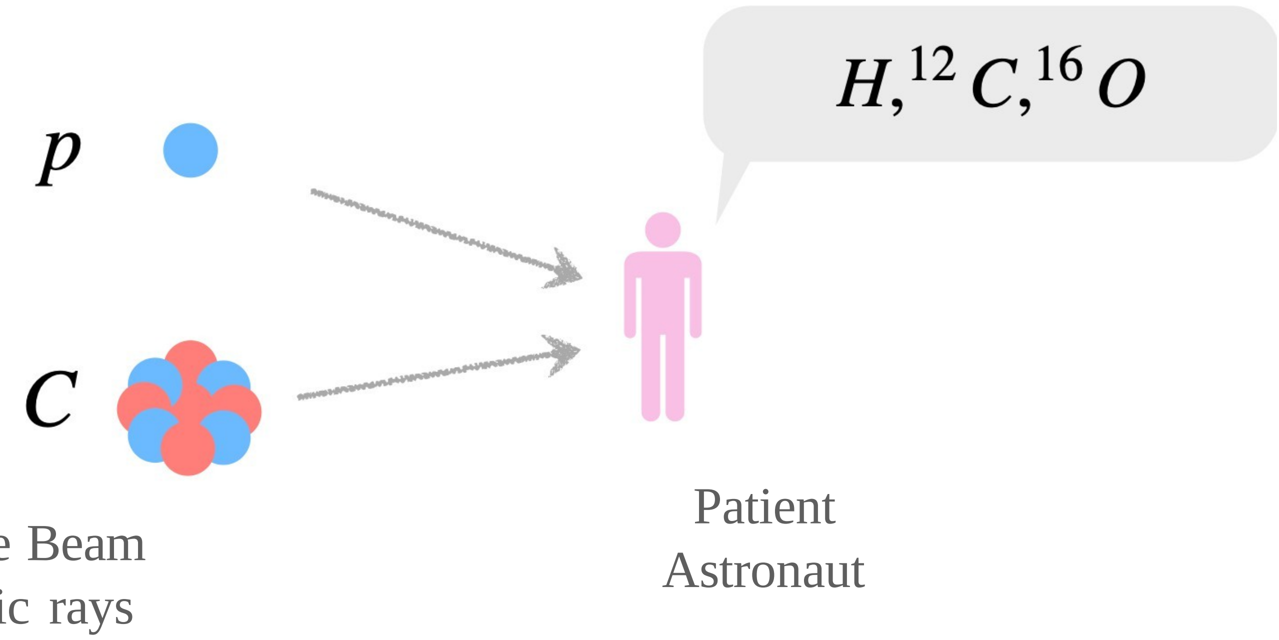
Study of the CALO BGO response

Work done by Laura Buonincontri on behalf of the Turin group

FOOT Collaboration Meeting 26/05/2025

The FOOT experiment

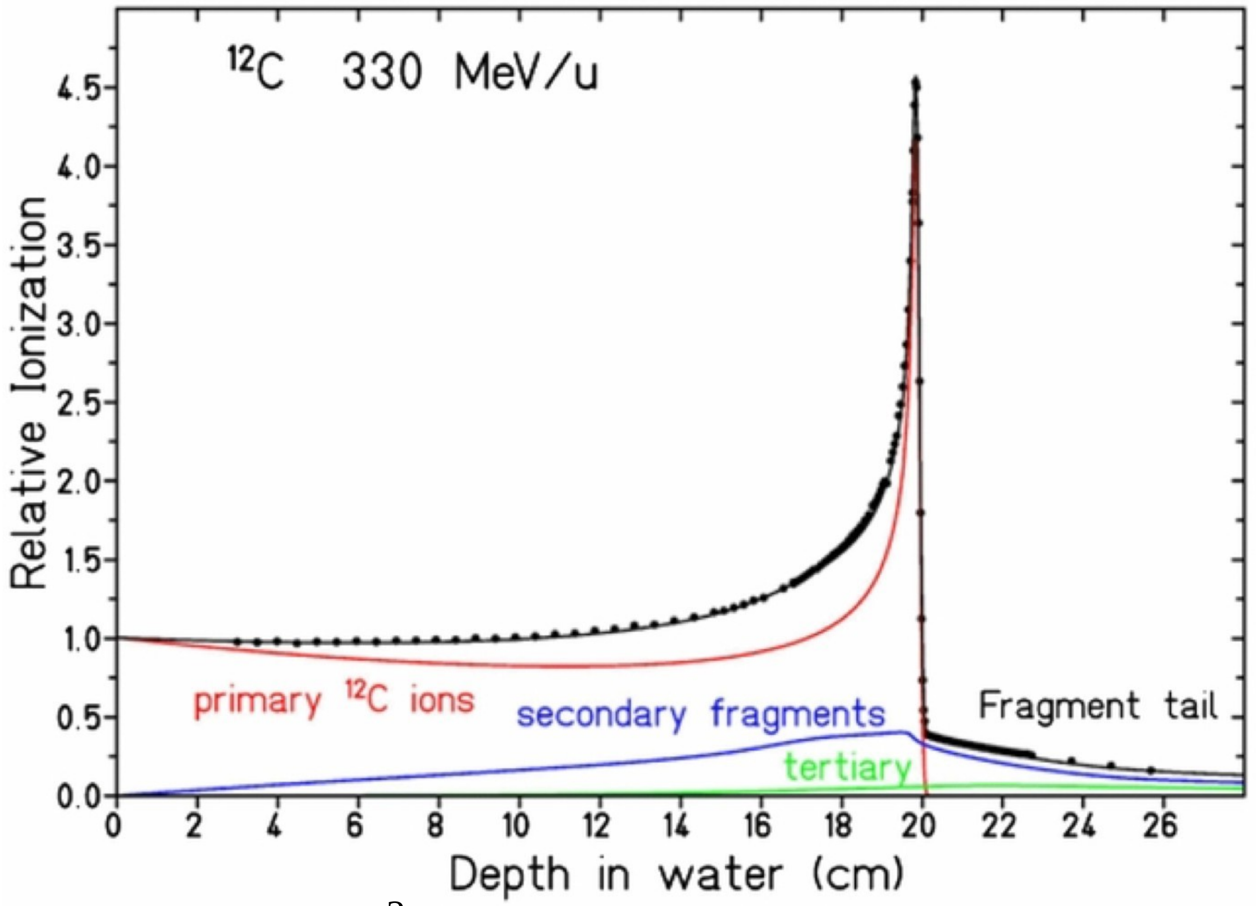
- Purpose: measure the fragmentation cross sections for light ion beams impinging on p/C rich targets
  - Useful to optimize hadron therapy treatments (where p/C ions are impinged to patients) and radio-protection in space

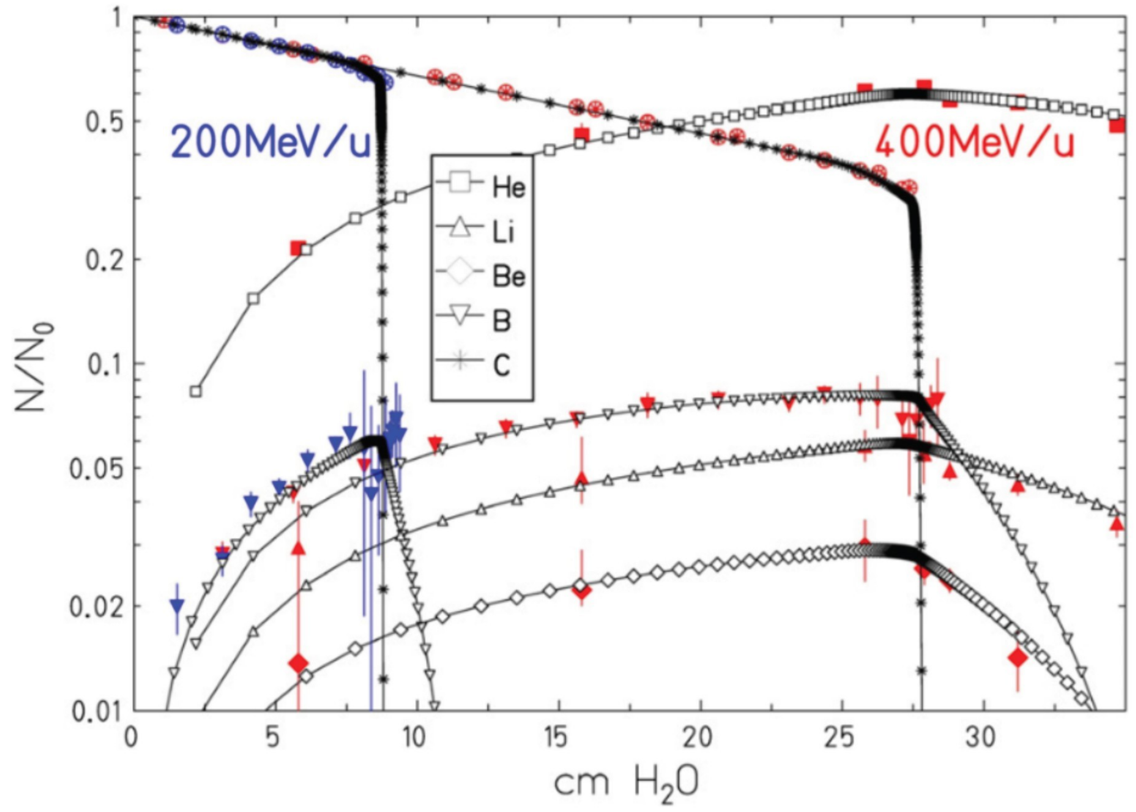


Hadronic inelastic interactions may lead to:

- **Target** fragmentation (p beam on C/O)
- **Projectile** fragmentation (C beam on H)
- Both **target** and **projectile** fragmentation (C on C/O)

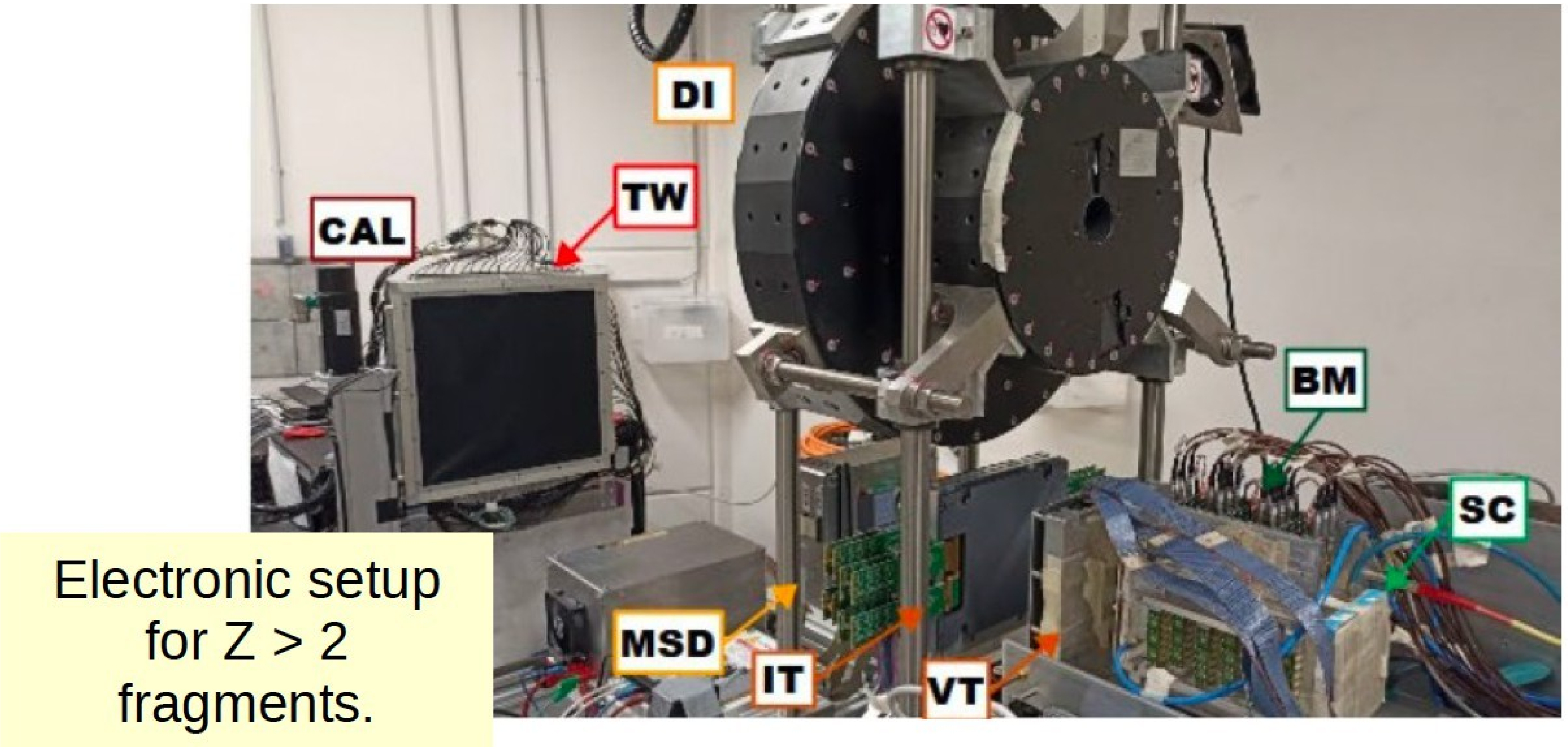
- FOOT measurements will allow to improve accuracy in dose calculation released by secondary fragments
- Goal: measure the beam and projectile fragment production cross sections with an accuracy better than 5%



