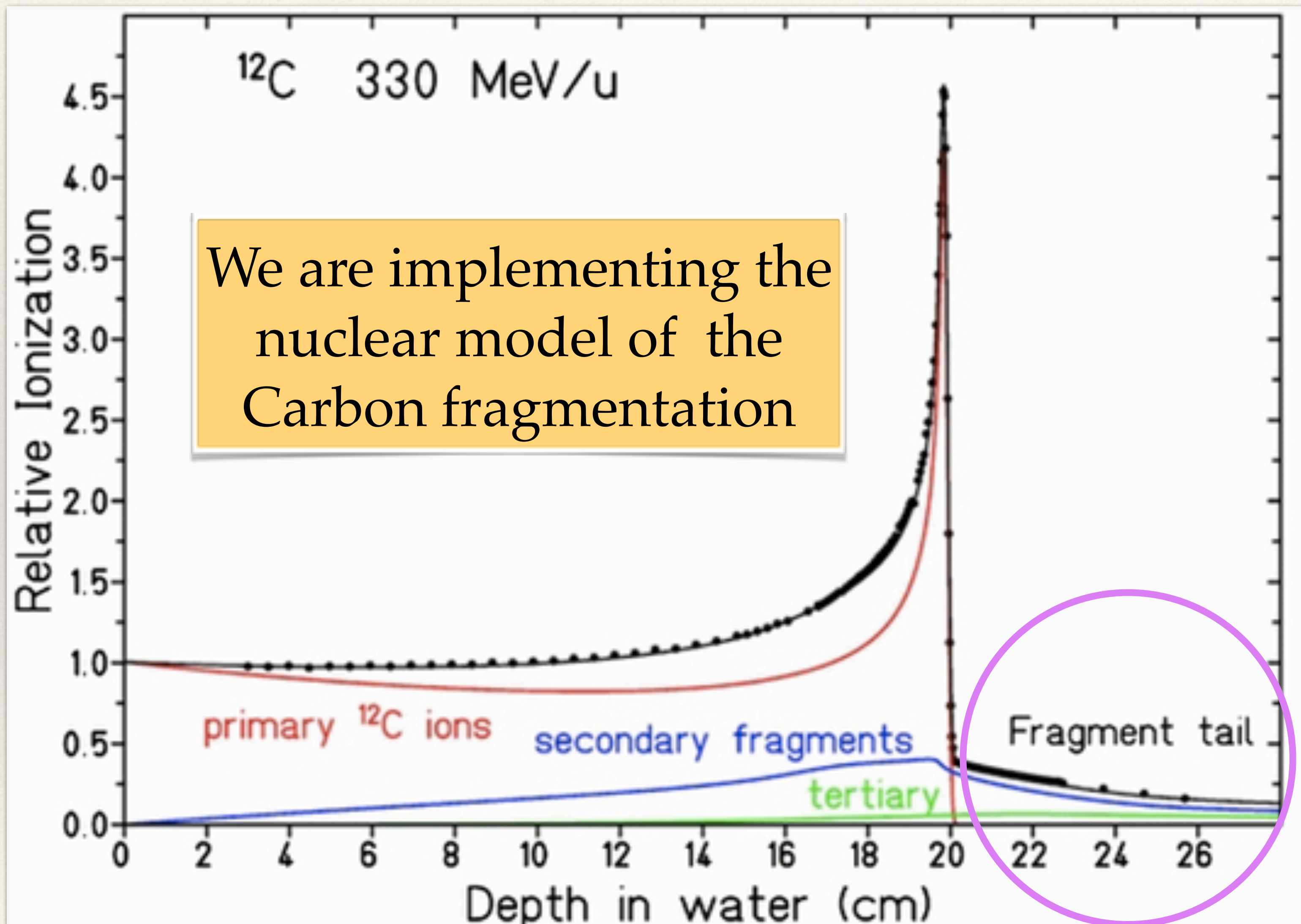
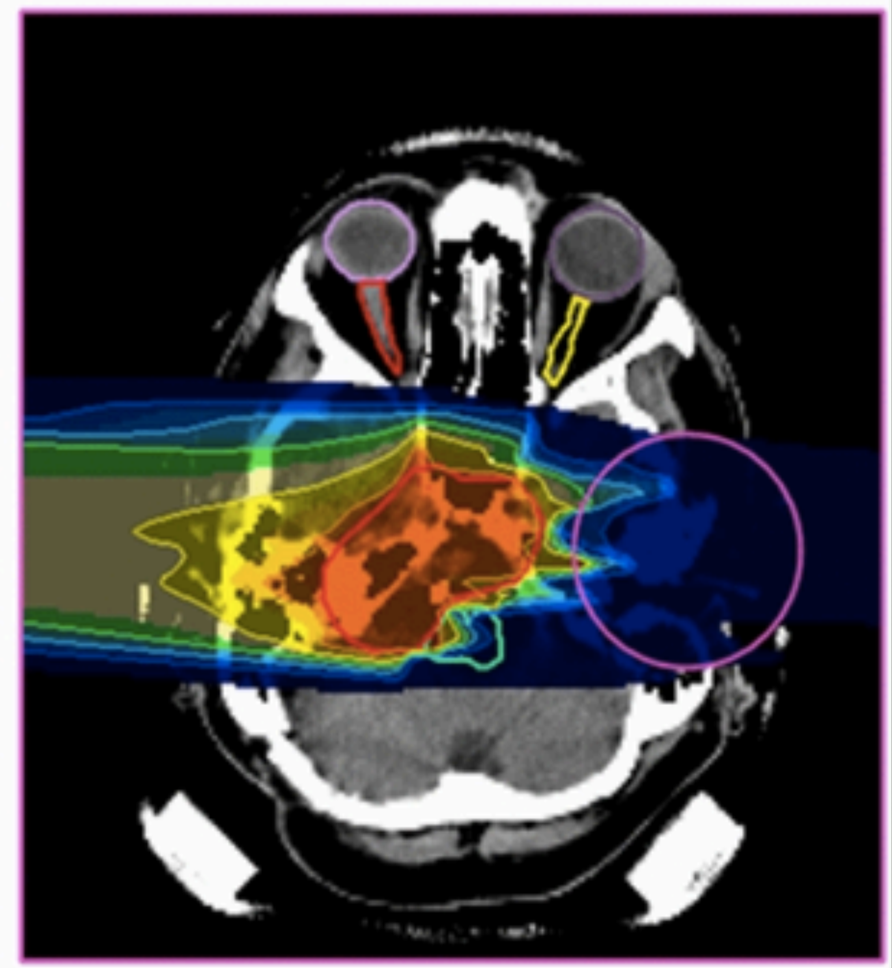
FRED for Carbon Ions

Micol De Simoni

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.





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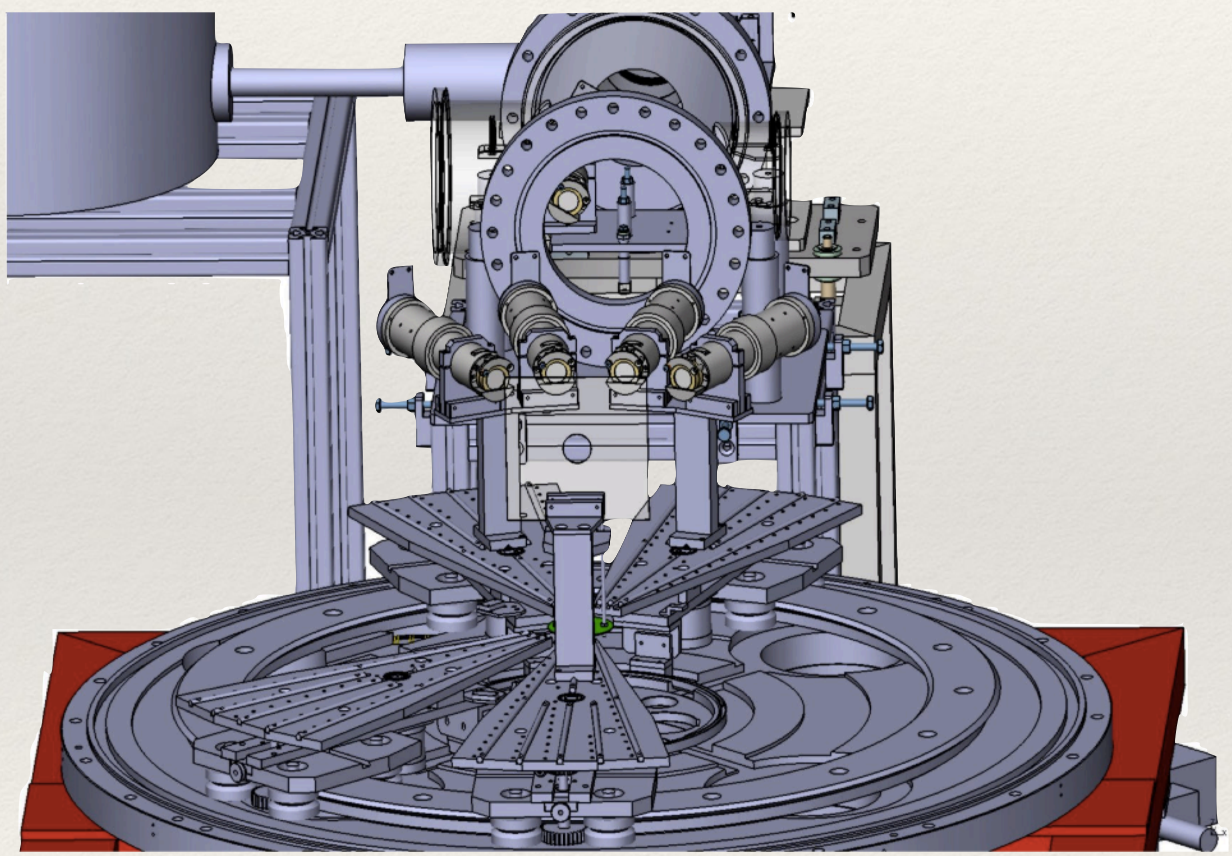
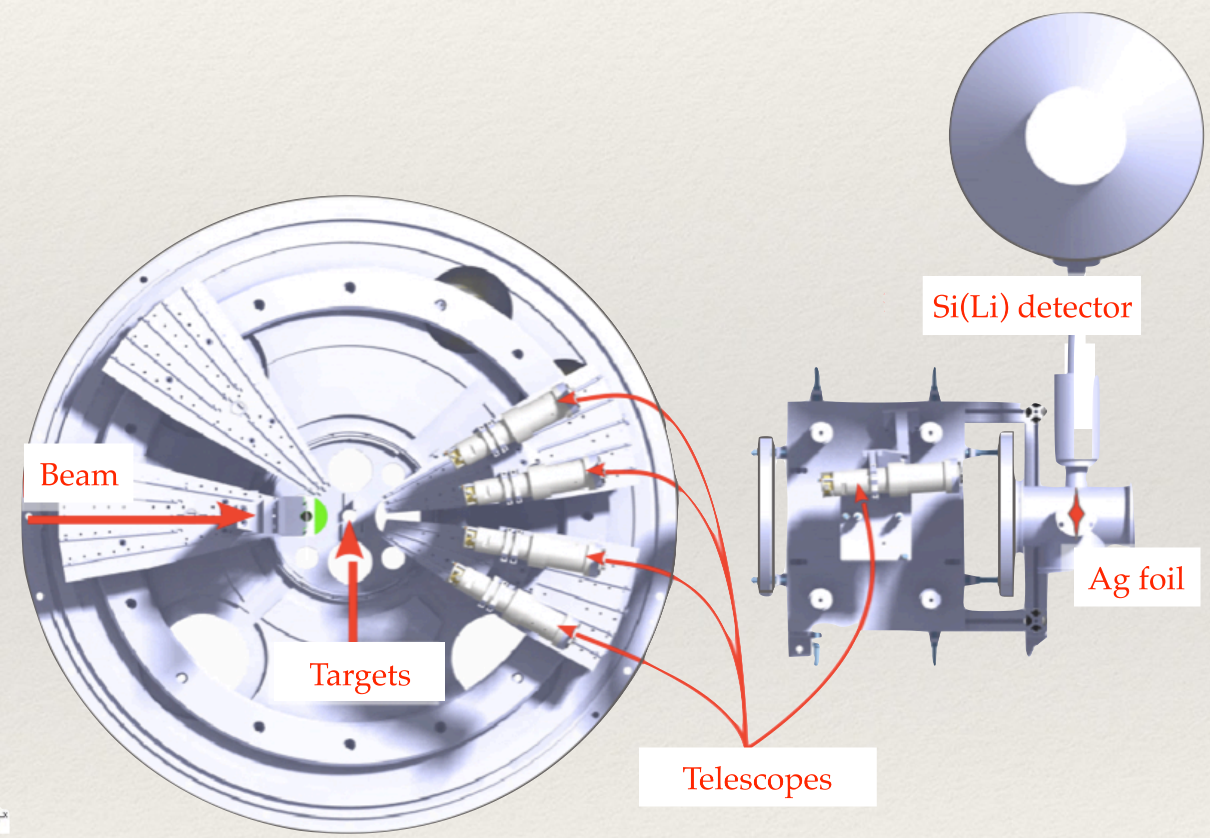
Ganil Experiment

