NEUT - Neutrino Interaction Generator Software Tool

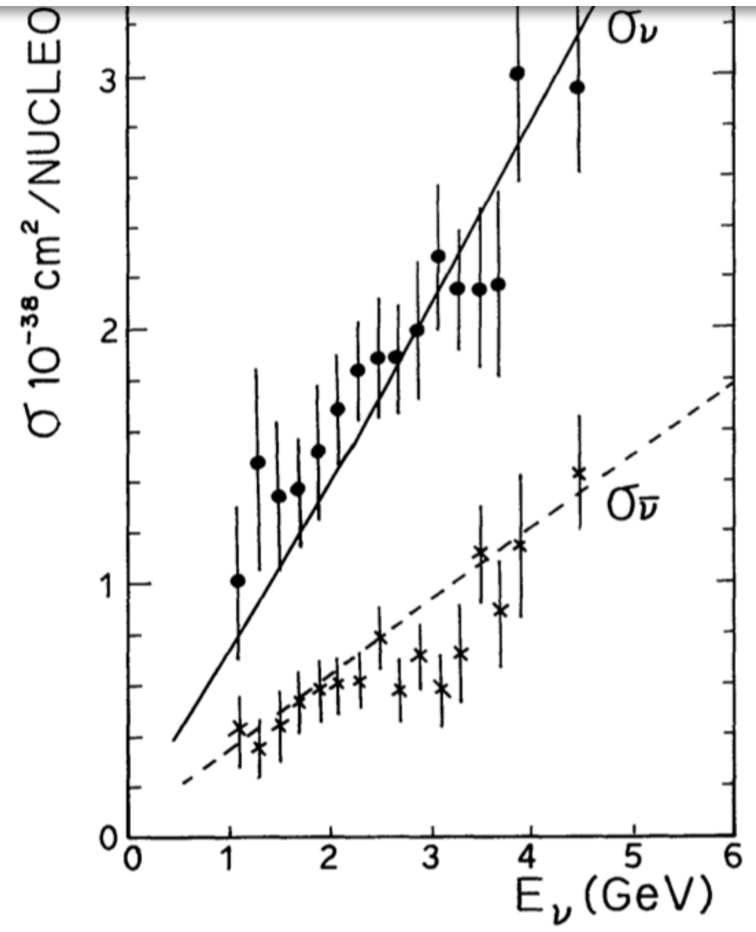
P. Stowell, Y. Hayato, L. Pickering, for the NEUT Collabrators

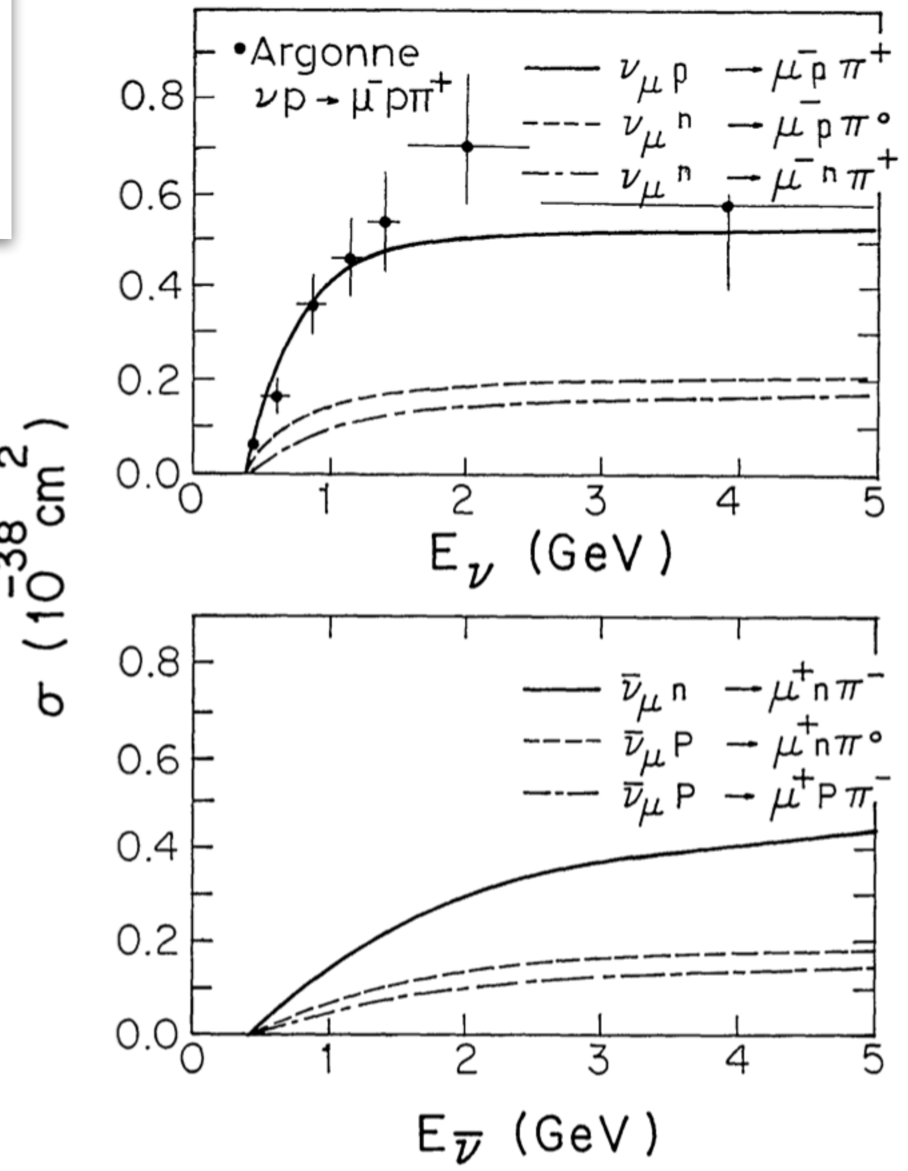
NuINT2024

University of Sheffield

- MeV to TeV scale neutrino interaction generator originally created in the 70s to support neutrino backgrounds at Kamioka.
- Long history of development driven by evolving requirements of KamiokaNDE, Super-KamiokaNDE, and T2K.
- Currently the primary interaction generator for SK and T2K, used in all oscillation/cross-section analyses.
  - See Laura, Stephen, Ulyesse, and Cesar's talks this NuINT!

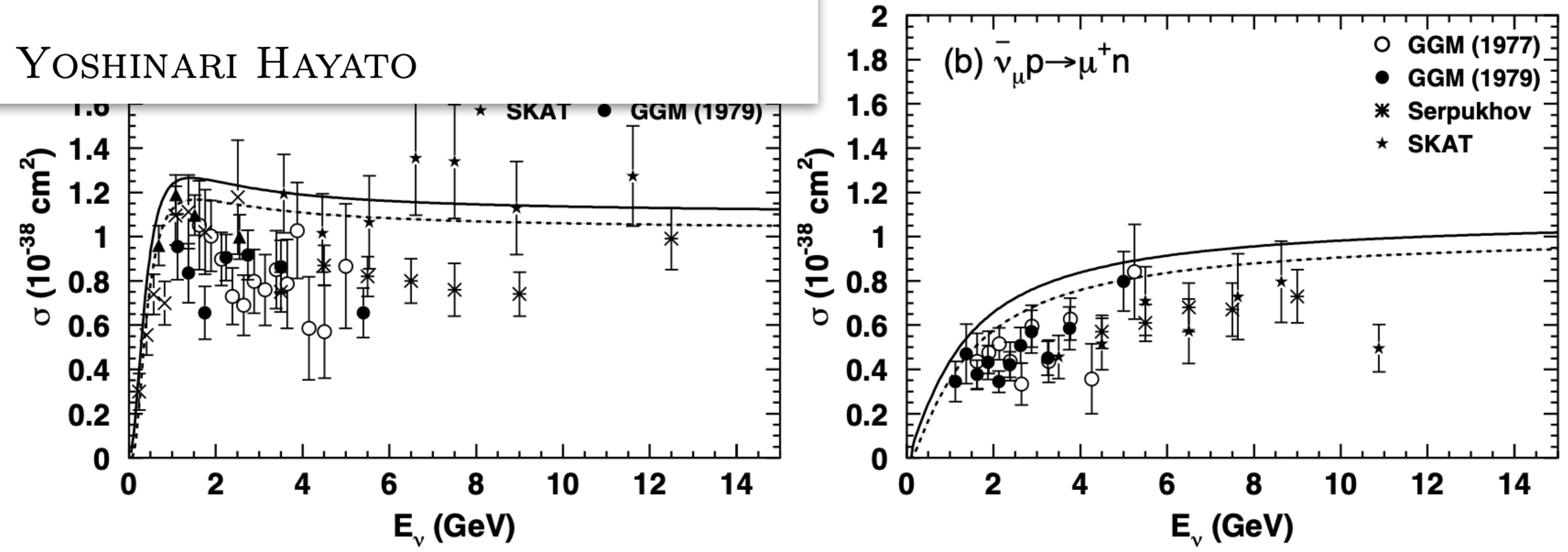
Atmospheric Neutrino Background and Pion Nuclear Effect for KAMIOKA Nucleon Decay Experiment





A NEUTRINO INTERACTION SIMULATION PROGRAM LIBRARY NEUT*

YOSHINARI HAYATO



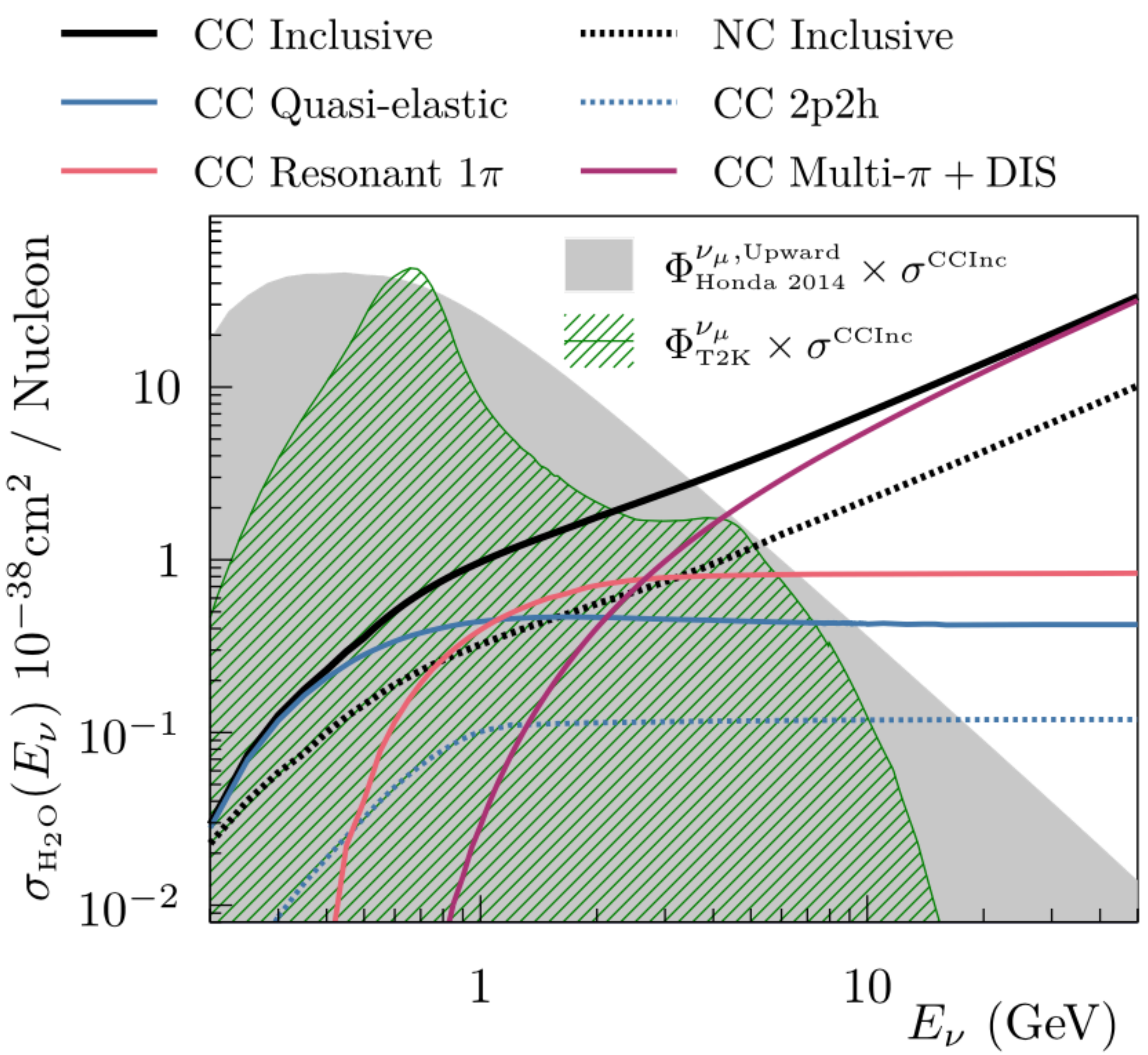
MODERN NEUT

- NEUT combines neutrino-nucleon level interactions with nuclear effects to describe exclusive interaction topologies
- Range of interaction channels/models have been added on the quest for full systematic coverage on SK/T2K experiments.
- Freedom for in-NEUT systematic studies using Reweighting approaches for several model components.

The NEUT neutrino interaction simulation program library

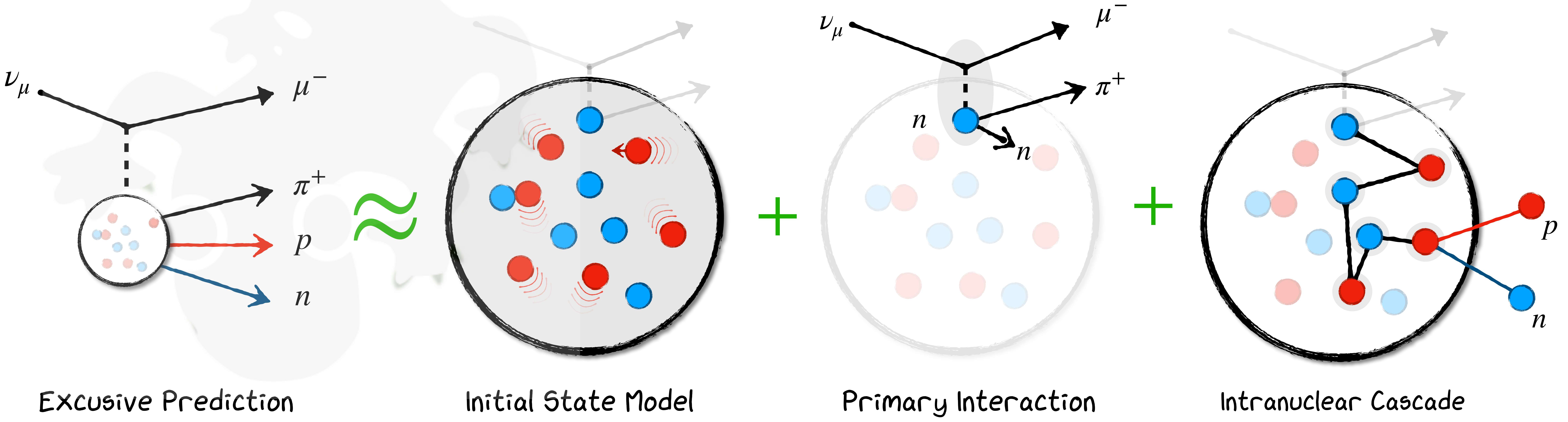
Yoshinari Hayato[1,a] and Luke Pickering[2]

The European Physical Journal Special Topics
volume 230, pages 4469–4481 (2021)



FACTORISATION

- Complex detector acceptances mean exclusive hadronic final state predictions are required. **Difficult problem for few GeV region due to many body nuclear effects.**
- NEUT employs factorisation to try to seperate out initial state, nucleon-level, and final-state interactions when describing heavy nuclei.

