Neutrino Interactions with Nuclei

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Motivation and Contents

- Determination of neutrino oscillation parameters requires neutrino energy
- Nuclear effects affect neutrino energy reconstruction
- Neutrino interactions in the ‚shallow inelastic regime' (Minerva,NOvA) :determination of cross sections

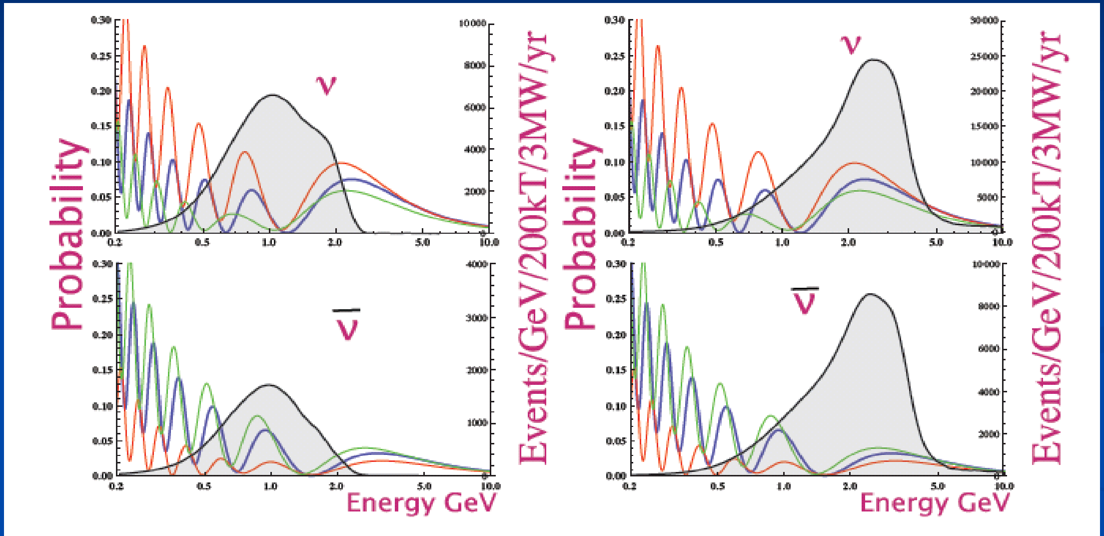
Neutrino Oscillations

- 2-Flavor Oscillation:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

Know: L, need E_ν to determine Δm^2, θ

Project X, δ_{CP} sensitivity



From:
Bishai et al
arXiv:1203.409

$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = -\pi/2$

8 GeV　　60 GeV

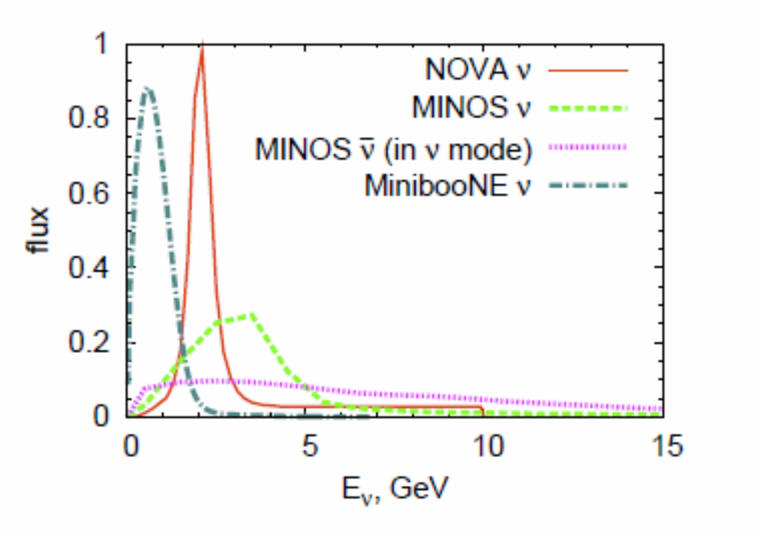
proton energy

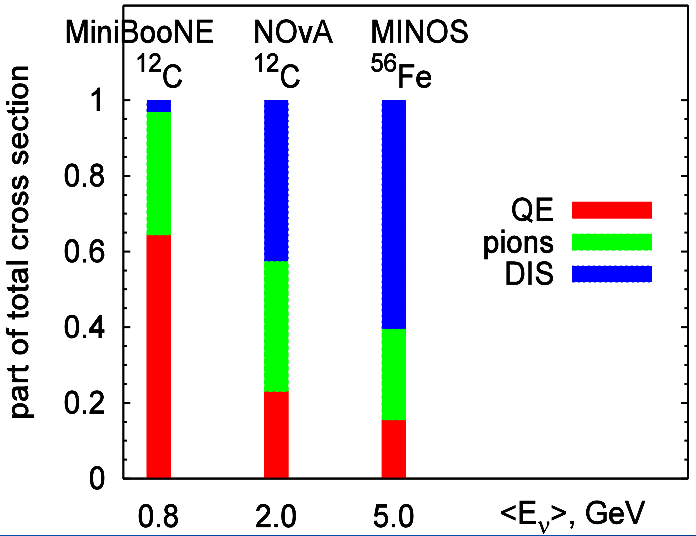
Need energy to distinguish between different δ_{CP}

Now to ongoing experiments

Neutrino Beams

- Neutrinos do not have fixed energy:

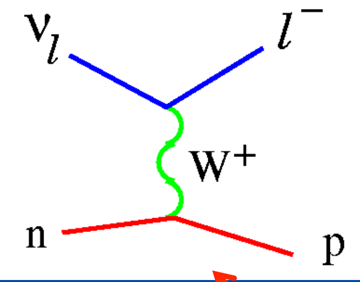




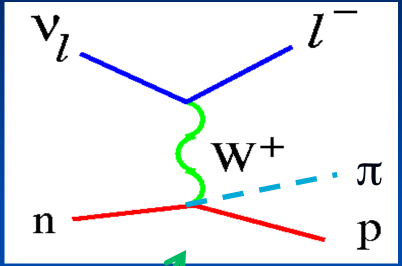
Have to reconstruct energy from final state of reaction

