Neutrino-Nucleus Interactions in Broad-Band Neutrino Experiments

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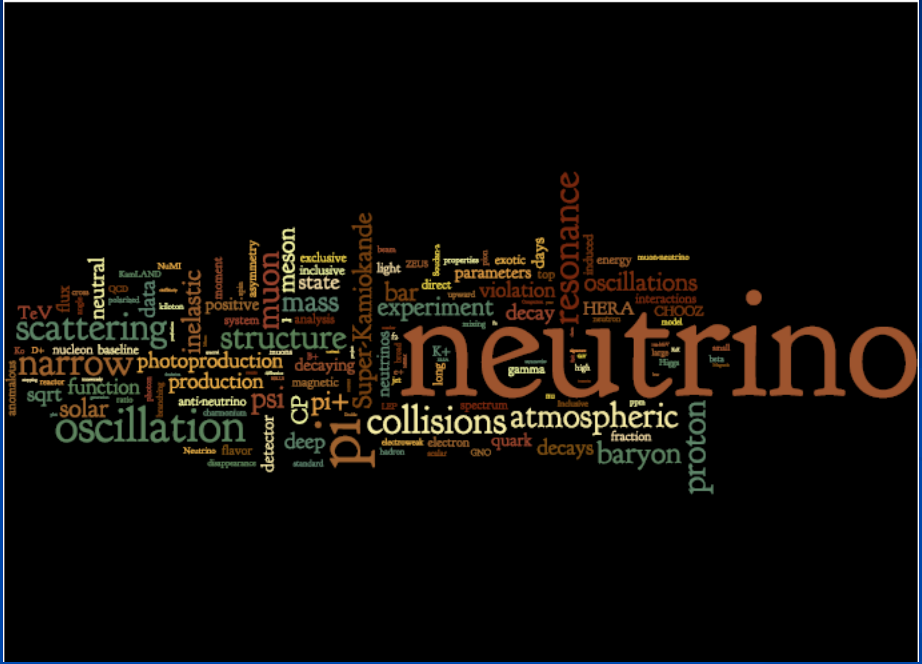
Words in 100 most cited papers in high energy physics



Fontsize reflects frequency

From: neutrino@wordle

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Motivation and Contents

- Determination of neutrino oscillation parameters requires neutrino energy
- MiniBooNE QE puzzle, effects on energy reconstruction
- Neutrino interactions in the ‚shallow inelastic regime‘: determination of cross sections

LBNE

Beam: 700 kW, 60-120 GeV, 5 years ν + 5 years anti-ν
on-axis, wide band, upgradable to 2.3 MW
Baseline: 1300 km FNAL to Homestake

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Neutrino Oscillations

- 2-Flavor Oscillation:

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

Know: L, need E_ν to determine Δm^2, θ

Neutrino Oscillations

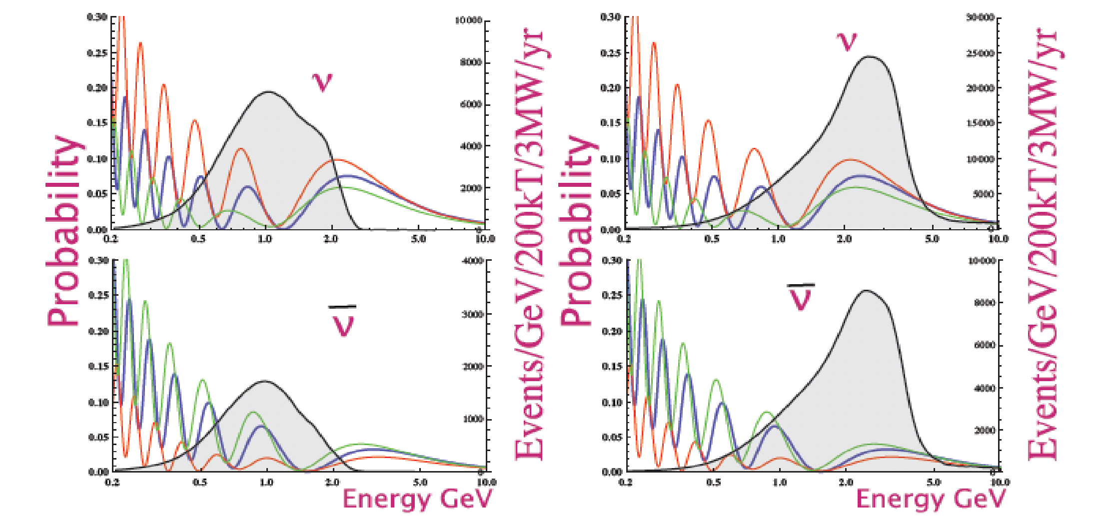
- 3-Flavor Oscillations: $\nu_{l\mathrm{L}}(x) = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}}(x)$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$ $\theta_{ij} = [0, \pi/2]$

CP violating phases: $\delta = [0, 2\pi]$ $\alpha_{21},\ \alpha_{31}$ δ goes with s_{13}

