Neutrino Interactions and Long-Baseline Physics

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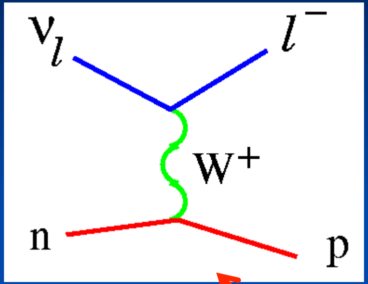
General Motivation

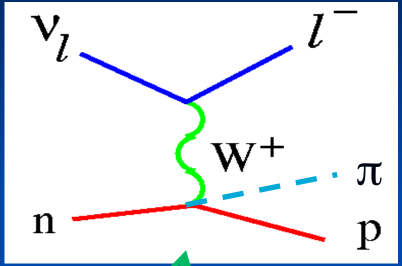
- Aspects of neutrino-nuclear reactions
  - Hadron physics:
    - axial couplings of nucleon resonances
    - reaction rates
  - Neutrino oscillation physics:
    - energy reconstruction
  - Dark Matter Background

Neutrino-nucleon cross section

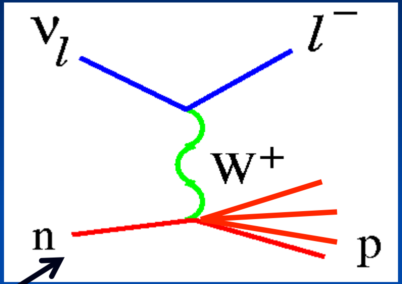
CCQE

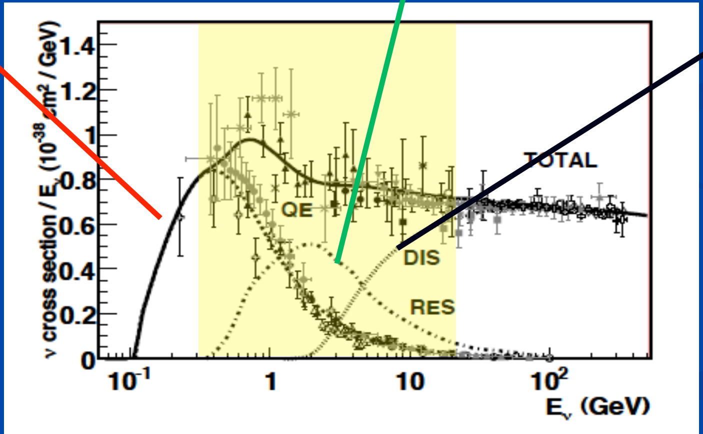


