GiBUU
and
Shallow Inelastic Scattering

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

Ulrich Mosel

2011

My Paradigm

- A good generator does not have to fit the data, provided it is right
- A good generator does not have to be right, provided it fits the data

NUINT 2011

Institut für Theoretische Physik

- Yesterday: Most importantly the generators should match measured data

Lesson from the past: fitting QE M_A hides true physics: MEC, 2p-2h

This talk : Most importantly the generators should contain the right physics

Outline

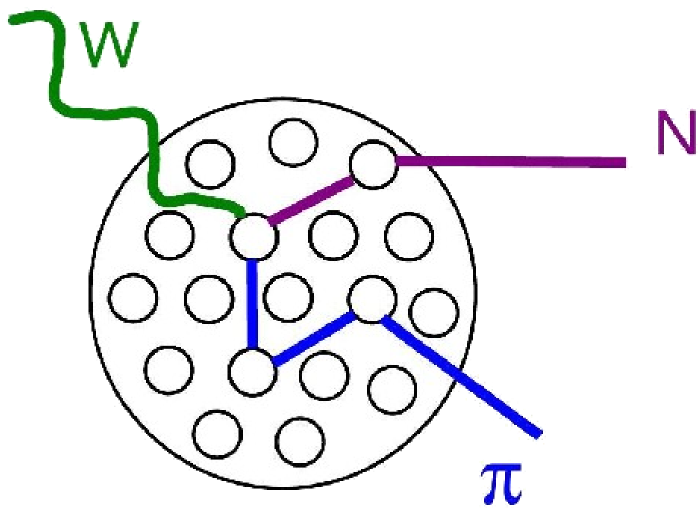
- Giessen Boltzmann-Uehling-Uehlenbeck project
  - model
  - verification
  - lessons from electron- and photon- induced reactions
- Shallow Inelastic Scattering: which reactions contribute
- Final state interaction may dramatically change the experimental signature of the primary interaction

Nuclei as targets

Nuclear effects are non-negligible for neutrinos in the GeV region

Initial State Interactions
change the inclusive xsec

- nuclear binding
- Fermi motion
- Pauli blocking



Final State Interactions
change the observables
in semi-inclusive reactions

- absorption of the outgoing nucleons
- rescattering, charge exchange
- redistribution of energy
- production of new particles

A realistic model must include realistic description of nuclear effects, both ISI and FSI

GiBUU model

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

– the semiclassical transport model in coupled channels –
simulates the transport of hadrons through nuclear matter in space and time

GiBUU describes several types of reactions both in resonance and high energy regions, is extensively checked against experimental data

for heavy ion collisions, pA, πA, γA, e^- A

Aim: many reactions with one microscopic model

Review: Buss et al., Phys Rep 512 (2012) 1-124
Open source code: http:/gibuu.physik.uni-giessen.de/GiBUU

Theoretical basis of GiBUU

- Kadanoff-Baym equation (1960s)
  full equation can not be solved yet
  not (yet) feasible for real world problems

- Boltzmann-Uehling-Uhlenbeck (BUU) models

  Boltzmann equation as gradient expansion of Kadanoff-Baym equations: GiBUU, ...

  The same mean-field potential for initial and final state interactions
  In-medium self-energies and spectral functions

- Cascade models (typical event generators, NUANCE, GENIE, NEUT)
  no mean-fields
  primary interactions and FSI not consistent

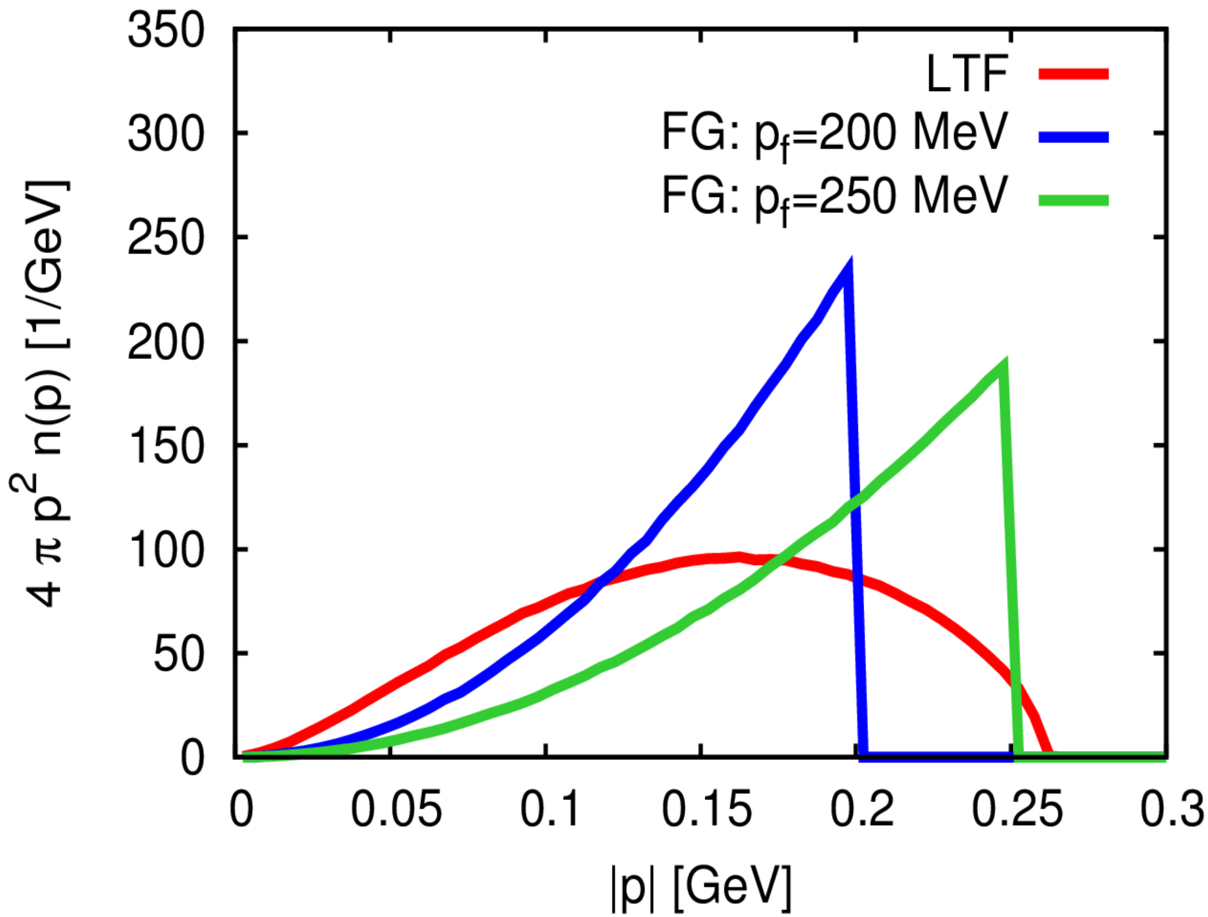
1. Initialize nucleus

- local Thomas-Fermi gas model

! very different from global Fermi gas

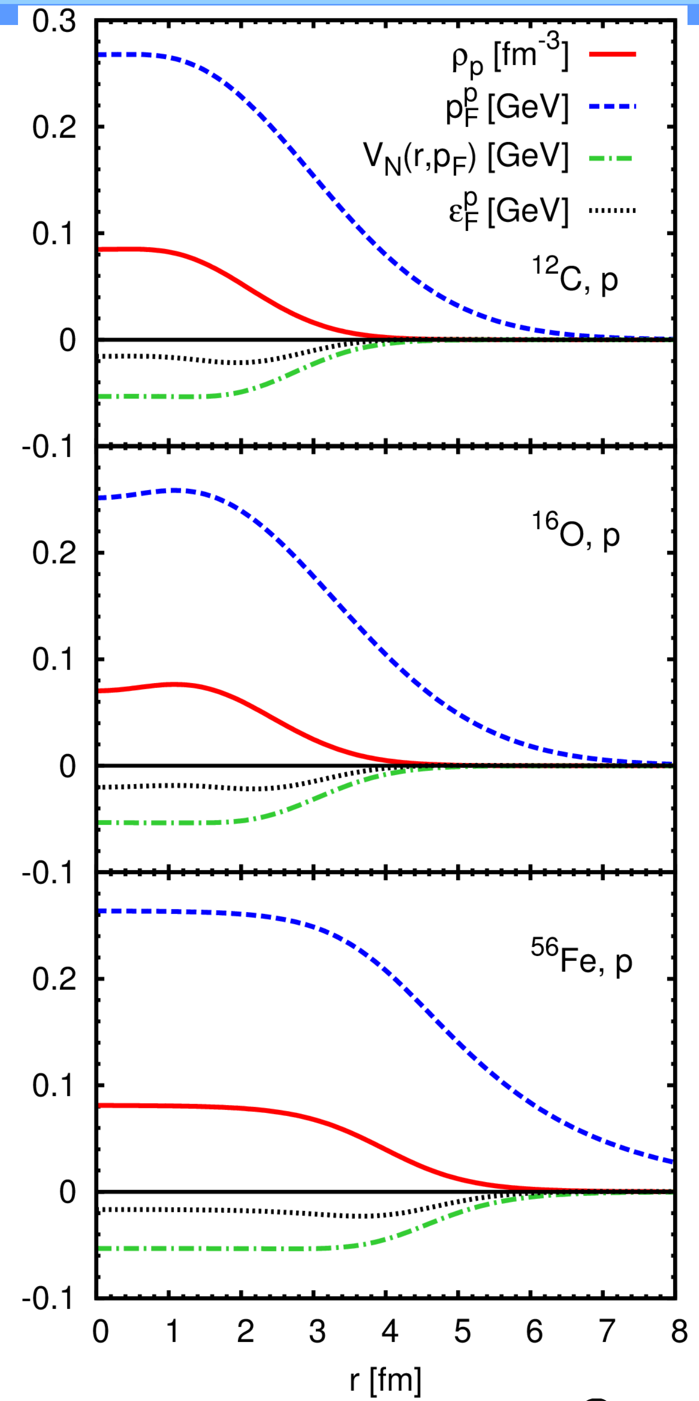
example:

Momentum density distribution of proton in oxygen



1. Initialize nucleus

- local density approximation with realistic density profile
- density- and momentum-dependent mean-field potential



Density (ρ),
Fermi momentum (p_F),
mean-field potential (V_N)
and Fermi energy (ε_F)
of protons as functions of nucleon radius

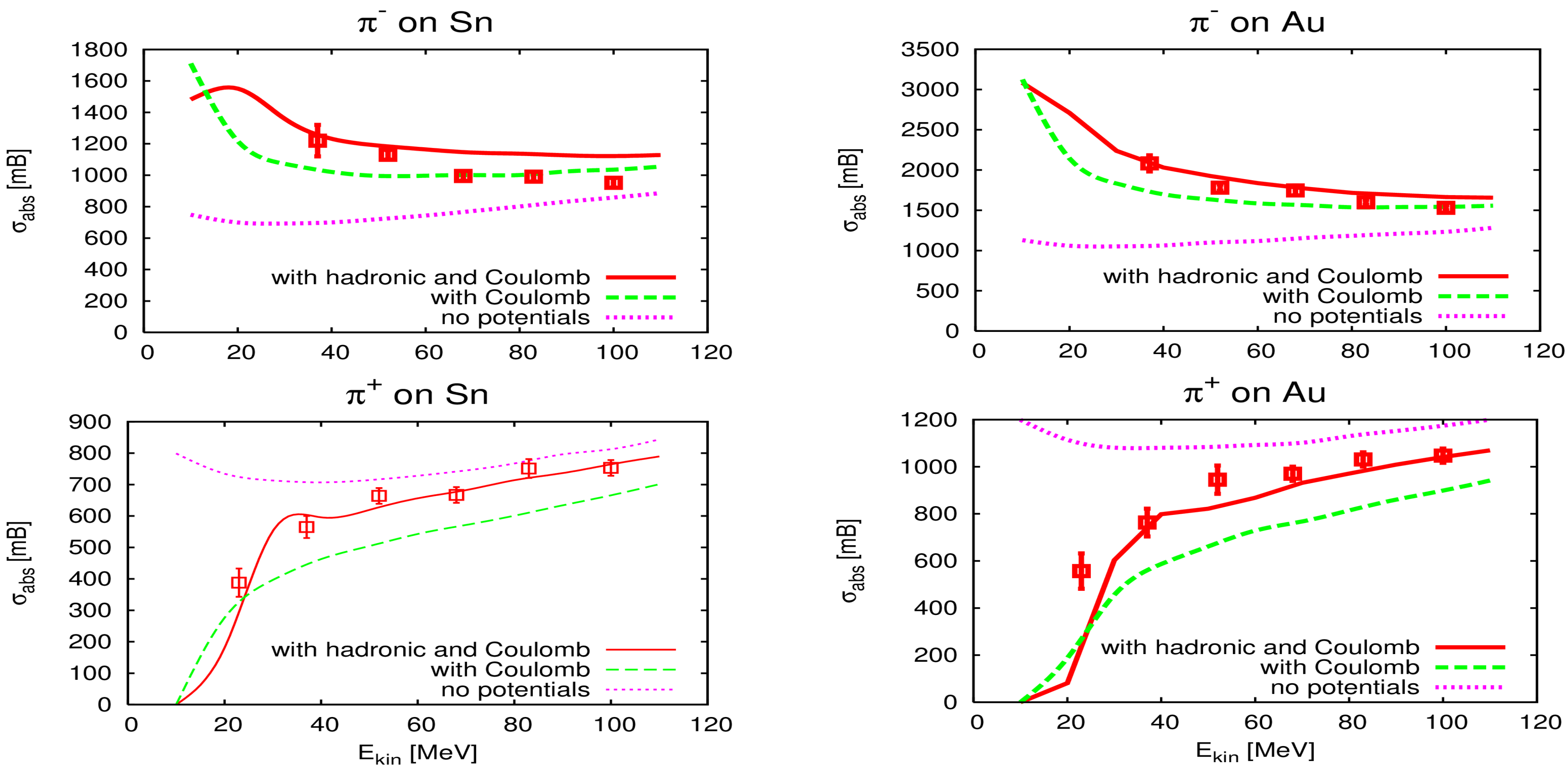
Distributions are correlated

Low momentum nucleons tend to sit at low densities

Validation of the model -1

Pion absorption (Buss EPJA 29 (2006))

first test of πNΔ dynamics in nuclei – potential does matter



Necessary but not sufficient test. Pions get stuck mainly on surface. Nuclear volume is not tested. Photon- and electron- induced required

