Neutrino Interactions with Nuclei

Ulrich Mosel

Institut für Theoretische Physik

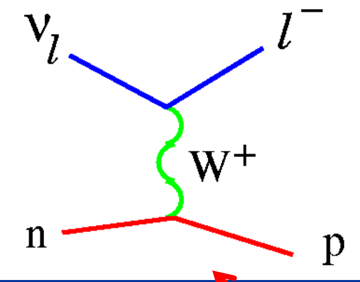
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Motivation and Contents

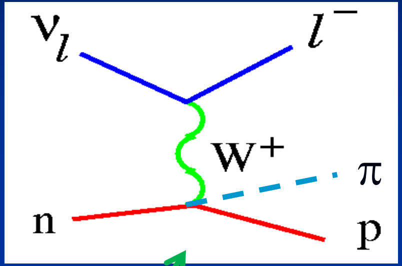
- Determination of neutrino oscillation parameters and particle production cross sections (axial properties of nucleons and resonances) requires knowledge of neutrino energy
- Modern experiments use nuclear targets
- Nuclear effects affect cross section measurements, event identification and neutrino energy reconstruction
- Precision era of neutrino experiments requires quantitatively reliable generators, more so than any other nuclear physics experiment (except, maybe, QGP searches)

Neutrino-nucleon cross section

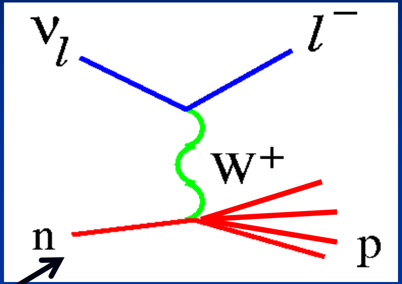
CCQE

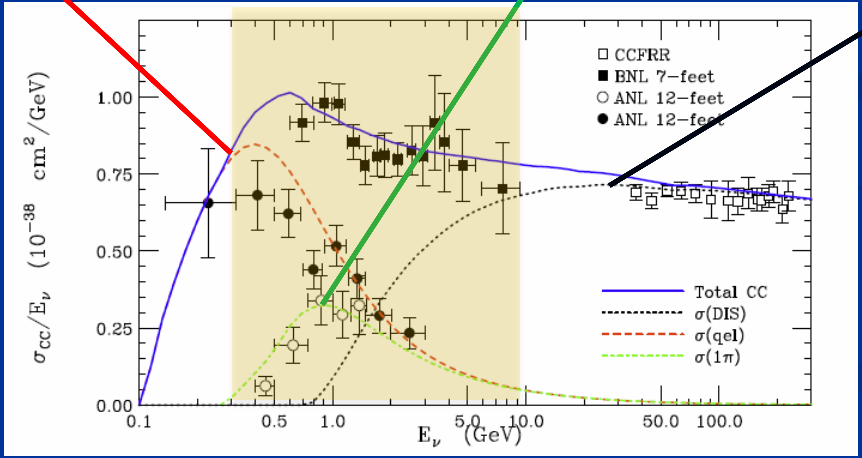


1π



DIS



