Simulation of light ion collisions from Intra Nuclear Cascade (INCL-Fermi Breakup) relevant for medical irradiations and radioprotection.

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- Treatment of tumors by light ion beams
  (C of a few 100 MeV/nucleon, H,O,C…Ca targets)
- Radio protection of manned spacecraft irradiated by cosmic rays
  (protons, He…up to Fe, Higher energies ~1 GeV/nuc.)
- Subsidiary: damage to spacecraft electronics (Si targets).

Good success of INC-Deexcitation as event generator
(p-Nucleus, spallation processes)

Nuclear reaction treated by a Monte-Carlo: gives all outgoing particles (except γ), all correlations, all outgoing channels without parameter tuning.

We have extended here INCL4 (well established for spallation processes) for light ion beams (up to C-O) and perform tests including light targets and low energies.

(Nothing new in itself, only one more model on the market with its own success and defects, useful for the evaluation of systematic uncertainties).

Ingredients of the model

1) Target preparation

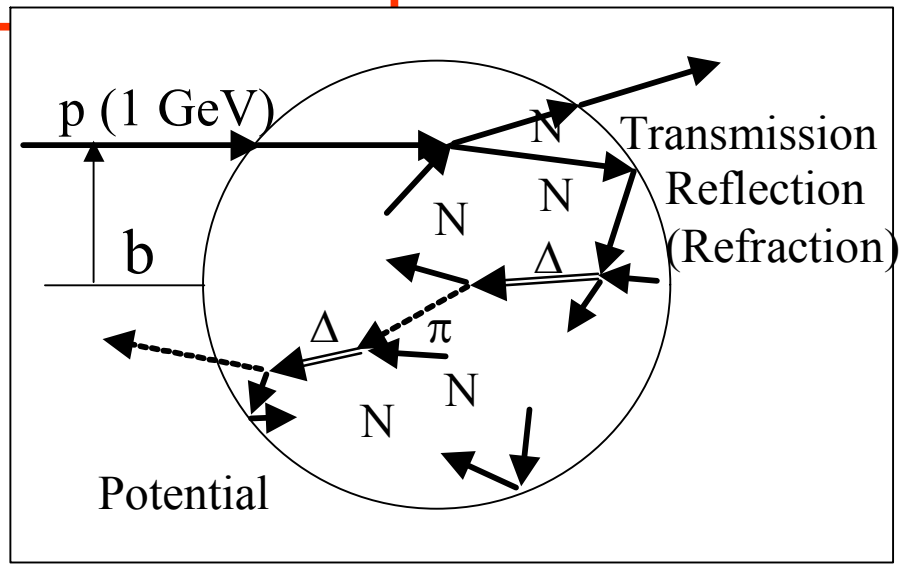
2) Entering particles

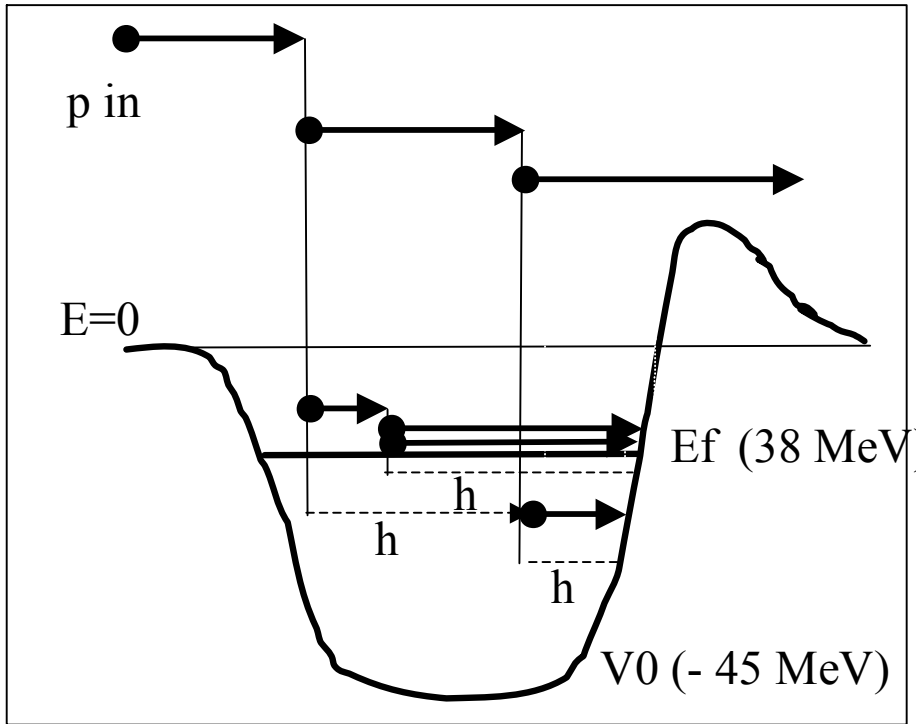
3) Propagation (t dependence)

4) Interactions

5) Escaping particles

6) End of the cascade



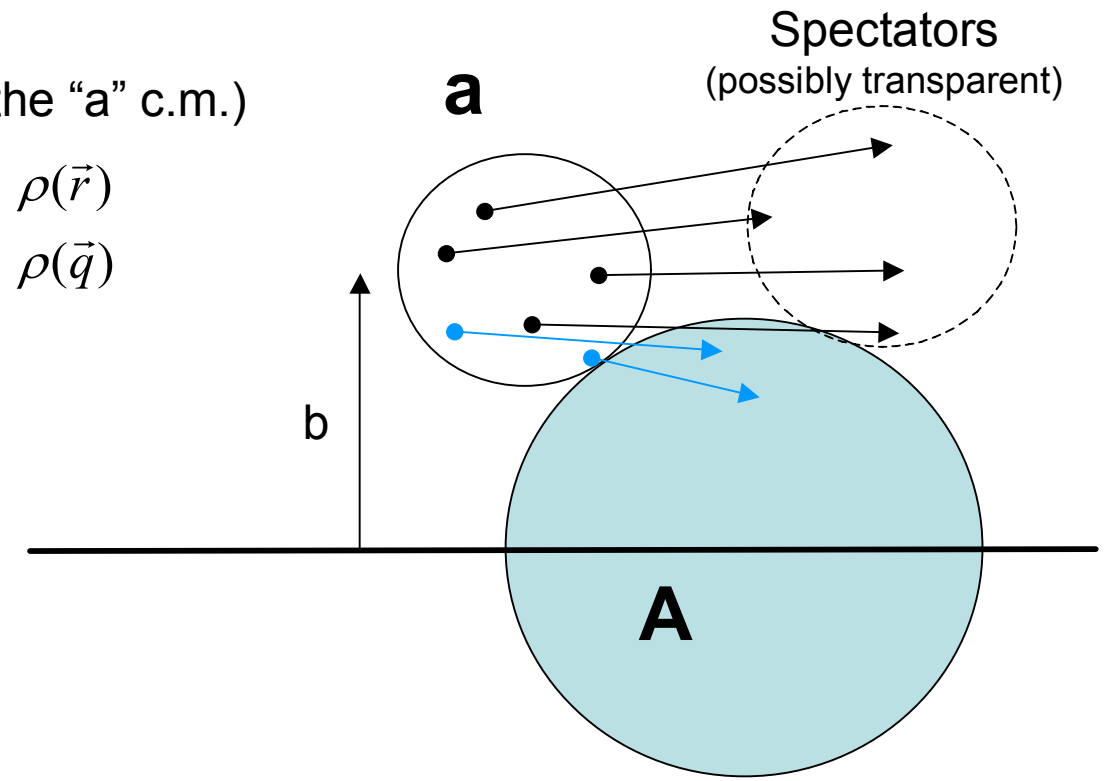


Nucleus-Nucleus: a+A

(in the “a” c.m.)

