Neutrino Interactions with Nucleons and Nuclei

Olga Lalakulich, Tina Leitner and Ulrich Mosel

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

The Impossible Experiment

- Beam composition not fully known
- Beam energy badly known
- Beam diameter ~ 0.5 m at its source
- Beamline ~ 300 – 1000 km
- Beam diameter ~ 600 m at the detector
- Cross sections ~ 10^{-11} mb
- Only a small part of the final state known
- From all of this:

  extract physics beyond the standard model!

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Motivation

- 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

Neutrino Oscillations

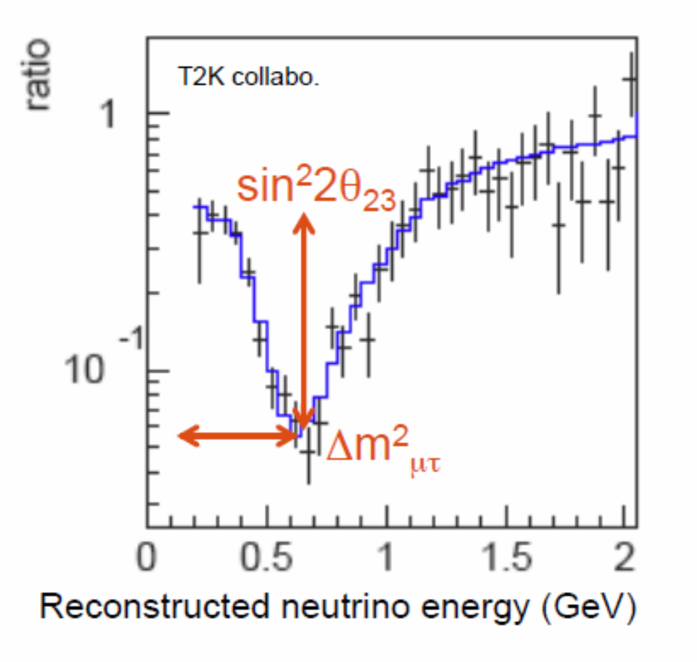
- 2-Flavor Oscillation:

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

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

Observable Oscillation Parameters

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



Neutrino Oscillations

Even more interesting:
3-Flavor Oscillation allows for CP violating phase δ_{CP} → matter/antimatter puzzle

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &\simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&- \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
&\equiv O_1 + O_2(\delta) + O_3(\delta) + O_4 .
\end{aligned}
$$

appearance probability

$$\Delta = \frac{\Delta m^2_{21} L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \xi = \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23})$$

$$\hat{A} = \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}} \qquad \delta = \text{CP violating phase}$$

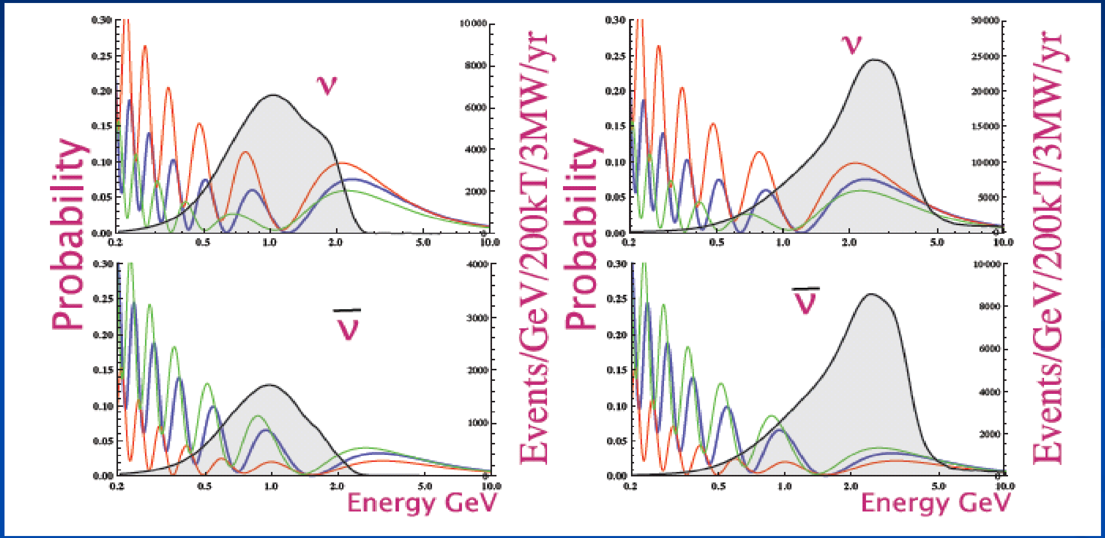
Vacuum oscillation

Matter effects,
n_e = electron density
Depends on sign of Δ_{31}

Oscillation depends on difference of (squared) masses only

LBNE, δ_{CP} Sensitivity

From: Bishai et al., hep-ex 12034090



8 GeV

60 GeV

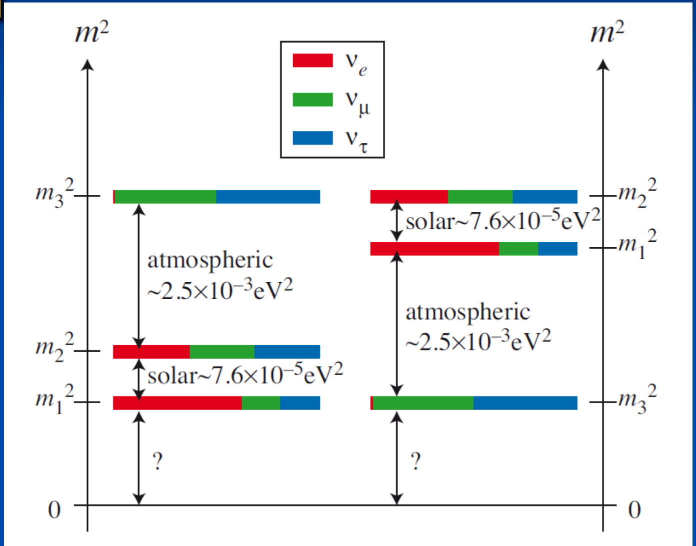
proton energy

From:
Bishai et al
arXiv:1203.409

δ_{CP} = 0
δ_{CP} = π/2
δ_{CP} = - π/2

Need energy to distinguish between different δ_{CP}

Oscillation Signal
Dependence on Hierarchy and Mixing Angle



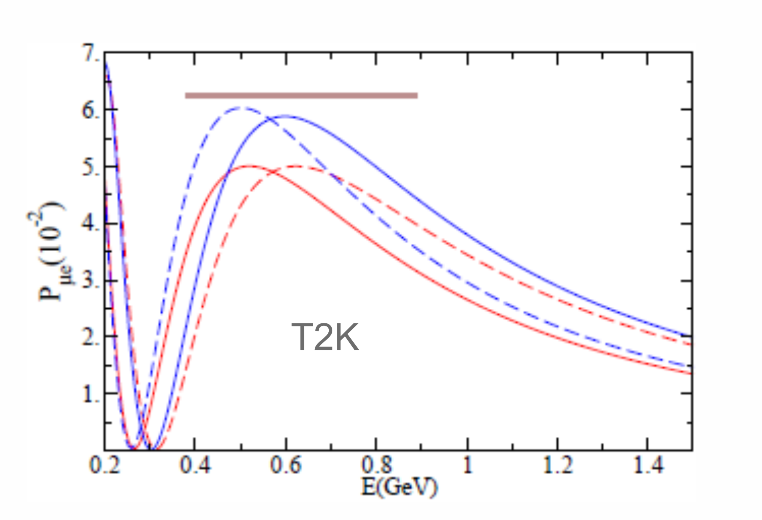


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

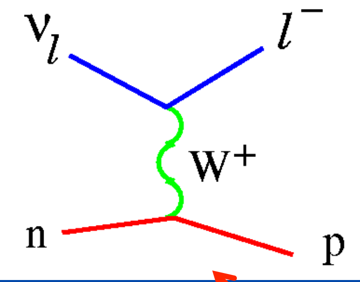
D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

Energy has to be known better than 50 MeV
Shape sensitive to hierarchy and sign of mixing angle