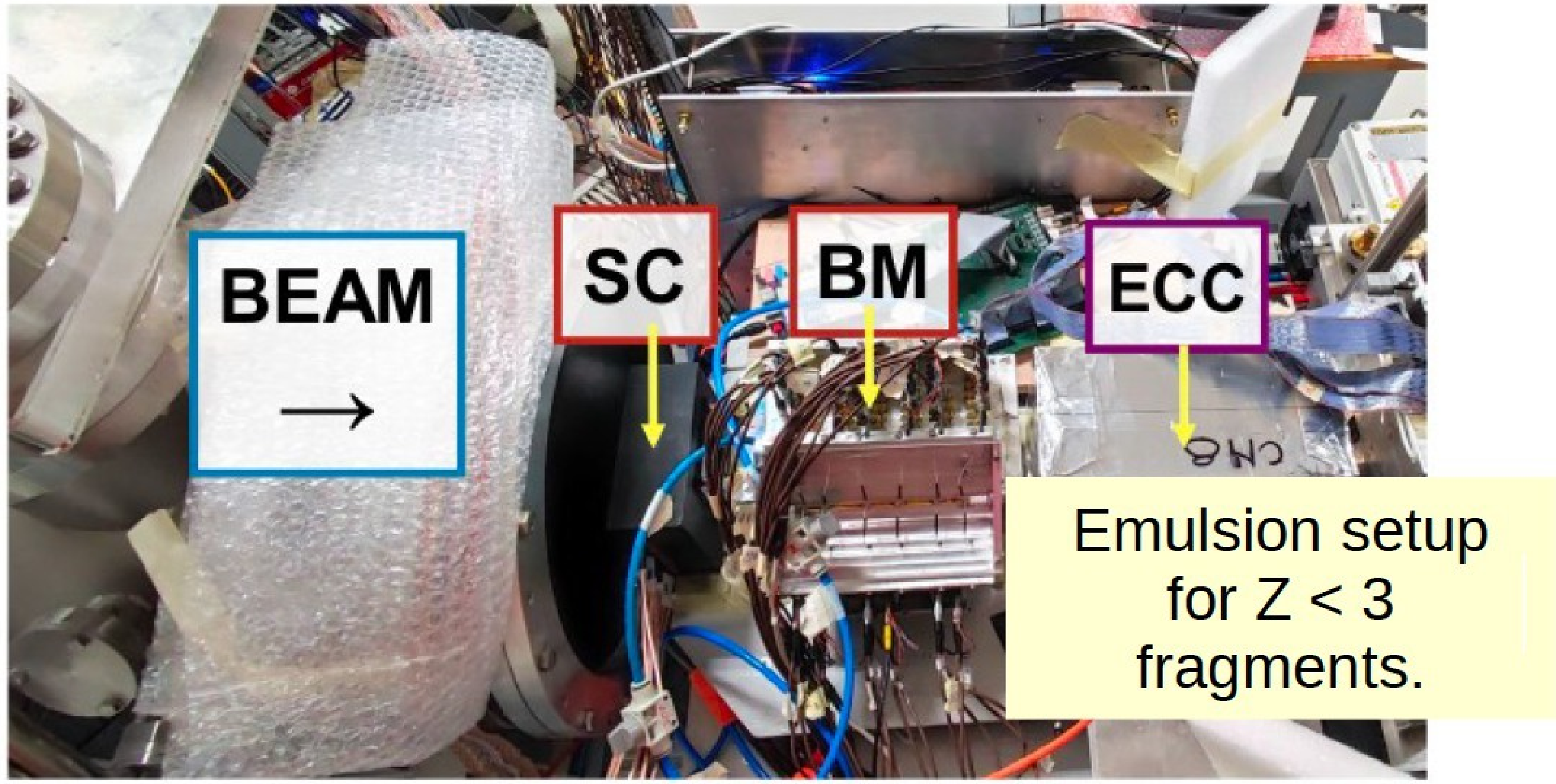


Experimental setup

Electronic spectrometer



Emulsion spectrometer

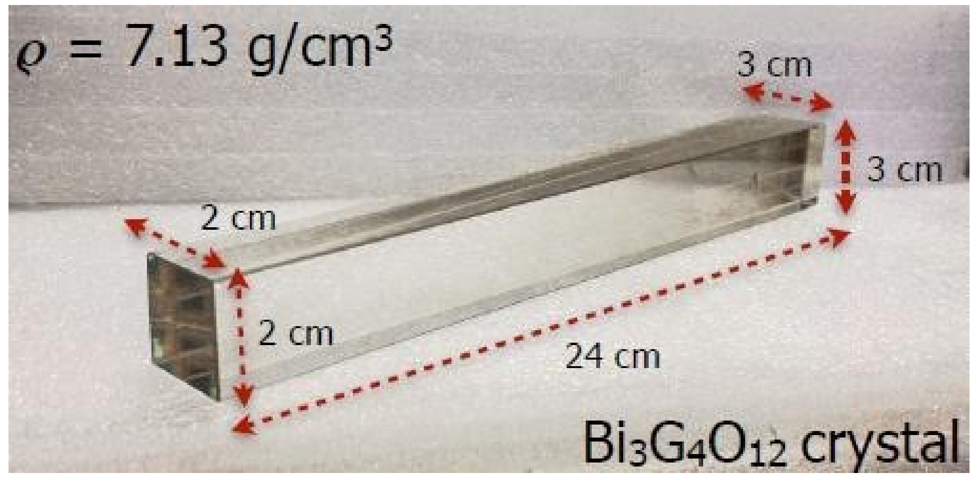


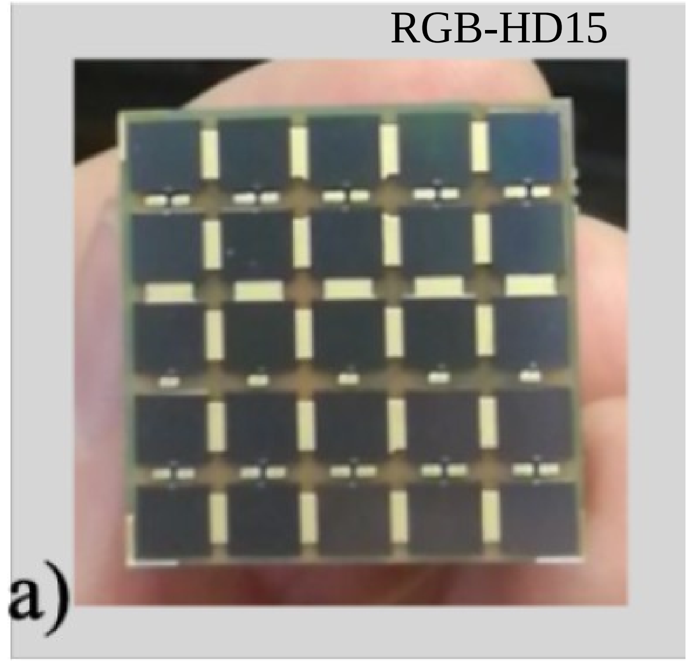
Beam particles: ^{4}He, ^{12}C, ^{16}O

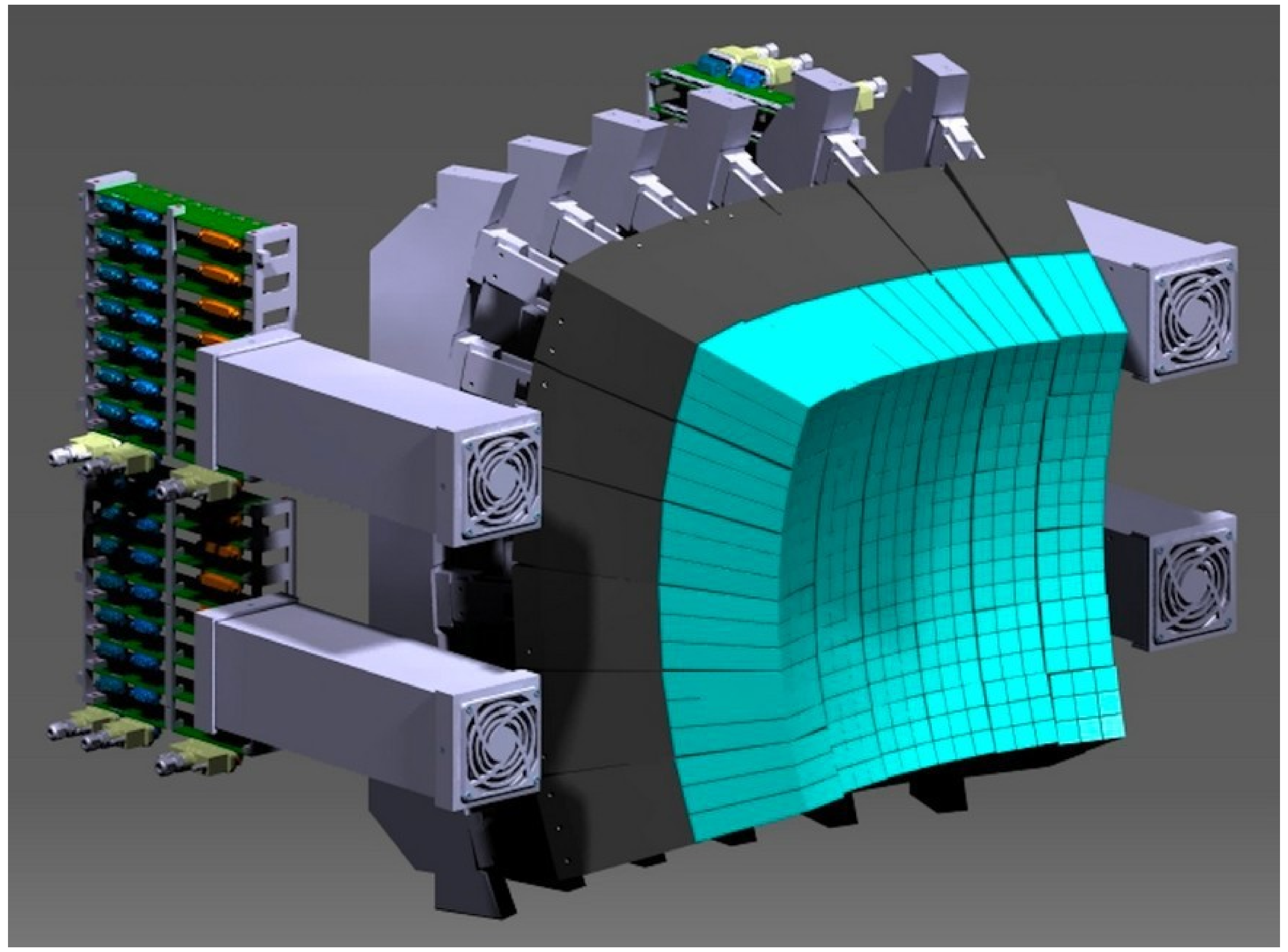
Targets: polyethylene, polymethyl methacrylate ($C_5O_2H_8$), polyethylene (C_2H_4)

Calorimeter Calibration

- Calorimeter composed by BGO crystals
- Readout system:
  - SiPM board
  - WaveDAQ