Project X, δ_{CP} sensitivity



From:
Bishai et al
arXiv:1203.409

δ_{CP} = 0
δ_{CP} = π/2
δ_{CP} = - π/2

8 GeV   60 GeV

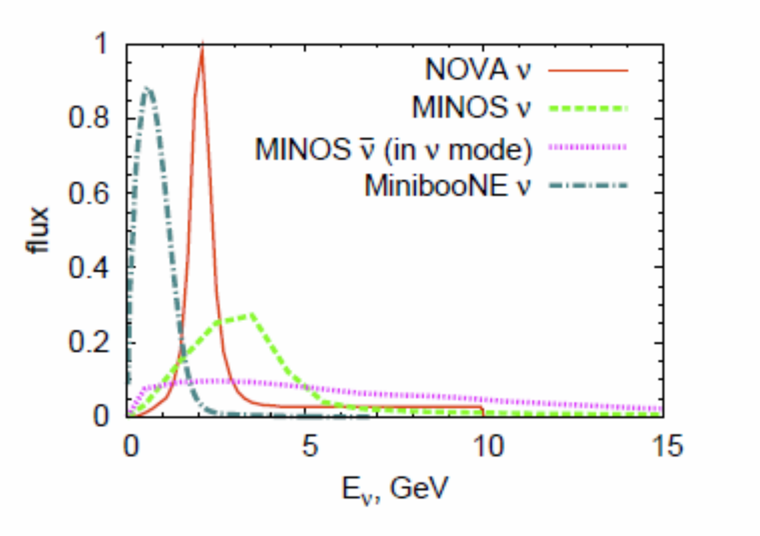
proton energy

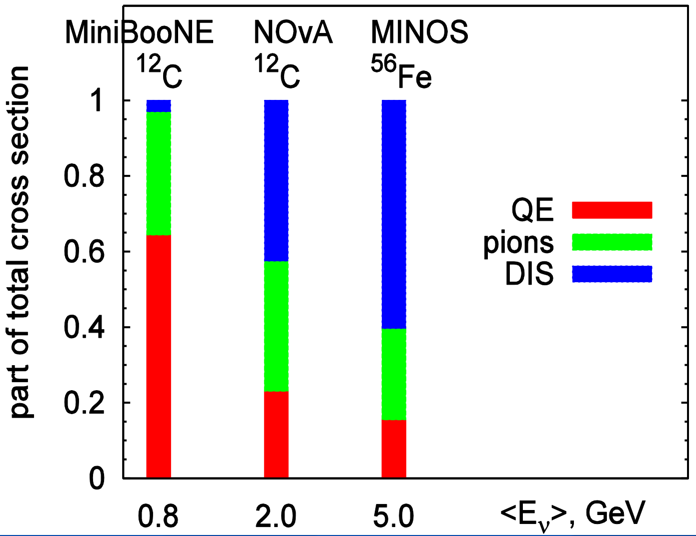
Need energy to distinguish between different δ_{CP}

Now to ongoing experiments

Neutrino Beams

- Neutrinos do not have fixed energy:

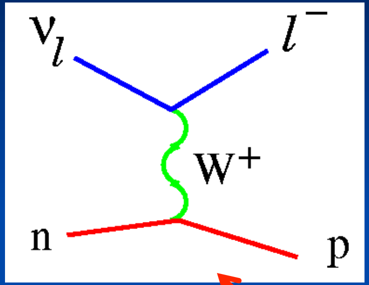




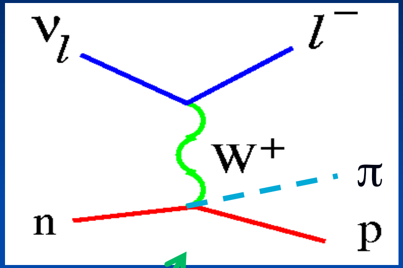
Have to reconstruct energy from final state of reaction

Neutrino-nucleon cross section

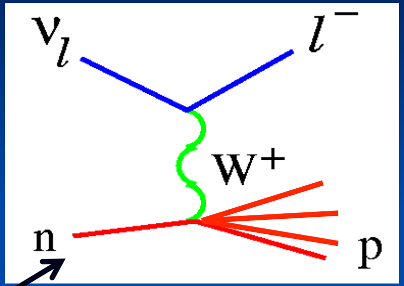
CCQE

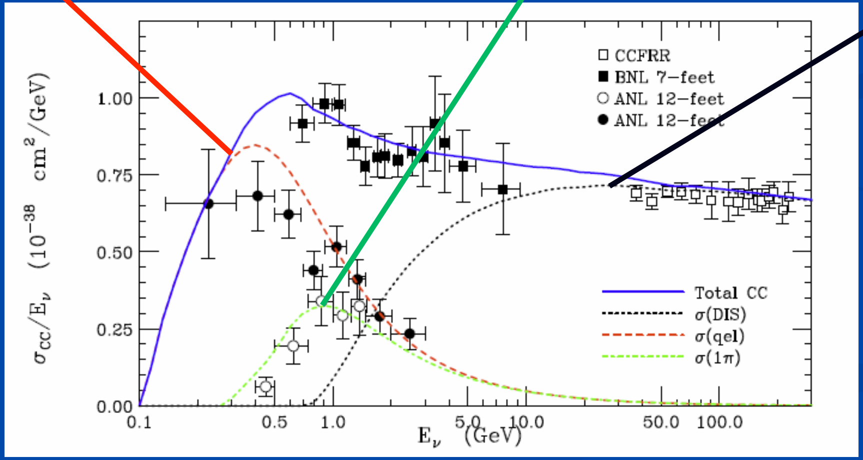


1π



DIS



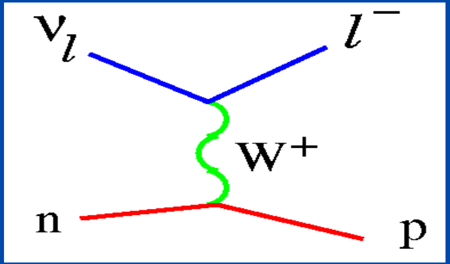


note:

10^{-38} cm^2 = 10^{-11} mb

Energy Reconstruction by QE

- In pure QE scattering on nucleon at rest outgoing lepton determines neutrino energy!



