

Validation in Geant4

Hadronic Shower Simulation Workshop
FNAL, 6-8 September 2006
Koi, Tatsumi (SLAC/SCCS)
for the Geant4 Collaboration

Overview

- Lowest energy ($E < 170\text{MeV}$)
 - Capture
 - Isotope productions
- Intermediate energies ($170\text{MeV} < E < 20.0\text{GeV}$)
 - Bertini Cascade
 - Binary Cascade
 - Low Energy Parameterization Model
- High energy models ($20\text{GeV} < E$)
 - Quark Gluon String Model
 - High Energy Parameterization Model
- Special topics
 - Elastic
 - Gamma-nuclear
 - Low Energy Neutrons ($E < 20\text{MeV}$)
 - Ions

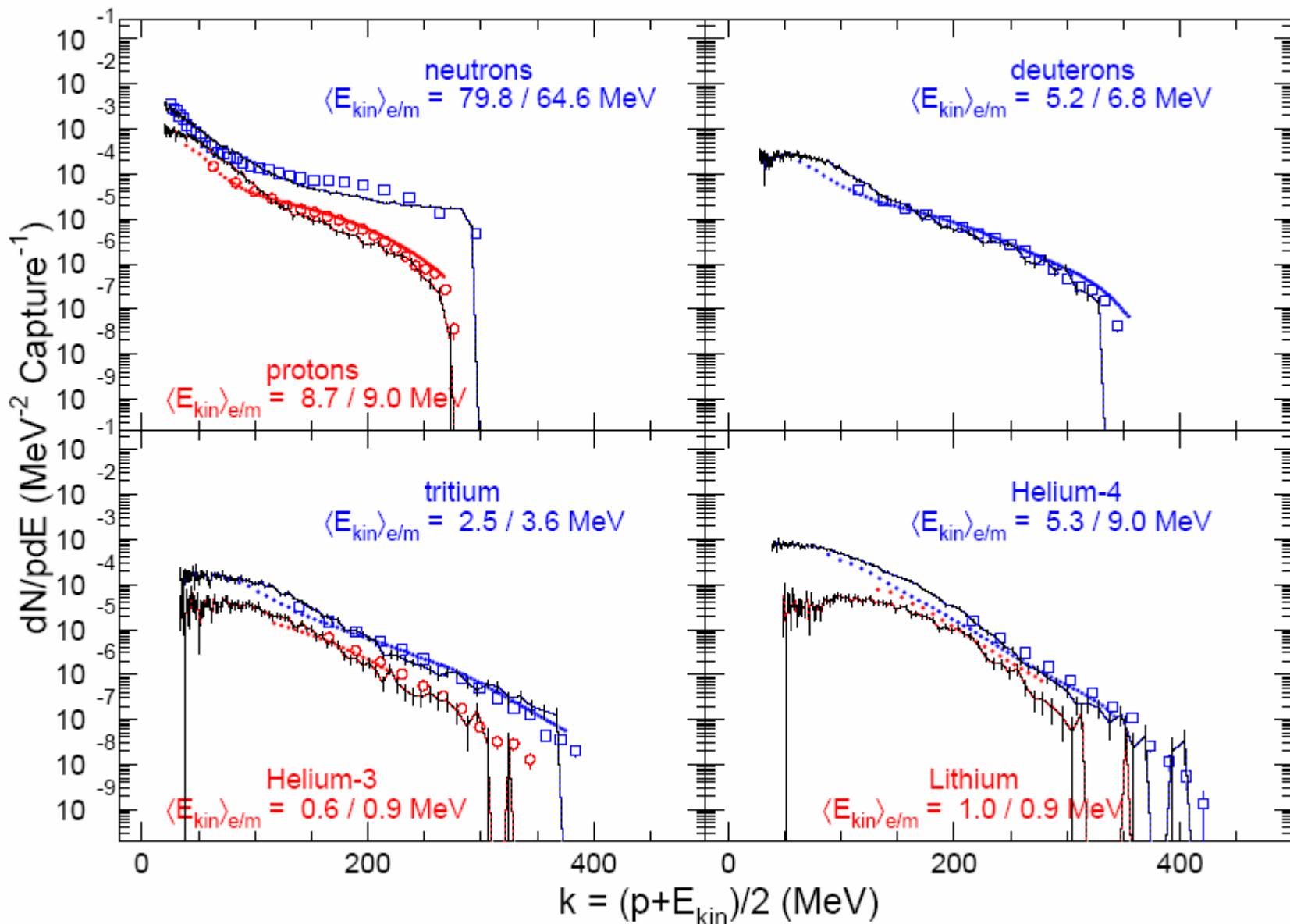
Hadron capture at rest on nuclei

Following processes implemented
by CHIPS model
(LEP models also available,
however not as detailed)

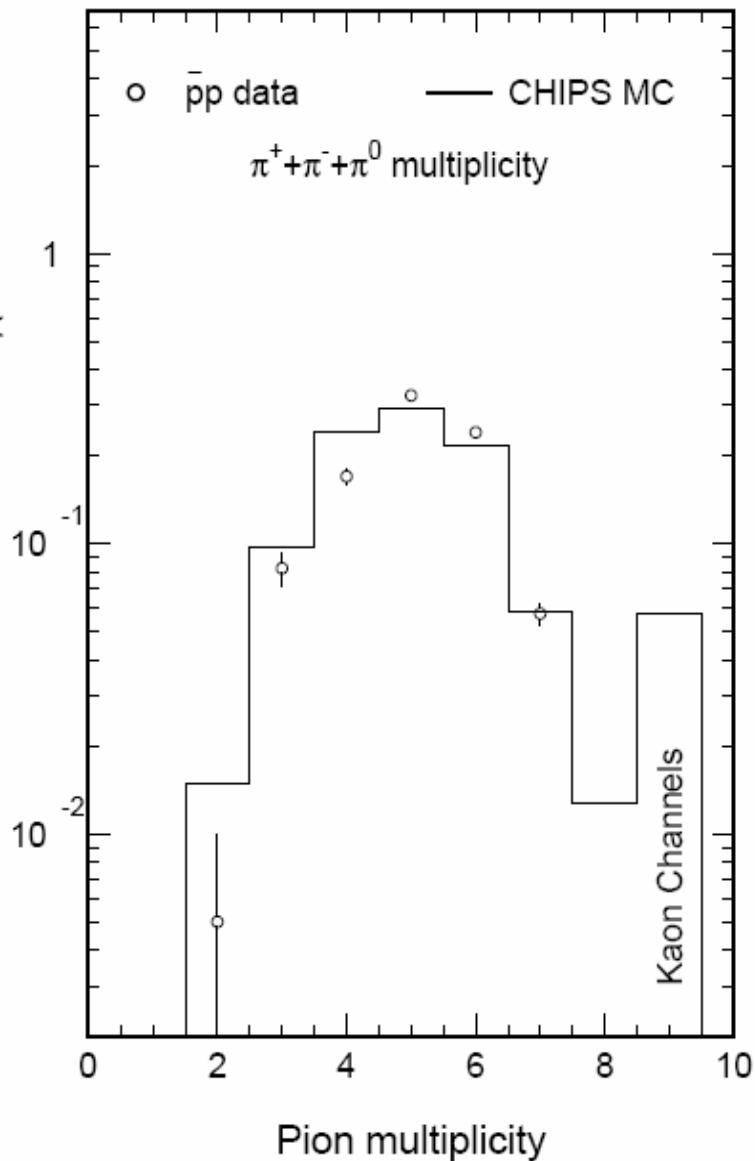
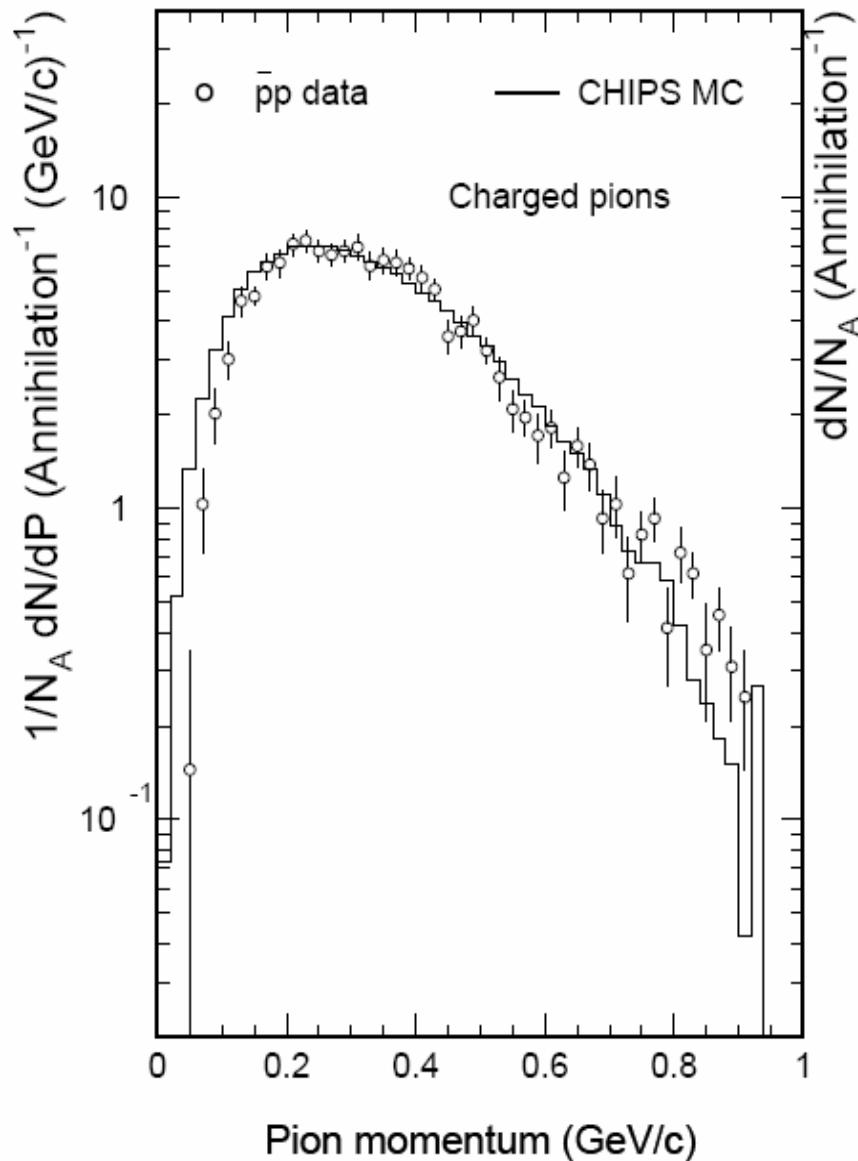
Verification of nuclear capture at rest

CHIPS Model

Pion capture on ^{12}C nucleus

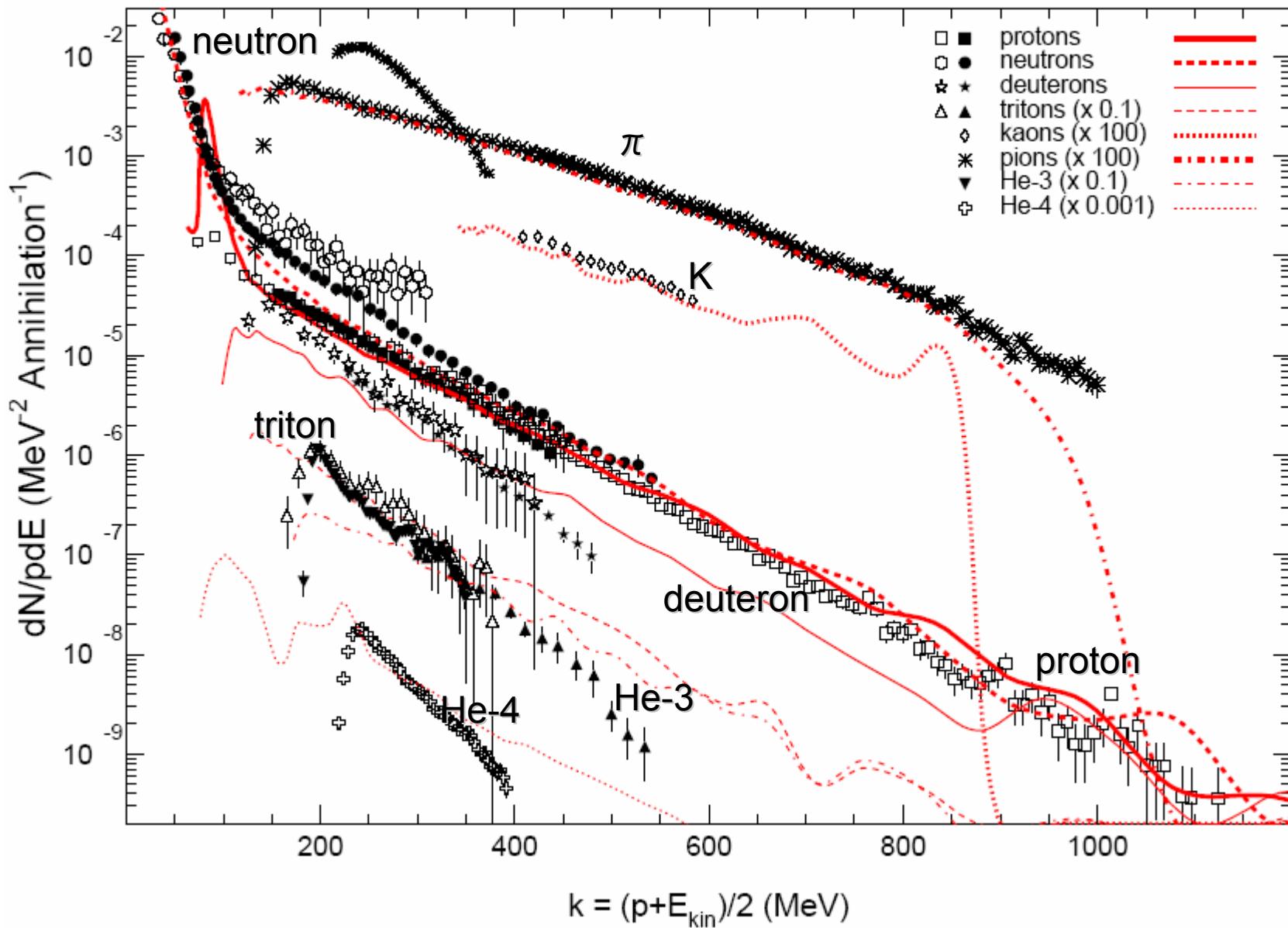


Verification of nuclear capture at rest CHIPS Model



CHIPS Model

Antiproton annihilation on ^{238}U nucleus



Pre-compound model

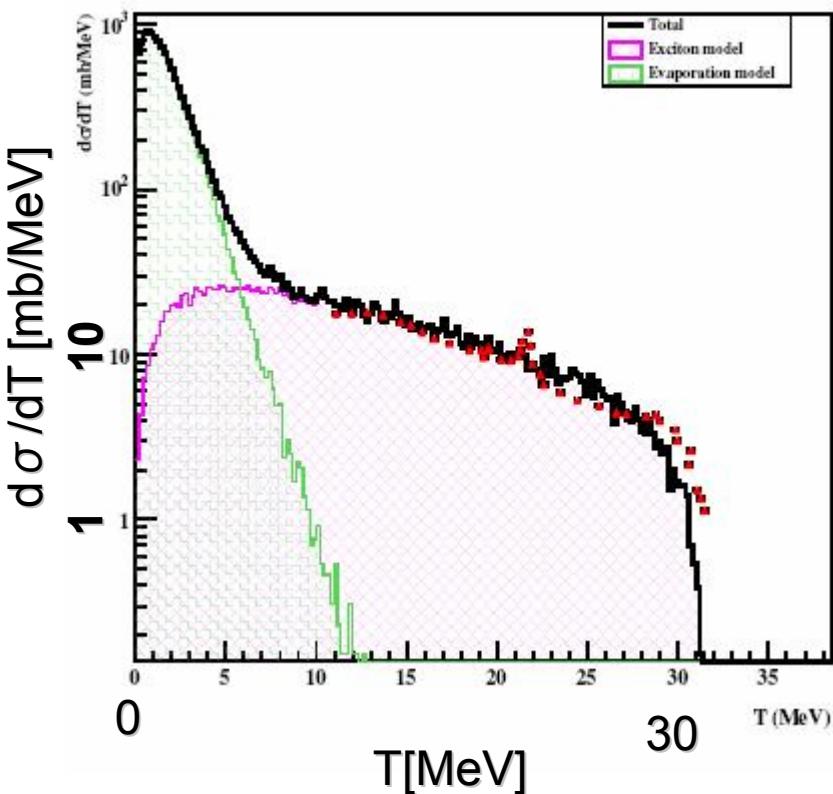
- In following plots the Geant4 pre-compound model coupled with evaporation model to handle low energy de-excitation of nucleus
- Pre-compound is exciton model

Neutron Production Cross Section

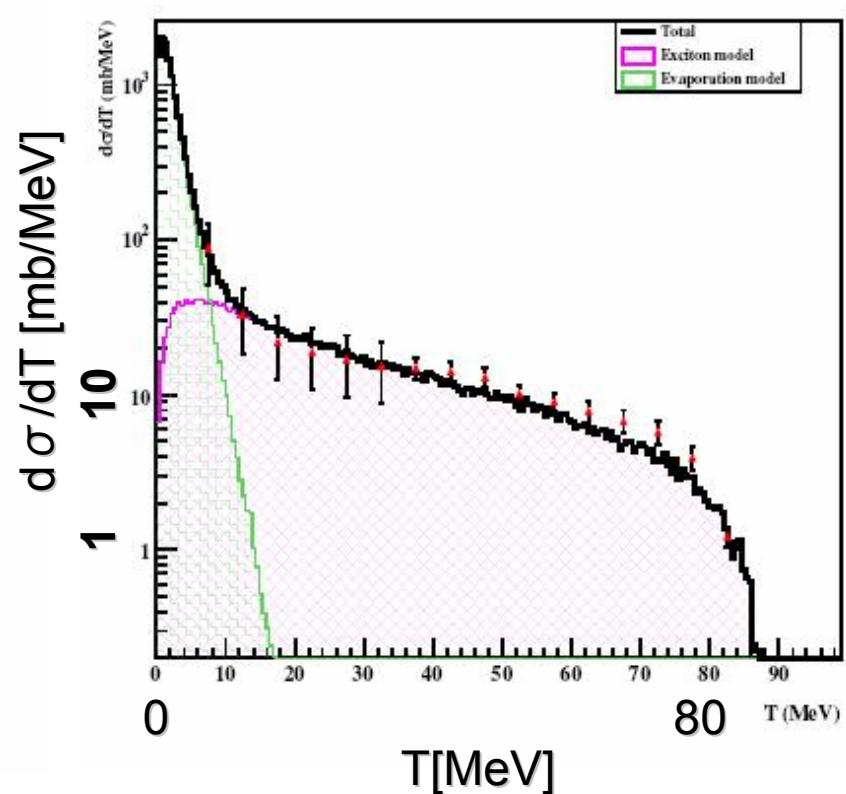
Secondary neutrons are created in

Exciton (Pre-compound)

Evaporation



Sn (p, X n) 35MeV



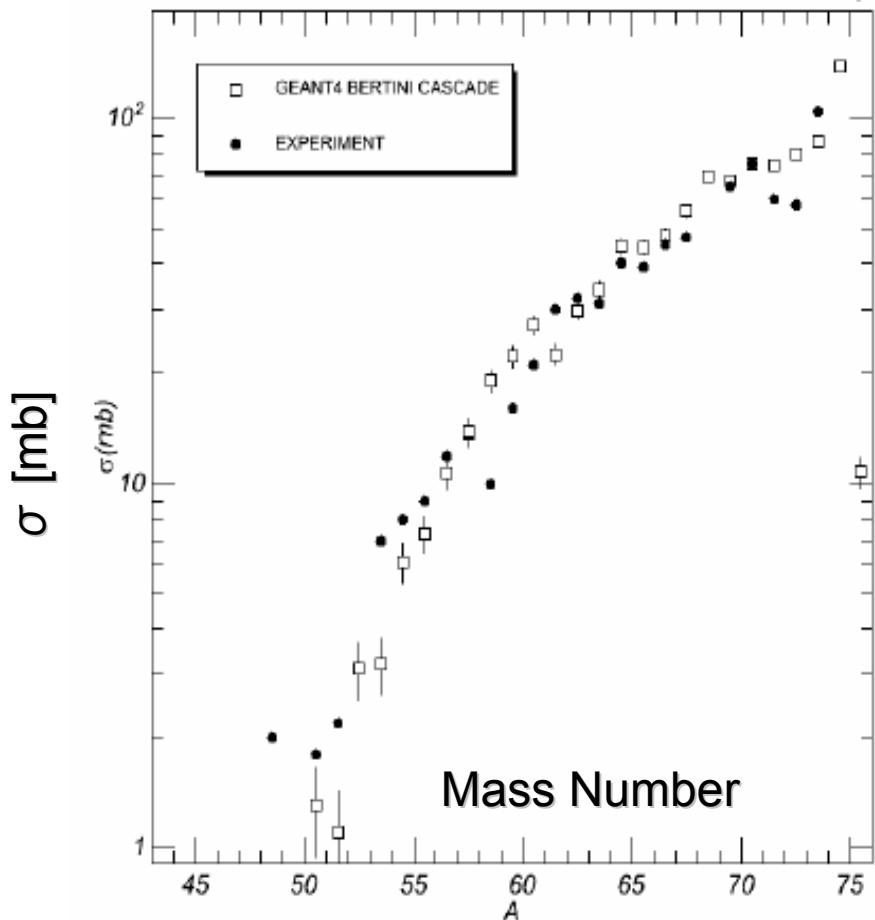
Bi (p, X n) 90MeV

Isotope production by pre-compound models

- We have two pre-compound models.
 - One is currently integrated within Bertini Model
 - Another is implemented independently, so that it can be used by itself or coupled to Binary and/or High energy Models
- The range of nuclear excitation energies handled by these pre-compoud models are most important to isotope production
- Next two slides compare the two models to data.

