^{12}C-FRED

A DOSE CALCULATION TOOL ON GPU FOR CARBON THERAPY

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FRED FOR PROTONS

- FRED (Fast Particle thErapy Dose evaluator) has been benchmarked for proton therapy with less than 1% error on dose delivery calculation.

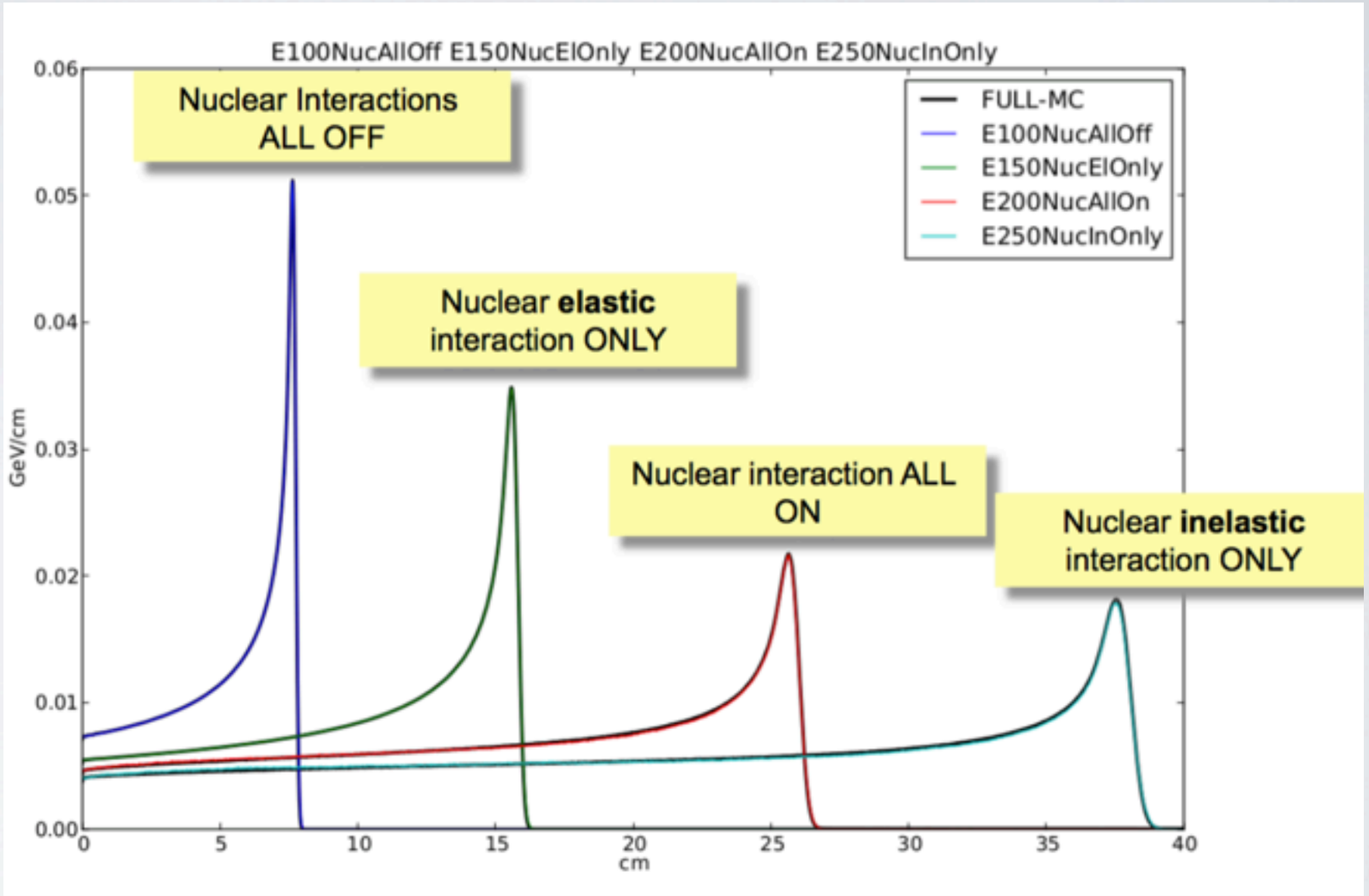
- Physics models implemented in the code are:

  - Stopping Power
  - Energy Fluctuations
  - Multiple Coulomb Scattering (MCS)
  - Nuclear interactions (elastic and inelastic)

- At CNAO hadrontherapy centre in Pavia, 90% of the patiens are treated with carbon ion therapy. There is need to develop a fast MC tool for dose recalculation with carbon ions.

MAIN THESIS GOALS

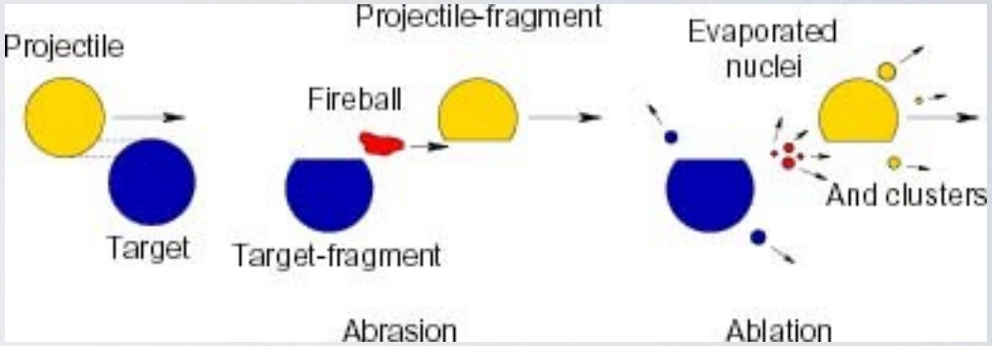
- Good capability in modelling carbon ion fragmentation inside the patient
- Minimize the error in predicted dose delivery at about 1%
- I.E., reach the same accuracy level obtained for protons



Simulated Bragg curves for protons in water, switching on/off nuclear models: image from M. Senzacqua, "*Optimization of hadron therapy proton beam using Monte Carlo code on GPU*", *2016*

