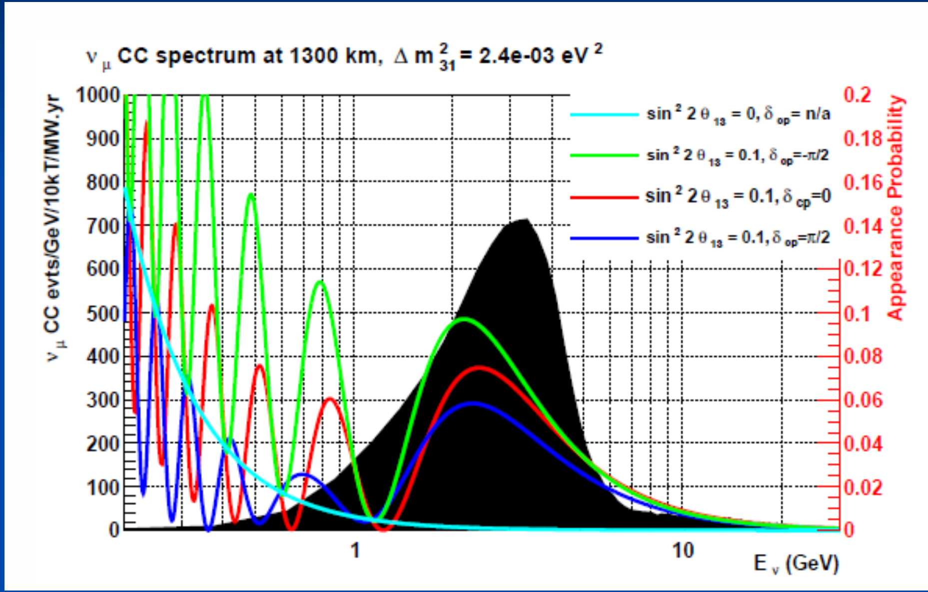
Final State Nucleons in Neutrino-Nucleus Interactions

Ulrich Mosel

Institut für
Theoretische Physik

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

DUNE, δ_{CP} Sensitivity



Appearance probability:
$P_{\mu \rightarrow e}$

Need energy to distinguish between different δ_{CP}

Need to know neutrino energy to better than about 100 MeV

FSI and Transport Theory

- Need to reconstruct energy from final state observables
- All modern experiments use nuclear targets

Need to describe

ν + A -> X + many hadrons

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Nuclear Theory

- Necessary Ingredients
  - Nuclear groundstate (correlations, spectral functions)
  - Nuclear reaction mechanisms (IA vs. 2p2h, coll. excit.)
  - Electroweak interaction vertices, in medium
  - Particle production, also in secondary colls
  - *Propagation of all particles to final state, incl fsi*
- Only capable method: Transport Theory, guidance from QGP generators (MC is poor man‘s transport theory)

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** describes (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

using the same physics input! And the same code!

Most widely tested generator available

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**

  based on a BM solution of Kadanoff-Baym equation
- Code from *gibuu.hepforge.org*
- Physics content and details of implementation in:

  Buss et al, Phys. Rept. 512 (2012) 1- 124

  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Transport Equation

Collision term

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

Drift term

$$\left[\left(1 - \frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial}{\partial \mathbf{p}} + \frac{\partial H}{\partial t}\frac{\partial}{\partial p^0} + \text{KB term}\right] F(x,p)$$

$$= \text{- loss term} + \text{gain term}$$

$$F(x,p) = 2\pi g f(x,p) A(x,p).$$

Spectral function

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

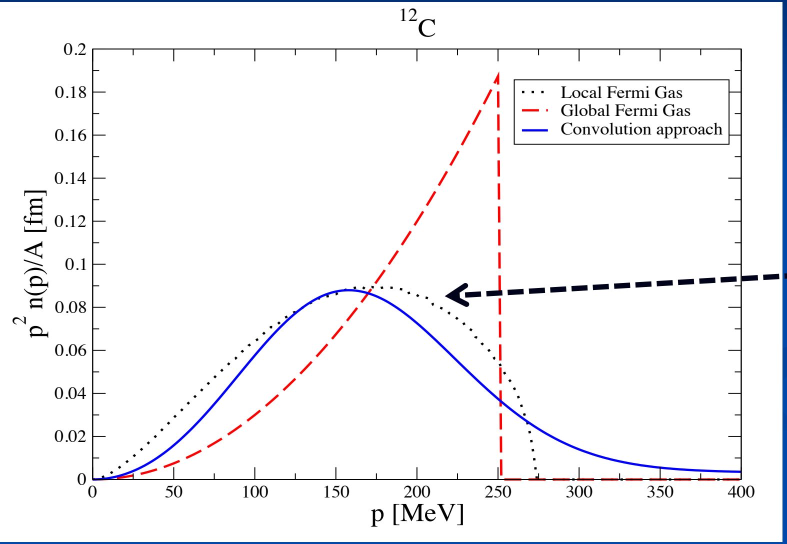
GiBUU Ingredients

- In-medium corrected primary interaction cross sections for QE, 2p2h, N* resonances, DIS, boosted to rest frame of bound nucleon, moving in *bound local Fermigas*
- Includes spectral functions for baryons and mesons (binding + collision broadening)
- *Hadronic* couplings for FSI taken from PDG
- *Vector* couplings taken from electro-production (MAID)
- *Axial* couplings modeled with PCAC and dipole FF

GiBUU Output

- GiBUU produces
  1. Full event file: four-vectors of all particles in final state
  2. Hundreds of cross sections, directly in Gnuplottable format: energy and angle differential
  3. Energy and Q^2 reconstruction files incl migration files

Momentum Distribution GiBUU

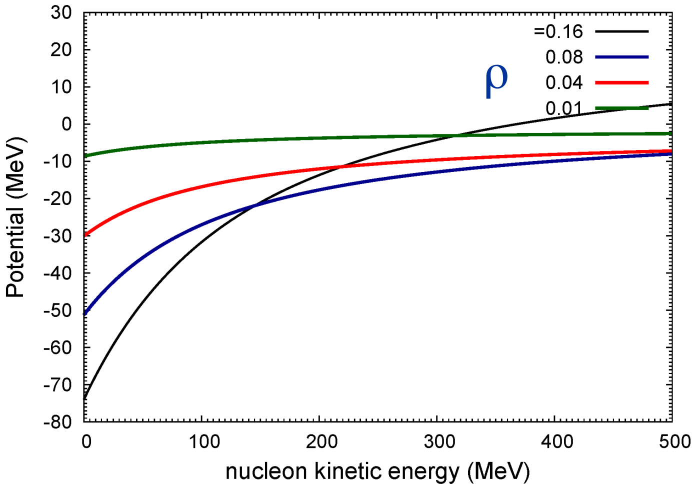


GiBUU uses
Local Fermi Gas
Energy-distribution smooth because of r-dependent potential

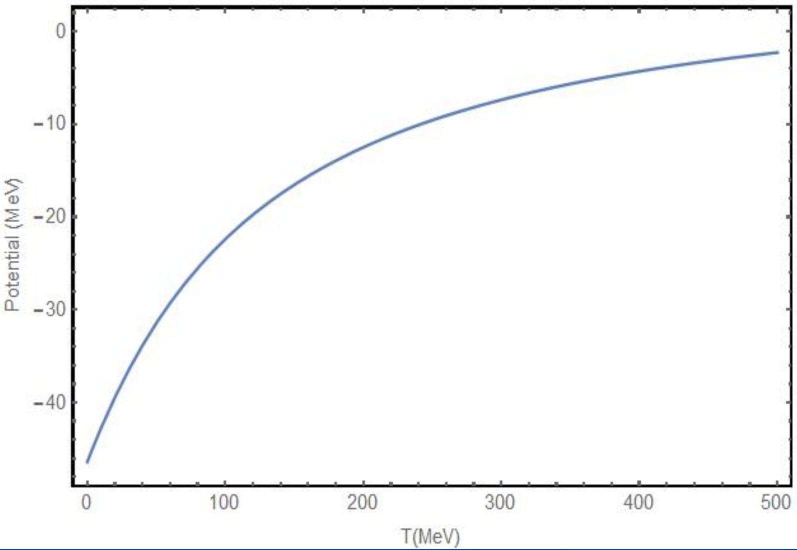
$$P_h(\vec{p}, E) \propto \int d^3r \, [\Theta(p_F(\vec{r}) - p)\, \delta(E + T_p + V(\vec{r}, \vec{p}))]$$

