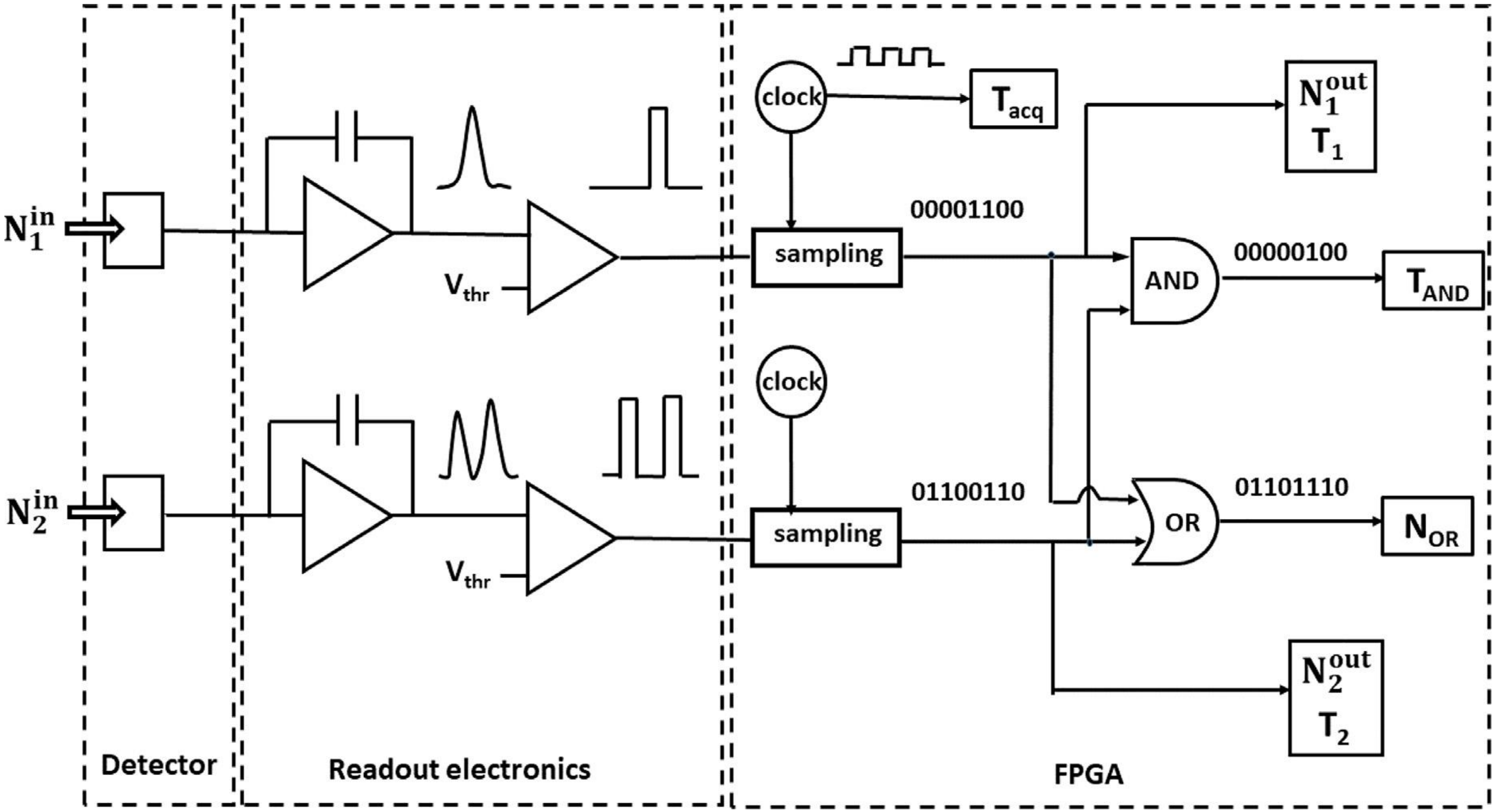
The MPV is approximately 70 % of the mean value calcultated with Bethe-Bloch

- $$Charge = 0.7 \frac{\rho \left.\frac{dE}{\rho dx}\right|_{el}^{(carbon)} \Delta x}{w} e \cong 80\ fC$$

Considering gain ~ 1.5 mV/fC the amplifier signal amplitude is ~ 120 mV

- The amplifier of ABACUS is expected to be linear between **4** and **120 fC** !

