Physics of ν-A Interactions

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Neutrino 2018

What is (not) measured in a LBL exp?

- LBL experiments measure only flux-averaged cross sections
- The neutrino energy is not measured
- Oscillation Patterns as function of neutrino energy must be reconstructed → needs nuclear theory and modeling
- Experiments require few % accuracy

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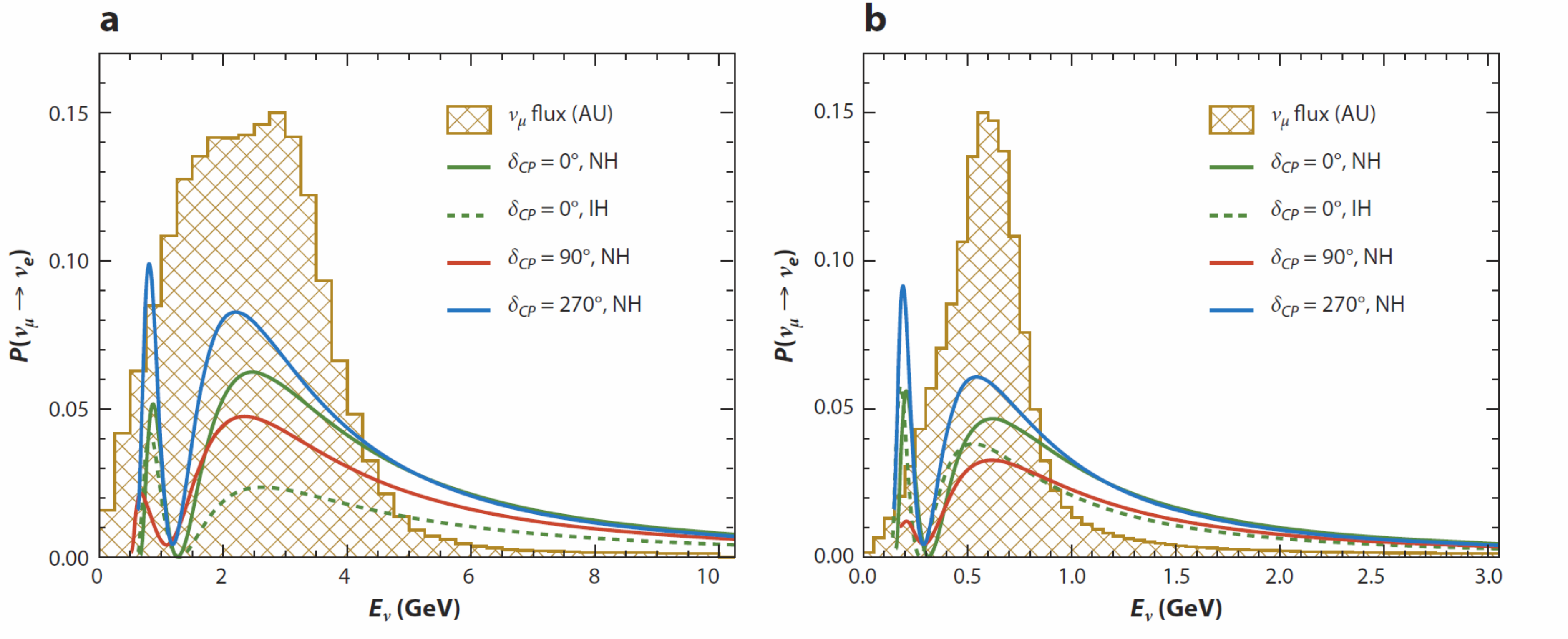
Oscillation Signals as $F(E_\nu)$



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%

Problem: Neutrino Energy

- The incoming neutrino energy on the abscissa of all such plots is not known, but must be reconstructed; very different from Nuclear Physics and High Energy Physics where the beam energy is accurately known.

- The reconstruction has to start from an only partially observed final state (detector limitations!) and proceeds from there ‚backwards' to the initial state.

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Generators

- Generators are needed for this ‚backwards calculation‘
- The accuracy of the energy reconstruction and thus the precision of any neutrino mixing parameters depends crucially on the precision of these generators
- Generators must be an integral part of any experiment
- Generators must be able to handle:
  - the extended target size complications
  - the primary neutrino-nucleus interaction
  - the final state interactions

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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

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Generators for energy reconstruction

- Present day‘s neutrino generators combine different physics processes and models into one patchwork, creating artificial degrees of freedom
- Present day‘s neutrino generators often use outdated physics (RS)
- Present day‘s generators do not bind the nucleus
- To make up for these deficiencies, present day‘s neutrino generators rely on tuning, i.e. fitting to data
- Time to build new, consistent generators, based on present day‘s nuclear physics, both for initial interaction and the final state interactions (transport)

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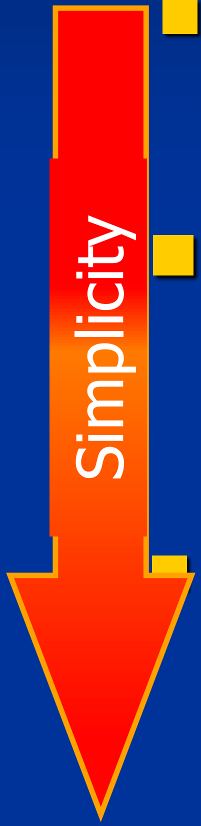
GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, new version GiBUU 2017
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

Theoretical Basis of GiBUU



- Kadanoff-Baym equation (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models: GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s)
- Cascade models (typical event generators, GENIE, NEUT, NuWro, …)
  - no mean-fields, primary interactions and FSI not consistent, reweighting of different interaction types, ….

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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 on nuclei
  - photon and electron induced reactions on nuclei
  - neutrino induced reactions on nuclei

using the same physics input! And the same code!

NO TUNING!

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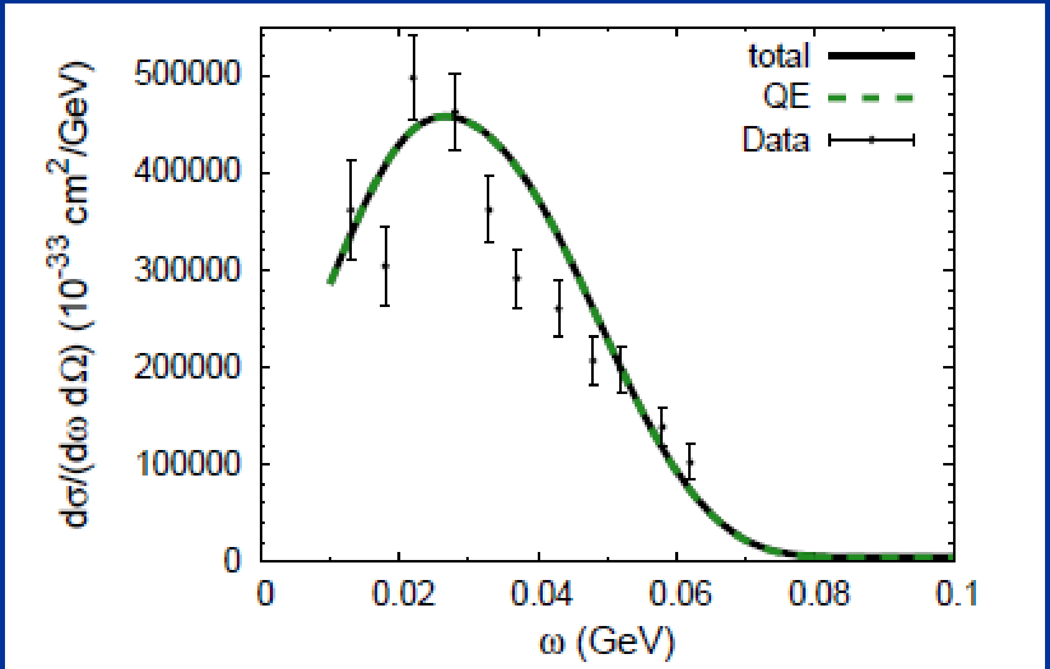
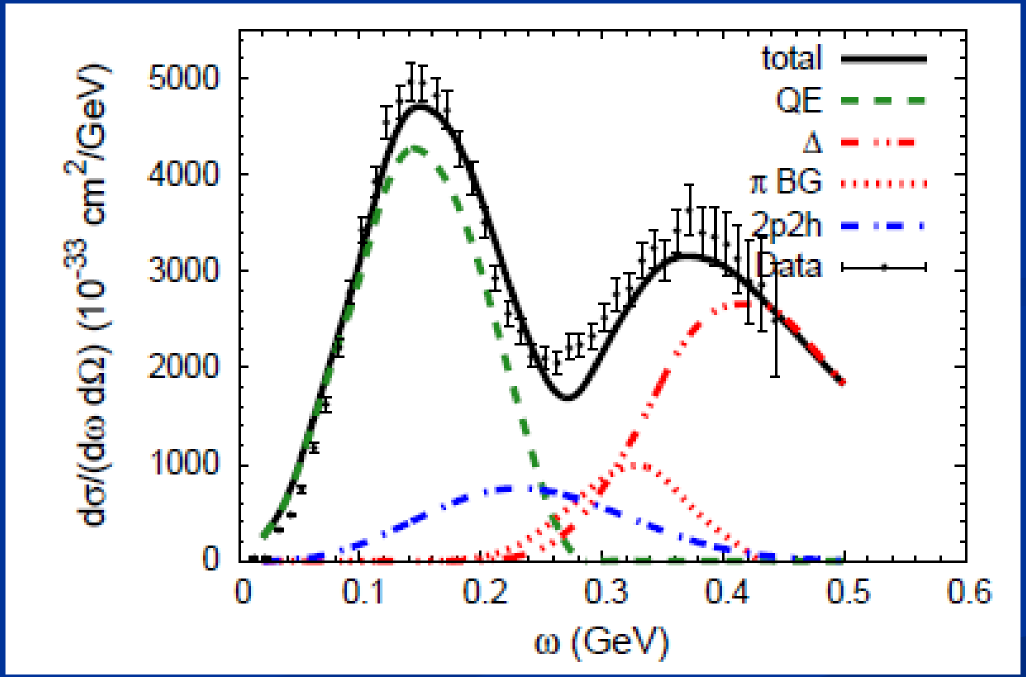
Inclusive QE Electron Scattering

