Inclusive and Exclusive Pionless Cross Section Measurements with MicroBooNE

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NuFACT Parallel

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On behalf of the MicroBooNE Collaboration

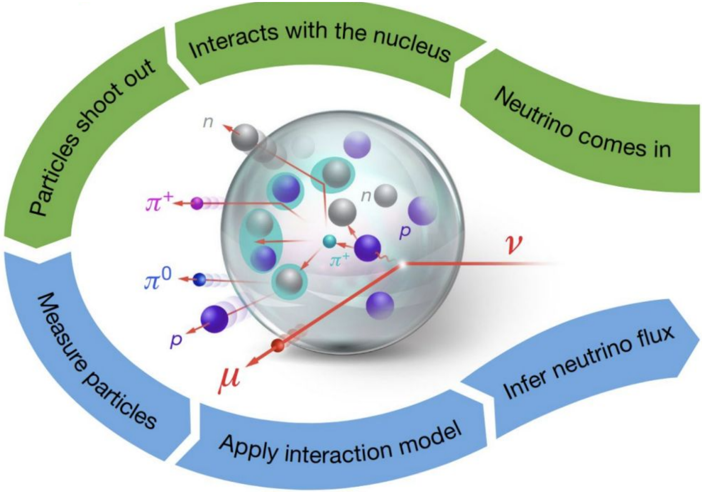
UNIVERSITY OF OXFORD

μBooNE

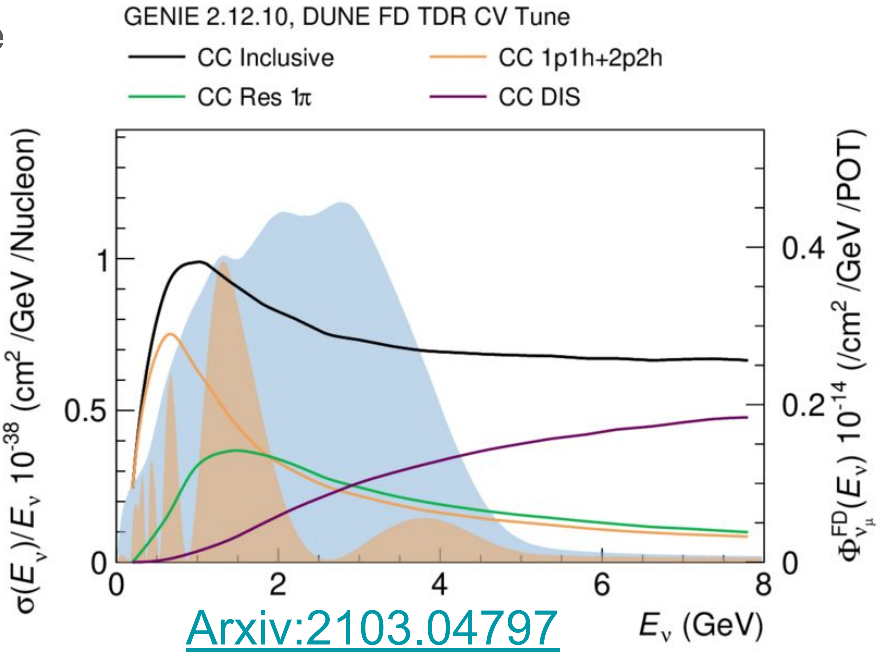
Motivation

Broad spectrum of neutrino energies used within the future precision neutrino experiments:

- Requires accurate understanding of neutrino interactions
- Mismodeling can limit experimental sensitivity



[Nature 599, 565–570 (2021)]



[Arxiv:2103.04797]

Covering the pionless cross-section results:

- See [P. Green's talk] for pion production results

MicroBooNE

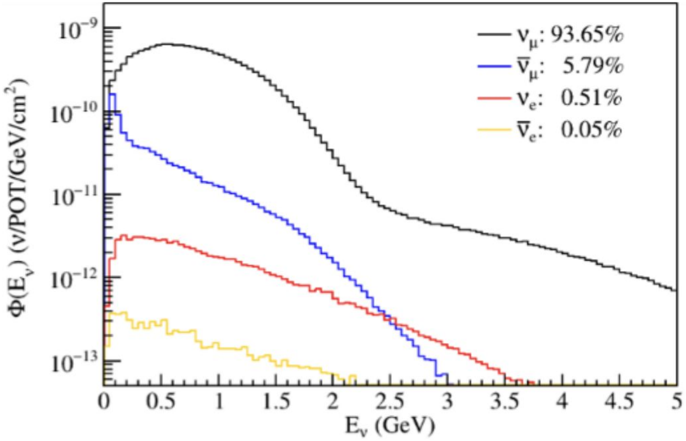
MicroBooNE: 85-tonne active mass liquid Argon TPC

