Nuclear effects in the extraction of oscillation parameters

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Motivation and Contents

- Neutrino energy and Q^2 needed for
  - Hadron physics, electroweak couplings to nucleons and resonances
  - Neutrino oscillations
- Neutrino beams are broad in energy
- Modern experiments use nuclear targets
- Nuclear effects affect cross section measurements, neutrino energy and Q^2 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

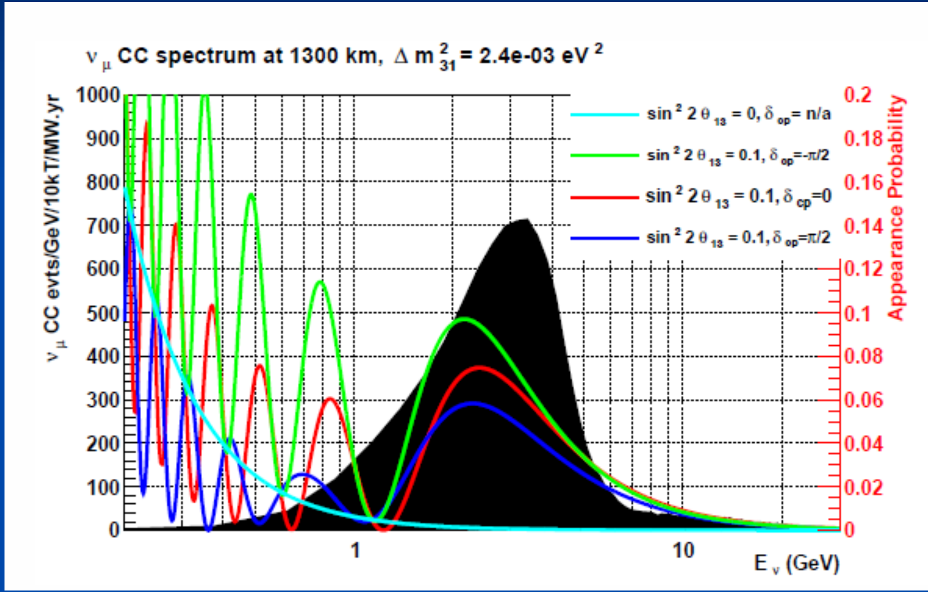
$$\Delta = \frac{\Delta m^2_{21} L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \xi = \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23})$$

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

Vacuum oscillation

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

LBNE, δ_{CP} Sensitivity



Need to know neutrino energy to better than about 100 MeV

Need energy to distinguish between different δ_{CP}

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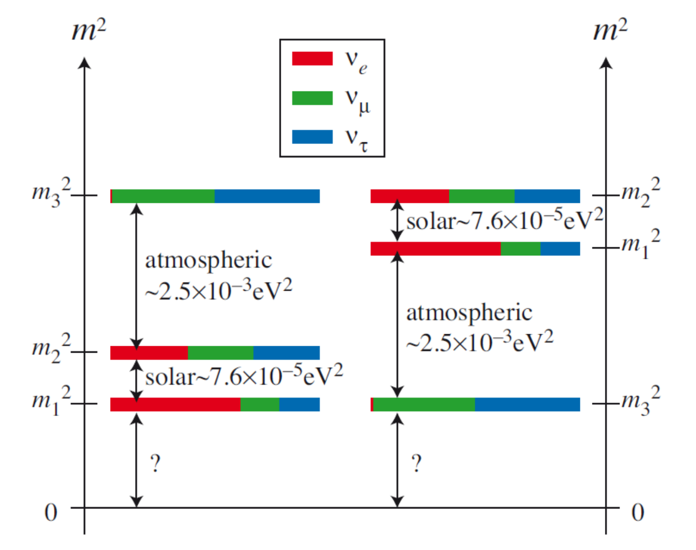
Oscillation Signal
Dependence on Hierarchy and Mixing Angle



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

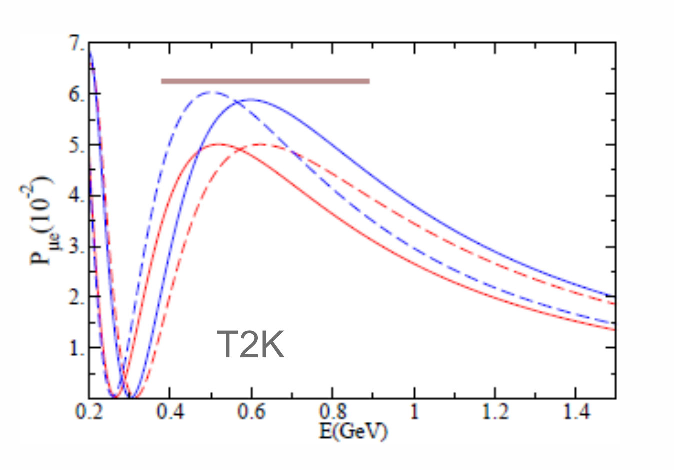


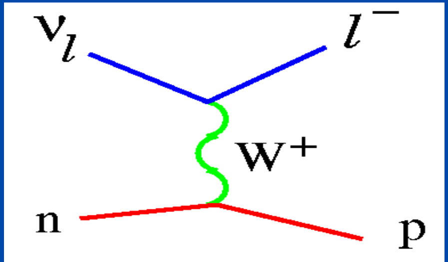
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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, ***no*** π, is outgoing. lepton determines neutrino energy:

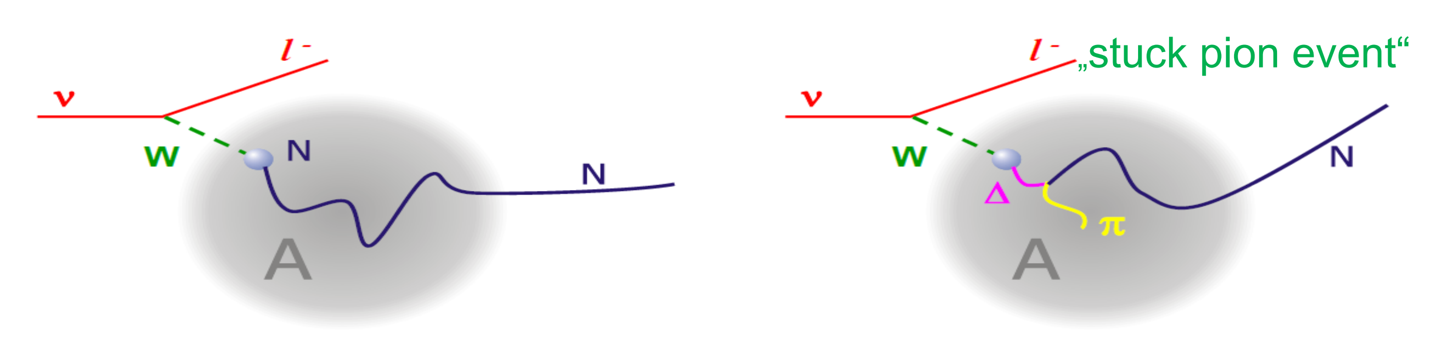


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- 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, ….)

Need for a Neutrino Generator

- Need final state for event reconstruction
- Inclusive cross sections are not enough, need semi-inclusive for event identification
- Must describe complete final state of ($\nu A \rightarrow l\, X$) for 0 pion condition (incl. ‚stuck pions‘)
- Only practical theory: MC or transport code

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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 num. implementation:
  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

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: 8d-Spectral phase space density

Kadanoff-Baym equation

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

Collision term

$$C^{(2)}(x,p_1) = C^{(2)}_{\rm gain}(x,p_1) - C^{(2)}_{\rm loss}(x,p_1) = \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{d^4 p_2}{(2\pi)^4 2p_2^0} \int \frac{d^4 p_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{d^4 p_{2'}}{(2\pi)^4 2p_{2'}^0}$$
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_{1'} - p_{2'}) \overline{|\mathcal{M}_{12\to 1'2'}|^2} [F_{1'}(x,p_{1'}) F_{2'}(x,p_{2'}) \overline{F}_1(x,p_1)$$
$$\times \overline{F}_2(x,p_2) - F_1(x,p_1) F_2(x,p_2) \overline{F}_{1'}(x,p_{1'}) \overline{F}_{2'}(x,p_{2'})]$$

For two-body collisions

with

$$F(x,p) = 2\pi g A(x,p) f(x,p)$$
$$\bar{F}(x,p) = 2\pi g A(x,p) \left[1 - f(x,p)\right]$$

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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**!

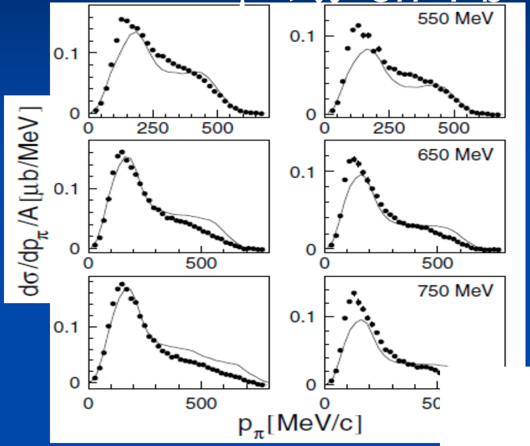
NO TUNING!

GiBUU Ingredients

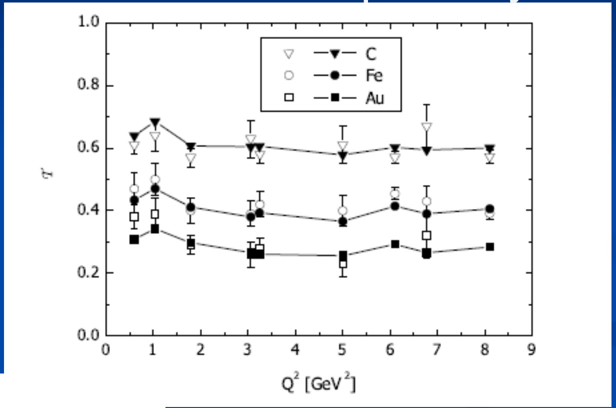
- In-medium corrected primary interaction cross sections, nucleons bound and moving in local Fermigas
- Includes spectral functions for baryons and mesons (binding + collision broadening)
- *Vector* couplings taken from electro-production (MAID)
- *Axial* couplings modeled with PCAC
- *Hadronic* couplings for FSI taken from PDG
- Events for W > 2 GeV (DIS) from PYTHIA

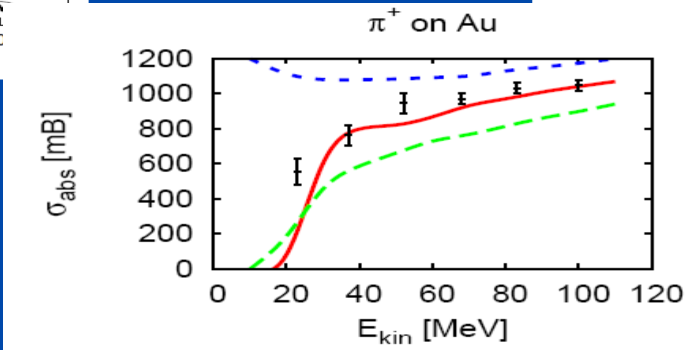
Check: pions, protons

$\gamma \rightarrow \pi^0$ on Pb



Proton transparency





Pion reaction Xsect.

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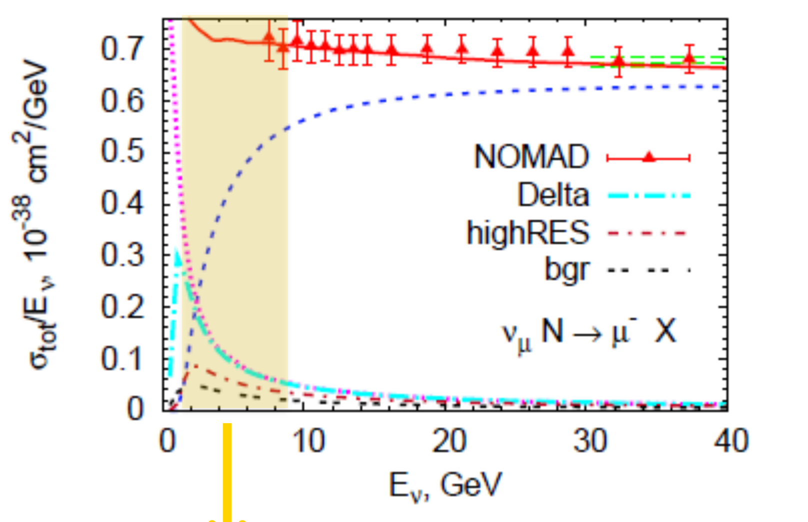
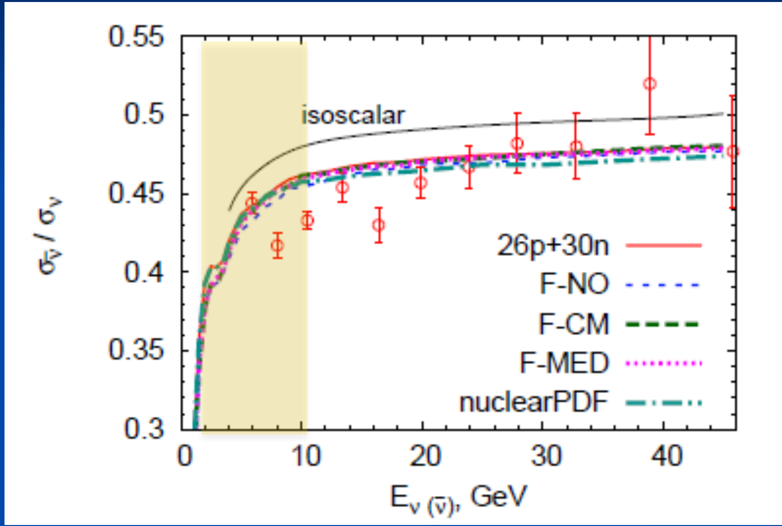
SIS - DIS





Shallow Inelastic Scattering,
interplay of different reaction mechanisms

Curves: GiBUU

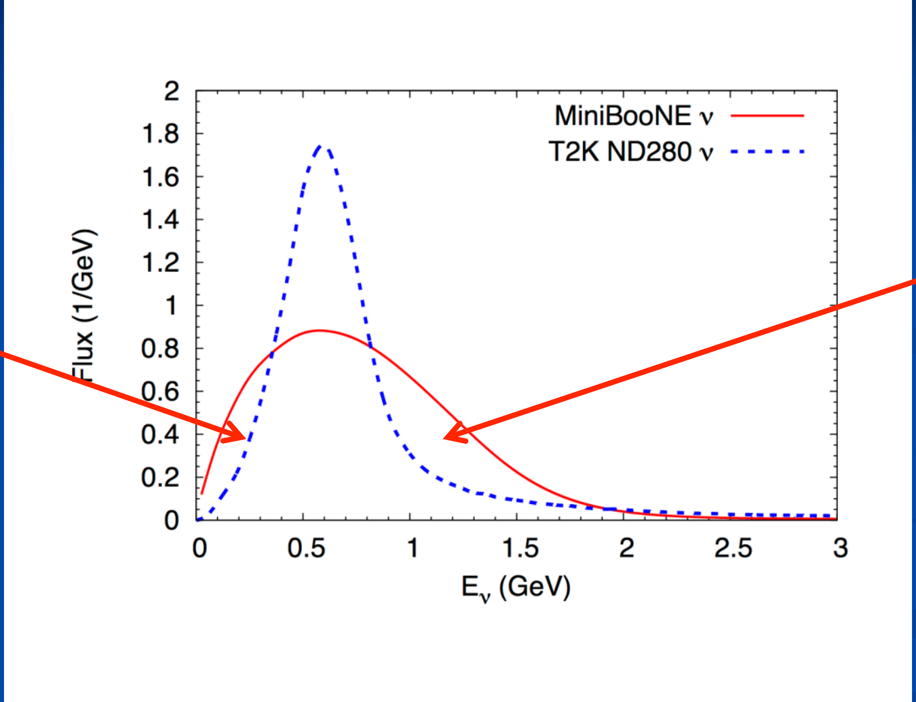
Reaction Types

- 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

T2K vs MB Flux



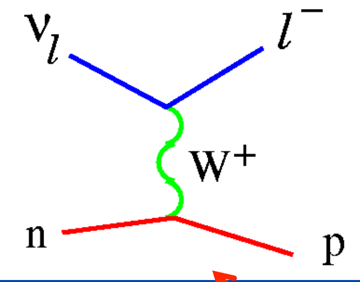
less RPA

T2K ND280
205kA flux

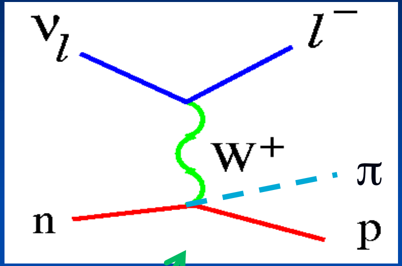
less pions

Neutrino-nucleon cross section

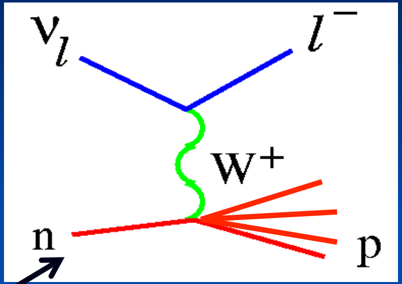
CCQE

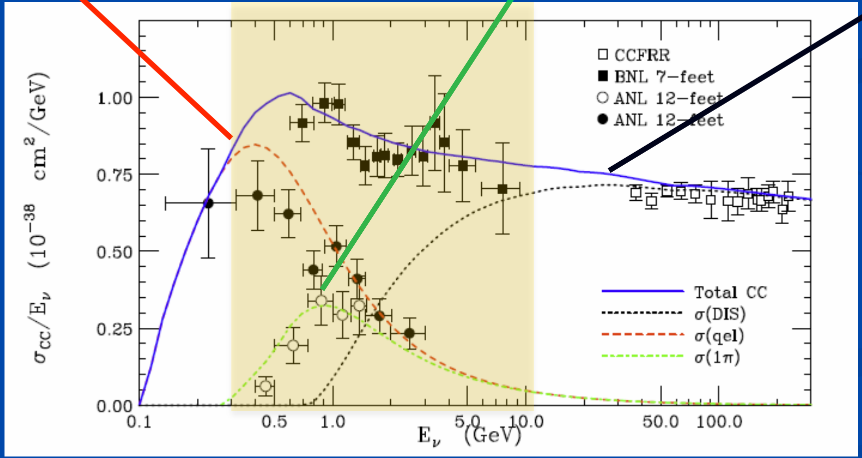


1π



DIS





JPARC 02/2014

note:
10^{-38} cm² = 10^{-11} mb

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

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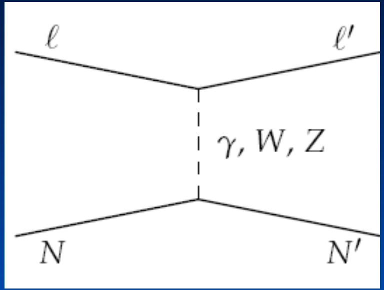
Quasielastic scattering



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

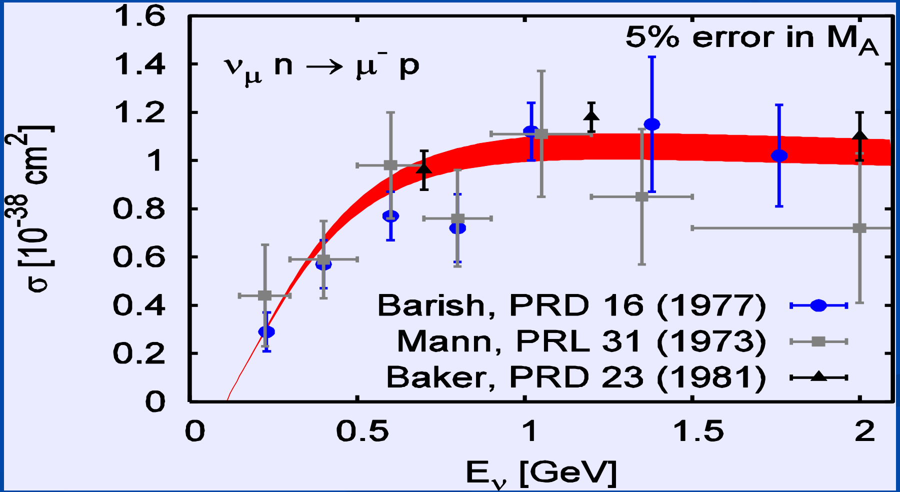
- Vector form factors from *e* –scattering
- axial form factors

  F_A ⬄ 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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2p-2h Processes

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

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

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

Ansatz for *W*: $W_{\mu\nu} = g_{\mu\nu} F(Q^2)$

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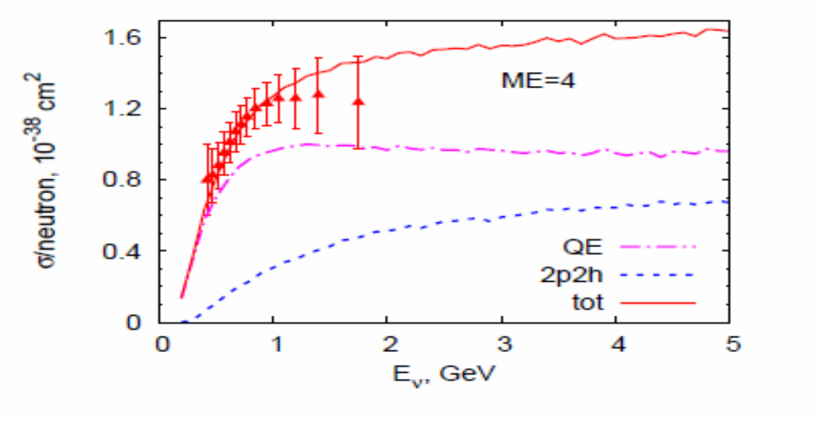
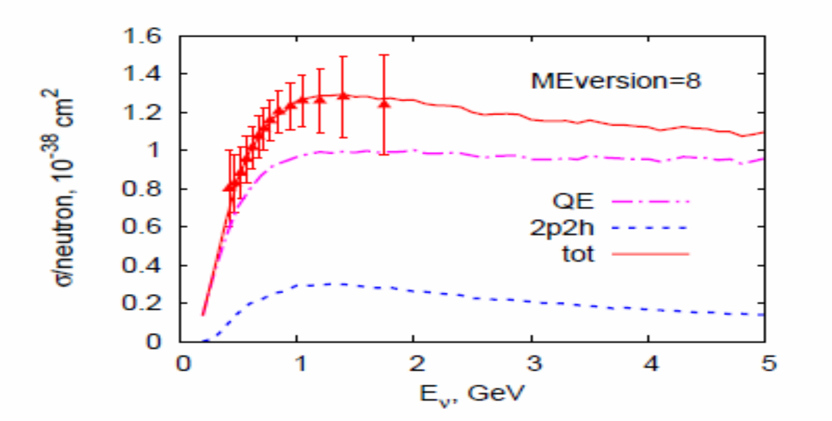
The MiniBooNE QE Puzzle

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





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

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Pion Production

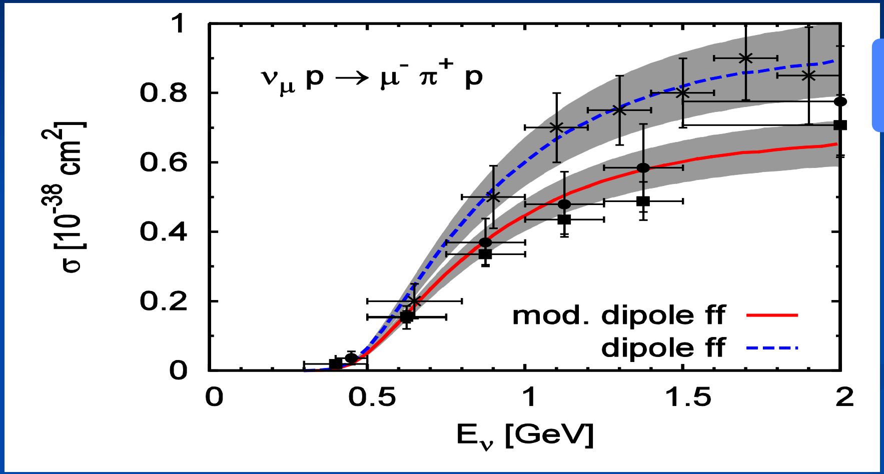
- Pion production dominated by **P_{33}(1232) resonance (not just a heavier nucleon)**

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

- ***$C^V(Q^2)$*** 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 $C_5^A(0)$

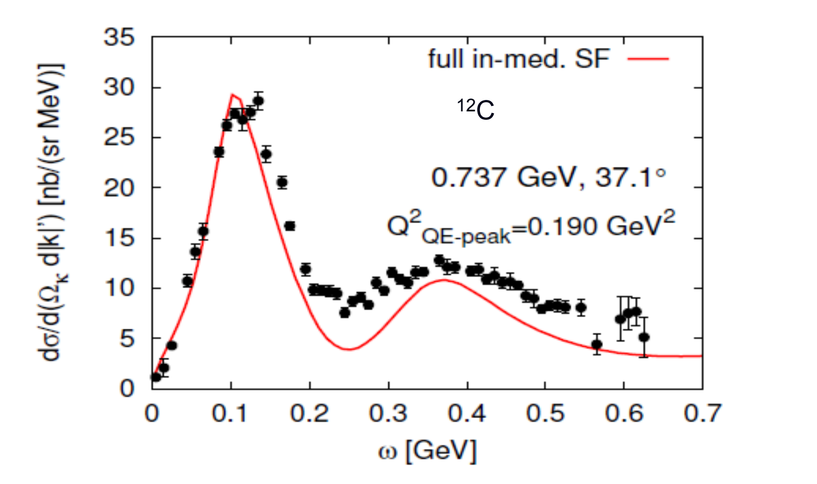
data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)

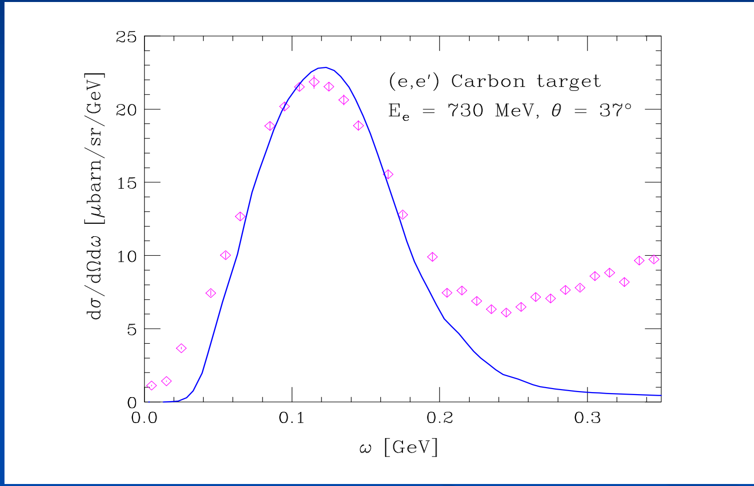
discrepancy between elementary data sets
→impossible to determine 3 axial formfactors

New pion data on elementary target desparately needed!

Electrons as Benchmark for GiBUU

Trouble for neutrinos: ω must be reconstructed

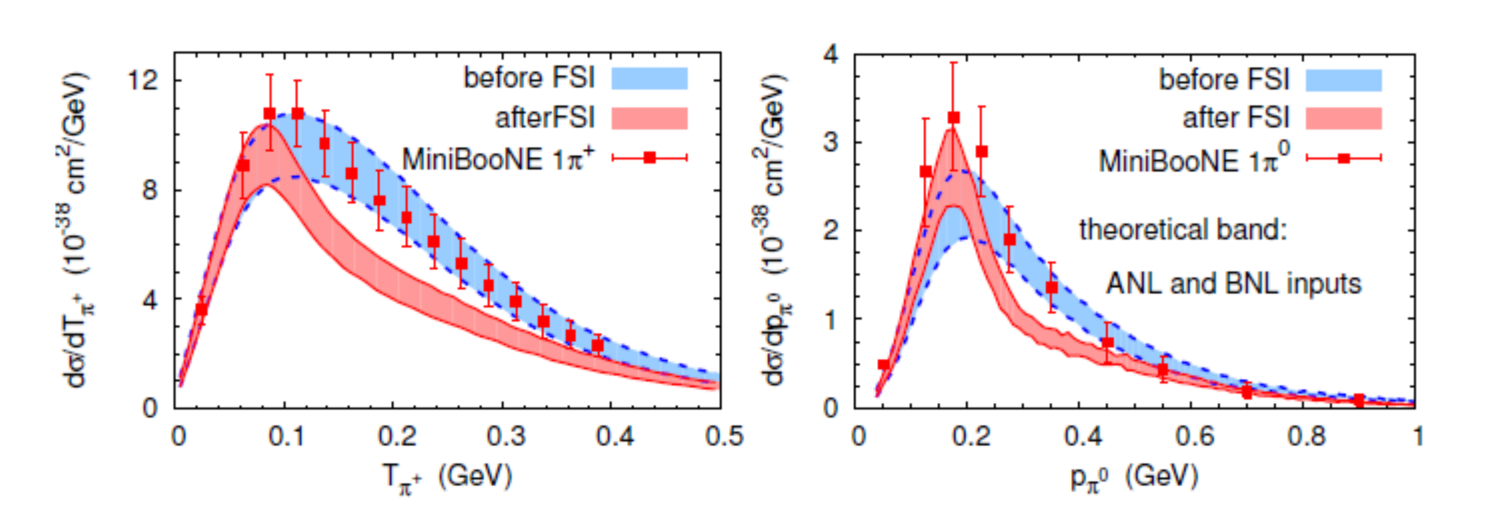




No free parameters!
no 2p-2h, contributes
in dip region and under Δ

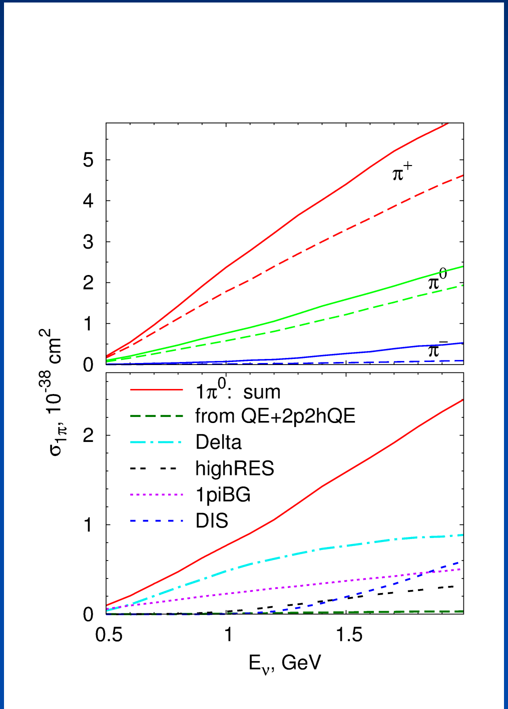
O. Benhar, spectral fctn

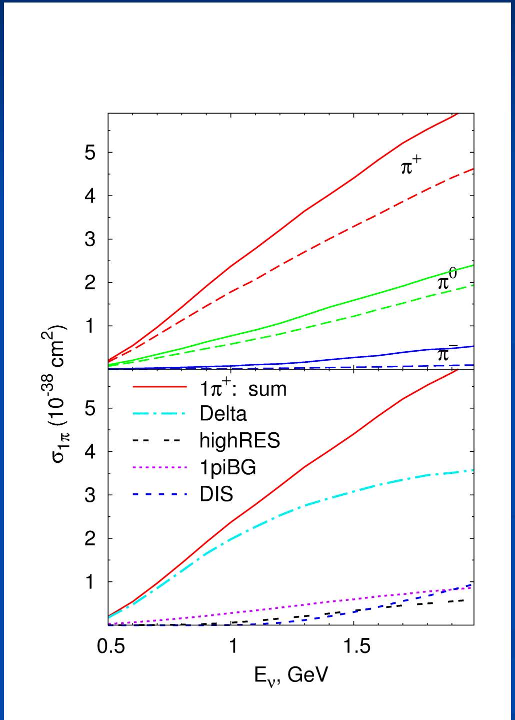
Pion Spectra in MB



Strong fsi effect (π + N → Δ, Δ + N → NN) not seen in data

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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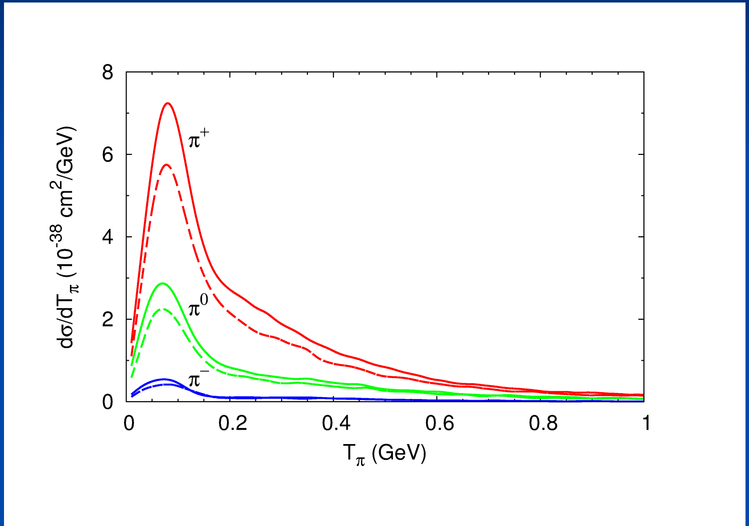
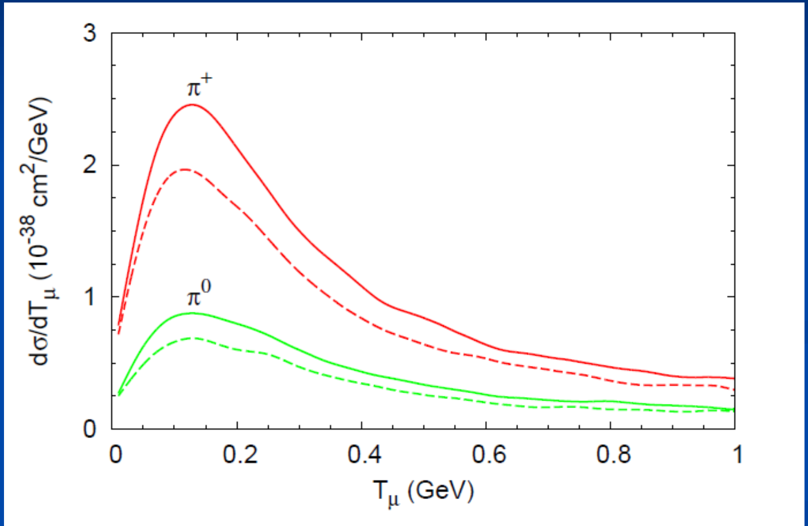
Pion Production in T2K

O.L., U.M.: Phys.Rev. C88 (2013) 017601





Upper curve: BNL input, lower curve: ANL input

T2K pion data may help to distinguish between ANL and BNL input

Oscillation and Energy Reconstruction

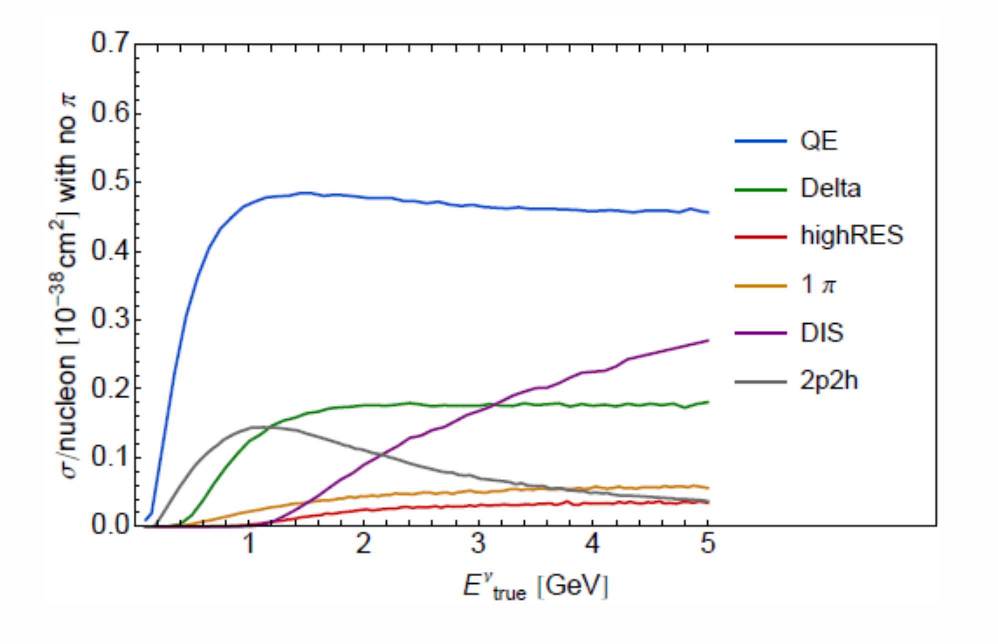
- For nuclear targets QE reaction must be identified to use the reconstruction formula for E_ν
  exp: 1 lepton, no pion, any number of other hadrons
- *But:* exp. definition of QE cannot distinguish between true QE (1p-1h), N* and 2p-2h interactions
- Many different reaction mechanisms, besides true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

Energy Reconstruction by QE

- CCQE scattering on neutron at rest
  - Energy
    $$E_\nu^{\rm rec} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu\right]}$$
  - Q^2
    $$Q^2_{\rm rec} = -m_\mu^2 + 2E_\nu^{\rm rec}(E_\mu - |\vec{k}_\mu|\cos\theta_\mu)$$
- Energy reconstruction tilts spectrum, affects Q^2 distribution at small Q^2

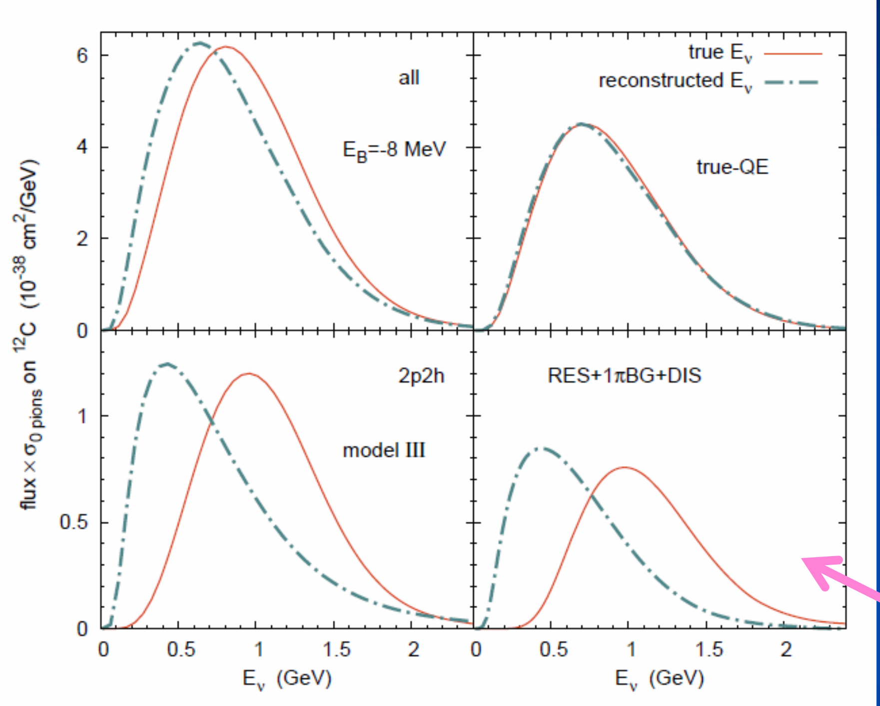
0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1



Energy reconstruction in MB

Event rates = flux x crosssection



MiniBooNE flux

Reconstructed energy shifted to lower energies for all processes beyond QE

Reconstruction must be done for 0 pion events

Not only 2p-2h important

NOT contained in Nieves model

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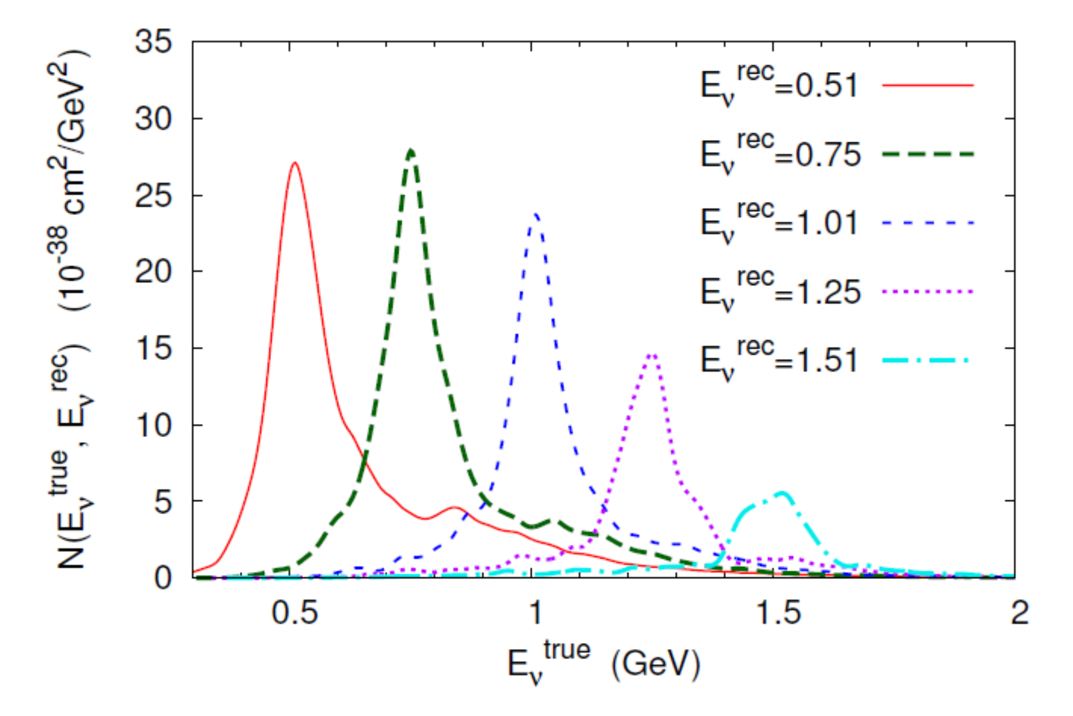
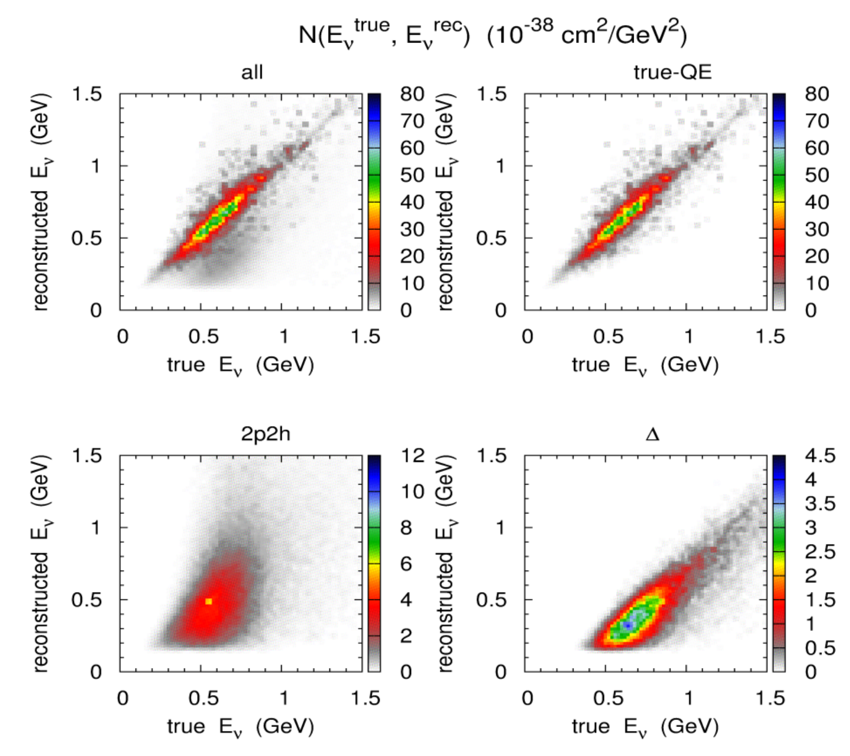
Energy-Reconstruction



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

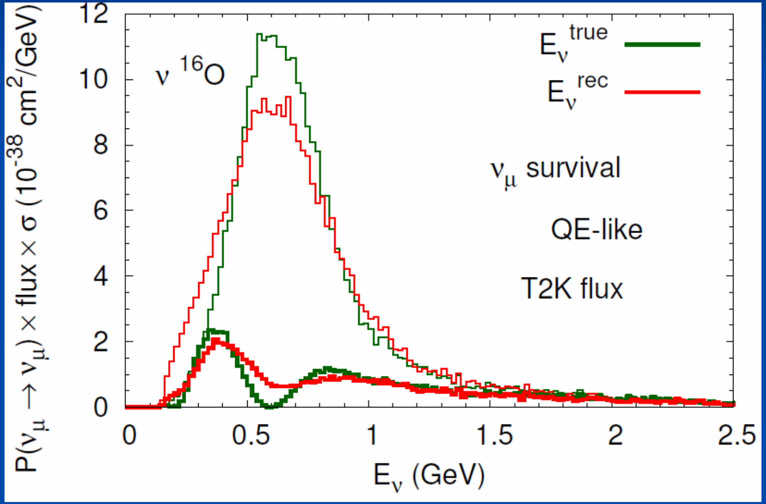
T2K migration matrix



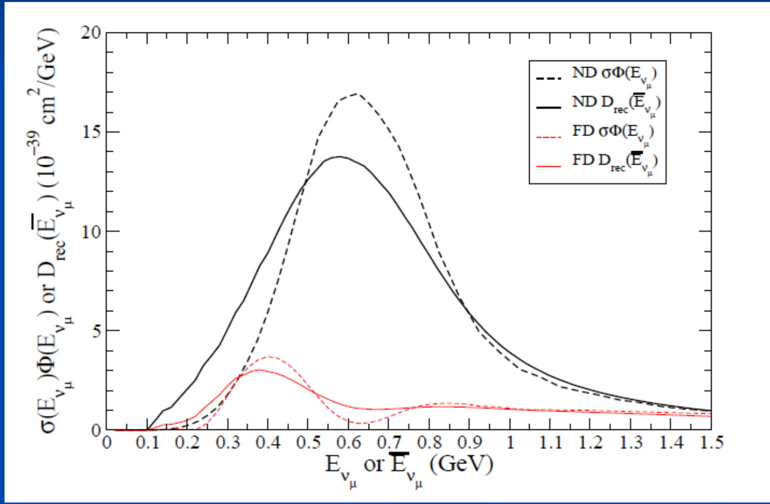
T2K Flux
Target: ^{16}O

Oscillation signal in T2K

ν_μ disappearance



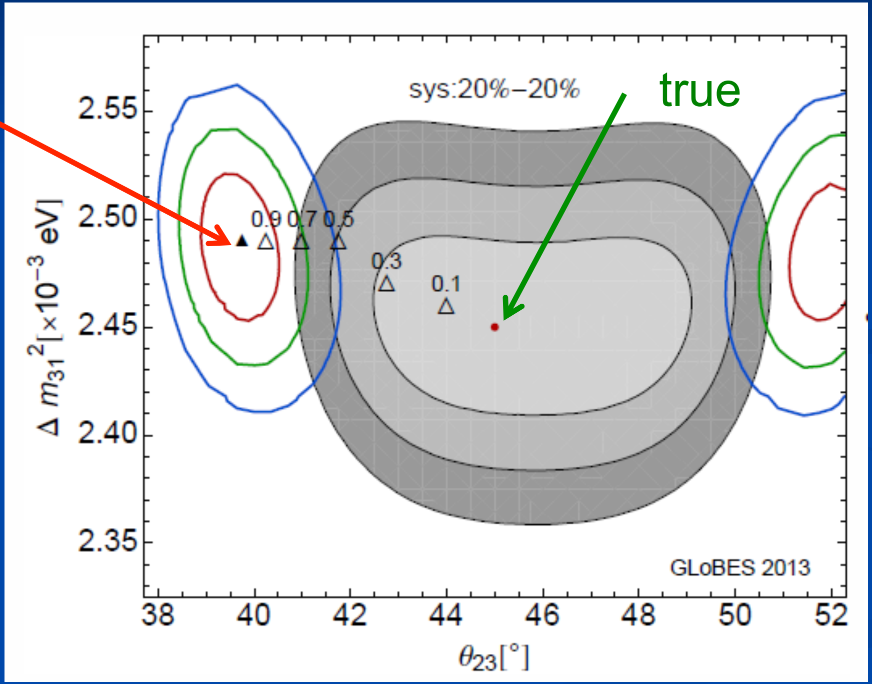
GiBUU



Martini

Sensitivity of oscillation parameters to nuclear model

reconstructed from naive QE dynamics

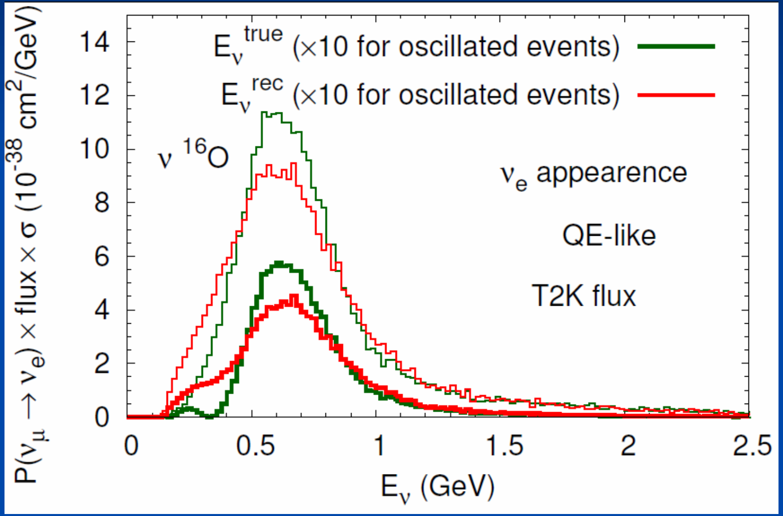


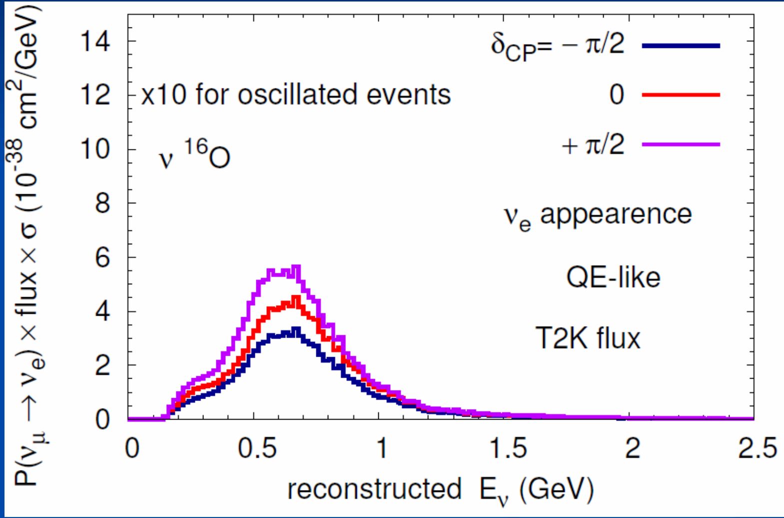
P. Coloma, P. Huber, arXiv:1307.1243, July 2013

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

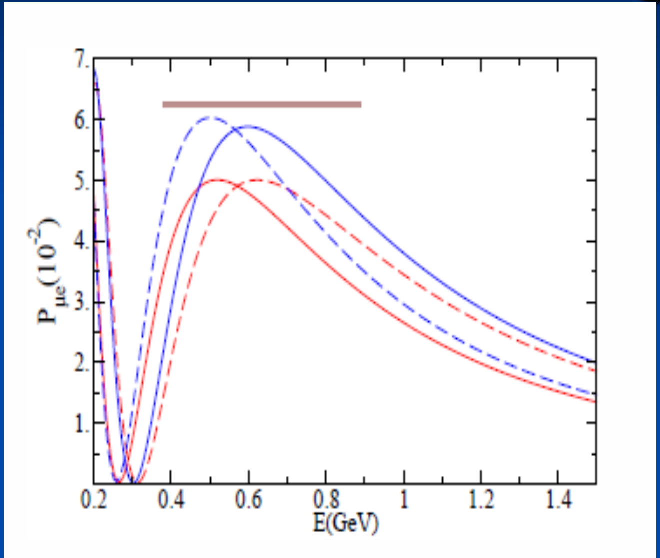
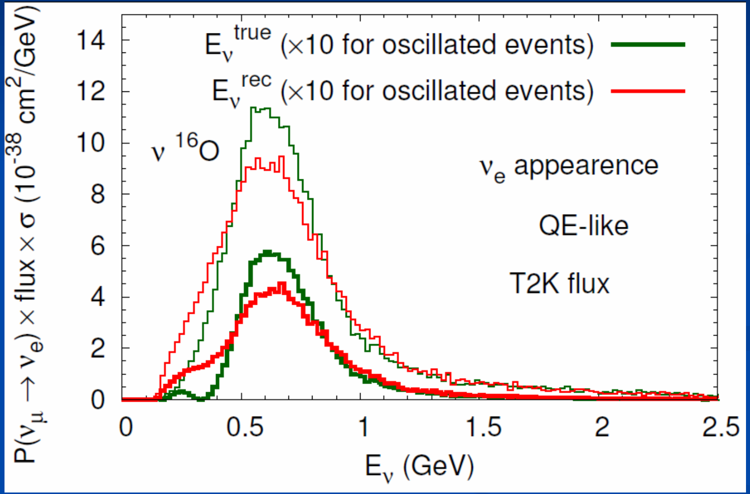


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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



Summary

- Energy and Q^2 reconstruction essential for precision determination of neutrino oscillation parameters (and neutrino-hadron cross sections)
- Energy and Q^2 reconstruction requires reliable event generators, of same quality as experimental equipment
- Precision era of neutrino physics requires much more sophisticated generators and a dedicated effort in theory

Generators

- 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)!

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Precision era requires better generators

- Present generators have evolved into a patchwork of theories, recipes and fit parameters without any theoretical justification and loose predictive power

- It is thus time to critically scrutinize existing generators, take the best parts from any of them, supplement them with consistent theory and build a

  ν-GENIE (or NEUT)

Precision era requires better generators What needs to be done? Theory

1. Develop consistent framework for many-body effects: spectral functions + couplings, consistent groundstates
2. Theory must comprise besides QE also pion and DIS region because all are entangled
3. Parametrize hadron tensors as function of relevant kinematical variables for use in generators
4. Consistency of inclusive and exclusive X-sections
5. Improve all important final state interactions

Guiding Principles for a new Generator

- ***Consistency:***
  e.g., same ground state for all subprocesses (negative example: combine free uniform Fermi gas with bound state local gas)
- ***Detailed balance:***
  e.g.: $\Delta + N \rightarrow NN$ (pionless Delta decay) must be related to $N + N \rightarrow \Delta + N$ (negative example: just take out 20% Δs)
- ***Relativity:***
  e.g., generator collision criterion $\sigma = \pi\, d^2$ is incorrect
- ***Correct:*** in nuclear structure and reaction theory