Neutrino Cross Sections, Nuclear Physics and Oscillations

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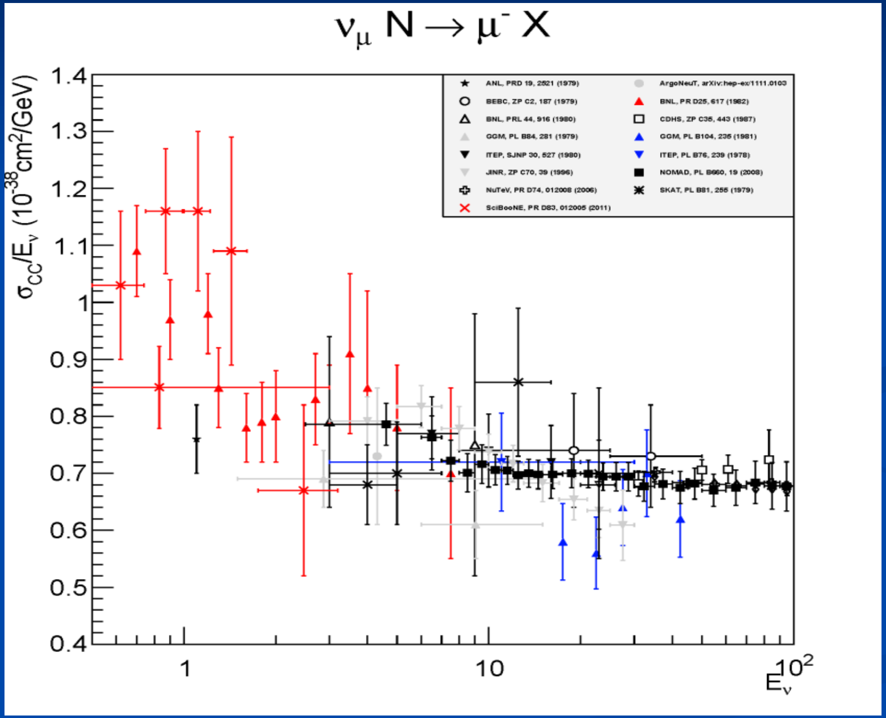
General Motivation

- Aspects of neutrino-nuclear reactions:
  - Hadron physics
  - Neutrino oscillation physics

Hadron Physics

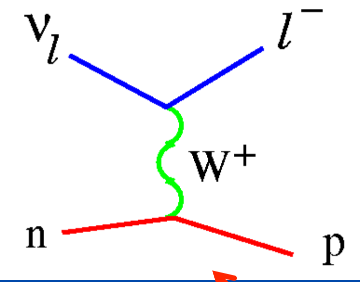
Neutrino-Nucleon Total Cross Sections



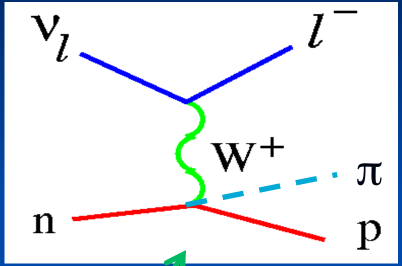
Obviously,
Large error bars
in the energy-range
of present and
planned experiments
(300 MeV - 30 GeV)

