Physics of ν-A Interactions

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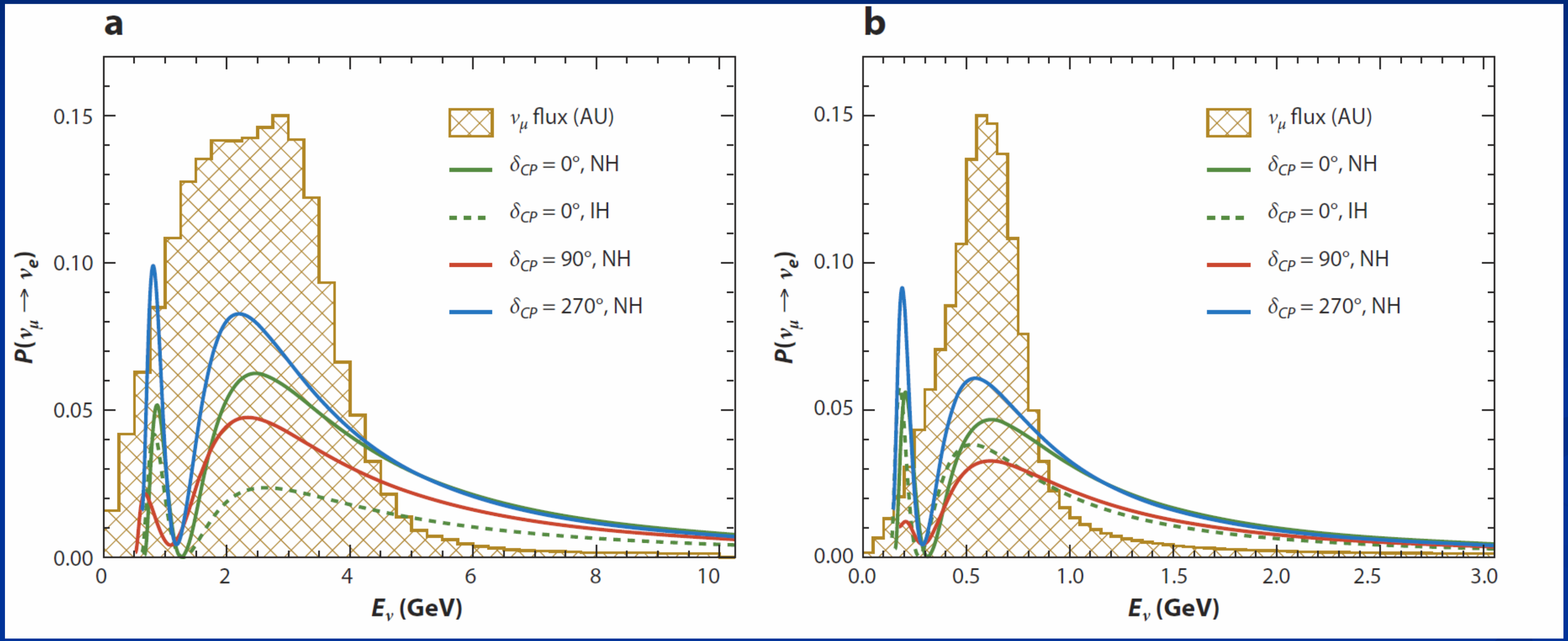
What is (not) measured in a LBL exp?

- LBL experiments measure only flux-averaged cross sections
- The neutrino energy is not measured
- Extraction of neutrino oscillation parameters requires neutrino energy → needs nuclear theory and modeling

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%

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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, leads to smearing of reconstructed energies

detailed recent study in: A. Friedland and S. W. Li, arXiv: 1811.06159

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

} Nuclear Physis

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"Wake up, Dr. Erskine—you're being transferred to low energy physics."

Nuclear Reactions and Structure determine response of nuclei to neutrinos

Wake up, Dr. G…. -- you have been transferred to low energy physics

Generators describe νA interactions?

- Take your favorite neutrino generator (GENIE, …):
  „a good generator does not have to be right,
  provided it can be made to fit 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- Generators use outdated physics: e.g. Rein-Segal for resonances

Generators for energy reconstruction

- Present day‘s neutrino generators combine different physics processes and models into one patchwork, creating artificial degrees of freedom

- To make up for these deficiencies, present day‘s neutrino generators rely on tuning, i.e. fitting to data → no predictive power

- Time to build new, consistent generators, based on present day‘s nuclear physics, both for initial interaction and the final state interactions (quantum-kinetic 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

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- ν-A reaction proceeds in 3 Steps:
  1. Prepare groundstate: r and p-dependent mean field potential from E[rho,p] + local Fermi-gas momentum distribution *bound in this potential*
  2. Describe first initial ν-A interaction in this potential
  3. Propagate particles out of the nuclear volume in the same potential