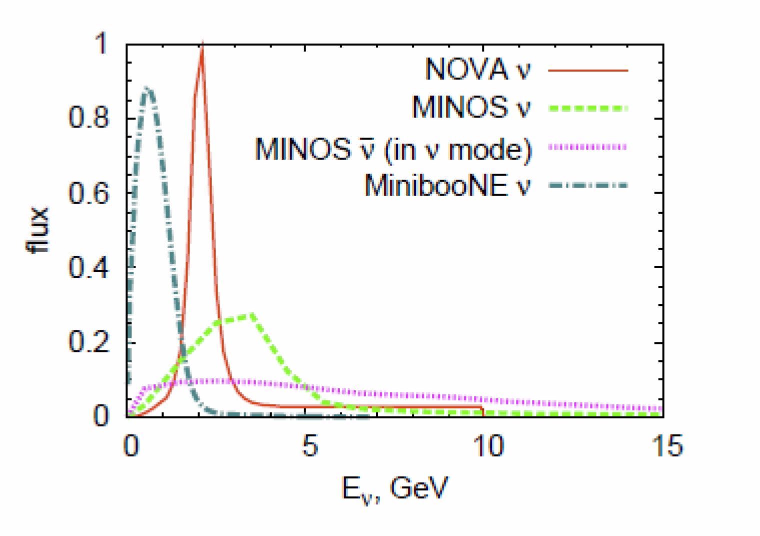


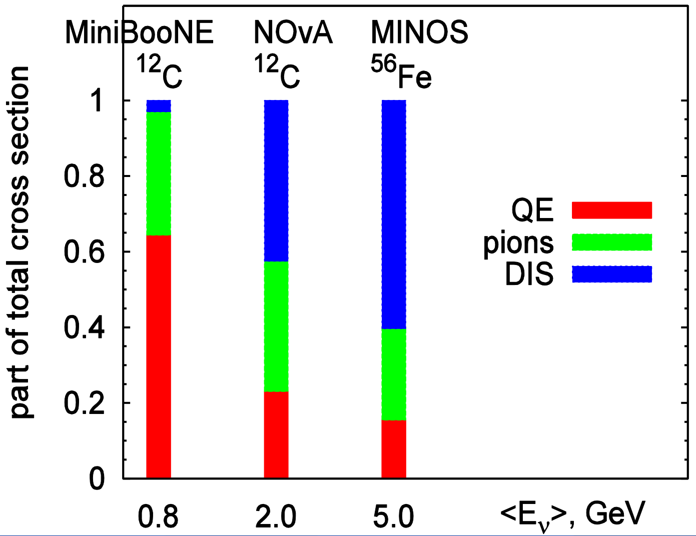
note:
10^{-38} cm² = 10^{-11} mb

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

Neutrino Beams

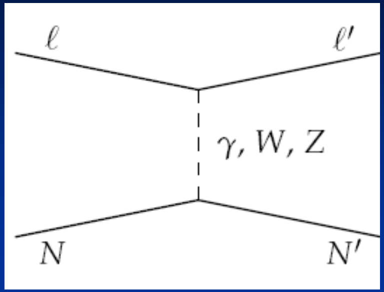
- Neutrinos do not have fixed energy nor just one reaction mechanism





Have to reconstruct energy from final state of reaction

Quasielastic scattering



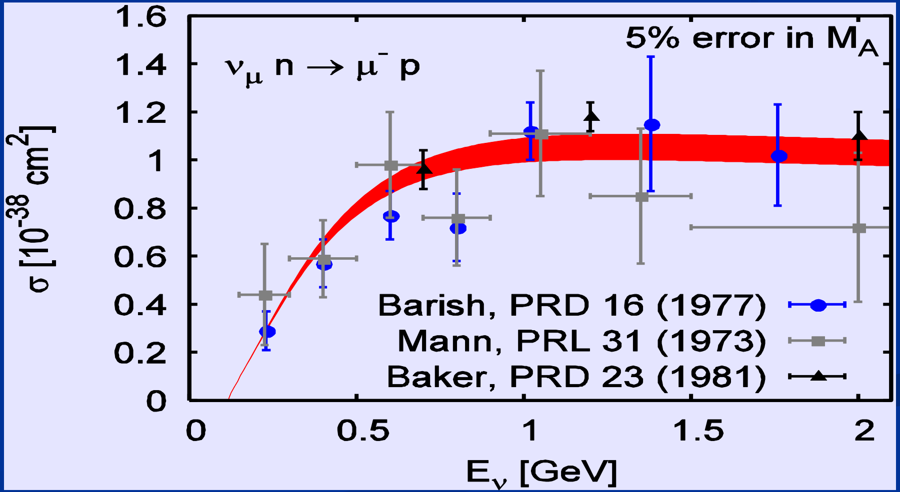
$$J^\mu_{QE} = \left(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu\gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$

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

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

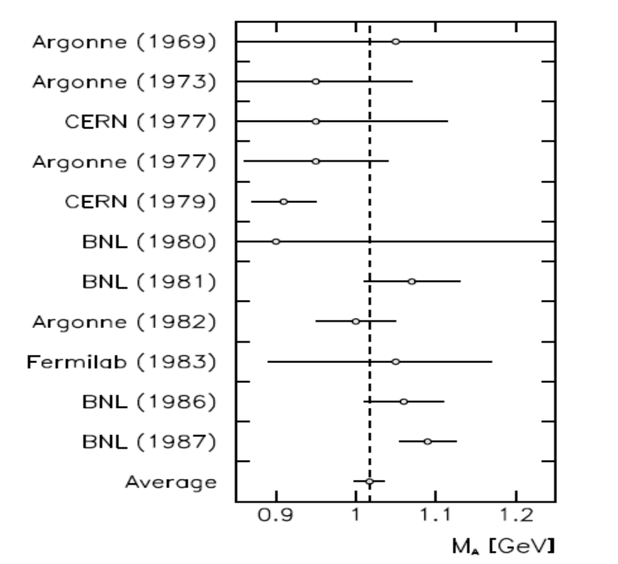
  dipole ansatz for F_A with

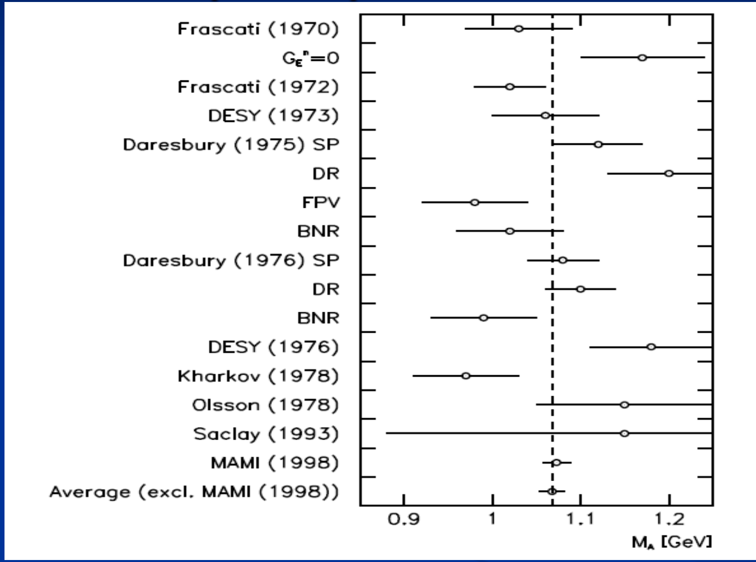
  M_A = 1 GeV**:** $$F_A(Q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$