$\rho(\vec{r})$

$\rho(\vec{q})$



$$E = \sum \vec{e}_i$$

$$P = \sum \vec{p}_i$$

$$M = f(Z, A)$$

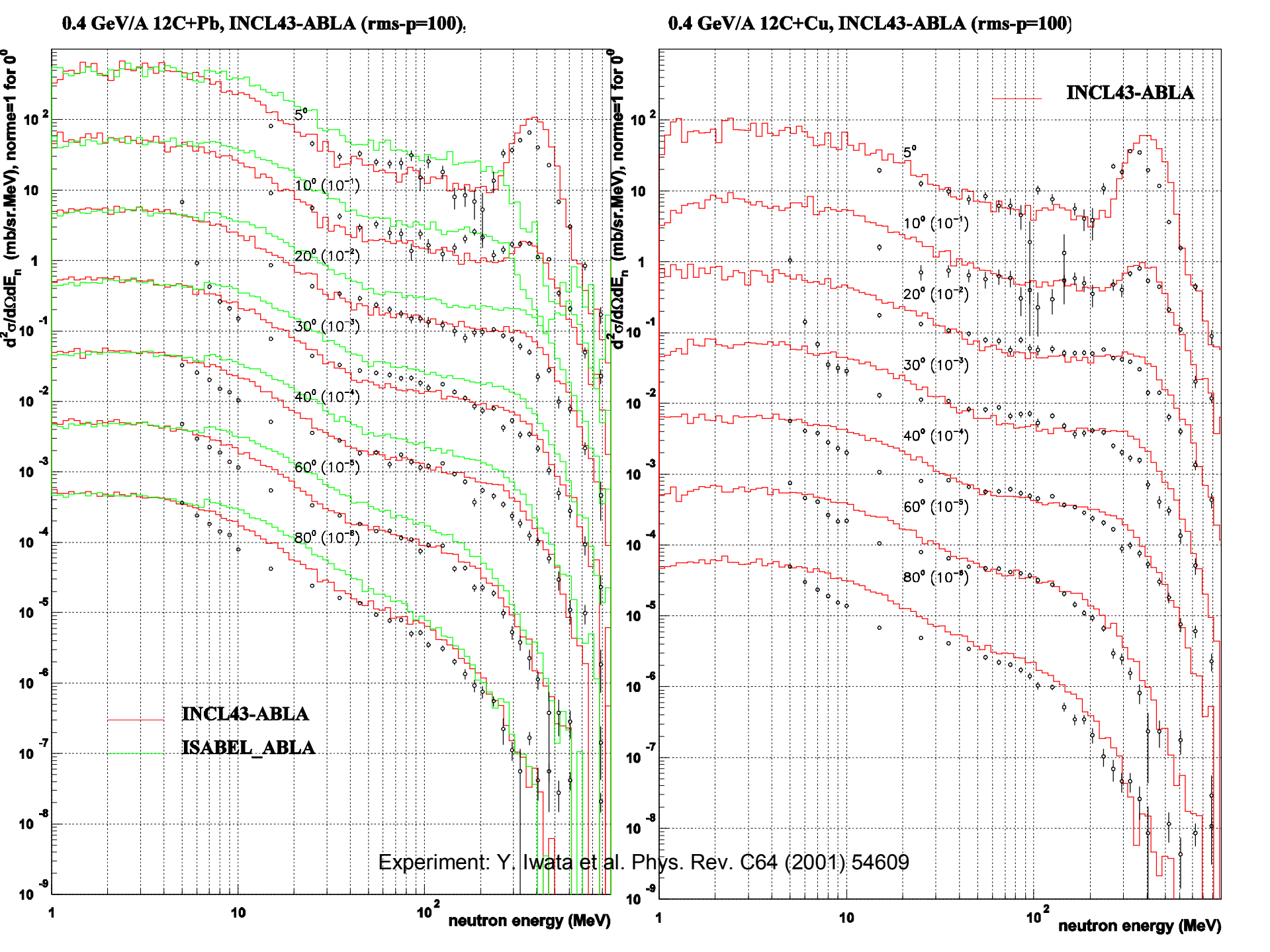
$$S = \sqrt{E^2 - \vec{P}^2}$$

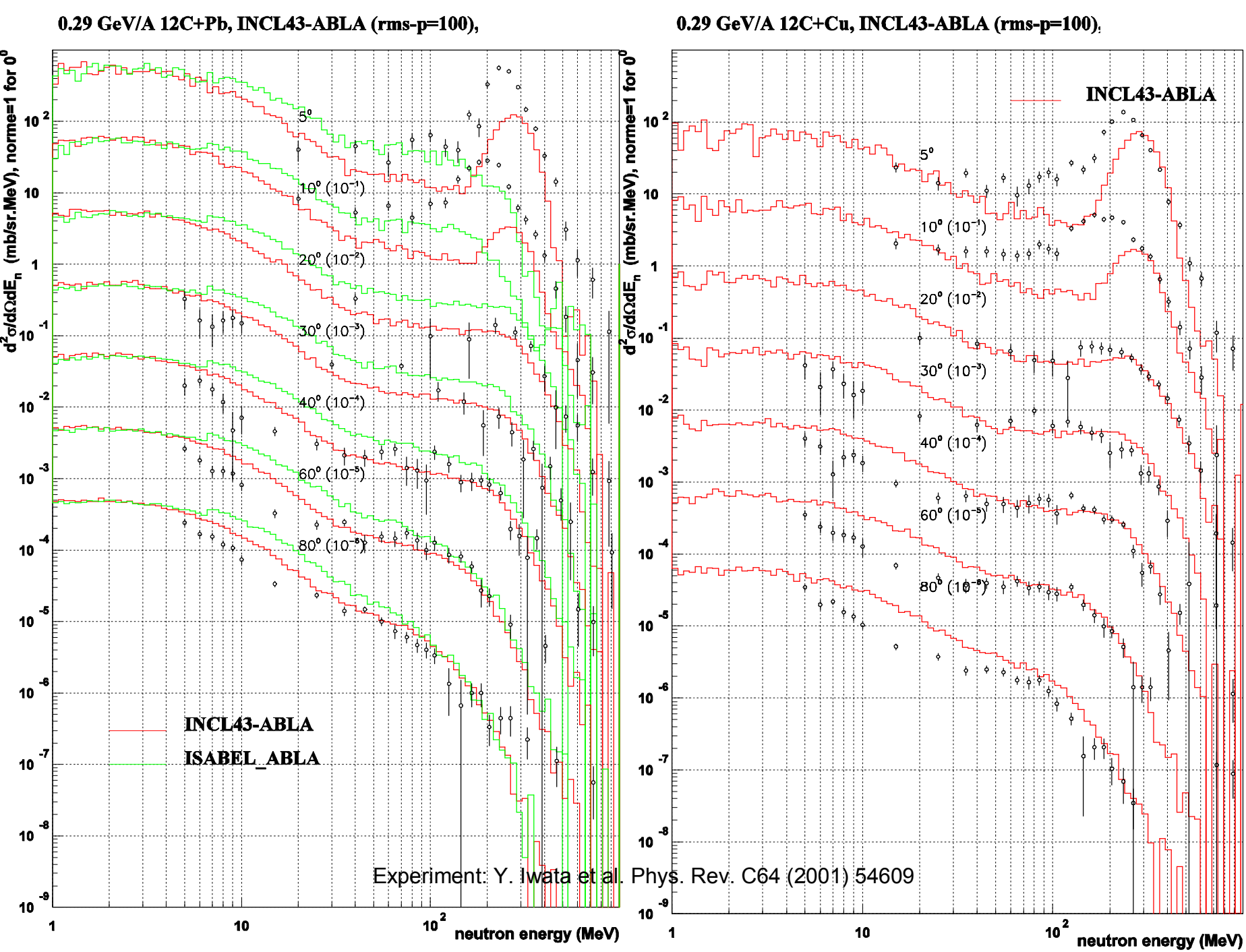
$$E^* = S - M$$

Spectators: Fermi-Breakup (possibly evaporation)

Excitation energy (per nucleon) comparable to the binding energy.
Sequential emission not justified: Partition in one step.
(Probability of various partitions statistically evaluated.)