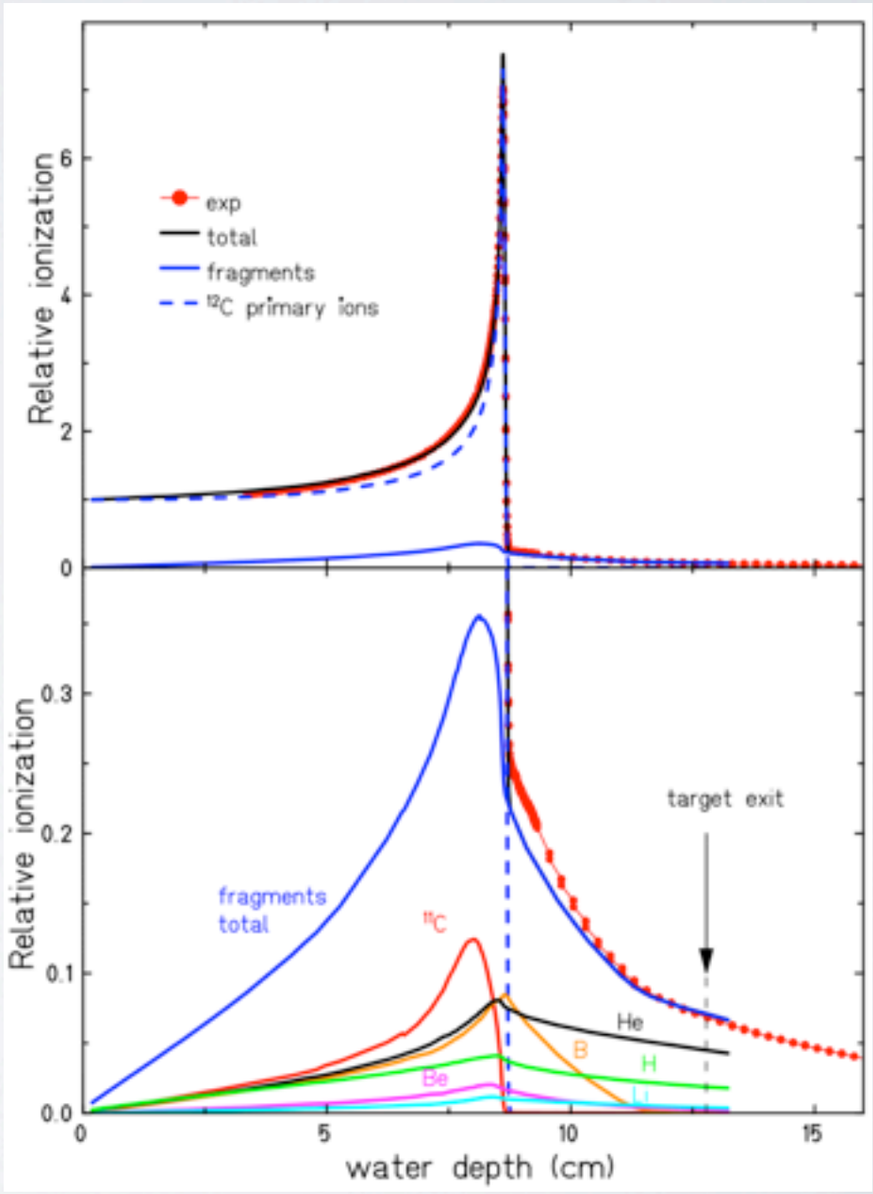
THESIS PROJECT

Toy model of 12C nuclear interaction with biological tissues



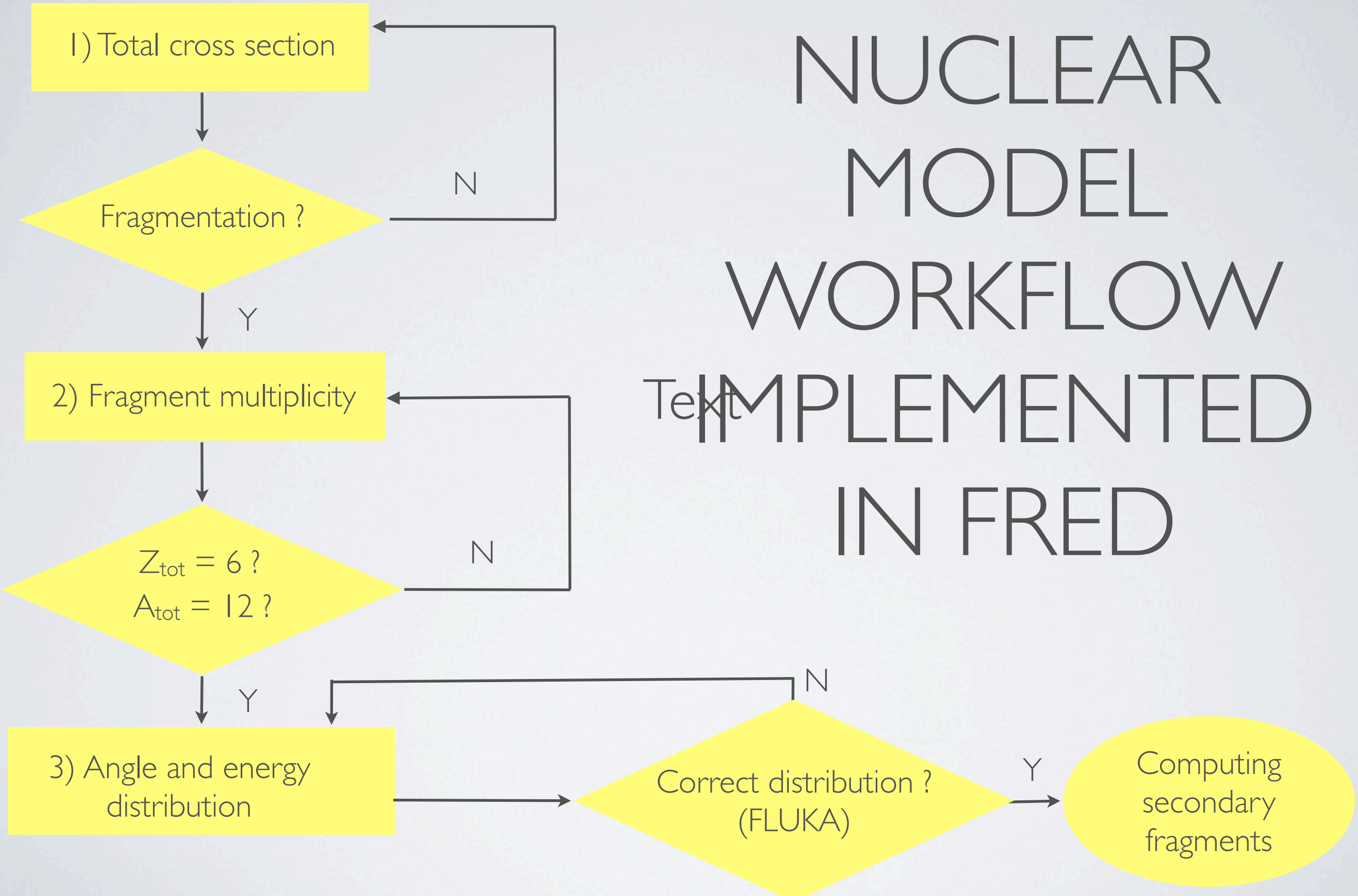
- **Continuous processes:**
  stopping power, multiple Coulomb scattering ⟶ easy model based on cross section and kinematics

- **Discrete processes:**
  elastic processes, carbon ion multifragmentation ⟶ complex task, need for fast implementation



"Secondary beam fragments produced by 200 MeV u−12C ions in water and their dose contributions in carbon ion radiotherapy", K. Gunzert-Marx, 2008

NUCLEAR MODEL WORKFLOW IMPLEMENTED IN FRED



Text

1) COMPUTING TOTAL CROSS SECTION

Experimental survival fraction of carbon ions in a thick water absorber: curves at different beam energies show the same slope.

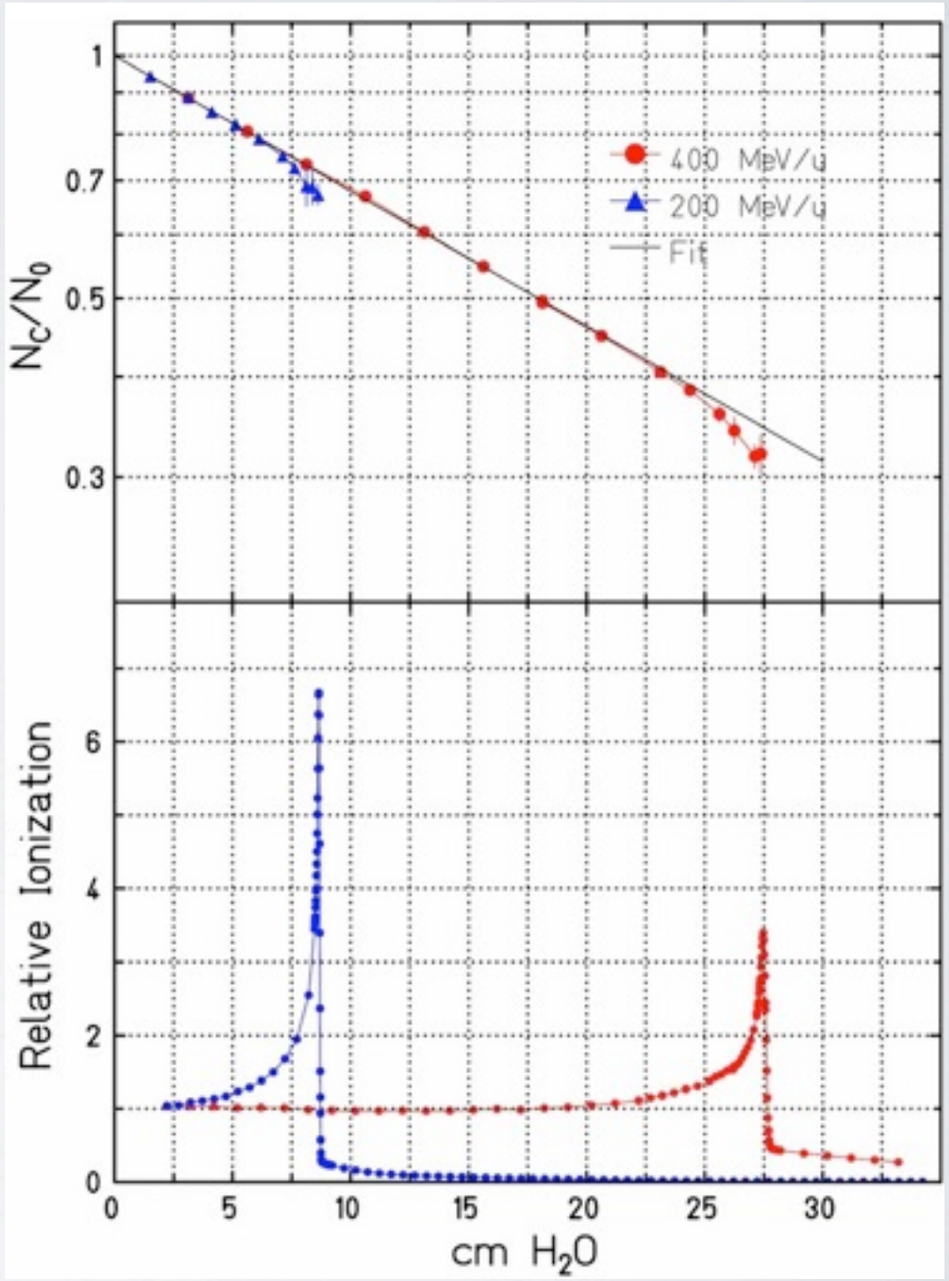
Fitting the two data sets, it is possible to derive the mean free path of the ions in water applying the exponential law:

$$\frac{N_c}{N_0} = e^{-\frac{x}{\lambda}} \quad \rightarrow \quad \lambda = mean\,free\,path$$

