Physics performances and benchmarking of INCL++

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17th Geant4 Collaboration meeting, Chartres 10-14 September 2012.

Introduction - reminders

Physics: π, p, n, d…..α on nuclei 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 ……)

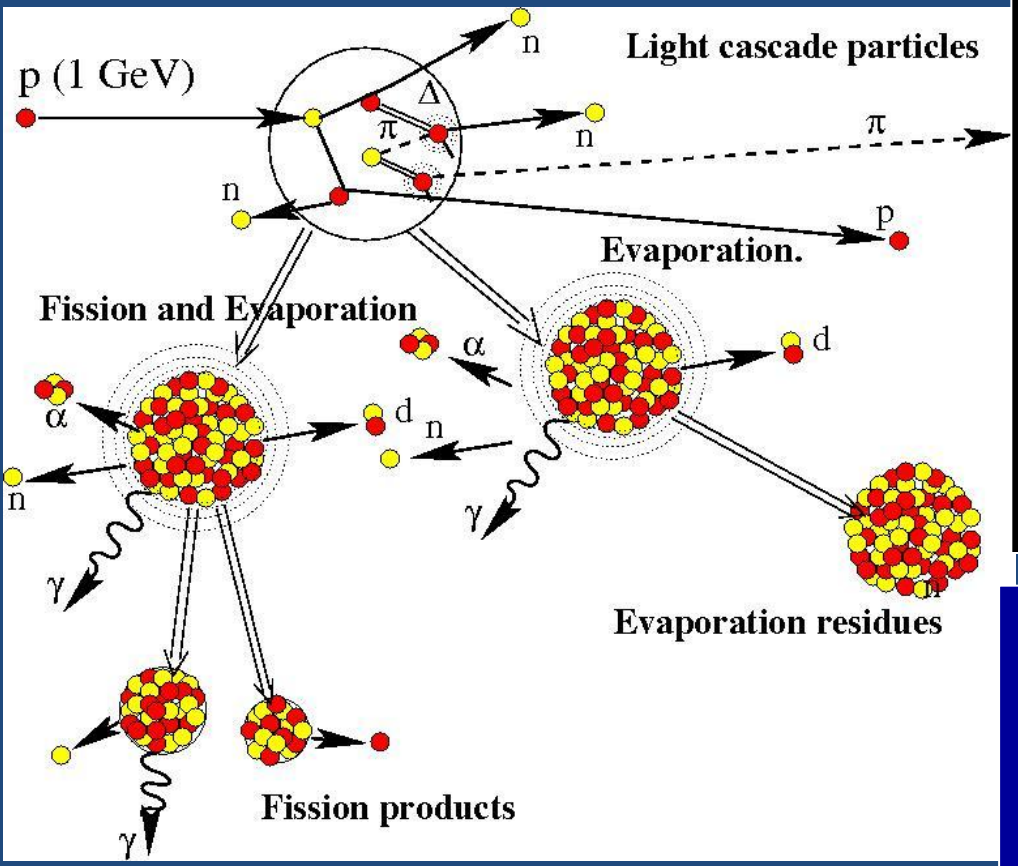
De-excitation step: Multifragmentation, Fermi Breakup, Fission, Evaporation

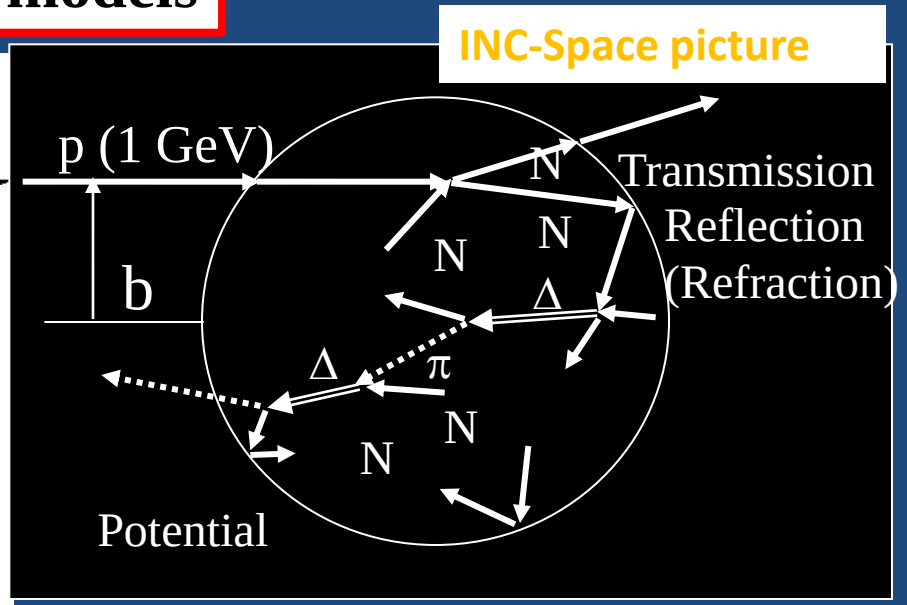
ABLA07, Gemini++, SMM, GEM, Dresner...

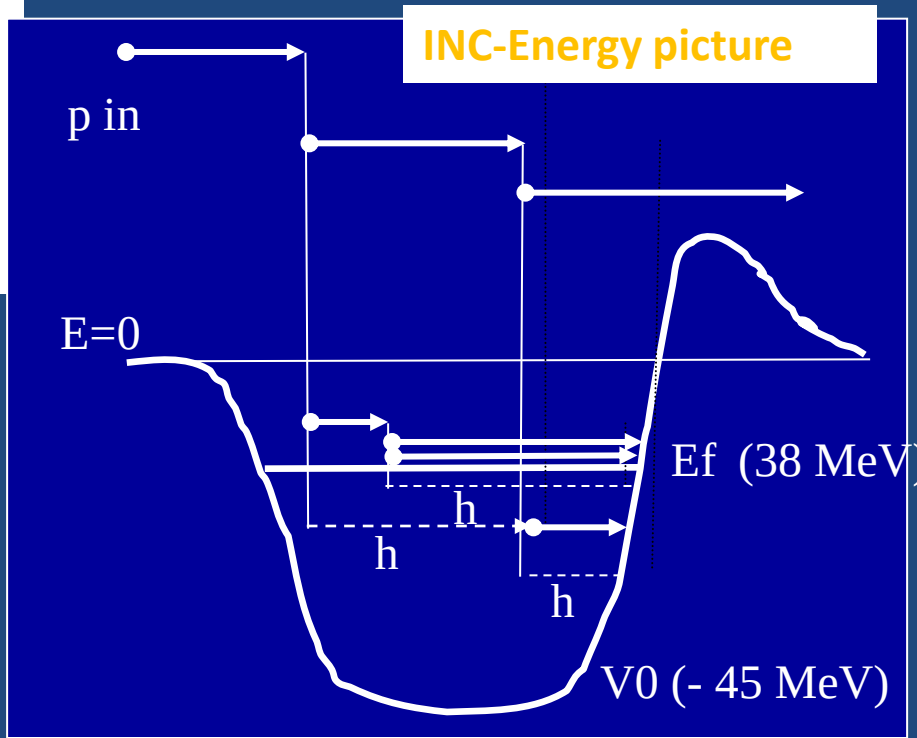
Final state fully specified with statistical fluctuations (Monte-Carlo)

γ and β decays

Spallation models







Toy model of reactions (semi classical)

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

Versioning

INCL4.2 originally in FORTRAN + ABLA (KHS-V3p) C++ translations ~2007 Geant4

A. Heikkinen, P. Kaitaniemi, (C. Schmidt C++ version of ABLA)

Physics: beams up to α, No LCP produced, Only evapo of p, n and α

INCL4.5 (Fortran) **IAEA intercomparison** 2009 Vienne

(structure less projectiles, Fe and Pb targets)

Physics: projectiles up to α, cluster production (d to A=8),
low energy and π physics improved, V(Isospin,Energy).

INCL4.6 INCL4.5 + Some bug corrections + projectiles up to α + exact Q-Values

INCL++5.0 Full redesign of INCL4.5 in C++ 12/2011 v. pub Geant4 9.5

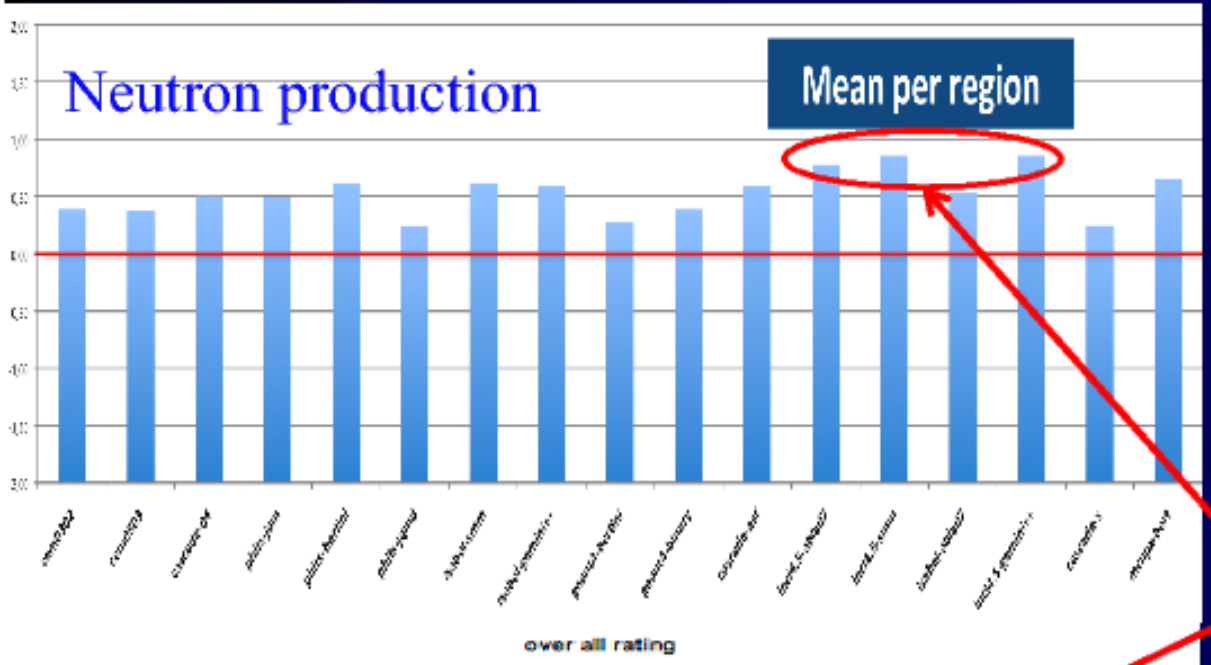
D. Mancusi and P. Kaitaniemi

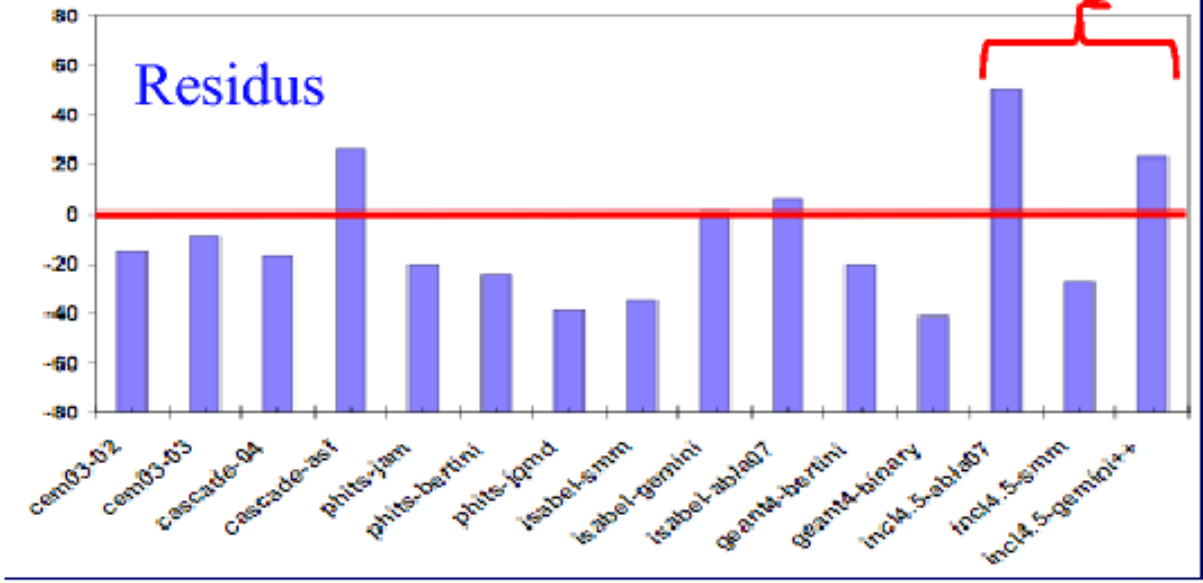
INCL++5.1 **Ahead of INCL4.6 !** (projectiles up to A=18…) 6/2012 v. β Geant4 9.6

Stand alone versions: INCL4.6 and INCL++5 with ABLA07,SMM,Gemini++,GEM,Dresner;
Ntuples or Root trees.