(Version used: DRESNER from LAHET), ABLAv3p for target evaporation


0.4 GeV/A 12C+Pb, INCL43-ABLA (rms-p=100),
0.4 GeV/A 12C+Cu, INCL43-ABLA (rms-p=100)
d²σ/dΩdE_n (mb/sr.MeV), norme=1 for 0°
neutron energy (MeV)
5°
10° (10⁻¹)
20° (10⁻²)
30° (10⁻³)
40° (10⁻⁴)
60° (10⁻⁵)
80° (10⁻⁶)
INCL43-ABLA
ISABEL_ABLA
Experiment: Y. Iwata et al. Phys. Rev. C64 (2001) 54609


0.29 GeV/A 12C+Pb, INCL43-ABLA (rms-p=100),
0.29 GeV/A 12C+Cu, INCL43-ABLA (rms-p=100),
d²σ/dΩdE_n (mb/sr.MeV), norme=1 for 0°
neutron energy (MeV)
5°
10° (10⁻¹)
20° (10⁻²)
30° (10⁻³)
40° (10⁻⁴)
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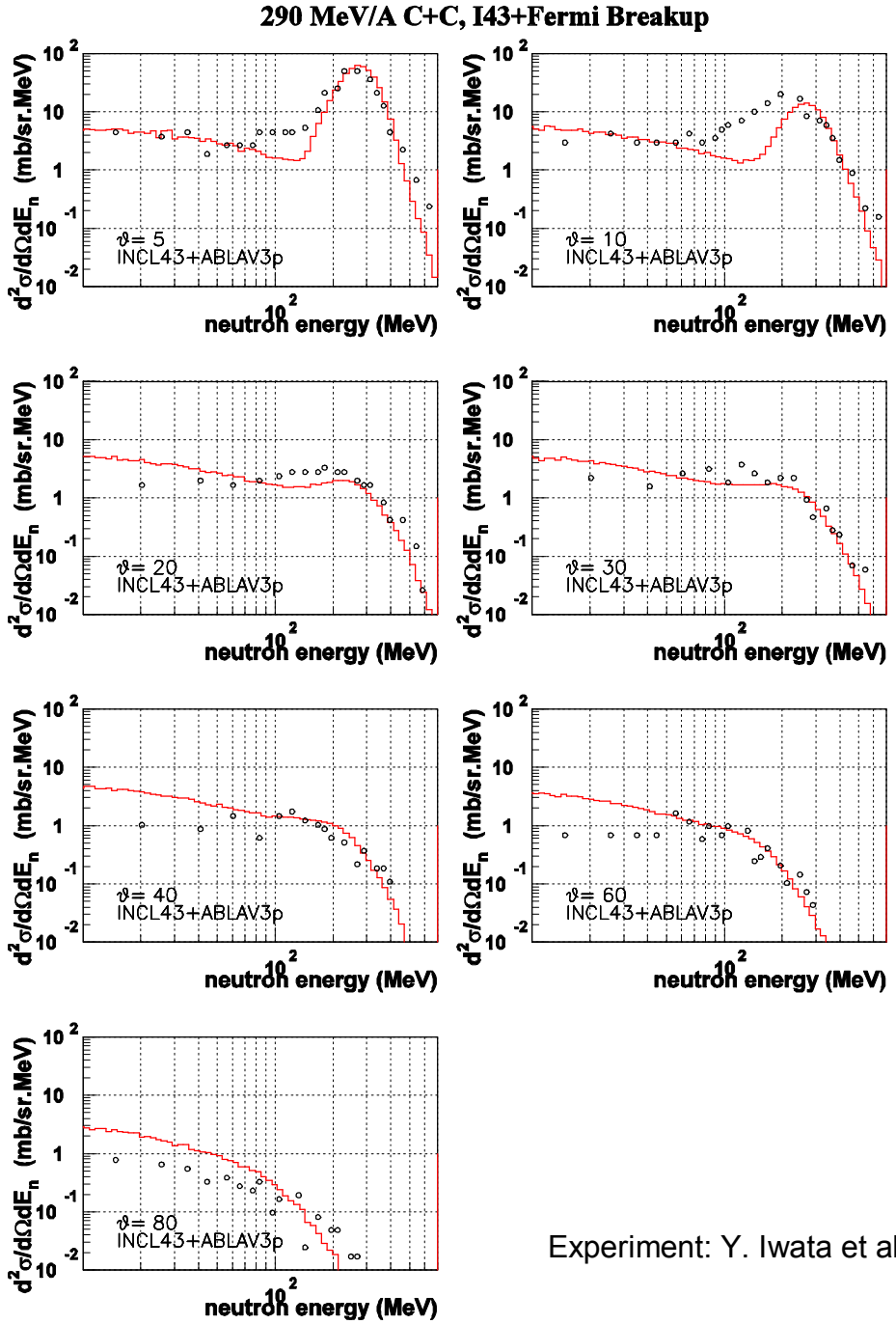
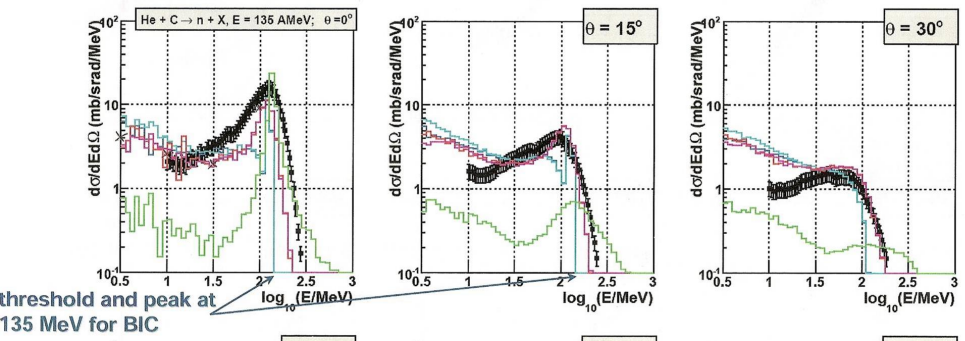


Experiment: Y. Iwata et al. Phys. Rev. C64 (2001) 54609

He + C → n + X

T=135 MeV/nucl.

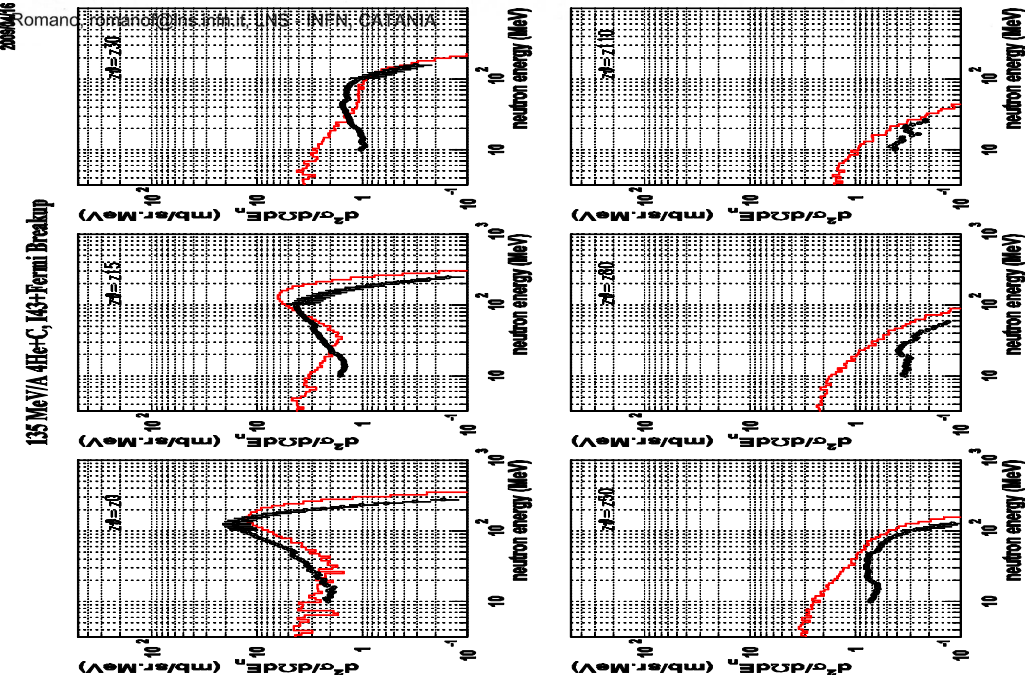


threshold and peak at 135 MeV for BIC

GEANT4 calculations with various models from
F. Romano, G. Cirrone, G. Cuttone (INFN, Catania)
BIC: Binary Intranuclear Cascade
QMD: Quantum Molecular Dynamics
ABRABLA: Abrasion-Ablation

