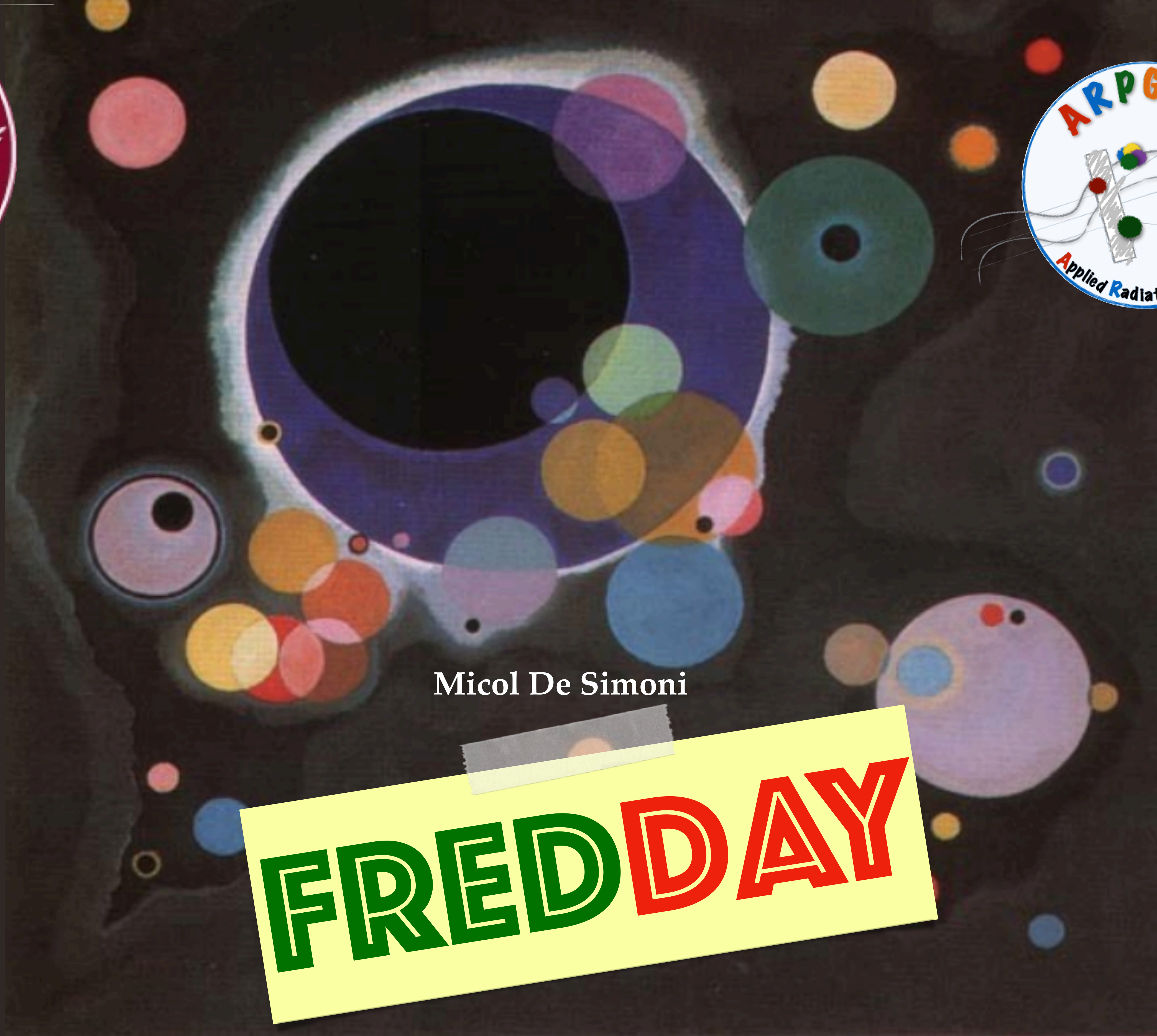
# FRED for Carbon Ions: State of Art

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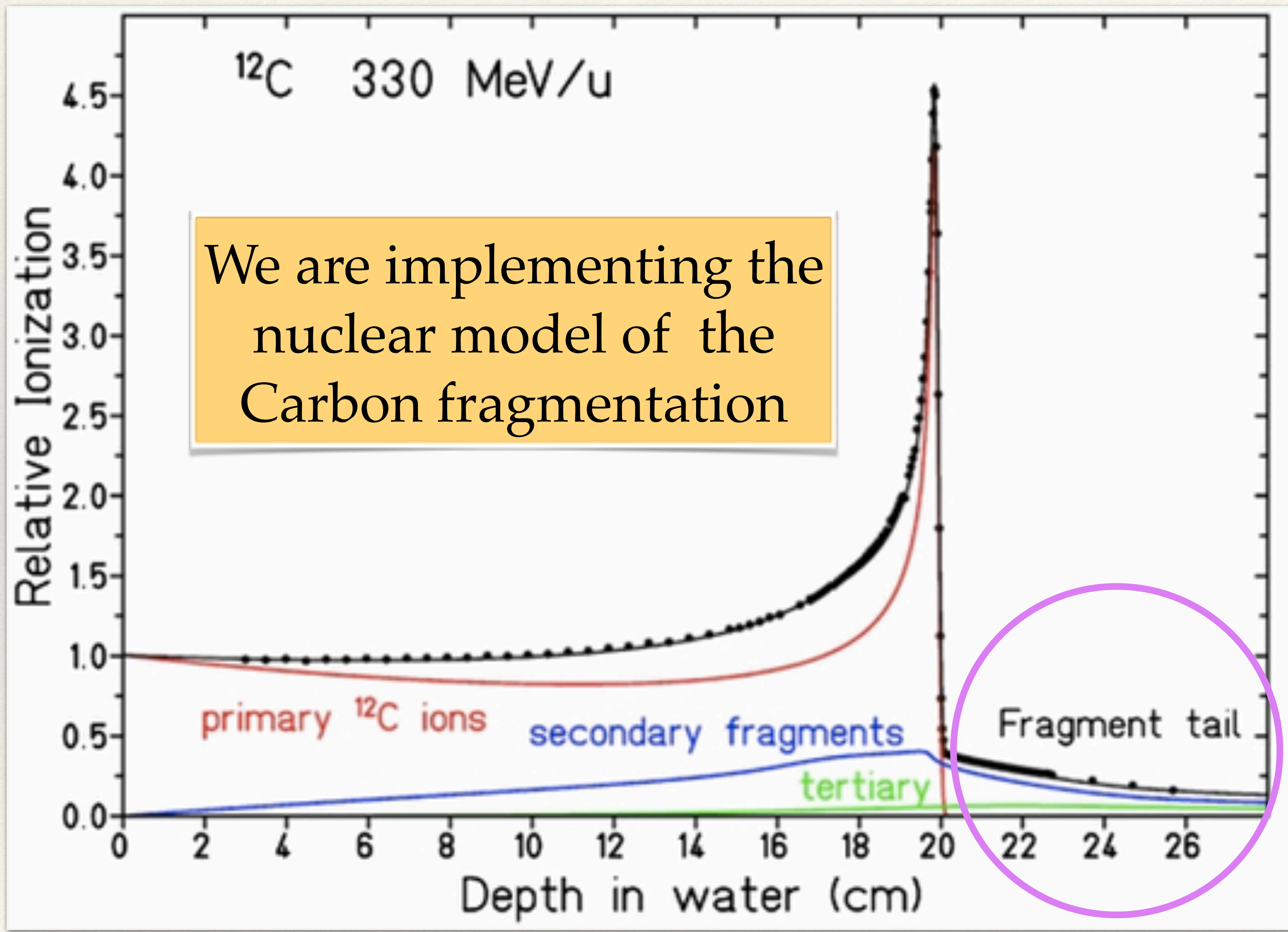
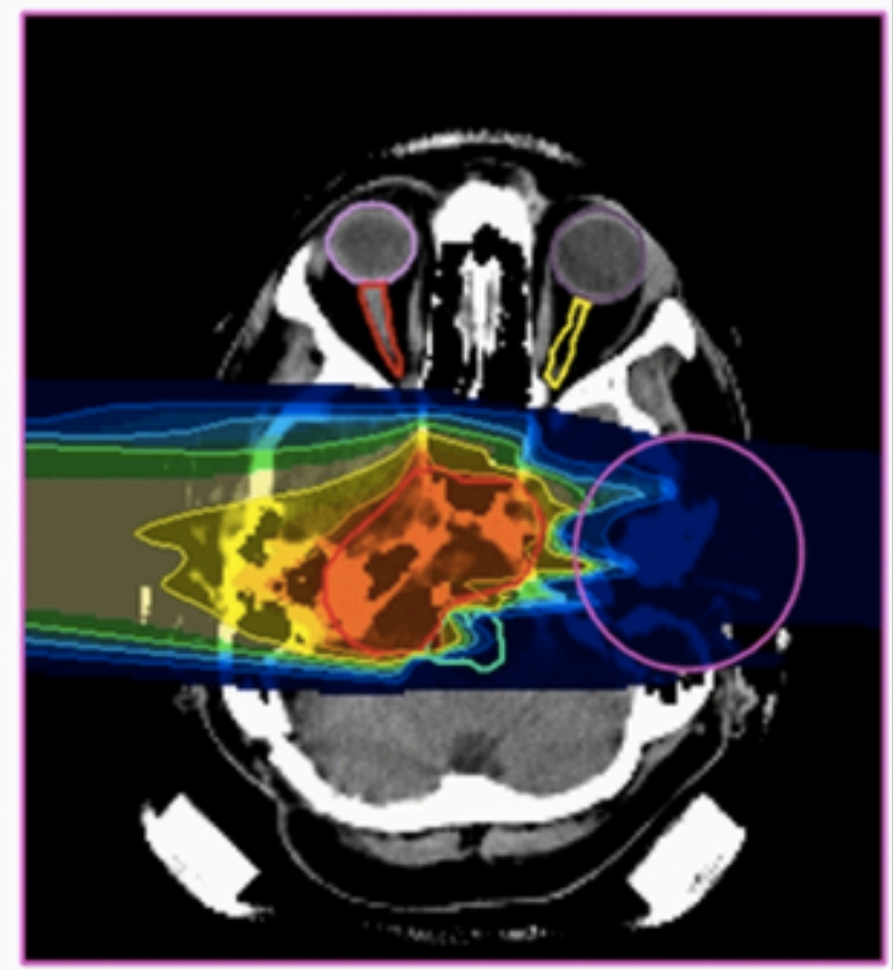
# Heavy Ion Beams