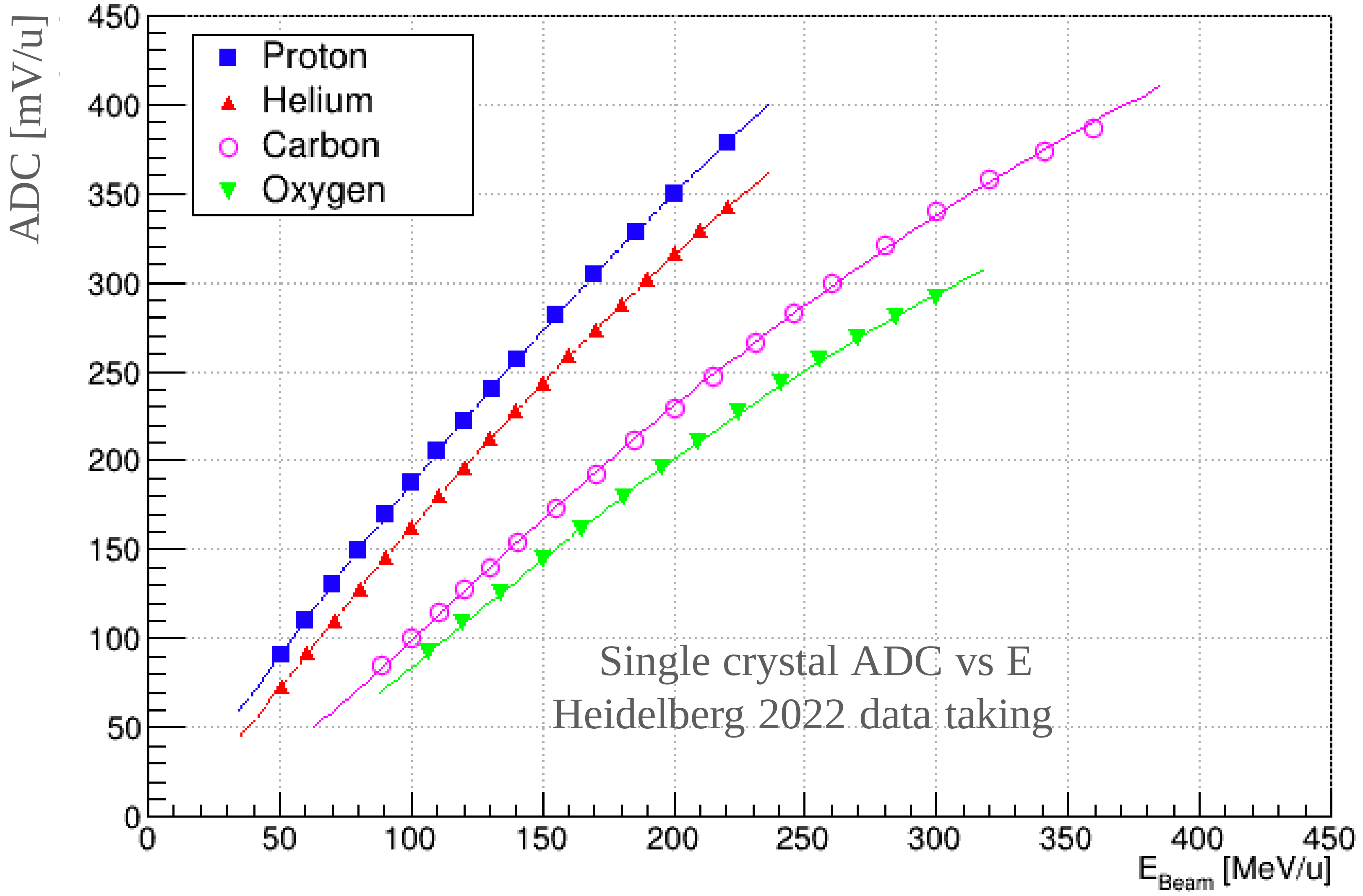


- Turin group focused on the **ADC-Energy calibration** of the calorimeter
  - Fit with the Modified Birk's Function (MBF)

$$ADC(E) = \frac{p_0 E^2}{1 + P_1 E + P_2 E^2}$$

- Goof fitting of experimental data

$$\frac{|E_{fit} - E_{ADC}|}{E_{fit}} < 1\%$$



The Calorimeter Calibration

- The calorimeter response linearity is affected by the Birk's law

$$\frac{dS}{dx}=\frac{A\frac{dE}{dx}}{1+KB\frac{dE}{dx}}$$

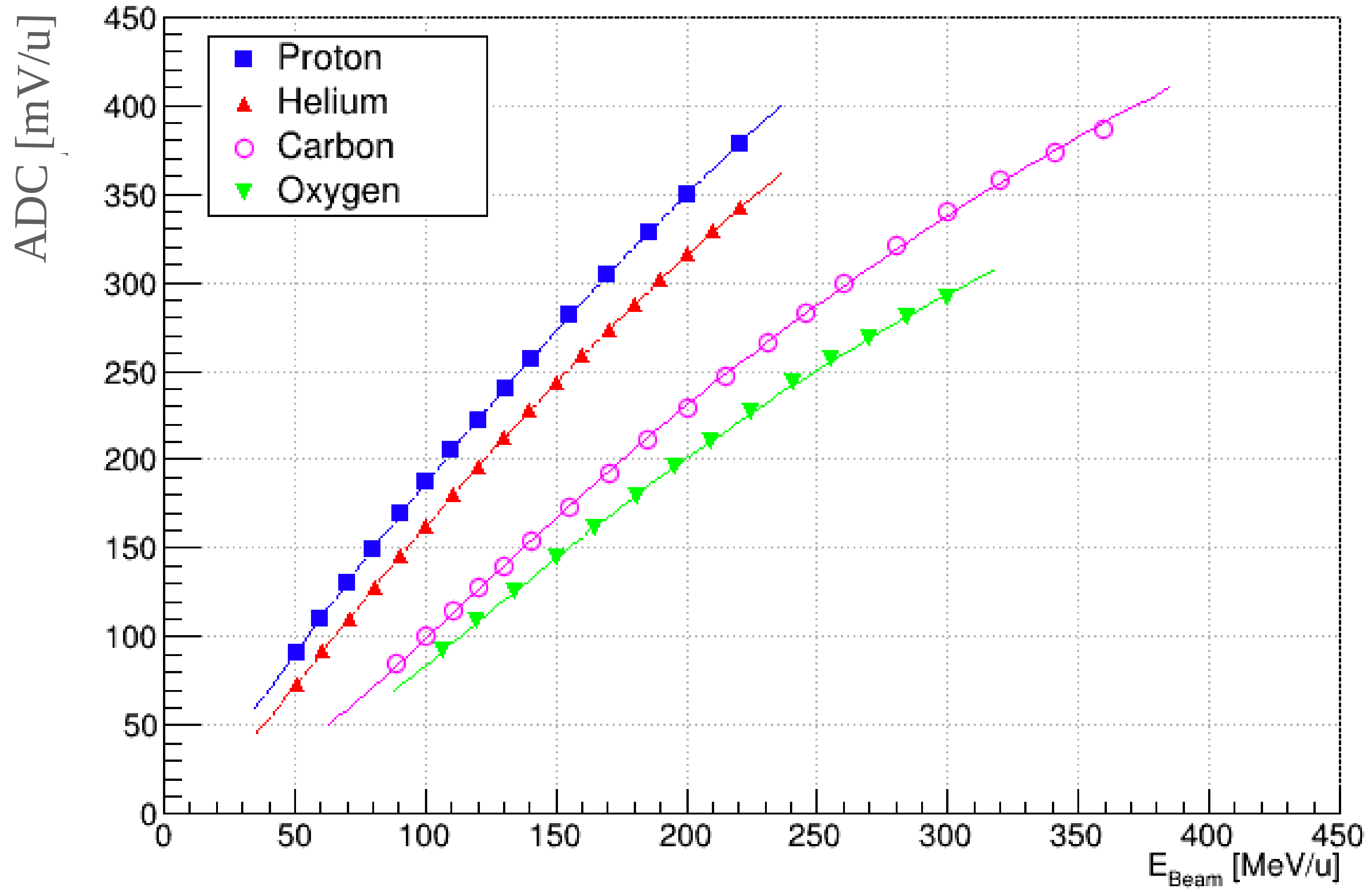
- The fit function is the Modified Birk's Function, that depends on three parameters:

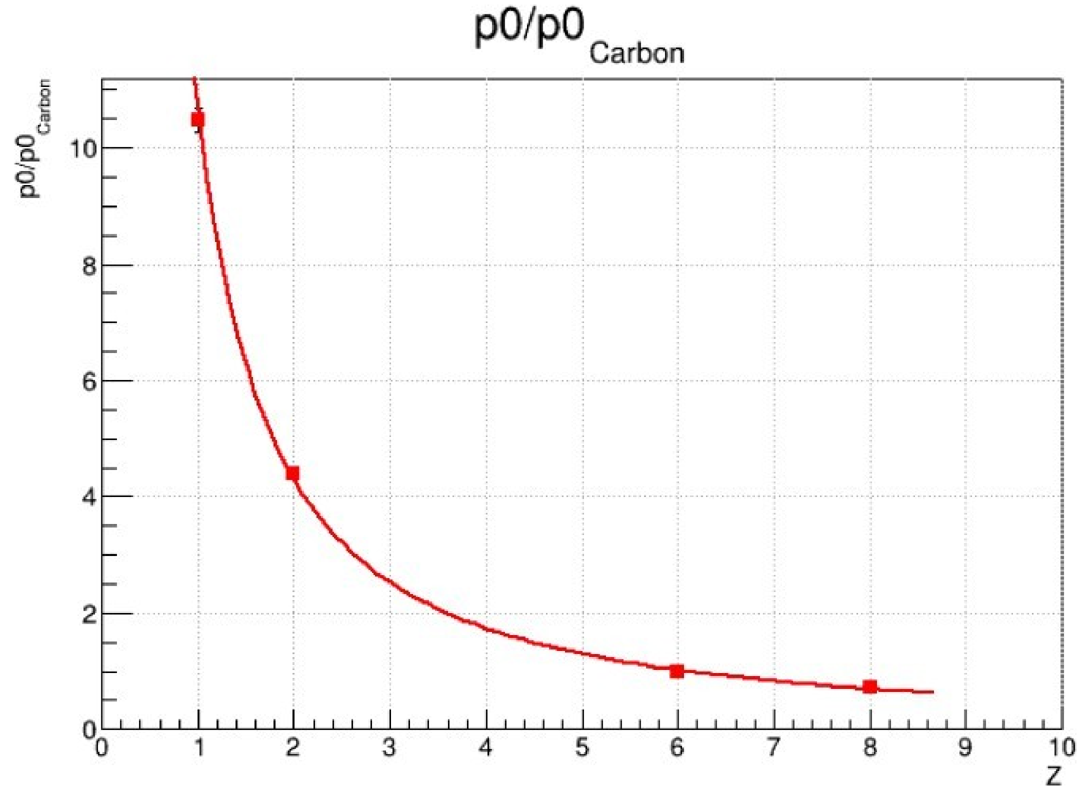
$$ADC(E)=\frac{p_0 E^2}{1+P_1 E+P_2 E^2}$$

