Neutrino Interactions with Nuclei

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Motivation and Contents

- Determination of neutrino oscillation parameters and particle production cross sections (axial properties of nucleons and resonances) requires knowledge of neutrino energy
- Modern experiments use nuclear targets
- Nuclear effects affect event cross section measurements, event characterization and neutrino energy reconstruction
- Will discuss: QE + 2p2h, Pion Production, Resonances and DIS transition

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Relevant Refs

- *Pion production in the MiniBooNE experiment.*

Olga Lalakulich, Ulrich Mosel (Giessen U.). Oct 2012. 21 pp.
Published in Phys.Rev. C87 (2013) 014602

- *Energy reconstruction in quasielastic scattering in the MiniBooNE and T2K experiments.*

O. Lalakulich, U. Mosel (Giessen U.). Aug 2012. 15 pp.
Published in Phys.Rev. C86 (2012) 054606

- *Neutrino- and antineutrino-induced reactions with nuclei between 1 and 50 GeV.*

O. Lalakulich (Giessen U.), K. Gallmeister (Frankfurt U.), U. Mosel (Giessen U.). May 2012.
Published in Phys.Rev. C86 (2012) 014607

- *Many-Body Interactions of Neutrinos with Nuclei - Observables.*

O. Lalakulich (Giessen U.), K. Gallmeister (Frankfurt U.), U. Mosel (Giessen U.). Mar 2012. 22 pp.
Published in Phys.Rev. C86 (2012) 014614

- *Transport-theoretical Description of Nuclear Reactions.*

O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A.B. Larionov, T. Leitner, J. Weil, U. Mosel (Giessen U.). Jun 2011. 170 pp.
Published in Phys.Rept. 512 (2012) 1-124

Axial Structure of the Nucleon

- Various explanations for new QE data:

  1. Large axial mass $M_A \approx 1.3 - 1.6$ GeV
  2. Change of axial FF (Hill), $M_A \approx 1.0$ GeV
  3. Change of vector FF (Bodek), $M_A \approx 1.0$ GeV

- Axial coupling to resonances

Neutrino Oscillations

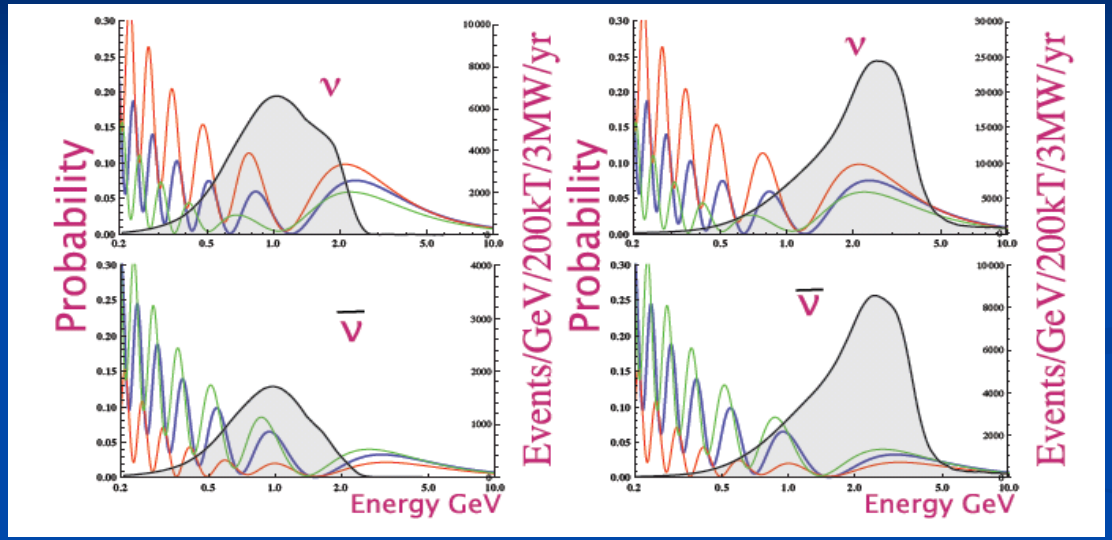
- 2-Flavor Oscillation:

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

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

Project X, δ_{CP} sensitivity

From: Bishai et al., hep-ex 12034090



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}

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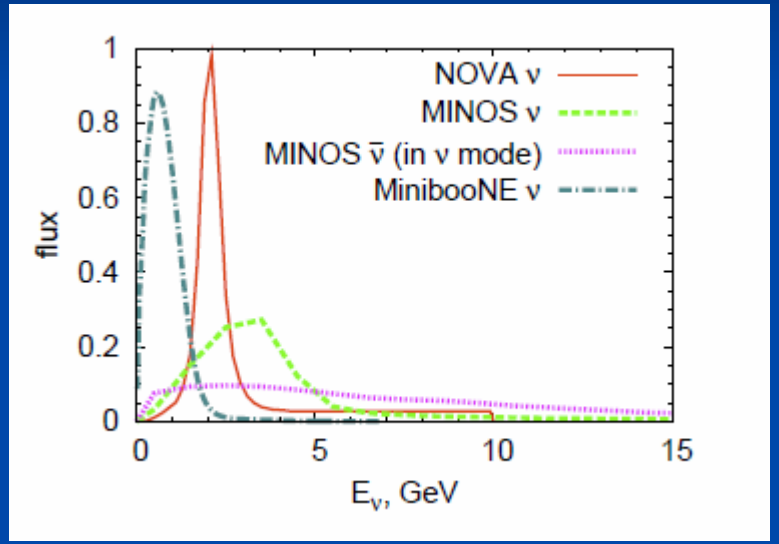
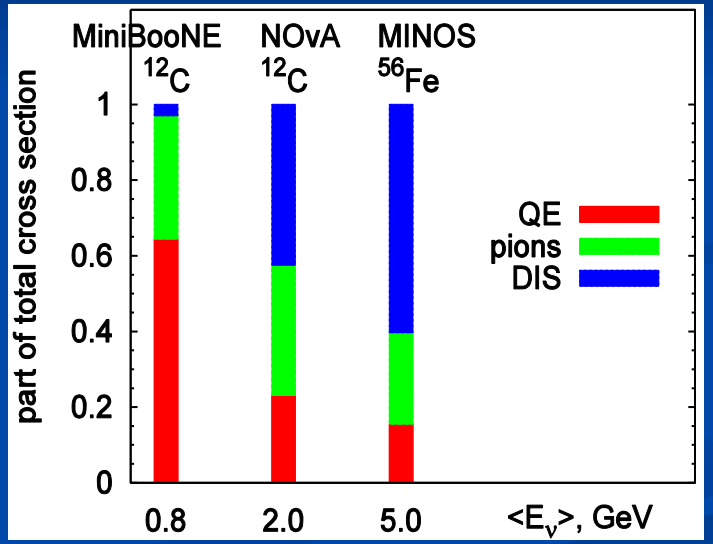
Now to ongoing experiments

Neutrino Beams

- Neutrinos do not have fixed energy:

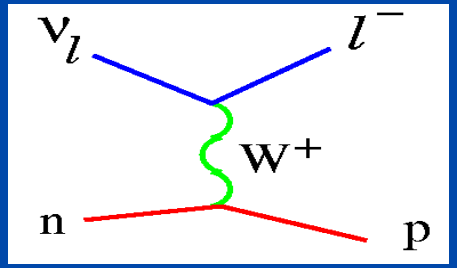




Have to reconstruct energy from final state of reaction

Energy Reconstruction by QE

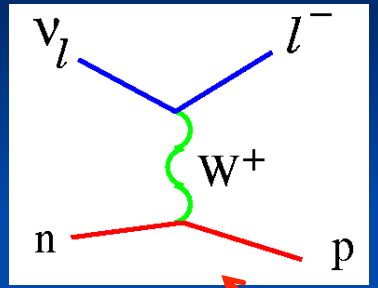
- In pure QE scattering on nucleon at rest outgoing lepton determines neutrino energy:



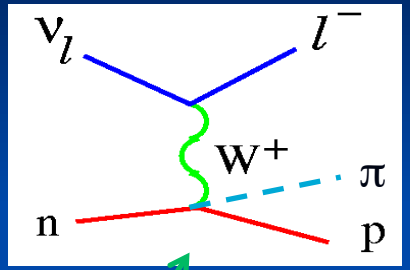
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

Neutrino-nucleon cross section

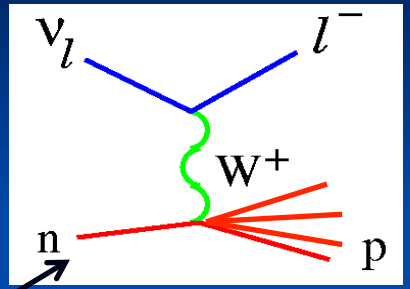
CCQE

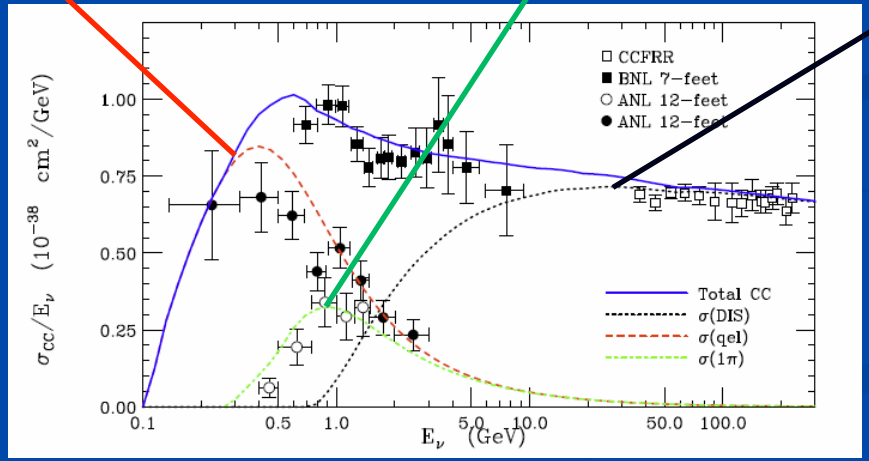


1π



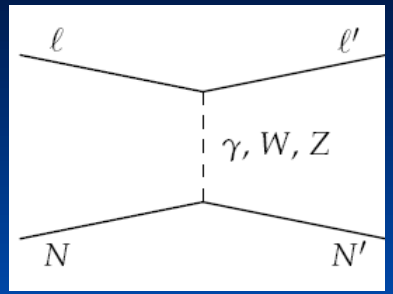
DIS





note:
10^{-38} cm² = 10^{-11} mb

Quasielastic scattering



$$J^\mu_{QE} = \left(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu\gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$

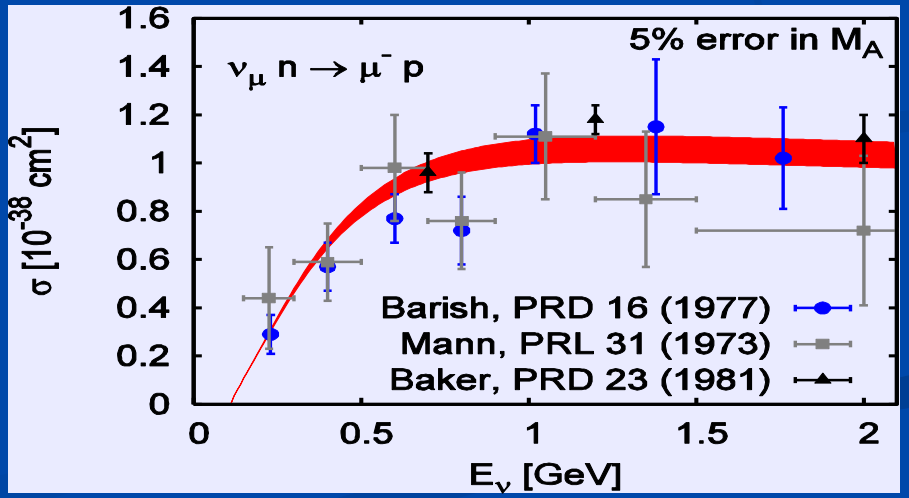
- Vector form factors from *e* –scattering
- axial form factors

  $F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**

  dipole ansatz for F_A with

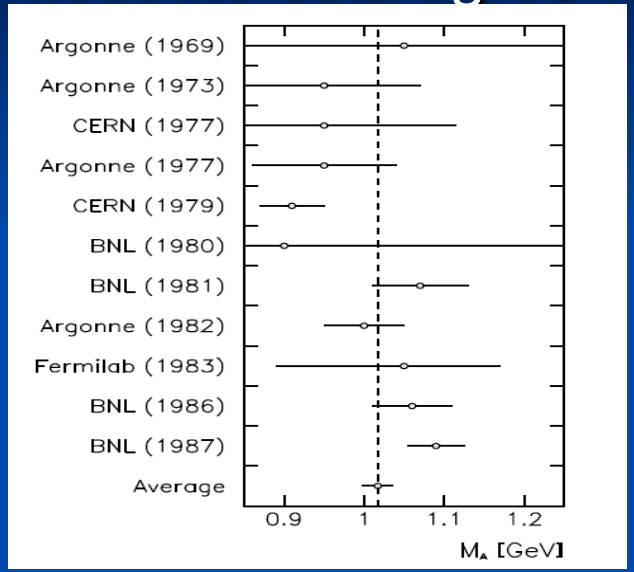
  M_A= 1 GeV:

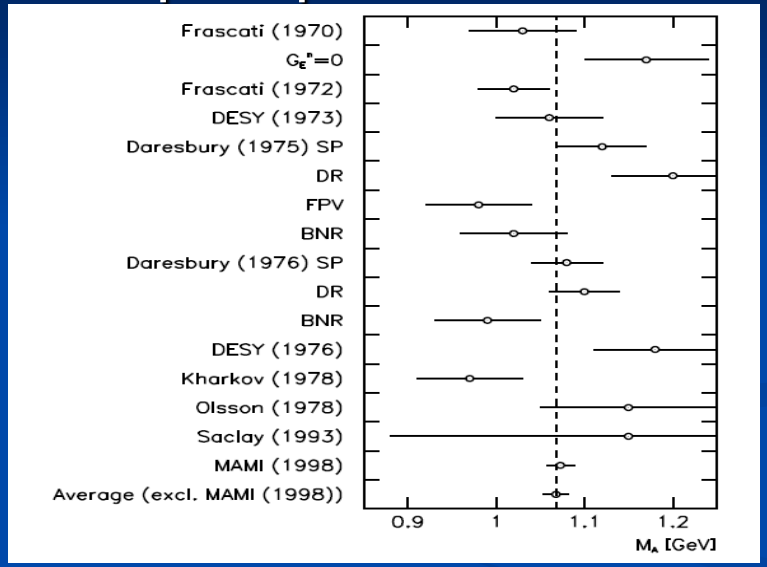
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data





$M_A \cong 1.02$ GeV world average

$M_A \cong 1.07$ GeV world average

Dipole ansatz is simplification, not good for vector FF

Pion production

- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance**:

$$J_\Delta^{\alpha\mu} = \left[\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu)\right]\gamma_5$$
$$+\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2}q^\alpha q^\mu$$

- **C^V** from electron data (MAID analysis with CVC)

- **C^A** from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

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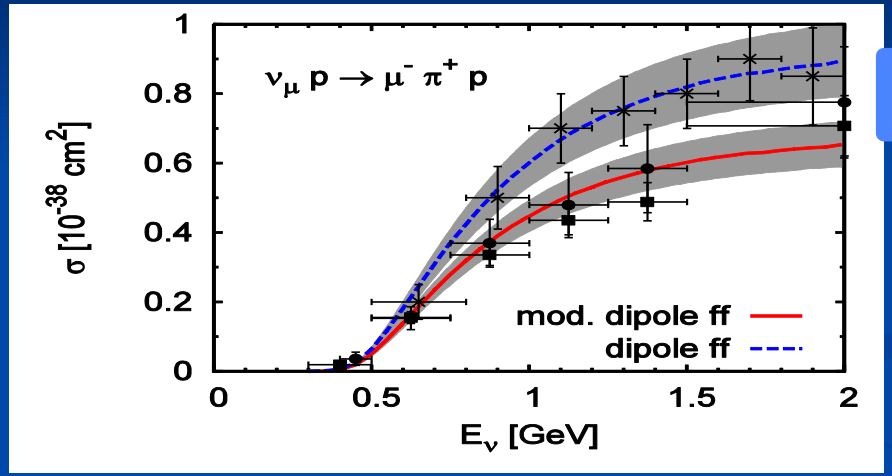
Pion Production



