Nuclear Physics for Galactic Cosmic Rays in the AMS-02 era (LPS-Grenoble 3-4 December 2012)

What can be expected from fragmentation codes?

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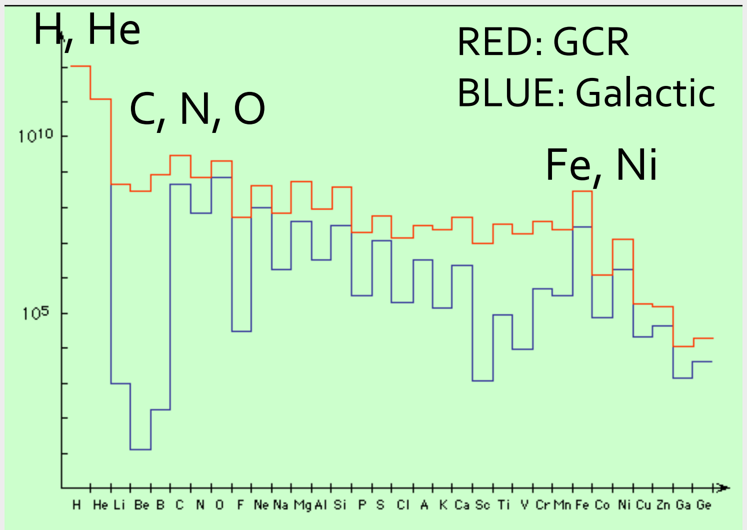
Introduction

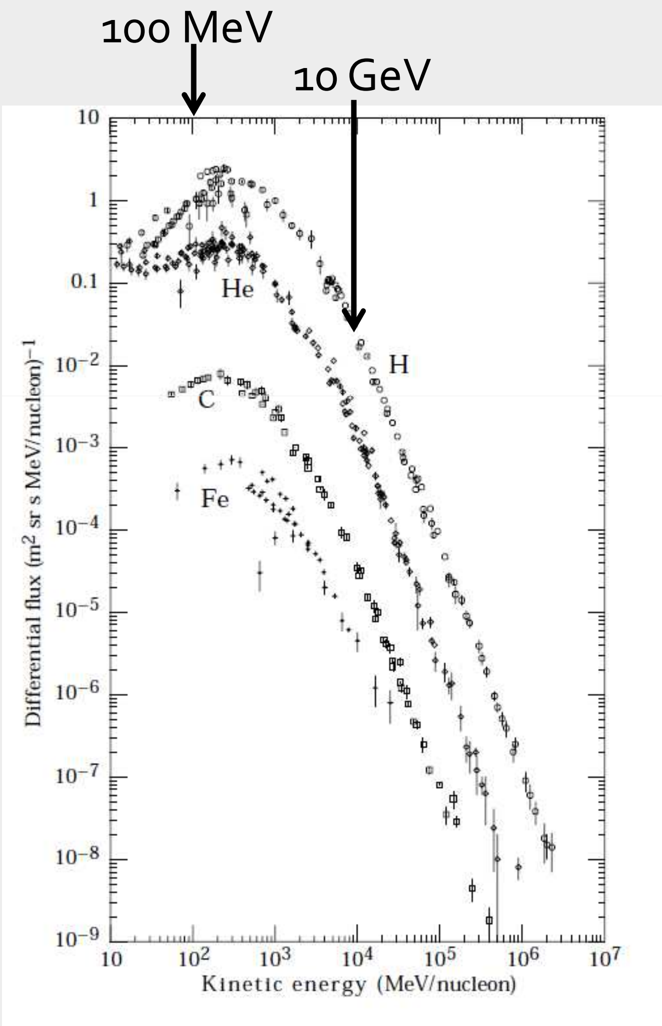
How GCR are fragmented, transformed and slowed down by nuclear interactions ?

Domain:

Projectiles: from p to ~Fe-Ge
Energies: maxi at ~ 300A MeV to ~ 10A GeV (% of max)
Low energy (10 MeV/nucl.) ALSO important.
Medium: H and He; + C,N,O for terrestrial atmosphere



Abundance (From web OAMP lectures)



From web int.washington.edu/PHYS554/ lectures

Content

Preamble:

- No matter what is the target what is the projectile!
- Can always perform RIGOROUSLY the Lorentz boost from one system to the other.

a+A ≈ A+a at the same energy per nucleon.

Empirical formulas (Webber, Silberberg-Tsao, EPAX ...)

Illustration with p+Fe

Fast but limited predictive power

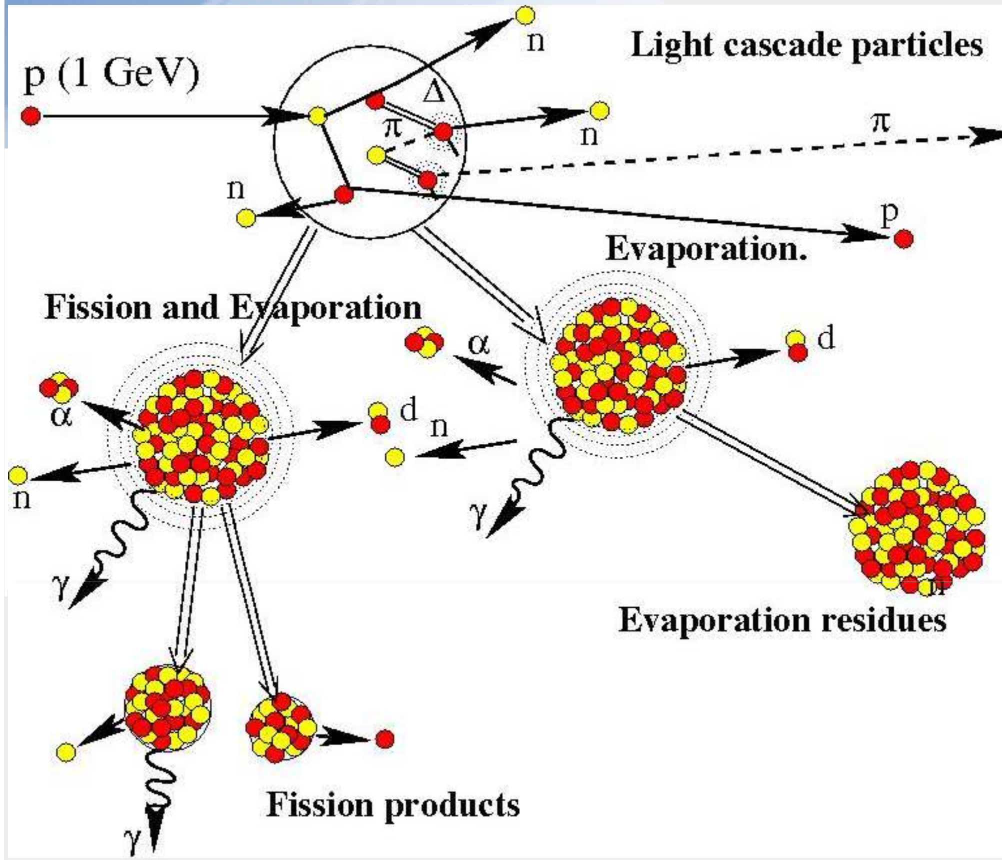
Spallation codes; THE tool! (event generators)

Intercomparison of codes (IAEA)

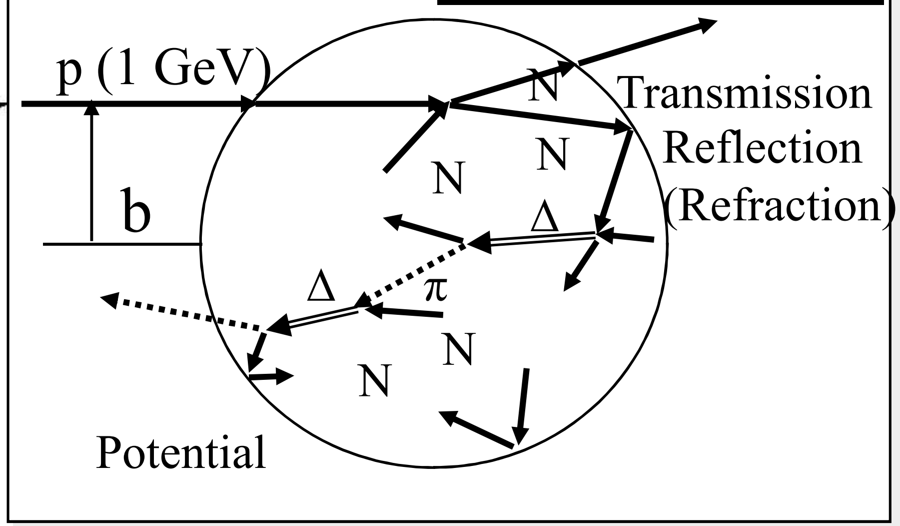
Present and future developments of INCL

My bias: I am developer of INCL....

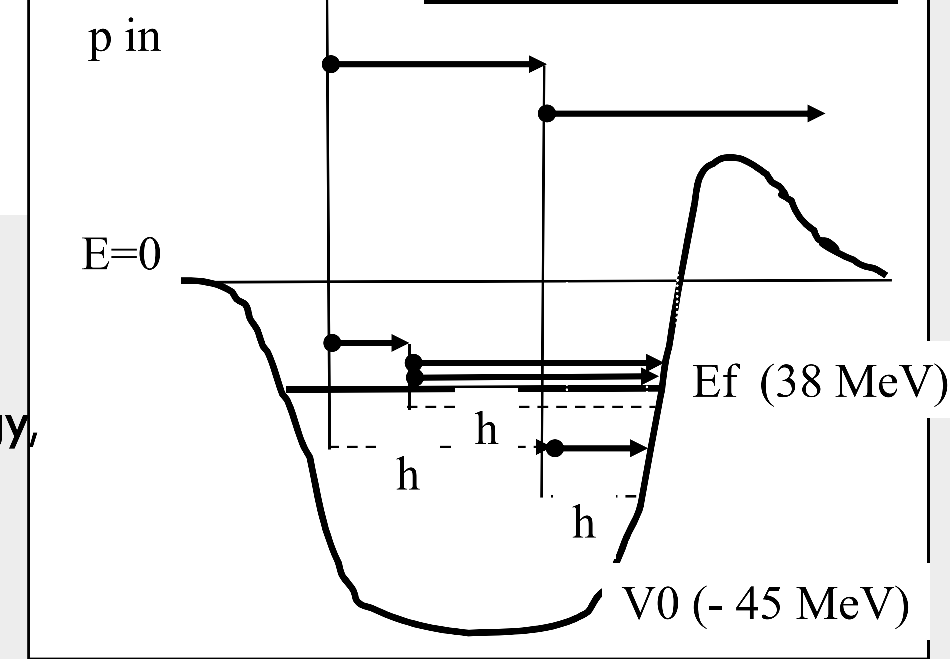
Spallation models



INC-Space picture



INC-Energy picture



Toy model of reactions (semi classical)

Physical ingredients, reduced phenomenology,
Parameters fixed one time for ever
(in a given version).
Predictive power

Spallation models (2)

Physics: π, p, n, d.....α on nuclei (~Li-U) from ~ 100 MeV to ~ 2 GeV

Spallation reactions

INC step: Production of π, nucleons, Light Charged Particles and a Remnant nuclei (A,Z,E*,J,$\vec{p}$)

INCL (but also "Bertini", BIC, Isabel ......)

De-excitation step: Fission, Evaporation, Multifragmentation, Fermi Breakup

ABLA07, Gemini++, SMM, GEM, Dresner...

Final state fully specified with **statistical fluctuations** (**Monte-Carlo**) and **ALL correlations**

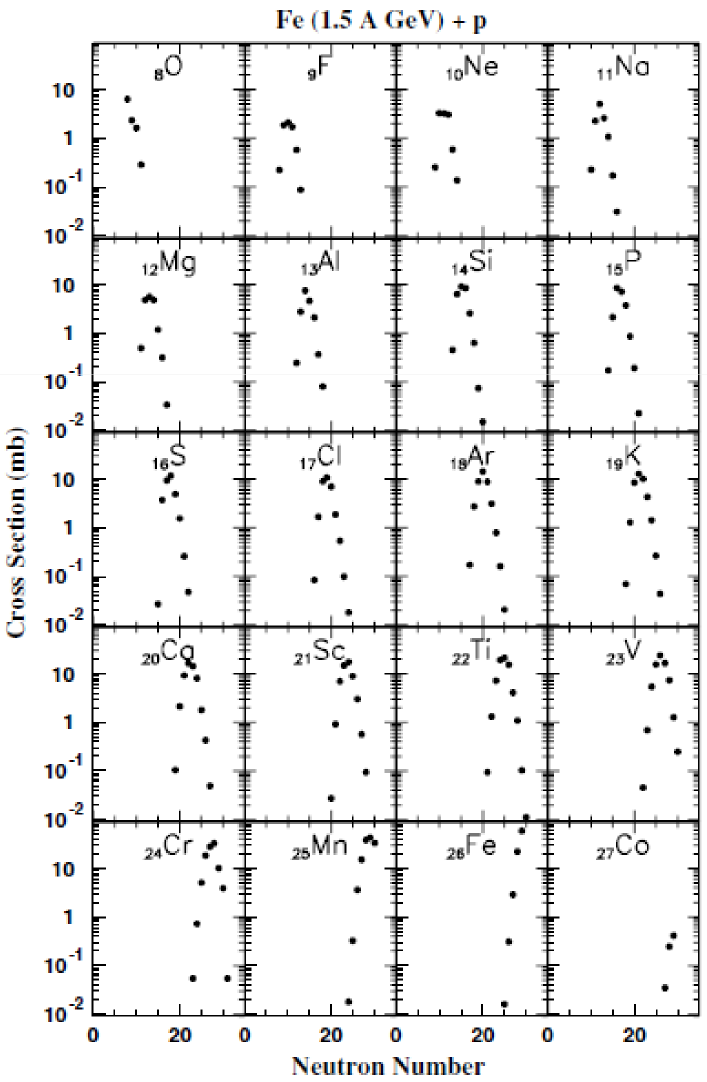
γ and β decays

Elementary models in **transport codes** for shower development (MCNPX, GEANT4, FLUKA, PHITS .....)

Empirical formulas (1)

Experiment: C. Villagrasa et al. Pys. Rev. C75 (2007) 44603 **Fe (0.3 to 1.5 A GeV)+H at GSI**

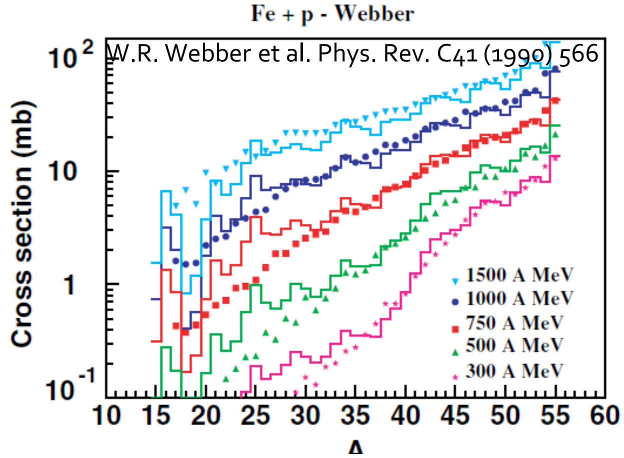
(All isotopes identified and cross section measured)

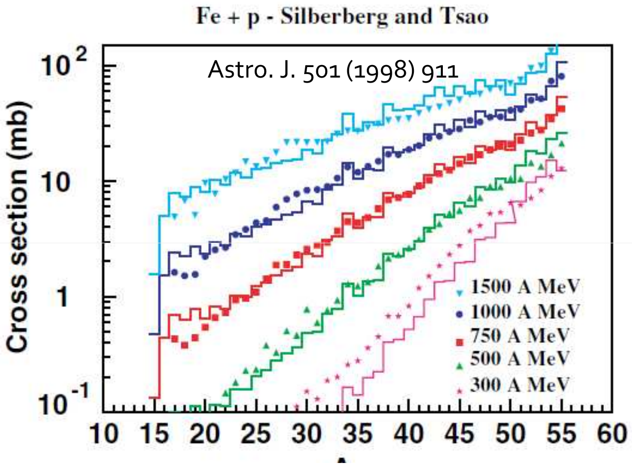


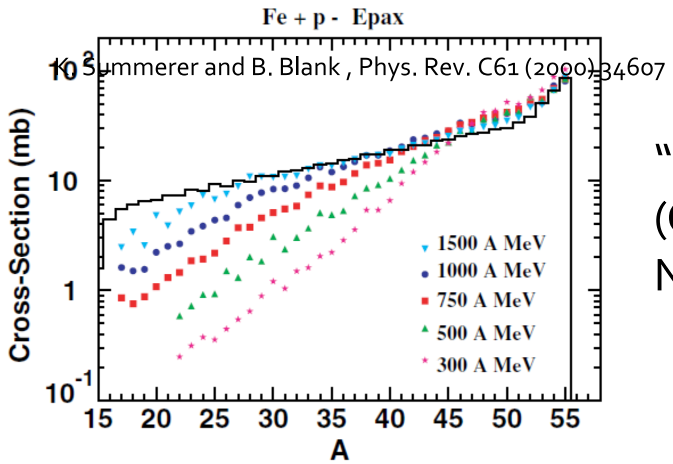
→ Summed as a function of A or of Z

→ For a given Z; Mean and r.m.s. of the A/Z distribution

Empirical formulas (2)



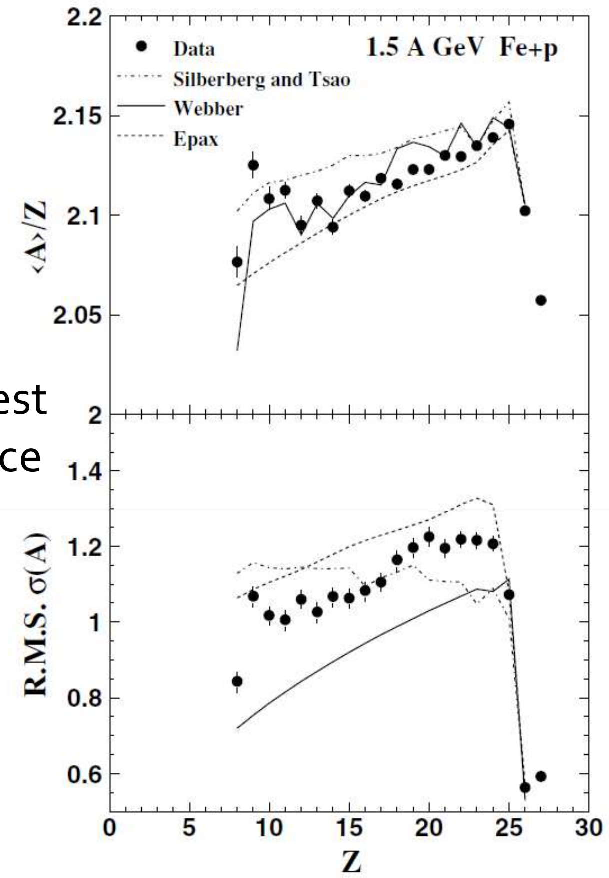




Few light residues and isotopes in the base!