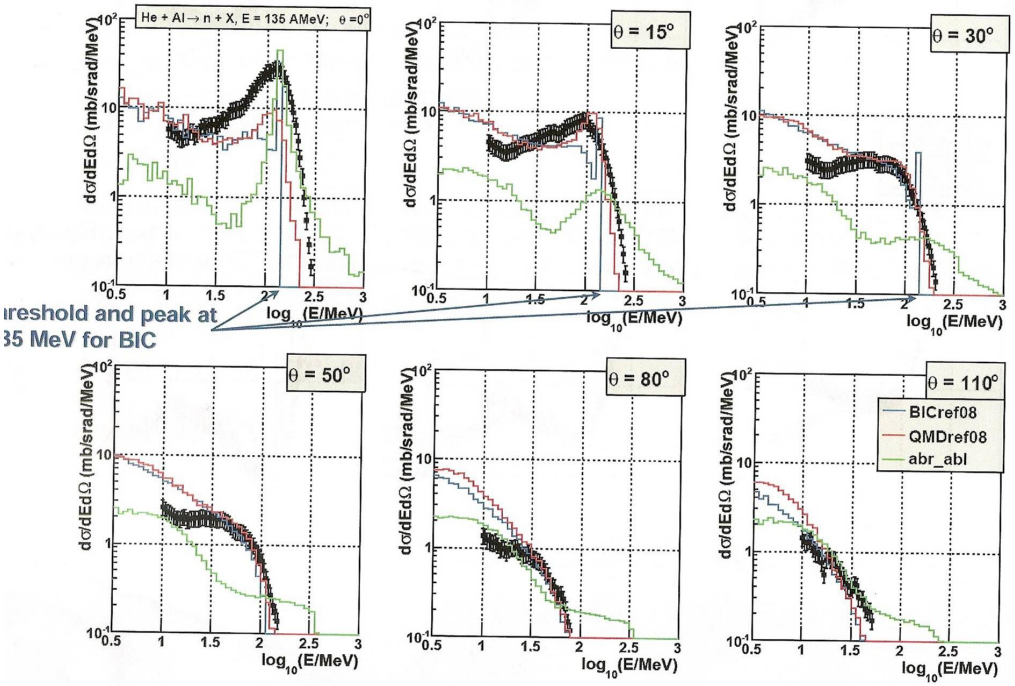
Data: H. Sato et al. Phys. Rev C64 (2001) 34607

Romano, romano@lns.infn.it, LNS - INFN, CATANIA



INCL4+ABLA+Fermi Breakup

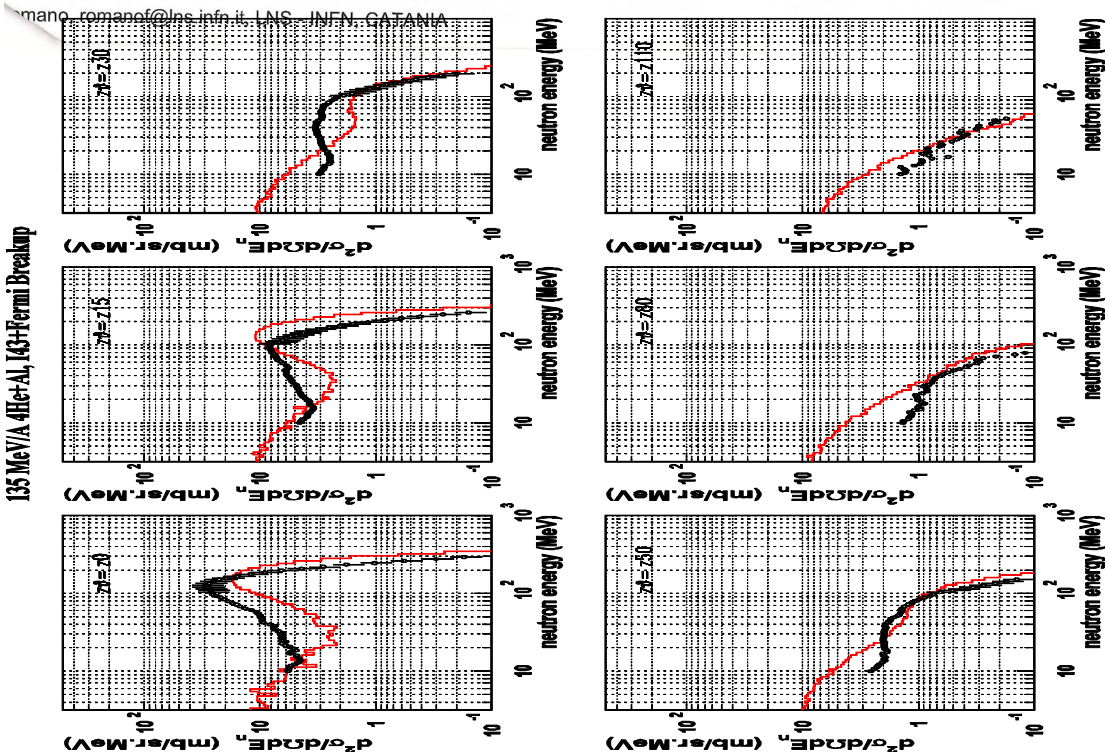
He+Al -> n+X, 135 MeV/nuc



ireshold and peak at
35 MeV for BIC

GEANT4 (F. Romano et al.)

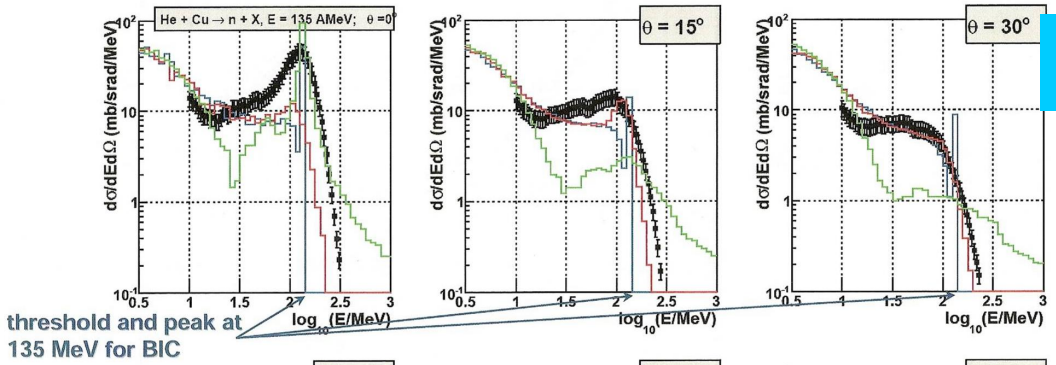
Data: H. Sato et al. Phys. Rev C64 (2001) 34607