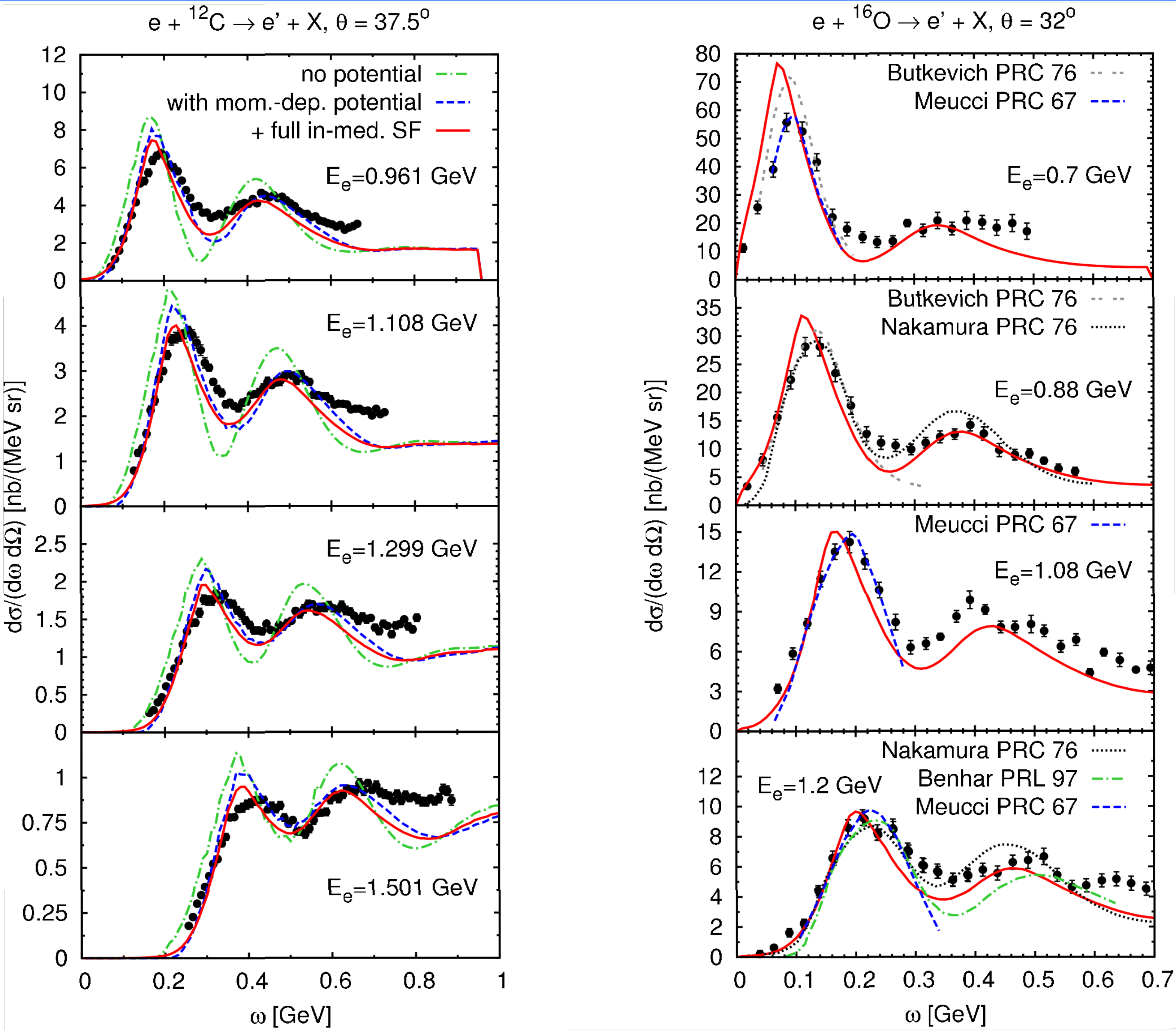
2. Calculate in-medium cross section

- vacuum form factors for QE and RES production
- broadening of the resonances (collisional or Oset/Salsedo)
- in-medium modified cross section
- full in-medium kinematics
- Pauli blocking

typical result:

Medium cross sections are suppressed and smeared as compared to elementary

Validation-2: electroproduction



El-m couplings from MAID (up-to-date unitary isobar model for photo- and electro-production, Mainz group)

Thus fully consistent with photo-induced reactions

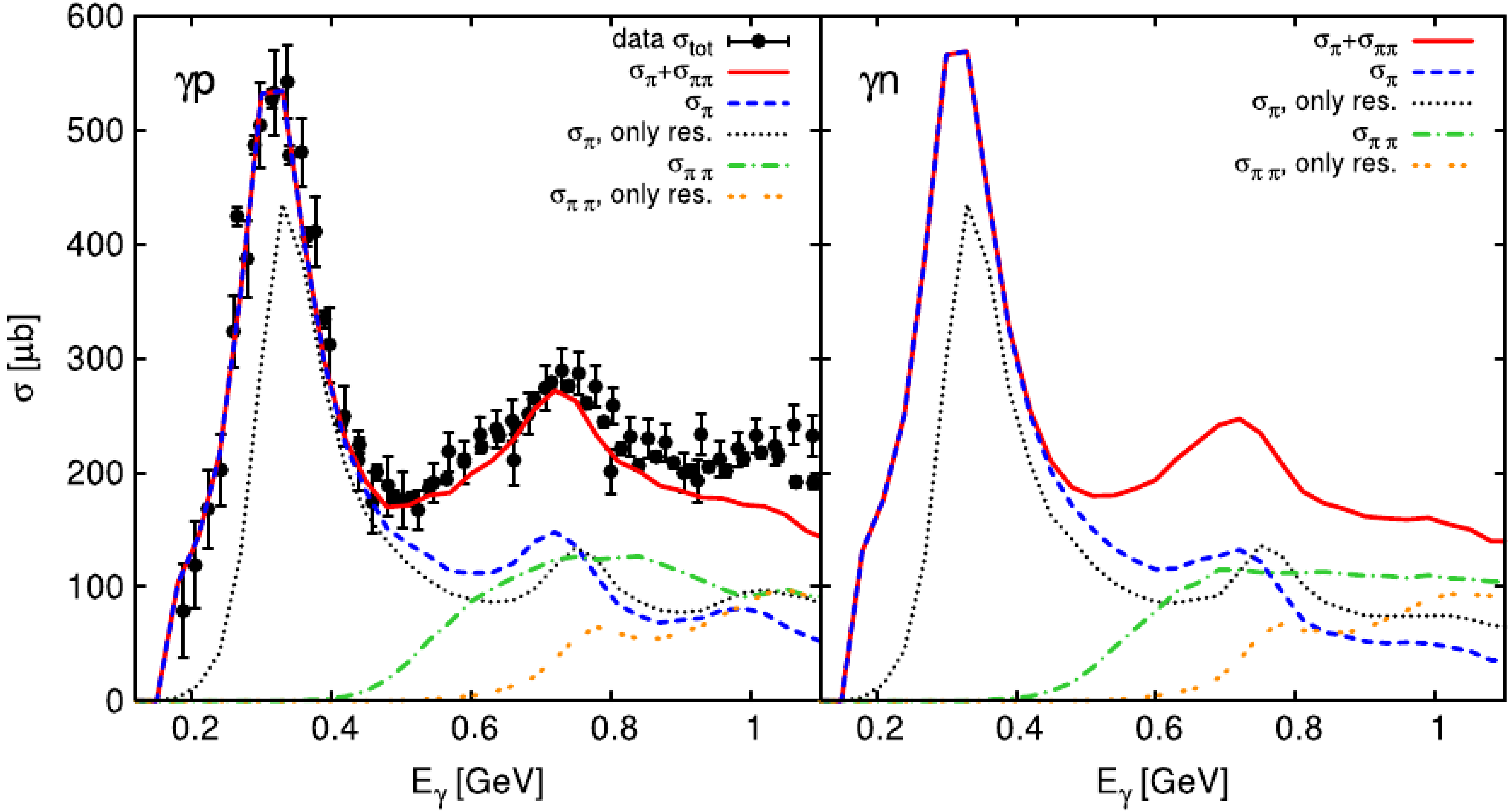
Buss PRC 76

Leitner PRC 79

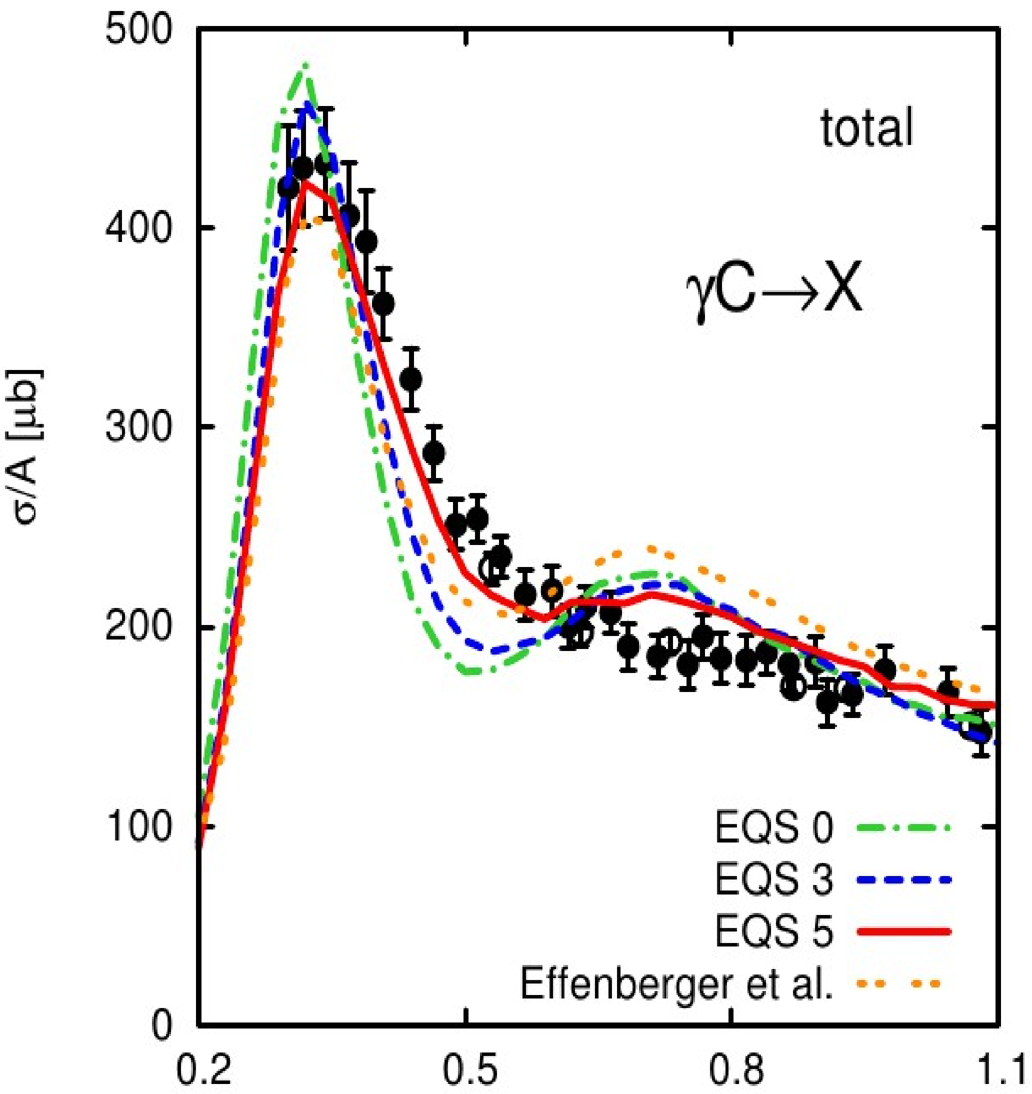
Lesson-2: resonances on proton ...

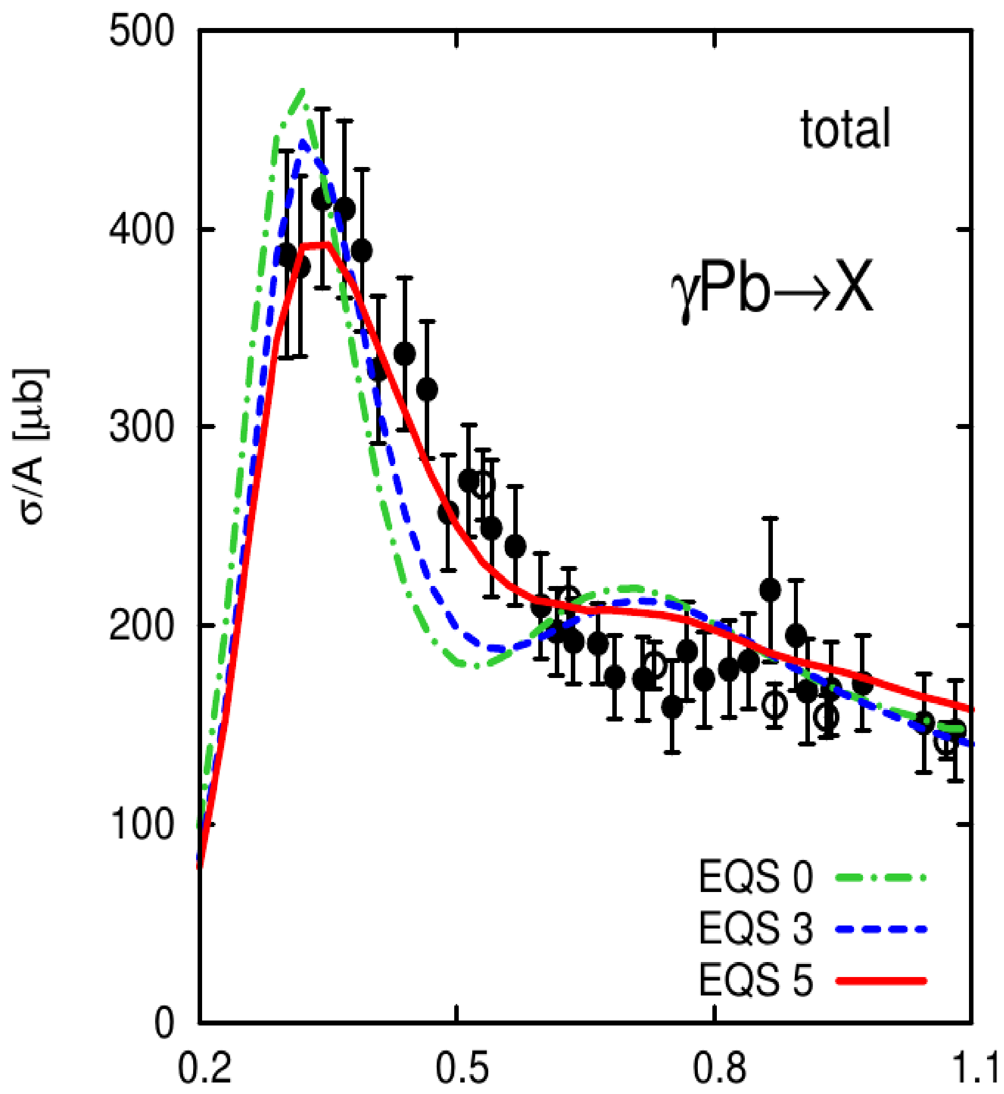
Photoabsorption on proton and neutron targets: Delta, 2nd and 3rd resonance regions are clearly seen

