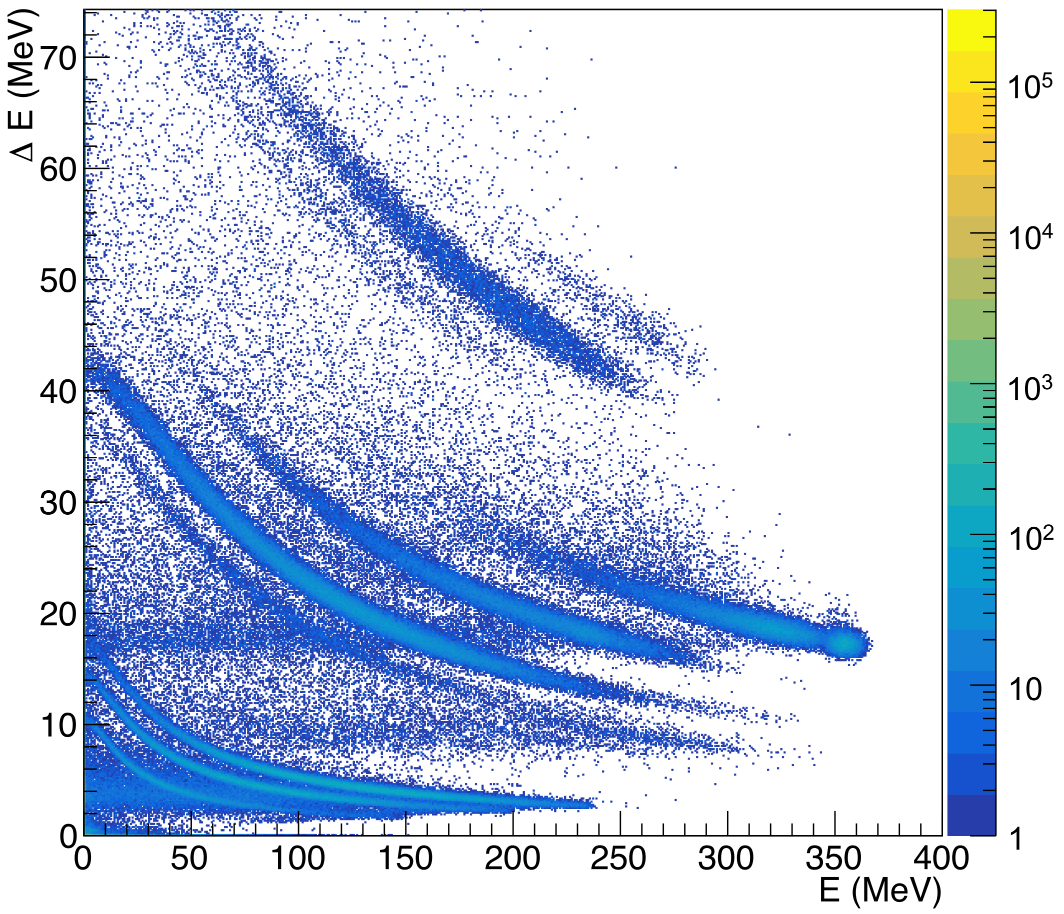
Evaluation of the possible advantages and comparison of radioactive ion beams (RIB) for hadrontherapy by Monte Carlo simulation

Presented by Laurine SCHNELZAUER & Samuel VALENTIN
under the supervision of M.VANSTALLE & E.TRAYKOV

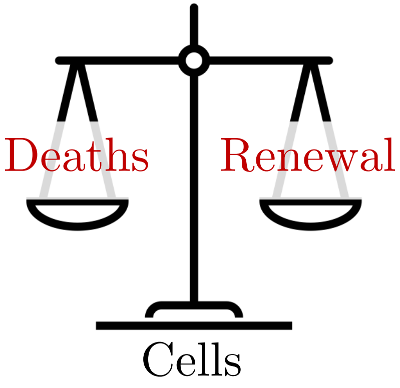
University of Strasbourg
2021-2022

Table of contents



Introduction

Cancer:

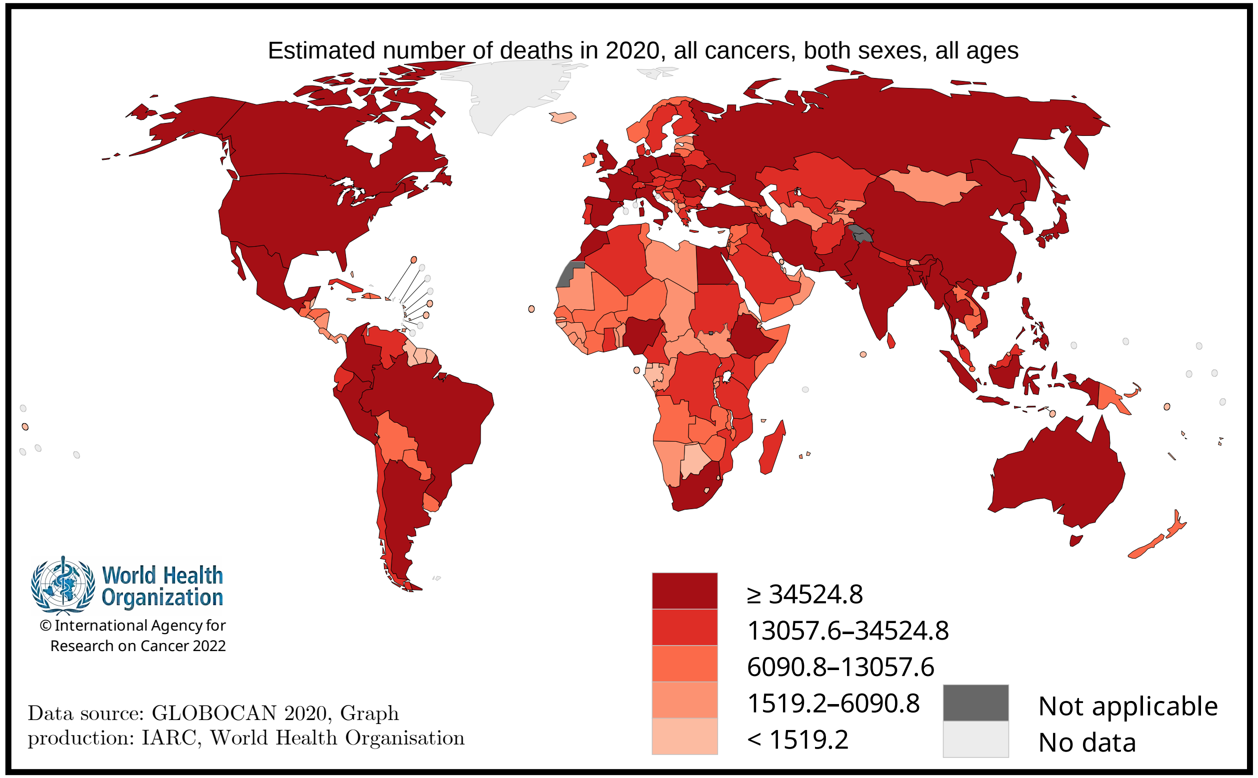


if → broken

Invasion of the surrounding

↓

Potential death of the patient



Treatments:

- Surgery, old technic, localised tumour
- Chemotherapy, stops cell division
- Radiotherapy, X-Rays and possibly RIB

} Usually combined

Radiotherapy: type of therapy using X-rays to treat cancer.

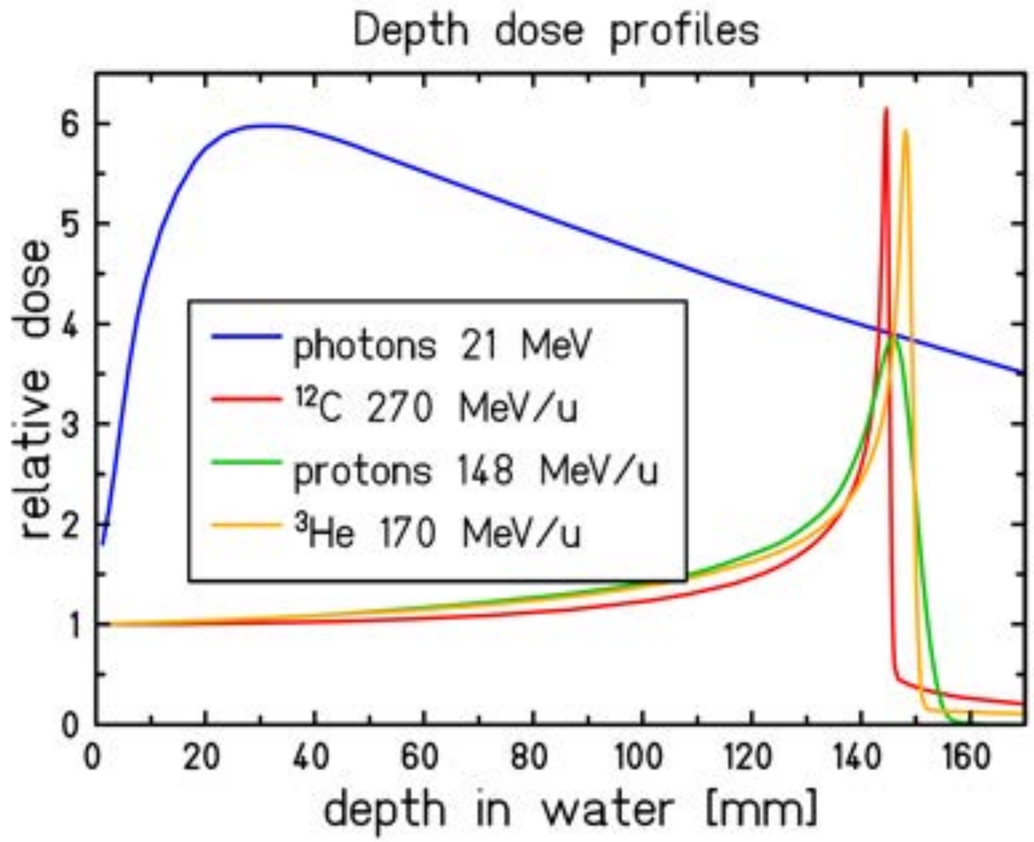
- More widely used (cheaper than hadrontherapy)
- Irradiation of healthy tissues

Hadrontherapy: type of therapy using energetic protons or heavy ions to treat cancer.

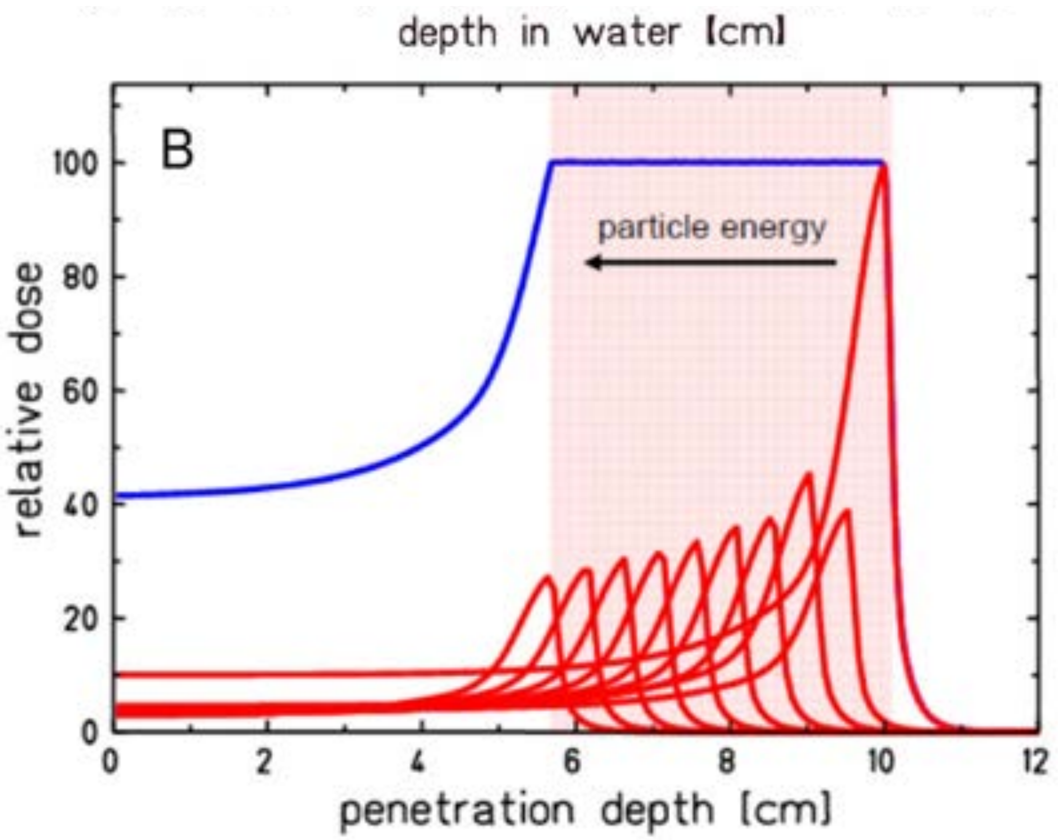
- Precise dose deposition
- Higher dose at the end of the path (Bragg Peak)
- Lower irradiation of healthy tissues

