Measurement of charged fragments production cross sections (dσ/dE) in the interactions of C-ions with C,H,O targets

IlaMi for Roma and Milano, March 2019

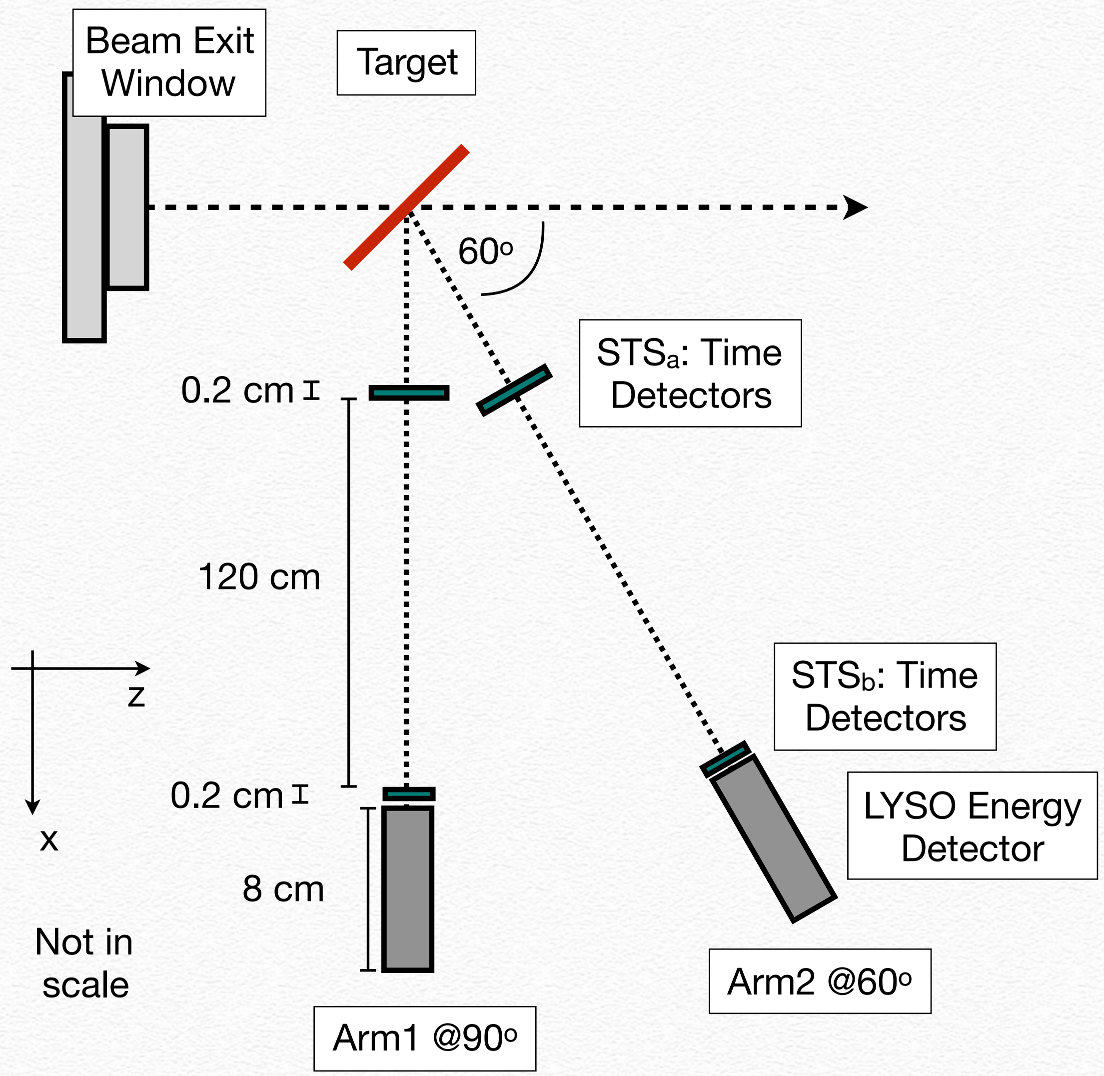
Experimental SETUP

CNAO

Thin Targets based on C,H and O elements: PMMA, Graphite and Plastic Scintillator

- The fragments production (Z=1) has been measured as a function of the kinetic energy for 4 angles;
- The Time of Flight in thin plastic scintillators and the energy deposit in the inorganic crystals has been used for PID and kinetic energy measurements;

The thin targets (1-2 mm) do not require, as a first approximation, the implementation of a correction for the fragments absorption inside the target.

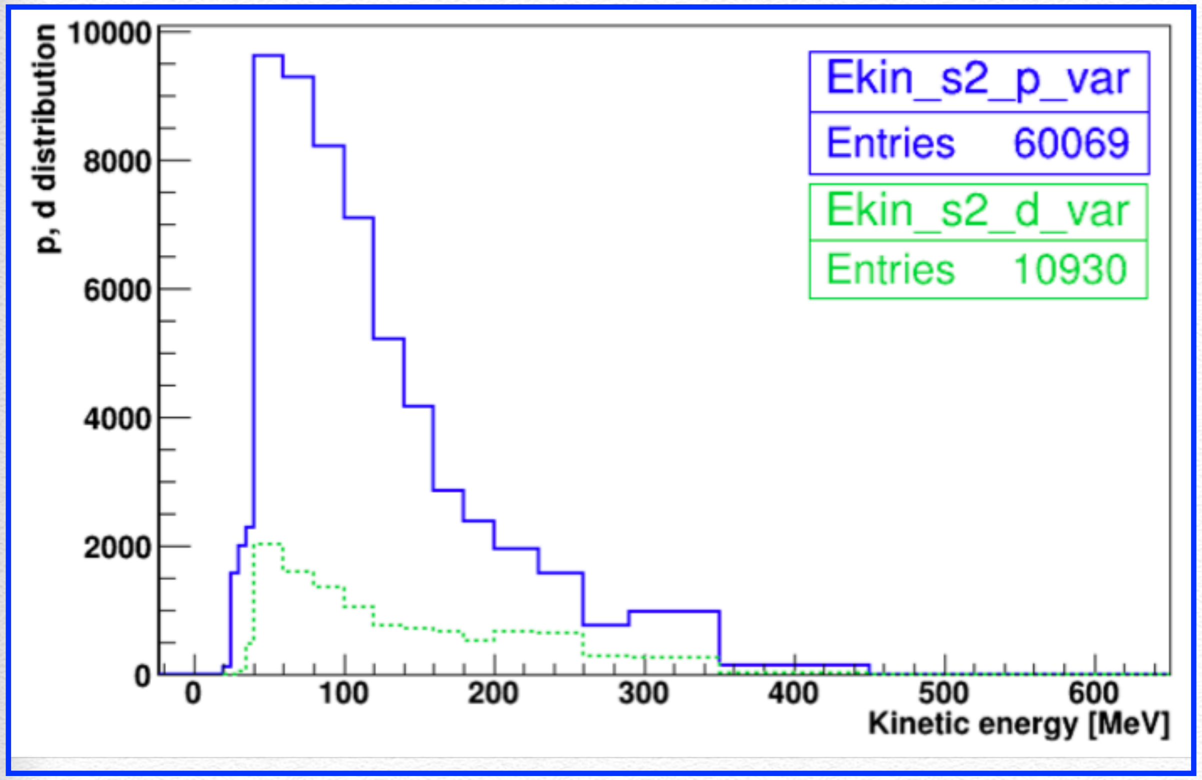


- 4 STS: thicknesses 2 mm for ToF measurements (Time Resolution ~400-600 ps) and Deposited Energy measurements (dE)
- 2 LYSO: 8 cm thick for Deposited Energy measurements (E)

Cross section

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

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



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Information of the target composition:

Target	Composition	Thickness $[mm]$	Density $[g/cm^3]$
PMMA	$C_5O_2H_8$	2	1.19
Graphite	C	1	0.94
Plas.Scint.	C_bH_a	2	1.024

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

From CNAO Dose Delivery

$N_{^{12}C}$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$	$\cdot 10^6$
Target	115 [MeV/u]	153 [MeV/u]	222 [MeV/u]	281 [MeV/u]	353 [MeV/u]
PMMA	49866	46512	49395	49601	42000
Graphyte	49454	46583	47484	47288	49328
Plast. Scint.	49728	50600	49347	49787	49653

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Solid angle and efficiencies

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

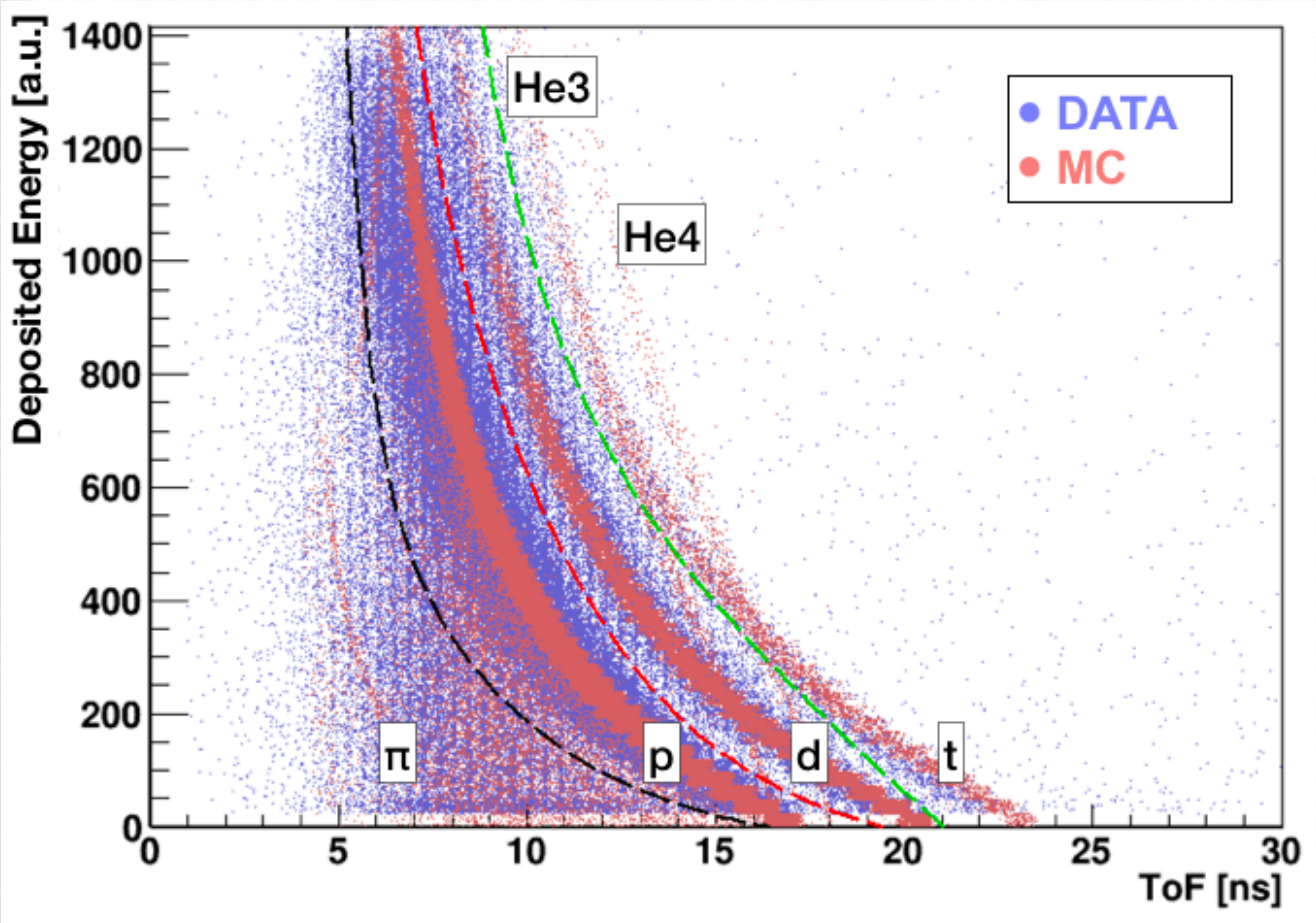
Protons and deutons impinged on the experimental setup to calculate the geometrical acceptance and the trigger+detection efficiency

Measurements of the DAQ dead time for each run (rate dependent)

Full simulation (C on Targets and fragments production). On the E (and dE) vs ToF distributions application of the PID selections tuned from data: evaluation of fragments (p, d) mis-identification.