Lesson-1: both resonances and background 1- and 2-pion production matter



… "disappear" on nuclei





… and remember, that nuclear potential matter

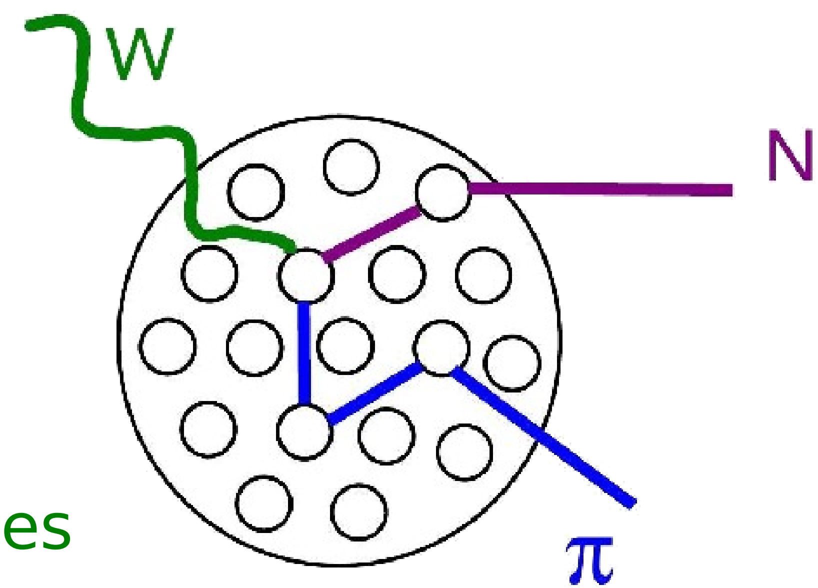
and this is **validation-3**

Steps in the GiBUU code

3. Propagate outgoing particles through nucleus according to the Boltzmann-Uehling-Uhlenbeck equation

$$\frac{df_i}{dt} = \left(\partial_t + (\nabla_{\vec{p}} H_i)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i)\nabla_{\vec{p}}\right) f_i(\vec{r}, p, t) = I_{coll}\left[f_i, f_N, f_\pi, f_\triangle, \ldots\right]$$

- 61 baryons and 21 mesons coupled through the collision integral
- decay of unstable particles
- elastic and inelastic 2- and 3- body scattering
- Pauli blocking for fermions



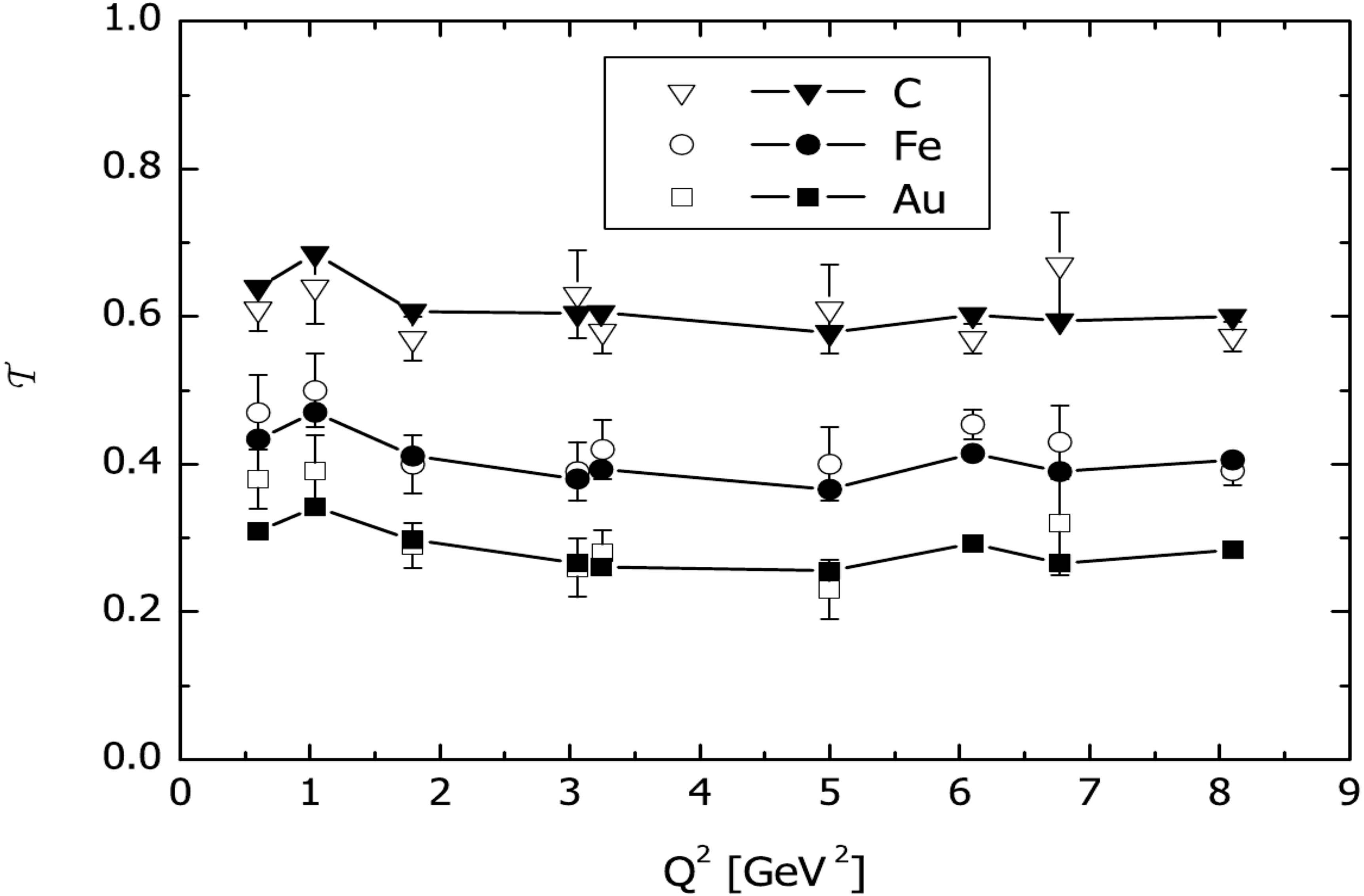
result: spectra of the outgoing particles with and without FSI are different

Validation of the model -4

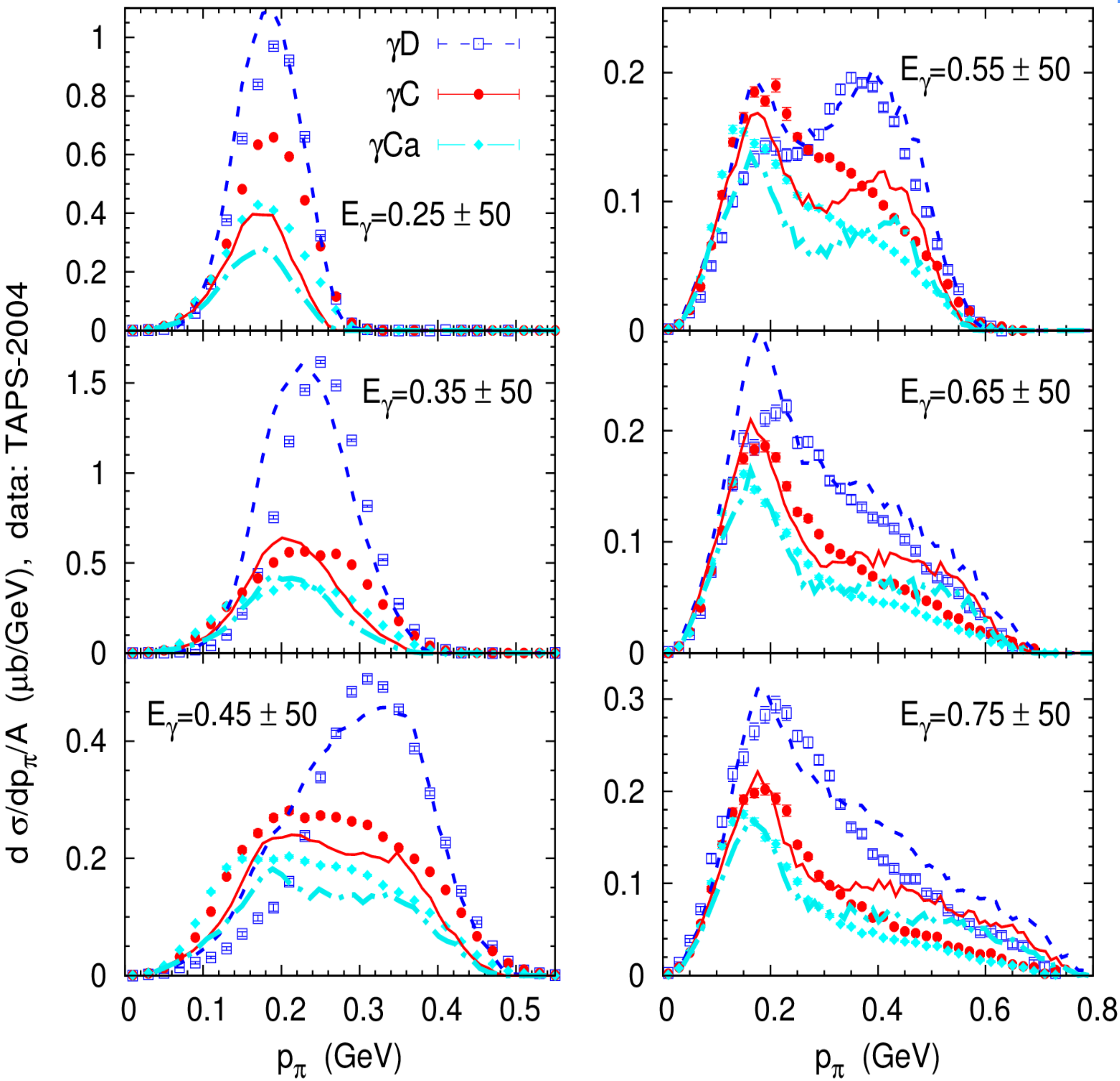
Transparency A(e, e' p) (Lehr NPA 699 (2002))

protons leaving the nucleus with/without Final State Interactions

data: Jlab 1995, 2002
SLAC 1998



Validation of the model -5



Neutral pion photoproduction on D, C, Ca

Krusche, Lehr, EPJA 22 (2004),

recalculated with the current version of the code

Lesson-3: Final state interactions matter!

Final State Interactions of pions

- Absorption

  $\pi N \to \Delta$ (dominant) $\pi N \to \eta\Delta$ followed by $\Delta N \to NN$

  $\pi N \to$ R followed by RN $\to$ NN, $\pi NN \to NN$

  $\pi N \to \omega N, \phi N, \Sigma K, \Lambda K, K\bar{K}N$

- Charge exchange

  $\pi^+ n \leftrightarrow \pi^0 p$

  $\pi^0 n \leftrightarrow \pi^- p$

Hadronic couplings for FSI taken from PDG

- Redistribution of energy

  $\pi N \to \pi N, \omega\pi N, \phi\pi N, \Sigma K\pi, \Lambda K\pi$

- Production

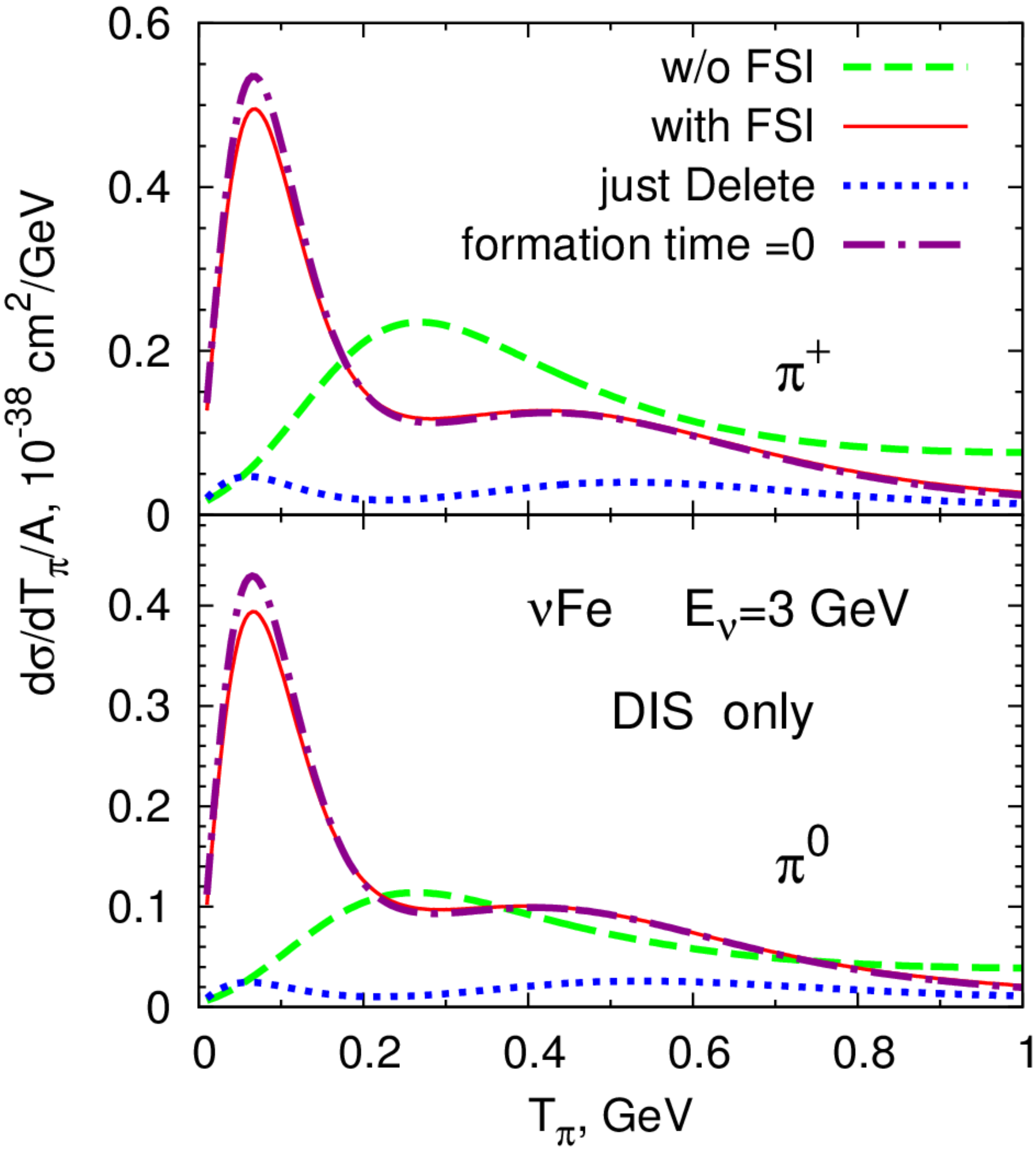
  $NN \to \Delta N$ followed by $\Delta \to \pi N$, also via other R

  $\omega N, \phi N \to \pi N$

  $\pi N \to \pi\pi N$

Pions seen in the detector

are NOT those produced initially



Pion production without (w/o) and with Final State Interac.

