University of Texas at Arlington

A GiBUU-Based Monte Carlo Simulation for Neutrino Experiments

Leo Aliaga

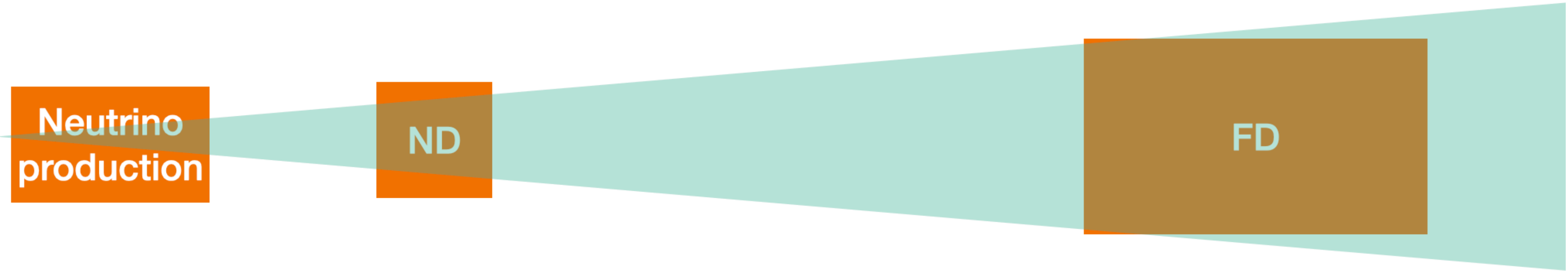
(leonidas.aliagasoplin@uta.edu)

University of Texas at Arlington

September 17, 2024

The 25th International Workhop on Neutrinos from Accelerators (NuFact-2024), Argonne National Lab

Why do we need alternative generators?



Neutrino oscillation experiments use models of the neutrino flux, target material, detector geometry, and interaction cross sections to produce realistic event samples

$$N_{pred}^{FD}(E_{\nu}^{reco}) = \Phi(E_{\nu}^{true})\ \sigma(E_{\nu}^{true})\ P(\alpha \rightarrow \beta, E_{\nu}^{true})\ \epsilon(E_{\nu}^{true})\ S(E_{\nu}^{true}, E_{\nu}^{reco})$$

In neutrino oscillations, the prediction at the FD needs to know (**φ x σ**) to interpret $\mathbf{N_{obs}}$ as **P(α->β)**:

In US-based experiments, **σ** is commonly modeled with GENIE (*Nucl. Instrum. Meth. A 614, 87, 2010*)

Why do we need alternative generators?

Fermilab oscillation experiments (e.g., SBN, NOvA, and DUNE) rely on the visible energy in the detector

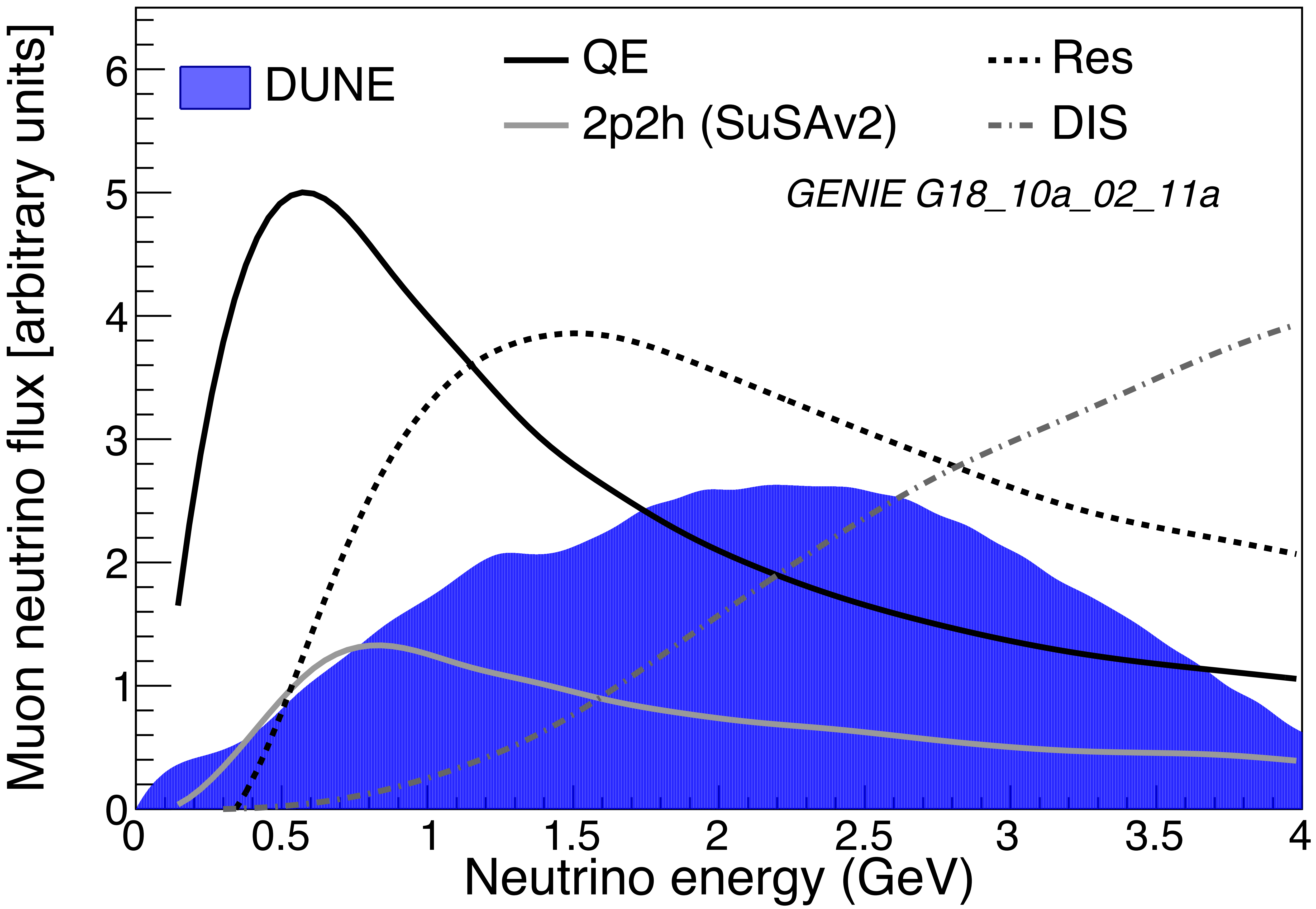
$$E_\nu = E_{\mu/e} + E_{hadrons/showers}$$

requires a thorough understanding of the final states of the reaction

Particularly challenging for DUNE

DUNE's peak at 2-4 GeV has contributions from all interaction types:

- QE
- Res
- 2p2h
- DIS



Alternative generators crucial for DUNE

Energy Reconstruction Challenge

- Reconstructing neutrino energy from the total energy deposited in the detector is complex.
- It requires accounting for all hadronic energy and comes with significant systematics.

Key Consideration: Neutron Contributions from models

- 2p2h: contributions from np, nn, pp initial state pairs
- FSI: neutrons produced through FSI
- Res and DIS: neutron energy fraction

Alternative generators crucial for DUNE

Energy Reconstruction Challenge

- Reconstructing neutrino energy from the total energy deposited in the detector is complex.
- It requires accounting for all hadronic energy and comes with significant systematics.

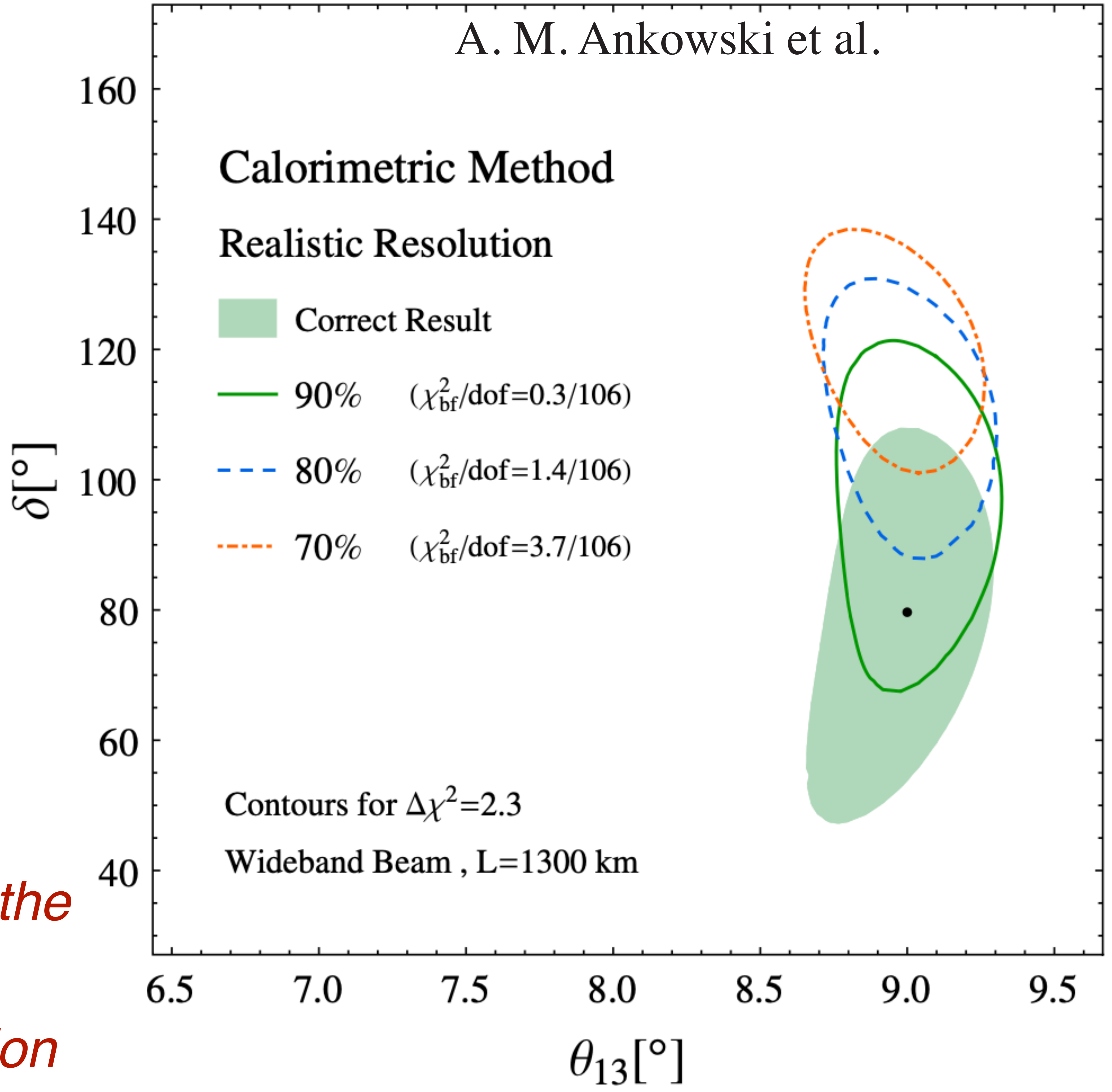
Key Consideration: Neutron Contributions from models

- 2p2h: contributions from np, nn, pp initial state pairs
- FSI: neutrons produced through FSI
- Res and DIS: neutron energy fraction

Physics Impact:

- *Underestimating the missing energy could significantly affect the physics output*
- *It may lead to biases in energy reconstruction and interpretation*

PHYSICAL REVIEW D **92,** 091301(R) (2015)



Why do we need alternative generators to GENIE?

Improve simulation-based correction and estimation in

- *Signal-to-background migrations (purity)*
- *Efficiency*
- *Neutrino energy reconstruction*

Oscillation Analysis:

- *Crucial for extrapolations in model-dependent analyses*

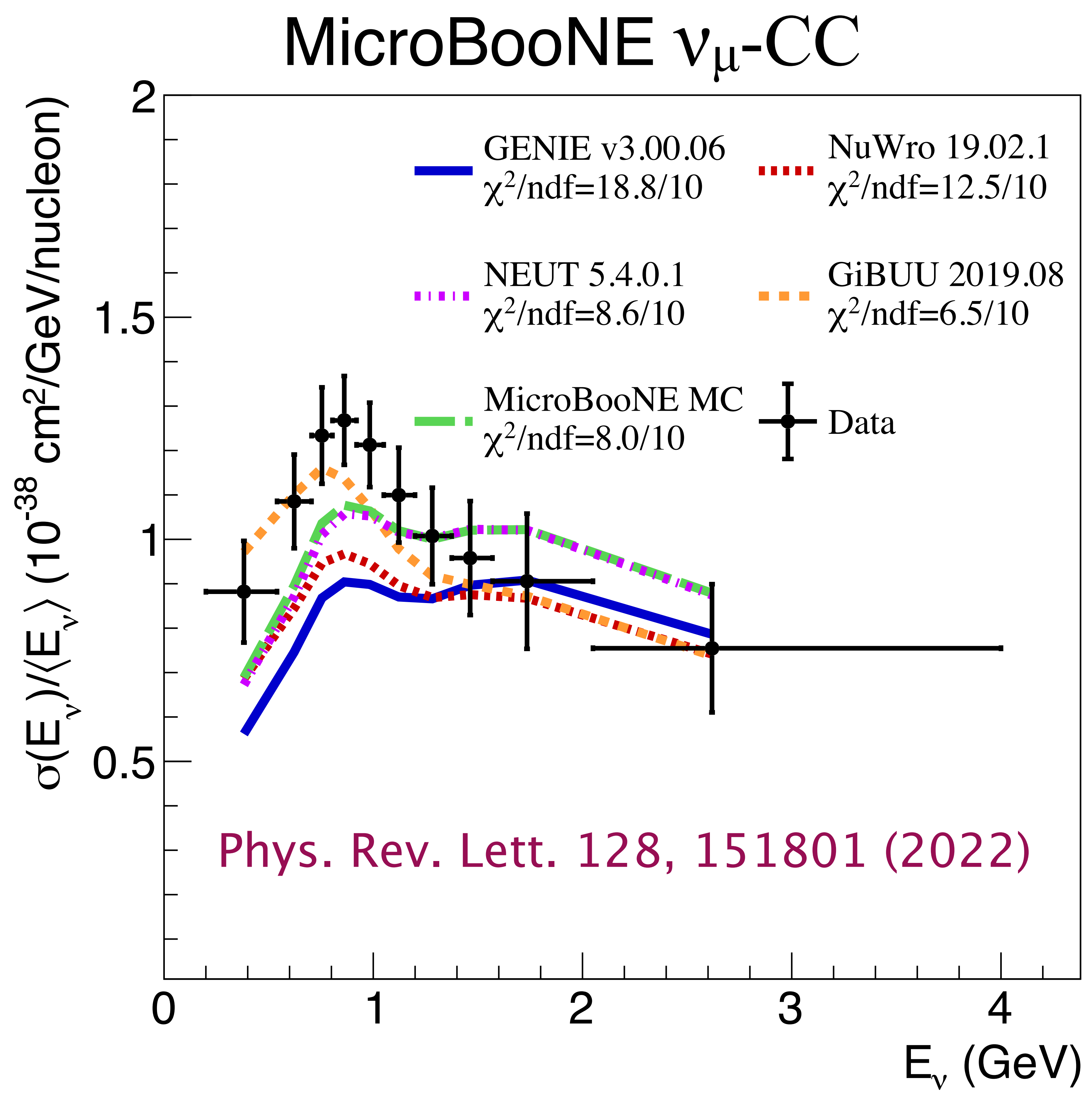
Model-Independent Measurements

- *Essential for Neutrino-argon cross sections and and to Beyond Standard Model searches*

GiBUU (https://gibuu.hepforge.org)

The GiBUU Project (Giessen Boltzmann-Uehling-Uhlenbeck), authored by the Giessen group:

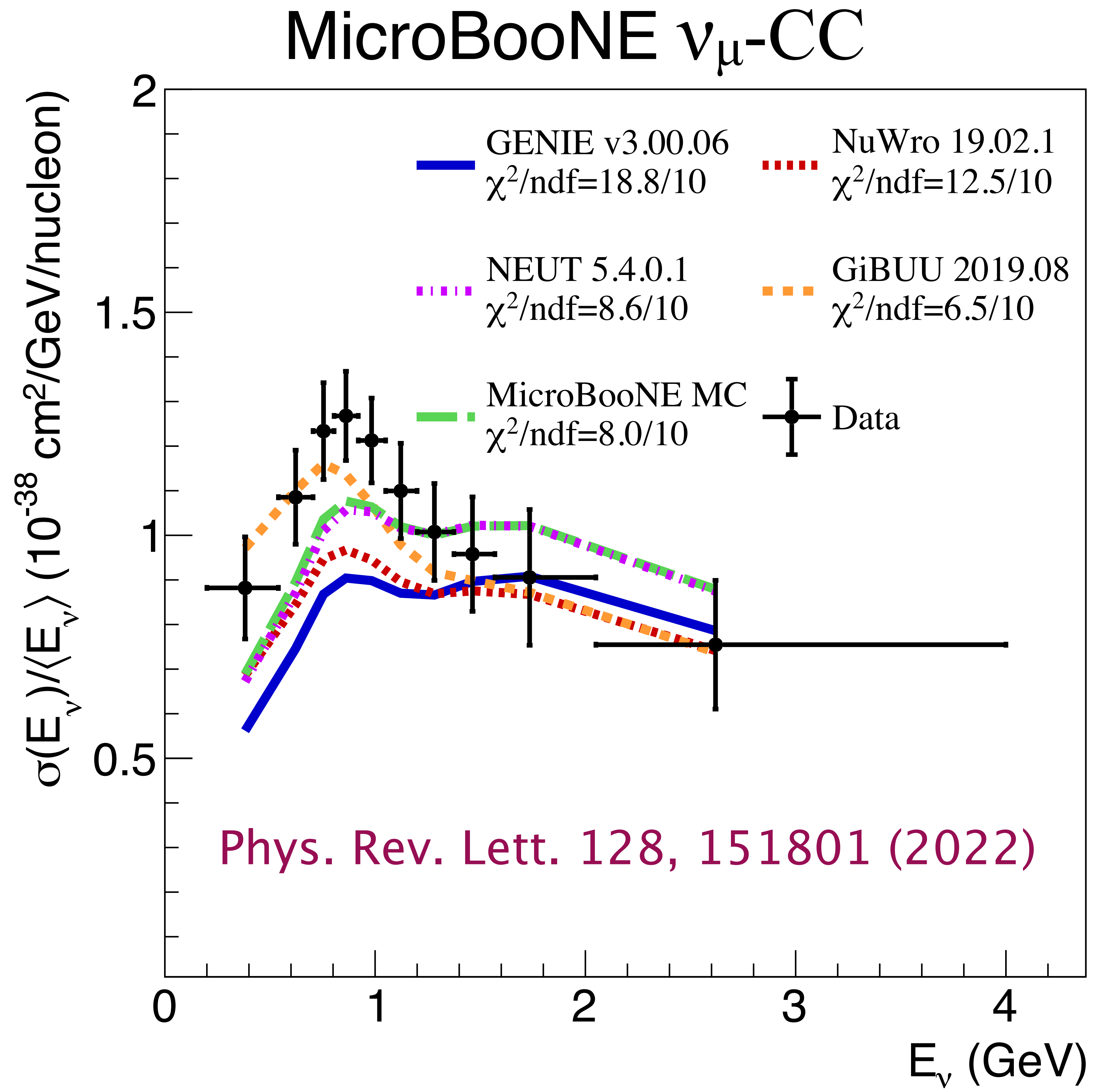
- *Offers a unified theoretical and simulation framework for particle-nucleus interactions, spanning energies from MeV to TeV*
- *Is based on first-principles interactions.*
- *Propagates particles from the initial interaction using a transport model (the BUU equation).*



GiBUU (https://gibuu.hepforge.org)

The GiBUU Project (Giessen Boltzmann-Uehling-Uhlenbeck), authored by the Giessen group:

- *Offers a unified theoretical and simulation framework for particle-nucleus interactions, spanning energies from MeV to TeV*
- *Is based on first-principles interactions.*
- *Propagates particles from the initial interaction using a transport model (the BUU equation).*



Why GiBUU stands out:

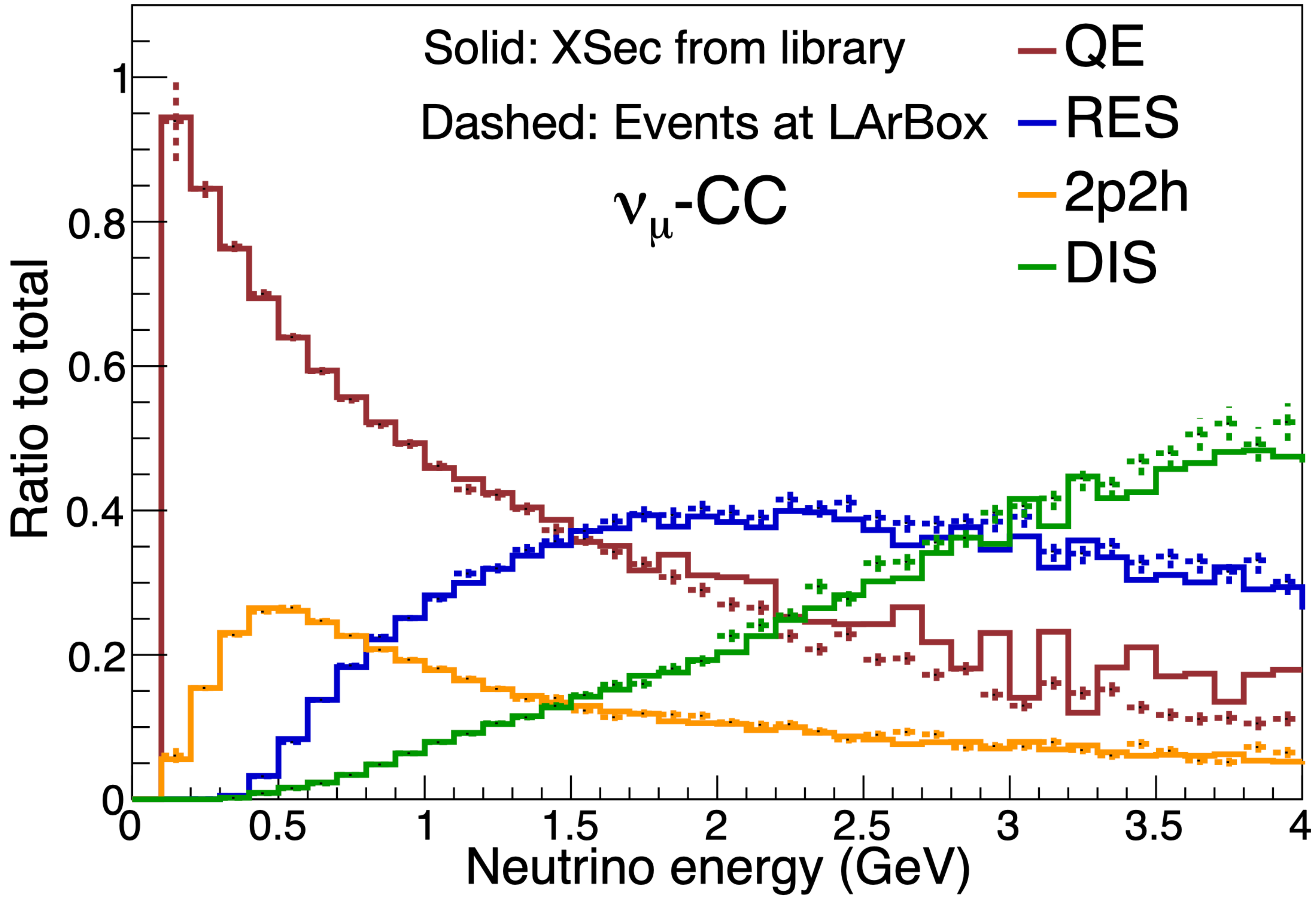
- *Uses a common nuclear potential across different interaction modes*
- *Treats particle propagation in the nucleus differently from GENIE*
- *Not tuned to neutrino data, relying solely on hadron and electron scattering data*
- *Shows strong agreement with neutrino interactions in argon (e.g., MicroBooNE data)*

GiBUU as generator (arXiv:2311.14286 [hep-ex])

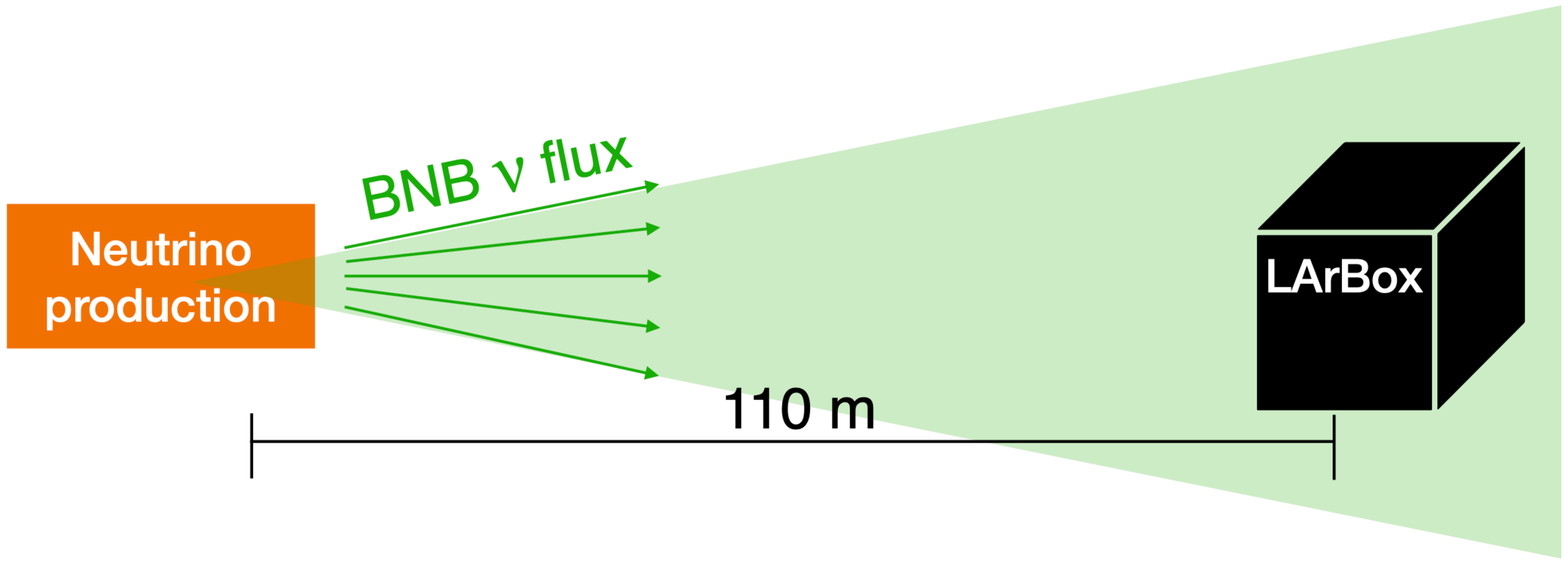
Our goal is to fully implement the GiBUU model and its systematics as an alternative event-by-event generator

We present today the model implementation

1. *Built a comprehensive statistical library of GiBUU-generated events*
2. *Leveraged GENIE's geometry and flux drivers and produced output events in a GENIE-compatible format*
3. *Applied cross-section weights using an acceptance-rejection method to select events*



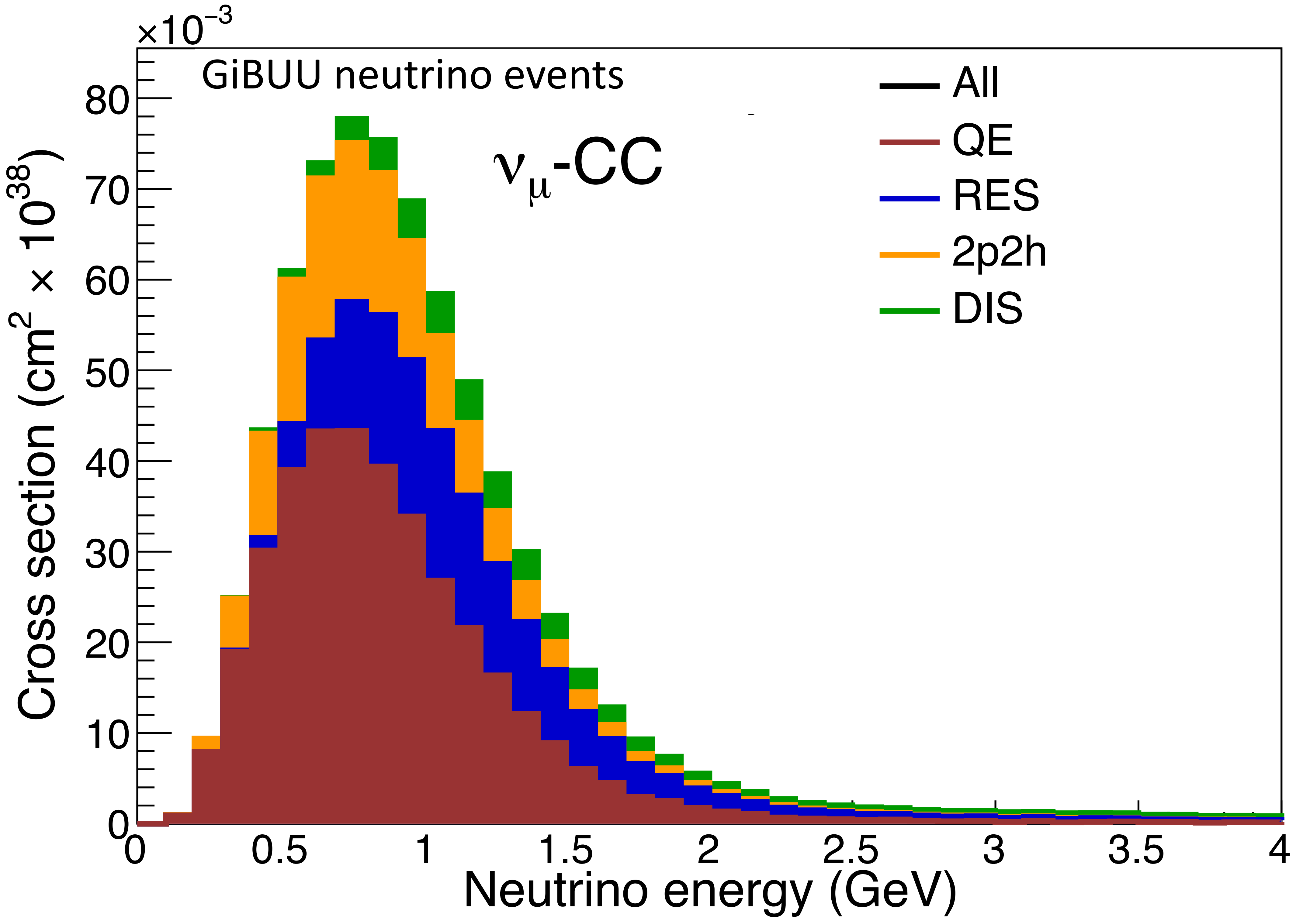
Studies with the implementation



We performed studies with our simulation, implementing it into LArSoft* using a hypothetical geometry (LArBox) and the BNB flux

- Box dimensions 2 x 2 x 2 m^3
- Filled with liquid argon
- Located 110 m from the BNB target