FSI Potential

density and momentum dependent



density-averaged potential for ^{12}C

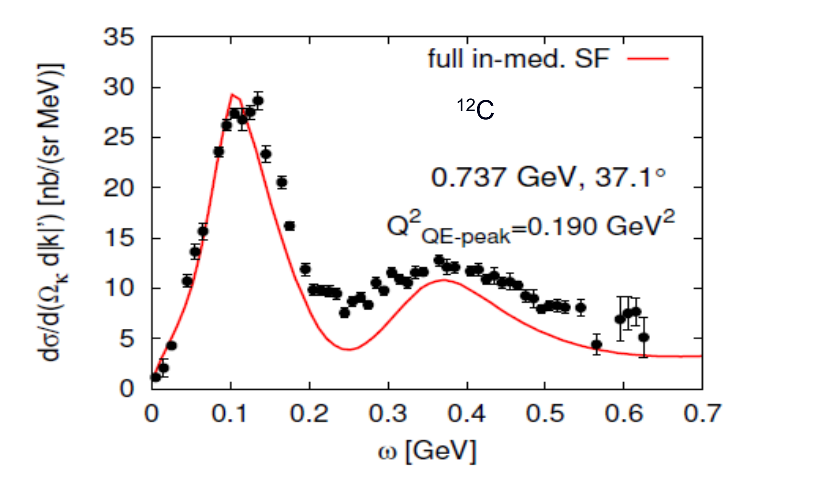


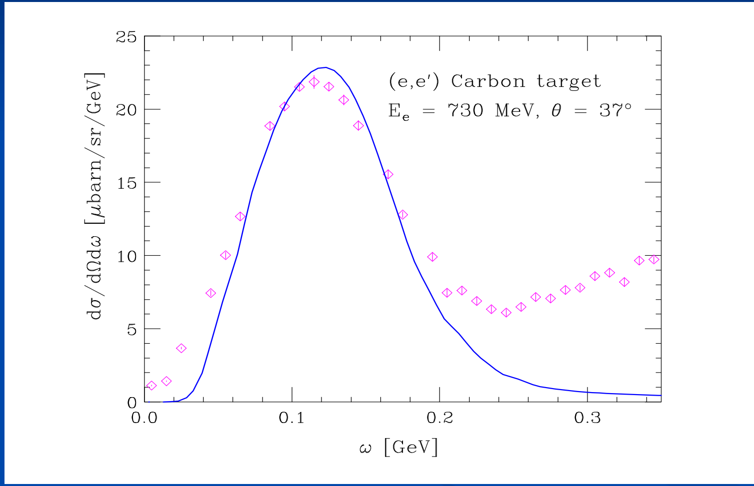
Consistent with binding potential for all nucleons, also for fsi

Test with electron data

Electrons as Benchmark for GiBUU

Trouble for neutrinos: ω must be reconstructed

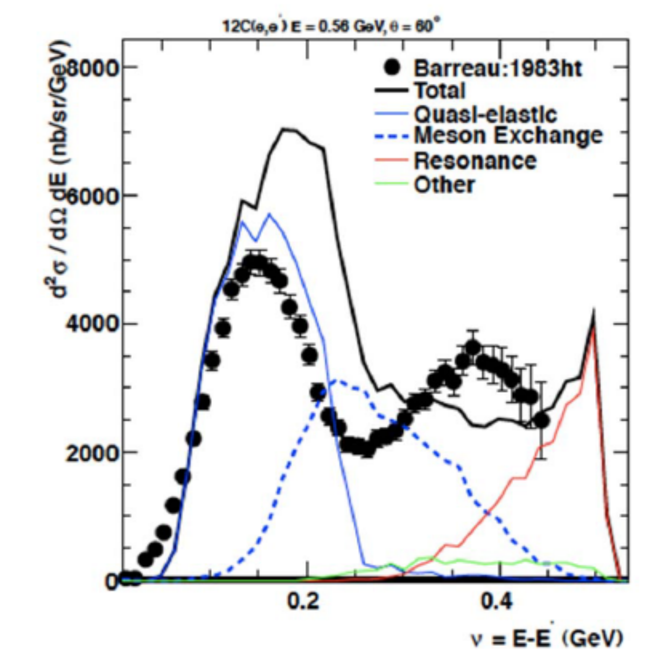




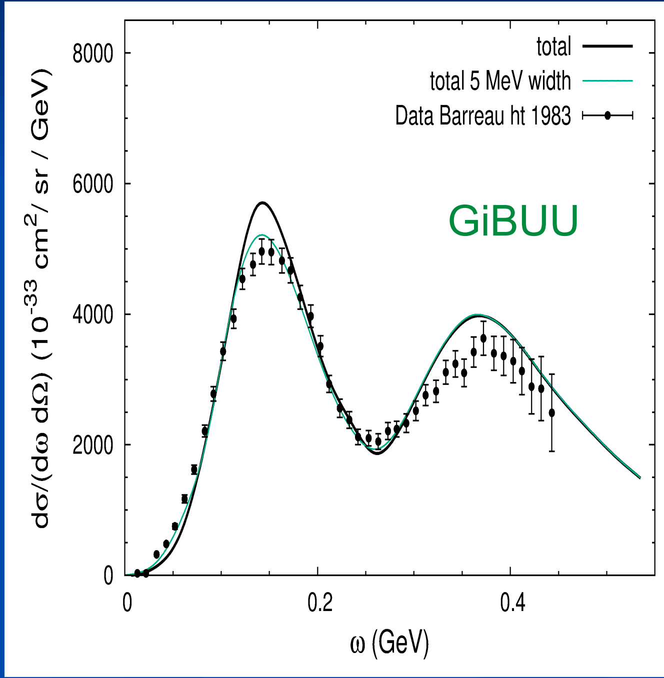
No free parameters!
no 2p-2h, contributes
in dip region and under Δ

