Differential Cross Sections Measurement of 12C fragmentation on C target in the Energy Range of interest for Carbon Ion Therapy Applications

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on behalf of the FOOT collaboration

5th Jagiellonian Symposium on Advances in Particle Physics and Medicine

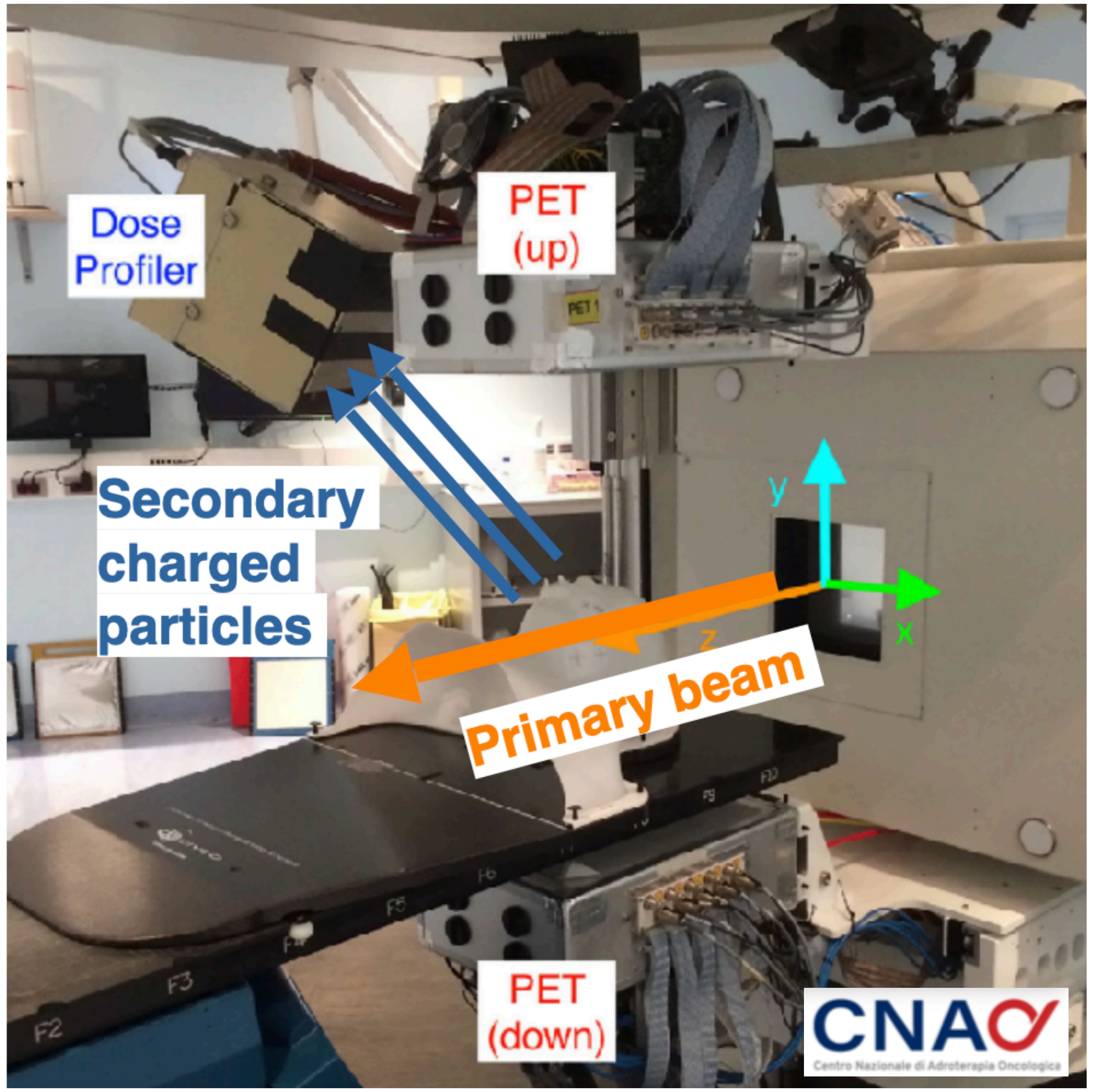
The Rationale

The measurements of C-C differential cross section at large angles

- Improve the precision of **Carbon Ion beam Particle Therapy treatment plans based on Monte Carlo codes (FLUKA)** including the effects of secondary charged fragments produced at large angles

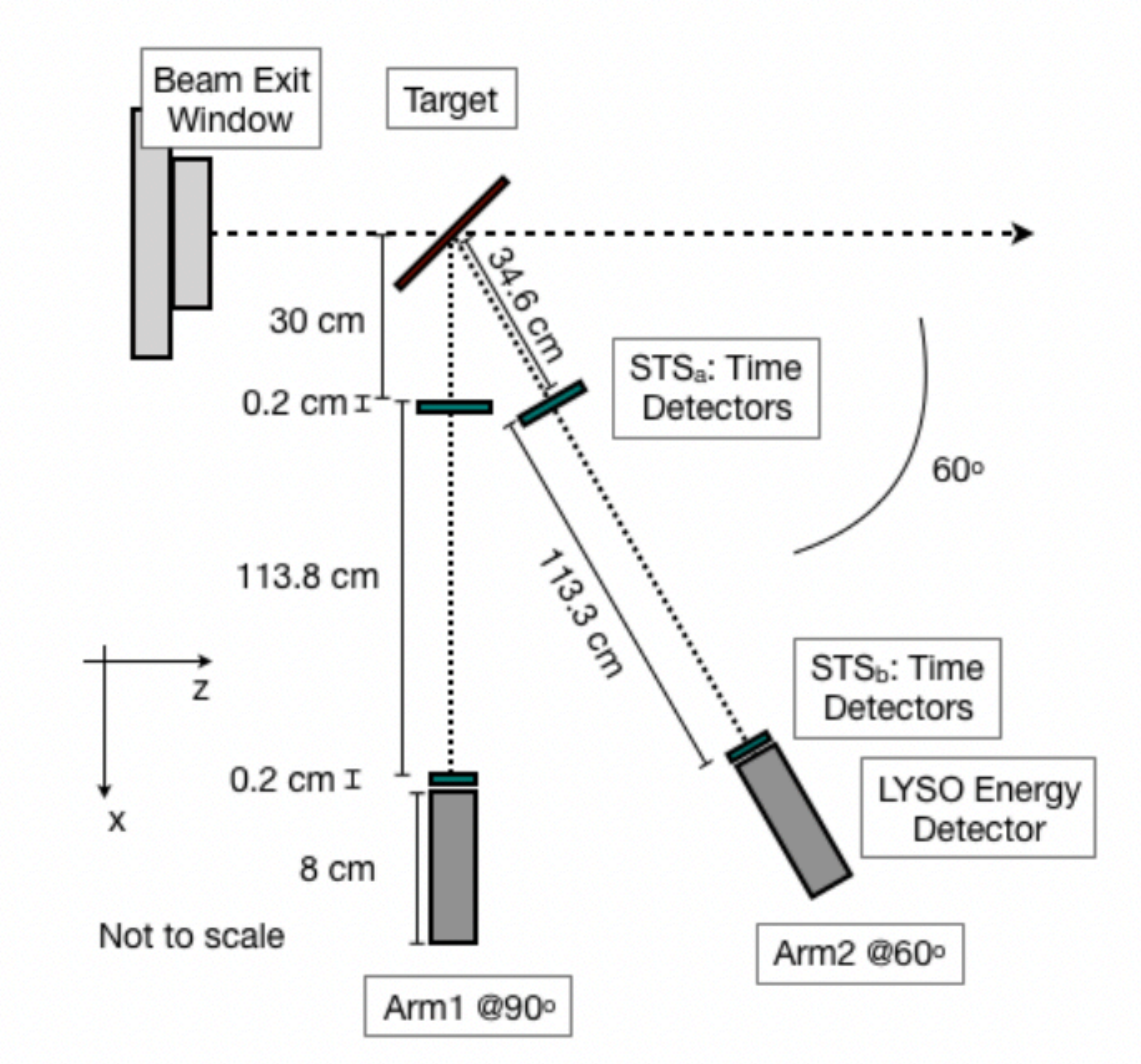
- Of interest for **Particle Therapy range monitoring techniques** based on the detection of secondary charged fragments

- Benchmark with the FLUKA Monte Carlo code



Experimental Setup

- 5 Carbon Ion beam energies:
  115, 150, 221, 279, 351 MeV/u
- **1** target (1 mm thick) based on C element
- 2 detection angles: **90º, 60º**



- Fragments production (**Z=1, A = 1, 2, 3**) as a function of the production kinetic energy
- Time of Flight in thin plastic scintillators and energy deposit in the inorganic crystals for PID and Ekin measurements
- Experimental Data - FLUKA Monte Carlo simulation comparison

2 STSs 2mm thick for ToF measurement (time resolution ~ 400-600 ps) and Deposited Energy measurement (dE);
1 LYSO 4x4x8 cm^3 for Deposited Energy measurement (E);

Cross Section Formula

The ^{12} C fragmentation cross section for a $^{A}_{Z}X$ fragment is obtained as:

$$\frac{d^2\sigma}{d\Omega dEk}(^{A}_{Z}X) = \frac{N_{^{A}_{Z}X}}{\Delta\Omega\Delta E_k} \cdot \frac{1}{N_{^{12}C}N_{Y}} \cdot \frac{1}{\epsilon}$$

Cross Section Formula: Normalization

The ^{12}C fragmentation cross section for a $^{A}_{Z}X$ fragment is obtained as:

$$\frac{d^2\sigma}{d\Omega dEk}(^{A}_{Z}X) = \frac{N_{^{A}_{Z}X}}{\Delta\Omega\Delta E_k} \cdot \frac{1}{N_{^{12}C} N_Y} \cdot \frac{1}{\epsilon}$$

From CNAO
Dose Delivery System

$N_{^{12}C}$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$
Target	115 [MeV/u]	153 [MeV/u]	222 [MeV/u]	281 [MeV/u]	353 [MeV/u]
Graphyte	49454	46583	47484	47288	49328

Information on the target composition:

Target	Composition	Thickness $[mm]$	Density $[g/cm^3]$
Graphite	C	1	0.94

$$N_Y = \frac{\rho_Y \cdot th_Y \cdot N_A}{A_Y}$$

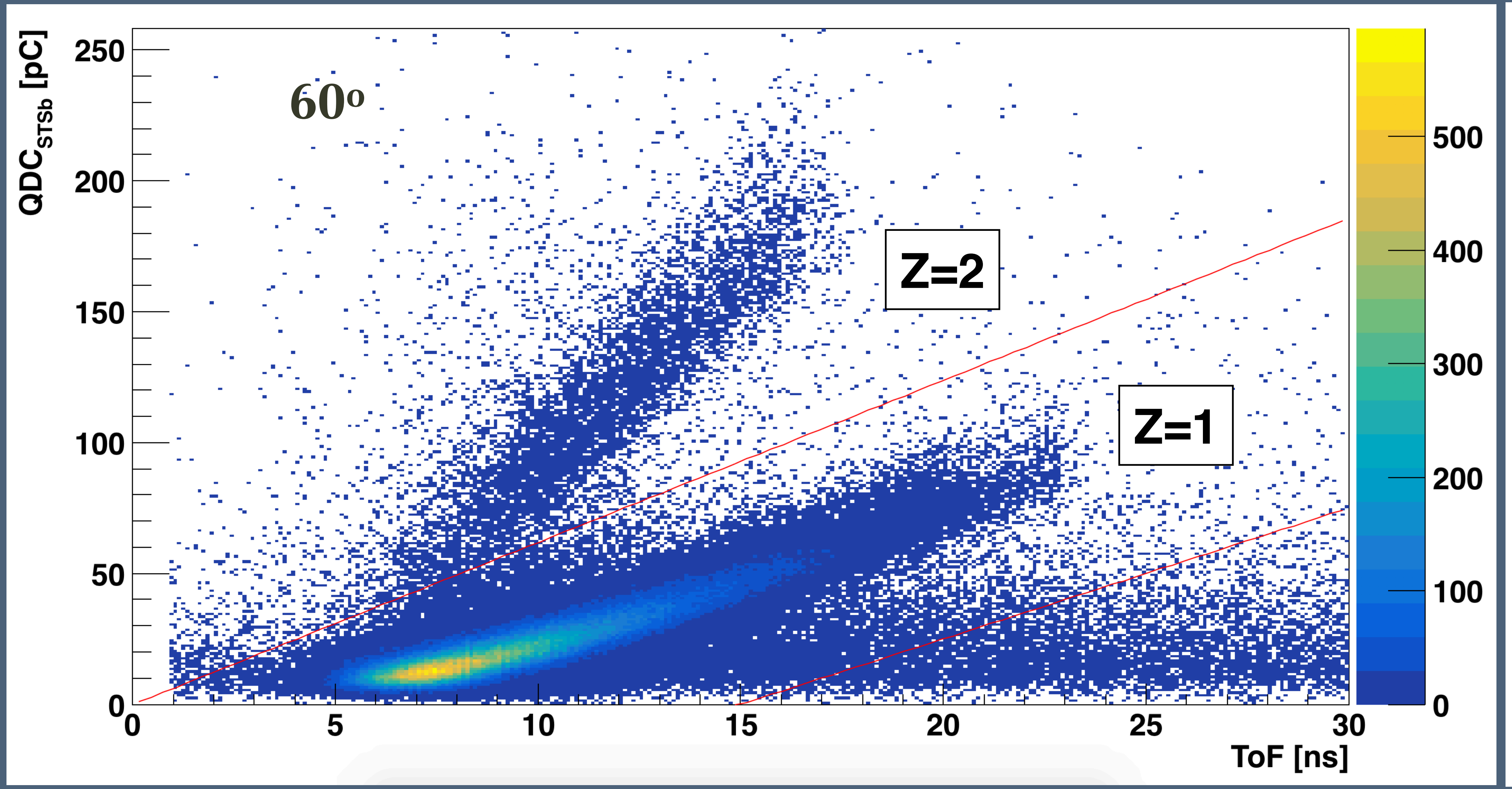
$$th_Y = th_Y * \sqrt{2}$$

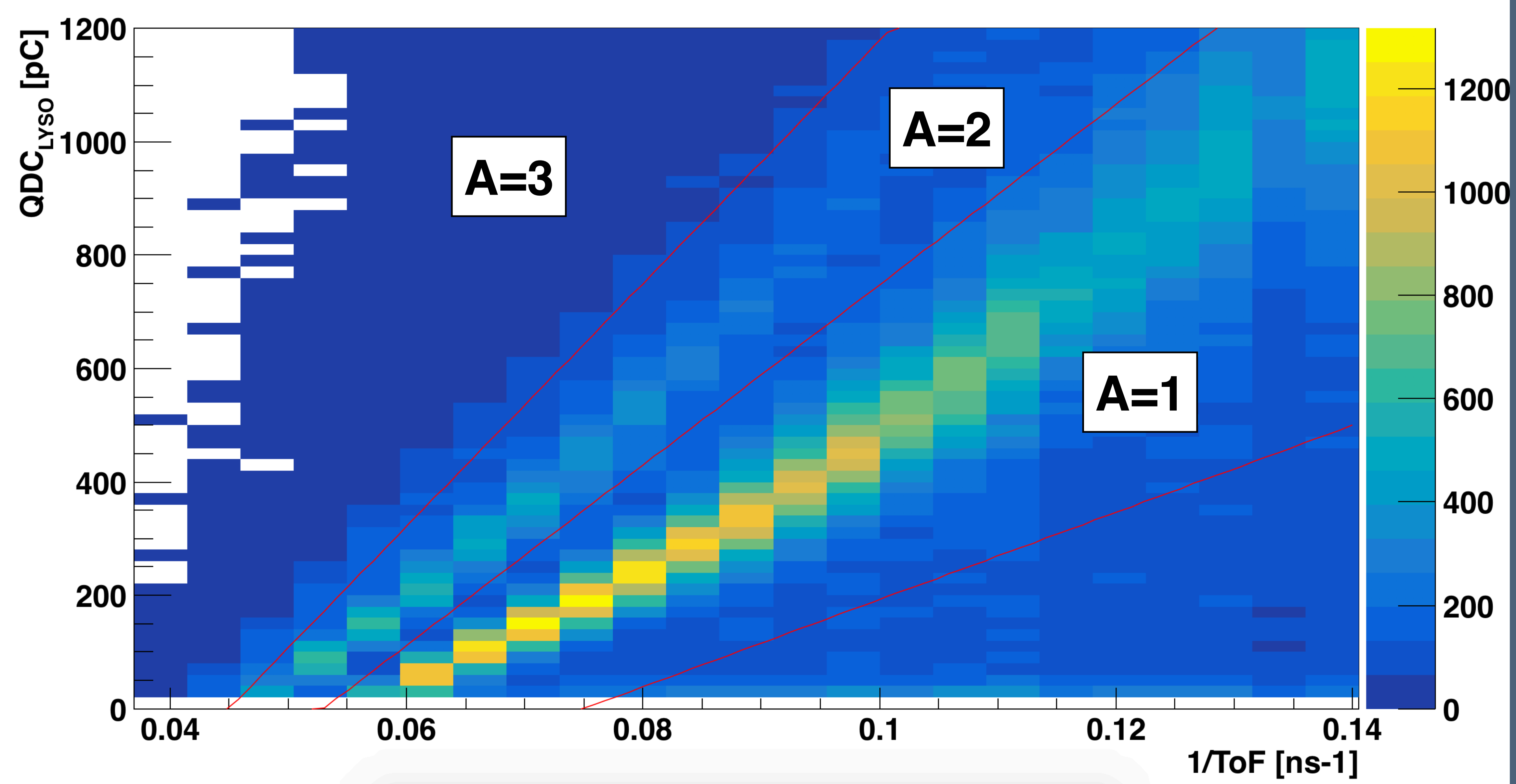
Cross Section Formula: Yield

The ^{12}C fragmentation cross section for a $^{A}_{Z}X$ fragment is obtained as:

$$\frac{d^2\sigma}{d\Omega dEk}(^{A}_{Z}X) = \boxed{\frac{N_{^{A}_{Z}X}}{\Delta\Omega\Delta E_k}} \cdot \frac{1}{N_{^{12}C}N_Y} \cdot \frac{1}{\epsilon}$$

- Particle identification (Z,A) from combining the information of QDC LYSO, QDC STSs, ToF STSs





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$$\beta_i = L/(ToF_i \cdot c)$$

$$E_{kin} = m_i \cdot (\gamma - 1)$$

- The raw fragment yield (as a function of E_{kin} meas) is corrected for purity

Purity = $\dfrac{\text{number of true p (d,t) in p (d,t) selection}}{\text{number of particles selected as p (d,t)}}$

Cross Section Formula: Yield

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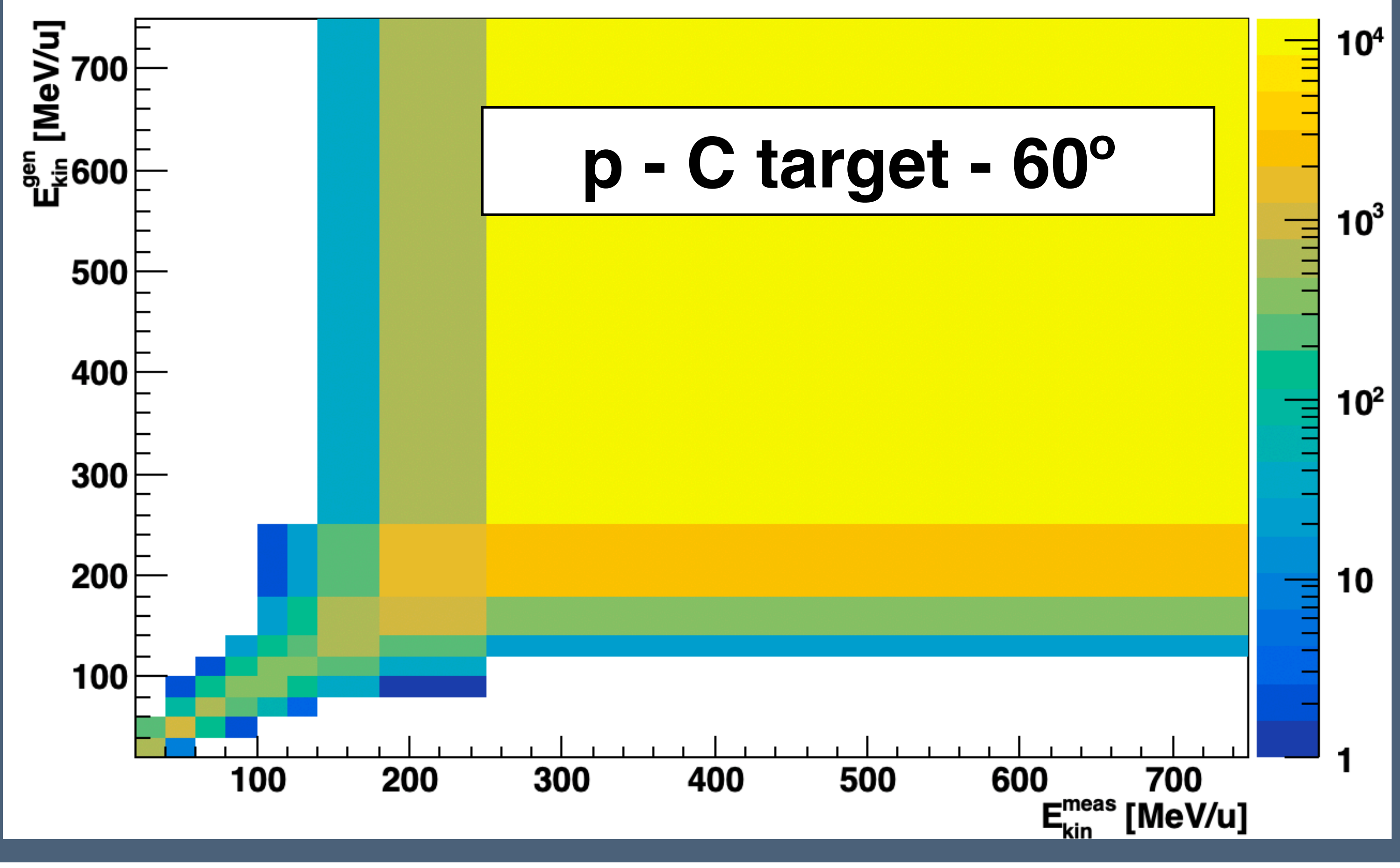
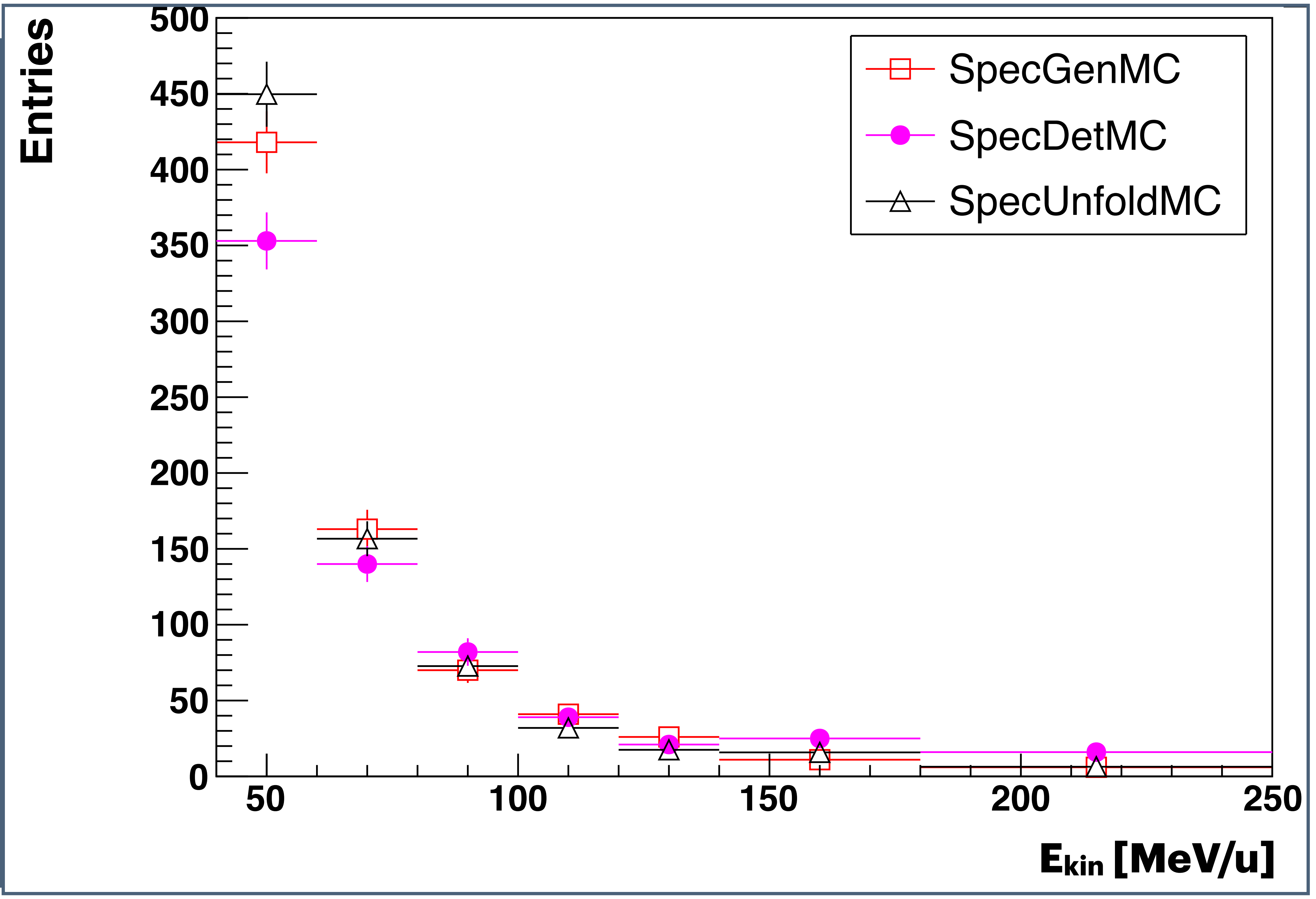
- Unfolding technique (RooBayesUnfold) to obtain the fragments E_{kin} gen from E_{kin} meas

