

# Neutrino Oscillations and Nuclear Physics

Ulrich Mosel



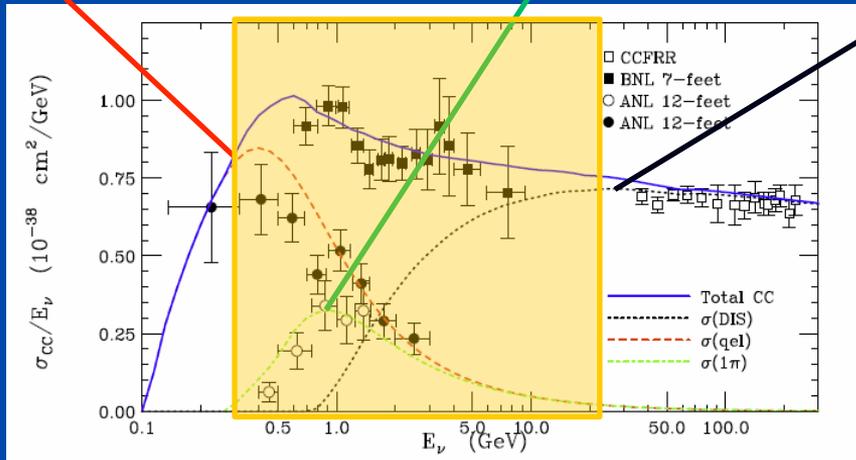
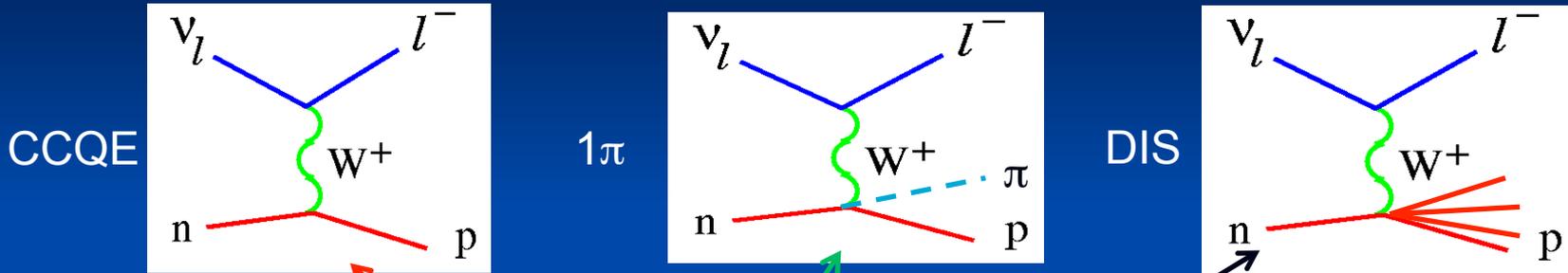
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# General Motivation

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

# Neutrino-nucleon cross section



note:  
 $10^{-38} \text{ cm}^2 = 10^{-11} \text{ mb}$

# Hadron Physics

DNP Townmeet

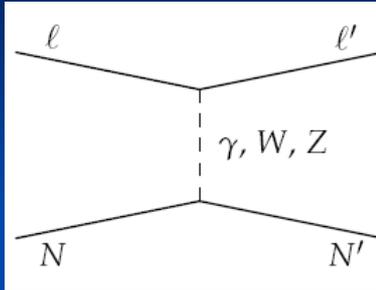


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# Quasielastic Scattering



- Vector form factors from  $e$ -scattering
- axial form factors

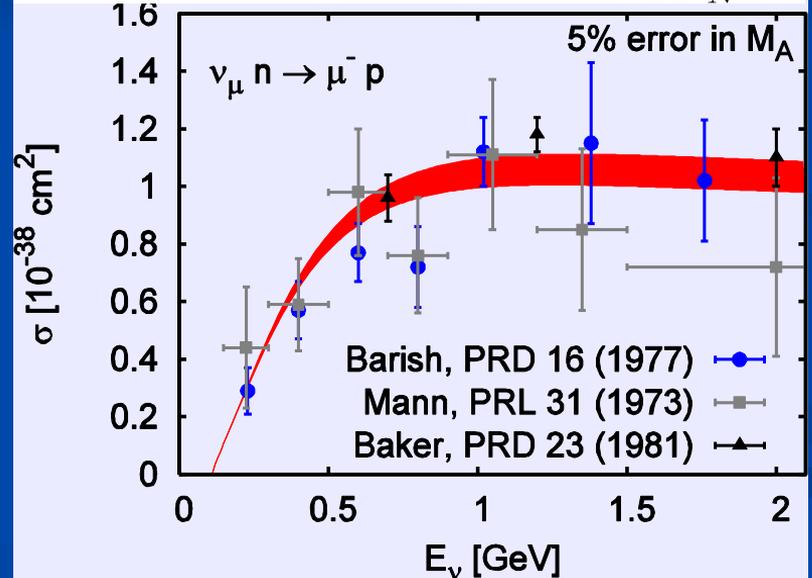
$F_A \leftrightarrow F_P$  and  $F_A(0)$  via **PCAC**

dipole ansatz for  $F_A$  with

$M_A = 1 \text{ GeV}$ :

