Rising Researchers Seminar Series

The Rising Researchers Seminar Series is committed to creating an **environment which is welcoming and safe** for all speakers, attendees, organizers, and other affiliated persons, hereinafter ``participants". It is the responsibility of all participants to foster such an environment.

Participants shall **treat each other professionally and respectfully**. Participants shall refrain from any inappropriate behaviour, including discriminatory actions and comments based on individual characteristics such as age, race, ethnicity, sexual orientation, gender identity, gender expression, marital status, nationality, immigration status, political affiliation, ability status, or educational background. Disruptive or harassing behavior will not be tolerated including but not limited to inappropriate or intimidating language and unwelcome jokes or comments.

Violations of this code of conduct should be reported to any member of the executive committee (see About Us page on the website). The Executive committee may also act of their own accord should they notice violations. Sanctions may range from verbal warning, to ejection from the meeting or, in severe cases, partial or total bans from future meetings.

References: This code of conduct is based heavily on that of the INT and the APS. We are also grateful to Roxanne Springer for valuable discussion and guidance.

Exploring nucleon-nucleon forces in-medium with the GiBUU model and MicroBooNE neutrino-nuclei data.

Benjamin Bogart

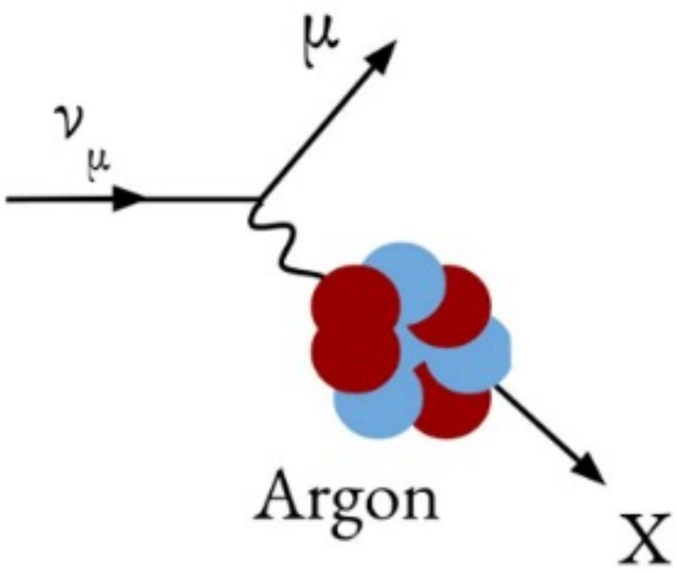
Rising Researchers Seminar

May 20th, 2025

UNIVERSITY OF MICHIGAN

For more details, see Phys. Rev. C 110, 044001 (2024)

Overview



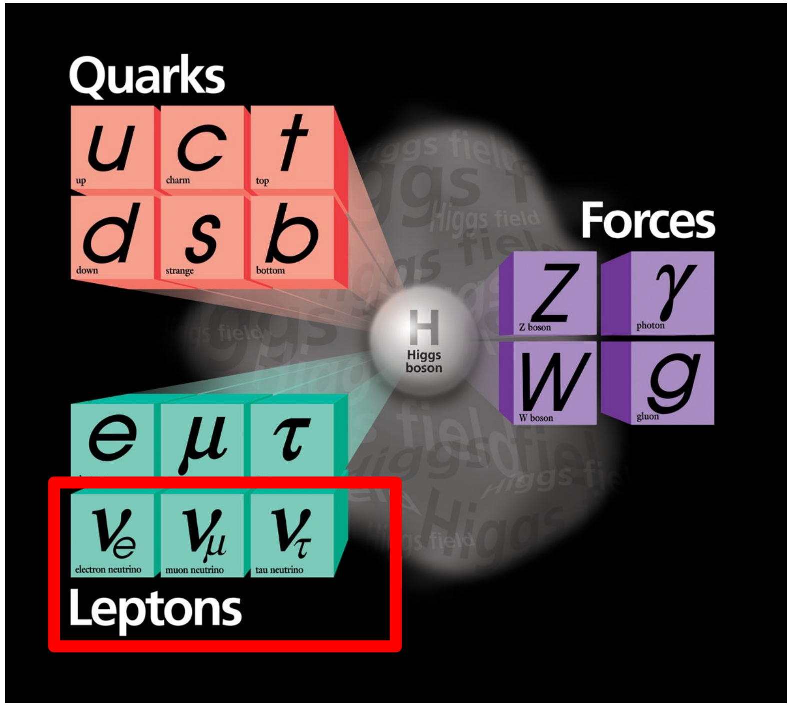
Today, I hope to describe:

- Why understanding neutrino-nuclei cross sections is vital to studying the fundamental properties of neutrinos.
- The GBUU model.
- The sensitivity of MicroBooNE neutrino-argon data to in-medium modifications of NN cross sections.

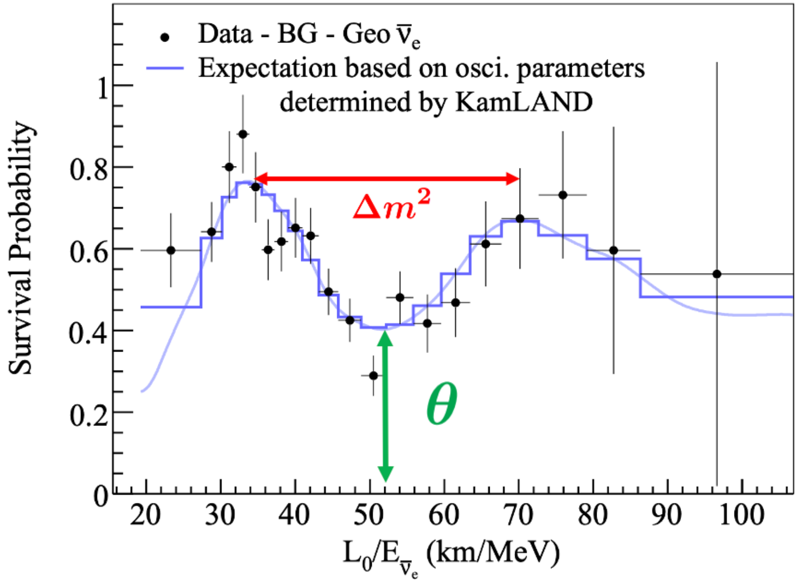
μBooNE

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Neutrinos



- Neutrinos are abundant but challenging to study because they rarely interact and only via the weak force.
- They come in three flavors, one for each charged lepton.
- Neutrinos oscillate between flavors.
  - Oscillation probability is a function of the energy of the neutrino and the propagation distance.



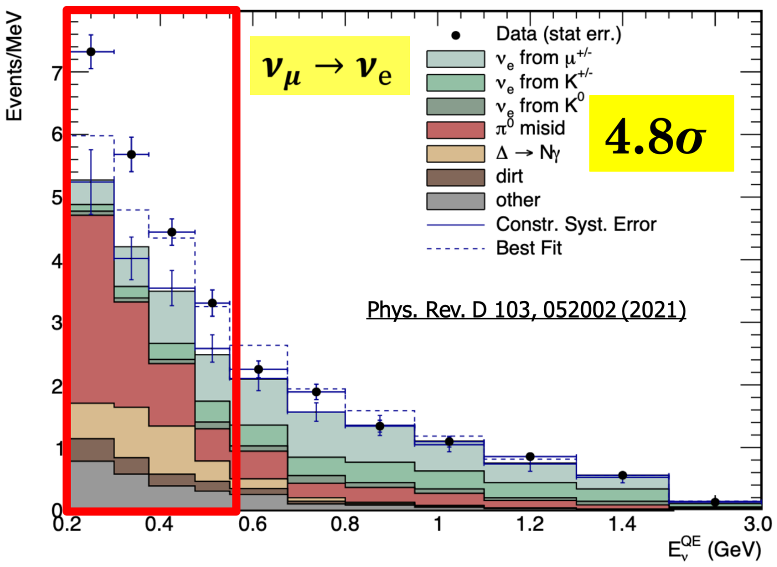
$$\theta_{12} = 33.4 \pm 0.8$$
$$\theta_{13} = 49.2 \pm 1.3$$
$$\theta_{23} = 8.57 \pm 0.13$$

$$\Delta m^2_{12} = (7.42 \pm 0.21) \times 10^{-5} \mathrm{eV}^2$$
$$\Delta m^2_{l3} = (2.515 \pm 0.028) \times 10^{-3} \mathrm{eV}^2$$

$$P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

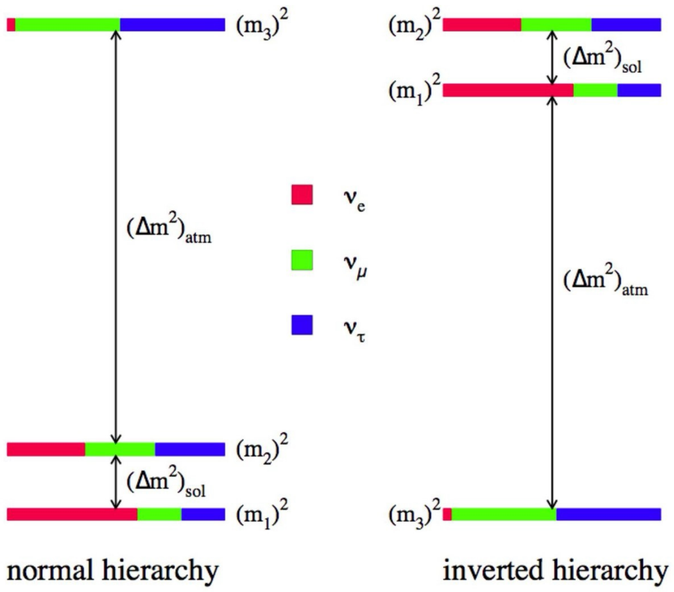
Mysteries in the Neutrino Sector

Is there a fourth neutrino?



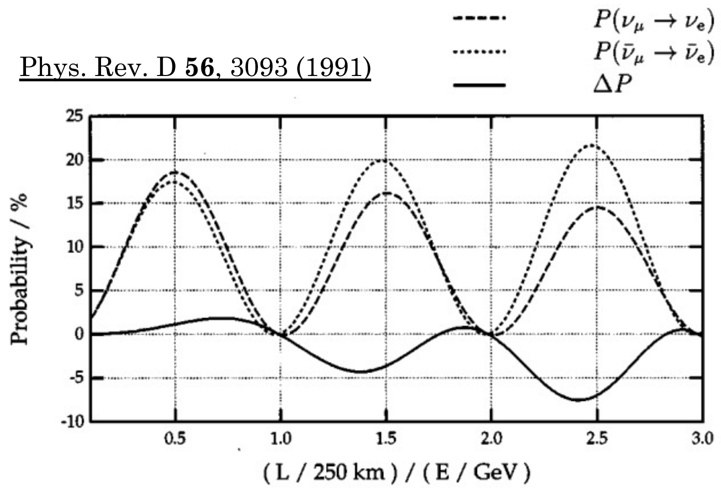
Several experiments suggest the existence of an eV scale neutrino.

Which neutrino is the heaviest?



We know the magnitude of the mass splittings, but not their sign.

Do anti-neutrinos behave differently than neutrinos?



$$P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e] \ ?$$

We are yet to make a definitive measurement of the degree of CP violation in the neutrino sector.

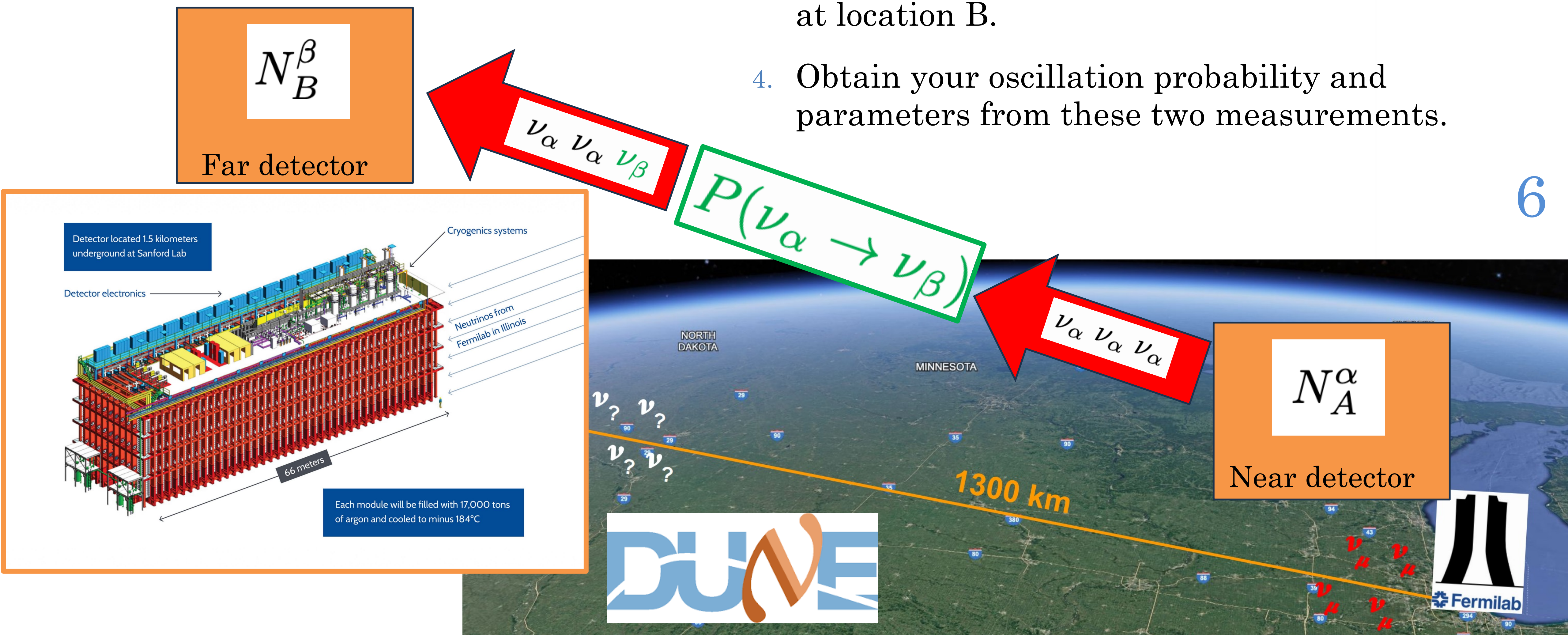
Solving these mysteries requires precise measurements of neutrino oscillations!

Measuring Oscillations

$$N_A^\alpha \sim \Phi_A(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_A(E_\nu)$$

$$N_B^\beta \sim \Phi_B(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_B(E_\nu)\ \boxed{P(\nu_\alpha \to \nu_\beta)}$$

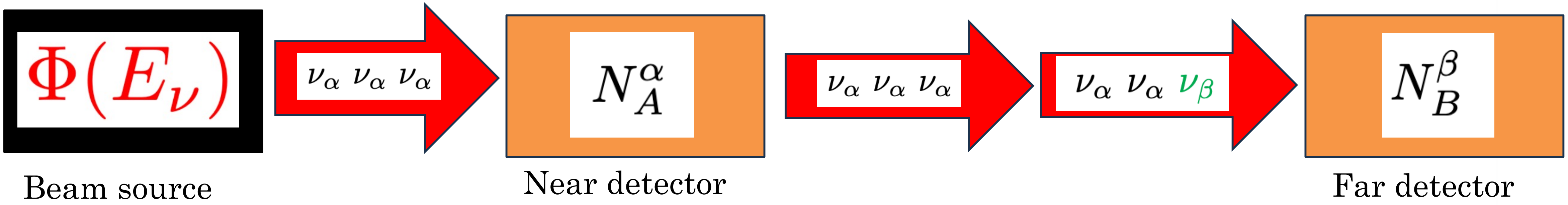
1. Produce a lot of neutrinos.
2. Count how many neutrinos of each flavor you see at location A.
3. Count how many neutrinos of each flavor you see at location B.
4. Obtain your oscillation probability and parameters from these two measurements.



Measuring Oscillations:

$$P_{osc} \propto \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Easy, right? Well, maybe not so fast…
- Neutrino oscillations depend on the **energy** of the neutrino.



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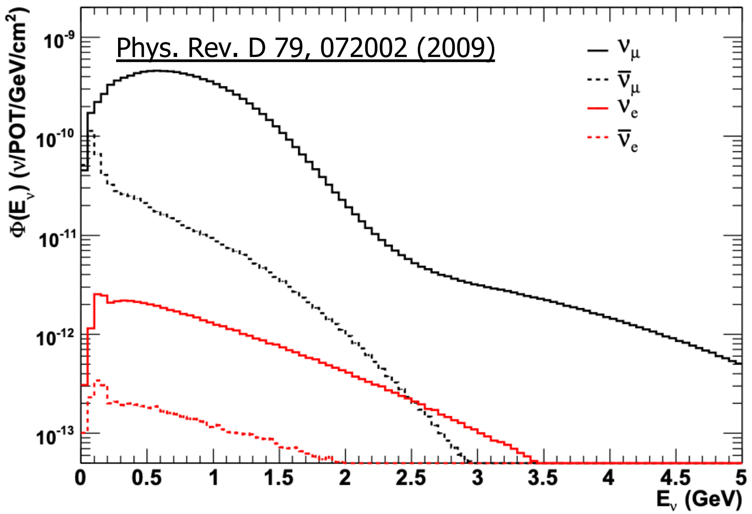
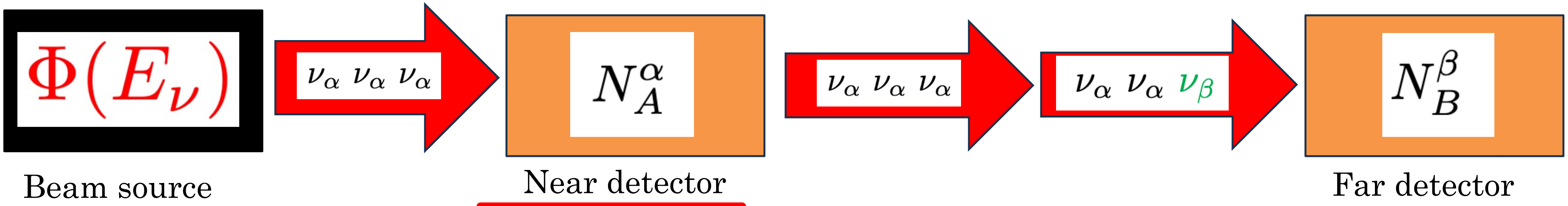
- Easy, right? Well, maybe not so fast…
- Neutrino oscillations depend on the **energy** of the neutrino.
- But, neutrino beams have a broad energy spectrum, we do not know the energy of the neutrino on an event-by-event basis.