Unfolding Matrix from FLAT simulation





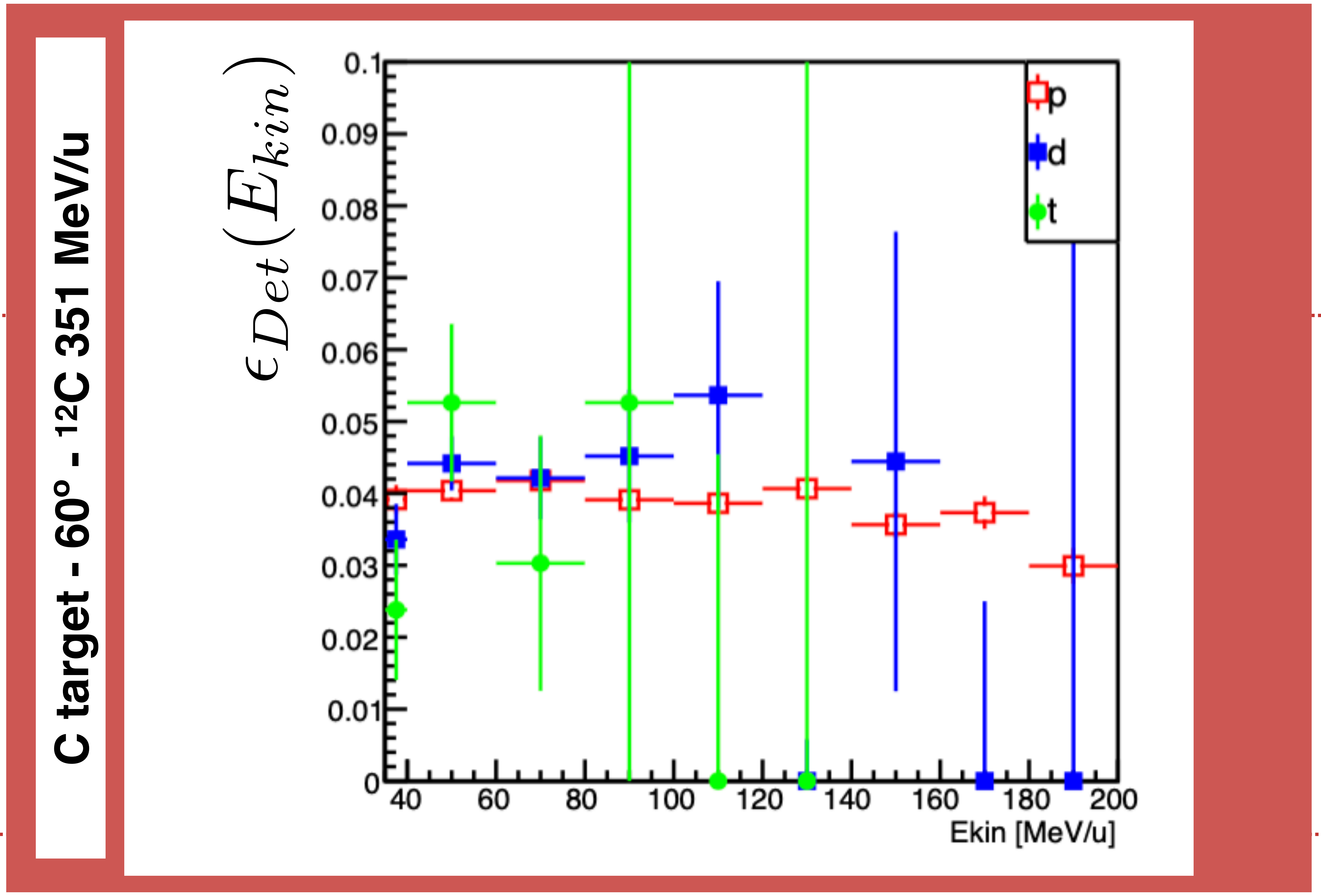
Cross Section Formula: Efficiency

The ^{12} C fragmentation cross section for a ^A_ZX fragment is obtained as:

$$\frac{d^2\sigma}{d\Omega dEk}(^A_ZX) = \frac{N_{^A_ZX}}{\Delta\Omega\Delta E_k} \cdot \frac{1}{N_{^{12}C}N_Y} \cdot \frac{1}{\epsilon}$$

$$\epsilon = \epsilon_{Det} \cdot \epsilon_{Sel} \cdot \epsilon_{DT}$$

Full simulation (~1.e^{10} primaries) to calculate the **trigger + detection + geometrical efficiency** as a function of fragment production Ekin



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$$\epsilon = \epsilon_{Det} \cdot \epsilon_{Sel} \cdot \epsilon_{DT}$$

Measurements of the **DAQ dead time** for each run

Full simulation (~1.e[10] primaries) to compute the **selection efficiency** of PID from E (dE) vs ToF distributions, tuned from data: probability that a fragment of type *u* is measured in the region *v* (*u*, *v* = *p*, *d*, *t*)

$$\epsilon^{uv}_{Sel} = \frac{N^{uv}}{N^u}$$

Systematics to the measurement

1) Monte Carlo Closure Test:

study of the Monte Carlo reliability in assessing the efficiencies to be applied to experimental data:

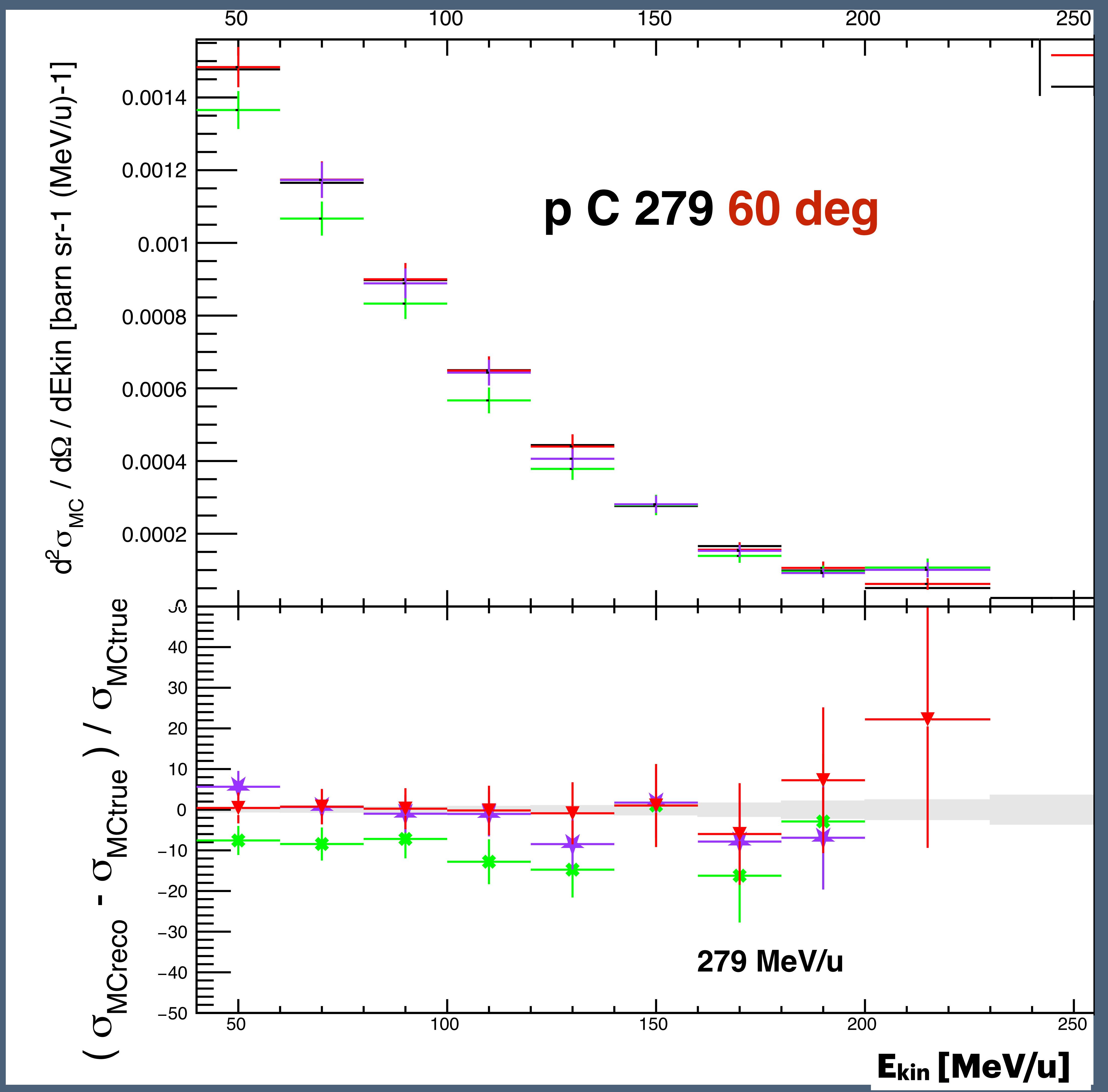
- define the **MCtrue** = p (d, t), born in target, generated by a primary particle, exiting the target, in the solid angle seen by the LYSO
- reconstruction of the MC with efficiencies applied (**MCreco**)
- comparison of MCreco with MCtrue

$$sys_{MC} = \frac{|\,\sigma MCreco - \sigma MCtrue\,|}{\sigma MCtrue}$$

Systematics to the measurement

1) Monte Carlo Closure Test:

- **mctrue: mc @ generation**
- **mc reco(Ekin MEAS)**
- **mcreco_meas UNFOLDED (Ekin@gen)**
- **mc reco(Ekin GEN)**



Systematics to the measurement

2) PID systematic: moving the p, d, t selection bands (hard and soft selection) and computing the average difference of XSec wrt the nominal PID selections (**sys_{PID}**)

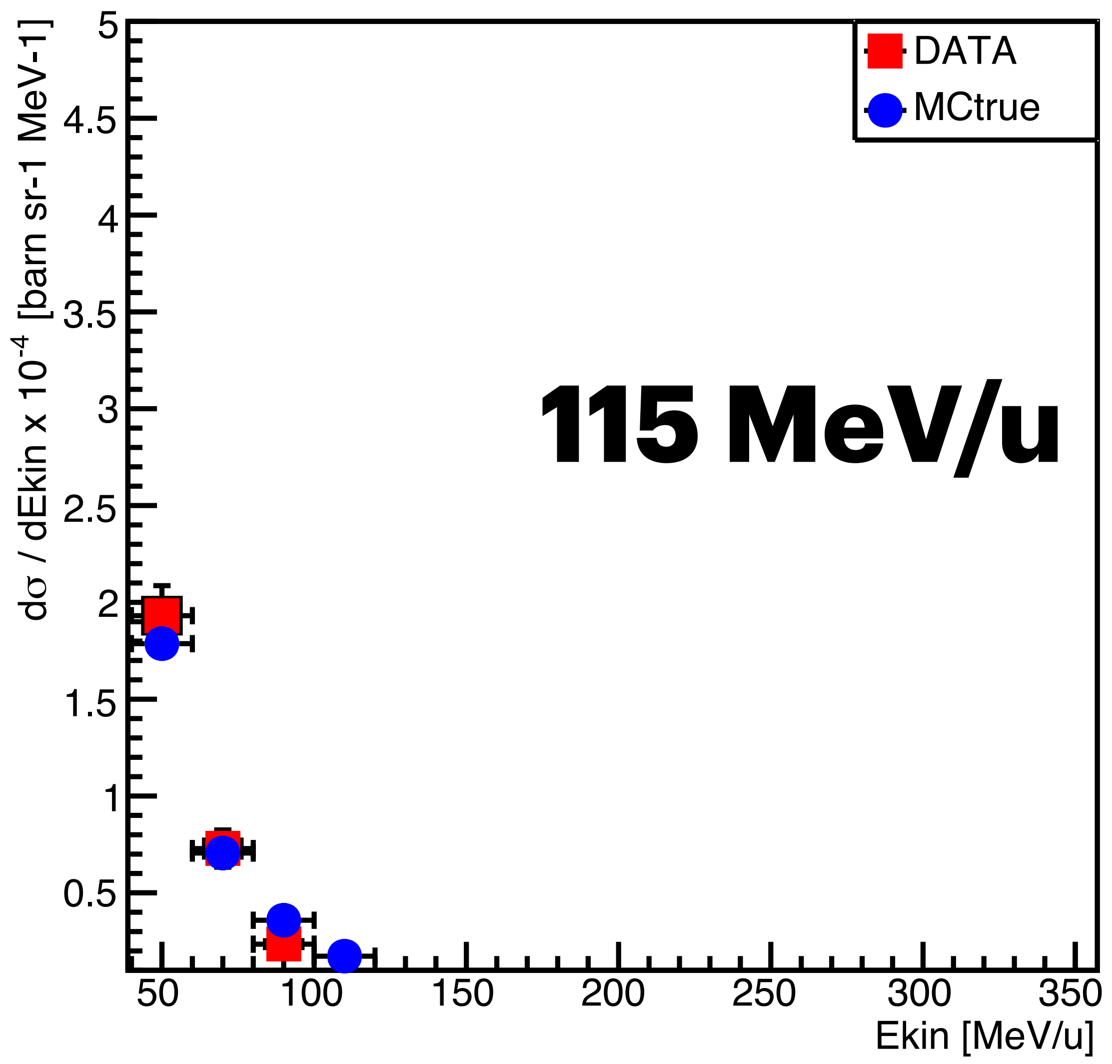
3) EpsDet from a different simulation: instead of the FULL simulation use of the FLAT simulation, i.e. p,d,t produced 4π within the target with a FLAT Ekin spectrum in the range [5 MeV/u - 1 GeV/u] (**sys_{EpsDet}**) => *computation is on going, not added yet to the results*

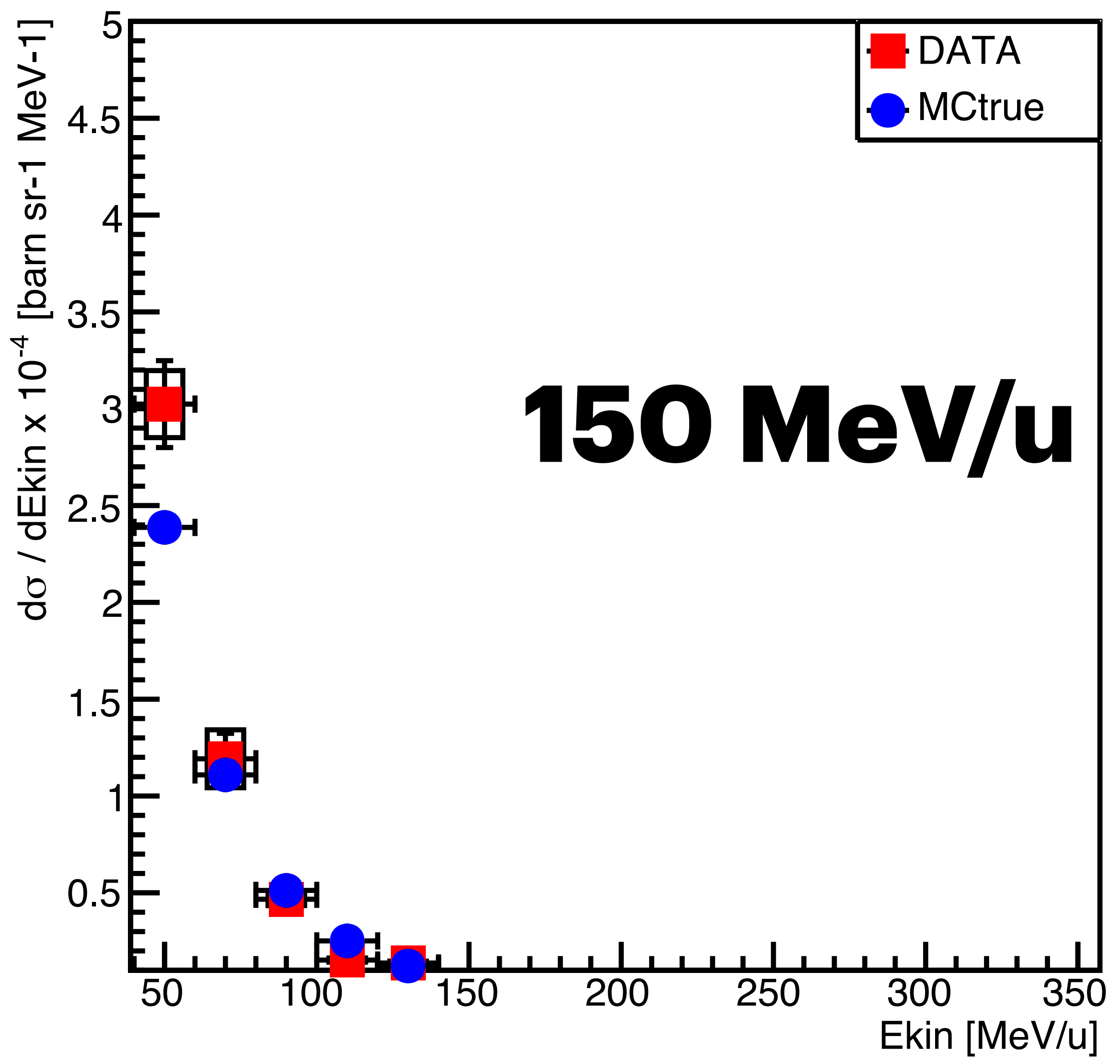
4) Unfolding procedure: changing unfolding technique (RooUnfoldIDS) wrt the nominal one (RooUnfoldBayes) and compute the XSec difference (**sys_{unf}**)

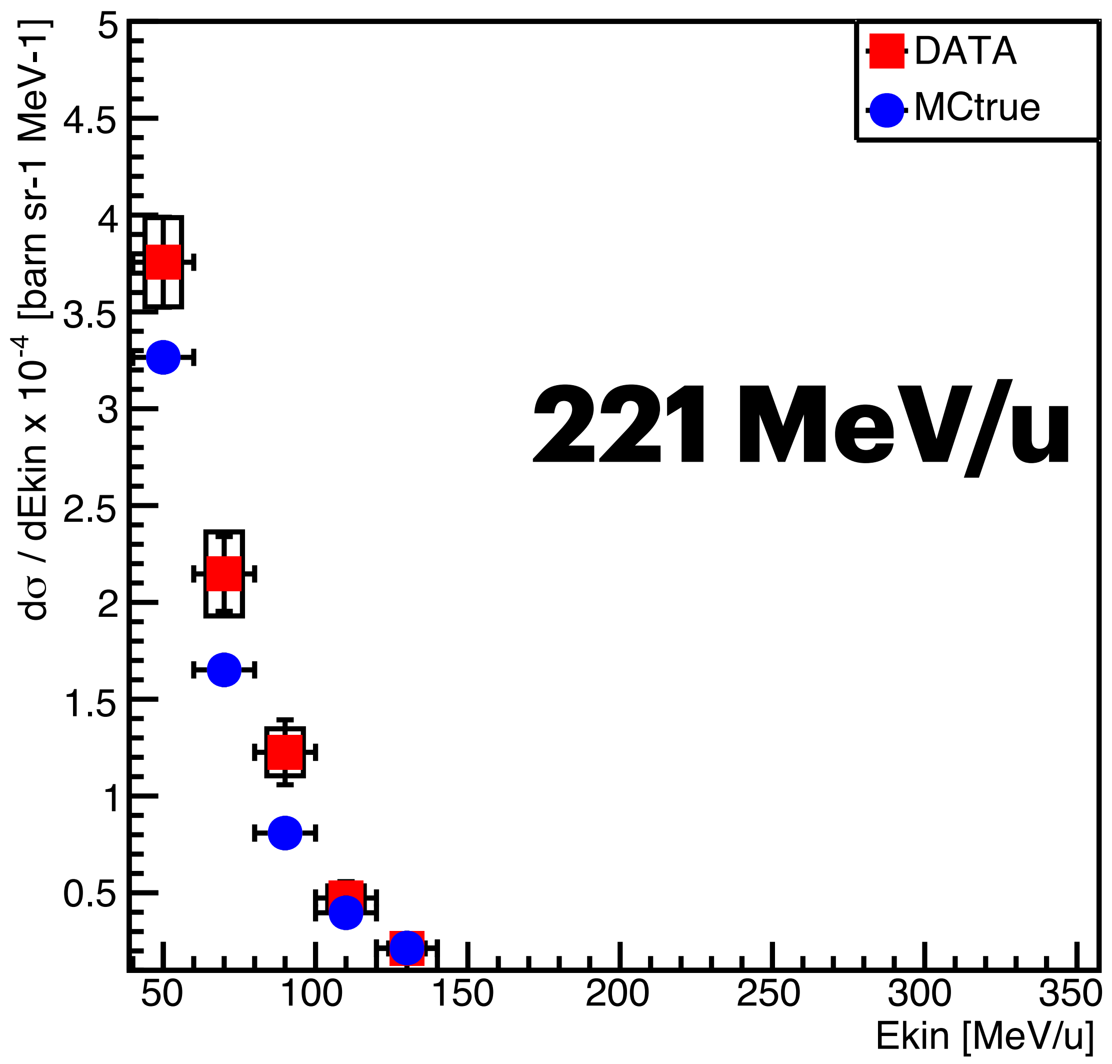
5) $N^{12}C$ from CNAO DDS: 4% relative error from dose-current conversion uncertainty (**sys_{N12C}**)

