Neutrino Interactions with Nucleons and Nuclei

Olga Lalakulich, Kai Gallmeister
and Ulrich Mosel

Institut für
Theoretische Physik

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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 event cross section measurements, event characterization and neutrino energy reconstruction

Motivation and Contents

- Intro
- GiBUU: physics and techniques
- Spectral functions in GiBUU (and elsewhere)
- Pions
- Energy reconstruction
- Oscillation signal

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

- Even more interesting:
  3-Flavor Oscillation allows for CP violating phase δ_{CP} → matter/antimatter puzzle

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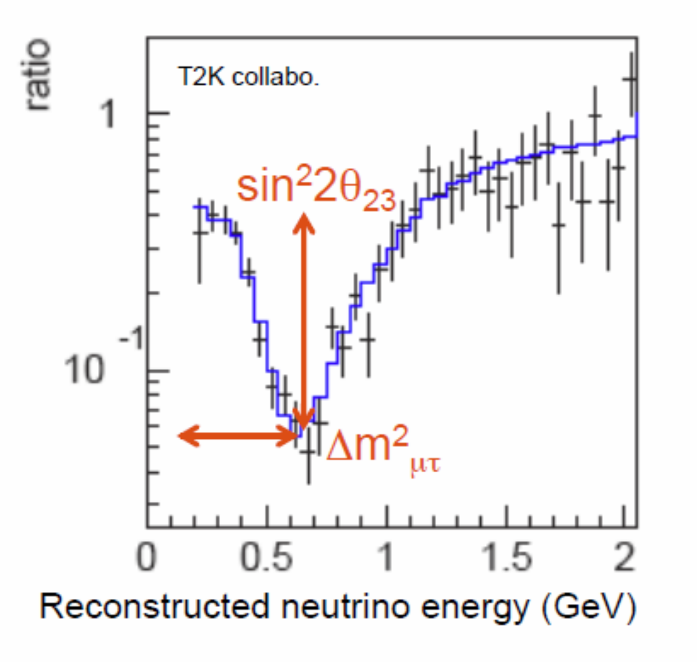
Observable Oscillation Parameters

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



Neutrino Oscillations

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

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

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

appearance probability

Vacuum oscillation

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

Oscillation depends on difference of (squared) masses only

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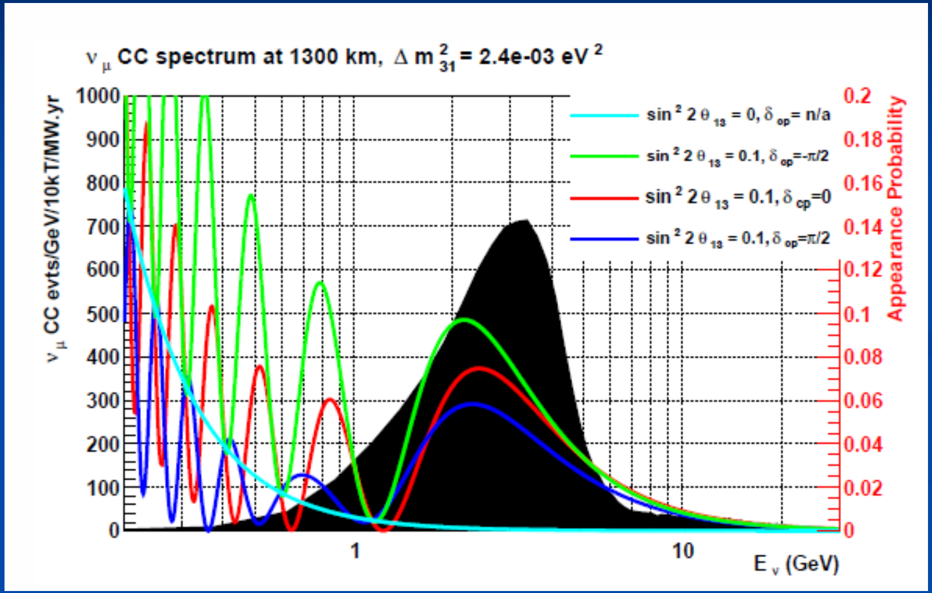
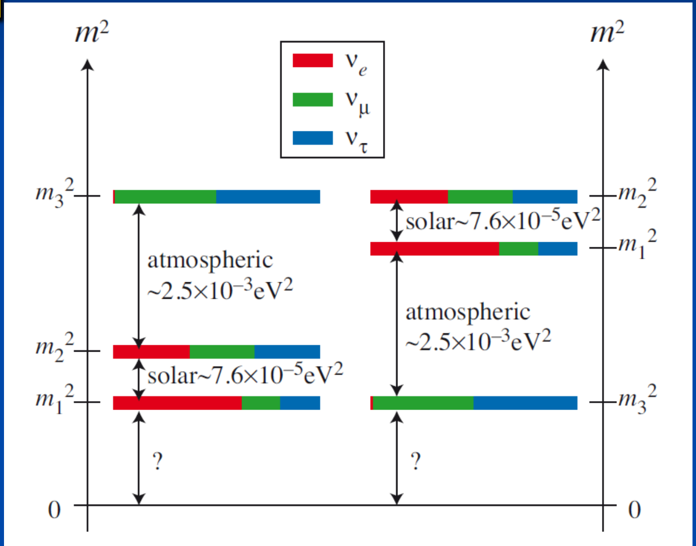
LBNE, δ_{CP} Sensitivity



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



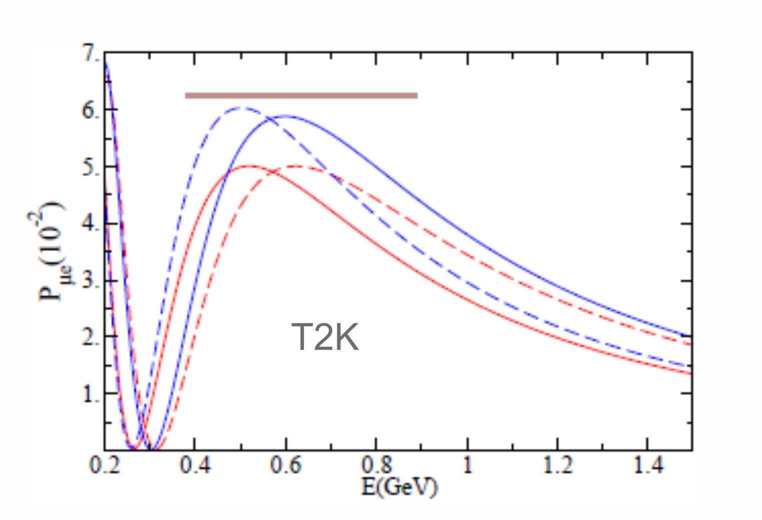


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

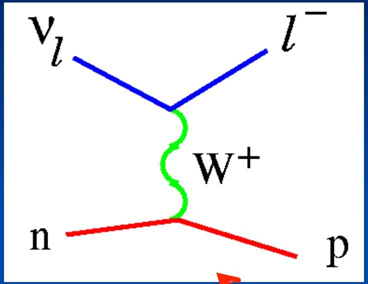
D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

Energy has to be known better than 50 MeV
Shape sensitive to hierarchy and sign of mixing angle

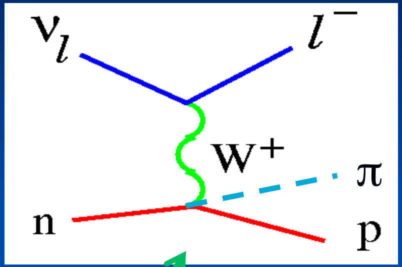
Neutrino-Nucleon Interactions

Neutrino-nucleon cross section

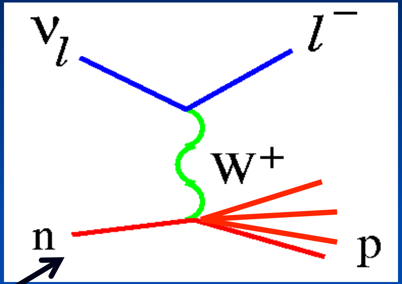
CCQE

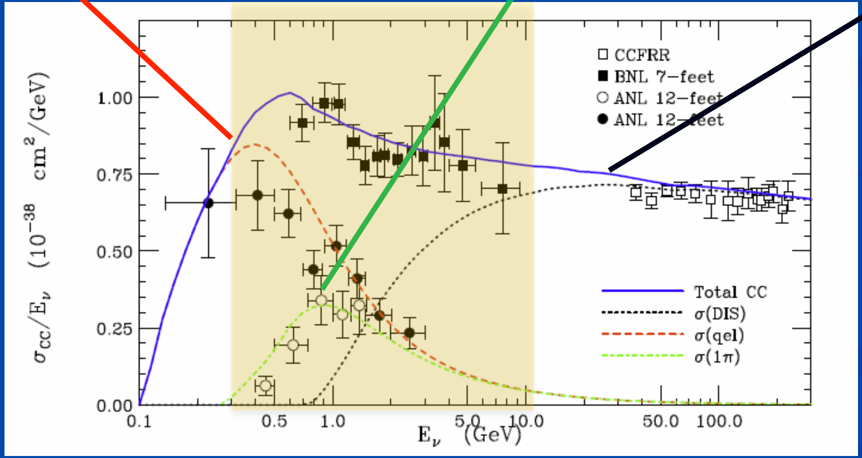


1π



DIS



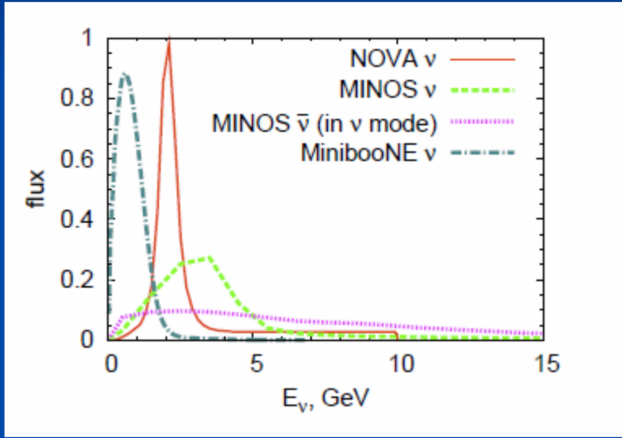


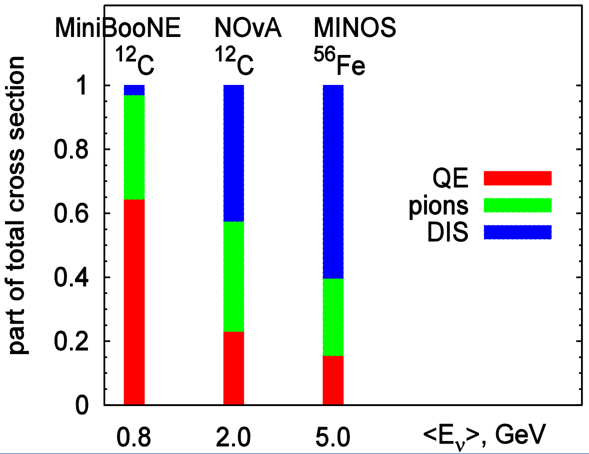
note:
10^{-38} cm² = 10^{-11} mb

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

Neutrino Beams

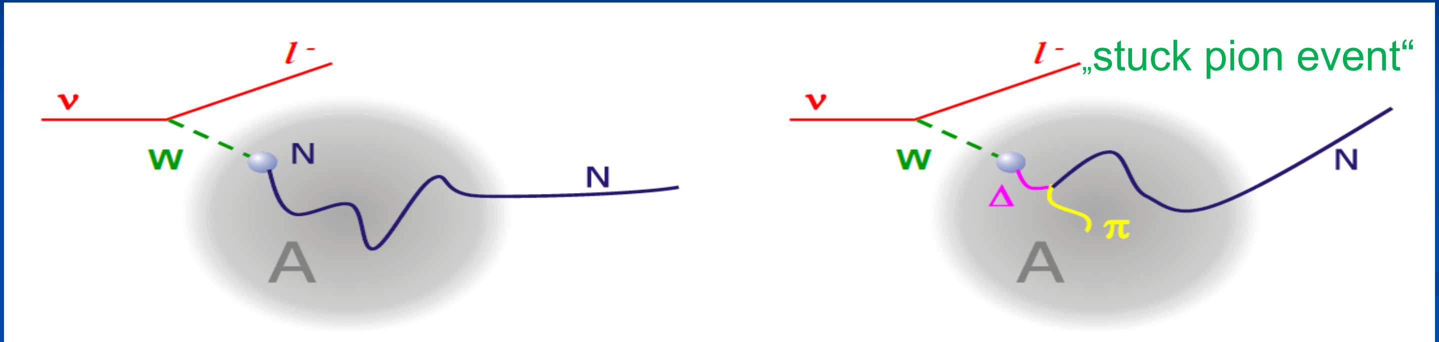
- Neutrinos do not have fixed energy nor just one reaction mechanism





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

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, ….)

Pion Production

- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance (not just a heavier nucleon)**

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

- $C^V(Q^2)$ 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

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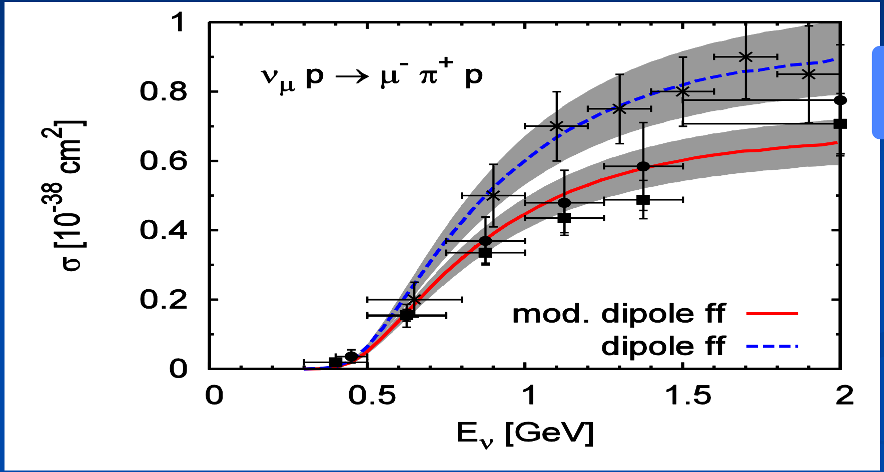
Pion Production

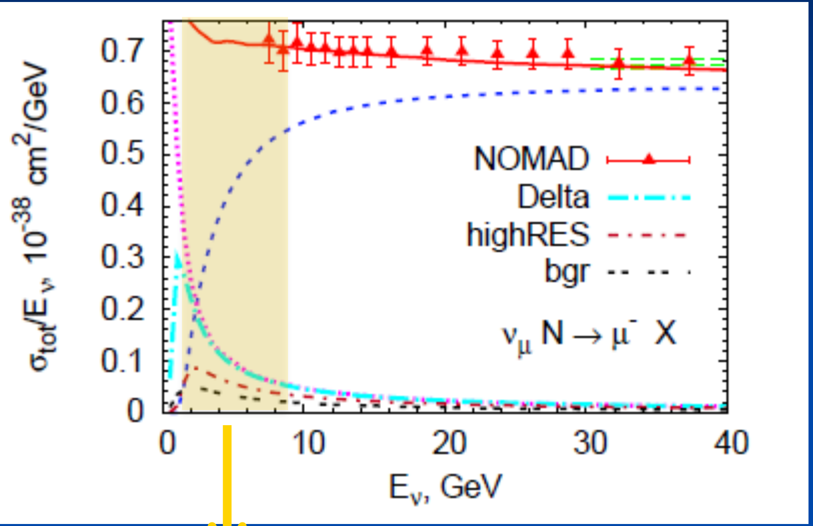


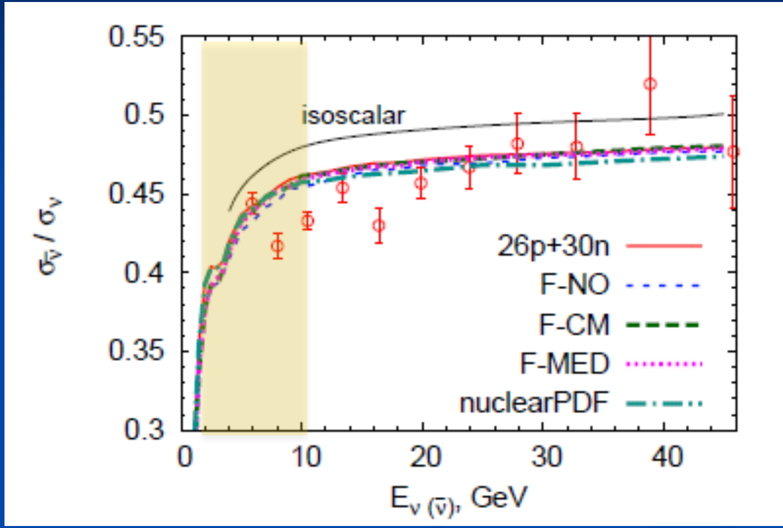
10 % error in $C_5^A(0)$

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

discrepancy between elementary data sets
→impossible to determine 3 axial formfactors
New pion data on elementary target desparately needed