Particle Identification

Protons and Deutons have been selected from all other particles exploiting **deposited Energy vs ToF**, dE vs E and dE vs ToF information.



The use of MC allows to clearly identify the fragments and define our identification strategy.
In the plot the separation lines that are applied on data to separate in mass the fragments are reported.

The deposited energy in the LYSO crystal is shown as a function of the time of flight of the measured particles for data and MC-data. For the data and the MC, the deposited energy is in arbitrary units. The fragments identity is shown in order to confirm the described data selection strategy.

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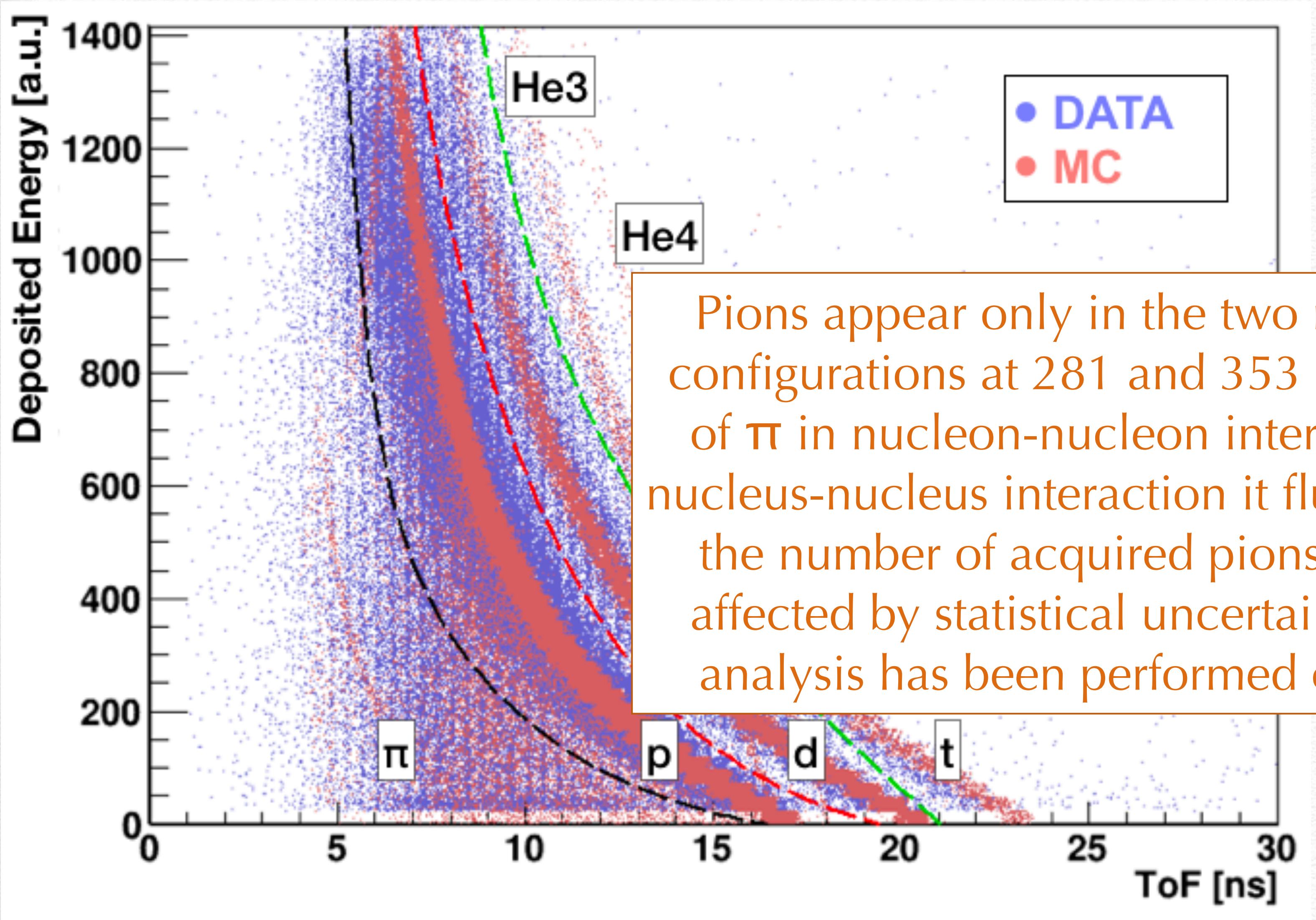

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Pions appear only in the two most energetic carbon ion beam configurations at 281 and 353 MeV/u (the production threshold of π in nucleon-nucleon interaction is 290 MeV/u, while in a nucleus-nucleus interaction it fluctuates around this value). Since the number of acquired pions is very low and is dramatically affected by statistical uncertainty, the cross section evaluation analysis has been performed only for protons and deuterons.

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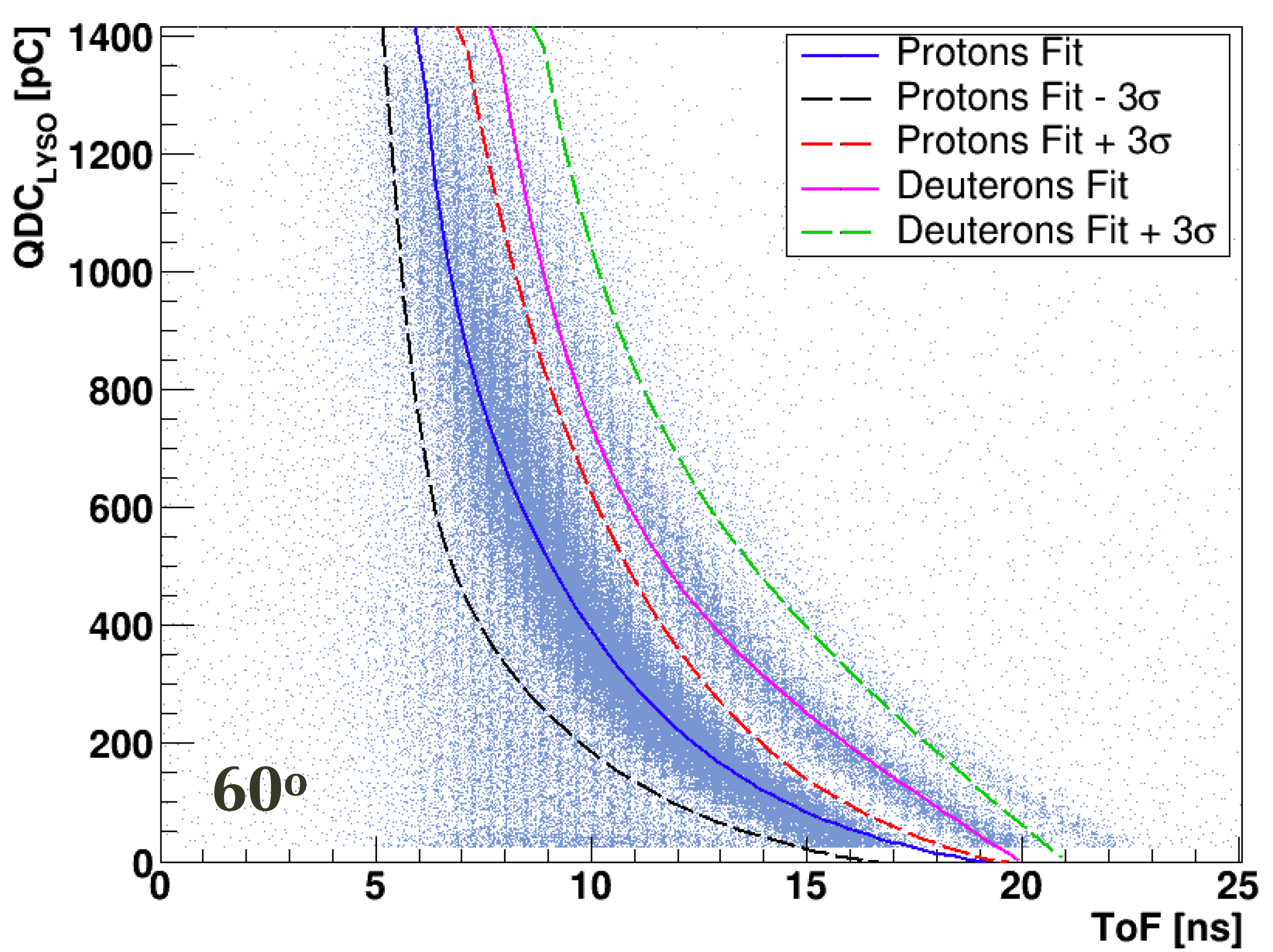

The central distribution is calculated by applying a peak-finder analysis on the ToF distribution for slices of fixed deposited energy in the LYSO. Protons are therefore selected between the black and red lines, while deuterons are between the red and the green ones.

The deposited energy in the LYSO crystal (in pC) is shown as a function of the time of flight of the measured particles. The populations of fragments at 60 degrees are selected applying 3 sigma deviation from the central proton and deuteron distributions.

Protons and deuterons are reasonably abundant in all the specific data sets: about 80% and 15% of the fragments respectively at 60º.

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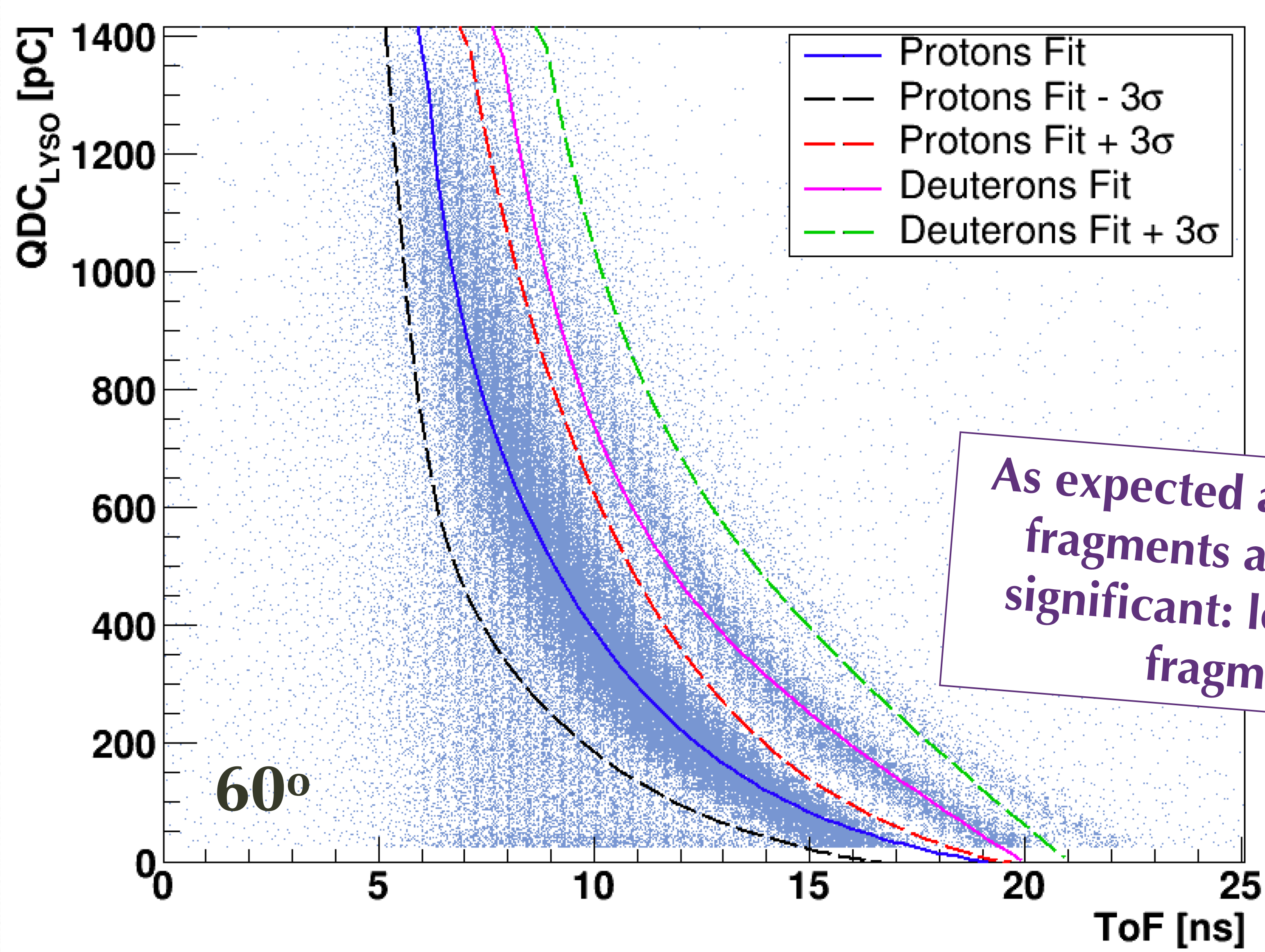