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

- BUT: all modern experiments contain nuclei as targets → expect effects of binding energy and Fermi motion

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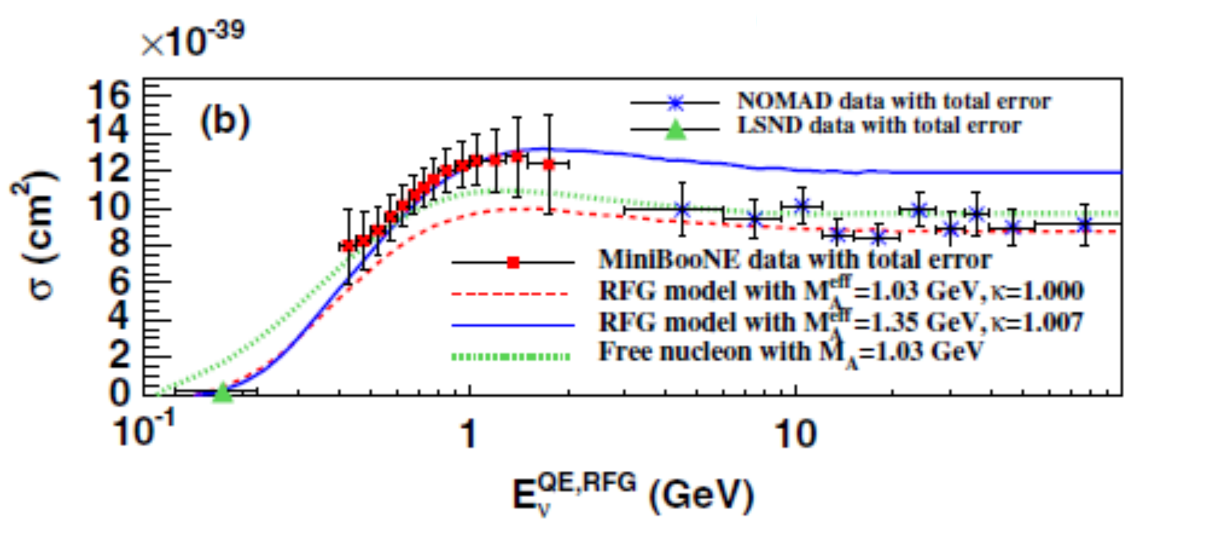
MiniBooNE QE puzzle



World average axial mass:
M_A = 1.03 GeV

MB employs Cerenkov counter: identifies QE by muon and zero pion, corrects for ‚stuck pions‘

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GiBUU

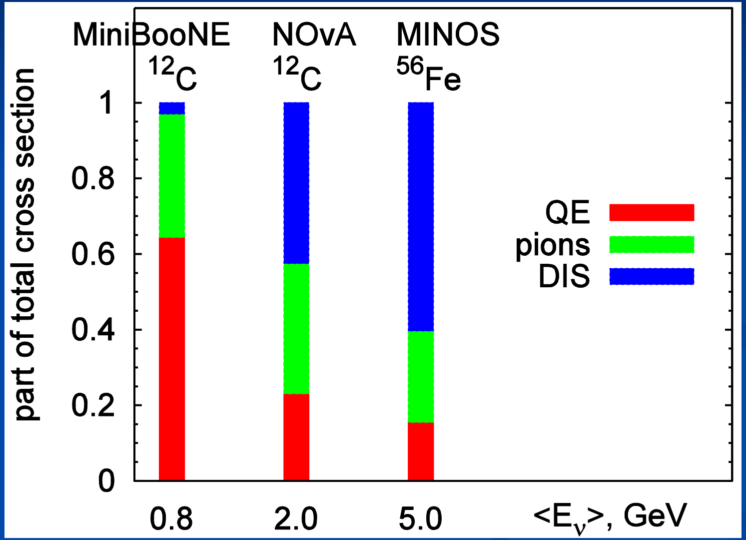
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- GiBUU : **Event Generator**
  based on an approx. solution of Kadanoff-Baym equations
  -> contains off-shell transport
- general information (and code available): Phys. Rept. 512 (2012) 1
  http://theorie.physik.uni-giessen.de/GiBUU/
- 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!

Model Ingredients

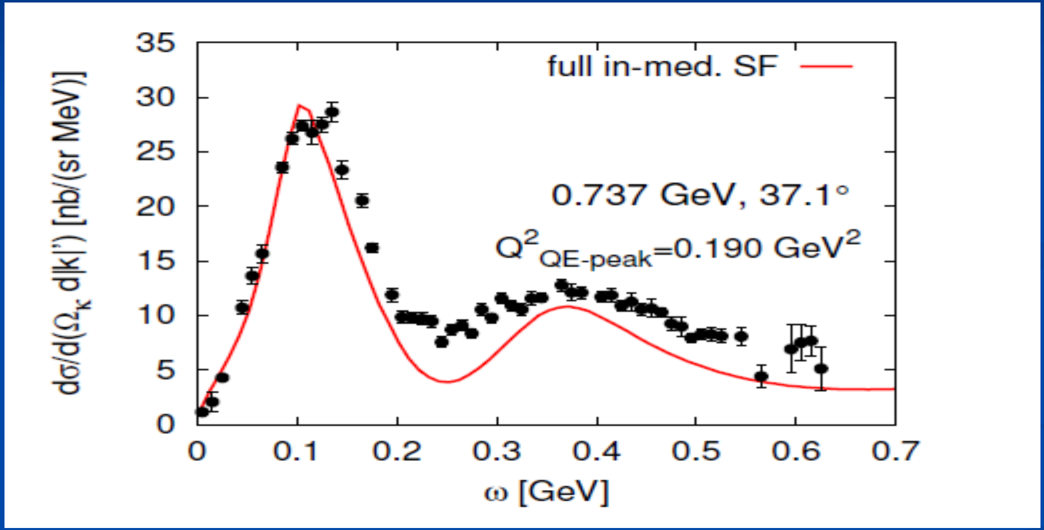
- Processes included:
  - CC + NC QE scattering
  - Resonance excitation
  - DIS
- CC FSI for all produced particles