SIS - DIS





Shallow Inelastic Scattering,
interplay of different reaction mechanisms

Curves: GiBUU

Now to Nuclear Targets

Energy Reconstruction

- Energy reconstruction
  1. Through QE: needs event identification
  2. Calorimetric: needs simulation of thresholds and non-measured (e.g. neutral) events
- In both methods nuclear many-body structure and reaction theory are needed to generate full final state, inclusive X-section not sufficient

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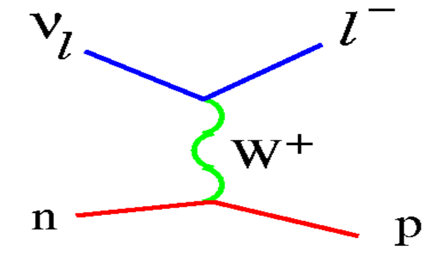
Energy Reconstruction by QE

- 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

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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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Now to Transport

FSI and Transport Theory

- All modern experiments use nuclear targets
- Need to model final state interactions
  1. to identify reaction mechanism
  2. to reconstruct incoming neutrino energy from final state

Quantum mechanical description not possible to describe

ν + A -> X + many hadrons

→ Need Transport Theory

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Transport Equation

- Kadanoff-Baym equation for space-time development of one particle spectral phase space density *F* after gradient expansion

  in Wigner repres.:

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

F = spectral phase-space density: $F(x,p) = -2f(x,p)\mathrm{tr}[\mathrm{Im}\,(\tilde{S}^{\mathrm{ret}}(x,p))\gamma^0],$

$$\mathcal{D}F = \{p_0 - H, F\}_{\mathrm{pb}} \quad \text{with } H = E^*(x,p) - \mathrm{Re}\tilde{\Sigma}_V^0(x,p).$$

Transport Equation

Collision term

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -i\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

Drift term

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

Kadanoff-Baym equation

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

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 and potentials

8D-Spectral phase space density

Collision term

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

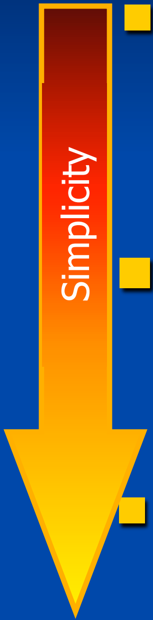
Collision term

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

with

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

Theoretical Basis of GiBUU



- 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 interactions and FSI not consistent

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

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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!

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Factorization of GiBUU

- GiBUU is factorized into
  - initial, first interaction
  - final state interactions (2nd, 3rd, ... coll.)
- Particular strength: FSI treatment
- Detailed infos from
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  and website
  gibuu.hepforge.org

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Practical Basis: GiBUU

- one transport equation for each particle species (61 baryons, 21 mesons)
- coupled through the potential in *H* and the collision integral *C*
- W < 2.5 GeV: Cross sections from resonance model (PDG and MAID couplings), consistent with electronuclear physics
- W > 2.5 GeV: particle production through string fragmentation (PYTHIA)

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GiBUU Ingredients

- In-medium corrected primary interaction cross sections, boosted to rest frame of bound nucleon, moving in local Fermigas
- Includes spectral functions for baryons and mesons (binding + collision broadening)
- *Hadronic* couplings for FSI taken from PDG
- *Vector* couplings taken from electro-production (MAID)
- *Axial* couplings modeled with PCAC

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GiBUU: numerical implementation

- Hadrons feel potentials (nuclear + Coulomb), either RMF or Skyrme-type pots: essential for nucleon spectral functions
- Wigner functions represented by testparticles (100 – 1000 per nucleon). Collision criterion respects relativity (as far as possible), not just $\sigma = \pi r^2$ prescription.
- Off-shell transport of hadrons (spectral functions) with proper asymptotics

GiBUU Ingredients

- Various options in code are controlled by extended job card with all relevant switches.
- Output are (many) cross sections, reconstructed and true event distributions, full final state with four-vectors of all particles in Les Houches or ROOT format.
- Website *gibuu.hepforge.org* contains extensive documentation for code and explanation of output

GiBUU

- Code can be obtained from *gibuu.hepforge.org*
- Inclusive X-section needs only initial interaction: Running time for a full flux distribution ≈ 1 hour on PC
- About 200.000 full events (incl all semi-incl. X-sections) need running time of order weeks for reasonable statistics, statistics can also be obtained by several shorter parallel runs
- Code is open source, users are encouraged to find bugs, improve code, implement new features

Spectral Functions

- Single particle spectral functions absorb effects of interactions in particle properties
- Free Fermi gas (in generators):

$$P_h(\mathbf{p}, E) = \Theta(\mathbf{p_F} - \mathbf{p})\,\delta(E + T_p)$$

spiky E-dep. leads to artifacts in response

- Now: dress particle with interactions, mean field and/or additional interactions → quasiparticles

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Spectral Function in GiBUU

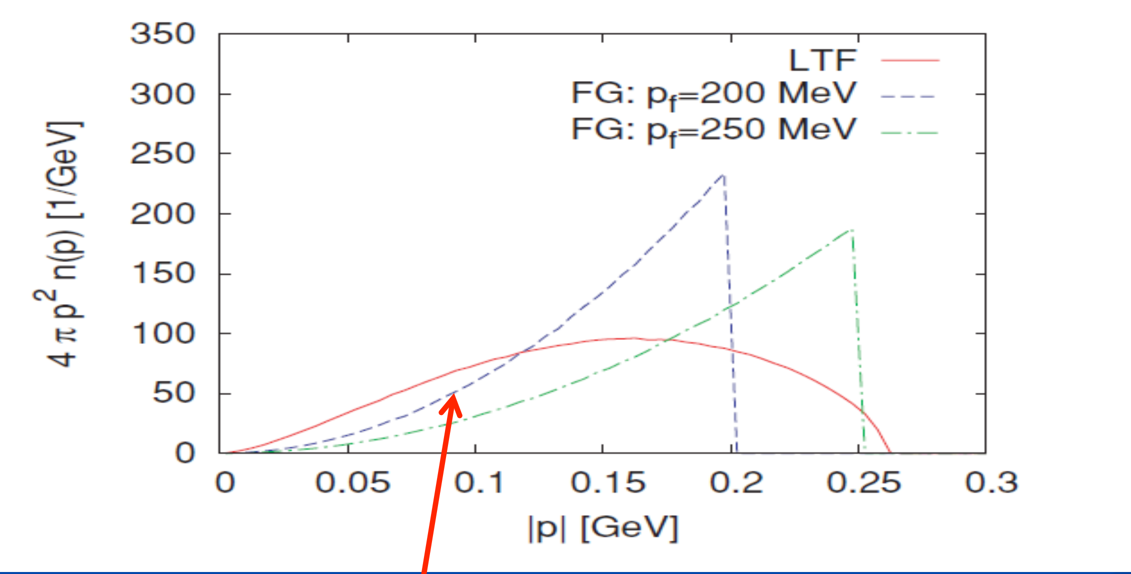
$$P_h(\mathbf{p},E) = \int d^3x \left[\Theta(\mathbf{p_F}(\mathbf{x}) - \mathbf{p})\, \delta(E + T_p + V(\mathbf{x},\mathbf{p}))\right]$$

Two essential features:

1. Local TF momentum distribution removes artifacts of sharp cut at p_F
2. Particles bound in momentum- and coordinate-dependent potential, integration removes delta-function spikes in energy

Spectral function in GiBUU contains interactions in mean field
There may be contribs from correlations in addition at large E

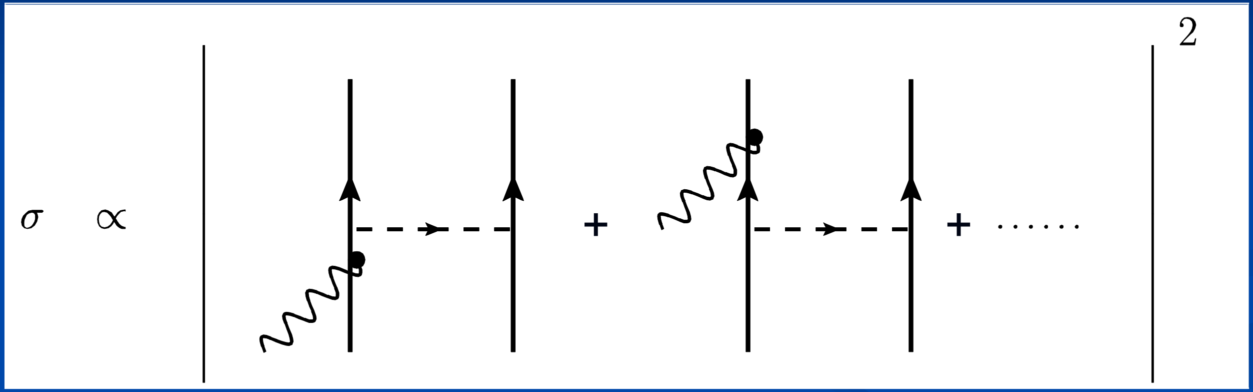
Local Fermi Gas Momentum Distribution



More strength at low momenta

2p-2p excitations and spectral functions

FSI ISI

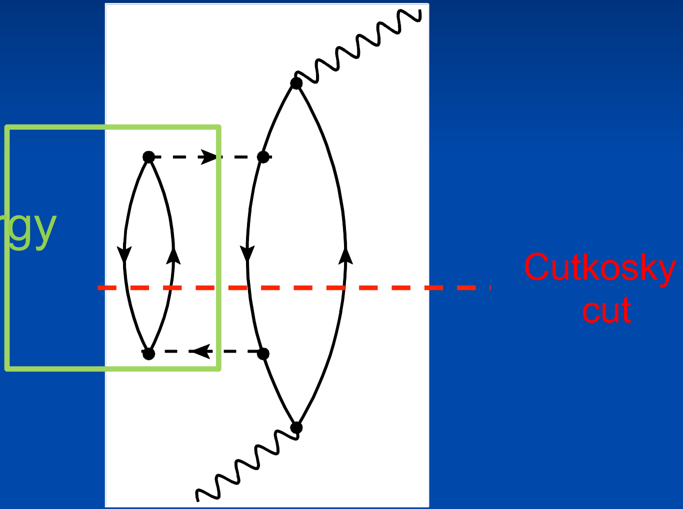


Can also be obtained by cutting selfenergy diagrams (Cutkosky rules)

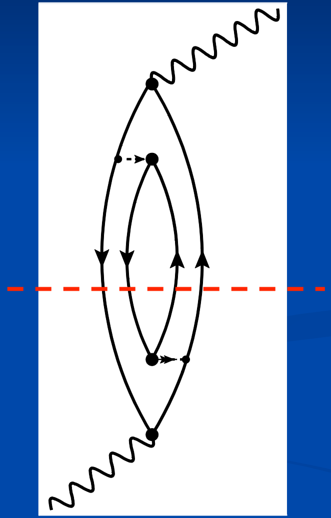
2p-2p excitations and spectral functions

2nd ampl. squared

hole
selfenergy
Σ



Interference term squared



No selfenergy,
Vertex correction,
not included in spectral
function

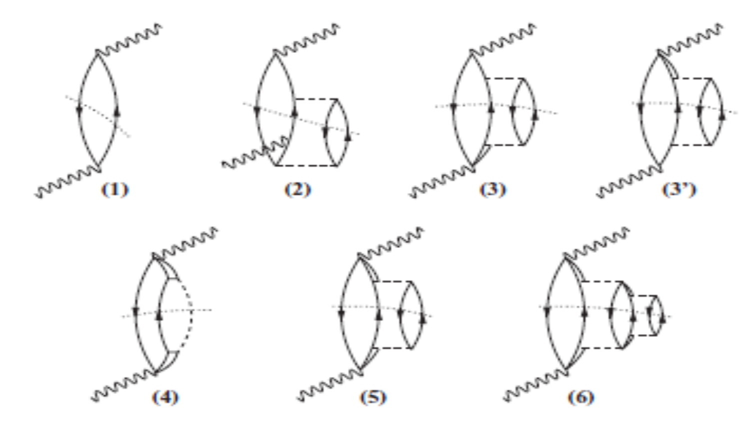
Hole Spectral Function

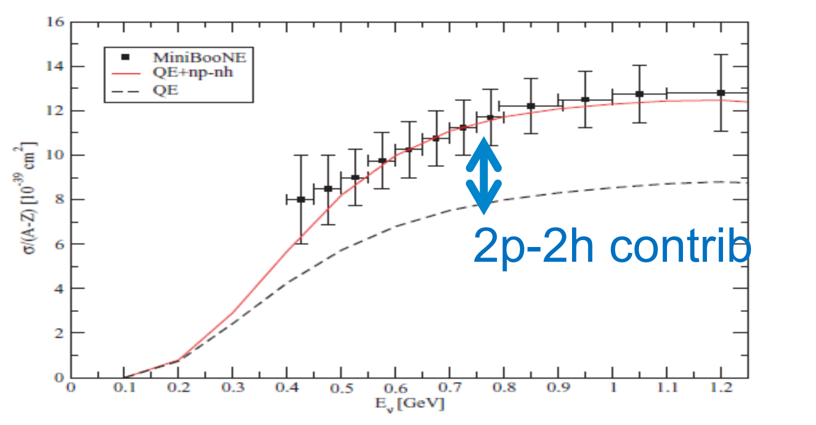
$$\mathcal{A}(x, p) = \frac{1}{\pi} \frac{\sqrt{p^{*2}}\Gamma_{\text{med}}}{[p^{*2} - m^{*2}]^2 + p^{*2}\Gamma^2_{\text{med}}}$$

Interference of ISI and FSI

The MiniBooNE QE Puzzle Explanations

Martini et al, PRC80, 2009





Exp: both σ and E_ν are reconstructed!

