Neutrino Interactions with Nucleons and Nuclei

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Motivation and Contents

- Determination of neutrino oscillation parameters and axial properties of nucleons and resonances in accelerator experiments requires knowledge of neutrino energy, but the neutrino beam is broad in energy
- Modern experiments use nuclear targets
- Will show:

  Nuclear effects affect event characterization and neutrino energy reconstruction and limit oscillation parameter determination

Neutrino Oscillations

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

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

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

Vacuum oscillation

Matter effects,
n_e = electron density

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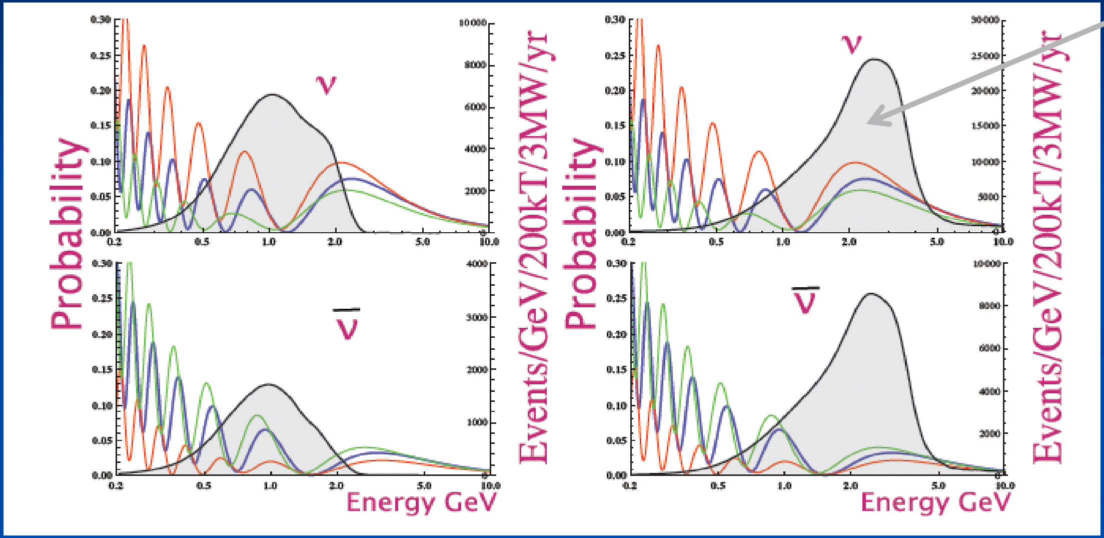
LBNE, δ_{CP} sensitivity

From: Bishai et al., hep-ex 12034090



Flux distribution

From:
Bishai et al
arXiv:1203.409

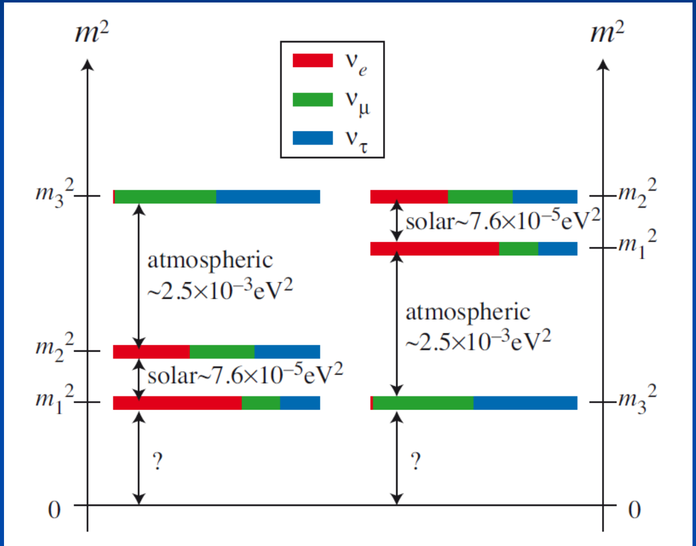
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = -\pi/2$