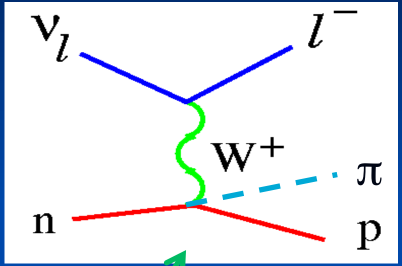
Neutrino-Nucleon Interactions

Neutrino-nucleon cross section

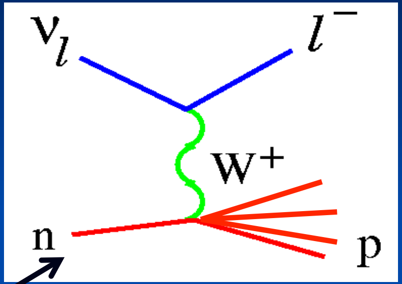
CCQE

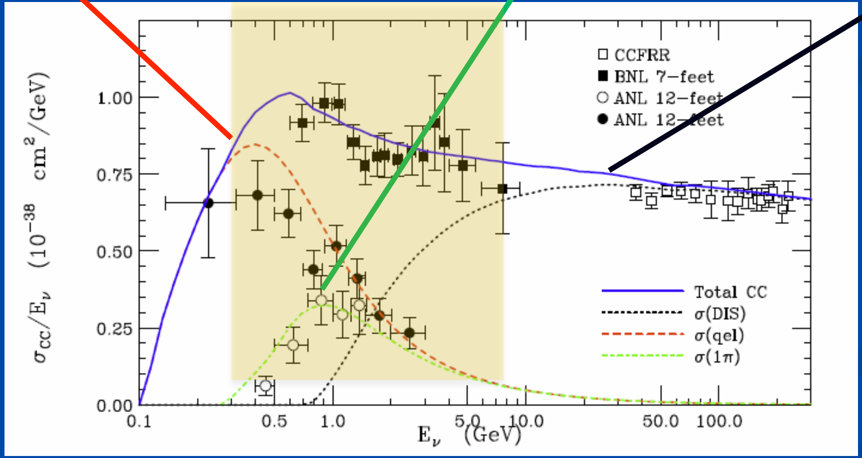


1π



DIS

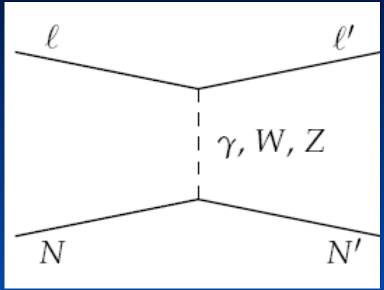




note:
10^{-38} cm² = 10^{-11} mb

In the region of modern experiments (0.5 – 10 GeV) all 3 mechanisms overlap

Quasielastic scattering



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

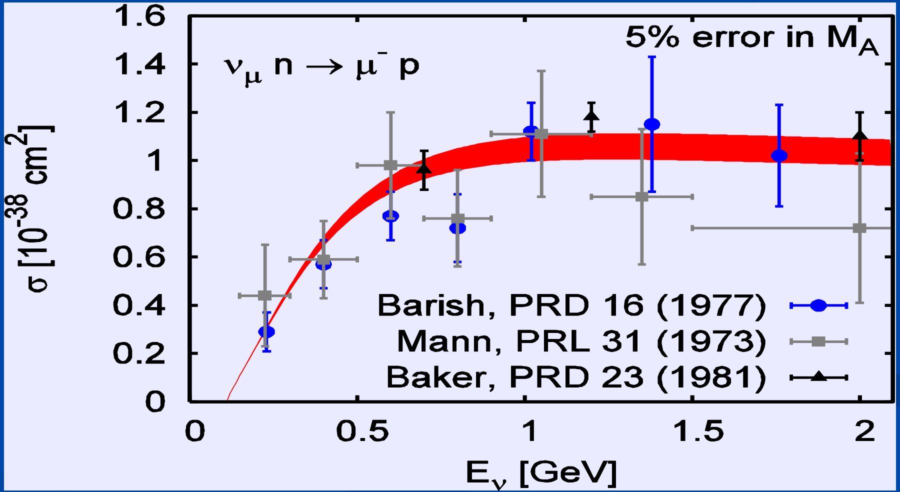
- Vector form factors from *e* –scattering
- axial form factors

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

dipole ansatz for F_A with

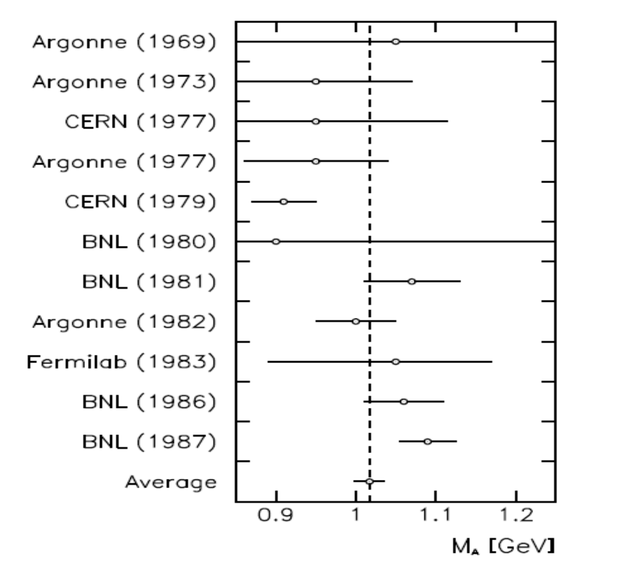
M_A= 1 GeV:

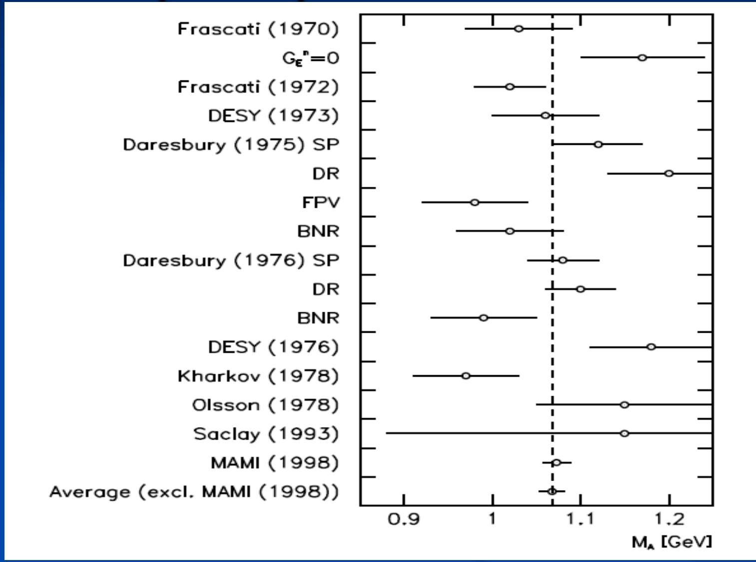
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data





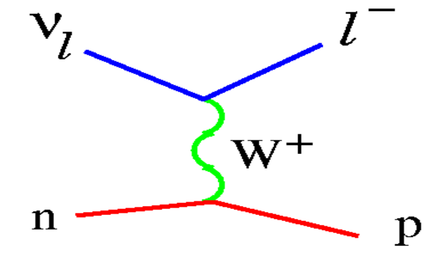
$M_A \cong 1.02$ GeV world average

$M_A \cong 1.07$ GeV world average

Dipole ansatz is simplification, not good for vector FF

Energy Reconstruction by QE

- In QE scattering on nucleon at rest outgoing lepton incoming neutrino energy can be uniquely reconstructed



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

Pion Production

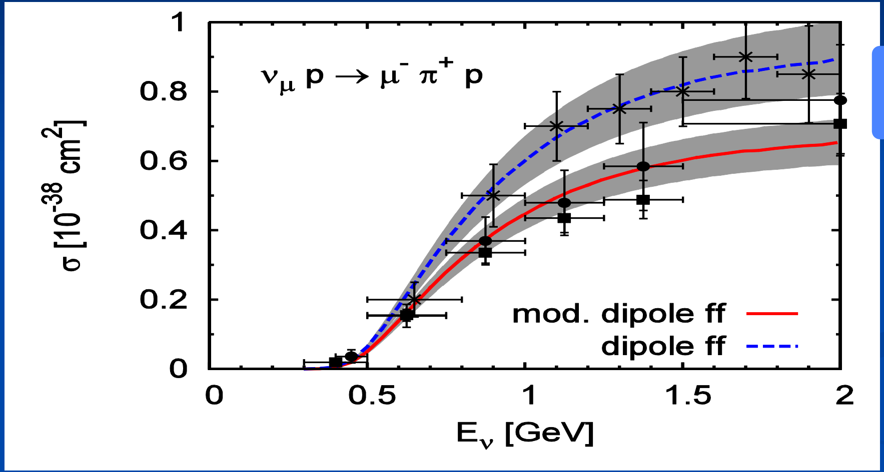
- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance (not just a heavier nucleon)**

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

- $C^V(Q^2)$ from electron data (MAID analysis with CVC)

- $C^A(Q^2)$ from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

Pion Production

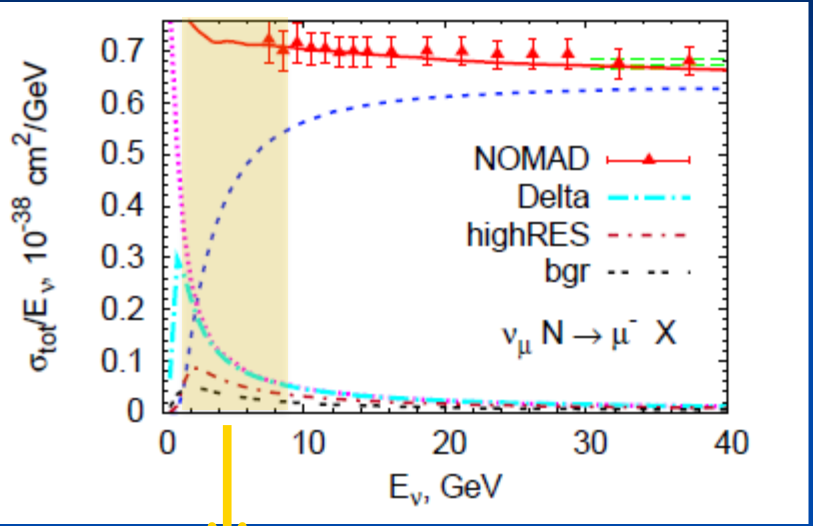


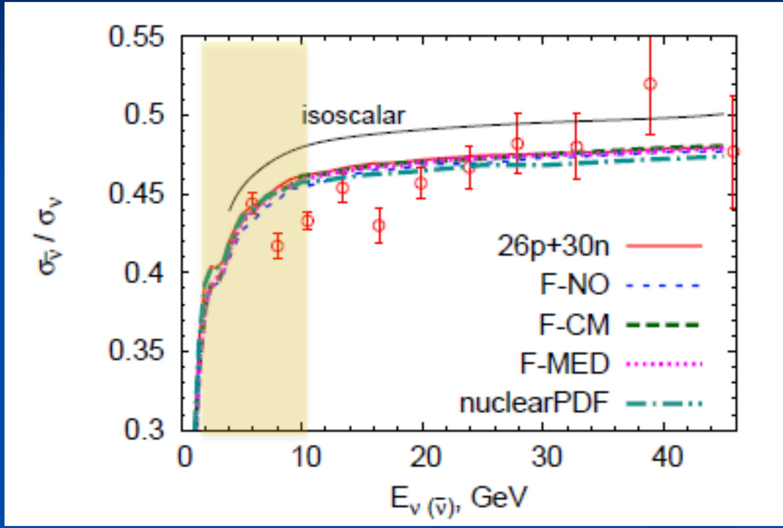
10 % error in $C_5^A(0)$

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

discrepancy between elementary data sets
→impossible to determine 3 axial formfactors