2p-2h in Generators

- Mandatory: same nuclear ground state for 1p-1h and 2p-2h processes
  - Generators: free Fermi gas
  - Nieves 2p-2h model: dressed Fermi gas in mean field potential
- Nieves model cannot be simply added to generators: inconsistent → inconclusive

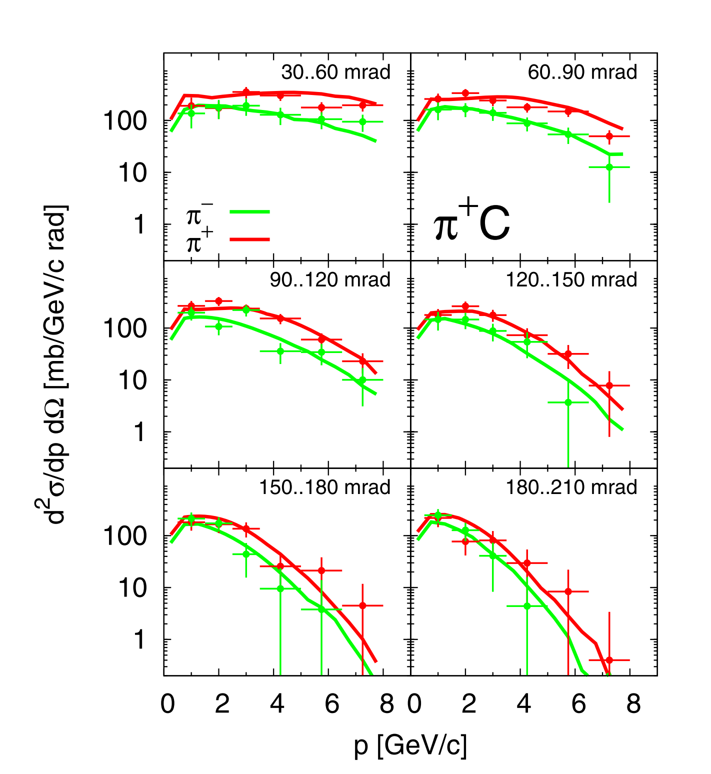
Check of GiBUU

Check: pions in HARP

HARP small angle analysis
12 GeV protons

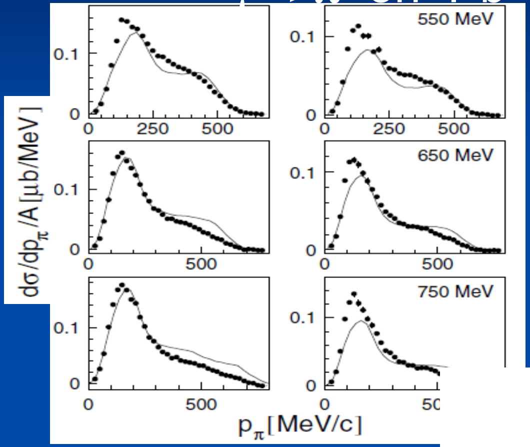
Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)

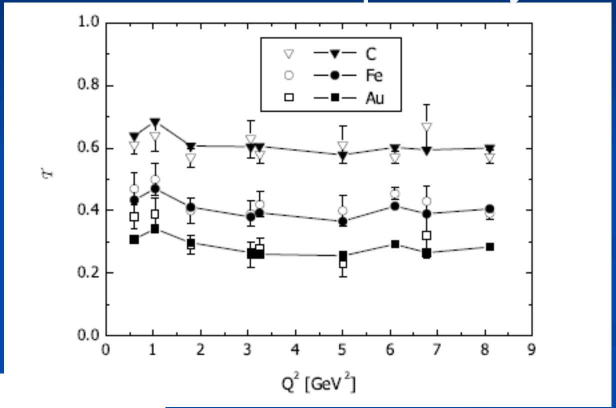


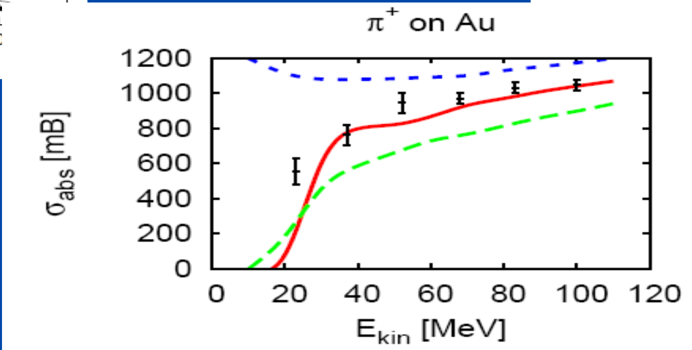
Check: pions, protons

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



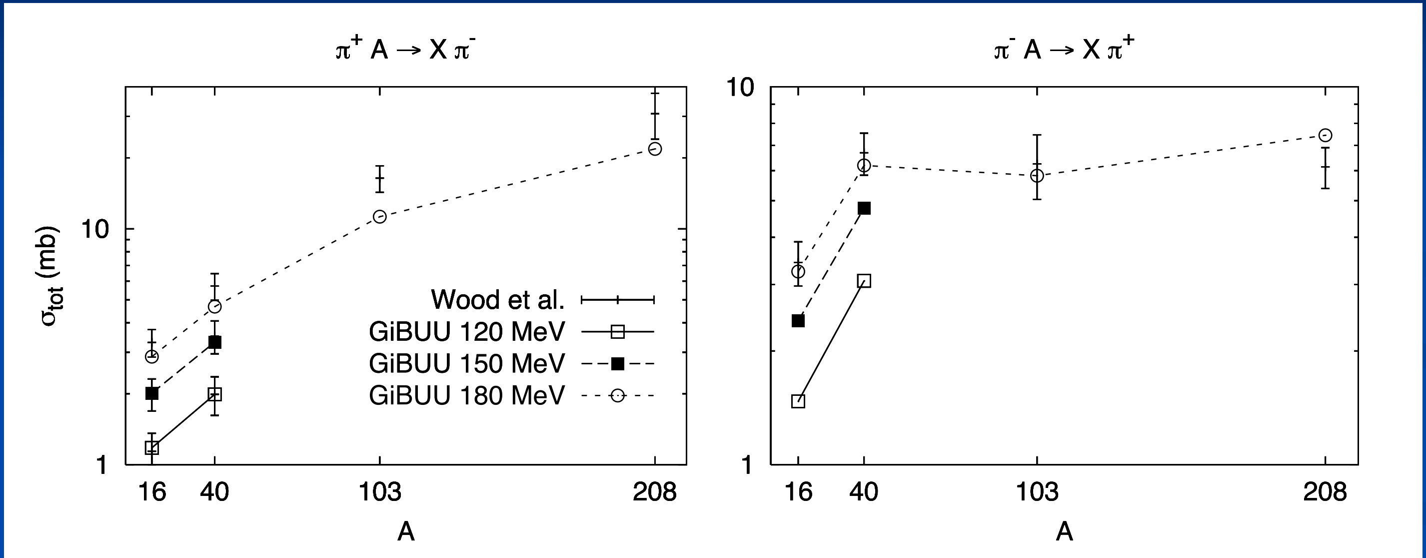
Proton transparency





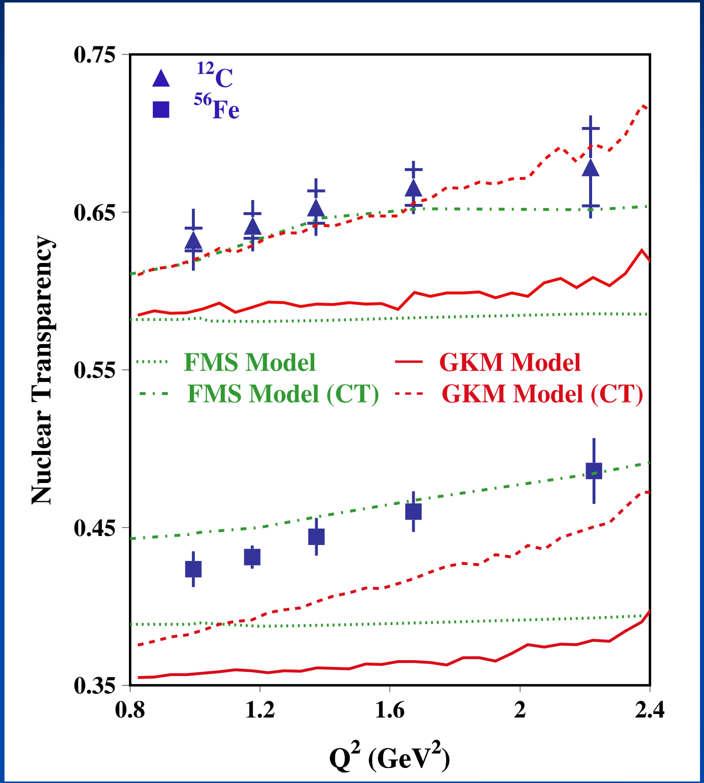
Pion reaction Xsect.

Check: Pion DCE



Data: Wood et al, GiBUU: Buss et al, **Phys.Rev. C74 (2006) 044610**

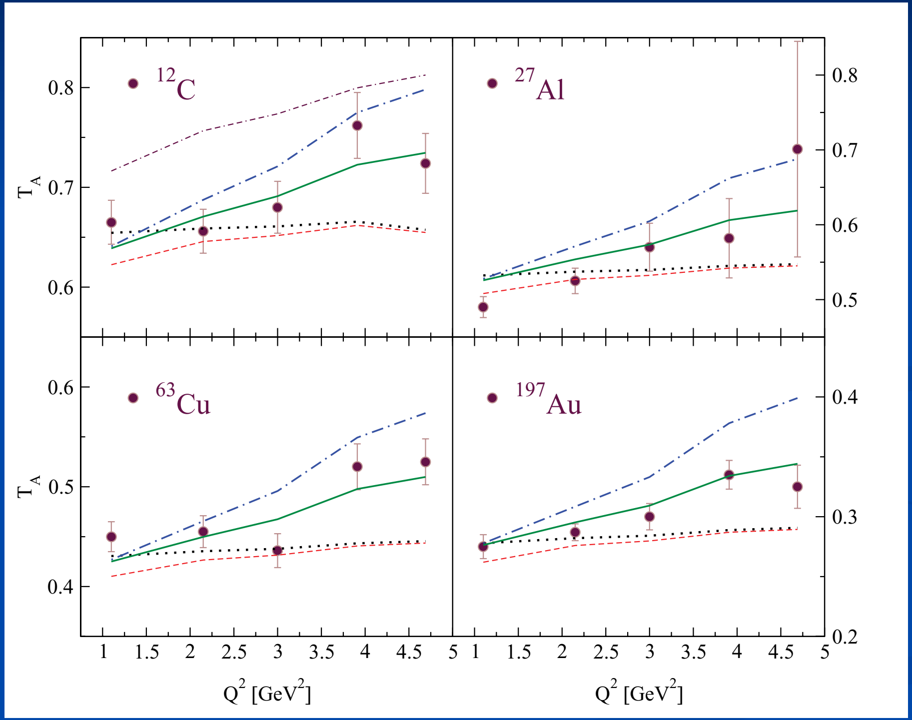
JLAB Rho Production



Exp: Hafidi et al,
Phys.Lett. B712 (2012) 326-330

GiBUU: Gallmeister et al.
Phys.Rev. C83 (2011)

JLAB Pion Production

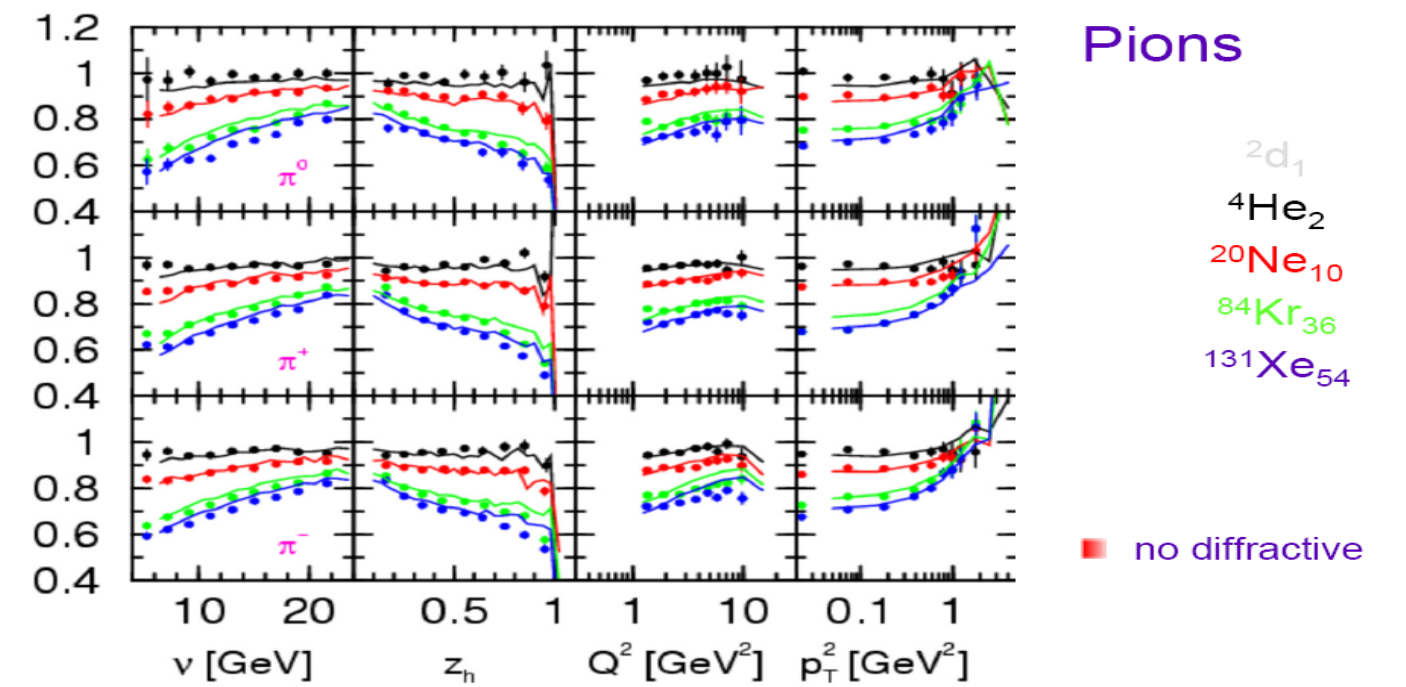


Exp: B. Clasie et al.
Phys. Rev. Lett. 99, 242502 (2007).

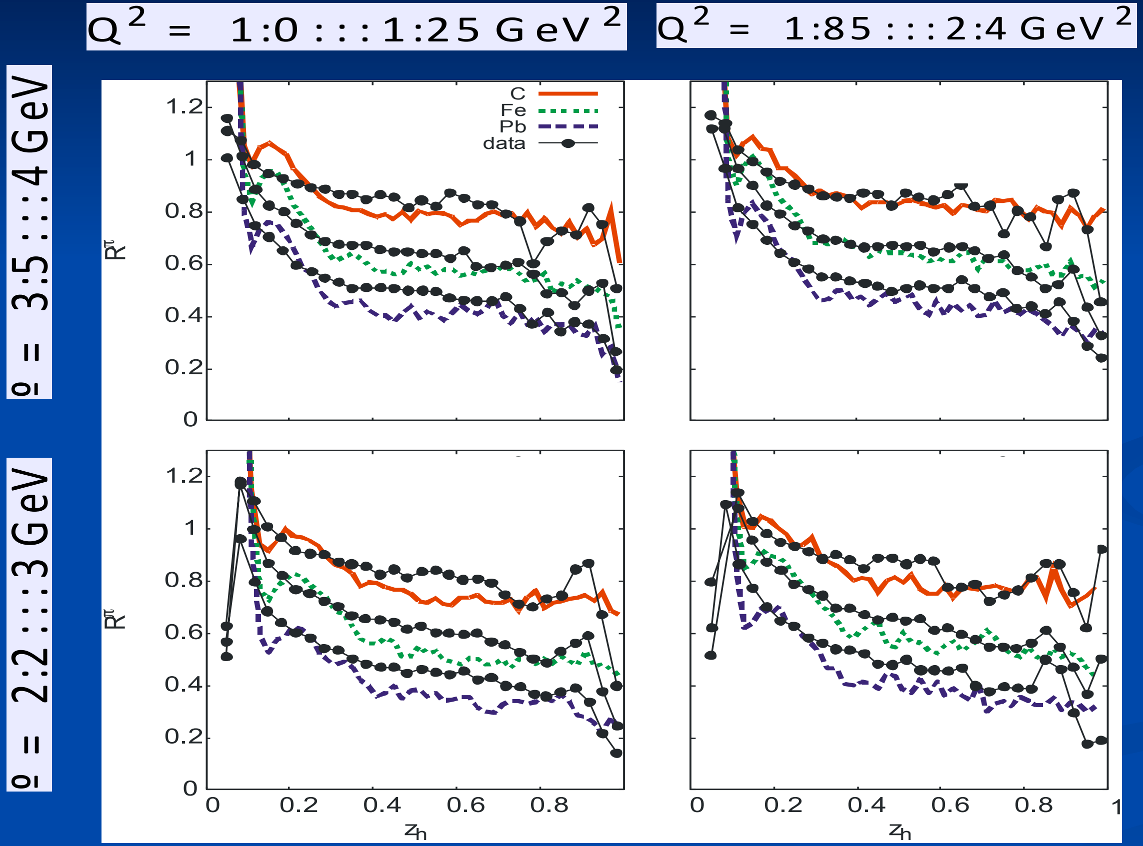
GiBUU: Kaskulov et al,
Phys.Rev. C79 (2009) 015207

HERMES@27 GeV and GiBUU

Airapetian et al.