Quantum-kinetic Transport Theory

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

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

For each particle one such equation,
all coupled by the collision term *C*

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

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

Wigner-distribution of the one-body density matrix = spectral function

Kadanoff-Baym equations

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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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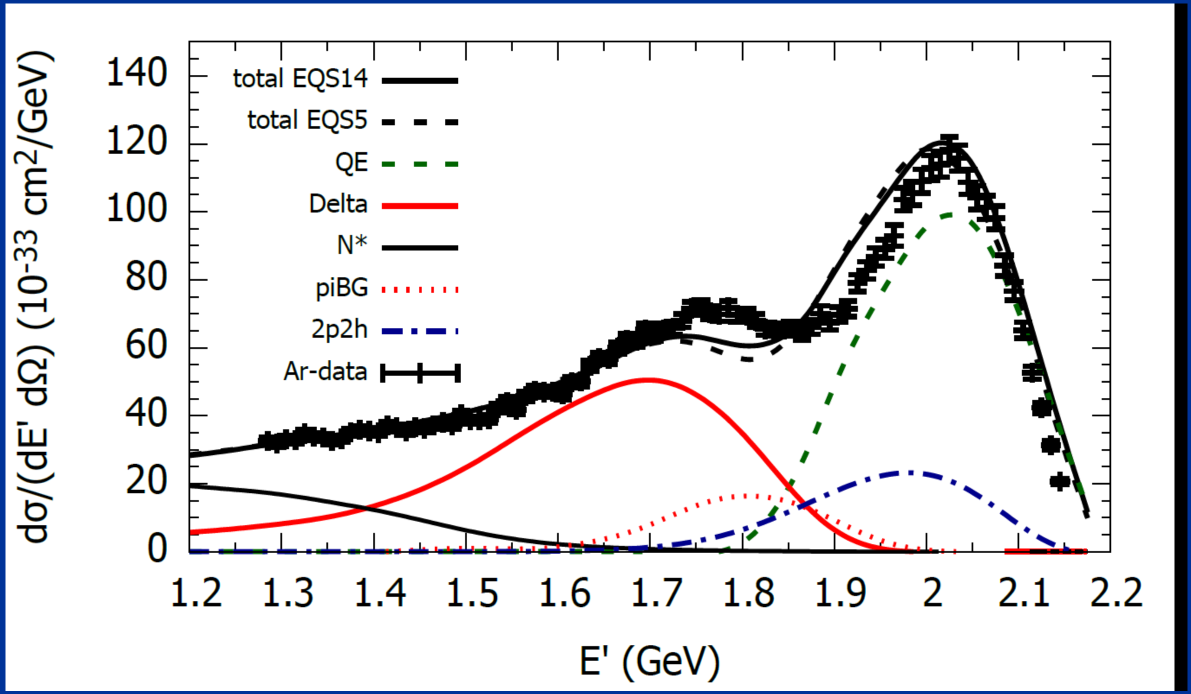
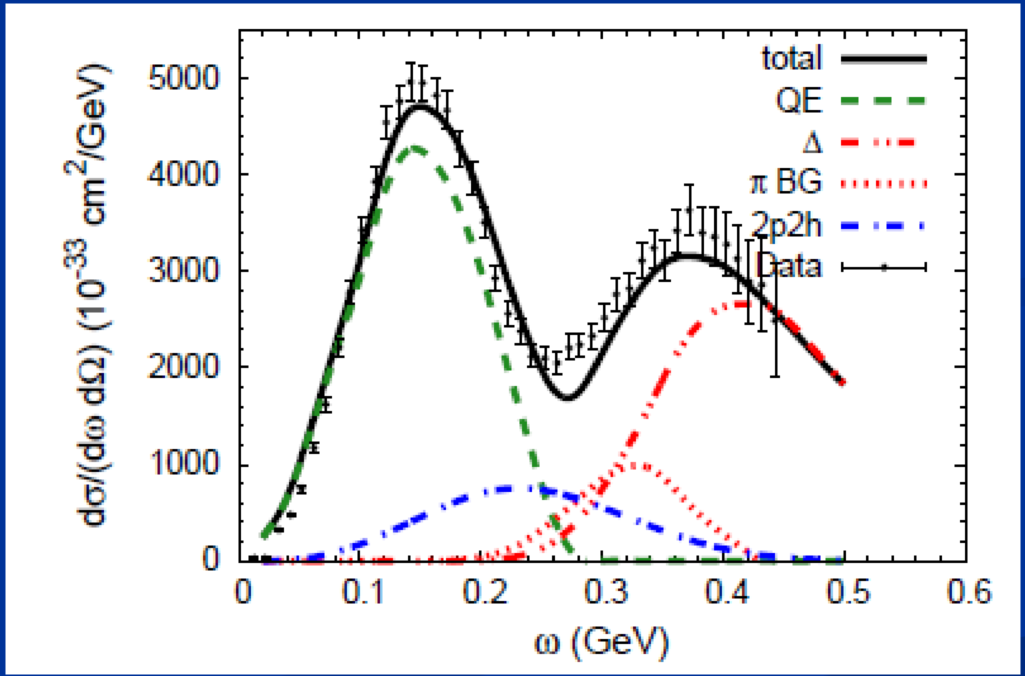
Inclusive QE Electron Scattering

