Muon Neutrino Cross Section measurements from MicroBooNE:
a detailed examination of muon neutrino-argon scattering.

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BNL Seminar

October 10th, 2024

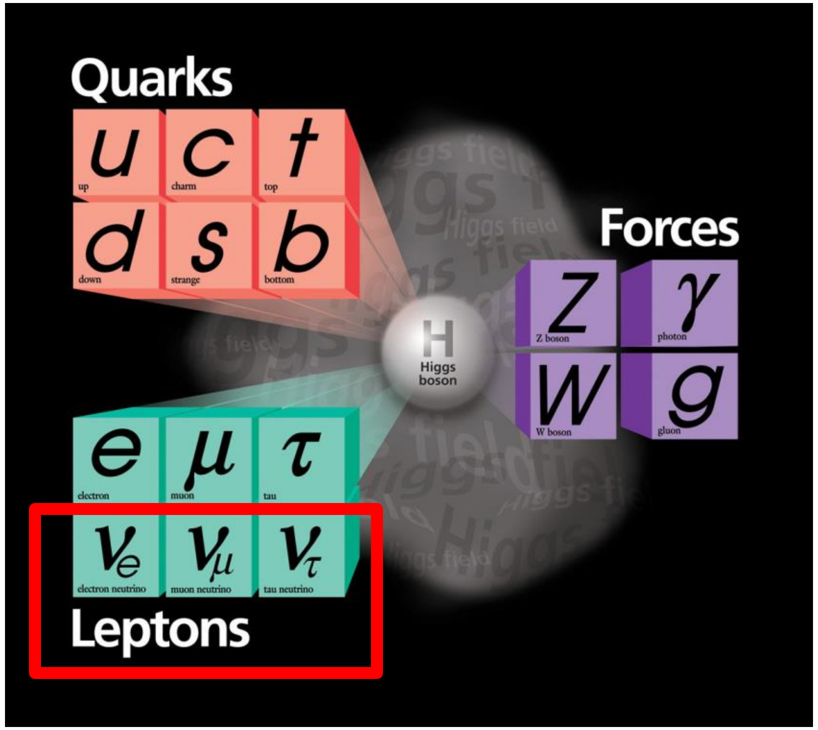
Overview

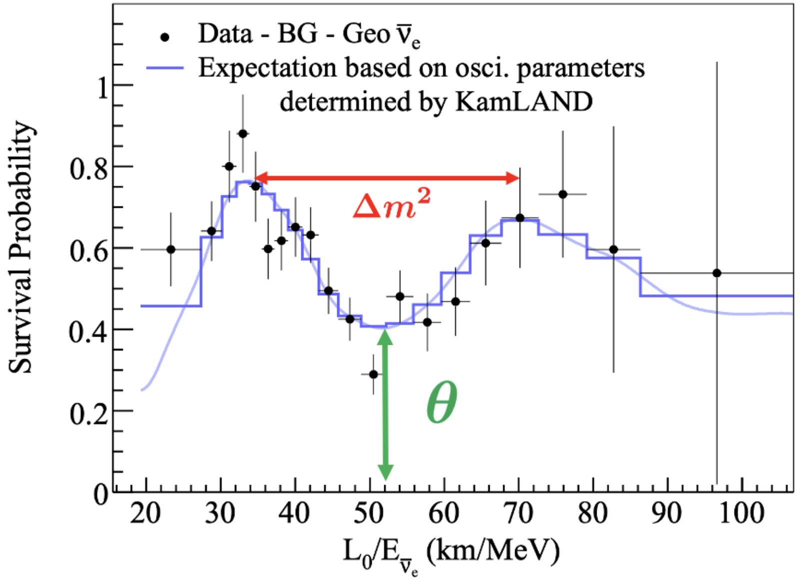
- Neutrinos, oscillations and experimental goals in the neutrino sector.
- Measuring neutrino interaction cross sections with MicroBooNE.
- Recent MicroBooNE results for muon-neutrino scattering on argon.

The MicroBooNE Collaboration

Neutrinos

- Neutrinos are abundant but challenging to study because they rarely interact.
  - Trillions are passing through your body every second.
  - Only interact via the weak force.
- They come in three flavors, one for each charged lepton.
  - Electron, muon and tau.
- Neutrinos oscillate between flavors.
  - Oscillation probability is a function of the energy of the neutrino and the propagation distance.





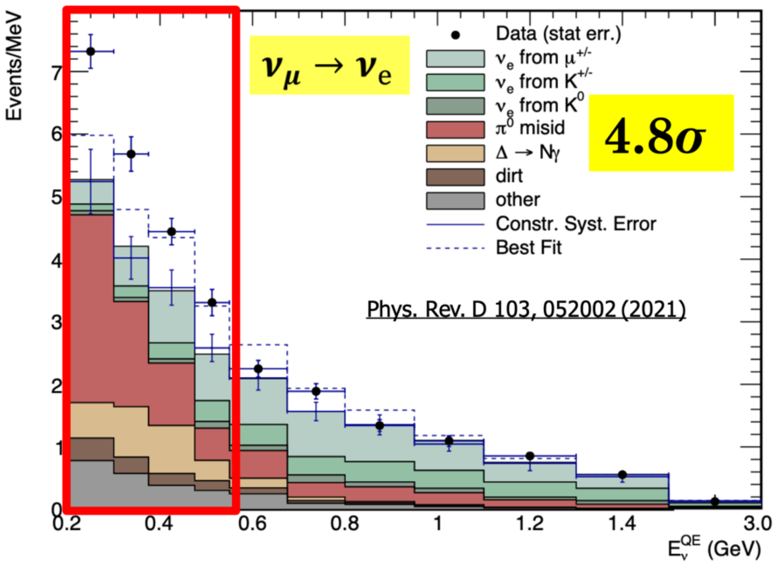
$$\theta_{12} = 33.4 \pm 0.8$$
$$\theta_{13} = 49.2 \pm 1.3$$
$$\theta_{23} = 8.57 \pm 0.13$$

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

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

Mysteries in the Neutrino Sector

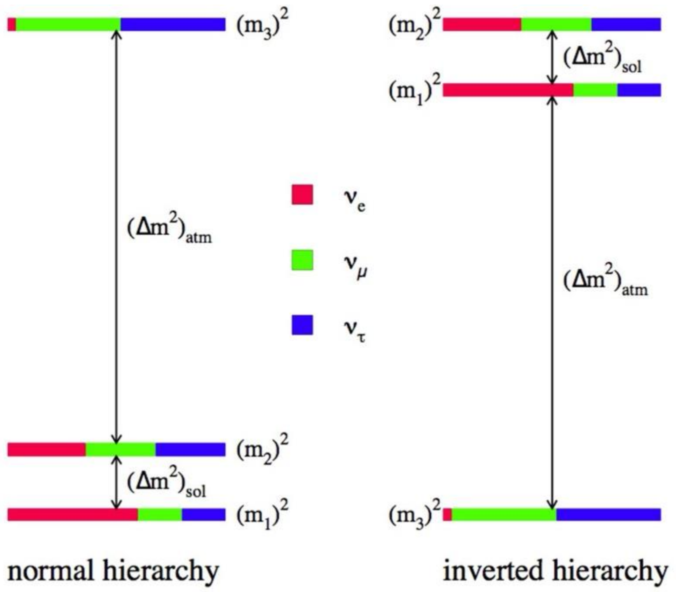
Is there a fourth neutrino?



Several experiments suggest the existence of an eV scale neutrino.

Z boson decay width indicates this new neutrino would be **sterile**; no weak interactions. Only detectable through its effects on oscillations.

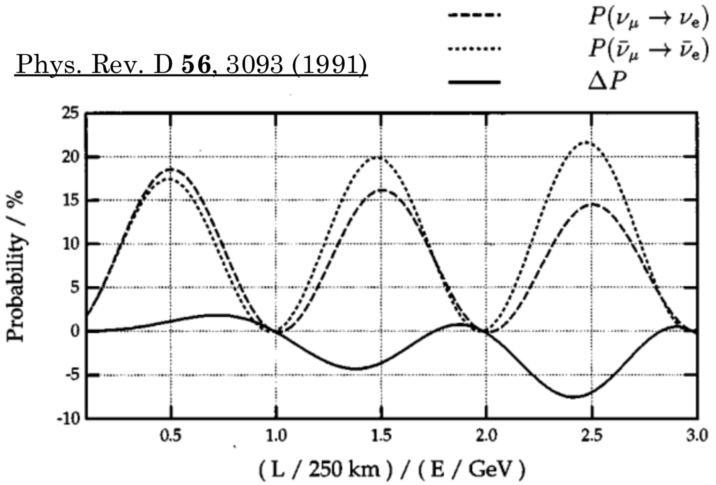
Which neutrino is the heaviest?



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

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

Do anti-neutrinos behave differently than neutrinos?



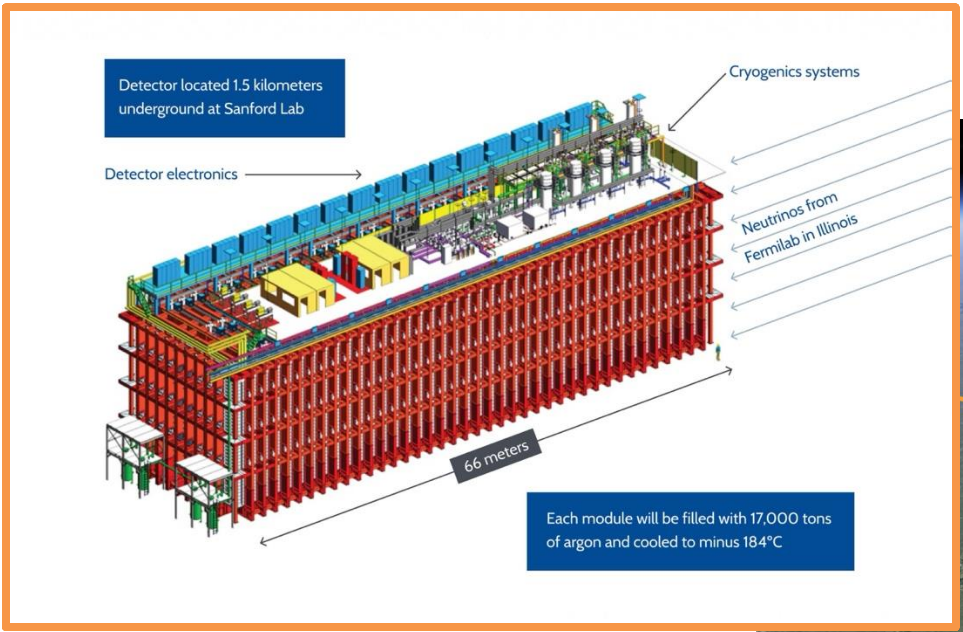
The PMNS matrix has a phase that allows neutrinos and anti-neutrinos to behave differently.

We are yet to make a definitive measurement of this CP violating phase.

$$P[\nu_\mu \to \nu_e] \neq P[\bar{\nu}_\mu \to \bar{\nu}_e]\ ?$$

DUNE

- Immanent long baseline experiments are aiming for a definitive measurement of the CP violating phase and determination of the neutrino mass hierarchy.
- DUNE is the flagship long baseline experiment in the United States
  - Neutrinos are produced in Illinois and are observed in South Dakota from one mile underground.
  - Will be the largest liquid argon time projection chamber (LArTPC) detector ever constructed.
  - Begins collecting neutrino beam data in the early 2030s.

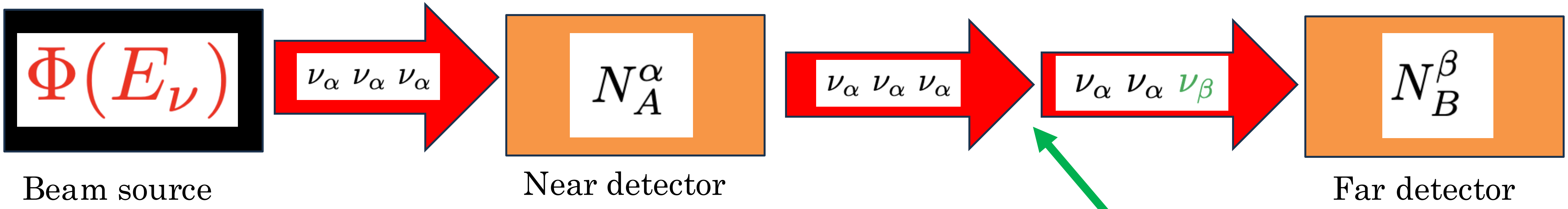


Measuring Oscillation

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

Measuring neutrino oscillations are easy:

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



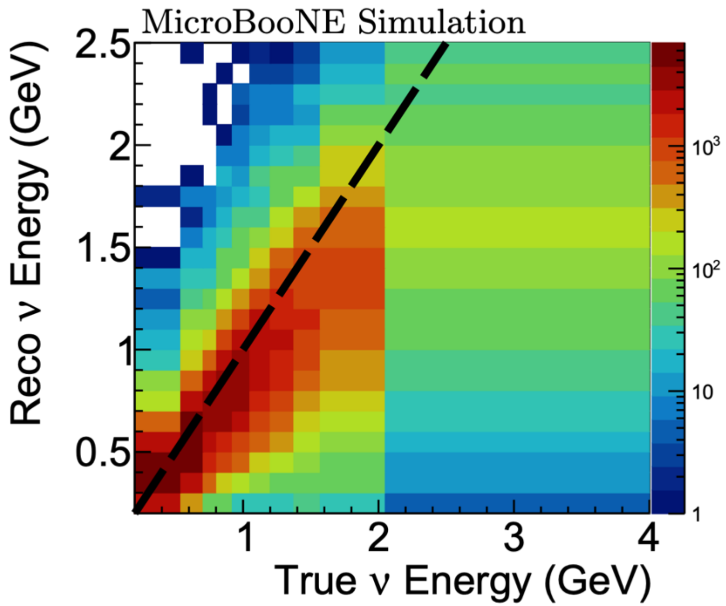
Oscillation probability (what we are interested in)

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

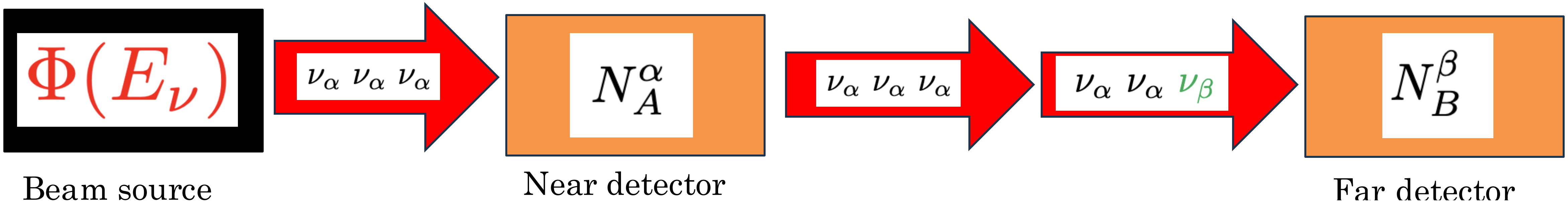
$$N_B^\beta \sim \Phi_B(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_B(E_\nu)\ P(\nu_\alpha \rightarrow \nu_\beta)$$

Measuring Oscillation: Challenges

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



- Neutrino oscillations depend on the energy of the neutrino.
- BUT, we do not know the incoming neutrino's energy, this needs to be reconstructed from observed final state particles.
- **Necessitates detailed flux, detector and cross section models!**
  - An incorrect model can bias measurements of oscillation parameters.



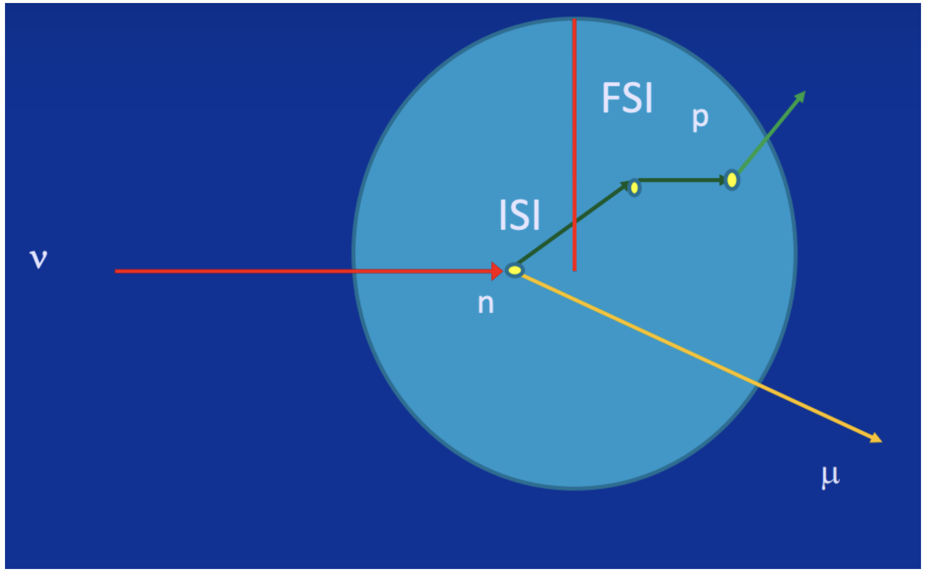
$$N_A^\alpha \sim \Phi_A(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_A(E_\nu)$$

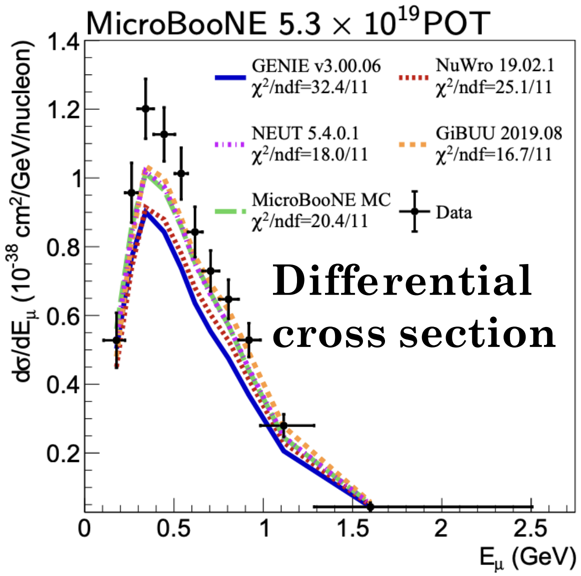
$$N_B^\beta \sim \Phi_B(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_B(E_\nu)\ P(\nu_\alpha \to \nu_\beta)$$

The cross section part is the subject of today's talk

Cross Sections

- Cross sections are the "effective size" of a particle. They tell you how likely it is to interact.
- Complexity increases as you go from point like scattering, to scattering off a nucleon, to scattering off a nucleus (or a nucleon bound within 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.



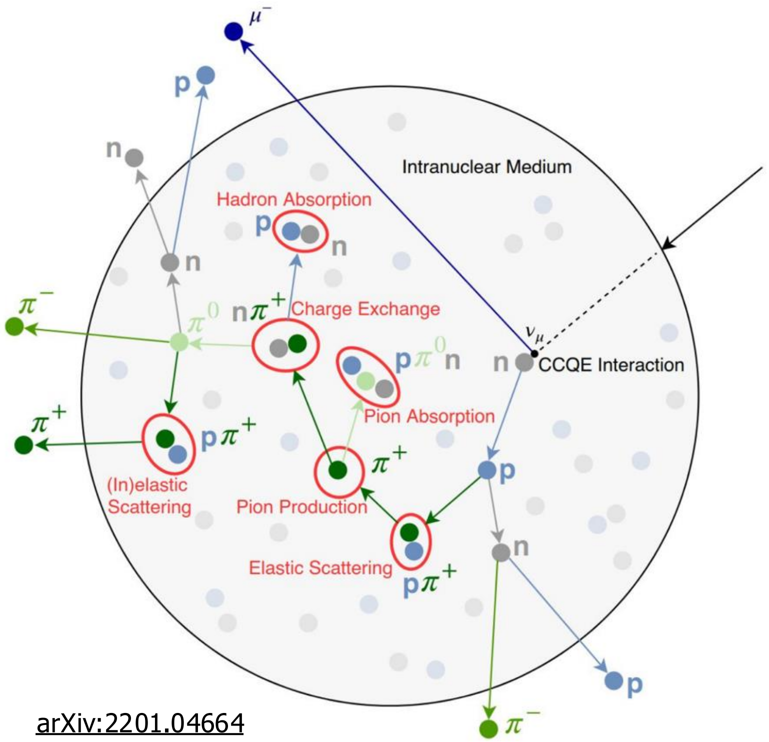


Phys. Rev. Lett. **128**, 151801 (2022)

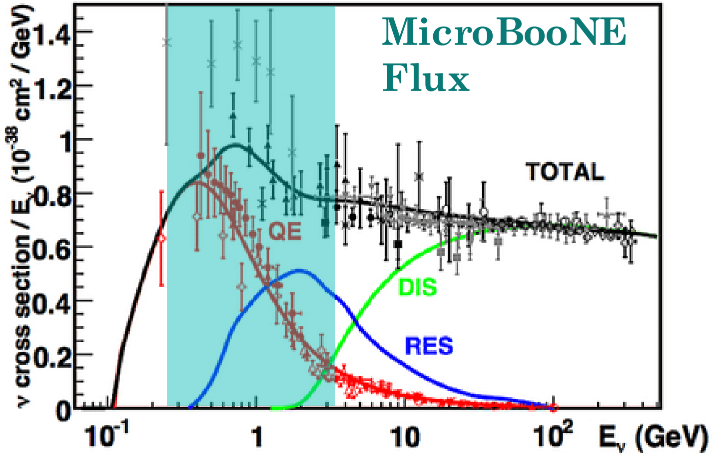
Neutrino-Nucleus Cross Section Models

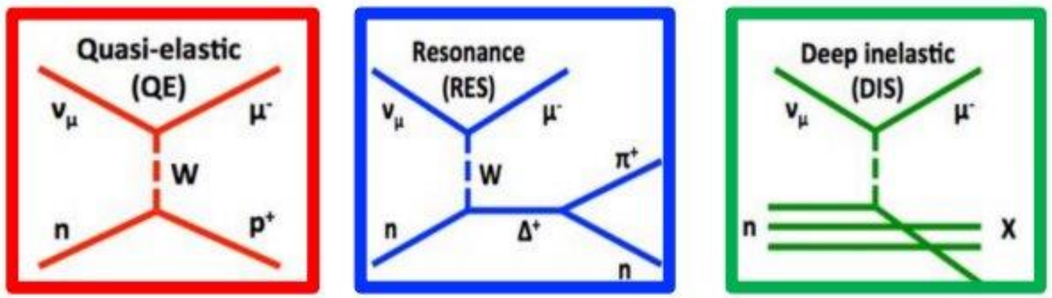
A neutrino-nucleus cross section model must:

- Predict the full final state.
  - All particles must be accounted for energy reconstruction.
- Incorporate a variety of interaction channels:
  - Quasi-Elastic (QE)
  - Resonance Production (RES)
  - Deep Inelastic Scattering (DIS)
- Account for complicated nuclear effects:
  - nuclear modification to the initial interaction.
  - final state interactions (FSI).



arXiv:2201.04664





Scattering off single nucleon

Inelastic scattering: Excites the nucleon

Breaks up nucleon

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

Neutrino Event Generators

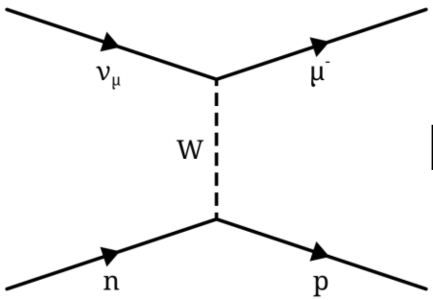
- Event generators combine models for different interaction modes along with a simulation of nuclear effects to produce a prediction.
- Different generator predict different efficiencies and mappings between reconstructed and true neutrino energy.
- No current generator can describe all data with sufficient accuracy!
- **More cross section data is required to drive improvements to event generators.**

NuWro

GENIE

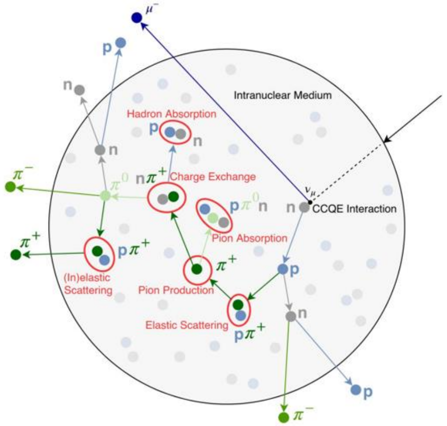
GiBUU

NEUT



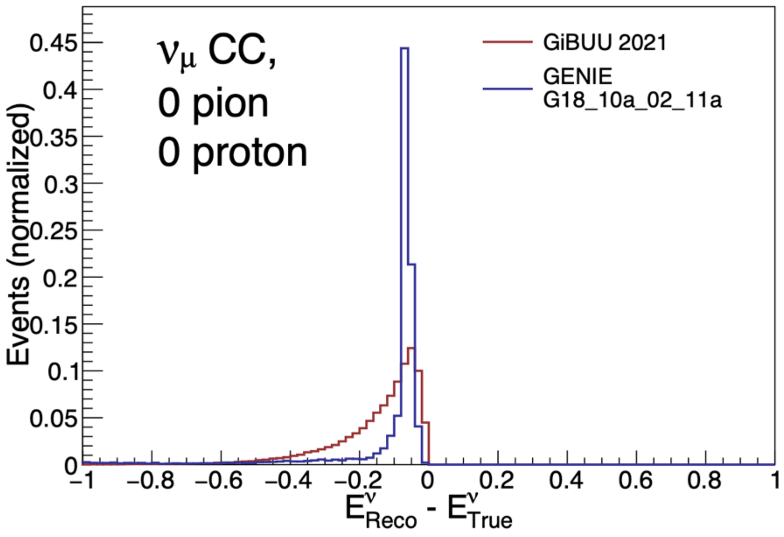
Nucleon level

+



Nuclear effects

=



Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where is can detect a lot of neutrinos.
2. Reconstruct the neutrino interaction events from your raw data.
3. Select the events with the type of interaction you want to measure.
4. Quantify your uncertainties and extract the cross section from the events you selected.
5. Report your great measurement and learn lots of new physics.
6. Improve the event generator modeling.