The most recent and the best

...but bad rms Z dependence



“semi empirical”; limiting fragmentation regime,

(CX independent of the beam energy at high energy)

Not bad may be above 1.5 GeV.

Useful but in restricted domains.

Care to EXTRAPOLATIONS

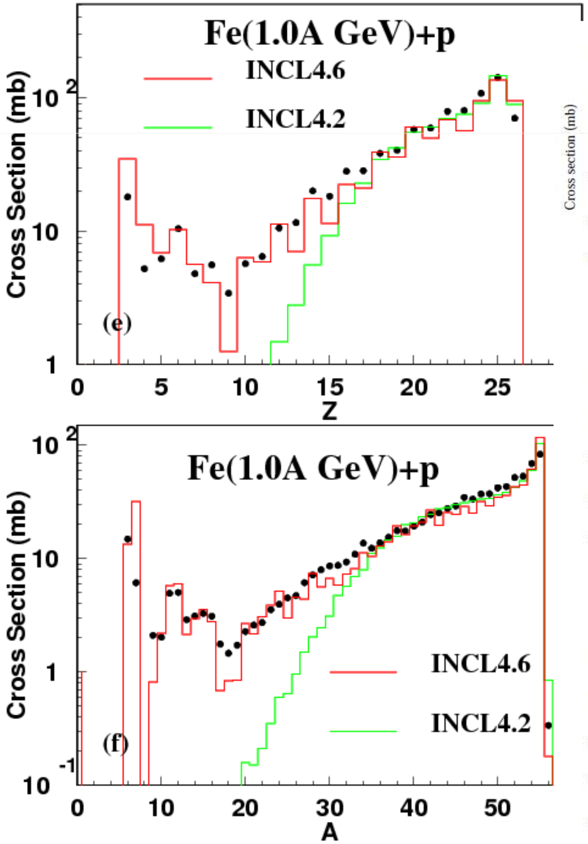
Spallation models

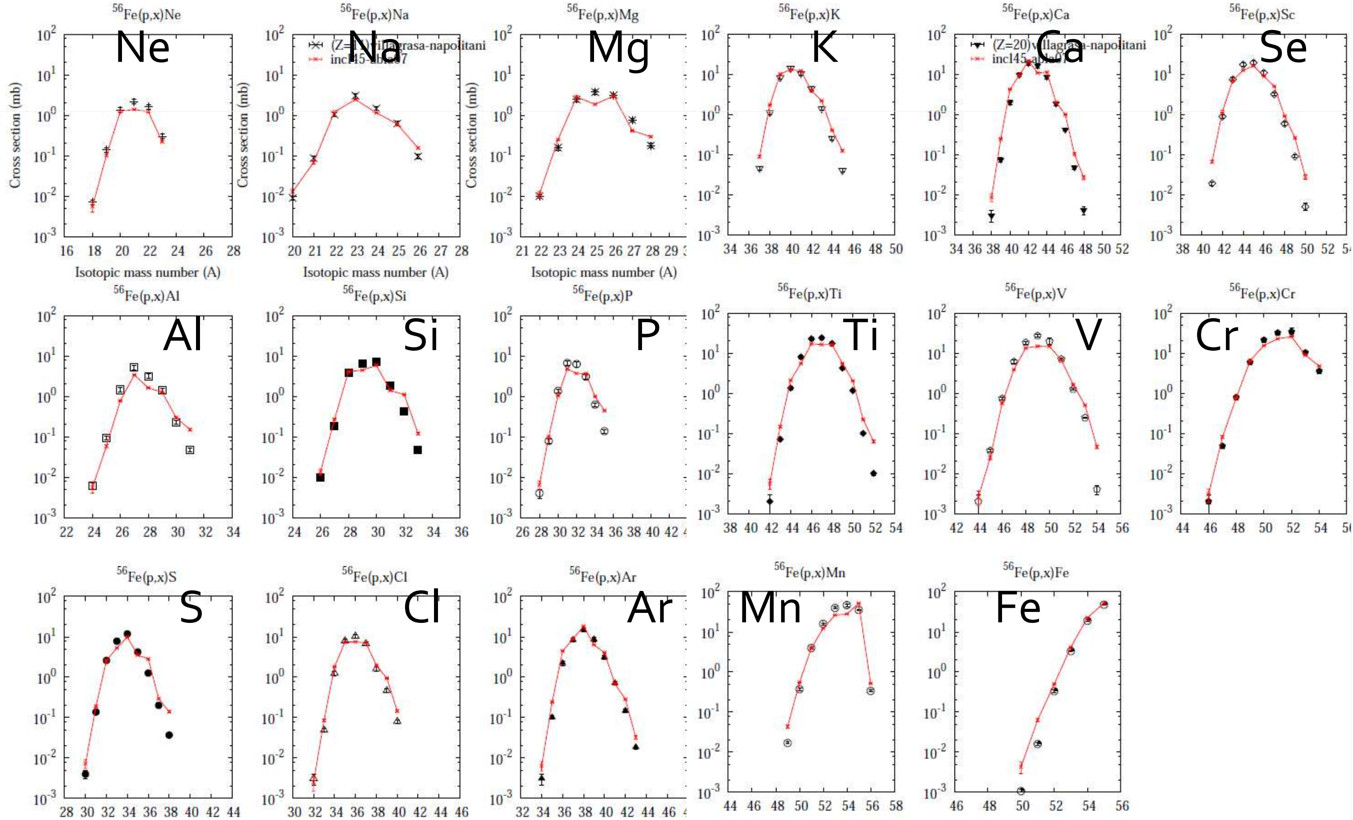
INCL4.6 + ABLA07 Last official

INCL: arXiv: 1210.3498, Phys. Rev. accepted
ABLA: A. Kelic et al, Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions. ed D. Filges et al. IAEA-INDC(NDS-0530), Vienna 2008, p 181

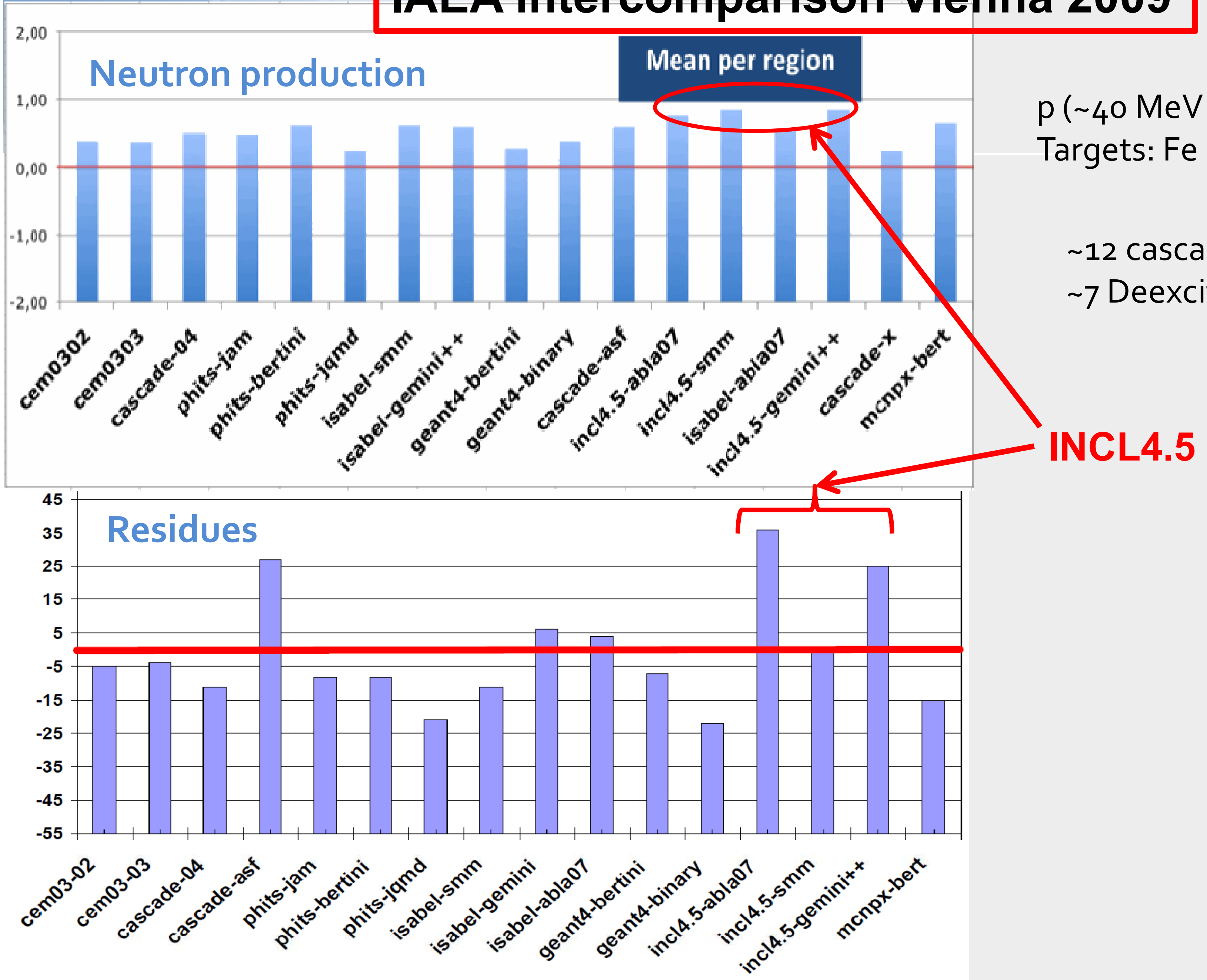
INCL4.2 + ABLAv3p Previous official

INCL: Phys. Rev. C66(2002) 44615
ABLA: J. Gaimard,KHSchmidt Nucl. Phys. A531 (1991) 709
ARJunghans et al. Nucl. Phys. A629 (1998) 635





IAEA intercomparison Vienna 2009



p (~40 MeV – 2.6 GeV)
Targets: Fe and Pb

~12 cascades
~7 Deexcitations

www-nds.iaea.org/spallations/spal_cal.html http://www-nds.iaea.org/spallations/spal_cal.html

International Atomic Energy Agency

Nuclear Data Services

Section Données Nucléaires, AIEA

IAEA.org | NDS Mis

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Meetings

- WS 2010 (Saclay)
- CM 2009 (Vienna)
- SM 2009 (Vienna)
- WS 2008 (Trieste)

Reports

- Trieste 2008
- ND2010
- SNA+MC 2010

Contacts

- D.Filges (FZJ)
- S.Leray (CEA)
- G.Mank (FZJ)
- N.Otsuka (IAEA)
- Y.Yariv (Soreq)

Links

- Geant4
- PHITS
- Nuclear Data Services
- Nuclear Data Section
- Old page (Internal)

IAEA Benchmark of Spallation Models - Calculation Results

This section contains an overall status of the participants, the intercomparison results (both Figures and Data) of experiments to model calculations, and the Figures of Merit (FOM) of this intercomparison. The FOM has been extracted using various numerical/statistical analysis methods and techniques (such as the deviation factors, chi-square values and parameters, ratios of experiment to calculated values) as the indicators for the smooth and advanced ways of treating the results. This method represents a mathematical measure/numerical evidences as additional tools for performing this intercomparison exercise.

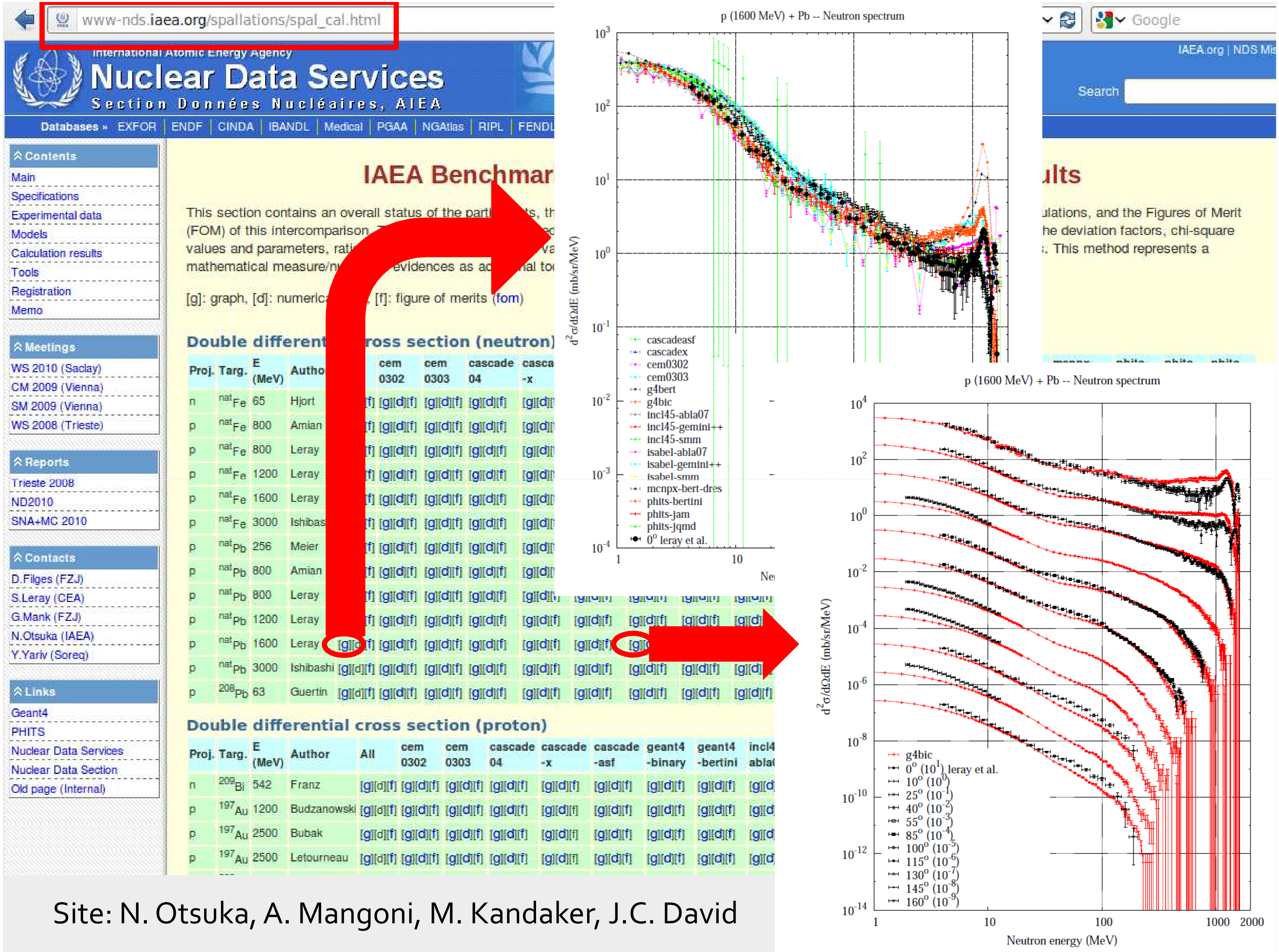
[g]: graph, [d]: numerical data, [f]: figure of merits (fom)

Double differential cross section (neutron)

Proj.	Targ.	E (MeV)	Author	All	cem 0302	cem 0303	cascade 04	cascade -x	cascade -asf	geant4 -binary	geant4 -bertini	incl45-abla07	incl45-gemin++	incl45-smm	isabel-abla07	isabel-gemini++	isabel -smm	mcnpx-bert-dres	phits-bertini	phits -jam	phits -jqmd
n	^{nat}Fe	65	Hjort	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Fe	800	Amian	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Fe	800	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Fe	1200	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Fe	1600	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Fe	3000	Ishibashi	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	256	Meier	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	800	Amian	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	800	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	1200	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	1600	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{nat}Pb	3000	Ishibashi	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{208}Pb	63	Guertin	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]