JLAB@5, π^+ : selected (ν,Q^2) bins



Data:

CLAS preliminary

(Brooks et al)

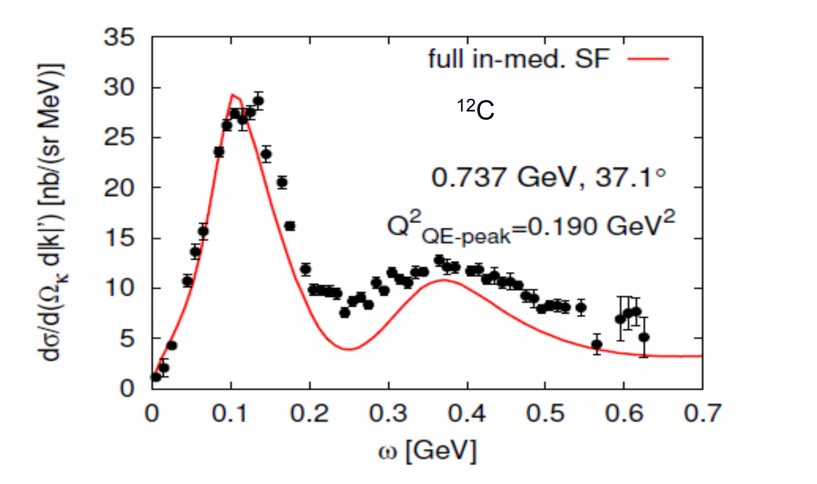
no error bars shown

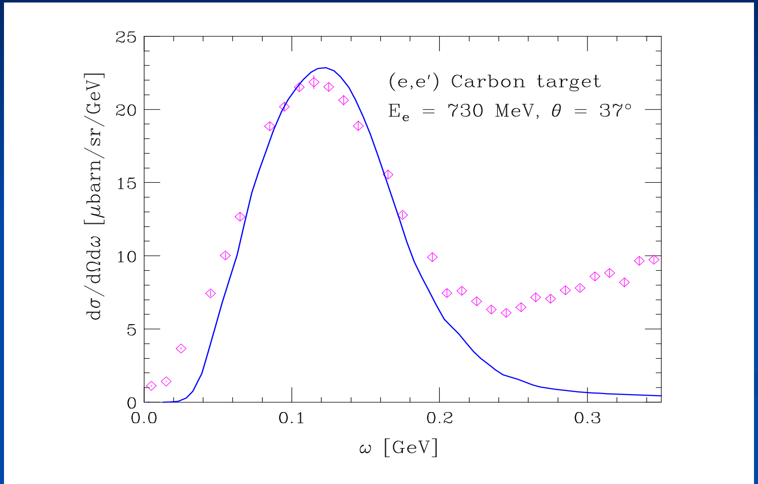
Calculations:

not tuned !!!

no potentials

Electrons as Benchmark for GiBUU





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

O. Benhar, spectral fctn

Comparison shows that NN correlations are not so important

Experiments

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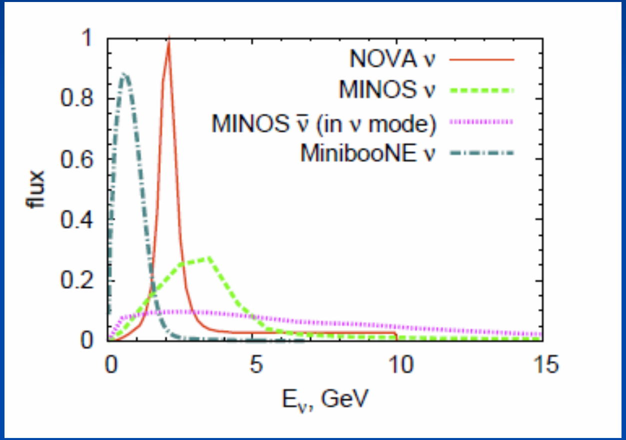
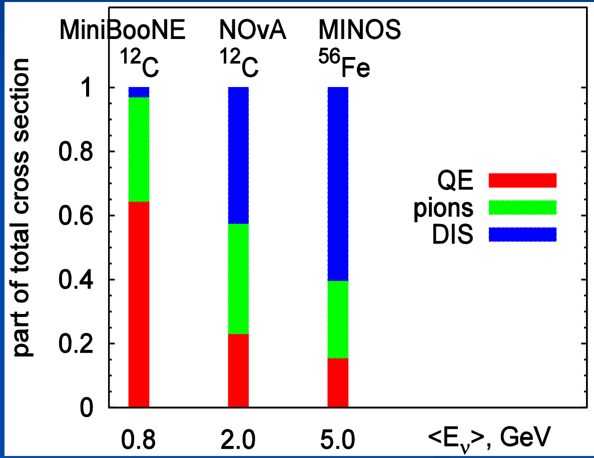
Neutrino Beams

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





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

0-pion Constraint in Experiments

- Experimental analyses impose condition of 0 pions for QE identification (QE-like)
- 0-pion events can involve pion production with subsequent pion absorption → ‚stuck pion events'
- All published QE data have removed these stuck pion events in a model-dependent way

2p-2h Processes

The MiniBooNE QE Puzzle
Explanations

- 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

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

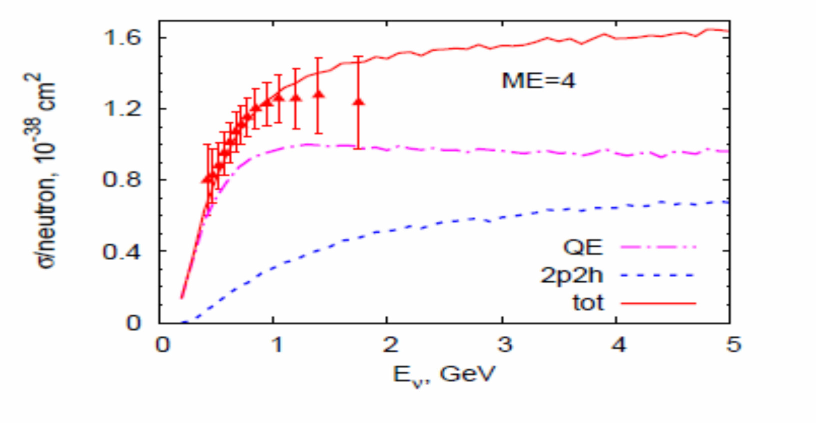
Flux smears out details in hadron tensor *W*
W contains 2p-2h and poss. RPA effects

Only adhoc ‚tune‘ in GiBUU

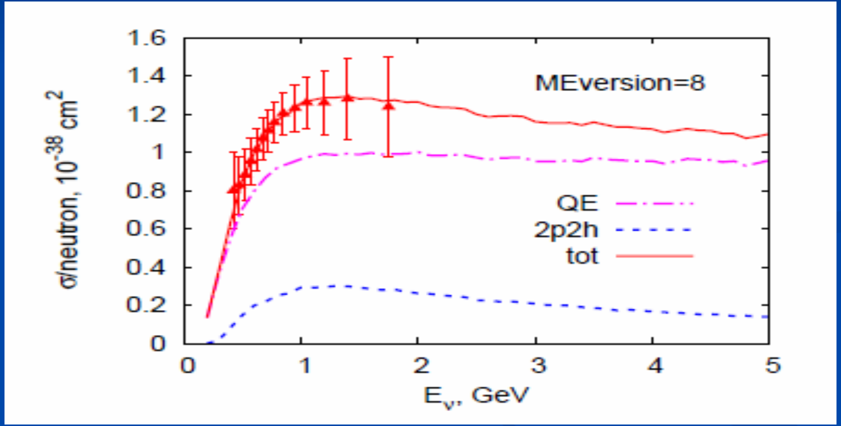
- Educated guess for 2p2h in GiBUU with tuned strength
- Big open question: up to which neutrino energies (or Q^2,ν) are models good?
- Compare with Lightbody-Bosted analysis

The MiniBooNE QE Puzzle Explanations

$M = const$

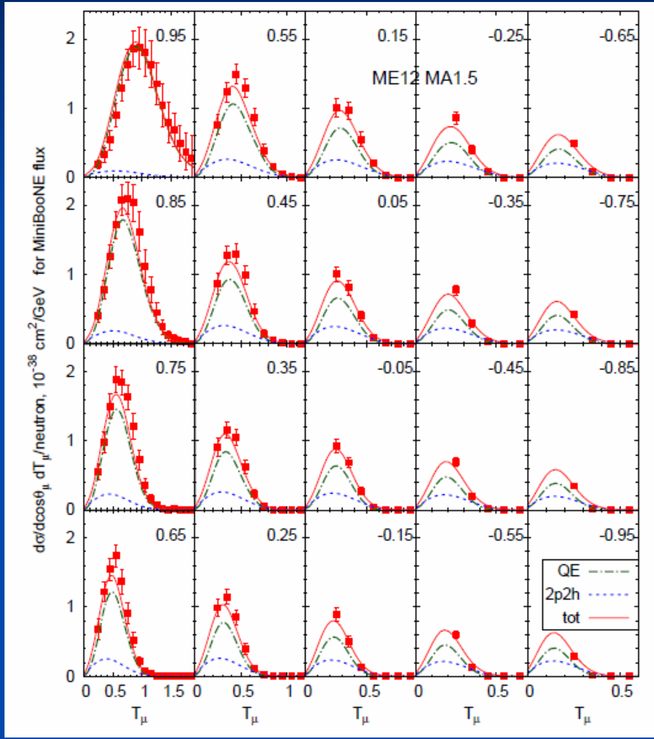


$M = M(E,q),\ W^{\mu\nu} \sim P_T^{\mu\nu}(q)$



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

The MiniBooNE QE Puzzle
Explanations



ME12, MB flux averaged

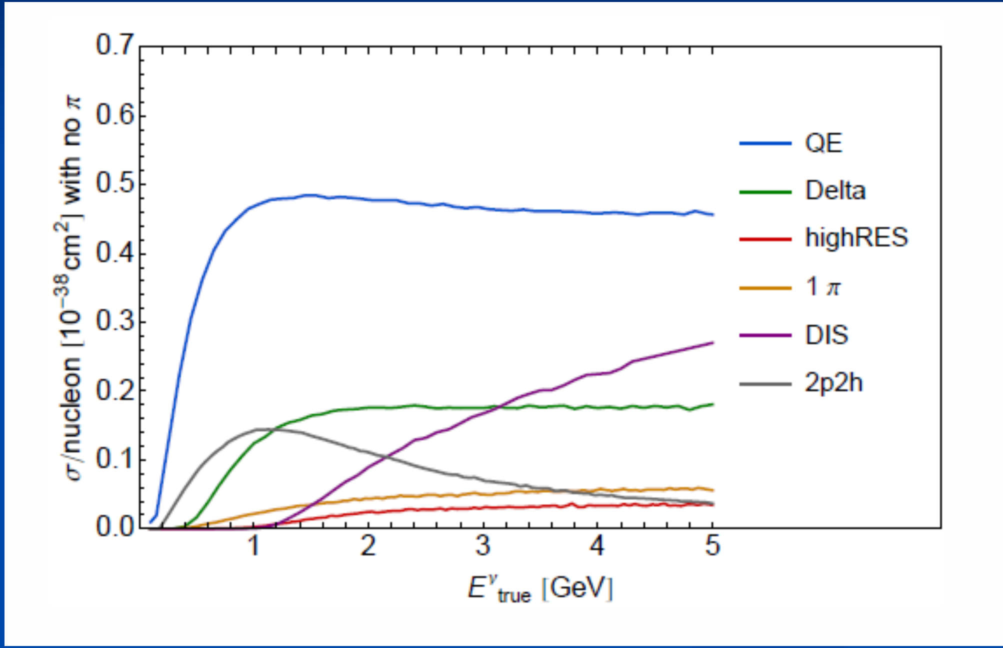
Data corrected
for stuck-pion events!

$W^{\mu\nu} \sim P_T^{\mu\nu}(q)\, F(Q^2)$, educated guess

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

0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1



The MiniBooNE QE Puzzle

- How to decide if this explanation is correct?

- Must not only consider inclusive X-sections, but also exclusive ones:

  Nucleon Knock-out, numbers and spectra

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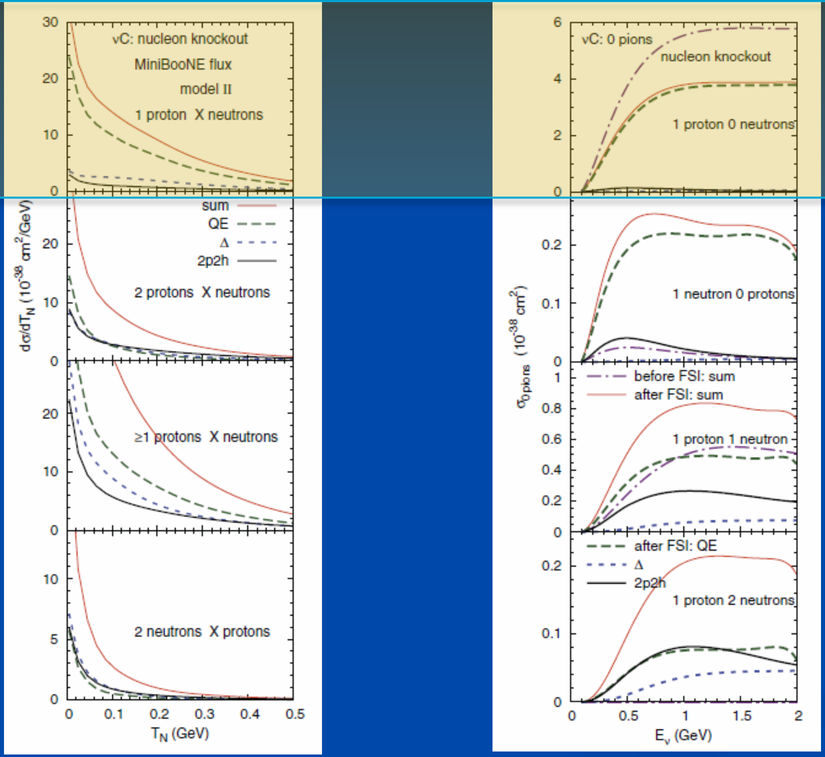
QE Identification



1p xn xπ: fairly clean QE event

1p 0n 0π: very clean QE event

No clean signal for 2p-2h because of FSI

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Pion Production

Pion Production

from: Phys.Rev. C87 (2013) 014602

1p-1h-1π X-section:

$$\mathrm{d}\sigma^{\nu A \to \ell' X \pi} = \int \mathrm{d}E \int \frac{\mathrm{d}^3 p}{(2\pi)^3} P(\mathbf{p}, E) f_{\mathrm{corr}}\, \mathrm{d}\sigma^{\mathrm{med}}\, P_{\mathrm{PB}}(\mathbf{r}, \mathbf{p}) F_{\pi}(\mathbf{q}_{\pi}, \mathbf{r}) \ .$$

Hole spectral function

$$P(\mathbf{p}, E) = g \int_{\mathrm{nucleus}} \mathrm{d}^3 r\, \Theta\left[p_{\mathrm{F}}(\mathbf{r}) - |\mathbf{p}|\right] \Theta(E) \delta\left(E - m^* + \sqrt{\mathbf{p}^2 + m^{*2}}\right)$$

Pion fsi (scattering, absorption, charge exchange) handled by transport, Includes Δ transport, consistent width description of Delta spectral function, detailed balance

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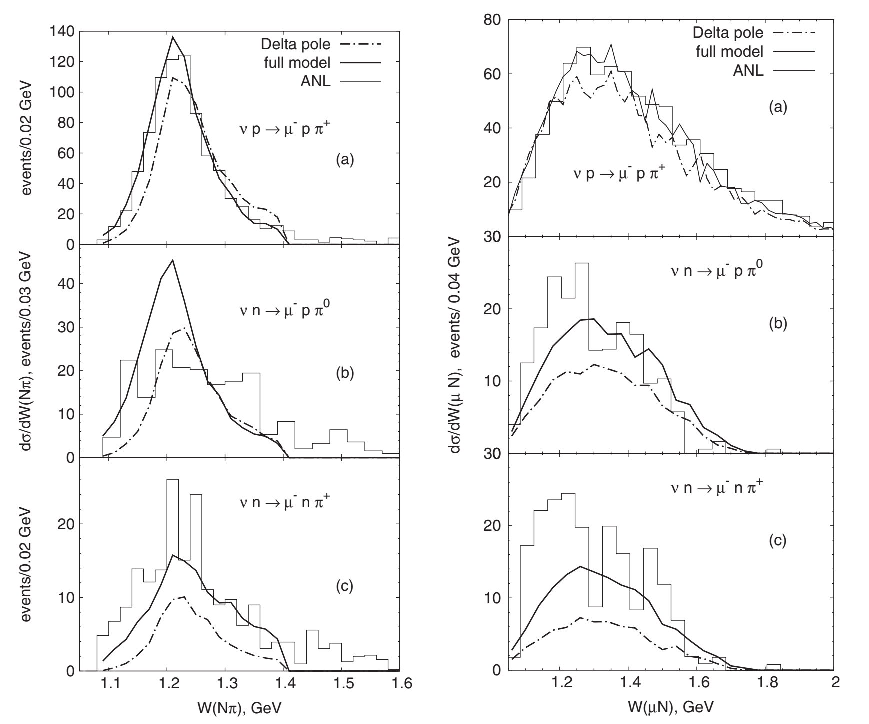
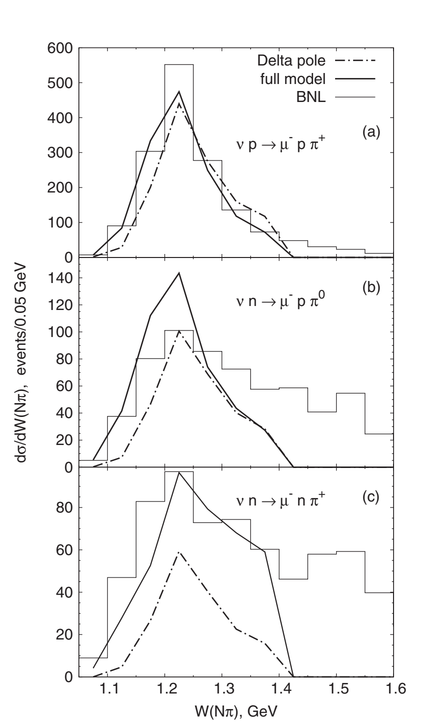
Pi-N inv. Mass Distributions