Final Results and MC comparison

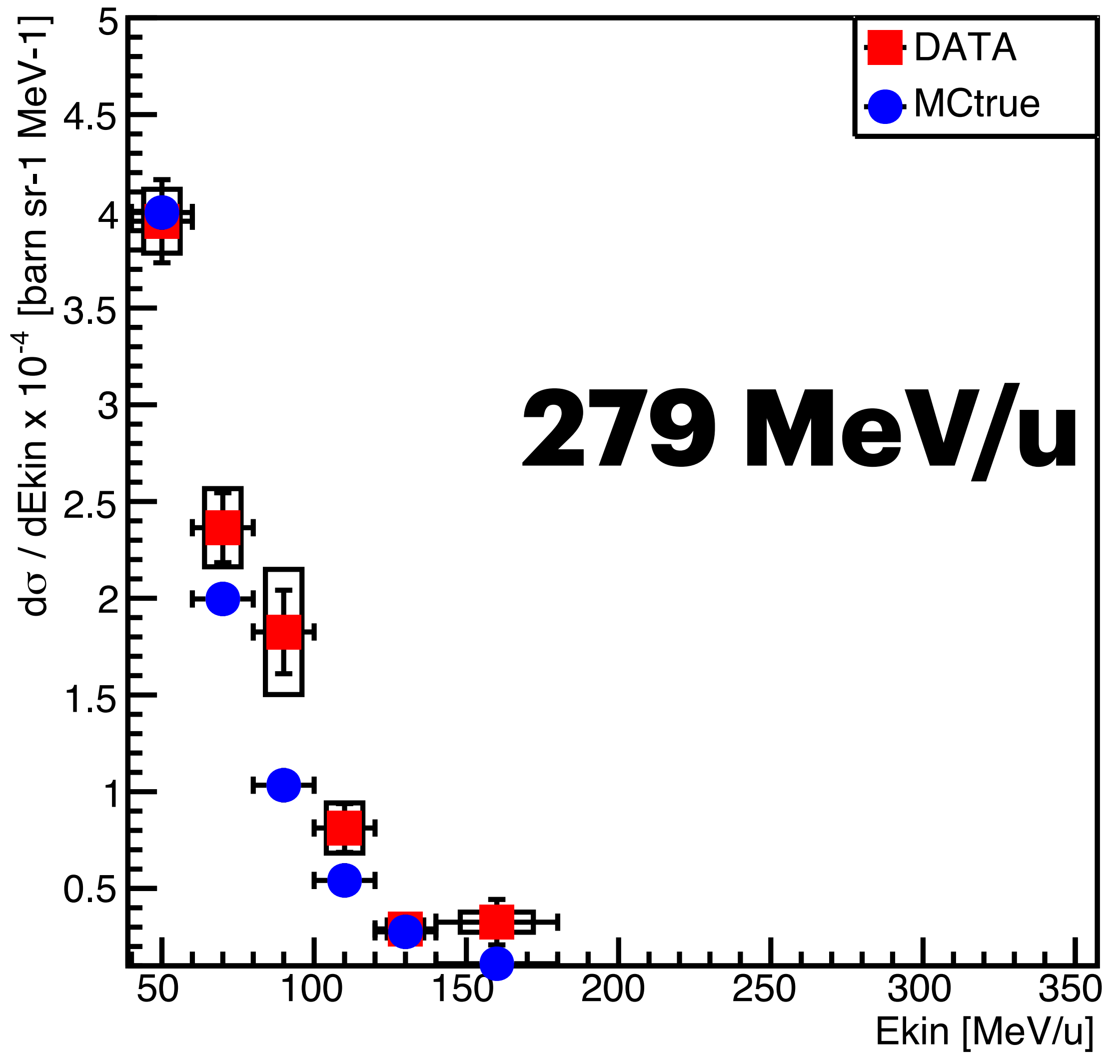
PRELIMINARY

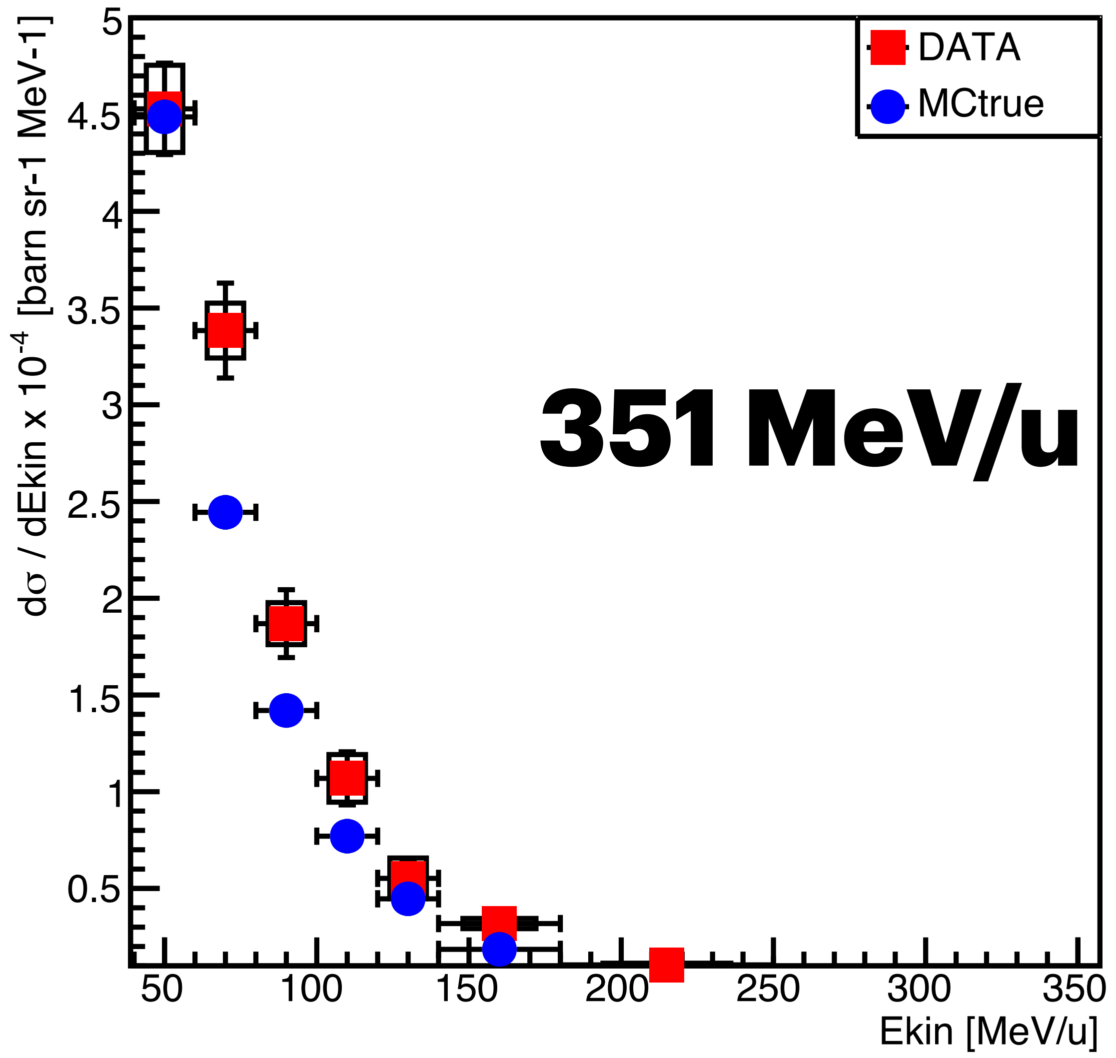






DATA
MCtrue
stat error
sys error

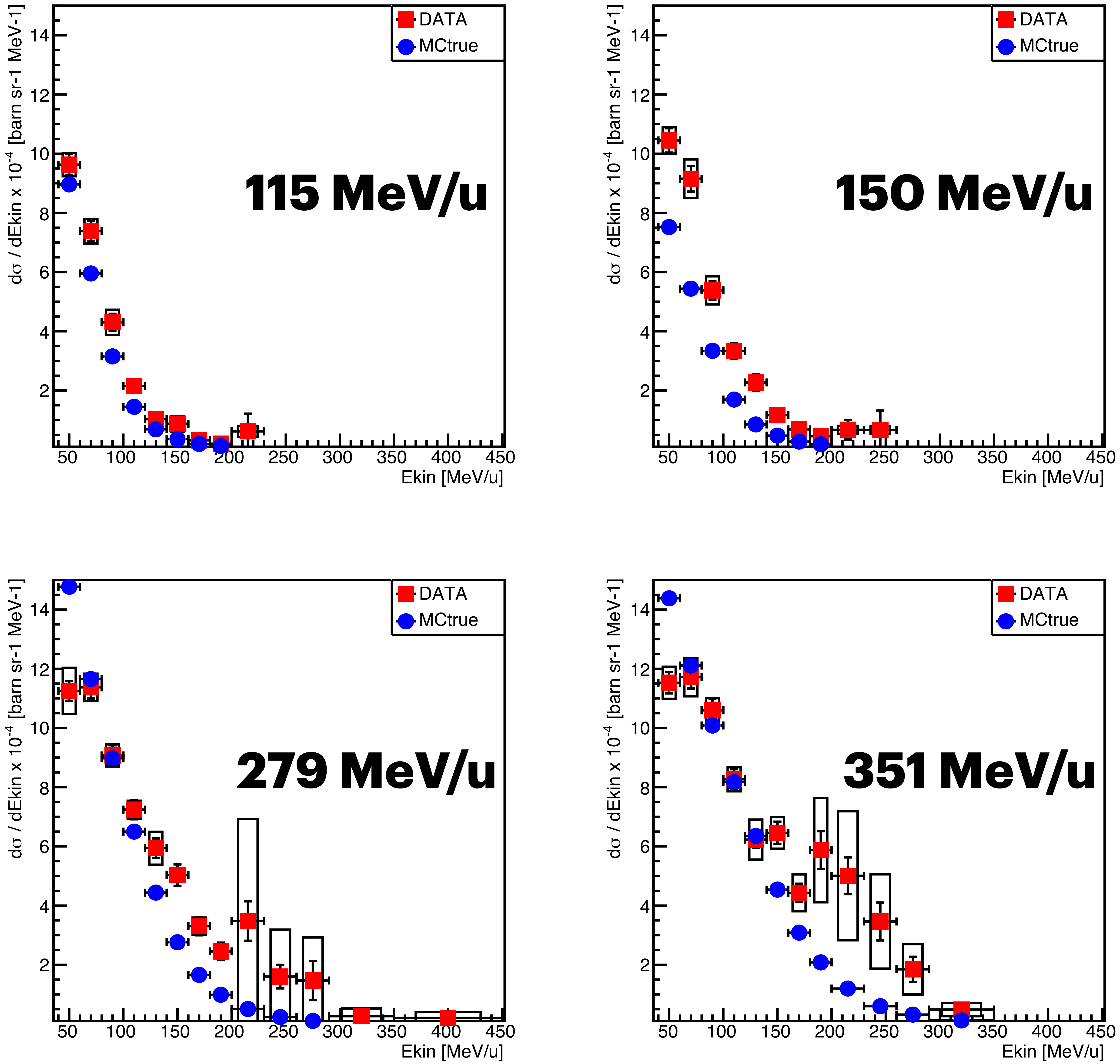


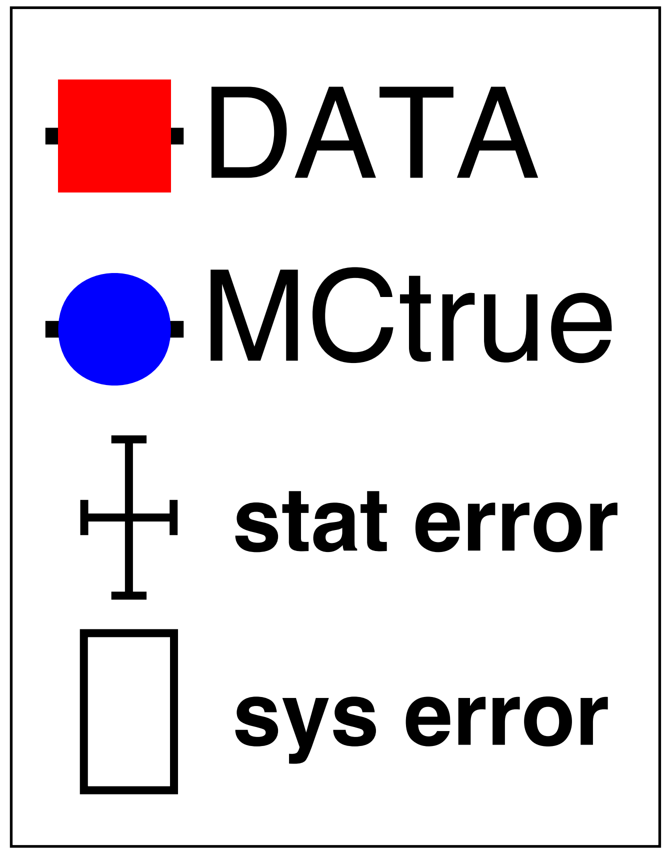


Protons detected at 90º Production XSection from 12C on C target

Final Results and MC comparison

PRELIMINARY

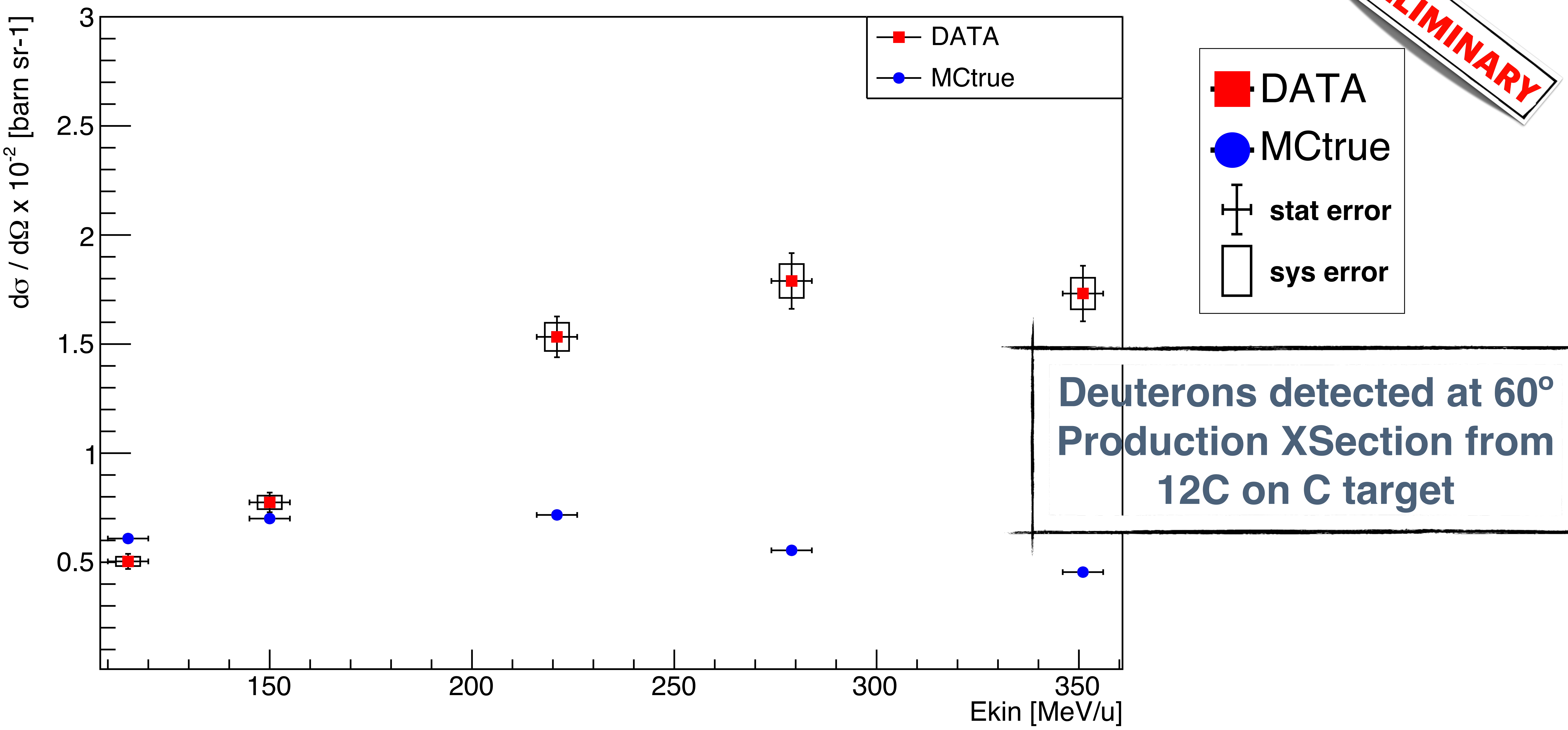




Protons detected at 60°
Production XSection from
12C on C target

Final Results and MC comparison

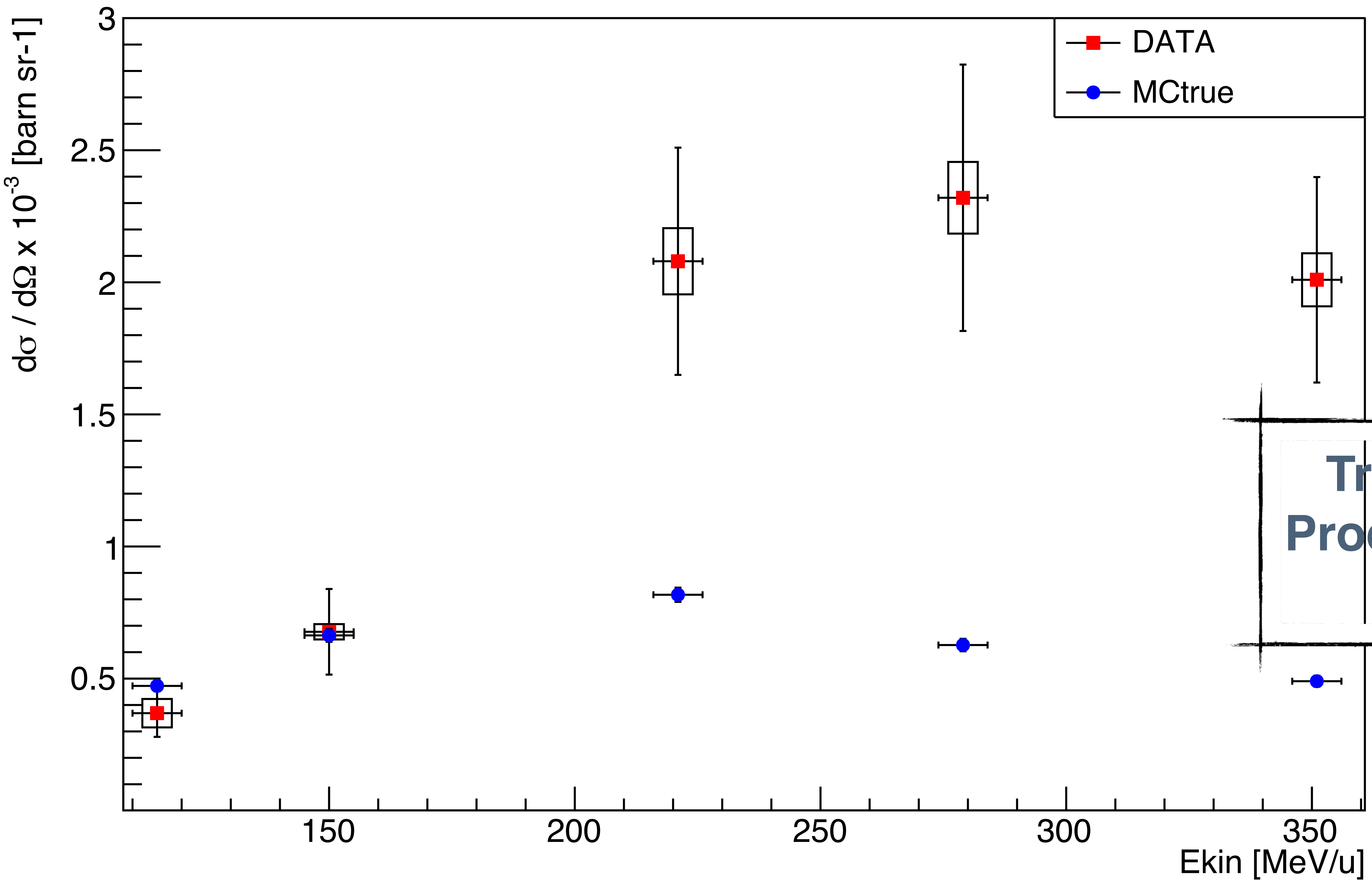
Final Results and MC comparison



Deuterons detected at 60°
Production XSection from 12C on C target

Final Results and MC comparison

PRELIMINARY