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As expected at large angle, triton fragments are not statistically significant: less than 5% of the fragments at 60°.

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Particle Identification

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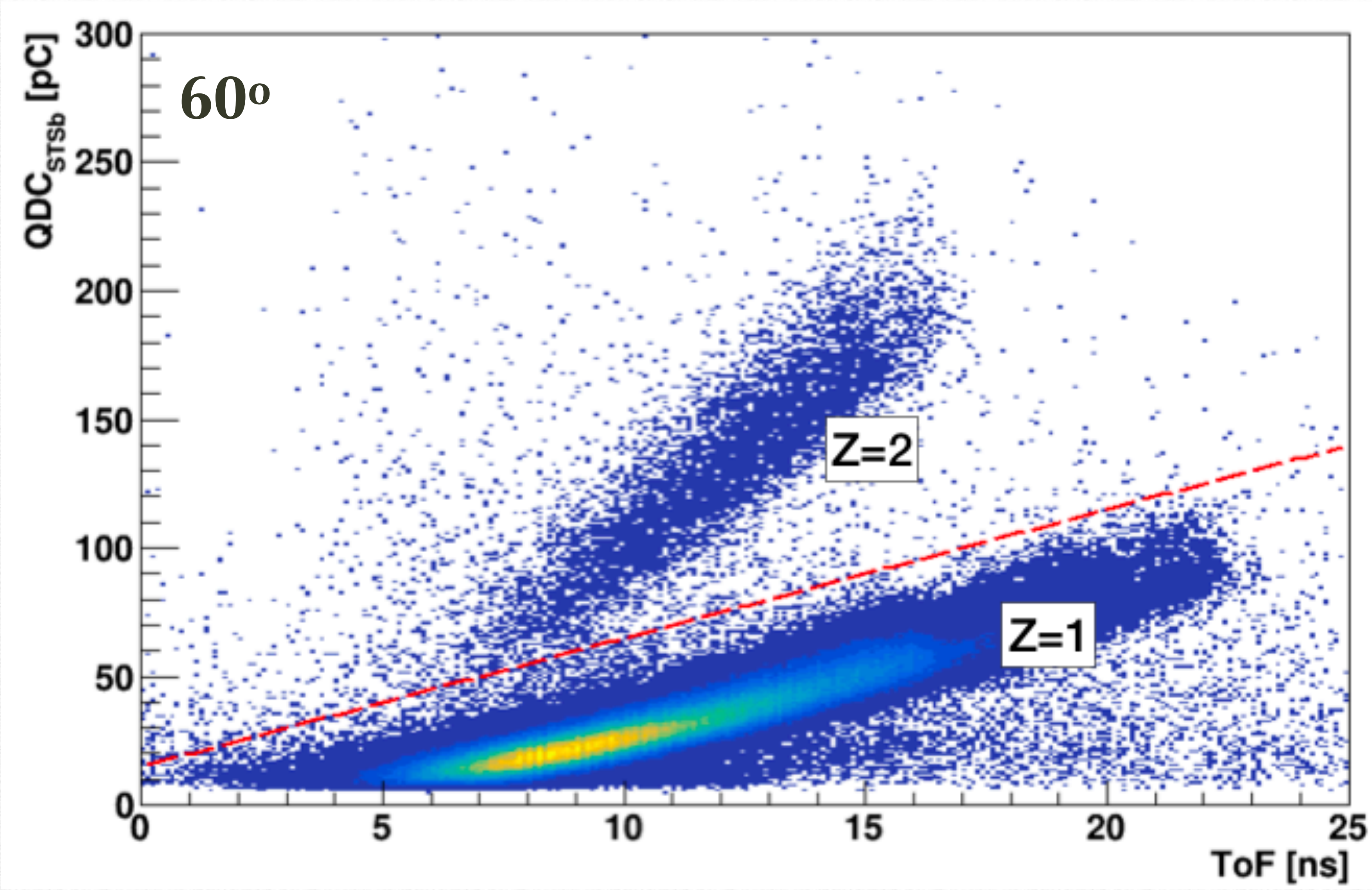


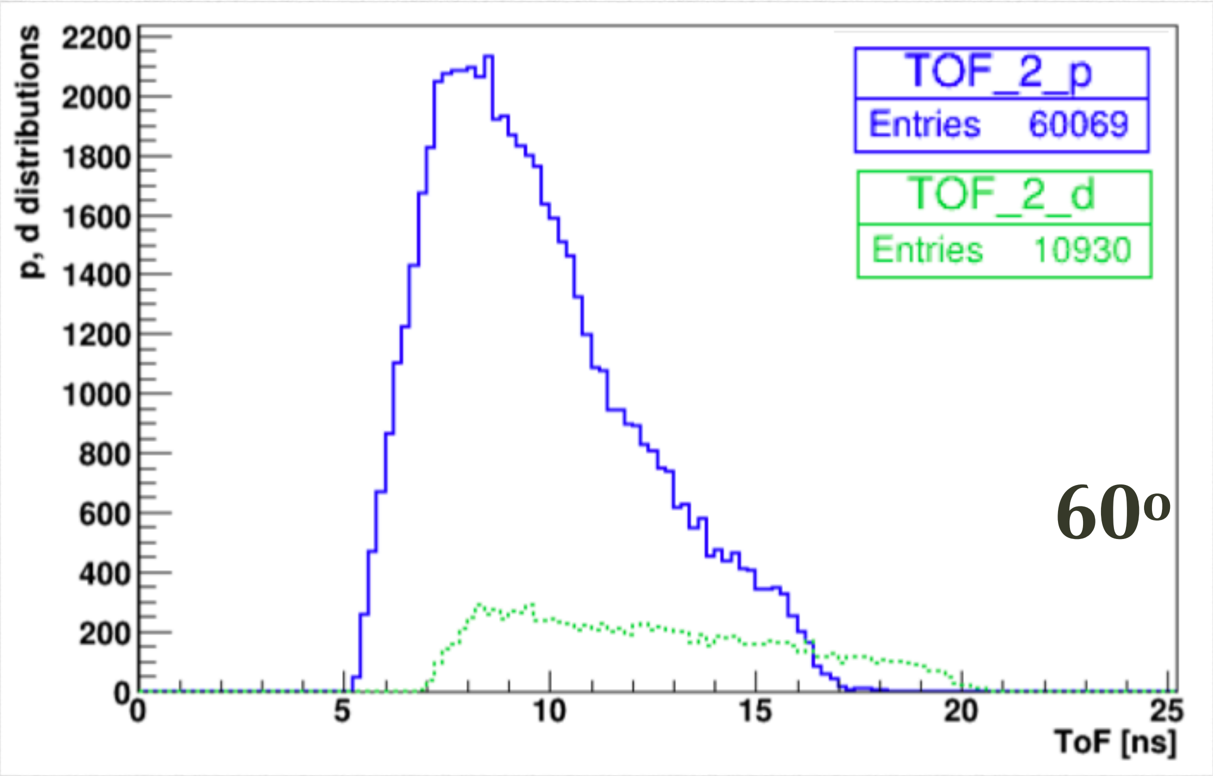
The energy loss in the STSb (in pC) is shown as a function of the time of flight of the measured particles. The populations of Z=1 and Z=2 at 60 degrees are clearly separated by the red line.

The helium fragments, as well as tritons, are not very abundant at such large angles (90º, 60º), thus do not represent a statistically significant sample (about 2% of the fragments are Z=2, at 60º).

No cross section analysis has been performed for Z>1 fragments, however, they have been removed from the analysed data sample.

Kinetic Energy Spectra

Time of Flight distributions of protons (blue solid line) and deuterons (green dashed line) shown in the top plot are converted in the kinetic energy distributions shown in the bottom plot. Data refer to Arm2, graphite target with C-ion beam at 352 MeV/u:

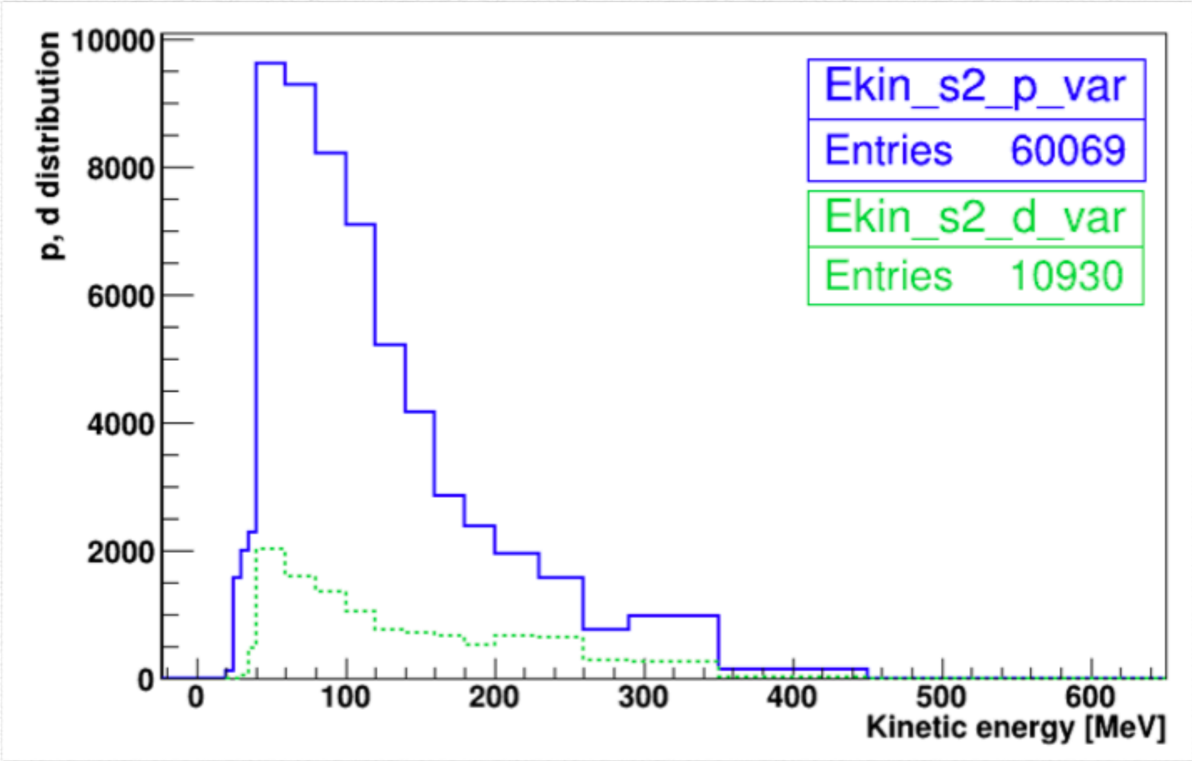


Time resolution evaluated from dedicated run:

- 90°: 590 ps
- 60°: 430 ps

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

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



Energy resolution as a function of proton kinetic energy ranges from **8% up to 29% (22%)** for 90° (60°) (worsening with increasing energy) for both p and d.