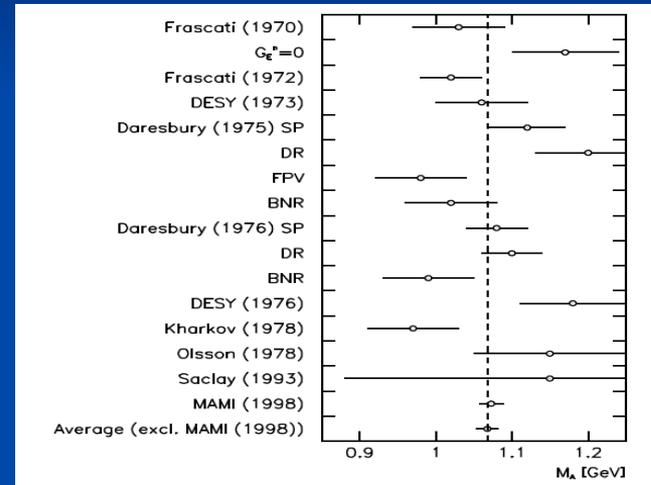
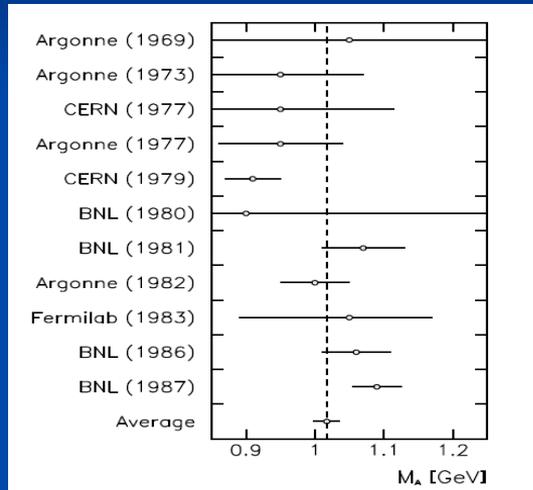
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

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



# Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data



$M_A \approx 1.02$  GeV world average

$M_A \approx 1.07$  GeV world average

Dipole ansatz is simplification, not good for vector FF

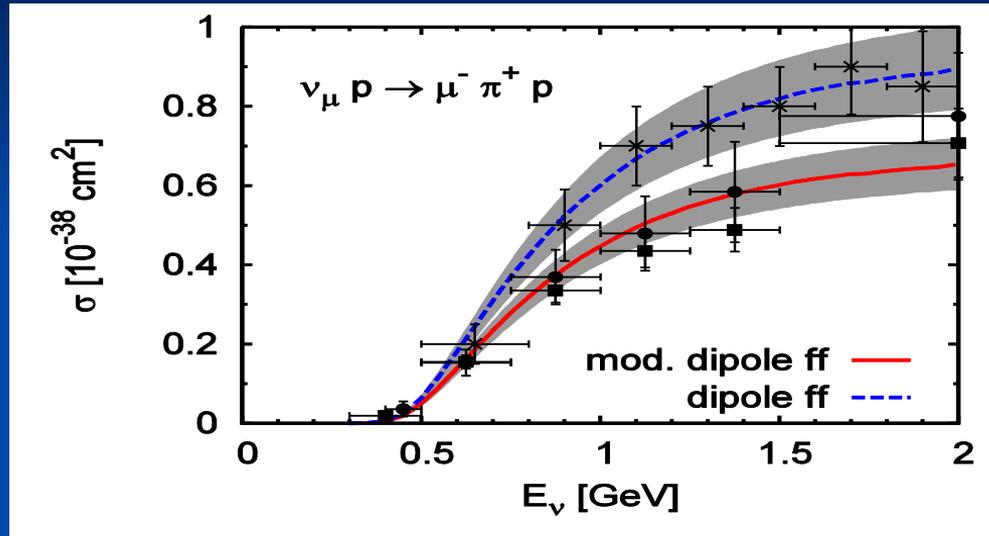
# Pion Production

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

$$+ \frac{C_3^A}{M_N} (g^{\alpha\mu} \not{q} - q^{\alpha} \gamma^{\mu}) + \frac{C_4^A}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^{\alpha} p'^{\mu}) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^{\alpha} q^{\mu}$$

- 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  $C_5^A$  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 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