The simulation of the fragmentation of the ions of the beam, actually not considered in the code, gives an important contribution for the dose deposition for heavy ion treatments.




We are implementing the nuclear model of the Carbon fragmentation



# Fragmentation of Carbon Ions

1. Calculation of the Coefficient of Mass Attenuation -> is there fragmentation?

2. Choice the target;

3. Fragmentation:
   I. Choice the Fragments (both target and projectile fragments with conservation of A and Z);
   II. Choice of their Energy and Angles of emission
   III. Energy and Angle scaling considering the beam energy
   IV. Check on Energy conservation (if $\Sigma E_f > E_{proj}$ repeat from I.)

4. Generation of Fragments

# Step 1: Calculation of the Coefficient of Mass Attenuation

Calculation of the total cross section:

$$\sigma = a_1 + a_2 e^{-a_3 E}$$

Scaling using the **Sihver formula** which takes into account the type of target and projectiles. In case of H target, the formula considers also a energy-dependance for E<200 MeV/u *(L. Sihver, Total reaction and partial cross section calculations in proton-nucleus and nucleus-nucleus reactions)*

$$\sigma_{H_2O} = 2\sigma_H + \sigma_O$$
$$\sigma_{tot} = \sigma \cdot \sigma_{scaling}, (\sigma_{scaling} = 1 \text{ if target} = H_2O)$$

If the projectile is a neutron or a proton the total cross section is zero

So the mass attenuation is:

$$\mu = \frac{\sigma_{tot}}{\rho}$$

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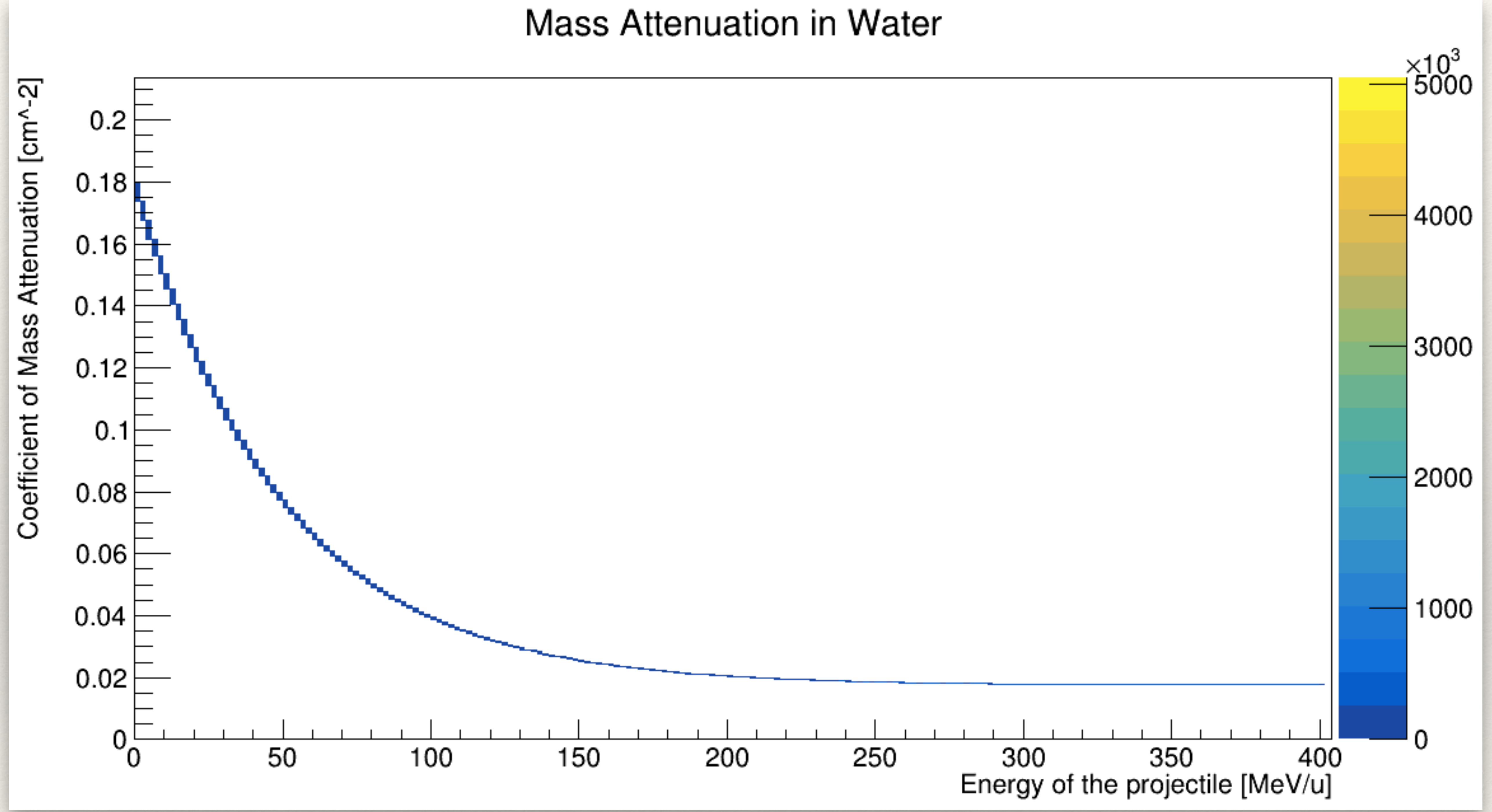
# Step 1: Calculation of the Coefficient of Mass Attenuation