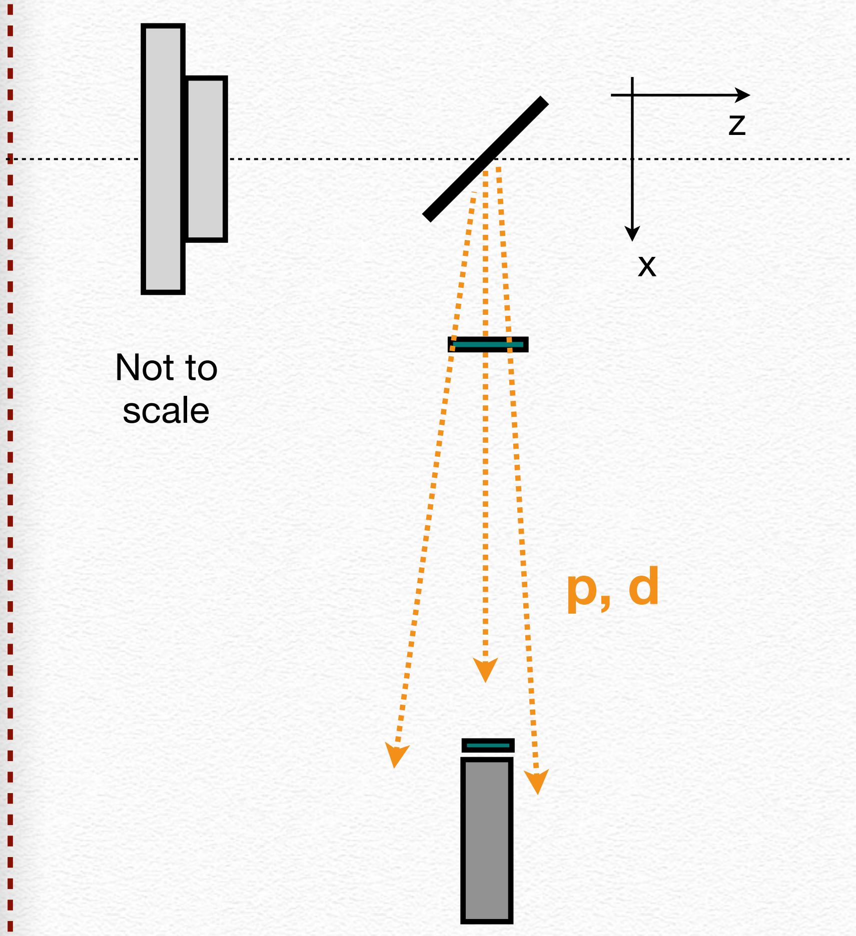
The kinetic energy has been therefore reconstructed in variable size bins that have been chosen as a compromise between the energy resolution and the available statistics in each bin (in the final differential cross section evaluation). Since the time resolution and the statistics of the two different arms is different, the bin size has been chosen differently for the two angular setups.

Efficiency evaluation:

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

The efficiency $\epsilon_{Det}(E_{kin})$ and ϵ_{Sel} have been evaluated using dedicated Monte Carlo simulations developed with the FLUKA code.

- To evaluate $\epsilon_{Det}(E_{kin})$: detector, angular, trigger, signal selection efficiency = > MC FLAT (no triggered MC: all events recorded): p, d sources with no target, 4π production



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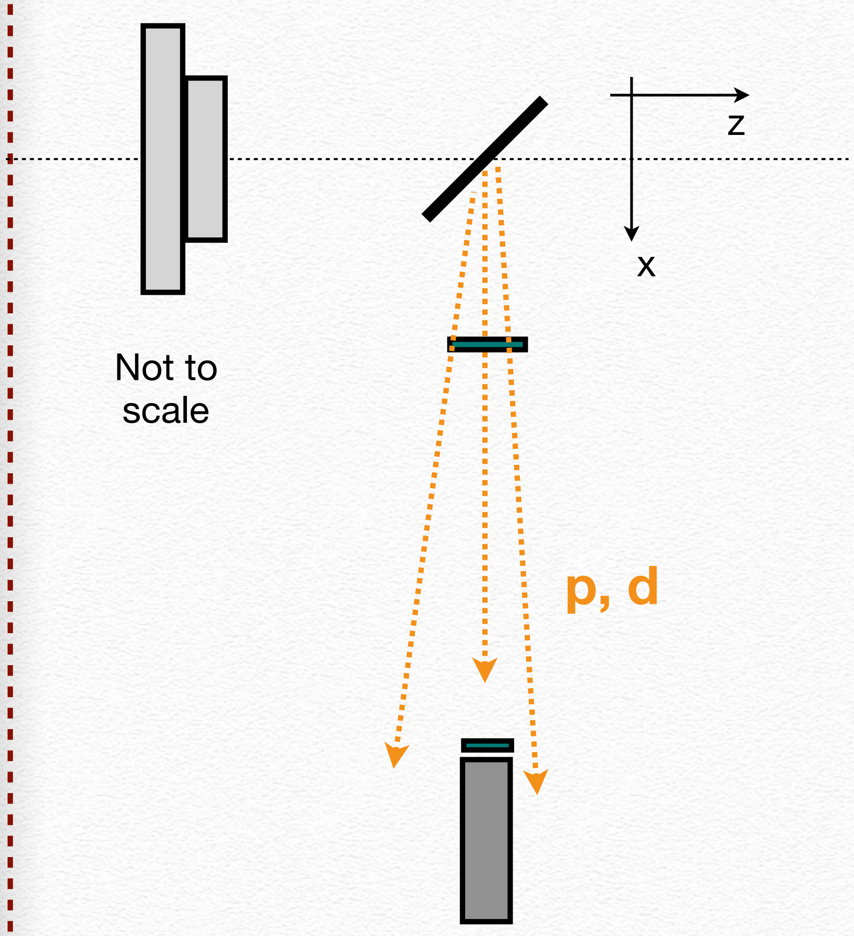
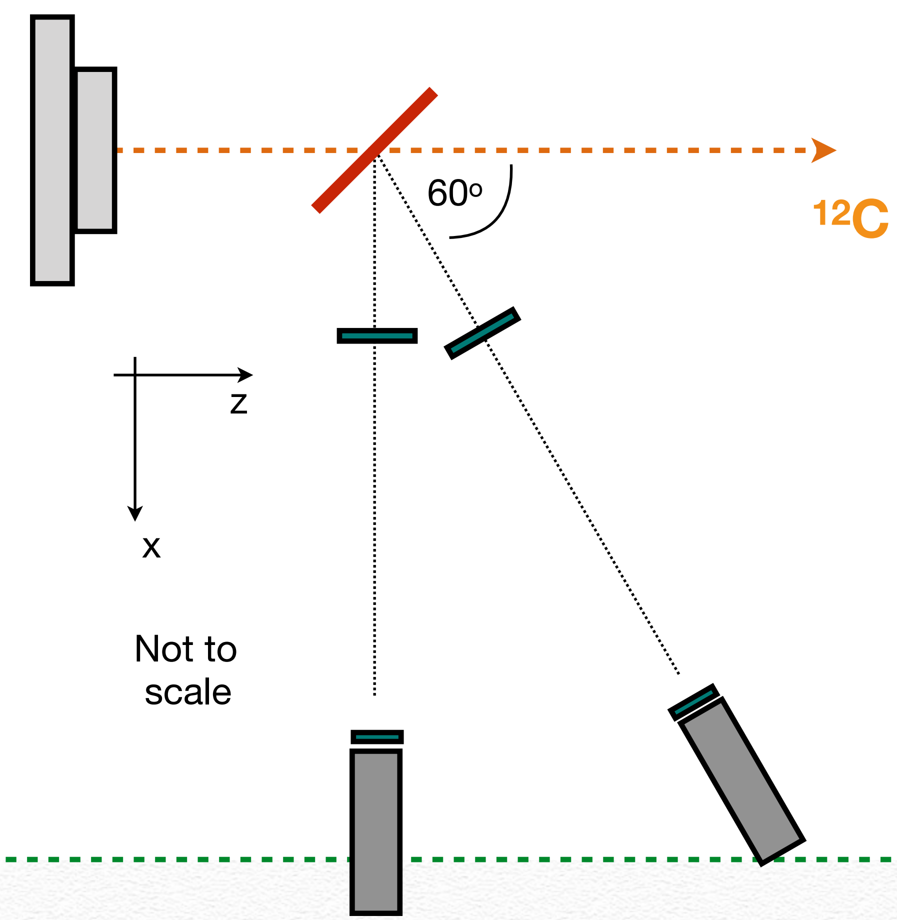


- To evaluate ϵ_{Sel}: p, d identification efficiency using the PID bands = > MC FULL (target, beam, etc..)

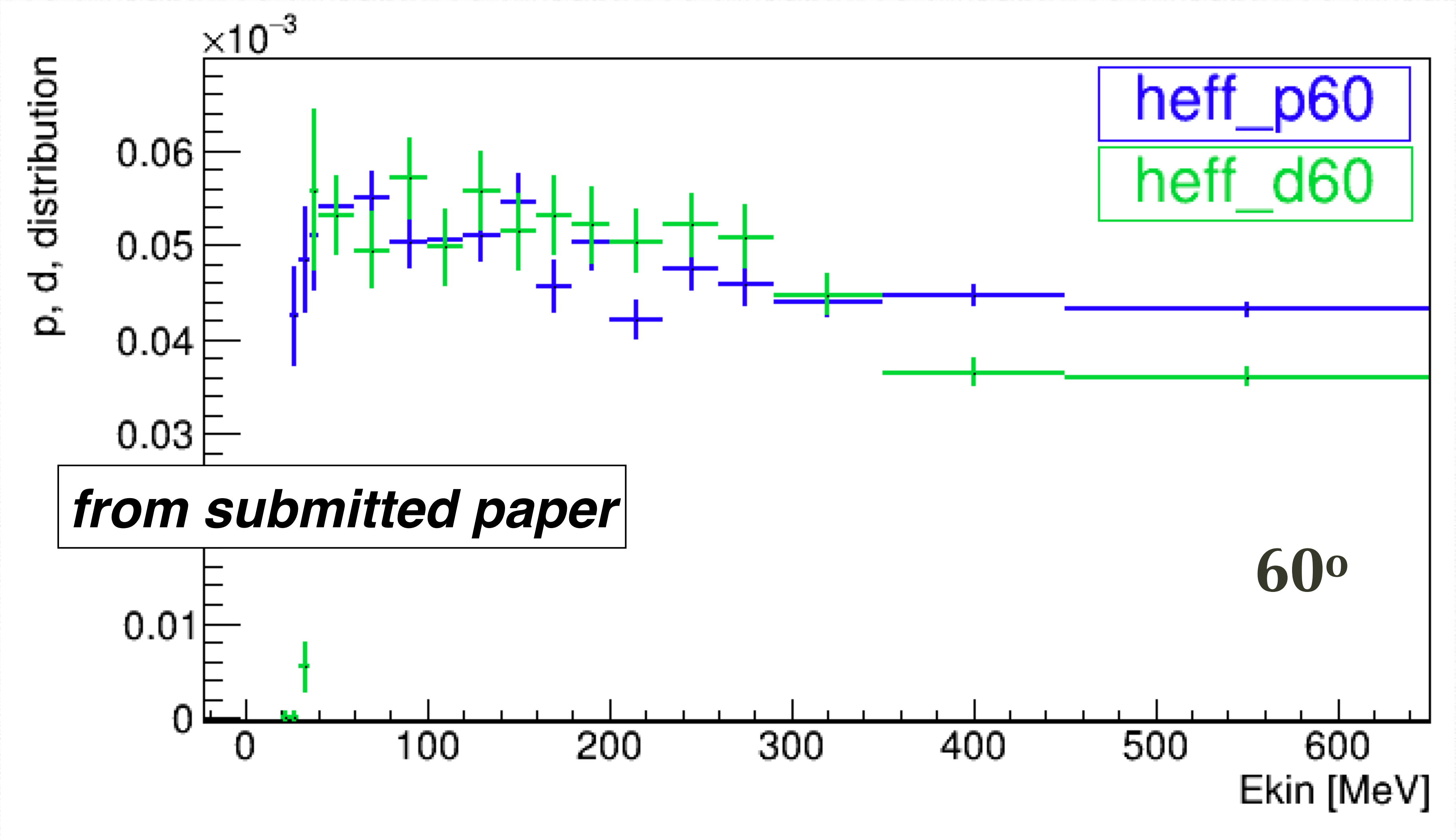


Det Efficiency: Trig + Det + Geo

Probability that a fragment of type *u* is measured by our detectors (*u = p, d*)