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

- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance**:

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

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

- C^A 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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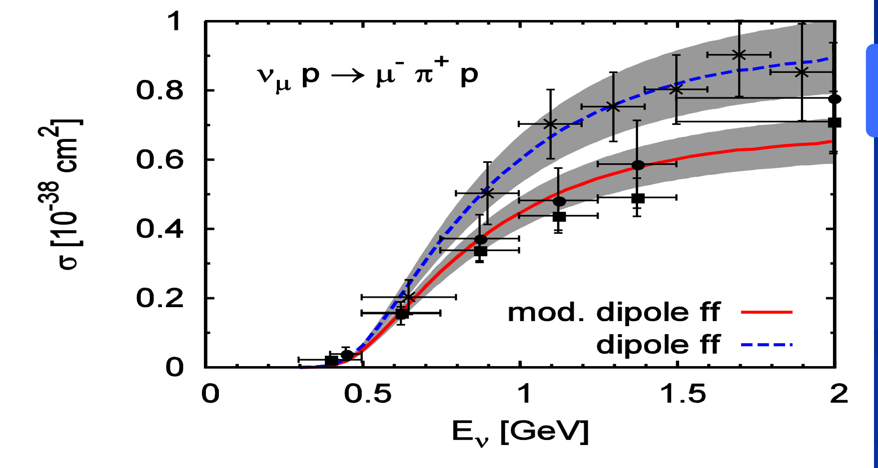
Pion Production

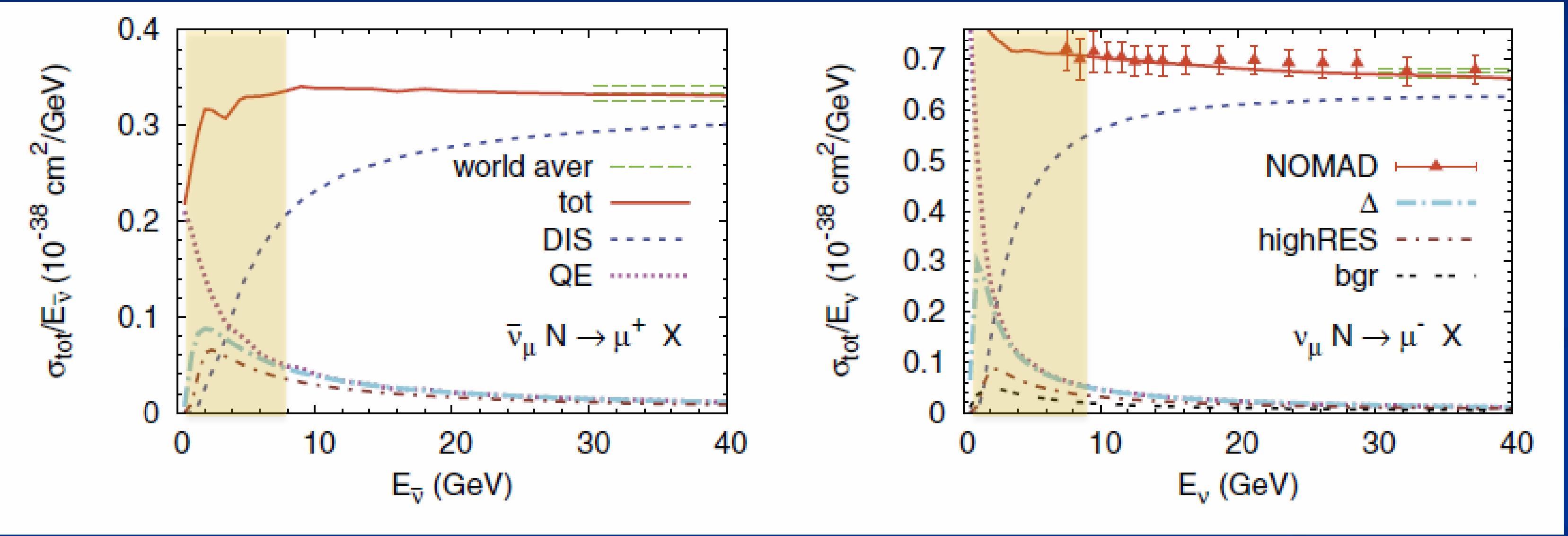


10 % error in $C_5^A(0)$

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

discrepancy between elementary data sets
→uncertainty in axial form factor

SIS - DIS



Problems in overlap between resonance and DIS region (~ 2 GeV)

Shallow Inelastic Scattering,interplay of different reaction mechanisms

Elementary Reactions understood?