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)

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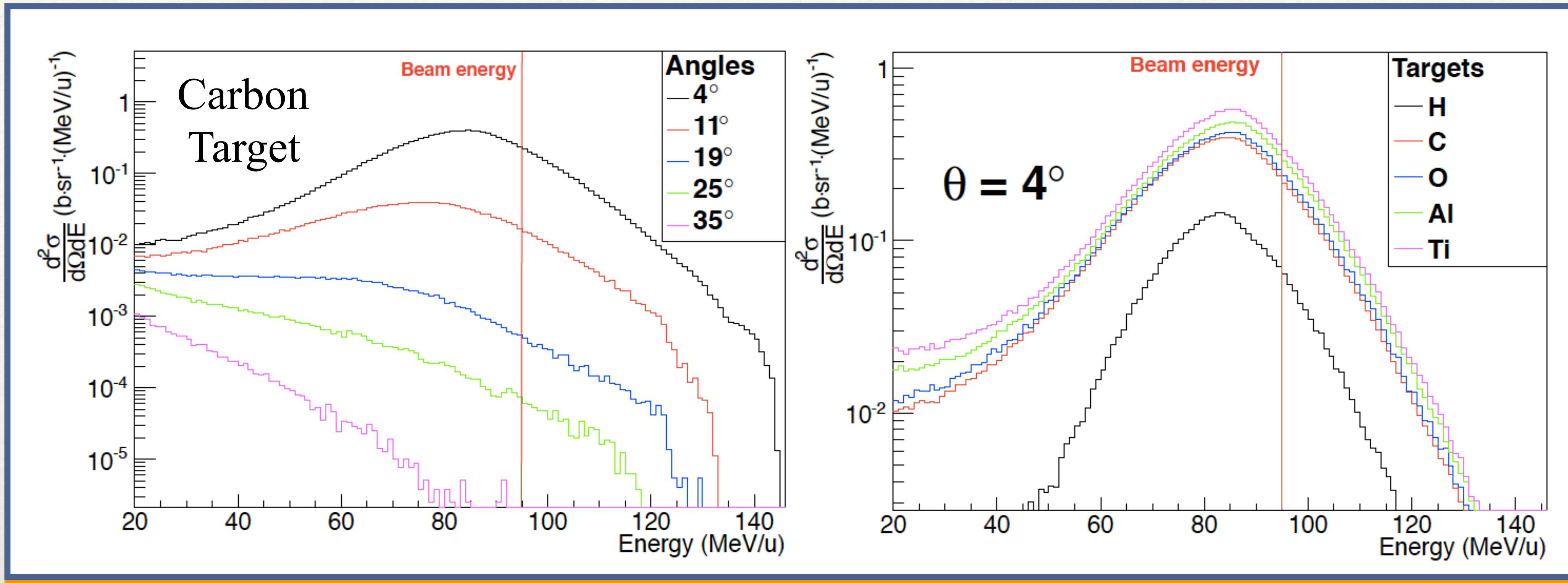
Ganil Experiment

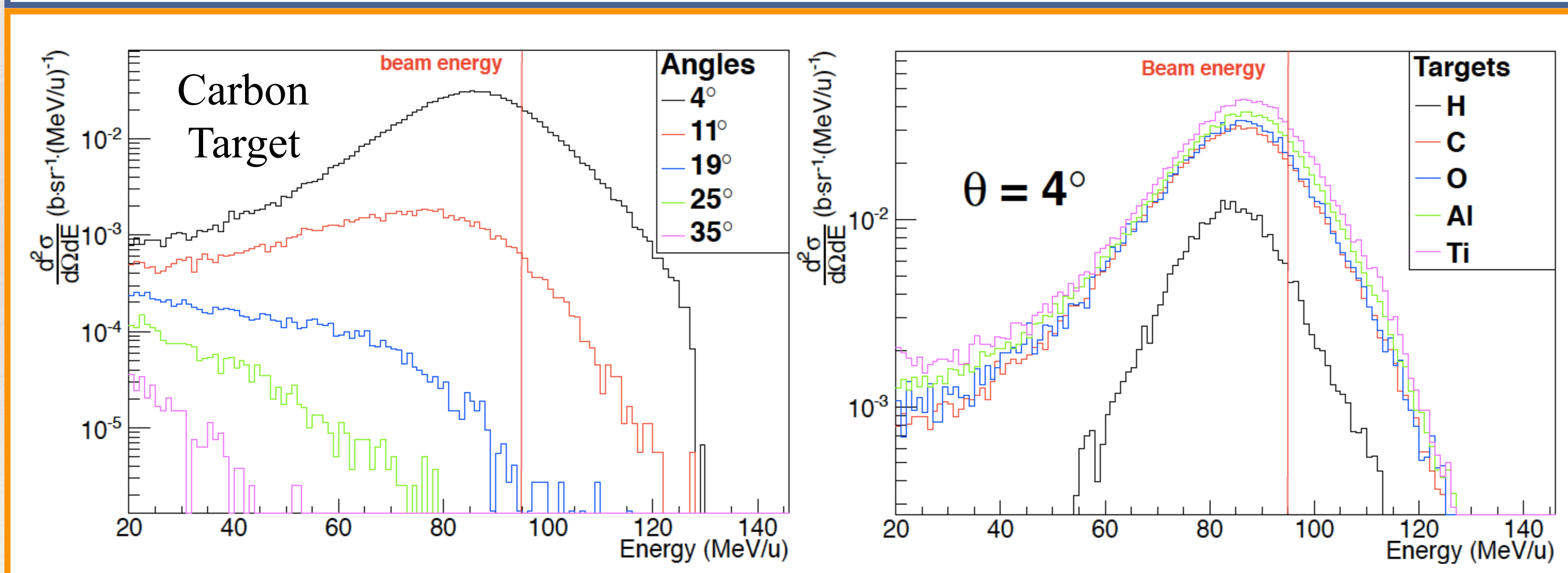
^{4}He energy distribution

Beam: ^{12}C [95MeV/u]



^{6}Li energy distribution

Beam: ^{12}C [95MeV/u]

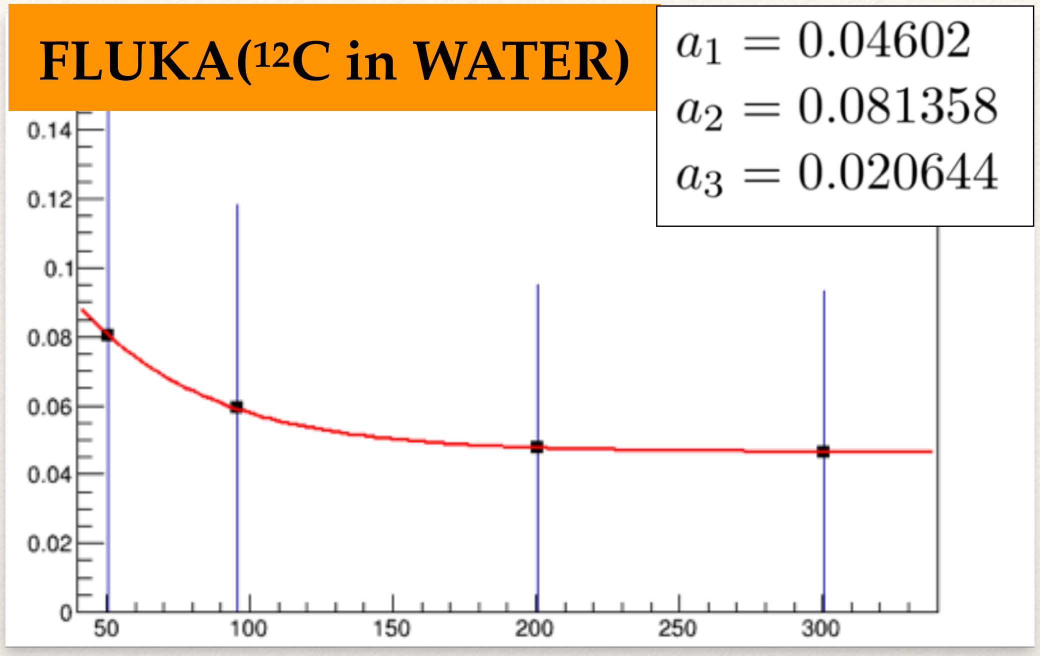


J. Dudouet, et al, C, PHYSICAL REVIEW American Physical Society, 2013

Step 1: Coefficient of Mass Attenuation

Calculation of the total cross section:

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



Scaling considering the type of projectile and the target using the **Sihver formula**:

$$\sigma_{scaling} = \frac{\pi r_o^2 [A_p^{1/3} + A_t^{1/3} - b_o [A_p^{-1/3} + A_t^{-1/3}]]^2}{\pi r_o^2 [12^{1/3} + 14.3255^{1/3} - b_r [12^{-1/3} + 14.3255^{-1/3}]]^2}$$

$$r_o = 1.36 fm$$
$$b_o = 1.581 - 0.876(A_p^{-1/3} + A_t^{-1/3})$$
$$b_r = 1.581 - 0.876(12^{-1/3} + 14.3255^{-1/3})$$

Where the A of the target is calculated as the sum of the A_i of each element of the target for the weight of the element

$$\sigma_{tot} = \sigma \cdot \sigma_{scaling}$$

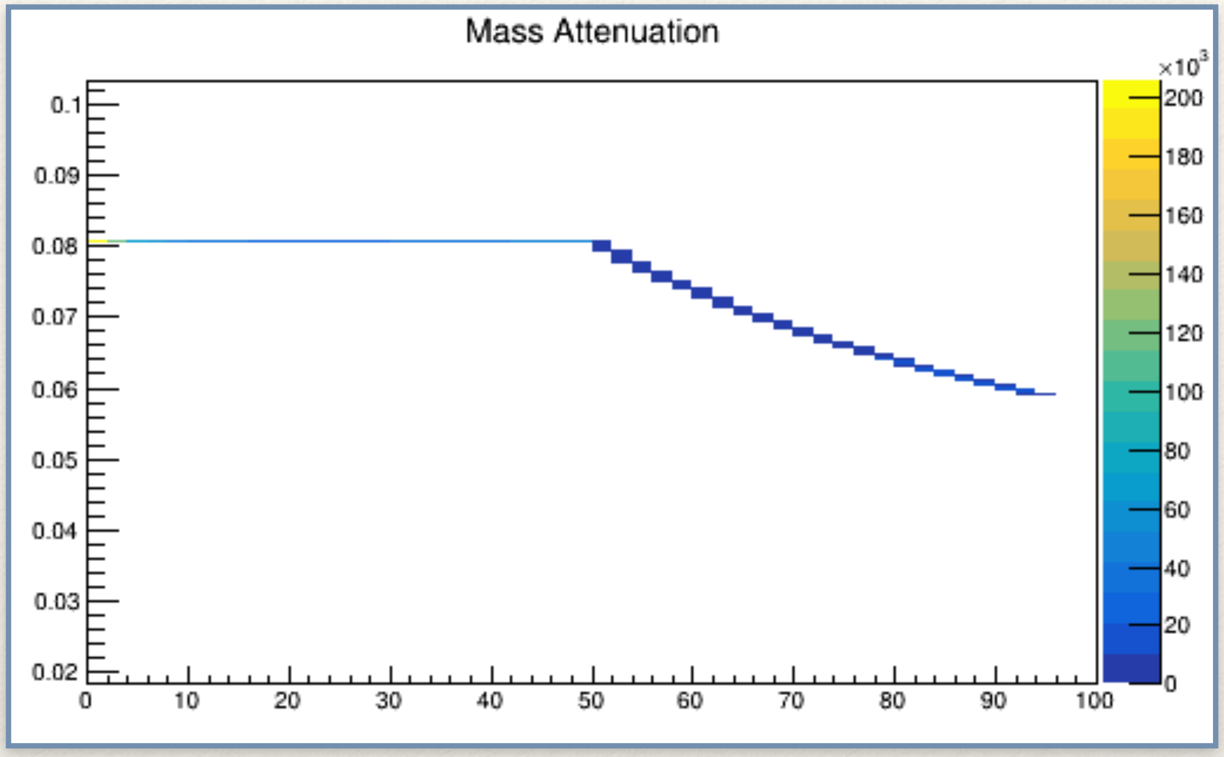
If the projectile is a neutron or a proton the total cross section is zero

