Muon Neutrino Cross Section Measurements from MicroBooNE:
a detailed investigation of final states with and without protons

Benjamin Bogart

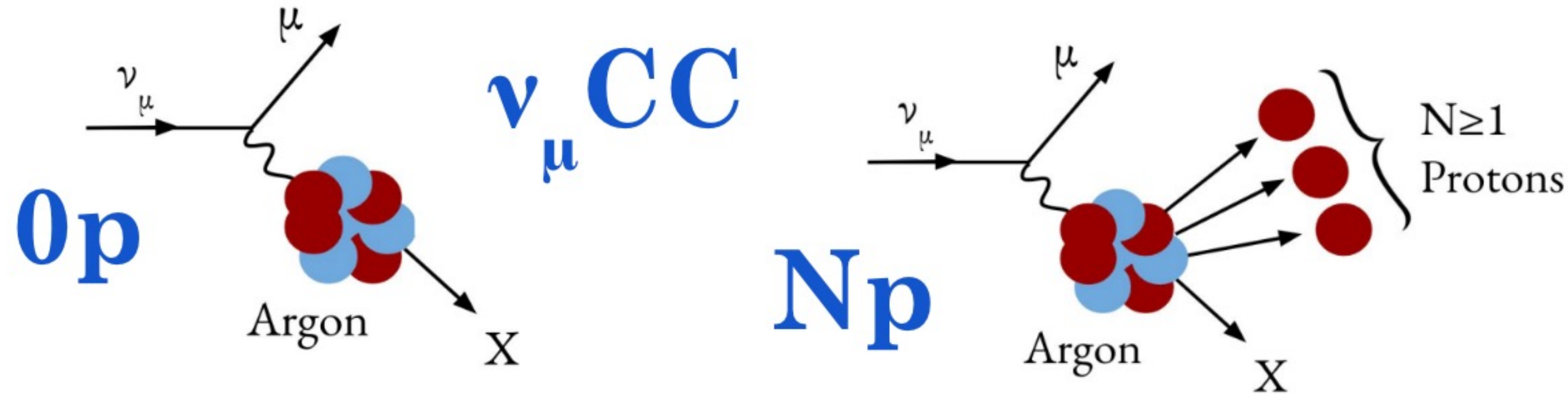
Fermilab Wine and Cheese

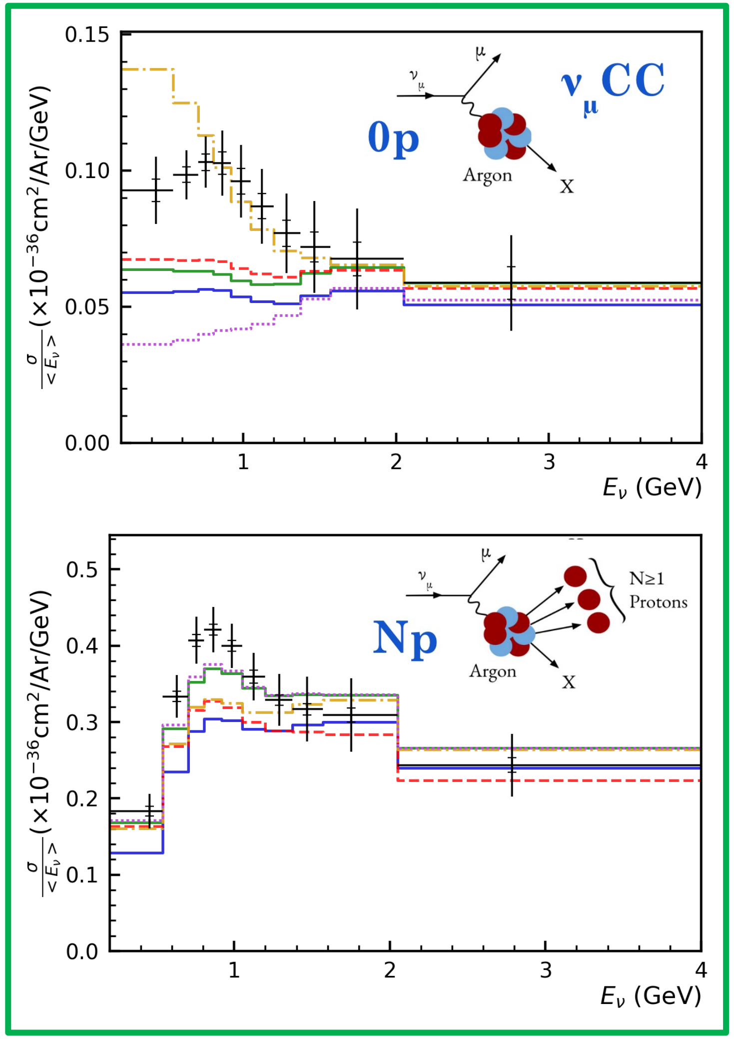
December 6th, 2024

µBooNE

UNIVERSITY OF MICHIGAN

Measuring Hadronic States In Inclusive Muon Neutrino Scattering



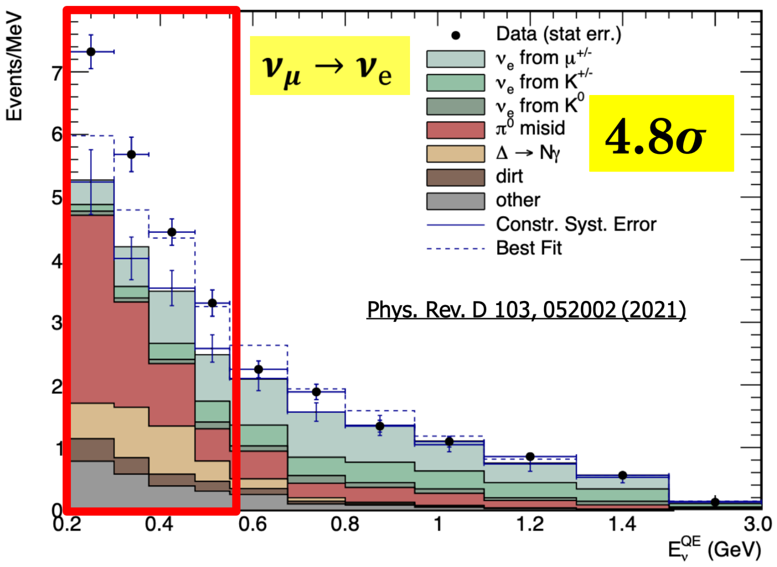


- First simultaneous measurements of final states with (Np) and without (0p) protons in muon neutrino argon scattering.
- Today, I hope to describe
  - what went into making these measurements.
  - what interesting things it can teach us about interaction modeling.
  - how this unique dataset will help enable discovery level physics in the neutrino sector.

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

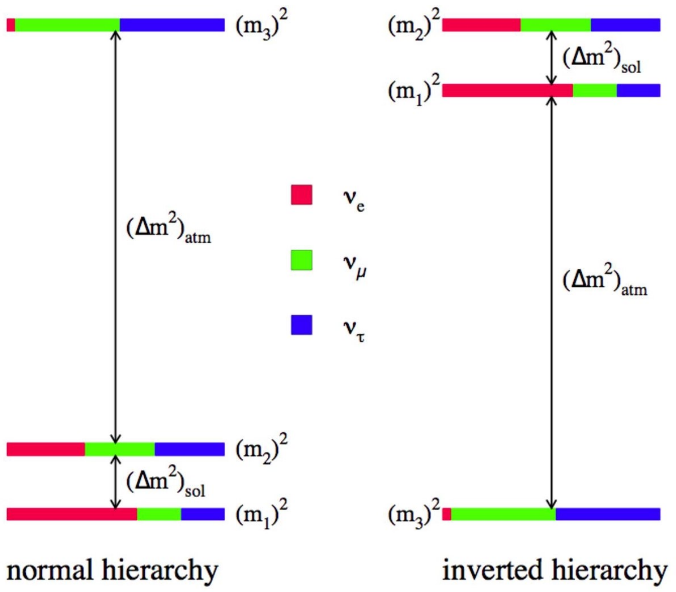
Mysteries in the Neutrino Sector

Is there a fourth neutrino?



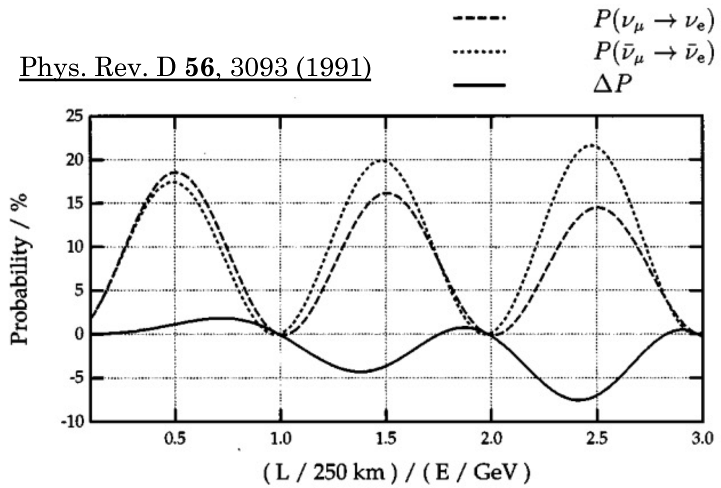
Several experiments suggest the existence of an eV scale neutrino.

Which neutrino is the heaviest?



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

Do anti-neutrinos behave differently than neutrinos?



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

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

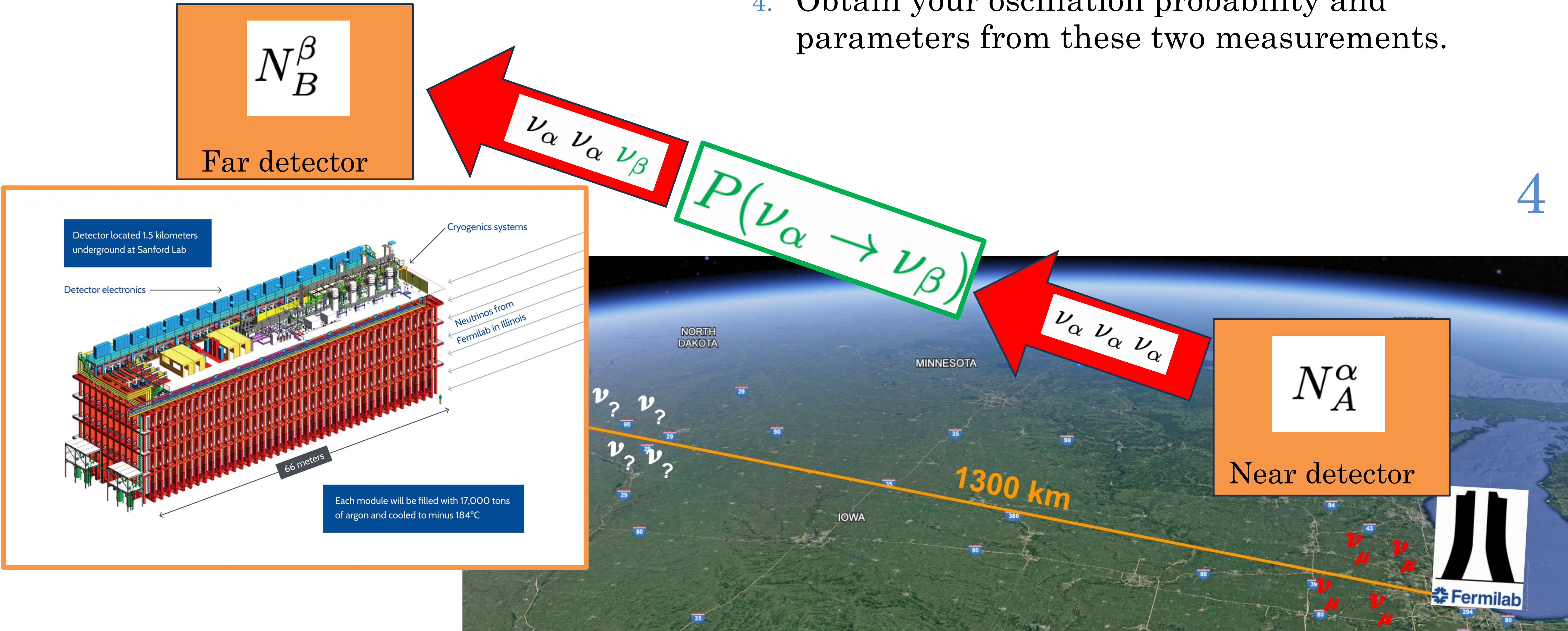
Solving these mysteries requires precise measurements of neutrino oscillations!

Measuring Oscillations

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

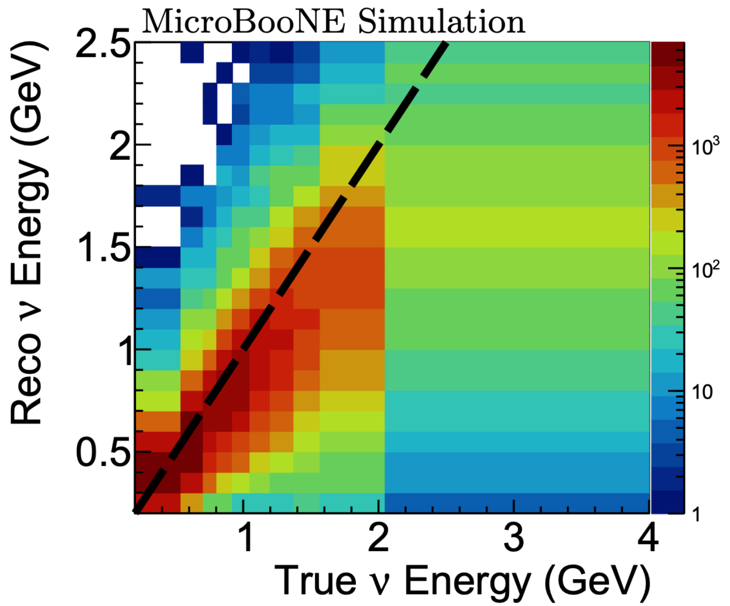
$$N_B^\beta \sim \Phi_B(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_B(E_\nu)\ \boxed{P(\nu_\alpha \to \nu_\beta)}$$

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

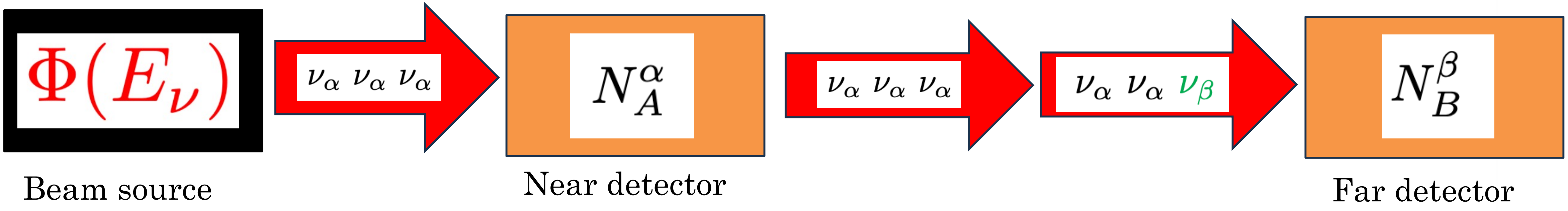


Measuring Oscillations:

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



- Easy, right? Well, maybe not so fast…
- Neutrino oscillations depend on the energy of the neutrino.
- Incoming neutrino's energy is unknown, needs to be reconstructed from observed final state particles.
- **Necessitates detailed flux, detector and cross section models!**

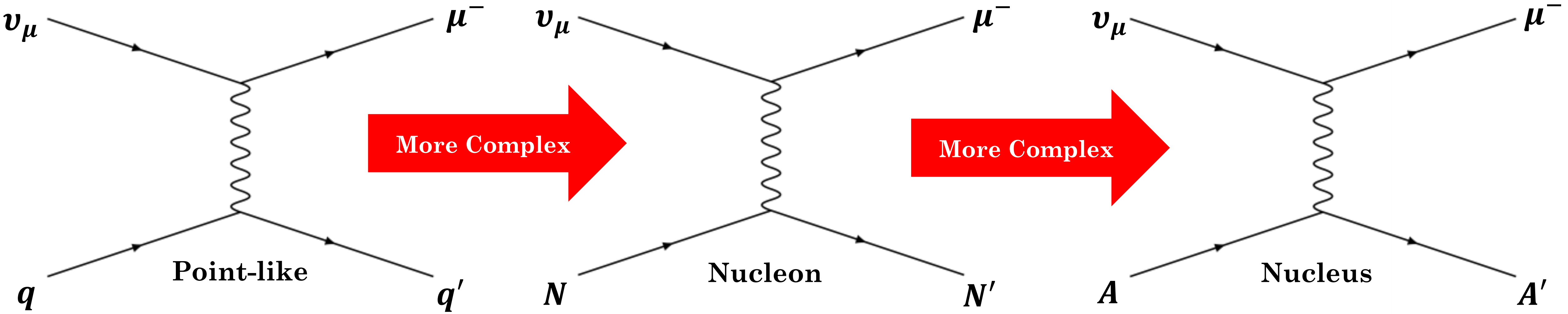


$$N_A^\alpha \sim \Phi_A(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_A(E_\nu)$$

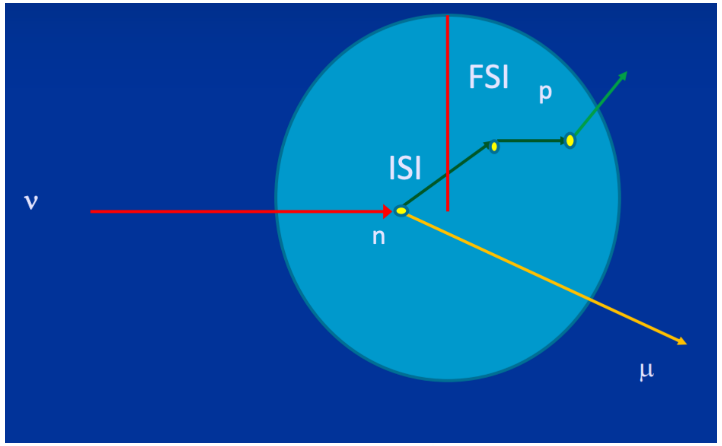
$$N_B^\beta \sim \Phi_B(L, E_\nu)\ \sigma(E_\nu)\ \epsilon_B(E_\nu)\ P(\nu_\alpha \rightarrow \nu_\beta)$$

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

Neutrino-Nucleus Cross Section Models



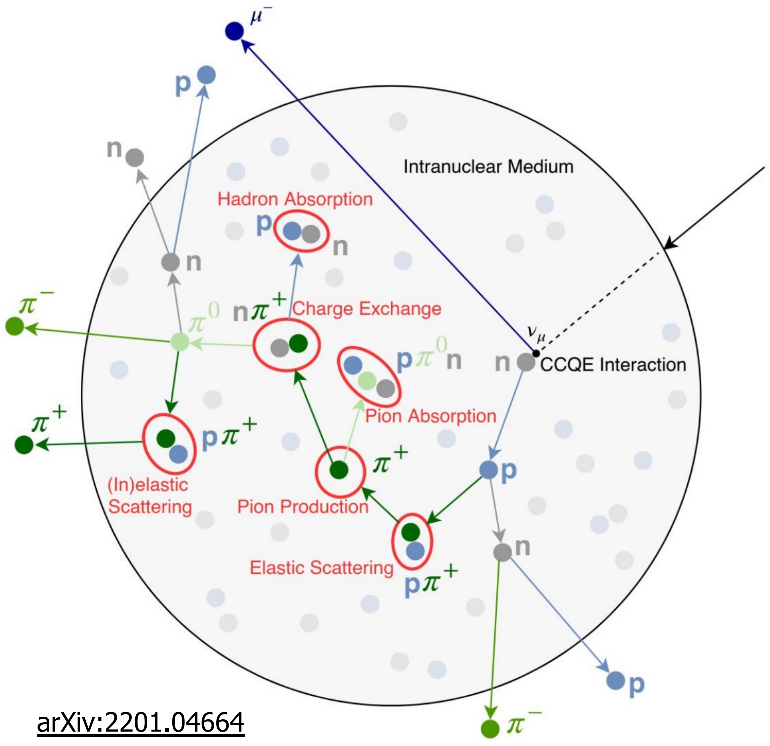
- Complexity increases from point like scattering, to scattering off a nucleon to scattering off a nucleus (or nucleon[s] bound in a nucleus).
  - Modern detectors utilize nuclei like, O, C or Ar, as their target material.
- Can approximately factorize neutrino-nucleus interactions:
  - **Initial state interaction (ISI)** between a neutrino and a nucleon.
  - **Final state interactions (FSI)** of the initial interaction products as they exit the nucleus.



Neutrino-Nucleus Cross Section Models

A neutrino-nucleus cross section model must:

- Predict the full final state.
  - All particles must be accounted for in energy reconstruction.

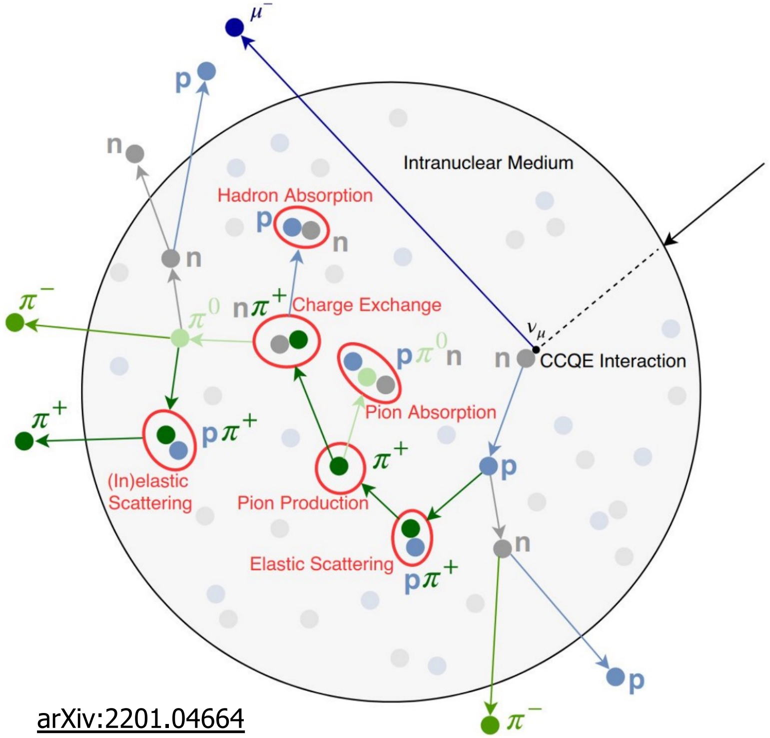


arXiv:2201.04664

Neutrino-Nucleus Cross Section Models

A neutrino-nucleus cross section model must:

- Predict the full final state.
  - All particles must be accounted for in energy reconstruction.
- Incorporate a variety of interaction channels:
  - Quasi-Elastic (QE)
  - Resonance Production (RES)
  - Deep Inelastic Scattering (DIS)



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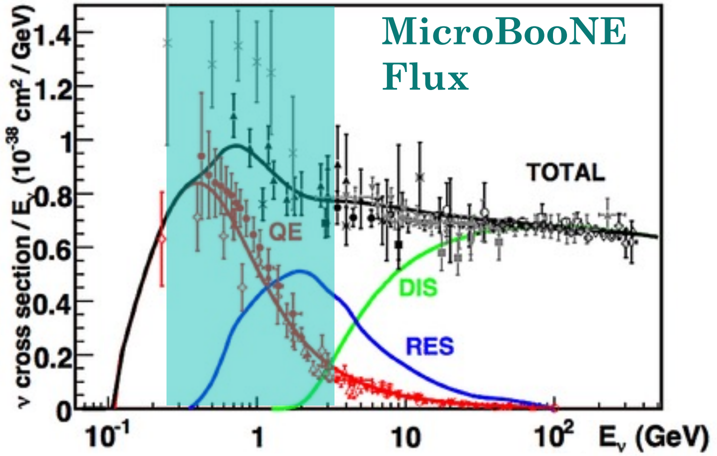
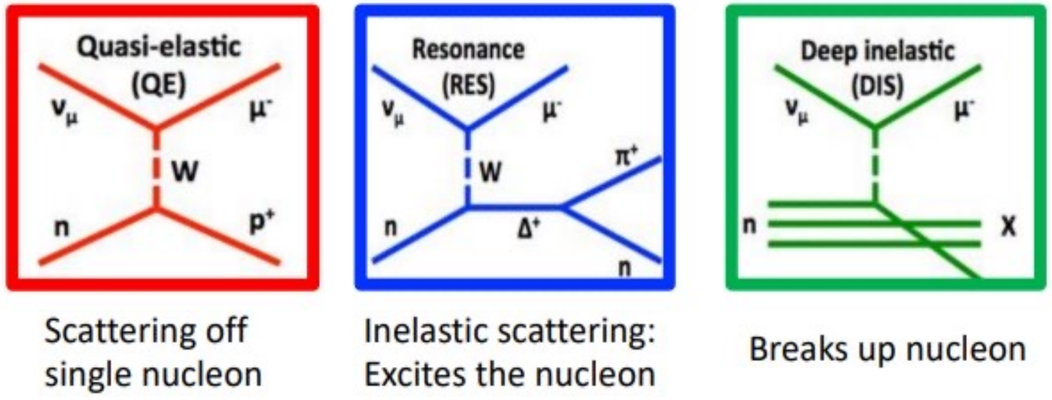


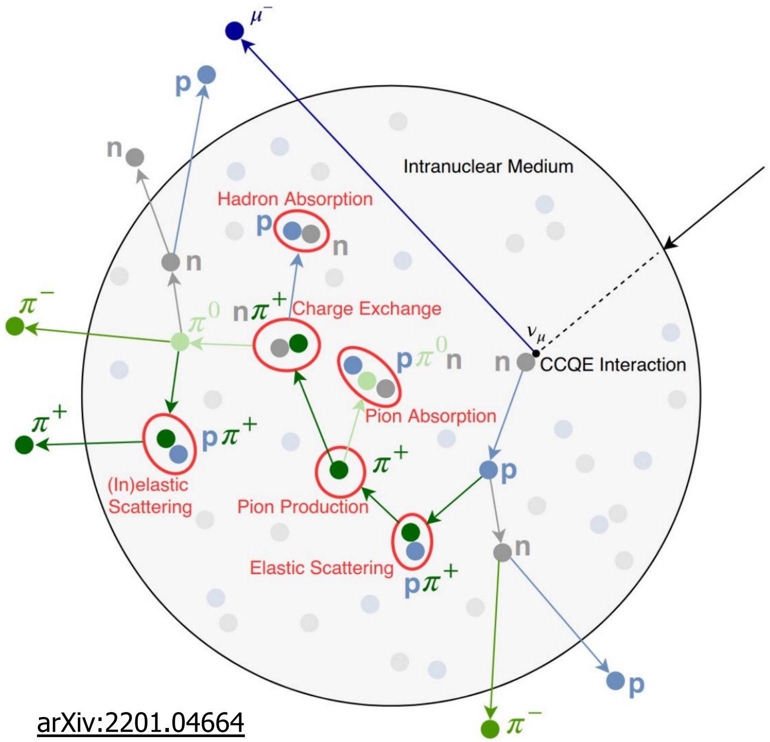
Rev. Mod. Phys. 84, 1307 (2012)



Neutrino-Nucleus Cross Section Models

A neutrino-nucleus cross section model must:

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



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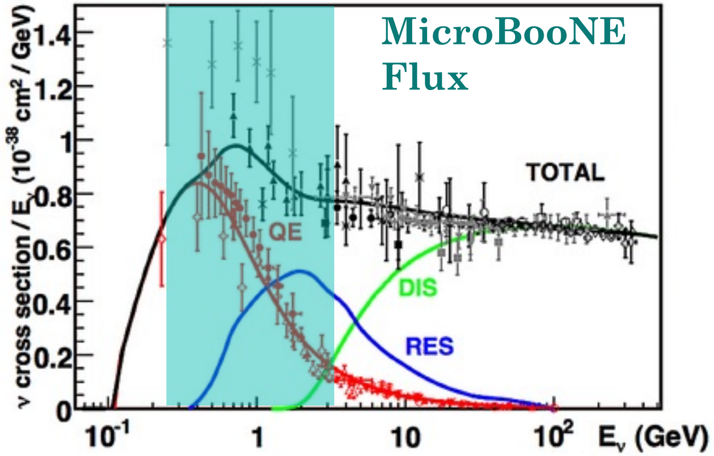

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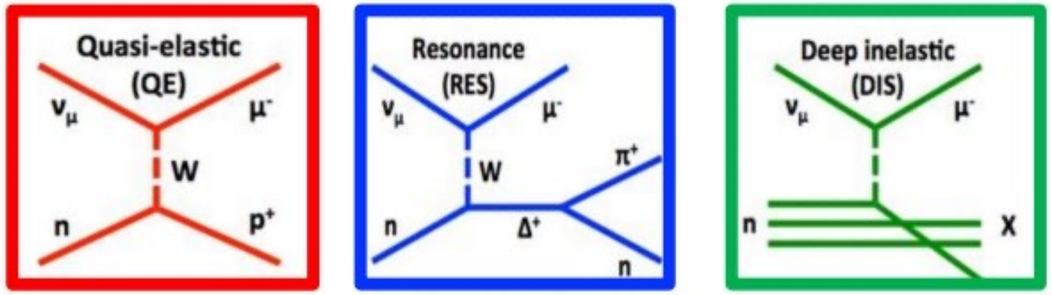


Scattering off single nucleon

Inelastic scattering: Excites the nucleon

Breaks up nucleon

Neutrino Event Generators

- Event generators combine models for different interaction modes with a simulation of nuclear effects.
- Different generators predict different mappings between reconstructed and true quantities.