*(*): Liquid Argon Software, 2017 J. Phys.: Conf. Ser. **898** 042057)*

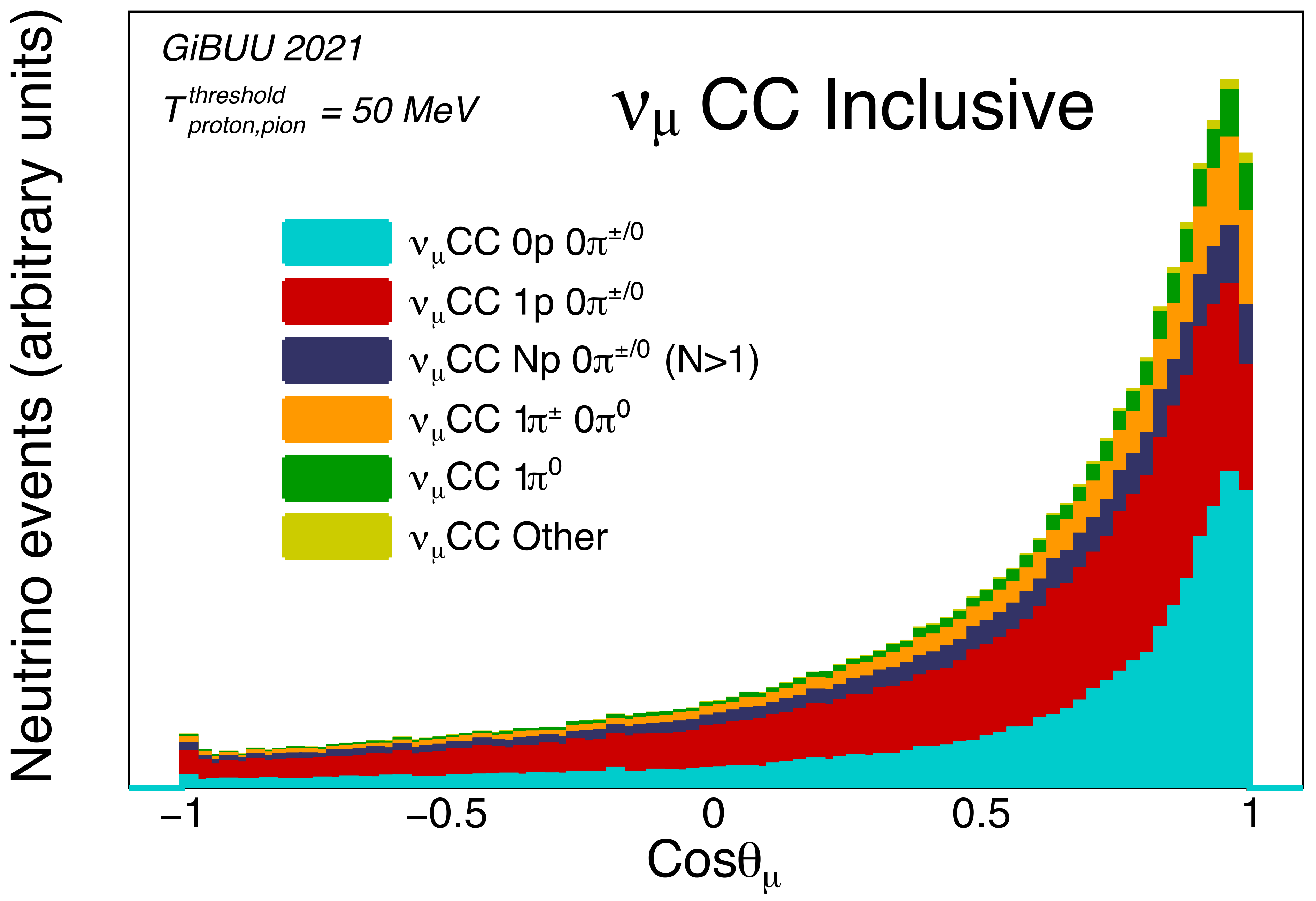


The BNB physics program, with neutrino energies around 1 GeV on argon targets, provides an excellent opportunity to constrain neutrino interaction systematics for DUNE

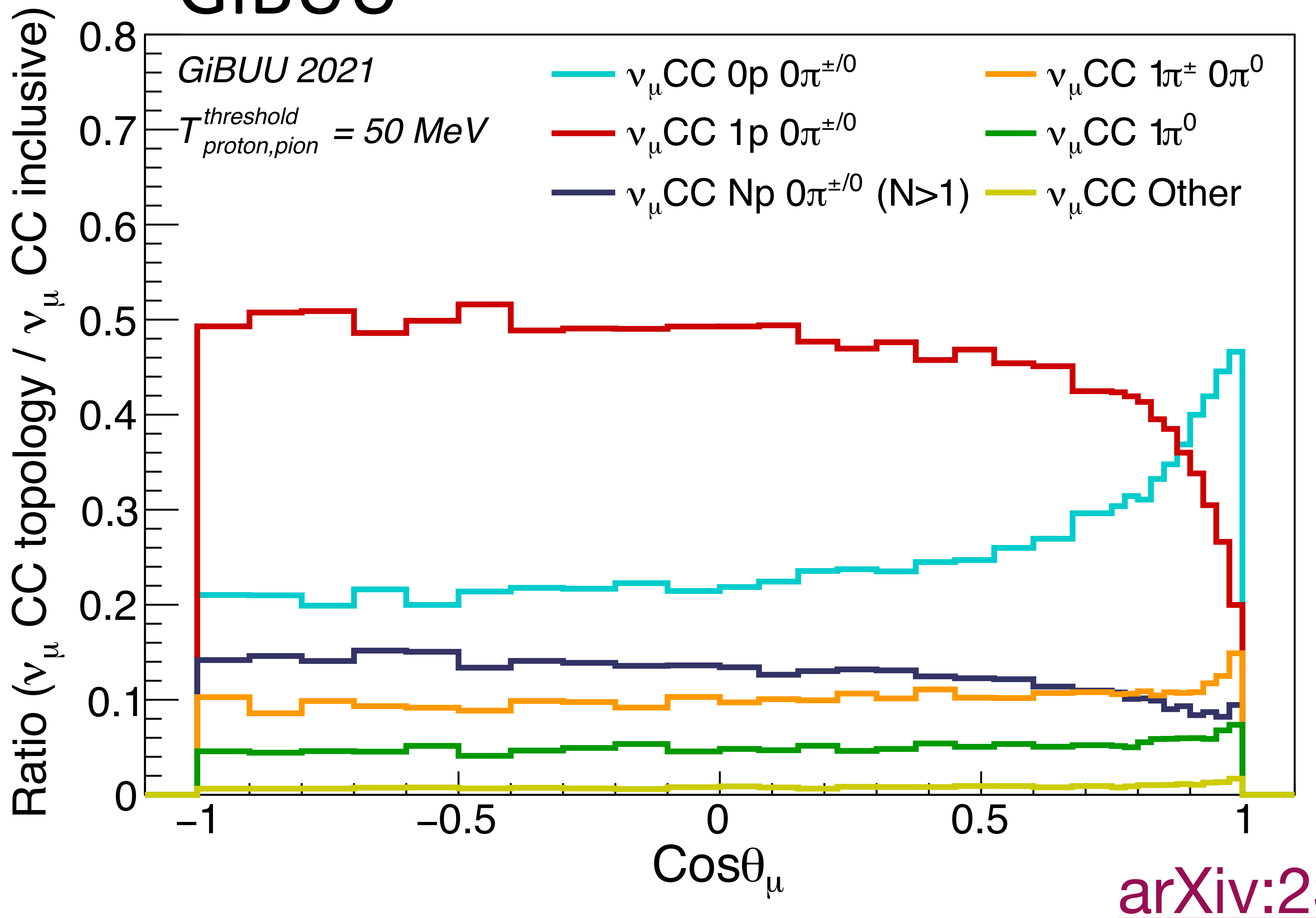
Comparison in muon kinematics

We show the inclusive and exclusive topologies in terms of the **muon cosine w.r.t. the neutrino beam direction** comparing GiBUU and GENIE in LArBox

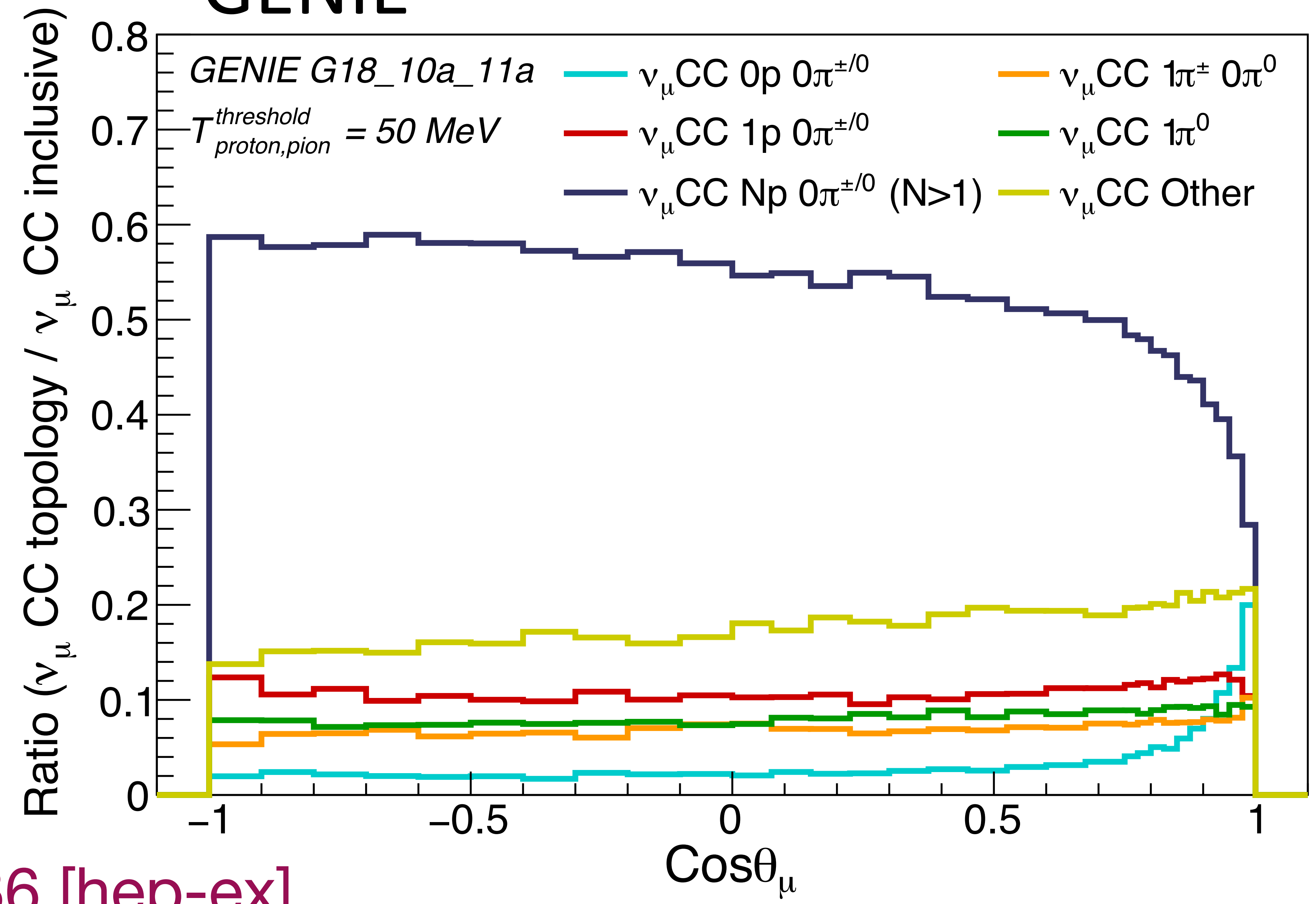
- *Found significant differences in the composition between generators in direct observables at SBND and DUNE*



GiBUU



GENIE

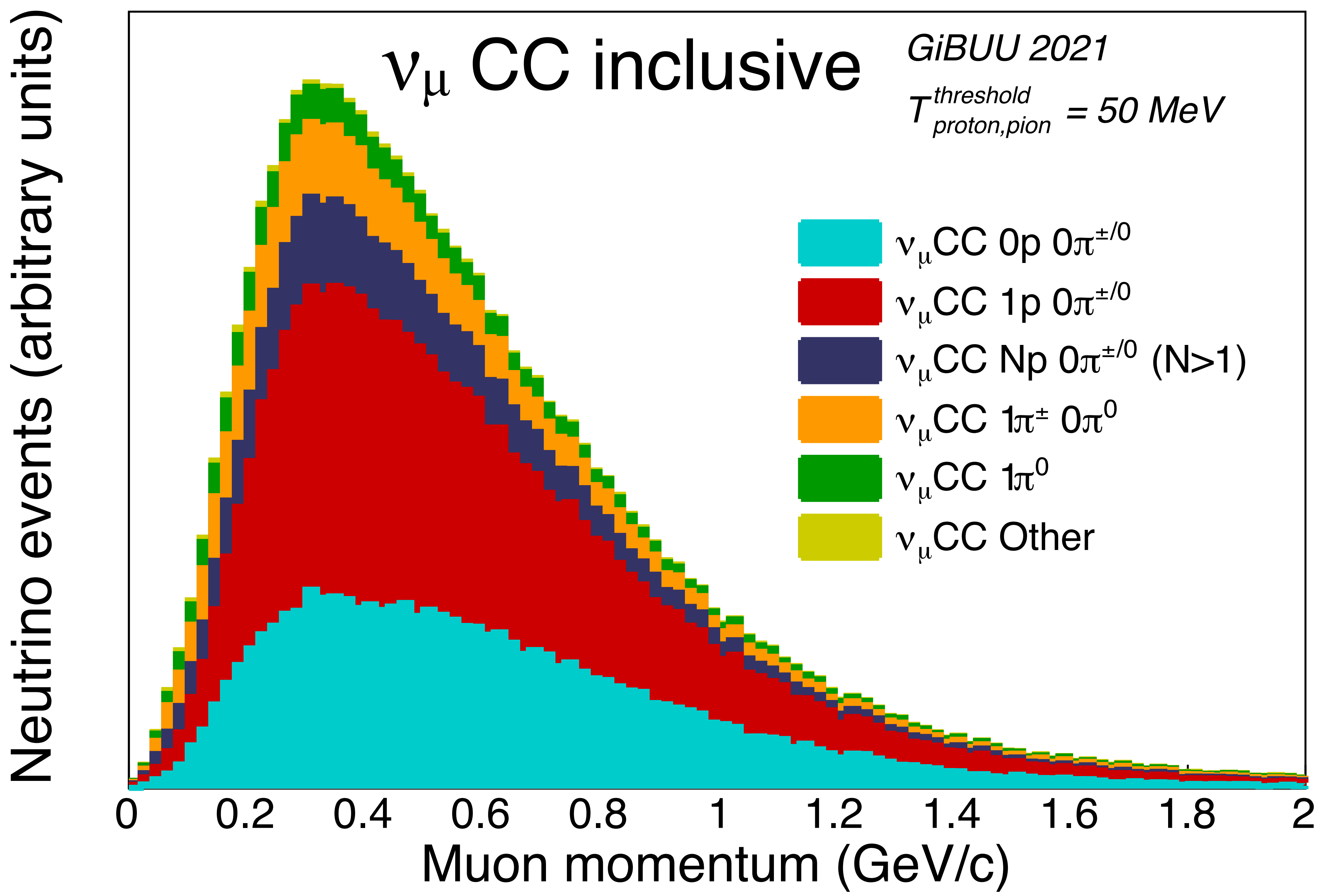


arXiv:2311.14286 [hep-ex]

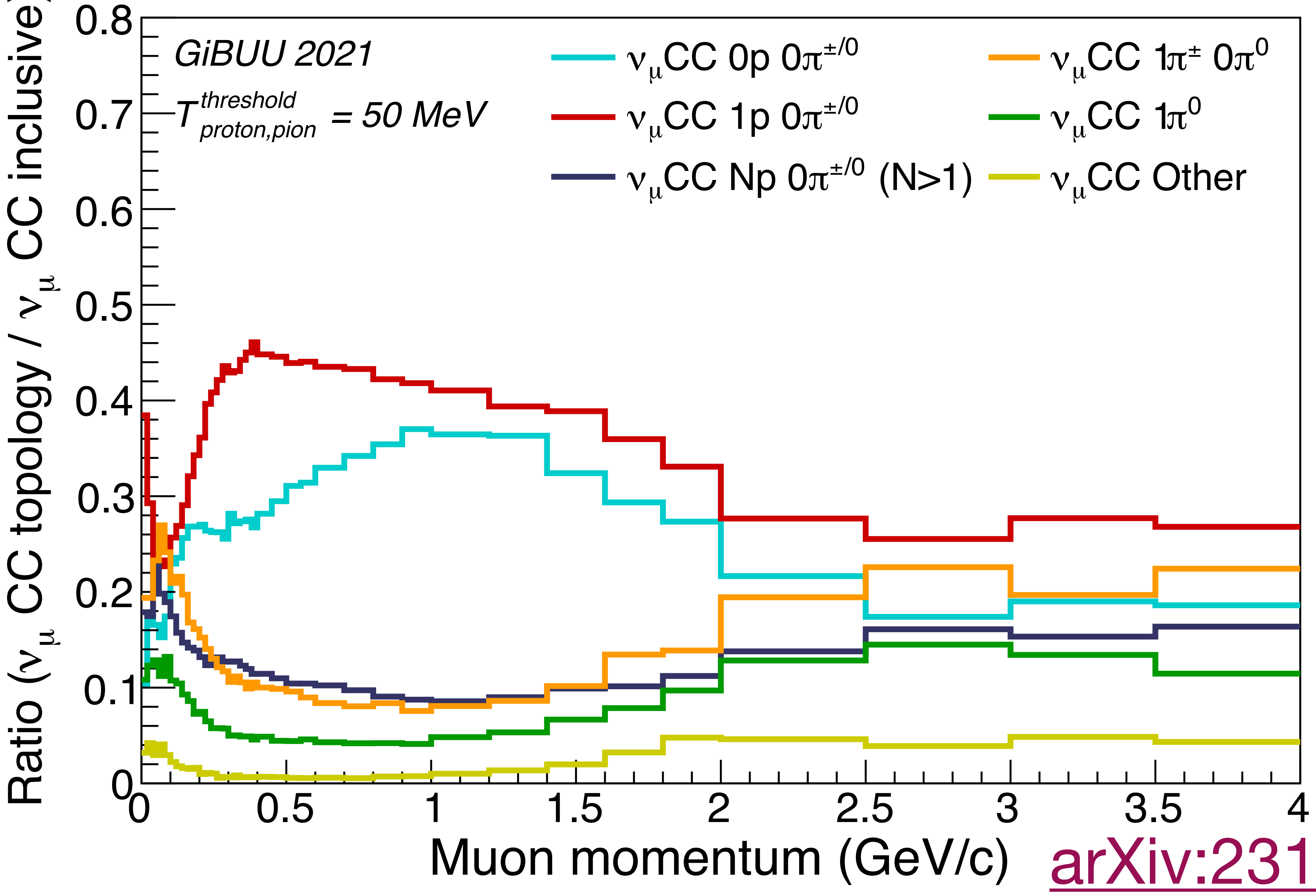
Comparison in muon kinematics

We show the inclusive and exclusive topologies and in terms of the **muon momentum** comparing GiBUU and GENIE in LArBox