So the mass attenuation is:

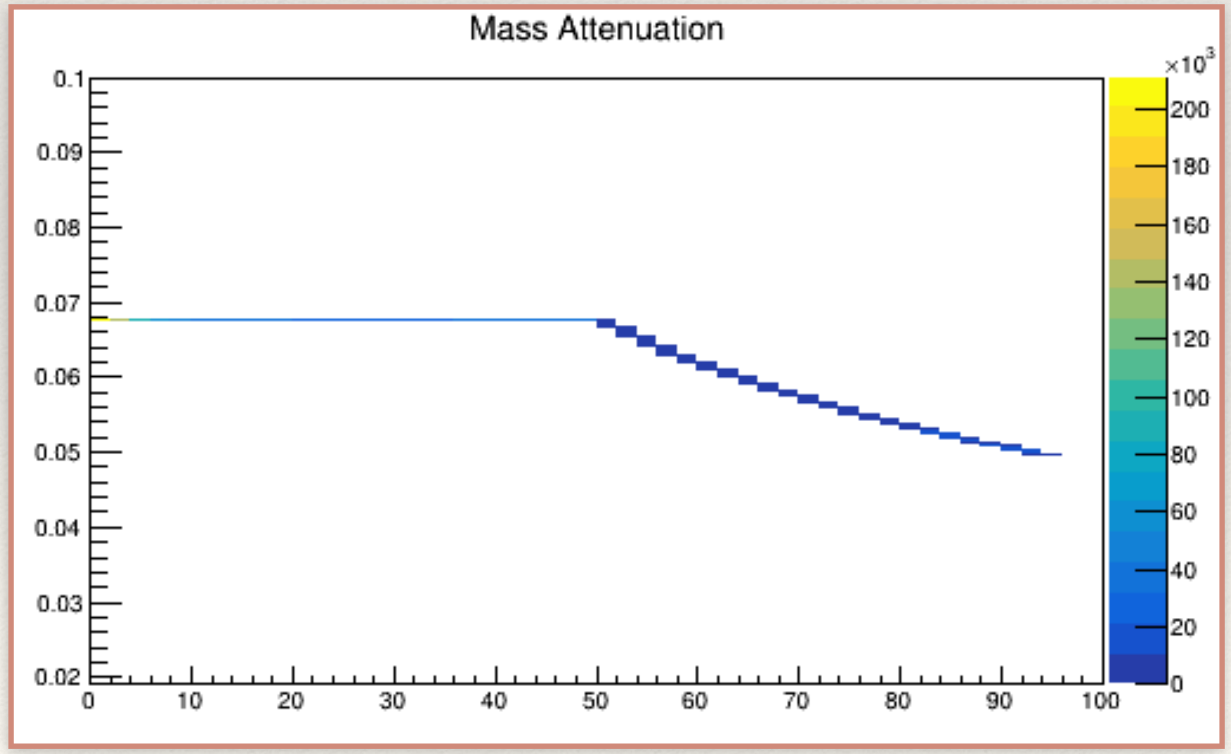
$$\mu = \frac{\sigma_{tot}}{\rho}$$

Step 1: Coefficient of Mass Attenuation

Target WATER



Target PMMA



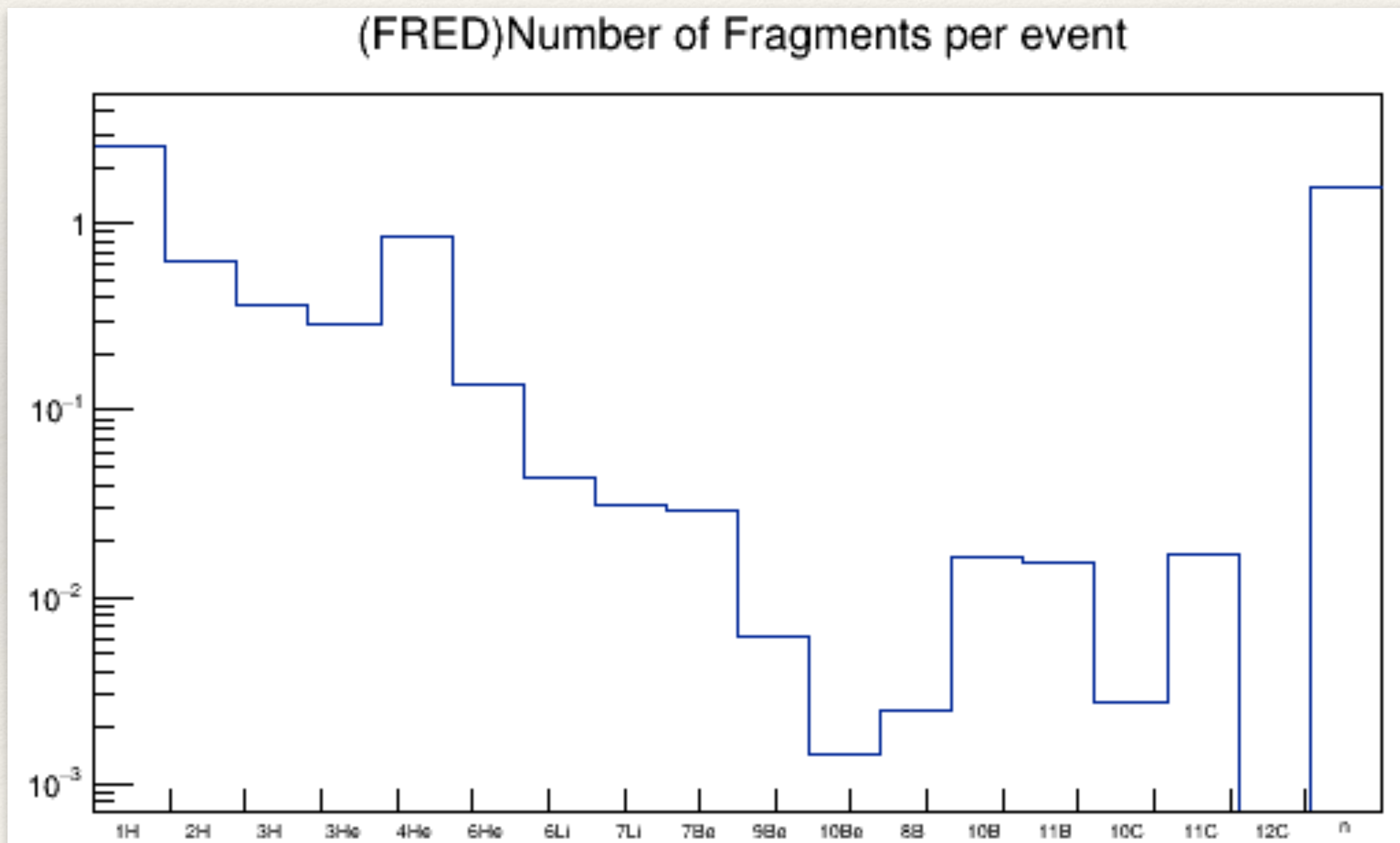
Step 2.1: Choose the Fragments emitted by the Projectile

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

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

If $\Sigma A_i \neq A_{projectile}$

Fred chooses $A_{projectile} - \Sigma A_i$ neutrons



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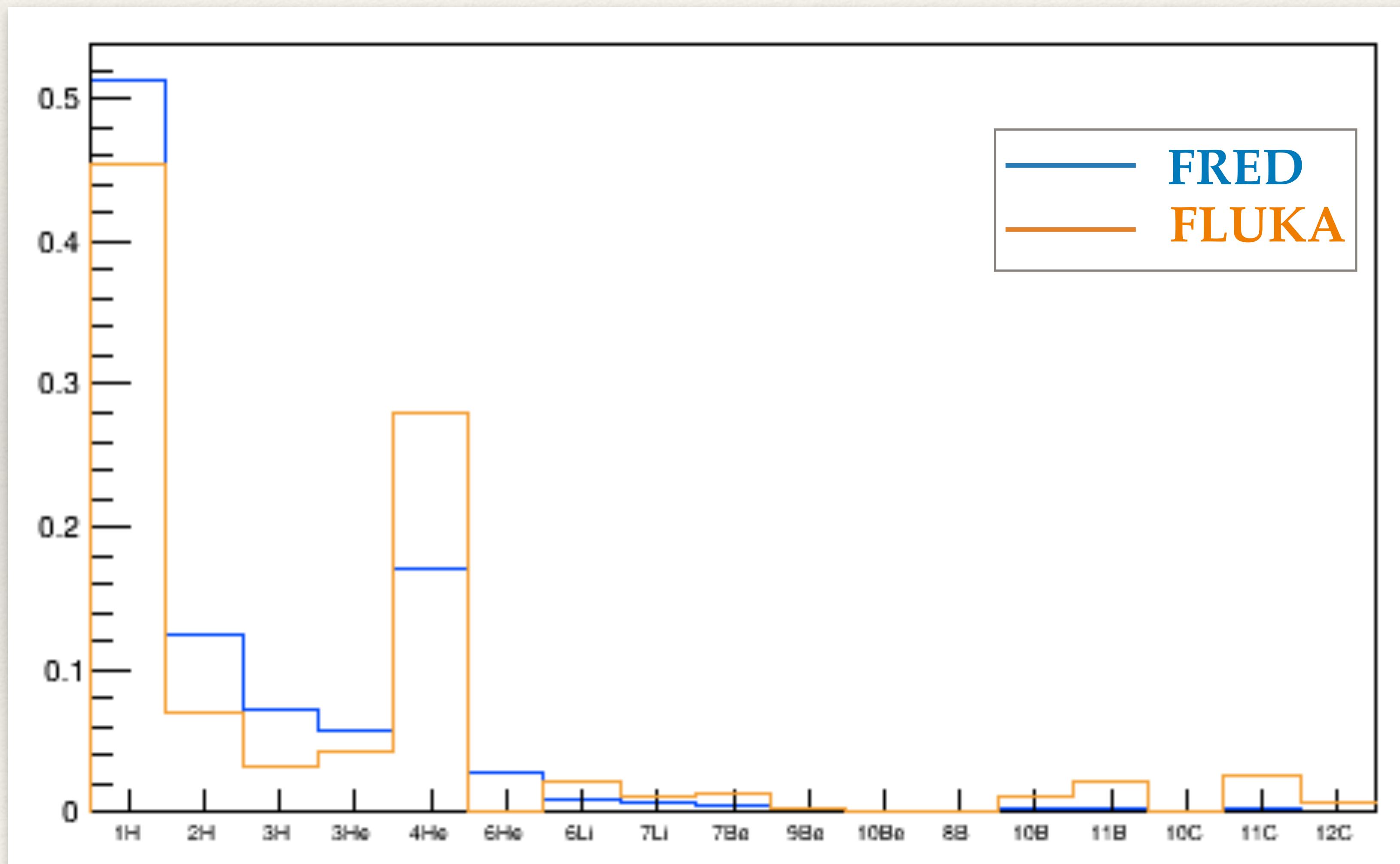