8 GeV 60 GeV

proton energy

Need energy to distinguish between different δ_{CP}

Oscillation Signal
Dependence on Hierarchy and Mixing Angle



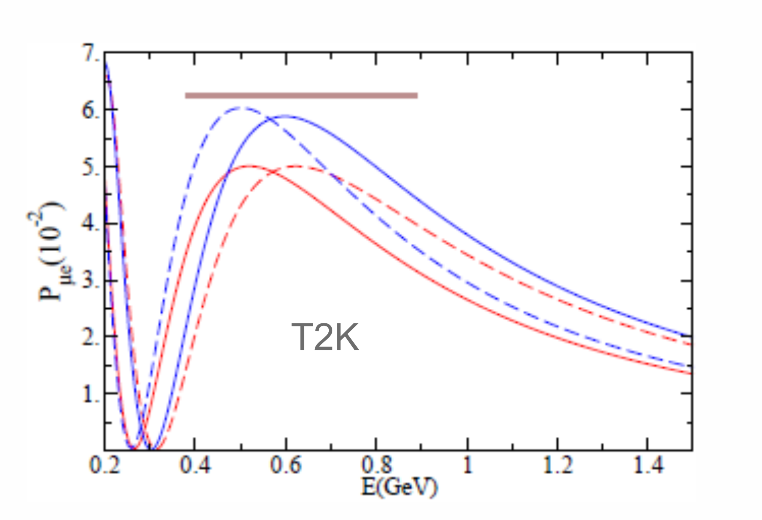


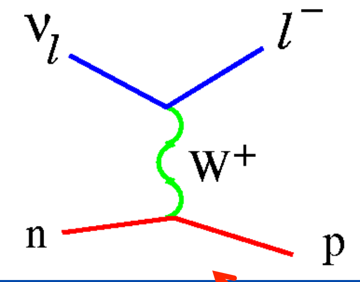
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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

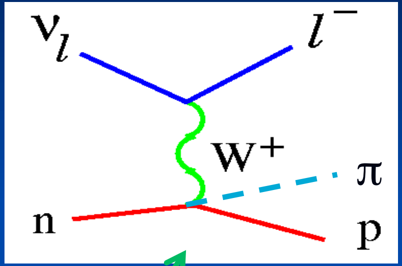
Energy has to be known better than 100 MeV
Shape sensitive to hierarchy and sign of mixing angle

