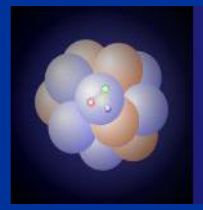
Neutrino Generators an introductory talk

Ulrich Mosel



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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

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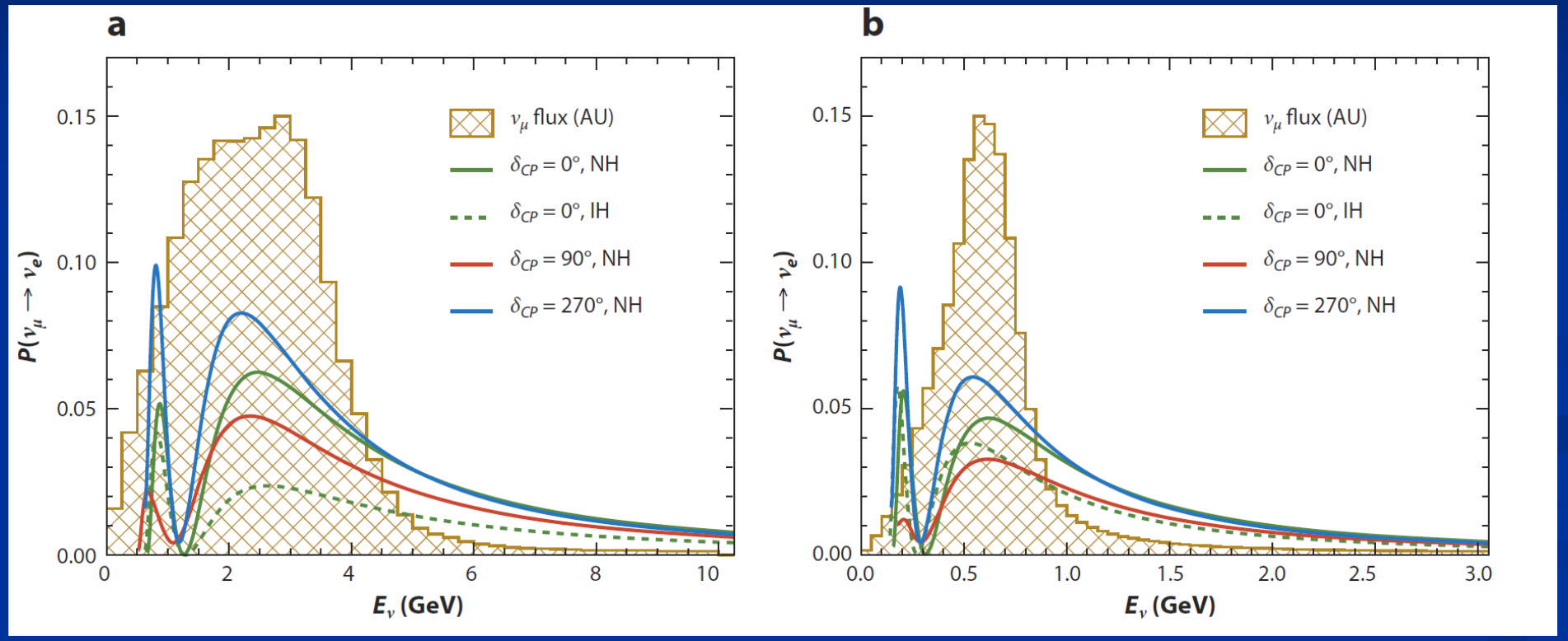
Oscillation Signals as $F(E_\nu)$



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%

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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, **Phys.Rev. D99 (2019) no.3, 036009**

