Study of the CALO BGO response

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The Calorimeter Calibration

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

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

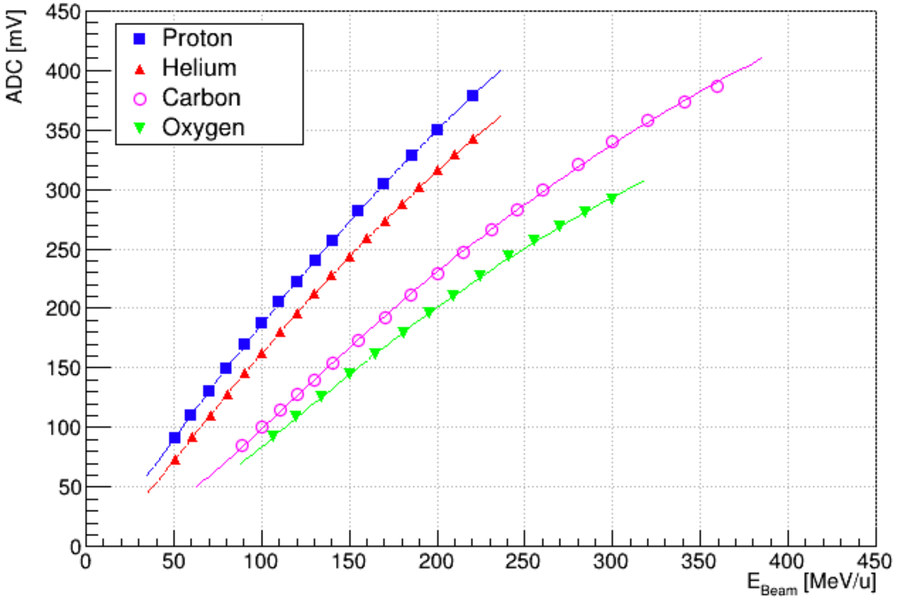
- The fit function is the Modified Birk's Function, that depends on three parameters:

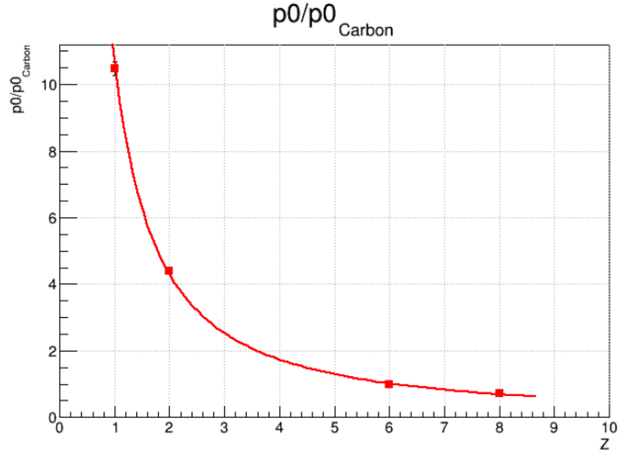
$$ADC(E) = \frac{p_0 E^2}{1 + p_1 E + p_2 E^2}$$

- 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

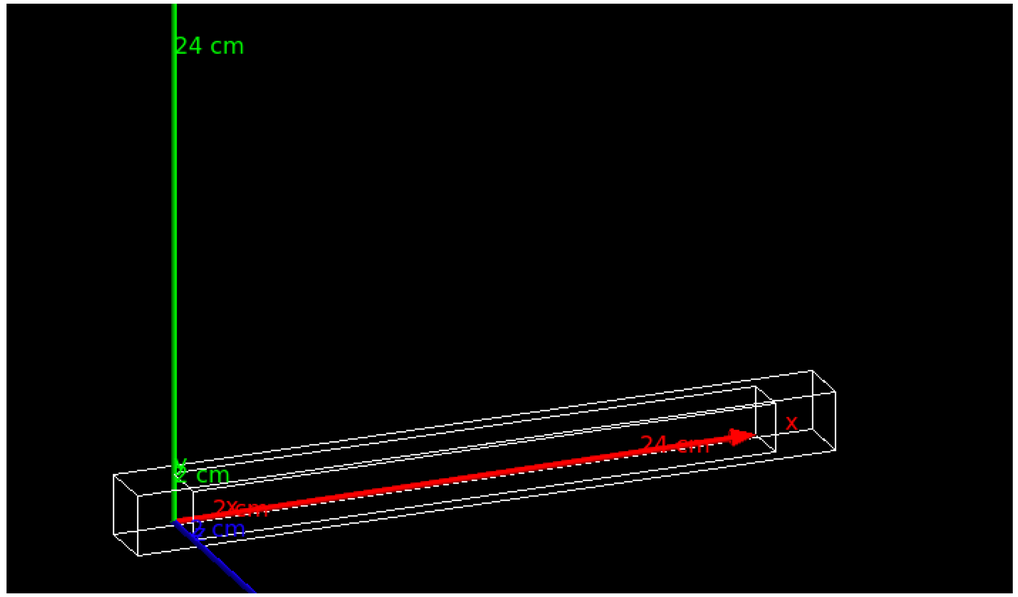




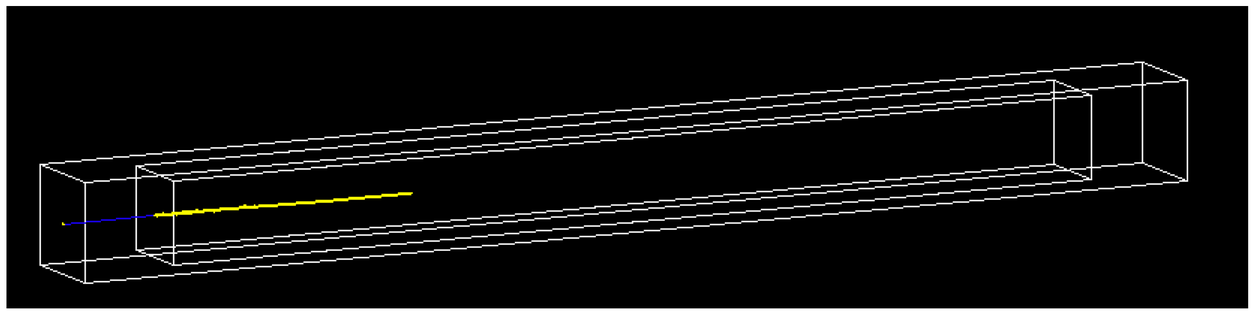
The goal of these studies is to understand these assumptions and the variation of the BGO response curve due to:

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

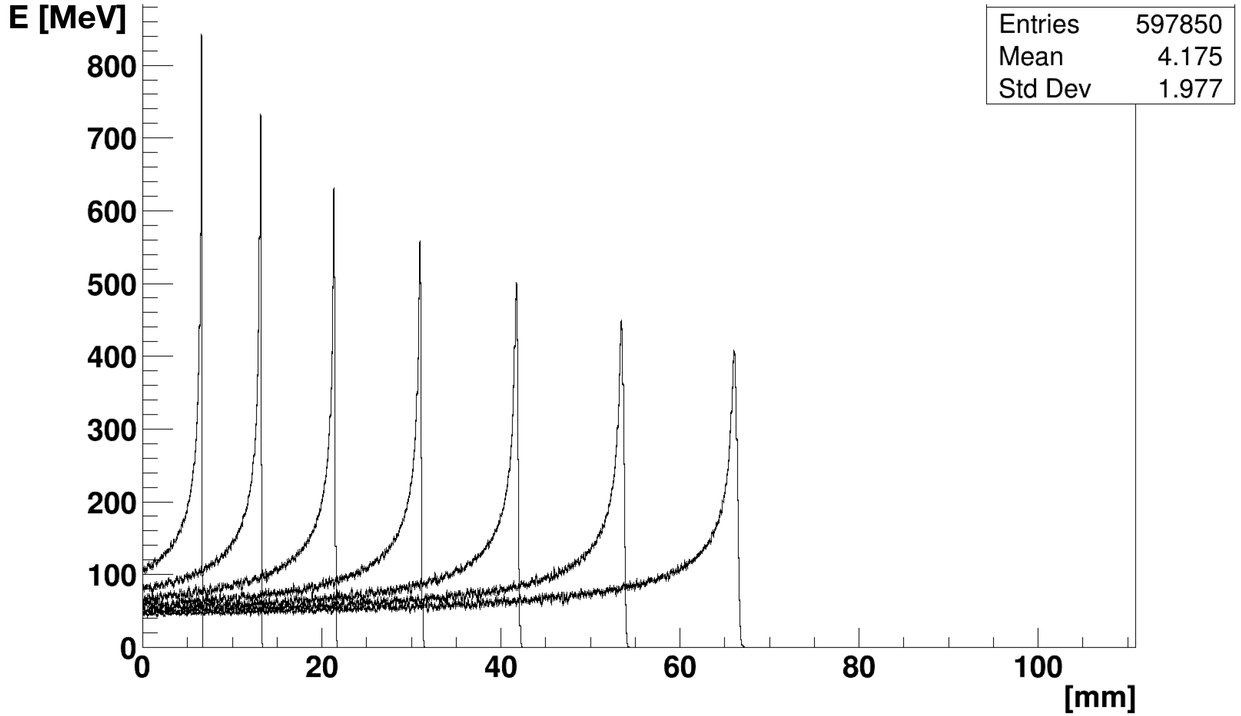
BGO crystal simulation with GEANT4



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:

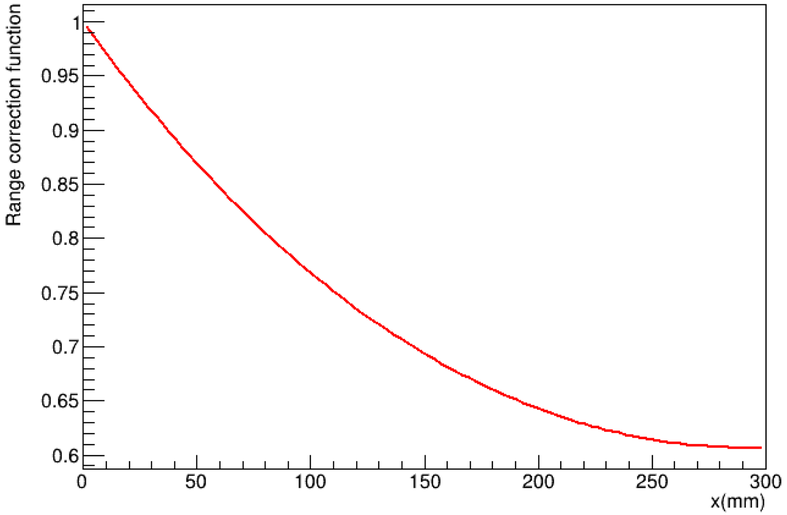
$$\frac{dS}{dx} = \frac{A\frac{dE}{dx}}{1 + KB\frac{dE}{dx}}$$

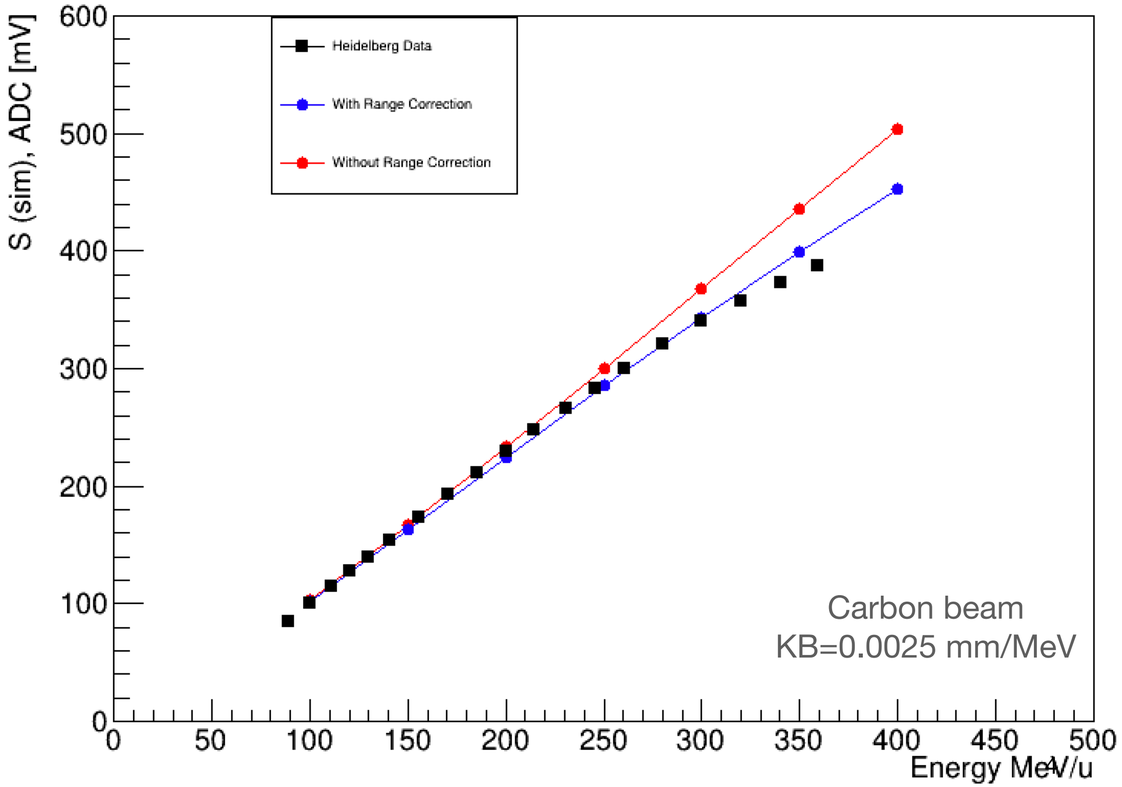
$$S = \sum_{i=1}^{N} \frac{dS}{dx} \cdot dx$$