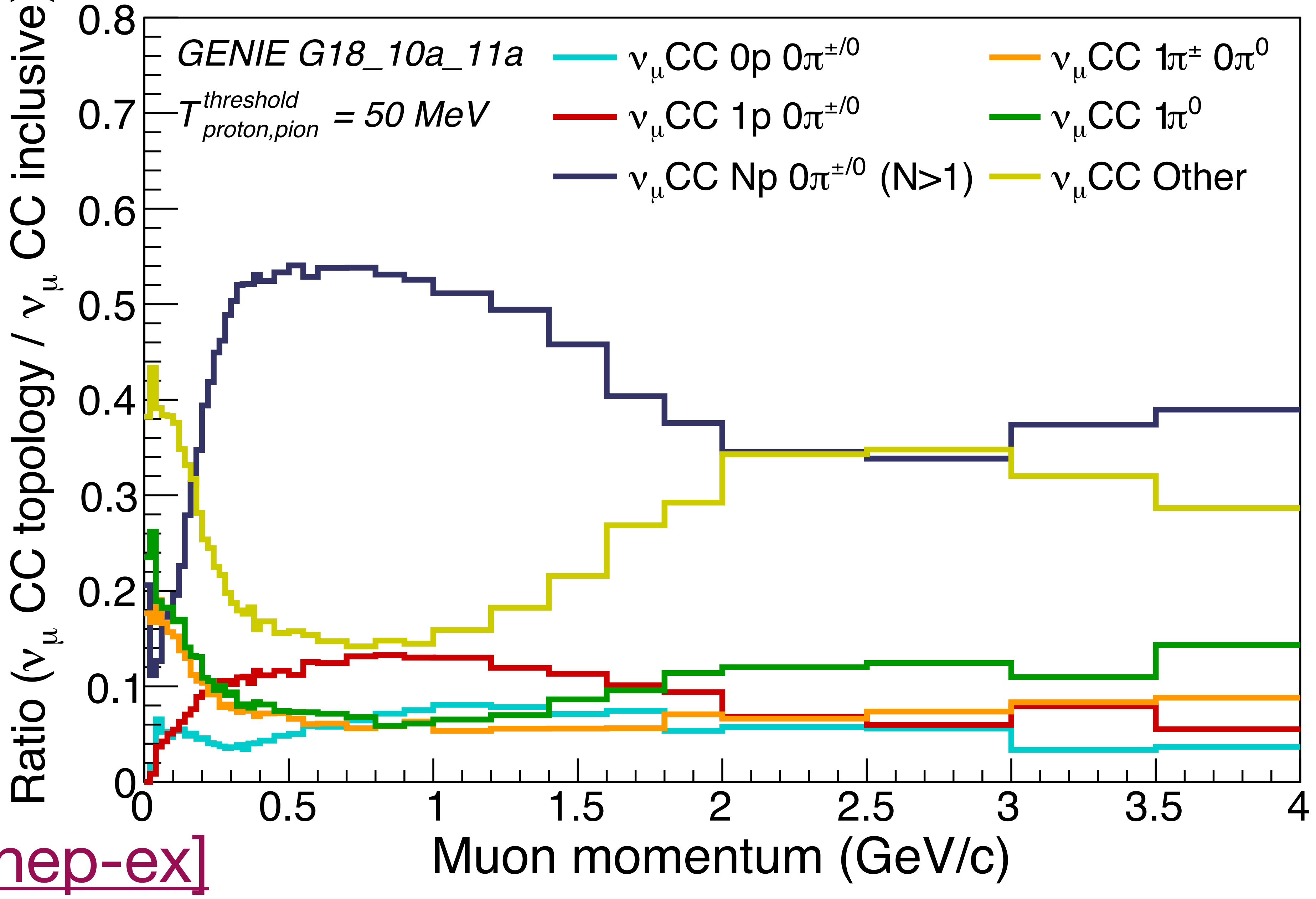
- Found significant differences in the composition between generators in direct observables at SBND and DUNE



GiBUU



GENIE

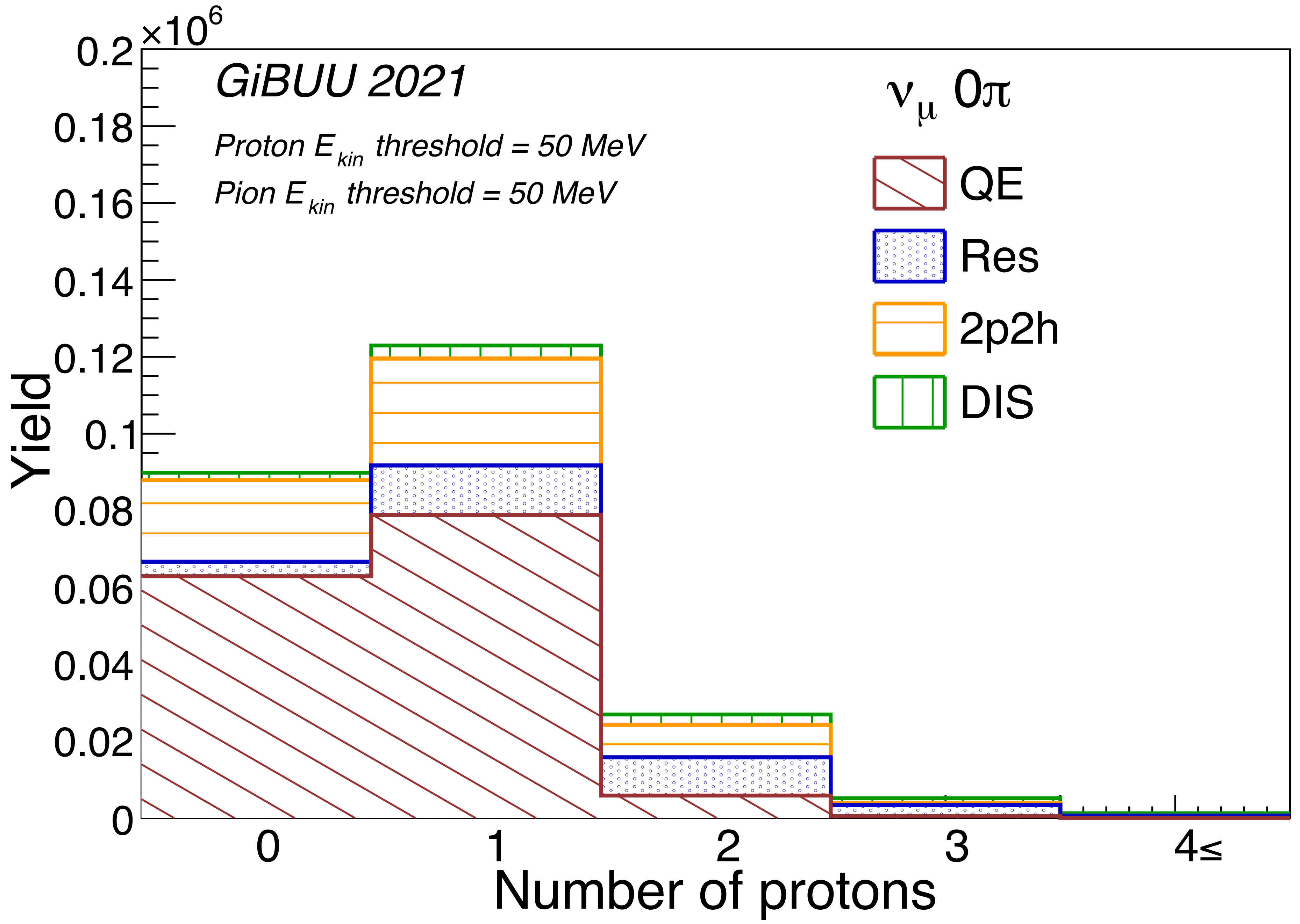


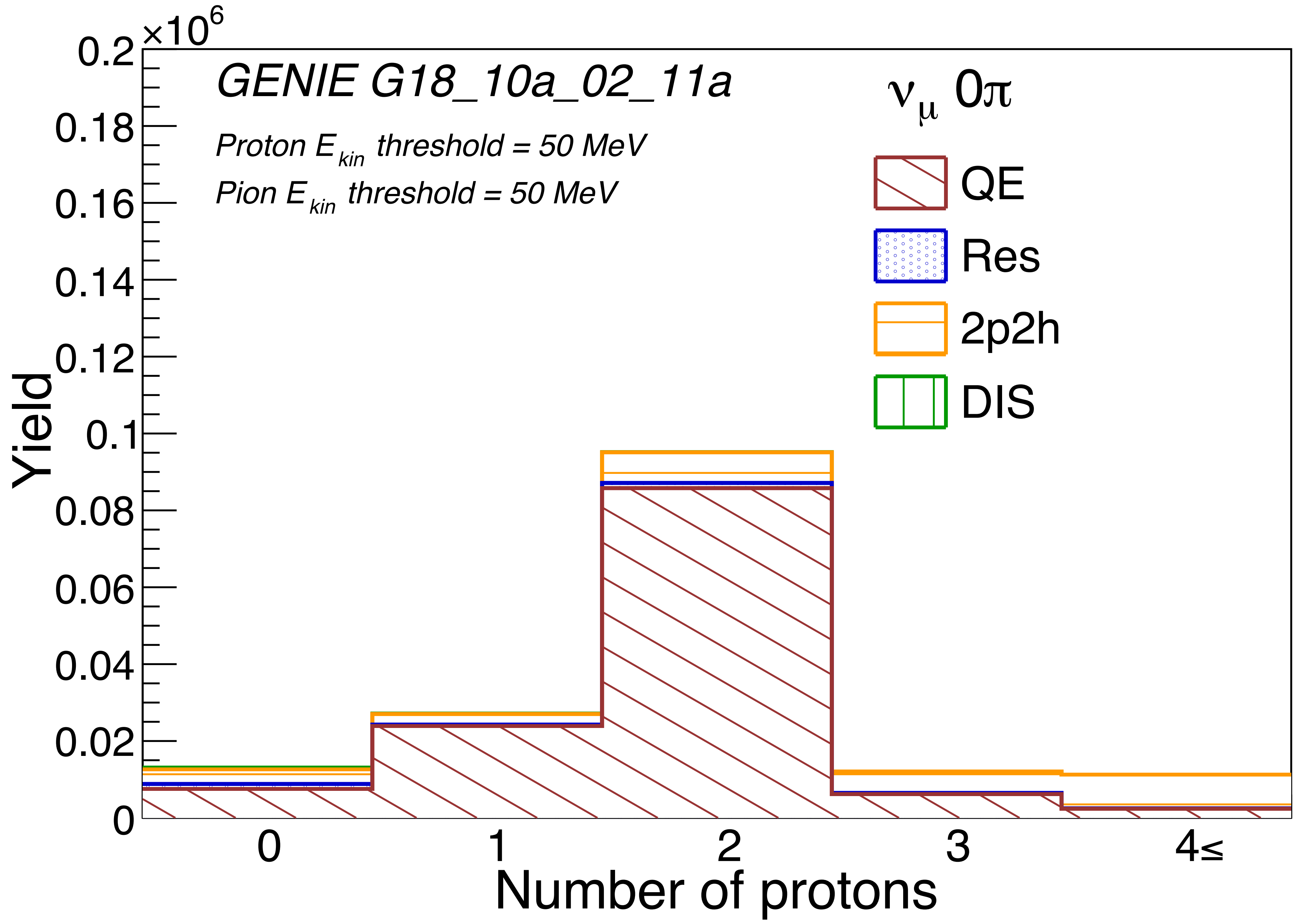
arXiv:2311.14286 [hep-ex]

Comparison in the pionless channel (protons)

We show the proton multiplicty per interaction mode

- *Found significant differences on the composition between generators*
- These differences highlight the challenge of reconstructing neutrino energies in a model-independent way at experiments such as SBN and DUNE

