Neutrino Interactions with Nuclei

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Theoretische Physik

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Contents

- Axial couplings to nucleons (axial mass)
- Neutrino oscillation parameters
  - Masses, phases
  - CP violating phase

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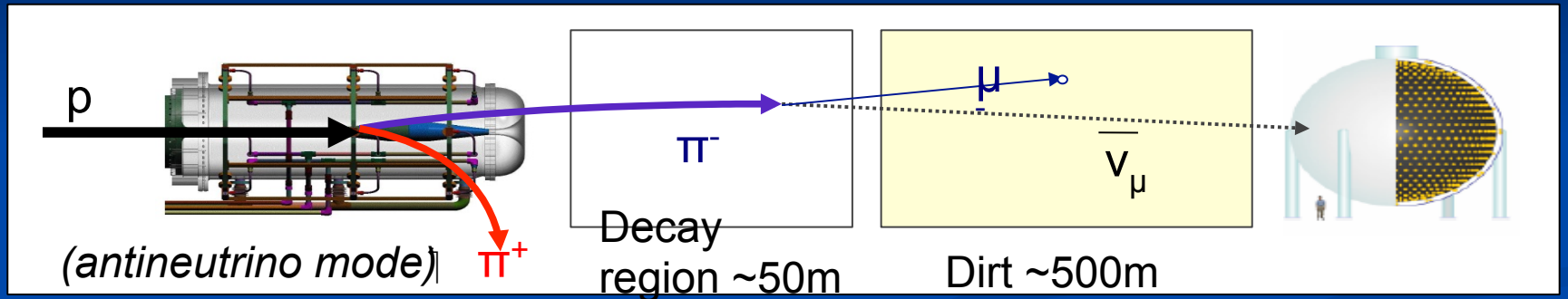
MiniBooNE Setup



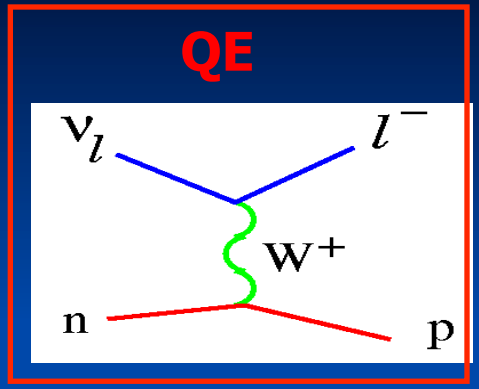
W.C.Louis, NUFACT11

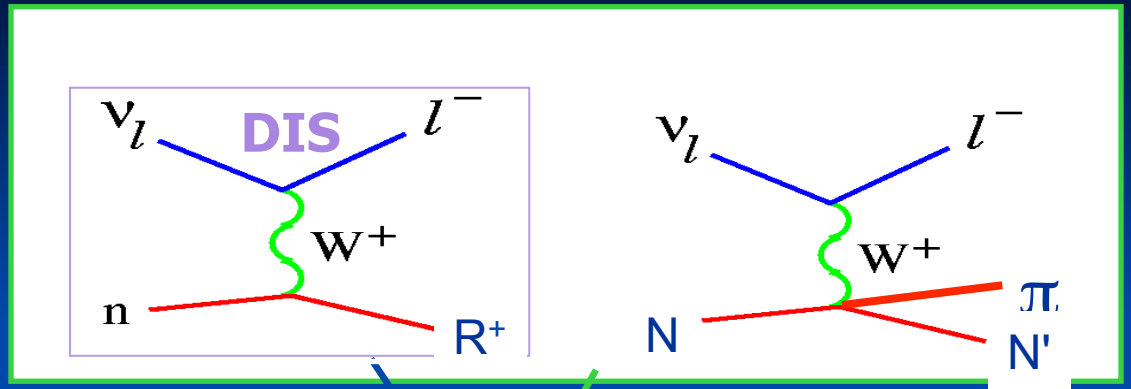
- MB is a Cerenkov detector, sphere filled with oil
- MB is a muon disappearance experiment
- MB identifies QE scattering by gating on muon, zero pions (nucleons not visible)