Light yield without range correction

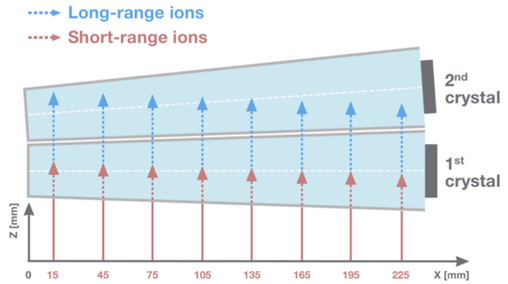
$$S_r = \sum_{i=1}^{N} \frac{dS}{dx} \cdot f(x) \cdot dx$$

Light yield with range correction





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



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 pile-up

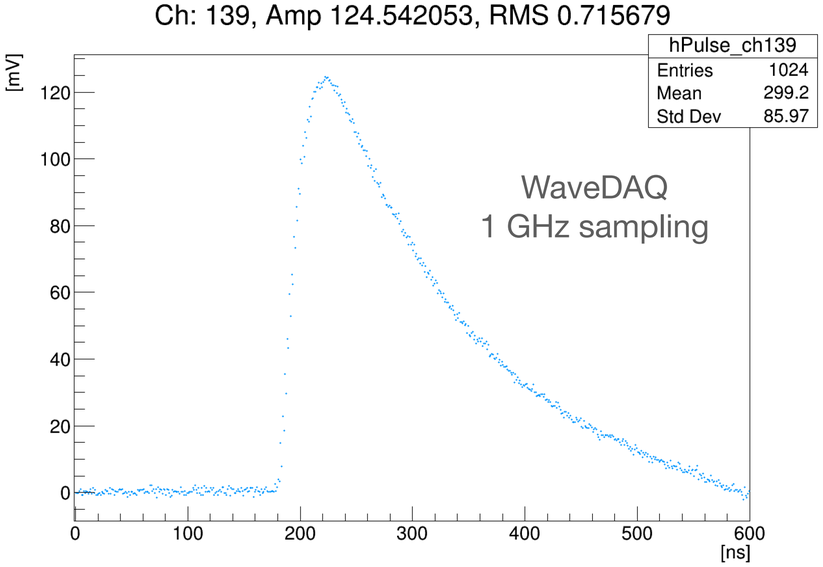
Basic idea: each pixel in the SiPM has a recovery time τ-> Signal loss may be due to photon Pile-Up

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

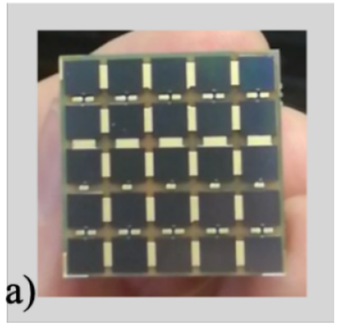
$$N^{peak}_{ph,scint} = LY \cdot E_{particle}(MeV)\frac{A_{tot,SiPM}}{A_{Crystal}} \cdot PDE \cdot \frac{WF_{peak}}{WF_{integral}}$$ Number of photons at peak

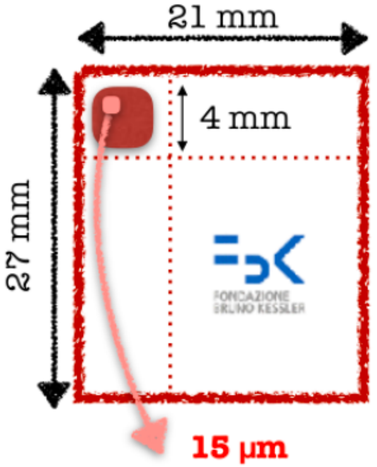


$$D_{ph} = \frac{N_{ph}}{cell} = N^{peak}_{ph,scint} \cdot \frac{A_{microcell}}{A_{tot,SiPM}}$$

