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Nuclear fragment energy measurements up to 400 MeV/A with BGO crystals coupled to SiPM arrays

TREDI 2019

S. Argirò[1], N. Bartosik[1], P. Cerello[1], M. Pullia[2], L. Ramello[1], L. Scavarda[1]

[1]INFN Torino, [2]CNAO

The FOOT Experiment

FragmentatiOn Of Target

Goals

Measurement of proton and light nuclei fragmentation cross sections up to:

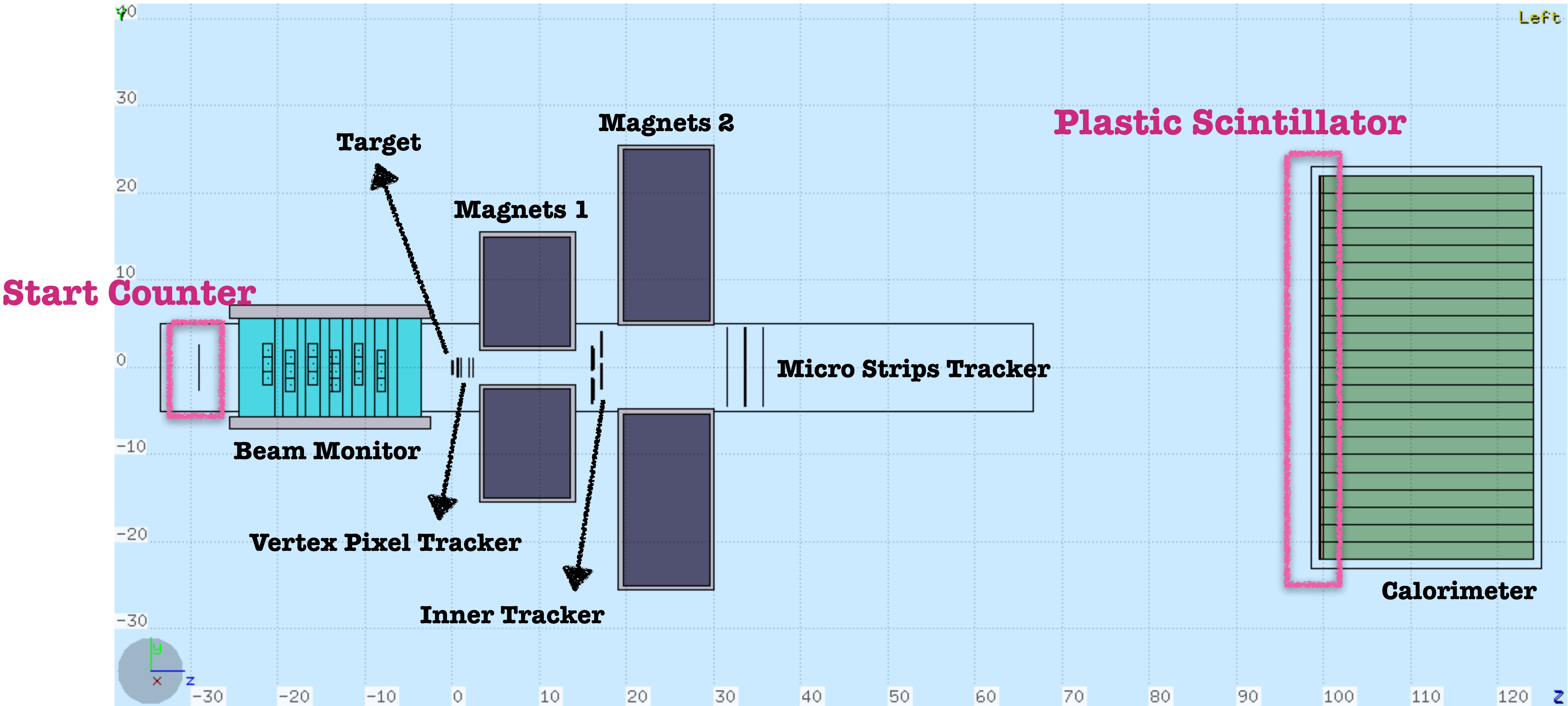
- 400 MeV/A → hadron therapy
- 700 MeV/A → radioprotection in space missions

Strategy: Reverse Kinematics

Momentum / Time of flight / Energy → Mass of fragments → Fragmentation Cross Sections

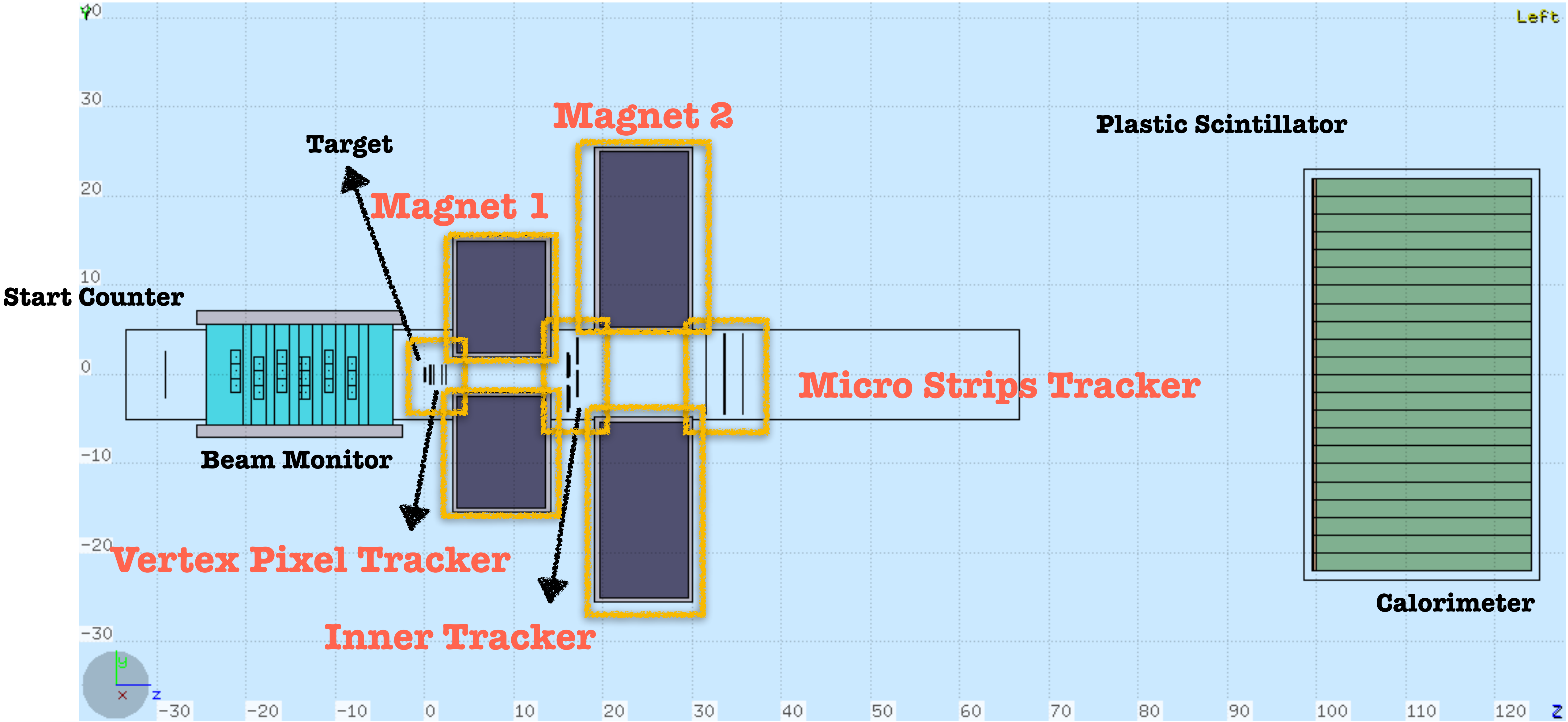
Reverse Kinematic

FOOT Setup



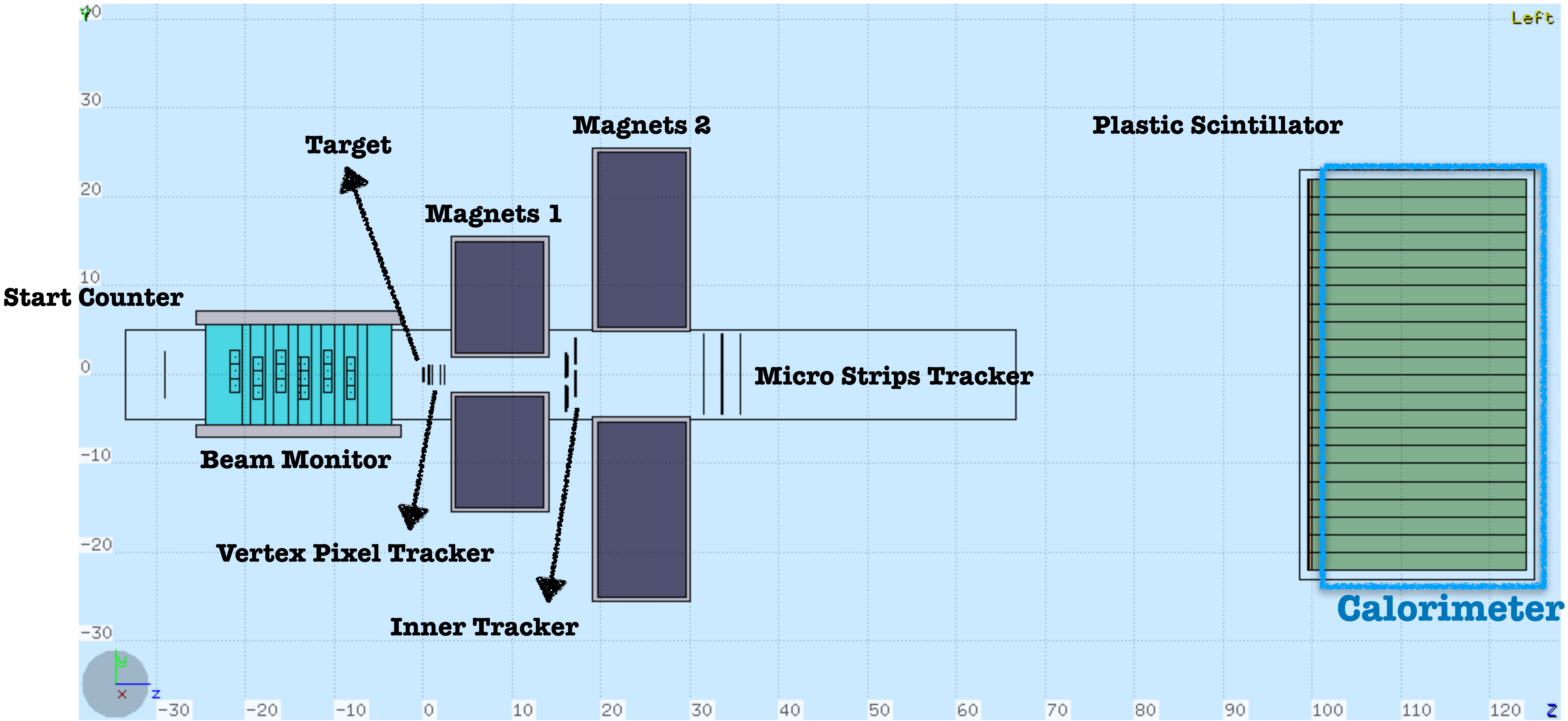
StartCounter/ Scintillator → Time Of Flight