- a necessary check for any generator development

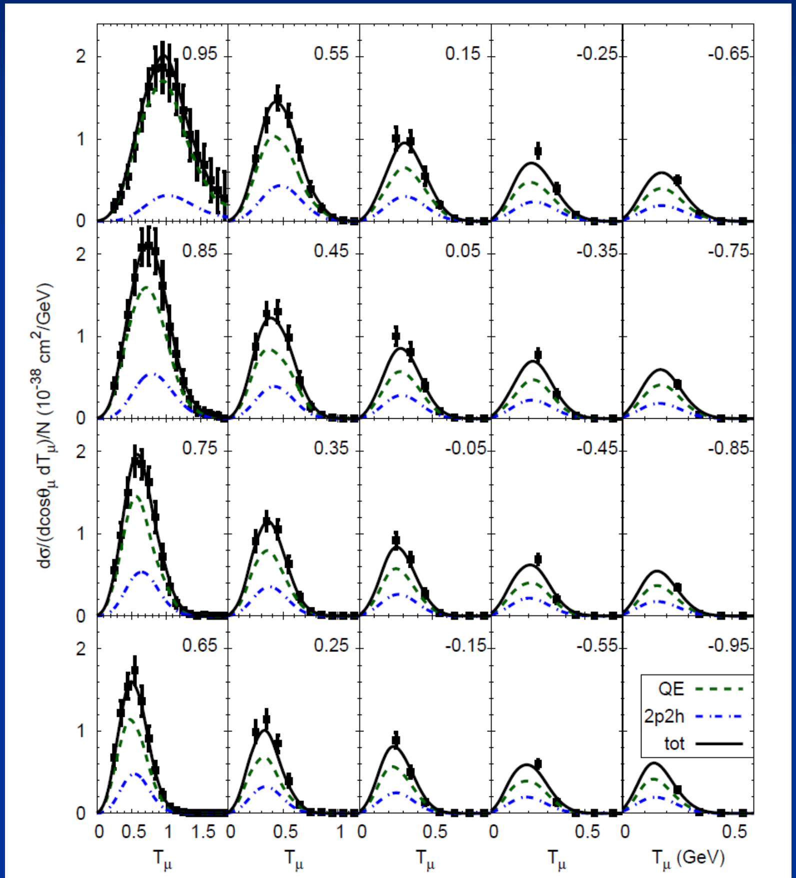


0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2



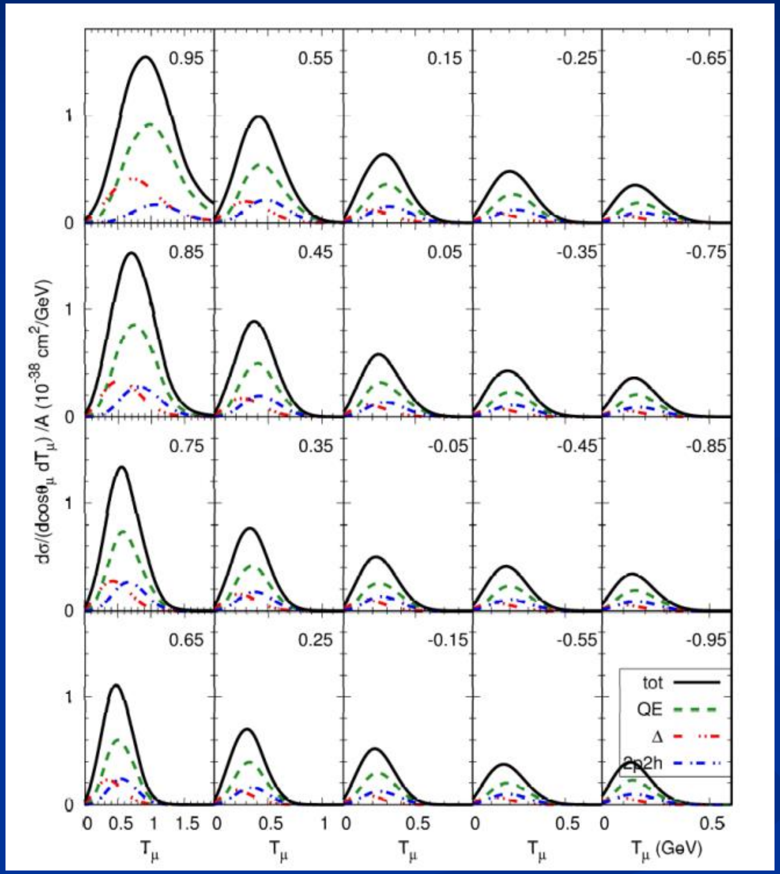
Target: C 0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Inclusive Lepton Kinematics



MiniBooNE C12 (QE + 2p2h)

