Neutrino-Nucleus Interactions

Ulrich Mosel

Institut für
Theoretische Physik

JUSTUS-LIEBIG-
UNIVERSITÄT
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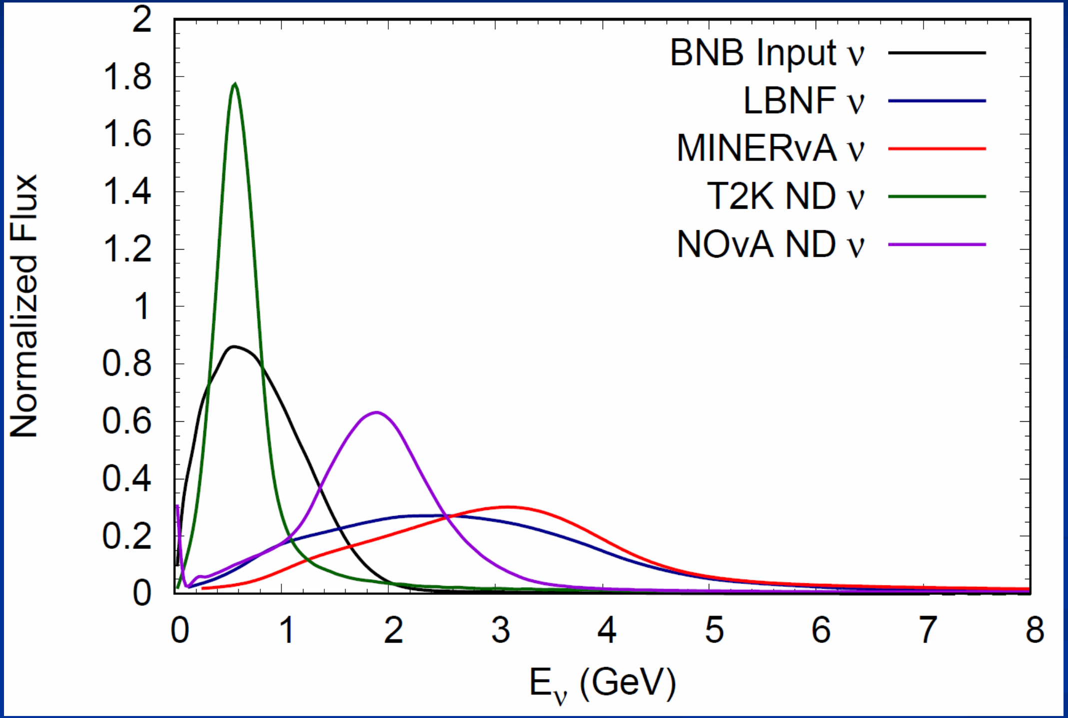
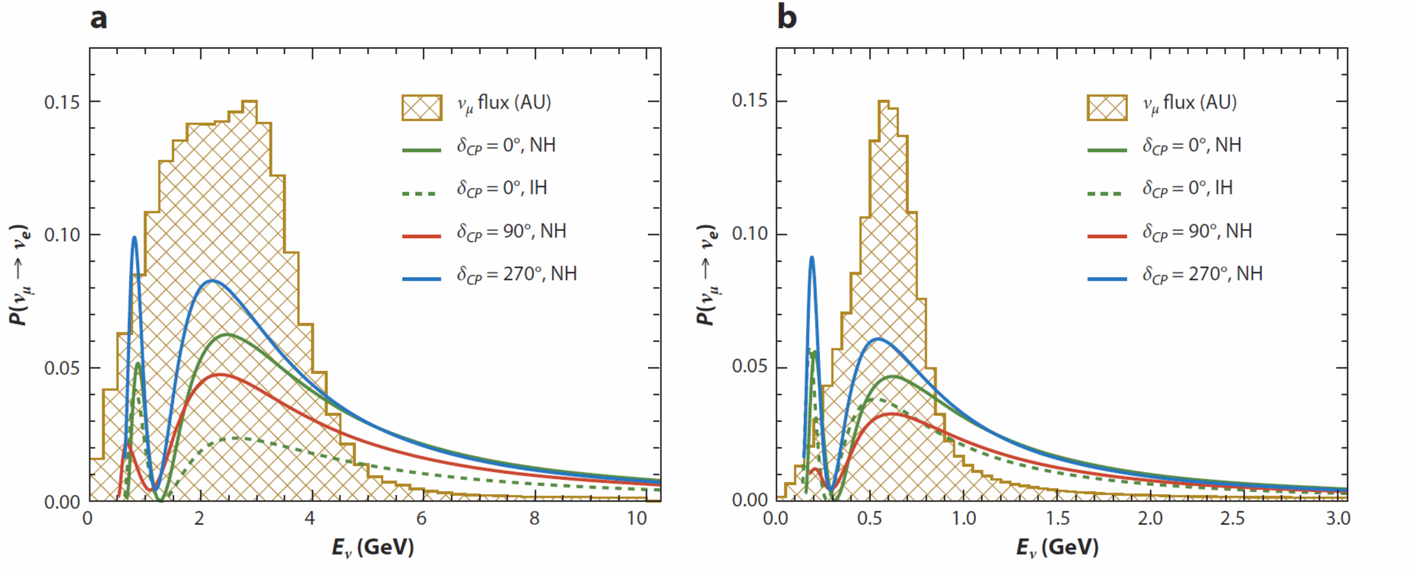
Motivation

Energy-Distributions of Neutrino Beams



Energy must be reconstructed event by event, within these distributions

Oscillation Signals as F(E_ν)



From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

DUNE, 1300 km   HyperK (T2K) 295 km

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

- What is measured in neutrino LBL experiments: fully inclusive X-section, 1 number
- What is needed for oscillation signal: fully inclusive X-section as function of E_ν
- What is needed to get inclusive X-section (E_ν) : Exclusive X-sections for many-particle final states

Inclusive Cross sections

- What is measured in an inclusive experiment

$$\sigma_{incl} = \int_0^\infty \Phi(E_\nu)\sigma(E_\nu)\,dE_\nu$$

One number!

can (in principle) be calculated ab initio

- For oscillation analysis needed is more:

$$\sigma(E_\nu) = \sum_{allchannels} \sigma_{excl}(E_\nu)$$

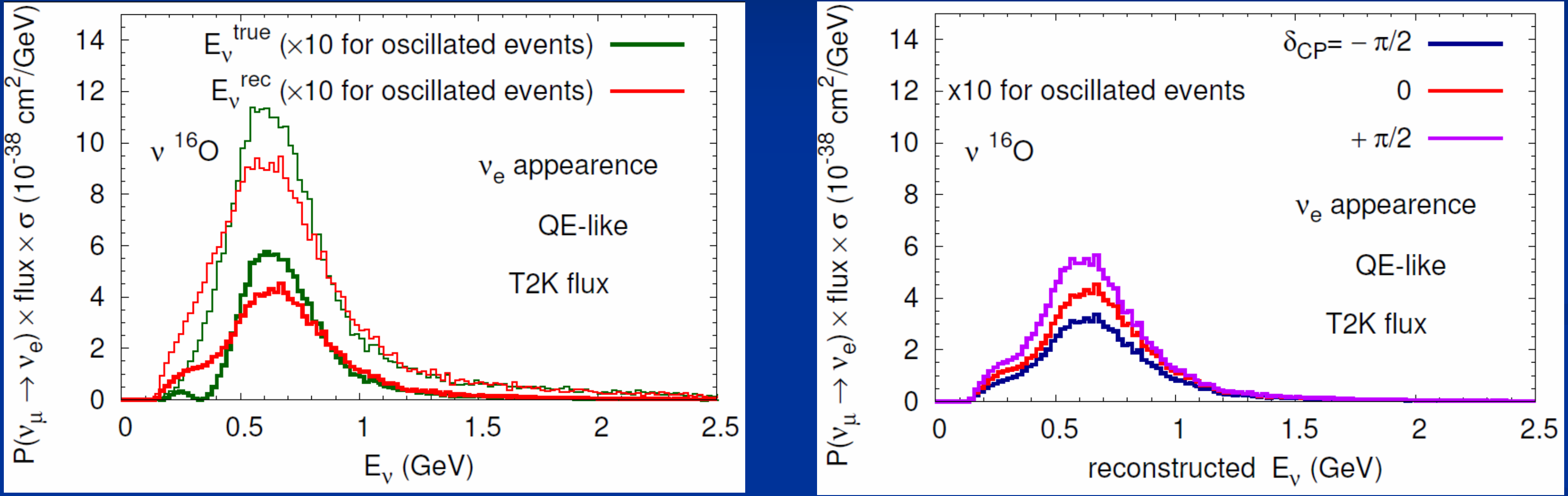
Energy Reconstruction

- Need neutrino energy to extract neutrino mixing angles and δ_{CP}, but how to get it??