FOOT Setup



Magnetic Spectrometer → Momentum

FOOT Setup



Calorimeter → Energy

FOOT Requirements

$$\frac{\delta E_k}{E_k} < 2\,\%$$

$$\frac{\delta p}{p} < 5\,\%$$

$$TOF < 100\ ps$$

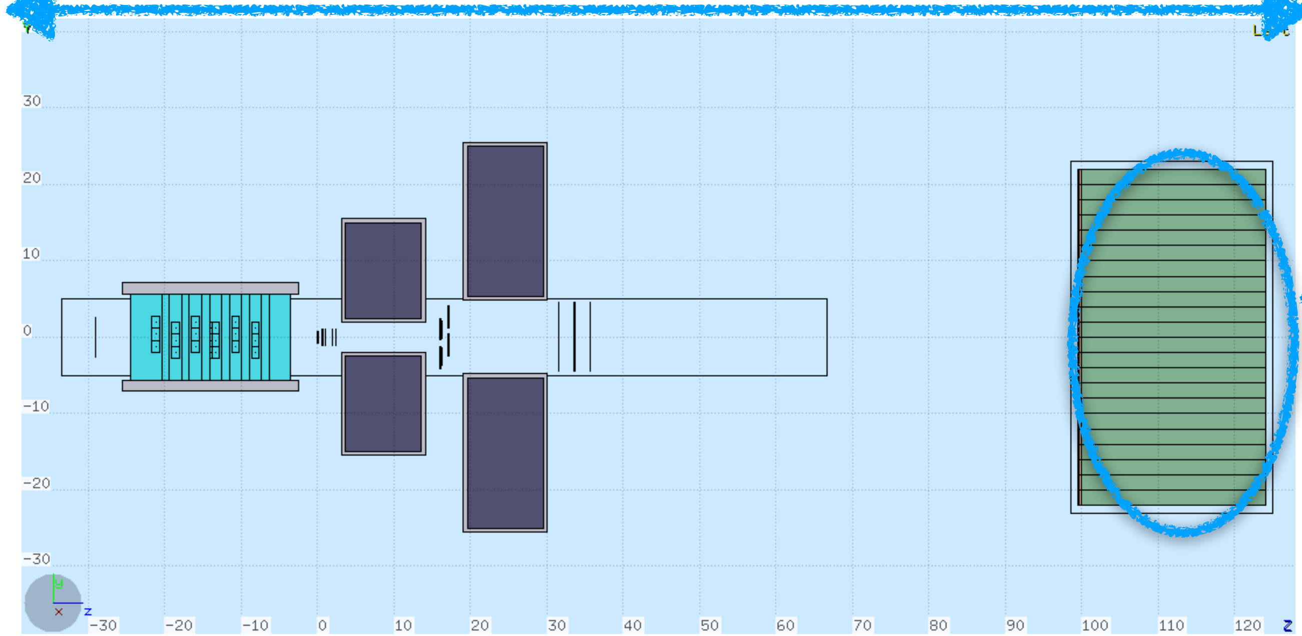
Fragment mass

$$5\,\% < \frac{\delta A}{A} < 10\,\%$$

Cross sections

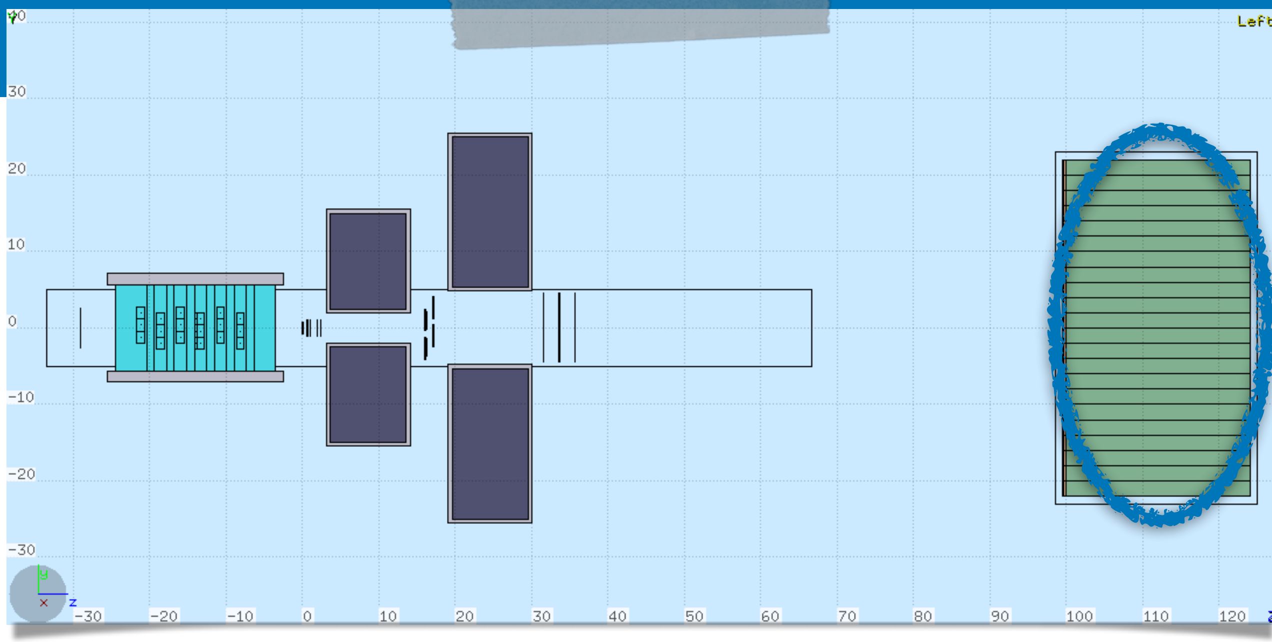
$$\frac{\delta(d\sigma/dE_k)}{d\sigma/dE_k} < 5\,\%$$

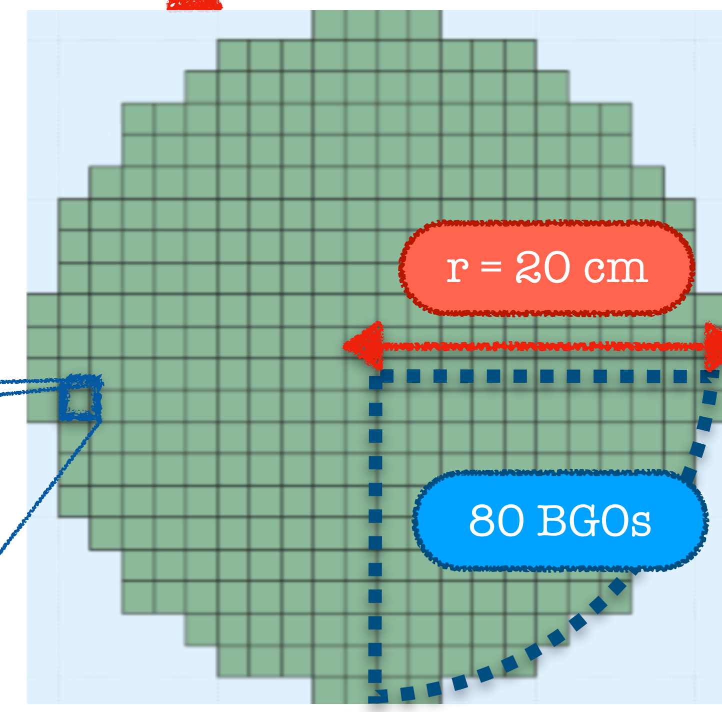
~ 2 m



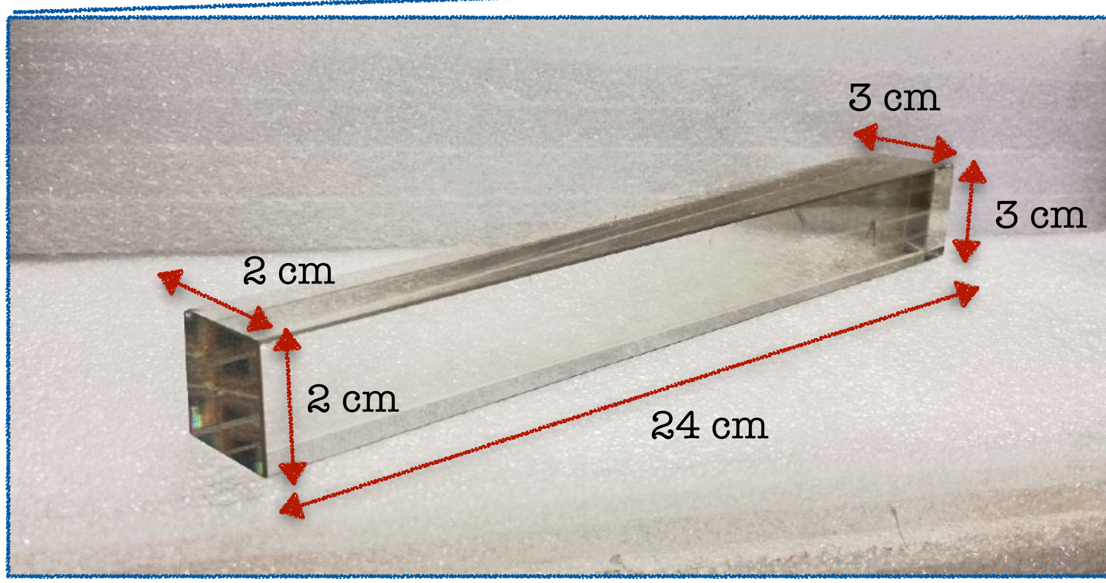
Main task of the Turin group

FOOT Calorimeter





$B_4Ge_3O_{12}$ (Bismuth Germanate)

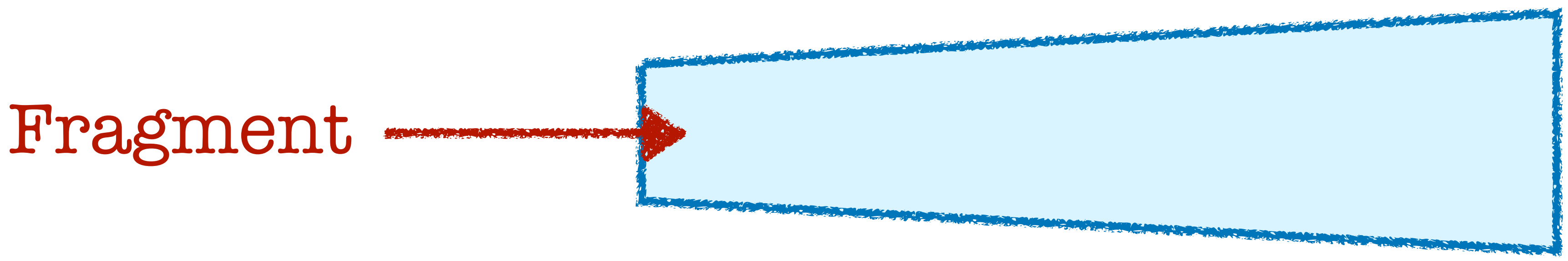


$$\rho_{BGO} = 7.13 \ g/cm^3$$

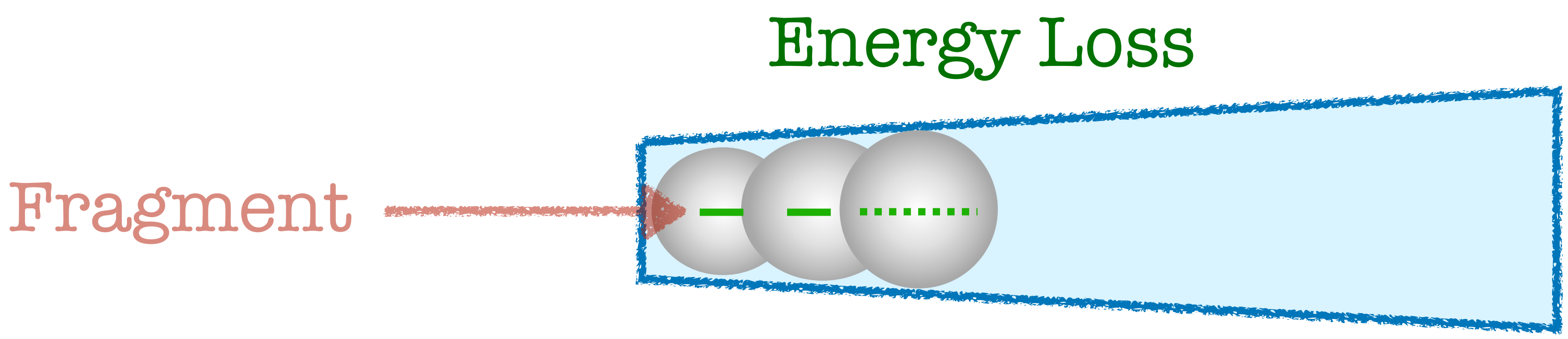
$$Z_{Bi} = 83$$

→ High stopping power!

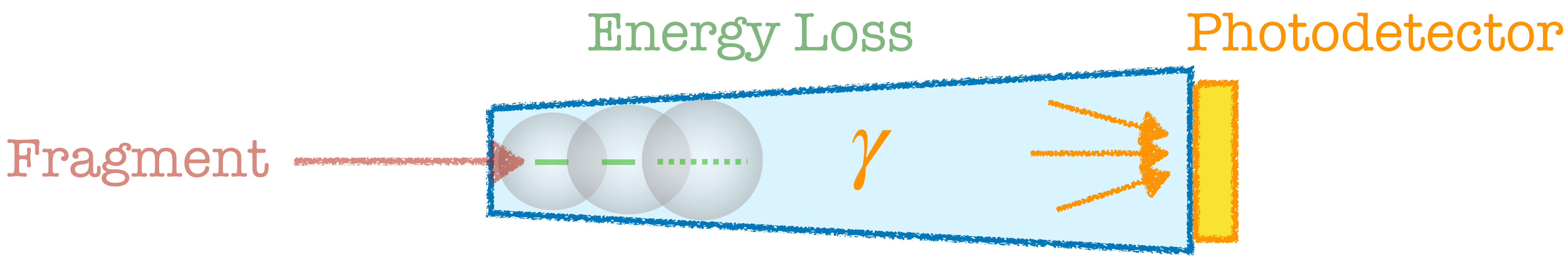
Principle of the FOOT Calorimeter



Principle of the FOOT Calorimeter



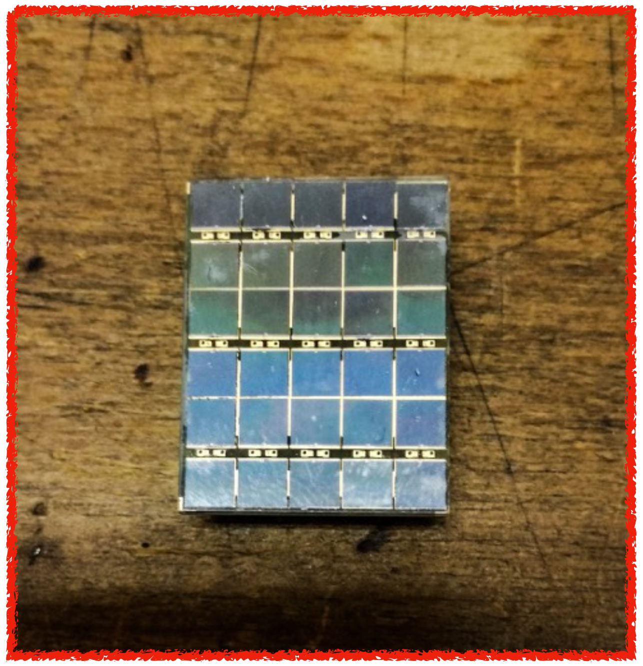
Principle of the FOOT Calorimeter



Photodetector Tests

Photodetector options:

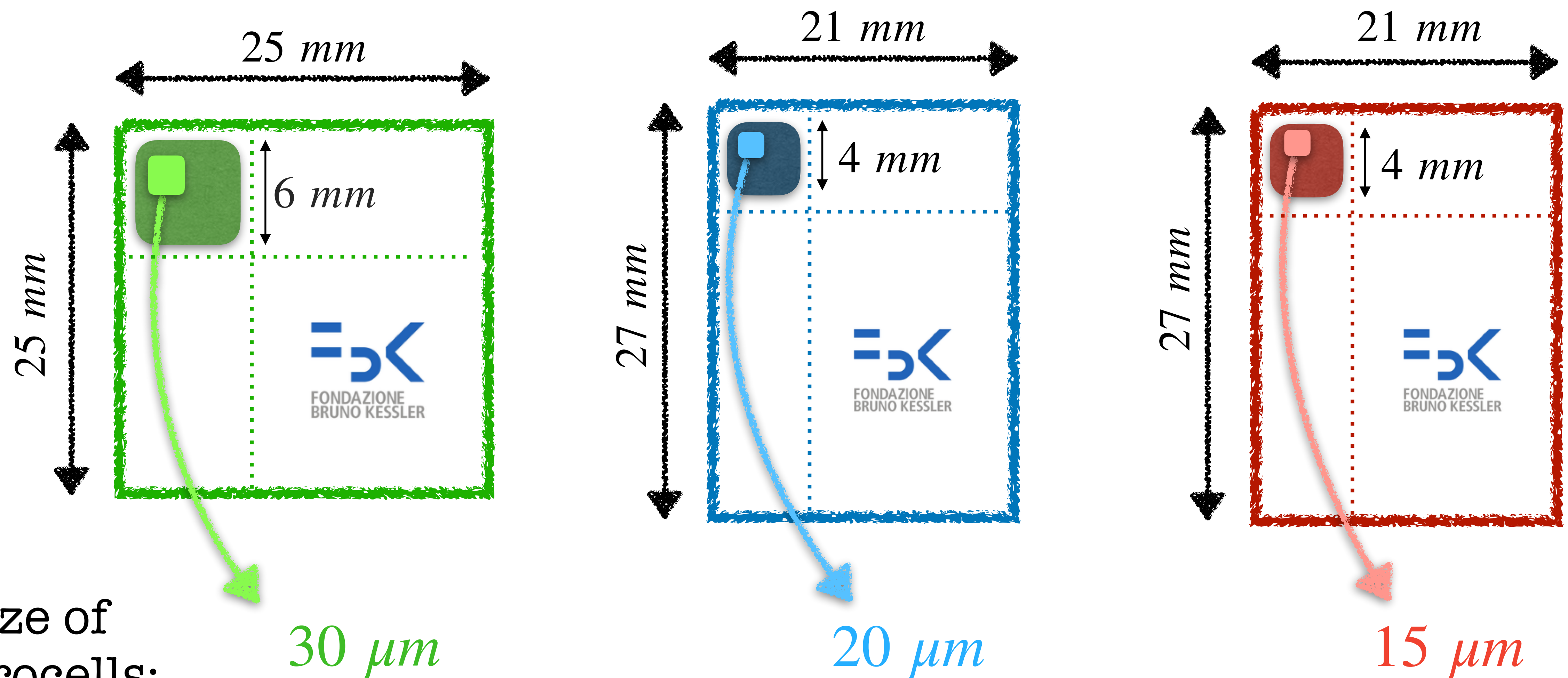
1. **Photo-Multiplier tubes**:



2. **SiPMs**:
    - Linearity
    - Energy Resolution

Calorimeter Preliminary Test

Candidates:



Size of microcells:

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

Beam Test Overview

Proton Beam:

- $70\ MeV$
- $120\ MeV$
- $170\ MeV$
- $220\ MeV$

Carbon Beam:

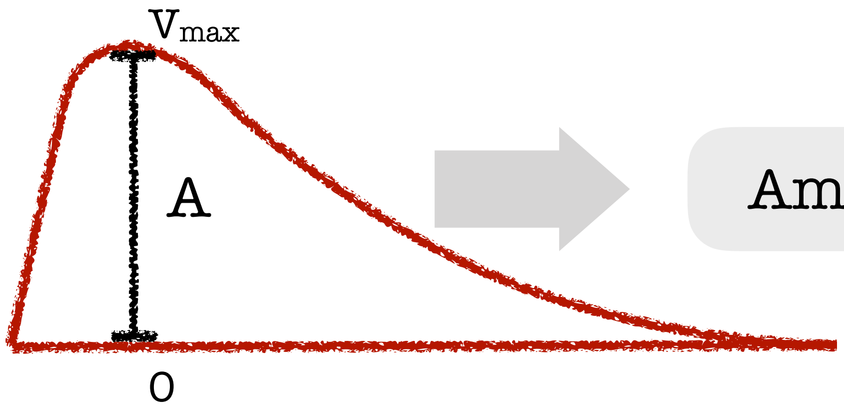
- $120\ MeV/u$
- $190\ MeV/u$
- $260\ MeV/u$
- $330\ MeV/u$
- $400\ MeV/u$

$30\ \mu m$, $20\ \mu m$ → coupled to → BGO with black tape

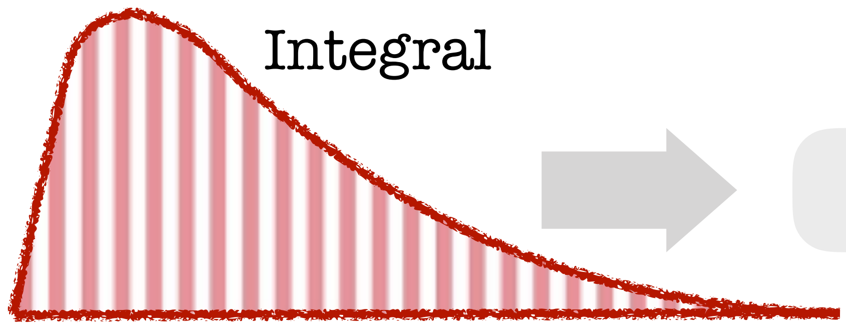
$15\ \mu m$ → coupled to → BGO with black tape + Aluminium

Amplitude & Charge Analysis

From one signal:

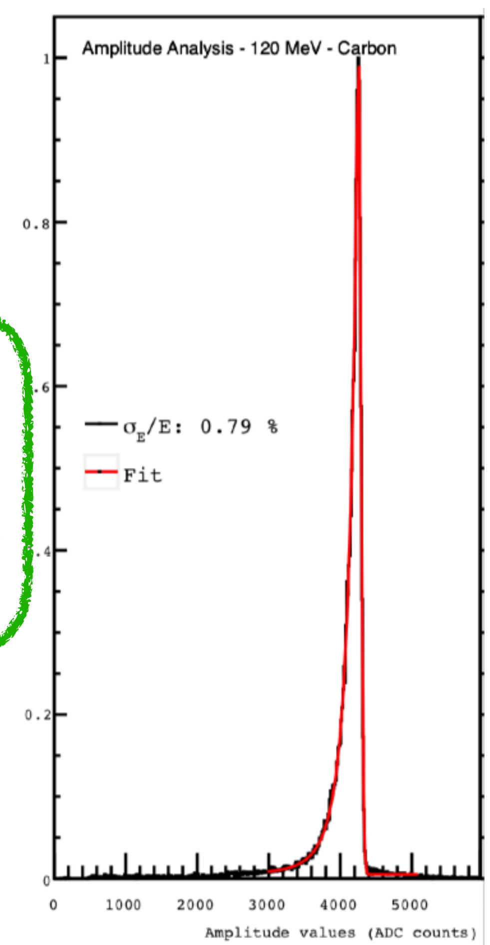


→ Amplitude



→ Charge

From all events:



$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \frac{x-\bar{x}}{2\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \frac{x-\bar{x}}{2\sigma} \leq -\alpha \end{cases}$$