Neutrino-nucleon cross section

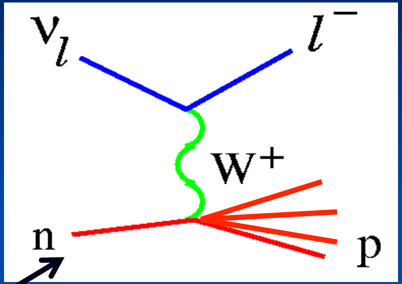
CCQE

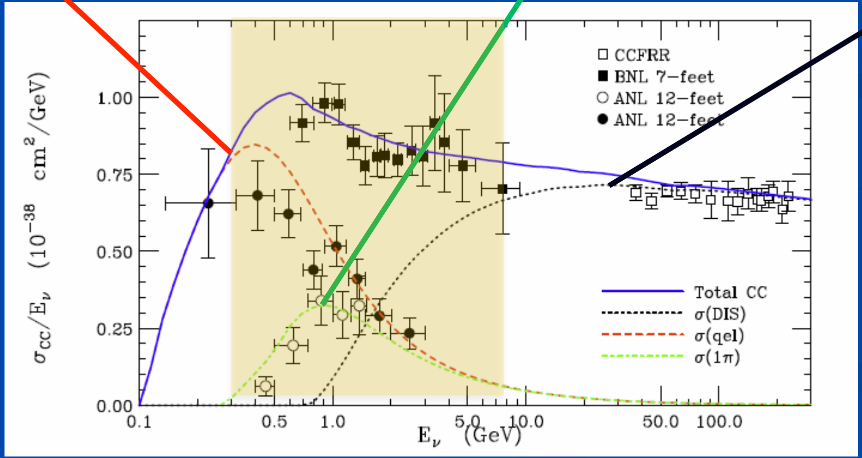


1π



DIS

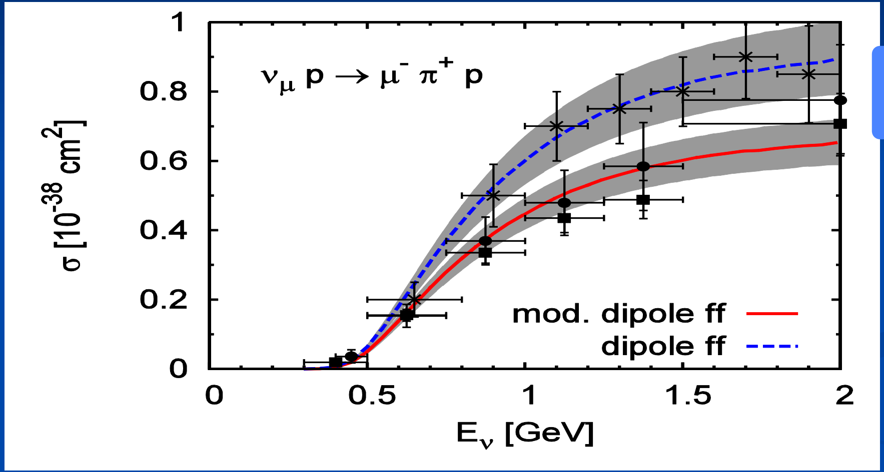




note:
10^{-38} cm² = 10^{-11} mb

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

Pion Production



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

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

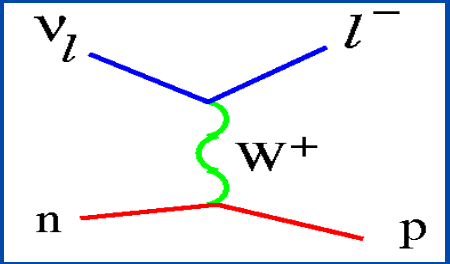
discrepancy between elementary data sets
→ impossible to determine 3 axial formfactors from these data

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

Energy Reconstruction by QE

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



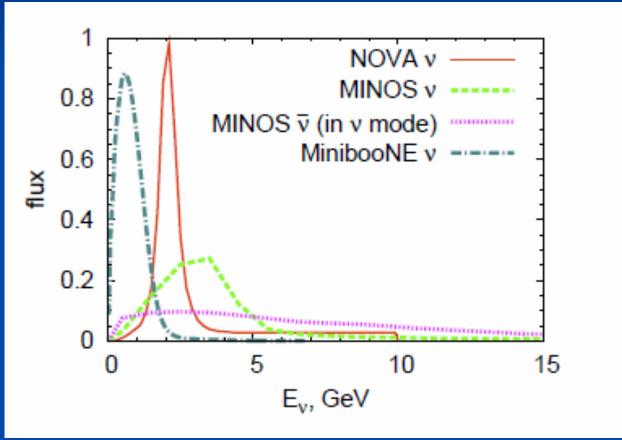
$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

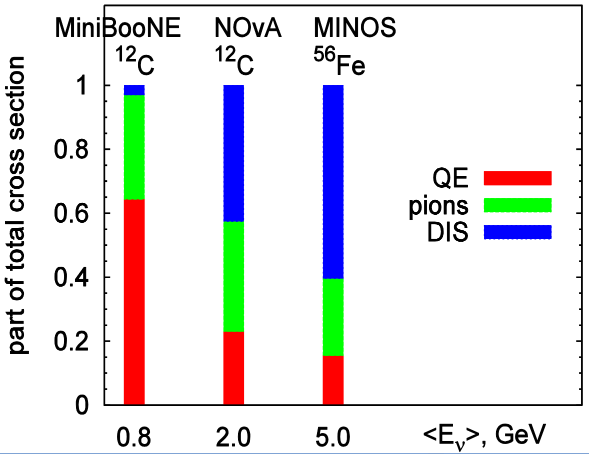
- Trouble: all presently running exps use nuclear targets