- Only way: from the final state!
  → Need cross sections for initial interaction *and* final state interactions

Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps



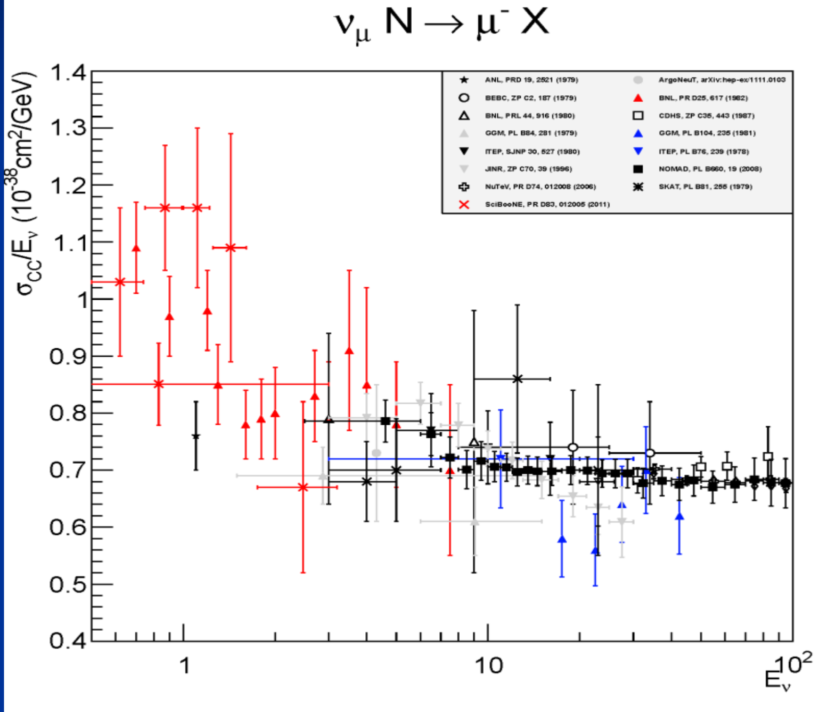
Uncertainties due to energy reconstruction as large as δ_{CP} dependence

Cross Sections

Neutrino Cross Sections: Nucleus

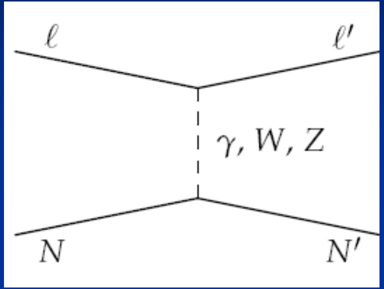
- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe
- Cross sections on the *nucleus*:
  - QE + final state interactions (fsi)
  - Resonance-Pion Production + fsi
  - Deep Inelastic Scattering → Pions + fsi
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production

Neutrino-Nucleon Cross Sections

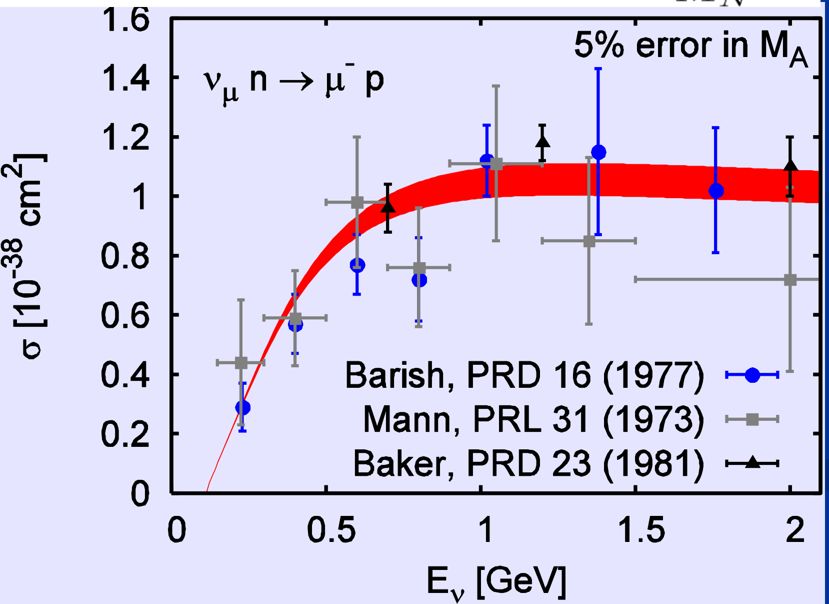


Experimental error-bars directly enter into nuclear cross sections and limit accuracy of energy reconstruction

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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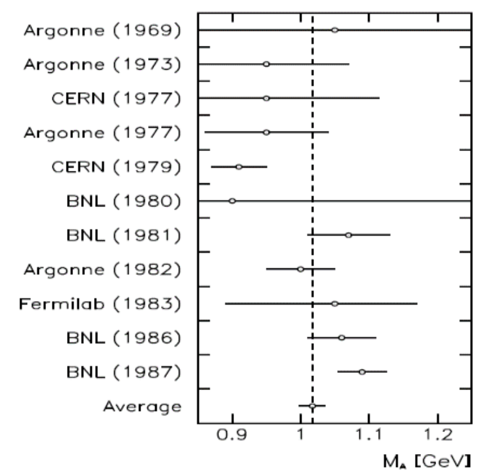
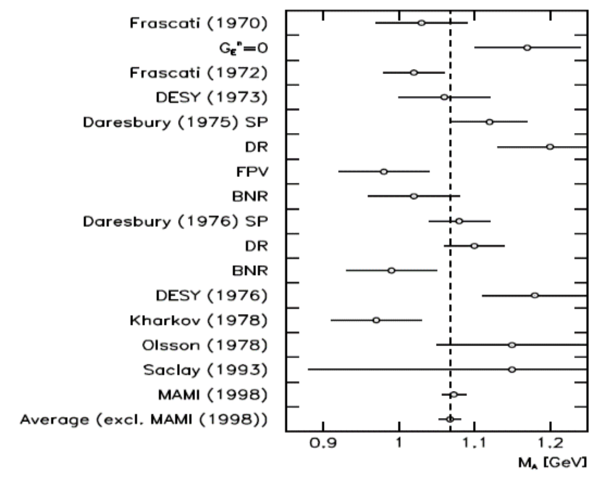
Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data

Bernard et al, J.Phys. G28 (2002) R1-R35





$M_A \cong 1.02$ GeV world average

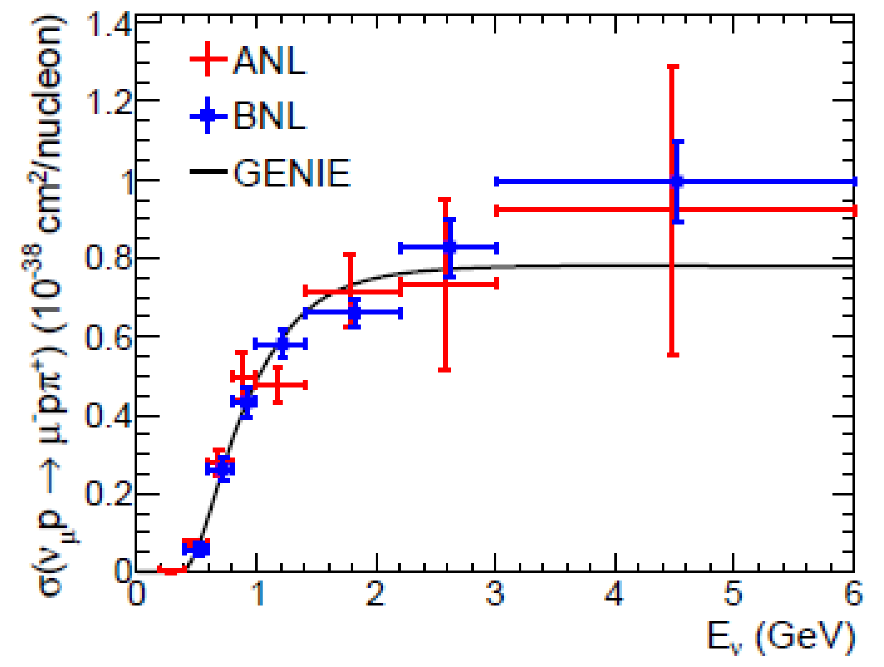
$M_A \cong 1.07$ GeV world average

Are there still neutrino generators out there with $M_A = 1.3$ GeV???