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

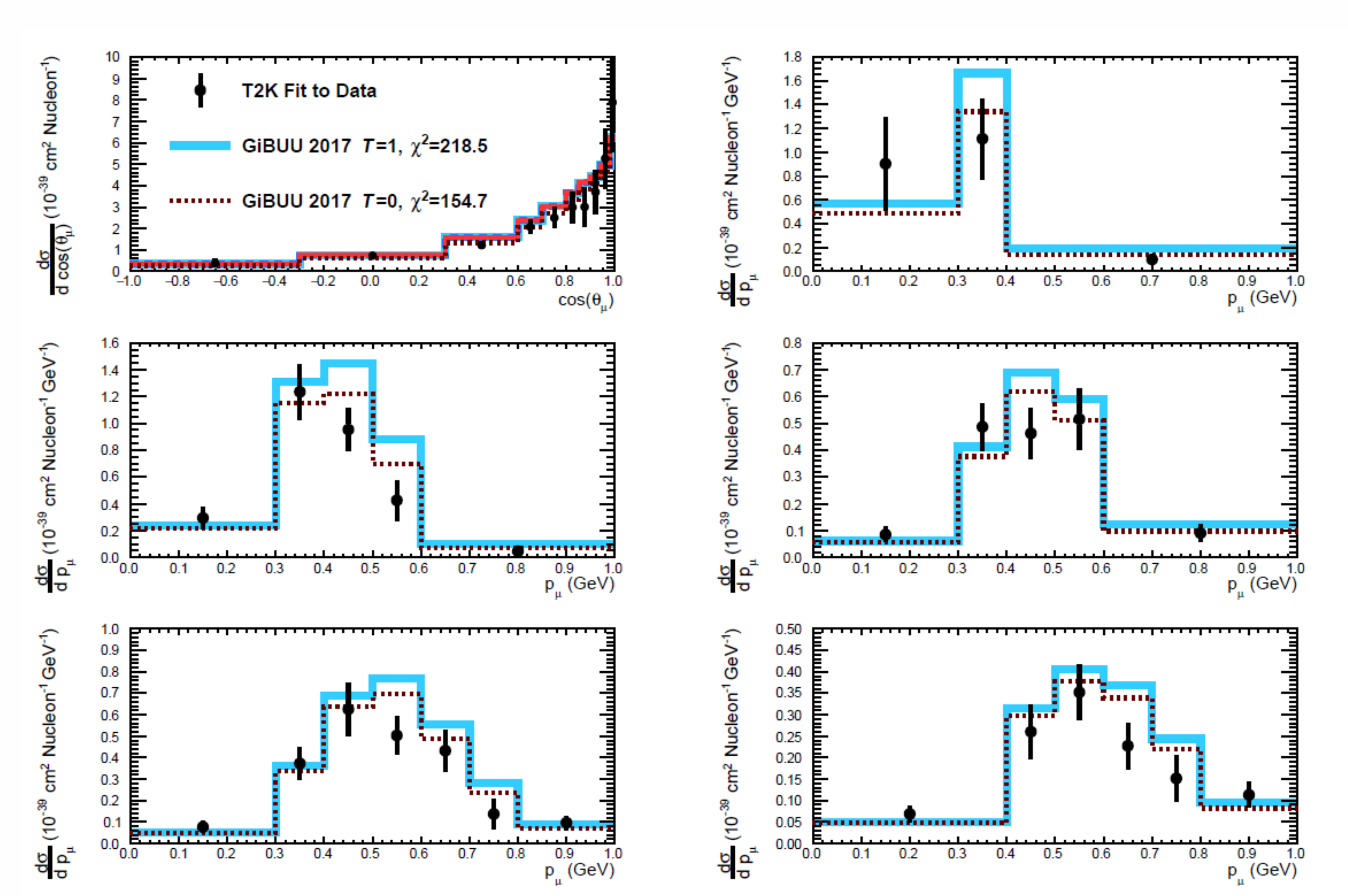


MicroBooNE Ar40 (fully inclusive)

2p2h $\sim \Delta$

T2K Inclusive Cross Section

Target:
CH



Dolan et al,
arXiv:1804.09488

Poster:
S. Dolan et al
Wednesday, #104

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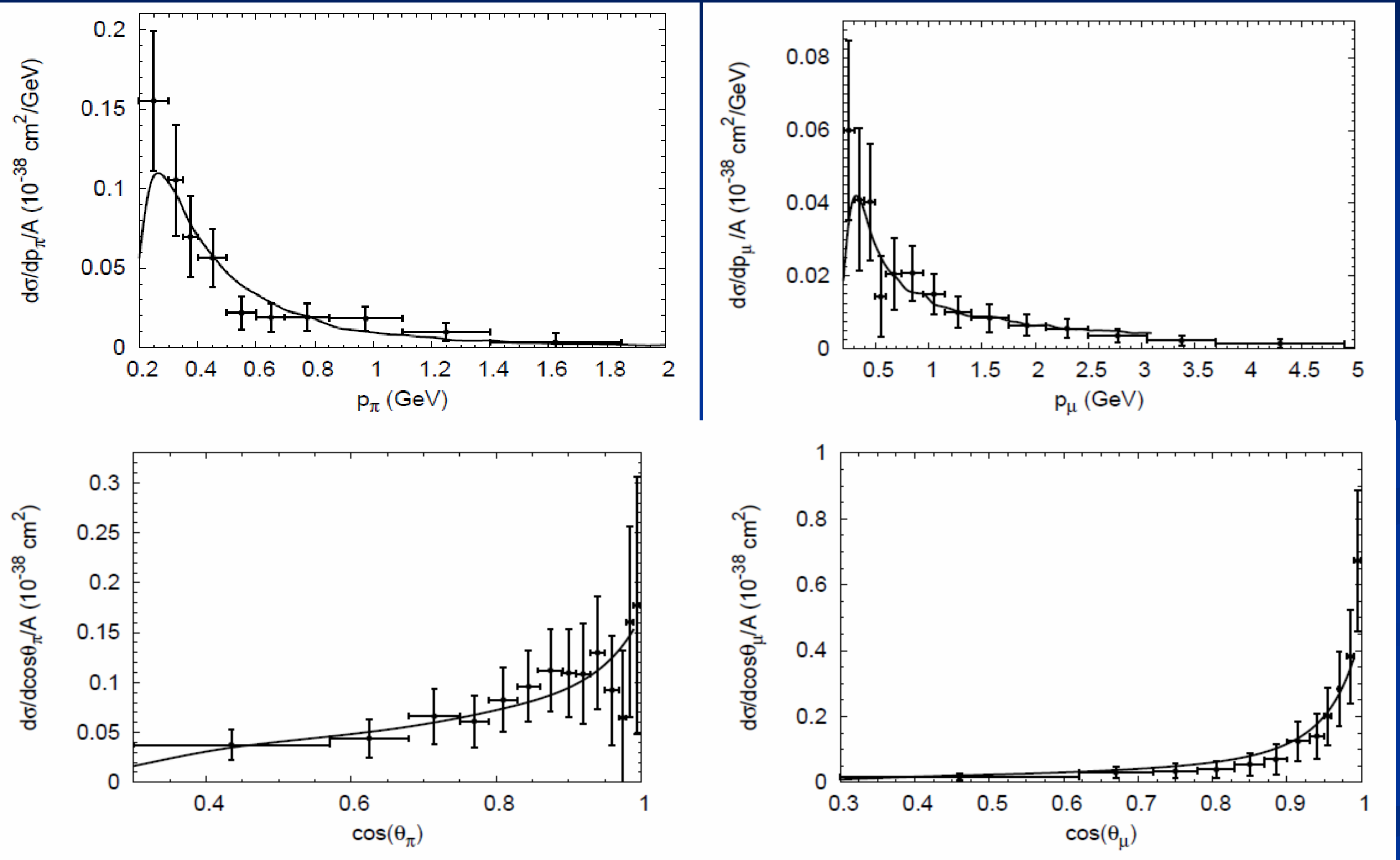
T2K ND280 Pi+



H_2O target

Mosel, Gallmeister,
Phys.Rev. C96 (2017) no.1, 015503

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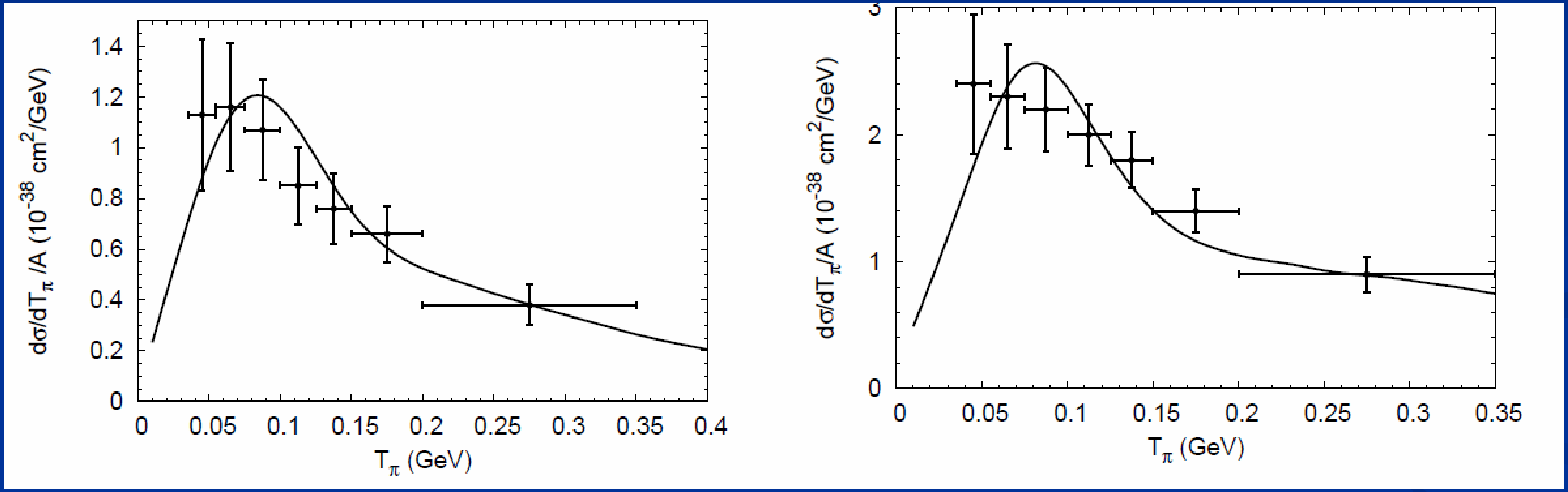
MINERvA Pions