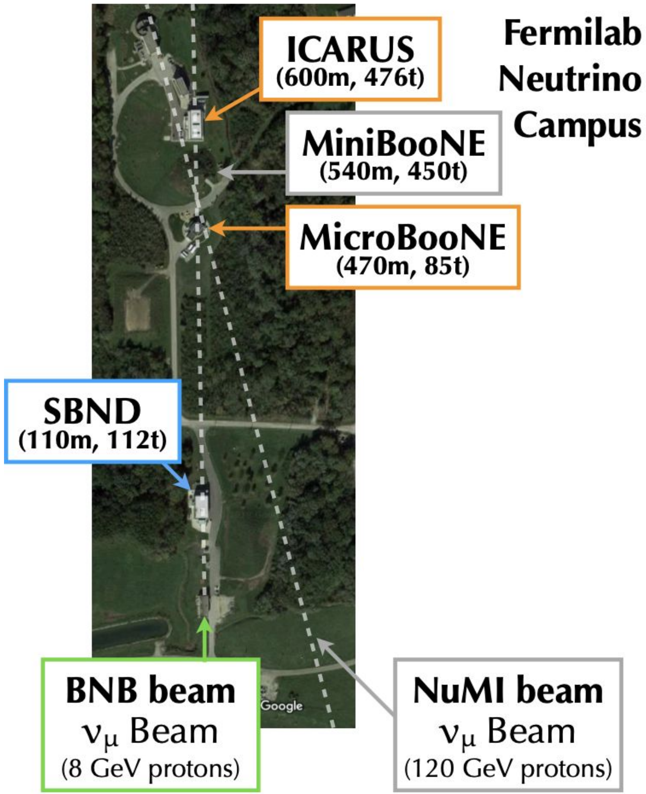
- Observes two neutrino beams at Fermilab: BNB and NuMI

Completed 5 years of data taking (2015-2020):

- World's largest dataset of neutrino interactions on Argon
- ~ 0.5 million events

BNB Neutrino Flux at MicroBooNE:

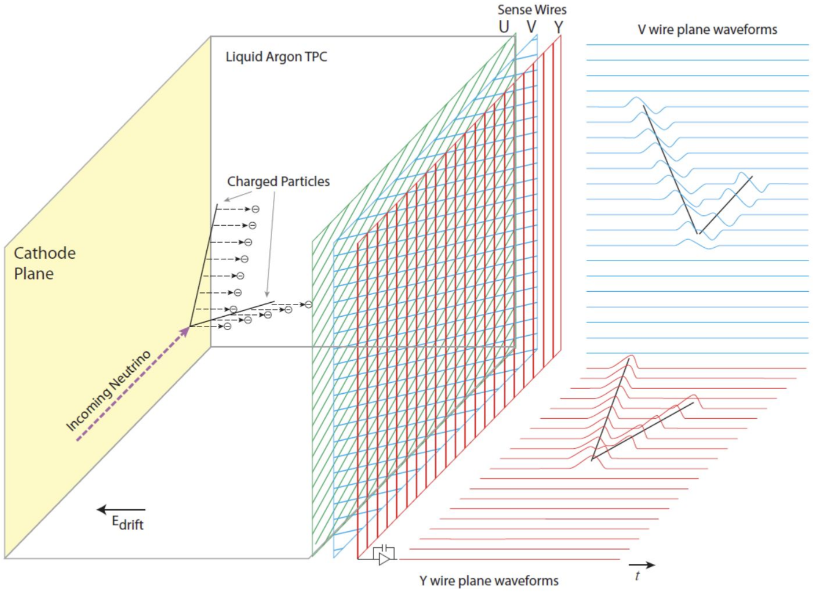


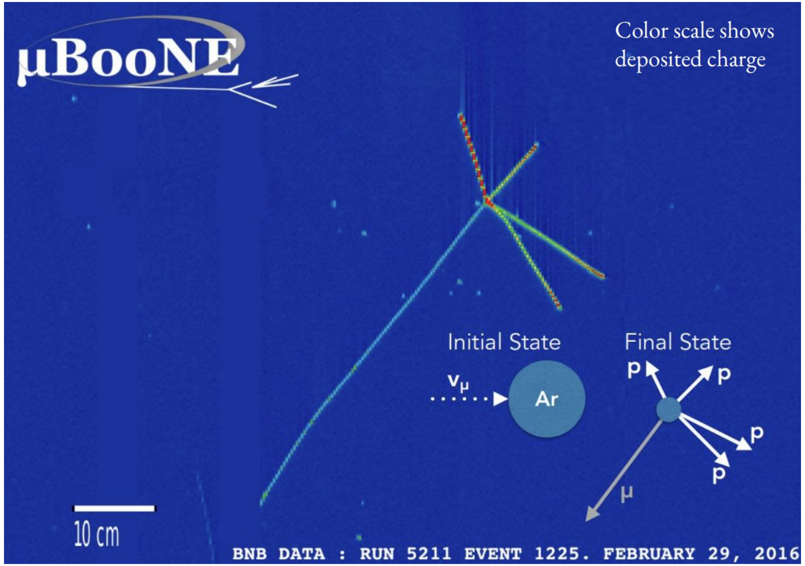


Detector Technology

MicroBooNE is a tracking calorimeter (fully active TPC)

- Multi-plane readout on induction and collection wires
- PMTs detect scintillation light and T0 of interaction





[Appl. Sci. 2021, 11(6), 2455]

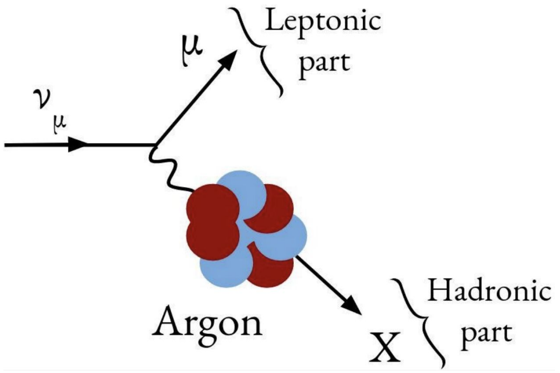
Addressing Modeling Issues

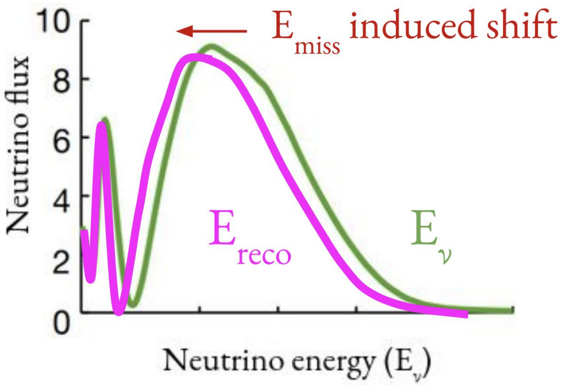
- Oscillation measurements require accurate reconstruction of both the lepton and hadronic kinematics