O. Benhar, spectral fctn

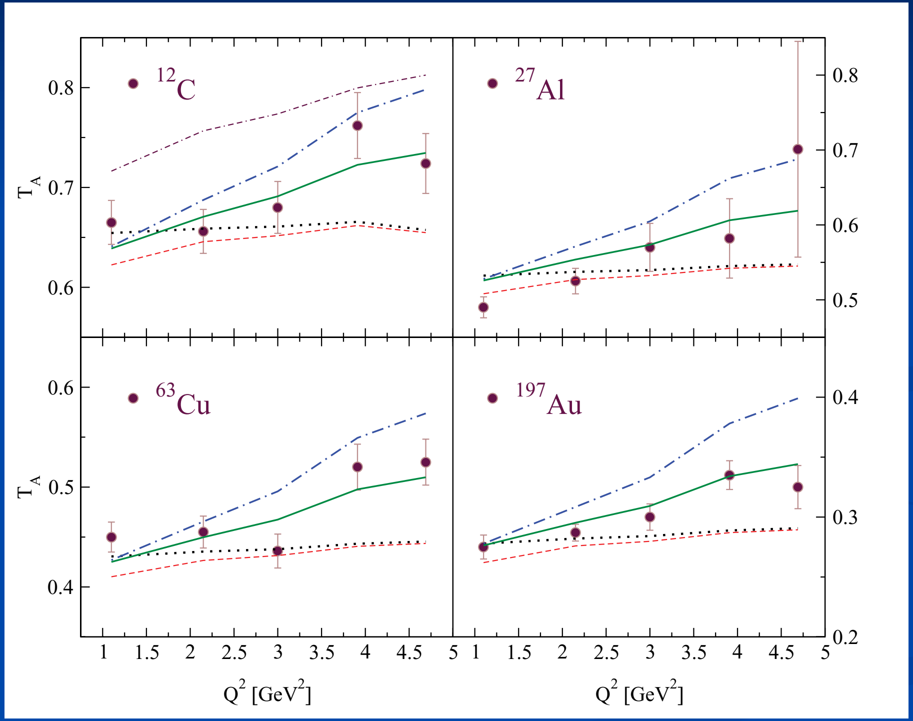
GENIE vs GiBUU



GENIE, from S.Dytman, BNL meet, Febr. 2015



JLAB Pion Production

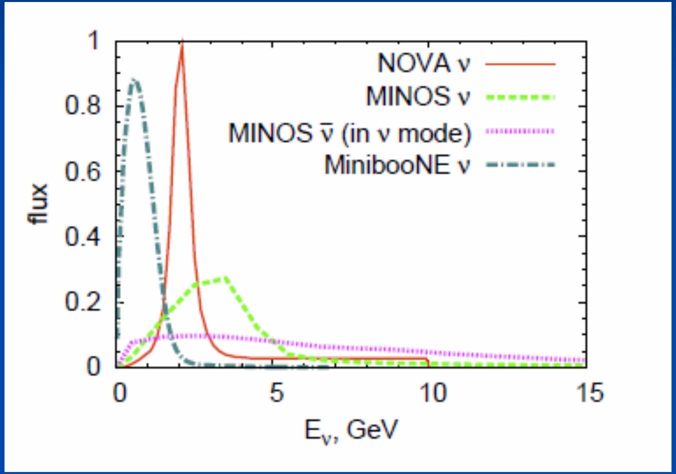


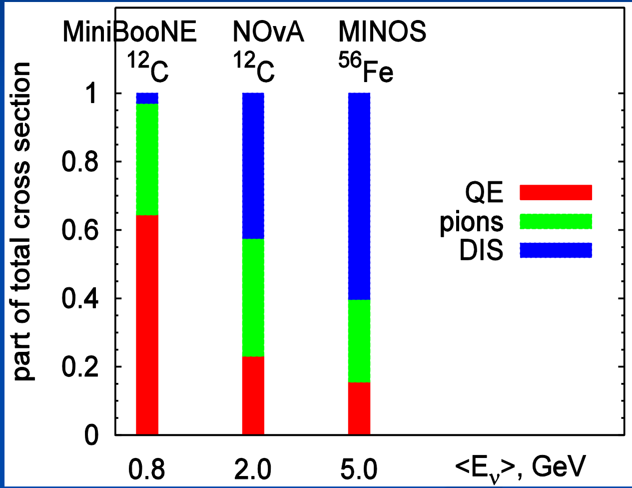
Exp: B. Clasie et al.
Phys. Rev. Lett. 99, 242502 (2007)

GiBUU: Kaskulov et al,
Phys.Rev. C79 (2009) 015207

Neutrino Beams

- Neutrinos do not have fixed energy nor just one reaction mechanism

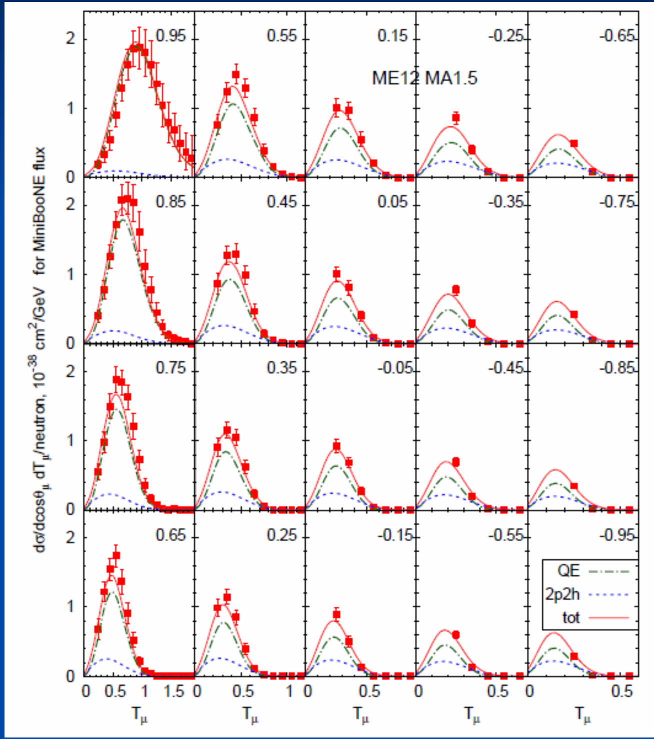




Have to reconstruct energy from final state of reaction
Different processes are entangled

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

The MiniBooNE QE Puzzle
Explanations



ME12, MB flux averaged

Data corrected
for stuck-pion events!

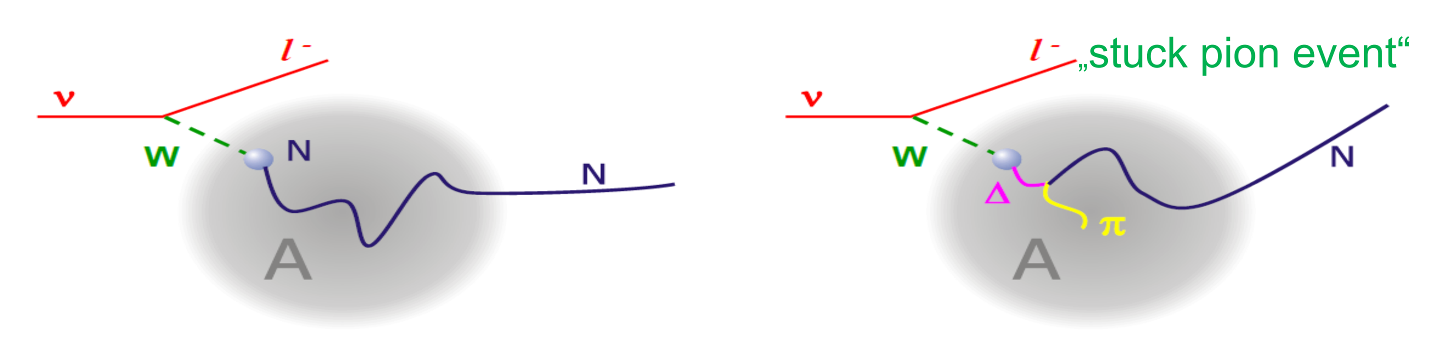
$W^{\mu\nu} \sim P_T^{\mu\nu}(q)\, F(Q^2)$, educated guess

Inclusive double-differential X-sections fairly insensitive to details of interaction

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Final State Nucleons from Nuclear Targets



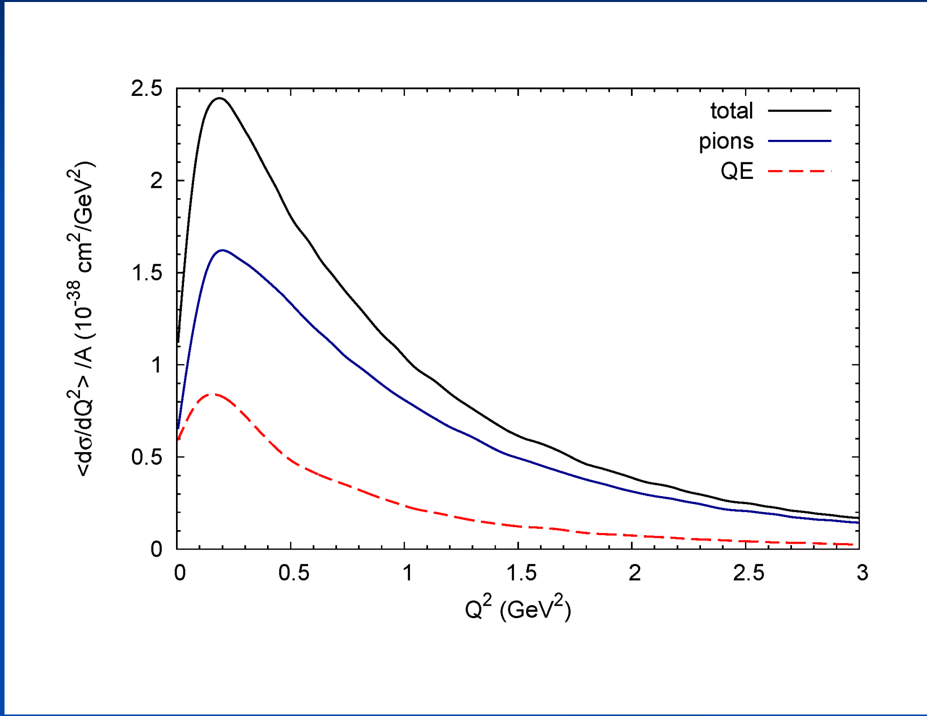
Complication to identify QE, entangled with π production