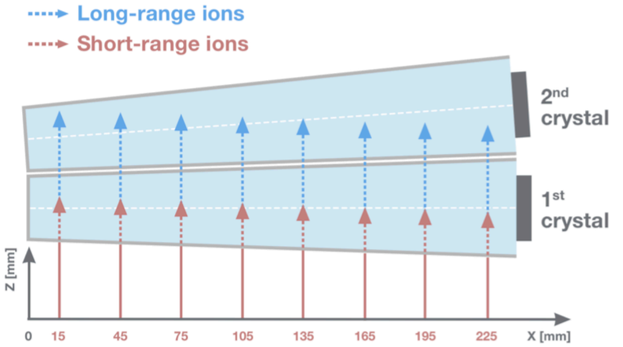
Photon density per cell

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





RGB-HD15



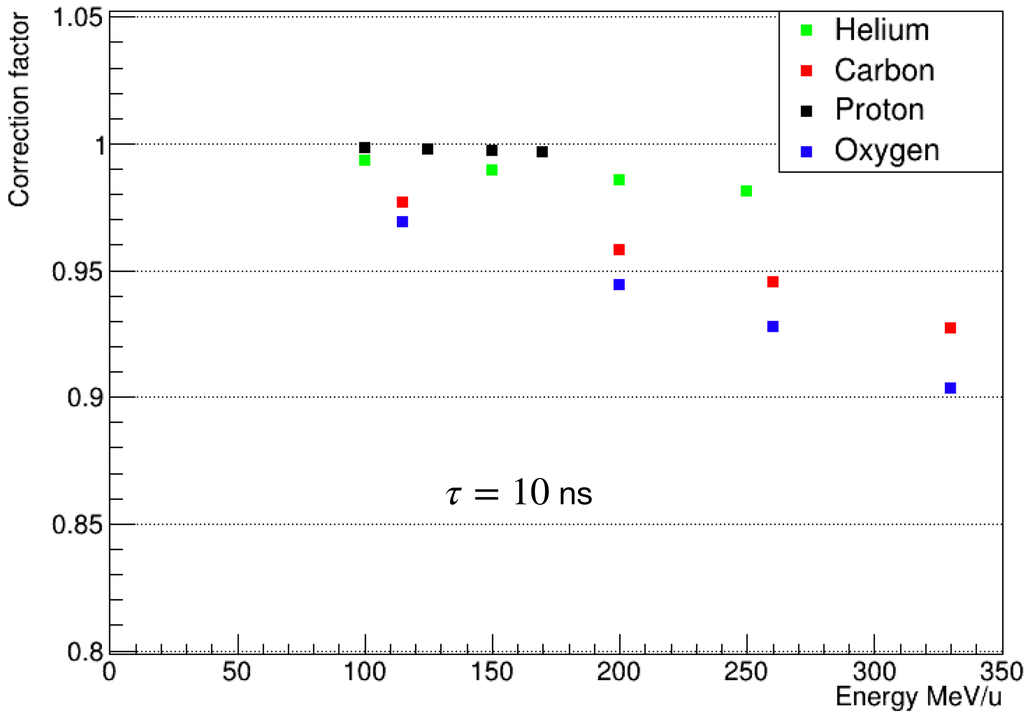
Pile-Up calculation

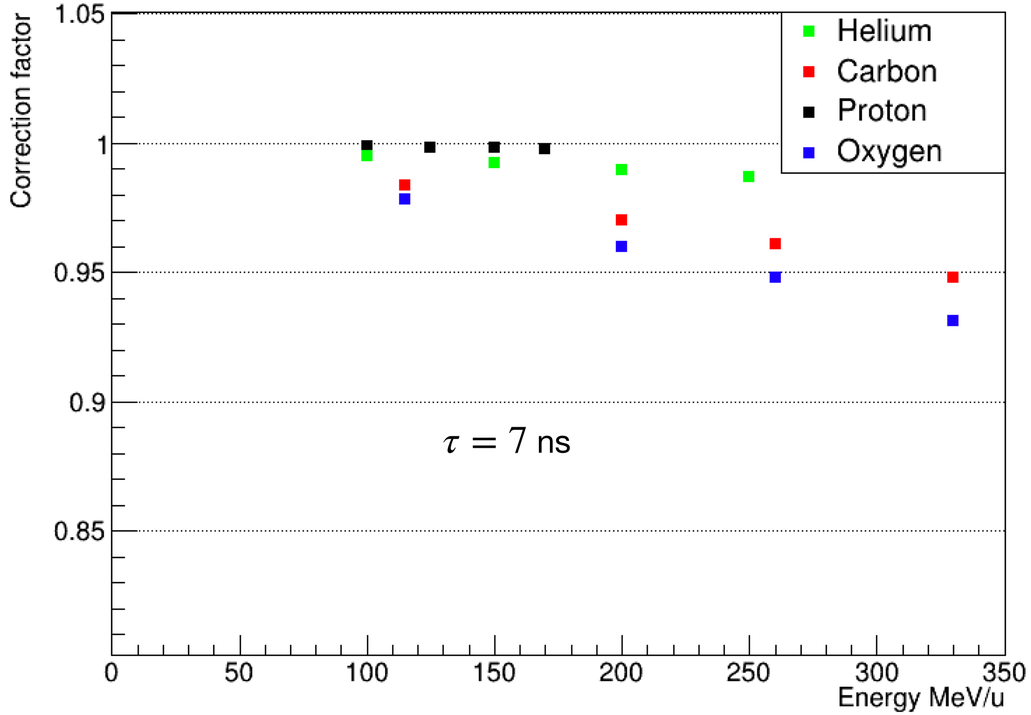
$$p(D_{ph}, k) = \frac{D_{ph}^{k}}{k!} e^{-D_{ph}}$$

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

Correction factor to account for signal loss:

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

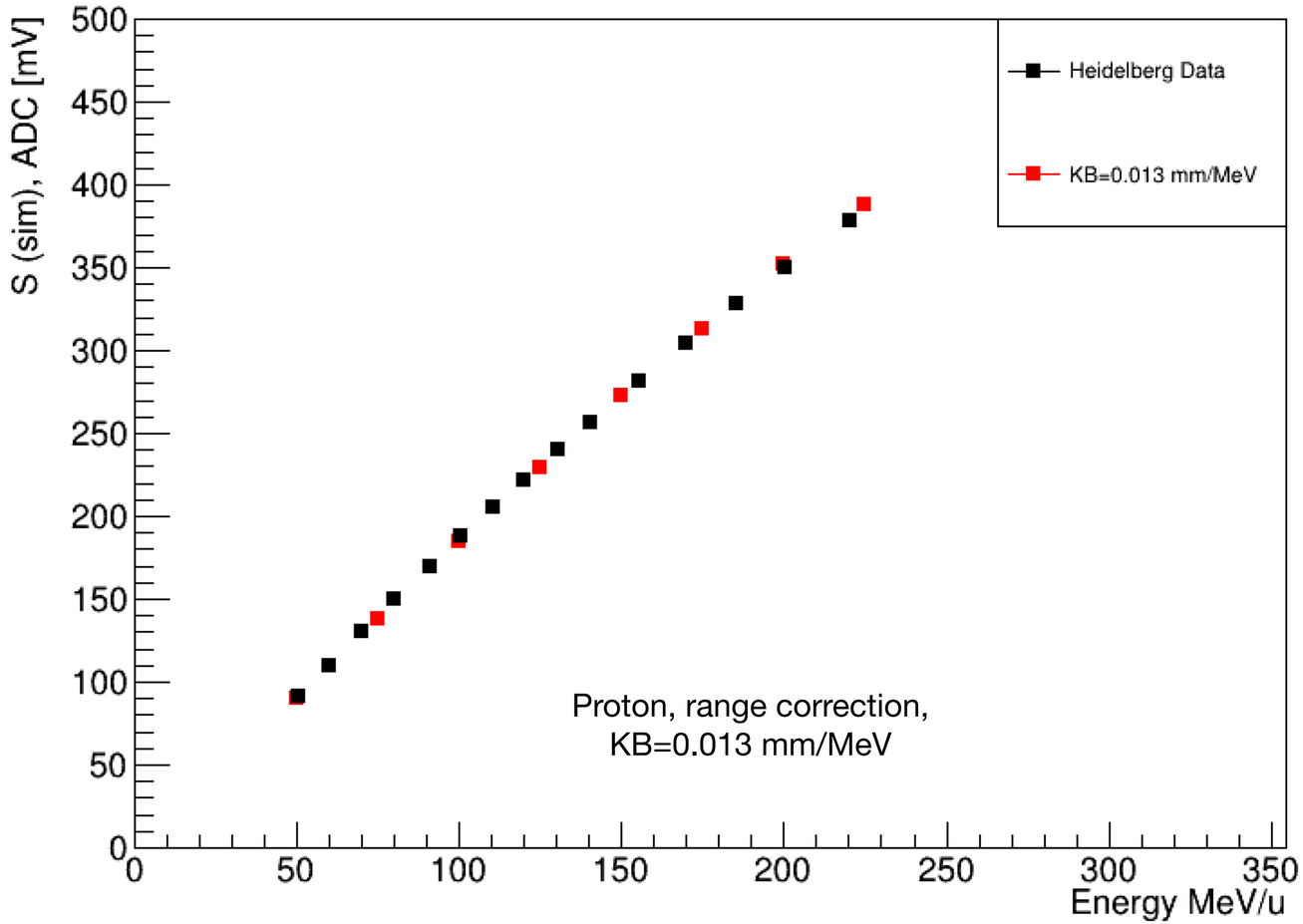




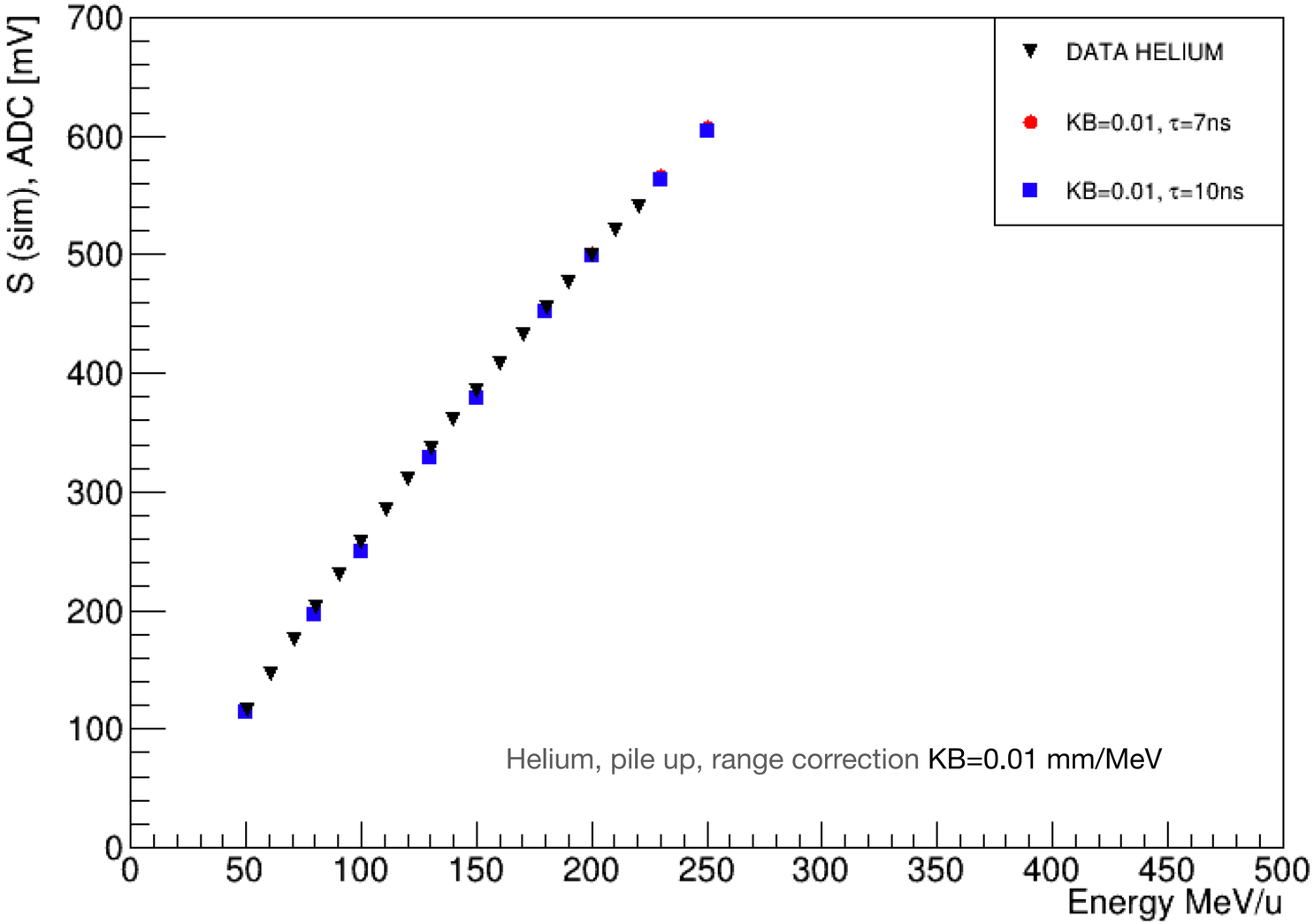
Calculation of best KB to match data