For ^{12}C in water, λ_{exp} = 25.9 cm [1]

The total nuclear cross section is then computed as follows:

$$\lambda = \frac{1}{\Sigma_{tot}}$$



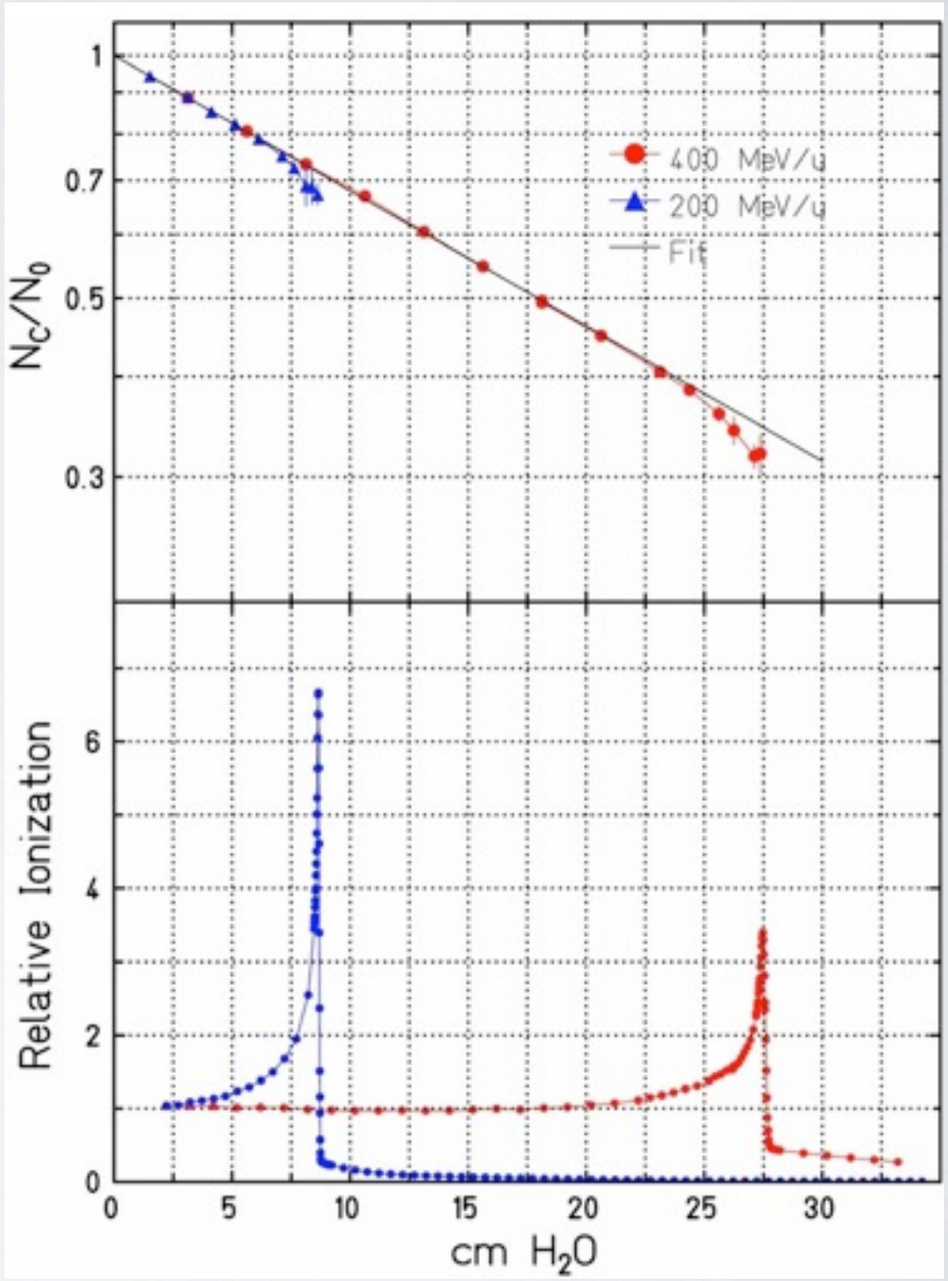
[1] E. Heattner et al. , “Experimental study of nuclear fragmentation of 200 and 400 MeV/u ^{12}C ions in water for applications in particle therapy”, 2013

I) COMPUTING TOTAL CROSS SECTION

- Each generated carbon ion is associated with a number of mean free paths N_{mfp} normalized to λ and exponentially distributed

- At each step N_{mfp} is decreased by a factor $dN = \frac{ds}{\lambda}$, where ds is the range step computed in FRED

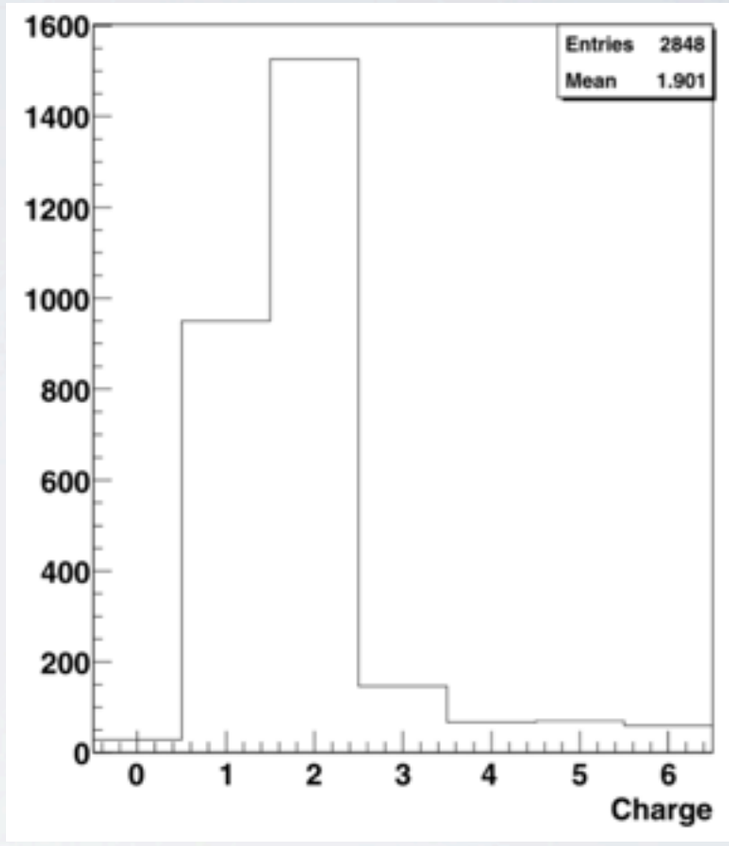
- Fragmentation of the carbon ion only occurs if N_{mfp} reaches zero

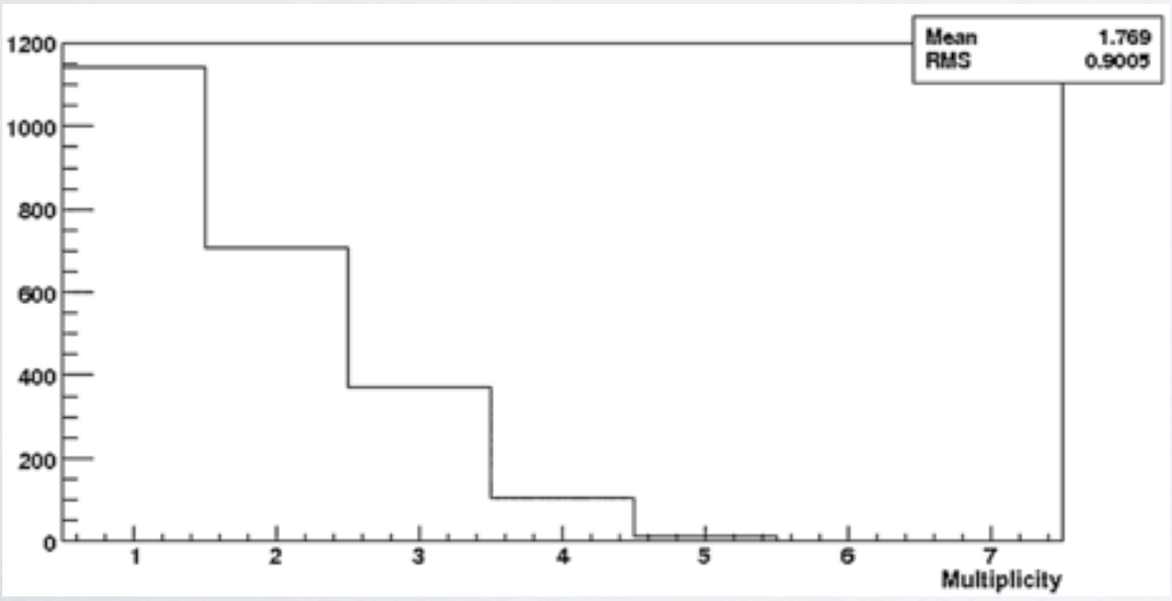


2) COMPUTING FRAGMENT MULTIPLICITY

- A cumulative distribution sampled out from [2] has been implemented in the generation of the single fragment charge