1π



DIS





From: J.A. Formaggio, G.P. Zeller

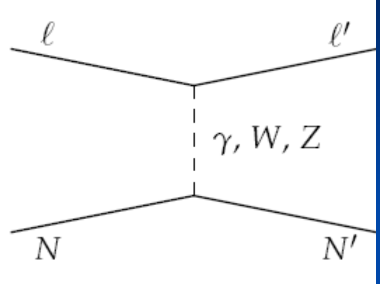
note:
10^{-38} cm² = 10^{-11} mb

Yellow: energy range of present experiments

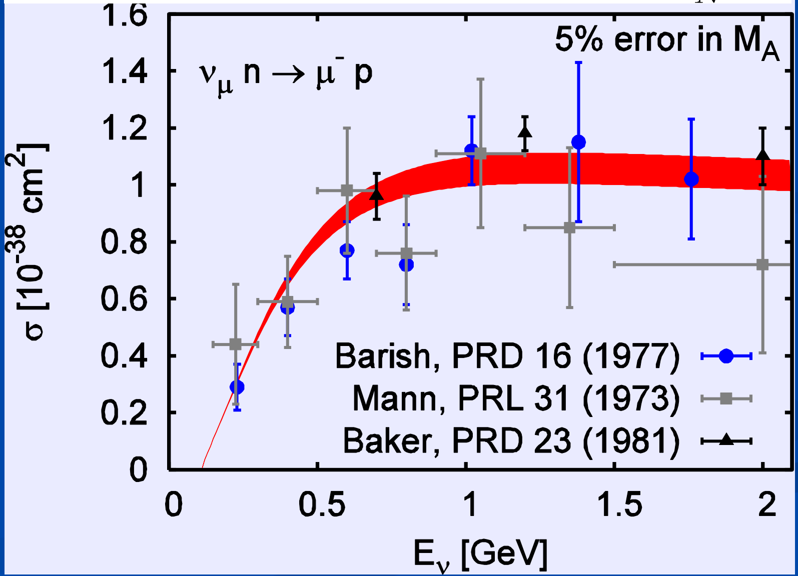
Neutrino Cross Sections

- Cross sections on the *nucleon*:
  - QE
  - Resonance-Pion Production + Born terms
  - Deep Inelastic Scattering → Pions

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**

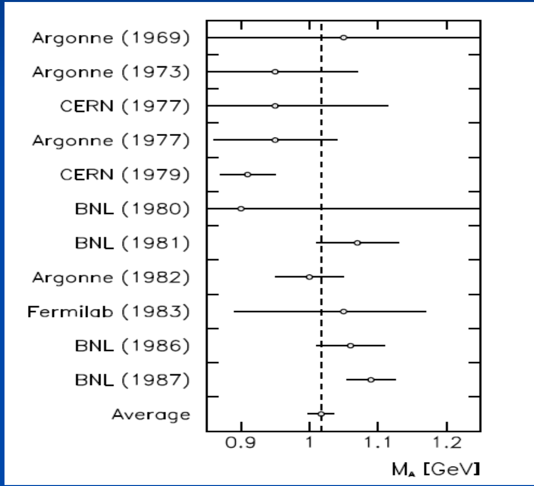
  dipole ansatz for F_A with

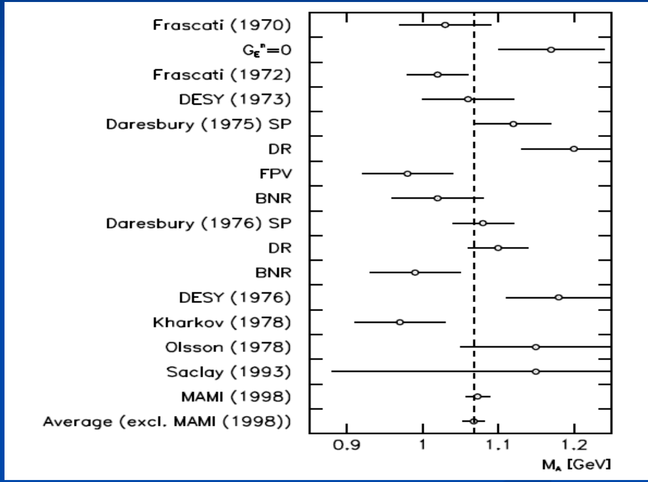
  M_A= 1 GeV:

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

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

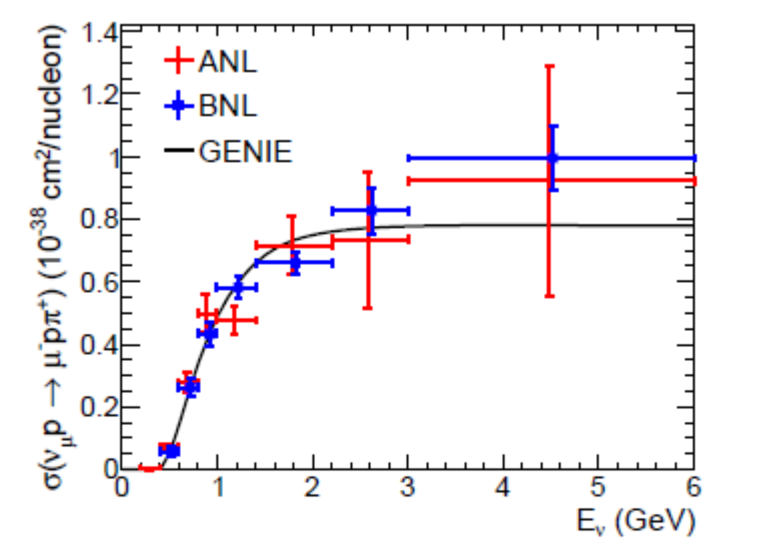
Pion Production

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

- 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

Pion Production



C. Wilkinson et al, arXiv:1411.4482 [hep-ex]

Reanalysis of BNL data (posthumous flux correction) by T2K group:
C.Wilkinson et al,
Arxiv:1411:4482 [hep-ex]

Agrees with earlier findings in
Graczyk et al, Phys.Rev. D80 (2009) 093001
Lalakulich et al, Phys.Rev. D82 (2010) 093001

One pion puzzle solved: ANL data preferable, but only C_5 determined
BUT: Sato et al find extraction of p X-section from D-measurement doubtful!

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Neutrino Cross Sections

- Cross sections on the *nucleus*:
  - QE + fsi
  - Resonance-Pion Production + reabsorption
  - Deep Inelastic Scattering → Pions + reabsorpt
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and pion production

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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 : **Buss et al, Phys. Rept. 512 (2012) 1**
- code available : 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!

Transport Equation

Collision term

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

Drift term

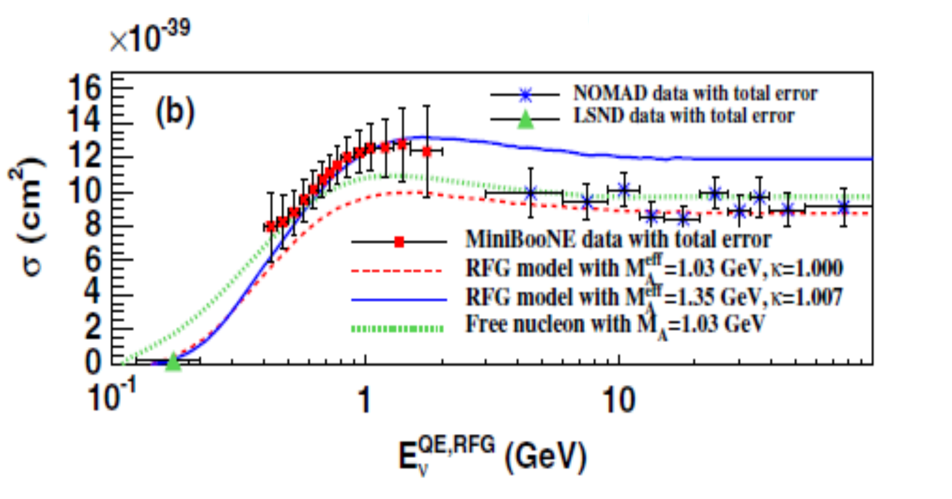
$$\left[\left(1-\frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial}{\partial \mathbf{p}} + \frac{\partial H}{\partial t}\frac{\partial}{\partial p^0} + \mathrm{KB\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