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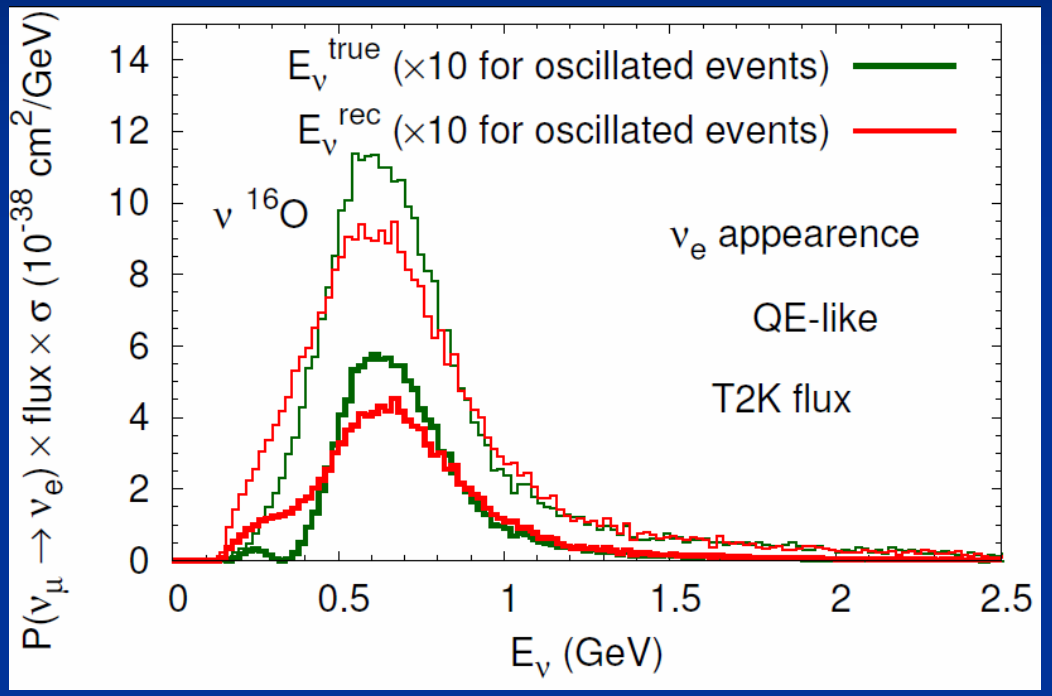
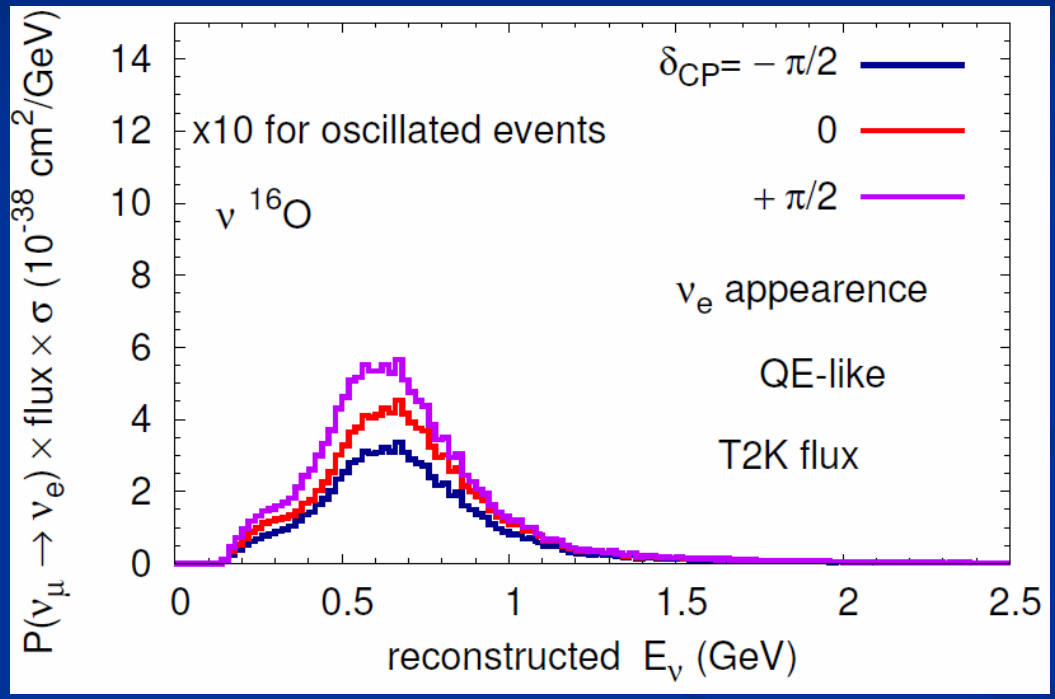
Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps





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

Reconstruction error
as large as δ_{CP} dependence

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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
- Generators describe νA interactions?

} Nuclear Physis

The fsi are often linked to original production process.
For example: π N <-> Delta, related by time reversal Invariance.

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Generators describe νA interactions?

- Take your favorite neutrino generator (GENIE, NuWro):
  „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

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Generators describe νA interactions?

- Generators use outdated physics: e.g. Rein-Segal for resonances, determines pion production, pion absorption is taken from an entirely different model (Valencia cascade).

- Generators use outdated physics: fsi treatment in GENIE hA is outrageously outdated, e..g. pions are always absorbed on a Fe nucleus and then scaled to actual target mass. GENIE folks have missed all the nuclear physics developments during the last 30 years, starting with the Cugnon cascade.

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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

- 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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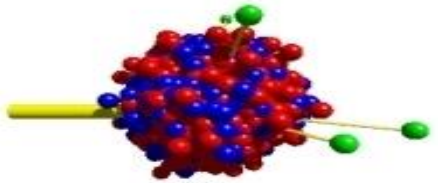

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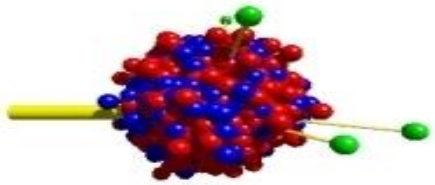
GiBUU

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 2019



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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

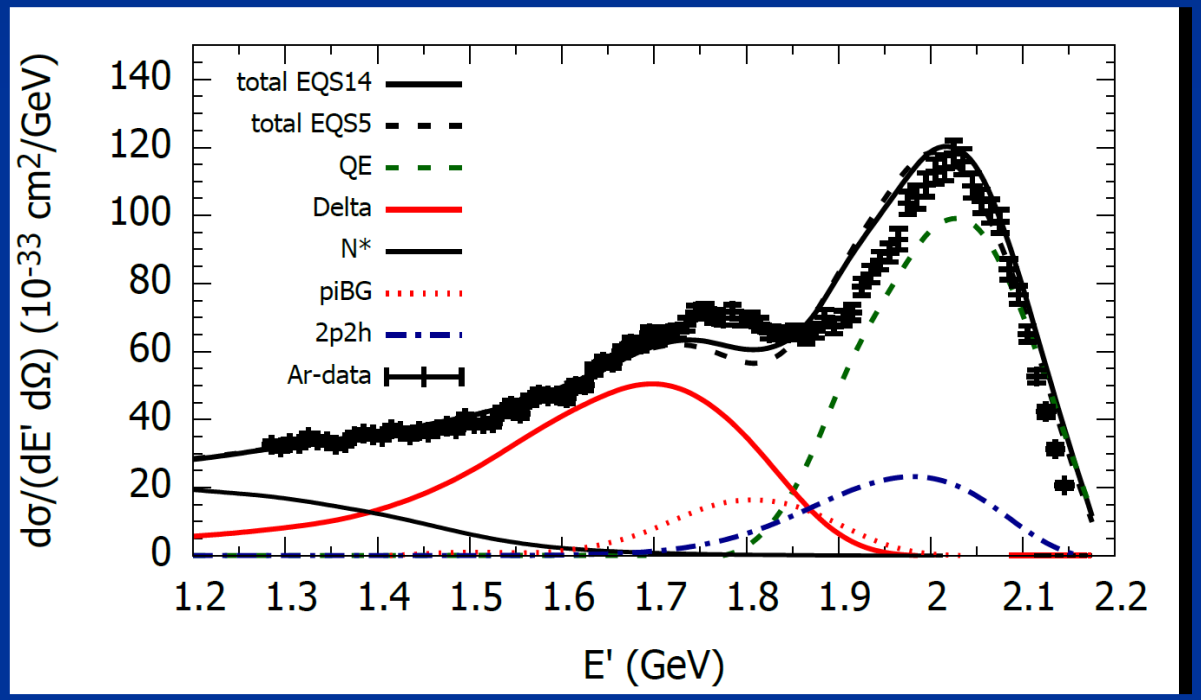
- **GiBUU** describes: (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions on nuclei
  - photon and electron induced reactions on nuclei
  - neutrino induced reactions on nuclei

