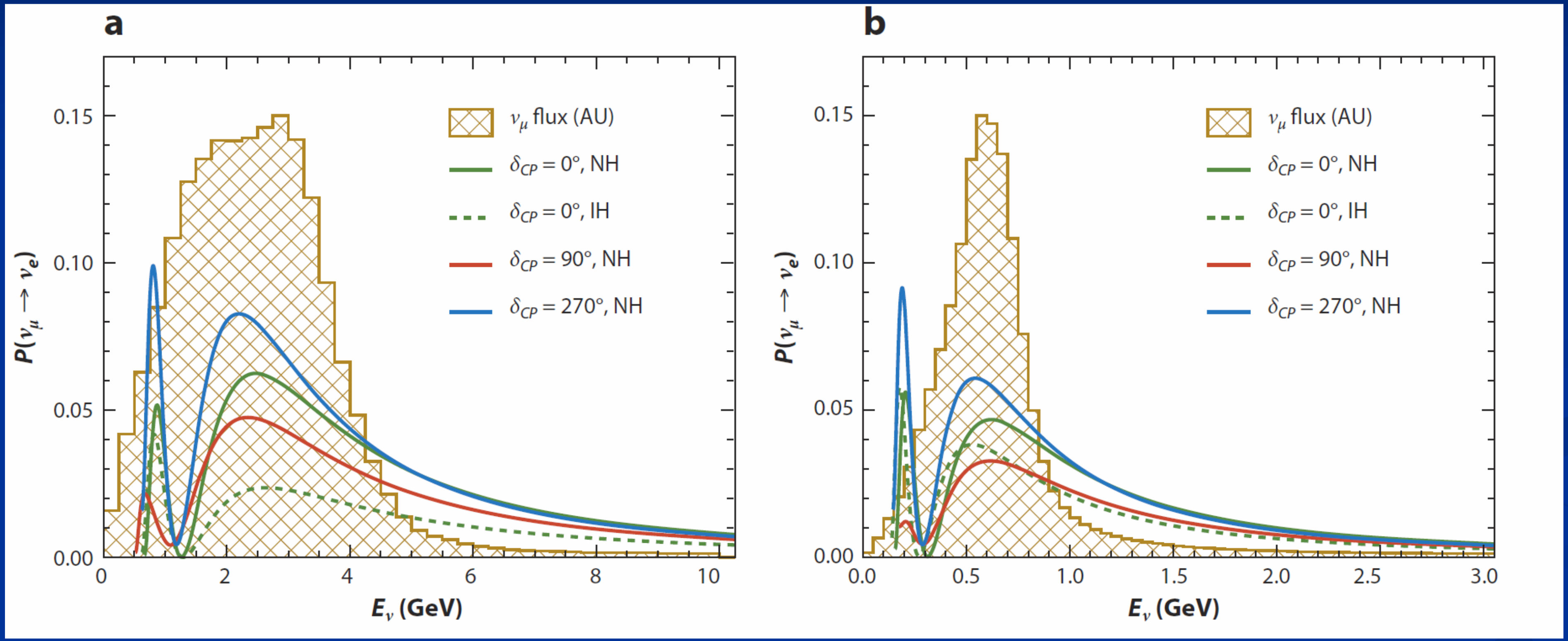
Physics of ν-A Interactions

Ulrich Mosel

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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%

What is (not) measured in a LBL exp?

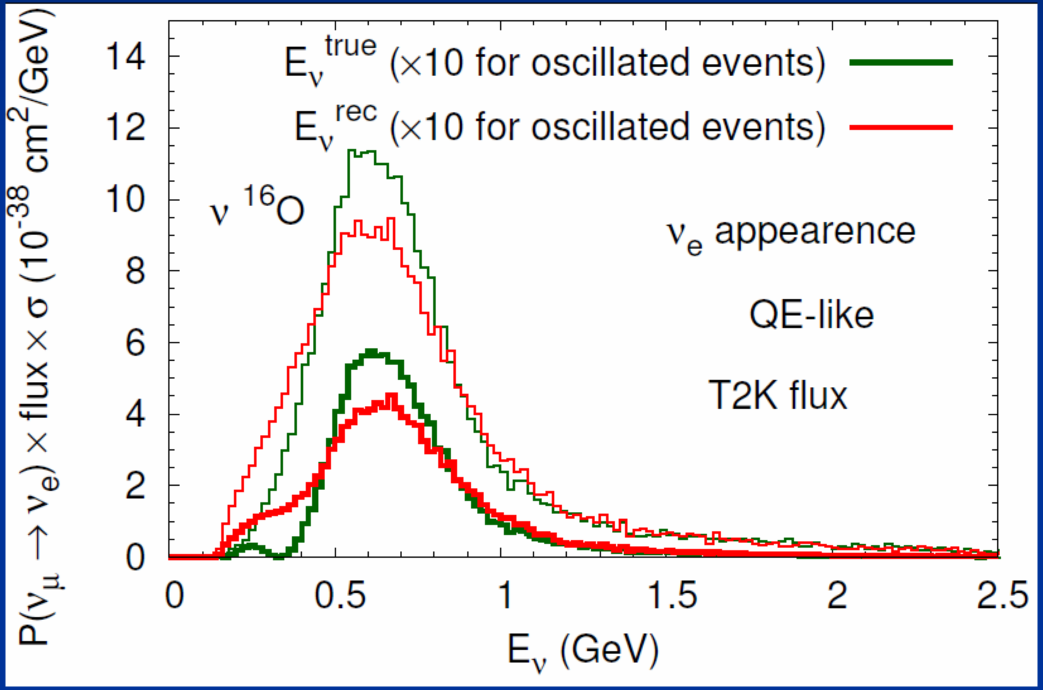
- The neutrino energy on this plot is not measured
- LBL experiments measure only flux-averaged cross sections