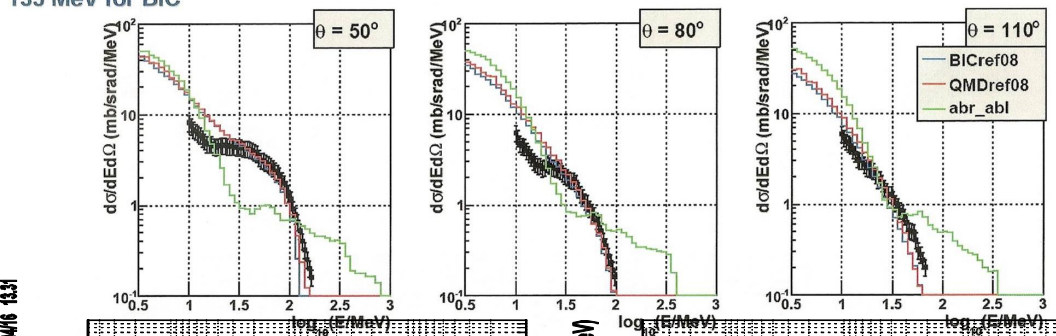
INCL4+ABLA+Fermi Breakup

romano, romanof@lns.infn.it, LNS - INFN, CATANIA

He+Cu -> n+X, 135 MeV/nuc



threshold and peak at 135 MeV for BIC



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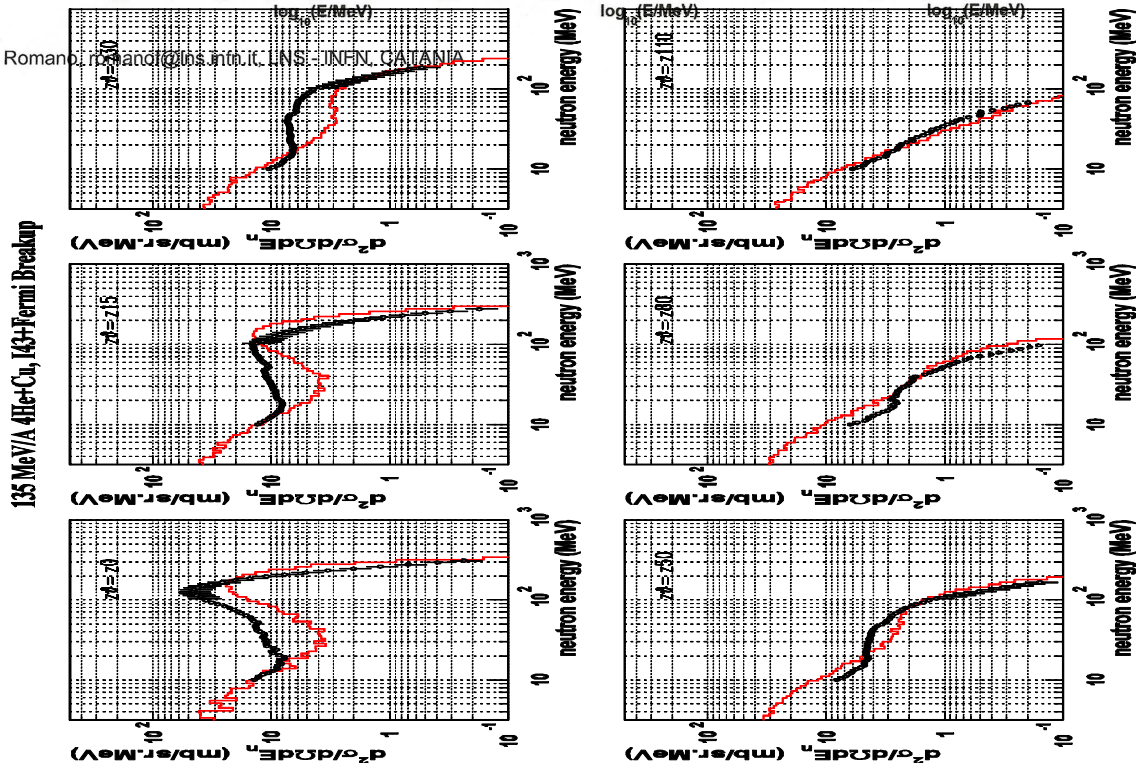
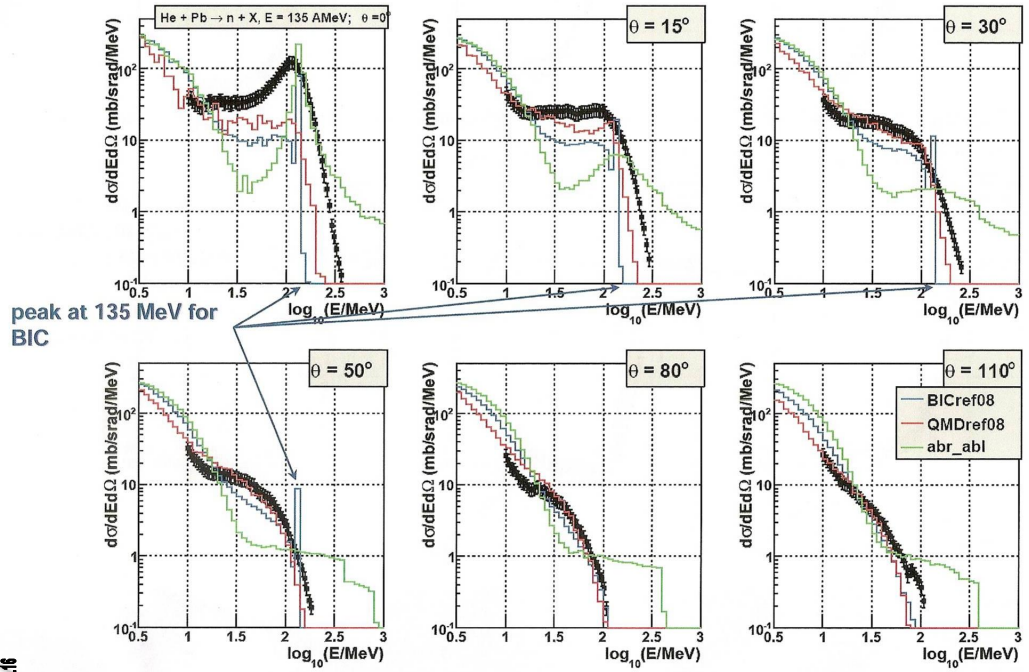


INCL4+ABLA+Fermi Breakup

He+Pb -> n+X, 135 MeV/nuc



peak at 135 MeV for BIC

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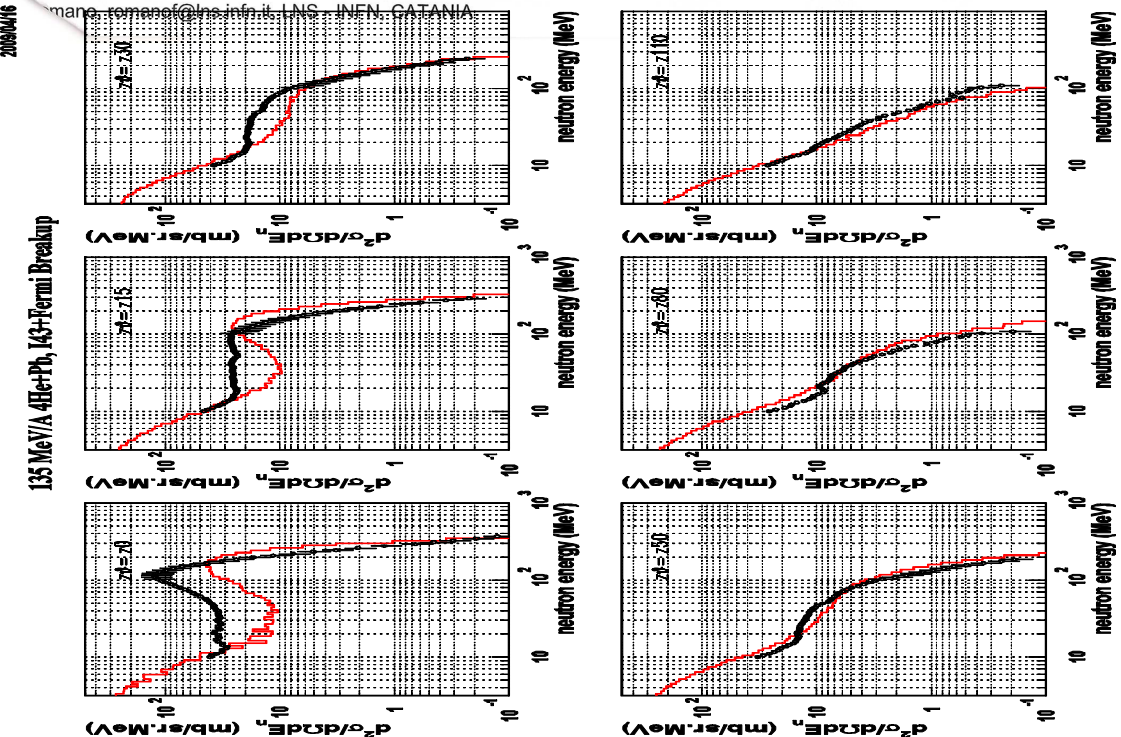
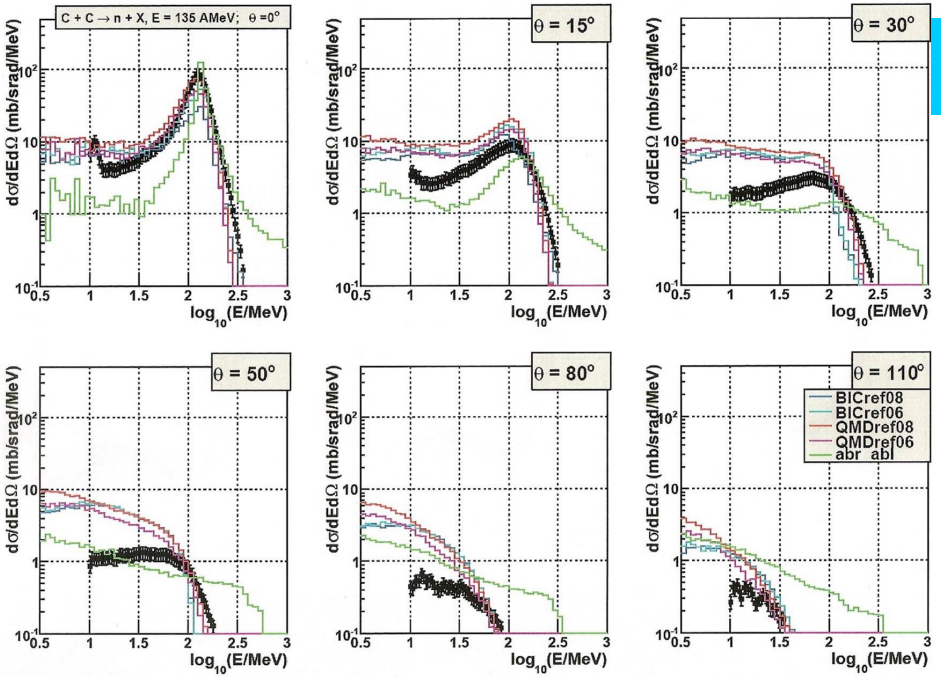
Data: H. Sato et al. Phys. Rev C64 (2001) 34607