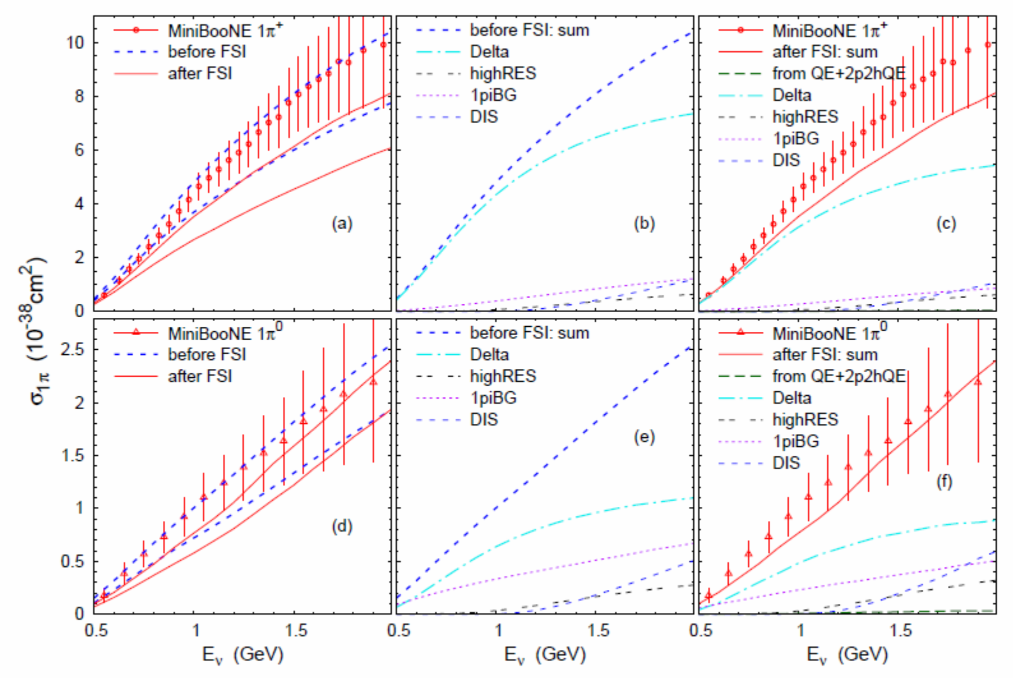


Lalakulich et al.,
Phys. Rev. D 82, 093001 (2010)

ANL data

BNL data

Pion Production



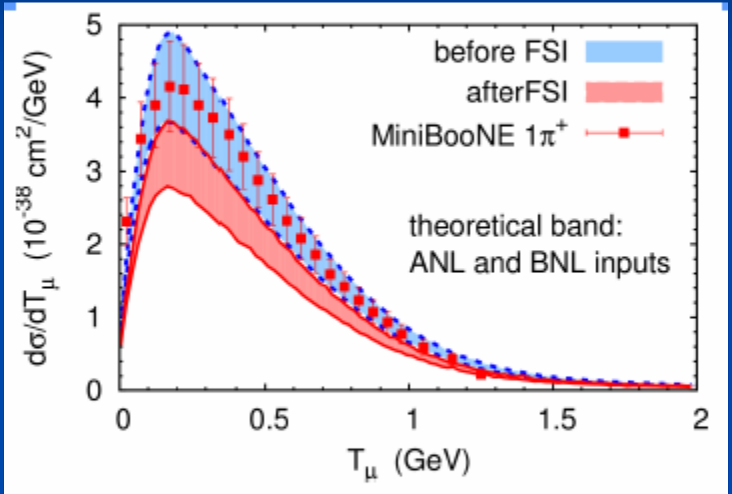
Upper line: BNL input
Lower line: ANL input

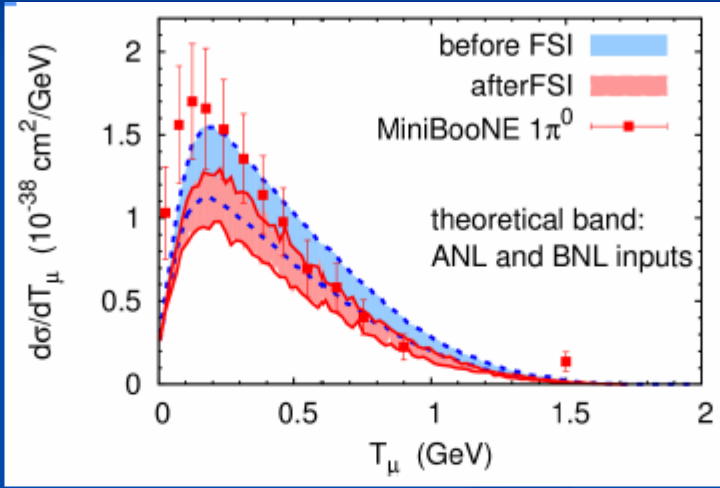
Tendency for theory too low, more so for π+, at E > 1 GeV

DIS and higher resonances contribute for E > 1 GeV, not contained in Hernandez calcs.

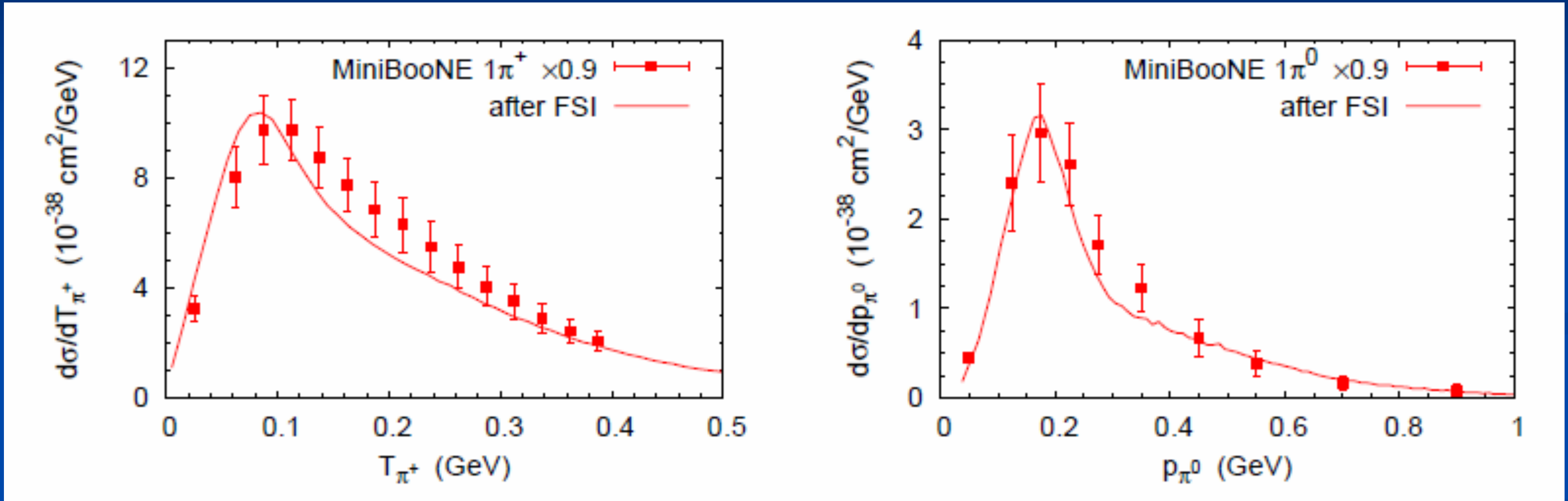
Discrepancy mainly in tail of flux distributions (large uncertainty)

Pion Production in MB



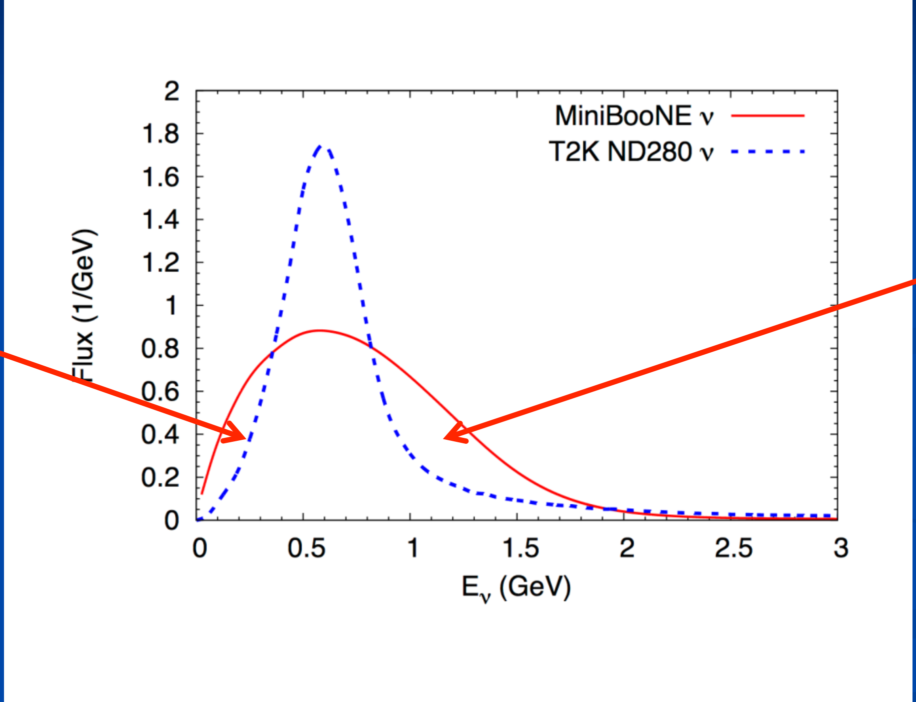


Pion Production in MB



Flux renormalization (data x 0.9 (cf. Nieves QE analysis))

T2K vs MB Flux



T2K ND280
205kA flux

less RPA

less pions

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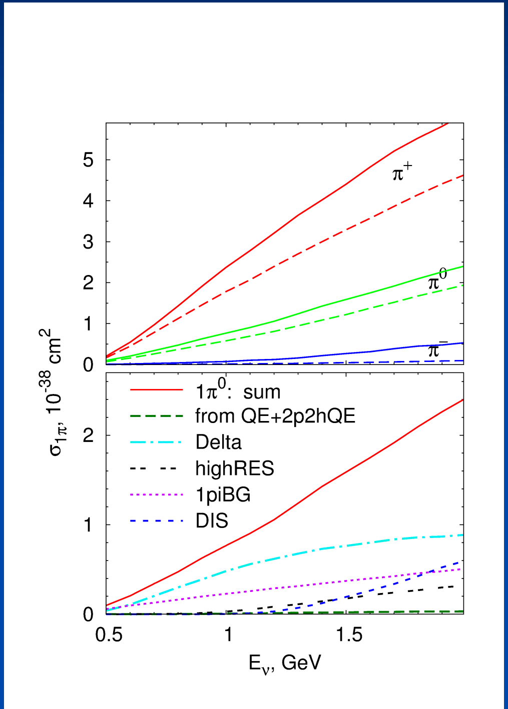
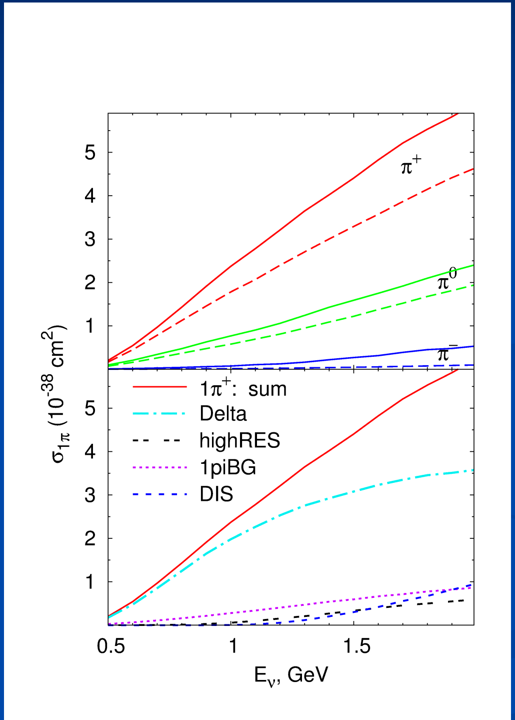
Pion Production in T2K