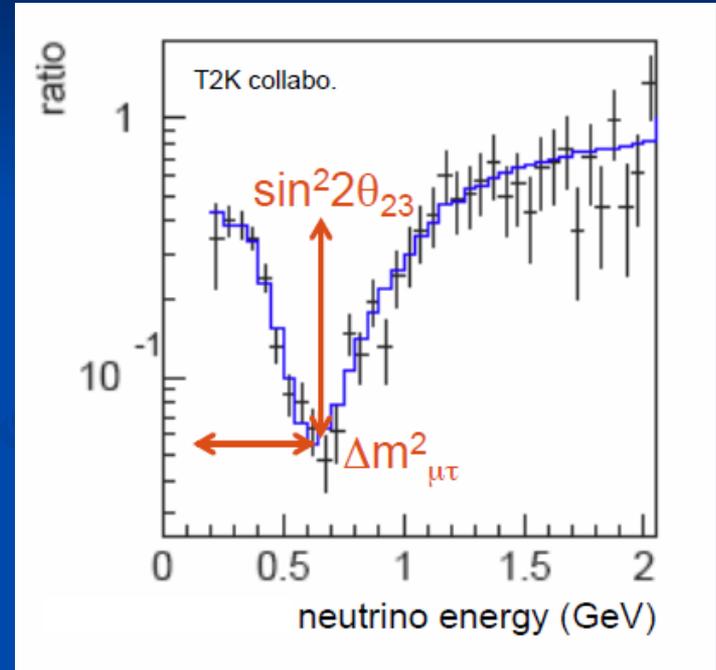
# Neutrino Oscillations

Compare neutrino reaction  
X-section

- at near detector
- at far detector

and plot ratio as function of  $E_\nu$

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



# Neutrino Oscillations

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



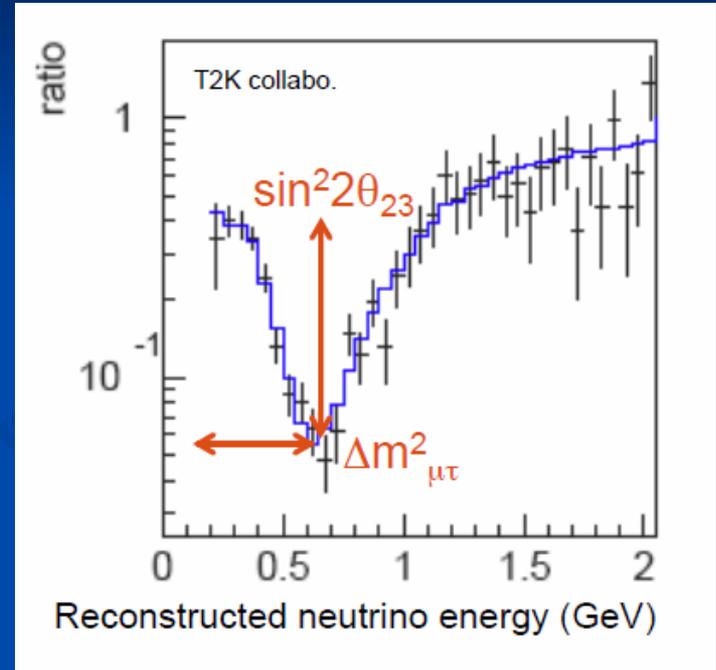
# Neutrino Oscillations

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# Oscillation Signal Dependence on Hierarchy and Mixing Angle

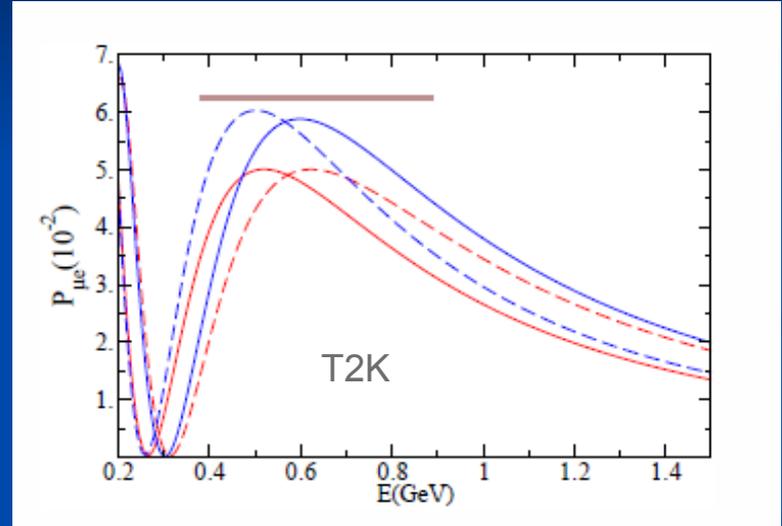
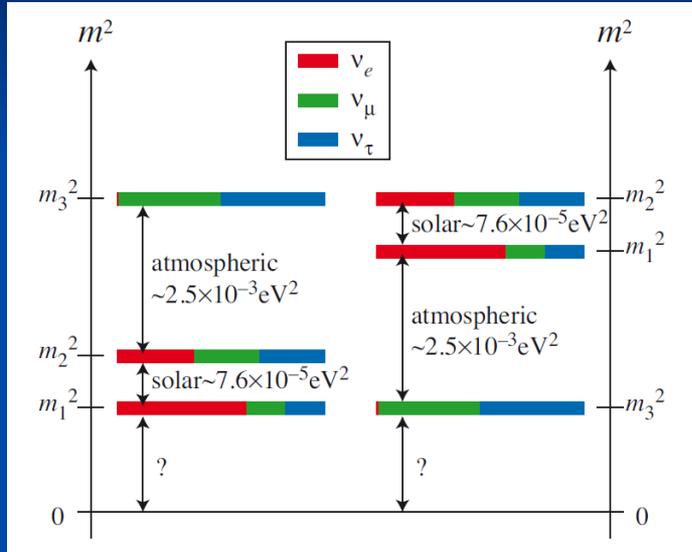


Fig. 2.  $P_{\mu e}$  in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive  $\theta_{13}$ , dashed curves negative  $\theta_{13}$ .