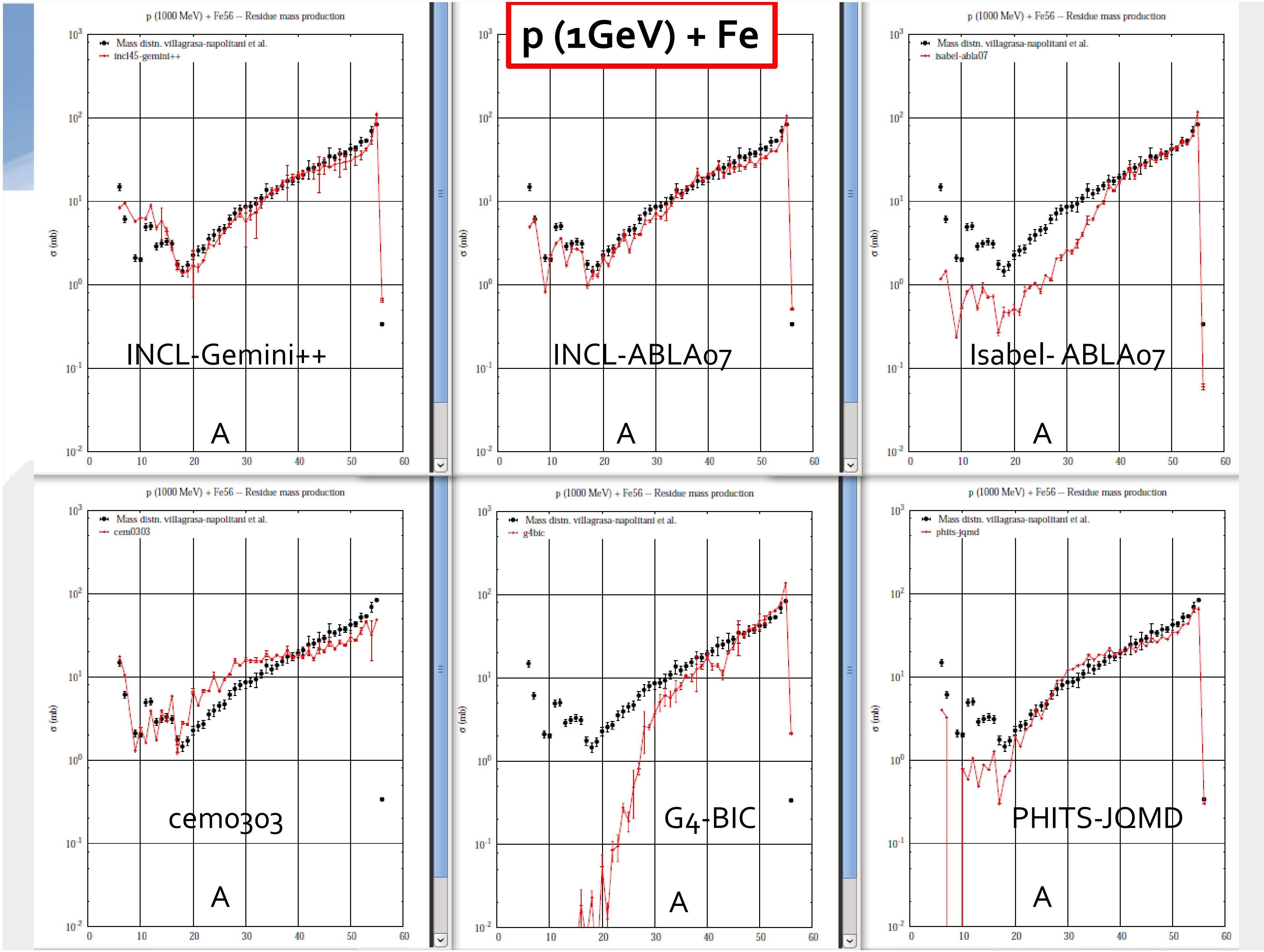
Double differential cross section (proton)

Proj.	Targ.	E (MeV)	Author	All	cem 0302	cem 0303	cascade 04	cascade -x	cascade -asf	geant4 -binary	geant4 -bertini	incl45-abla07	incl45-gemin++	incl45-smm	isabel-abla07	isabel-gemini++	isabel -smm	mcnpx-bert-dres	phits-bertini	phits -jam	phits -jqmd
n	^{209}Bi	542	Franz	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{197}Au	1200	Budzanowski	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{197}Au	2500	Bubak	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]
p	^{197}Au	2500	Letourneau	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]

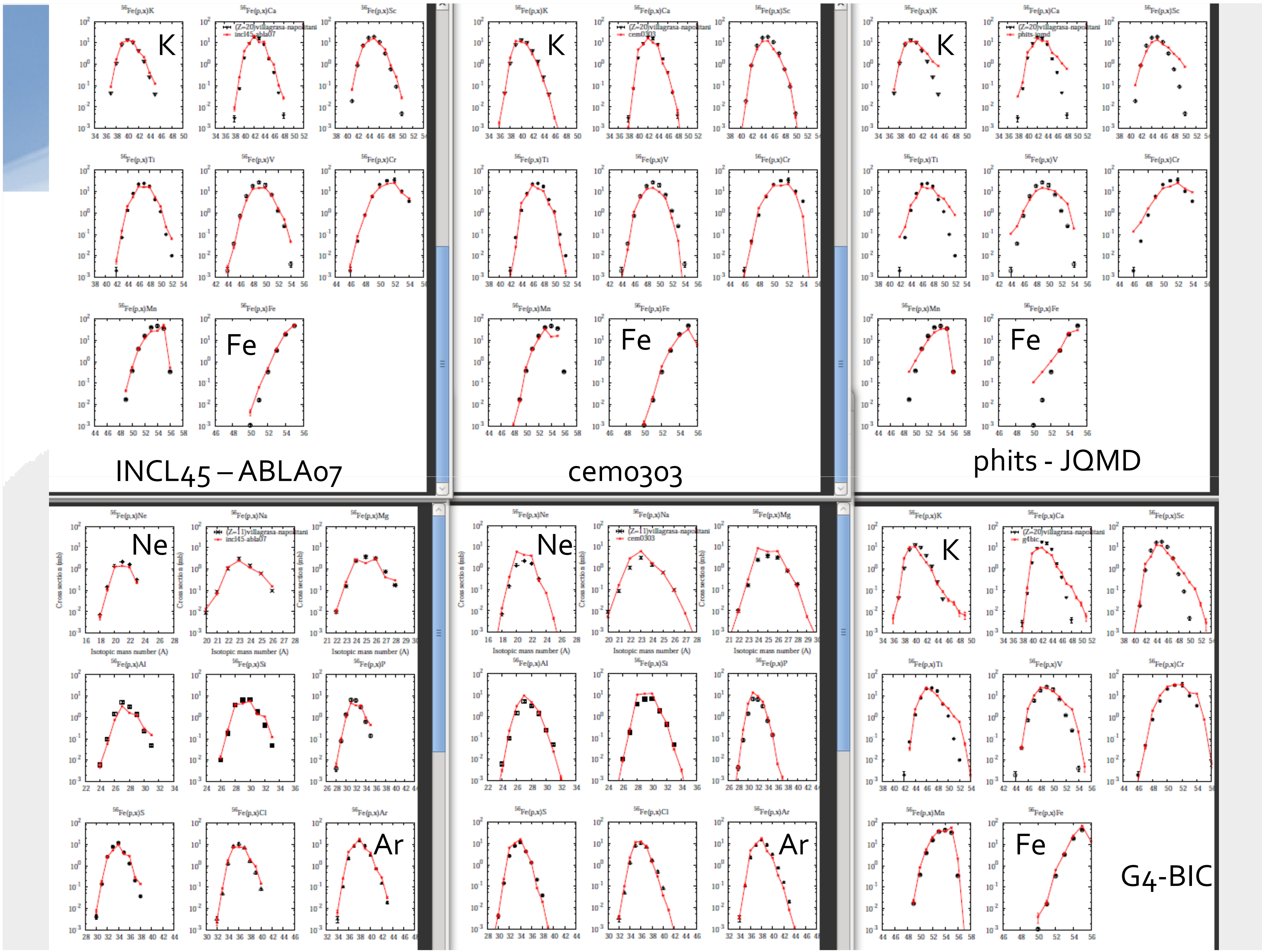


Site: N. Otsuka, A. Mangoni, M. Kandaker, J.C. David

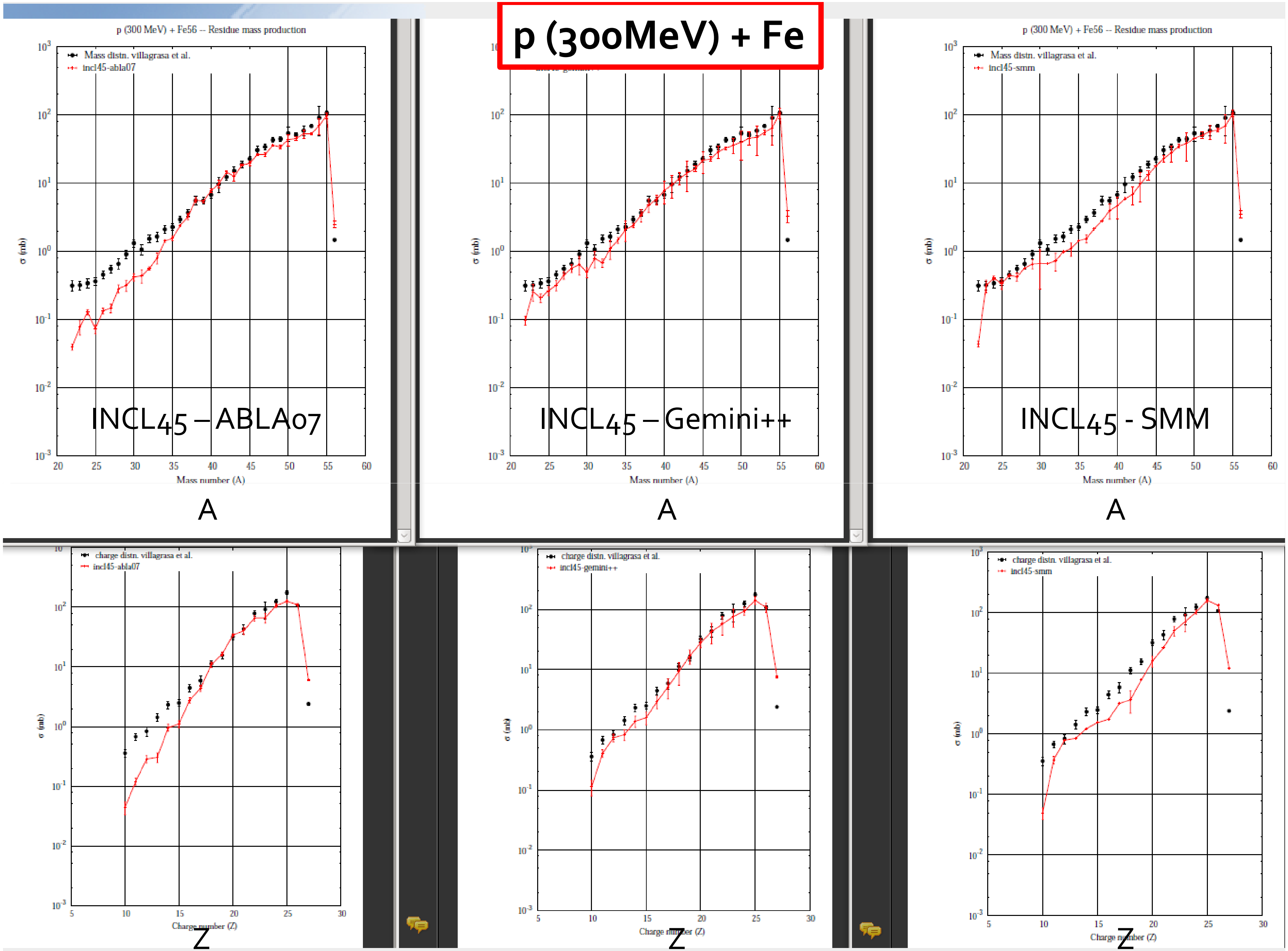
p (1GeV) + Fe



p (1000 MeV) + Fe56 -- Residue mass production
Mass distn. villagrasa-napolitani et al.
incl45-gemini++
INCL-Gemini++
INCL-ABLA07
isabel-abla07
Isabel- ABLA07
cem0303
g4bic
G4-BIC
phits-jqmd
PHITS-JQMD
σ (mb)
A

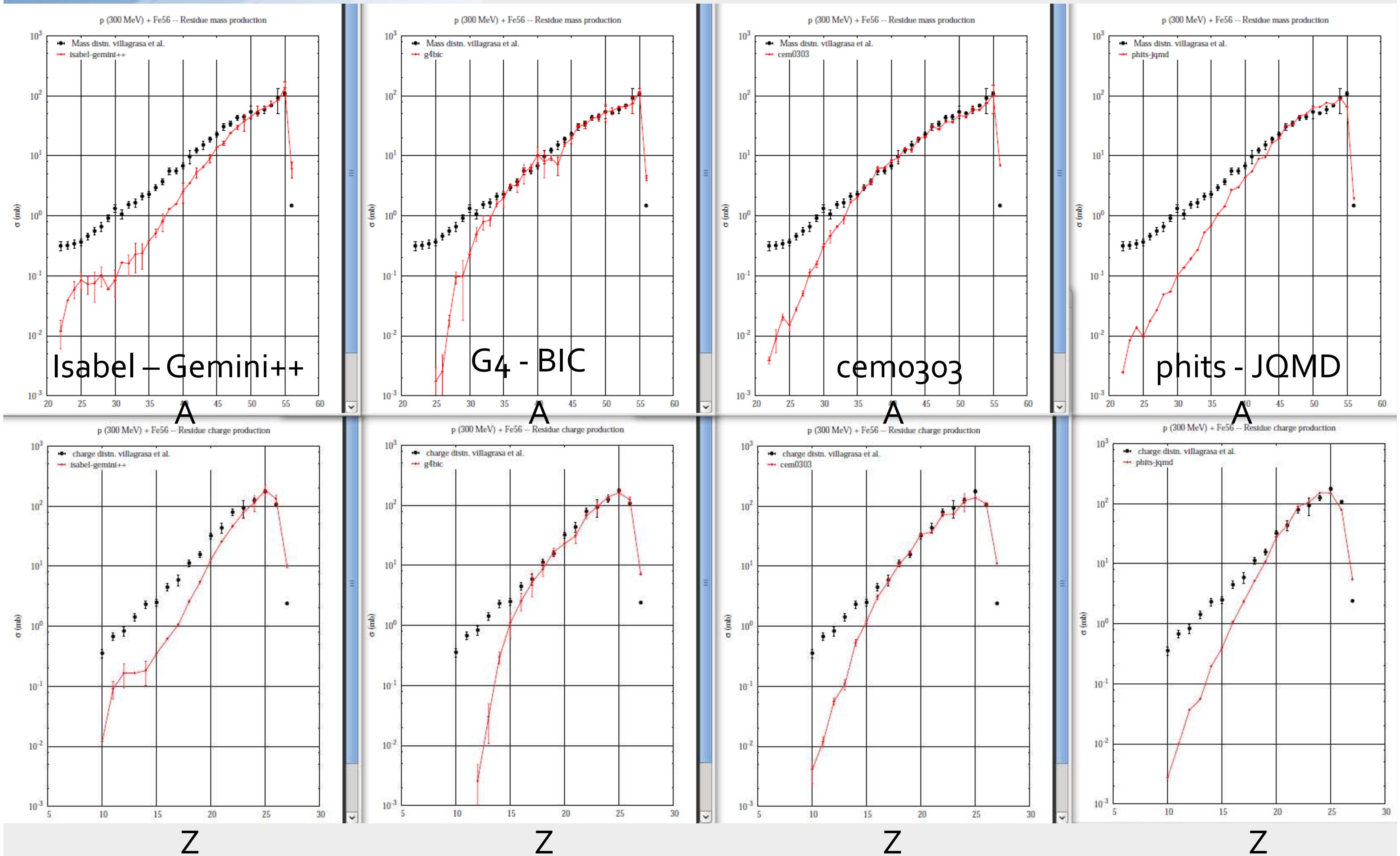

K
Fe
INCL45 – ABLA07
K
Fe
cem0303
K
Fe
phits - JQMD
Ne
Ar
Ne
Ar
K
Fe
G4-BIC

p (300MeV) + Fe



p (300 MeV) + Fe56 -- Residue mass production
Mass distn. villagrasa et al.
incl45-abla07
INCL45 – ABLA07
incl45-gemini++
INCL45 – Gemini++
incl45-smm
INCL45 - SMM
σ (mb)
Mass number (A)
A
charge distn. villagrasa et al.
Charge number (Z)
Z