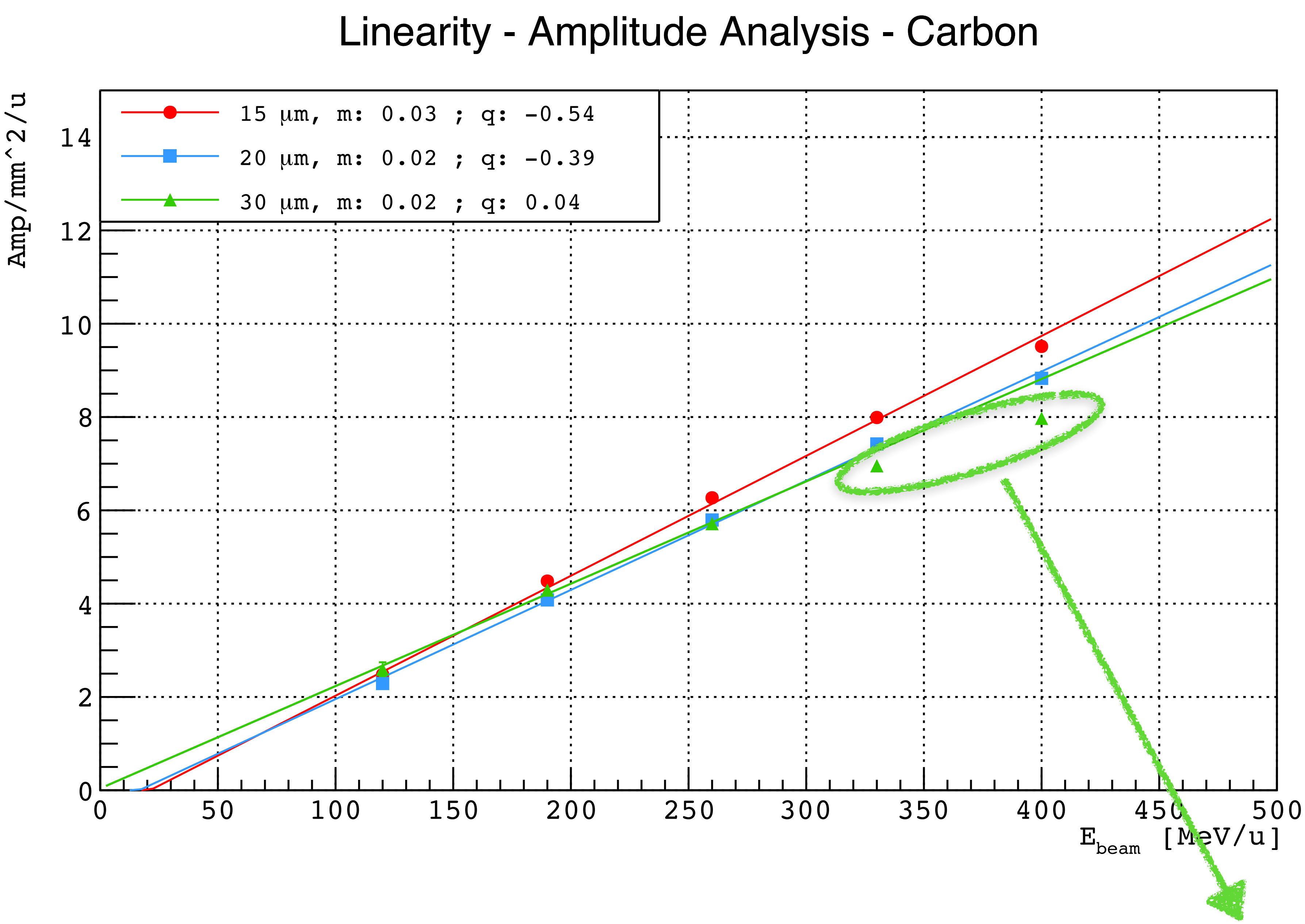
σ → Width of the gaussian peak

$\bar{x}$ → Mean value of the gaussian peak

$\sigma/\bar{x}$ → Energy Resolution

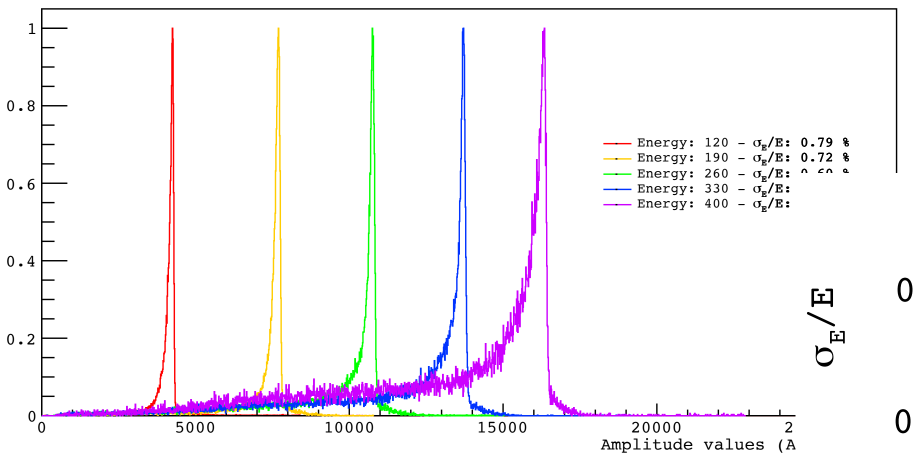
Results

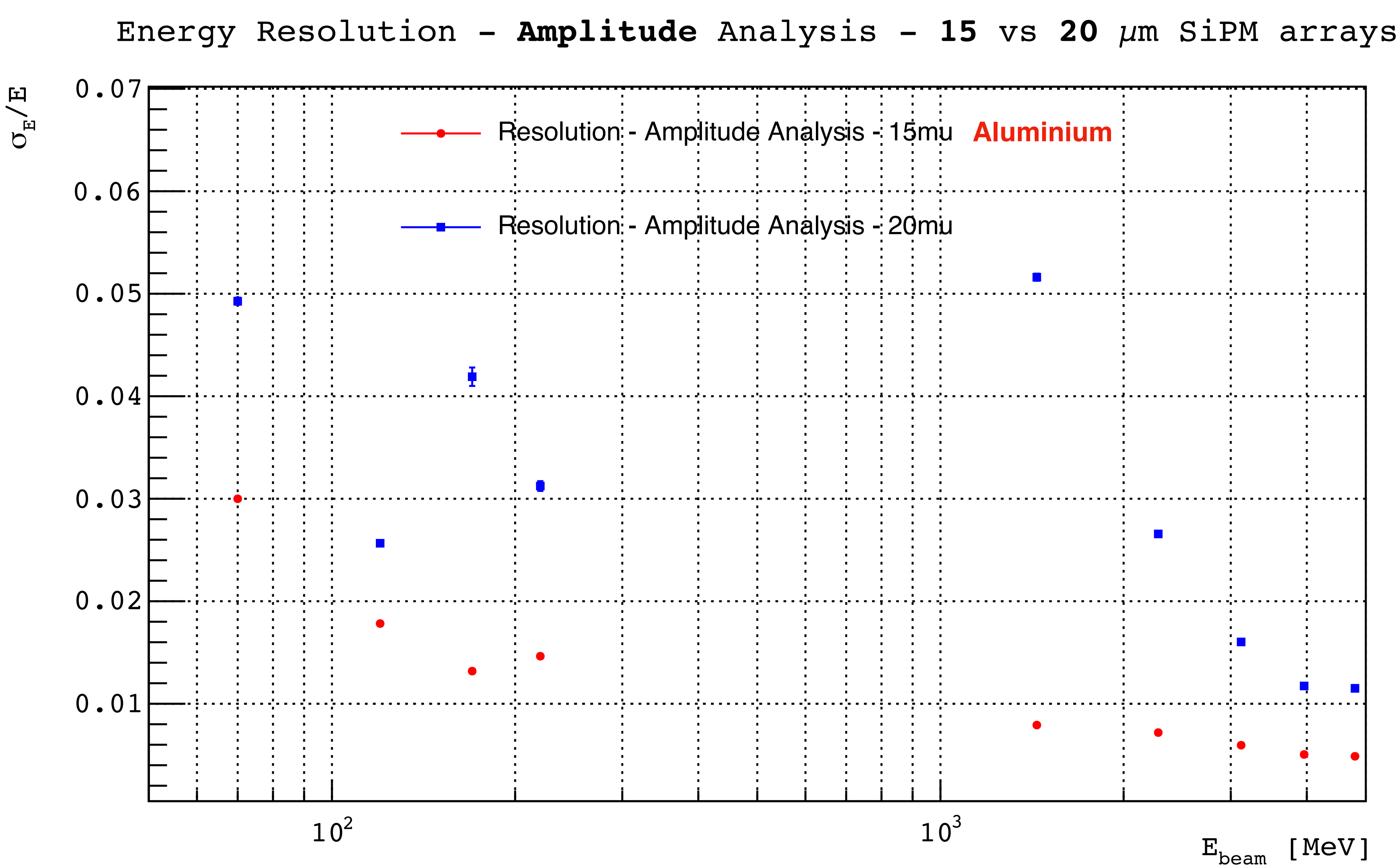
Linearity



Dynamic range saturation

Energy Resolution



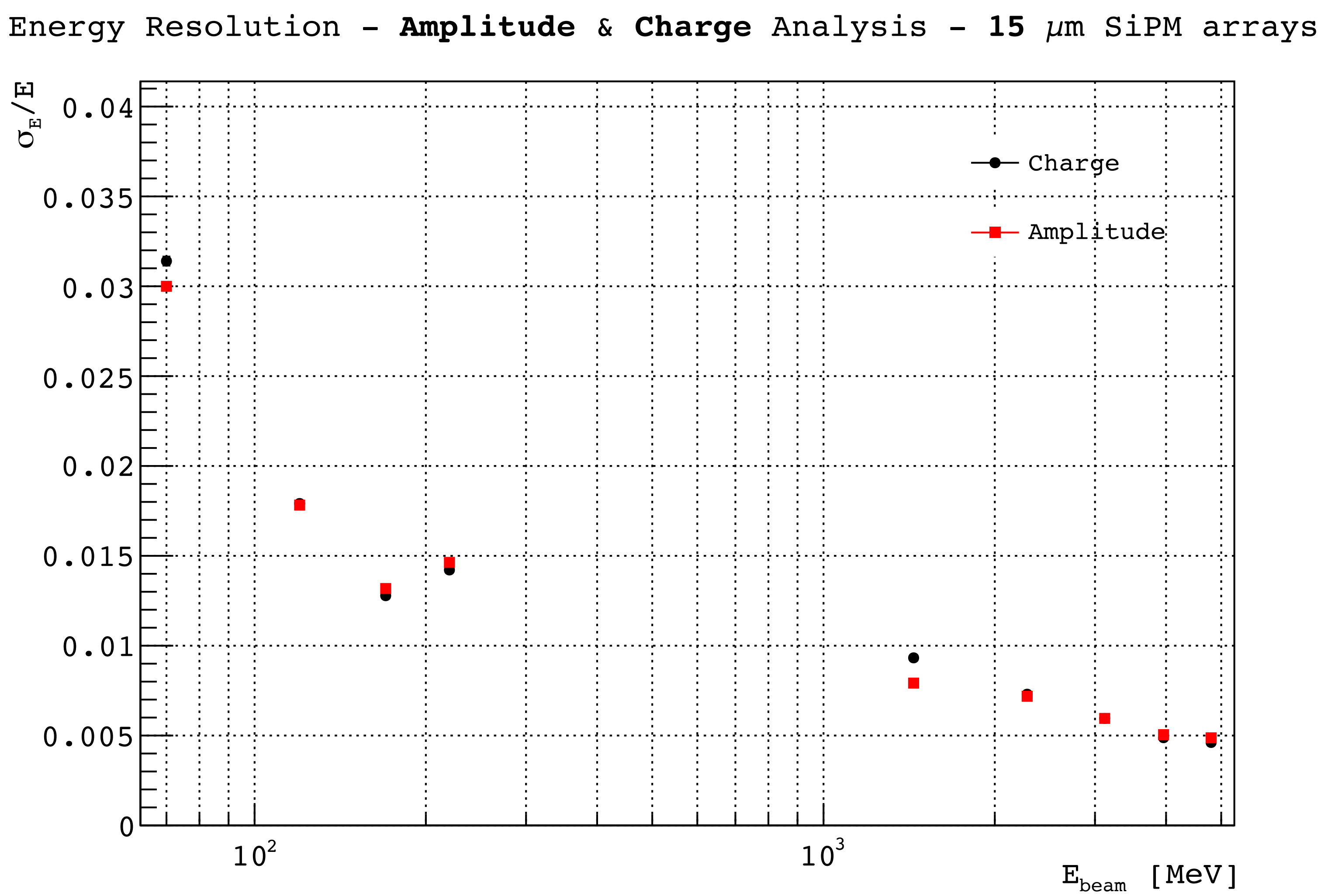


Reflecting configuration improves significantly the energy resolution

Energy Resolution

15 μm

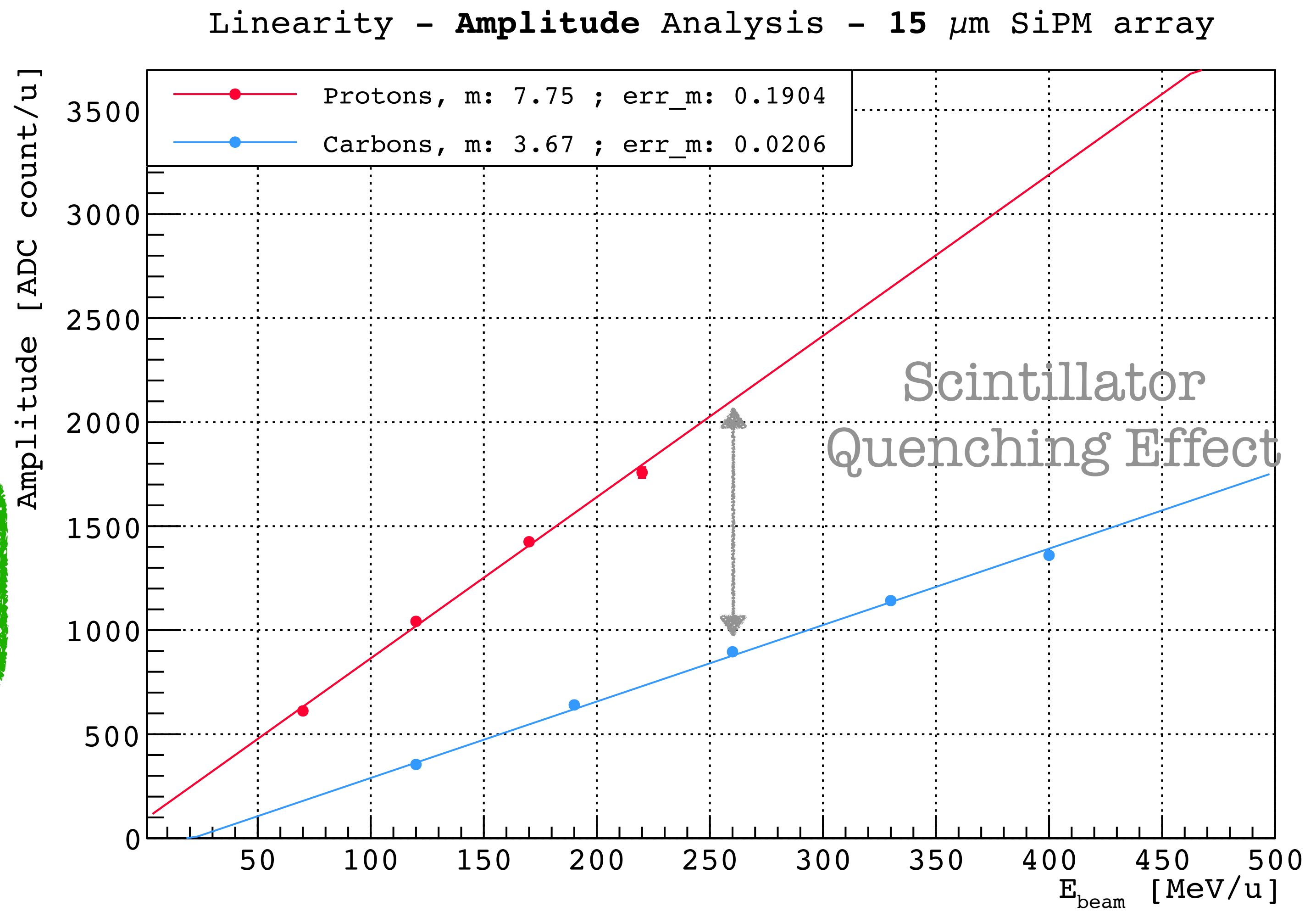
Comparison between Amplitude & Charge Analysis:



Energy resolution below **2%** up to 120 MeV

Linearity

15 μm



"Calibration of CsI(Ti) scintillators for heavy ions (3 ≤ Z ≤ 54) in a wide energy range (E/u ≤ 60 MeV/u)", P. Mastinu, P. Milazzo, M. Bruno, M. D'Agostino, L.Manduci

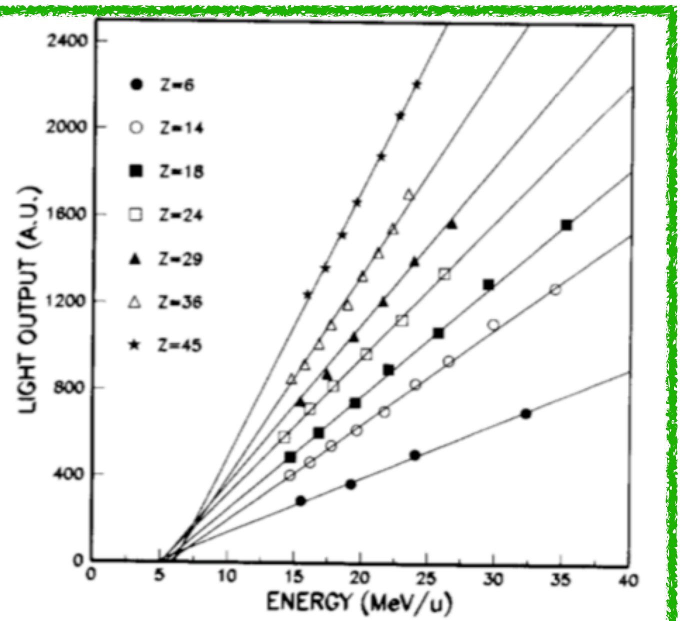


Fig. 1. Light output as a function of the energy per nucleon for different incident ions. The solid lines are the fit of the data for energy above 15 MeV/u.