SIS - DIS





Shallow **I**nelastic **S**cattering,
interplay of different reaction mechanisms → Ambiguity to switch

Now to Nuclear Targets

because of

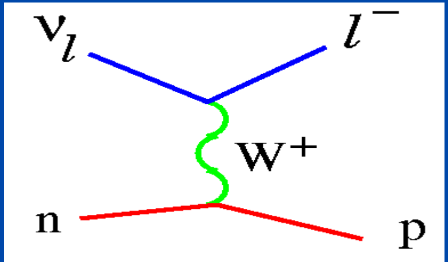
- Higher event rates
- Safety concerns

Energy Reconstruction

- Energy reconstruction
  1. Through QE: needs event identification
  2. Calorimetric: needs simulation of thresholds and non-measured events
- In both methods nuclear many-body structure and reaction theory are needed to generate full final state, inclusive X-section not sufficient

Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only *l* +*p*, no π, is outgoing lepton determines neutrino energy:

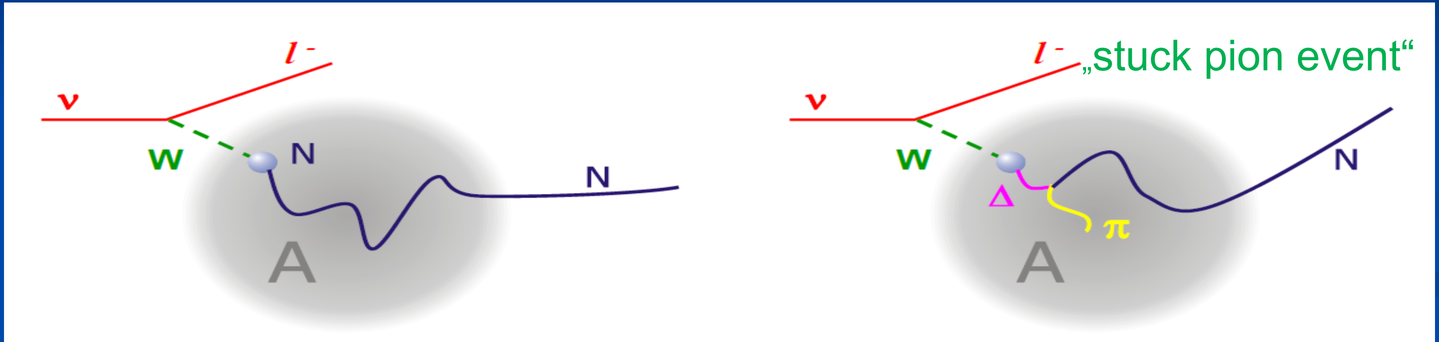


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

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

Final State Interactions in Nuclear Targets



Complication to identify QE, entangled with π production

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

A wake-up call for the high-energy physics community:

"Wake up, Dr. Erskine—you're being transferred to low energy physics."

Nuclear Physics determines response of nuclei to neutrinos

FSI and Transport Theory

- All modern experiments use nuclear targets
- Need to model final state interactions
  1. to identify reaction mechanism
  2. to reconstruct incoming neutrino energy from final state

Quantum mechanical description not possible to describe

ν + A -> X + many hadrons

→ Need Transport Theory

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

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

Transport Equation

Collision term

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

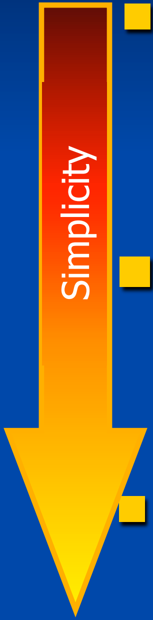
Drift term

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

Kadanoff-Baym equation

- LHS: drift term + backflow (KB) terms
- RHS: collision term = - loss + gain terms

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, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations

- Physics content (and code available): **Phys. Rept. 512 (2012) 1**
  http://gibuu.hepforge.org

- **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!

GiBUU Ingredients: ISI

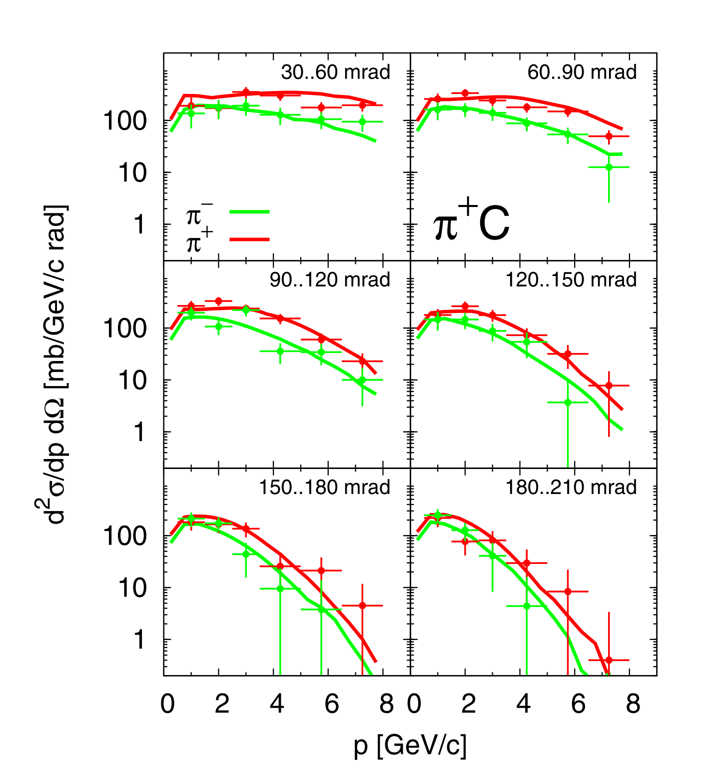
- In-medium corrected primary interaction cross sections, boosted to rest frame of bound nucleon, moving in local Fermigas
- Includes spectral functions for baryons and mesons (binding + collision broadening)
- *Hadronic* couplings for FSI taken from PDG
- *Vector* couplings taken from electro-production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

Check: pions in HARP

HARP small angle analysis
12 GeV protons

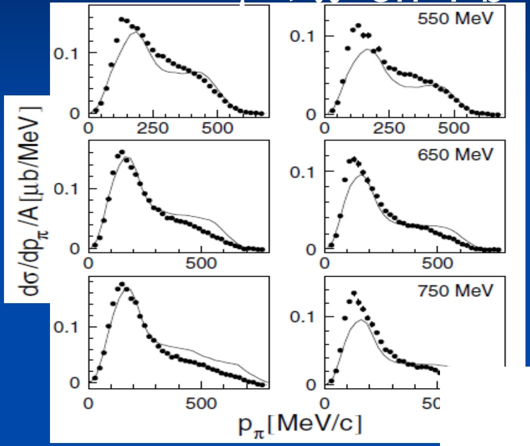
Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)