Isotope production by Bertini Model

Mass Yield curve for 78As with 380 MeV protons



Average production number of neutron and proton

$p(2.5 \text{ GeV}) + \text{Au}:$

ABLA $\langle n \rangle = 18.0, \langle p \rangle = 6.7$
Bertini $\langle n \rangle = 24.5, \langle p \rangle = 8.8$

$p(1.0 \text{ GeV}) + 208\text{Pb}:$

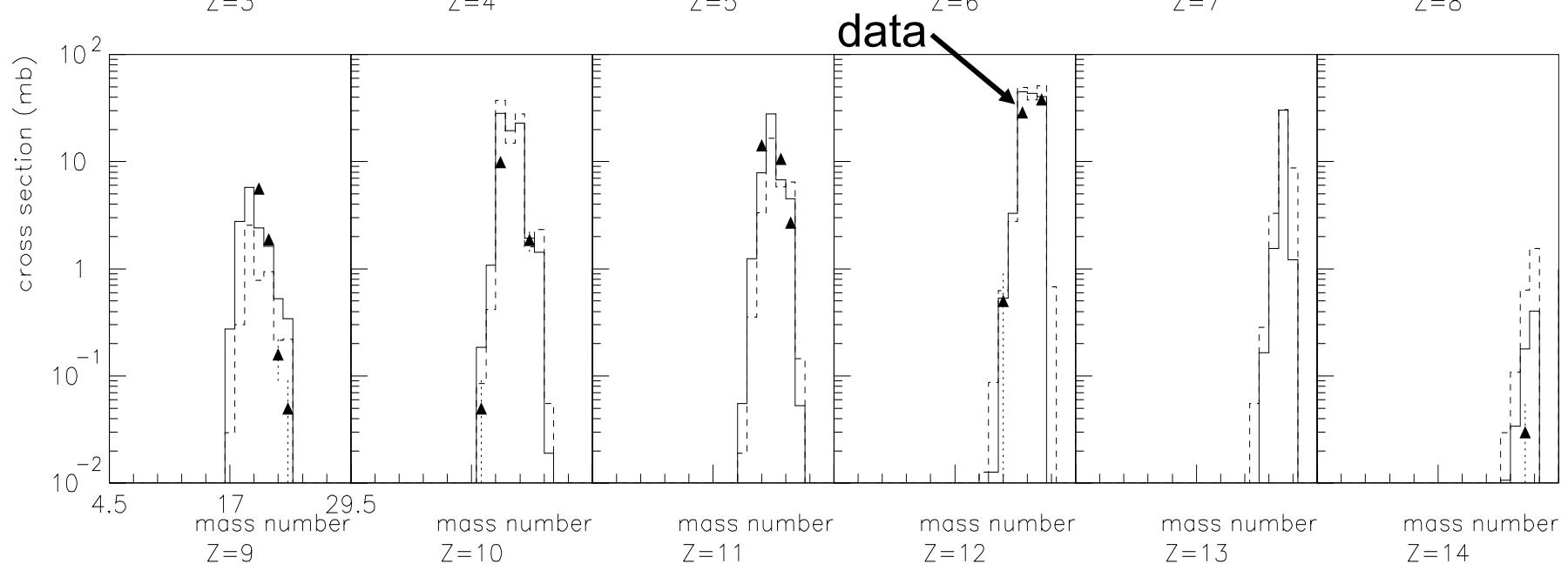
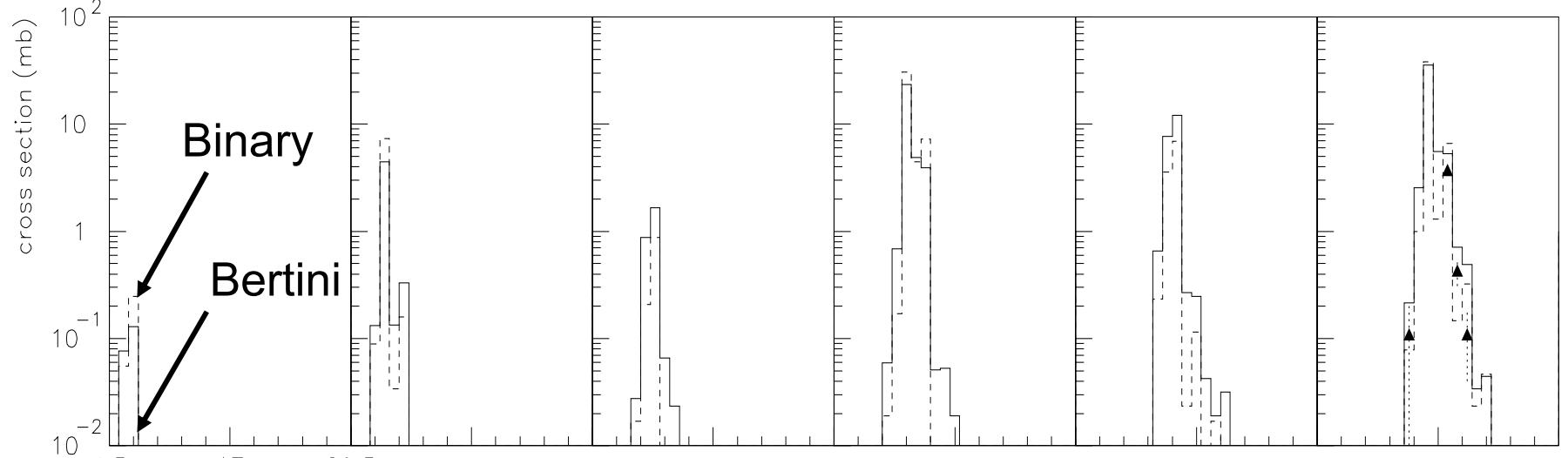
GEM $\langle n \rangle = 15.4, \langle p \rangle = 4.5$
Bertini $\langle n \rangle = 17.4, \langle p \rangle = 3.8$

$p(1.2 \text{ GeV}) + 208\text{Pb}:$

ABLA $\langle n \rangle = 16.6, \langle p \rangle = 4.9$
Bertini $\langle n \rangle = 19.0, \langle p \rangle = 4.4$

Typical performance of Bertini is found to be comparable to codes such as
ABLA (A.R. Junghans *et al.*, *Nucl. Phys. A629* 1998 635)
and GEM (S. Furihata, *Nucl. Inst. & Meth. B171* 2000 251)
which are describing the de-excitation stage

Cross section(mb) vs A (for Element Z) in Al(p,X) at 800 MeV



Intermediate energies ($170 \text{ MeV} < E < 3.0 \text{ GeV}$)

**Binary Cascade
Bertini Cascade
and
LEP**

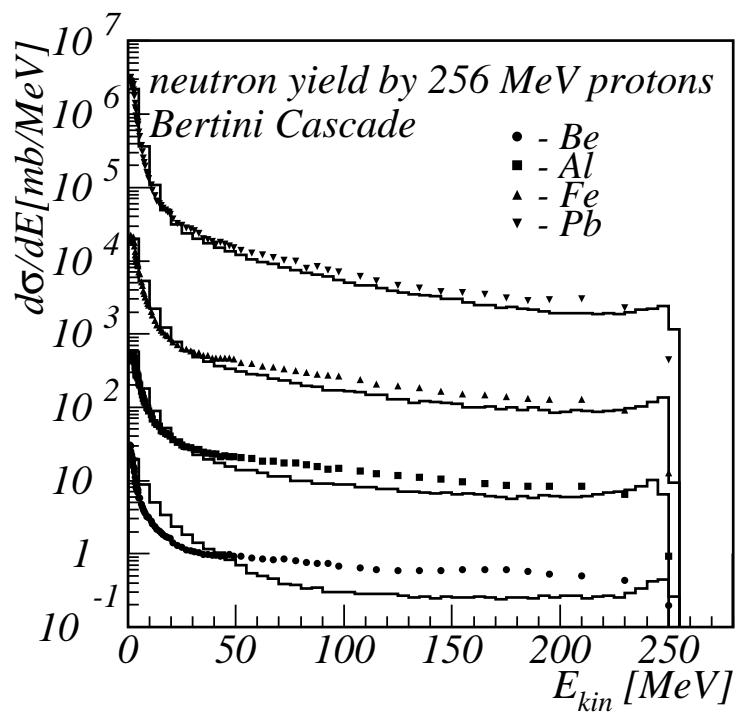
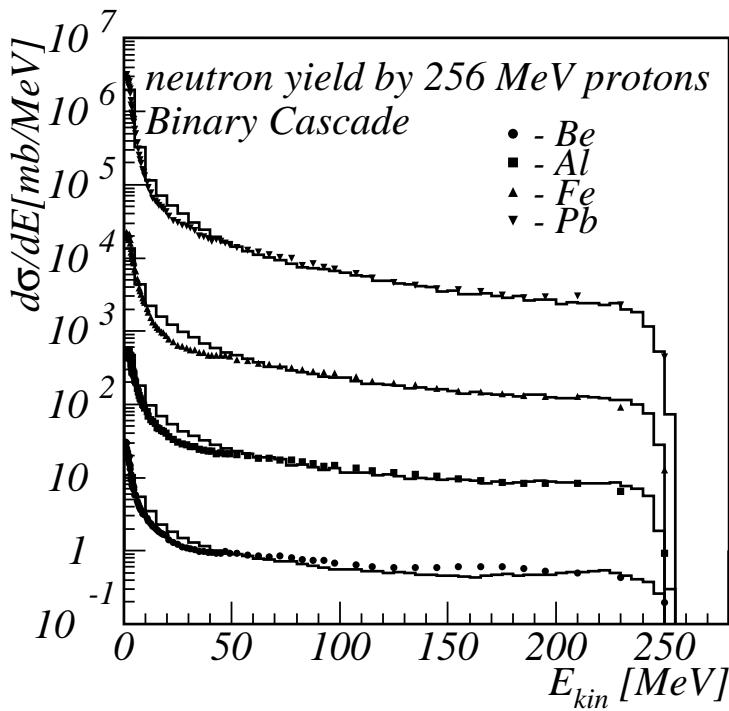


Verification Suite for the Cascade Energy Region

- We have developed since 2002 as test30
- Neutron production by p, d, α , ^{12}C with $E < 3 \text{ GeV}$
 - $P + A \rightarrow n + X$
 - $d + A \rightarrow n + X$
 - $\alpha + A \rightarrow n + X$
 - $^{12}\text{C} + A \rightarrow n + X$
- Pion production
 - $P + A \rightarrow \pi^\pm + X$
- 73 thin target experiments with reasonably small systematic
- Control on differential spectra (63 histograms)
- Models under testing:
 - Binary Cascade
 - Binary Light Ion Cascade
 - Bertini Cascade
 - Wilson-Abrasion model
 - CHIPS
 - LEP
- Additionally to double differential spectra for comparisons with the data a set of histograms with inclusive spectra is produced

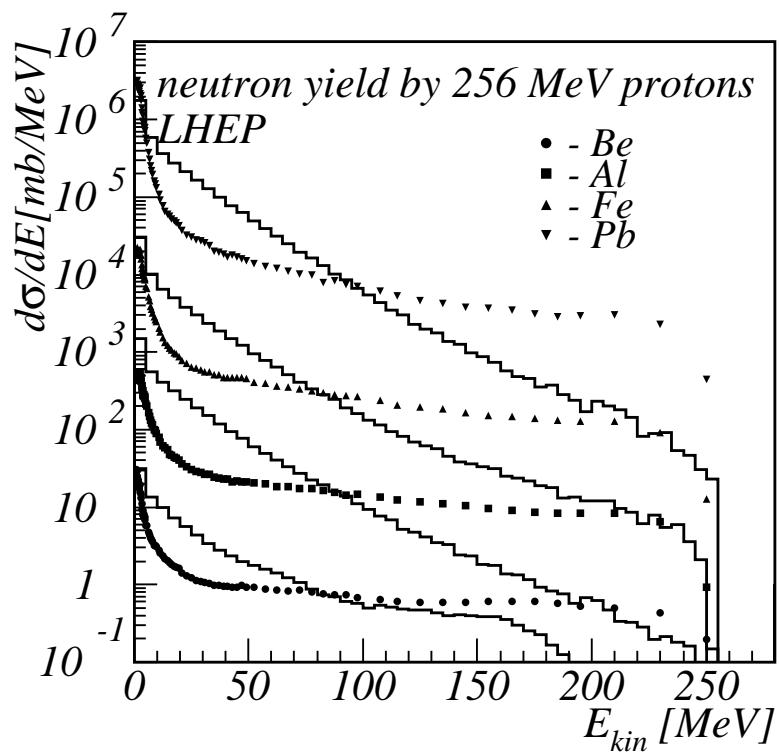
Neutron spectra by 256 MeV protons

Binary and Bertini Cascades



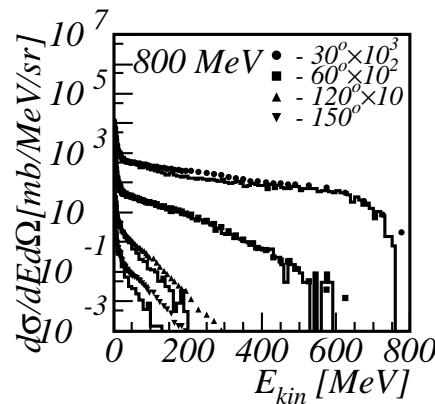
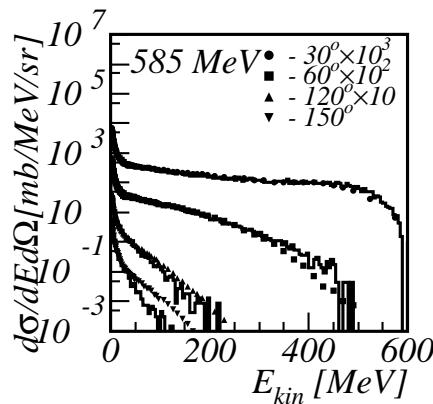
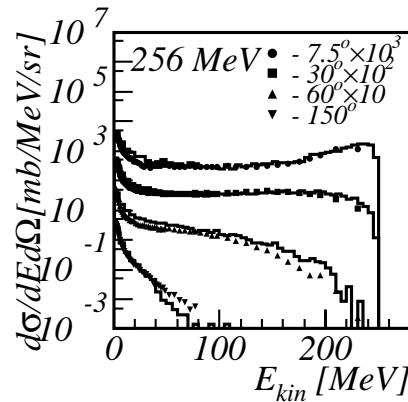
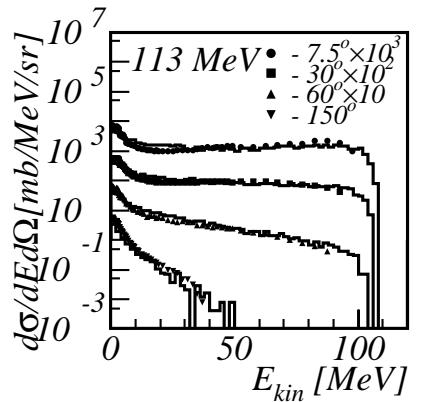
Neutron spectra by 256 MeV protons

LEP

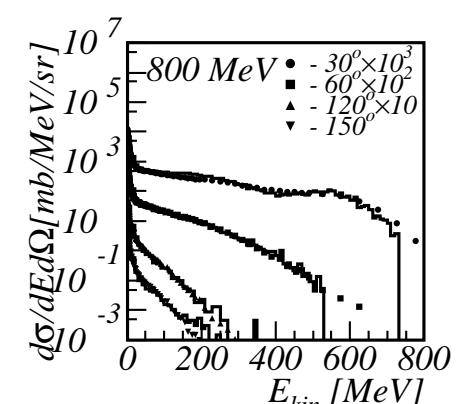
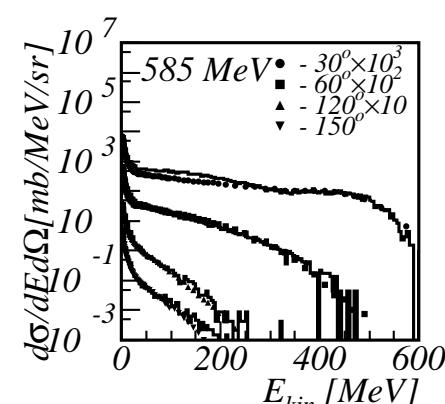
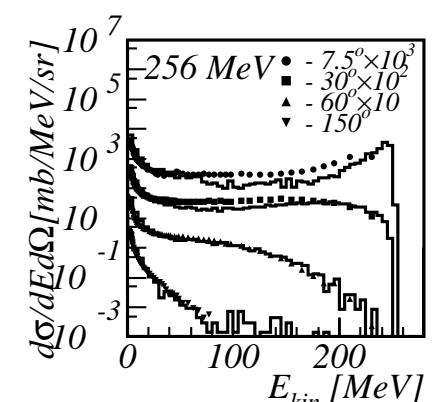
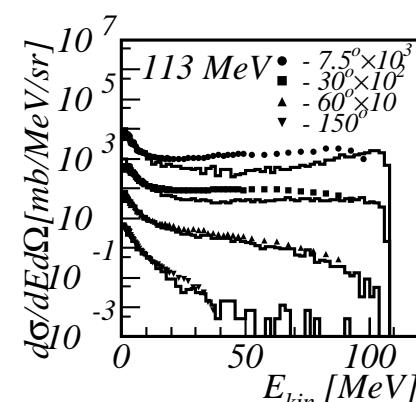


Neutron spectra by protons in Aluminum

Binary Cascade

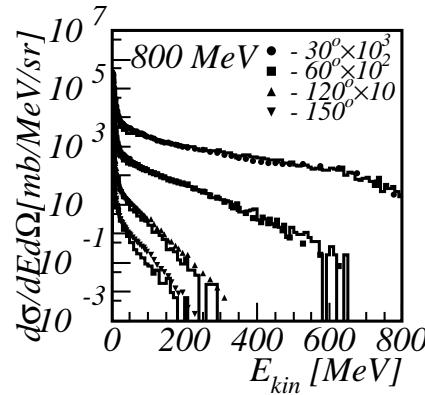
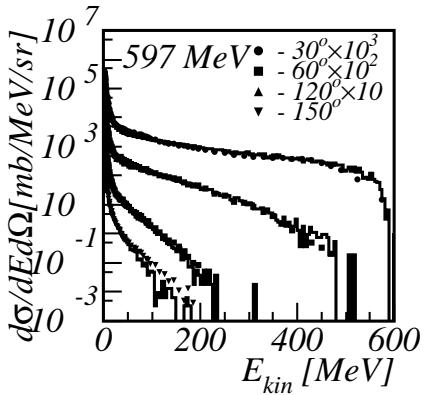
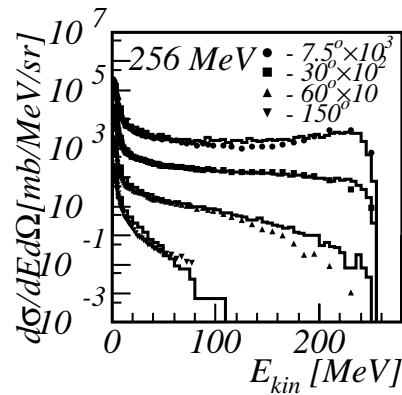
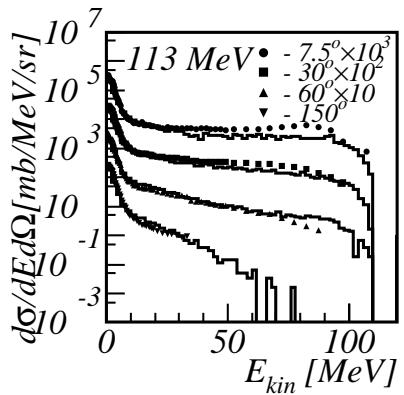


Bertini Cascade

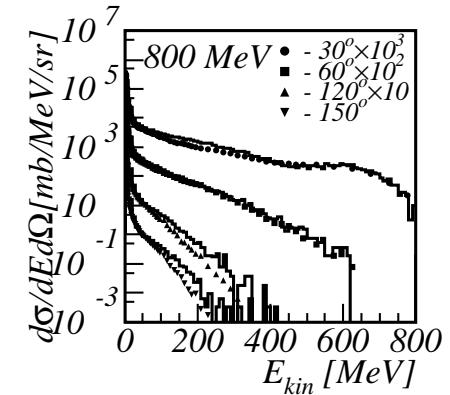
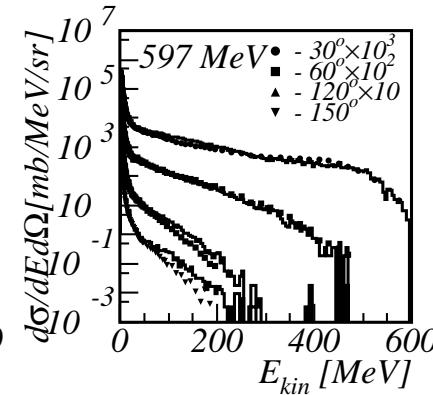
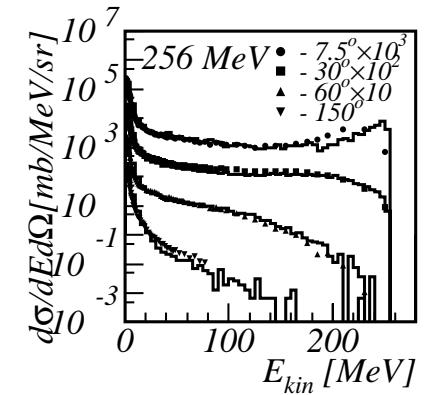
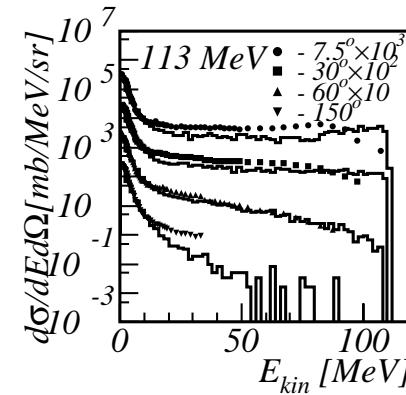


Neutron spectra by protons in Lead

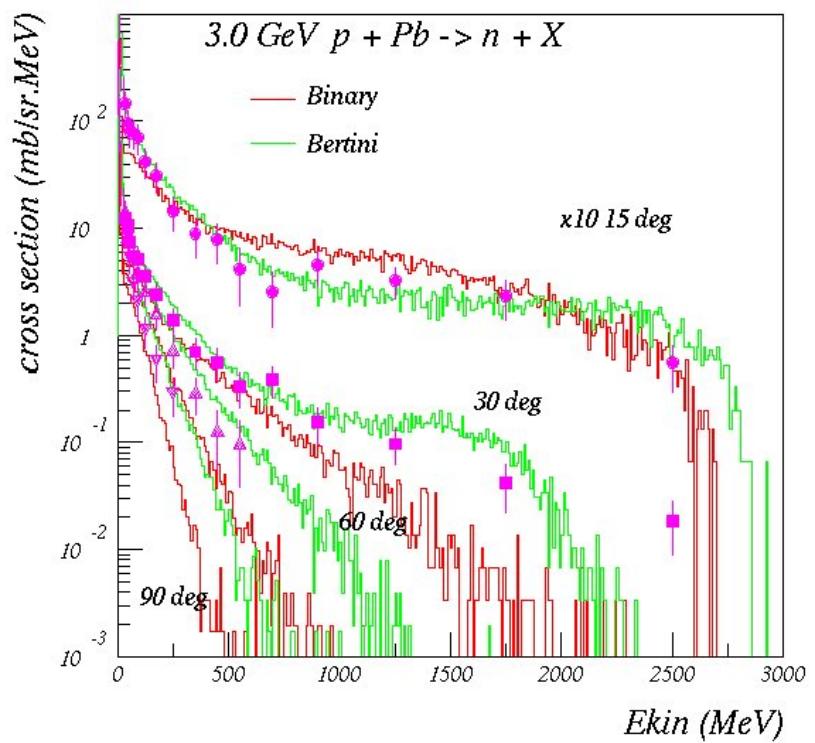
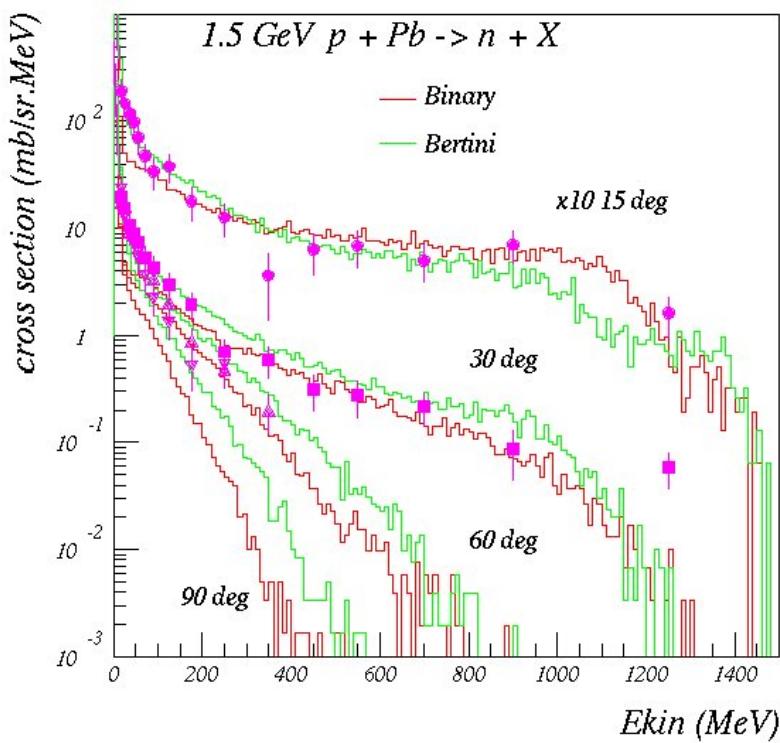
Binary Cascade



Bertini Cascade

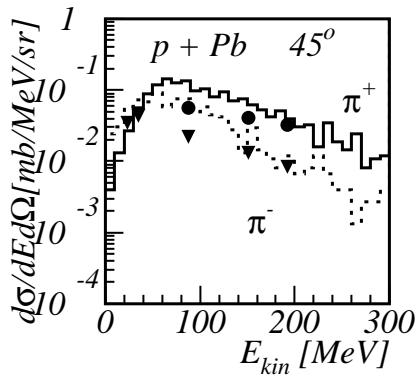
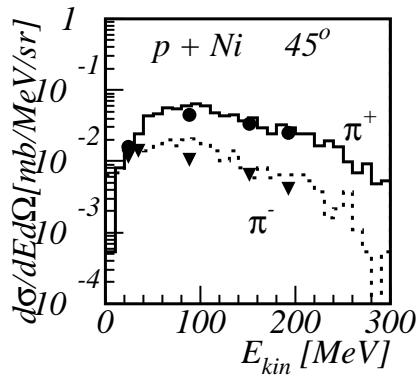
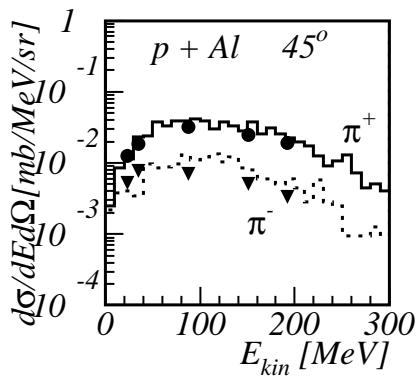
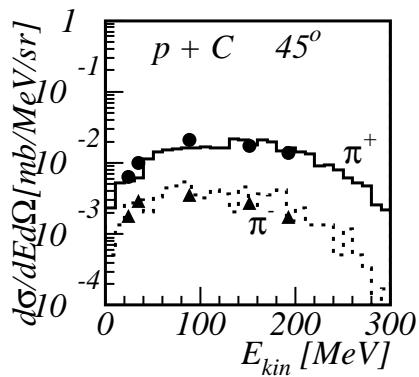


Neutron spectra by 1.5 and 3 GeV protons on lead

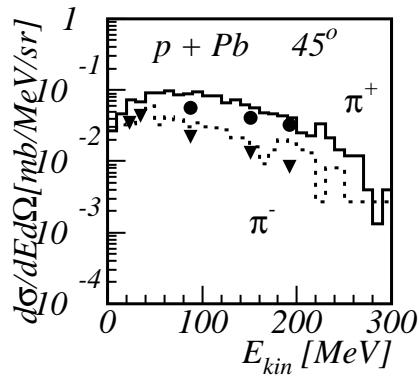
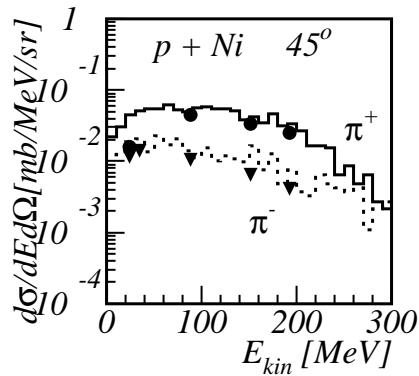
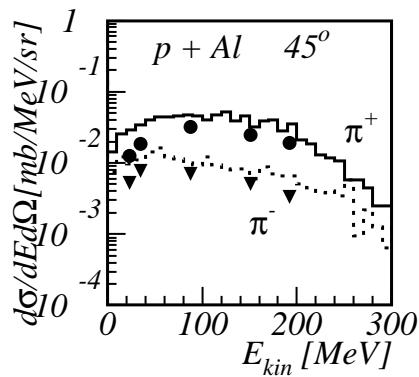
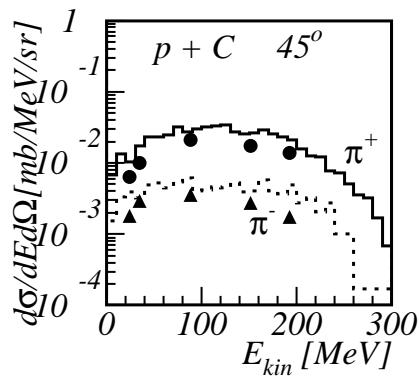


Charged pions spectra produced by 600 MeV protons at 45 degrees

Binary Cascade



Bertini Cascade



Around a few 10 of GeV
we only have parameterization
models (LEP and HEP).