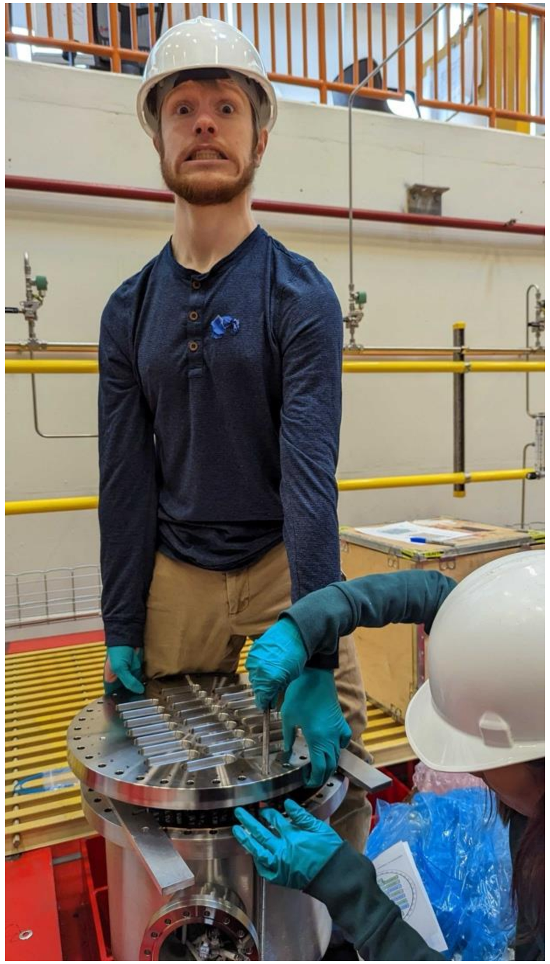
Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where is can detect a lot of neutrinos.

Luckily, building a device to detect neutrinos is really easy…

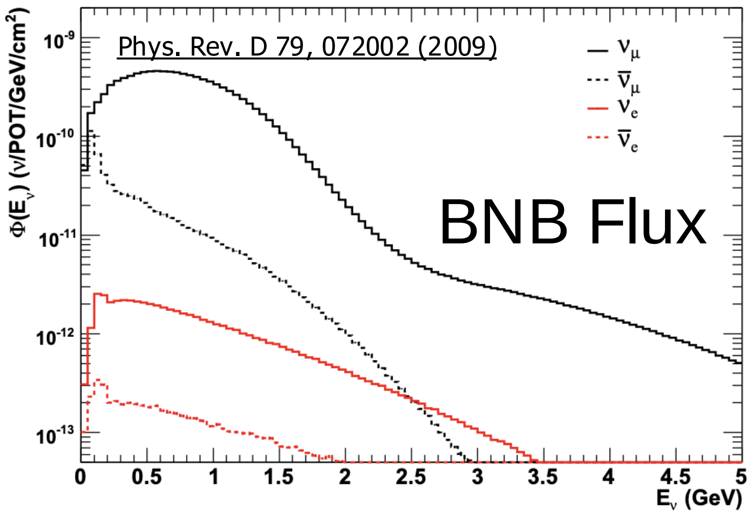
I have done a terrible thing: I have postulated a particle that cannot be detected. After postulating the existence of the neutrino, a particle with no mass and no electric charge, in order to balance an equation.

-Wolfgang Pauli



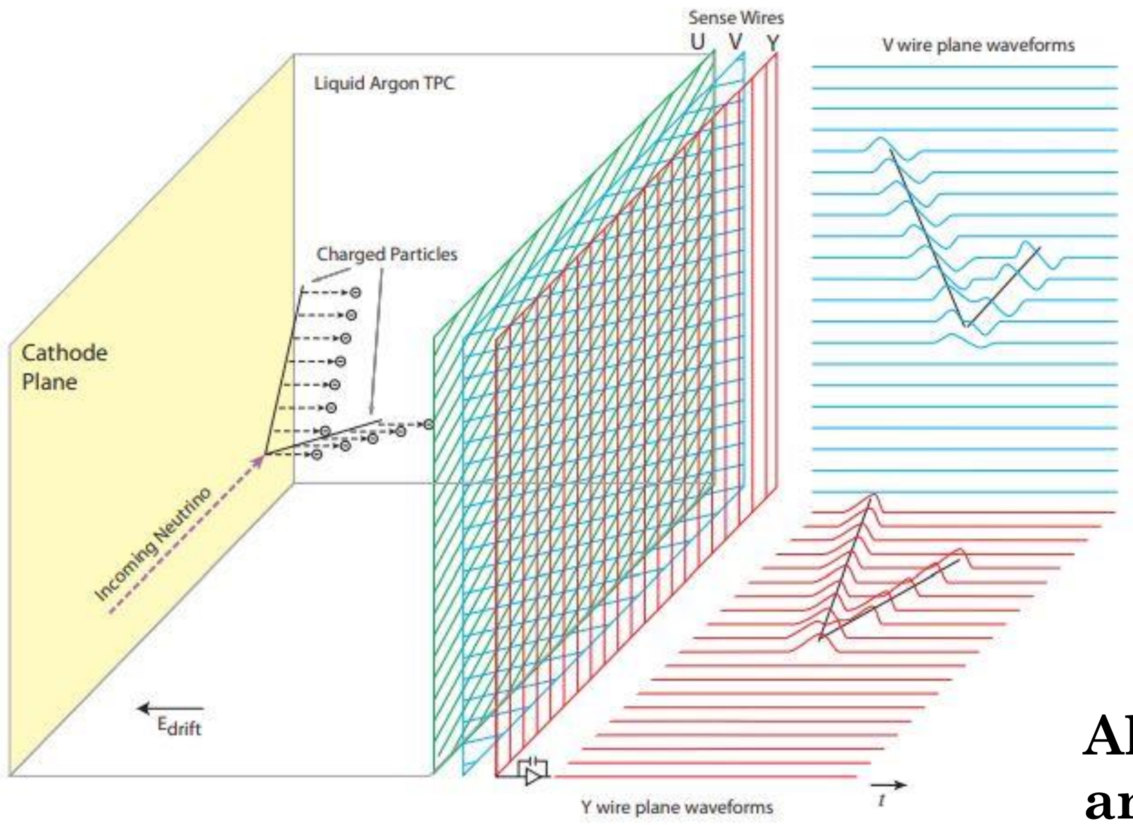
MicroBooNE

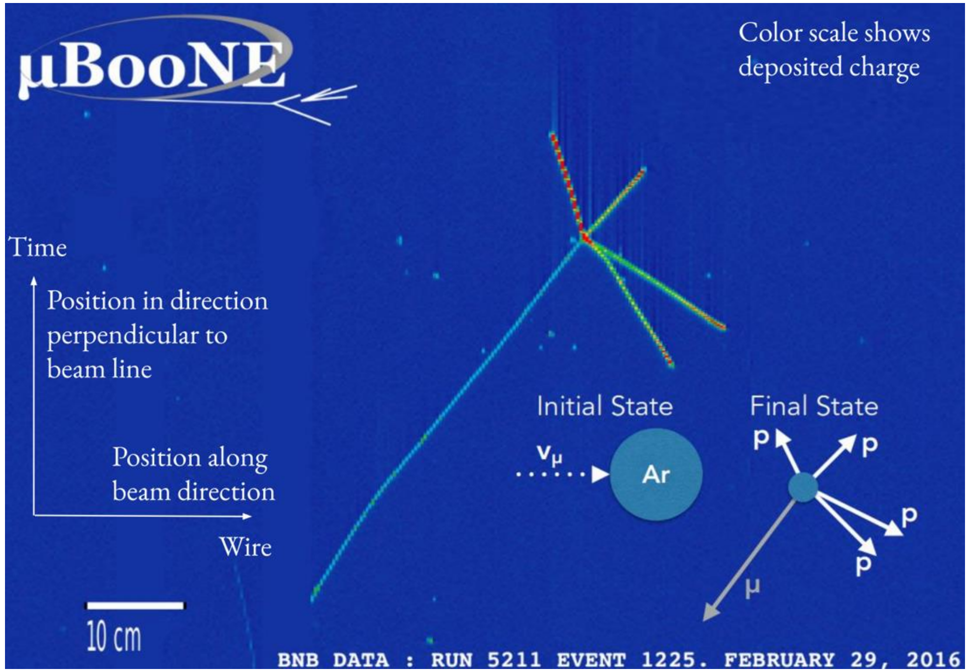
- LArTPC detector located in Booster Neutrino Beam (BNB) at Fermilab.
- Collected data from 2015 to 2021.
  - First large scale LArTPC to collect high statistics data.
- Physics goals:
  - Test the Low Energy Excess (LEE).
  - Demonstrate capabilities of LArTPC.
  - Explore BSM physics
  - **Study neutrino-argon interactions.**



LArTPC

- A LArTPC consists of a large volume of liquid argon flanked by wire readout planes and an array of PMTs.
- Interactions produce ionization electrons and scintillation light. LArTPCs leverage both signals.
  - PMTs provide timing measurement from light.
  - High voltage field draws electrons to the wire planes. This allows for high resolution imaging based on charge deposited on each wire.

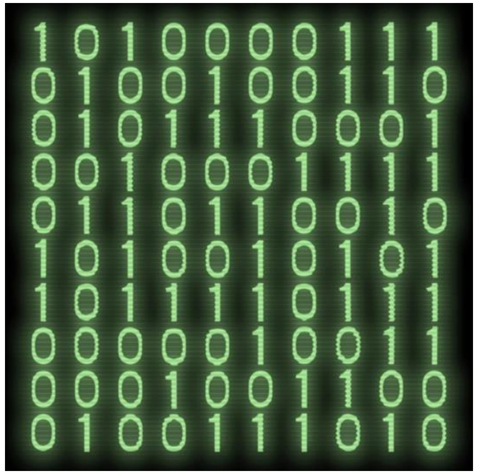


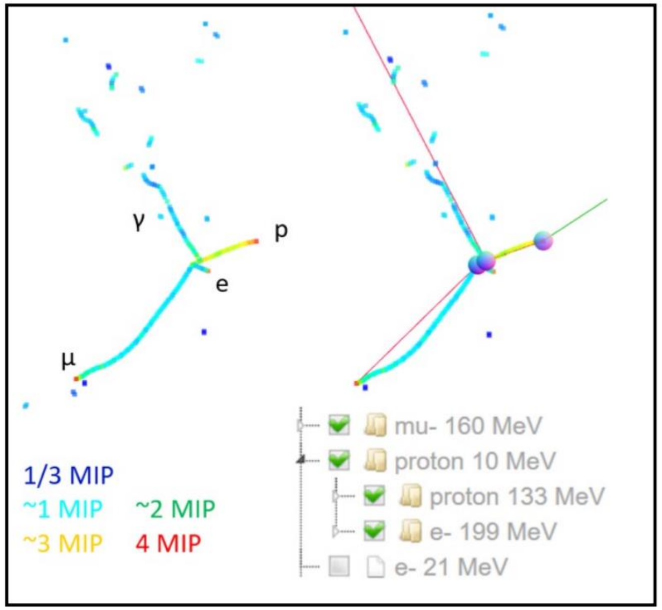


Allows for excellent particle identification and detailed event reconstruction.

Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where is can detect a lot of neutrinos.
2. Reconstruct the neutrino interaction events from your raw data.

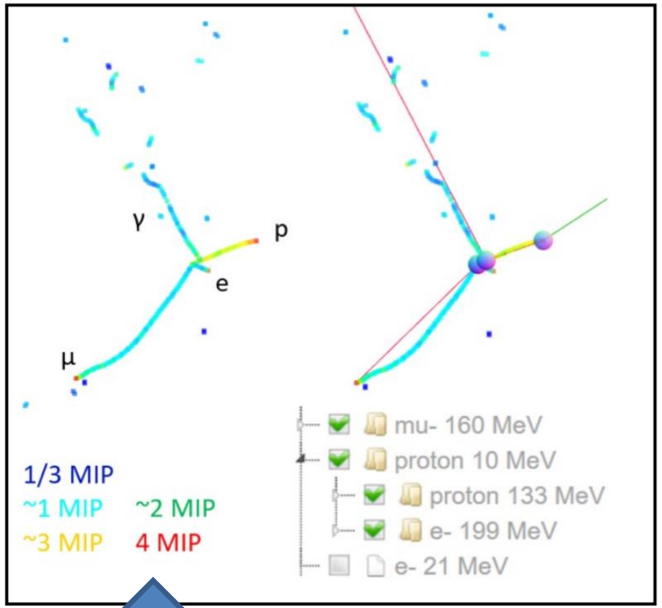


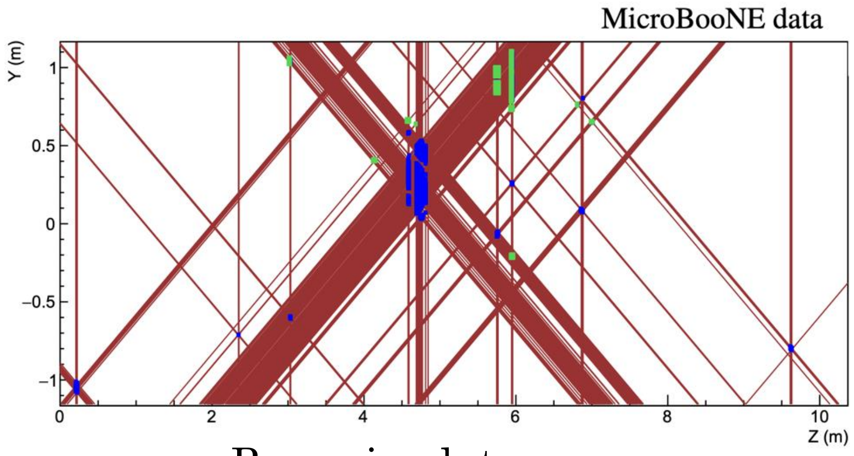


3D Event Reconstruction

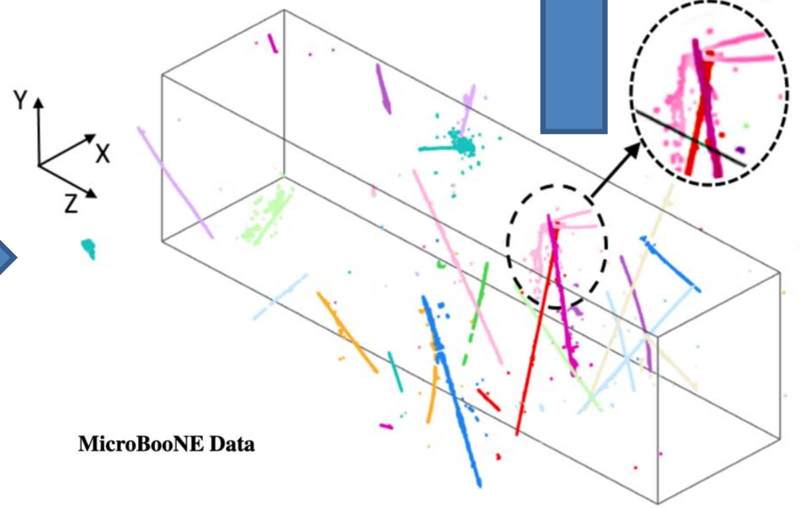
- Reconstructing wire and PMT information into physics quantities is an immense challenge with many aspects:
  - clustering activity associated with individual particles.
  - determining the neutrino interaction vertex.
  - ...
- "Wire-Cell" event reconstruction utilizes tomographic techniques to create 3D images of interactions.
  - Reconstructs the 2D image of the ionization electrons for a given time slice, then stitches 2D time slices into a 3D image.

Particle identification and neutrino vertexing





Raw wire data

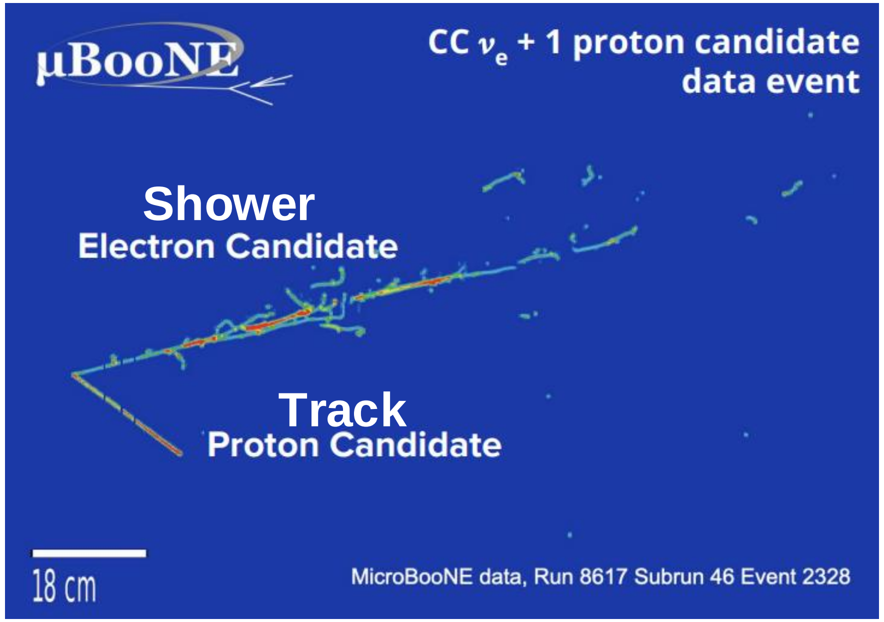


Wire-Cell

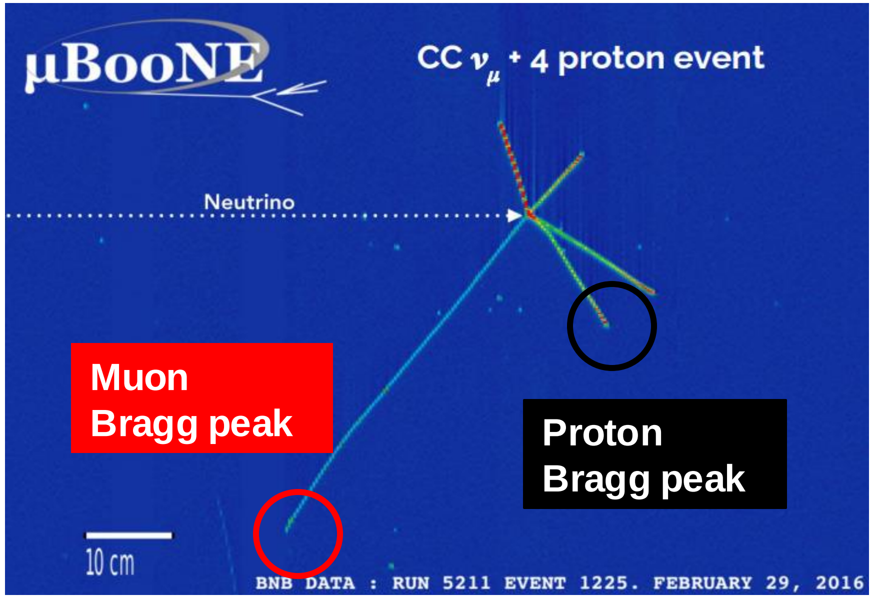
Reconstructed 3D event display with clustering

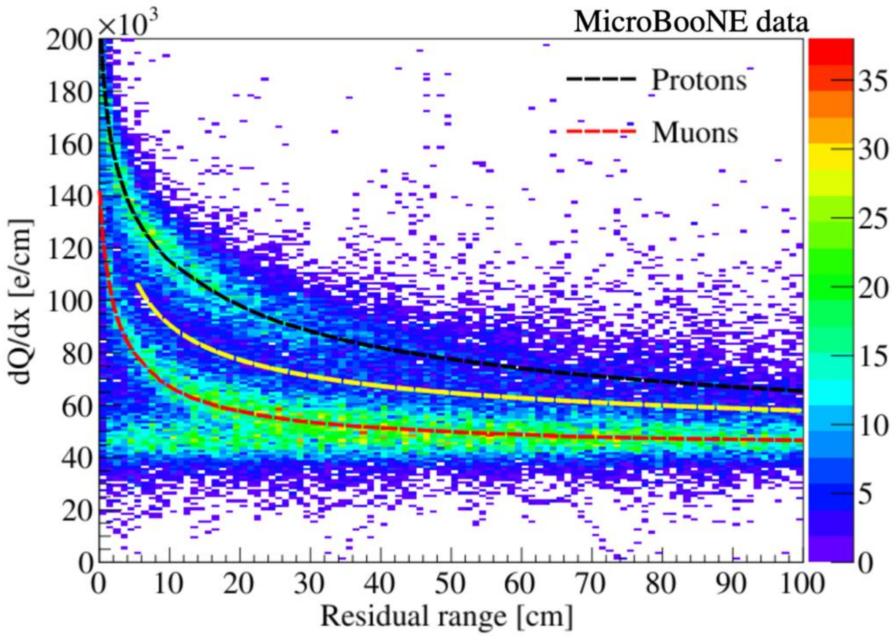
JINST 13 P05032 (2018)
JINST 16 P06043 (2021)
JINST 17 P01037 2022
Phys. Rev. Applied 15, 064071 (2021)

Particle Identification



- Two distinct particle topologies in LArTPCs:
  - Showers produced by electrons and photons.
  - Tracks produced by charged pions, muons and protons.
- Proton and muon tracks are distinguished based on differences in their dQ/dx profile.
  - Protons have a sharper Bragg peak than muons.