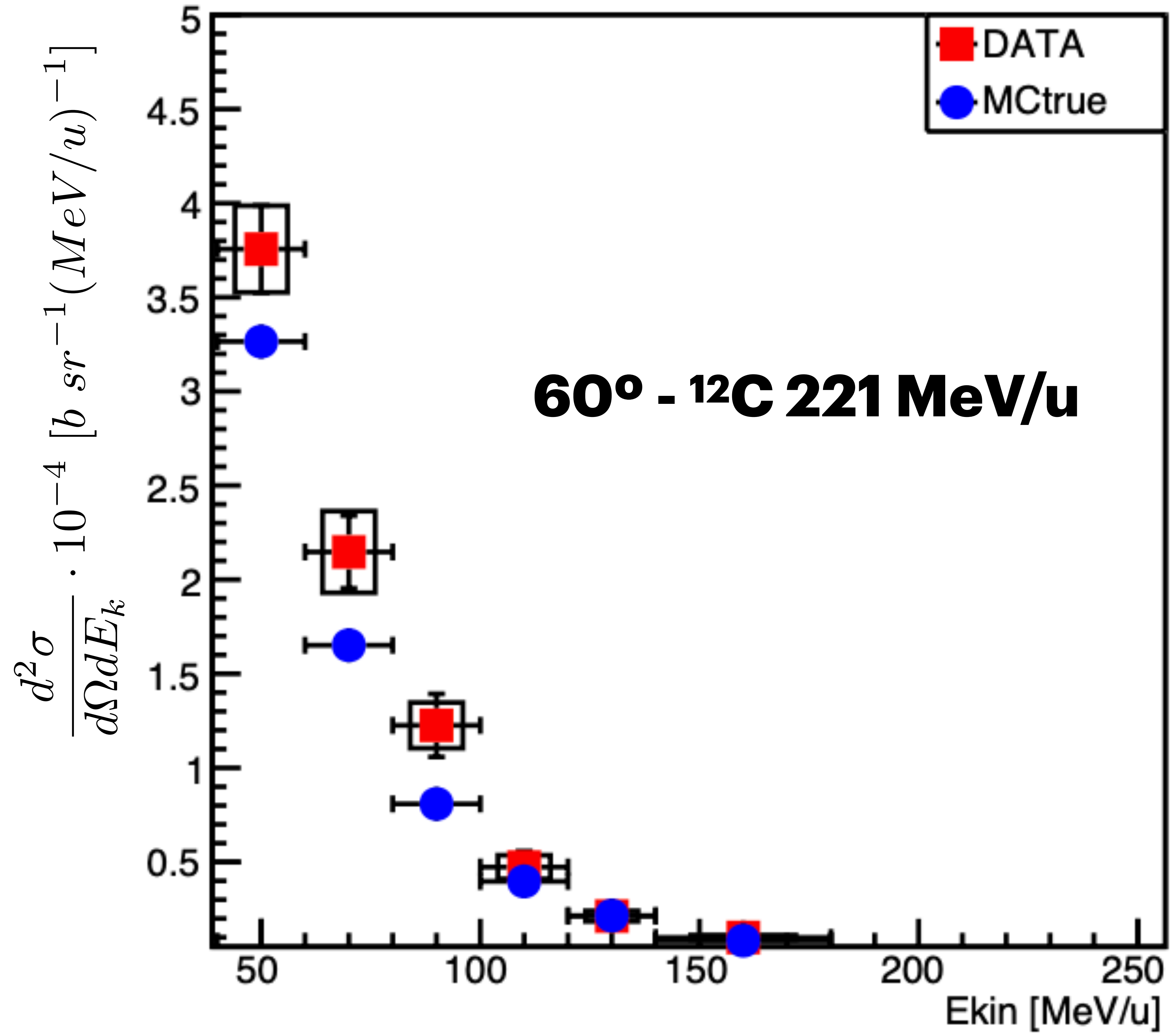


DATA
MCtrue
stat error
sys error

Tritons detected at 60°
Production XSection from
12C on C target

Conclusions

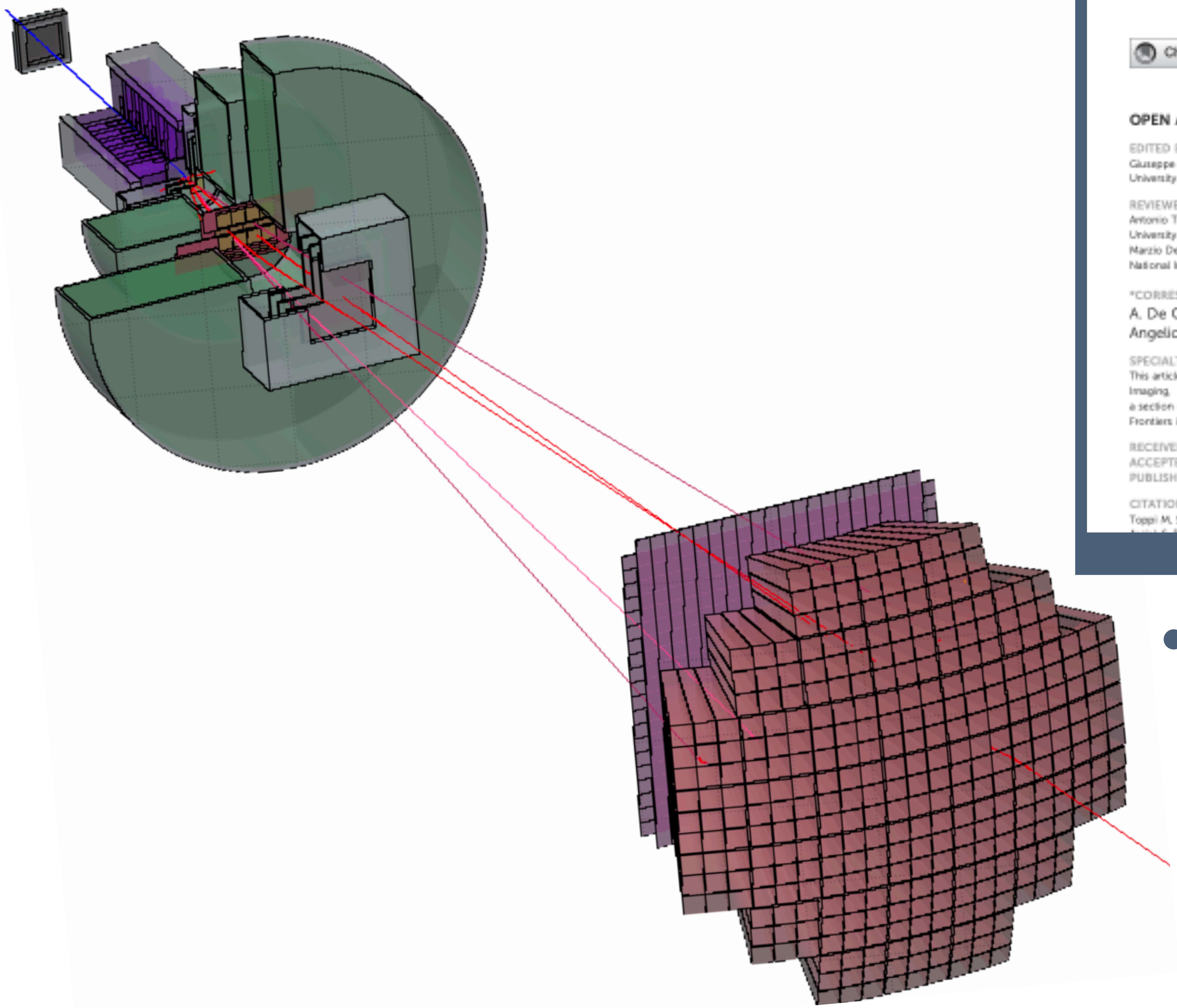
- We are finalizing the shown results
- Good agreement DATA - FLUKA MC at large angles



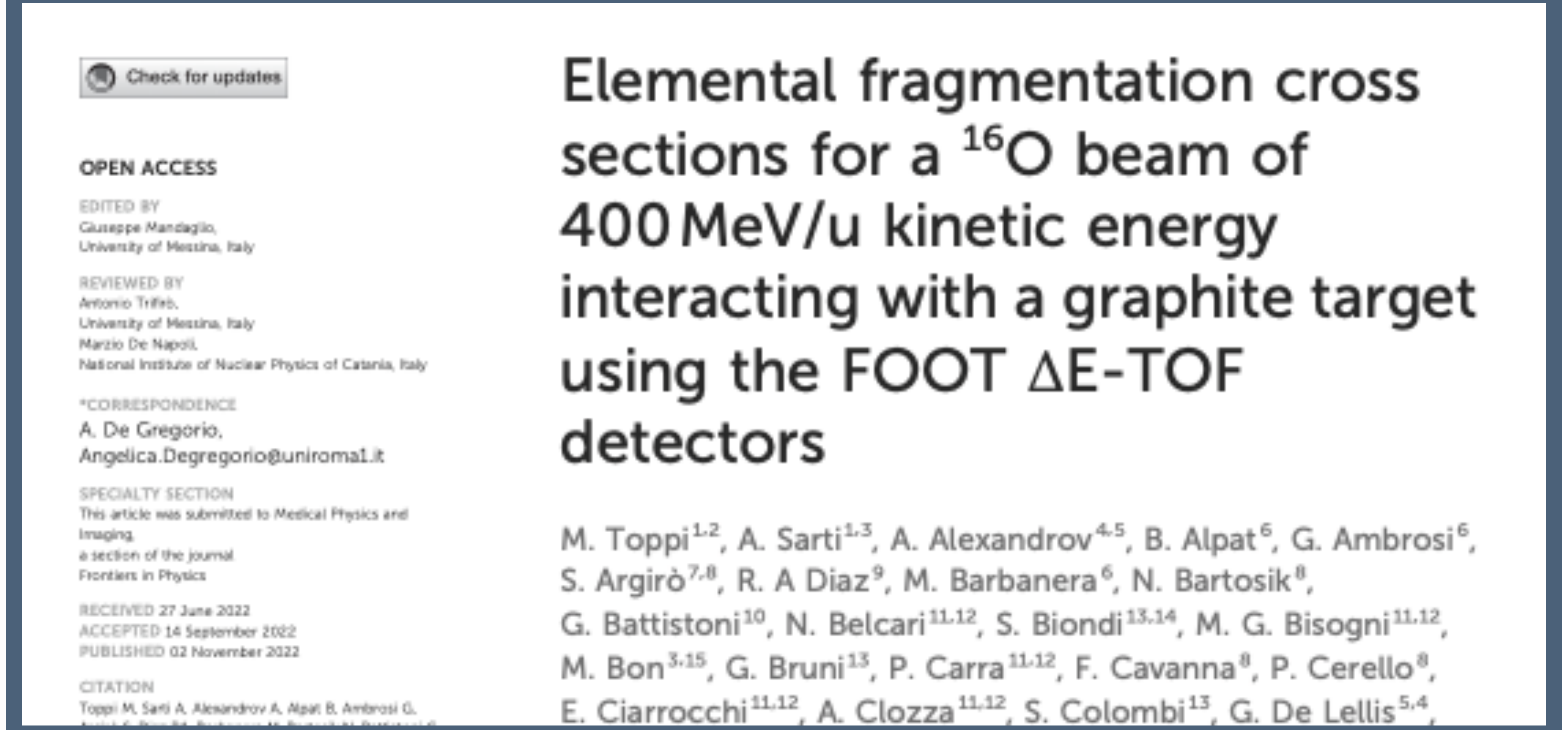
PRELIMINARY

p C 221				
E^p_{kin} [MeV/u]	$\frac{d\sigma^{MC}_{true}}{dE_k}$	$\frac{d\sigma^{data}}{dE_k}$	$stat^{data}$	sys^{data}
90^o	$\cdot 10^{-4}$ [b/sr/MeV]	$\cdot 10^{-4}$ [b/sr/MeV]	[%]	[%]
40 - 60	3.26 ± 0.04	3.8 ± 0.2± 0.2	6.2	6.1
60 - 80	1.65 ± 0.03	2.1 ± 0.2± 0.2	9.0	10.1
80 - 100	0.81 ± 0.02	1.2 ± 0.2± 0.1	13.7	9.9
100 - 120	0.40 ± 0.01	0.5 ± 0.1± 0.1	17.8	13.2