Lepton Hadrons

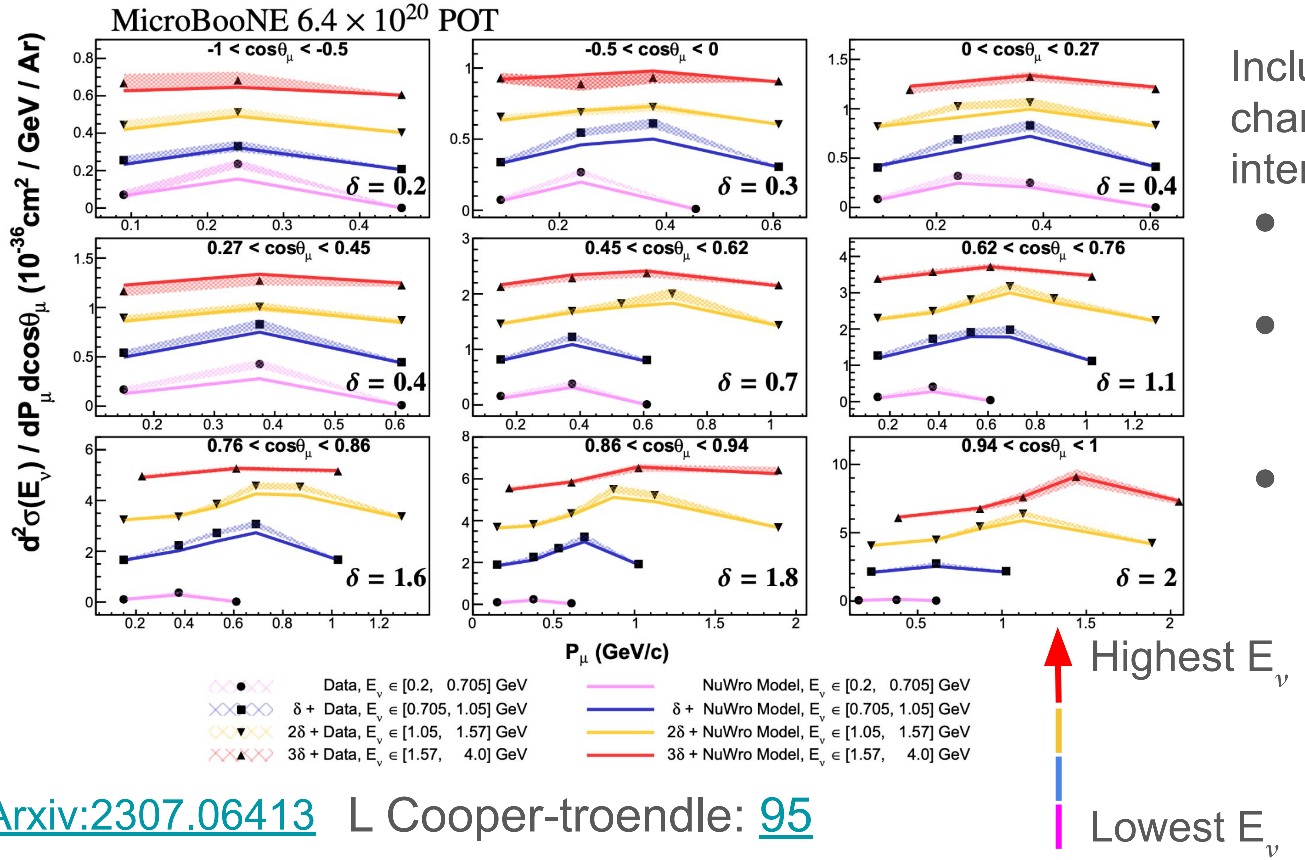
$$E_\nu = E_L + E_{had} + E_{miss}$$

- Leverage LArTPC reconstruction and particle identification to obtain $E_{reco} \cong E_\nu$
- TPC cannot reconstruct all particles (e.g. neutrons or particles below threshold) → missing energy, E_{miss}
- Dedicated analyses targeting all parts





Leptonic System Modeling



Inclusive measurements of charged current (CC) ν_μ-Ar interactions:

- First three-dimensional cross-section results
- Novel data-driven validation to detect potential missing energy mismodelling
- Enables cross-section as function of E_ν