Proton therapy and carbon ion therapy - Heidelberg University Hospital

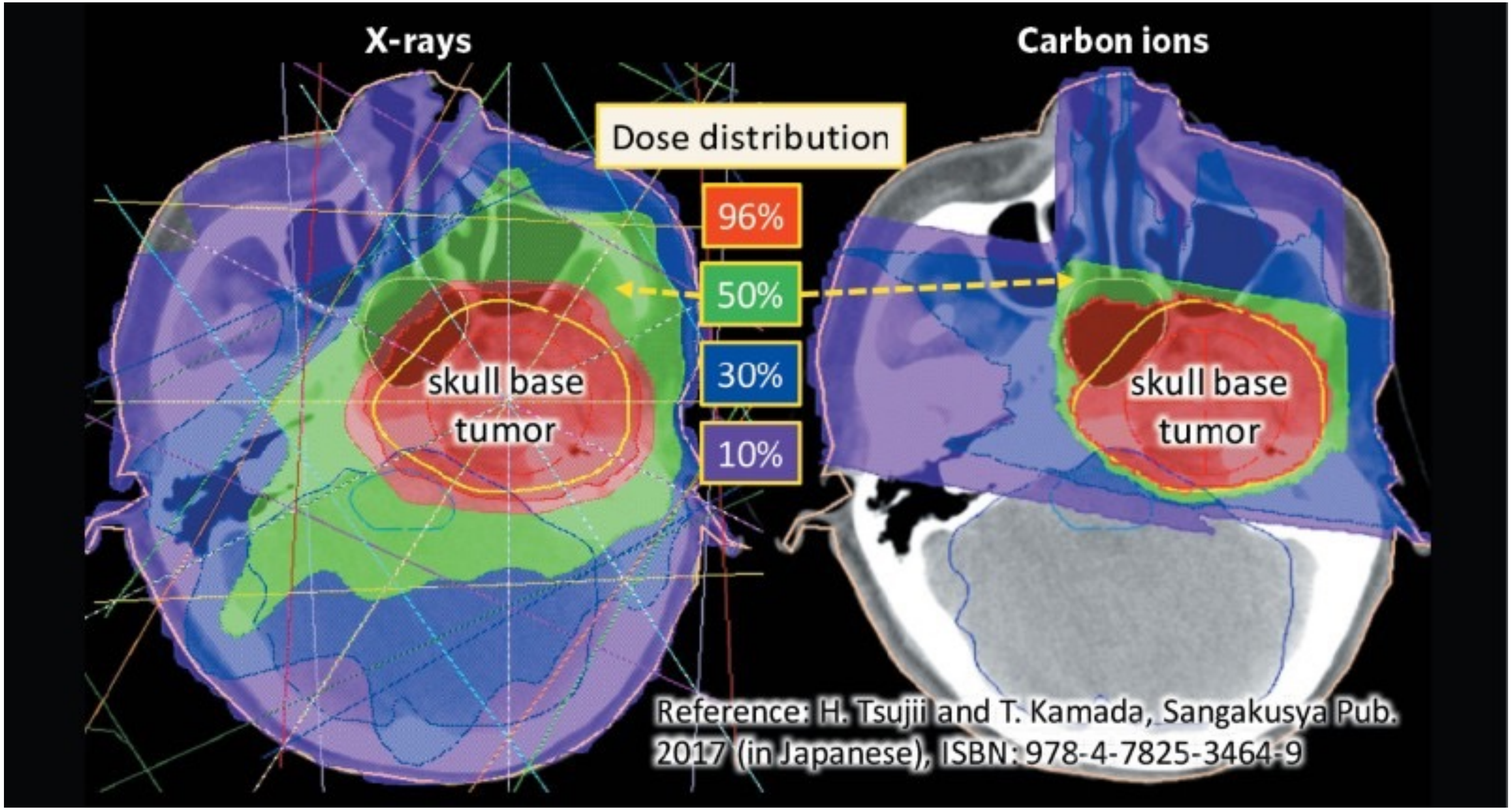
Spread-Out Bragg Peak (SOBP)



M. Krämer and al., Helium ions for radiotherapy? Physical and biological verifications of a novel treatment modality : Medical Physics, 43(4) :1995–2004, Mar. 2016. ISSN 00942405



M. Durante 2016, Nuclear physics in particle therapy: a review, Research Gate


X-rays
Carbon ions
Dose distribution
96%
50%
30%
10%
skull base tumor
skull base tumor
Reference: H. Tsujii and T. Kamada, Sangakusya Pub. 2017 (in Japanese), ISBN: 978-4-7825-3464-9

- Find lighter ions with dose deposition close to ^{12}C and lower the costs

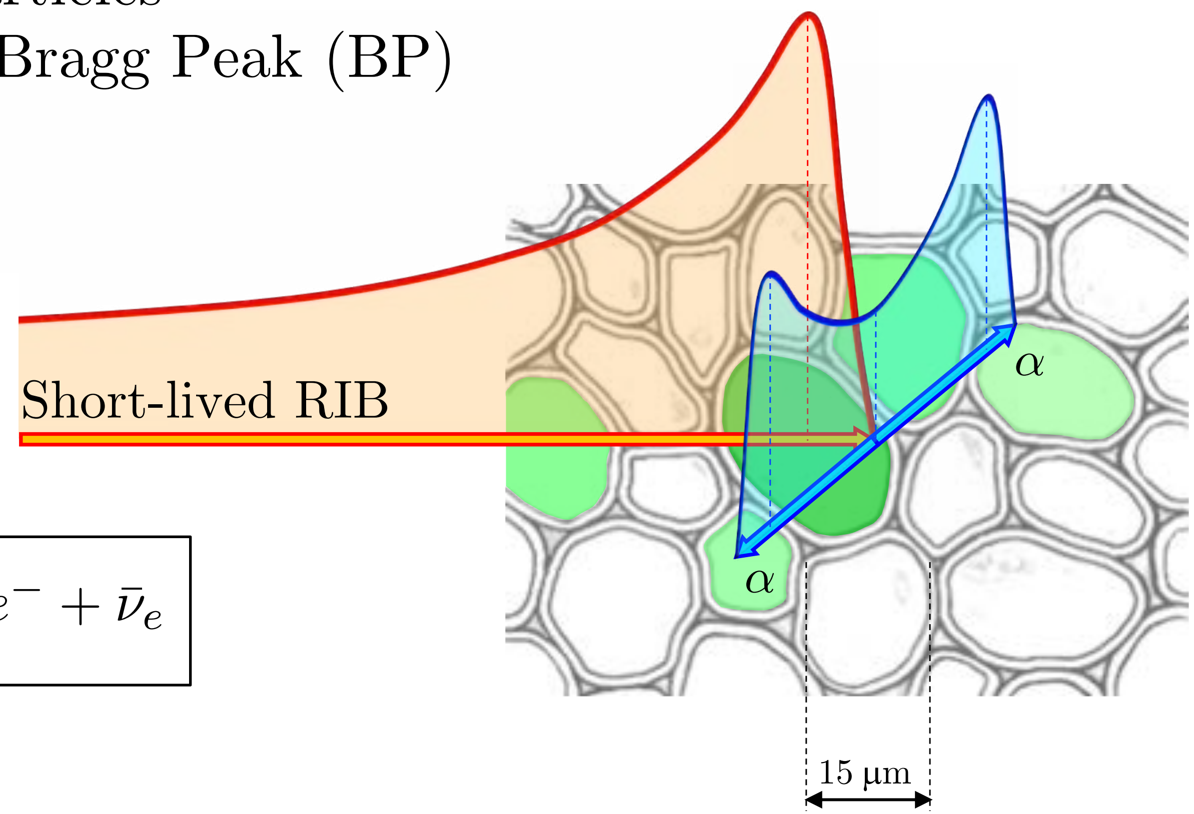
- Renewed interest for RIB:
  1. Dose monitoring with secondary particles
  2. Therapeutic, dose enhancement in Bragg Peak (BP)

$\longrightarrow$ Decay equations for ^{8}He and ^{8}Li:

$$^{8}_{2}\mathrm{He}_{6} \rightarrow {}^{8}_{3}\mathrm{Li}_{5} + \mathrm{e}^{-} + \bar{\nu}_e$$

$$^{8}_{3}\mathrm{Li}_{5} \rightarrow {}^{8}_{4}\mathrm{Be}^{*}_{4} + \mathrm{e}^{-} + \bar{\nu}_e \rightarrow \alpha + \alpha + e^{-} + \bar{\nu}_e$$

$\searrow$ 2 α decay



E847_21 Proposal - Study of high energy ^{8}Li beam on biomolecule – E. Traykov

GANIL experiment in 2023:

- Measurement of dose distribution
- Secondary particles generated by ^{8}Li with tissue equivalent material (PMMA)

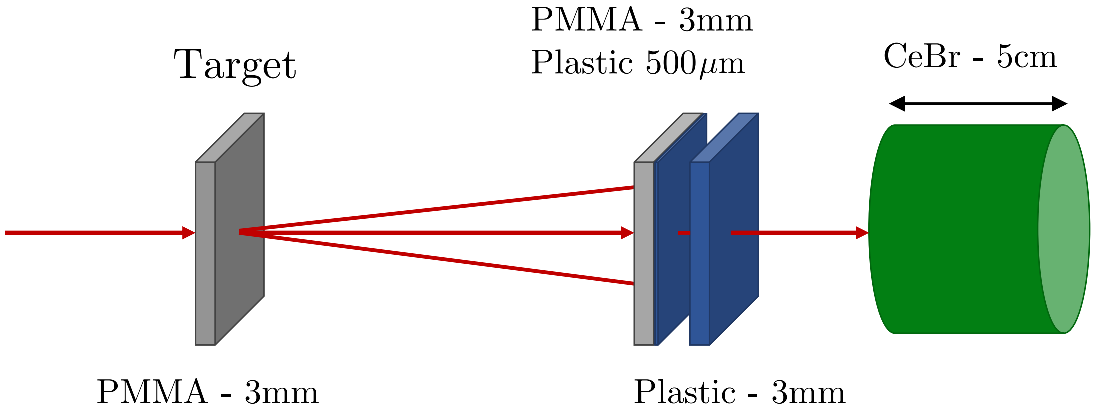
Main goals of the internship:

1. Comparison of the dose distribution for different ions
2. Determine the optimal setup for the experiment
3. Gamma distribution for dose monitoring

Material & Methods

Detectors

- $\underbrace{\Delta E_1}-\underbrace{\Delta E_2}-\underbrace{E}$ configuration
  - E → $CeBr_3$ scintillator
  - ΔE_2 → 2nd plastic scintillator or Si
  - ΔE_1 → (PMMA support + 1st plastic scintillator)?



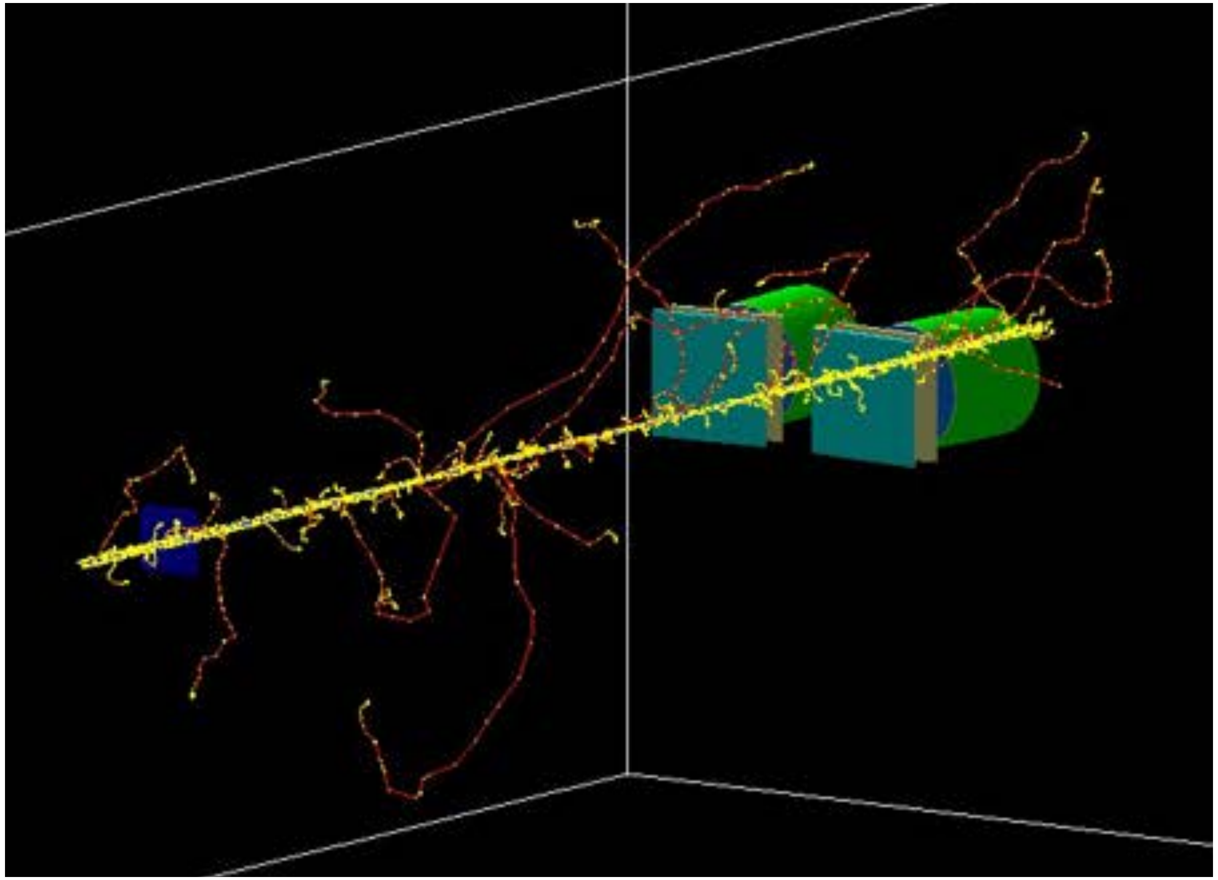
- Plot $\Delta E_2 - E \longrightarrow$ energy loss/full energy
- Plot $\Delta E_1 - \Delta E_2 \longrightarrow$ energy loss/full energy, low energy particles

} Identification of particles

Geant4

Toolkit developed by CERN to create simulations for the passage of particles through matter:

- C++
- Uses different classes
- Monte Carlo



Changing the parameters:

- Physics
- Detectors configuration

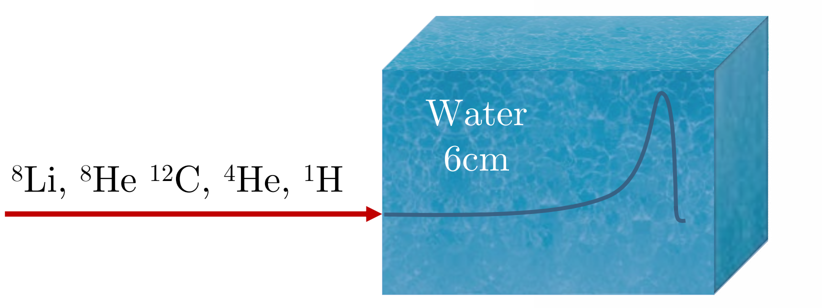
Results

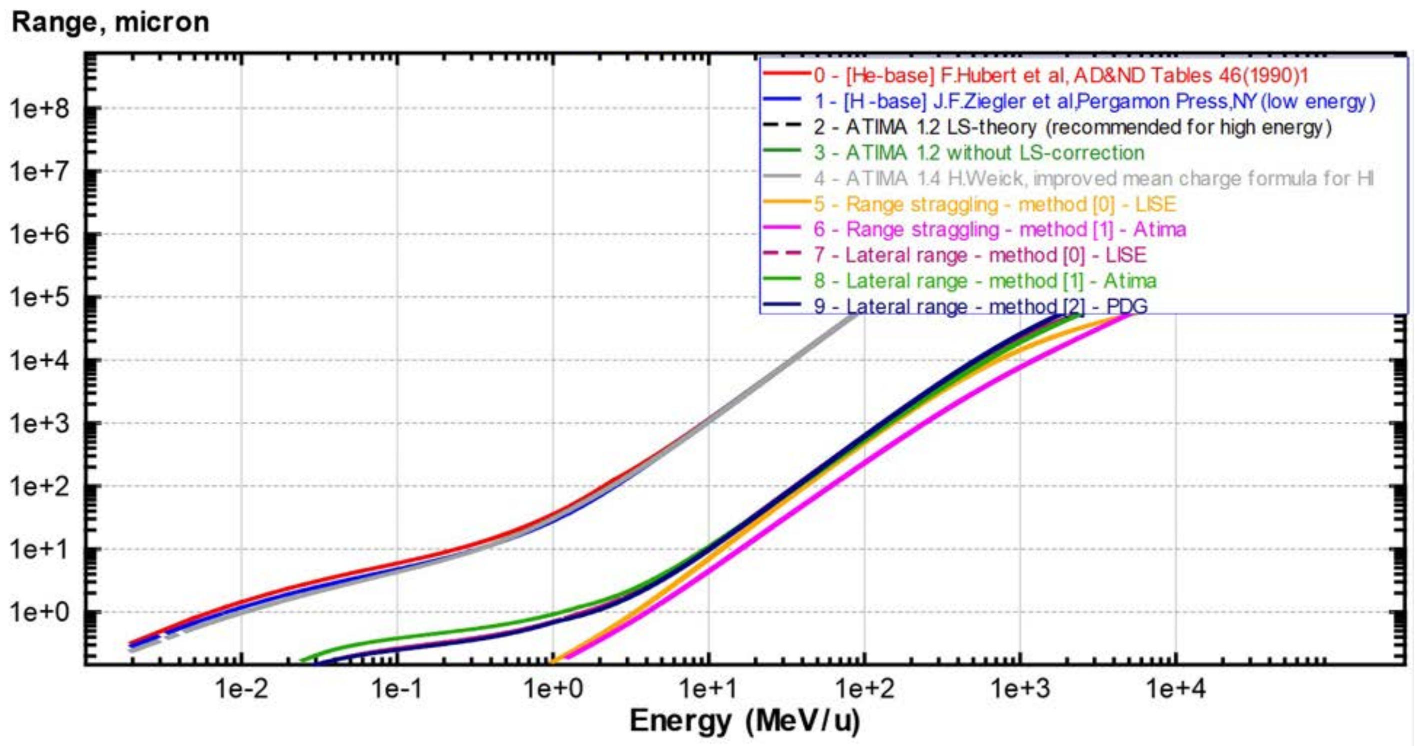
Dose distribution

Comparing the BP of different ions:

- Not much statistics
- Good energy for same range:

- Lise++ for first approximation
- Simulate to increase precision





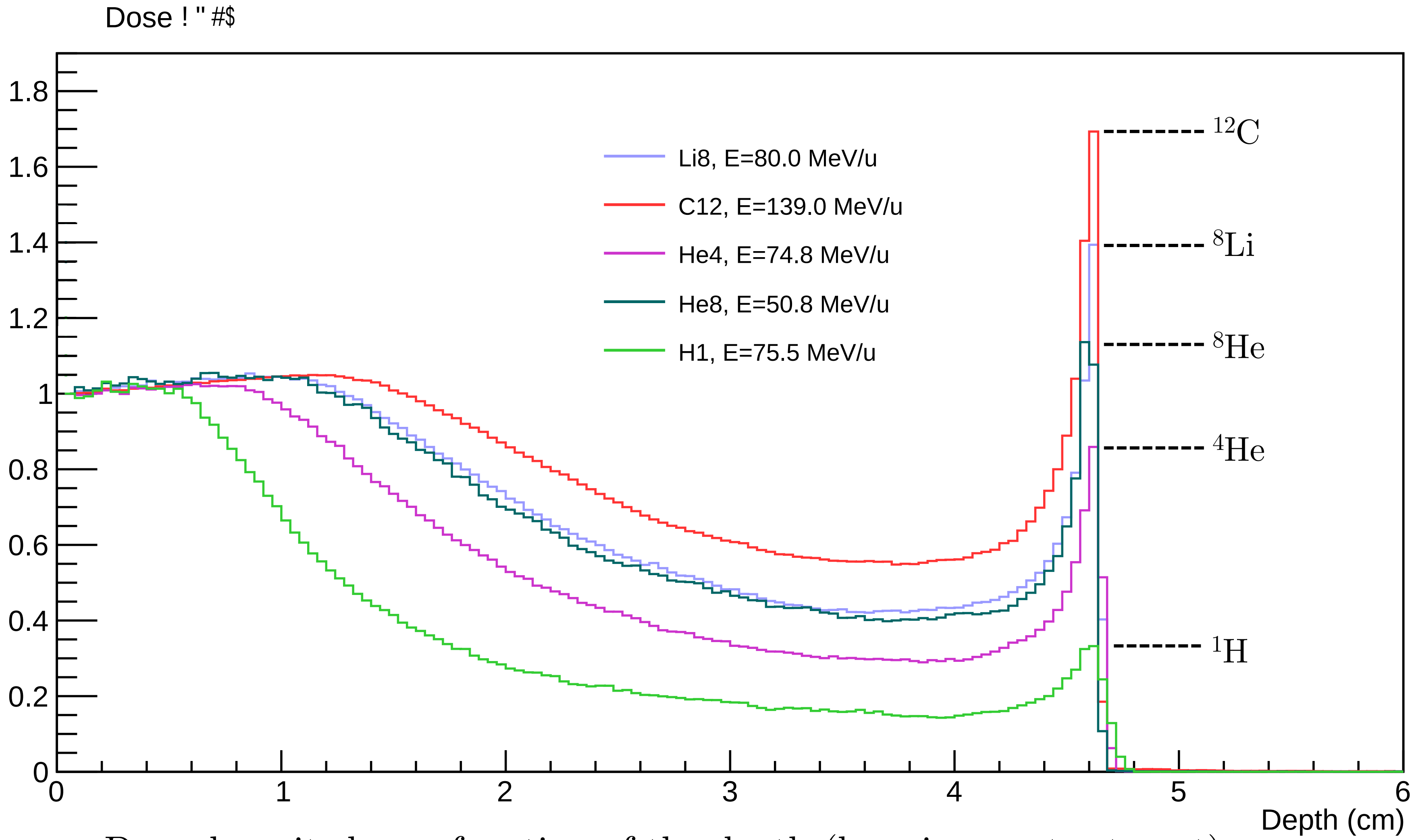
Graph of the range of a ^{8}Li beam in water as a function of its energy per nucleus

Comparison of the BP for different ions:

Ion	Dose in BP (Gy)
^{12}C	1.700
^{8}Li	1.375
^{8}He	1.100
^{4}He	0.850
^{1}H	0.500

- ^{8}Li close to ^{12}C thanks to 2α decay

$\longrightarrow$ Decay products matter



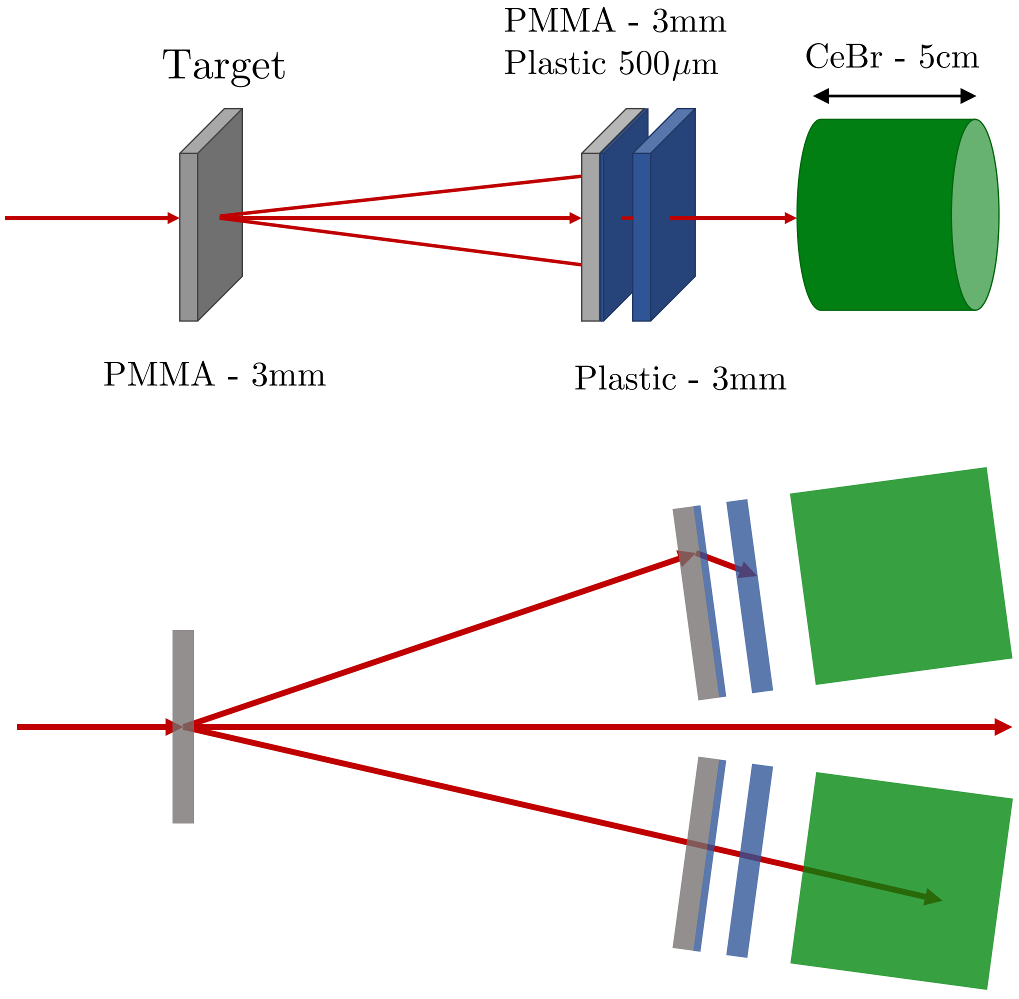
Dose deposited as a function of the depth (here in a water target)

Setup optimisation

First configuration at 0°

Problem: most detected particles come from the beam

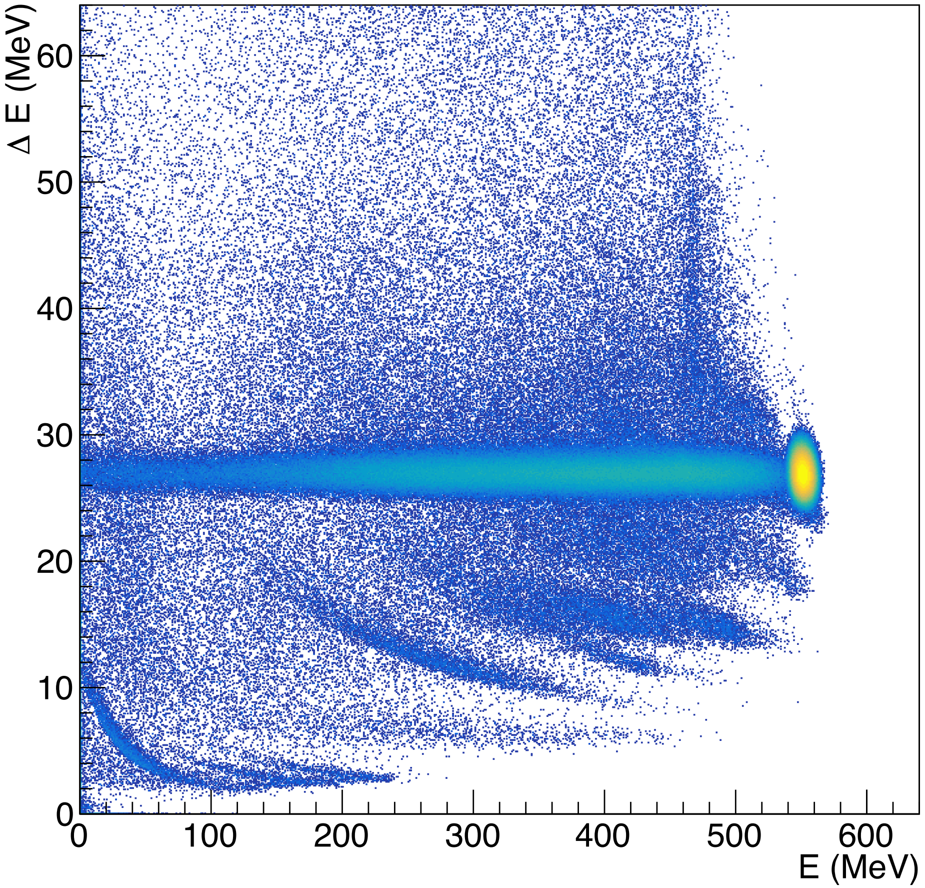
Solution: place two detectors at 5° from the normal of the surface of the target