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

Neutrino Beams

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

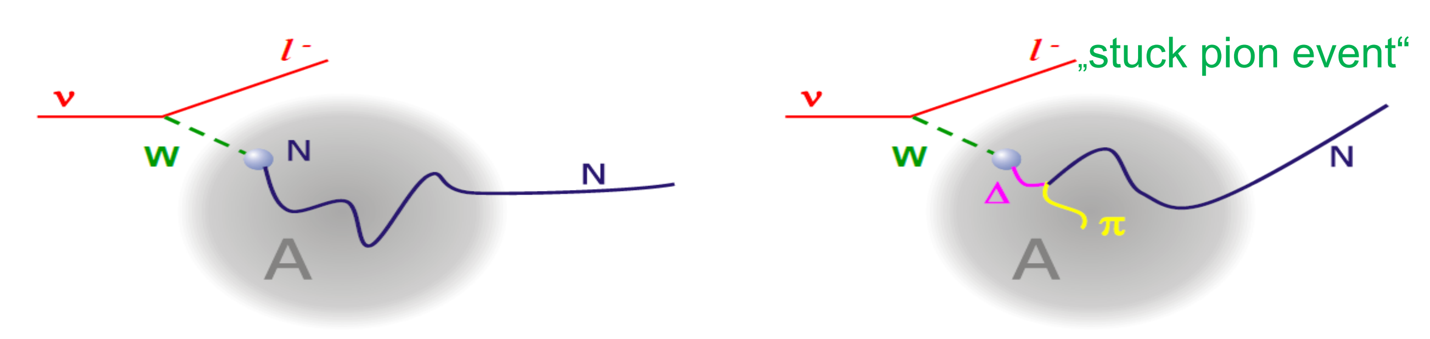




Have to reconstruct energy from final state of reaction

Different initial processes entangled: can lead to same final states!

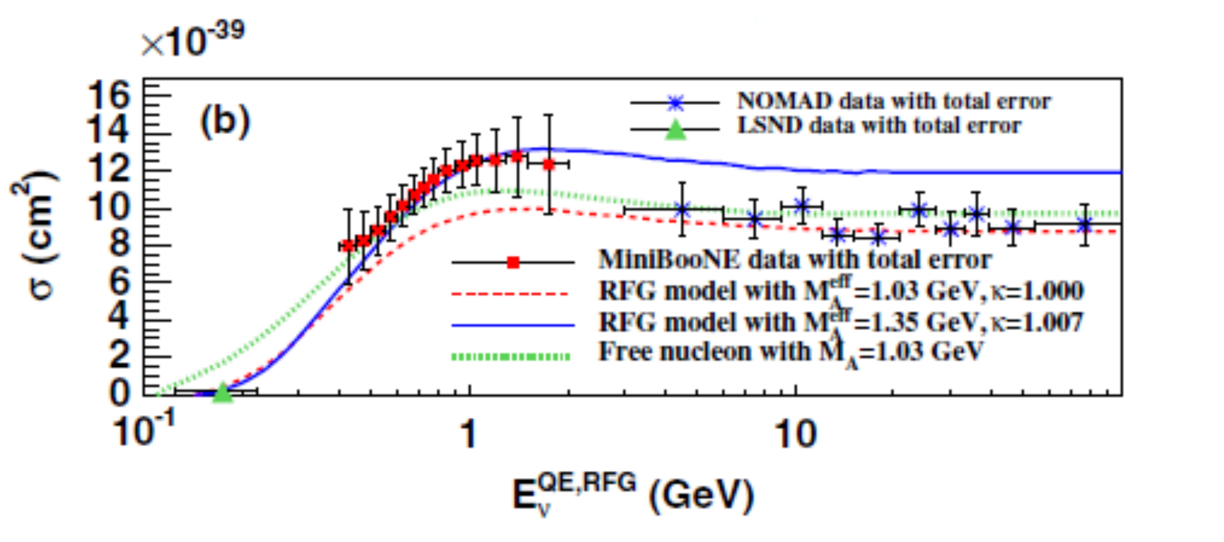
Final State Interactions in Nuclear Targets



Complication to identify QE, entangled with π production

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

MiniBooNE QE puzzle



World average axial mass:
$M_A = 1.03$ GeV

MB employs Cerenkov counter: identifies QE by muon and 0 pion, corrects for ‚stuck pions‘

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 (event generators)