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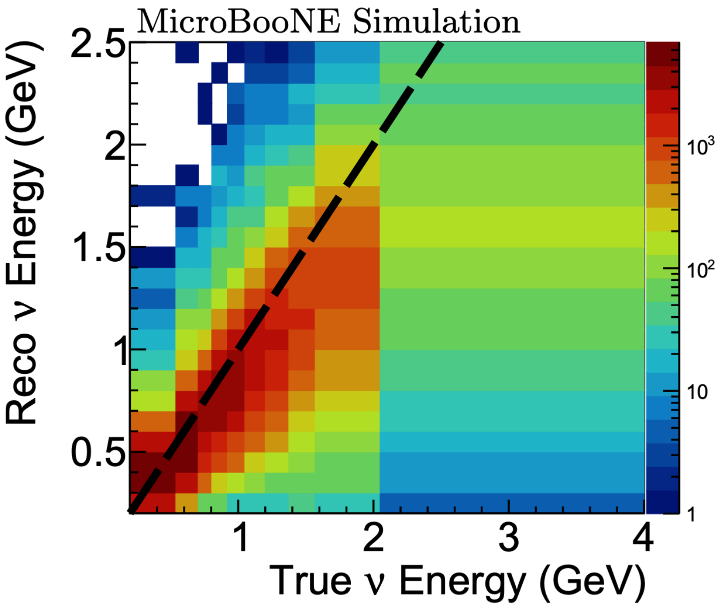
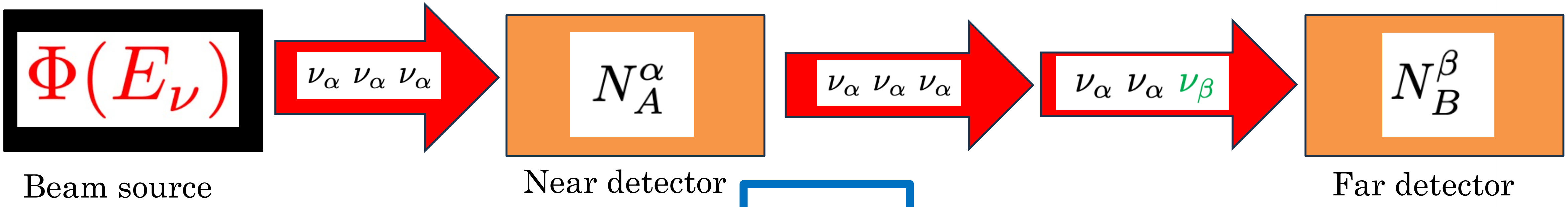


- Easy, right? Well, maybe not so fast…
- Neutrino oscillations depend on the **energy** of the neutrino.
- But, neutrino beams have a broad energy spectrum, we do not know the energy of the neutrino on an event-by-event basis.
- Incoming neutrino's energy must be reconstructed from observed final state particles.
- **Necessitates a detailed cross section model capable of predicting the full final state for a broad range of energies!**



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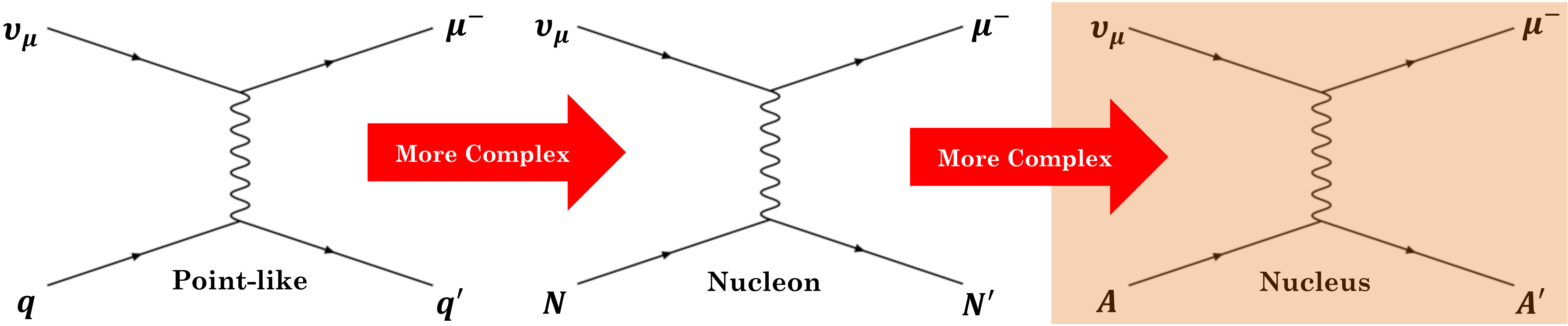
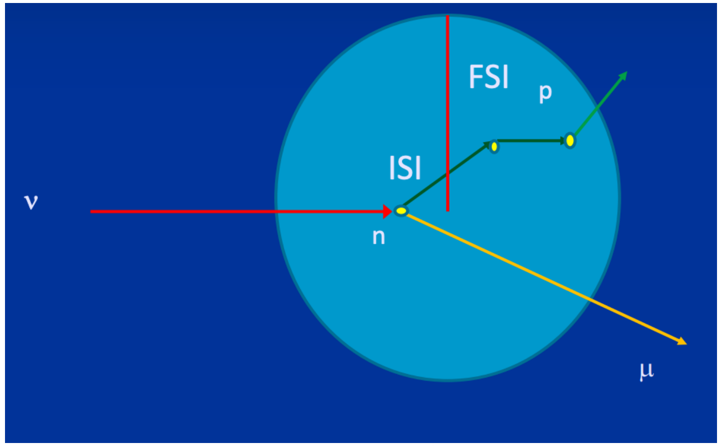
Neutrino-Nucleus Cross Sections



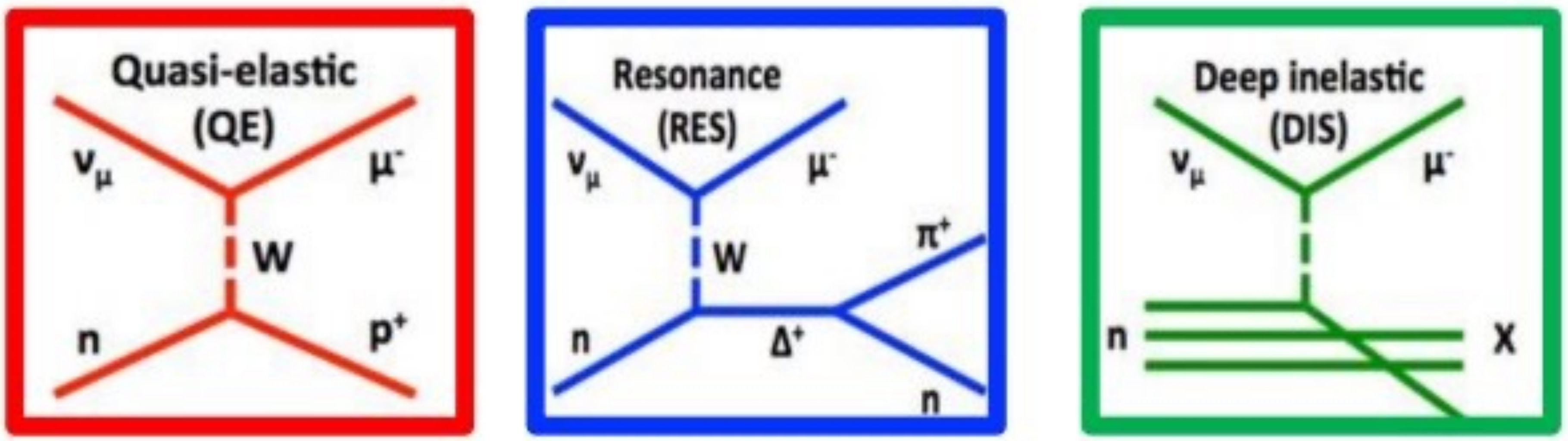
- Complexity increases from point like scattering, to scattering off a nucleon to scattering off a nucleus.
- Can approximately factorize neutrino-nucleus interactions:
  - **Initial state interaction (ISI)** between a neutrino and a nucleon.
  - **Final state interactions (FSI)** of the initial interaction products as they exit the nucleus.



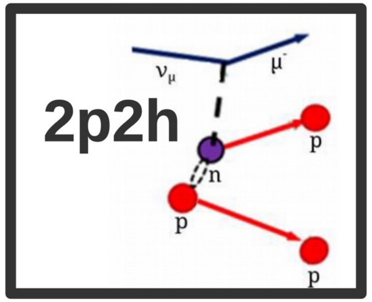
Initial State Interaction

- Initial neutrino-nucleon interaction may be:
  - Quasi-elastic, where the neutrino interacts with a single nucleon.
  - Resonance excitation, where the neutrino excites a nucleon to a resonance.
  - Deep-inelastic scattering, where the neutrino probes the quark structure of the nucleon.

- Broadband neutrino beams mean that interaction modes are not easily separated.



Initial State Interaction



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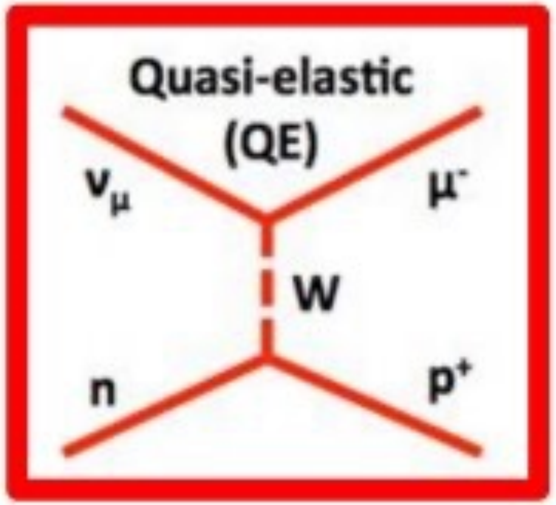
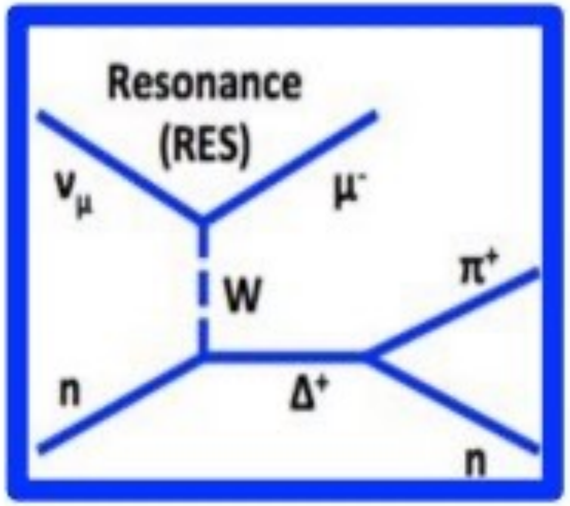
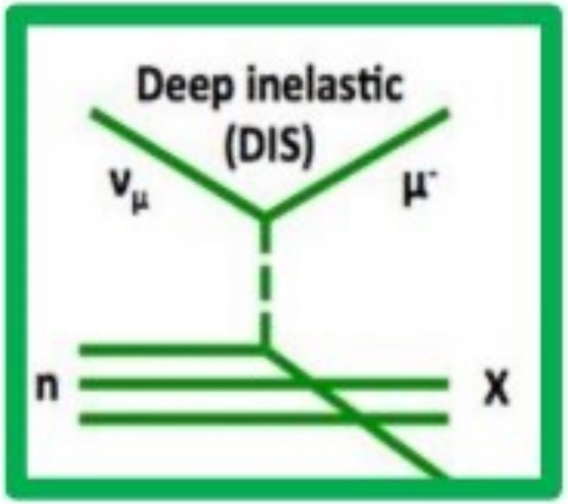
  - Quasi-elastic, where the neutrino interacts with a single nucleon.
  - Resonance excitation, where the neutrino excites a nucleon to a resonance.
  - Deep-inelastic scattering, where the neutrino probes the quark structure of the nucleon.
- Broadband neutrino beams mean that interaction modes are not easily separated.
  - Multinucleon effects (2p2h) further complicate the description of ISI.
  - Electron scattering provides guidance on the vector term, but the axial term is unique to neutrinos.
- **ISI determines the inclusive cross section.**
  - Necessary, but insufficient requirement for oscillation analyses.

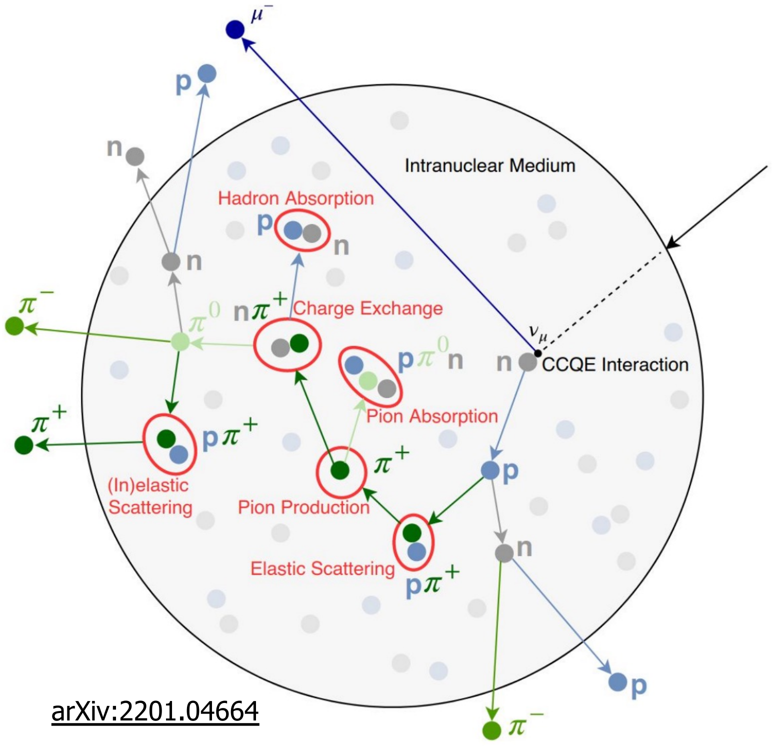






Final State Interactions

- FSI is an umbrella term for a broad class of phenomena:
  - Nucleon knockout, absorption, charge exchange and scattering.
  - Resonance production, absorption and decay.
  - Meson production/absorption, charge exchange and scattering.
  - Leptons (to a very good approximation) are not impacted.



arXiv:2201.04664

Final State Interactions

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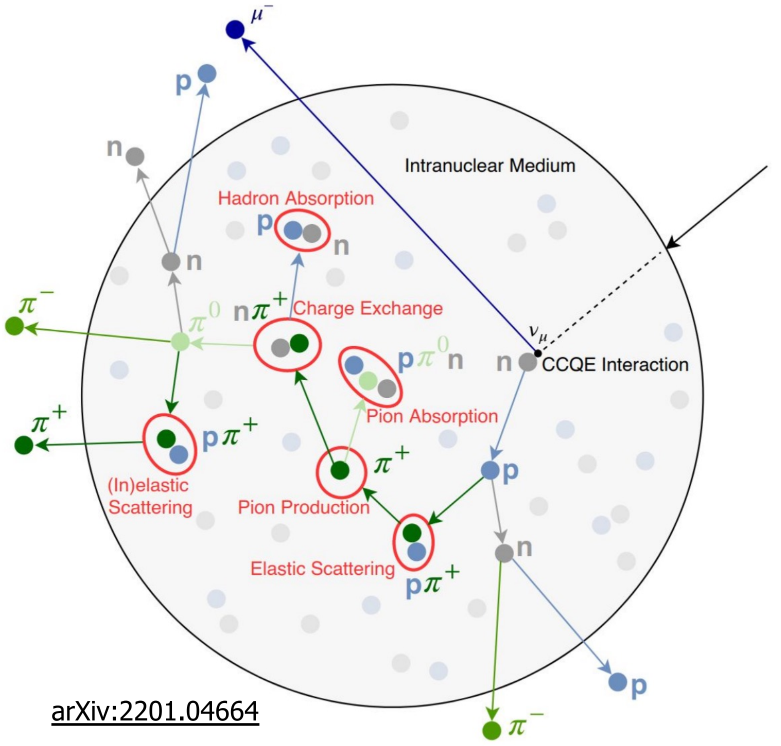
  - Nucleon knockout, absorption, charge exchange and scattering.
  - Resonance production, absorption and decay.
  - Meson production/absorption, charge exchange and scattering.
  - Leptons (to a very good approximation) are not impacted.
- **FSI determines the observed final state.**
  - Very important for neutrino energy reconstruction.
- Hadron+nucleus scattering data can provide modeling guidance, but the senarios are not identical.
  - Neutrinos “illuminate the whole target nucleus”.
  - Hadron “hits the nucleus from its outside”.



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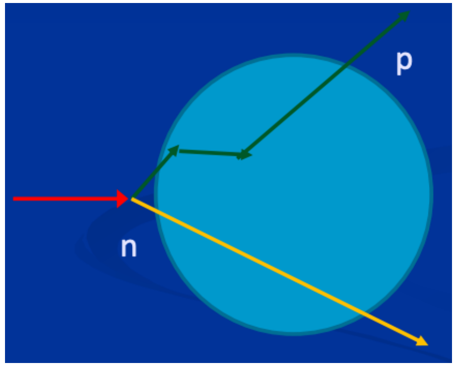
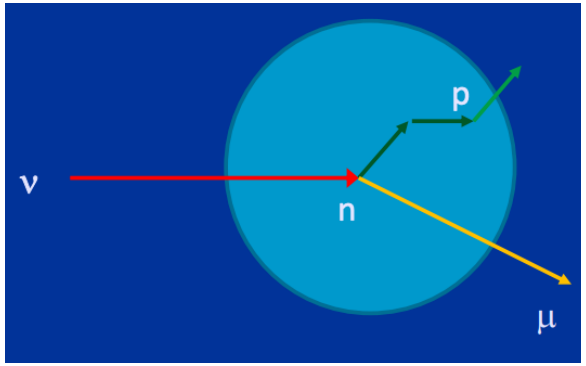
“Hadron-nucleus” scattering



“Neutrino-nucleus” scattering



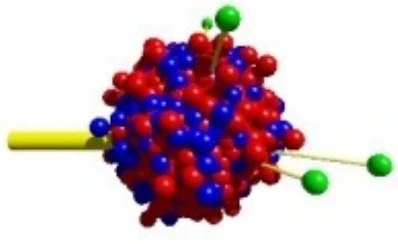
*cartoons, don’t take too seriously

Neutrino Event Generators

- Event generators combine models for different nucleon level interaction modes with a simulation of nuclear effects and FSI.
- Different generators predict different mappings between reconstructed and true quantities.
- At times vastly different approaches taken in event generator modeling, especially when it comes to nuclear effects and FSI.

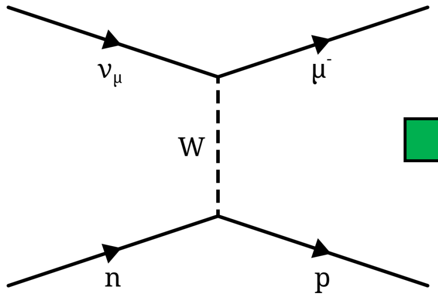
NuWro

GENIE

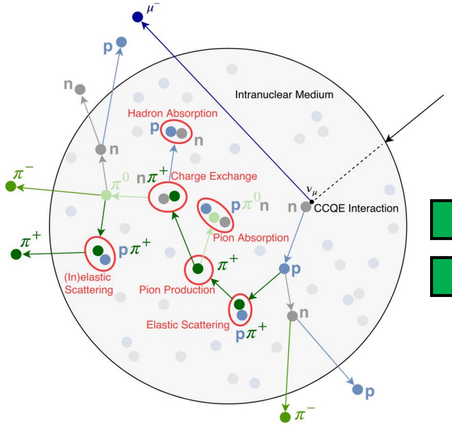


GiBUU

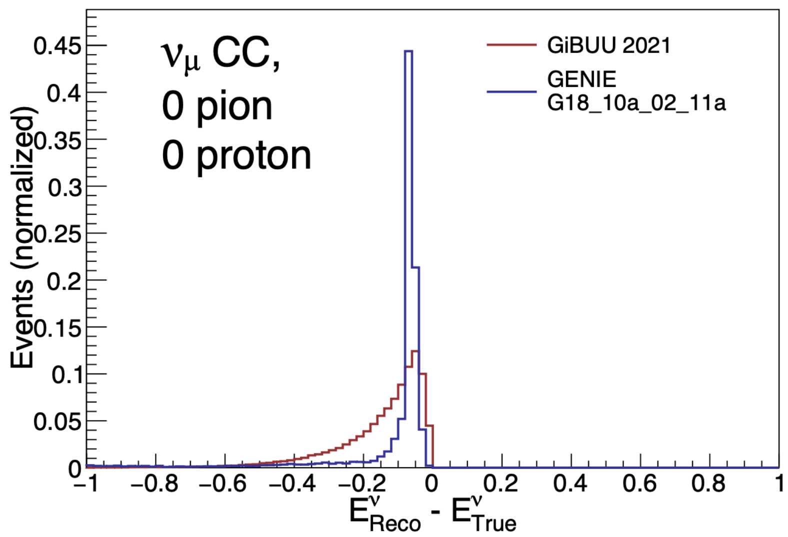
NEUT



Nucleon level



Nuclear effects

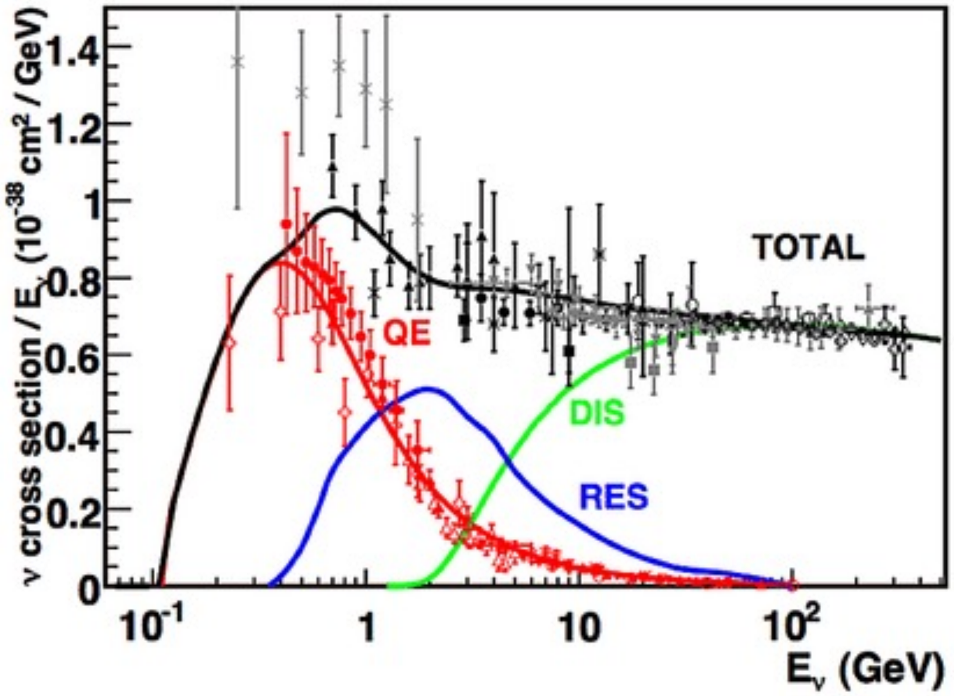


ACHILLES

Need for Neutrino Data

- Neutrinos are a unique probe!
  - Sensitive to the axial component of the weak interaction.
  - Illuminate the whole nucleus.
- Potential to be uniquely sensitive to various aspects of nuclear physics.
- Essential to benchmark any neutrino event generator on neutrino data in addition to any baseline checks on other scattering data.
- Immense ongoing effort by many collaborations!