10 % error in $C_5^A(0)$

data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)

discrepancy between data sets
→uncertainty in axial form factor

Transport Theory and GiBUU

Fermilab 2013

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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

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 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**

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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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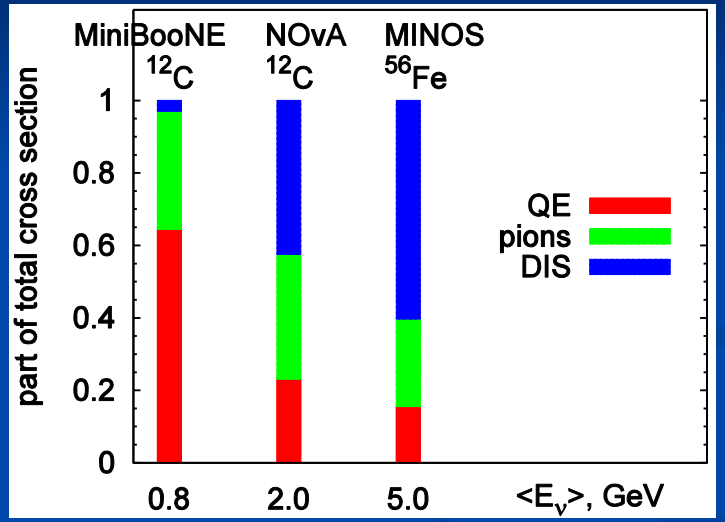
GiBUU Ingredients

- Processes included:
  - CC + NC QE scattering
  - 2p-2h interactions
  - Resonance excitation
  - DIS
- FSI for all produced particles



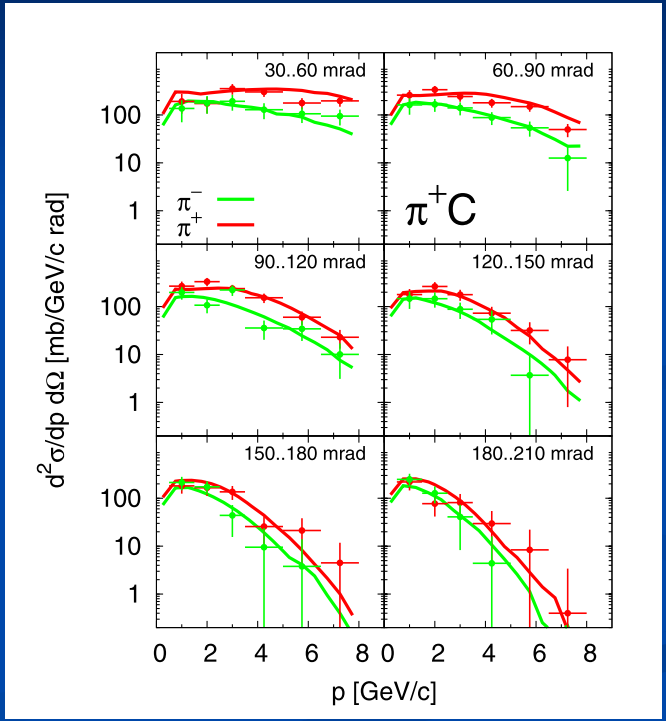
A complete model has to describe all of them

Check: pions in HARP

HARP small angle analysis
12 GeV protons

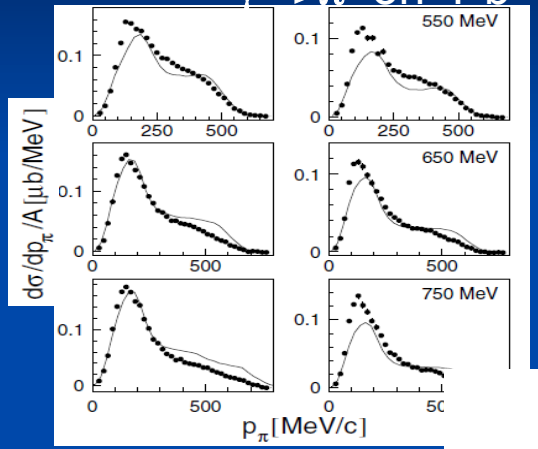
Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)

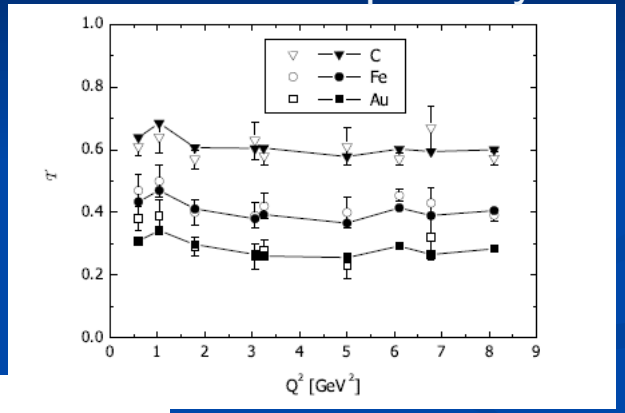


Check: pions, protons

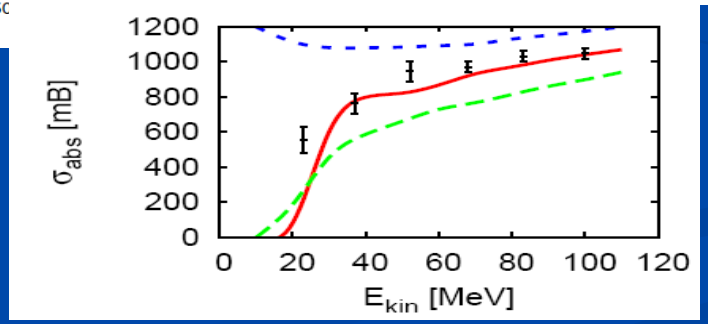
$\gamma \rightarrow \pi^0$ on Pb



Proton transparency

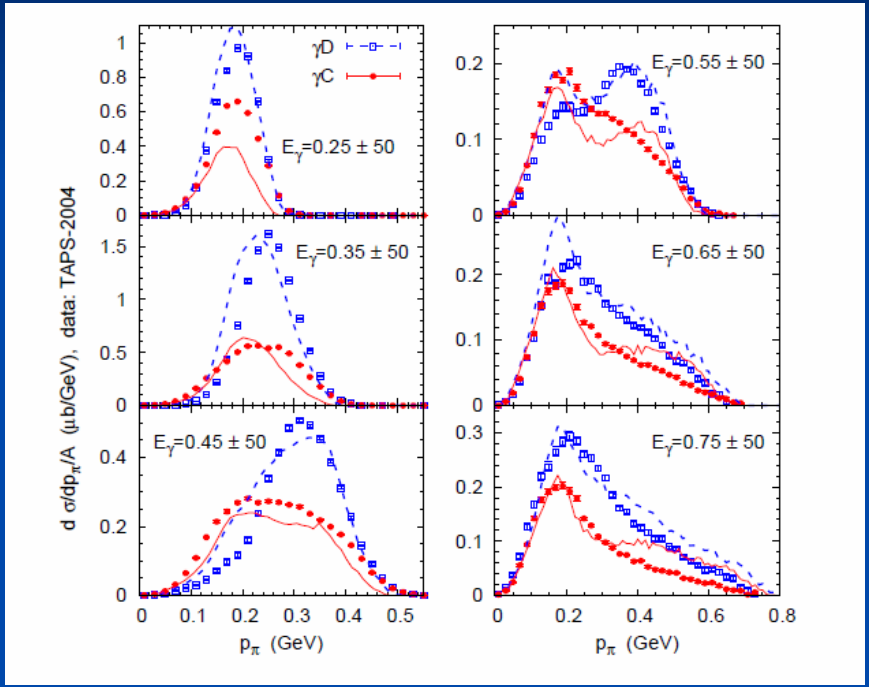


π^+ on Au

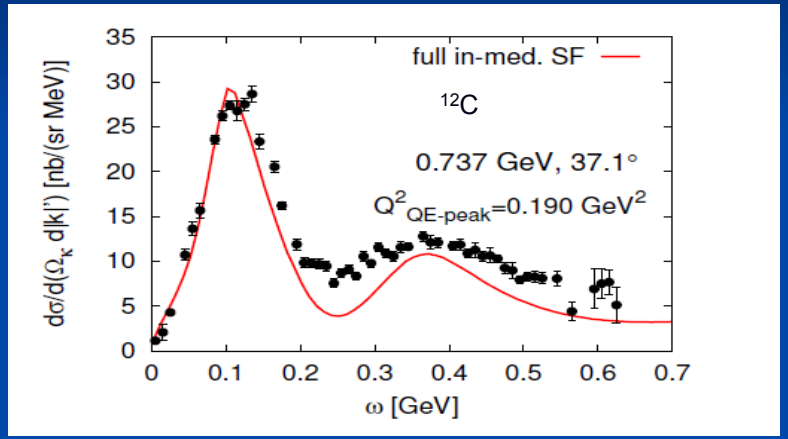


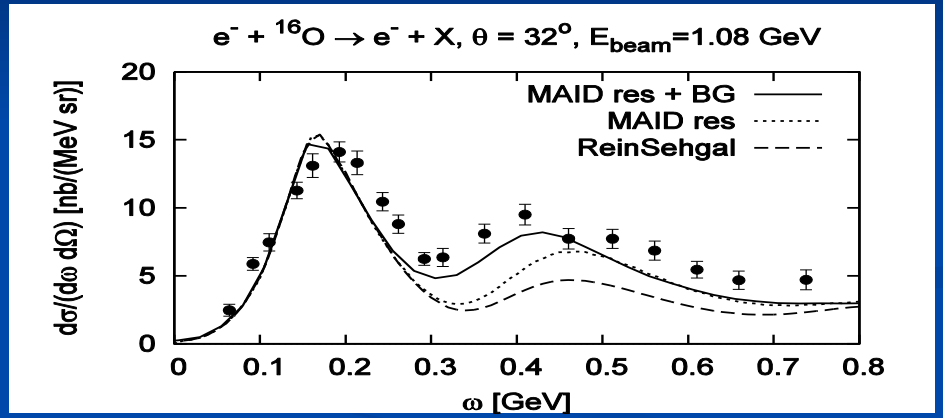
Pion reaction Xsect.

Pion Production



Electrons as Benchmark for GiBUU





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

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

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Event Identification

- Energy reconstruction
  1. Through QE: needs event identification
  2. Calorimetric: needs simulation of thresholds and non-measured events

Two Complications to identify QE

All modern experiments contain nuclei as targets

→

1. Effects of binding energy, Fermi motion, Pauli principle
2. Problem to identify QE, due to unknown energy *and* fsi

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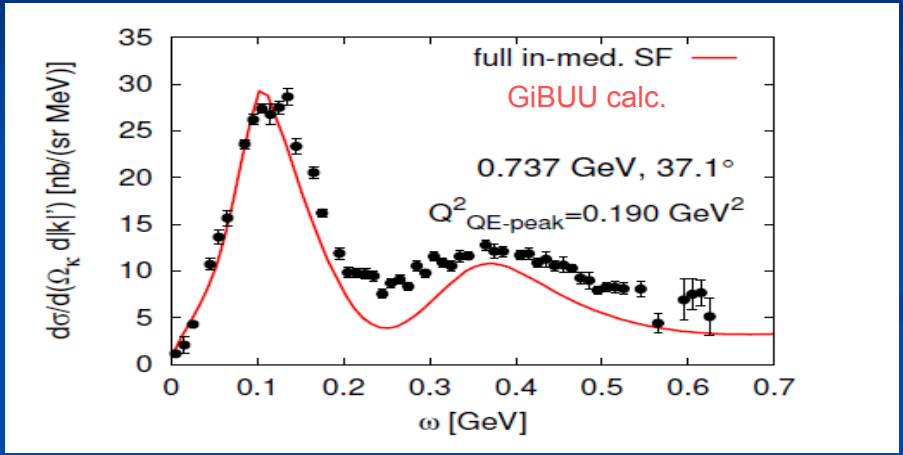
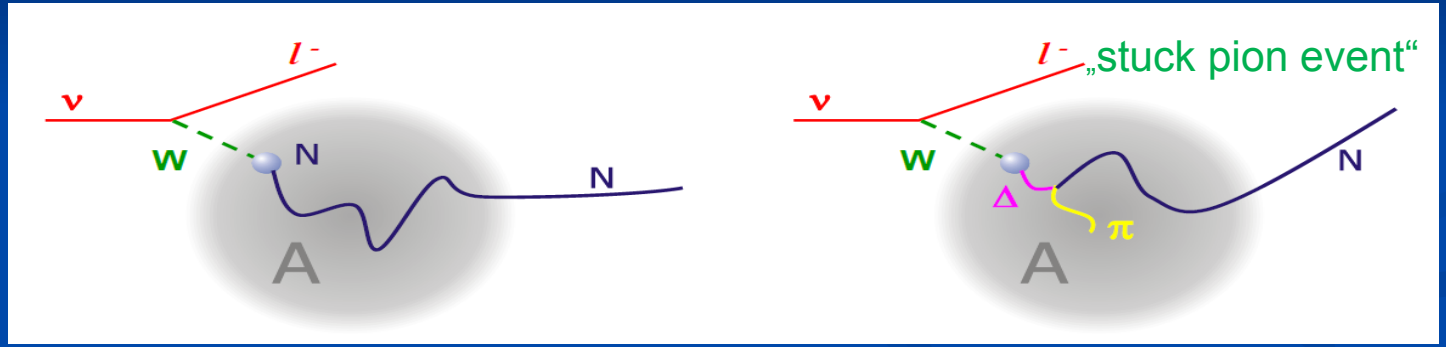
Identification of QE Scattering

electron scattering on C



Electrons: exp. separation of QE and Δ possible since ω is measured
Neutrinos: no exp. separation if neutrino energy (and thus ω) is not known

Final State Interactions in Nuclear Targets



Complication to identify QE

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

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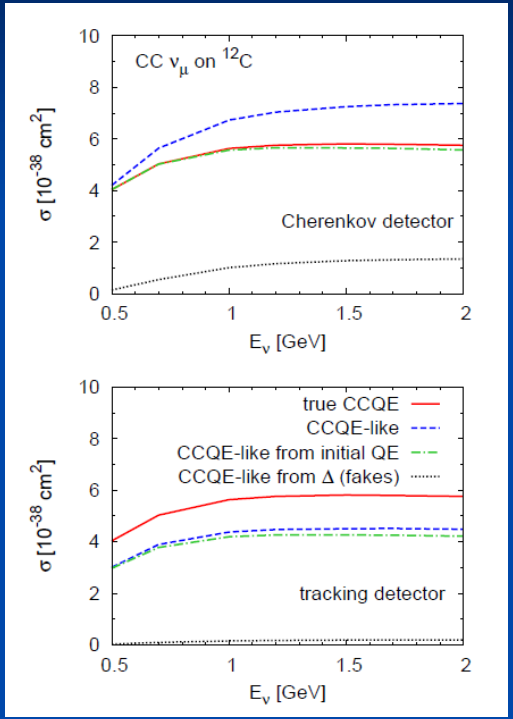
Event Identification



- 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

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Pion Production

from: Phys.Rev. C87 (2013) 014602

1p-1h-1π X-section:

$$\mathrm{d}\sigma^{\nu A\to \ell' X\pi} = \int \mathrm{d}E \int \frac{\mathrm{d}^3 p}{(2\pi)^3} P(\mathbf{p},E) f_{\mathrm{corr}}\, \mathrm{d}\sigma^{\mathrm{med}}\, P_{\mathrm{PB}}(\mathbf{r},\mathbf{p}) F_\pi(\mathbf{q}_\pi,\mathbf{r})\ .$$

Hole spectral function

$$P(\mathbf{p},E) = g \int\limits_{\mathrm{nucleus}} \mathrm{d}^3 r\, \Theta\left[p_{\mathrm{F}}(\mathbf{r}) - |\mathbf{p}|\right] \Theta(E) \delta\left(E - m^* + \sqrt{\mathbf{p}^2 + m^{*2}}\right)$$