Birks Formula

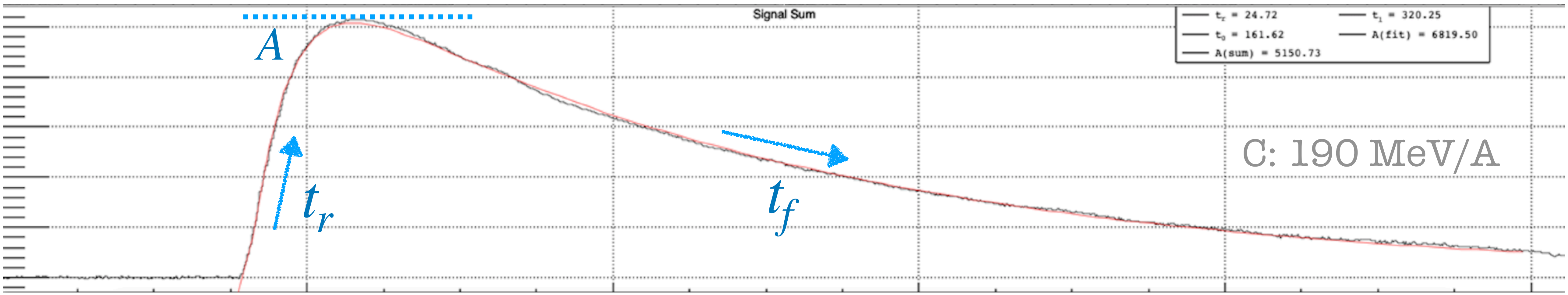
$$dL/dx = cost \cdot \frac{dE/dx}{1 + kB \cdot dE/dx}$$

where:

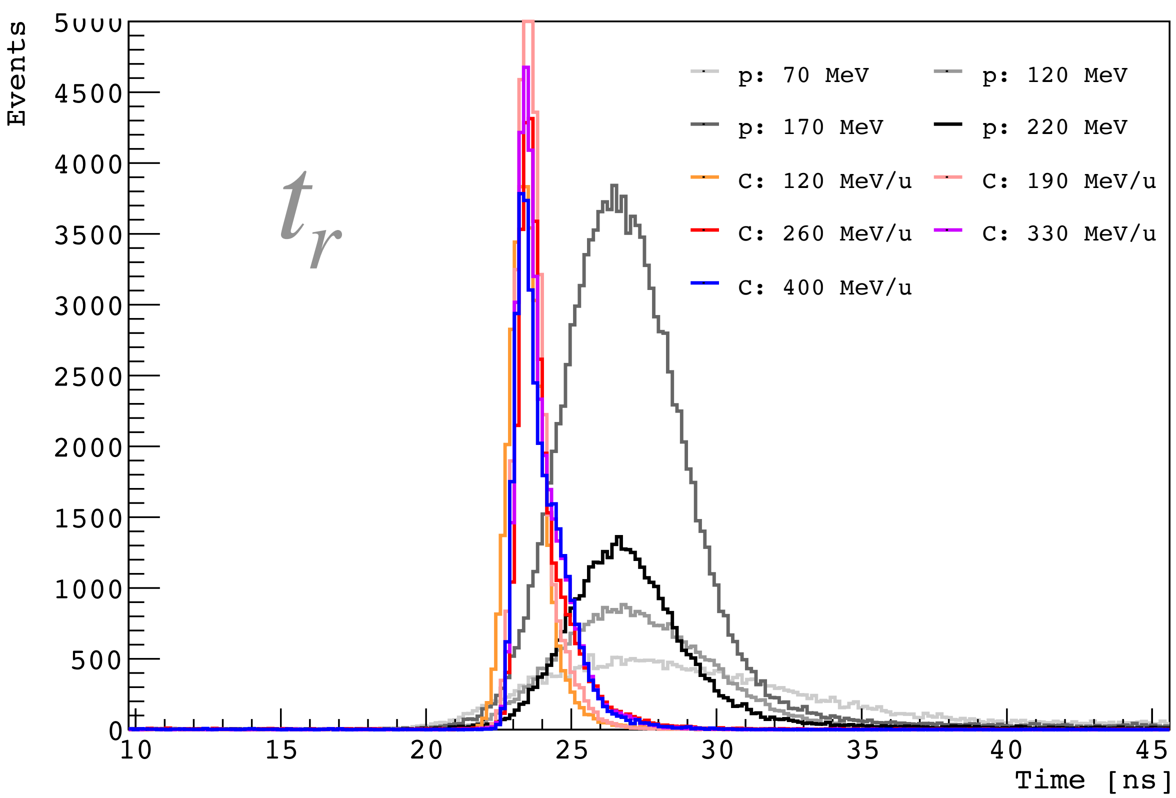
- **k** is the Quenching Parameter
- **BdE/dx** is the density of quenching centres per unit distance

Pulse Shape Analysis

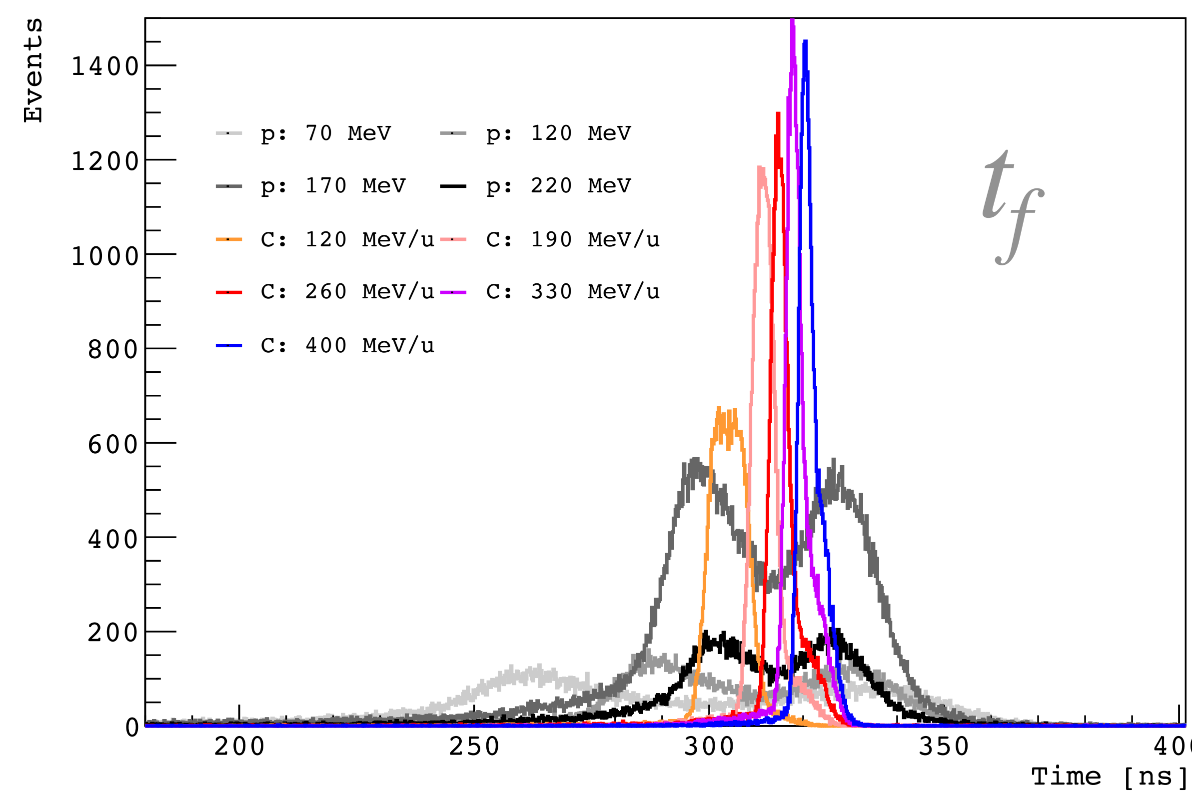
$$f(x) = A\cdot\left(exp\left(\frac{t_0 - x}{t_r}\right) - exp\left(\frac{t_0 - x}{t_f}\right)\right)$$



Rising Time - **15** μm SiPM array



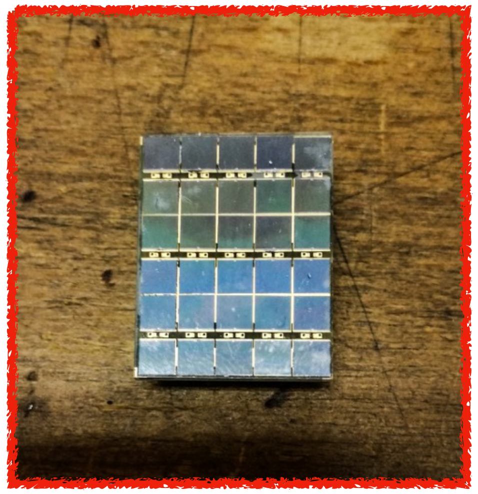
Falling Time - **15** μm SiPM array



Conclusions

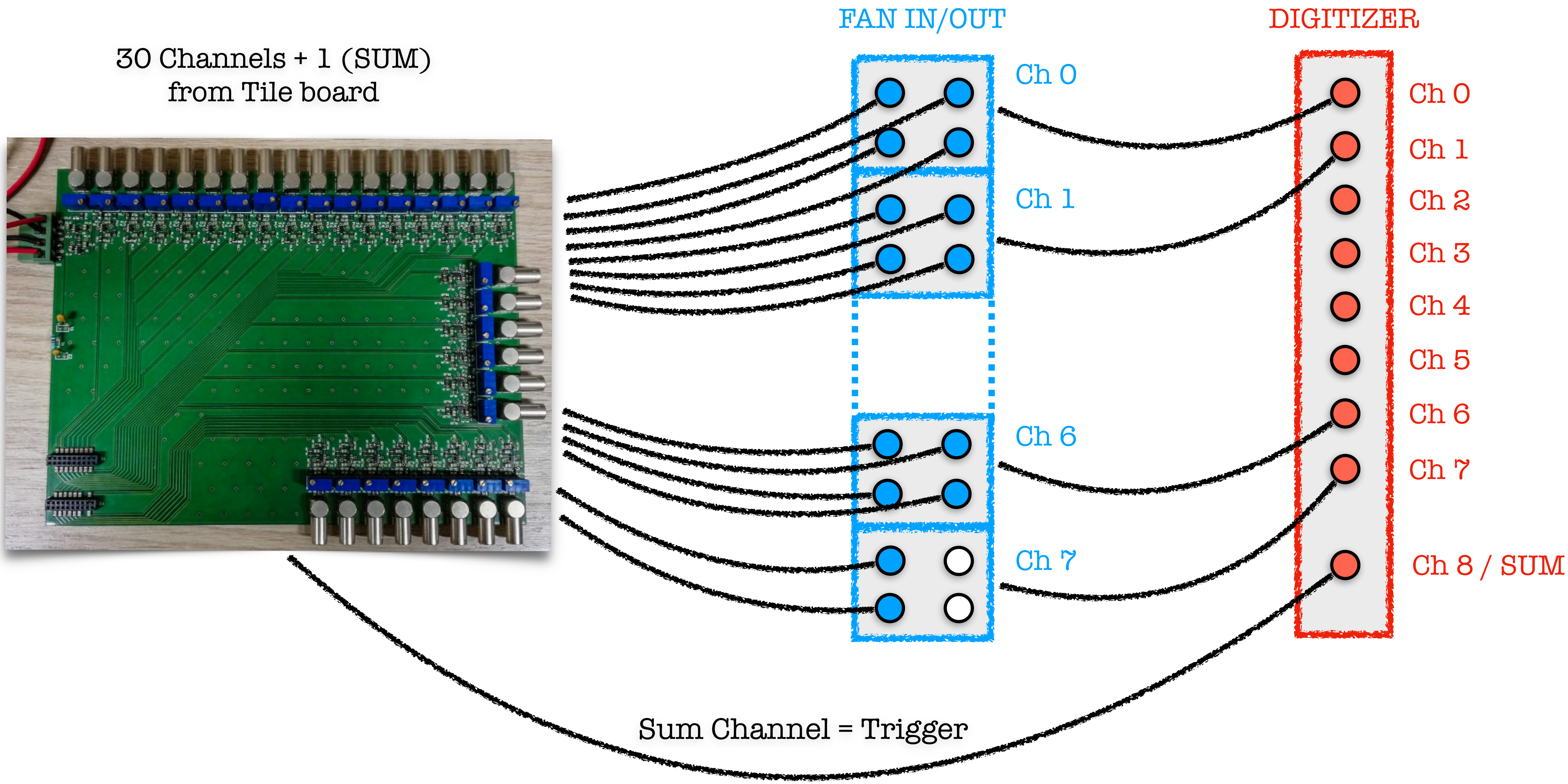
- Working configuration: **Reflecting Layer**
- Photodetector: **SiPMs**
  - ✓ No saturation of the dynamic range for 15 and 20 μm SiPM arrays up to 400 MeV/A
  - ✓ Energy resolution below 2% ~100 MeV
- 15 μm will guarantee no saturation of the dynamic range up to 700 MeV/A