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



MicroBooNE

NOvA

T2K

*non-exhaustive list

MINERvA

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 in nuclear systems:
  - heavy-ion
  - hadron-nuclei
  - electron-nuclei
  - photon-nuclei
  - neutrino-nuclei
- Describes the evolution of the nuclear system following the ISI with a quantum kinetic transport model.
  - Uses baryons and mesons as the relevant degrees of freedom.
  - Can handle both inclusive and exclusive channels.
    - Complete information on the final state; all particles' energy and momenta are accounted for.

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

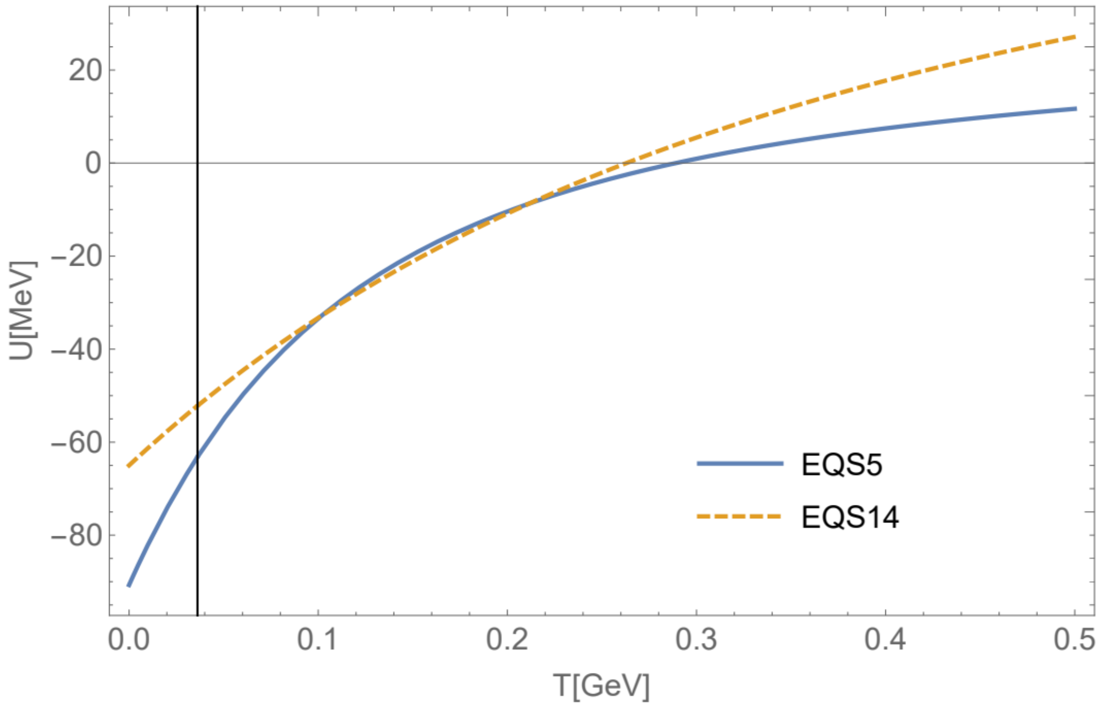
Neutrinos in GiBUU: Potentials

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

- Nucleons are bound in mean field potential with local Fermi-gas momentum distribution.
  - Momentum dependent potential: at small momenta (below fermi momentum) it produces binding and at larger momenta it disappears.
  - Parameters fit to the saturation density of nuclear matter, and to the momentum dependence of the nucleon optical potential measured in pA scattering.
- Consistent treatment: all ISI modes and subsequent FSI utilize this same potential.

$$U[\rho, p] = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2\frac{C}{\rho_0}g\int \frac{d^3p'}{(2\pi)^3}\frac{f(\vec{r},\vec{p}')}{1+\left(\frac{\vec{p}-\vec{p}'}{\Lambda}\right)^2}$$

$$f(\vec{r},\vec{p}') = \Theta[(|\vec{p}| - p_F(\vec{r})] \quad \text{with} \quad p_F(\vec{r}) = \left(\frac{6\pi^2}{g}\rho(\vec{r})\right)^{1/3}$$



Neutrinos in GiBUU: ISI

Phys. Rept. 512, 1-124 (2012)
arXiv:2308.16161 [nucl-th]
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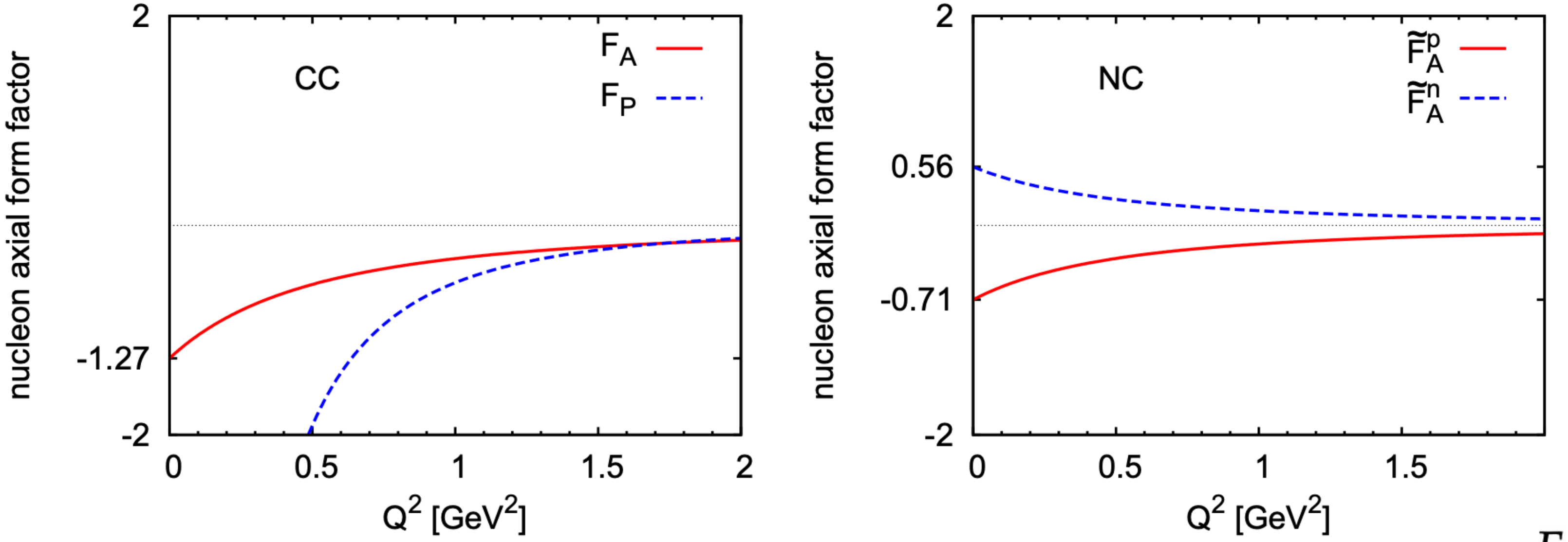
- QE scattering is modelled within the impulse approximation and axial dipole form factor.
  - Vector form factors from BBBA07 fit to electron data.



$$M_A = 0.999 \pm 0.011\,\mathrm{GeV}.$$

$$F_A(Q^2) = F_A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

Neutrino-nucleus interactions in a coupled-channel hadronic transport model, Tina J. Leitner (Giessen U.)

Phys. Rev. C **73**, 065502 (2006).

Neutrinos in GiBUU: ISI

Phys. Rept. 512, 1-124 (2012)
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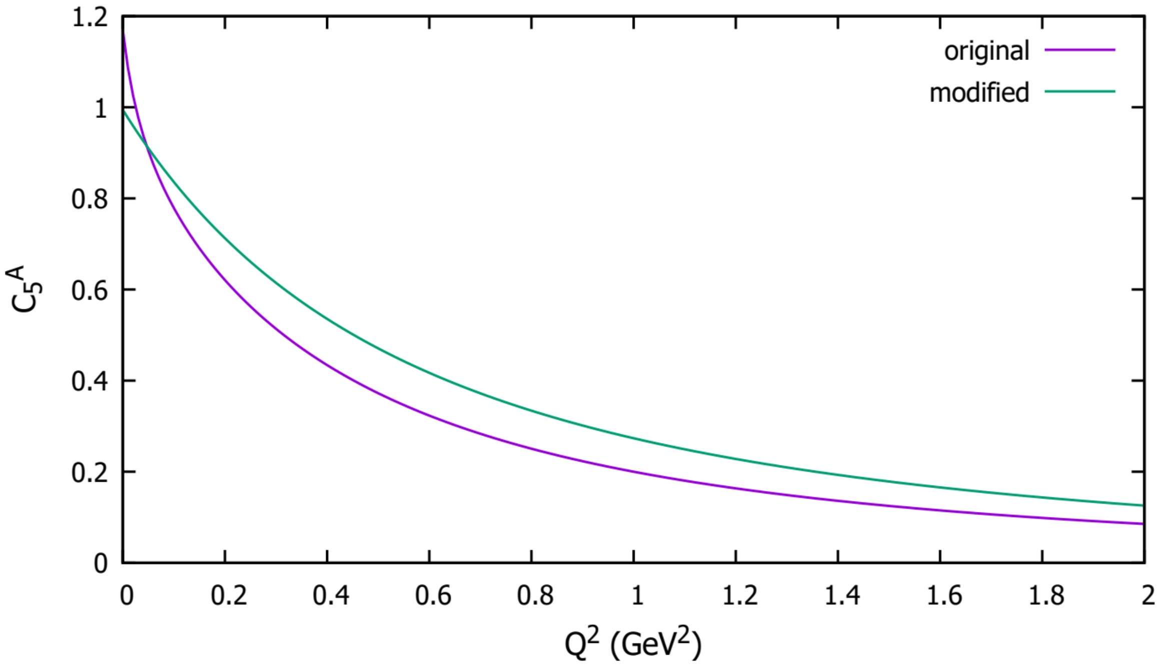
- RES uses vector couplings from MAID2007 and the axial couplings are obtained from PCAC with a modified dipole form factor fit to deuterium bubble chamber data.



$$C_5^{\Delta}(Q^2) = C_5(0)\left[1 + \frac{aQ^2}{b+Q^2}\right]\left(1 + \frac{Q^2}{{M_A^{\Delta}}^2}\right)^{-2}$$

Neutrinos in GiBUU: ISI

Phys. Rept. 512, 1-124 (2012)
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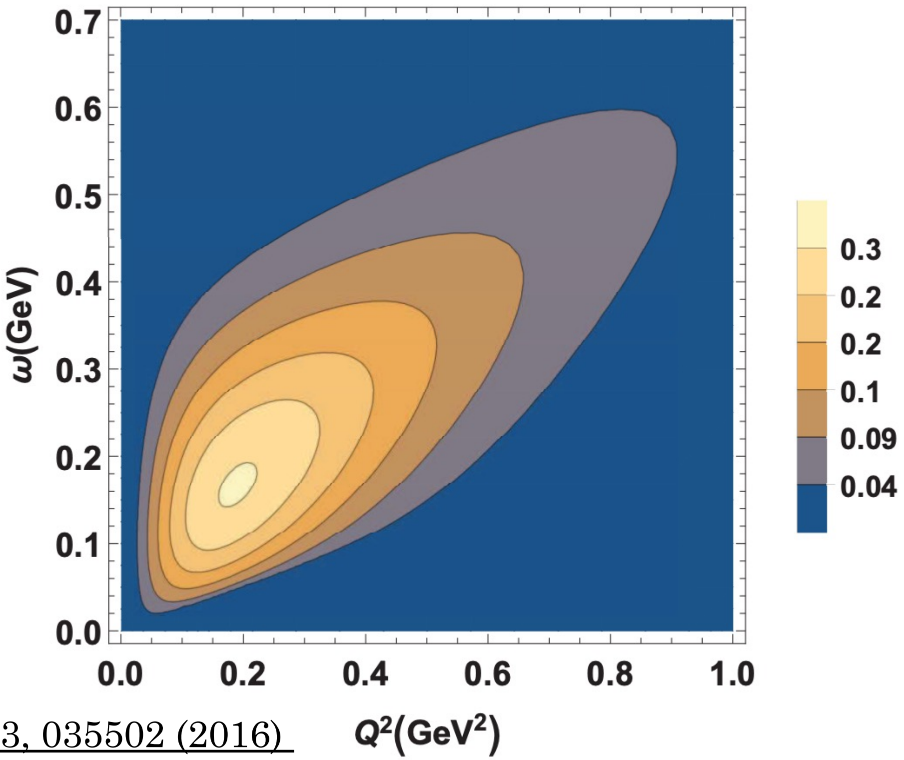
- QE scattering is modelled within the impulse approximation and axial dipole form factor.
  - Vector form factors from BBBA07 fit to electron data.
- RES uses vector couplings from MAID2007 and the axial couplings are obtained from PCAC with a modified dipole form factor fit to deuterium bubble chamber data.
- Meson exchange current (MEC, aka 2p2h) contribution is from a fit to electron data.
  - Covers the “dip” between the QE peak and Delta resonance excitation.



Phys.Rev.C 94 3, 035502 (2016)

$$W_1^\nu = \left[1 + \left(\frac{\mathbf{q}}{\omega}\frac{G_A}{G_M}\right)^2\right] 2\left(\mathcal{T}+1\right) W_1^e$$

DIS from PYTHIA, small contribution to today's discussion.

GiBUU FSI: Quantum-kinetic Transport

- Transport model utilizes Boltzmann-Uehling-Uhlenbeck (BUU) equations.
  - Describes the evolution of eight-dimensional phase-space distributions.
  - Start from the single particle Green's functions for the nucleons in the target nucleus and the incoming lepton.
- Each particle species has its own equation describing its phase-space distribution.

$$F(x,p) = 2\pi g \underbrace{f(x,p)}_{\text{Phase space distribution}} \underbrace{A(x,p)}_{\text{Spectral function}}$$

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma(x,p) f(x,p), \Re G^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)$$

GiBUU FSI: Quantum-kinetic Transport

- The Drift term describes the phase space evolution of particles in the mean fields.
  - The mean field couples together the equations for different particle species.
- Off-shell transport term ensures particles leaving the nucleus have returned to their vacuum spectral function and is thus vanishing for on-shell particles.

Single particle Hamiltonian containing the mean fields

$$\mathcal{D}F = [p_0 - H, F]_{\mathrm{PB}}$$

Drift term

Off-shell transport term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma(x,p)f(x,p), \Re G^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)$$

GiBUU FSI: Quantum-kinetic Transport

- Collison term describes particle interaction and decay which results in a loss or gain of phase space density.
    - Further couples the equations for different particle species.

$$C(x,p) = C^{(1)}(x,p) + C^{(2)}(x,p) + C^{(3)}(x,p) + \cdots$$

Drift term **Off-shell transport term** **Collision term**

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

GiBUU FSI: Quantum-kinetic Transport

- Collison term describes particle interaction and decay which results in a loss or gain of phase space density.
  - Further couples the equations for different particle species.
- Can be expressed in terms of differential cross section (or decay) for each reaction process.
  - Pauli-blocking and is accounted for in this term.

$$C(x,p) = C^{(1)}(x,p) + C^{(2)}(x,p) + C^{(3)}(x,p) + \cdots$$

$$C^{(2)}(x,p_1) = \int \frac{\mathrm{d}^4 p_2}{(2\pi)^4} \int \boxed{\mathrm{d}\sigma_{12\to 1'2'}} v_{\mathrm{rel}} [f_{1'}(x,p_{1'}) f_{2'}(x,p_{2'}) \overline{F}_1(x,p_1) \overline{F}_2(x,p_2) - F_1(x,p_1) F_2(x,p_2) \overline{f}_{1'}(x,p_{1'}) \overline{f}_{2'}(x,p_{2'})] ,$$

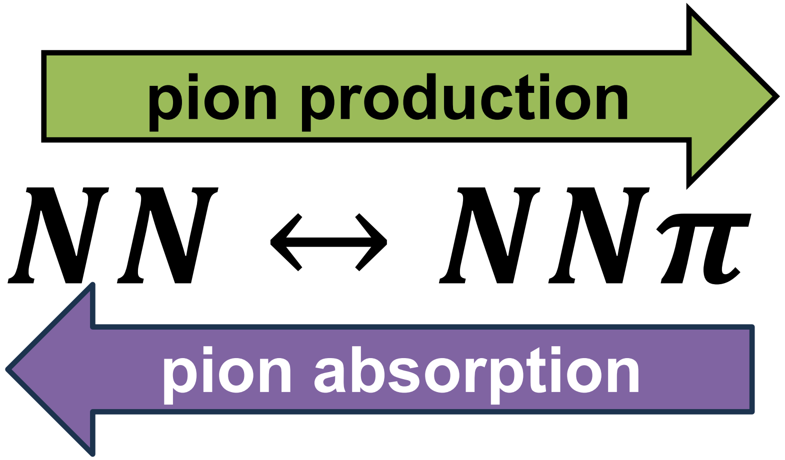
$$\overline{F}(x,p) = \begin{cases} 2\pi g A(x,p)[1 - f(x,p)] & \text{for fermions,} \\ 2\pi g A(x,p)[1 + f(x,p)] & \text{for bosons.} \end{cases}$$

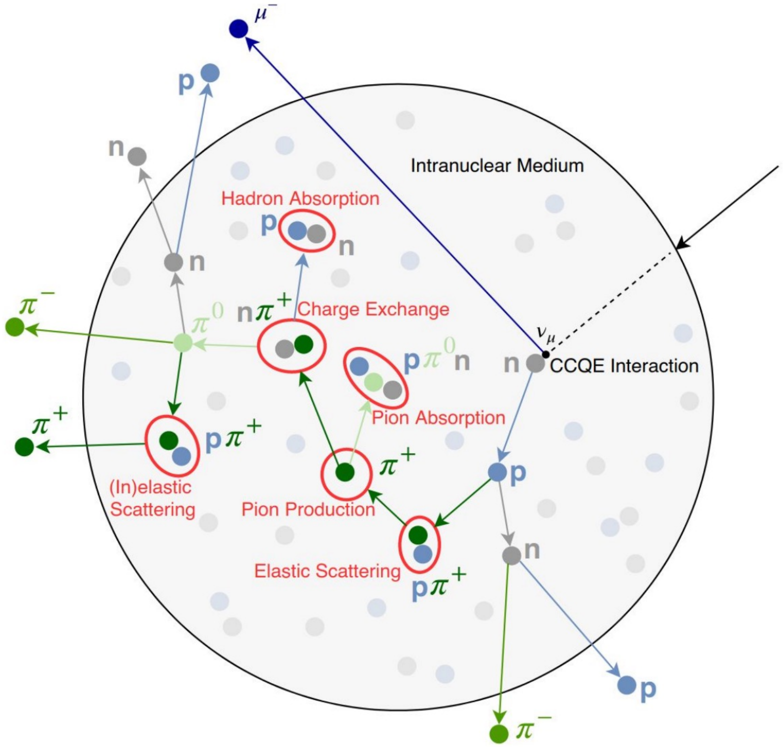
← **Final state Pauli blocking**

Neutrinos in GiBUU: FSI

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

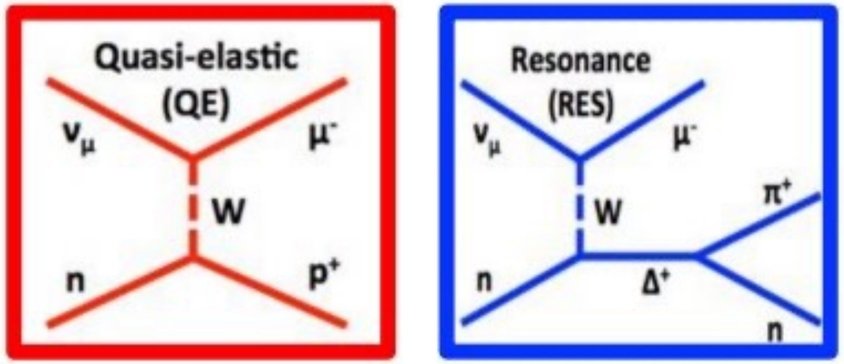
- Implementing FSI with a transport model allows for a precise and consistent treatment of nuclear effects.
  - Nuclear binding potential is naturally incorporated into the description of final state scattering.
  - Interaction rates respect time-reversal: ie. pion absorption and production come from the same model.
- Only inputs to the model are the cross sections and potentials for each particle species.
  - No unphysical degrees of freedom available for tuning.