Axial coupling to nucleons

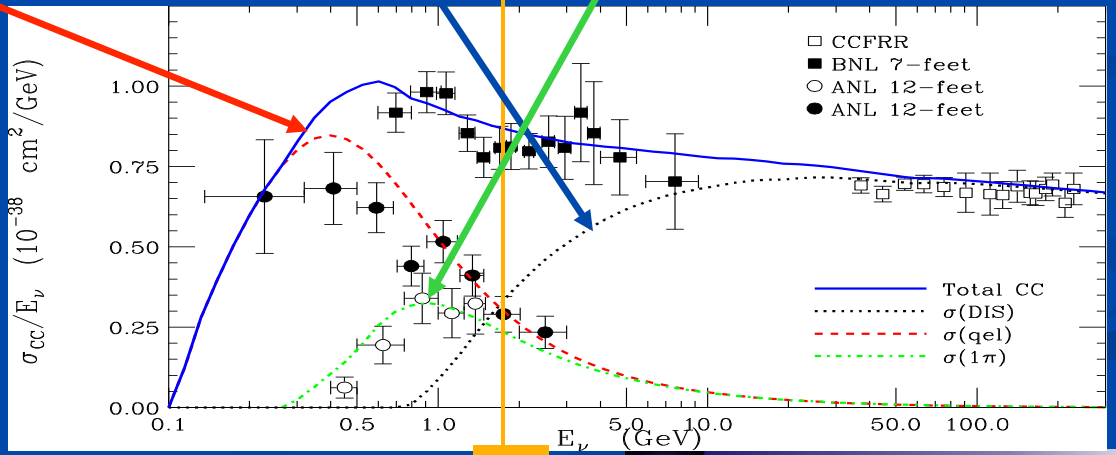
- Neutrino-nucleon interactions determined by axial coupling (‚axial mass‘)

Neutrino-nucleon cross section



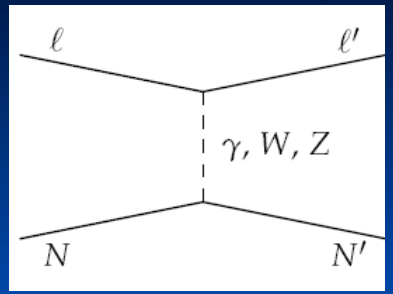


note:
10^{-38} cm² = 10^{-11} mb



Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002)

Quasielastic scattering

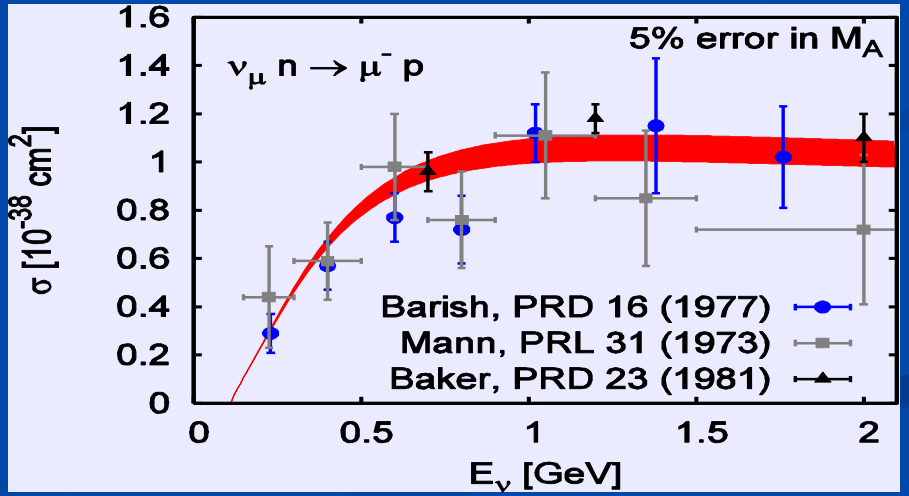


$$J^\mu_{QE} = \left(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu\gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$