And we are working on alternative
models in this energy range.

New parameterized model
and/or
Extended Bertini model

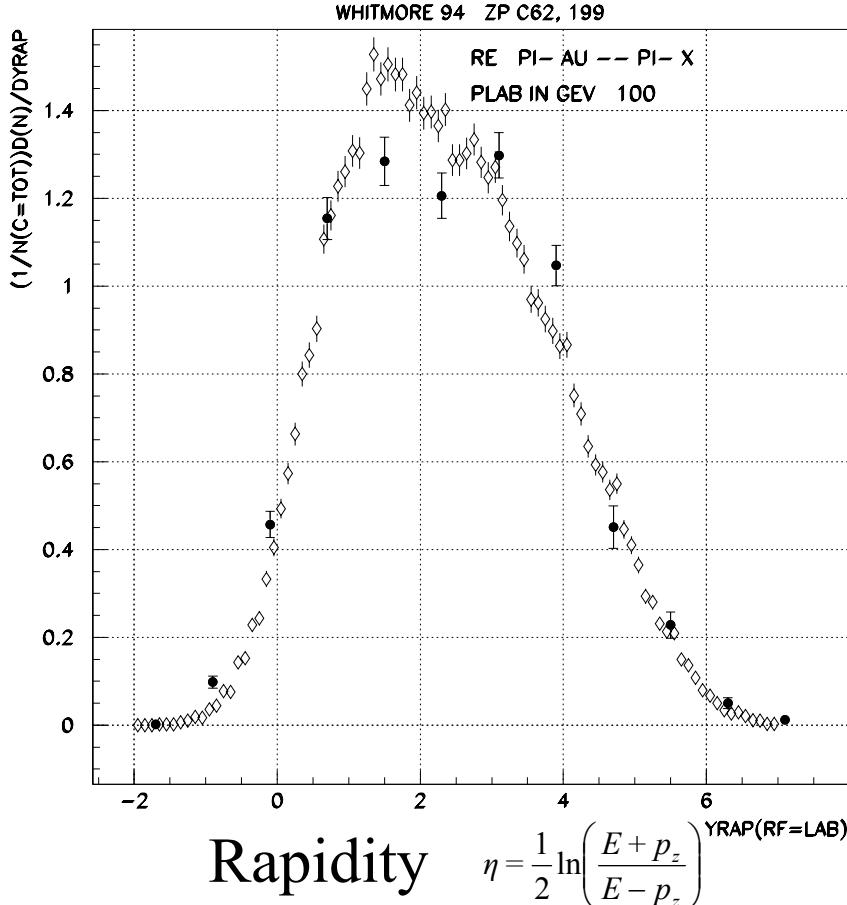
High Energy >50GeV

We have 3 models for these energies, however we mainly show results from QGS model.

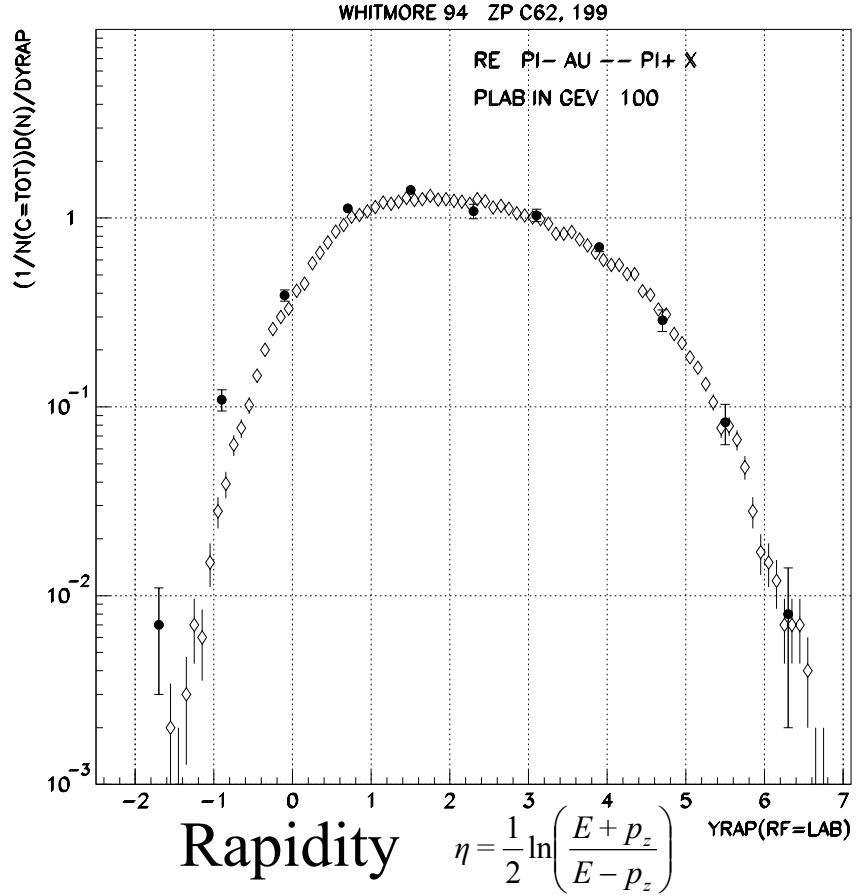
QGS Model

Pi- Scattering on Au, Plab 100 GeV/c

REAC PI- AU -- PI- X

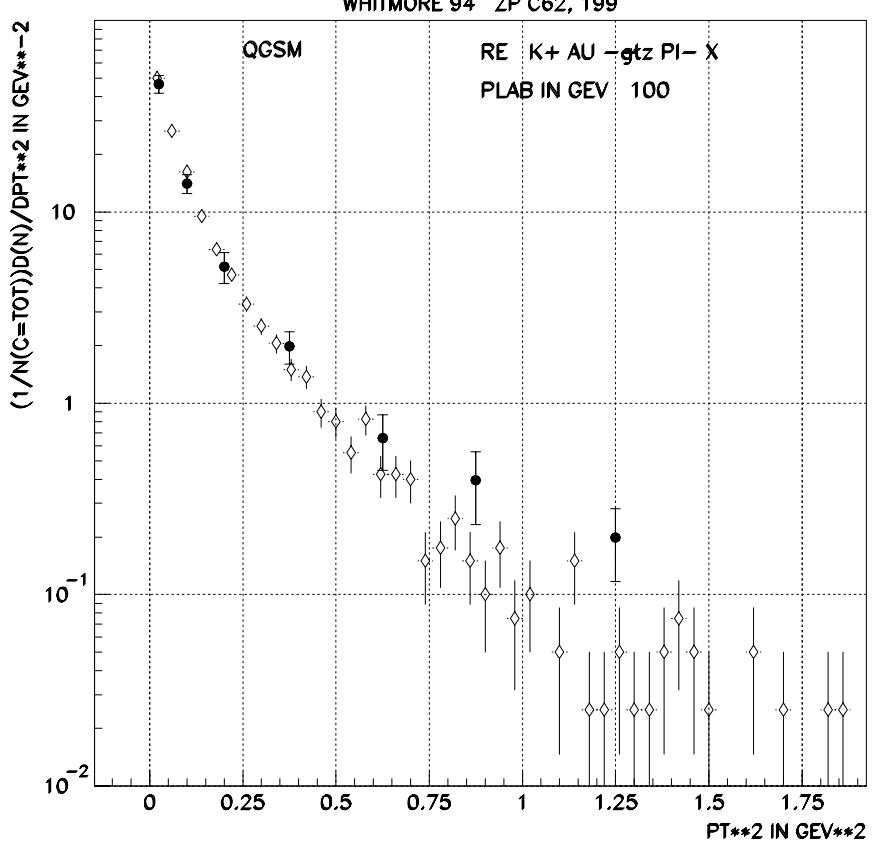


REAC PI- AU -- PI+ X

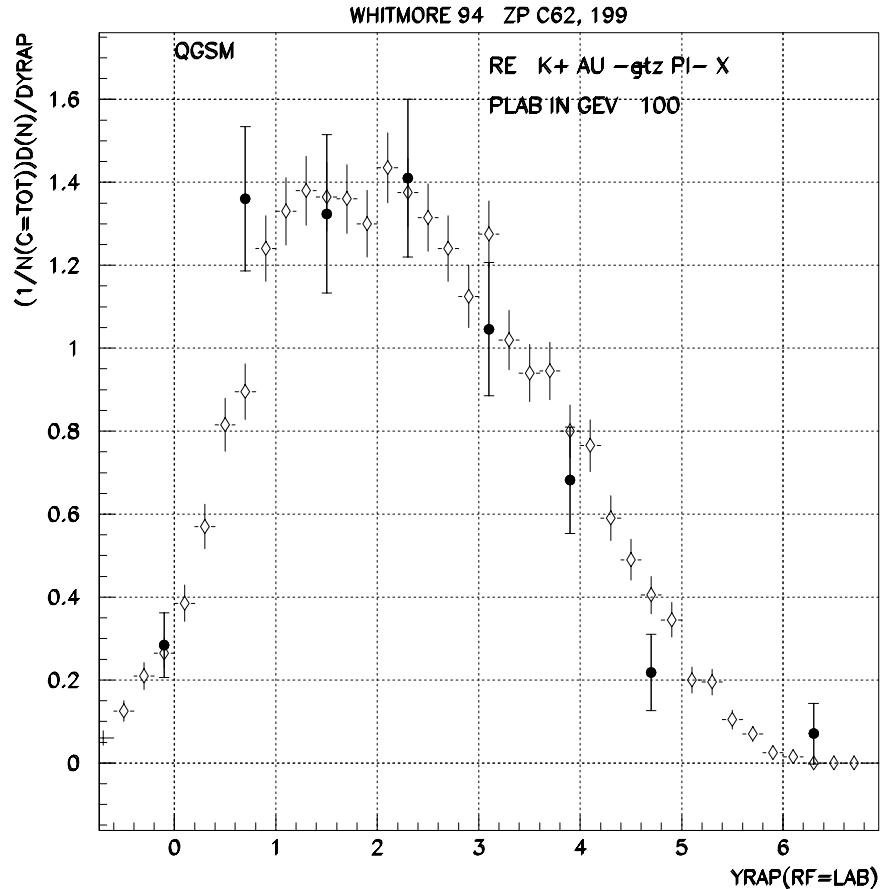


QGS Model

K+ Scattering on Au, Plab100GeV/c



$P_t^2 \text{ [GeV}^2]$

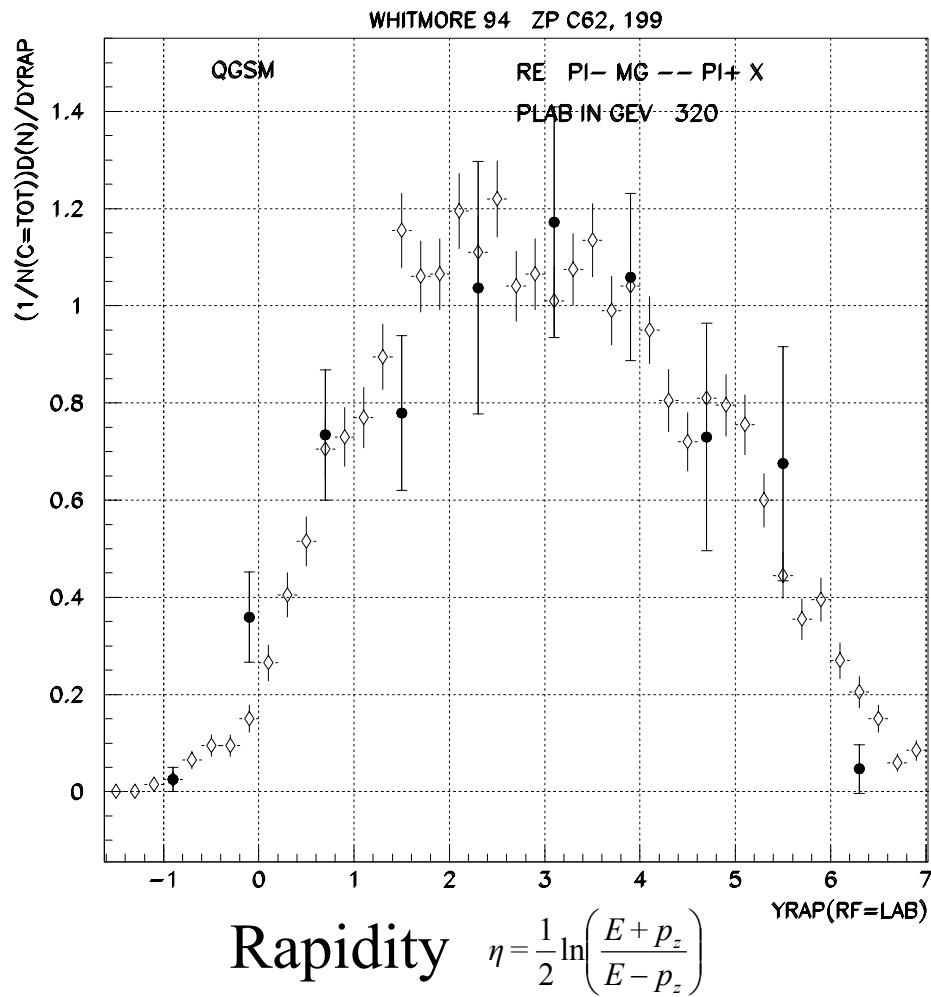
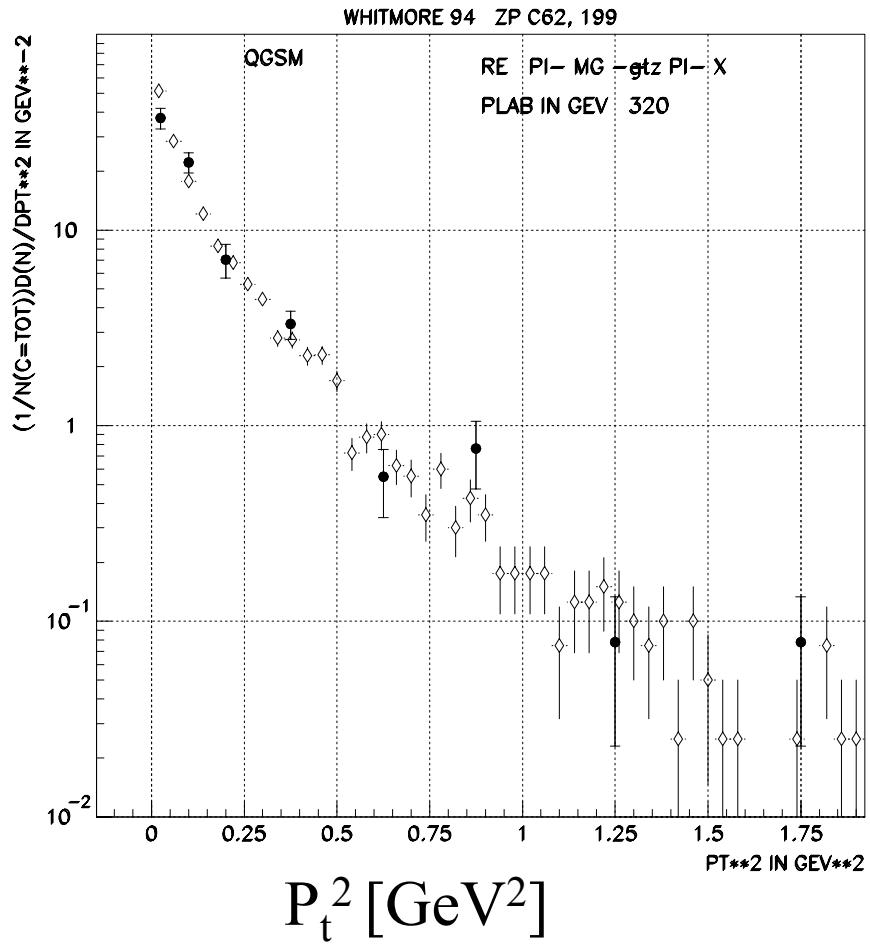