QE data can never be better than the pion subtraction method

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

QE vs. Pion Production at DUNE

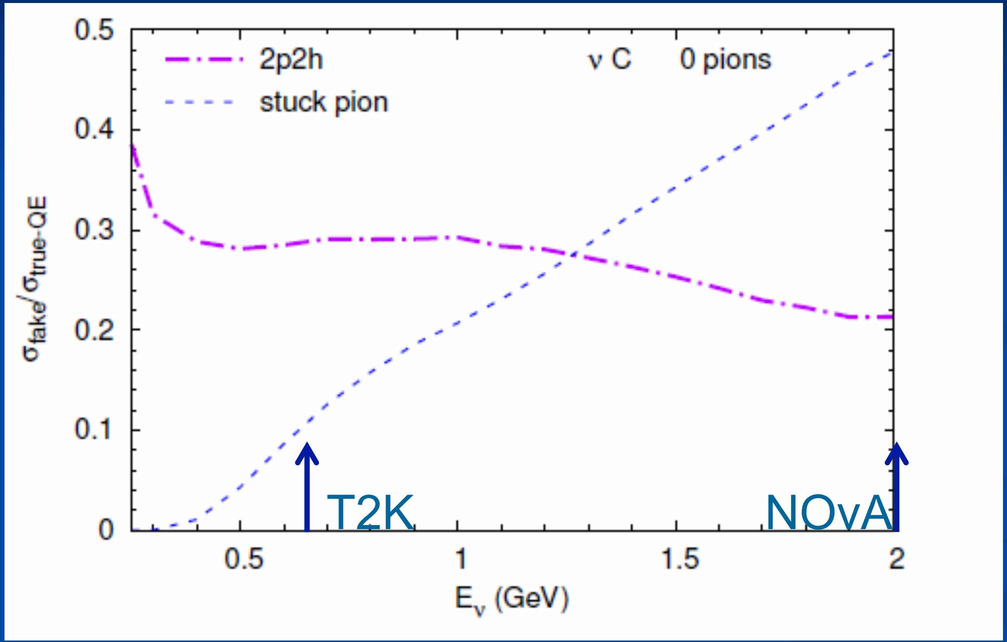
Target:
^{40}Ar



Pions: Resonance + DIS
QE: ‚true‘ QE + 2p2h

QE $\cong$ 1/3 total
Pions $\cong$ 2/3 total

2p-2h vs. ‚stuck pions‘



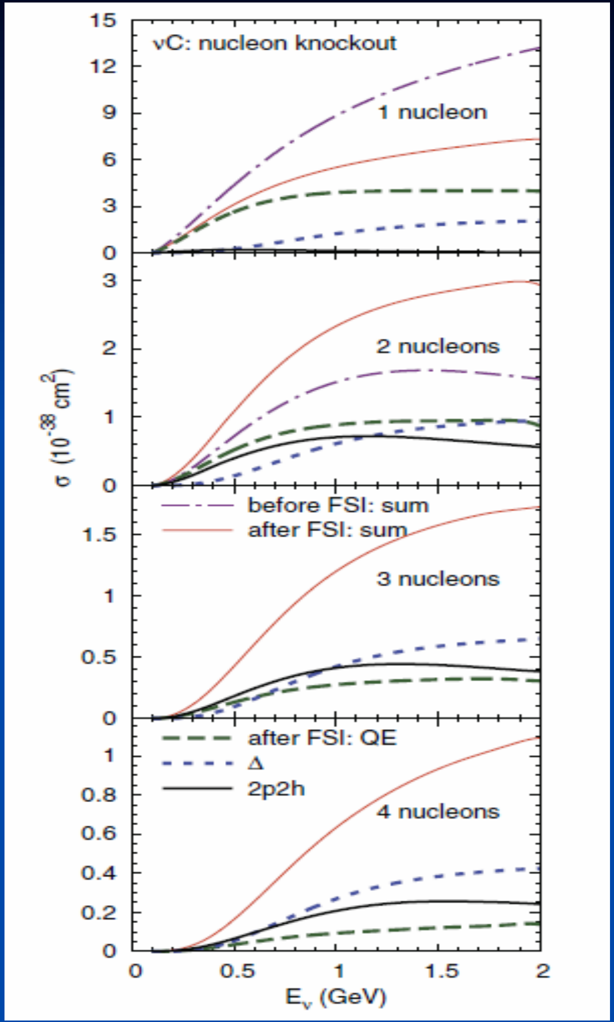
Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Neutrino QE Data

- Neutrino QE Data can be obtained from experiment only if pion production is under control
- Neutrino QE Data can never be better than the description of neutrino-induced pion production

Effects of FSI on nucleon multiplicities



GiBUU: Phys.Rev. C86 (2012) 1, 014614

Multiplicities do not distinguish between primary reaction mechanisms:

2 nucleons come to equal parts from

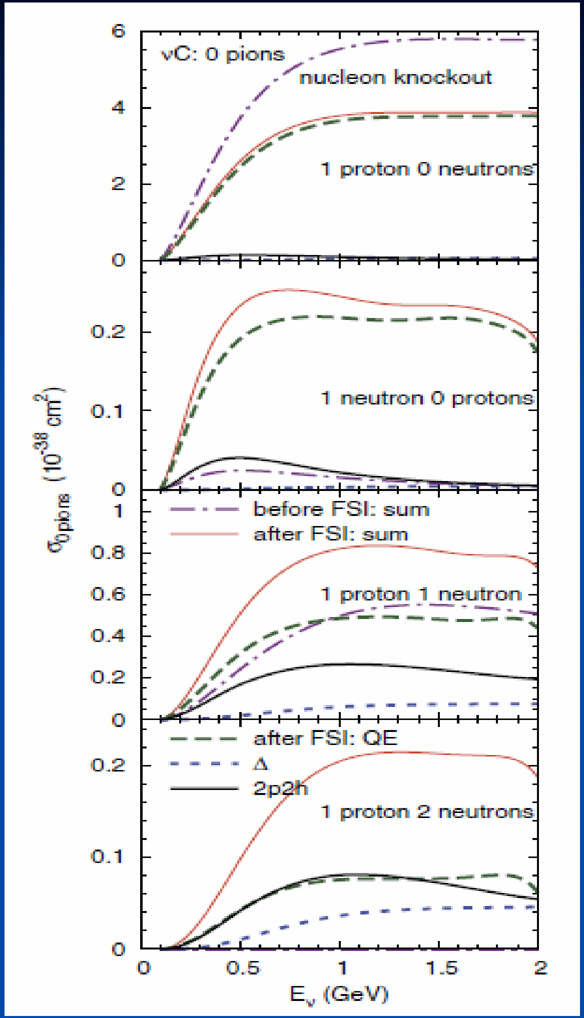
a. True (1-body) QE

b. 2p2h

c. Delta (Δ + N -> N + N)

