Neutrino Interactions with Nucleons and Nuclei

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The Impossible Experiment

- Beam composition not fully known
- Beam energy badly known
- Beam diameter ~ 0.5 m at its source
- Beamline ~ 300 – 1000 km
- Beam diameter ~ 600 m at the detector
- Cross sections ~ 10^{-11} mb
- Only a small part of the final state known
- From all of this:

T2K extracts physics beyond the standard model!

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Motivation and Contents

- Determination of neutrino oscillation parameters and axial properties of nucleons and resonances requires knowledge of neutrino energy and momentum transfer
- Neutrino beams are broad in energy
- Modern experiments use nuclear targets
- Nuclear effects affect event characterization, cross section measurements, neutrino energy reconstruction and, consequently, oscillation parameters

Neutrino Oscillations

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

appearance probability

mass hierarchy

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

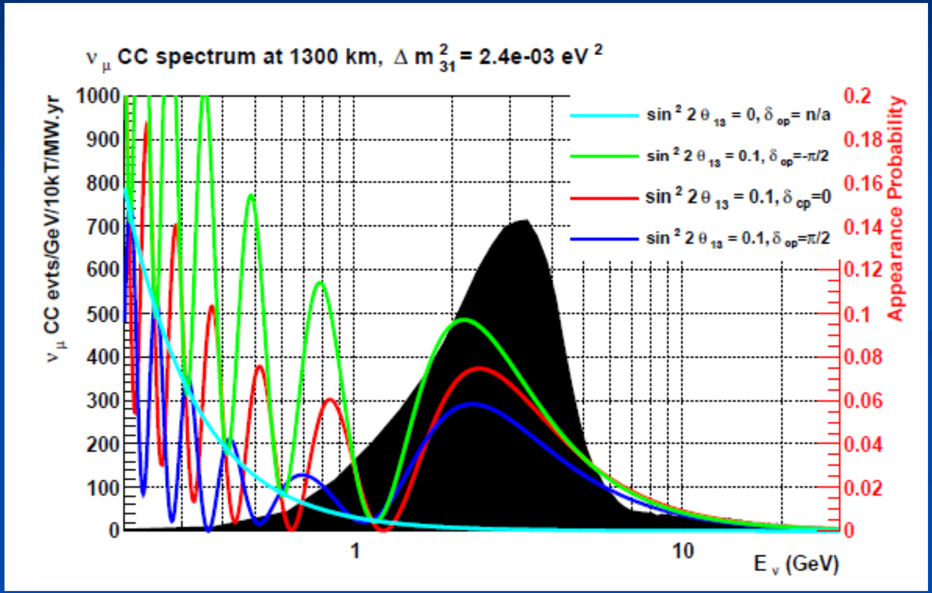
$$\hat{A} = \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}} \qquad \delta = \text{CP violating phase}$$

Vacuum oscillation

Matter effects,
n_e = electron density
depends on sign of Δ_{31}

Oscillation depends on difference of (squared) masses only

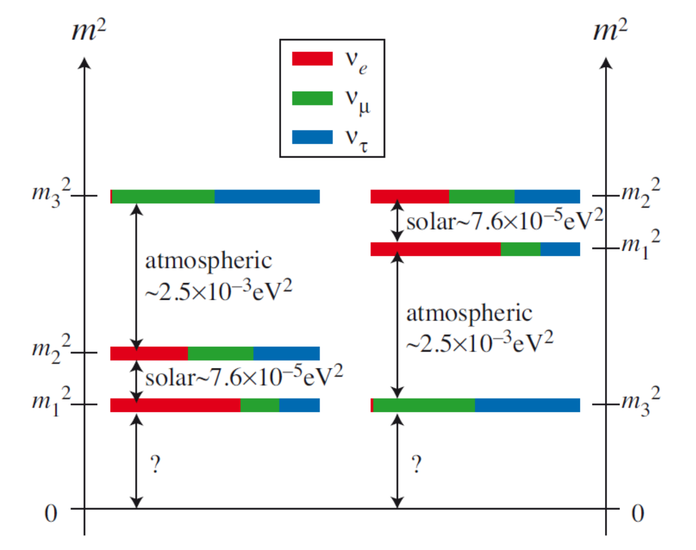
LBNE, δ_{CP} Sensitivity



Need to know neutrino energy to better than about 100 MeV

Need energy to distinguish between different δ_{CP}

Oscillation Signal
Dependence on Hierarchy and Mixing Angle



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

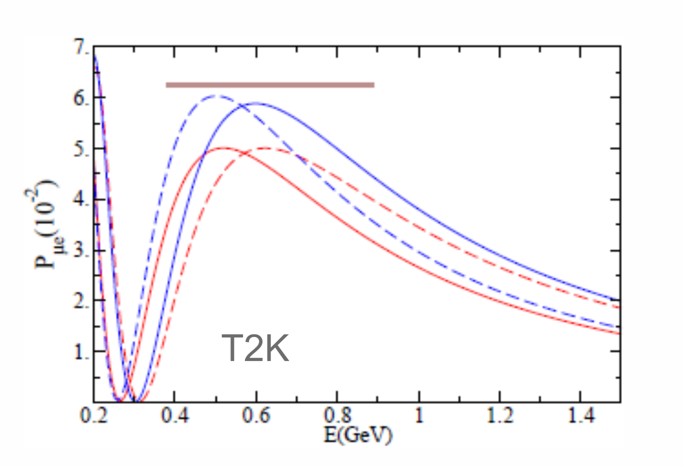


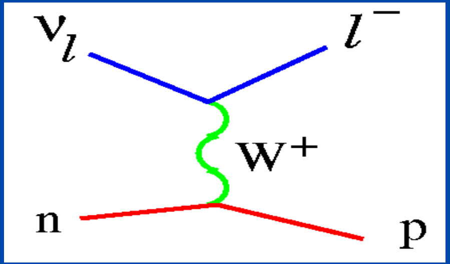
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

Shape sensitive to hierarchy and sign of mixing angle

Energy resolution of about 50 MeV is needed

Energy Reconstruction by QE

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

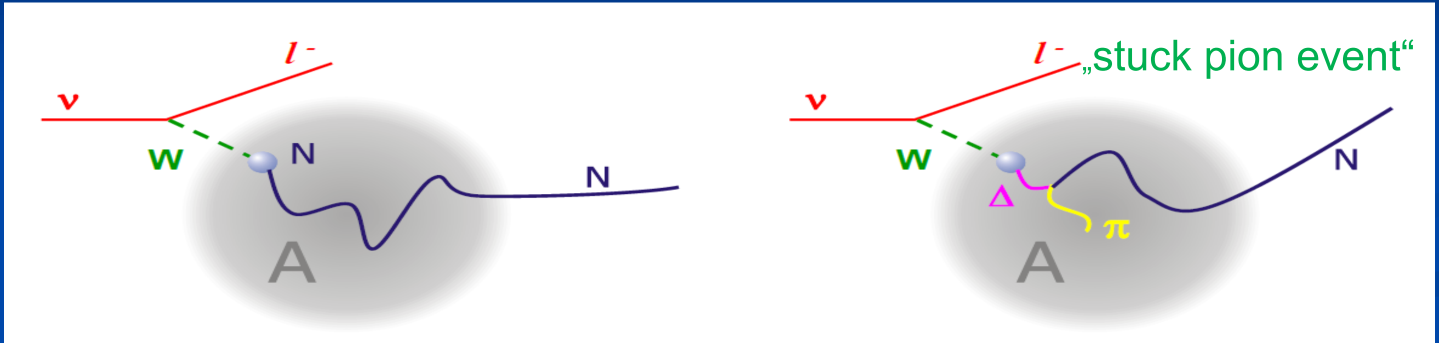


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

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

Final State Interactions in Nuclear Targets



Complication to identify QE, entangled with π production

Both must be treated at the same time!

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

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Energy Reconstruction by QE

- CCQE scattering on neutron at rest
  - Energy

$$E_\nu^{\mathrm{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_n E_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu| \cos\theta_\mu\right]}$$

  - Q^2

$$Q^2_{\mathrm{rec}} = -m_\mu^2 + 2E_\nu^{\mathrm{rec}}(E_\mu - |\vec{k}_\mu| \cos\theta_\mu)$$

- Energy reconstruction tilts spectrum, affects Q^2 distribution at small Q^2

Need for a Neutrino Generator

- Need final state for event reconstruction
- Inclusive cross sections are not enough, need semi-inclusive for event identification
- Need theory that can describe the complete final state of a ($\nu A \rightarrow l\, X$) interaction
- Only practical theory: MC or transport code

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

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

Nuclear Physics determines response of nuclei to neutrinos

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations
- Physics content and details of implemntation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  Code available from **gibuu.hepforge.org**

  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator

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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

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

F(x,p) = 8-d phase-space density

Kadanoff-Baym equation

- LHS: drift term + backflow (KB) terms
- RHS: collision term = - loss + gain terms (detailed balance)

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **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!

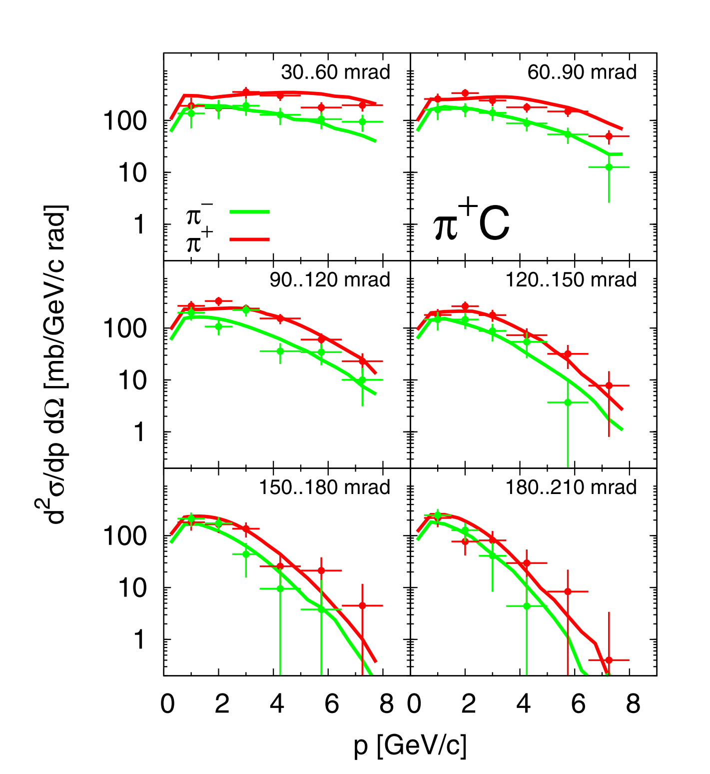
NO TUNING!

Check: pions in HARP

HARP small angle analysis
12 GeV protons

Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)



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Reaction Types

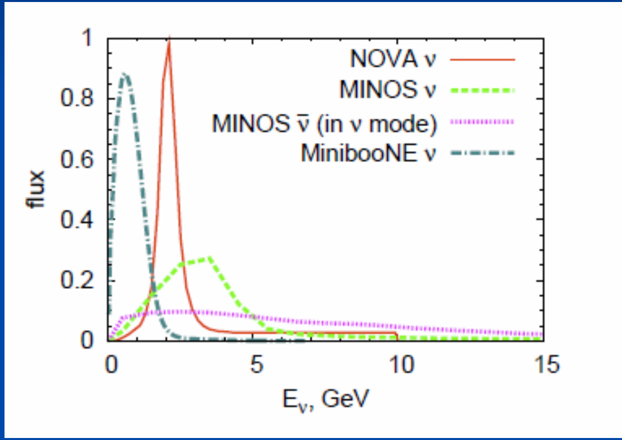
- 3 major reaction types relevant:

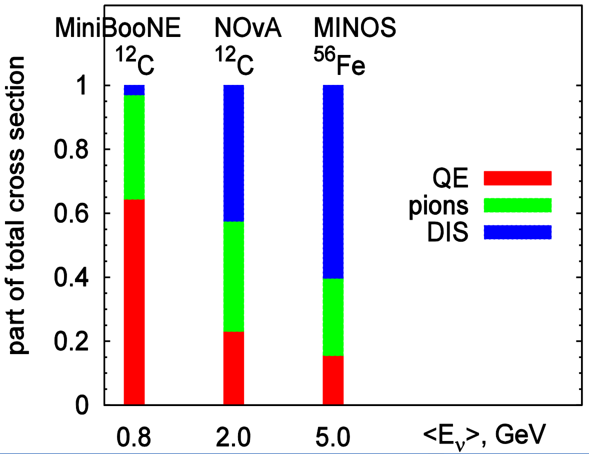
1. QE scattering
   1. true QE (single particle interaction)
   2. many-particle interactions (RPA + 2p2h + spectral functions)
2. Pion production
3. SIS and DIS (less important at T2K and MiniBooNE)

- All reaction types are entangled:
  final states may look the same

Neutrino Beams

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





Have to reconstruct energy from final state of reaction
Different processes are entangled

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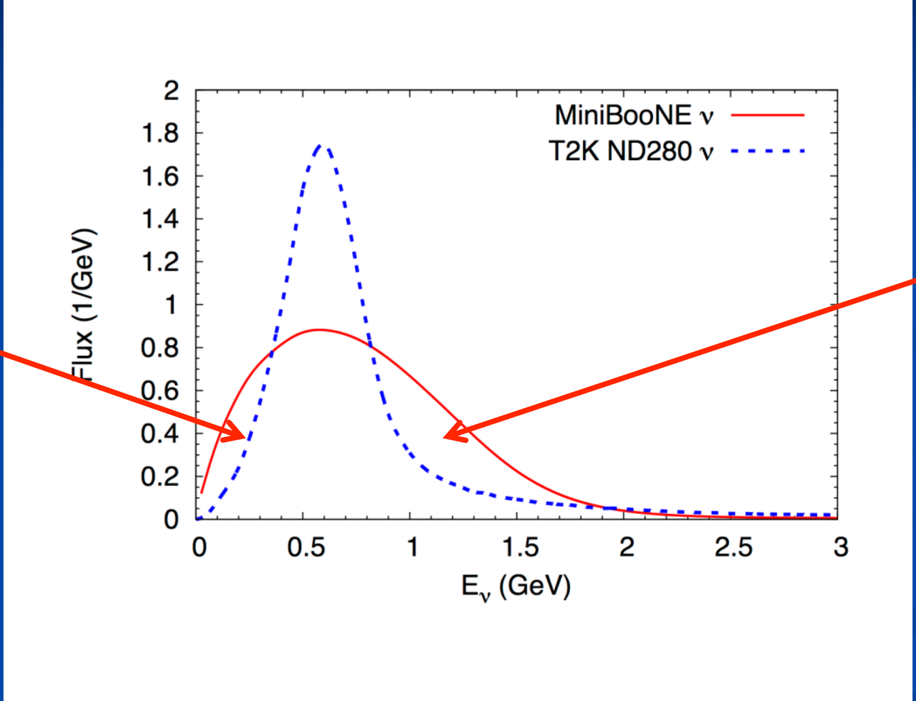
T2K vs MB Flux

less RPA



T2K ND280
205kA flux

less pions

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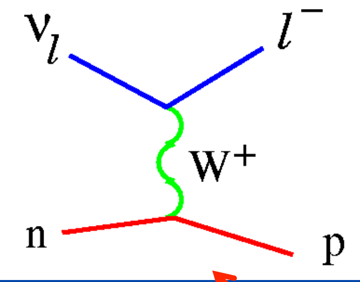
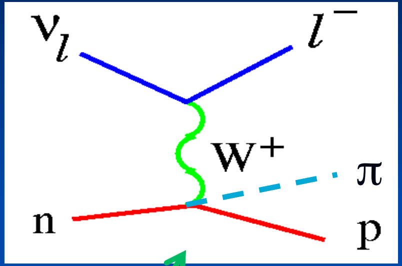
Neutrino-nucleon cross section

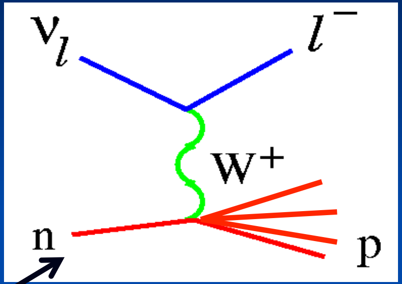
CCQE

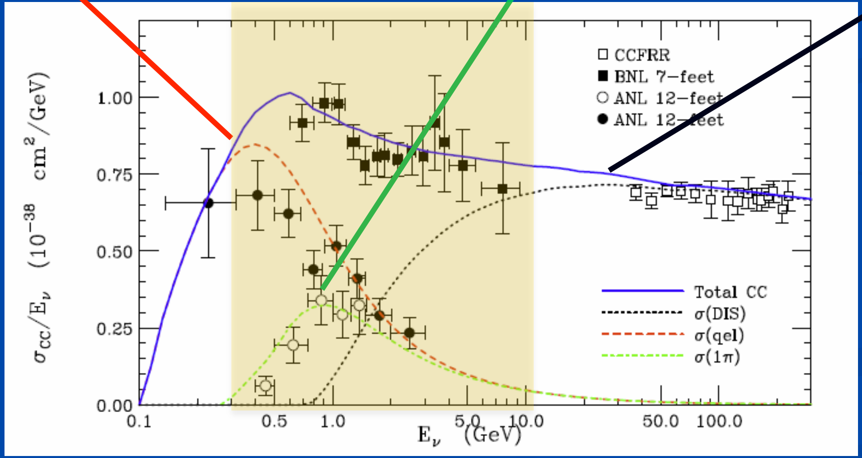


1π



DIS





note:
10^{-38} cm² = 10^{-11} mb

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

JPARC 02/2014

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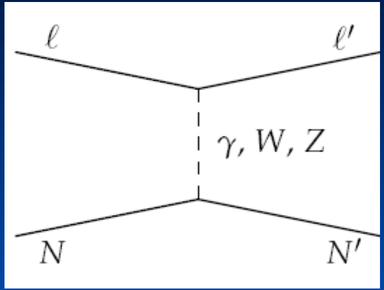
Quasielastic scattering



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

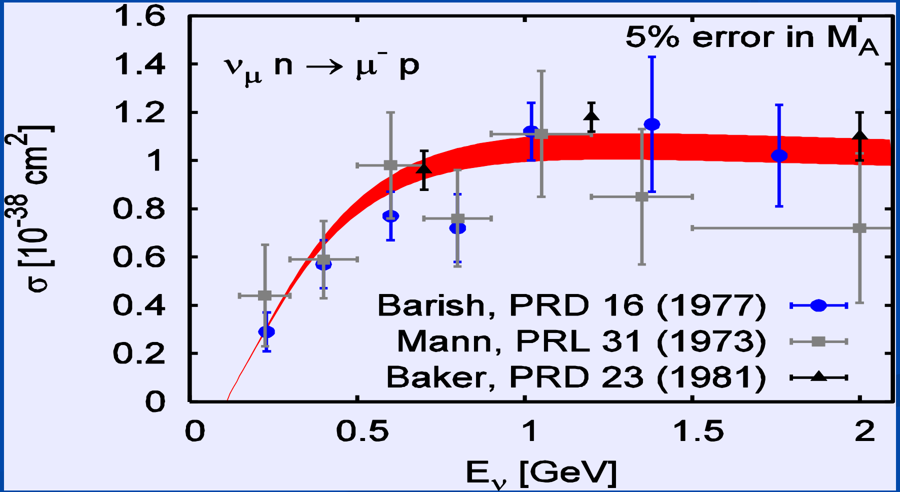
- Vector form factors from *e* –scattering
- axial form factors

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

  dipole ansatz for F_A with

  M_A= 1 GeV**:**

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



Beyond Impulse Approx: 2p2h Interactions

- Model for $\nu + p_1 + p_2 \rightarrow p_3 + p_4 + l$ (no recoil)

$$\frac{d^2\sigma}{dE_l' d(\cos\theta')} \propto \frac{k'}{k} \int_{NV} d^3r \int \prod_{j=1}^{4} \frac{d^3 p_j}{(2\pi)^3 2E_j} f_1 f_2 \overline{|M|^2} (1-f_3)(1-f_4)\delta^4(p)$$

with flux averaged matrixelement

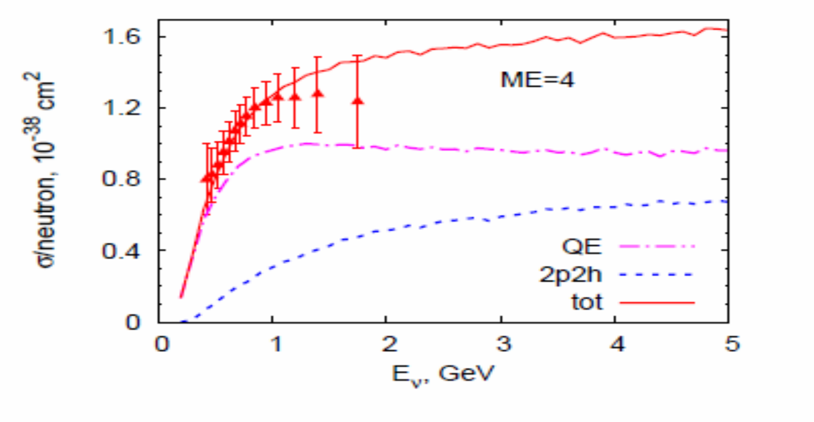
$$\overline{|M|^2} = \int \Phi(E_\nu)\, L_{\mu\nu} W^{\mu\nu}\, \mathrm{dE}_\nu$$

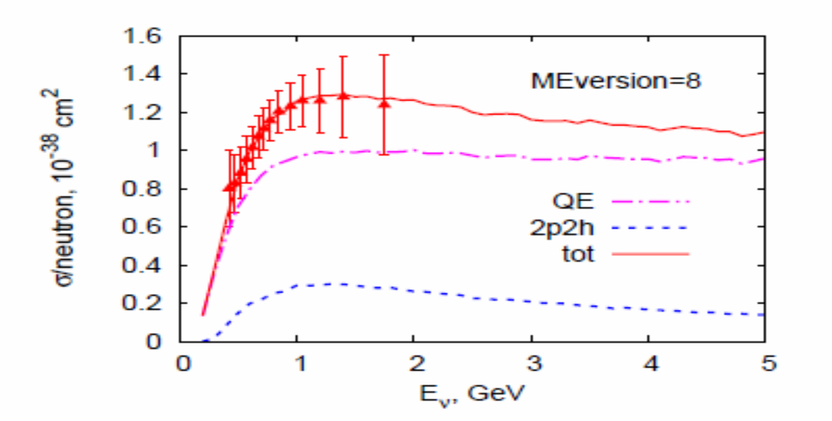
Flux smears out details in hadron tensor *W*

W contains 2p-2h and poss. RPA effects

The MiniBooNE QE Puzzle Explanations

- *M = const* — *M = M(E,q), $W^{\mu\nu} \sim P_T^{\mu\nu}(q)$*





Phase-space model for 2p-2h
Absolute value fitted to data.

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Pion Production

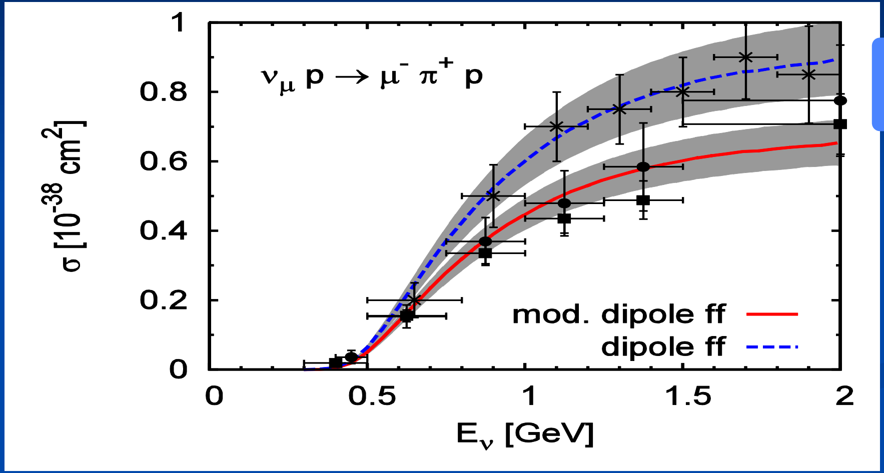
- Pion production dominated by **P_{33}(1232) resonance (not just a heavier nucleon)**

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

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



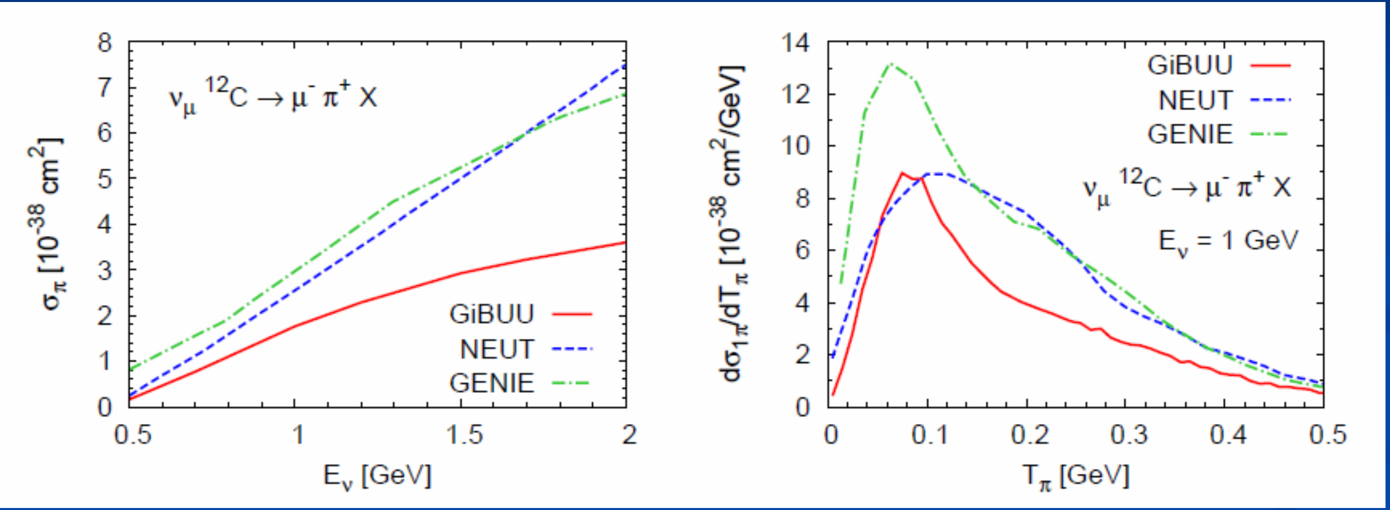
10 % error in $C_5^A(0)$

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

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

New pion data on elementary target desparately needed!

Comparison with other generators



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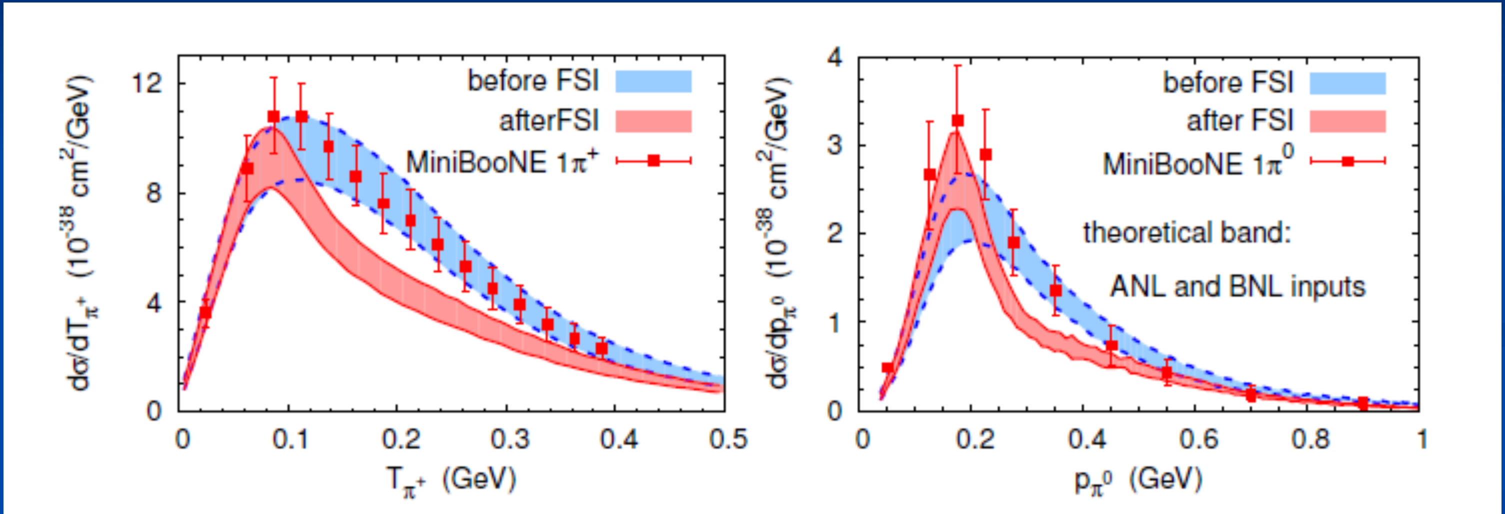
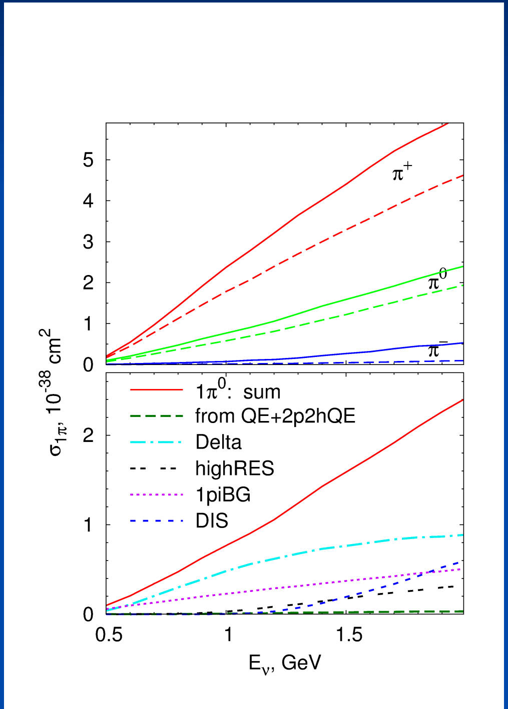
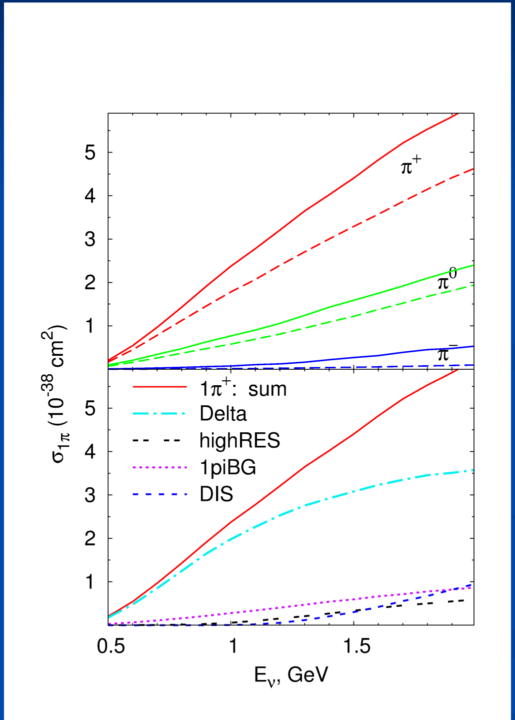
Pion Spectra in MB



Pion Production in T2K





Δ dominant
only up to 0.8 GeV

Measurement of π^+ production between about 0.5 and 0.8 GeV would be clean probe of Δ dynamics.

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Oscillation and Energy Reconstruction

- For nuclear targets QE reaction must be identified to use the reconstruction formula for E_ν
  exp: 1 lepton, no pion, any number of other hadrons
- *But:* exp. definition of QE cannot distinguish between true QE (1p-1h), N* and 2p-2h interactions
- Many different reaction mechanisms, besides true QE, can contribute to the same outgoing lepton kinematics

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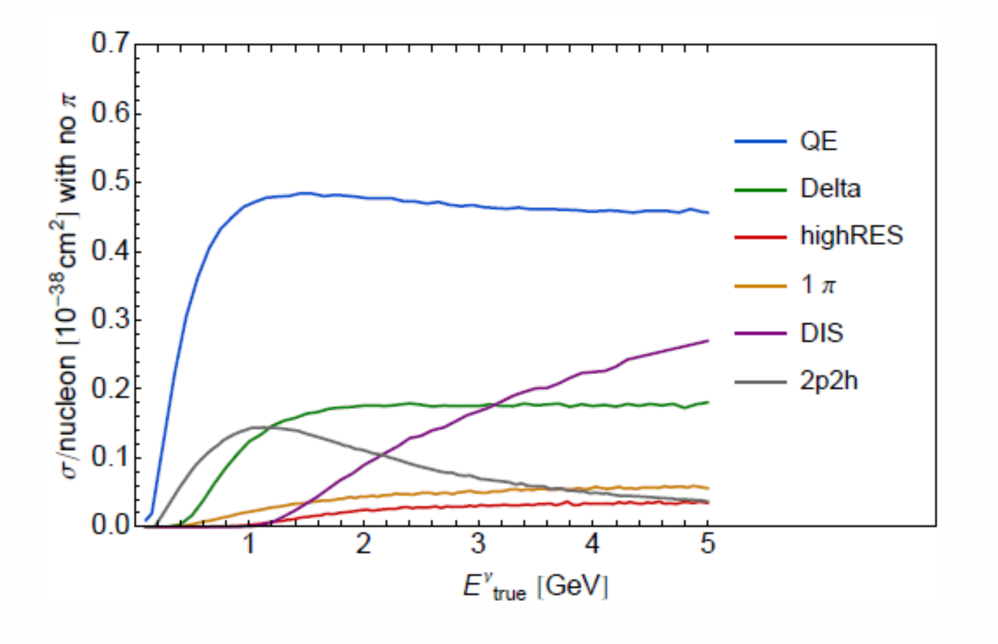
0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1



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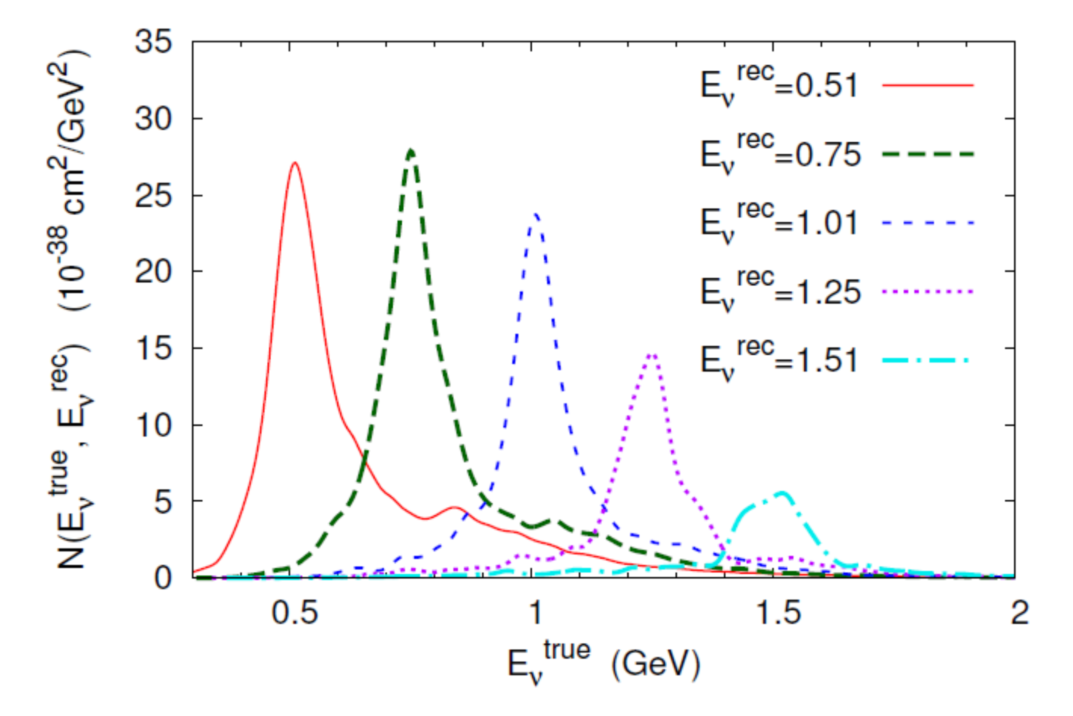
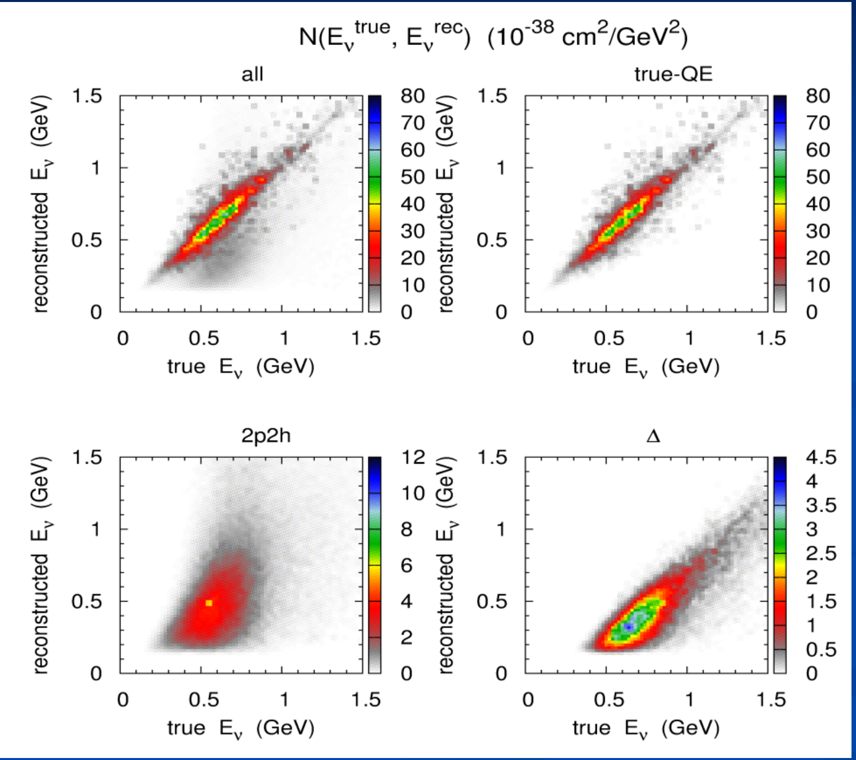
Energy-Reconstruction



Reconstr. energy contains a superposition of many true energies:

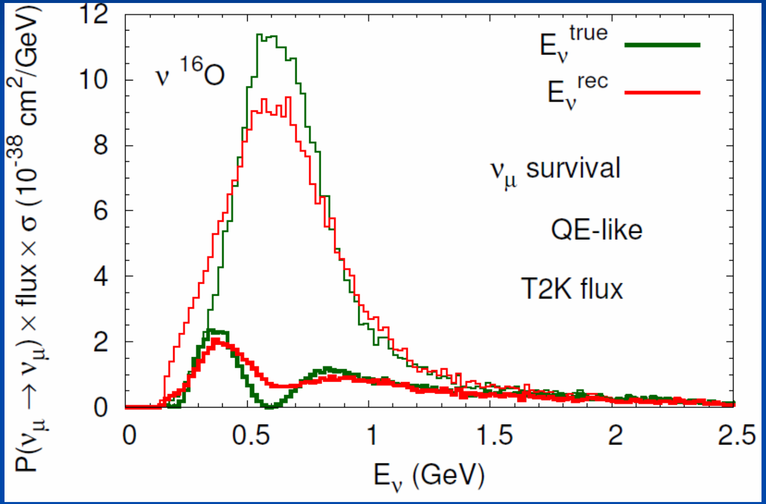
1. broadening due to Fermi motion
2. High energy tails due to reaction mechanisms other than QE

T2K migration matrix

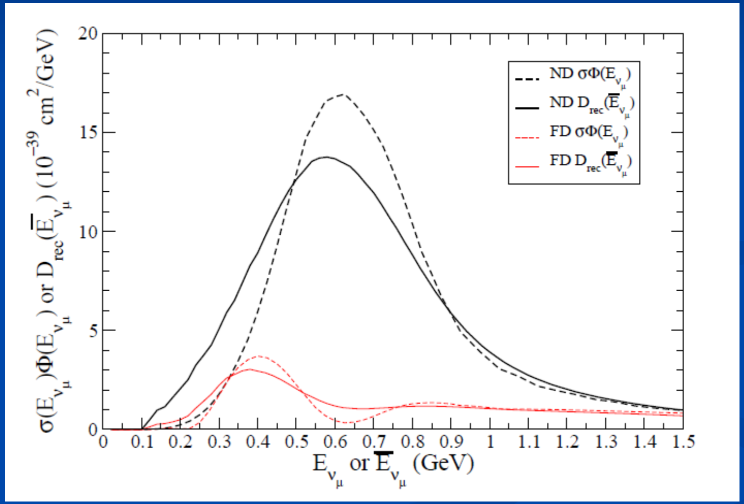


T2K Flux
Target: ^{16}O

Oscillation signal in T2K
ν_μ disappearance



GiBUU



Martini

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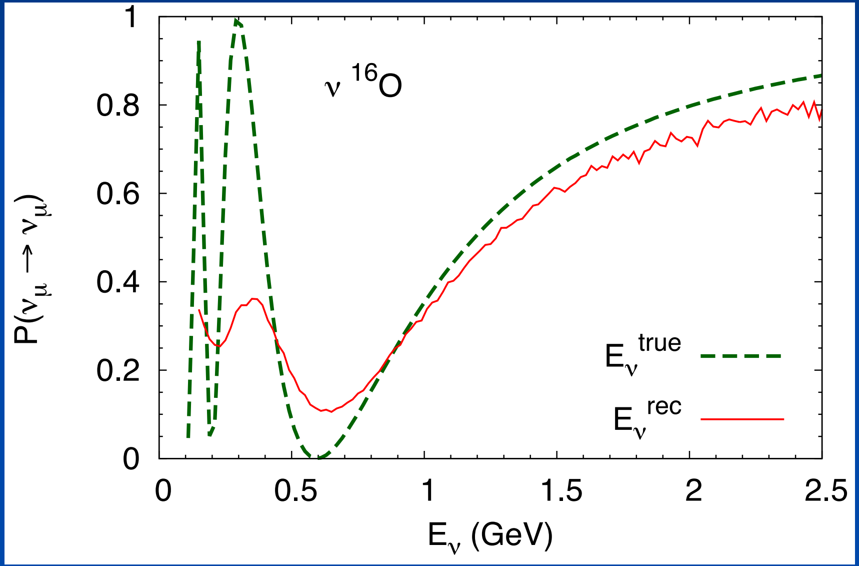
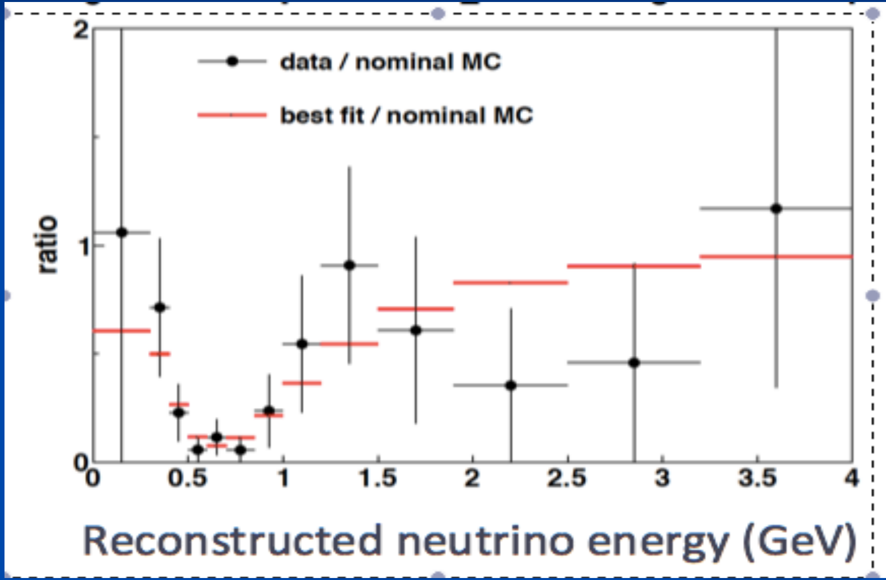
Oscillation signal in T2K

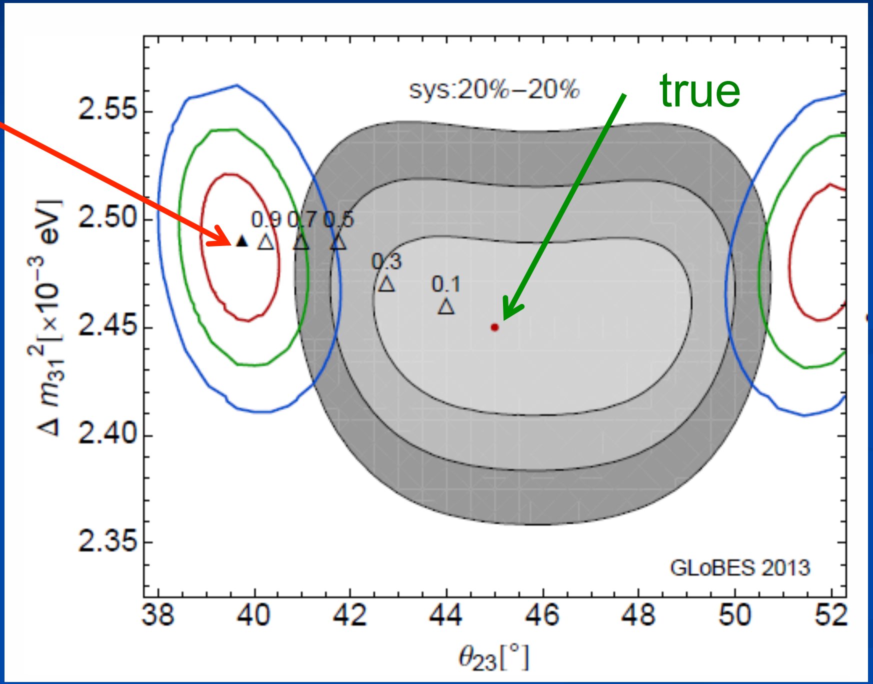
ν_μ disappearance





Sensitivity of oscillation parameters to nuclear model

reconstructed from naive QE dynamics

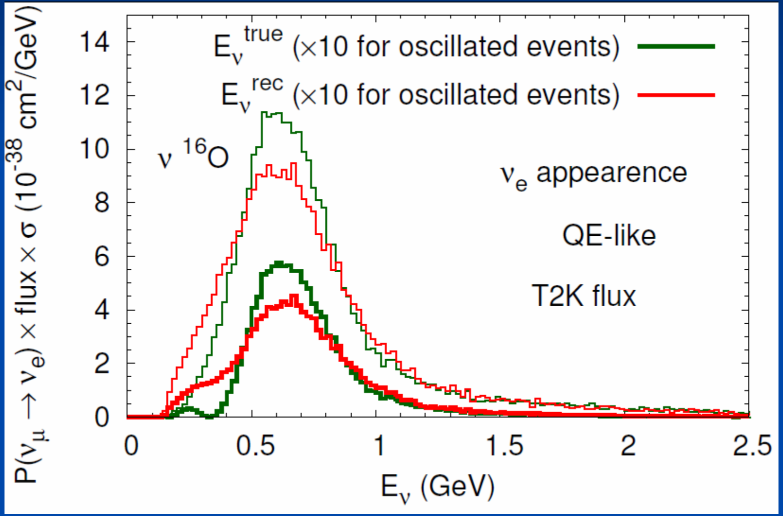


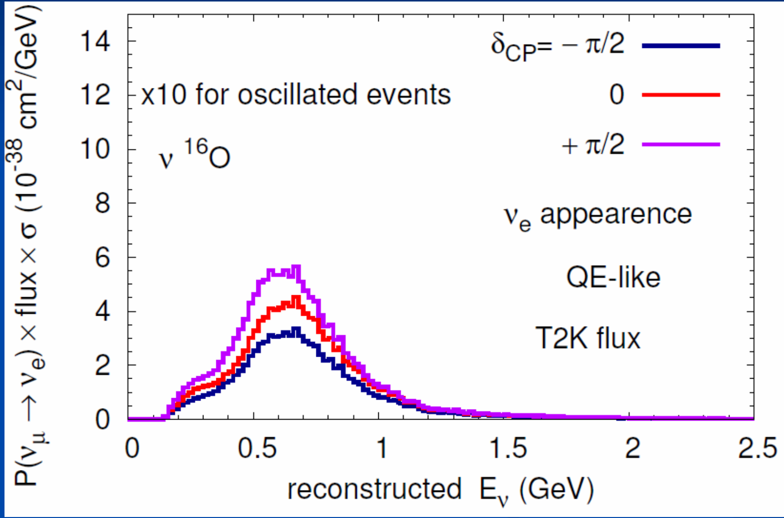
P. Coloma, P. Huber, arXiv:1307.1243, July 2013

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

Sensitivity of T2K to Energy Reconstruction

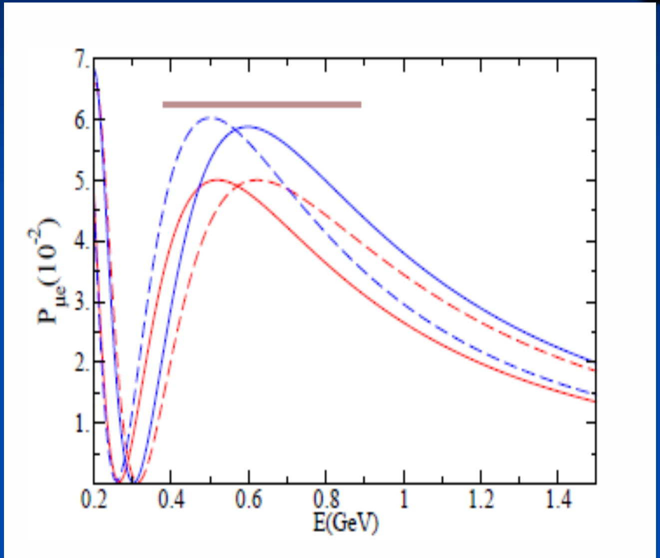
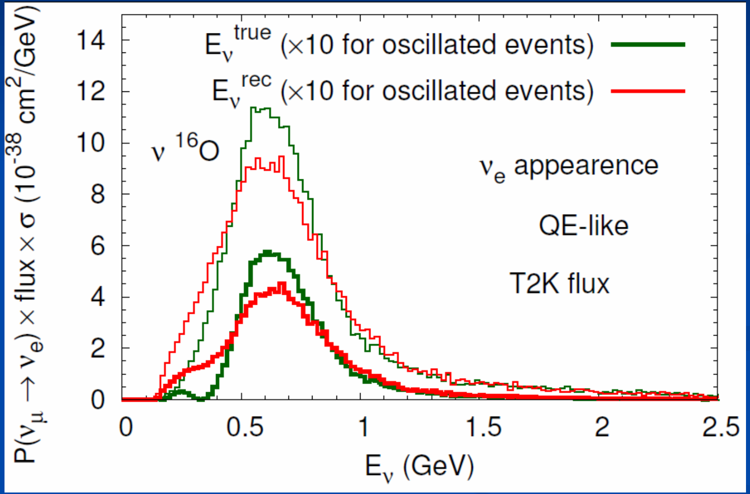
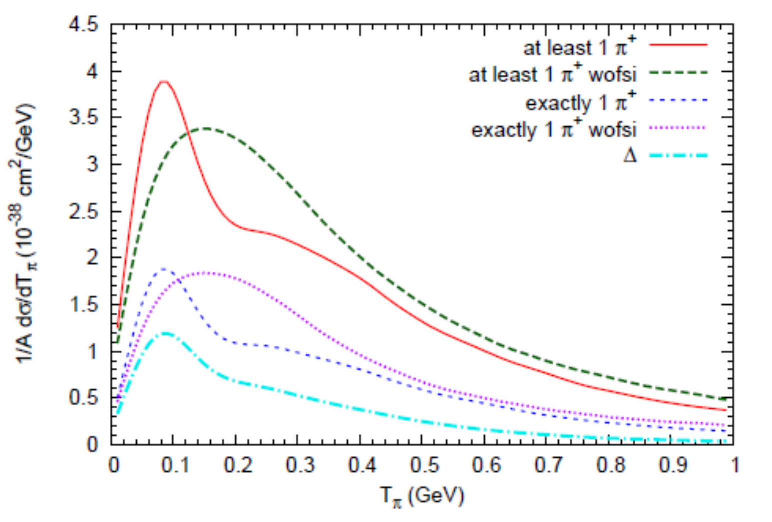


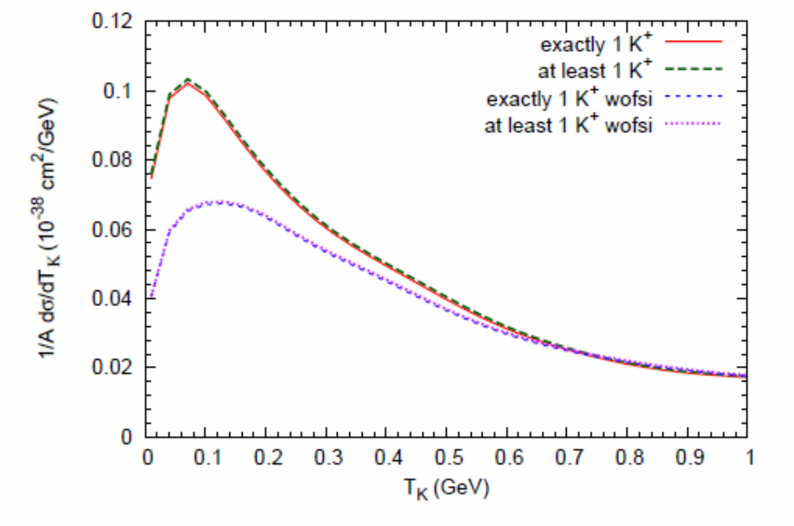
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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



MINERvA





Fsi are most important, but different, for pions and kaons

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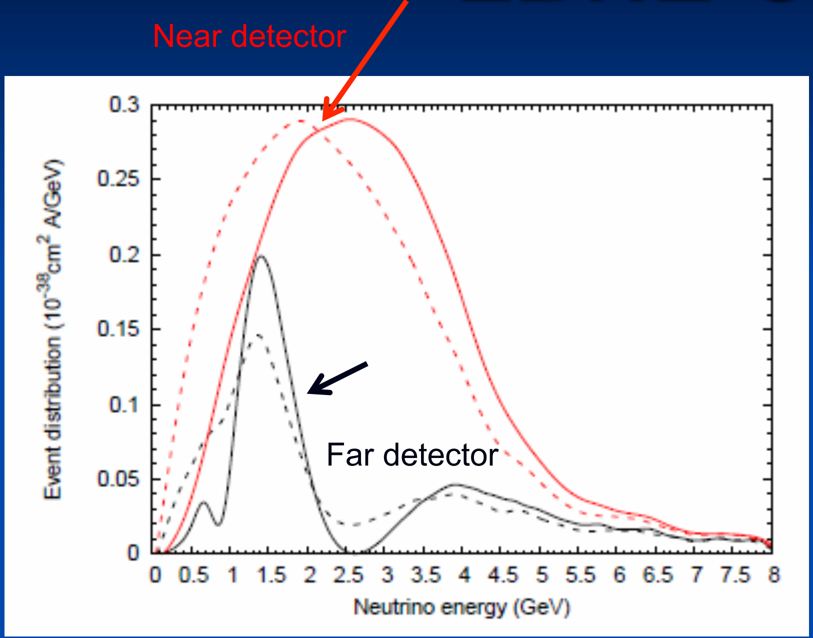
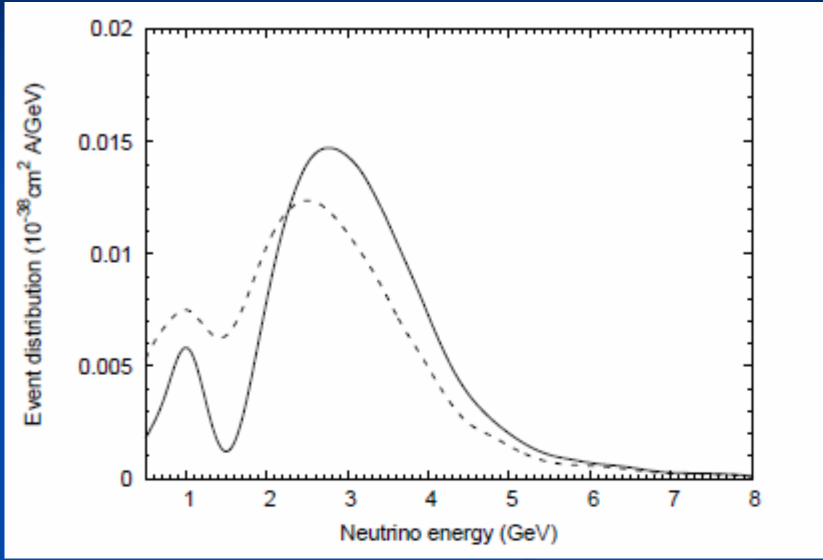
LBNE Oscillations





Survival $\mu \rightarrow \mu$

Appearance $\mu \rightarrow e$

Solid: true, dashed: reconstructed

How to proceed

- Generator is an important part of any experiment: Need generator for transformation reconstructed energy → true energy
- at the end of a very sophisticated experiment you do not want to have someone with a ‚crummy' code to mess up your data!
- Generator-Development must be integral part of any experiment (and its funding)!

Summary

- Energy reconstruction essential for precision determination of neutrino oscillation parameters (and neutrino-hadron cross sections)
- Energy reconstruction requires a quantitative understanding of all reaction mechanisms
- Precision era of neutrino physics requires much more sophisticated generators and a dedicated effort in theory

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