- No constraints on fragment number has been used in FRED





Experimental measurements of charge multiplicity (above) and number of fragments (left) from 300 MeV/A carbon beam on a thick water target [2]

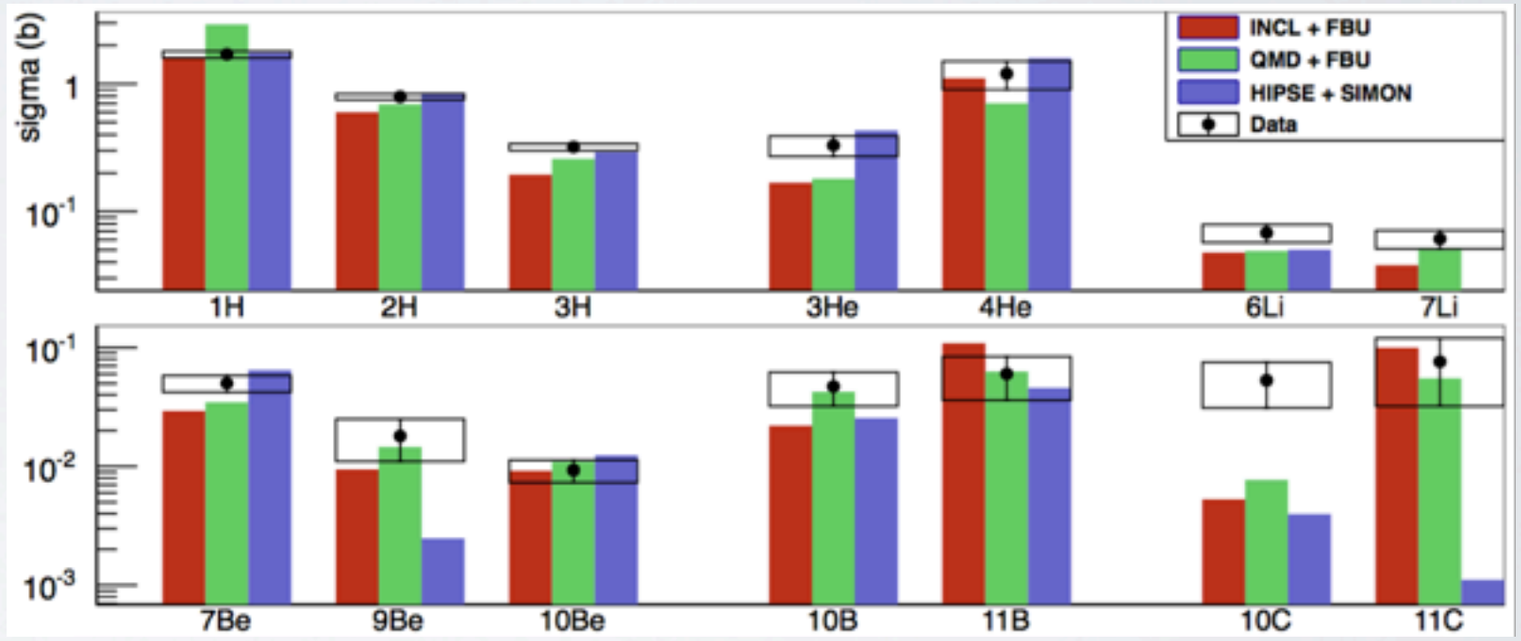
[2] G. De Lellis et al. , “Measurement of the fragmentation of Carbon nuclei used in hadron-therapy”, Nuclear Physics A 853 (2011)

2) COMPUTING FRAGMENT MULTIPLICITY

- For each primary carbon ion, a maximum set of 5 fragments is generated with its charge Z extracted in the range [1,6]

- The fragment mass is generated following the single isotope distributions according to Ganil data on the right [3]

- The extraction of a set of fragments is carried out only if the sum of generated fragments charges $Z_{tot} = 6$

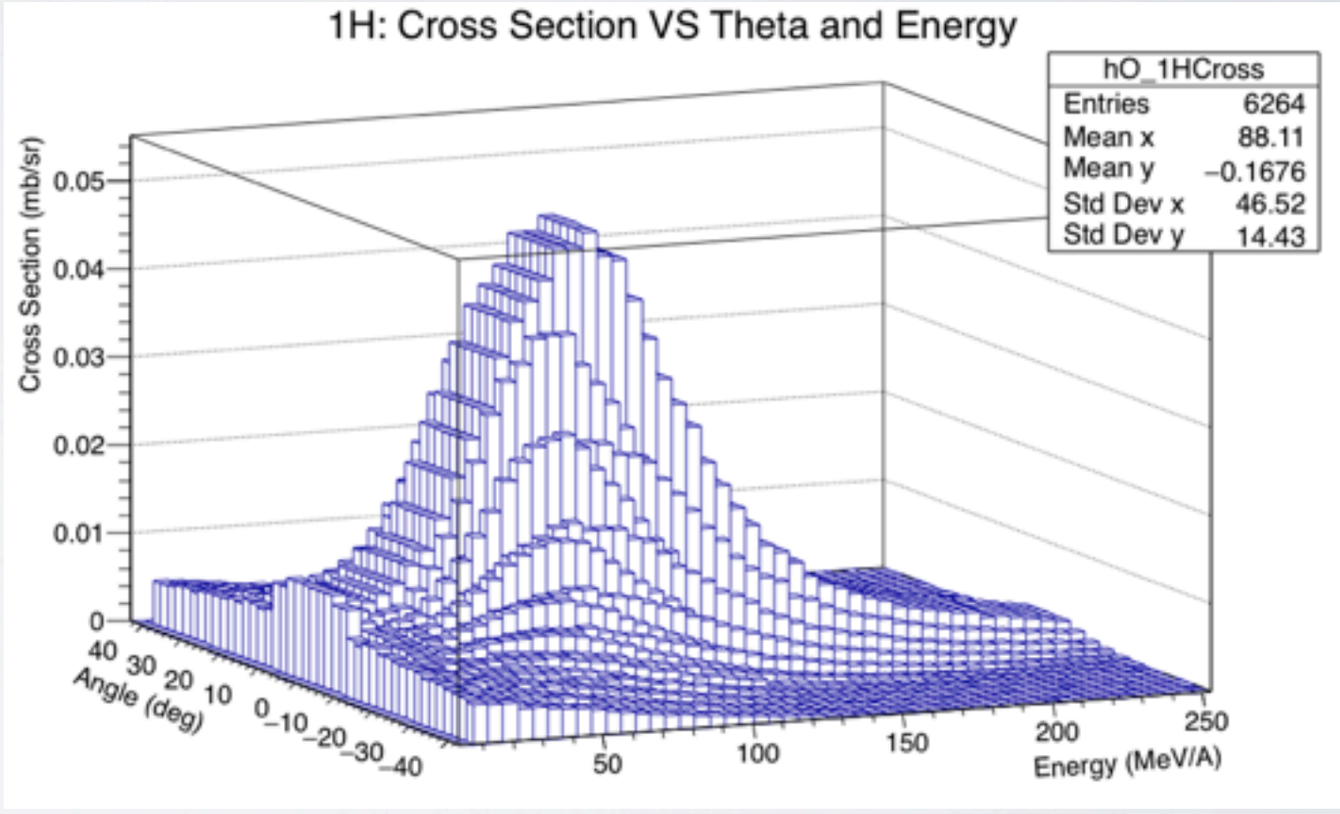


[3] J. Dudouet et al. , "Carbon fragmentation measurements at 95 MeV/A for hadrontherapy and comparisons with simulations ", XVIIIth Colloque GANIL (2013)

3) ENERGY AND ANGLE DISTRIBUTION

- Data of GANIL E600 Experiment have been stored in 2D histograms, one for each target atom (C,H,O) and for each of 15 possible fragments