Step 2.1: Choose the Fragments emitted by the Projectile

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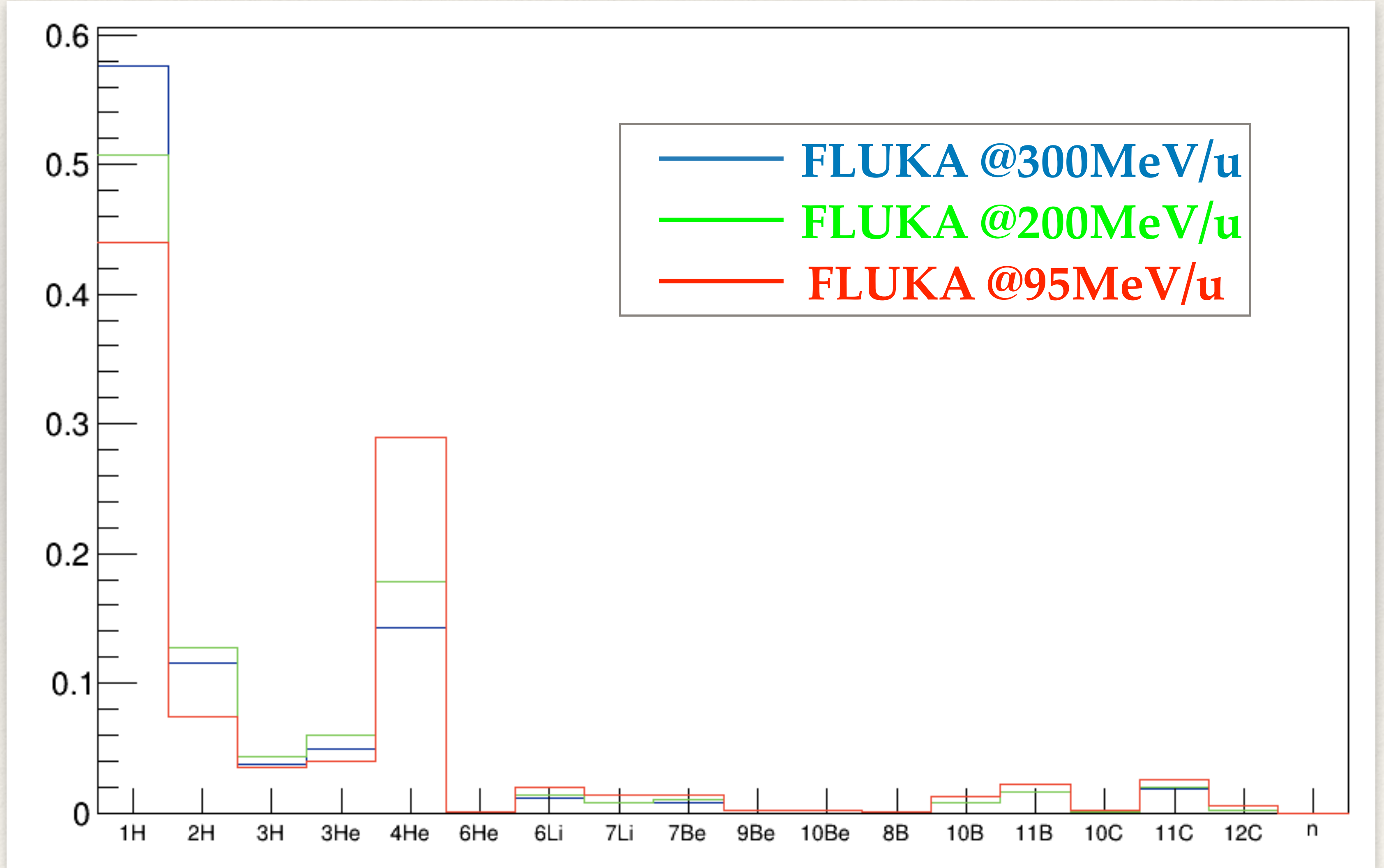
$\Sigma A_i \leq A_{projectile}$ **AND** $\Sigma Z_i = Z_{projectile}$

If $\Sigma A_i \neq A_{projectile}$

Fred chooses $A_{projectile} - \Sigma A_i$ neutrons

PROBLEM:
With FLUKA the multiplicity changes with energy while in FRED is always the same

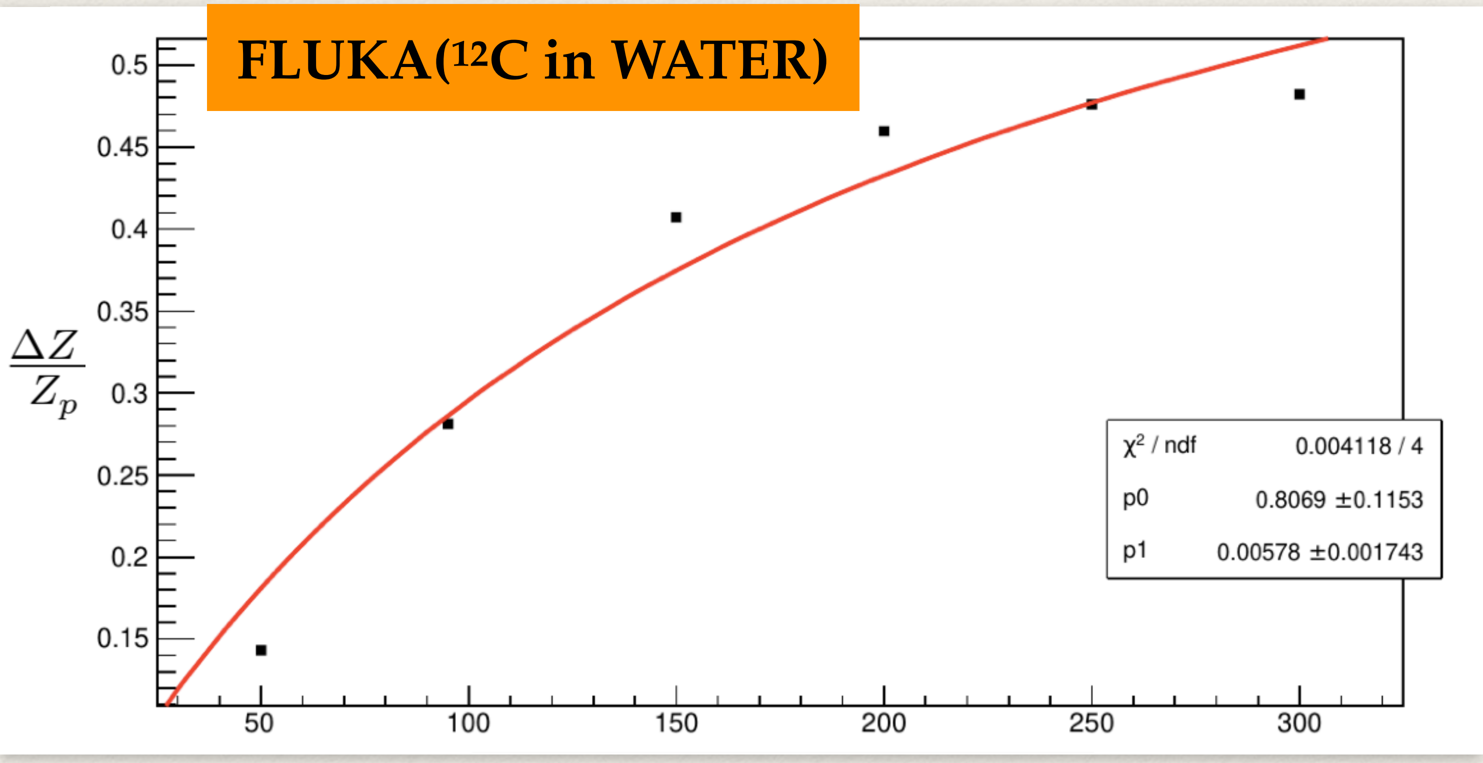


Step 2.2: Choose the Fragments emitted by the Target

Calculation of the Probability for a specific projectile with an energy E_p to have fragments with Z_{tot} more that its charge Z_p using **Poisson**

$$< m >= \left(\frac{\Delta Z^{Fluka}}{Z_p^{Fluka}}\right) Z_p = p_0 \left(1 - \frac{1}{1+p_1 E_p}\right) Z_p$$

FLUKA(^{12}C in WATER)



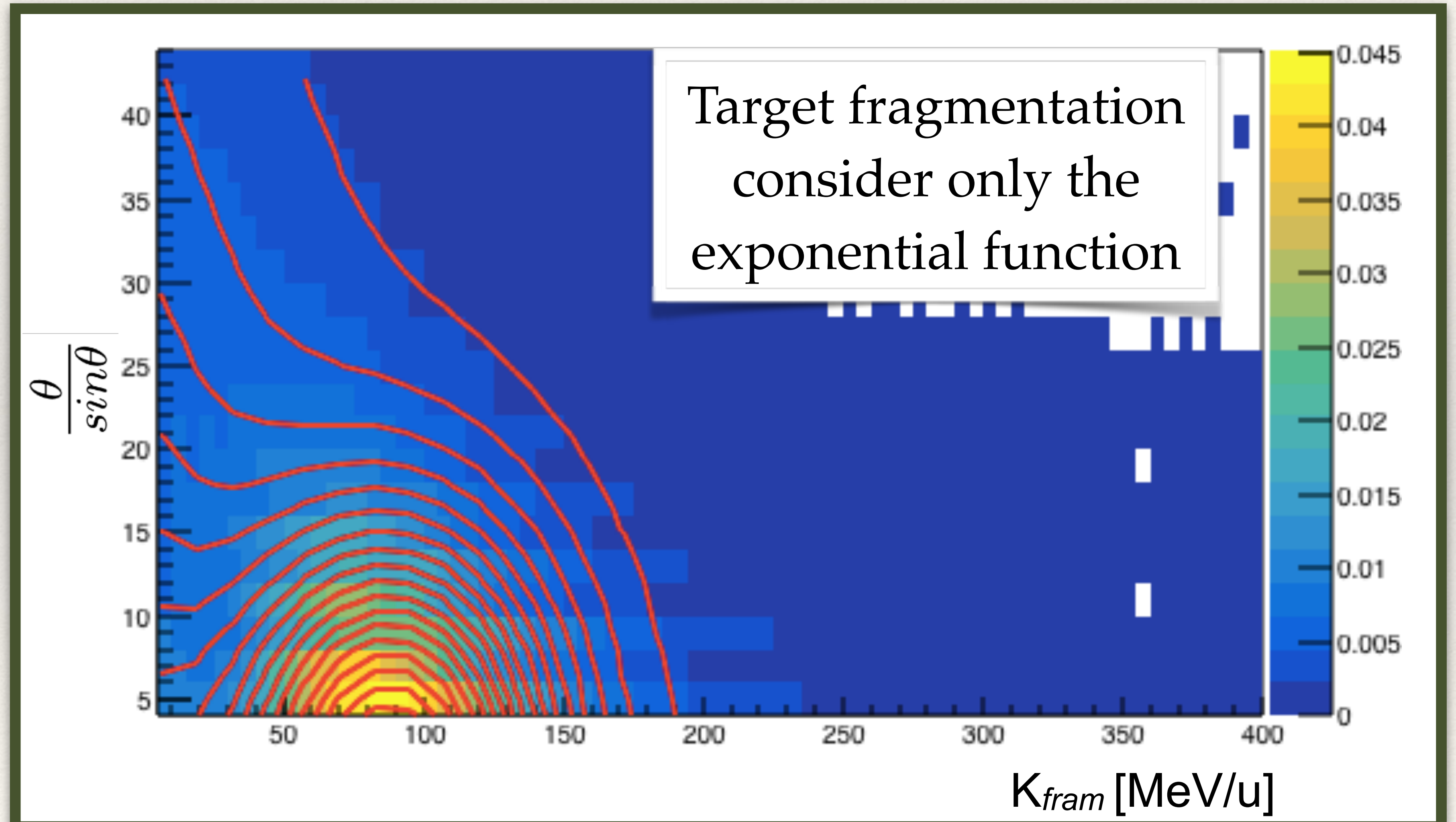
$$P_{Zi} = \frac{<m>^{Z_i}}{Z_i!} e^{-<m>}$$