Energy has to be known better than 50 MeV

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

# LBNE/F

## Long-Baseline Neutrino Experiment

**SANFORD LAB**  
Lead, South Dakota

**FERMILAB**  
Batavia, Illinois

20 miles

800 miles

**SANFORD LAB**

North Dakota

Minnesota

Wisconsin

South Dakota

(Proposed)

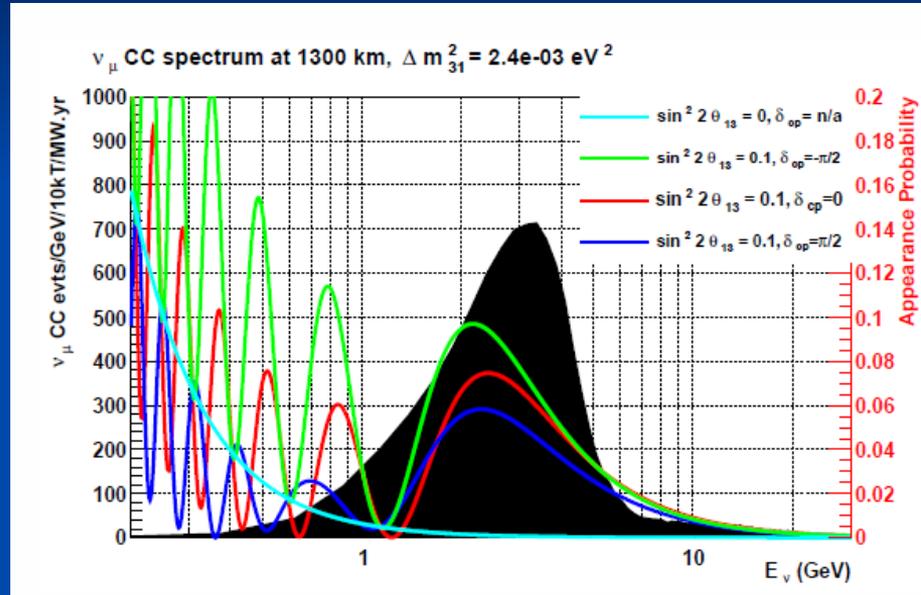
Iowa

Nebraska

**FERMILAB**

Illinois

# LBNE, $\delta_{CP}$ Sensitivity



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

Need to know neutrino  
energy to better than  
about 100 MeV

Need energy to distinguish between different  $\delta_{CP}$

# Neutrino Oscillations

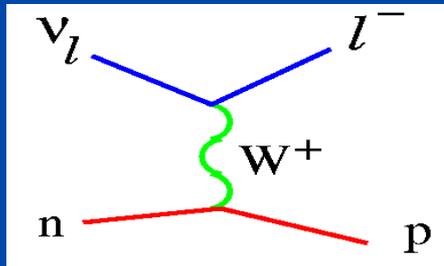
- Complications:
  - Neutrino beam energy not known
    - → Have to infer beam energy from final state
  - Nuclear targets (*O, C, Ar, Fe, ...*)

# 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

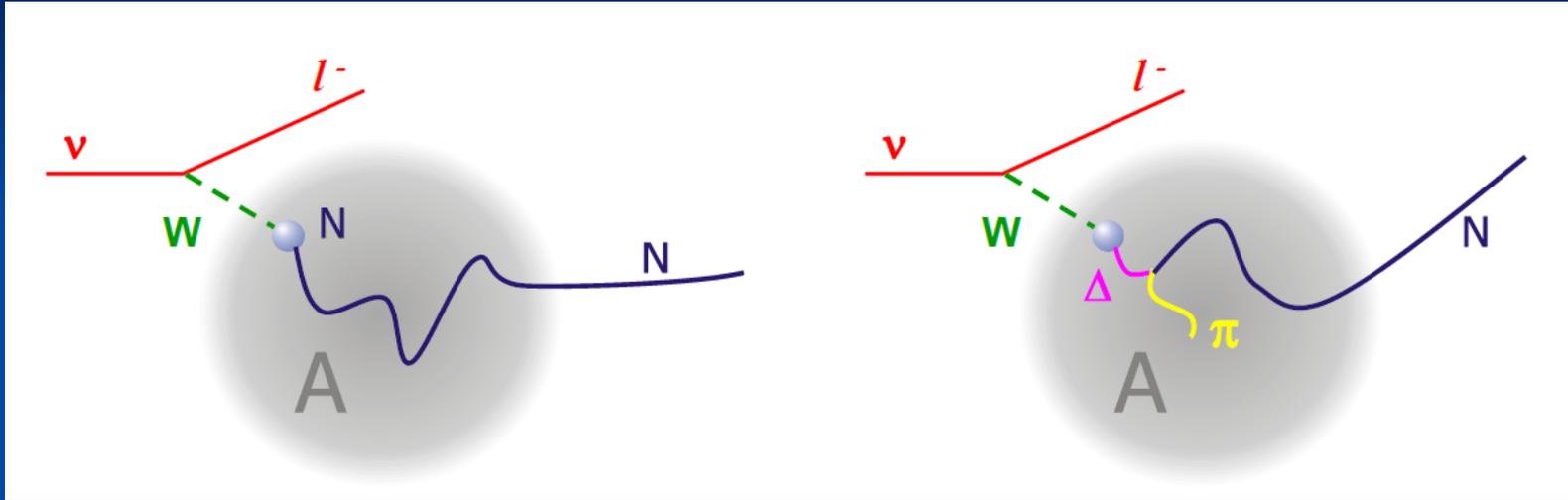
- In QE scattering on neutron at rest, only  $l + p, 0 \pi$  is outgoing. lepton determines neutrino energy:



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

- **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  $\pi$  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 event
    - Similar to event generators for ultrarelativistic heavy ion collisions
- 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



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



Low-Energy  
Nuclear Physics  
determines response  
of nuclei to neutrinos

NuSTEC School Initiative  
goes into this direction

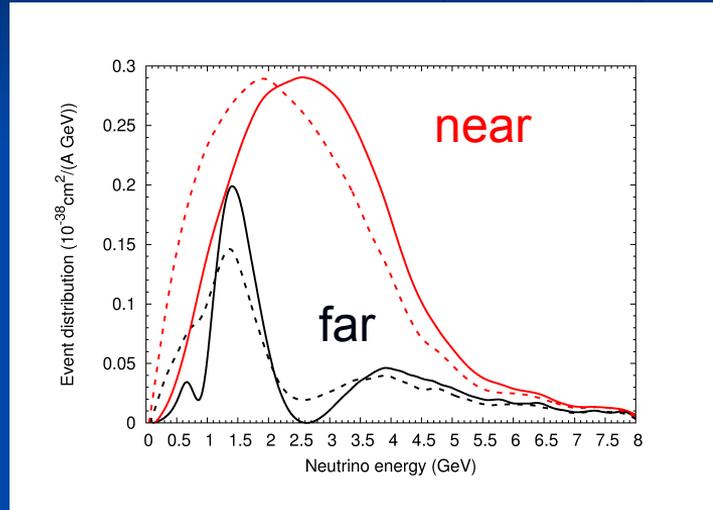
# Nuclear Theory

- 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)