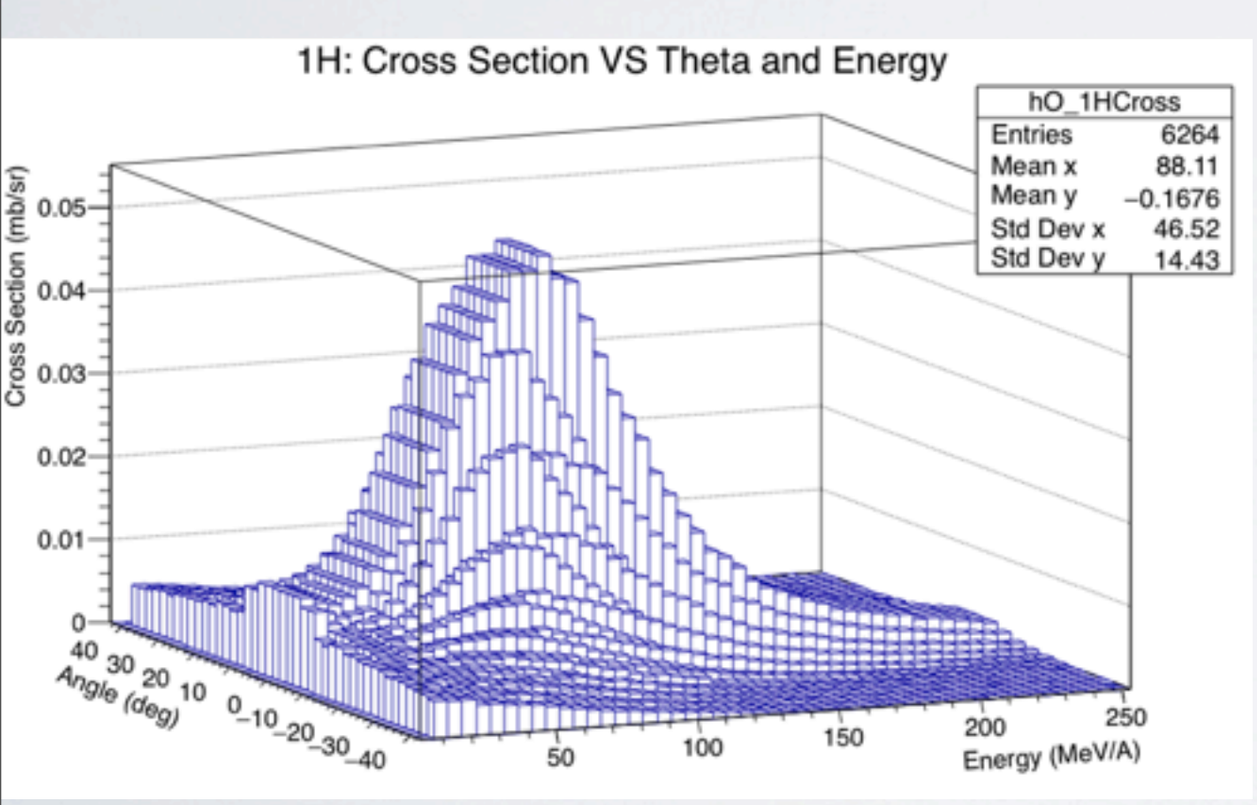
- The extraction algorithm has been implemented using a hit-or-miss method on the 2D histograms, in order to correctly reproduce the data distribution



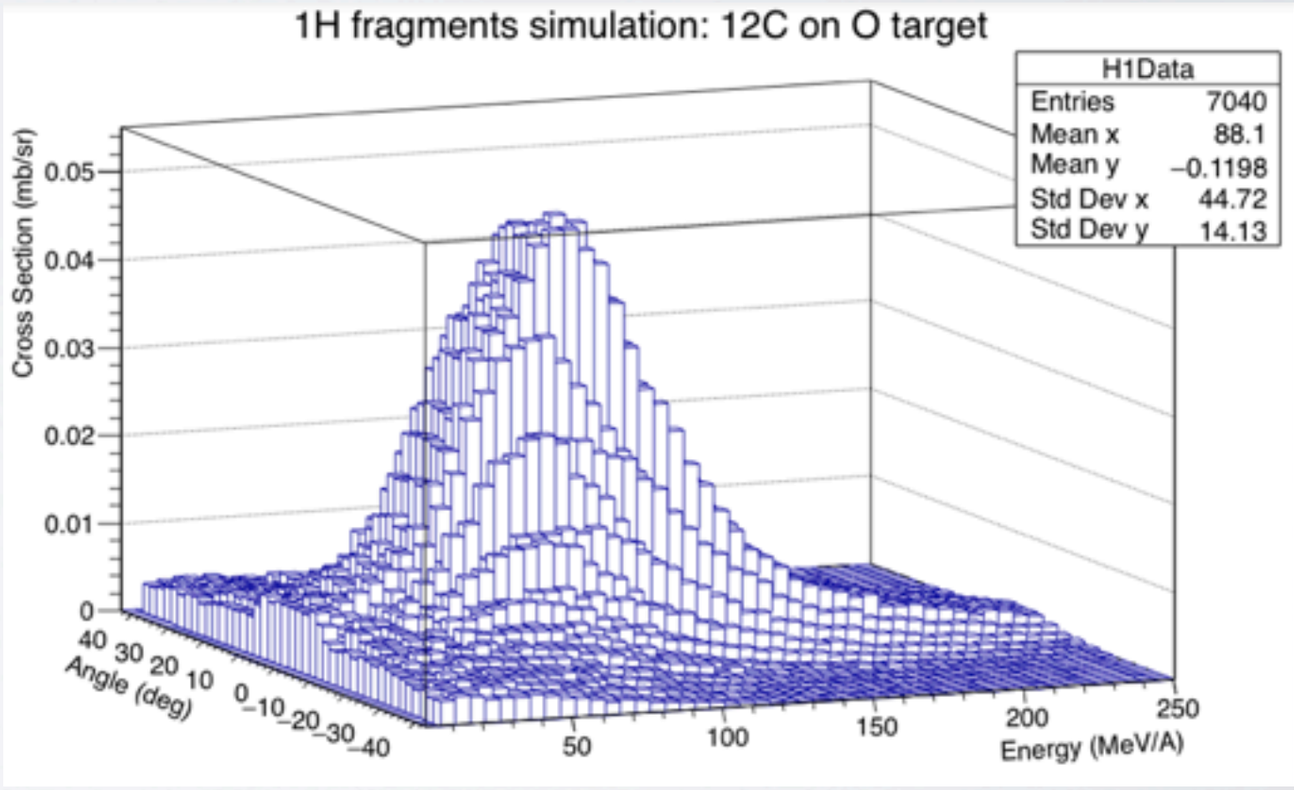
An example of 2D histogram for 1H production cross section on O target

3) ENERGY AND ANGLE DISTRIBUTION

ROOT CROSS SECTION DATA ANALYSIS



Hydrogen cross section data on oxygen target
(Ganil Experiment)



Simulation generated data with hit-or-miss techniques on oxygen target

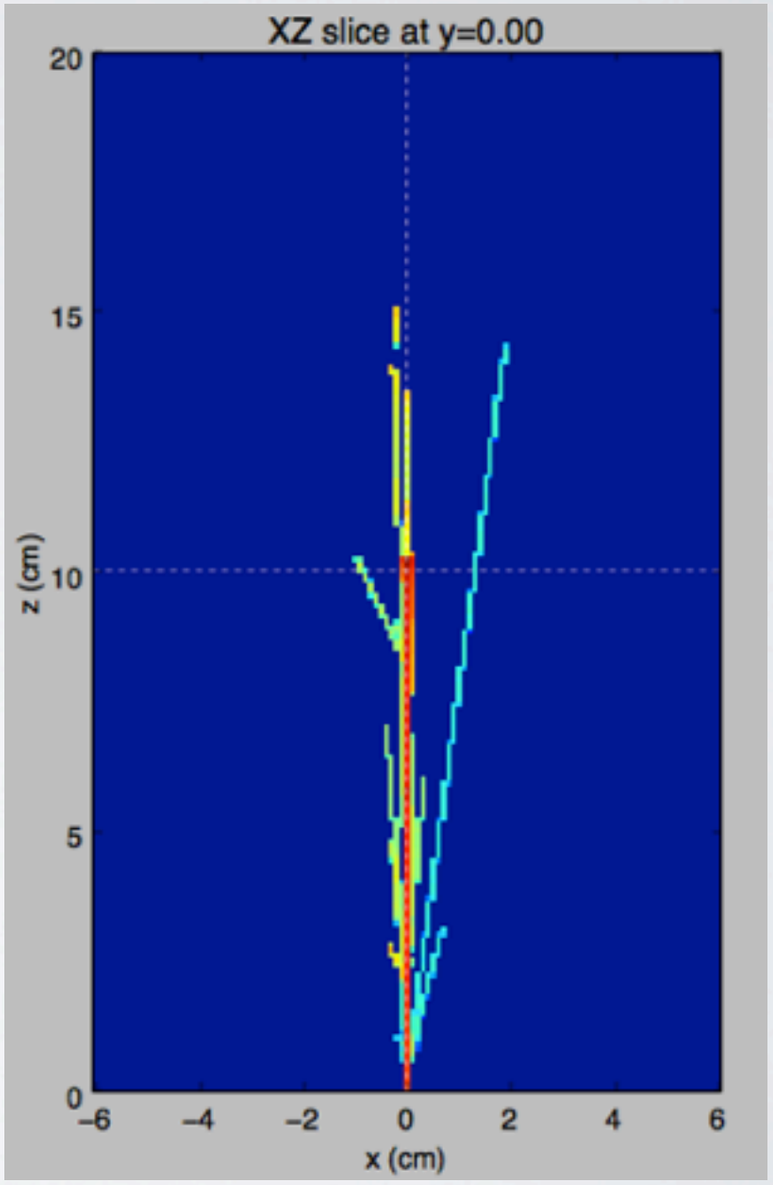
3) ENERGY AND ANGLE DISTRIBUTION

- The only data available are at 95 and 50 MeV/A, so it is necessary to scale data
- As a first approximation, energy and angle have been scaled with respect to the primary beam energy