CC charged pions on CH target



W < 1.4 GeV

W < 1.8 GeV, multiple pions

Challenge: ^{40}Ar

- ^{40}Ar not isospin symmetric, N > Z.
- QE and pion production are one-body processes
- and easy to handle, but what about 2p2h Isospin-dependence?
- Relation of 2p2h to electron scattering process?
- CHECK: how well does GiBUU do on ArgoNeut data? Now: pion production, fully inclusive to come

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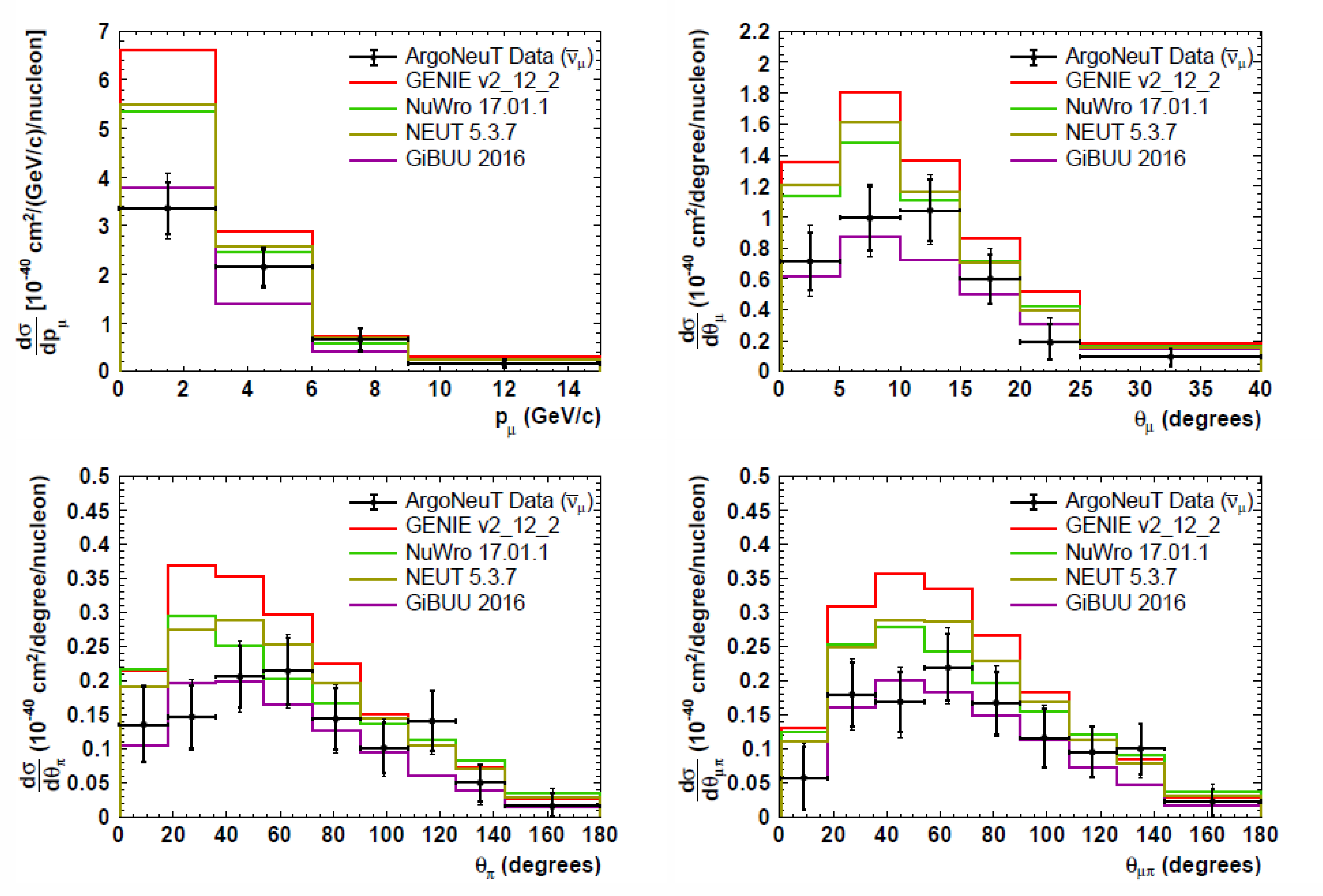
Pion Production on LAr