# QE Energy Reconstruction for LBNE

Muon survival in 0 pion sample



Dashed: reconstructed,  
solid: true energy

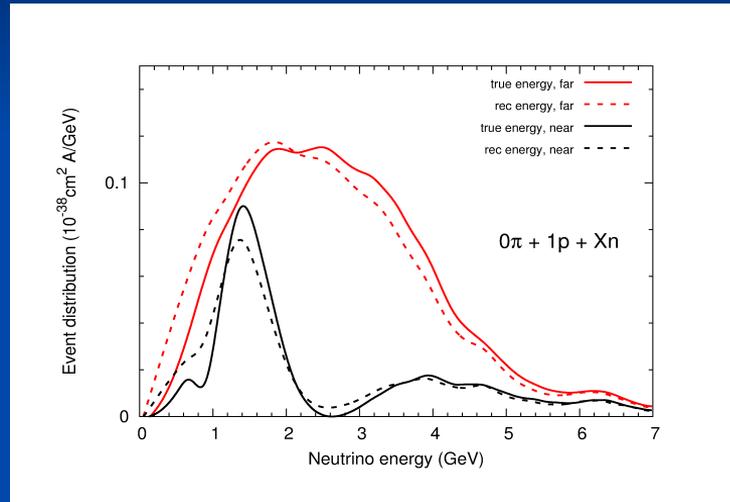
All calculations from GiBUU

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

Nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

# QE Energy Reconstruction for LBNE

Muon survival in  $0\pi + 1p + Xn$  sample

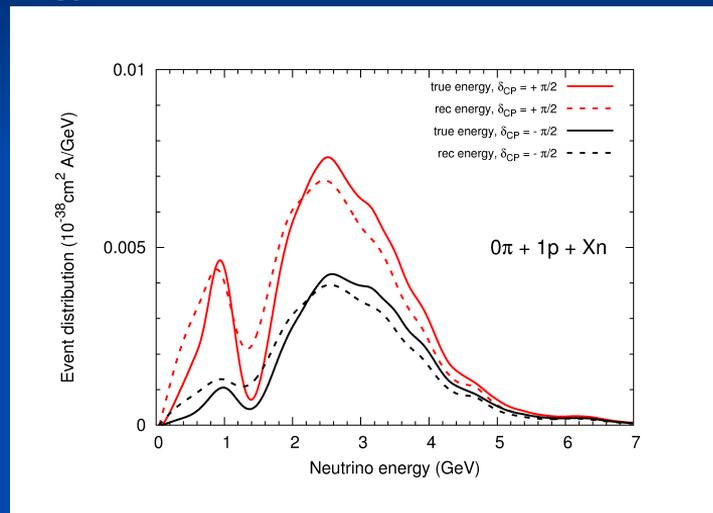
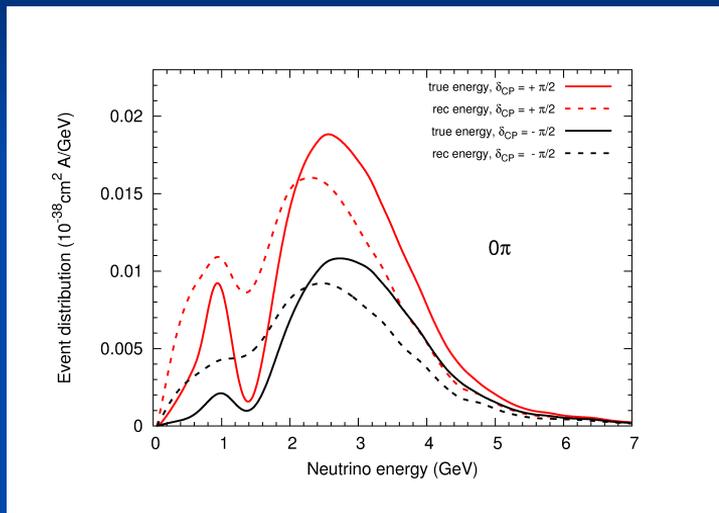


Dashed: reconstructed,  
solid: true energy

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

# LBNE e-appearance

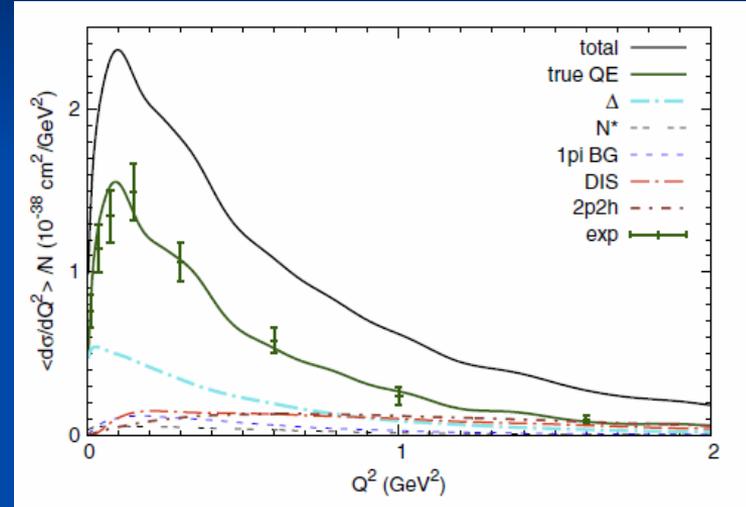
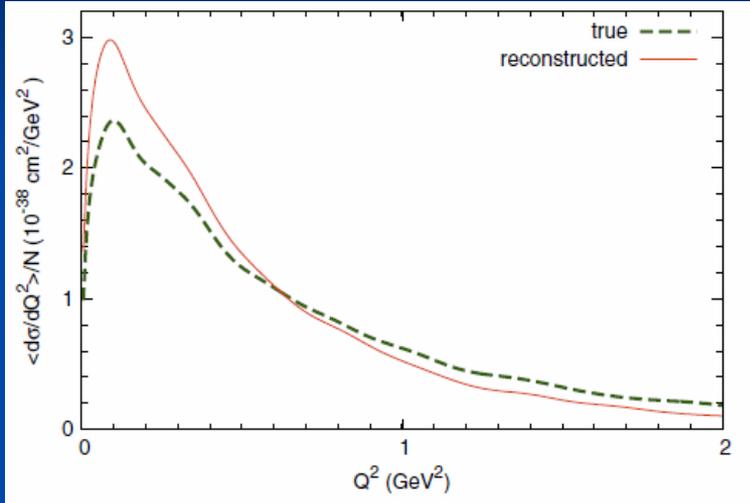
## Sensitivity to $\delta_{CP}$