$$\mu = \frac{\sigma_{tot}}{\rho}$$

# Step 2: Choose the Target

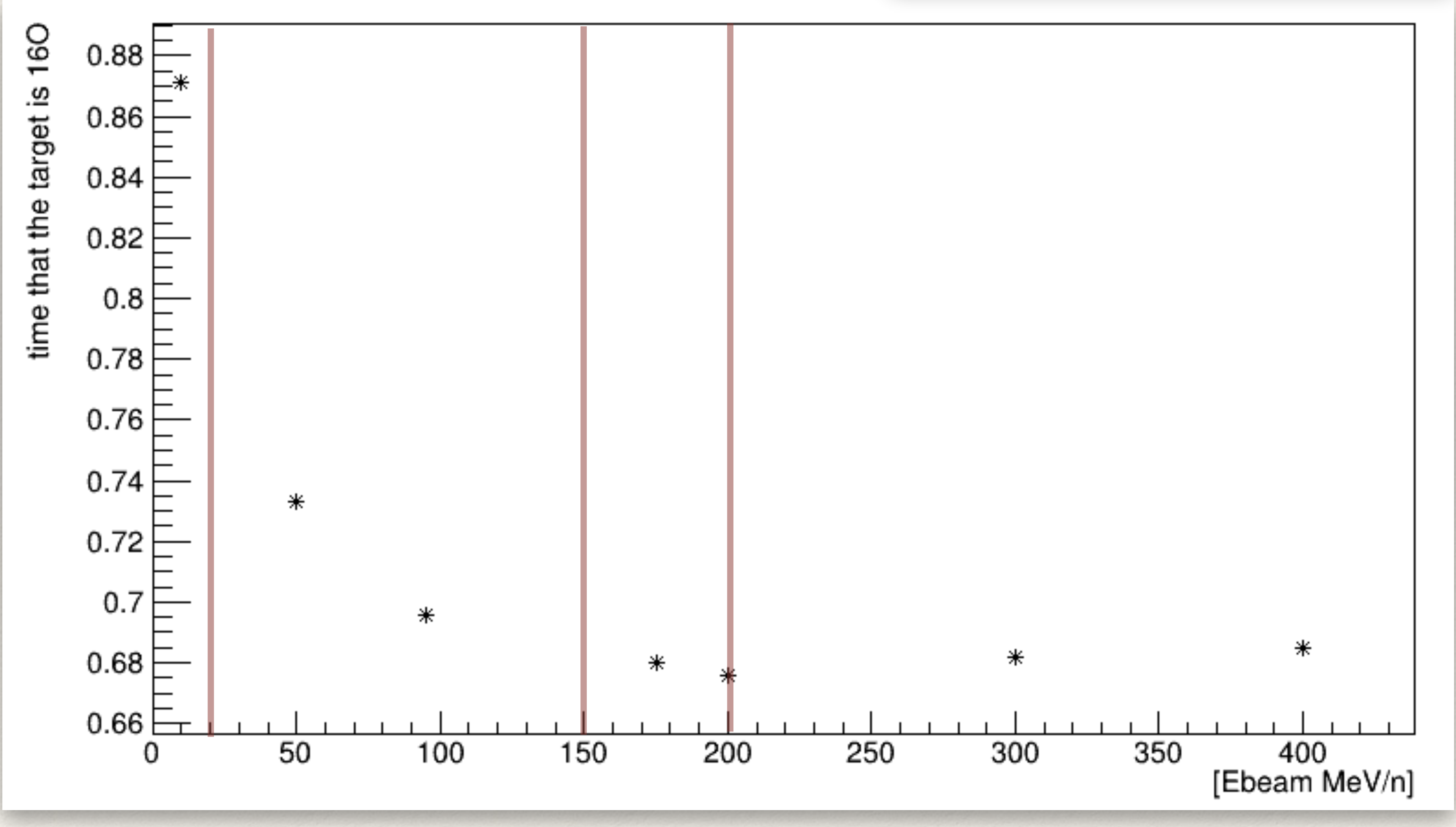
HIT OR MISS with Cumulative (C) obtained from the cross section of Sihvert:

$$\sigma_{H_2O} = 2\sigma_H + \sigma_O$$

$$C_H = \frac{2\sigma_H}{\sigma_{H_2O}}$$

$$C_O = \frac{\sigma_O}{\sigma_{H_2O}}$$

$$C_H + C_O = 1$$



# Step 3.I: Choose the Fragments

HIT OR MISS with cumulative obtained with data from the Ganil Experiment adding the constraint:

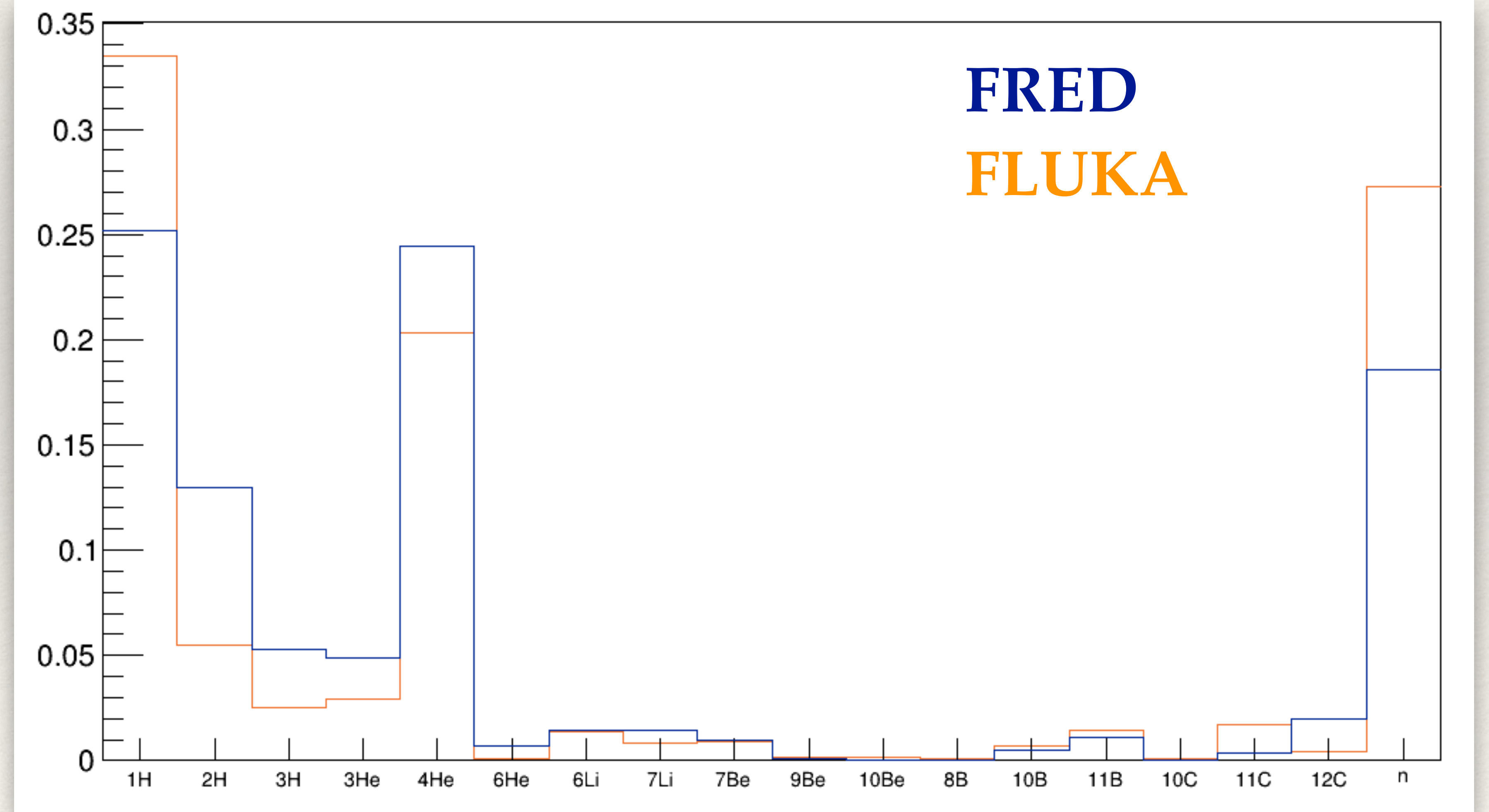
If projectile fragments:

$\Sigma A_i = A_{projectile}$ **AND** $\Sigma Z_i = Z_{projectile}$

If target fragments:

$\Sigma A_i = A_{target}$ **AND** $\Sigma Z_i = Z_{target}$

Ganil Experiment has not data about neutrons, they have been added using the cumulative of protons.