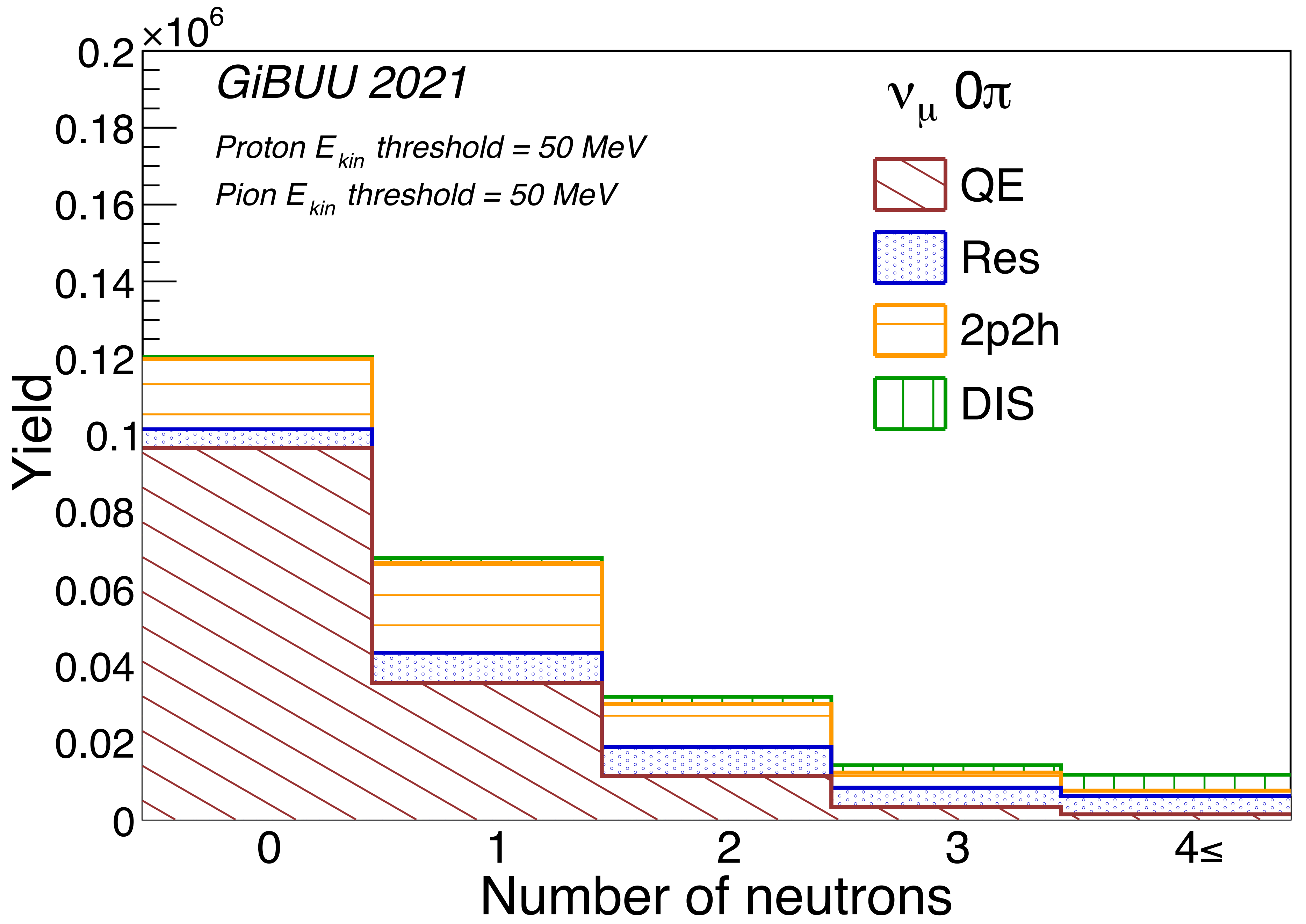


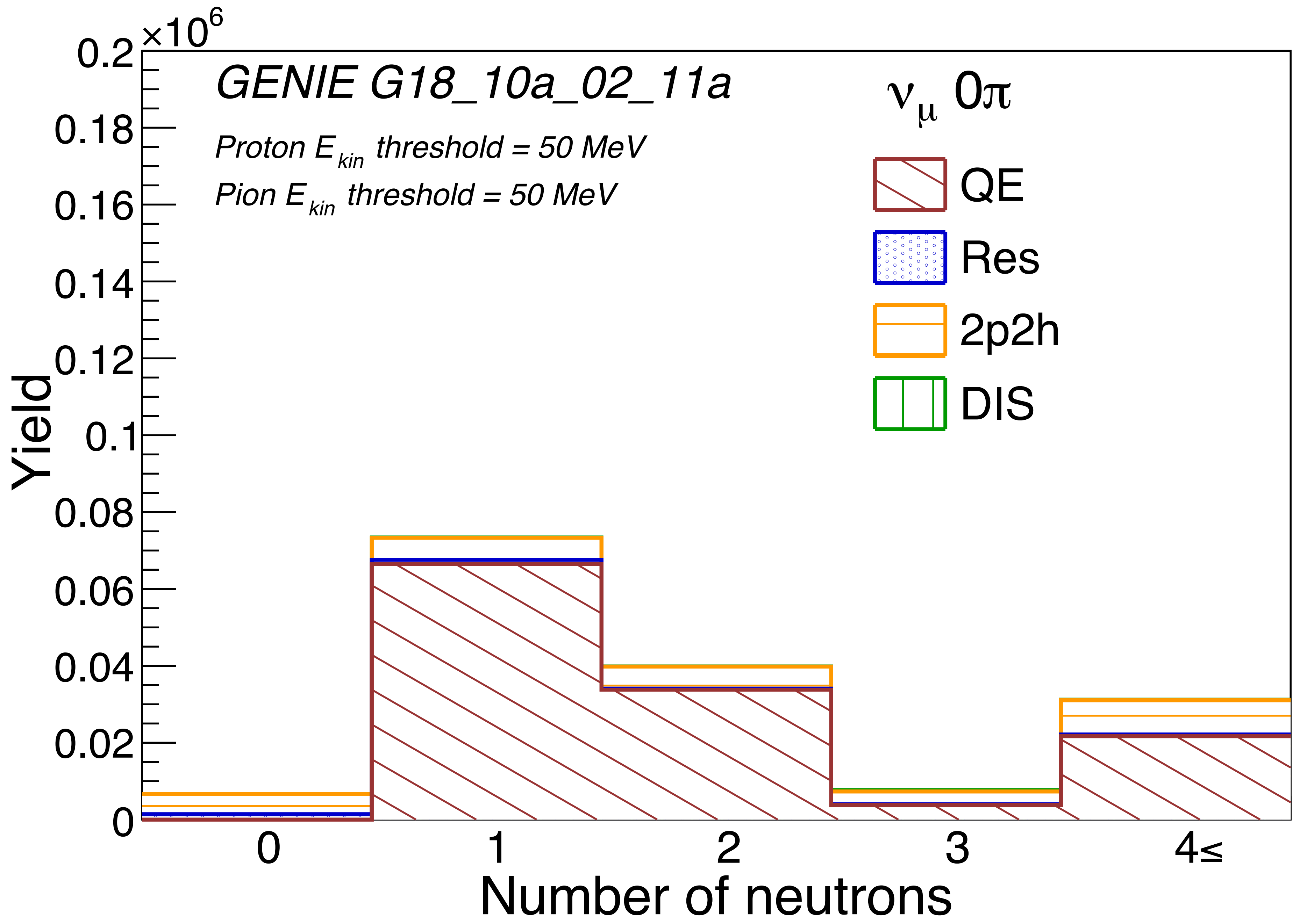


Comparison in the pionless channel (neutrons)

We show the neutron multiplicty per interaction mode

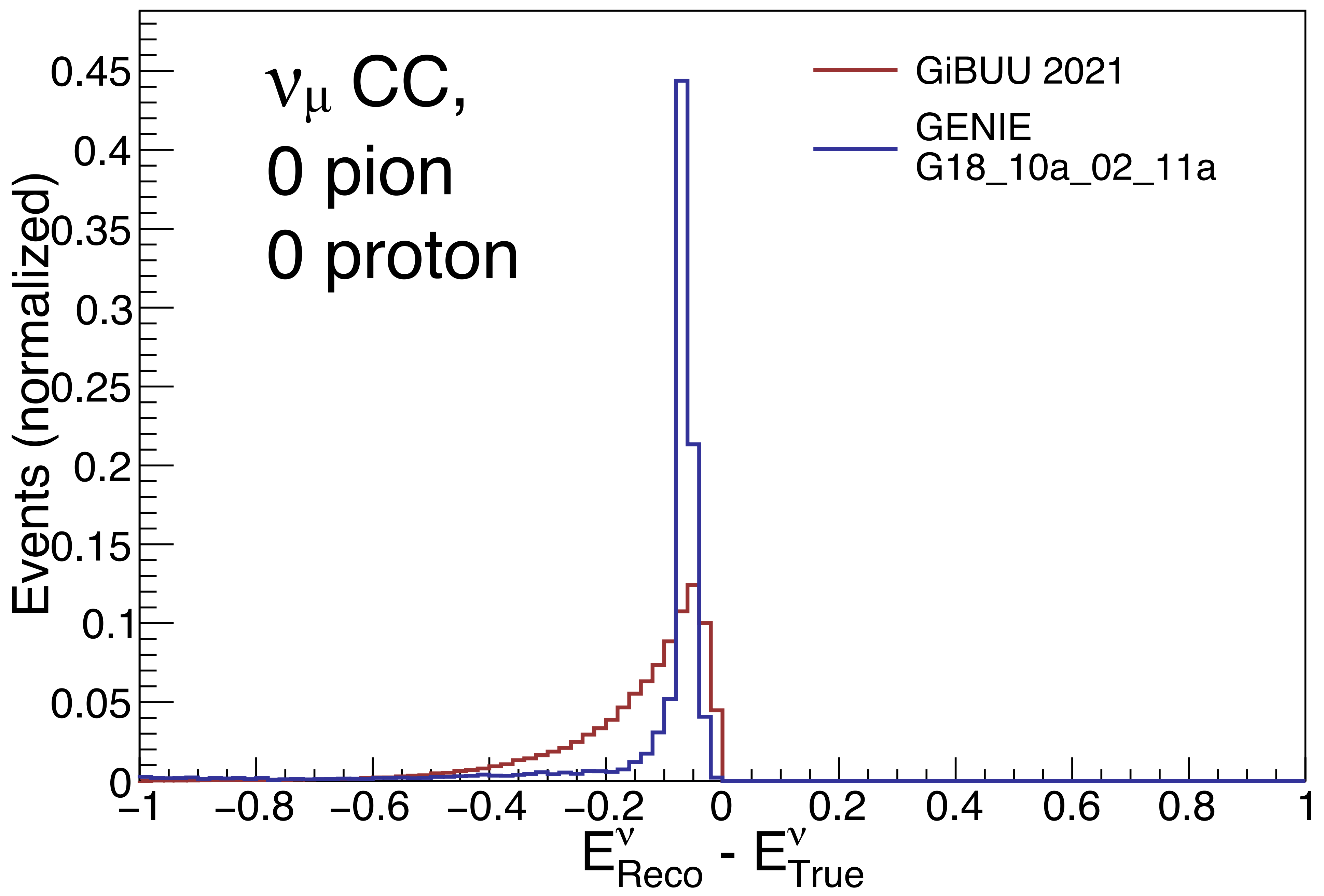
- *Found significant differences on the composition between generators*
- These differences highlight the challenge of reconstructing neutrino energies in a model-independent way at experiments such as SBN and DUNE

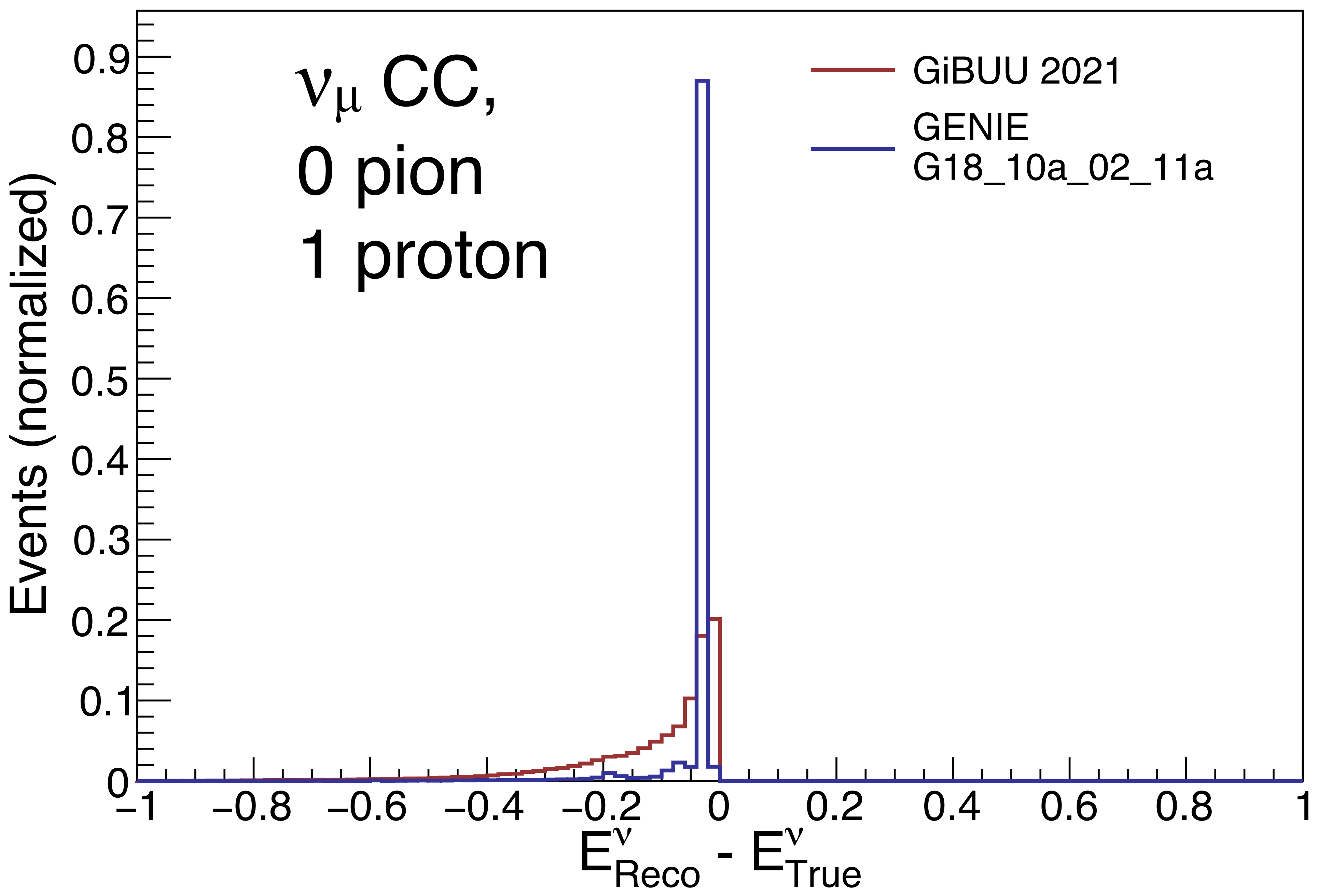




Resolution

A simple calculation to see the potential impact on the neutrino energy resolution. Here we assume perfect reconstruction using an estimated correction coming from ArgoNeuT (Phys. Rev. D **90**, 012008)





$$E_\nu = (E_\mu + T_{p1} + T_{p2} + T_{A-2} + E_{miss})$$

ArgoNeuT:

$$T_{A-2} \approx (P^T_{miss})^2 / 2M_{A-2}$$

$$E_{miss} = 30 \text{ MeV}$$

Critical in understanding the energy resolution, corrected by MC, in oscillations

Current work: systematics

Understanding and quantifying uncertainties associated with the model is crucial for robust data analysis and extracting meaningful physics results in neutrino experiments

Some of the main potential contributions come from:

- *Nuclear effects and medium modification (transport model systematics)*
- Resonance dynamics (widths and coupling constants)
- *Neutrino cross-section systematics*

Current work: systematics

Understanding and quantifying uncertainties associated with the model is crucial for robust data analysis and extracting meaningful physics results in neutrino experiments

Some of the main potential contributions come from:

- *Nuclear effects and medium modification (transport model systematics)*
- Resonance dynamics (widths and coupling constants)
- *Neutrino cross-section systematics*

Taking advantage of the fact that GiBUU is not tuned to any neutrino data, we are addressing systematics in 3 consecutive steps:

Step 1: comparison with hadron scattering data

Step 2: comparison with electron scattering data

Step 3: comparison with neutrino scattering data to account for any residual discrepancy

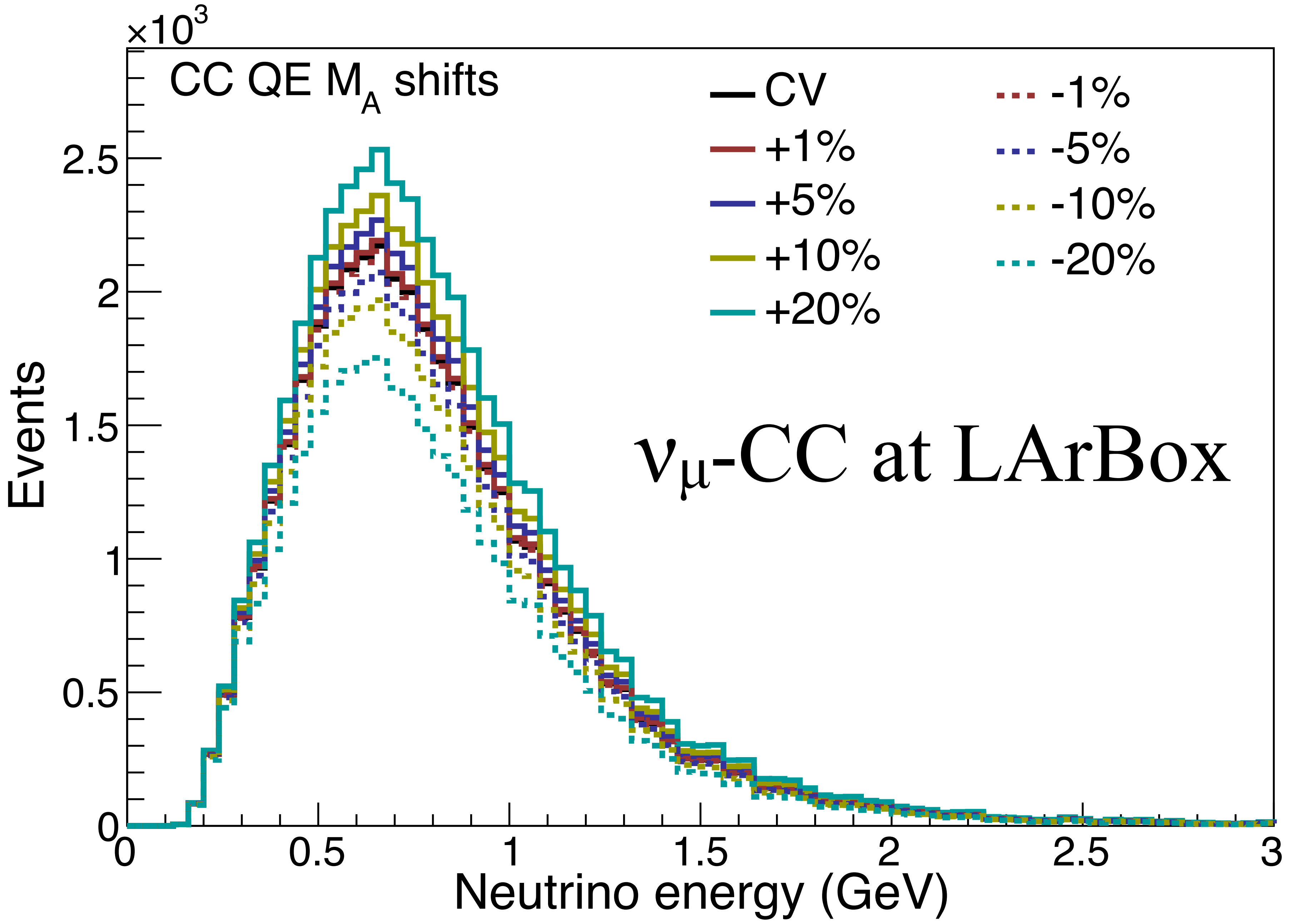
Current work: systematics

For step 1 (similar for step 2) we are exploring the use of data such as:

- **LADS**: pion absorption at 70 - 330 MeV with different particle multiplicity
- **LArIAT**: total pion scattering 100 - 700 MeV
- **Proto-DUNE**: pion scattering 1, 6 and 7 GeV

For step 3 we are adding new functions to GiBUU to modify neutrino interactions parameters

Prof-of-principle: shift to M_A CC QE



Systematics shifts are carried out to the model output as weights without interfering with the nominal simulation