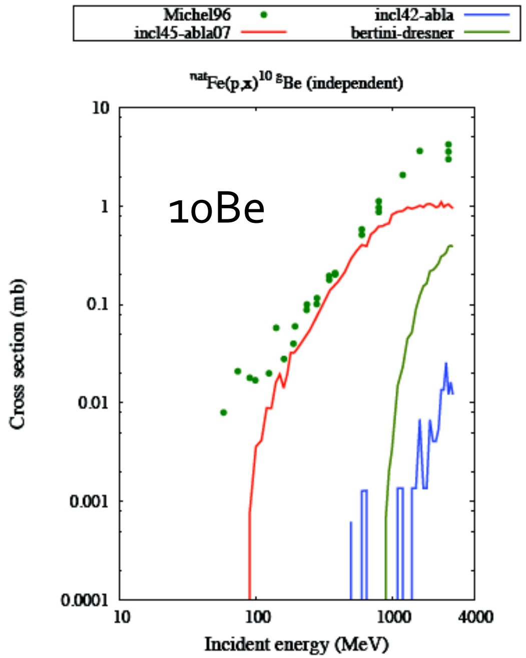
p (300MeV) + Fe

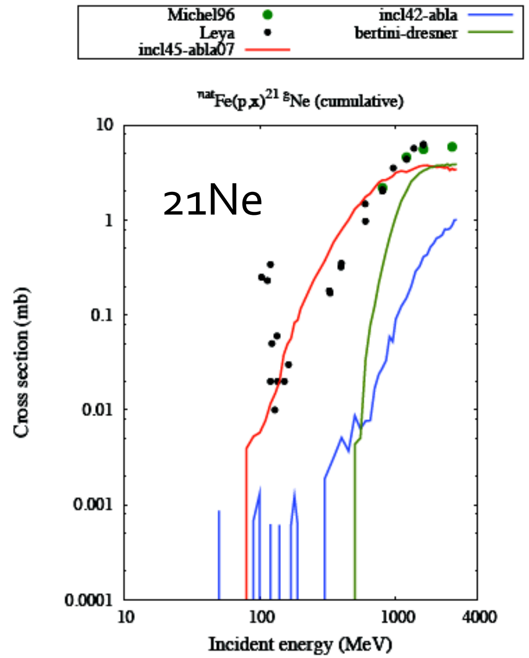


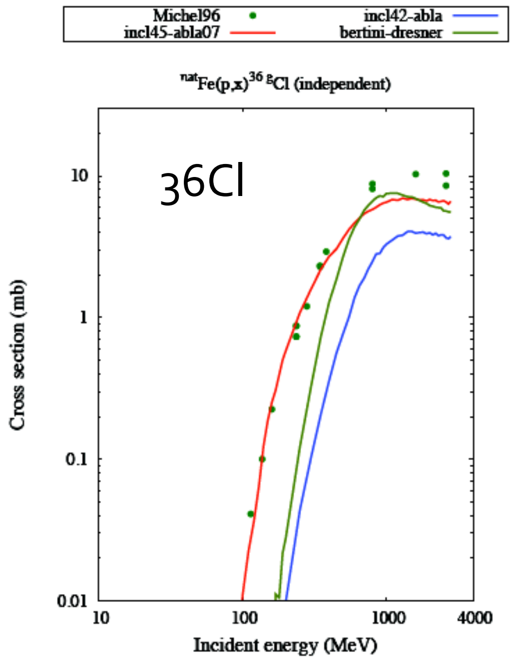
(Low energy IS also important in the GCR Spectra)

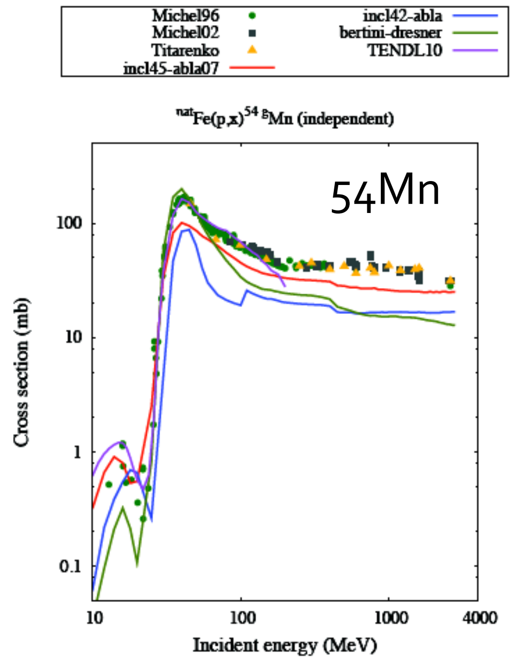
Excitation functions

p+Fe

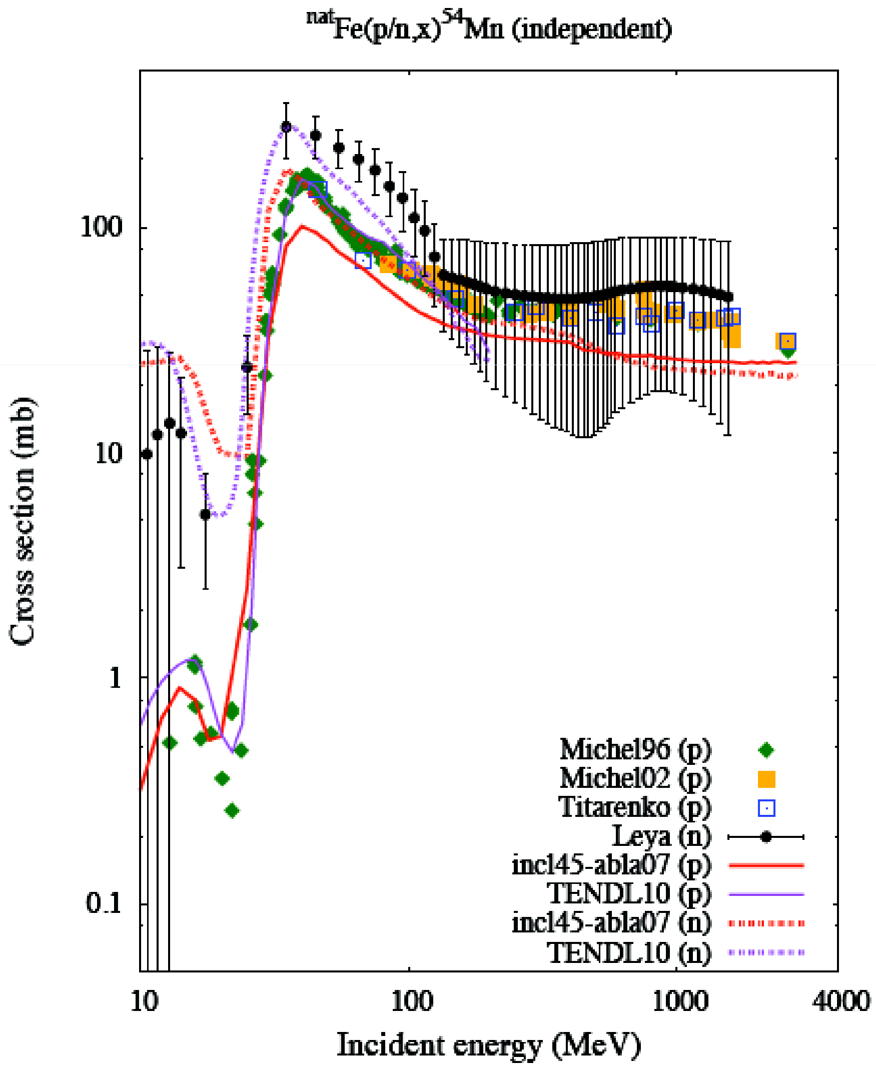




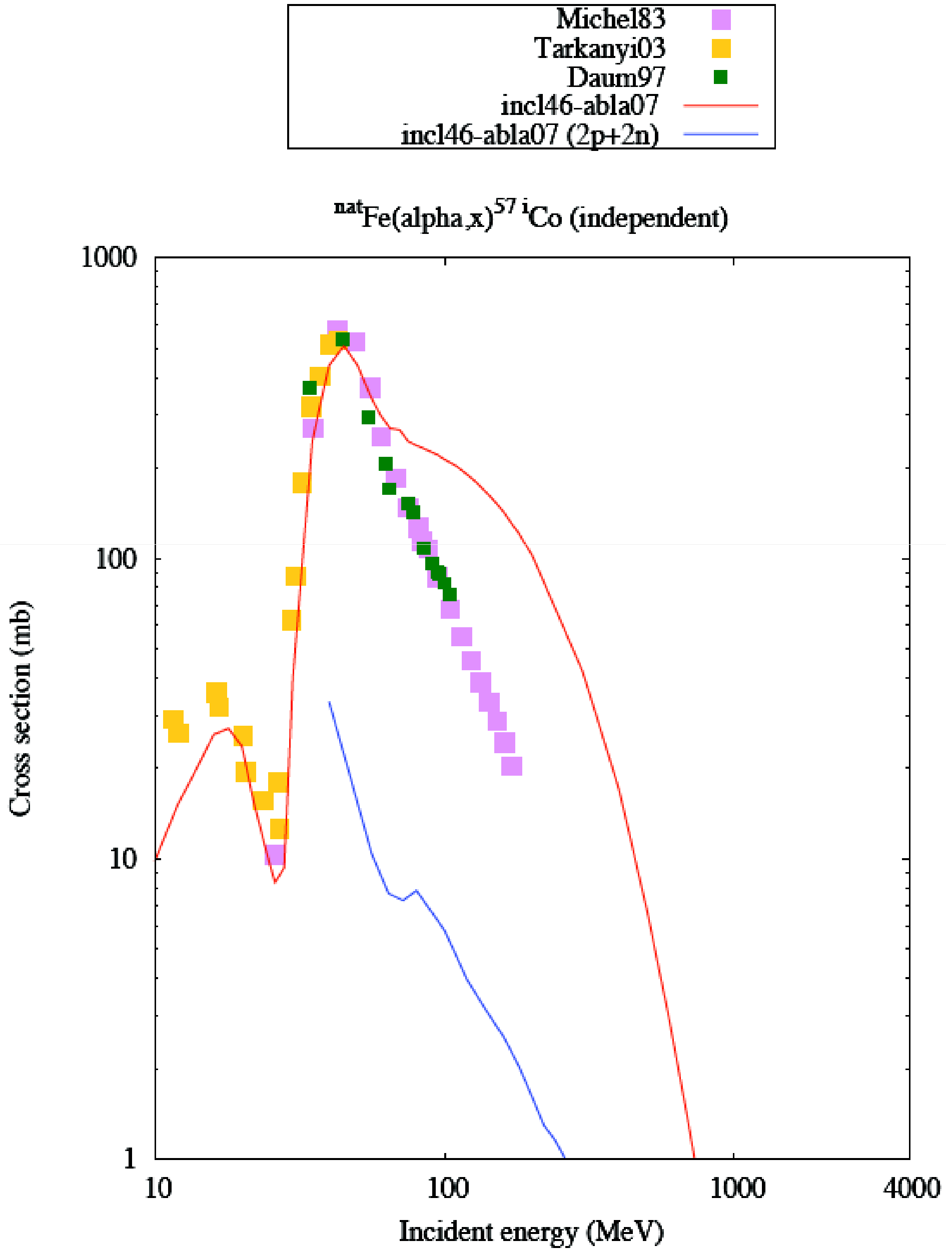




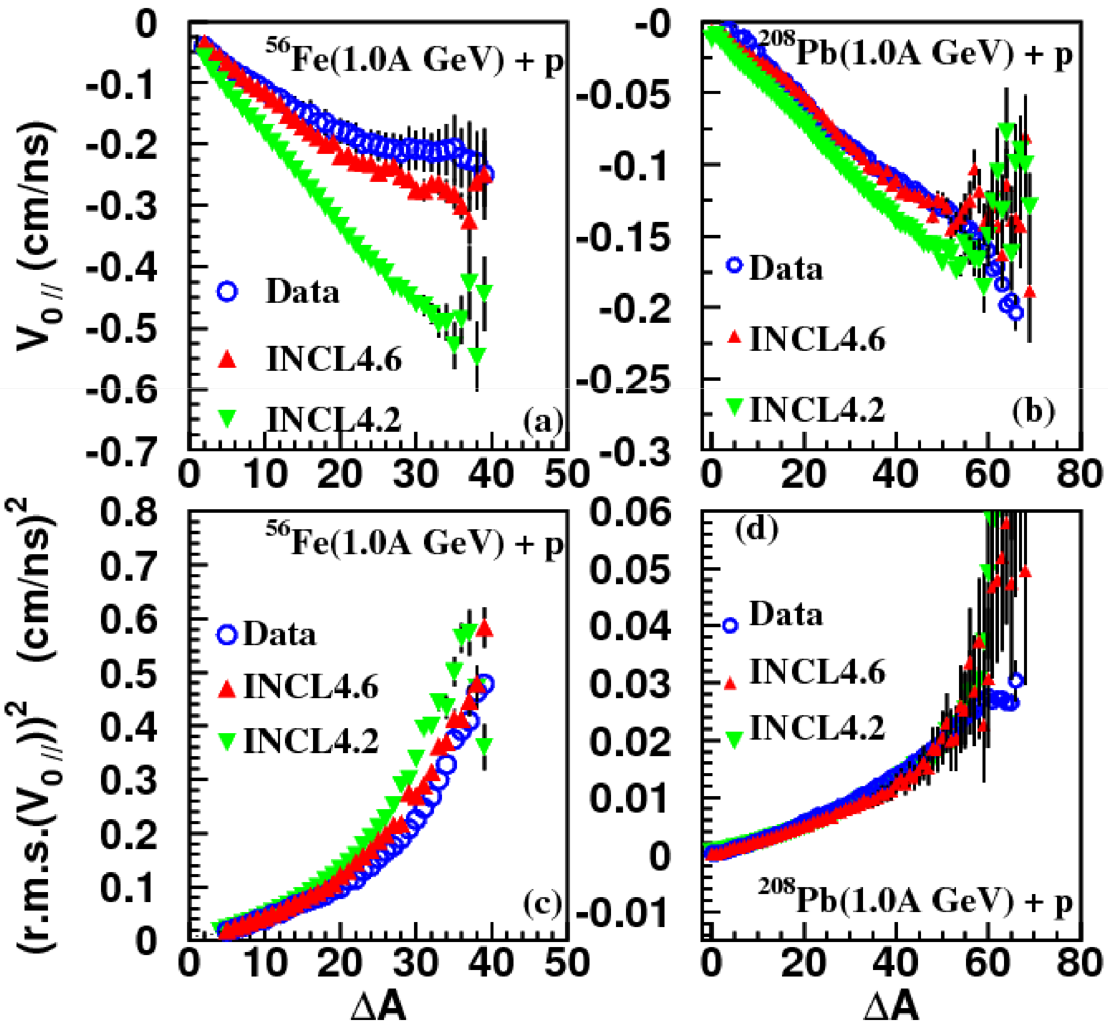
p+Fe is NOT n+Fe



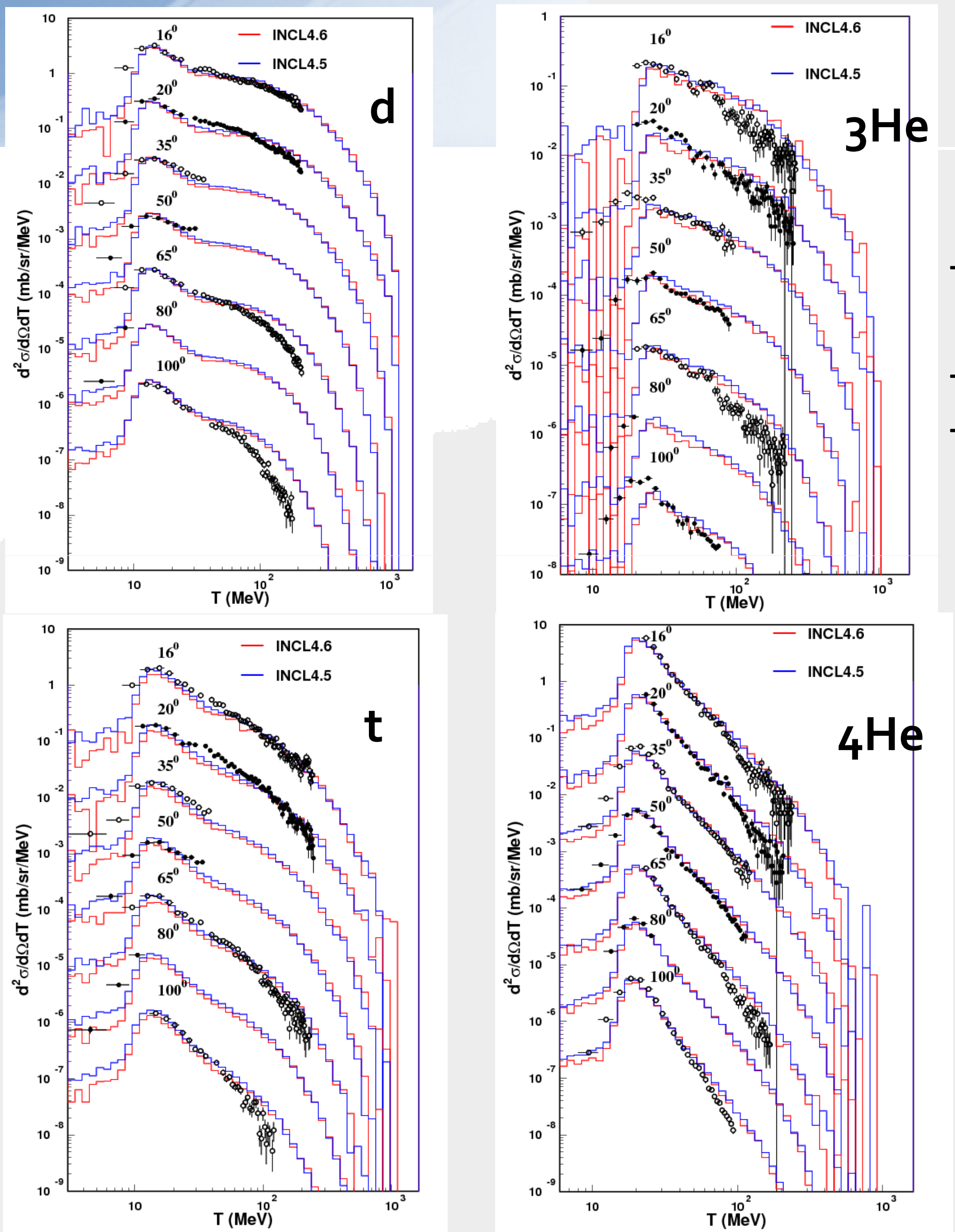
Alpha + Fe is NOT (2p+2n) + Fe



Fragment velocity distributions



Light cluster produced (high energy)



p (1.2 GeV)+Au

Data: Budzanowski et al. Phys. Rev. C80(2009) 54604

→Coalescence at the surface around emitted nucleons.