$$= \text{- loss term} + \text{gain term}$$

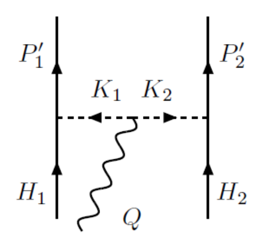
$$F(x,p) = 2\pi g f(x,p) A(x,p).$$

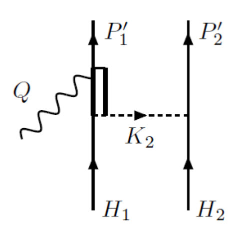
Spectral function

CCQE and Many-Body Interactions



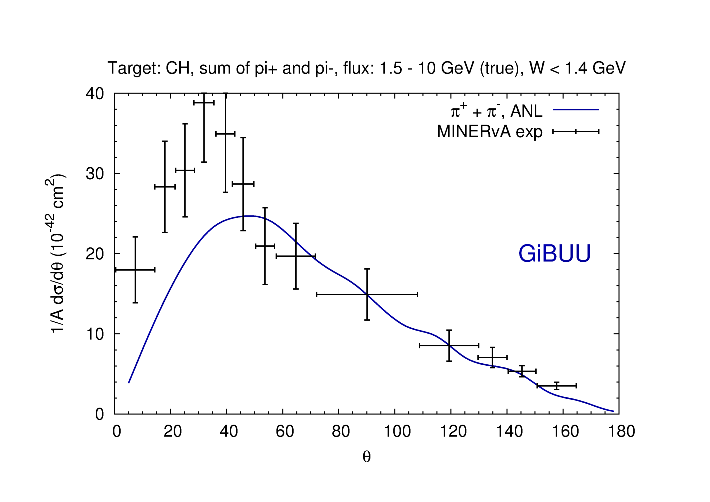
MiniBooNE

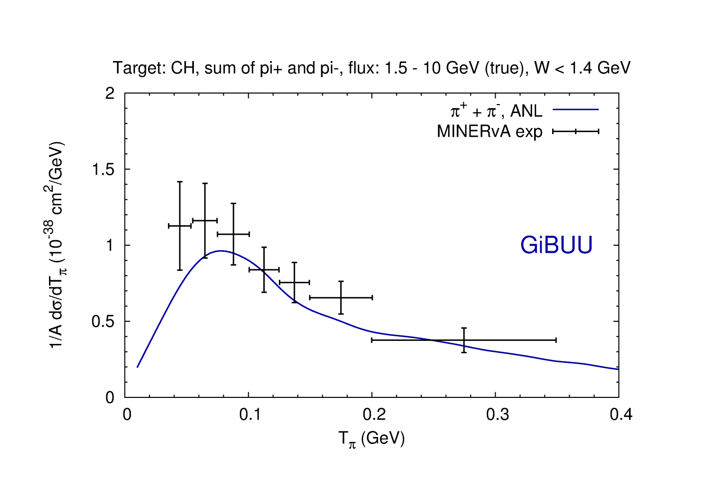




QE-like
= CCQE + 2p2h + stuck pions

MinervA Pions





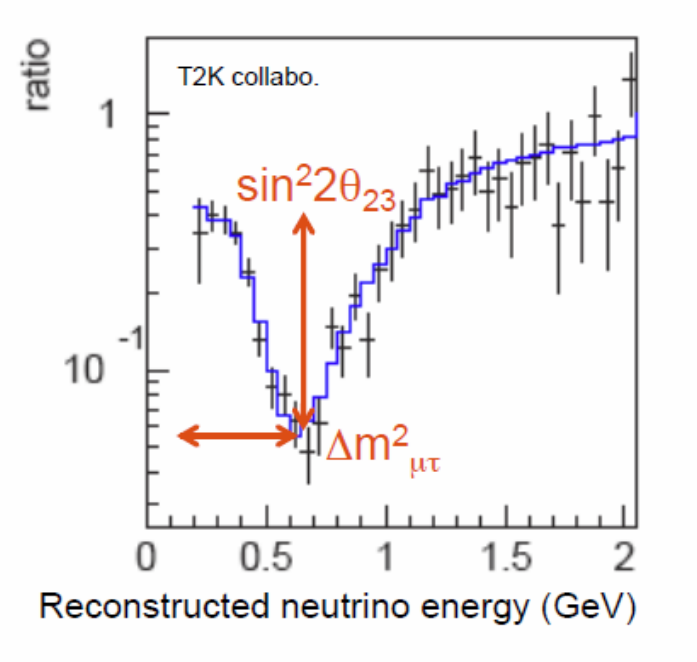
Discrepancy at small Θ/T_{π};
Coherent contribution?