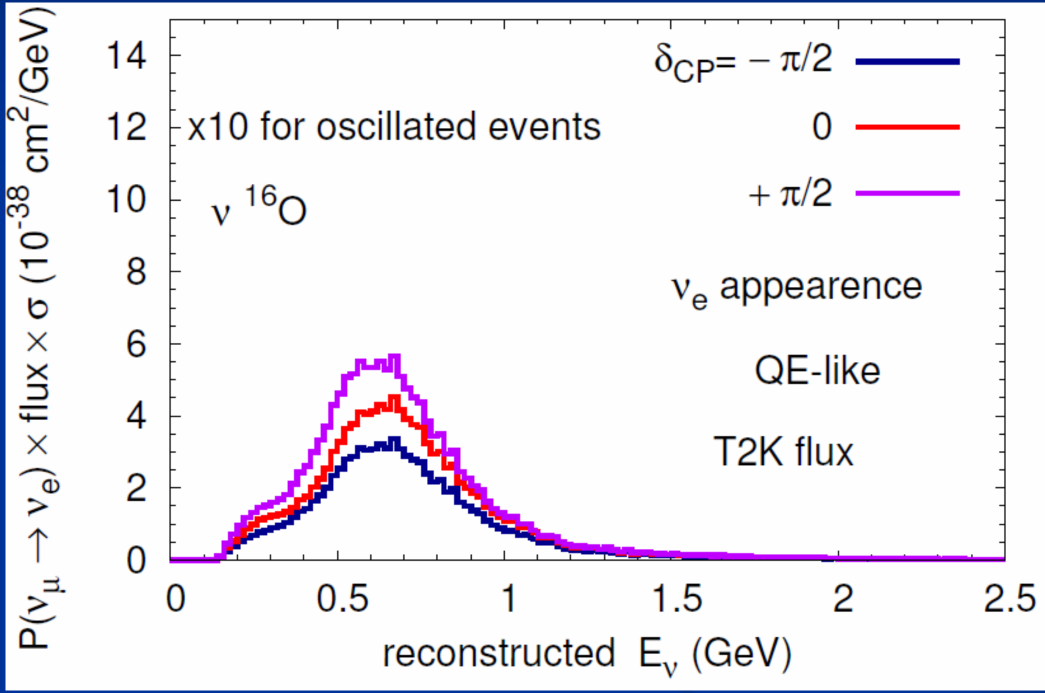
BUT:

- Extraction of neutrino oscillation parameters requires neutrino energy event by event
  ➔ needs nuclear theory and modeling

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

First Take-Home Message

- Whenever you see a plot with the neutrino-energy on an axis:
  ask yourself where this energy comes from!

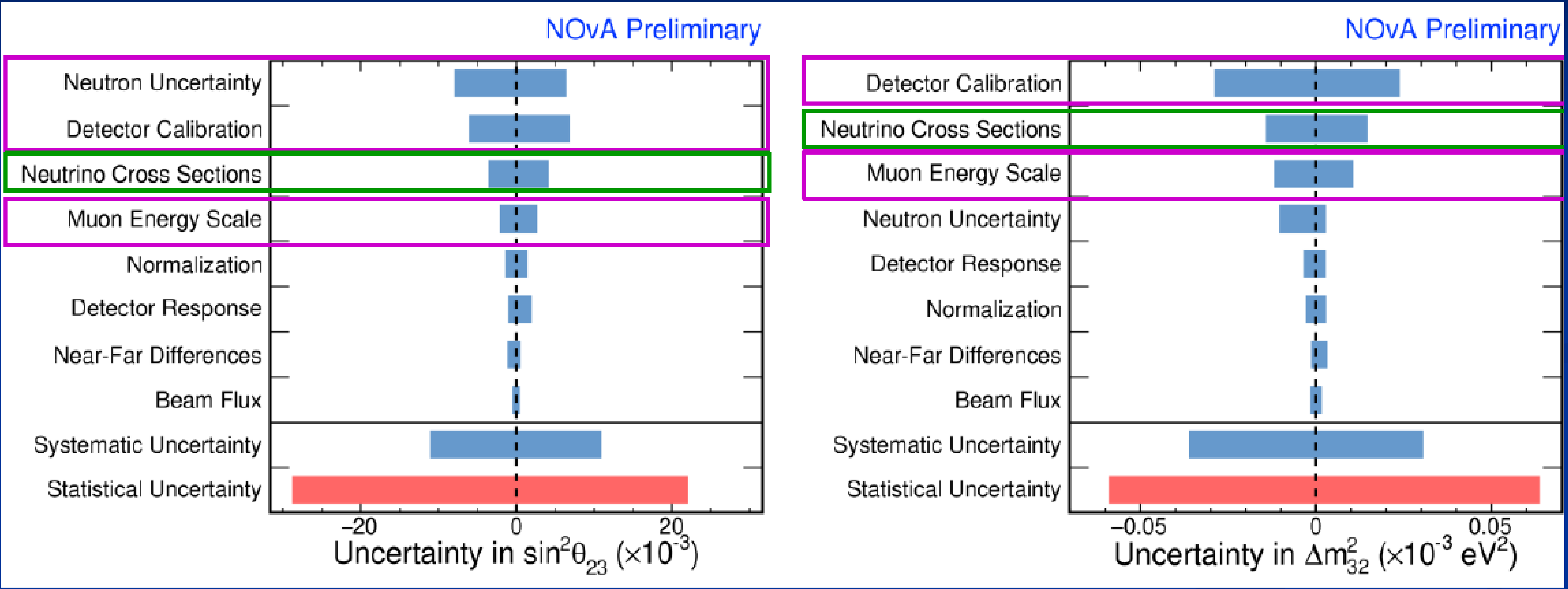
Problem: Neutrino Energy

- The incoming neutrino energy on the abscissa of all such plots is not known, but must be reconstructed from an only partially observed final state (detector limitations!), backwards‘ to the initial state

- This reconstruction requires:
  1. Knowledge of neutrino-nucleus cross sections