A numerical experiment:
If any particle produced in neutrino vertex undergoes a secondary interaction, just Delete it

Result:
Most of the pions reinteract while propagating throughout the nucleus

Final State Interactions of baryons

- Absorption of Δ and other resonances

$\Delta N \rightarrow NN$, $RN \rightarrow NN$

- Charge exchange

$\Delta^{+} n \leftrightarrow \Delta^{0}\ p$

$\Delta^{0} n \leftrightarrow \Delta^{-}\ p$

- Redistribution of energy

$\Delta N \rightarrow\ \Delta N,\ \ NN \rightarrow\ NN,\ \ NR \rightarrow\ NR,\ \ NN \rightarrow\ NN\pi$

- Production

$NN \rightarrow\ \Delta N,\ \ NN \rightarrow\ NR$

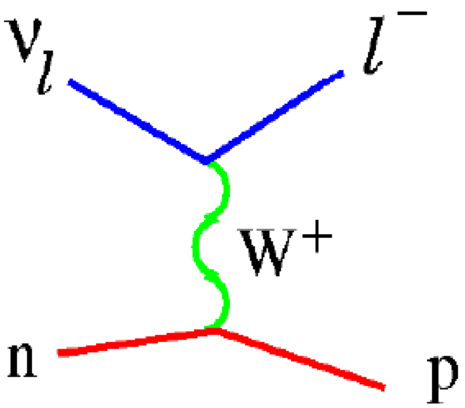
$\pi N \rightarrow\ \Delta,\ \ \pi N \rightarrow\ \eta\Delta,\ \ \pi N \rightarrow\ R$

Neutrino reactions

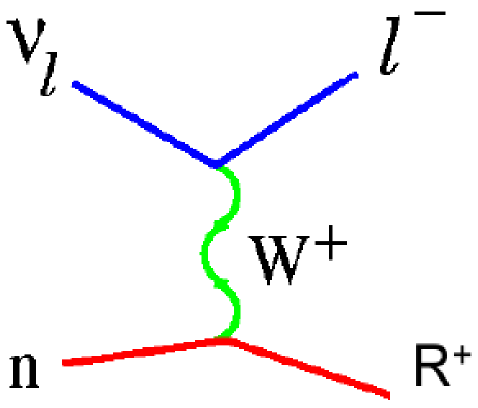
at intermediate energies

Primary interactions

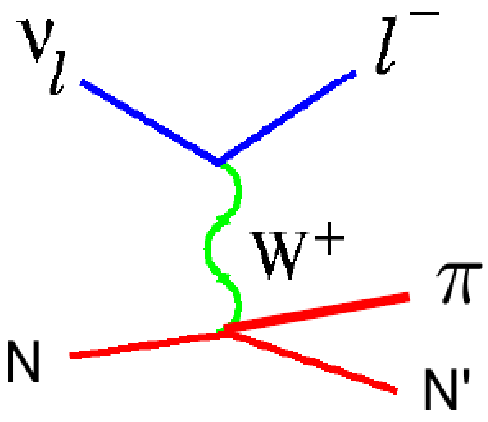
QE



RES



single-π BG

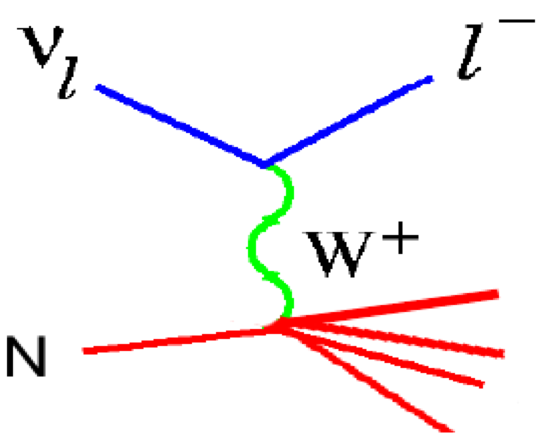


13 resonances

from 19 PDG 3* and 4*

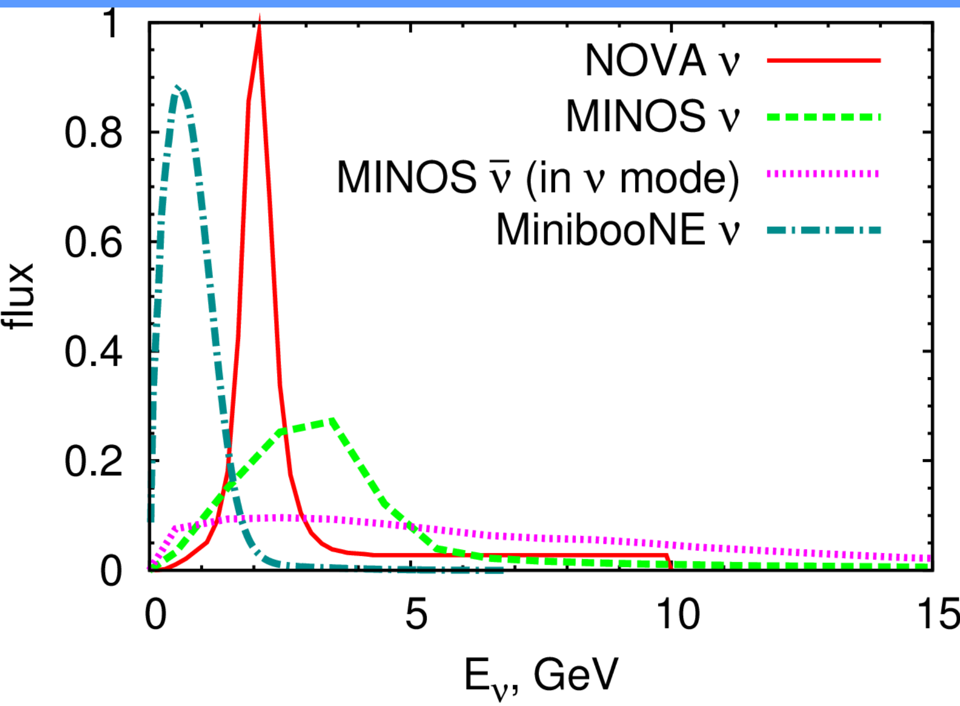
The electro-magnetic couplings of others are not known

DIS



via PYTHIA code

Wide-band neutrino beams



All neutrino experiments necessarily use wide-band beams

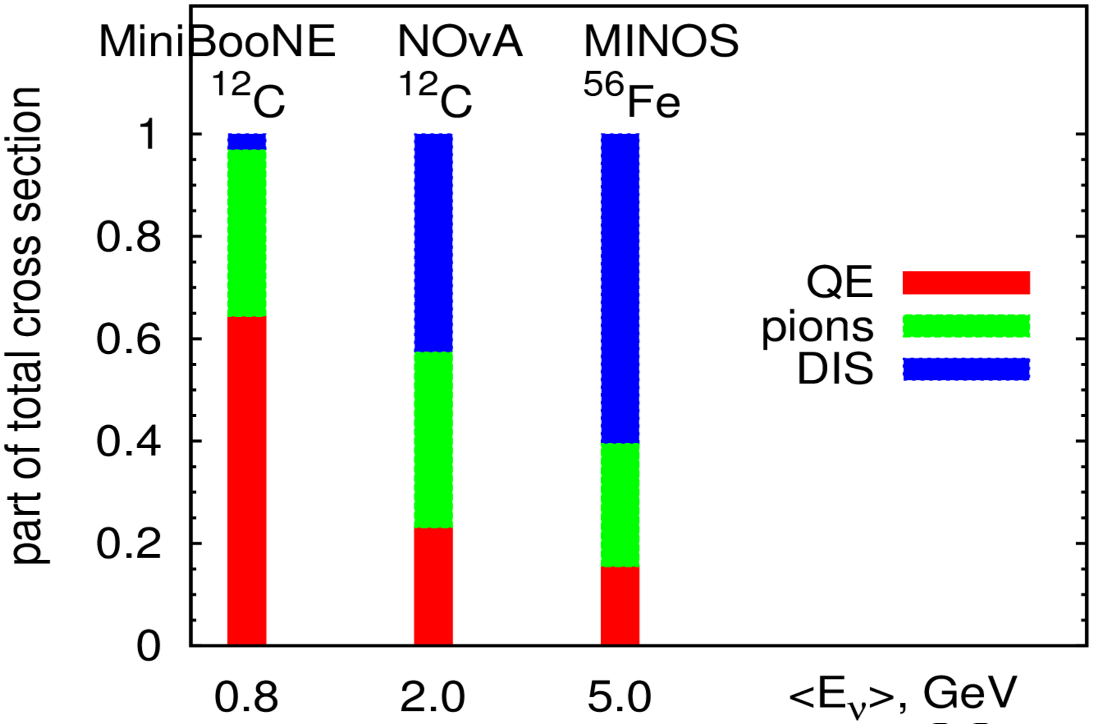
All reaction mechanisms ...

- quasielastic scattering (QE)
- pion production (resonance excitation, non-resonant background)
- DIS

… must be modeled equally well

No dominant process for any of the experiments

A realistic model must include all reaction mechanisms



Elementary input

- QE: vector FF BBBA2007, axial FF M_A=1 GeV
- RES: vector FF: related to el-m FF by CVC, MAID parametriz

(MAID, Drechsel EPJA 34: Mainz unitary isobar model for pion photo- and electroproduction on the nucleon; it provides the resonance helicity amplitudes, from which el-m transition form factors are derived;)

axial FF: PCAC, fitted to ANL $p\pi^+$ data

- Single-π BG: vector part based on MAID, axial part fitted to ANL
- Joining RES and DIS

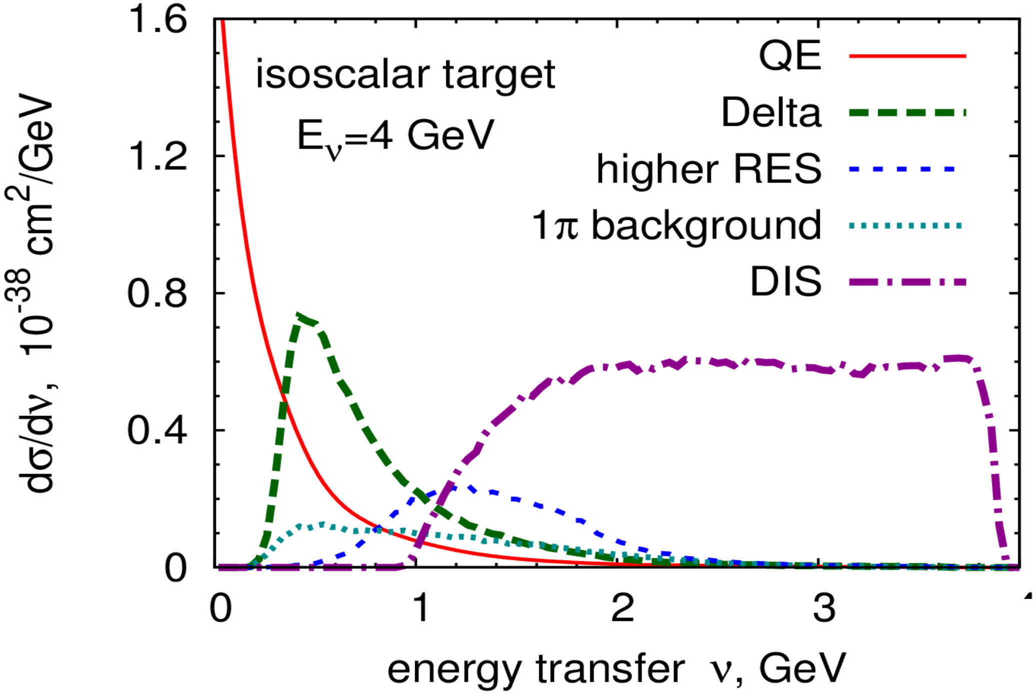
W>1.6 - 1.65 GeV: DIS is smoothly turned ON