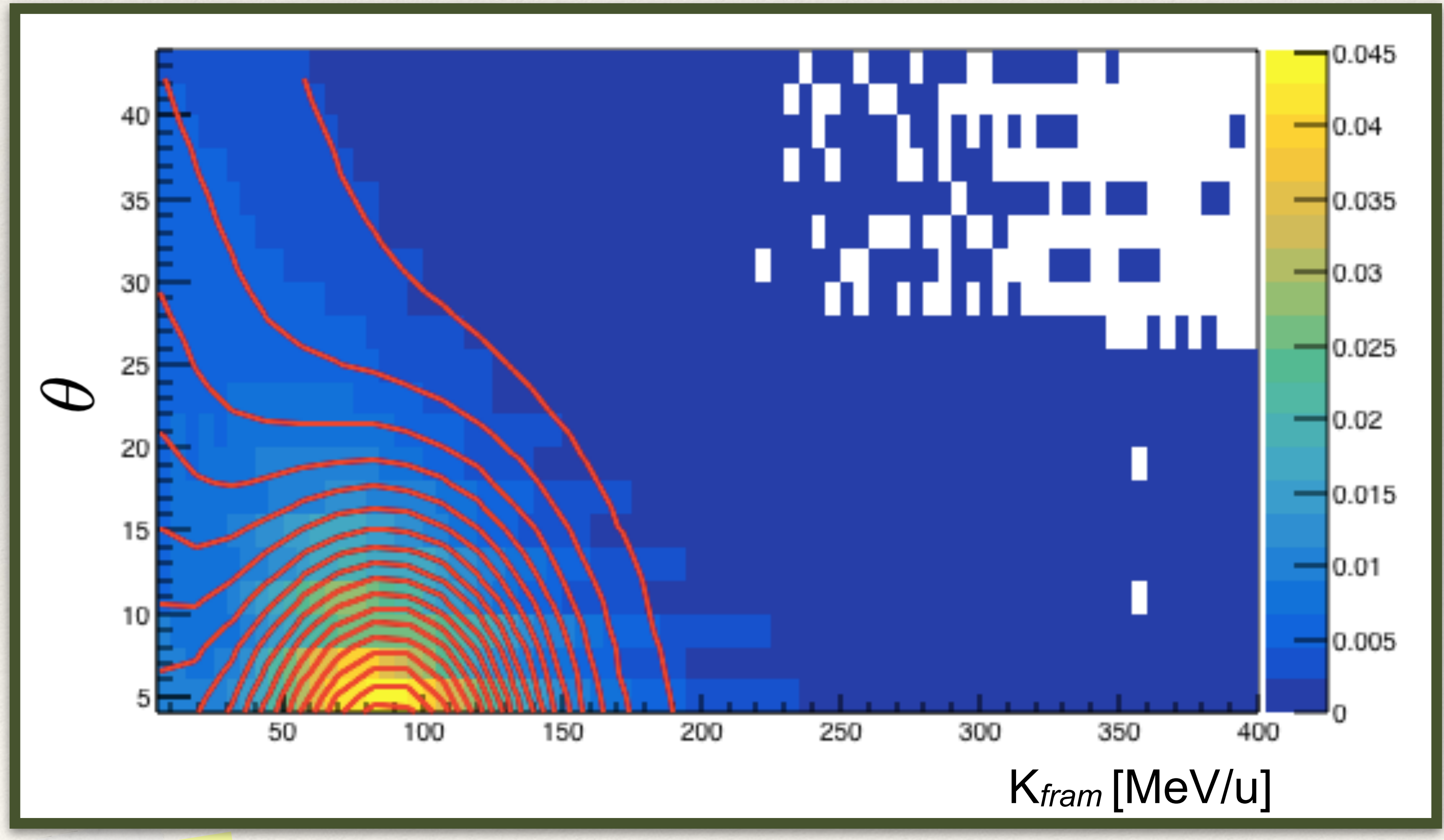


# Step 3.II: Choice of their Energy and Angles of emission

To obtain an Angle and Energy Cross Section, have been fitted with Ganil data

$$f(E,\theta) = A_1 e^{-(\alpha_E E + \alpha_\theta \theta)} + A_2 e^{-\left(\frac{(E-<E>)^2}{2\sigma_E} + \frac{(\theta-<\theta>)^2}{2\sigma_\theta}\right)}$$

Gaussian parameters used for the energy and angle distribution of **Projectile fragments**




**Proton angle and energy distribution**
**$^{12}$C [95MeV/u]**
**Oxygen Target**

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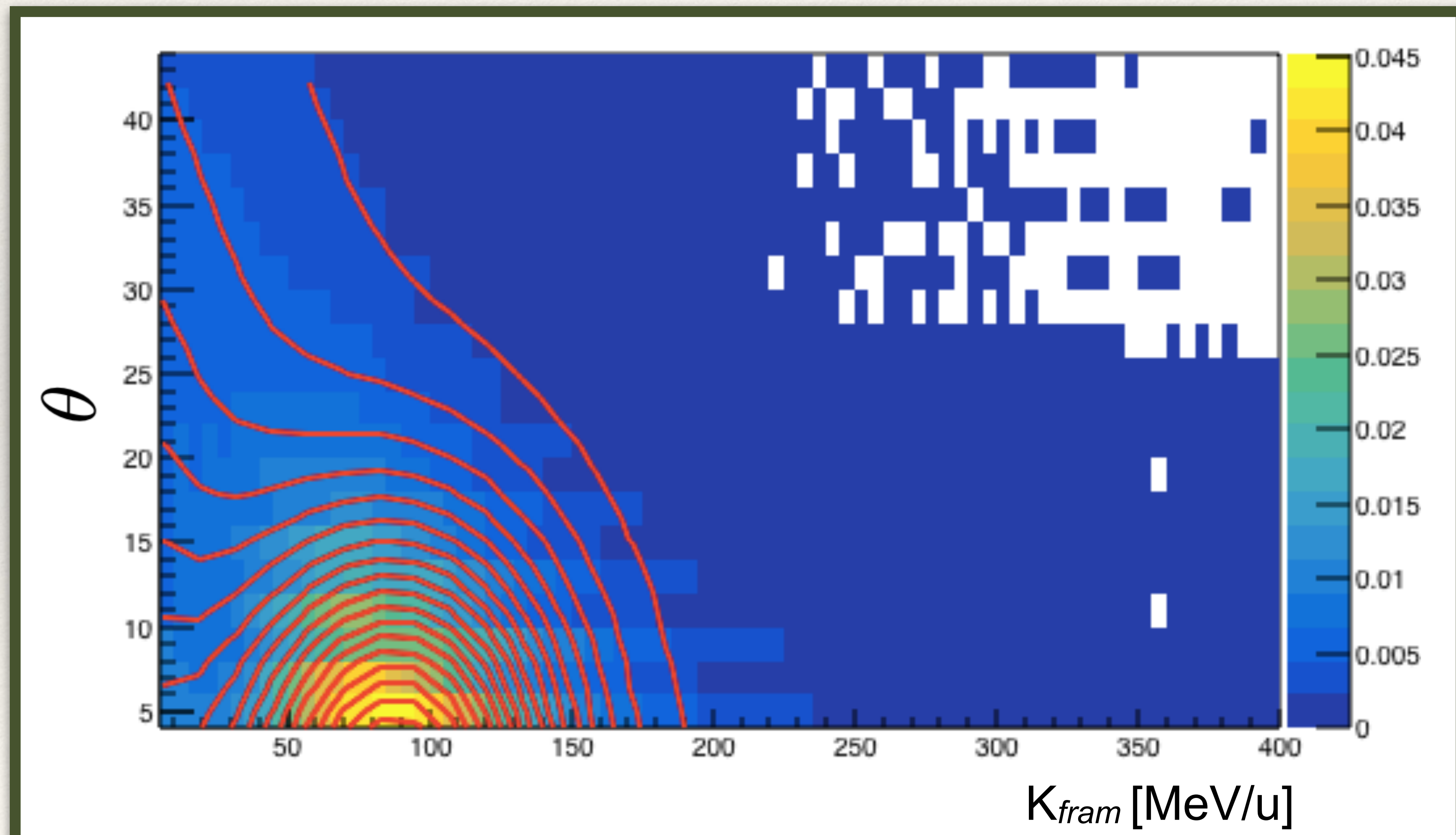
Exponential parameters used for the energy and angle distribution of **Target fragments**




**Proton angle and energy distribution**
**$^{12}C$ [95MeV/u]**
**Oxygen Target**

# Step 3.II: Choice of their Energy and Angles of emission

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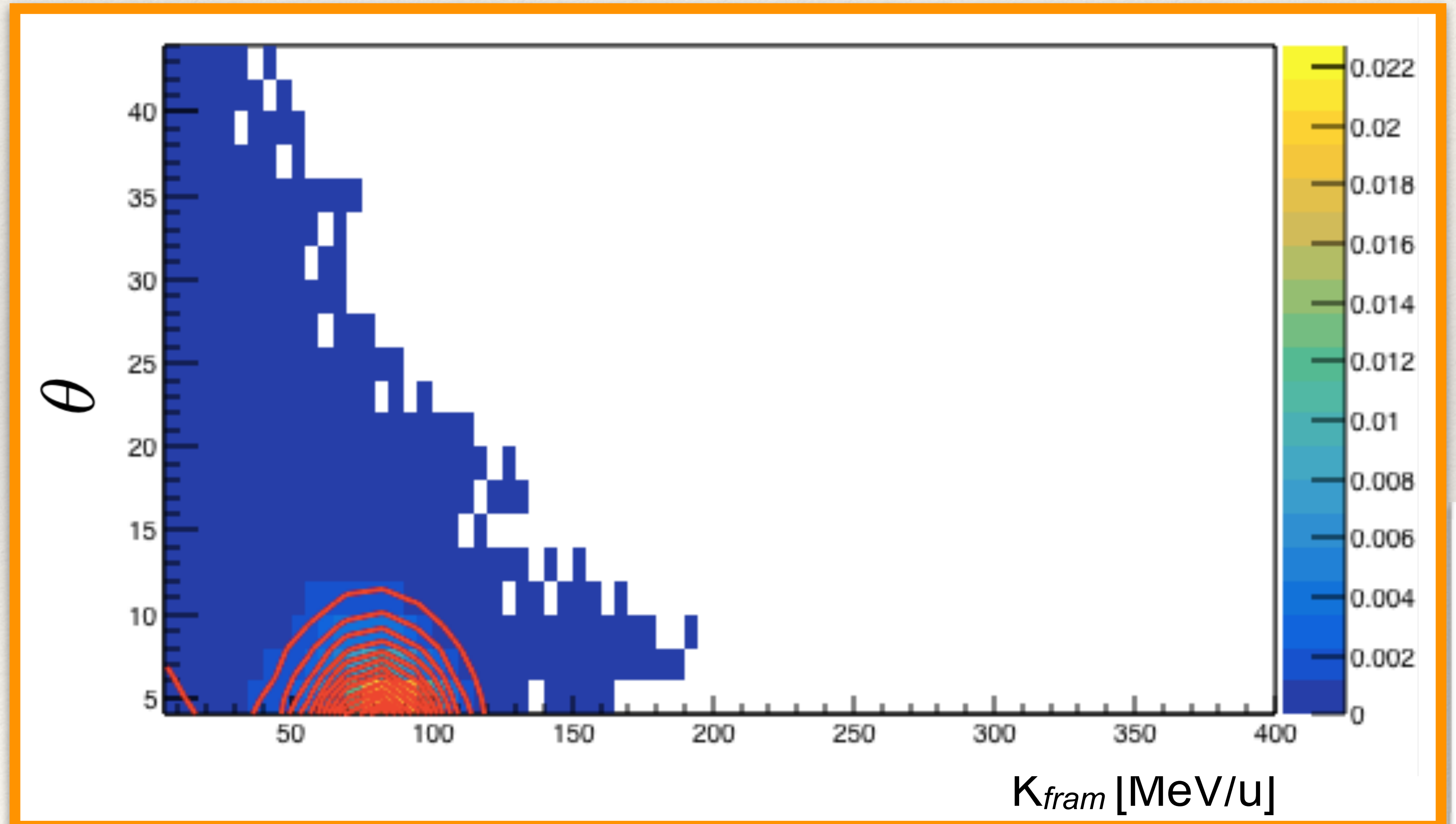