Neutrino-nucleon cross section

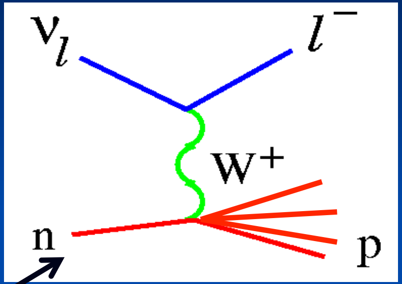
CCQE

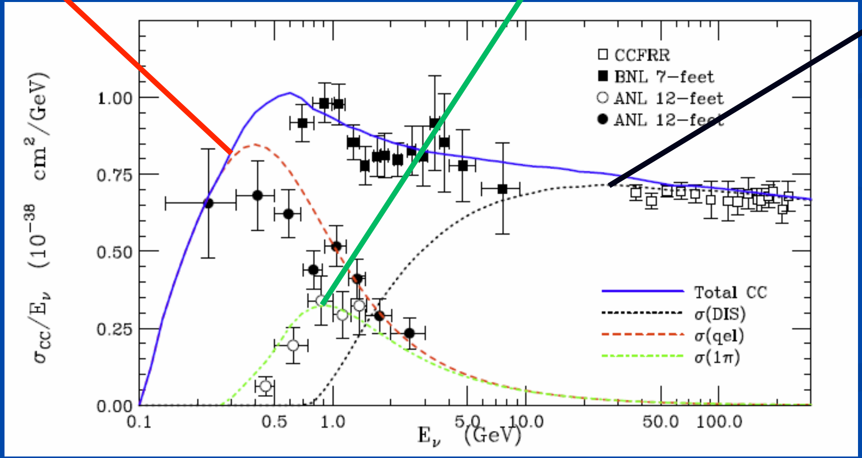


1π



DIS



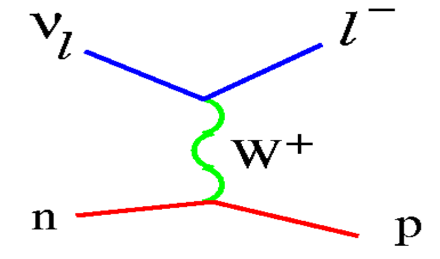


note:
10^{-38} cm² = 10^{-11} mb

NUFACT 2012

Energy Reconstruction by QE

- In pure QE scattering on nucleon at rest outgoing lepton determines neutrino energy:



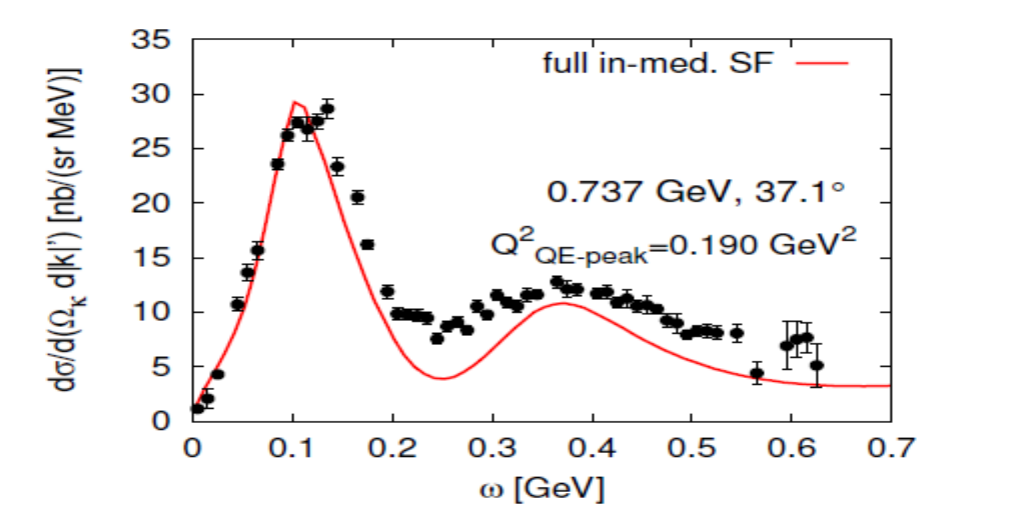
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- BUT: all modern experiments contain nuclei as targets →
  1. Problem to identify QE
  2. effects of binding energy, Fermi motion, Pauli principle

Two Complications to identify QE

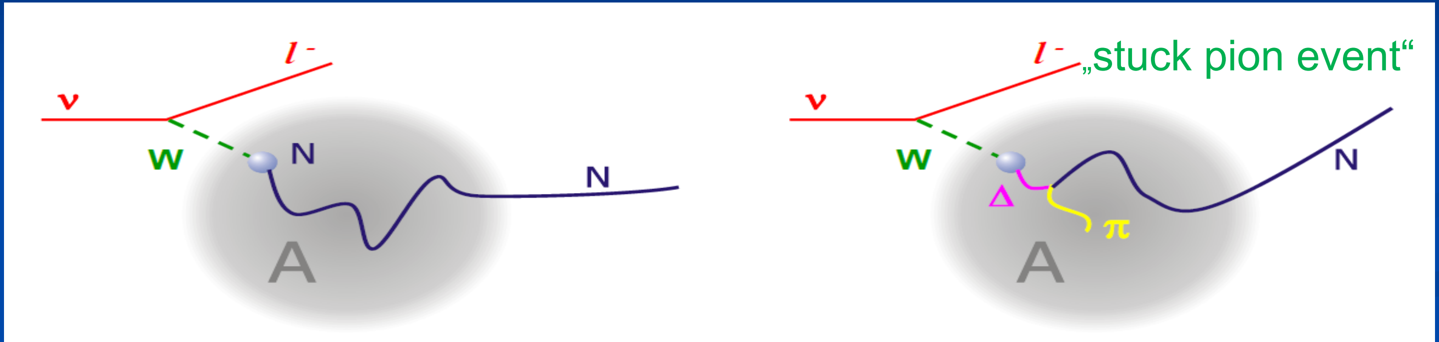
Identification of QE Scattering

Electron scattering on C



Difficulty to separate processes if neutrino energy is not known

Final State Interactions in Nuclear Targets



Complication to identify QE

Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva, ….)

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

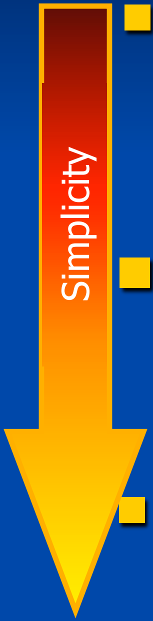
- **GiBUU : Theory and Event Generator**
  based on an approx. solution of Kadanoff-Baym equations

- Physics content (and code available): **Phys. Rept. 512 (2012) 1**
  http://theorie.physik.uni-giessen.de/GiBUU/

- **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!

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 interacts and FSI not consistent

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

8D-Spectral phase space density

Collision term

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

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**: Only `Neutrino Event Generator´ that has widely been tested with various hadronic and em reactions, **NO TUNING**

GiBUU Ingredients: ISI

- In-medium corrected primary interaction cross sections, boosted to restframe of moving bound nucleon in 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

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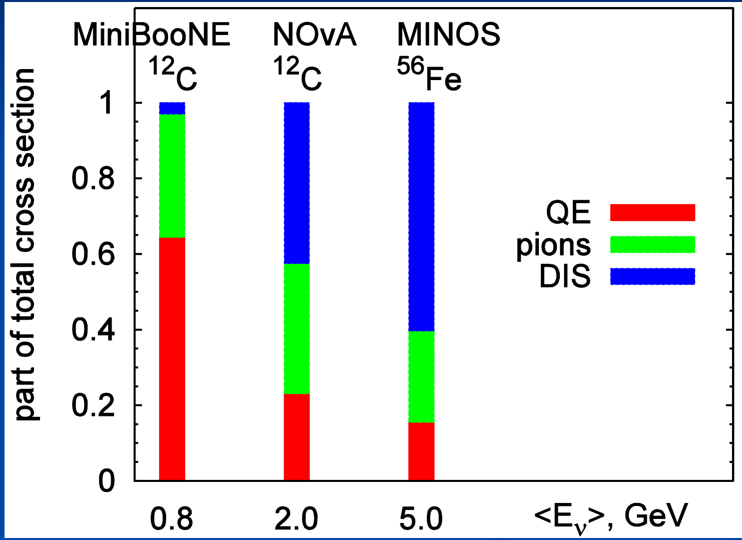
GiBUU Ingredients