INCL4.6 in MCNPX and PHITS

IAEA Intercomparison Vienna 2009





p(~40Mev-2.6GeV)
Targets: Fe and Pb

~12 cascades
~7 deexcitations

INCL4.5

(from J.C. David presentation)

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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]

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

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IAEA Benchmar

ults

This section contains an overall status of the parti ts, th
(FOM) of this intercomparison. ec
values and parameters, rati va
mathematical measure/n evidences as ac al to

ulations, and the Figures of Merit
he deviation factors, chi-square
. This method represents a

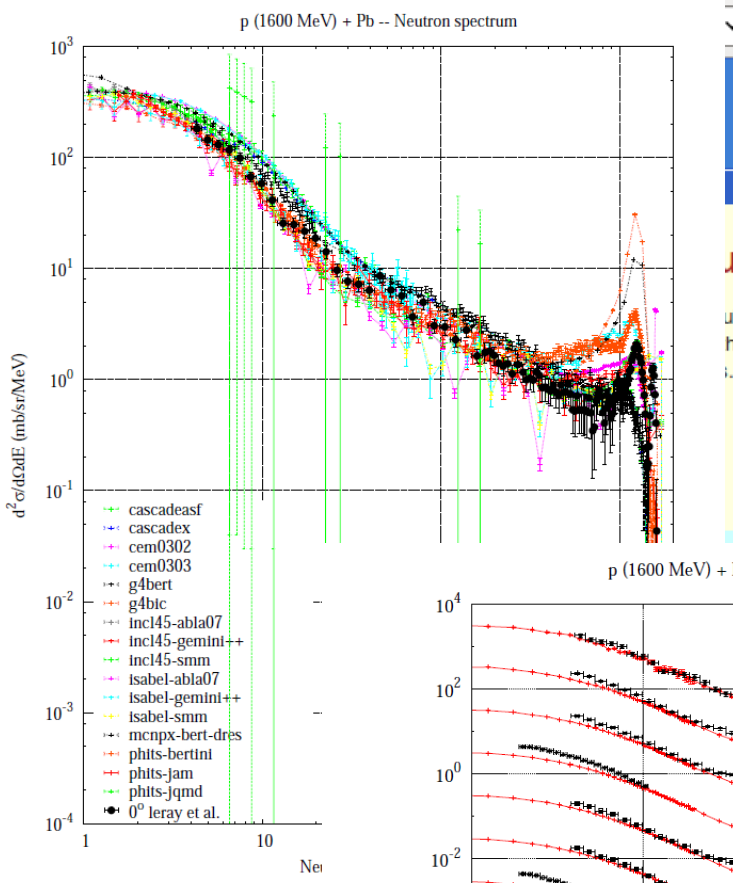
[g]: graph, [d]: numeric , [f]: figure of merits (fom)

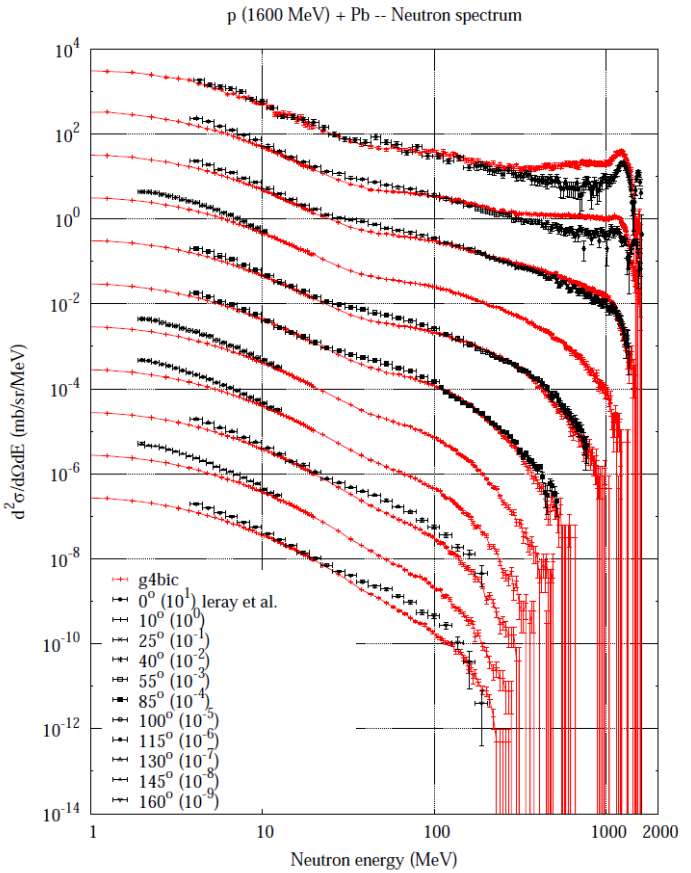
Double differen ross section (neutron)

Proj.	Targ.	E (MeV)	Autho	cem 0302	cem 0303	cascade 04	casca -x
n	^{nat}Fe	65	Hjort	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Fe	800	Amian	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Fe	800	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Fe	1200	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Fe	1600	Leray	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Fe	3000	Ishibas	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Pb	256	Meier	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Pb	800	Amian	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][
p	^{nat}Pb	800	Leray	[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]
p	^{nat}Pb	1600	Leray	[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]
p	^{208}Pb	63	Guertin	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]

Double differential cross section (proton)

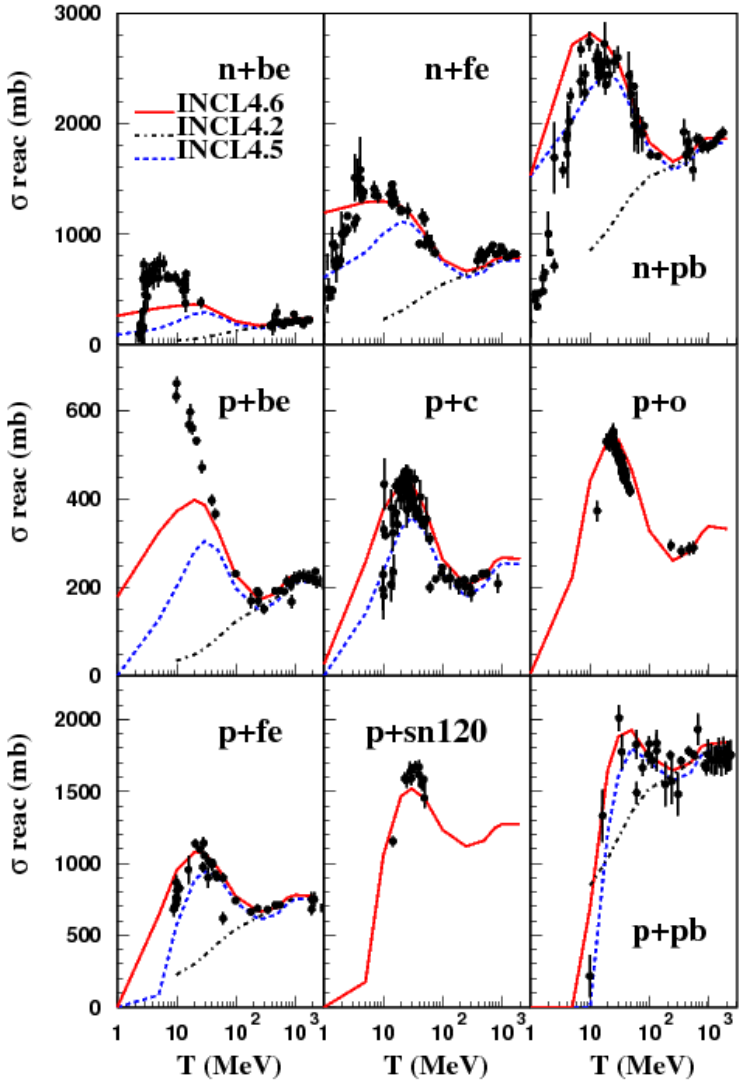
Proj.	Targ.	E (MeV)	Author	All	cem 0302	cem 0303	cascade 04	cascade -x	cascade -asf	geant4 -binary	geant4 -bertini	incl4 abla
n	^{209}Bi	542	Franz	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d
p	^{197}Au	1200	Budzanowski	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d][f]	[g][d
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
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





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

Reaction cross sections improved at low energy



Confidence in the model (INC)

…But not strictly needed in transport codes

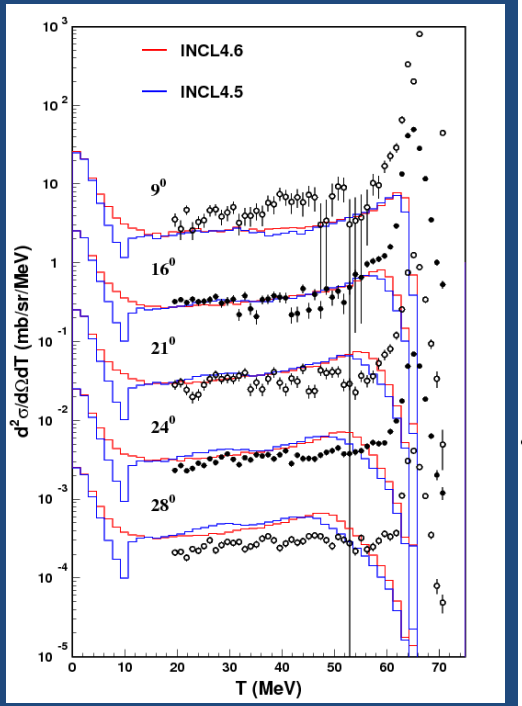
Still some difficulties with very light targets