Pions

- Pion production amplitude
  = resonance contrib + background (Born-terms)
- Resonance contrib
  - *V* determined from e-scattering (MAID)
  - *A* from PCAC ansatz
- Background:
  - Up to about Δ obtained from effective field theory
  - Beyond Δ unknown
  - 2 pi BG totally unknown

Pion Production



Reanalysis of BNL data (posthumous flux correction) by T2K group:

C.Wilkinson et al,

Phys.Rev. D90 (2014) no.11, 112017

Agrees with earlier findings in
Graczyk et al, Phys.Rev. D80 (2009) 09300
Lalakulich et al, Phys.Rev. D82 (2010) 0930

10 – 15 % uncertainty in pion production cross sections

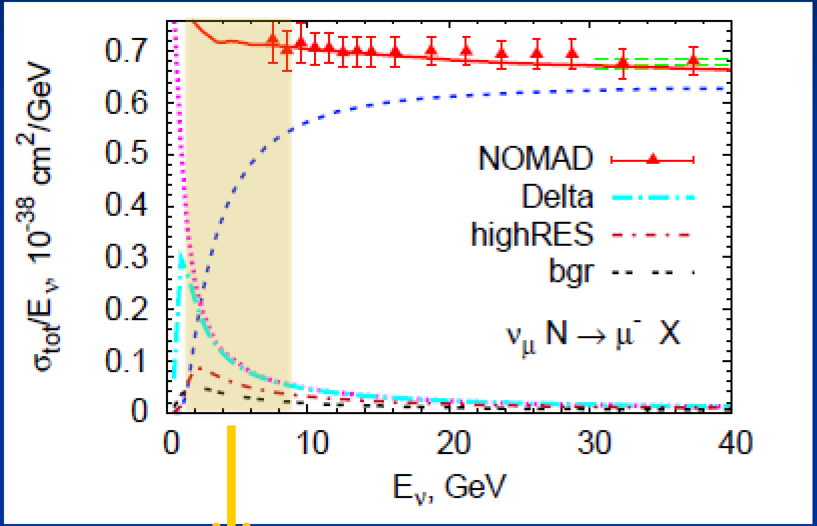
Pion production: Resonance

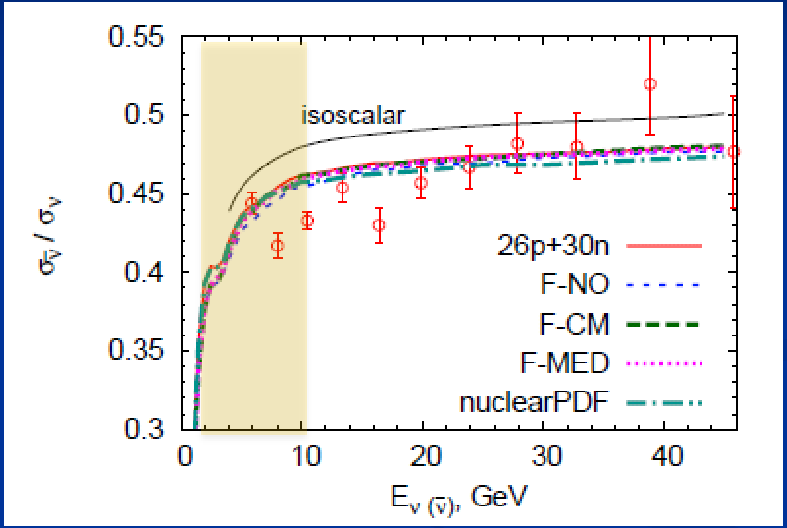
- pion production dominated by **P_{33}(1232) resonance**:

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

- **C^V** from electron data (MAID analysis with CVC)
- **C^A** from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

SIS – DIS by PYTHIA





Shallow Inelastic Scattering,

interplay of different reaction mechanisms

→ Ambiguity to switch from one mechanism to the other

Lalakulich et al, Phys.Rev. C86 (2012) 014607, recently measured by MINERvA

First Conclusion

- Uncertainties on elementary cross sections are (too) large
- Need new data on H and D to pin down the elementaries
- Data in the BNB would give info on QE and pion production

Energy Reconstruction

- Need neutrino energy, but how to get it??

  Only way: from the final state!

Energy-Reconstruction

- Generators are used to construct ‚Migration Matrices'
to go from reconstructed (measured) final-state energies to true incoming energies
- How good are these generators?? How well are they founded in Nuclear Physics?

Generators describe νA interactions?

- Take your favorite neutrino generator (GENIE, NEUT, …):
  „a good generator does not have to be right, provided it fits the data“
- Indeed, all of these generators neglect from the outset:
  - Nuclear binding
  - Final state interactions in nuclear potential
  - Not even the same ground states for different processes
- Generators are patchworks of undocumented physics and algorithms, have a long history, so long that ingredients are forgotten

Time for new, getter generators!

νA Reaction

- General structure: **approximately** factorizes

full event (four-vectors of all particles in final state)

$$\cong$$

initial interaction *x* final state interaction

↙ ↘

Determines inclusive X-section

Determines the final state particles

Motivation for GiBUU

- Need the full event for energy reconstruction
- Need to ‚compute backwards‘ from final state to initial incoming neutrino energy
- Need initial neutrino-nucleon interactions and hadron-hadron final state interactions
- Need to do this in the energy range 0 – 30 GeV

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- GiBUU was constructed with the aim to encode the „best possible“ theory
- „BEST POSSIBLE“ requires
  - All neutrino energies, -> relativistic from outset, includes resonances and DIS
  - All targets, all channels
  - Not just inclusive X-sections, but full events
  - Reasonable bound nuclear ground states

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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
- **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!

→ Perfect test for final state interactions

GiBUU Ingredients

- GiBUU groundstate from energy-density functional, supplemented by p-A data for momentum dependence of mean field potential
- Momentum distribution from local Thomas Fermi

→ Nucleons are bound and Fermi-moving

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Initial interactions:*
  - Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
  - Initial interactions calculated by summing over interactions with all bound, Fermi-moving nucleons
  - 2p2h from electron phenomenology
- *Final state interaction:*
  - propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, fully relativistic (off-shell transport possible).
    Initial and final interactions come from the same Hamiltonian.
    CONSISTENCY of inclusive and semi-inclusive X-sections
- Calculations give final state phase space distribution of all particles, four-vectors of all particles → generator

2p-2h Interactions

- **Assume**: 2p2h transverse, structure function W_1 for electrons from experimental fit of MEC contribution by Bosted and Mamyan (arXiv:1203.2262) and Christy (priv. comm.) to world data for $0 < W < 3.2$ GeV and $0.2 < Q^2 < 5$ GeV^2

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2}{Q^4} E'^2 2 \left(\frac{Q^2}{2\vec{q}^{\,2}} \cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2} \right) W_1(Q^2, \omega)$$

- Transversity established around 1990, Ericsson, Marteau

2p2h excitations: from electrons to neutrinos

- 2p2h: purely transverse, response from e-scattering

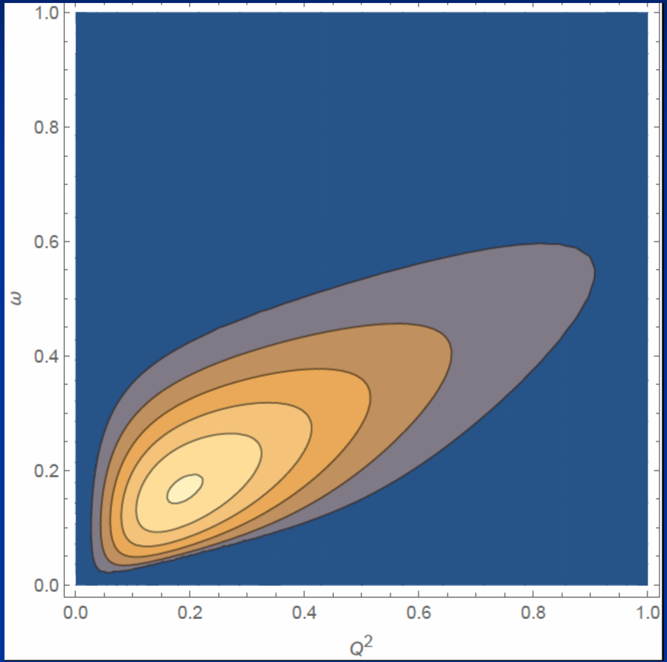
$$
\begin{aligned}
\frac{d\sigma}{d\Omega dE'} = \; & \frac{G^2}{2\pi^2}E'^2\left[\frac{Q^2}{\vec{q}^{\,2}}\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\cos^2\frac{\theta}{2}\right.\\
& +2\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}\\
& \left.\pm 2\frac{E+E'}{M}G_A G_M R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}\right]
\end{aligned}
$$

from: Martini et al.