A complete model has to describe all of them

Electrons as Benchmark for GiBUU

Electron scattering on C

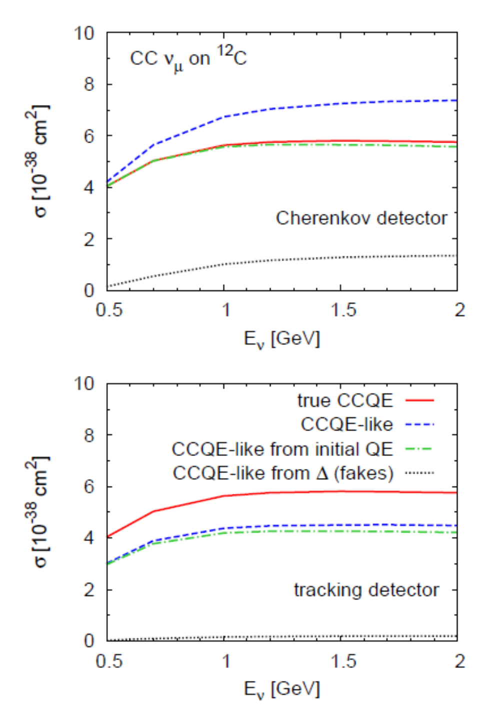


Red curve:
GiBUU

Res. Props
from MAID
UU

Difficulty to separate processes if neutrino energy is not known

QE-Pion Entanglement



- Cerenkov detector (MiniBooNE, K2K 1kt, T2K) defines QE by:

$$\begin{array}{llllll} \text{CCQE:} & 1\mu^- & 0\pi^+ & 0\pi^- & 0\pi^0 & xp\ xn \\ \text{CC}1\pi^+\text{:} & 1\mu^- & 1\pi^+ & 0\pi^- & 0\pi^0 & xp\ xn \end{array}$$

Too high QE: misidentifies about 20%, pion-induced fakes

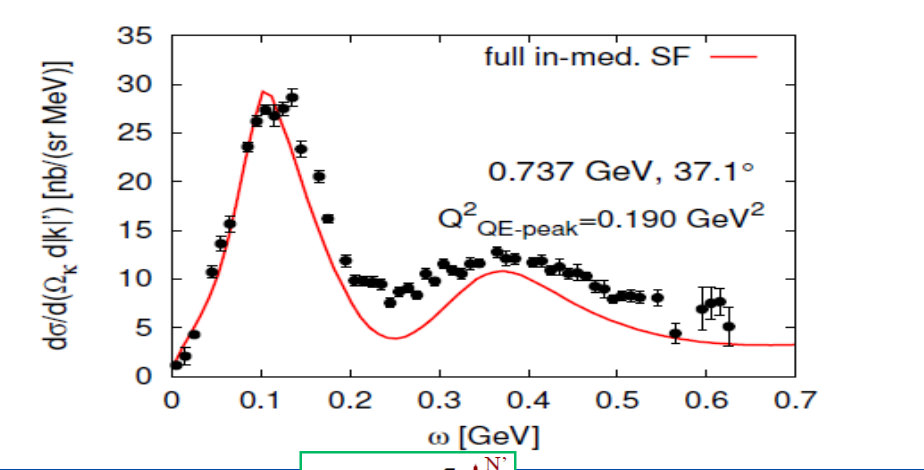
- Tracking detector (Sci-BooNE, K2K, SciFi, T2K) defines QE by

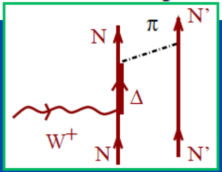
$$\begin{array}{llllll} \text{CCQE:} & 1\mu^- & 0\pi^+ & 0\pi^- & 0\pi^0 & 1p\ xn \\ \text{CC}1\pi^+\text{:} & 1\mu^- & 1\pi^+ & 0\pi^- & 0\pi^0 & xp\ xn \end{array}$$

QE identification is clean, but 30% of total QE cross section is missed

The MiniBooNE QE Puzzle Explanations

- QE scattering has to be identified
  for energy reconstruction formula to work.





Difficult to separate QE, Δ excitation and 2p-2h

The MiniBooNE QE Puzzle Explanations

- Various expanations for MB puzzle:
  - Larger axial mass $M_A \approx 1.3$ GeV (exp)
  - Change of axial FF (Hill)
  - Change of vector FF (Bodek)
  - 2p-2h (Ericsson, Martini)

The MiniBooNE QE Puzzle Explanations

- A Toy Model for $\nu + p_1 + p_2 \rightarrow p_3 + p_4 + \mu$ (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 *M*
M contains 2p-2h and poss. RPA effects

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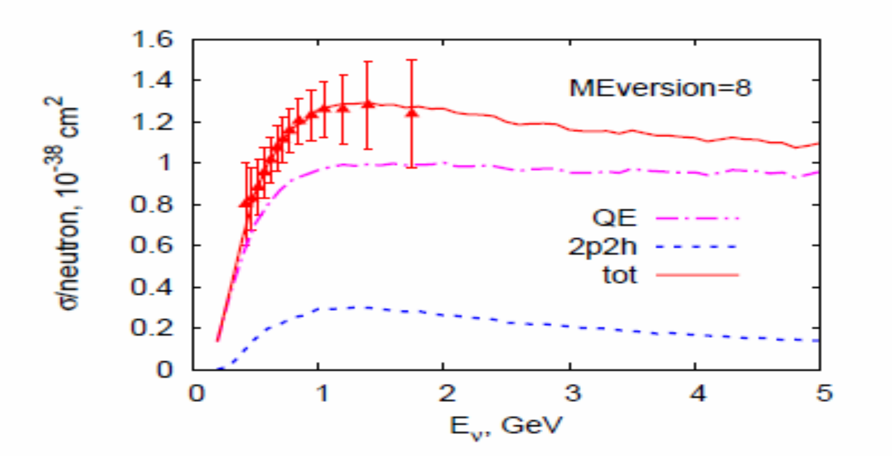
The MiniBooNE QE Puzzle Explanations