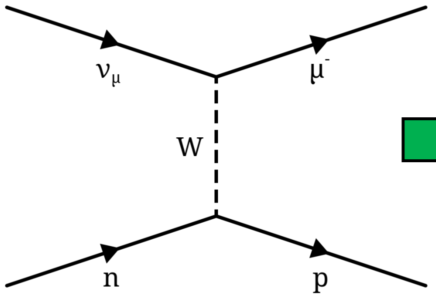
NuWro

GENIE

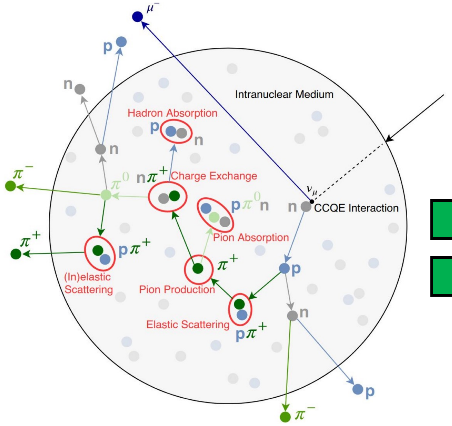
GiBUU

NEUT

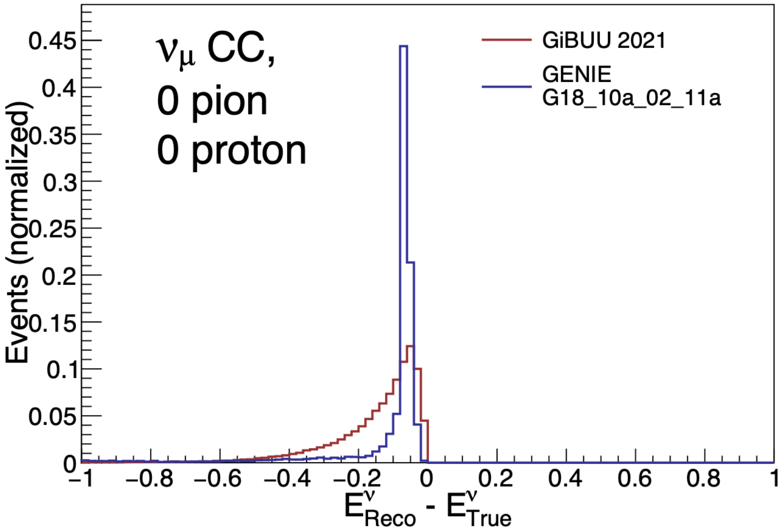
ACHILLES



Nucleon level

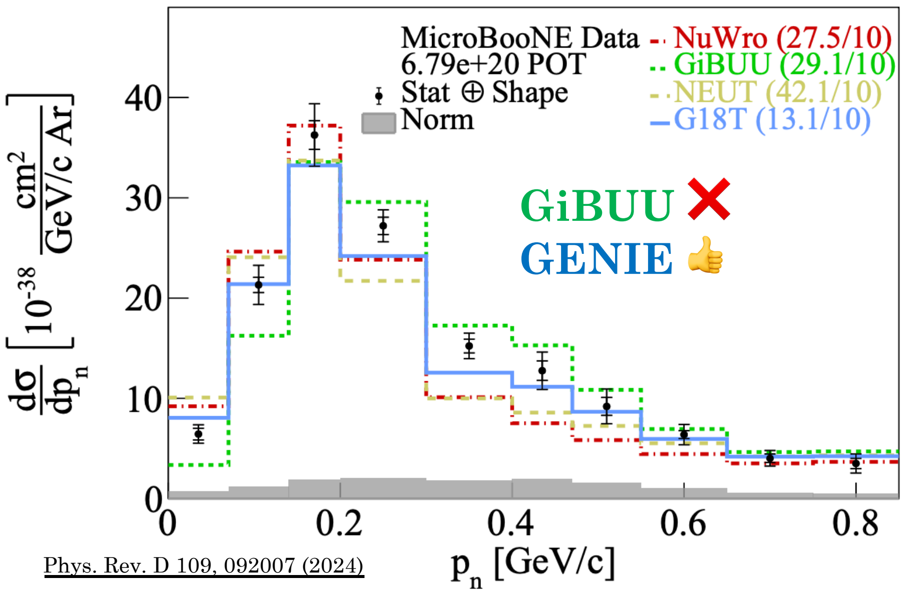


Nuclear effects

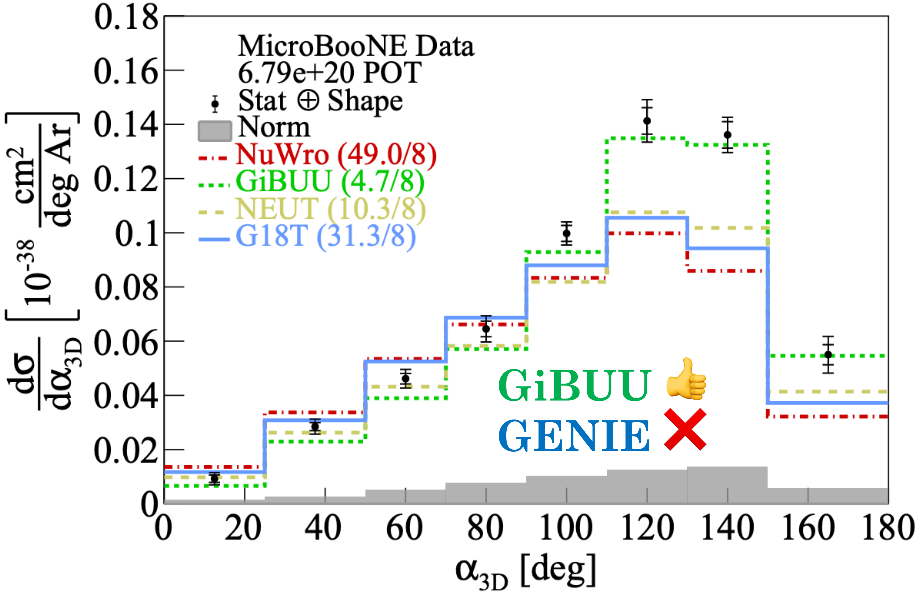


Neutrino Event Generators

- Event generators combine models for different interaction modes with a simulation of nuclear effects.
- Different generators predict different mappings between reconstructed and true quantities.
- No current generator can describe all data.
- **Cross section data is required to drive improvements to event generators.**



Phys. Rev. D 109, 092007 (2024)



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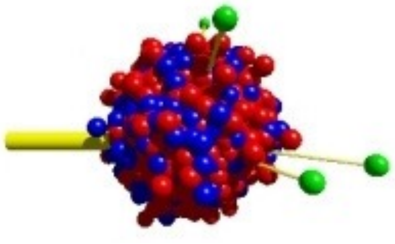

GiBUU

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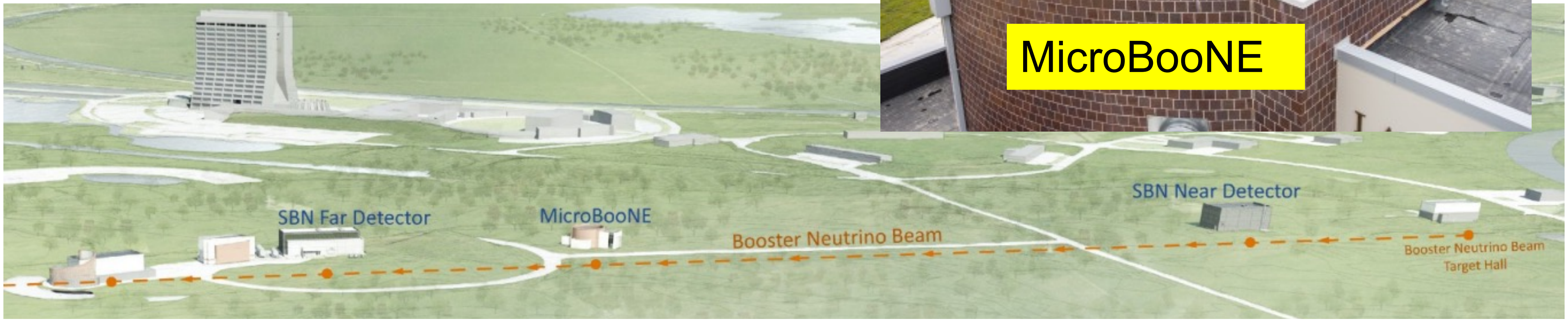
ACHILLES

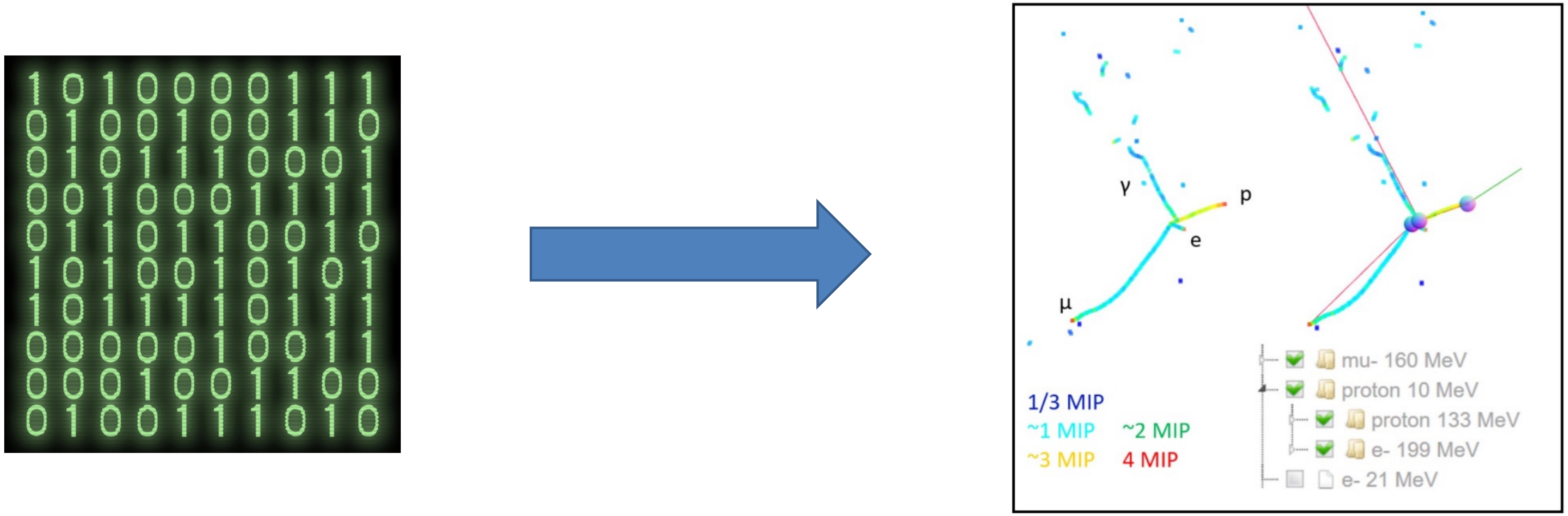
Measuring Neutrino-Nucleus Cross Sections

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



Measuring Neutrino-Nucleus Cross Sections

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



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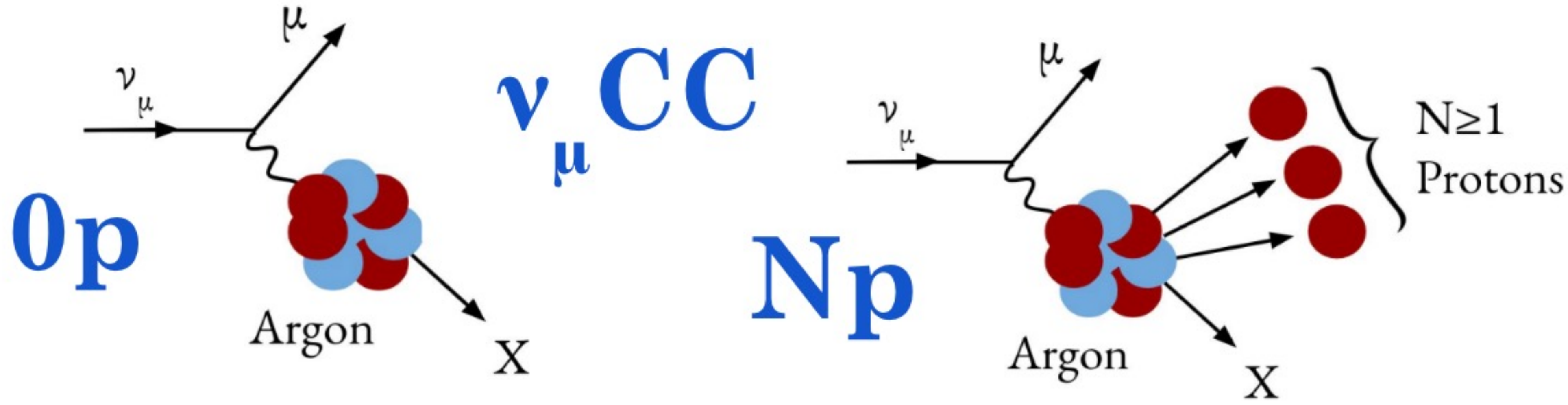

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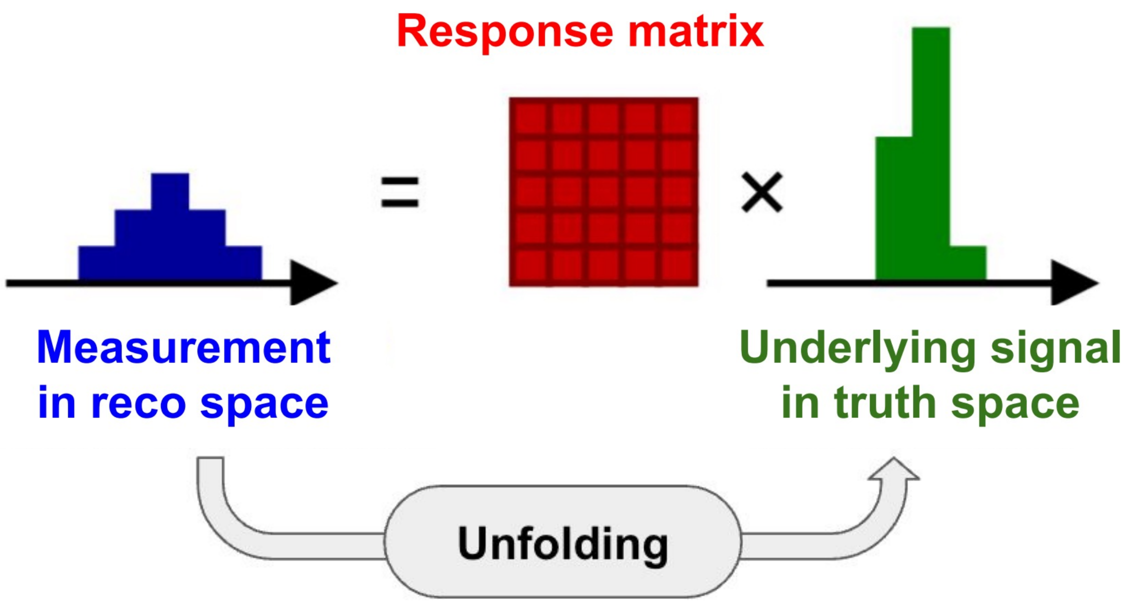
4. Quantify your uncertainties and extract the cross section from the events you selected.



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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)

Measuring Neutrino-Nucleus Cross Sections

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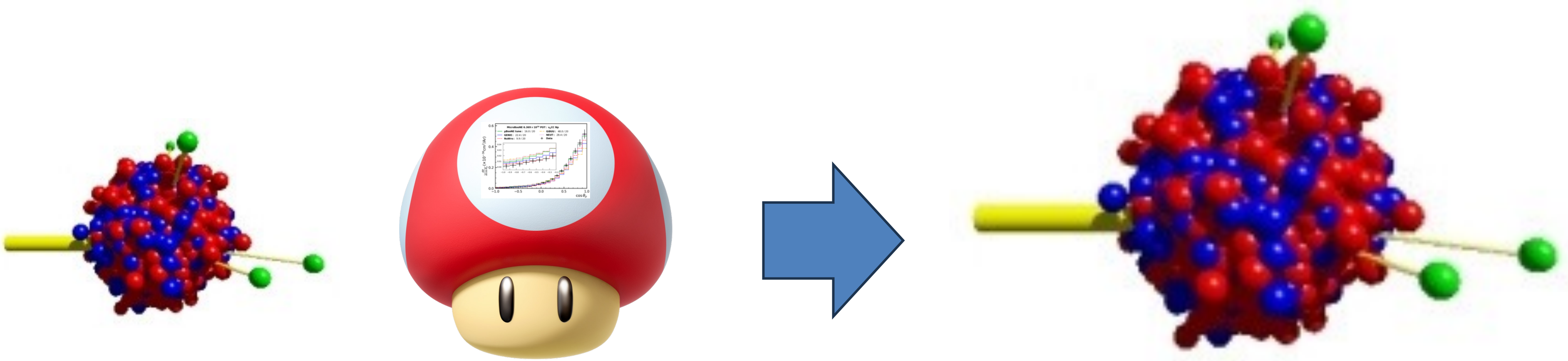
4. Quantify your uncertainties and extract the cross section from the events you selected.
5. Report your great measurement and learn lots of new physics.
6. Improve the event generator modeling.



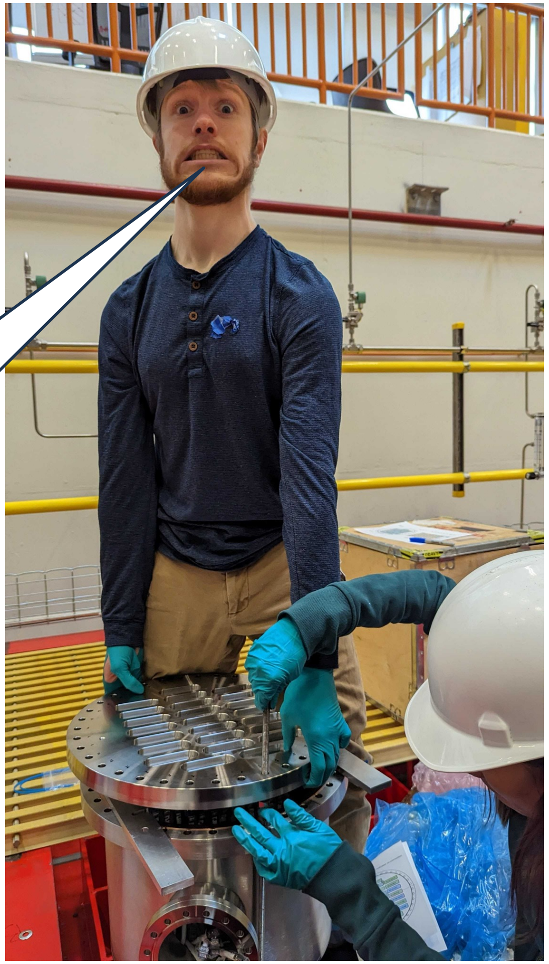
Measuring Neutrino-Nucleus Cross Sections

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

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

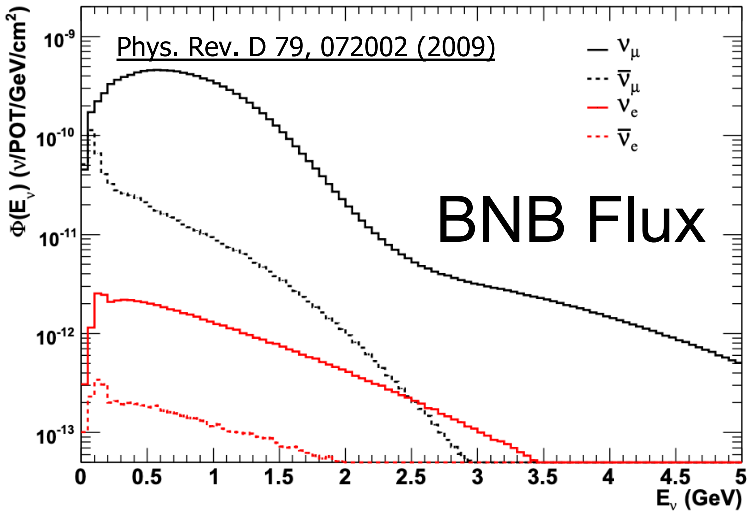
I have done a terrible thing:
I have postulated a particle that cannot be detected.
-Wolfgang Pauli

Challenge accepted.



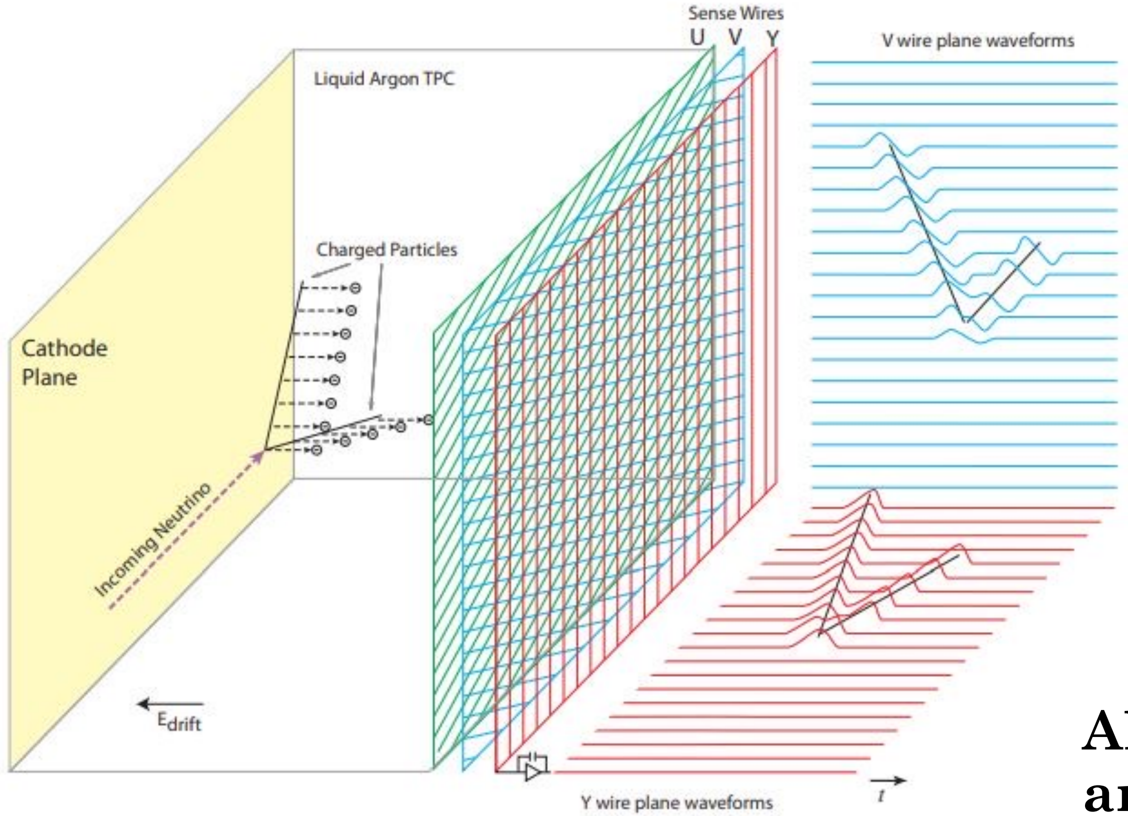
MicroBooNE

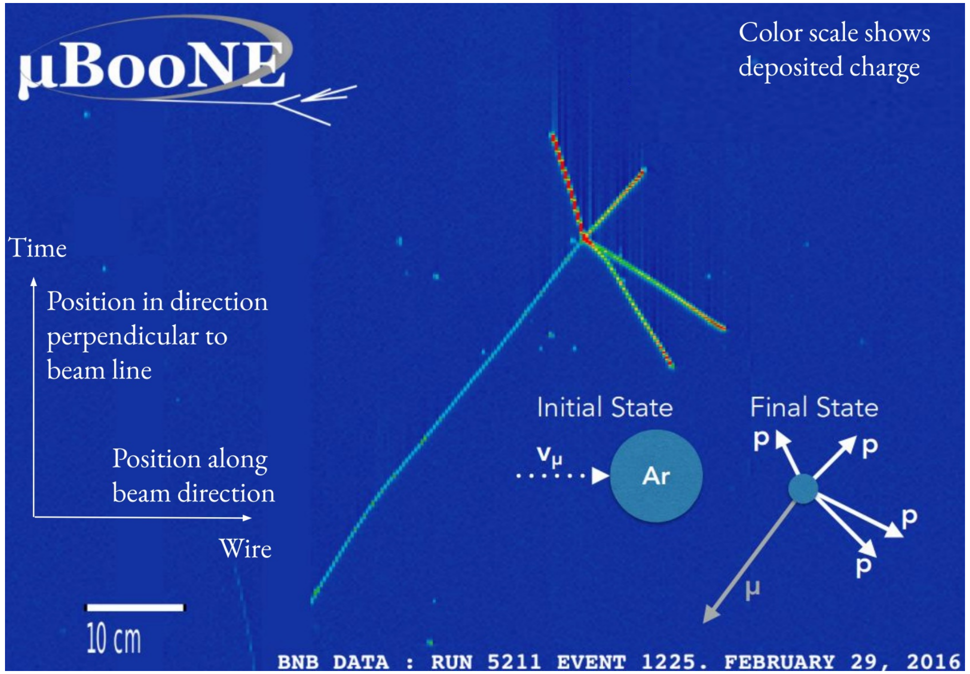
- LArTPC detector located in the Booster Neutrino Beam (BNB) at Fermilab.
- Collected data from 2015 to 2021.
- Physics goals:
  - Test the Low Energy Excess (LEE).
  - Demonstrate capabilities of LArTPC.
  - Explore BSM physics
  - **<u>Study neutrino-argon interactions.</u>**



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.
  - PMTs provide timing measurement from light.
  - High voltage field drifts electrons to the wire planes enabling imaging based on charge deposited on each wire.

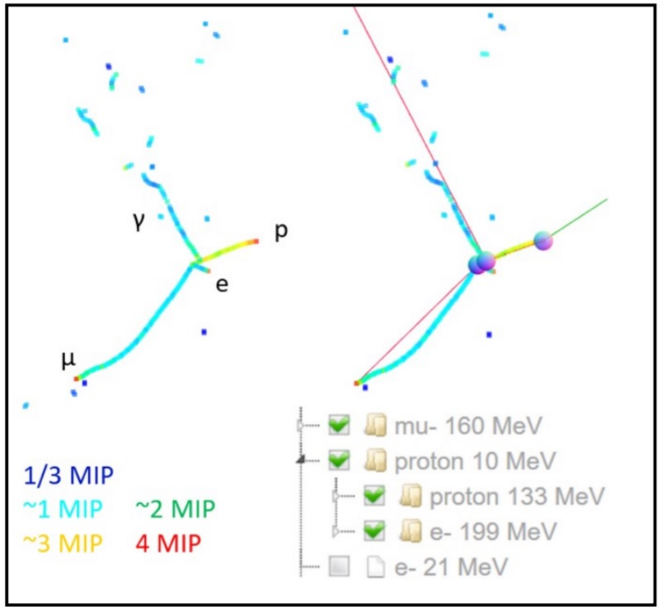




Allows for excellent particle identification and detailed event reconstruction.

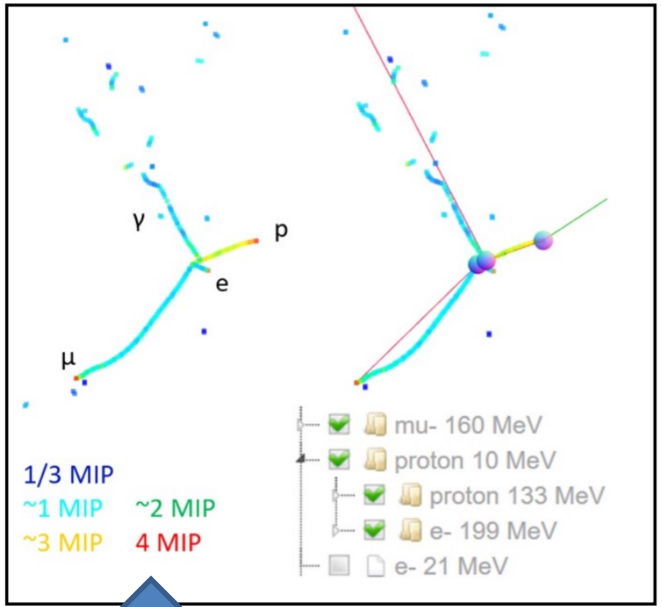
Measuring Neutrino-Nucleus Cross Sections

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

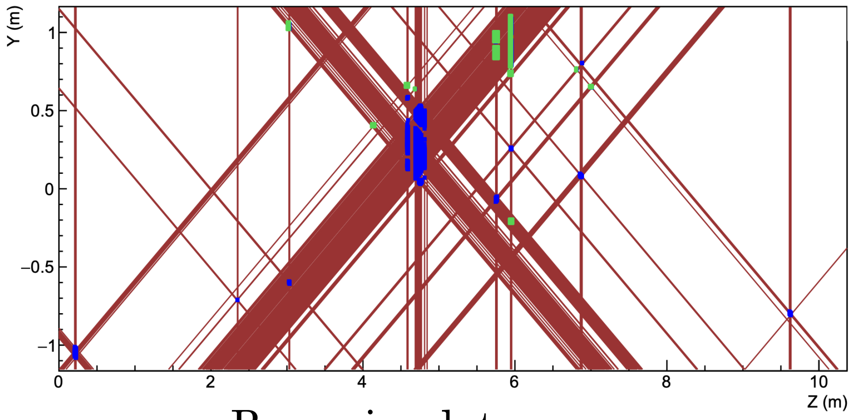


3D Event Reconstruction

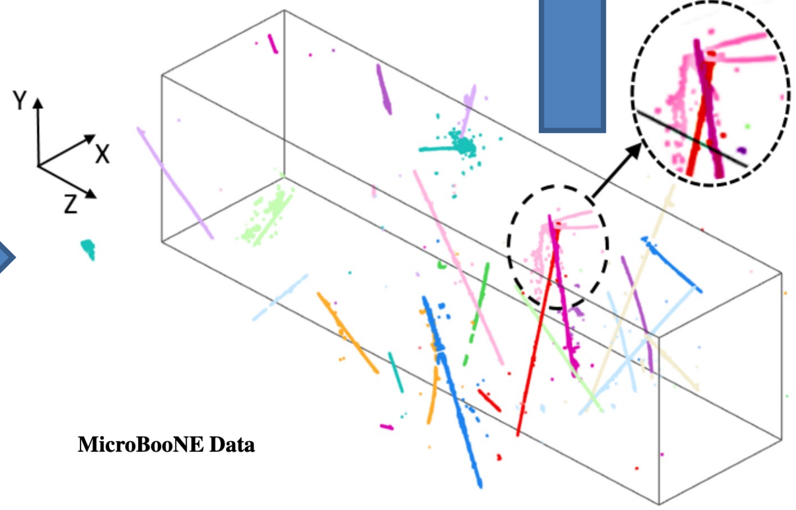
Particle identification and neutrino vertexing



- Reconstructing TPC and PMT information into physics quantities has many challenging aspects:
  - clustering activity associated with individual particles.
  - determining the neutrino interaction vertex.
  - ...
- "Wire-Cell" reconstruction utilizes tomographic techniques to create 3D images of interactions.
  - Reconstructs the 2D image for each time slice, then stitches the 2D time slices into a 3D image.