using the same physics input! And the same code!

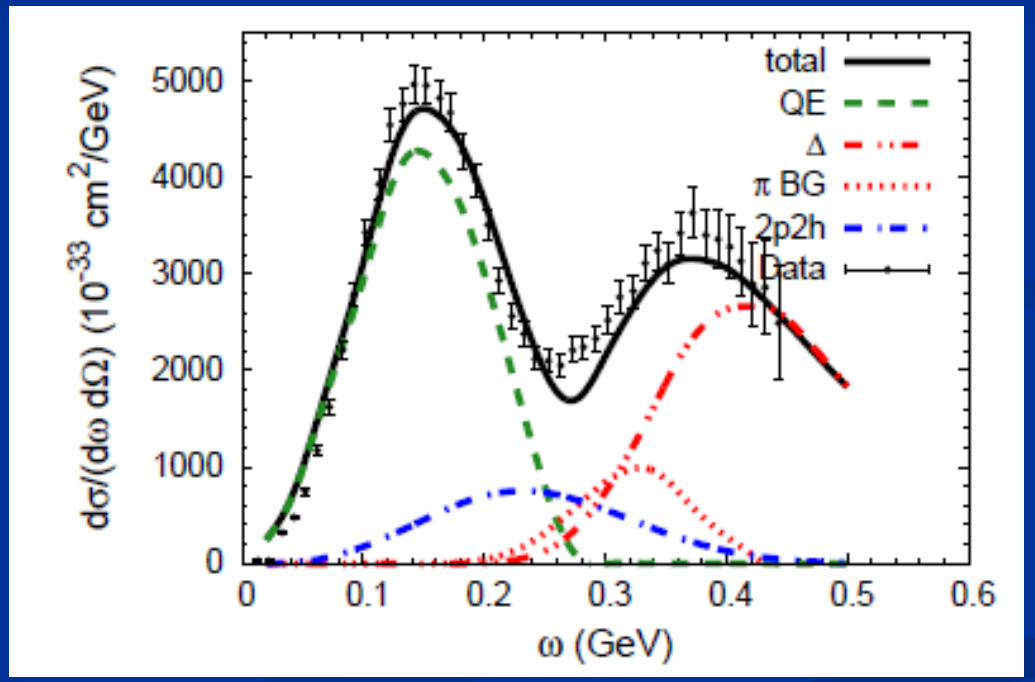
NO TUNING!