Measuring Neutrino-Nucleus Cross Sections

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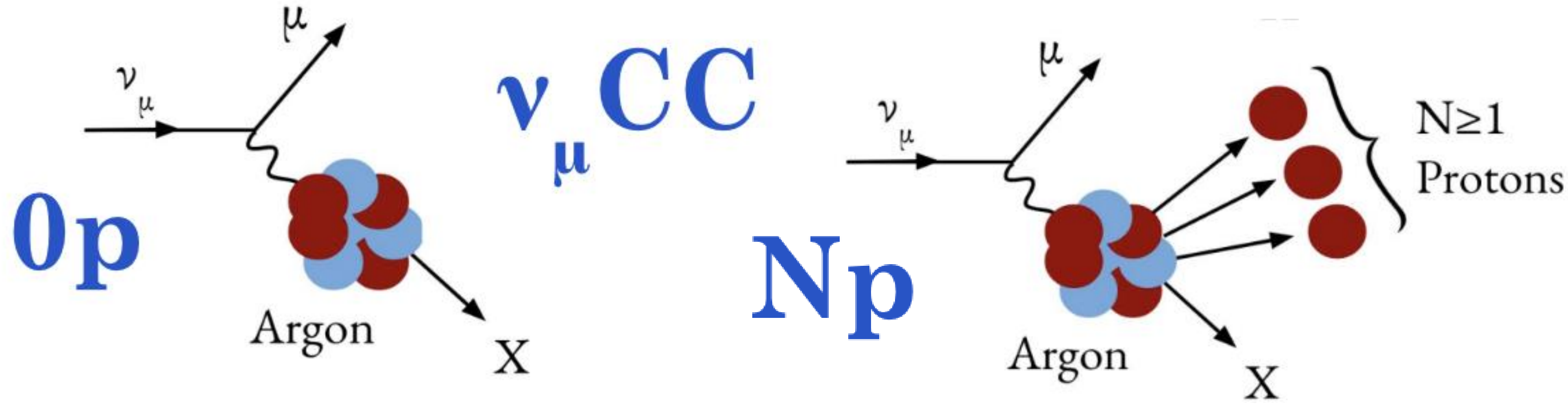
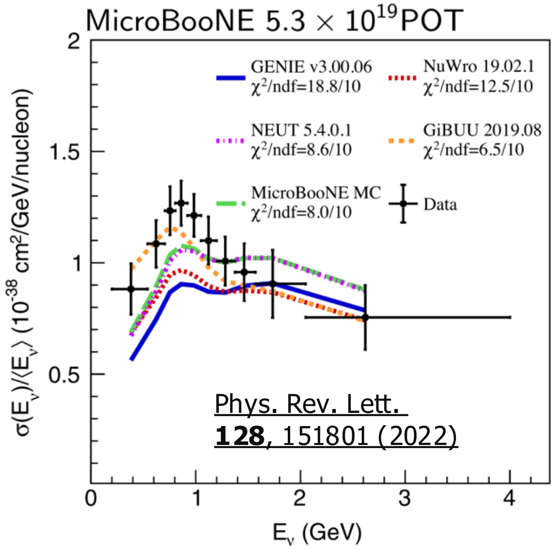
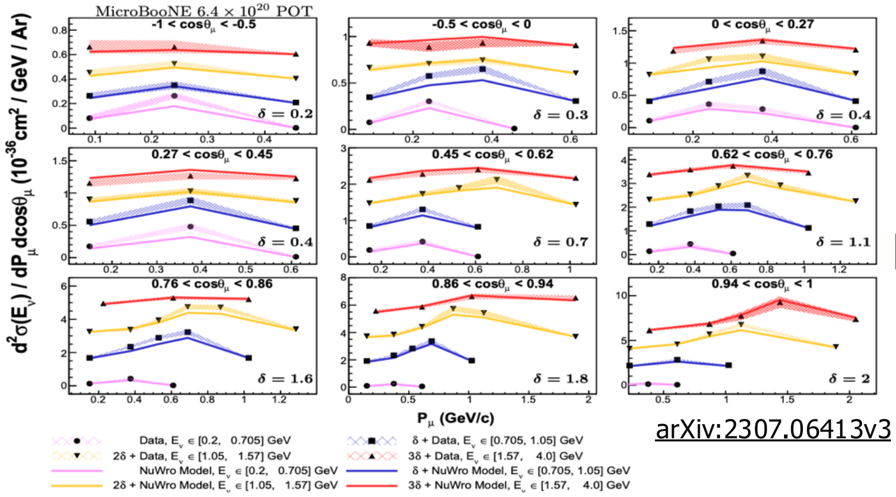


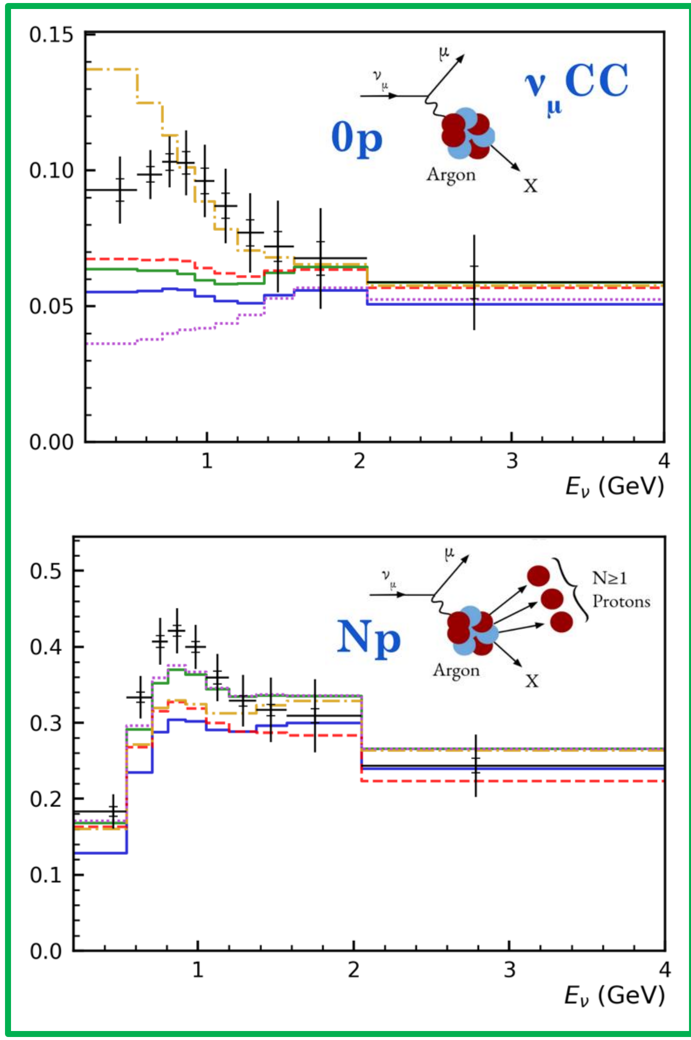
To Hadronic States

Phys. Rev. D 110, 013006 (2024)
Phys. Rev. Lett. 133, 041801 (2024)

This Talk!



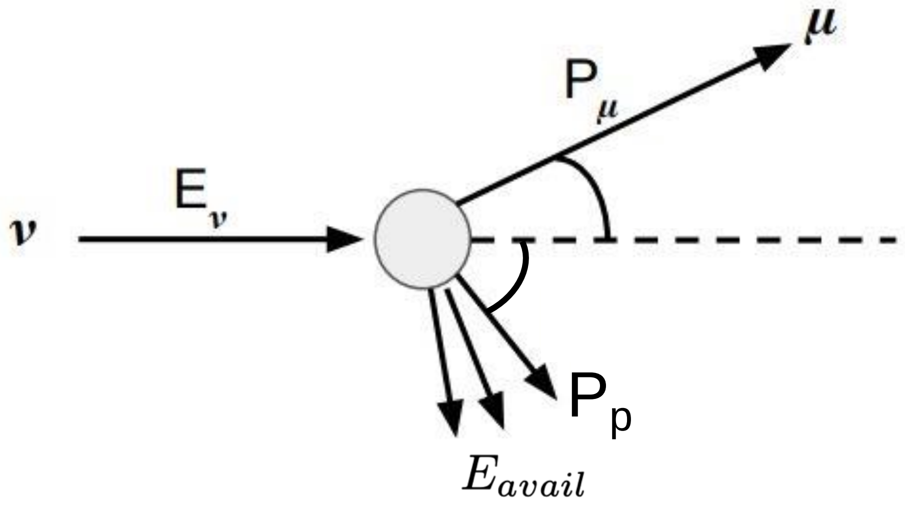




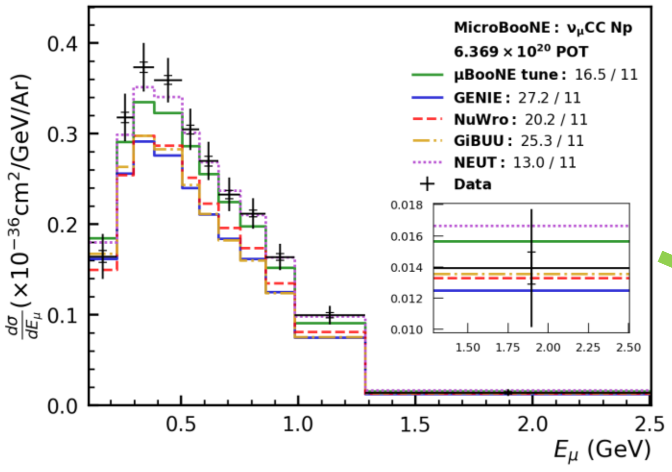
- Need to understand ν_μCC cross sections and hadronic final states to properly interpret oscillation measurements.
  - ν_μ are the dominate component of the neutrino flux.
  - Different reconstructed to true energy mapping for different final states.
- First simultaneous measurements of final states with (Np) and without (0p) protons in muon neutrino argon scattering.
  - Builds off extensive MicroBooNE inclusive ν_μCC work.

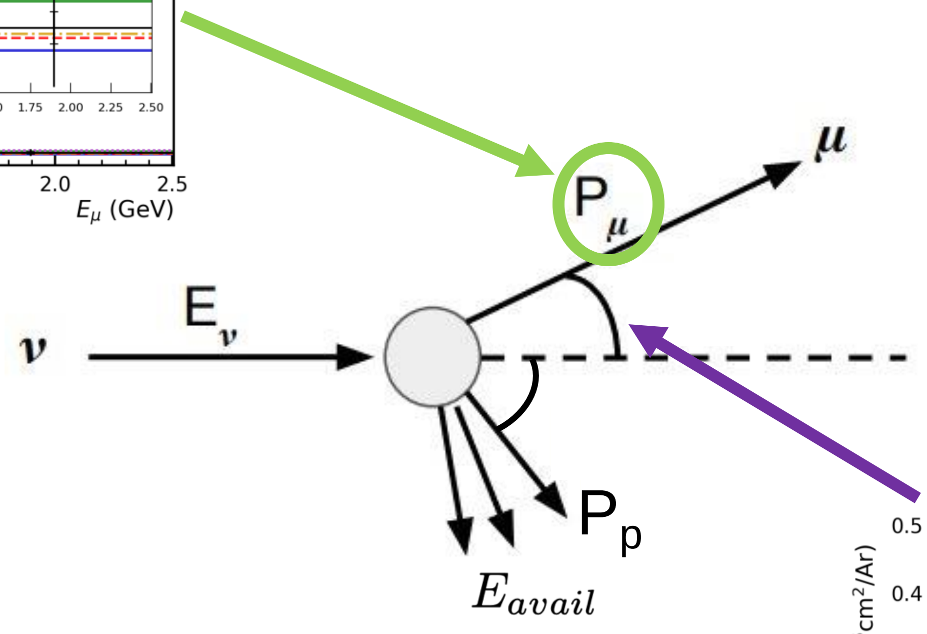
First energy-dependent total charged-current cross section on argon → **More detail** → Expansion to 3d → **More sensitivity to nuclear effects** → Expansion to 0p and Np hadronic states

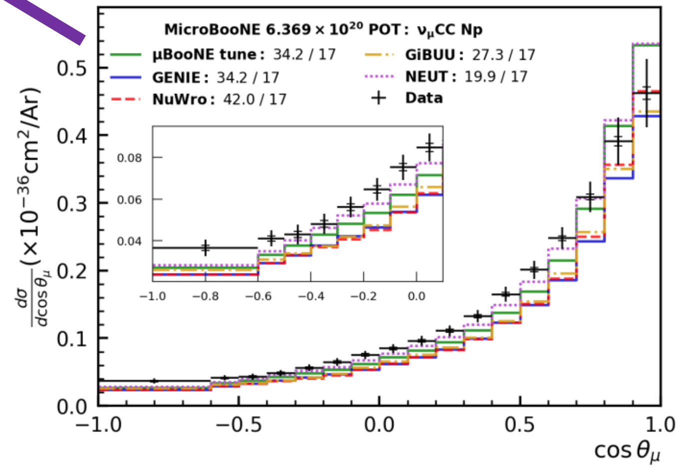
Measured Cross Sections: 14 measurements in total!



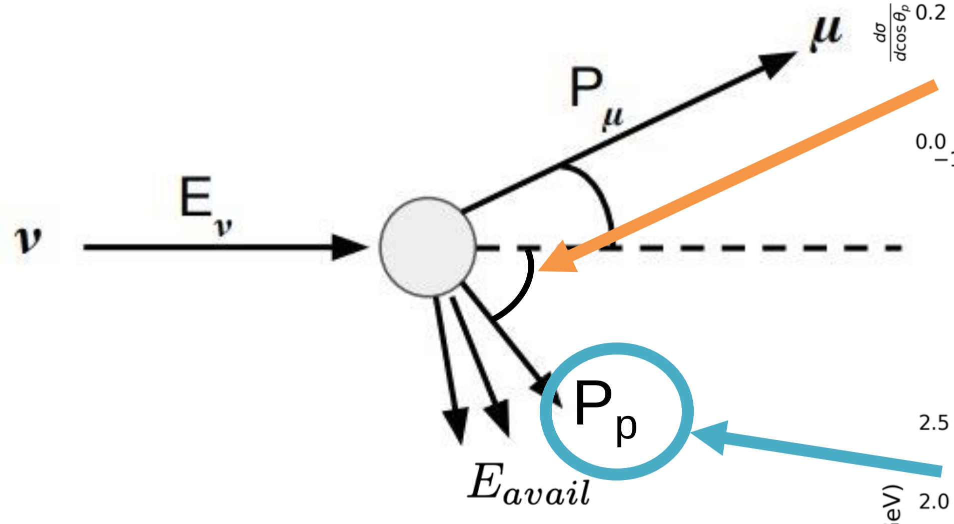
Measured Cross Sections: muon energy, muon scattering angle

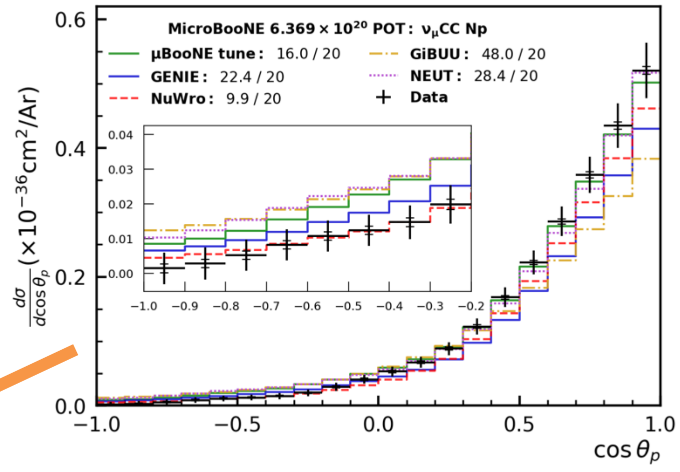


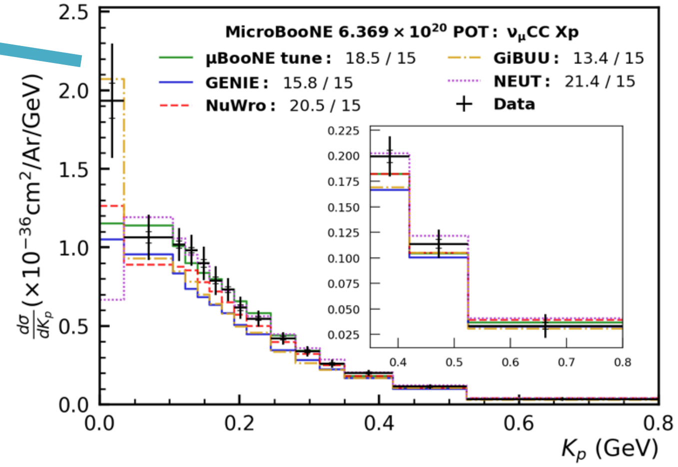




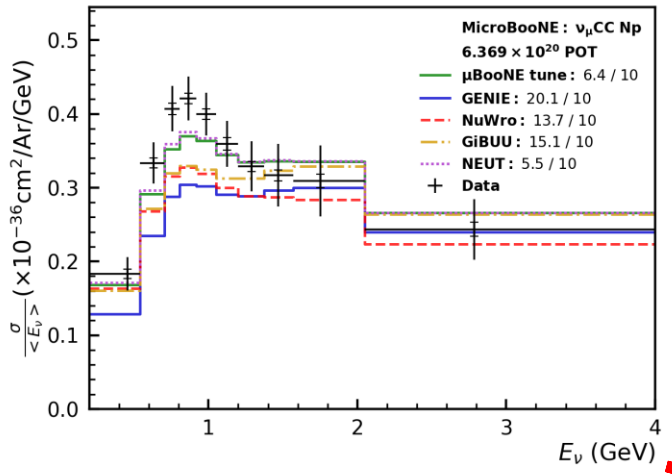
Measured Cross Sections: proton energy, proton scattering angle

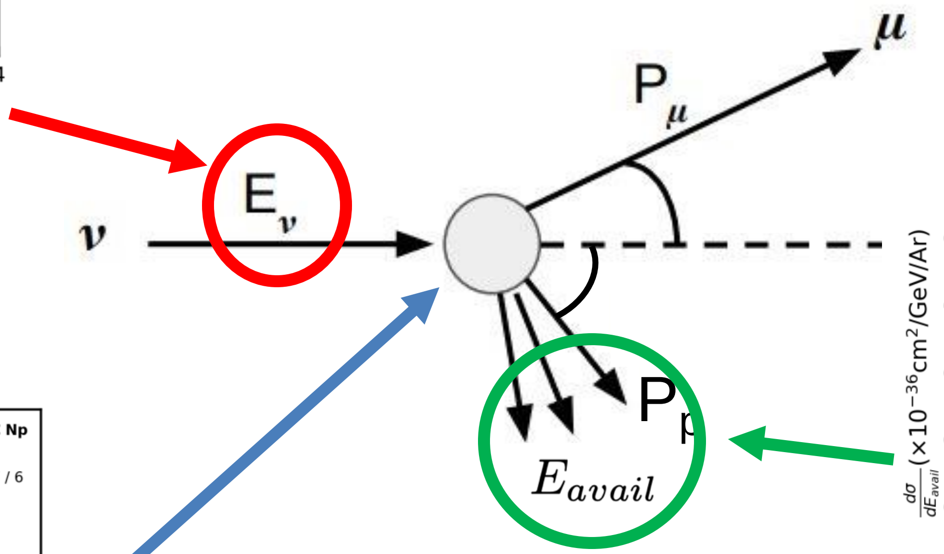


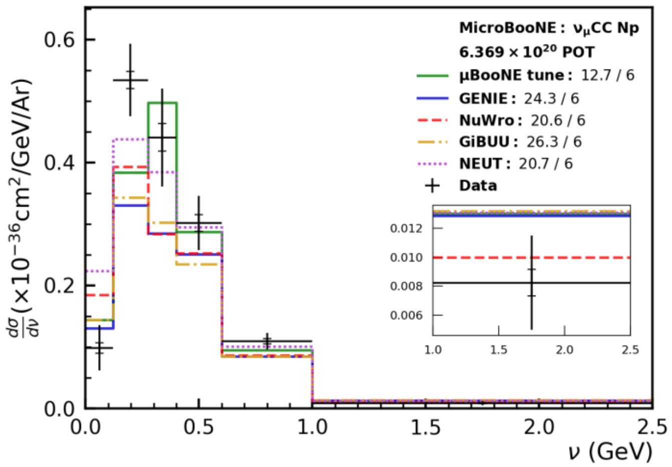


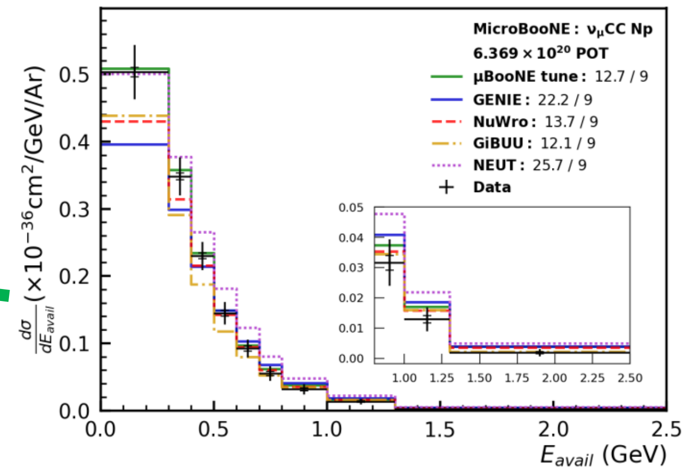


Measured Cross Sections: neutrino energy, energy transfer, available energy





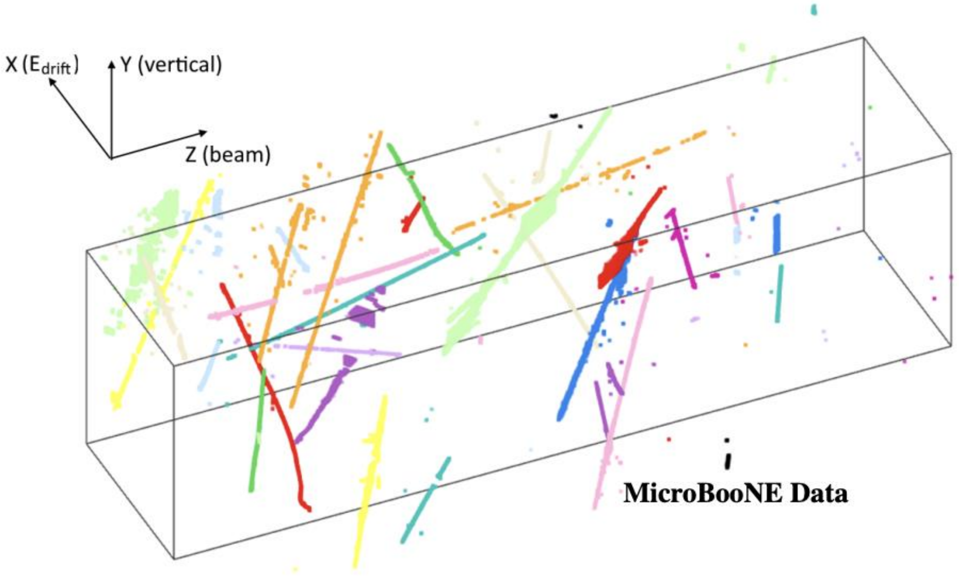




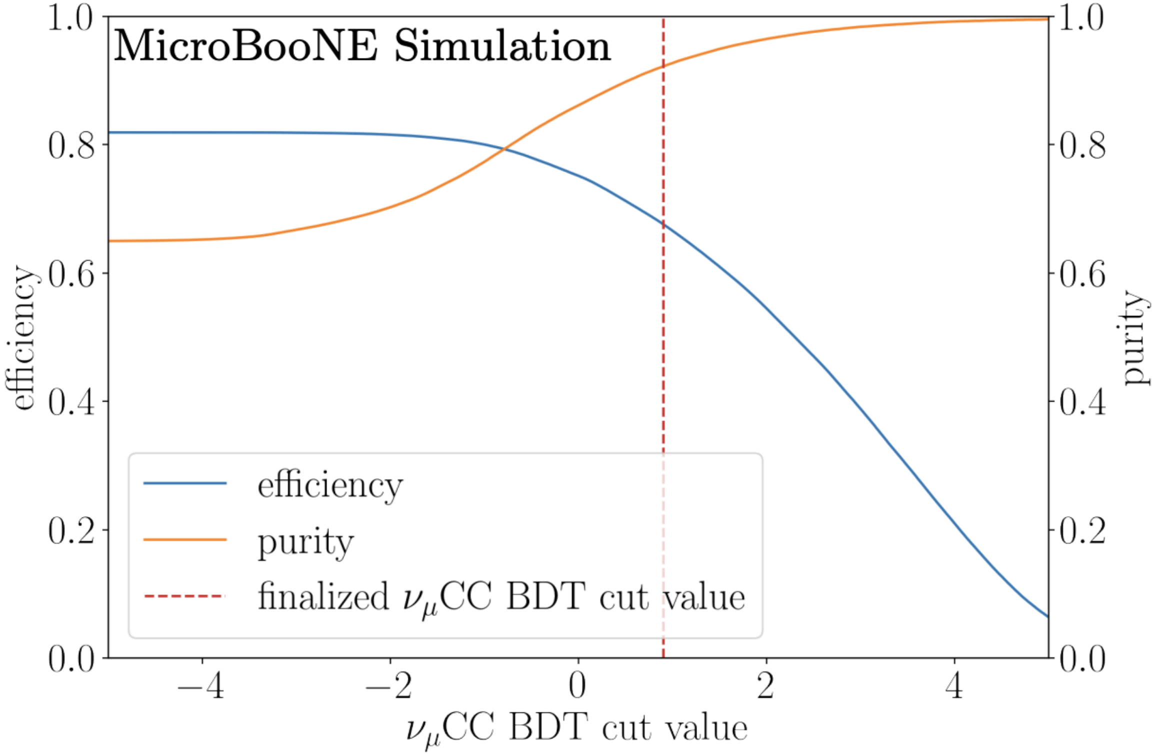
$$E_{avail} = \sum_{\pi^\pm} K_{\pi^\pm} + \sum_{p} K_p + \sum E_{particle}$$

Event selection

- MicroBooNE is on earth's surface. This means lots of cosmic rays!
  - There are 20000 cosmic rays for every 1 neutrino interaction.
- Cosmic rays are rejected by matching TPC charge to PMT light information.
  - Reduces cosmic ray contamination from 20000:1 to 1:6.
- A BDT is then to used select ν_μCC events.
  - Achieves 68% efficiency and 90% purity.