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

Low energy

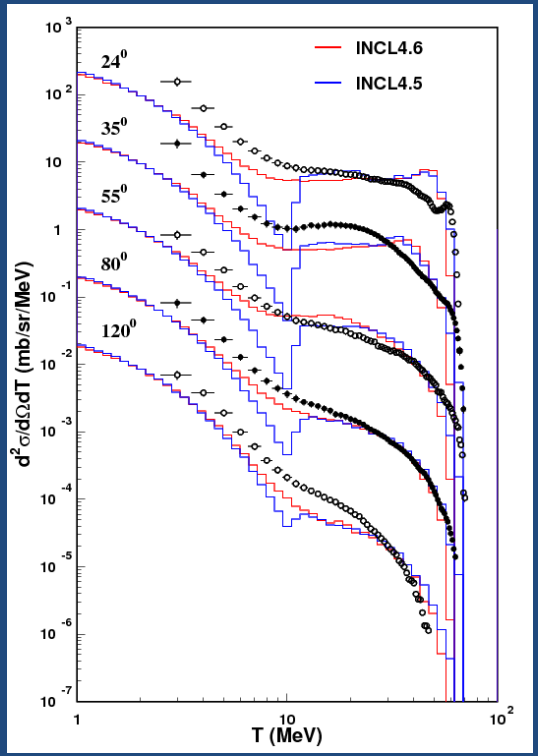
(Needed in thick targets!)

n (65MeV)+56Fe →n



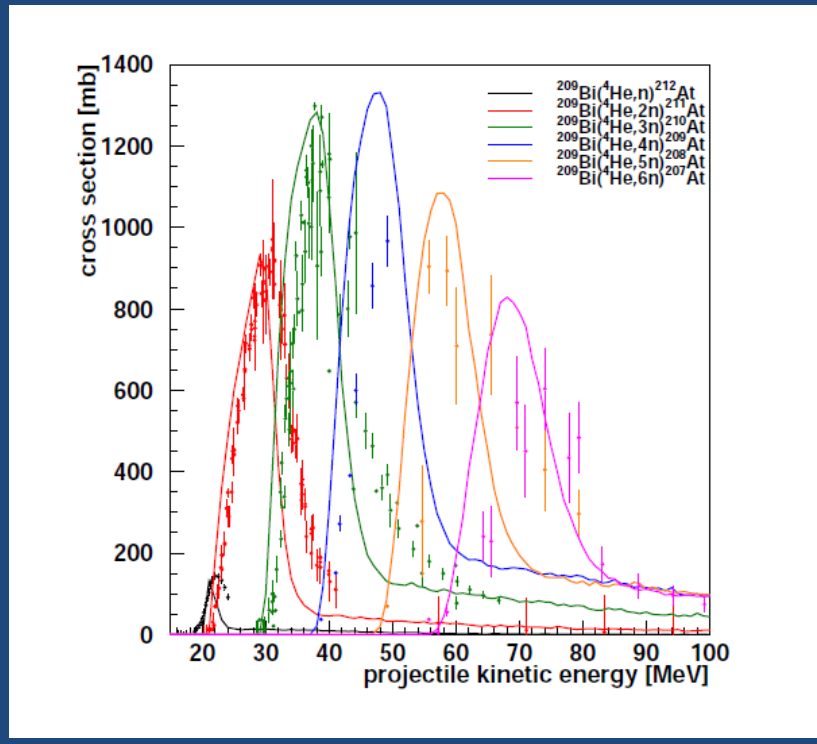
Data: Hjort et al. Phys. Rev. C53(1996)237

p (63 MeV)+208Pb→n



Data: Guertin et al. Eur. Phys. J A23(2005)49

α+Bi→xn (at thresholds!)

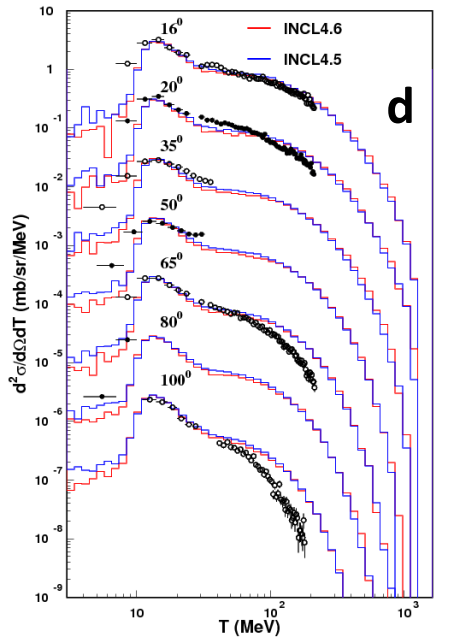


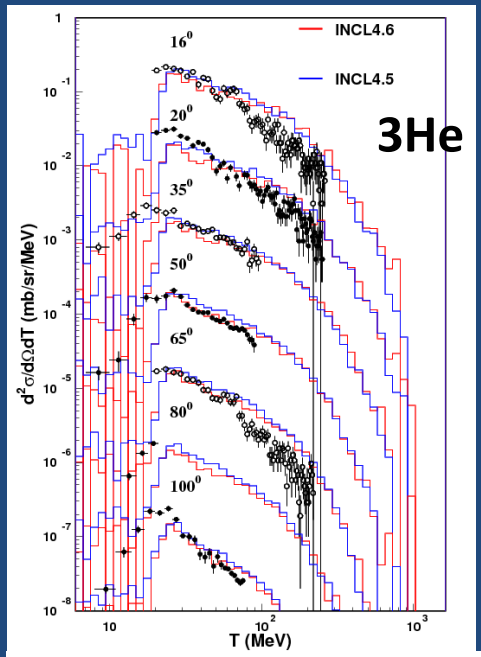
Data: Barnett PRC9(1974), Hermanne ARI63(2005), Rizvi ARI41(1990)

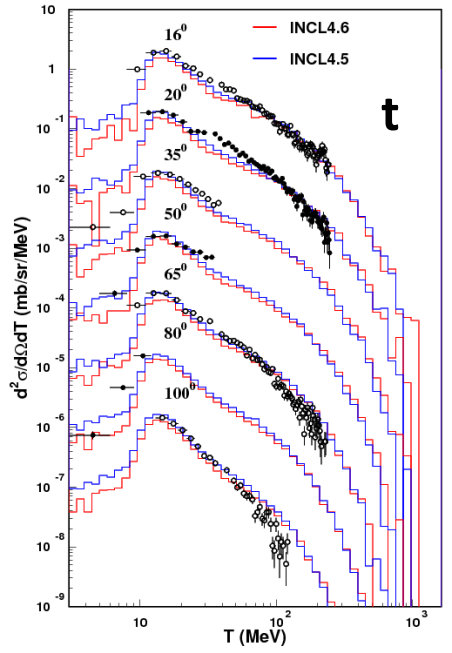
→Coulomb deviation of the beam trajectory
→Local momentum of the nucleon for the NN interaction (at the nuclear surface)
→Module of total-partial absorption matching INC for composite beams
→Exact mass of nuclei (right Q-values)

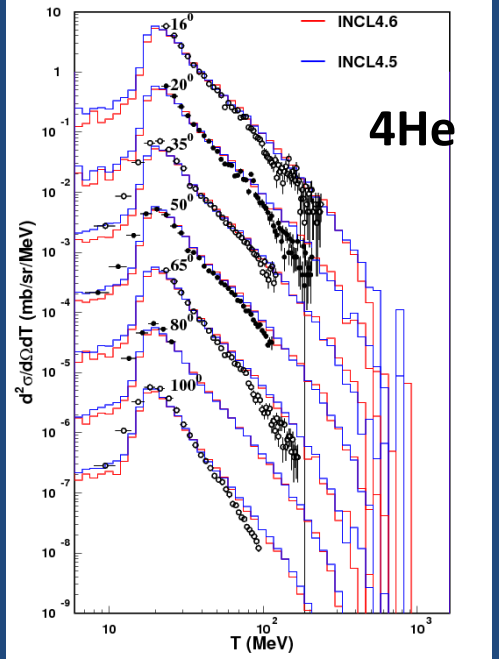
(more detailed in D. Mancusi talk on Wednesday)

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.

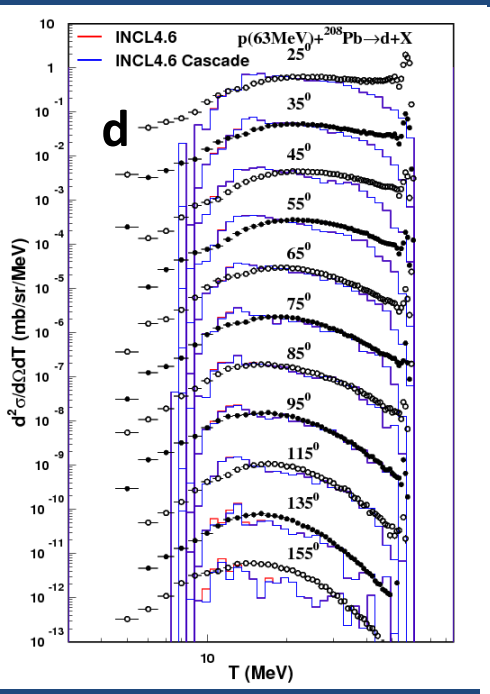
→Δr.Δp criteria and "more bound" selected.

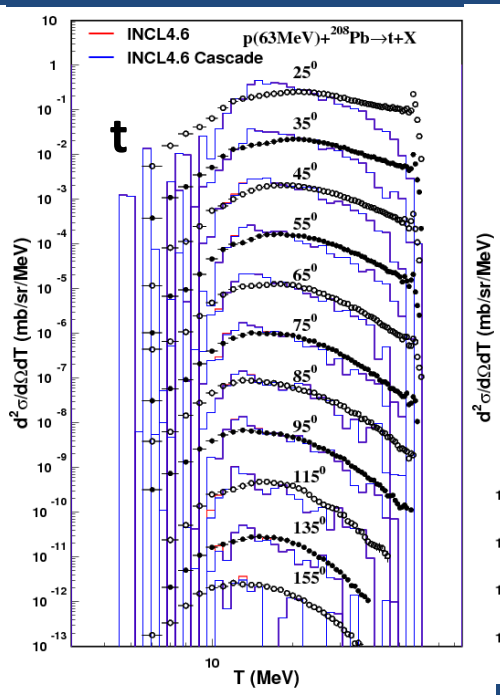
→Phenomenology introduced (fixed one time for ever)

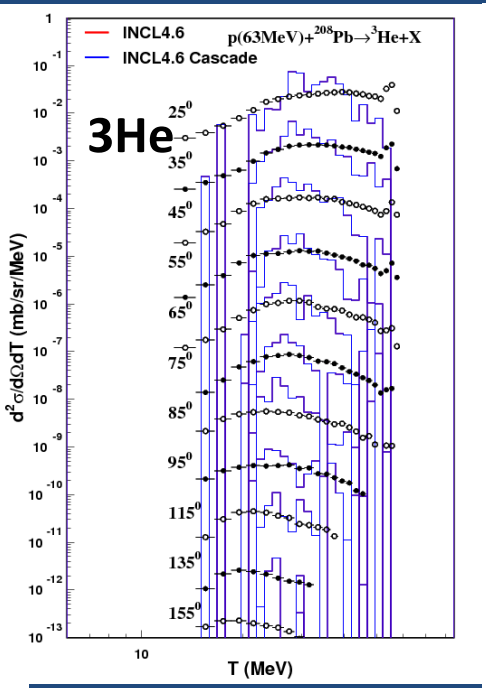
Light cluster produced (low energy)