- QE scattering: reasonably well understood, shape of axial formfactor uncertain
- Pion production: significant (~ 30%) uncertainty in data, formfactors largely unknown
- SIS: large uncertainties in transition region between resonance and DIS region

➔ Need data on elementary targets (p,D) as crucial input to generators for nuclear targets

Energy Reconstruction

- Energy reconstruction
  1. Through QE: needs event identification
  2. Calorimetric: needs simulation of thresholds and non-measured events
- In both methods generators are needed

Energy Reconstruction: Two Complications to identify QE

All modern experiments contain nuclei as targets

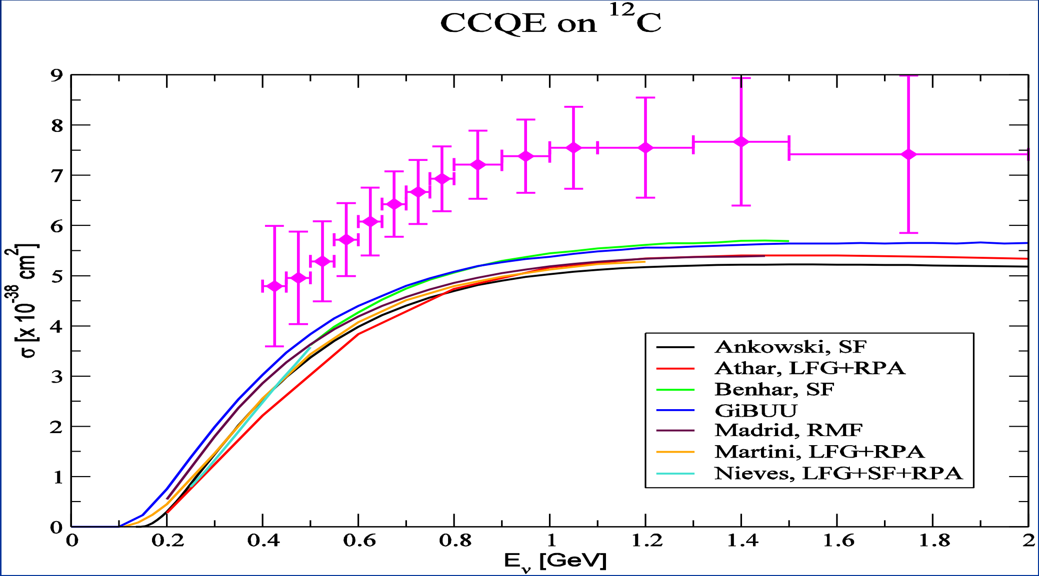
1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

↓

Nuclear Physics based generators needed

The MiniBooNE QE Puzzle

or: why tuning generators to data can be grossly misleading



L. Alvarez-Ruso

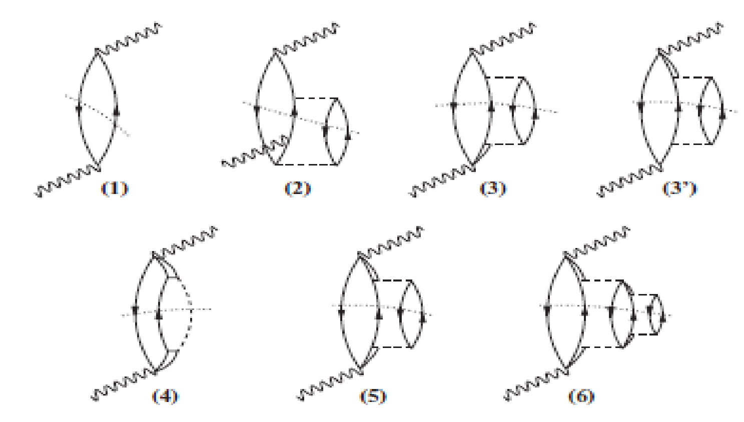
All calculations with axial mass ~ 1.0 GeV in IA(1p-1h)

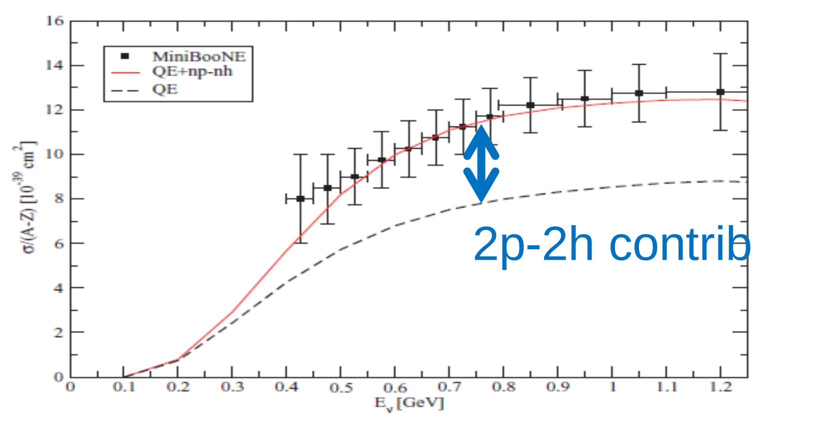
All generators agree for QE scattering on *C*

What is difference to data?