So many cosmic rays! Can you find the neutrino?



Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where is can detect a lot of neutrinos.
2. Reconstruct the neutrino interaction events from your raw data.
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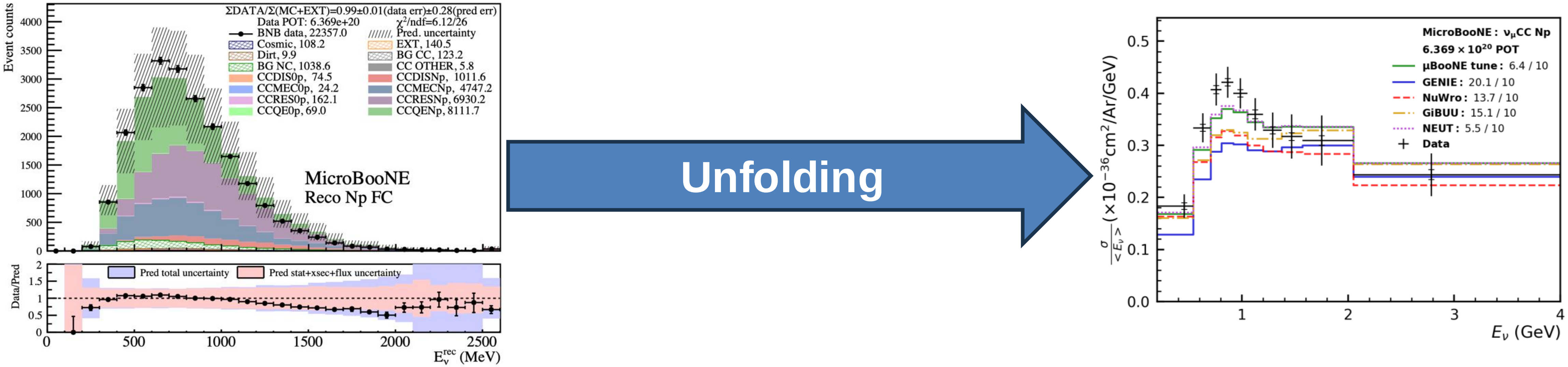
4. Quantify your uncertainties and extract the cross section from the events you selected.

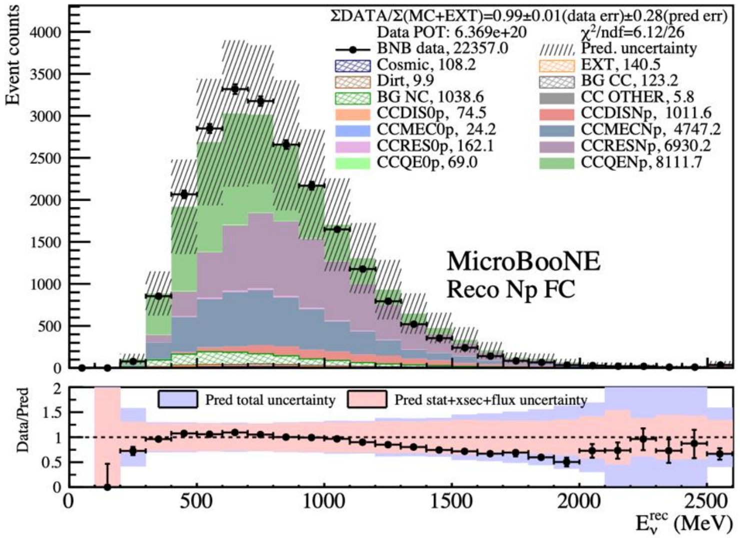
Uncertainties, Unfolding and Model Validation

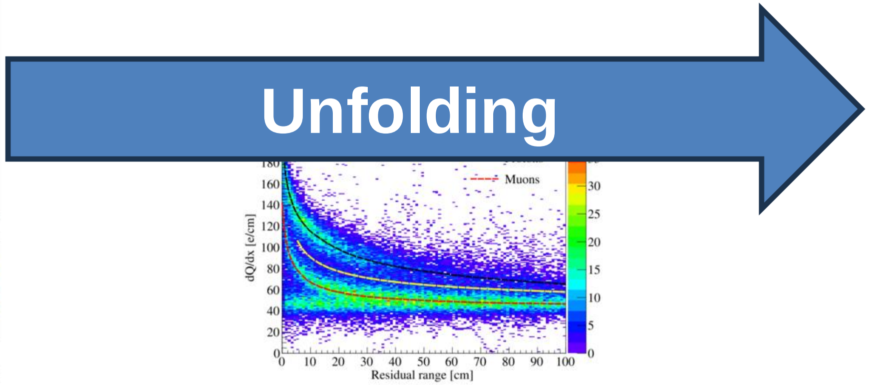
- We measure event rates and need to translate this into a cross section.
  - **Unfolding**: using a model to map the reconstructed distributions onto physics quantities.
- Many effects to correct for.

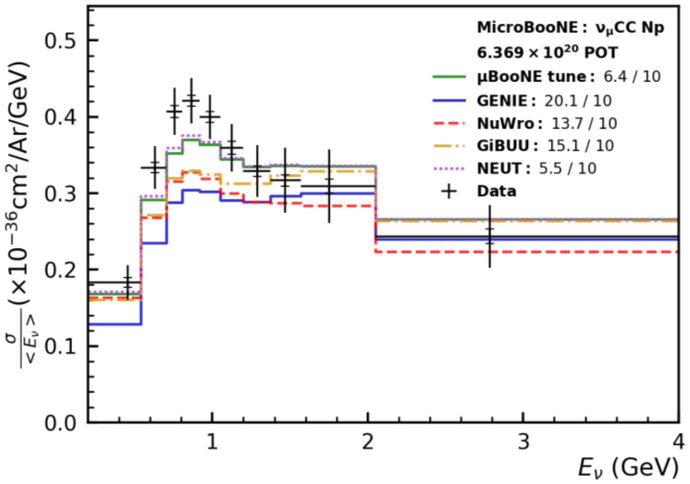


Uncertainties, Unfolding and Model Validation

- We measure event rates and need to translate this into a cross section.
  - **Unfolding**: using a model to map the reconstructed distributions onto physics quantities.
- Many effects to correct for.
  - Detector smearing: How does your detector perform?
    - Proper modeling of the detector's performance is needed to correct for finite resolution and efficiencies.

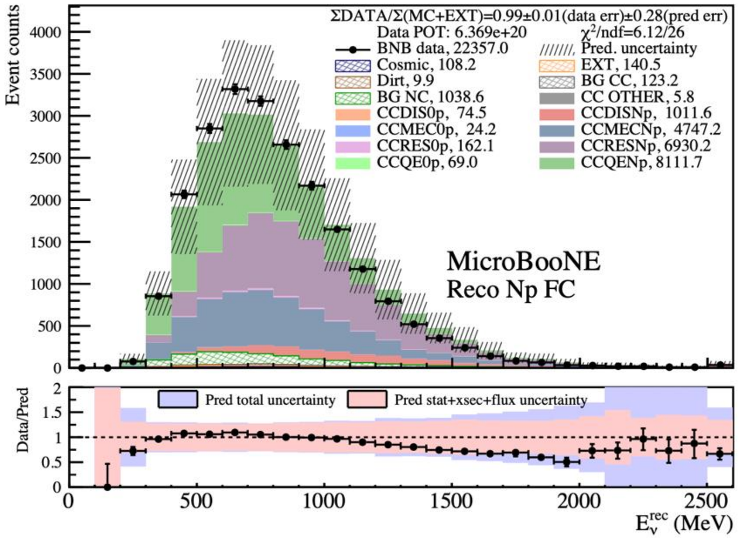


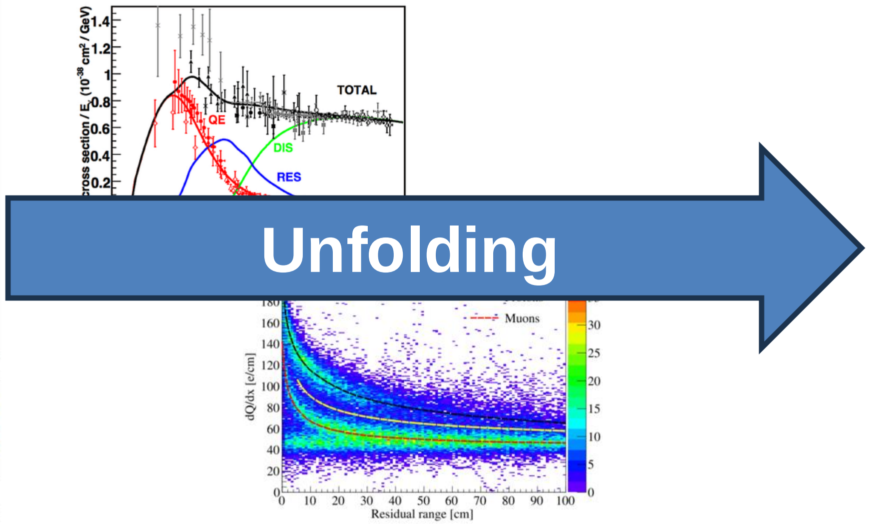


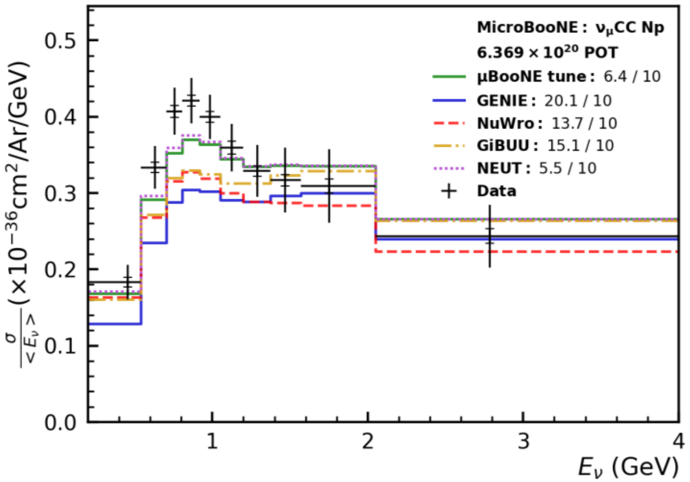


Uncertainties, Unfolding and Model Validation

- We measure event rates and need to translate this into a cross section.
  - **Unfolding**: using a model to map the reconstructed distributions onto physics quantities.
- Many effects to correct for.
  - Detector smearing: How does your detector perform?
    - Proper modeling of the detector's performance is needed to correct for finite resolution and efficiencies.
  - Flux: What neutrino are impingent on your detector?
    - Impacts both shape and normalization of the cross section result.







Uncertainties, Unfolding and Model Validation

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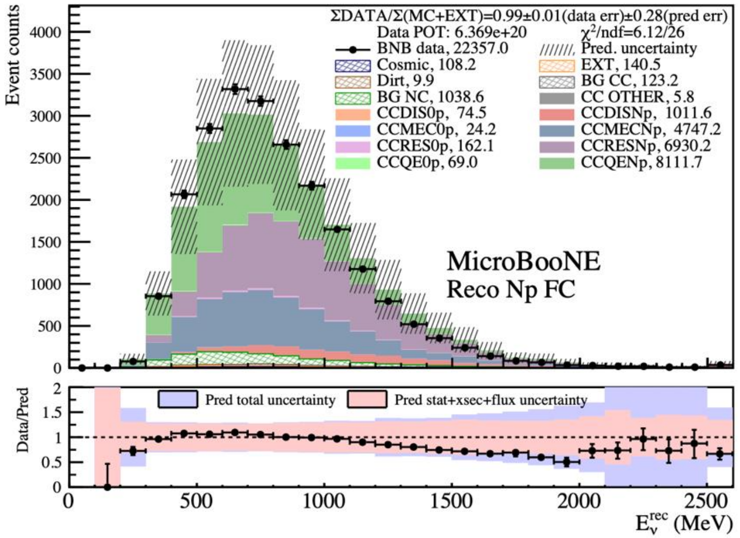
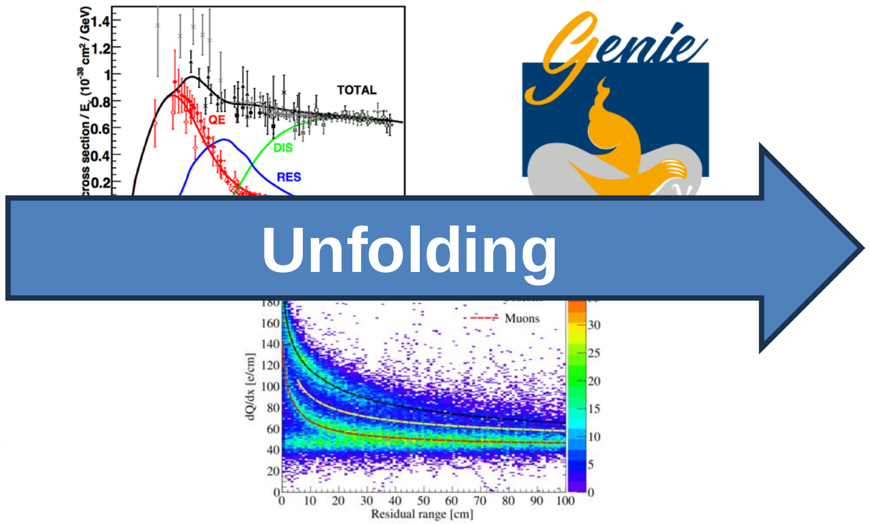
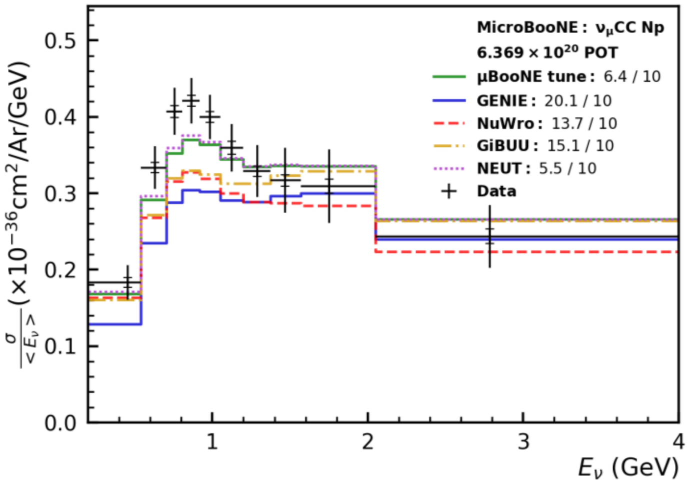
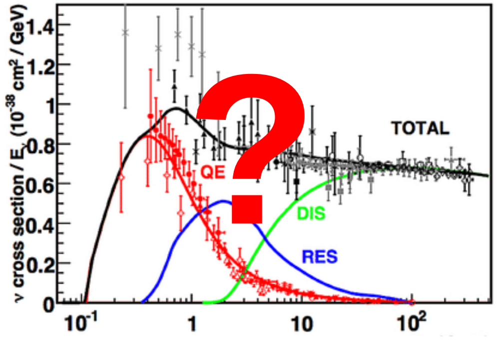
  - Flux: What neutrino are impingent on your detector?
    - Impacts both shape and normalization of the cross section result.
  - Interaction modeling: What cross section is assumed?
    - Different interaction rates or final states may alter the mapping between reconstructed and true quantities.

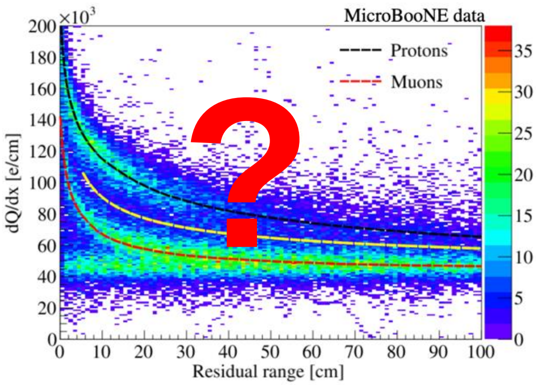




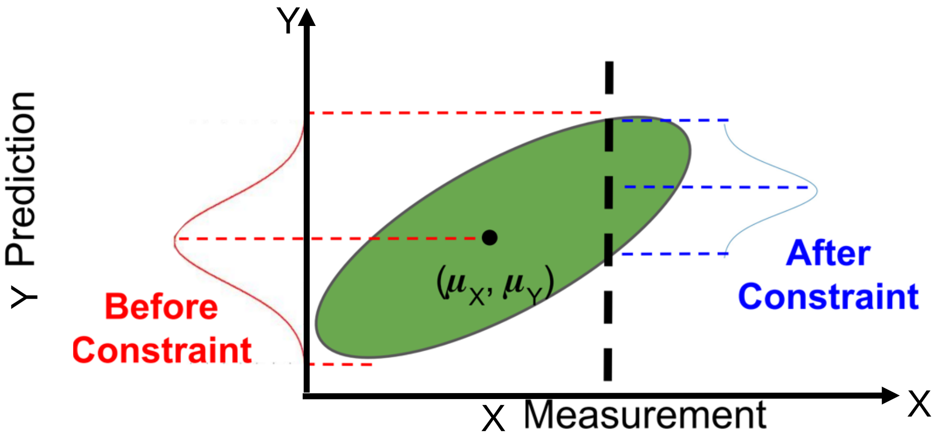


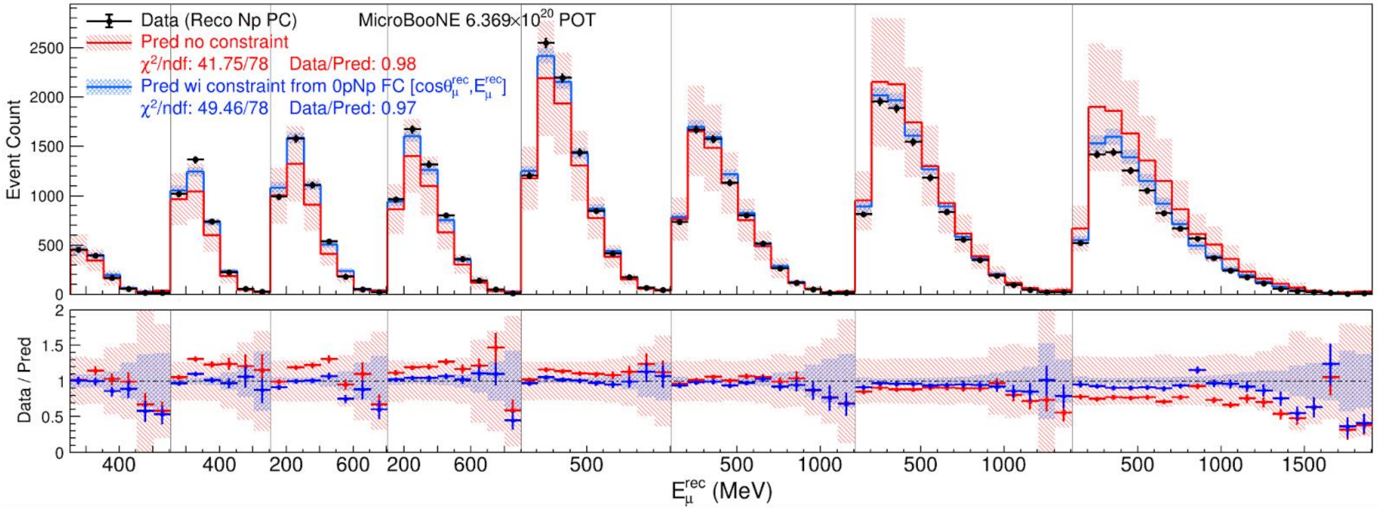
Model Validation





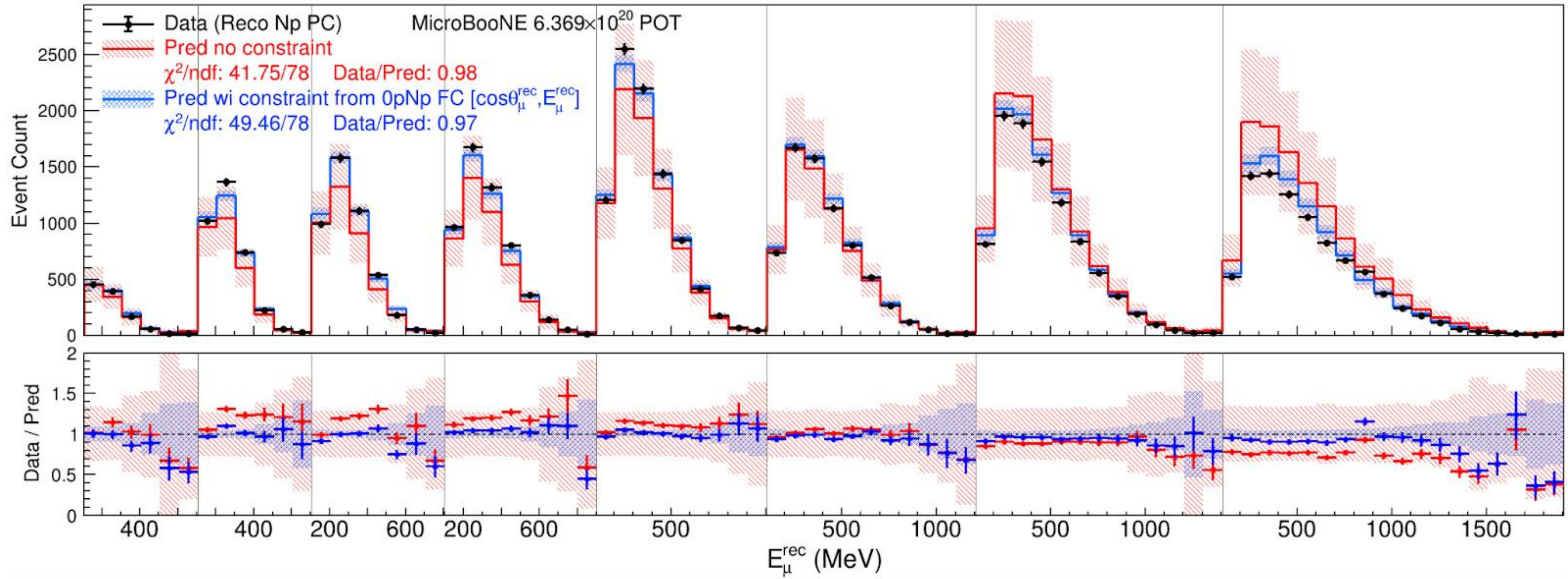
- Many uncertainties related to these corrections!
  - Does the model used to map from reconstructed to true quantities introduce bias into the result?
  - Need to verify that the model and its uncertainties are sufficient for the desired cross section measurement.
- Data-driven model validation is utilized to ensure that the model is sufficient.
- The validation is based off conducting a variety of GoF tests and data-driven constraints to determine if the model describes the data within uncertainties.
  - When this condition is met, it builds confidence that any unfolding bias will likewise be within uncertainties.