- a necessary check for any generator development





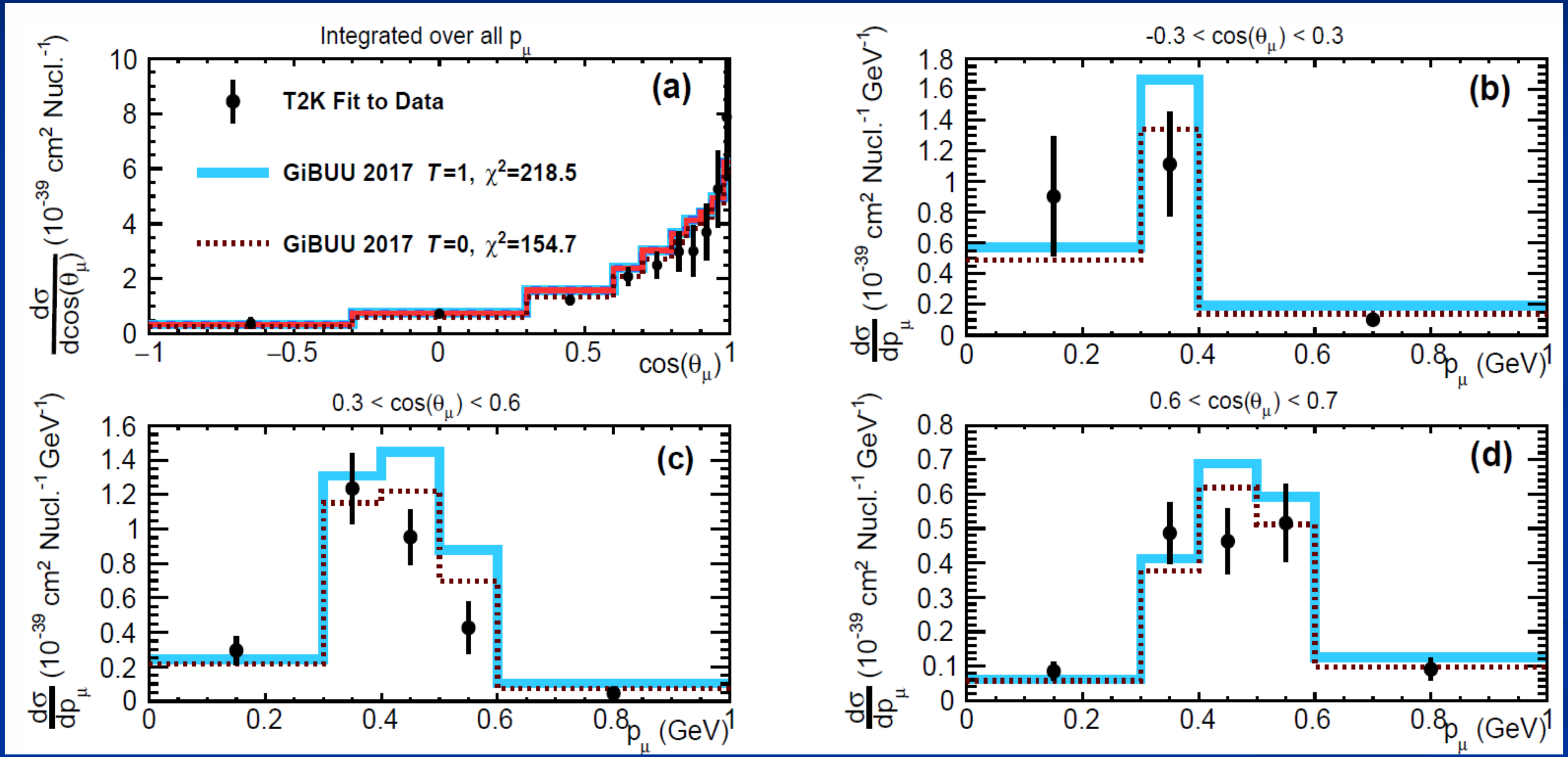
2.2 GeV, 15 deg, $Q^2 = 0.3$ GeV^2

Target: C

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

Jlab data: Phys.Rev. C98 (2018) 014617

T2K Inclusive Cross Section



S. Dolan et al, Phys. Rev. C 98, 045502 (2018)

GiBUU curves differ by factor 2 in 2p2h

Target:
CH

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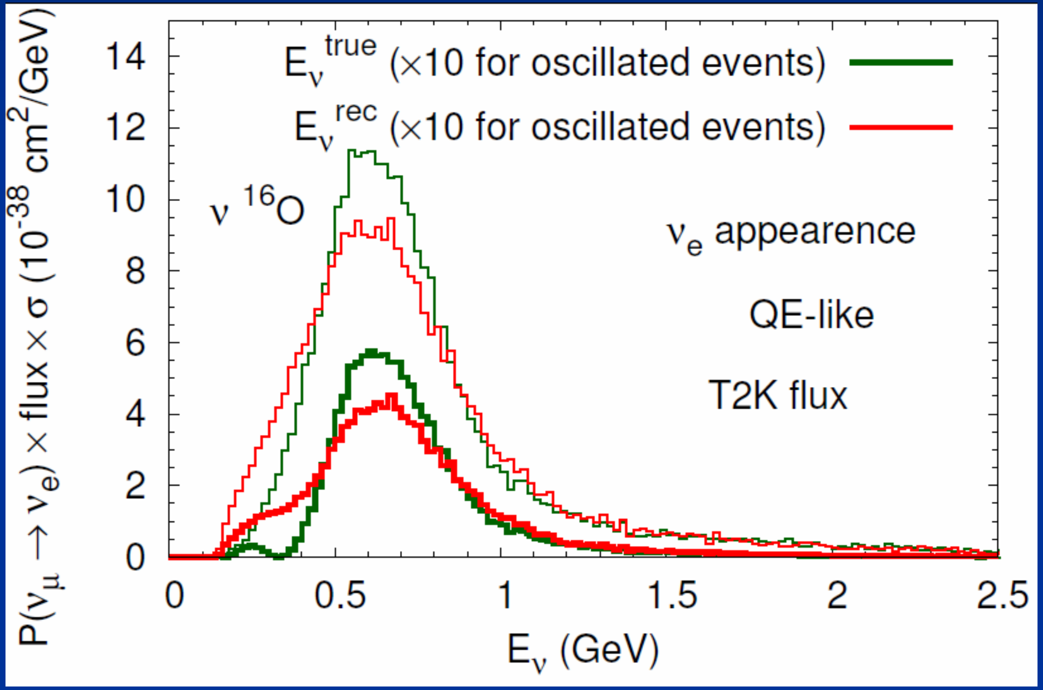