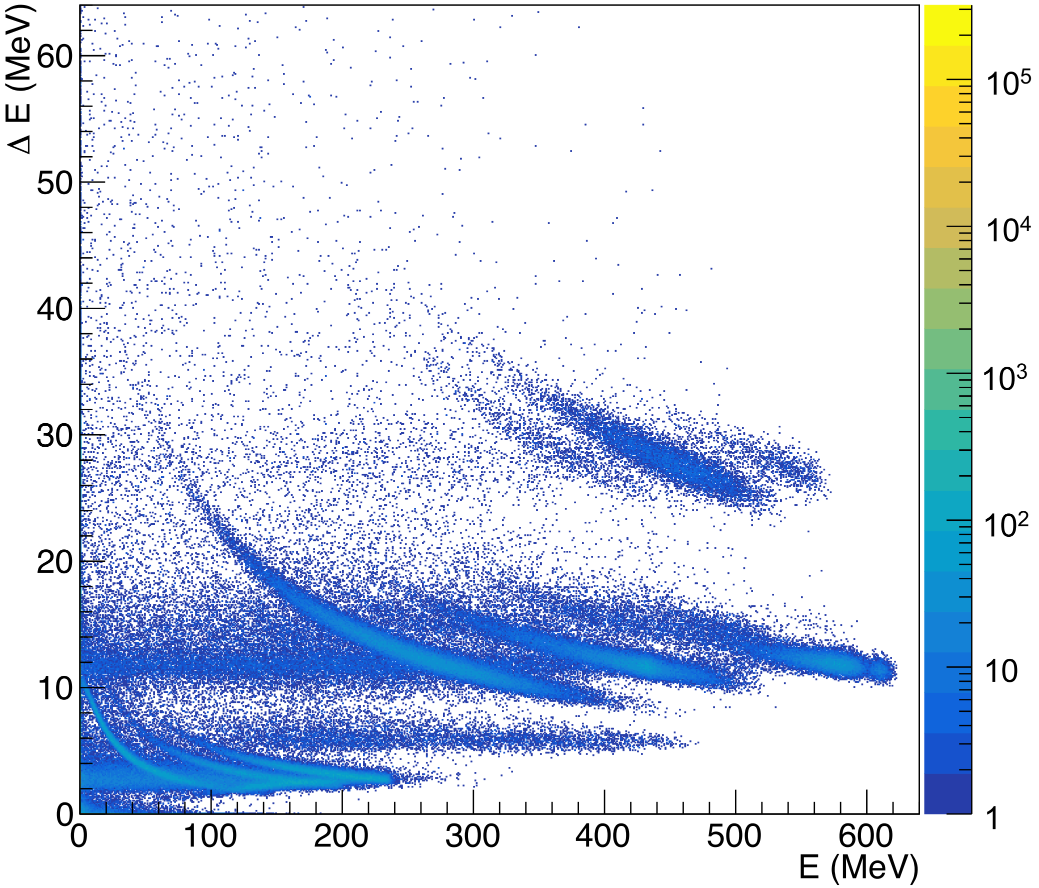
Schematics of the simulated setup

Comparison between 0° and 5° configurations:

$\Delta E_2 - E$ between plastic and CeBr in the 0° configuration

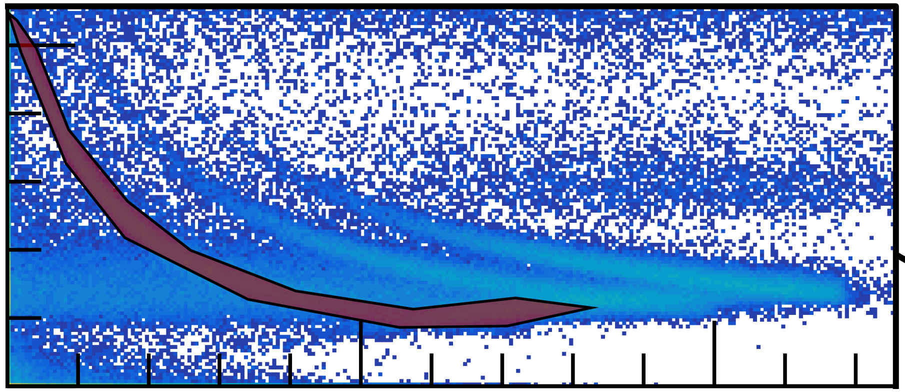


$\Delta E_2 - E$ between plastic and CeBr in the 5° configuration



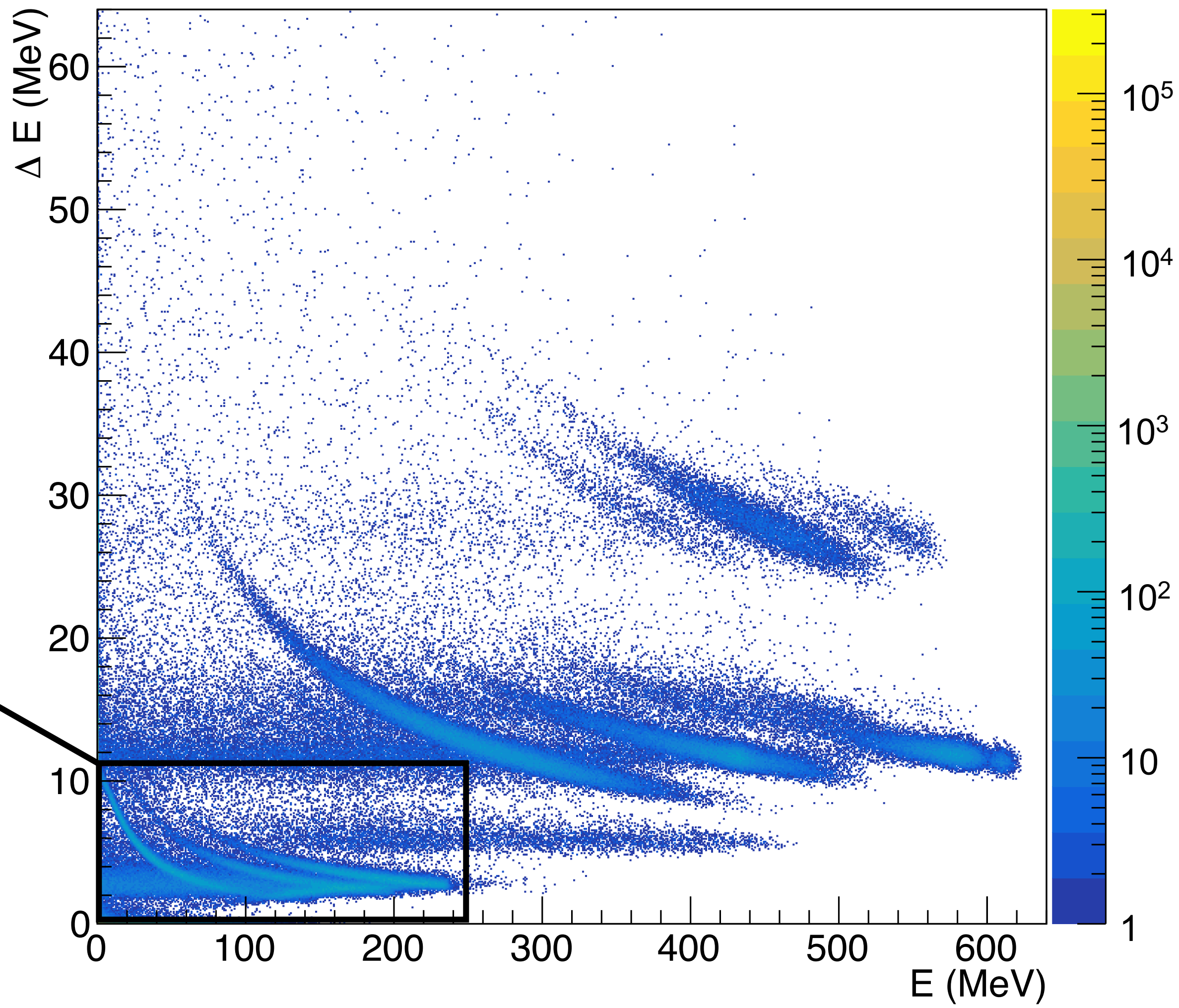
Identification of particles:

- One “banana” $\longrightarrow$ one kind of particle



What kind particle is it?

$\Delta E_2 - E$ between plastic and CeBr in the 5° configuration

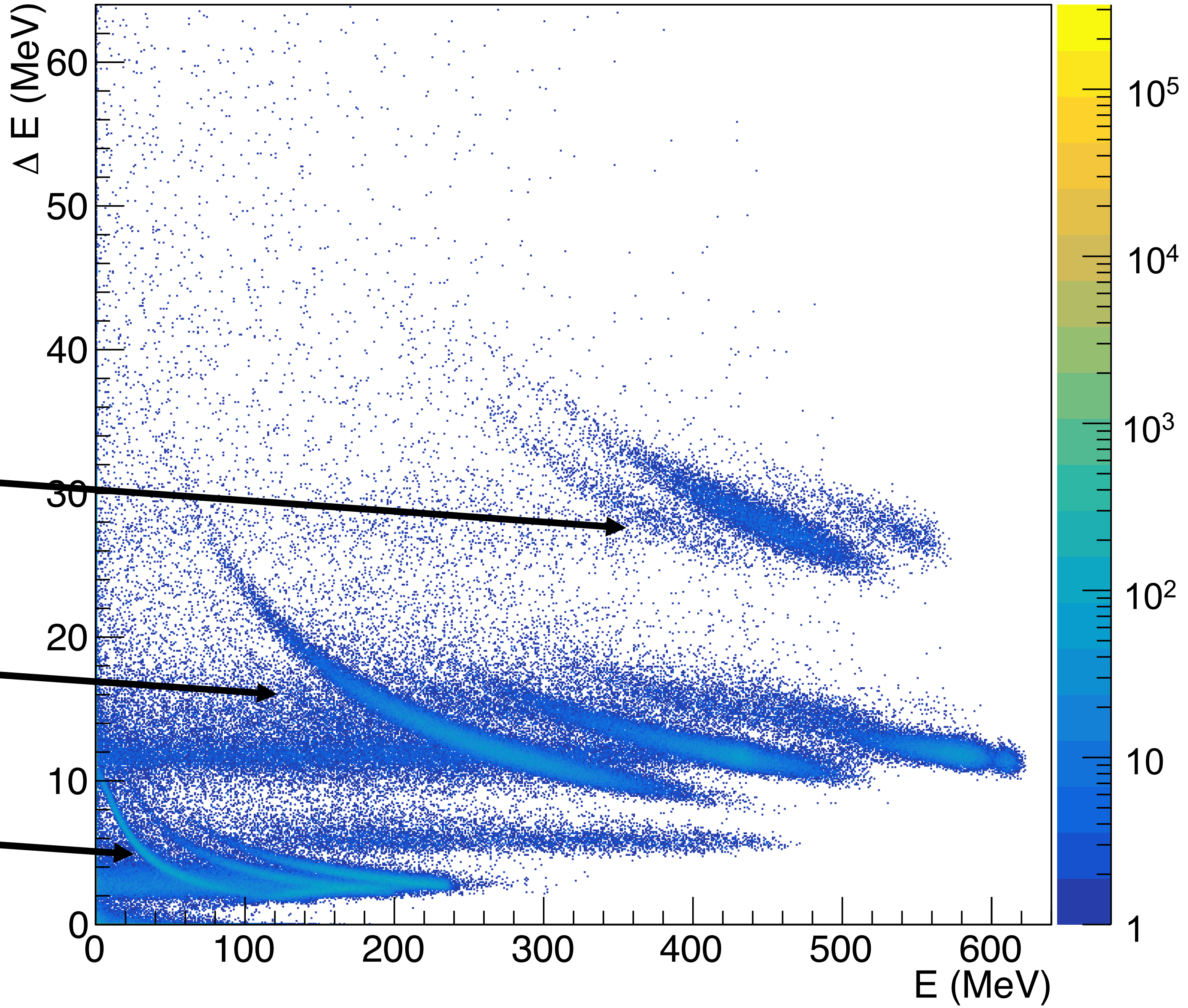


Identification of the populations:

^{6}Li, ^{7}Li, ^{8}Li (beam)

^{3}He, ^{4}He, ^{6}He, triple α

^{1}H, ^{2}H, ^{3}H

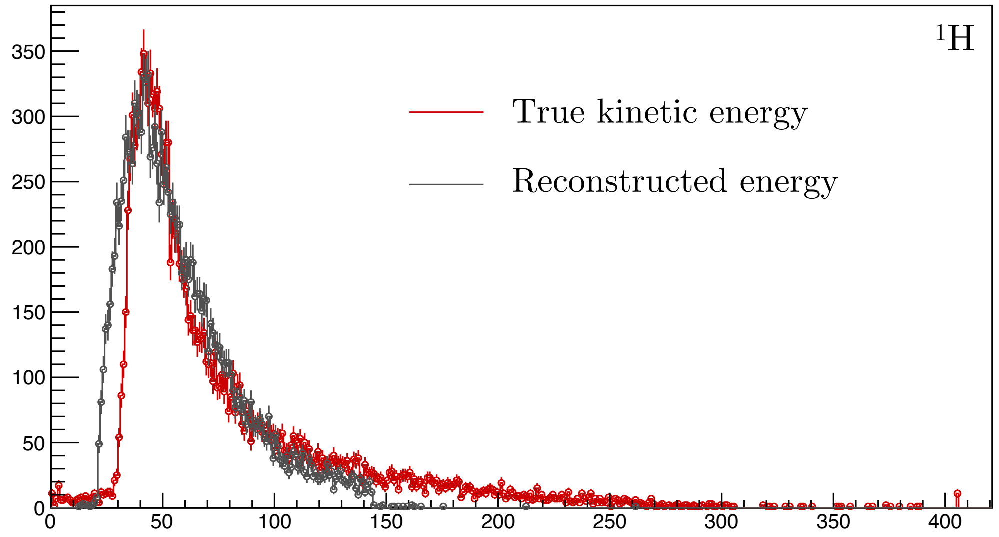


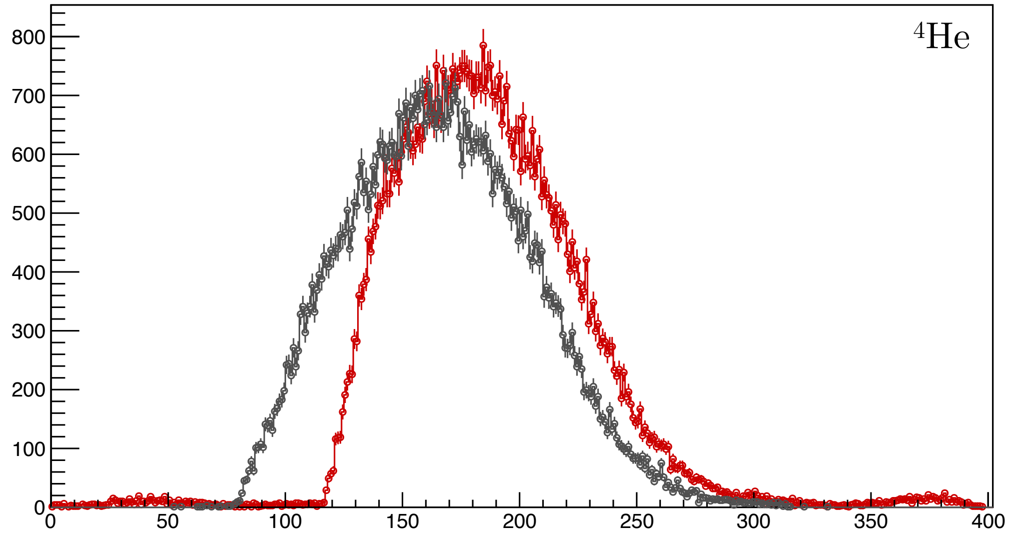
Cut for different products:

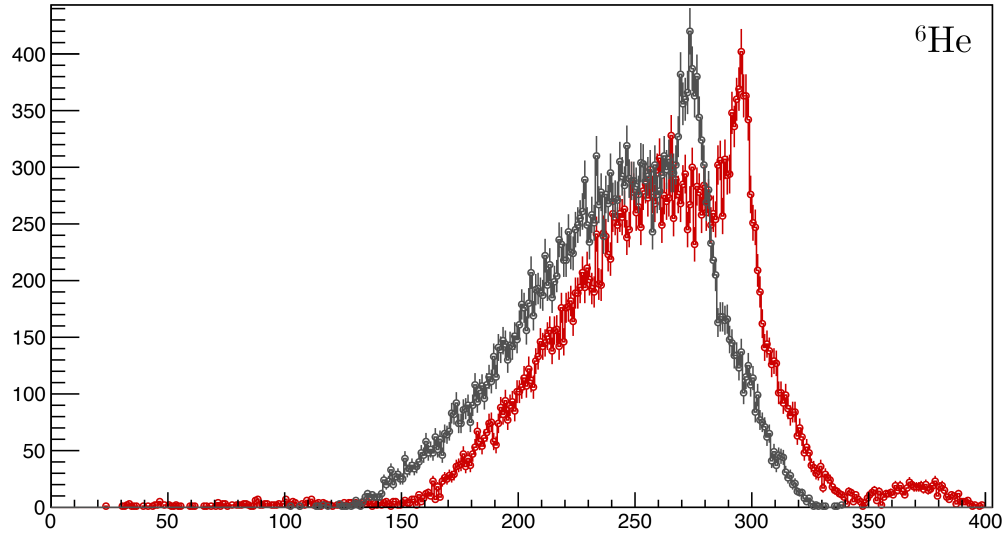
True kinetic energy = energy of the particle when it is created

Reconstructed energy = energy detected by the detector

Shift to lower reconstructed energies
⟶ CeBr entrance window

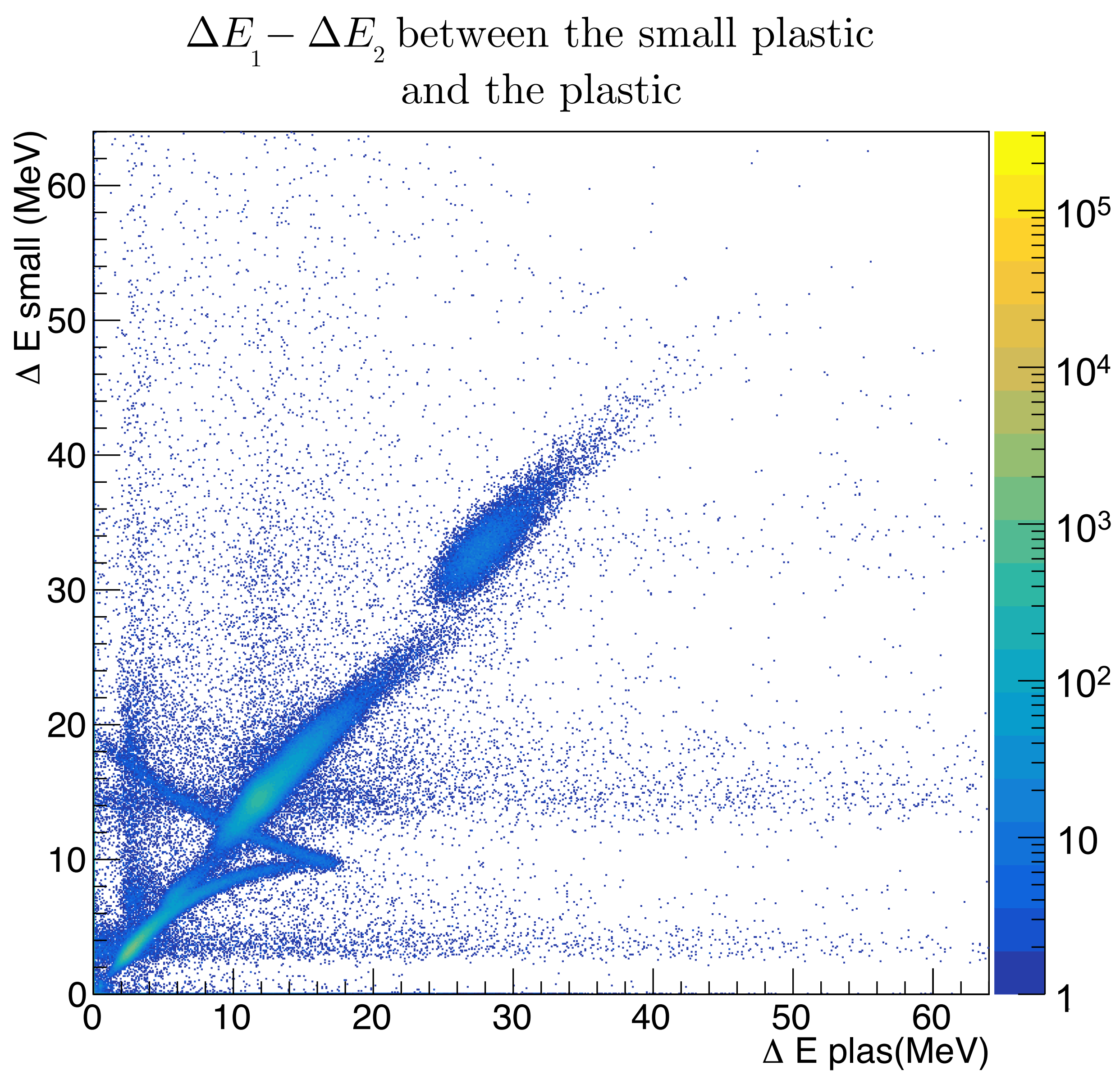






Relevance of using two telescopes:

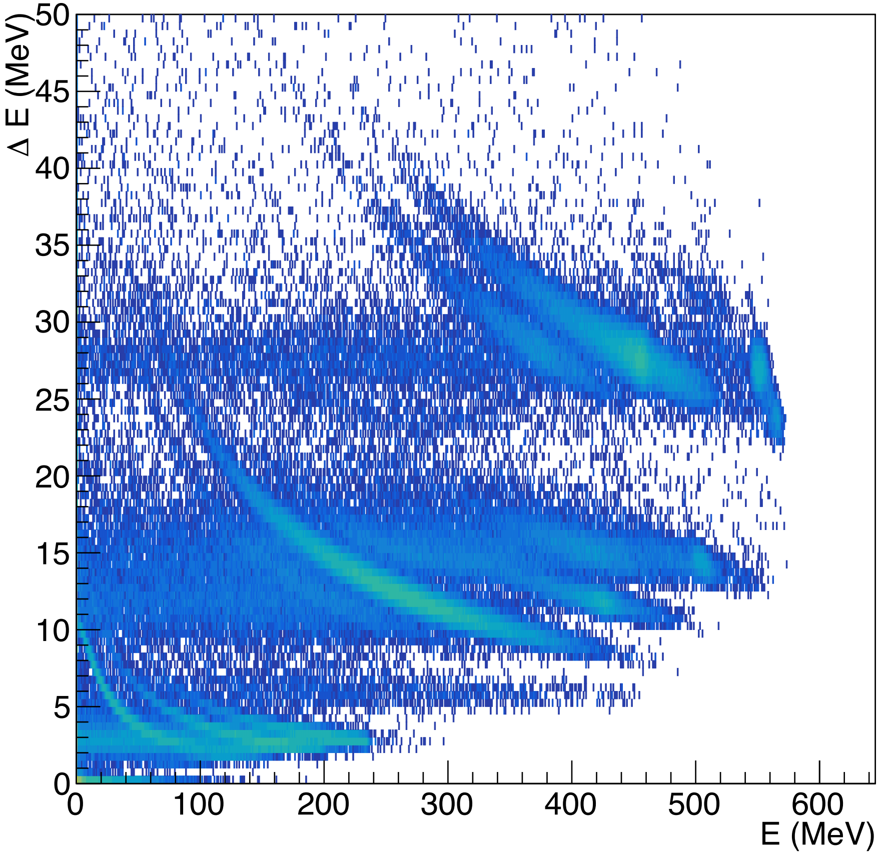
- Particles with low energies are stopped
- Particles with high energies go through both small detectors (back bend point)



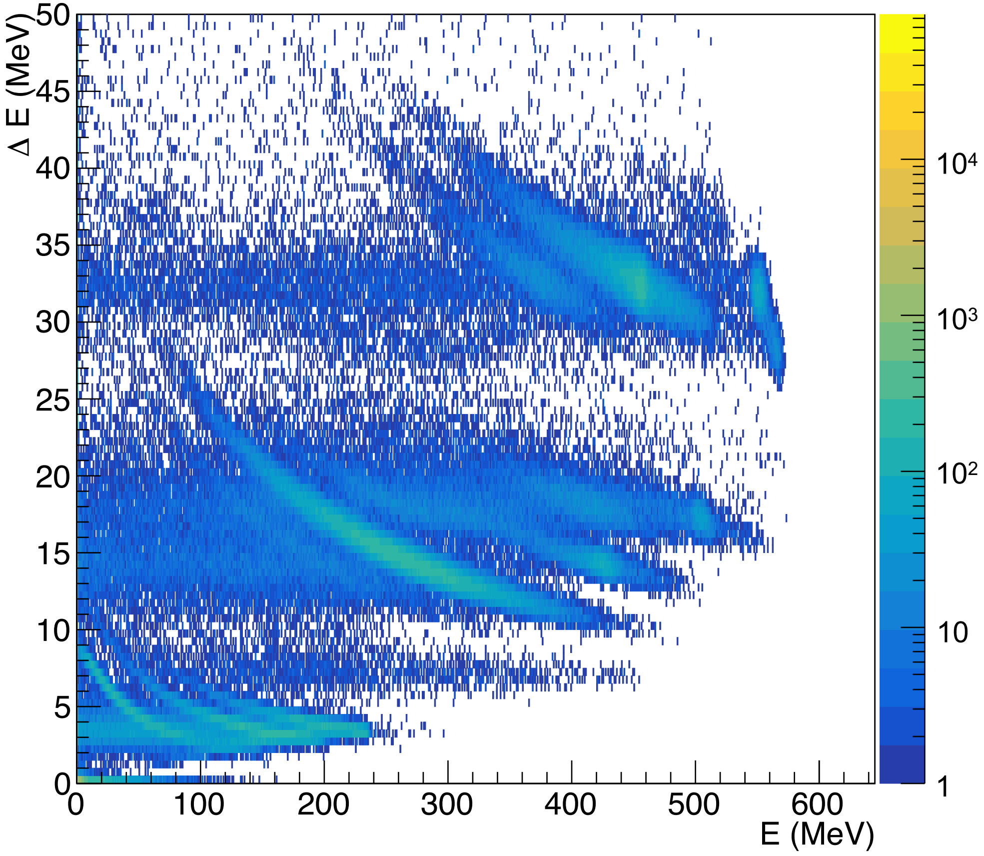
Relevance of using higher resolution silicon telescopes:

Higher resolution has no significant effect → ~ 5% for plastic; → 1% for silicon

$\Delta E_2 - E$ between CeBr and plastic



$\Delta E_2 - E$ between CeBr and silicon



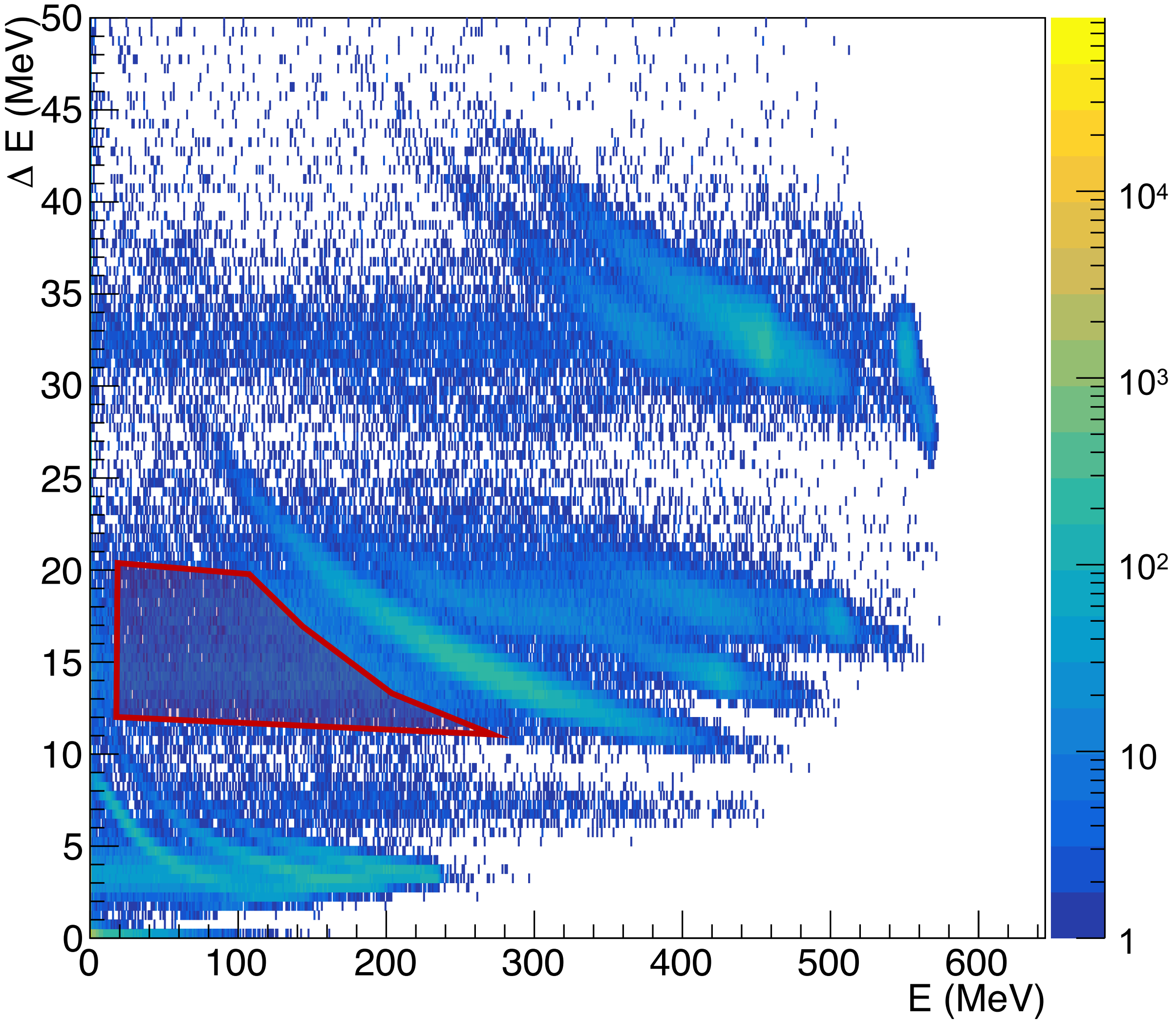
Problem: lot of noise
$\longrightarrow$ difficult to identify

Are these particles intrinsic to the ^{8}Li decay?

- Check the type of particle
- Test with other beams

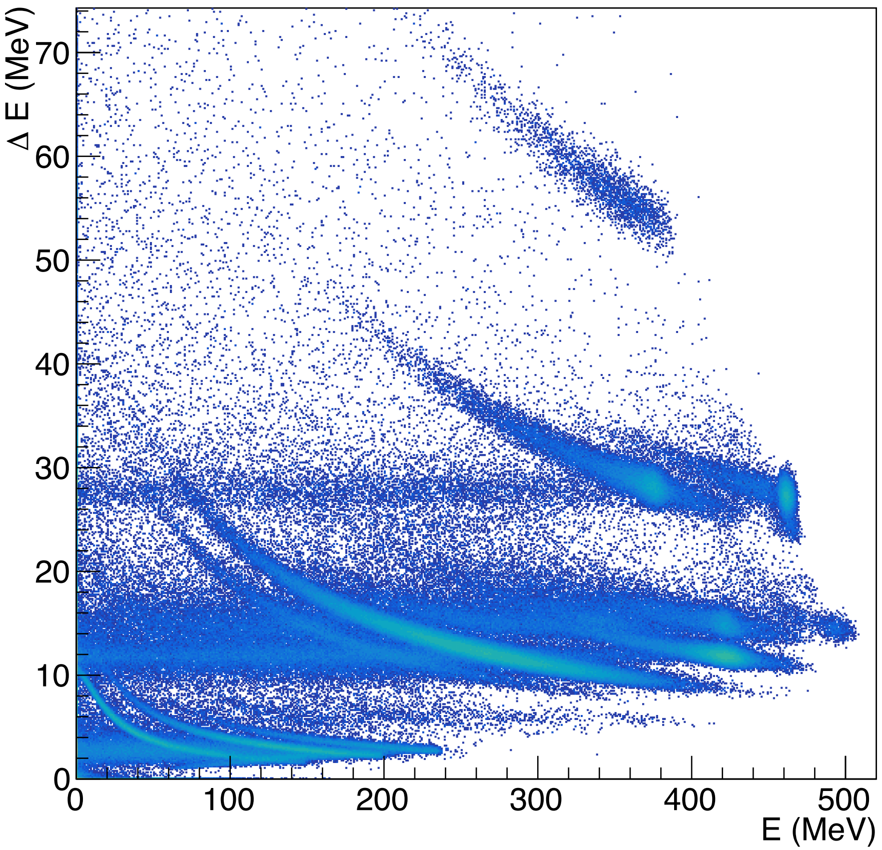
These are α particles

$\Delta E_2 - E$ between CeBr and silicon

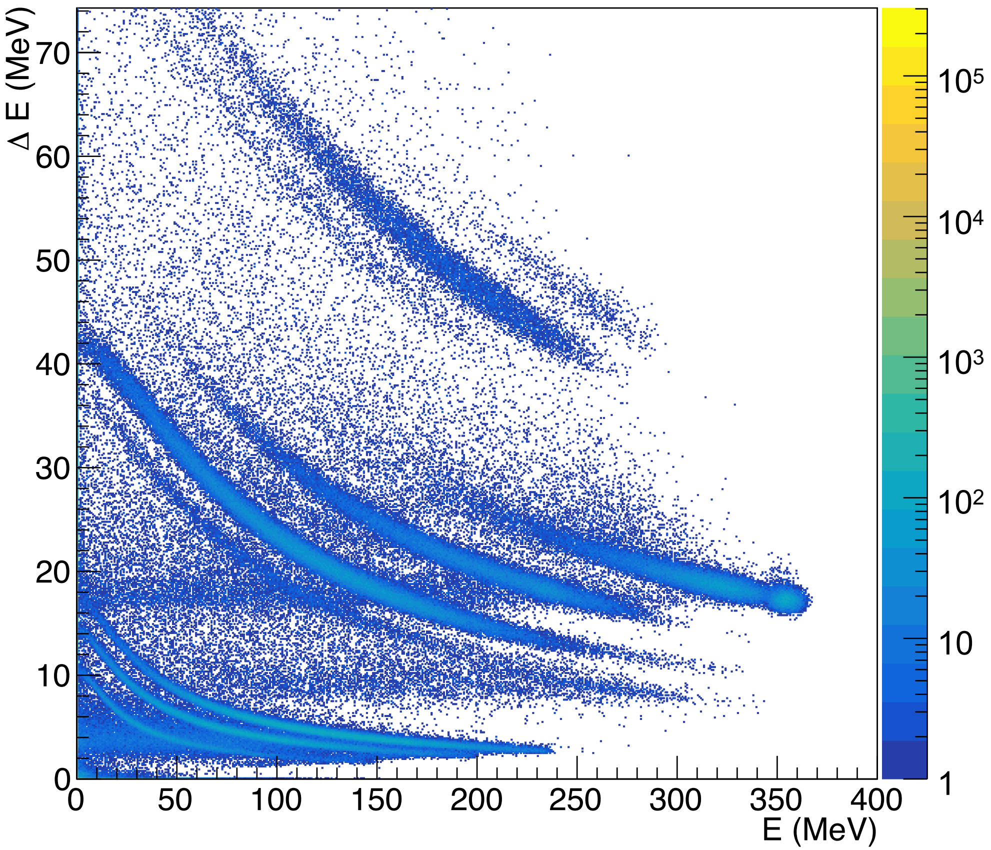


Tests with other beams:

$\Delta E_2 - E$ between plastic and CeBr using a ^{7}Li beam



$\Delta E_2 - E$ between plastic and CeBr using a ^{8}He beam



- Population only for ^{7}Li not for ^{8}He

$^7\mathrm{Li} + \mathrm{p} \rightarrow 2\alpha$

lithium reaction

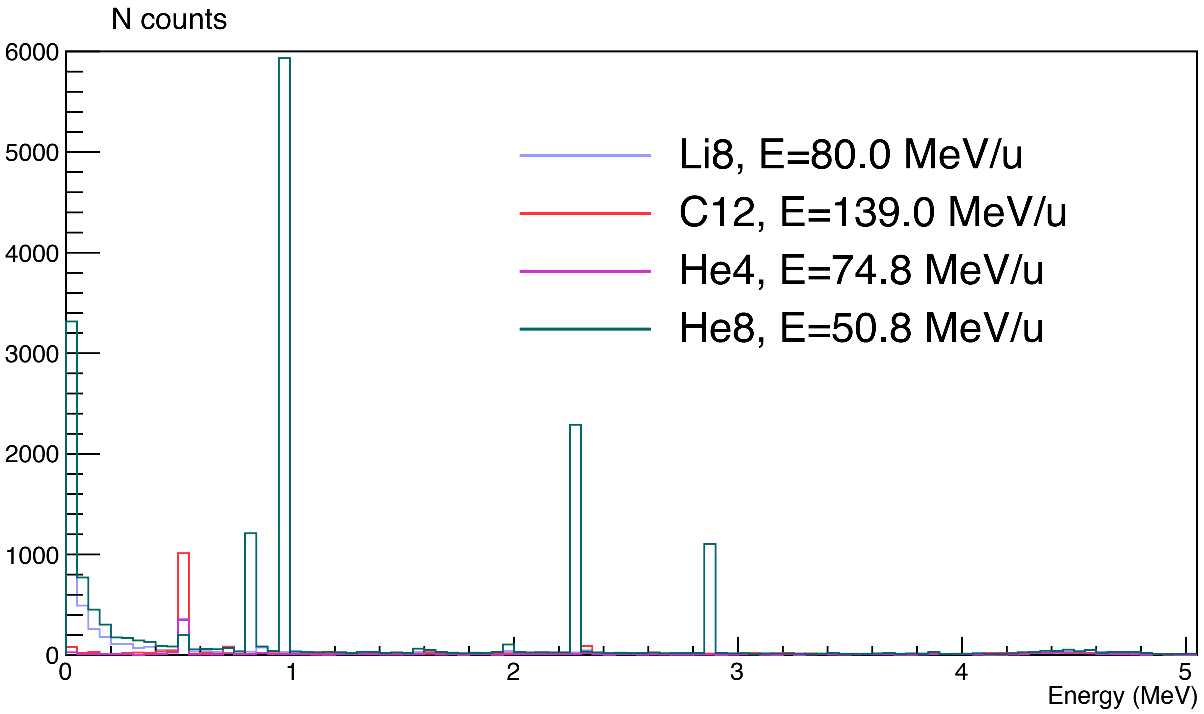
Gamma distribution

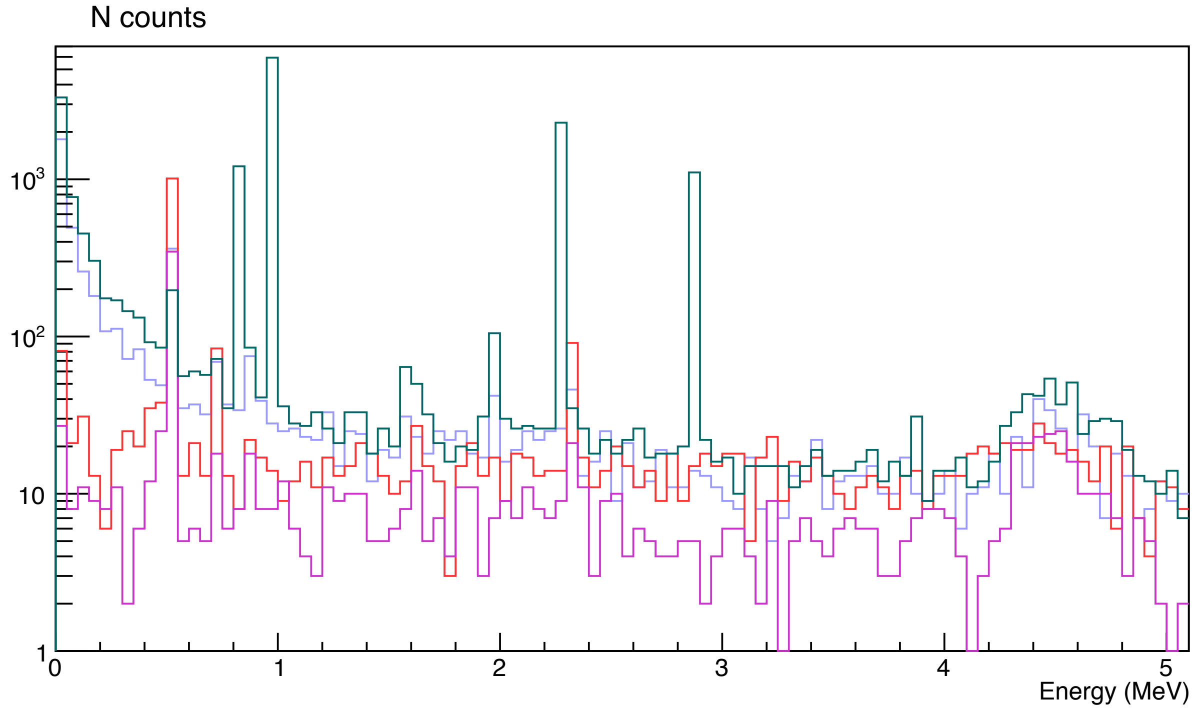
- Decay of ^{8}He $\longrightarrow$ 981keV

$$^8_2\mathrm{He}_6 \rightarrow {}^8_3\mathrm{Li}_5 + e^- + \bar{\nu}_e$$

- 511keV peak for every ion

Can we detect these gammas?