Neutrino-nucleon cross section

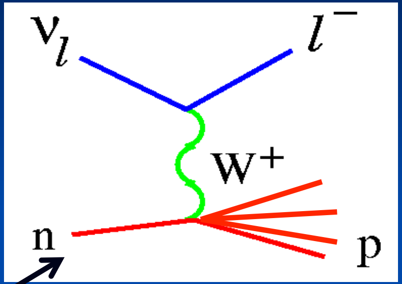
CCQE

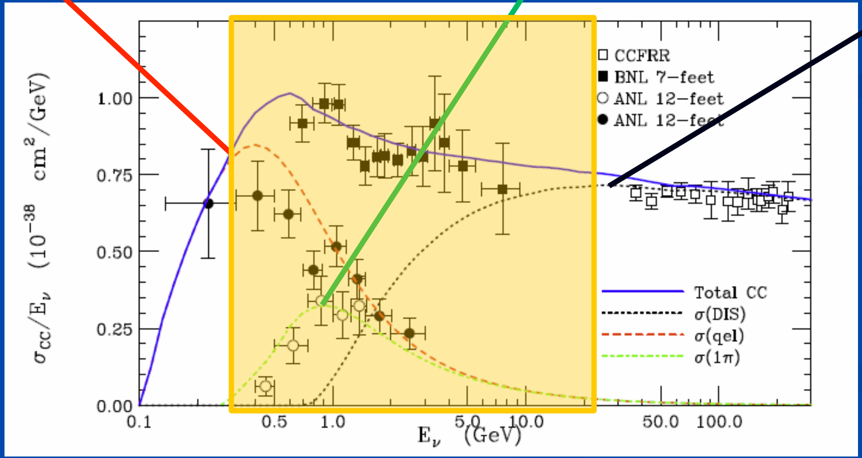


1π



DIS

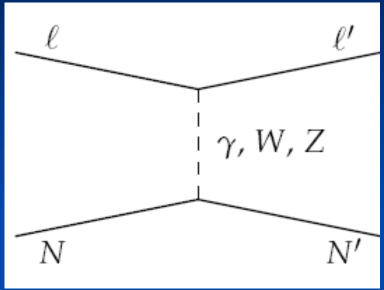




note:
10^{-38} cm² = 10^{-11} mb

yellow overlay:
relevant energy range

Quasielastic Scattering



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

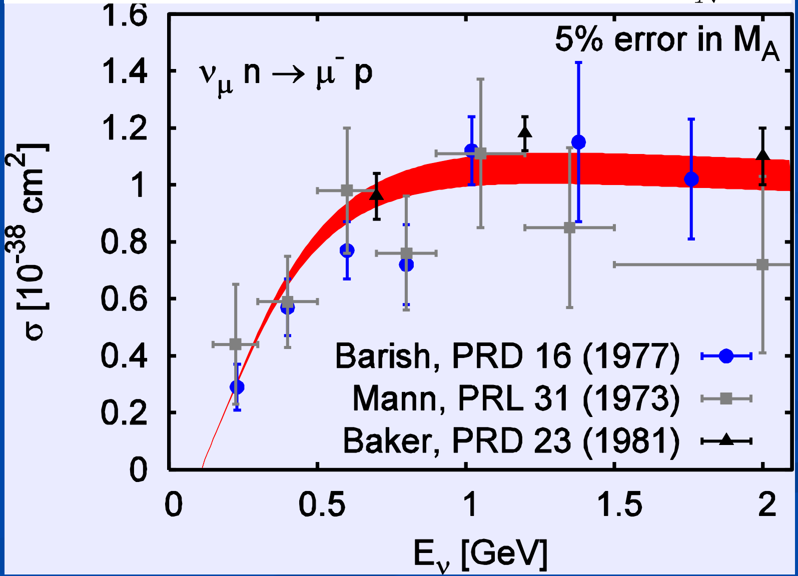
- Vector form factors from *e* –scattering
- axial form factors

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

  dipole ansatz for F_A with

  $M_A = 1$ *GeV*:

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



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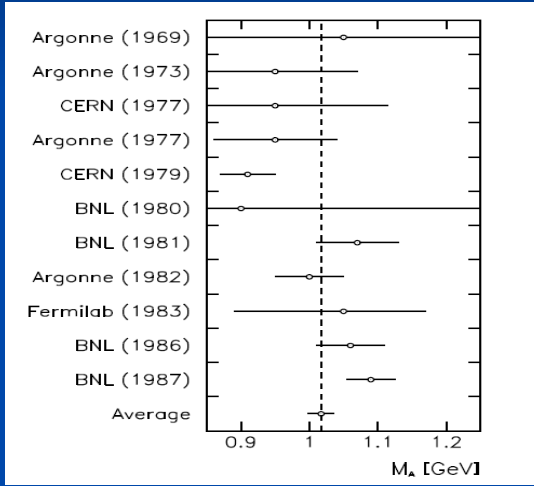
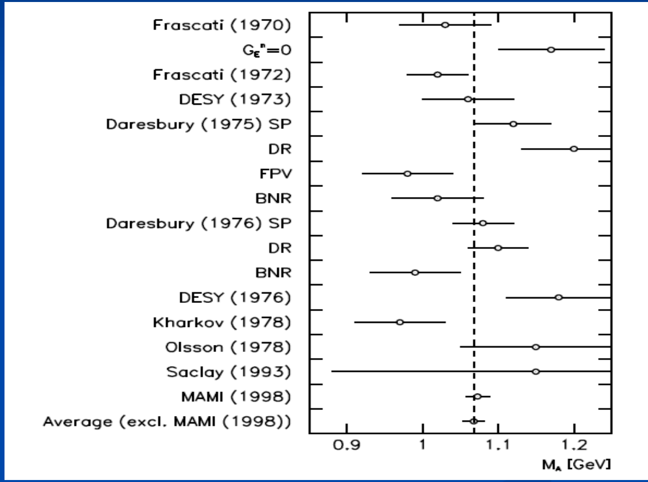
Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data