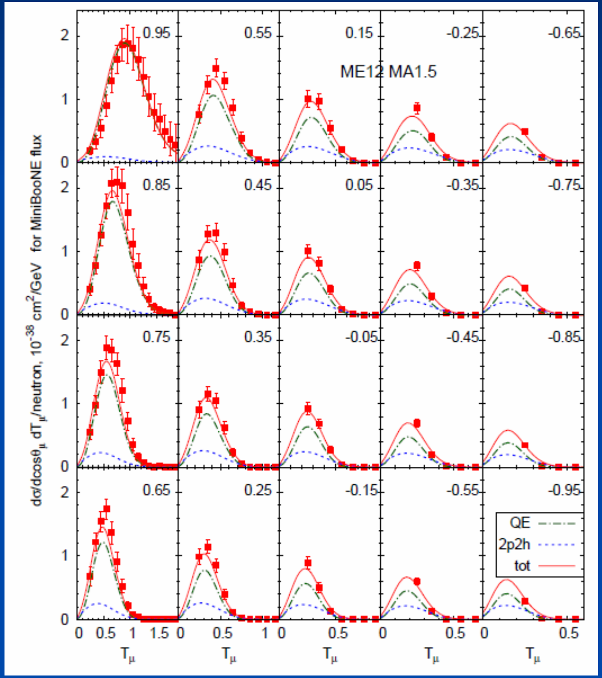
- Educated guess for flux-averaged matrixelement

$$M = M(E,q),\ w^{\mu\nu} \sim P_T^{\mu\nu}(q)$$



Absolute value fitted to data.

The MiniBooNE QE Puzzle
Explanations



MB flux averaged

Data corrected
for pion production
followed by
pion absorption!

Inclusive double-differential
X-sections insensitive to
details of interaction

The MiniBooNE QE Puzzle
Explanations

- Angle dependence:
  - Transverse 2p-2h contrib increases with angle
  - QE contrib decreases strongly with angle
    ➔ Ratio 2p-2h increases steeply with angle

- Inclusive Cross section insensitive to specifics of 2p-2h interaction model
  ➔ Need experimental check

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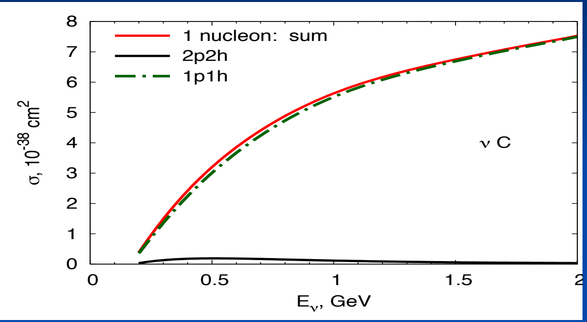
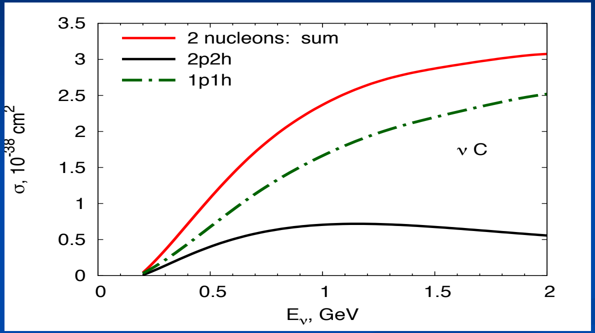
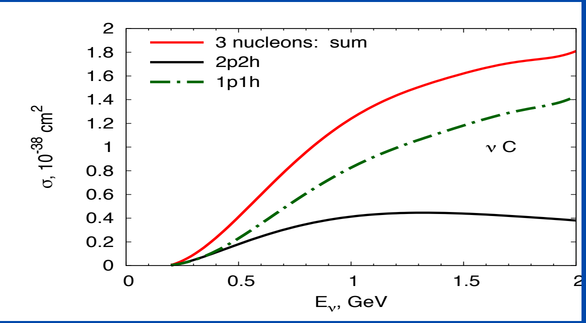
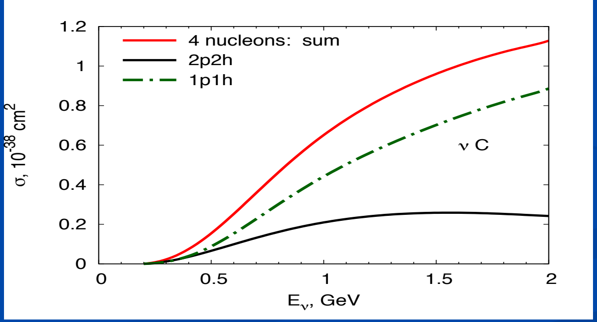
The MiniBooNE QE Puzzle
Knock-Out