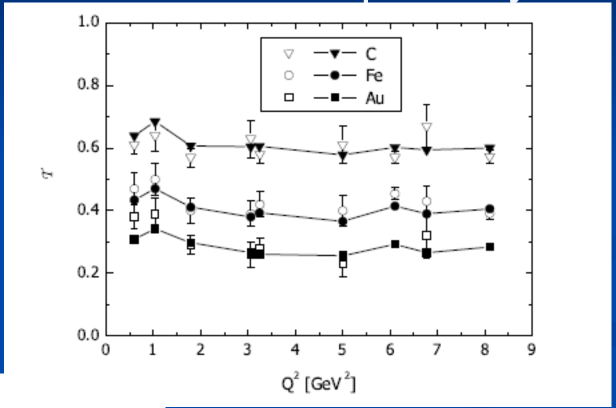


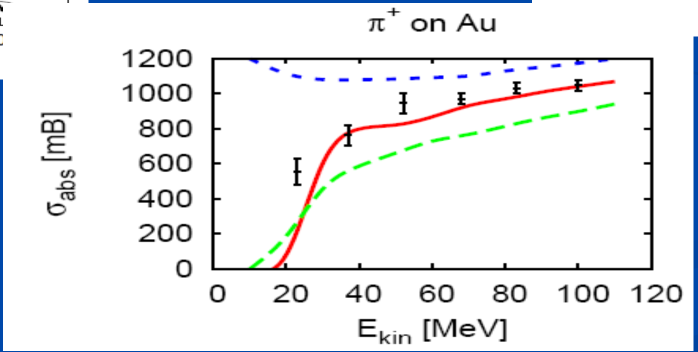
Check: pions, protons

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



Proton transparency

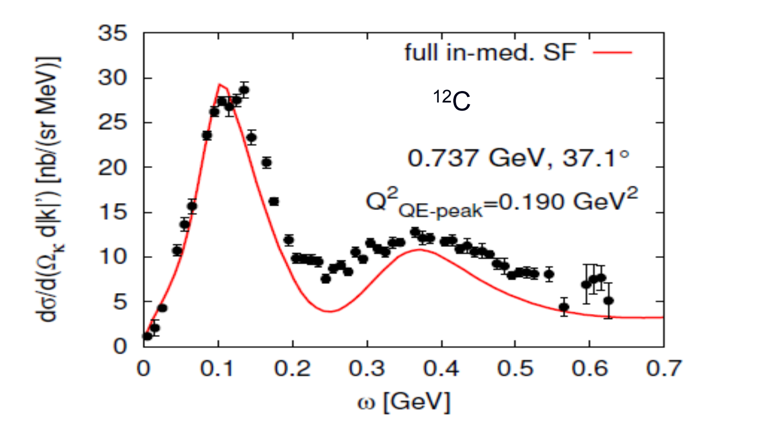


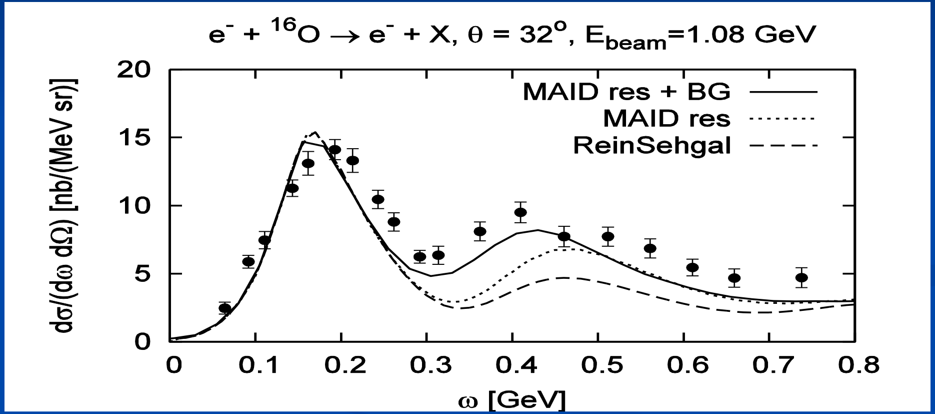


Pion reaction Xsect.

Institut für Theoretische Physik
Justus-Liebig-Universität Giessen

Electrons as Benchmark for GiBUU



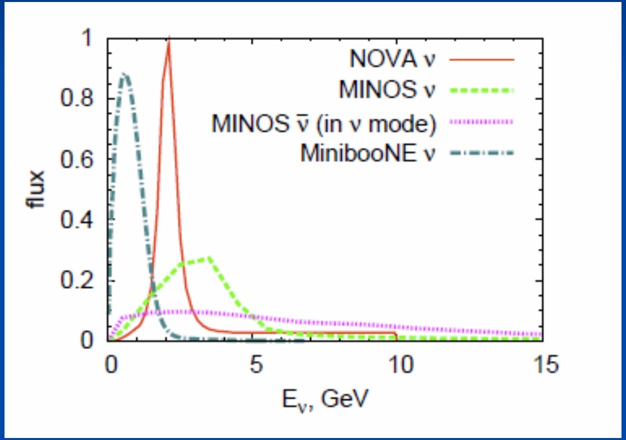


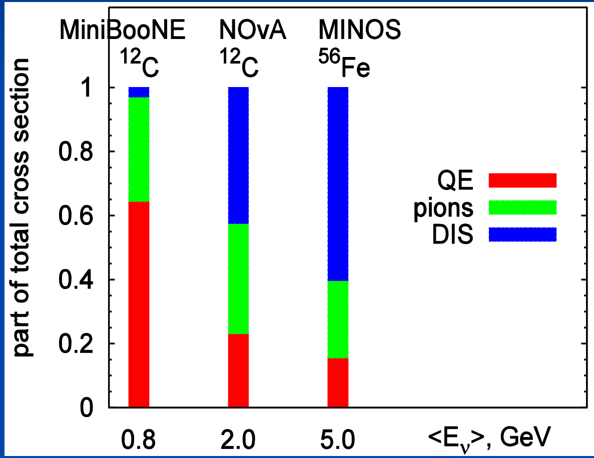
No free parameters!
no 2p-2h, contributes
in dip region and under Δ

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

Neutrino Beams

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

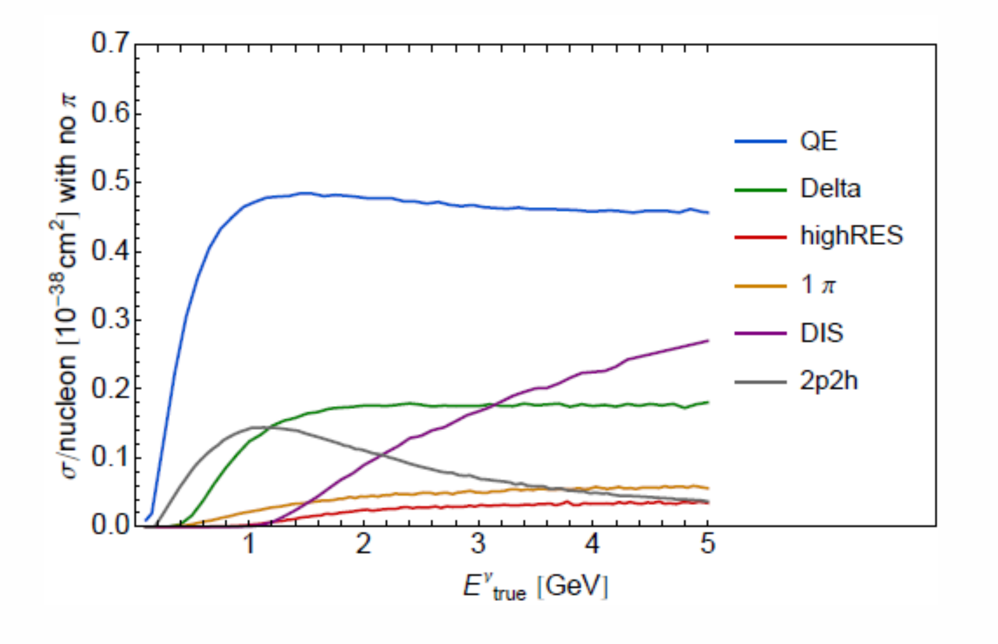




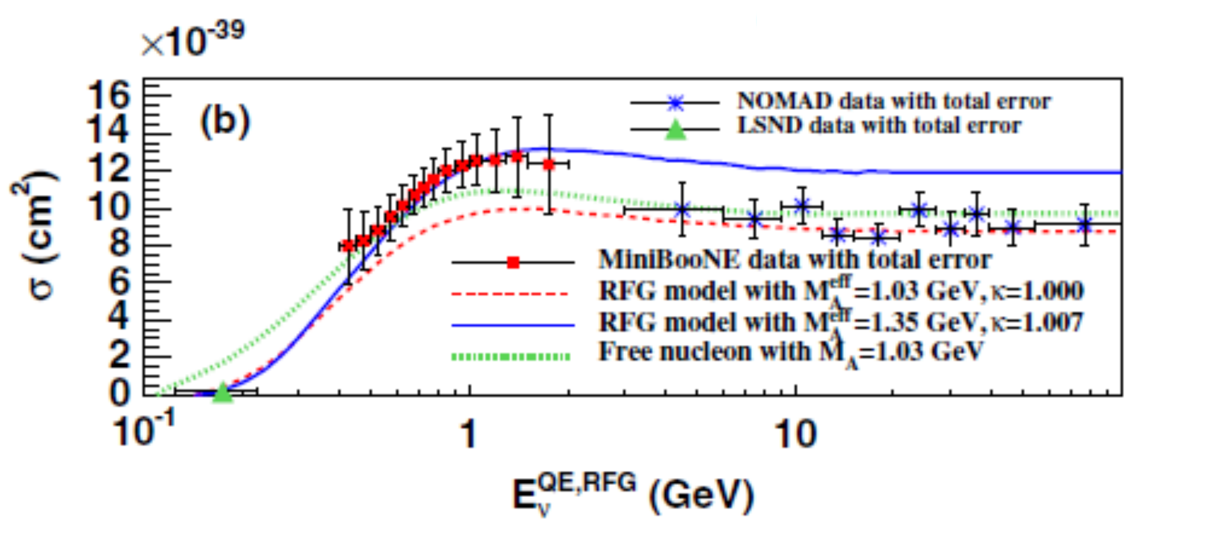
Have to reconstruct energy from final state of reaction
Different processes are entangled