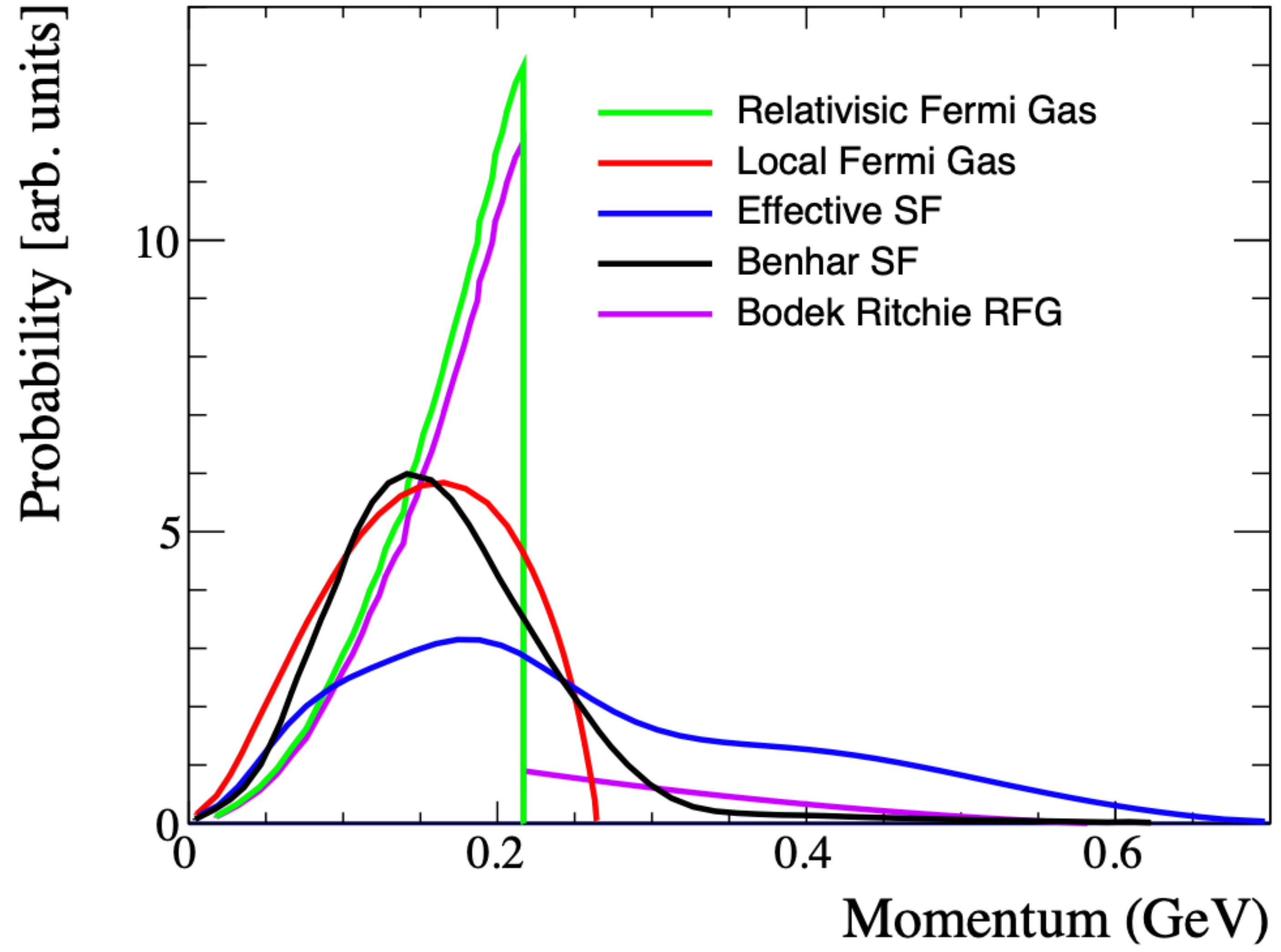


INITIAL STATE

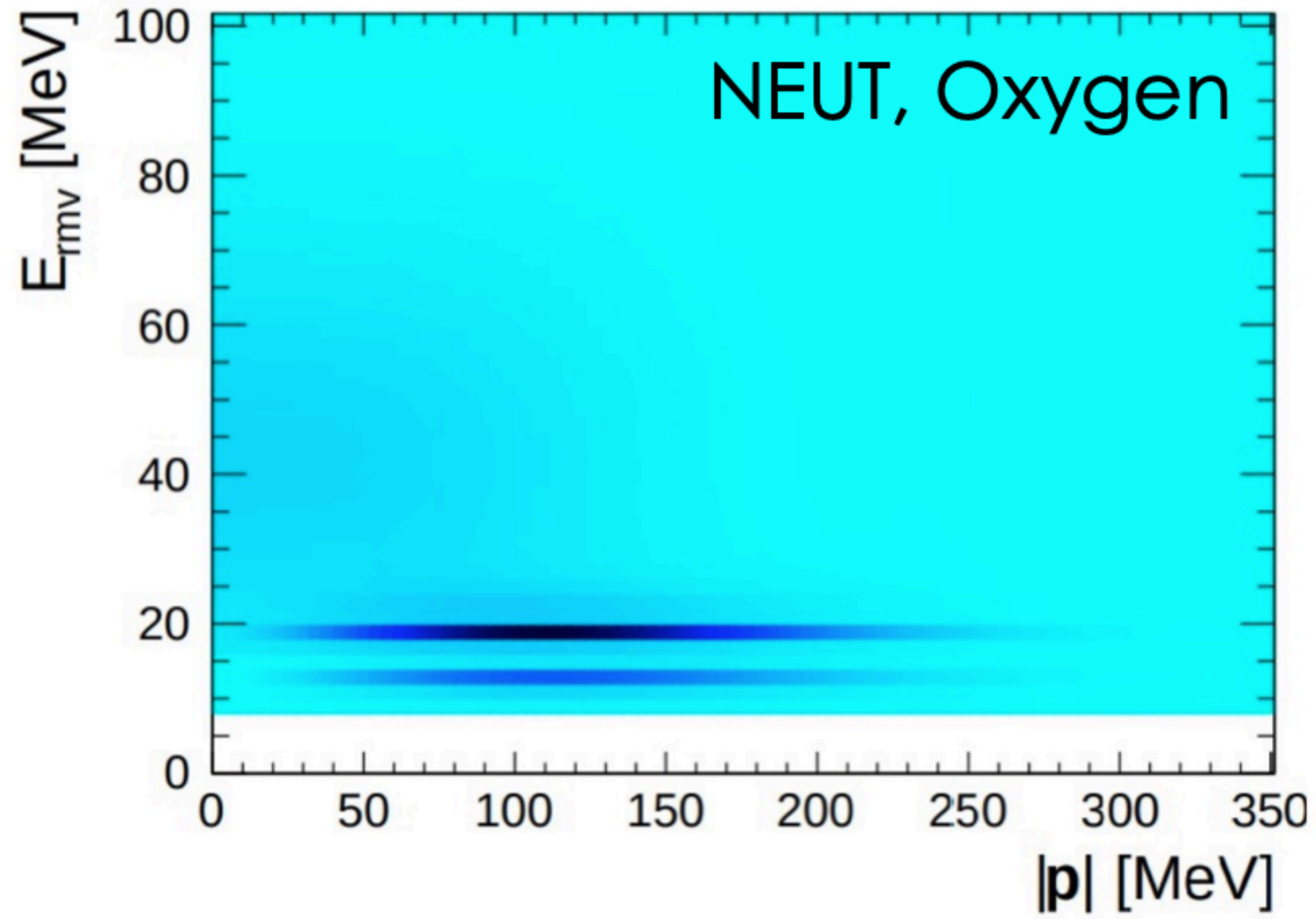
- Pauli blocking effects and initial state nucleon momenta distribution and can significantly modify low energy interactions.

- NEUT has three different initial state nuclear model implementations.

  - Relativistic Fermi Gas with Bodek-Yang Correction (Many nuclei)
  - Local Fermi Gas (Many nuclei)
  - Benhar Spectral Function (C12, O16, Fe56)