W<2.0 -2.05 GeV : RES are smoothly turned OFF

Motivated by fitting electron data

Double counting? NO Taking into account 2-, 3-, 4- ...pion, ... bgr

Each channel contributes in SIS

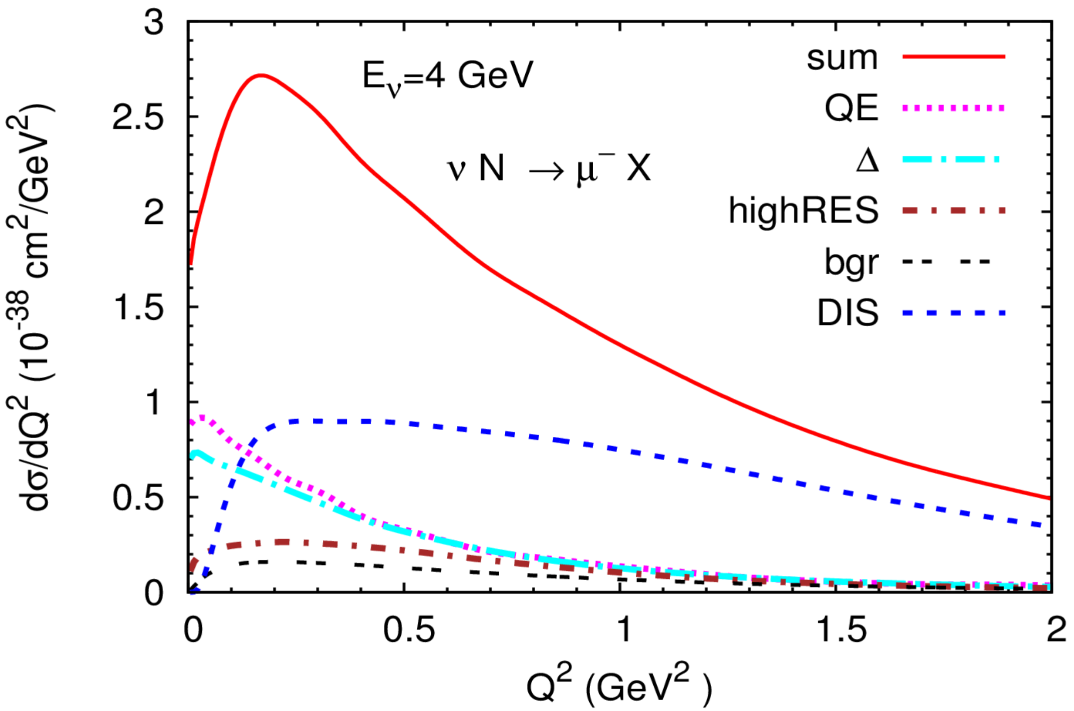


PRC76 “Neutrino- and antineutrino-induced reactions with nuclei between 1 and 50 GeV”

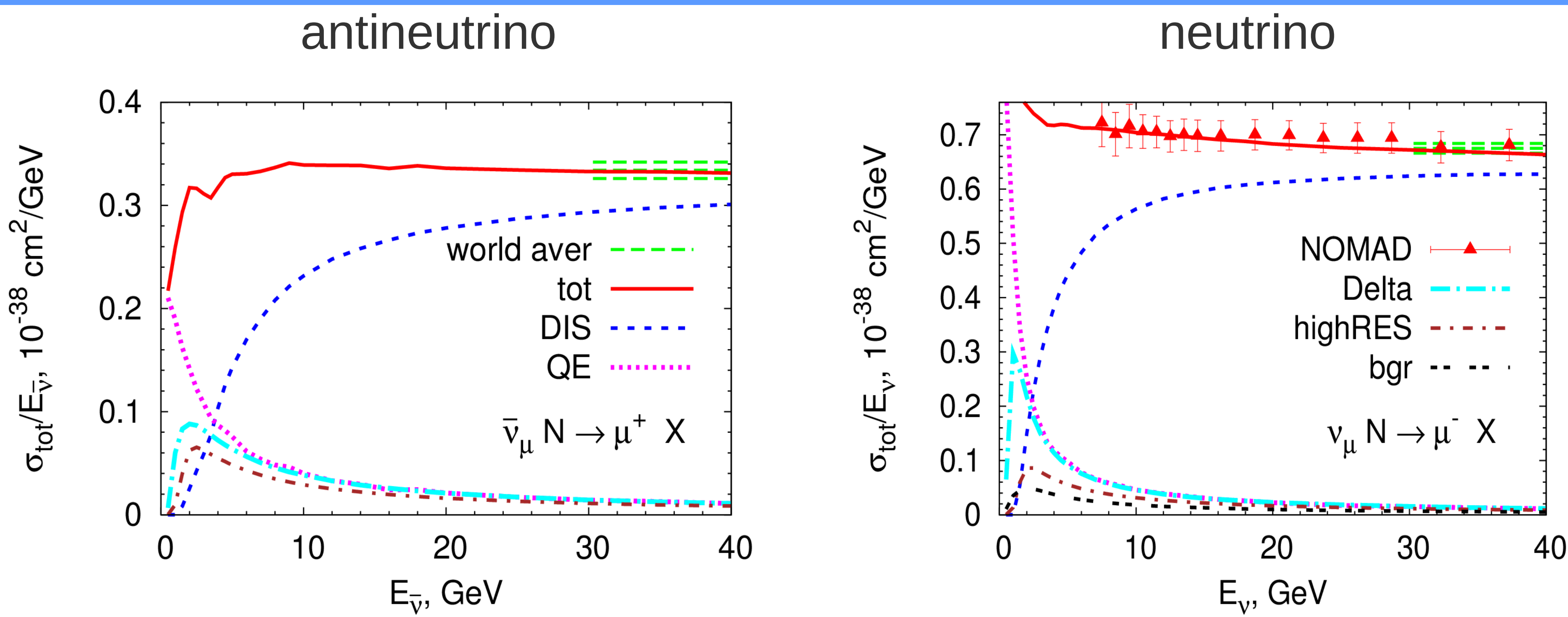
All processes contribute

in the SIS region,

overlapping



Isoscalar cross section



Dip at 3-4 GeV ? Minor in neutrino reaction

Maybe because the 2-pion background is missing (recall **lesson-1**)

Seen in antineutrino reaction

Both 1- and 2-pion background are missing in the model

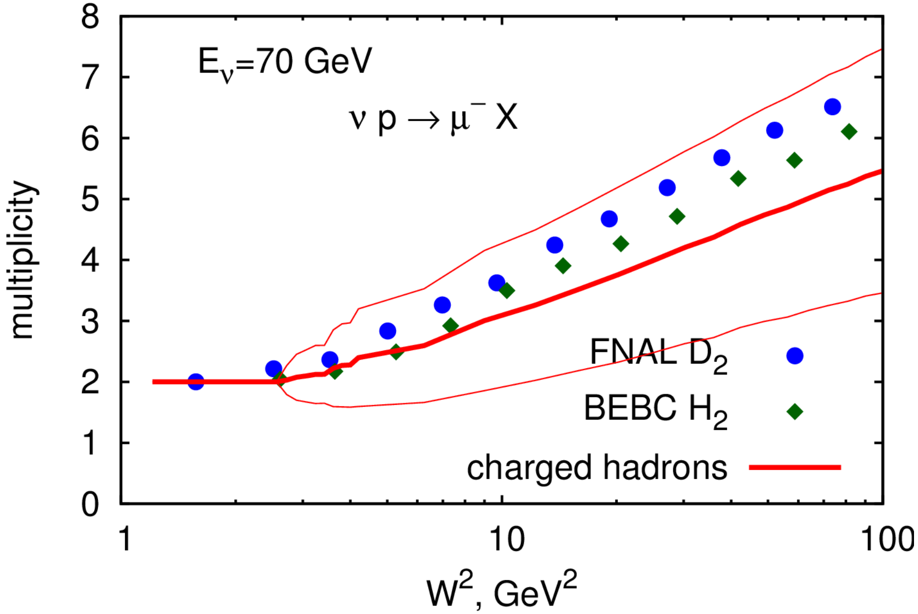
SIS region is sensitive to each contribution

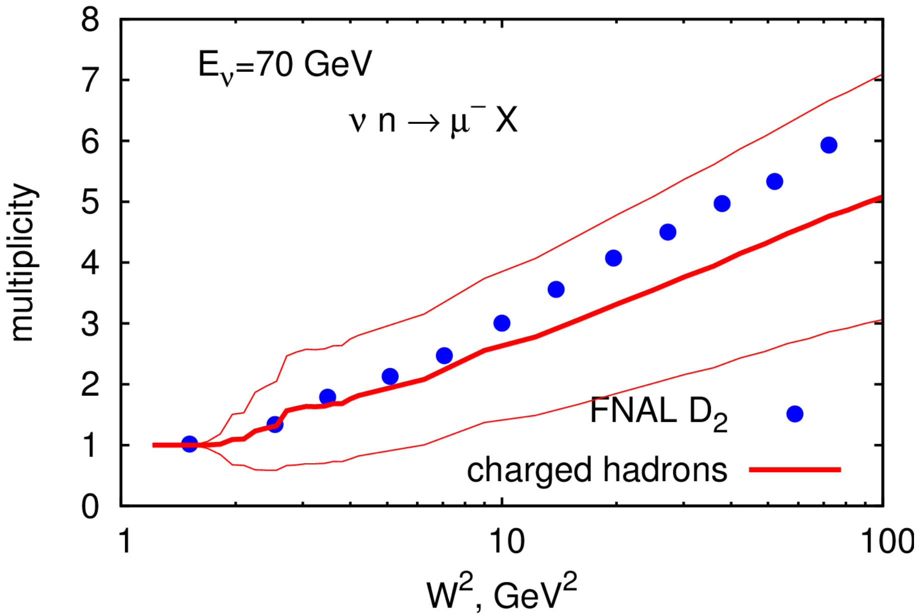
Multiplicities

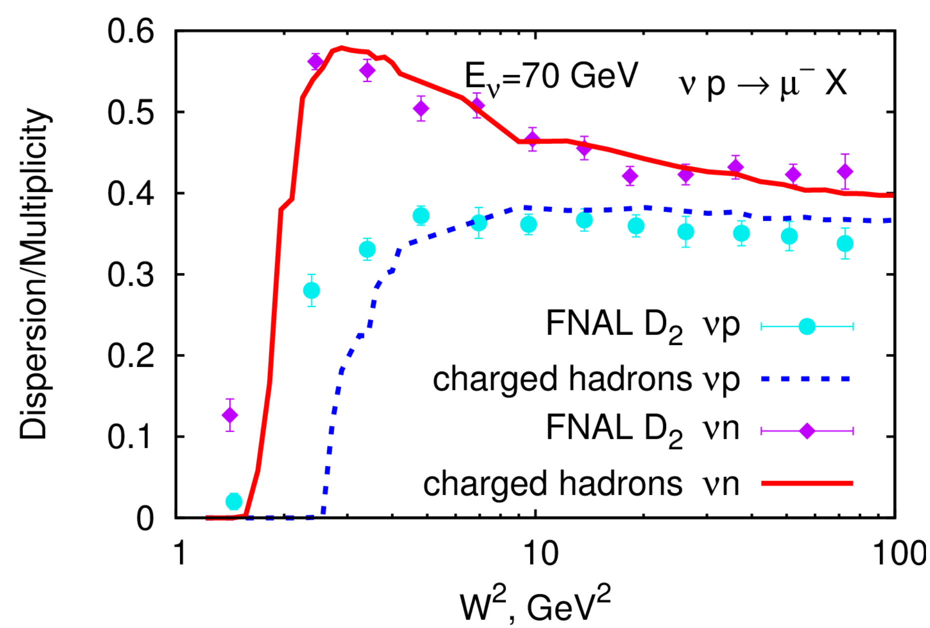
independent check of your model in SIS region

first performed for GENIE in EPJC 63 (2009) “A hadronization model for few-GEV neutrino interactions”

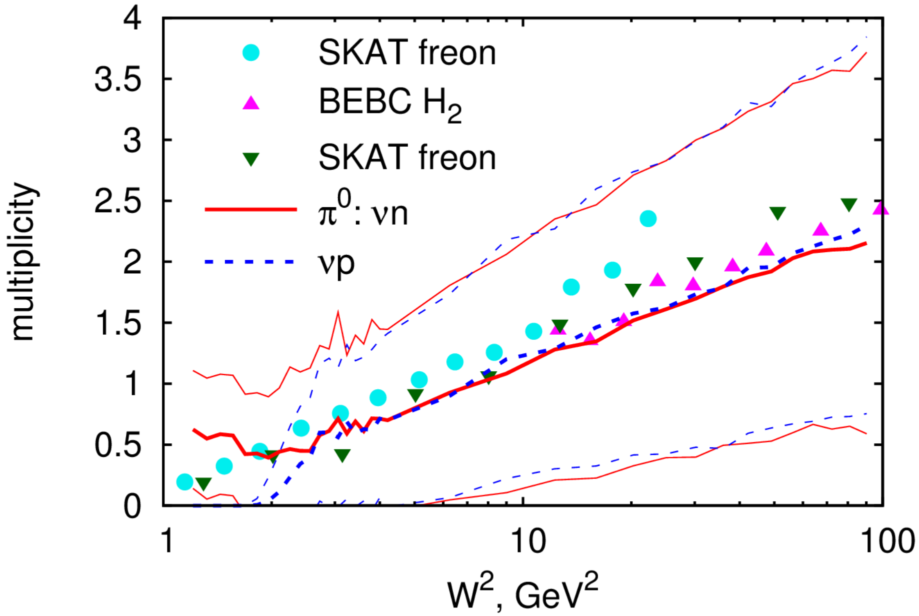
Here the results (average multiplicity ± dispersion) as calculated within GiBUU **(PRELIMINARY)**

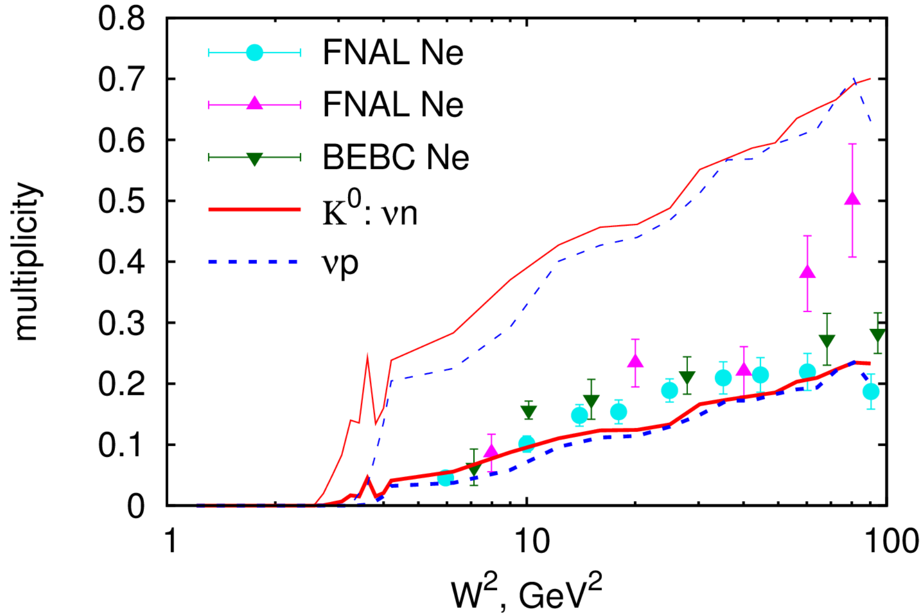


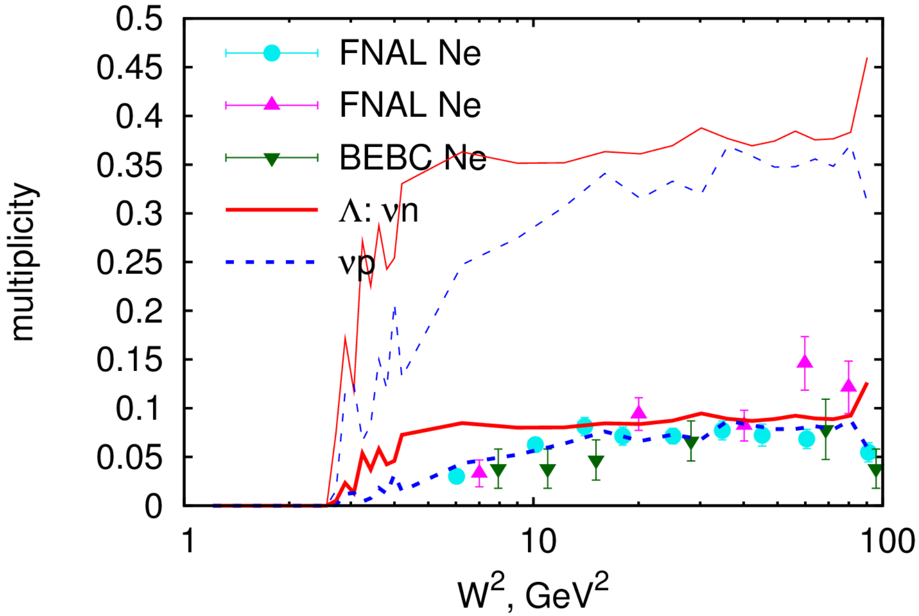




More multiplicities ...