Best KB for protons determined by minimizing the

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

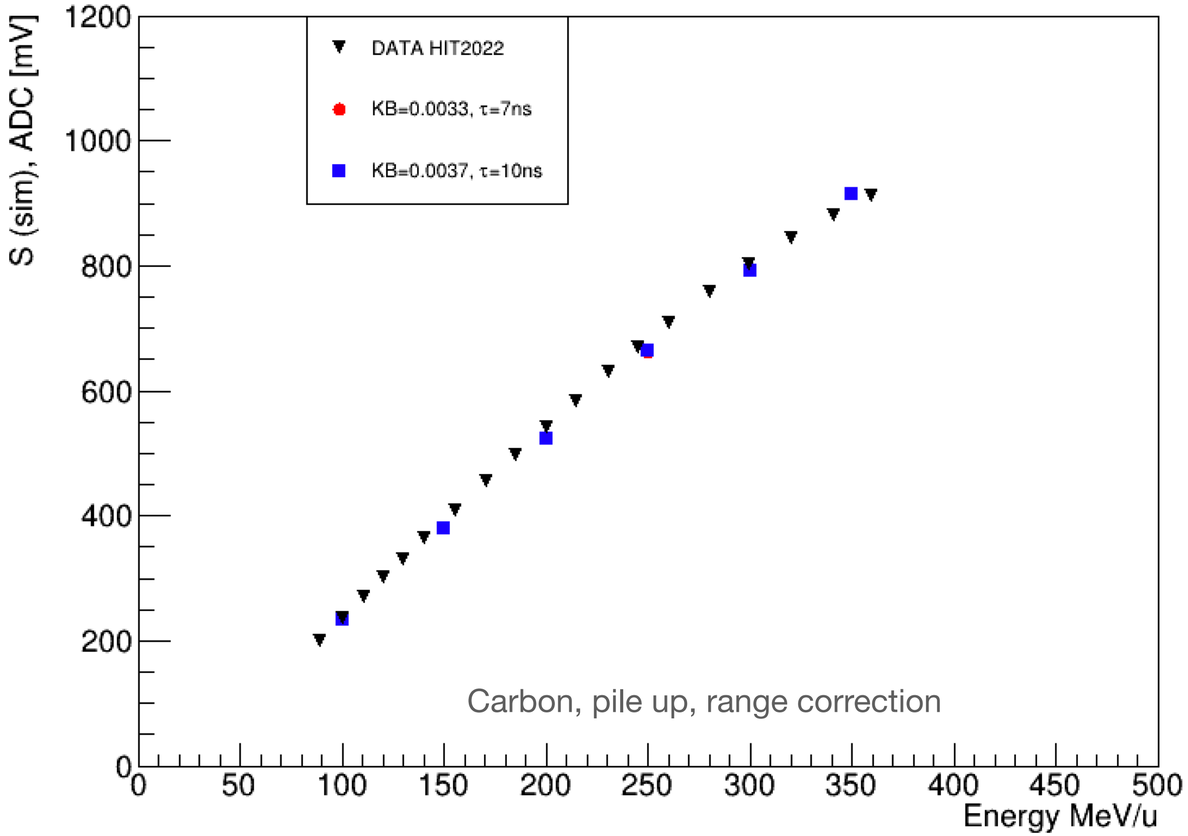


Best match Helium

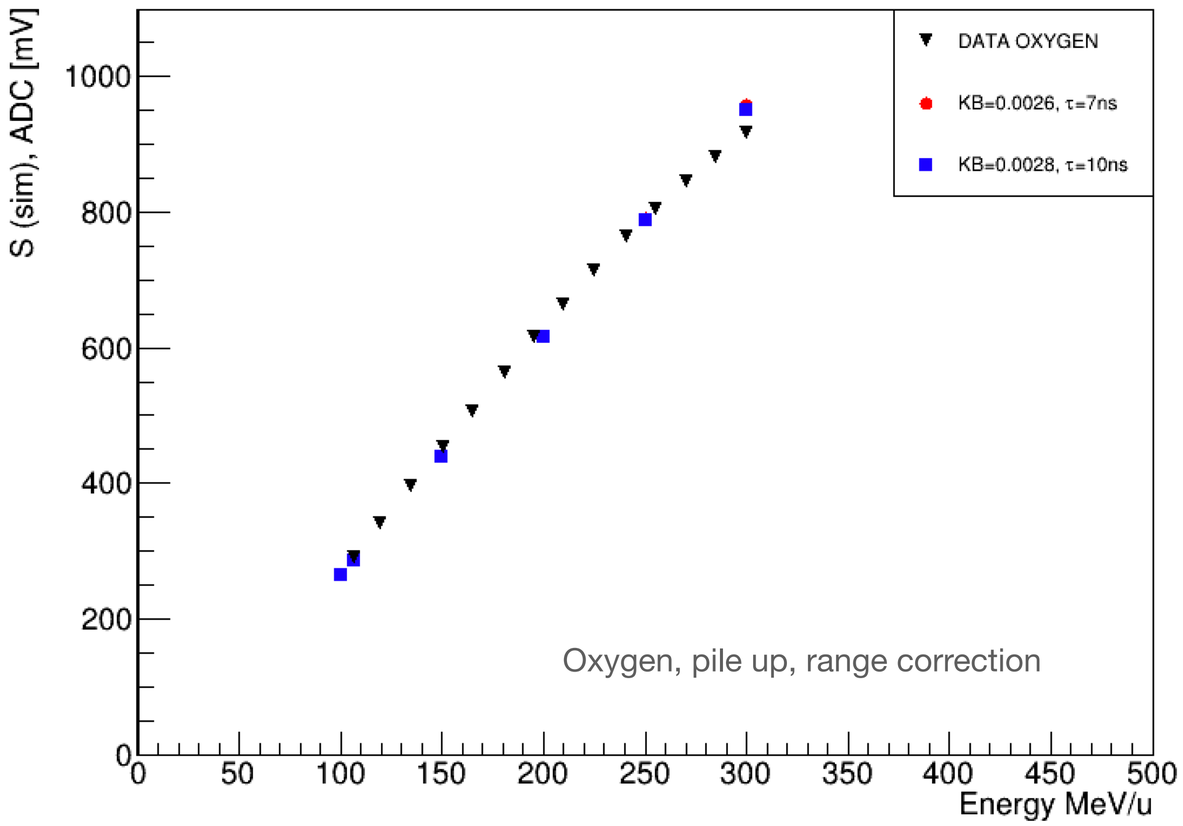