QE + 2p2h Identification with 0 pion events

GiBUU: Phys.Rev. C86 (2012) 1, 014614



1p Xn Xπ: fairly clean QE event

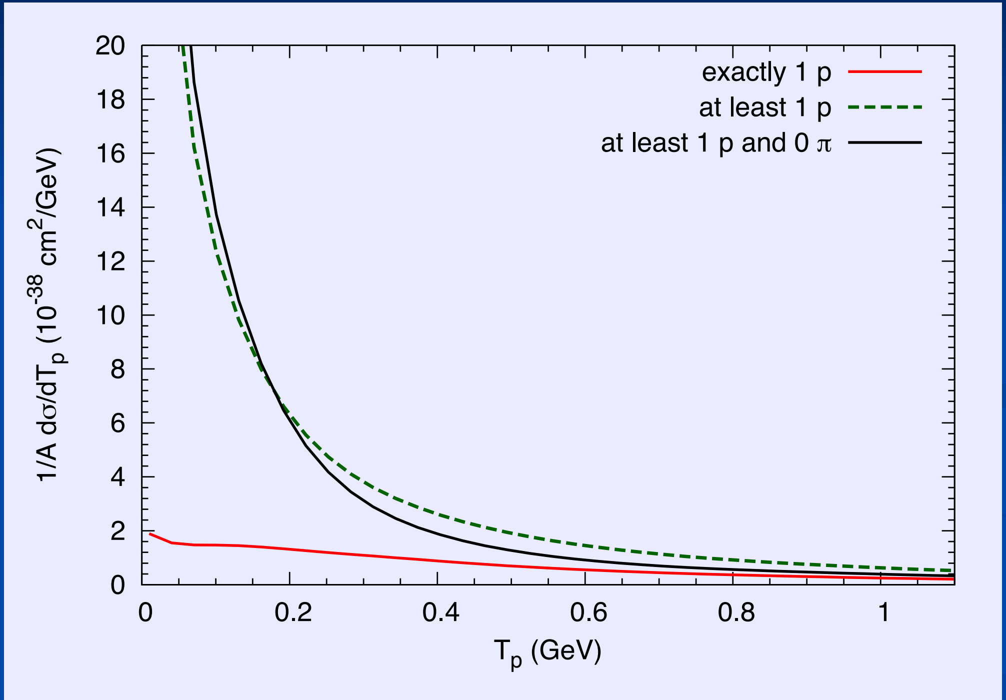
1p 0n 0π: very clean QE event

No clean signal for 2p-2h because of FSI

True QE can be rather well identified by 1p, Xn, 0pi exploited by MINERvA

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

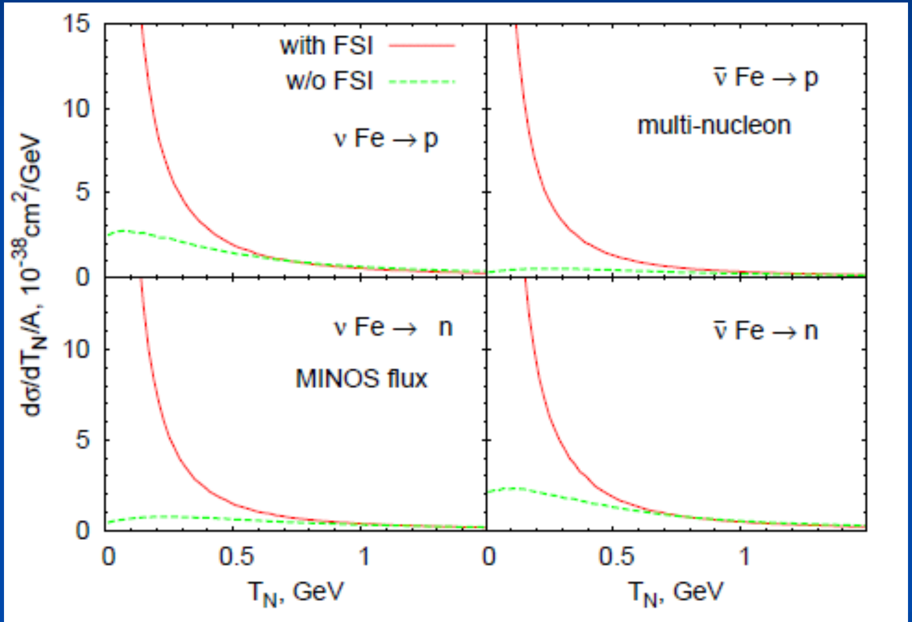
Protons at MINERvA



Strong fsi effect

Experiments at higher energies

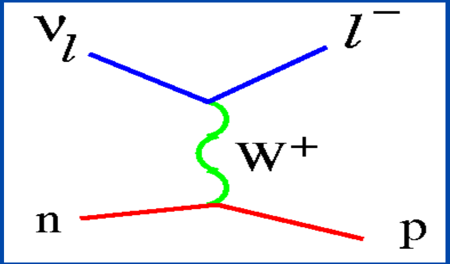
Knock-out Nucleons



Strong rise below 300 MeV, dominated by FSI:
Avalanche Effect: one initial nucleon kicks out many others

Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only l +*p*, *0* π, is outgoing. lepton determines neutrino energy:



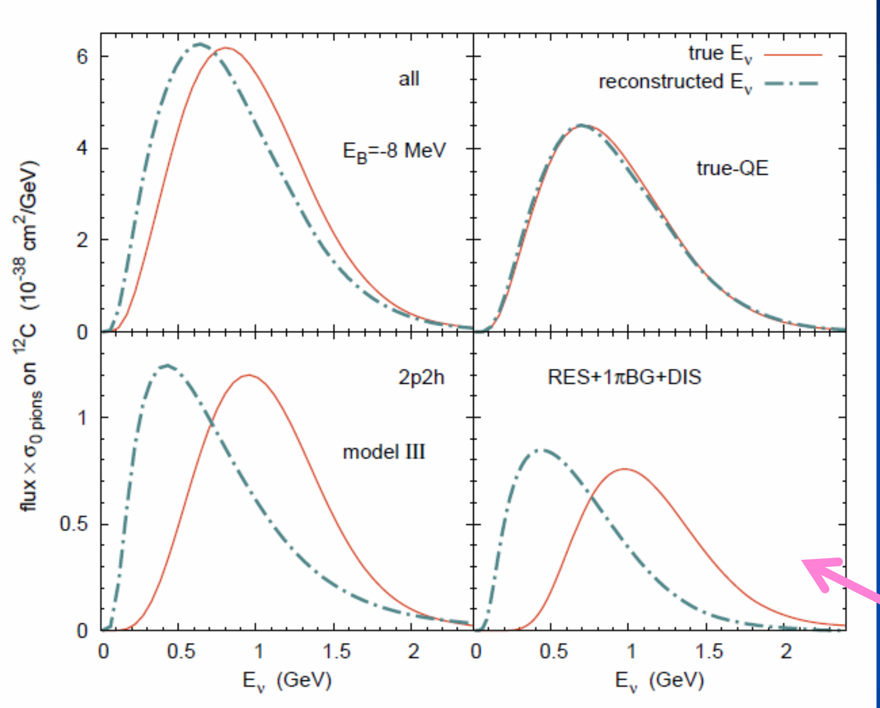
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

Energy reconstruction in MB

Event rates = flux x crosssection



MiniBooNE flux

Reconstructed energy shifted to lower energies for all processes beyond QE

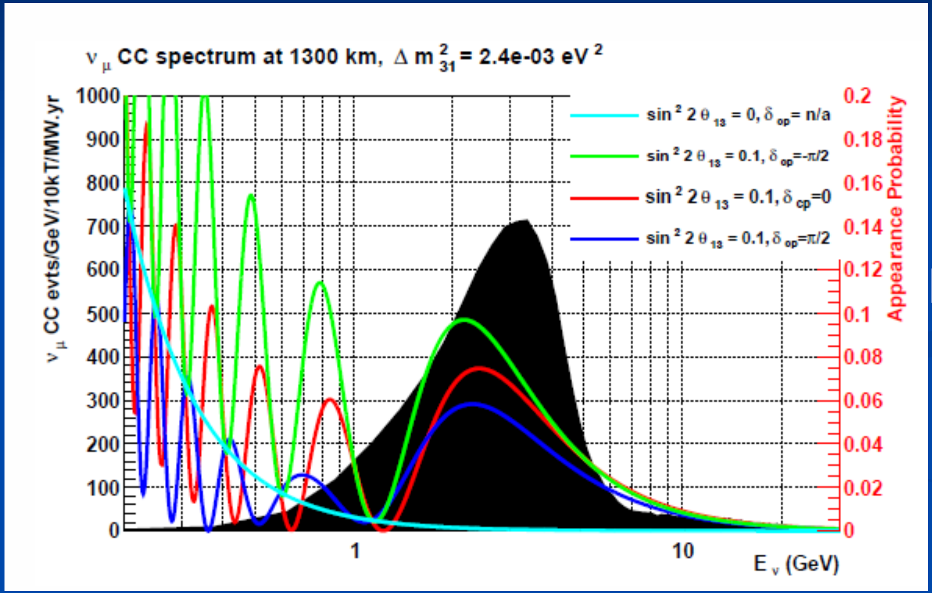
Reconstruction must be done for 0 pion events

Not only 2p-2h important

NOT contained in Nieves model

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

DUNE, δ_{CP} Sensitivity

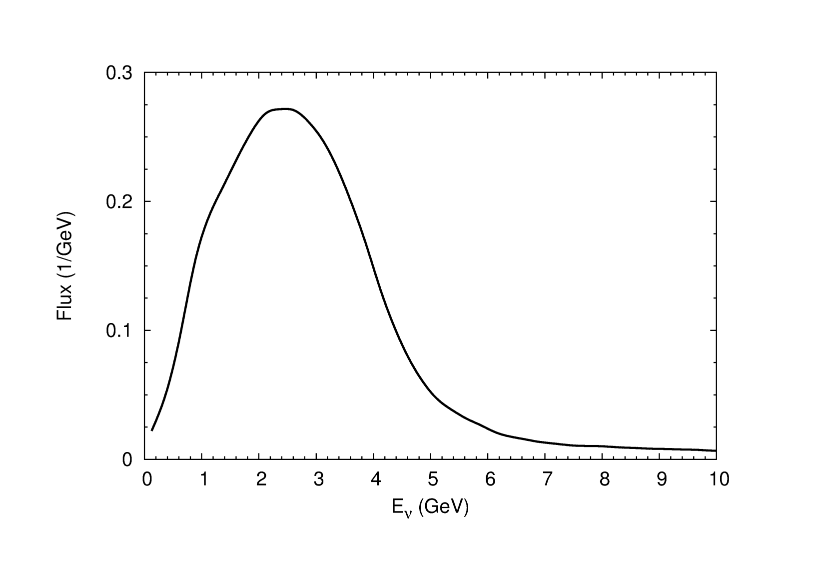


Appearance probability:
$P_{\mu \to e}$

Need energy to distinguish between different δ_{CP}

Need to know neutrino energy to better than about 100 MeV

Energy Reconstruction for DUNE

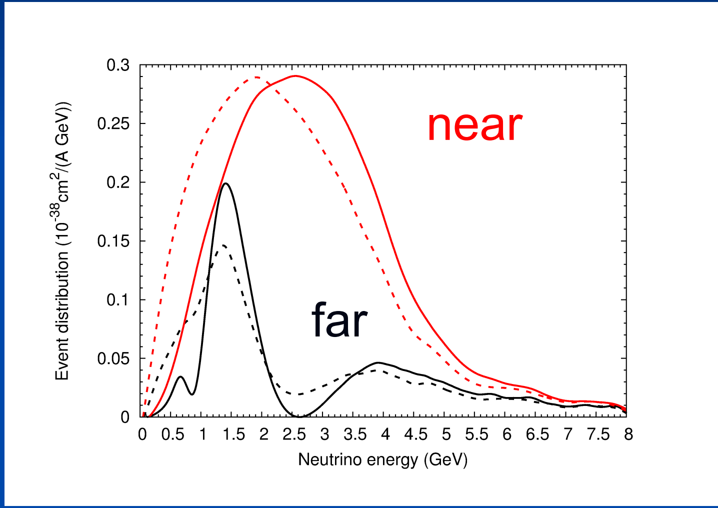


Flux of incoming neutrinos (energy distribution)