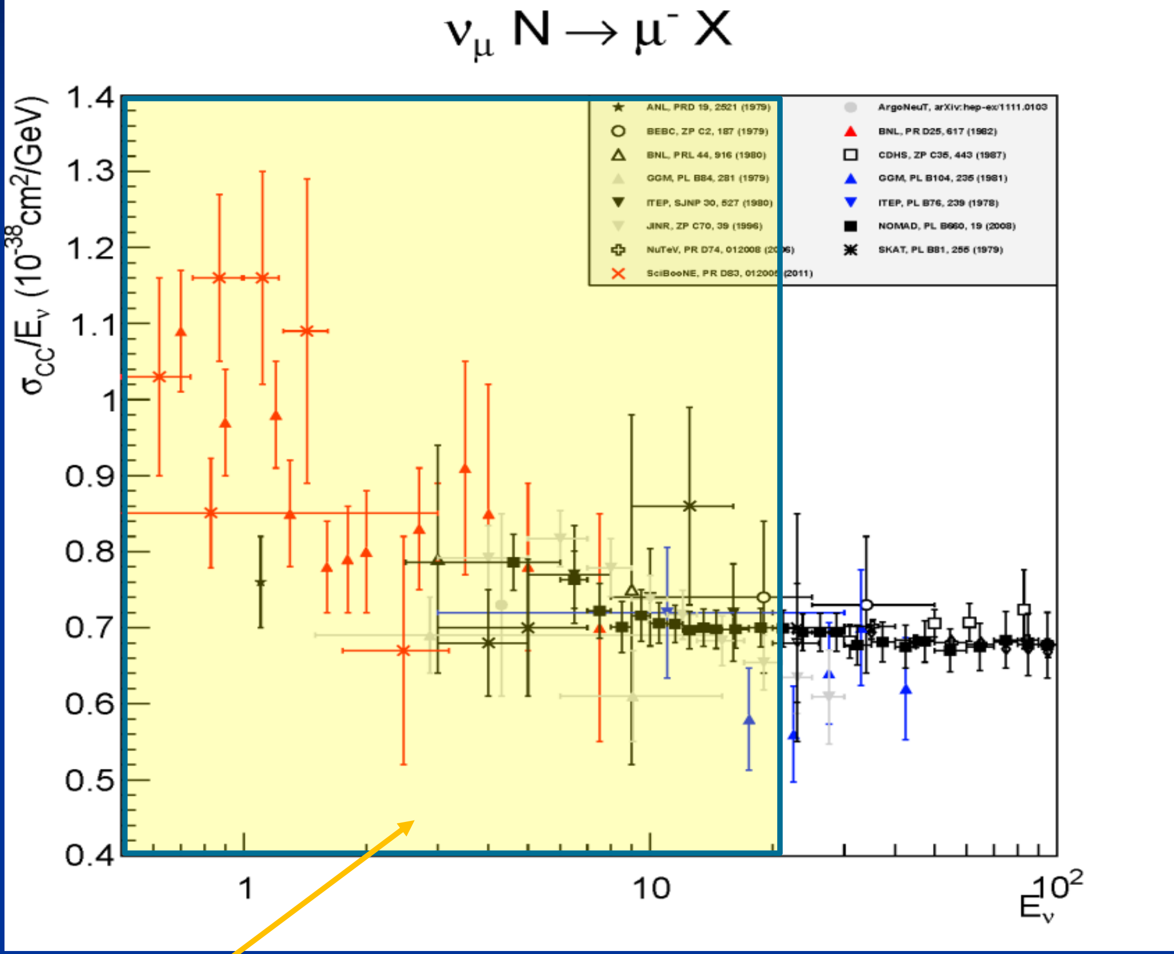
     <→ knowledge of neurino-nucleon cross sections
  1. Transport of initially produced hadrons through the nuclear volume, needs good knowledge of hadron-hadron FSI cross sections

Neutrino Parameter Uncertainties



From J. Wolcott, NUINT2018

Neutrino-Nucleon Cross Sections



All modern long-baseline experiments

Experimental error-bars directly enter into neutrino-nuclear cross sections and limit accuracy of energy Reconstruction, most of these data ~ 35 years old

BUT: this is only part of the problem, The other part is FSI, since experiments use nuclear targets

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First Conclusion

- The elementary cross sections for
  neutrino + nucleon
  can only be improved by new measurements on *H* and *D* targets
- Theory cannot deliver these observables (within the next 10 years)

  not even in LQCD

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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A wake-up call for the high-energy physics community:

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

Nuclear Physics determines response of nuclei to neutrinos

Wake up, Dr. ….., you're being transferred to low energy physics

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Nuclear Physis

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 ‚standard' 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-Sehgal for resonances
- Time to build new, consistent generators, based on present day's nuclear physics, both for initial interaction and the final state interactions

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Proto-Dune Generator

- Quantum-kinetic Transport is the state-of-the-art method to describe non-equilibrum nuclear processes (e.g. QGP ALICE physics)
- Transport can also be used to describe νA reactions: it evolves an 8-dimensional phase-space distribution $F(x,p)$ in time.
- Theoretical Basis: Kadanoff-Baym equations in the gradient approximation, Botermans-Malfliet off-shell handling

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Quantum-kinetic Transport Theory

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

Cross sections go here

For each particle species 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 : 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!

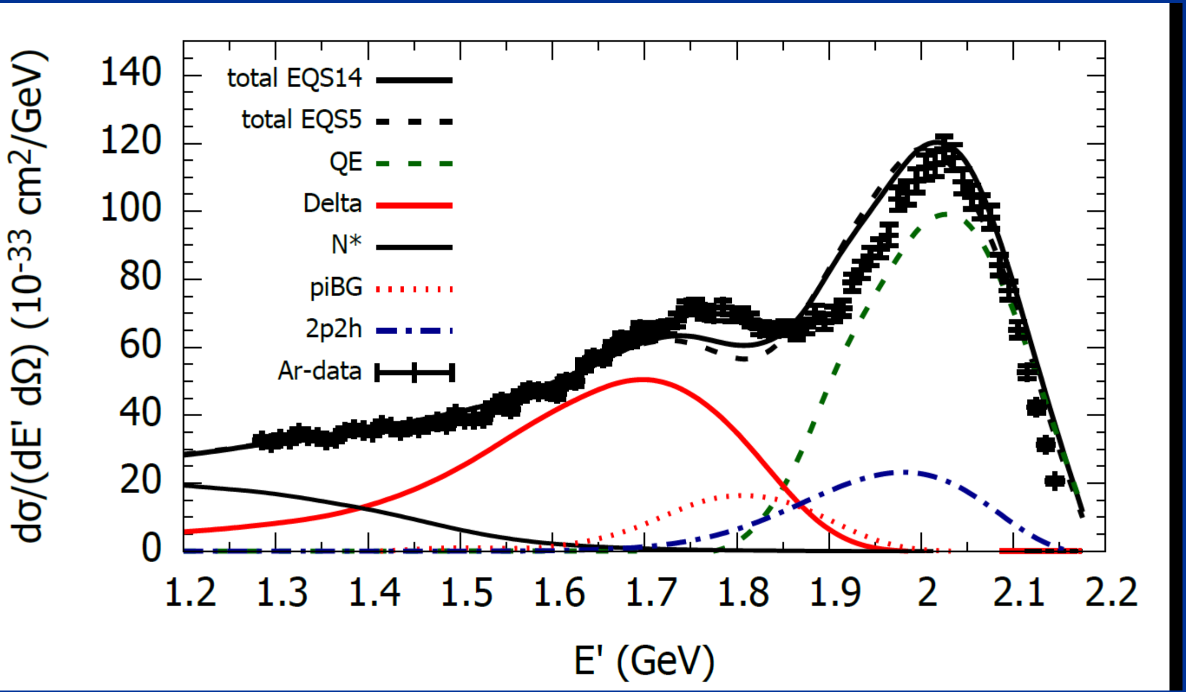
NO TUNING!