Raw wire data



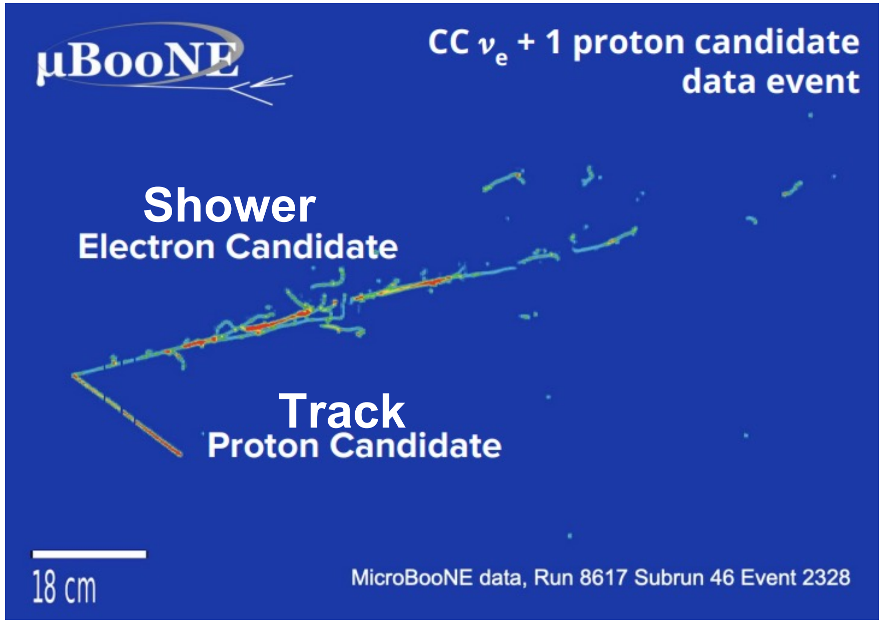
Reconstructed 3D event display with clustering

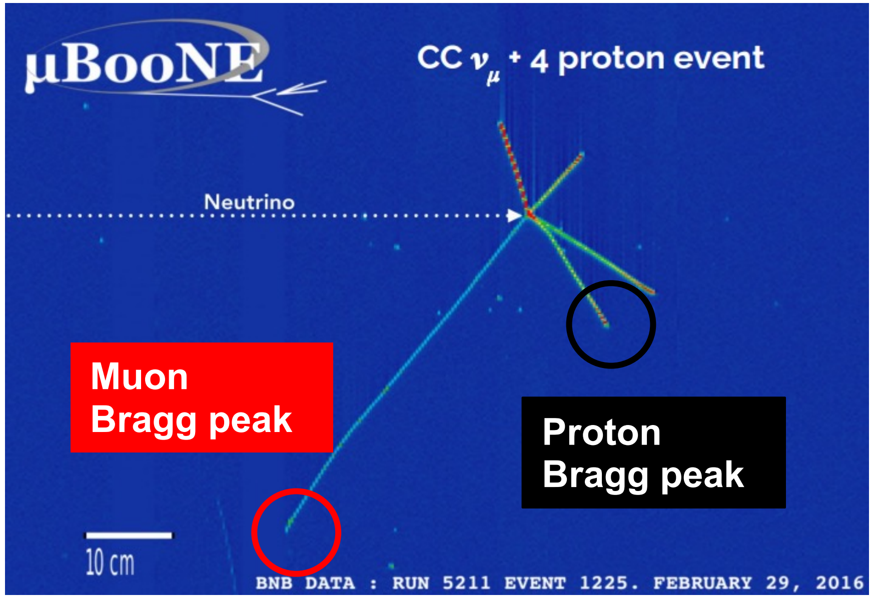
Wire-Cell

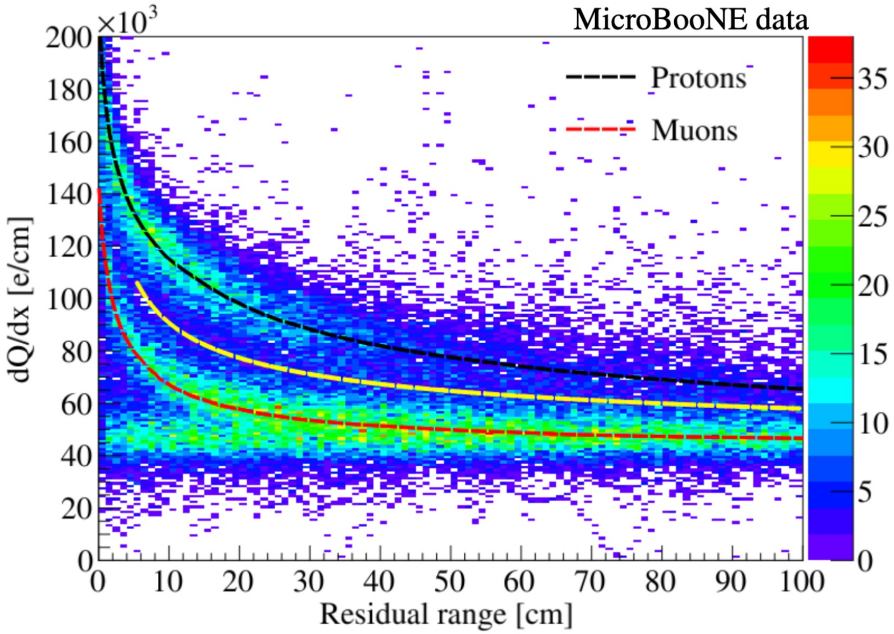
JINST 13 P05032 (2018)
JINST 17 P01037 2022
JINST 16 P06043 (2021)
Phys. Rev. Applied 15, 064071 (2021)

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.







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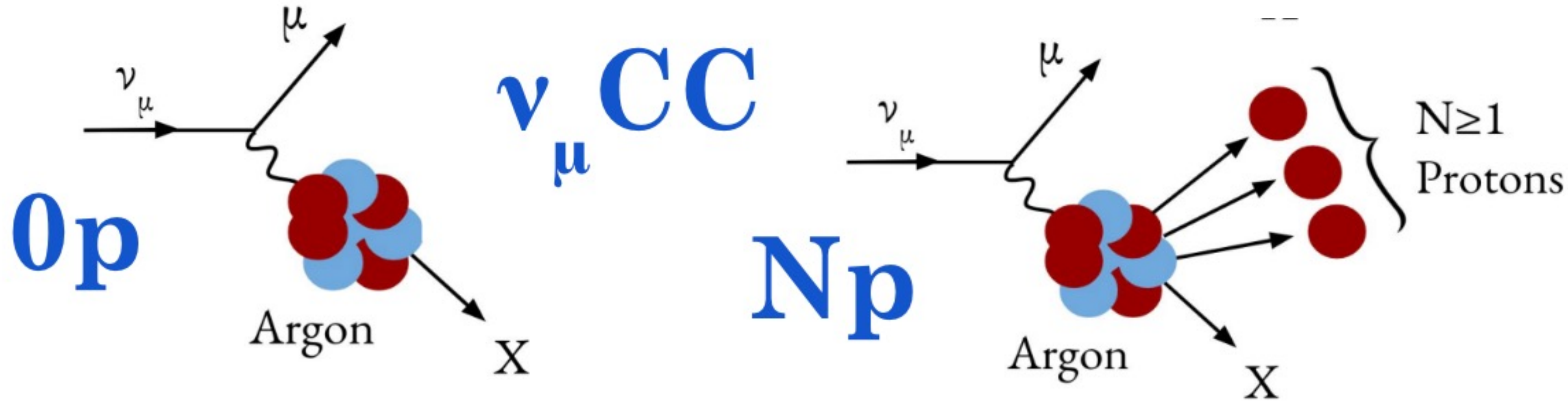
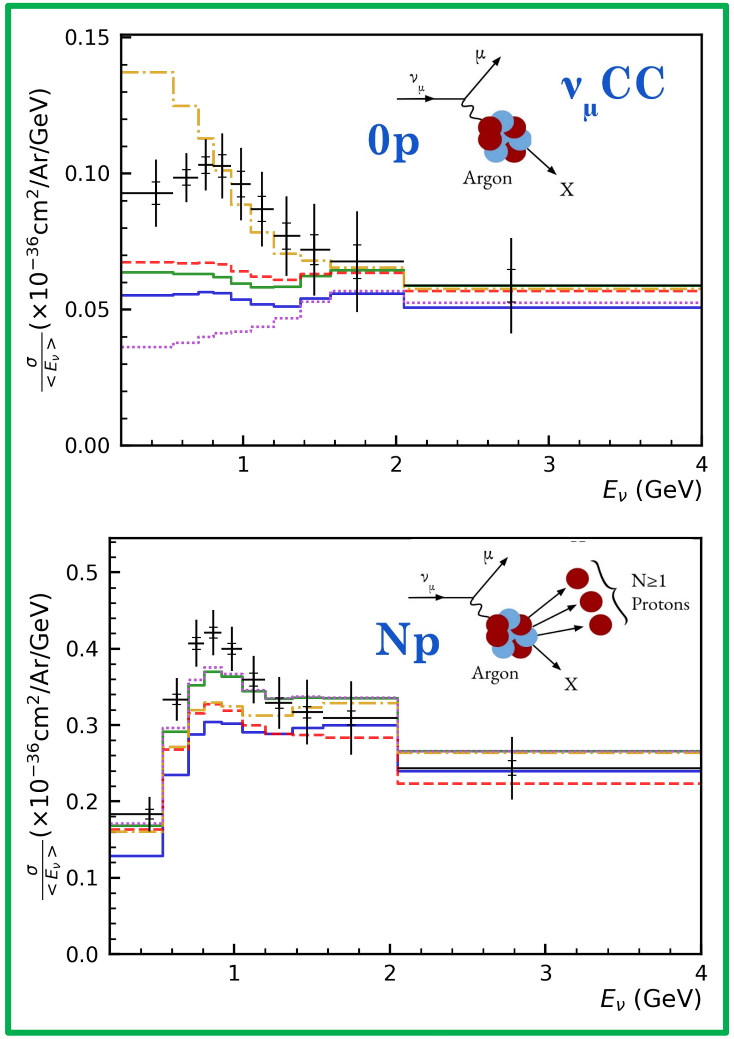
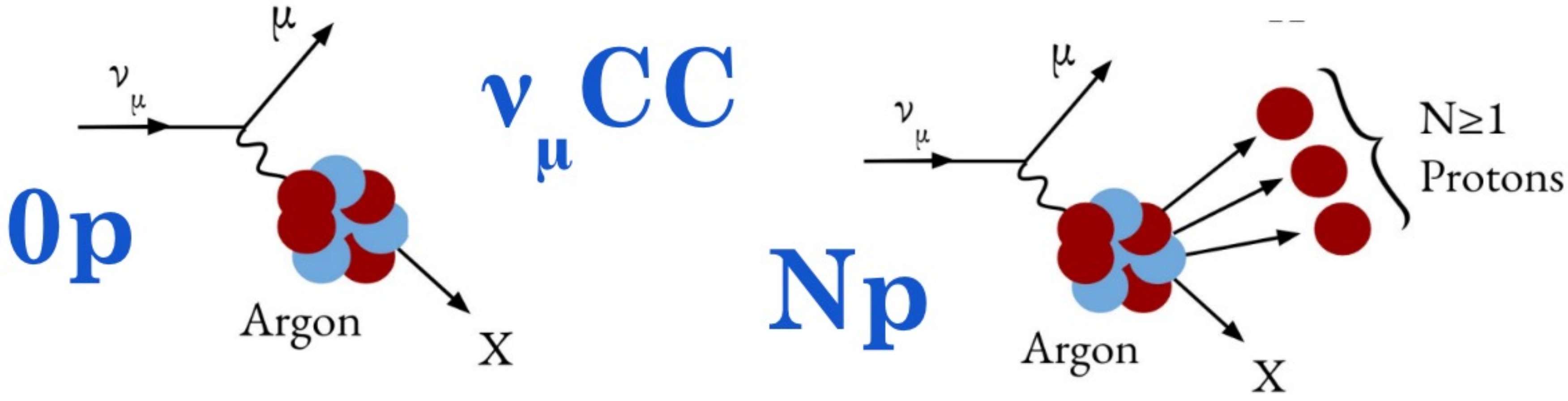


ν_μCC and Hadronic States

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

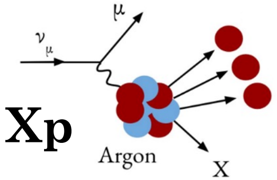
- Need to understand ν_μCC cross sections to interpret oscillation measurements.
  - Proper modeling of hadronic final states is essential.
- First simultaneous measurements of final states with (Np) and without (0p) protons in muon neutrino argon scattering.
- 0p defined by a 35 MeV kinetic energy threshold and includes events without a final state proton.

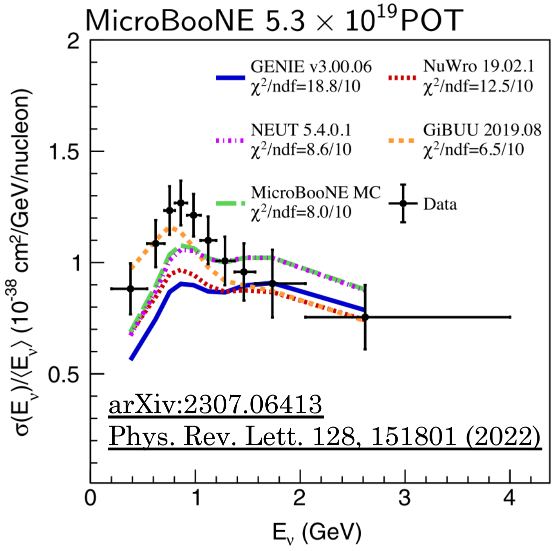




Xp: Any number of protons (Xp = 0p+Np)
Np: At least 1 proton > 35 MeV
0p: No protons >35 MeV

ν_μCC Xp



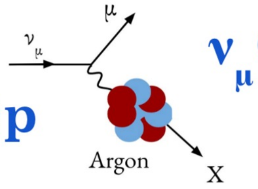


arXiv:2307.06413
Phys. Rev. Lett. 128, 151801 (2022)

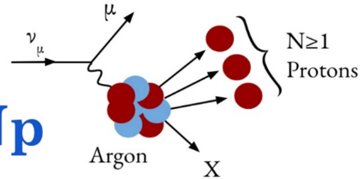
Same signal, but adds 0pNp

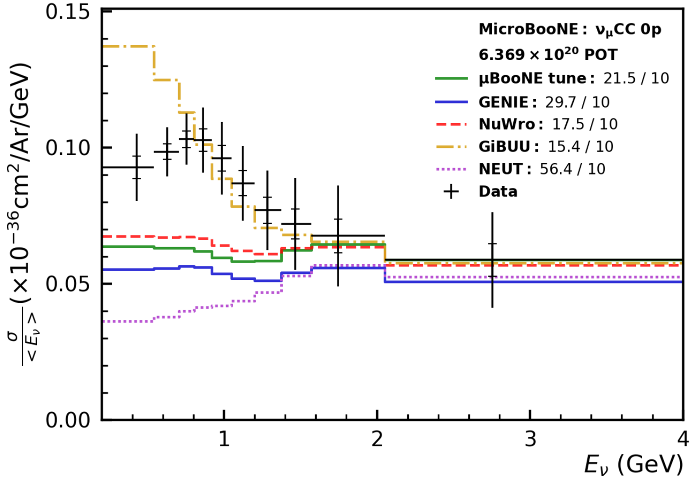
ν_μCC

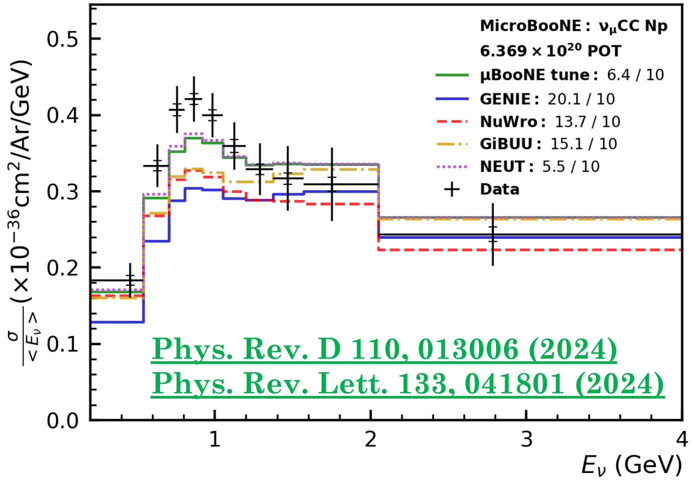
0p



Np

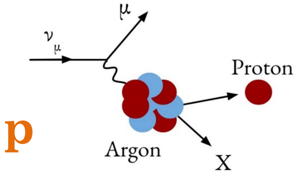


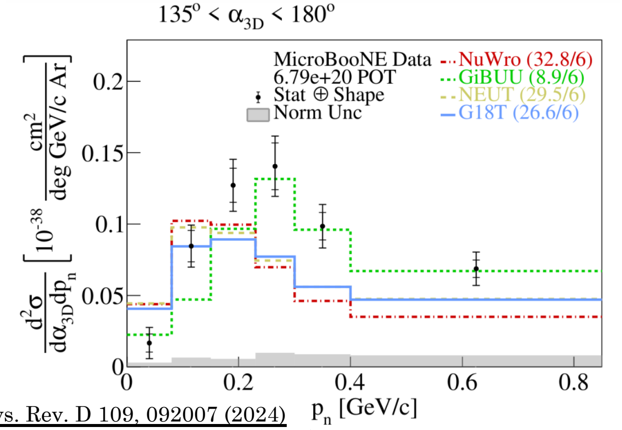




Phys. Rev. D 110, 013006 (2024)
Phys. Rev. Lett. 133, 041801 (2024)

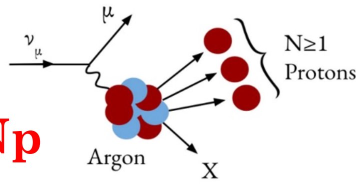
CC1p

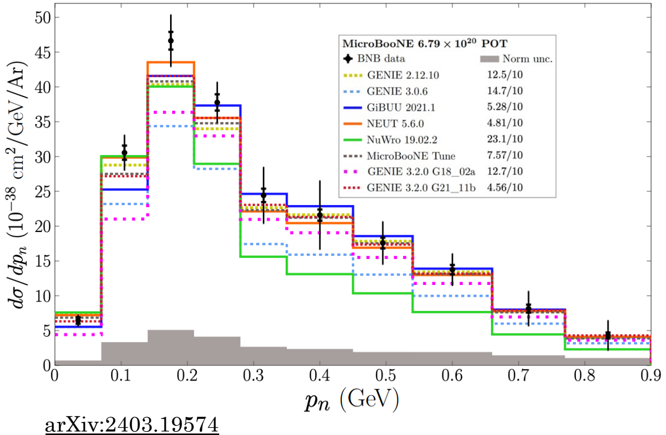




Phys. Rev. D 109, 092007 (2024)
Phys. Rev. Lett. 131, 101802 (2023)
Phys. Rev. D 108, 053002 (2023)

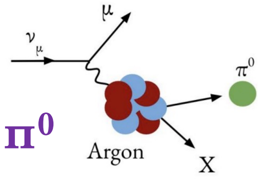
CCNp

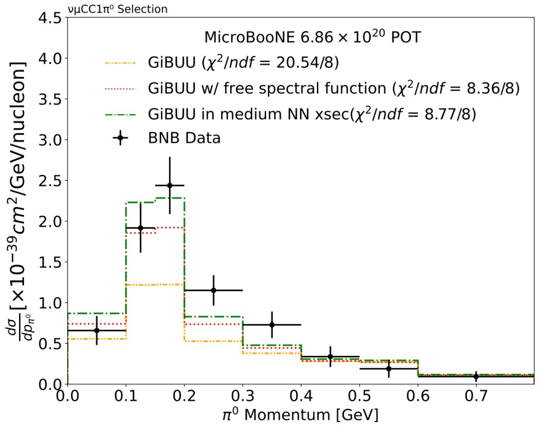




arXiv:2403.19574

CCπ^0



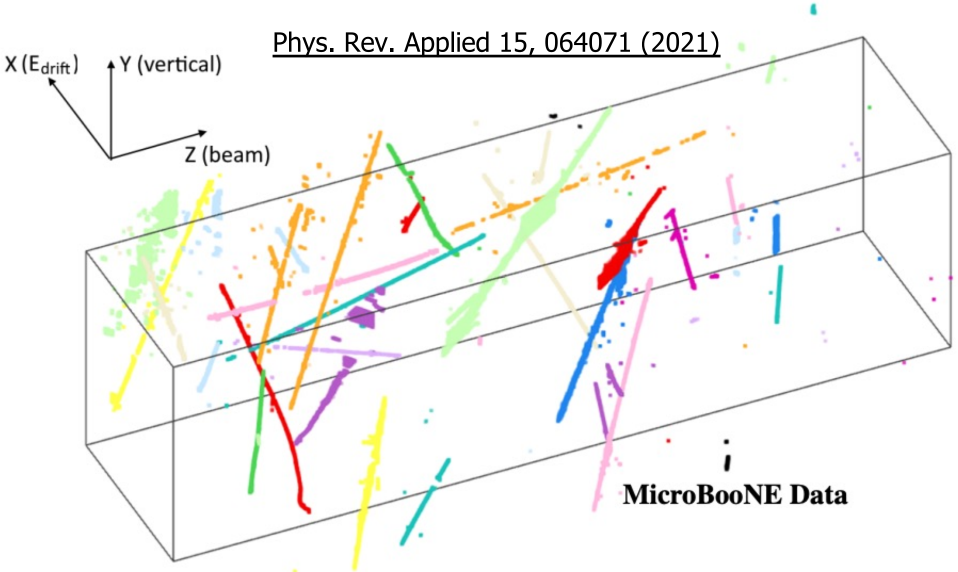


Phys. Rev. D 110, 092014 (2024)

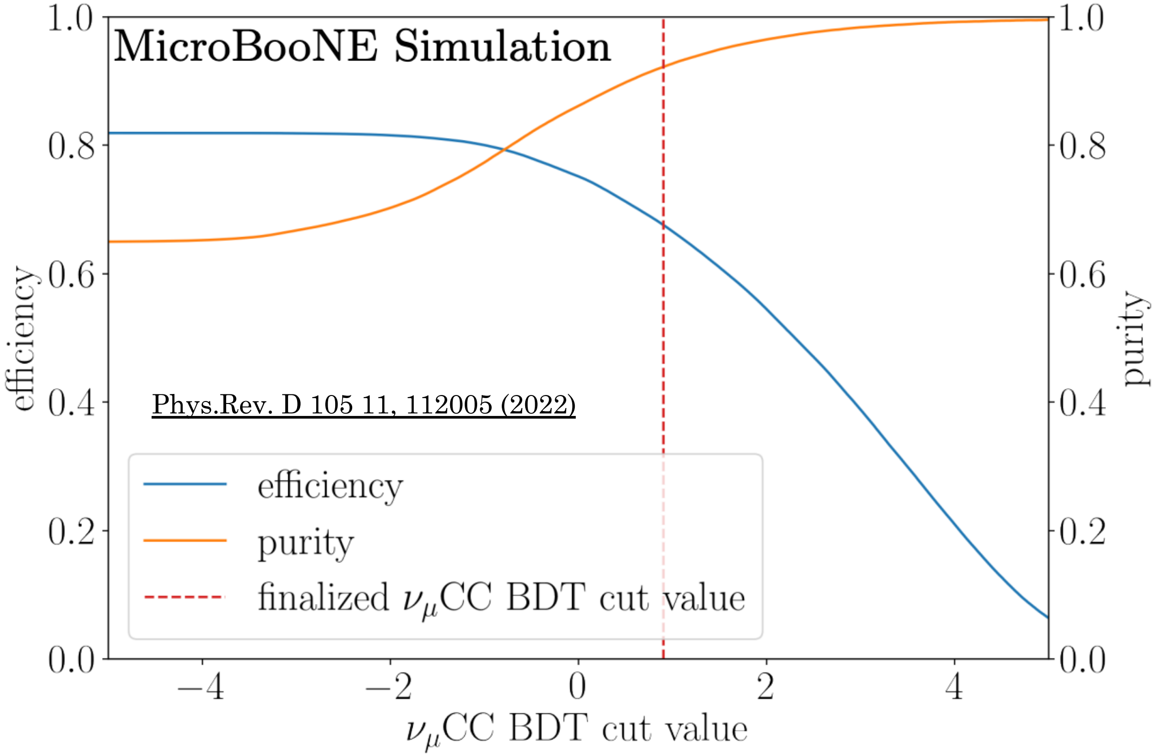
More inclusive

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 92% purity.

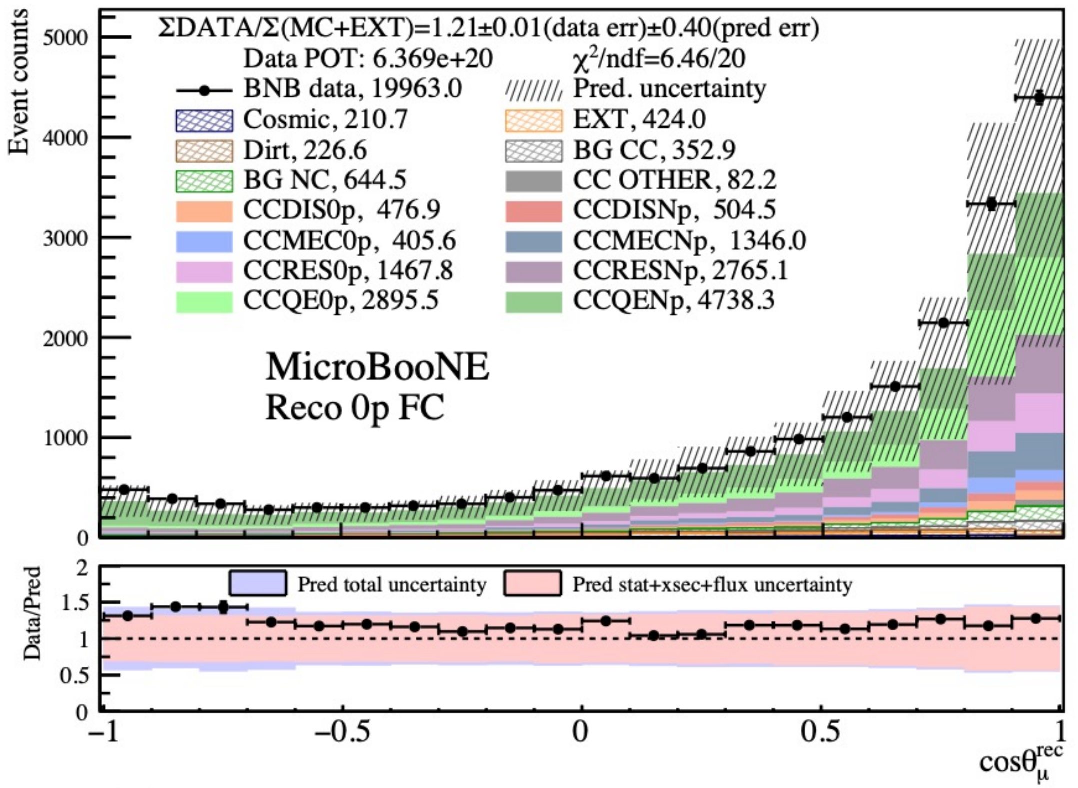


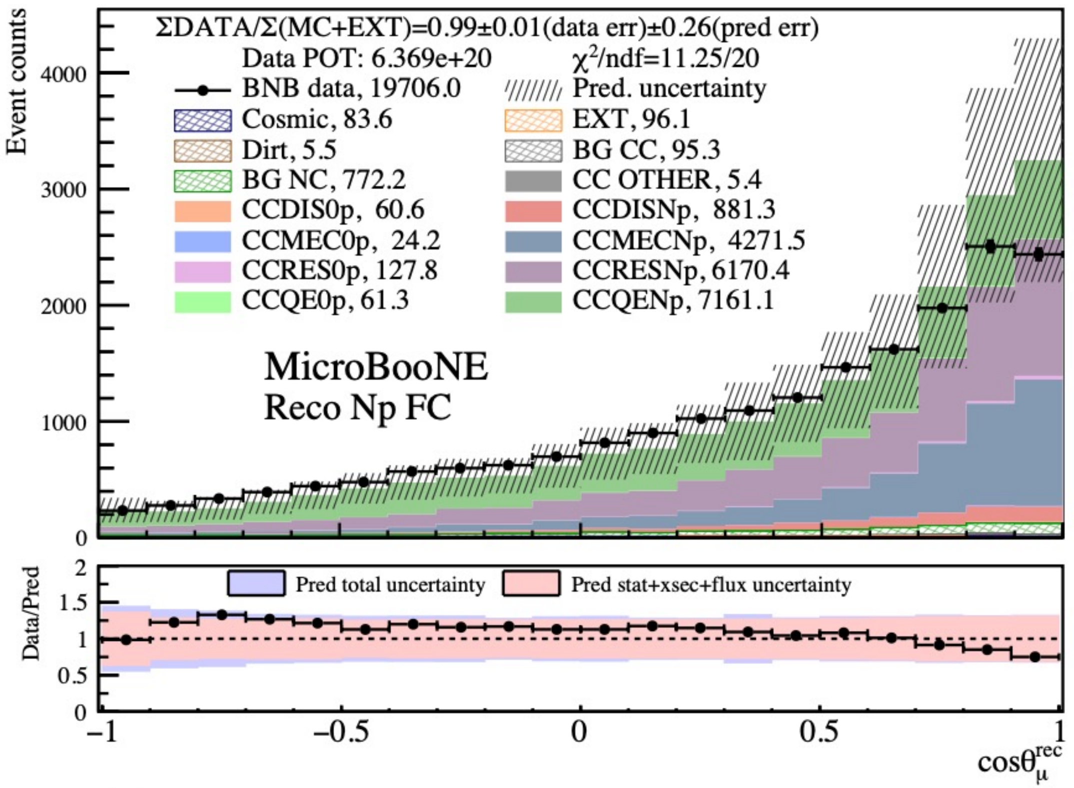
So many cosmic rays! Can you find the neutrino?