axial form factors

- $F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**
- Dipole ansatz for F_A
- **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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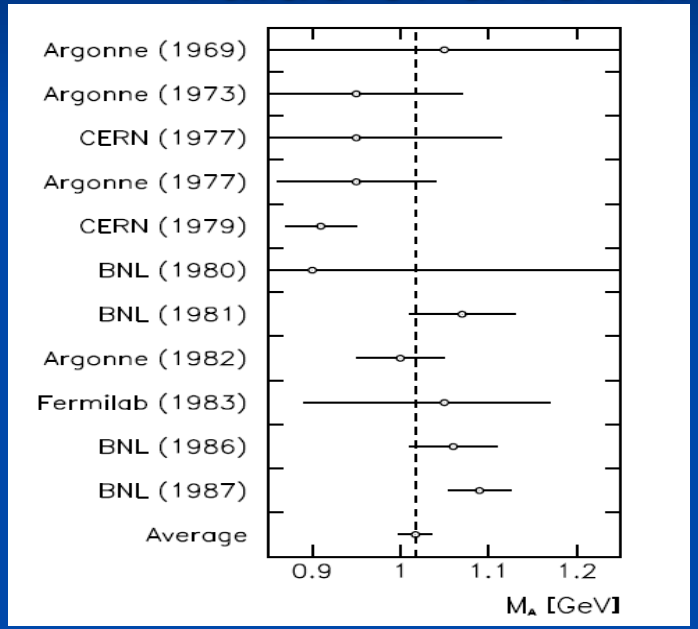
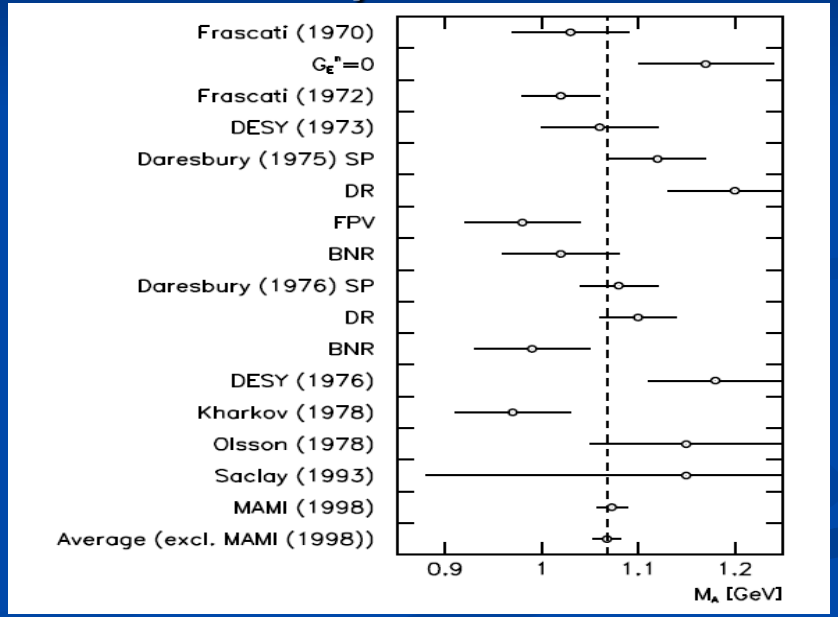
Axial Masses in Dipole FF

- Value of axial mass reasonably well known





ν (e,π)

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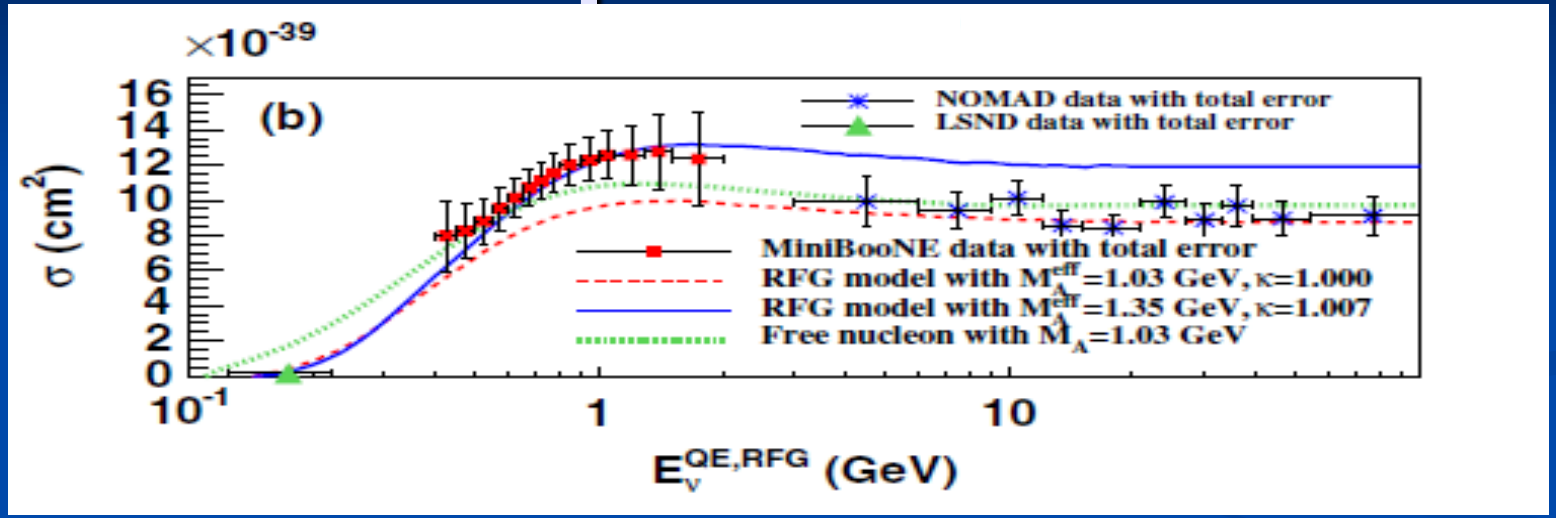
The MiniBooNE QE Puzzle
Explanations