ArgoNeut

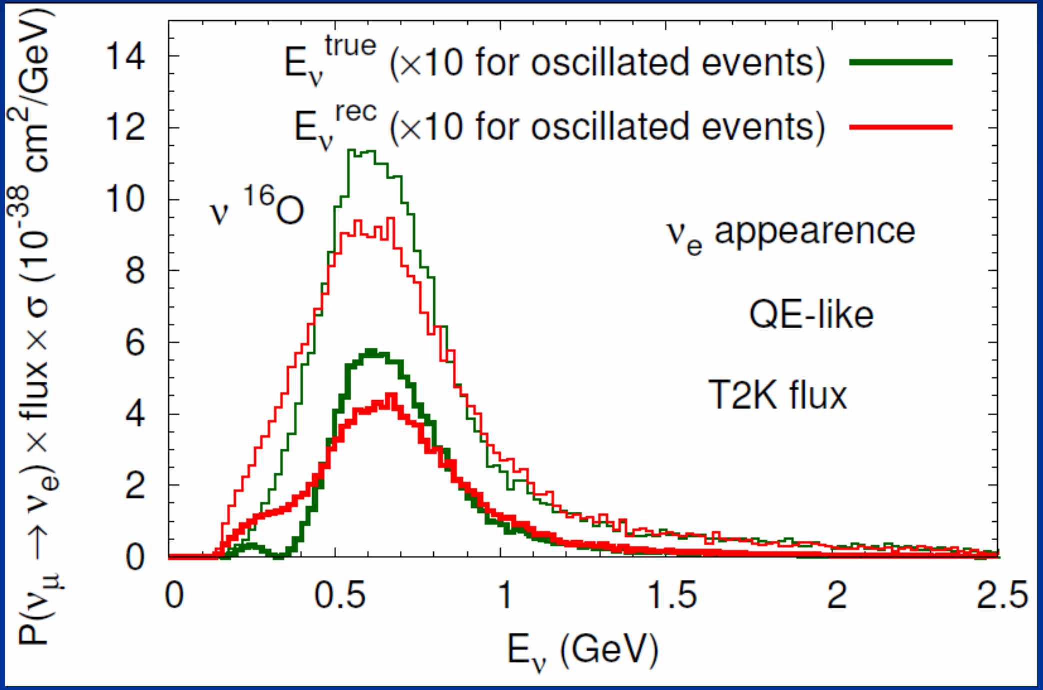
arXiv:1804.10294

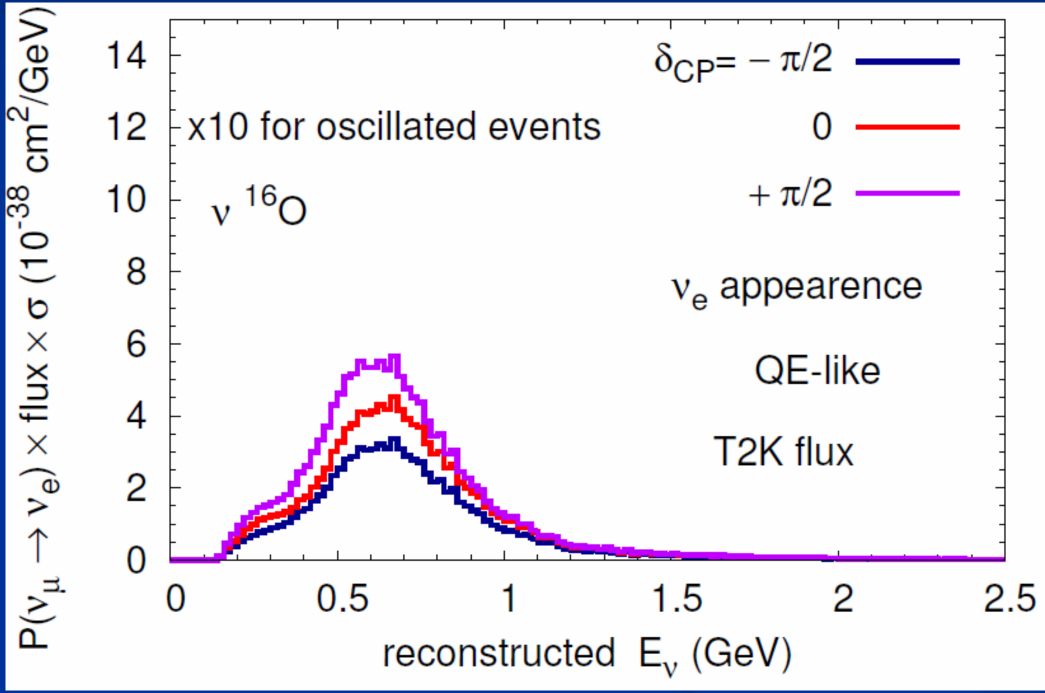
Antineutrinos

Excellent agreement of GiBUU with Ar data NO Tune

Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps





O. Lalakulich et al,
Phys.Rev. C86 (2012) 054606

Reconstruction error
as large as δ_{CP} dependence

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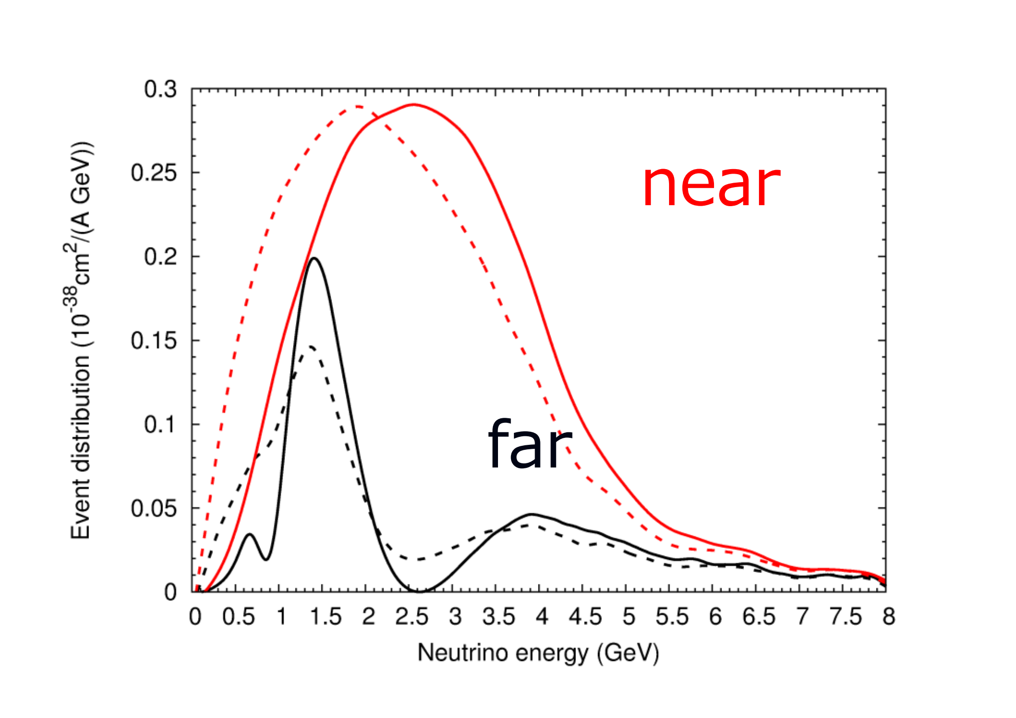
QE Energy Reconstruction for DUNE

Muon survival in 0 pion sample



Dashed: reconstructed,
solid: true energy

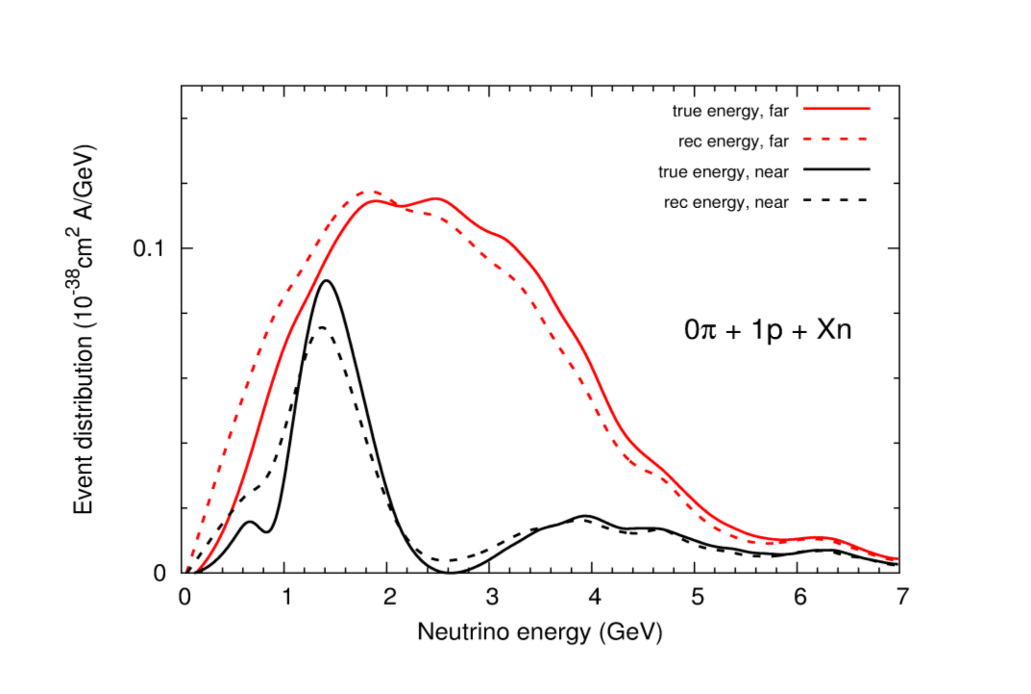
Reconstruction by kinematic method

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

Muon survival in 0π + 1p + Xn sample

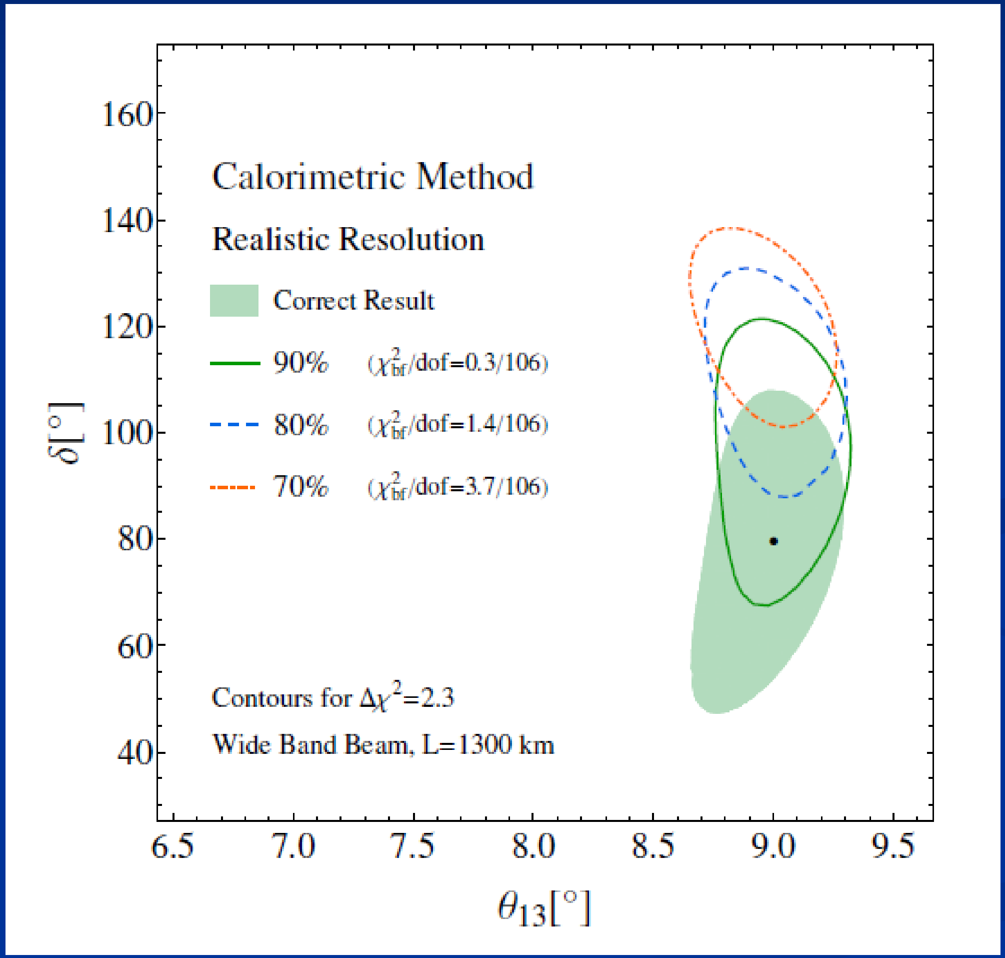


Dashed: reconstructed,
solid: true energy

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

Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3
➔ Kinematic reconstruction useful also at DUNE energies