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

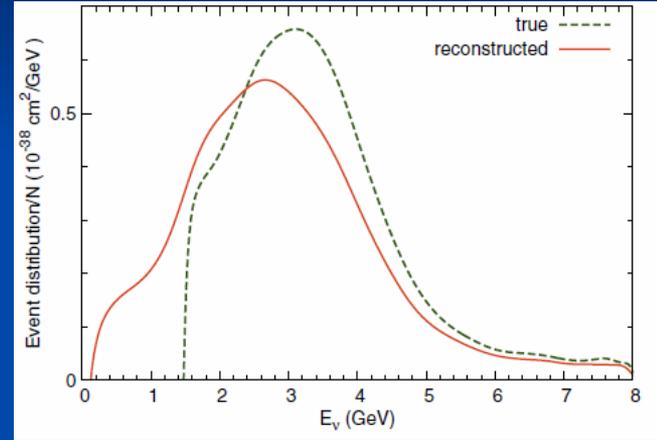
# MINERvA $Q^2$ Reconstruction

Only 0-pion events

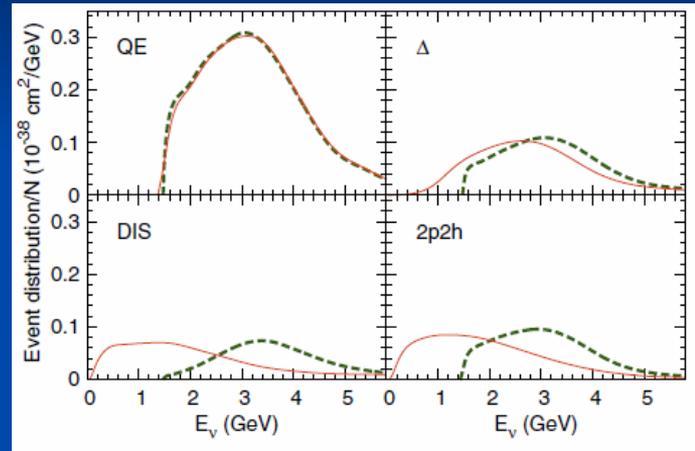


Dramatic sensitivity to reconstruction in peak area: can be removed with generator,  
But: how good is your generator? accuracy of 'data'??

# MINERvA Analysis



only 0-pion events



Mosel et al.,  
PR D89 (2014) 093003

Reconstruction changes not only energy, but also flux distributions

# What is needed?

- Need new data on elementary targets, input to all event simulations
- Need reaction studies on nuclear targets (MINERvA, CAPTAIN, ArgoNeut, ..)
- Need dedicated and computational physics effort to construct a reliable generator



# Precision era requires better generators

- Present (MINERvA, T2K, NOvA, ...) and future experiments (LBNE) must use generators (GENIE, NEUT, ..) to extract the relevant physics
- 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

# Backup Infos

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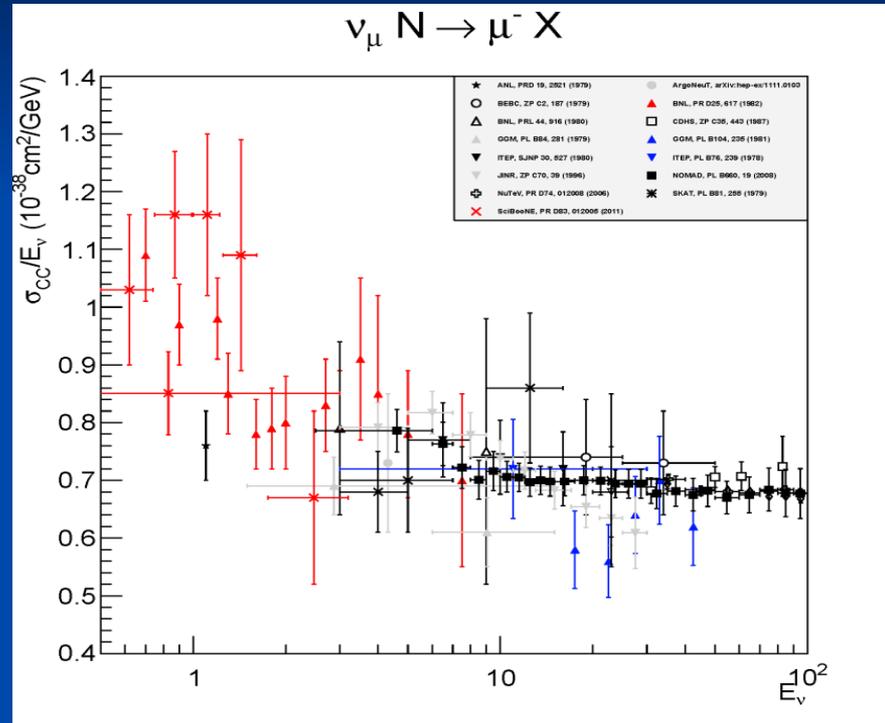
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# LBNE/F Objectives

- The **primary objectives** of LBNE, in priority order, are the following experiments:
  1. precision measurements of, the parameters that govern  $\nu_\mu \rightarrow \nu_e$  oscillations; this includes precision measurement of the third mixing angle, measurement of the CP violating phase  $\delta_{CP}$ , and determination of the mass ordering (the sign of  $\Delta m^2_{32}$ ).
  2. precision measurements of  $\theta_{23}$  and  $|\Delta m^2_{32}|$  in the  $\nu_\mu$ -disappearance channel.
- This precision can only be achieved with a state-of-the-art nuclear theory based generator (→ Computational Nuclear Physics)