Neutrino Oscillations

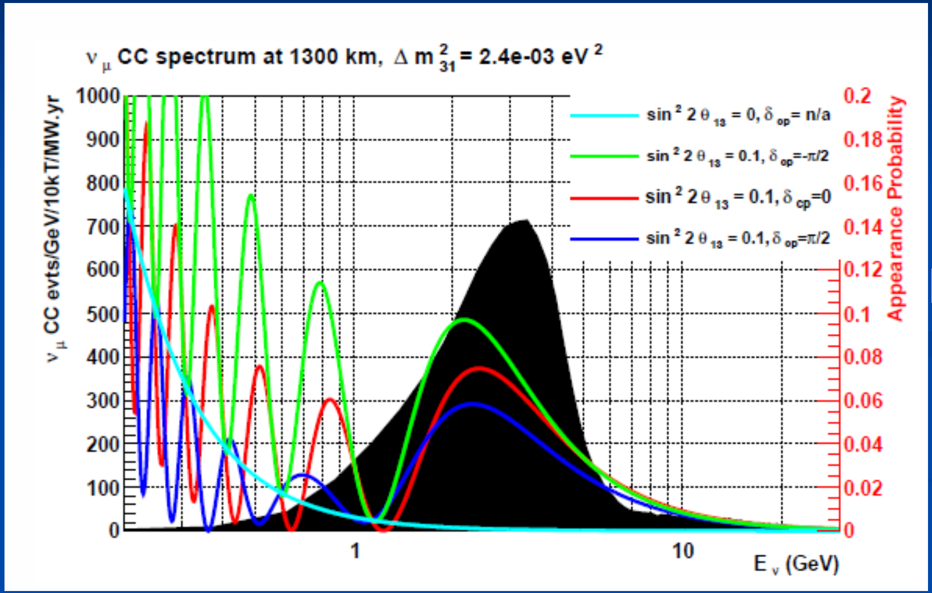
- State of affairs:
  - All mixing angles are known, with some errors
  - Mass hierachy not known
  - Possible CP violating phase not known
- Errors determined by total event rates and energy reconstruction:
  How well do we have to know the neutrino energy?