- Processes included:
  - CC + NC QE scattering
  - Resonance excitation
  - DIS
- CC FSI for all produced particles



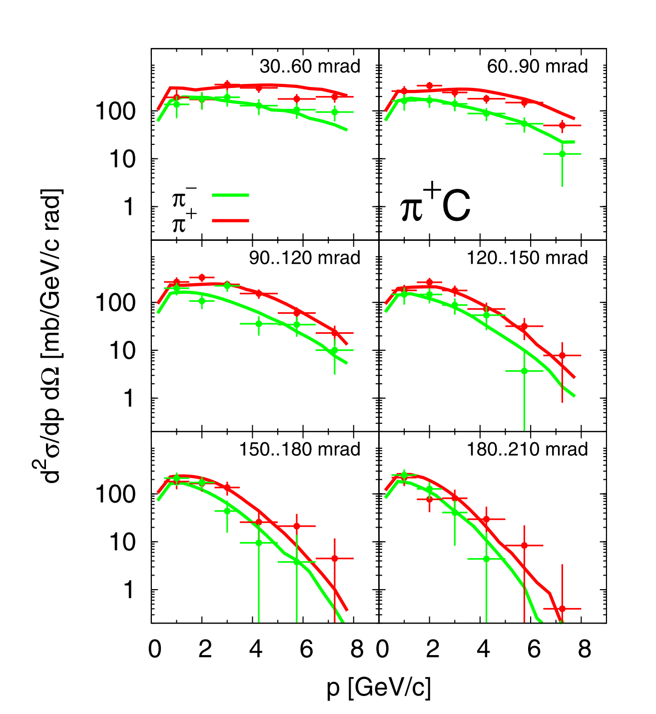
A complete model has to describe all of them

Check: pions in HARP

HARP small angle analysis
12 GeV protons

Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)



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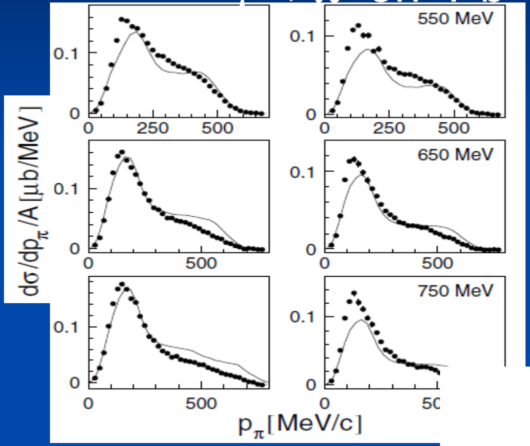
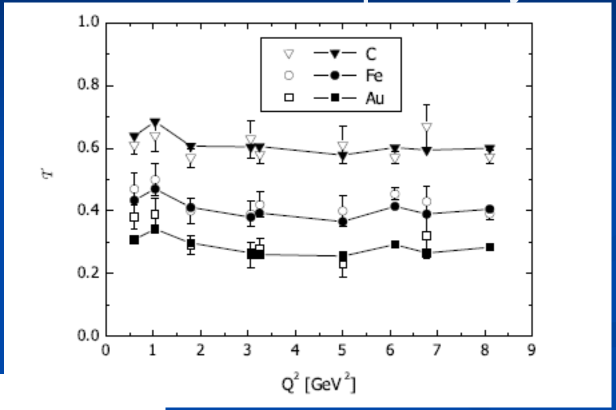
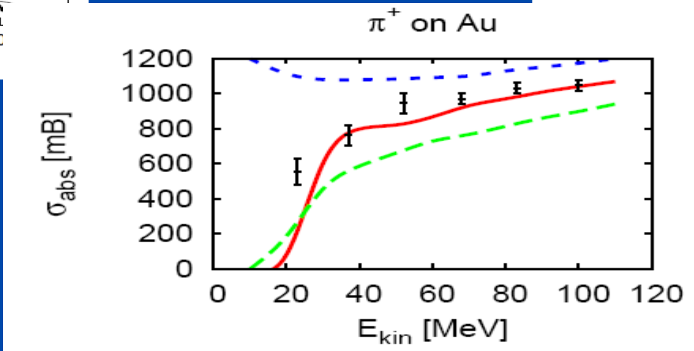
Check: pions, protons

$\gamma \to \pi^0$ on Pb



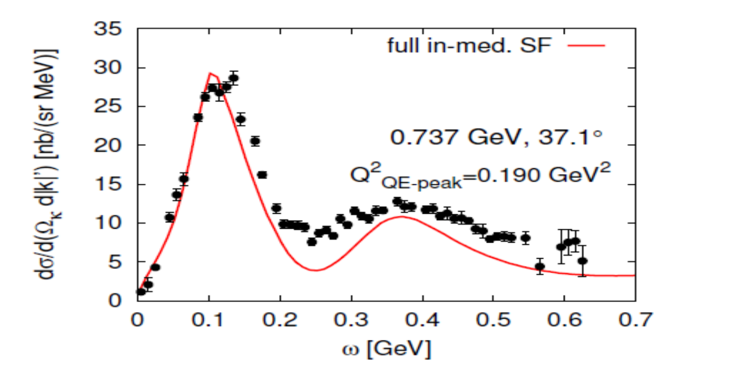
Proton transparency

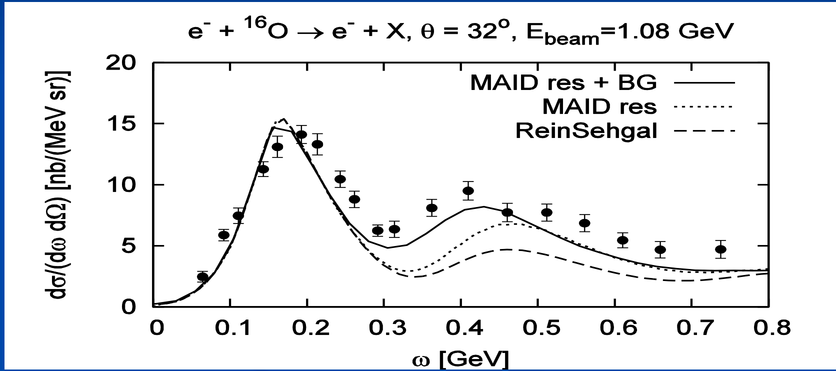




Pion reaction Xsect.