Rapidity $\eta = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$

Solid dots: J.J.Whitmore et.al., Z.Phys.C62(1994)199

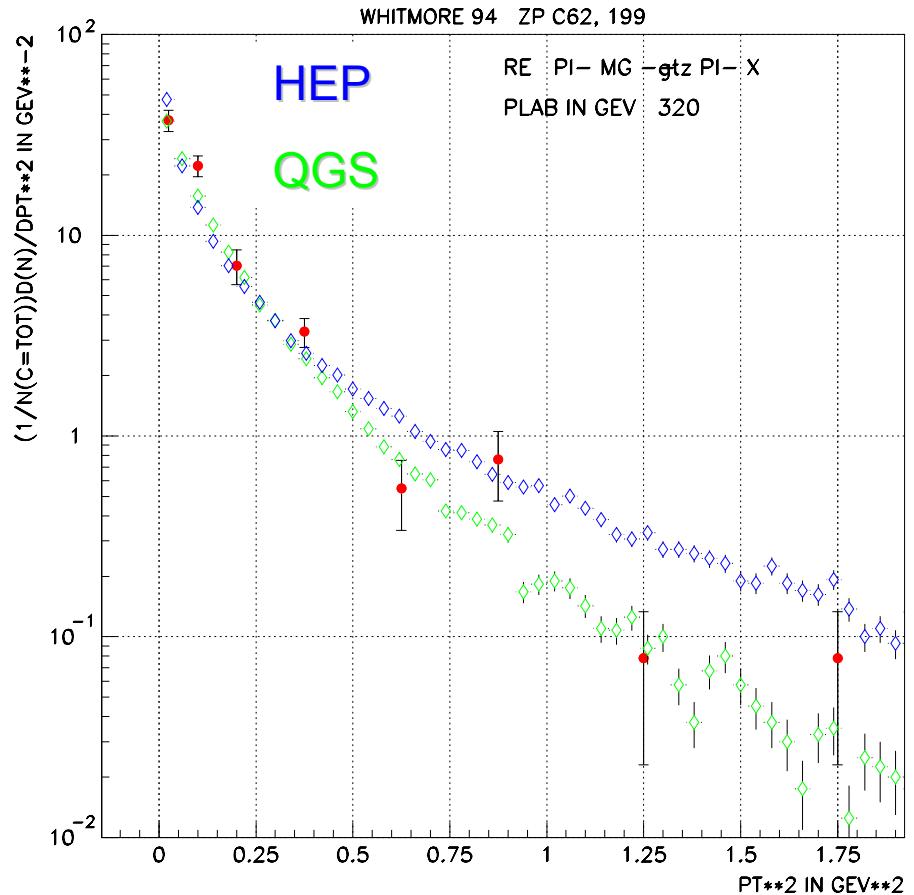
QGS Model

pi- Scattering on Mg, Plab 320 GeV/c

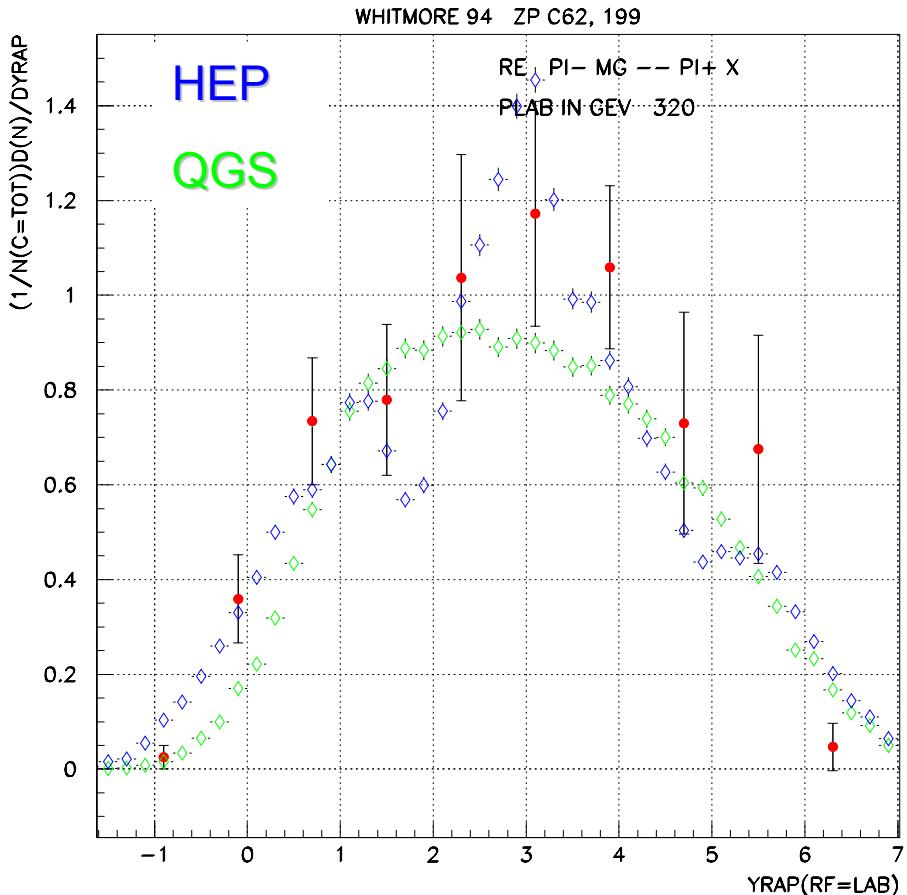


HEP Model

π^- Scattering on Mg, Plab 320 GeV/c



$P_t^2 [\text{GeV}^2]$



Rapidity $\eta = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$

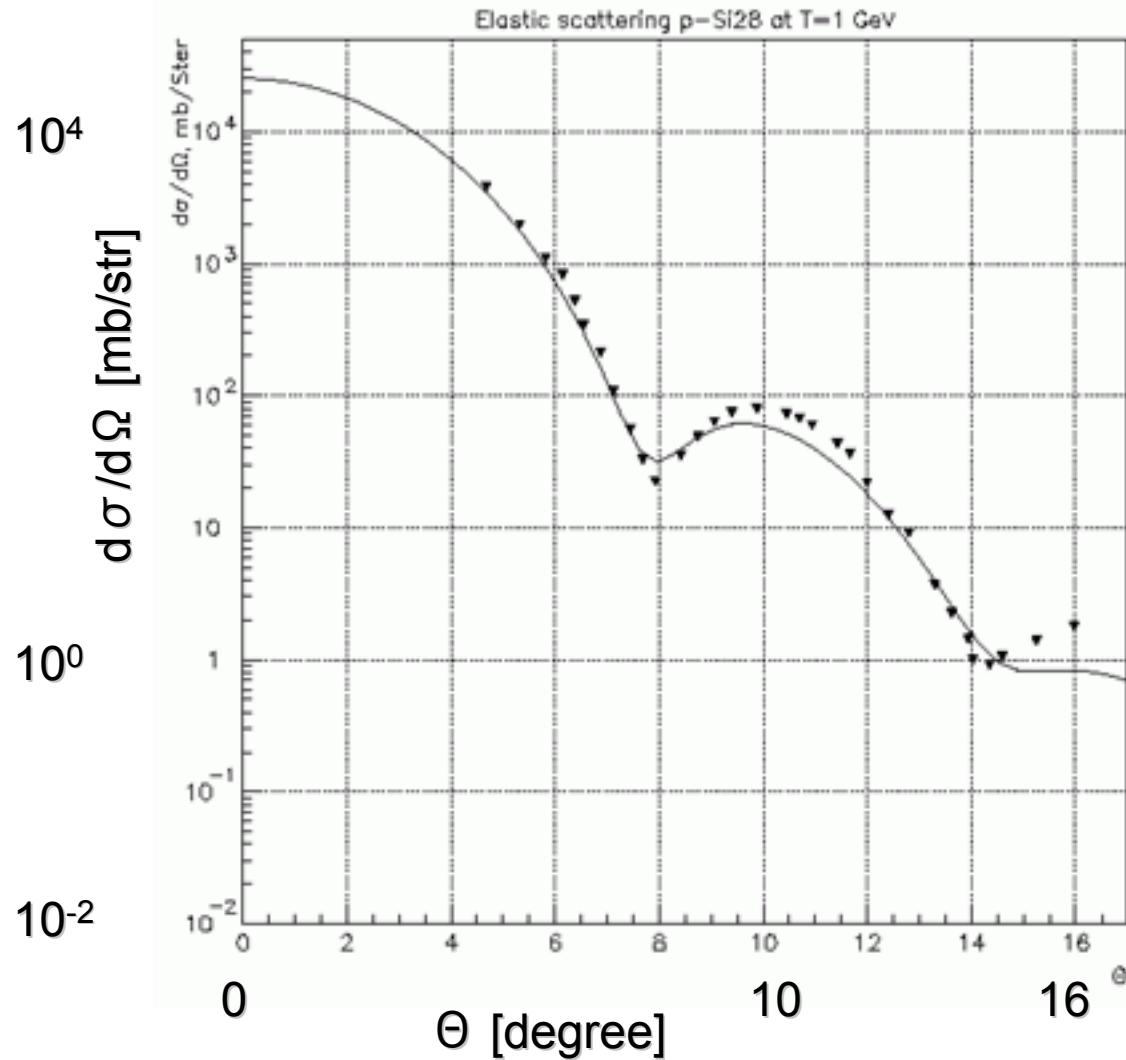
Elastic Scattering

Several models are available

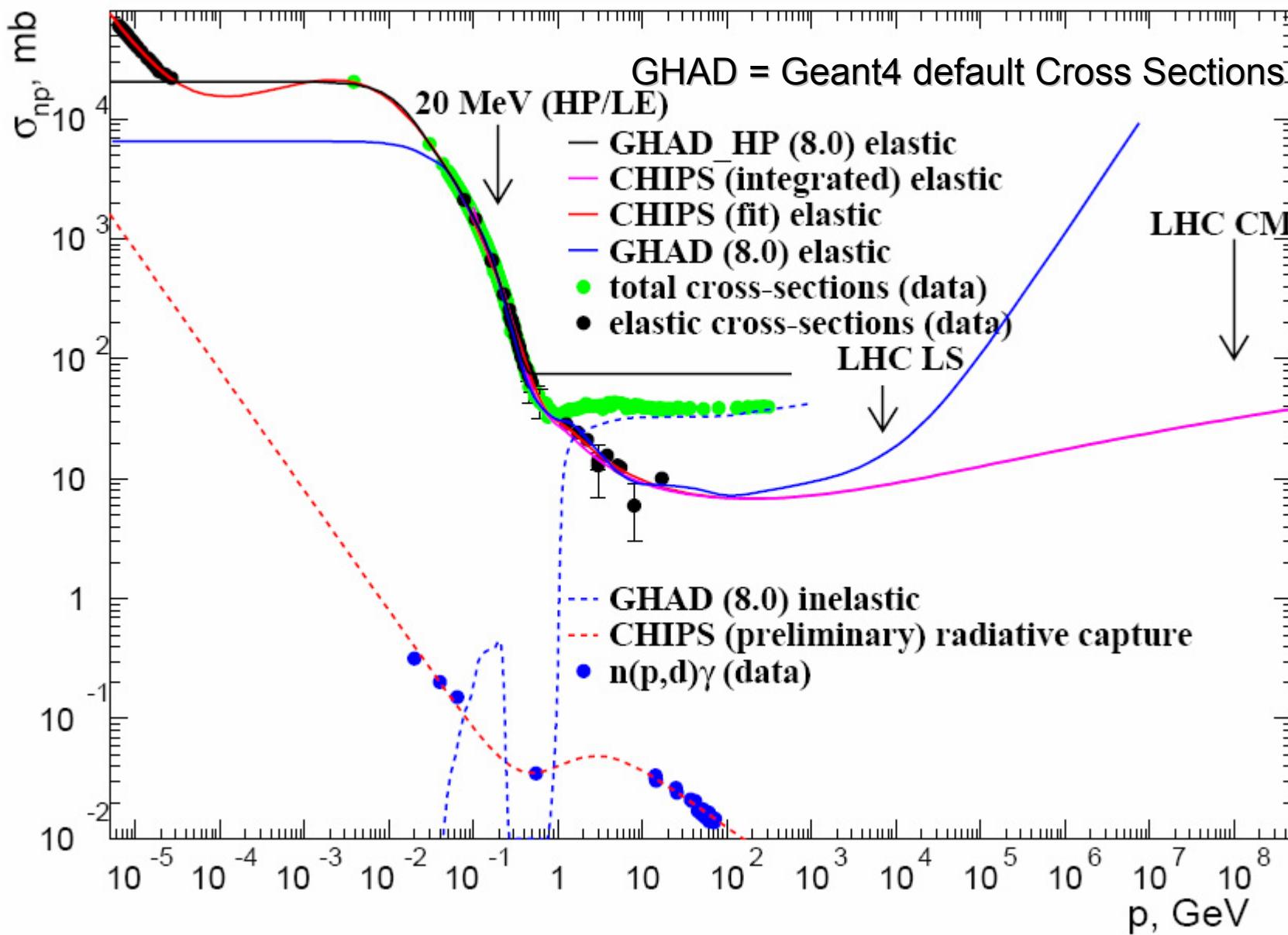
- LElastic (based on GHEISHA) is most widely used elastic model.
- We have several alternative models:
 - LEnp and LEpp (coherent elastic for proton and neutron based on phase shift analysis)
 - HPElastic (neutron nucleus elastic scattering below 20MeV)
 - Coherent Elastic (Glauber model for $> 1\text{GeV}$, hadron nucleus elastic scattering)
 - QElastic (CHIPS implementation of pp pn np elastic scattering)
 - Hadron nucleus elastic scattering under development

Coherent Elastic Model

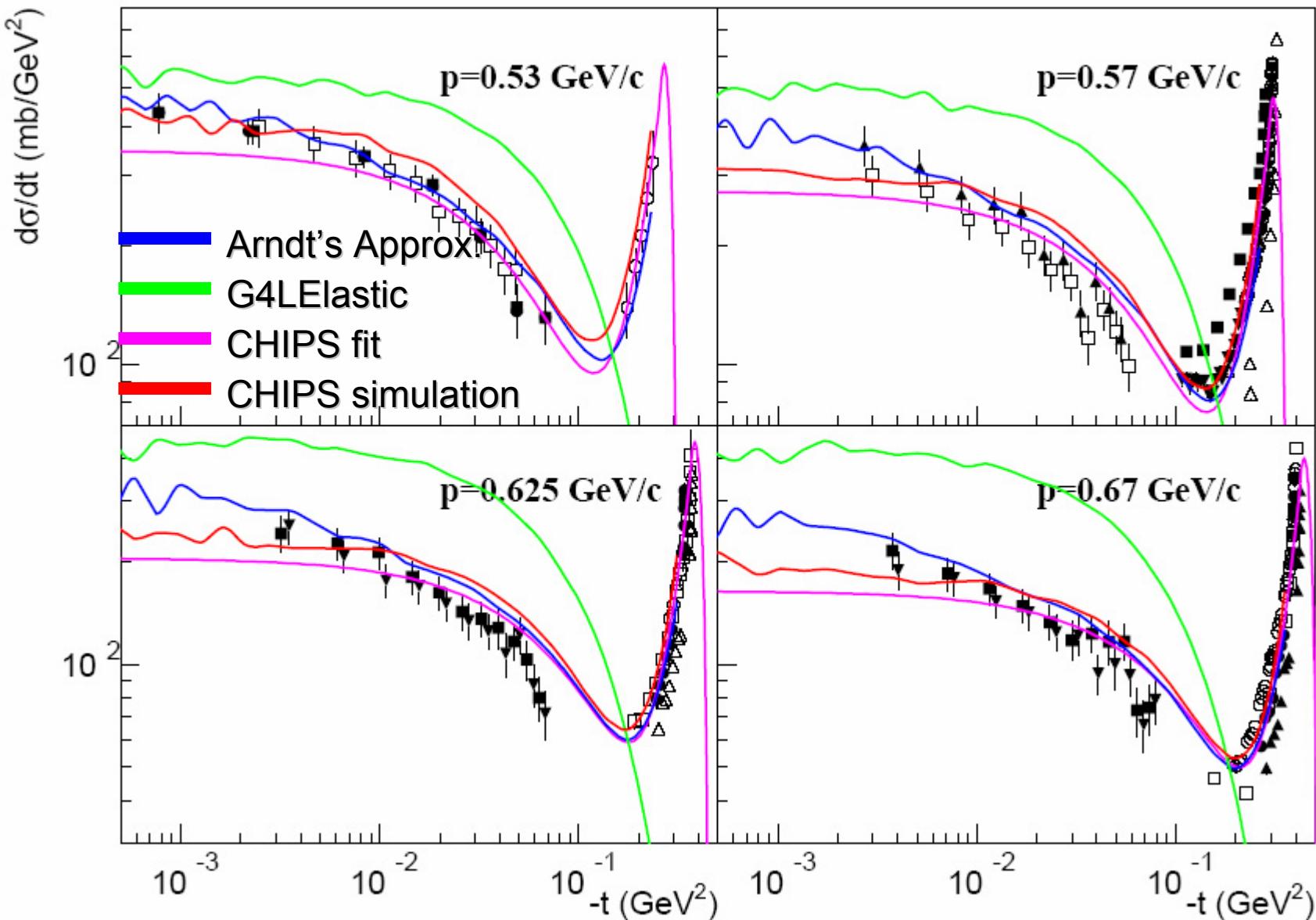
proton 1GeV on ^{28}Si



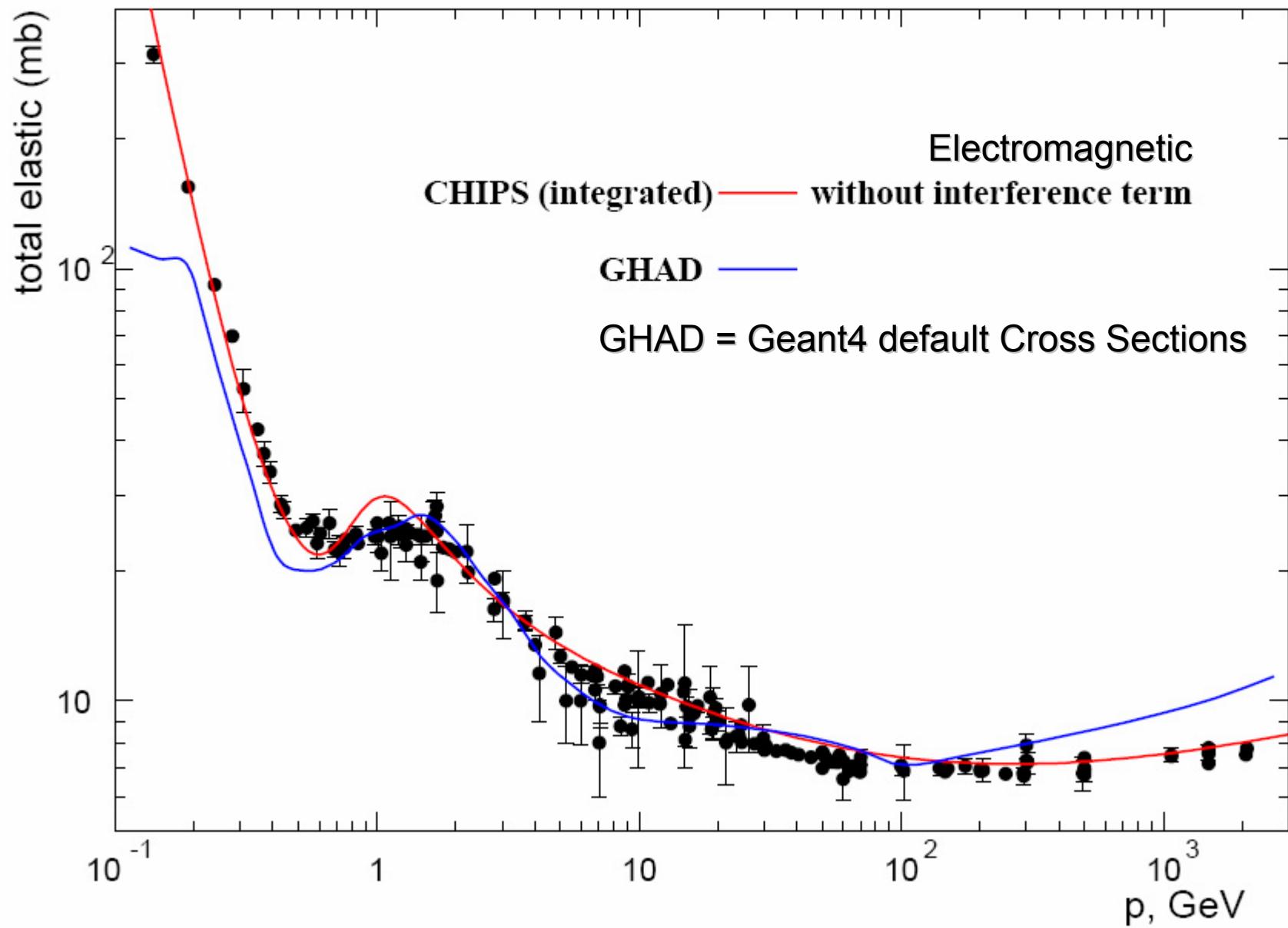
np Elastic Cross Section



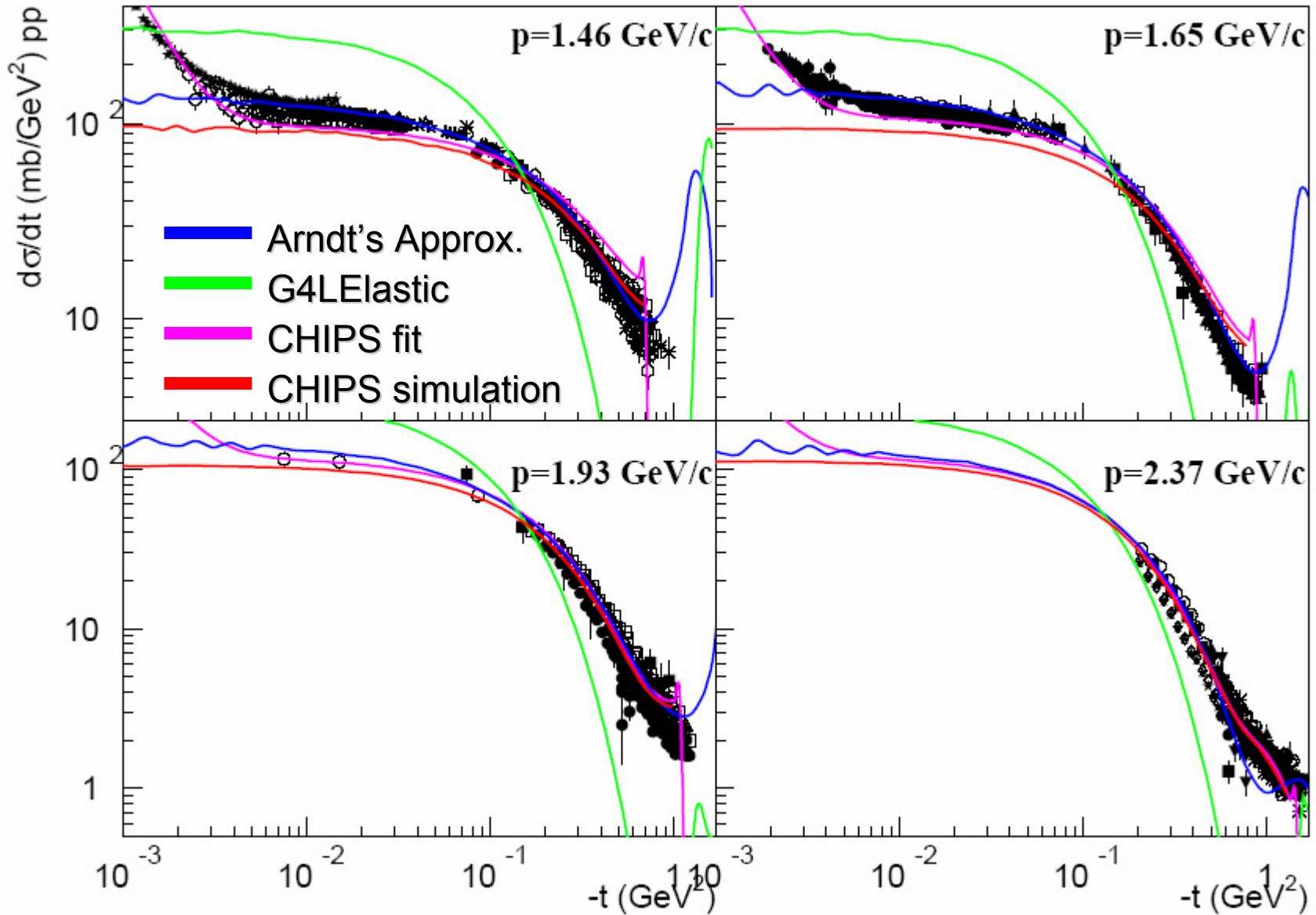
CHIPS improvement of np elastic scattering



pp Elastic Cross Section



CHIPS improvement of pp elastic scattering



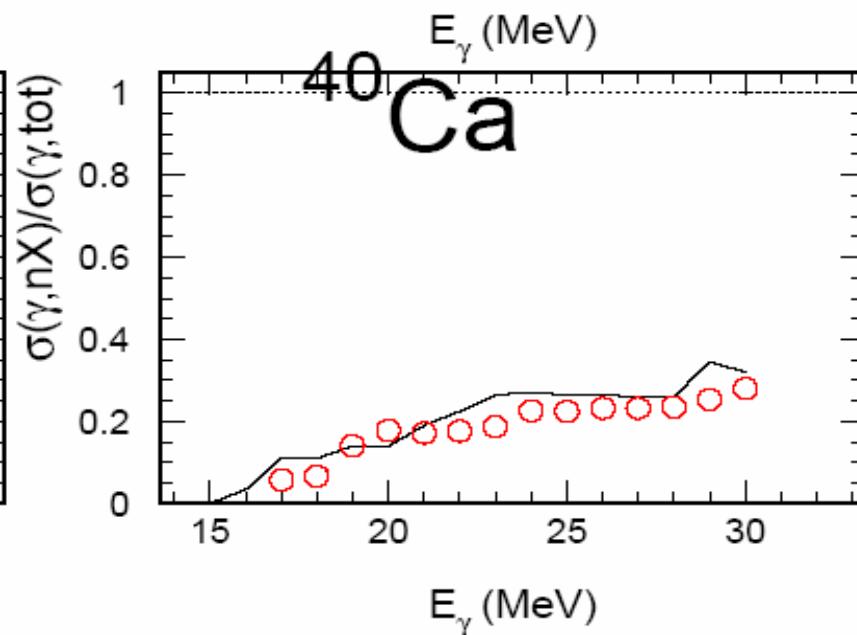
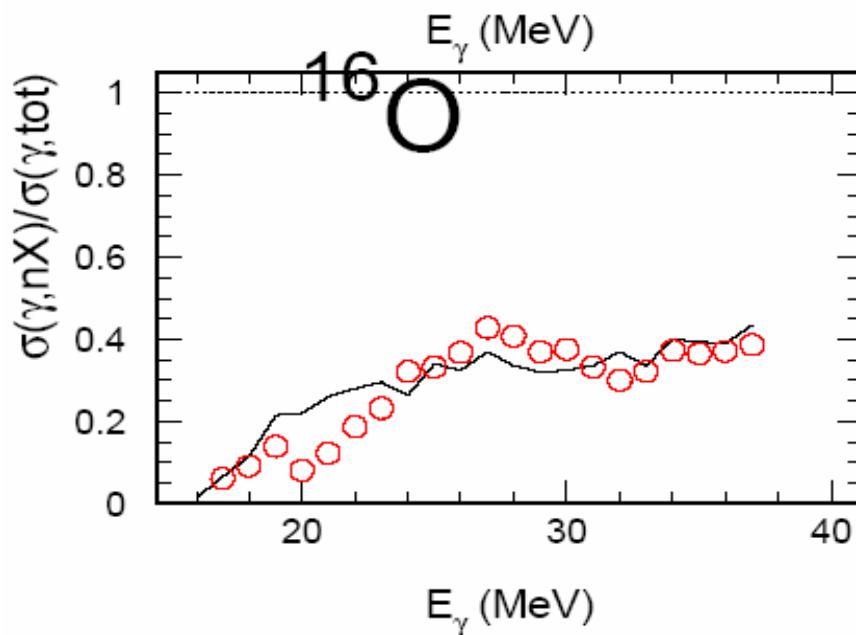
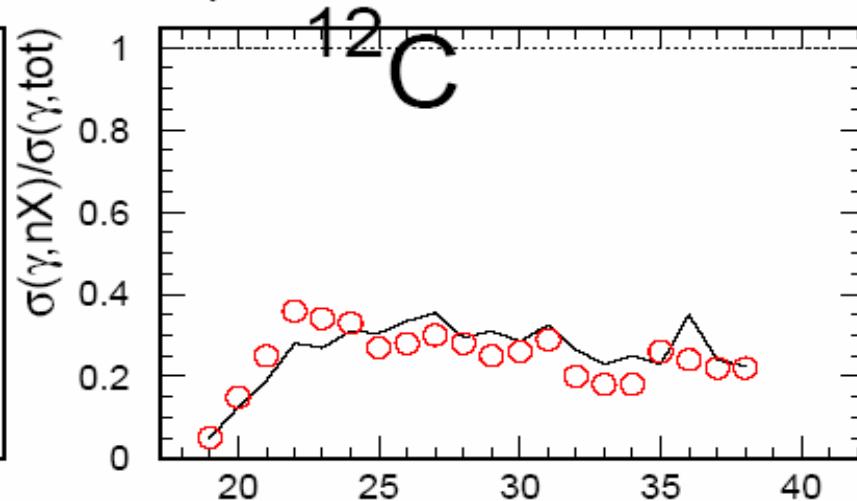
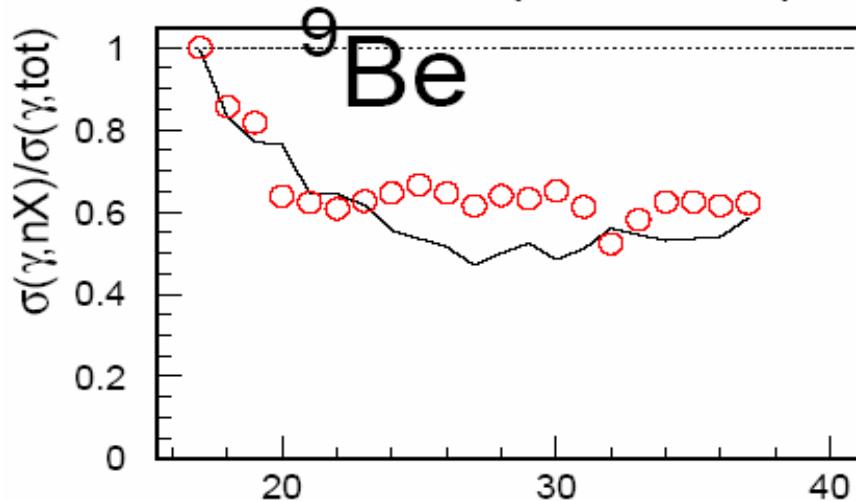
gamma-nuclear reactions