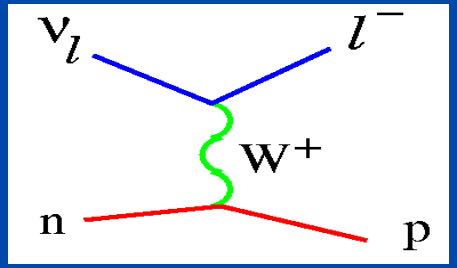


Calculations within IA (1p -1h), M_A ~ 1.35 GeV fits data

Only axial part changed, no changes in vector interaction

Energy Reconstruction by QE

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

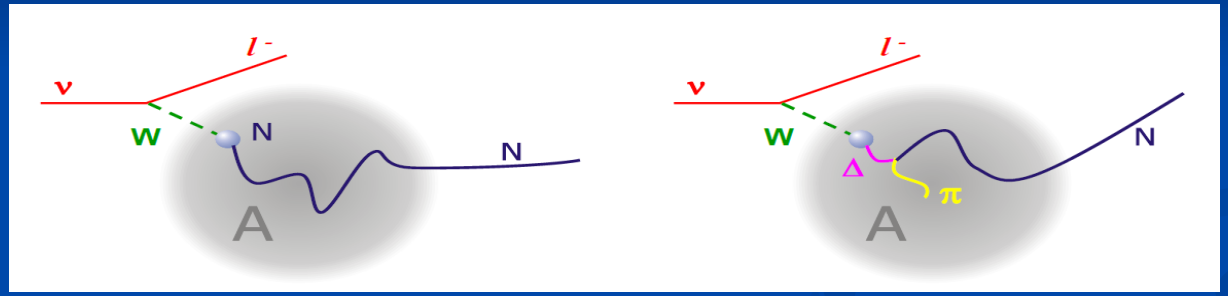


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- BUT: all modern experiments contain nuclei as targets →
  1. Effects of binding energy, Fermi motion, Pauli principle
- 2. Problem to identify QE

Neutrino-nucleus interactions

- All modern LBL experiments with neutrinos have nuclear targets (C, O, Fe, ..)



- →Final state interactions complicate event identification, e.g. QE and pion prod. entangled

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Theory and Event Generator**
  based on an approx. solution of Kadanoff-Baym equations

- Physics content (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!

Theoretical Basis of GiBUU

Simplicity

- Kadanoff-Baym equation (1960s)
  - full equation can not be solved yet
    - – not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s): **GiBUU**
- Cascade models (typical event generators, NUANCE, GENIE, NEUT,..)
  - no mean-fields, primary interacts and FSI not consistent

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Theoretical Basis: GiBUU

Time evolution of spectral phase space density (for $i = N, \Delta, \pi, \rho, \ldots$) given by KB equation in Botermans-Malfliet form:

$$\left[\left(1-\frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t}+\frac{\partial H}{\partial p}\frac{\partial}{\partial x}-\frac{\partial H}{\partial x}\frac{\partial}{\partial p}+\frac{\partial H}{\partial t}\frac{\partial}{\partial p_0}\right]F_i(x,p)=C[F_i(x,p),F_j(x,p)]$$

Hamiltonian *H* includes off-shell propagation correction

8D-Spectral phase space density

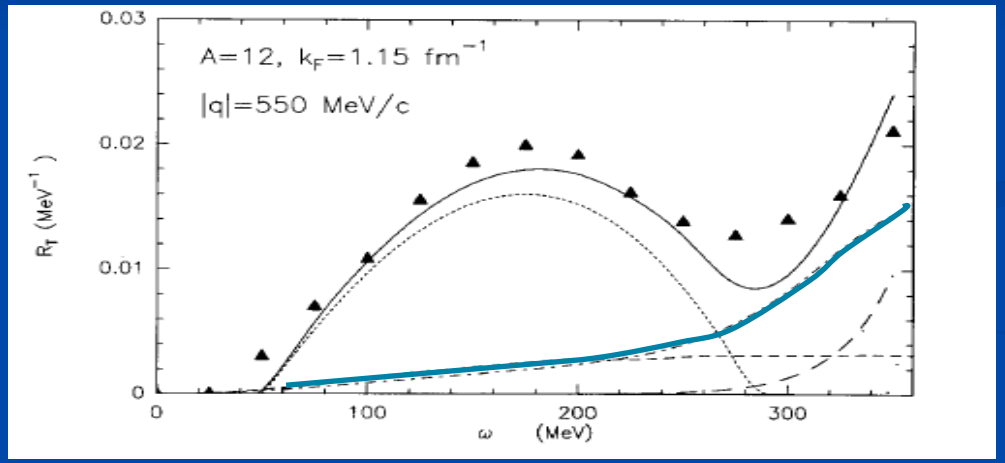
Collision term

Off shell transport of collision-broadened hadrons included with proper asymptotic free spectral functions