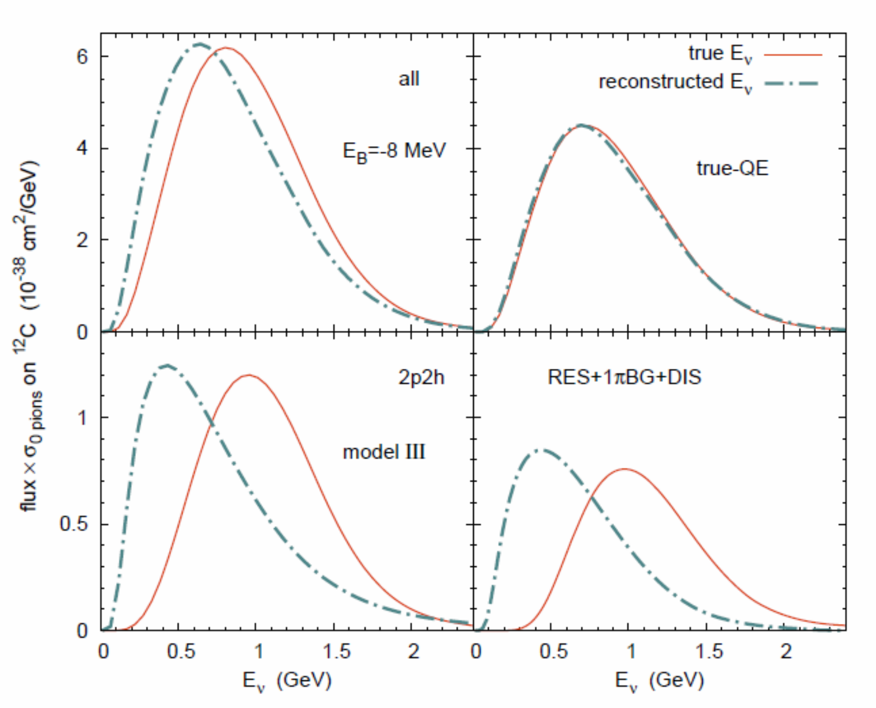




Energy Reconstruction by QE

- All modern experiments use heavy nuclei as target material: C, O, Fe → nuclear complications
- Quasifree kinematics used for QE on bound nucleons: Fermi-smearing of reconstructed energy expected
- For nuclear targets QE reaction must be identified to use the reconstruction formula for E_ν
- But: exp. definition of QE cannot distinguish between true QE (1p-1h), N* and 2p-2h interactions

Energy reconstruction in MB



Reconstructed energy shifted to lower energies for all processes beyond QE

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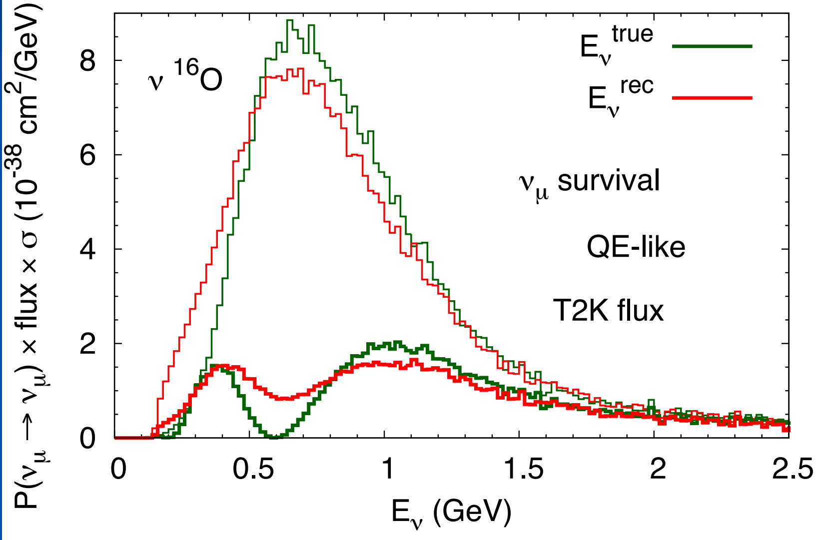
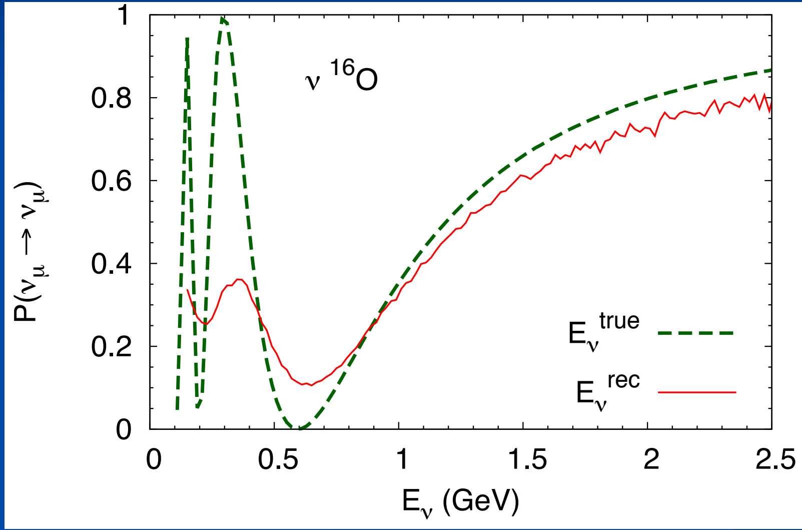
Energy reconstruction and Oscillation signal in T2K





Ratio = oscillation probability

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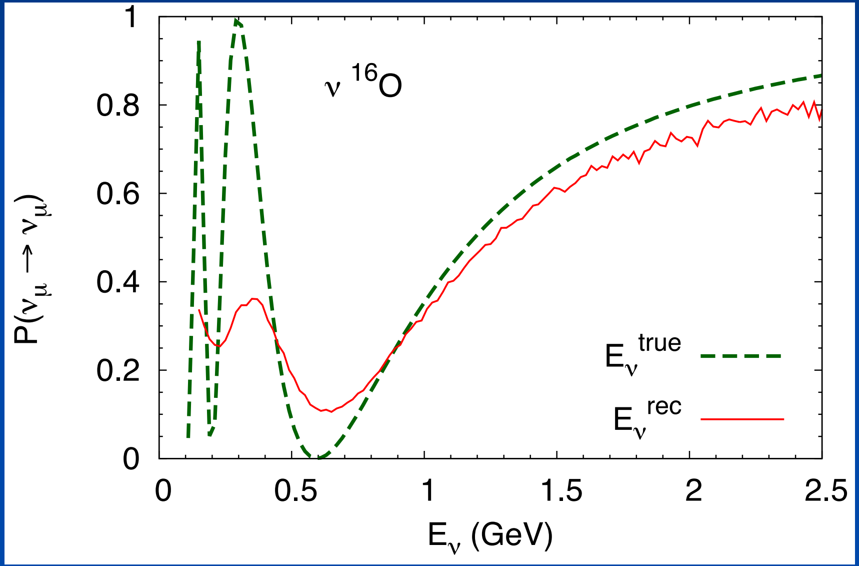
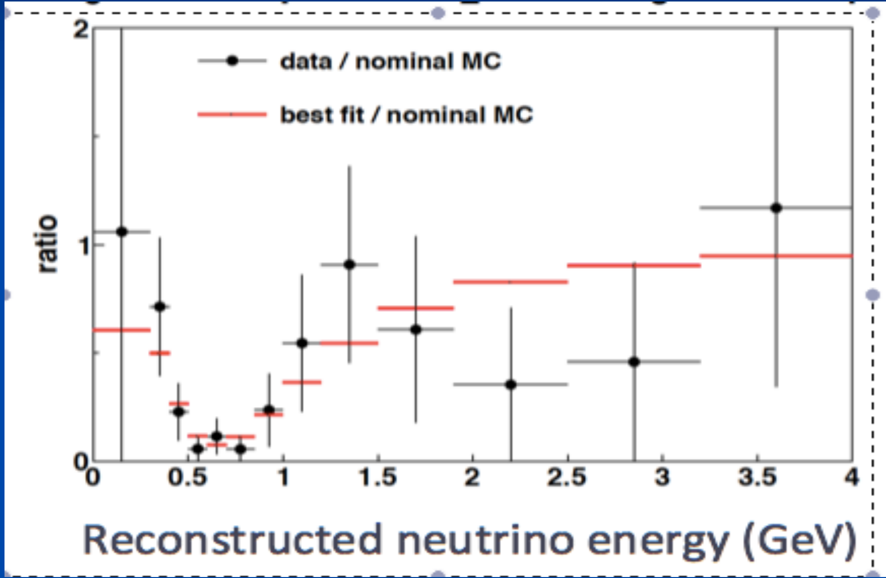
Energy reconstruction and Oscillation signal in T2K





