Angular differential cross sections GSI2021: Comparison with FLUKA and GEANT4 predictions

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In view of the revision of the article recently submitted to PRC, $d\sigma / d\Omega$ for the production of the different fragments have been evaluated from FLUKA model and GEANT4 in the energy and angular range of GSI2021 data

FLUKA 1 approach (Milano)

Method:

Using the stand alone FLUKA generator the double differential cross section for the reaction $^{12}C+^{nat}C \rightarrow (A,Z)+X$ is sampled using a huge statistics, then, for each given Z:

$$\frac{d\sigma}{d\Omega} = \sum_{all\ A(Z)} \int_{E_{min}}^{E^*} dE\ \frac{d\sigma}{dEd\Omega}$$

E^*= suitable very high upper limit

E_{min} corresponding to the ToF cut in the analysis: 50 MeV/u

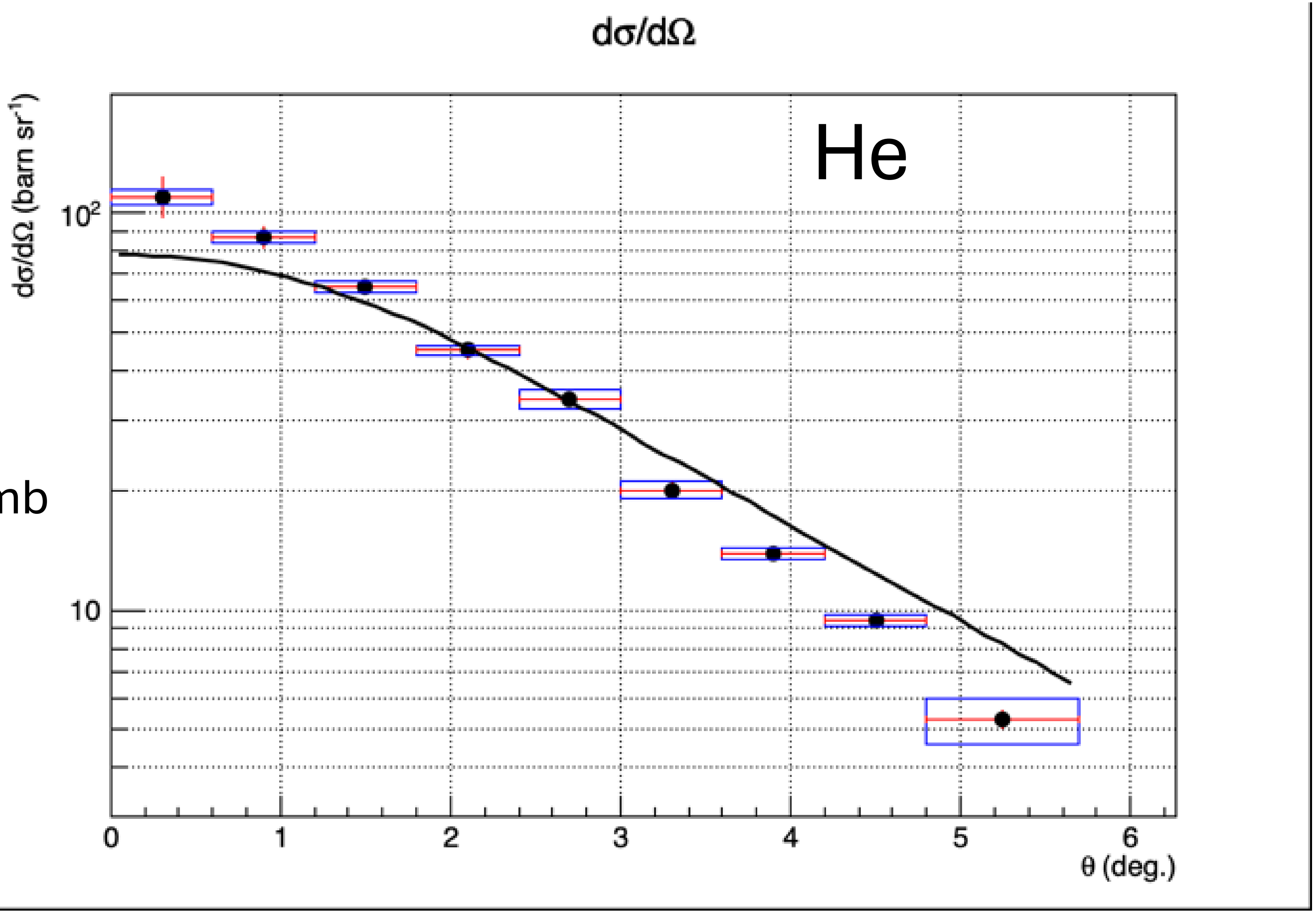
Angular intervals of 0.1 degrees have been considered in the range $0\ - 5.7^o$ (57 points)
The nominal beam energy is used (400 MeV/u)

We suggest that MC predictions should be presented as continuos lines, as very often appears in the publication of other experiments

$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

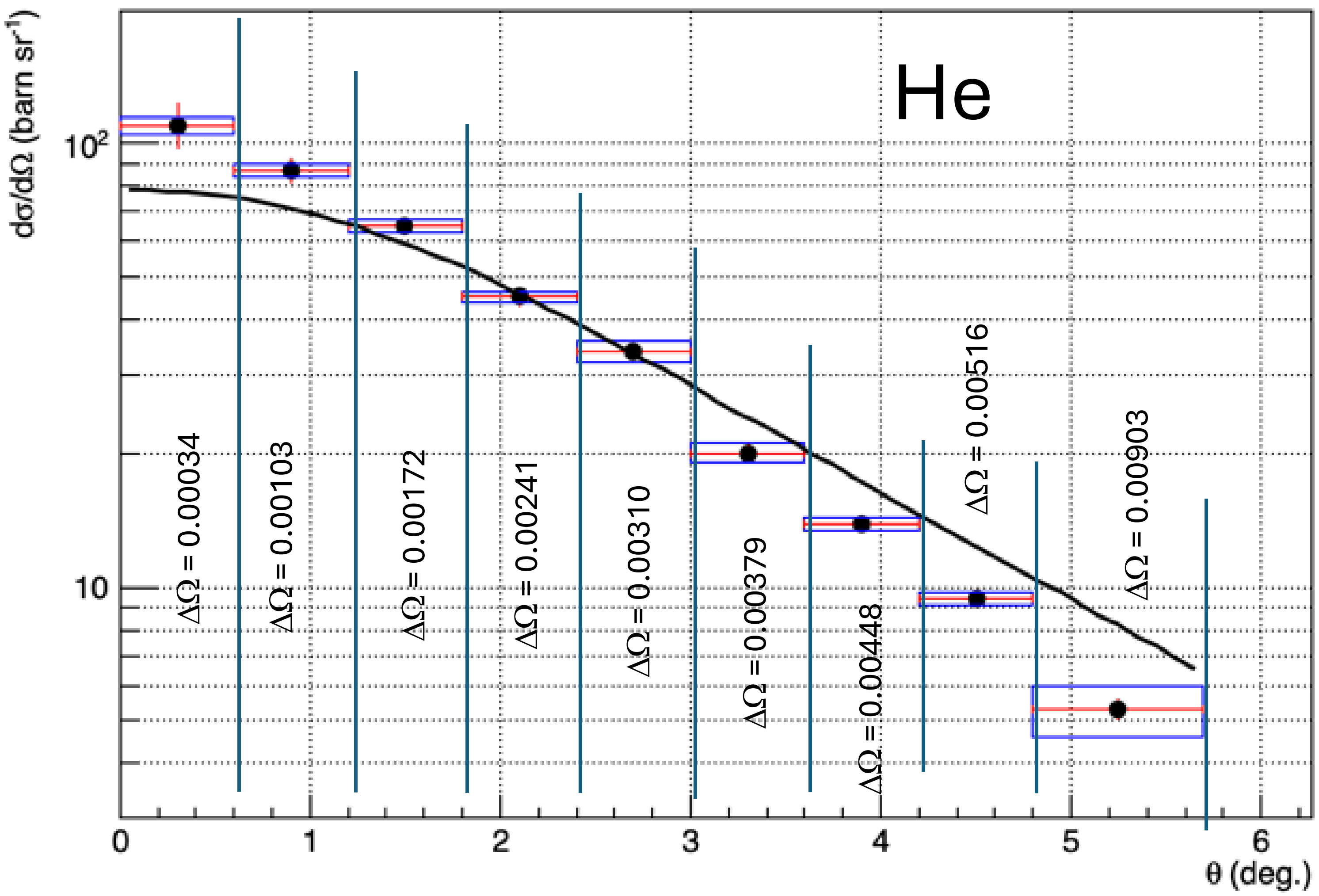
σ_{exp} = 687±13±30 mb

σ_{FLUKA} = 721 mb



More details on the integrated cross section

Integration range	Solid angle (sr)	σ_{exp} (mb)	σ_{FLUKA} (mb)
0.0 – 0.6°	0.00034	38	27
0.0 – 1.2°	0.00137	128	100
0.0 – 1.8°	0.00309	240	201
0.0 – 2.4°	0.00550	348	311
0.0 – 3.0°	0.00860	454	415
0.0 – 3.6°	0.01239	529	506
0.0 – 4.2°	0.01687	592	583
0.0 – 4.8°	0.02203	640	647
0.0 – 5.7°	0.03106	687	721

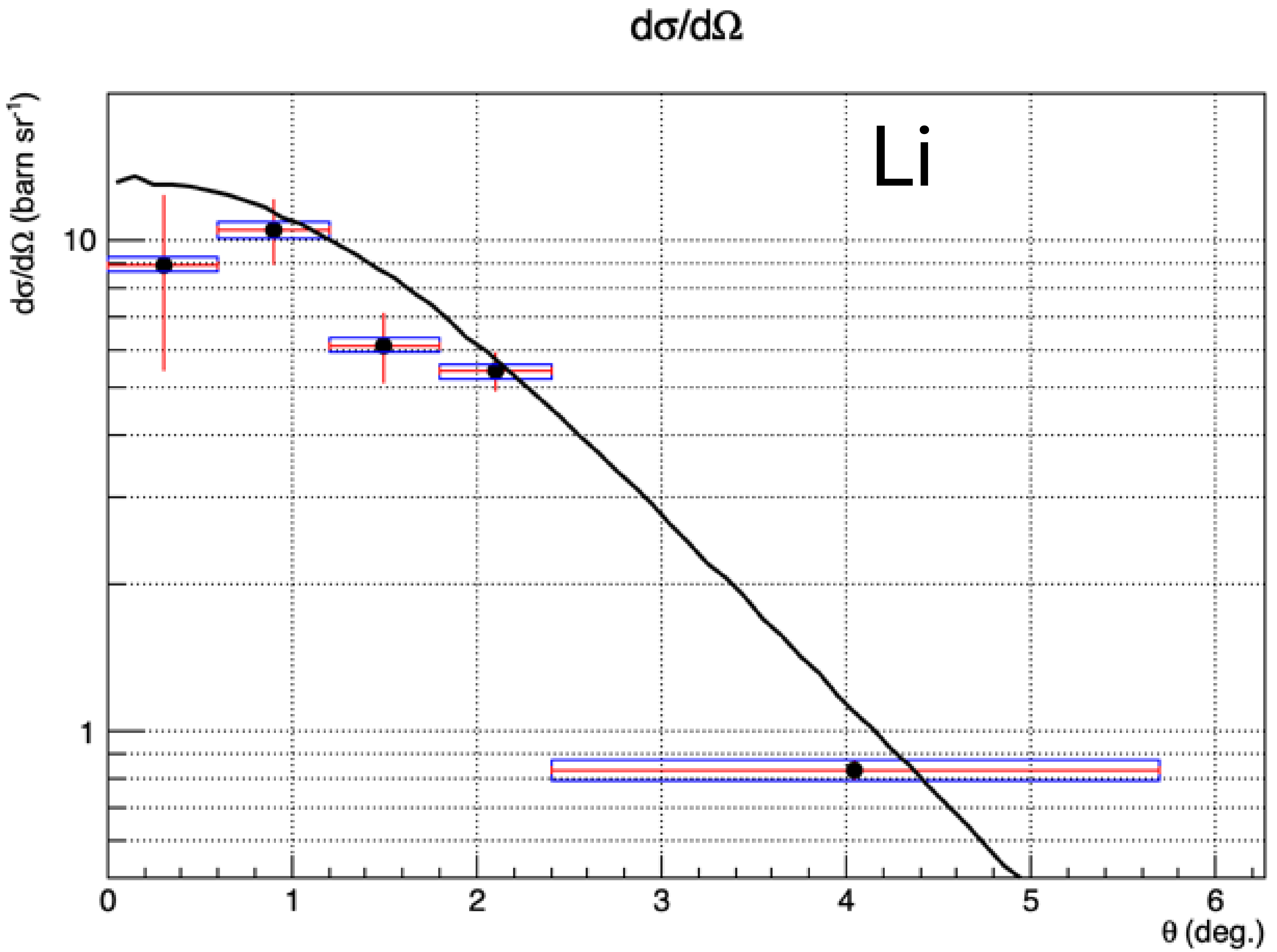


For fixed θ bin widths, the value of ΔΩ rapidly grows as θ increases, so the last bins have a larger weight

$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

σ_{exp} = 59±3±2 mb

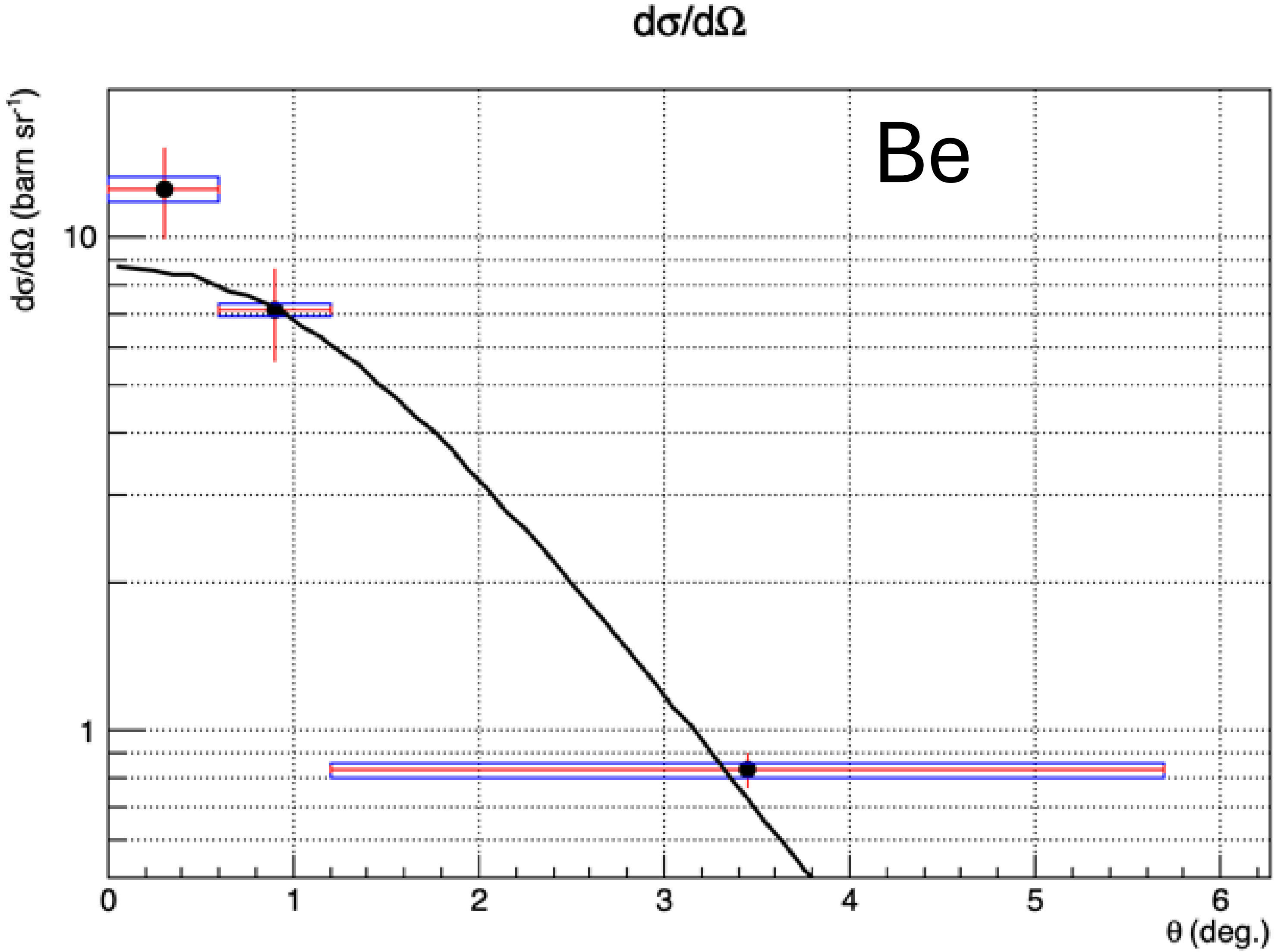
σ_{FLUKA} = 76 mb



$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

σ_{exp} = 36±3±1 mb

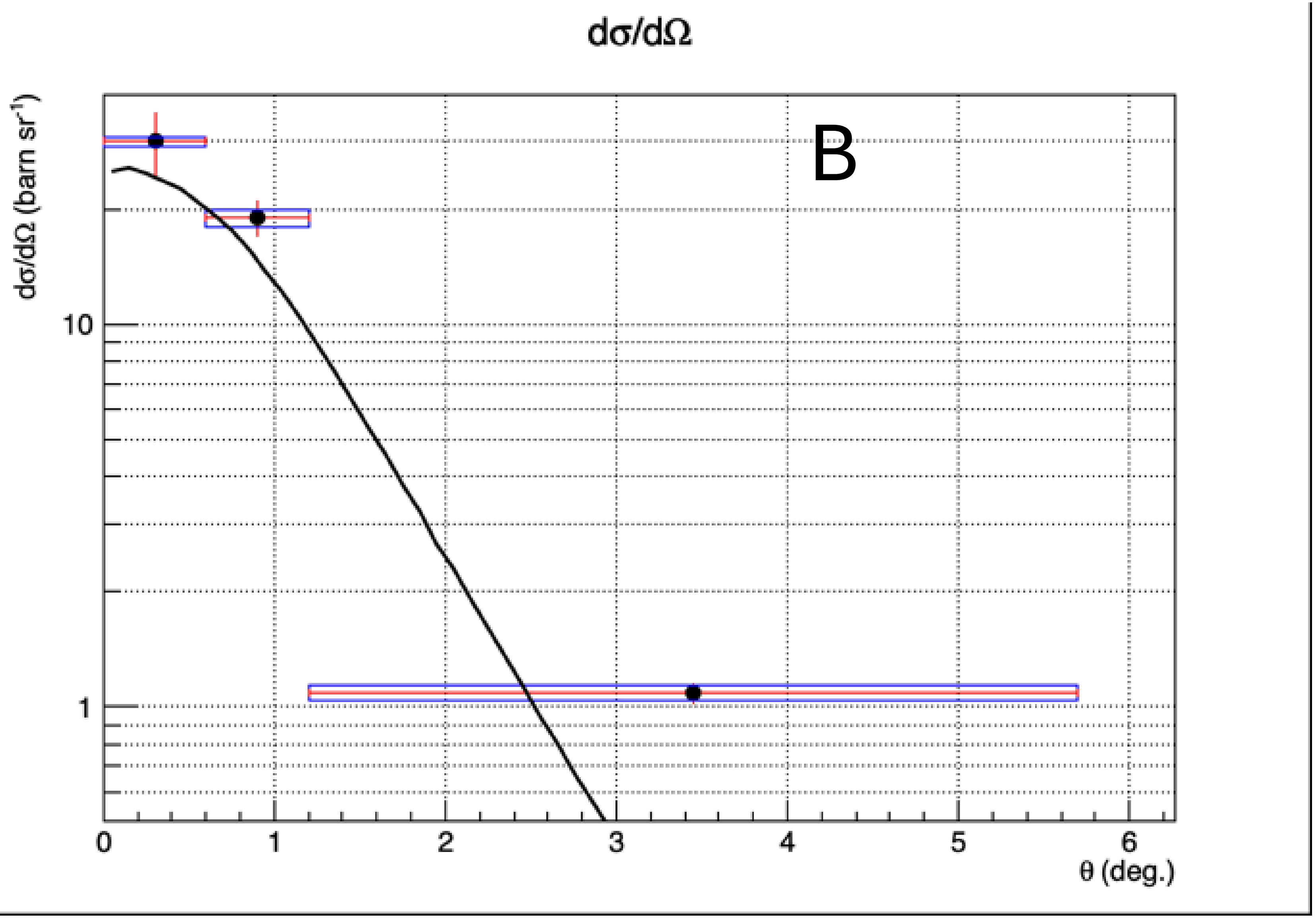
σ_{FLUKA} = 38 mb



$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

σ_{exp} = 63±4±3 mb

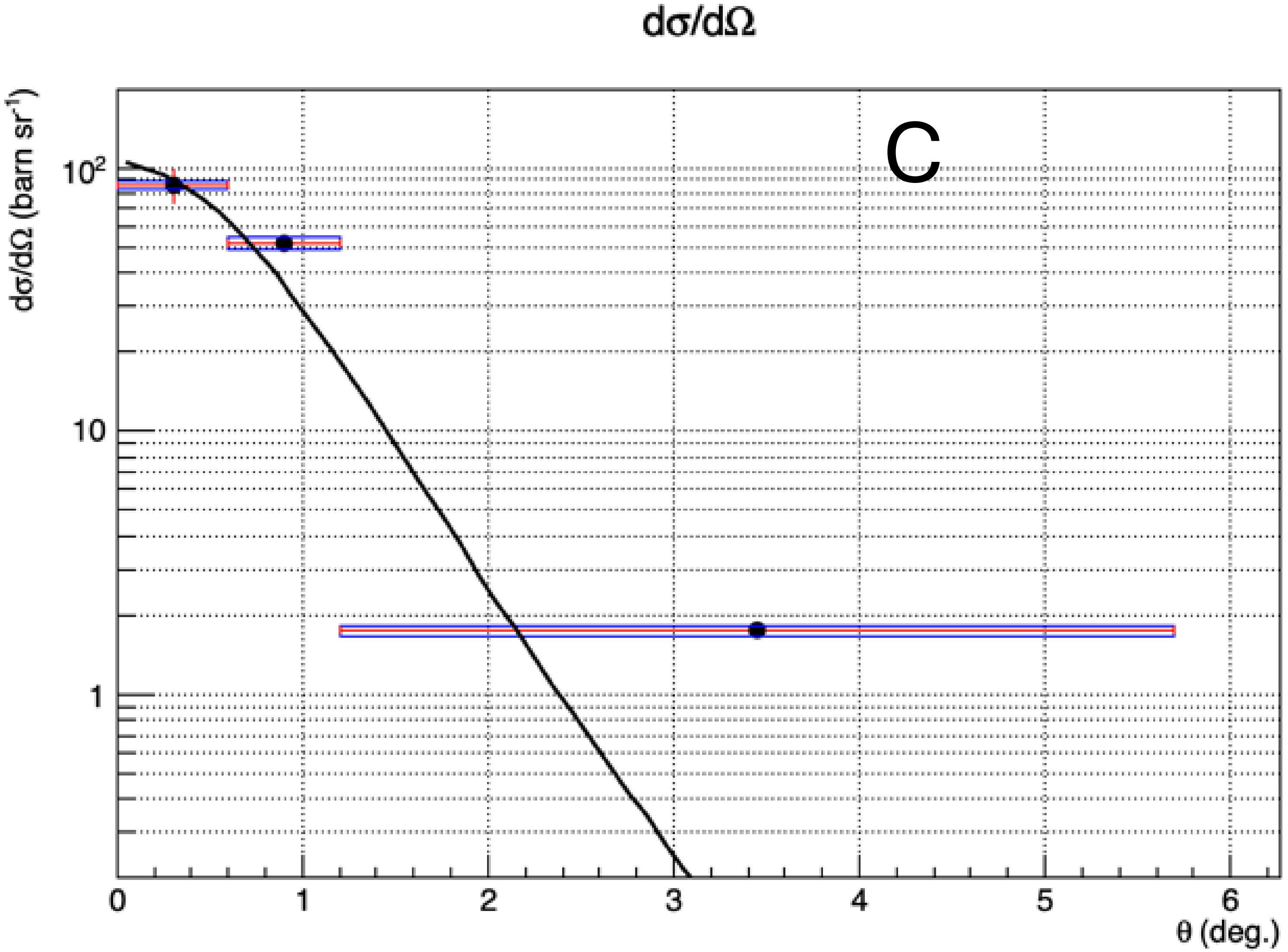
σ_{FLUKA} = 42 mb



$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

σ_{exp} = 135±6±5 mb

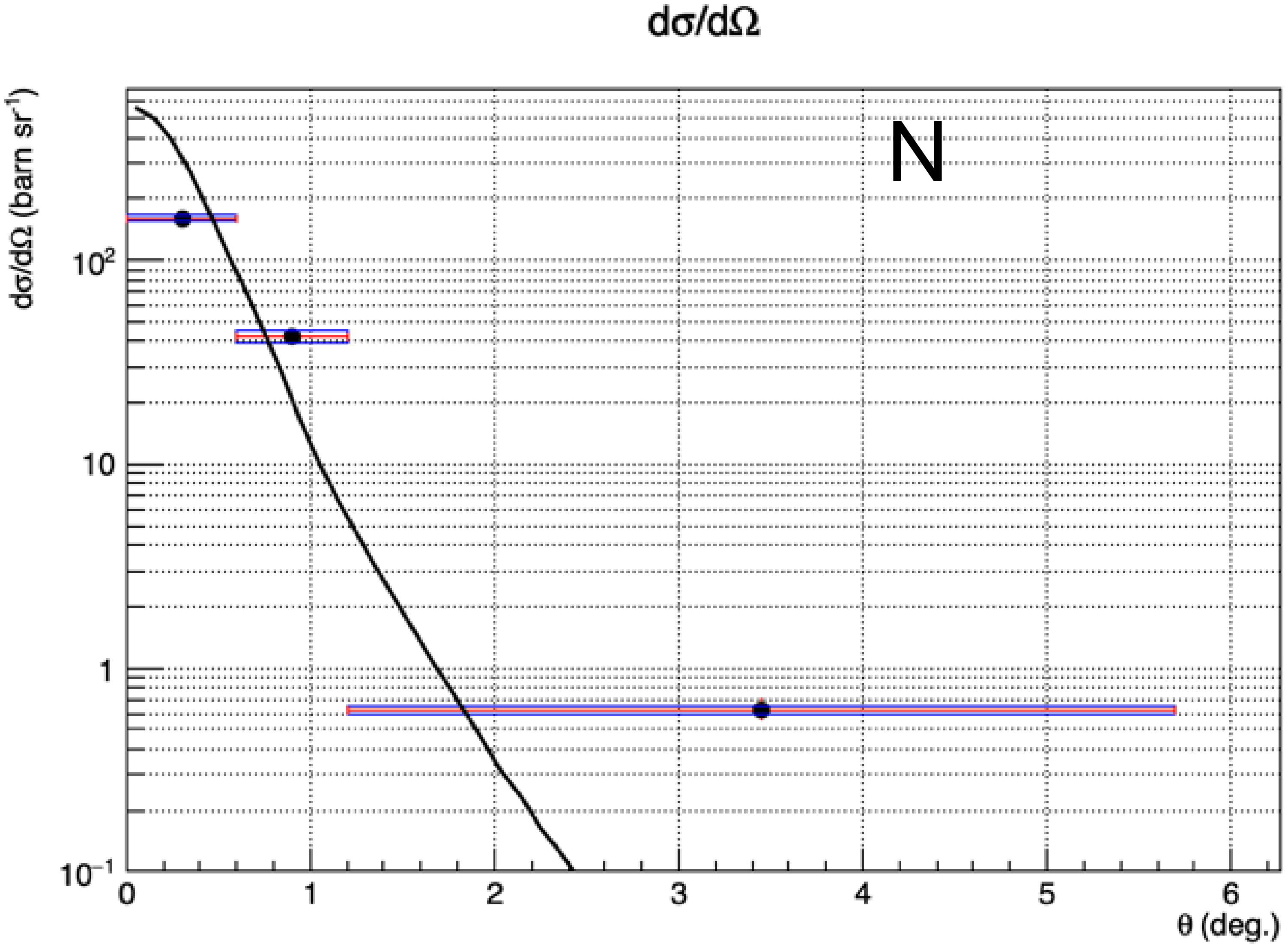
σ_{FLUKA} = 87 mb



$$\int_0^{5.7^o} \frac{d\sigma}{d\Omega} d\Omega$$

σ_{exp} = 117±6±4 mb

σ_{FLUKA} = 112 mb



Comment

- The integrated cross section values are of course ~the same as published in the exploratory paper for GSI2019 data *(M.Toppi et al, Front. Phys. 10:979229 doi: 10.3389/fphy.2022.979229)*
- The main differences depend on the energy integration range: in GSI2019 analysis E_{min} = 100 MeV/u
- Actually, the analysis of generator result shows that relaxing E_{min} value down to 0 is not relevant for Z>2, small for Z=2. It would have been important for Z=1.

Details on the FLUKA model to be added in the paper

- For projectile energies above 150 MeV/u, nucleus-nucleus collisions are treated in FLUKA using an interface to a modified rQMD-2.4 (relativistic Quantum Molecular Dynamics) model. Although initially developed for high energies, the model could be extended down to the energies of interest of FOOT experiment.

H. Sorge, H. Stocker, W. Greiner, Relativistic quantum molecular dynamics approach to nuclear collisions at ultrarelativistic energies, Nucl. Phys. A 498, 567 (1989); H. Sorge, Flavor production in Pb (160 A GeV) on Pb collisions: Effect of color ropes and hadronic rescattering, Phys. Rev. C 52, 3291 (1995).

- The model is also coupled to a pre-equilibrium stage which, in FLUKA, is managed by the PEANUT (PreEquilibrium Approach to Nuclear Thermalization) model

A. Ferrari, P.R. Sala, The physics of high energy reactions, in Proceedings of Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety, World Scientitic, p. 424, Miramare-Trieste, Italy, 15 April-17 May 1996, edited by A. Gandini, G. Reffo (1998); A. Ferrari, P.R. Sala, Nuclear reactions in Monte Carlo codes, Rad. Prot. Dosim. 99, 29 (2002).

- The late stages of the interaction (fragmentation and evaporation) are then modelled, for nuclei with A<17, by means of a phase space Fermi Break-up mode

E. Fermi, High-energy nuclear events, Prog. Theor. Phys. 5, 570 (1950); M. Epherre and E. Gradsztajn, Calcul de la Spallation de ^{12}C et ^{16}O par des protons de 70 a 200 MeV, J. Phys. 18, 48 (1967).

FLUKA and GEANT4 approach (Roma, Strasbourg)

Method:

MC simulation using SHOE derived inputs for FOOT simulation have been used for both FLUKA and GEANT4, considering all fragments produced in the target.

Main difference with respect to Approach 1: energy loss of beam in target is considered. Therefore, primary energy has also some spread.

No energy cut on secondary products.

With respect to Approach 1, the statistical sample may be smaller.

In the case of GEANT4 the 3 following different models have been considered in the Physics List:

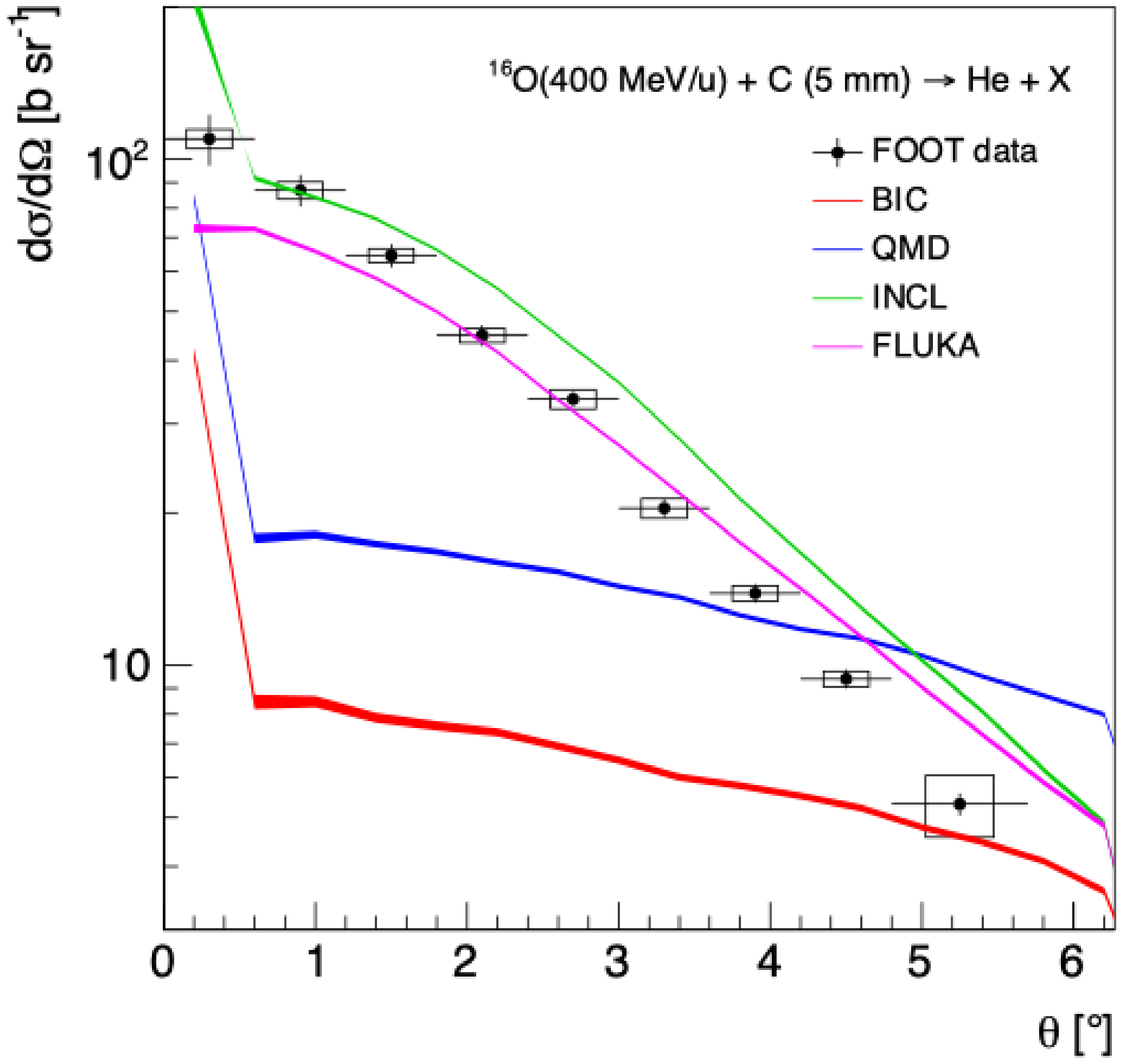
QMD

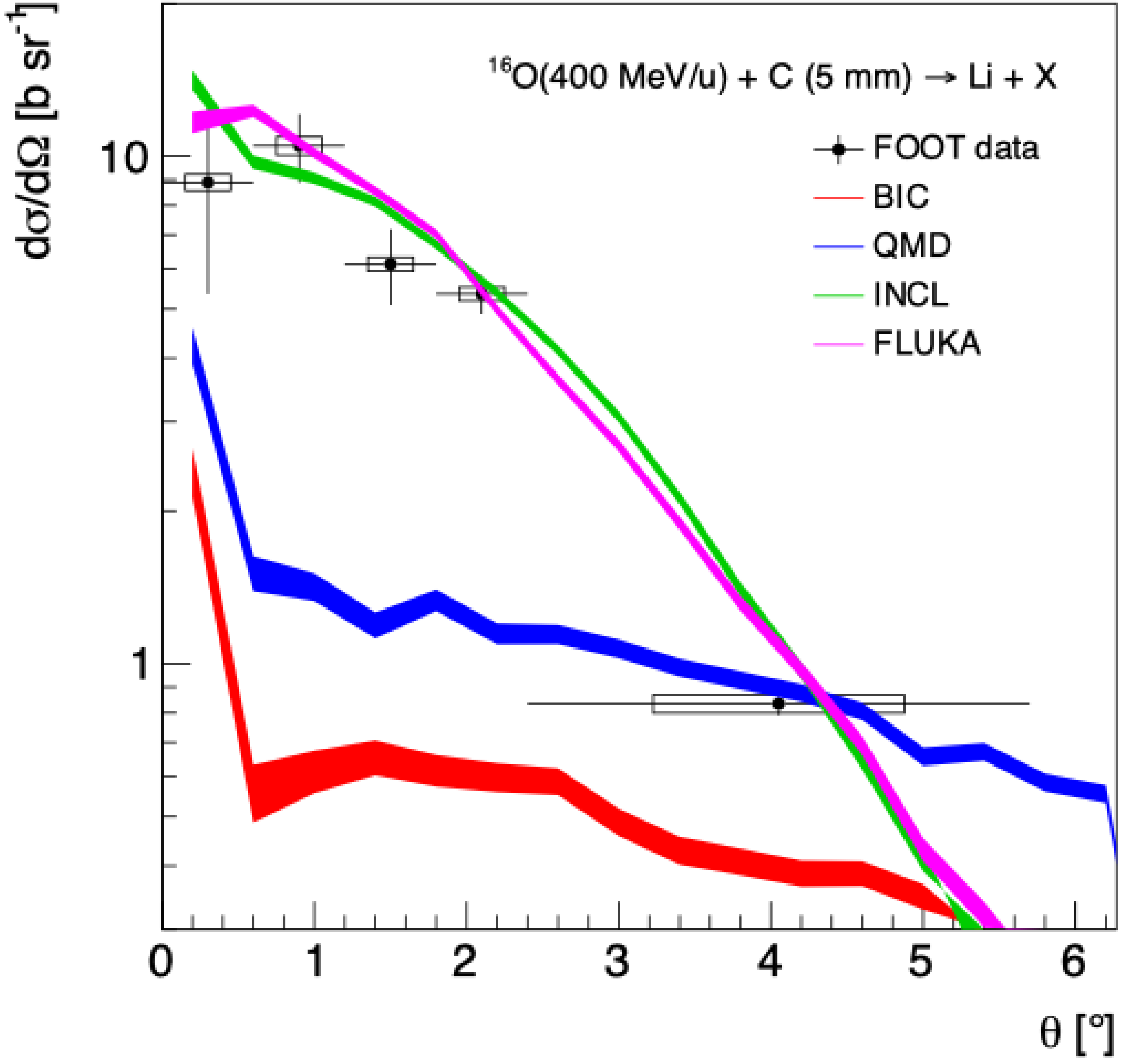
BIC

INCL++

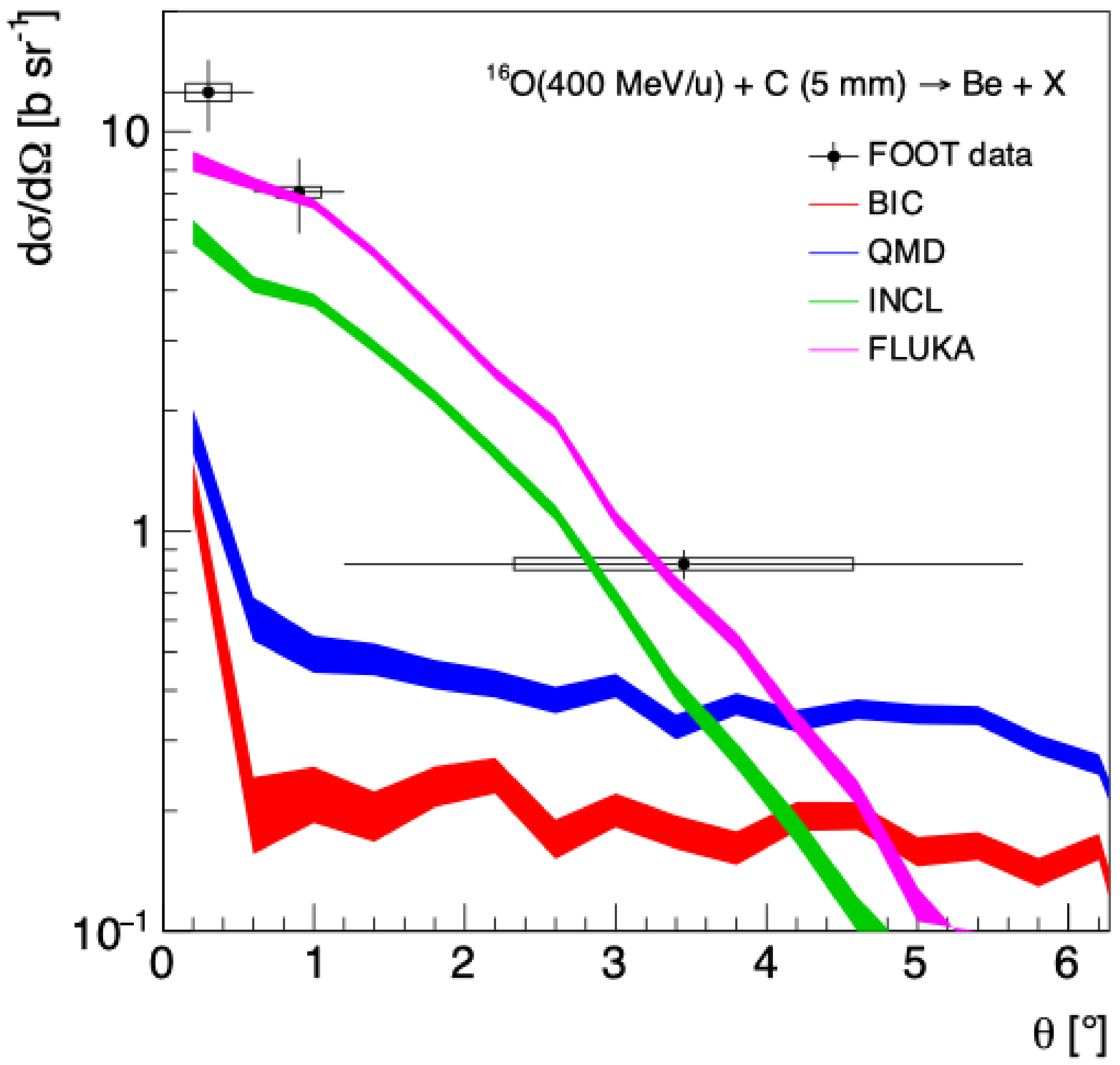
For non expert people:
contrary to the Toolkit philosophy of GEANT4, FLUKA does not allow to the user to choose a model

Actually, there are no significant difference in the FLUKA numbers between Approach 1 and 2

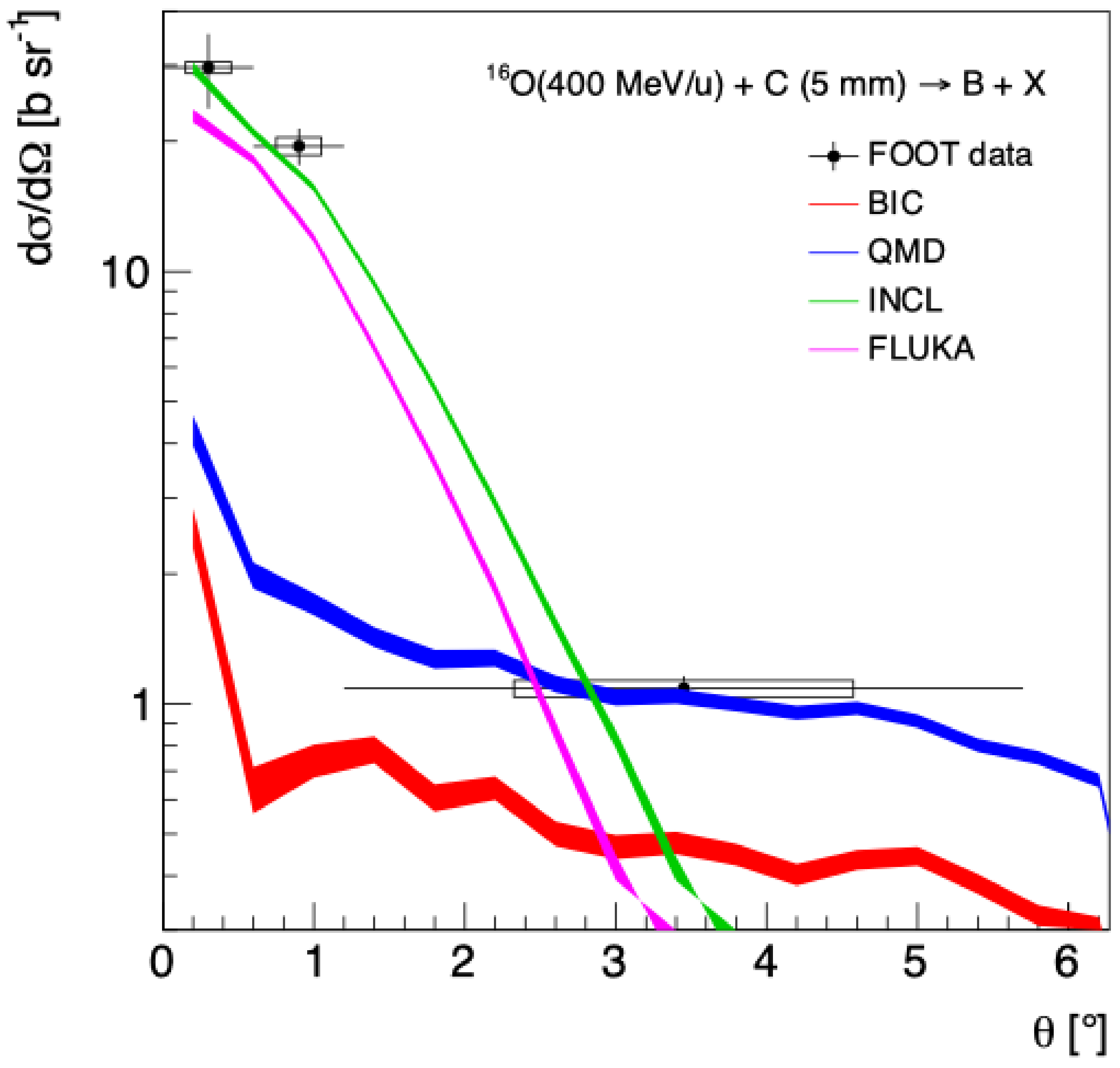




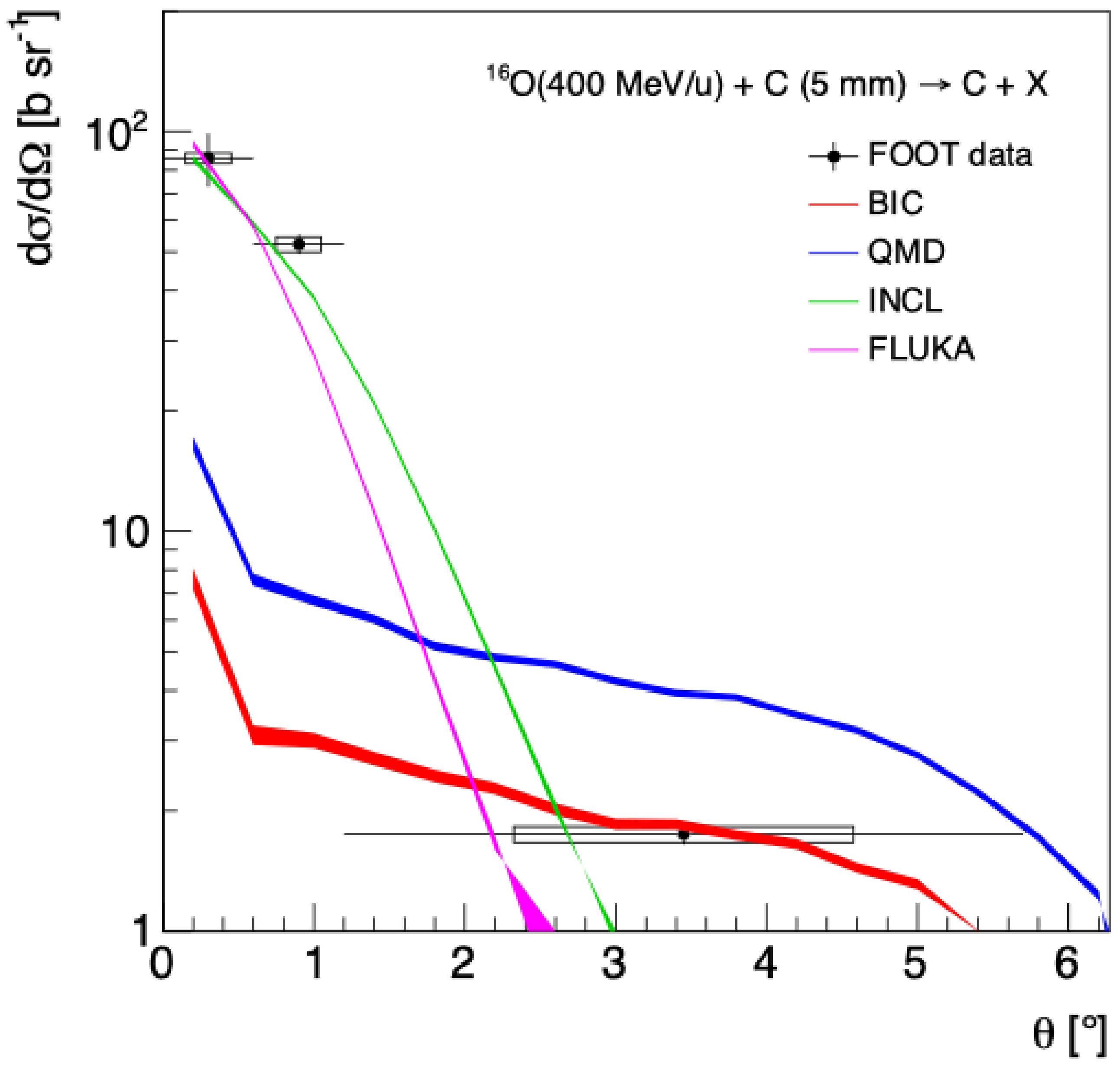
^{16}O(400 MeV/u) + C (5 mm) → Li + X
FOOT data
BIC
QMD
INCL
FLUKA
dσ/dΩ [b sr^{-1}]
θ [°]
10
1
0
1
2
3
4
5
6



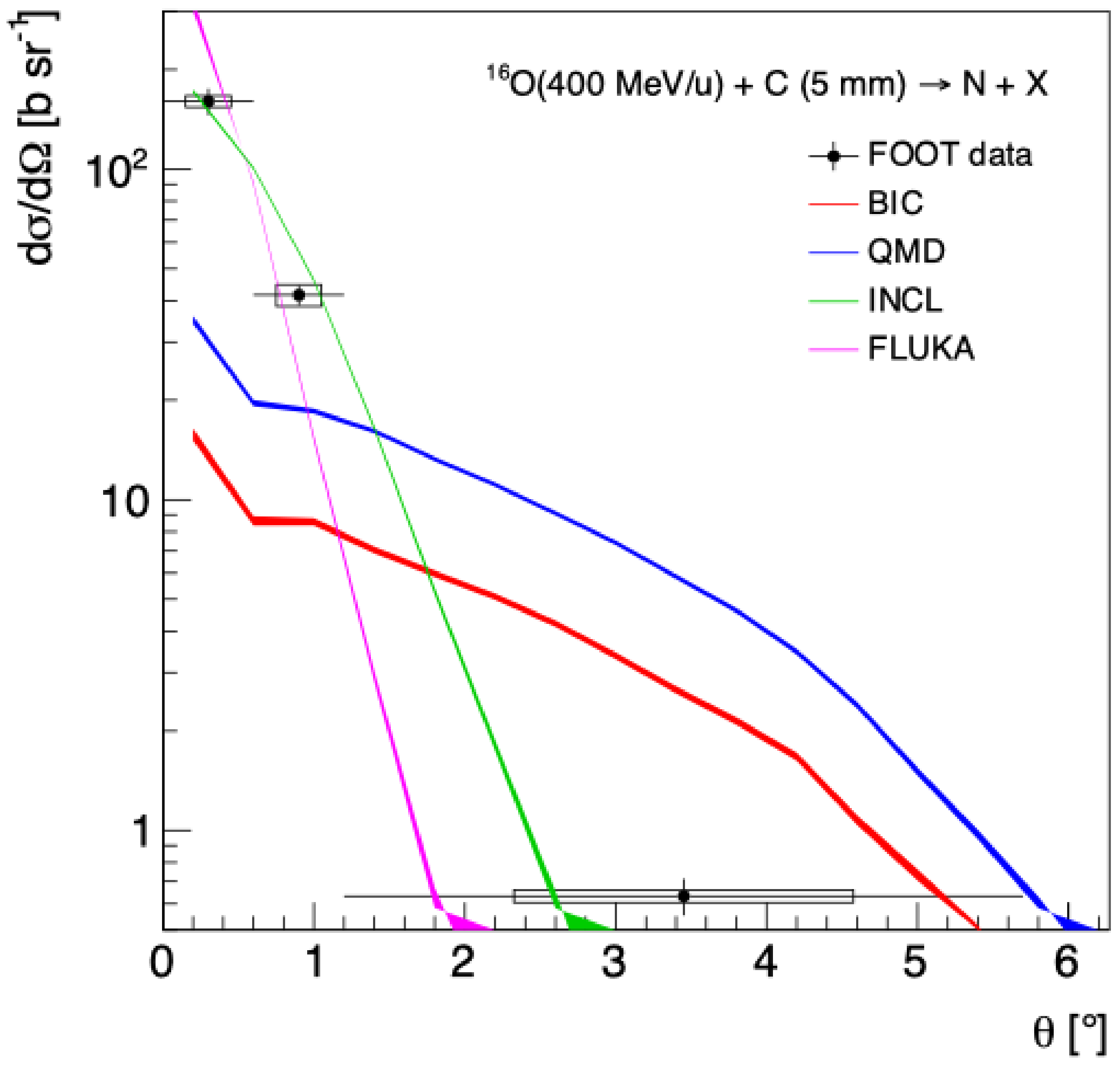
^{16}O(400 MeV/u) + C (5 mm) → Be + X
FOOT data
BIC
QMD
INCL
FLUKA
dσ/dΩ [b sr^{-1}]
θ [°]
10
1
10^{-1}
0
1
2
3
4
5
6



^{16}O(400 MeV/u) + C (5 mm) → B + X
FOOT data
BIC
QMD
INCL
FLUKA
dσ/dΩ [b sr^{-1}]
θ [°]
10
1
0
1
2
3
4
5
6



^{16}O(400 MeV/u) + C (5 mm) → C + X
FOOT data
BIC
QMD
INCL
FLUKA
dσ/dΩ [b sr^{-1}]
θ [°]



^{16}O(400 MeV/u) + C (5 mm) → N + X
FOOT data
BIC
QMD
INCL
FLUKA
dσ/dΩ [b sr^{-1}]
θ [°]
10^2
10
1
0
1
2
3
4
5
6