120 - 140	0.22 ± 0.01	0.21 ± 0.05± 0.03	23.7	13.2
140 - 180	0.082 ± 0.004	0.10 ± 0.03± 0.01	32.8	13.2
180 - 250	0.017 ± 0.001	-	-	-
60^o	$\cdot 10^{-4}$ [b/sr/MeV]	$\cdot 10^{-4}$ [b/sr/MeV]	[%]	[%]
40 - 60	12.9 ± 0.1	11.4 ± 0.4± 0.8	3.2	6.6
60 - 80	9.5 ± 0.1	11.3 ± 0.4± 0.6	3.7	5.3
80 - 100	6.7 ± 0.1	8.4 ± 0.4± 0.5	4.3	5.4
100 - 120	4.27 ± 0.04	6.2 ± 0.3± 0.3	5.6	4.2
120 - 140	2.41 ± 0.03	4.6 ± 0.4± 0.4	7.7	9.4
140 - 160	1.32 ± 0.02	3.6 ± 0.4± 0.1	10.5	4.1
160 - 180	0.70 ± 0.02	2.6 ± 0.4± 0.3	15.4	10.4
180 - 200	0.41 ± 0.01	2.5 ± 0.6± 0.3	23.4	10.4
200 - 230	0.19 ± 0.01	1.9 ± 0.6± 0.2	29.9	10.4
230 - 260	0.09 ± 0.01	1.0 ± 0.4± 0.1	43.7	10.4
260 - 290	0.047 ± 0.004	0.27 ± 0.11± 0.03	40.9	10.4
290 - 350	0.017 ± 0.002	-	-	-