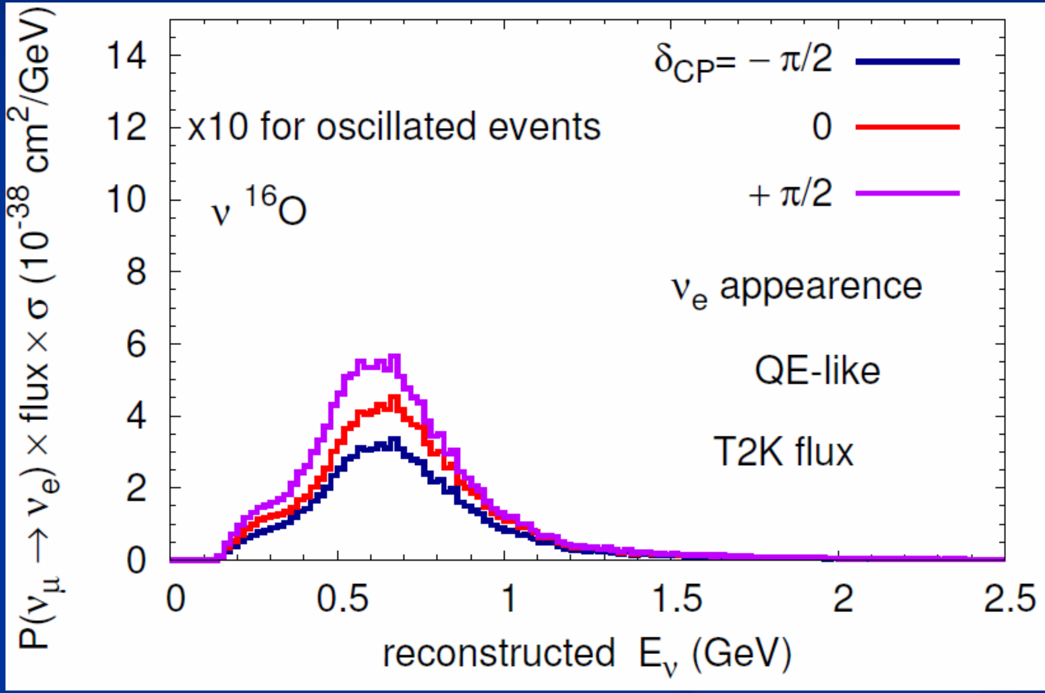
Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps





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

Reconstruction error
as large as δ_{CP} dependence

DUNE Challenge: ^{40}Ar

- T2K is ‚easy‘ because it needs only QE, 2p2h and Delta excitation
- ^{40}Ar not isospin symmetric, N > Z: isospin T = 2, needs more resonances
- Isospin dependence of nuclear processes?
- Relation to electron scattering process?