$$E_{frag} \propto \frac{E_{primary}}{E_0}$$

$$A_{frag} \propto \sqrt{\frac{p_0}{p_{primary}}}$$

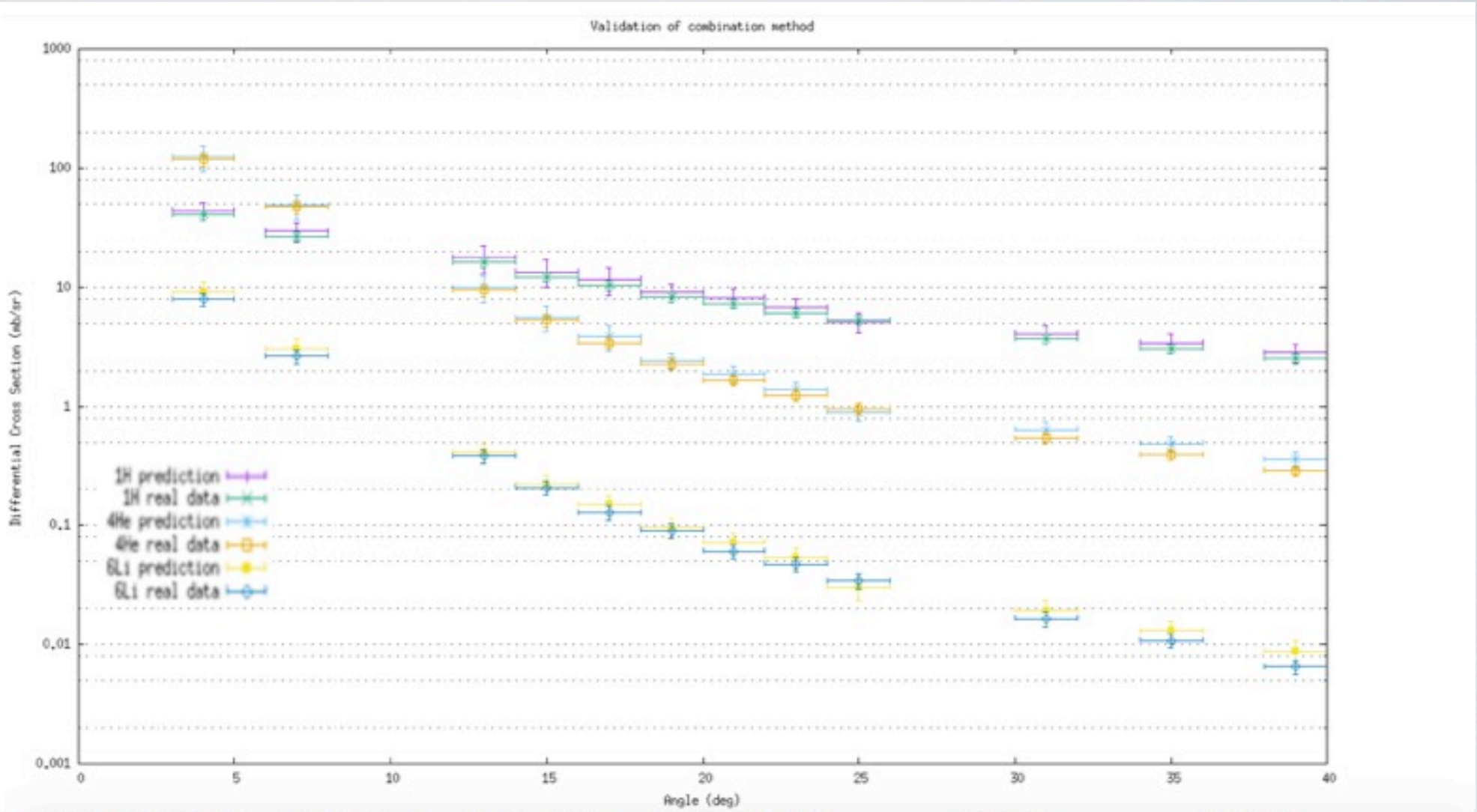
- The reference beam energy is 95 MeV/A
- Scaling has been checked with data at the two different energies



STOICHIOMETRIC MODEL

- Evaluating single element target ^{12}C cross sections allows to compute dose delivery on complex targets

- The model has been validated on PMMA ($C_5H_8O_2$)



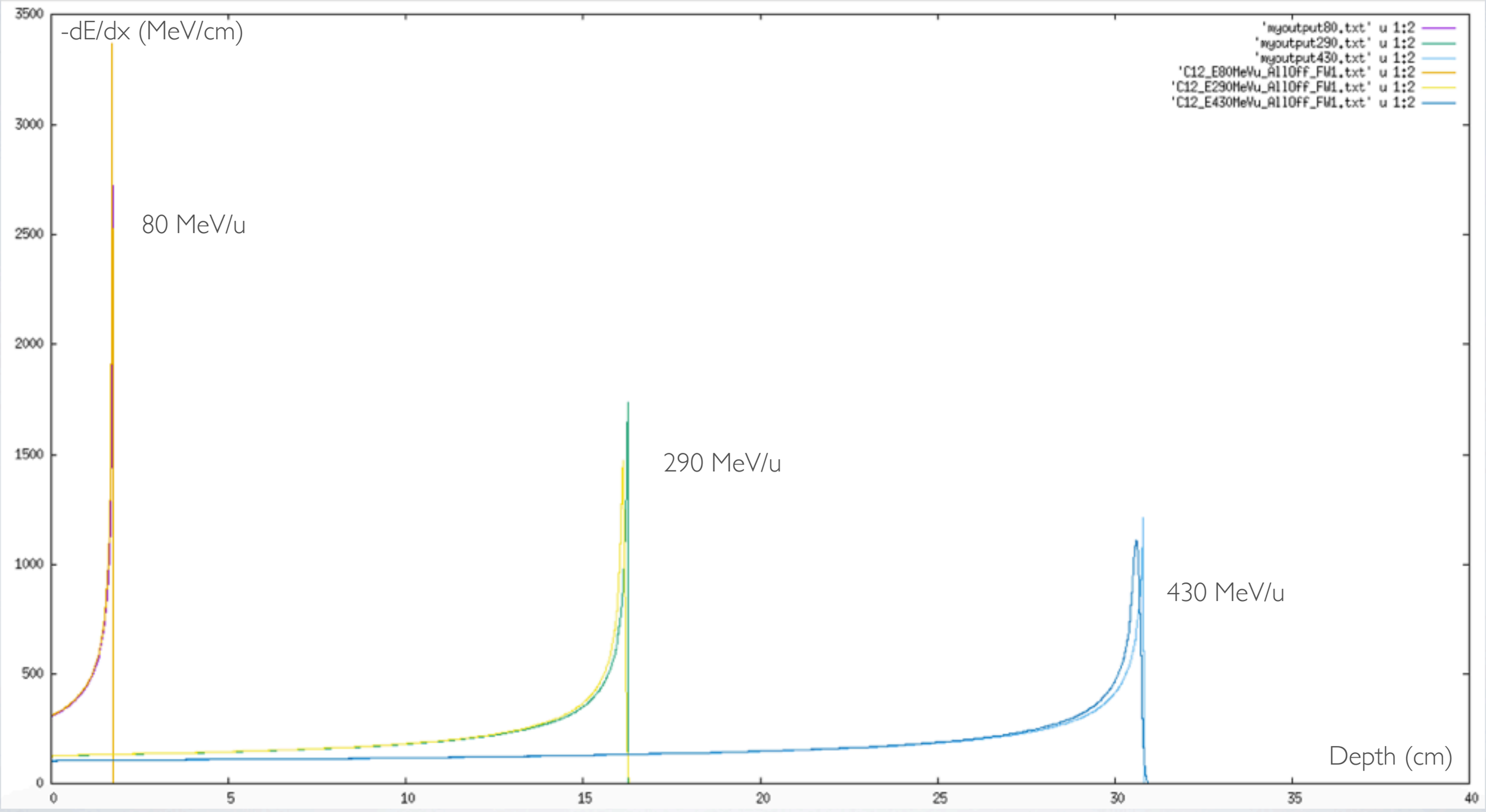
#theta	errtheta	1H	err1H	4He	err4He	6Li	err6Li	real1H		real4He		real6Li	
4	1	43.89	7.18	123.8	30	9.05	2.13	40.2523	3.68329	118.234	15.0922	7.90917	1.0456
7	1	29.55	5.08	48.7	11.46	3.001	0.742	26.5454	2.55223	47.2216	5.65057	2.62376	0.355663
13	1	17.65	4.63	9.8888	2.45	0.4095	0.075	16.2079	1.55878	9.41373	1.14424	0.383805	0.0522854
15	1	13.44	3.61	5.548	1.341	0.223	0.042	12.2082	1.17355	5.27606	0.617344	0.208142	0.0282661
17	1	11.61	3.08	3.854	0.921	0.1493	0.0286	10.3977	0.999528	3.40495	0.39105	0.128799	0.0175269
19	1	9.038	1.649	2.439	0.372	0.0973	0.0192	8.22994	0.791151	2.27589	0.250341	0.0911094	0.0123967
21	1	8.16	1.47	1.872	0.289	0.0724	0.0145	7.34315	0.705912	1.65166	0.179271	0.0611202	0.00833539
23	1	6.742	1.203	1.38	0.212	0.0538	0.0108	6.06949	0.583491	1.24665	0.132151	0.0474686	0.00648955
25	1	5.109	0.921	0.888	0.132	0.03035	0.0065	5.31708	0.511233	0.949256	0.100125	0.0343589	0.00469905
31	1	4.052	0.726	0.6395	0.096	0.0194	0.0042	3.69773	0.355692	0.536875	0.0561379	0.0165317	0.00241876
35	1	3.422	0.613	0.485	0.0735	0.013	0.00276	3.05689	0.293919	0.394098	0.0411116	0.0108486	0.00153054
39	1	2.814	0.513	0.359	0.055	0.00877	0.0019	2.53067	0.243332	0.289108	0.0301755	0.00650215	0.000937262