**$^6$Li angle and energy distribution**
**$^{12}$C [95MeV/u]**
**Oxygen Target**

# Step 3.III: Energy and Angle Scaling

Scaling of fragments **kinetic energy**:

$$K_f = K_f^{Ganil} R$$

Scaling of fragments **angle emission**:

$$\theta = \theta^{Ganil} \frac{1}{R}$$

$$R = \frac{K_b}{K_b^{Ganil}}$$

$K_f =$ Kinetic Energy of fragments produced by a beam with kinetic energy $K_b$

$K_f^{Ganil} =$ Kinetic Energy of fragments produced by the beam used in the GANIL experiment

$K_b =$ Kinetic Energy of the beam

$K_b^{Ganiil} =$ Kinetic Energy of the beam used in the GANIL experiment

$\theta_f =$ Angle of fragmentation with a beam of kinetic energy $K_b$

$p_f =$ Transverse momentum of the fragment

$p_b =$ Transverse momentum of the beam

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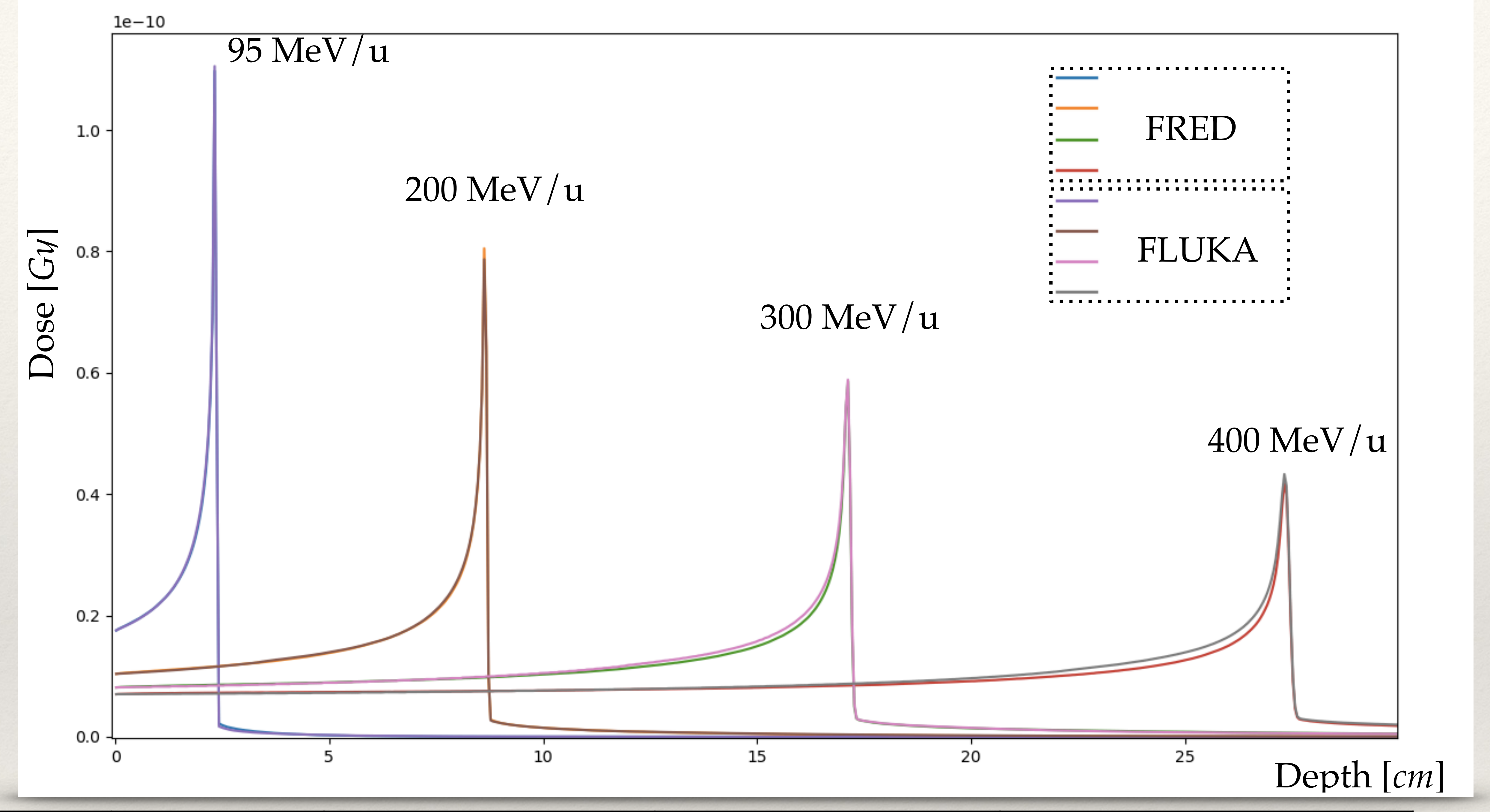
# Results




| | 95MeV/u | 200MeV/u | 300MeV/u | 400MeV/u |
|---|---|---|---|---|
| Δint | -0.4% | -0.7% | -2% | -7.8% |
| Δpeak | -0.7% | +2.3% | -0.4% | -3.6% |

# To do list

- Compare FRED with "Michela  data"
- Compare FRED with data of Haettner experiment

Measurement of 12C Fragmentation Cross Sections on C, O and H in the Energy Range of interest for Particle Therapy Applications

February 2020
DOI: 10.1109/TRPS.2020.2972197
Project: FOOT Experiment

Ilaria Mattei · Andrey Alexandrov · Luisa Alunni Solestizi · Show all 87 authors · Alessio Sarti

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. 58 (2013) 8265–8279 — doi:10.1088/0031-9155/58/23/8265