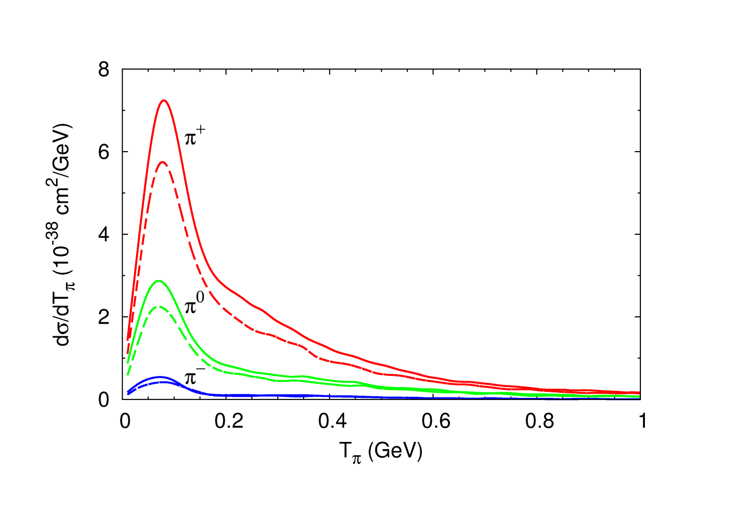


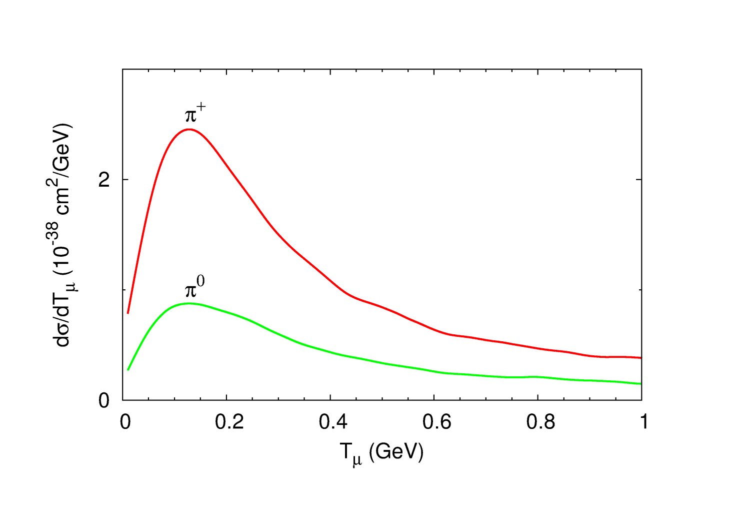


Δ dominant
only up to 0.8 GeV

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

Pion Production in T2K

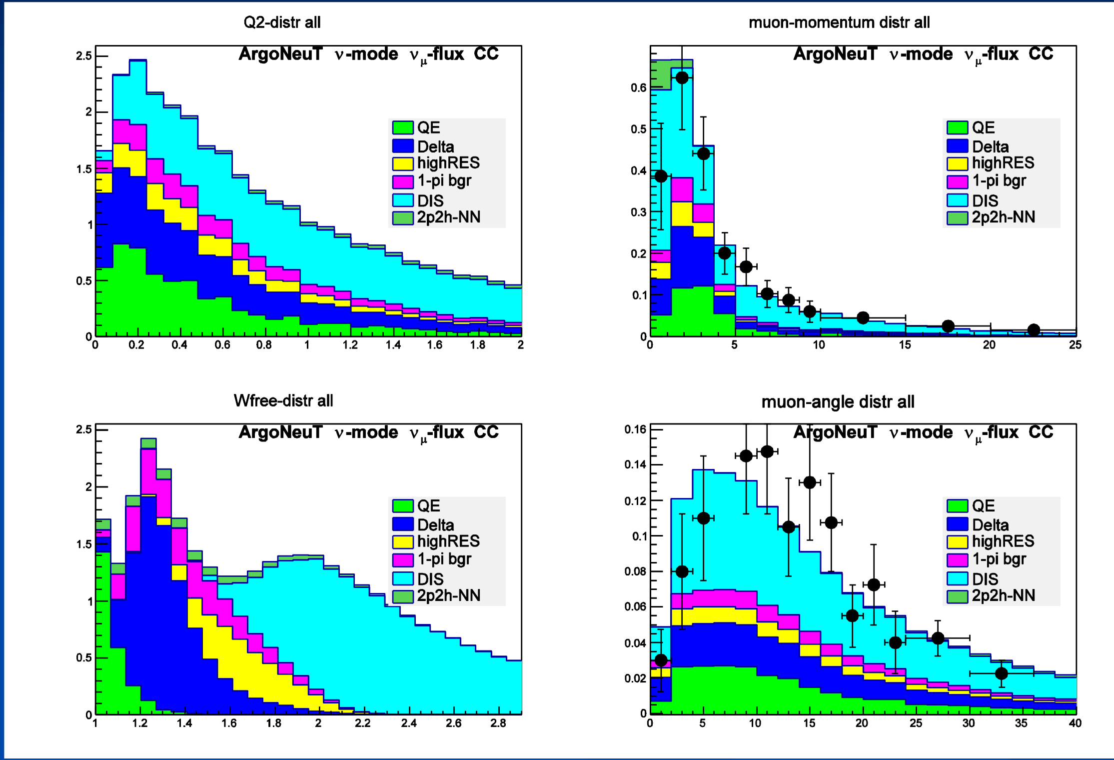




T2K pion data may help to distinguish between ANL and BNL input

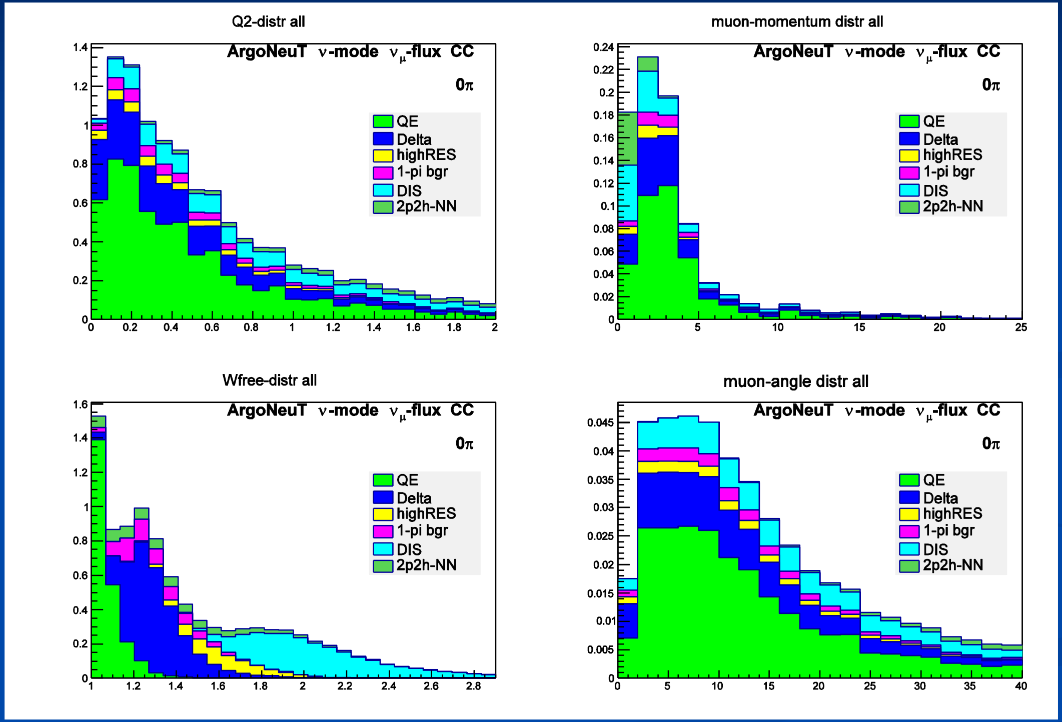
MINERvA, MINOS, NOVA & LBNE

ArgoNeuT



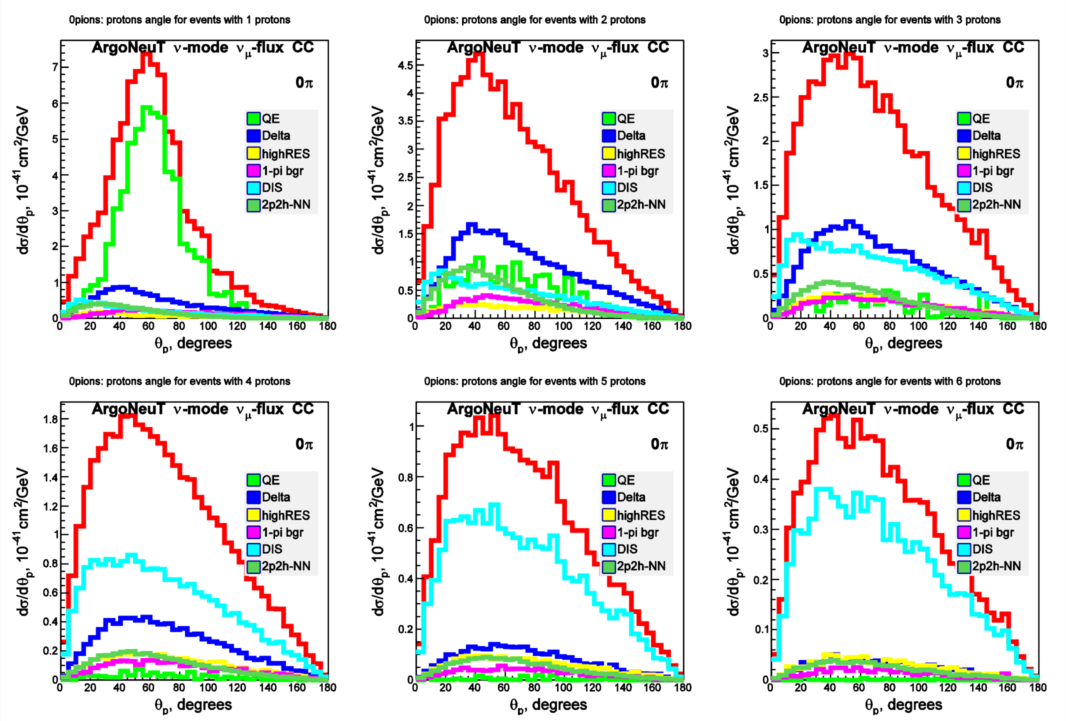
All events, large DIS contribution

ArgoNeuT



0 pion events suppresses DIS

ArgoNeuT



Reaction mechanism can be distinguished by proton number, for QE and DIS

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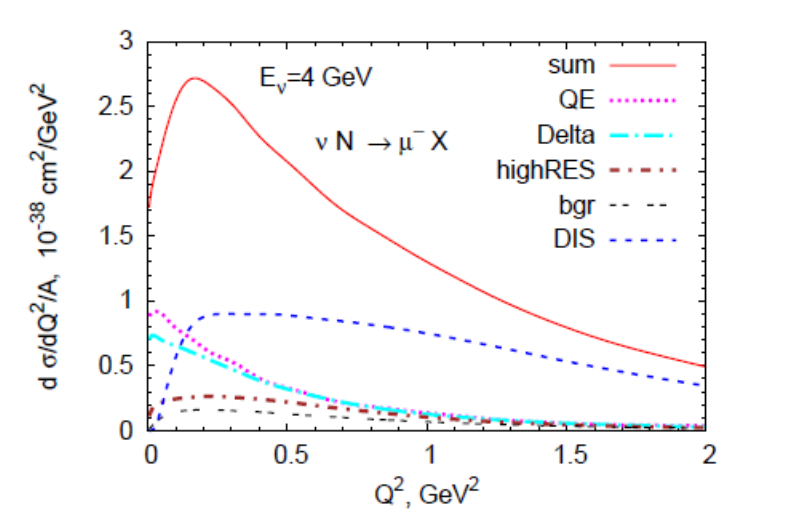
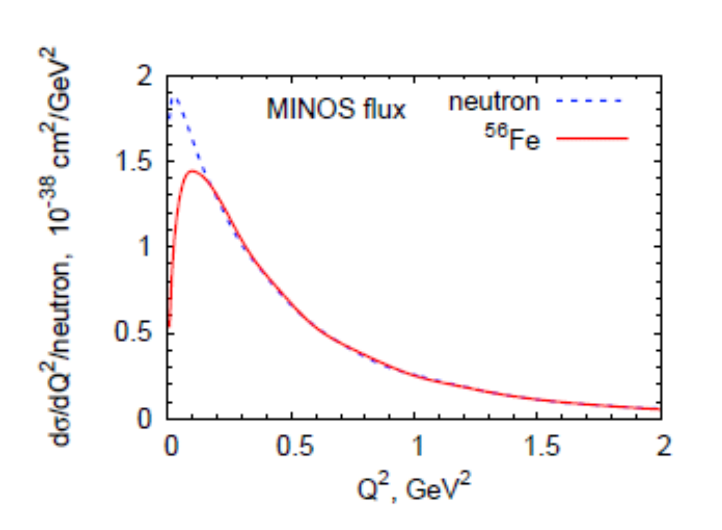
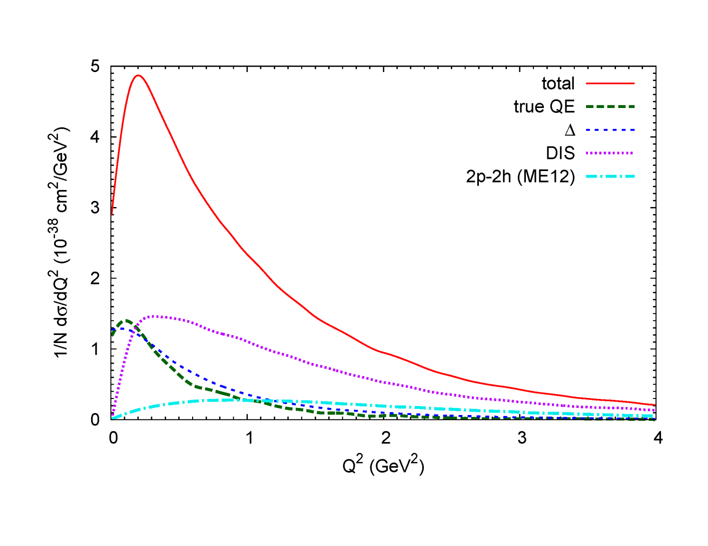
Experiments at higher energies

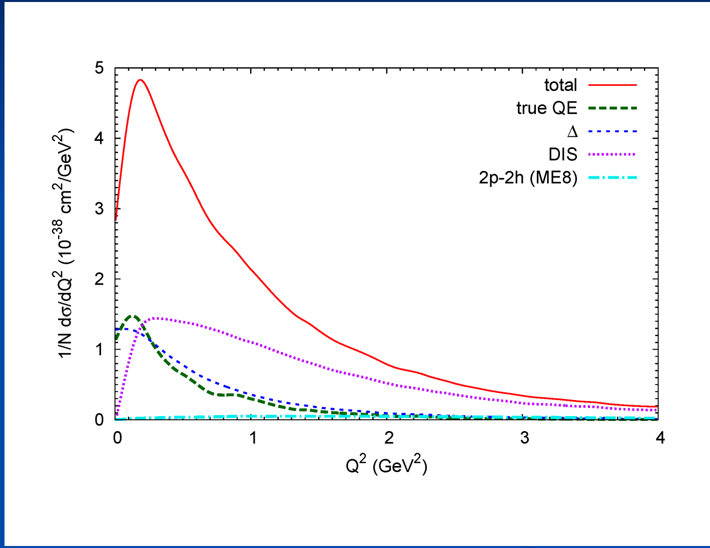




Q^2 dependence reaches out farther than at lower-energy MB experiment: DIS effect

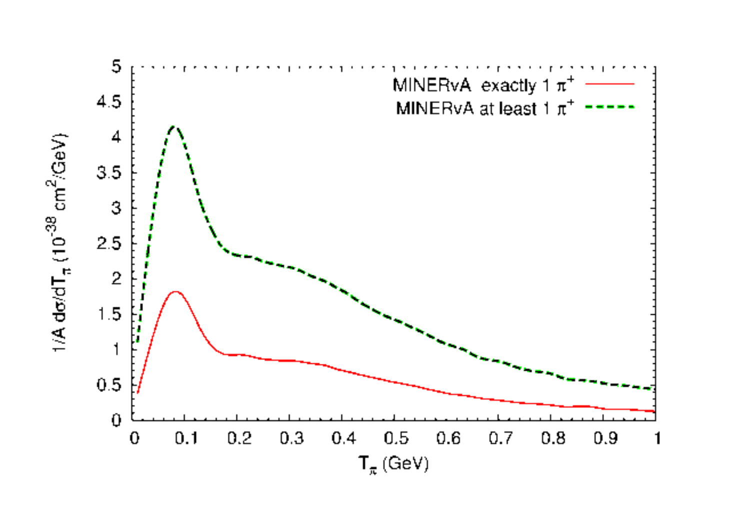
MINERνA Results

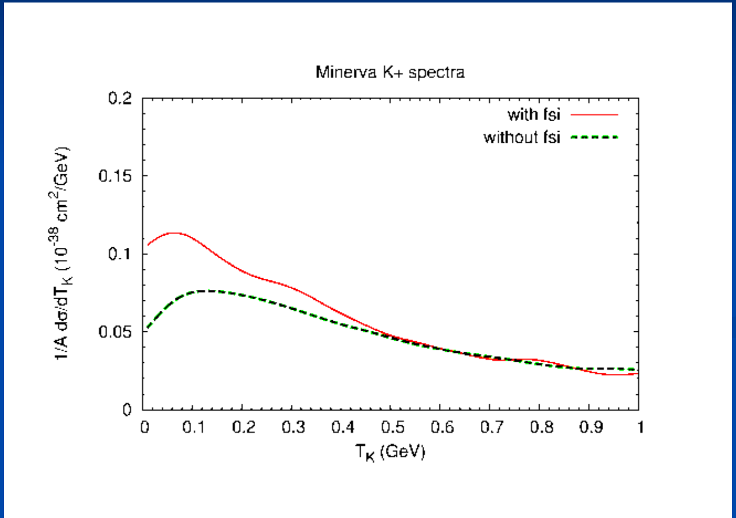




1. 2p2h accounts only for small part of total X-section
2. DIS dominates for $Q^2 > 0.3$ GeV, QE = Delta

MINERvA Results





Semi-inclusive pion production

Kaon production
fsi brings X-section up!

Energy Reconstruction by QE

- CCQE scattering on neutron at rest
  - Energy

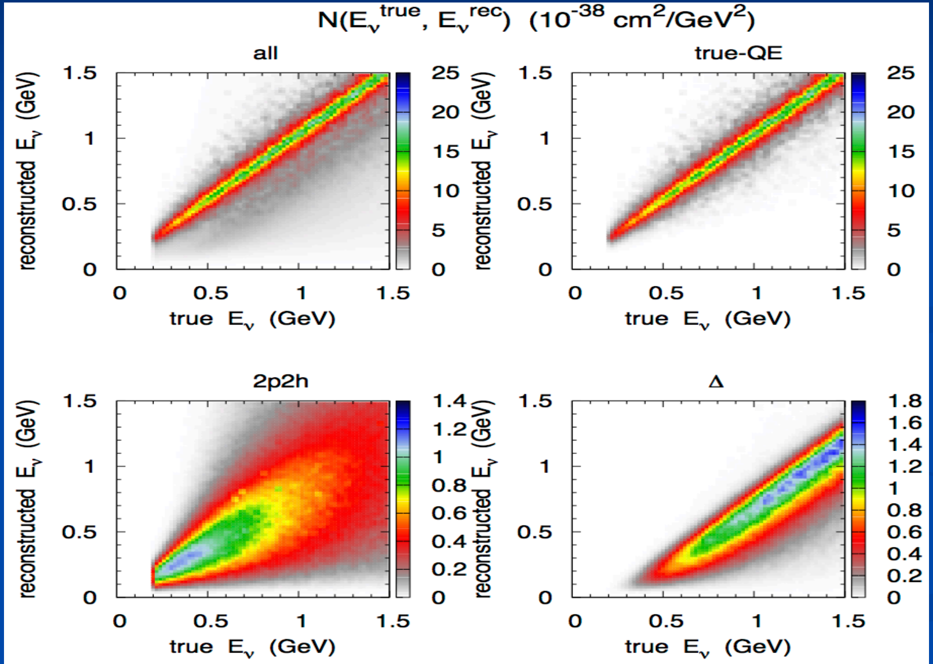
$$E_\nu^{\mathrm{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu\right]}$$

  - Q^2

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

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

Migration Matrix for C and MB flux



Distributions
for 0 pion events!