Key aspects to validate:

- Modeling of events partially contained within the detector.
  - Critical for including these in the analysis, big boost in statistics!
  - Validated by using fully contained events to constrain partially contained events.



Key aspects to validate:

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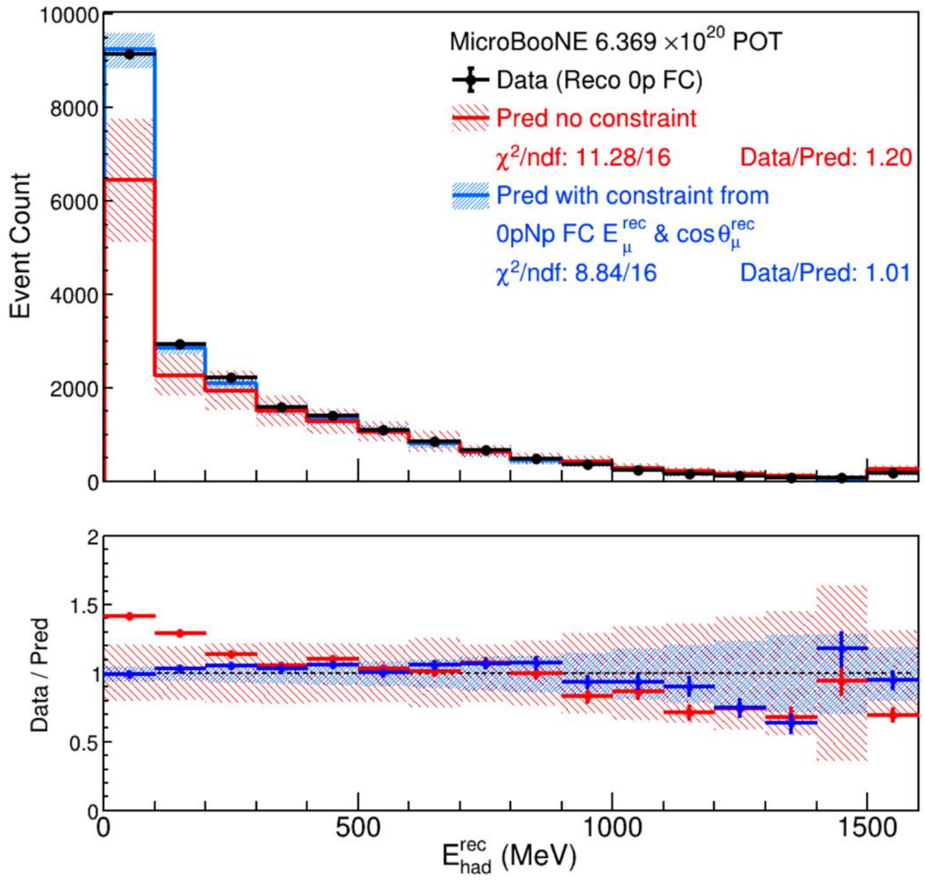
  - Critical for measurements of E_ν and ν.
  - Validated by using the muon kinematics to constrain the hadronic energy.



$$E_\nu = E_\ell + \nu = E_\ell + E_{had}^{vis} + E_{had}^{missing}$$

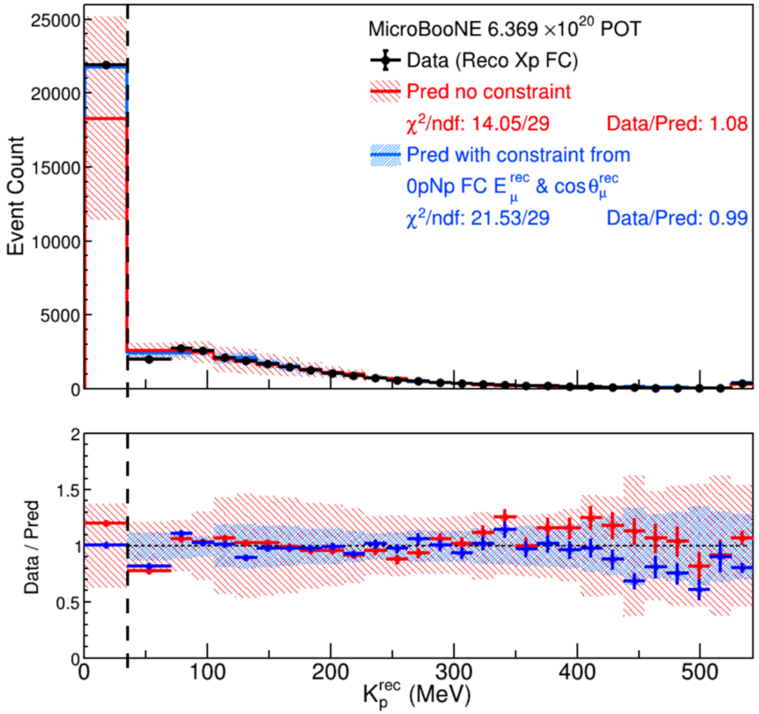
We can measure the leptonic and hadronic energy, but not the missing energy (undetected particles, etc.).

But, conservation of energy means the predicted correlation between the leptonic and hadronic energy are dictated by the modeling of the missing energy.

Constraint probes these correlations and thus provides sensitivity to the modeling of the missing energy.

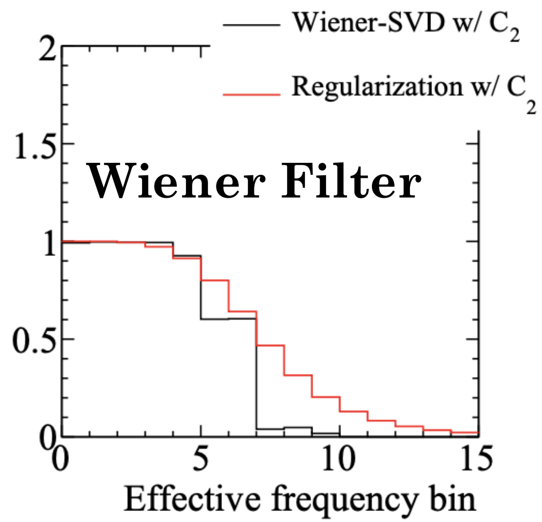
Key aspects to validate:

- Modeling of events partially contained within the detector.
  - Critical for including these in the analysis, big boost in statistics!
  - Validated by using fully contained events to constrain partially contained events.
- Modeling of missing hadronic energy in mapping from true to reconstructed neutrino energy.
  - Critical for measurements of E_ν and ν.
  - Validated by using the muon kinematics to constrain the hadronic energy.
- Modeling of proton kinematics, especially near the detection threshold.
  - Critical for the division into 0p and Np final states and measurements of protons at low kinetic energies.
  - Validated by using the muon kinematics to constrain the proton kinematics.

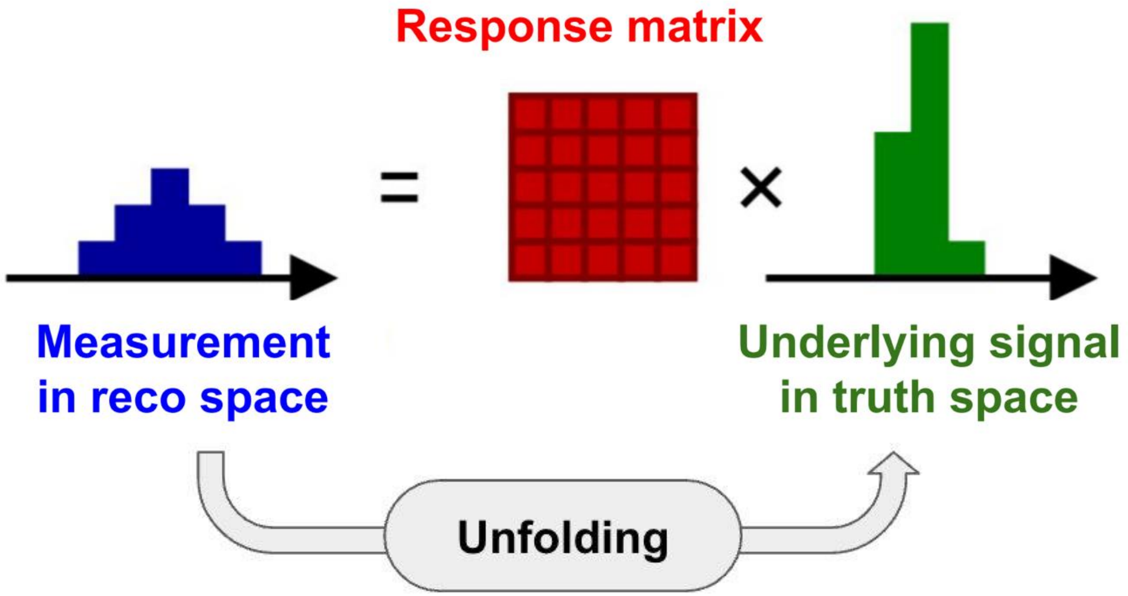


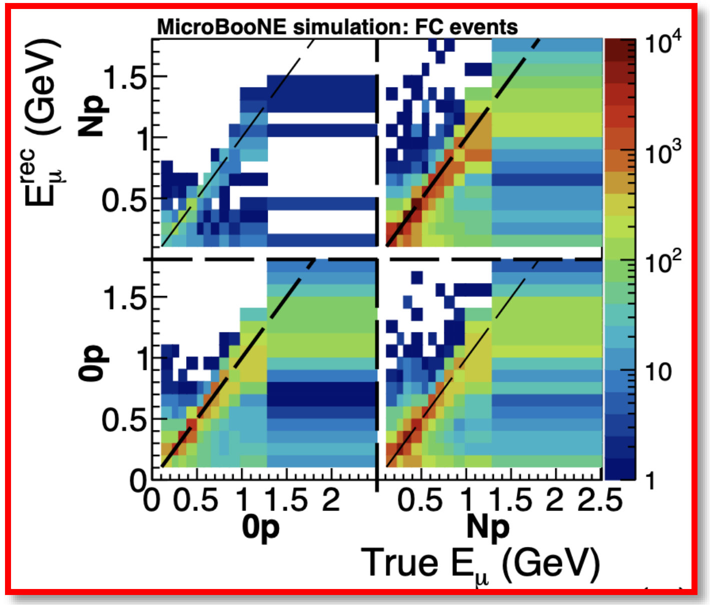
Wiener-SVD Unfolding

- Cross sections are extracted from the reconstructed distributions with the Wiener-SVD unfolding method.
- Analogous to digital signal processing with a Wiener Filter.
  - Maximizes the signal to noise ratio in an effective frequency domain.
- 0p and Np results are extracted simultaneously.
  - Allows for a data-driven estimation of the Np background in the 0p selection (and vice versa).



JINST, Volume 12, October 2017





Response matrix has separate blocks for 0p and Np events.

Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where is can detect a lot of neutrinos.
2. Reconstruct the neutrino interaction events from your raw data.
3. Select the events with the type of interaction you want to measure.
4. Quantify your uncertainties and extract the cross section from the events you selected.
5. Report your great measurement and learn lots of new physics.

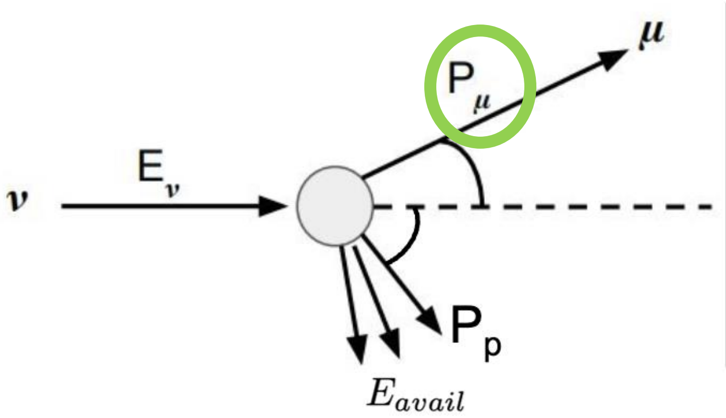
PHYSICAL REVIEW LETTERS **133,** 041801 (2024)

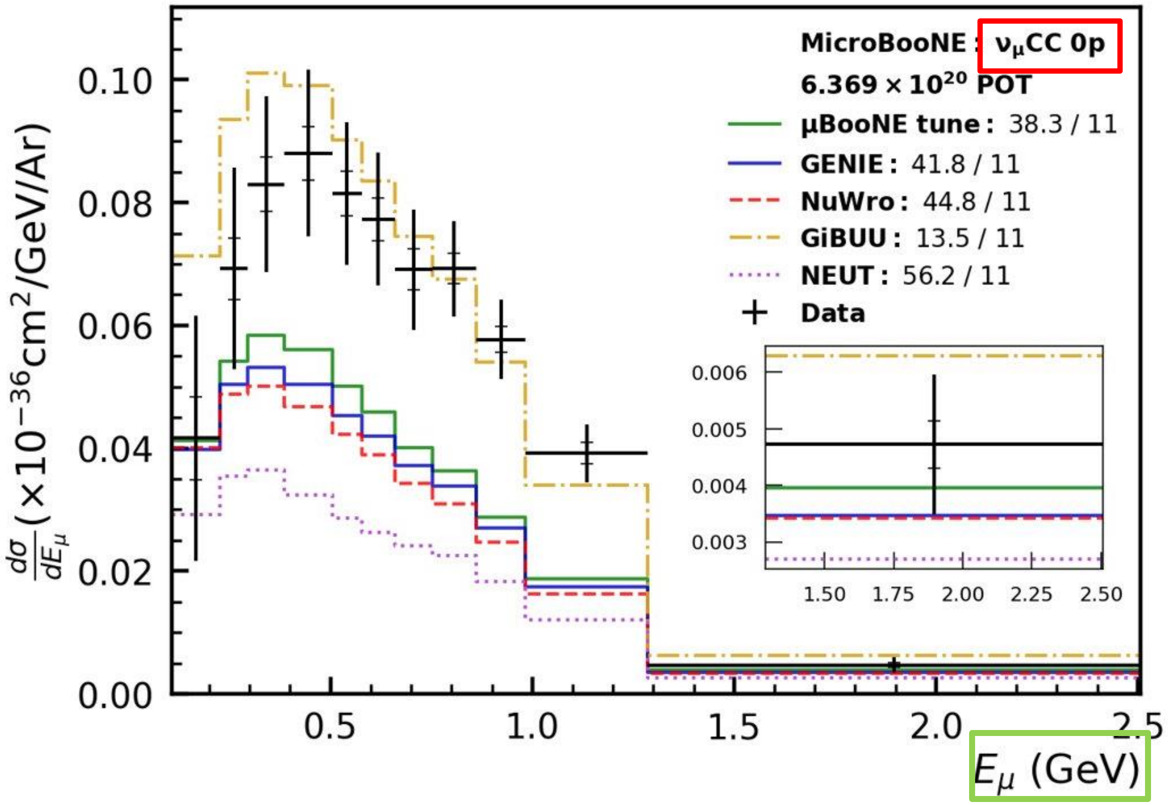
First Simultaneous Measurement of Differential Muon-Neutrino Charged-Current Cross Sections on Argon for Final States with and without Protons Using MicroBooNE Data

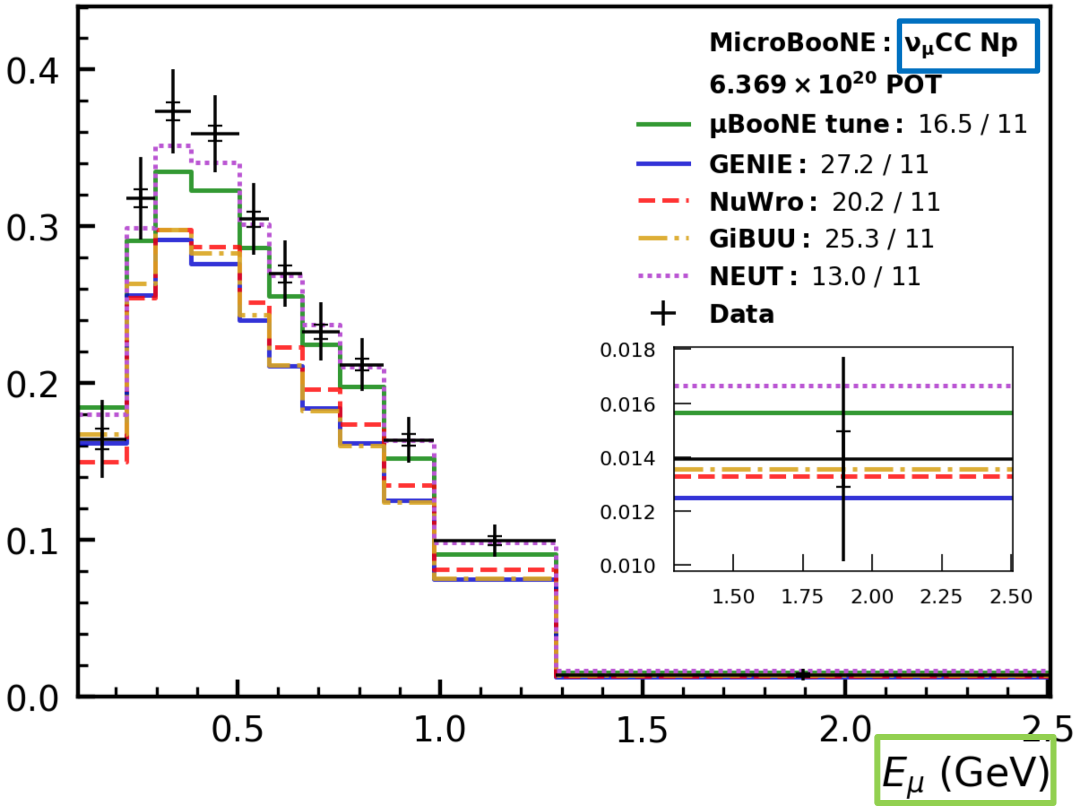
Phys. Rev. D 110, 013006 (2024)
Phys. Rev. Lett. 133, 041801 (2024)

Results: Mismodeling of 0p Final States

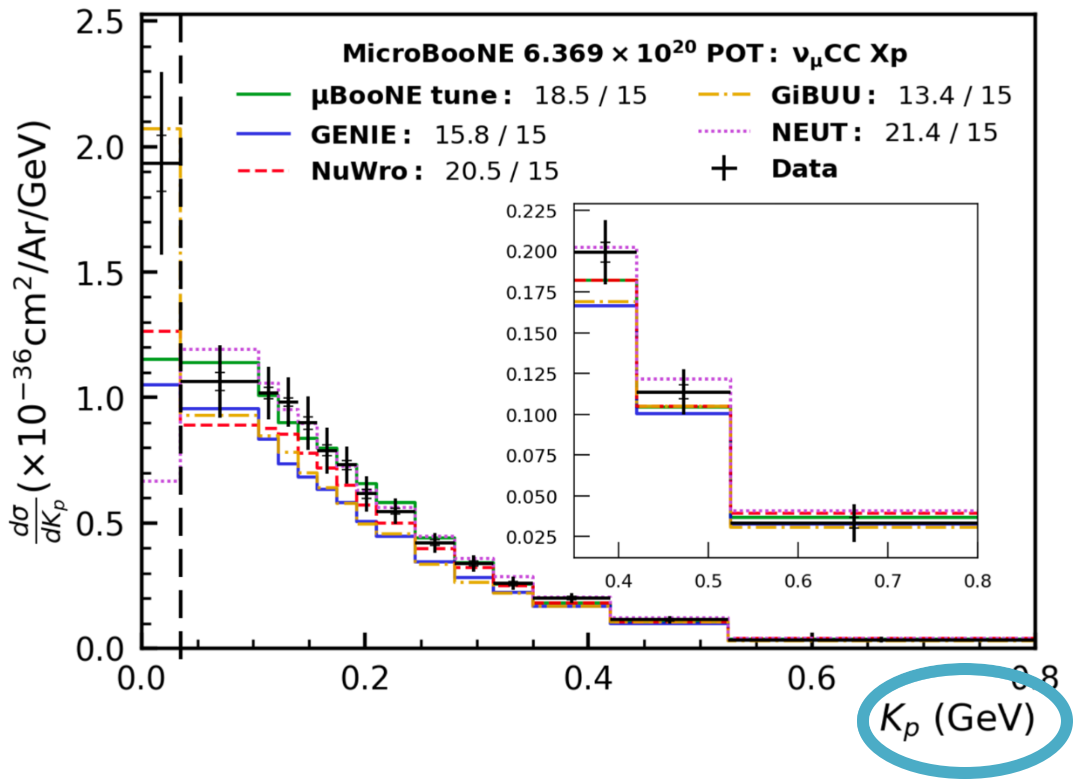
- Our measurements indicate that commonly used event generators mismodel final states without protons.
  - **GiBUU** is the only exception.
- Better agreement seen for final states with protons.