Neutrino-Induced Reactions: MicroBooNE Data

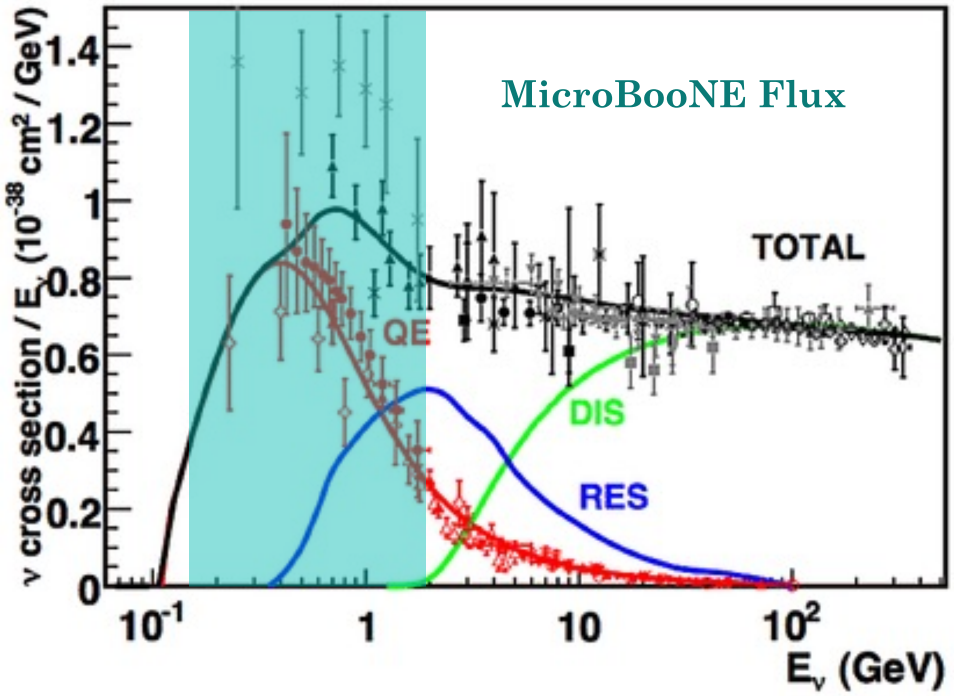
- MicroBooNE data are ideal for studying FSI:
  - Low energy neutrino beam -> "simple" interactions.
    - Primarily quasi-elastic and delta resonance production.
  - Ability to track protons down to 35 MeV kinetic energy.
  - Argon target increases the prominence of FSI



Scattering off single nucleon

Inelastic scattering: Excites the nucleon

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



MicroBooNE

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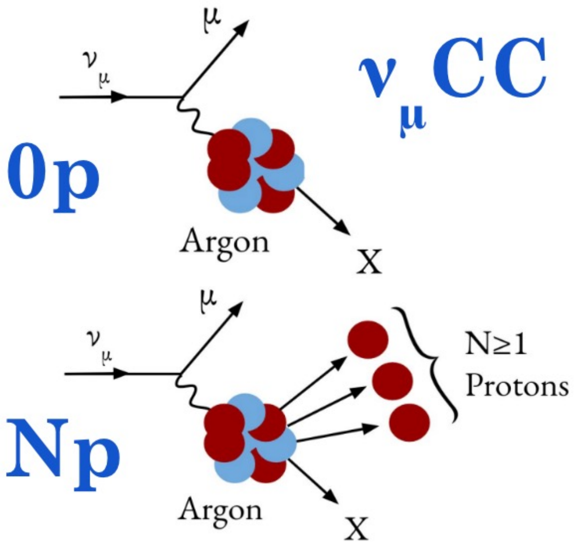
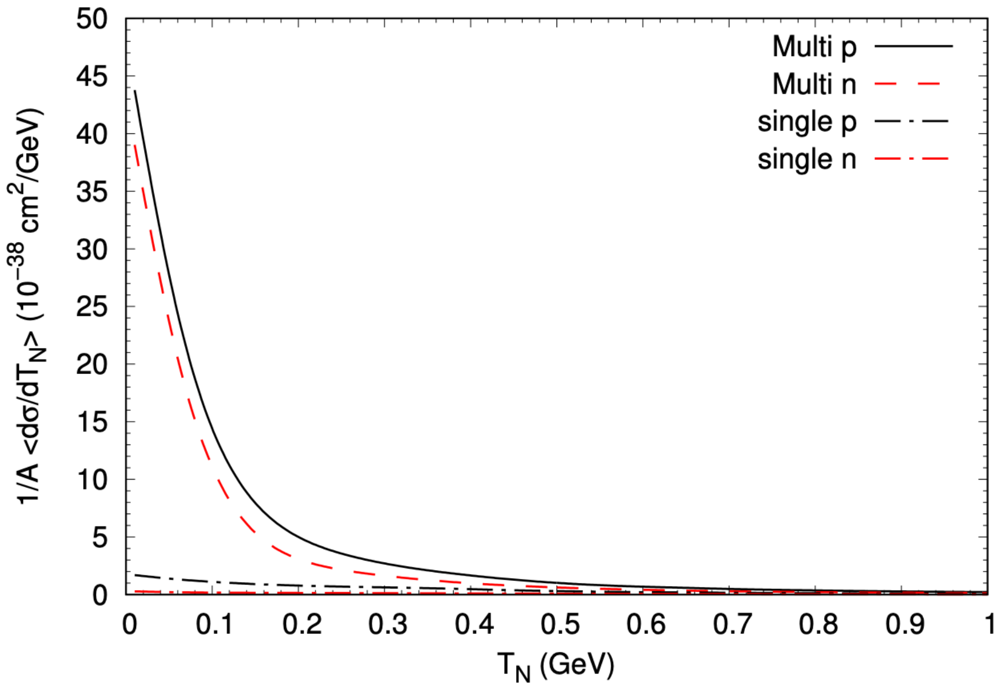
MicroBooNE

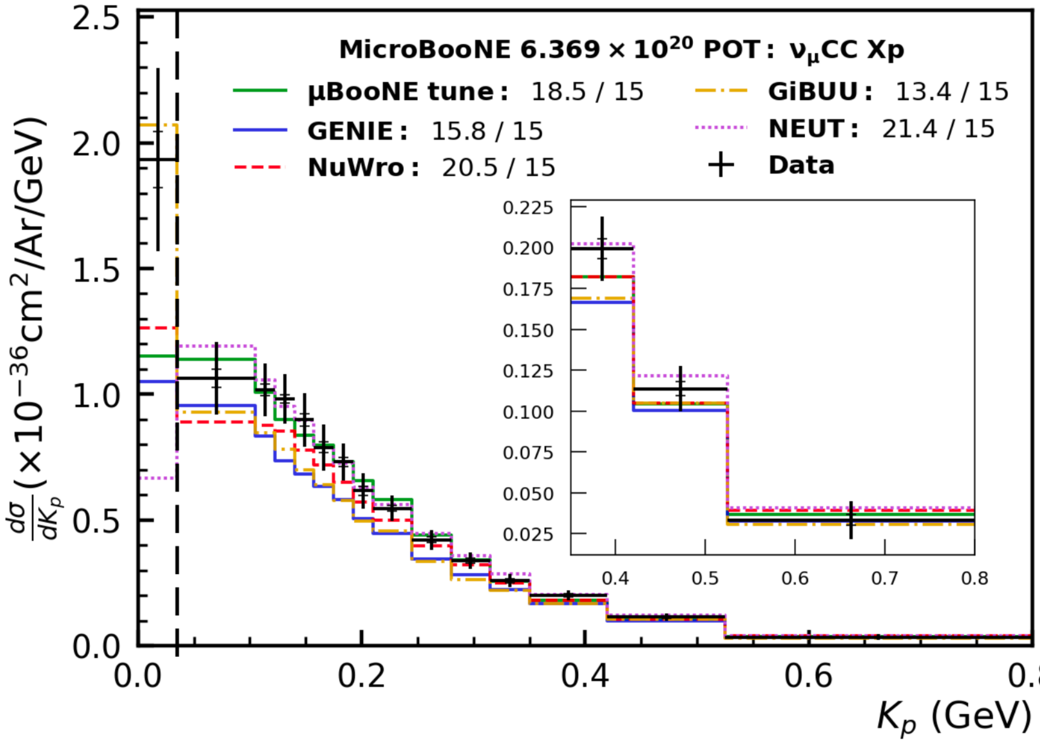


Studying FSI: Low energy protons

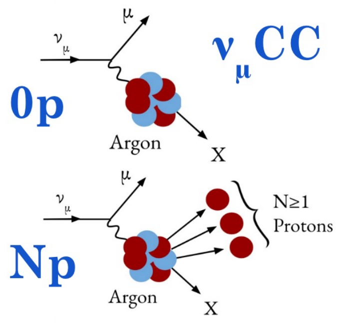
- "Avalanche effect": buildup of protons at low kinetic energies from FSI.
  - Re-interactions may deplete initial proton of its energy and cause the ejection of multiple protons.
- This effect is apparent in MicroBooNE data.
  - GiBUU is the only event generator to reproduce this feature.



J. Phys. G: Nucl. Part. Phys. **46** 113001 (2019)



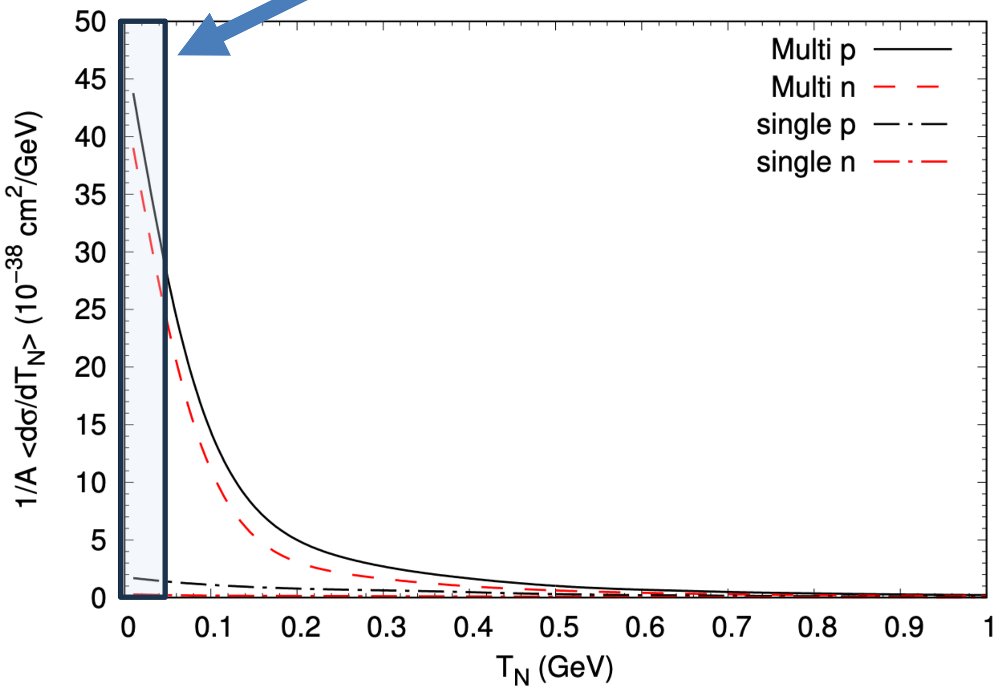
Phys. Rev. D 110, 013006 (2024)



Studying FSI: The 0p channel

- The "Avalanche effect" has a big impact on 0p channel.
  - "0p" is defined based on the 35 MeV MicroBooNE detection threshold, 0p events may have a proton, but it is very low in energy.
  - Most 0p events are ones where the proton has experience significant FSI.
- GiBUU demonstrates a consistent ability to describe MicroBooNE data in this channel.
  - Other models significantly underpredict the 0p data.

0p channel: Kp<35 MeV



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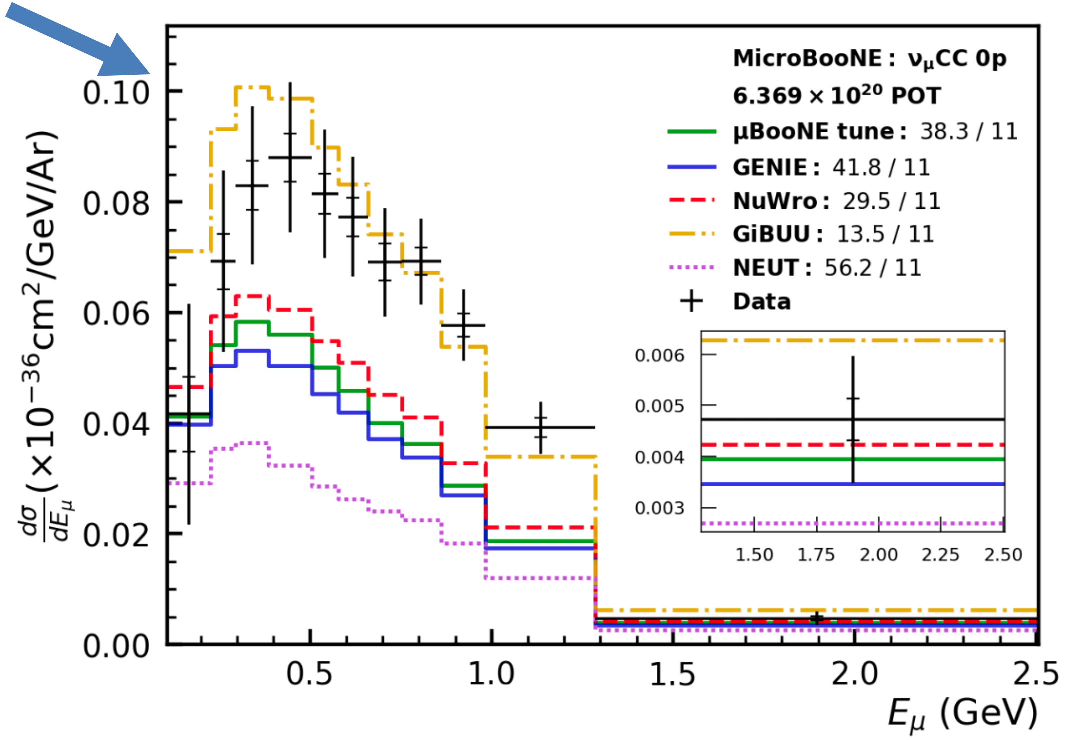
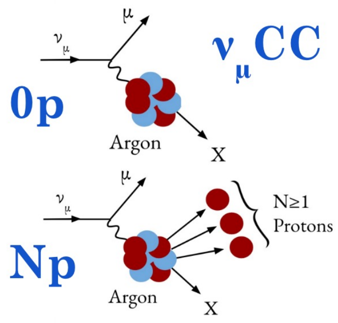


Phys. Rev. D 110, 013006 (2024)



FSI Modeling Differences

- Why is GiBUU's prediction distinct from the other models?
- Largely two classes of FSI models used in neutrino generators.
- Internuclear cascade model (INC):
  - Propagate the particles out of the nucleus in discrete timesteps, with the probability of an interactions dictated by the mean free path.
    - Mean free path governed by total cross section and density of the nucleus.
    - Particles propagated as point-like on-shell free particles and in straight line paths, potentials are ignored.
  - ie: GENIE hN model, NuWro, NEUT.

$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

Probability of interaction over a given distance

$$\tilde{\lambda} = \left(\sigma_p \rho_p(r) + \sigma_n \rho_n(r)\right)^{-1}$$

Mean free path, governed by the elementary cross sections and nuclear density

NuWro

GENIE

NEUT

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    - Particles propagated as point-like on-shell free particles and in straight line paths, potentials are ignored.
  - ie: GENIE hN model, NuWro, NEUT.
- Transport model:
  - Solve a coupled set of differential equations describing the evolution of phase space distributions.
  - ie: GiBUU

$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

Probability of interaction over a given distance

$$\tilde{\lambda} = (\sigma_p \rho_p(r) + \sigma_n \rho_n(r))^{-1}$$

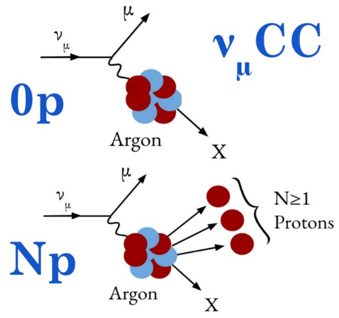
Mean free path, governed by the elementary cross sections and nuclear density

On-shell drift term — Off-shell transport term — Collision term

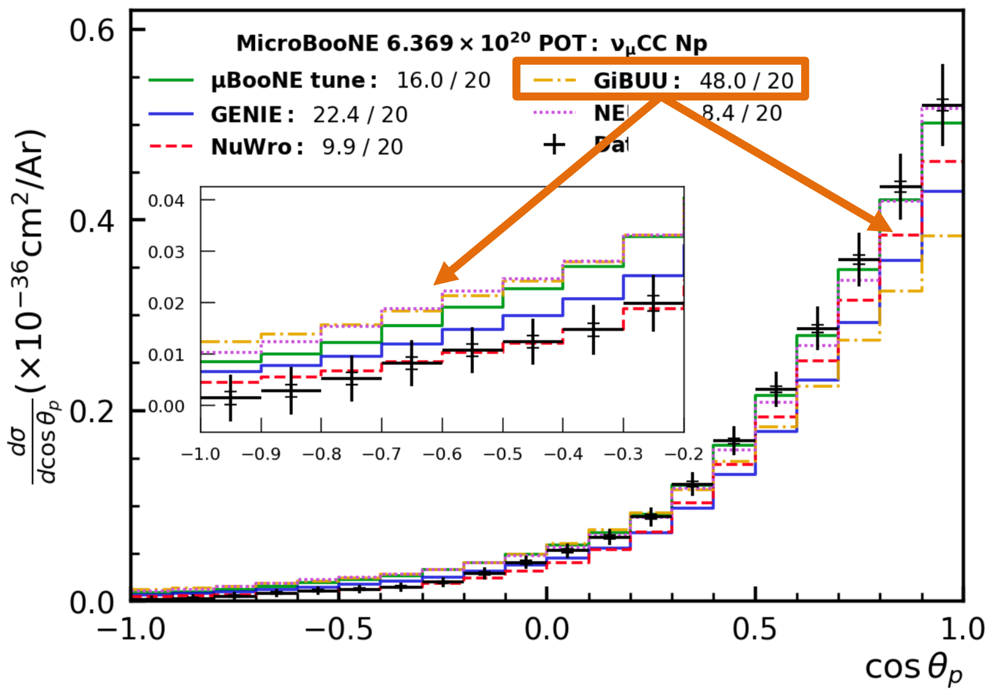
$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)$$

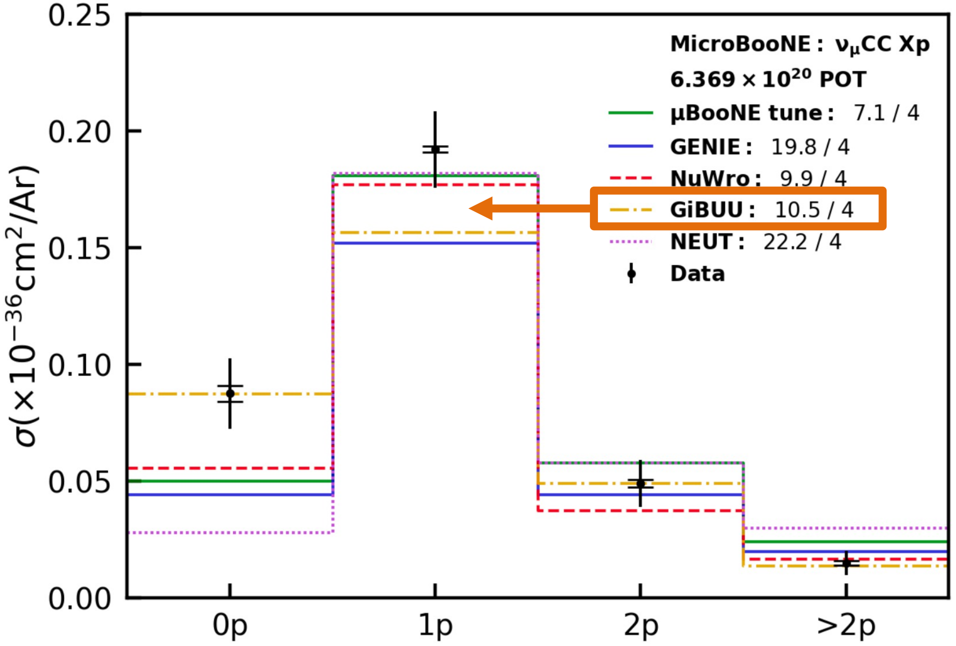
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Learning from MicroBooNE ν_μCC data



- Data suggests avenues for improvements to the description of FSI.
  - Overprediction of ν_μCC proton spectra at forward angles
  - Underprediction of of 1p events.
- All potentially linked to too many proton re-interactions?
  - Too much re-scattering redistributing strength to backwards angles.
  - Too many QE events migrating from 1p -> 0p.