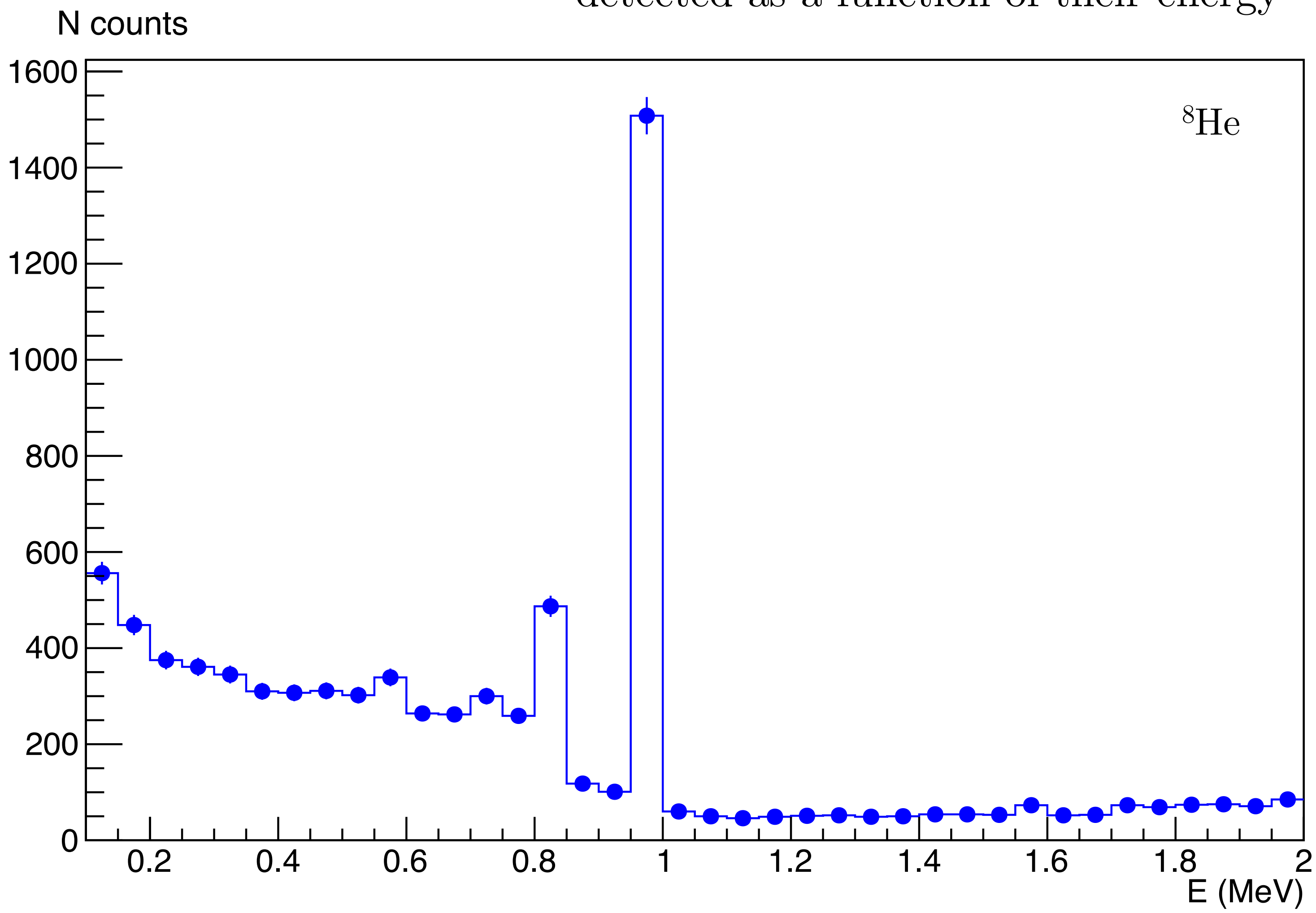
Gamma emitted for four different incident ions, left in decimal scale and right in log scale

Gamma peaks detected in the CeBr (5°) detector:

- Distinct peak at 981keV

"Prompt $-\gamma$" detection possible
$\longrightarrow$ advantage for ^{8}He

Histogram of the number of gammas detected as a function of their energy



Conclusion

- Plastic scintillators are sufficient, no need to use silicon detectors

- For ^{8}He and ^{8}Li $\longrightarrow$ high dose deposition in the BP

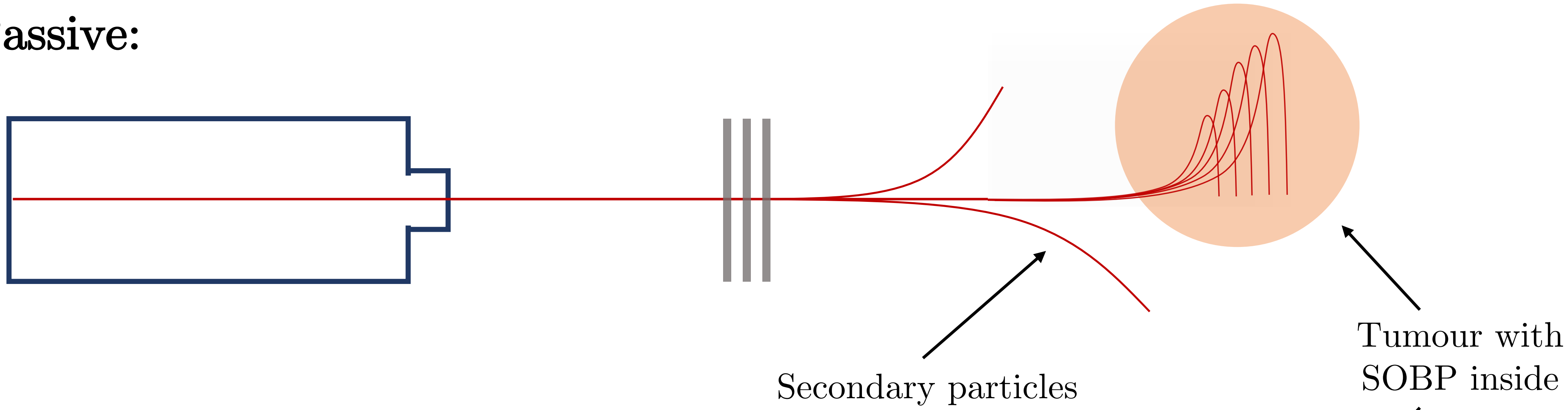
- The 981keV gamma peak of ^{8}He is easily detectable $\longrightarrow$ dose monitoring with "prompt-γ" is possible

- Better detection of secondary products for ^{8}He than for ^{8}Li

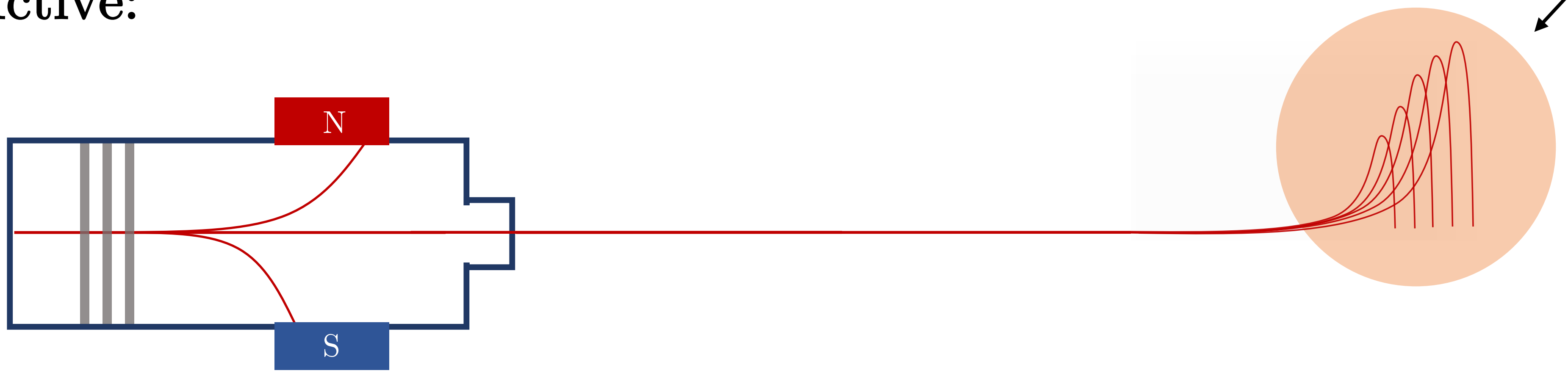
How easy would it be to use ^{8}He in the medical field?
What would be the constraints?

Appendix

Passive:



Active:

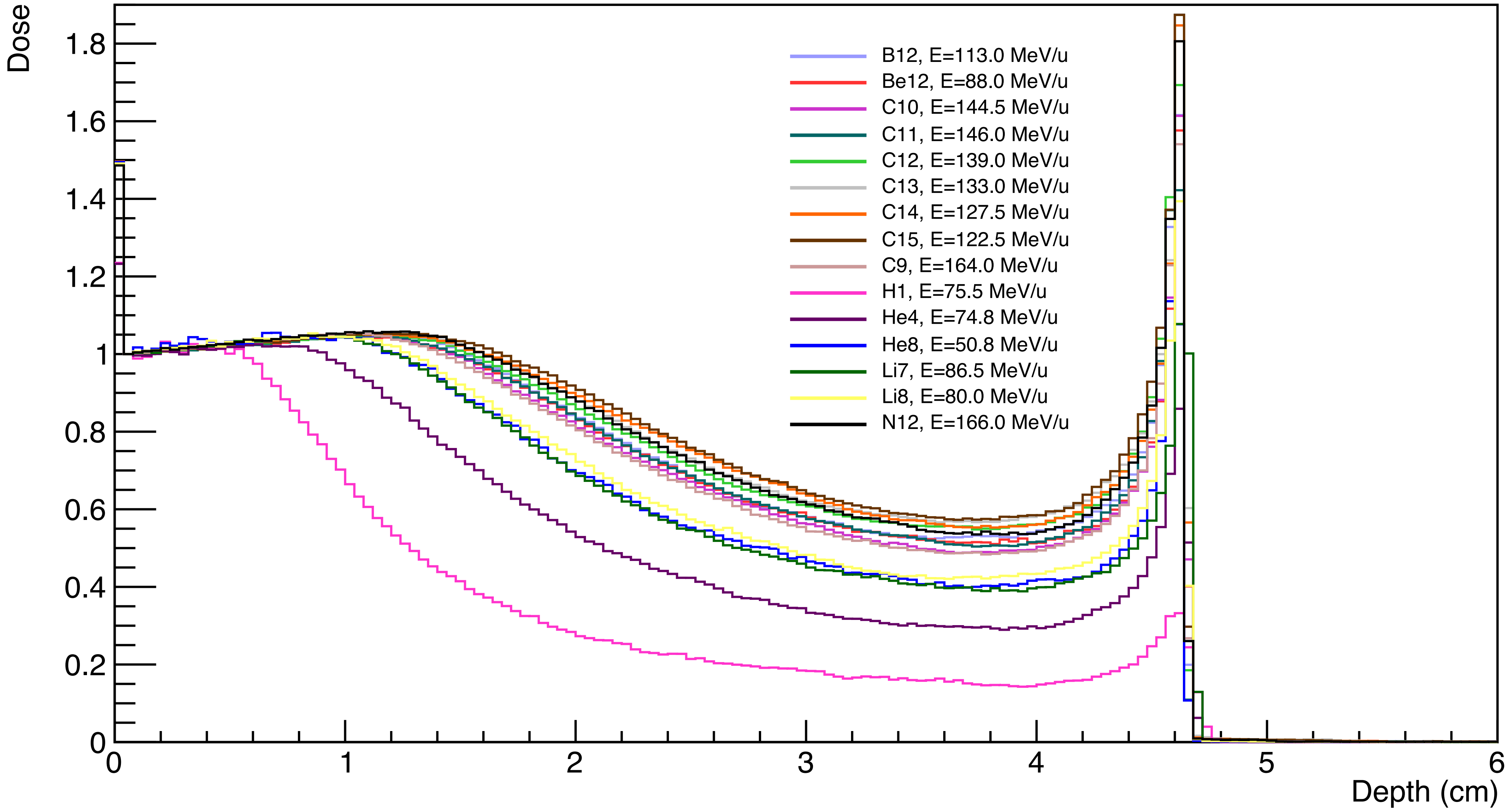


Relative Biological Effectiveness (RBE)

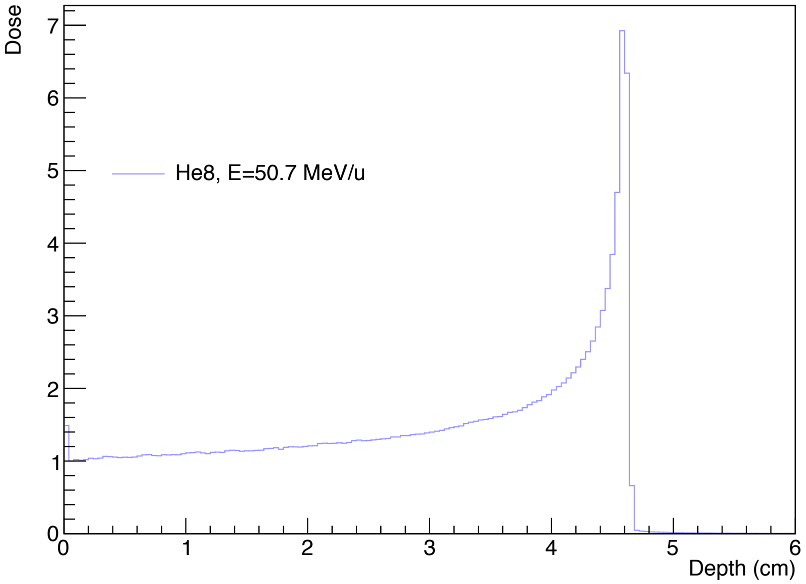
$$RBE = \frac{D_{X\text{-}rays}}{D_{Ion}}$$

where $D_{X\text{-}rays}$ and D_{ion} are doses computed to kill the same amount of cells