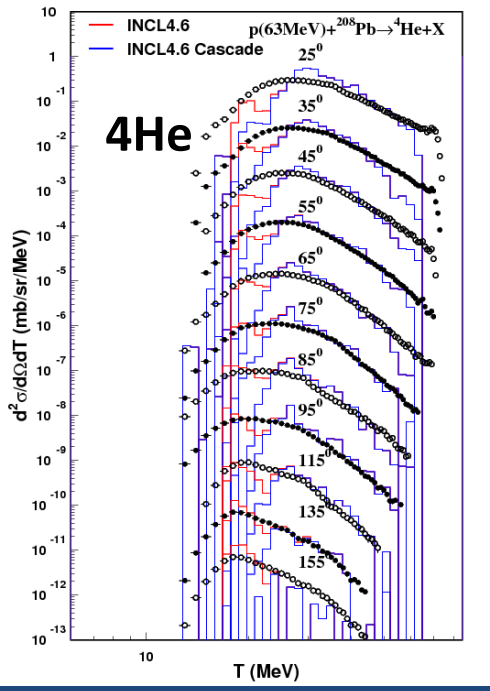
p (63 MeV) + Pb

Data: Guertin et al. Eur. Phys. J. A23(2005)49







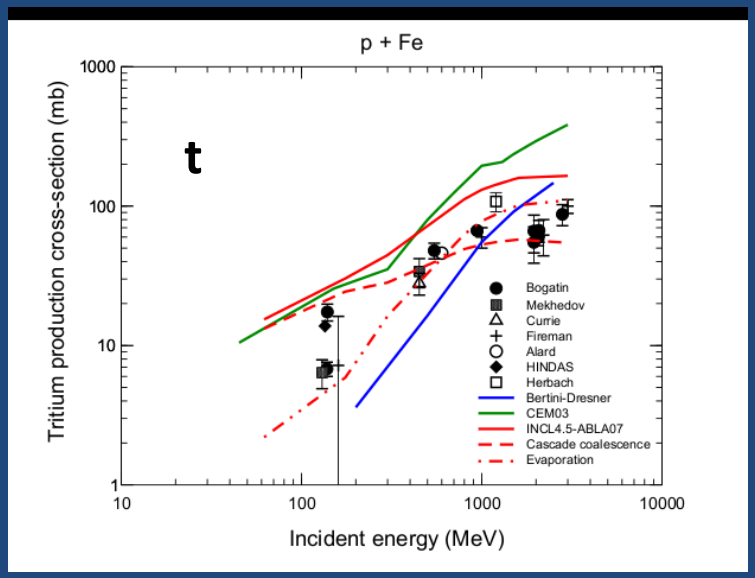


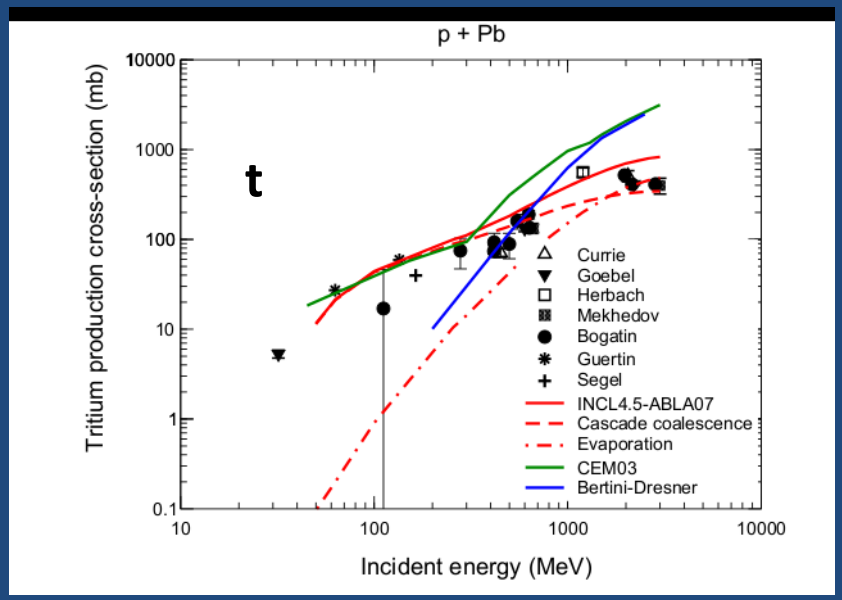
→Dominantly from the INC part

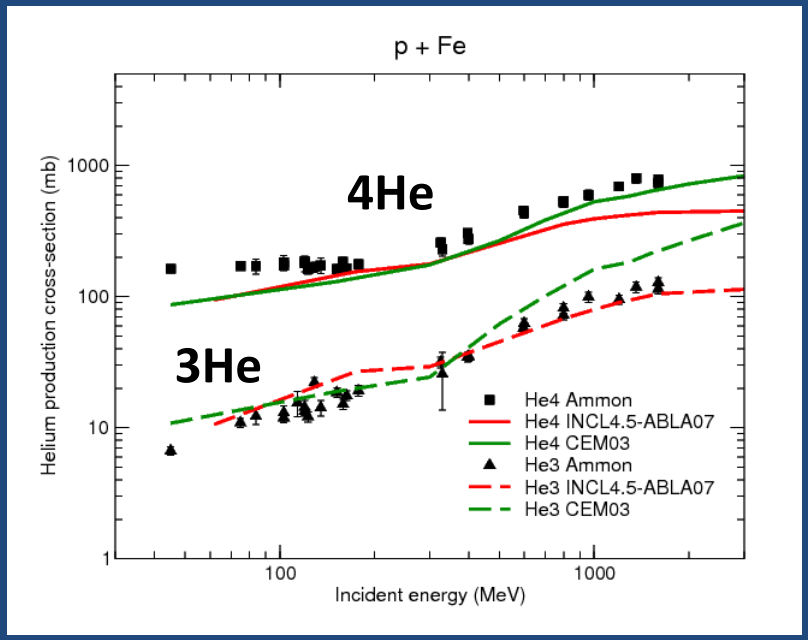
→Missing coherent nuclear states (forward and energy max) as expected

→Evaporation too small (here ABLA07); Not enough E* ?

He and t production (applications)





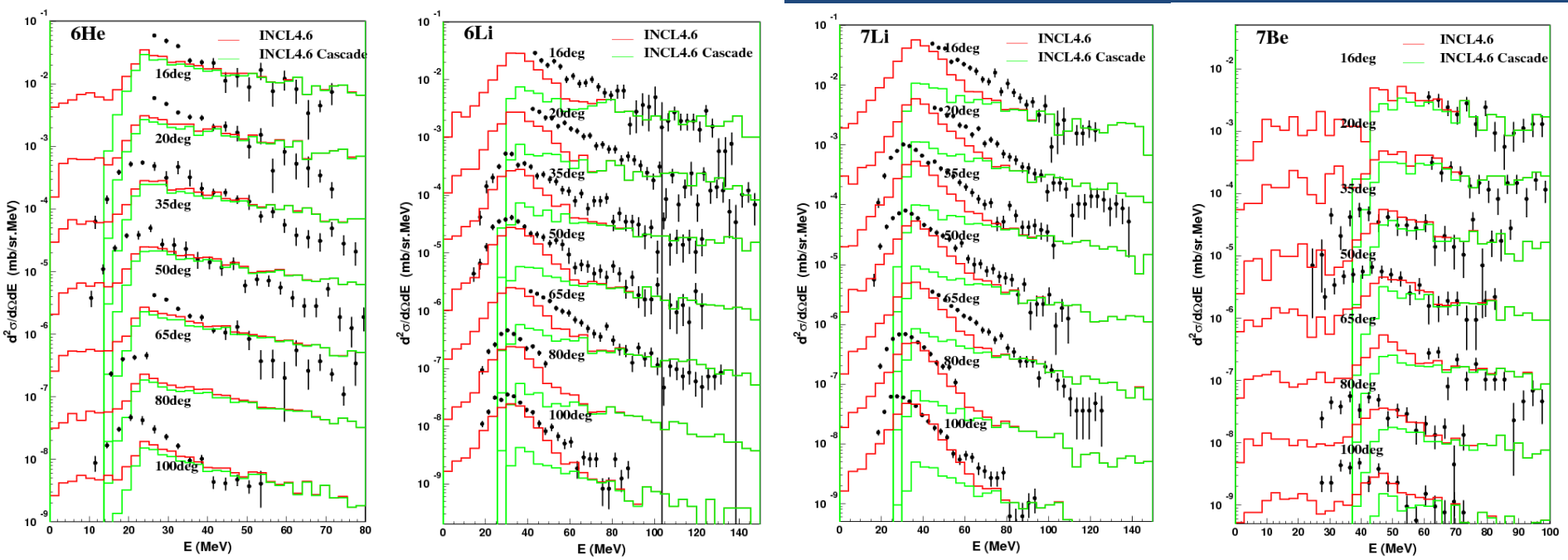


From S. Leray et al.N.I.M. B268(2010)581

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

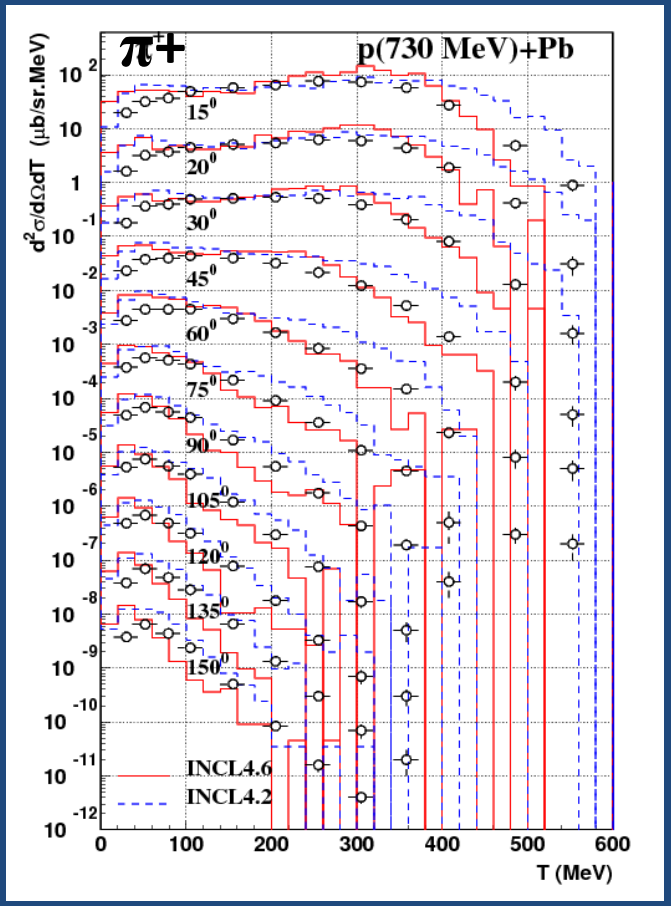
→Exciding computation time (due to exact combinatory)

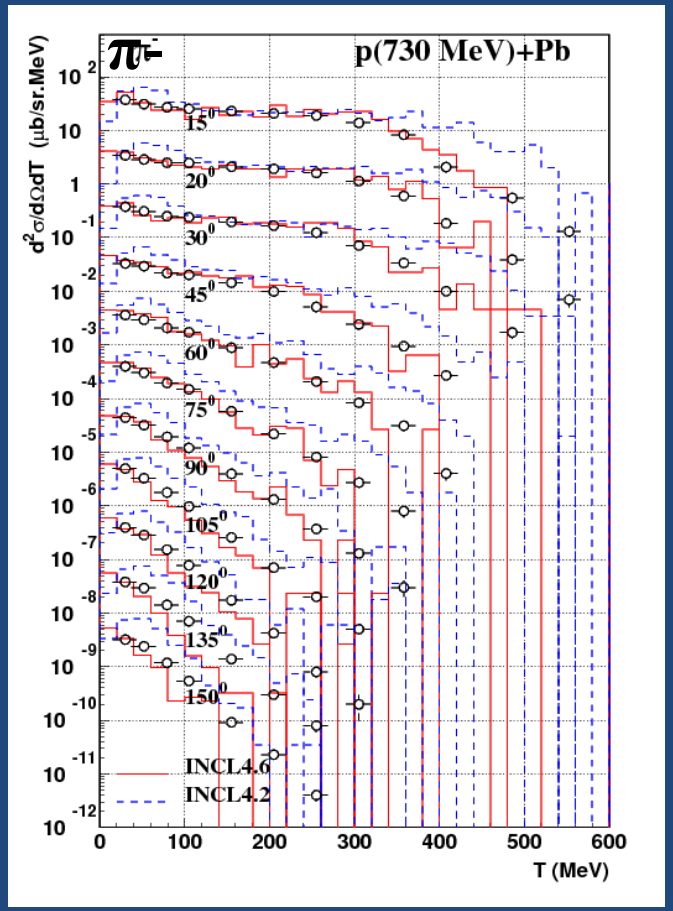
→Not steep enough with the cluster energy (more apparent at ~200 MeV)

Work in progress !