Following plots are validation of
CHIPS implemented processes

Verification of gamma-nuclear reactions

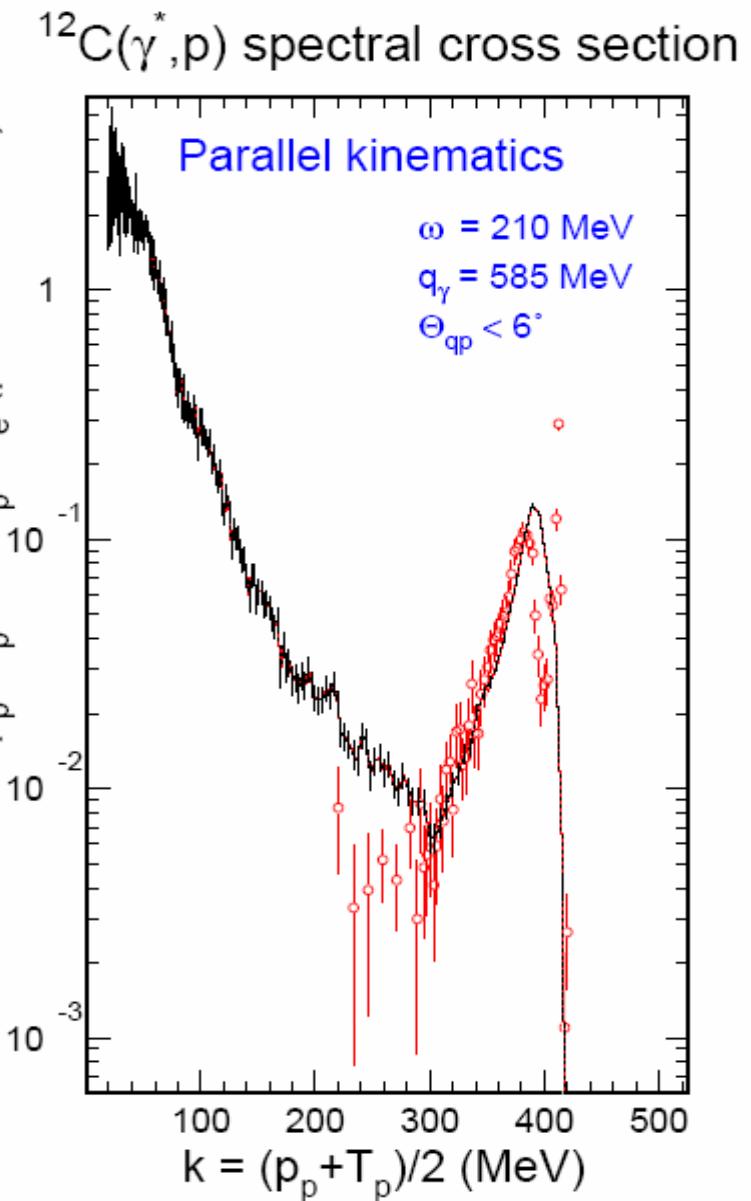
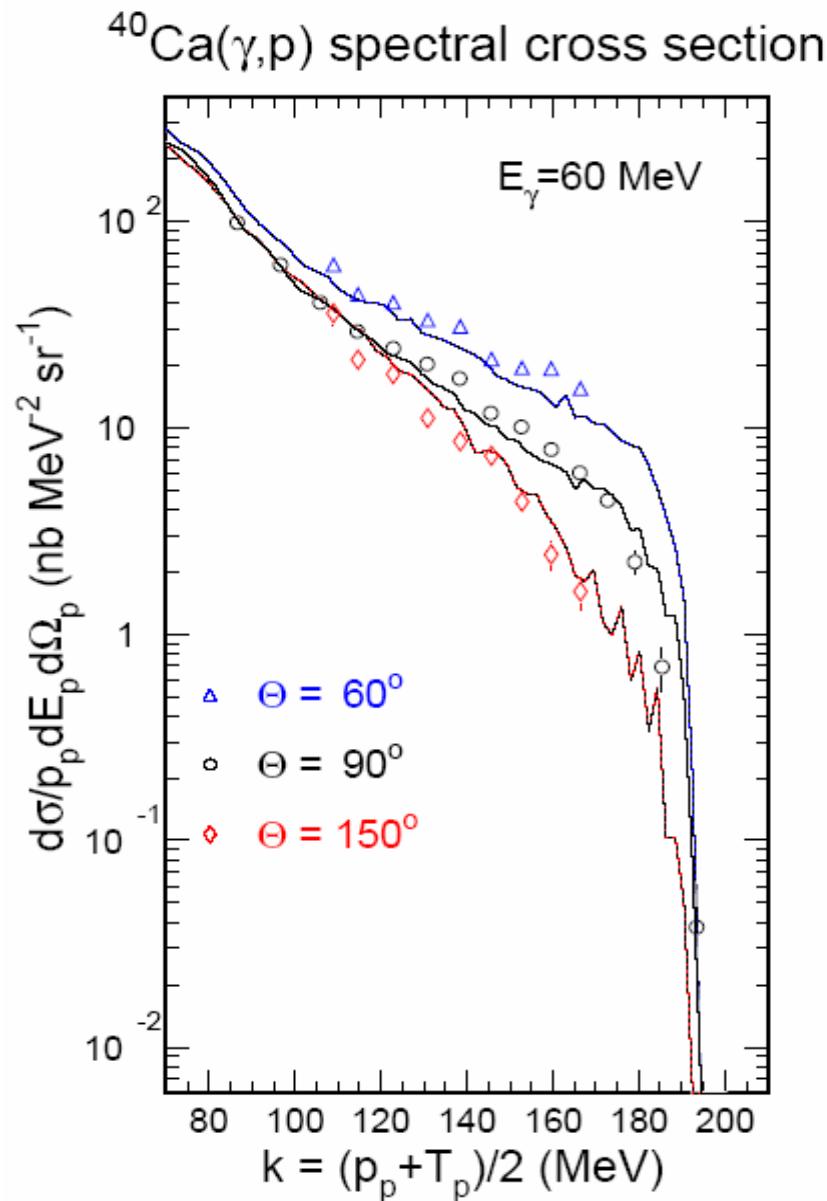
CHIPS Model

Photoneutron production part of total photonuclear cross section



Verification of gamma-nuclear reactions

CHIPS Model



Low Energy (<20MeV) Neutrons

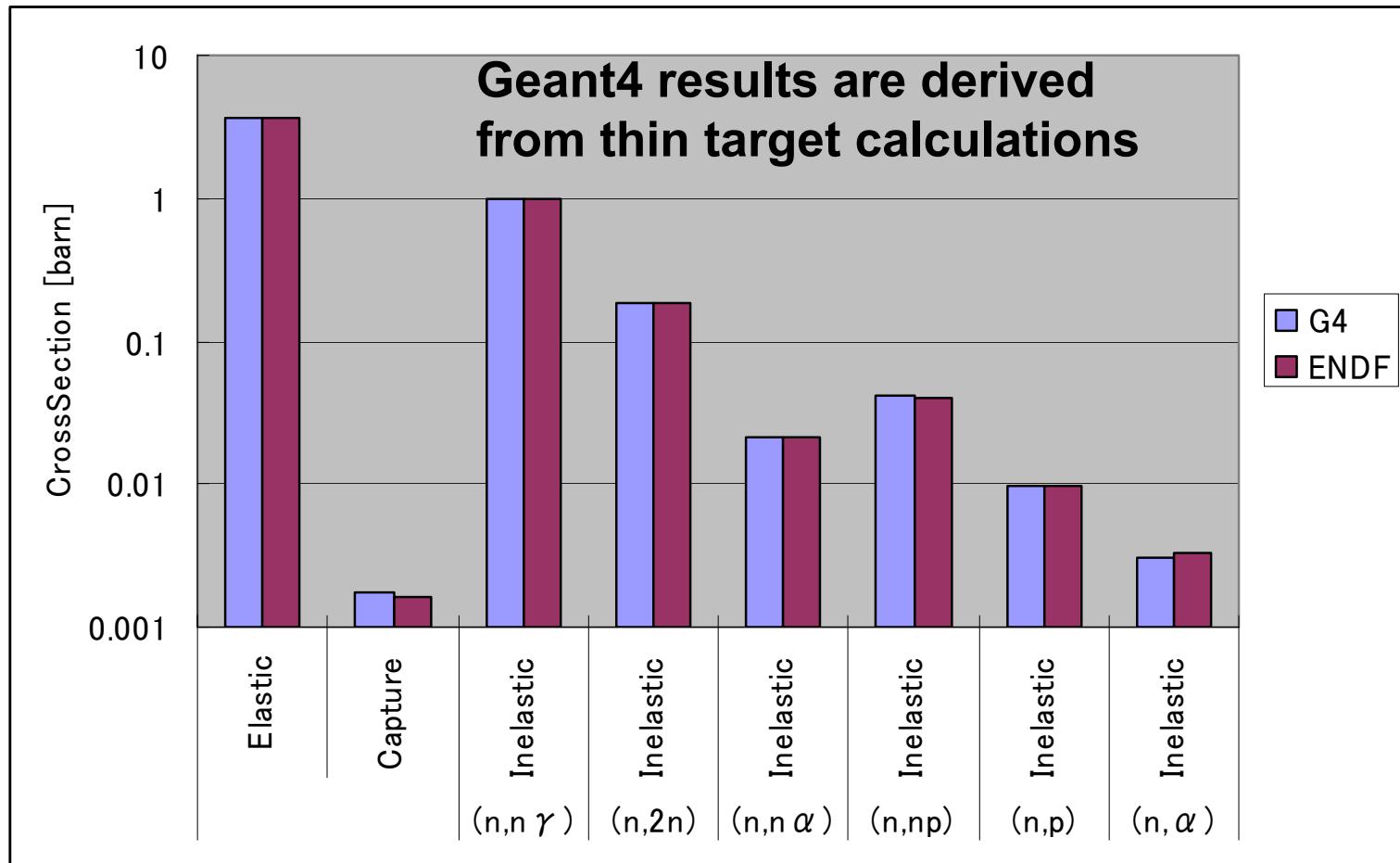
Neutron High Precision Models and Data Sets

These are data driven models,
therefore comparison results to the
ENDF data should be very close.

Verification of High Precision Neutron models

Channel Cross Sections

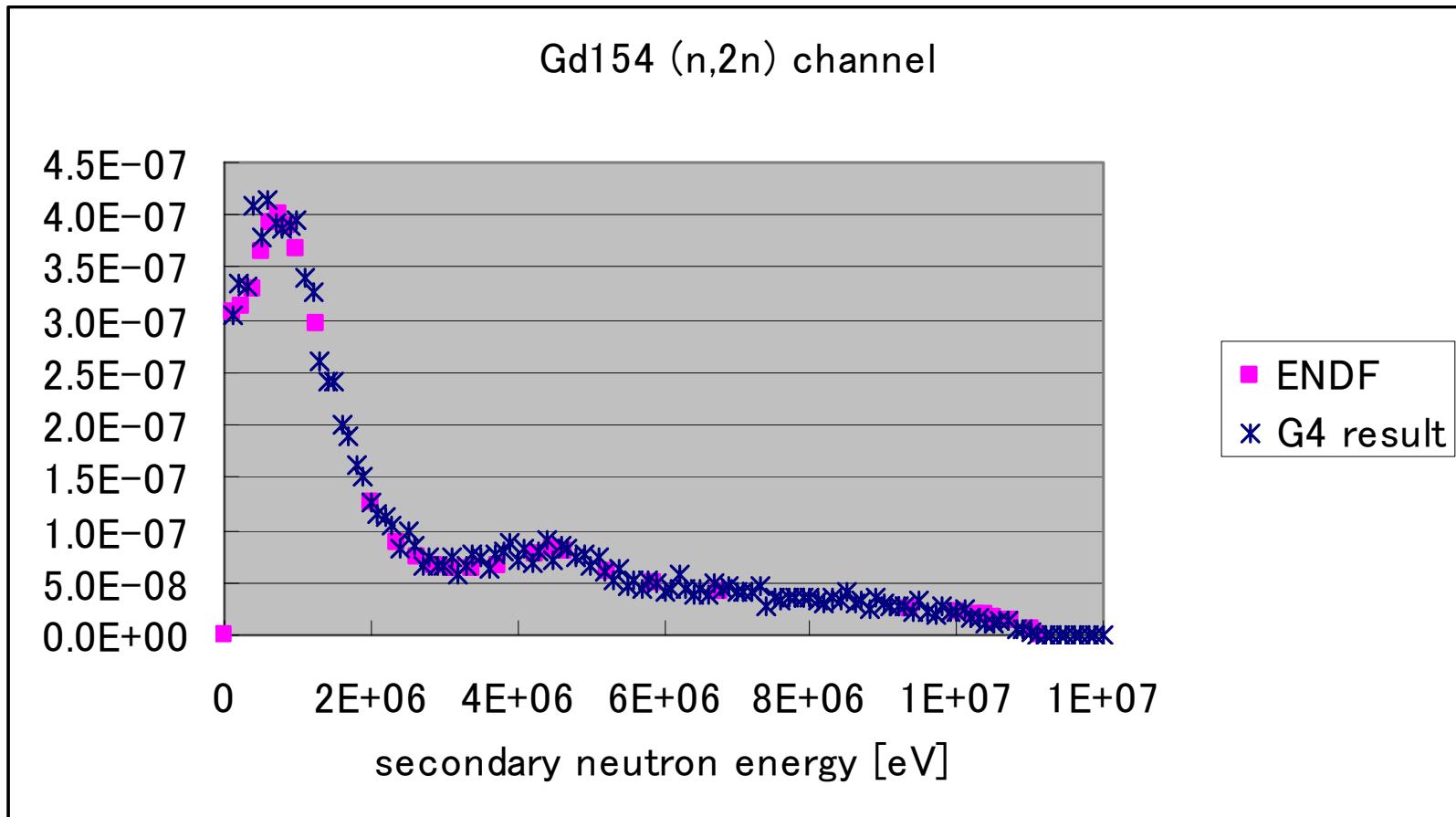
20MeV neutron on ^{157}Gd



Verification of High Precision Neutron Models

Energy Spectrum of Secondary Particles

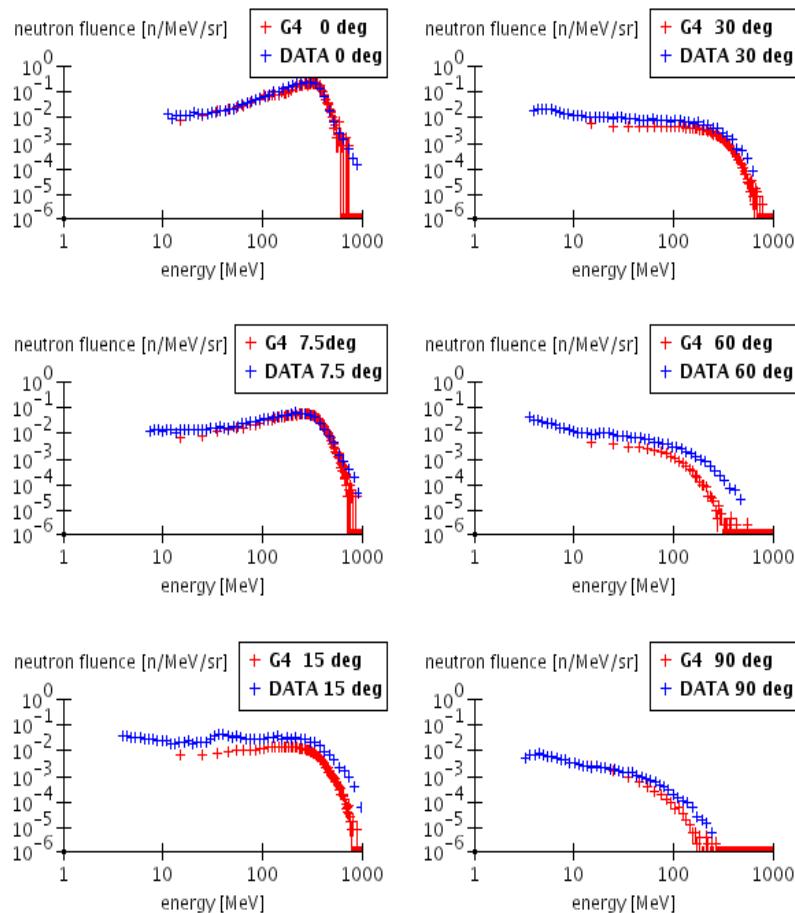
20MeV neutron on ^{154}Gd



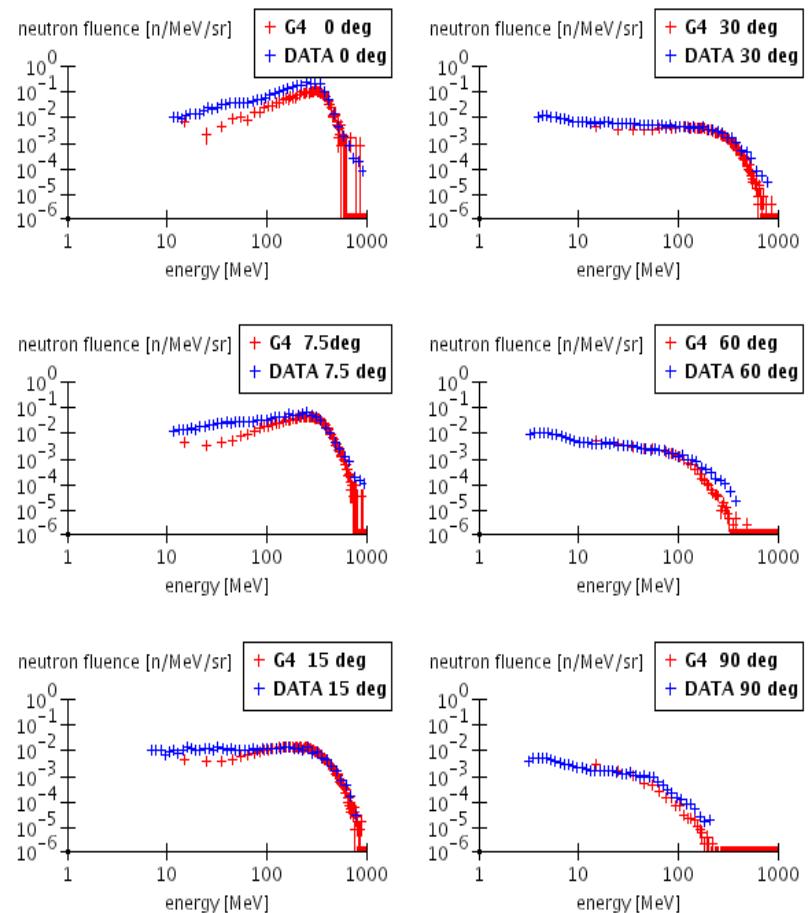
Ions
Binary Light Ions Cascade
Wilson Abrasion Ablation
Electromagnetic Dissociation

Neutron Yield Fe 400 MeV/n beams

Carbon



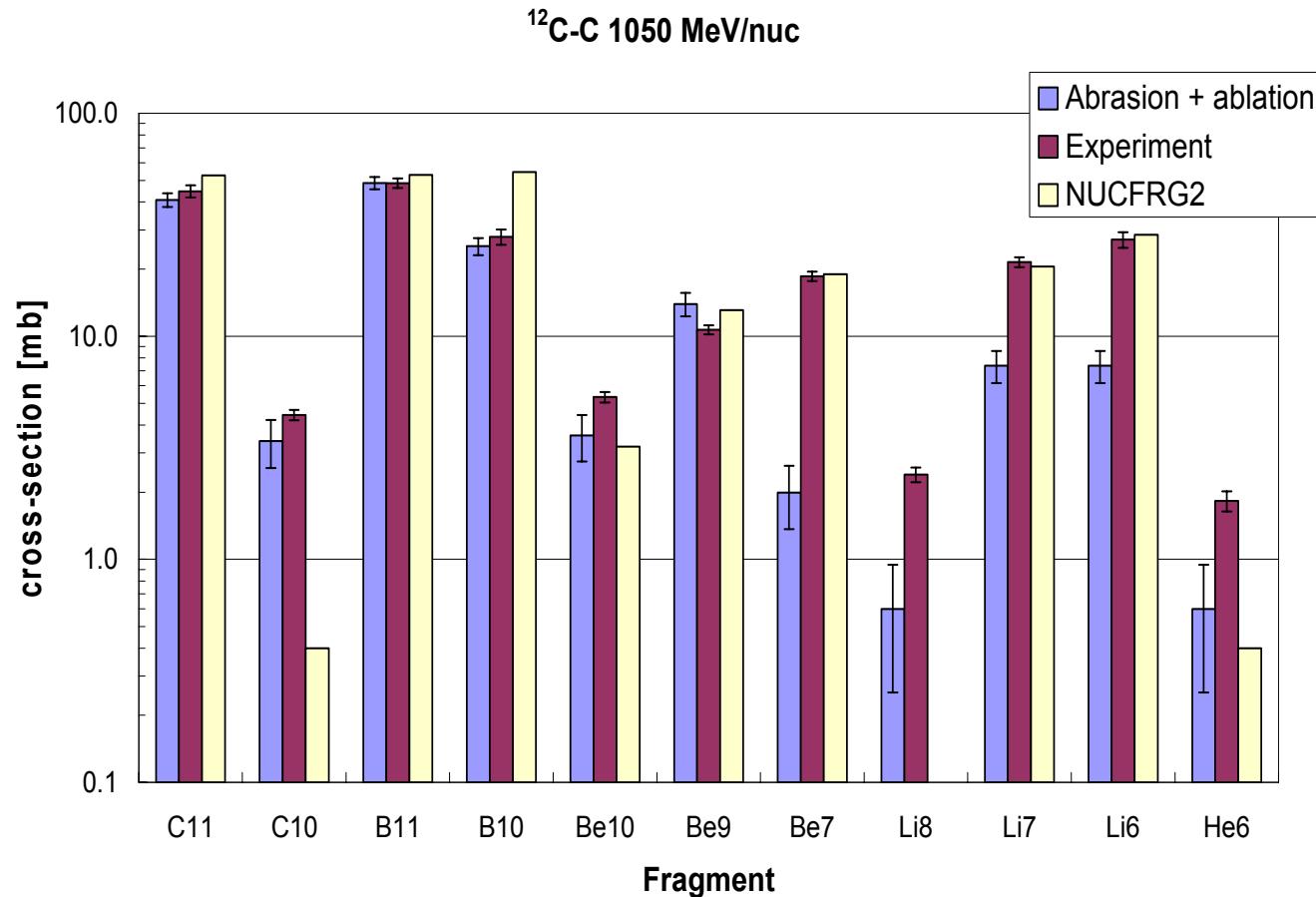
Aluminum



Binary Light Ions Cascade

T. Kurosawa et al.,
Phys. Rev. C62
pp. 04461501 (2000)

Validation of Wilson Abrasion Ablation Model



J W Wilson et al., "NUCFRG2: An evaluation of the semi-emperical nuclear fragmentation database," NASA Technical Paper 3533, 1995.

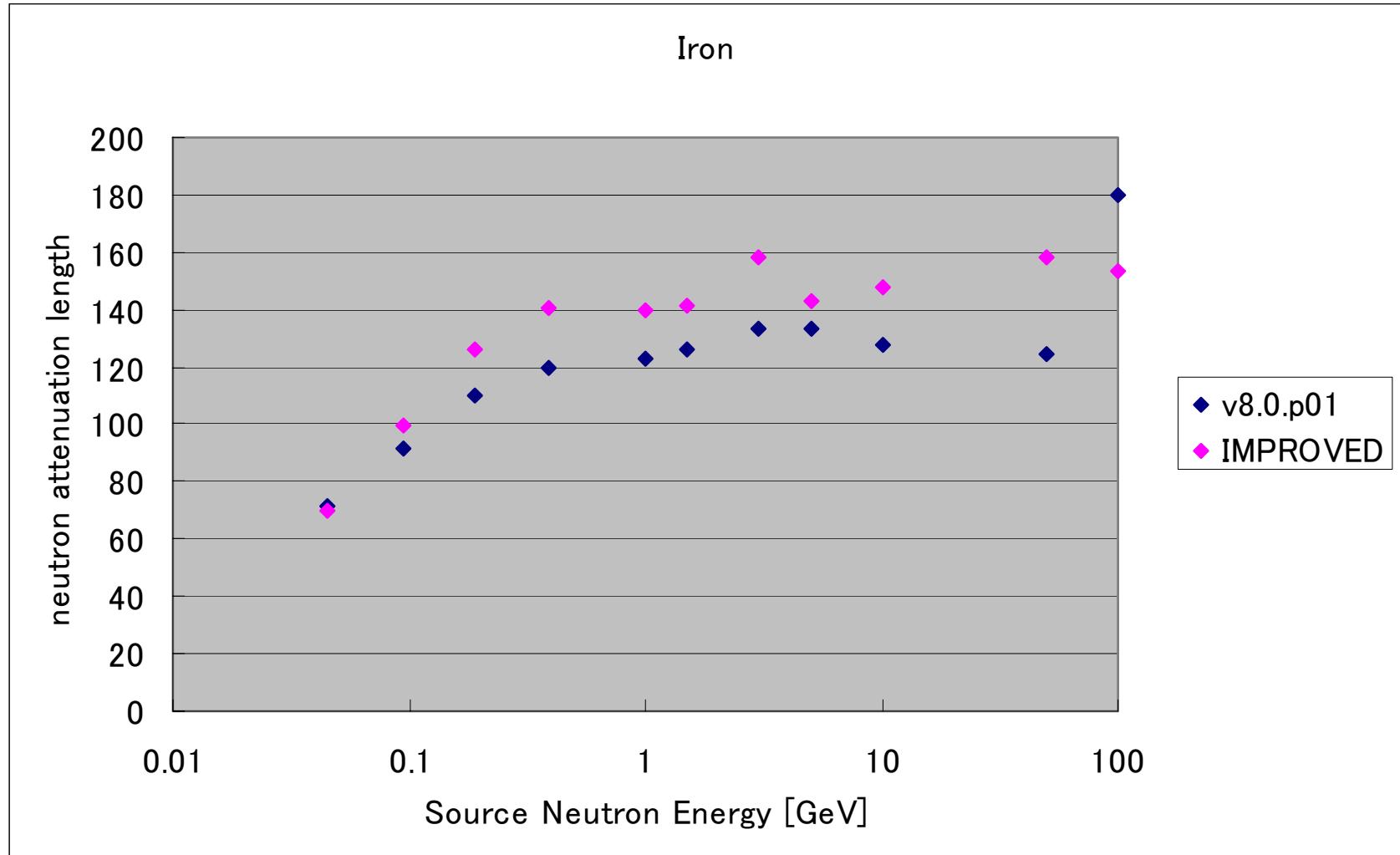
Validation of G4EMDissociation Model

Target Emulsion nuclei: Ag 61.7%, Br 34.2%, CNO 4.0% and H 0.1%

Projectile	Energy [GeV/nuc]	Product from ED	G4EM Dissociation [mbarn]	Experiment [mbarn]
Mg-24	3.7	Na-23 + p	124 ± 2	154 ± 31
Si-28	3.7	Al-27 + p	107 ± 1	186 ± 56
	14.5	Al-27 + p	216 ± 2	$165 \pm 24^\dagger$ $128 \pm 33^\ddagger$
O-16	200	N-15 + p	331 ± 2	$293 \pm 39^\dagger$ $342 \pm 22^*$

M A Jilany, “Electromagnetic dissociation of 3.7 A GeV 24Mg and 28Si projectiles in nuclear emulsion,” *Nucl Phys*, **A705**, 477-493, 2002.