Arxiv:2307.06413 L Cooper-troendle: 95

Inclusive Measurements - Proton Multiplicity

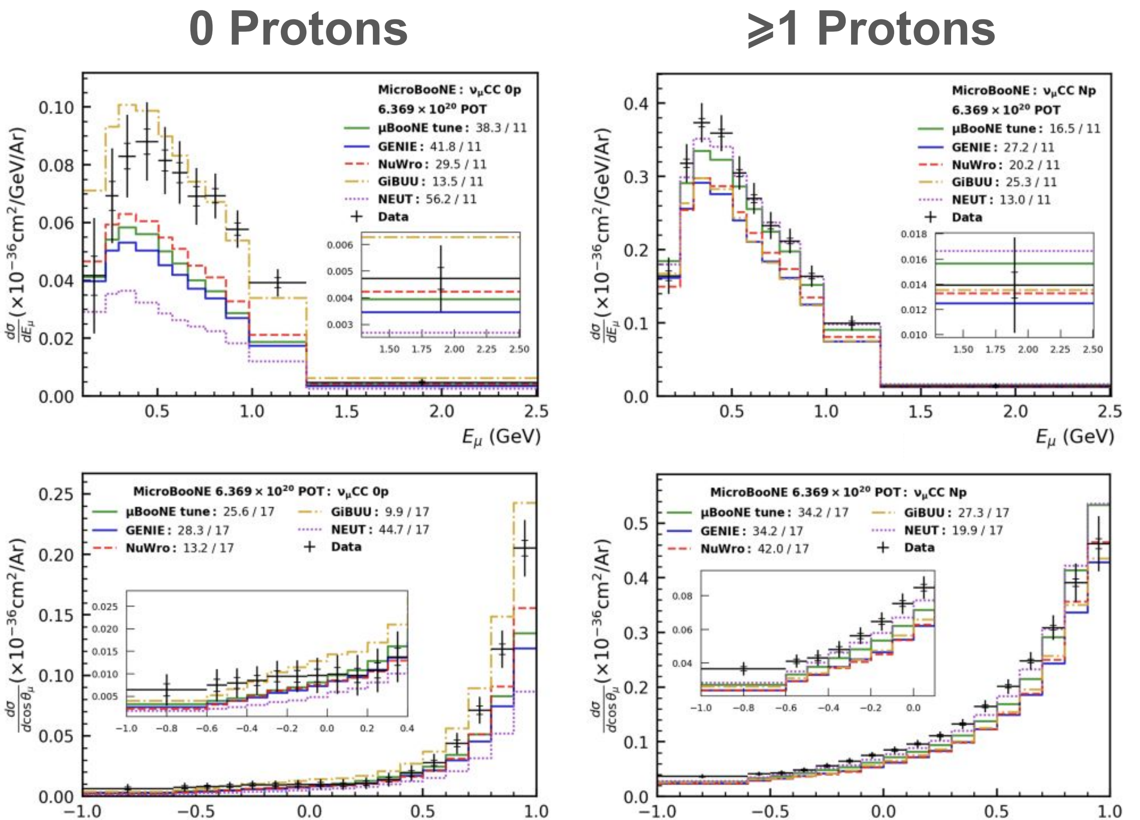
µBooNE

Use inclusive selection to separate events with and without protons:

- Make measurements of leptonic system

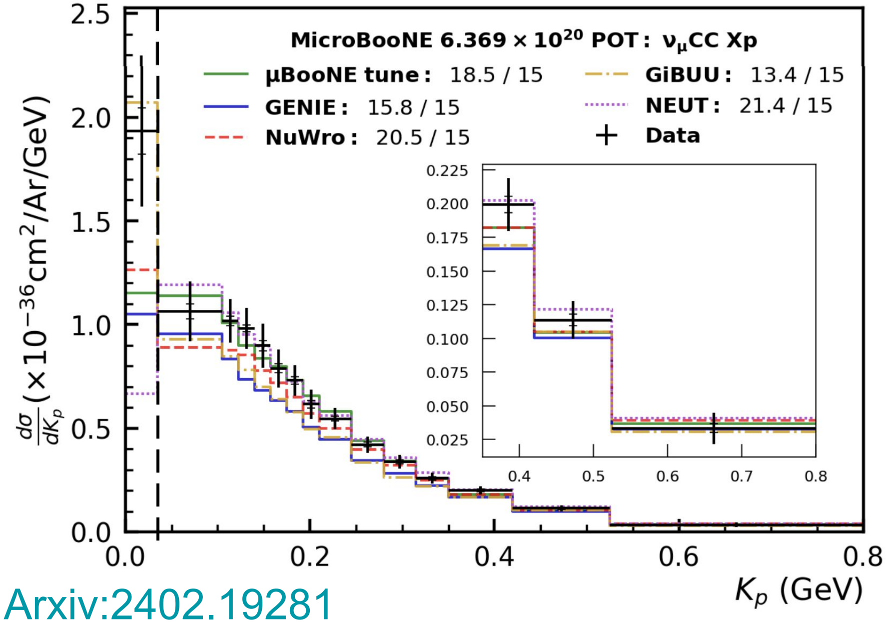
Models disagree with data for 0-proton final state interactions:

- Best agreement for GiBUU

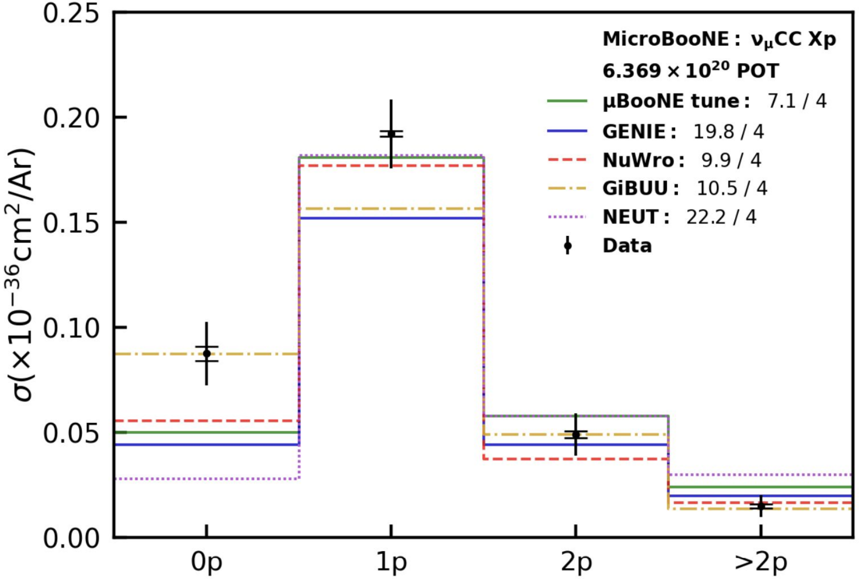


Phys. Rev. D 110, 013006 (2024)

Inclusive Measurements - Proton Multiplicity



[Arxiv:2402.19281](https://arxiv.org/abs/2402.19281)



[PhysRevD.110.013006](https://doi.org/10.1103/PhysRevD.110.013006) Proton Multiplicity

Leveraging low proton detection threshold to investigate events with/without detected protons:

- Stressed need for sophisticated treatment of low energy hadron re-interactions

Deeper Dive into Nuclear effects

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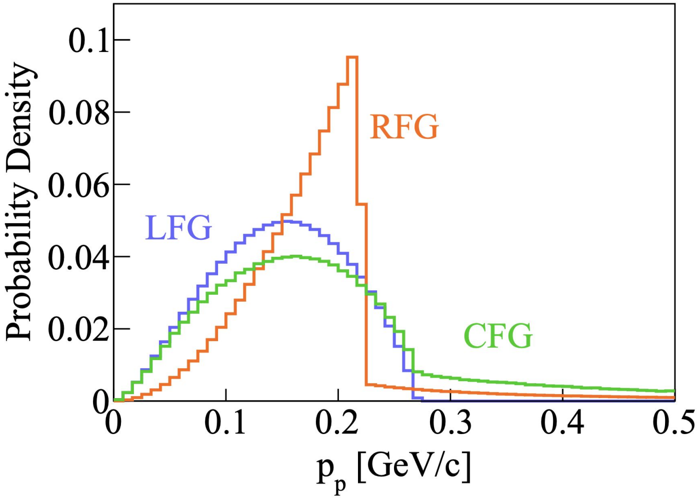
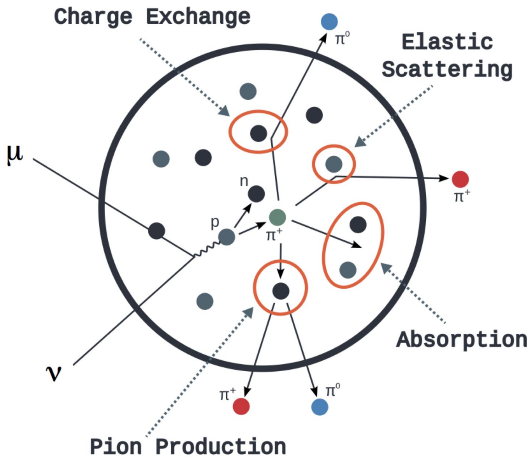
[Eur. Phys. J. Spec. Top. 230, 4449–4467](https://doi.org/)

Different models of the initial nuclear state result in different distributions of initial nucleon momentum:

- Result in different outgoing momentum



Hadronic re-interactions also modifies the final state particle kinematics and multiplicity