In medium effects in Delta propagator and – possibly – in many- body production

$$\mathrm{d}\sigma^{\mathrm{med}} = \mathrm{d}\sigma^{\mathrm{med}}_{1p1h1\,\pi} + \mathrm{d}\sigma^{\mathrm{med}}_{2p2h\,1\pi} + \ldots$$

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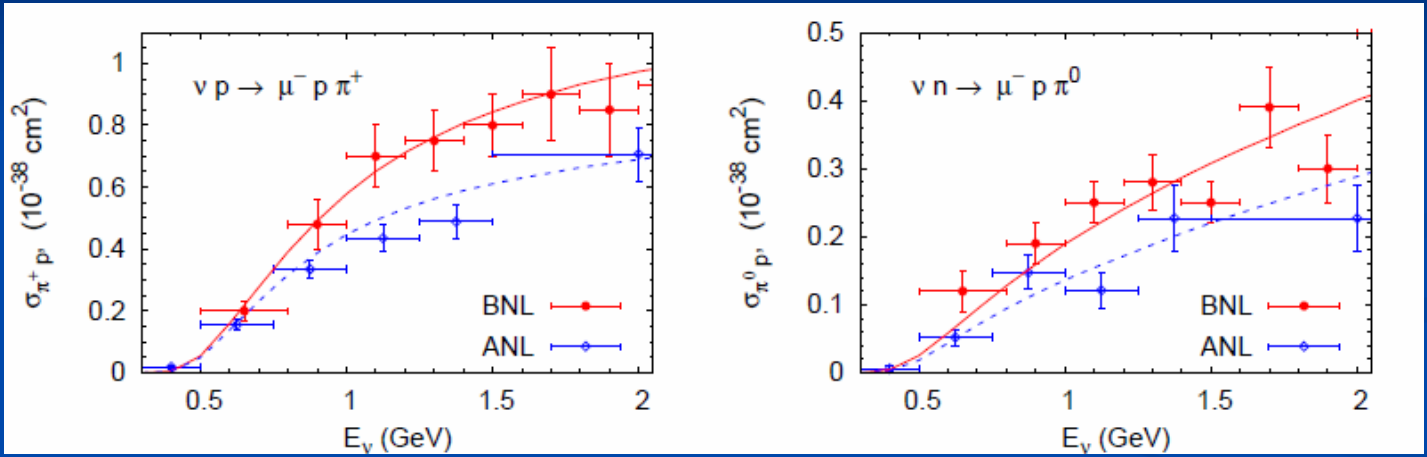
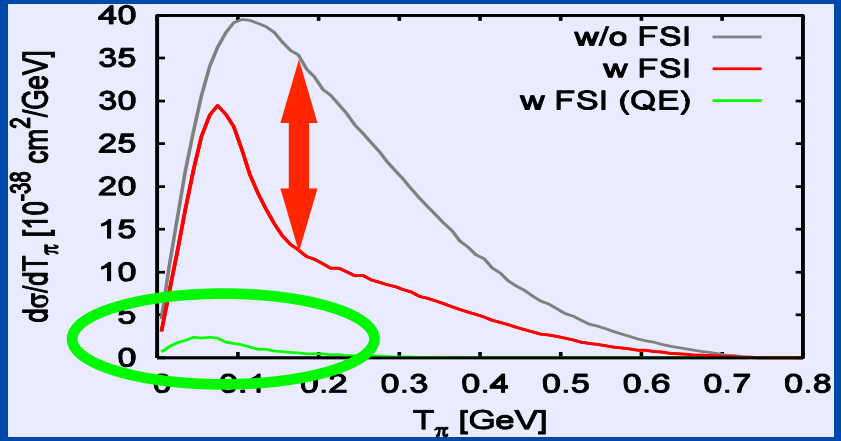
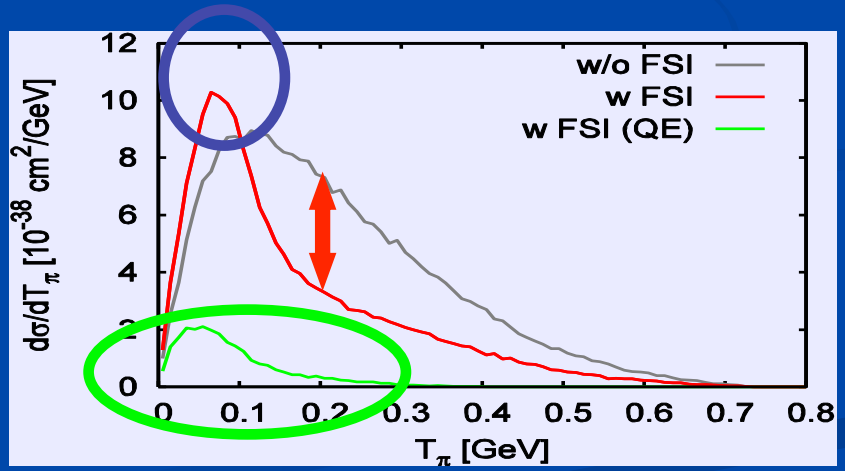
Pion Production



CC pion production: $\nu_\mu {}^{56}Fe \rightarrow \mu^- \pi X$

- effects of FSI on pion kinetic energy spectrum at E_ν = 1 GeV
  - strong absorption in Δ region
  - side-feeding from dominant π^+ into π^0 channel
  - secondary pions through FSI of initial QE protons





Spectra determined by π–N-Δ dynamics

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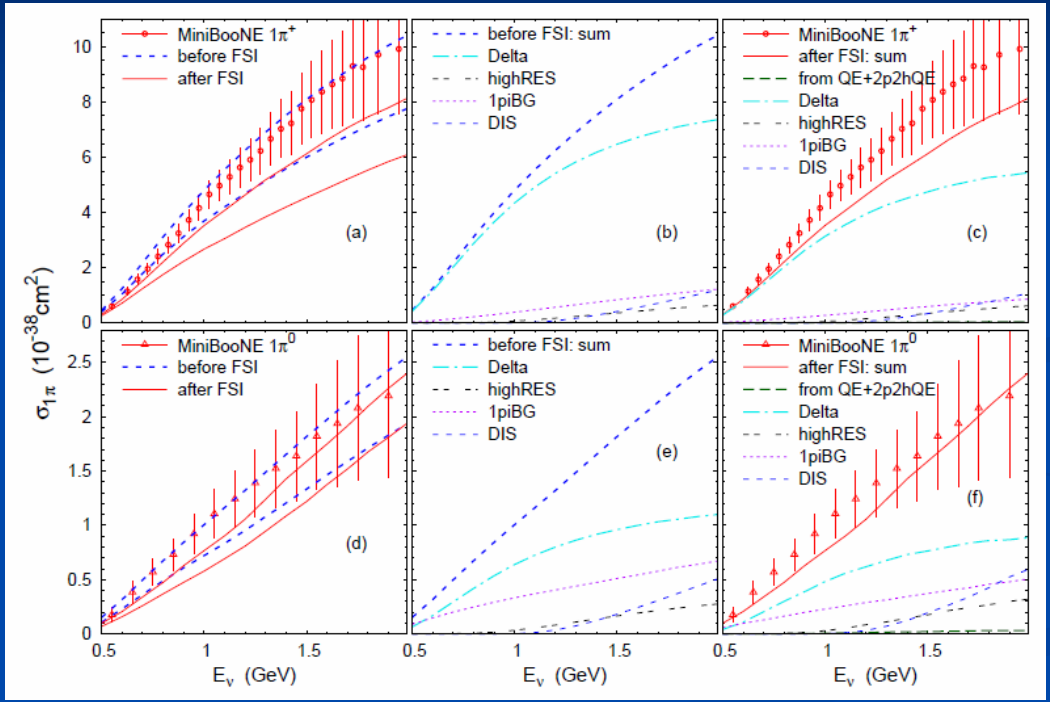
Pion Production

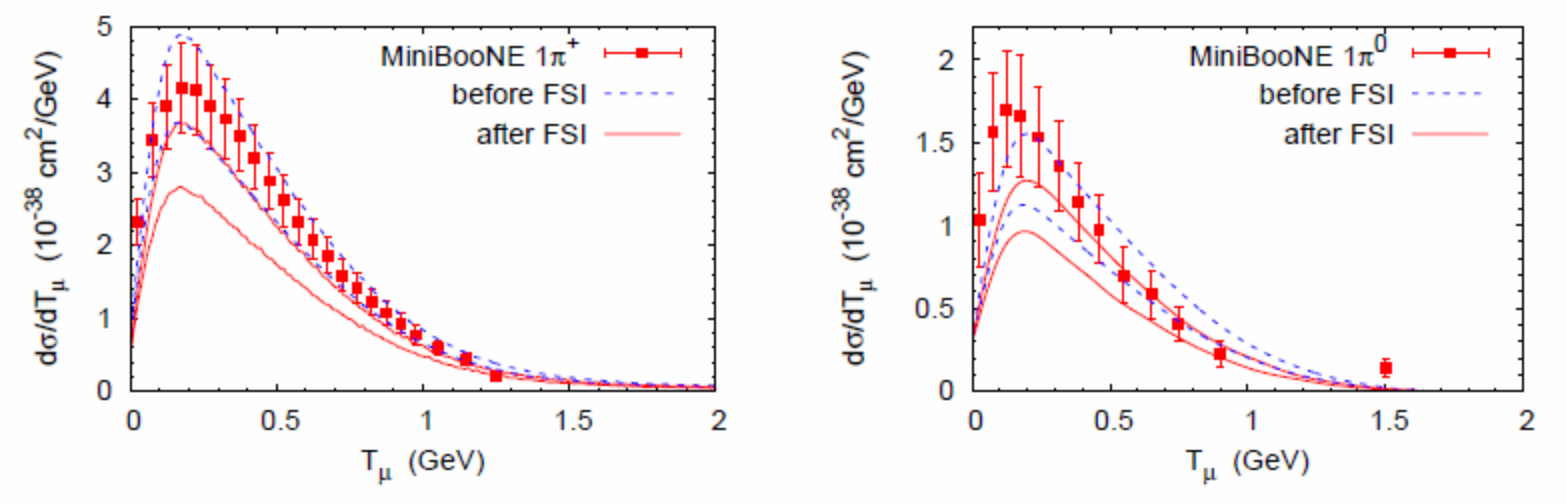


Upper line: BNL input
Lower line: ANL input

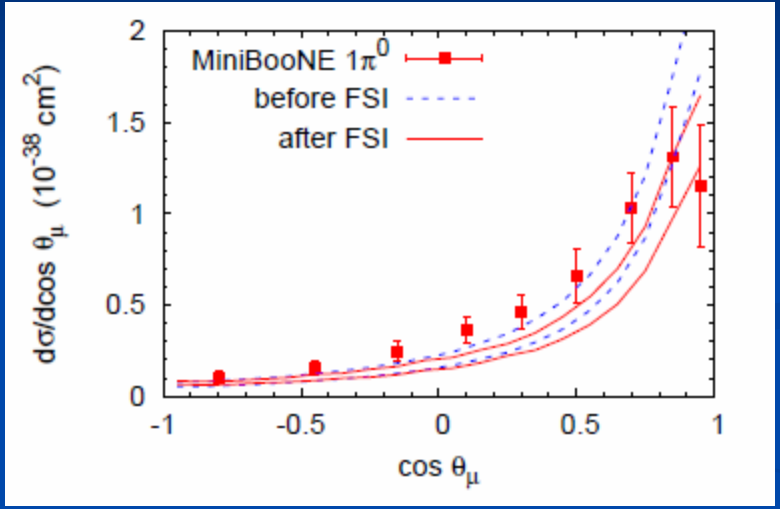
Tendency for theory too low, more so for π+