INCL4+ABLA+Fermi Breakup

C+C -> n+X, 135 MeV/nuc



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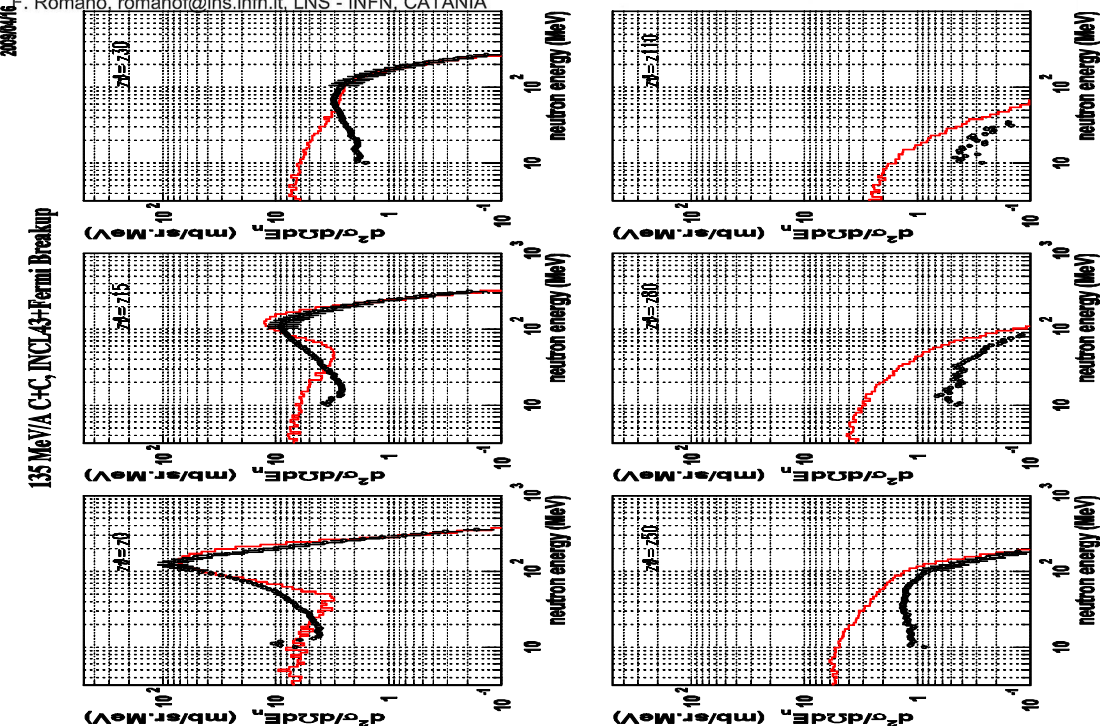
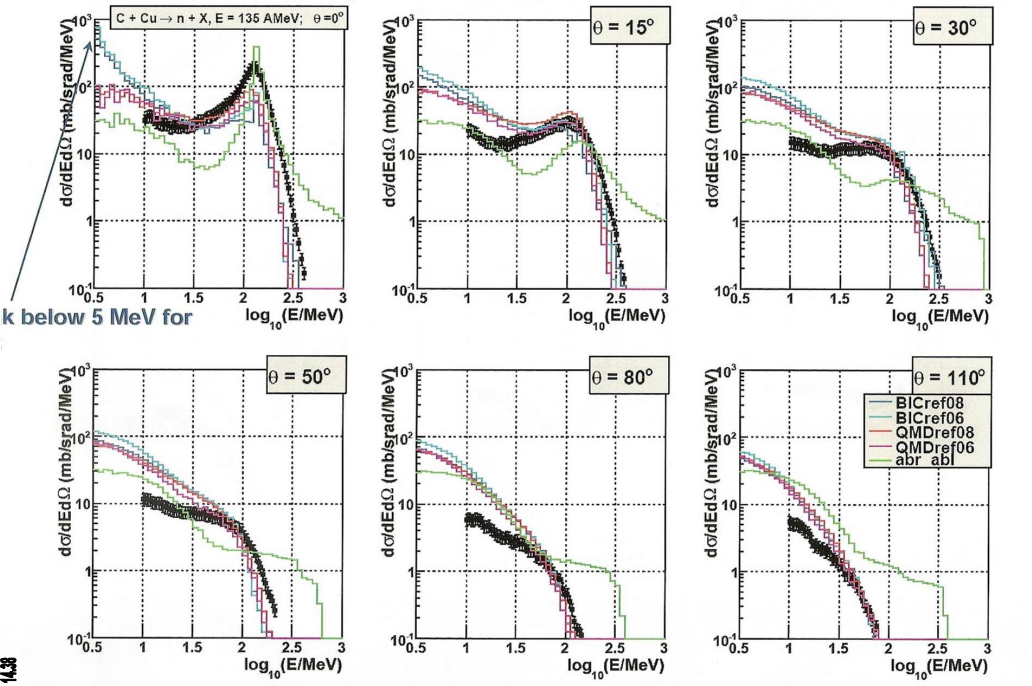
F. Romano, romanof@lns.infn.it, LNS - INFN, CATANIA