In literature https://doi.org/10.1016/j.nimb.2015.07.127, KB(He)=0.01 mm/MeV

Best match Carbon



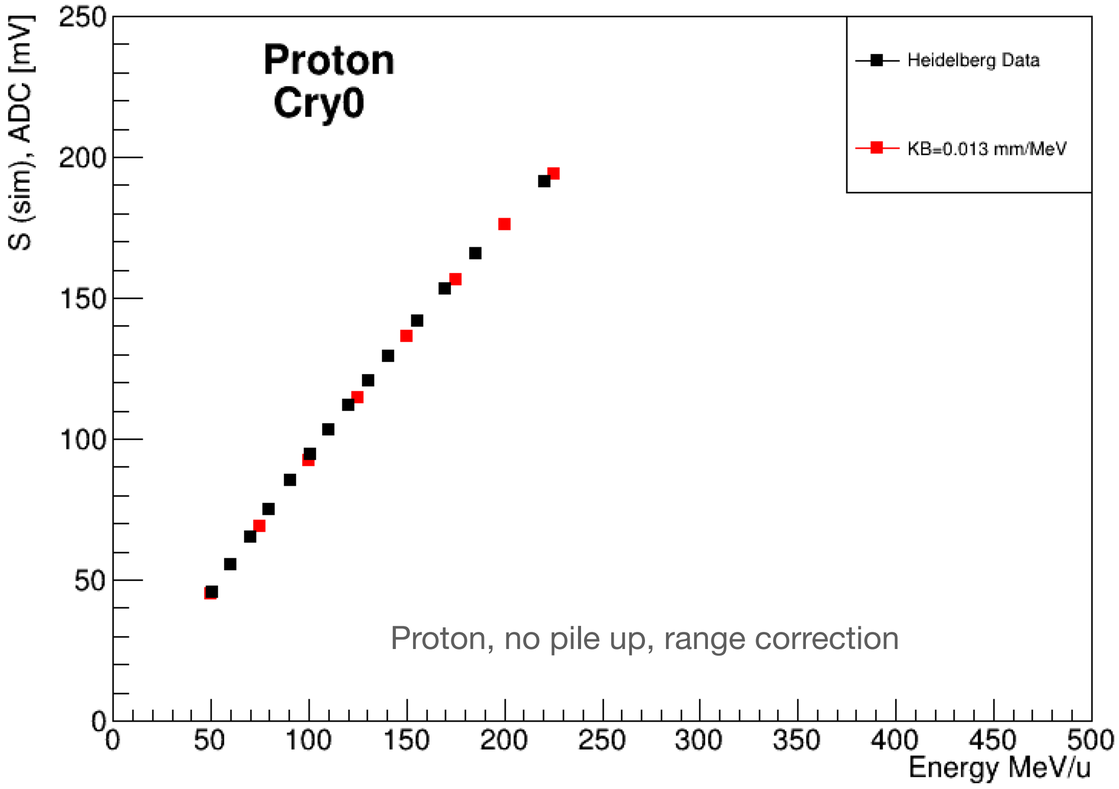
In literature https://doi.org/10.1016/j.nimb.2015.07.127
KB (C)=0.0048 mm/MeV