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

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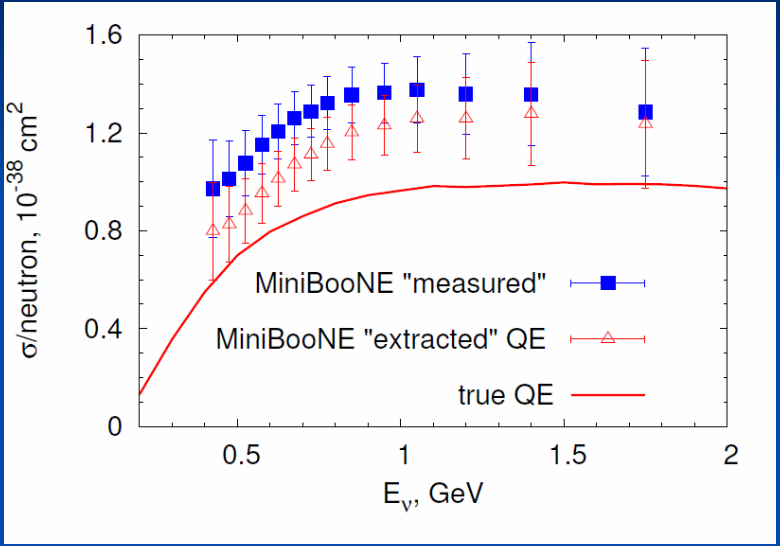
MiniBooNE QE puzzle



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 !?

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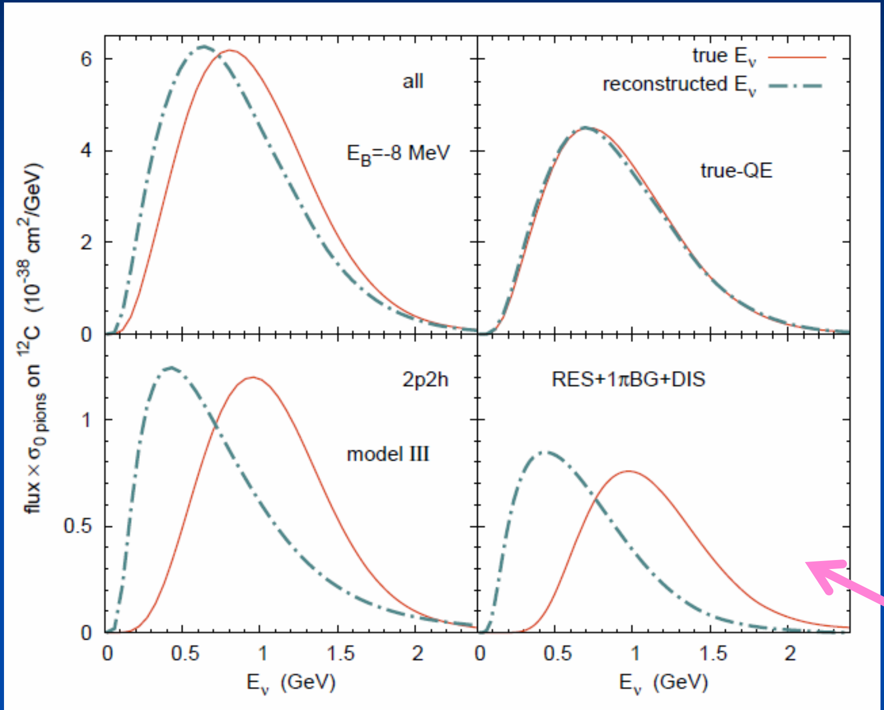
Energy reconstruction in MB

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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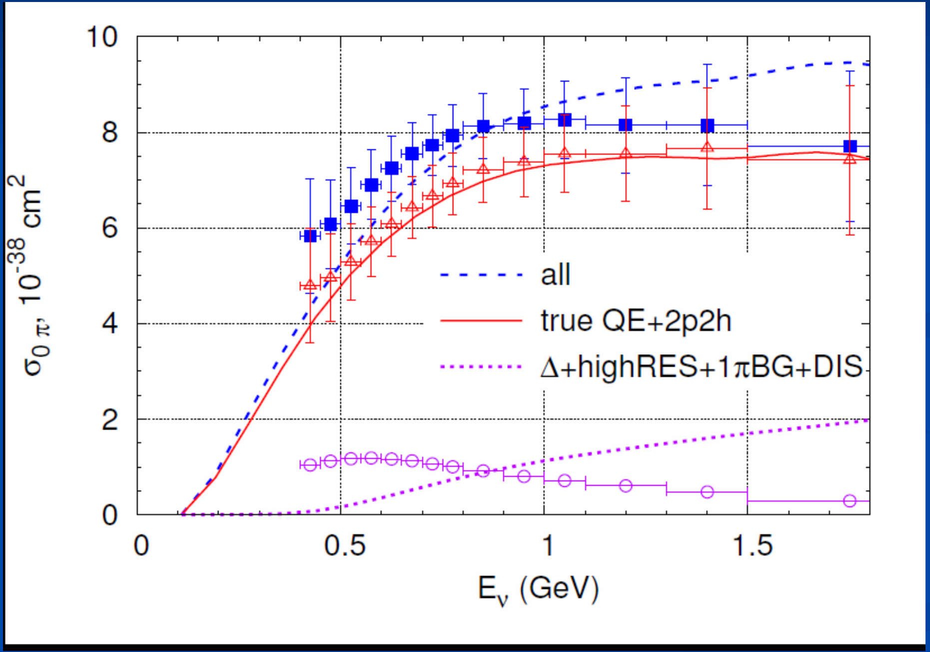
Energy reconstruction in MB

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

Energy reconstruction in MB



Data: plotted vs *reconstructed* energy

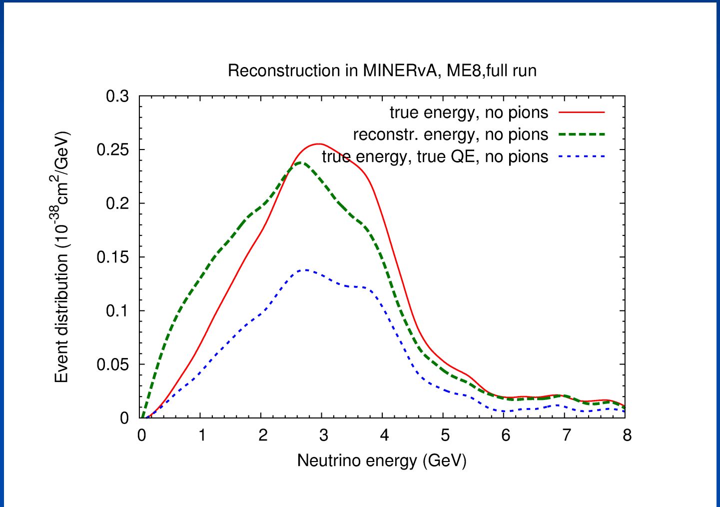
Curves: plotted vs. *true* energy

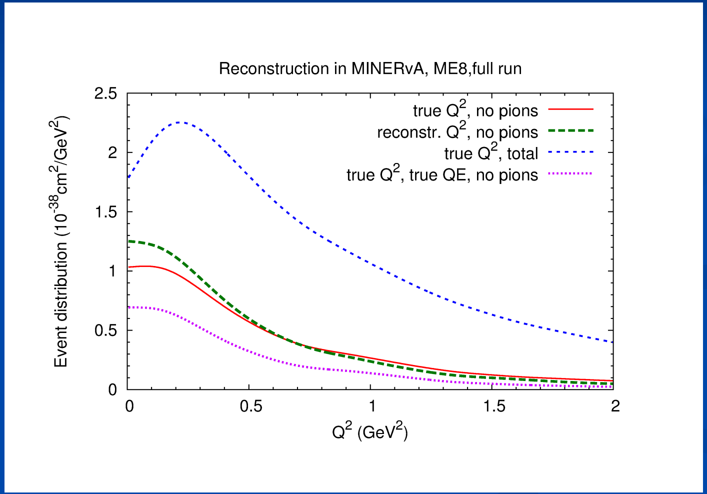
Explains strange energy-dependence of stuck pion events

Energy reconstruction in MB

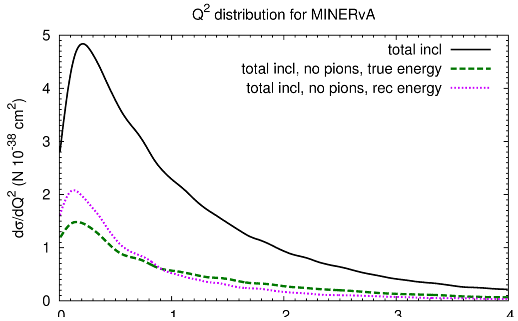
- Energy reconstruction does not just change energy-axis, but also tilts funtional dependence of X-section on neutrino energy

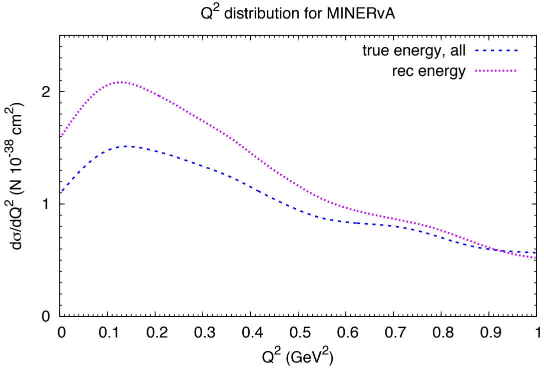
MINERvA Results

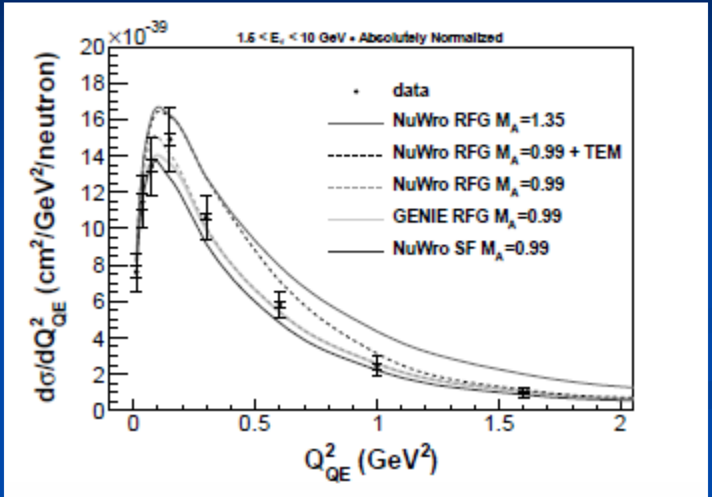




MINERvA Results







Minerva QE analysis, big error in Q^2 analysis if event sample is not clean QE

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Energy Reconstruction and Oscillation Analysis

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GiBUU is Nature

- GiBUU is used to simulate nature:
  generate events with known, *true energy*
- Analyze these events with exp. methods, obtain *reconstructed energy* for each event
- Compare event rates as functions of true and reconstructed energies

Oscillation and Energy Reconstruction

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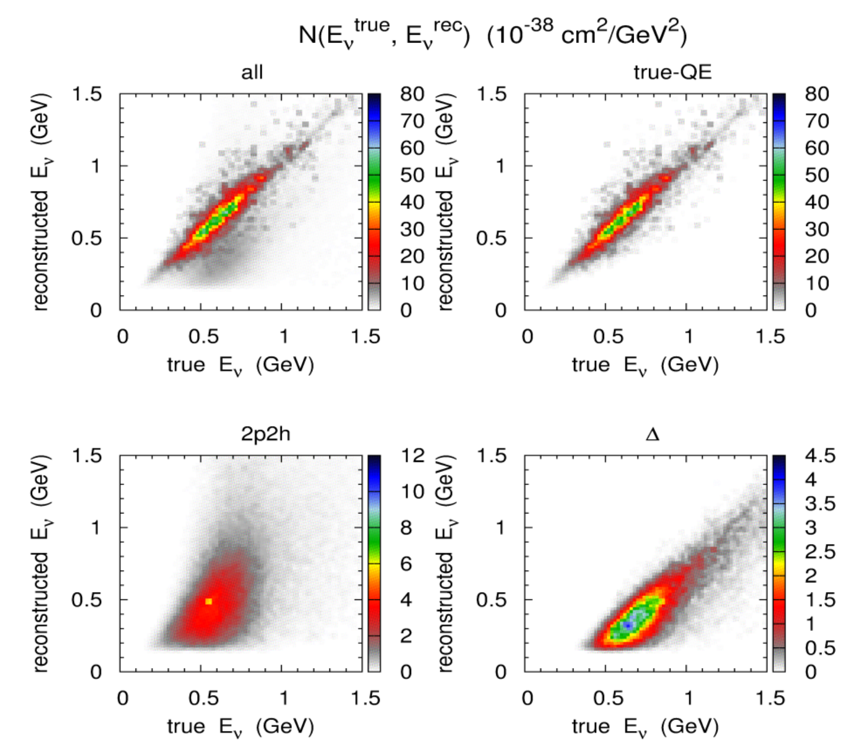
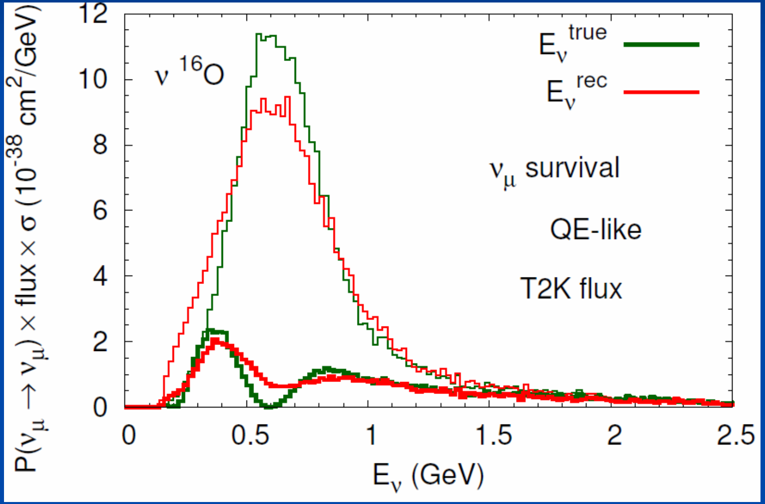
T2K migration matrix