SATIF8 Inter-comparison with JENDL HE Cross Section

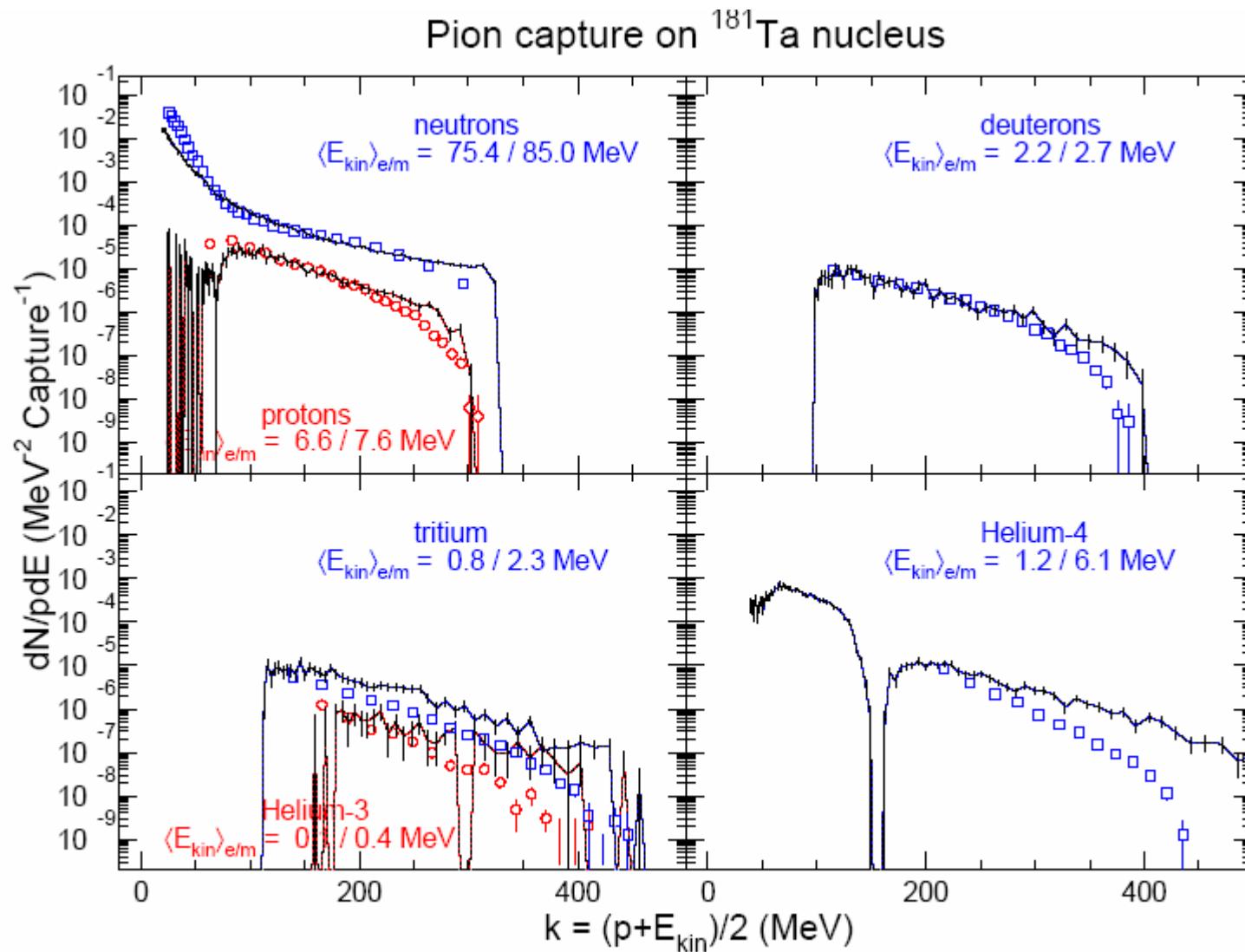


Conclusions

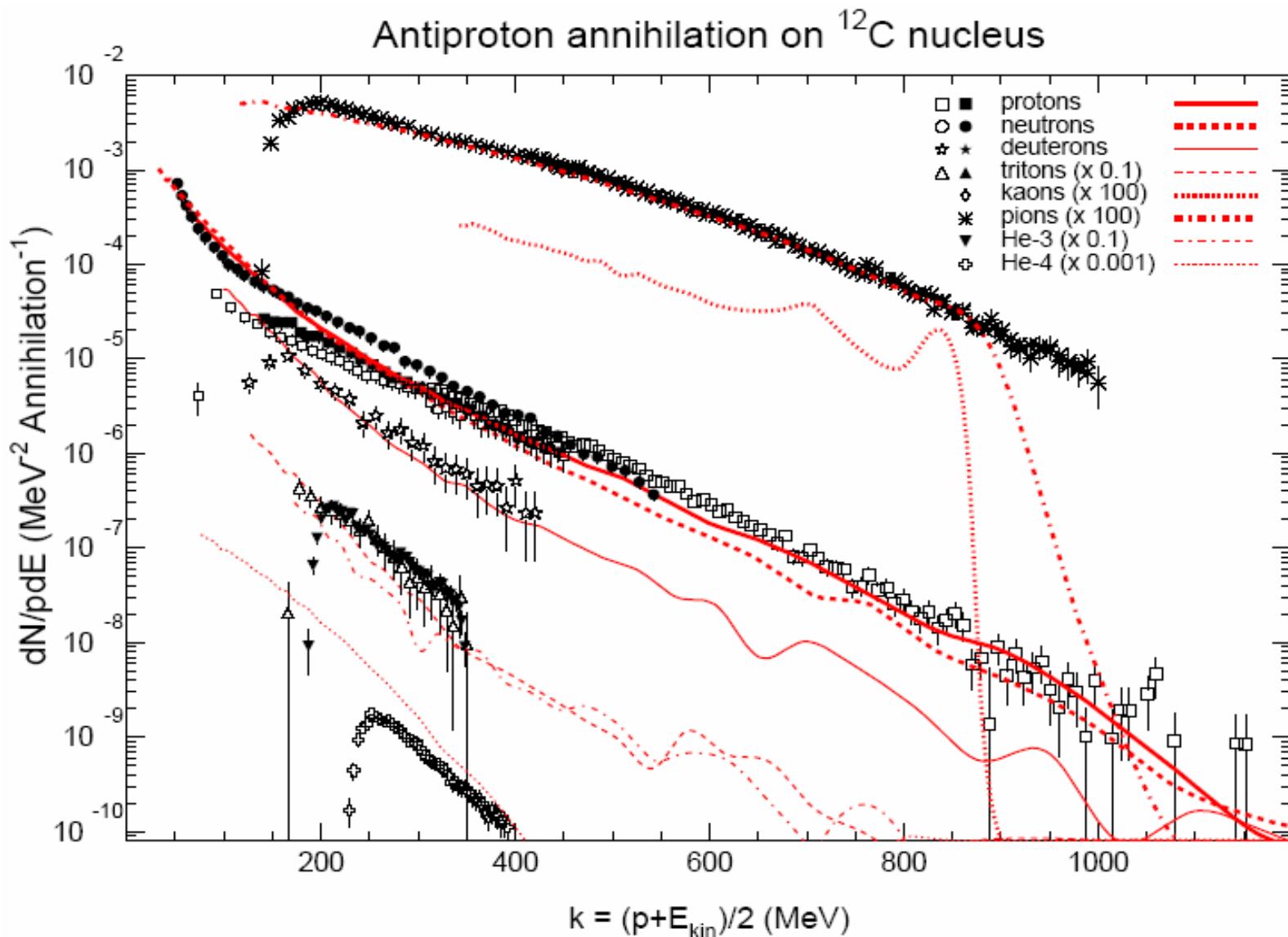
- We have shown validations from low energy neutrons, precompound, cascade, high energy and elastic models
 - These are most important for hadronic shower shape.
 - We did not show many validation from 20 to 50 GeV, because we are still developing new models for those energies.
 - Agreements with data is good for most case, disagreement indicates that improvements are needed in
 - diffraction part of QGS model
 - nuclear model of Bertini model
- hadron capture, ions and gamma nuclear
 - These are also useful
 - CHIPS based hadron capture model agrees well with data
 - Binary Light Ions Cascade have unexpectedly good agreement for heavy ions collision but improvement needed in correlation of participant nucleons and transition to precompound model

Back Up Slides

Verification of nuclear capture at rest CHIPS Model

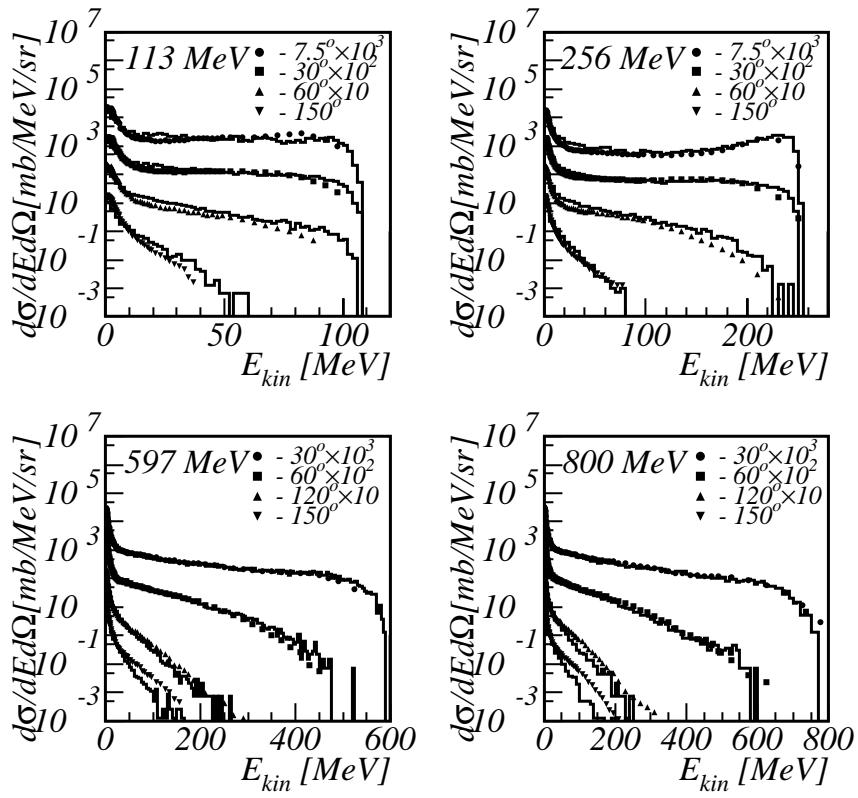


Verification of nuclear capture at rest CHIPS Model

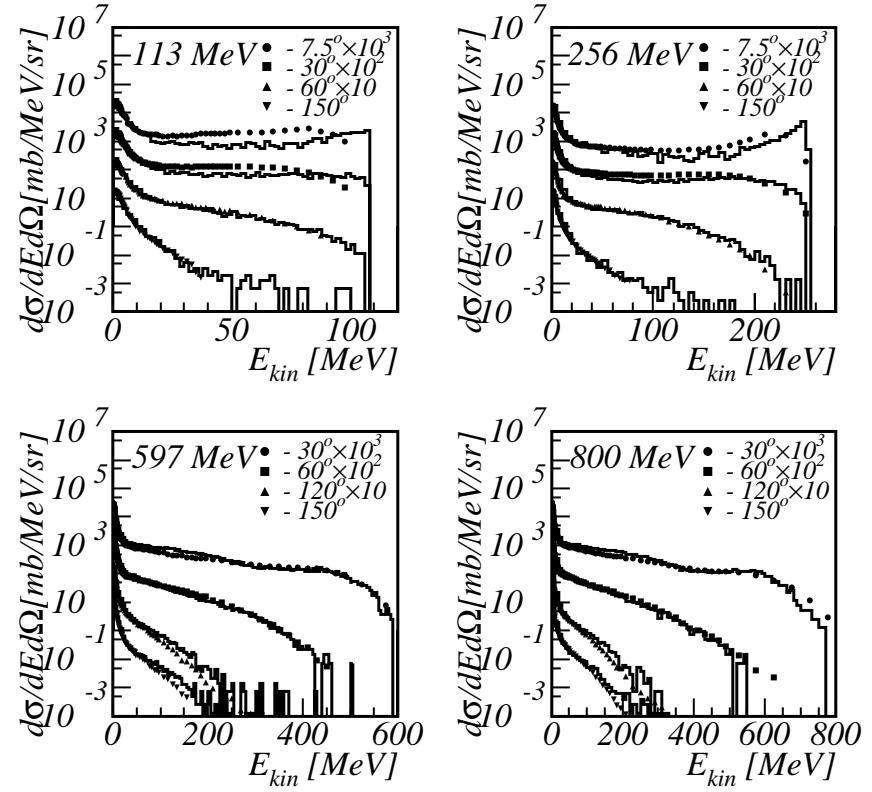


Neutron spectra by protons in Iron

Binary Cascade

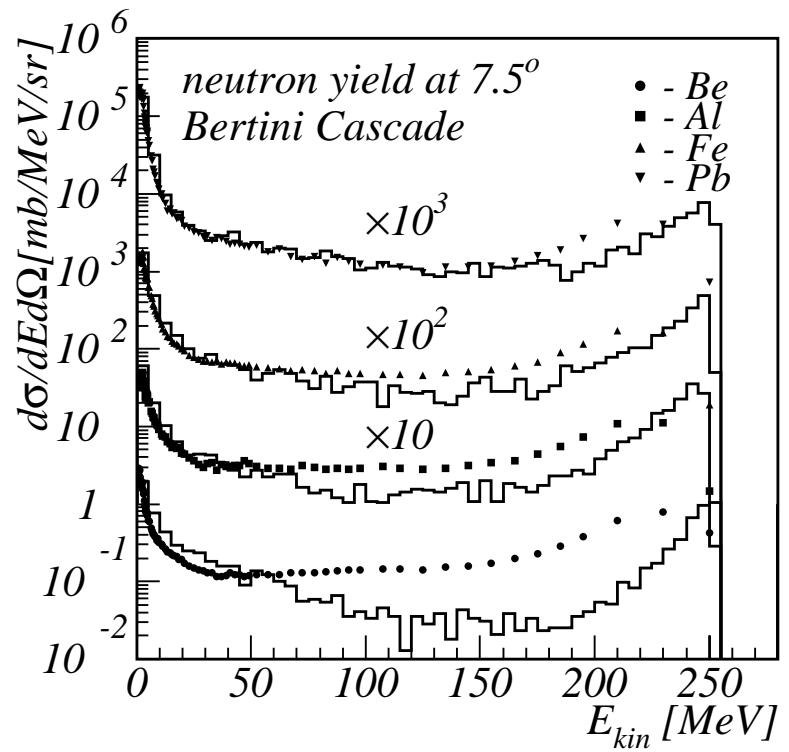
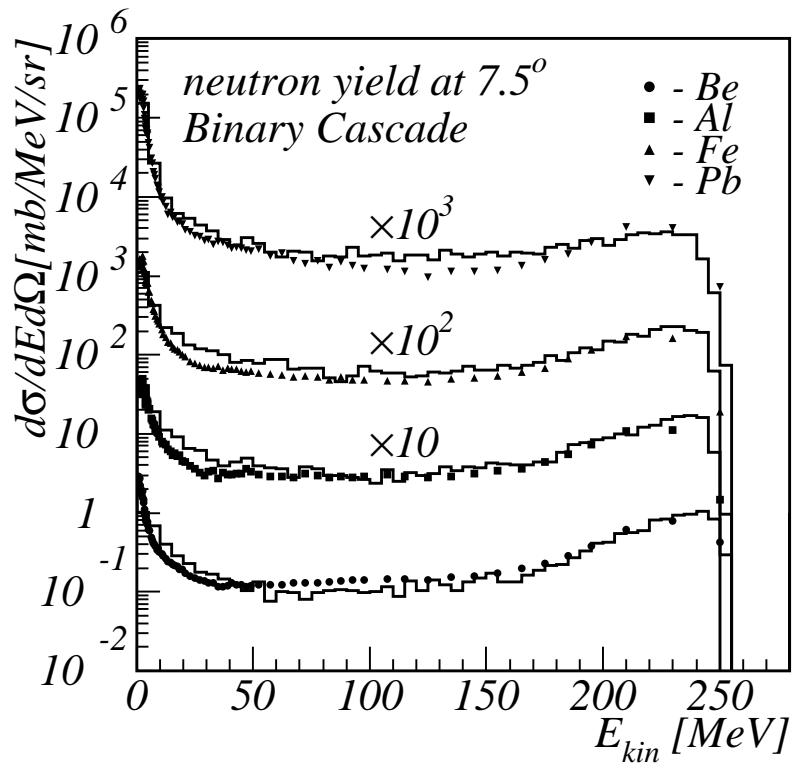


Bertini Cascade

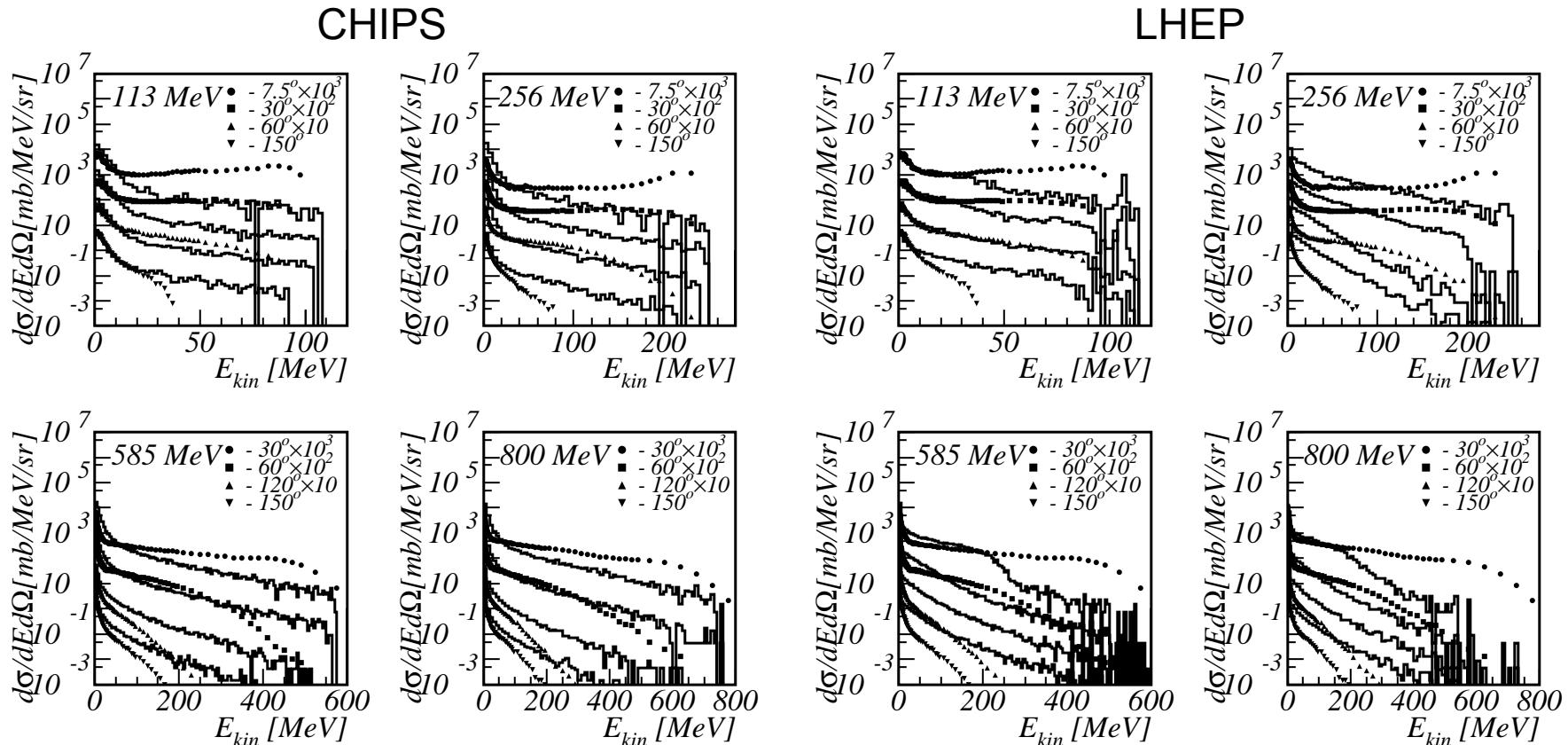


Neutron spectra by 256 MeV protons

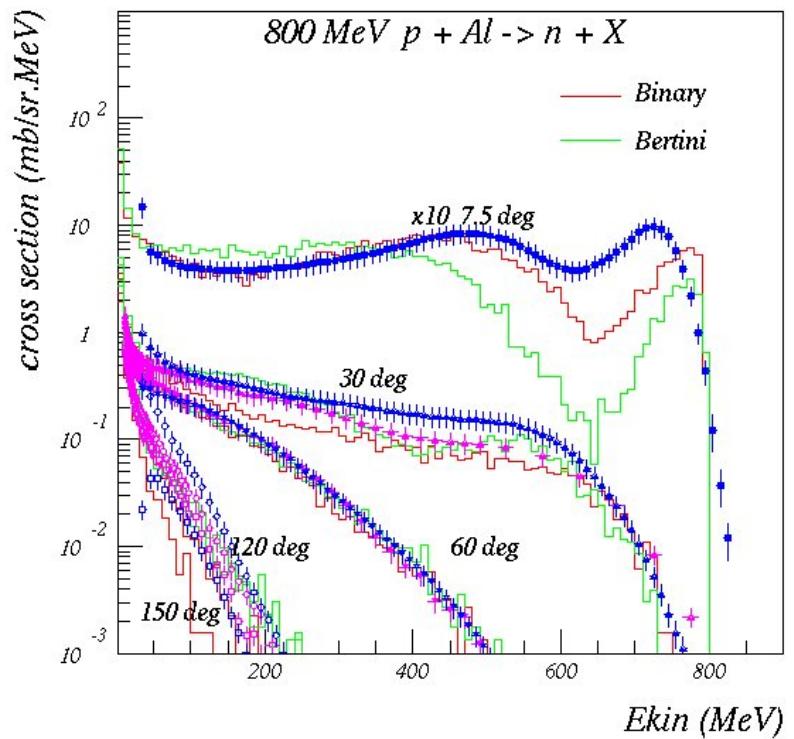
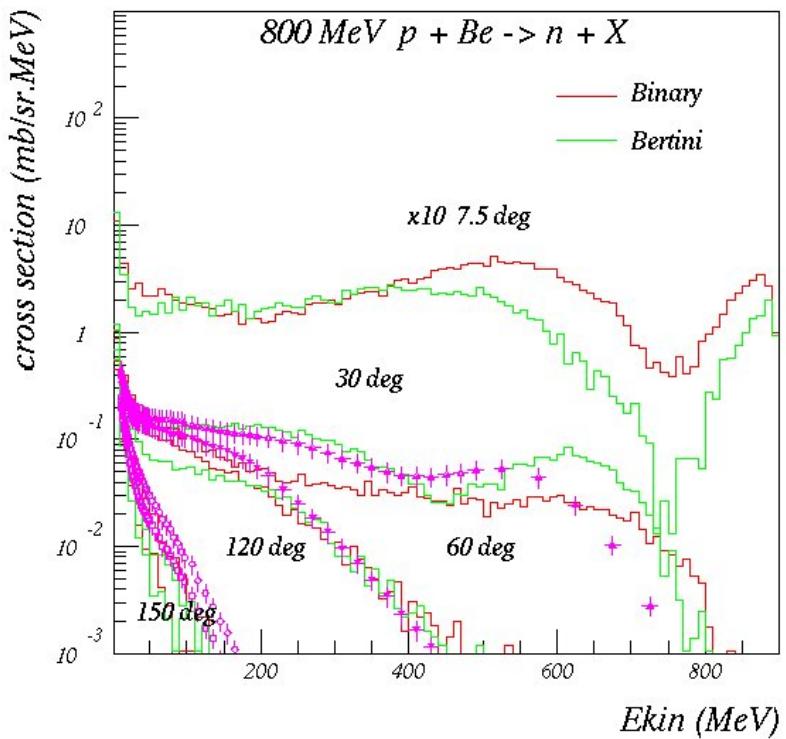
Binary and Bertini Cascades



