Neutrino Interactions and Long-Baseline Experiments

Ulrich Mosel

Institut für Theoretische Physik

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LBL Experiments

- Neutrino Long-Baseline Experiments use Nuclear Targets, H_2O, C, Ar, ···
- →
  Have to understand response of the nucleus to the incoming Neutrino and the final state interactions of outgoing particles
- THIS IS A NUCLEAR PHYSICS PROBLEM

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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."

Low-Energy Nuclear Physics determines response of nuclei to neutrinos

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Nu-Experiments need Event Generators

- *High-energy physicists* like *MC cascade generators*, interactions of free particles, appropriate for free, high-energy interactions
- *Nuclear physicists* have to take care of nucleus and interactions of bound nucleons at lower energies
  → *quantum kinetic transport theory* developed over the last 20 years to deal with such systems, used in QGP physics and supernova neutrino transport, but also in material science

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : Quantum-Kinetic **Theory and Event Simulation** based on Kadanoff-Baym equations
- Physics content : **Buss et al, Phys. Rep. 512 (2012) 1**
- code available : http://**gibuu.hepforge.org**
- **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!

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Quantum-Kinetic Transport Equation

Kadanoff-Baym Equation

Collision term

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

Drift term

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

$$= -\ \mathrm{loss\ term} + \mathrm{gain\ term}$$

$$F(x,p) = 2\pi g f(x,p) A(x,p).$$

Spectral function

Wigner-transformed of 1p propagator

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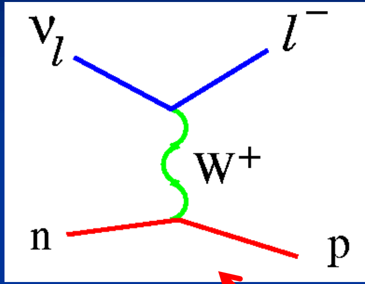
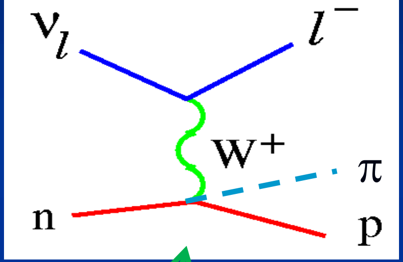
Input: X-sections on Nucleon

Neutrino Cross sections: Nucleon

CCQE



1π



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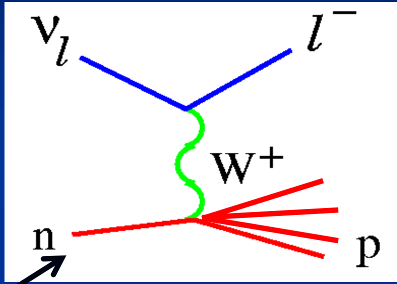
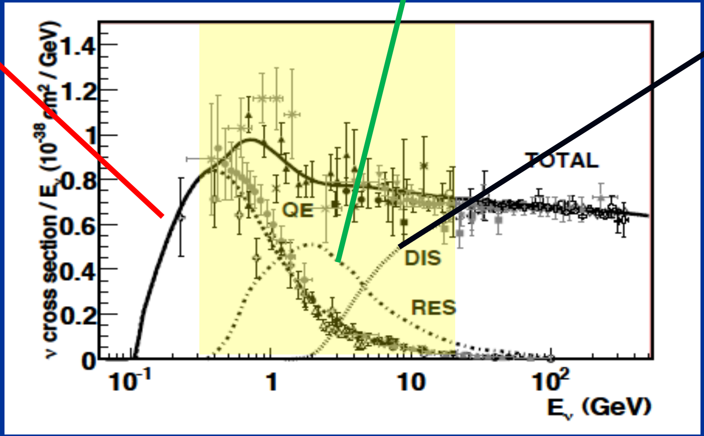
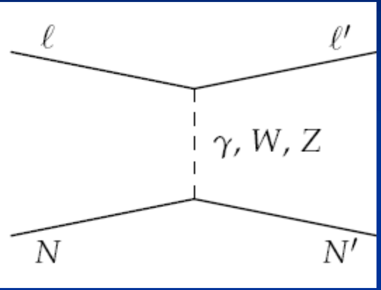