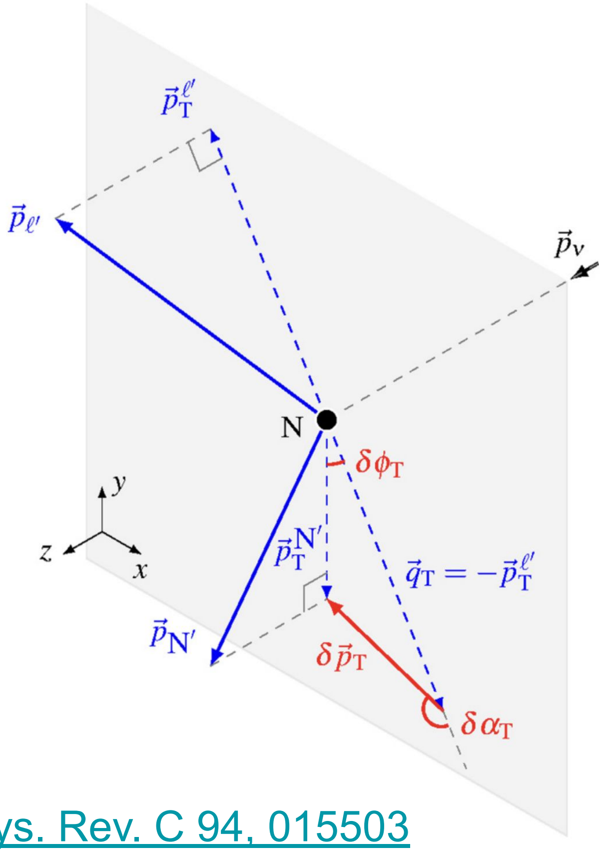


Utilise low proton detection threshold to probe nuclear ground state distributions and hadron re-interactions:

- Transverse and generalized kinematic imbalance variables

Nuclear effects with pionless analyses

μBooNE



Phys. Rev. C 94, 015503

We know initial momentum perpendicular to beam direction is zero:

- Measuring non-zero transverse momentum tells us about missing momentum

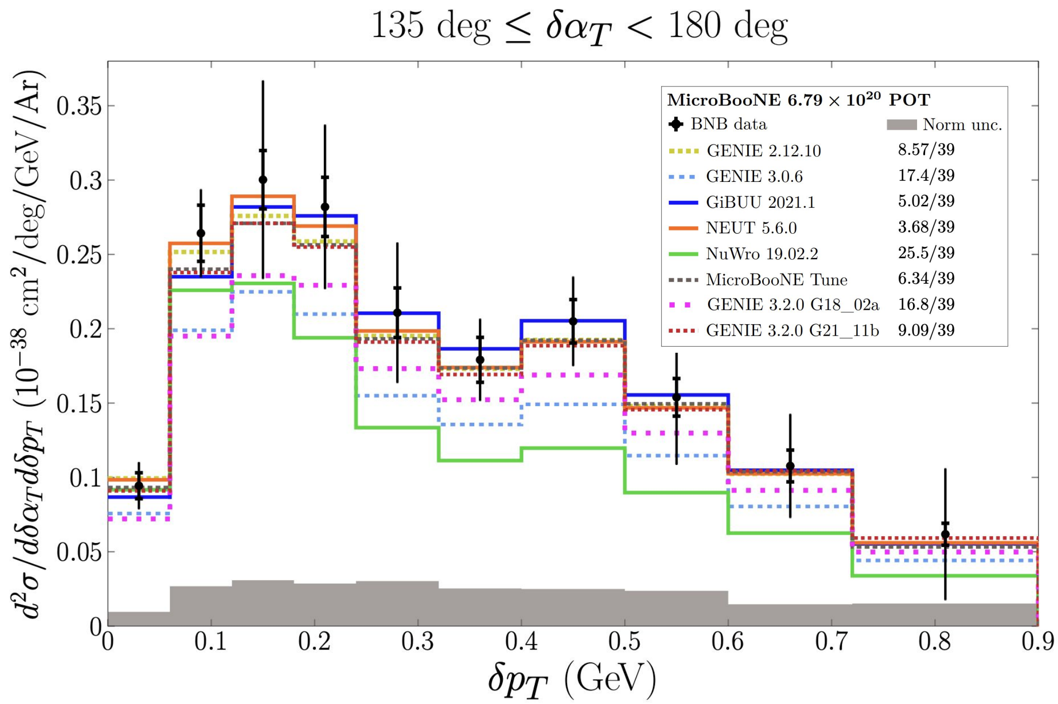
$$\delta P_T = | \mathbf{P}_T^{\mu} + \mathbf{P}_T^{P} |$$

Imbalance due to initial nucleon motion or hadronic final state interactions (FSI)

In the absence of FSI, the transverse kinematic imbalance (TKI) parameters:

- $\boldsymbol{\delta P_T}$: momentum of the struck momentum
- $\boldsymbol{\delta\alpha_T}$: angle between momentum transfer and initial state nucleon momentum