After have chosen how much will be the Z to add from the target fragmentation, new fragments will be choose considering the cumulative described in the previously slide (considering only fragments: 1H 2H 3H 3He 4He 6He)

Step 3: Choose Energy and angle of Fragments emitted

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

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



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

<E> = 90.671684
σ_E = 36.531088
<θ> = 0.000000
σ_θ = 9.805276
α_E = 0.013709
α_θ = 0.029889
Exp/Gauss = 0.316909

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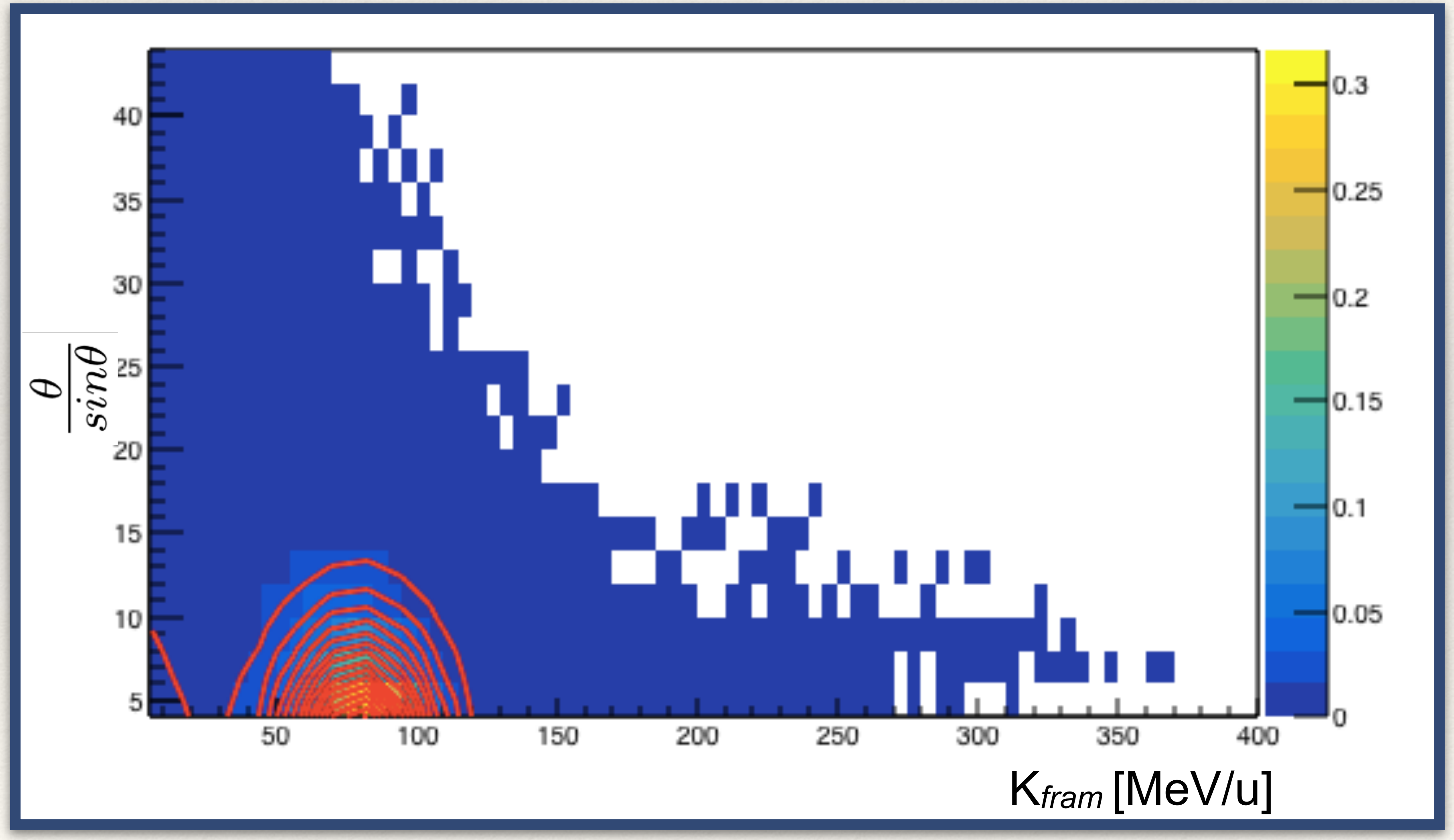
Step 3: Choose Energy and angle of Fragments emitted

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

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



^{4}He angle and energy distribution

^{12}C [95MeV/u]

Oxygen Target

$<E> = 79.755656$

$\sigma_E = 15.347413$

$<\theta> = 0.000000$

$\sigma_\theta = 5.331252$

$\alpha_E = 0.032361$

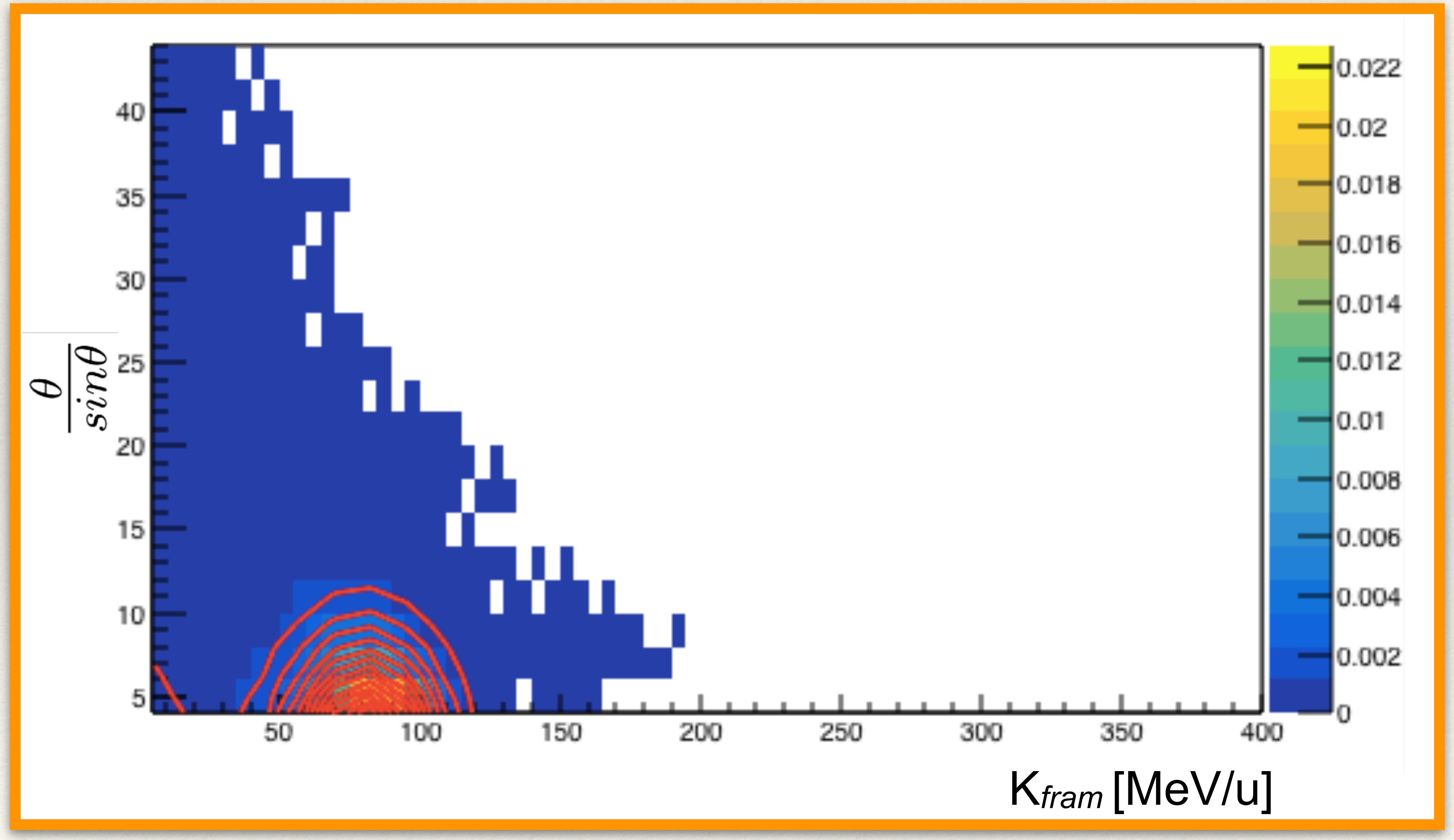
$\alpha_\theta = 0.074388$

Exp/Gauss = 0.079492

Step 3: Choose Energy and angle of Fragments emitted

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

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



^{6}Li angle and energy distribution

^{12}C [95MeV/u]

Oxygen Target

<E> = 80.775685

σ_E = 14.808873

<θ> = 0.000010

σ_θ = 4.563475

α_E = 0.030777

α_θ = 0.100689

Exp/Gauss = 0.074359

Step 4: 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

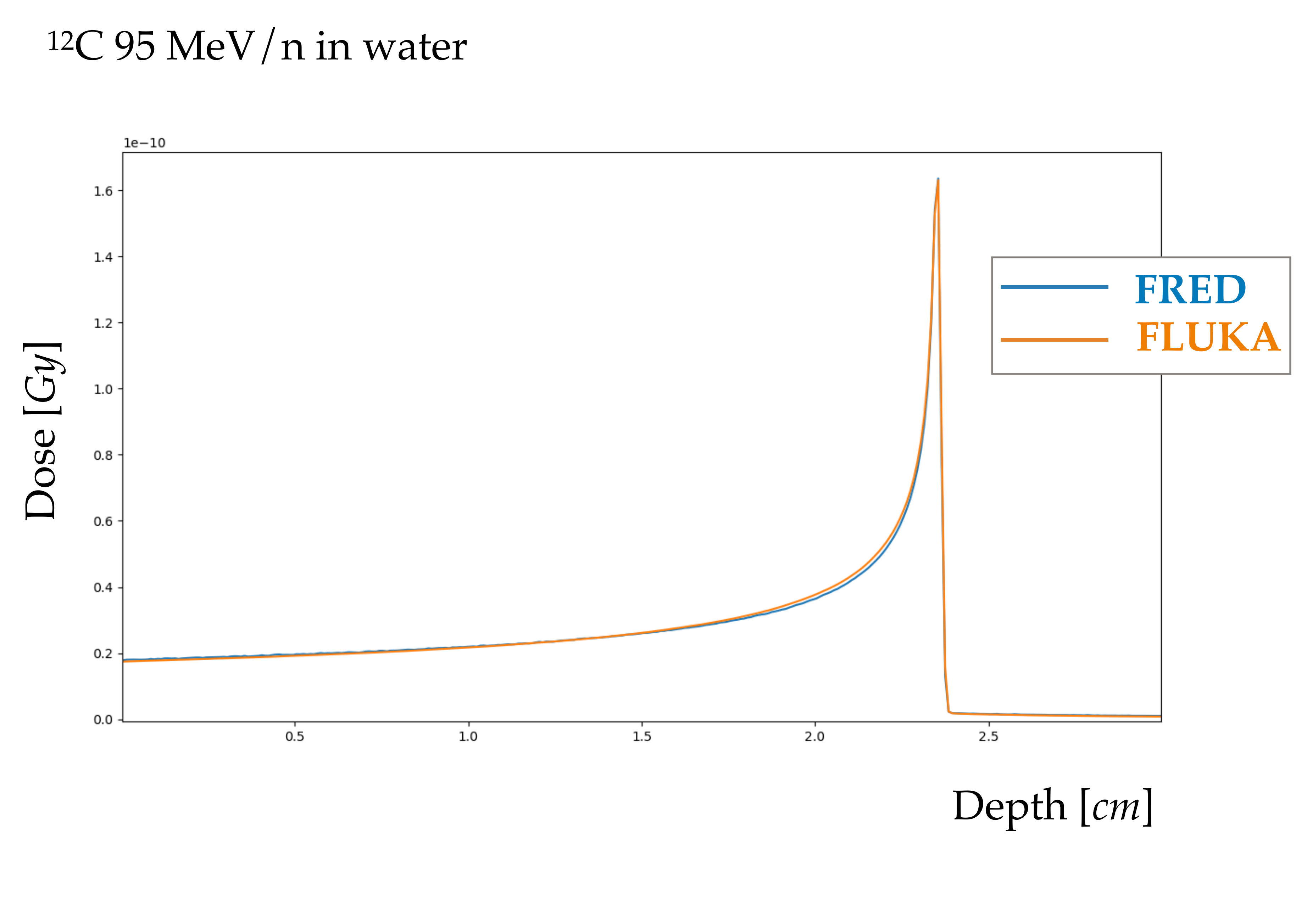
$p_f =$ Transverse momentum of the fragment