Wigner-Eckart theorem gives factor T + 1 = 3 for neutrino/electron:

$$\sigma_\nu = \sigma_{el} * 2\,(T + 1)$$

- Only available test: ArgoNeuT data

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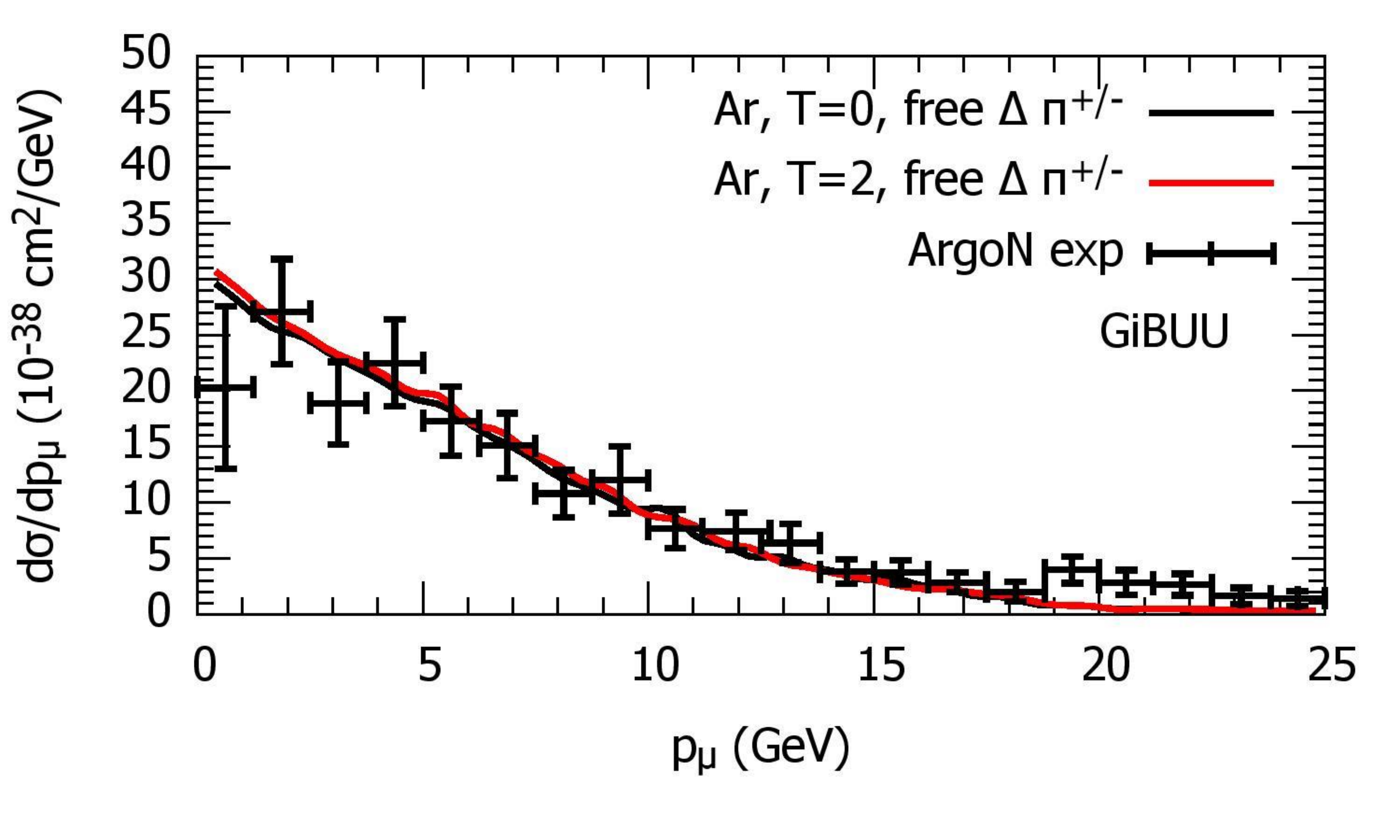
ArgoNeut inclusive