Pion production

...and Pion absorption, look at
Th. Aoust and J. Cugnon Phys. Rev. C74(2006) 64607



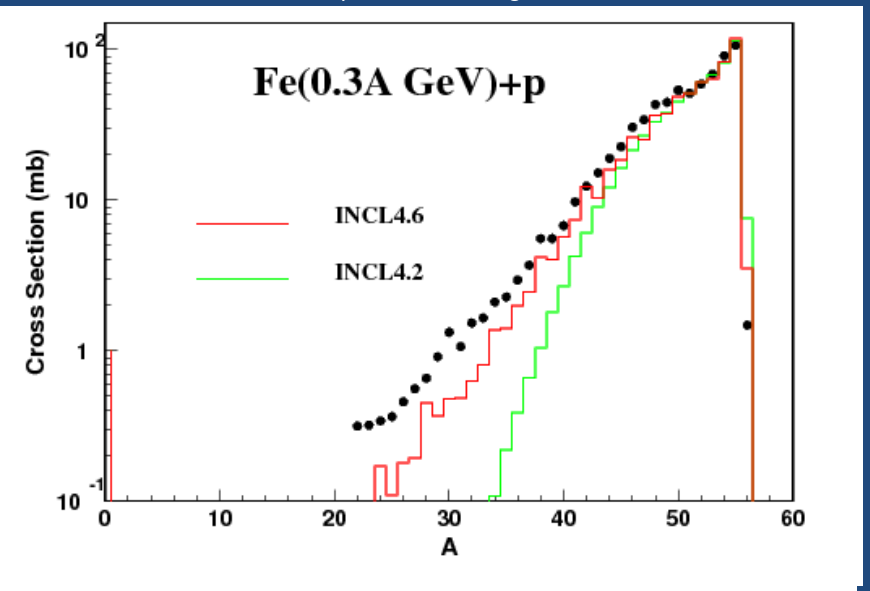


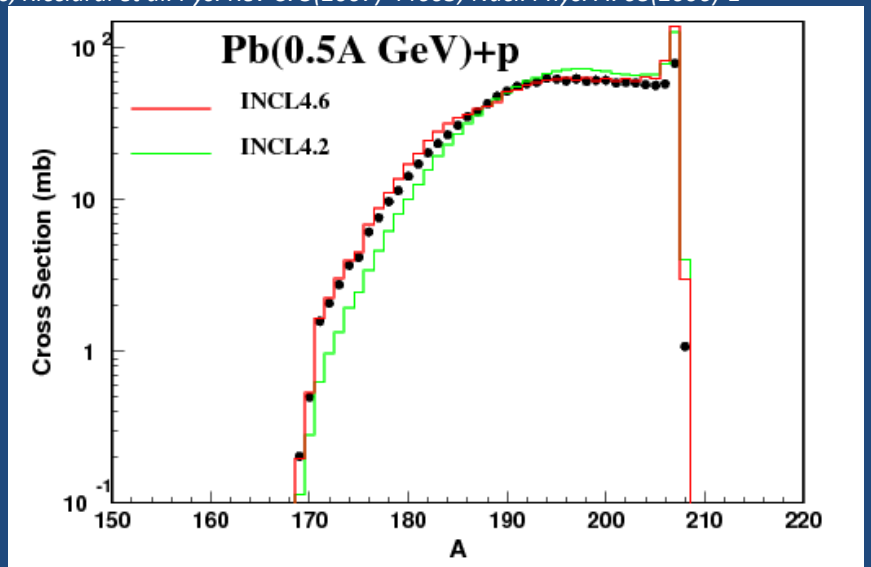
Data: Cochran et al. Phys. Rev. D6 (1972) 3085

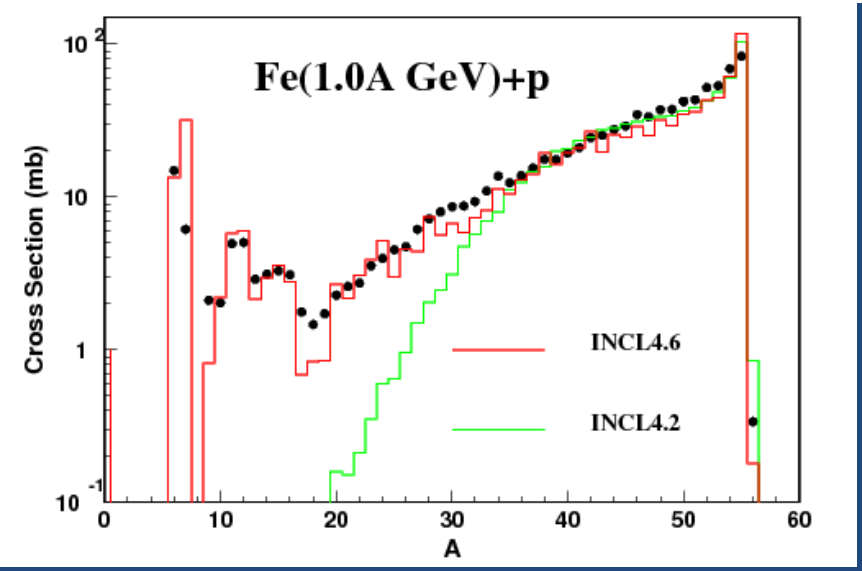
→Pion potential introduced
→Coulomb deviation
→Significant improvements.

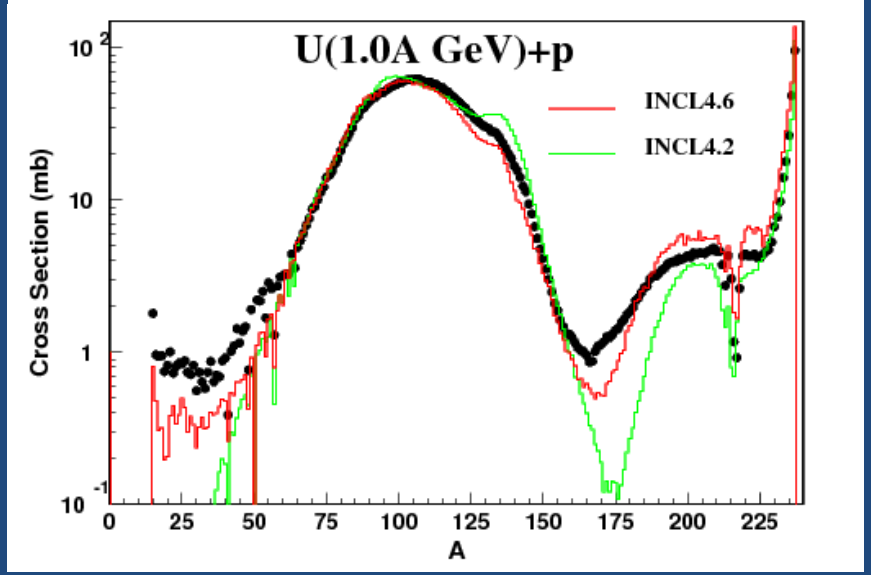
Residual nuclei

Data: GSI experiments, Villagrasa-Canton, Audouin, Taieb, M.Bernas, Ricciardi et al. Pys. Rev C75(2007) 44603, Nucl. Phys. A768(2006) 1







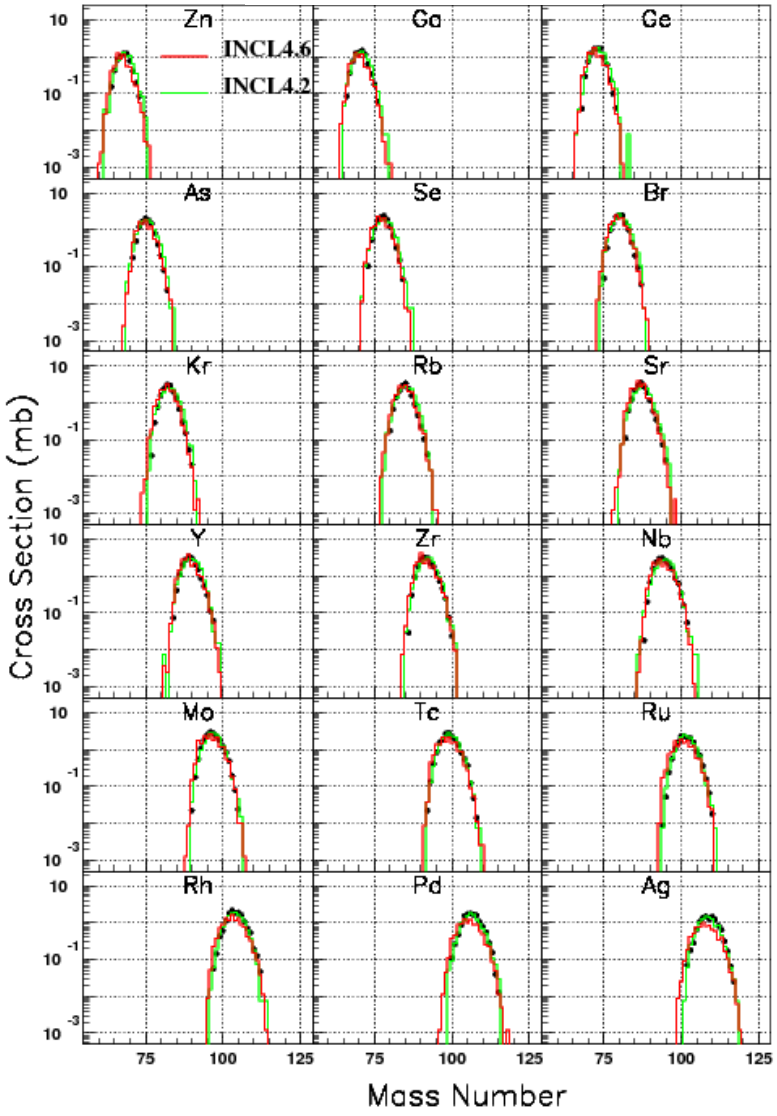


Improved: More E* (INCL) , light nuclei production and fission (ABLA07)