Conclusions

» Having an alternative generator has the advantage of an independent account for all corrections coming from simulations

» We have implemented GiBUU as an alternative generator, event by event, in LArSoft

- Currently being used by SBND

» We are focused on incorporating realistic systematic uncertainties

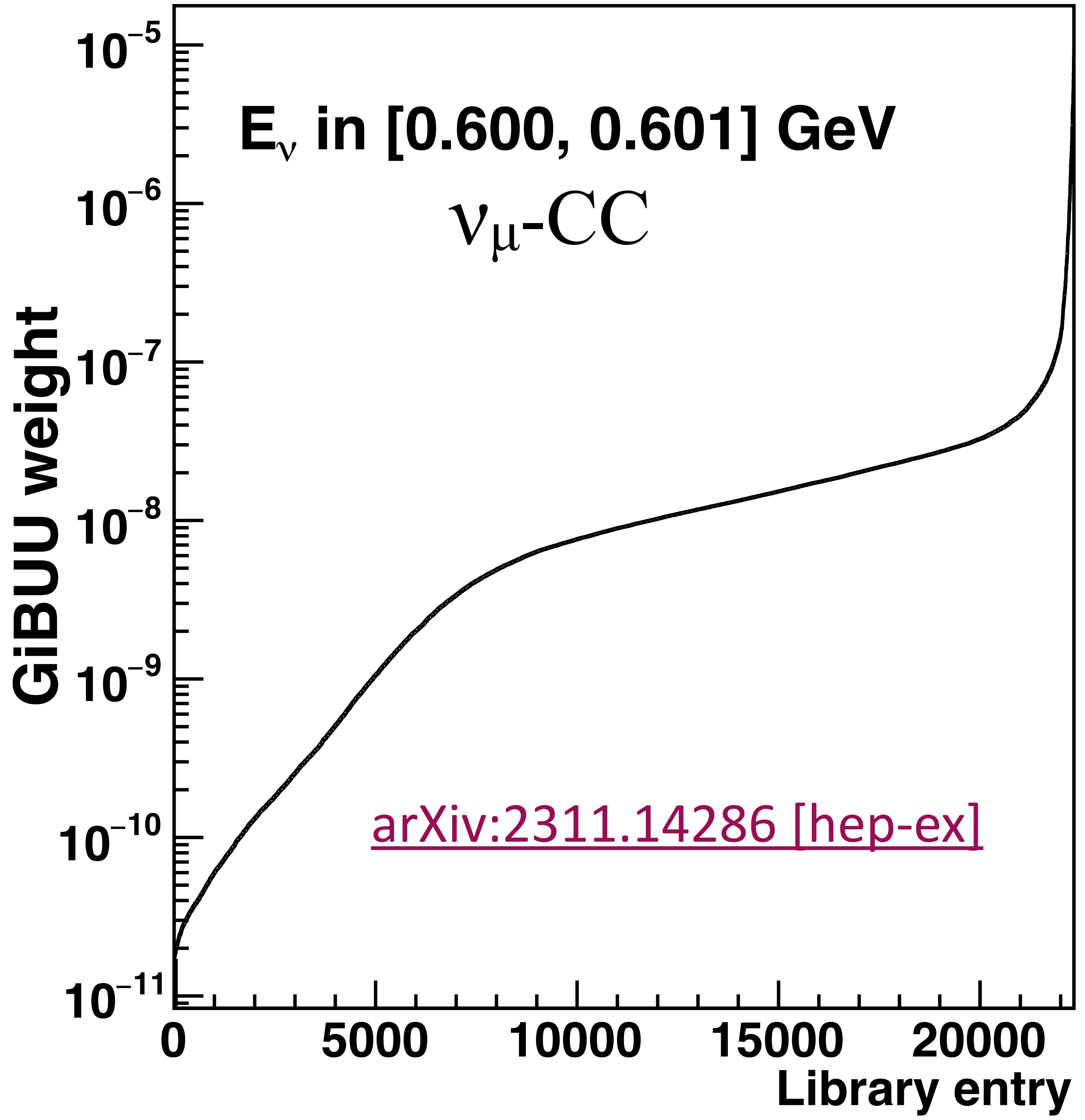
- We are collaborating with **Ulrich Mosel** and **Kai Gallmeinster** and Giessen group (GiBUU authors) to be loyal to the physics
- We, from the University of Texas at Arlington, are collaborating with the University of Warwick to finalize the implementation of the systematics

Backup

Validation: interaction modes

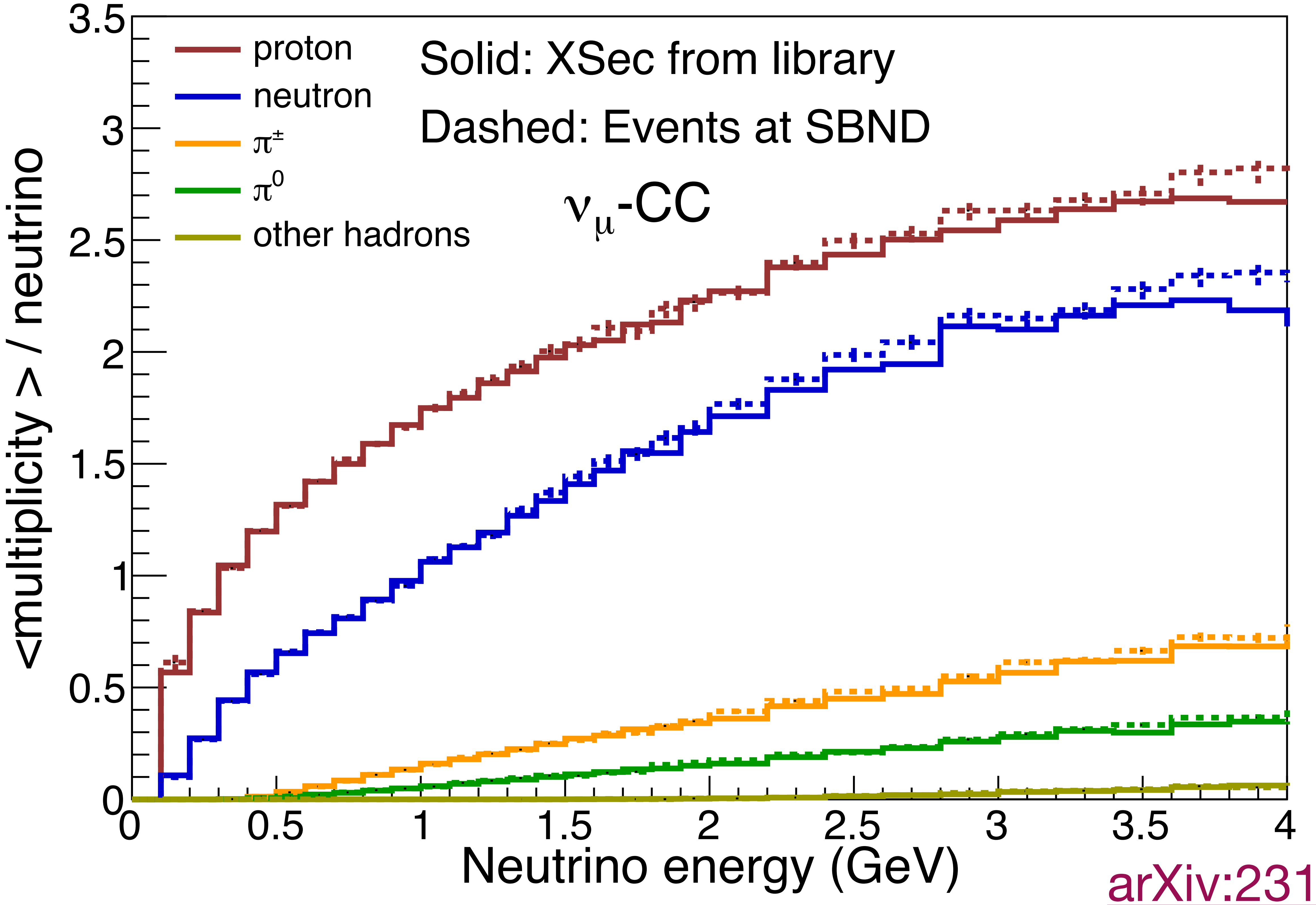
We checked if the interaction modes are propagated correctly in the GiBUU events from the library

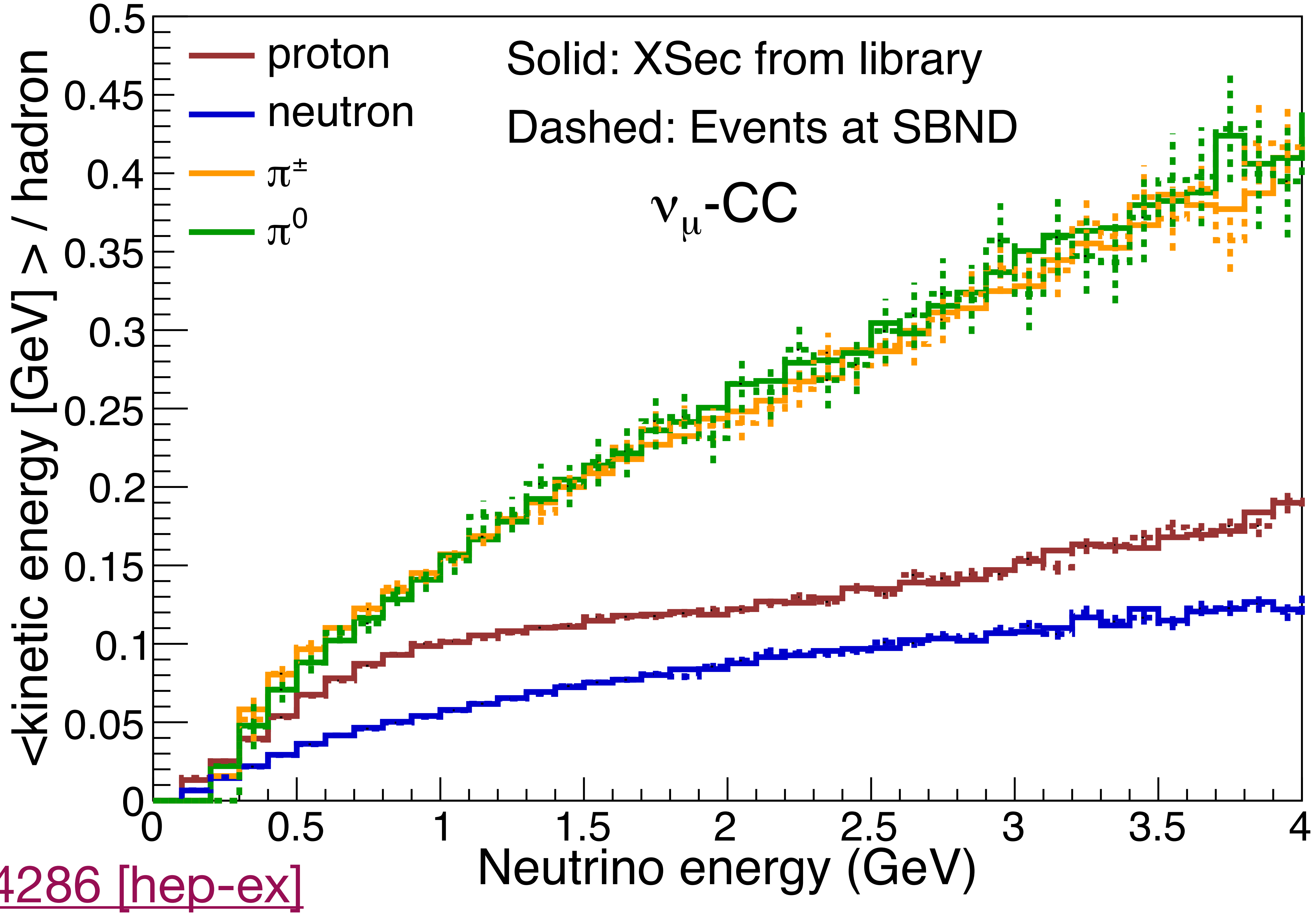
- This information is crucial to calculate the neutrino interaction systematics



Validation: hadron production

We checked the average multiplicity and average kinetic energy per neutrino interaction energy of several hadrons: protons, neutrons, and pions