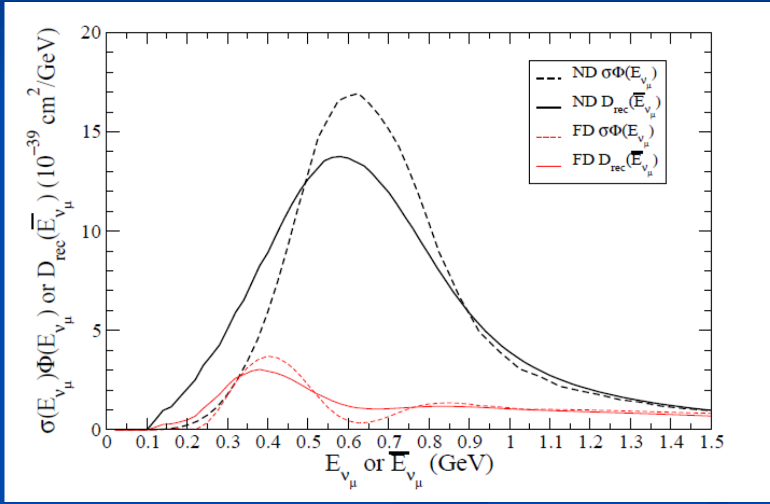
T2K Flux
Target: ^{16}O

Oscillation signal in T2K

ν_μ disappearance

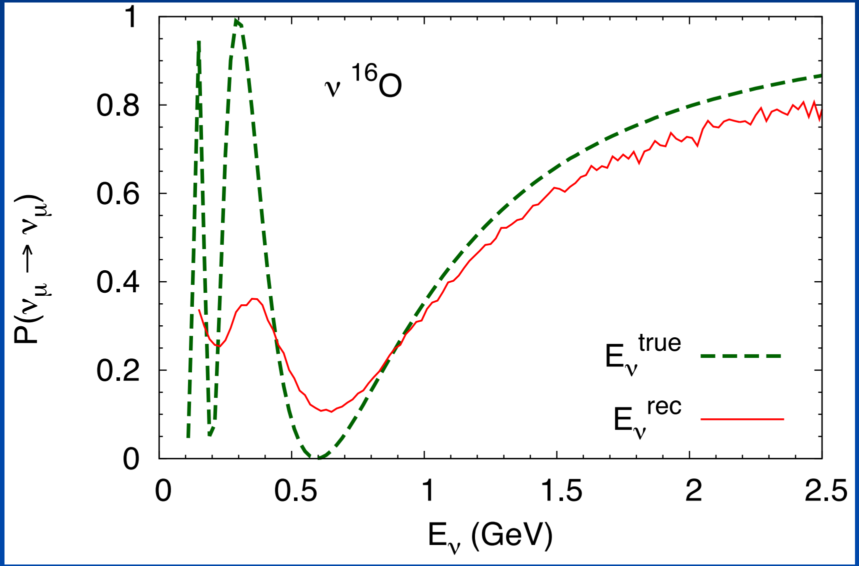


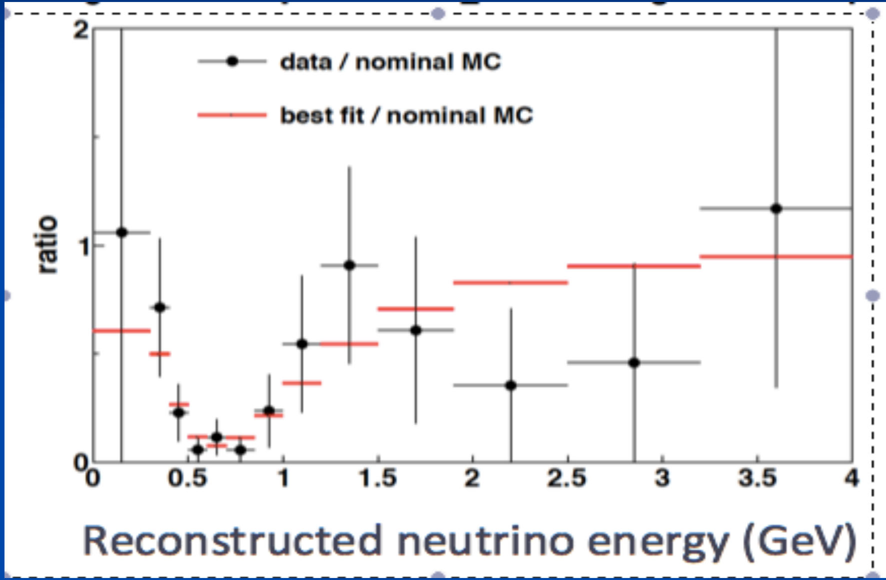
GiBUU



Martini

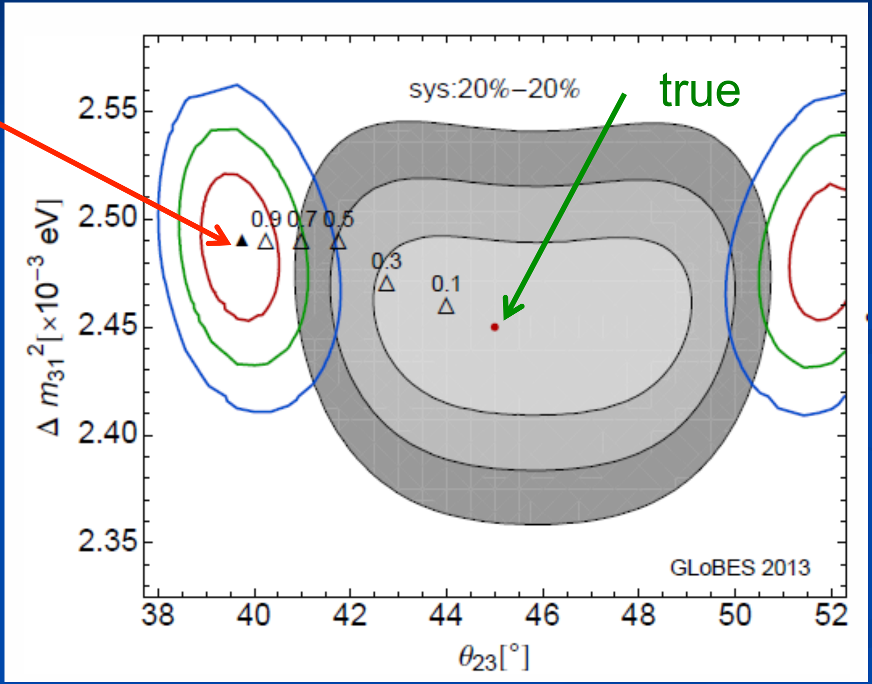
Oscillation signal in T2K
ν_μ disappearance





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

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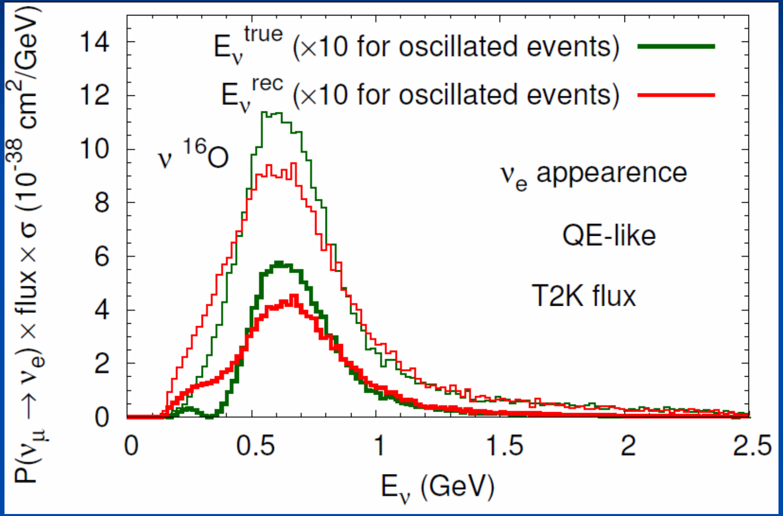
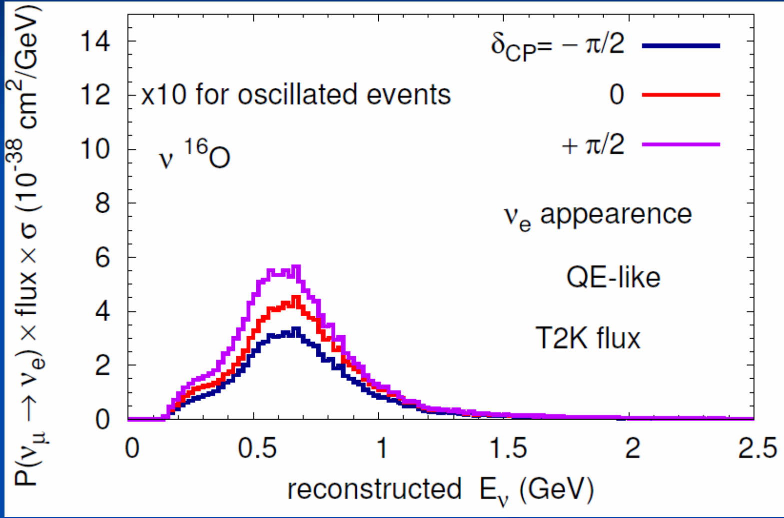
Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps





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

Sensitivity of T2K to Energy Reconstruction

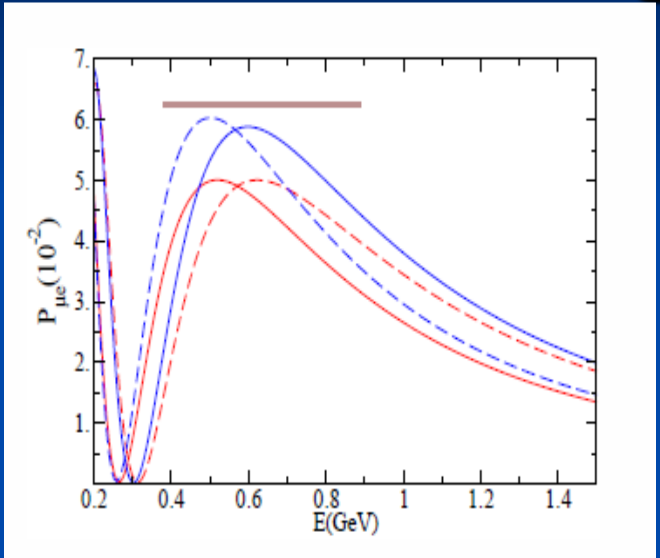
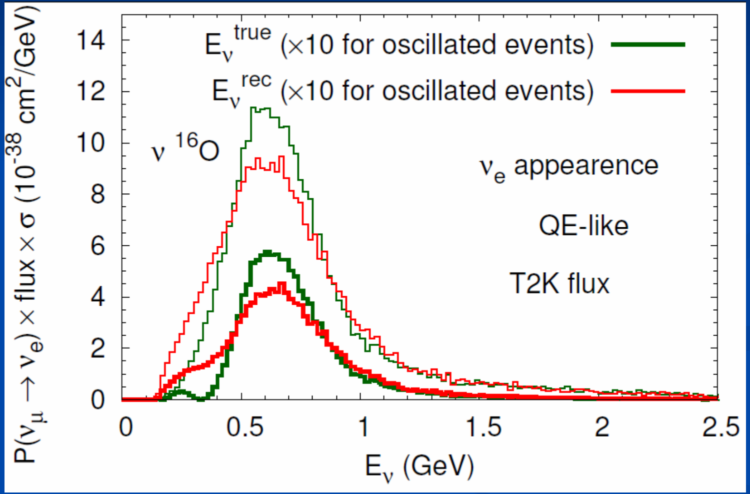


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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



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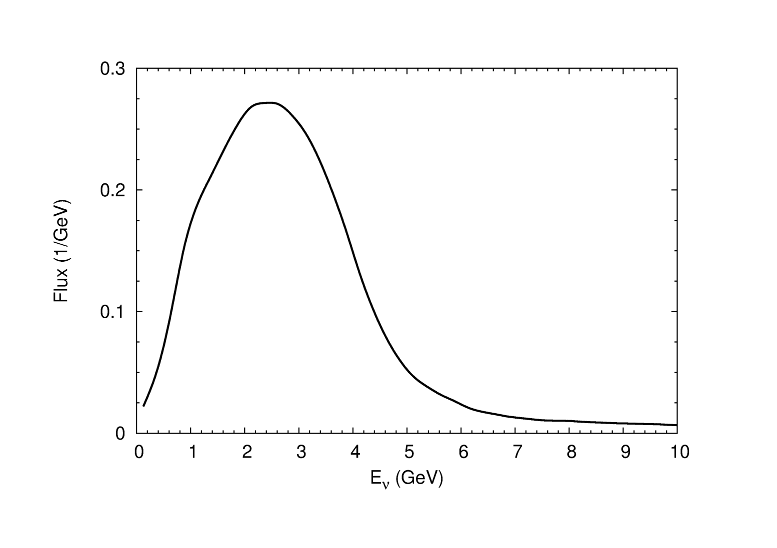
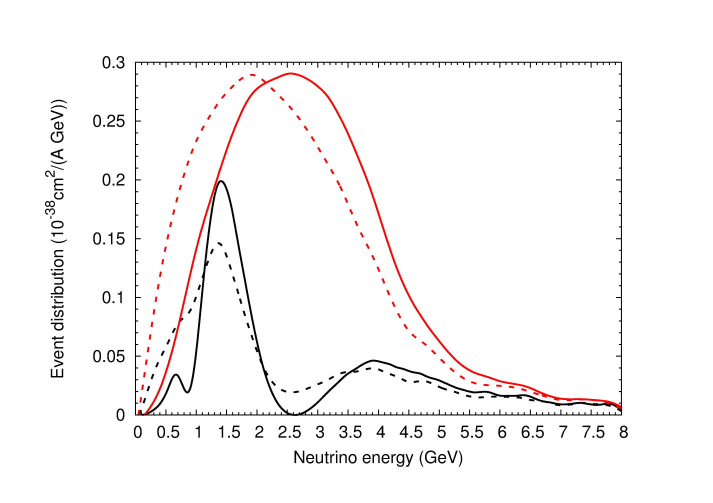
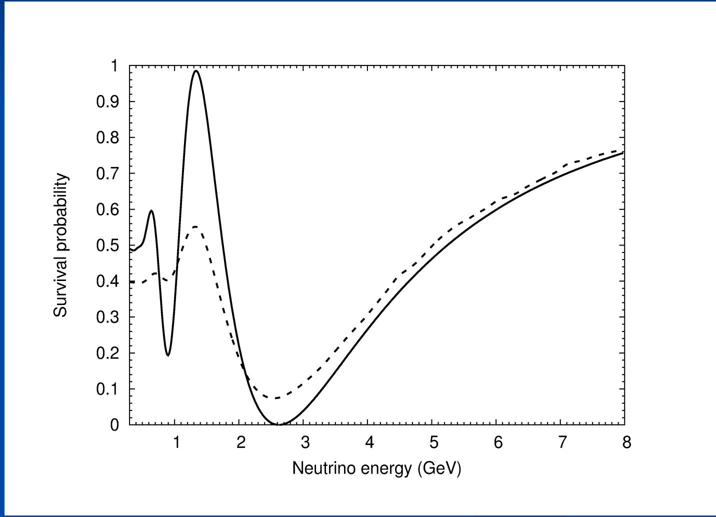
Energy Reconstruction for LBNE



Energy Reconstruction for LBNE

Muon survival

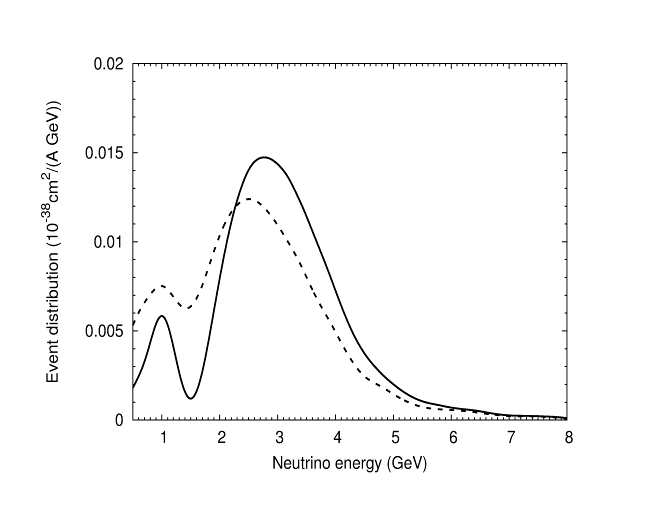




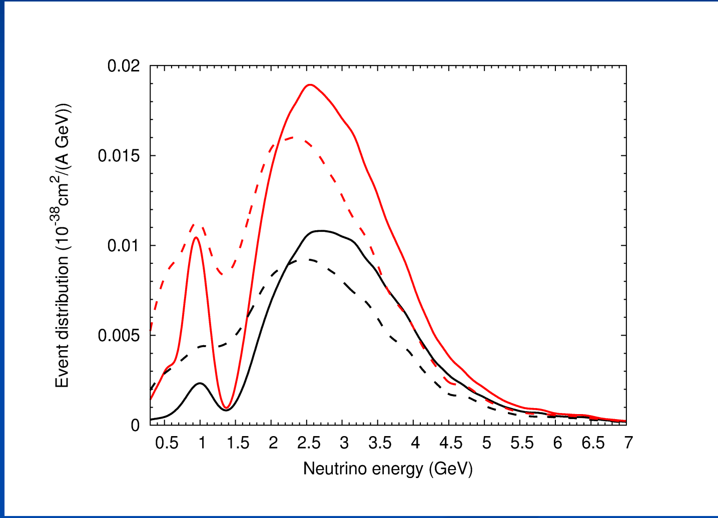
Dashed: reconstructed, solid: true energy

Energy Reconstruction for LBNE

electron appearance



$\delta_{CP} = 0$



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

Summary

- Energy reconstruction essential for precision determination of neutrino oscillation parameters
(and neutrino-hadron cross sections)

- Energy 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