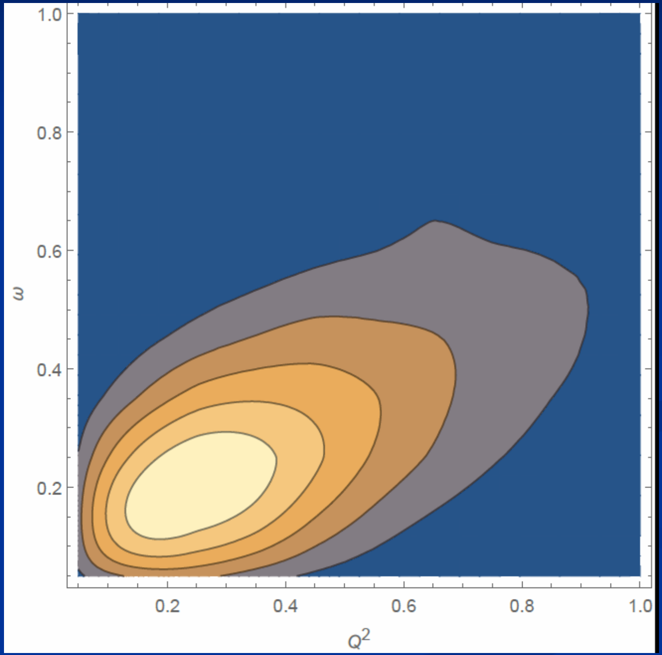
$R_{\sigma\tau} \sim W_1$ from electron scattering

Same transverse response in V + A as in $V \cdot A \sim W_1$, Walecka 1975

2p2h Q^2-ω Distribution for 2p2h



W_1



ddiff cross section, MINERvA flux

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Final state interaction:* propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, not just MC
- Fully relativistic. Initial and final interactions come from the same Hamiltonian. → Consistency of inclusive and semi-inclusive X-sections
- Calculations give the final state phase space distribution of all particles, four-vectors of all particles → generator

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator**

  based on a BM solution of Kadanoff-Baym equations
- Physics content and details of implementation 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
- Code from gibuu.hepforge.org, new version GiBUU 2017

  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

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

Spectral Function in GiBUU

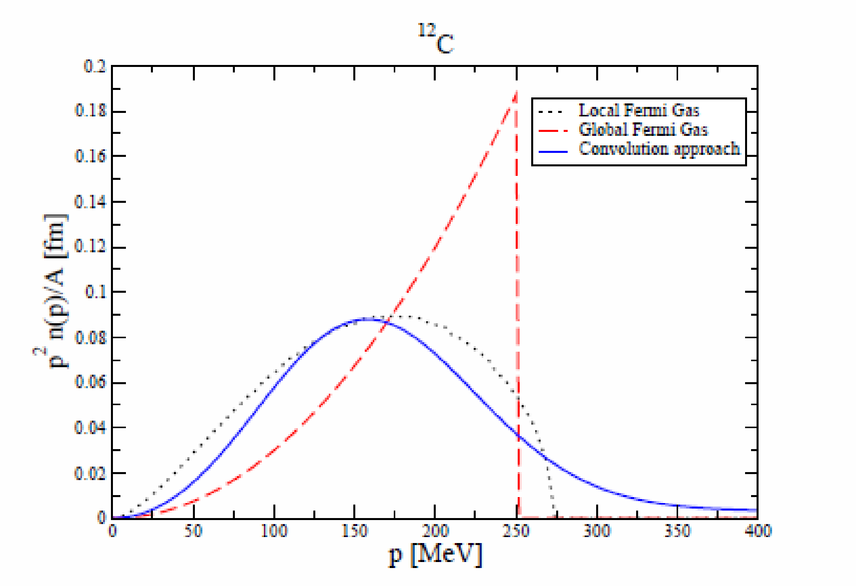
$$P_h(\mathbf{p},E) = \int_{NV} \mathrm{d}^3x \left[\Theta(p_F(\mathbf{x}) - \mathbf{p})\, \delta\left(E + T_p + V(\mathbf{x},\mathbf{p})\right)\right]$$

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

Nuclear Groundstate



From:
Alvarez-Ruso, Hayato, Nieves

GiBUU uses Local Fermi Gas + Nucleon mean field potential

Kadanoff-Baym Equations Derived

- Start with one-body Green's functions, merge all many-body correlations into a selfenergy
- Make a gradient approximation: slow changes -> applicable only to larger nuclei (> C12)

Quantum-kinetic Transport Theory

$$\overbrace{\mathcal{D}F(x,p)}^{\text{On-shell drift term}} - \overbrace{\mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}}}^{\text{Off-shell transport term}} = \overbrace{C(x,p)}^{\text{Collision term}} \ .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g\,\underset{\substack{\uparrow\\ \text{Phase space distribution}}}{f}(x,p)\,\mathcal{P}(x,p) \longleftarrow \text{Spectral function}$$

Initial Conditions for KB Eqs

- Quasiparticle approximation (on-shell, but not free):

$$F(x,p) = 2\pi g f(x,\mathbf{p})\,\delta(p_0 - E)$$

- Initial condition:

$$f(\mathbf{x},0,\mathbf{p}) = \frac{1}{(2\pi)^3}\int e^{-i\mathbf{p}\cdot\mathbf{s}}\rho\left(\mathbf{x}-\frac{\mathbf{s}}{2},\mathbf{x}+\frac{\mathbf{s}}{2}\right)d\mathbf{s}$$

determined by one-particle density matrix (could be obtained from any good theory)

BM Simplification

Problem: ‚backflow‘ term does not directly depend on *F*

Botermans-Malfliet simplification for equilibrium, correction terms are of higher order in gradients

$$\tilde{\Sigma}^{<}_{\mathrm{eq}}(x,p) = \mathrm{i}\Gamma_{\mathrm{eq}}(x,p) f_{\mathrm{eq}}(x,p),$$

$$\tilde{\Sigma}^{>}_{\mathrm{eq}}(x,p) = -\mathrm{i}\Gamma_{\mathrm{eq}}(x,p)[1 - f_{\mathrm{eq}}(x,p)]$$

$$\Gamma(x,p) = -2\mathrm{Im}\tilde{\Sigma}^{ret}(x,p)$$

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

BM term now ~ Γ, controls off-shell transport

Collision term

$$
\begin{aligned}
C^{(2)}(x,p_1) \quad = \quad & C^{(2)}_{\text{gain}}(x,p_1) - C^{(2)}_{\text{loss}}(x,p_1) = \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{\mathrm{d}^4\mathrm{p}_2}{(2\pi)^4 2p_2^0} \int \frac{\mathrm{d}^4\mathrm{p}_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{\mathrm{d}^4\mathrm{p}_{2'}}{(2\pi)^4 2p_{2'}^0} \\
& \times (2\pi)^4 \delta^{(4)}\left(p_1 + p_2 - p_{1'} - p_{2'}\right) \overline{|\mathcal{M}_{12\to1'2'}|^2} [F_{1'}(x,p_{1'}) F_{2'}(x,p_{2'}) \overline{F}_1(x,p_1) \\
& \times \overline{F}_2(x,p_2) - F_1(x,p_1) F_2(x,p_2) \overline{F}_{1'}(x,p_{1'}) \overline{F}_{2'}(x,p_{2'})]
\end{aligned}
$$

with

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

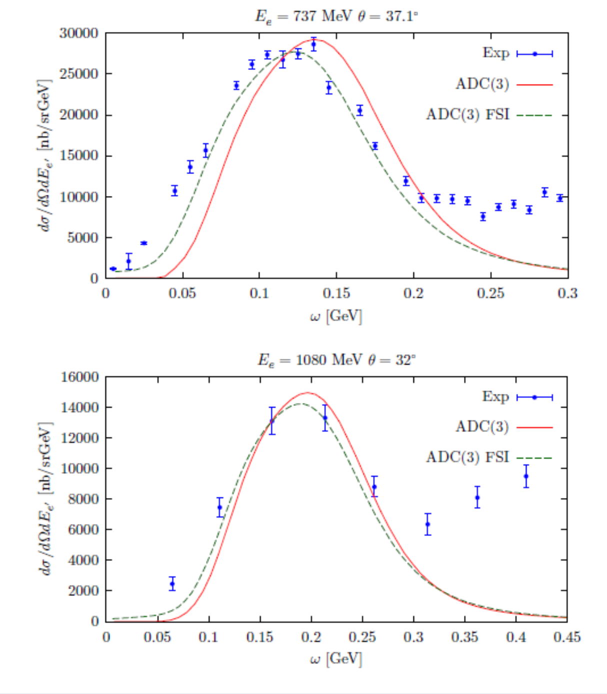
Inclusives

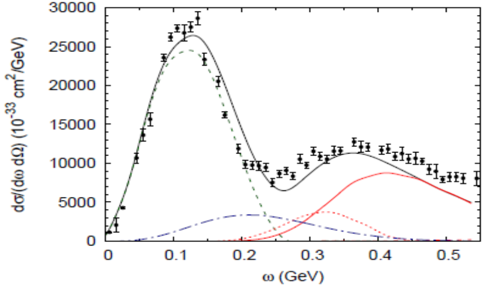
- Necessary Test: inclusive electron data