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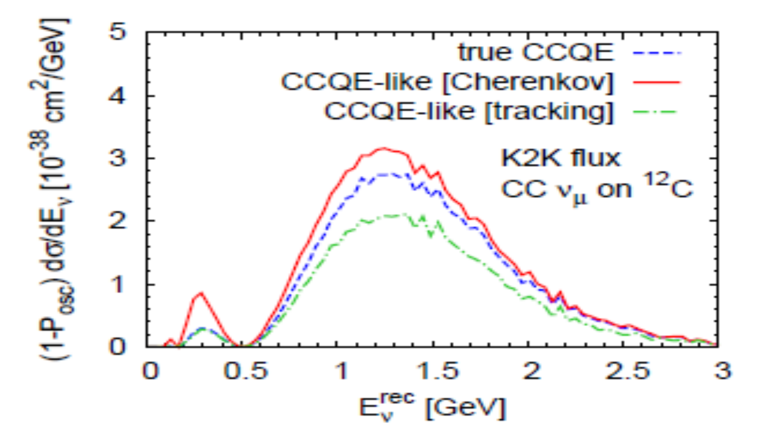
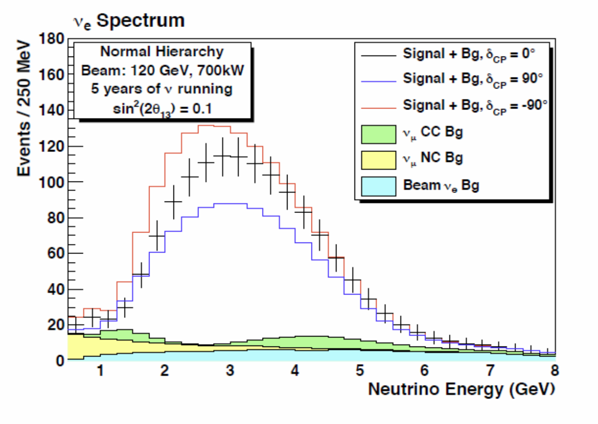
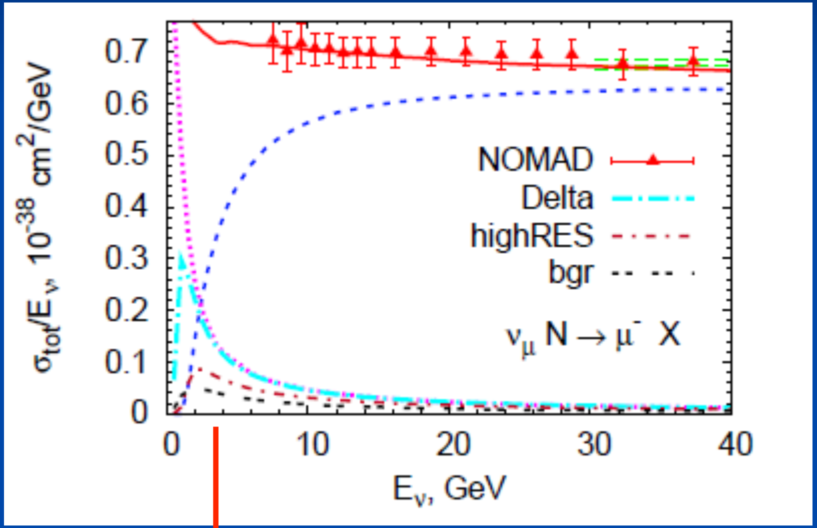
δ_{CP} with LBNE

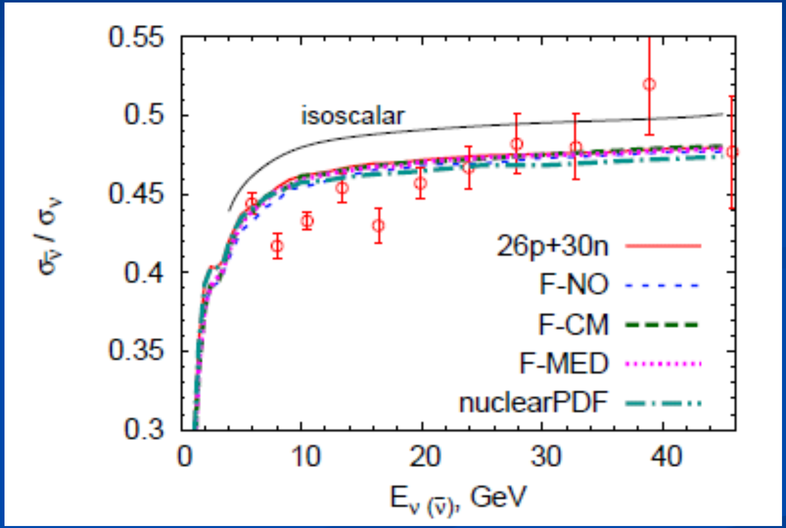




Uncertainties at the oscillation maximum due to detector as large as dependence on CP violating phase