0pNp Event Selection

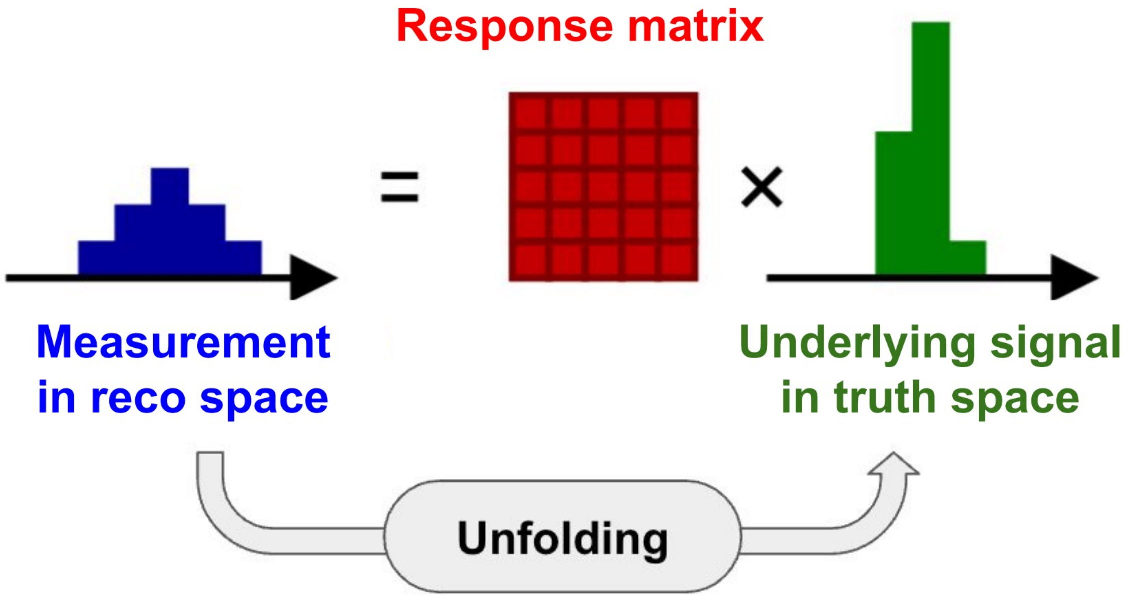
- Selection divided into 0p and Np based on a 35 MeV kinetic energy threshold.
  - True 0p events have no protons, or no proton with more than 35 MeV of kinetic energy.
- Np selection has 49% efficiency for Np events and 0p selection has 54% efficiency for 0p events.
  - Enables high statistics measurements of both channels.





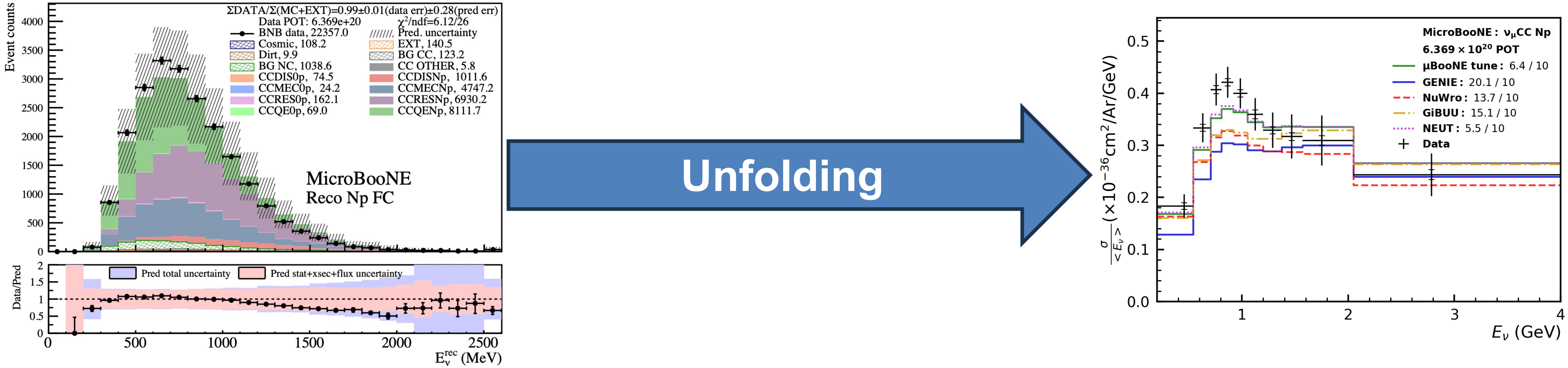
Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where it 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.



Unfolding and Uncertainties

- Measure event rates but need to translate this into a cross section.
  - **Unfolding**: using a model to map the reconstructed distributions onto physics quantities.
- Unfolding corrects for a variety of effects.



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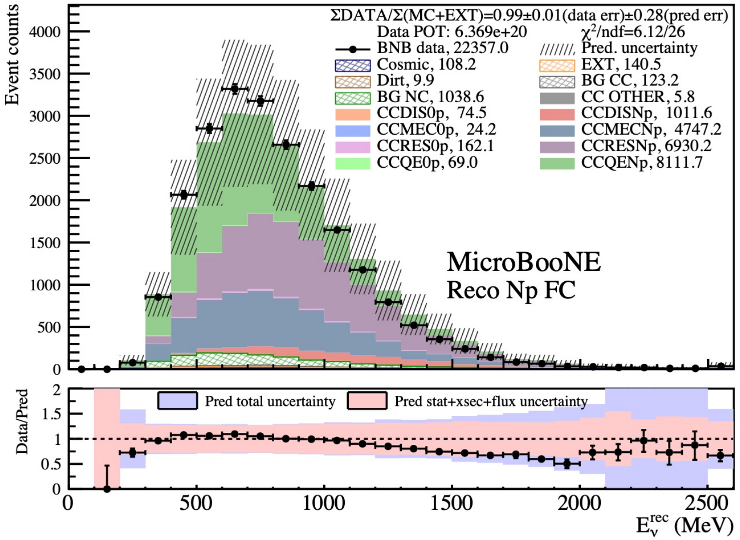
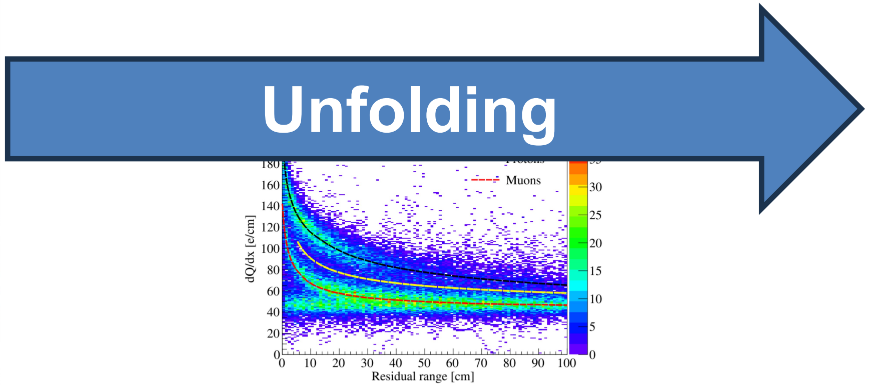
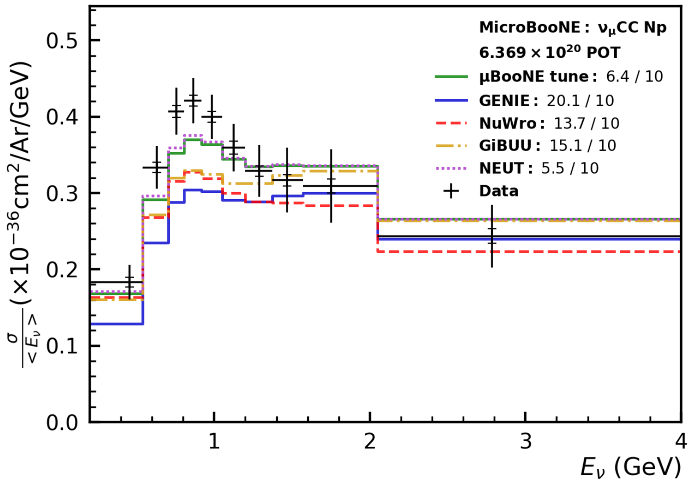
    - Proper modeling of the detector's performance is needed to correct for finite resolution and efficiencies.







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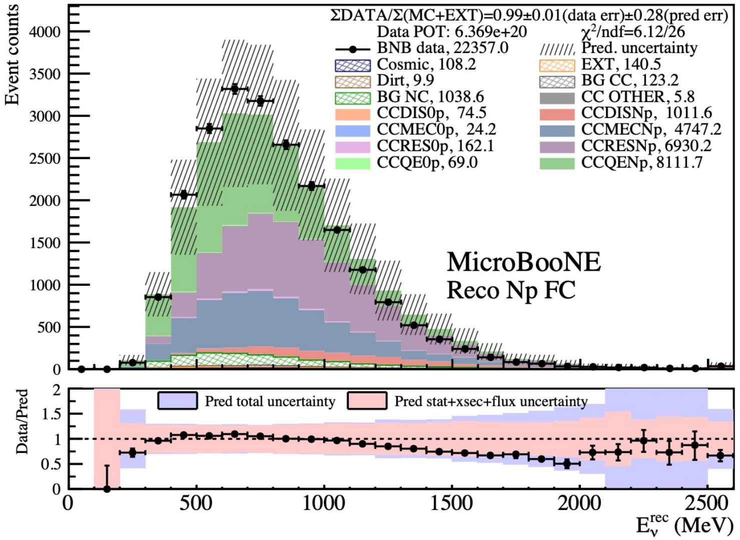
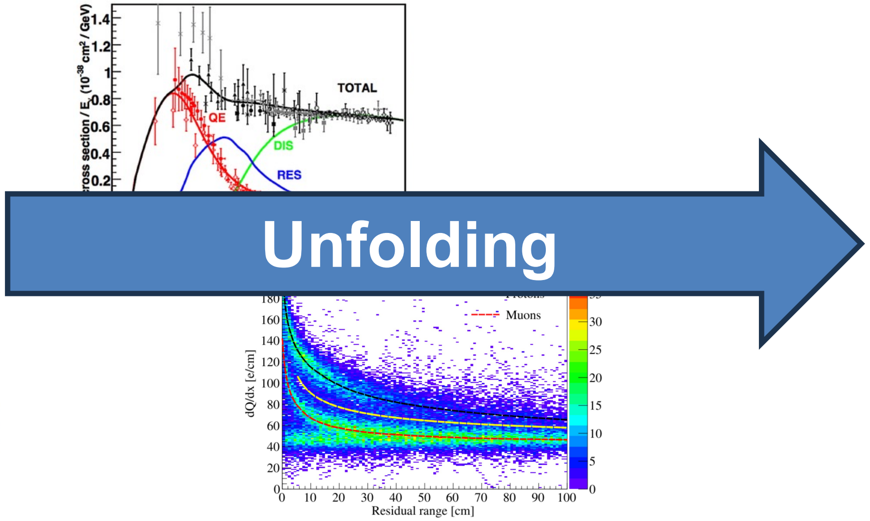
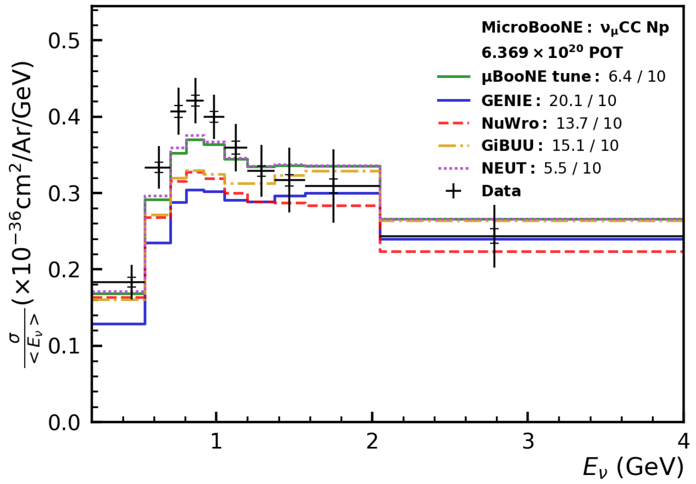
    - Impacts both shape and normalization of the cross section result.







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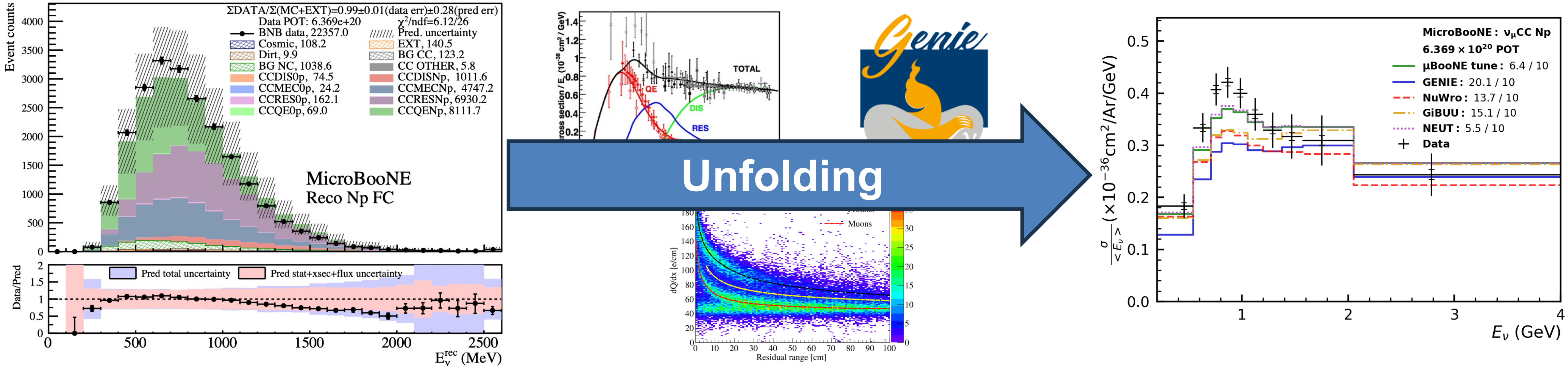
  - Interaction modeling: What cross section is assumed?
    - Different interaction rates or final states may alter the mapping between reconstructed and true quantities.



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  - Interaction modeling: What cross section is assumed?
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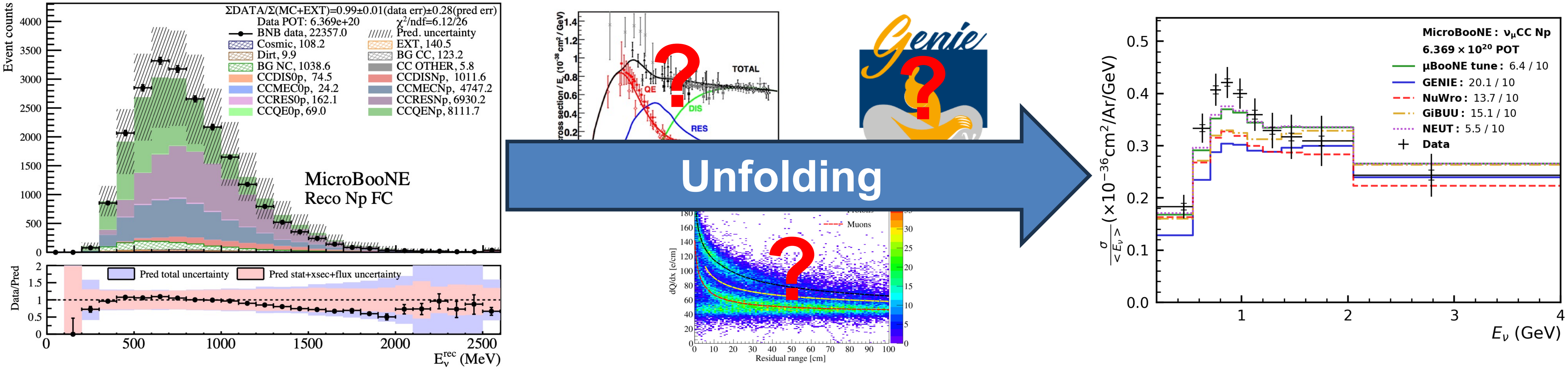
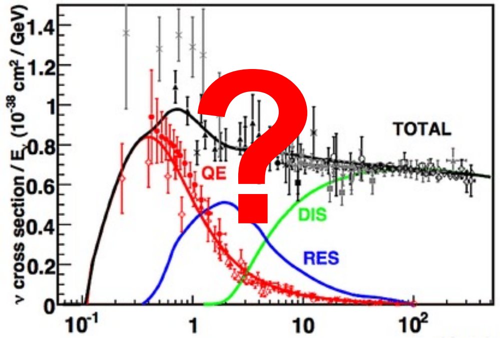
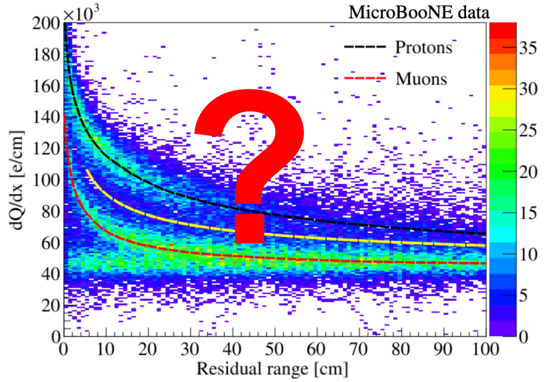
- Many uncertainties related to these corrections!

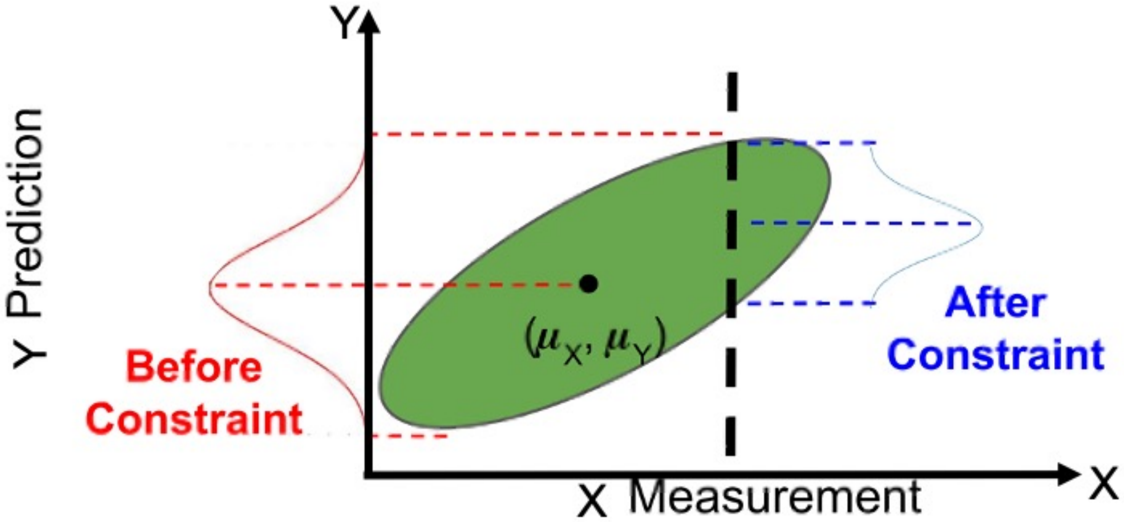


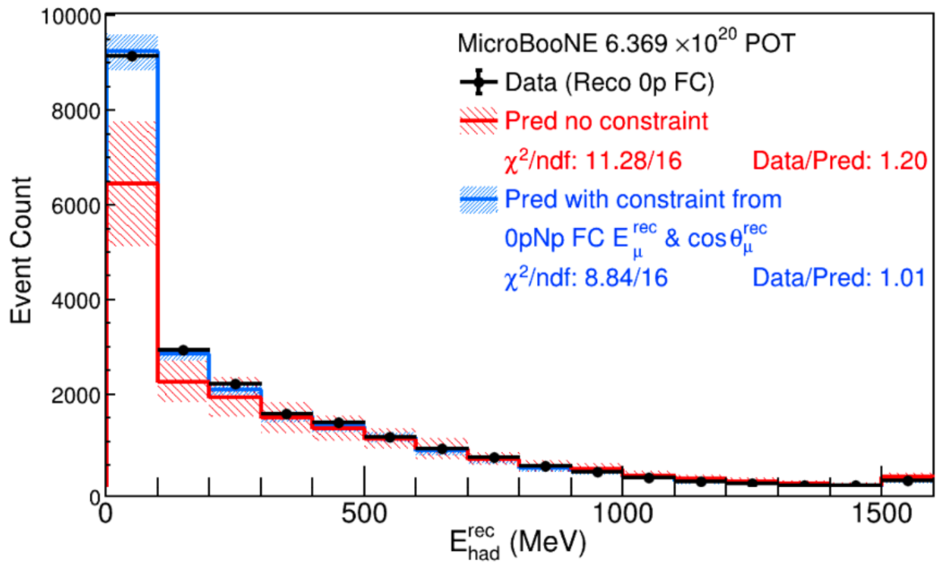
Model Validation





- Data-driven model validation is utilized to ensure that the model has sufficient uncertainties.
- Based off conducting a variety of GoF tests with data-driven constraints.
- Does the model describe the data within uncertainties?
  - Builds confidence that any unfolding bias will be within uncertainties.

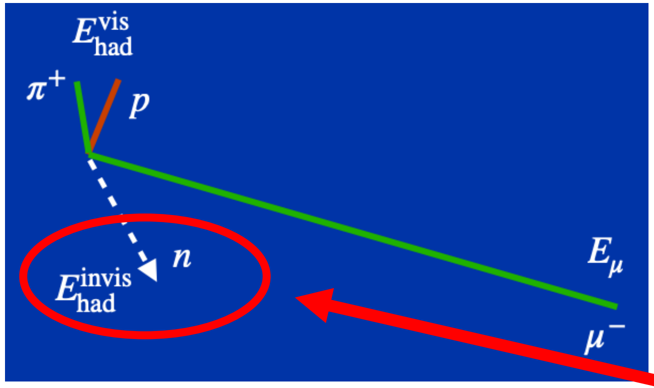




For more details, check out arXiv:2411.03280 and NuSTEC CEWG seminar

Key aspects to validate:

- Modeling of invisible hadronic energy.
  - Critical for measurements of E_ν and υ.
  - Validated by using the muon kinematics to constrain the visible hadronic energy.



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

Unknown

Not directly observable, requires model input during unfolding.

Key aspects to validate:

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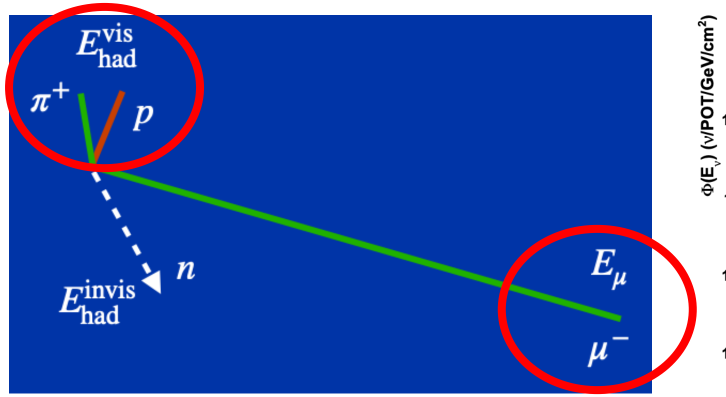

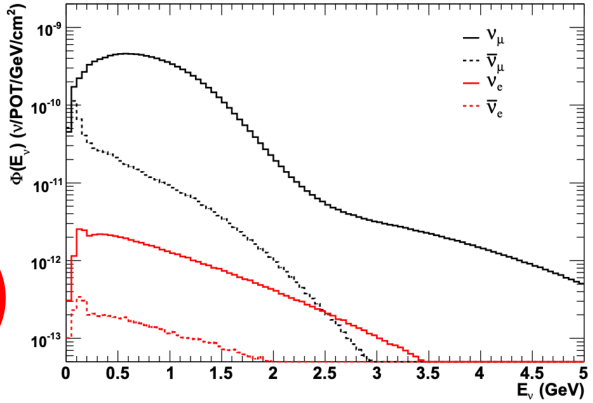

$$E_\nu = E_\ell + E_{\text{had}}^{\text{vis}} + E_{\text{had}}^{\text{invis}}$$

Unknown

- Measure the leptonic and hadronic energy and have an *a priori* model of the neutrino flux.

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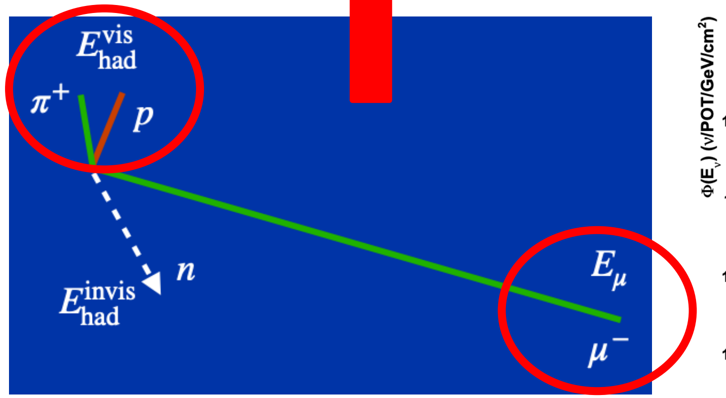

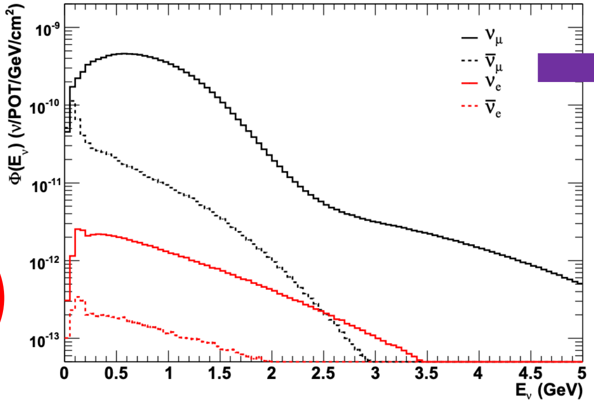

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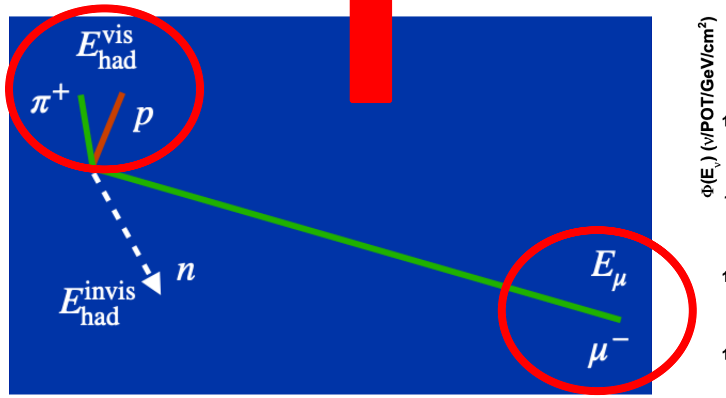
Unknown

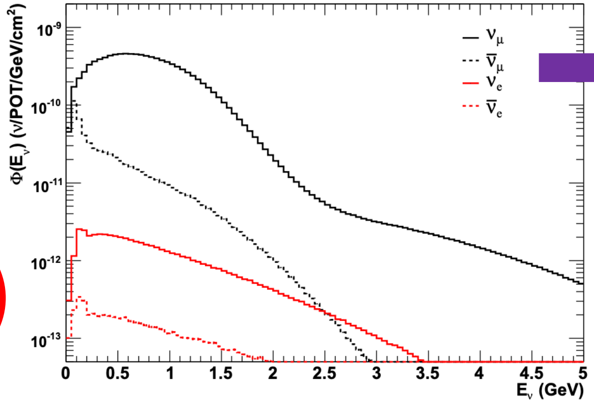
- Measure the leptonic and hadronic energy and have an *a priori* model of the neutrino flux.

- Conservation of energy means the predicted correlation between the leptonic and hadronic energy is dictated by the modeling of the invisible energy.

Key aspects to validate:

- Modeling of invisible hadronic energy.
  - Critical for measurements of E_ν and υ.
  - Validated by using the muon kinematics to constrain the visible hadronic energy.