- Parameters dependence on Z, modeled with the power law function

$$\frac{P_x}{P_{x_{Carbon}}}=a_{0,x} Z^{a_{1,x}}$$

- There is an (unknown) dependence on Z

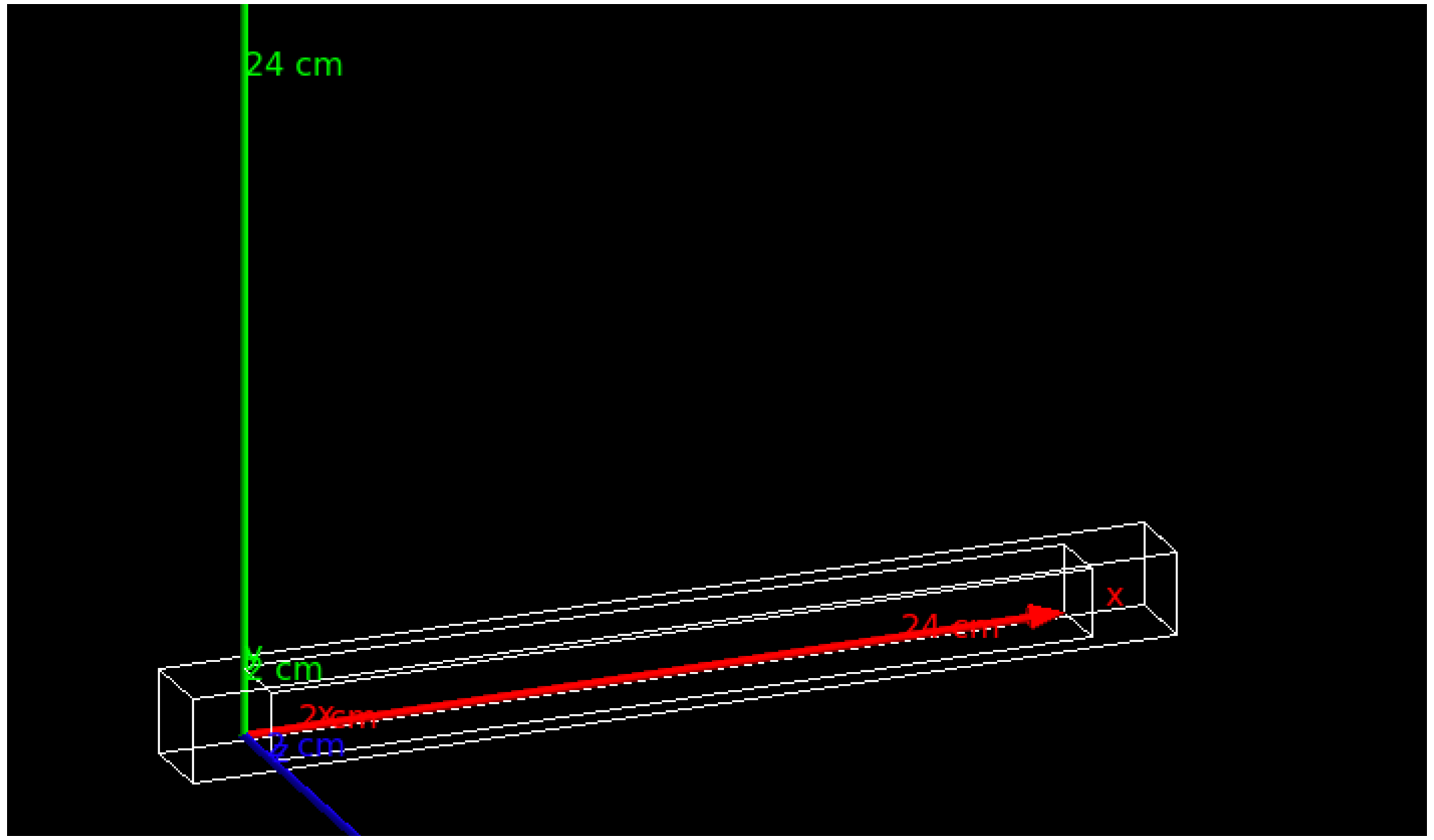




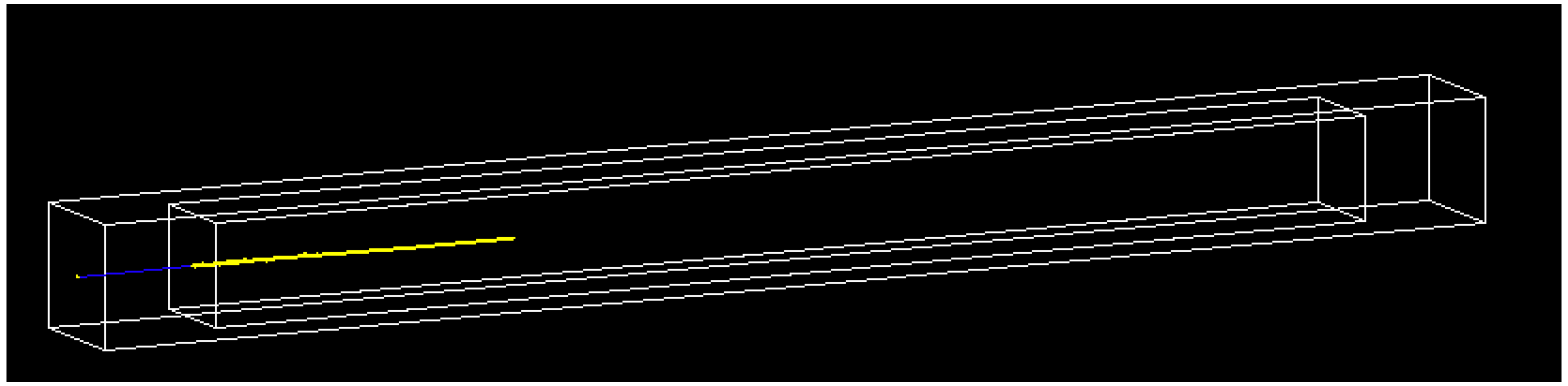
The goal of these studies is to understand these assumptions and the variation of the BGO response curve due to:

- Particle range variation
- Non-linearity related to optical pile up in the SiPM
- Different crossing ions species

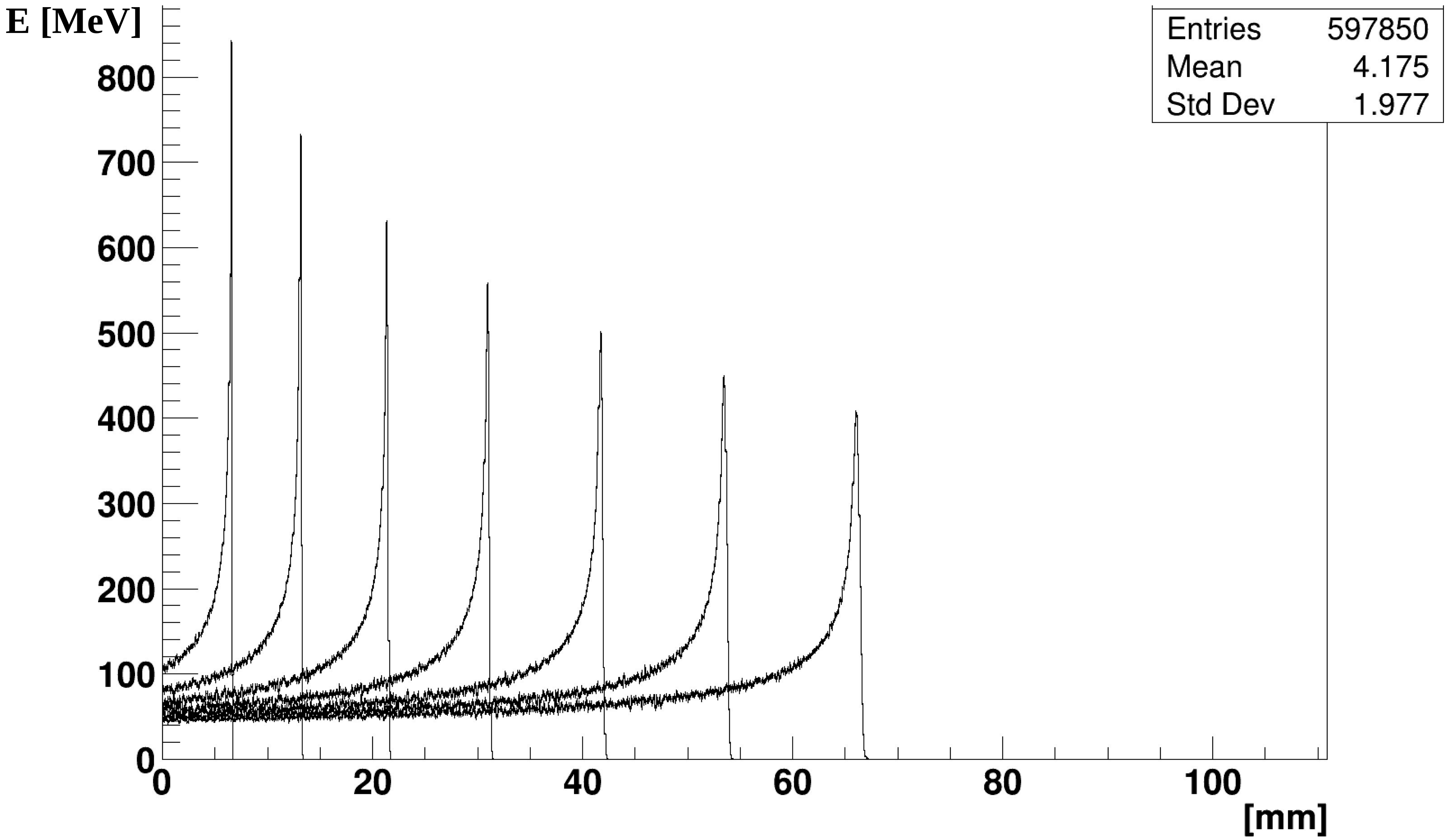
BGO crystal simulation with GEANT4



2x2x24cm BGO crystal within the world envelope



E=400MeV/u Carbon sent against the crystal



Bragg curve for Carbon E=100,150,200,250,300,350,400 MeV/u

Calculation of the integral of the Birk's law

Birk's law:

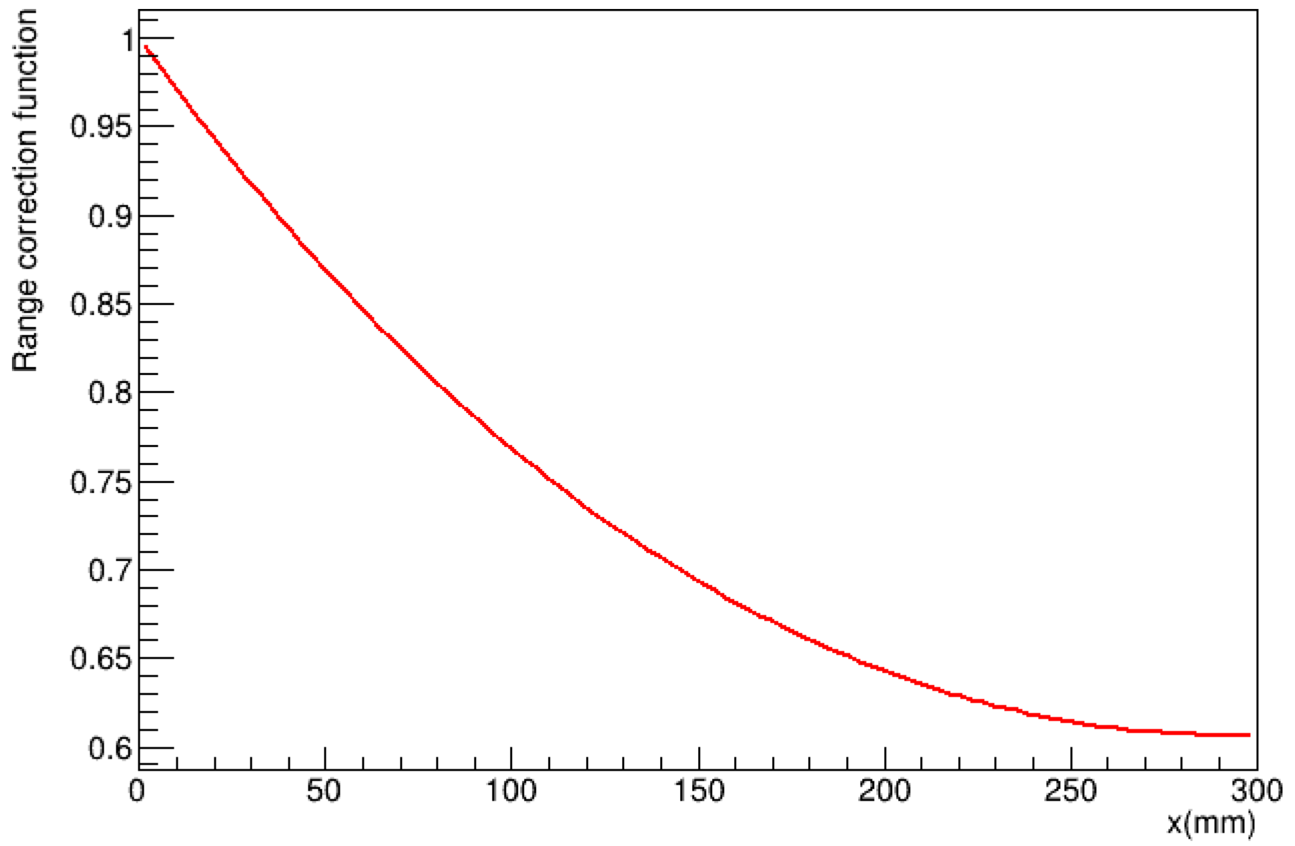
$$\frac{dS}{dx} = \frac{A\frac{dE}{dx}}{1 + KB\frac{dE}{dx}}$$

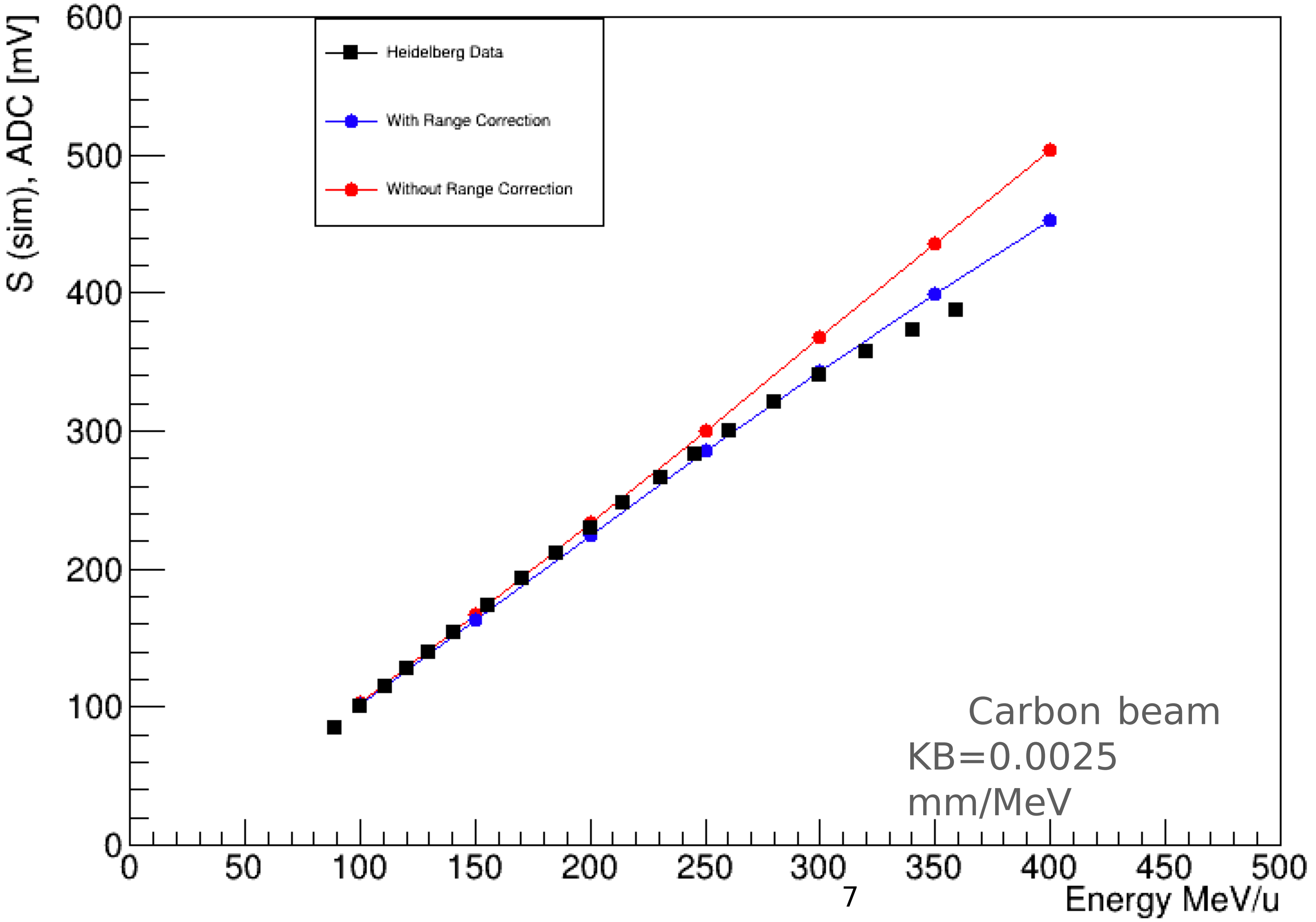
$$S = \sum_{i=1}^{N} \frac{dS}{dX} \cdot dx$$