$p_b =$ Transverse momentum of the beam

Step 5: Local deposition of Energy

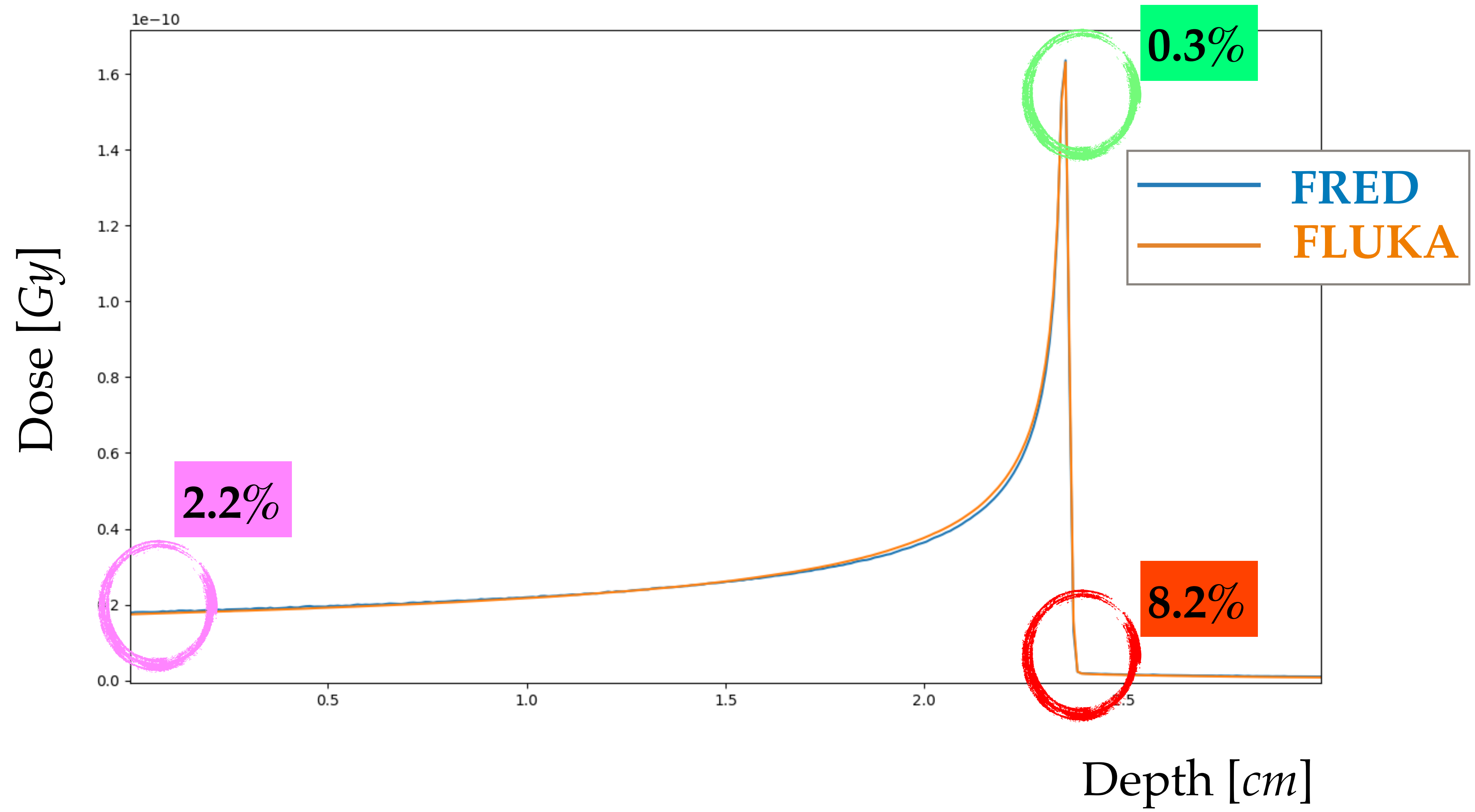
The energy which is not used for projectile and target fragmentation is deposited locally

Results



^{12}C 95 MeV/n in water
1e−10
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Dose [Gy]
0.5
1.0
1.5
2.0
2.5
Depth [cm]
FRED
FLUKA