The MiniBooNE QE Puzzle
Explanations

Martini et al, PRC80, 2009

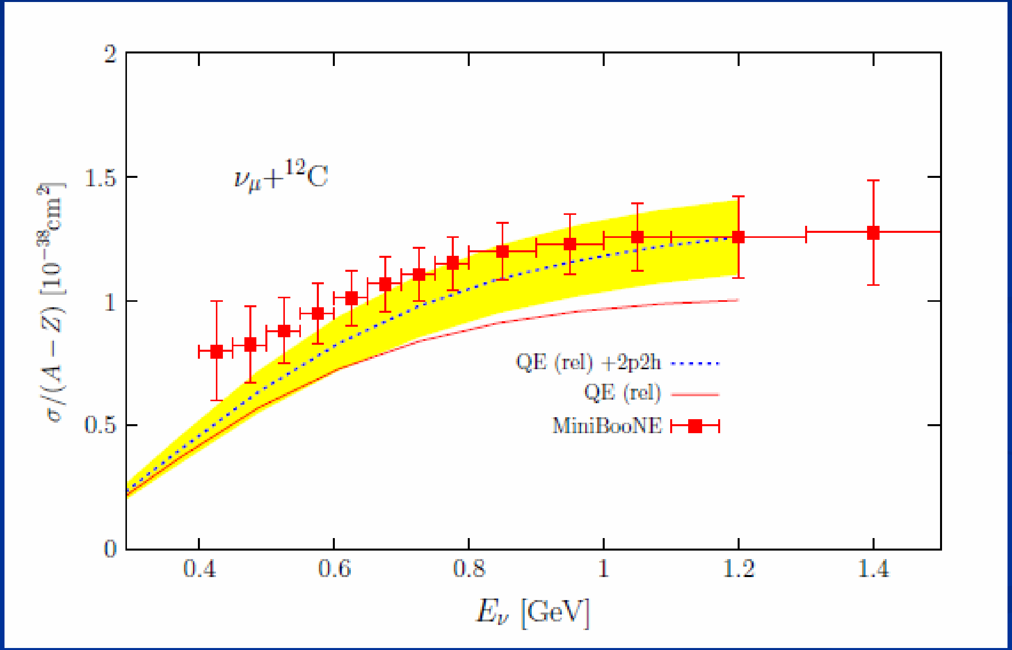




Exp: both σ and E_ν are reconstructed!

Calcs only up to 1.2 GeV!

The MiniBooNE QE Puzzle Explanations

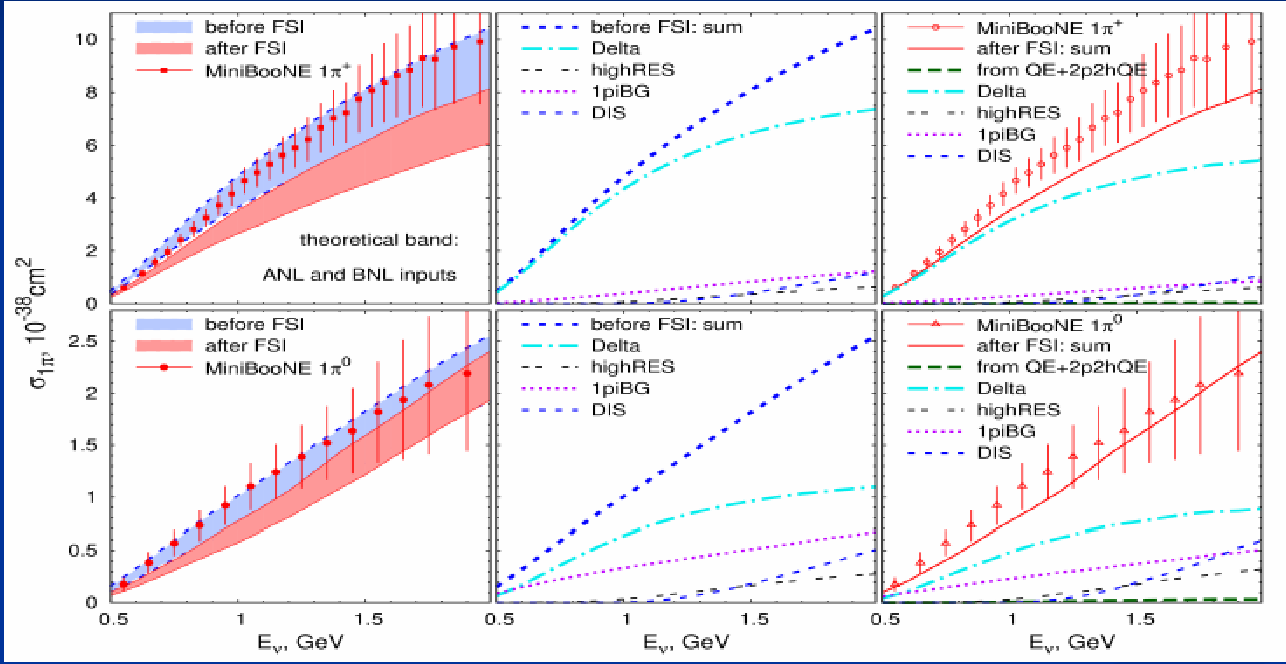


Method reliable up to ~ 1.2 GeV

Problem:
How large are 2p-2h contribs for higher energies??