QE Energy Reconstruction for DUNE

Muon survival in 0 pion sample

Target: ^{40}Ar



Dashed: reconstructed,
solid: true energy

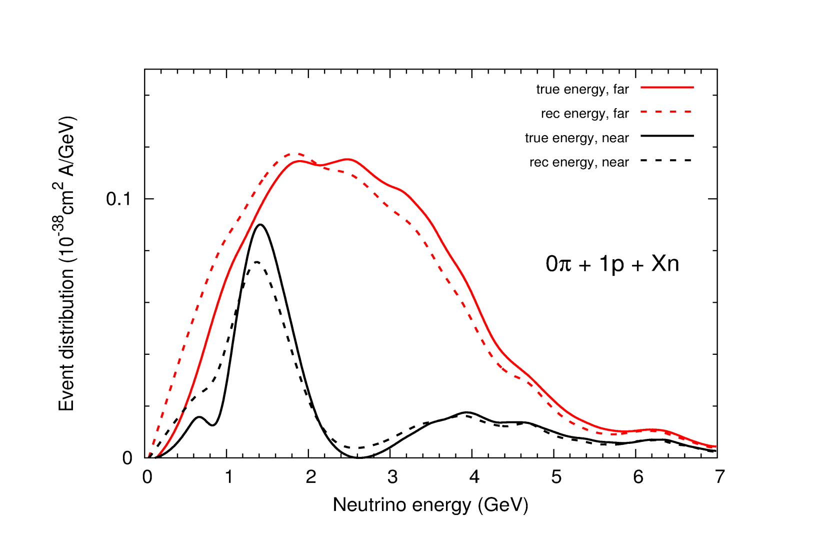
All calculations from GiBUU

Mosel et al.,
Phys.Rev.Lett. 112 (2014) 151802

Nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

QE Energy Reconstruction for DUNE

Muon survival in 0π + 1p + Xn sample

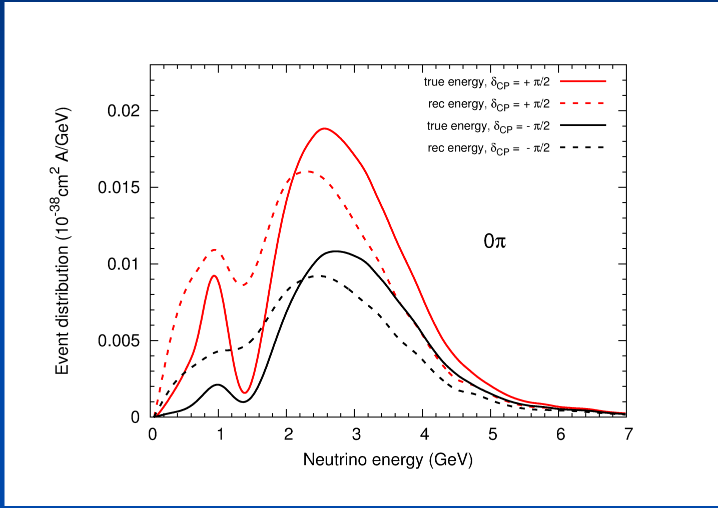


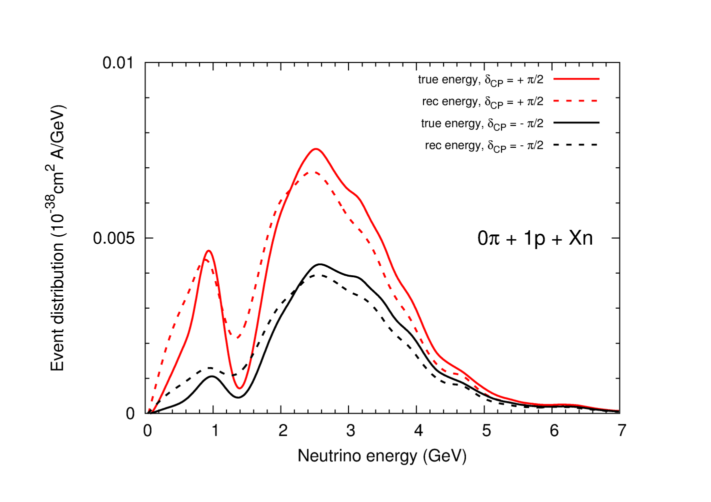
Dashed: reconstructed,
solid: true energy

Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

DUNE e-appearance

Sensitivity to δ_{CP}





Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

Summary

- QE scattering and pion production are always entangled in neutrino reactions on nuclei
- QE data can never be better than description of pion production
- Full event analysis is needed to help to identify QE
- Energy reconstruction (and neutrino oscillation parameter extraction) depends on a correct modeling of the final state

Backups

Theoretical Basis of GiBUU

Simplicity

- 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, in Botermans-Malfliet representation (1990s): **GiBUU**
- Cascade models (typical event generators, NUANCE, GENIE, NEUT,..)
  - no mean-fields, primary interactions and FSI not consistent

Factorization of GiBUU

- GiBUU is approximately factorized into
  - initial, first interaction
  - final state interactions (2nd, 3rd, ... coll.)
- Particular strength: FSI treatment
- Detailed infos from
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  and website
  gibuu.hepforge.org

Theoretical Basis: GiBUU

Time evolution of spectral phase space density (for $i = N, \Delta, \pi, \rho, \ldots$) given by KB equation in Botermans-Malfliet form:

$$\left[\left(1-\frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t}+\frac{\partial H}{\partial p}\frac{\partial}{\partial x}-\frac{\partial H}{\partial x}\frac{\partial}{\partial p}+\frac{\partial H}{\partial t}\frac{\partial}{\partial p_0}\right]F_i(x,p)=C[F_i(x,p),F_j(x,p)]$$

Hamiltonian *H* includes off-shell propagation correction and potentials

8D-Spectral phase space density

Collision term

Off shell transport of collision-broadened hadrons included with proper asymptotic free spectral functions

Transport Equation

- Kadanoff-Baym equation for space-time development of one particle spectral phase space density *F* after gradient expansion in Wigner repres.:

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

F = spectral phase-space density: $F(x,p) = -2f(x,p)\mathrm{tr}[\mathrm{Im}\,(\tilde{S}^{\mathrm{ret}}(x,p))\gamma^0],$

$$\mathcal{D}F = \{p_0 - H, F\}_{\mathrm{pb}} \quad \text{with } H = E^*(x,p) - \mathrm{Re}\tilde{\Sigma}^0_V(x,p).$$

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Collision term

$$
\begin{aligned}
C^{(2)}(x,p_1) &= C^{(2)}_{\text{gain}}(x,p_1) - C^{(2)}_{\text{loss}}(x,p_1) = \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{\mathrm{d}^4 \mathrm{p}_2}{(2\pi)^4 2p_2^0} \int \frac{\mathrm{d}^4 \mathrm{p}_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{\mathrm{d}^4 \mathrm{p}_{2'}}{(2\pi)^4 2p_{2'}^0} \\
& \times (2\pi)^4 \delta^{(4)}\left(p_1 + p_2 - p_{1'} - p_{2'}\right) \overline{|\mathcal{M}_{12\to 1'2'}|^2} [F_{1'}(x,p_{1'}) F_{2'}(x,p_{2'}) \overline{F}_1(x,p_1) \\
& \times \overline{F}_2(x,p_2) - F_1(x,p_1) F_2(x,p_2) \overline{F}_{1'}(x,p_{1'}) \overline{F}_{2'}(x,p_{2'})]
\end{aligned}
$$

with

$$
\begin{aligned}
F(x,p) &= 2\pi g A(x,p) f(x,p) \\
\bar{F}(x,p) &= 2\pi g A(x,p) \left[1 - f(x,p)\right]
\end{aligned}
$$

GiBUU: numerical implementation

- Hadrons feel potentials (nuclear + Coulomb): essential for nucleon spectral functs
- Wigner functions represented by testparticles (100 – 1000 per nucleon). Off-shell transport of hadrons (spectral functions) with proper asymptotics
- Fully relativistic treatment of interaction vertices and propagation. Collision criterion respects relativity (as far as possible), not just $\sigma = \pi r^2$ prescription.