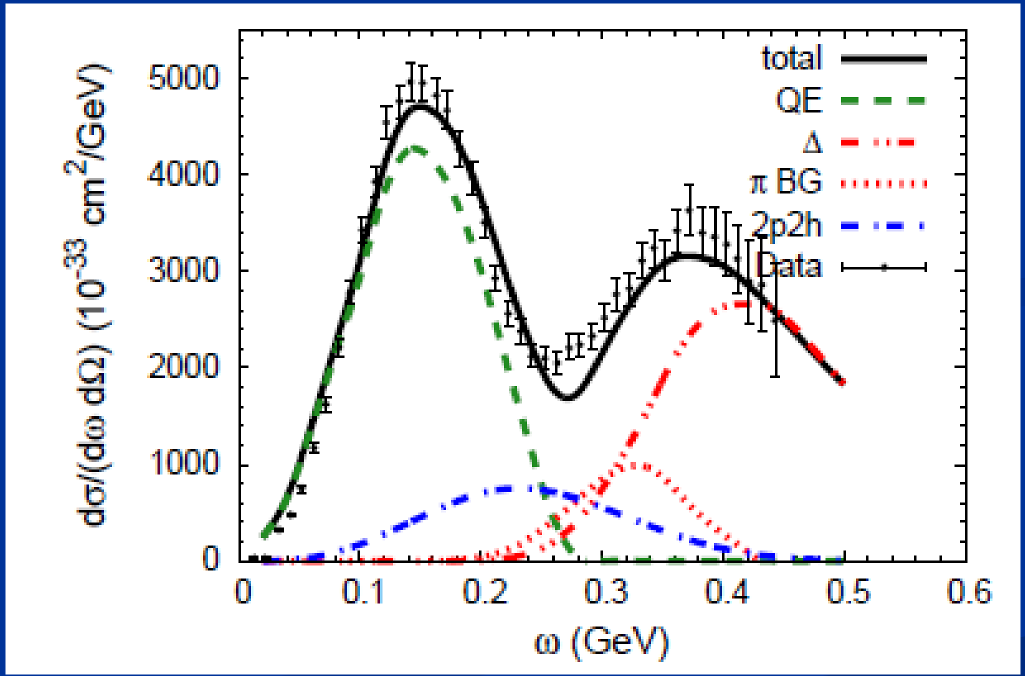
The GiBUU Generator

- Model and numerical algorithms well documented: Buss et al, Phys. Rept. 2012
- Code written in modern Fortran 2003, open source, well commented throughout
- Produces millions of events on ‚normal' PC, within a day of running time
- Gives result file with four-vectors of all final state particles on event-by-event basis, plus other relevant information, such as history-info on primary reaction mechanism (QE, DIS, Res,…)
- Allows for reweighting of events because of history info
- Applicable for quasiclassical regime: energy transfer >~ 50 MeV

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

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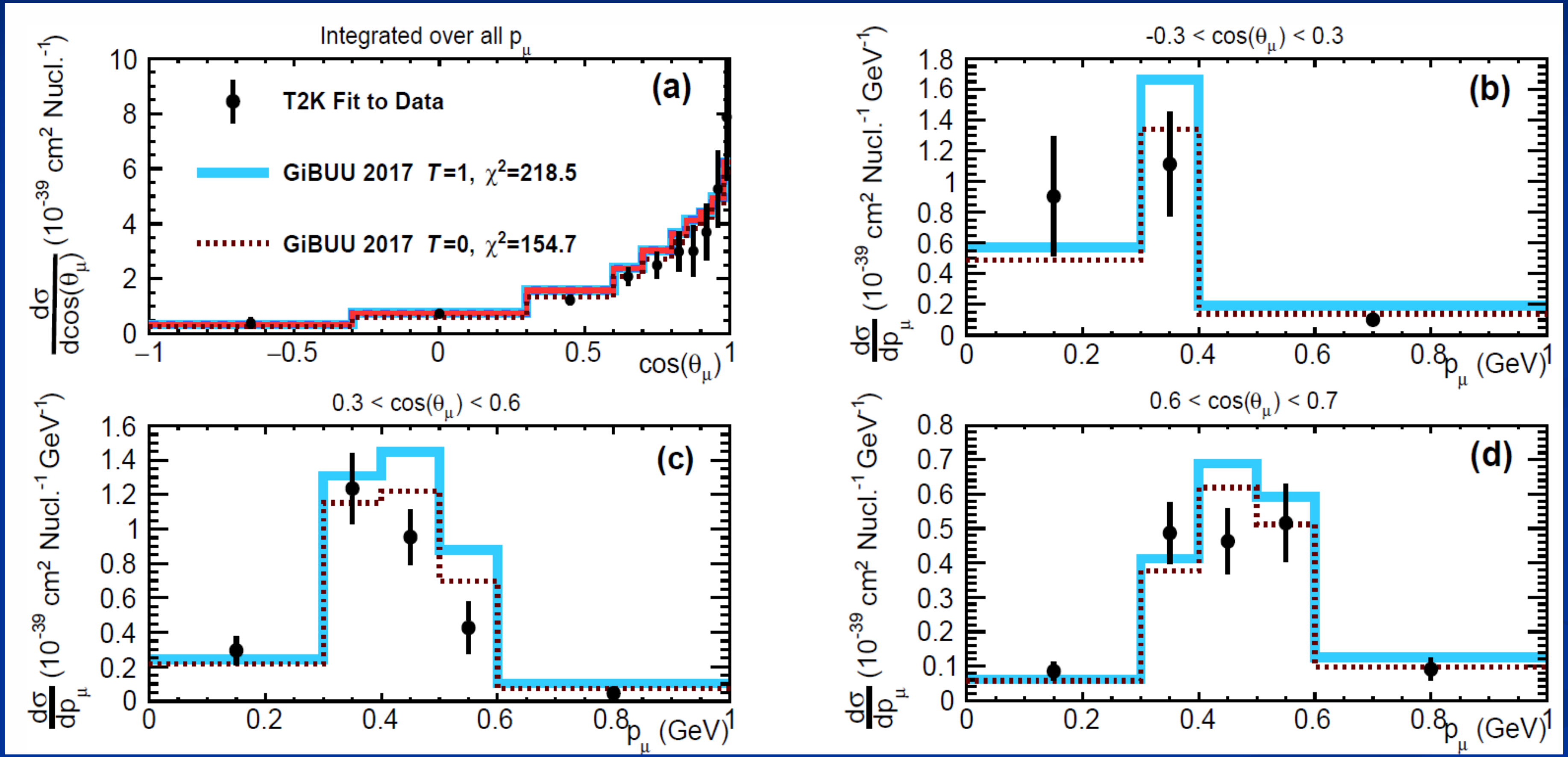
T2K Inclusive Cross Section