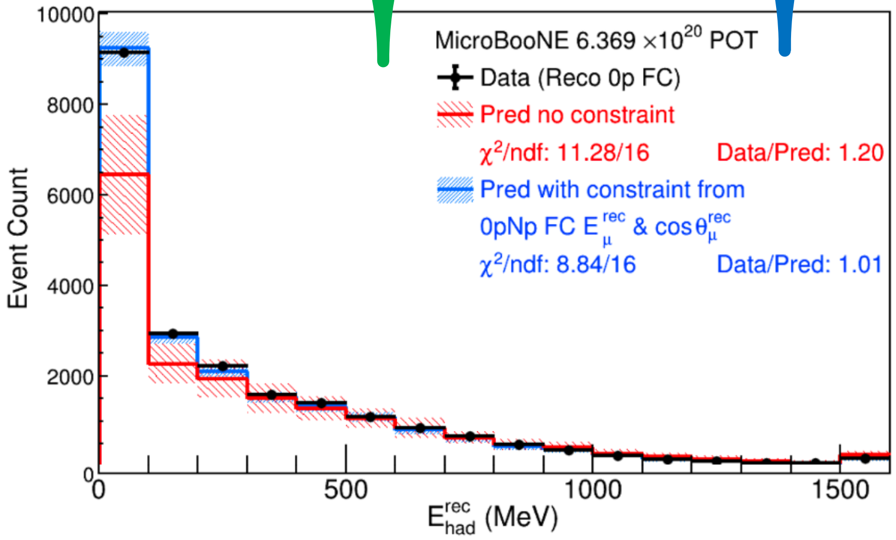
$$E_\nu = E_\ell + E_{\rm had}^{\rm vis} + E_{\rm had}^{\rm invis}$$

Constrained Unknown

- Measure the leptonic and hadronic energy and have an *a priori* model of the neutrino flux.

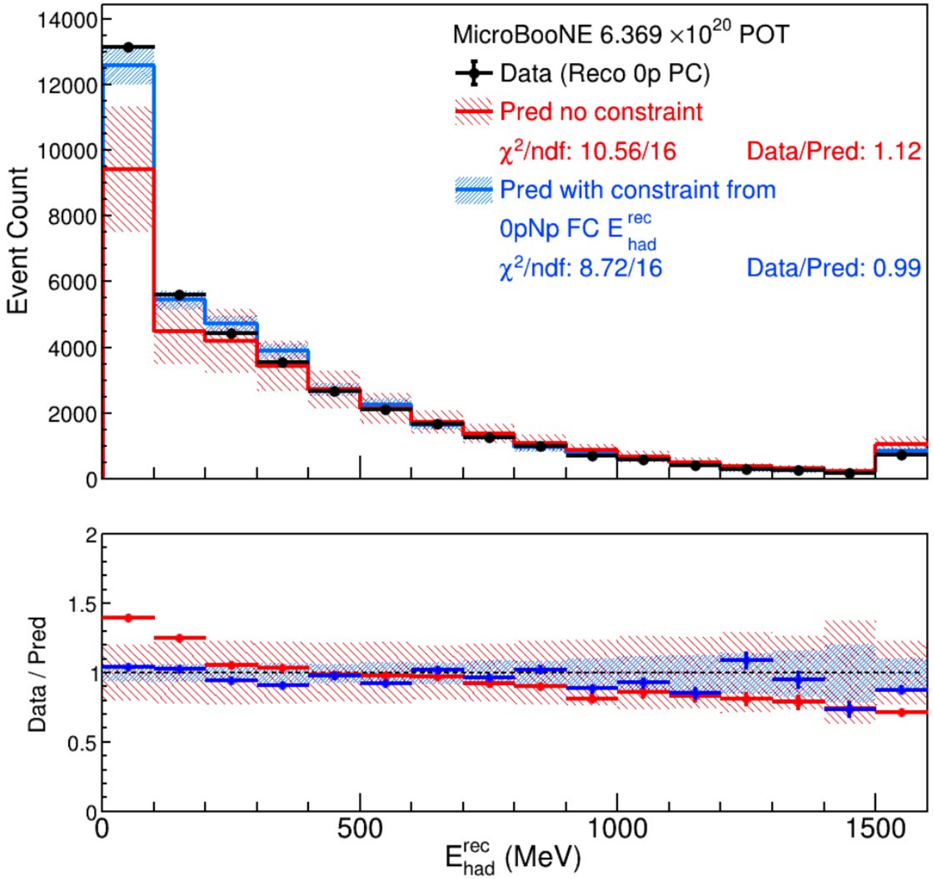
- Conservation of energy means the predicted correlation between the leptonic and hadronic energy is dictated by the modeling of the invisible energy.

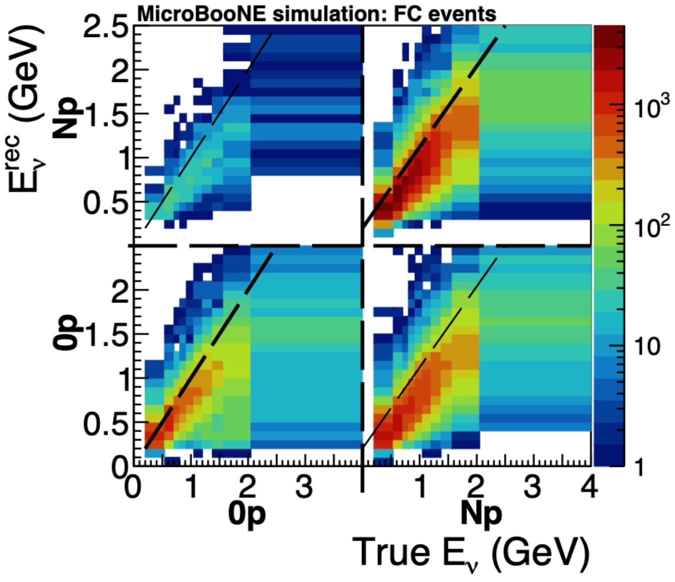
- Constraint probes the correlation providing sensitivity to the modeling of the invisible energy.



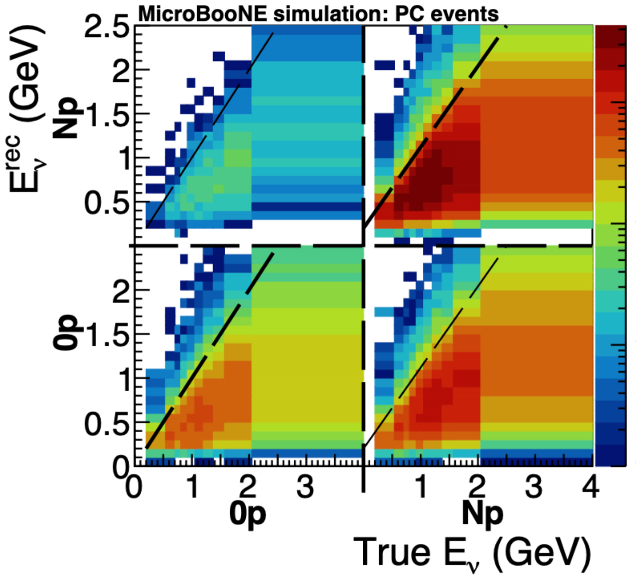
Key aspects to validate:

- Modeling of events partially contained (PC) within the detector.
  - Worse resolution on PC events, but they can still be utilized with sufficient modeling of detector and cross section effects.
  - Validated by using fully contained events to constrain partially contained events.





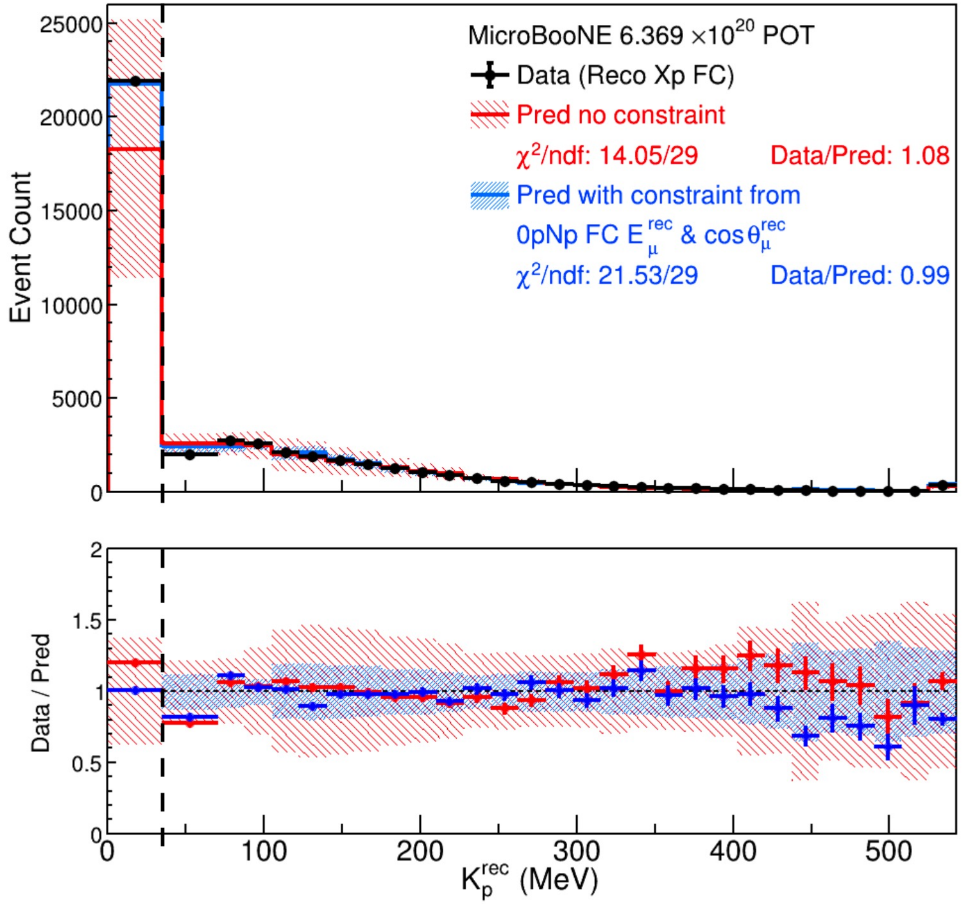
Fully Contained (FC) Events

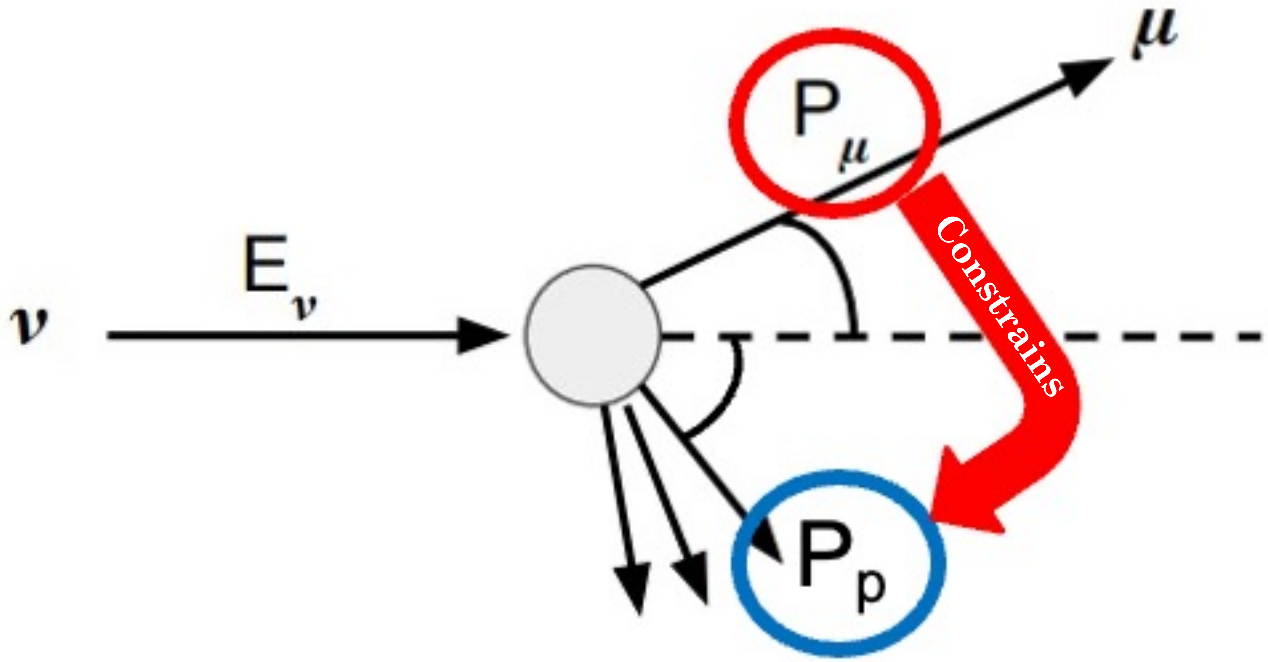


Partially Contained (PC) Events

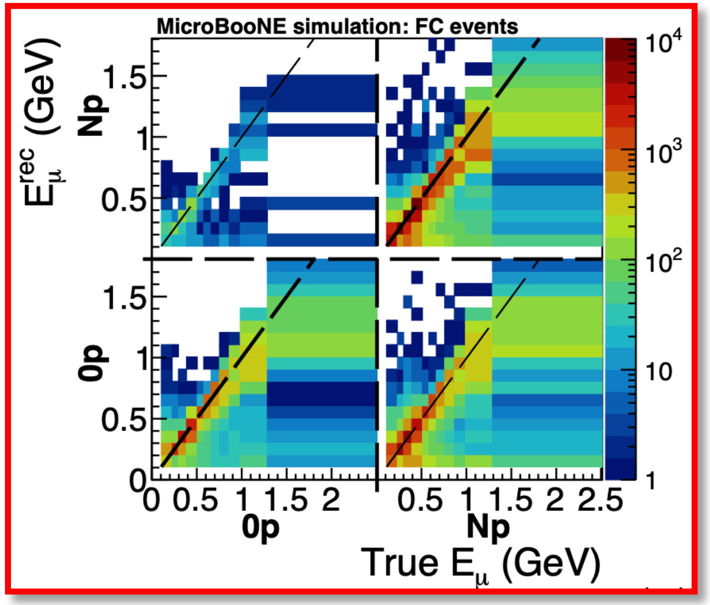
Key aspects to validate:

- 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.

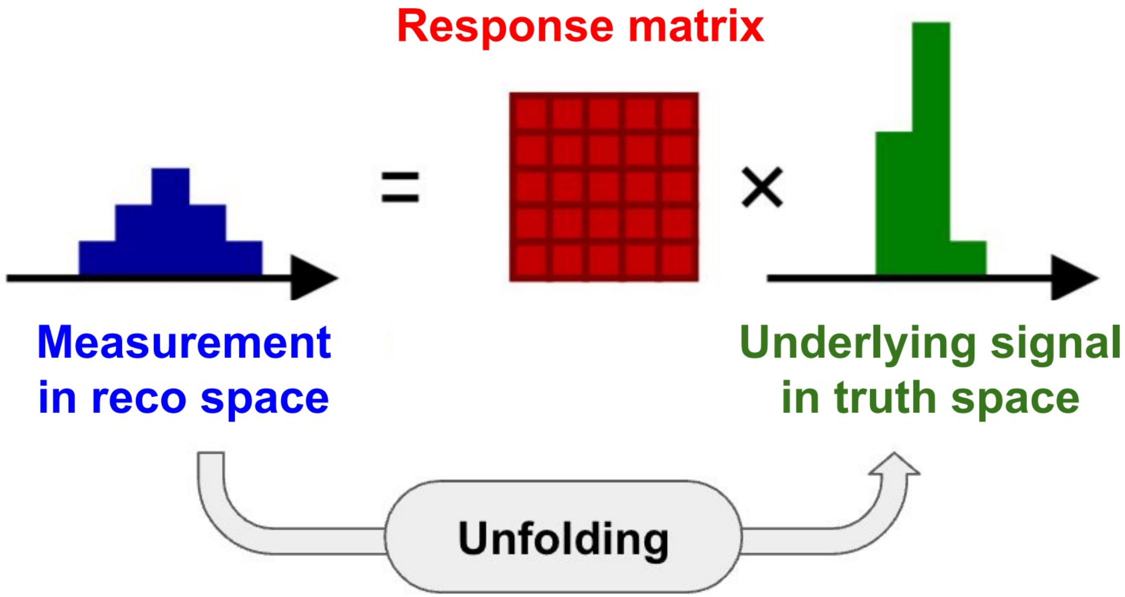


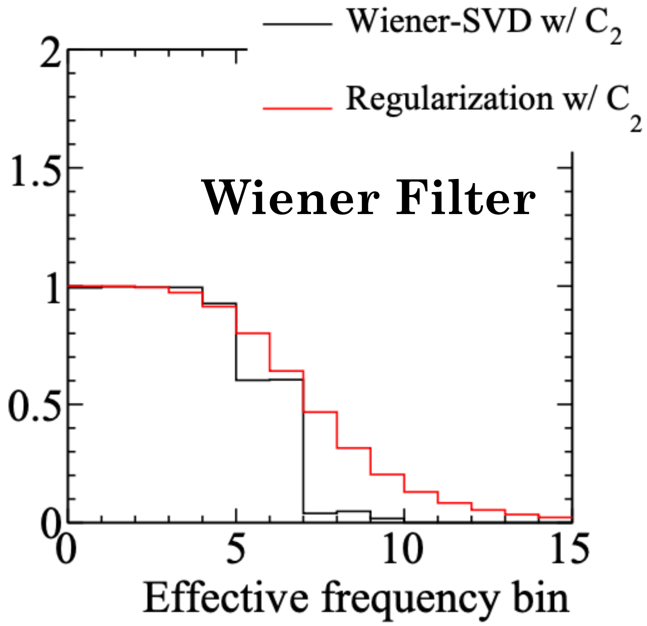


Wiener-SVD Unfolding



- 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 frequency domain.

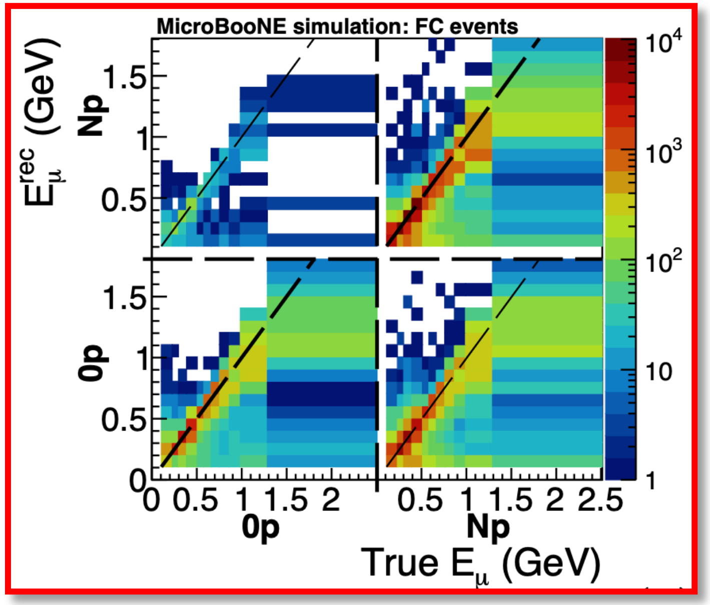




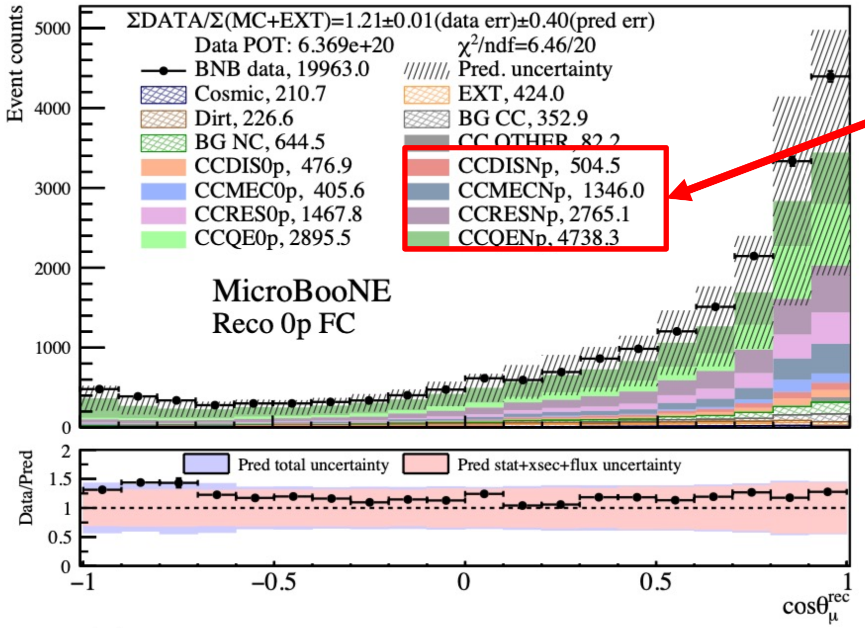
JINST, Volume 12, October 2017

Simultaneous Extraction

- Np sample much purer than 0p sample.
  - Dominate background in 0p sample is Np events where the proton was missed.
- 0p and Np results are extracted simultaneously.
  - Enables robust measurement through a data-driven estimation of the Np background in the 0p selection.

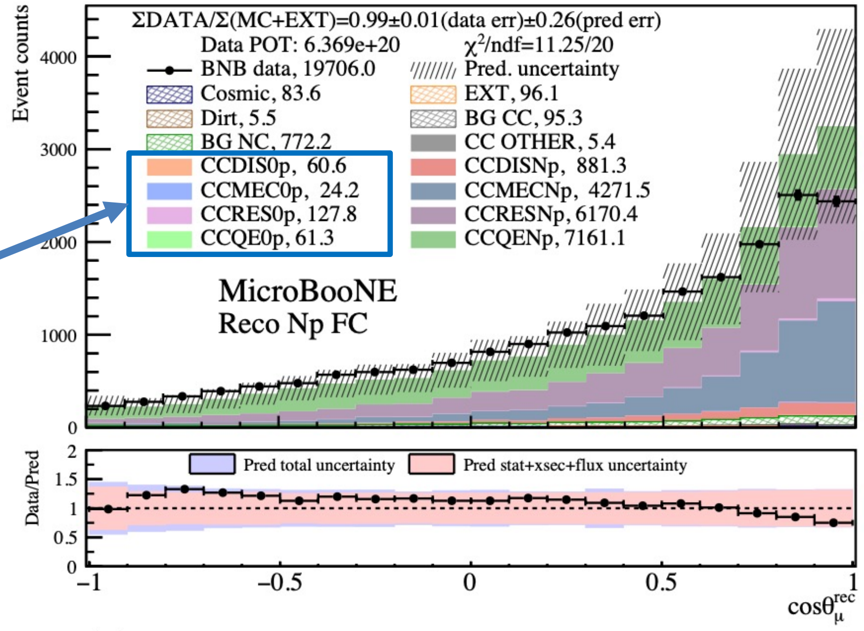


Response matrix has separate blocks for 0p and Np events.



0p sample has residual Np contamination

Np sample is very pure



Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where it 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.

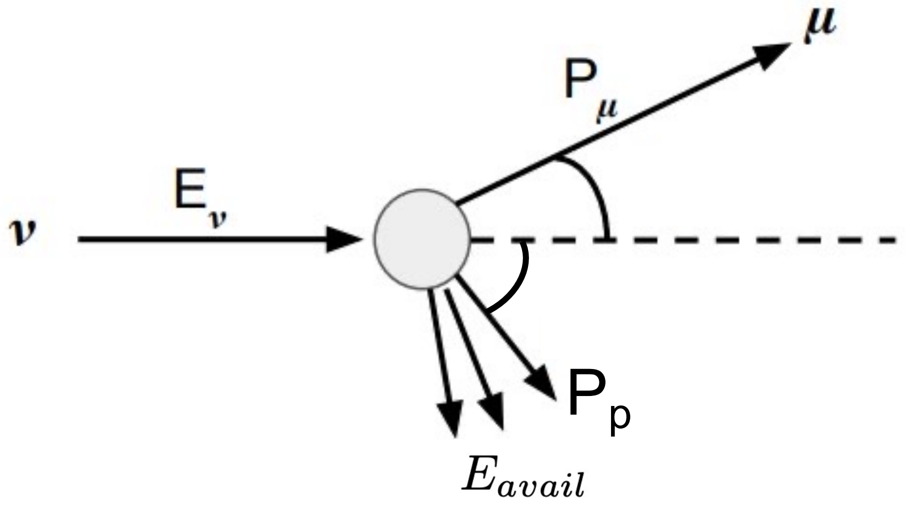
PHYSICAL REVIEW LETTERS **133,** 041801 (2024)

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

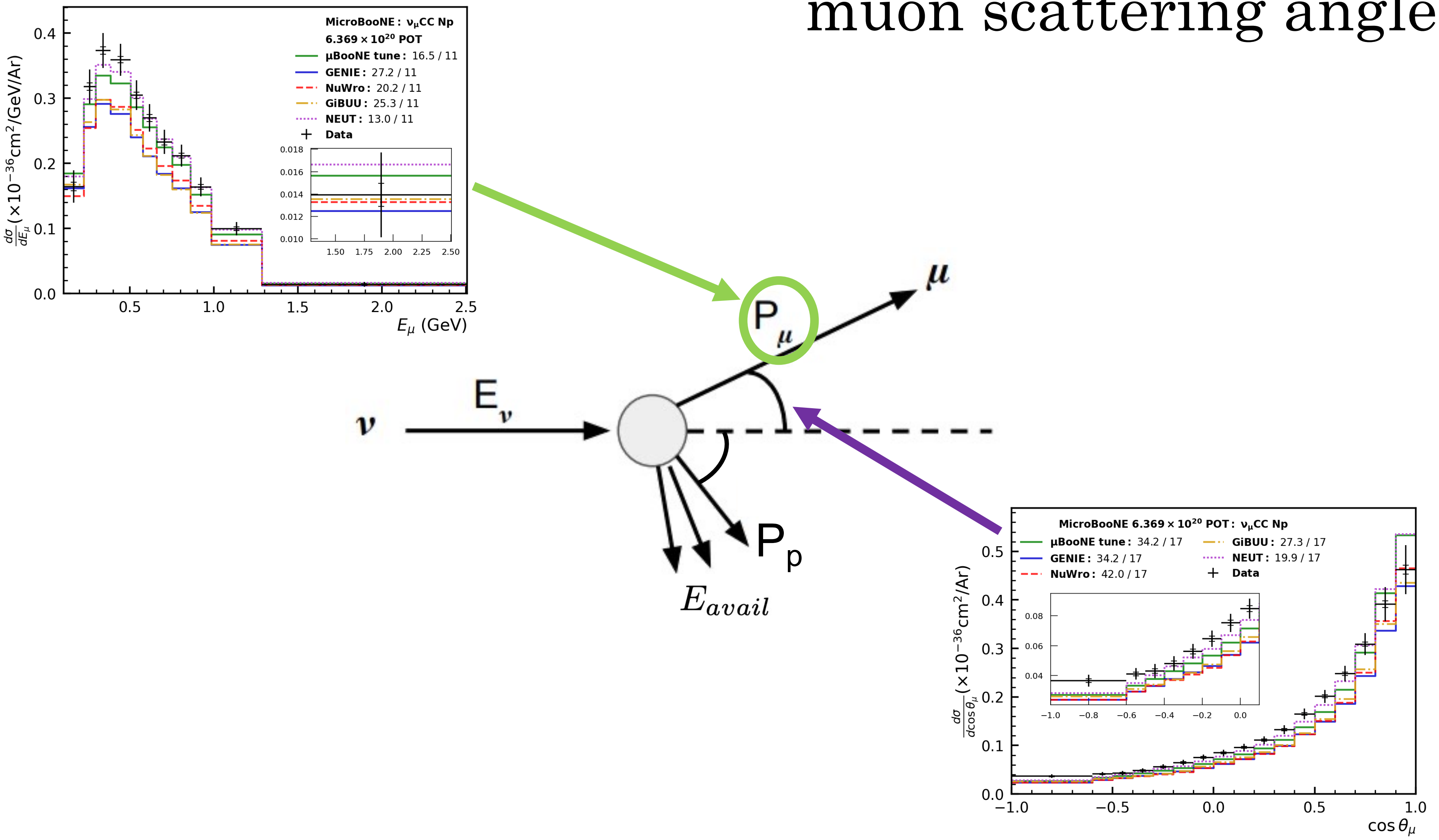
Phys. Rev. D 110, 013006 (2024)
Phys. Rev. Lett. 133, 041801 (2024)

Measured Cross Sections:

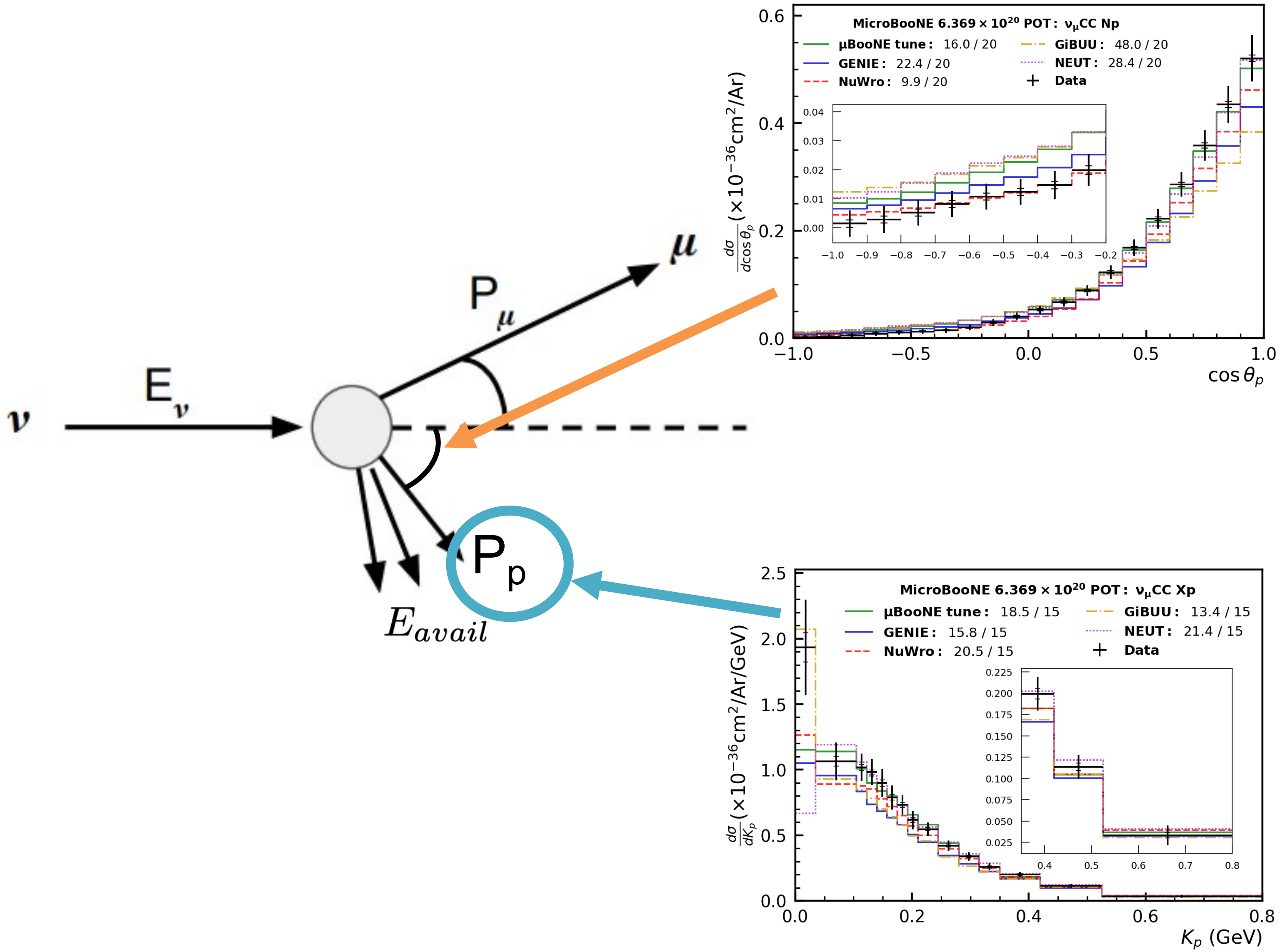
14 measurements in total!