0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1 [hep-ph] 4 Jul 2013



MiniBooNE QE puzzle



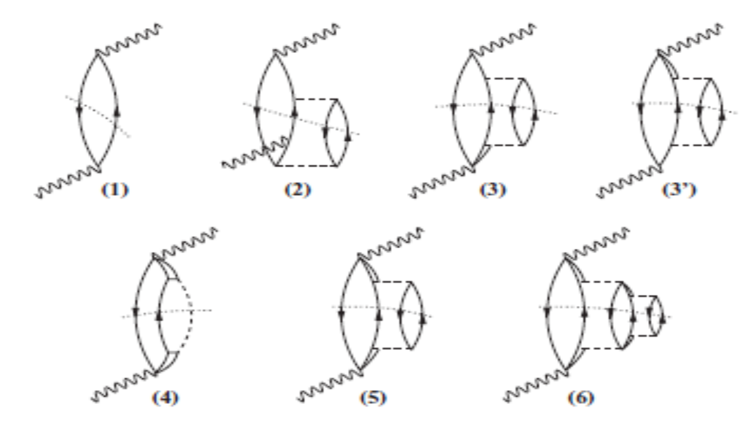
World average axial mass:
M_A = 1.03 GeV

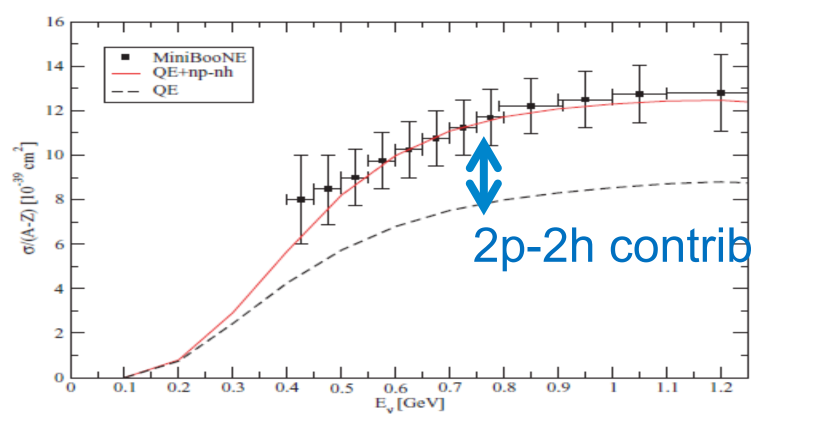
MB employs Cerenkov counter: identifies QE by muon and zero pion, corrects for ‚stuck pions'

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

The MiniBooNE QE Puzzle Explanations

Martini et al, PRC80, 2009





Exp: both σ and E_ν are reconstructed!

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

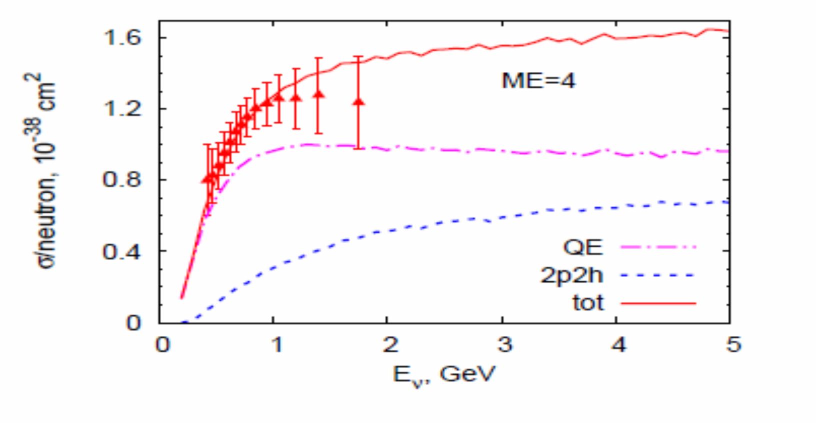
$$\overline{|M|^2} = \int \Phi(E_\nu)\, L_{\mu\nu} W^{\mu\nu}\, \mathrm{dE}_\nu$$

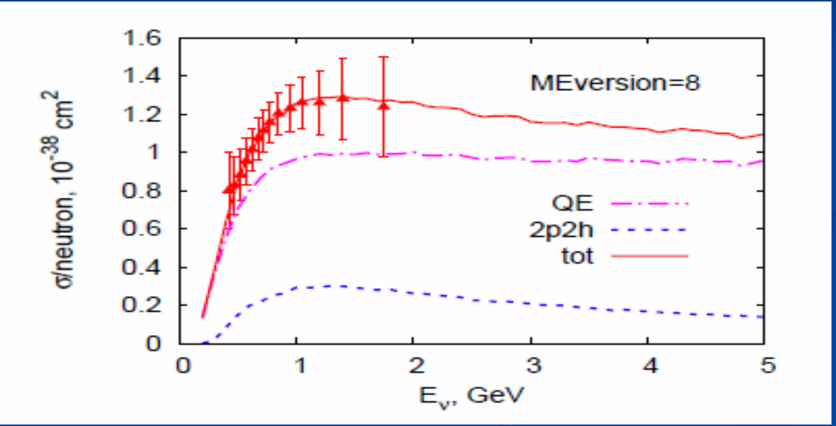
Flux smears out details in hadron tensor *W*
W contains 2p-2h and poss. RPA effects

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

The MiniBooNE QE Puzzle Explanations

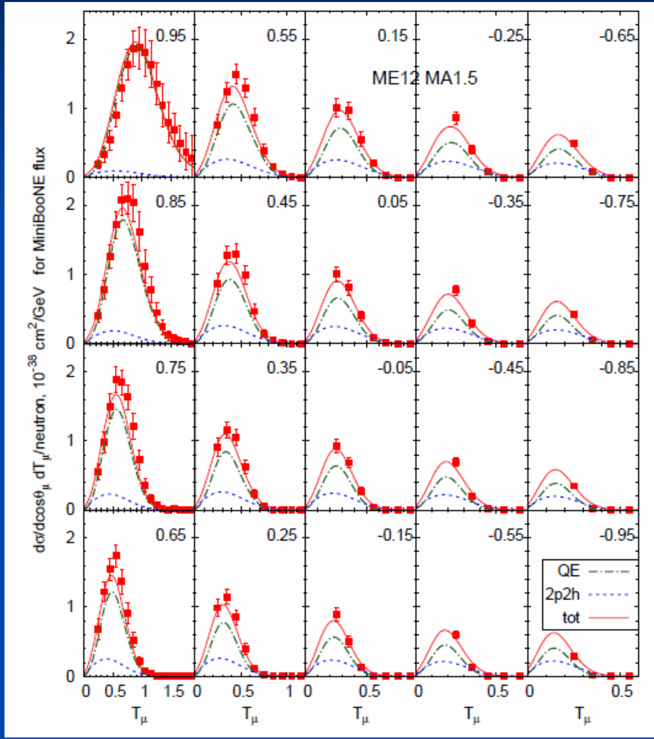
- *M = const* $\qquad$ $M = M(E,q)$, $W^{\mu\nu} \sim P_T^{\mu\nu}(q)$





Phase-space model for 2p-2h
Absolute value fitted to data.

The MiniBooNE QE Puzzle
Explanations



ME12, MB flux averaged

Data corrected
for stuck-pion events!

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

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

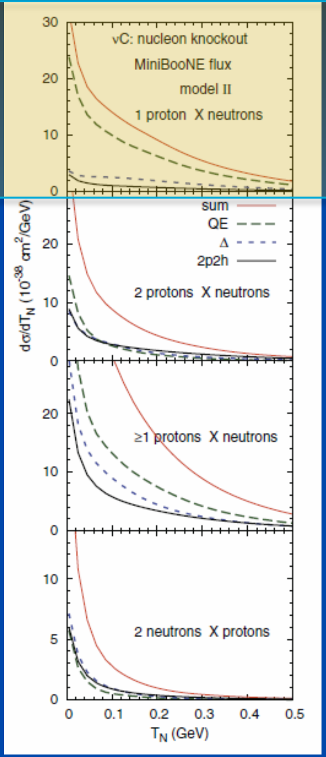
The MiniBooNE QE Puzzle
Explanations

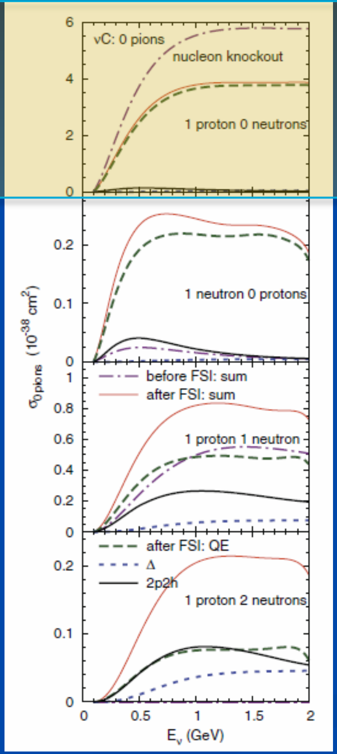
- How to decide which one is correct?