Light yield without range correction

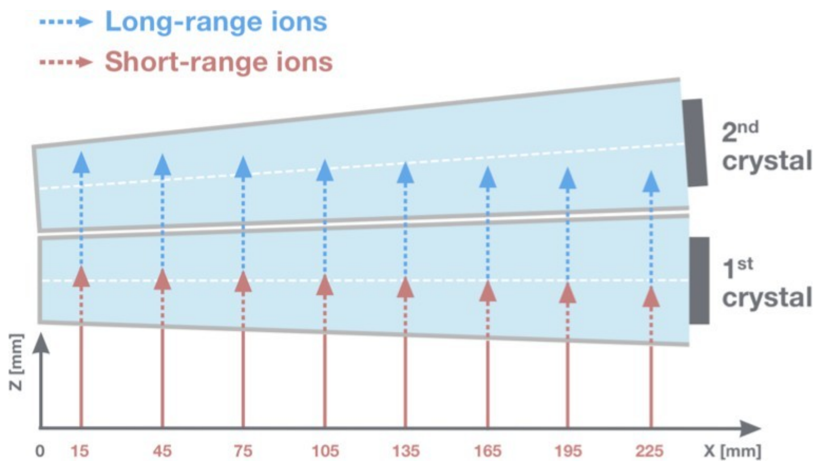
$$S_r = \sum_{i=1}^{N} \frac{dS}{dX} \cdot f(x) \cdot dx$$

Light yield with range correction





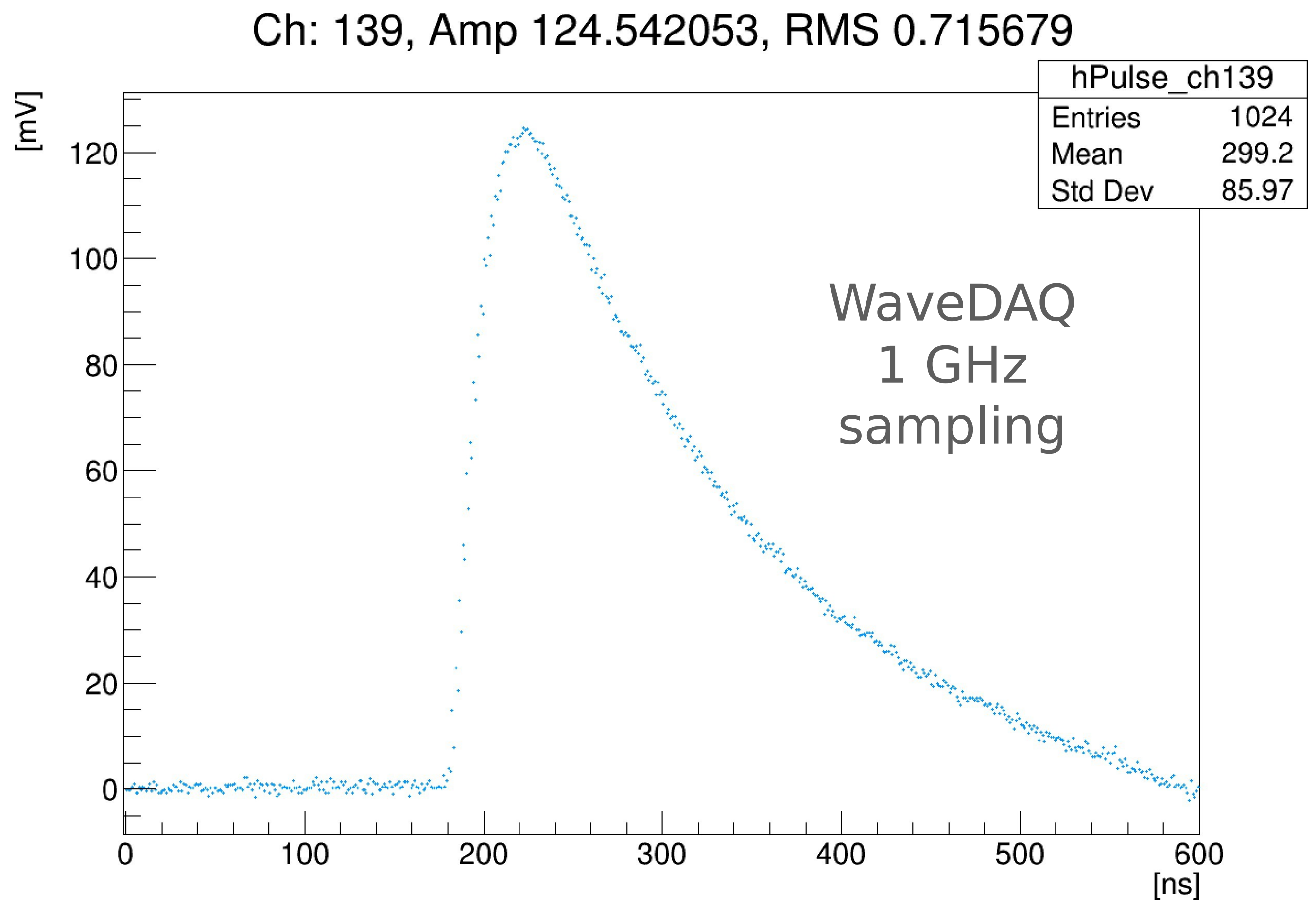
$$f(x) = A \cdot \left[R \cdot e^{-\alpha(L-x)} + (1-R)e^{-\alpha(L+x)}\right]$$



Beam	Maximum Amplitude	
	α (m^{-1})	R(%)
p70	4.0 ± 0.8	9.9 ± 1.4
p170	3.8 ± 2.6	10 ± 4
C115	3.9 ± 0.2	10.2 ± 0.4
C260	3.5 ± 0.2	10.3 ± 0.4

- The signal Maximum Amplitude decreases as a function of the distance from the front side of the BGO crystal (see *N. Bartosik et al 2025 JINST 20 P03021*)

Calculation of photon pile-up



Basic idea: each pixel in the SiPM has a recovery time τ -: Signal loss may be due to **photon Pile-Up**

Goal: calculation of the Pile-Up at the **maximum of the Wave Form**, within a time window (=7-10 ns)

- In the analysis, the ADC value for a certain energy is taken at the maximum WF amplitude

$LY = 8000 ph/MeV$ BGO Light Yield

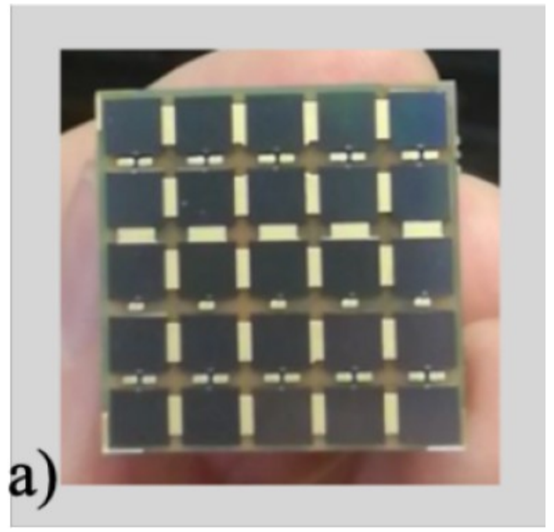
$$N^{peak}_{ph,scint} = LY \cdot E_{particle}(MeV) \frac{A_{tot,SiPM}}{A_{Crystal}} \cdot PDE \cdot \frac{WF_{peak}}{WF_{integral}}$$

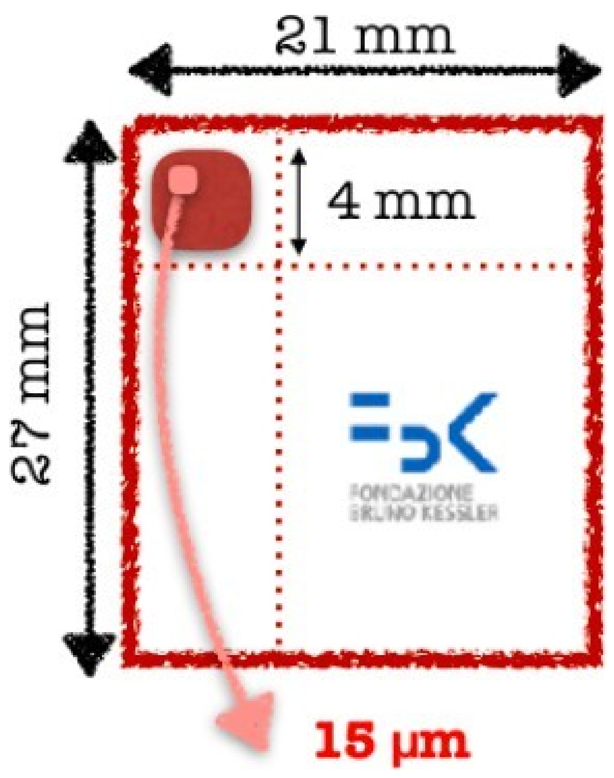
Number of photons at peak

- PDE assumed 25%
- SiPM surface does not cover the entire 2.8x2.8 cm^2 crystal face

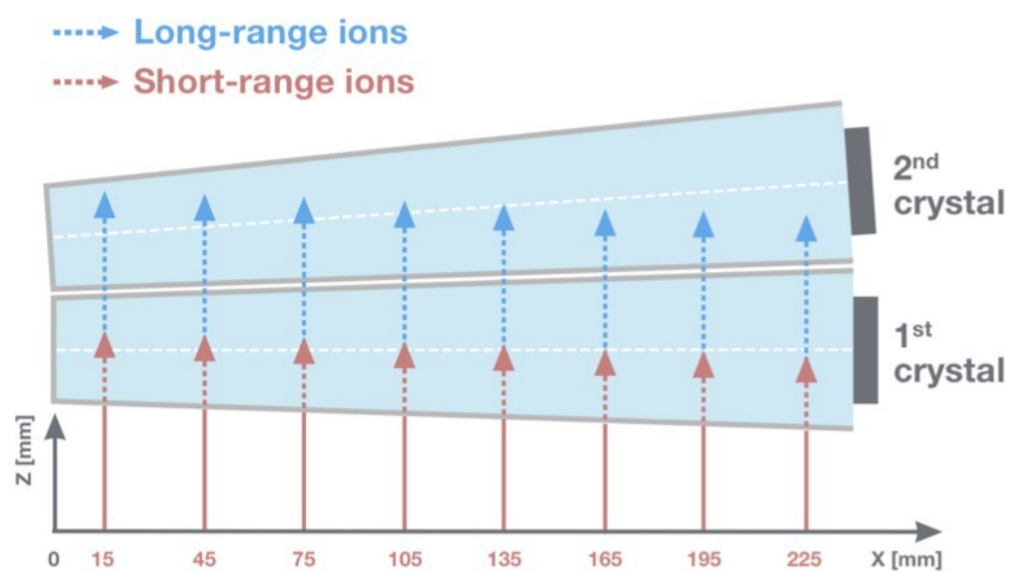
$$D_{ph} = \frac{N_{ph}}{cell} = N^{peak}_{ph,scint} \cdot \frac{A_{microcell}}{A_{tot,SiPM}}$$