Do it yourself:

Check your favorite model

Even more plots in EPJC63 cited above

? Medium DIS cross section ?

Medium effects for resonances are treated with default parameters of the GiBUU, no fine tuning; no medium effects for background

DIS? PYTHIA code calculates *free* DIS cross section

We should somehow “remove” (or do not remove) in-medium potential in order to provide the input kinematics for PYTHIA

No unique prescription how to do this. Several possibilities:

F-NO, F-CM, F-THRE

No difference between them for electroproduction

Neutrinos:

Difference between them is the intrinsic uncertainty of the GiBUU

EKS98 medium PDF

For comparison

Calculation without microscopic nuclear effects

(mean-field potential and Fermi motion switched off),

but with medium Parton Distribution Functions

K.J. Eskola, V.J. Kolhinen and C.A. Salgado,

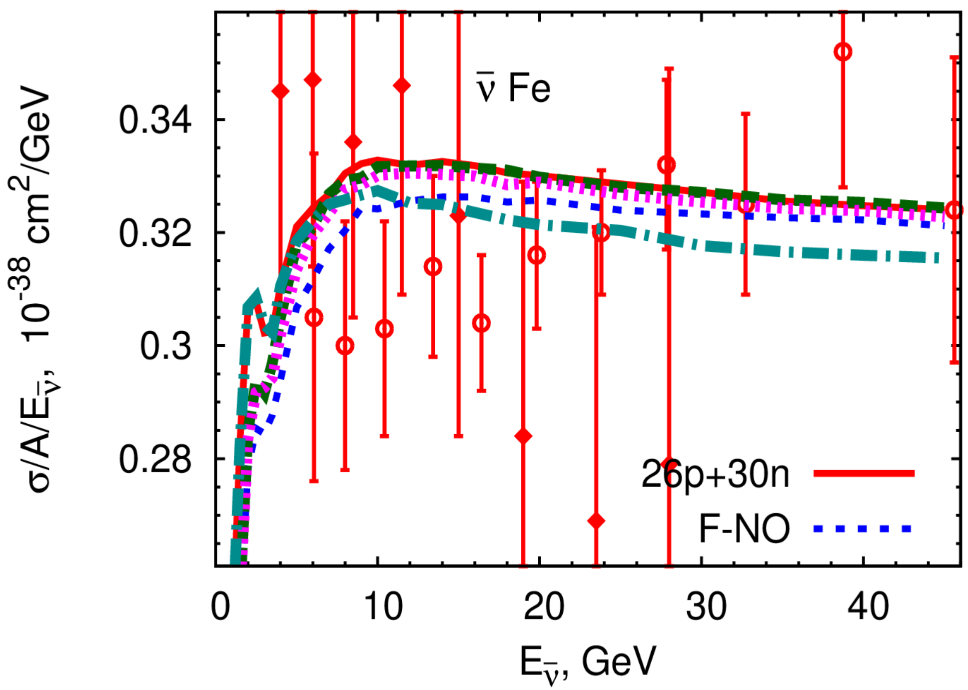
"The scale dependent nuclear effects in parton distributions for practical applications", Eur. Phys. J. C9 (1999) 61

“nuclear PDF”

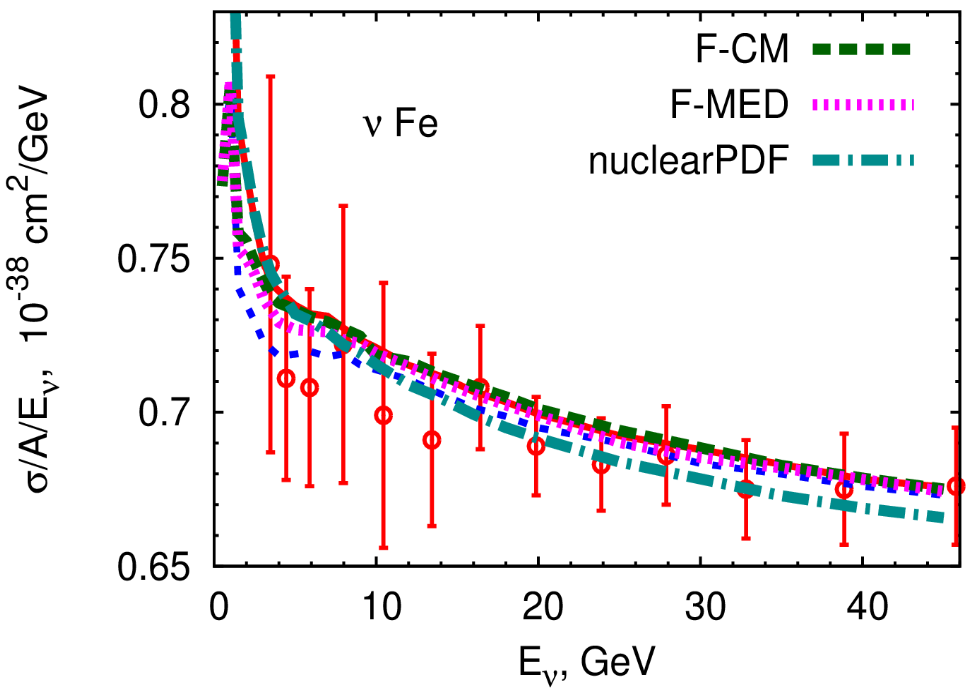
Medium DIS cross section

GiBUU uncertainty in DIS nuclear effects ~ 2%

antineutrino



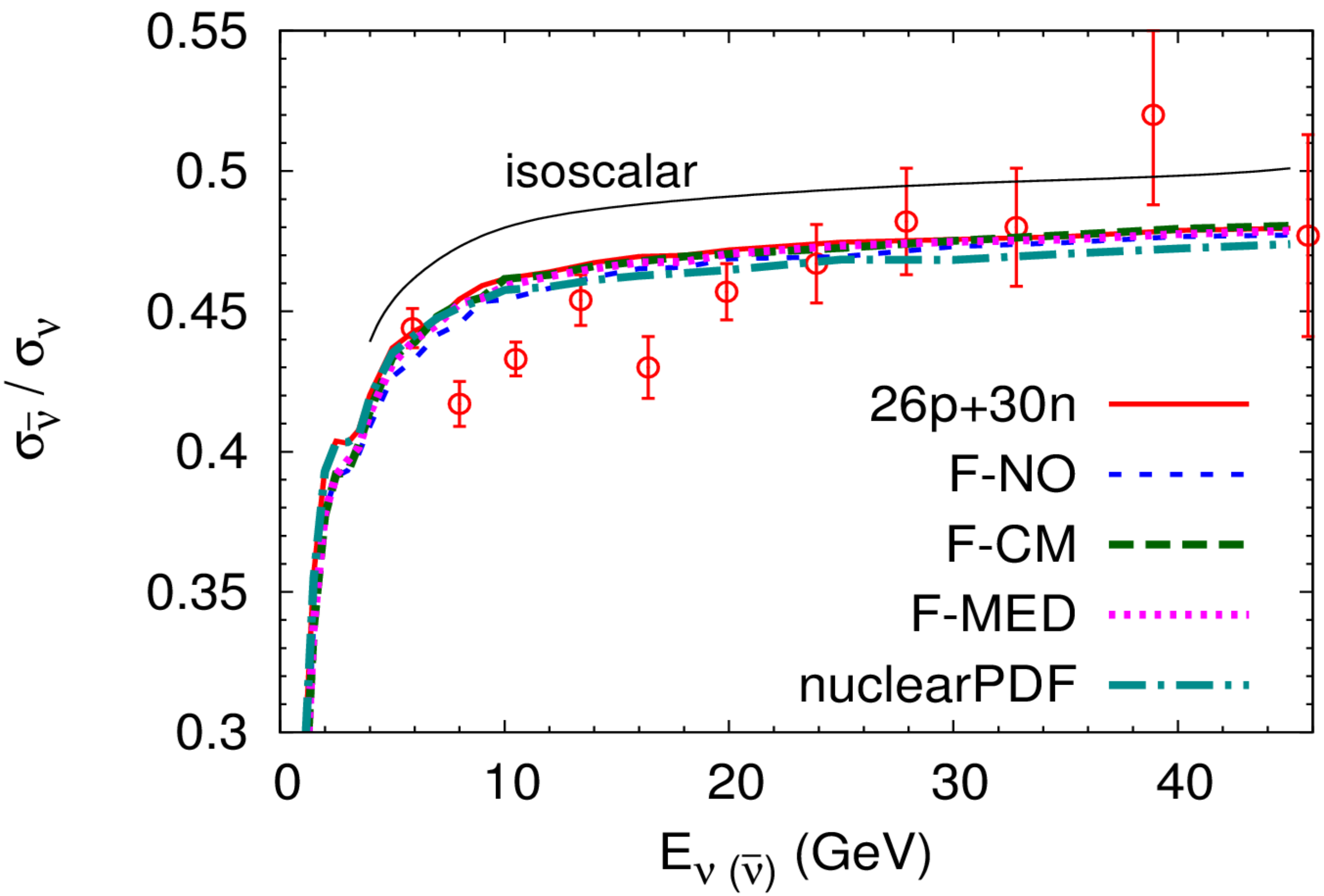
neutrino



Data: MINOS, IHEP-JINR

Medium DIS cross section

Neutrino/antineutrino ratio is remarkably insensitive to nuclear effects



Data: MINOS

Medium W - distributions

Are we completely satisfied with our model?

Maybe not.

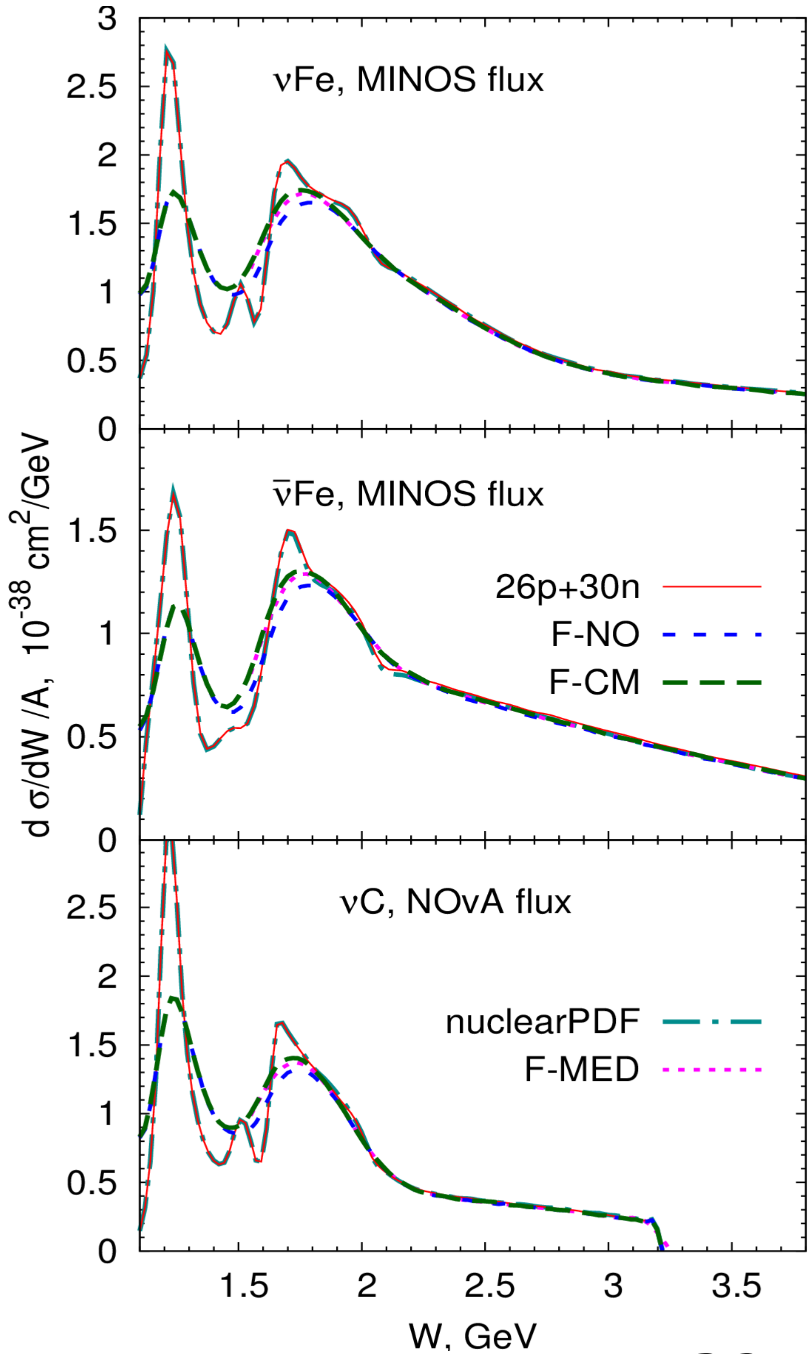
Recall **lesson-2**:
Resonances “disappear” in medium

Indeed, the 2nd resonance region is seen for “free” xsec, but not for Fe/C

However,
Shoudn't the dip between the Delta and the rest be even more shallow?