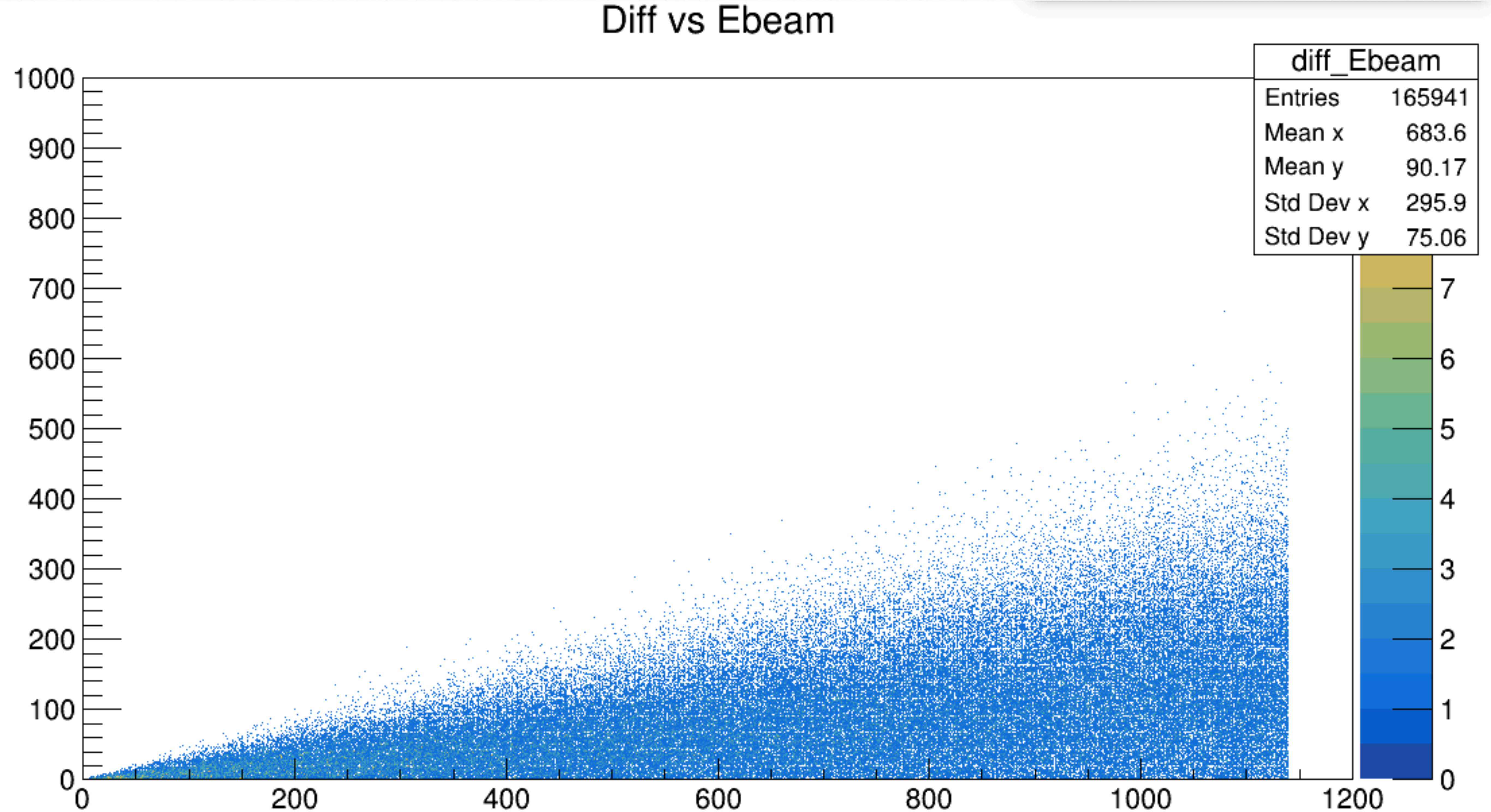
**Experimental study of nuclear fragmentation of 200 and 400 MeV/*u* $^{12}$C ions in water for applications in particle therapy**

E Haettner, H Iwase[1], M Krämer, G Kraft and D Schardt

- Use FRED using a RTPLAN on a cube of water from CNAO
- Use FRED with a treatment plan of MedAustron

# Backup

# ENERGIA PERSA



# Sihvert formula

## N->1H

E>200 MeV/u

$$\sigma(p,N)_{\mathrm{reac}}=\pi r_0^2[1+A_t^{1/3}-b_0(1+A_t^{-1/3})]^2 ,$$

$$b_0=2.247-0.915(1+A_t^{-1/3}) ,$$

E<20 MeV/u

$$\sigma(E,p,N)_{\mathrm{reac}}=0.14e^{0.0985E}f(E,p,N)_{\mathrm{reac},1}\sigma(p,N)_{\mathrm{reac}} ,$$

20<E<150 MeV/u

$$\sigma(E,p,N)_{\mathrm{reac}}=f(E,p,N)_{\mathrm{reac},1}\sigma(p,N)_{\mathrm{reac}} ,$$

150<E<200 MeV/u

$$\sigma(E,p,N)_{\mathrm{reac}}=f(E,p,N)_{\mathrm{reac},1}f(E,p,N)_{\mathrm{reac},2}\sigma(p,N)_{\mathrm{reac}} + f(E,p,N)_{\mathrm{reac},3}f(p,N)_{\mathrm{reac}} ,$$

## N->N

$$\sigma(N,N)_{\mathrm{reac}}=\pi r_0^2[A_p^{1/3}+A_t^{1/3}-b_0[A_p^{-1/3}+A_t^{-1/3}]^2$$

$$b_0=1.581-0.876(A_p^{-1/3}+A_t^{-1/3}) .$$

$$f(E,p,N)_{\mathrm{reac},1}=1.15+\lambda_1 e^{-E/\lambda_2}(1-0.62e^{-E/200}) \times\sin(10.9E^{-0.28}) ,$$

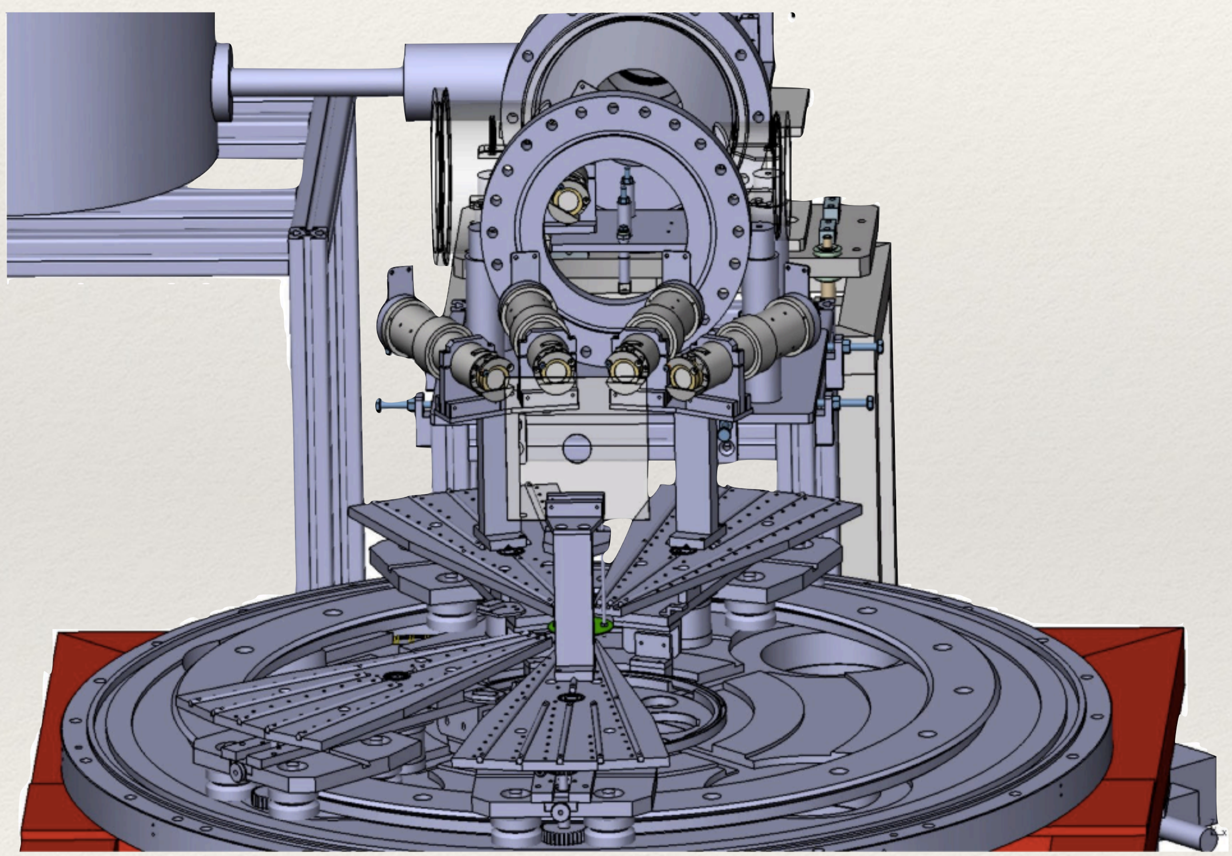
$$f(E,p,N)_{\mathrm{reac},2}=4.00-0.02E ,$$