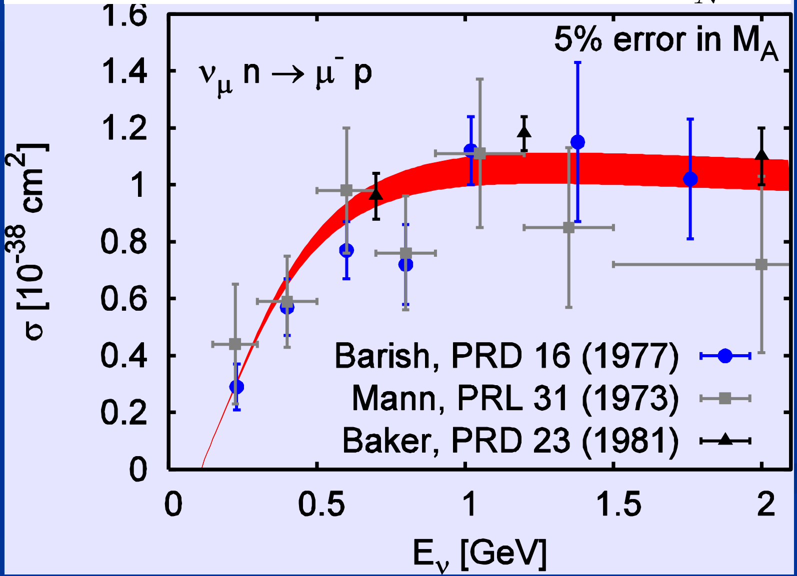
From: J.A. Formaggio, G.P. Zeller

Yellow: energy range of present long-baseline experiments:
Complicated superposition

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

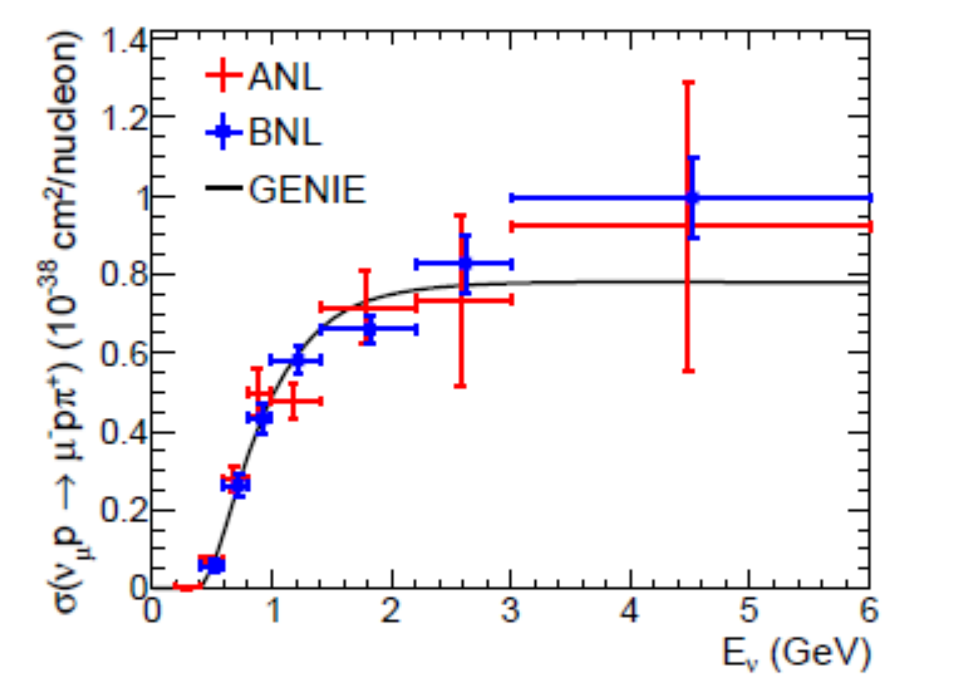
  $F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**

  dipole ansatz for F_A with

  $M_A = 1$ GeV:

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

Pion Production



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

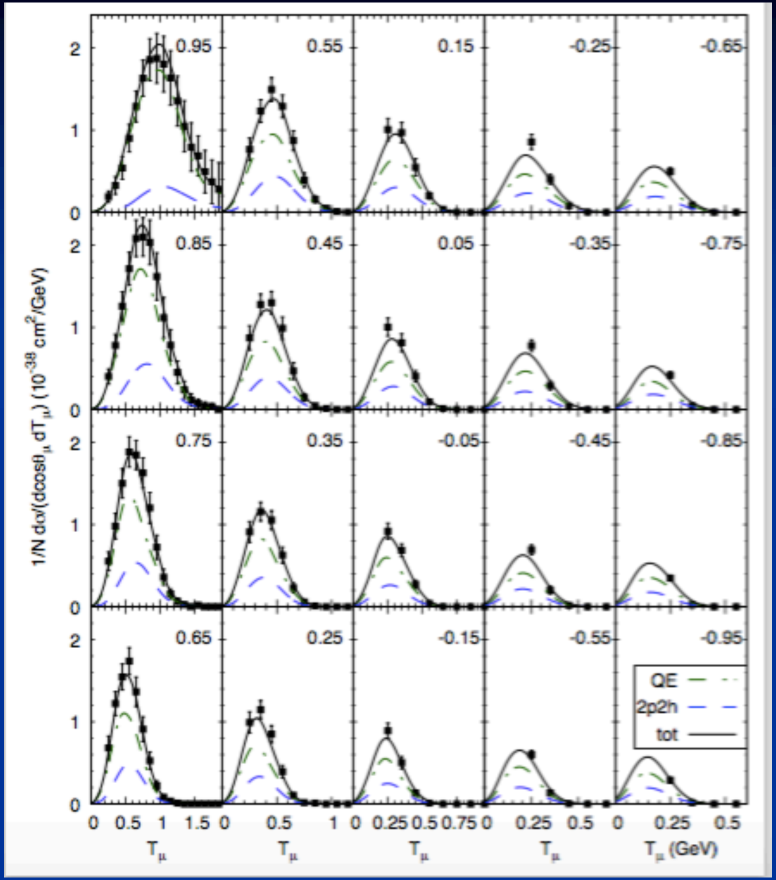
C.Wilkinson et al,

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

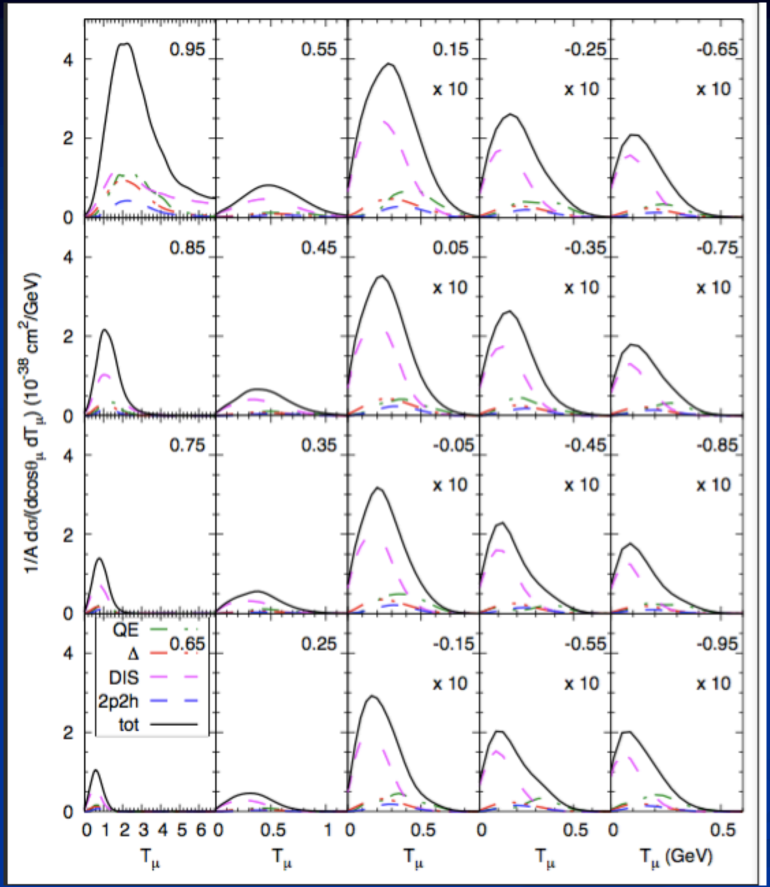
Agrees with earlier findings in
Graczyk et al, Phys.Rev. D80 (2009) 093001
Lalakulich et al, Phys.Rev. D82 (2010) 0930