Neutron spectra by protons in Aluminum

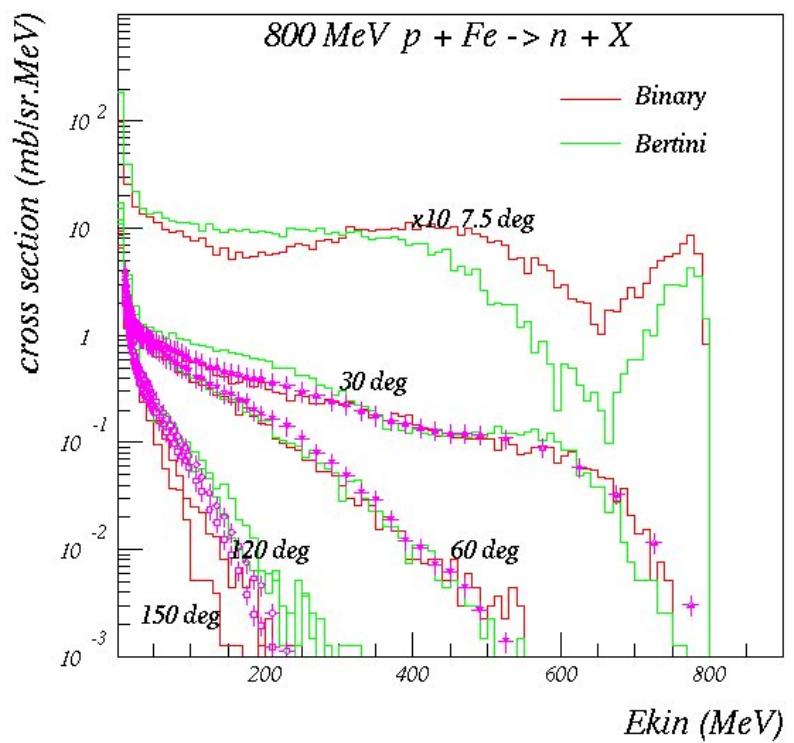
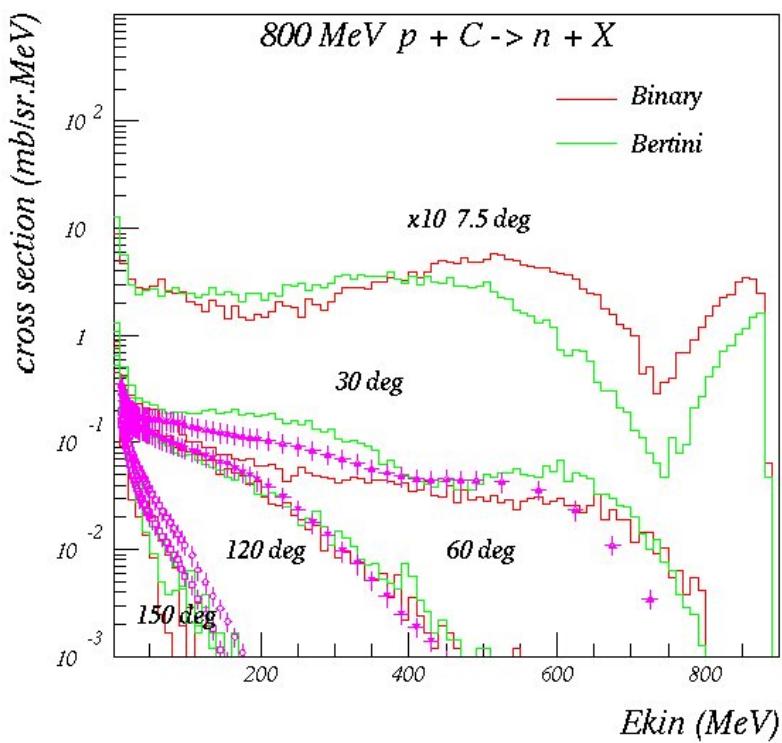


Neutron spectra by 800 MeV protons Binary and Bertini Cascades



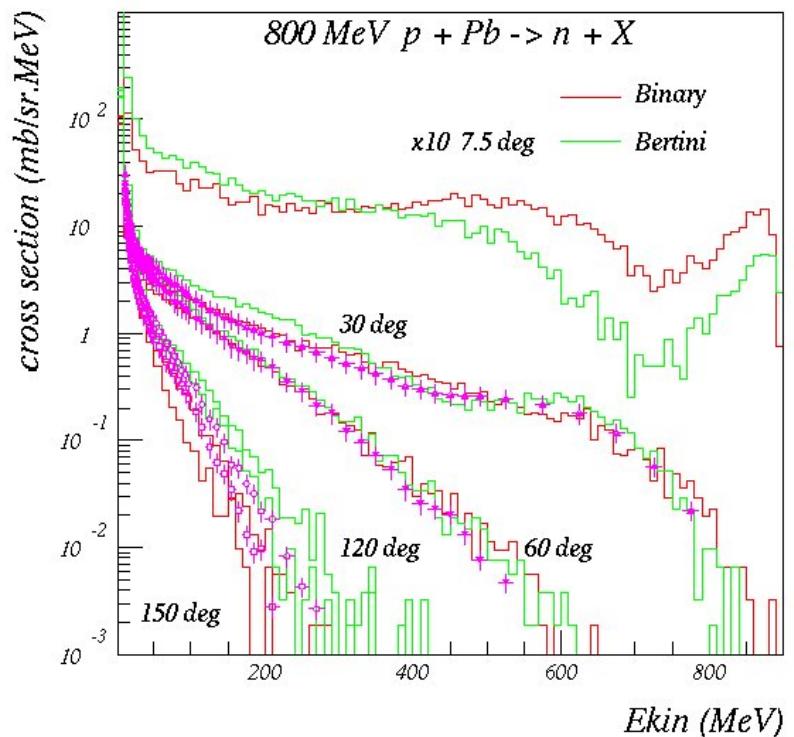
Neutron spectra by 800 MeV protons

Binary and Bertini Cascades



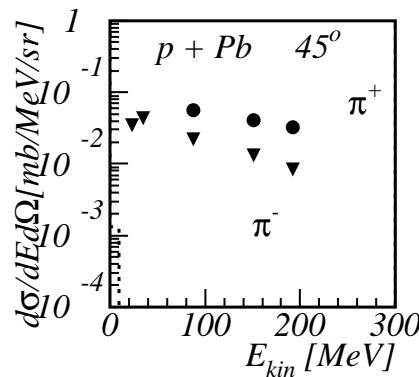
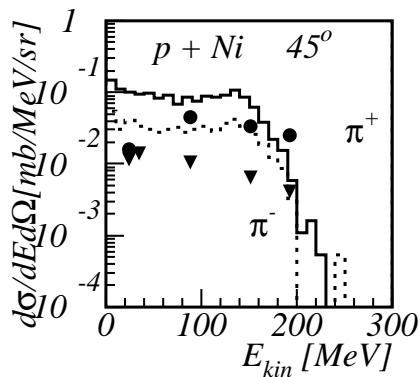
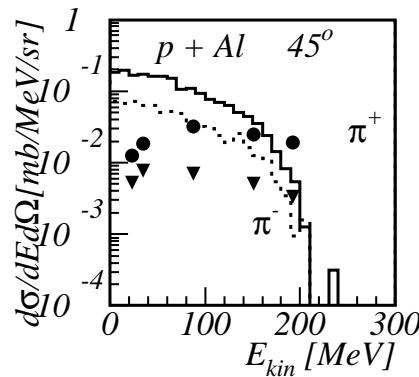
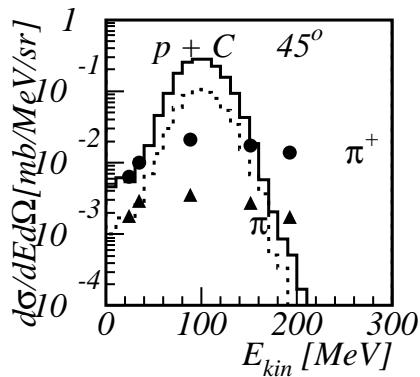
Neutron spectra by 800 MeV protons Binary and Bertini Cascades

- There are more forward neutrons produced by Binary Cascade
- There are more low-energy neutrons produced by Bertini Cascade
- There are more backward neutrons produced by Bertini Cascade

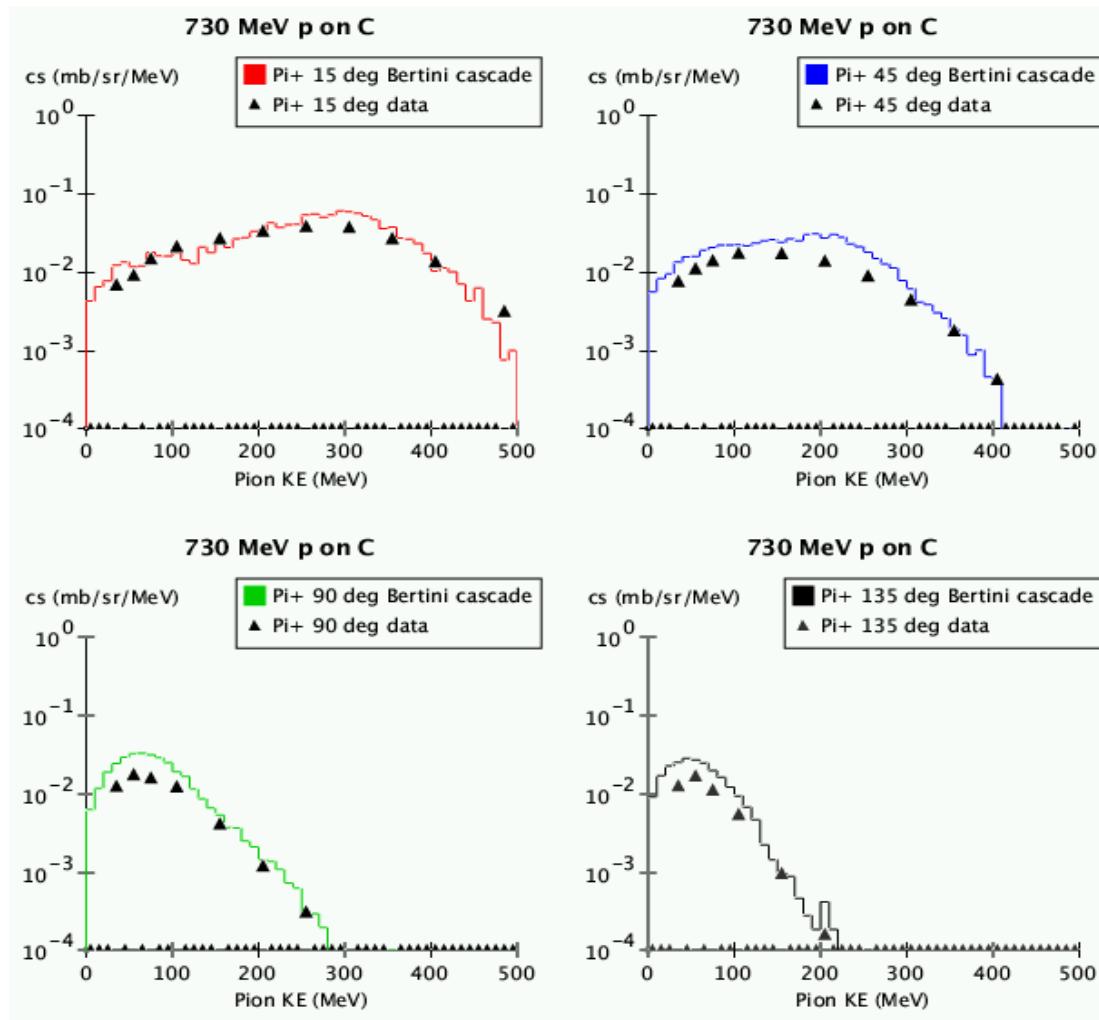


Charged pions spectra produced by 600 MeV protons at 45 degrees

LEP



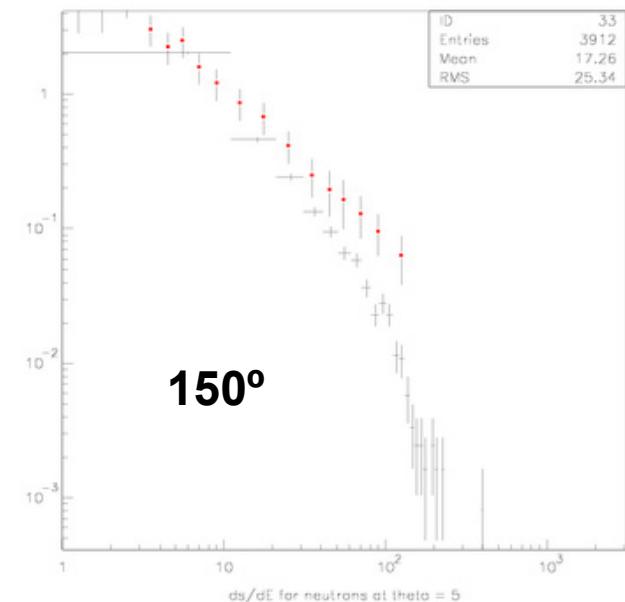
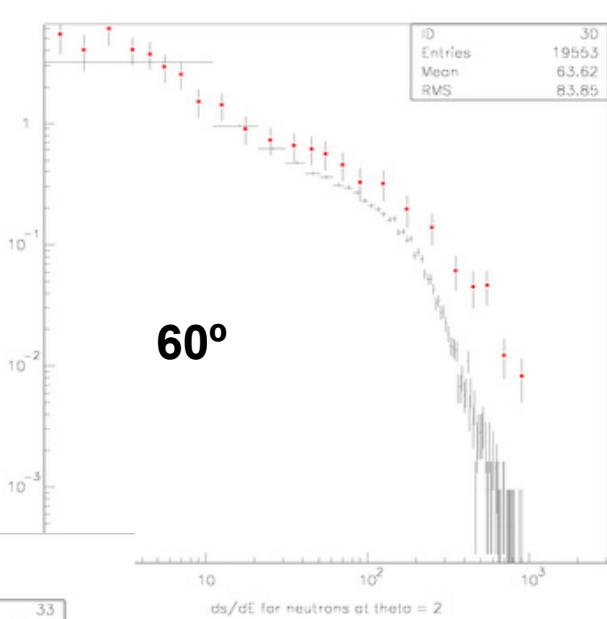
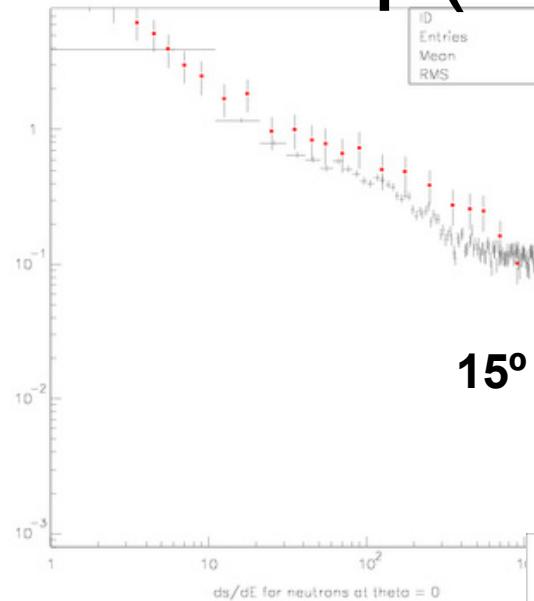
$\pi^-/+$ production from 730 MeV protons