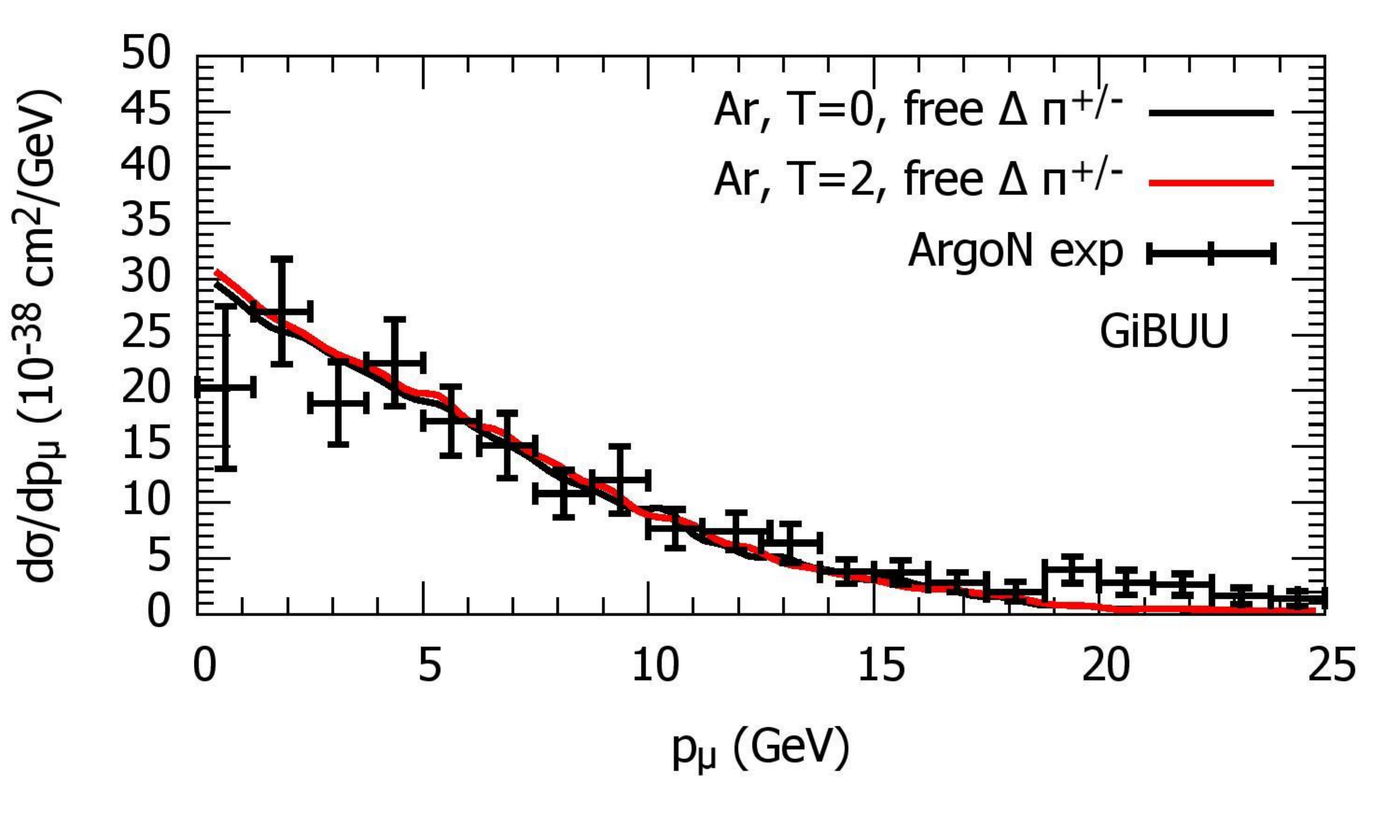


S. Dolan et al, Phys. Rev. C 98, 045502 (2018)

GiBUU curves differ by factor 2 in 2p2h

Target: CH

ArgoNeut inclusive

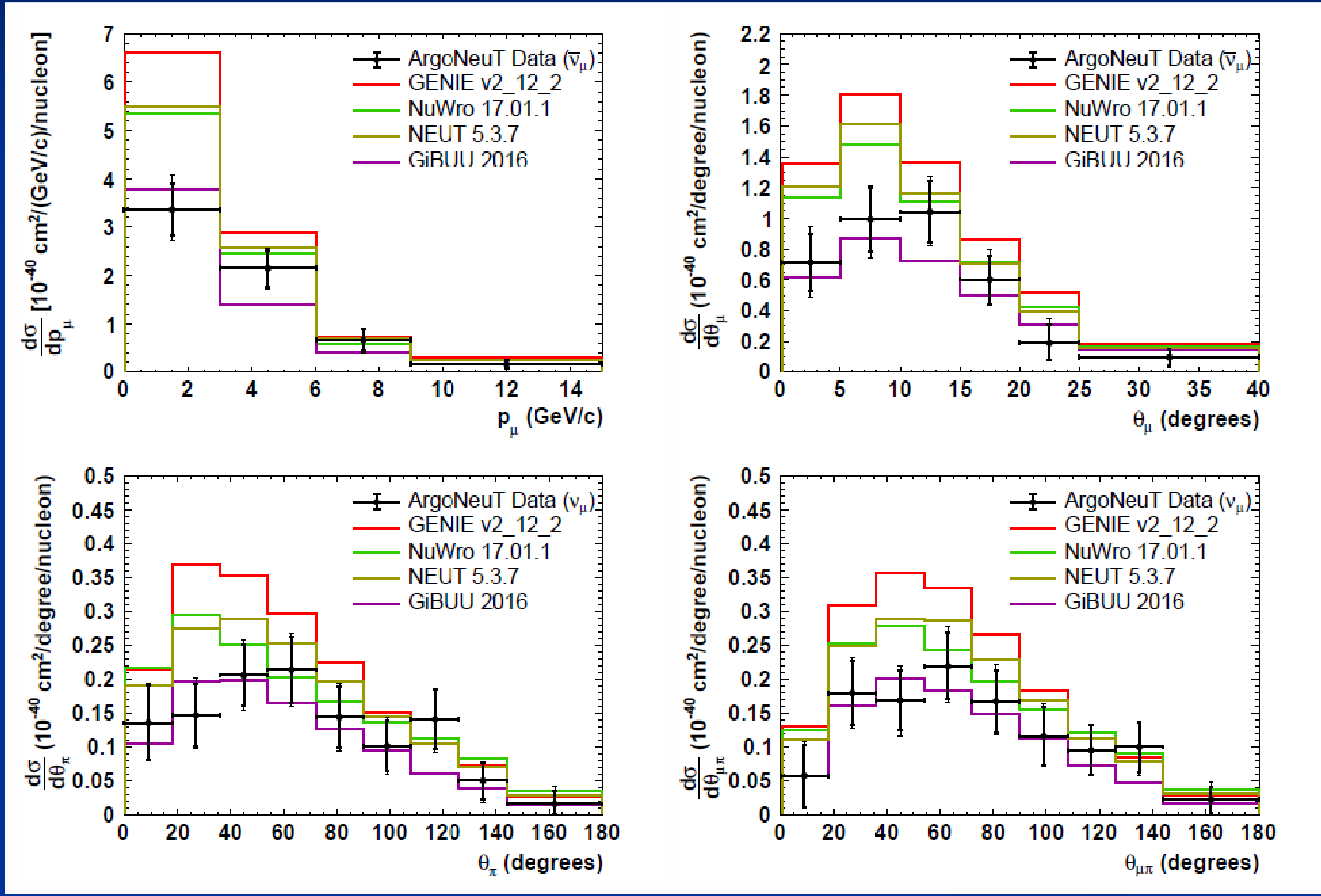


Data: ArgoNeuT

Phys.Rev. D89 (2014) 112003

ArgoNEUT used a high-energy beam close to DUNE