20 % uncertainty in pion production cross sections

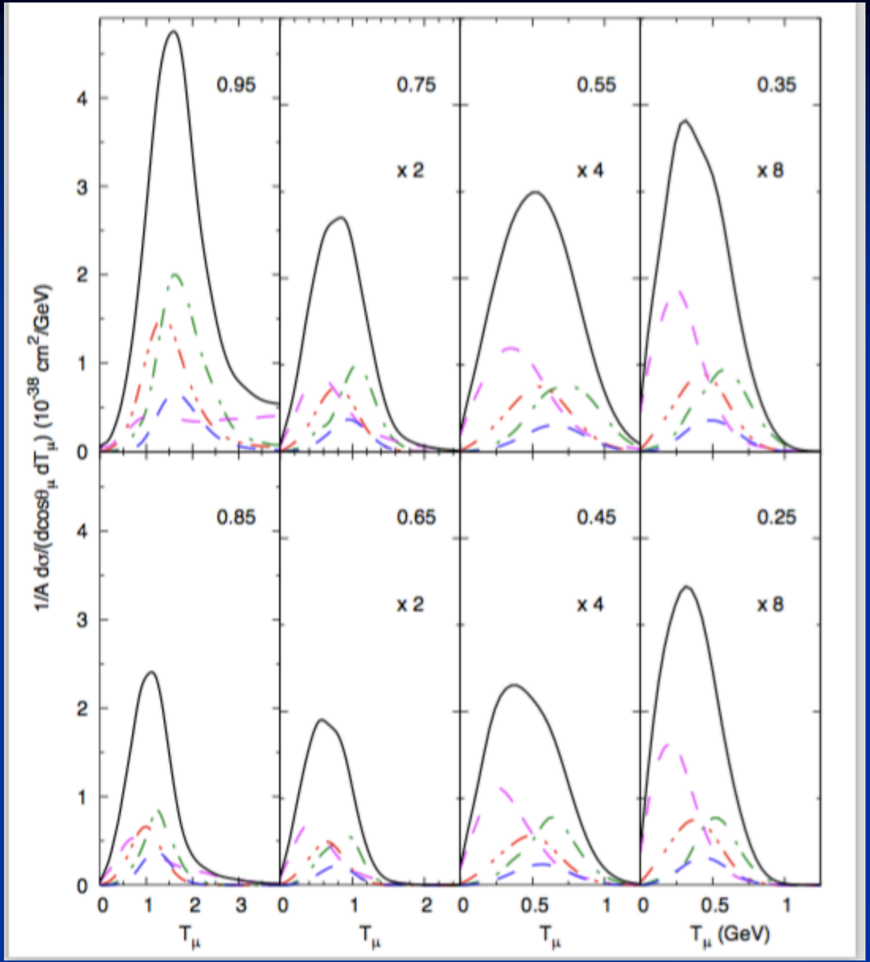
Now to the nucleus: Inclusive



MiniBooNE



DUNE ND



NOvA inclusive X-sections

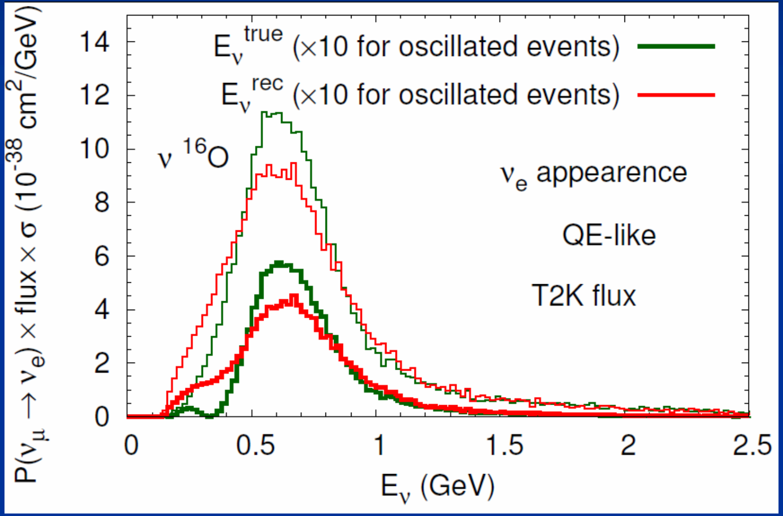
Dominant are
CCQE, Δ and DIS
2p2h much smaller