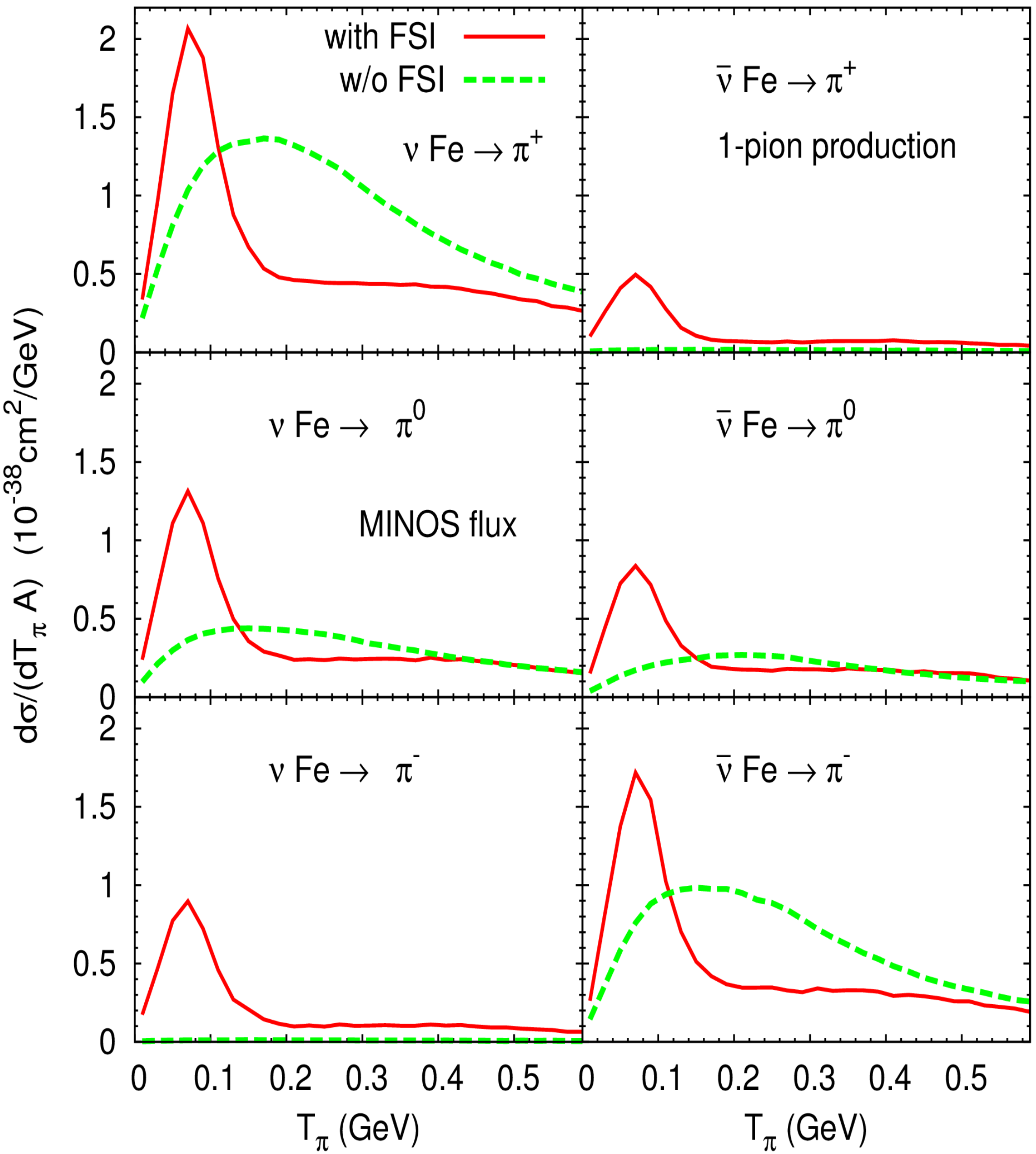
Aren't we missing 2pi-background?
(and 1pi-bgr for antineutrinos?)