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

  Nucleon Knock-out, numbers and spectra

QE Identification



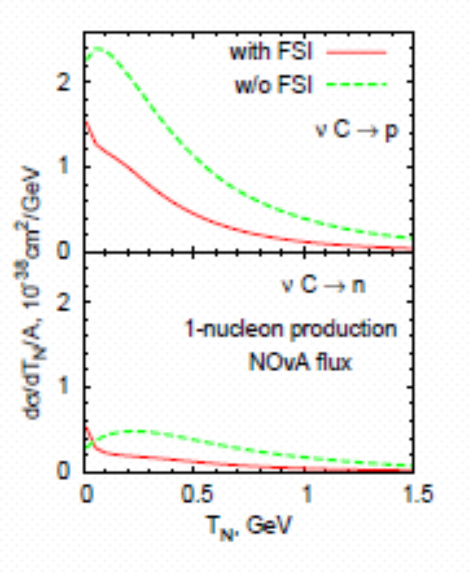


1p xn xπ: fairly clean QE event

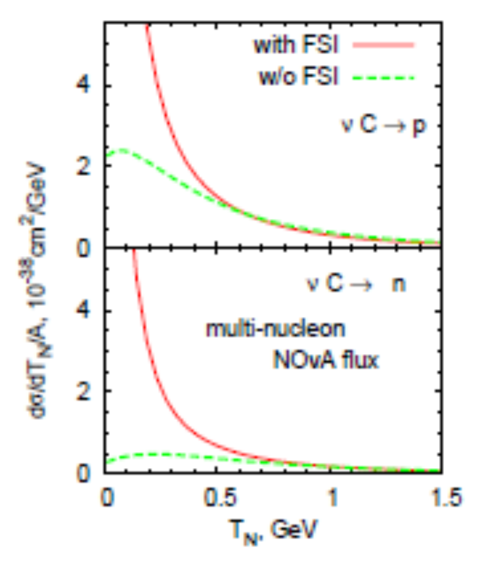
1p 0n 0π: very clean QE event

No clean signal for 2p-2h. Because of FSI

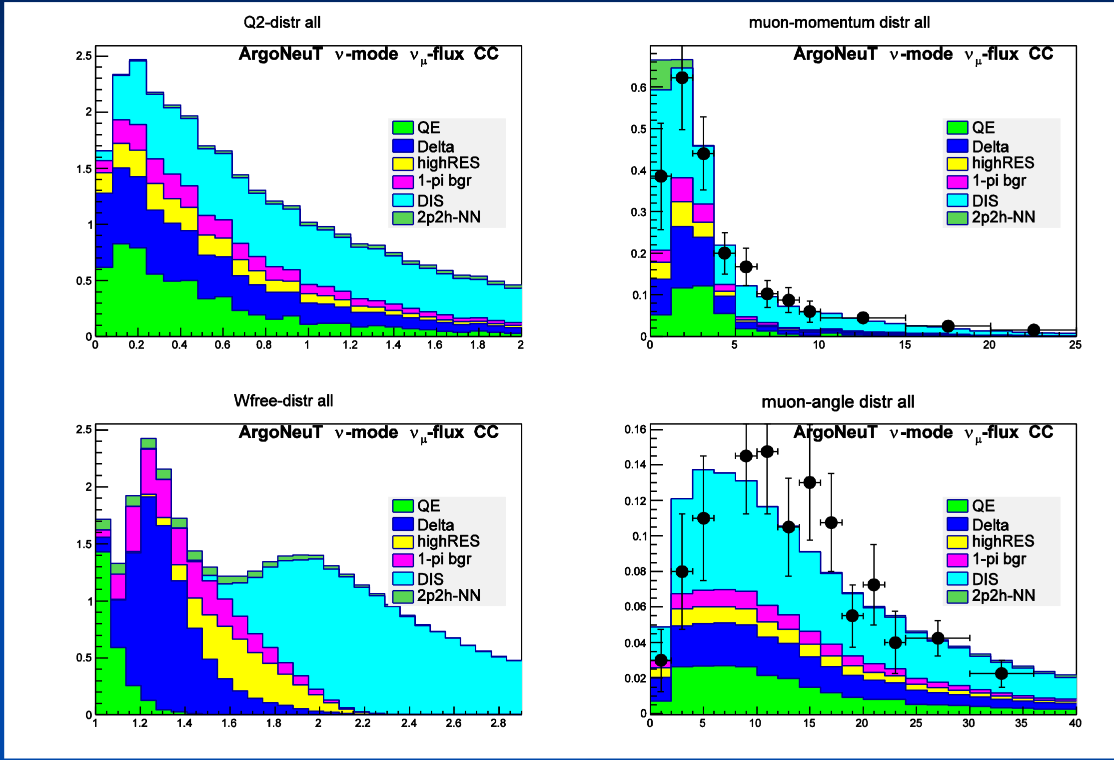
Nuclear Effects in Noνa



➔ FSI avalanche

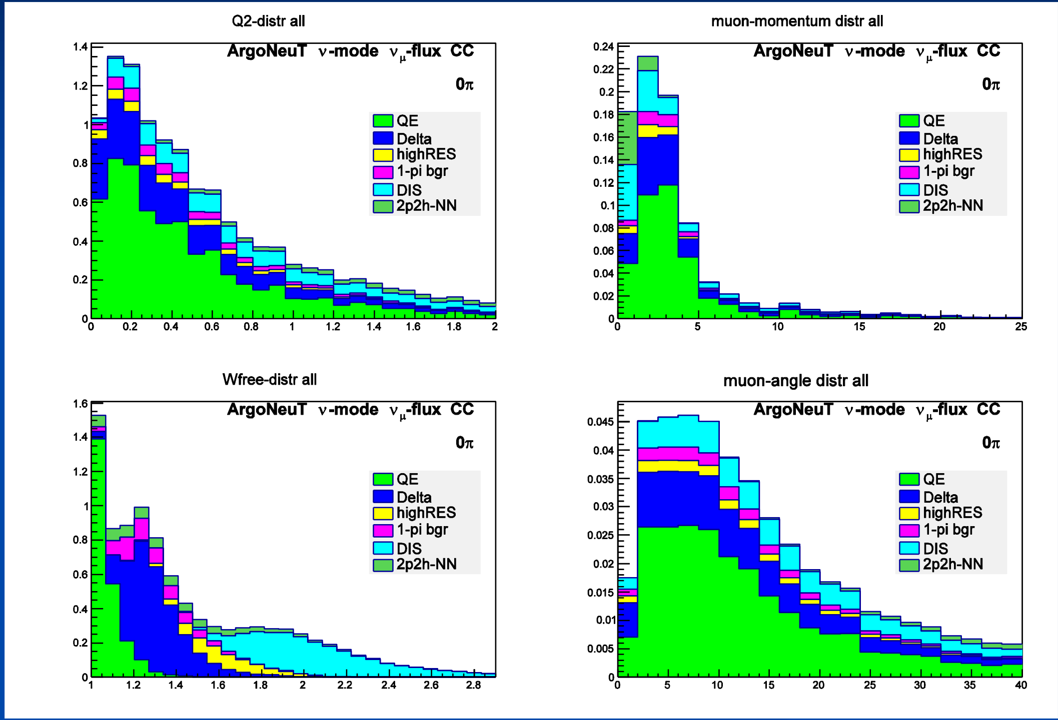


ArgoNeuT



All events, large DIS contribution

ArgoNeuT



0 pion events suppresses DIS

Energy Reconstruction and Oscillation Analysis

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

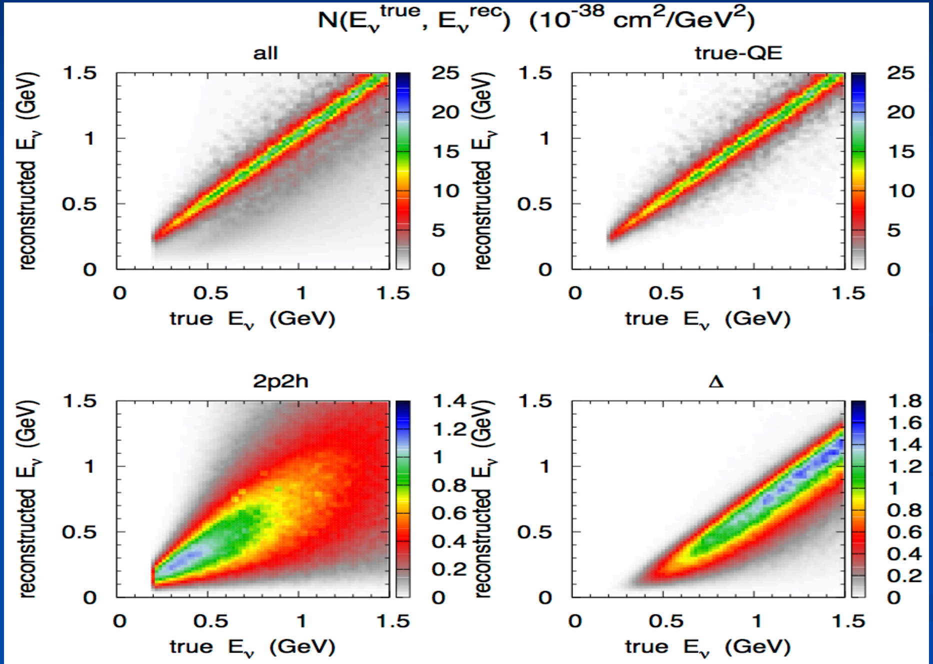
Energy Reconstruction by QE

- 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

GiBUU is Nature

- GiBUU is used to simulate nature: generate events with known, *true energy*
- Analyze these events with exp. methods, obtain *reconstructed energy* for each event
- Compare event rates as functions of true and reconstructed energies