Data: ArgoNeuT

Phys.Rev. D89 (2014) 112003

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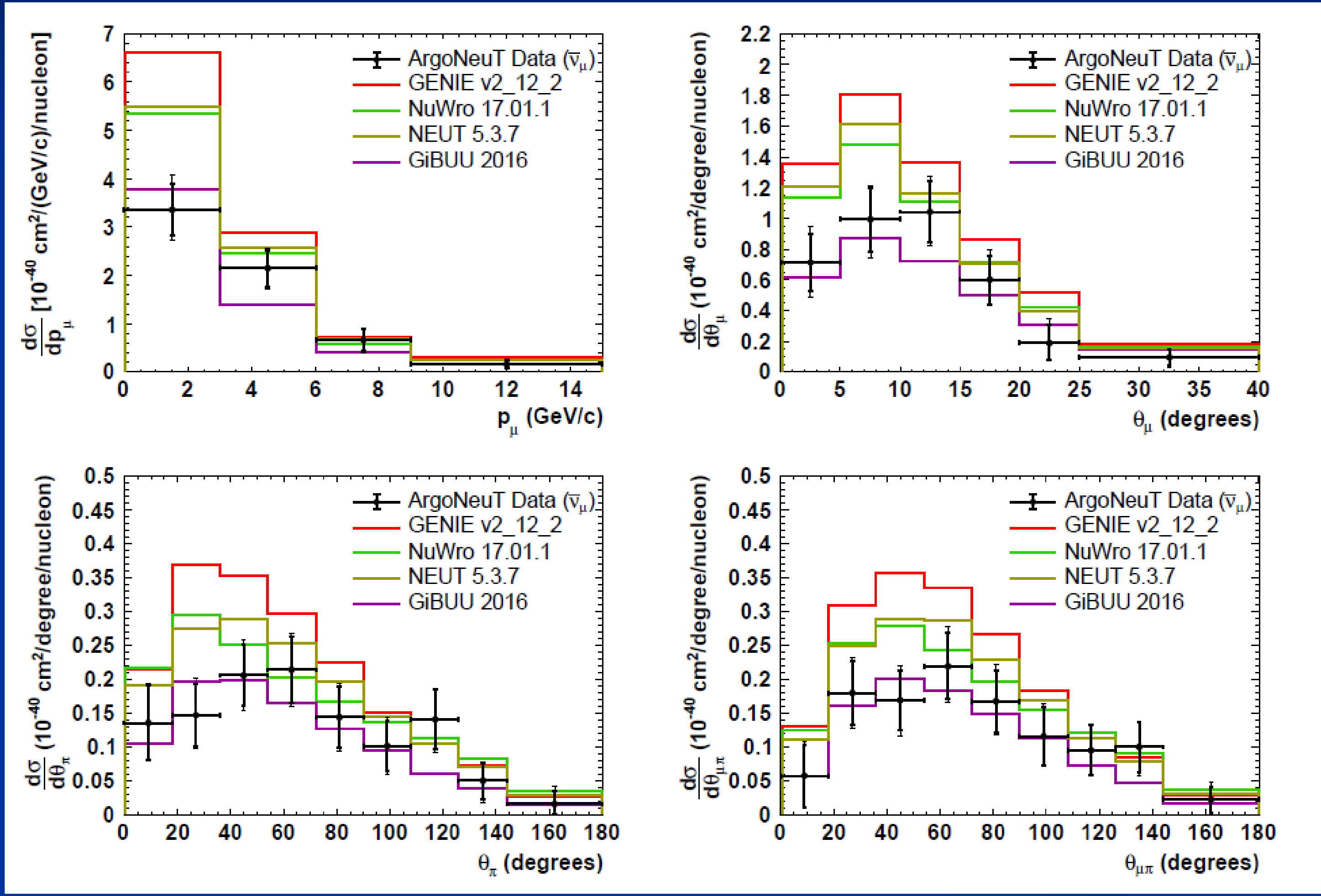
Pion Production on LAr



ArgoNeut
arXiv:1804.10294

Antineutrinos

Excellent agreement of GiBUU with Ar data
NO Tune

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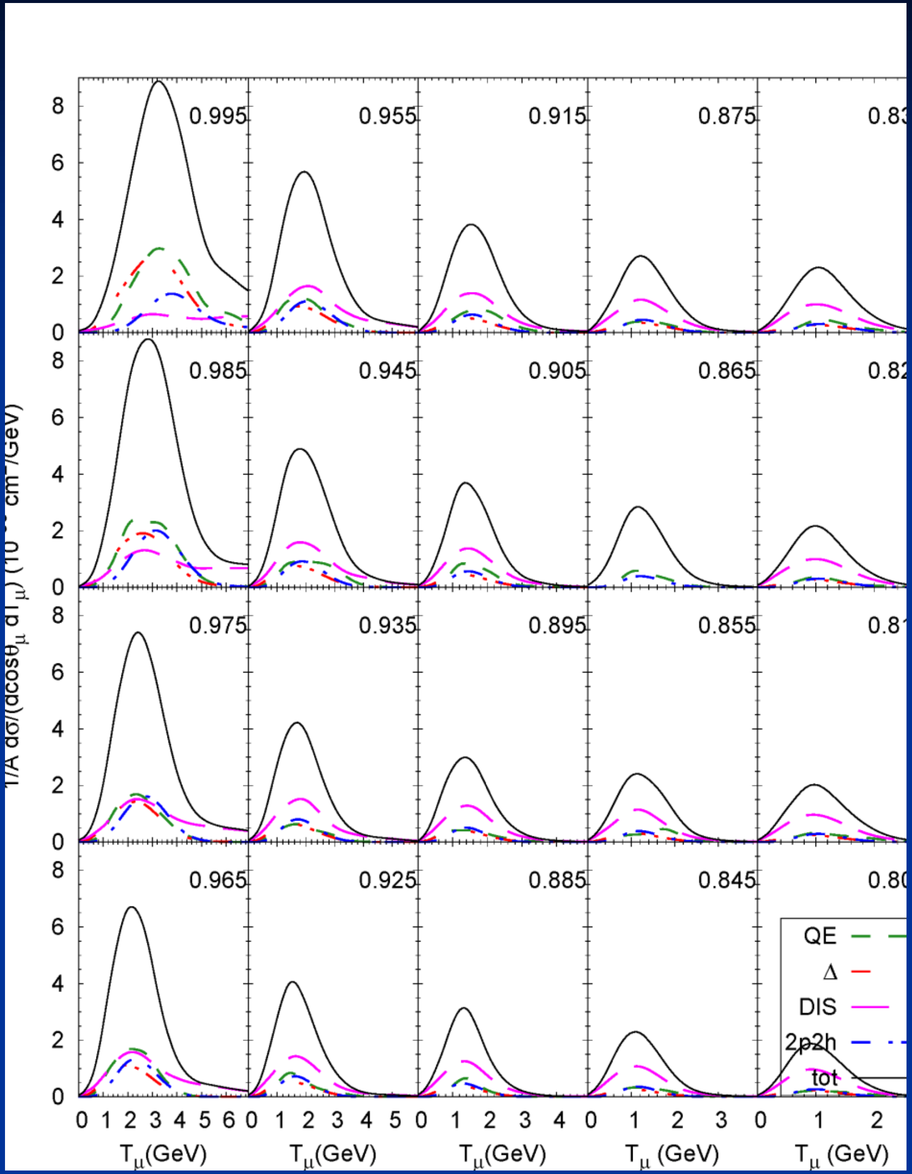
DUNE ND