DIS and higher resonances contribute for E > 1 GeV

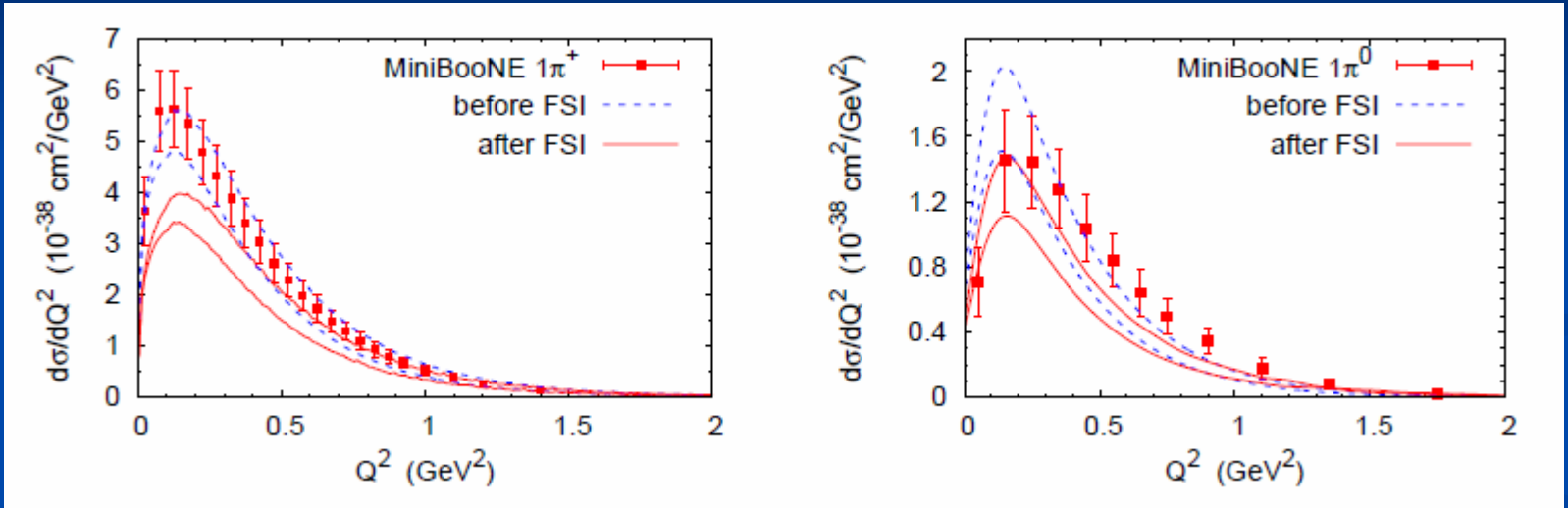
Pion Production



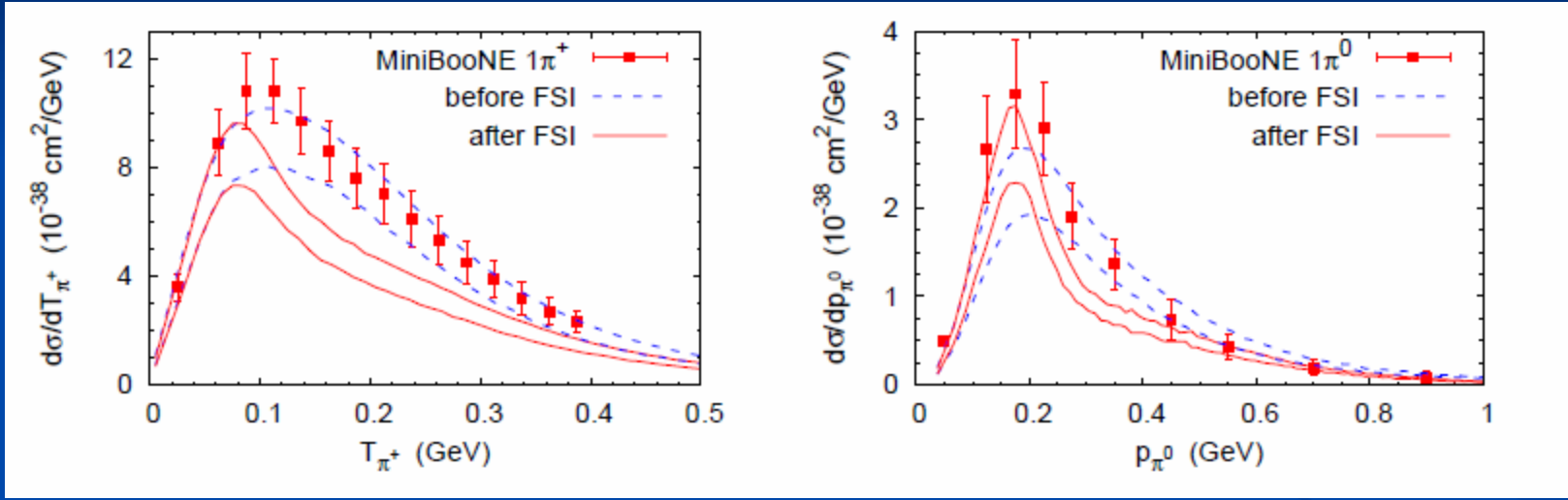
Pion Production



Pion Production

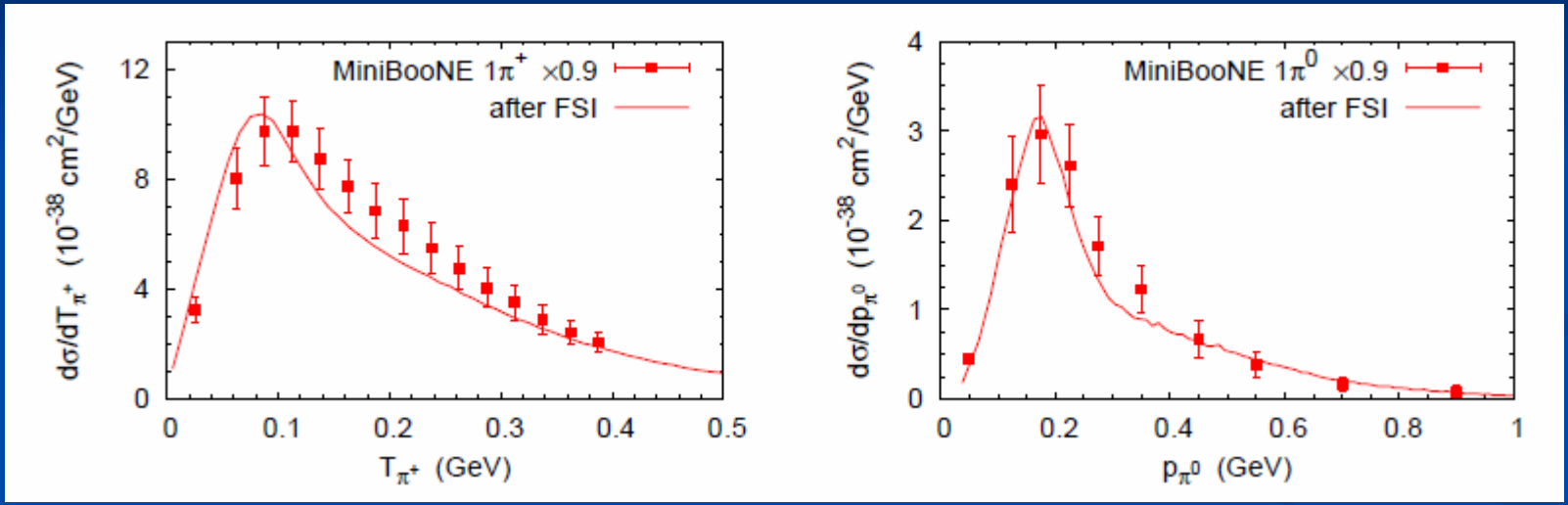


Pion Production



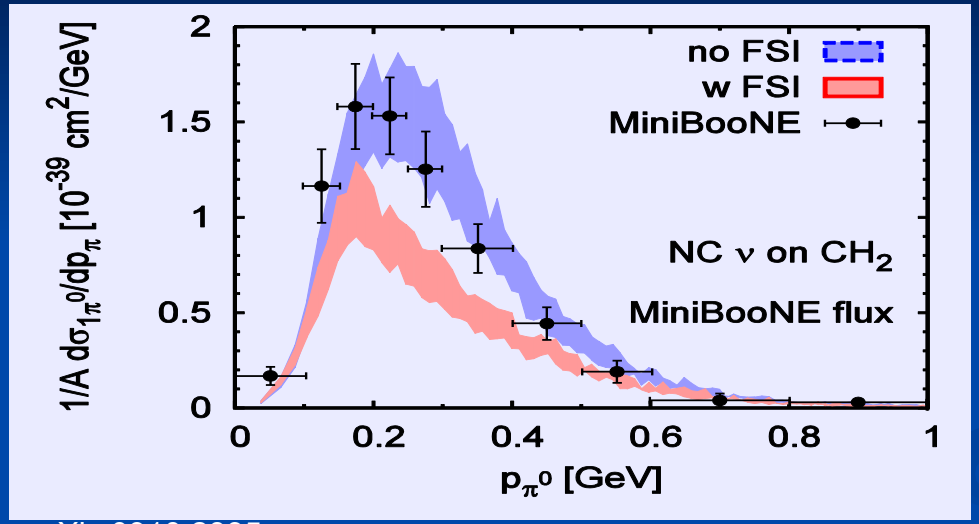
Spectral shape determined by pi-N-Delta dynamics in nuclei, spectral disagreement may account for discrepancy in totals

Pion Production



Flux renormalization (data x 0.9 (cf. Nieves QE analysis))

MiniBooNE NX $1\pi^0$



data: C. Anderson, NUINT09

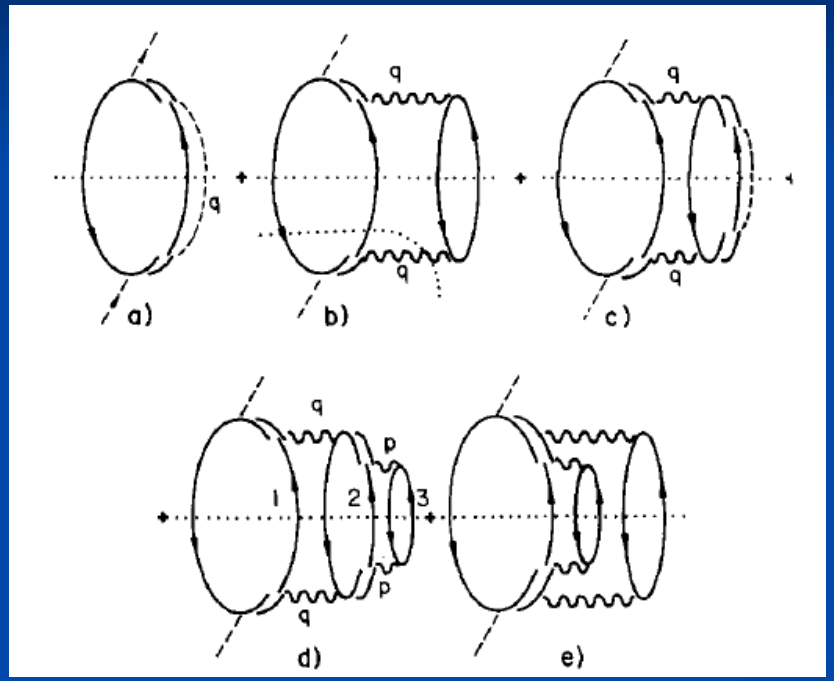
arXiv:0910.2835

Hard to understand: pion data agree with Fermi-motion folded free cross cection, but fsi must be there

bands: uncertainty of axial form factor

- **NC $1\pi^0$** data consistent with calculation without FSI!
- possible origins:
  - elementary cross section too small
  - neutrino-flux prediction (cf. discrepancy in QE channel)
  - "data" contains "MC": model dependence

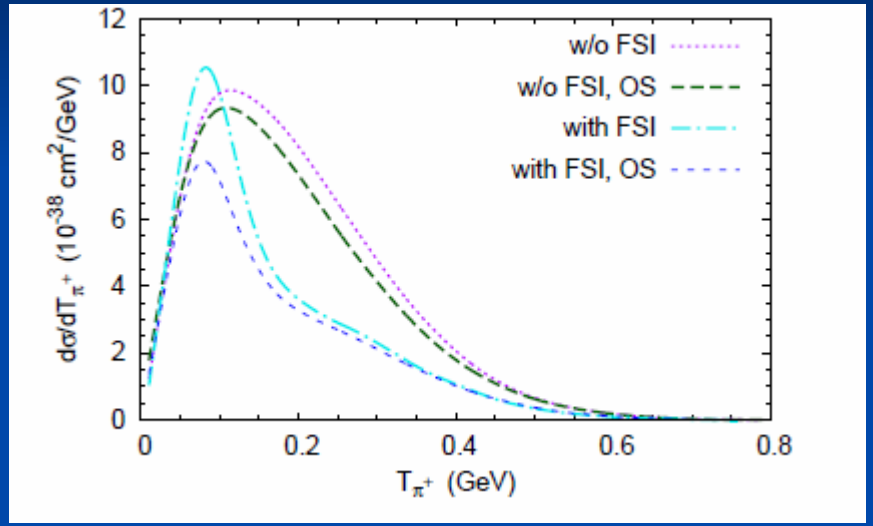
In-medium Pion Production



Oset et al

Difficult to separate
initial processes
from FSI
diagram c) contains 2p-2h-1π
also appears in fsi
1d and 1e contribute to Δ selfenergy

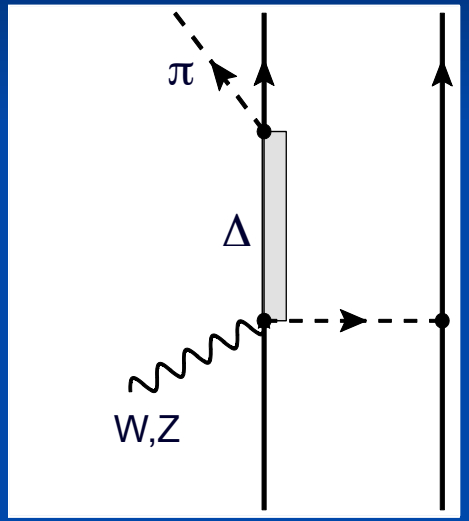
In-medium Pion Production



Based on Oset parametrization of Δ width:

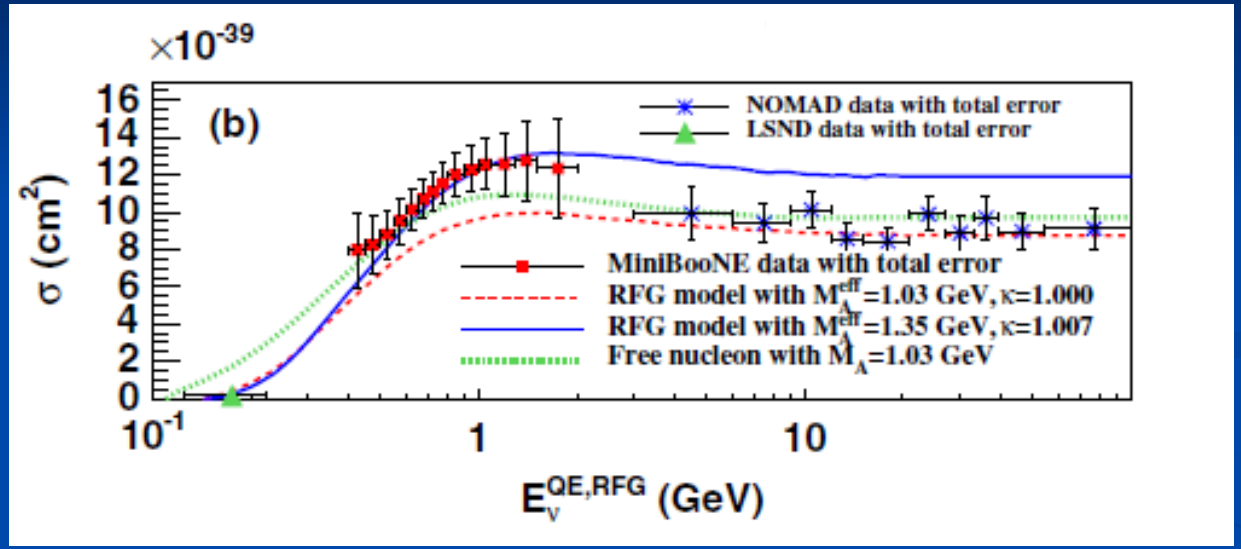
$$\Gamma_\Delta = \Gamma_\Delta(\rho, p_\Delta)$$

2p-2h-1π Contributions



Extra contribution in nuclei,
expected to contribute for energy transfers
beyond the Delta resonance

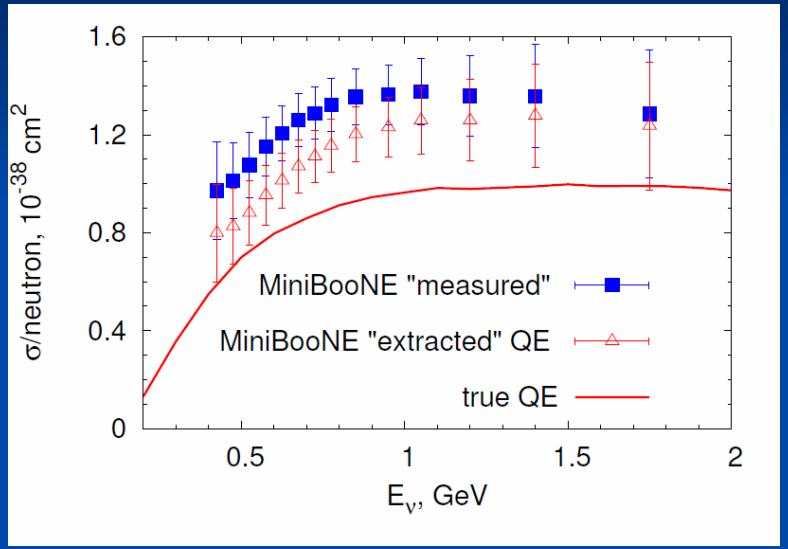
MiniBooNE QE puzzle



World average axial mass: M_A = 1.03 GeV

MB employs Cerenkov counter: identifies QE by muon and zero pion, corrects for ‚stuck pions'

MiniBooNE QE puzzle



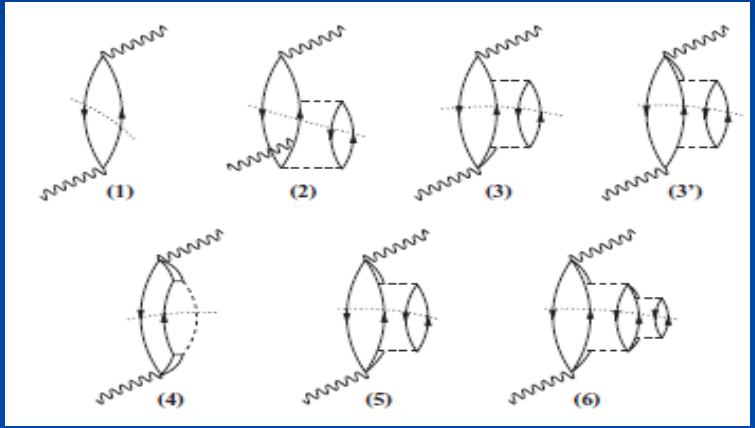
MB measured: 0 π events
MB extracted: 0 π events – stuck pions
(NUANCE generator dep.)

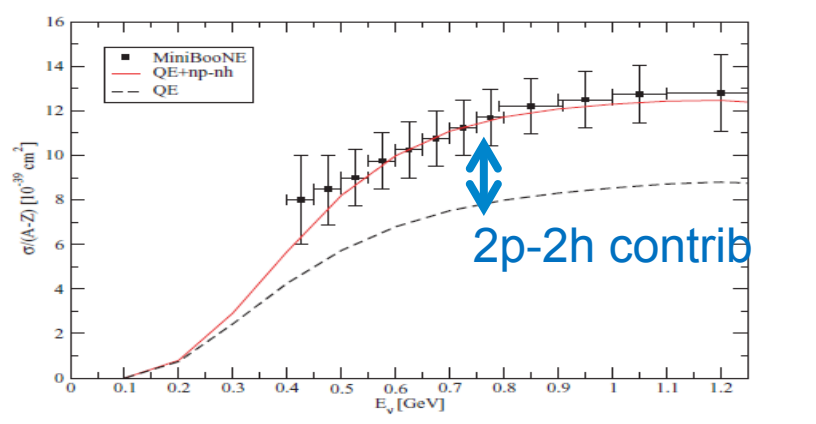
E_ν NUANCE generator dependence

Problem: Difference between data points decreases with E_ν !?