Electrons as Benchmark for GiBUU

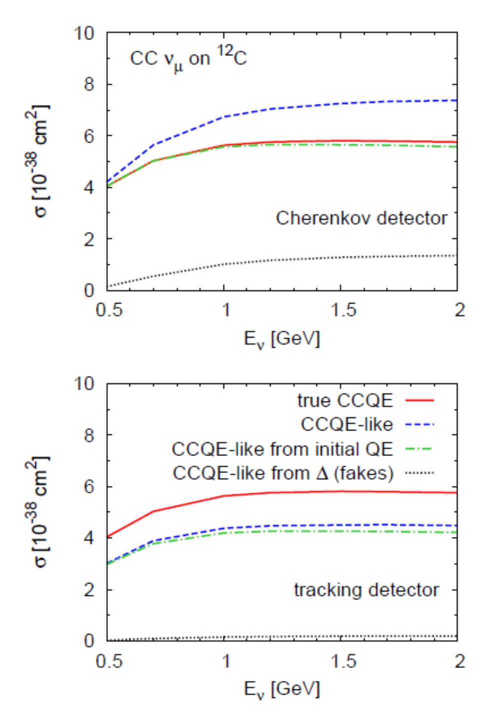




No free parameters!

Rein-Sehgal does not work for electrons!
Why should it work for neutrinos?

Event Identification



- Cerenkov detector (MiniBooNE, K2K 1kt, T2K) defines QE by:

$$\begin{array}{lllllll} \text{CCQE:} & 1\mu^- & 0\pi^+ & 0\pi^- & 0\pi^0 & xp & xn \\ \text{CC}1\pi^+\text{:} & 1\mu^- & 1\pi^+ & 0\pi^- & 0\pi^0 & xp & xn \end{array}$$

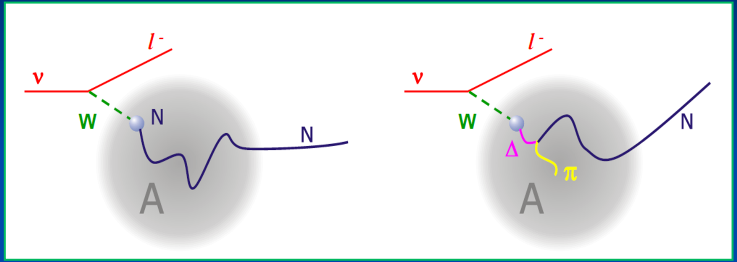
Too high QE: misidentifies about 20%, pion-induced fakes

- Tracking detector (Sci-BooNE, K2K, SciFi, T2K) defines QE by

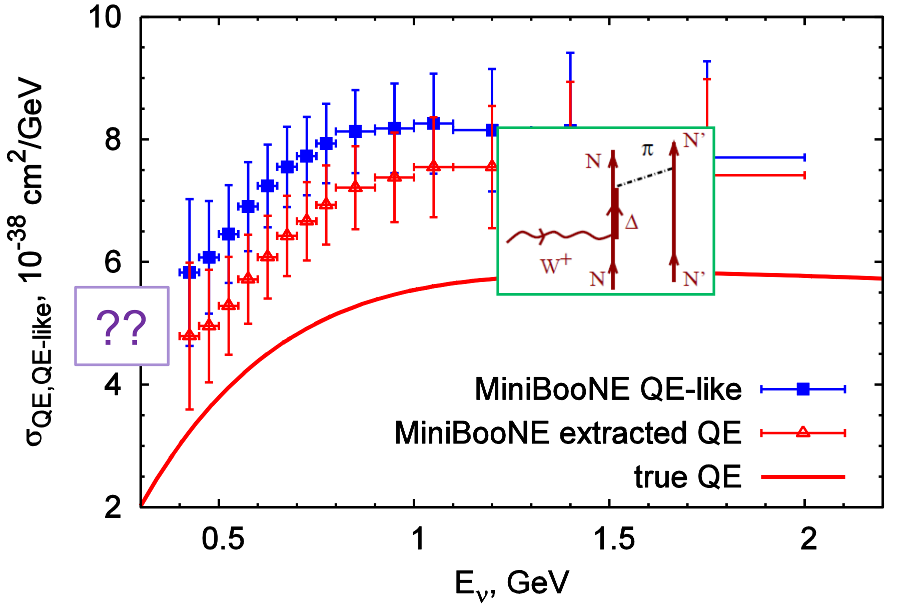
$$\begin{array}{lllllll} \text{CCQE:} & 1\mu^- & 0\pi^+ & 0\pi^- & 0\pi^0 & 1p & xn \\ \text{CC}1\pi^+\text{:} & 1\mu^- & 1\pi^+ & 0\pi^- & 0\pi^0 & xp & xn \end{array}$$

QE identification is clean, but 30% of total QE cross section is missed

MiniBooNE QE puzzle



QE with FSI — QE-like bgr



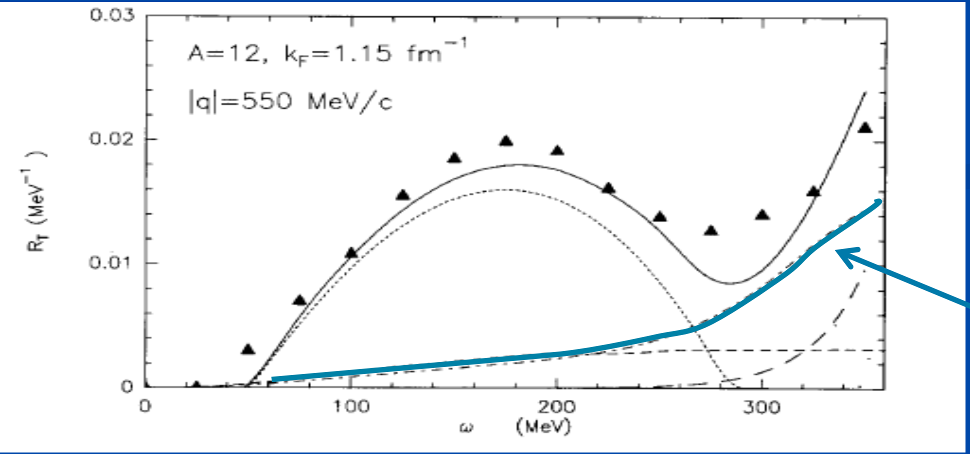
CCQE: $1\mu^- \; 0\pi^+ \; 0\pi^- \; 0\pi^0 \; xp \; xn$

Event generator is used to remove QE-like bgr from QE-like Xsect (blue) and to extract QE Xsect (red)

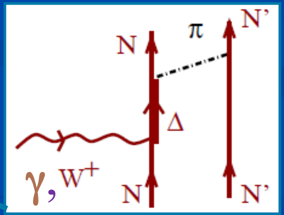
→ model dependence of QE data

The MiniBooNE QE Puzzle
Hint from Electrons: 2p-2h interacts.