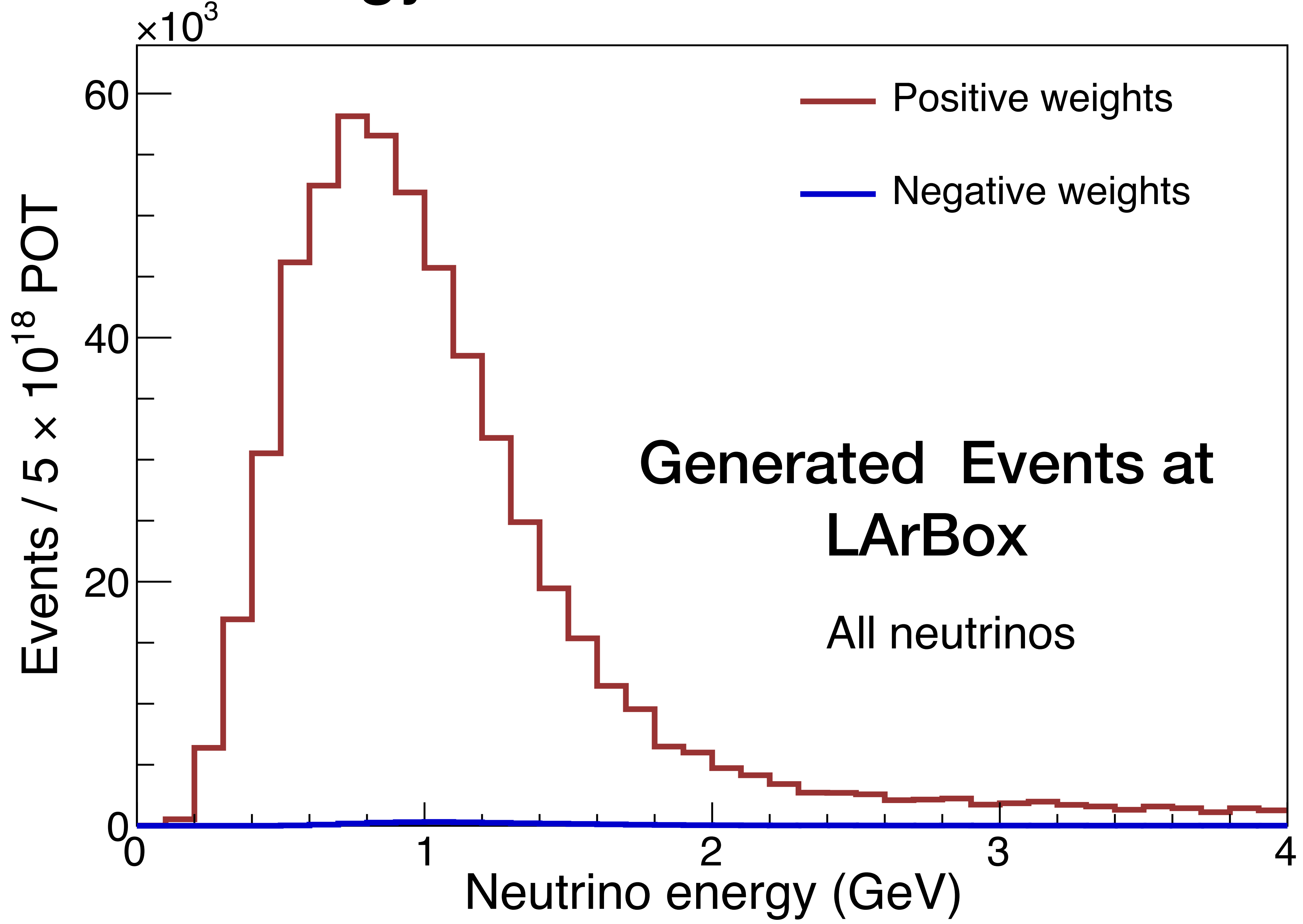




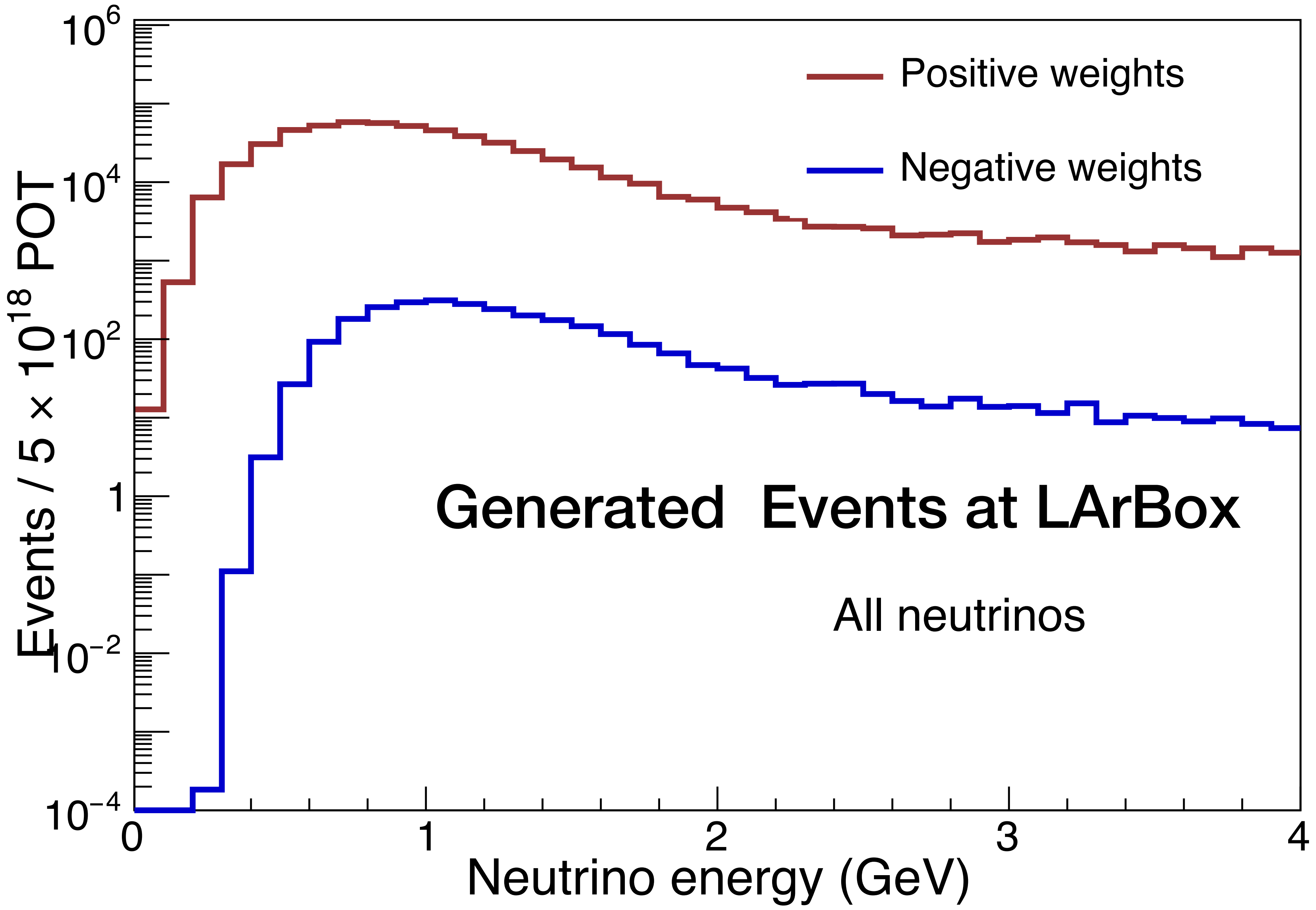
arXiv:2311.14286 [hep-ex]

Generated GiBUU events

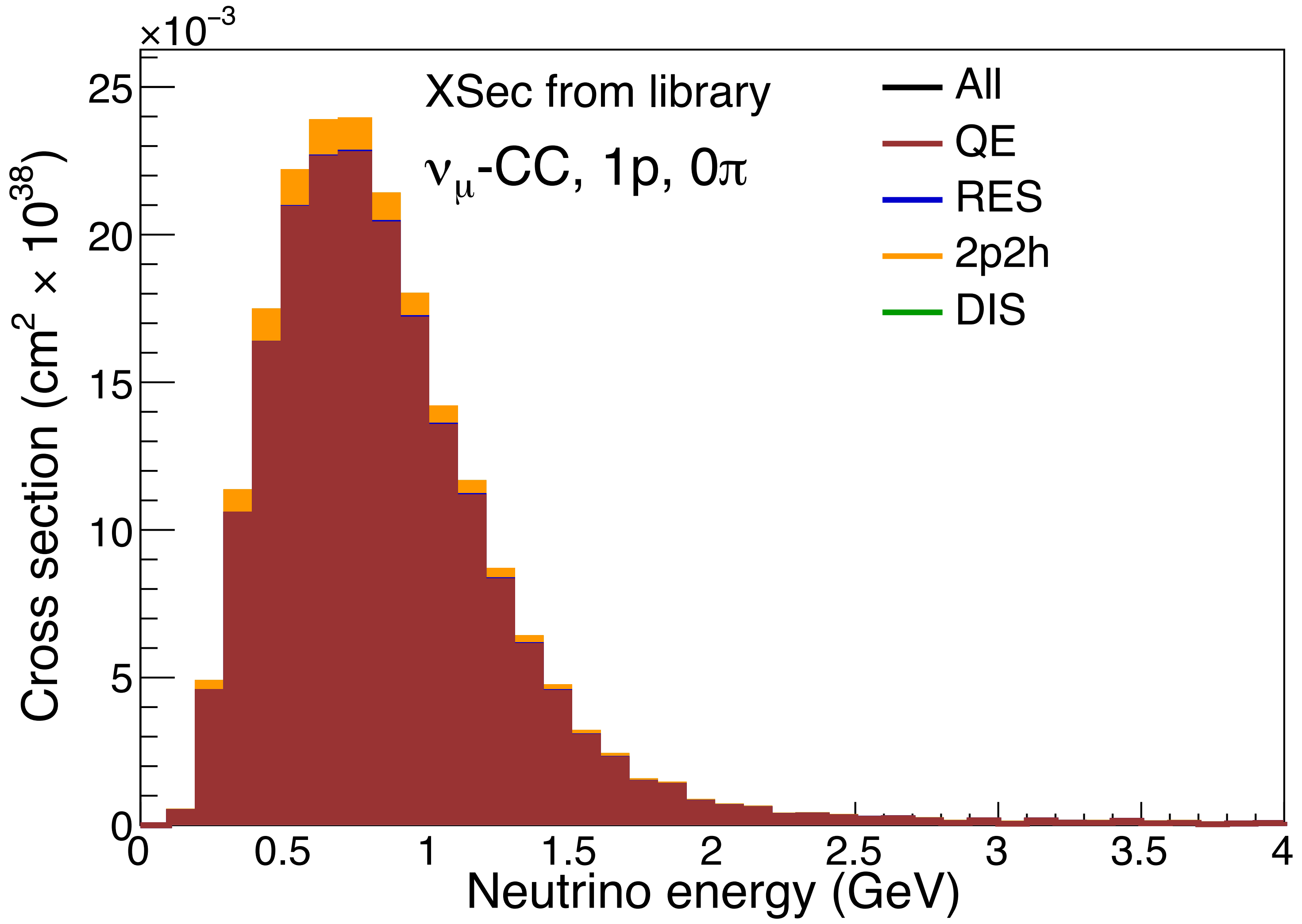
Energy distribution of all neutrinos

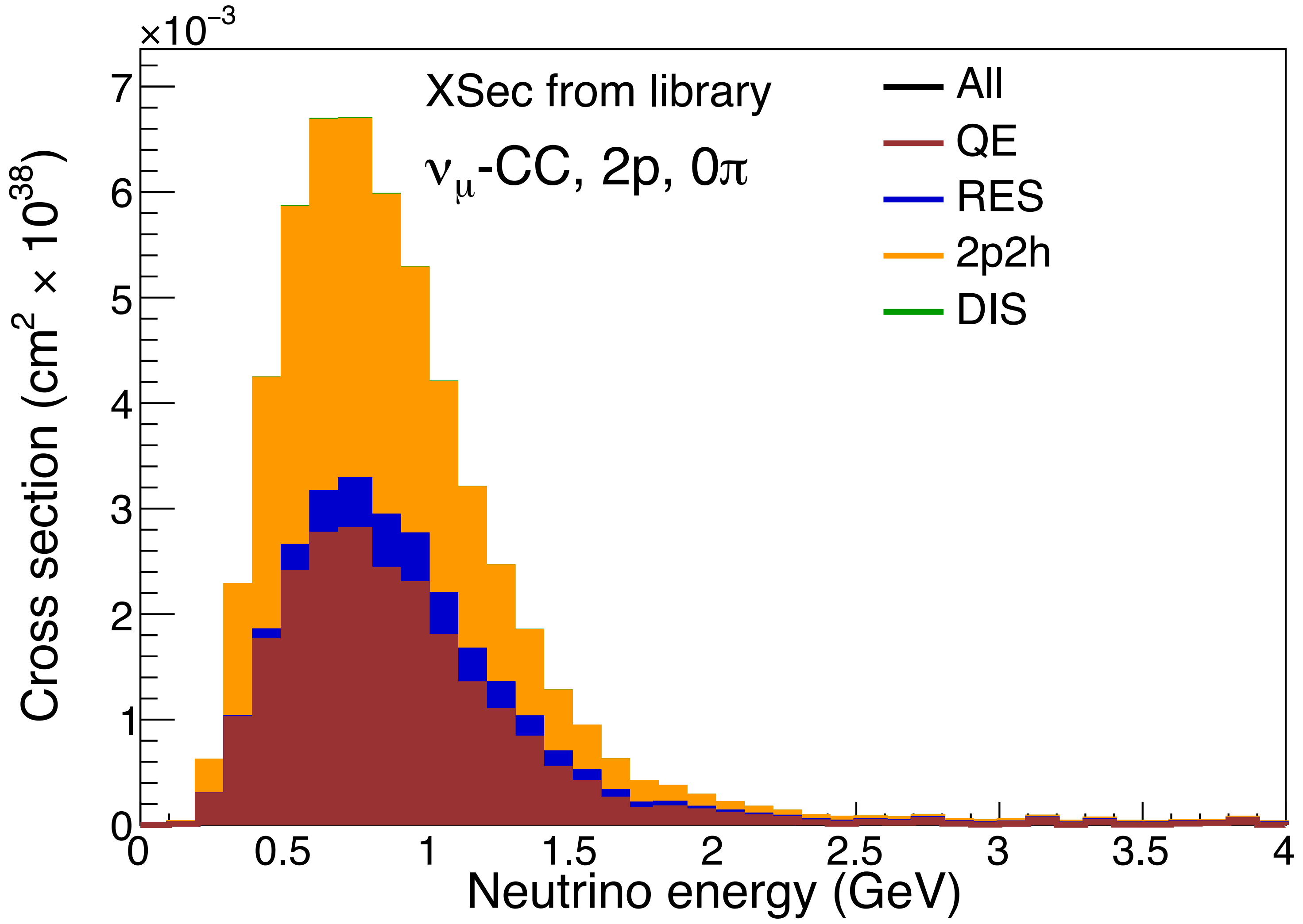


Log-scale version



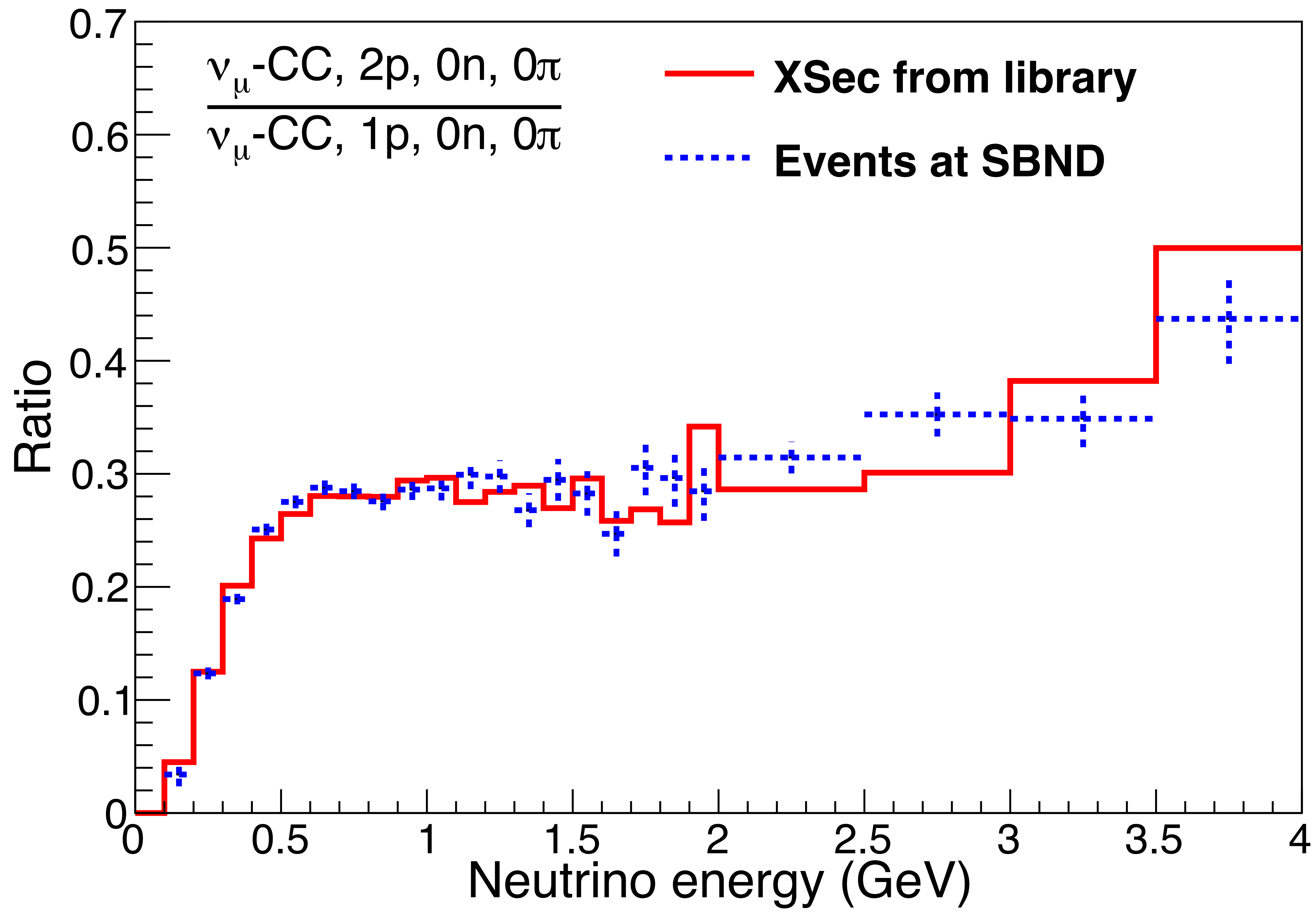
Validation: enhanced QE and 2p2h distributions





» NuMu-CC interactions with:

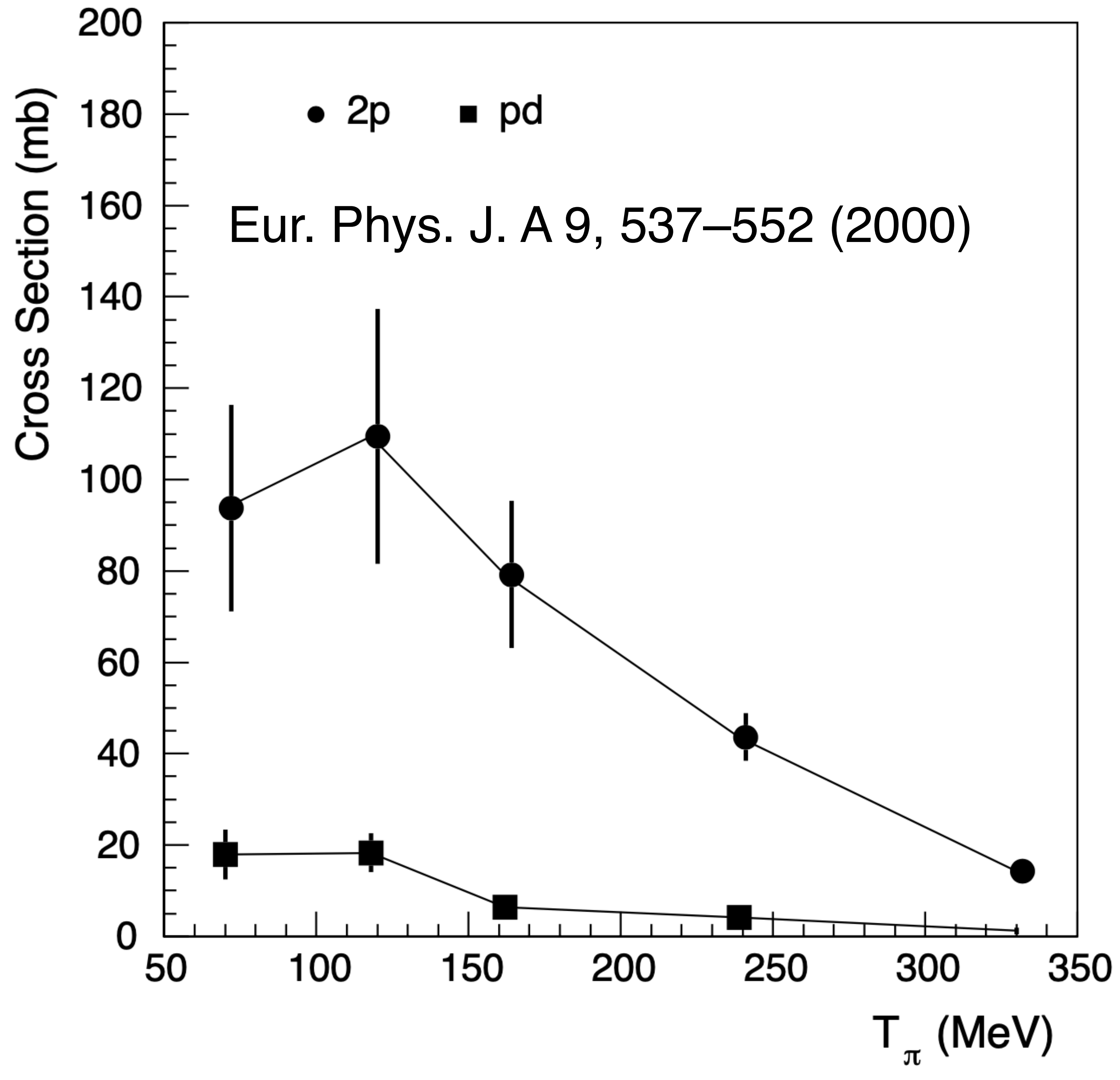
- 1p, 0n and 0pi: enhanced QE
- 2p, 0n and 0pi: enhanced 2p2h