The MiniBooNE QE Puzzle

Hint from Electrons

- Dekker, Brussaard, Tjon (1991):
  influence of two-body currents



Two-body currents *not* contained in generators → reaction mechanism misidentified

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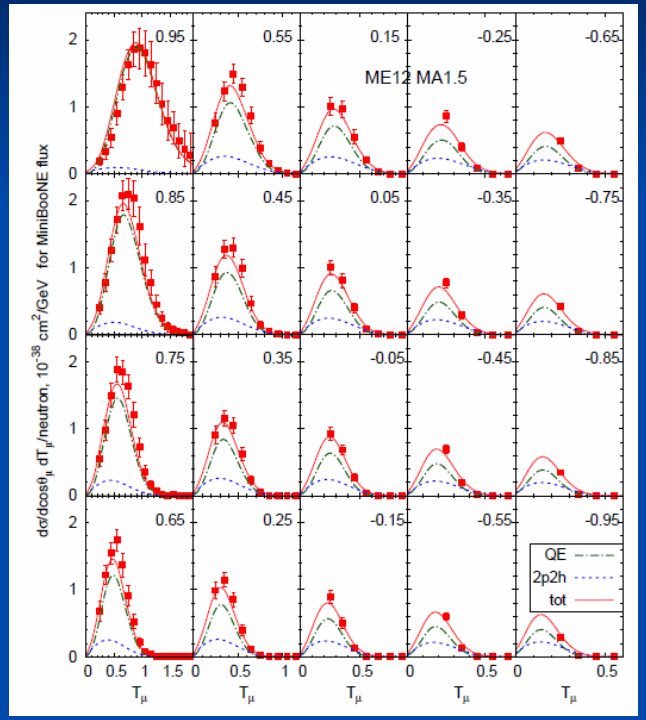
The MiniBooNE QE Puzzle
Explanations



MB flux averaged

Data corrected
for stuck-pion events!

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

RPA affects forward angles,
Two-body interactions affect backward angles

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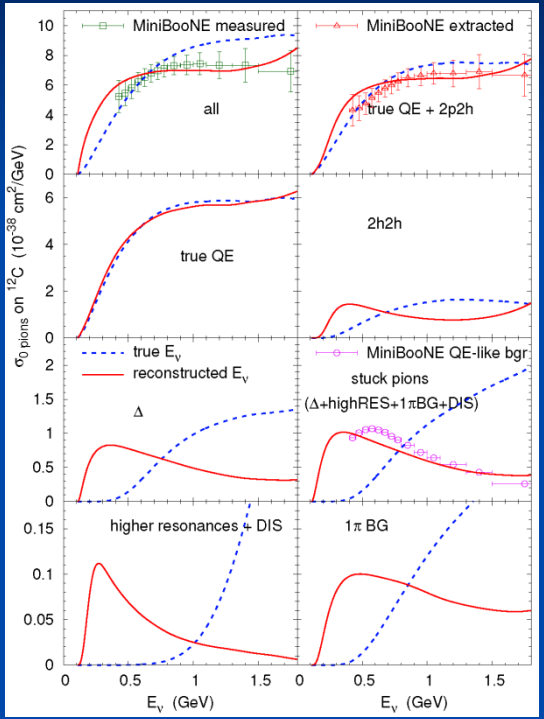
Energy Reconstruction in MB



Solution of the MB puzzle:

Reaction mechanisms ≠ QE scattering distort the functional dependence on energy and lead to wrong axial mass