- Dekker, Brussaard, Tjon (1991):
  influence of two-body currents



2p-2h events:



2p-2h in GiBUU

arXiv: 1203.2935, PR C (2012)

- Model for $\nu + p_1 + p_2 \rightarrow p_3 + p_4 + \mu$ (no recoil)

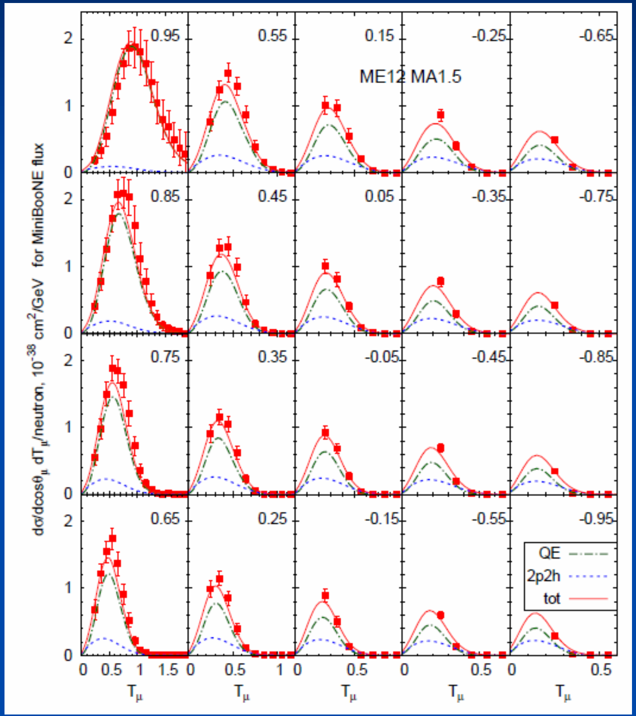
$$\frac{d^2\sigma}{dE_l' d(\cos\theta')} \propto \frac{k'}{k} \int_{NV} d^3r \int \prod_{j=1}^{4} \frac{d^3p_j}{(2\pi)^3 2E_j} f_1 f_2 \overline{|M|^2} (1-f_3)(1-f_4)\delta^4(p)$$

with flux averaged matrixelement

$$\overline{|M|^2} = \int \Phi(E_\nu)\, L_{\mu\nu} W^{\mu\nu}\, \mathrm{dE}_\nu$$

Flux smears out details in *W*
Constraint from e-scattering:
W contributes to transverse scattering

2p-2h in GiBUU



MB flux averaged

Data corrected
for stuck-pion events!

Dotted: 2p-2h contribs,
Relatively most important at backward angles (transverse!).

Inclusive double-differential X-sections fairly insensitive to details of 2p-2h interaction

The MiniBooNE QE Puzzle
Various, contradictory Explanations

- Change of axial FF only
  - Larger axial mass $M_A \approx 1.3$ GeV (exp)
  - Change of axial FF shape (Hill)
- Change of vector FF only (Bodek)
- 2p-2h (Ericsson, Martini, Nieves, Amaro et al)

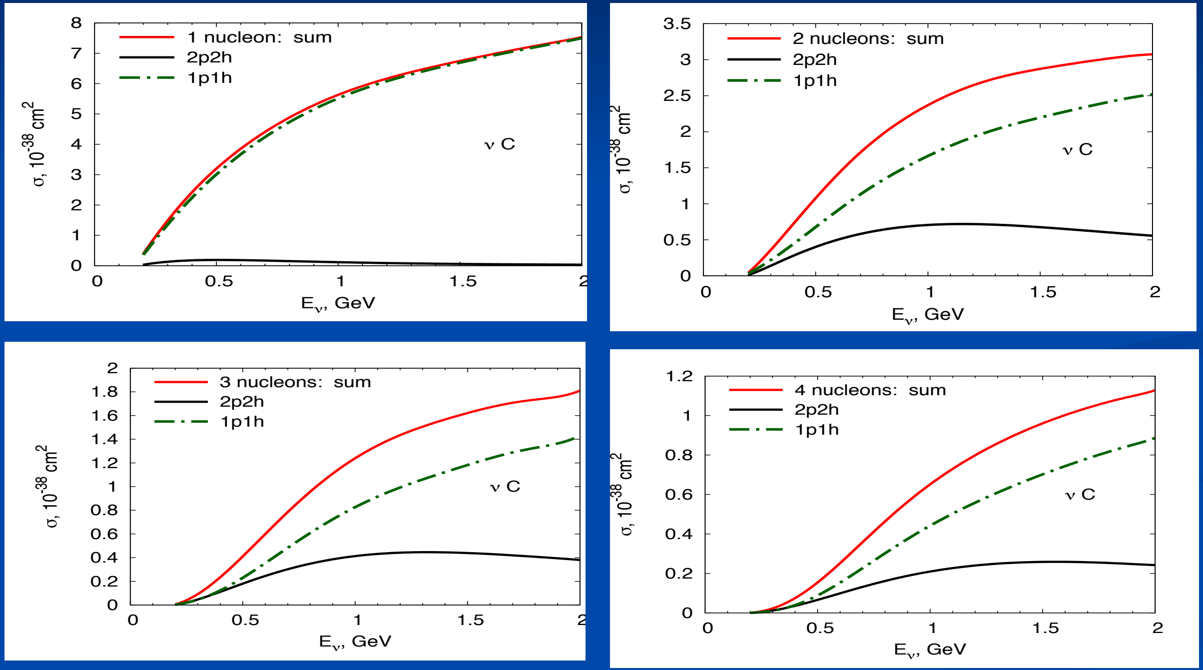
The MiniBooNE QE Puzzle
Explanations

- How to decide which one is correct?

- Must not only consider inclusive X-sections, but also exclusive ones:

Nucleon Knock-out, numbers and spectra

The MiniBooNE QE Puzzle
Nucleon Knock-Out



Only true QE can be identified,

FSI smear out characteristics of primary event

Energy Reconstruction by QE

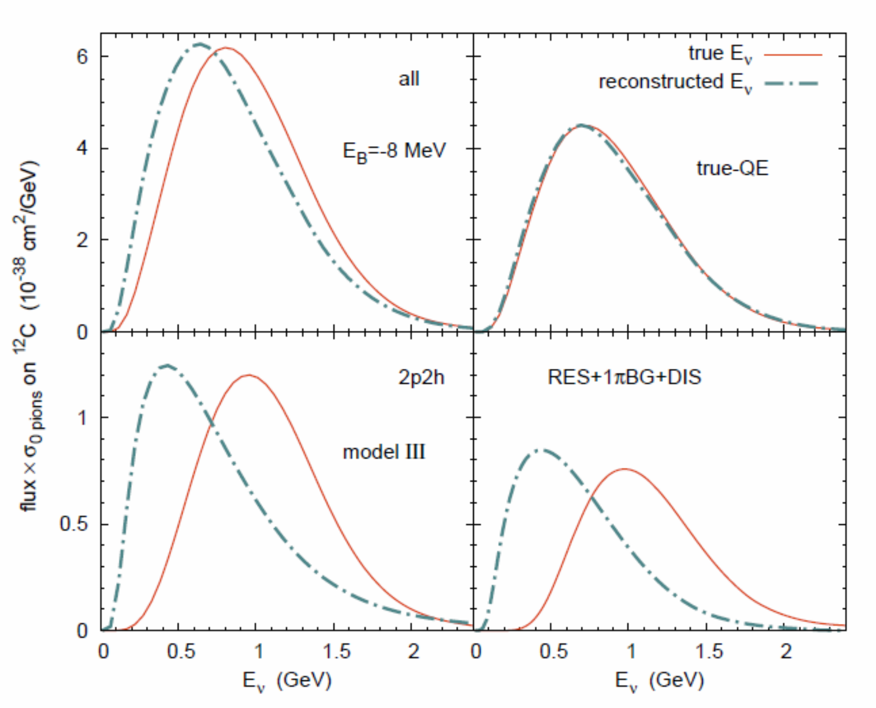
- All modern experiments use heavy nuclei as target material: C, O, Fe → nuclear complications
- Quasifree kinematics used for QE on bound nucleons: Fermi-smearing of reconstructed energy expected
- For nuclear targets QE reaction must be identified to use the reconstruction formula for E_ν
- But: exp. definition of QE cannot distinguish between true QE (1p-1h), N* and 2p-2h interactions