Extraction of Oscillation Parameters



Oscill parameters in dependence
% of true missing energy for DUNE

Ankowski et al,
Phys.Rev. D92 (2015) 091301

Summary I

- Energy reconstruction is essential for precision determination of neutrino oscillation parameters (and nu-hadron cross sections)
- Neutrino energy must be known within about 50 (T2K) or 100 (DUNE) MeV
- Nuclear effects complicate the energy reconstruction
- Need state-of-the-art generators for reconstruction, with predictive power and no artificial degrees of freedom

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Summary II

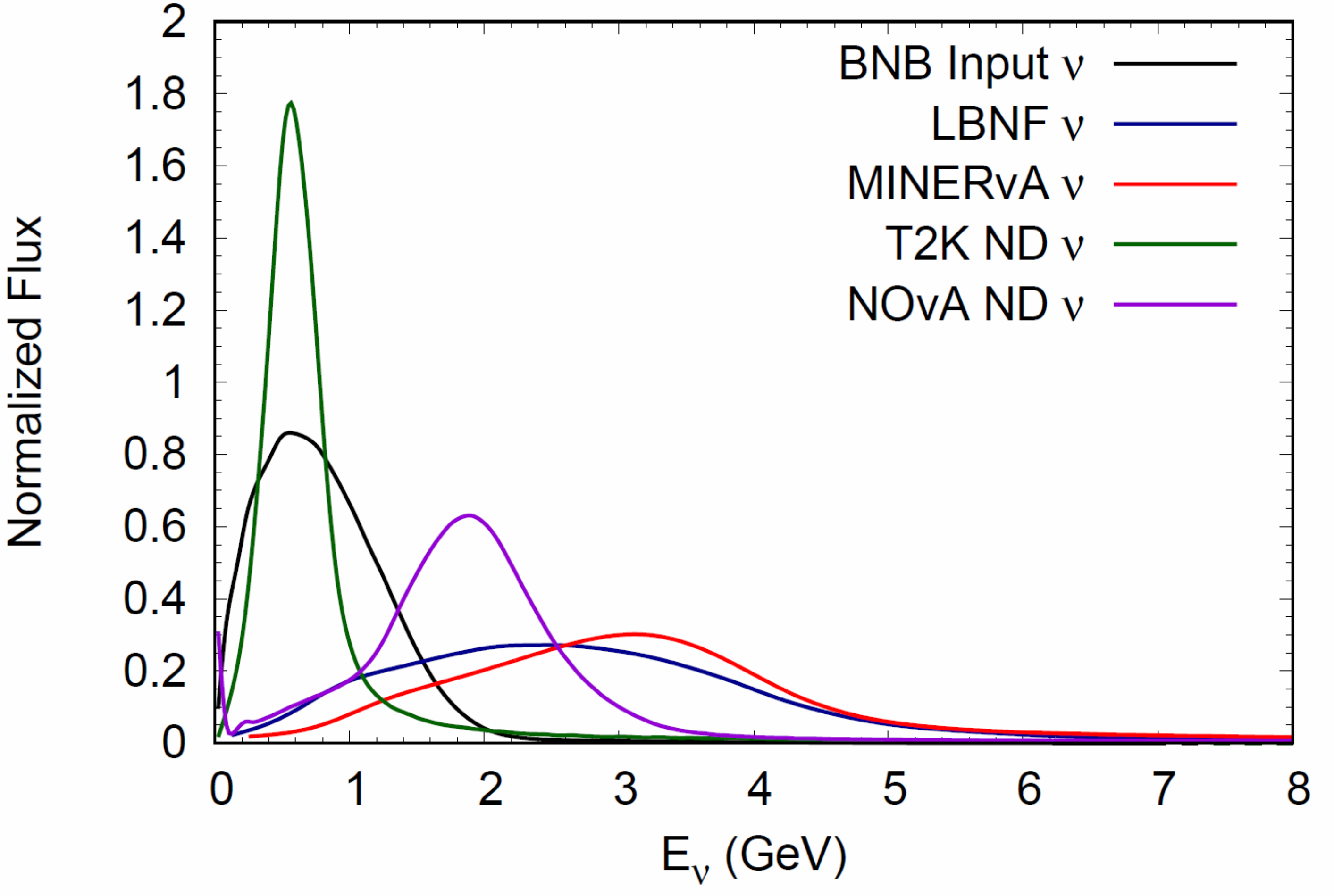
- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments
- Transport Theory has to find its way into neutrino generators!

GiBUU

- 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
- The work reported here was done in collaboration with Kai Gallmeister and Olga Lalakulich

Backups

Energy-Distributions of Neutrino Beams



Energy must be reconstructed event by event, within these distributions

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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“
- All of these generators neglect from the outset:
  - Nuclear binding
  - Final state interactions in nuclear potential
  - Same ground states for different processes
- Generators can possibly be tuned, but can they then have any predictive power? With their patchwork of recipes?

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GiBUU Ingredients

- Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
- Initial interactions are calculated by summing over interactions with all bound, Fermi-moving nucleons
  - 2p2h interactions taken from electron scattering
- Final state interactions are handled by quantum-kinetic transport theory (off-shell transport possible)
- Calculations give the final state phase space distribution of all particles

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Quantum-kinetic Transport Theory

On-shell drift term — Off-shell transport term — Collision term

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

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

H contains mean-field potentials

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

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

Spectral function

Phase space distribution

KB equations with BM offshell term

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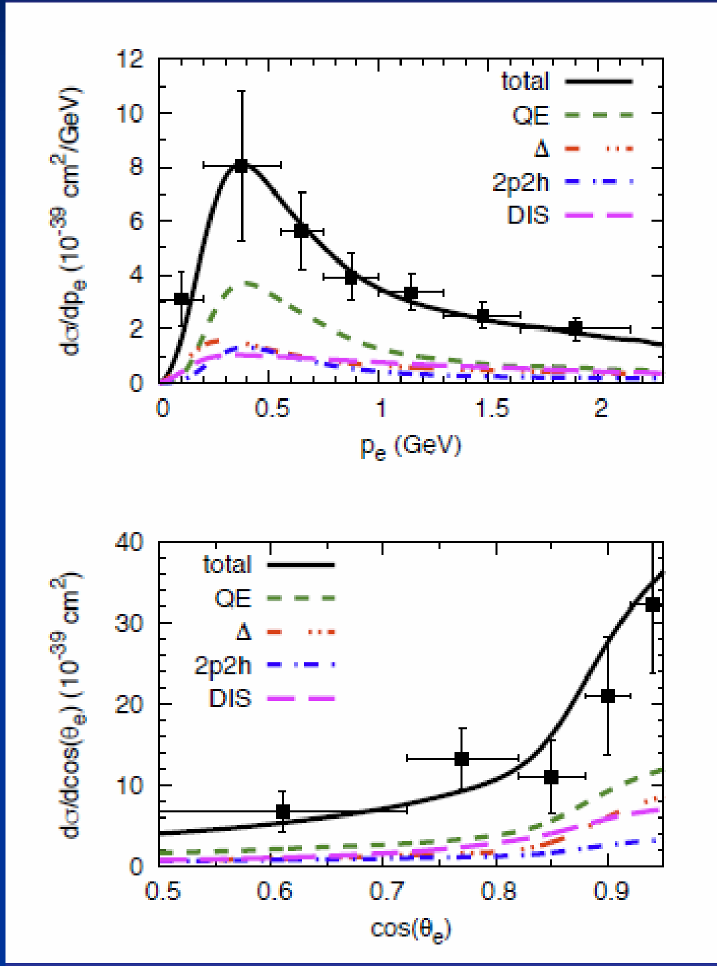
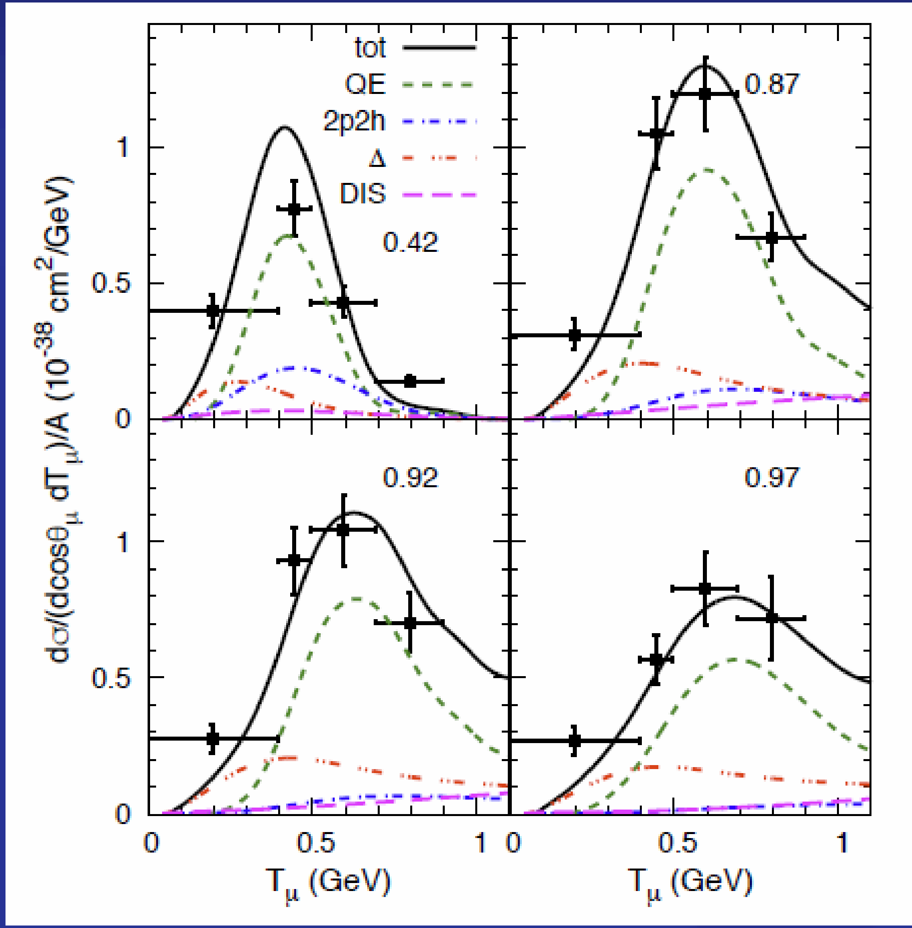
Comparison with T2K incl. Data