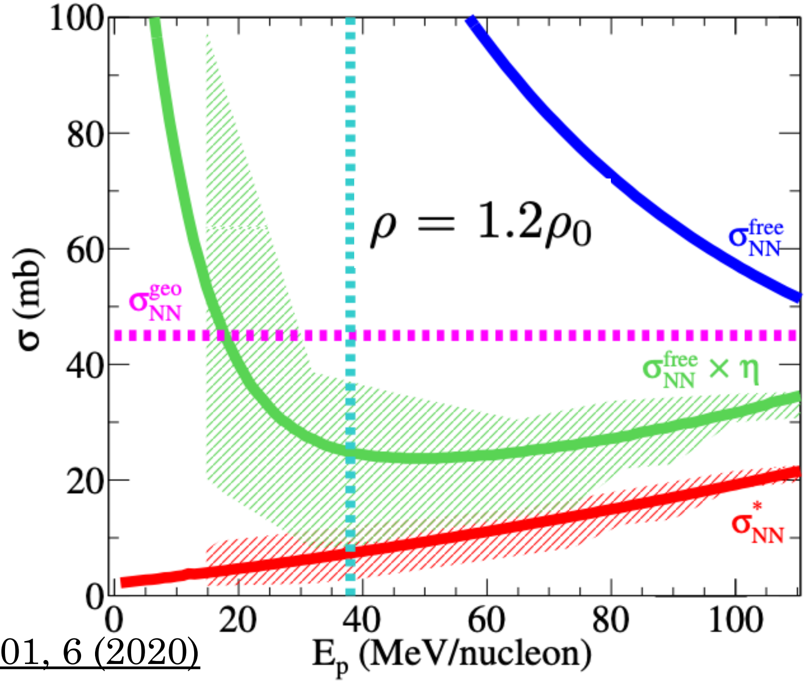


Phys. Rev. D 110, 013006 (2024)

In-medium Modifications to NN Cross Sections

- The collision term should utilize in-medium cross sections rather than vacuum ones.
- GiBUU nominally used vacuum cross section in its FSI model.
- The degree nucleon-nucleon cross sections are modified within the nucleus is unknown.
  - Theoretical investigation suggest a lowering of NN cross sections below resonance excitations.
  - Mostly investigated in the context of heavy-ion collisions.

$$C^{(2)}(x,p_1) = \int \frac{d^4 p_2}{(2\pi)^4} \int \boxed{d\sigma^*_{12\to 1'2'}}\, v^*_{\mathrm{rel}} \left[f_{1'}(x,p_{1'}) f_{2'}(x,p_{2'}) \overline{F}_1(x,p_1) \overline{F}_2(x,p_2) - F_1(x,p_1) F_2(x,p_2) \overline{f}_{1'}(x,p_{1'}) \overline{f}_{2'}(x,p_{2'}) \right] =: C^{(2)}_{\mathrm{gain}} - C^{(2)}_{\mathrm{loss}}\,,$$

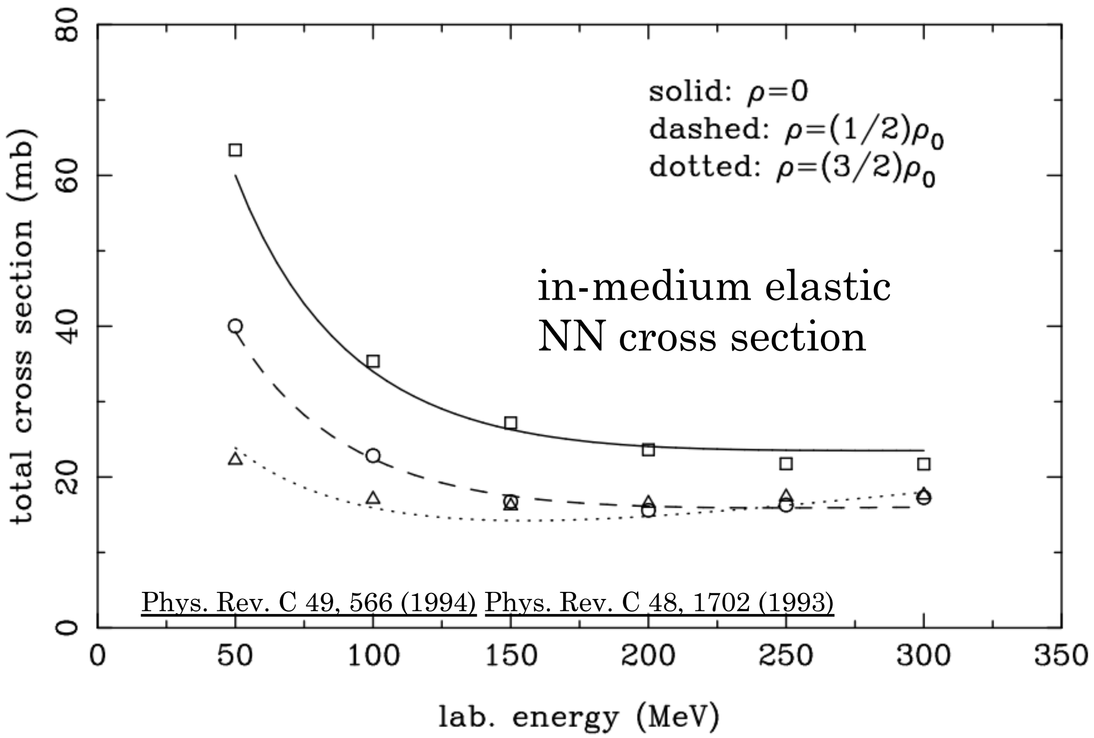


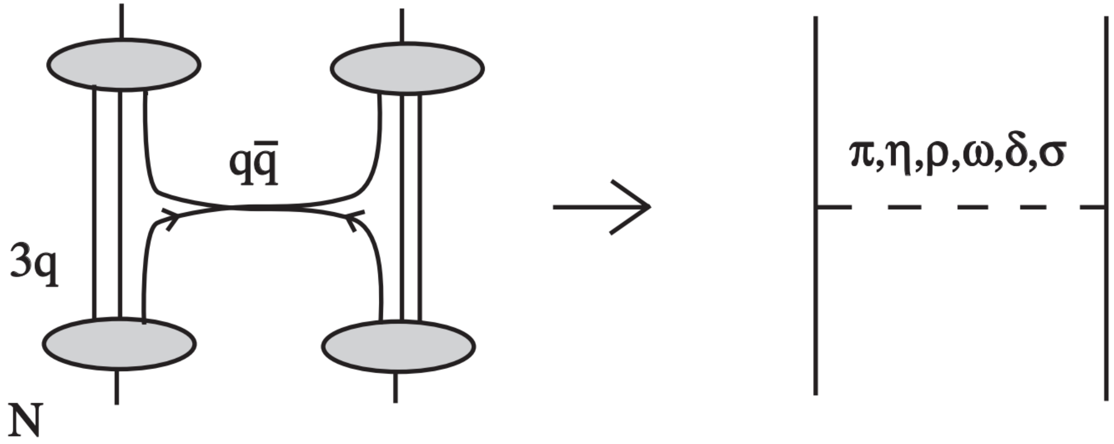
Phys. Rev. C 101, 6 (2020)

NN In-Medium Modification in GiBUU

- GiBUU implements in-medium modifications to elastic NN cross sections according to the work of Li and Machleidt.
  - Li and Machleidt calculation based on Bonn meson-exchange model for the NN interaction and the Dirac-Brueckner approach for nuclear matter.
  - Cross section lowered due to reduction in the in medium mass, Pauli blocking of intermediate states, and modifications to the exchange potential in the presence of other nucleons.

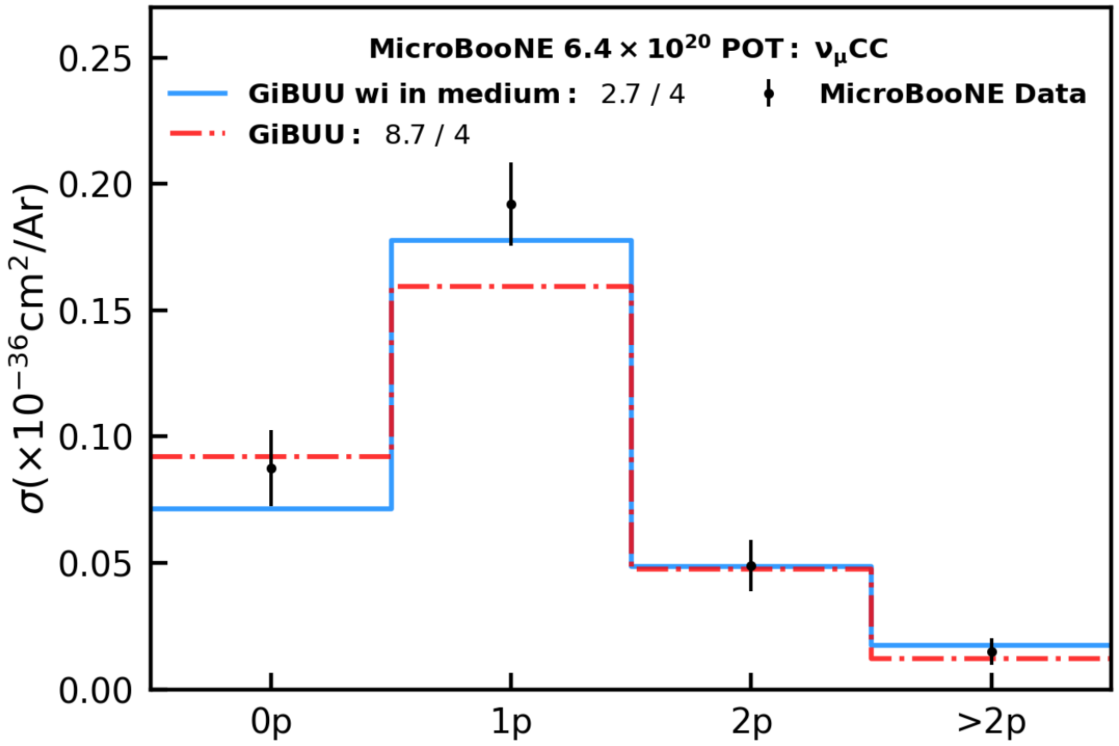
- Lower the elastic NN cross sections as a function of density.
  - More prominent impact on low energy nucleons.

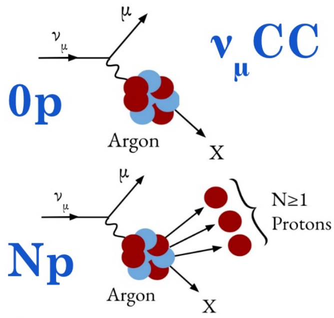




Comparison with Experiment: ν_μCC Data

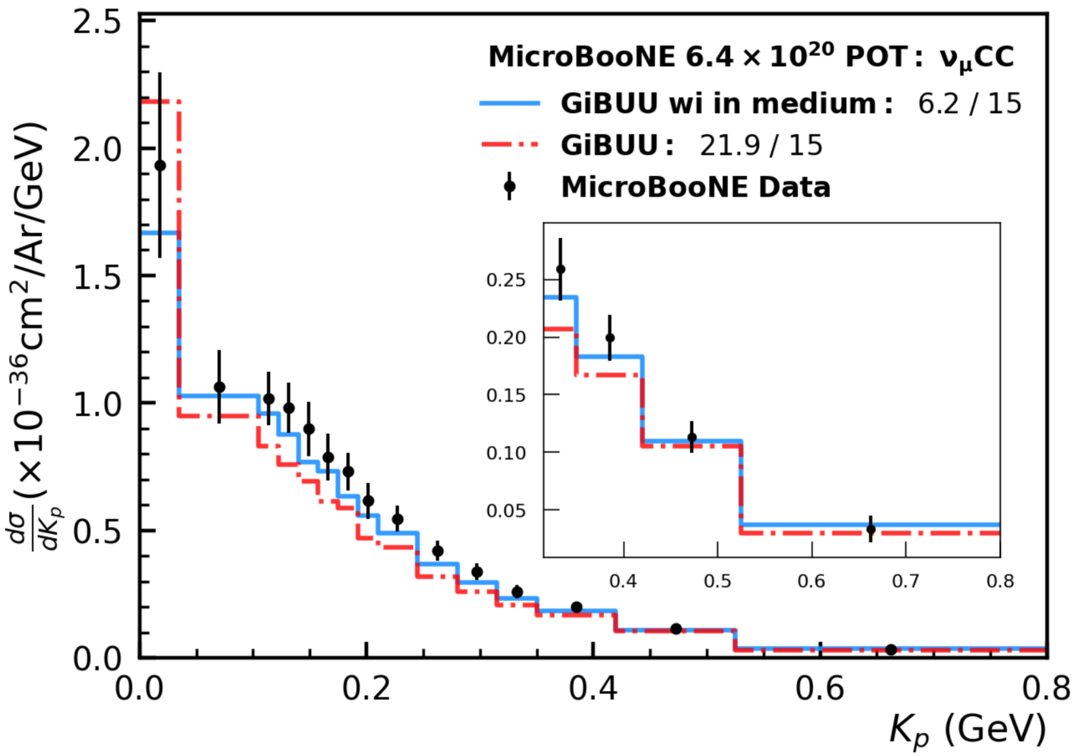
- Including these in-medium modifications shifts strength from 0p to Np.
- Multiplicity distribution shown this shift is primarily from 0p to 1p.
  - When the elastic NN cross sections are lowered there are less NN collisions which lead to migration of QE events from the 1p bin to the 0p bin.
- In-medium prediction is favored by the data.

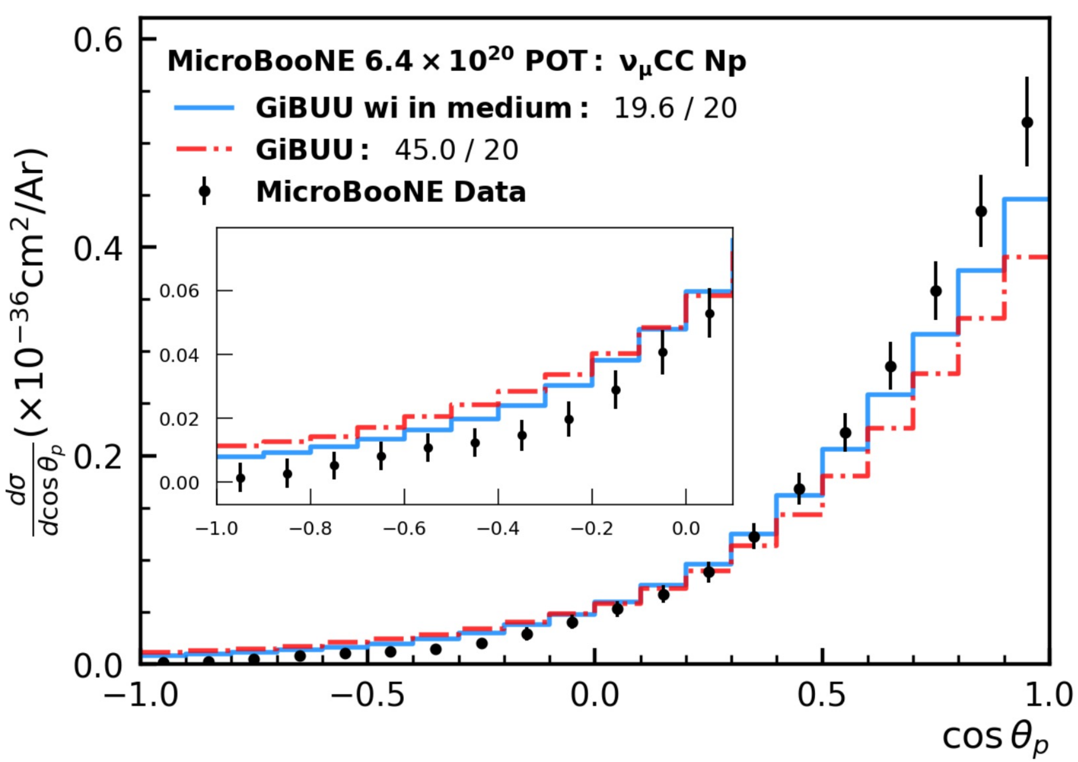


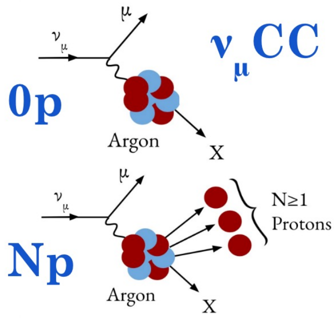


Comparison with Experiment: ν_μCC Data

- Noticeable improvement in the proton spectra when in-medium modifications 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.
- In-medium prediction is favored by the data.







Neutrino-Induced Reactions: MicroBooNE Data

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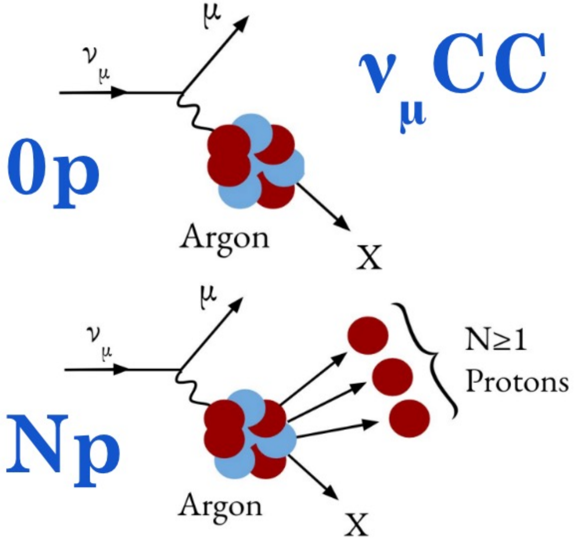
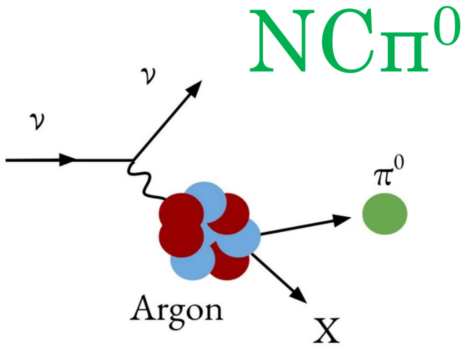
    - Primarily quasi-elastic and delta resonance production.
  - Ability to track protons down to 35 MeV kinetic energy.
  - Argon target increases the prominence of FSI
- We utilize the charge-current muon neutrino (ν_μCC) dataset from Phys. Rev. D 110, 013006 (2024).
  - Reports proton spectra and measurements of final states with (Np) and without (0p) protons.
- Also investigate neutral-current single pion production (NCπ^0) data from Phys. Rev. Lett. 134, 161802 (2025)
  - Features π^0 spectra and measurements of 0p and Np final states.