The MiniBooNE QE Puzzle
Explanations

Martini et al, PRC80, 2009

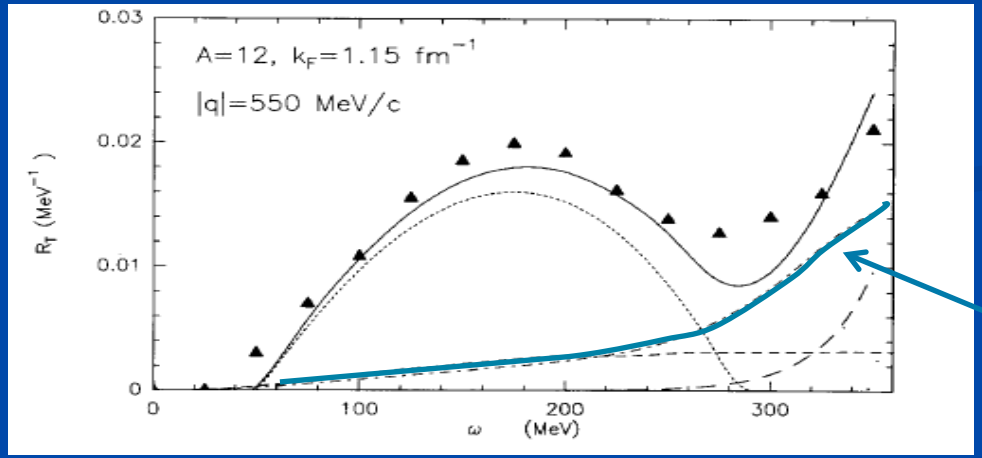




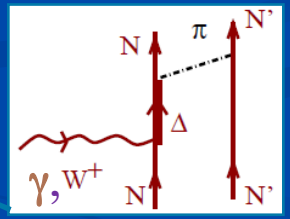
Exp: both σ and E_ν are reconstructed!

The MiniBooNE QE Puzzle
Hint from Electrons

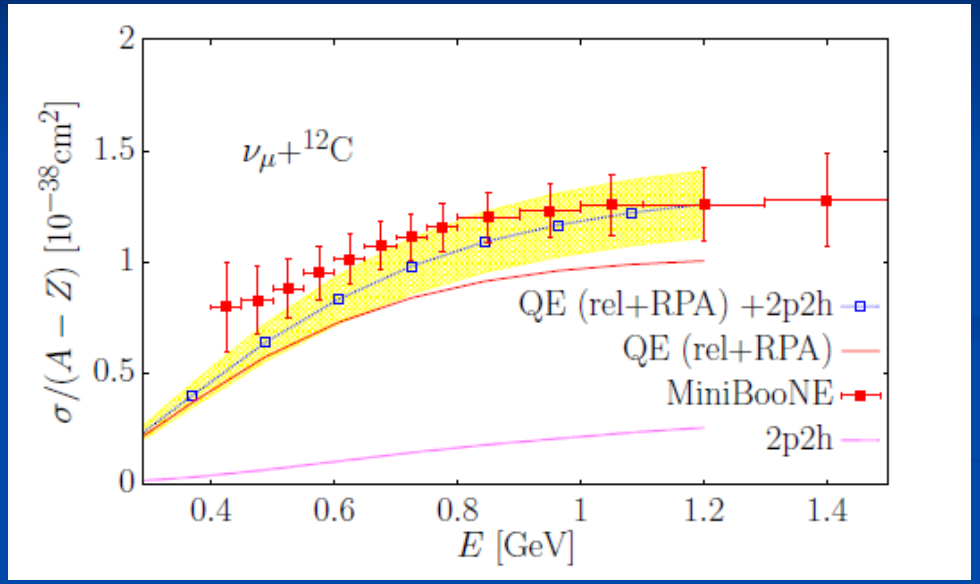
- Dekker, Brussaard, Tjon (1991):
  influence of two-body currents



2p-2h events:



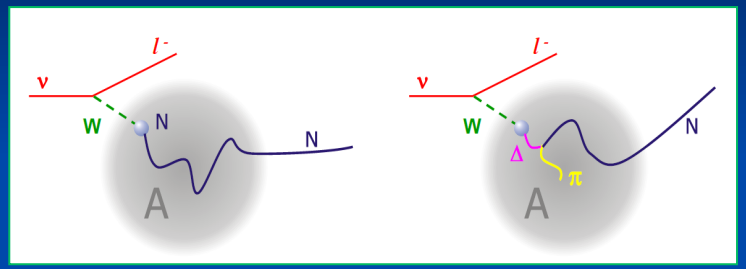
2p-2h contributions for neutrinos



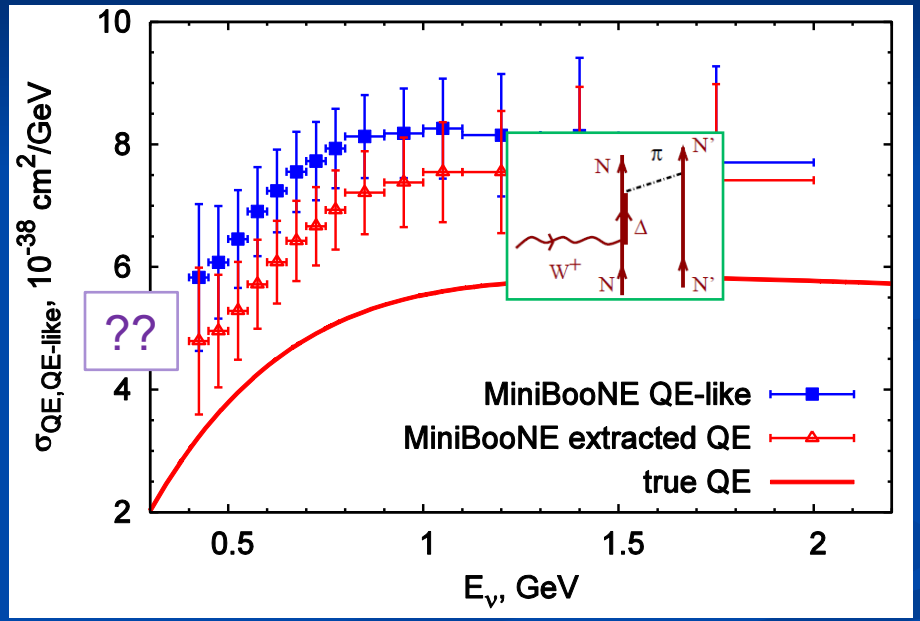
Nieves et al,
Phys.Rev. D85
(2012) 113008

model good
up to
about 1 GeV

MiniBooNE QE puzzle



QE with FSI QE-like bgr



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:
Extracted QE depends on pion production and absorption

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

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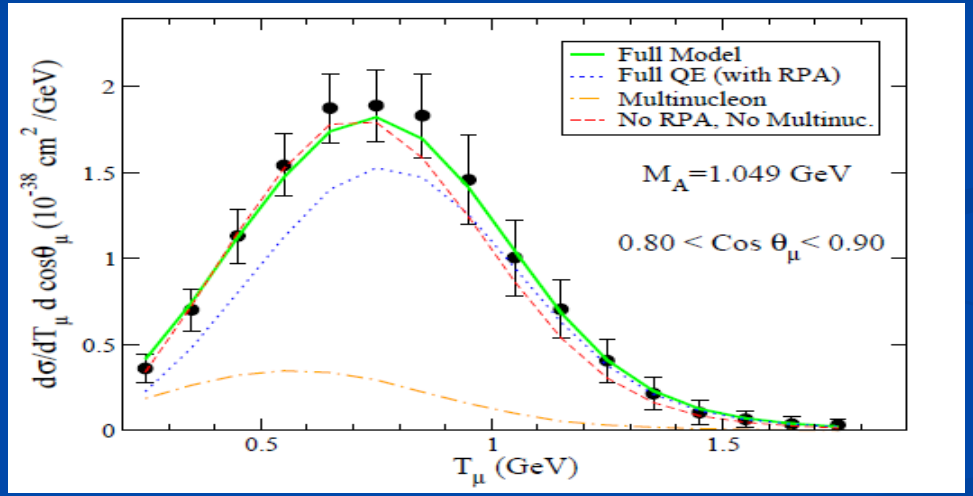
The MiniBooNE QE Puzzle
Explanations

- Directly measurable without energy reconstruction: double-diff X-section

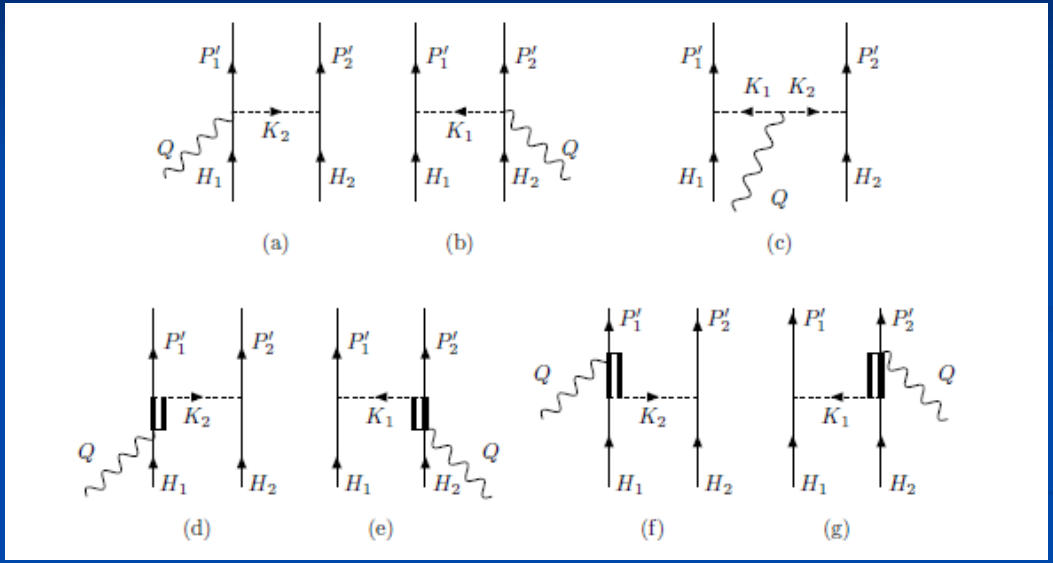


Nieves et al, 2011

RPA and 2p-2h compensate each other
Note: Data corrected for Absorbed pions!

No RPA, No Multinucl. Describes data reasonably well

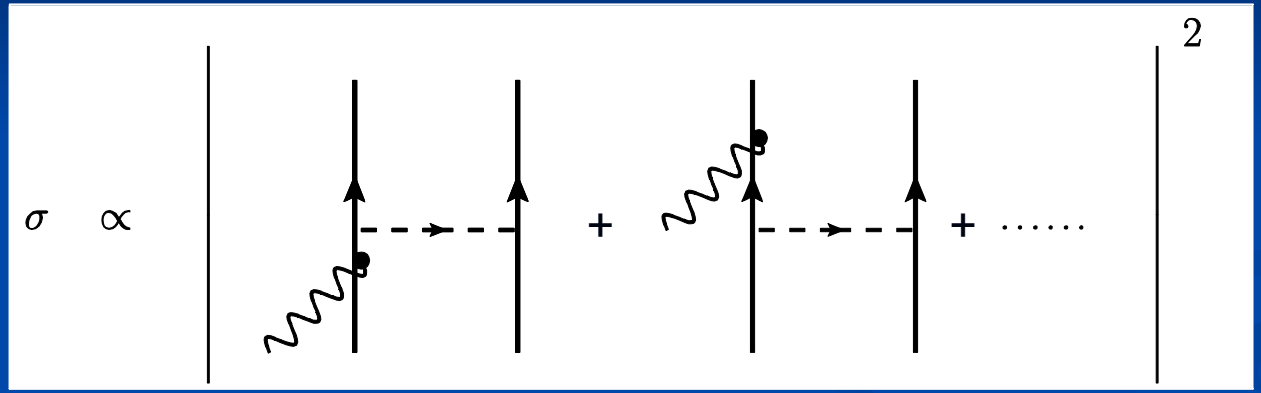
2p-2h and spectral functions



M.B. Barbaro et al, 2011

Cross section= sum over amplitudes squared

2p-2p excitations and spectral functions

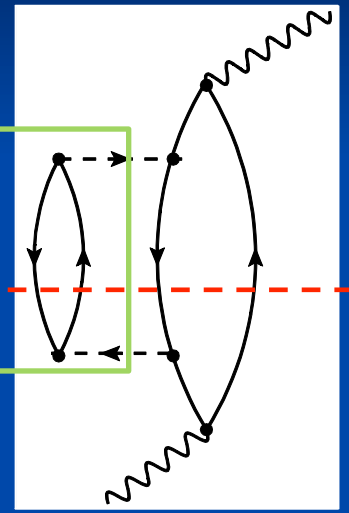


Can also be obtained by cutting selfenergy diagrams (Cutkosky rules)

2p-2p excitations and spectral functions

2nd ampl. squared

hole
selfenergy
Σ

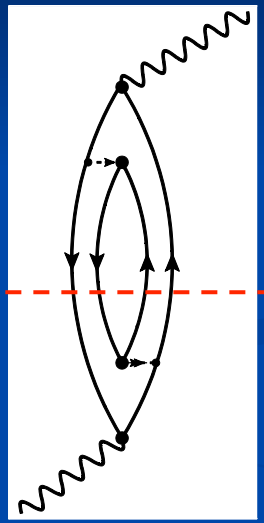


Cutkosky
cut

Hole Spectral Function

$$\mathcal{A}(x,p) = \frac{1}{\pi}\frac{\sqrt{p^{*2}}\Gamma_{\rm med}}{[p^{*2}-m^{*2}]^2 + p^{*2}\Gamma_{\rm med}^2}$$

Interference term squared



No selfenergy,
Vertex correction,
not included in spectral
function

Vertex correction
Not contained in spectral function

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2p-2h and spectral functions

- Double counting problem:
  How much of 2p-2h is contained in nucleon spectral functions ?????
- Many implementations of spectral functions contain them only in the very first step, not in FSI →off-shell propagation problem
- ‚Clean‘ calculations are demanding, must be realistic (i.e. describe electrons) and gauge-invariant

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2-body absorption

- Selfenergy in 2-body interaction

$$\Sigma(q) = \frac{1}{2q^0}\int \delta^4(q+p_1+p_2-p_1'-p_2')\frac{d^3p_1}{2p_1^0}\frac{d^3p_2}{2p_2^0}\frac{d^3p_1'}{2p_1'^0}\frac{d^3p_2'}{2p_2'^0} f_{N_1} f_{N_2} \; |\bar{M}|^2 \; (1-f_{N_1'})(1-f_{N_2'})$$

$$\frac{d^5\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_1 d\Omega_2 dT_{p_2}} = E_1 p_1 E_2 p_2 \sigma_{\mathrm{epp}}(k_+, k_-, q)\, F_{h_1,h_2}(P)$$

$$|\bar{M}|^2 \propto L_{\mu\nu} H^{\mu\nu}$$

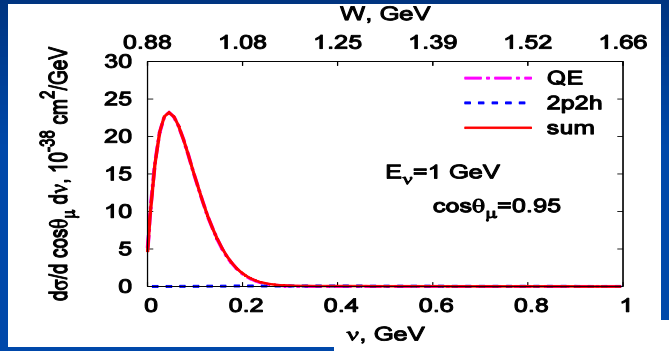
J. Ryckebusch, PLB 383 (1996)