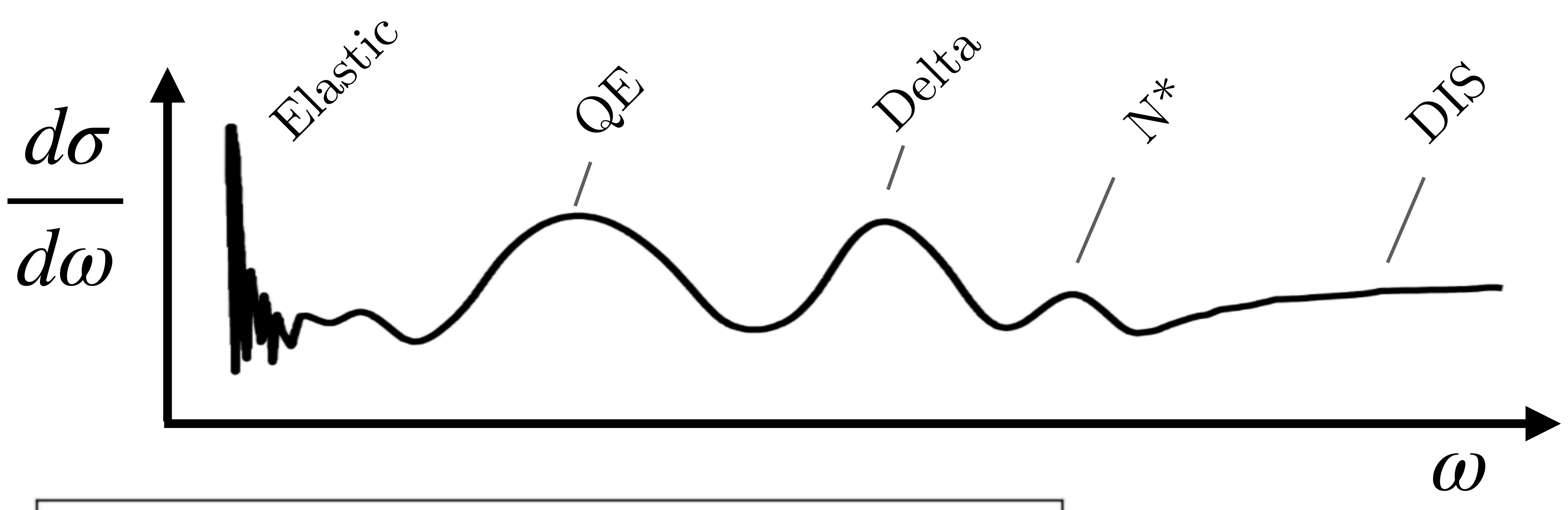


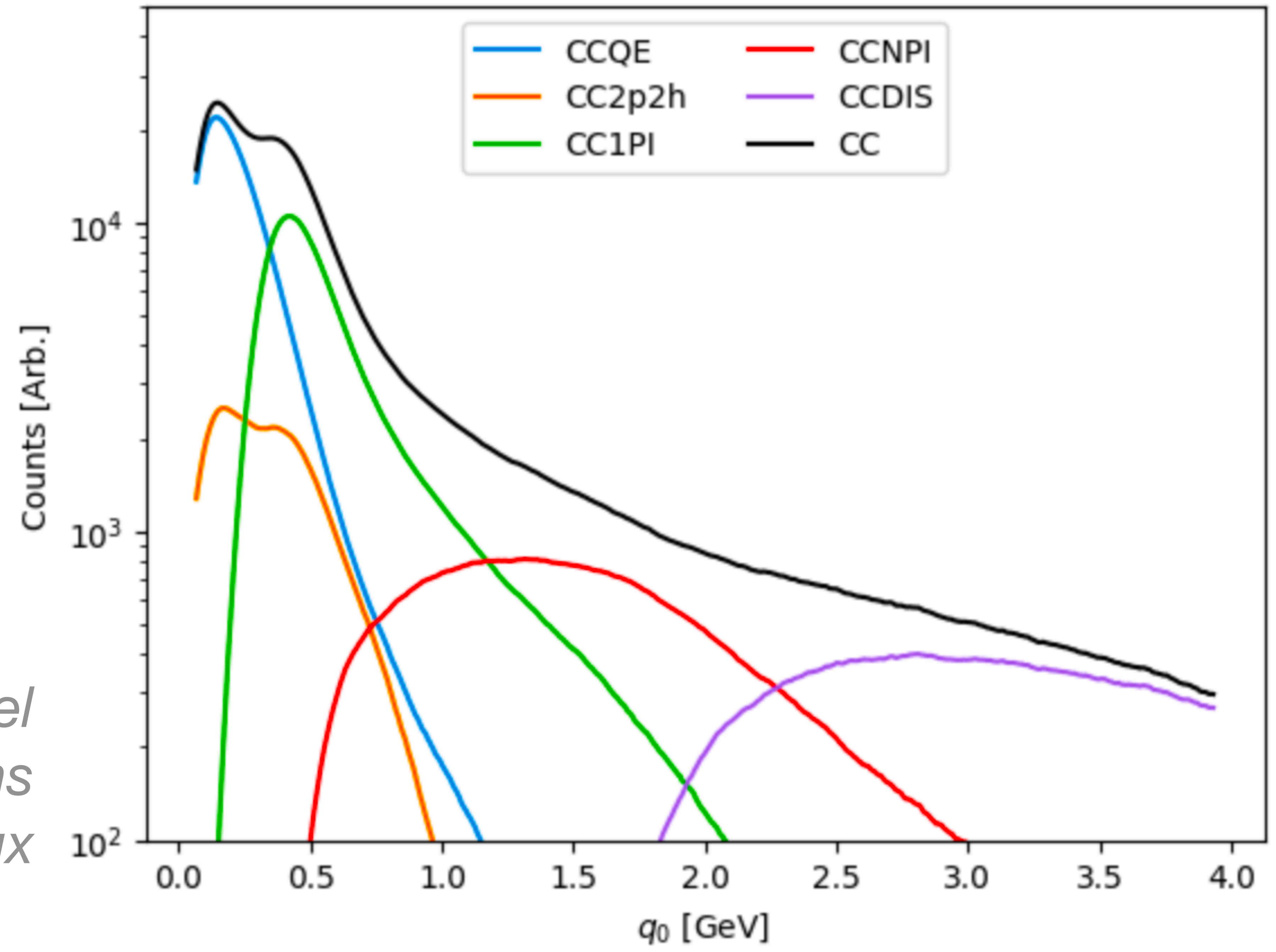
NEUT Initial State Models

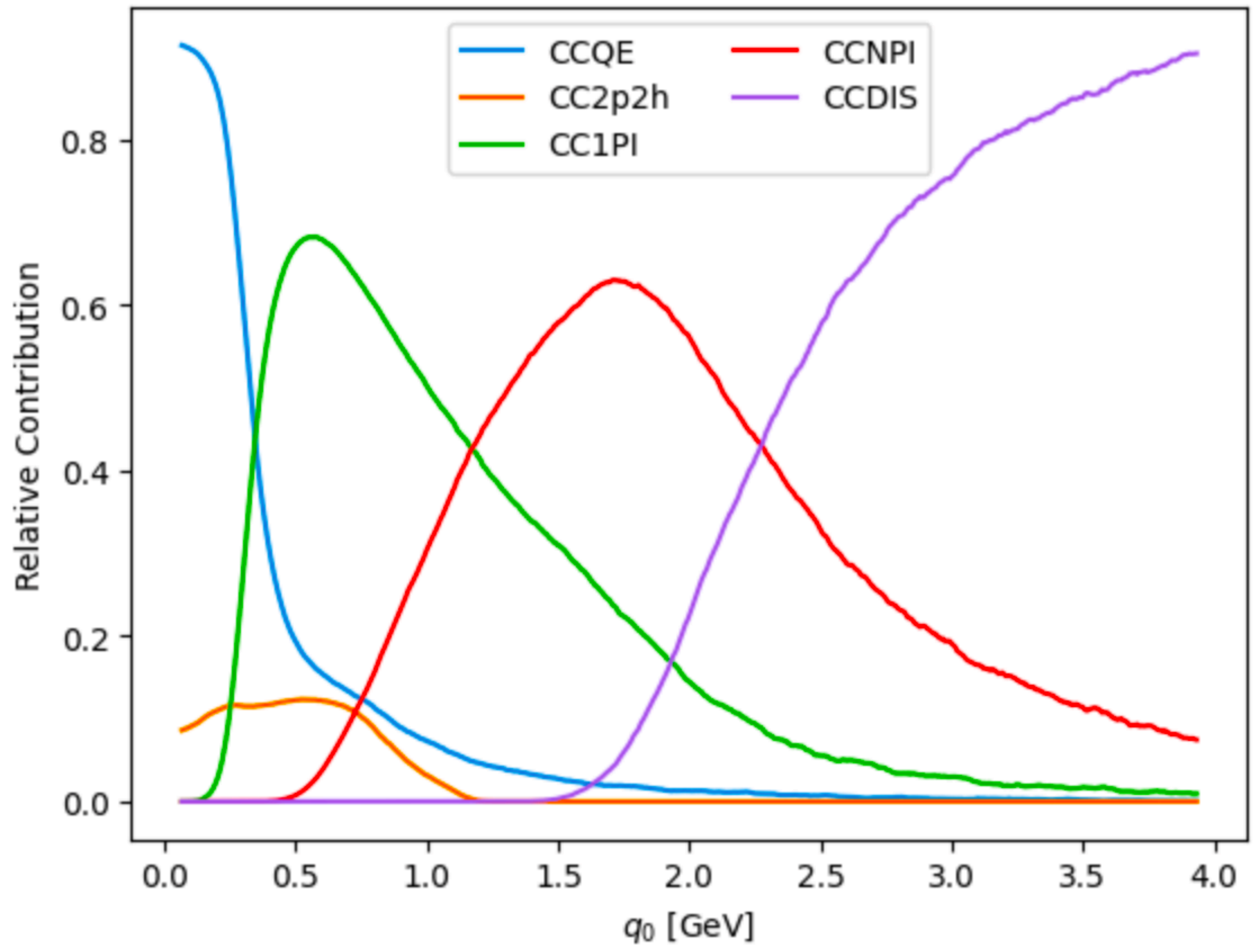


NEUT Benhar Spectral Function

- NEUT covers a range of possible neutrino-nucleon interactions for neutrino energies in the 100 MeV and TeV range.







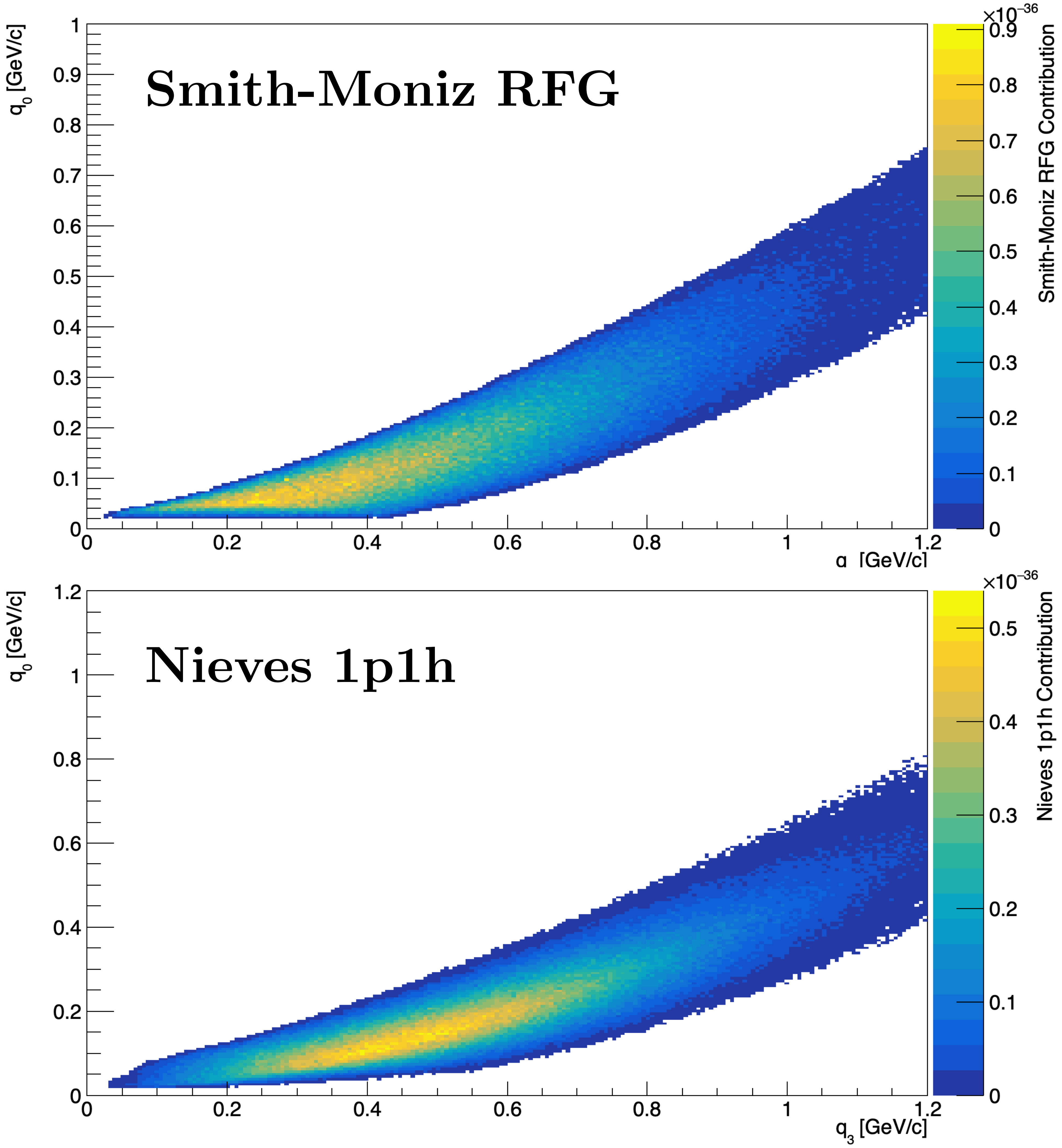
NEUT Channel Contributions T2K Flux

HARD SCATTER : QUASIELASTIC

- Inclusive CCQE Models:
  - Llewellyn Smith cross-section & kinematics with **Smith-Moniz RFG**
  - Llewellyn Smith cross-section & kinematics with **Benhar et al. SF**
  - **Nieves et al. 1p1h** (Valencia) w/Bourguille et al. removal energy

- Choice of Nucleon Form Factors:
  - **Vector**: Dipole, BBA05, BBBA07
  - **Axial**: Dipole, 3-component, Z-expansion

- Recent work by Clarence Wret and Kevin McFarland studying radiative corrections to QE process - ν_μ/ν_e ratios, and extra FS photons!

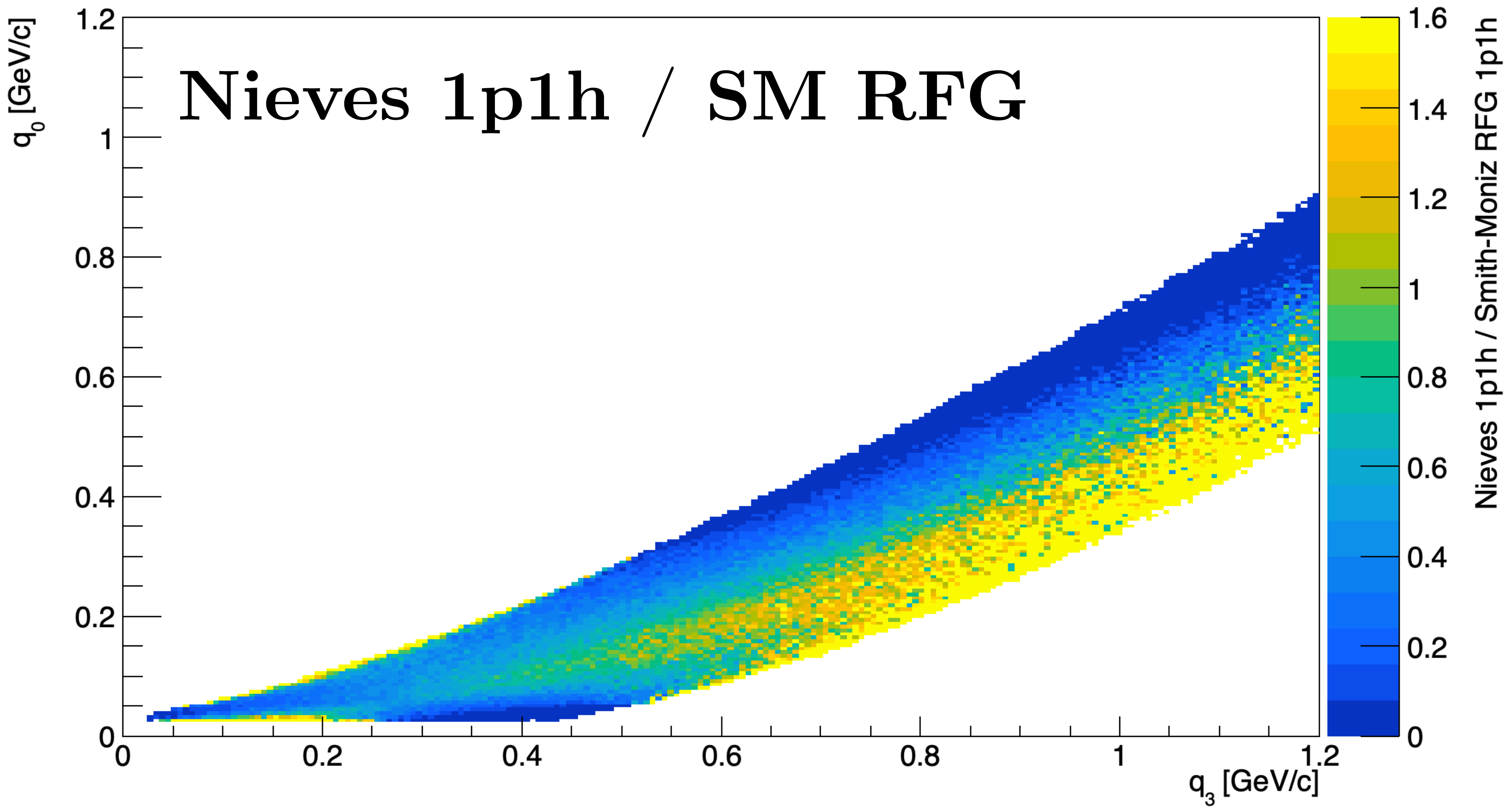


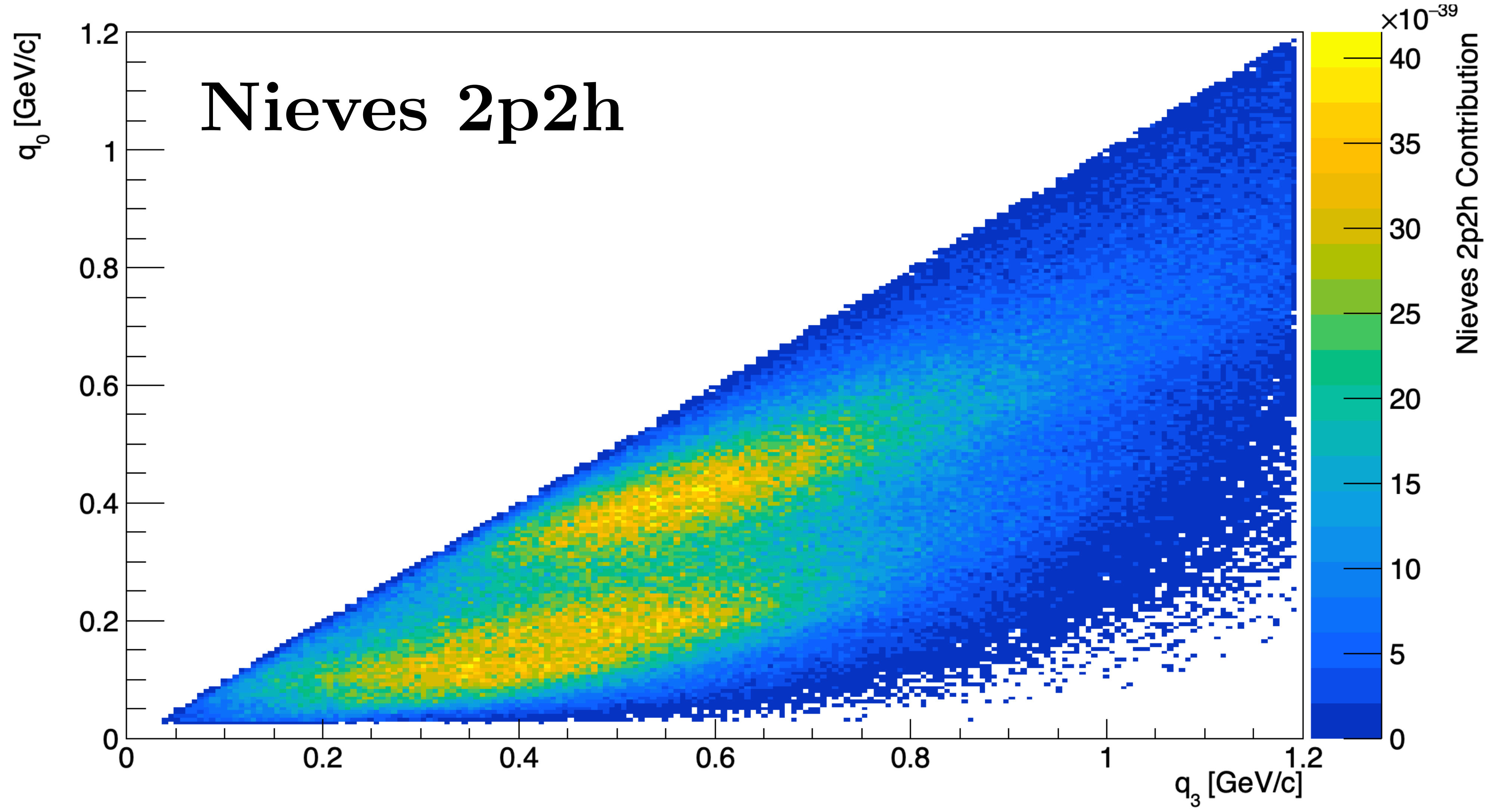
FACTORISATION MODIFICATIONS

- The factorisation assumption breaks down in the low-energy region where correlations signifcant.