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**
  based on a Botermans-Malfliet solution of Kadanoff-Baym equations
- Physics content: **Phys. Rept. 512 (2012) 1**
  Code available from 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

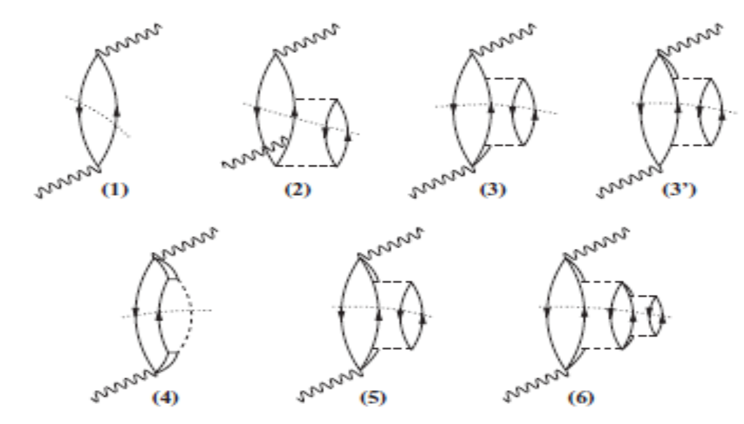
……..using the same physics input! And the same code!

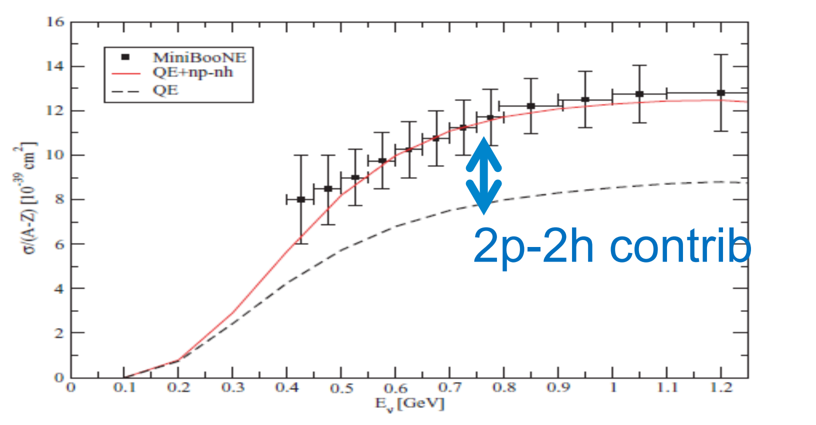
Nuclear Effects

- Impulse approximation,
  local Fermi gas or spectral functions
- RPA essential up to about 0.7 GeV and small Q^2, rather irrelevant for most exps.
- Coherent X-section negligeably small:
  $\sigma \approx 10^{-40}$ cm^2, per cent level

The MiniBooNE QE Puzzle
Explanations

Martini et al, PRC80, 2009





Exp: both σ and E_ν are reconstructed!

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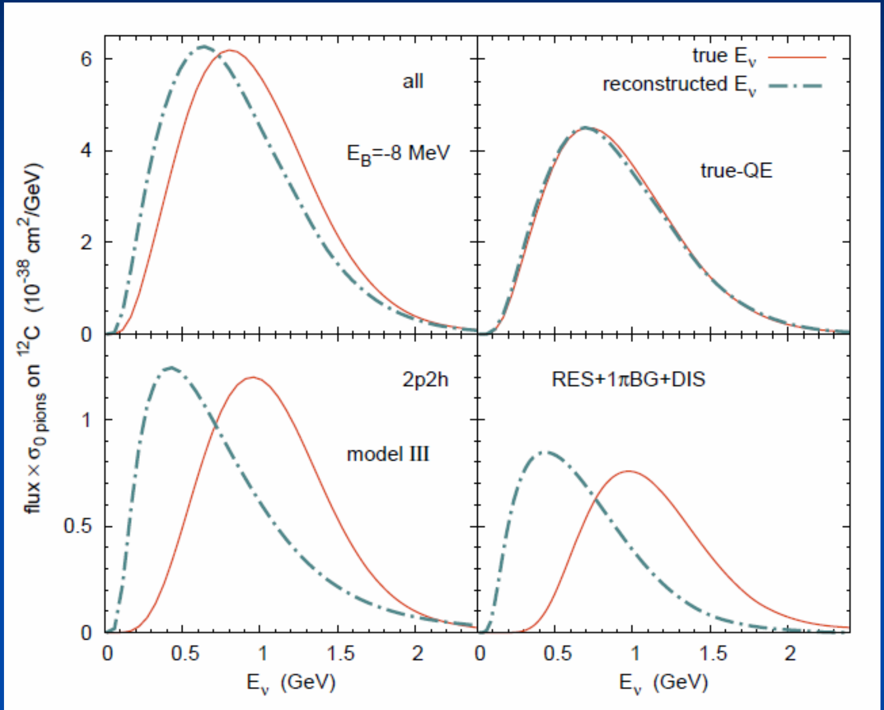
Energy reconstruction analysis