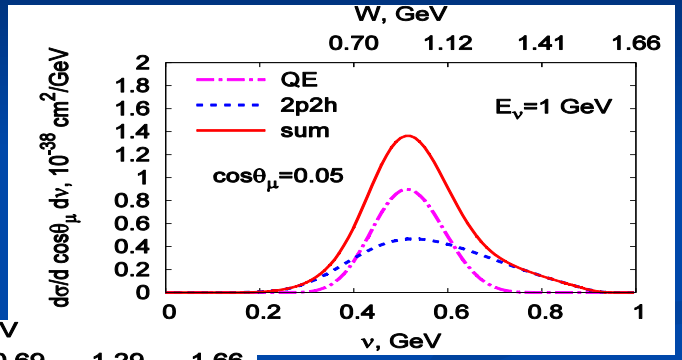
→

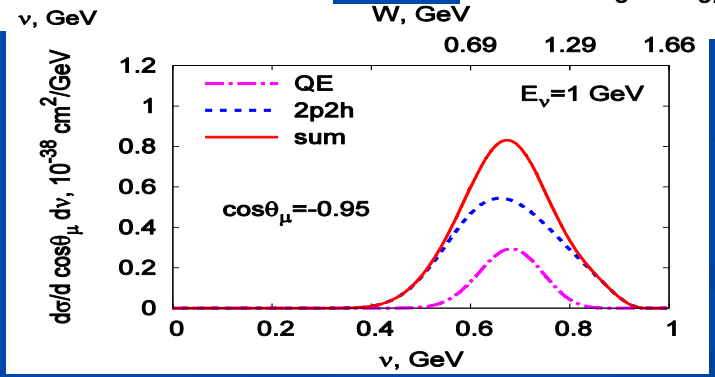
- TOY MODEL

with $H^{\mu\nu} \sim P_T^{\mu\nu}(q)$

The MiniBooNE QE Puzzle
Explanations







2p-2h wins at backwards muon angles, i.e. large momentum transfer

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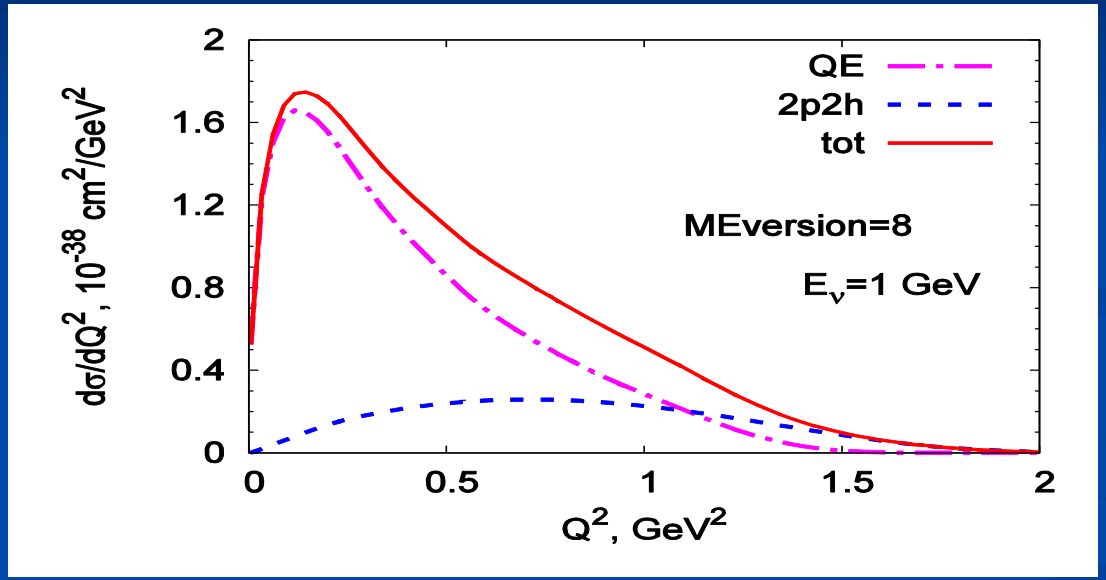
The MiniBooNE QE Puzzle
Explanations



2p-2h affect slope

2-body absorption

- Imaginary part of selfenergy in 2-body interaction

$$\Sigma(q) = \frac{1}{2q^0} \int \delta^4(q+p_1+p_2-p_1'-p_2') \frac{d^3p_1}{2p_1^0} \frac{d^3p_2}{2p_2^0} \frac{d^3p_1'}{2p_1'^0} \frac{d^3p_2'}{2p_2'^0} f_{N_1} f_{N_2} \left|\bar{M}\right|^2 (1-f_{N_1'})(1-f_{N_2'})$$

with

$$\left|\bar{M}\right|^2 \propto L_{\mu\nu} H^{\mu\nu}$$

- TOY MODEL

$$H^{\mu\nu} \sim P_T^{\mu\nu}(q)$$

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The MiniBooNE QE Puzzle
Explanations

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

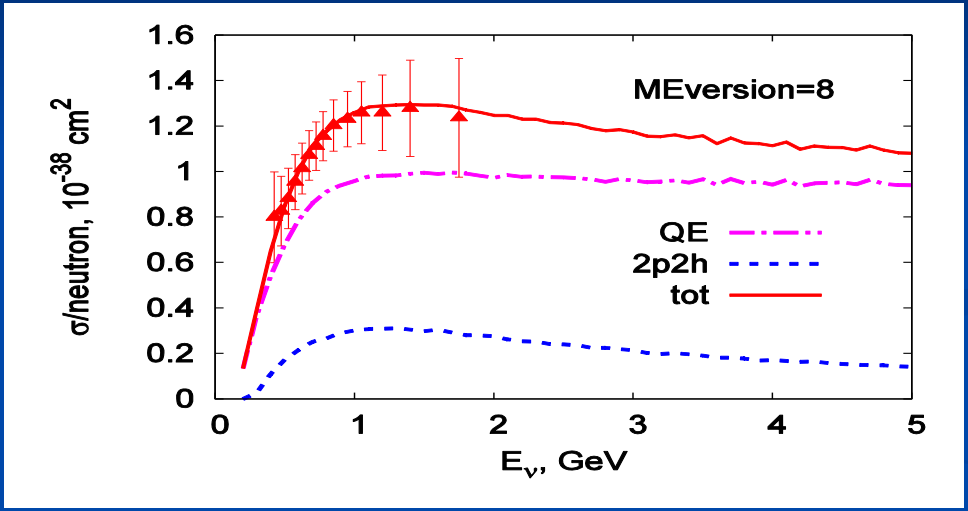
$$\frac{d^2\sigma}{dE_l' d(\cos\theta')} \propto \frac{k'}{k} \int_{NV} d^3r \int \prod_{j=1}^{4} \frac{d^3p_j}{(2\pi)^3 2E_j} f_1 f_2 \overline{|M|^2} (1-f_3)(1-f_4)\delta^4(p)$$

with flux averaged matrixelement

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

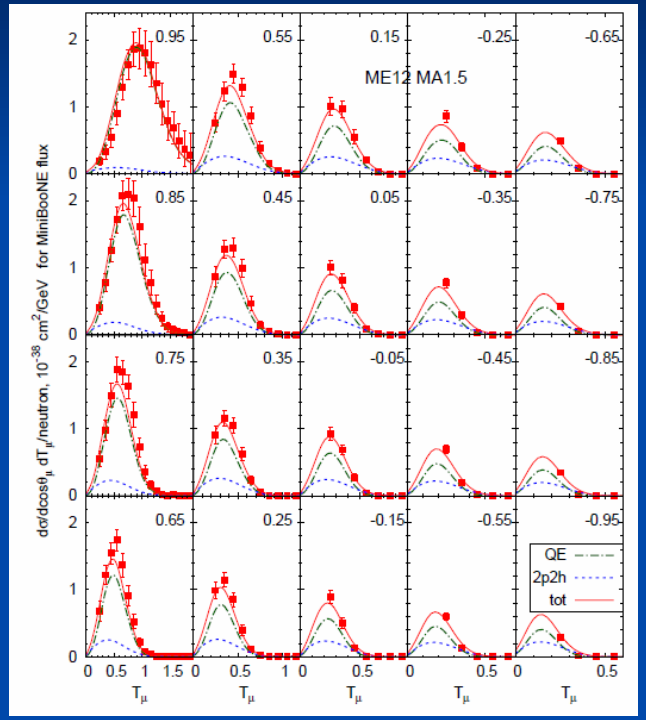
Flux smears out details in *W*

The MiniBooNE QE Puzzle
Explanations



Phase-space model for 2p-2h: Hadronic current modelled ~ P_T
Absolute value fitted to data, no predictive power

The MiniBooNE QE Puzzle
Explanations



MB flux averaged

Data corrected
for stuck-pion events!

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

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The MiniBooNE QE Puzzle
Explanations

- Various expanations for MB puzzle:
  - Larger axial mass $M_A \approx 1.3$ GeV (exp)
  - Change of axial FF (Hill), $M_A \approx 1.0$ GeV
  - Change of vector FF (Bodek), $M_A \approx 1.0$ GeV
  - 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

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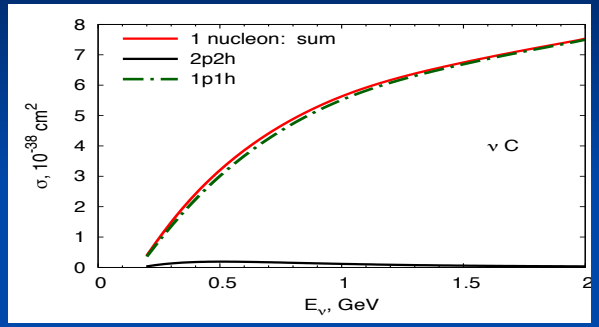
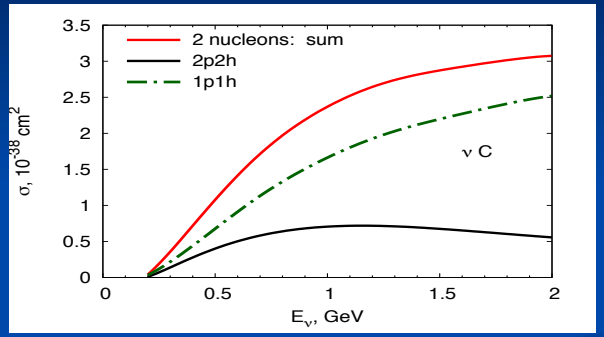
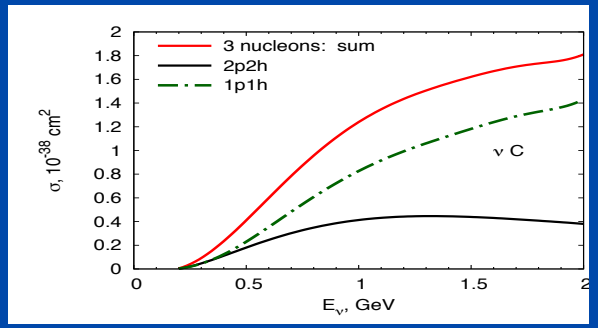
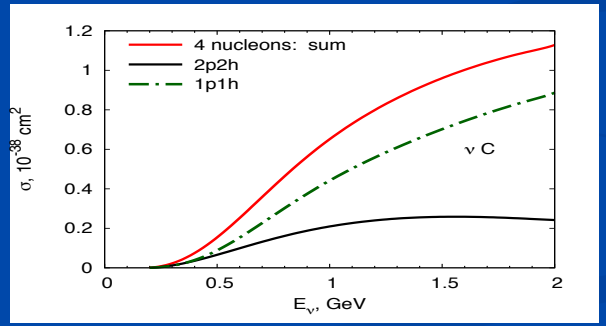
The MiniBooNE QE Puzzle

Nucleon Knock-Out









Only true QE
can be identified
in 1 N channel only

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Energy reconstruction

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Energy Reconstruction by QE

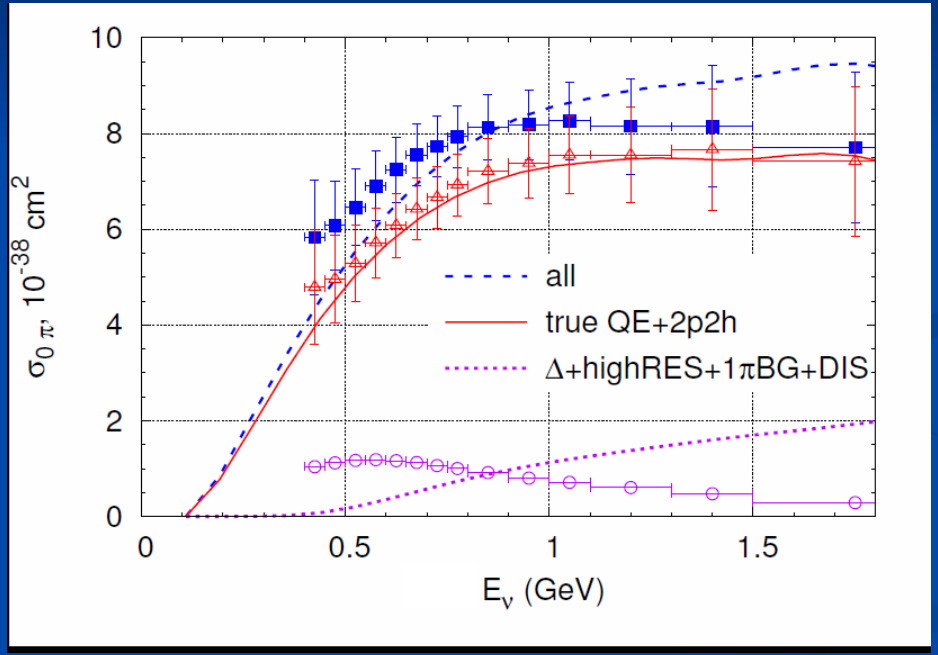
- All modern experiments use heavy nuclei as target material: C, O, Fe → nuclear complications
- Quasifree kinematics used for QE on bound nucleons: Fermi-smearing of reconstructed energy expected
- For nuclear targets QE reaction must be identified to use the reconstruction formula for E_ν
- *But:* 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 nucleons: slower nucleons are interpreted as lower neutrino energy!
  -> more bias to lower energies

Energy reconstruction in MB

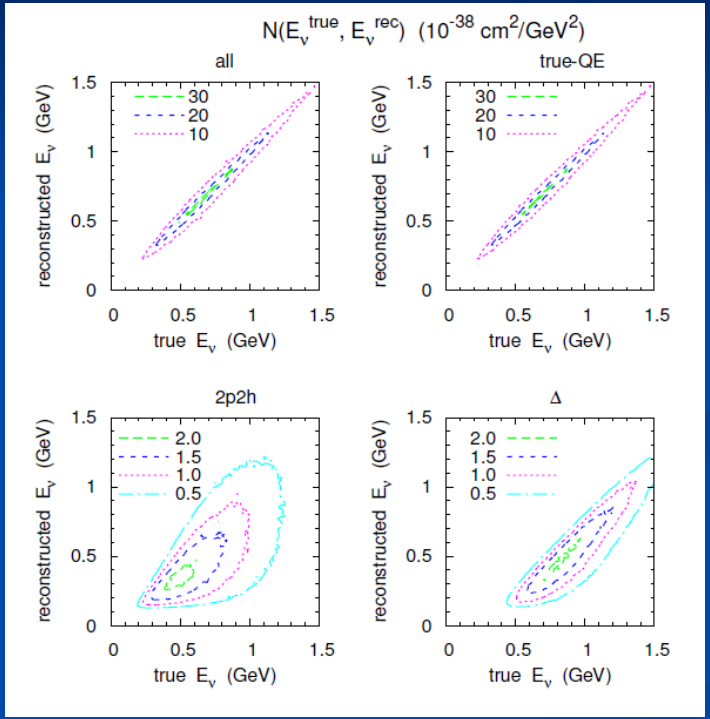


Data: plotted vs *reconstructed* energy

Curves: plotted vs. *true* energy

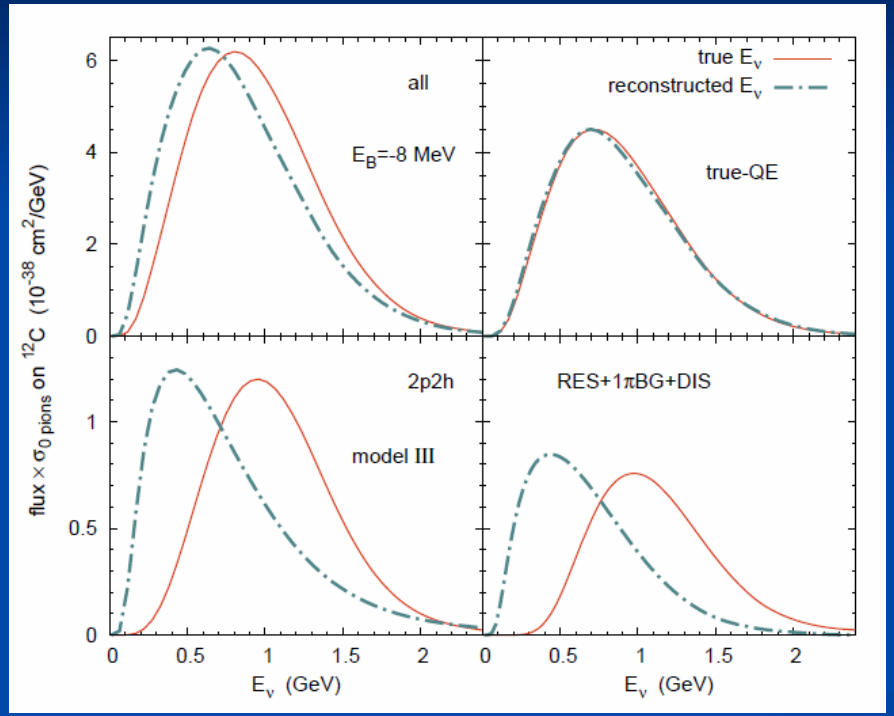
Explains strange energy-dependence of stuck pion events