Pion Production on LAr



ArgoNeut
arXiv:1804.10294

Antineutrinos

Excellent agreement of GiBUU with Ar data
NO Tune

DUNE Challenge: ^{40}Ar

- ^{40}Ar not isospin symmetric, N > Z: isospin T = 2

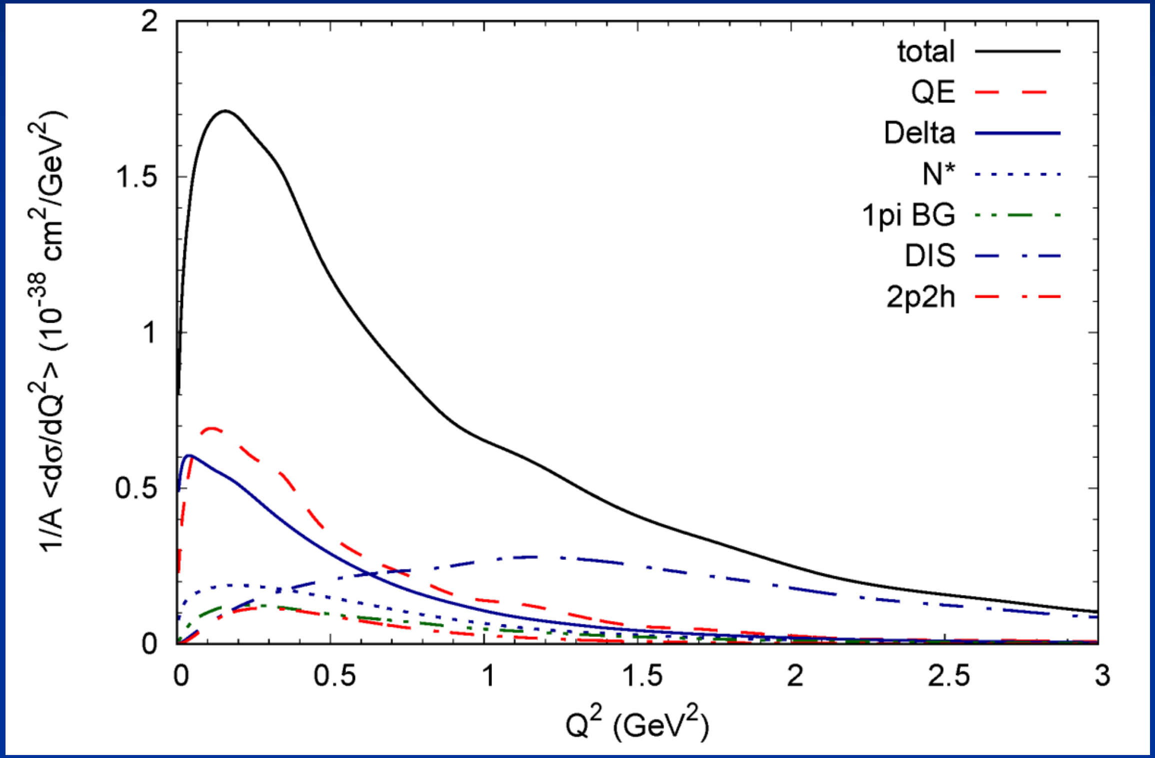
- Isospin dependence of nuclear processes?