*Bertini
Cascade
Model*

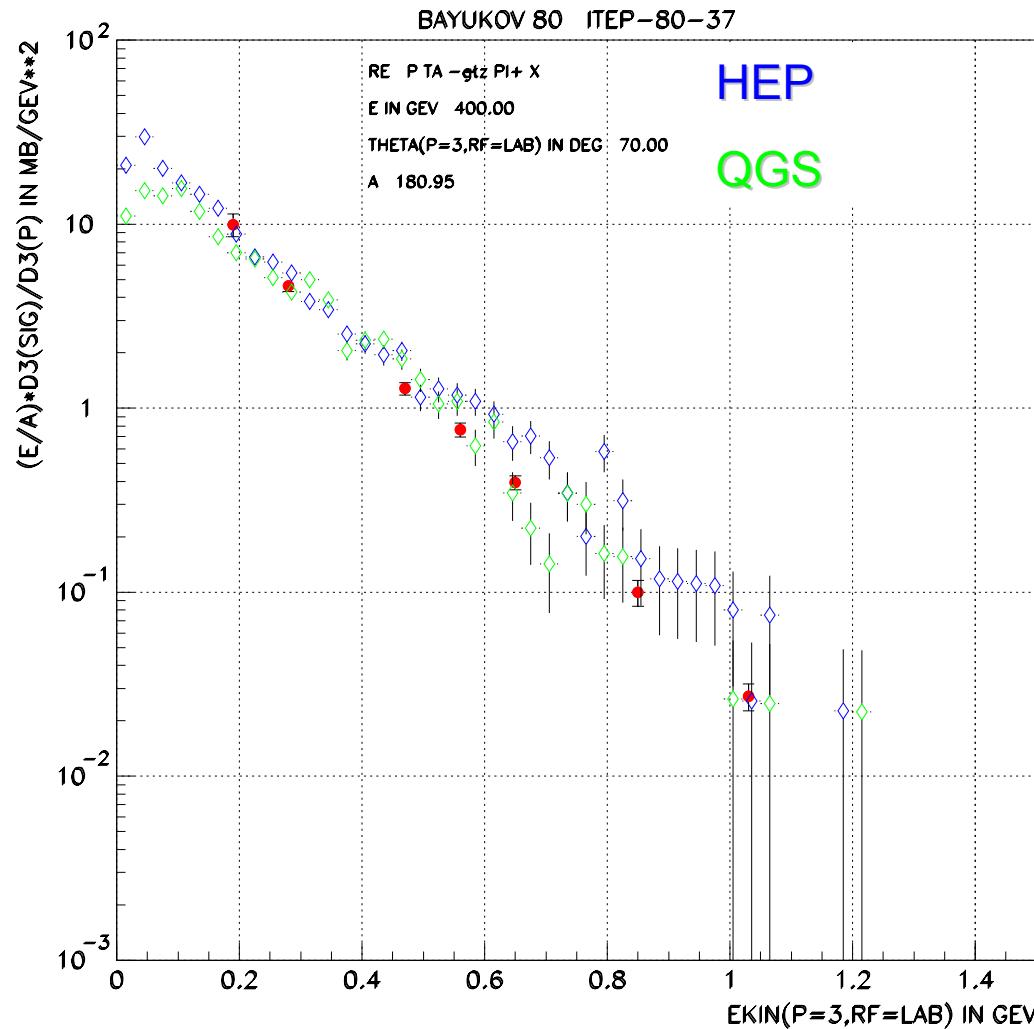
Binary Cascade Model

$p(3.\text{GeV}) \text{ Al} \rightarrow n X$



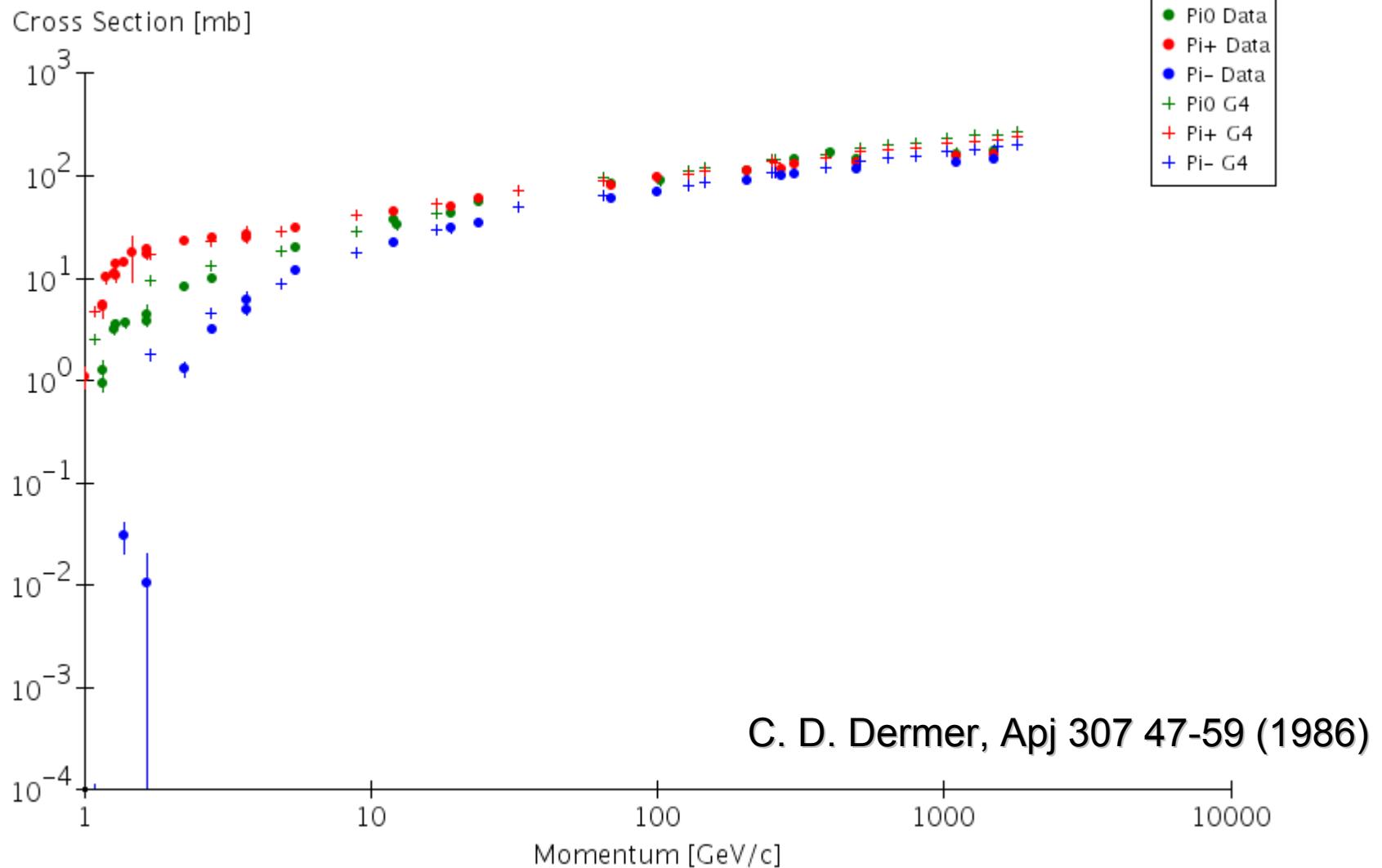
HEP Model

$\pi^+(70\text{deg})$ from proton (400GeV) on Ta



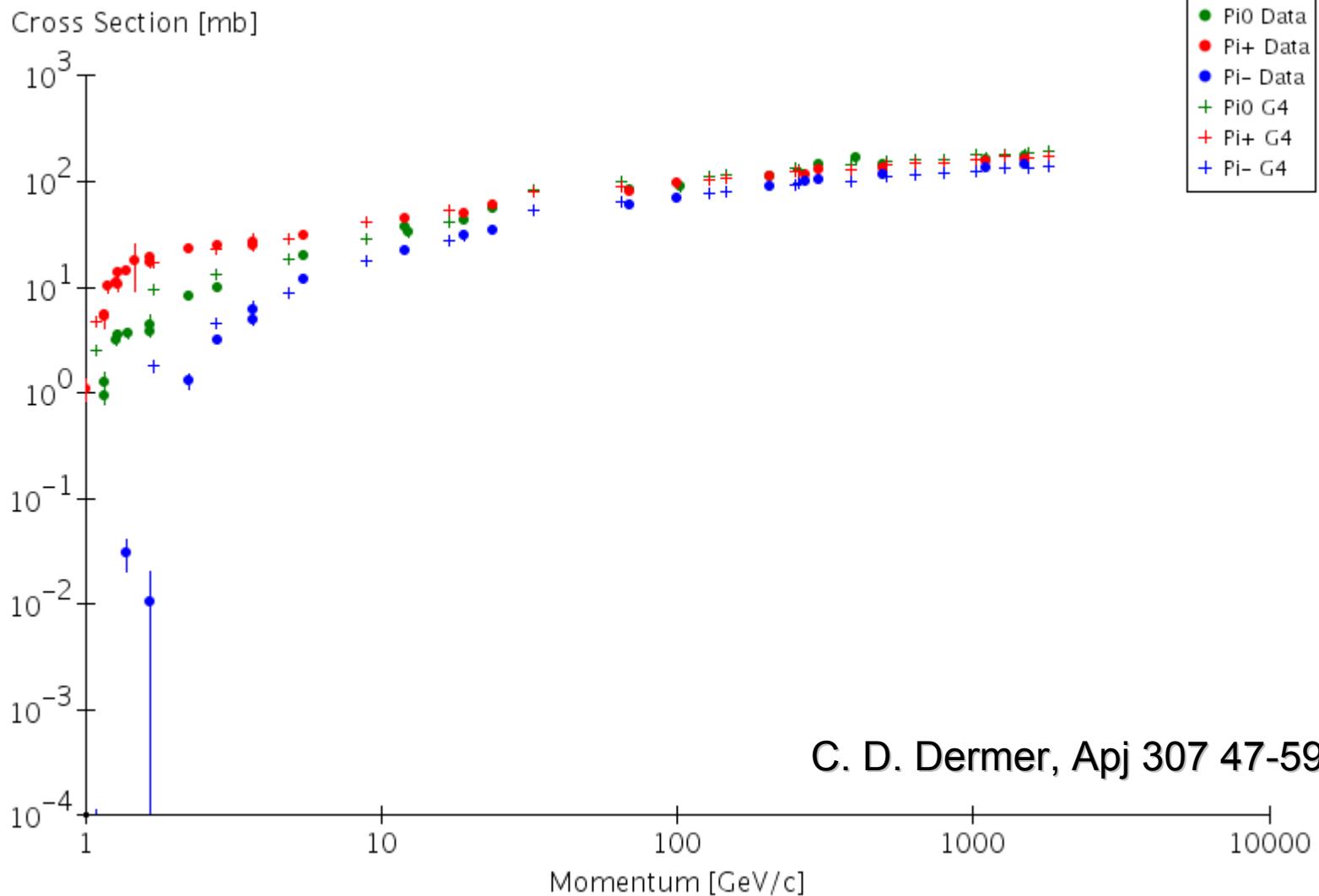
QGSP Physics List

QGS Model + Precompound Model

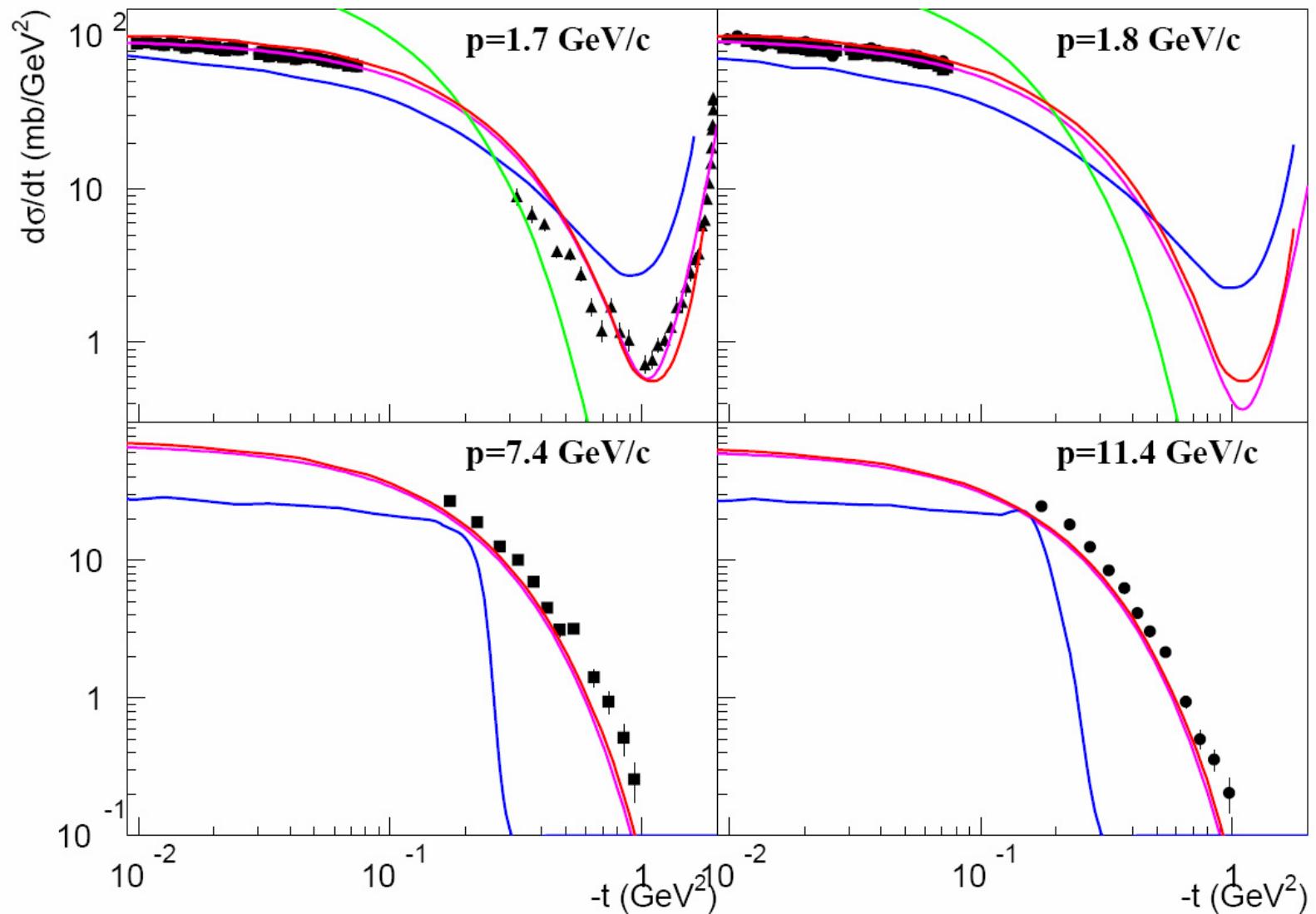


FTFP Physics List

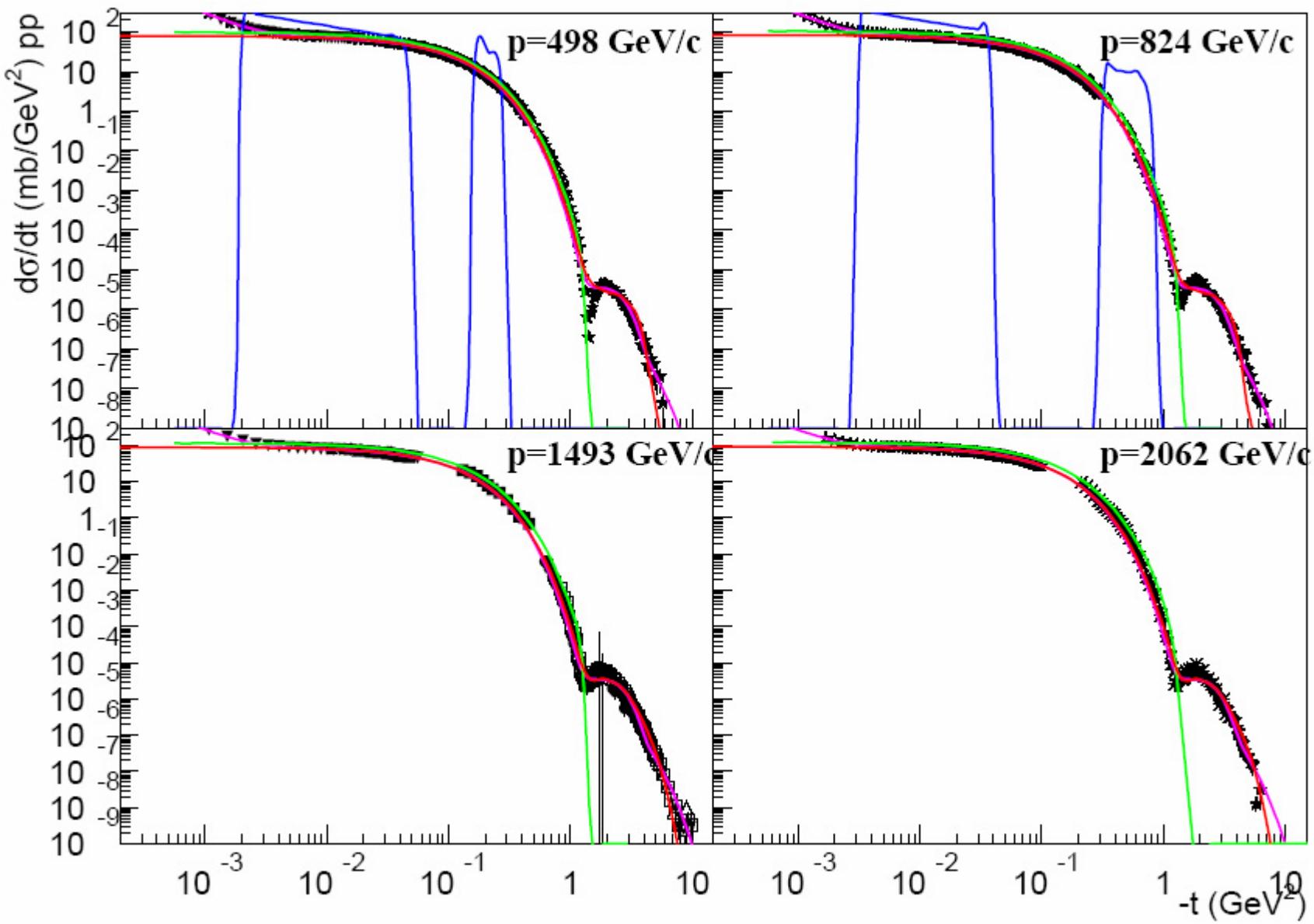
FTF Model + Precompound



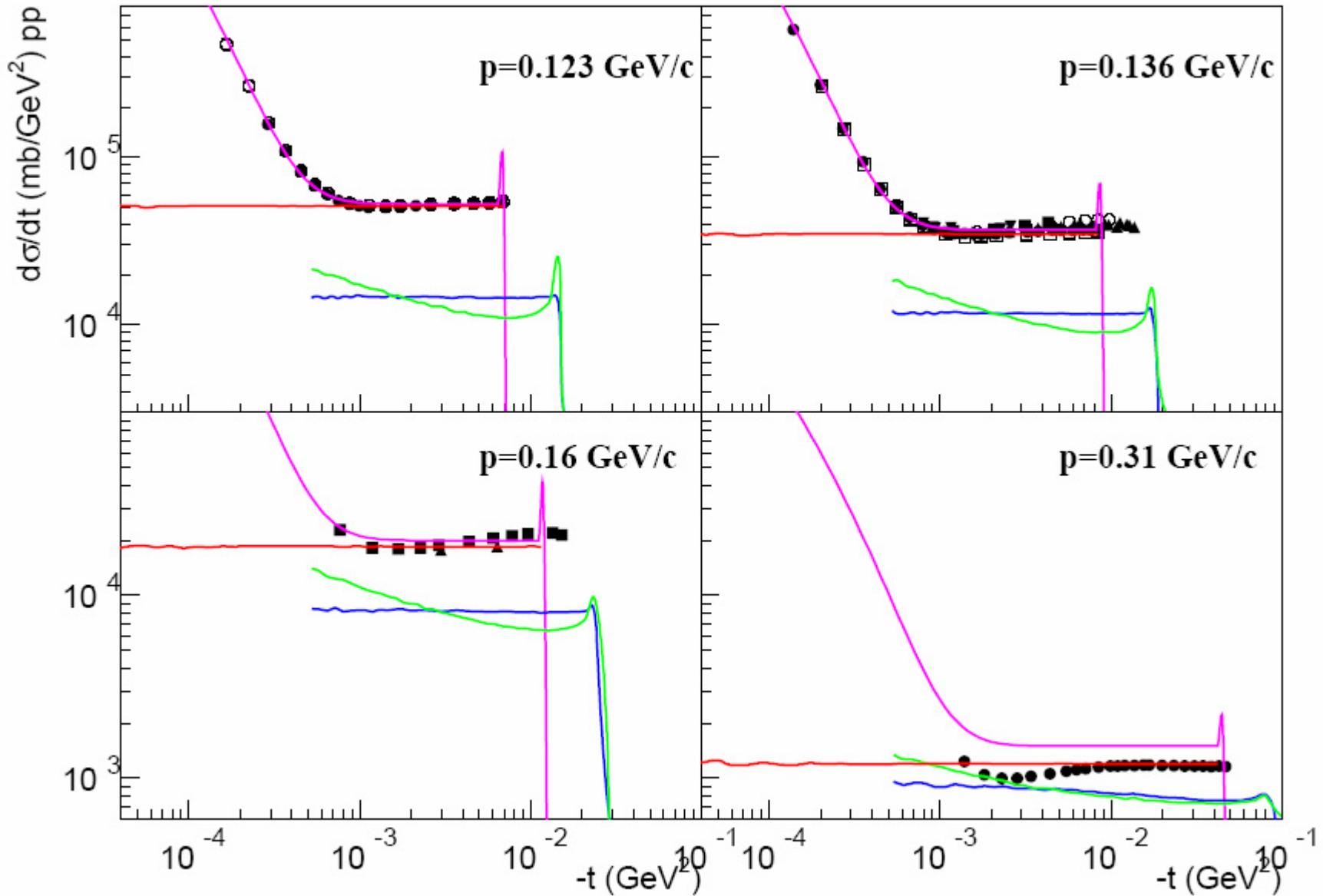
CHIPS improvement of np elastic scattering



CHIPS improvement of pp elastic scattering

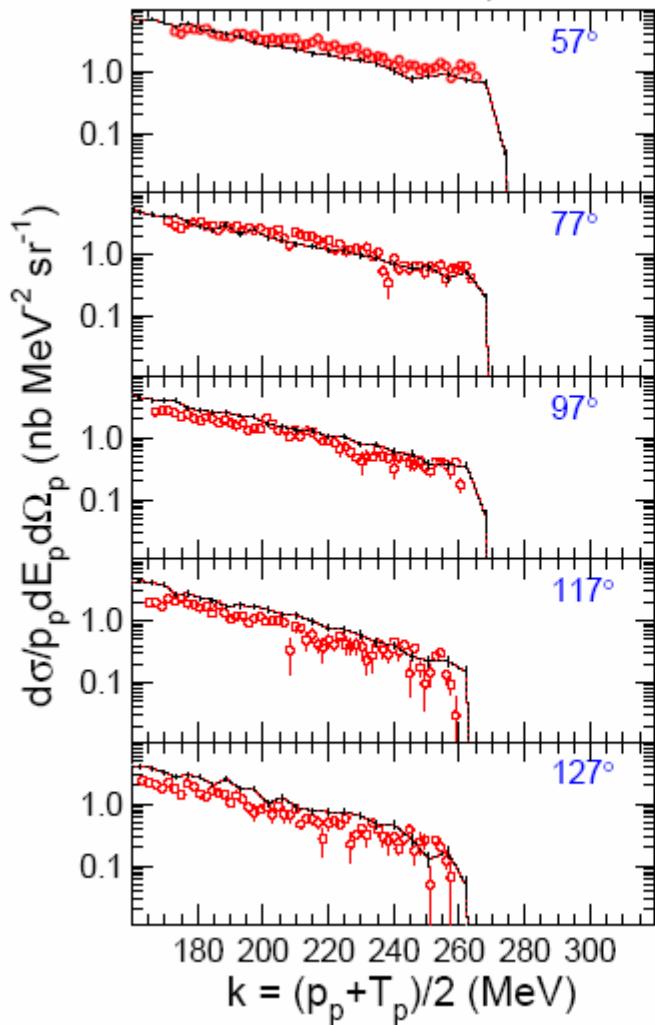


CHIPS improvement of pp elastic scattering

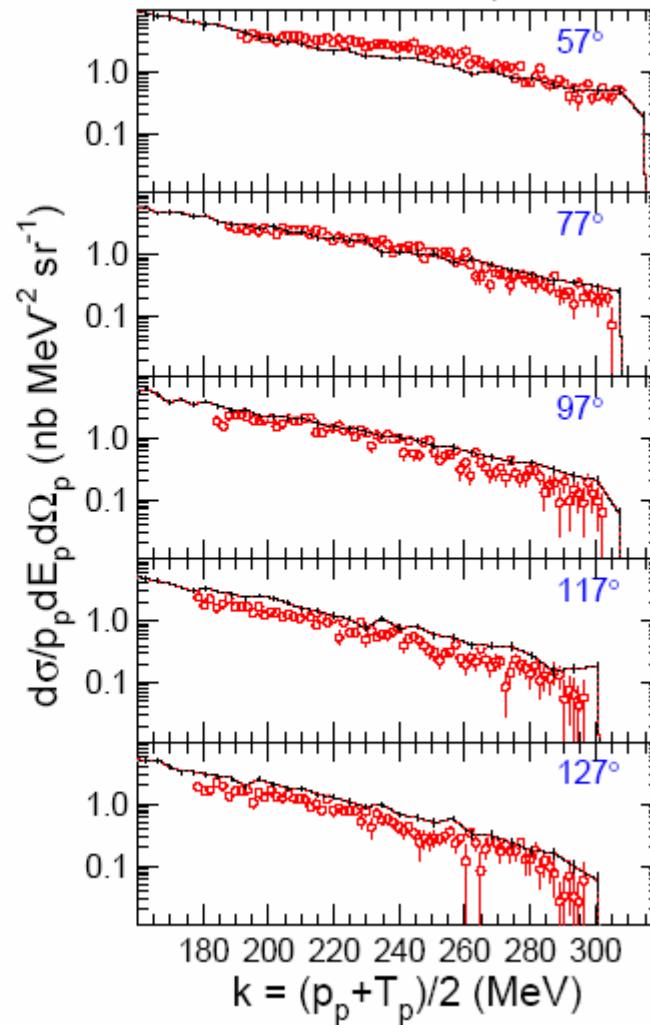


Verification of gamma-nuclear reactions CHIPS model

$^{12}\text{C}(\gamma, \text{p})$ reaction at $E_\gamma = 123$ MeV

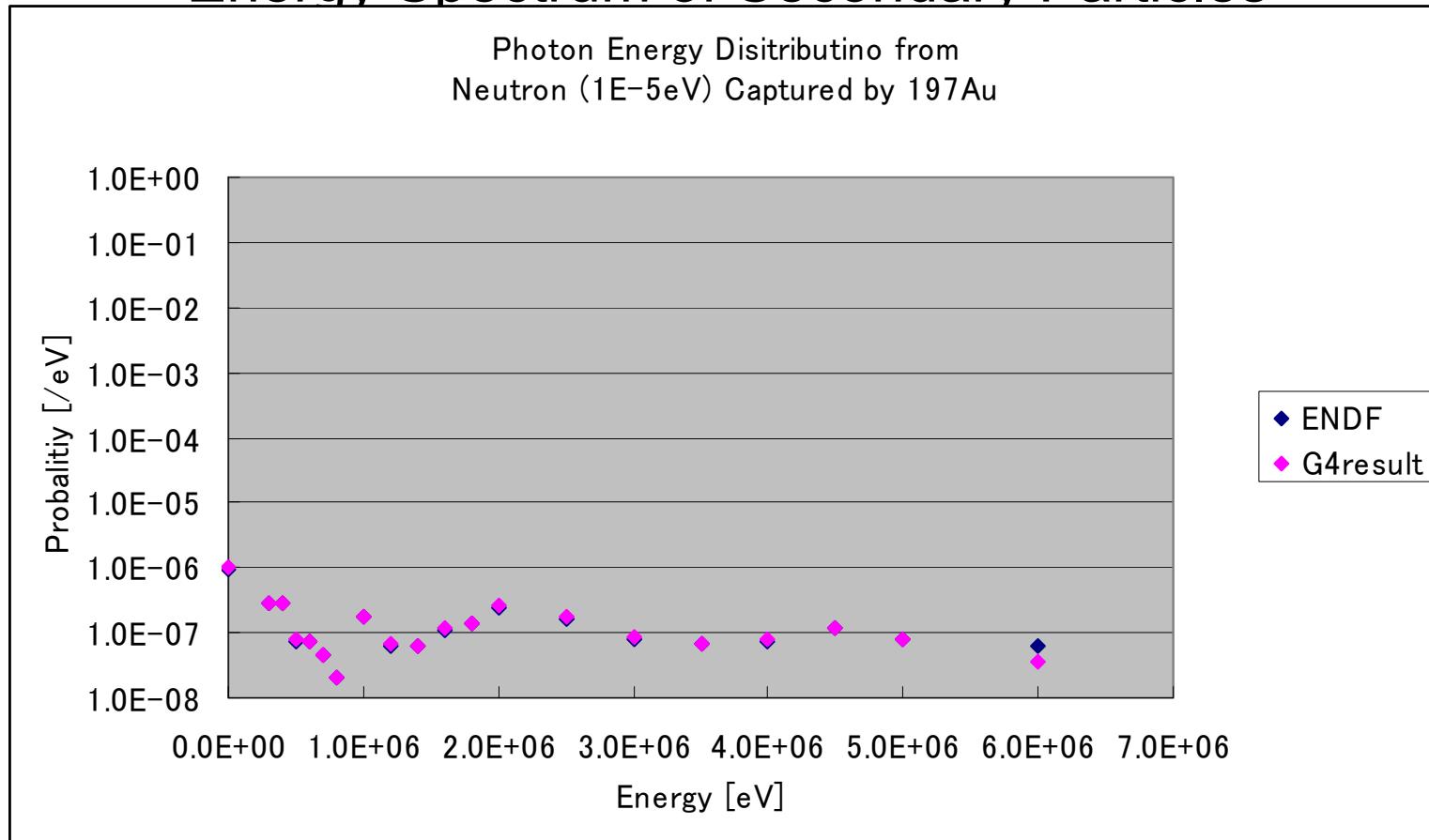


$^{12}\text{C}(\gamma, \text{p})$ reaction at $E_\gamma = 151$ MeV



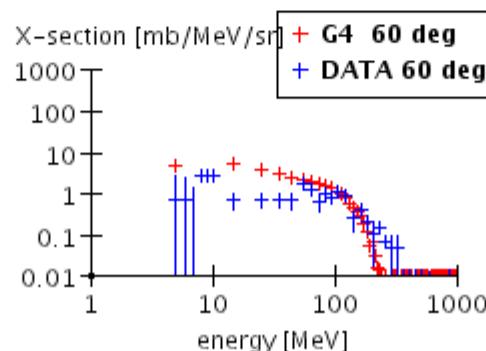
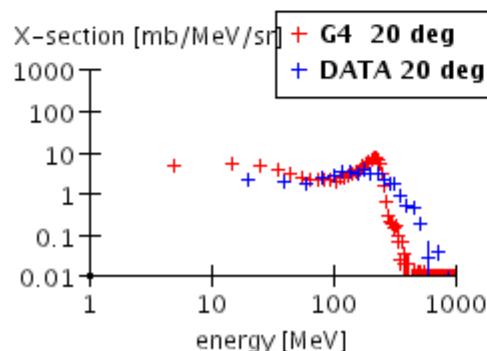
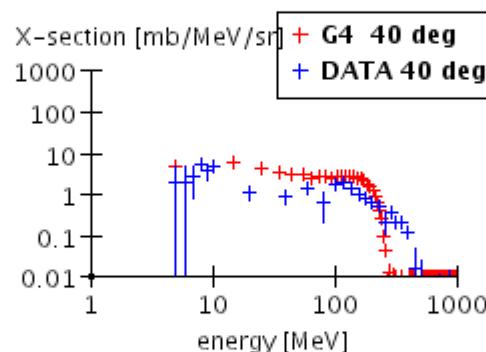
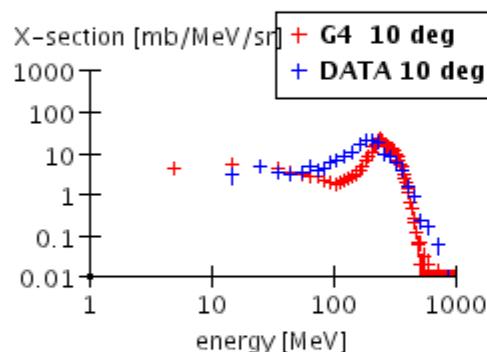
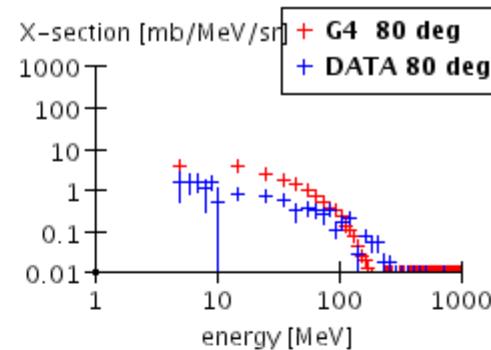
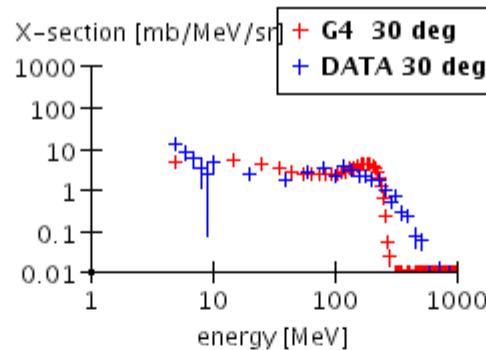
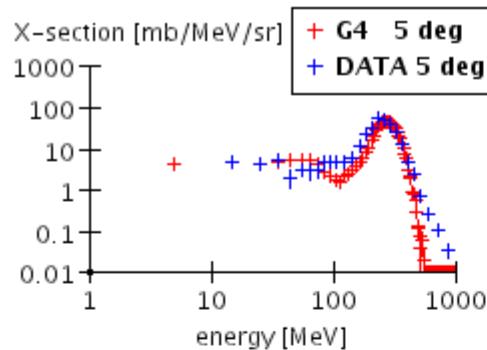
Verification of High Precision Neutron Models

Energy Spectrum of Secondary Particles



Cold Neutron Captured by ^{197}Au (0K)

Neutrons from C on C at 290 MeV/n



SATIF8 Inter-comparison with JENDL HE Cross Section