For pile-up correction algorithm



doi:10.1016/j.nima.2022.167195

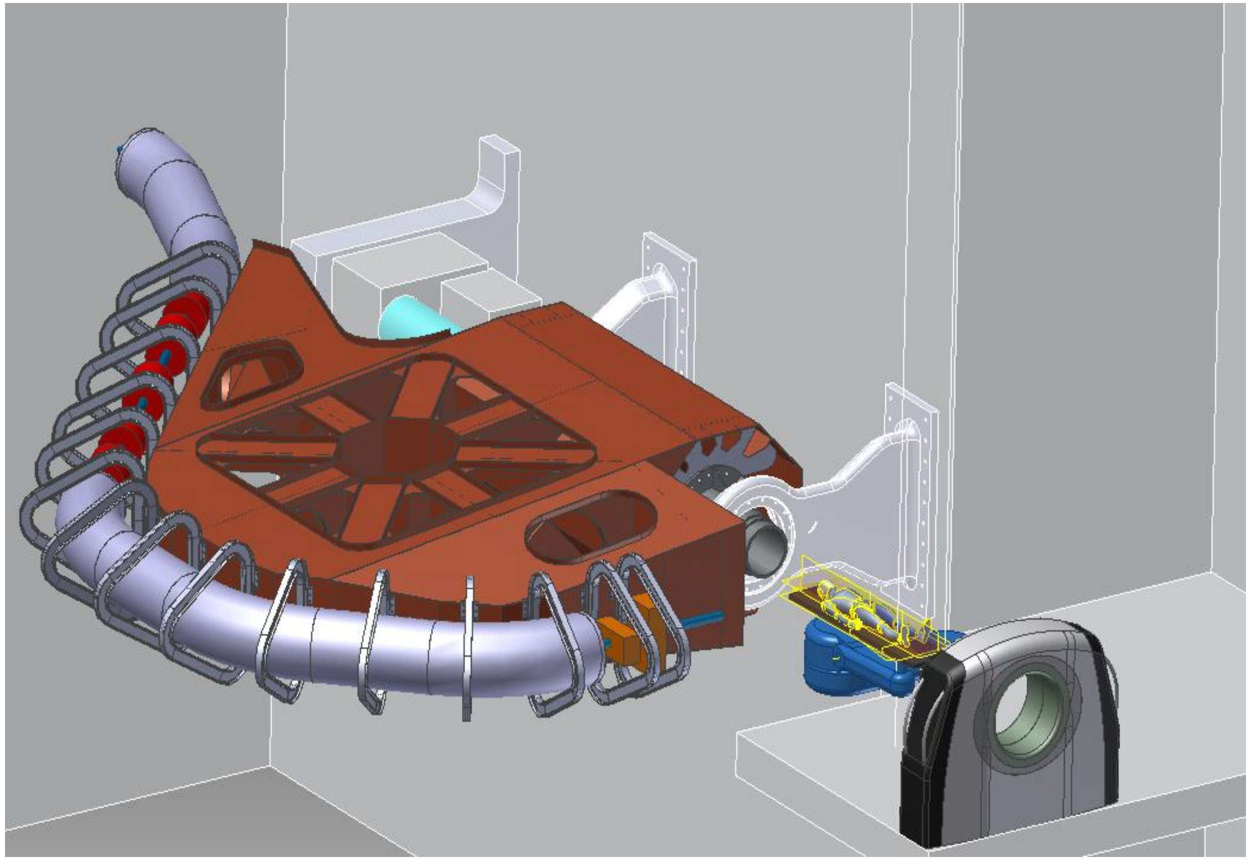
Two-channel Time Combination (TC) method

The count-loss correction is based on the comparison of the total time of the individual logic signals from the two channels with the time of their logical AND combination.

$$N_1^{in} = \frac{N_1^{out}}{1 - \frac{T_{AND}}{T_2}}$$

$$N_2^{in} = \frac{N_2^{out}}{1 - \frac{T_{AND}}{T_1}}$$

Development of a novel beam monitoring system for single particle 4D tracking (position and time) integrating a range verification system based on Prompt Gamma Timing (PGT)



Superconducting Ion Gantry

- Particles up to a rigidity of 6.6 Tm (430 MeV/u **carbon ions**)
- 14 m long, ~50 tons weight
- 4 T curved superconducting dipoles
- Superconducting spool piece quadrupoles
- Downstream scanning magnet system
- Dose Delivery and Range Verification Systems for adaptive cancer treatments

INFN GRV Call involving INFN-MI, INFN-GE, CERN, CNAO