Practical Basis: GiBUU

- one transport equation for each particle species (61 baryons, 21 mesons)
- coupled through the potential in *H* and the collision integral *C*
- W < 2.5 GeV: Cross sections from resonance model (PDG and MAID couplings), consistent with electronuclear physics
- W > 2.5 GeV: particle production through string fragmentation (PYTHIA)

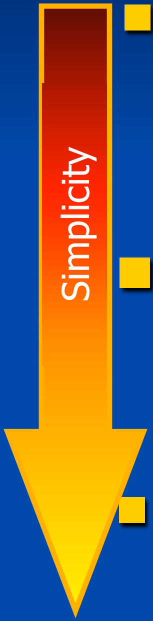
GiBUU Ingredients

- Various options in code are controlled by extended job card with all relevant switches.
- Output are (many) cross sections, reconstructed and true event distributions, full final state with four-vectors of all particles in Les Houches or ROOT format.
- Website *gibuu.hepforge.org* contains extensive documentation for code and explanation of output

GiBUU

- Code can be obtained from gibuu.hepforge.org
- Inclusive X-section needs only initial interaction: Running time $\approx$ 1 hour on PC
- Full event (incl all semi-incl. X-sections) needs running time of order weeks for reasonable statistics, statistics can be obtained by several parallel runs
- Code is open source, users are encouraged to find bugs, improve code, implement new features

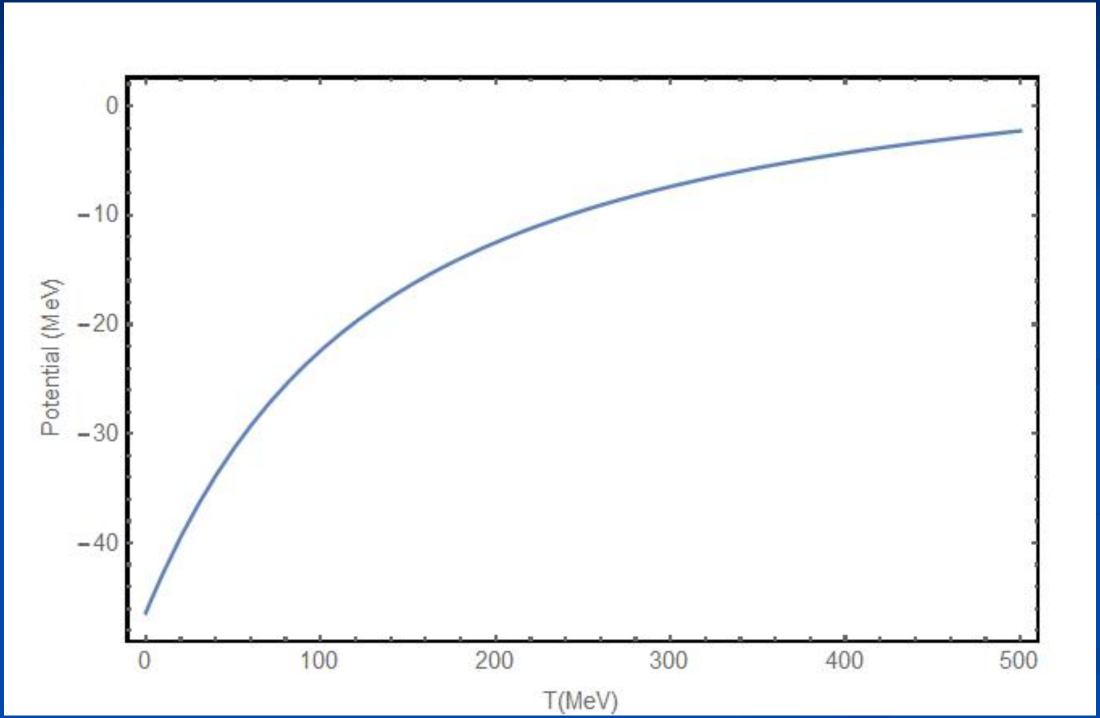
Theoretical Basis of GiBUU



- 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, in Botermans-Malfliet representation (1990s): **GiBUU**
- Cascade models (typical event generators, NUANCE, GENIE, NEUT,..)
  - no mean-fields, primary interactions and FSI not consistent

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

FSI Potential for 1st Interaction



Welke Potential averaged over density for C12, fitted to p+A data and nuclear EOS

used not only for primary reaction, but also for final state propagation

Model Ing ISI

Local Fermi momentum smoothes E-p distributions

Potential smoothes E-p distributions

- Hole spectral functi n (local TF)

$$P_\mathrm{h}(\vec{p},E) \sim \int d^3r \, [\Theta(p_F(r)-p)\,\delta(E+T_p+V(r))]$$

- Particle spectral function: collisional broadening

$$P_\mathrm{p}(\vec{p},E) \sim \frac{-\Im\Sigma(\vec{p},E)}{(p^2-M_0^2-\Re\Sigma(\vec{p},E))^2+(\Im\Sigma(\vec{p},E))^2}$$

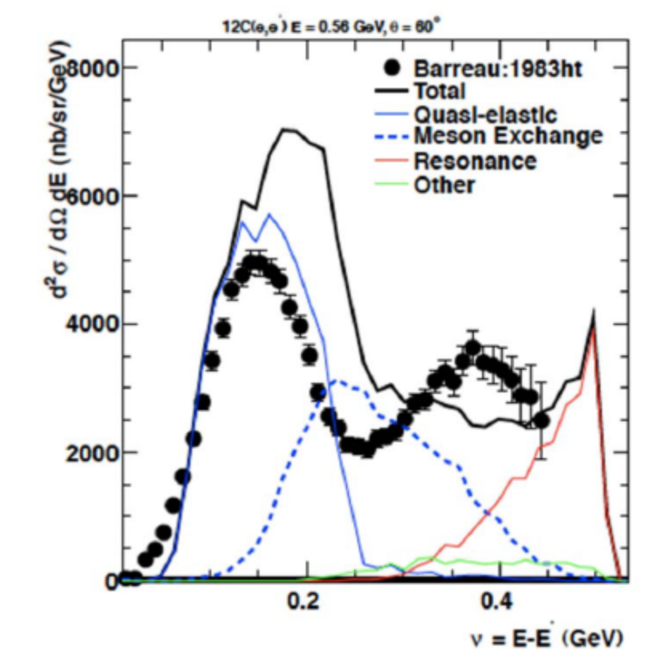
Consistency: Im(Σ) ~√s ρ σ v

- Inclusive cross section

$$d\sigma_\mathrm{tot}^{lA\to l'X} = g\int dE \int \frac{d^3p}{(2\pi)^3} P_h(\vec{p},E)\,\frac{k\cdot p}{k^0p^0}\,d\sigma_\mathrm{tot}^{lN}\,P_\mathrm{PB}(\vec{p},E)$$

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Generators must be tested and improved



GENIE, from S.Dytman, BNL meet, Febr. 2015

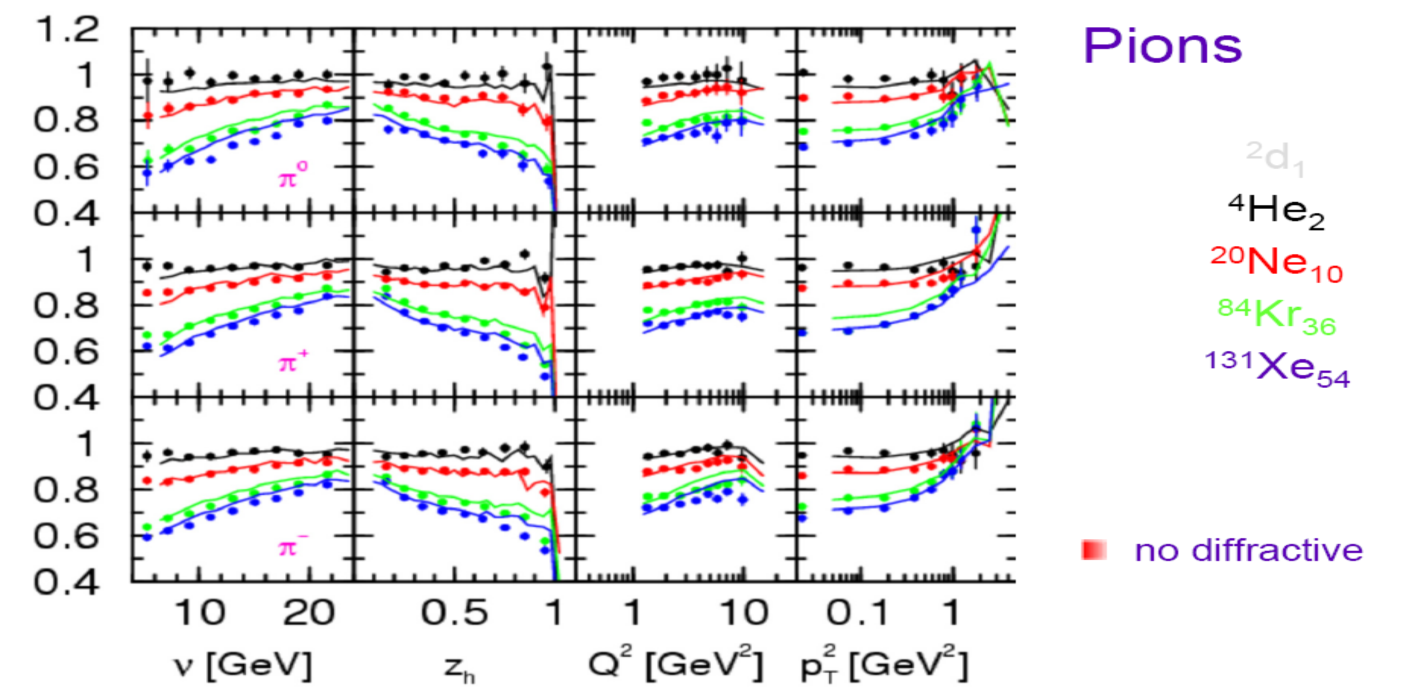
QE reasonable
MEC bad
Resonance miserable