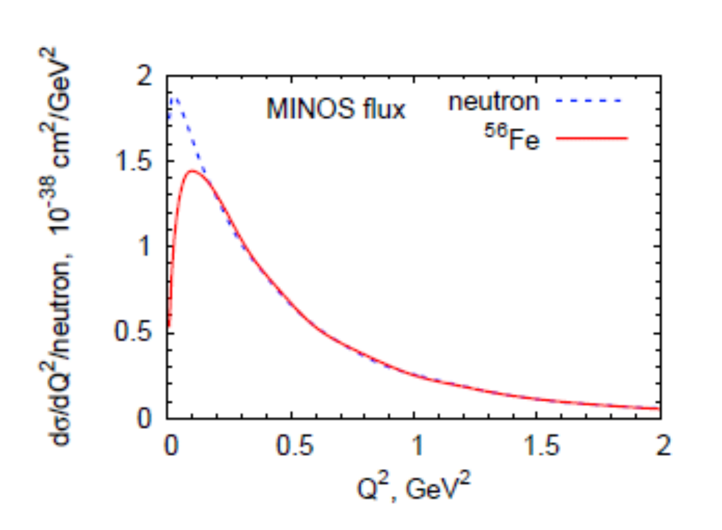
Experiments at higher energies





Shallow Inelastic Region

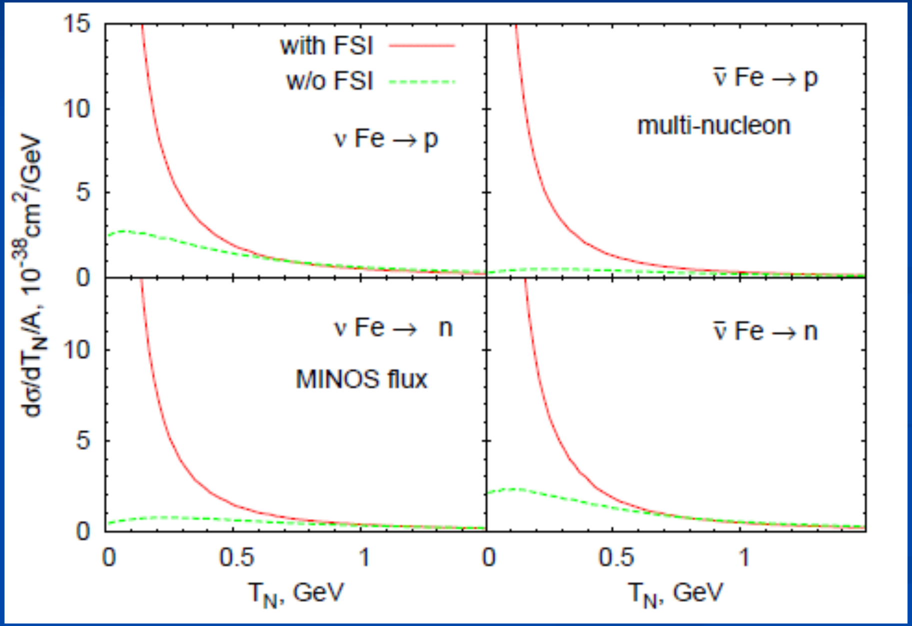
Experiments at higher energies



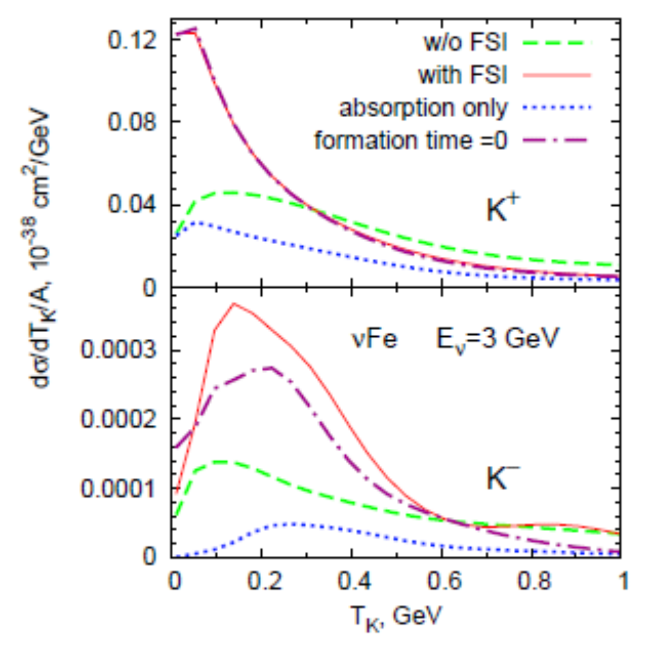
Q^2 dependence similar to lower-energy MB experiment

Experiments at higher energies

Knock-out Nucleons



Experiments at higher energies



Lesson for Minerva:

The particles you measure are not always those that the neutrino produced

Summary

- Event generators for neutrino-nucleus interactions have to describe QE, π produktion and DIS simultaneously
- Due to flux average reaction types are closely entangled
- MB puzzle of high axial mass explained:
  2p-2h processes fitted in terms of 1p-1h model
- Energy reconstruction based on QE leads in Cerenkov detectors to downward shift of reconstructed distribution
- FSI are extremely important, may make the extraction of elementary neutrino-particle production rates impossible