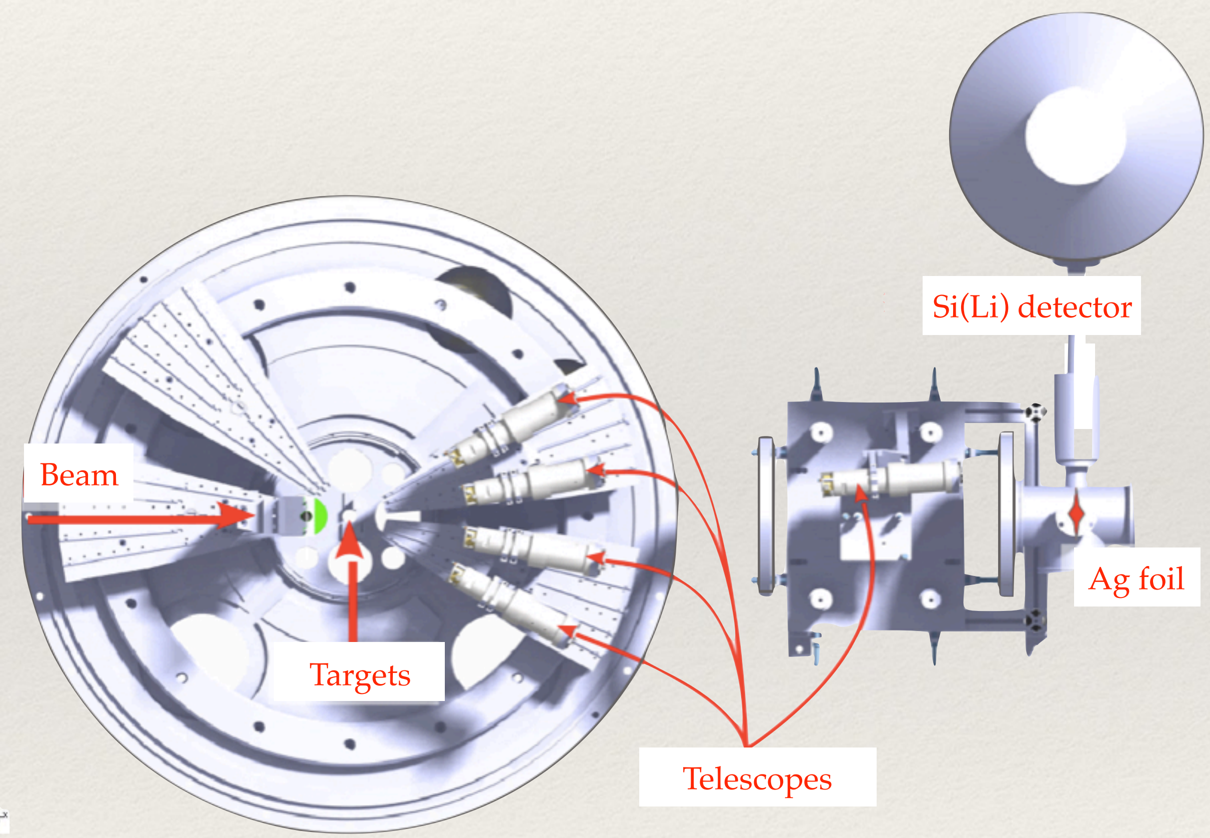
$$f(E,p,N)_{\mathrm{reac},3}=0.02E-3.00 .$$

# Ganil Experiment

Development of the model using data taken during experiments to study the fragmentation of $^{12}C$ beams on thin targets at GANIL (laboratory of CAEN, France, 2011-2017).

Data consist on: **energy and angular cross-section** distributions on H, C, O, Al, and Ti with beams of $^{12}C$ with energies of 50 and 95 MeV/n with a detection angle [-43°,+43°]



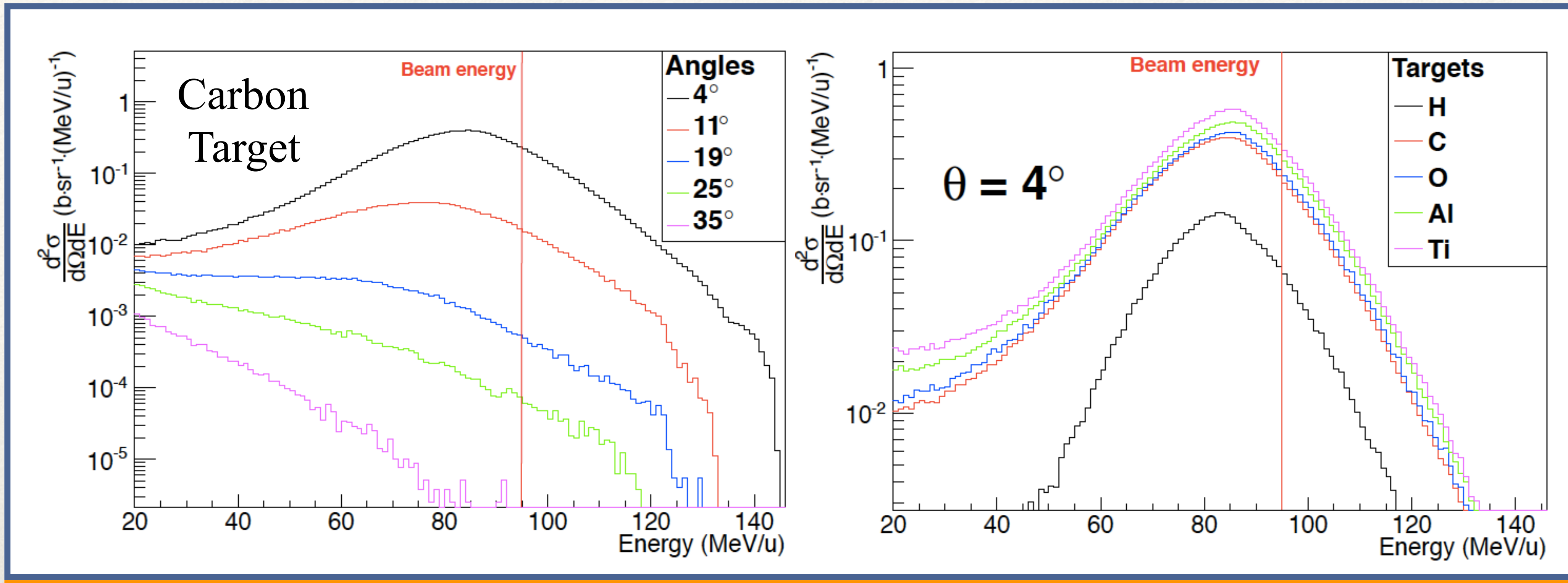



J. Dudouet, et al, C, PHYSICAL REVIEW American Physical Society, 2013

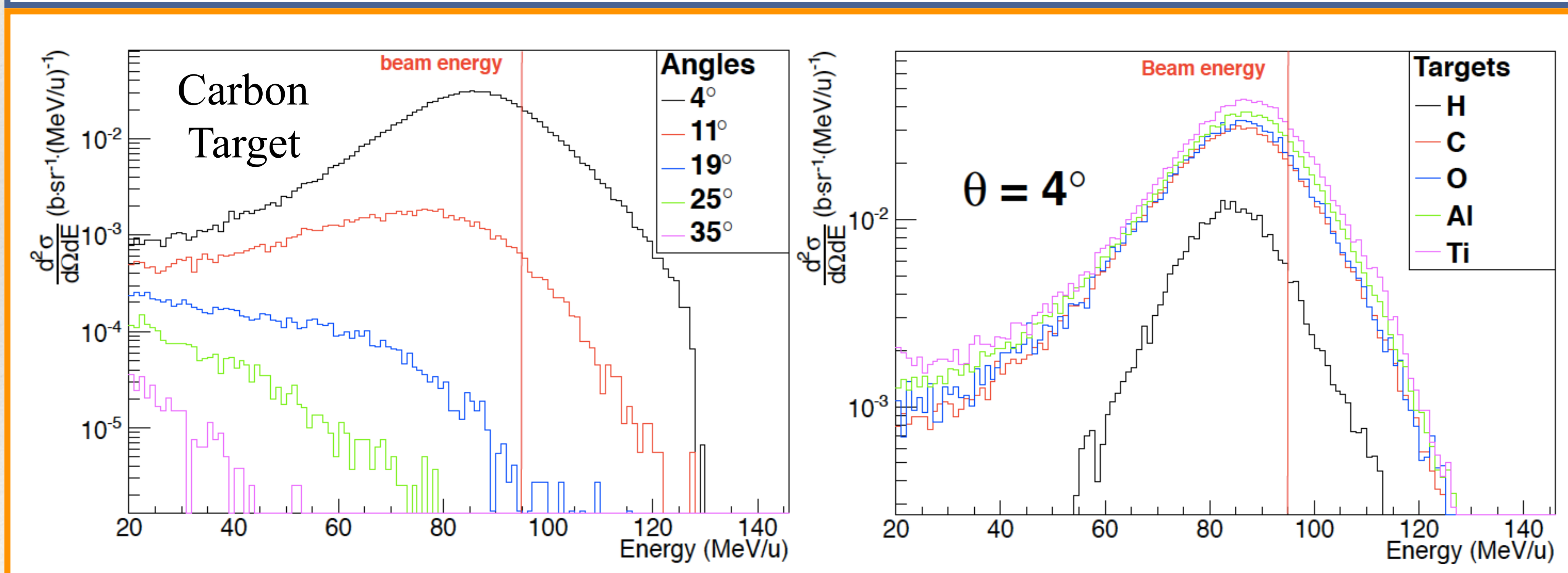
C. Divay et al, PHYSICAL REVIEW C 95, 044602 (2017)