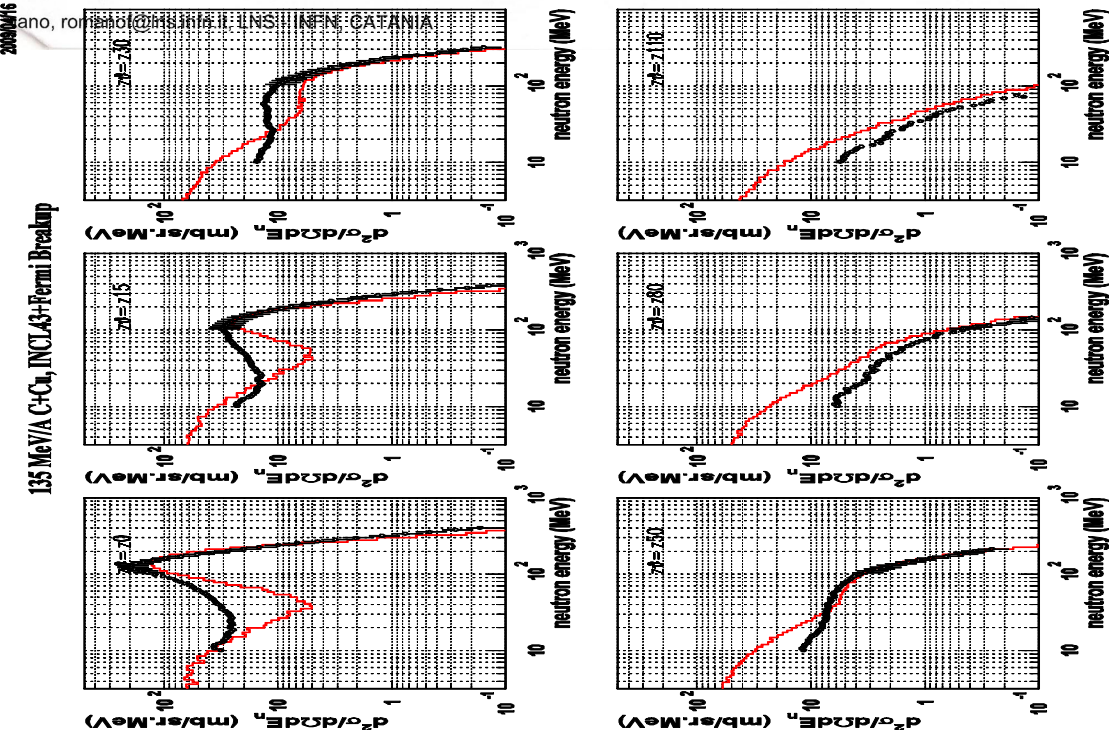
INCL4+ABLA+Fermi Breakup

C+Cu -> n+X, 135 MeV/nuc



k below 5 MeV for

ano, romano@ns.infn.it, LNS - INFN, CATANIA

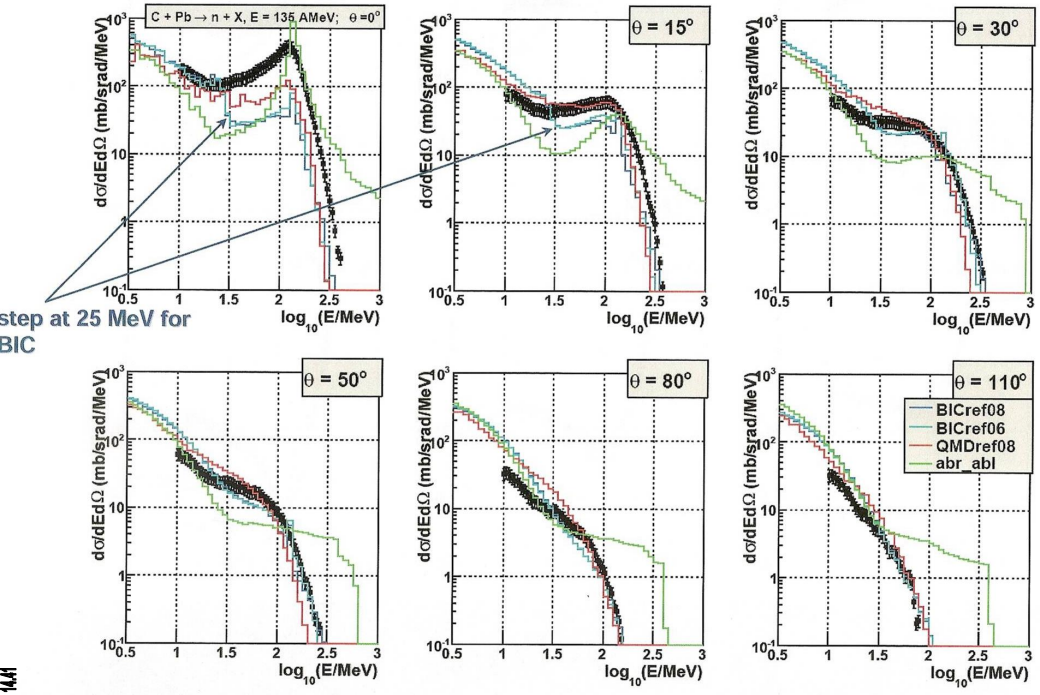


GEANT4 (F. Romano et al.)

Data: H. Sato et al. Phys. Rev C64 (2001) 34607

INCL4+ABLA+Fermi Breakup

C+Pb -> n+X, 135 MeV/nuc



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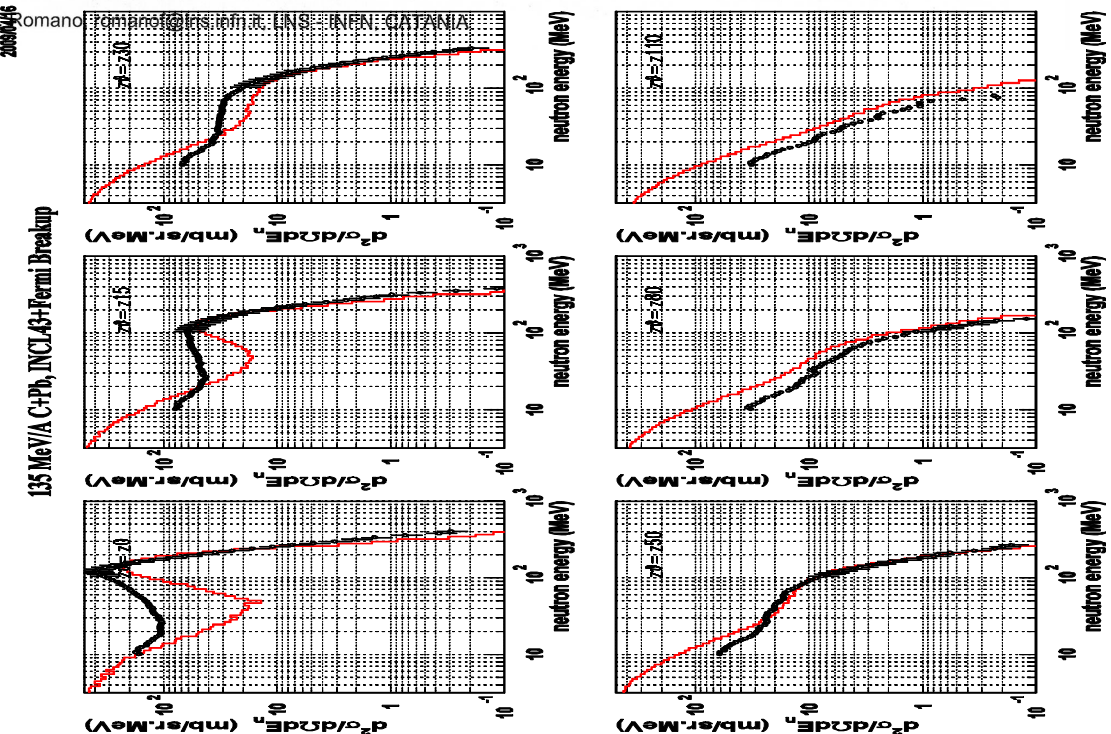

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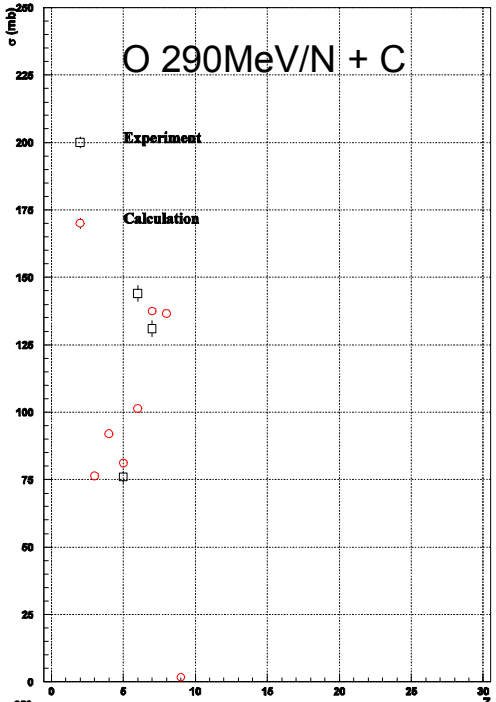
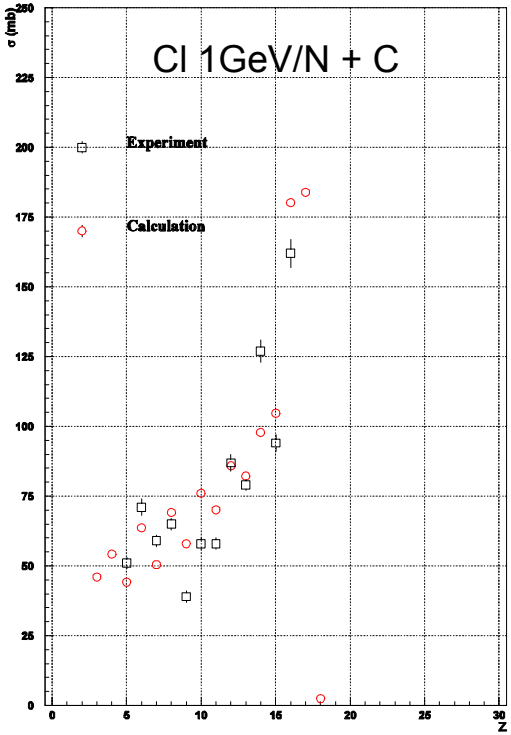
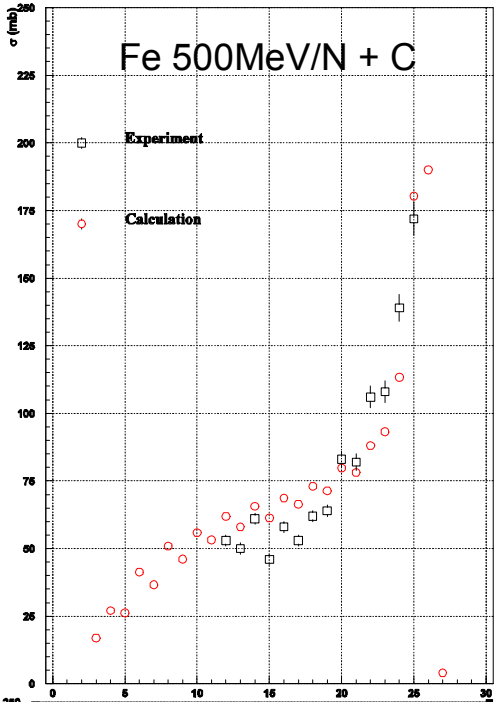
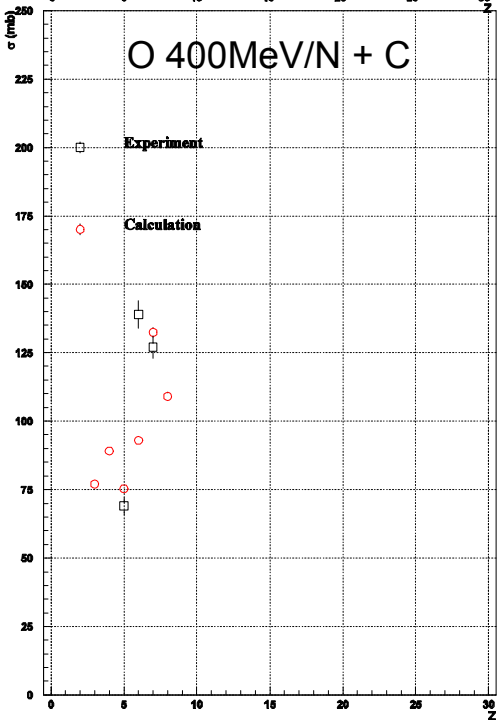