Dashed-blue: true energy
Solid-red: reconstructed energy

Long Baseline Experiments

T2K: JPARC-Kamioka ~ 300 km, OPERA: CERN –Gran Sasso ~730 km

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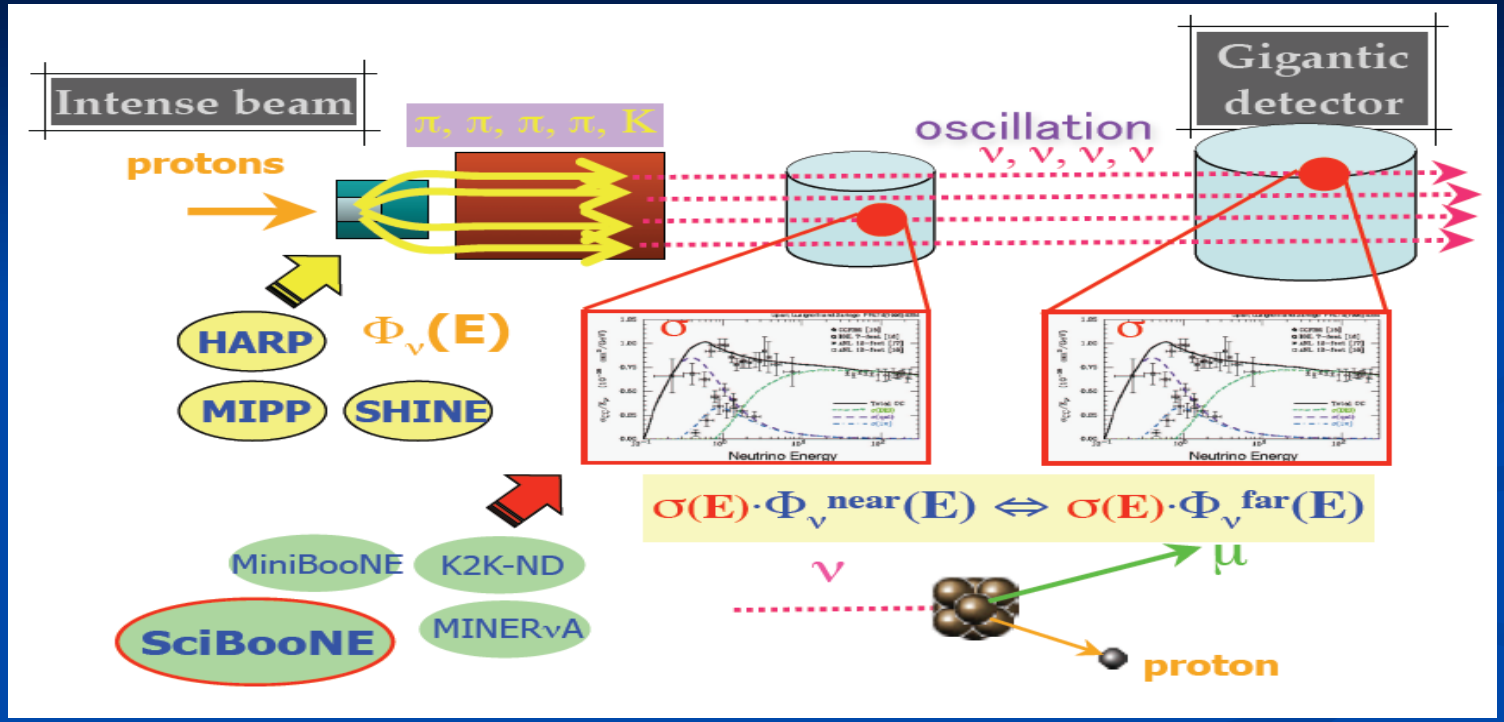
Long baseline experiments

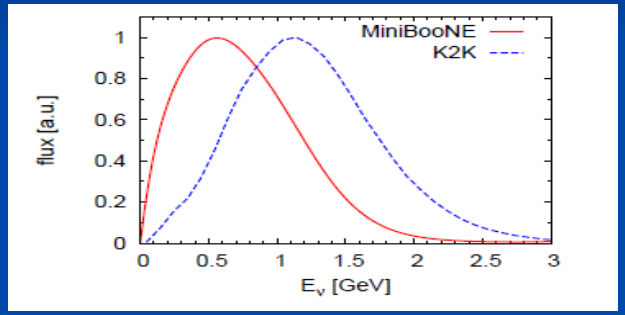


M. Wascko

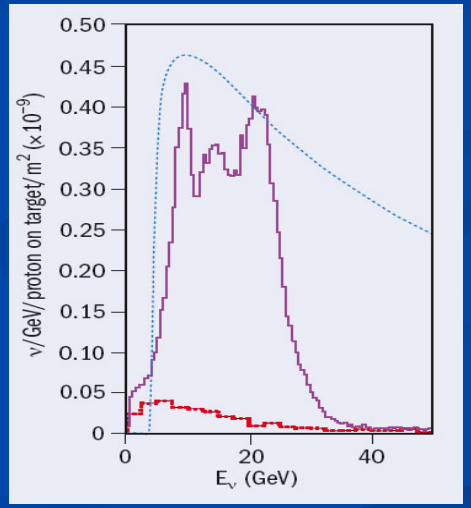
Energy of incoming neutrinos is not sharp, but broadly distributed