Energy reconstruction

- Entanglement of pion production and QE scattering leads to bias towards lower neutrino energies

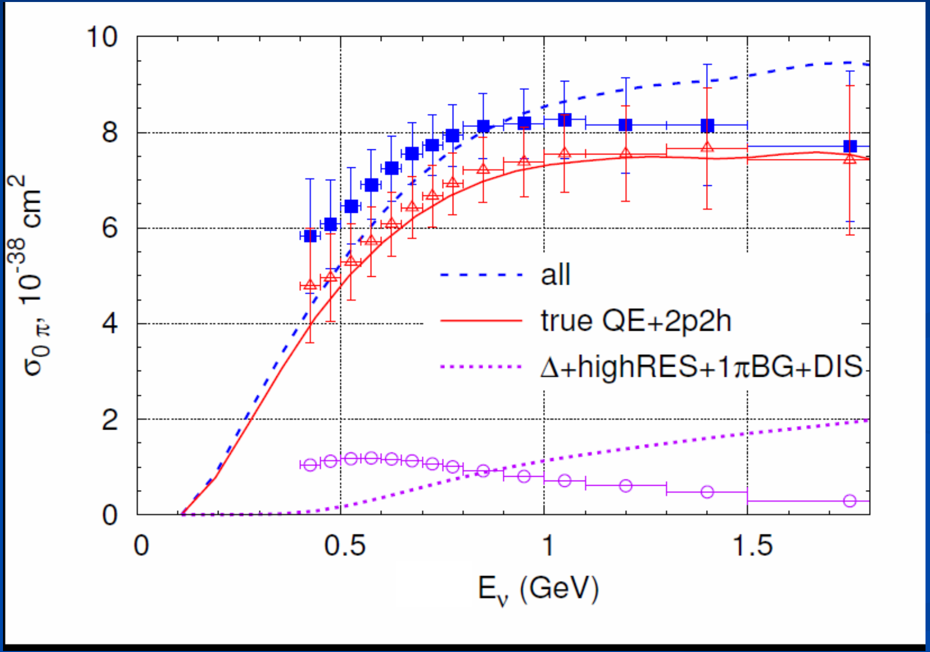
- Existence of 2p-2h component divides incoming energy transfer among two nuclei: slower nuclei are interpreted as lower neutrino energy!
  -> more bias to lower energies