15 μm SiPM



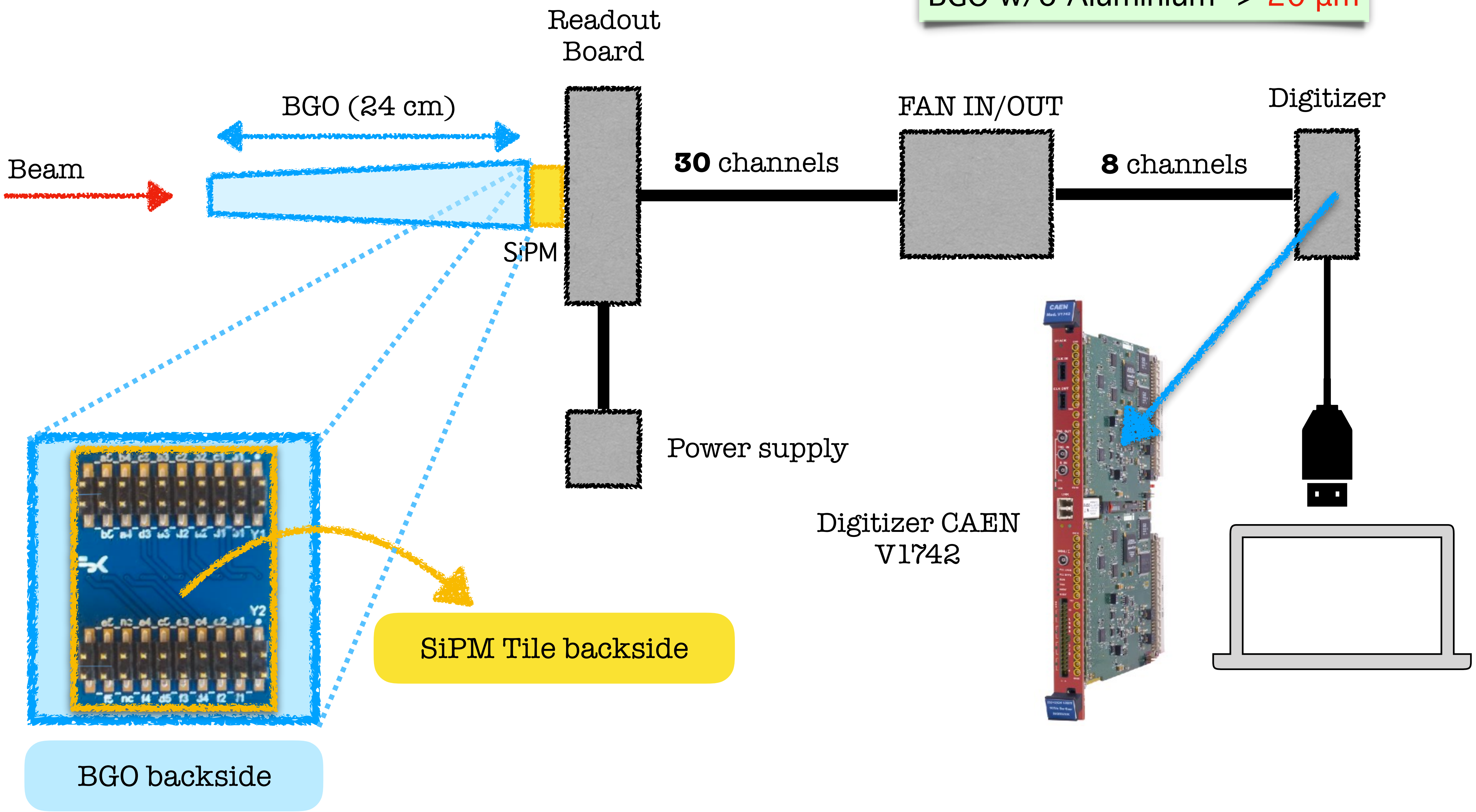
BackUp Slides

Experimental Setup



Experimental Setup

SiPM Tile from FBK
pitch: 15-20 µm
breakdown voltage: 28 V
bias voltage: 32 V
BGO w/ Aluminium -> 15 µm
BGO w/o Aluminium -> 20 µm



Readout

Present:

Digitizer **V1742** CAEN

12 bits

1 Ghz

1024 samplings

Vpp = 1 V

Future:

Digitizer **V1740** CAEN

12 bits

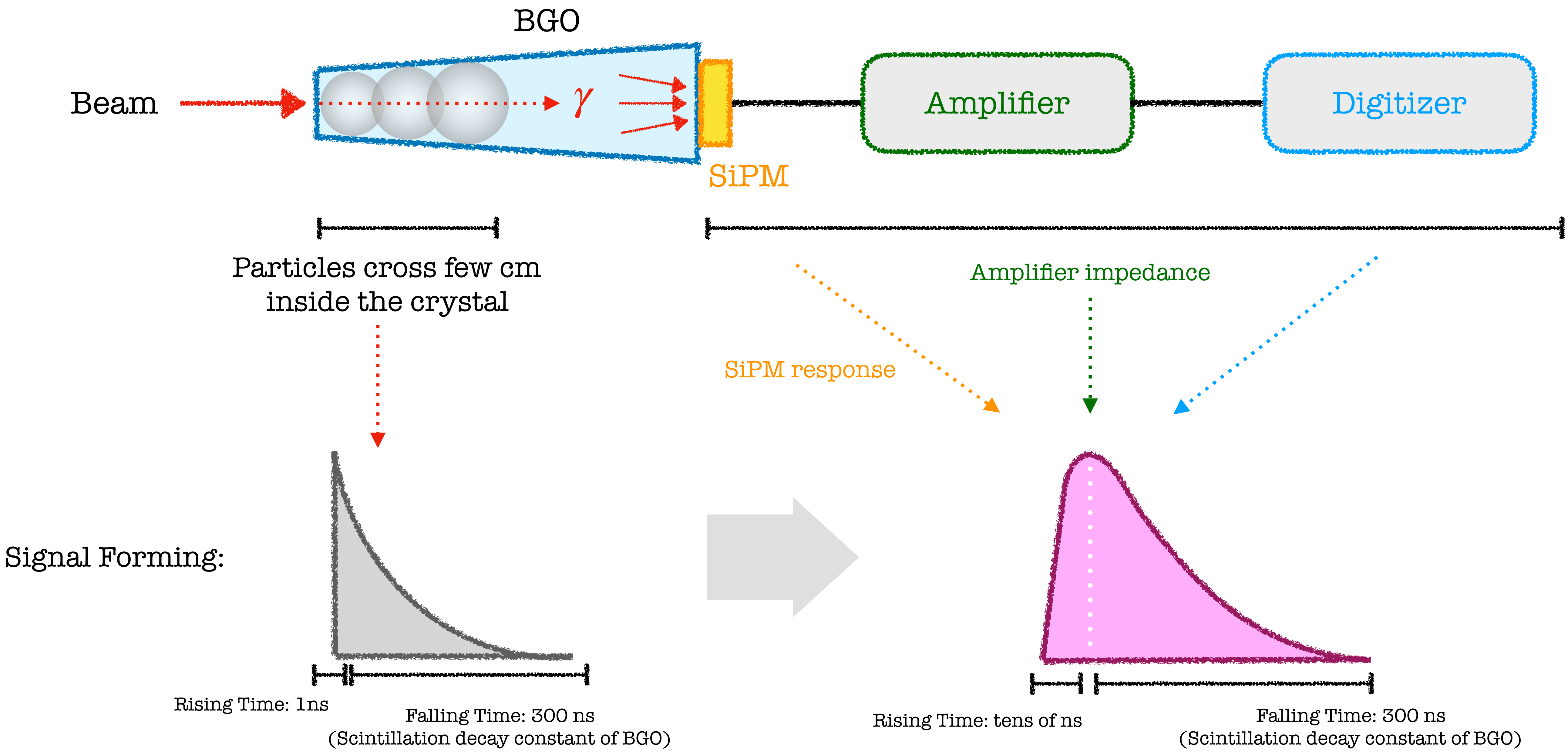
62.5 Mhz

1024 samplings

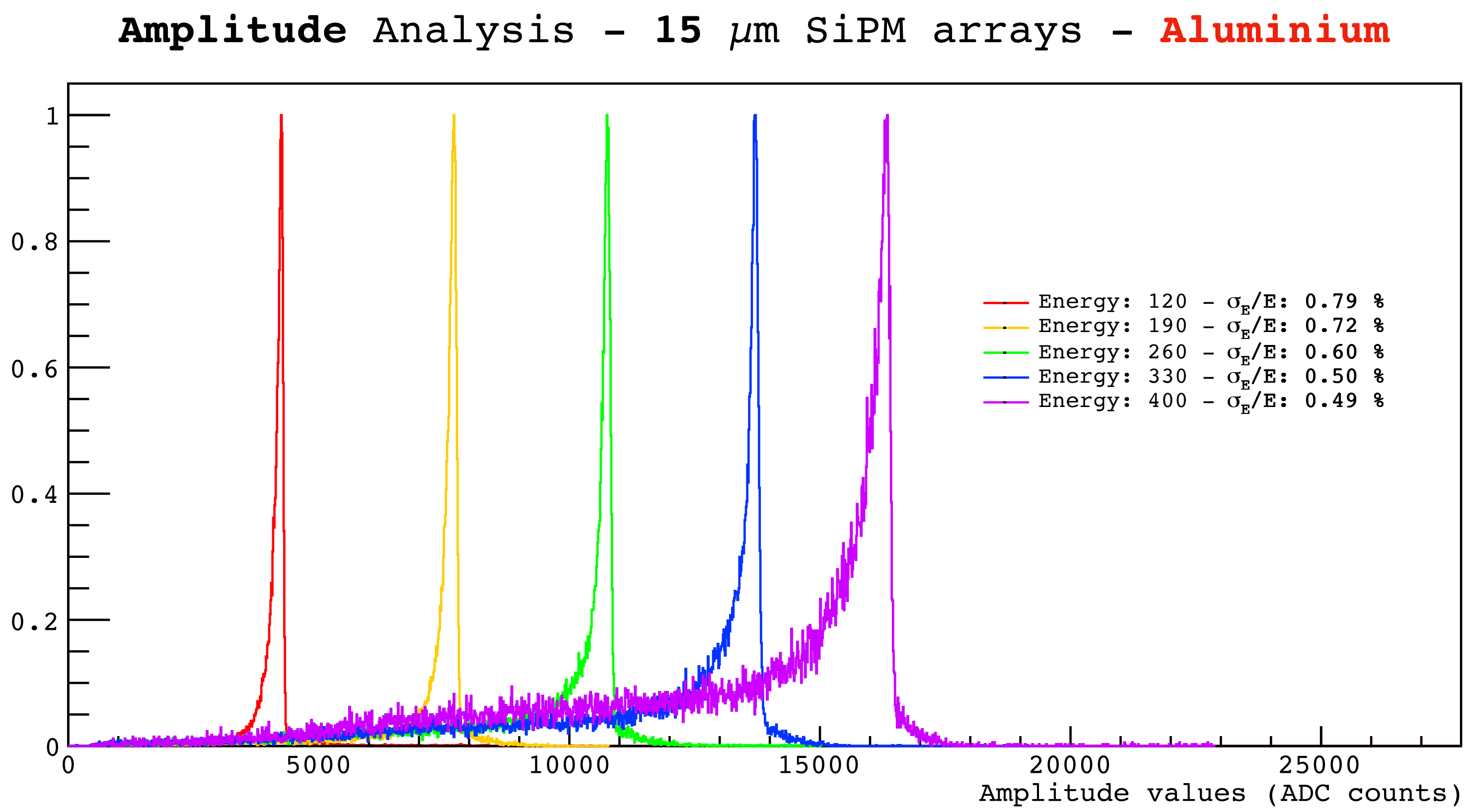
Vpp = 10 V

Experimental Setup

Signal Forming

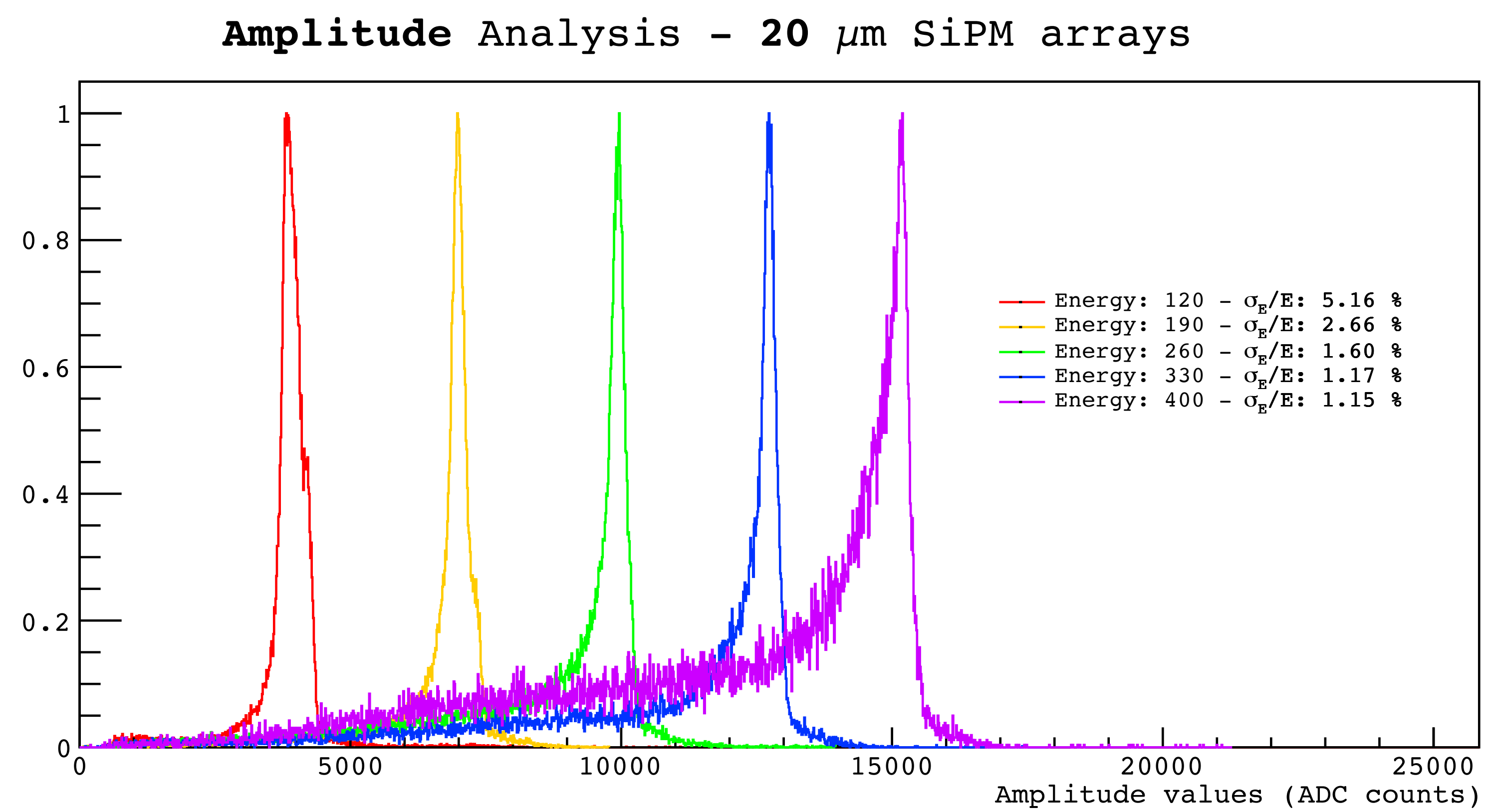


Amplitude Analysis - Carbon



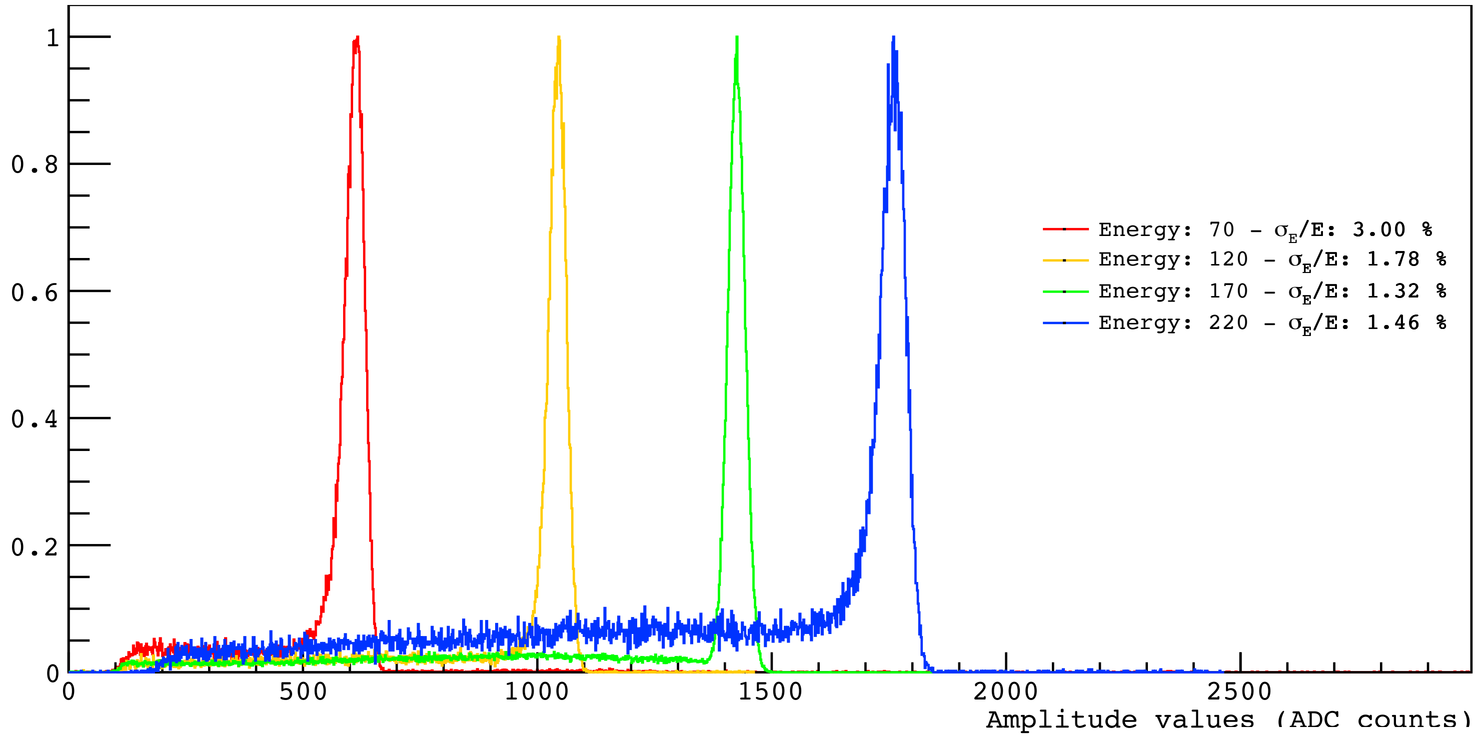
Analysis of the signal amplitudes both for 15 and 20 μm SiPM arrays

- A Crystal Ball function was used for the fits
- The distributions are normalised to the maximum peak height



Amplitude Analysis - Proton

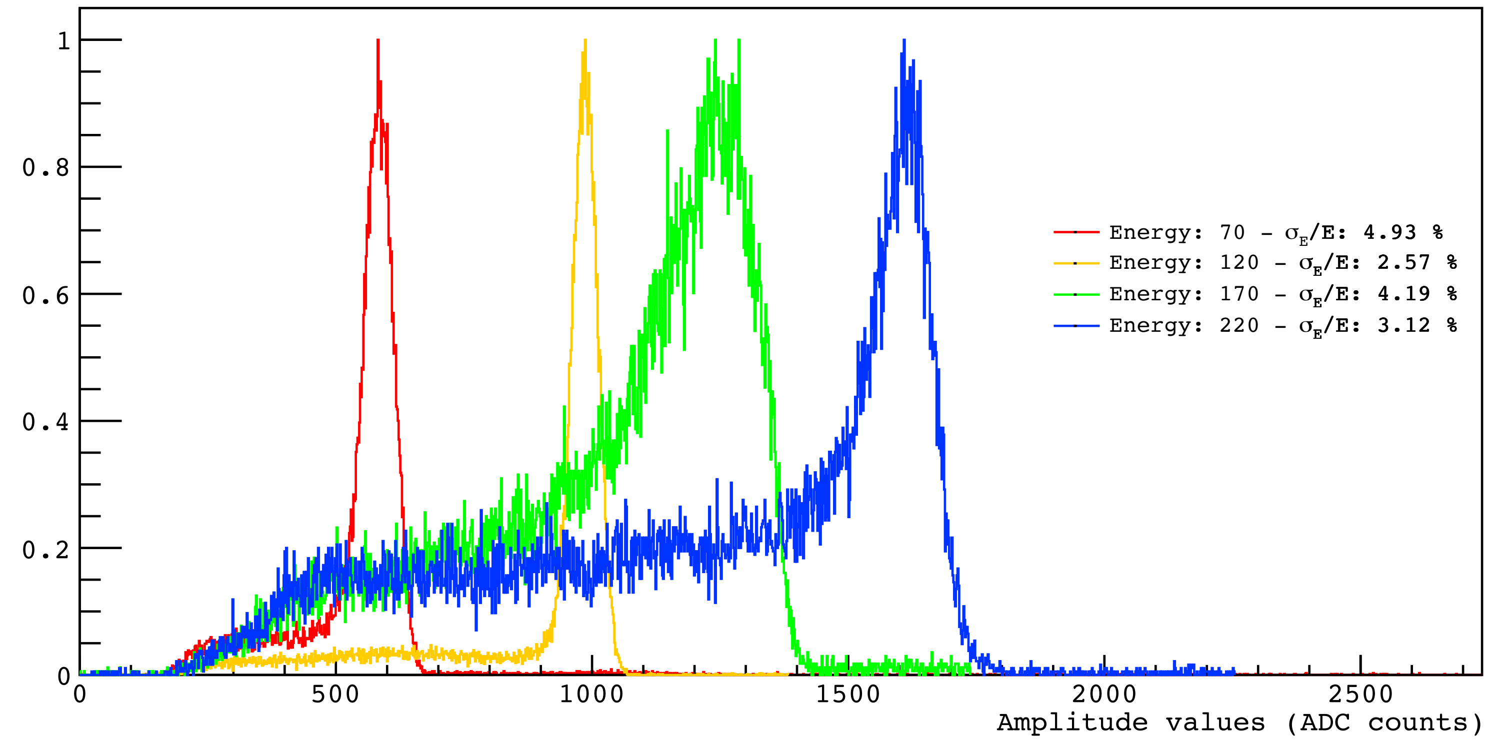
Amplitude Analysis - **15** μm SiPM arrays - **Aluminium**



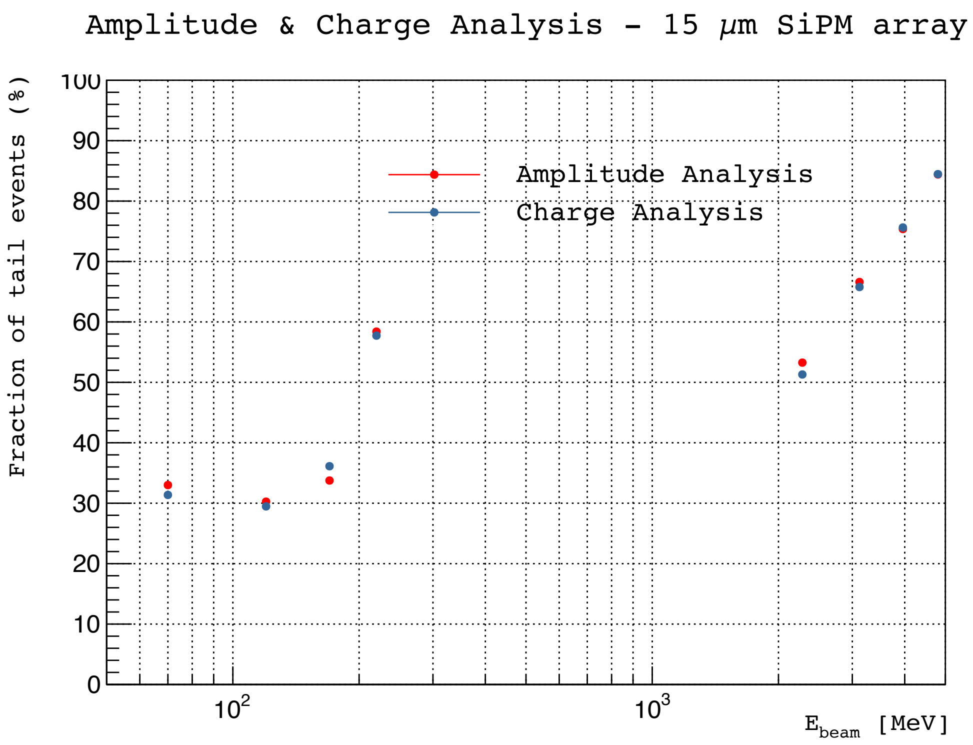
Analysis of the signal amplitudes both for 15 and 20 μm SiPM arrays

- A Crystal Ball function was used for the fits
- The distributions are normalised to the maximum peak height