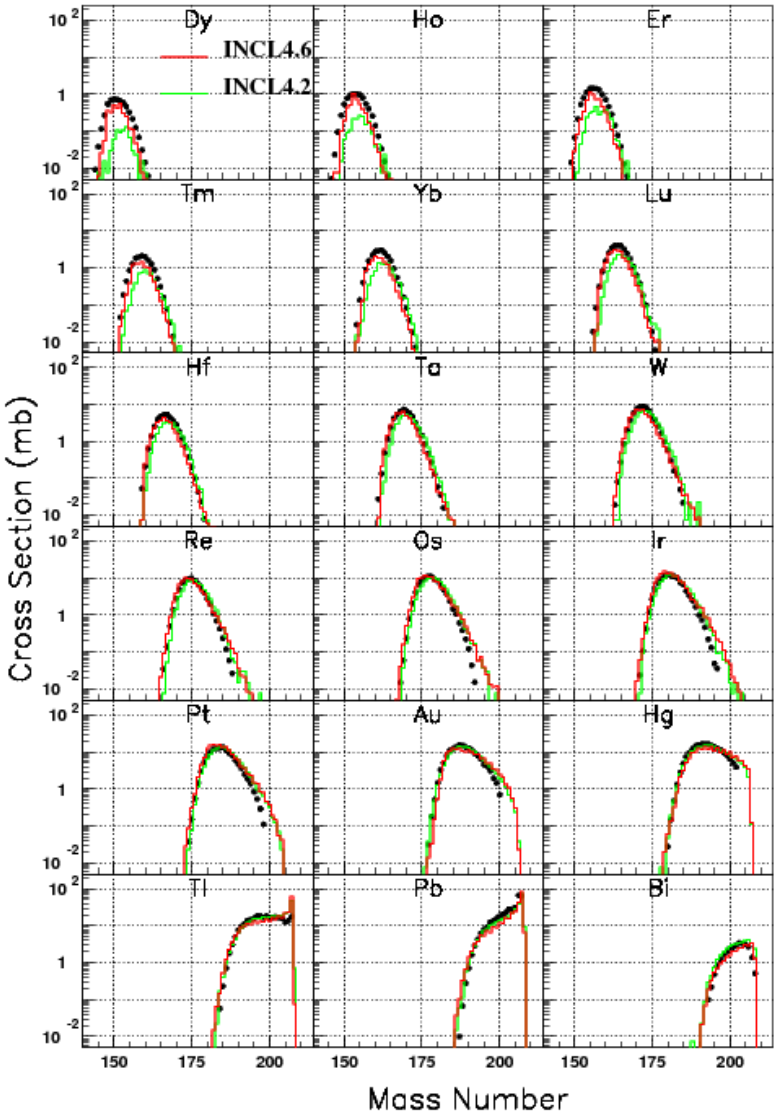
Residual nuclei (isotopic cross sections)

Data: Enqvist et al. Nucl. Phys.A686(2001)481

Fission products



Heavy residues

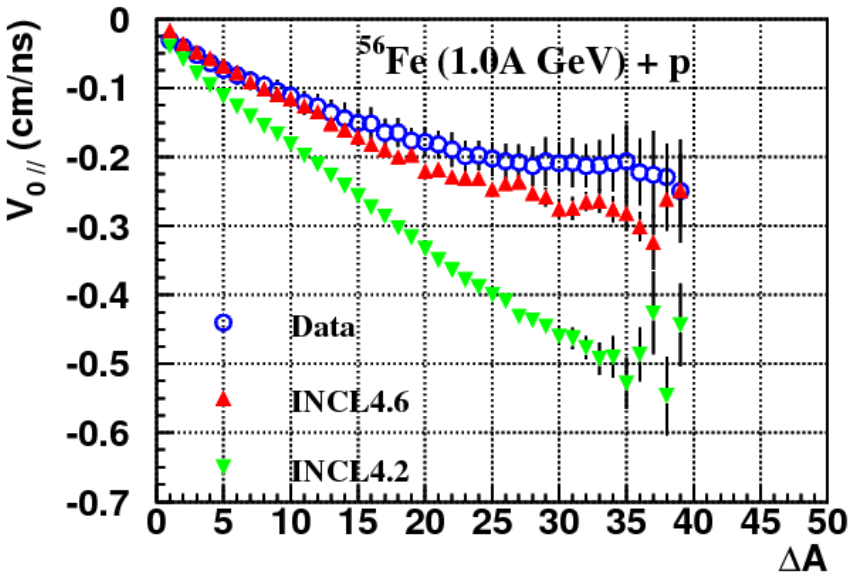


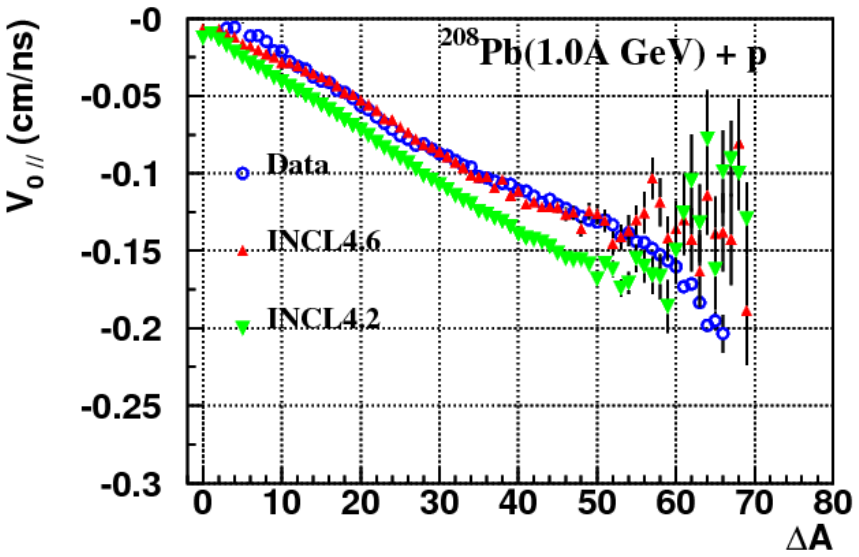
Still recurrent problems close to the target mass

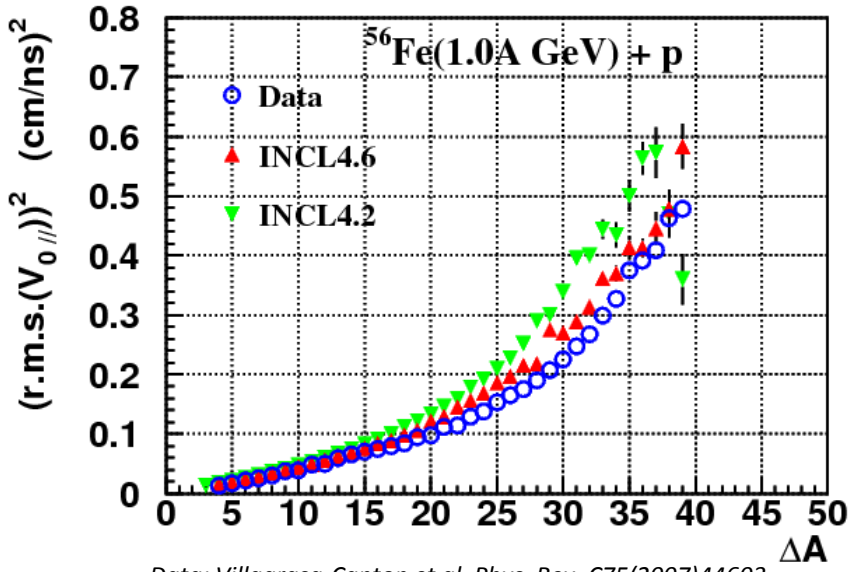
Recoil velocities of nuclear residues

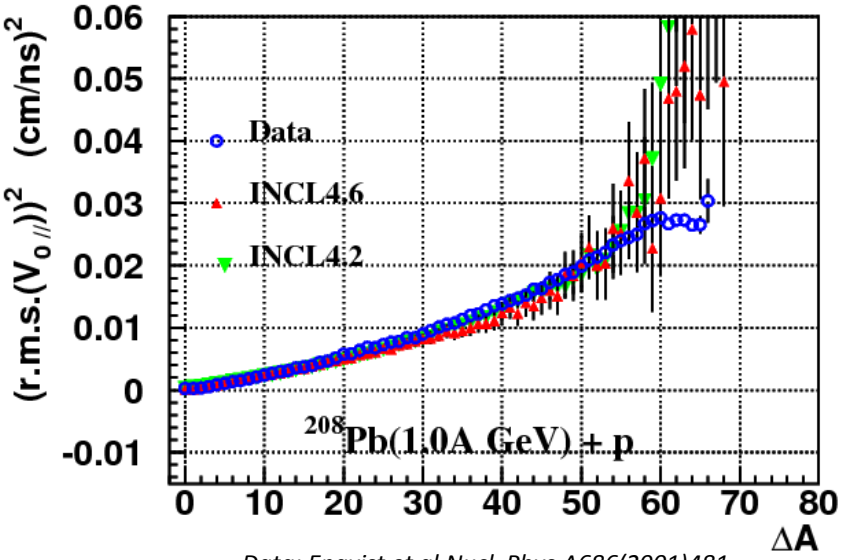
.... Very good... Comes naturally!

Recoil energies, damage evaluation in materials







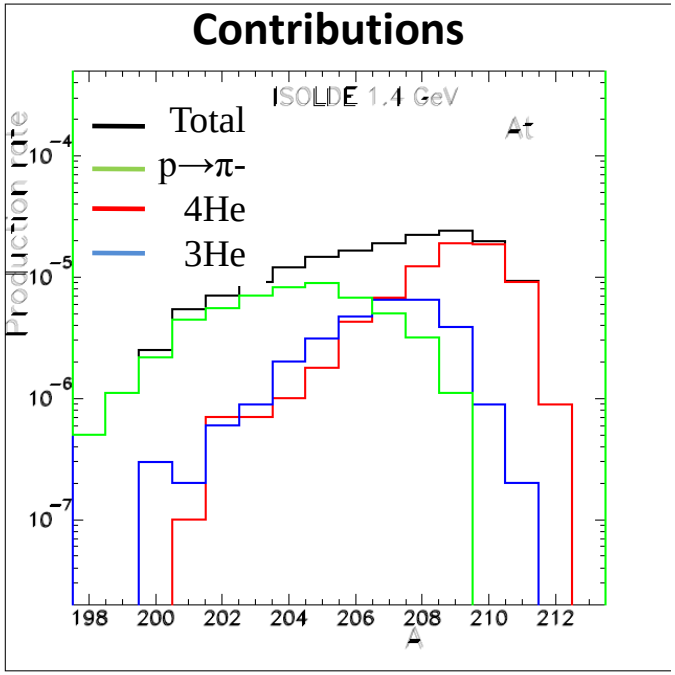


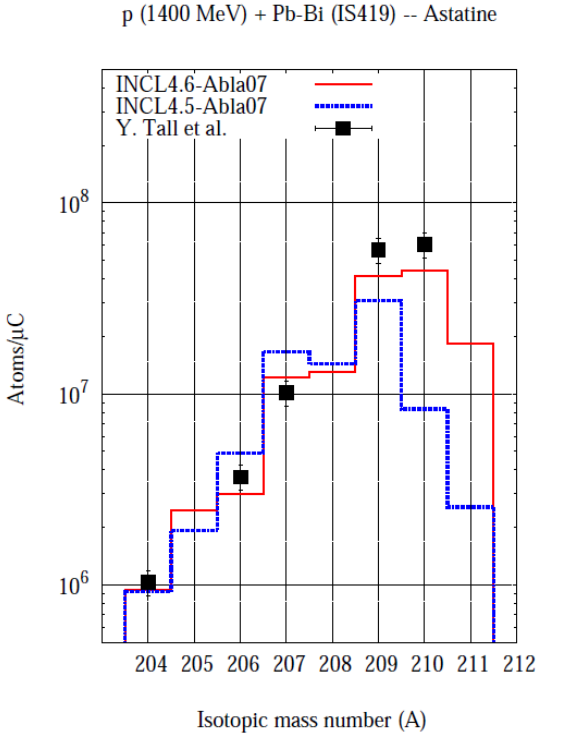
Data: Villagrasa-Canton et al. Phys. Rev. C75(2007)44603