T2K, ν_e

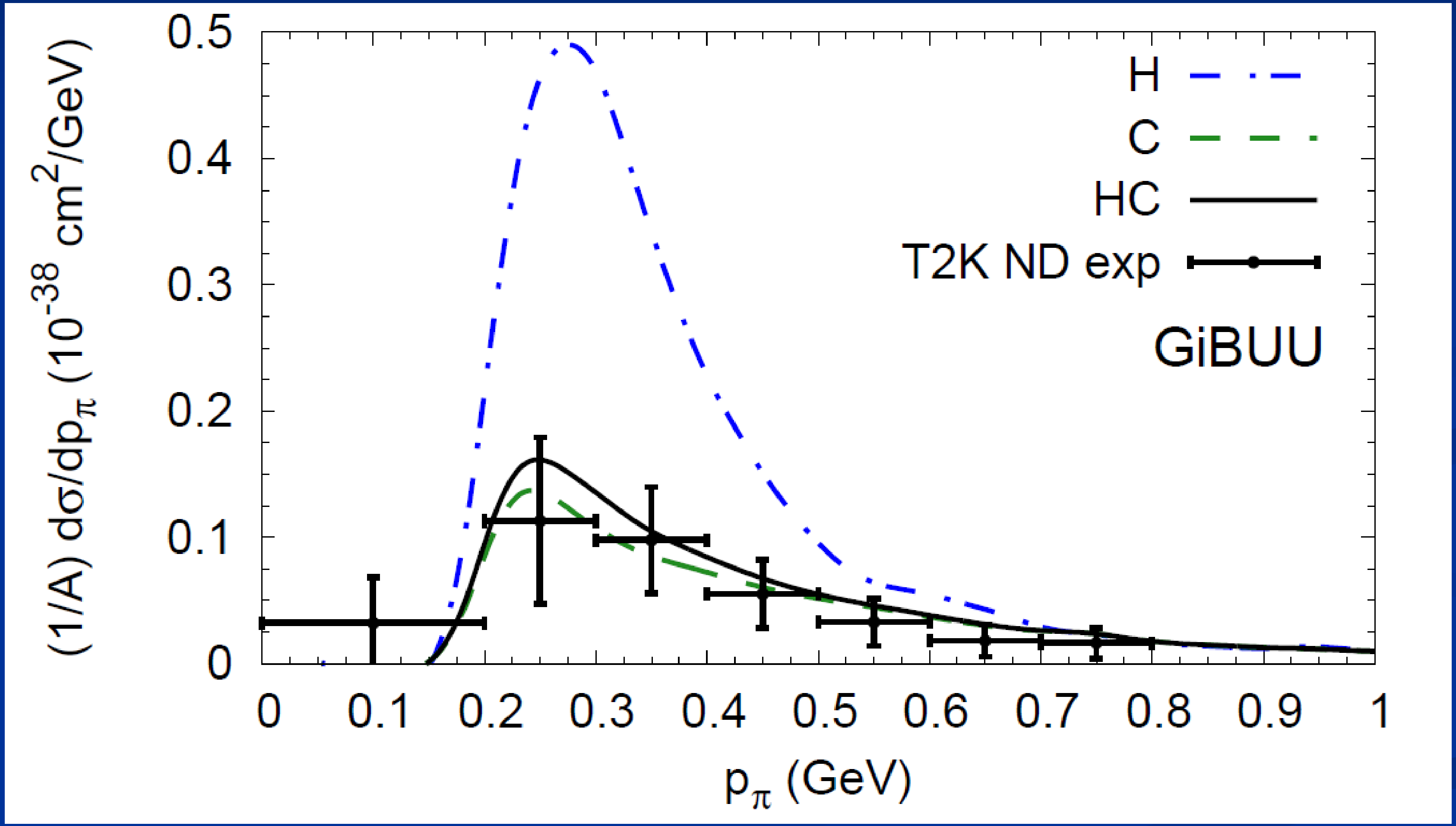




T2K, ν_μ

Agreement for different neutrino flavors

Neutrino-induced Reactions: Pion Production



T2K
CH target

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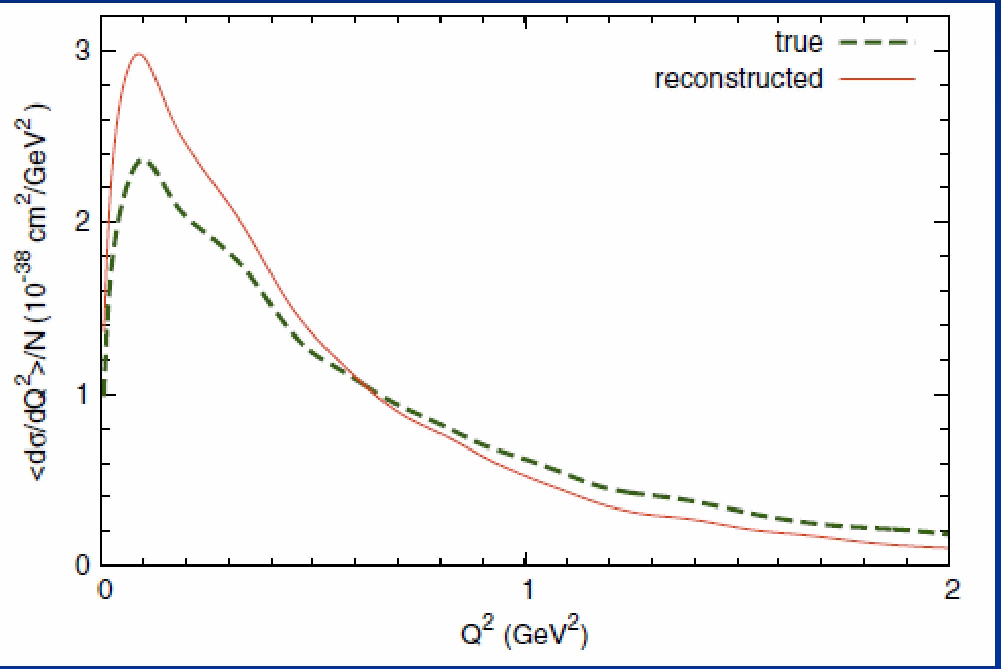
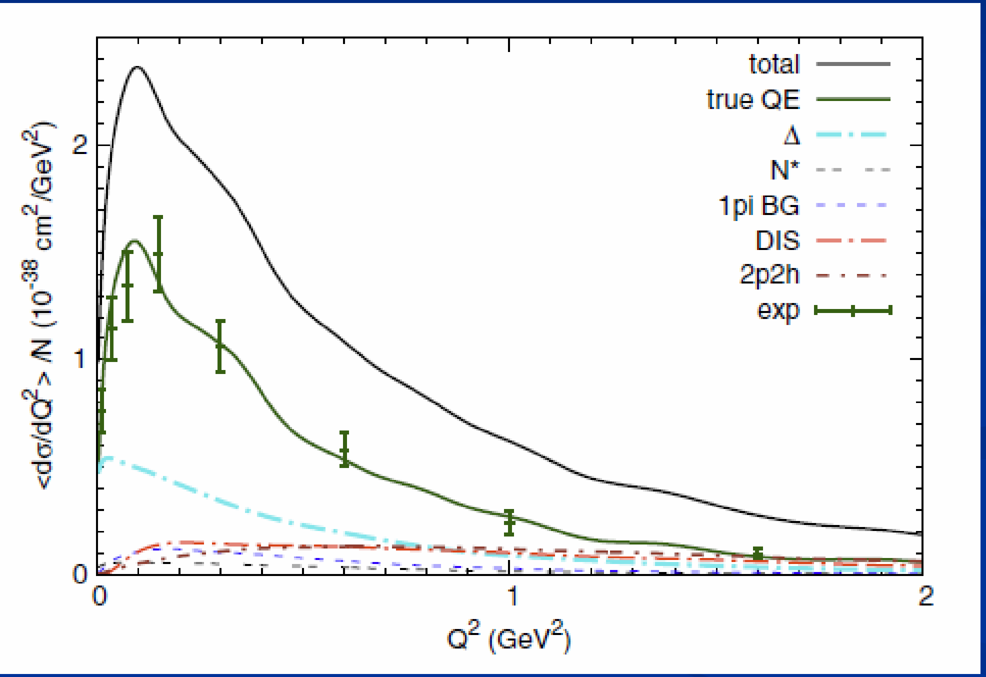
MINERvA Q^2 Reconstruction