Observable Oscillation Parameters

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



LBNE, δ_{CP} Sensitivity



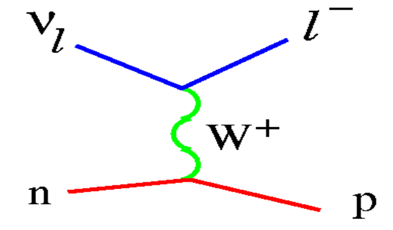
Appearance probability: $P_{\mu \to e}$

Need energy to distinguish between different δ_{CP}

Need to know neutrino energy to better than about 100 MeV

Energy Reconstruction by QE

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

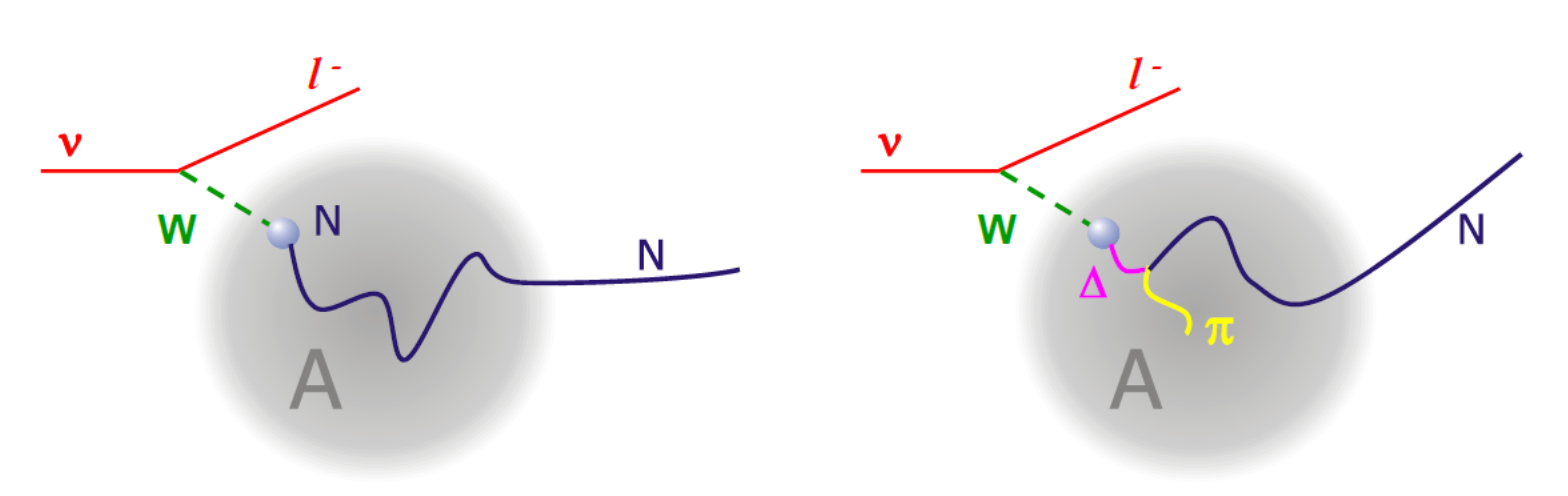


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

1. Nucleons are Fermi-moving → smearing around correct energy
2. Final state interactions hinder correct event identification
   → wrong energy reconstructed

FSI in Nuclear Targets

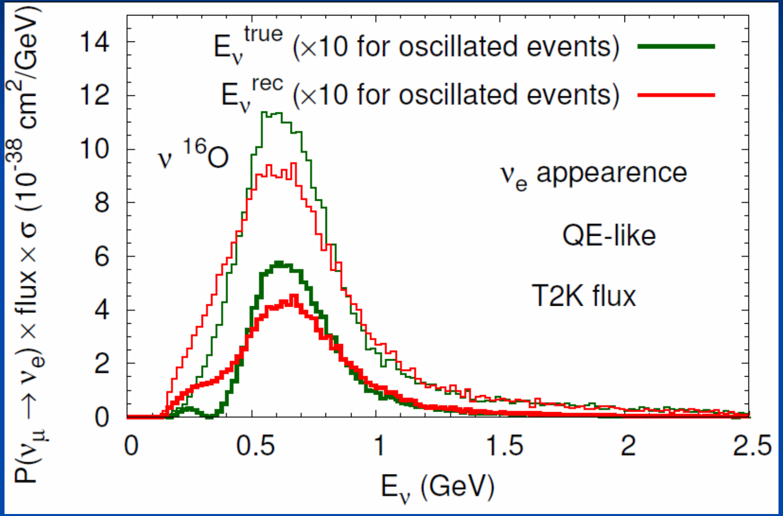


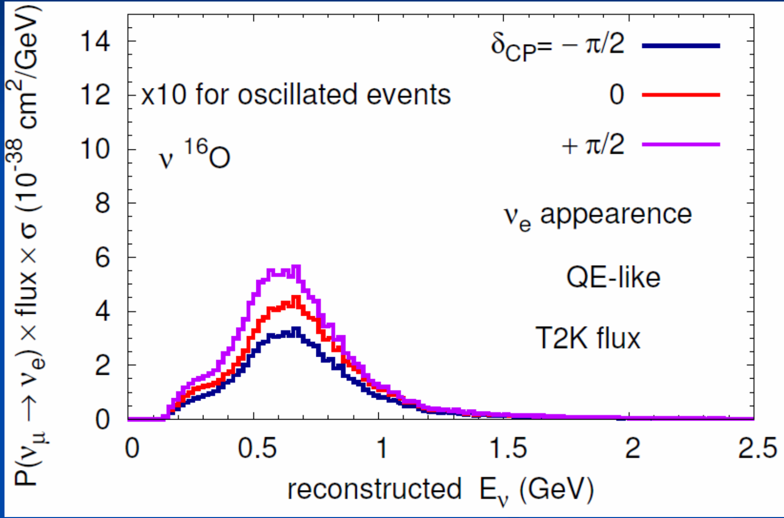
Complication to identify QE, **always** entangled with π production

Both must be treated at the same time!

‚pure' QE cannot be measured!!