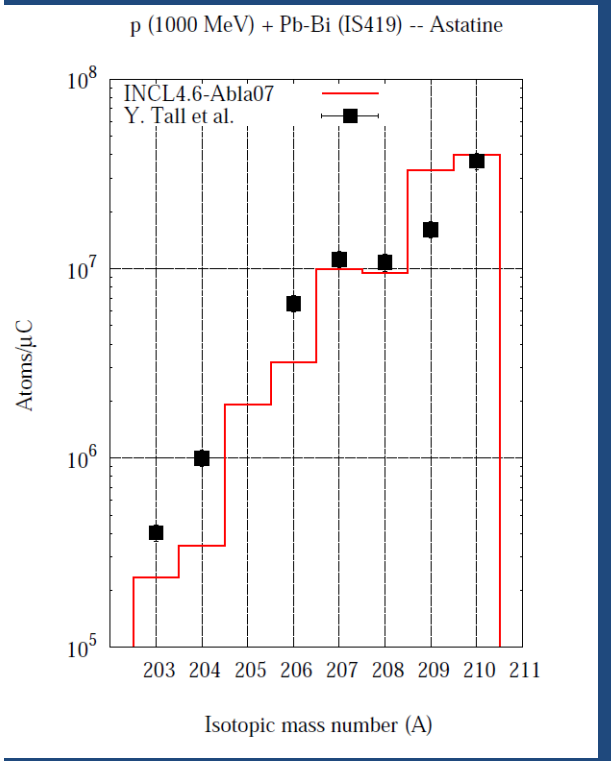
Data: Enqvist et al.Nucl. Phys.A686(2001)481

Thick target experiment: p(1.4 GeV) + (Pb-Bi 20cm) → At(Z+2)

Data: Y. Tall et al. ICND 2007, DOI 10.1051/ndata: 07762, (ISOLDE-IS419)







One step: p + Bi → π- + xn + At
Two steps: p + (Bi-Pb) → 3He, 4He
3He, 4He + Bi → xn + At

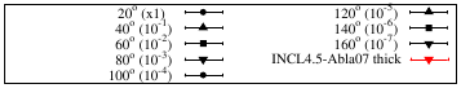
INCL4.6 in MCNPX + CINDER90 (history of irradiation)

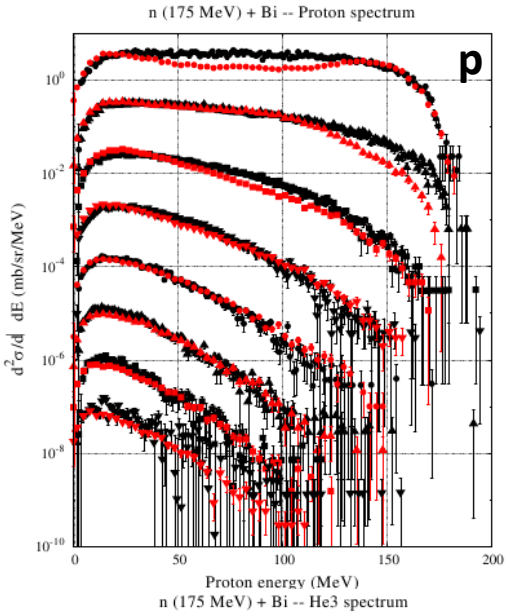
Good results due to: Transport, Pi production, He production and He induced reactions at very low energy

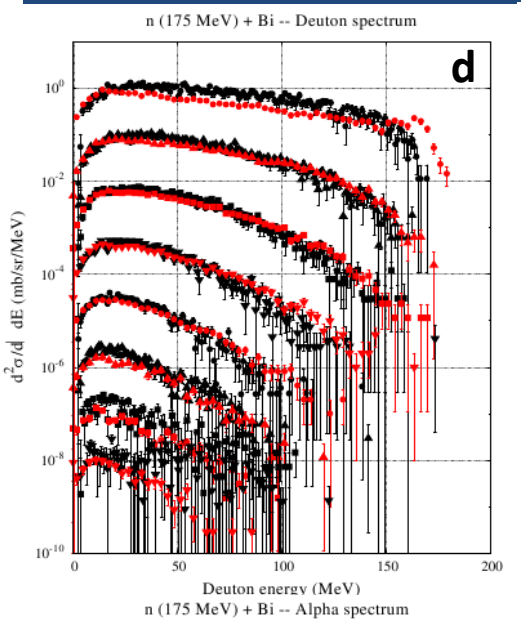
Thick target and n spectra: n “175” MeV + Bi

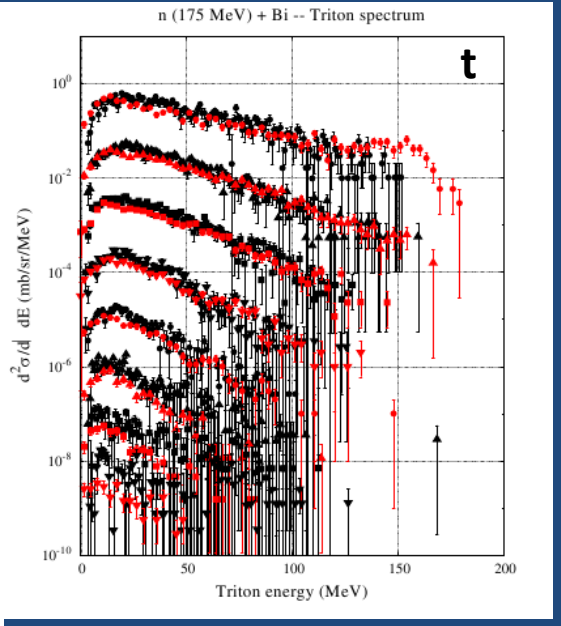
Data: Bevilacqua et al. Rad. Mes. 45(2010)1145

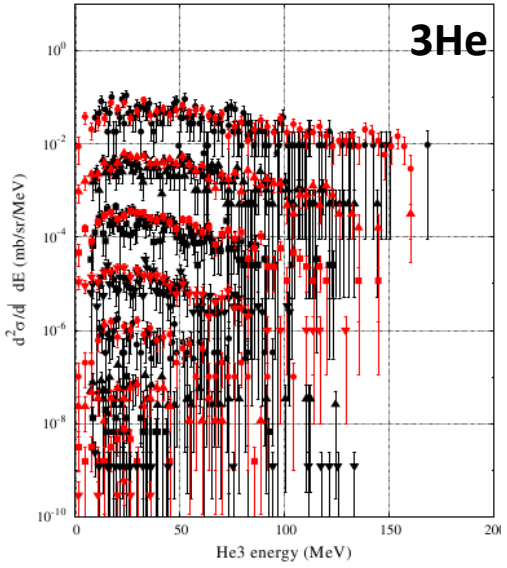
Red points: INCL4.6-ABLA07 in MCNPX

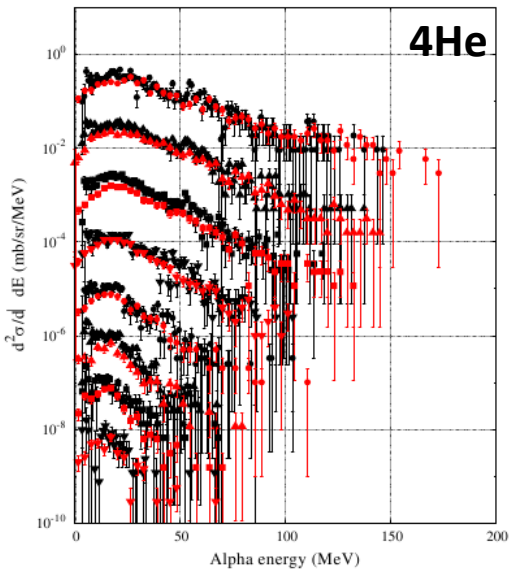








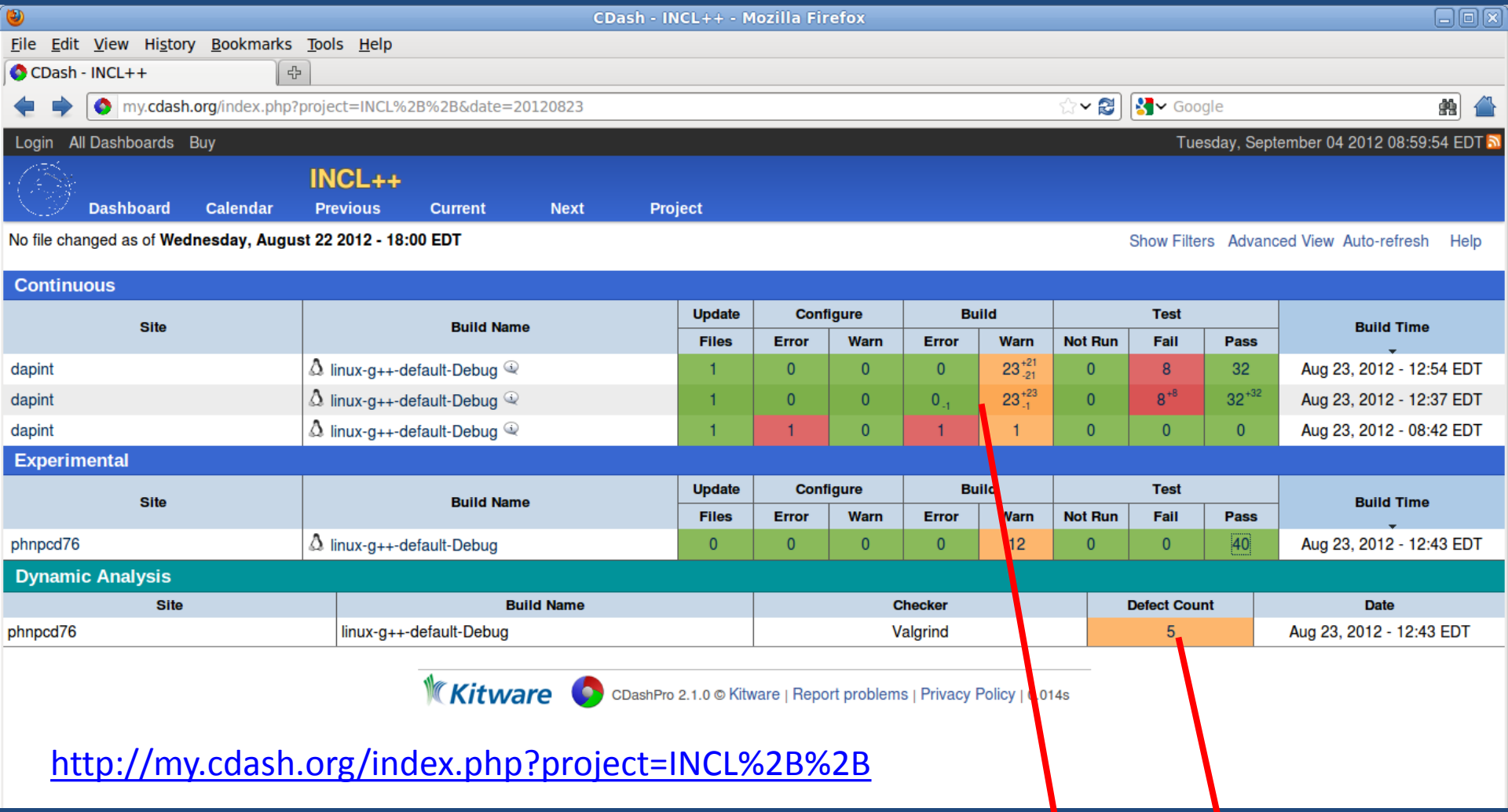




(More calculations with transport (geant4) in D. Mancusi talk)

INCL++ Benchmarking and controls

D. Mancusi work



http://my.cdash.org/index.php?project=INCL%2B%2B

INCL++ is developed under GIT

Automatically controlled (each night) under CTest/CDash

Compilation checks

No memory leaks in INCL++! (when in order….)