Energy reconstruction in MB



Reconstructed energy shifted to lower energies for all processes beyond QE

Energy reconstruction in MB



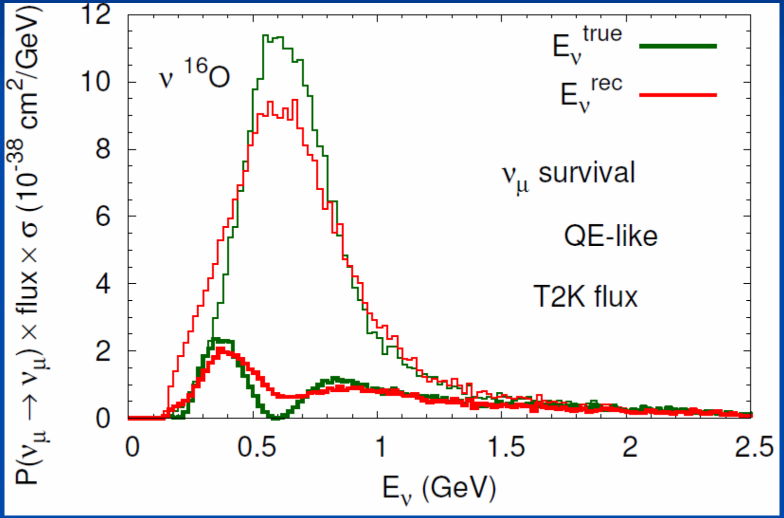
Data: plotted vs Reconstructed energy

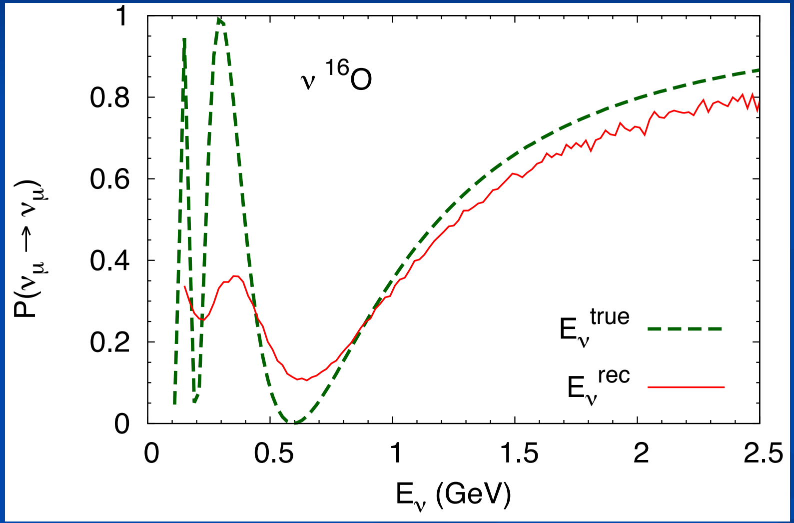
Curves: plotted vs. True energy

Explains strange energy-dependence of stuck pion events

Oscillation signal in T2K

ν_μ disappearance





Ratio = oscillation probability

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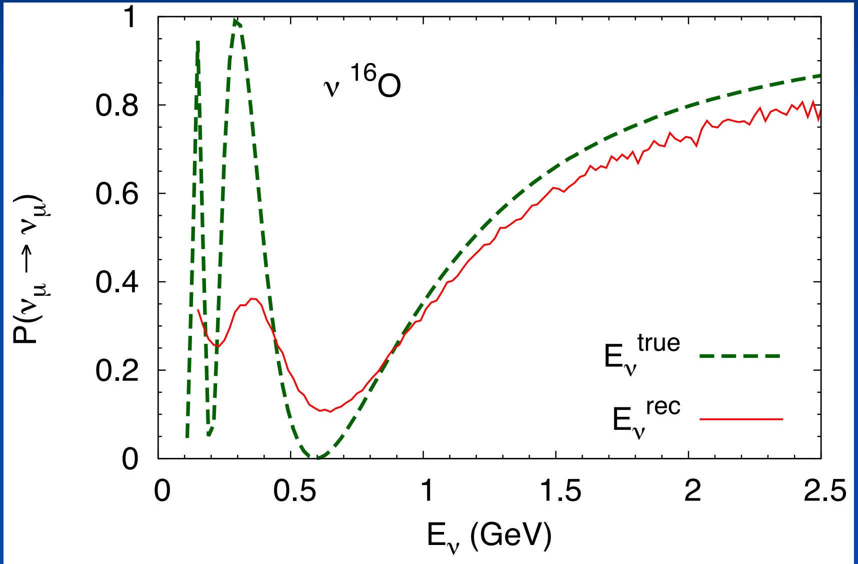
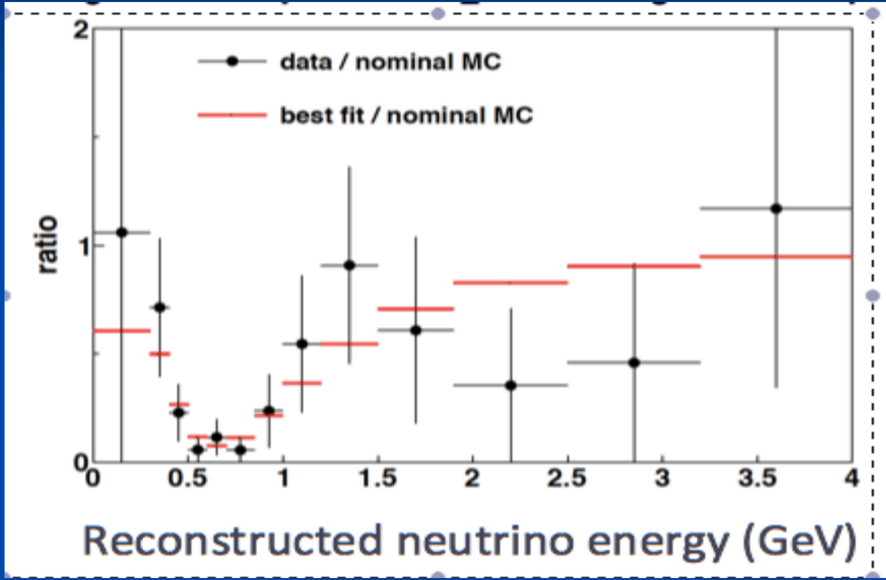
Oscillation signal in T2K

ν_μ disappearance





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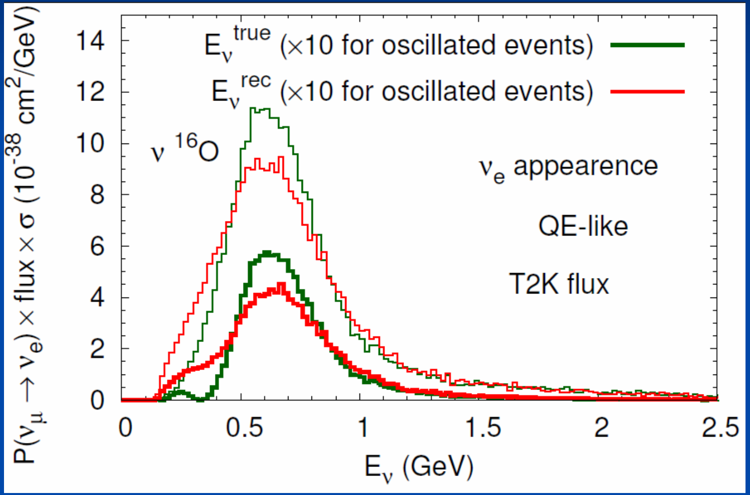
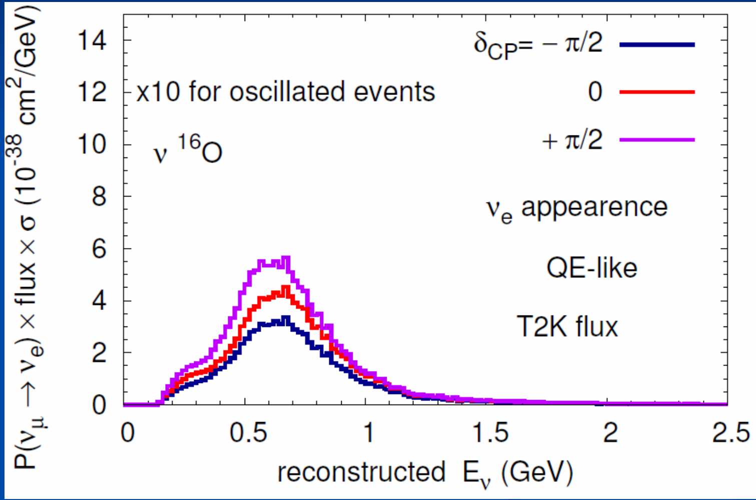
Oscillation signal in T2K

δ_{CP} sensitivity

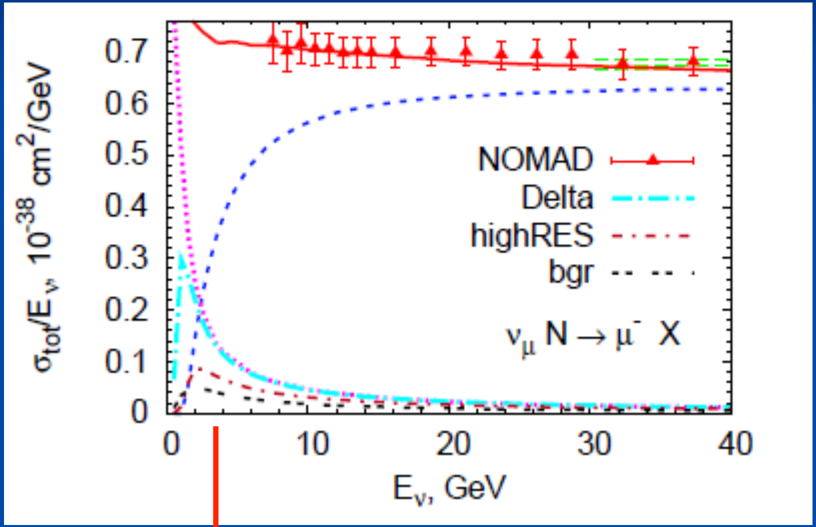




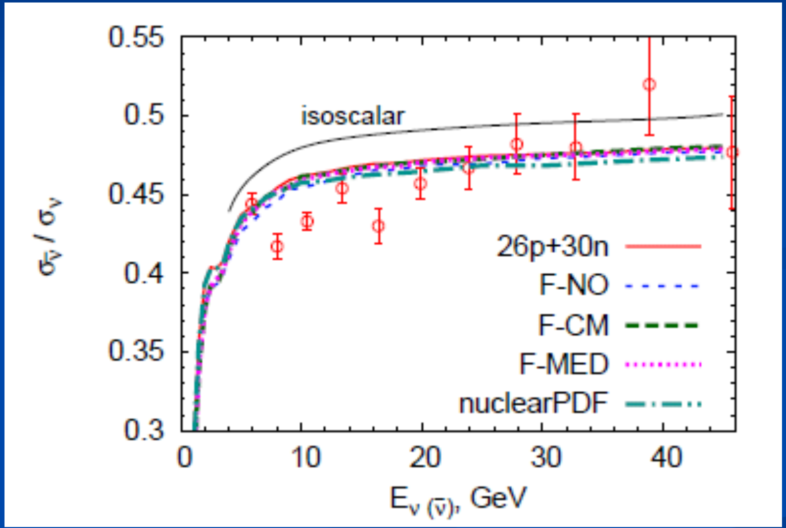
Uncertainties due to energy reconstruction as large as δ_{CP} dependence