J. Dudouet et al., "*Double differential fragmentation cross sections measurements of 95 MeV/u ^{12}C on thin targets for hadrontherapy*", 2013

MY THESIS CURRENT RESULTS

BRAGG PEAK: FLUKA VS FRED

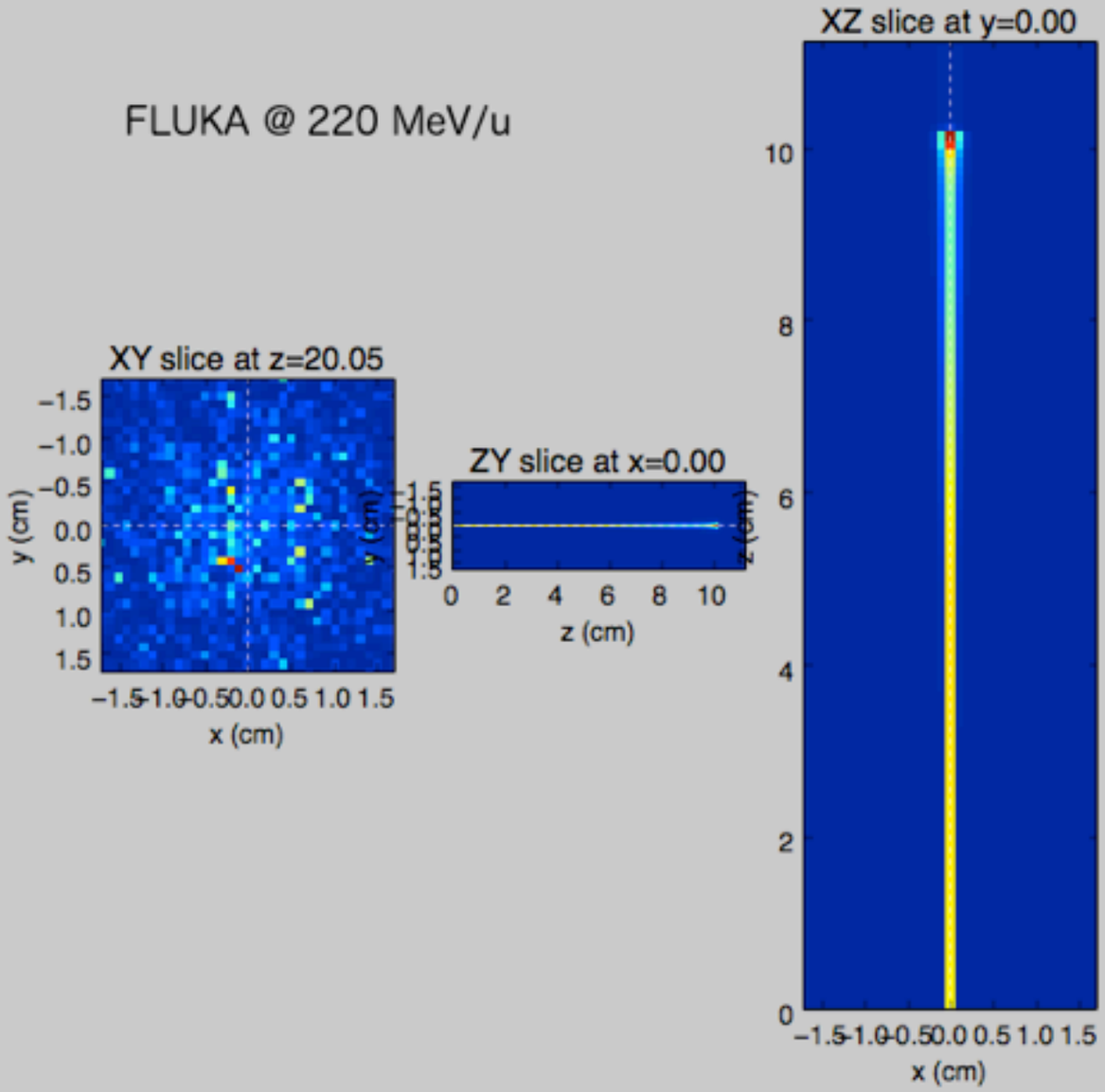
(ENERGY STRAGGLING NOT IMPLEMENTED HERE)