Energy-matrix for various processes



All processes other than true QE lead to too low reconstructed energy

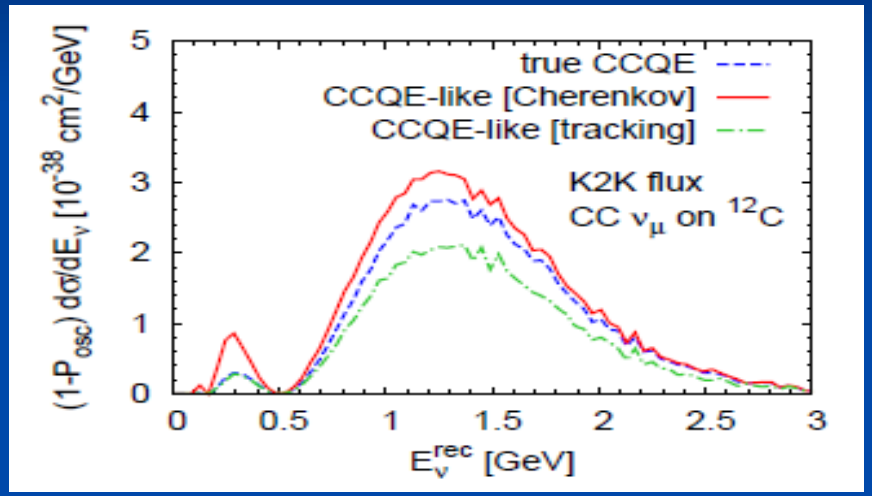
Energy reconstruction in MB

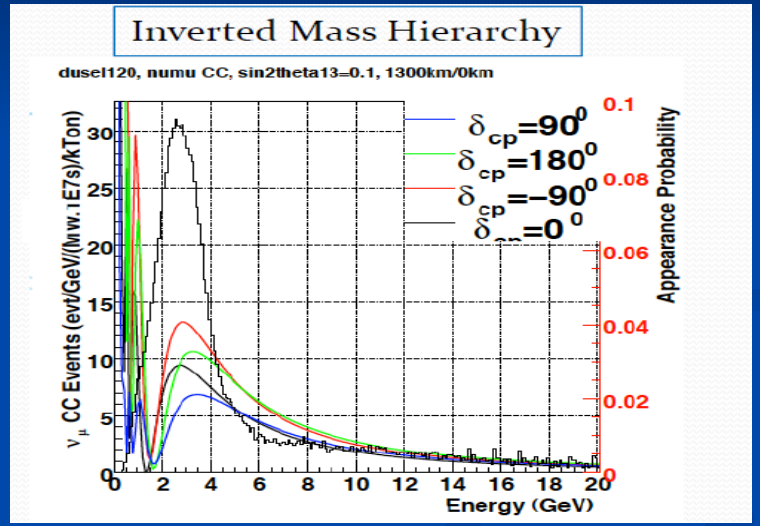


Reconstructed energy shifted to lower energies for all processes beyond QE

δ_{CP} with LBNE

Uncertainties at the oscillation maximum due to detector as large as dependence on CP violating phase



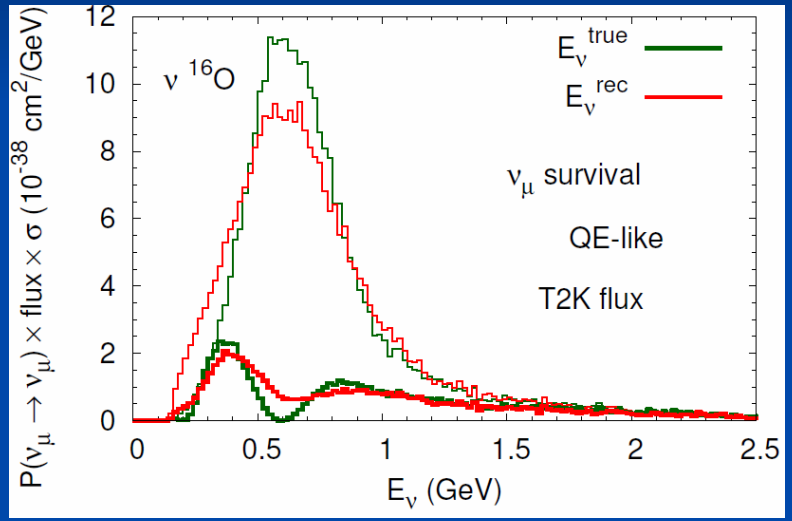


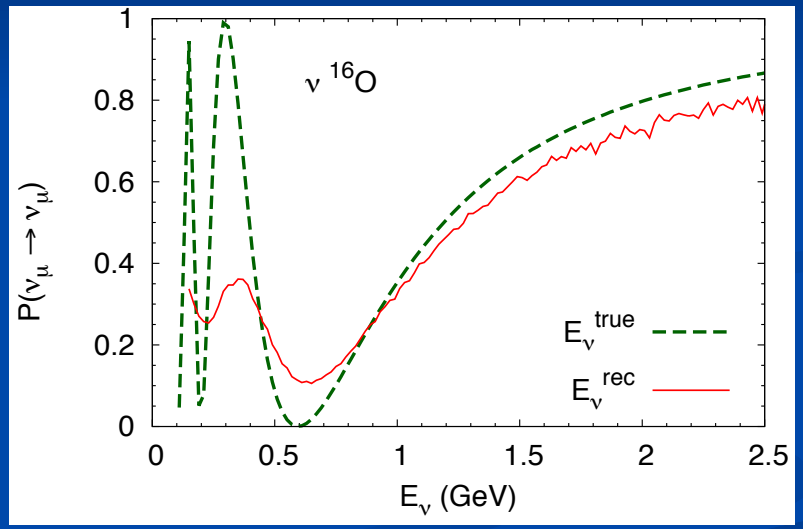
Wilson, LBNE workshop

Event reconstruction hampers determination of CP violating phase

Oscillation signal in T2K

ν_μ disappearance

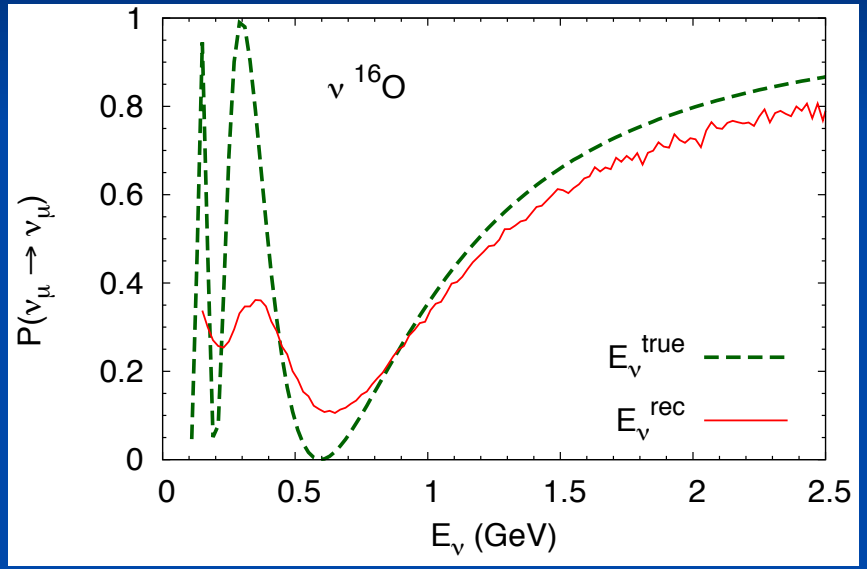


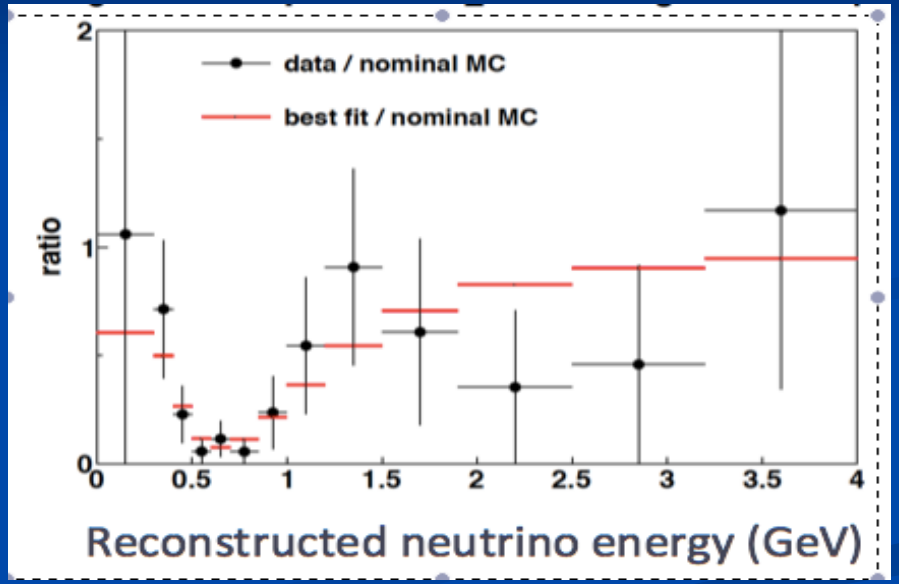


Ratio = oscillation probability

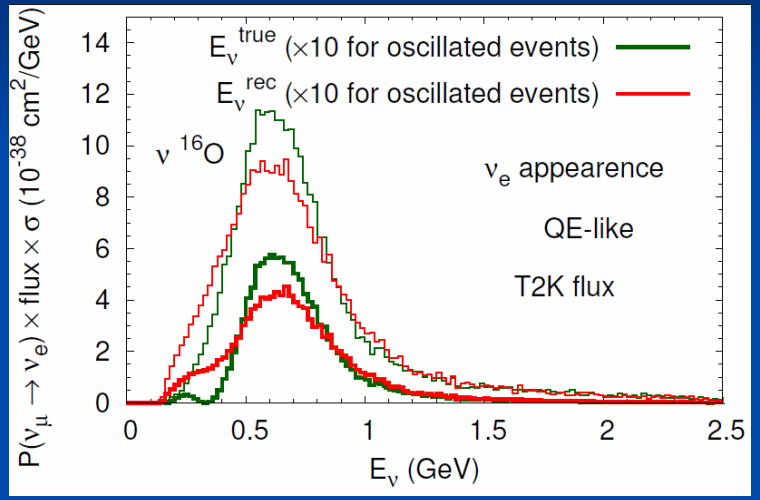
Oscillation signal in T2K

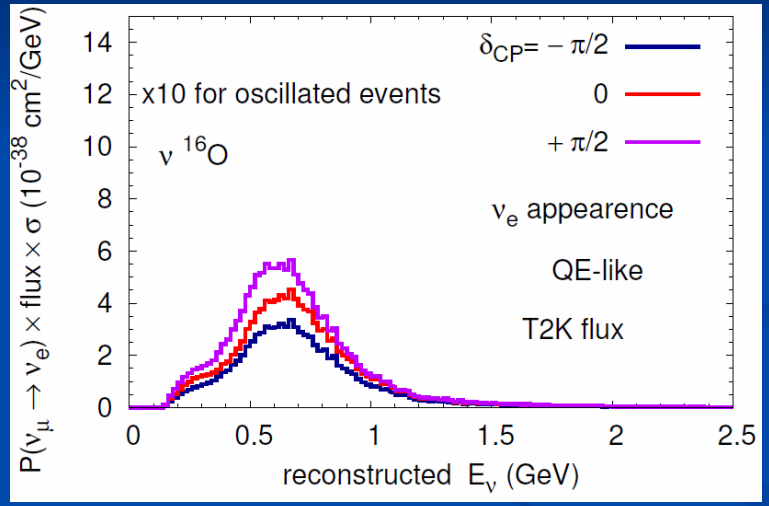
ν_μ disappearance





Oscillation signal in T2K
δ_{CP} sensitivity





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

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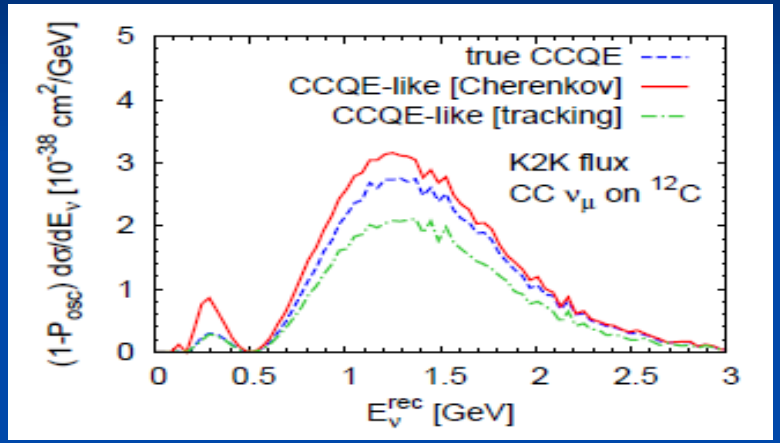
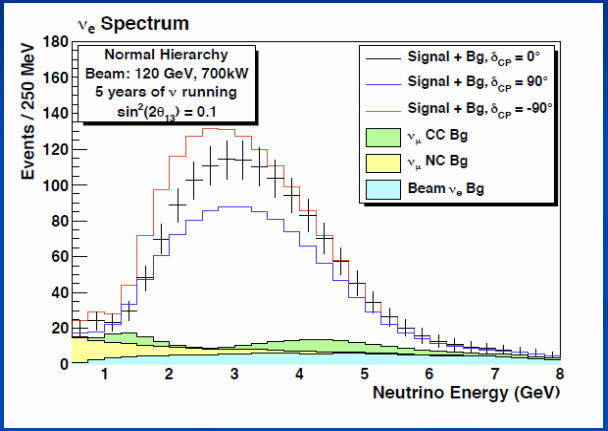
δ_{CP} with LBNE