Compare with ab initio

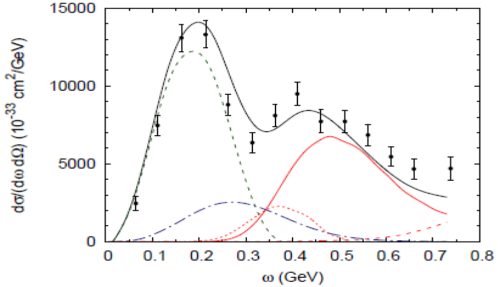
arXiv:1803.00825

Rocco, Barbieri





(b) E= 0.737 GeV, θ = 37.1 degrees

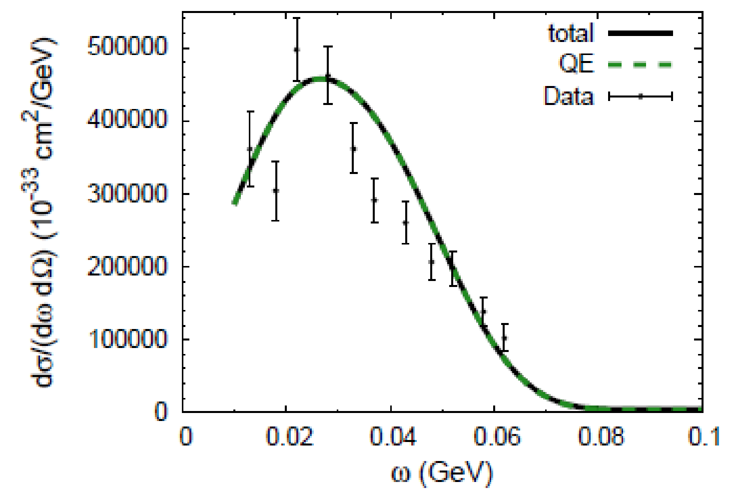


(d) E = 1.080 GeV, θ = 32 degrees

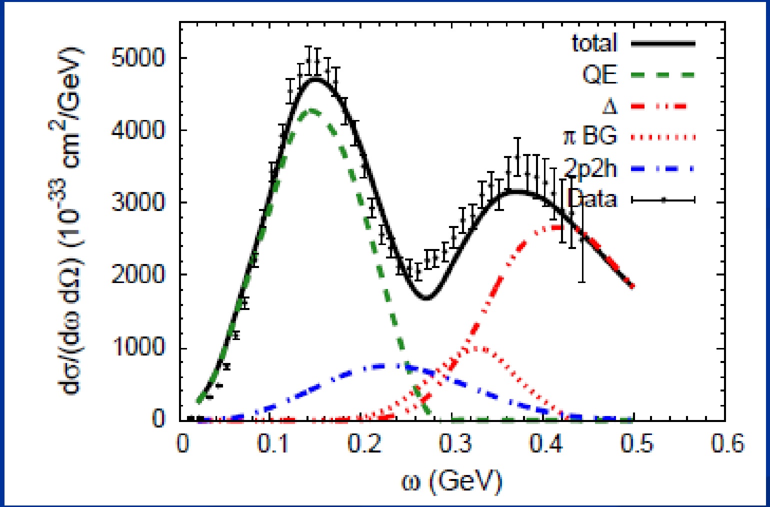
GiBUU

Inclusive QE Electron Scattering

- a necessary check for any generator development



0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2

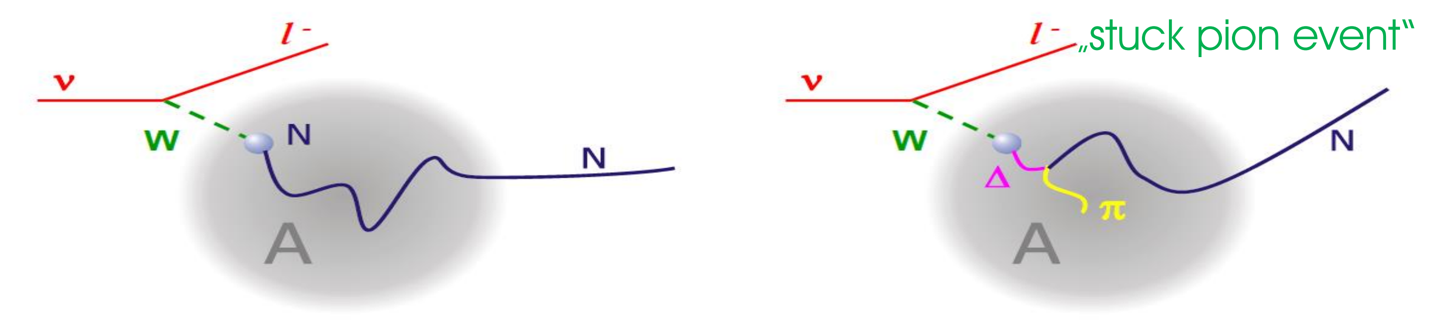


0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Now Neutrinos

- Test with data for muon and electron neutrinos, at different energy regimes
- Test for both QE and pion production
- NO tune, all results obtained with code ‚out of the box'

Final State Interactions in Nuclear Targets

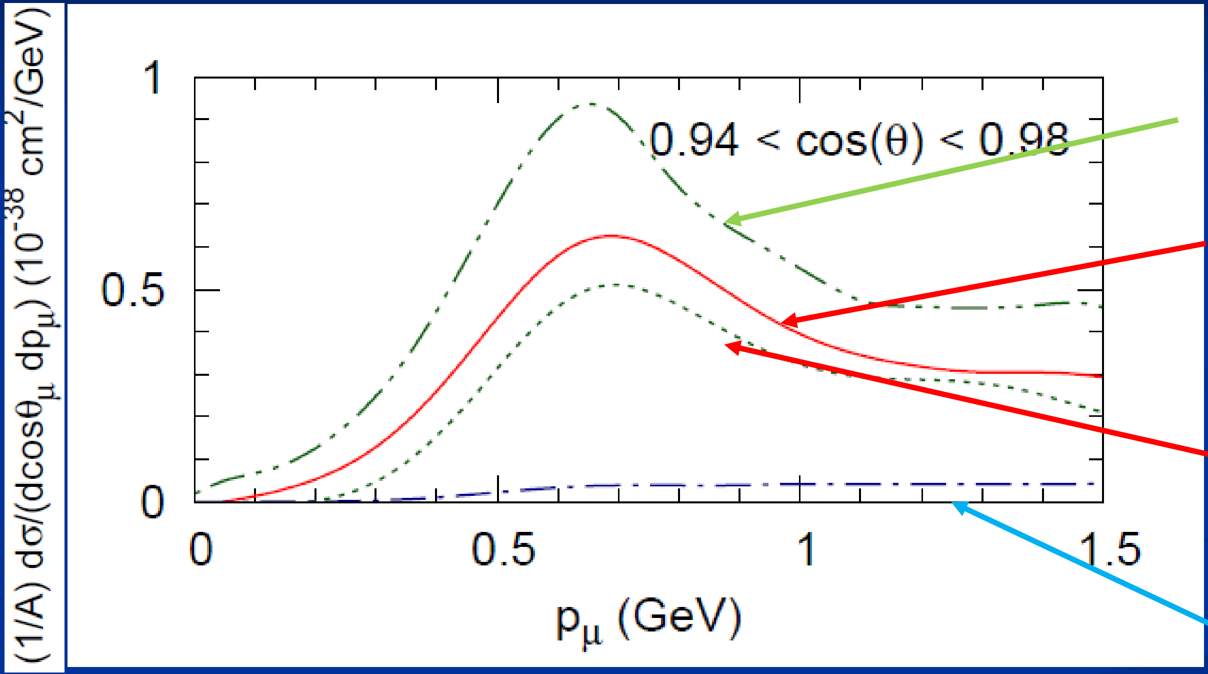


„stuck pion event“

Complication to identify QE, entangled with π production

Nuclear Targets (MiniBooNE, T2K, DUNE, NOvA, Minerva, ….)

Reaction Mechanisms at T2K



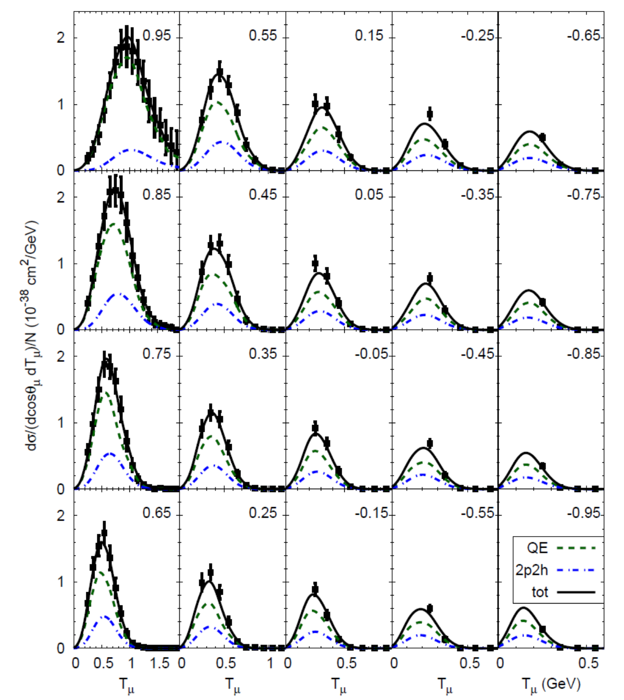
total inclusive

0-pion events

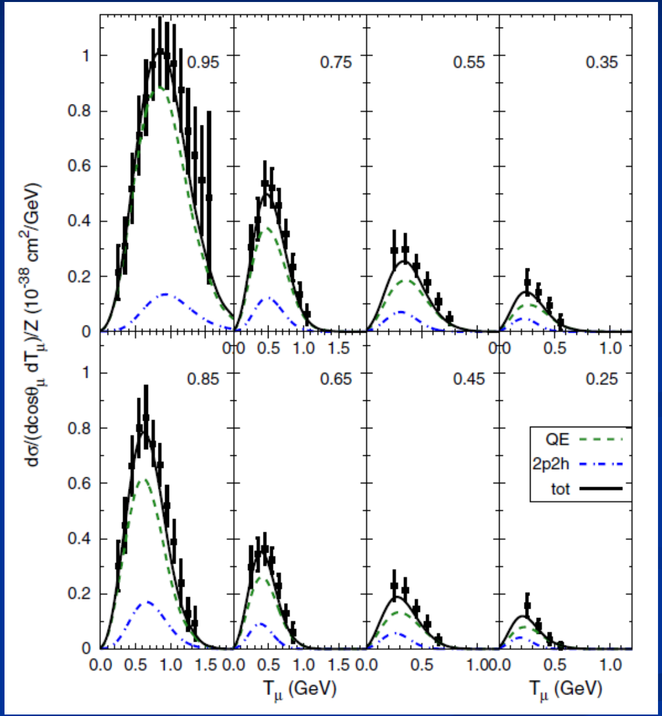
QE + 2p2h

2p2h

Inclusive 0-Pion Data (MiniBooNE)