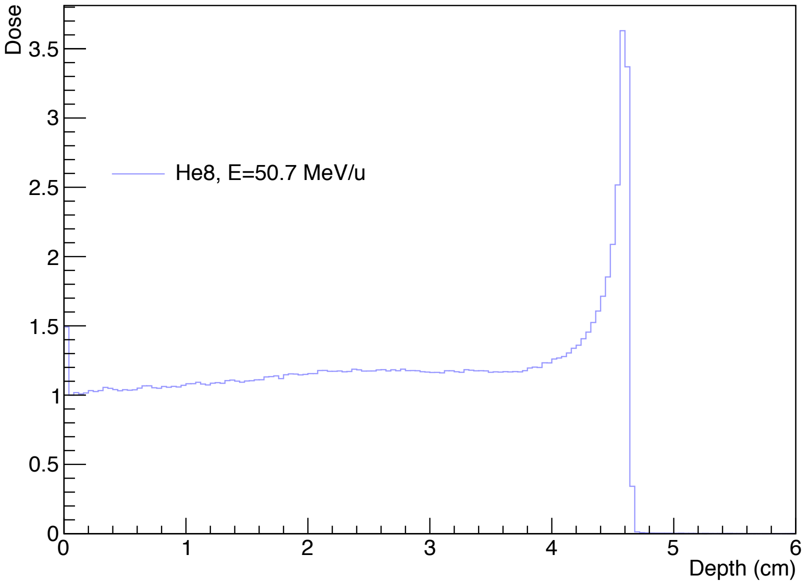
Comparison of the BP for different ions:



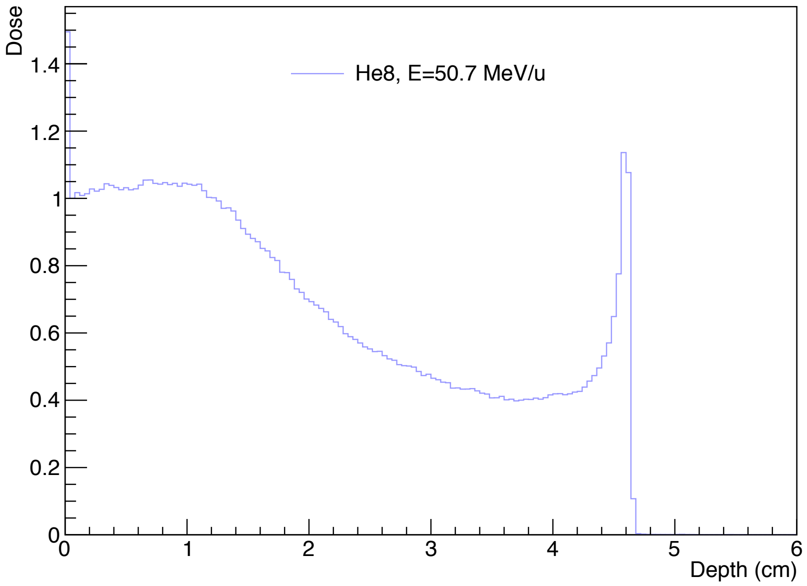
We can plot the Bragg peak using different widths each times giving very different results. Here we have 3 graphs plotting the dose deposition only for a section of the beam or for the whole width of the beam. The results are different and the approach we used here was the last one where only a small width is taken into account.



0.1mm

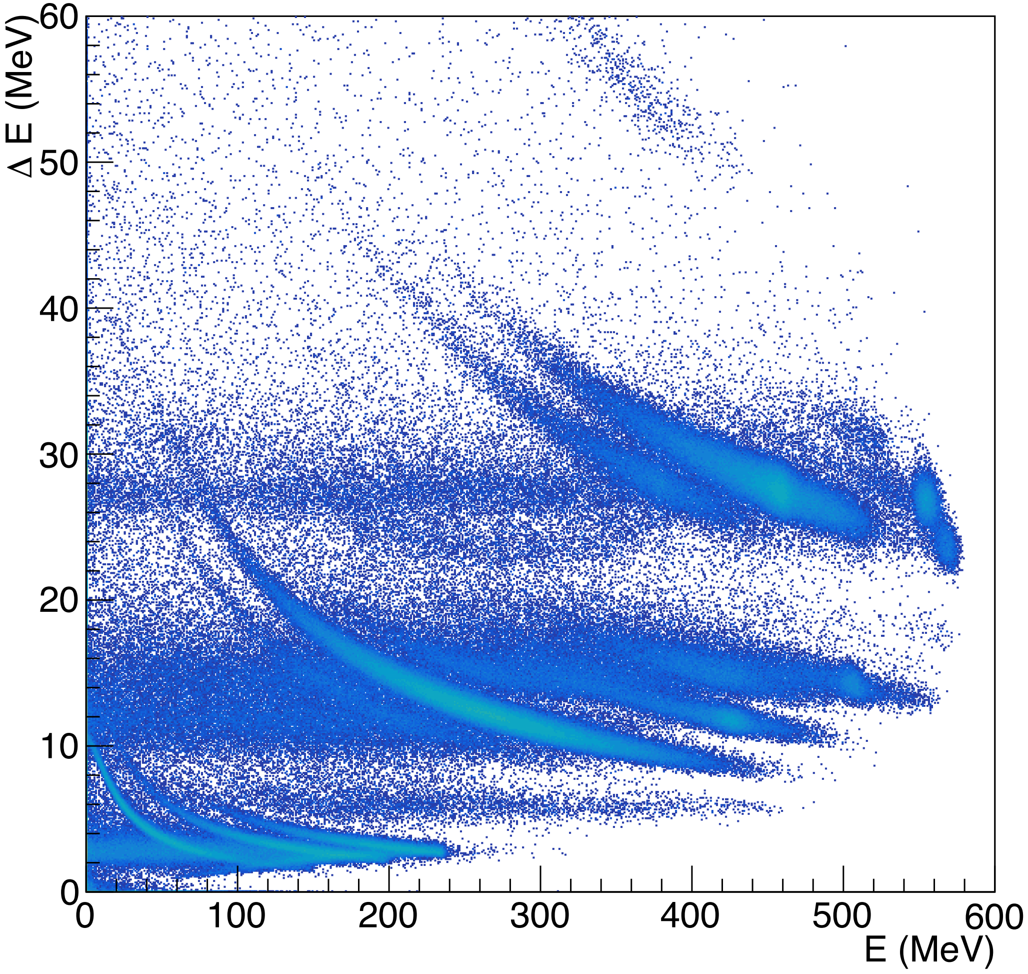


0.02mm

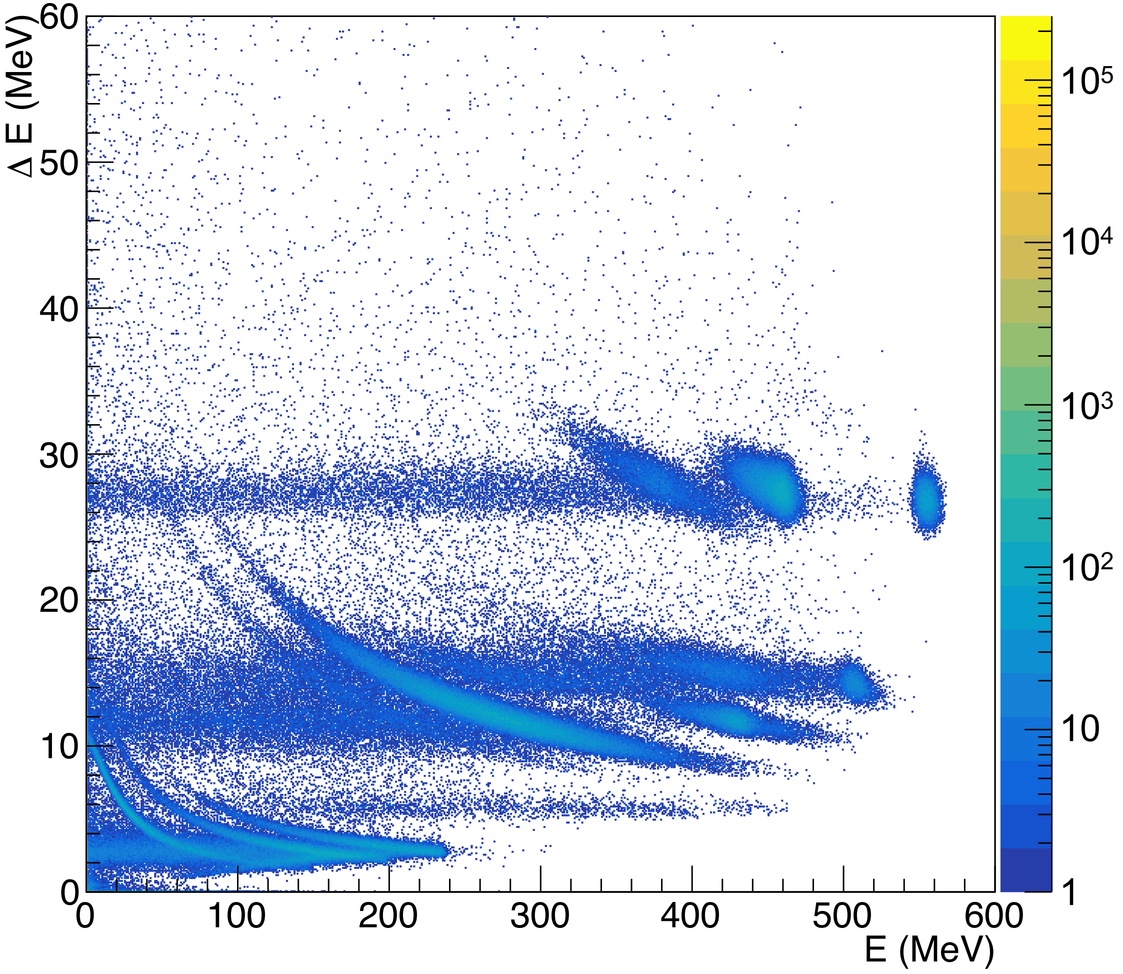


0.005mm

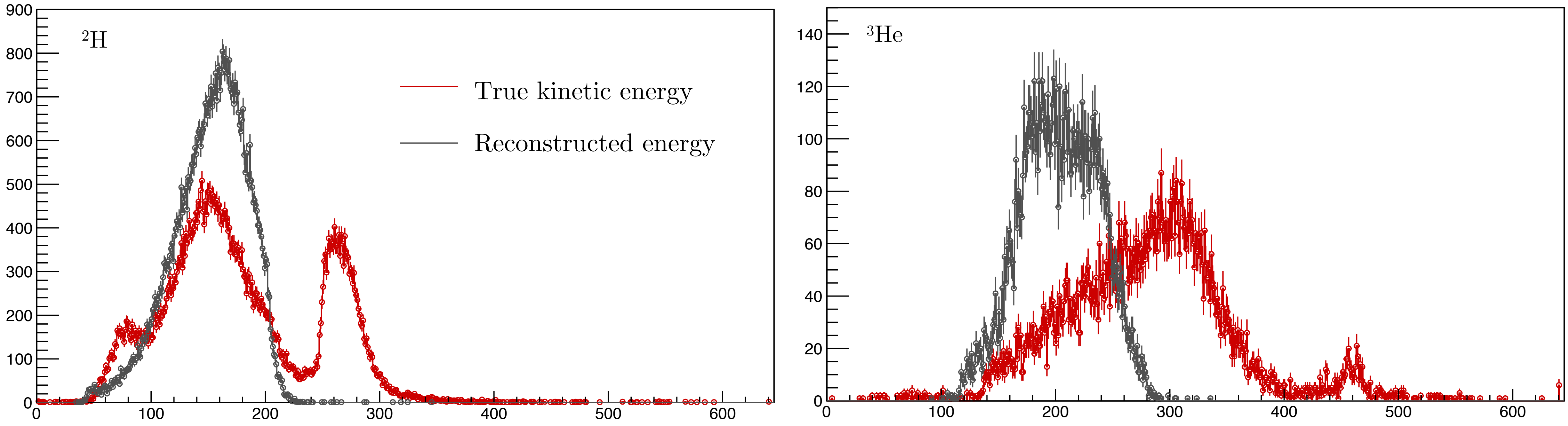
$\Delta E - E$ between plastic and CeBr using a ^{8}Li beam on a 3mm water target



$\Delta E - E$ between plastic and CeBr using a ^{8}Li beam on a 1.5mm ^{12}C target

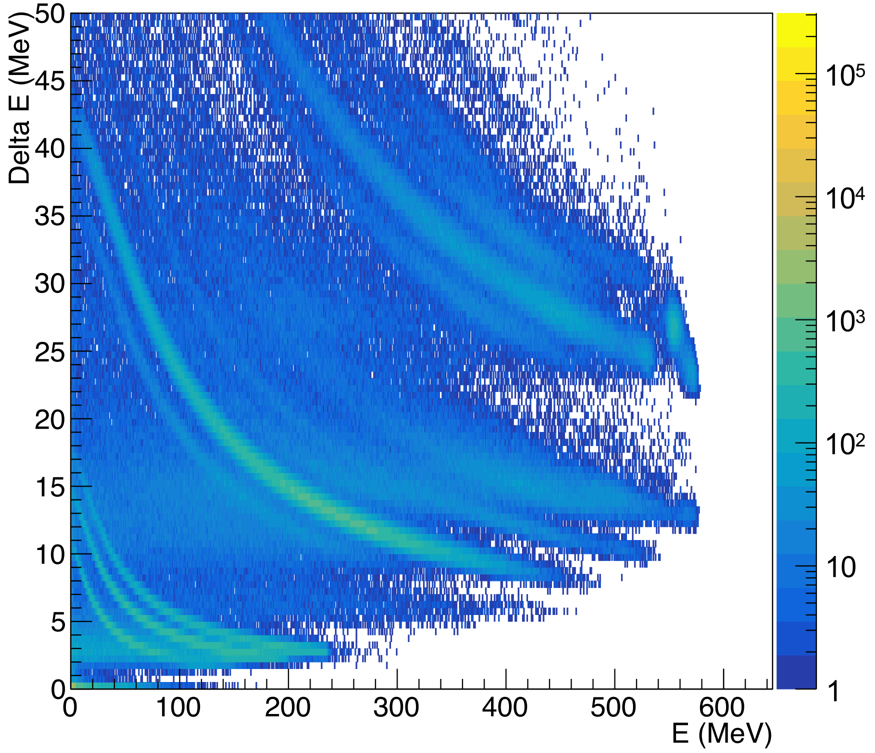


Cut for different products:



Try another physics list to check the consistence of our results:

$\Delta E - E$ between plastic and CeBr



Comparison of the gammas emitted using the BIC and INCL physics, top in decimal and bottom in log