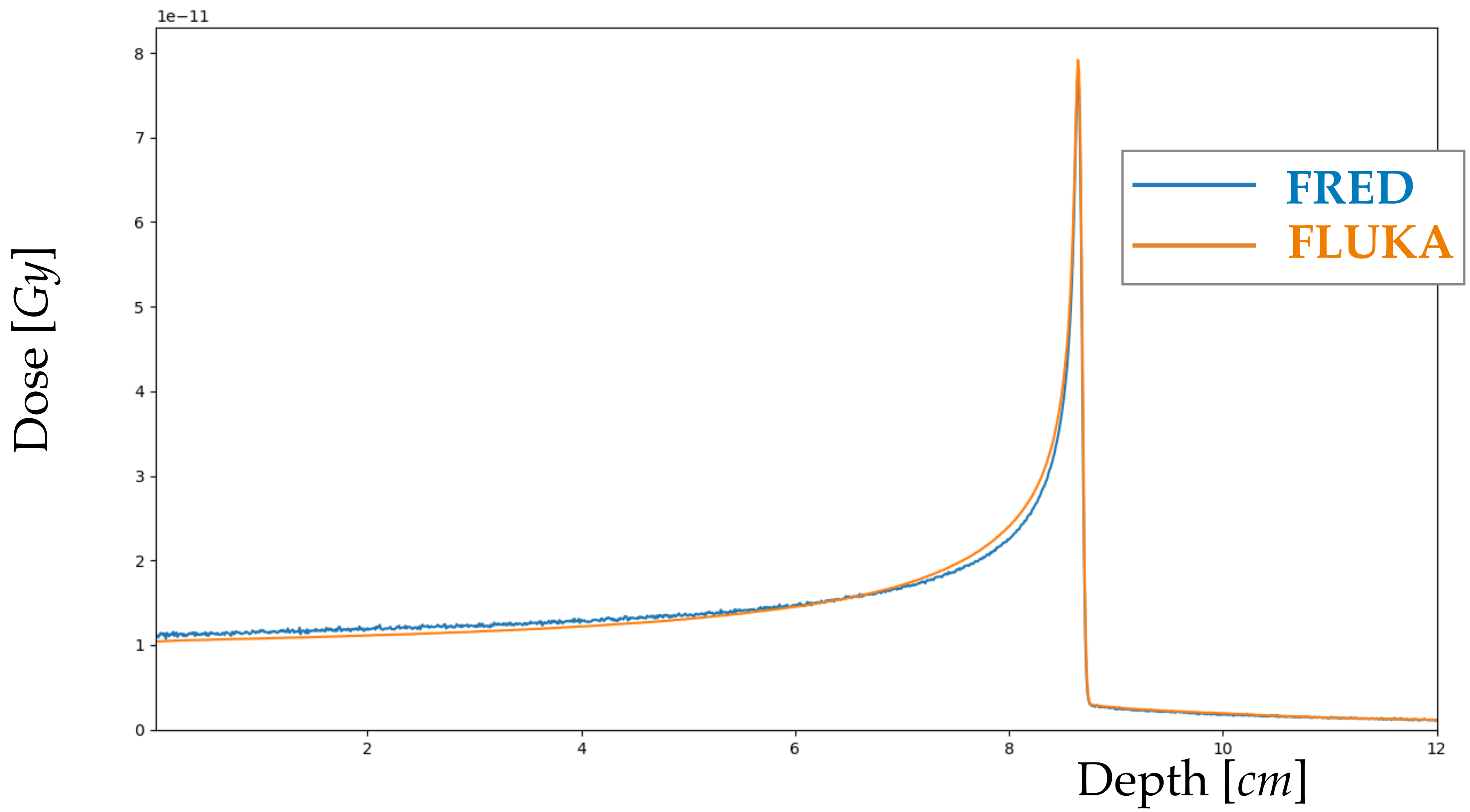
^{12}C 95 MeV/n in water



Integral: 0.6%

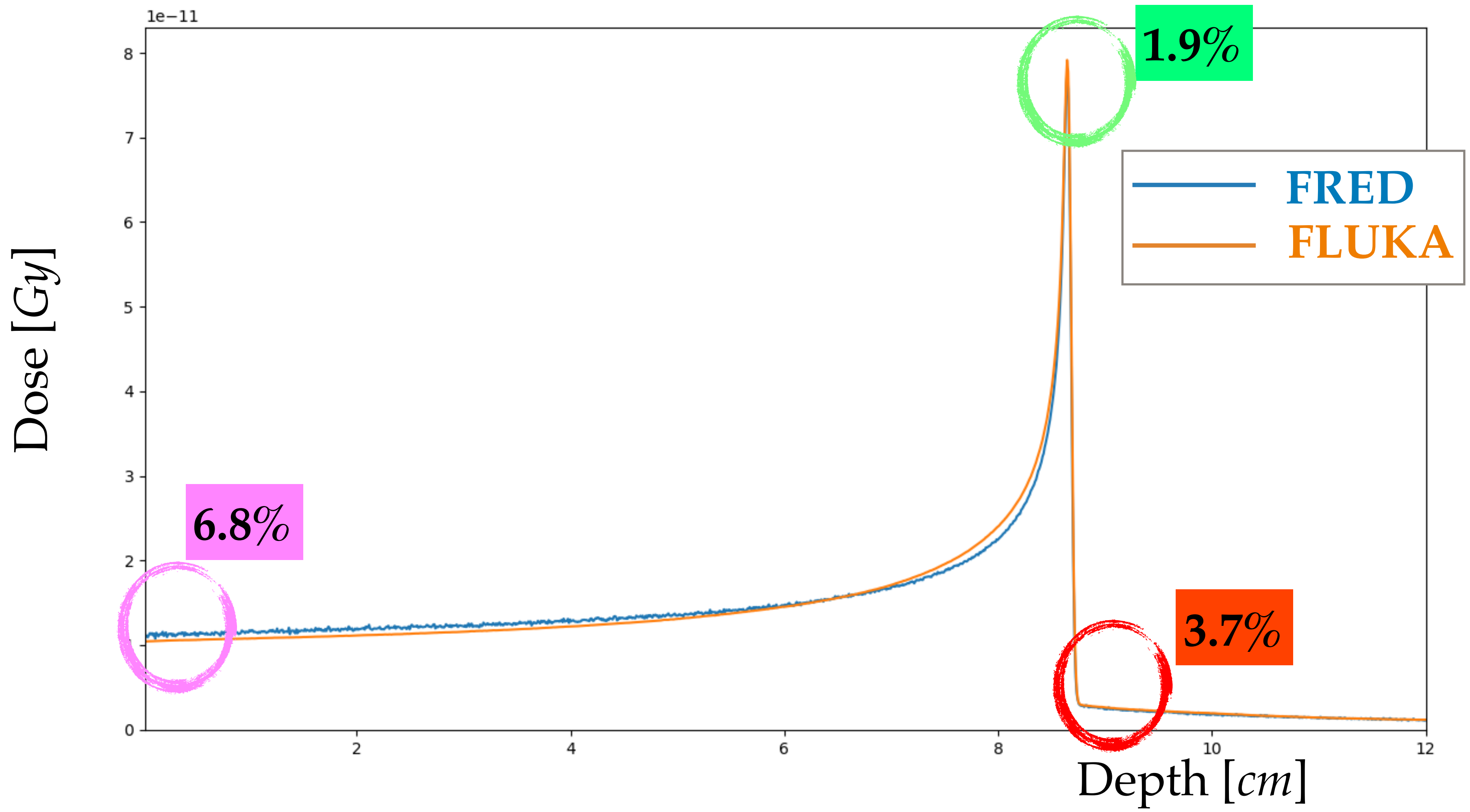
Results

^{12}C 200 MeV/n in water



Results

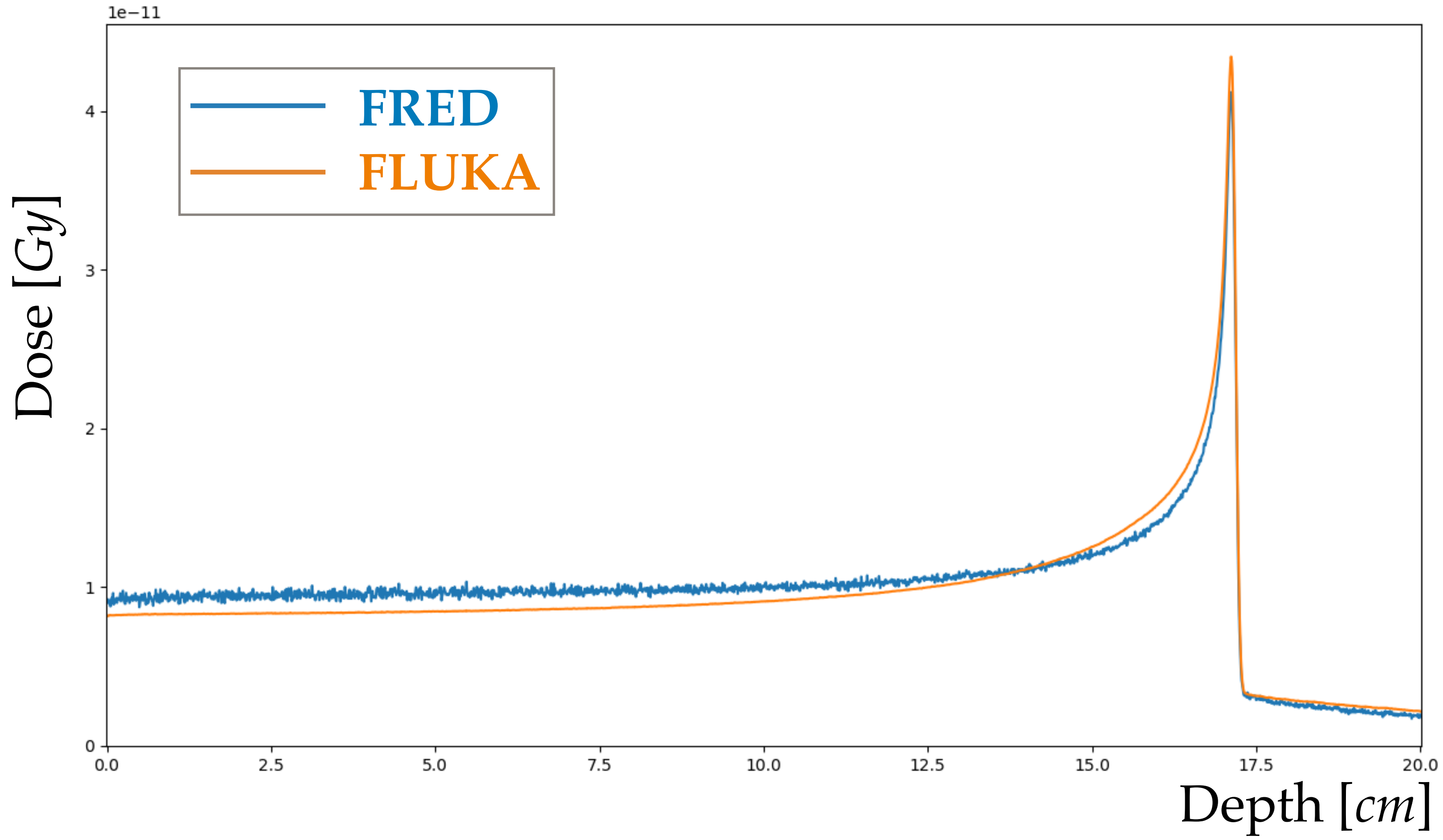
^{12}C 200 MeV/n in water



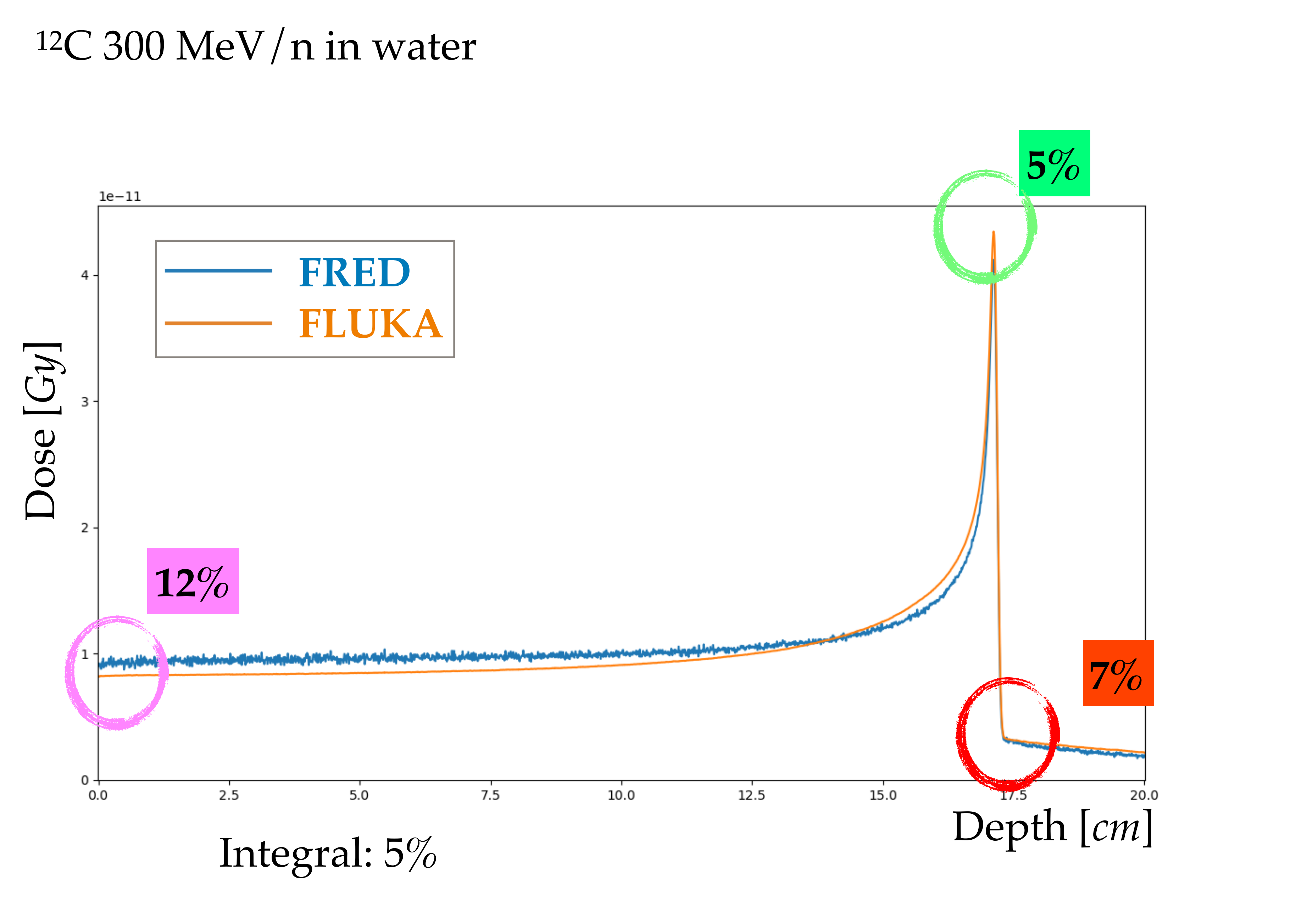
Integral: 0.9%

Results

^{12}C 300 MeV/n in water



Results



12C 300 MeV/n in water
1e−11
FRED
FLUKA
5%
12%
7%
Dose [Gy]
Depth [cm]
0
1
2
3
4
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Integral: 5%

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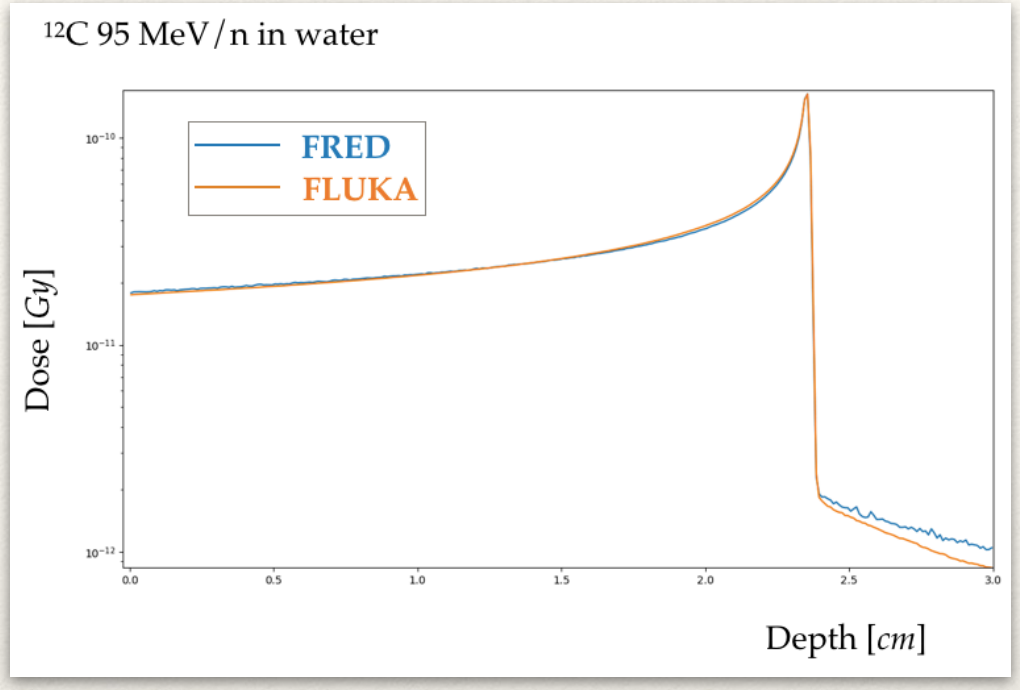
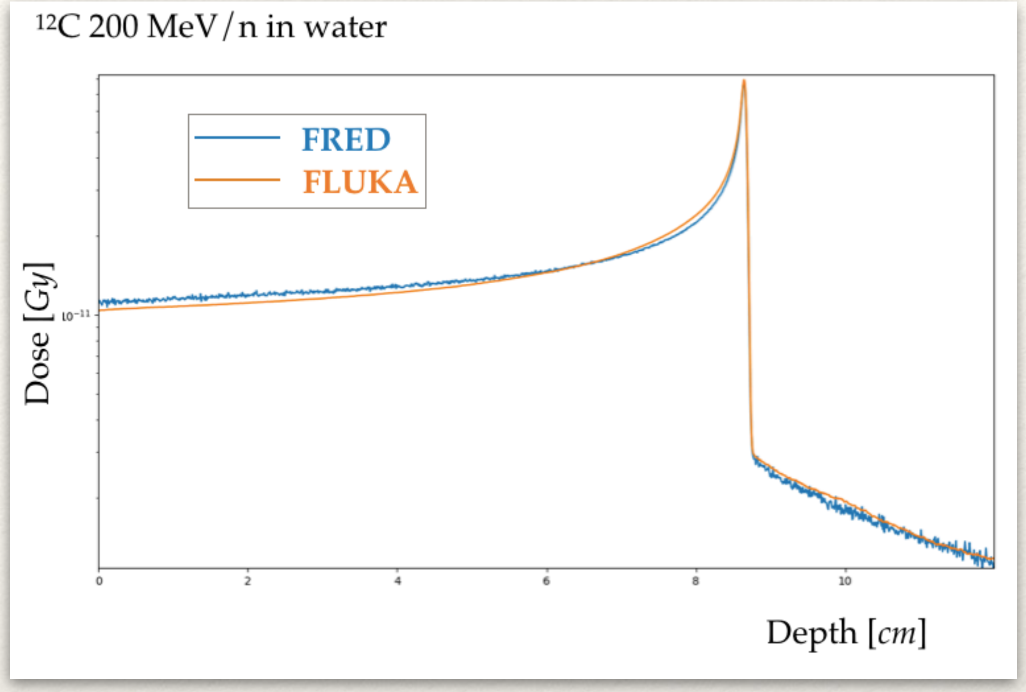
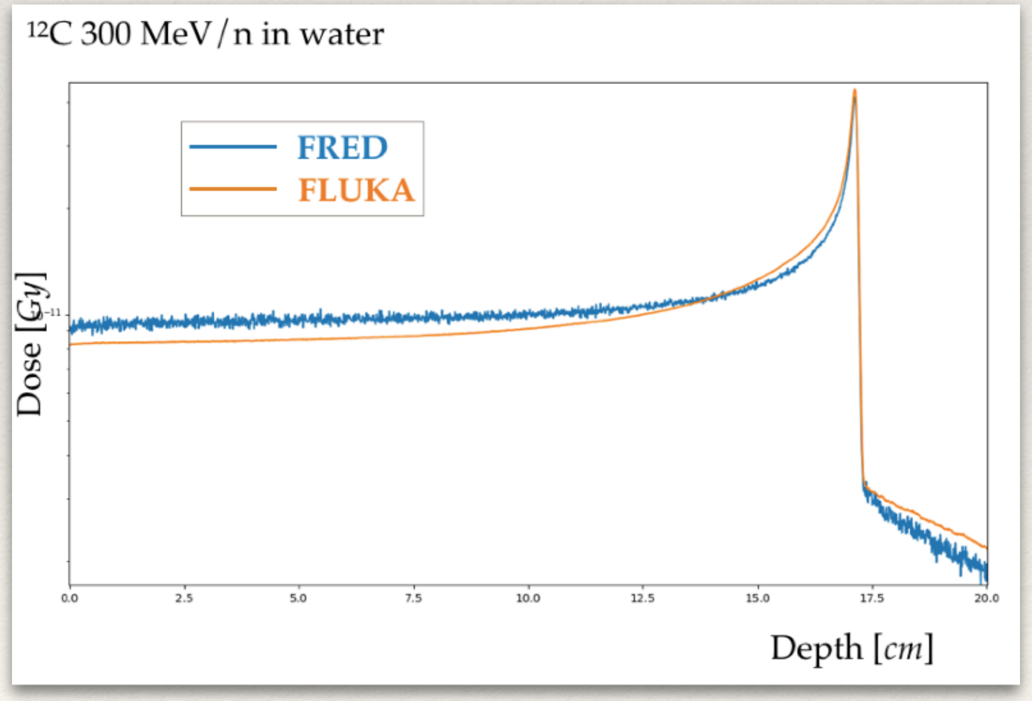
Results