Only 0-pion events

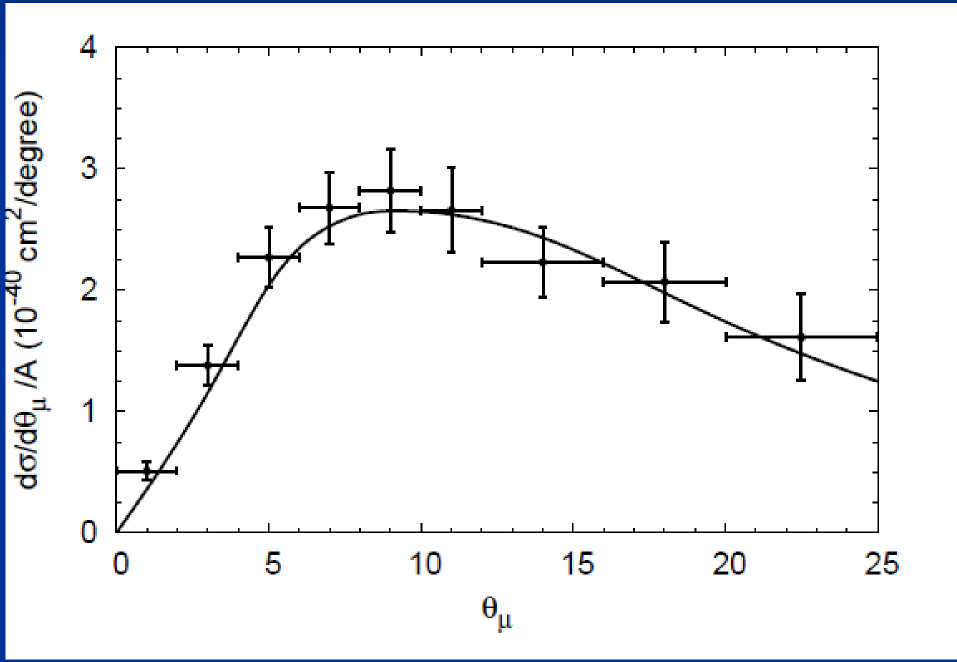


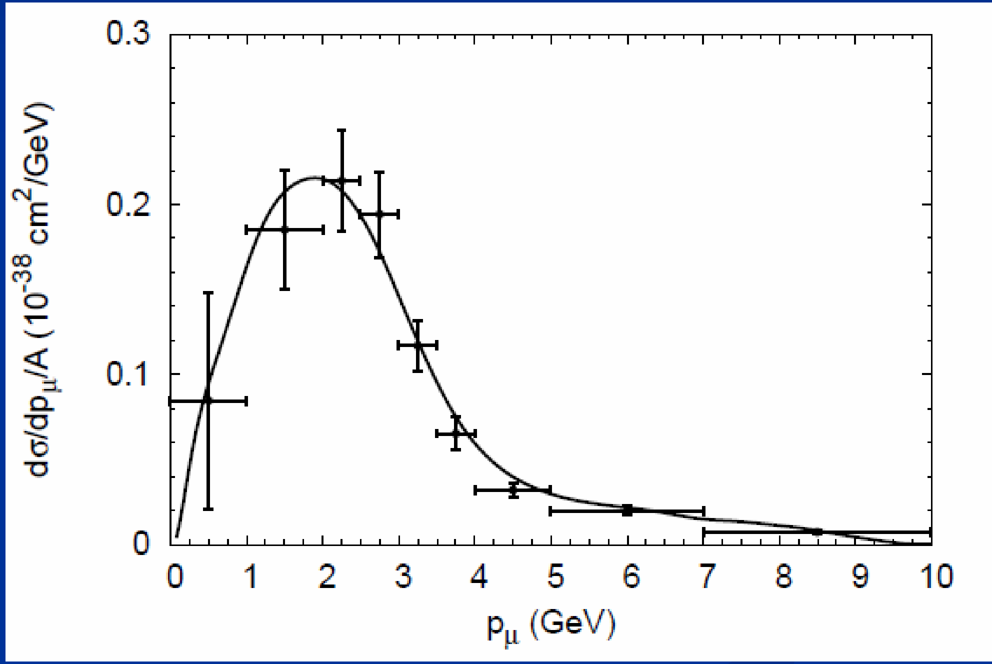


Dramatic sensitivity to reconstruction in peak area: accuracy of ‚data'??

Mosel et al.,
PR D89 (2014) 093003

MINERvA Pions



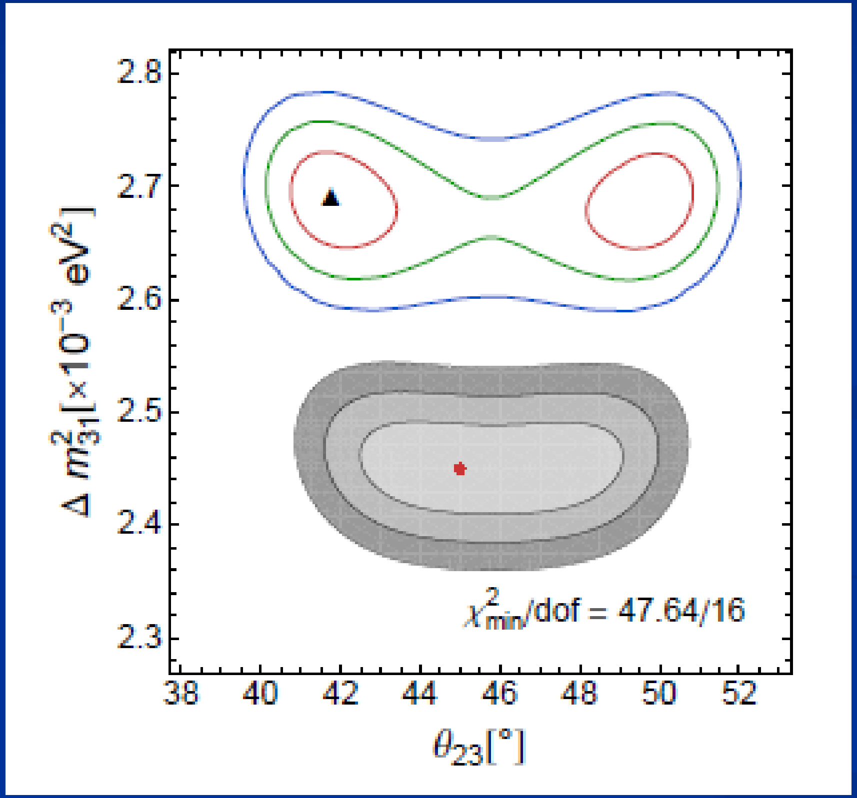


W < 1.8 GeV

Generator Dependence of Oscillation Parameters

GiBUU-GENIE

GiBUU-GiBUU



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

Nature: GiBUU
Generator: GENIE