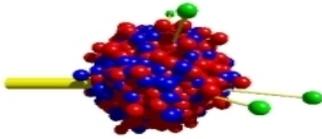
# Neutrino-Nucleon Total Cross Sections



# 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





Institut für Theoretische Physik, JLU Giessen

**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!

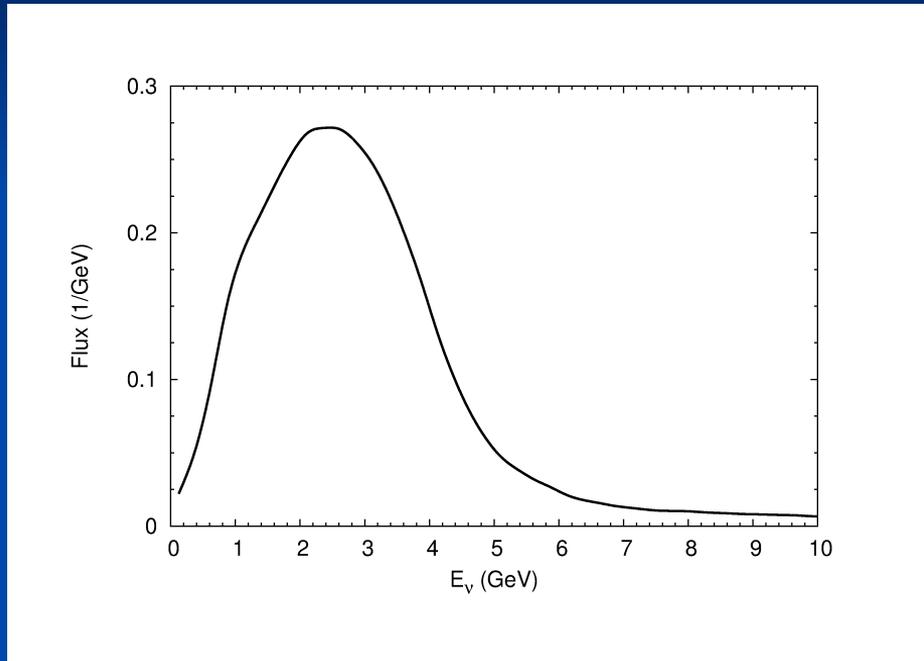


# Relation to e-scattering

- Explore axial couplings
- Inclusive X-sections comparable
- Relation to exclusive  $(e, e'p)$  not possible since neutrino energy not known



# Energy Distribution for LBNE



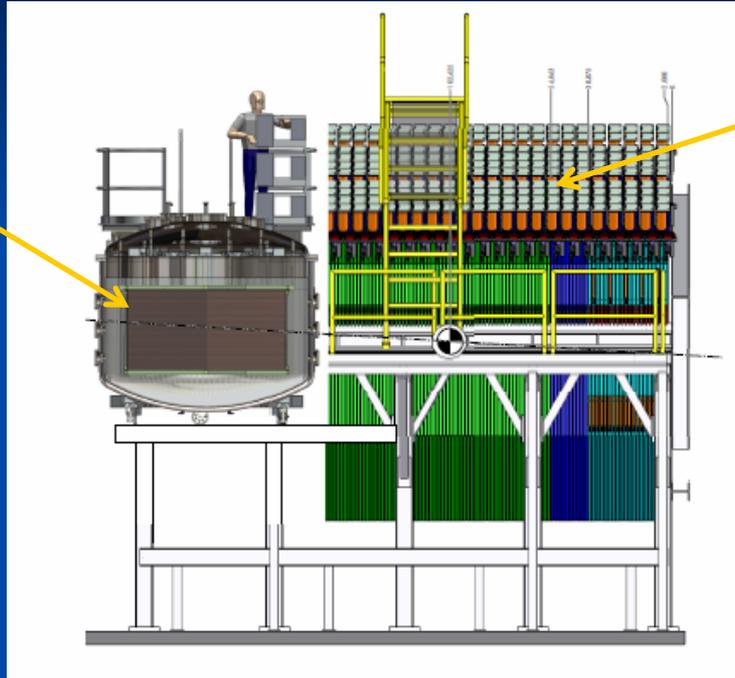
All following results  
from  
Mosel et al,  
PRL 112, 151802  
(2014)

# MINERvA/CAPTAIN

LAr TPC



NuMI beam



MINERvA

CAPTAIN:  
LAr as in LBNE

Corresponding electron  
experiment at JLAB  
PR12-14-012 approved

Good test ground for theory and preparation for LBNE

# Nuclear Theory for High Energy Experiments

- Generator is an important part of any experiment, more so than in any other nuclear physics experiment (except in QGP physics).
- At the end of a very sophisticated experiment you need to have an equally sophisticated code to extract the relevant physics
- **Generator-Development and Theory support must be integral part of any experiment (and its funding)!**



# How to proceed

- Abandon the firewall between High Energy Physics and Nuclear Theory
  - In publications: Phys. Rev. D vs. Phys. Rev C
  - In funding: A High-Energy experiment needs Nuclear Theory as an integral part.
- It is time to start development of a new state-of-the-art generator to be ready when LBNF is