Inclusive QE Electron Scattering

- a necessary check for any generator development



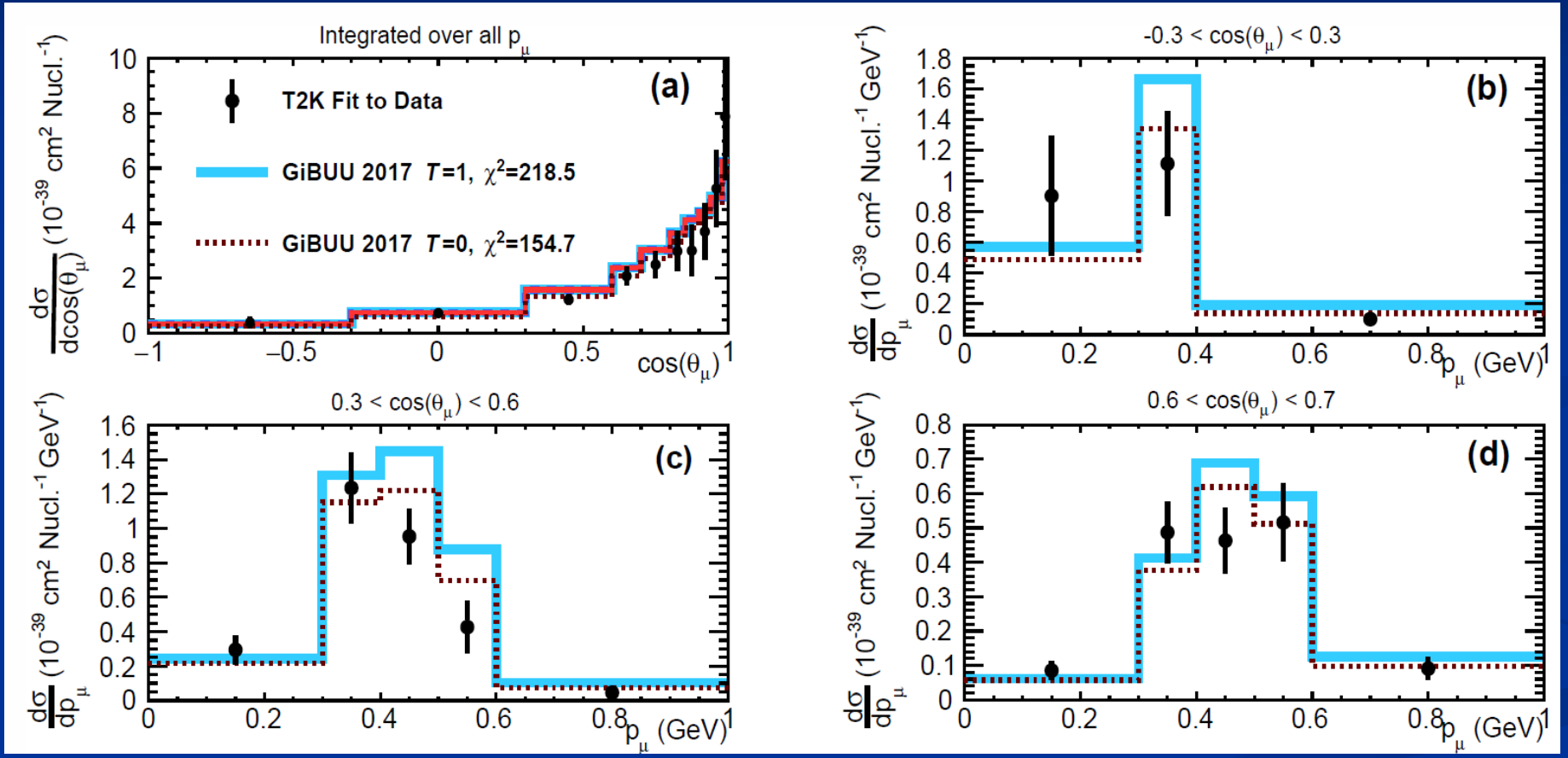
2.2 GeV, 15 deg, $Q^2 = 0.3$ GeV^2 Target: C



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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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 for Ar:

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

- Only available test: ArgoNeuT data

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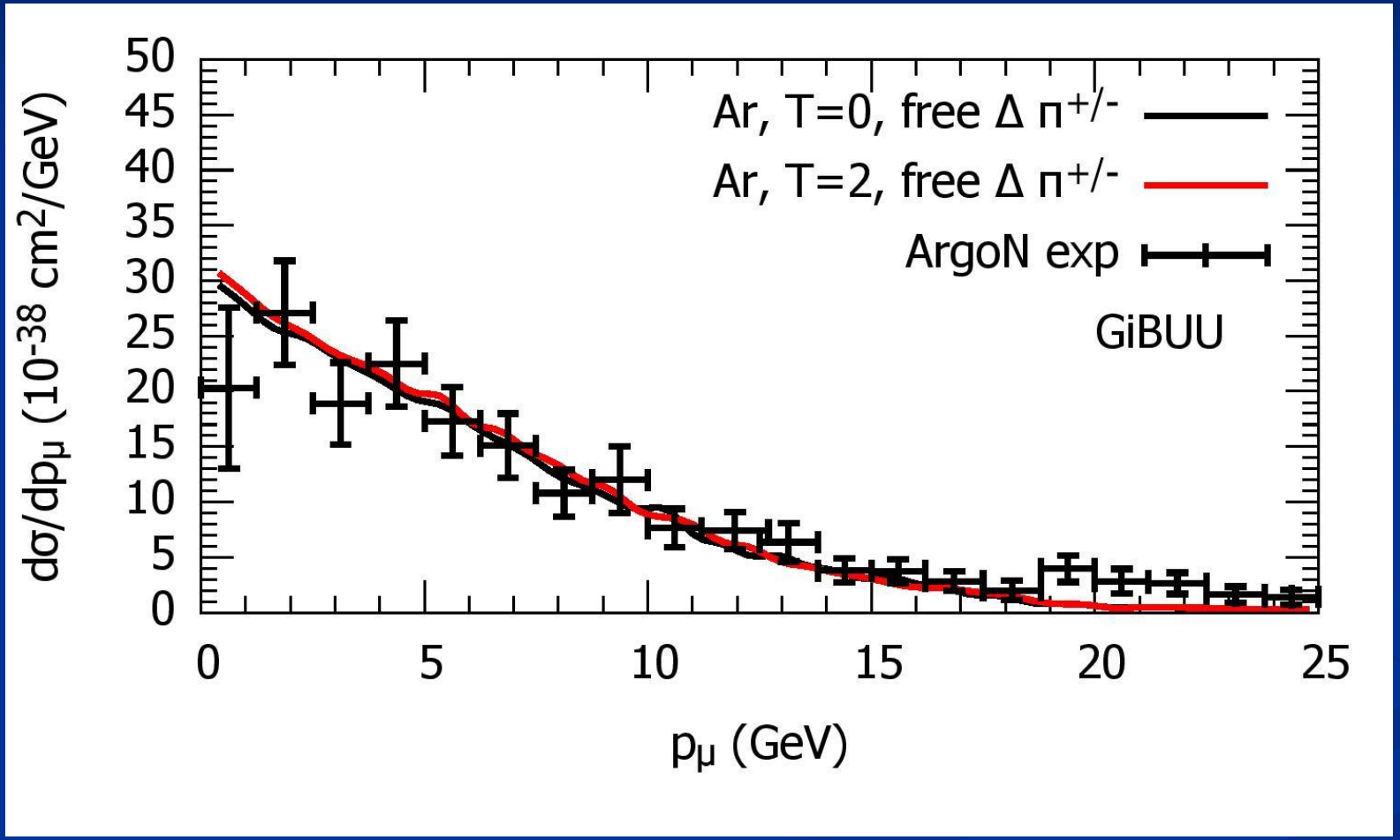
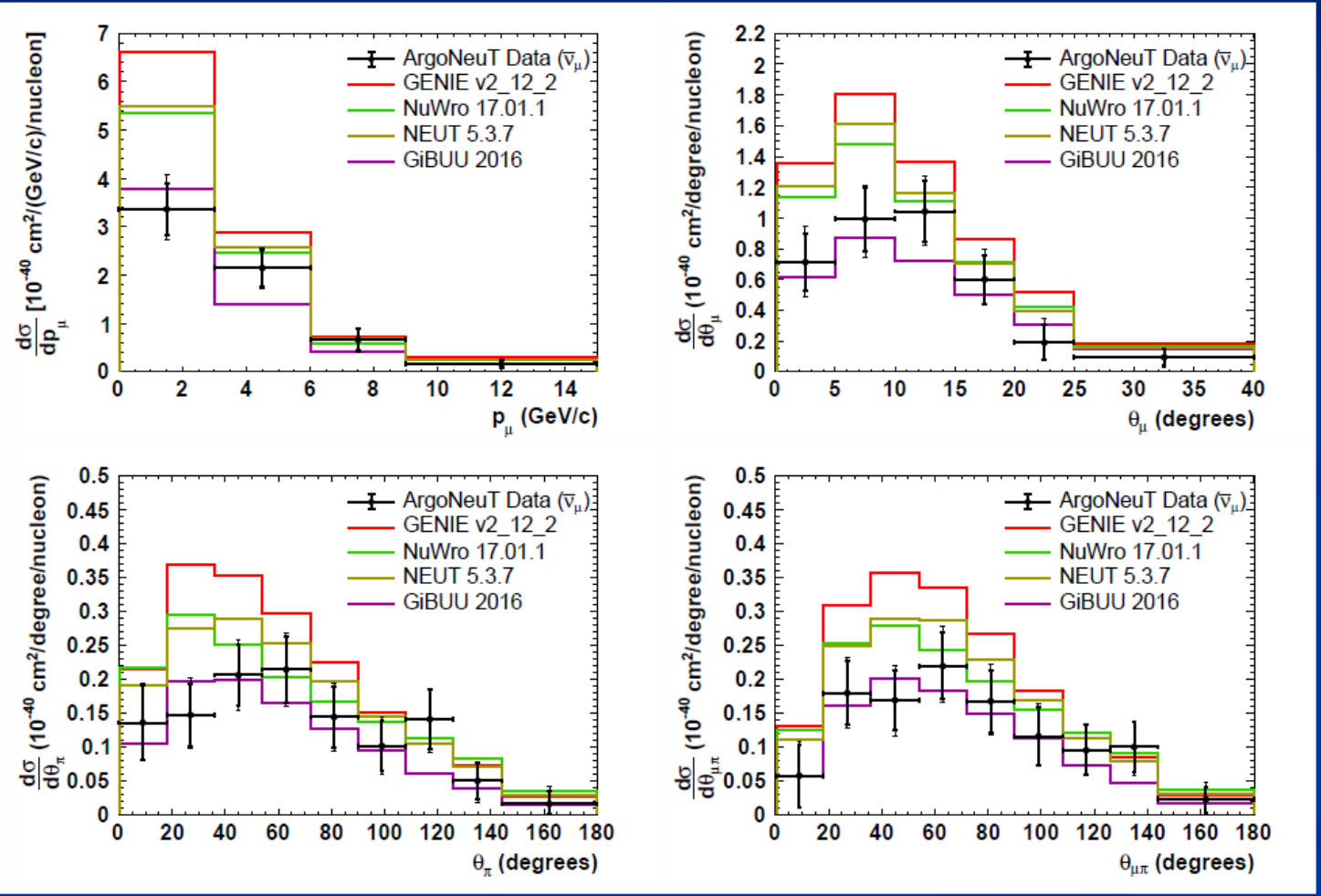
ArgoNeut inclusive