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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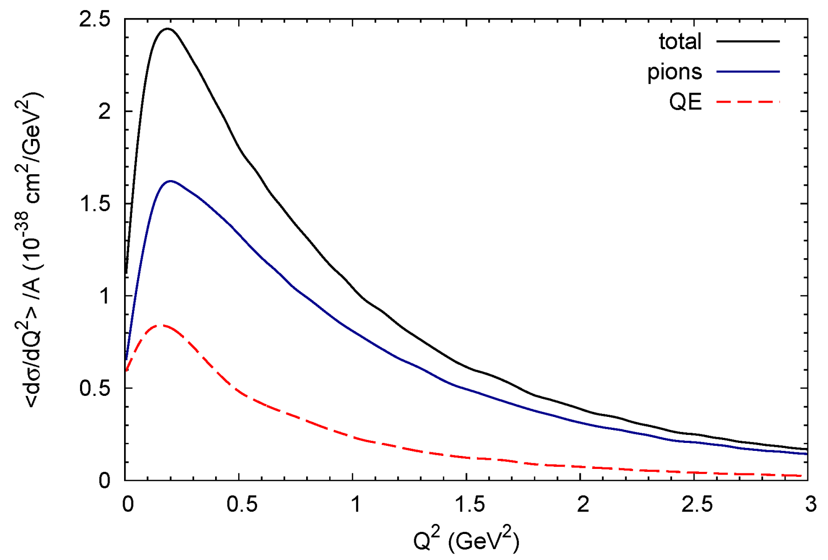
QE vs. Pion Production at DUNE

Target:
^{40}Ar



Pions: Resonance + DIS
QE: ‚true' QE + 2p2h

QE ≅ 1/3 total
Pions ≅ 2/3 total

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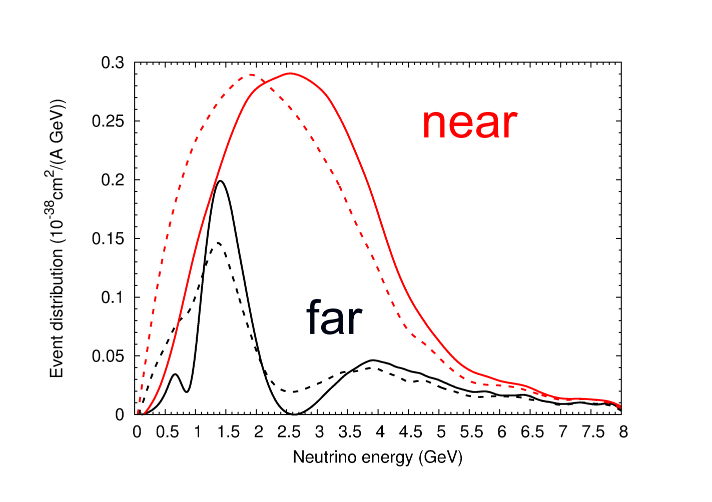
QE Energy Reconstruction fo DUNE

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

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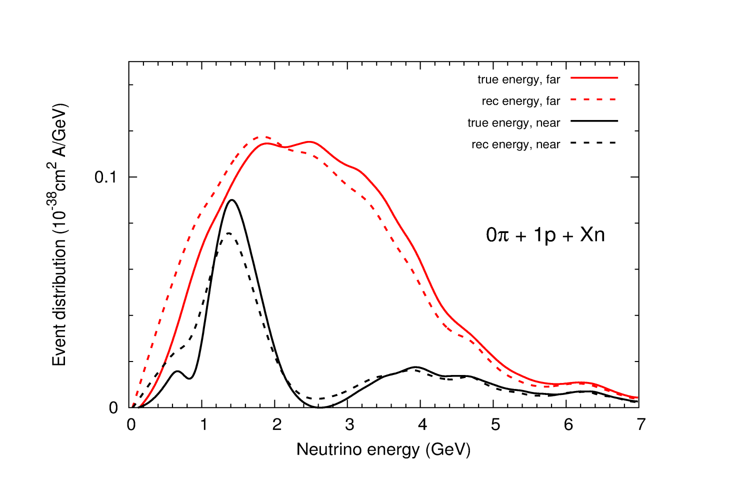
QE Energy Reconstruction for DUNE