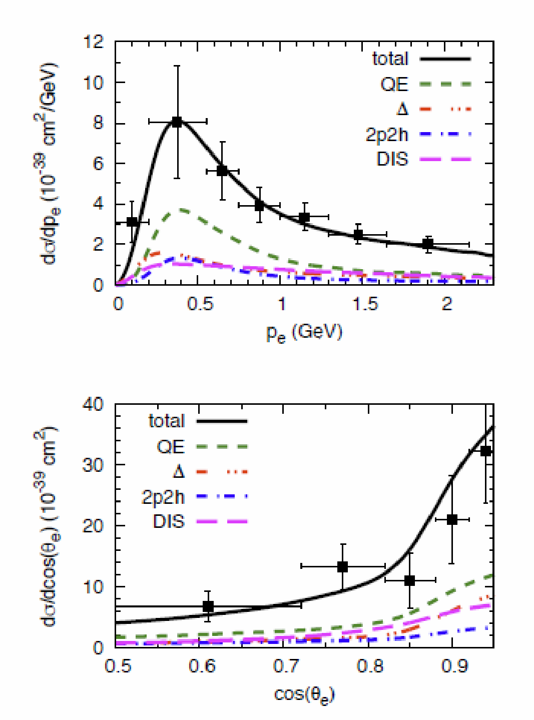
neutrino

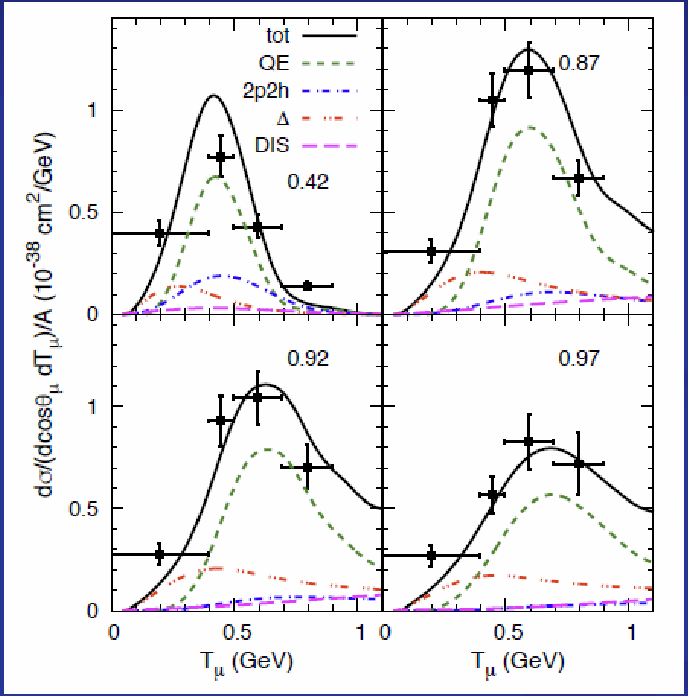


antineutrino

Comparison with T2K incl. Data

T2K, ν_e





T2K, ν_μ

Agreement for different neutrino flavors

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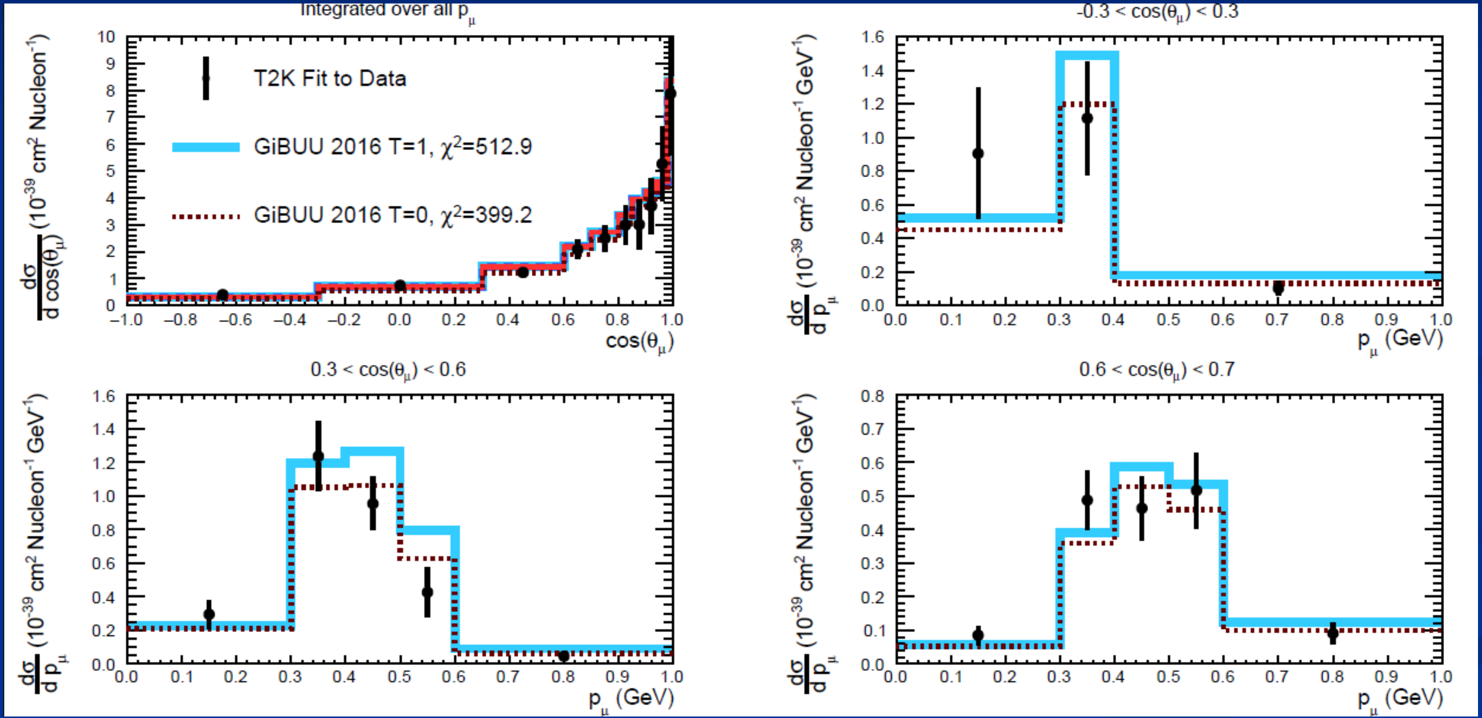
T2K, 0 p > 500 MeV