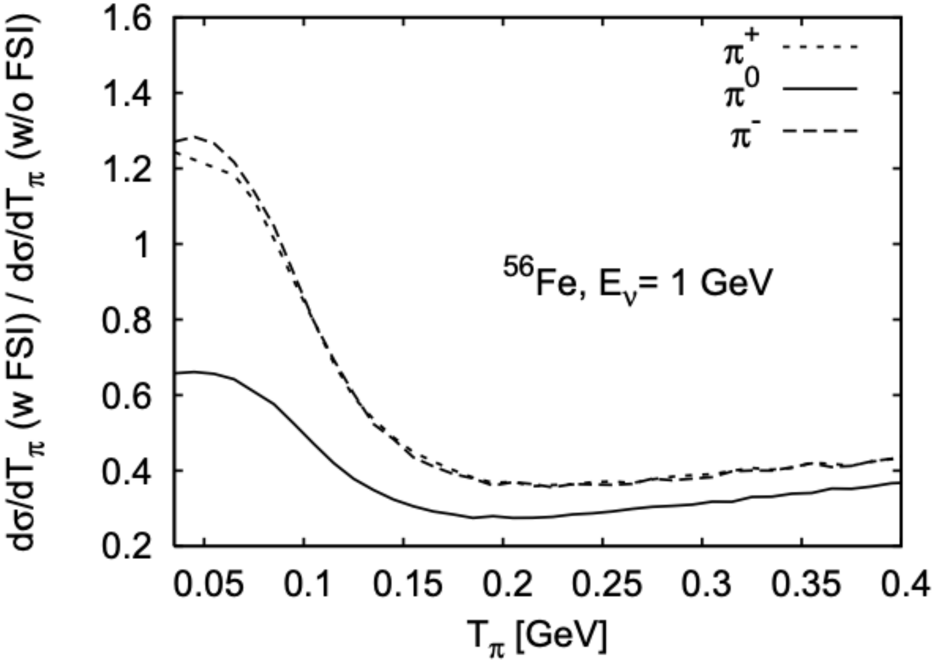
MicroBooNE



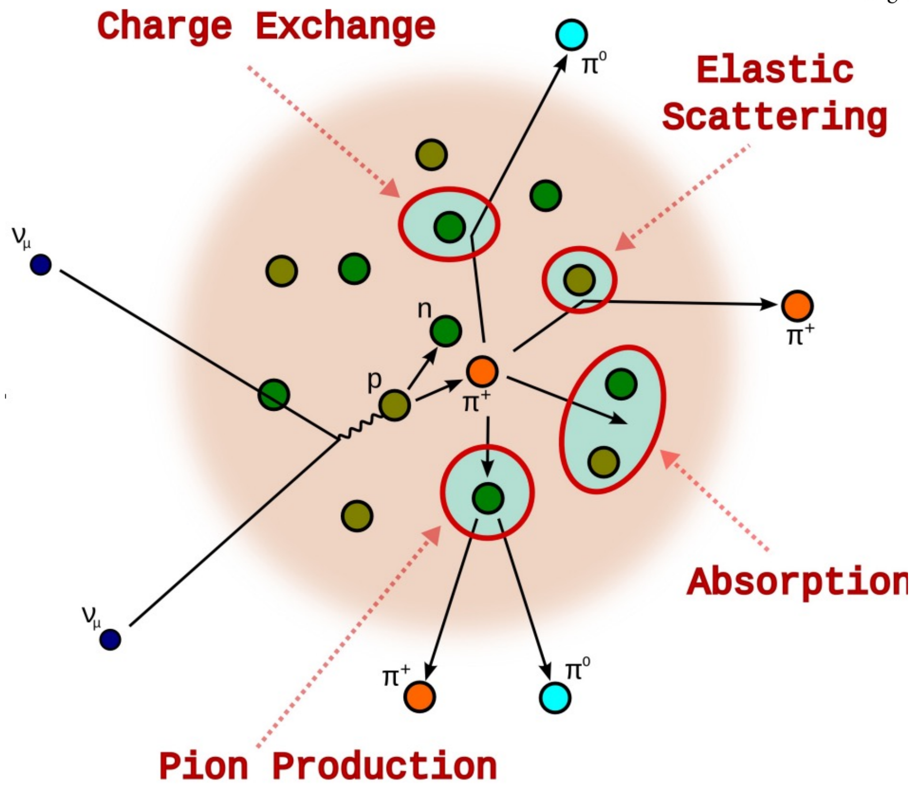


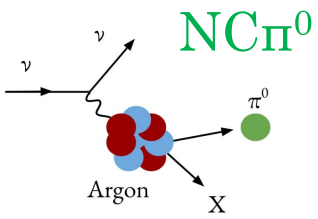
Studying FSI: Pion Observables

- Final state interactions have a significant impact on the observed pion spectra:
  - Charge exchanges changes pion flavor and modifies the balance of final states with different charge pions.
  - Pion and Delta absorption/production decreases/increases pion yield in final state.
  - (In)elastic scattering modifies energy and angular distributions.



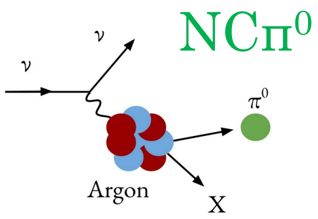
Phys. Rev. C **74**, 065502 (2006)

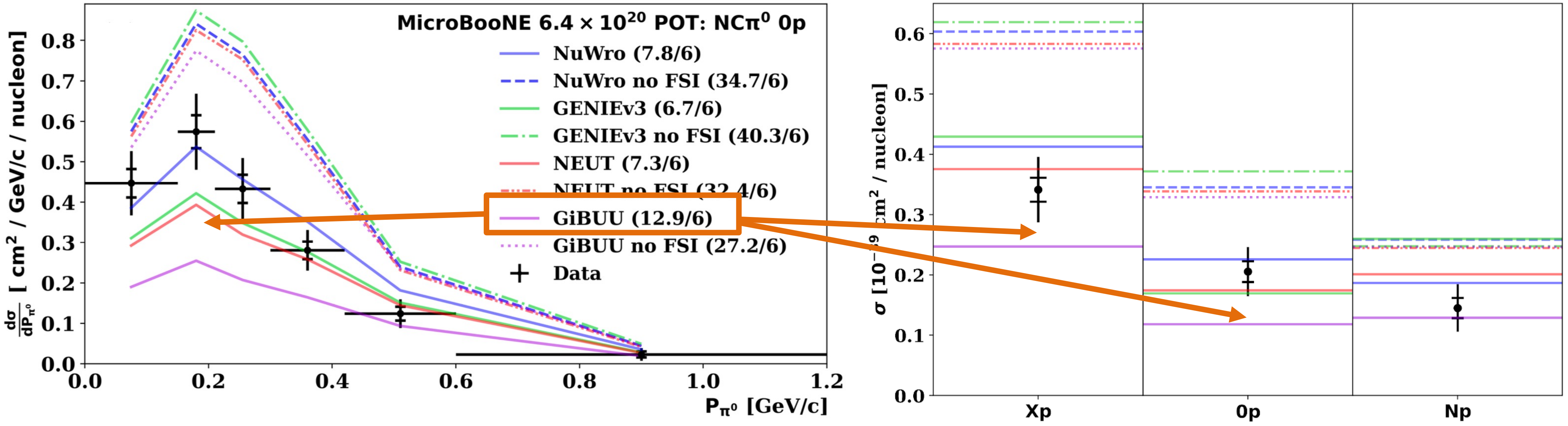




Learning from MicroBooNE NCπ^0 data

- Comparisons of the nominal GiBUU prediction to MicroBooNE pion data suggest a potential need for in-medium modifications.
  - Underprediction of NCπ^0 events, especially for 0p and at the peak of the momentum spectra.

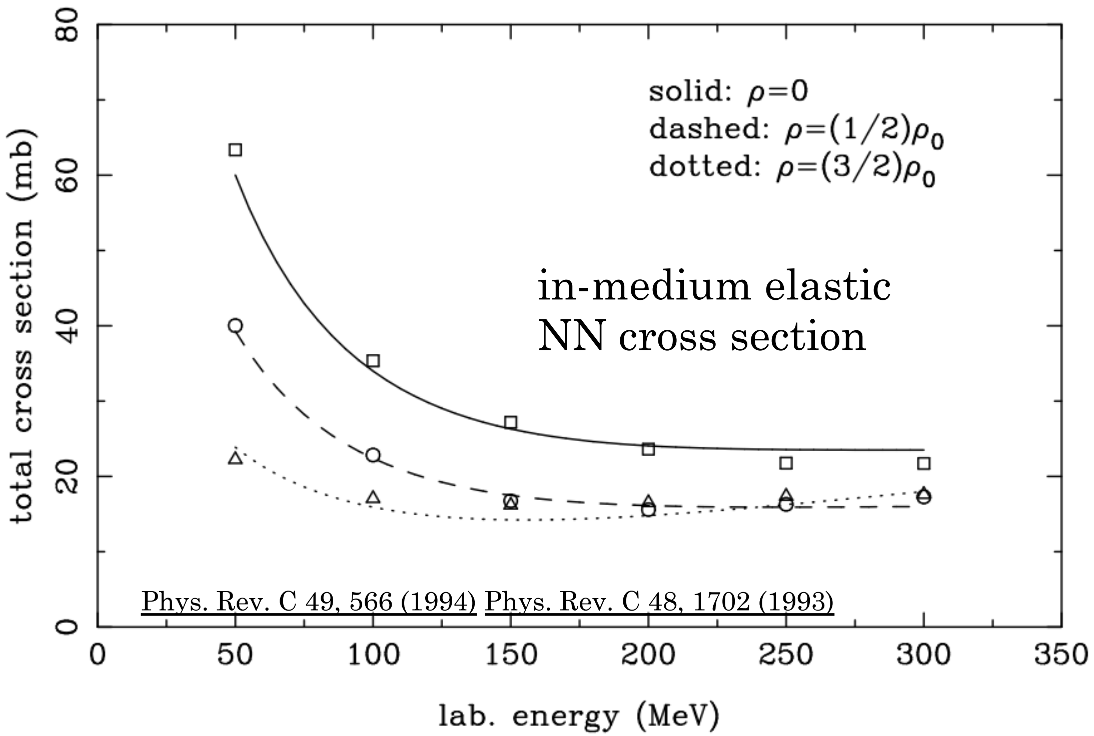


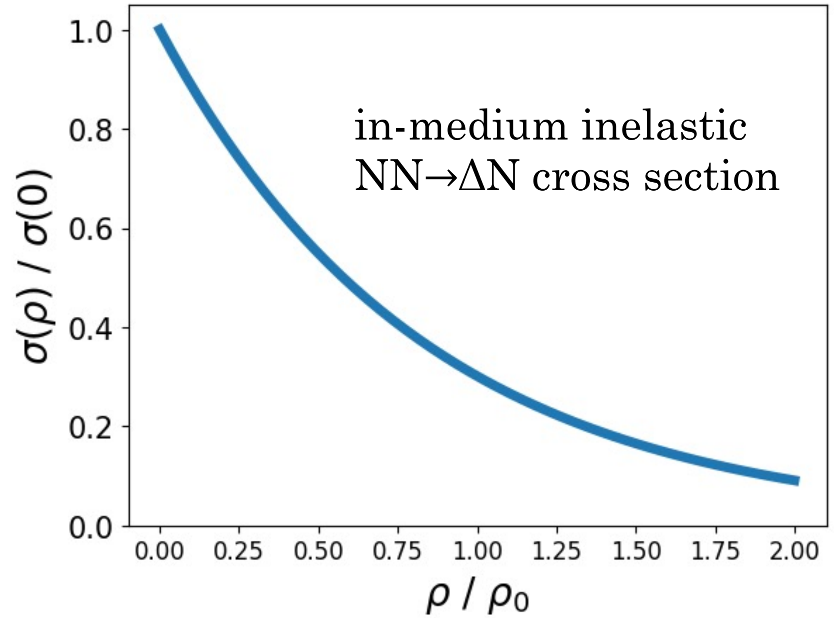


Phys. Rev. Lett. 134, 161802 (2025)

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.
- The inelastic NN→ΔN cross section modified according to the work of Song and Ko.
  - Decreases both Δ absorption and excitation through detailed balance.





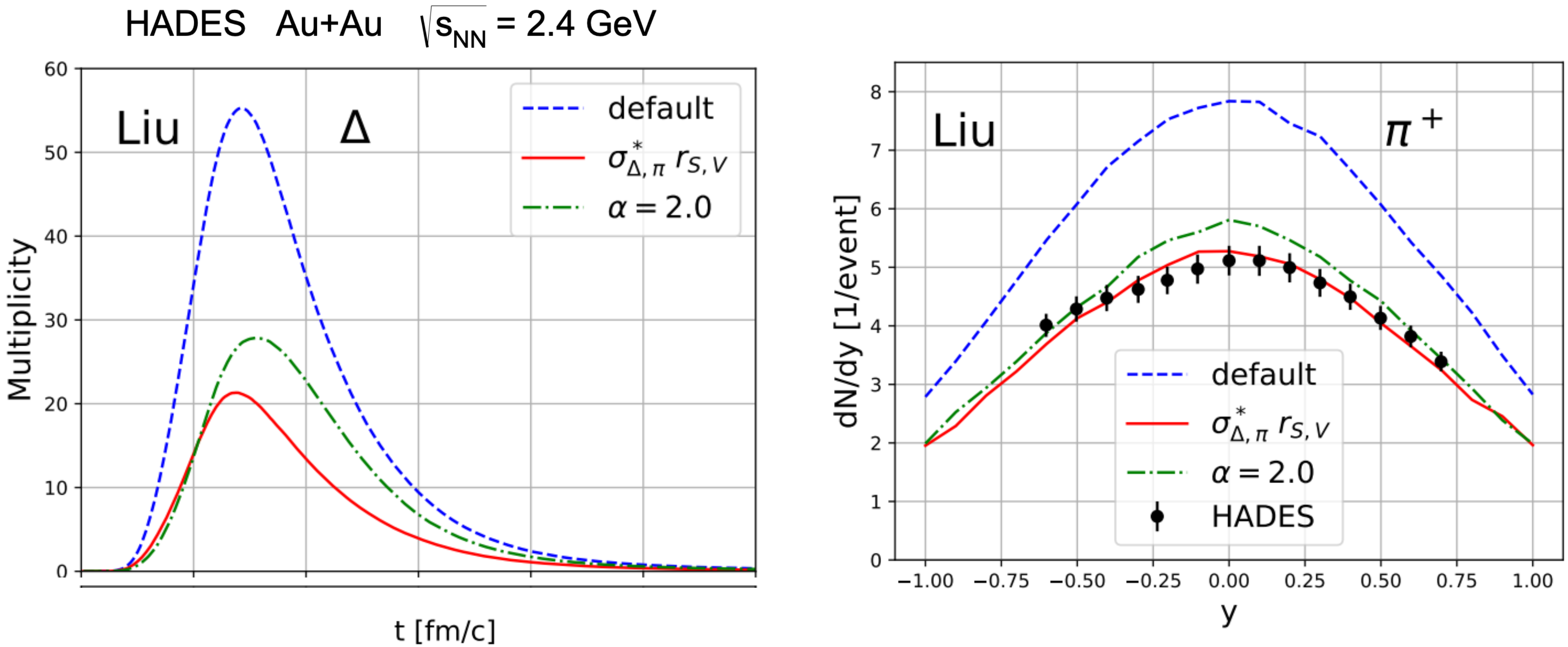
$$\sigma_{NN\to N\Delta}(\rho) = \sigma_{NN\to N\Delta}(0)\exp(-1.2\,\rho/\rho_0)$$

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

NN→ΔN Cross Section Suppression

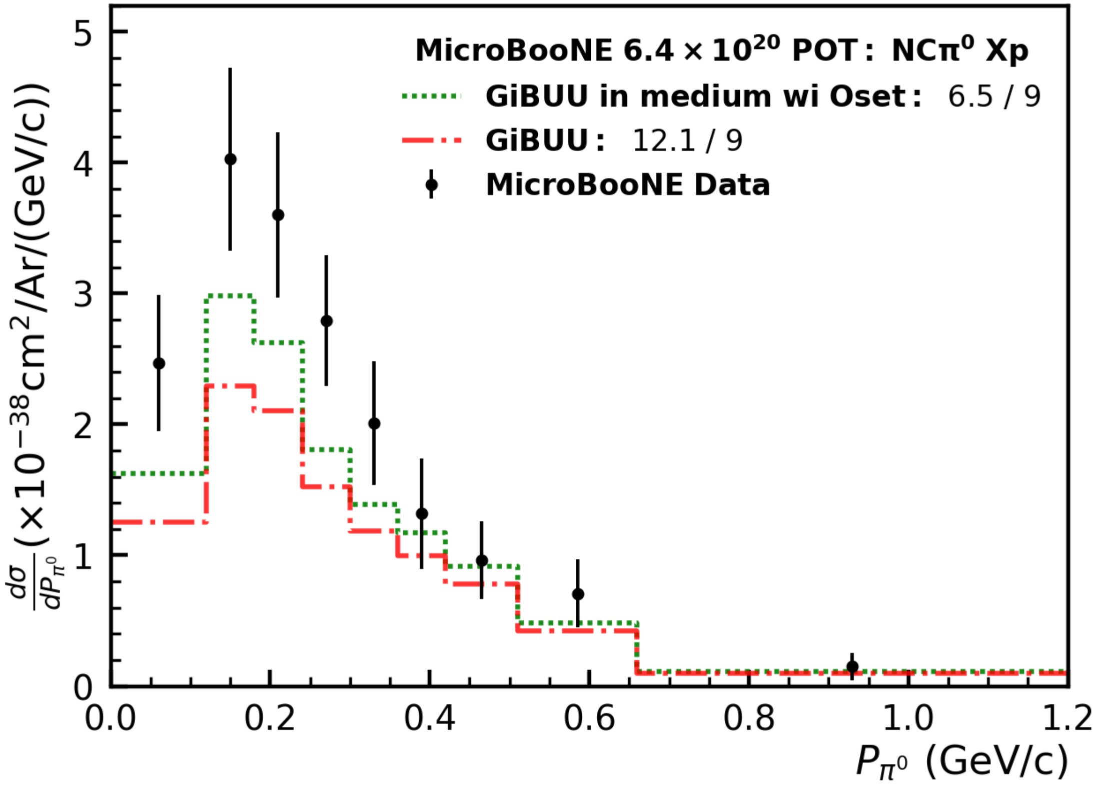
- Density dependent suppression of the NN→ΔN cross section is often used in transport codes to account for medium modifications and better reproduce pion multiplicity in heavy ion-collisions.

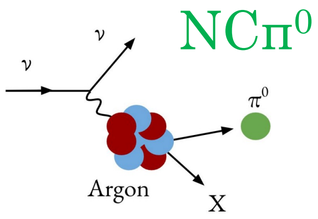
- Successful phenomenologically and produces similar results as more "theory driven" suppressions.
  - ie: Using GiBUU, Phys.Rev.C 109 5, 054901 (2024) shows the exponential suppression (green) produces similar results to a prediction with effective Dirac masses modified Δ- coupling to scalar and vector mean-fields (red).



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.
  - Increases pion production rather than suppresses it, the Δs are "already there" following the neutrino induced ℓN→ ℓΔ reaction.
- Better agreement with data, but still some underprediction of the cross section.

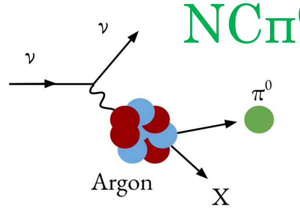




Comparison with Experiment: NCπ^0 Data

- Oset collision broadening increases the Δ width as a function of momentum and density.
  - Additional decay channels beyond Δ→Nπ which open in-medium increase the width.
  - Net effect in neutrino scattering is increased Δ absorption.