$$\epsilon^{u}_{Det}(E_{kin})_i = \left(\frac{N^{u}_{meas}}{N^{u}_{gen}}\right)_i$$

Simulation no trig of p (d) produced 4π with FLAT Ekin = [5 MeV - 1 GeV] (x2 if d)



Mixing Efficiency

Probability that a fragment of type *u* is measured in the region *v* (*u*, *v* = *p*, *d*)

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

FULL simulation of 12C ion beam impinging over a PMMA target.

$$\varepsilon_{\text{mix}} = \begin{pmatrix} \varepsilon^{pp} & \varepsilon^{pd} \\ \varepsilon^{dp} & \varepsilon^{dd} \end{pmatrix}$$

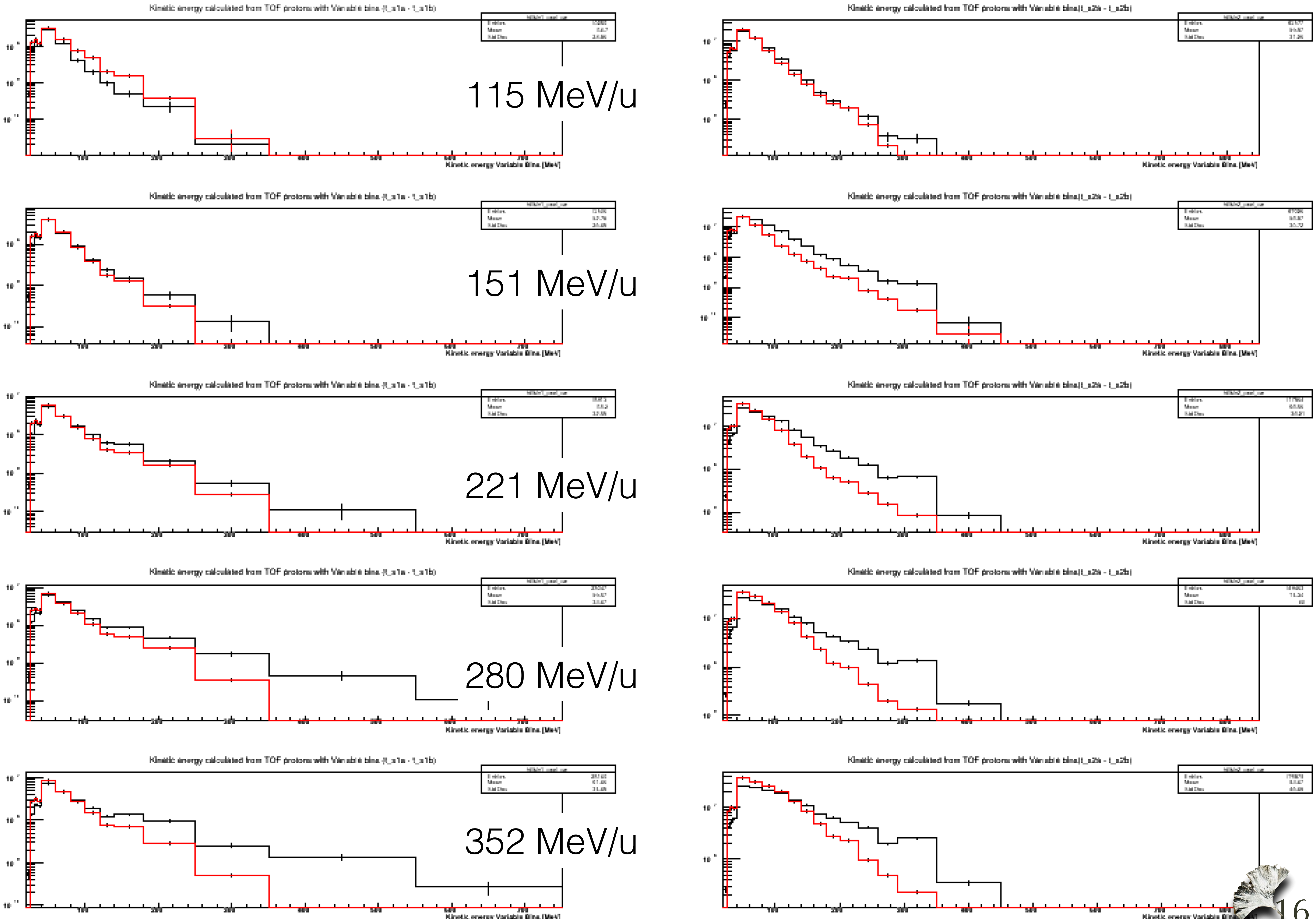
ϵ_{Sel}

E^{C}_{kin} $[MeV/u]$	ϵ^{pp} [%]	ϵ^{dd} [%]	ϵ^{dp} [%]	ϵ^{pd} $[10^{-4}]$
90^o				
115	97.9 ± 0.1	99.2 ± 0.2	0.7 ± 0.2	0.0 ± 0.5
153	97.9 ± 0.1	98.9 ± 0.2	0.5 ± 0.1	1.6 ± 1.2
221	97.4 ± 0.1	98.4 ± 0.2	1.1 ± 0.1	0.0 ± 0.3
281	97.0 ± 0.1	98.3 ± 0.2	1.2 ± 0.1	0.0 ± 0.2
353	96.9 ± 0.1	98.5 ± 0.2	0.7 ± 0.1	0.3 ± 0.4
60^o				
115	97.6 ± 0.1	97.5 ± 0.1	1.6 ± 0.1	0.9 ± 0.4
153	97.6 ± 0.1	97.4 ± 0.1	1.5 ± 0.1	0.7 ± 0.3
221	96.9 ± 0.0	96.8 ± 0.1	2.0 ± 0.1	1.1 ± 0.3
281	96.4 ± 0.0	96.1 ± 0.2	2.4 ± 0.1	2.1 ± 0.4
353	95.8 ± 0.0	96.6 ± 0.2	2.0 ± 0.1	1.4 ± 0.3

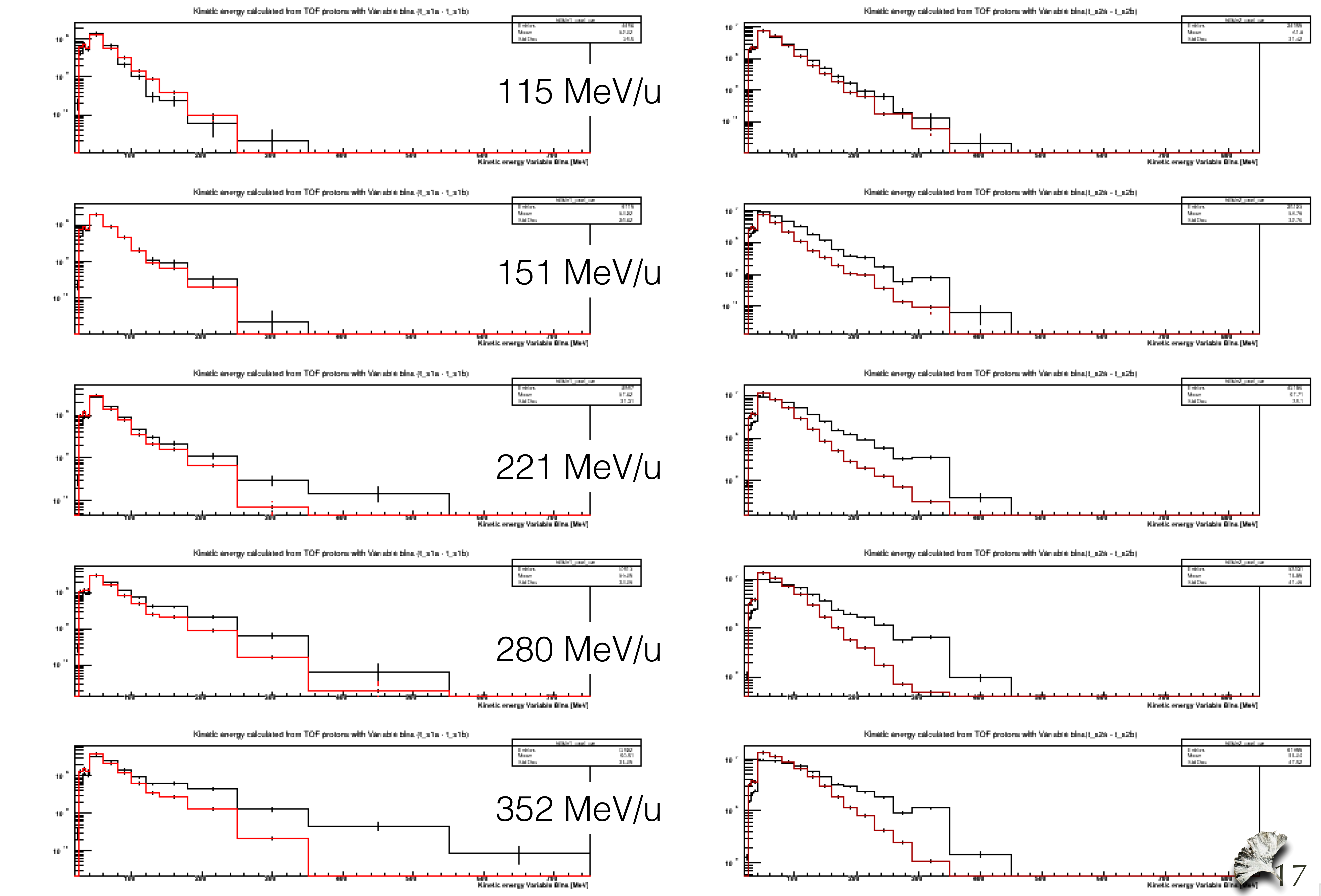
The deuterons contribution to the $XSec_p$ has been subtracted and viceversa:

$XSec_{p\_final} = XSec_p - (eps_{dp}/eps_{pp}) * XSec_d$

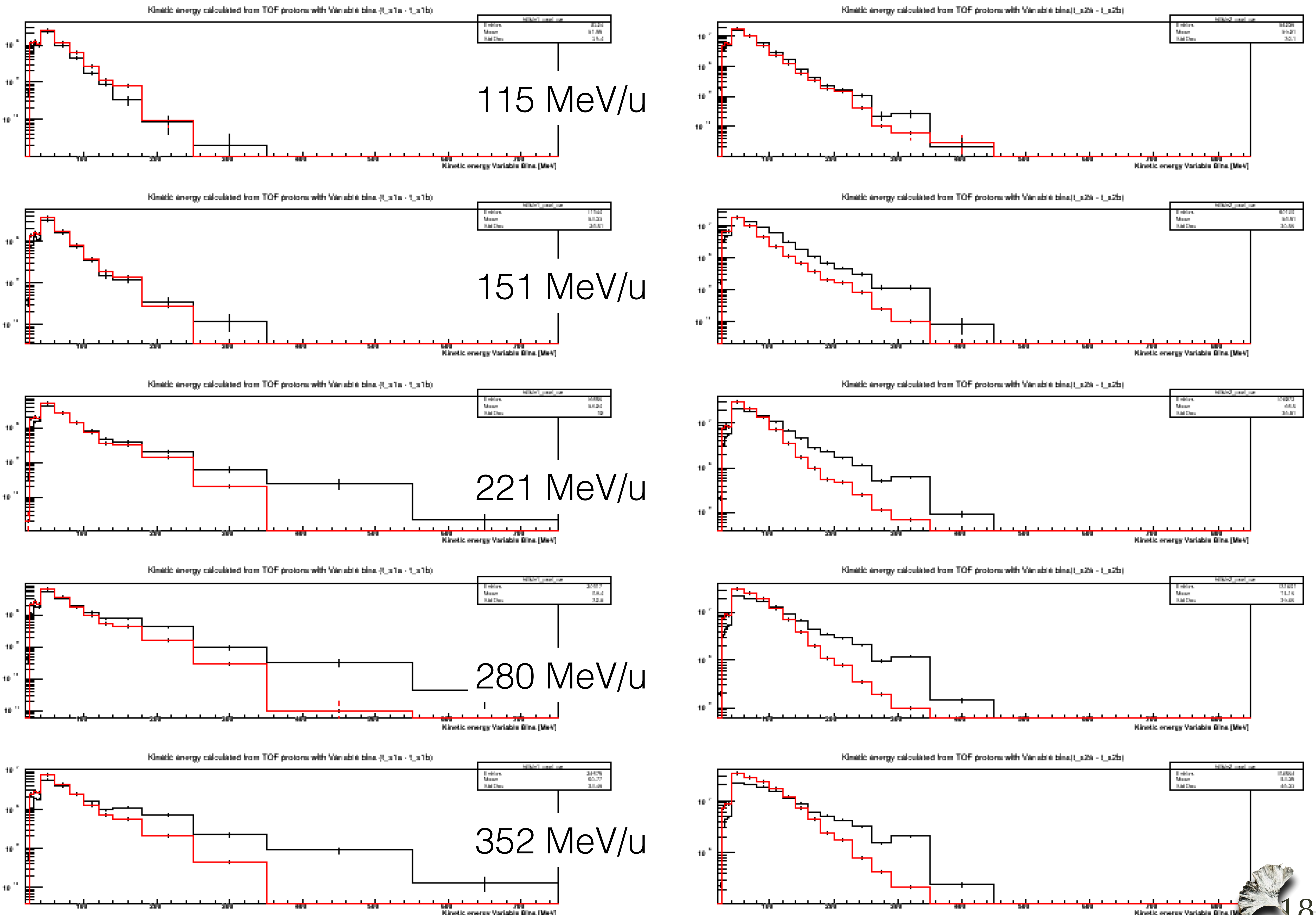
Ekin Spectra (Data - FLUKA) Protons :: 90 - 60 :: PMMA



Ekin Spectra (Data - FLUKA) Protons :: 90 - 60 :: Grafite

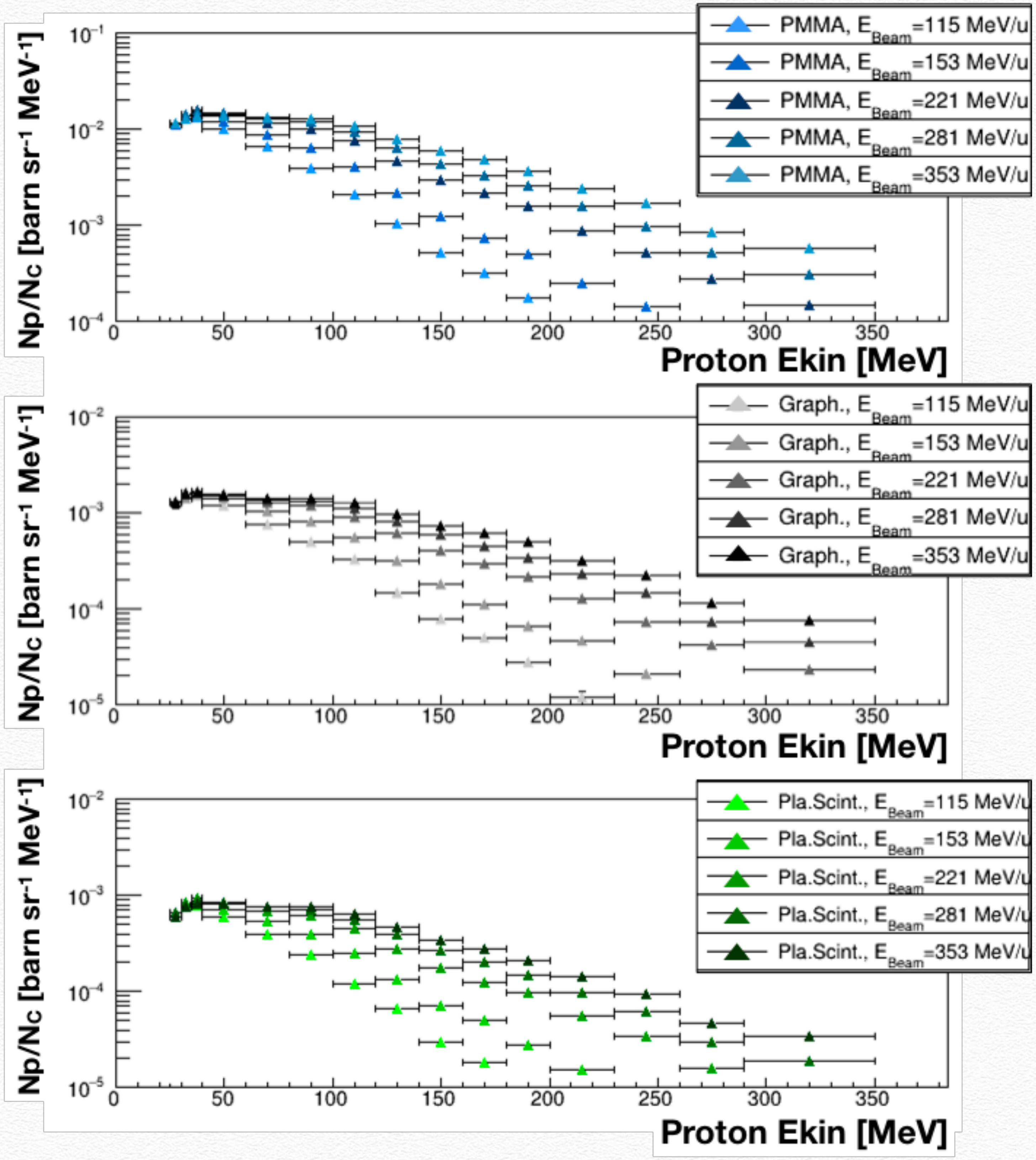


Ekin Spectra (Data - FLUKA) Protons :: 90 - 60 :: Scint



Cross section on TARGET

PMMA, Graphite and Plastic scintillator. All efficiencies included.



***Only statistical uncertainties**

- PMMA = $C_5O_2H_8$
- Graphite = C
- EJ-212 = C_bH_a

XSec: From the combination of the different targets (subtraction of C from C2H4 and of C and H from C5O2H8) we obtain the C, O, H proton production cross-sections as a function of the kinetic energy, at 90º and 60º.

- Graphite = **C**

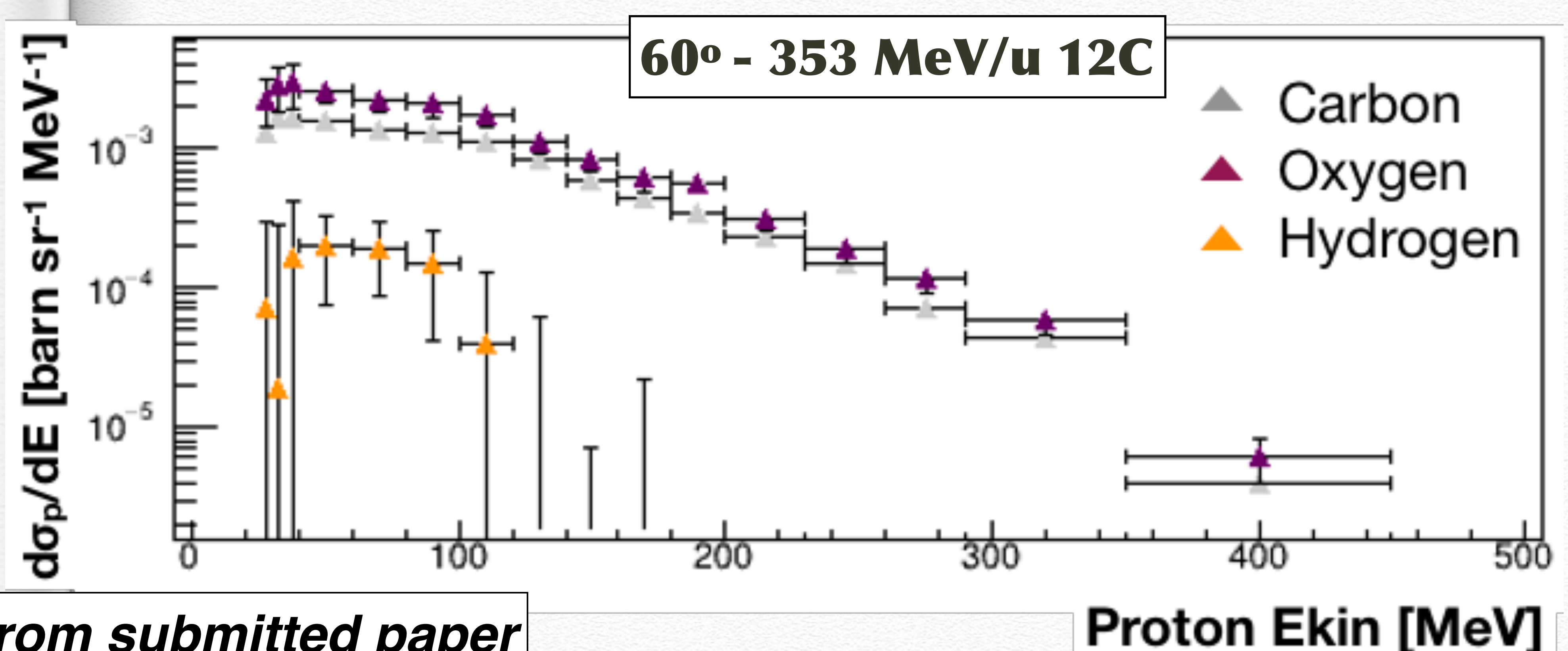
$$\frac{d\sigma_C}{dE_k} = \frac{d\sigma^{Graphite}}{dE_k}$$

- EJ-212 = C_b**H**$_a$

$$\frac{d\sigma_H}{dE_k} = \frac{1}{0.524} \cdot [\frac{d\sigma^{PS}}{dE_k} - 0.476 \cdot \frac{d\sigma_C}{dE_k}]$$