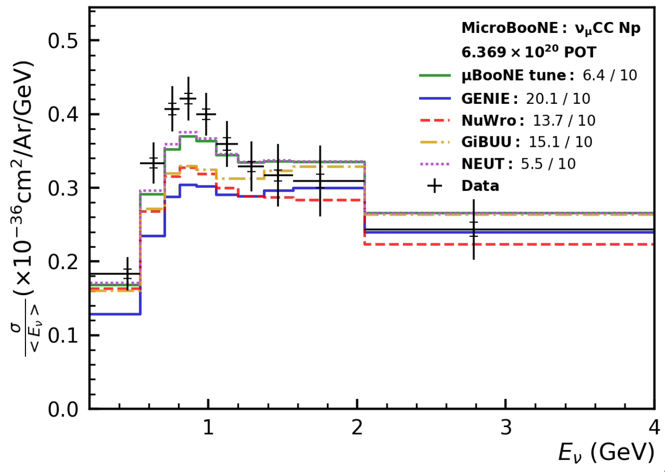
Measured Cross Sections: muon energy, muon scattering angle

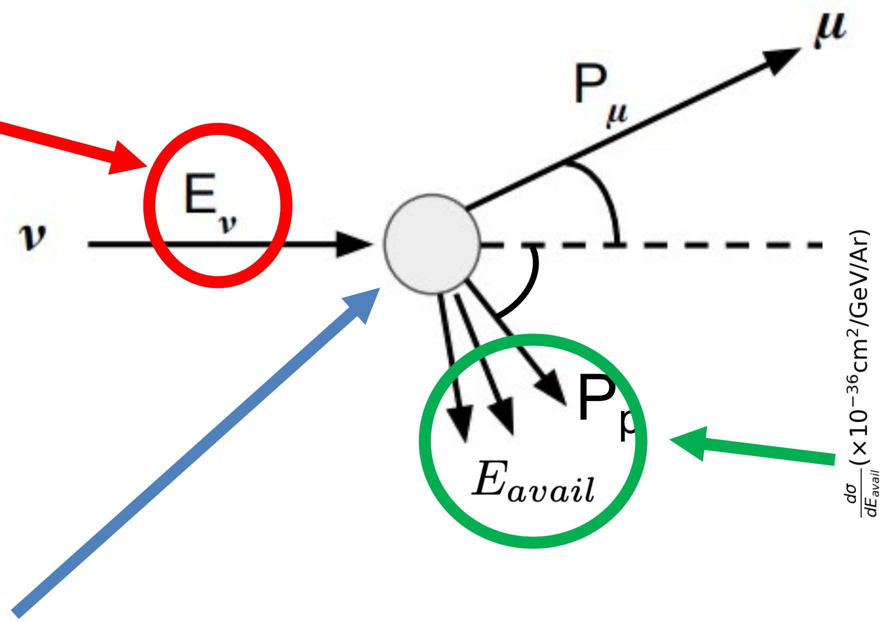


Measured Cross Sections: proton energy, proton scattering angle

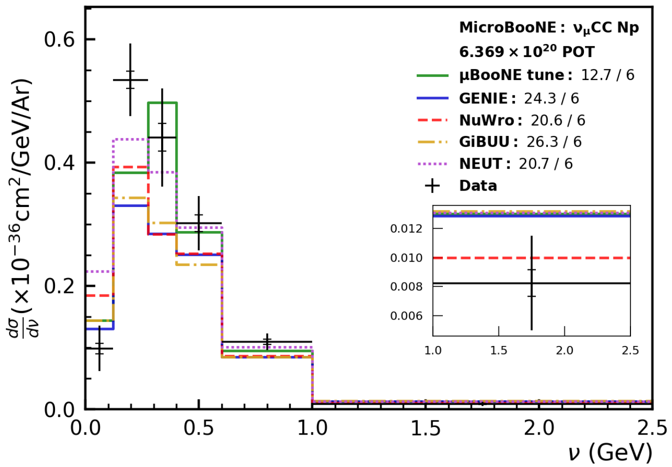


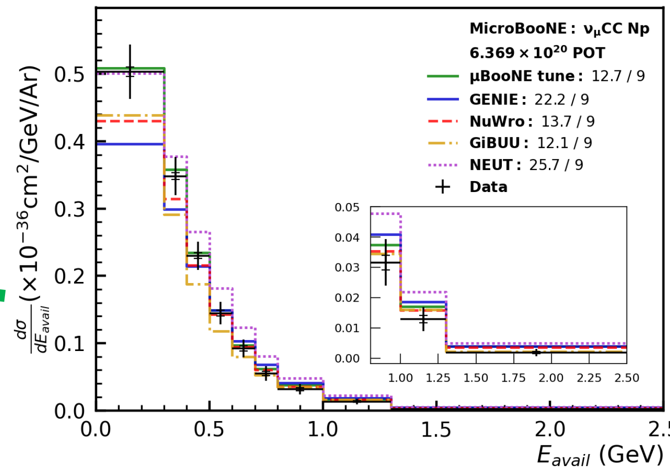
Measured Cross Sections: neutrino energy, energy transfer, available energy





$$E_\nu - E_\mu$$



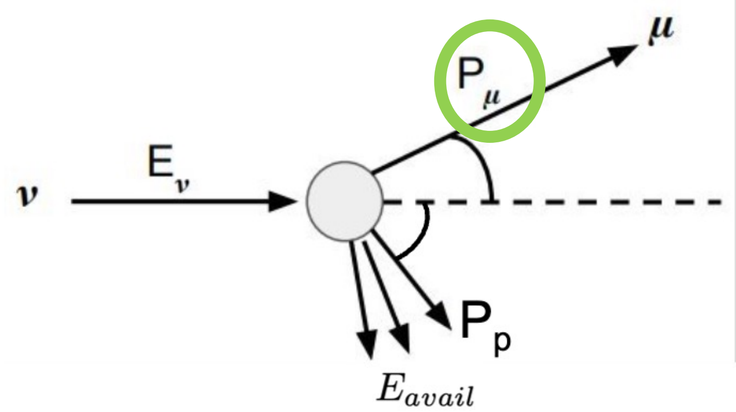


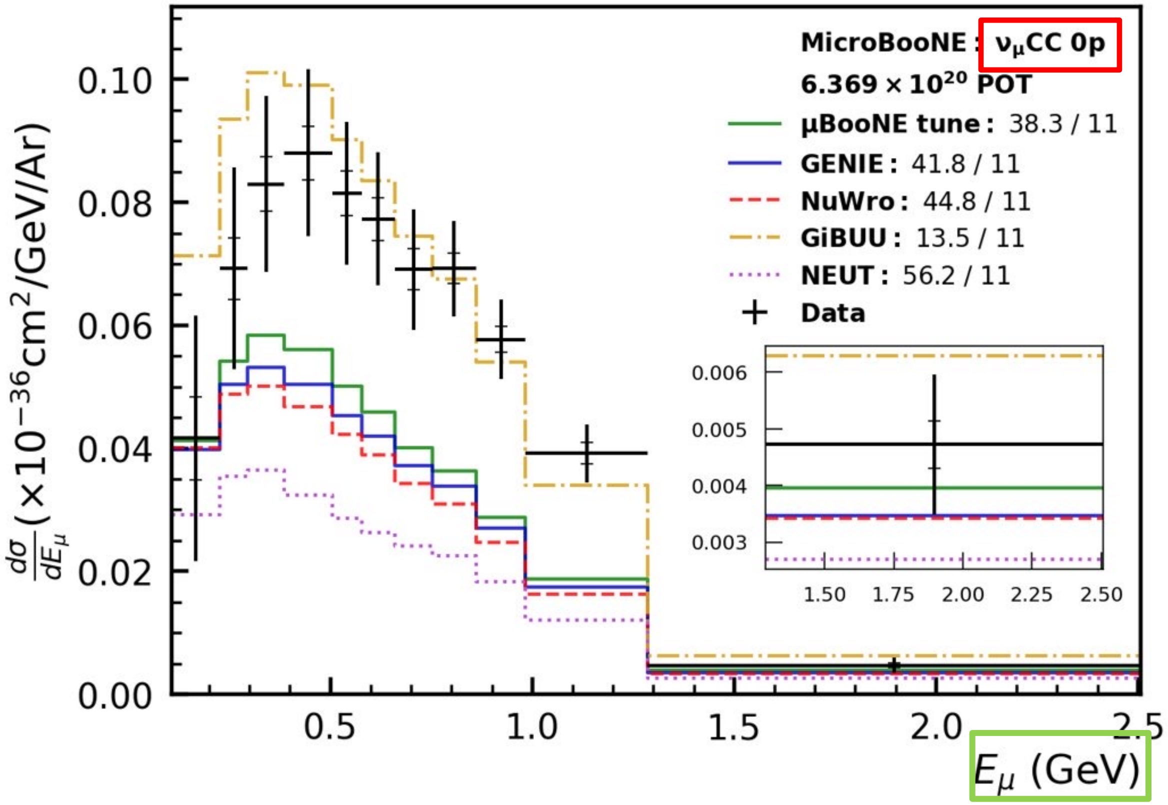
$$E_{avail} = \sum_{\pi^\pm} K_{\pi^\pm} + \sum_{p} K_p + \sum_{other} E_{particle}$$

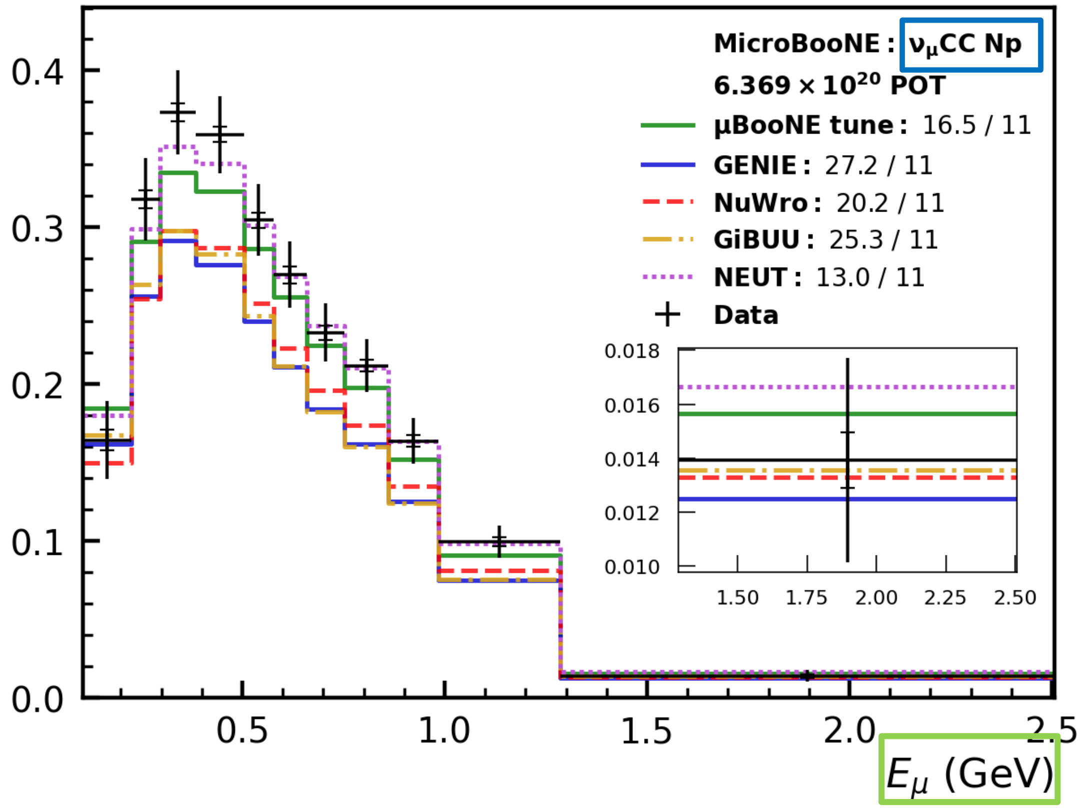
Available energy inspired by MINERvA measurements: Phys. Rev. Lett. 116, 071802 (2016)

Underprediction of 0p Final States

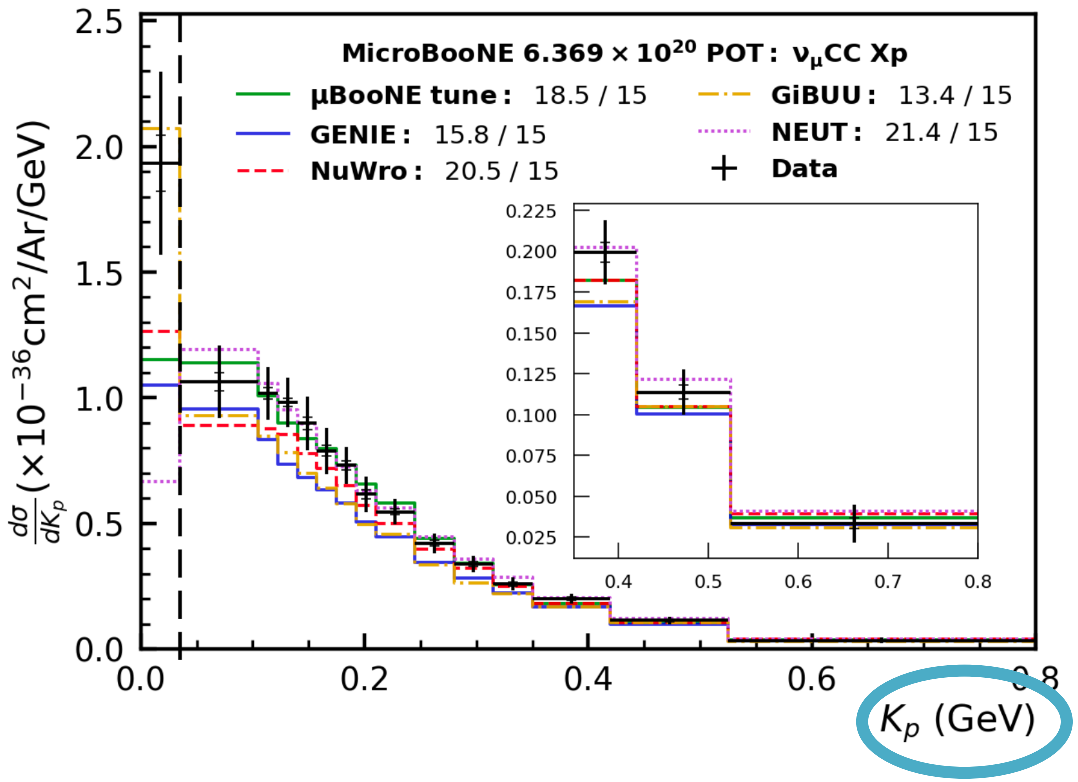
- Commonly used event generators mismodel final states without protons.
  - GiBUU is the only exception.
- Better agreement seen for final states with protons.

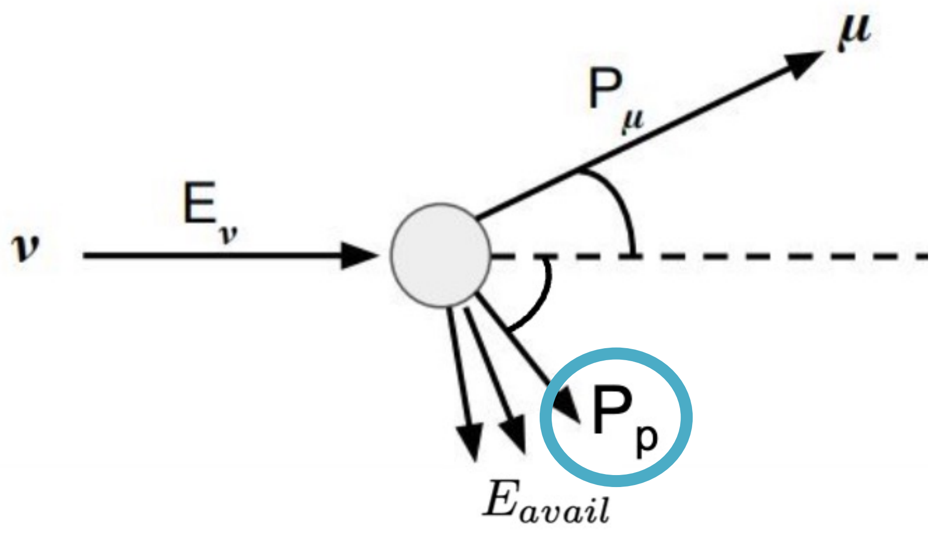




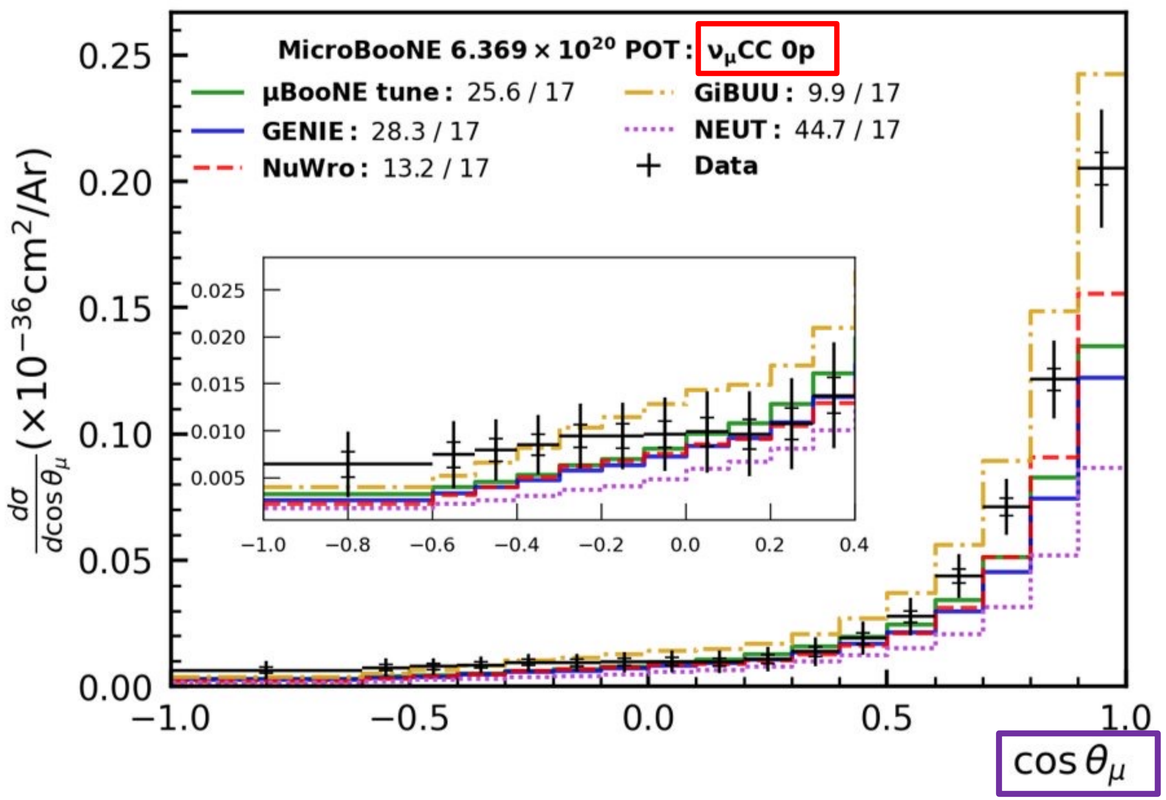


Proton Kinetic Energy and FSI

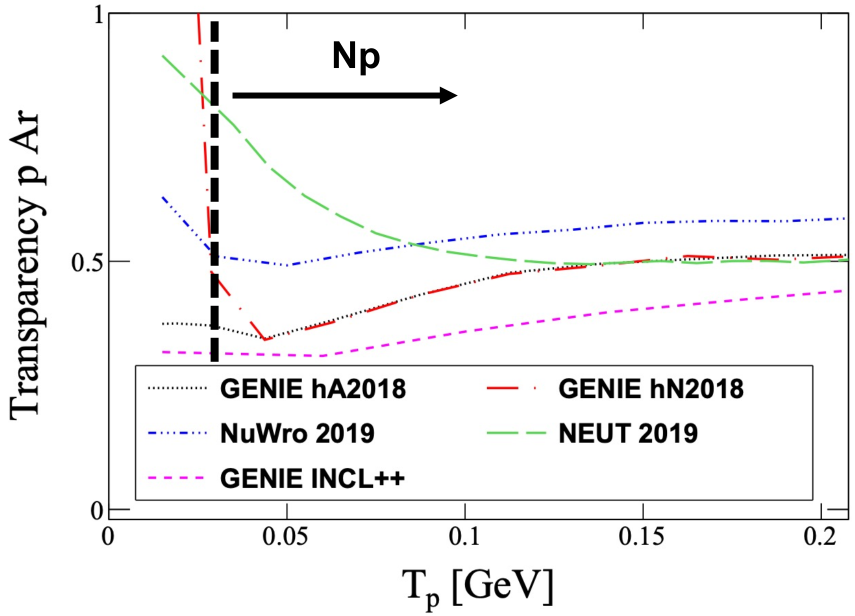




- Final state interactions (FSI) pull the proton energy distribution towards lower values.
  - Events may be shifted from Np to 0p.
- **GiBUU** has "strong" FSI, its prediction peaks sharply at low energies.
  - Good agreement with data!
- **NEUT** has "weak" FSI, its prediction drops off at low energies.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



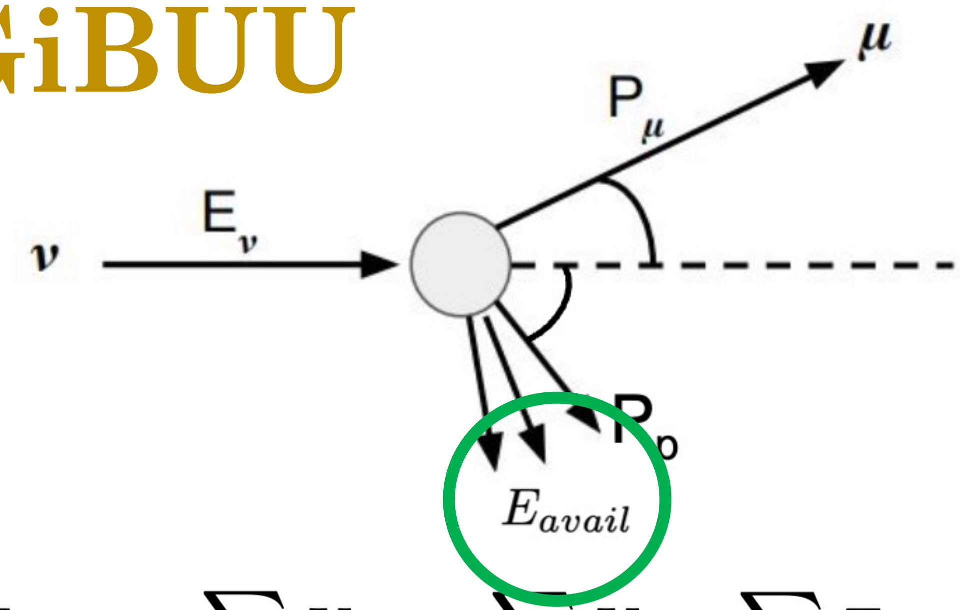
NEUT



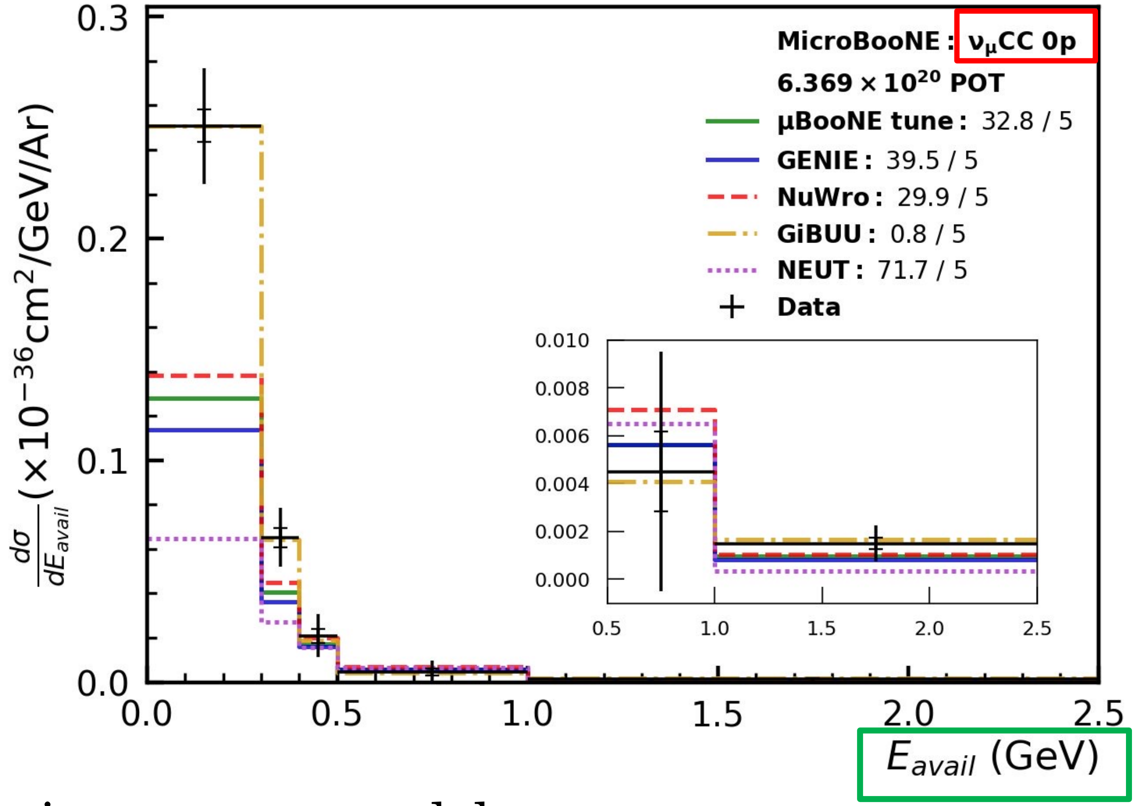
Phys. Rev. D 104, 053006 (2021)
Phys. J. Spec. Top. 230, 4469–4481 (2021)

- **NEUT** significantly underpredicts the 0p cross section.
- **NEUT**'s emulation of Pauli blocking in FSI suppresses low energy nucleon interactions.
  - Only allows nucleon interactions if the total energy is greater than 2x the nucleon mass.
  - Not guaranteed because an effective mass is used for bound nucleons.
- Fewer reinteractions leads to the low 0p prediction.
  - High transparency, low energy nucleons get out of the nucleus "for free".