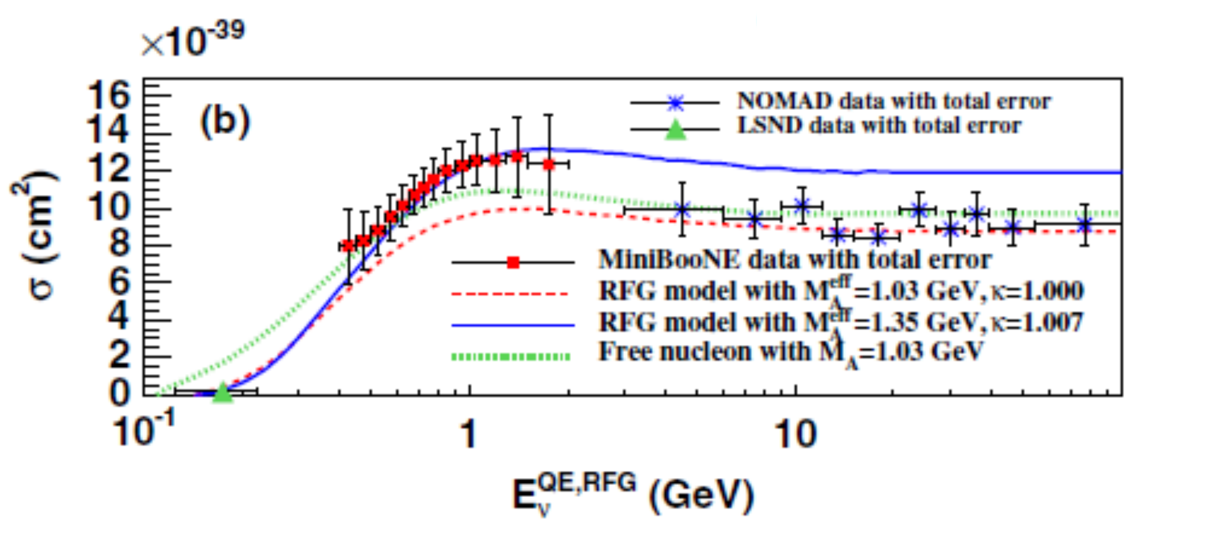




$M_A \cong 1.02$ GeV world average $M_A \cong 1.07$ GeV world average

Dipole ansatz is simplification, not good for vector FF

MiniBooNE QE puzzle



World average axial mass:
$M_A = 1.03$ GeV

Note: neither s nor E are directly measured

Pion Production

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

- pion production dominated by **P_{33}(1232) resonance**

- ***$C^V(Q^2)$*** 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

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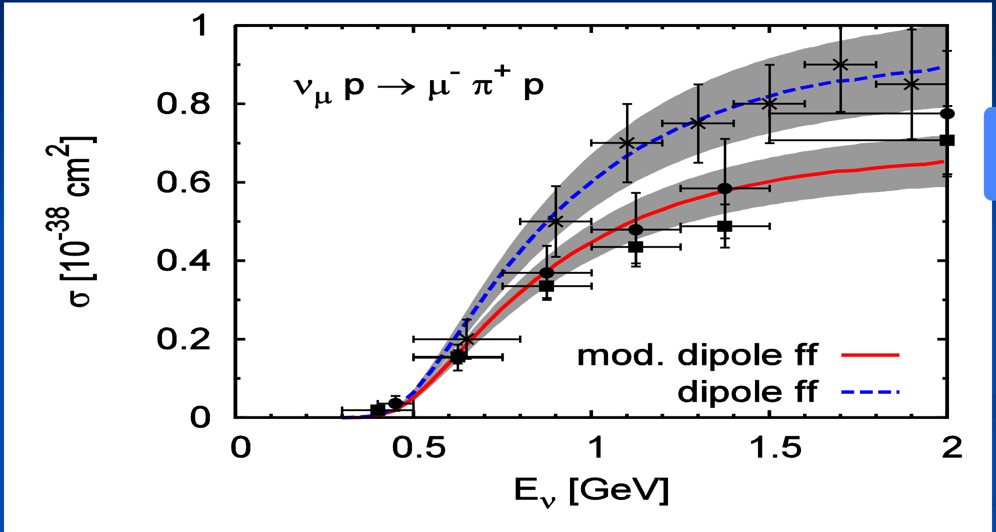
Pion Production



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

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

discrepancy between elementary data sets due to flux uncertainties (?)
→impossible to determine 3 axial formfactors

X-sections and Oscillations

- Need new, dedicated experiments for neutrino-nucleon interactions to explore axial hadron properties

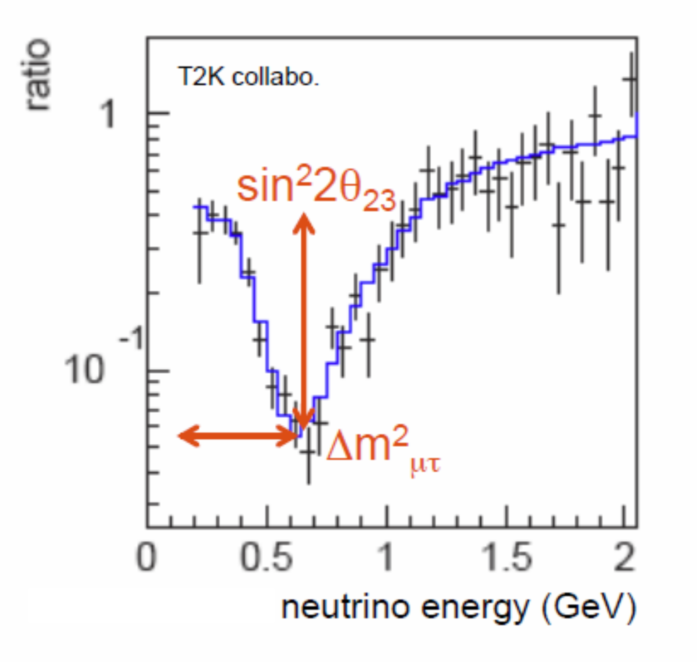
- Need neutrino-nucleon interactions also to extract neutrino properties from oscillation experiments

Neutrino Oscillations

Compare neutrino reaction X-section

- at near detector
- at far detector

and plot ratio as function of E_ν



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

Neutrino Oscillations

- State of affairs:
  - All mixing angles are known, with some errors
  - Mass hierachy not known
  - Possible CP violating phase not known
- Errors determined by total event rates and energy reconstruction

Neutrino Oscillations

Compare neutrino reaction X-section

- At near detector
- At far detector

and plot ratio as function of E_ν

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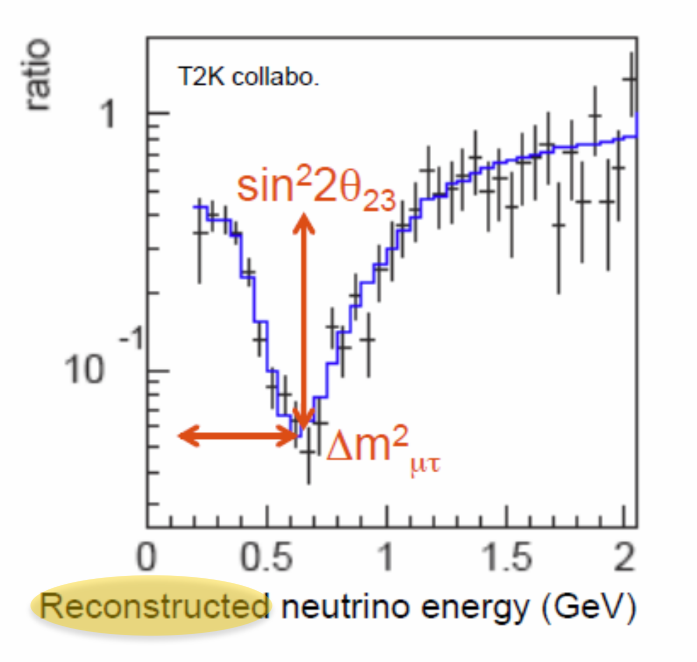
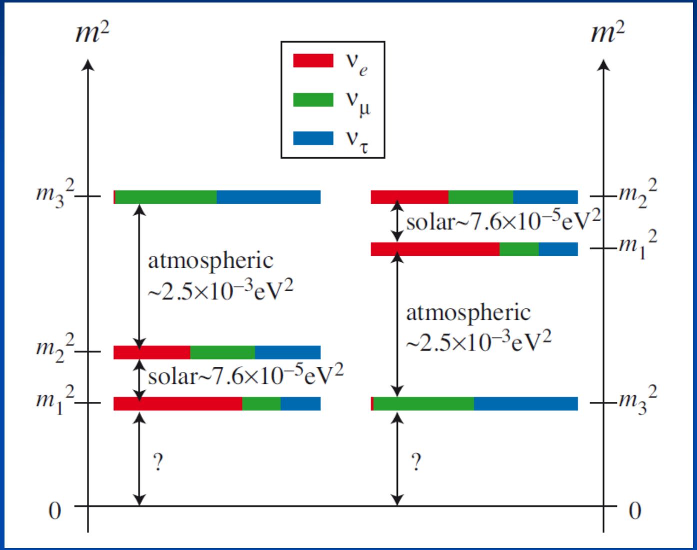


Neutrino Energy

- Neutrinos are produced as secondary decay products of pions and kaons.
- Neutrino energy distribution is broad
- How well do we have to know the incoming neutrino energy, event by event??