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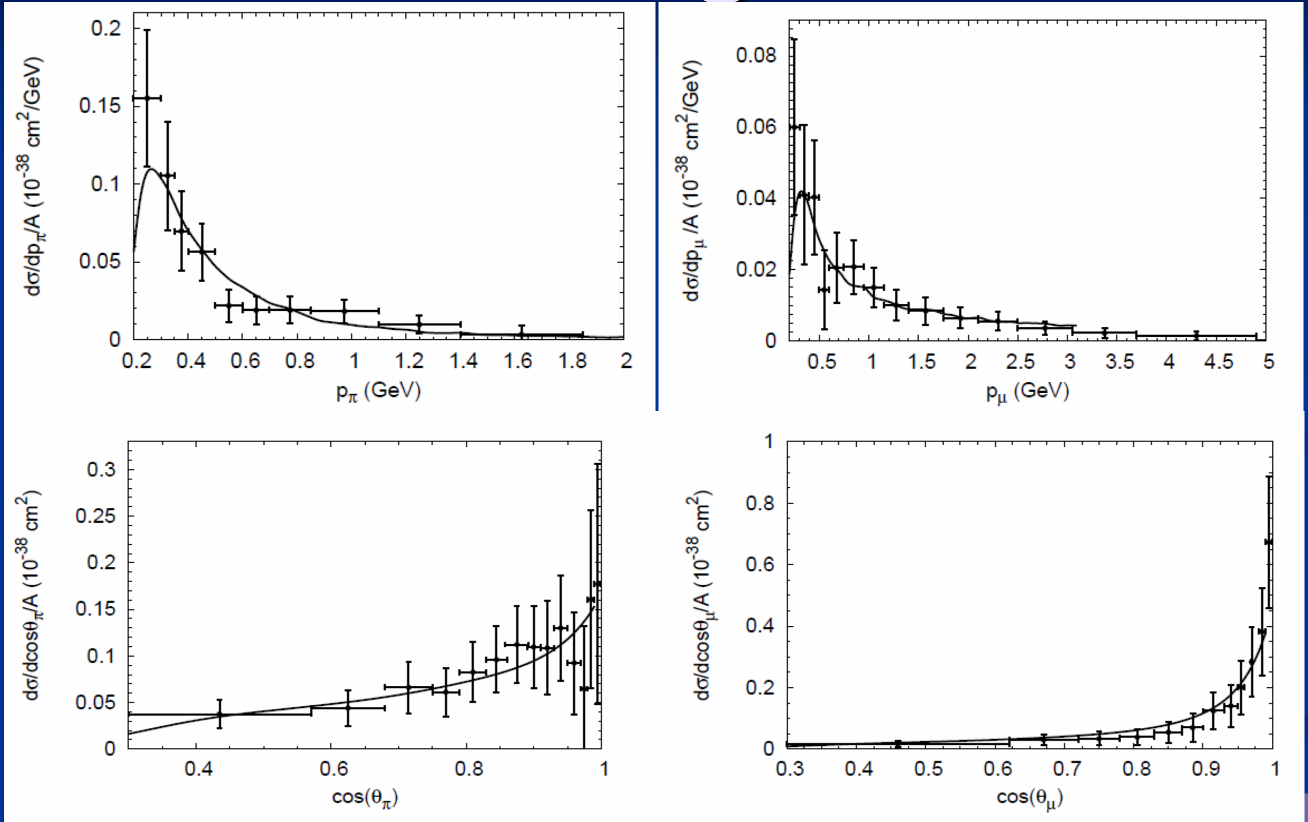
Pions

- Pions are an essential part of the cross section
  - For total signal
  - For ‚zero-pion‘ events

- → Pions have to be under control!

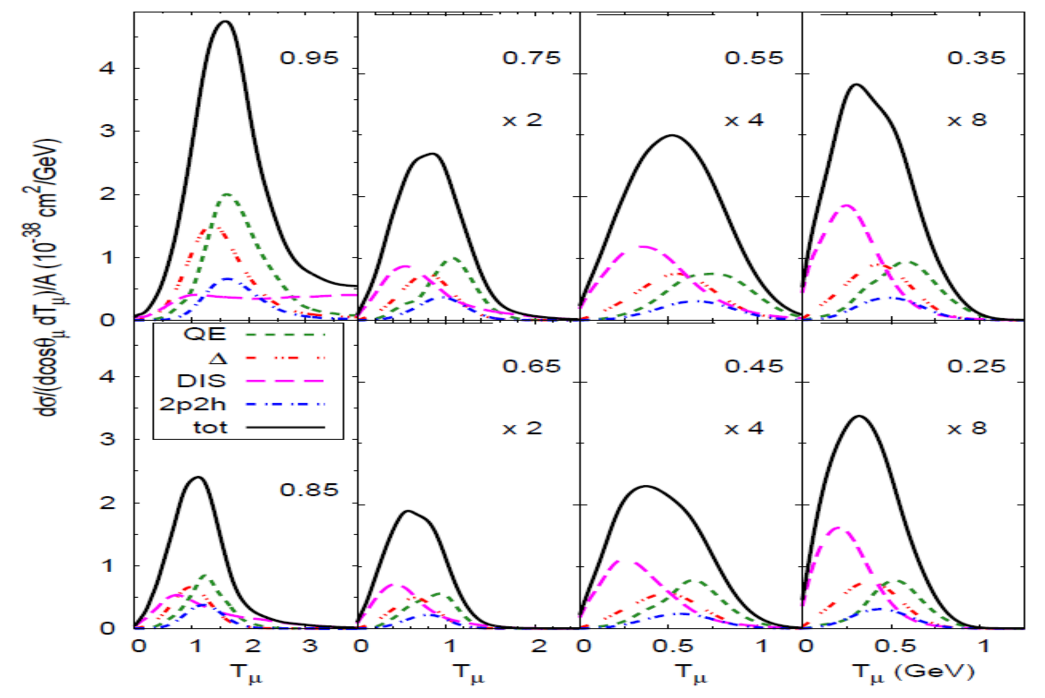
Pions at lower energies: T2K ND280



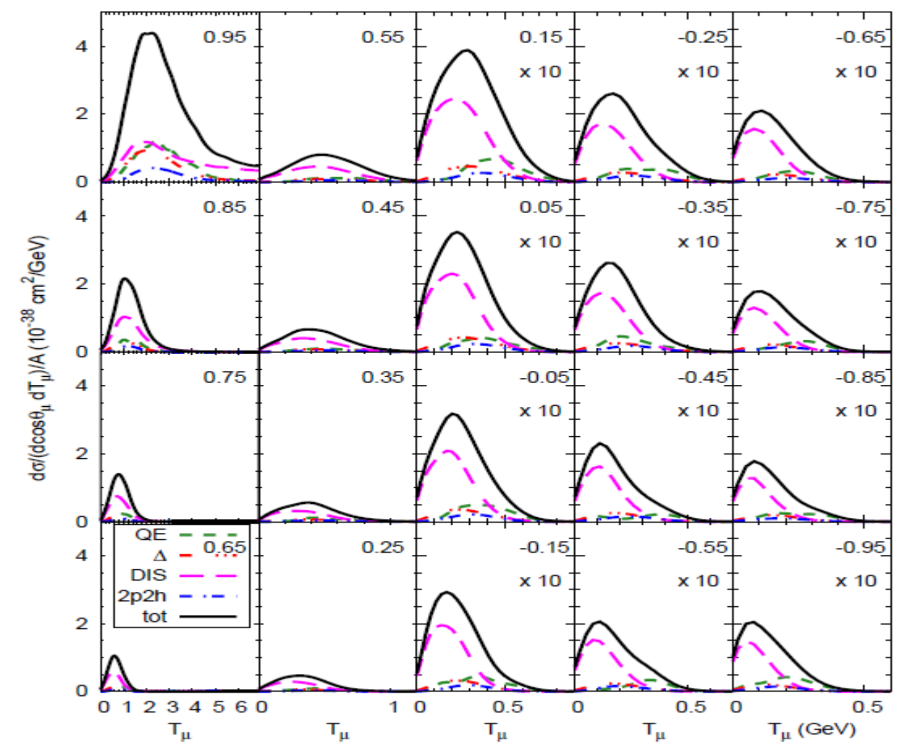
H_2O

Now Predictions

NOvA


dσ/(dcosθ_μ dT_μ)/A (10^-38 cm^2/GeV)
0.95
0.75
x 2
0.55
x 4
0.35
x 8
0.85
0.65
x 2
0.45
x 4
0.25
x 8
QE
Δ
DIS
2p2h
tot
T_μ
T_μ
T_μ
T_μ (GeV)
0
1
2
3
4

DUNE

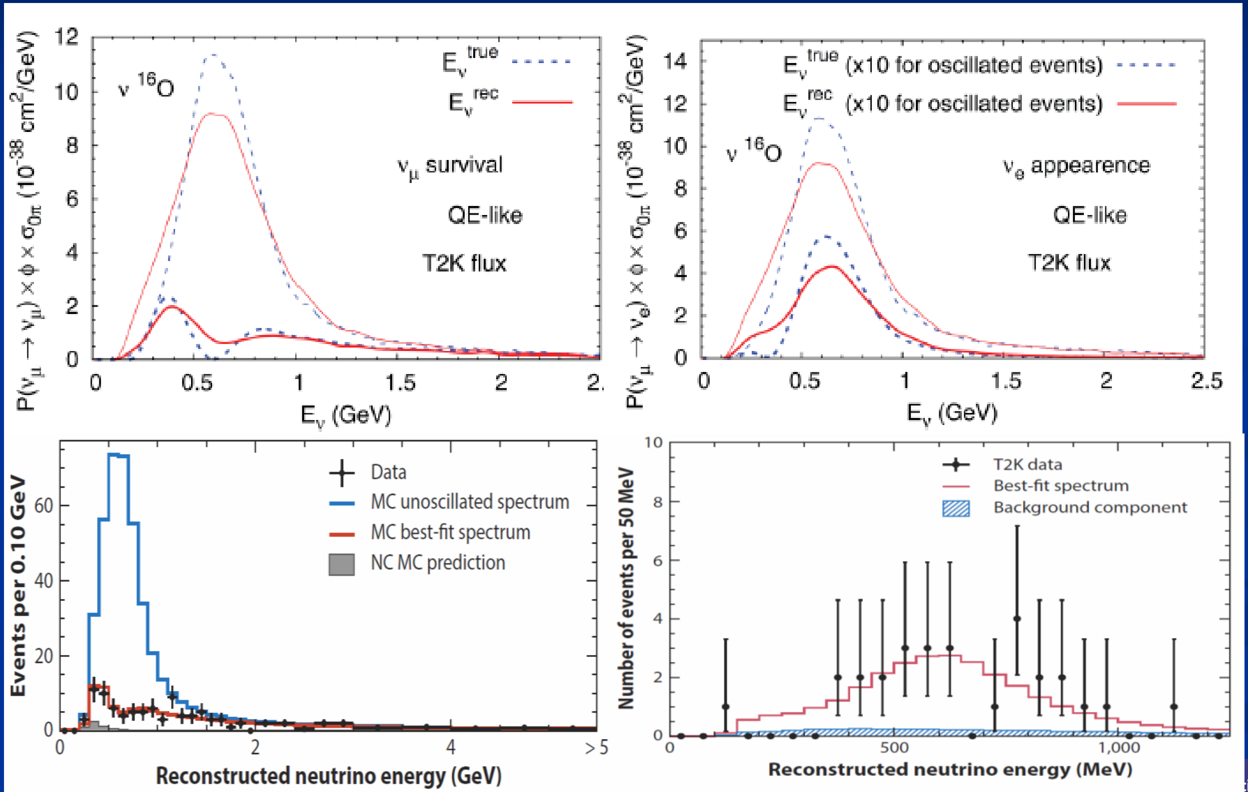


QE and 2p2h are minor components

DIS dominates

Now Influence on Oscillations

Oscillation Signals as F(E_ν)