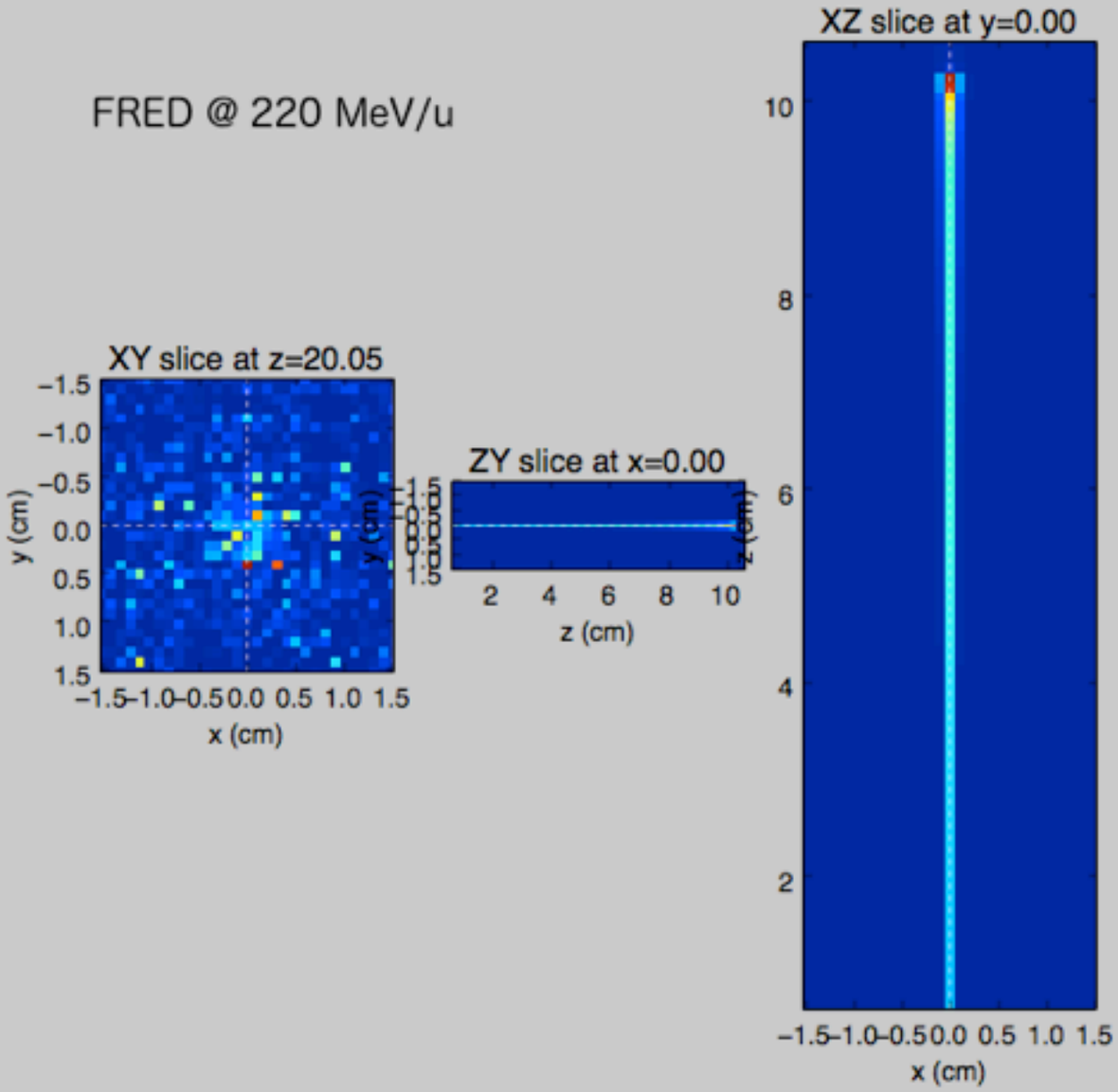
NUCLEAR INTERACTIONS

LINEAR DOSE SCALE

FLUKA @ 220 MeV/u



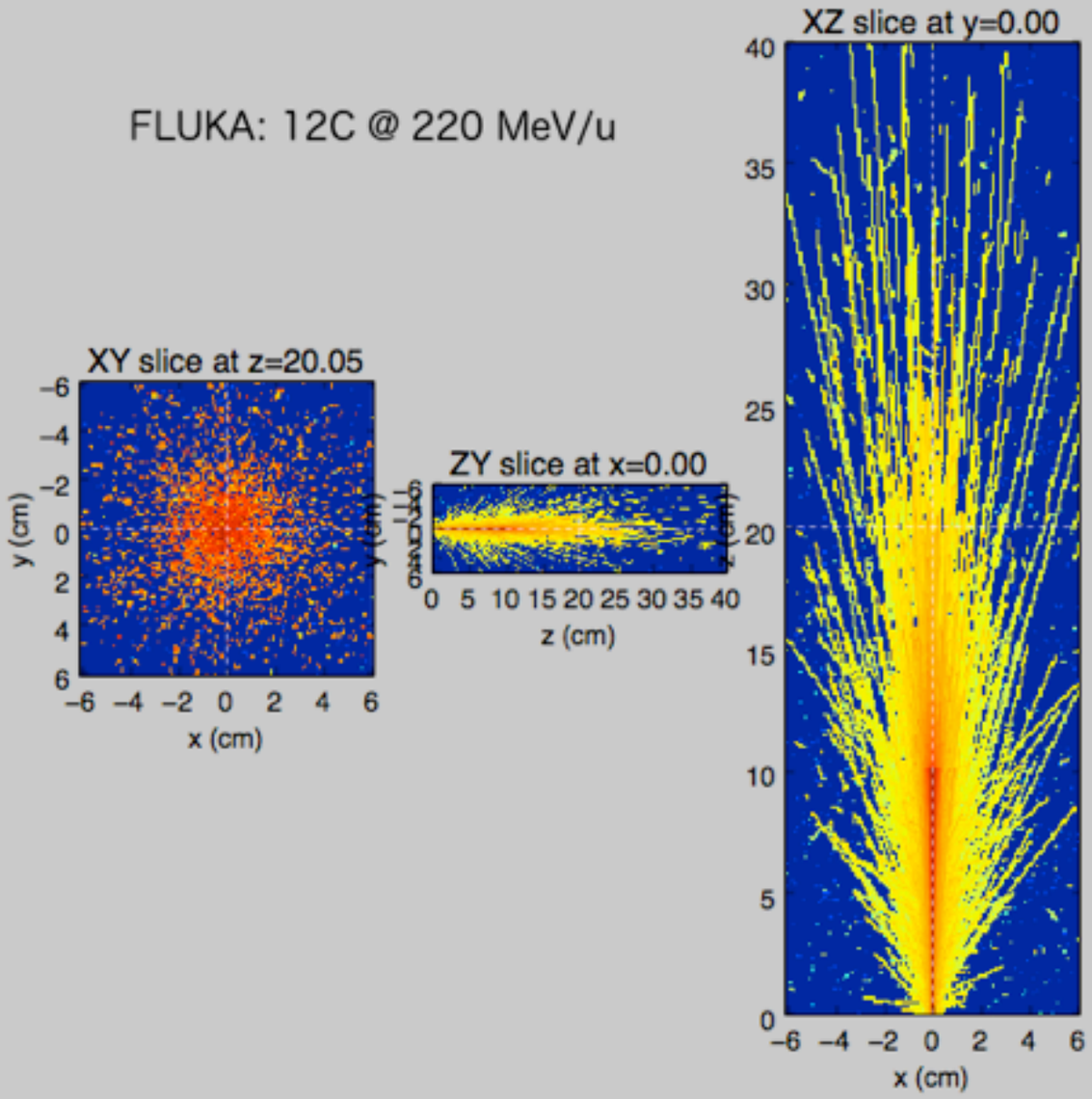
FRED @ 220 MeV/u



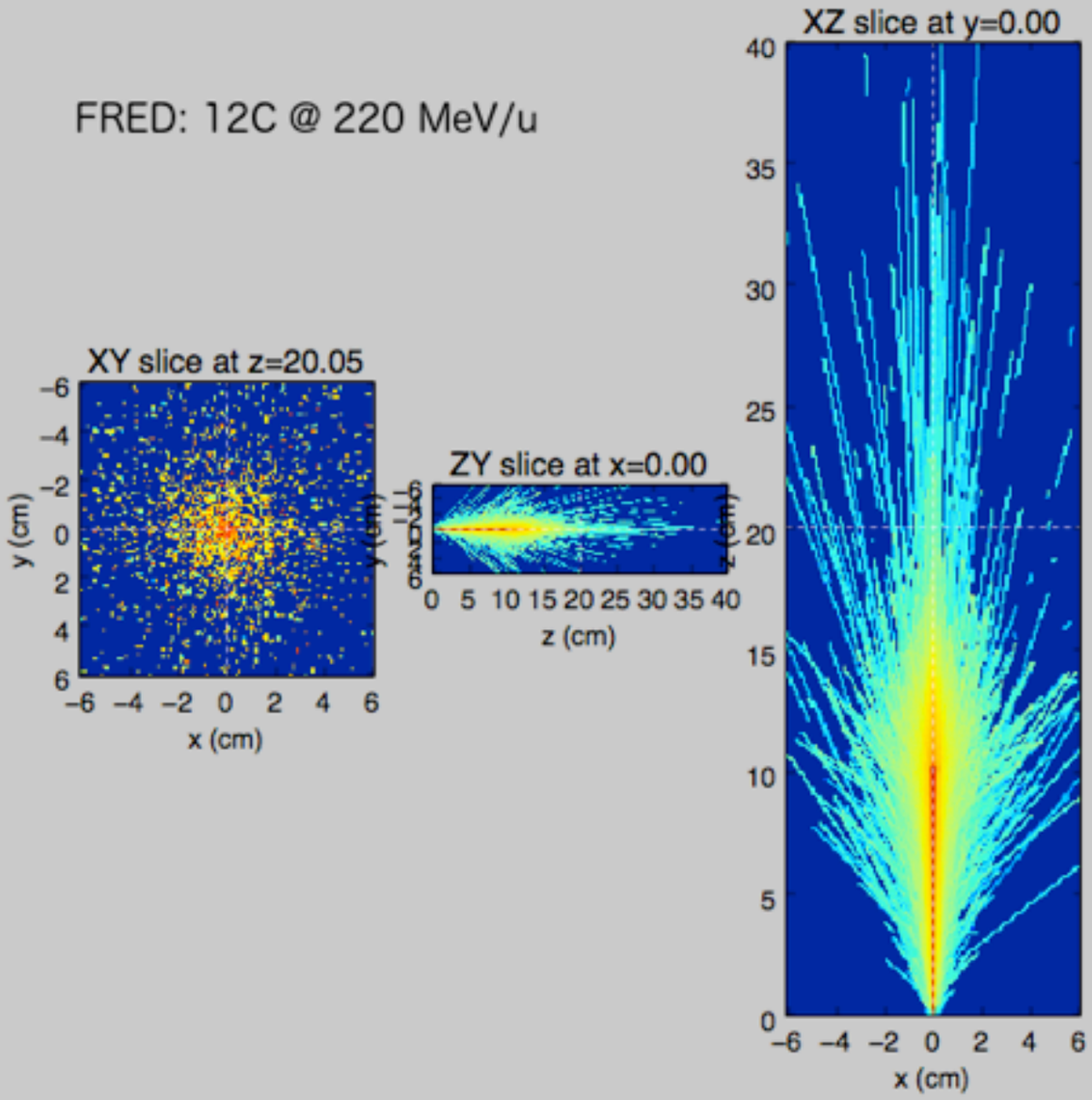
NUCLEAR INTERACTIONS

LOG DOSE SCALE (STILL IMPROVING)

FLUKA: 12C @ 220 MeV/u



FRED: 12C @ 220 MeV/u



OUTLOOKS

- Fast calculation with FRED to support carbon ion treatment planning
- Possible implementation in CNAO clinical routine
- Possibility to reduce patient QA measurements using "in silico" verification

REFERENCES

- S. Rossi, *Corso di formazione in Adroterapia: applicazione delle tecnologie degli acceleratori alla cura dei tumori, 2016, fondazioneCNAO*
- M. Senzacqua, *Optimization of hadron therapy proton beam using Monte Carlo code on GPU, 2016*
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- Particle Data Group, *Passage of Radiation in Matter, 2016, LBNL laboratories*
- J. Dudouet et al. , *Double differential fragmentation cross sections measurements of 95 MeV/u ^{12}C on thin targets for hadrontherapy, 2013, CAEN Laboratoires*
- D. Lacroix et al. , *Event generator for nuclear collision at intermediate energies, 2004, Laboratoire de Physique corpusculaire ENSICAEN*