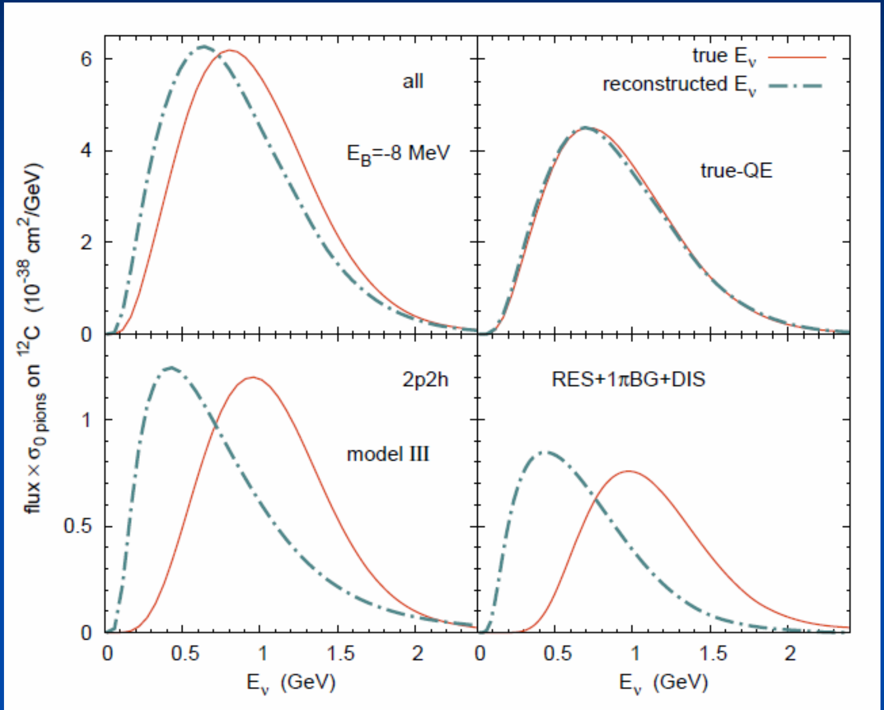
Migration Matrix for C and MB flux



Distributions
for 0 pion events!

Energy reconstruction in MB

Event rates = flux x crosssection



MiniBooNE flux

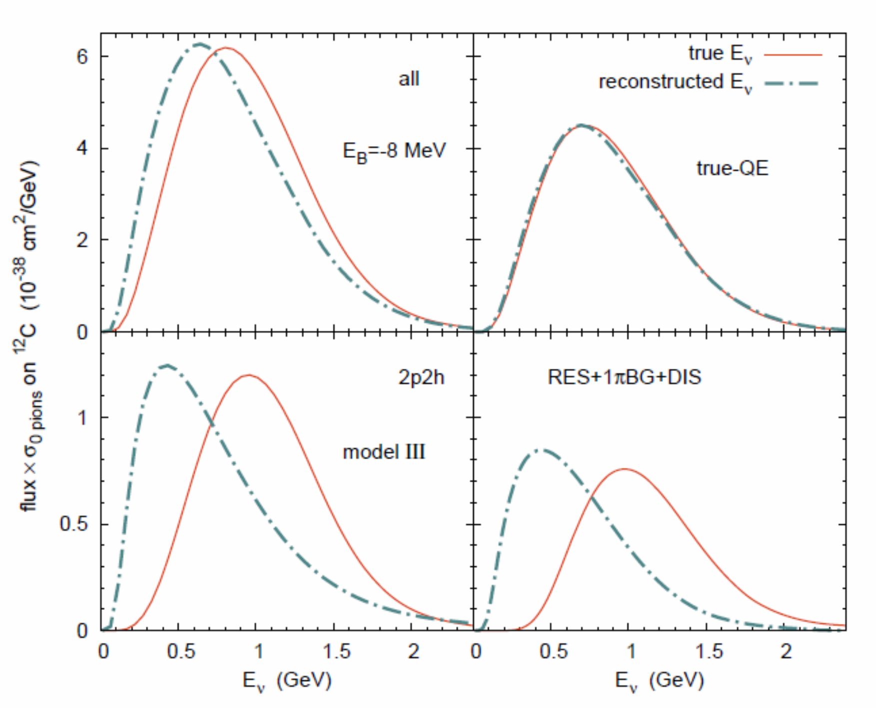
Reconstructed energy shifted to lower energies for all processes beyond QE

Reconstruction must be done for 0 pion events

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Energy reconstruction in MB

Event rates = flux x crosssection



MiniBooNE flux

Reconstructed energy shifted to lower energies for all processes beyond QE

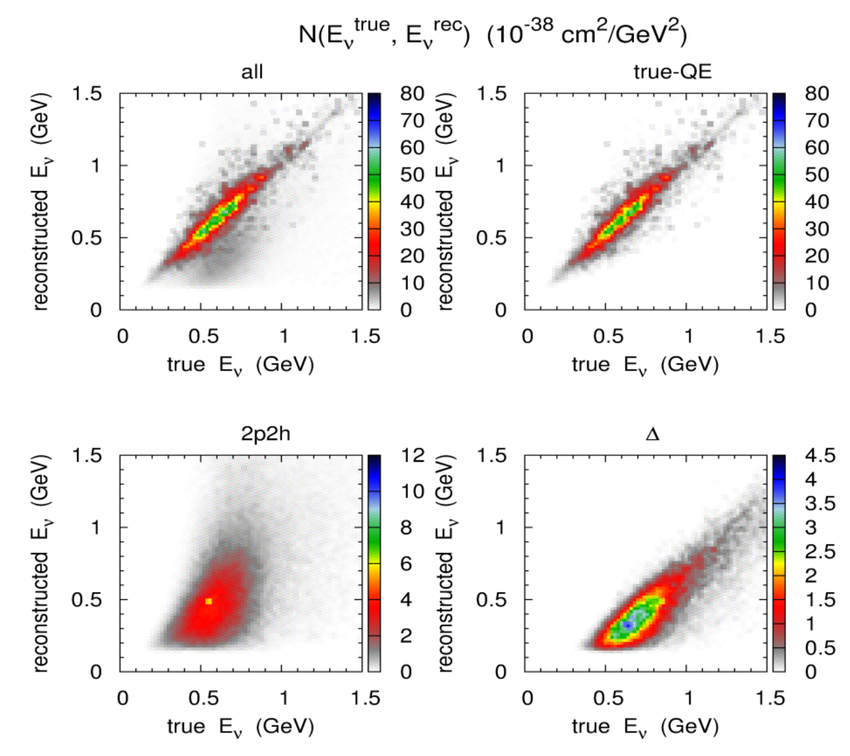
Reconstruction must be done for 0 pion events

Energy reconstruction in MB

- Energy reconstruction does not just change energy-axis, but also tilts funtional dependence of X-section on neutrino energy

Oscillation and Energy Reconstruction

T2K migration matrix

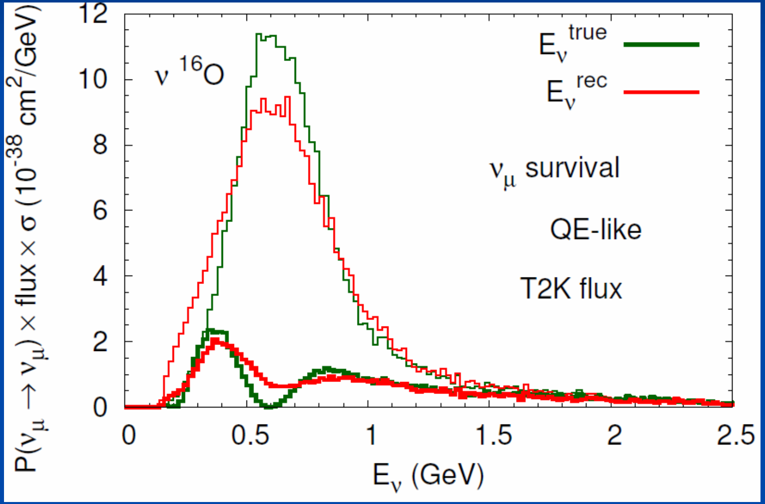


T2K Flux

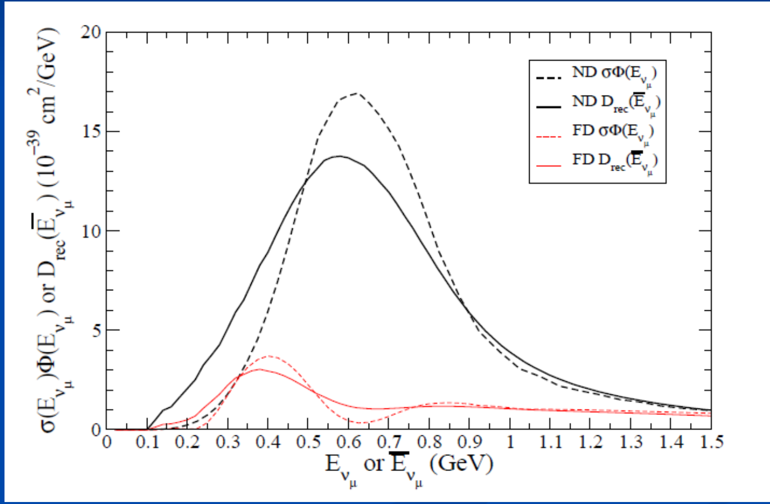
Target: ^{16}O

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Oscillation signal in T2K
ν_μ disappearance