- Assume: GiBUU is nature
- Smear all cross sections (QE, 2p2h, pion production, DIS) with exp. flux distribution to get measured distributions
- Assume QE kinematics to reconstruct E_ν

Energy reconstruction in MB

Event rates = flux x crossection



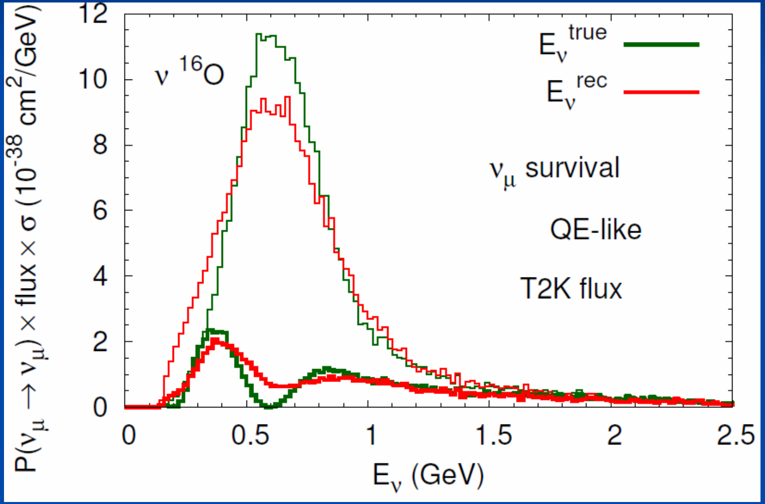
MiniBooNE flux

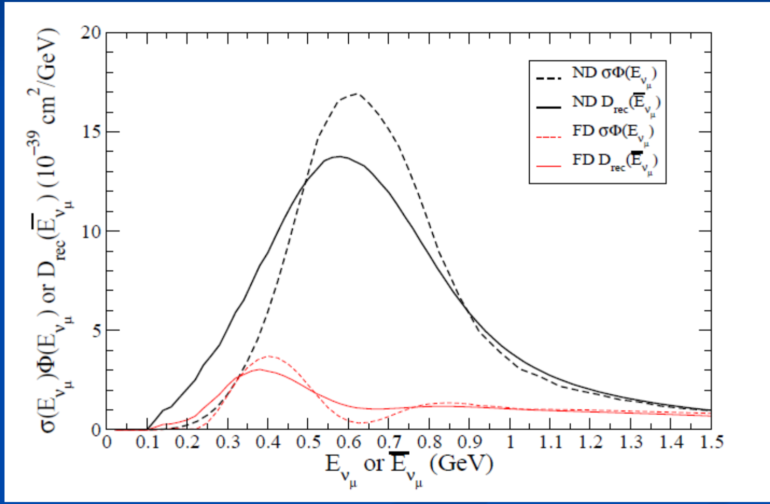
Reconstructed energy shifted to lower energies for all processes beyond QE