→Δr.Δp criteria and "more bound" selected.

→Phenomenology introduced (fixed one time for ever)

Calculations: INCL –ABLA07

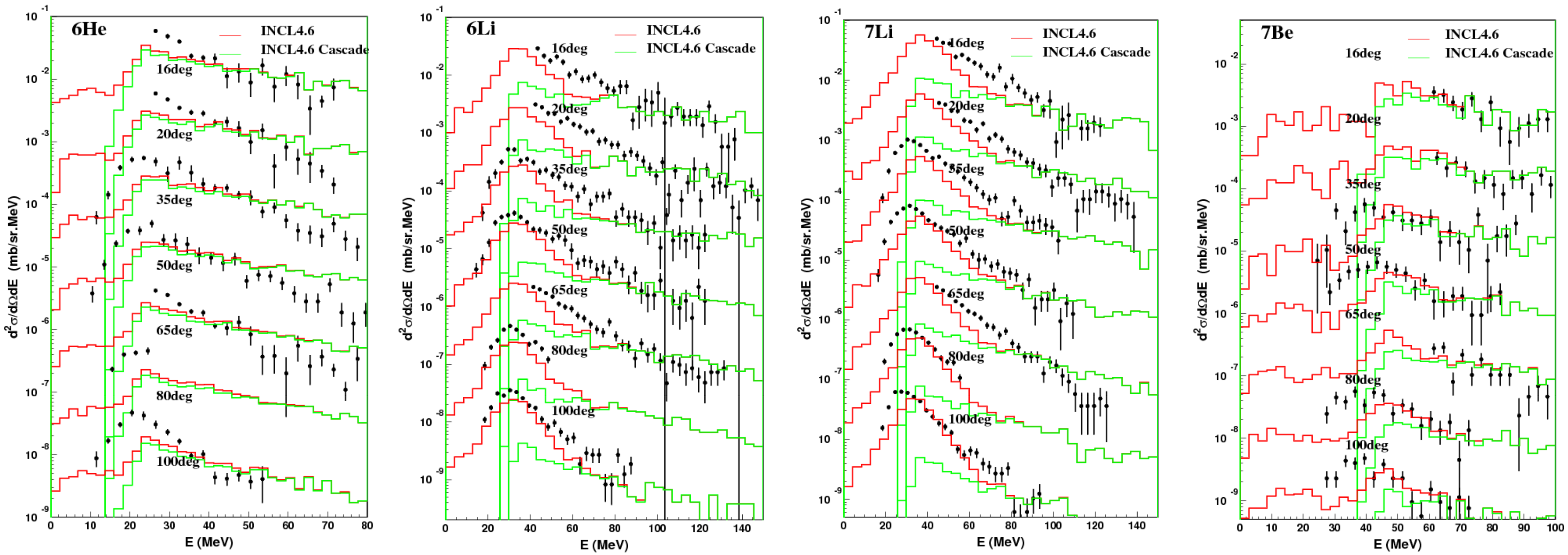
Calculations: INCL4.6 - ABLA07

Heavy clusters

(have been measured above evaporation)

p (1.2 GeV) + Au

Data: Herbach et al. Nucl. Phys. A765(2006)426



Coherent method in INCL (up to Amax=10) ; **reasonable but....**

→Slowly converging with Amax

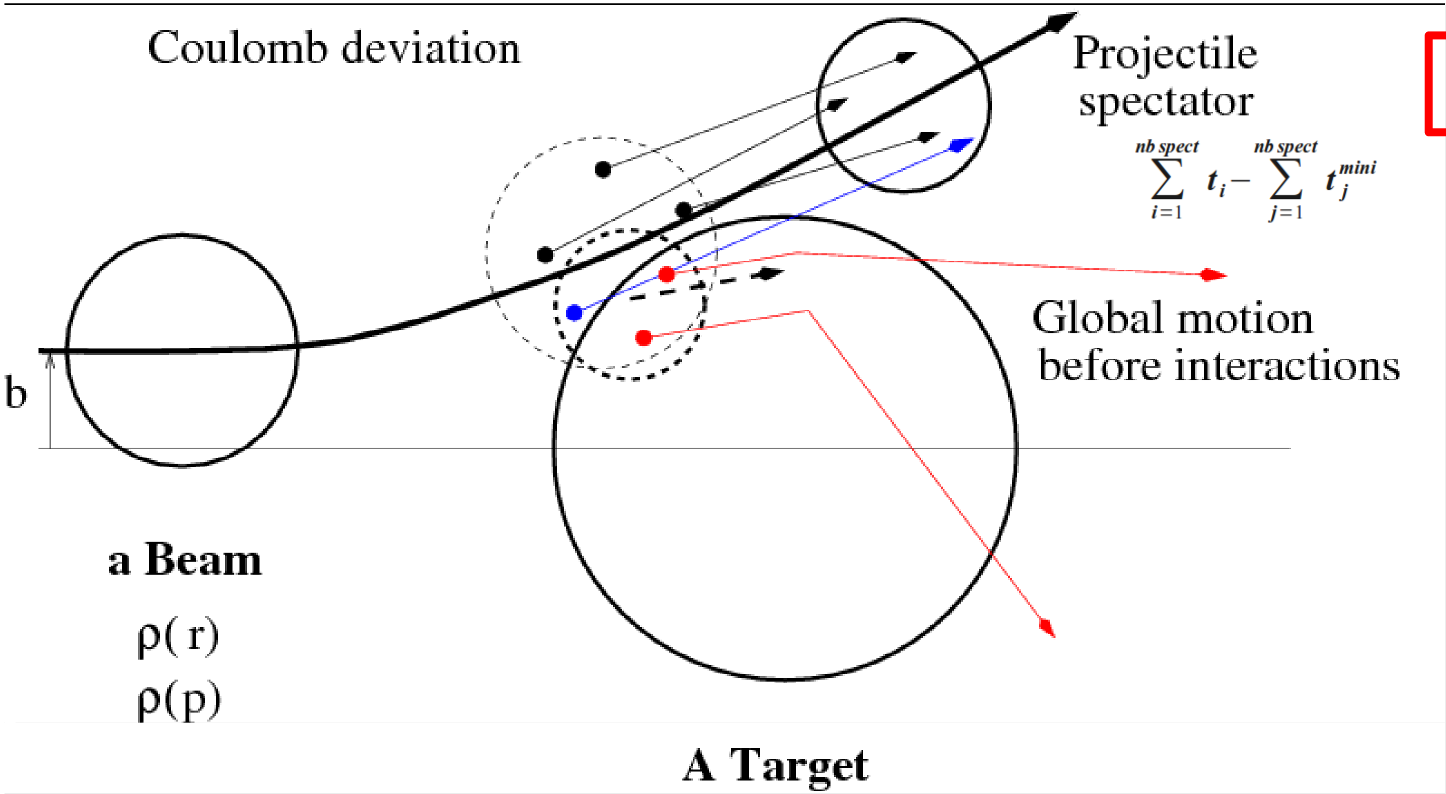
→Exciding computation time (due to exact combinatory) **Recently improved**

→Not steep enough with the cluster energy (more apparent at ~200 MeV)

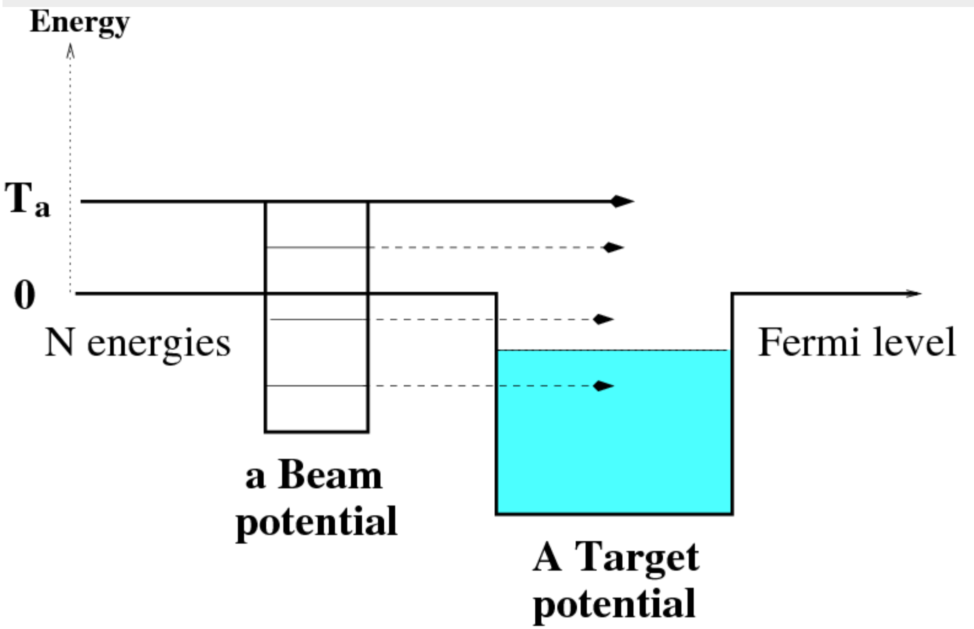
Work in progress !

a–A reactions

(a < 18)



Not symmetric!
(interaction region in the "target" only)

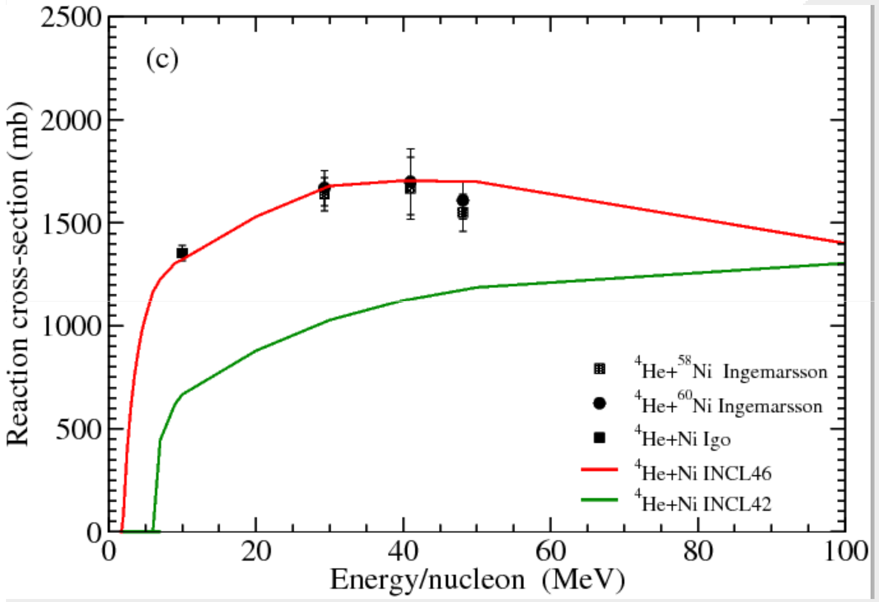


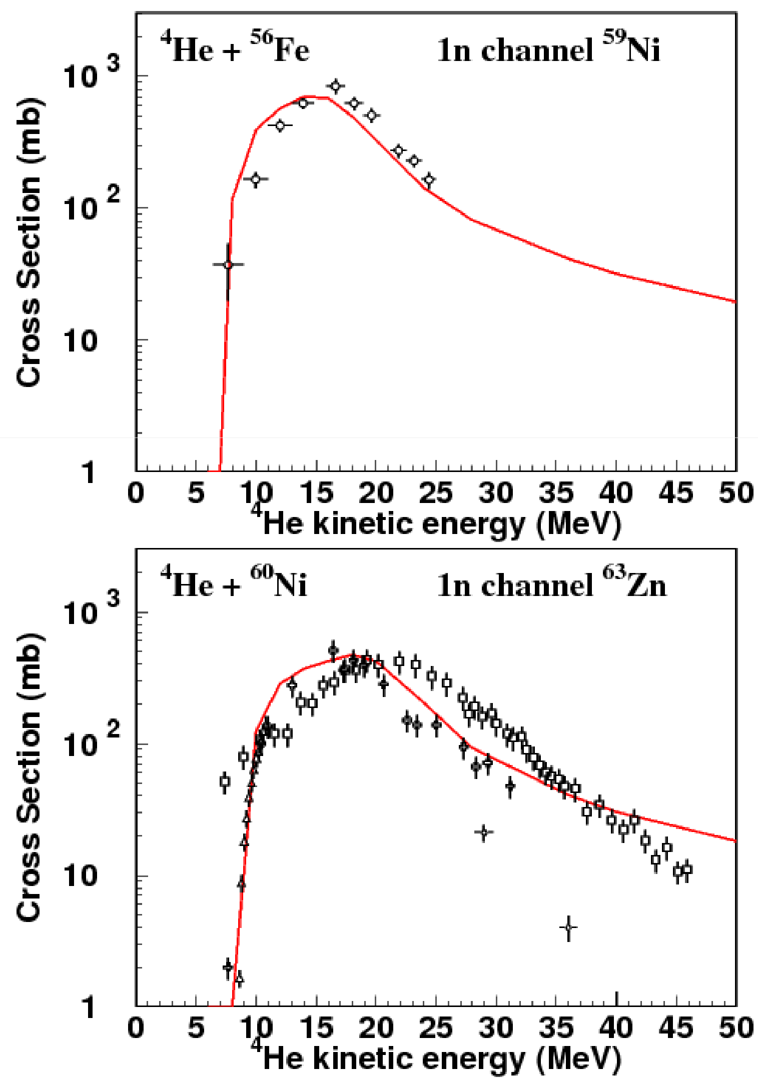
Low energy extension:

Compound nucleus with nucleons entering below the Fermi level.

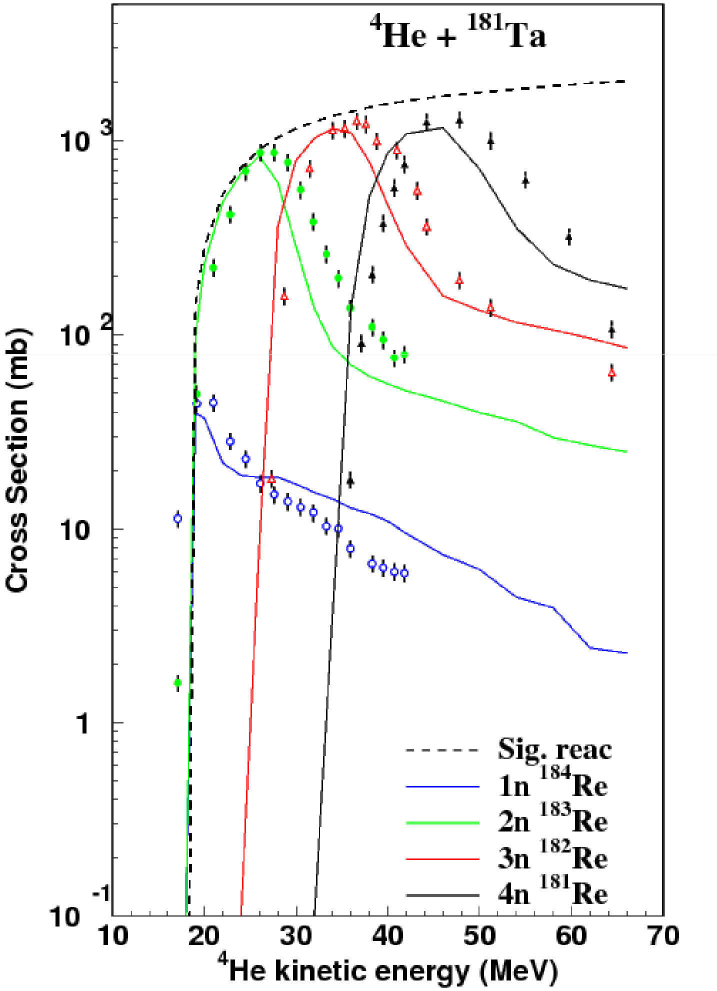
He - Nucleus

(some examples)