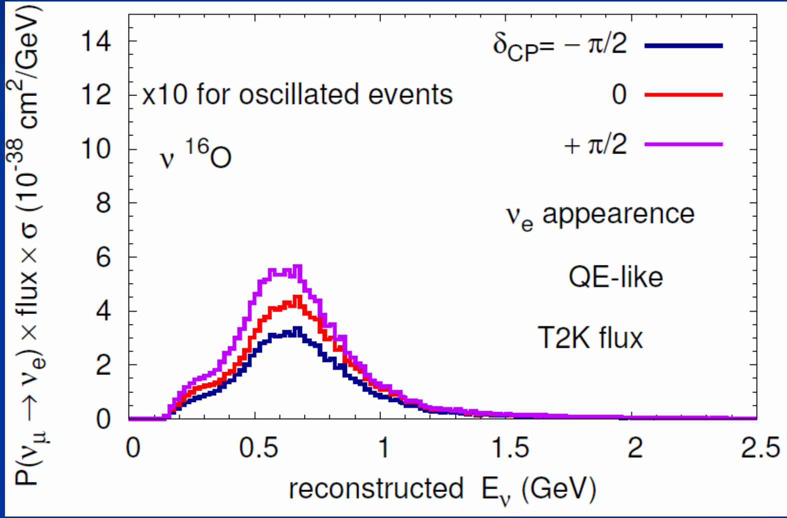
Now to Oscillations

- Must reconstruct neutrino energy
- Here: QE-based method

Oscillation signal in T2K

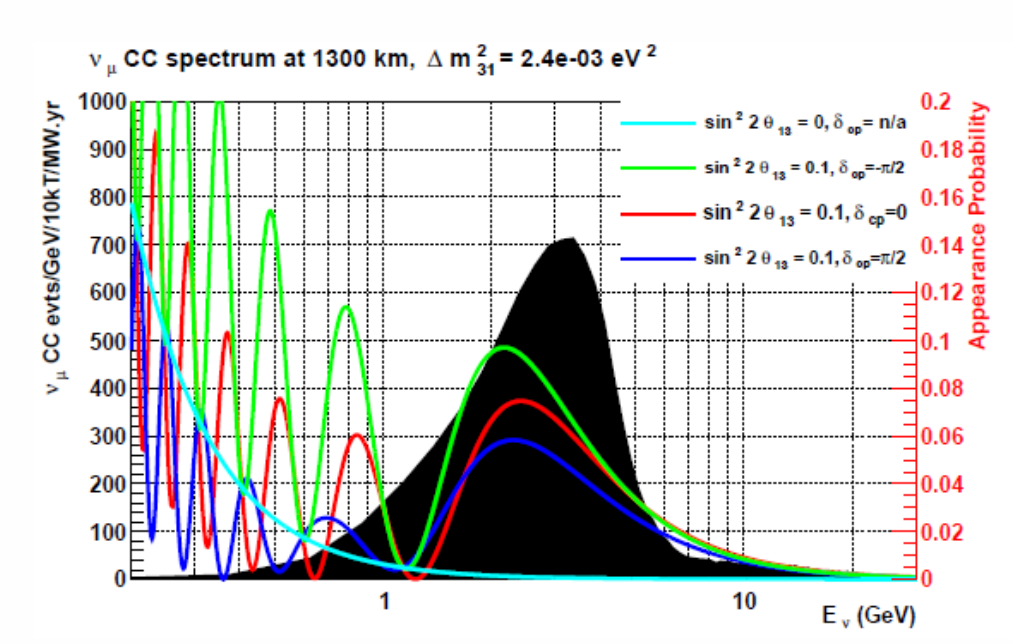
δ_{CP} sensitivity of appearance exps





Uncertainties due to energy reconstruction(left) as large as δ_{CP} dependence (right)