Neutrino oscillation search

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

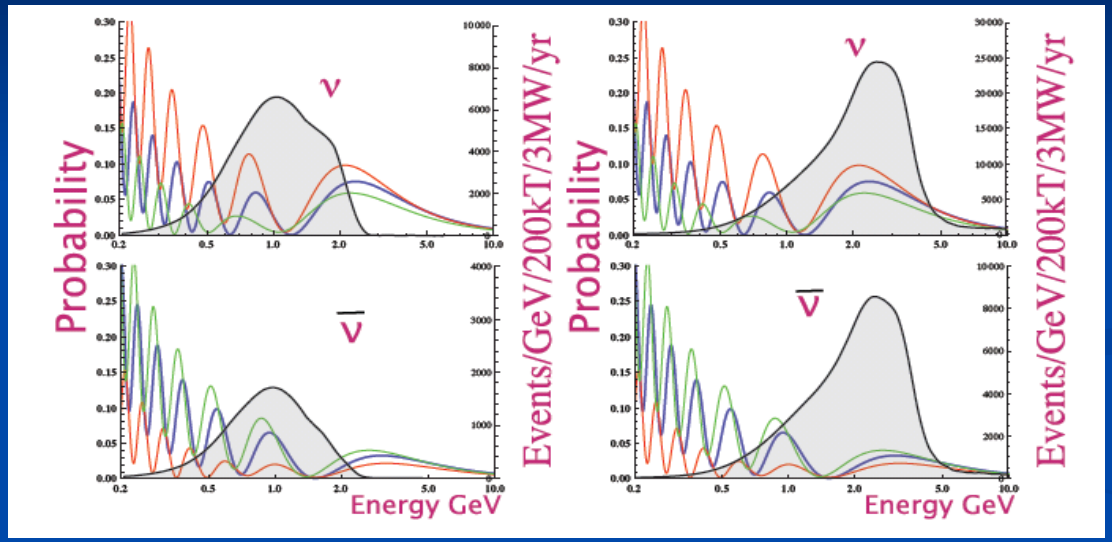


Energy must be reconstructed from hadronic final state
Reaction mechanism must be known for reconstruction