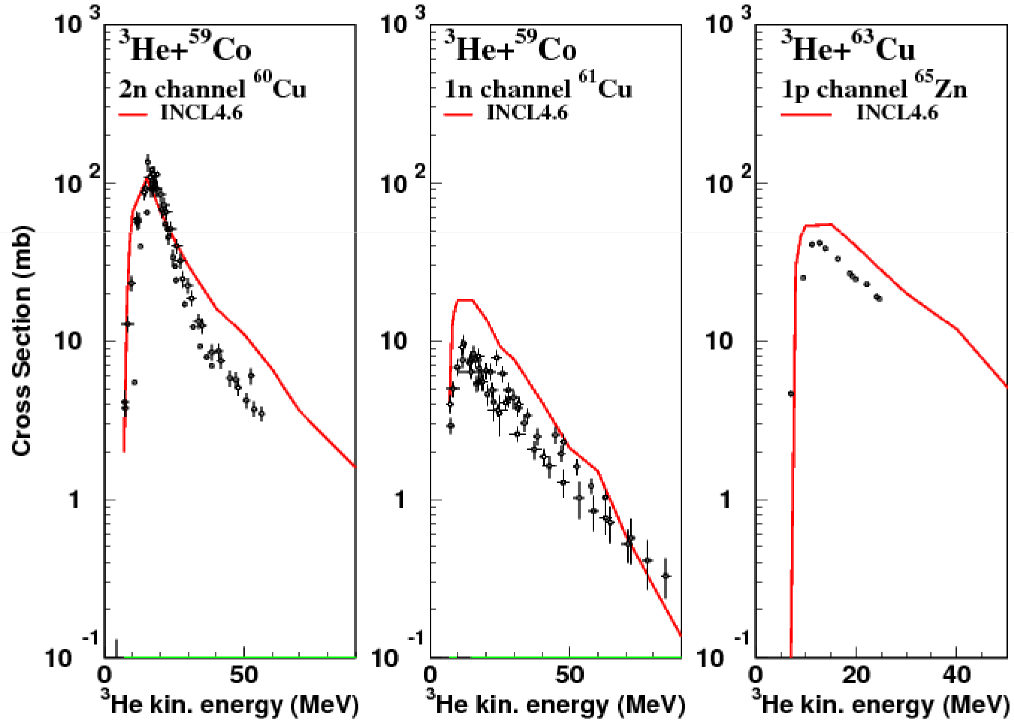




He - Nucleus

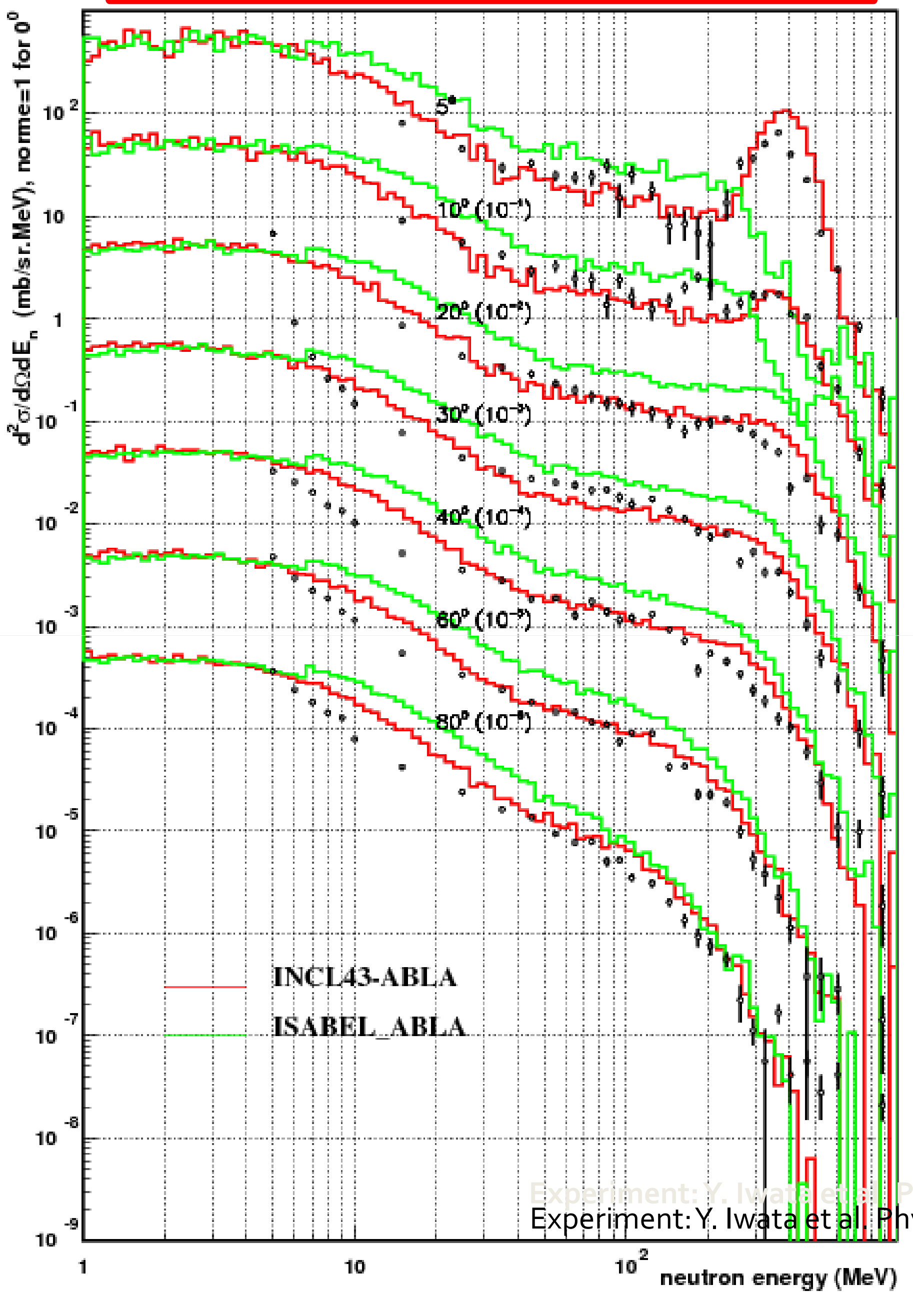


^{4}He + ^{181}Ta
Cross Section (mb)
^{4}He kinetic energy (MeV)
Sig. reac
1n ^{184}Re
2n ^{183}Re
3n ^{182}Re
4n ^{181}Re



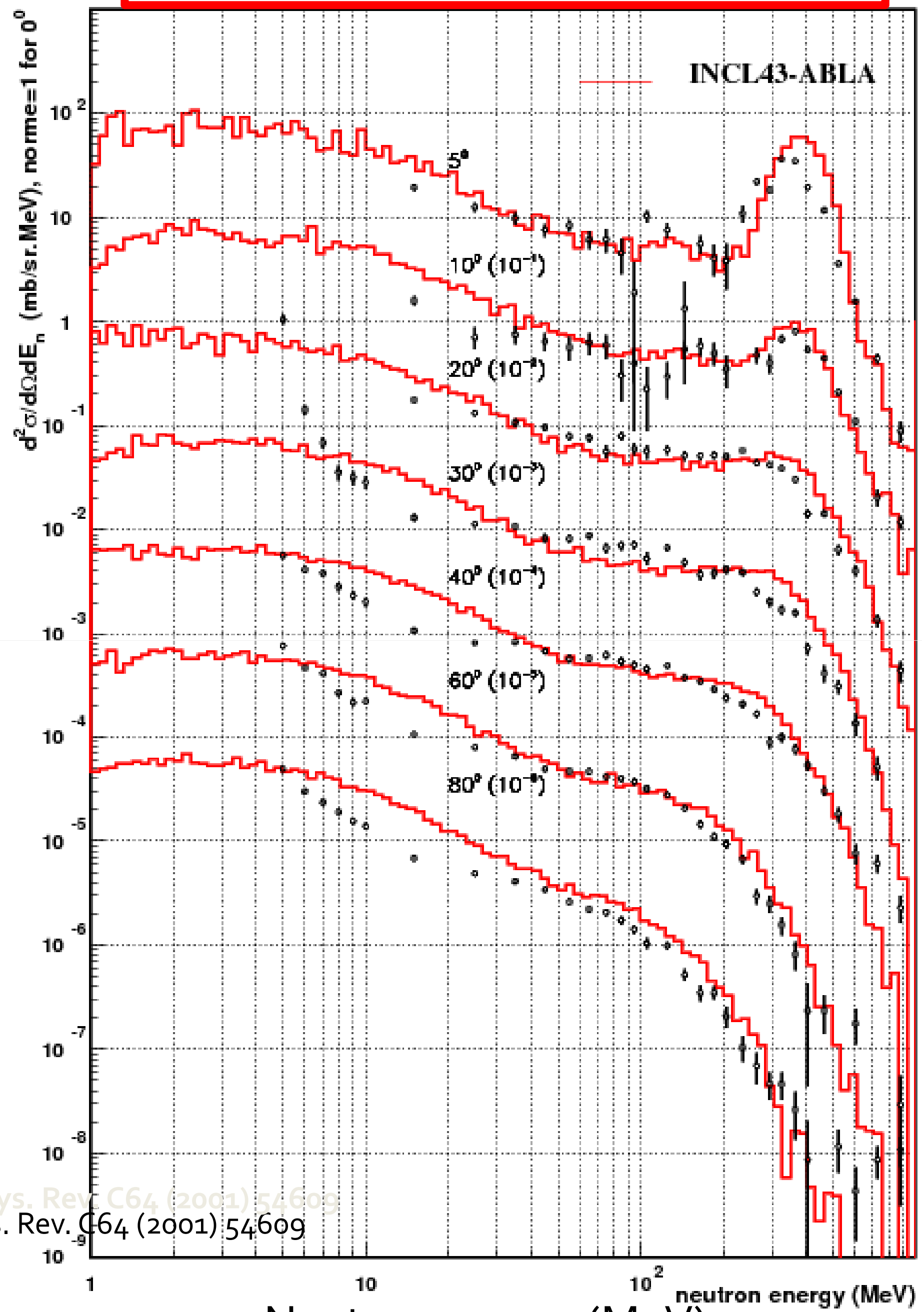
^{3}He+^{59}Co
2n channel ^{60}Cu
INCL4.6
^{3}He+^{59}Co
1n channel ^{61}Cu
INCL4.6
^{3}He+^{63}Cu
1p channel ^{65}Zn
INCL4.6
Cross Section (mb)
^{3}He kin. energy (MeV)

0.4 A GeV 12C + Pb -> neutrons



Neutron energy (MeV)

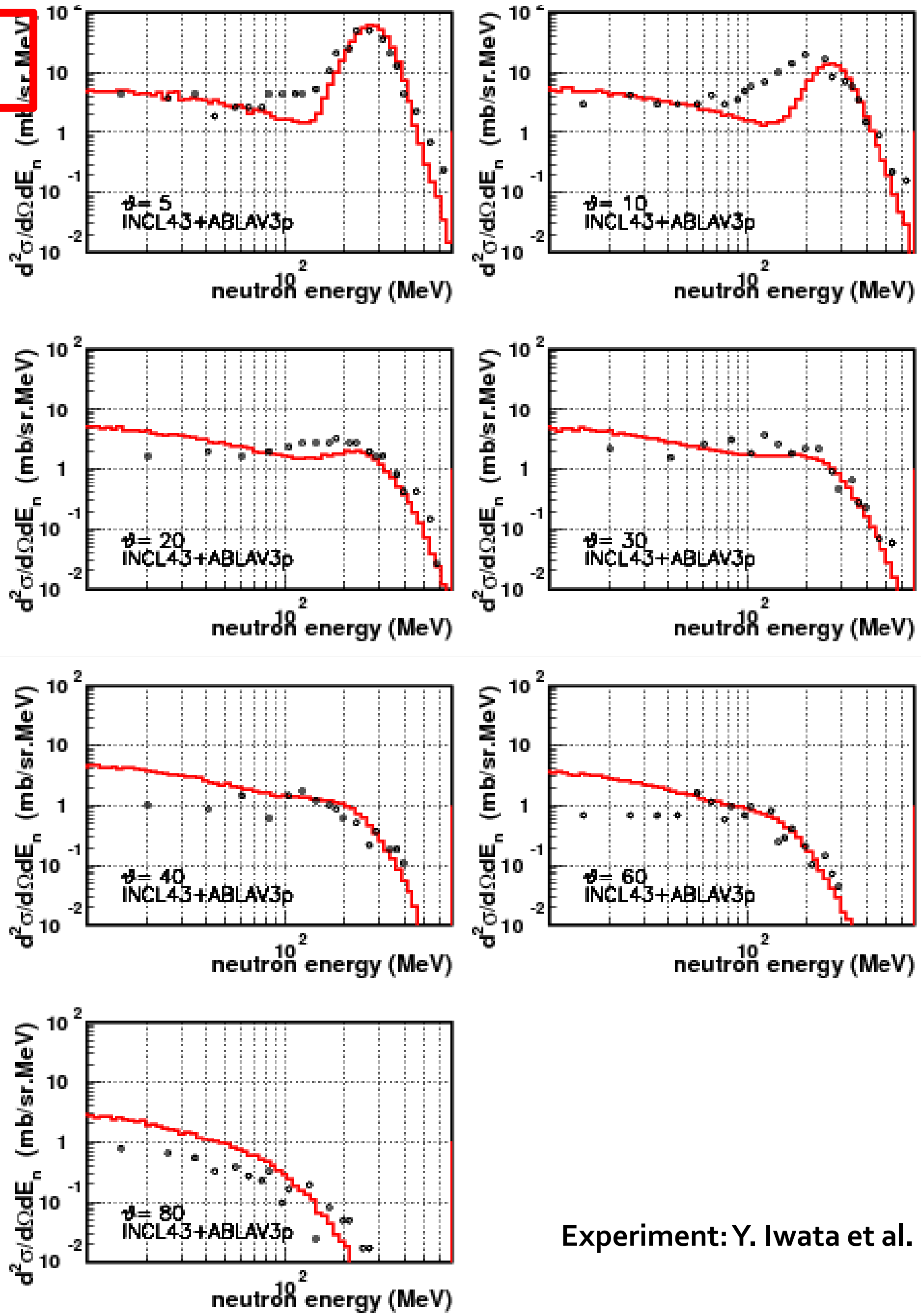
0.4 A GeV 12C + Cu -> neutrons



Neutron energy (MeV)

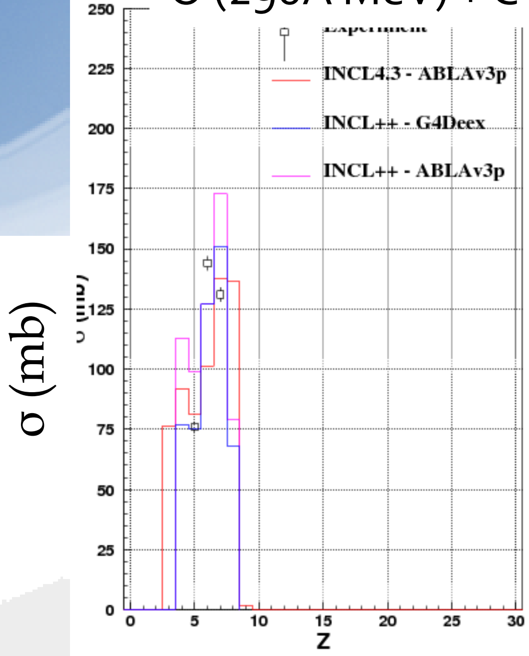
Experiment: Y. Iwata et al. Phys. Rev. C64 (2001) 54609