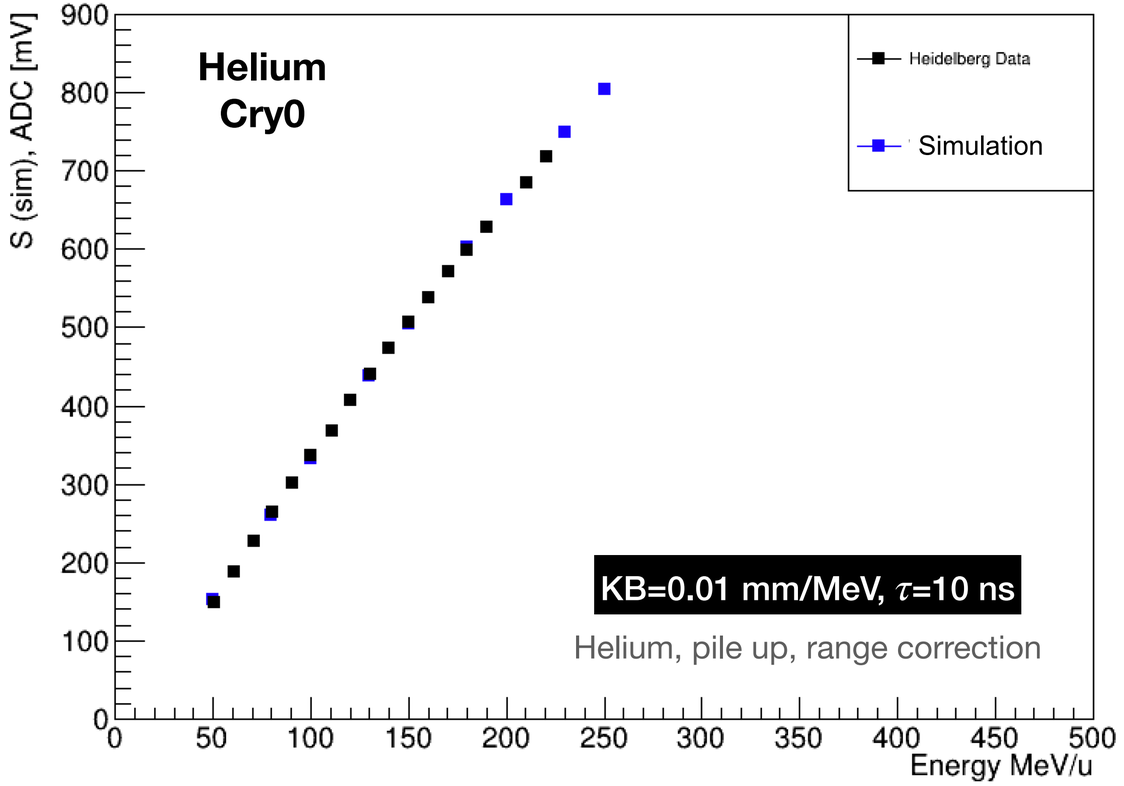


In literature https://doi.org/10.1016/j.nimb.2015.07.127
KB (O)=0.0029 mm/MeV

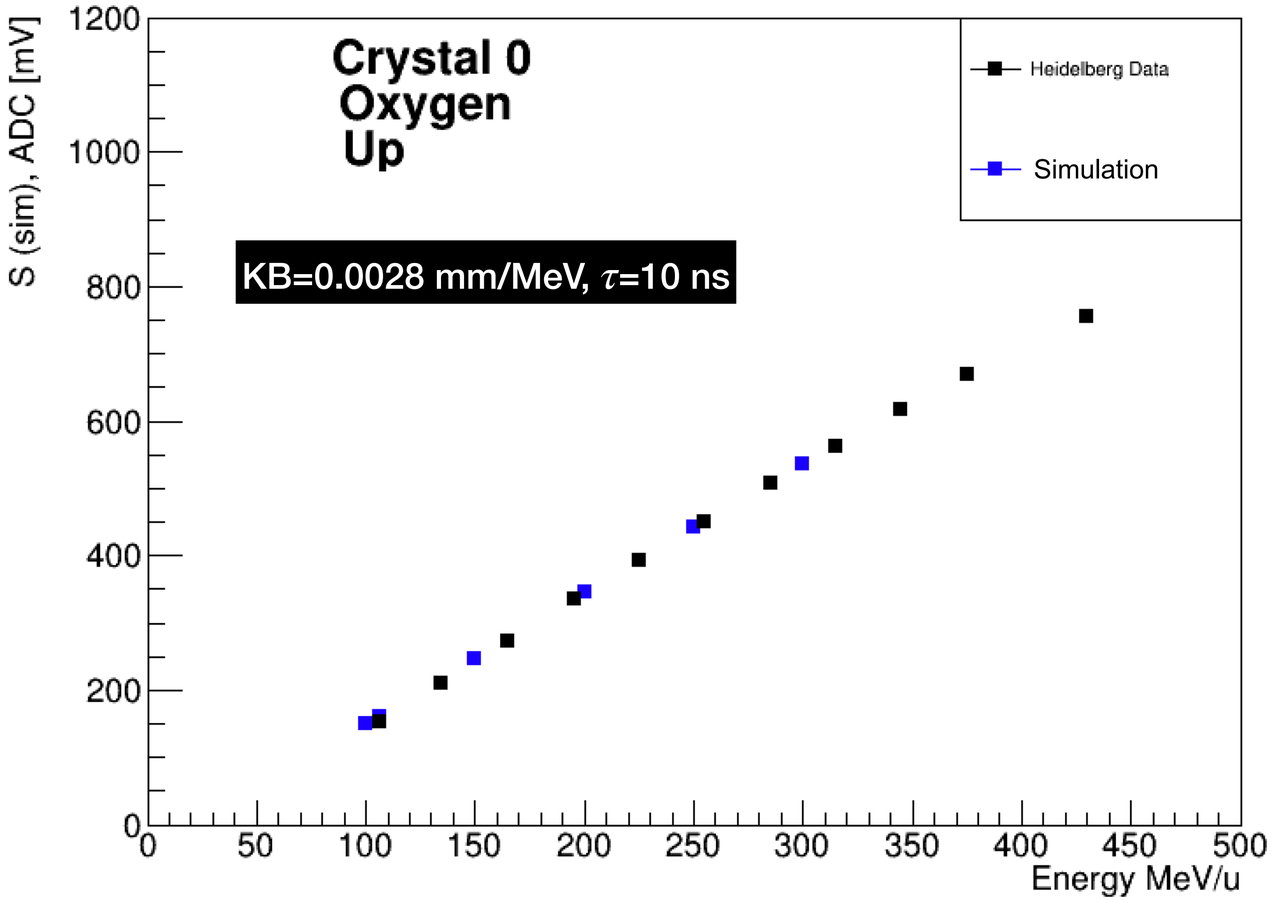
Comparison with crystal 0

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





Comparison with crystal 0 - Oxygen

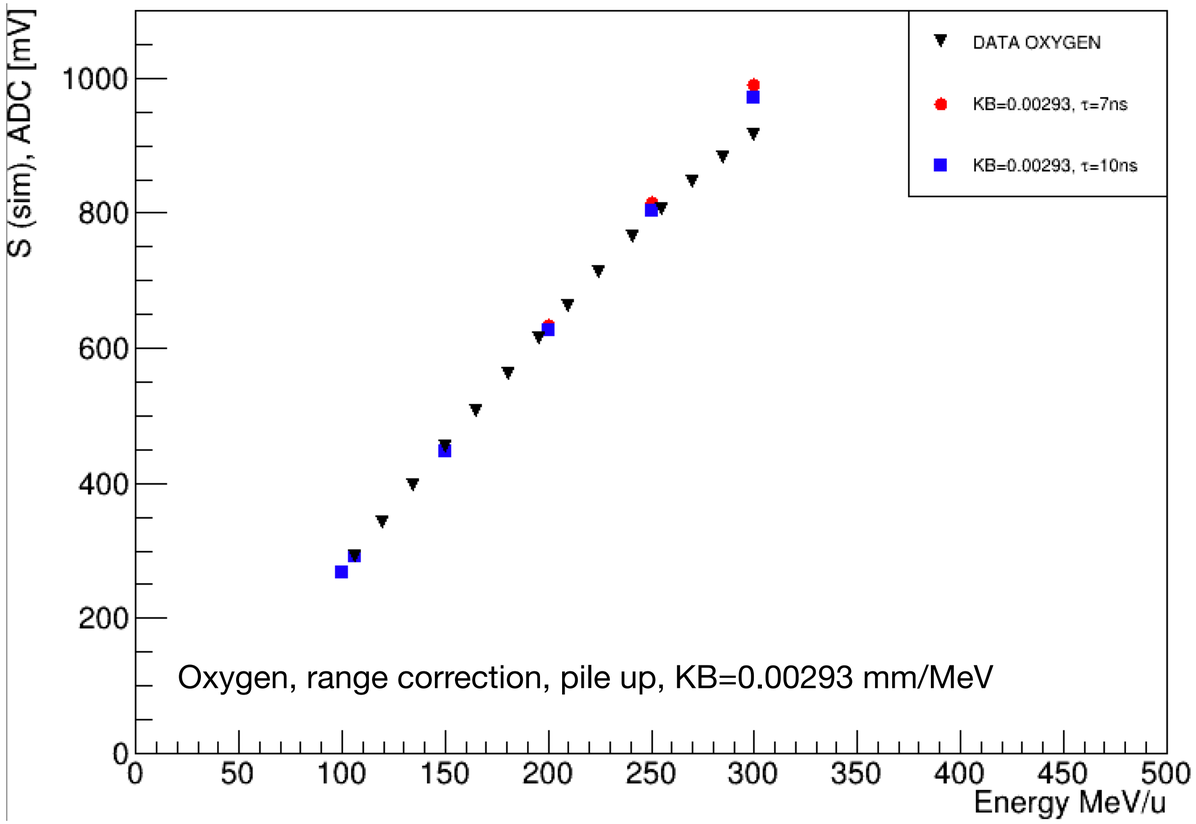


Conclusions and next steps

- The SiPM recovery time impacts the light output, but it not seems to be much difference between 7ns and 10 ns
- Values of KB are of the same order of the one found in literature
- By adding the particle range correction, non linearity due to pile up and the quenching factor (KB) to the simulation, data are reproduced

- Complete the comparison with crystal 0 for the Carbon

Oxygen paper value



Carbon paper value