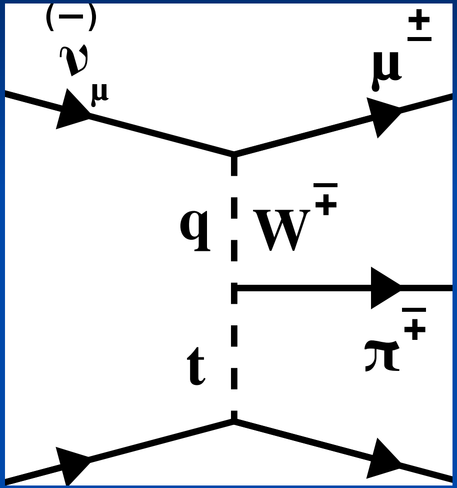
Muon survival in 0π + 1p + Xn sample

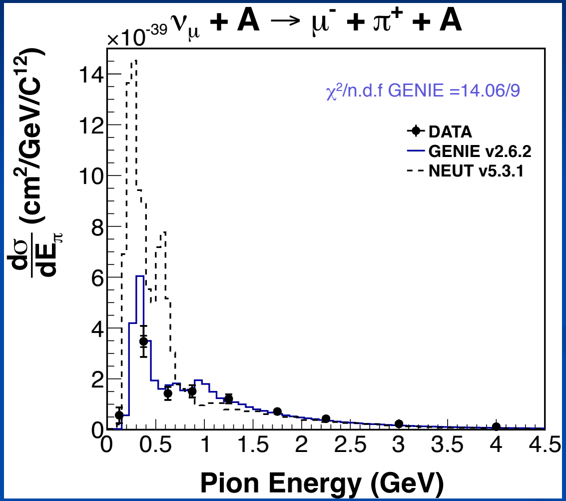


Dashed: reconstructed,
solid: true energy

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

Coherent CC Scattering



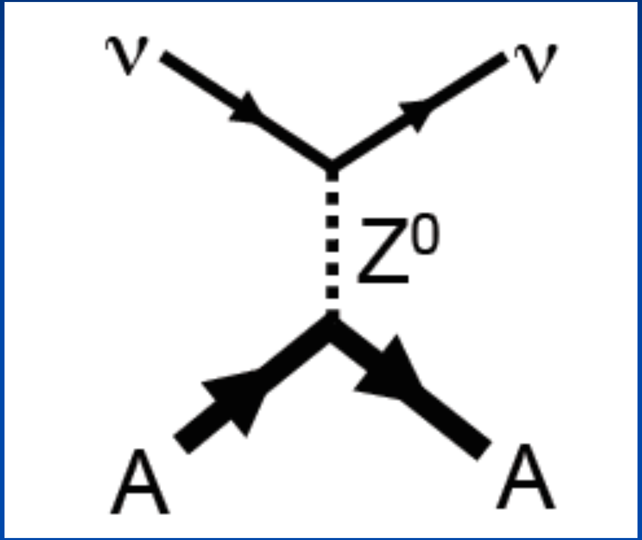


MINERvA
PRL 113 (2014)

Theorie of coherent pion production in bad shape: results of PCAC based theories differ significantly

(2 curves in right figure)

Coherent NC Scattering



So far not observed

$\sigma \sim N^2 E^2$

(N = neutron number)

Recoil energy

$E_R \sim E^2/A$

Higher Cross section for large N, but smaller recoil

Summary

- Elementary X-sections for neutrino-nucleon in range of 100 MeV to 20 GeV not well under control. Formfactors badly known (compared to electrons)
- Full event simulations needed to describe neutrino-nucleus interactions: quality of extracted neutrino properties depends directly on quality of generator
- No good theory for coherent pion production available, for coherent neutrino scattering so far no data

- Precision era experiments require precision era (new) generators

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 neutrinos