INCL++ Benchmarking and controls

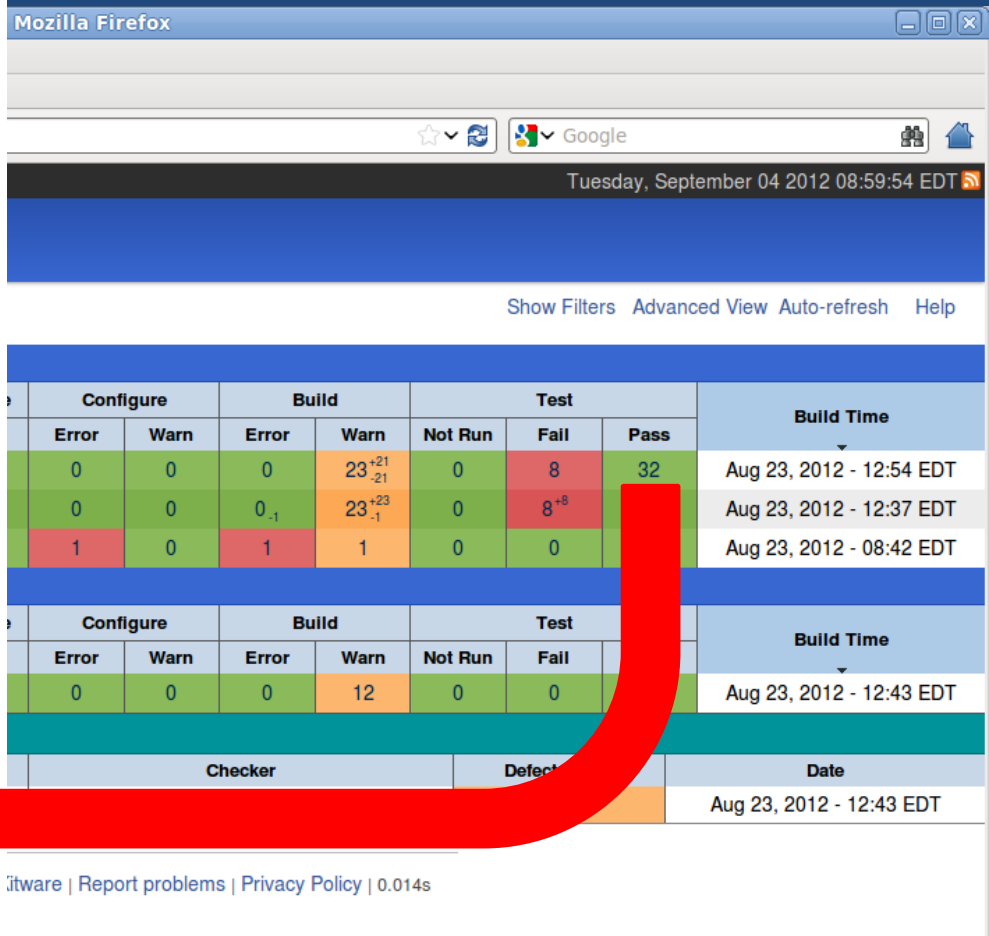
D. Mancusi work

Testing started on 2012-08-23 16:44:50

Site Name: phnpcd76
Build Name: linux-g++-default-Debug
Total time: 4m 33s 100ms
OS Name: Linux
OS Platform: x86_64
OS Release: 3.2.0-3-amd64
OS Version: #1 SMP Thu Jun 28 09:07:26 UTC 2012
Compiler Version: unknown

40 tests passed.

Name	Status	Time Status	Time
avatarPredictionTest	Passed	Passed	730ms
a_Ca40_4000_Test	Passed	Passed	4s 720ms
a_Ca40_40_Test	Passed	Passed	3s 970ms
C12_Ne20_2400_Test	Passed	Passed	3s 330ms
clusterBindingEnergyTest	Passed	Passed	600ms
clusterDecayTest	Passed	Passed	230ms
clusterTest	Passed	Passed	6s 650ms
clusterTransmissionProbabilityTest	Passed	Passed	620ms
deltaDecayTest	Passed	Passed	2s 90ms
deltaProductionCrossSectionTest	Passed	Passed	110ms
deltaProductionTest	Passed	Passed	8s 660ms
densityCMTest	Passed	Passed	1m 1s 560ms
densityROOTTest	Passed	Passed	2s 660ms
densityTest	Passed	Passed	1m 36s 240ms
deuteronDensityTest	Passed	Passed	1s 910ms
elasticCollisionTest	Passed	Passed	6s 390ms
elasticCrossSectionTest	Passed	Passed	310ms



34 Unit tests and 6 Full tests built
Comparison with a ref. Fortran version
(under development)

Future

High energy extension

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

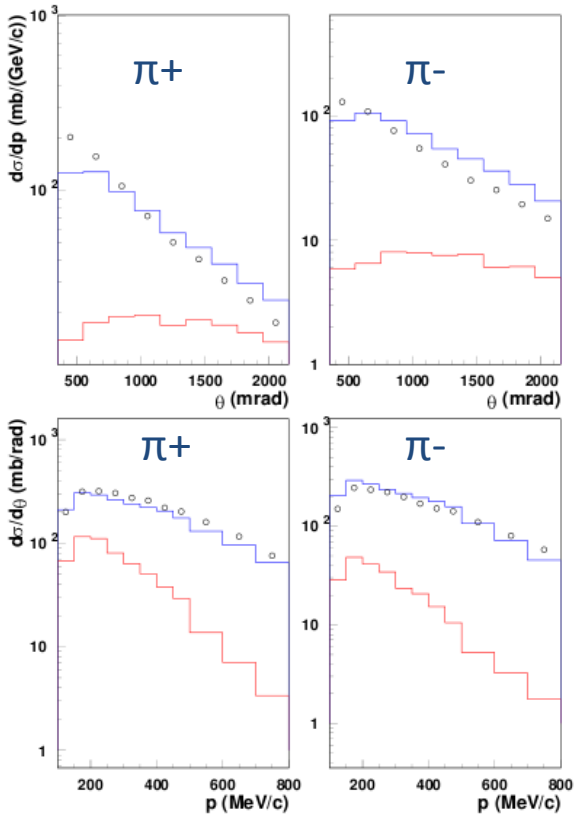
Multi-pion channels added:

πN -> xπ N x≤4
NN -> NN xπ

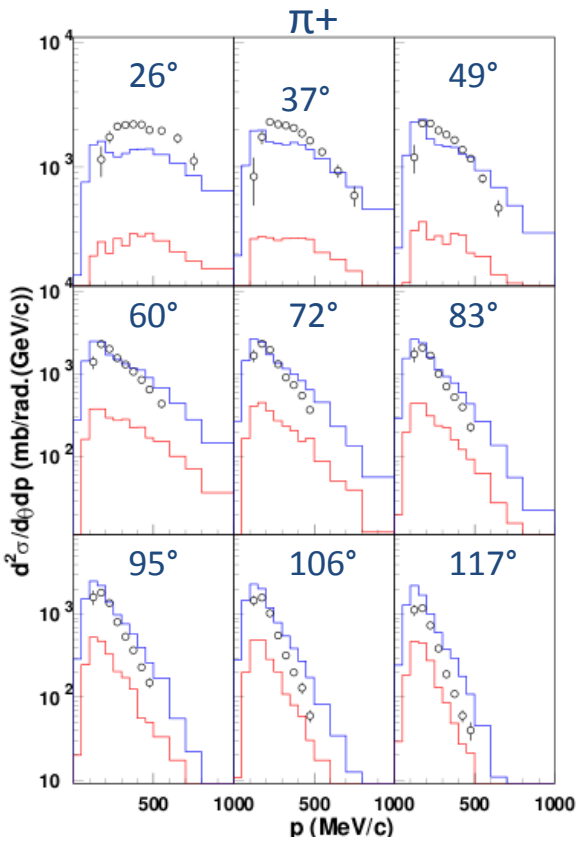
New calc; **BLUE LINE**
(INCL4.2 red line)

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

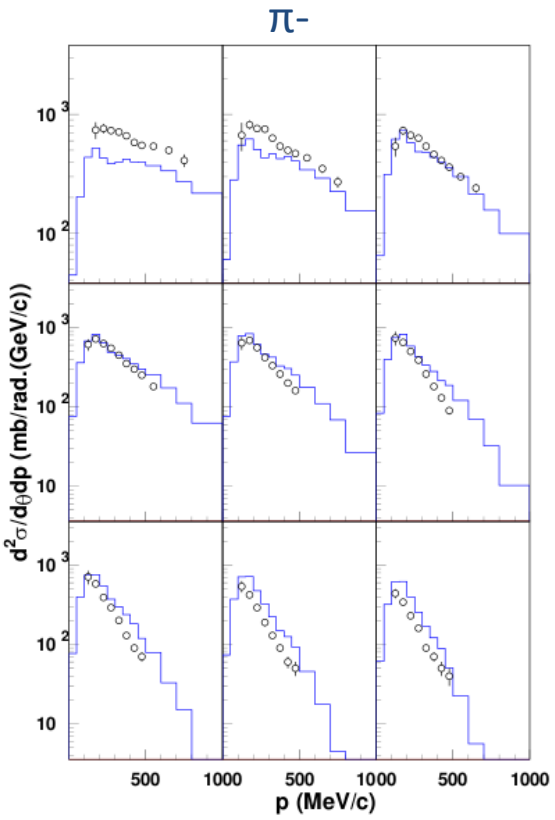
M.G.Catanesi et al P.R.C77(2008)55207; M.Apollonio et al P.R.C80(2009)65207;M.G. Catanesi Eur.Pgys. J C53(2008) 177;C54(2008)37



p(12 GeV/c) + C



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



(b) π+(5 GeV/c) + Cu

Conclusions

Alain Boudard

INCL++5: **INCL fully redesigned C++**

→Tested with the FORTRAN version
→Easy for future developments
→Modernly controlled (CTest/CDash)
→Robust (no memory leaks)
→Full potentiality of the FORTRAN
and even more!

INCL physics: **One of the best from thresholds to ~2GeV with a Monte-Carlo approach and a predictive power (reduced phenomenology)**

→π, p, n, d....α, ... C-O beams *(D. Mancusi talk tomorrow)*
→Any target nucleus
→Final state fully specified (π, N, clusters, Nuclear residues)

Enormous work and key position of Davide Mancusi.

(G4 De-excitation still to be more tested with INCL++)

Future:

√ High energy extension (~15 GeV) with multi pion channels
(in a next step, strangeness introduced with K channels)

√ Cluster production to be improved (heavy clusters, more efficient method)

√ Light ion beams (more symmetry projectile-target) medical and
space applications

Additional (cascade de-excitation contributions)