Photon density per cell





RGB-HD15



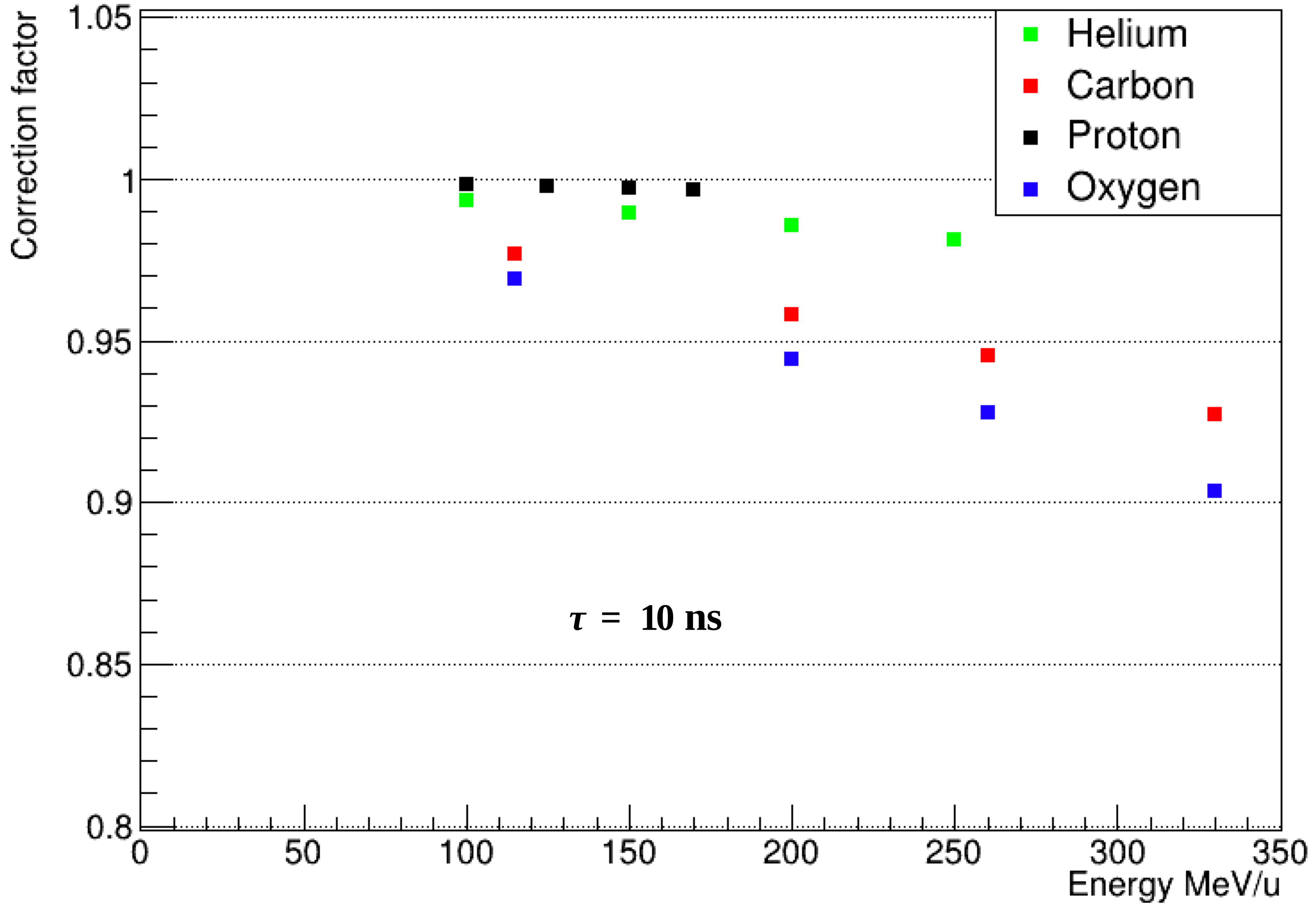
Pile-Up calculation

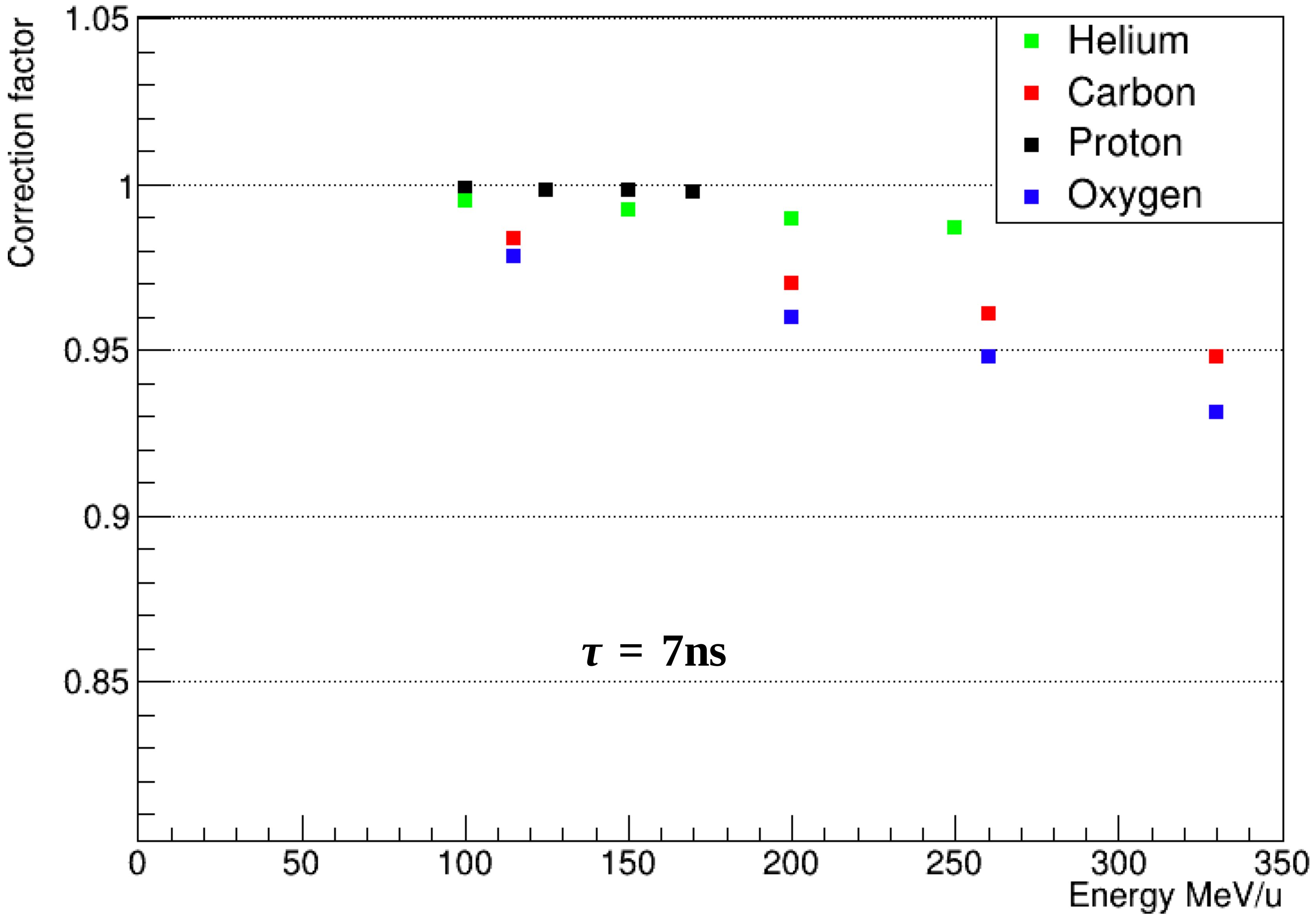
$$p(D_{ph},k)=\frac{D_{ph}^{k}}{k!}\cdot e^{-D_{ph}}$$

Probability to have k photons given a D_{ph} number of photons per cell

Correction factor to account for signal loss:

$$y=1-\frac{1-p(D_{ph},0)-p(D_{ph},1)}{1-p(D_{ph},0)}$$



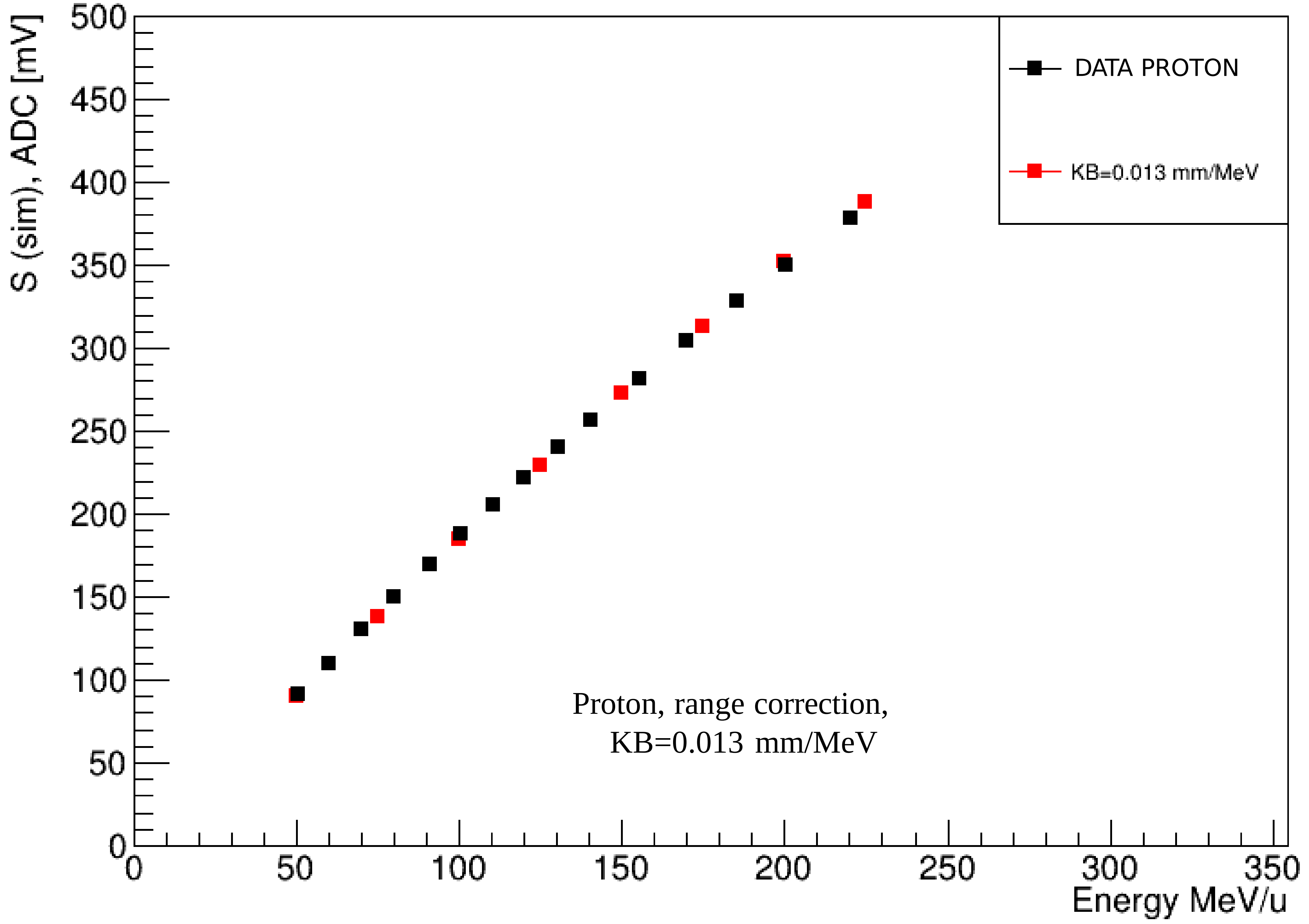


Calculation of best KB to match data

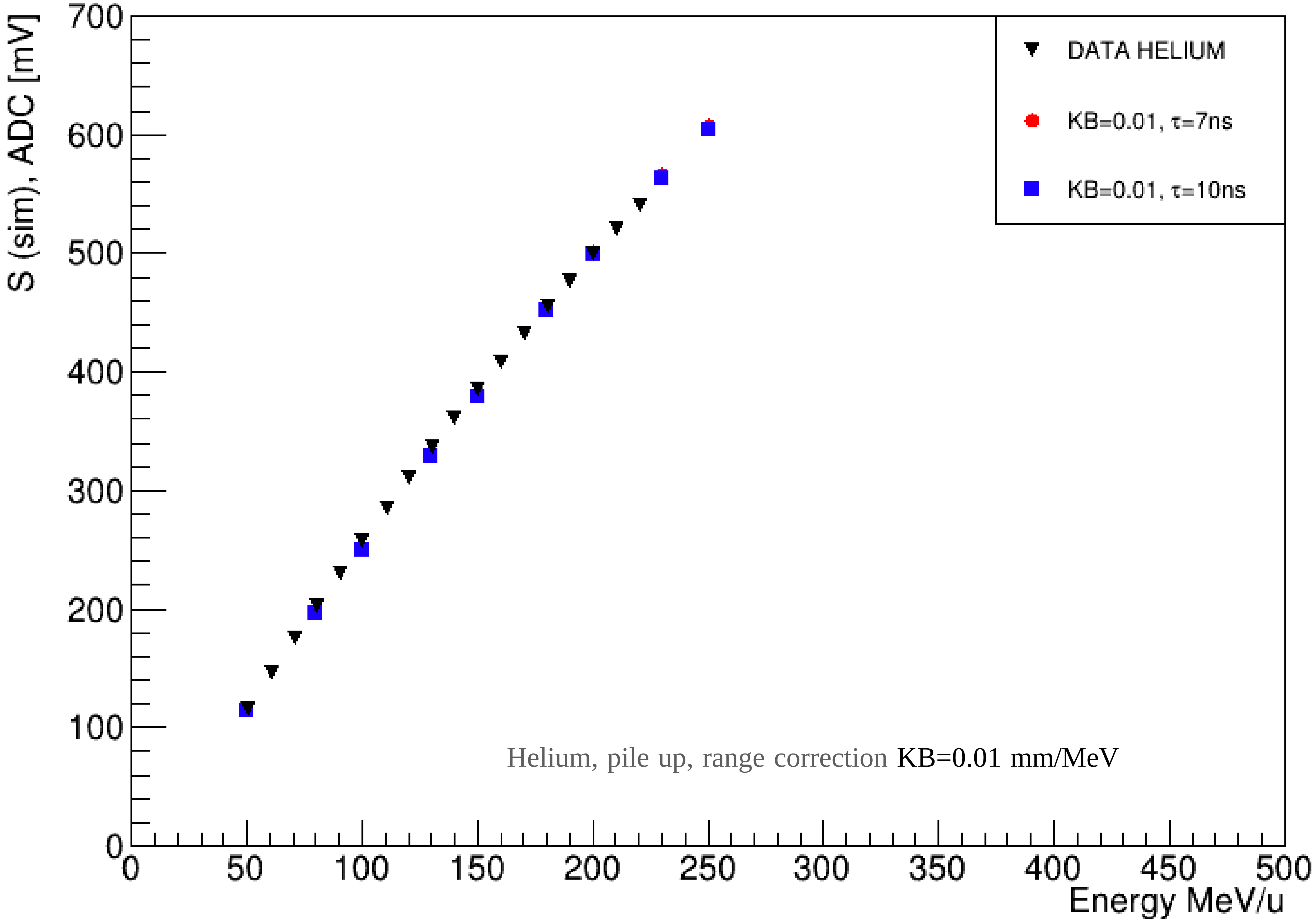
- Best KB for protons determined by minimizing the

$$\chi^2 = \sum_i \frac{(S(E_i) - ADC(E_i))^2}{\sigma^2_{ADC(E_i)}}$$

- Two crystals have been tested in Heidelberg: crystal 1 (used for KB determination)

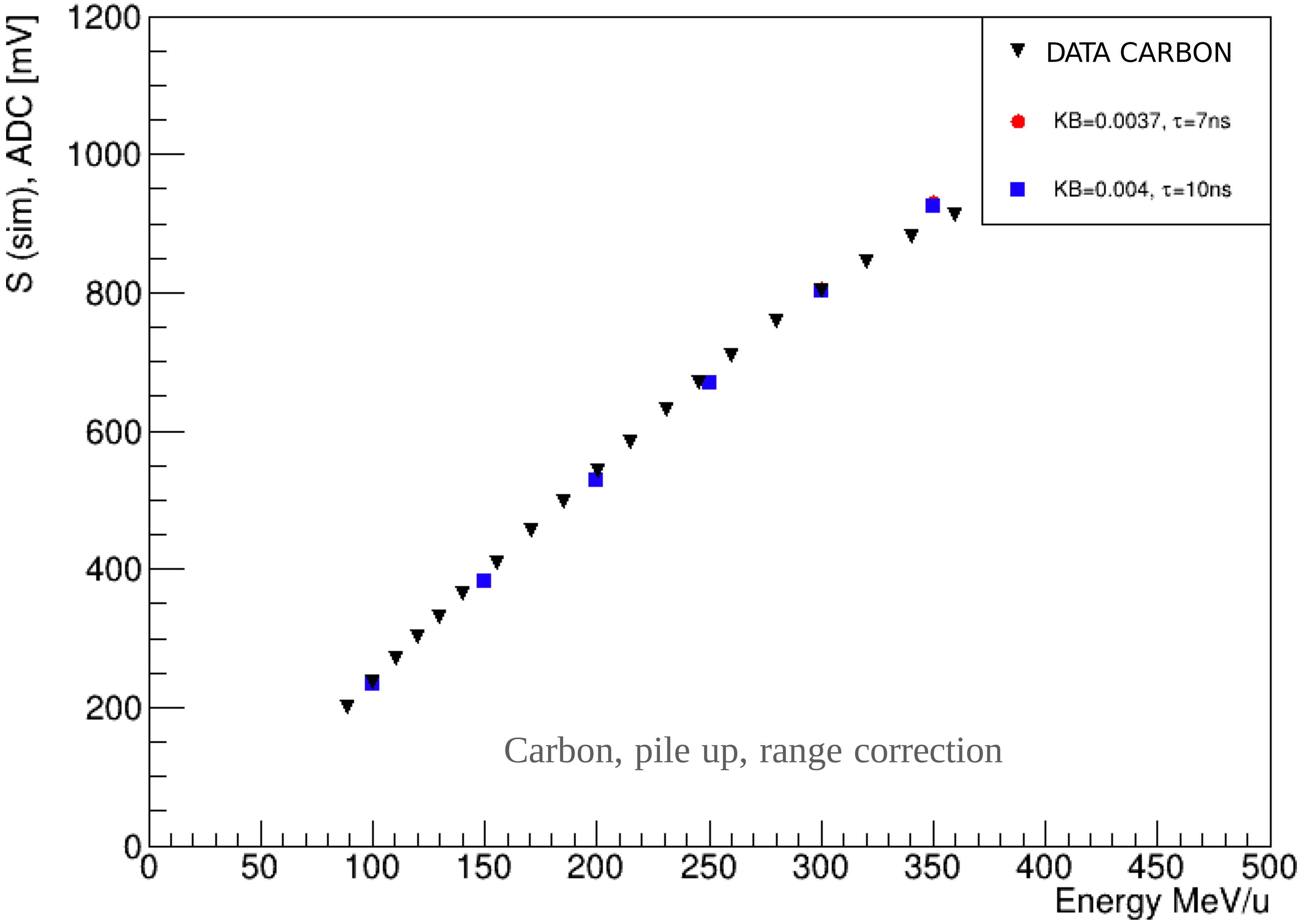


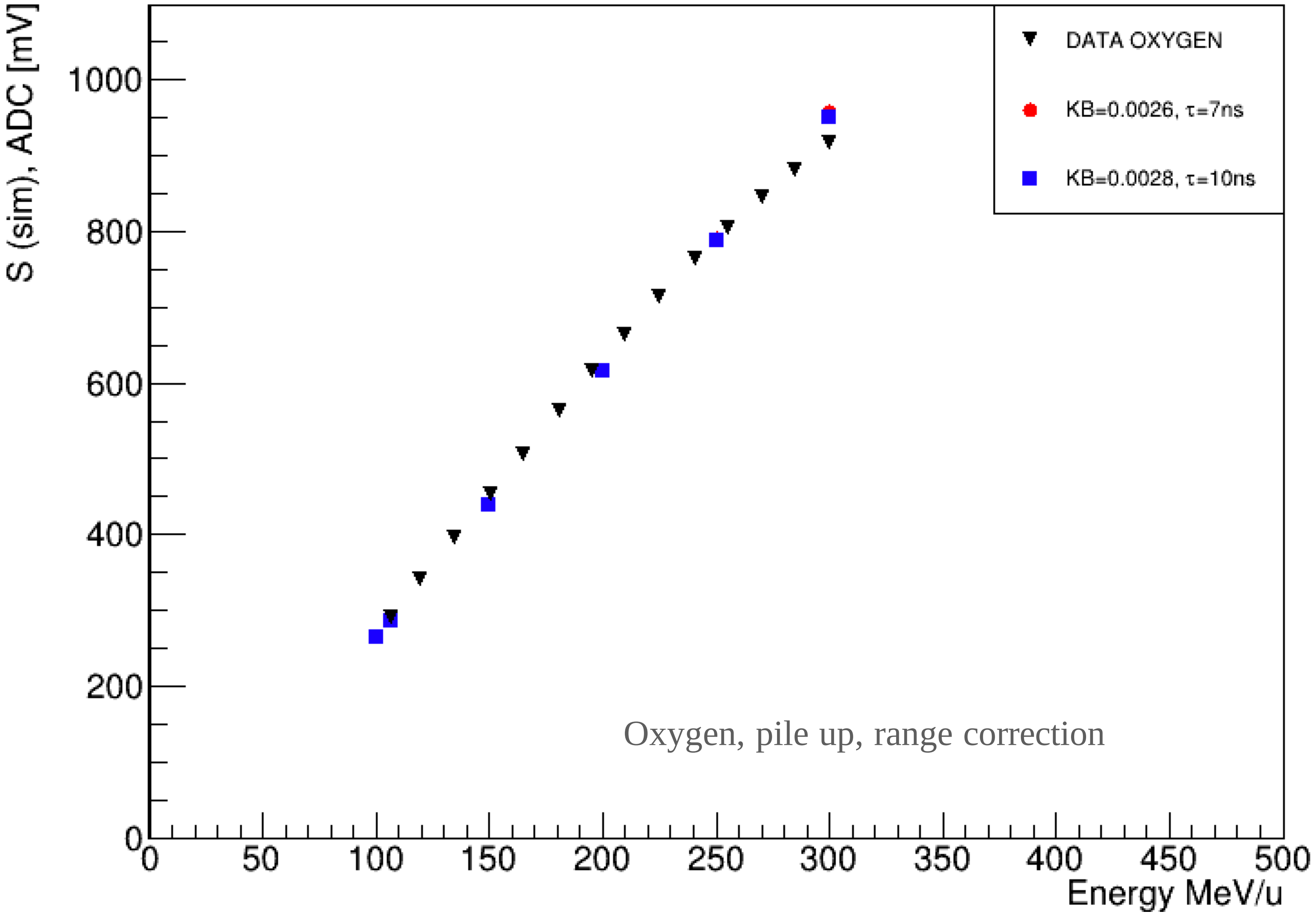
Best match Helium



In literature https://doi.org/10.1016/j.nimb.2015.07.127, KB(He)=0.01 mm/MeV

Best match Carbon and Oxygen



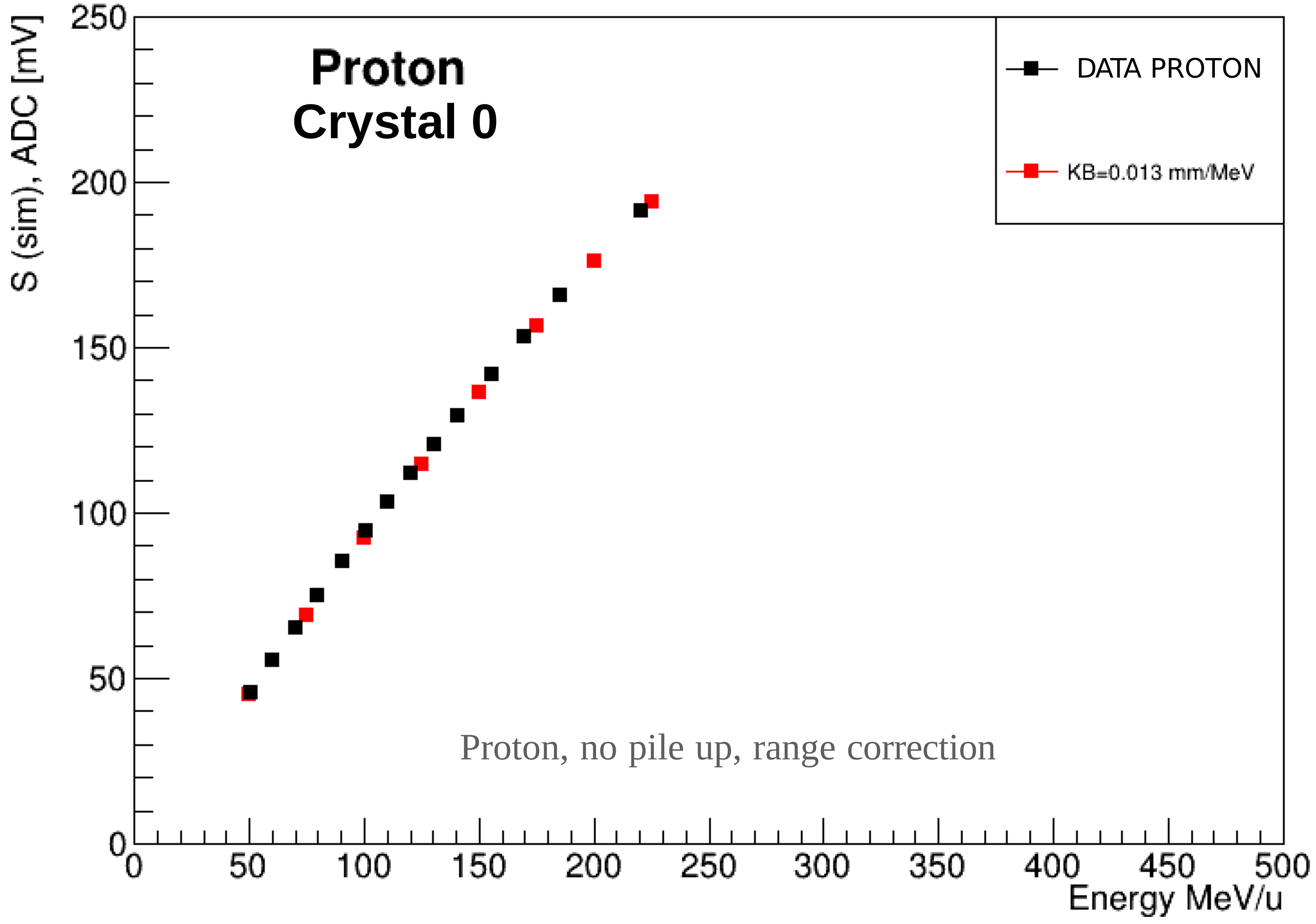


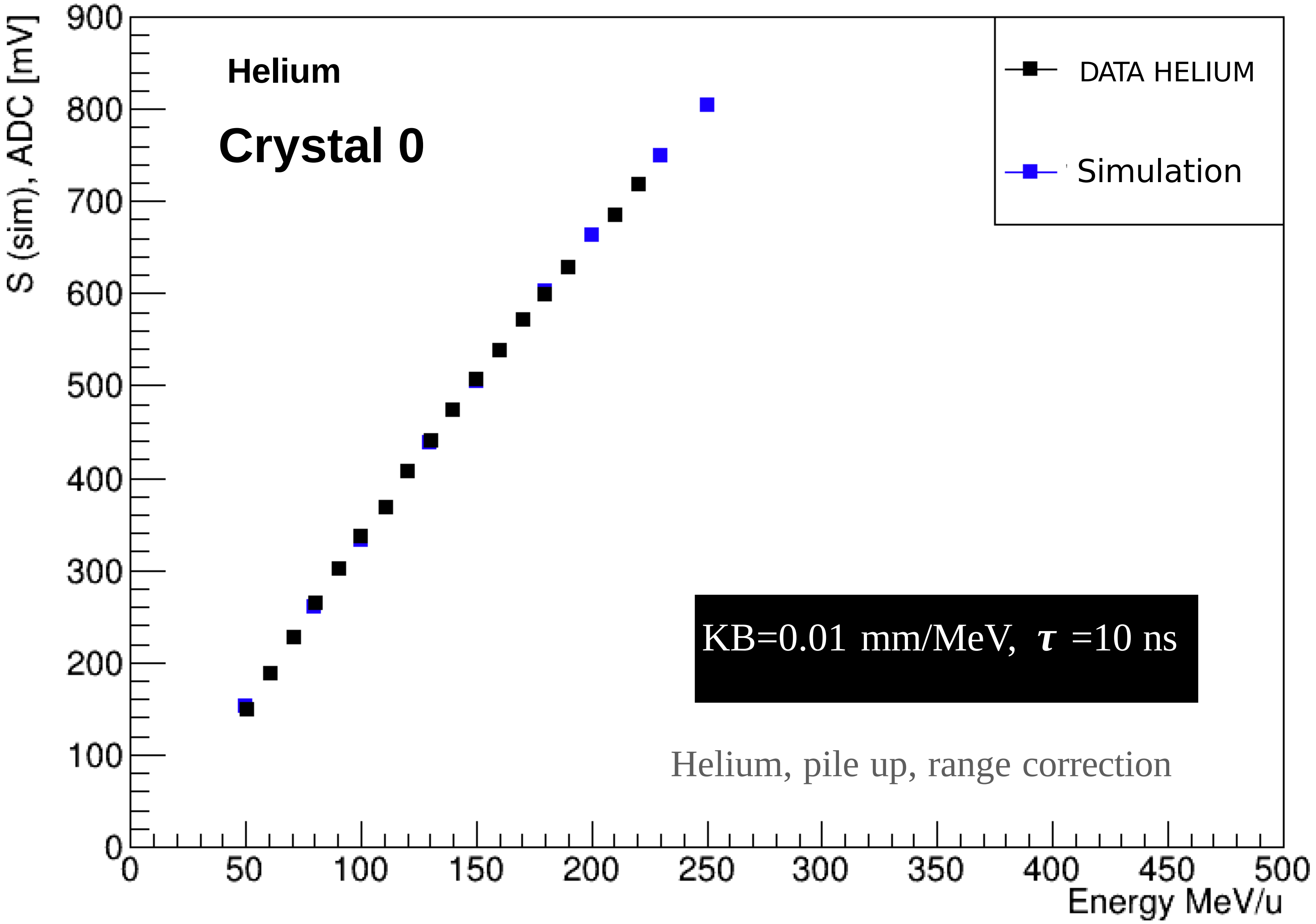
In literature https://doi.org/10.1016/j.nimb.2015.07.127
KB (C)=0.0048 mm/MeV

In literature https://doi.org/10.1016/j.nimb.2015.07.127
KB (O)=0.0029 mm/MeV

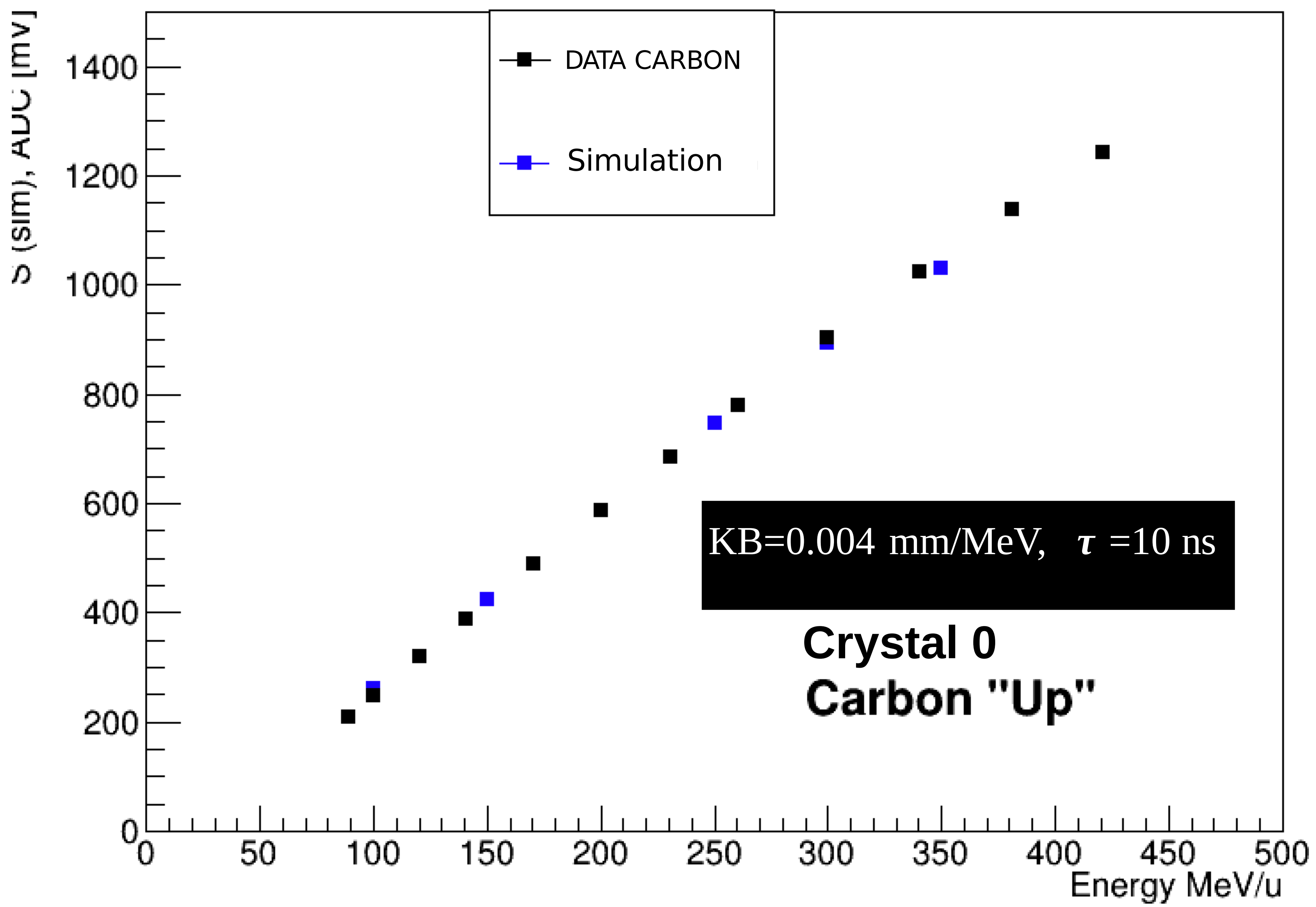
Comparison with HIT2022-crystal 0

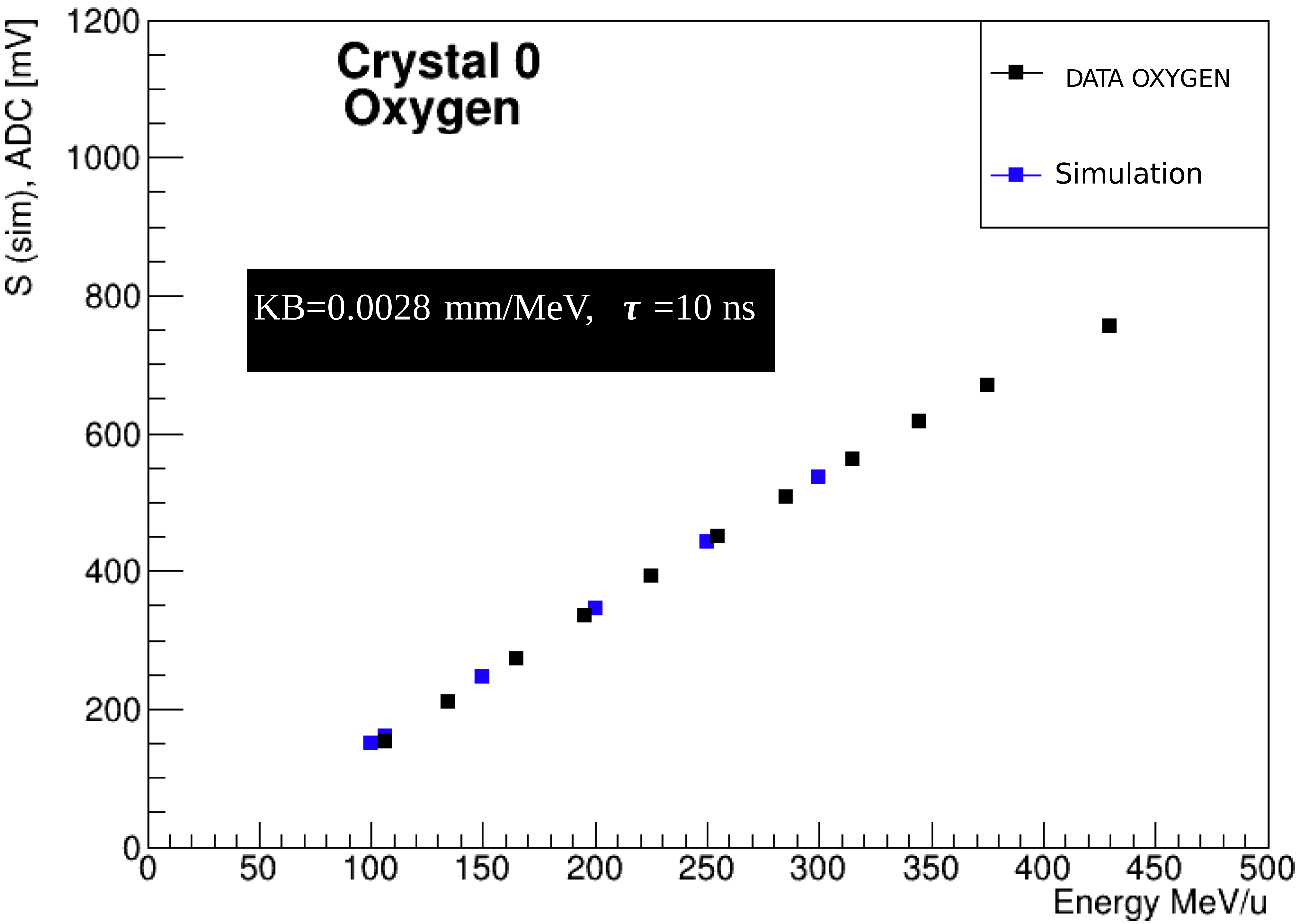
- Two crystals have been tested in Heidelberg: crystal 1 (used for KB determination)
- Cross check on the other **crystal 0**





Comparison with HIT2022-crystal 0





Summary and conclusion

- The goal of these studies is to understand the variation of the BGO response curve due to:
    - Particle range variation
    - Non-linearity related to optical pile up in the SiPM
    - Different crossing ions species

- The photon **pile-up** on SiPM may lead to a **non negligible signal reduction**, in particular for Z>1 particles
    - the SiPM **dead time** may impact the amount of signal loss, but it not seems to be much difference between 7ns and 10 ns

- Non-linearity in ADC vs Energy trends of data may be reproduced by including range correction, quenching and pile-up in the simulations

- Values of KB are of the same order of the one found in literature

Oxygen paper value

Carbon paper value