290A MeV C+C

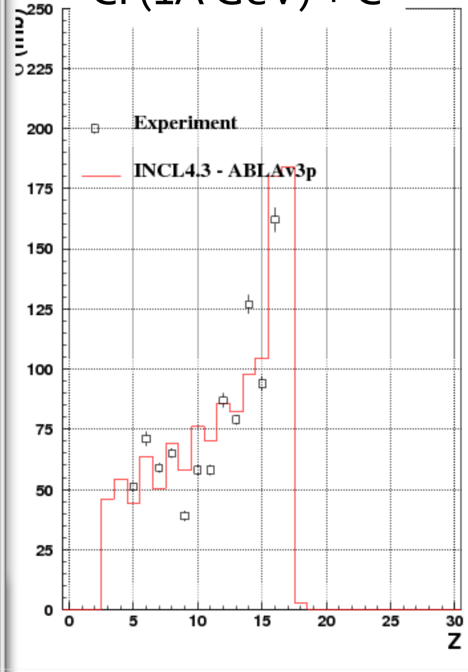


Experiment: Y. Iwata et al. Phys. Rev. C64 (2001) 54609

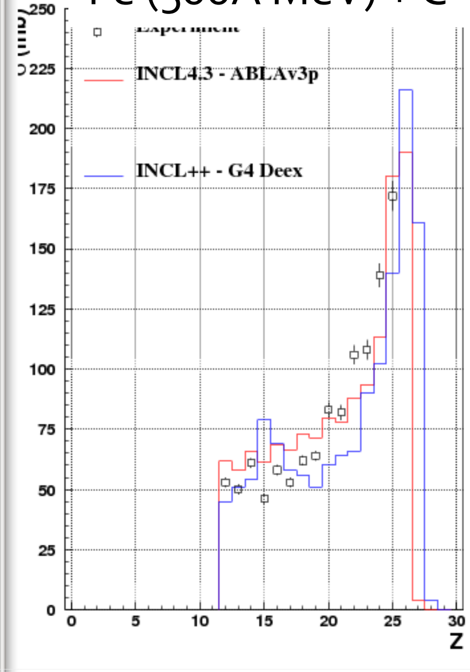
O (290A MeV) + C



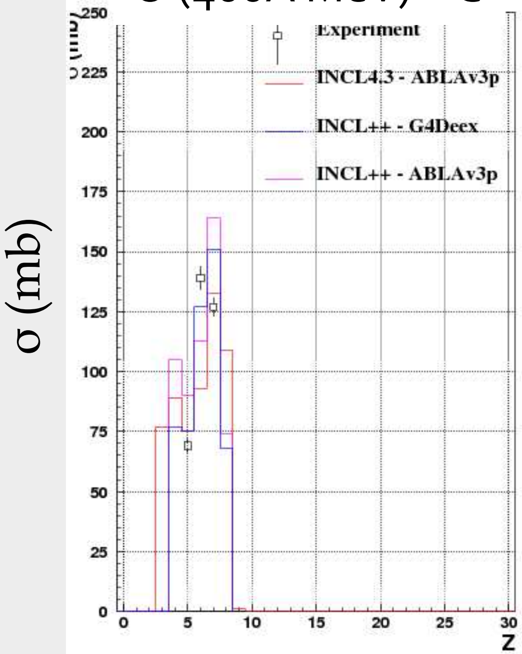
Cl (1A GeV) + C



Fe (500A MeV) + C



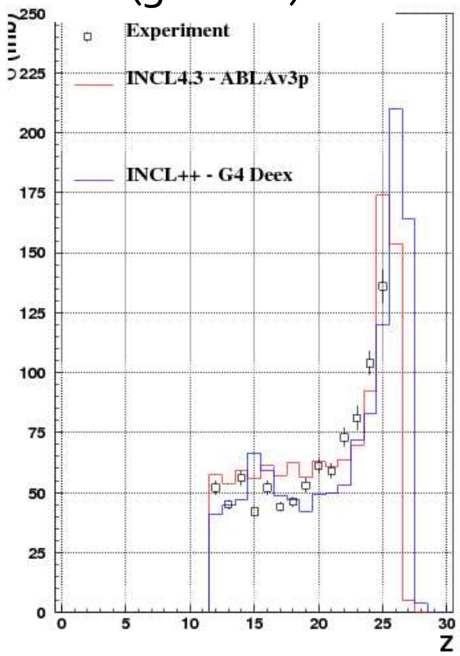
O (400A MeV) + C



Beam fragmentation on C targets

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

Fe (3A GeV) + C

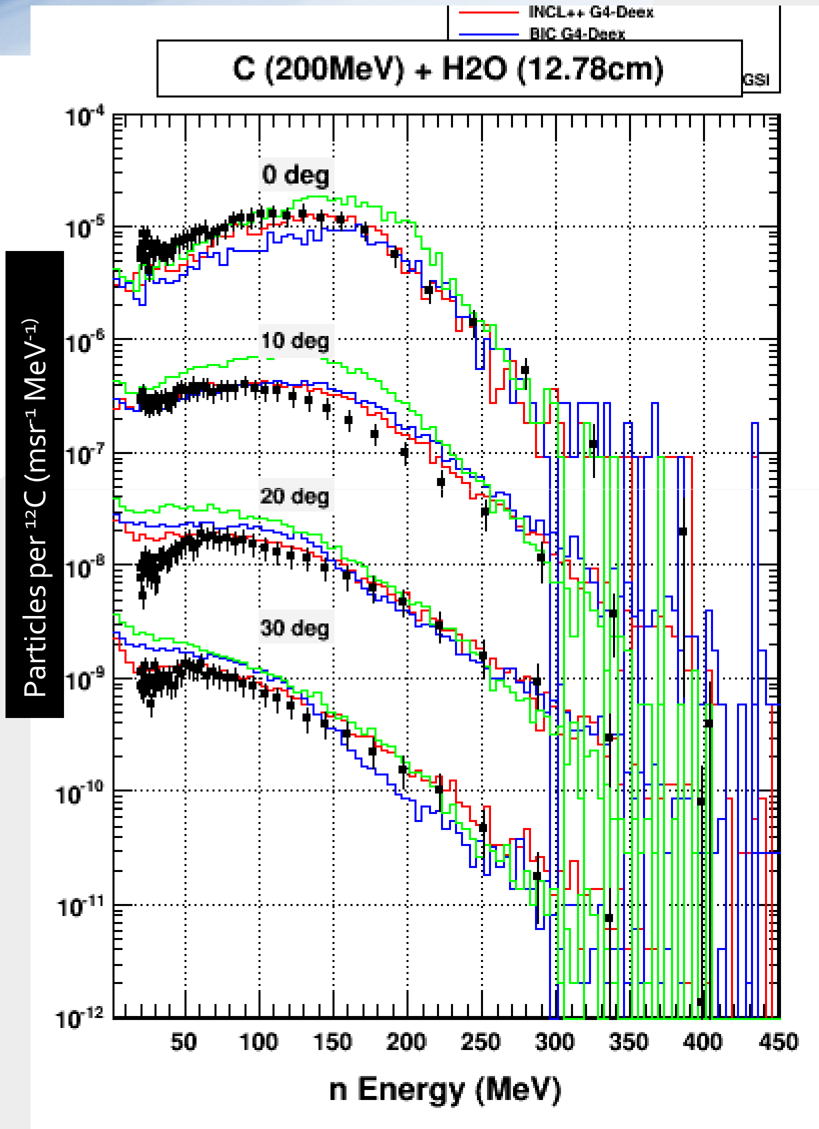


Experiment (GSI): ^{12}C (200A MeV) stopped in 12.78cm H2O

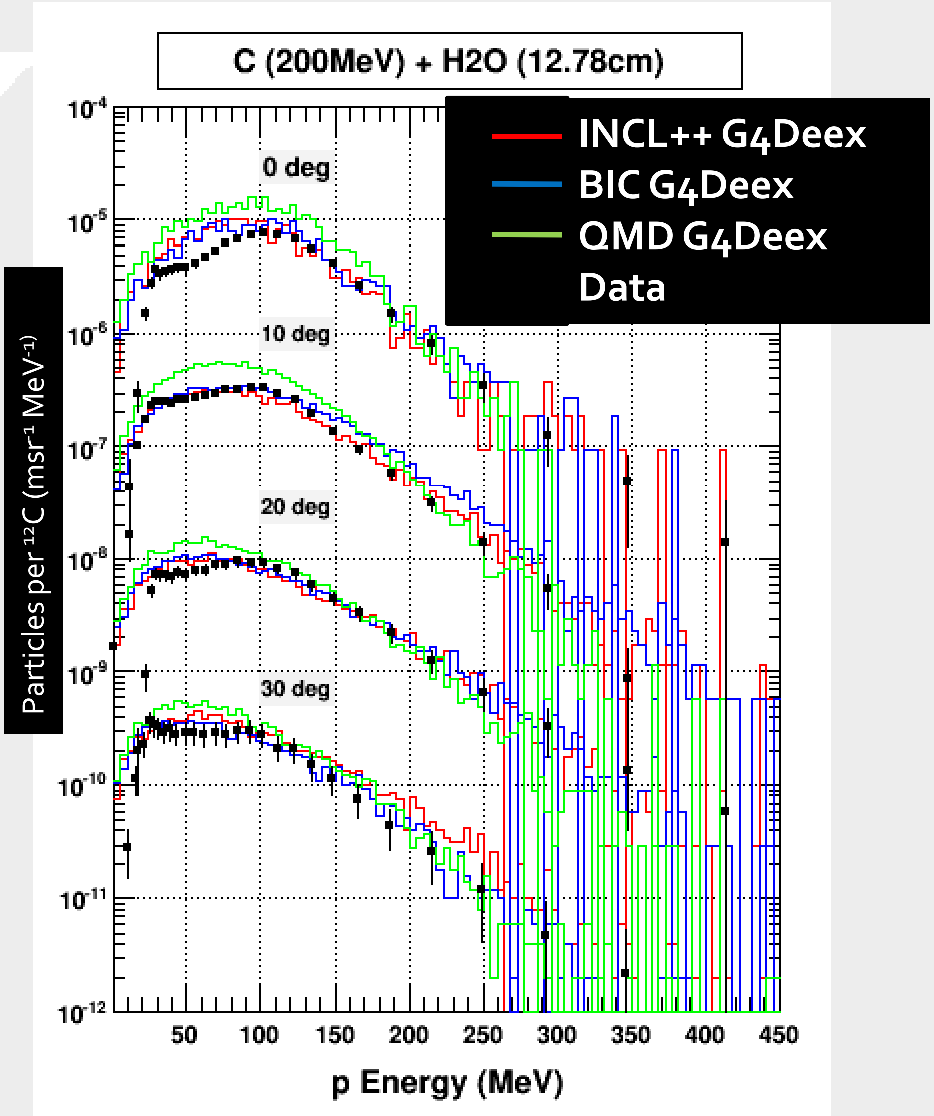
K. Gunzert-Marx et al. New Journal of Physics 10 (2008) 075003, GSI

Calculations: INCL++, BIC and QMD in Geant4

B. Brown



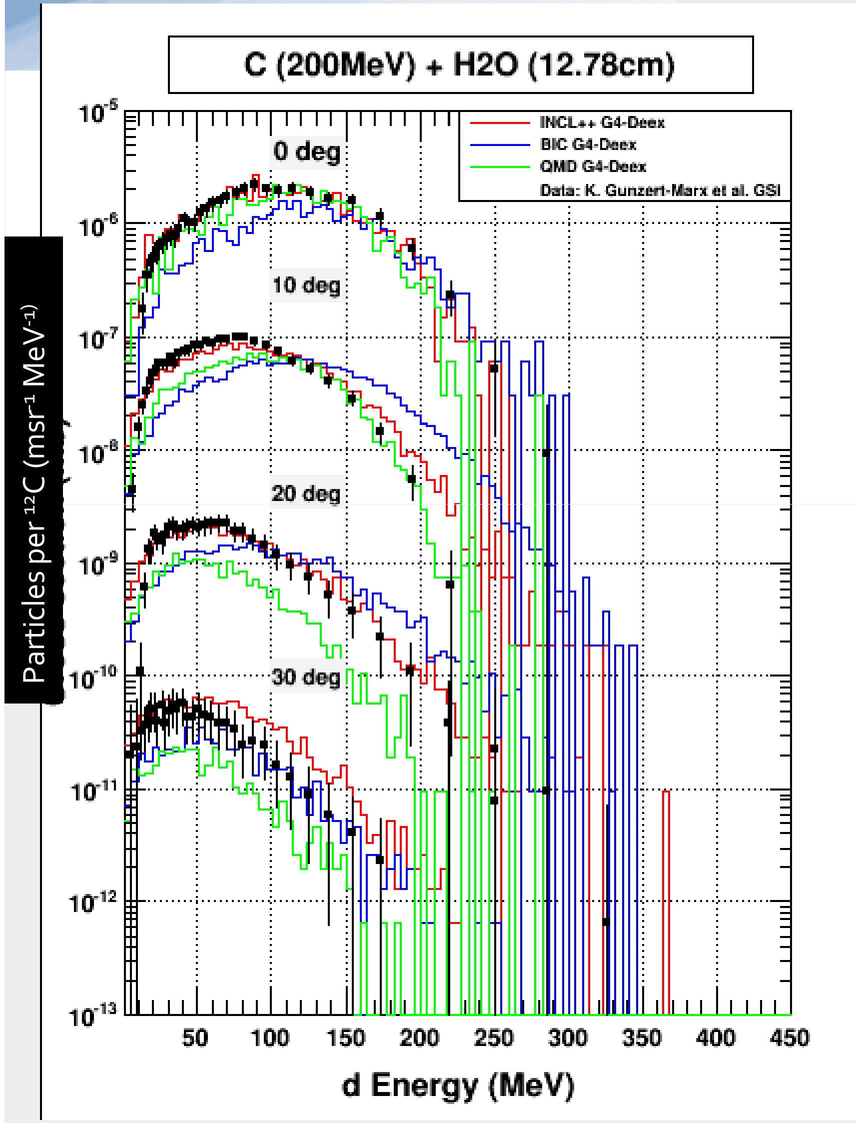
Neutrons



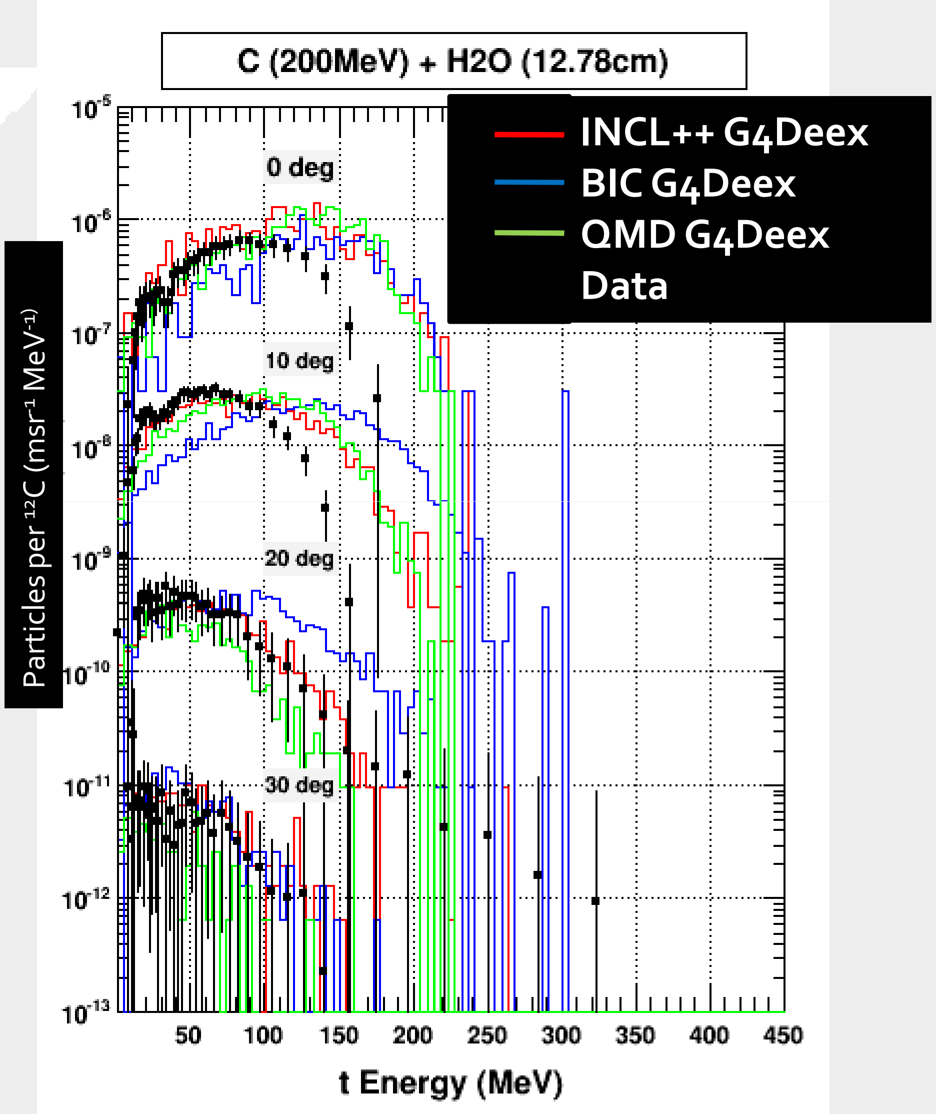
Protons

Calculations: INCL++, BIC and QMD in Geant4

All calculations divided by 3 ???