GiBUU



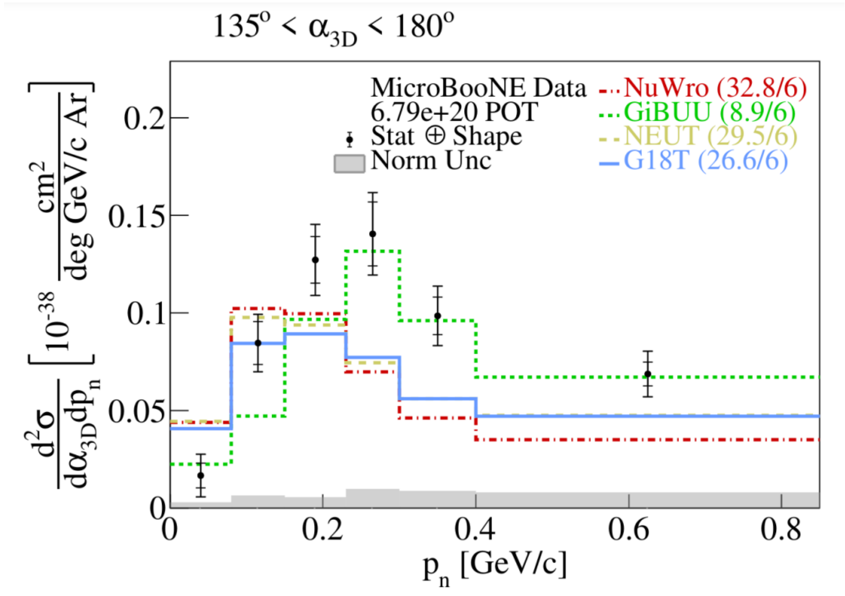
$$E_{avail} = \sum_{\pi^\pm} K_{\pi^\pm} + \sum_{p} K_p + \sum_{other} E_{particle}$$

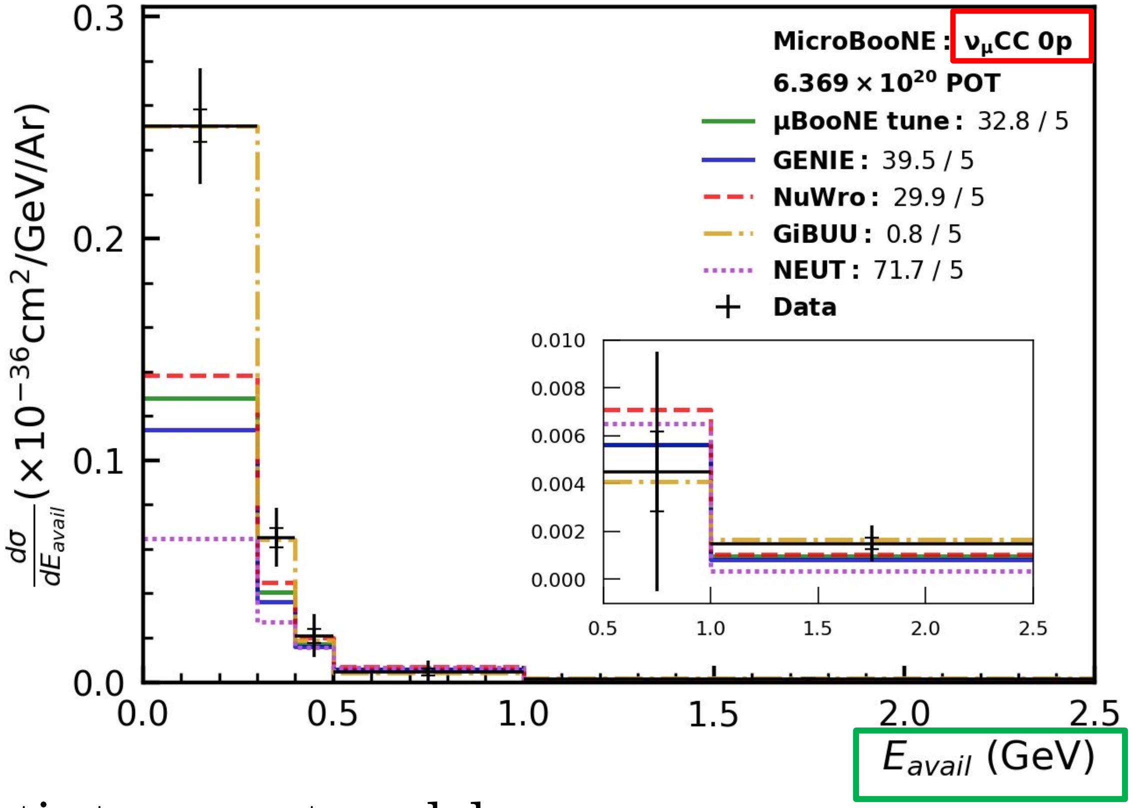


- **GiBUU** simulates FSI with a quantum kinetic transport model.
  - More detailed treatment than the cascade model used by other generators.
- Low energy protons are most impacted by FSI.
  - Good description of FSI is required for a robust 0p prediction.
- **GiBUU** consistently describes data better than other generators in FSI rich phase space.

Phys. Rept. 512, 1-124 (2012) arXiv:2308.16161 [nucl-th]

GiBUU





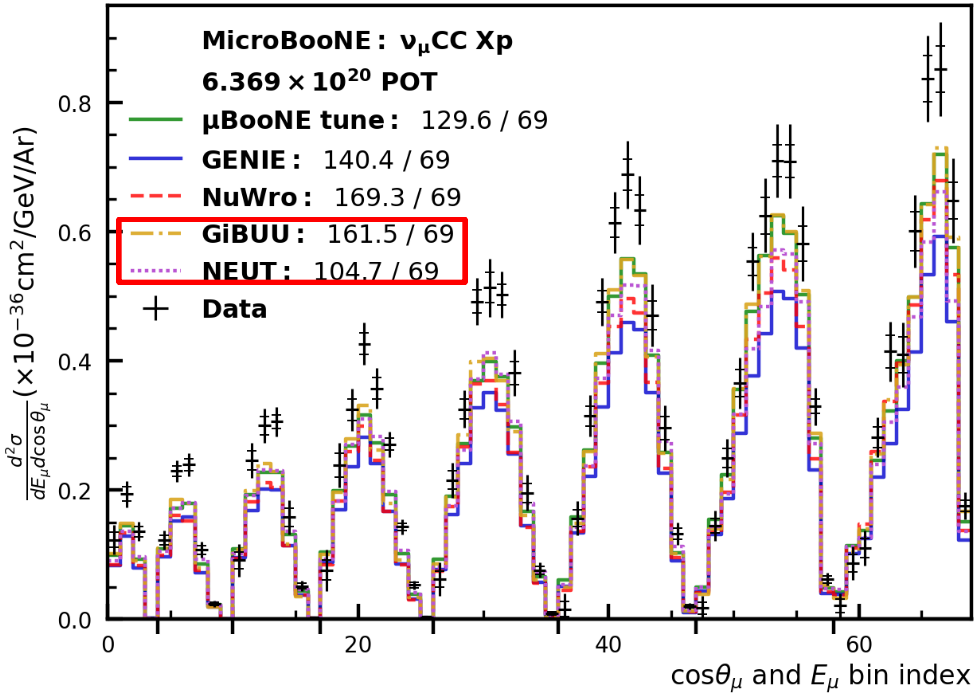
- **GiBUU** simulates FSI with a quantum kinetic transport model.
  - More detailed treatment than the cascade model used by other generators.
- Low energy protons are most impacted by FSI
  - Good description of FSI is required for a robust 0p prediction.
- **GiBUU** consistently describes data better than other generators in FSI rich phase space.
  - 0p channel
  - High α_{3D} in the CC1p channel as highlighted by Andy Furmanski in his W&C.

Phys. Rept. 512, 1-124 (2012) arXiv:2308.16161 [nucl-th]

Inclusive vs. 0p and Np Final States

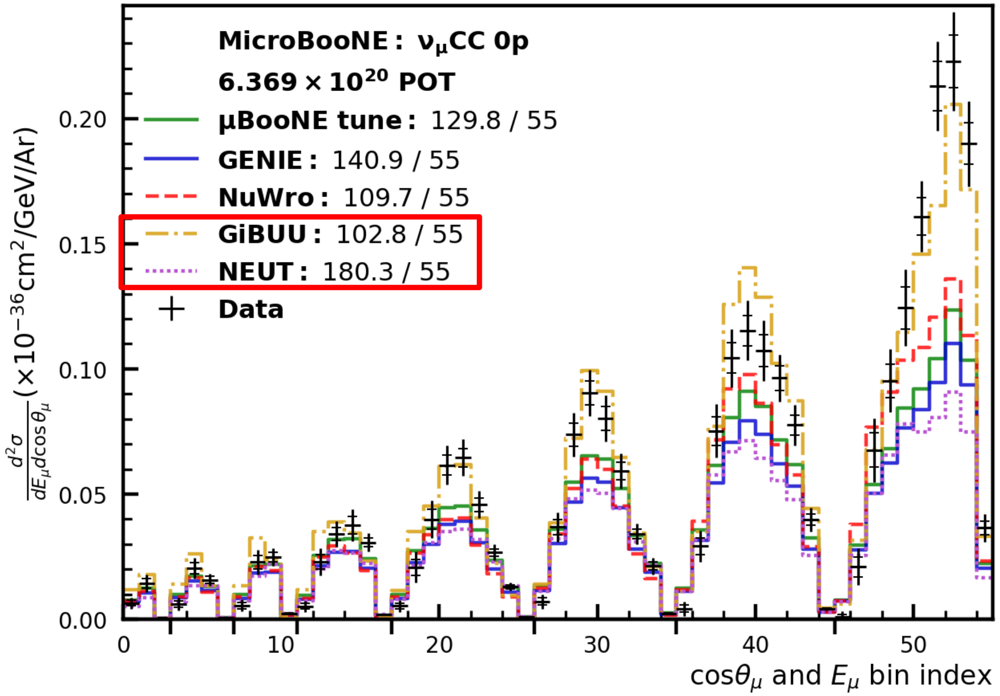
- A good description of inclusive scattering does not guarantee a good description of the hadronic final state:
  - **NEUT** describes the inclusive muon kinematics better than **GiBUU.**
  - **GiBUU** better describes the data when the channel is divided into 0p and Np final states.
- Important consideration when building models for a wide range of physics analyses.

Inclusive ("Xp")



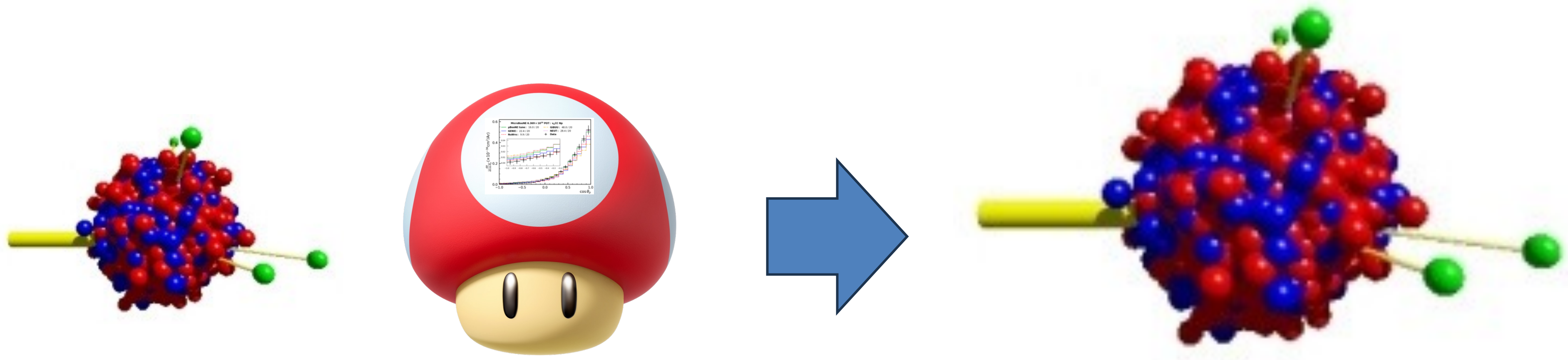
vs.

0p Final States



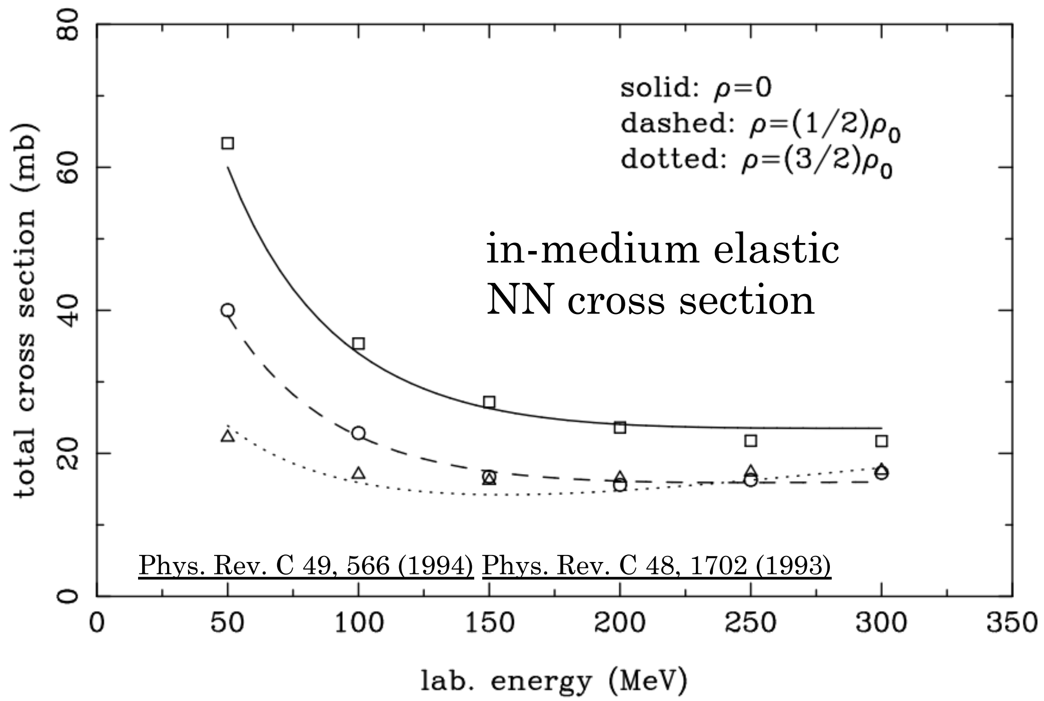
Measuring Neutrino-Nucleus Cross Sections

1. Build a detector and put it in a neutrino beam where it 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.



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 nucleon-nucleon (NN) cross sections inside the nuclear medium.
  - **GiBUU** nominally uses the vacuum cross section in its FSI model.



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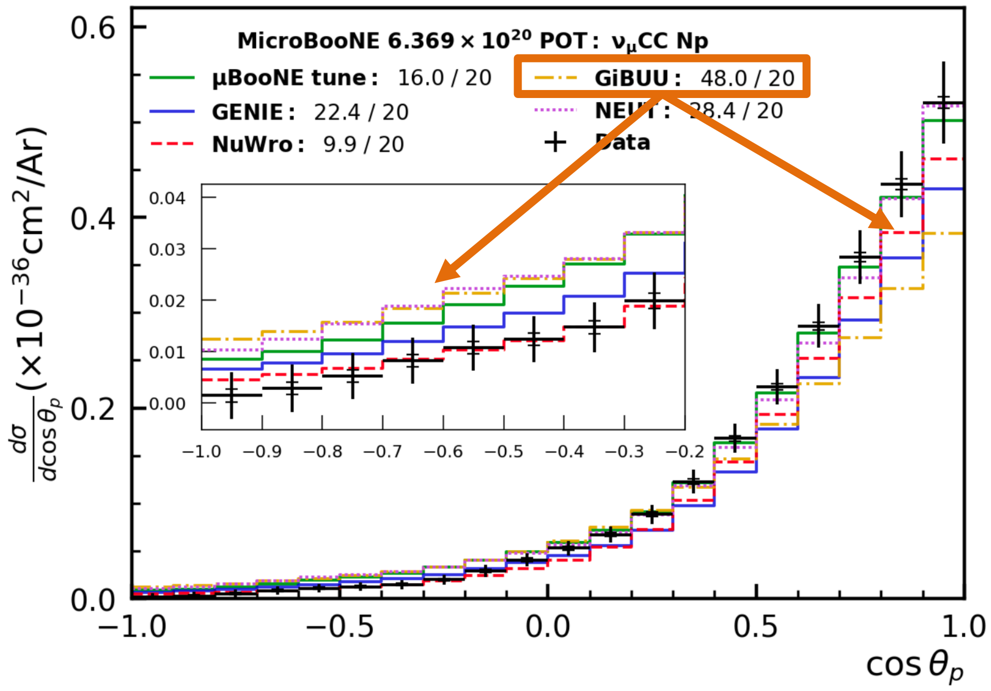
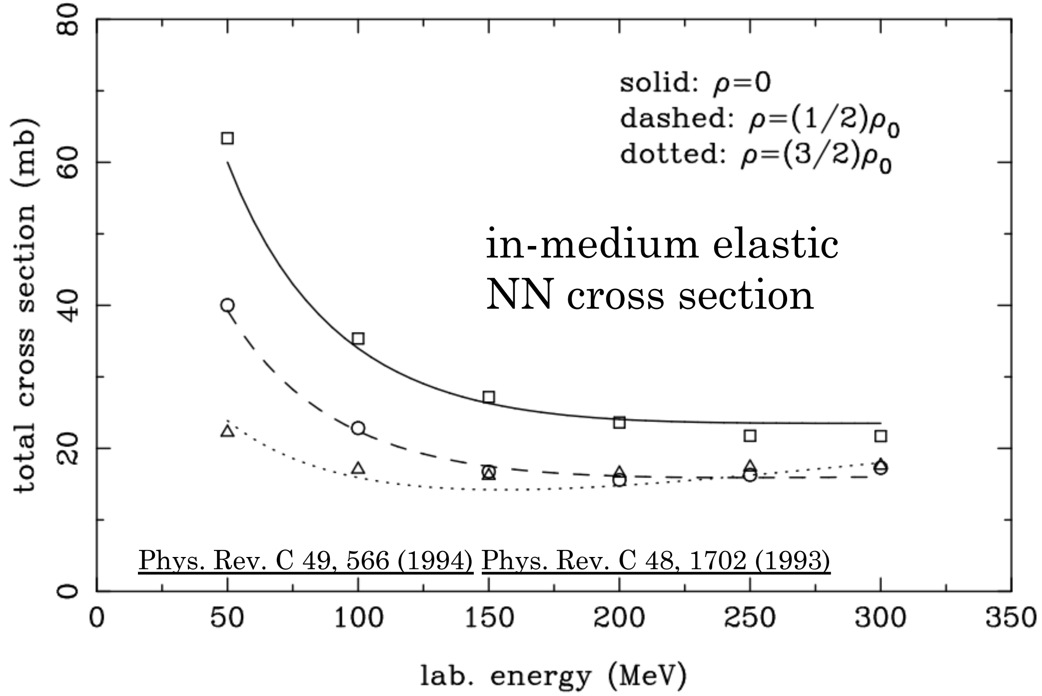
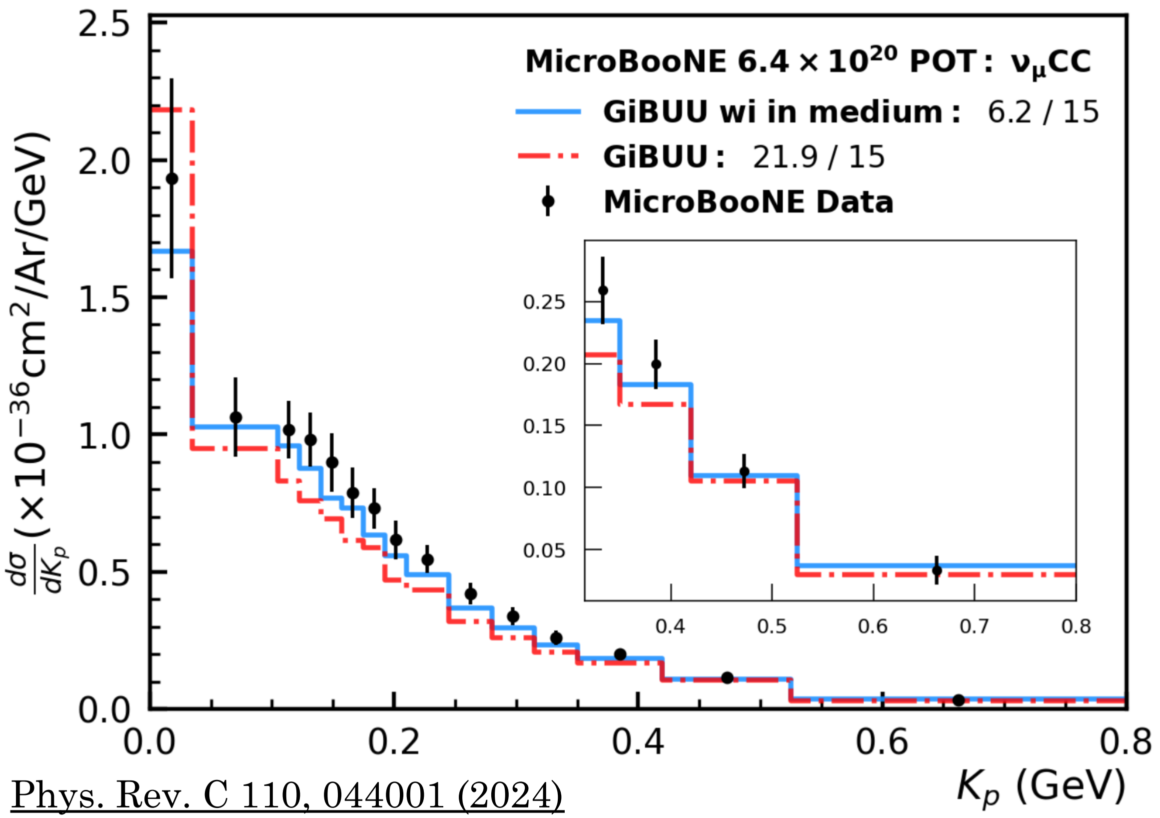
- Theoretical investigation suggest a lowering of nucleon-nucleon (NN) cross sections inside the nuclear medium.
  - **GiBUU** nominally uses the vacuum cross section in its FSI model.
- Features of the data suggest a need for in-medium modifications.
  - Underestimation of the proton spectra at forward angles, overestimation at backwards angles.

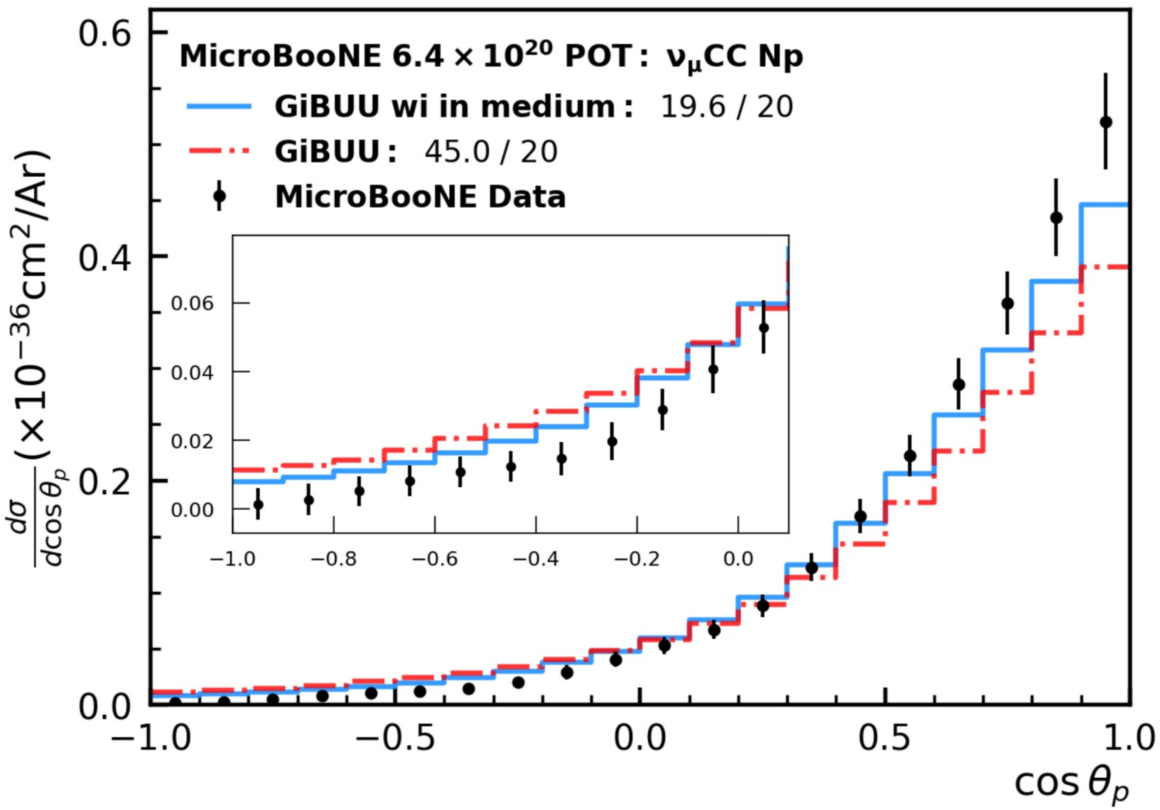




Utilizing the Data: In-medium Modifications

- Improvement in the proton spectra when in-medium modifications are included.
- Energy spectrum shifts higher from fewer interactions depleting the proton of its energy.
- Angular spectrum shifts forward due to less re-distribution towards backwards angles.

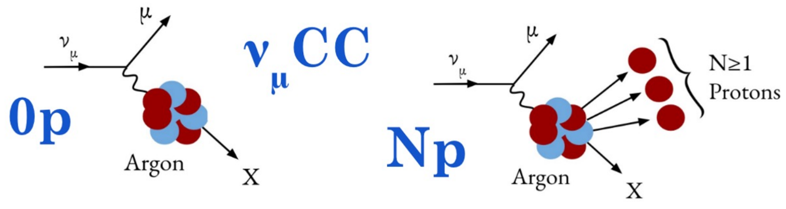


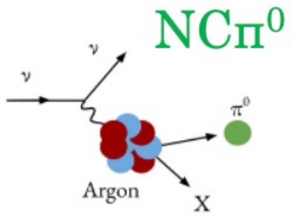


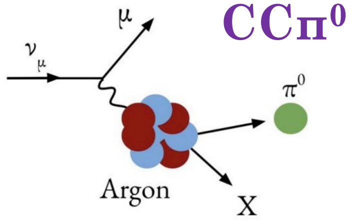
Phys. Rev. C 110, 044001 (2024)

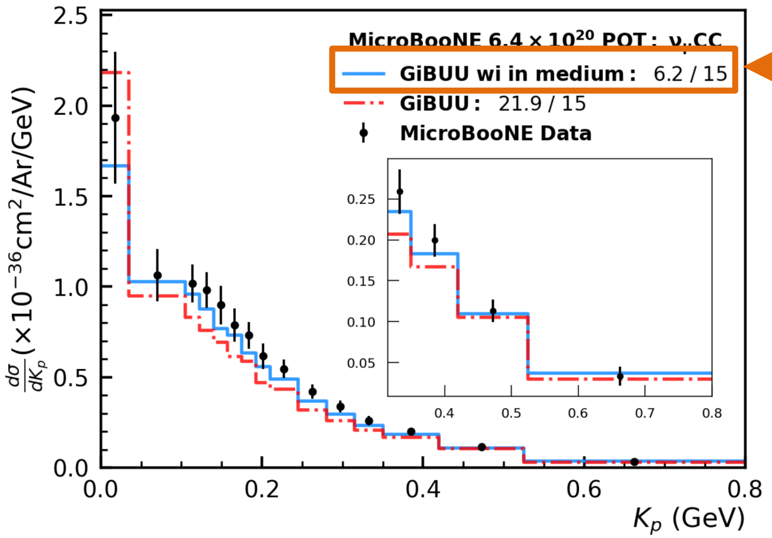
Nuclear Physics in MicroBooNE Data

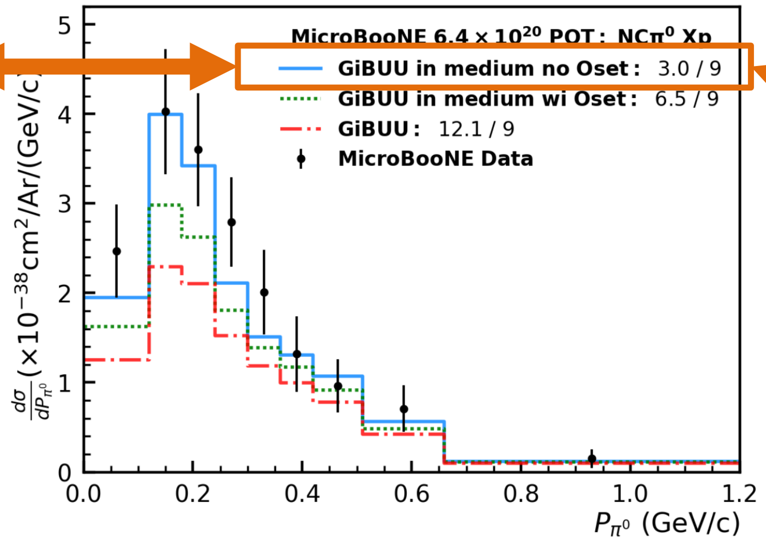
- Analogous trends seen in other MicroBooNE data.
  - Meghna Bhattacharya's W&C highlights in-medium effects in neutral pion production.
  - Accounting for in-medium effects is essential in obtaining a satisfactory description of the data.
- MicroBooNE data show sensitivity to nuclear physics modeling!



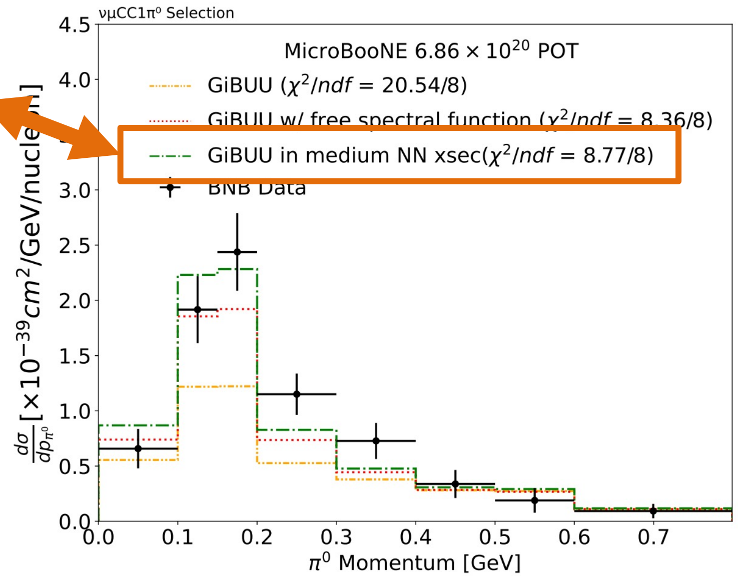








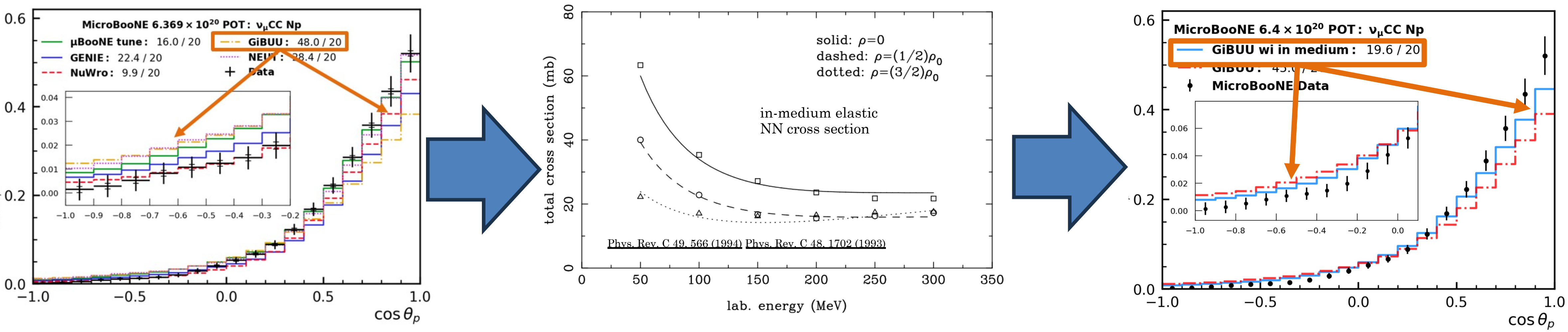
arXiv:2404.10948



Phys. Rev. D 110, 092014 (2024)

Summary

- Precise modeling of neutrino-nucleus interactions is need to address key topics in the neutrino sector.
- 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.