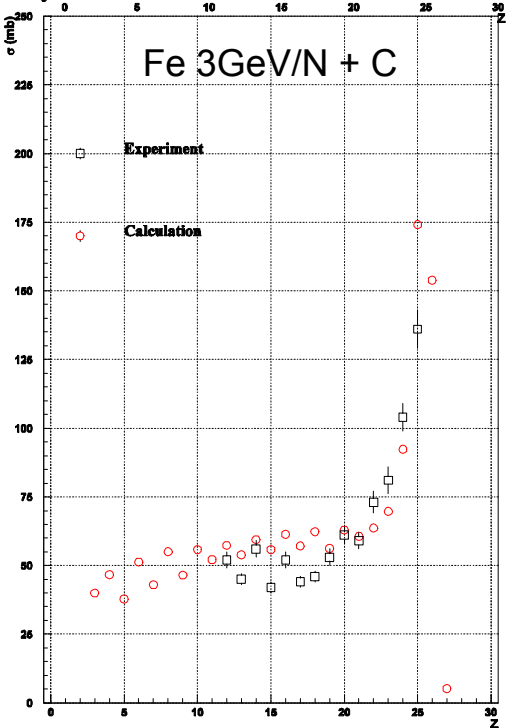




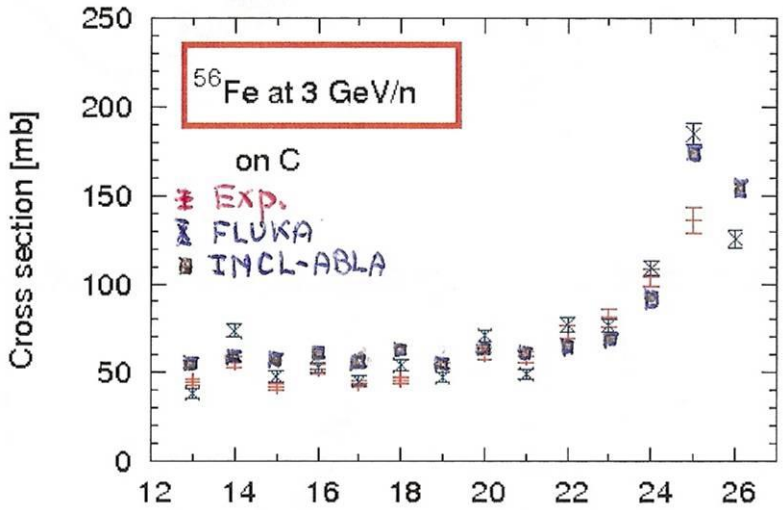
Beam fragmentation

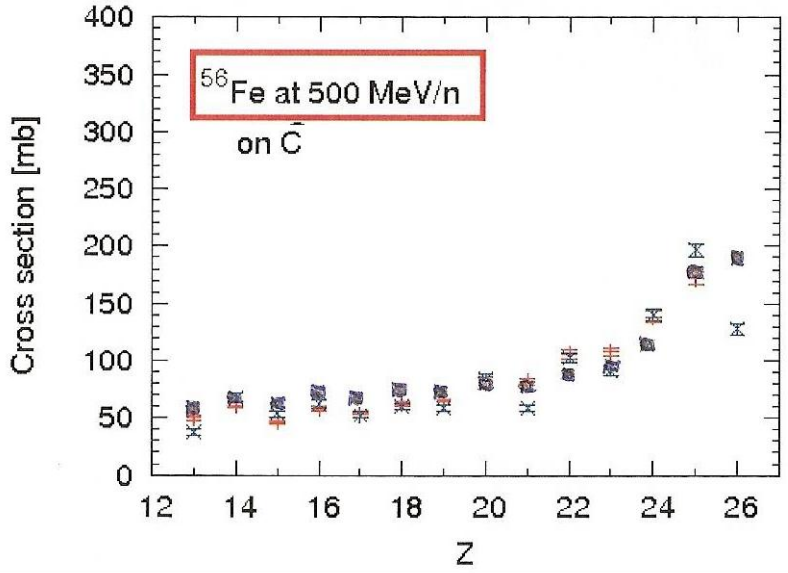
Experiments: C. Zeitlin et al. (http://fragserver.lbl.gov/)

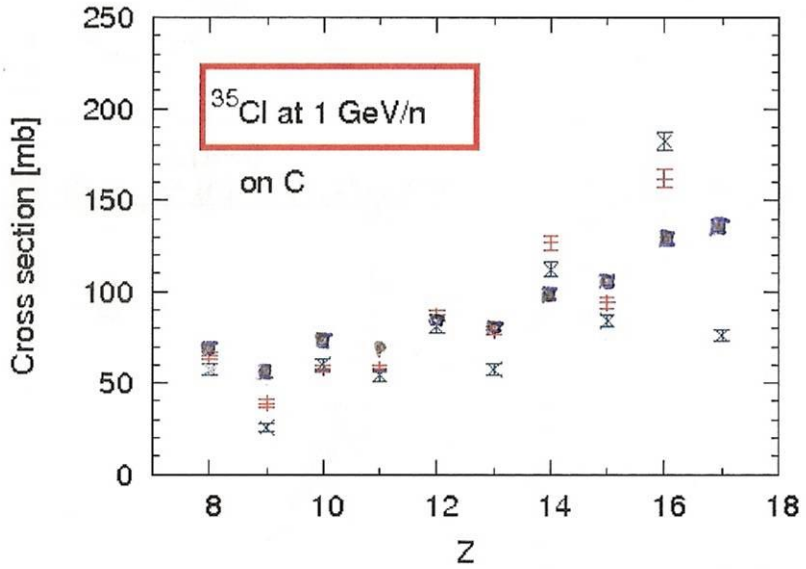
(Odd-Even not good enough, especially O-C)



Fragmentation: 3 GeV/n Fe, 1 GeV/n Cl ions







…Not worst than other models,
here FLUKA from A. Ferrari presentation

Exp. and **MC (FLUKA)** charge fragment cross sections for 3 GeV/n Fe and 1 GeV/n Cl ions (exp. data from http://fragserver.lbl.gov/main.html)

Alfredo Ferrari, NUFRA2007

Conclusions

INCL4 has been extended to heavy beams (up to C-O)

It gives **encouraging results**: For C-O…Pb from 135 MeV/nuc to a few GeV/nuc:
- n double diff cross sections
- Fragmentation of projectiles (residual nuclei)

Competitive with other existing models

INCL4-ABLA already **in GEANT4** should easily incorporate this extension
(Will be done soon)

Next steps:

- More symmetry between the target (light) and the beam
- Various approaches for the beam spectators
  (excitation energy at large impact parameters)
- **Tests on complex systems** (transport part with GEANT4)