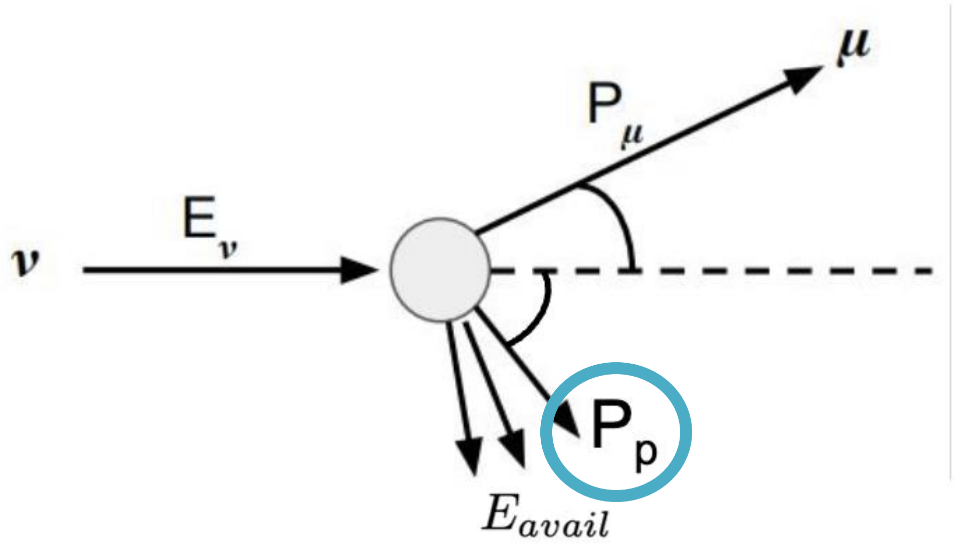






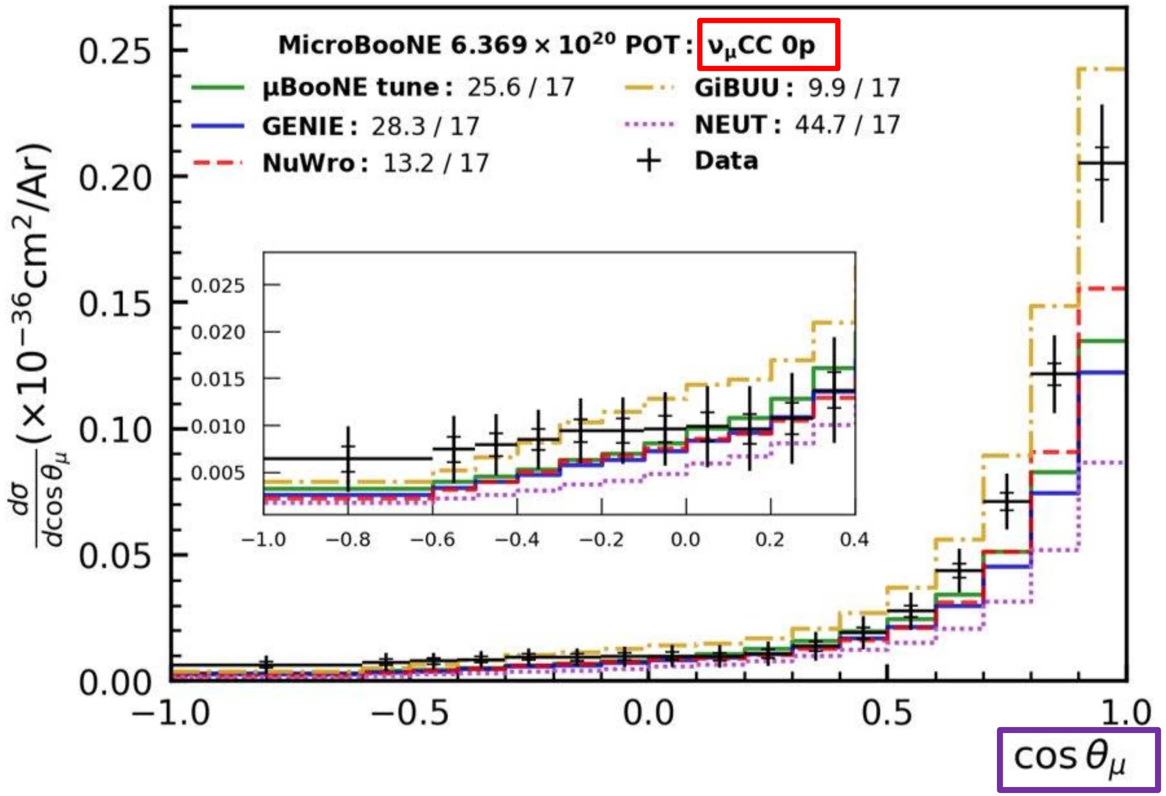
Impact on the proton kinetic energy

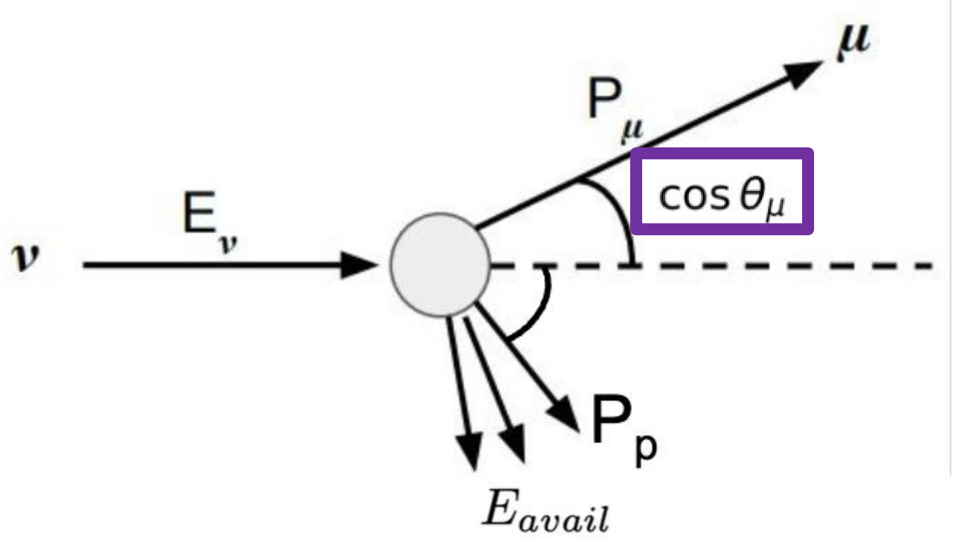




- FSI pulls the proton kinetic energy distribution towards lower values
  - Events may be shifted from Np to 0p.
- GiBUU has "strong" FSI, its prediction peaks sharply at low energies.
  - Good agreement with data!
- NEUT has "weak" FSI, its prediction drops off at low energies.
  - Poor agreement with data!

NEUT

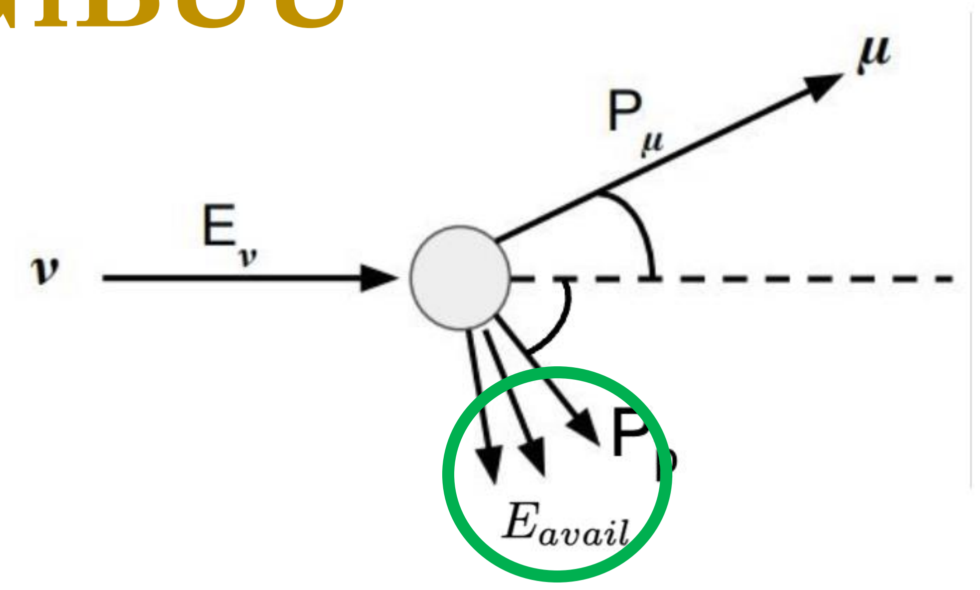




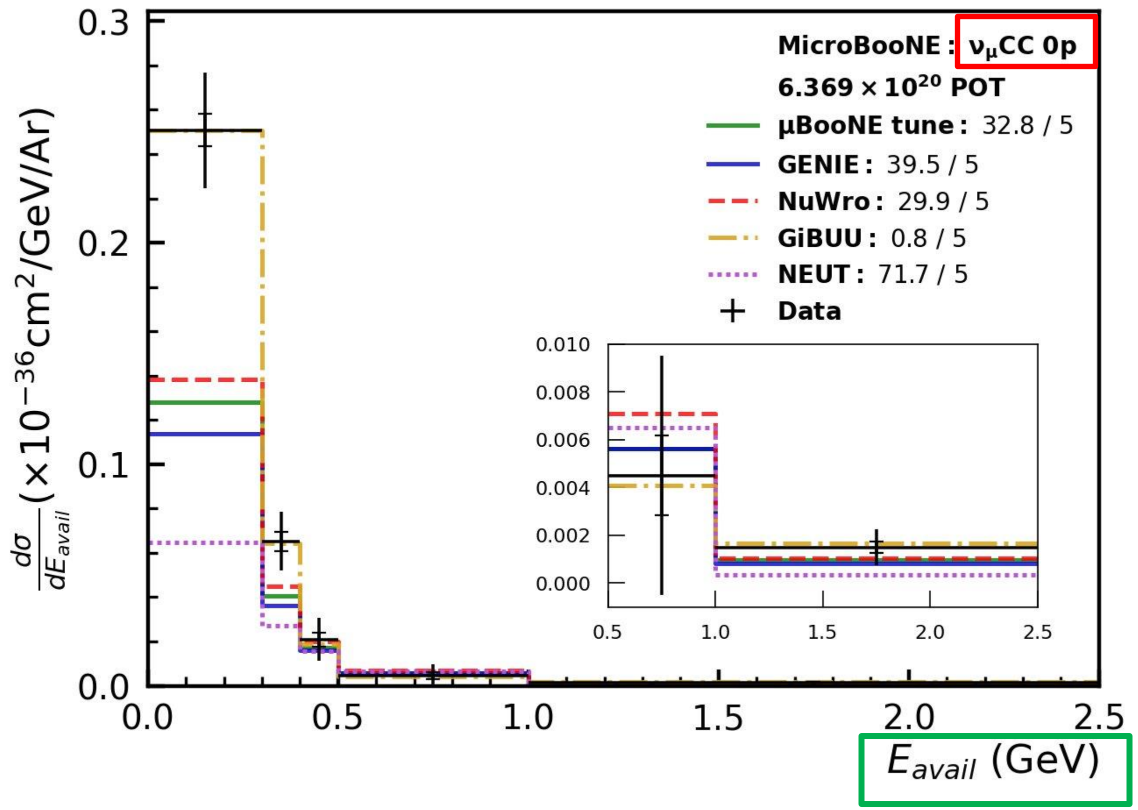
- **NEUT** significantly underpredicts the 0p cross section.
- **NEUT** only allows interacts if the total energy is greater than 2x the nucleon mass.
  - This is not guaranteed because **NEUT** uses an effective mass for bound nucleons.
- This suppresses the low energy interactions of nucleons leading to the poor 0p prediction.

$$M_N{}^{eff} = \sqrt{(M_N{}^{free} - 8MeV/c^2)^2 - (p_F^{surf})^2}$$

GiBUU



$$E_{avail} = \sum_{\pi^{\pm}} K_{\pi^{\pm}} + \sum_{p} K_p + \sum E_{particle}$$

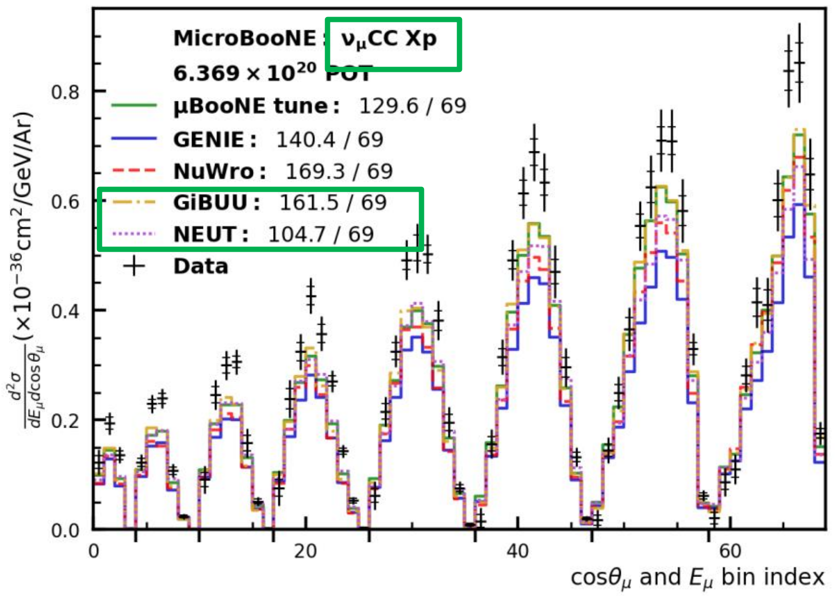


- **GiBUU** has a more sophisticated treatment of FSI with a model of the nuclear binding potential.
- Low energy protons are most impacted by FSI, and a strong description of FSI is required for a robust 0p prediction.
- **GiBUU** consistently describes the 0p data better than the other generators.

Inclusive vs. 0p and Np Final States

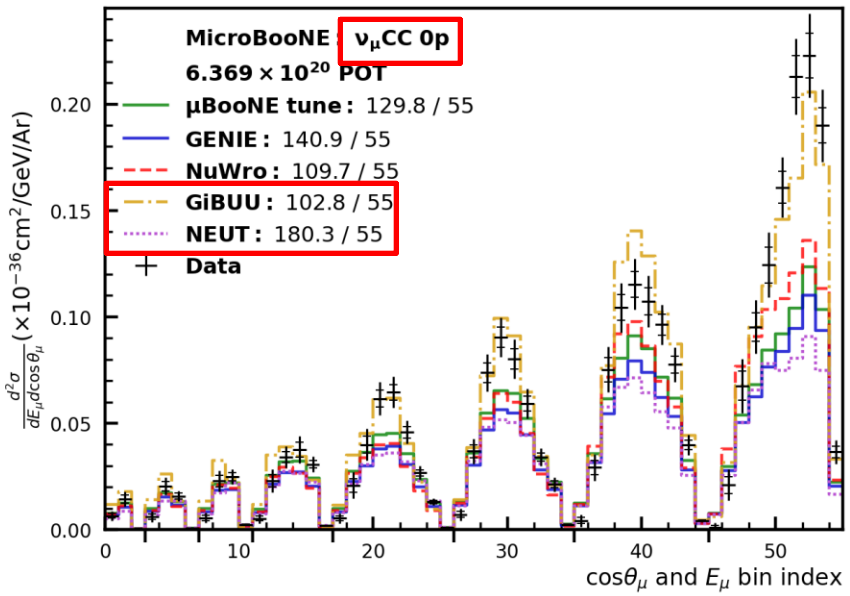
- A model that describes inclusive scattering may not be able to describe more exclusive scattering or the hadronic final state:
  - **NEUT** describes the inclusive muon kinematics better than **GiBUU.**
  - **GiBUU** better describes the data when the channel is divided into 0p and Np final states.
- Such modeling discrepancies may impact the sensitivity of neutrino experiments across a wide range of physics analyses.
  - Robust hadronic final state modeling is vital for accurate energy reconstruction!

Inclusive ("Xp")



vs.

0p Final States



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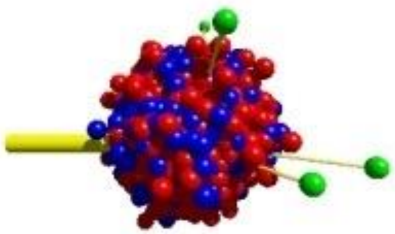
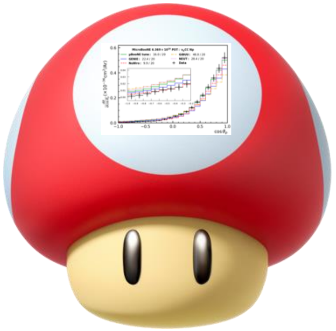
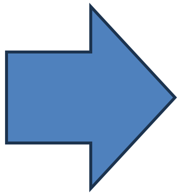
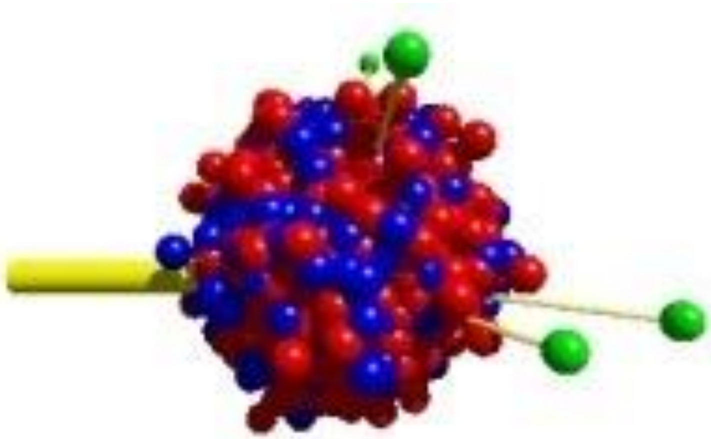
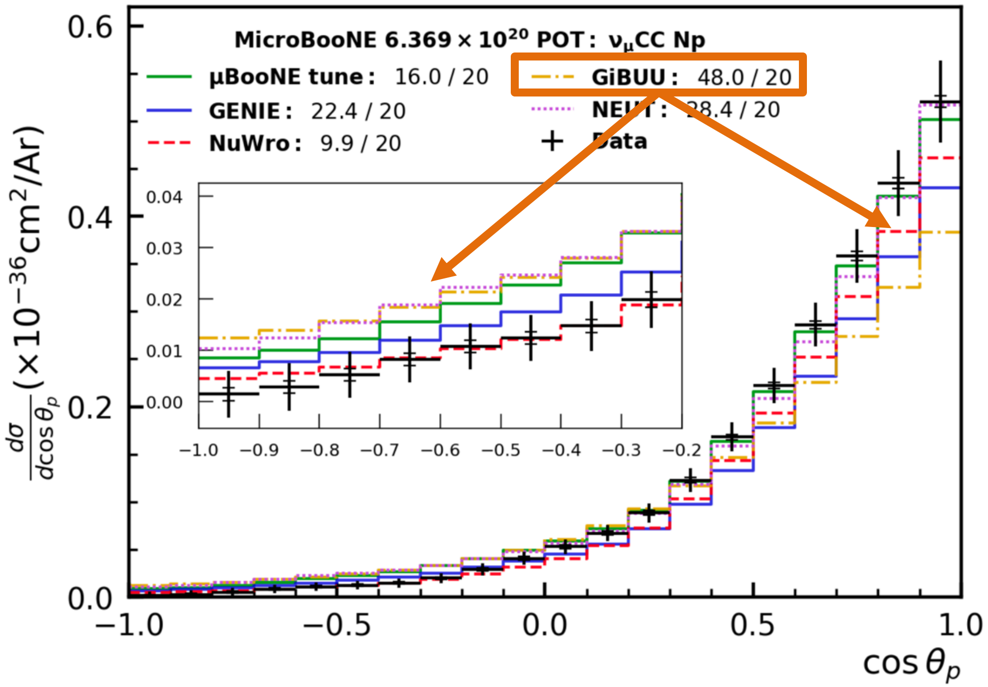
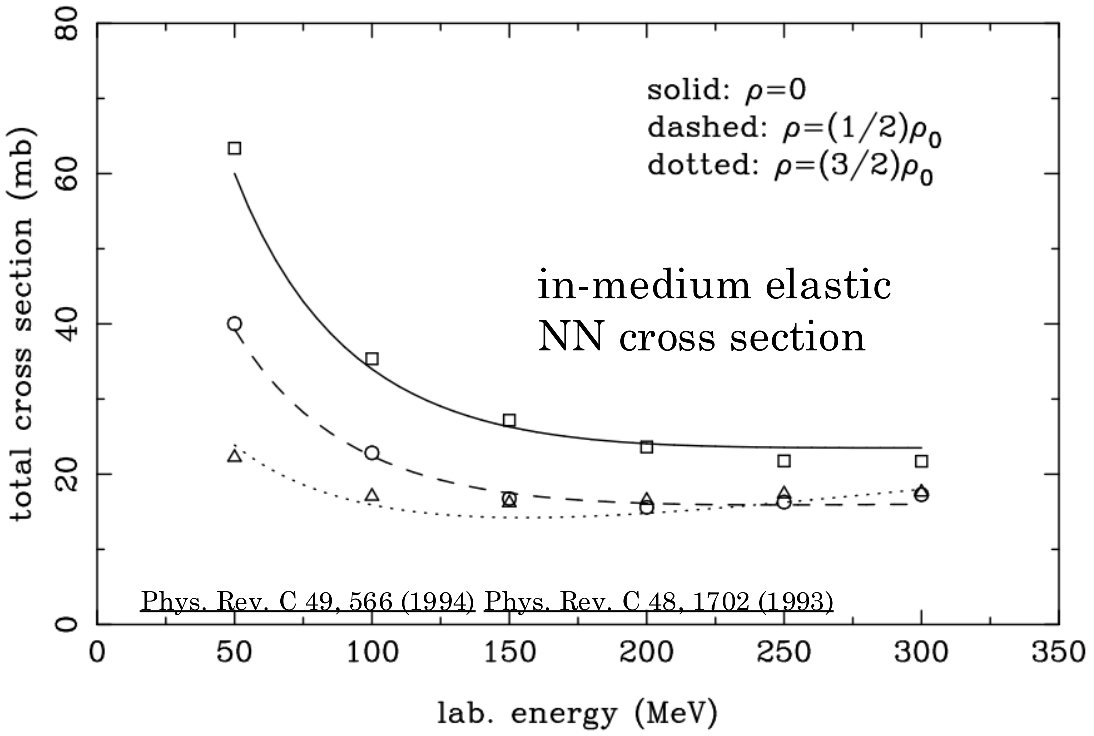
5. Report your great measurement and learn lots of new physics.
6. Improve the event generator modeling.

Utilizing the Data: In-medium Modifications

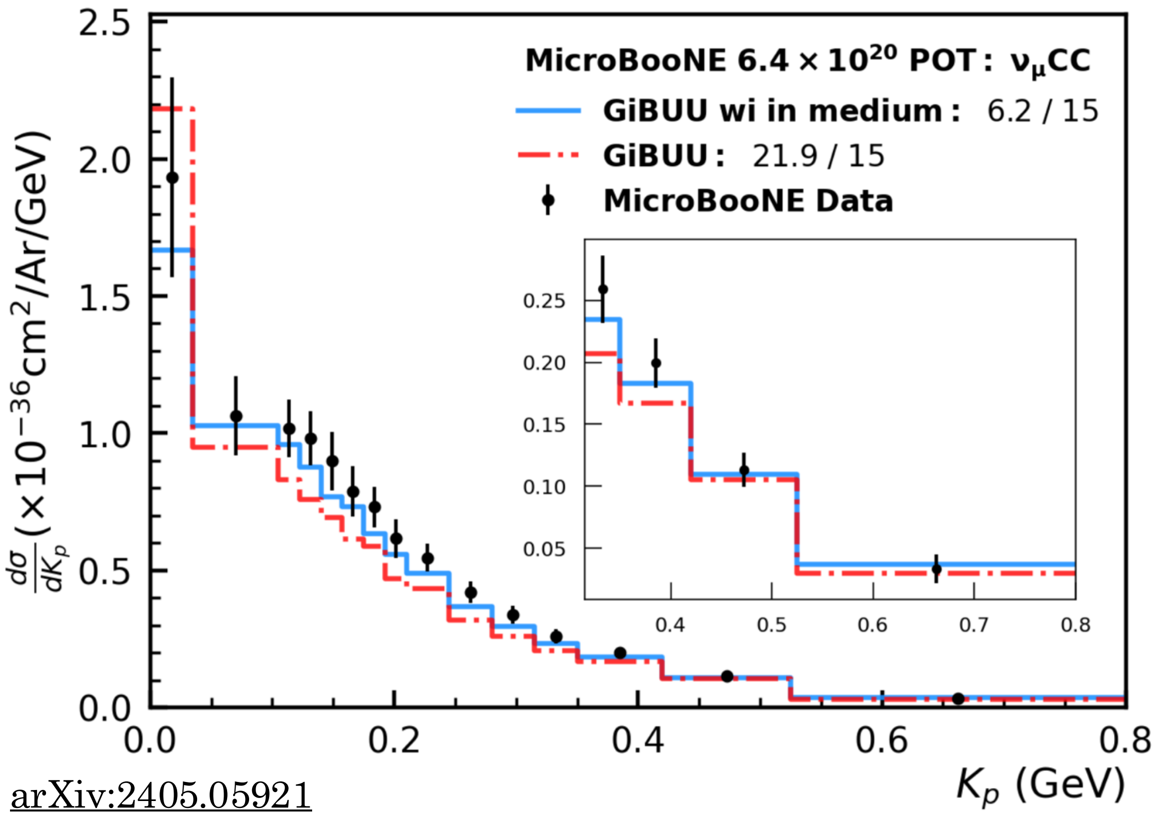
- The free parameters of **GiBUU**'s FSI model are the binding potentials and elementary cross sections of each particle species.
- Theoretical investigation suggest a lowering of NN cross sections when the nucleons are inside the nuclear medium.
  - **GiBUU** nominally uses the vacuum cross section in its FSI model.
- Features of the data suggest a need for in-medium modifications.
  - Overprediction of the proton spectra at forward angles, underprediction at backwards angles.