# Ganil Experiment

$^4$He energy distribution
Beam:
$^{12}$C [95MeV/u]




$^6$Li energy distribution
Beam:
$^{12}$C [95MeV/u]




J. Dudouet, et al, C, PHYSICAL REVIEW American Physical Society, 2013

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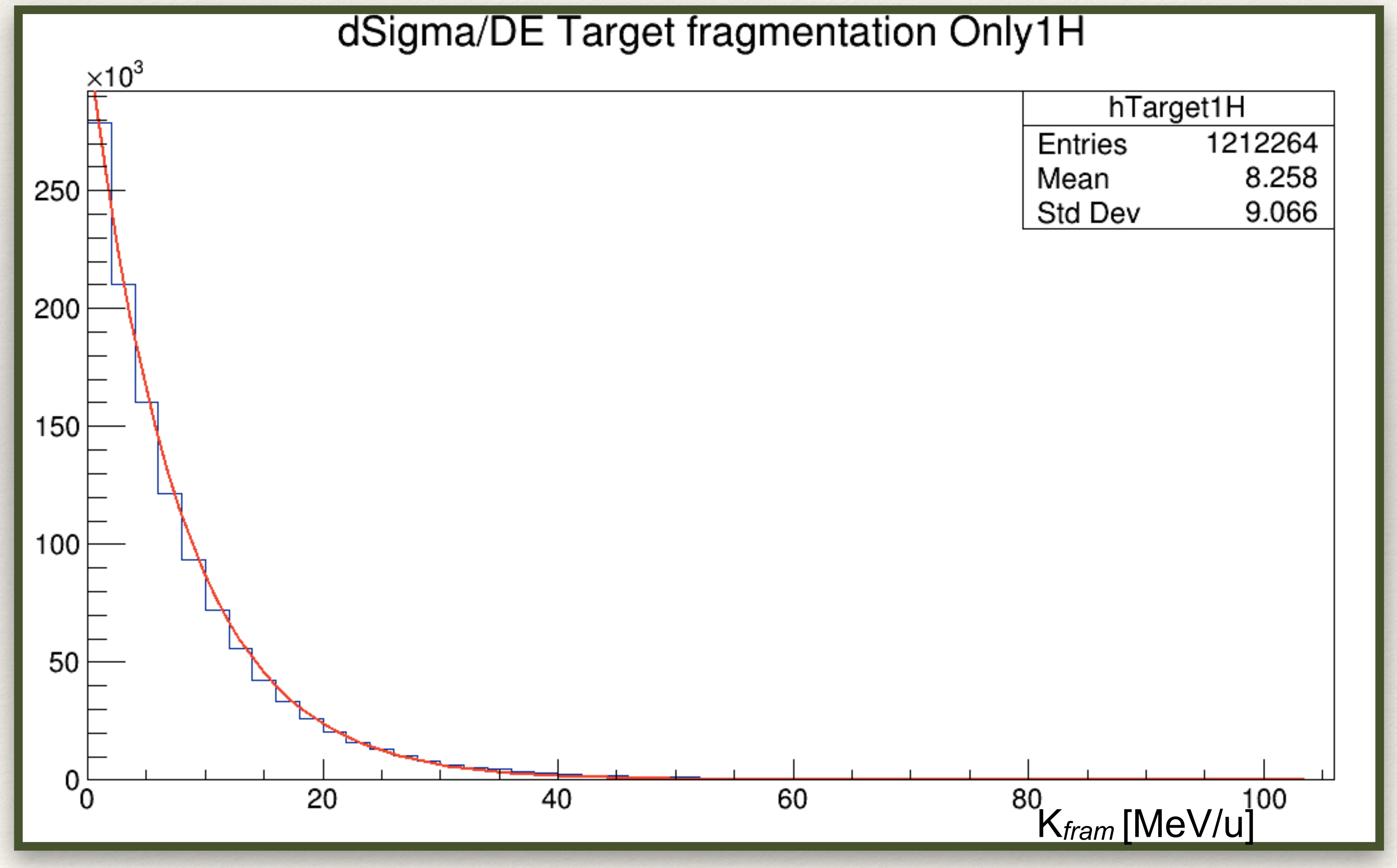


Fit parameters of FLUKA energy distribution of fragments in production used for **Target fragments**

**Proton energy distribution**

**$^{12}$C [95MeV/u]**

**Oxygen Target**

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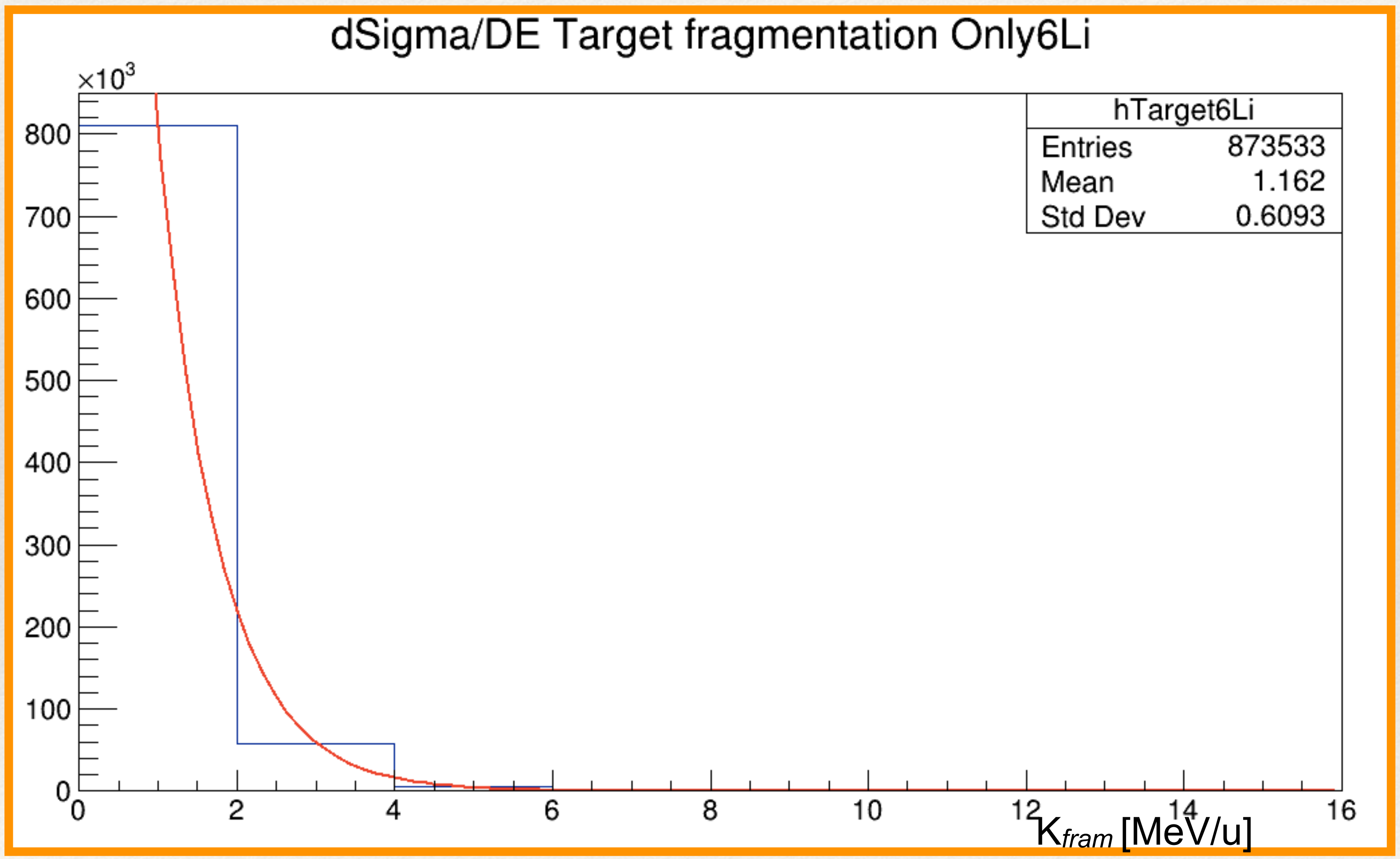
$$f(E,\theta) = A_1 e^{-(\alpha_E E+\alpha_\theta \theta)} + A_2 e^{-\left(\frac{(E-<E>)^2}{2\sigma_E}+\frac{(\theta-<\theta>)^2}{2\sigma_\theta}\right)}$$




Fit parameters of FLUKA energy distribution of fragments in production used for **Target fragments**

**$^{6}$Li energy distribution**
**$^{12}$C [95MeV/u]**
**Oxygen Target**