T2kK: Oscillation Signal
Dependence on Hierarchy and Mixing Angle



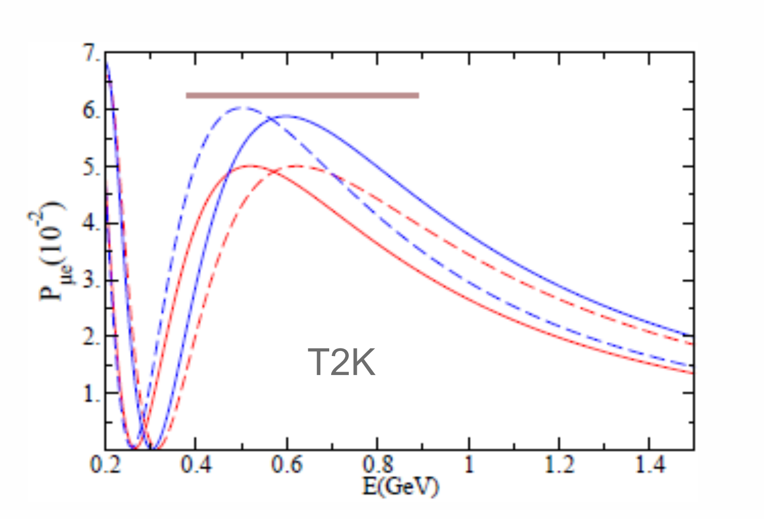


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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

Energy has to be known better than 50 MeV

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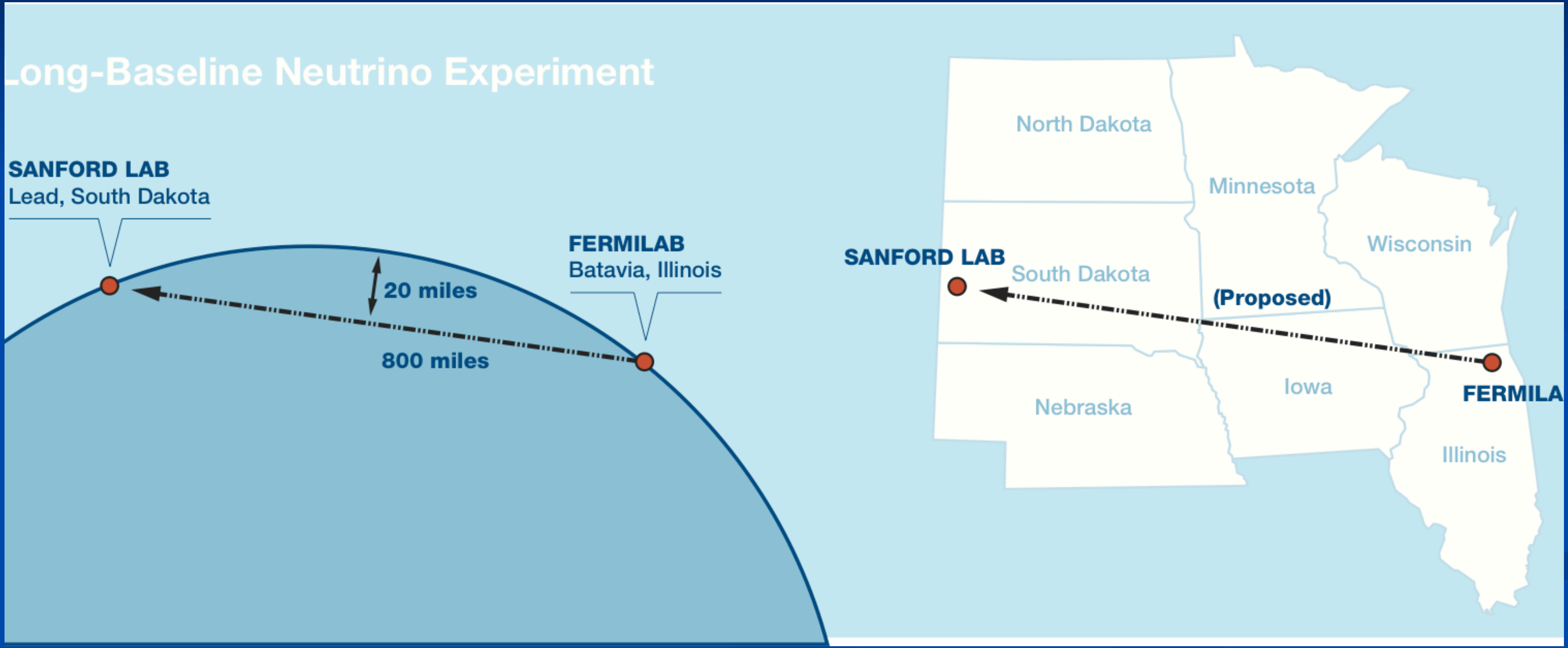
LBNE/F



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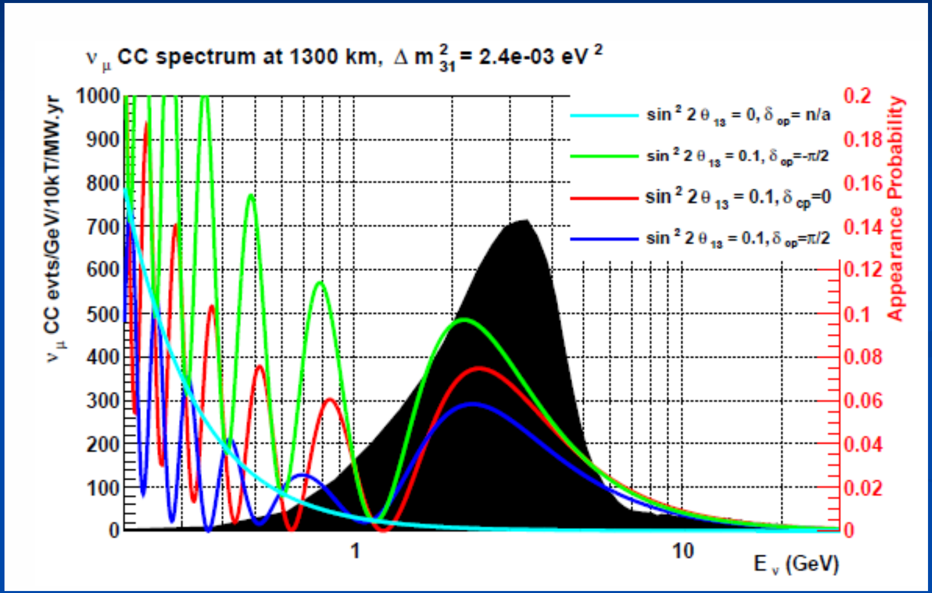
LBNE, δ_{CP} Sensitivity