Double-differential cross section

X-section strongly forward peaked

Δ excitation as strong as QE

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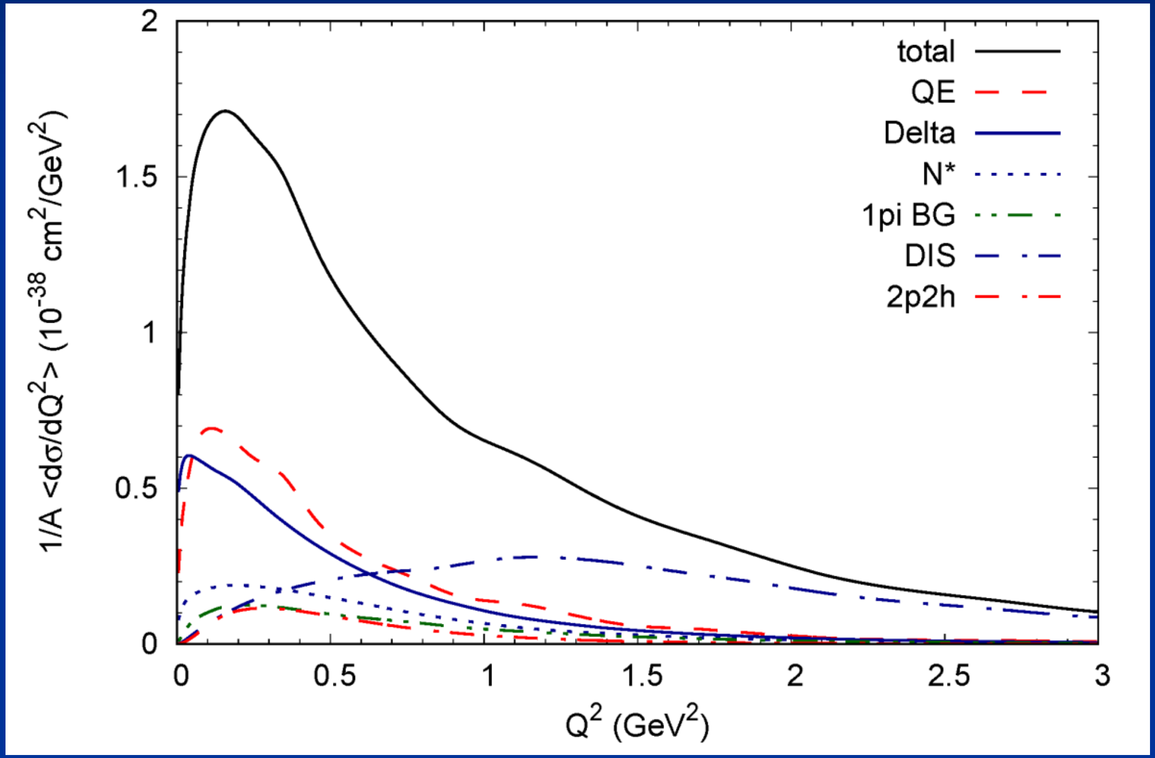
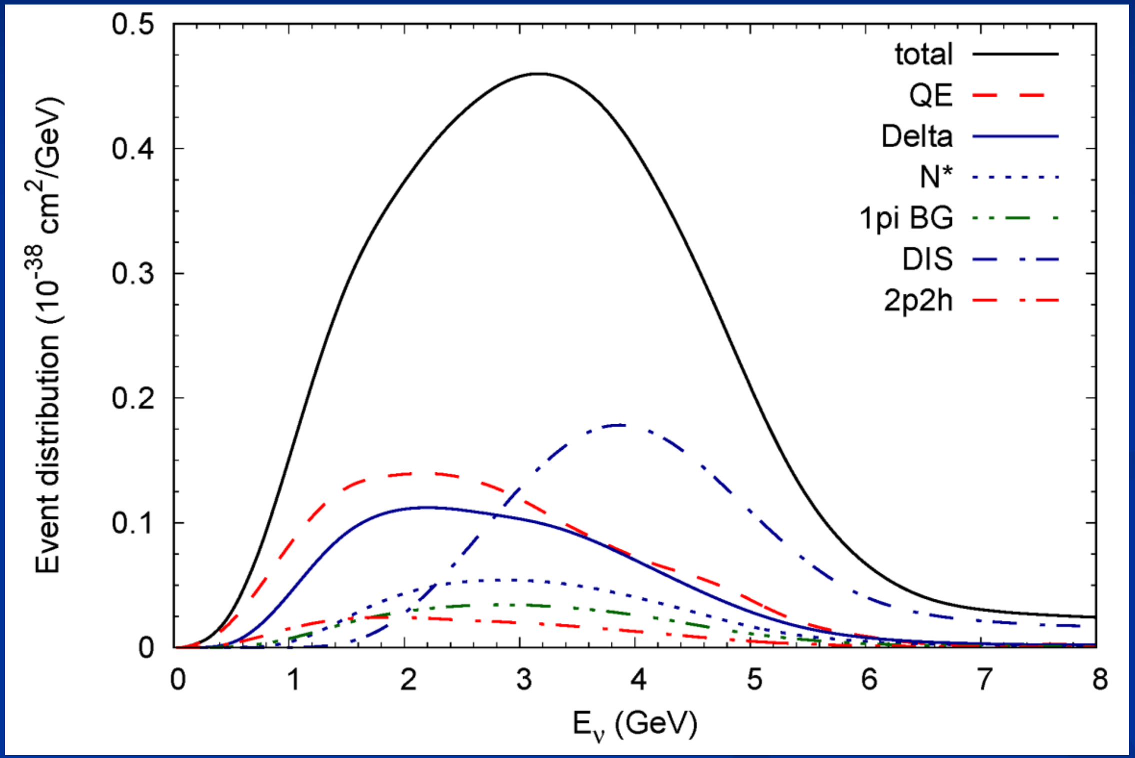
Event Distributions in DUNE ND