As energy increases, in FRED the plateaux increases and the tail decreases with respect to FLUKA

Why? What is not working when the energy increases?

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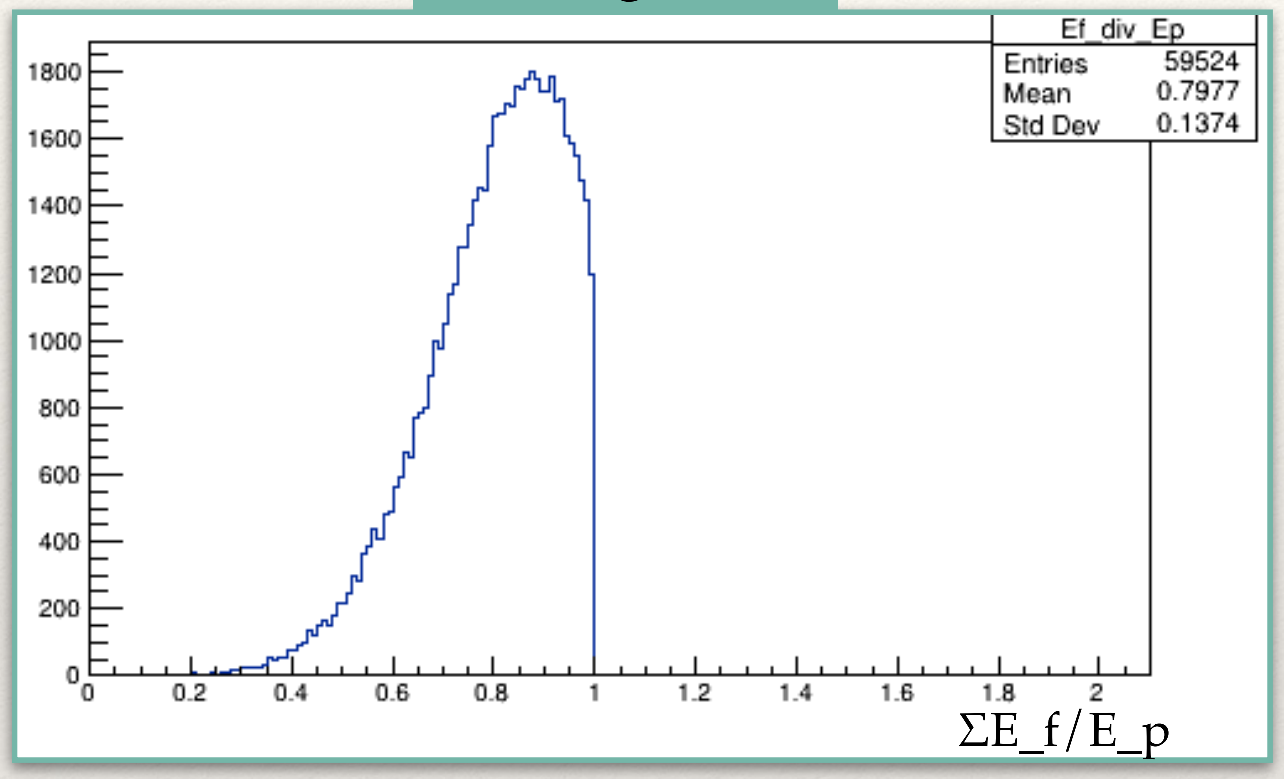
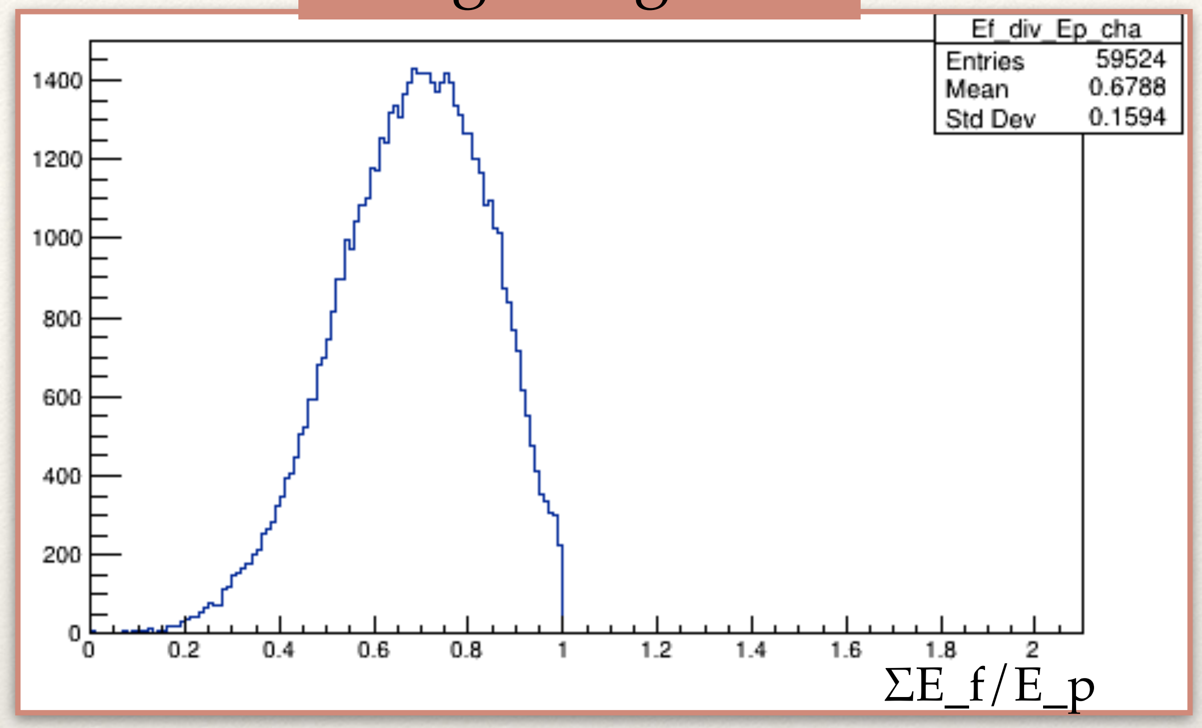
Backup

Energy of fragments emitted @95MeV/u

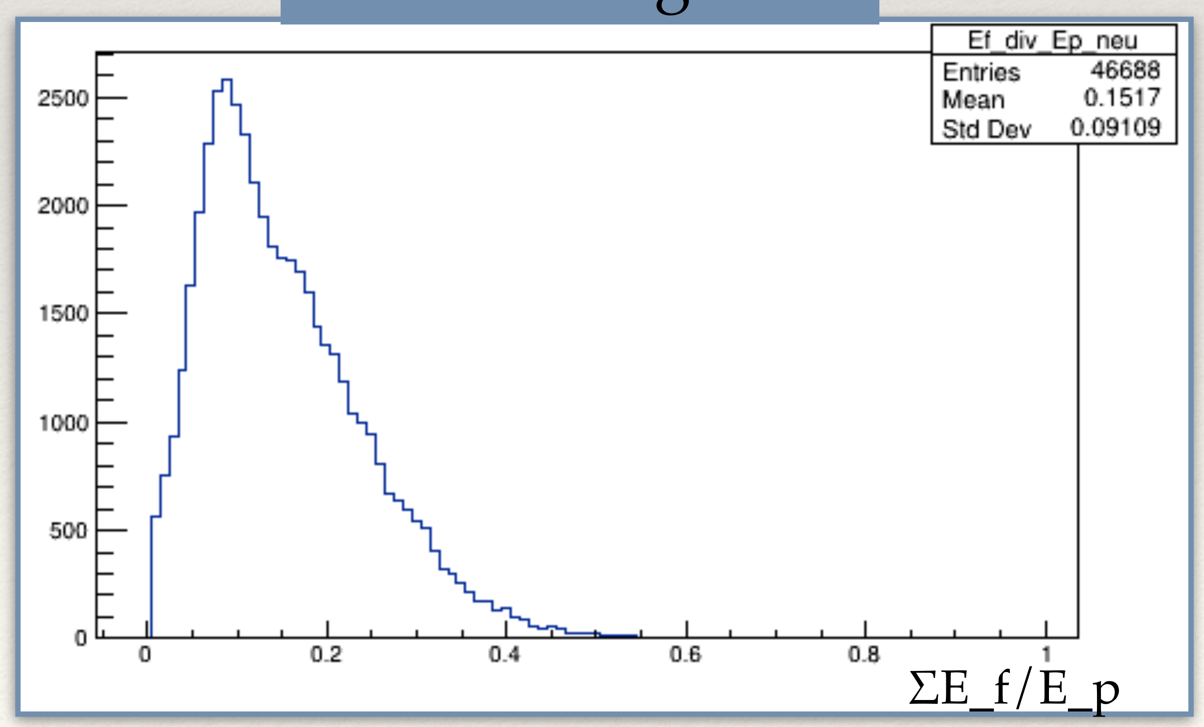
All fragments



Charge Fragments



Neutron Fragments



Energy of fragments emitted @95MeV/u