Thank you!

*Detector not to scale

Backup

MicroBooNE Cross Section Results

CC inclusive

- ν_μCC neutron production, BNB, arXiv:2406.10583
- 3D ν_μCC inclusive 0p/Np, BNB, Phys. Rev. Lett. 133, 041801 (2024), Phys. Rev. D 110, 013006 (2024)
- 3D ν_μCC inclusive, BNB, arXiv:2307.06413
- 1D ν_μCC inclusive E_ν, BNB, Phys. Rev. Lett. 128, 151801 (2022)
- 1D ν_eCC inclusive, NuMI, Phys. Rev. D105, L051102 (2022)
- One bin ν_eCC inclusive, NuMI, Phys. Rev. D104, 052002 (2021)
- 2D ν_μCC inclusive, BNB, Phys. Rev. Lett. 123, 131801 (2019)

Pion production

- 2D NC π^0, BNB, arXiv:2404.10948
- 1D CC π^0, BNB, Phys. Rev. D 110, 092014 (2024)
- 1D NC π^0, BNB, Phys. Rev. D 107, 012004 (2023)
- One bin CC π^0, BNB, Phys. Rev. D 99, 091102(R) (2019)

Rare channels

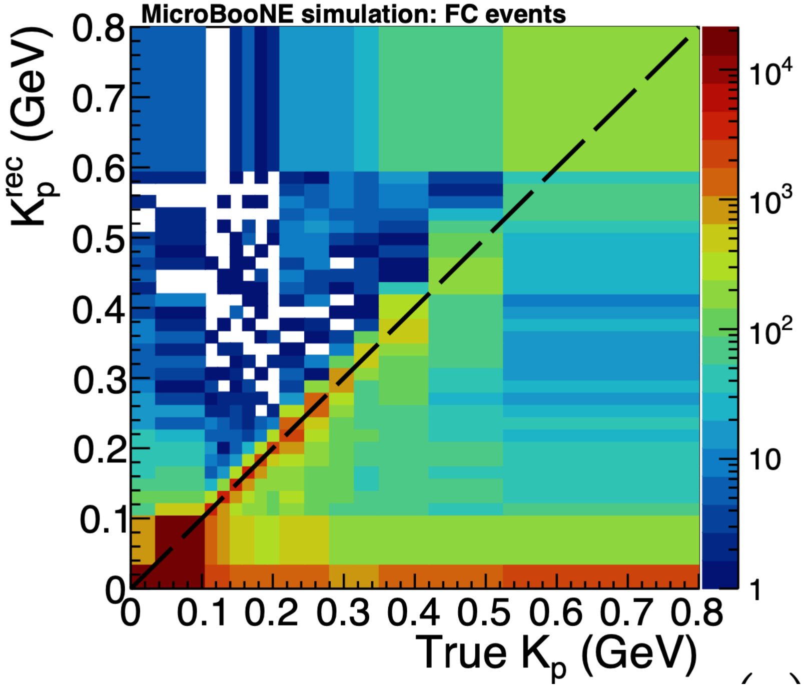
- η production, BNB, Phys. Rev. Lett. 132, 151801 (2024)
- Λ production, NuMI, Phys. Rev. Lett. 130, 231802 (2023)
- NC $\Delta \rightarrow N\gamma$ (interpreted as a limit on the cross section), BNB, Phys. Rev. Lett. 128, 111801 (2022)

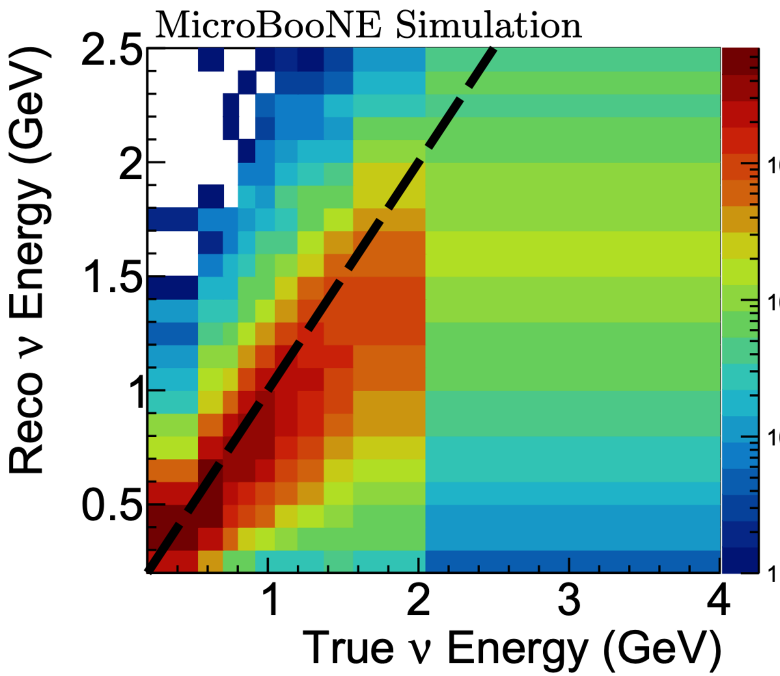
CC 0π

- 2D ν_μ CC Np0π, BNB, arXiv:2403.19574
- 1D & 2D ν_μ CC 1p0π Generalized Imbalance, BNB, Phys. Rev. D 109, 092007 (2024)
- 1D & 2D ν_μCC 1p0π Transverse Imbalance, BNB, Phys. Rev. Lett. 131, 101802 (2023), Phys. Rev. D 108, 053002 (2023)
- 1D ν_eCC Np0π, BNB, Phys. Rev. D 106, L051102 (2022)
- 1D ν_μ CC 2p0π, BNB, arXiv:2211.03734
- 1D ν_μ CC Np0π, BNB, Phys. Rev. D102, 112013 (2020)
- 1D ν_μ CC 1p0π, BNB, Phys. Rev. Lett. 125, 201803 (2020)

Energy Reconstruction

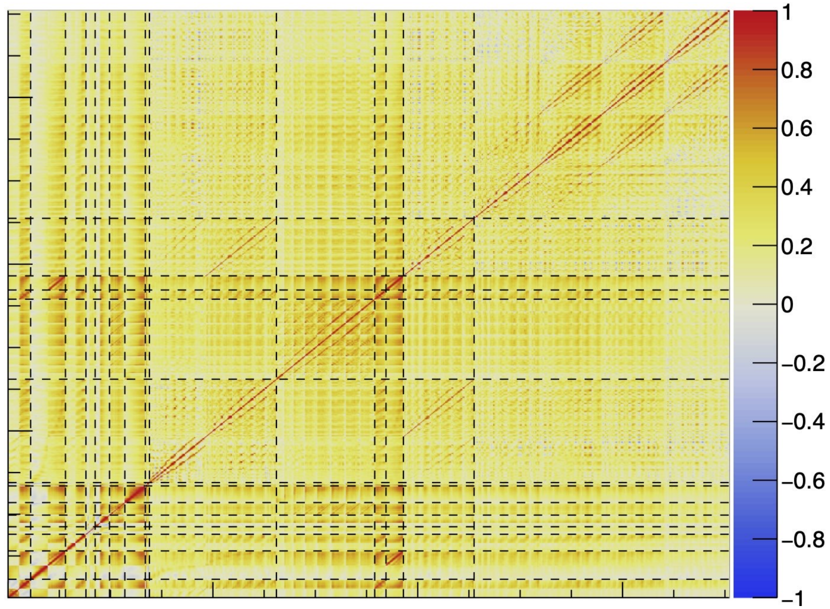
- Energy of tracks is estimated with particle range or summation of deposited charge per unit length:
  - Range used for all tracks >4cm that stop in the detector.
  - Summation of charge used for all other tracks.
- Energy of showers is estimated by scaling the total deposited charge.
  - Scaling factors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



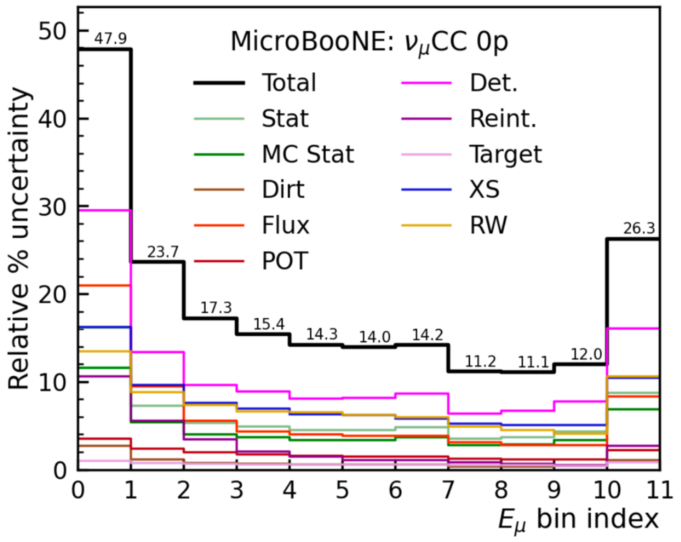


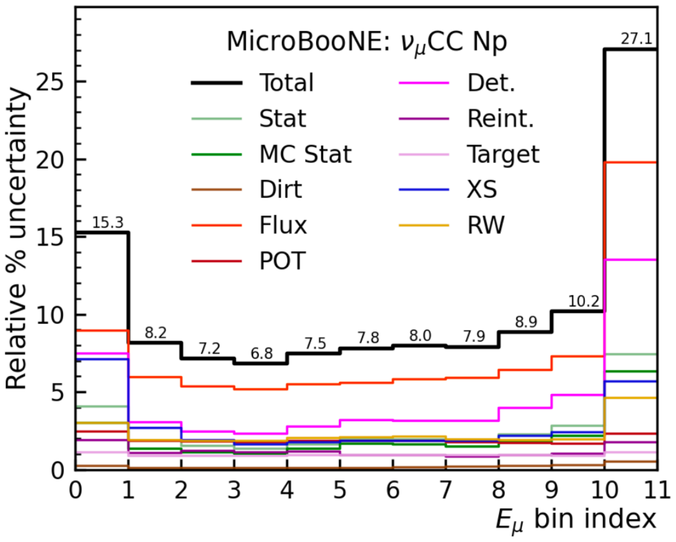
Systematic Uncertainties

- 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.



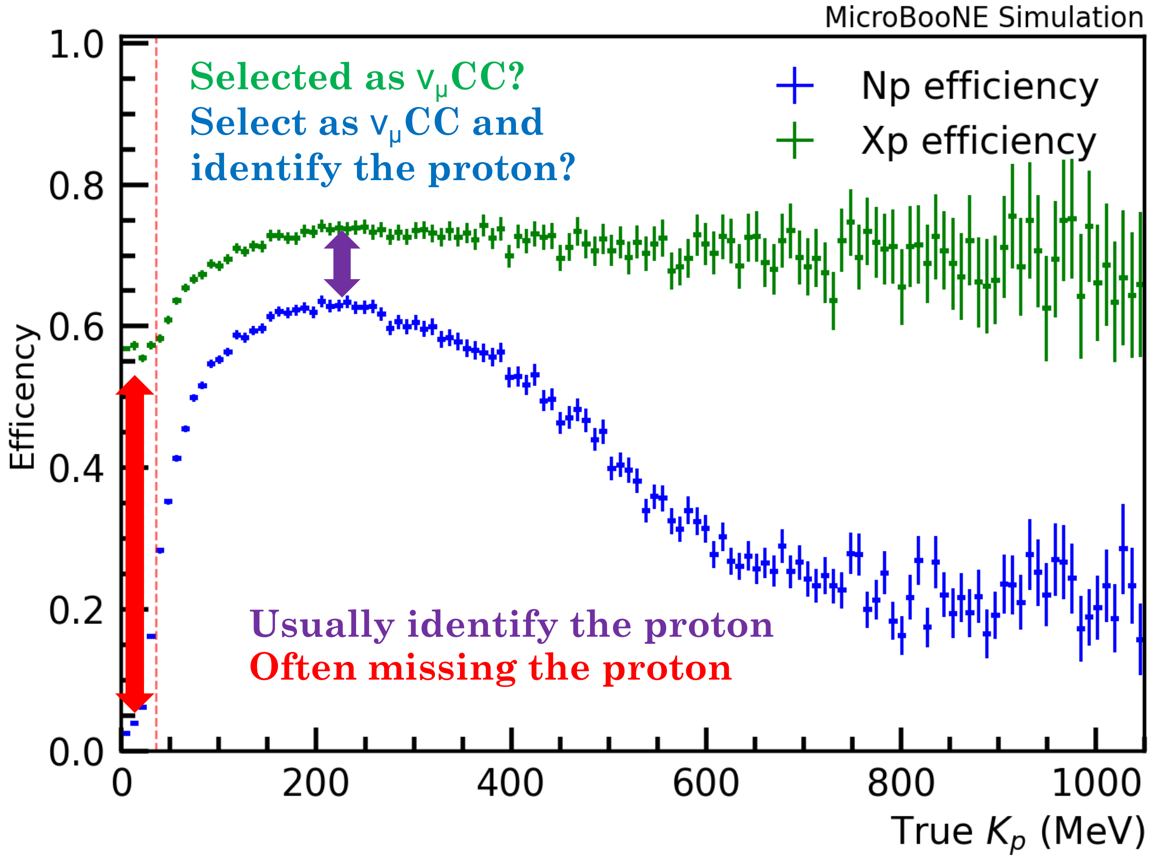
Correlation matrix for all 14 measurements.





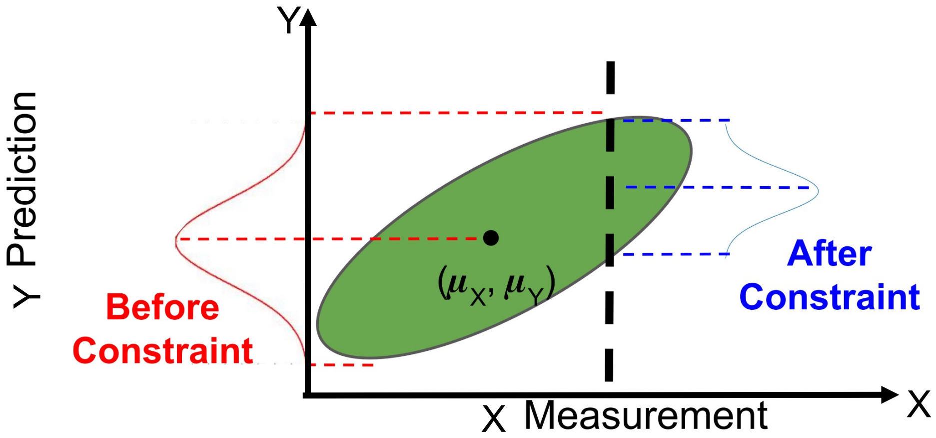
0pNp Event selection

- 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.

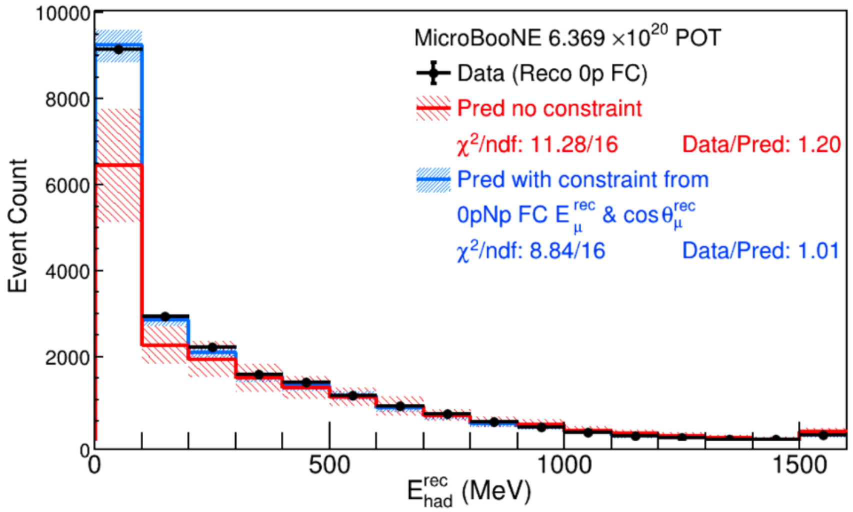


Conditional Constraint and GoF Tests

- Models predict correlations between measurement bins, including those corresponding to different distributions, variables, or channels.
- A χ^2 test statistic is chosen as the primary metric for GoF tests in model validation.
  - This accounts for these correlations when calculated with the covariance matrix formalism.
- Conditional constraint further leverages correlations by using Bayes' theorem to update the prediction and uncertainty on one channel after constraining with another channel.
  - More stringent test that can also examine the correlations between different distributions.



$$\chi^2 = (M - P)^T \cdot V^{-1} \cdot (M - P)$$



$$\Sigma = \begin{pmatrix} \Sigma^{XX} & \Sigma^{XY} \\ \Sigma^{YX} & \Sigma^{YY} \end{pmatrix},$$

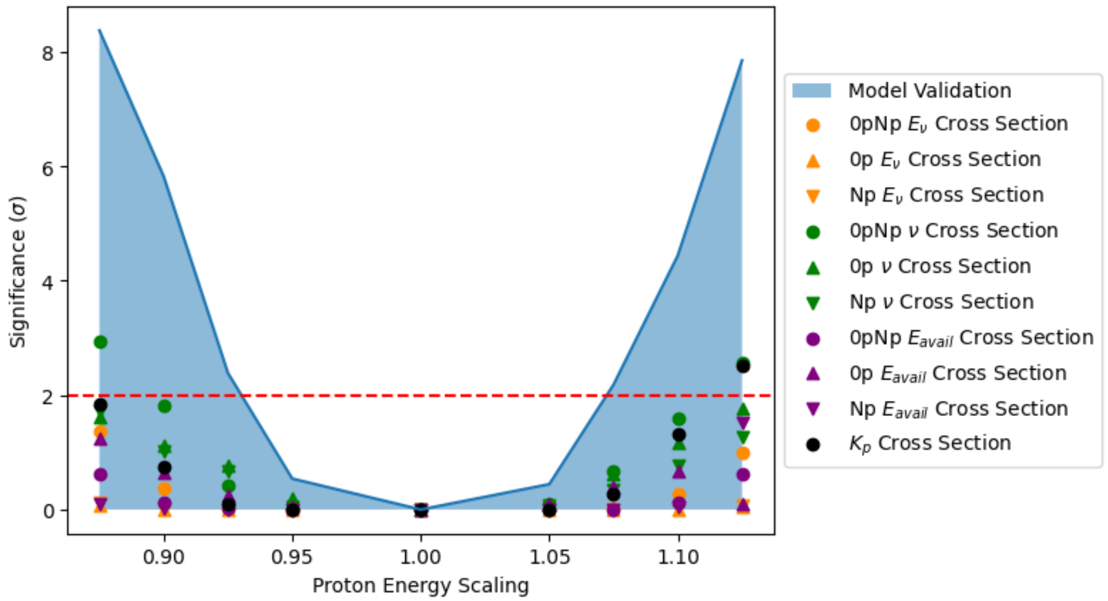
$$\mu^{X,\text{const.}} = \mu^X + \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot (n^Y - \mu^Y)$$

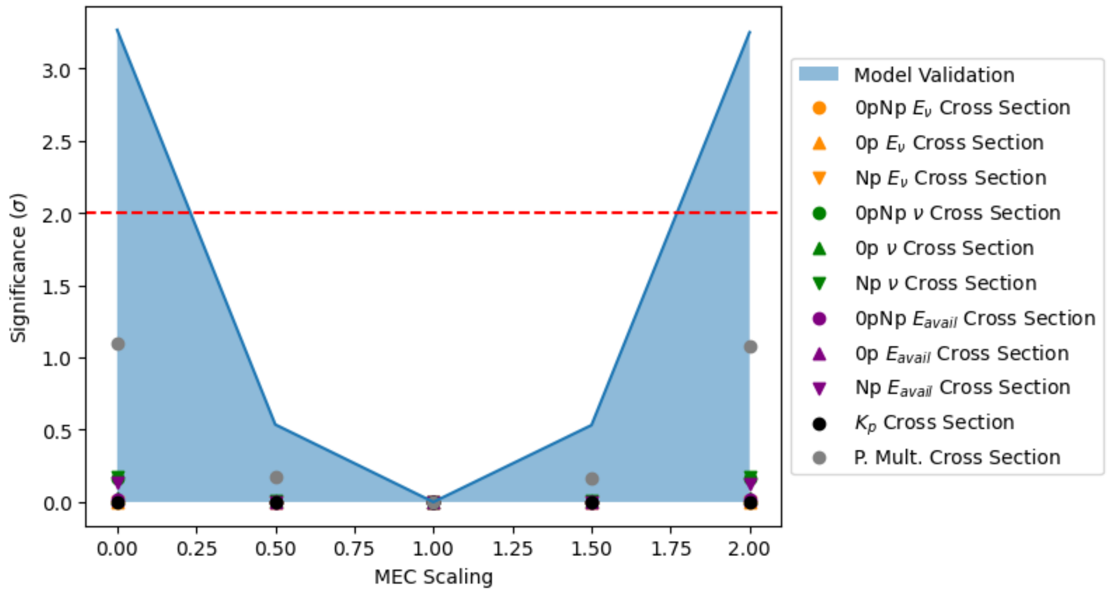
$$\Sigma^{XX,\text{const.}} = \Sigma^{XX} - \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot \Sigma^{YX}$$

n: measurement, μ: prediction

For more details, check out arXiv:2411.03280 and NuSTEC CEWG seminar

Fake Data Studies

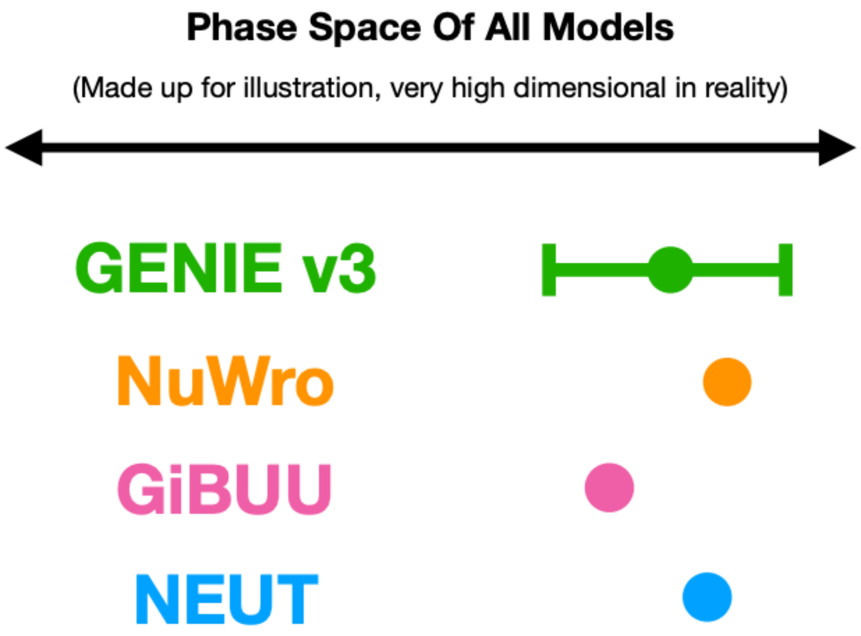




- Fake data studies designed to demonstrate that the model validation is able to detect relevant mismodeling before it begins to bias the XS extraction.
  - Analogous to the studies outlined in arXiv:2411.0328 [hep-ex].
- Generated fake data from MC by scaling:
  - Proton energy
  - MEC event weights
- 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.

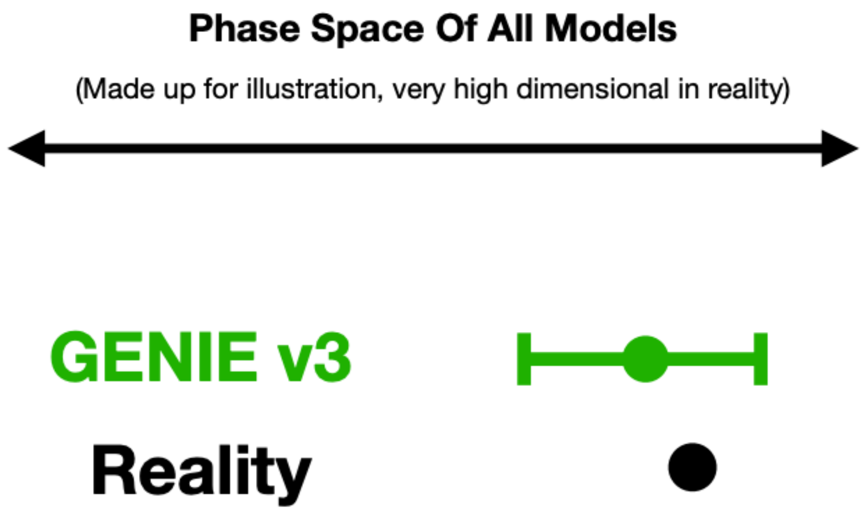
Fake-Data Closure Testing

- In traditional fake-data closure tests, we try to ensure that the cross section model used for the extraction is consistent with other cross section models in the relevant phase space



Data-driven Model Validation

- In data-driven model validation, we try to ensure that the cross section model used for the extraction is consistent with real data in the relevant phase space

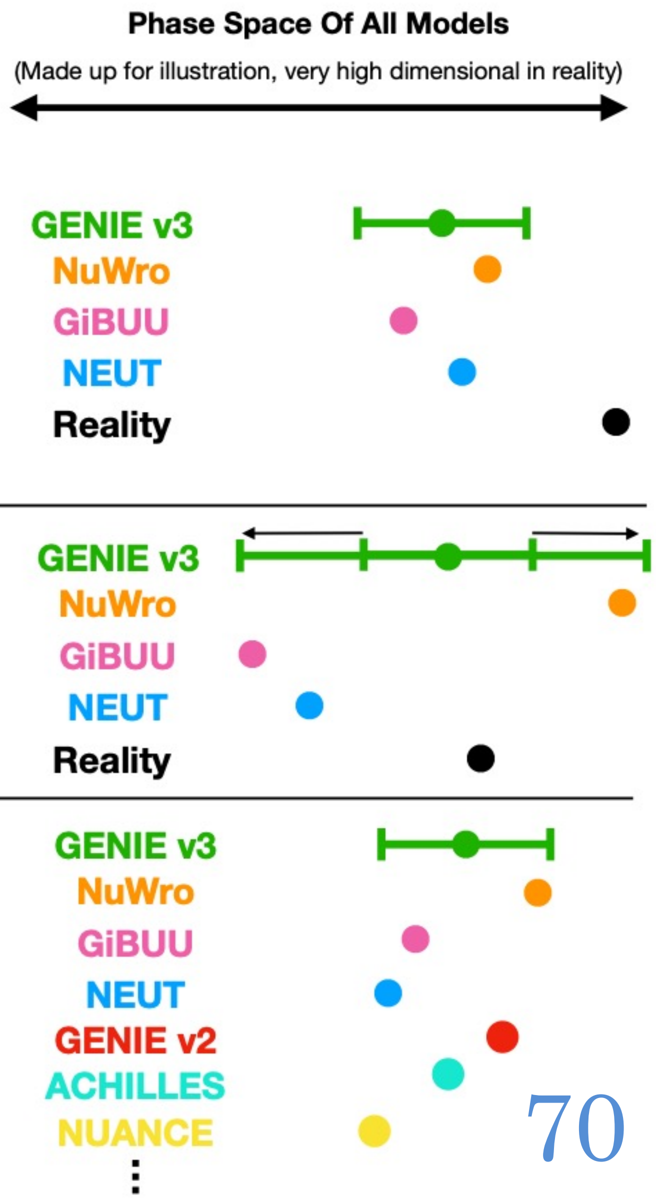


Adopted from Lee Hagaman's NuSTEC CEWG seminar

Fake-Data Closure Testing

Adopted from Lee Hagaman's NuSTEC CEWG seminar

- This procedure has some limitations
  - 1: What if the spread of models included in fake data tests do not describe the real cross section?
  - 2: What if the spread of models included in fake data tests is very large, and makes you expand to very large uncertainties, even when your original model is good?
  - 3: How do you know when to stop? There are many generators, and many configurations and tunes, is testing just one or a few alternate generators enough?



Data-driven Model Validation Has Its Own Similar Limitations

Traditional Fake-Data Closure Testing	Data-driven Model Validation
• 1: What if the spread of models included in fake data tests do not describe the real cross section?	• 1: What if the variety of model validation tests performed does not detect relevant mis-modeling?
• 2: What if the spread of models included in fake data tests is very large, and makes you expand to very large uncertainties, even when your original model is good?	• 2: What if a model validation test fails, but the failure is actually in a phase space irrelevant to the analysis (not significantly affecting the detector response, efficiency, and background prediction), leading to an unnecessary expansion of uncertainties?
• 3: How do you know when to stop? There are many generators, and many configurations and tunes, is testing just one or a few alternate generators enough?	• 3: How do you know when to stop? There are many model validation tests you can think of, how many should you perform?

Adopted from Lee Hagaman's NuSTEC CEWG seminar