2p2h contributes with $< 5\%$
Pion channels (Res + DIS) are dominant
(even more so with high-energy tune

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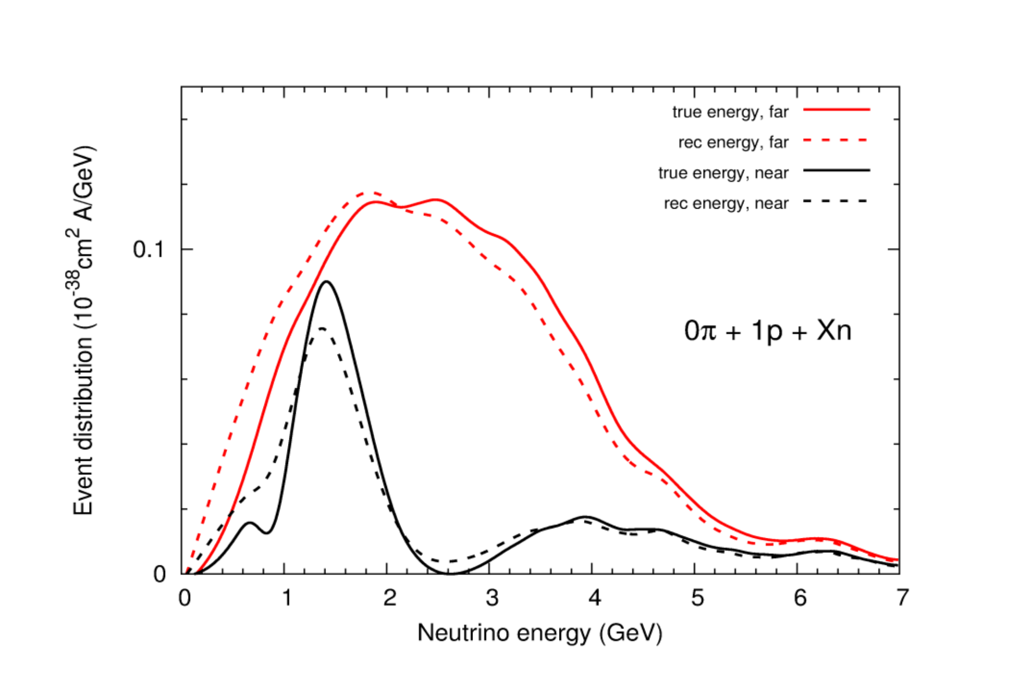
QE Energy Reconstruction for DUNE

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

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
- GiBUU is a first step into that direction, gives good description of all cross sections, both for electrons and neutrinos

Summary II

- Experiments at the DUNE ND are essential because they allow to test generators on an unexplored target (Ar) in an unoscillated beam.
- It would be helpful to have an Ar target in a higher energy beam (NUMI) already now, successir to ArgoNeuT
- Theory and Generator Development should be an integral part of any experiment (and its funding!).

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
- Most of the work reported here was done in collaboration
  with Kai Gallmeister

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