- PMMA = C_5**O**$_2H_8$

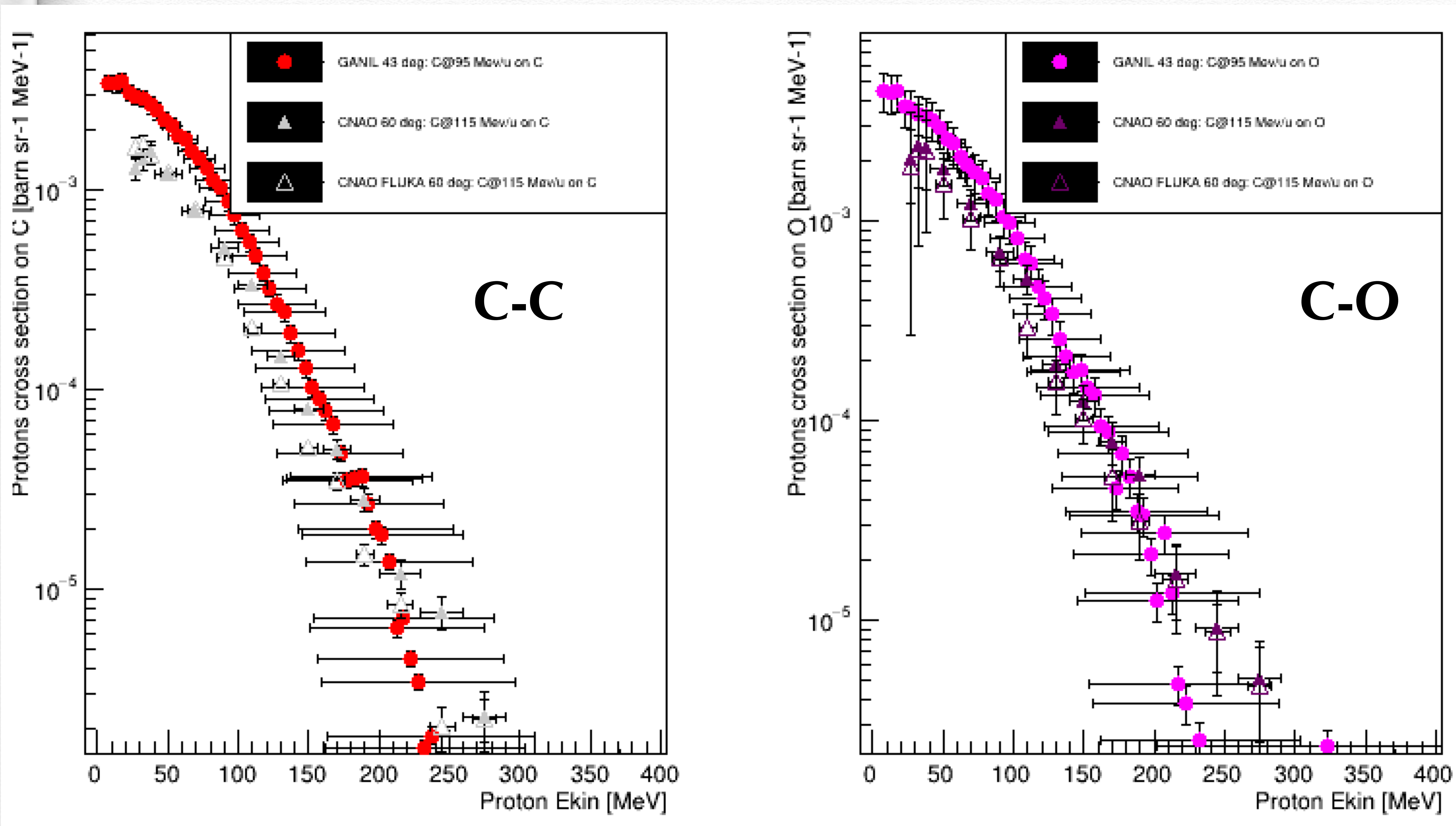
$$\frac{d\sigma_O}{dE_k} = \frac{1}{2} \cdot [\frac{d\sigma^{PMMA}}{dE_k} - 8 \cdot \frac{d\sigma_H}{dE_k} - 5 \cdot \frac{d\sigma_C}{dE_k}]$$



from submitted paper

***Only statistical uncertainties**

Comparison with GANIL & FLUKA

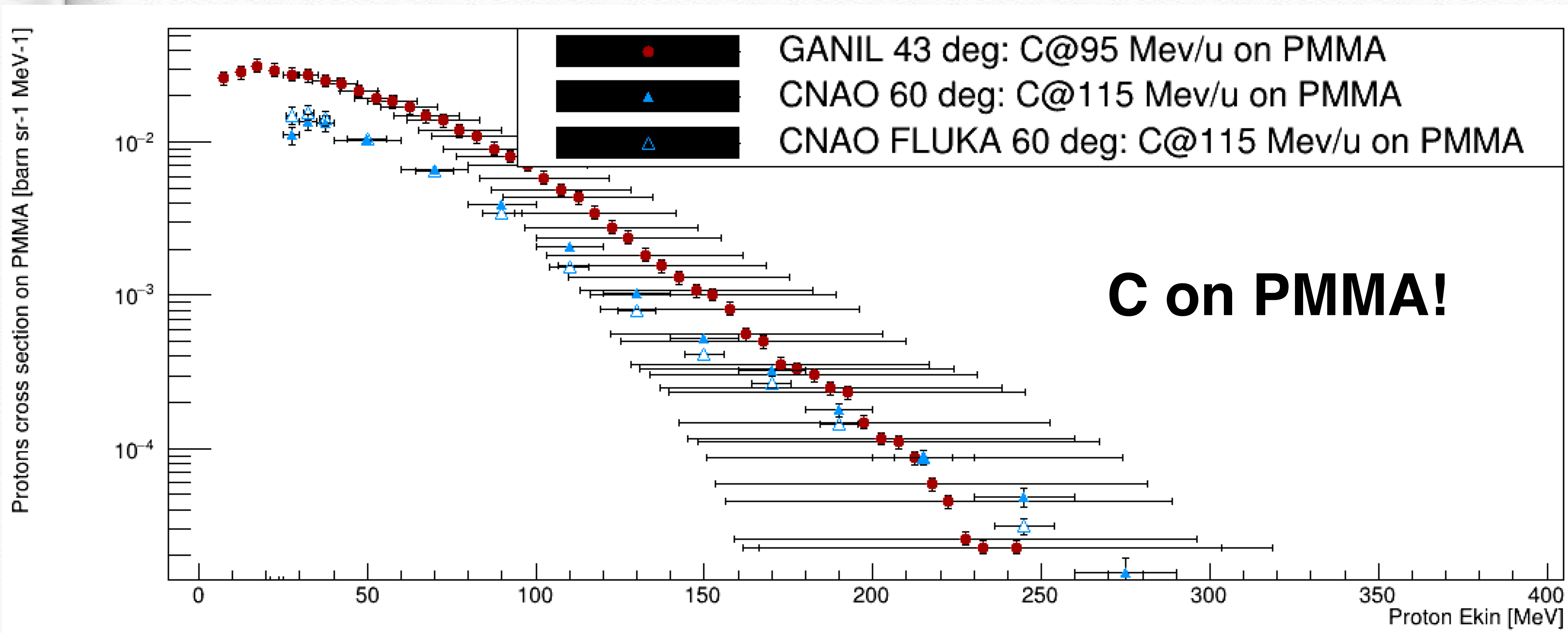


*Only statistical uncertainties

GANIL 43°, C@95 MeV/u

CNAO*/FLUKA 60°, C@115MeV/u

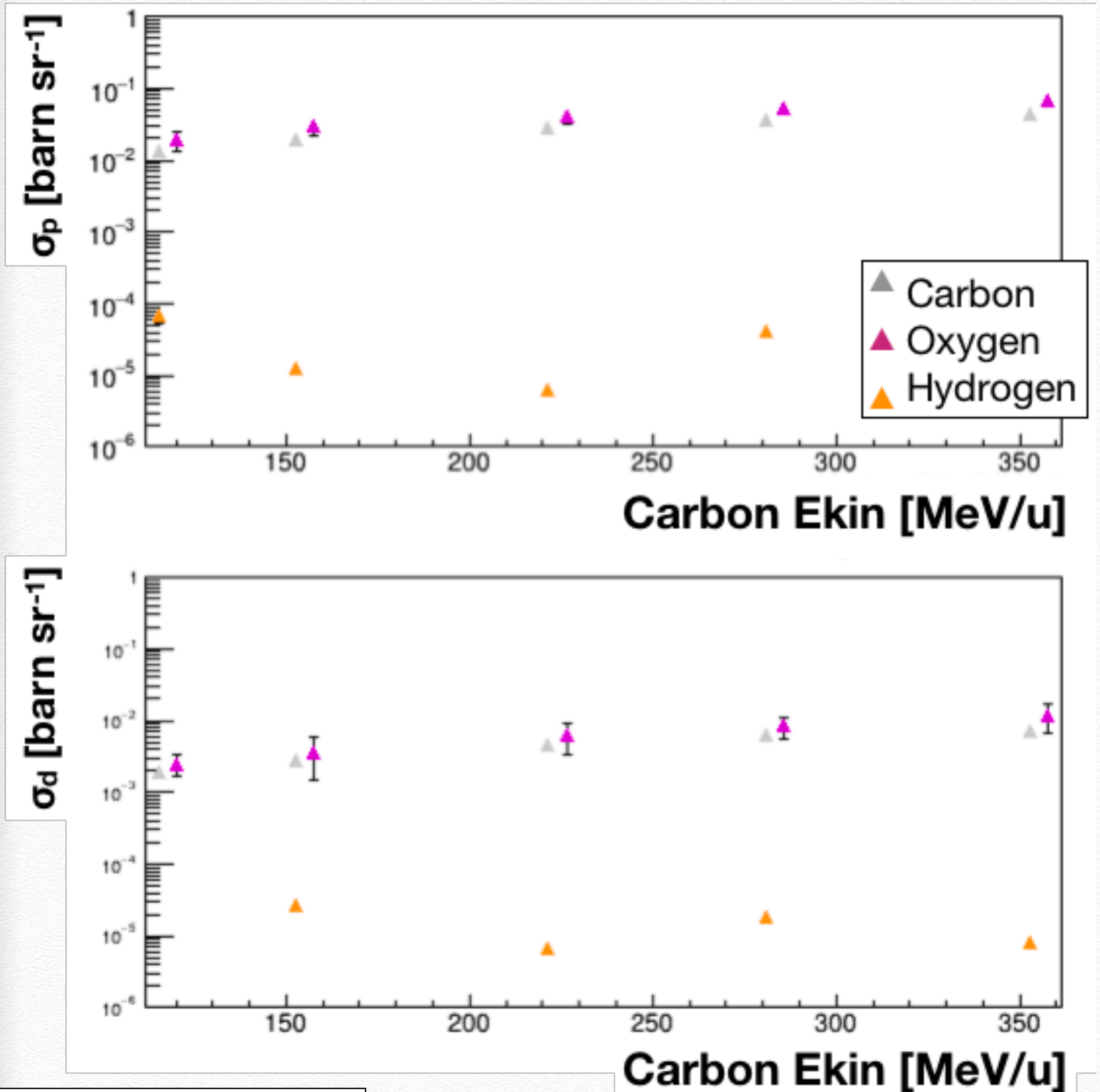
Comparison with FLUKA



*Only statistical uncertainties

Total XS

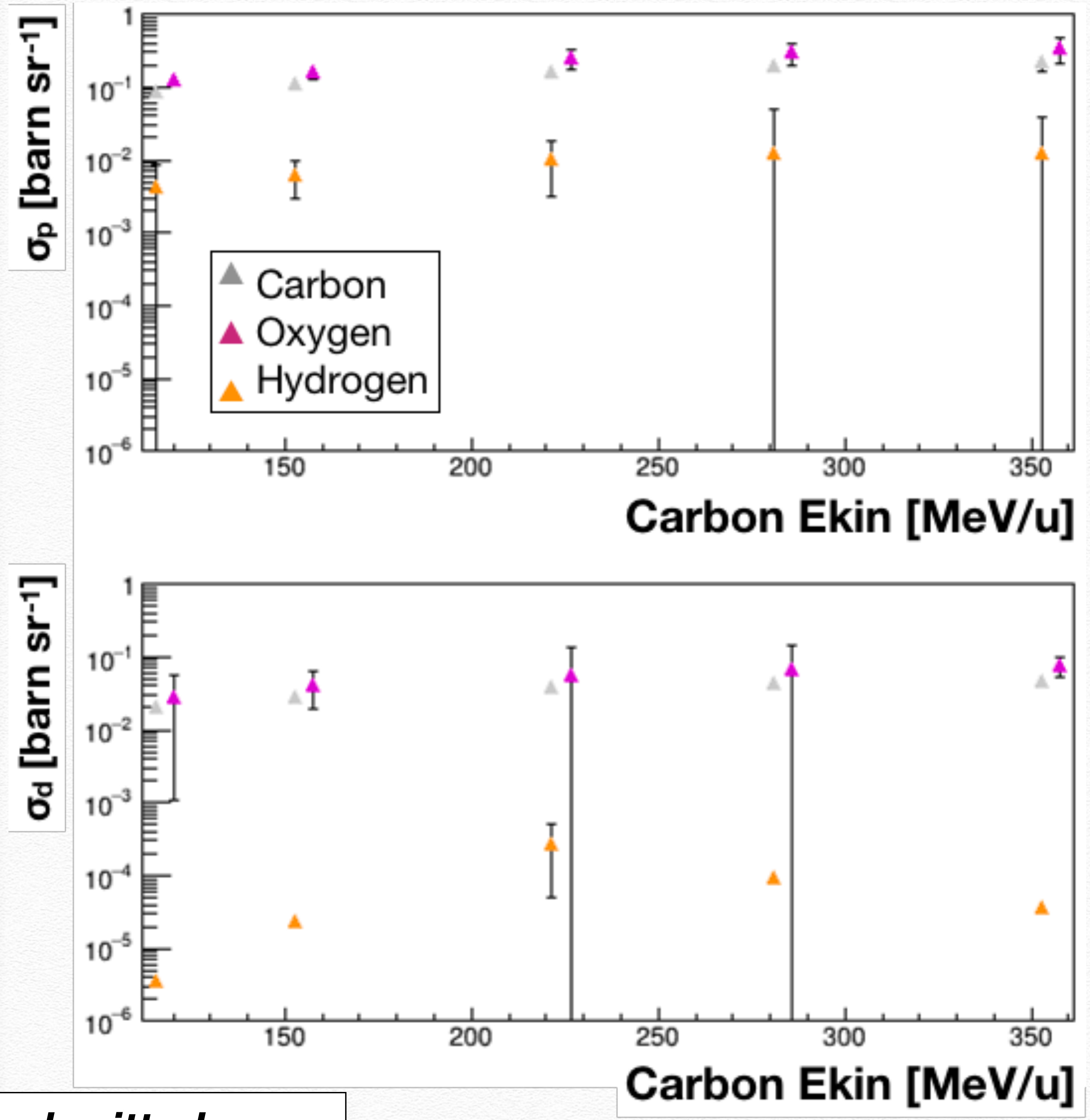
90°



from submitted paper

Total XS

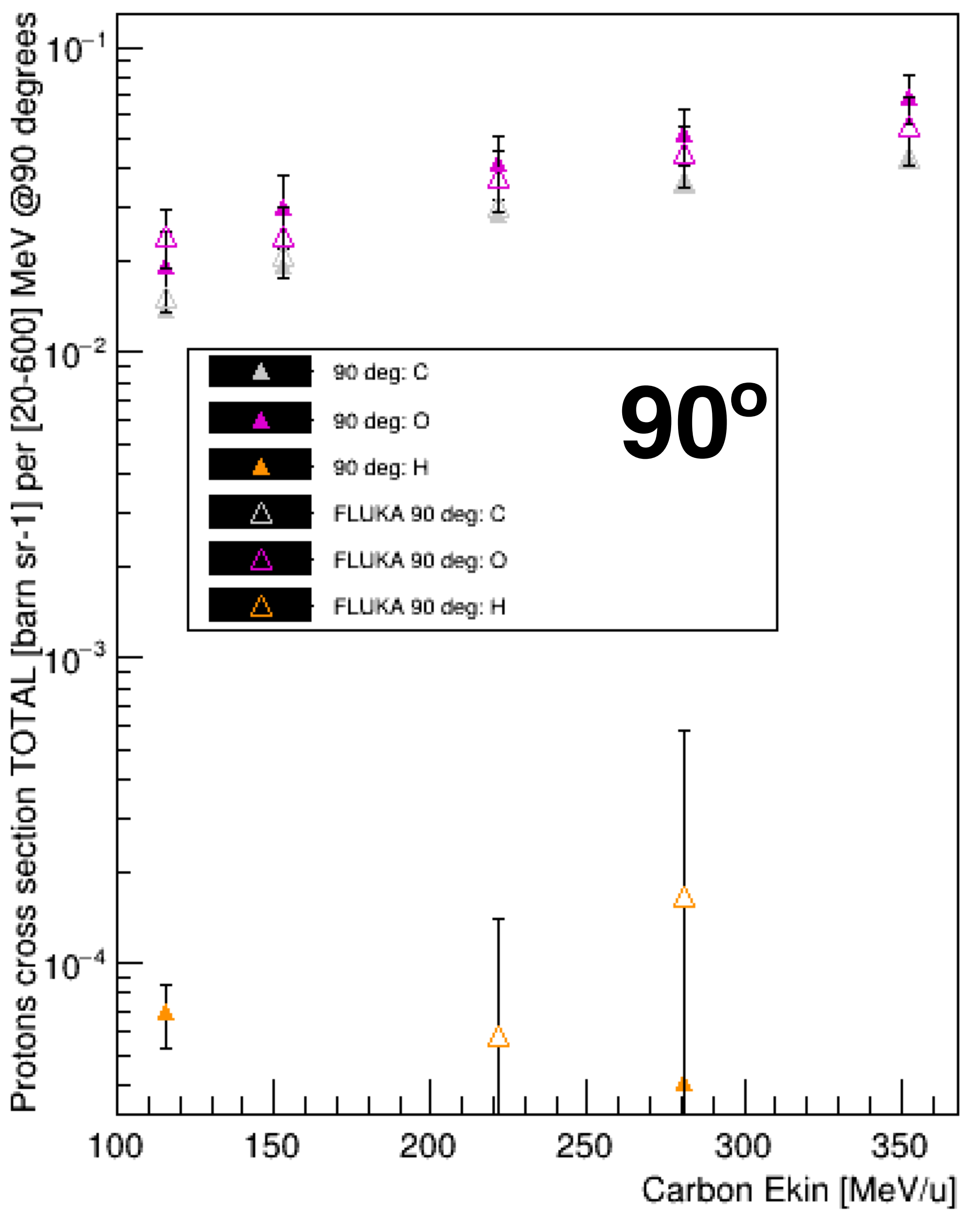
60°

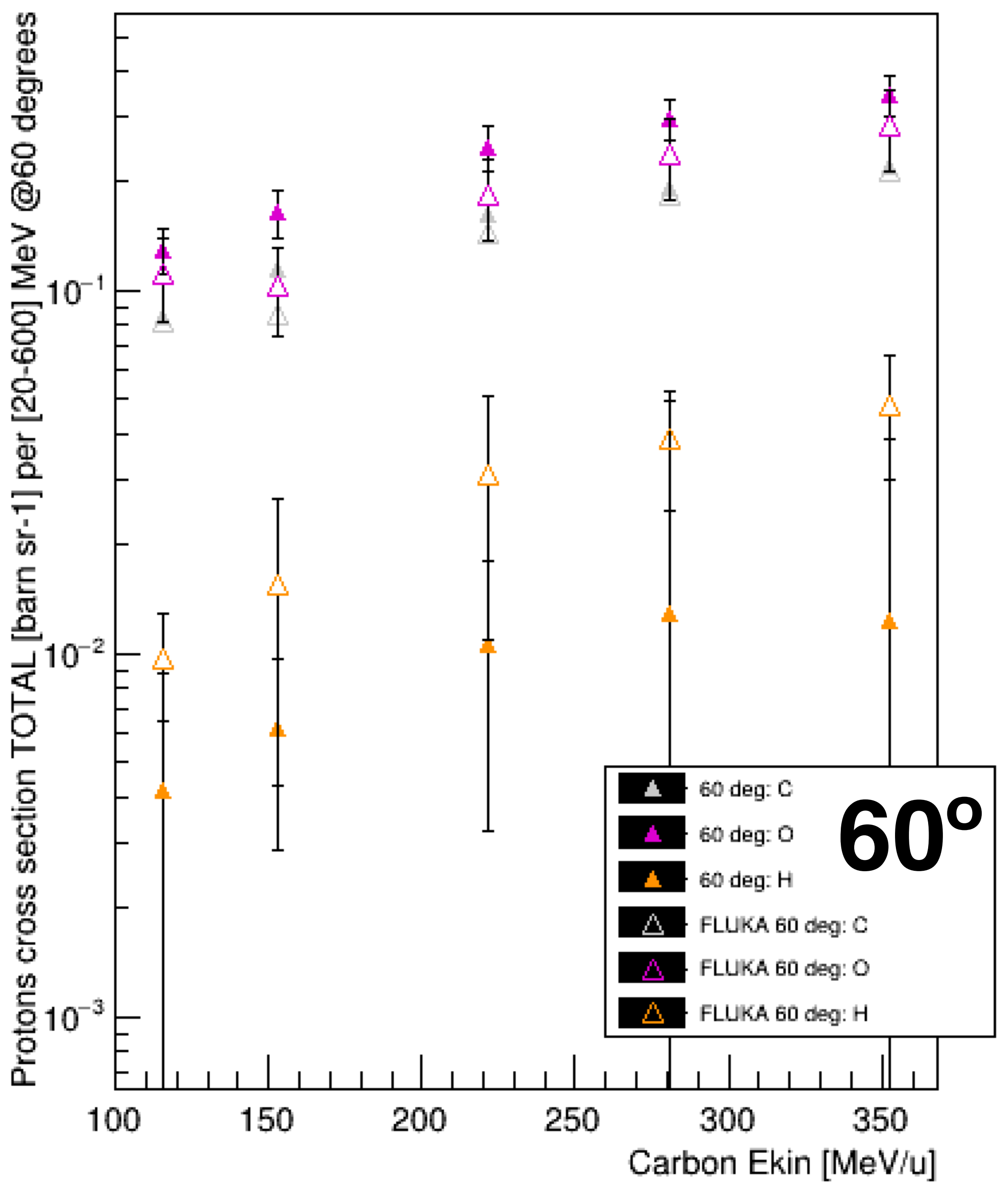


from submitted paper

Total XS vs FLUKA (protons)

C O H





Conclusions

- All the **differential and total cross sections** (for p and d) are **tabulated on the submitted paper** (all beam energies, all targets, 90º and 60º, with stat+sys error);

- Since the XS_H is at least 2 order of magnitude smaller than XS_C, in order to obtain **Hydrogen xsec** from "CH - C" target (subtraction method), a **large statistics** of the CH target data is needed (wrt the C target): in our case the H errors (mainly from statistics) are of ~100%!;

- For the **Oxygen xsec**, in order to avoid the perpetuation of the XS_H error, a good option would be the use of **Al** and **AlO_2** targets (in subtraction) as GANIL group did;

- A better energy resolution (faster ToF detectors, longer particles path, different "calorimeter") would allow to perform more precise measurements, at least for higher energy particles.