- **1p1h Model (QE) :**
  - **Nieves et al. 1p1h** (Valencia) w/Bourguille et al. removal energy

- **2p2h Model :**
  - **Nieves et al. 2p2h (Valencia)** with custom hadron kinematics model and Bourguille et al. removal energy.
  - Full HT or Look-up Table implementations





RELATIVISTIC MEAN FIELD THEORY MODELS

- First implementation of a macroscopic model based on a Relativistic Mean Field optical models into NEUT
  - Jake McKean, Raul González-Jiménez, Monireh Kabirnezhad

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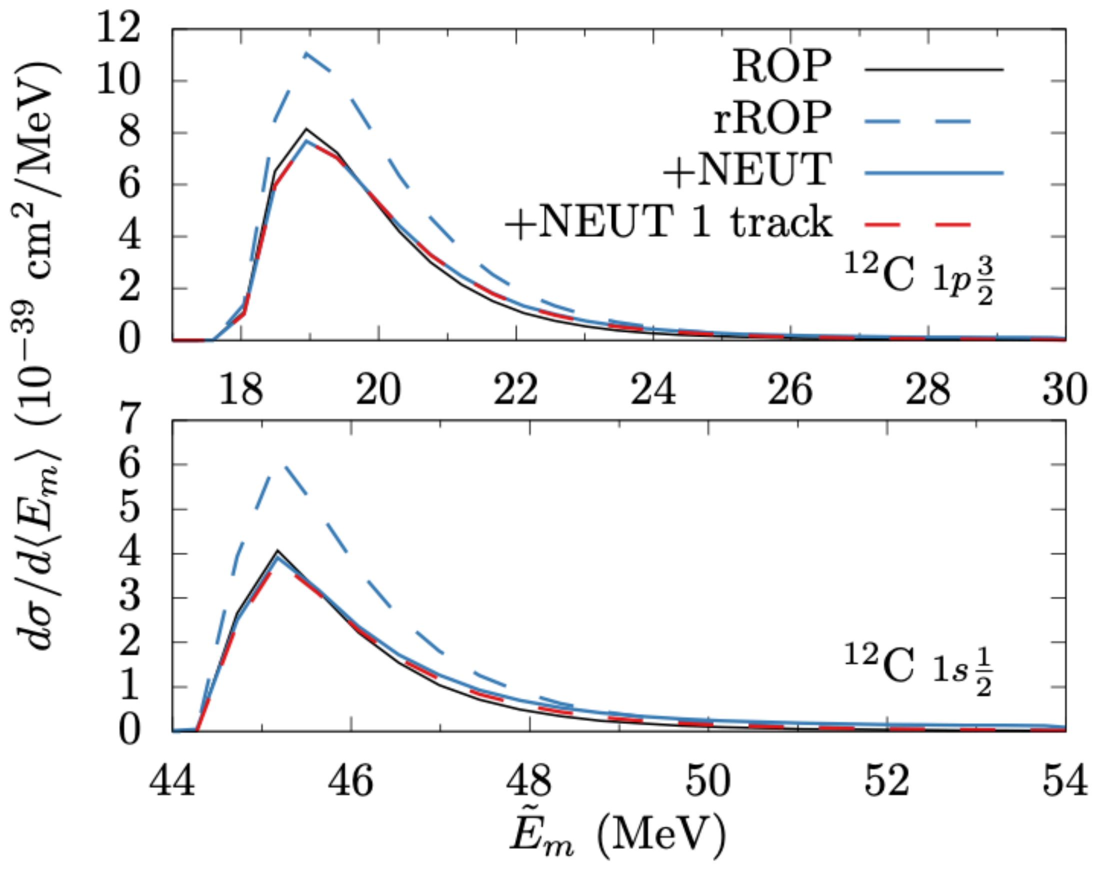
- Potentia for new theory-motivated systematic uncertainty studies in NEUT.
- Possible consideration of alternative operators for different processes.
  - E.g. future extensions to the Kabirnezhad model operator for inelastic pion production.

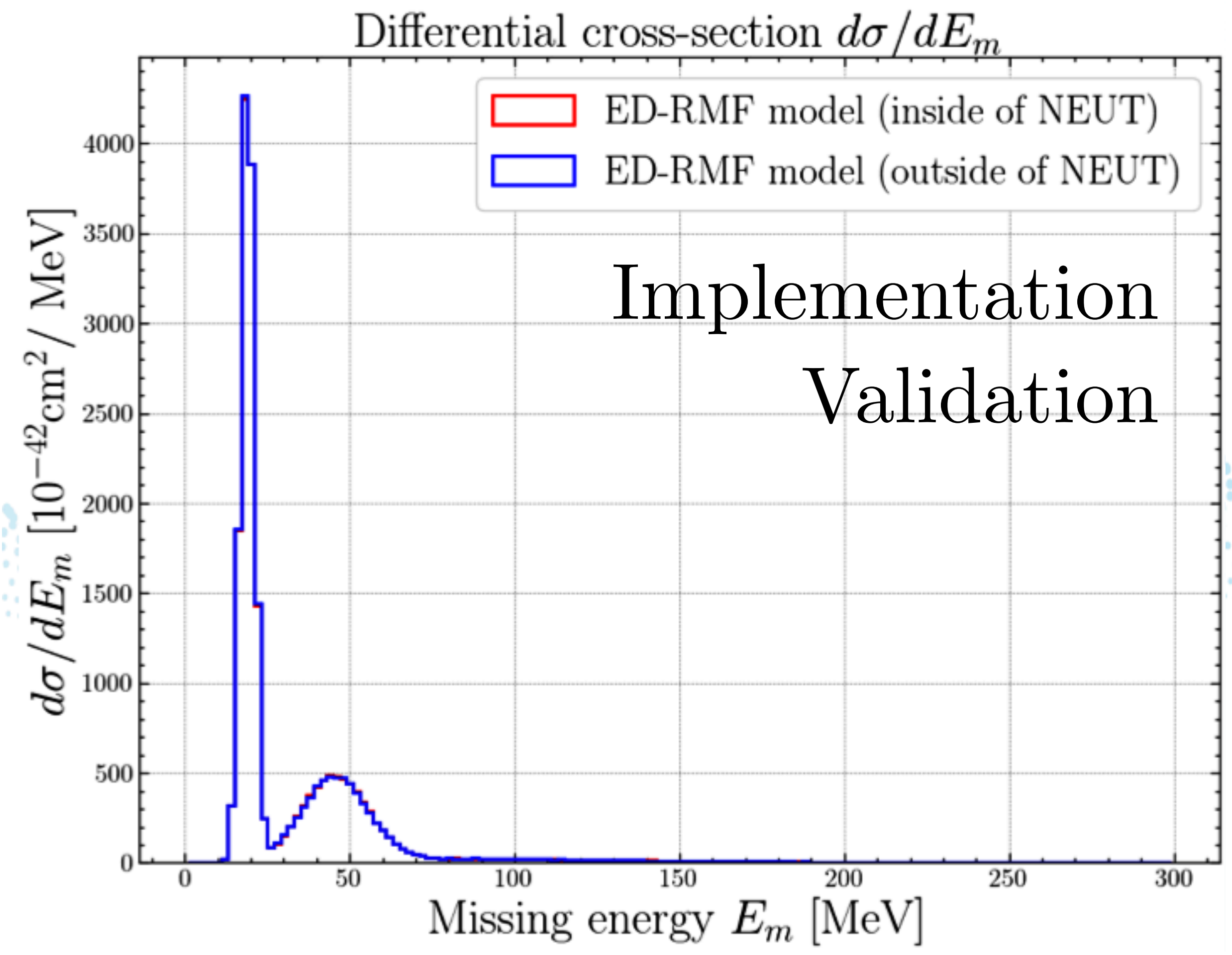
Neutrino-nucleon Operator

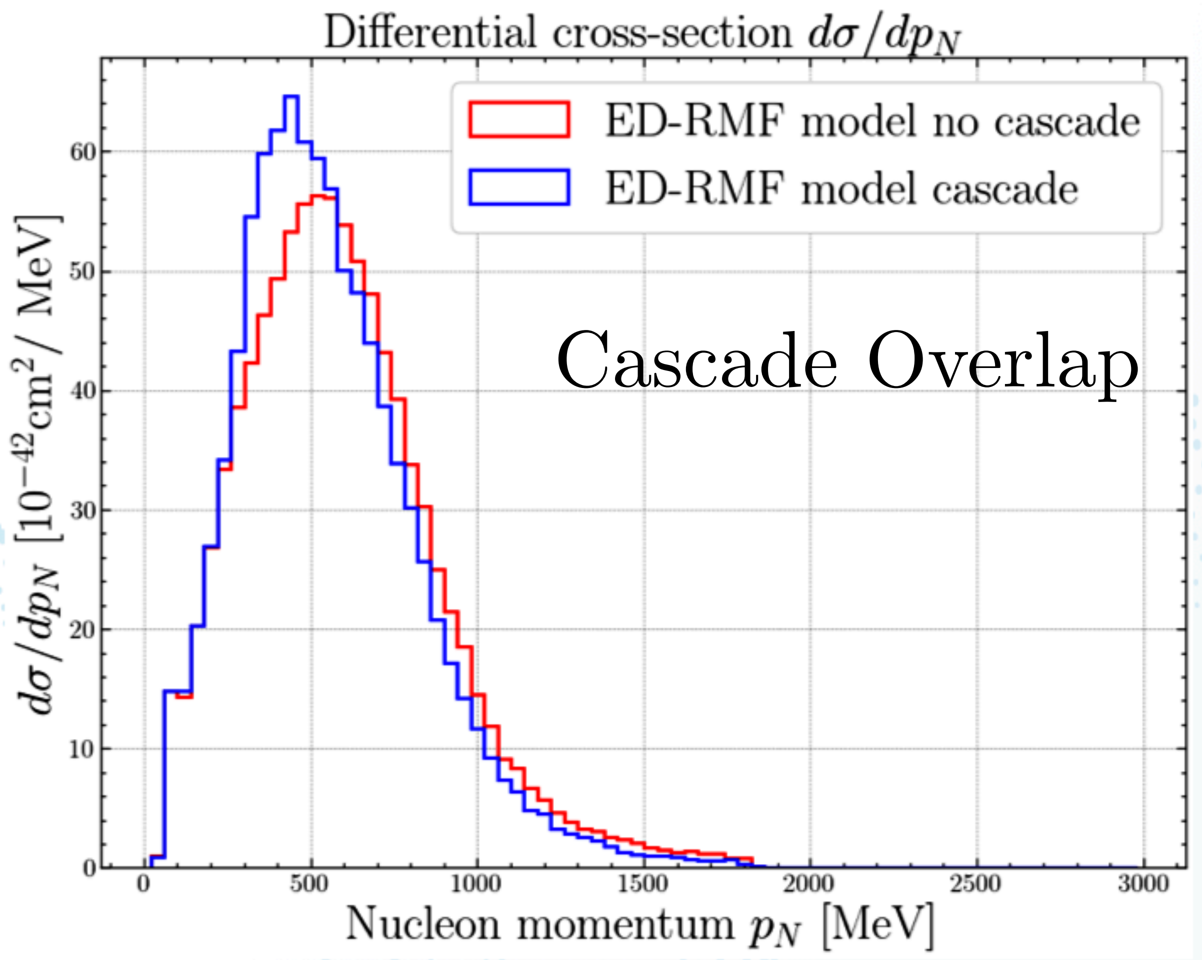
$$J^\mu \propto \int d\mathbf{p}\ \bar{\Psi}_{Scattered}\ \mathcal{O}^\mu\ \Psi_{Bound}$$

Hadronic Current — Scattering Potential — Bound State Wavefunction



Nikolakopoulos, Alexis, et al. "Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials." Physical Review C 105.5 (2022): 054603.

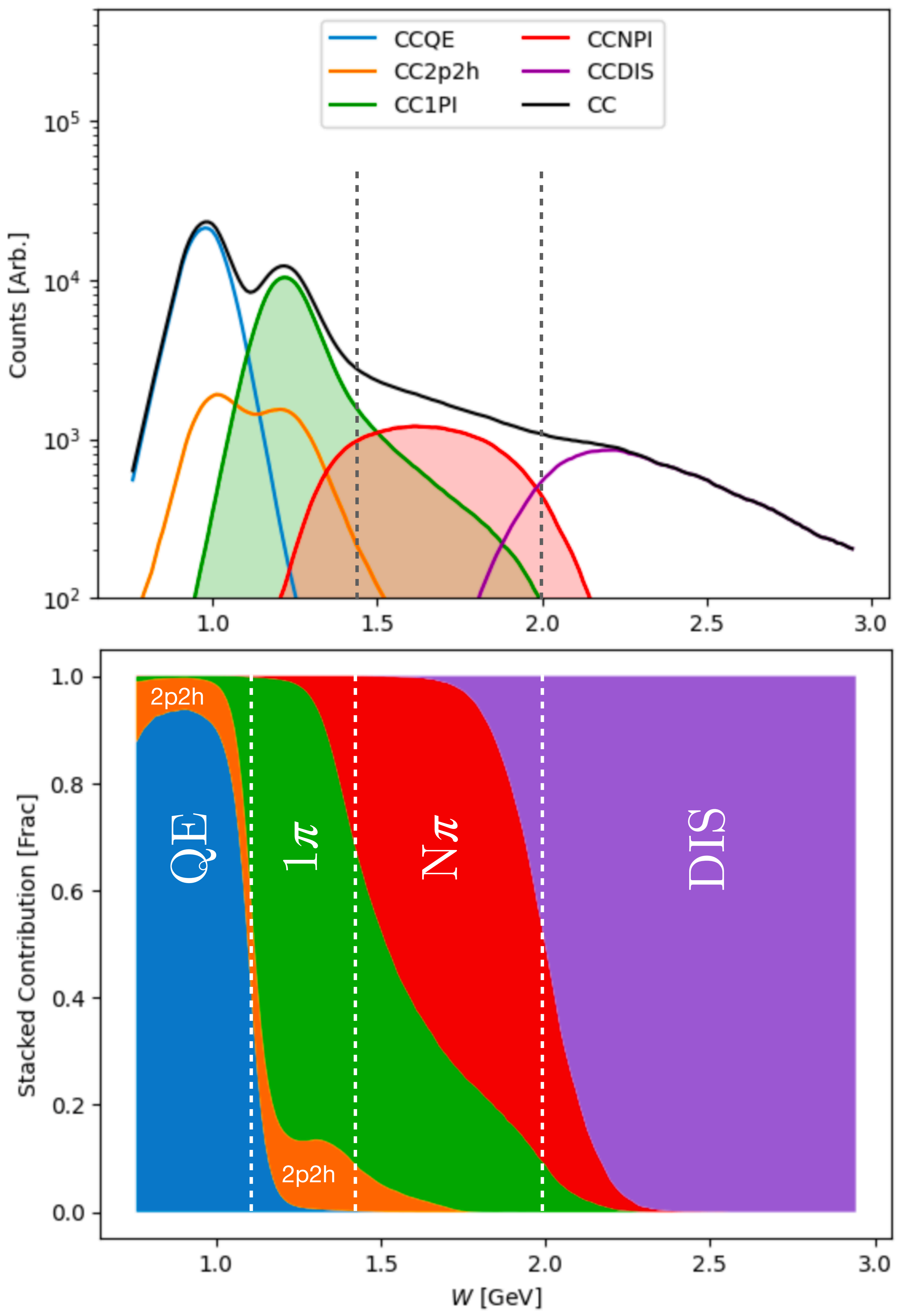




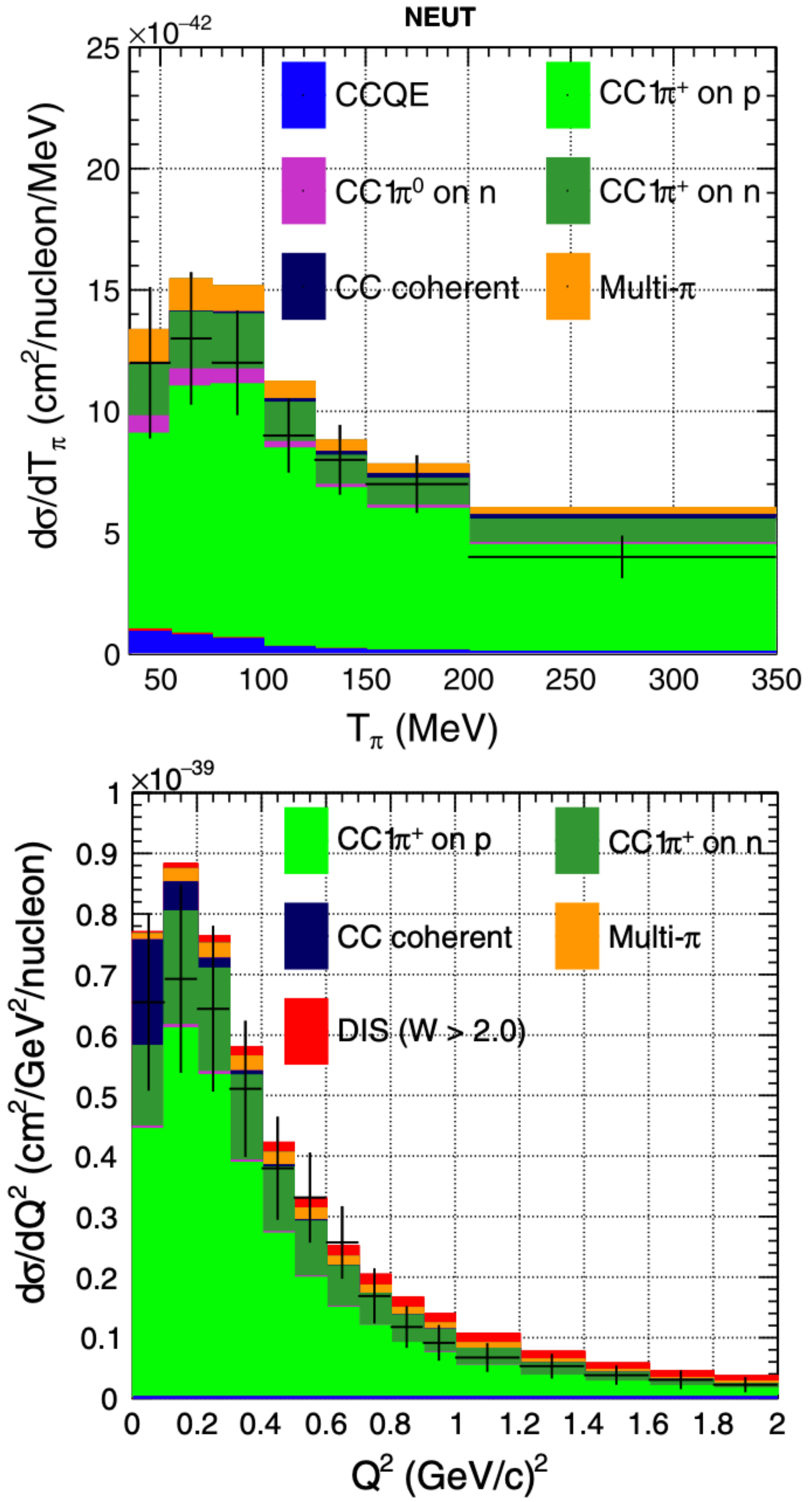
Jake McKean. "First results from a relativistic mean field theory implemented in the NEUT neutrino interaction event generator." IOP Joint APP, HEPP and NP Annual Conference 2024

HARD SCATTER : RESONANT

- NEUT defult 1π model up to $W < 1.4$ GeV based on Rein-Sehgal with Berger Sehgal lepton mass effects included.
  - Consistent account of inter-resonance interferences in RS model.
  - Uses Graczyk–Sobczyk form factors
  - Multi-pion events based on KNO scaling and measured pion W-multiplicities.
- Non-res. background added incoherently.
- Single Eta, Lambda, Kaon production also modelled.
- RS/BS model tunings of form factors and background from external data fits.



Contributions vs Reconstructed Invariant Mass : T2K Flux



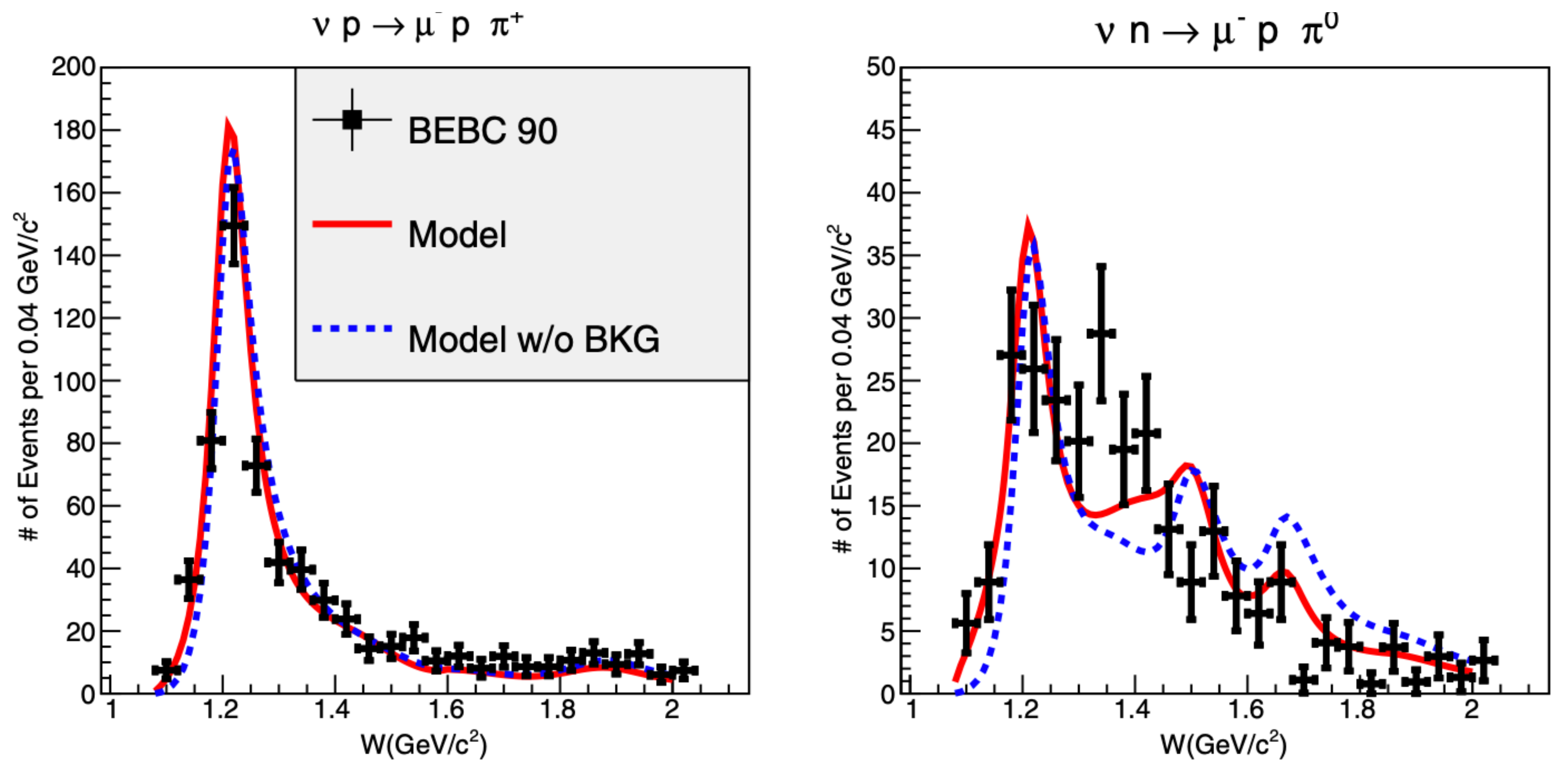
Pion Modelling in NEUT : Comparisons and Challenges of Modern Neutrino Scattering Experiments.

PION MODELS

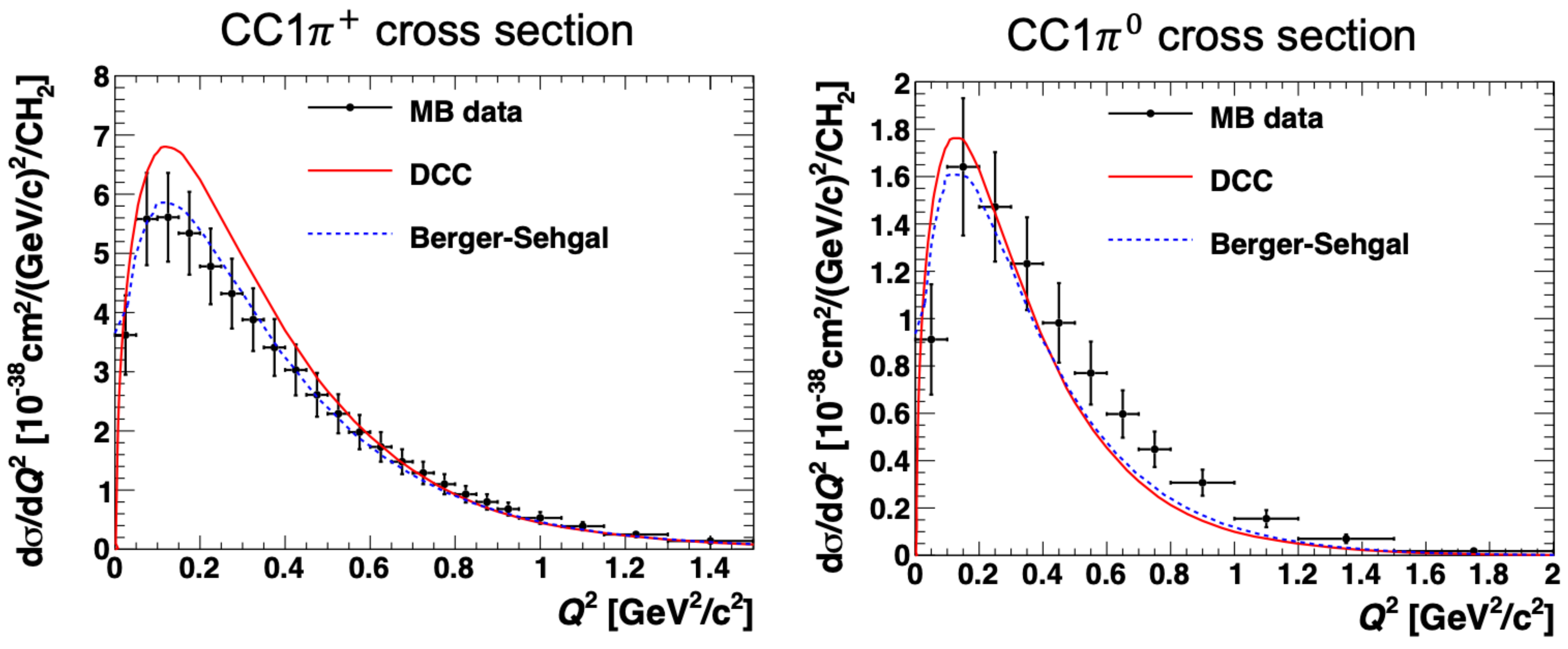
- Alternative Pion Models a key development focus
- **MK2018 implementation:**
  - Key improvement: Non-resonant channels contribute coherently
  - Significantly improved model on the way, using updated tables - see MK talk this NuINT!

- **DCC 1π [PRD 92, 074024 (2015)]:**
  - State-of-the-art 1π model
  - Inclusive predictions recently implemented as a model option NEUT

- **Coherent 1π**: Rein-Sehgal and **Berger-Sehgal**
- **Diffractive 1π:** Rein Model



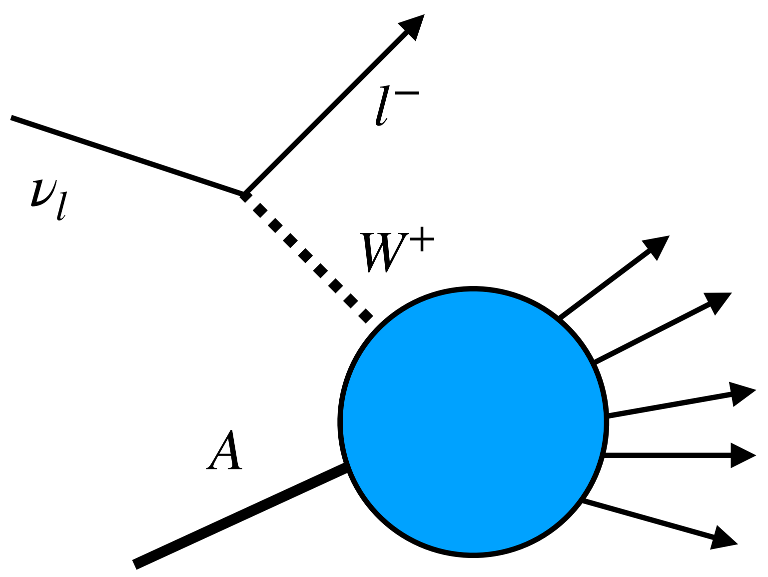
Kabirnezhad, Monireh. "Single pion production in neutrino-nucleon interactions." Physical Review D 97.1 (2018): 013002.



Yamauchi, Koki, Masaki Ishitsuka, and Yoshinari Hayato. "Comparison of cross section models for neutrino-induced single pion production."

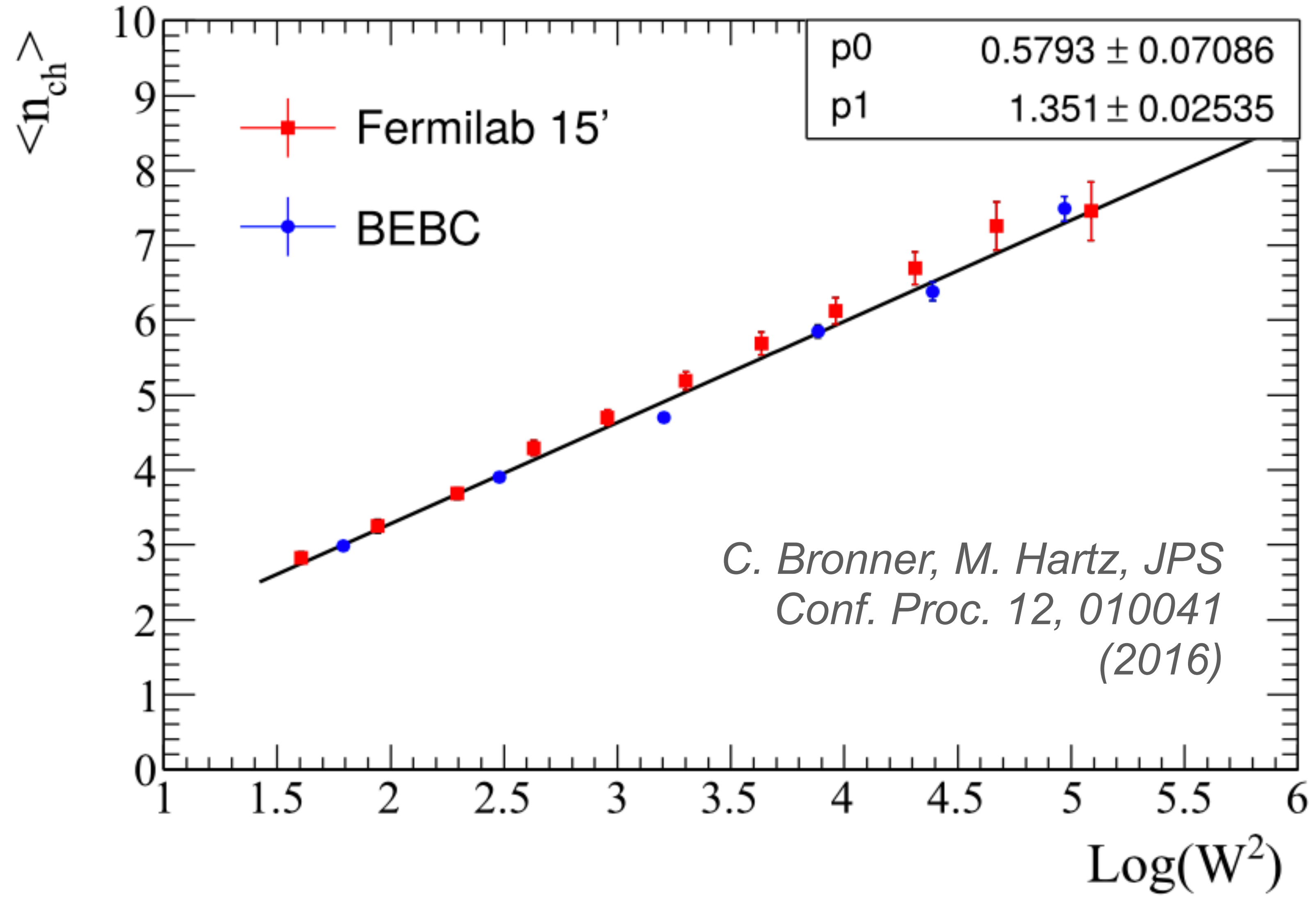
HARD SCATTER : DIS

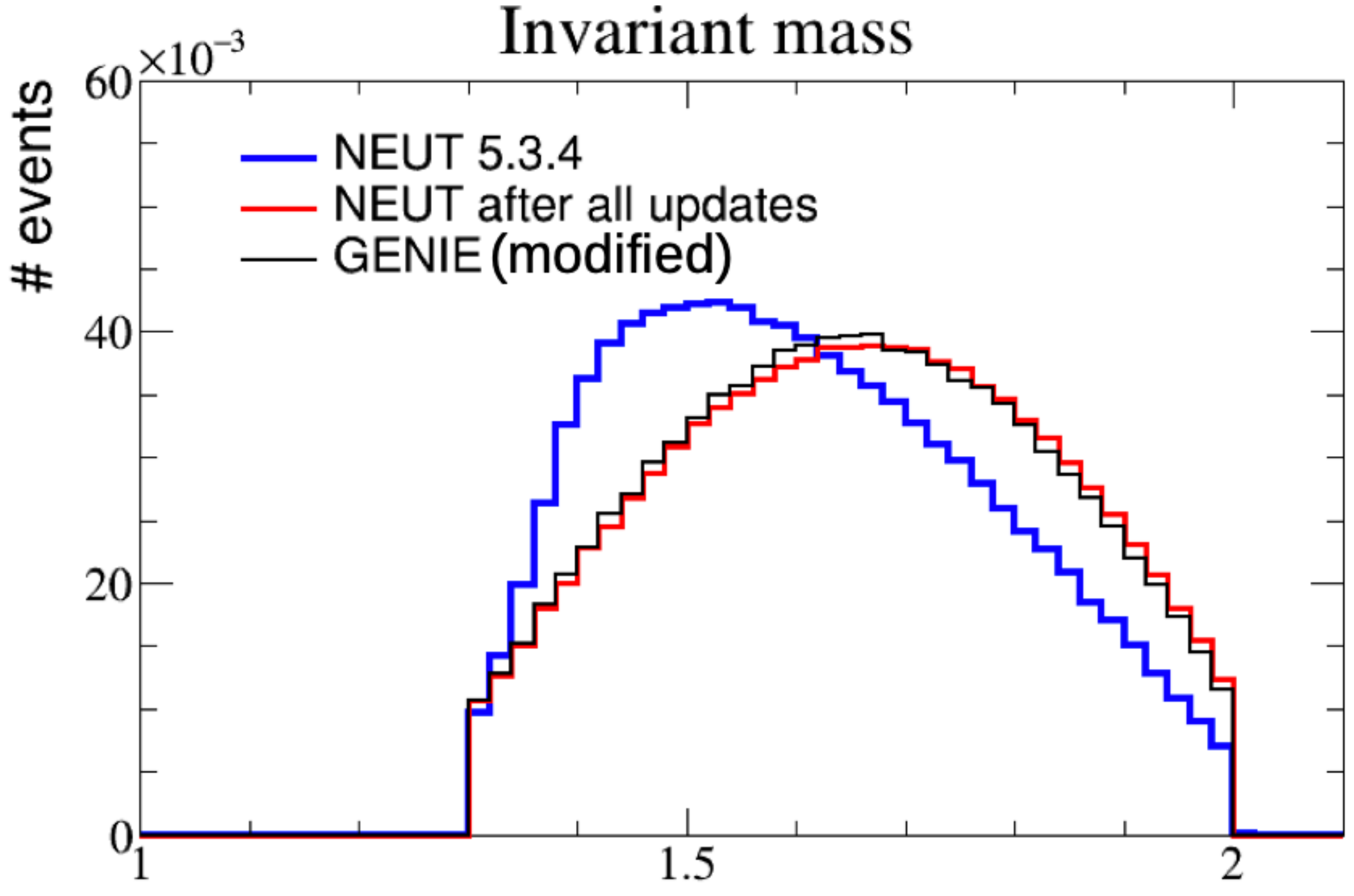
- NEUT SIS+DIS Model:
  - Base model is GRV98 + Bodek Yang.



- **DIS** : Pythia 5.7 for $W > 2\ GeV$.
  - Pythia JETSET model used for particle production.
- **SIS** : Custom model for $1.4\ GeV < W < 2\ GeV$
  - Alternative model for SIS transition region.
  - Requires more than one pion produced in the event.
  - Custom tunings to BC data.

- Reweighting sytematics allow variation of particle normalisations, and multiplicities.

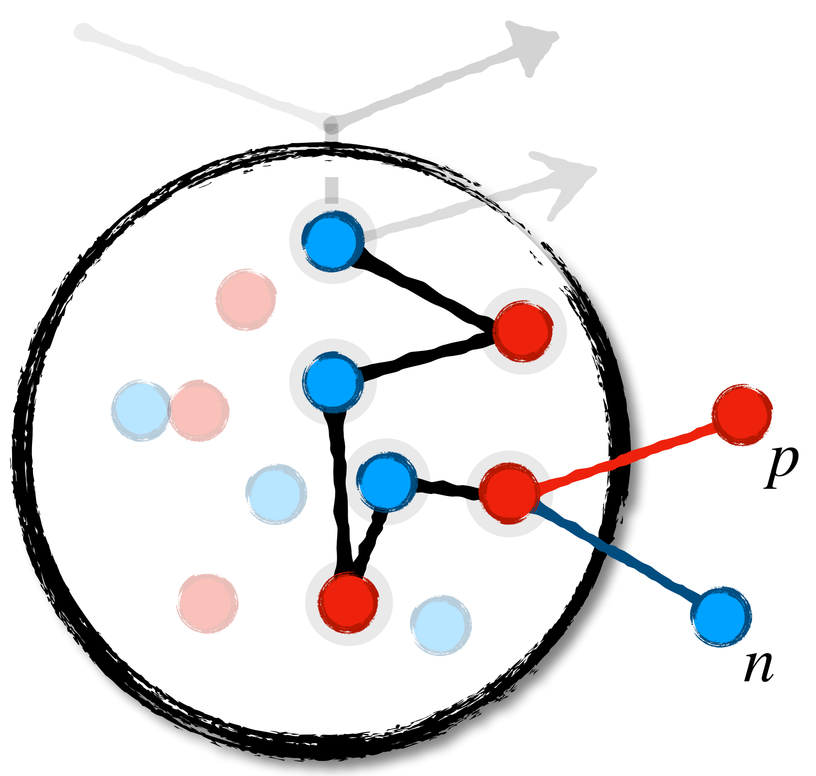


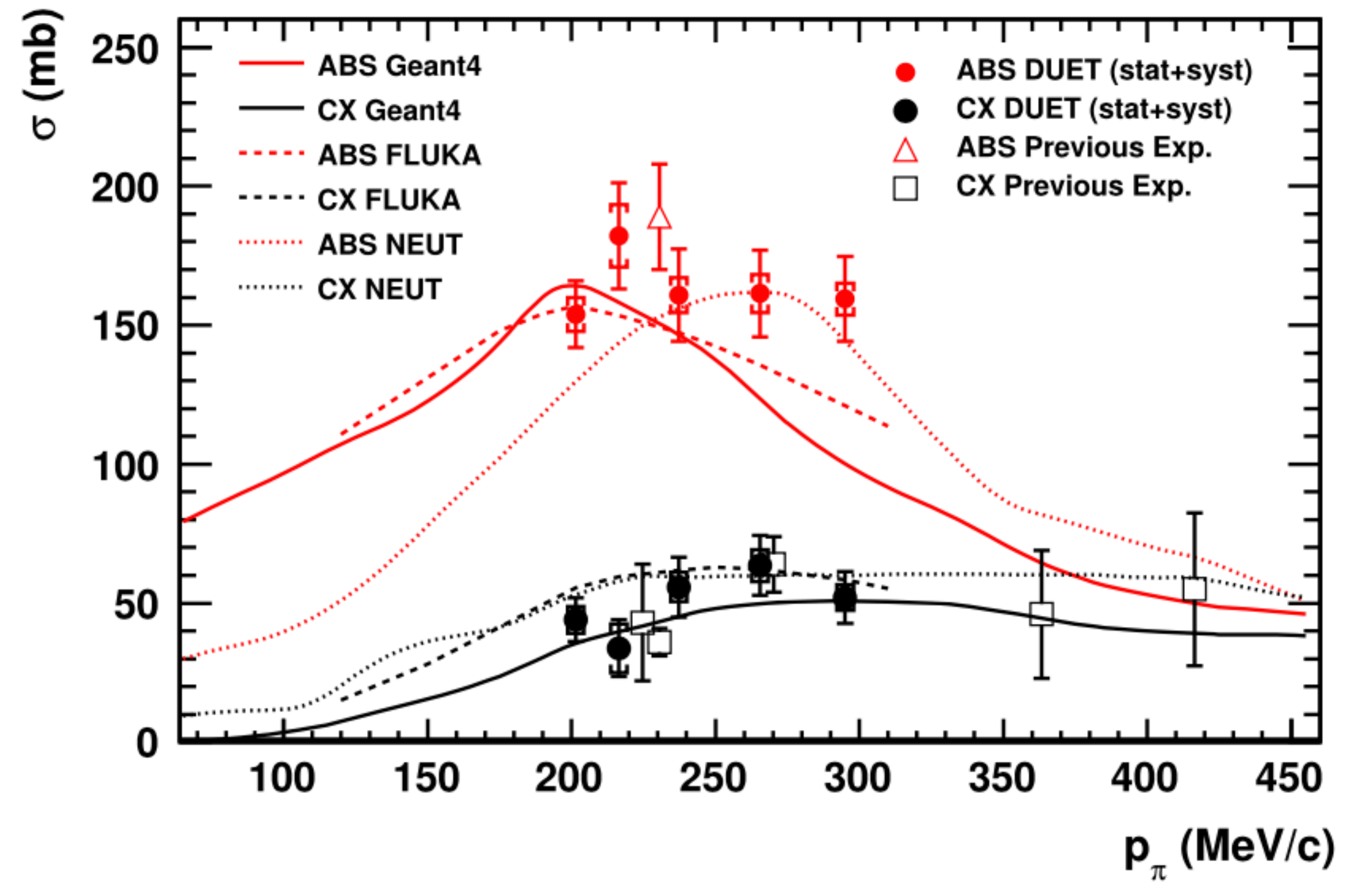


C. Bronner, Generators in the SIS/DIS Region

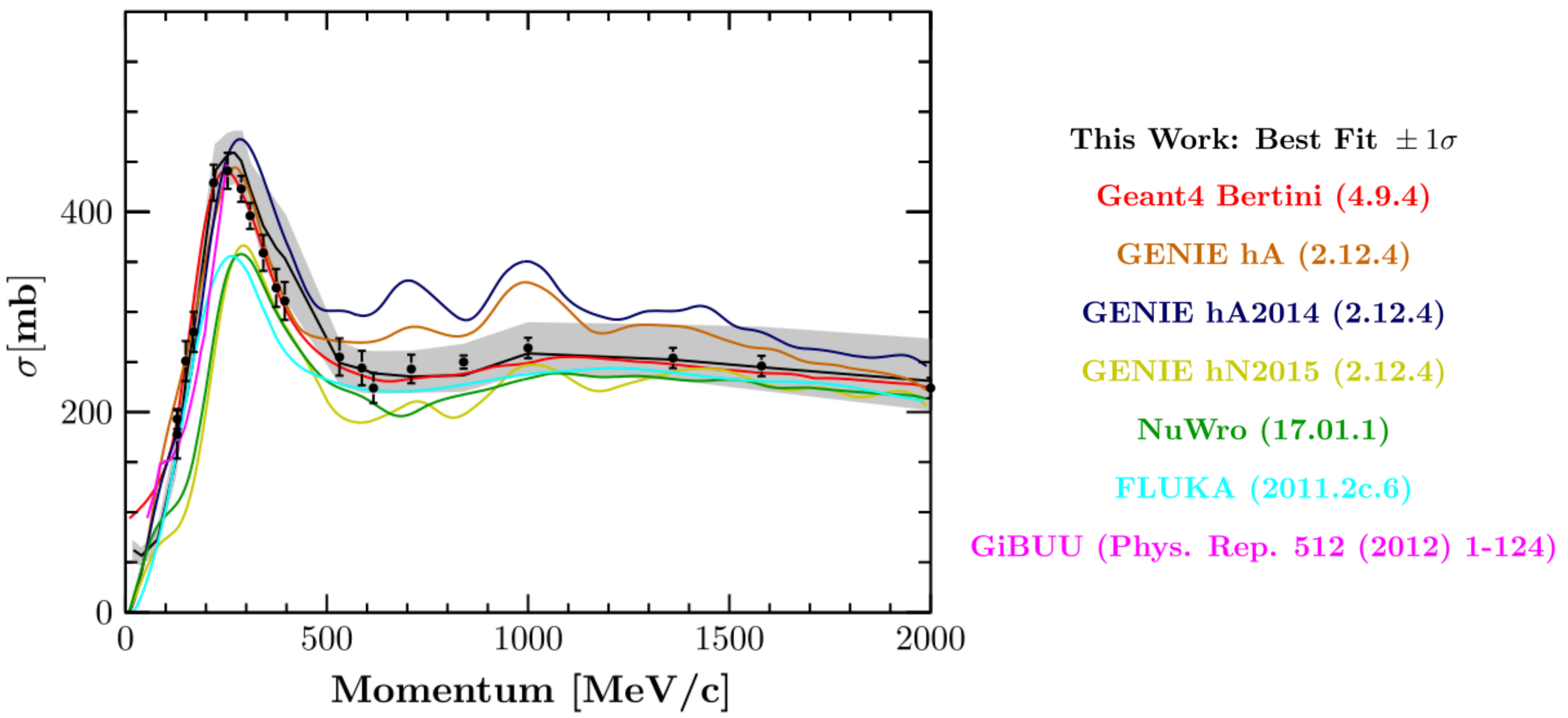
FINAL STATE INTERACTIONS

- NEUT uses a semi-classical cascade model for final state interactions. Particles stepped out of the nucleus considering reinteractions.
  - Salcedo-Oset Cascade model for mesons.
  - Bertini MECC-7 model for nucleons.
- Woods-Saxon nucleon density assuming LFG spectral function.
- Particle reinteraction probabilities tuned using heavy target scattering data.
  - Pions : mean free paths tuned to π-A exclusive scattering data (total, absorption and charge exchange).
  - Nucleons : scattering process freedom largely in normalisation of nucleon reaction cross-section.



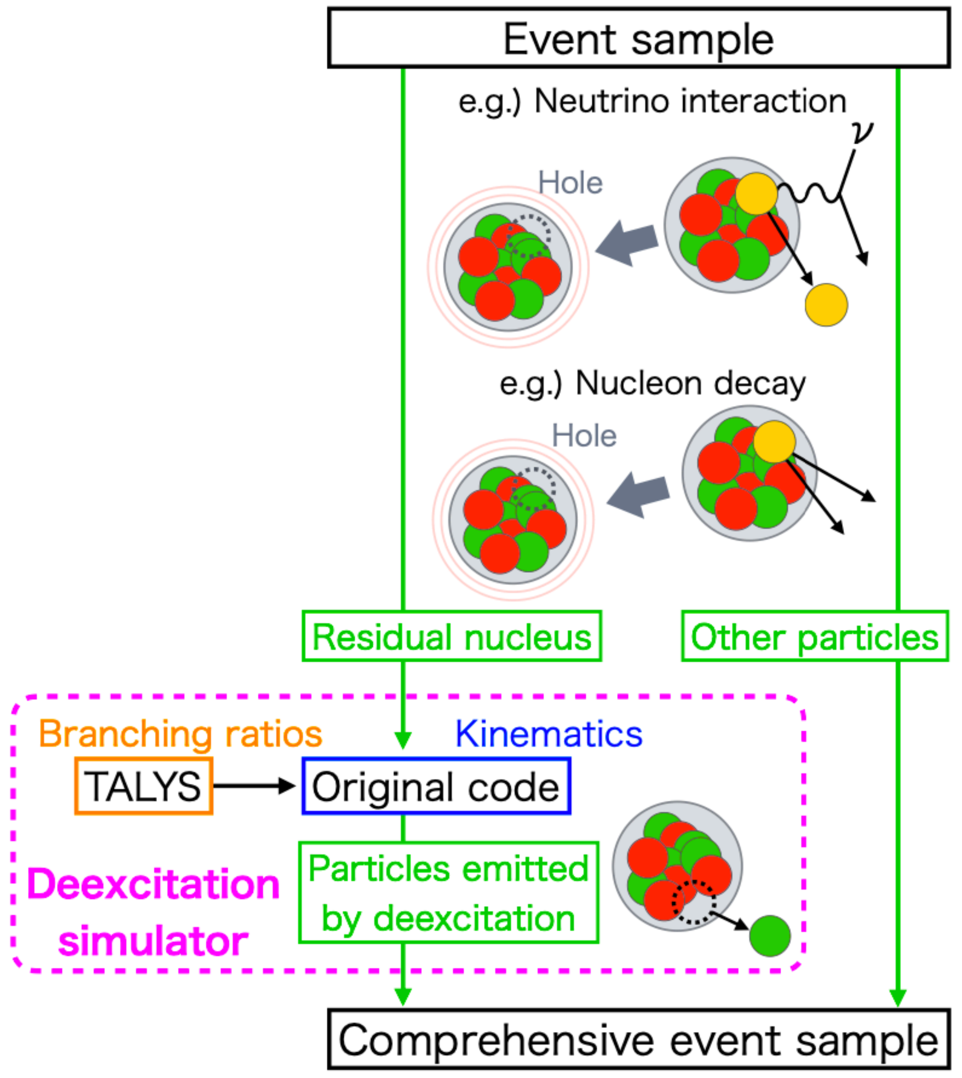


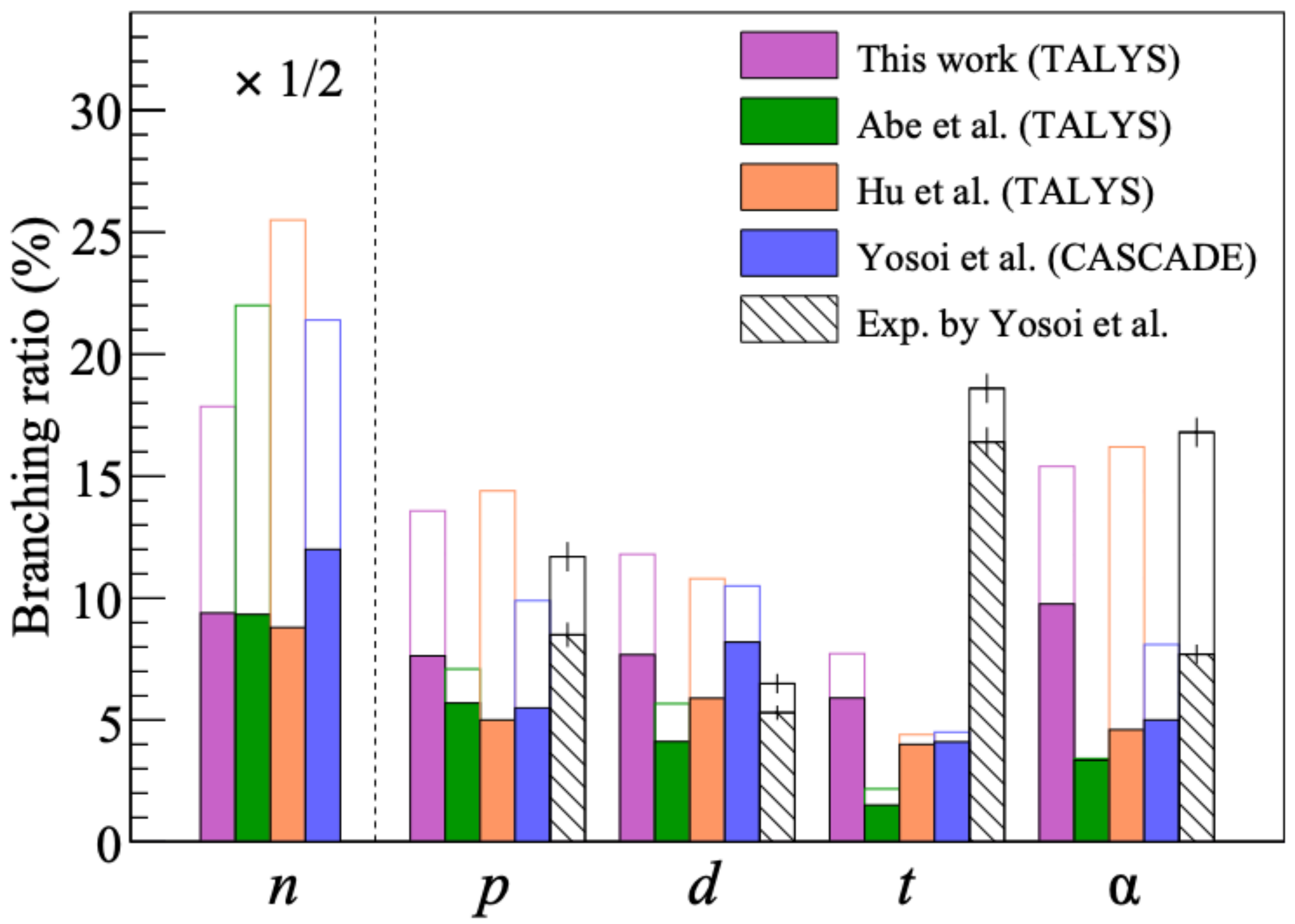
E.S. Pinzon Guerra et al., Phys. Rev. D 99, 052007 (2019)

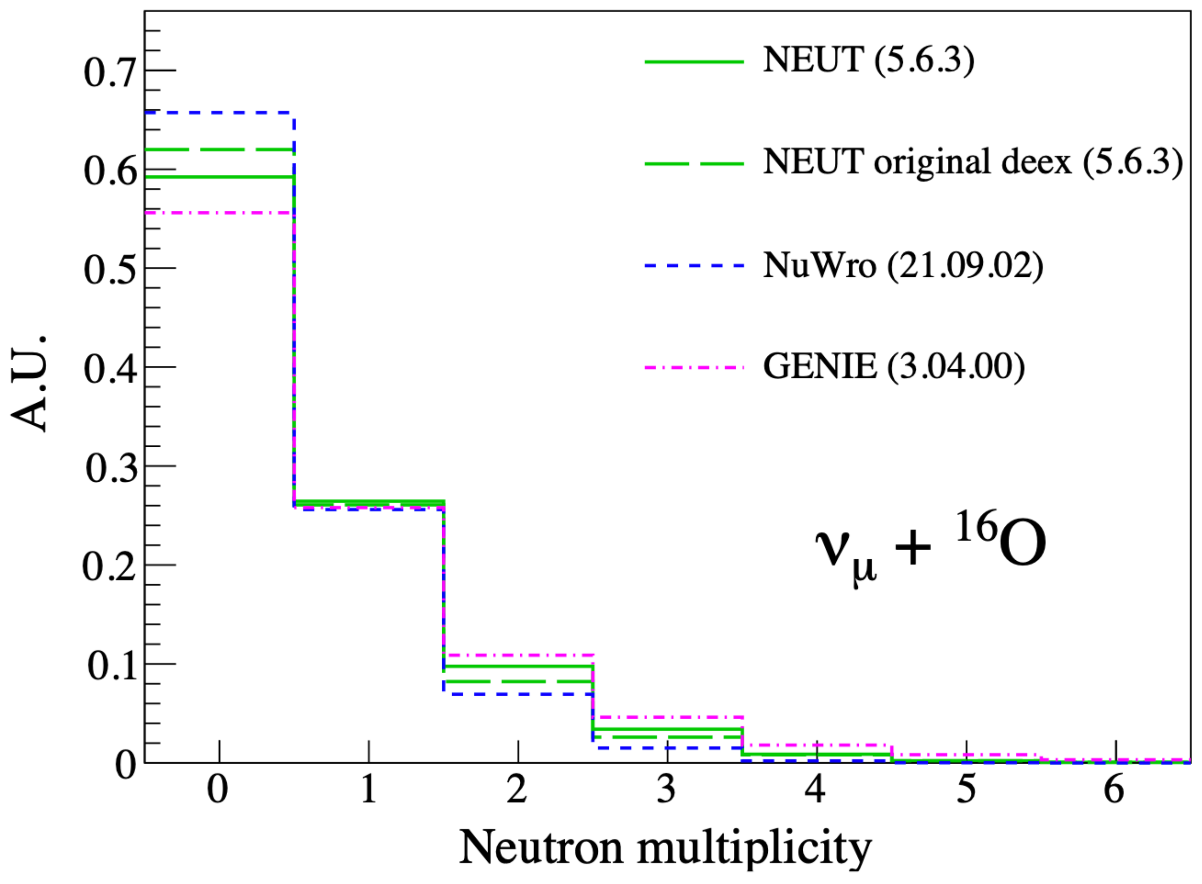


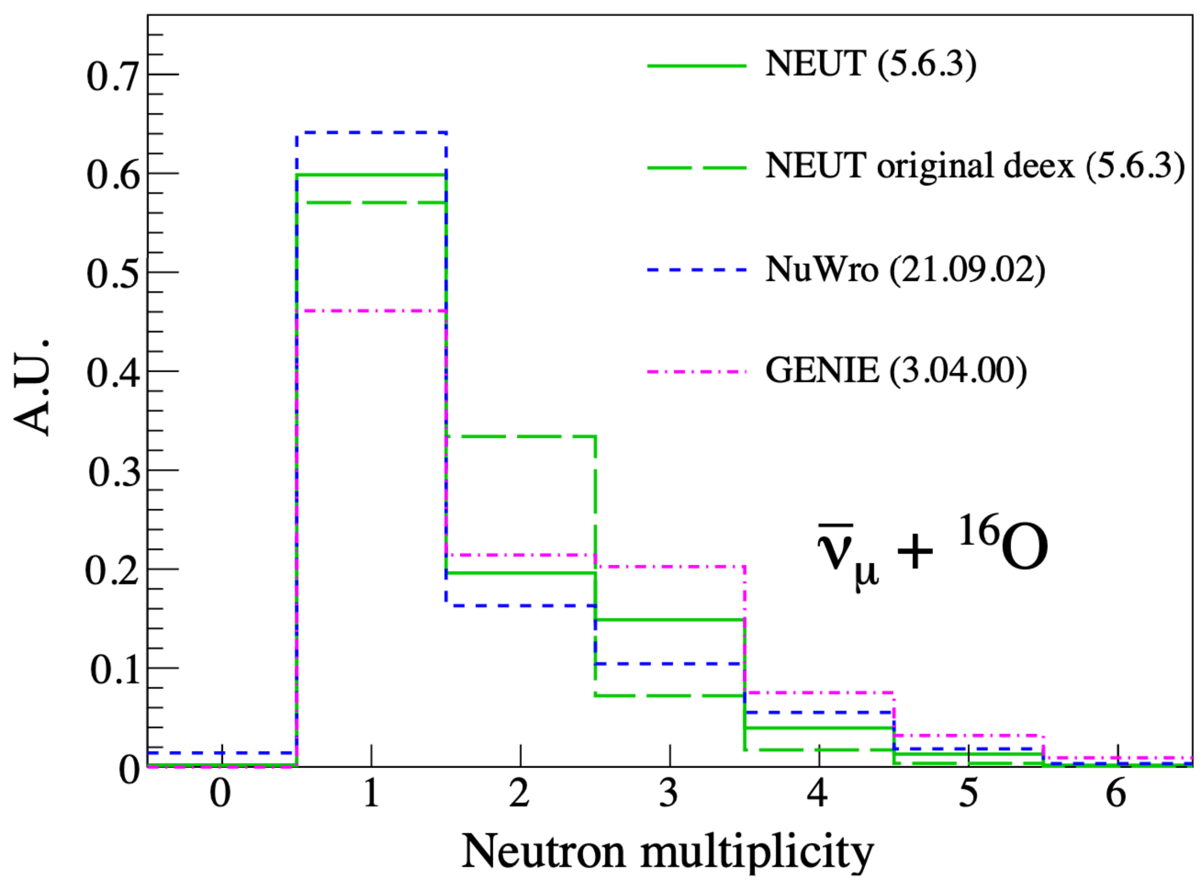
TALYS NucDeEx MODEL

- Neutrino interactions can leave residual nucleus in an excited state which subsequently decays to emit secondary nucleons/gamma rays.
- NEUT models this only for oxygen targets.
- Recent Work by Seisho Abe to implement TALYS based NucDeEx model as an alternative option in NEUT (modular generator agnostic design).
- See Seisho Abe's Poster this NuINT!
  "Development and application of the nuclear deexcitation simulator NucDeEx for precise prediction of neutrino-nuclear interactions"





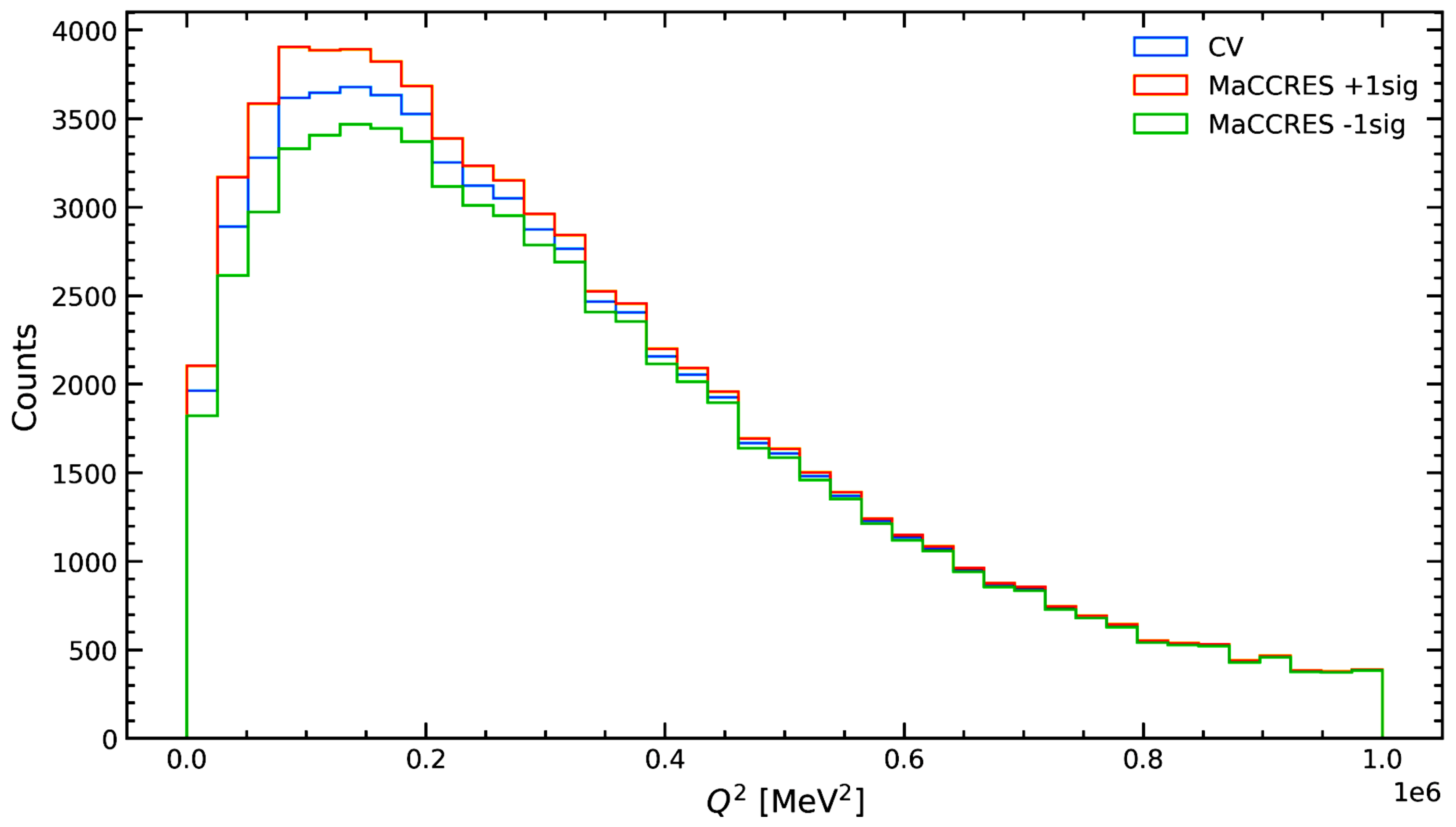




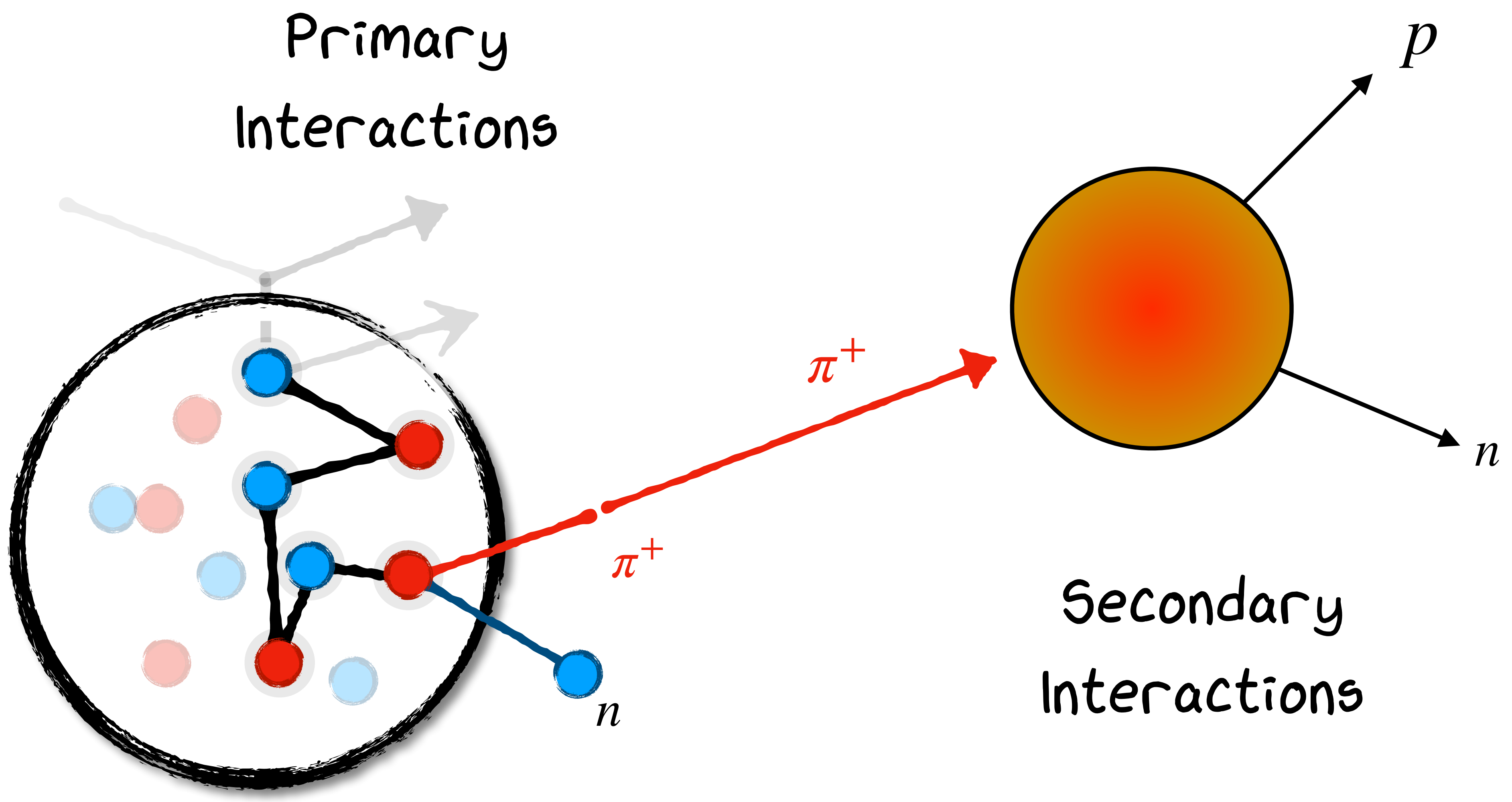
Abe, Seisho. "Nuclear deexcitation simulator for neutrino interactions and nucleon decays of C 12 and O 16 based on TALYS." Physical Review D 109.3 (2024): 036009.

Model Systematics

- NEUT ReWeight:
  - Calculate the relative probability of an already-generated event under some model variation.
  - Implemented for QE and Res1π form factors.
  - Reweighting for low/high energy pion FSI variations, and nucleon FSI normalisation.
  - Central values and uncertainties tuned to experimental cross-section data. See Clarence's NUISANCE Talk!



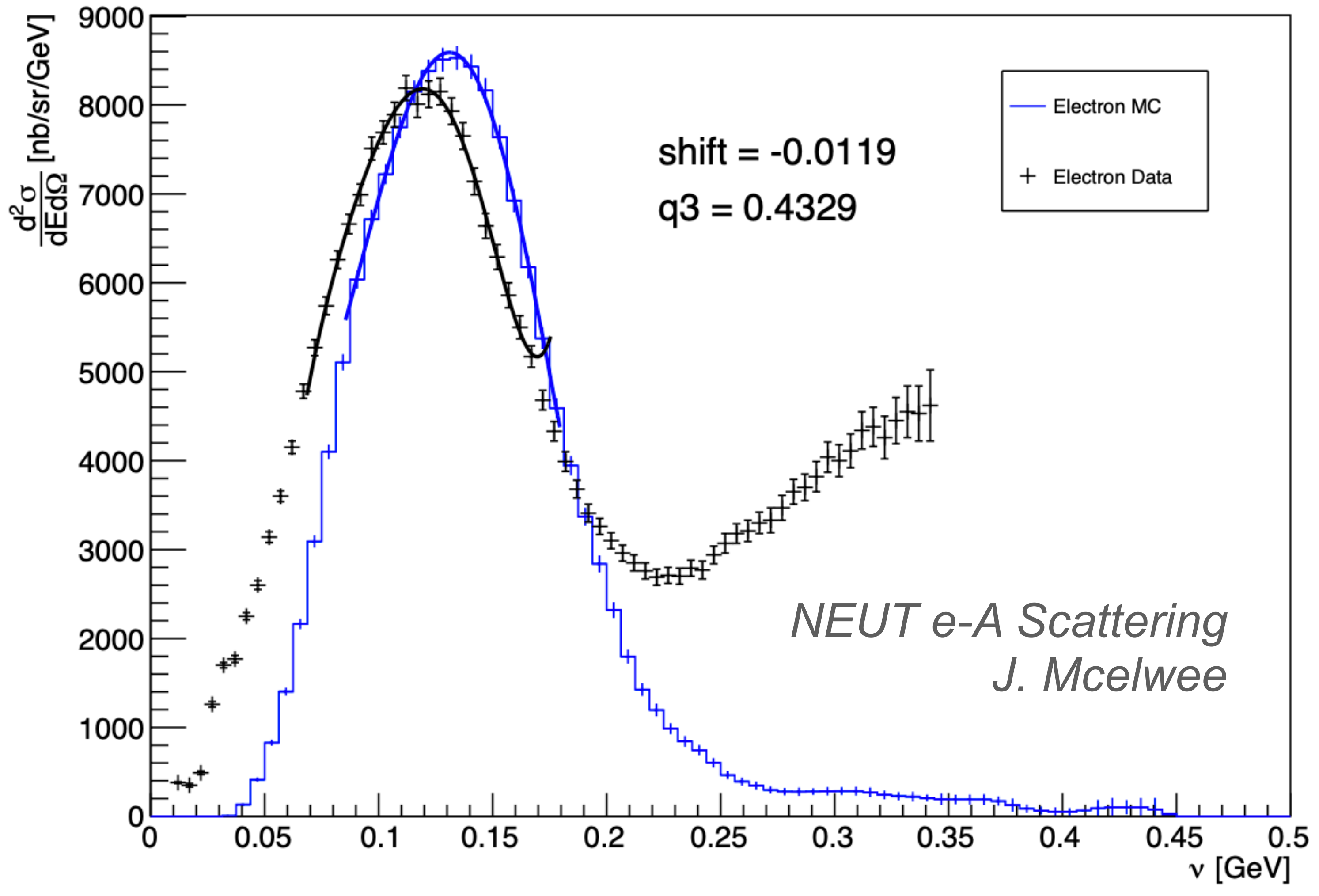
- GEANT interface:
  - Can use the NEUT hadron transport model as an inelastic model in GEANT4
  - Enables correlation of Final State Interaction (intra-nuclear) and Secondary Interaction (in-detector) models

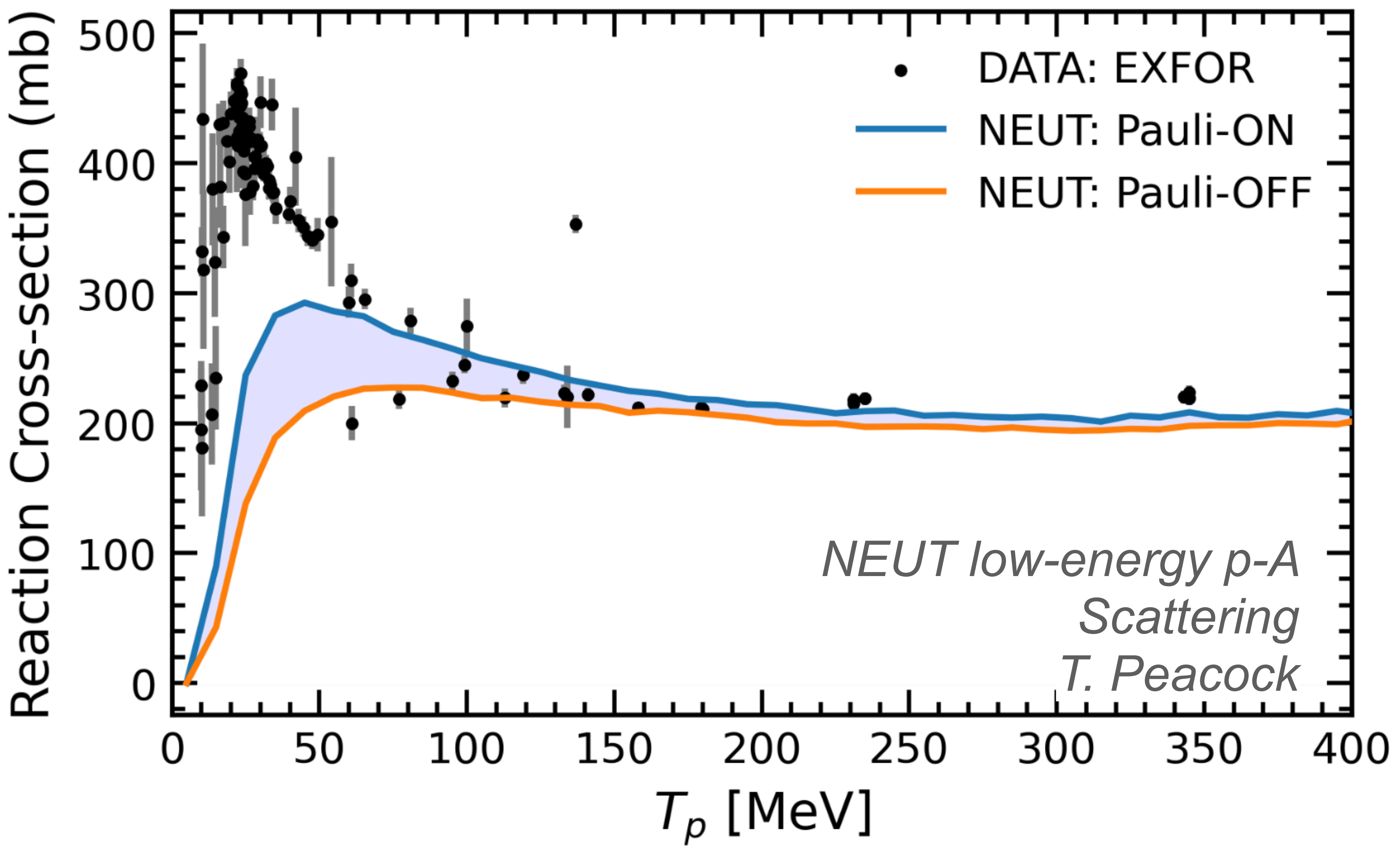


NEUT6

- Extensive development on NEUT6 in the last two years - Targeted at HK and final T2K analyses:
  - Significant reorganisation of code-base with modern C/Fortran interoperability.
  - Moved to modern CERNLIB 2023.
  - Working implementation of HepMC3-based event format.
  - Working conversion tools for ***neutvect*** to ***NuHepMC3***.

- **Planning open source NEUT6 under the GPL.**
  - New code developments largely being written in NEUT6.
  - Minor updates from NEUT5.7 planning to be merged before future release.
  - Work is underway to reevaluate the model using extensive data comparisons (p-A, π-A, ν-A, e-A).





SUMMARY

- NEUT provides a complete model for interpreting neutrino-scattering data
  - But significantly improved predictions are needed for the precision generation of experiments

- Factorisations are mathematically and computationally necessary, but we know their usages misses important physical effects:
  - Ongoing effort to understand, quantify, and implement effective corrections.

- NEUT has a long, rich history and we want to make sure that it not only survives, but becomes a more useful community tool into the next generation.
  - Effort on opening up the source code for NEUT6

Have a new model you would like to see in NEUT? Come speak to us!