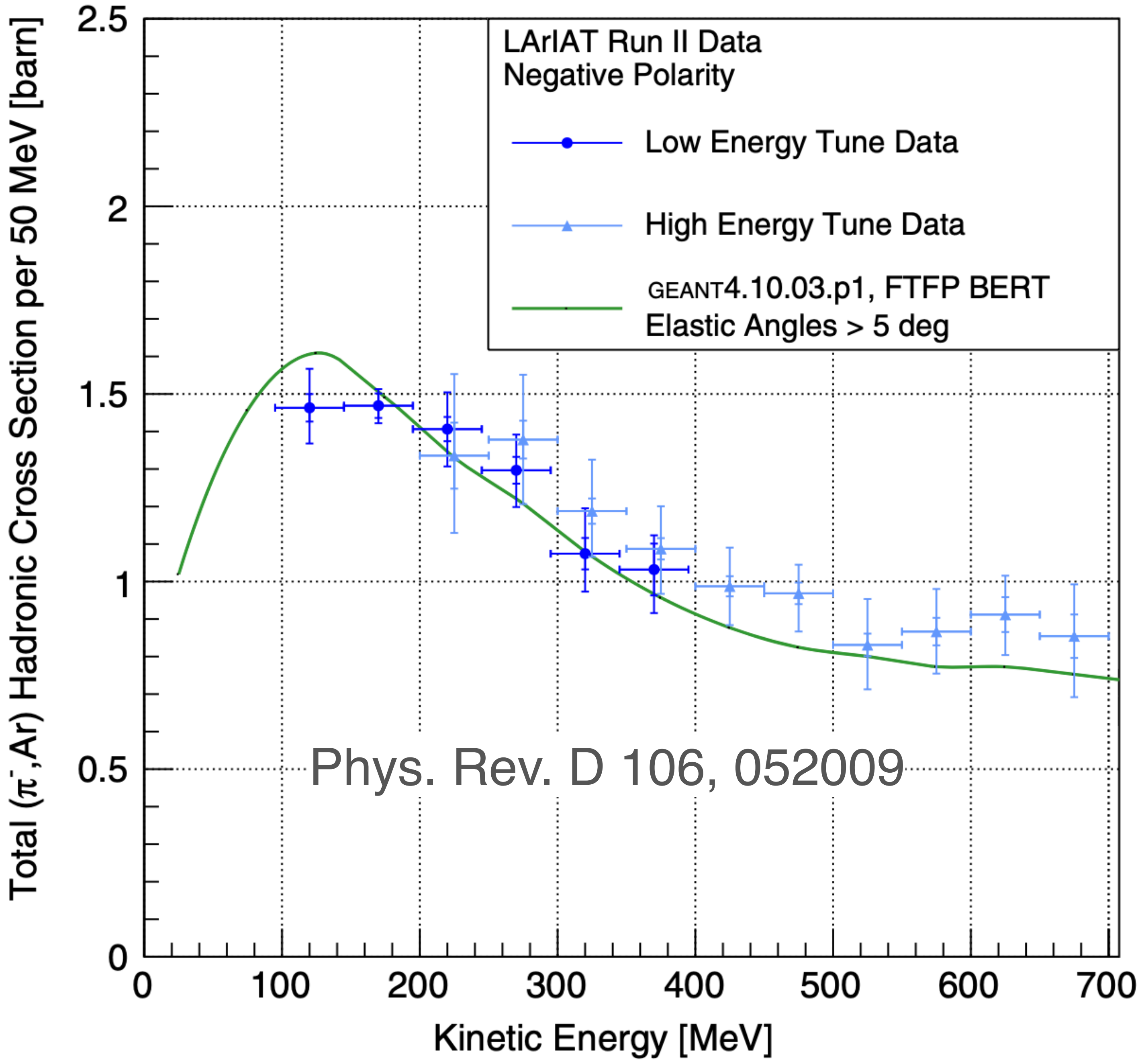
Systematics: hadron scattering data in Argon

We have available measurements we can use, such as:

LADS: pion absorption at 70 - 330 MeV with different particle multiplicity



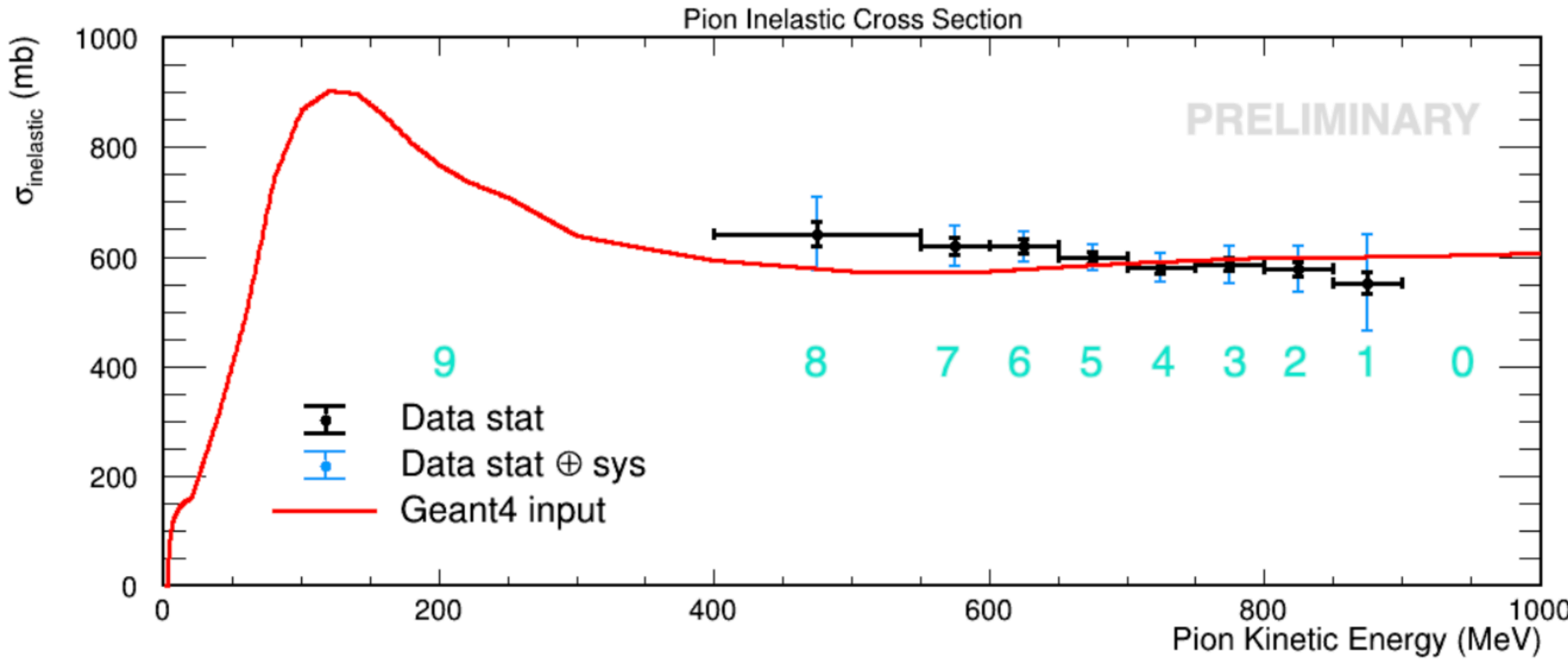
LArIAT: Total pion scattering 100 - 700 MeV



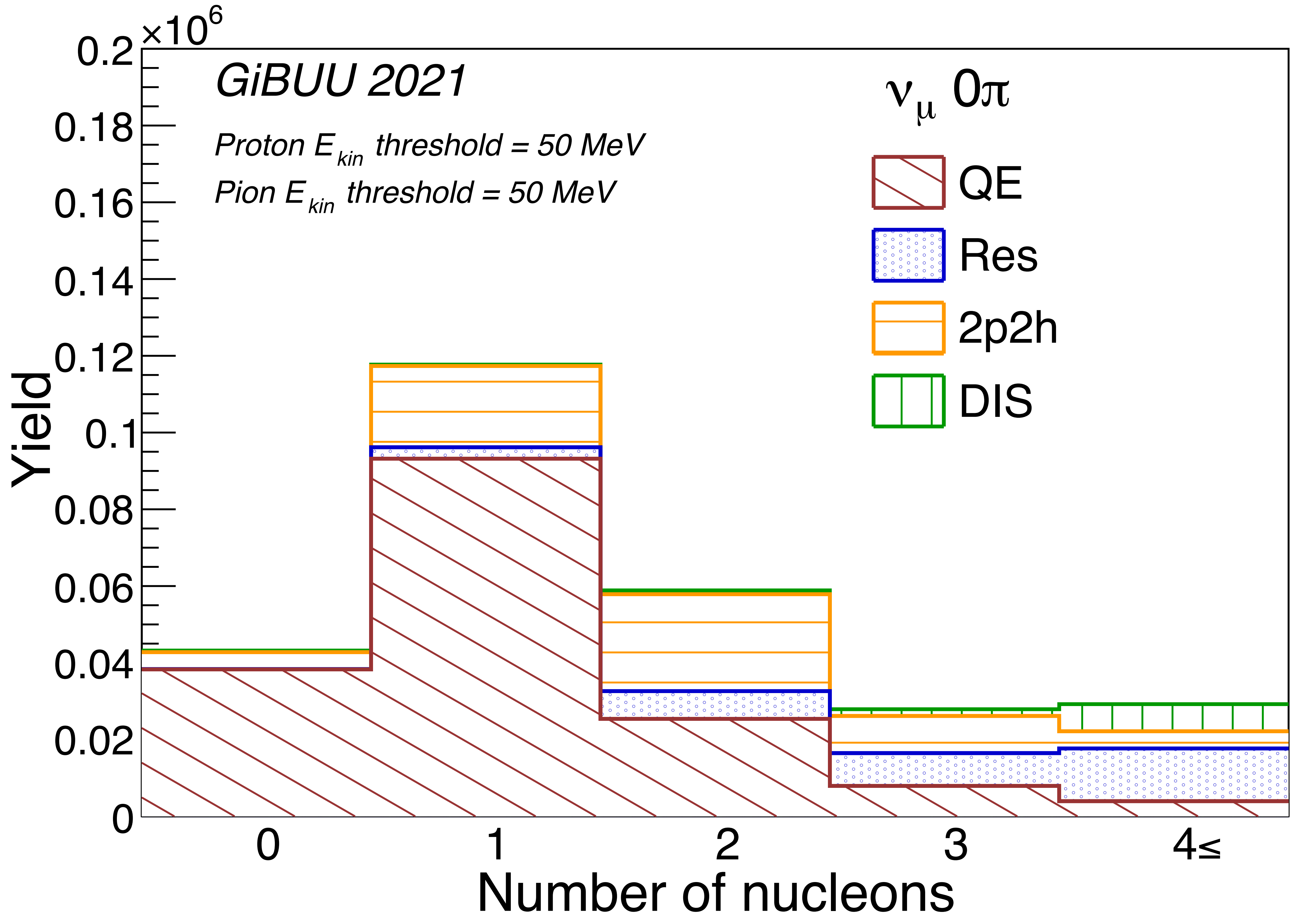
Proto-DUNE: Pion scattering 1, 6 and 7 GeV

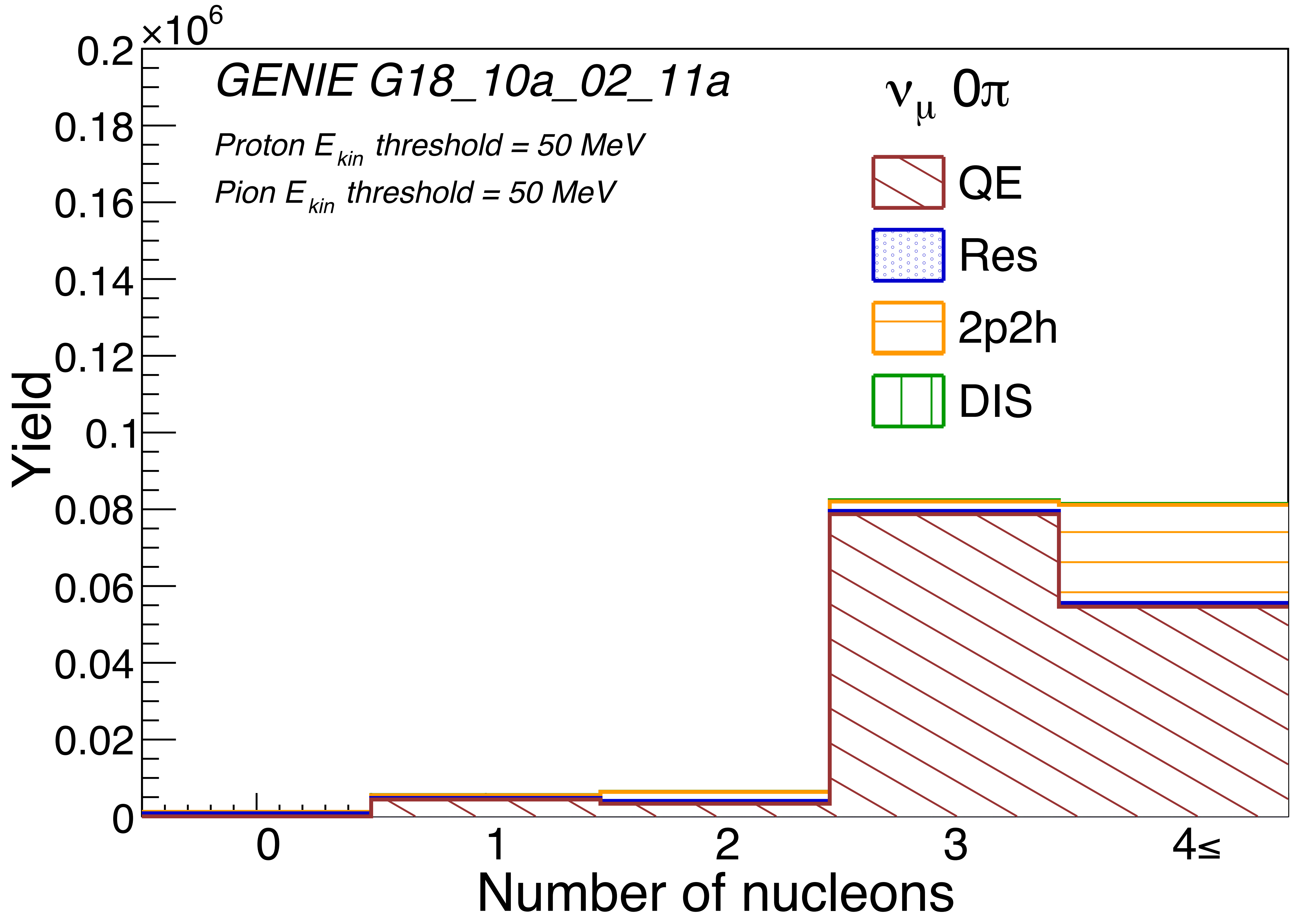
Not published yet

NP04 2023 Annual Report to the CERN-SPSC



0pi 0prt nucleon multiplicity





proton multiplcity per neutrino