NCπ^0



Δ
+N→NNπ
→Nπ
+N→NN
+NN→NNN

$$\sigma_{1p1h\,1\pi} = \sigma_R \frac{\Gamma_\pi}{\Gamma_{\text{tot}}} + \sigma_{\text{BG}}$$

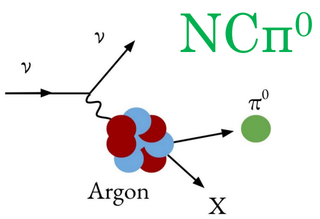
$$\Gamma_{tot}^{med} = \tilde{\Gamma} + \Gamma_{coll}$$

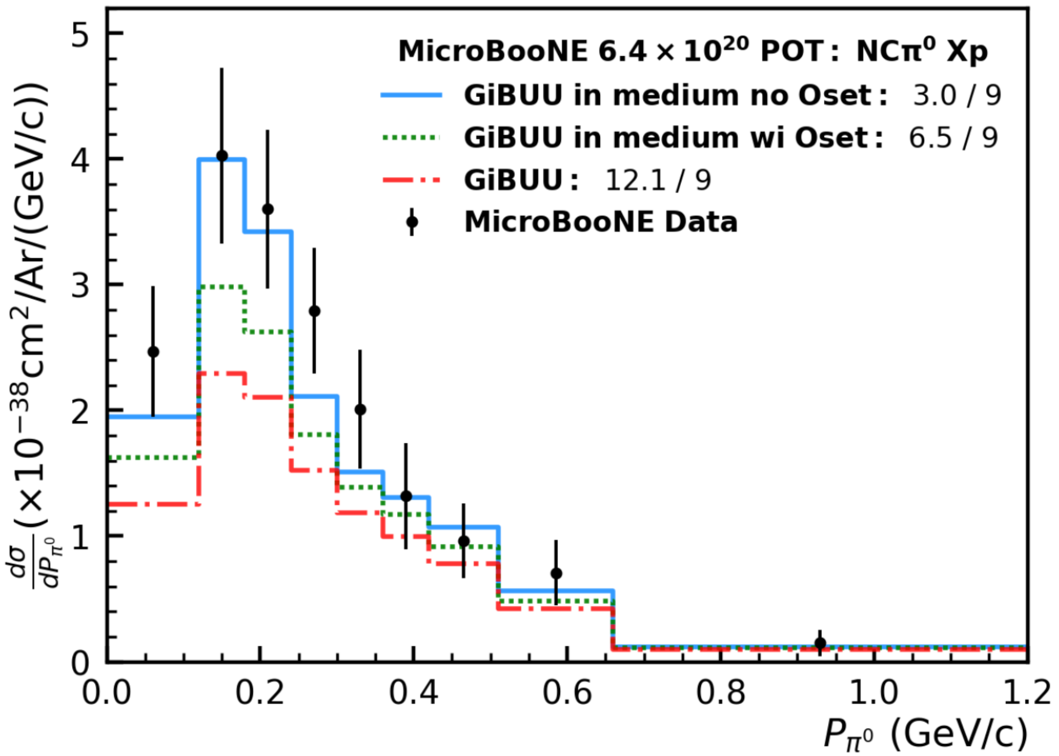
Incorporating Oset broadening requires some extrapolation in this context, can view the difference between predictions with and without this effect as a "theoretical uncertainty".

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

- Oset collision broadening increases the Δ width as a function of momentum and density.
  - Additional decay channels beyond Δ→Nπ which open in-medium increase the width.
  - Net effect in neutrino scattering is increased Δ absorption.
- Removing Oset Δ broadening further increases the cross section.
- The prediction without Oset is slightly favored.
  - However, this could be an artifact of a lack of coherent pion production in GiBUU.





$$\sigma_{1p1h\,1\pi} = \sigma_R \frac{\Gamma_\pi}{\Gamma_{\rm tot}} + \sigma_{\rm BG}$$

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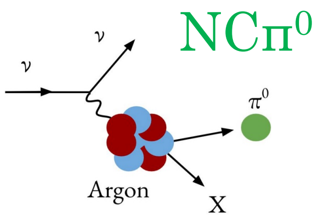
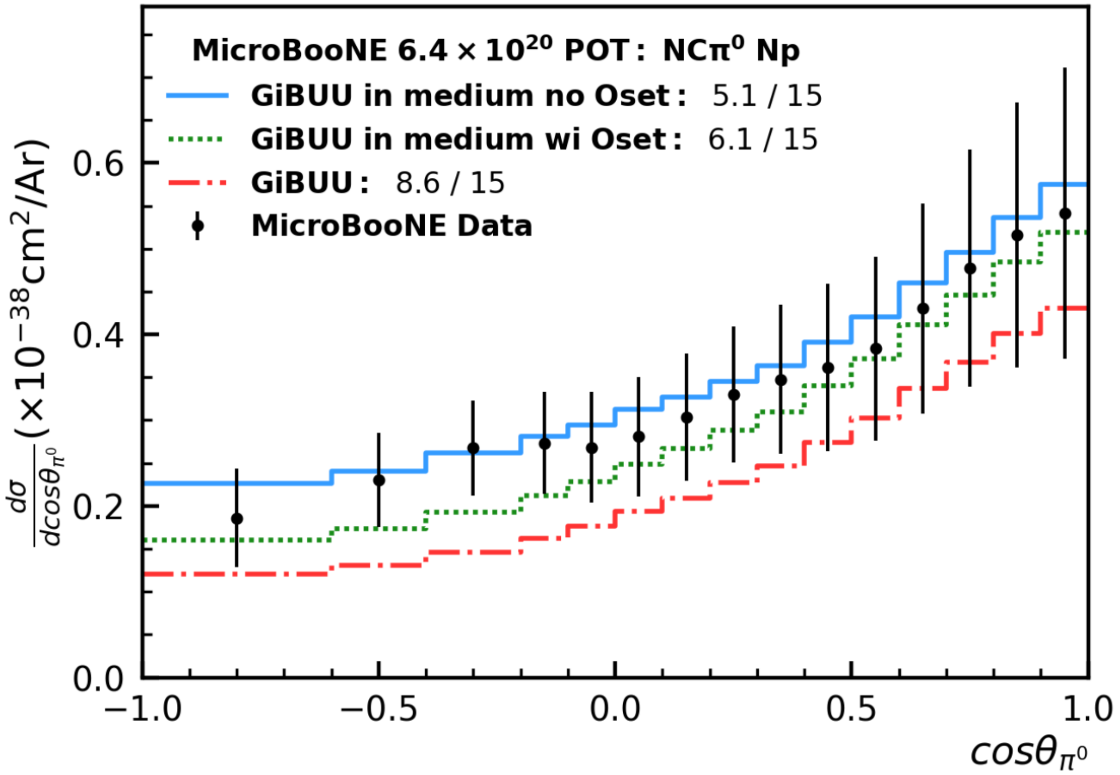
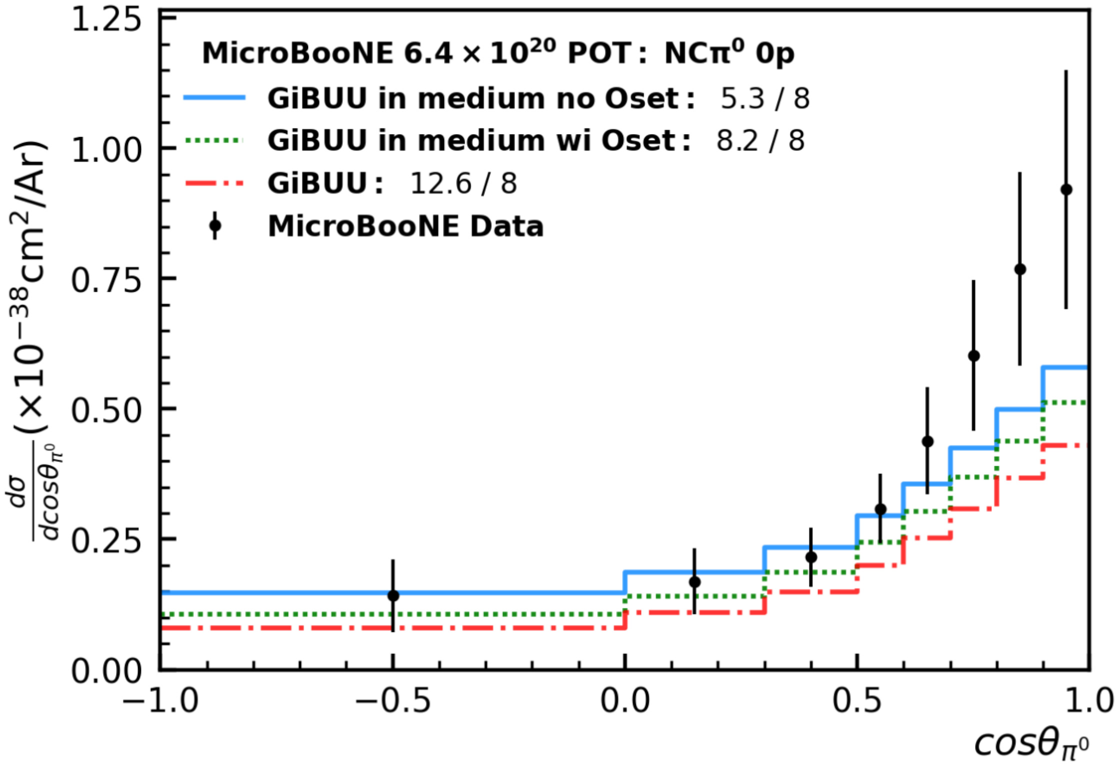


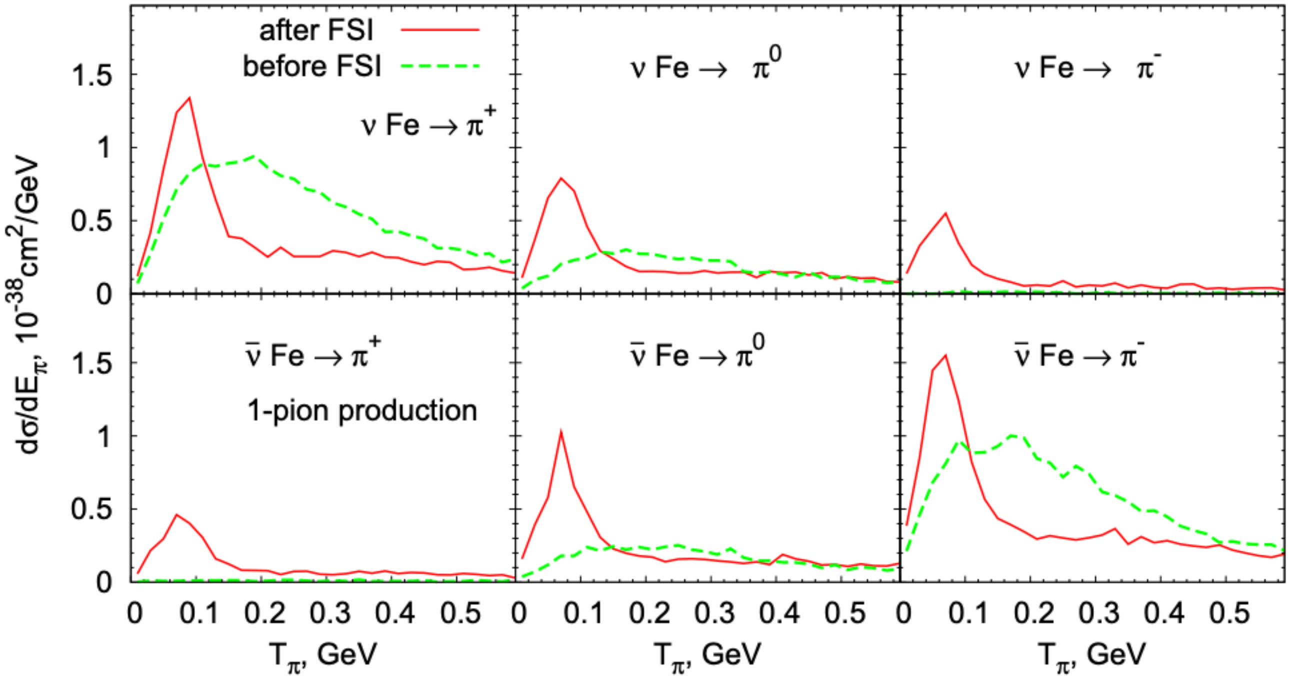
- In-medium modification improve agreement in both the 0p and Np channels.
- Predictions with and without Oset fall within the uncertainties of the data except at forward scattering angles for the 0p channel.
  - Coherent pion production's primary contribution is in this region of phase space.





Studying FSI: Pion Observables

- The same physics may impact various observables in different ways.
  - Charge exchange FSI depletes the NCpi0 channel (dominate NC production mode).
  - Charge exchange FSI feeds CCπ^0 channel (in CC, π$^+$ dominates, more charge exchange in than out).
  - This contrasts suppression of the ΔN→ NN cross section, which increases production in both channels.
- Pion production channels are all connected through FSI and examining multiple channels can shed further light.



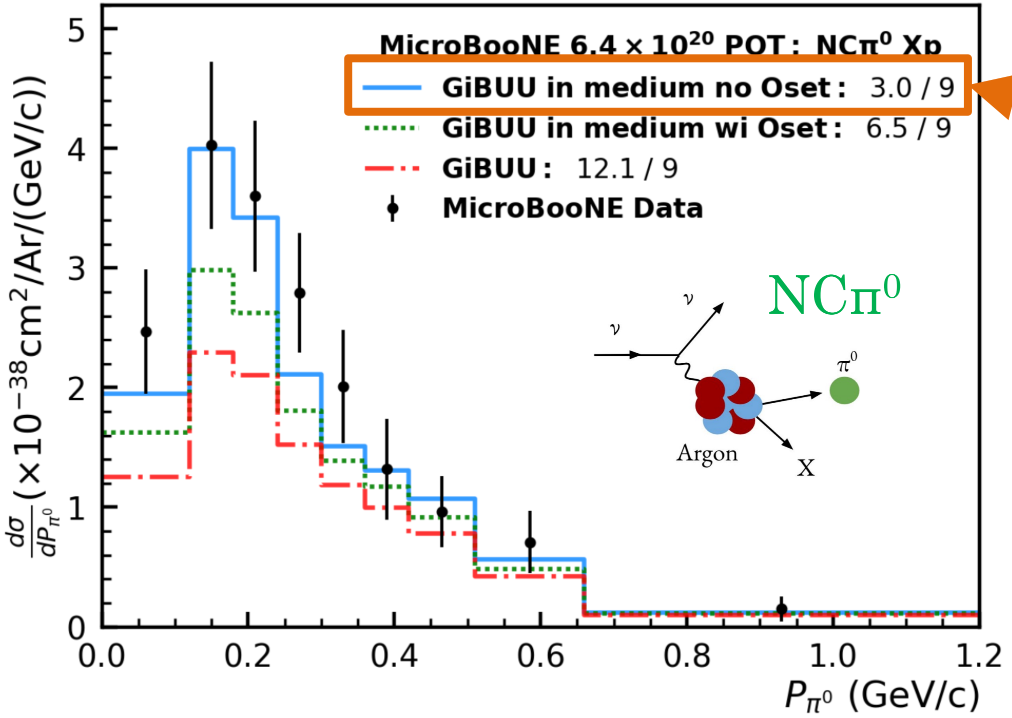
J. Phys.: Conf. Ser. **408** 012053 (2013)

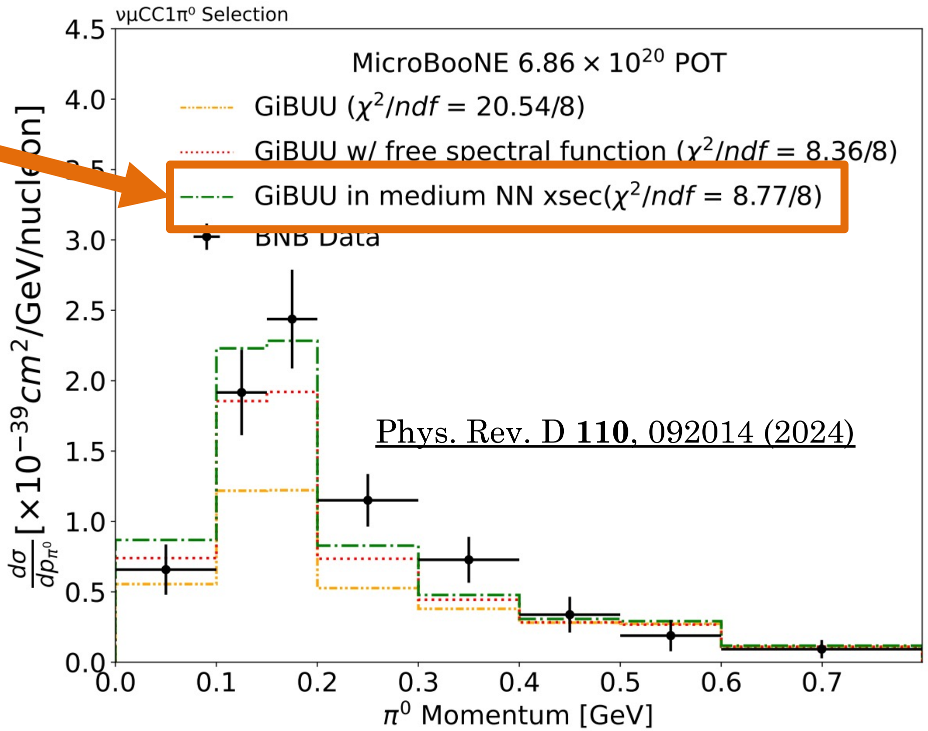
	ν	$\bar{\nu}$
CC	$\nu p \to \mu^- p \pi^+$	$\bar{\nu} n \to \mu^+ n \pi^-$
	$\nu n \to \mu^- p \pi^0$	$\bar{\nu} p \to \mu^+ n \pi^0$
	$\nu n \to \mu^- n \pi^+$	$\bar{\nu} p \to \mu^+ p \pi^-$
NC	$\nu p \to \nu p \pi^0$	$\bar{\nu} p \to \bar{\nu} p \pi^0$
	$\nu p \to \nu n \pi^+$	$\bar{\nu} p \to \bar{\nu} n \pi^+$
	$\nu n \to \nu n \pi^0$	$\bar{\nu} n \to \bar{\nu} n \pi^0$
	$\nu n \to \nu p \pi^-$	$\bar{\nu} n \to \bar{\nu} p \pi^-$

Learning from MicroBooNE NCπ^0 and CCπ^0 data

- Another recent MicroBooNE analysis featuring the CCπ^0 channel includes comparisons to GiBUU predictions with and without the in-medium modifications.

- Similar trends are observed:
  - Nominal predictions underestimate the data.
  - In-medium modification improve agreement with experiment.

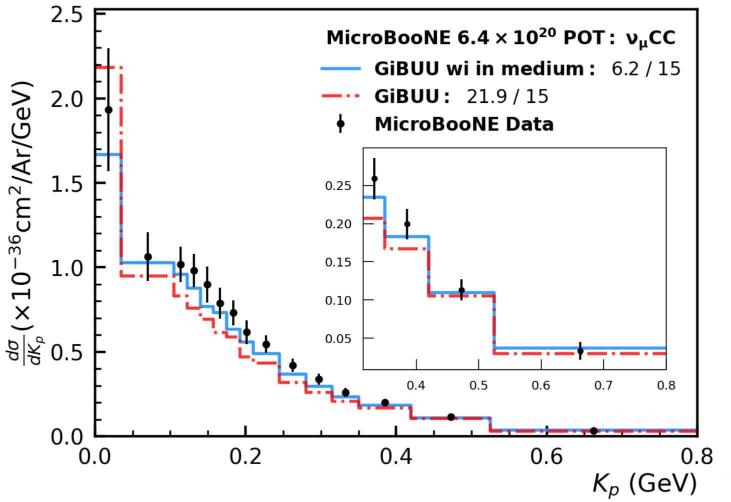


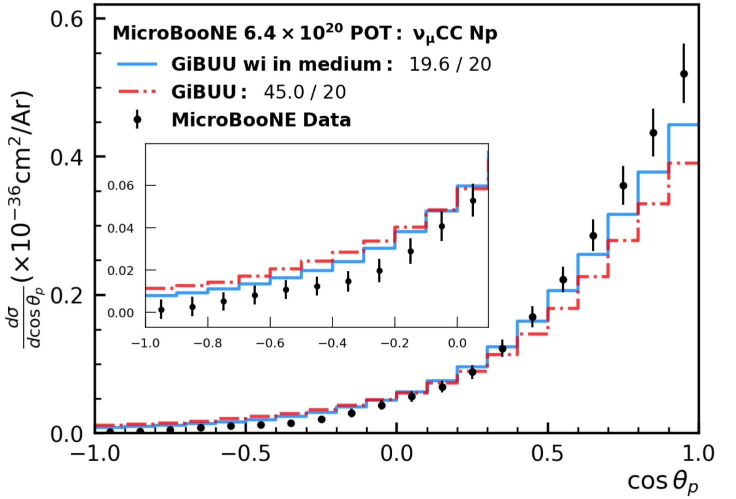


Phys. Rev. D **110**, 092014 (2024)

Summary and Conclusions

- Using GiBUU, we have shown that MicroBooNE neutrino-argon scattering data are sensitive to in-medium modifications of NN cross sections.
- Accounting for these modifications is necessary for a satisfactory description of the data.
  - In-medium lowering of the NN cross sections better reproduces the proton and π^0 spectra.
- Exemplifies how neutrino scattering data can be used to benchmark and improve the event generators which will be used in current and future experimental efforts.