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

Need to know neutrino energy to better than about 100 MeV

Need energy to distinguish between different δ_{CP}

Neutrino Oscillations

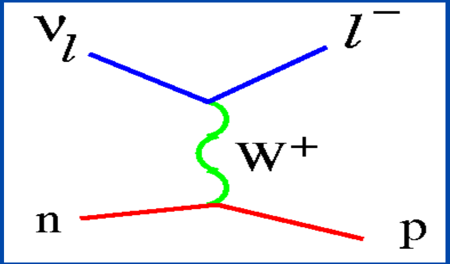
- Complications:
  - Neutrino beam energy not known
    - →Have to infer beam energy from final state
  - Nuclear targets *(O, C, Ar, Fe, …)*

Energy Reconstruction

- 2 methods to determine beam energy:
  - Calorimetry: $E_\nu = E_\mu + E_{vis} + E_{invis}$
  - QE-based
- *Both* measure only part of the final state, need theory for full final state, i.e. info on outgoing lepton *and* all hadrons

Energy Reconstruction by QE

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

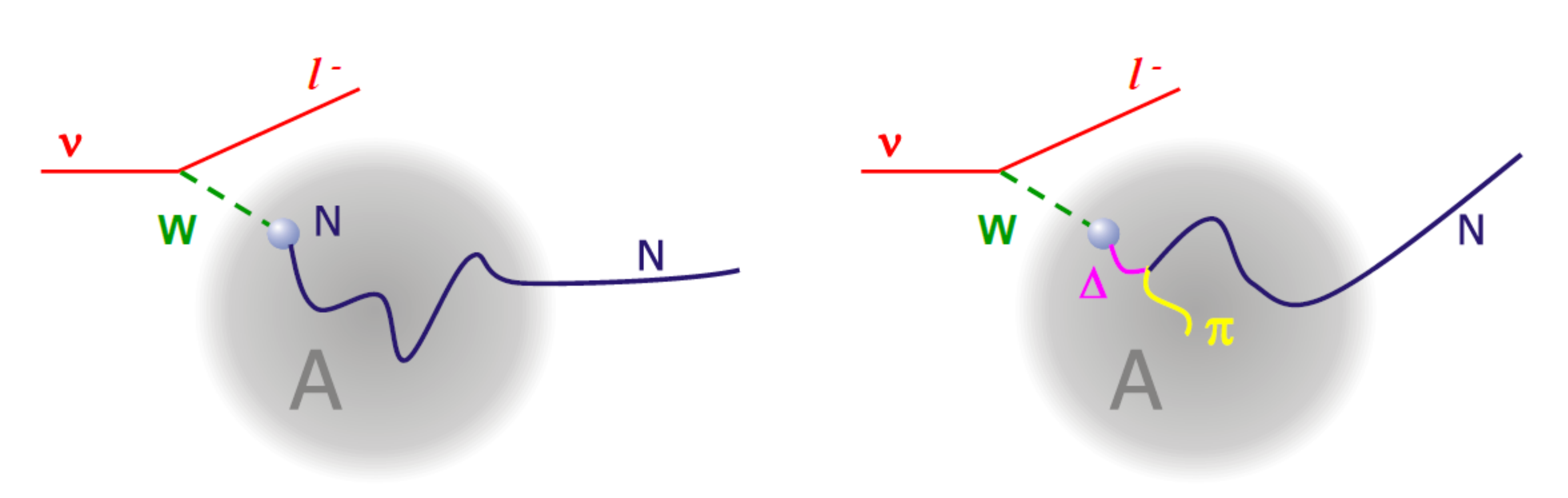


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

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

FSI in Nuclear Targets



Complication to identify QE, entangled with π production

Both must be treated at the same time

Need for Nuclear Theory

- Needed: Full event simulation for $\nu + A$ to
  - determine invisible energy
  - identify QE events

- Obtain transform. matrix from reconstructed to true energy

- Realize: not high energy of incoming neutrino beam is relevant, but instead energy- and momentum transfer
  ➔ ‚classical' nuclear physics is relevant

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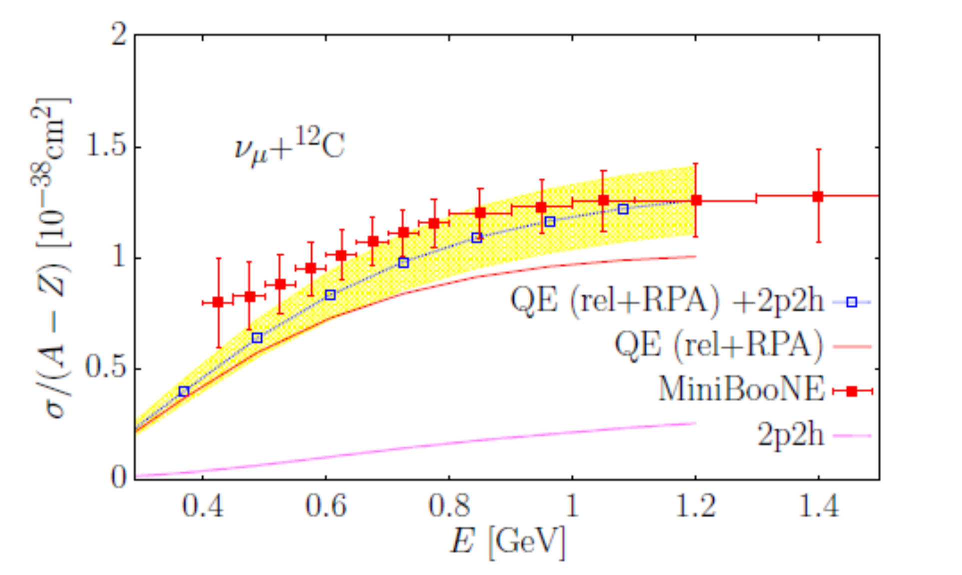
A wake-up call for the high-energy physics community:

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

Nuclear Theory

- Necessary Ingredients
  - Nuclear groundstate (correlations, spectral functions)
  - Nuclear reaction mechanisms (IA vs. 2p2h, coll. excit.)
  - Electroweak interaction vertices, in medium
  - Particle production
  - Propagation of all particles to final state
- Only capable method: Transport Theory, guidance from QGP generators

2p-2h contributions for neutrinos



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

A good example for processes beyond the Impuls approximation

Nuclear Theory

- Ground states, initial ew interactions and reaction mechanisms can (and must!) be tested with multitude of nuclear reactions, mainly $\gamma + A$ and $e + A$ (JLAB physics)
- Description of fsi can and must be tested with multitude of nuclear reactions in general
- Ultimate test: dedicated neutrino-nucleus reaction studies (e.g. MINERvA)
- All results in this talk obtained with GiBUU

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

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

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

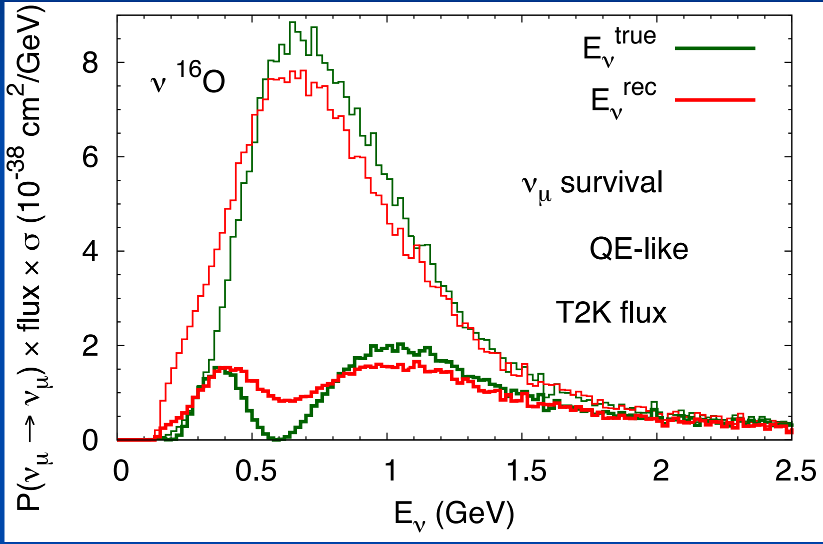
- **GiBUU** describes (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

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

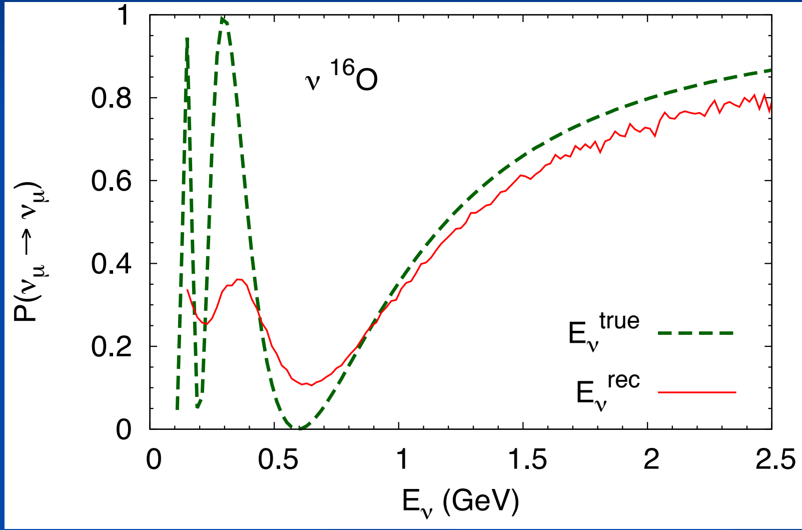
GiBUU is Nature

1. Generate millions of events with GiBUU
2. Analyze them as real data, reconstruct energy
3. Compare true with reconstructed energies and Q^2