Amplitude Analysis - **20** μm SiPM arrays



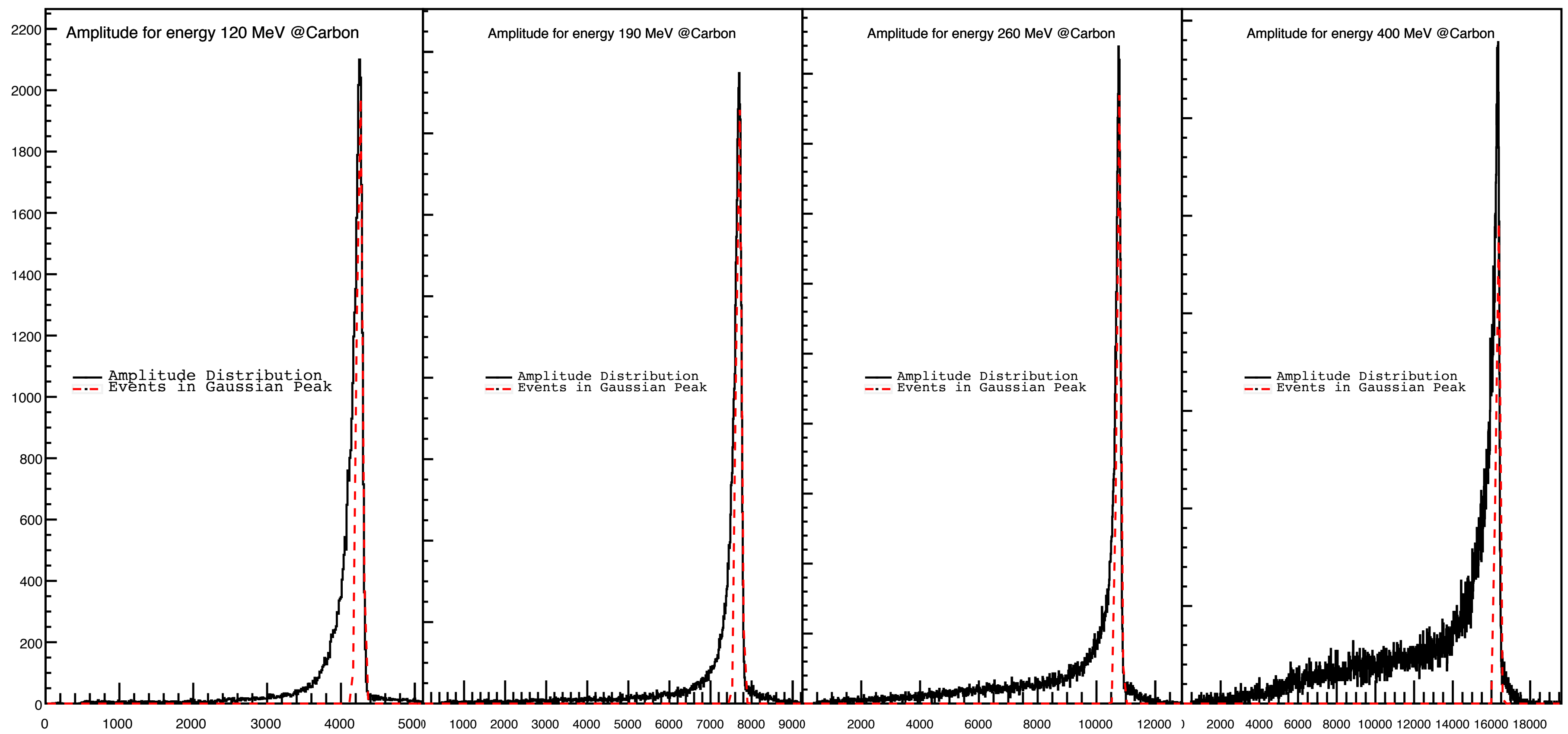
Events in the tail



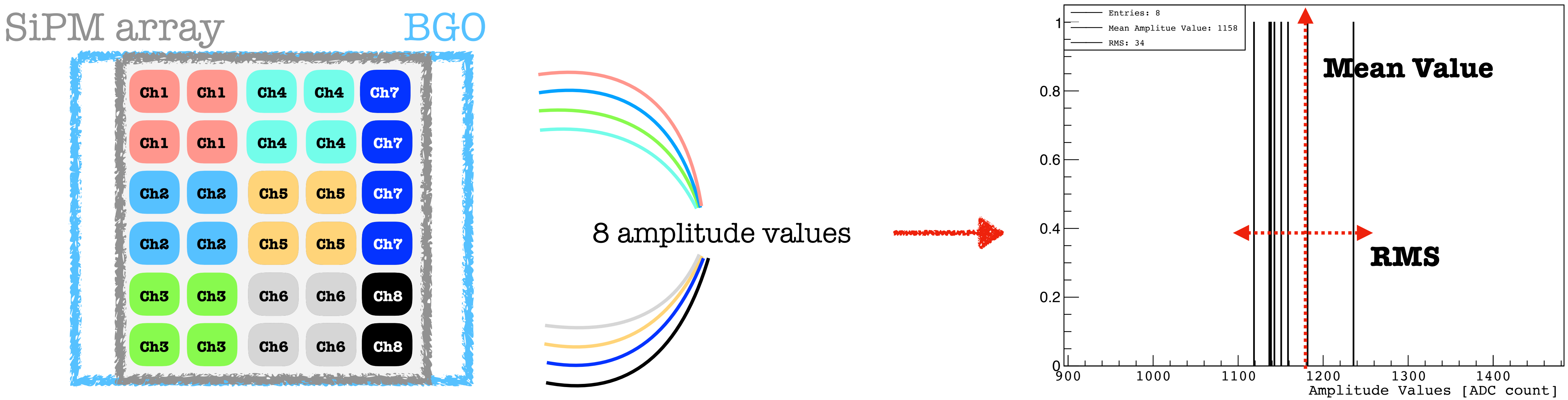
- Fraction of events in the tail grows with the energy
- Events in the peak << Events in the tail

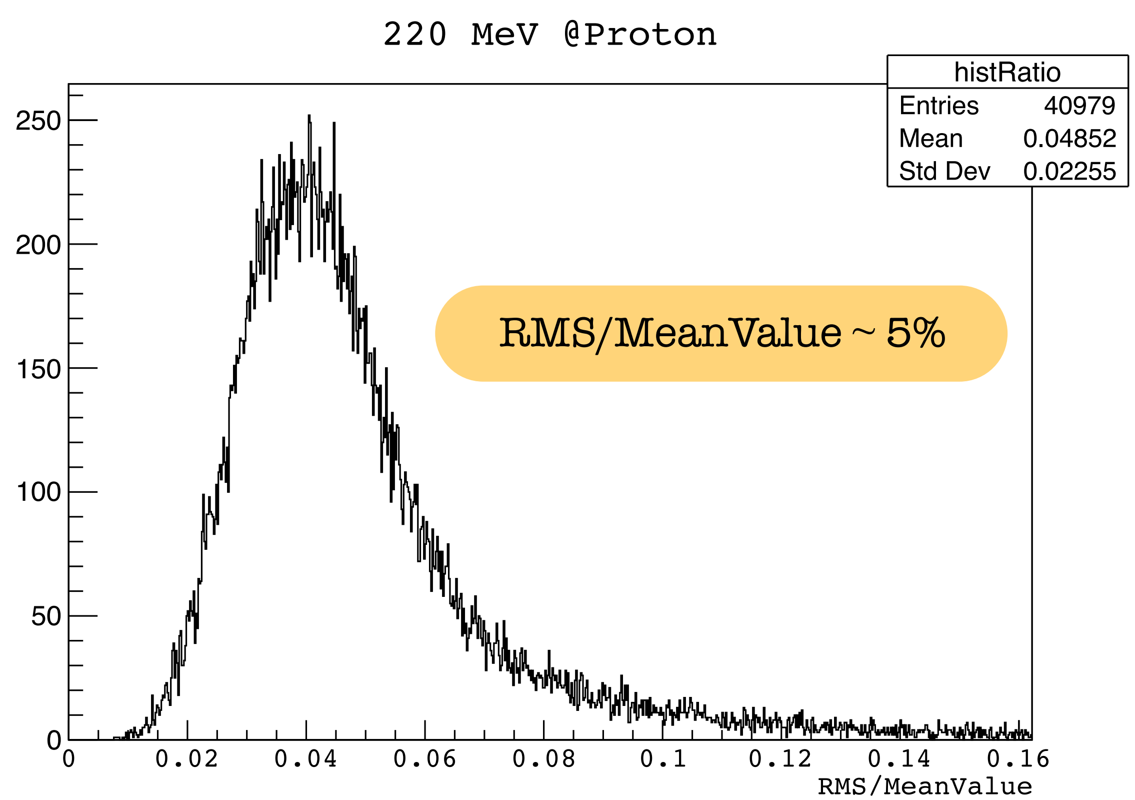
To improve:

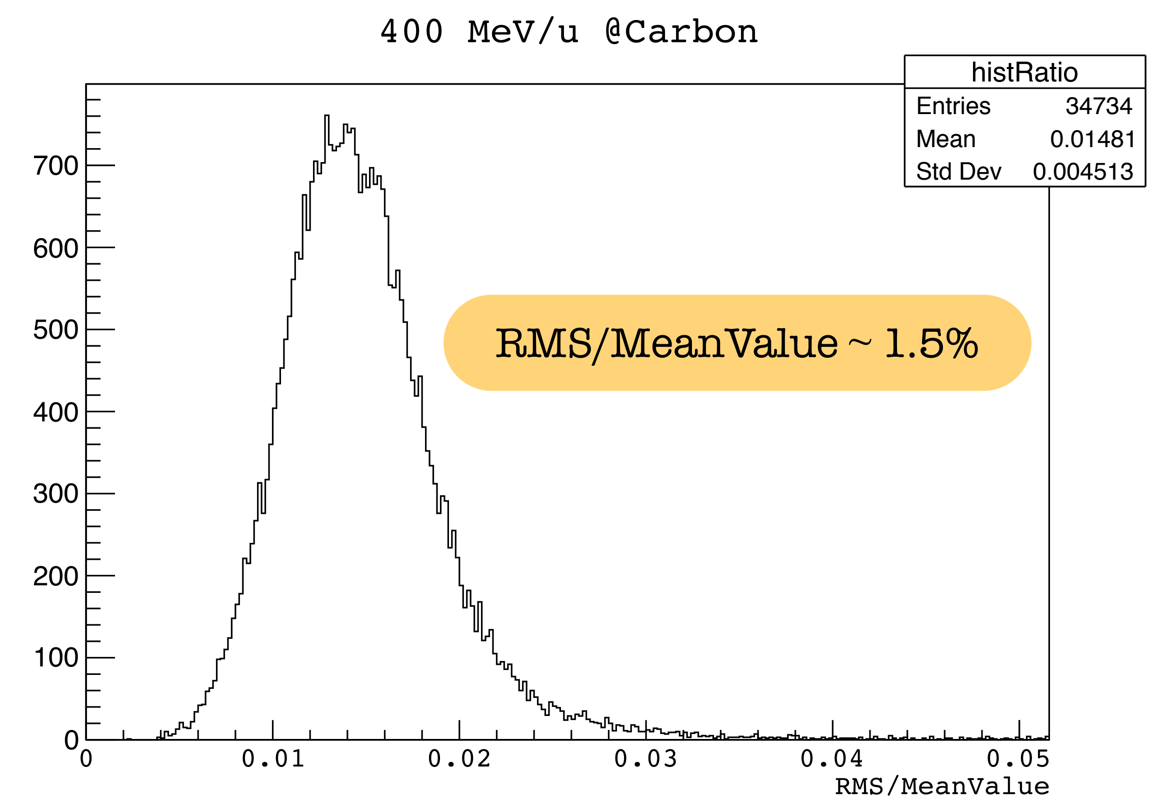
Use two plastic scintillators as external trigger



Optical Photons Uniformity

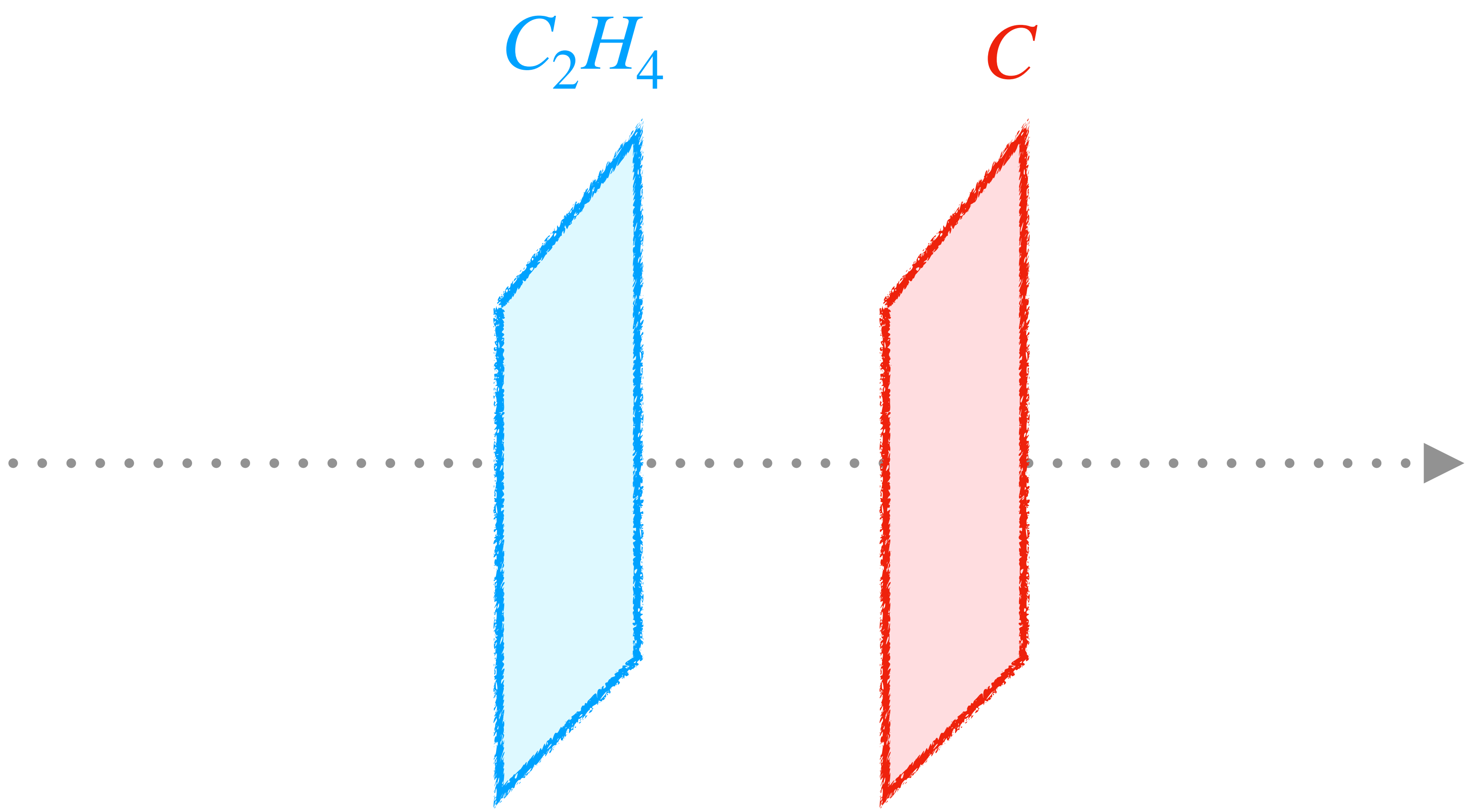






Energy resolution is affected by the non-uniformity of the light collection

H Cross Section



$$\frac{d\sigma}{dE_k}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_k}(C_2H_4) - 2\frac{d\sigma}{dE_k}(C)\right)$$

SiPMs parameters

SiPM Type			# SPADs		Fill Factor (%)		Capacitance (≈)	
Technology	Cell size (μm)	SiPM size (mm^2)	1 mm^2	SiPM	Single SPAD	SiPM	pF/mm^2	SiPM (pF)
RGB-HD	15	16	3832	61314	54	52	40	620
RGB-HD	20	16	2158	34532	65	60	40	620
NUV-HD	30	36	1122	40410	77	71	35	1260