Experiments at higher energies

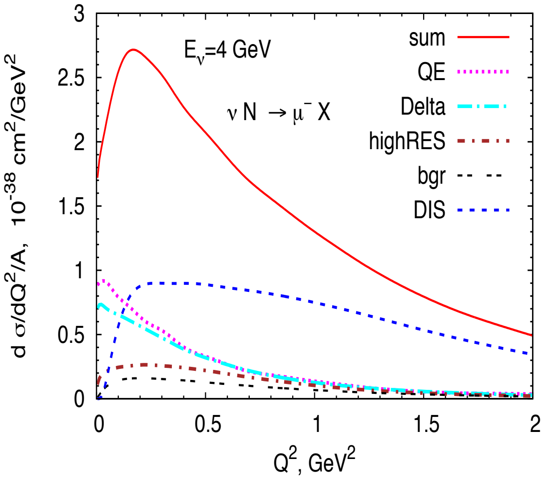
Phys. Rev. C86 (2012) 014607

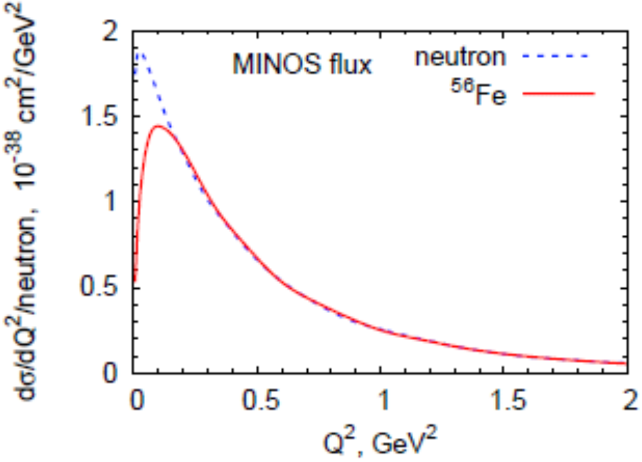


Shallow Inelastic Region



Experiments at higher energies

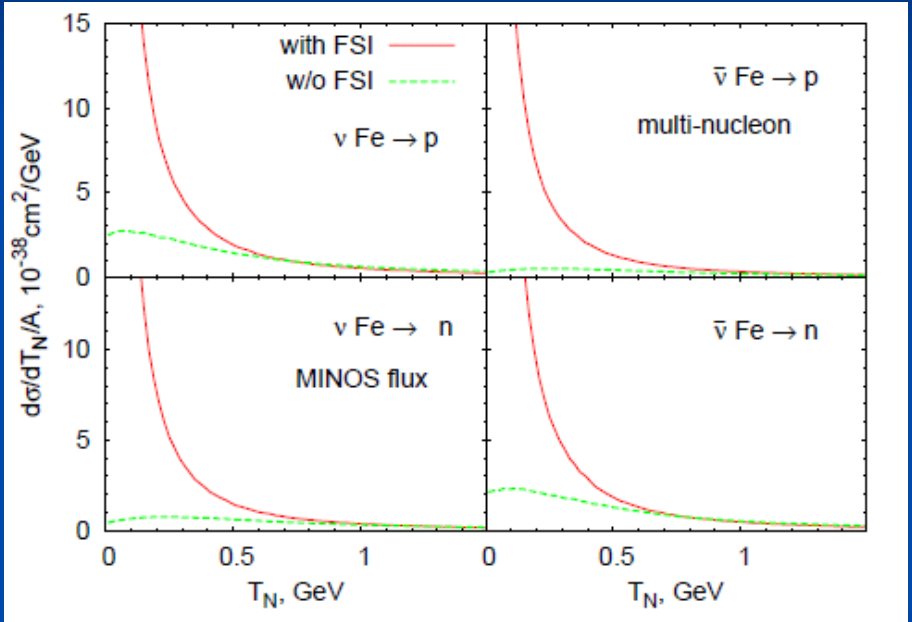




Q^2 dependence similar to lower-energy MB experiment

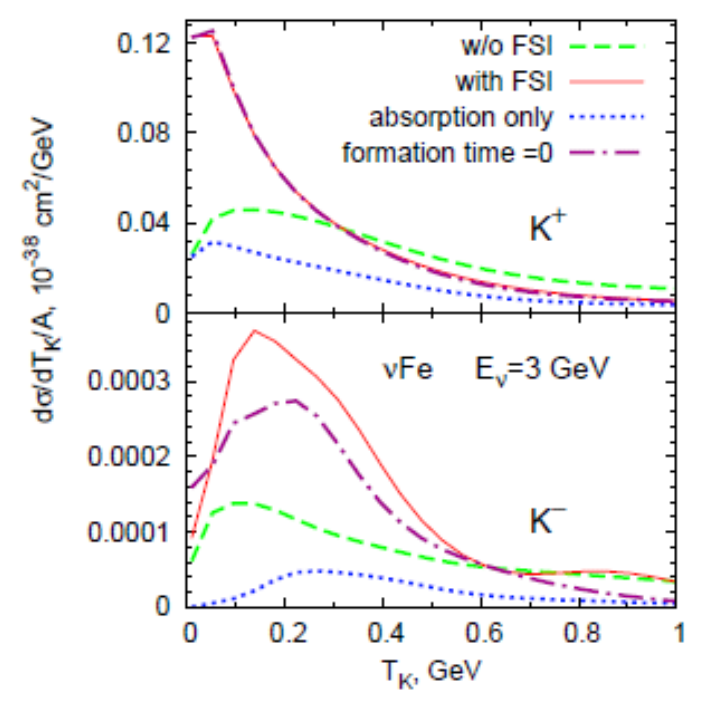
Experiments at higher energies

Knock-out Nucleons



Strong rise below 300 MeV, dominated by FSI

Experiments at higher energies



Lesson for Minerva:

The particles you measure are not those that the neutrino produced. Secondary production is important

Summary

- Event generators for neutrino-nucleus interactions have to describe QE, π produktion and DIS simultaneously
- Due to flux average reaction types are closely entangled
- MB puzzle of high axial mass explained: contains 2p-2h
- Energy reconstruction based on QE leads in Cerenkov detectors to downward shift of reconstructed distribution
- FSI are extremely important, may make the extraction of elementary neutrino-particle production rates impossible

Importance of Generators

- Two points of view:
  - 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
- Let us strive for a generator that is ‚right' and as much state-of-the-art as the experimental equipment is!

Need for solid nuclear physics theory suport in Neutrino Physics