Nieves et al

Pion Production



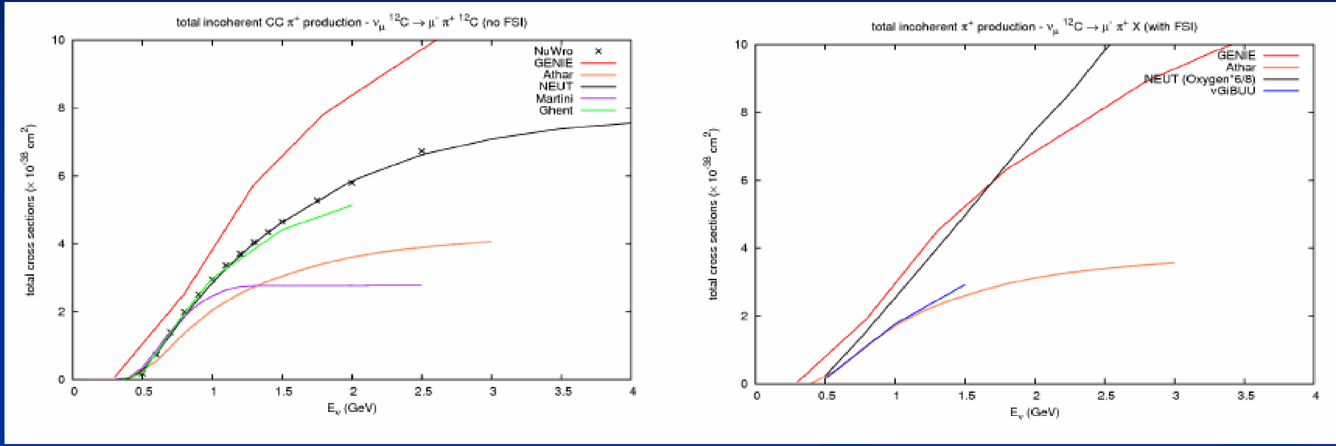
GiBUU calculations

Upper line: BNL input
Lower line: ANL input

Tendency for theory too low, more so for π+

DIS and higher resonances contribute for E > 1 GeV

Pion-Discrepancies in Generators

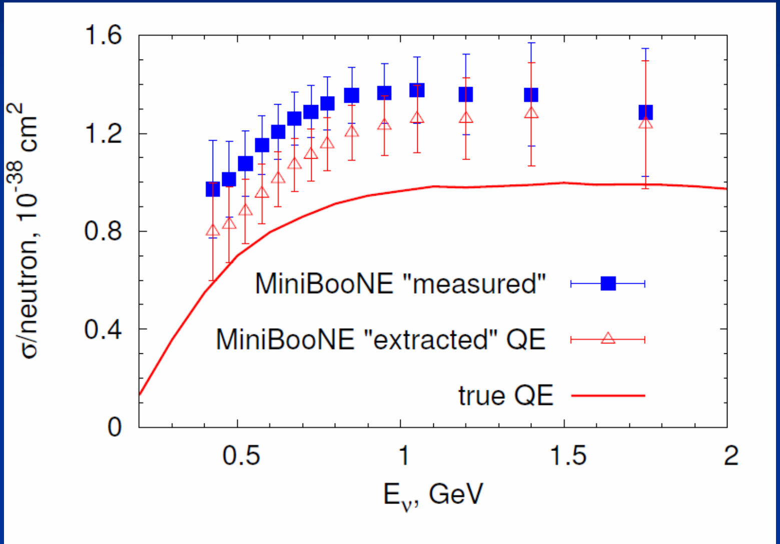


Sobczyk, NUINT09

Huge discrepancies between theoretical predictions for pion production, before *and* after FSI

→ Need to clarify reasons for discrepancies!!!