Energy reconstruction and Oscillation signal in T2K

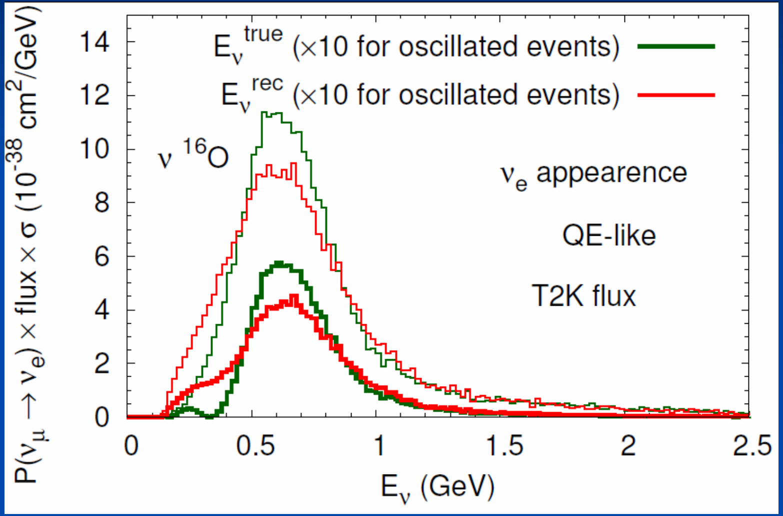


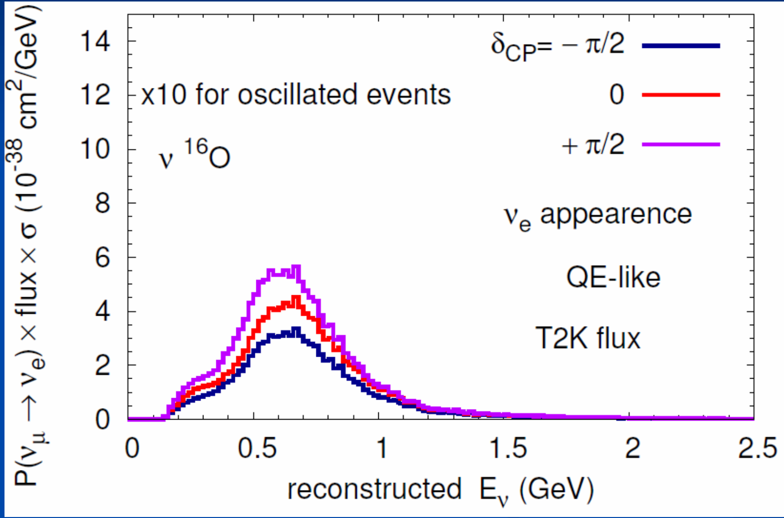
First minimum strongly affected



Ratio = oscillation probability

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





Uncertainties due to energy reconstruction(left) as large as δ_{CP} dependence (right)

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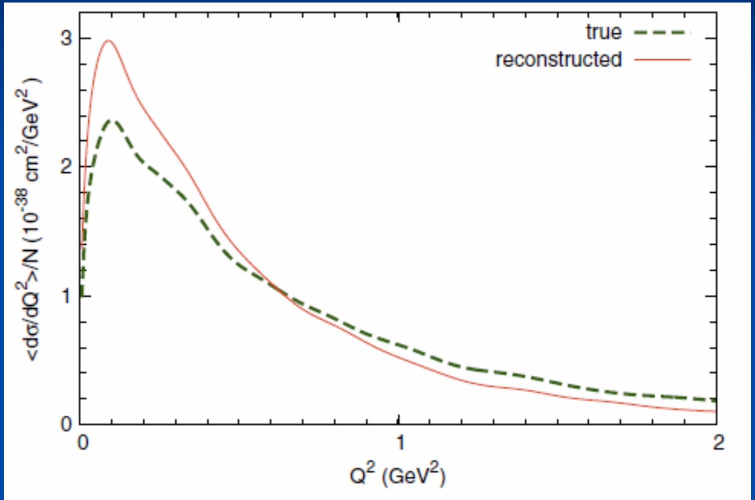
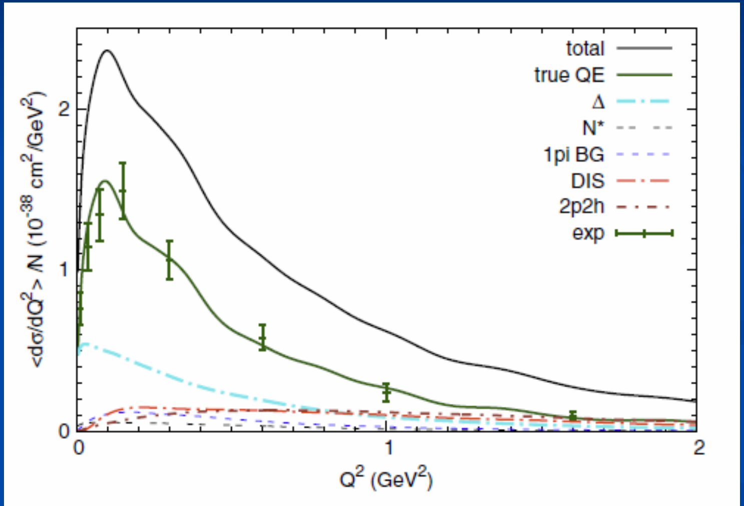
MINERνA Q^2 Reconstruction

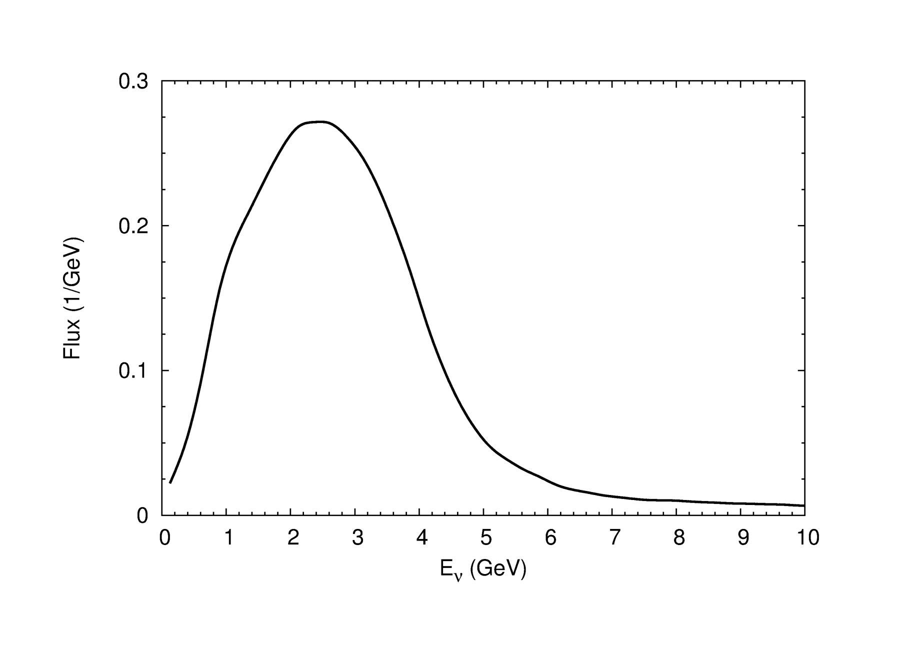
Only 0-pion events





Dramatic sensitivity to reconstruction in peak area: can be removed with generator,
But: how good is your generator? accuracy of ,data'??