NOTE: GENIE still uses Rein-Sehgal for resonance excitations !!

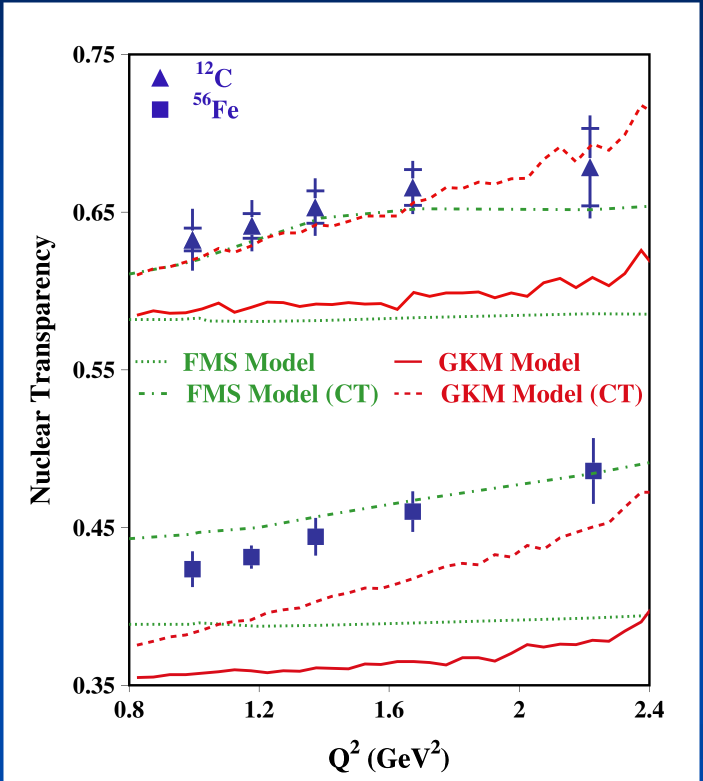
Shortcomings of RS known since ~ NUINT09

HERMES@27 GeV and GiBUU

Airapetian et al.



JLAB Rho Production



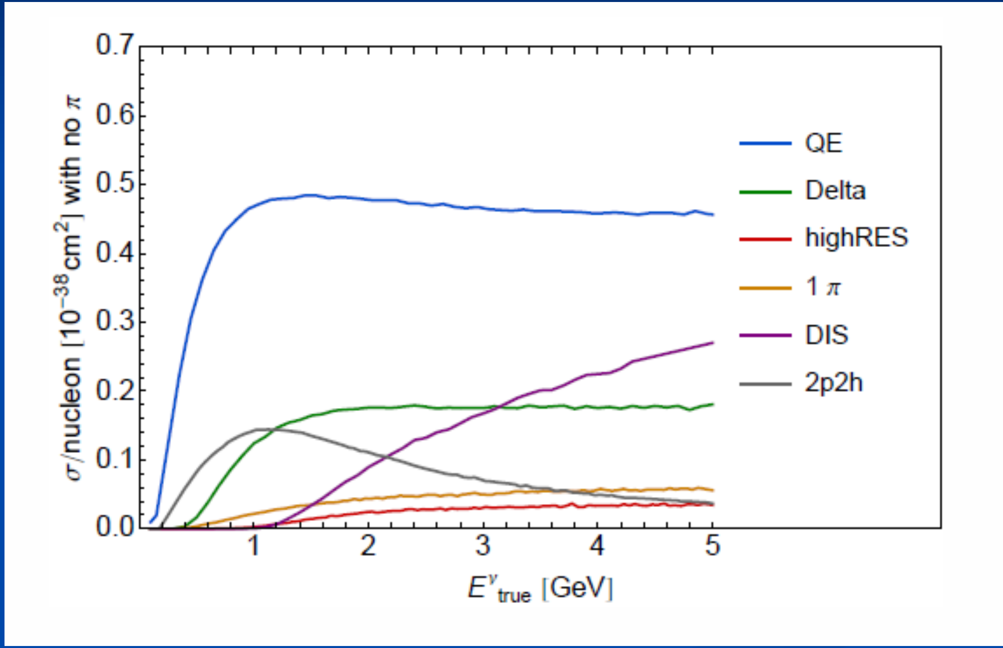
Exp: Hafidi et al,
Phys.Lett. B712 (2012) 326-330

GiBUU: Gallmeister et al.
Phys.Rev. C83 (2011)

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

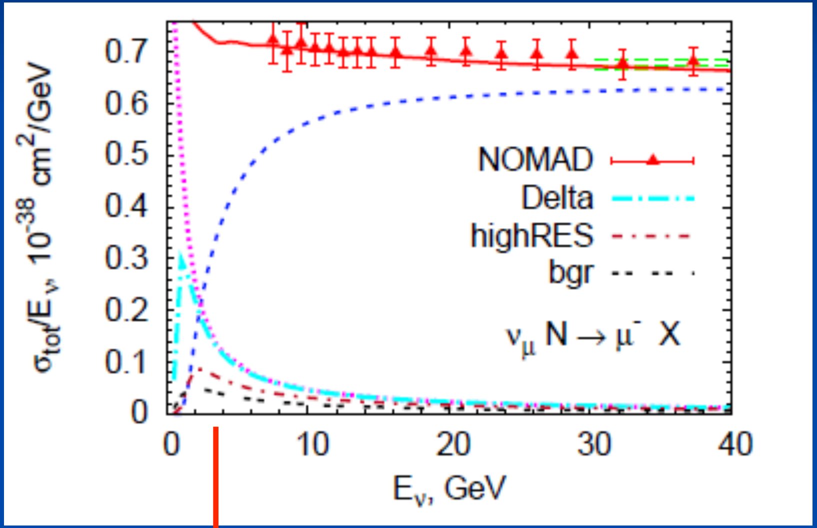
0 Pion Events from GiBUU

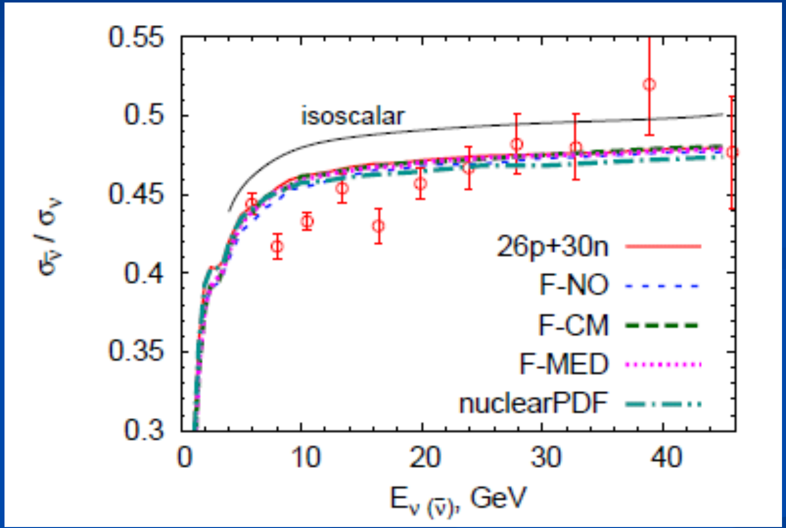
From Coloma & Huber: arXiv:1307.1243v1



Experiments at higher energies

Phys. Rev. C86 (2012) 014607





Shallow Inelastic Region, very sensitive to interplay of different reaction mechanisms

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN