In-medium changes of nucleon cross sections tested in neutrino-induced reactions:

exploring nucleon-nucleon forces in-medium with the GiBUU model and MicroBooNE data.

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NuFact 2024

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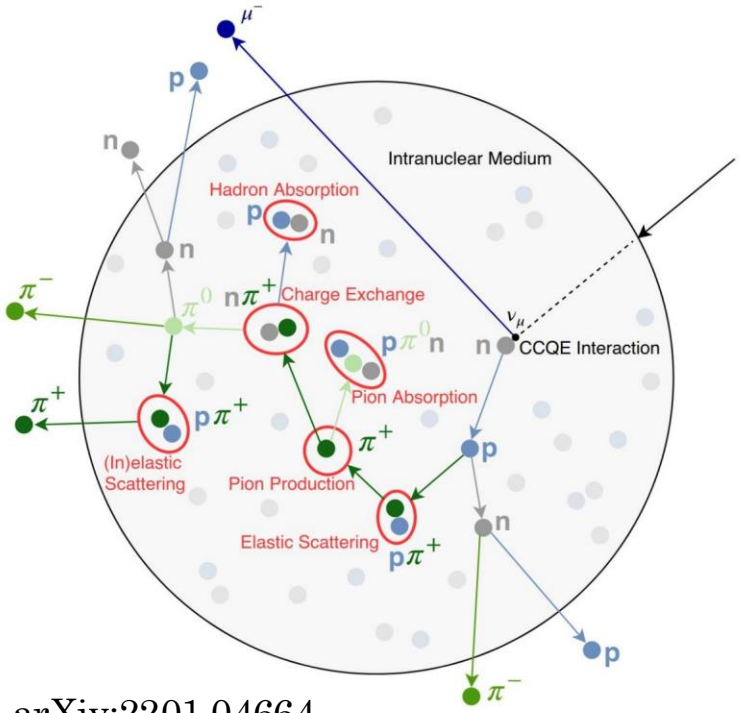
For more details, see arXiv:2405.05921

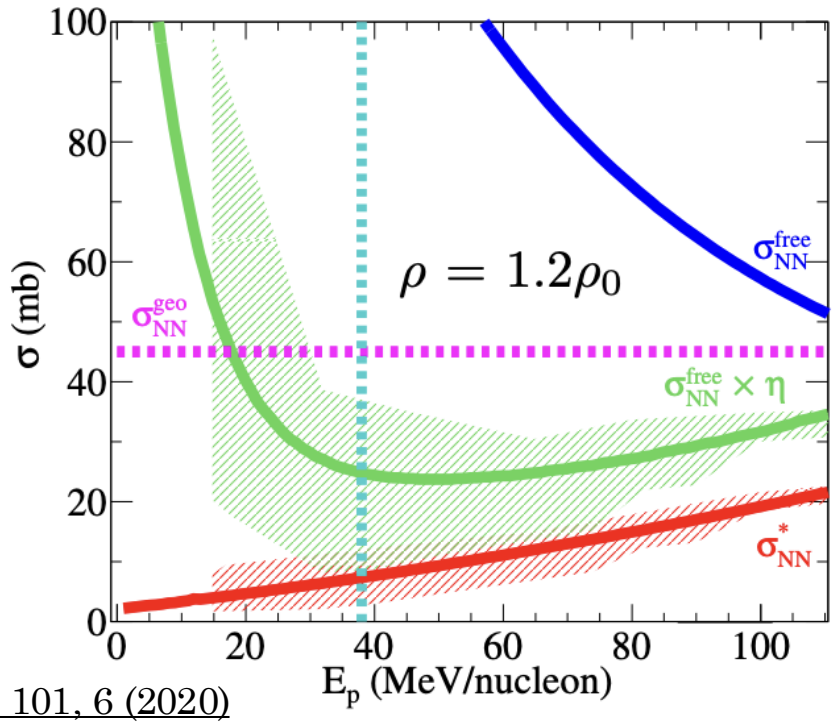
In-medium Modifications to NN Cross Sections

- The degree free nucleon-nucleon cross sections are modified within the nucleus is an open question. The in-medium cross sections may be very different than the vacuum ones.
  - Theoretical investigation suggest a lowering of NN cross sections below resonance excitations.
  - Mostly investigated in the context of heavy-ion collisions.
- Lepton induced reaction never examined in this light. Until now! arXiv:2405.05921
  - Established need for a robust description of the final state interactions (FSI) suggests that neutrino-nucleus measurements will be sensitive to in-medium effects.



arXiv:2201.04664

$$NN \leftrightarrow NN$$



Phys. Rev. C 101, 6 (2020)

GiBUU

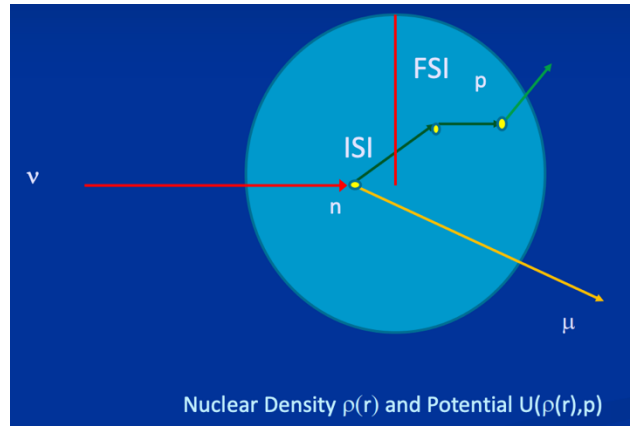
Phys. Rept. 512, 1-124 (2012)
arXiv:2308.16161 [nucl-th]
Download the code at gibuu.hepforge.org

- The GiBUU theory framework simulates a variety of reactions: heavy-ion, hadron-nuclei, electron-nuclei, photon-nuclei, and (most importantly) neutrino-nuclei.
- All initial state interaction (ISI) processes utilize the same ground state.
- Implements FSI with a quantum-kinetic transport model which allows for a precise treatment of nuclear effects.
  - Nuclear binding potential is consistent between the ISI and FSI.
  - Interaction rates respect time-reversal: ie. pion absorption and production come from the same model.
  - Inputs to the model are the cross sections and potentials for each particle species.

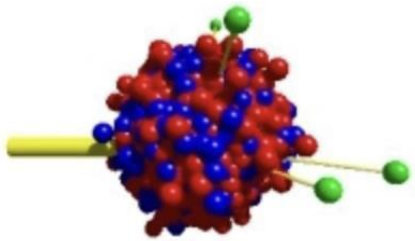
pion production

$$NN \leftrightarrow NN\pi$$

pion absorption



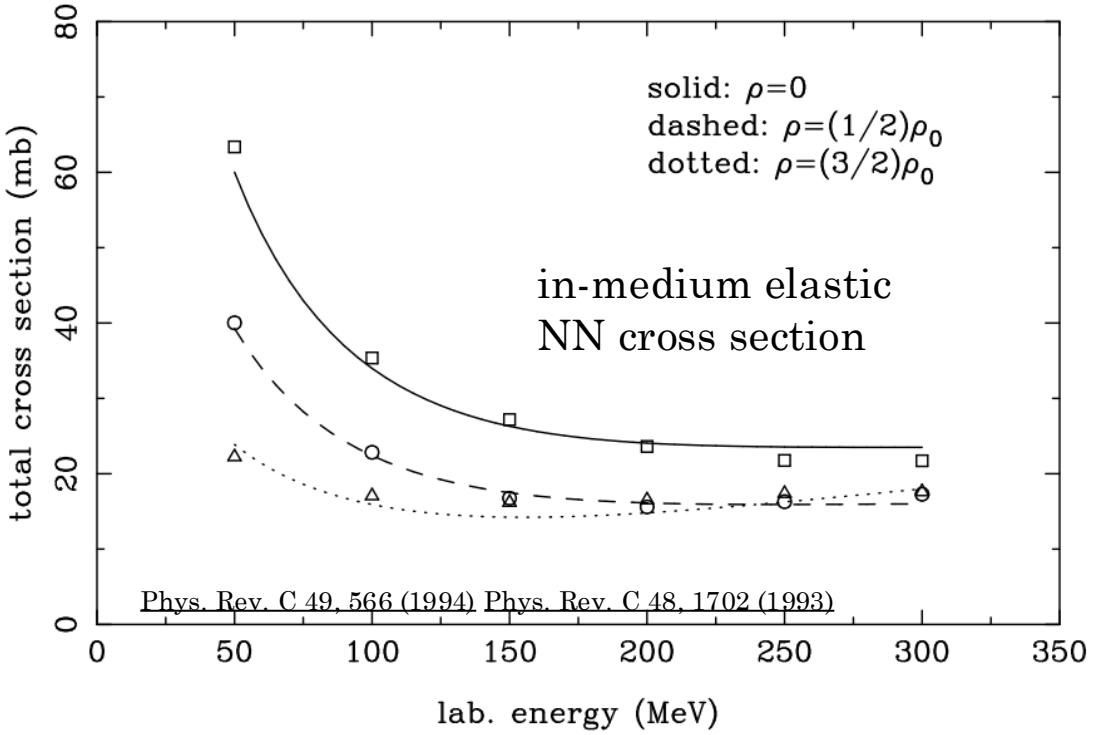
$$|\mathcal{M}_{N_a N_b \to N_A N_B \pi}(s)| = |\mathcal{M}_{N_A N_B \pi \to\ N_a N_b}(s)|$$



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

NN In-Medium Modification in GiBUU

- GiBUU implements in-medium modifications to elastic NN cross sections according to the work of Li and Machleidt.
  - Lower the elastic NN cross sections as a function of density.
  - More prominent impact on low energy nucleons.



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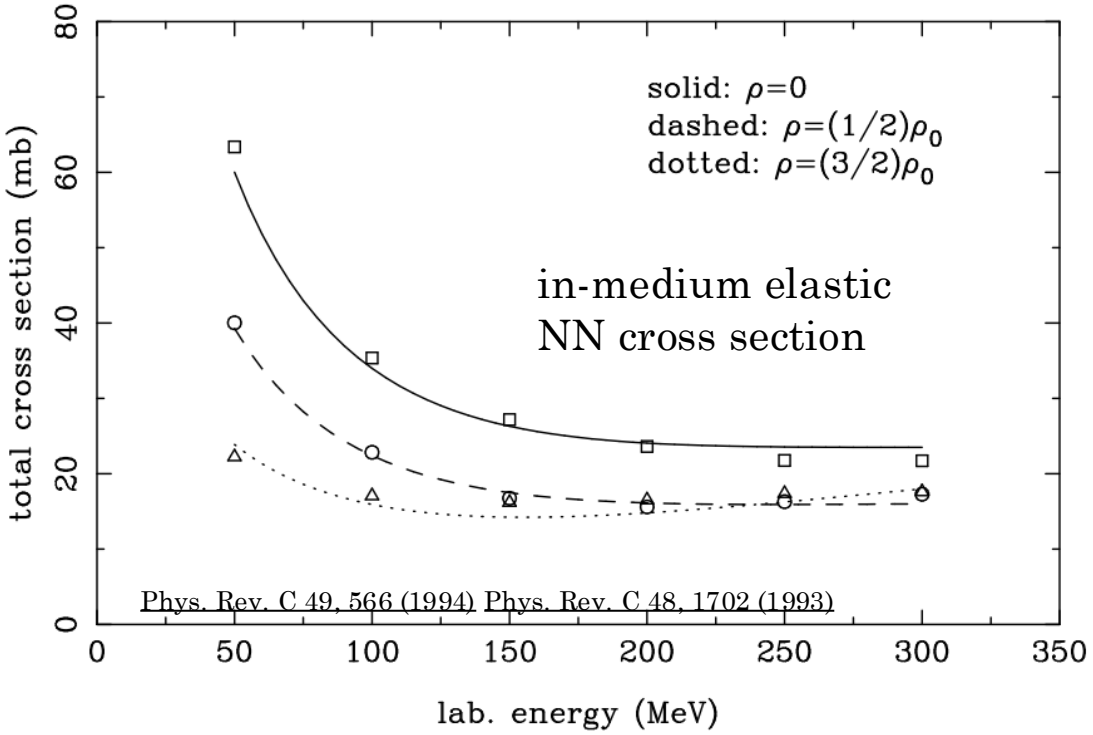
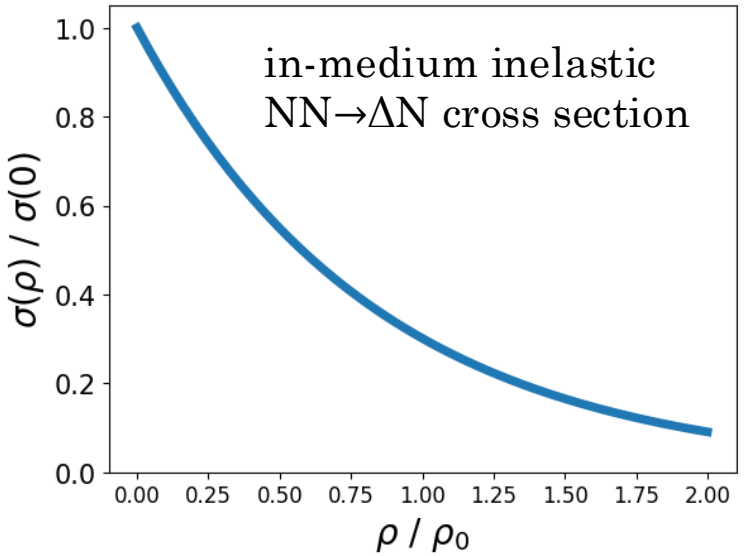
  - Lower the elastic NN cross sections as a function of density.
  - More prominent impact on low energy nucleons.
- The inelastic NN→ΔN cross is modified according to the work of Song and Ko.
  - Decreases both Δ absorption and excitation through detailed balance.
  - Improves theoretical description of charged pion yields in heavy ion collision data.



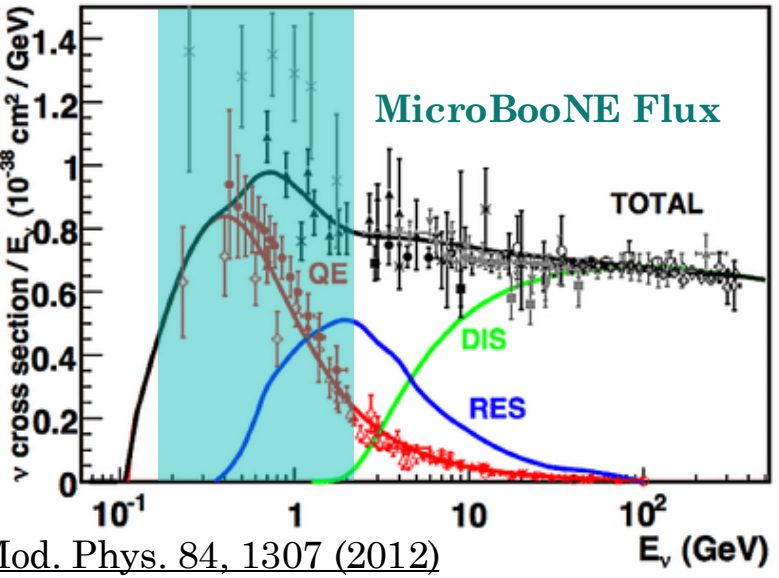


$$\sigma_{NN\to N\Delta}(\rho) = \sigma_{NN\to N\Delta}(0)\exp(-1.2\,\rho/\rho_0)$$

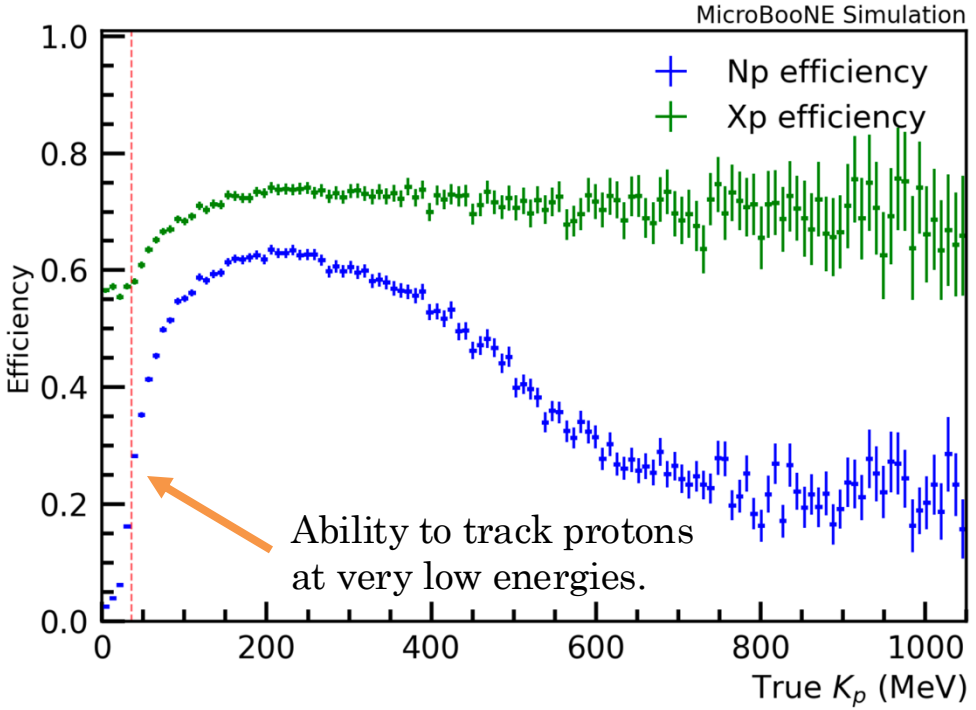
Phys. Rev. C 91, 014901(2015) Phys. Rev. C 109, 054901 (2024)

Neutrino-Induced Reactions: MicroBooNE Data

- MicroBooNE data are ideal for investigating in-medium effects:
  - Low energy neutrino beam.
  - Ability to track protons down to 35 MeV kinetic energy.
  - Argon target increases the prominence of FSI



Rev. Mod. Phys. 84, 1307 (2012)



Phys. Rev. D 110, 013006 (2024)

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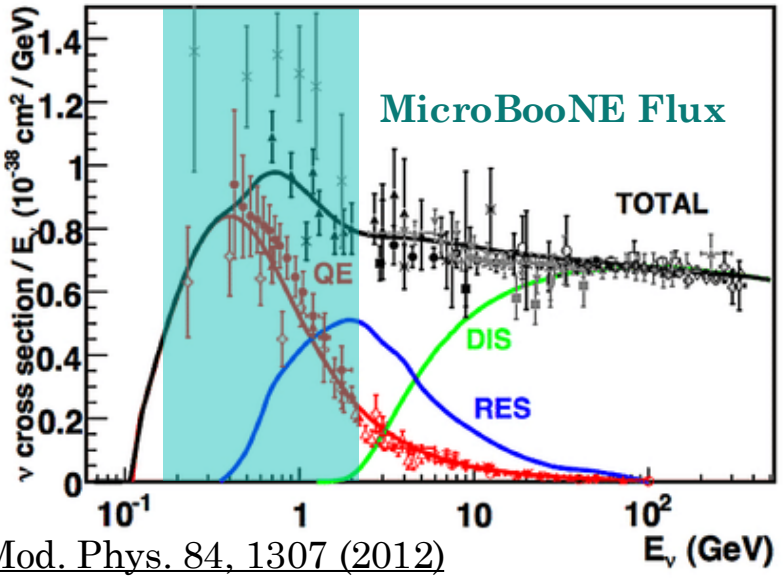
- We utilize the charge-current muon neutrino (ν_μCC) dataset from Phys. Rev. D 110, 013006 (2024).
  - Reports proton spectra and measurements of final states with (Np) and without (0p) protons.
- Also investigate neutral-current single pion production (NCπ^0) data from arXiv:2404.10948.
  - Features π^0 spectra and measurements of 0p and Np final states.



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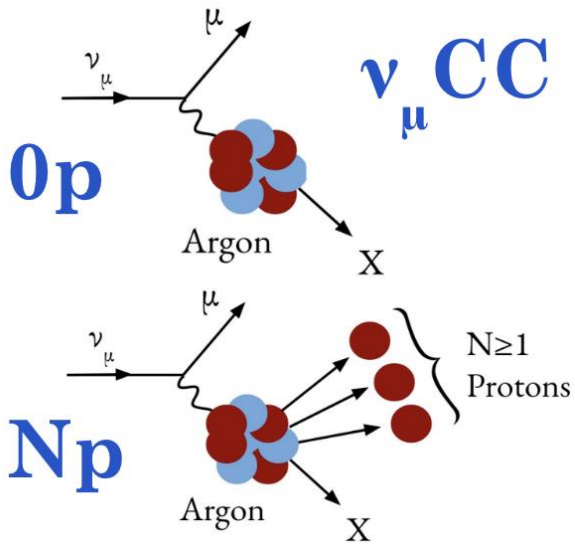
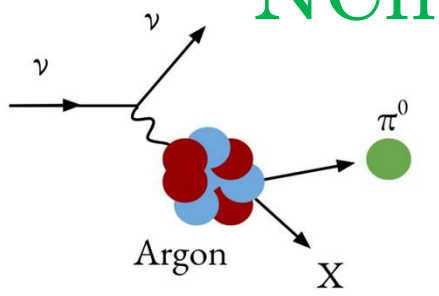


ν_μCC



NCπ^0

GiBUU and MicroBooNE Data

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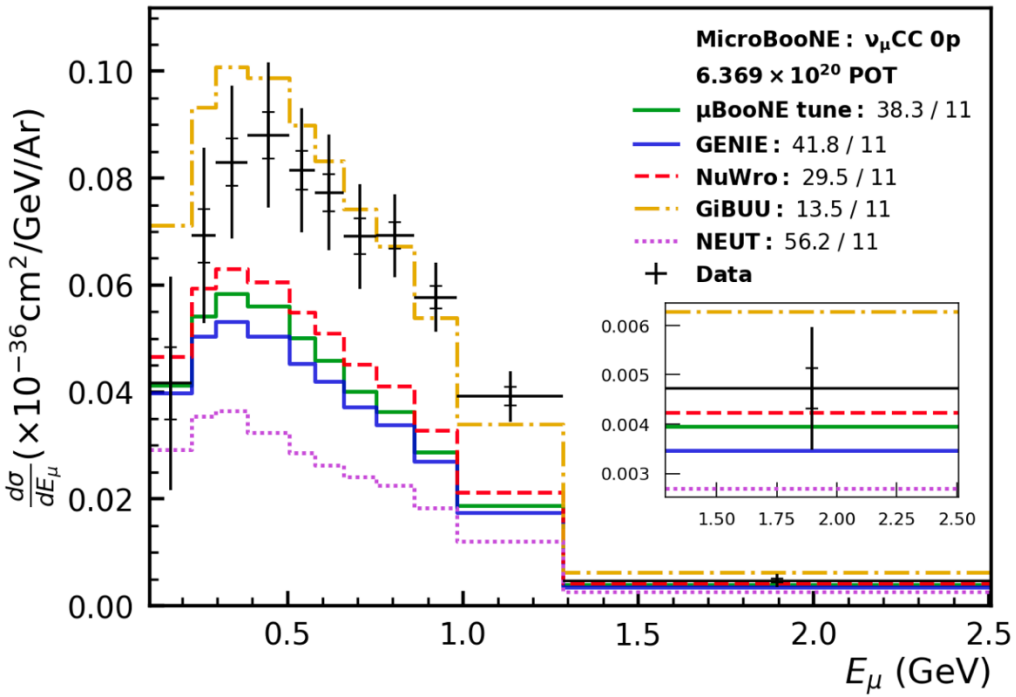
  - Especially true in FSI rich regions of phase space, such as the 0p channel.

Phys. Rev. D 110, 013006 (2024)



Other GiBUU comparisons to MicroBooNE data: Phys. Rev. D 109, 092007 (2024), Phys. Rev. Lett. 131, 101802 (2023), arXiv2403.19574: [hep-ex]

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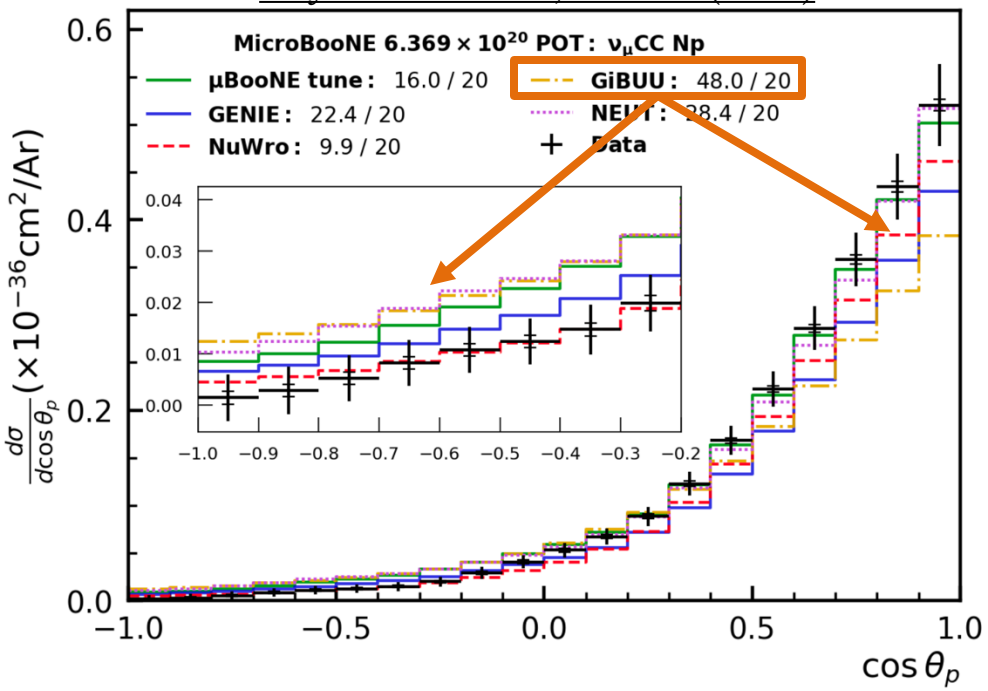
Phys. Rev. D 110, 013006 (2024)



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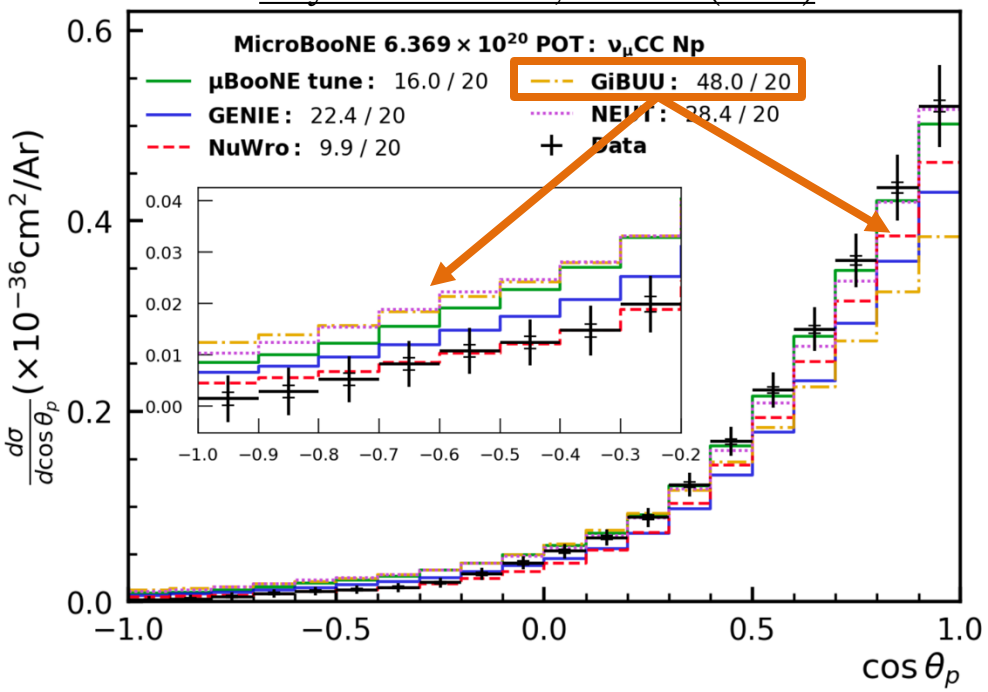
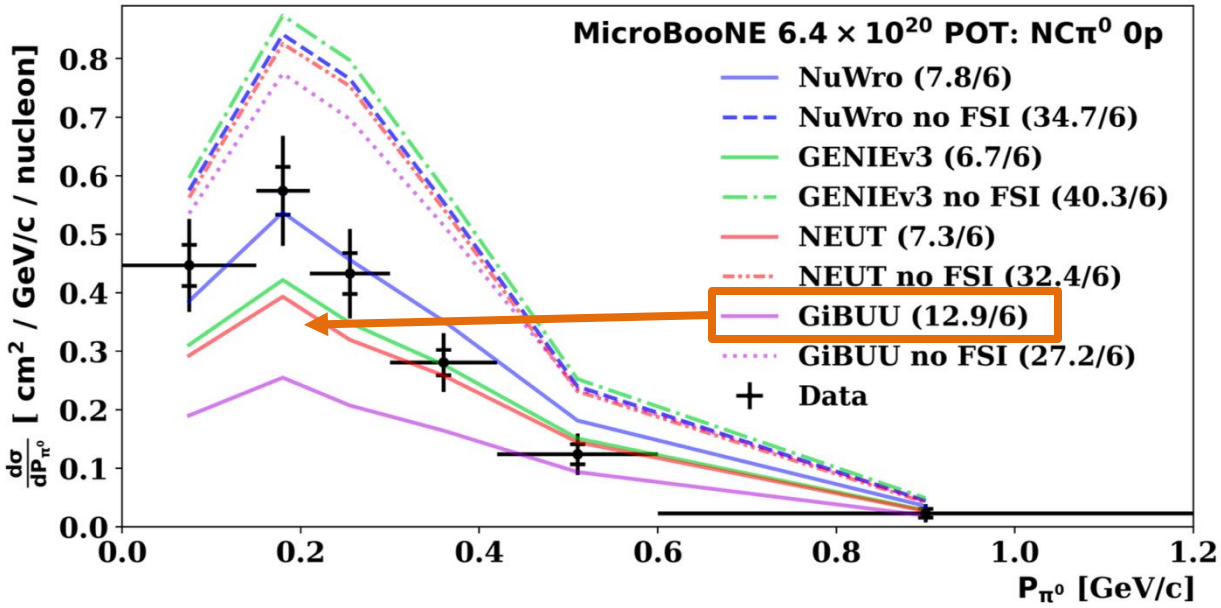
  - overprediction of ν_μCC proton spectra at forward angles, underprediction at backwards angles.
  - underprediction of NCπ^0 events at the peak of the kinetic energy spectra, especially for 0p.

Phys. Rev. D 110, 013006 (2024)



arXiv:2404.10948



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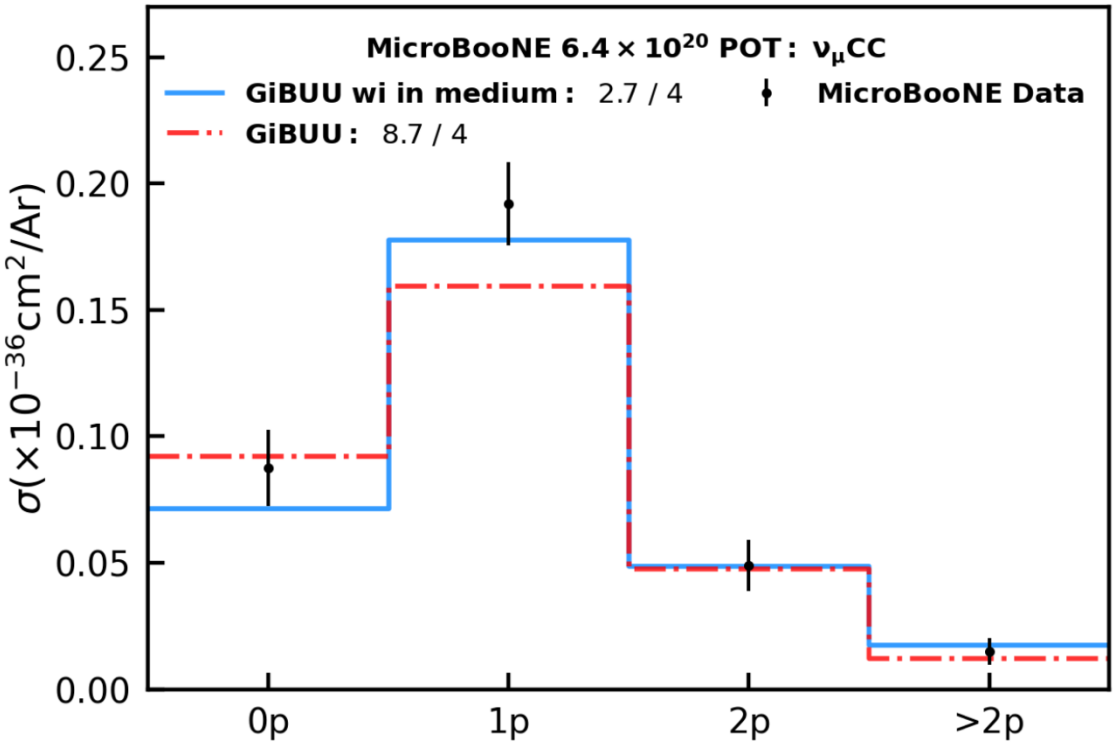
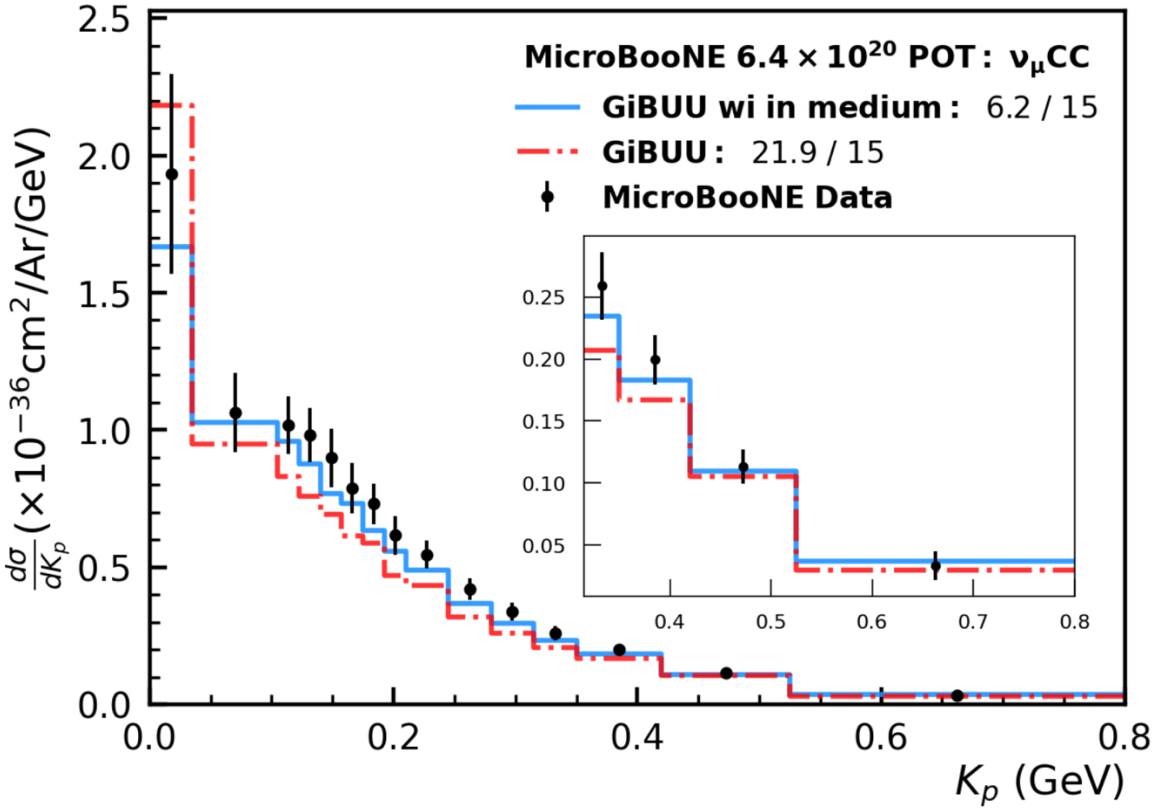
Comparison with Experiment: ν_μCC0pNp Data

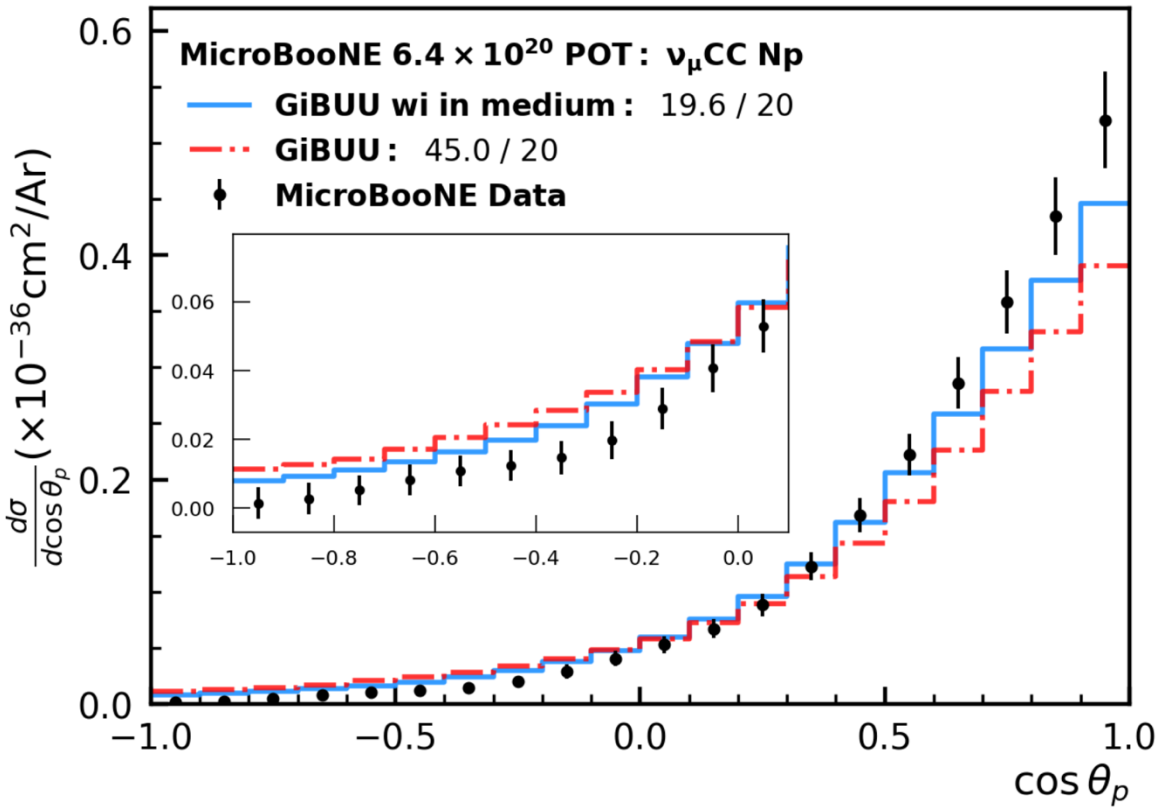
- Including in-medium modification shifts strength from 0p to Np.
- Multiplicity distribution shown this shift is primarily from 0p -> 1p.
  - When the NN cross sections are lowered there are less NN collisions which leads to migration of QE events from the 1p bin to the 0p bin.
- In-medium prediction is favored by the data.
  - All multiplicity bins fall within the measurement uncertainties and χ^2 is significantly reduced.



Comparison with Experiment: ν_μCC0pNp Data

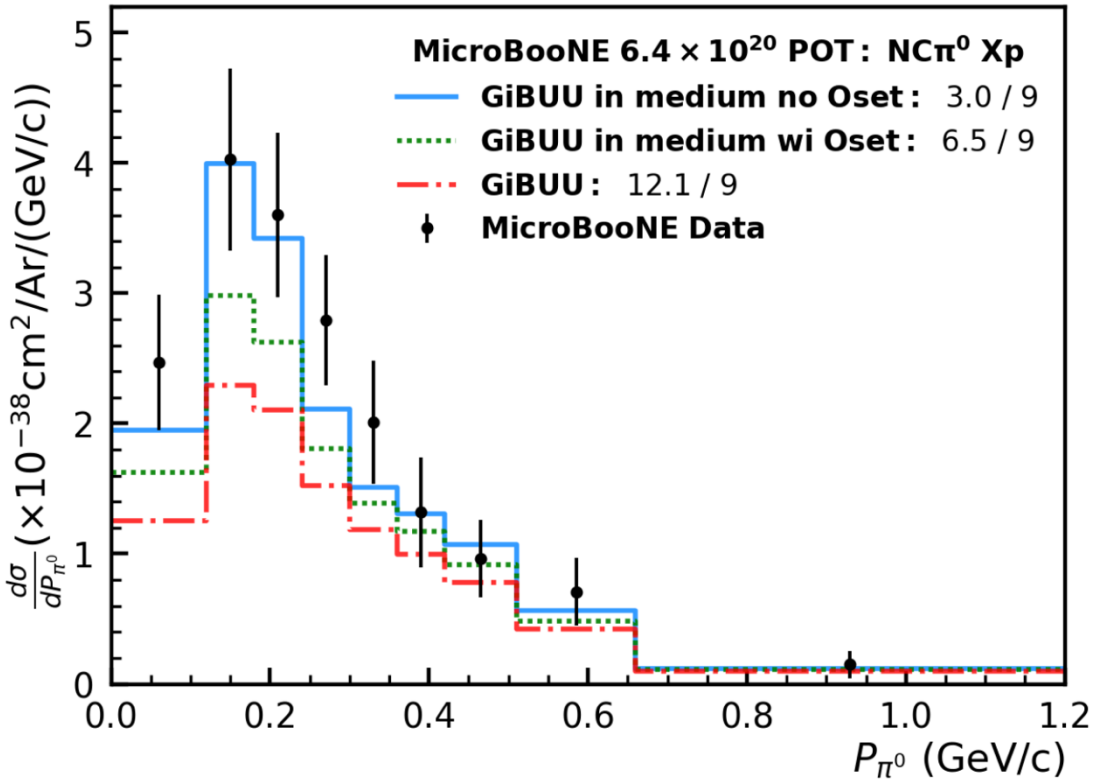
- Noticeable improvement in the proton spectra when in-medium modification are included.
  - Energy spectrum shifts to higher energies due to less re-interaction that deplete the primary proton of its energy.
  - Angular spectrum shifts forward due to less re-distribution towards backwards angles when the NN cross section is lowered.





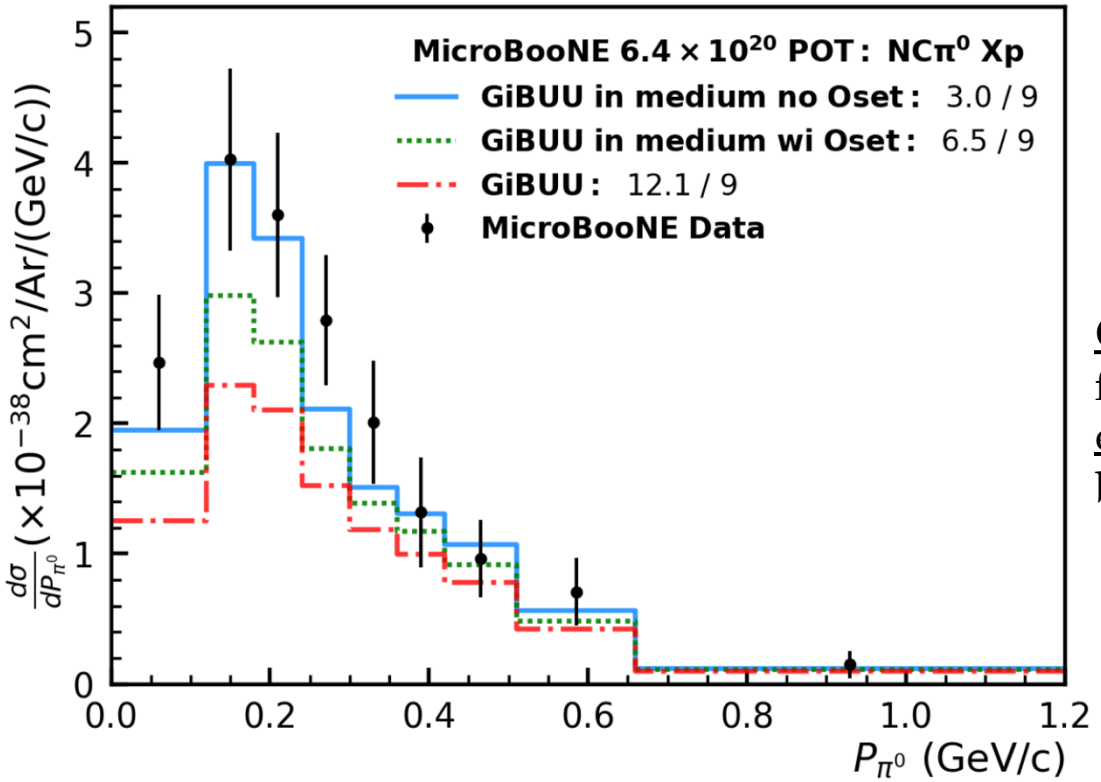
Comparison with Experiment: NCπ^0 Data

- Including in-medium density dependence for Δ excitation increases the NCπ^0 cross section by reducing Δ absorption through ΔN→NN.
  - Excitation and absorption are both impacted due to detailed balance.



Comparison with Experiment: NCπ^0 Data

- Including in-medium density dependence for Δ excitation increases the NCπ^0 cross section by reducing Δ absorption through ΔN→NN.
  - Excitation and absorption are both impacted due to detailed balance.
- Prediction without Oset Δ broadening is slightly favored, but this could be an artifact of a lack of coherent pion production in GiBUU.
  - Net effect of Oset broadening is reduced Δ production in ISI and increased Δ absorption.



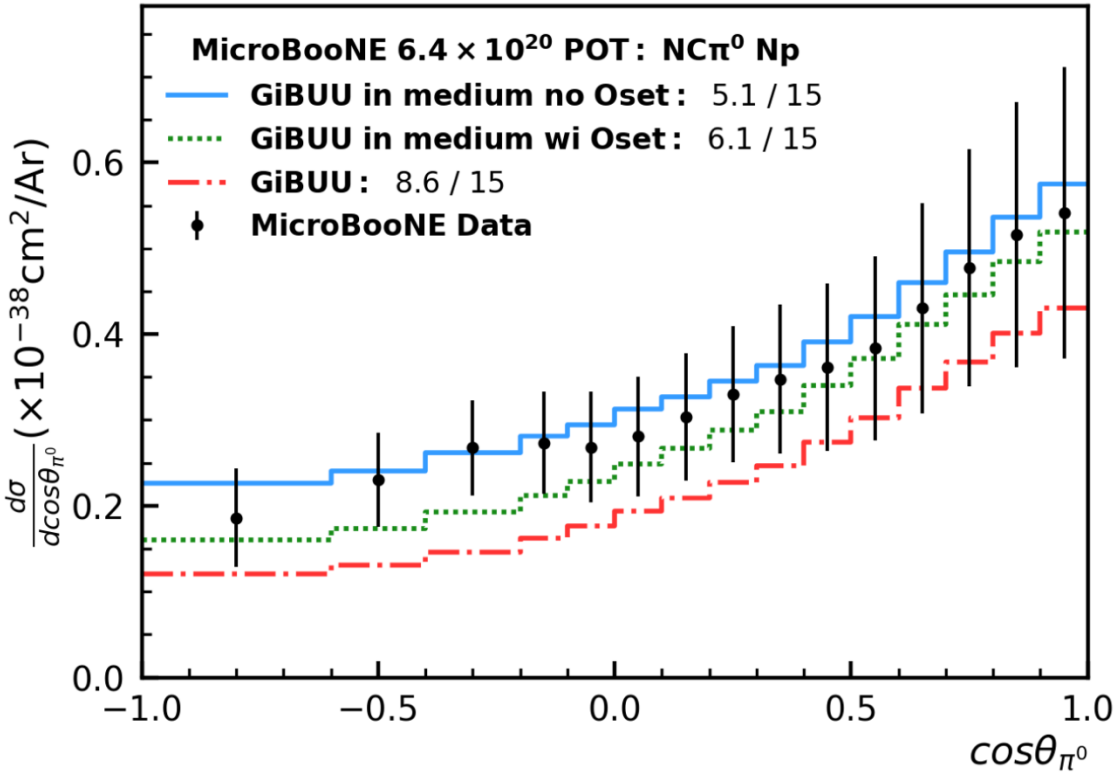
$$\Gamma_{tot}^{med} = \tilde{\Gamma} + \Gamma_{coll}$$

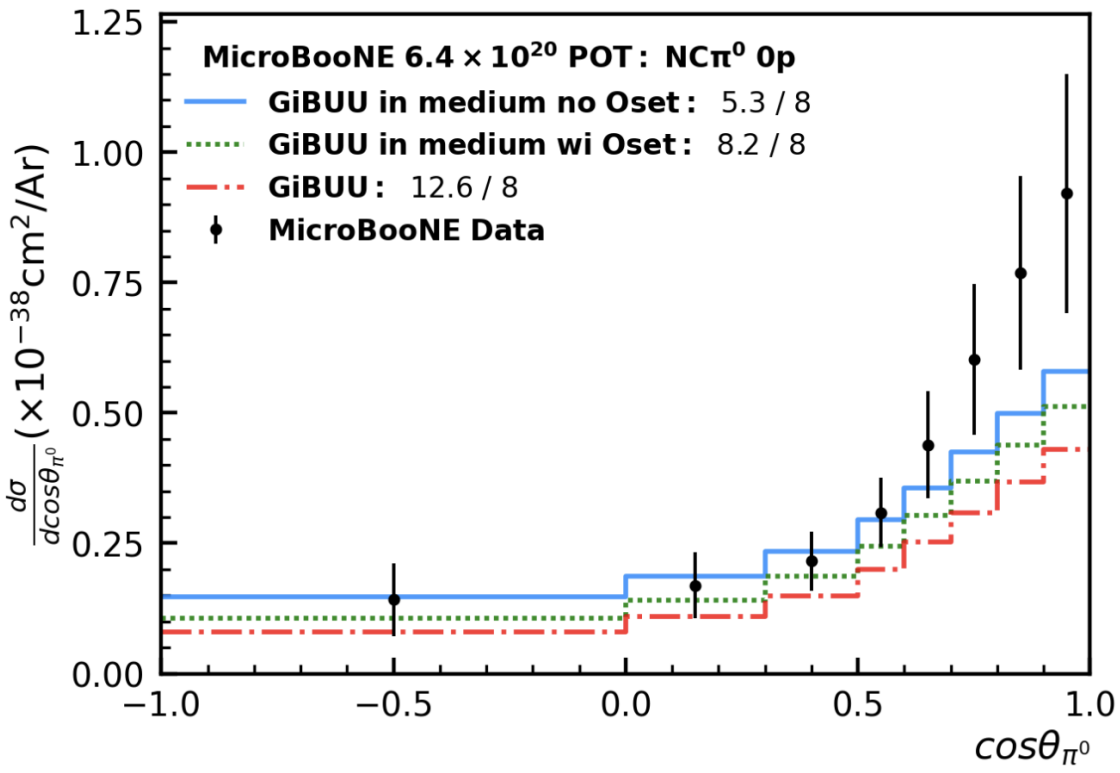
Oset collision broadening increases the Δ width as a function of momentum and density. It requires some extrapolation in this context, can view the difference between the curves as a "theoretical uncertainty".

Phys. Rev. C 87, 014602 (2013)
Nucl. Phys. A 468, 631-652 (1987)
Phys. Rev. D 97, 013004 (2018)

Comparison with Experiment: NCπ^0 Data

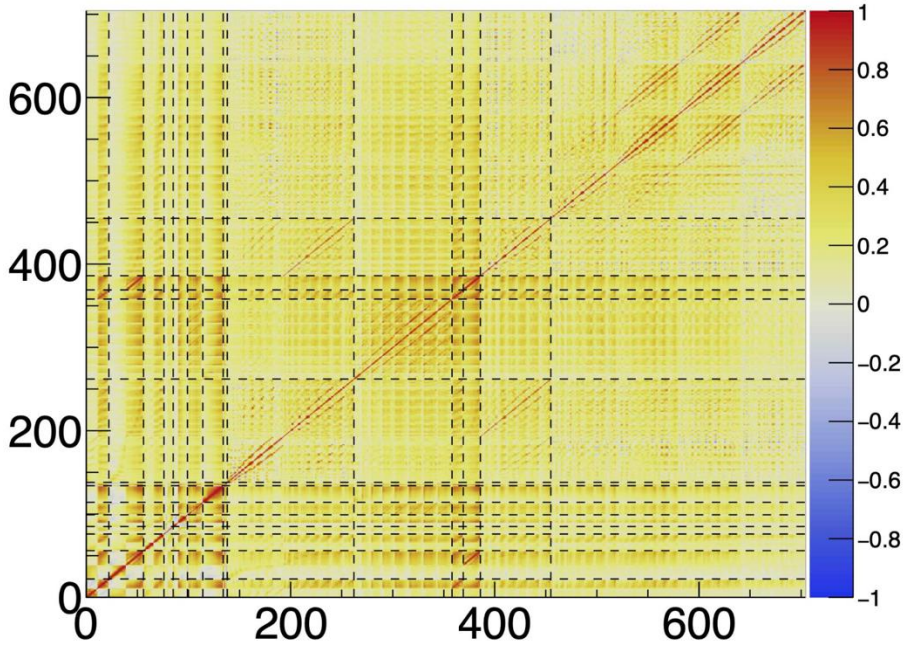
- In-medium modification improve agreement in both the 0p and Np channels.
- Predictions with and without Oset fall within the uncertainties of the data except at forward scattering angles for the 0p channel.
  - Coherent pion production's primary contribution is in this region of phase space.





Comparison with Experiment: Global Comparisons

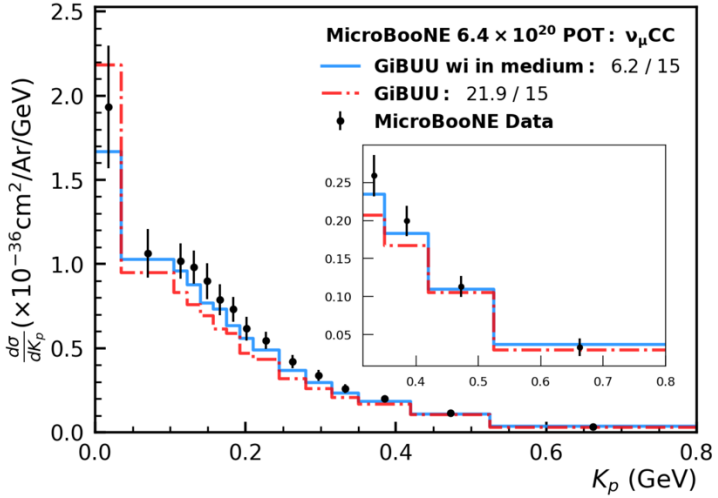
- Both dataset utilize "blockwise-unfolding" and thus include correlations between all measurement bins.
  - Allows for a rigorous χ^2 comparison across multiple distributions.
- For the ν_μCC data, NN modifications improves the χ^2/ndf from **1064 / 704** to **795 / 704**.
  - For the proton spectra and multiplicity, the improvement is **70 / 39** to **25 / 39**.
  - The χ^2/ndf calculated with the blockwise NCπ^0 results is less sensitive and only reduces from 43 / 78 to 32 / 78.

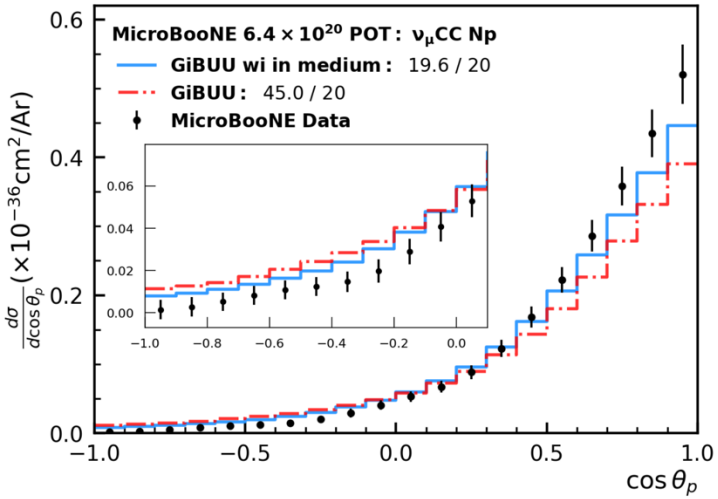


Correlation matrix including all measurement bins reported by Phys. Rev. D 110, 013006 (2024).

Summary and Conclusions

- Using GiBUU, we have shown that MicroBooNE neutrino-argon scattering data are sensitive to in-medium modifications of NN cross sections.
  - Including in-medium lowering of the NN cross sections and density dependence of Δ excitation better reproduces the proton and π^0 spectra from these datasets.
  - The NCπ^0 data are well described both with and without the collision broadening of the Δ.
- Accounting for these modifications is essential in obtaining a satisfactory description of the data.





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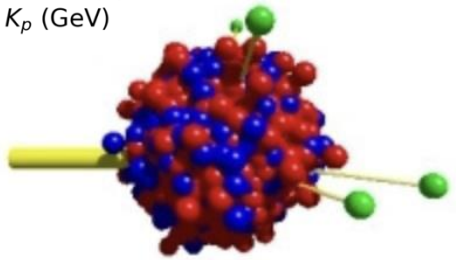

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Comparison with Experiment: Global Comparisons

- The χ^2/ndf calculated with the full blockwise NCπ^0 results are less sensitive to these differences and only reduces from 43 / 78 to 32 / 78.
  - Bins sensitive to coherent pion production are excluded, the known discrepancy here dominates the test statistic and reduces its sensitivity to the modeling in the rest of phase space.
- Another recent MicroBooNE analysis featuring the CCπ^0 channel includes comparisons to GiBUU prediction with and without the in-medium modifications.
  - Similar trends are observed, the in-medium modification improve agreement with experiment.