Conclusions



First FOOT total cross section measurement



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CITATION
Toppi M, Sarti A, Alexandrov A, Alpat B, Ambrosi G,

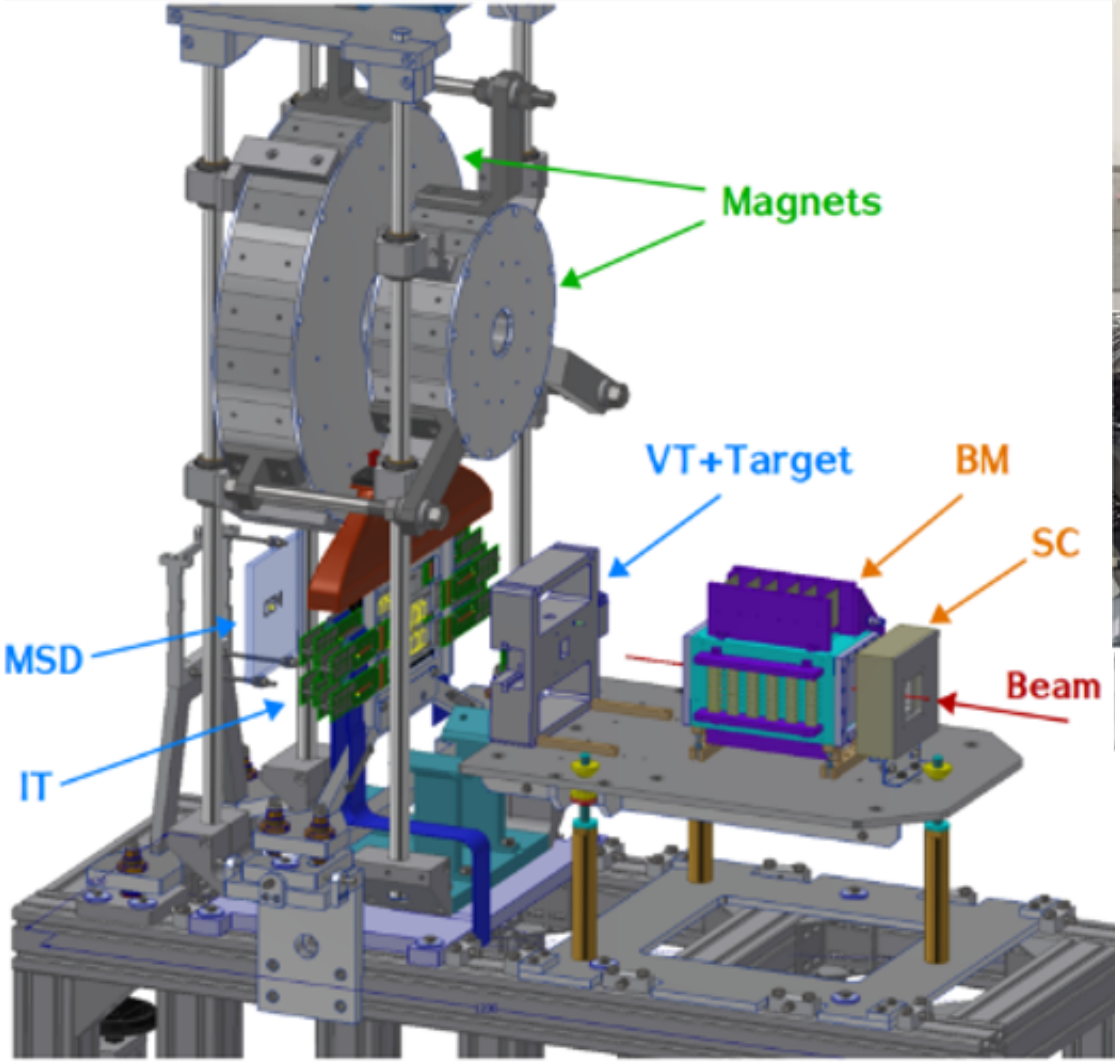
Elemental fragmentation cross sections for a ^{16}O beam of 400 MeV/u kinetic energy interacting with a graphite target using the FOOT ΔE-TOF detectors

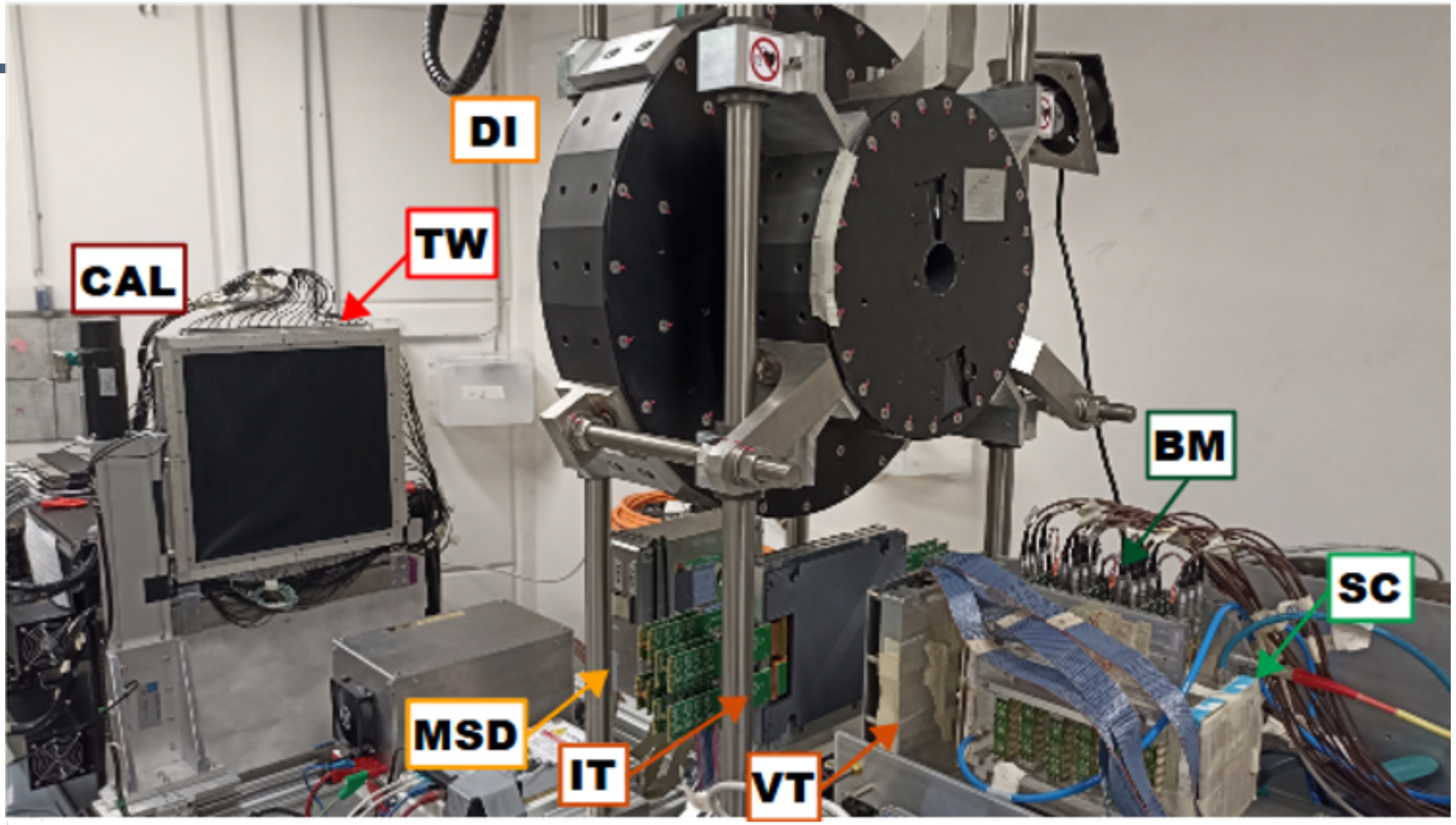
M. Toppi[1,2], A. Sarti[1,3], A. Alexandrov[4,5], B. Alpat[6], G. Ambrosi[6], S. Argirò[7,8], R. A Diaz[9], M. Barbanera[6], N. Bartosik[8], G. Battistoni[10], N. Belcari[11,12], S. Biondi[13,14], M. G. Bisogni[11,12], M. Bon[3,15], G. Bruni[13], P. Carra[11,12], F. Cavanna[8], P. Cerello[8], E. Ciarrocchi[11,12], A. Clozza[11,12], S. Colombi[13], G. De Lellis[5,4],

- FOOT (FragmentatiOn Of Target) experiment with tracker for double differential cross section measurements (direct and inverse kinematics)

Conclusions

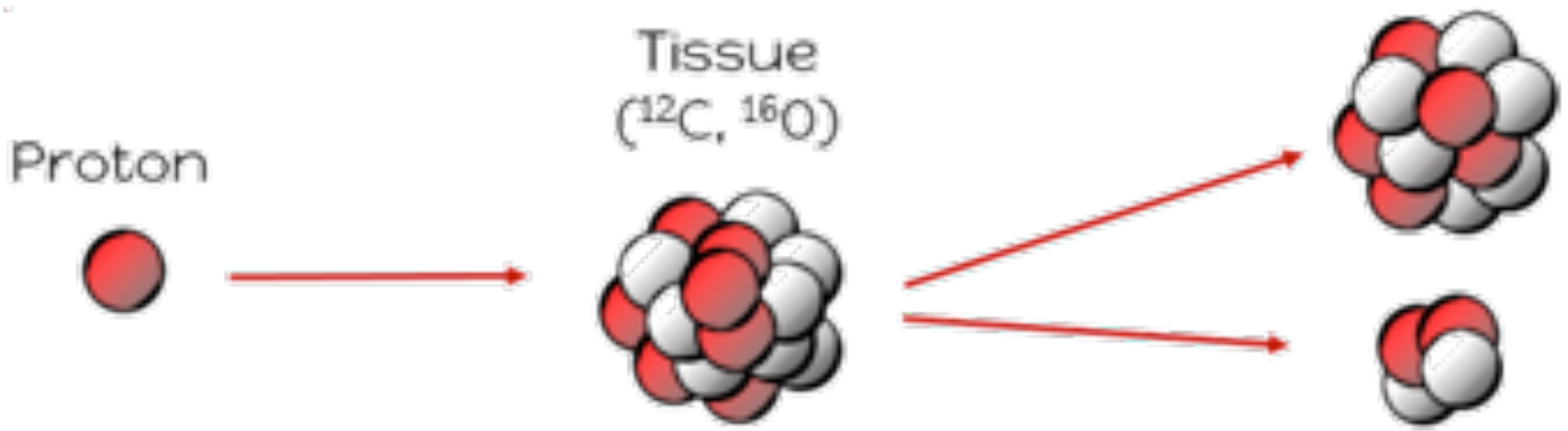
Full setup mounted for the first time at CNAO in late 2023!!





…and more to come:
400MeV/u C - C
100-200 MeV/u He - C
200 MeV/u C - C,C_2H_4

MILANO



Thank you for the Attention

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