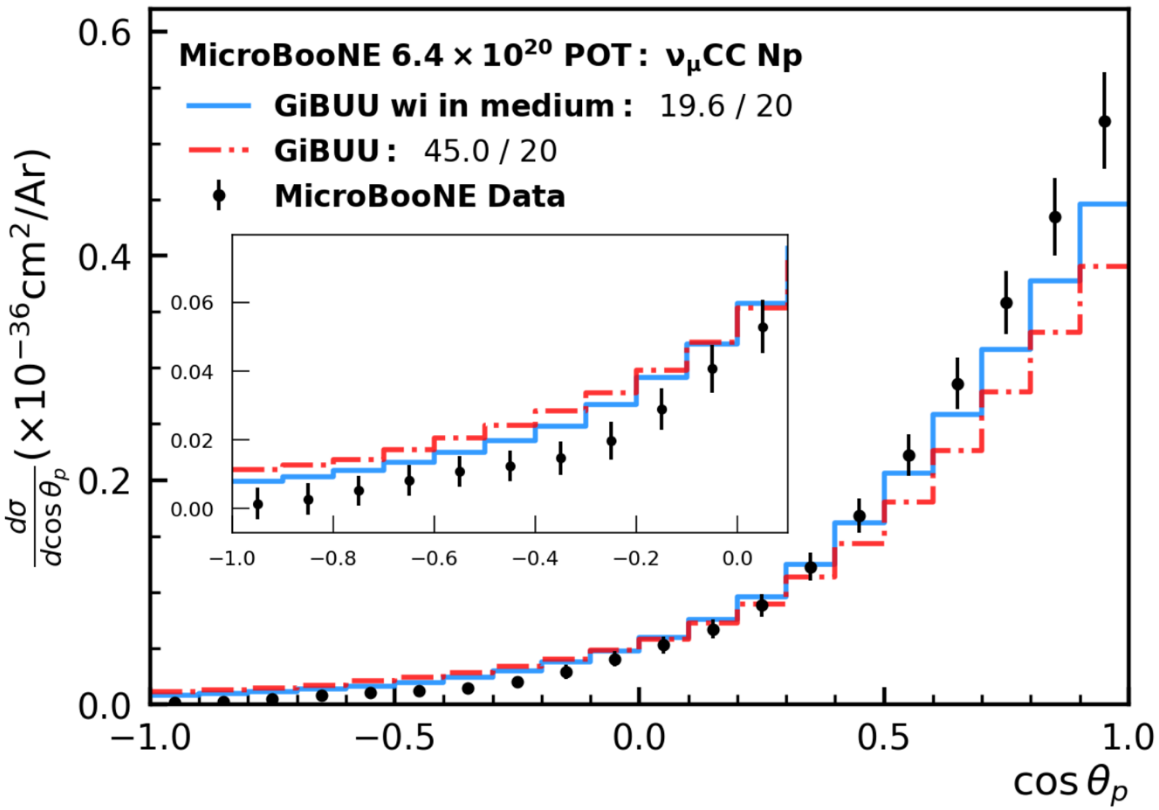




Utilizing the Data: In-medium Modifications

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

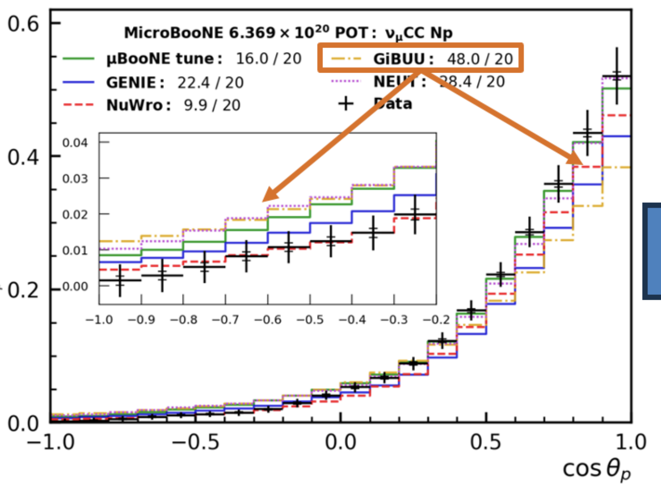


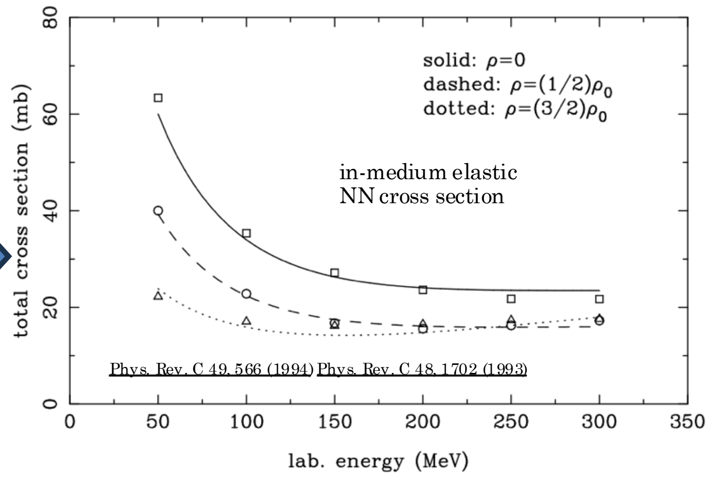


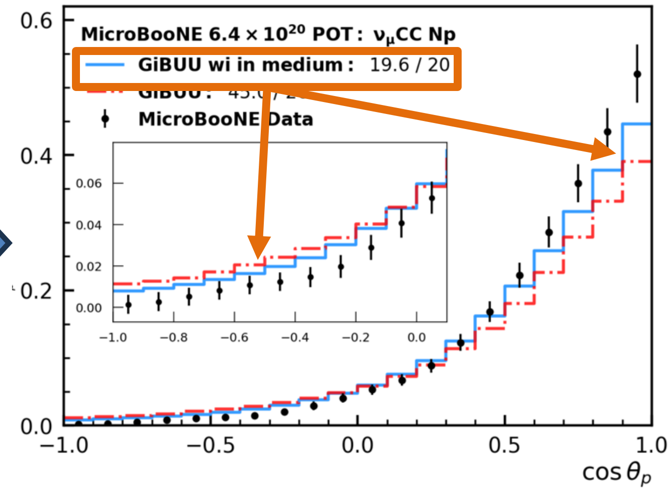
arXiv:2405.05921

Summary

- Precise modeling of neutrino-nucleus interactions is need to address a key topics in the neutrino sector.
  - These include determining the mass hierarchy and measuring CP violation.
- As a LArTPC, MicroBooNE is filling this need with cross section measurements that characterize neutrino-argon scattering in unprecedented detail.
- Recent results includes the first simultaneous measurements of final states with and without protons for muon neutrino scattering on argon.
  - Expose significant mismodeling of 0p final states by commonly used event generators.
  - Show sensitive to the modeling of nuclear effects and will drive improvements to the description of hadronic final states.



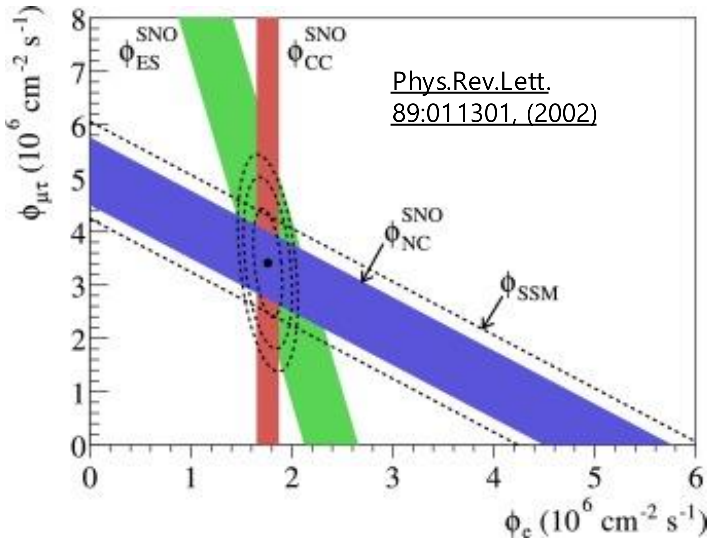




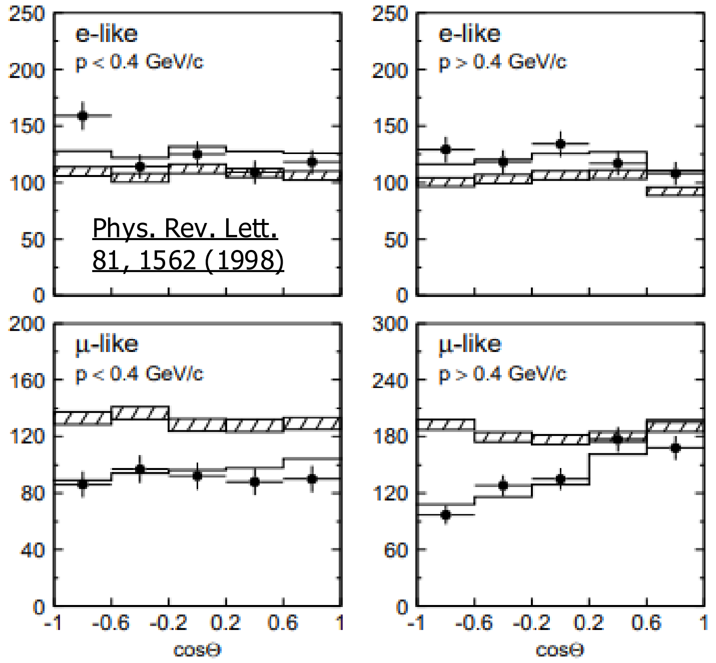
Backup

Masses and Oscillations: Discovery

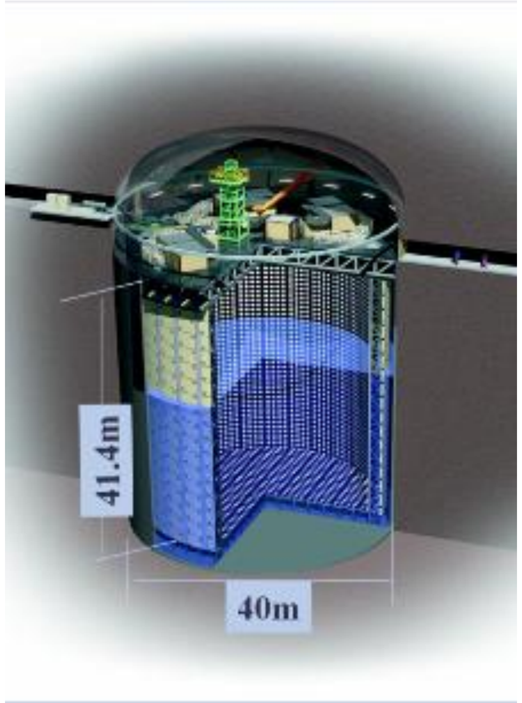
- Neutrinos were initially thought to be massless.
- In the early 2000s, SNO and SuperK discovered that neutrinos could oscillate between different flavors.
  - This also showed neutrinos had mass.
- One of the few decisive discoveries of non-SM physics.

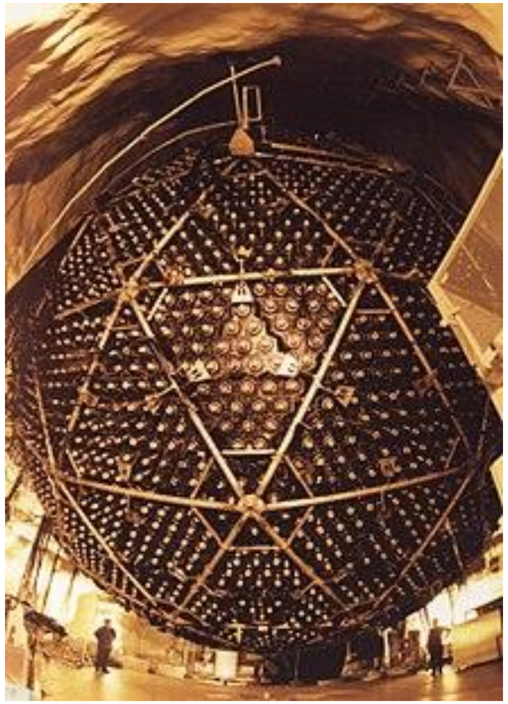


Colored bands intersecting with dotted lines indicates SNO data is consistent with oscillations.



Bold line is prediction with oscillation and hatched is without. SuperK data is consistent with oscillations.





Masses and Oscillations

- Nuetrinos also have three mass eigenstates, $|\nu_{m_n}\rangle$ where n = 1,2,3. These are **NOT** the same as the flavor eigenstates. Any flavor eigenstate can be described as a linear combination of the mass eigenstates:

$$|\nu_f\rangle = \sum_n U_{fn}|\nu_{m_n}\rangle \qquad \text{where } f = e, \mu, \tau$$

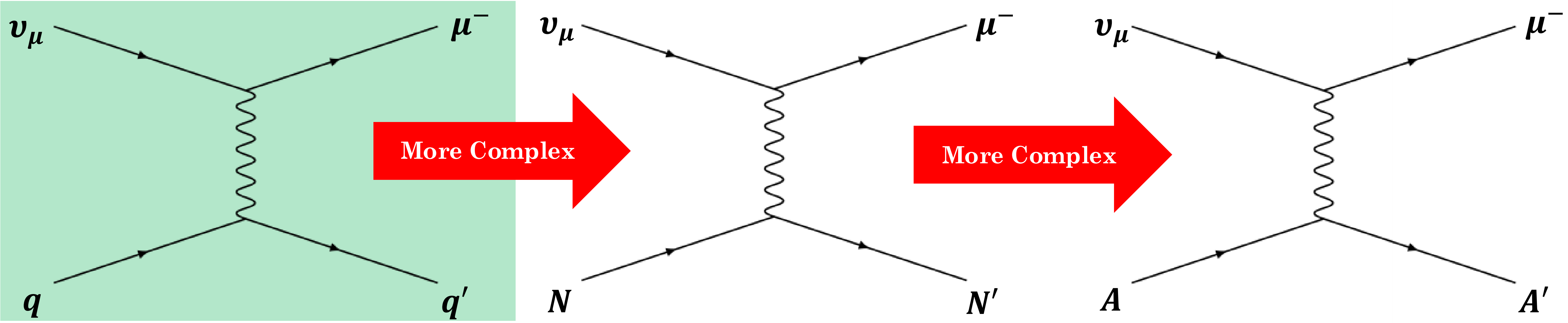
- $|\nu_f\rangle \neq |\nu_{m_n}\rangle$ means that $|\nu_f\rangle$ will evolve in time. This phenomena is called **neutrino oscillations.**

PMNS matrix describes the relation between mass and flavor eigenstates. It contains the **mixing angles**.

$$U_{\mathrm{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
θ = mixing angle

Modeling Cross Sections: Point-like to Nucleon to Nuclei

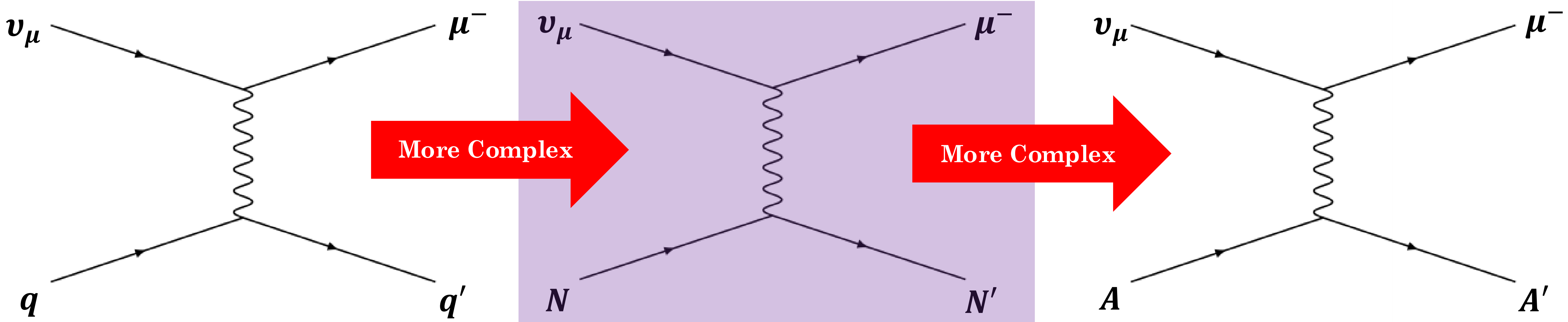


- **Neutrino scattering off point-like particles is "easy", you can do this with "basic" QFT.**
- However, modern detectors utilize nuclei as their target material.
  - Common examples are O, C, and Ar.
- Complexity increases as you go from point like scattering, to scattering off a nucleon to scattering off a nucleus (or a nucleon bound within a nucleus).

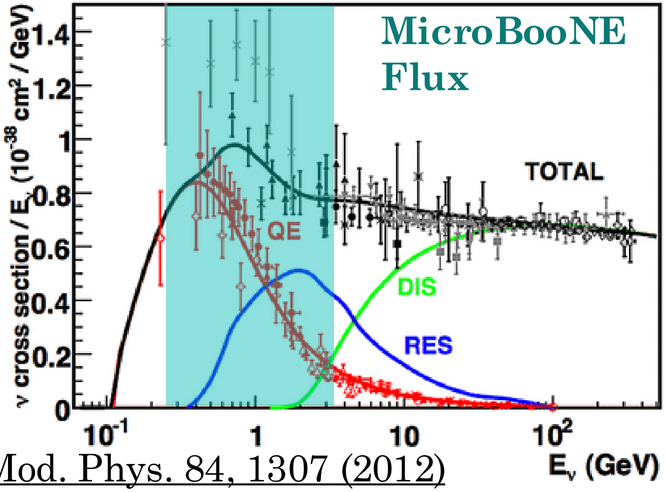
$$\frac{d\sigma}{d\Omega^*} = \frac{1}{64\pi^2 \hat{s}}\langle |M_{fi}|^2 \rangle = \frac{G_F^2}{4\pi^2}\hat{s}$$

$$M_{fi} = \frac{g_W^2}{2m_W^2} g_{\mu\nu} \left[\overline{u}_\downarrow(p_3)\gamma^\mu u_\downarrow(p_1)\right] \left[\overline{u}_\downarrow(p_4)\gamma^\nu u_\downarrow(p_2)\right]$$

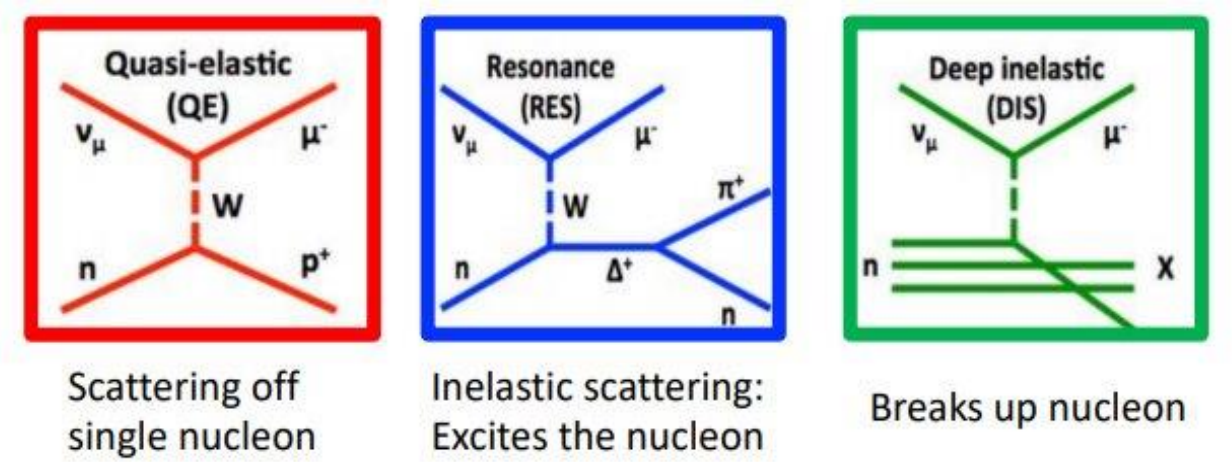
Modeling Cross Sections: Point-like to Nucleon to Nuclei



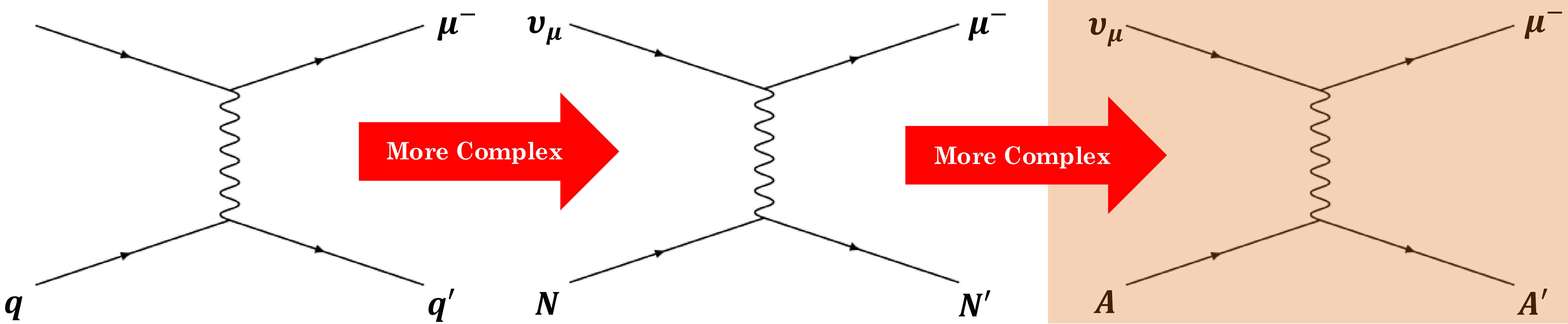
- **Neutrino-nucleon interactions are harder.**
- Different reaction mechanisms open up depending on the energy transfer and neutrino energy.
  - Neutrino beams are broadband, so models must account for all mechanisms simultaneously.