MiniBooNE QE puzzle

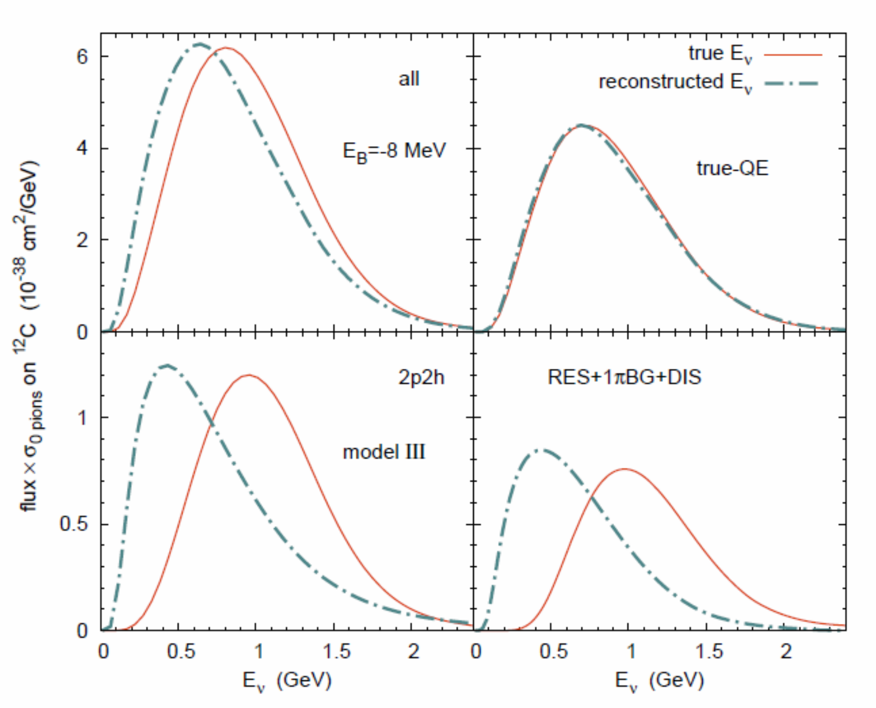


MB measured: 0 π events
MB extracted: 0 π events – stuck pions
(NUANCE generator dep.)

E_ν NUANCE generator dependence

Problem: Difference between data points (= stuck pion events) decreases with E_ν !?

Energy reconstruction in MB

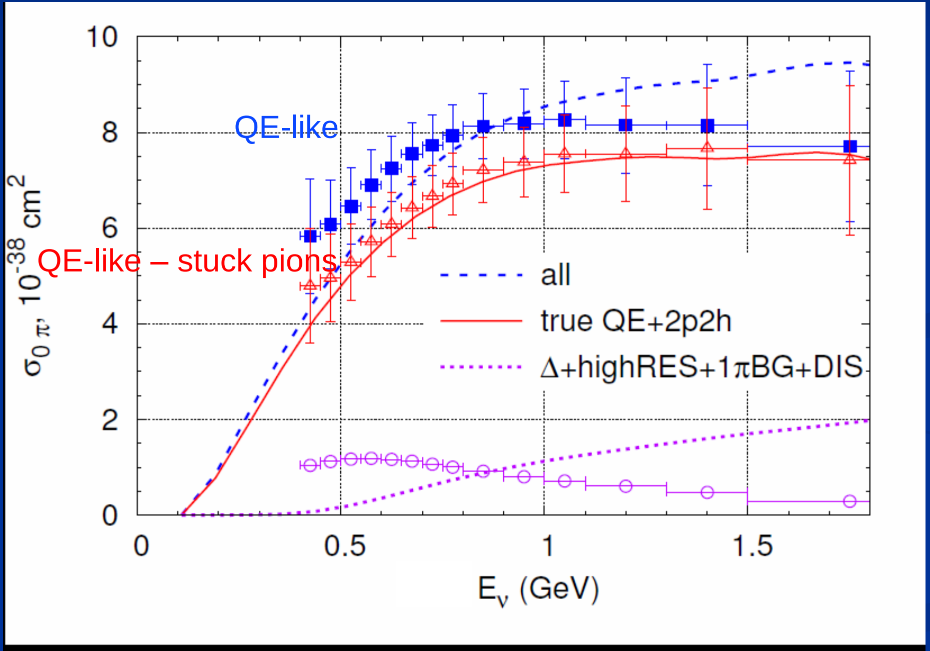


GiBUU calculations

Reconstructed energy shifted to lower energies for all processes beyond QE

Functional shapes of event rates changed!