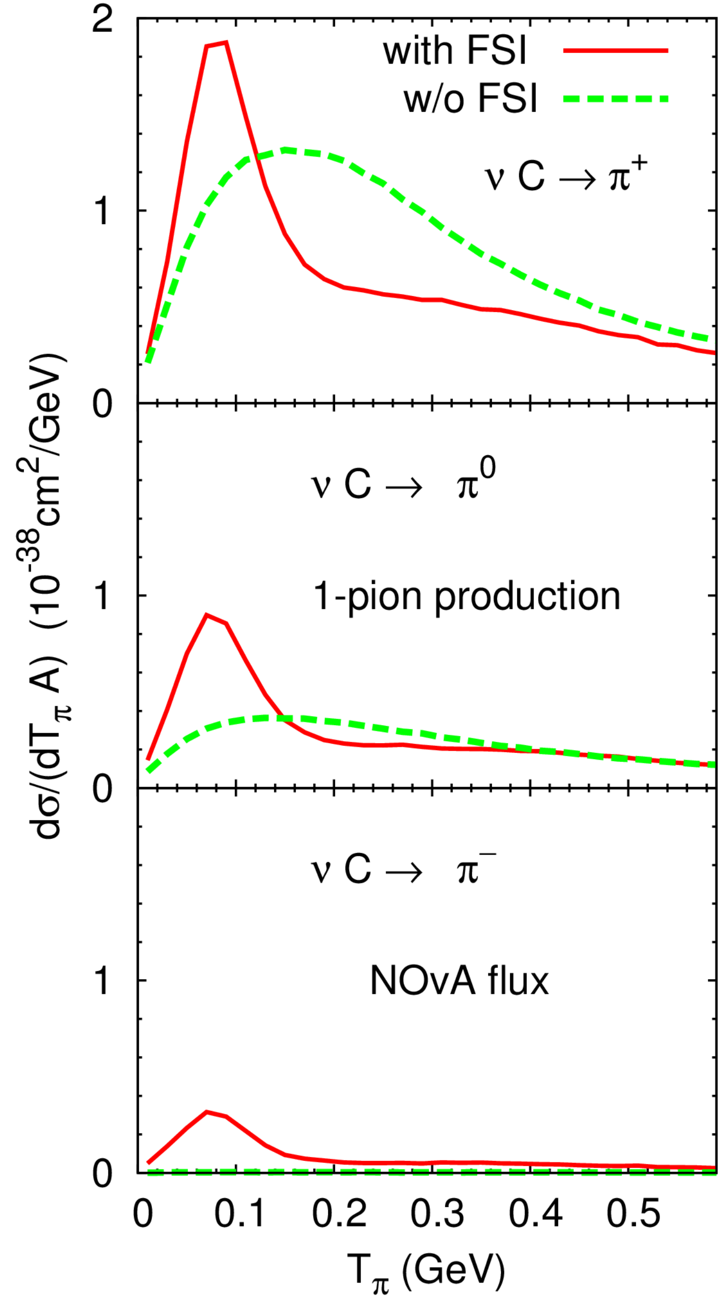
Only experiment can answer



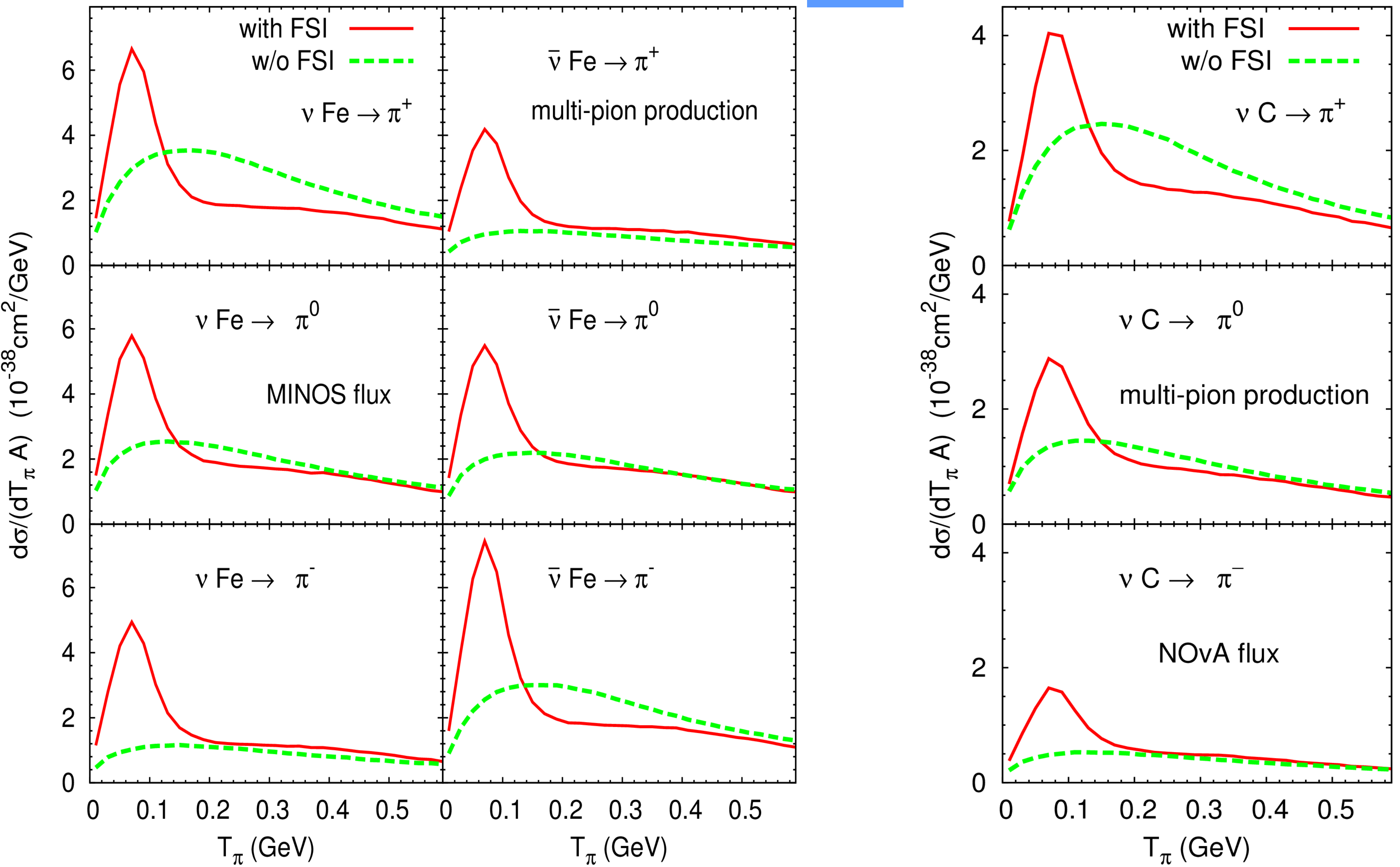
1-Pion produc: with and w/o FSI

Recall **lesson-3**: Final State Interactions matter



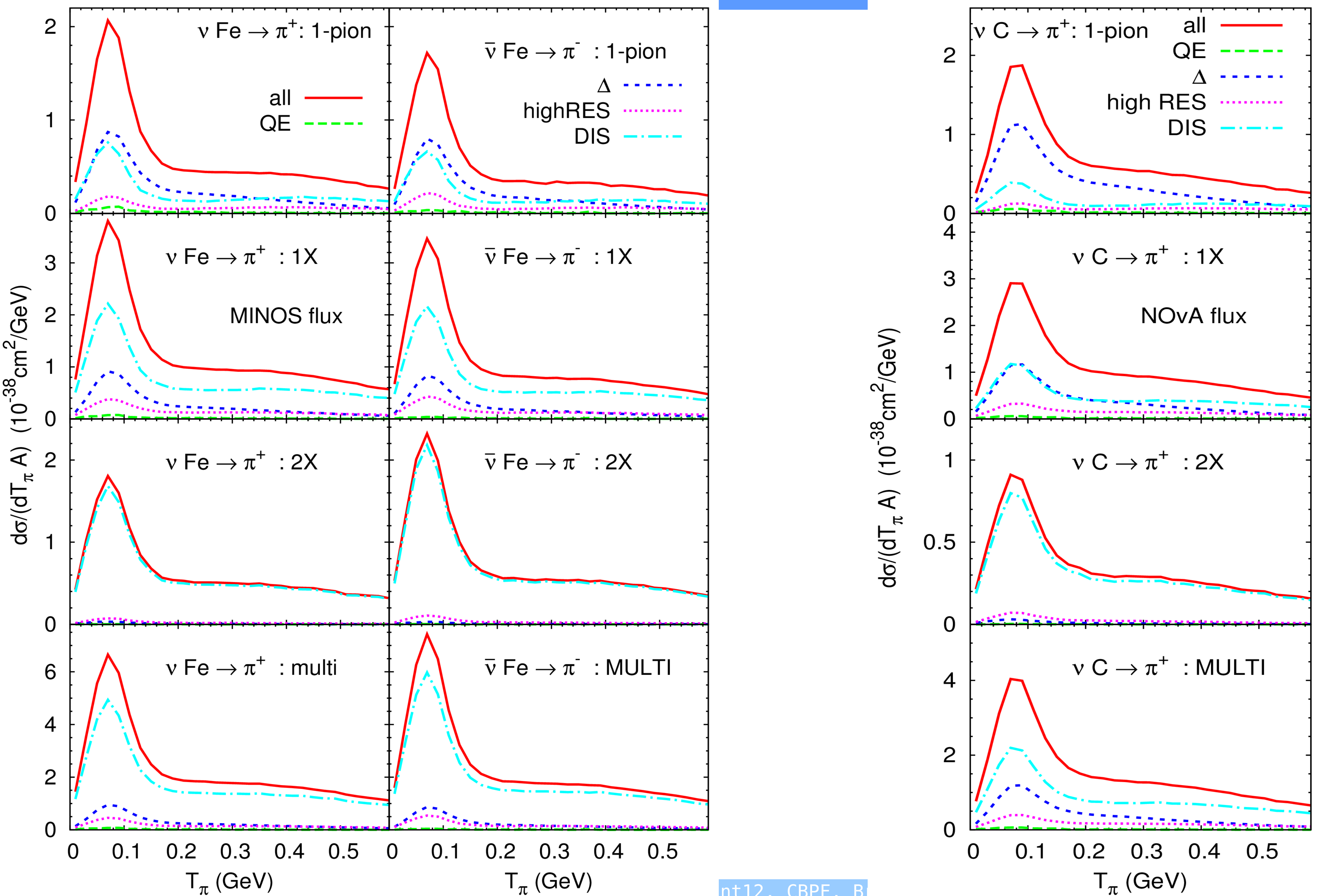


Multi-Pion produc: with and w/o FSI

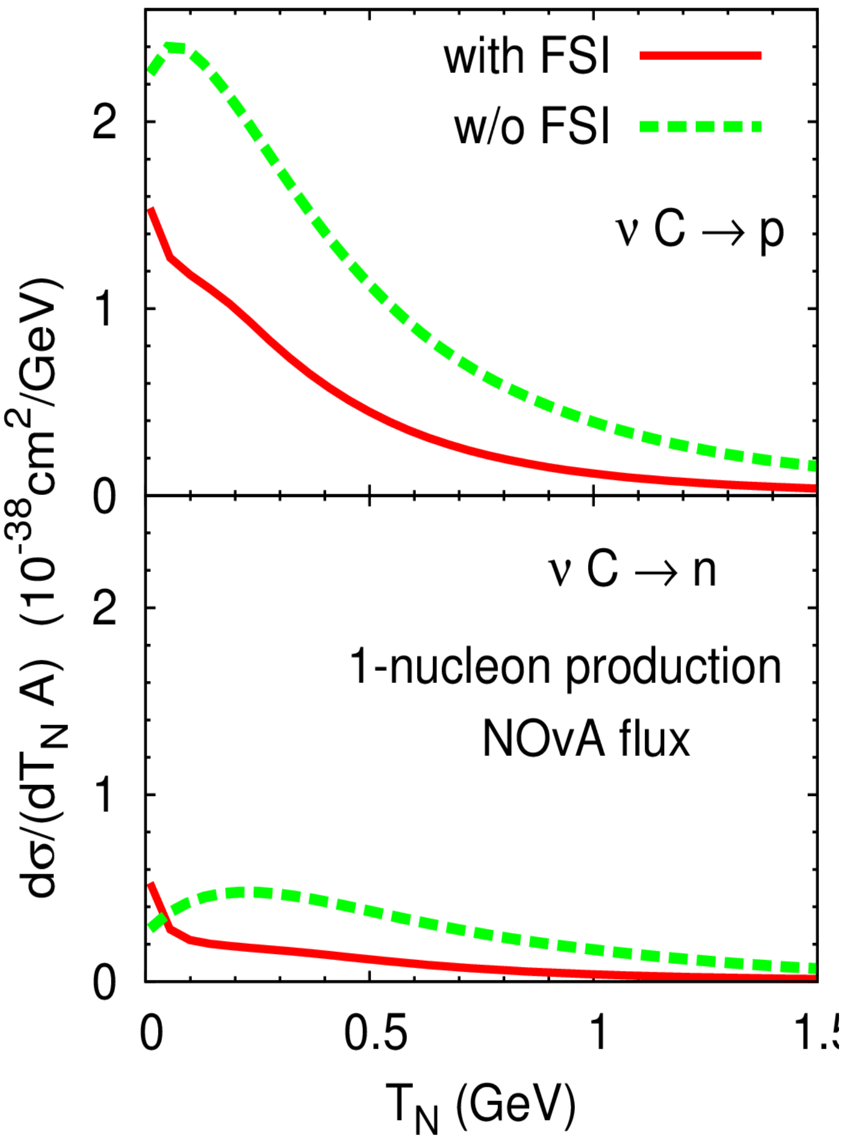


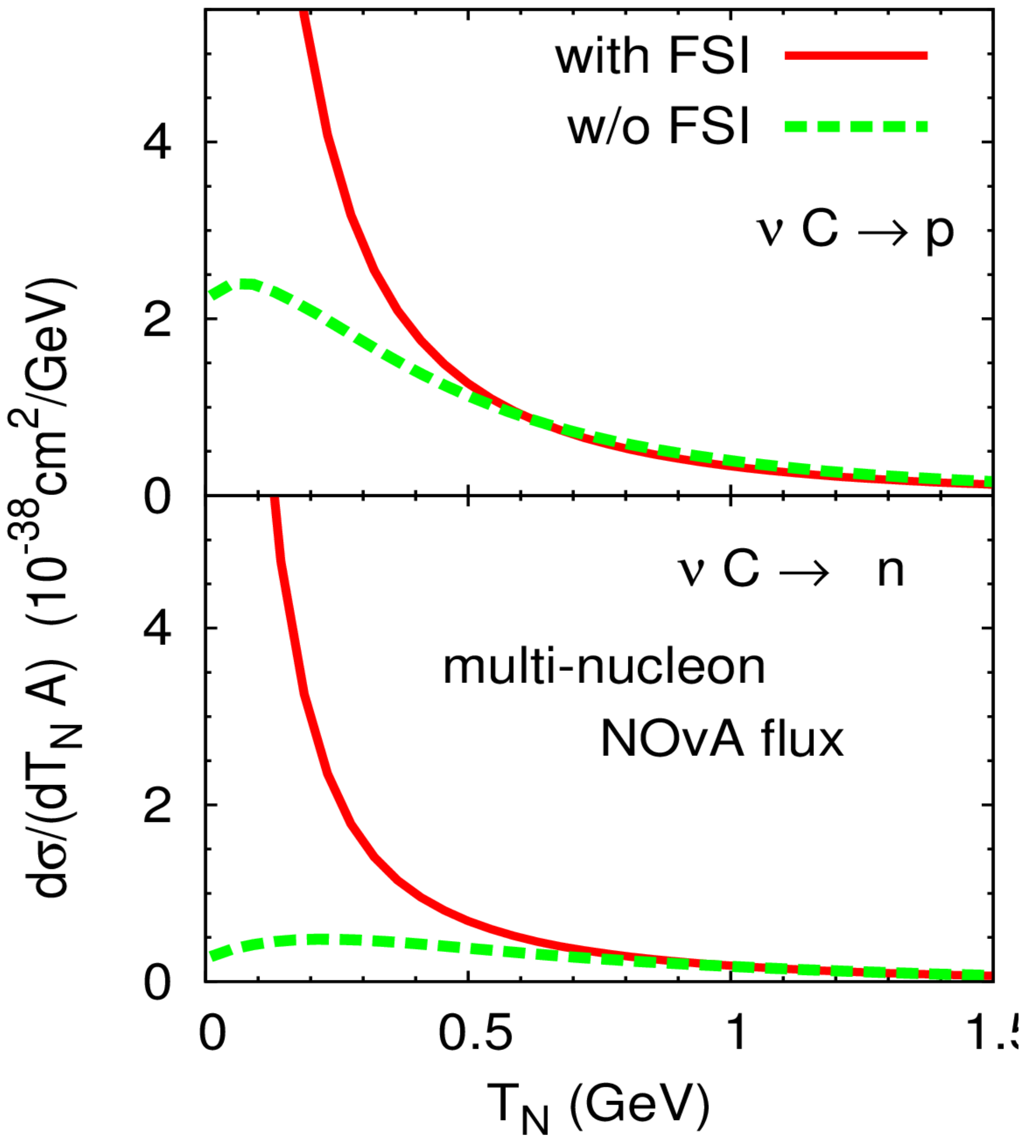
MINOS flux: predictions for MinervA experiment

Pions: origins



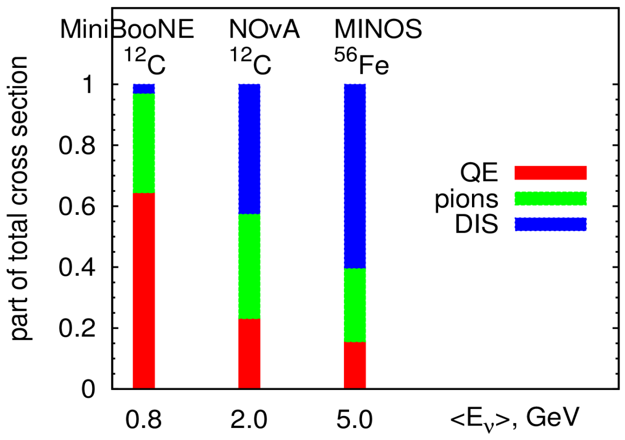
Nucleons: with and w/o FSI



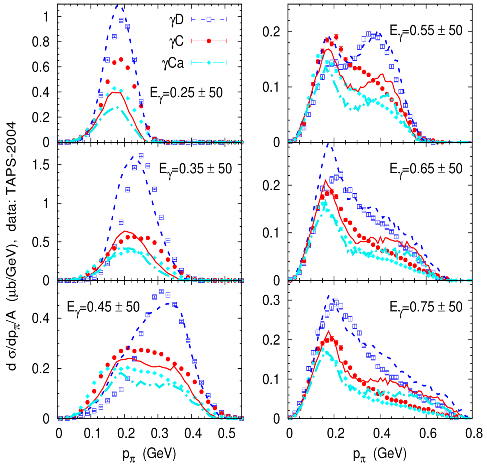


Conclusions

- In your generator, have all the relevant processes under control, especially in the SIS region
- Experiments are sitting in SIS



- Check your nuclear dynamics with electron- and photon- induced
- Pions and nucleons in your detector are not those produced in the initial interaction vertex



- Elementary inputs are needed (1-, 2-pion background at SIS)

Backup slides

Code ...

is written in Fortran 95/2003 (very different from Fortran77)

- modern features: function overloading, allocatable arrays, optional arguments, possibility to derive new types
- module structure with philosophy that each module should initialize itself on the first call; private and public variables

Can one change the parameters?

many of them **YES** reading data out of the "jobcard"

```
$neutrino_induced
includeQE=.true.
includeRES=.true.
includeDIS=.true.
$end
```

ASCII file

Kaons:

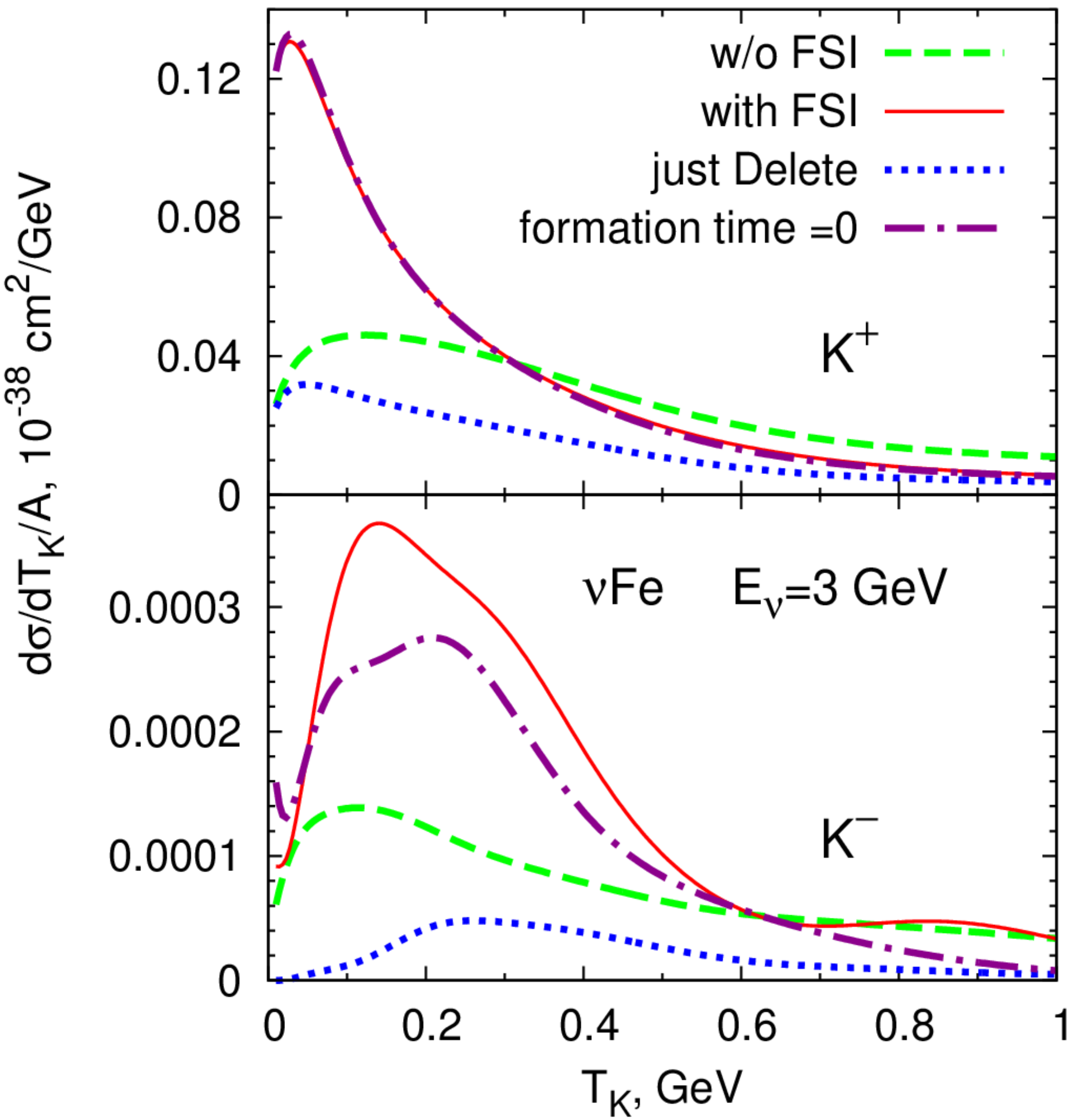
Primary interactions (before FSI):

- Kaon production in low-energy region not implemented (xsec ~ 10^{-41} cm^2 flattens out quickly)
- Kaons only from DIS (xsec grows with energy)

- FSI:
  - Outgoing pions/nucleons/resonances can rescatter
    $\pi N \rightarrow \Sigma K, \Lambda K, K\bar{K}N$
    $NN \rightarrow N\Sigma K, N\Lambda K$
    $NN \rightarrow NR, NR' \rightarrow NR$ with R decaying to kaons
  - Kaons can rescatter $KN \rightarrow KN, \Lambda\pi, \Sigma\pi$

Kaons seen in the detector

are NOT those produced initially



Kaon production without (w/o) and with Final State Interactions

A numerical experiment: If any particle produced in neutrino vertex undergoes a secondary interaction, just Delete it

Result:
Most of the kaons reinteract while propagating throughout the nucleus