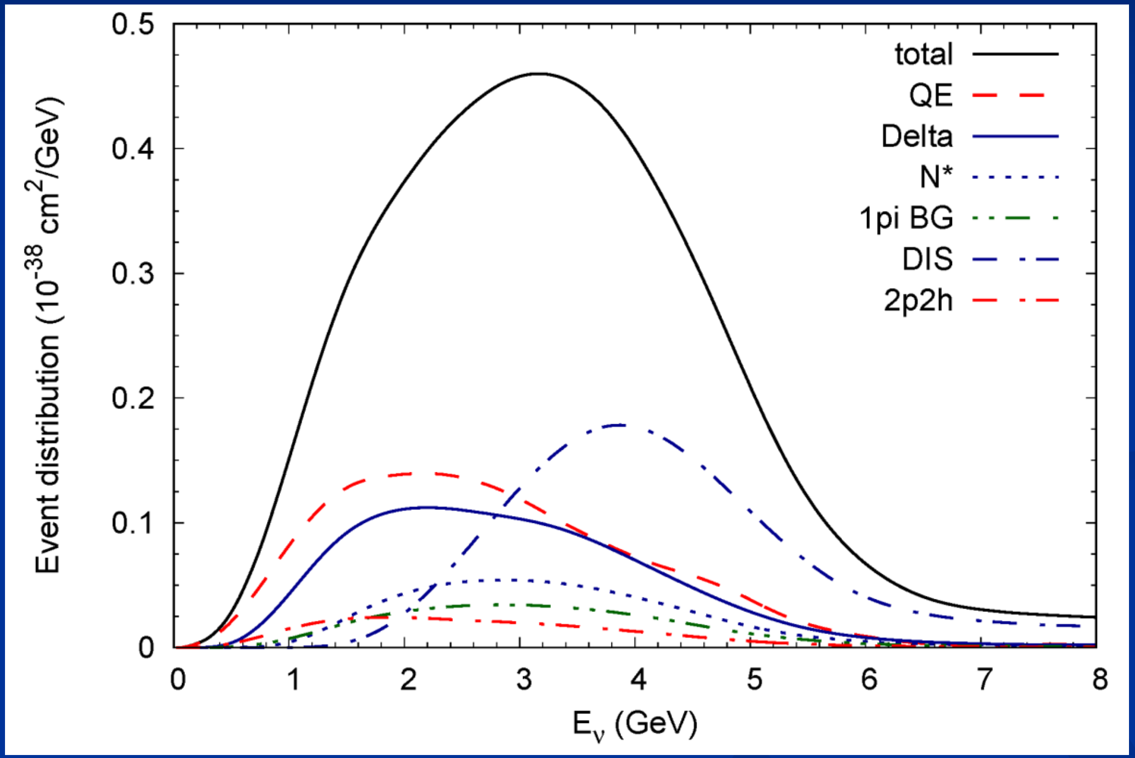
- Relation to electron scattering process?

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

- CHECK: how well does GiBUU do on ArgoNeut data?