For more details, see Phys. Rev. C 110, 044001 (2024)

Thank you for your Attention!

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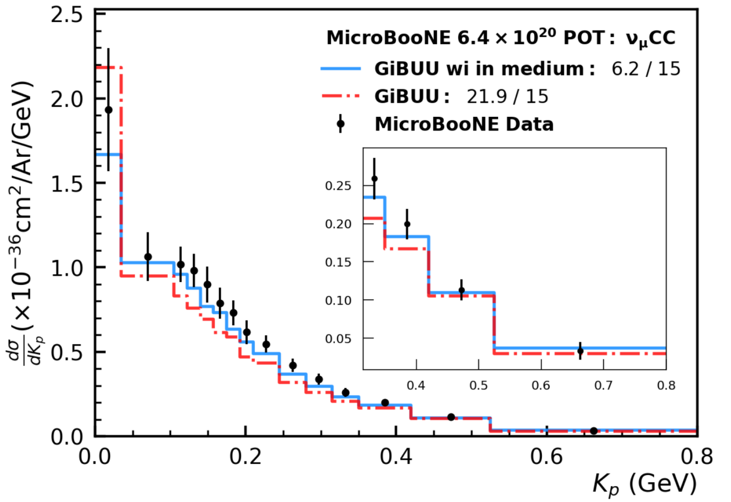
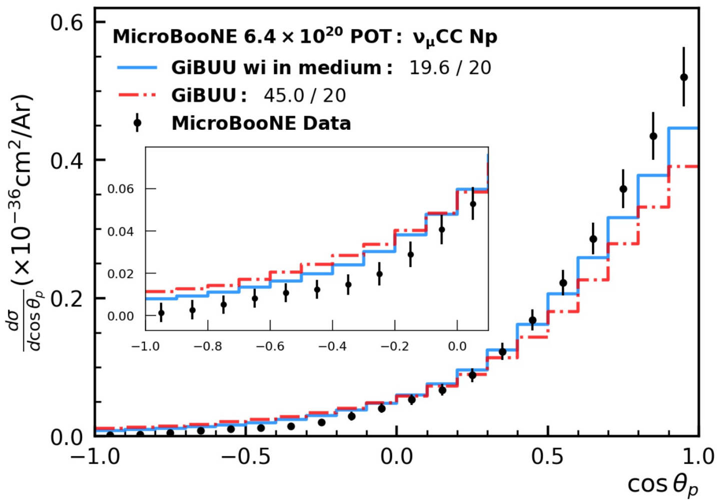




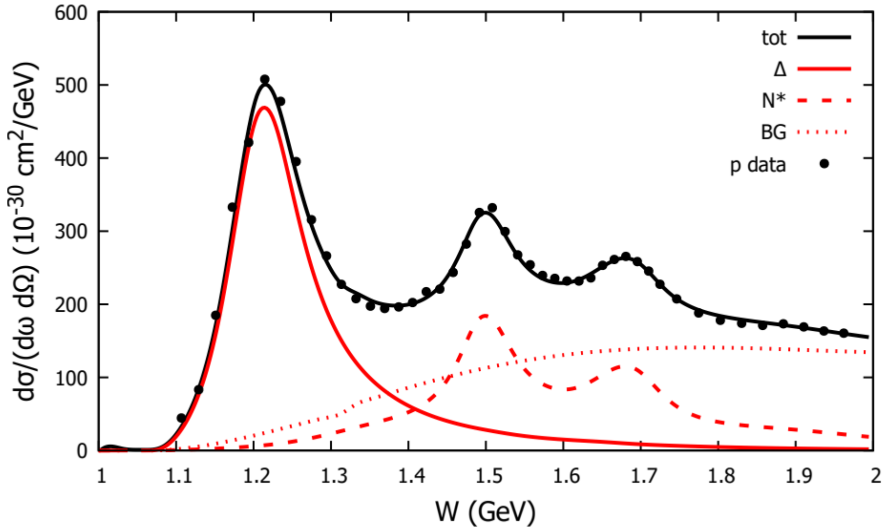
For more details, see Phys. Rev. C 110, 044001 (2024)

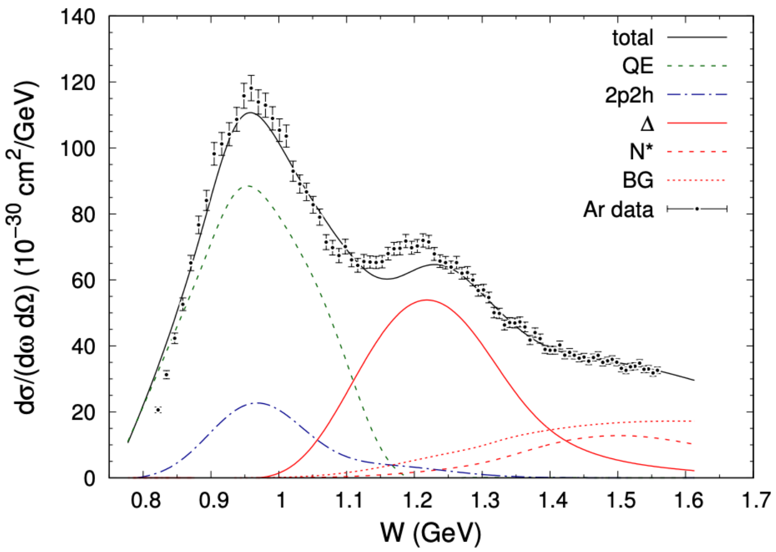
Special thank you to Ulrich Mosel and the MicroBooNE collaboration!

Neutrinos in GiBUU: ISI

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

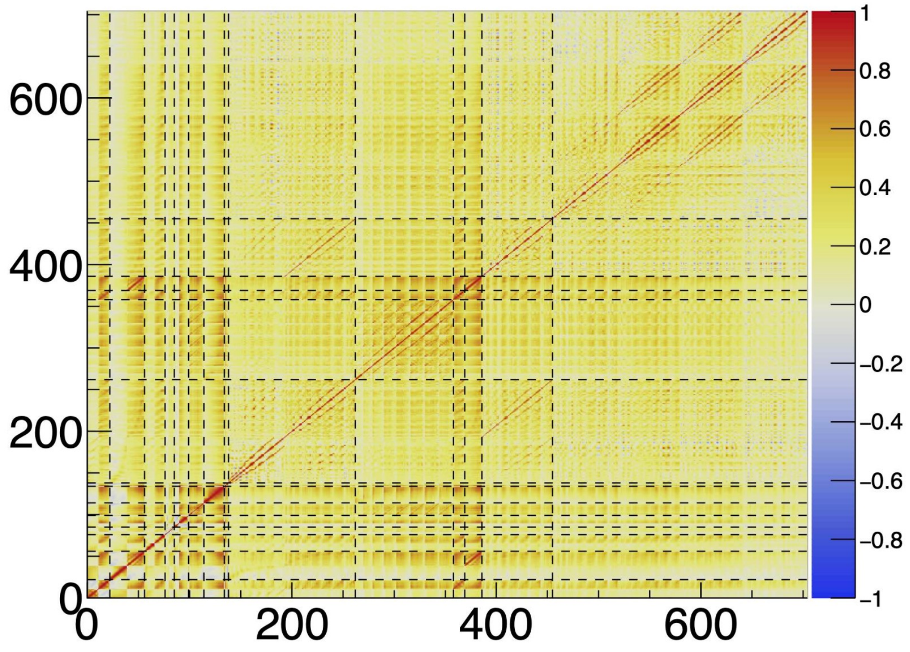
- QE scattering is modelled within the impulse approximation and an axial dipole form factor according to the theory described in Phys. Rev. C **73**, 065502 (2006).
- RES uses vector couplings from MAID2007 and the axial couplings are obtained from PCAC with dipole form factors fit to deuterium bubble chamber data.
- Meson exchange current (MEC, aka 2p2h) contribution is from a fit to electron data.
  - Covers the "dip" between the QE peak and Delta resonance excitation.
- Able to describe electron scattering well.





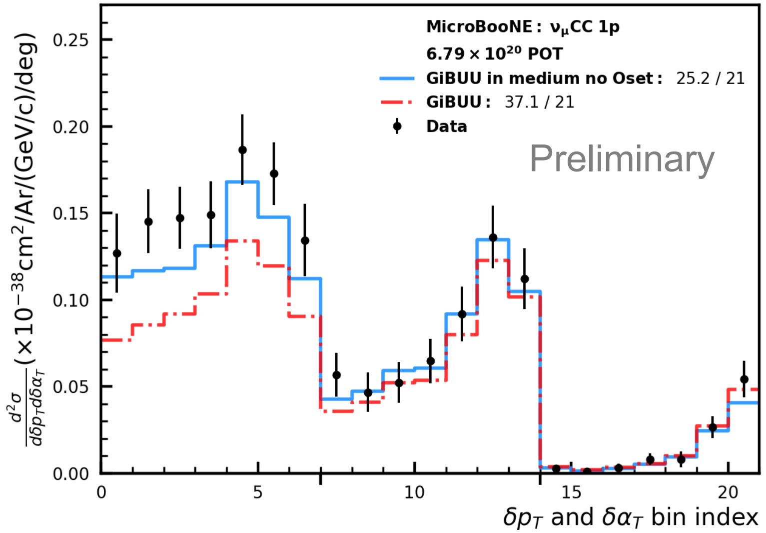
Comparison with Experiment: Global Comparisons

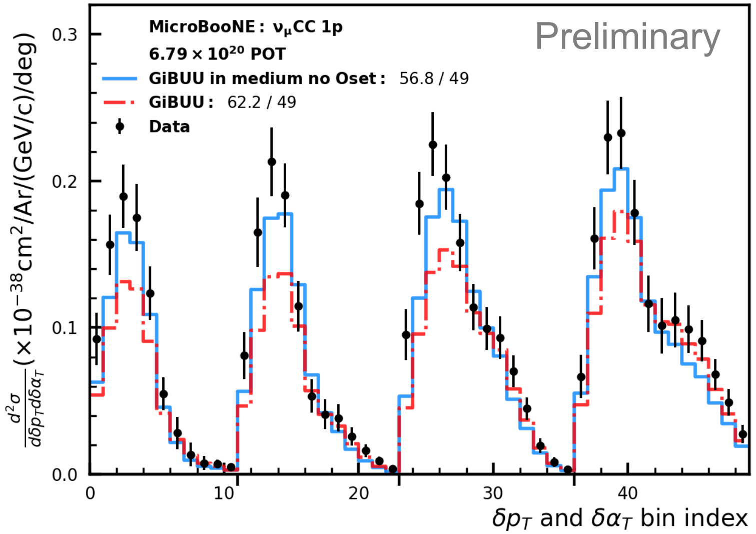
- For the ν_μCC data, NN modifications improves the χ^2/ndf from **1064 / 704** to **795 / 704**.
  - For the proton spectra and multiplicity, the improvement is **70 / 39** to **25 / 39**.
  - The χ^2/ndf calculated for the entire set of NCπ^0 results is less sensitive and only reduces from 43 / 78 to 32 / 78.

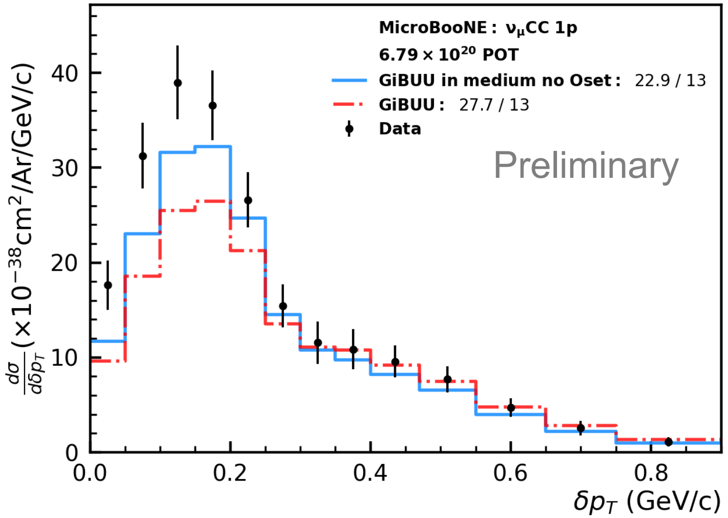


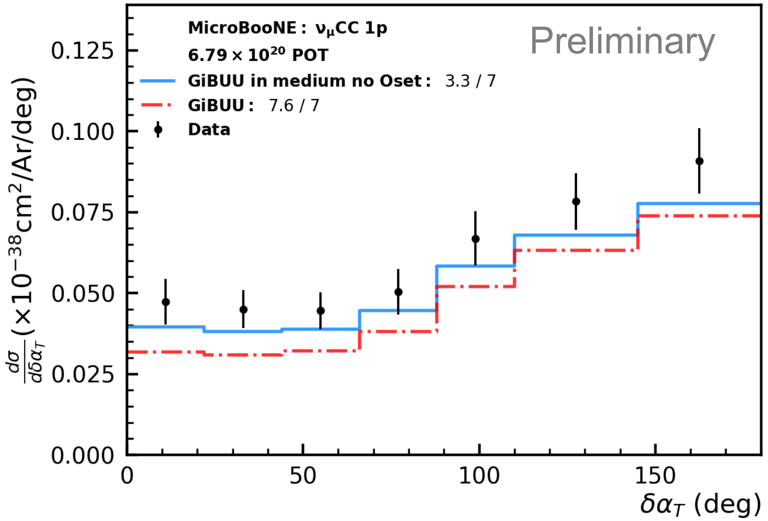
Correlation matrix including all measurement bins reported by Phys. Rev. D 110, 013006 (2024).

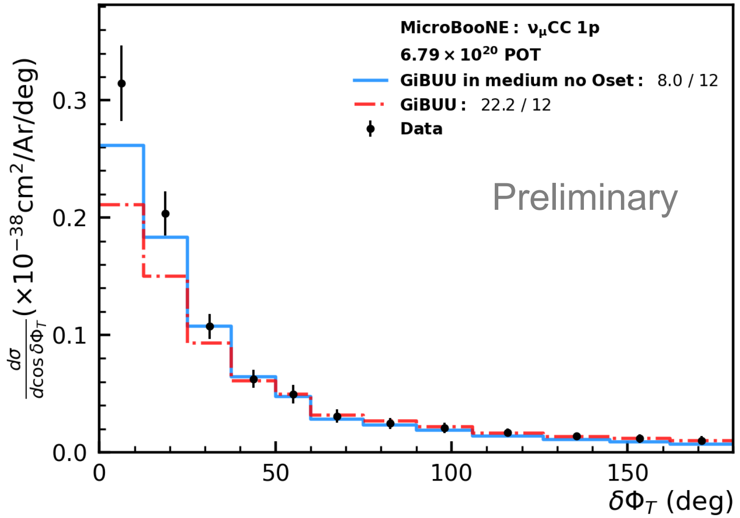
Bonus Material











- In-medium modifications improves the description of TKI variables reported in MicroBooNE's quasielastic-like data from Phys. Rev. Lett. 131, 101802 (2023) and Phys. Rev. D **108**, 053002 (2023).
- Seen for both single and double-differential measurements and in individual slices of phase-space.

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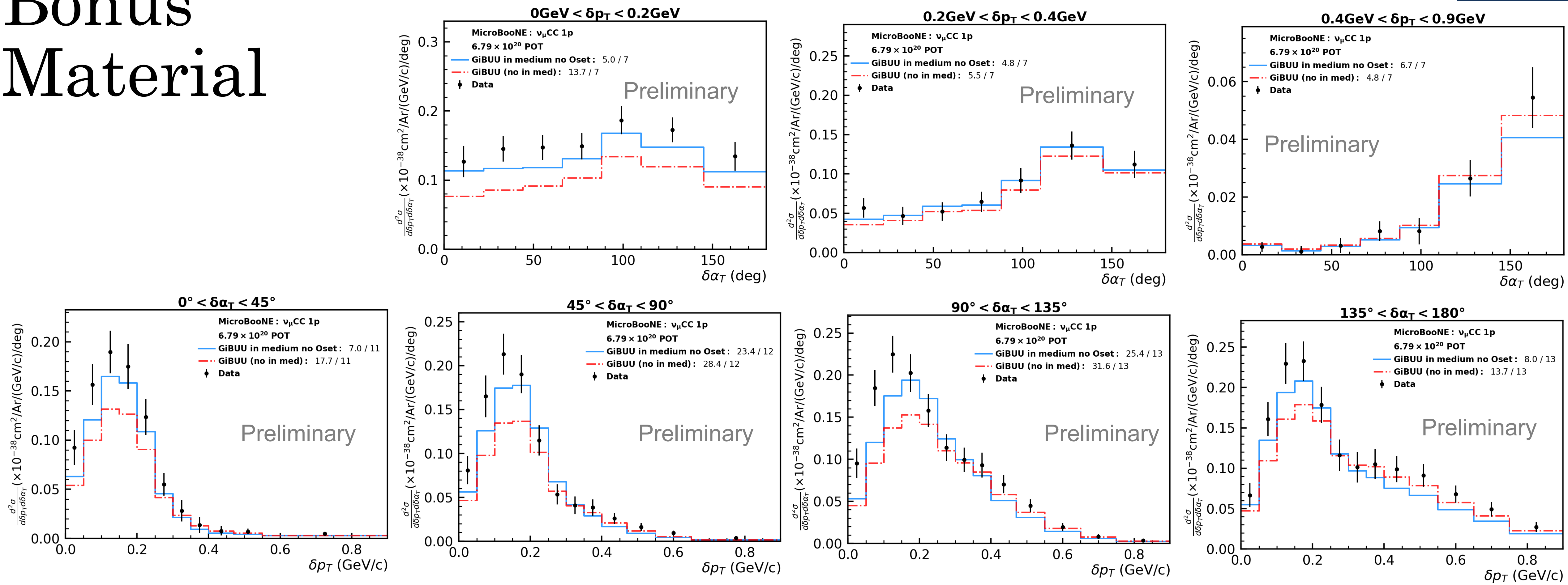

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Li and Machleidt Calculation

- Li and Machleidt calculation based on Bonn meson-exchange model for the NN interaction and the Dirac-Brueckner approach for nuclear matter.
  - The Bonn potential treats conventional hadrons as the relevant degrees of freedom.
  - Nucleon propagator is "dressed" to account for its effective interactions with other nucleons.
- Three effects reduce the cross section.
  - Pauli blocking of intermediate states.
    - Distinct from Pauli blocking of final states, which is accounted for in GiBUU's transport model rather than the calculation of the in-medium cross sections.
  - Nucleon mean field reduces the mass of the nucleon.
  - Potential is evaluated by using the in-medium Dirac spinors of instead of the free ones.
    - Leads to a suppression of the attractive σ exchange.

$$R(\mathbf{q}',\mathbf{q}) = V(\mathbf{q}',\mathbf{q}) + \mathcal{P}\int \frac{d^3k}{(2\pi)^3} V(\mathbf{q}',\mathbf{k}) \frac{m^2}{E_k^2} \frac{1}{2E_q - 2E_k} R(\mathbf{k},\mathbf{q})$$

Free

$$\tilde{G}(\mathbf{q}',\mathbf{q}|\mathbf{P},\tilde{z}) = \tilde{V}(\mathbf{q}',\mathbf{q}) + \mathcal{P}\int \frac{d^3k}{(2\pi)^3} \tilde{V}(\mathbf{q}',\mathbf{k}) \frac{\tilde{m}^2}{\tilde{E}^2_{(1/2)\mathbf{P}+\mathbf{k}}} \frac{Q(\mathbf{k},\mathbf{P})}{\tilde{z} - 2\tilde{E}_{(1/2)\mathbf{P}+\mathbf{k}}} \tilde{G}(\mathbf{k},\mathbf{q}|\mathbf{P},\tilde{z})$$

$$\tilde{m} = m + U_S$$

$$\tilde{E}_k = (\tilde{m}^2 + \mathbf{k}^2)^{1/2}$$

In-med

G (R) matrix describing the effective in-medium (free) interaction

Phys. Rev. C 49, 566 (1994) Phys. Rev. C 48, 1702 (1993)