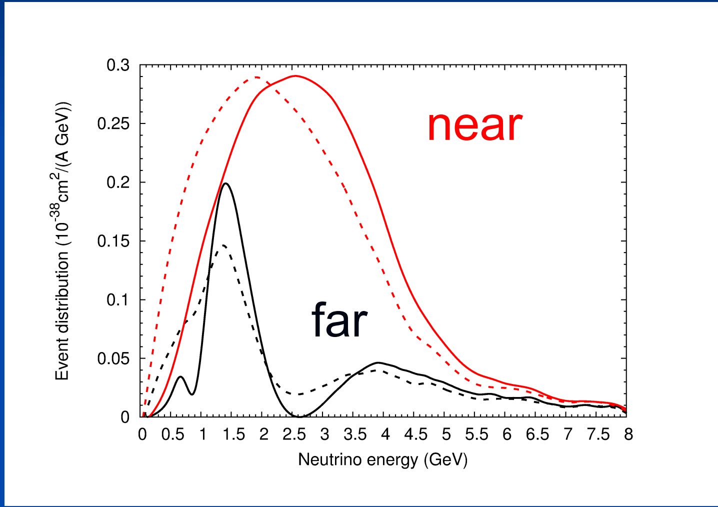
Energy Distribution for LBNE



All following results from
Mosel et al,
PRL 112, 151802 (2014)

QE Energy Reconstruction for LBNE

Muon survival in 0 pion sample



Dashed: reconstructed, solid: true energy

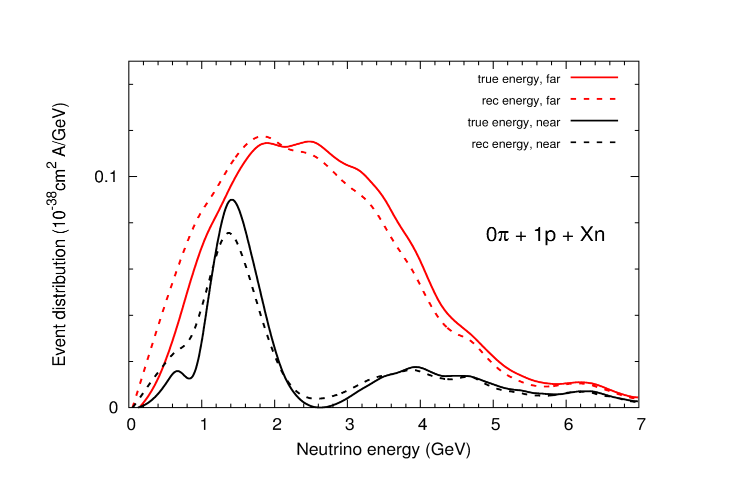
All calculations from GiBUU

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

In 0 pi event sample nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

QE Energy Reconstruction for LBNE

Muon survival in 0π + 1p + Xn sample

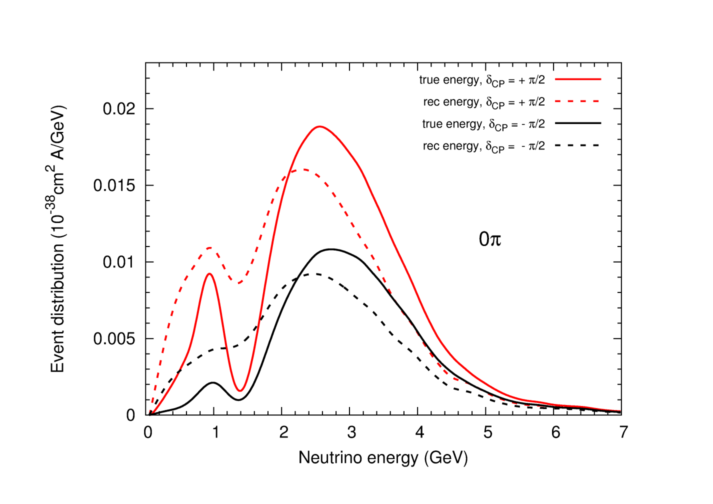


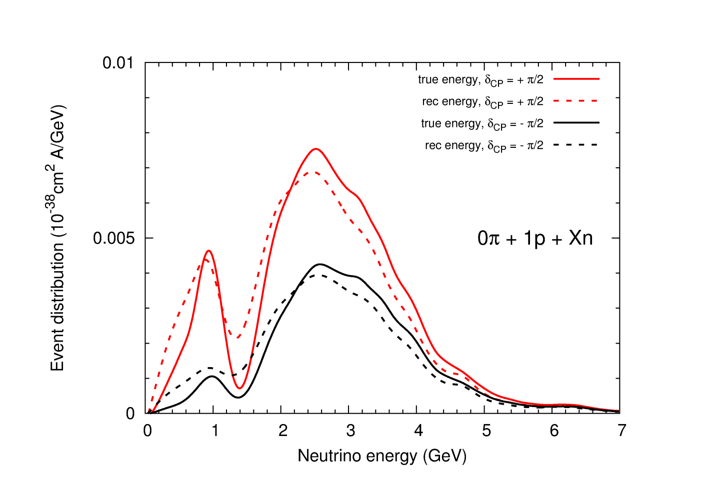
Dashed: reconstructed, solid: true energy

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

LBNE e-appearance

Sensitivity to δ_{CP}





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

Importance of Generators

- Generator is an important part of any experiment, more so than in any other nuclear physics experiment (except in QGP physics).
- Present (MINERvA, T2K, NOvA, …) and future experiments (LBNE) must use generators (GENIE, NEUT, ..) to extract the relevant physics
- At the end of these very sophisticated experiments you need to have an equally sophisticated code to extract the relevant physics.

Precision era requires better generators

- Present-day generators have evolved into black boxes with a patchwork of inconsistent theoretical recipes, fit parameters and tunes without solid theoretical justification and little predictive power
  - Partly due to insufficient theory support for generator development
- Needs a new effort to build on previous generator experience to construct a new, nuclear theory based, well-documented generator

What is needed?

- Need new data on *elementary targets*, primarily on pion production, input to all event simulations
- Need reaction studies on *nuclear targets* (MINERvA, CAPTAIN, ArgoNeut, ..) to control many-body effects and fsi
- Need a dedicated theory support program and a computational physics effort to construct a reliable generator

Need for solid Nuclear Physics Theory Support in Neutrino Physics

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