Data: ArgoNeuT

Phys.Rev. D89 (2014) 112003

Pion Production on LAr



ArgoNeut

arXiv:1804.10294

Antineutrinos

Excellent agreement of GiBUU with Ar data

NO Tune

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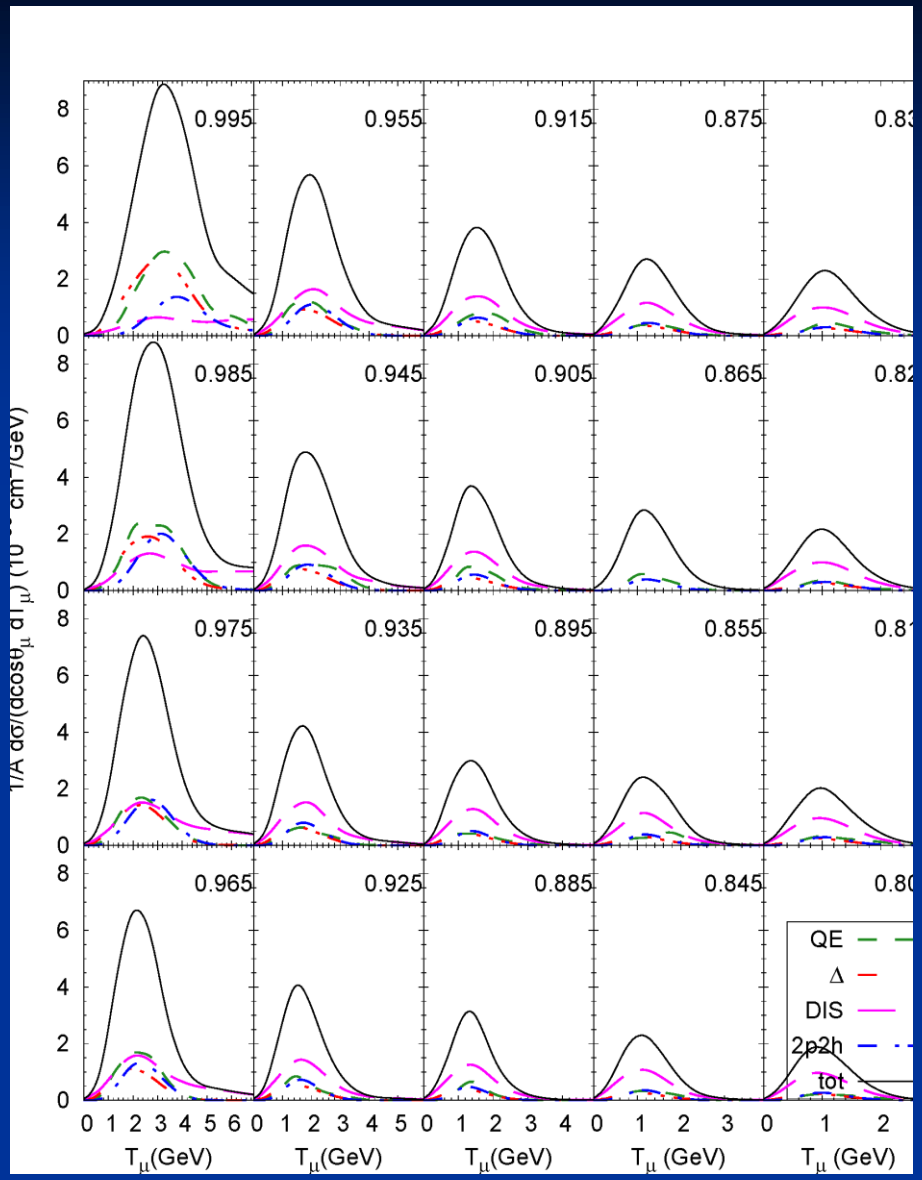
DUNE ND



Double-differential cross section

X-section strongly forward peaked

Δ excitation as strong as QE

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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

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Summary II

- Electron-induced reactions provide crucial test of generator physics, but so far only for inclusive X-sections available
- For calorimetric energy reconstruction at DUNE need (e,Ar) data for nucleon spectra and multiplicities.

- Theory and Generator Development should be an integral part of any experiment (and its funding!).

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