Reconstruction must be done for 0 pion events

Oscillation signal in T2K

ν_μ disappearance

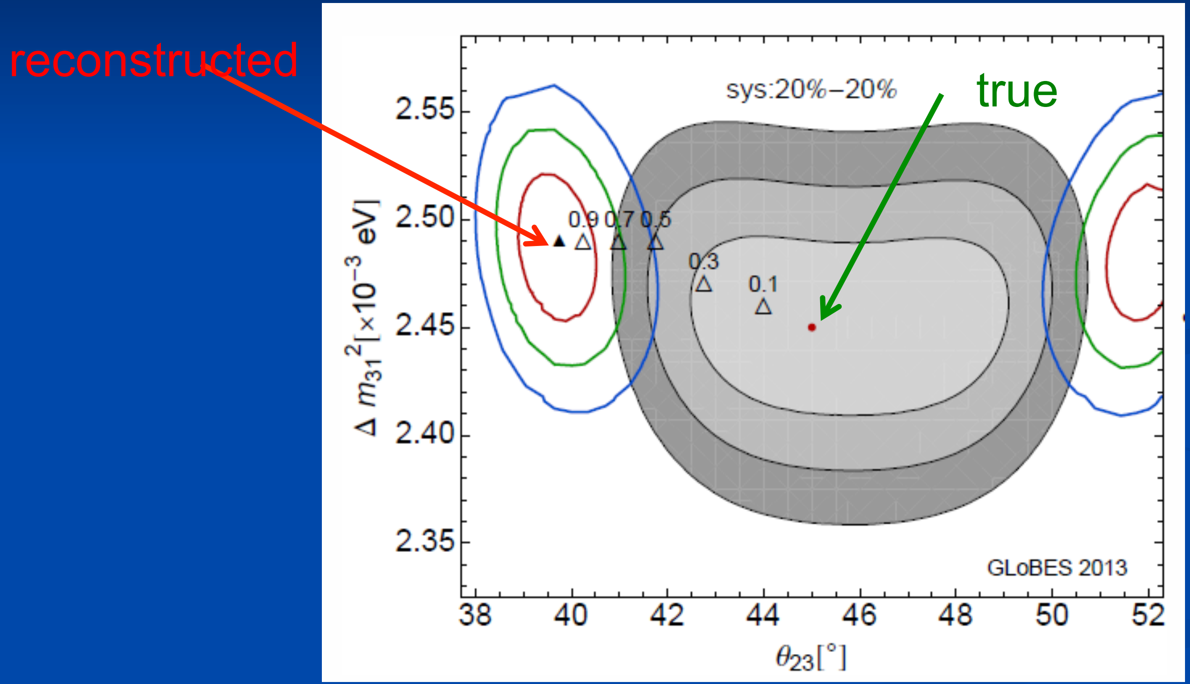




GiBUU

Martini. Chanfray et al

Sensitivity of oscillation parameters to nuclear model

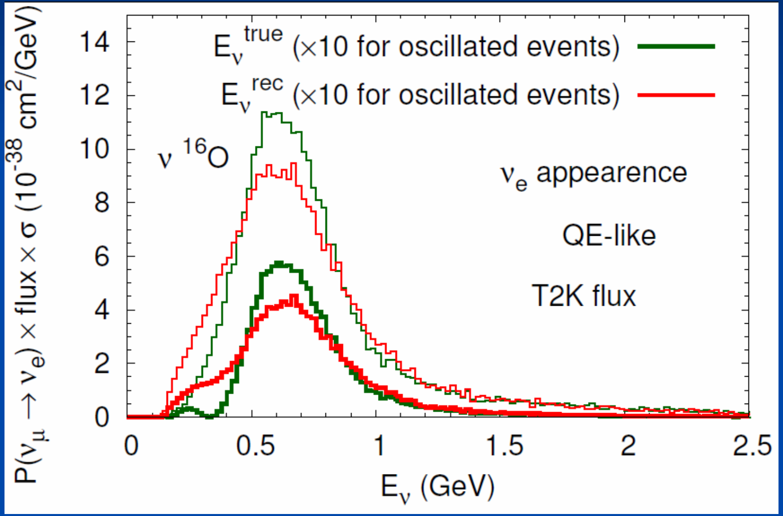


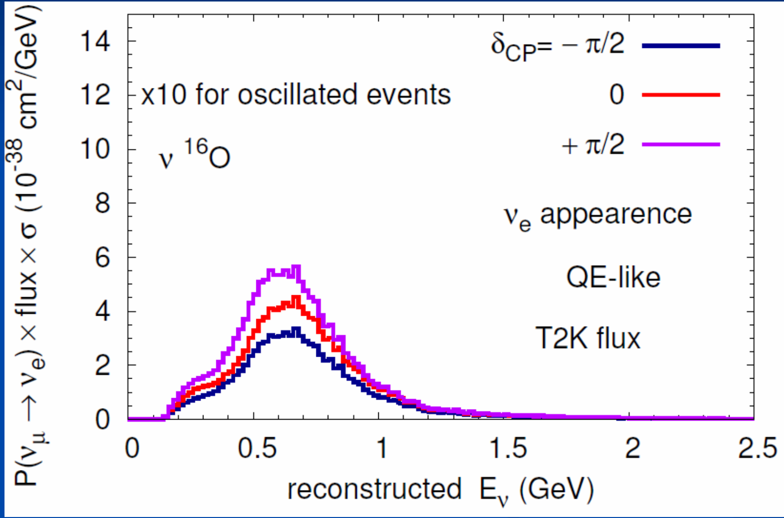
P. Coloma, P. Huber, arXiv:1308.6822

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

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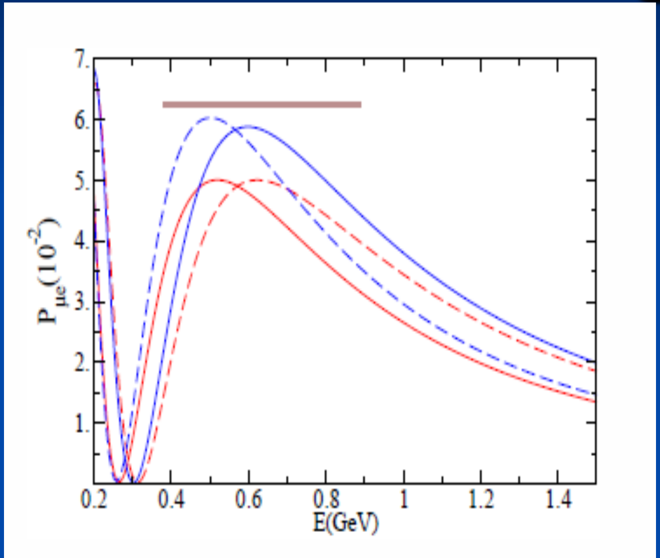
Sensitivity of T2K to Energy Reconstruction



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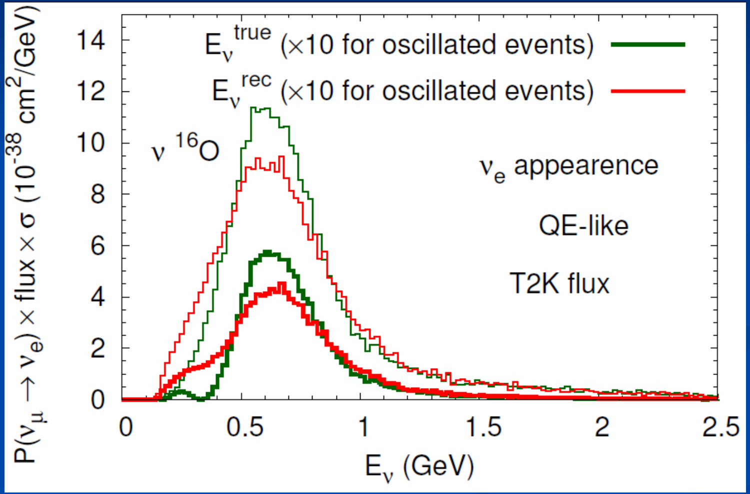

Summary

- Event generators for neutrino-nucleus interactions have to describe QE, π produktion and DIS simultaneously
- Energy reconstruction based on QE leads to downward shift of reconstructed distribution
- δ_{CP} determination depends crucially on energy reconstruct.

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

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

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

Low-Energy
Nuclear Physics
determines response
of nuclei to high-energy
neutrinos

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