DUNE, δ_{CP} Sensitivity

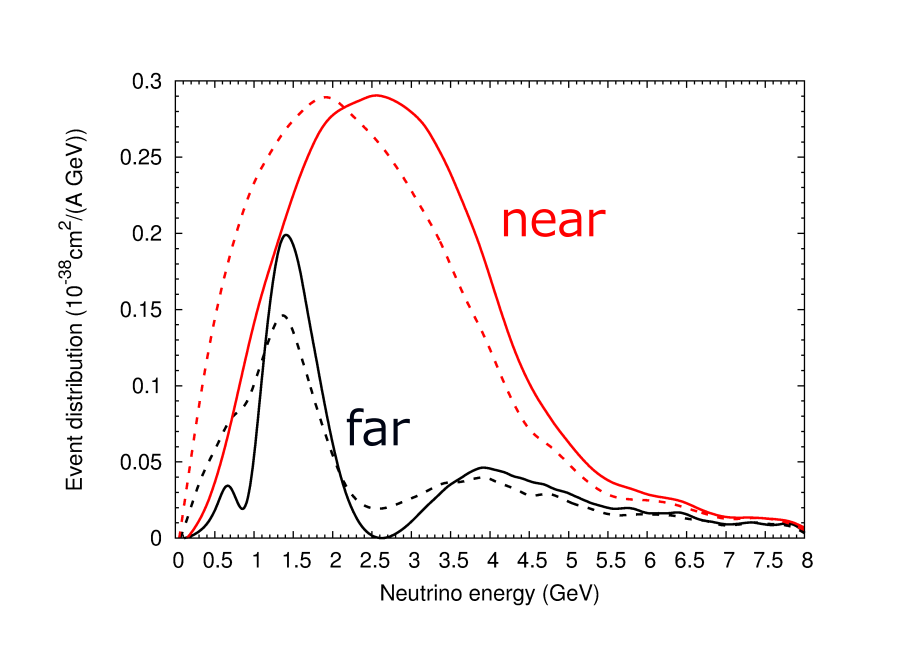


Appearance probability: $P_{\mu \rightarrow e}$

Need energy to distinguish between different δ_{CP}

Need to know neutrino energy to better than about 100 MeV

QE Energy Reconstruction for DUNE



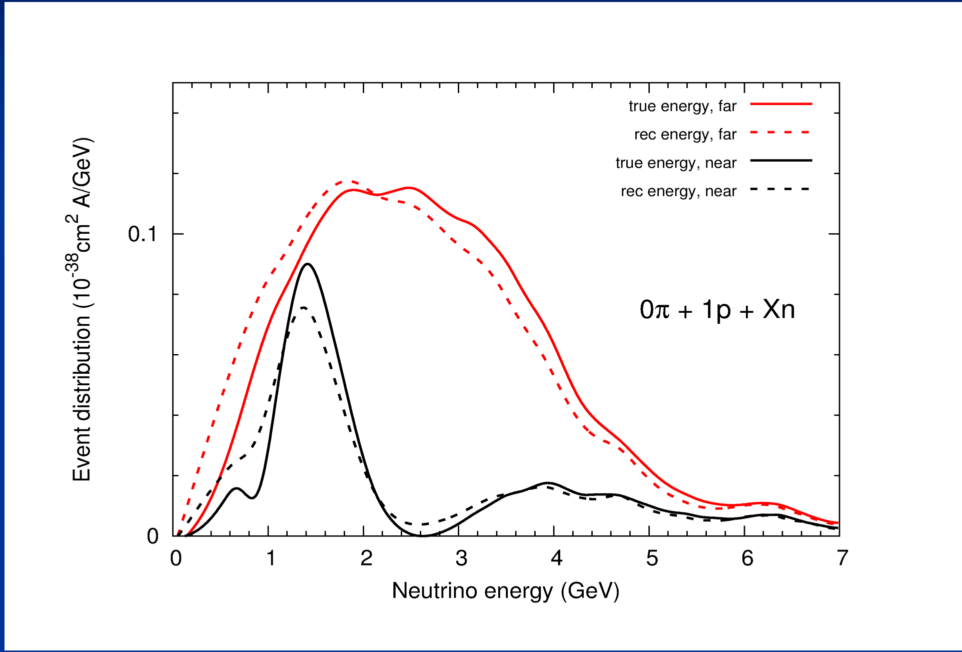
Dashed: reconstructed,
solid: true energy

Muon survival
in 0 pion sample

All calculations from GiBUU
Mosel et al.,
Phys.Rev.Lett. 112 (2014) 151802

Nearly 500 MeV difference between true and reconstructed event distributions → not a useful method

QE Energy Reconstruction for DUNE



Dashed: reconstructed,
solid: true energy

Muon survival in
$0\pi + 1p + Xn$ sample

Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

Summary

- Neutrino-nucleus events are determined by nuclear response and nuclear final state interactions
- Quantum-kinetic transport theory goes beyond MC cascade generators in treating nuclear effects
- Precision era experiments require precision era (new) generators: use best available theory

Literature

- Material in this talk taken from:
  - Gallmeister et al, arXiv:1605.09391
  - Buss et al, Phys. Rep. 512 (2012) 1
  - Mosel et al, Phys.Rev.Lett. 112 (2014) 151802
  - Lalakulich et al, Phys. Rev. C 86, 054606 (2012)

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