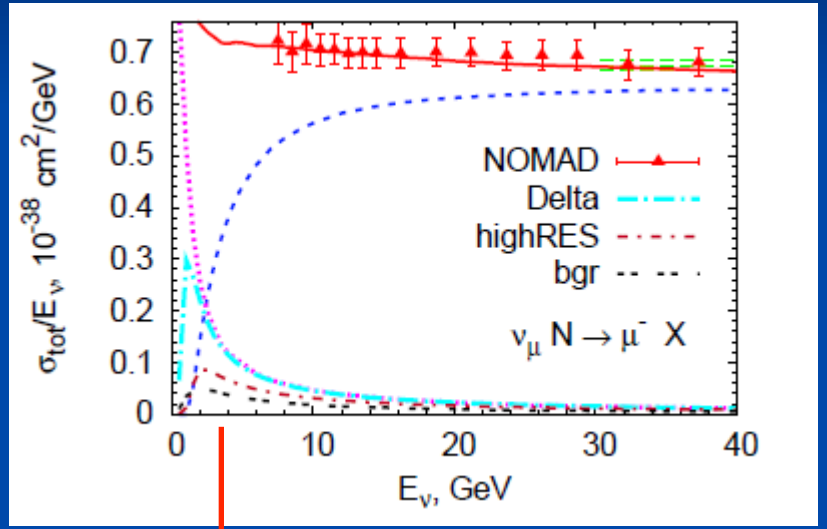


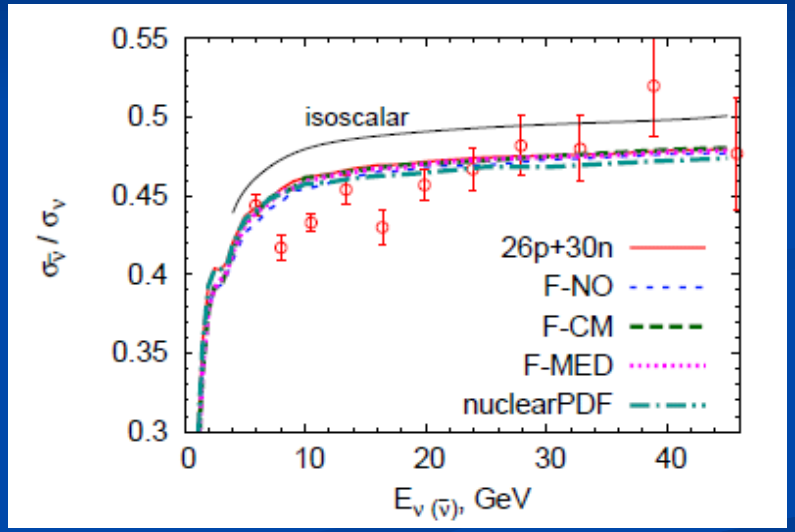


Uncertainties at the oscillation maximum due to detector as large as dependence on CP violating phase

Experiments at higher energies

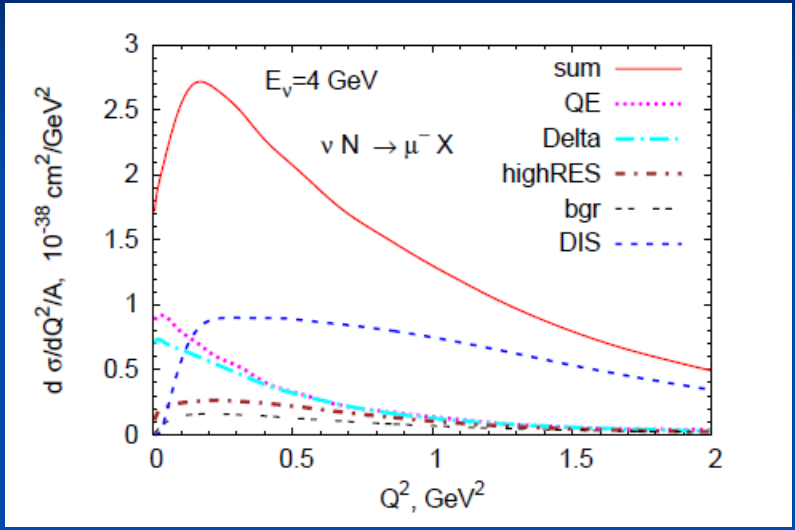
Phys. Rev. C86 (2012) 014607

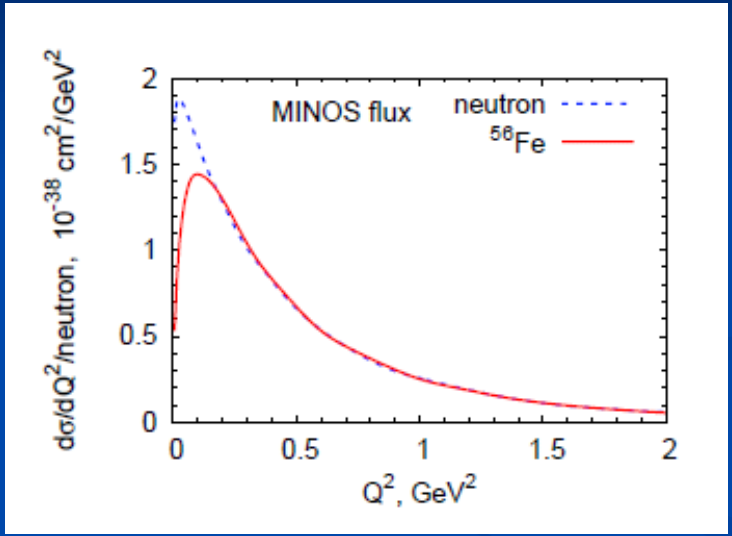




Shallow Inelastic Region, very sensitive to interplay of different reaction mechanisms

Experiments at higher energies

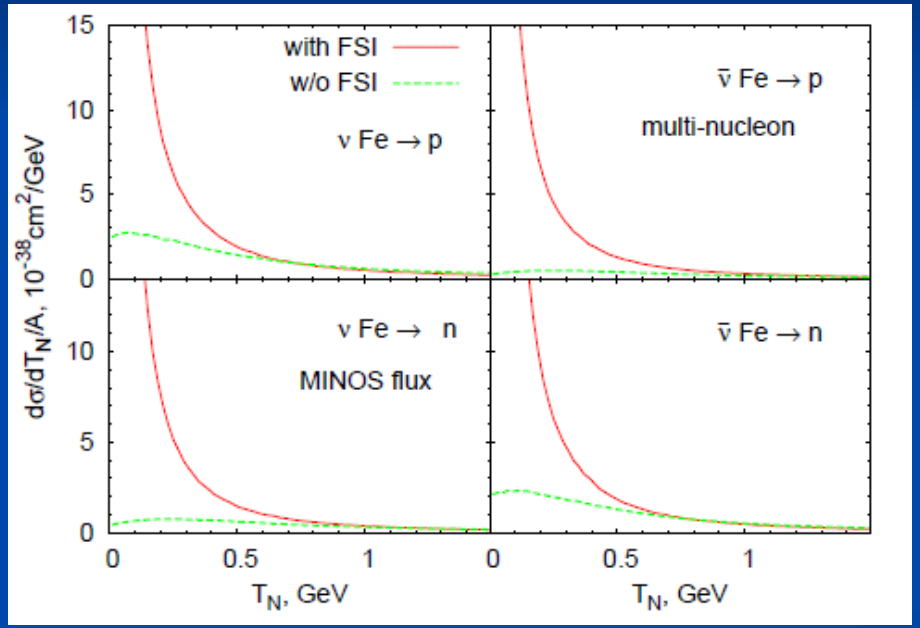




Q^2 dependence reaches out farther than at lower-energy MB experiment: DIS effect

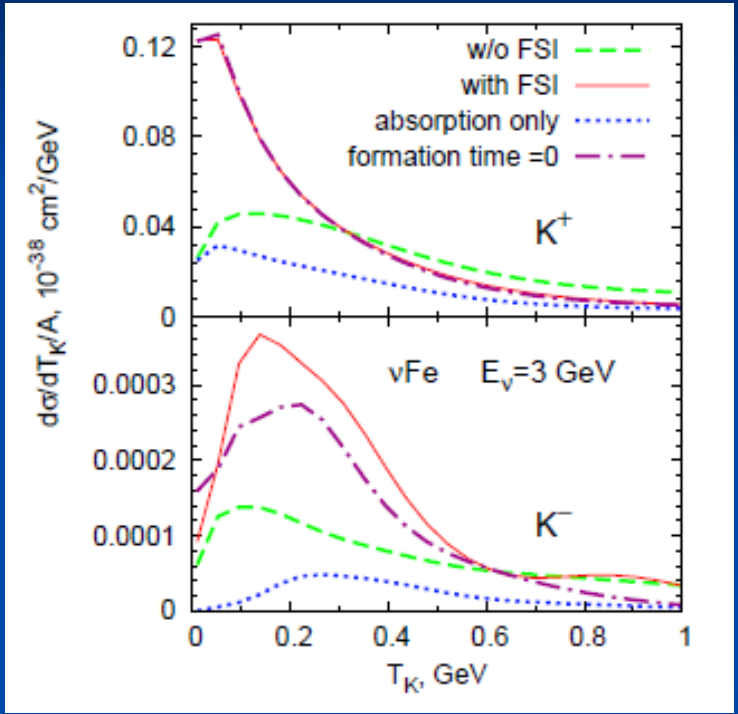
Experiments at higher energies

Knock-out Nucleons



Strong rise below 300 MeV, dominated by FSI

Experiments at higher energies

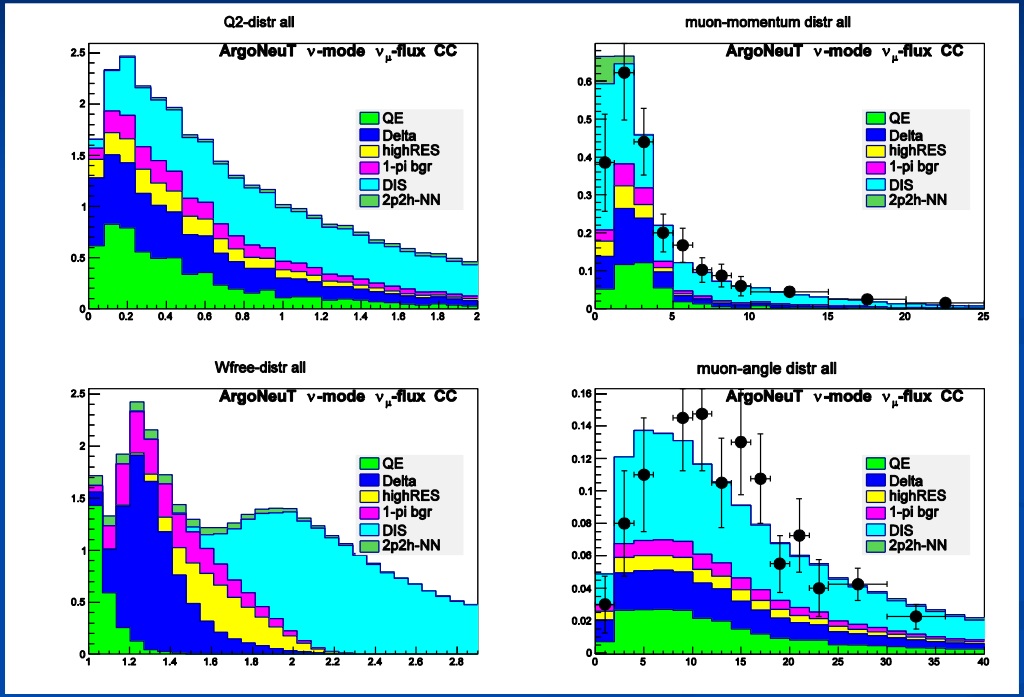


Lesson for Minerva:

The particles you measure are not those that the neutrino produced!

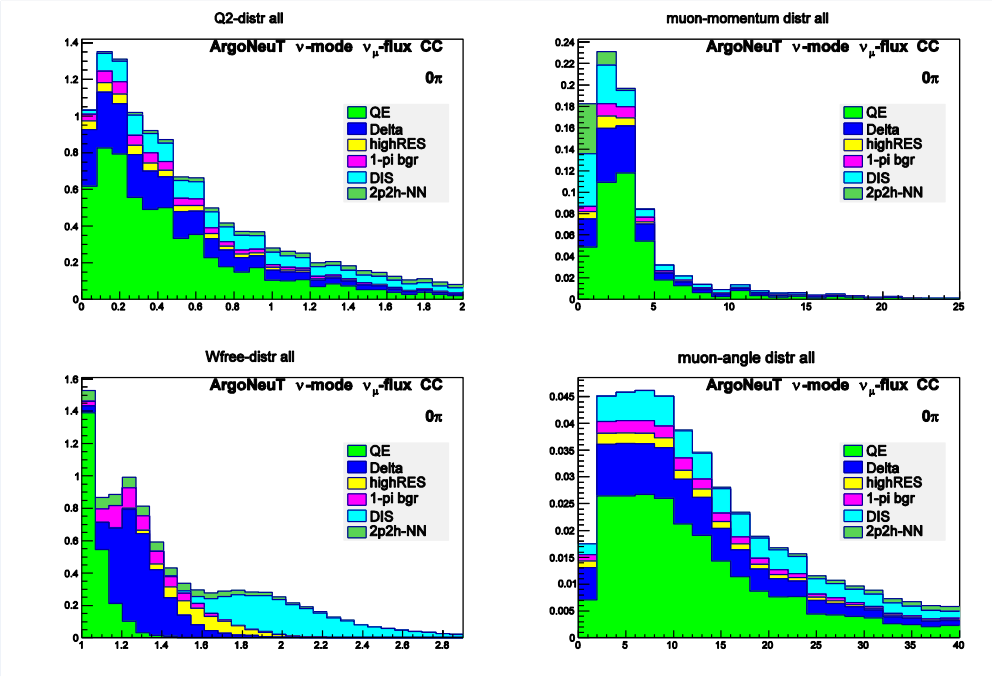
Secondary production is important

ArgoNeuT



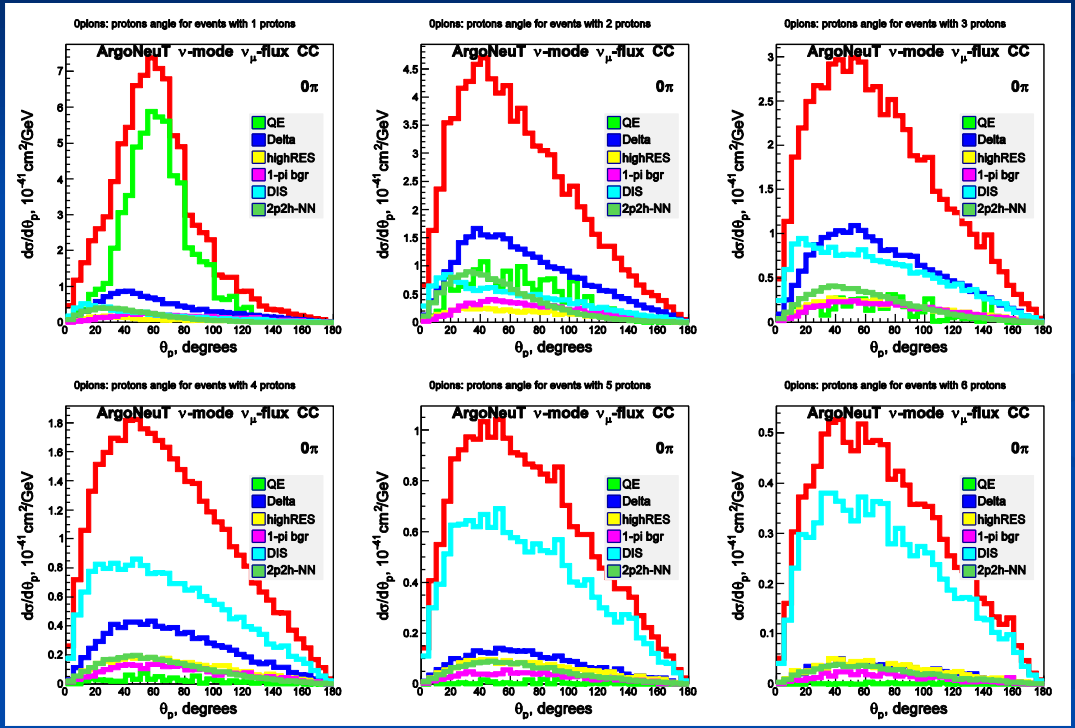
All events, large DIS contribution

ArgoNeuT



0 pion events suppresses DIS

ArgoNeuT



Reaction mechanism can be distinguished by proton number, for QE and DIS

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, make the extraction of elementary neutrino-particle production rates impossible

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Importance of Generators

- 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!

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Need for solid nuclear physics theory suport in Neutrino Physics

"What we especially like about these theoretical types is that they don't tie up thousands of dollars worth of equipment."

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