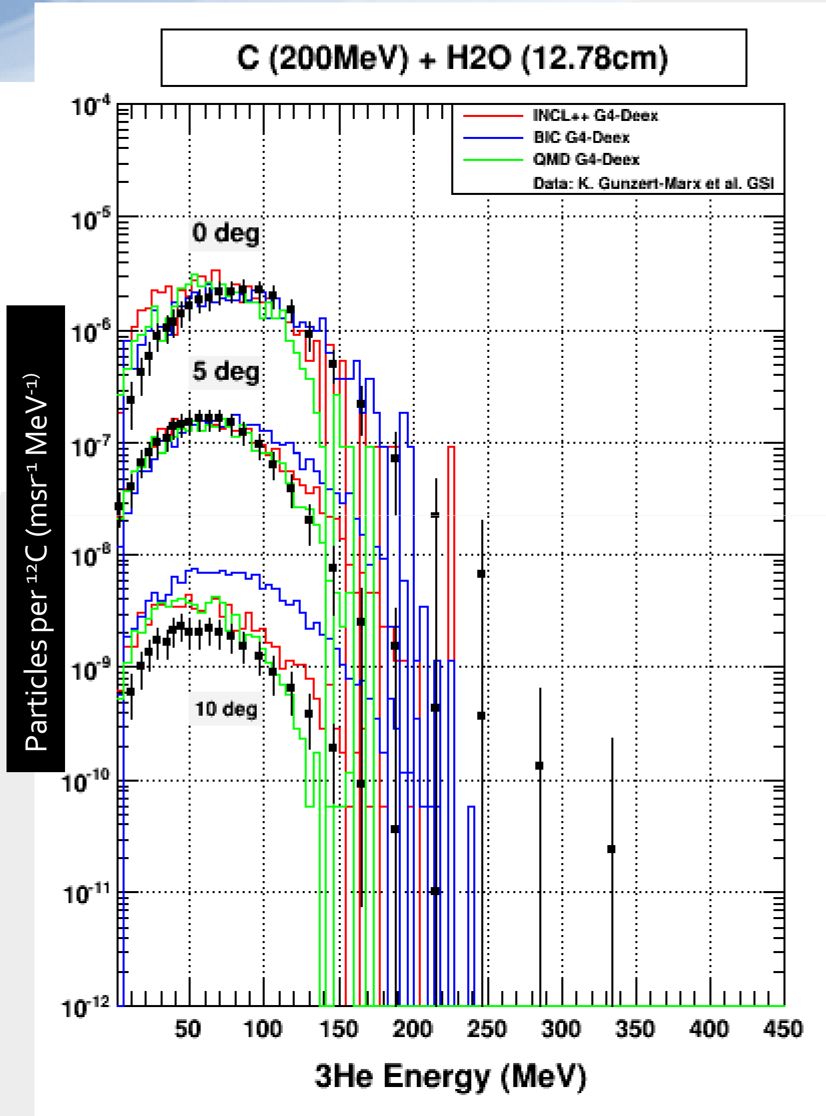
Deuterons



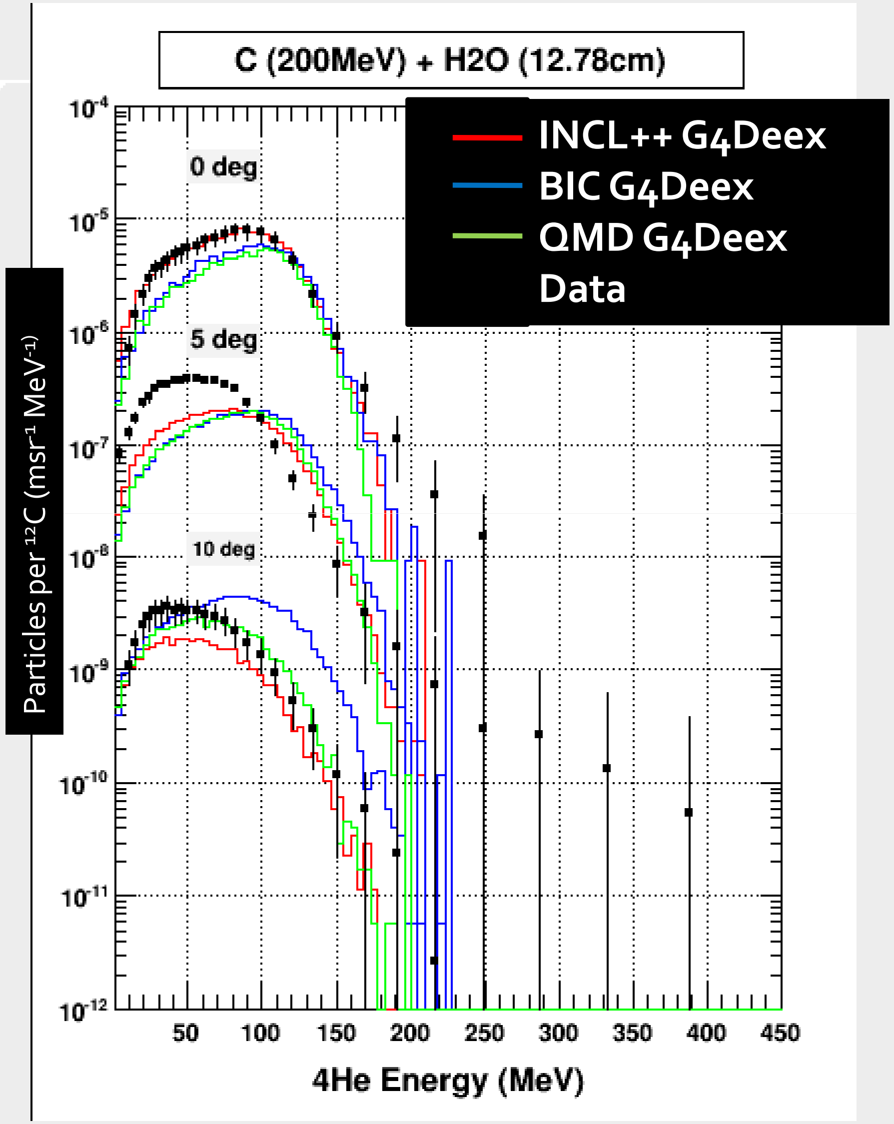
Tritons

Calculations: INCL++, BIC and QMD in Geant4

All calculations **for 4He** divided by 10 ??????



3He



4He

High energy extension

Future

S. Pedoux PhD. Liège 9/2011
S. Pedoux J. Cugnon, Nucl Phys A866(2011)16

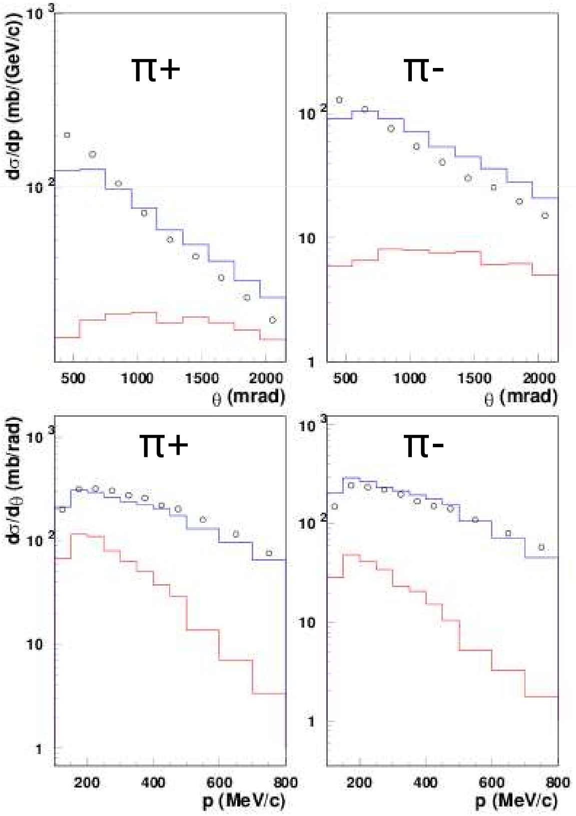
Multi-pion channels added:

πN -> xπ N x≤4
NN -> NN xπ

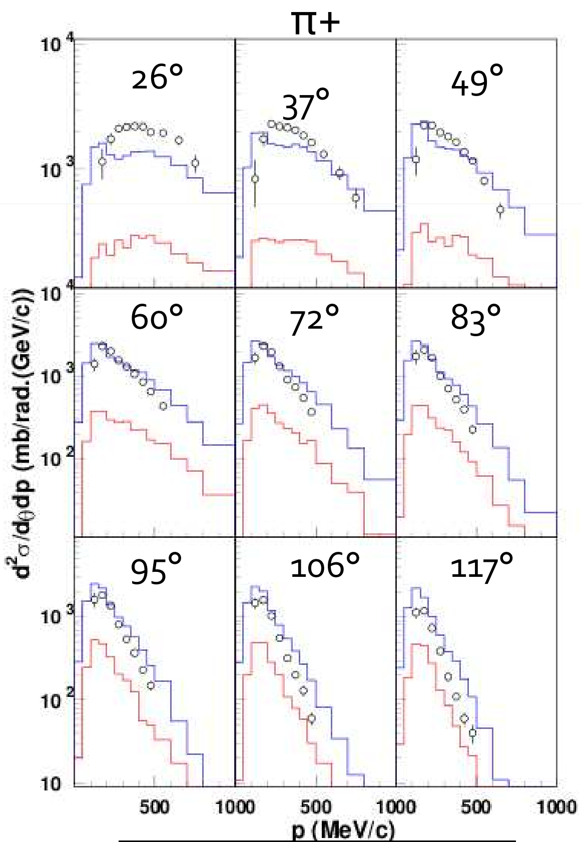
New calc; **BLUE LINE**
(INCL4.2 red line)

Tested on HARP data (p, π+,π- 3 GeV/c to 12 GeV/c on C…Pb)

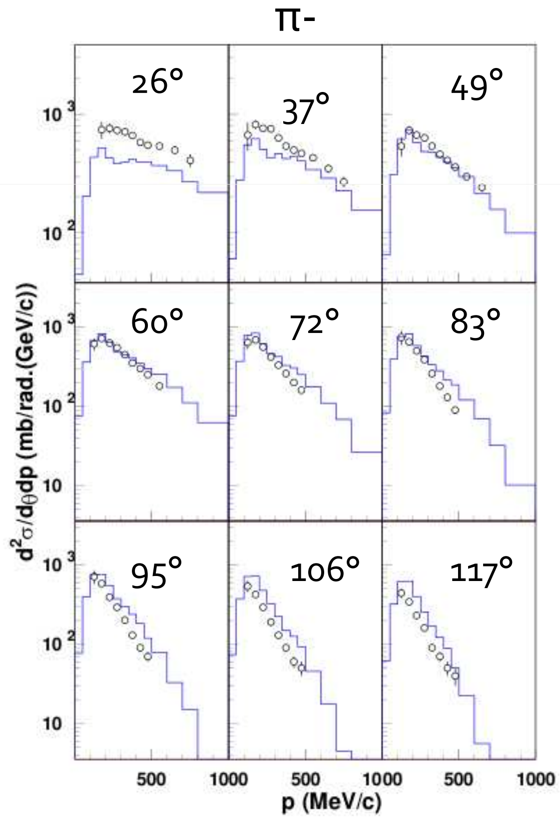
M.G.Catanesi et al P.R.C77(2008)55207; M.Apollonio et al P.R.C80(2009)65207;M.G. Catanesi Eur.Pgys. J C53(2008) 177;C54(2008)37



p(12 GeV/c) + C



(c) p(8 GeV/c) + Pb



(b) π+(5 GeV/c) + Cu

Conclusions (1)

Alain Boudard (CEA/Irfu/SPhN)
Alain.Boudard@cea.fr

Good spallation codes (INC+De-excitation) are available

Domain: π to ~O beams; 20 MeV to 2 GeV
~C to U targets
(A on A for QMD but very long and not so good p-Fe; p-Pb (IAEA)
light targets (He – B) to be tested

Components (INC and De-excitation) can be compared – tested (IAEA Bentch)

Events generators ⟶ All fluctuations, all correlations

Realistic and precise cross sections and dynamics (energy, momentum)
.... but locally wrong may be by fact 2 -5 possibly 10

One of the best and most complete: INCL coupled with ABRA07, Gemini++ or G4 Deex

- Extended down to very low energies (~thresholds)
- Extension to ~15 GeV in 2013
- Available in GEANT4, PHITS, MCNPX,

Conclusions (2)

Alain Boudard (CEA/Irfu/SPhN)
Alain.Boudard@cea.fr

Technical questions (INCL):

INCL4.6 (Fortran)

INCL++5 (C++) →

- In GEANT4
- The most advanced version
- Priority for the future

Thin targets (no transport): → Available coupled with several de-excitations (ABLA07, Gemini++, GEM, SMM, Dresner)

With transport: → Language: Fortran or C++ ?
Limited deexcitations

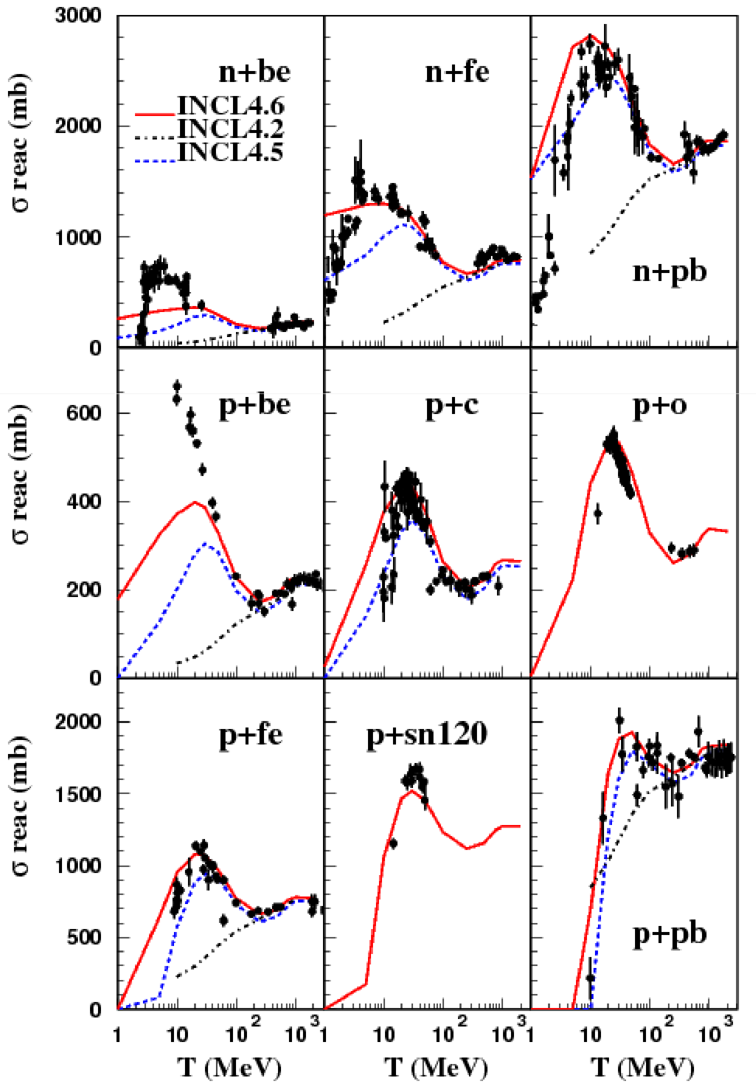
Future: →

- High energy (for sure) 2013
- More symmetry in A-A
- Strangeness physics (K-Λ channels)
- Possibly anti-p beams

INCL Developed by J. Cugnon, S. Leray, J.C. David, D. Mancusi, (A.B.)
ABLA Developed by K.H. Schmidt, A. Kelic, M.V. Ricciardi (J. Benlliure)

Many thanks to them.

Reaction cross sections improved at low energy



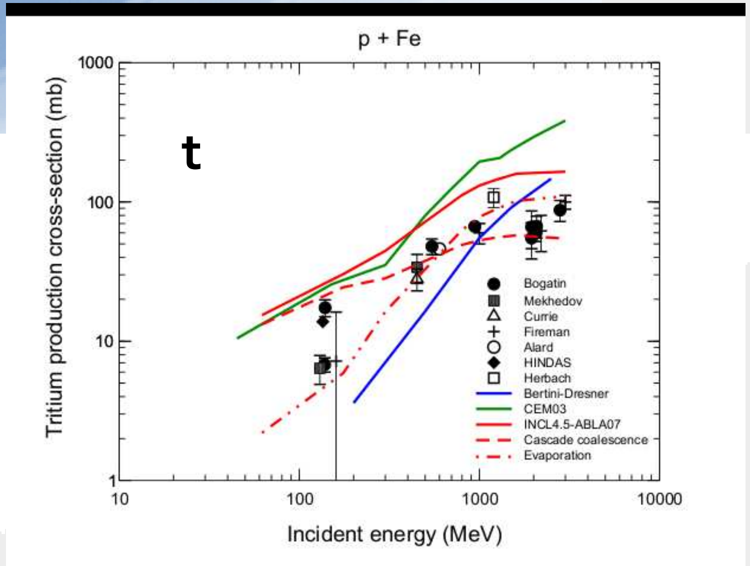
Confidence in the model (INC)

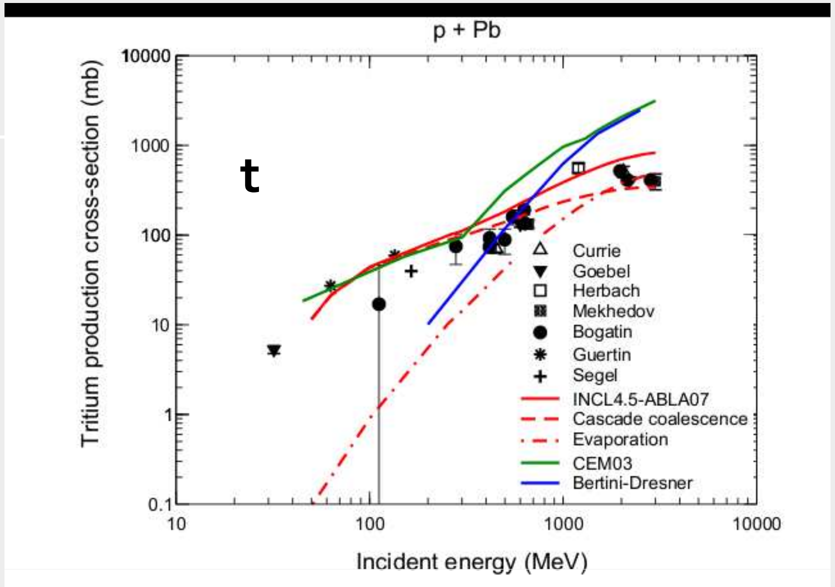
…But not strictly needed in transport codes

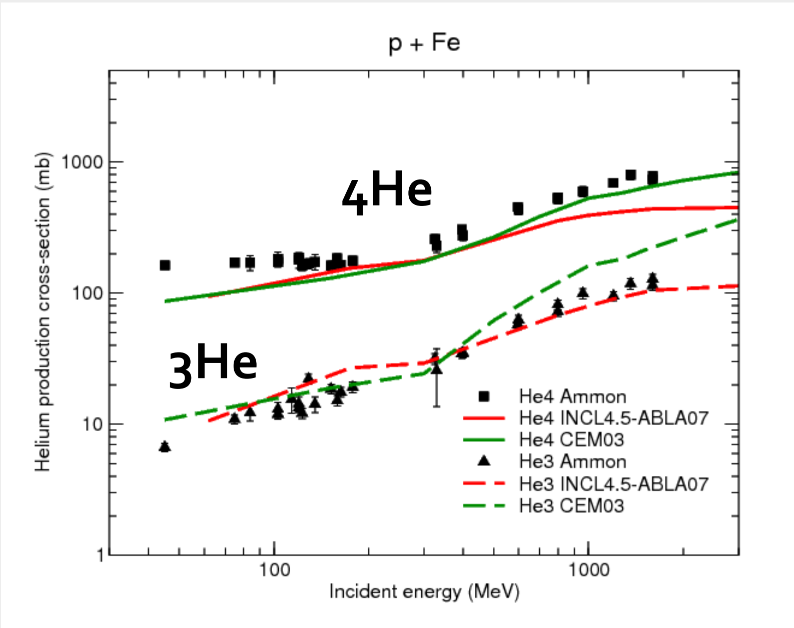
Still some difficulties with very light targets

Data: Prael and Chadwick, LANL 1997
Barashenkov, Dubna 1993
Carlson ADNDT 1996

He and t production (applications)







From S. Leray et al.N.I.M. B268(2010)581

Additional (cascade de-excitation contributions)