Opera

Project X, δ_{CP} sensitivity



From:
Bishai et al
arXiv:1203.409

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

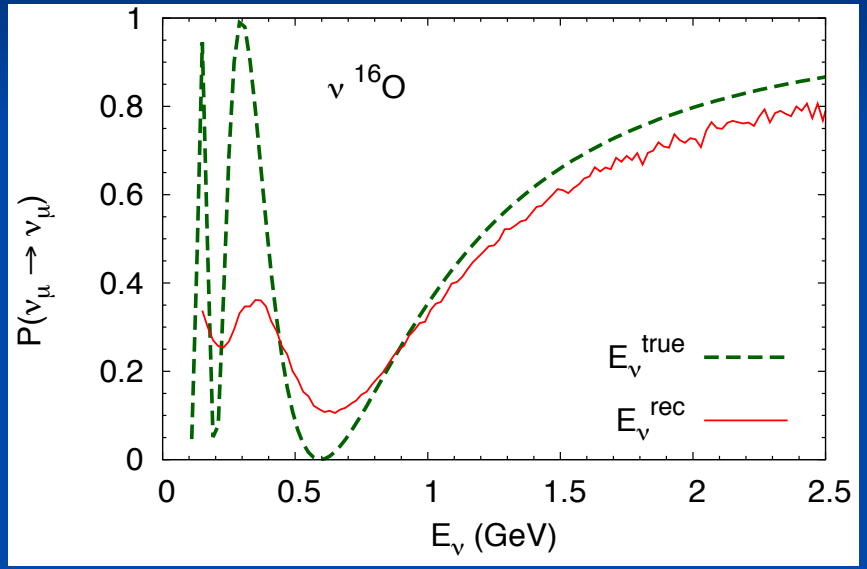
8 GeV 60 GeV

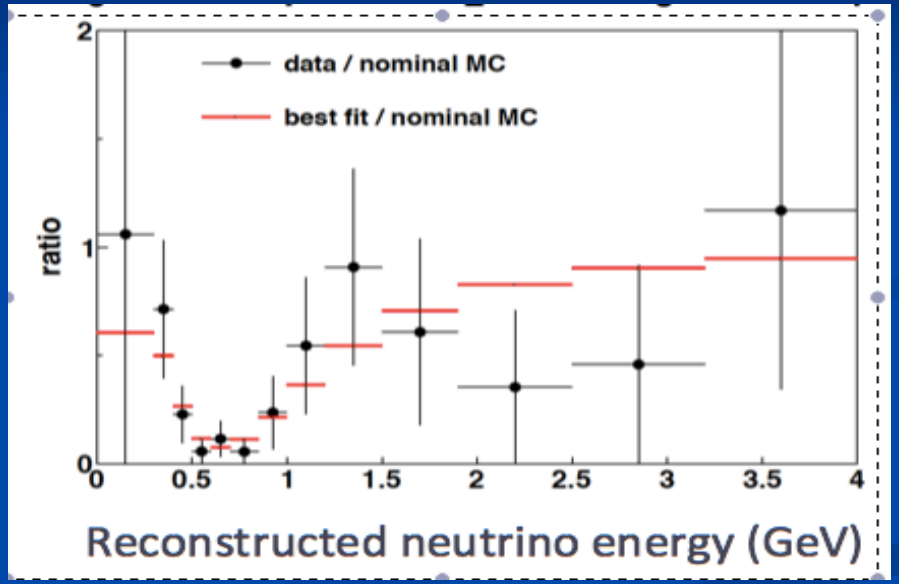
proton energy

Need energy to distinguish between different δ_{CP}

Oscillation signal in T2K

ν_μ disappearance





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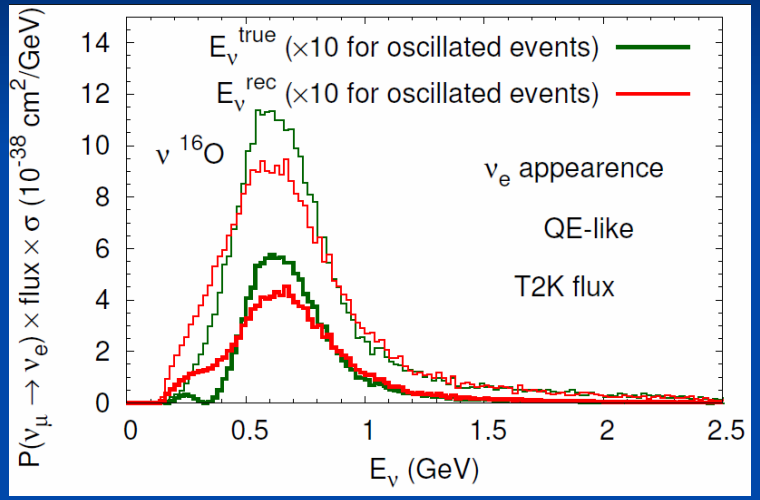
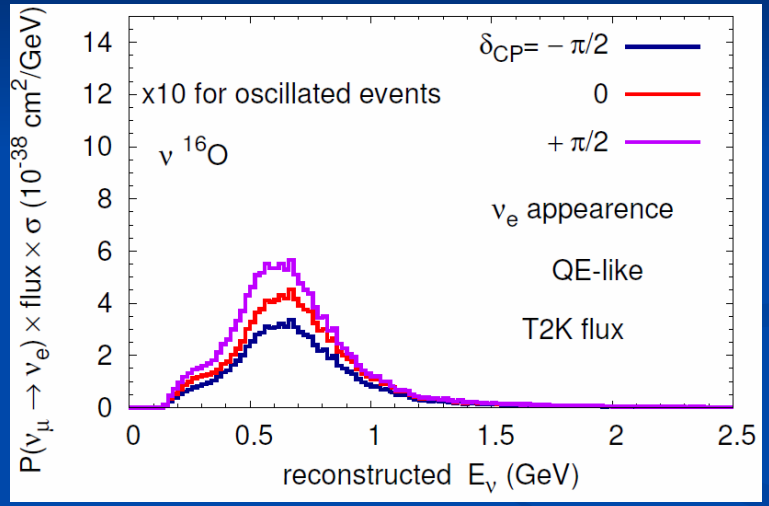
Oscillation signal in T2K
δ_{CP} sensitivity





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

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Summary

- Neutrino long baseline experiments nowadays all use nuclear targets. Transport theory is needed for a realistic modeling of neutrino-nucleus interactions
- The MiniBooNE axial mass puzzle is now understood: 2p-2h contributions were described with a 1p-1h model
- Energy reconstruction method widely used has larger than expected uncertainties, affects extraction of neutrino oscillation parameters.

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My connection to George and Transport

- Energetic photons from intermediate energy proton- and heavy-ion-induced reactions.
  W. Bauer, G.F. Bertsch, Wolfgang Cassing, Ulrich Mosel
  Published in **Phys.Rev. C34 (1986) 2127-2133**
  DOI: 10.1103/PhysRevC.34.2127

- A Guide to microscopic models for intermediate-energy heavy ion collisions.
  G.F. Bertsch, S. Das Gupta. 1988. 45 pp.
  Published in **Phys.Rept. 160 (1988) 189-233**

has helped to lay the foundations of practical transport theory

Happy Birthday to George!

Many more happy, productive years to the Silver Swan Singer!

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