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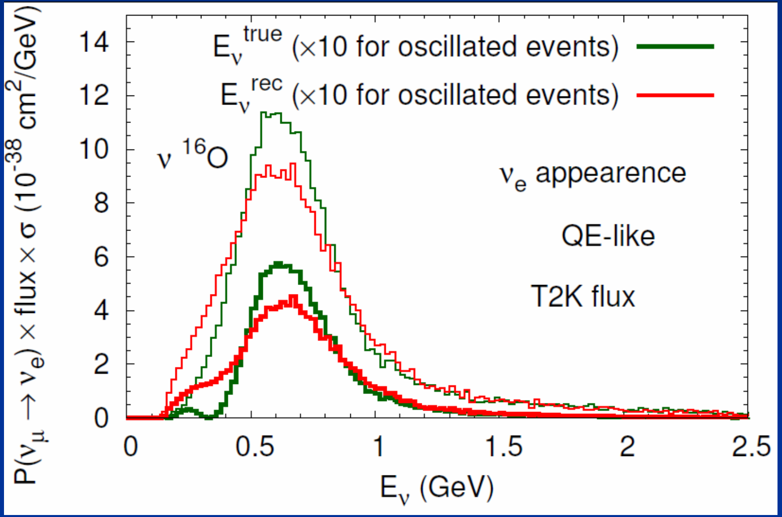
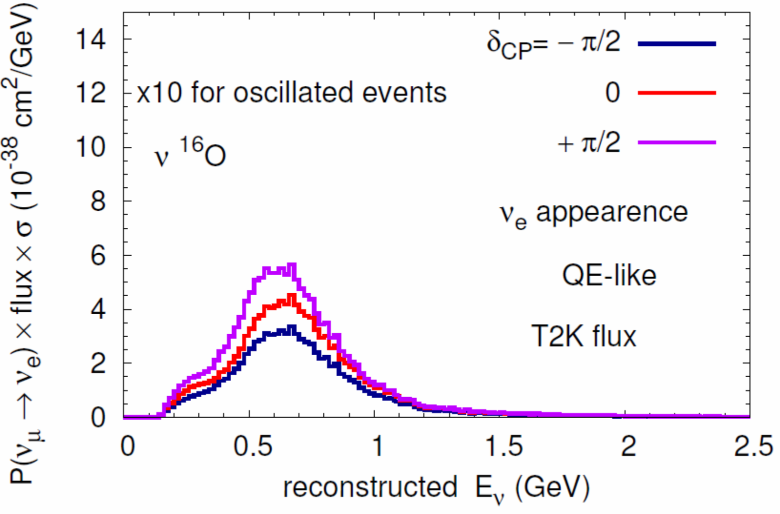
From:

Diwan et al.

Oscillation signal in T2K

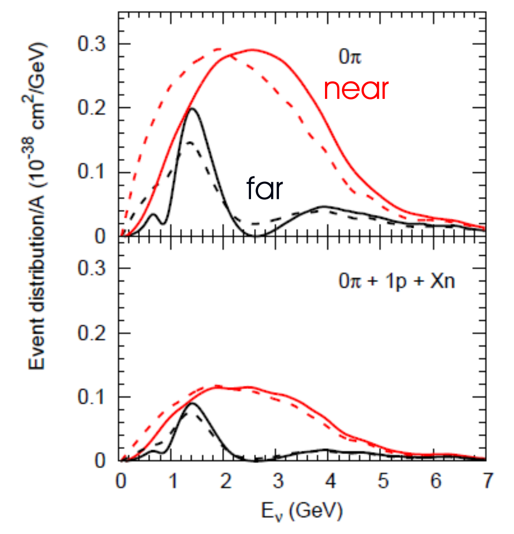
δ_{CP} sensitivity of appearance exps



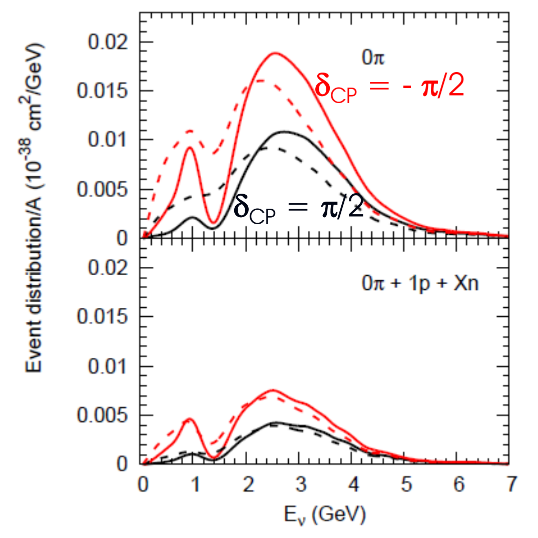


Uncertainties due to energy reconstruction
as large as δ_{CP} dependence

Proton Tagging and Multi-Nucleons



Event rates at near (LBNF) and far detector (DUNE)



δ_{CP} sensitivity at DUNE

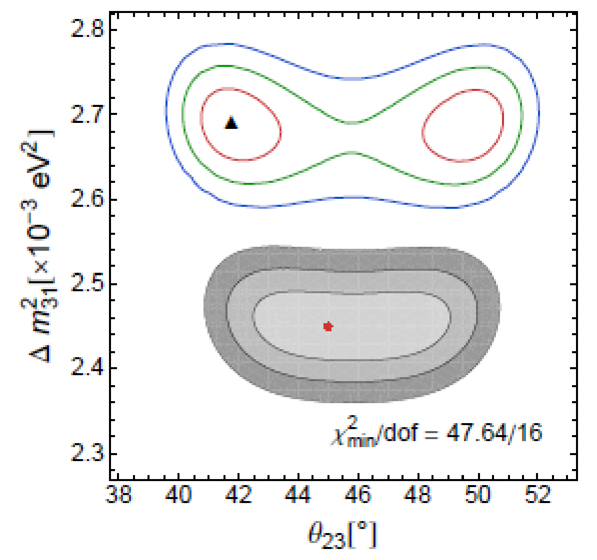
Mosel et al,
Phys.Rev.Lett. 112 (2014) 151802

Solid: true E
Dashed: reconstructed E

Generator Dependence of Oscillation Parameters

GiBUU-GENIE

GiBUU-GiBUU



From: P. Coloma et al, Phys.Rev. D89 (2014) 073015

Nature: GiBUU
Generator: GENIE

Summary I

- Neutrino energy must be known within about 50 (T2K) or 100 (DUNE) MeV
- Neutrino energy must be reconstructed from final state observations
- Nuclear effects complicate the energy reconstruction
- The larger the step from reconstructed to true energies, the larger is the uncertainty in the oscillation parameters
  → Need good Nuclear Theory

Summary II

- Quantum-kinetic Transport Theory is the (well established, and – in other fields of physics - widely used) method to deal with potentials and binding in non-equilibium processes, allows for off-shell transport
- GiBUU is an implementaton of transport theory
- GiBUU describes, without any tune:
    - Double-differential 0-pion data from MiniBooNE, neutrino and antineutrino
    - Fully inclusive T2K ND280 data for mu- and electron-neutrinos
    - Pions at T2K (water) and MINERvA

What is needed?

- Need reaction studies on *nuclear targets* (MINERvA, T2K ND, NOvA ND, ANNIE, ..) to control many-body effects and fsi
- Need data without ‚generator contamination‘:

  e.g.: no flux cuts, no W cuts, no special reaction mechanism
- Need theory for full events, not just (fully) inclusive.
- Need a dedicated theory support program and a computational physics effort to construct a new, reliable generator for the precision era of neutrino physics

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- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
  4. Mosel et al, Phys.Rev. C96 (2017), 015503
     pion production comparison of MiniBooNE, T2K and MINERvA