Event Distributions in DUNE ND

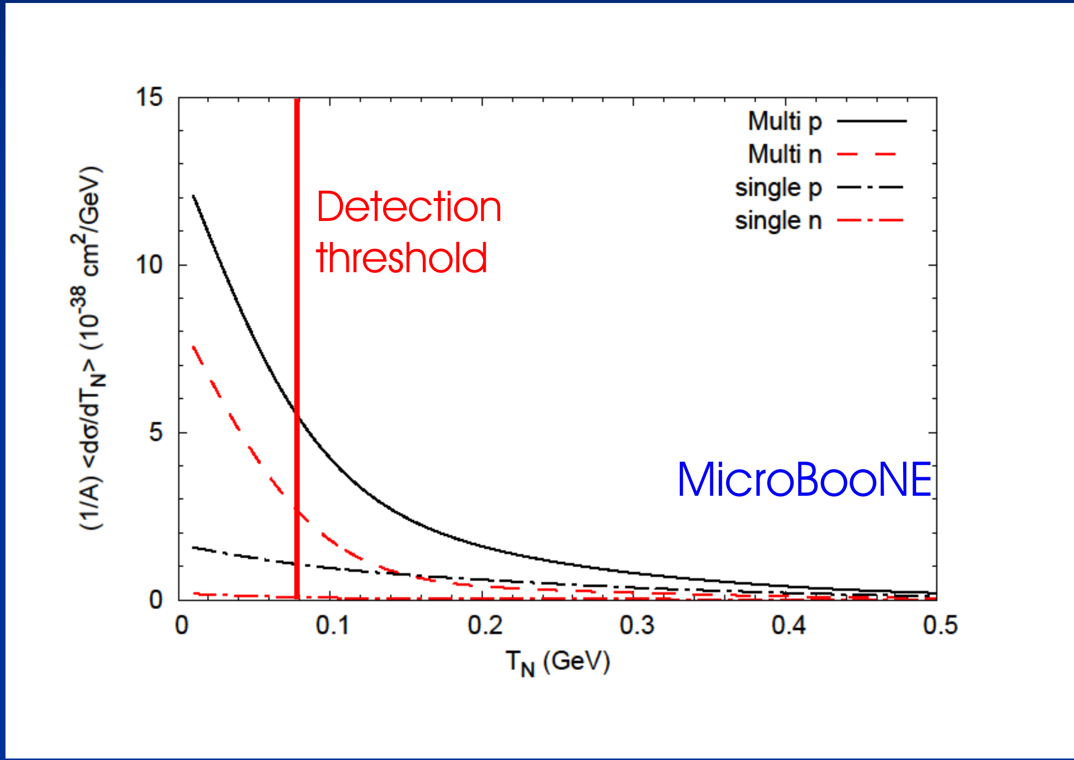


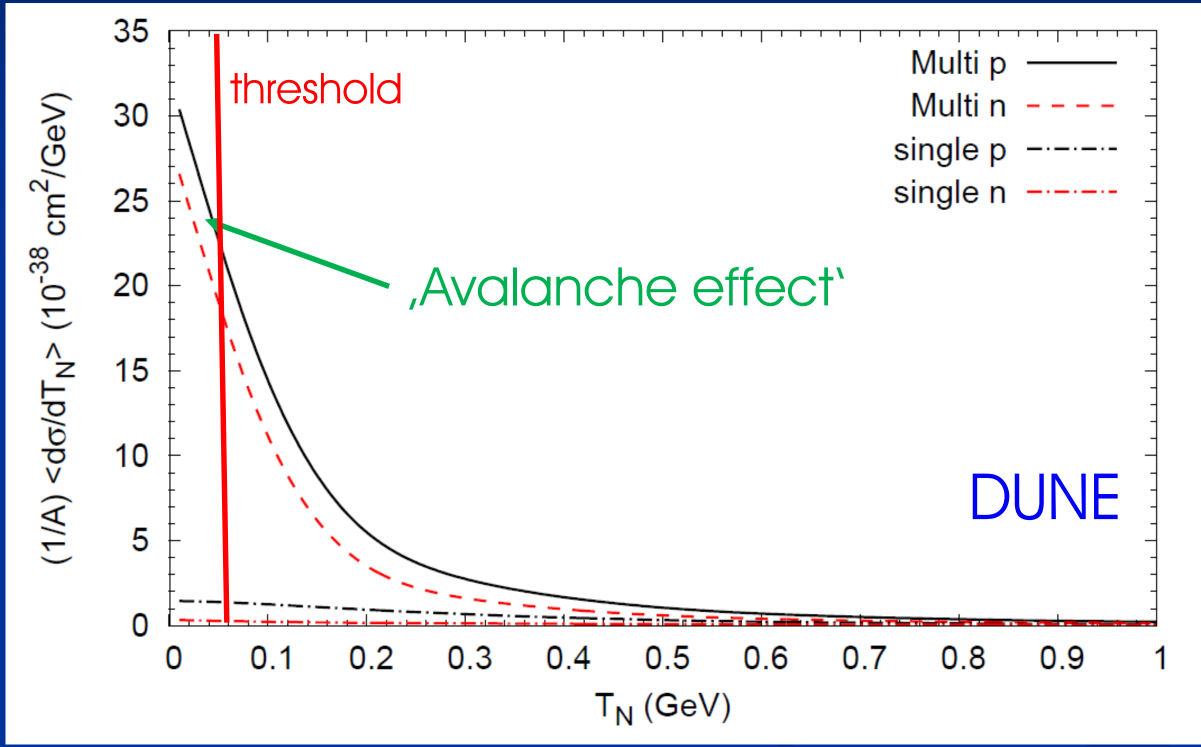


2p2h contributes with $< 5\%$

Pion channels (Res + DIS) are dominant

Nucleon Spectra

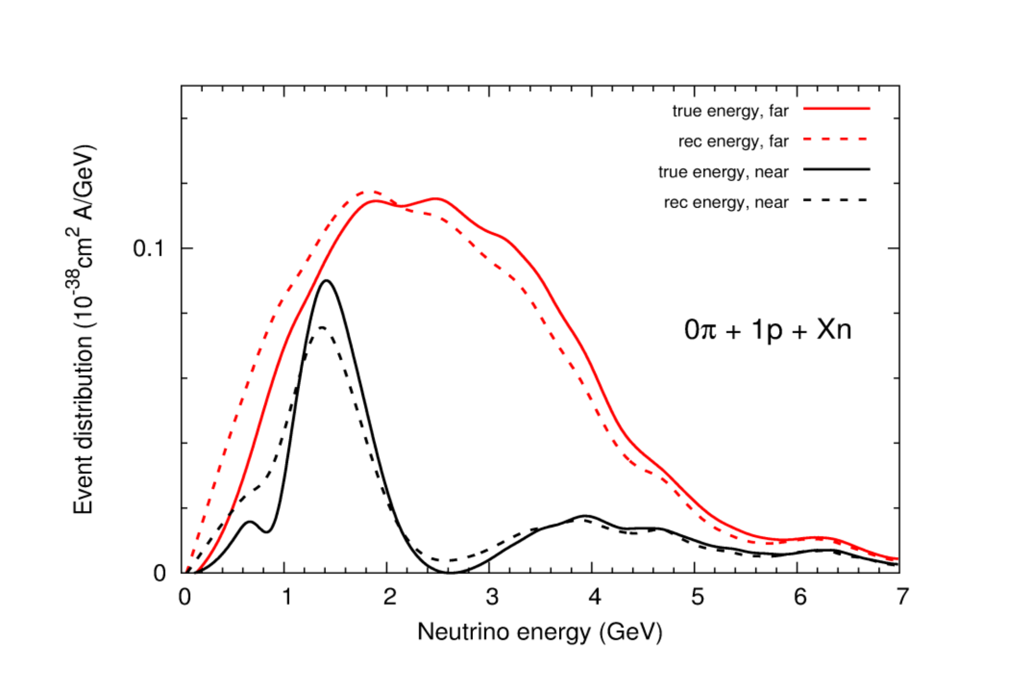




At MB $n < p$, at DUNE $n \sim p$:
n not suppressed at DUNE because of pi-production channels

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 at least about 50 (T2K) or 100 (DUNE) MeV

- Uncertainties in *elementary* νN *cross sections* limit any reconstruction
- *Nuclear effects* complicate the energy reconstruction even further
- Need generators for E-reconstruction, based on up-to-date Nuclear Theory with predictive power and no artificial degrees of freedom

Summary II

- GiBUU is a first step into that direction (ProtoDUNE generator), gives good description of all cross sections, both for electrons and neutrinos, without tune
- Experiments at the DUNE ND are essential because they allow to test generators on an unexplored target (Ar) in an unoscillated beam.
- Until DUNE operates: have an Ar target (ProtoDUNE ?) in a higher energy beam (at CERN?).
- Theory and Generator Development should be an integral part of any such 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
  4. Mosel, J. Phys. G 46, no 11 (2019):
     https://dx.doi.org/10.1088/1361-6471/ab3830
     general review of neutrino generators

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