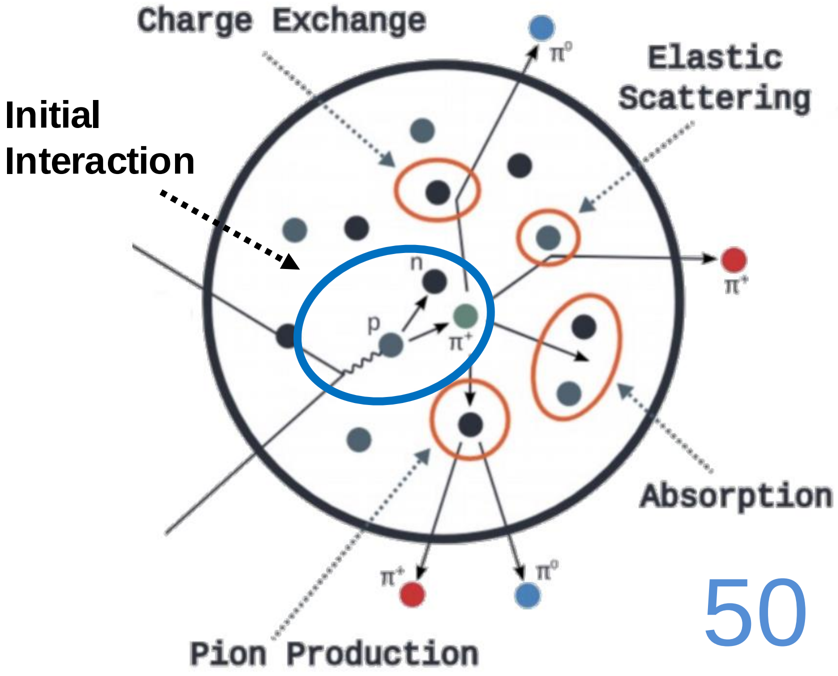
Rev. Mod. Phys. 84, 1307 (2012)



Modeling Cross Sections: Point-like to Nucleons to Nuclei

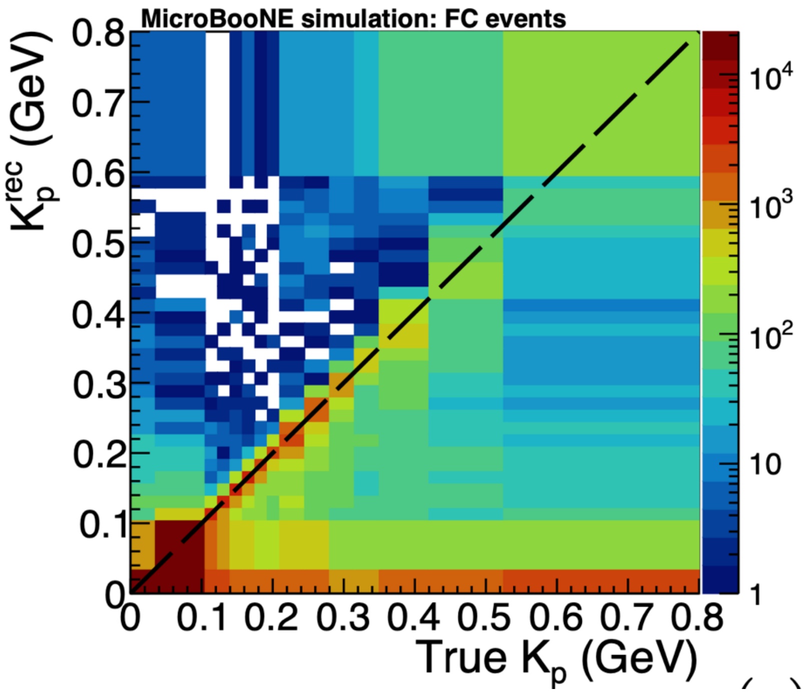


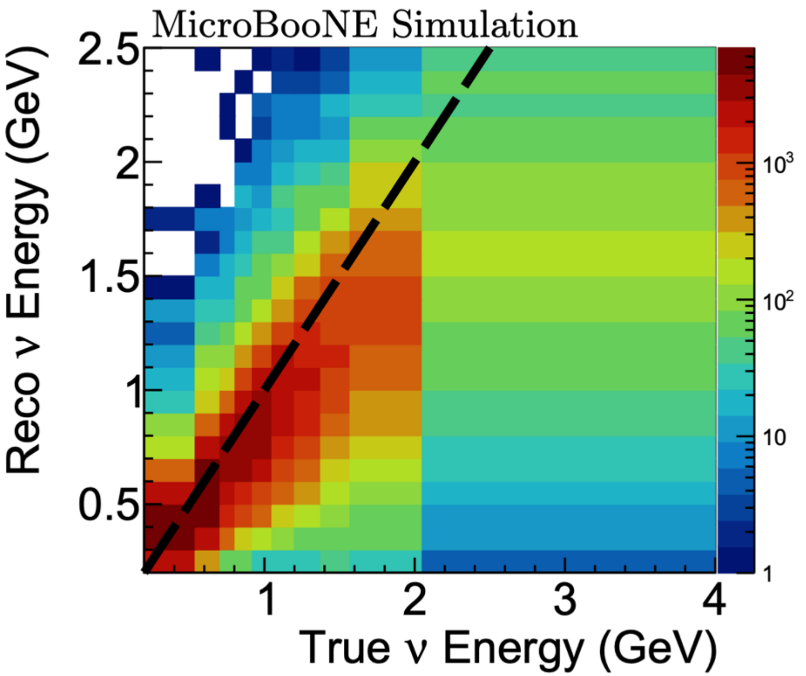
- **Neutrino-nucleus interactions are extremely complicated.**
- Can approximately factorize:
  - **Initial state interaction** between a neutrino and a nucleon.
  - **Final state interactions** experienced by products of the initial interaction as they exit the nucleus.
- Complicated nuclear effects modify the initial interaction:
  - nucleon-nucleon correlations.
  - structure of the nuclear ground state.
- FSI modifies multiplicity, energy and angular distributions of final state particles.



Energy Reconstruction

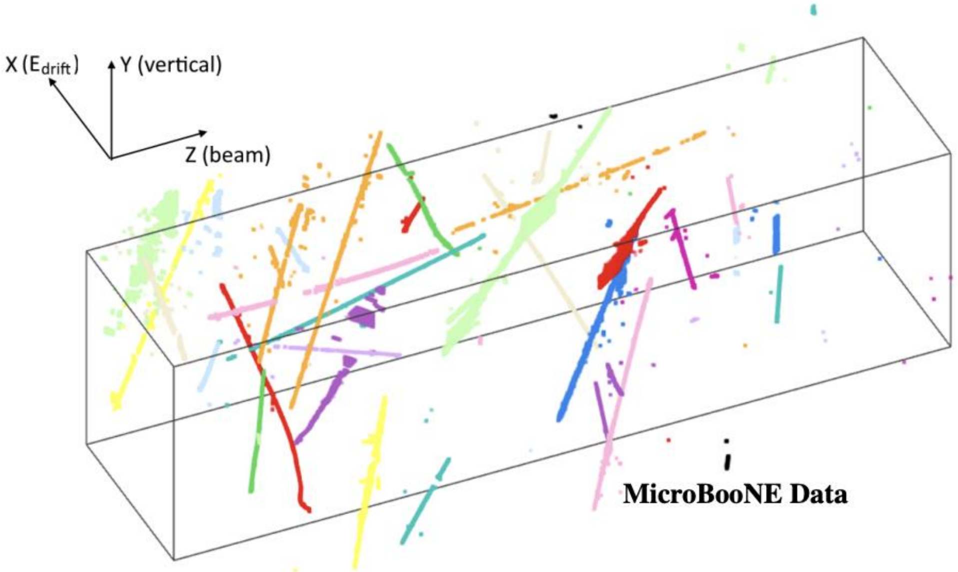
- Energy of tracks is estimated with particle range or summation of deposited charge per unit length:
  - Range used for all tracks >4cm that stop in the detector.
  - Summation of deposited charge used for all other tracks.
- Energy of showers is estimated by scaling the total deposited charge.
  - Scaling factors derived from simulation and calibrated based on pi0 mass reconstruction.
- ~10% resolution achieved on proton and muon energy.
- Neutrino energy is estimated with "calorimetric" sum of all particles' energies.
  - Includes identified particles masses and binding energies.
  - ~10-20% resolution achieved on neutrino energy.



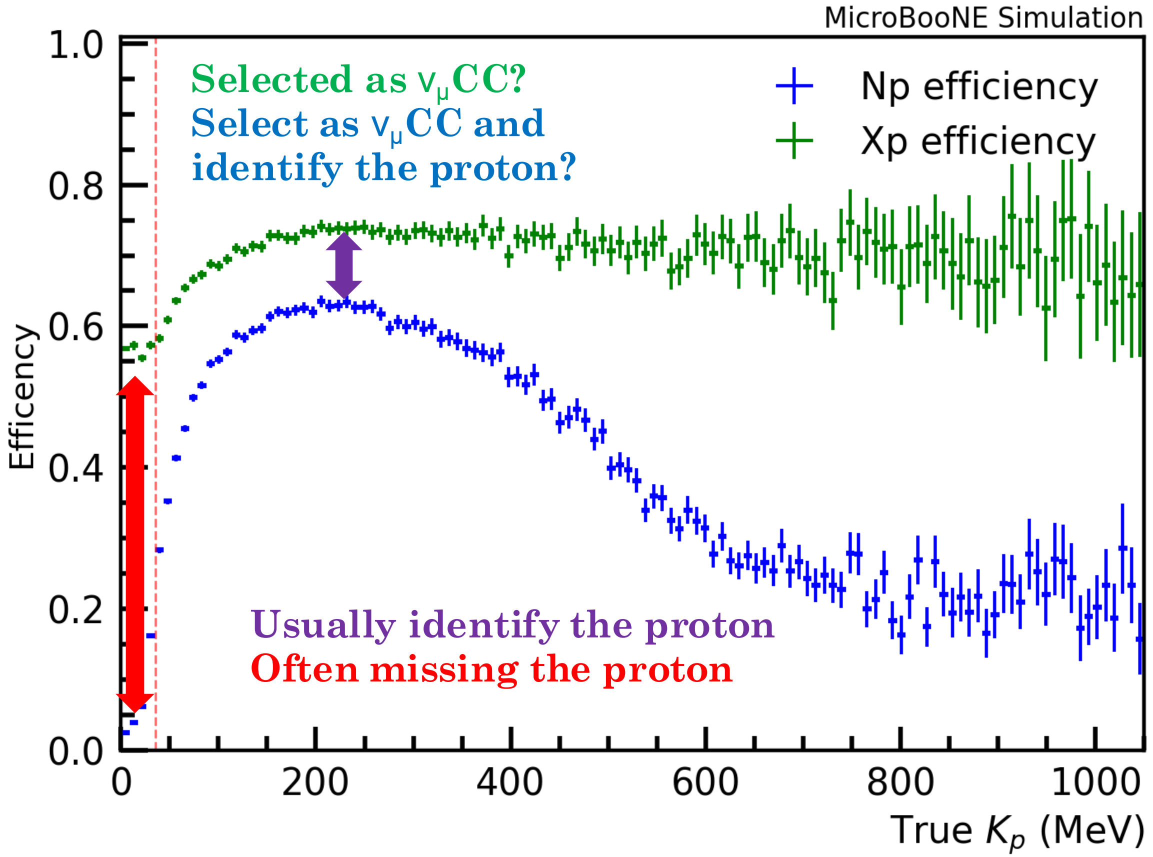


Event selection

- Selection divided into 0p and Np based on a 35 MeV kinetic energy threshold.
  - Signal definition divided in the analogous way, true 0p events have no protons, or no proton with more than 35 MeV of kinetic energy.
- Np selection has 49% efficiency for Np events and 0p selection has 54% efficiency for 0p events.

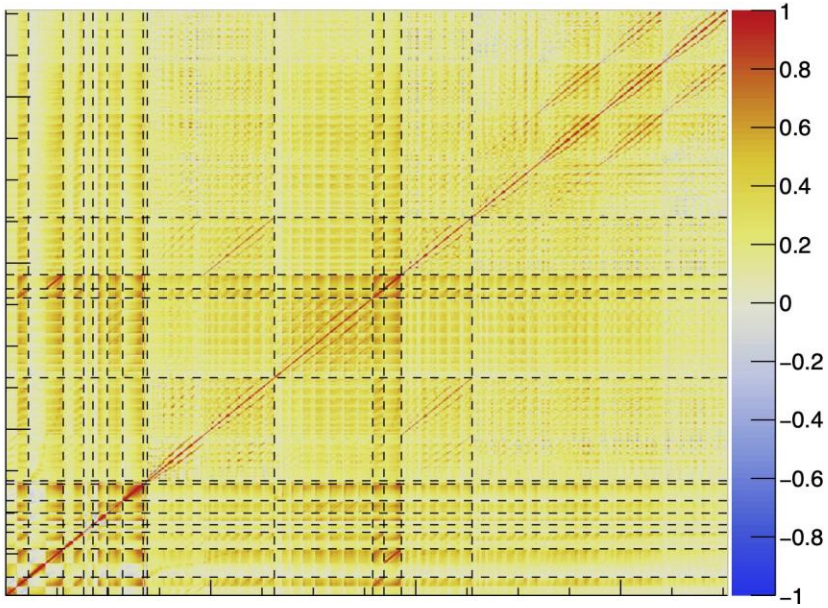


So many cosmic rays! Can you find the neutrino?

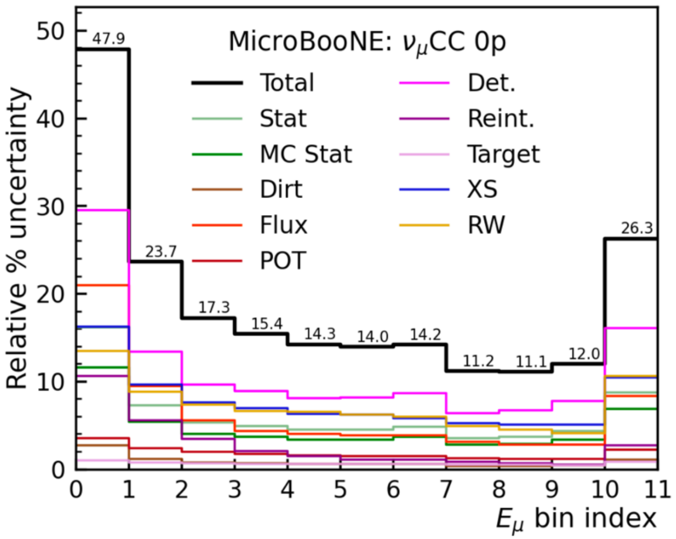


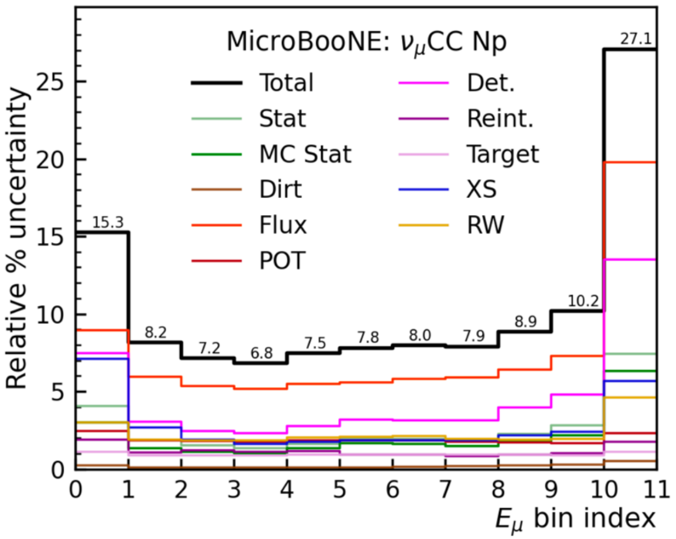
Systematic Uncertainties

- Consider multiple sources of systematic uncertainty:
  - Detector (Det, Target, reint)
  - Flux (Flux, POT)
  - Neutrino-nucleus interaction (XS, Dirt, RW).
- Systematics on the reconstructed distributions are estimated with the covariance matrix formalism.
- Report correlations across all measurements.
  - Ensures maximal statistical power, distributions are often highly correlated due to shared systematic uncertainties.



Correlation matrix for all 14 measurements.





MicroBooNE Cross Section Program

numuCC (charged current muon-neutrino):

CC Inclusive Phys. Rev. Lett. 123, 131801 (2019)

1D CC inclusive energy dependent Phys. Rev. Lett. 128, 151801 (2022)

3D CC inclusive energy dependent arXiv:2307.06413

CC1p0π Transverse Imbalance Phys. Rev. Lett. 131, 101802 (2023) and Phys. Rev. D 108, 053002 (2023)

CC1p0π Generalized Imbalance arXiv:2310.06082

CC1p0π Phys. Rev. Lett. 125, 201803 (2020)

CC2p arXiv:2211.03734

CCNp0π Phys. Rev. D102, 112013 (2020)

nueCC (charged current electron-neutrino):

CCNp0π Phys. Rev. D 106, L051102 (2022)

CC Inclusive Phys. Rev. D105, L051102 (2022)

CC Inclusive Phys. Rev. D104, 052002 (2021)

NC (neutral current):

NCπ^0 Phys. Rev. D 107, 012004 (2023)

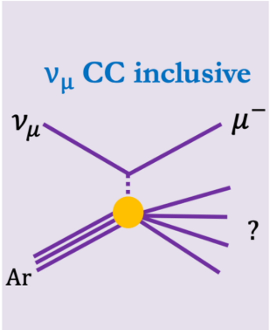
Rare channels:

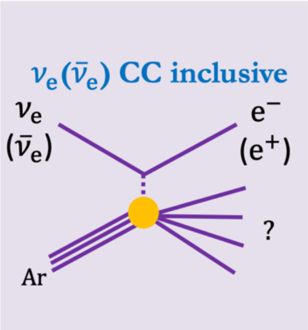
η production arXiv:2305.16249

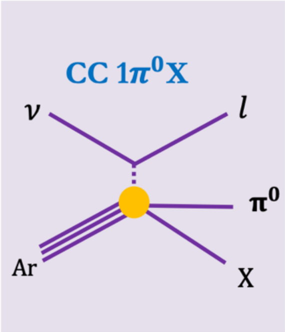
Λ production Phys. Rev. Lett. 130, 231802 (2023)

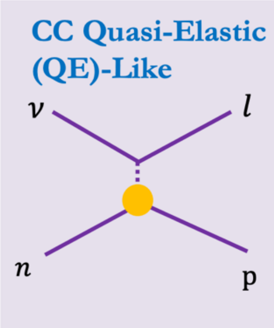
MicroBooNE has made good use of its existing data set with 15 public cross section measurements!

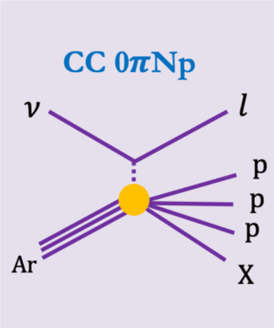
Includes cross section measurements for charged current muon-neutrinos, charged current electron-neutrinos, neutral-current pion production and rare channels.



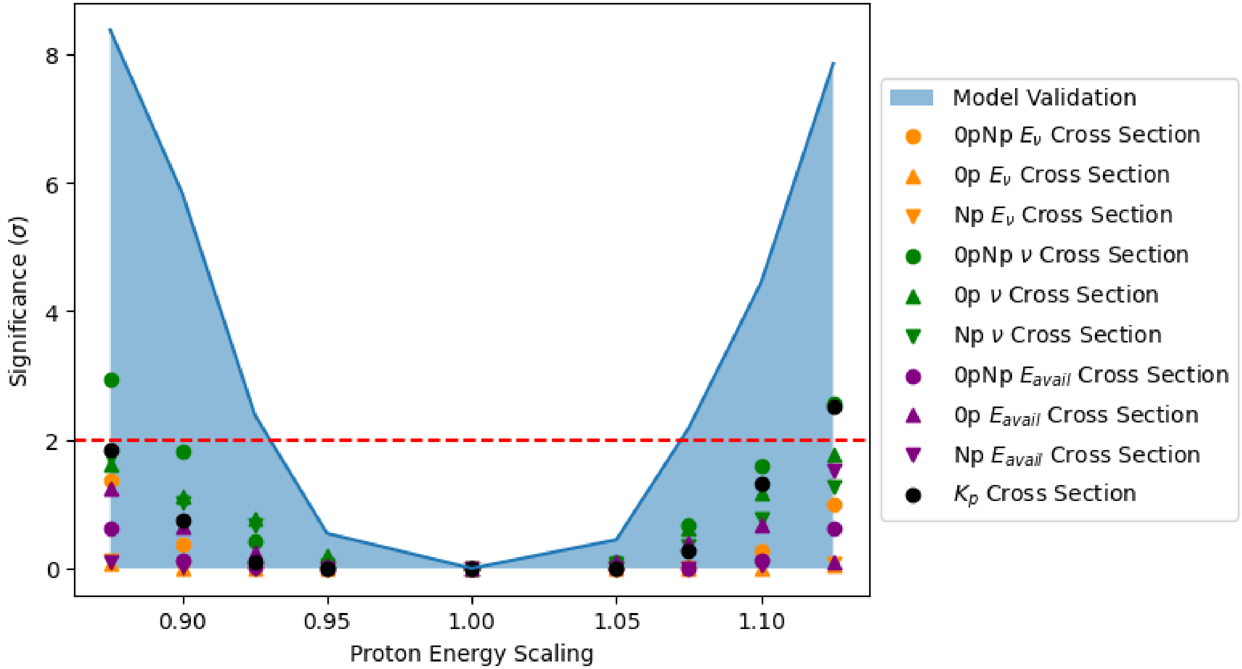


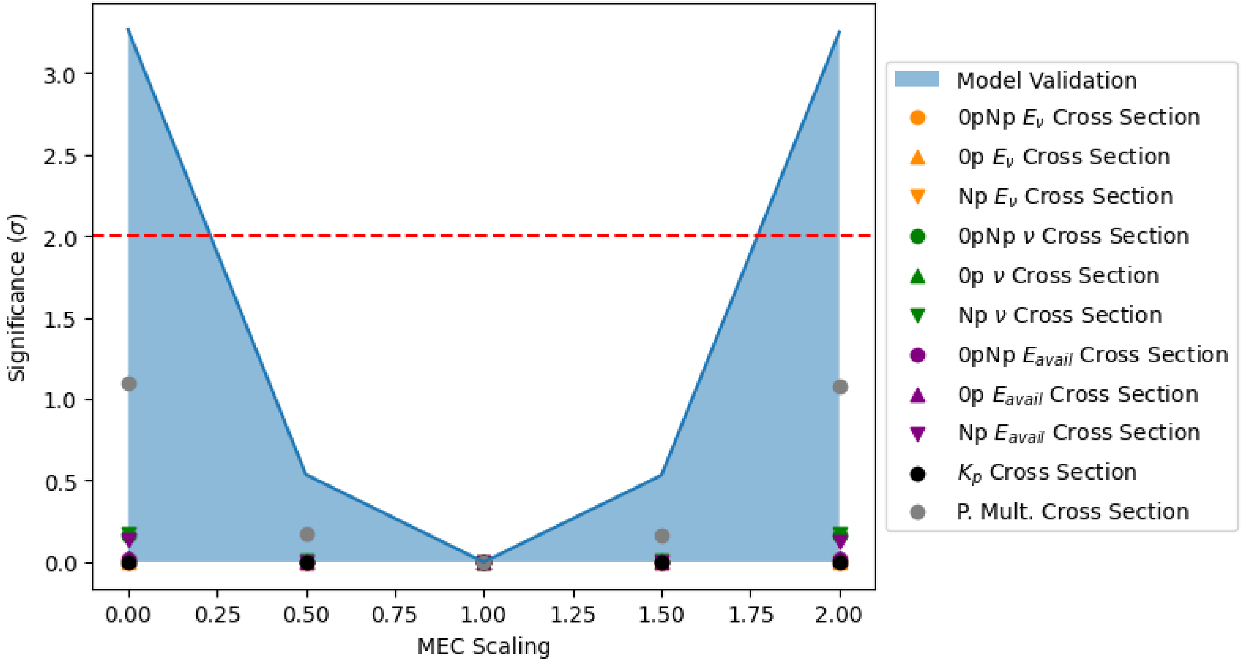






Fake Data Studies





- Additional fake data studies designed to demonstrate that the model validation is able to detect relevant mismodeling before it begins to bias the XS extraction.
- Generated fake data from MC by scaling:
  - Proton energy
  - MEC event weights
- In all cases, the amount of mismodeling detected by the validation is (significantly) greater than the amount of biased induced in the XS extraction.
- With these studies, we gain confidence that when a model passes validation, it will not induce significant bias.