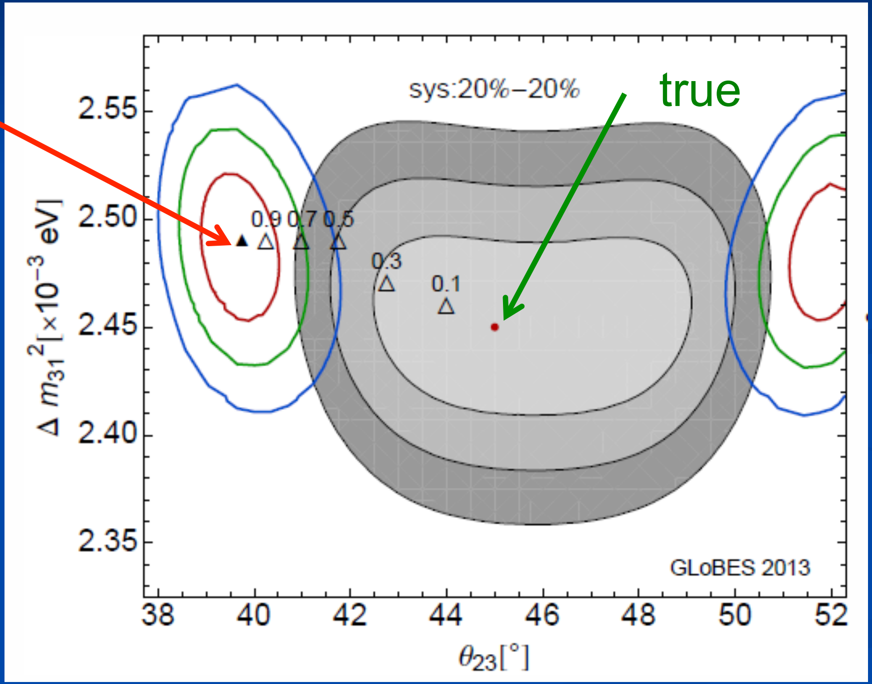
GiBUU



Martini

Sensitivity of oscillation parameters to nuclear model

reconstructed from naive QE dynamics

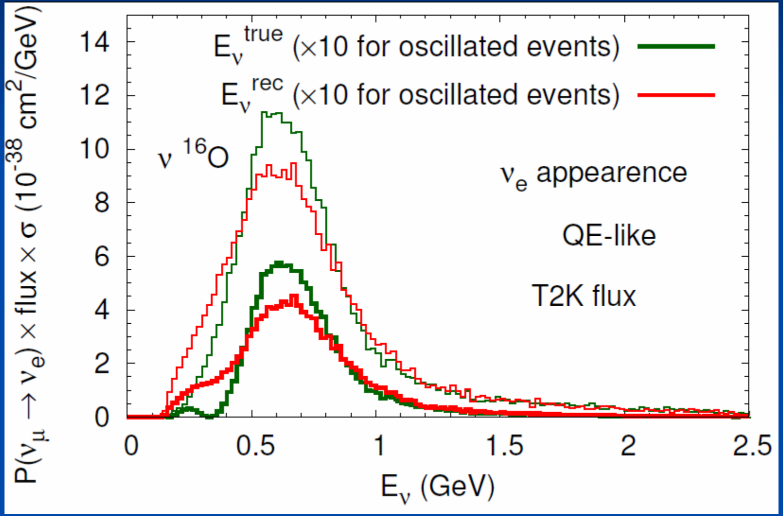


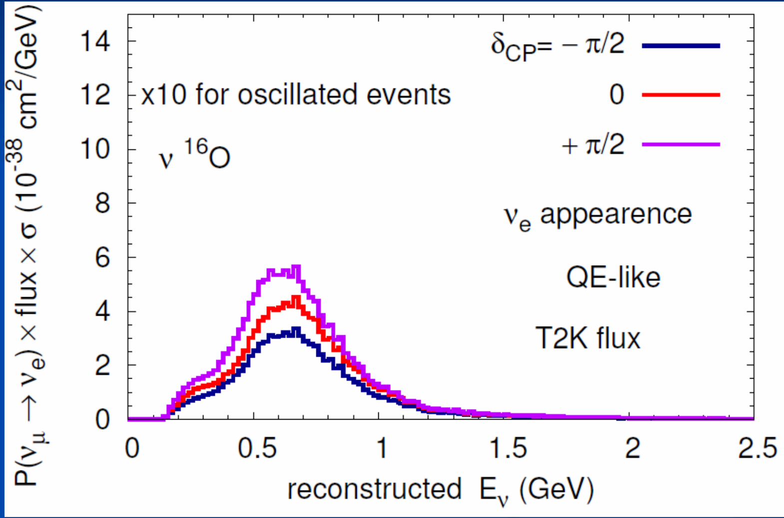
P. Coloma, P. Huber,
arXiv:1307.1243, July 2013

Analysis based on GiBUU

T2K

Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps





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

Sensitivity of T2K to Energy Reconstruction

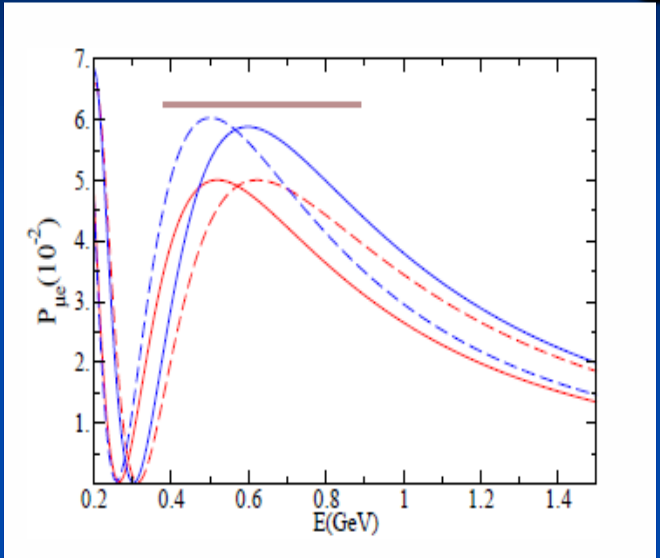
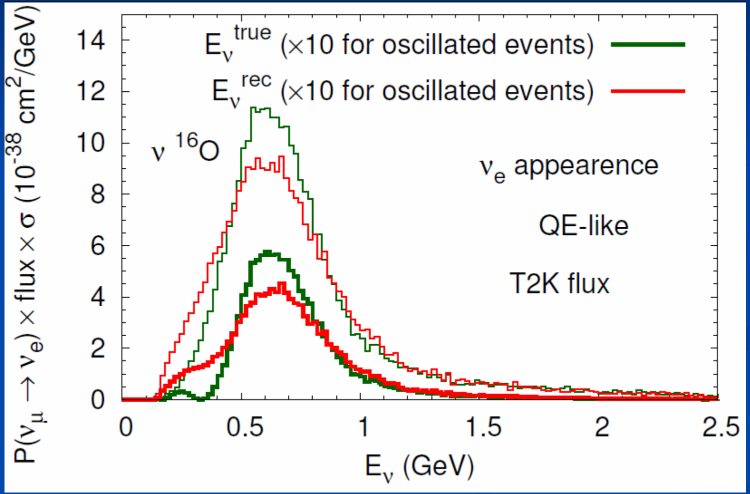


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

D.J. Ernst et al., arXiv:1303.4790 [nucl-th]



Summary

- Energy reconstruction essential for precision determination of neutrino oscillation parameters
(and neutrino-hadron cross sections)

- Energy reconstruction requires reliable event generators,
of same quality as experimental equipment.

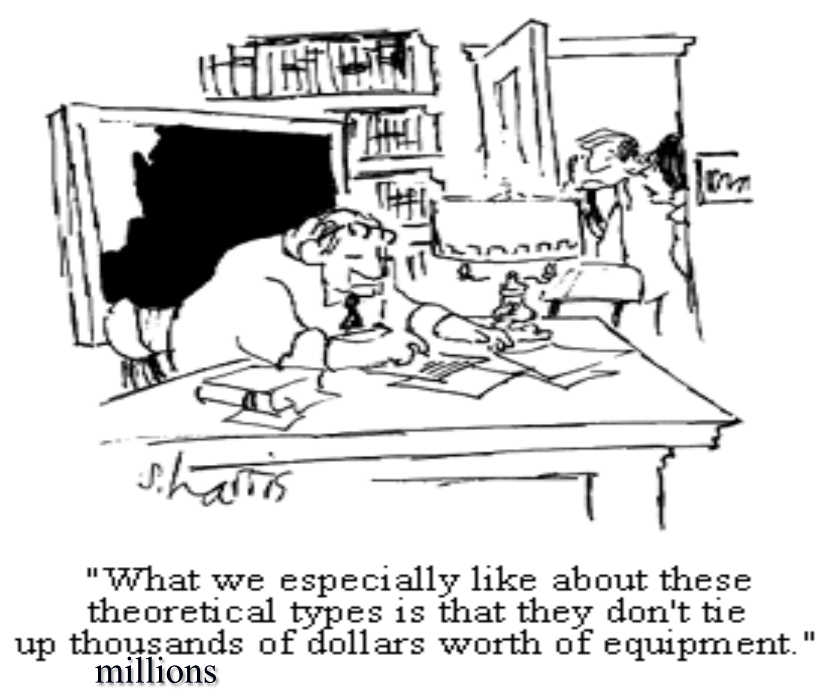
- Precision era of neutrino physics requires much more sophisticated generators and a dedicated effort in theory

Neutrino generators in precision era

- Systematic errors
  - Uncertainties in input cross sections
  - Mis-identification of reaction mechanisms
  - Generator-specific numerical implementation
    - Treatment of relativity in collision terms
    - Mean field potentials
    - Off-shell transport ....

Need for solid nuclear physics theory

- Generators are a crucial part of any experiment
- Must be of same quality as the experimental equipment itself!
- Needed resources are relatively small, but still not available



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