Energy reconstruction in MB



GiBUU calculations

MiniBooNE data

Data: plotted vs *reconstructed* energy

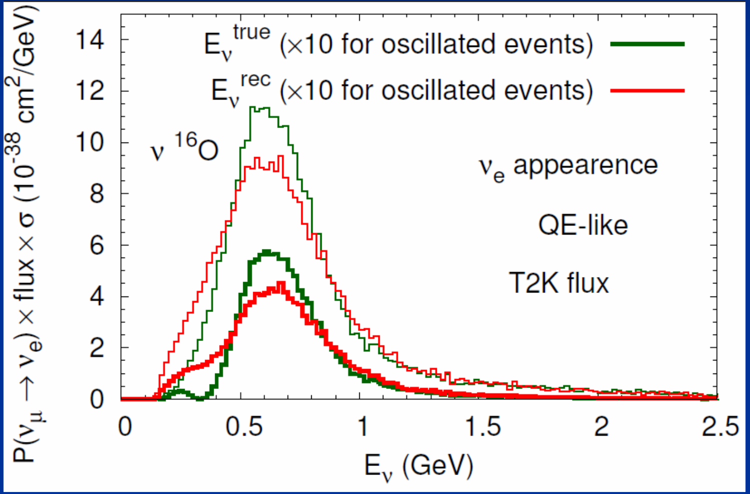
Curves: plotted vs. *true* energy

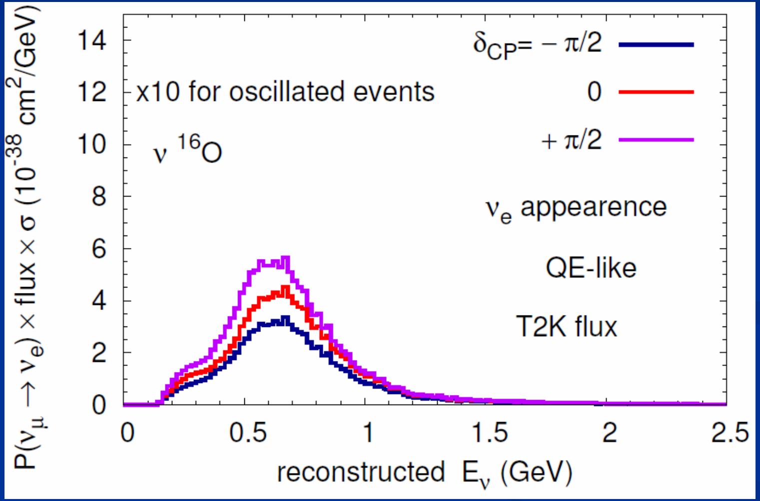
Explains strange energy-dependence of stuck pion events

Energy reconstruction in MB

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

Oscillation signal in T2K
δ_{CP} sensitivity

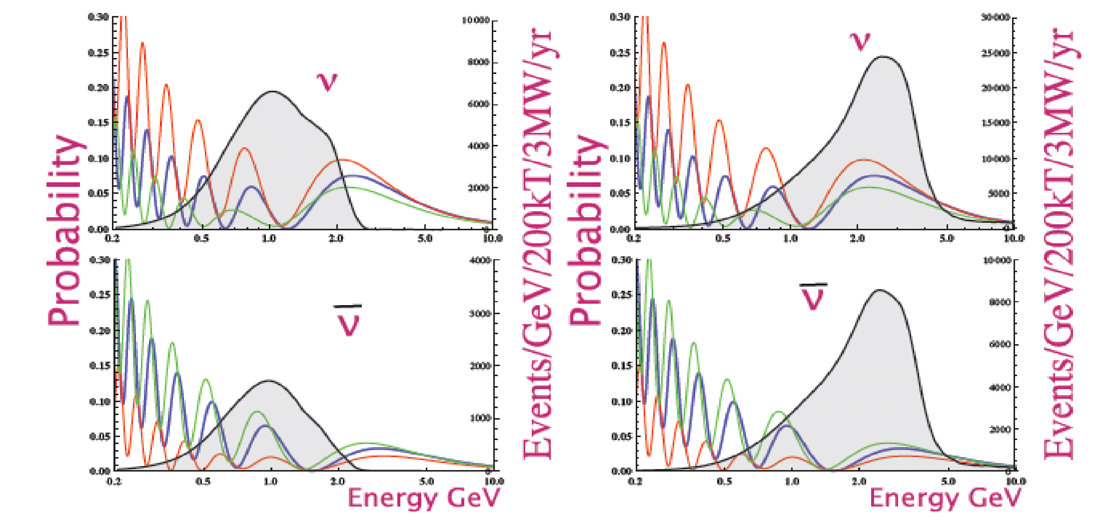




Uncertainties due to energy reconstruction as large as δ_{CP} dependence!

LBNE, δ_{CP} sensitivity

From: Bishai et al., hep-ex 12034090



8 GeV

60 GeV

proton energy

From:
Bishai et al
arXiv:1203.409

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

Need neutrino energy very precisely to distinguish between different δ_{CP}

Summary

- Event generators for neutrino-nucleus interactions have to describe QE, π produktion and DIS simultaneously
- True QE is understood, generators agree
- Lots of problems for other processes:
  - 2p-2h processes disappear with energy? How?
  - Pion production uncertain, huge discrepancies in generators
- Need data for elementary targets as input to generators!

Summary

- δ_{CP} (and mass hierarchy?) determination depends crucially on energy reconstruction, elementary cross section measurements on nuclear targets get swamped by FSI

- Energy reconstruction difficulties have been underestimated (problem not even discussed in LBNE proposal); need more, sophisticated studies with state-of-the-art nuclear physics methods

Need for solid Nuclear Theory support for Neutrino Experiments in Precision Era

- Need to understand more Nuclear Physics *quantitatively*, connect to NP community
- Need to understand generators, not just compare them! Need write-ups of physics content (cf. Pion discrepancies)!
- Need to support LBL exps with dedicated theory program, focussed on running and future LBL experiments!

Wake up, Dr. N., you´re being transferred to low energy Nuclear Physics

Relevant (own) 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