CCNp0π Selection - TKI



Arxiv:2403.19574

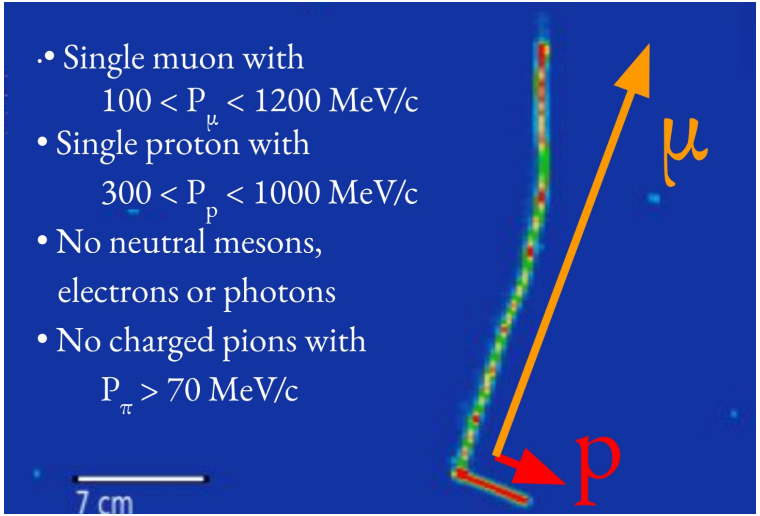
Using events with at least one proton in the final state:

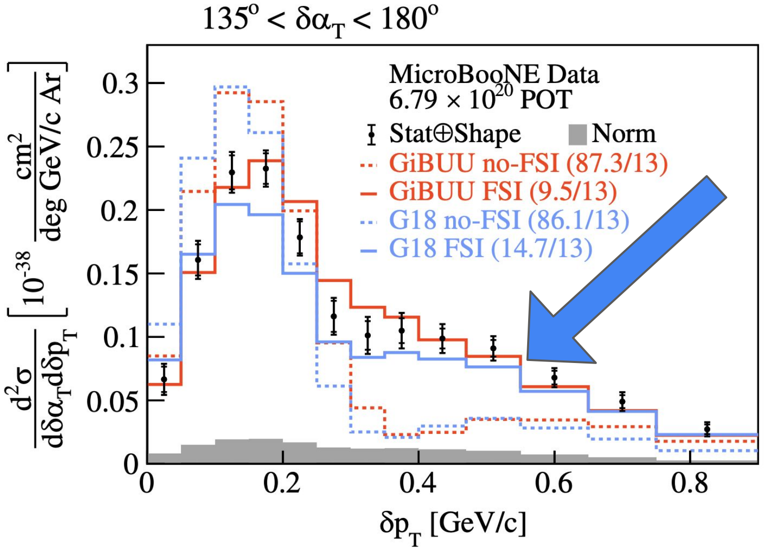
- Double-differential measurements of TKI variables using the leading proton
- Novel full treatment of correlations across 359 bins
  - Correlations between kinematics reported
- Poor agreement suggests correlations between kinematic distributions are not well modeled

CC1p0π Selection - TKI

Double-differential measurement of TKI variables studying nuclear effects of event with exactly one proton in final state:

- Distinguishes regions of large nuclear effects more completely than single variable measurements

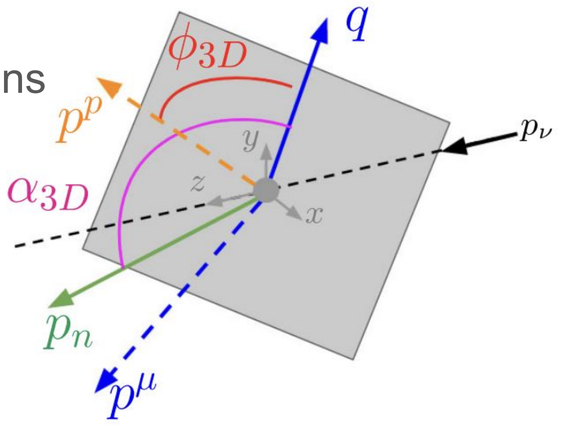




Phys. Rev. Lett. 131, 101802

CC1p0π Selection - GKI

Generalise kinematic imbalance (GKI) variables to three dimensions by considering longitudinal component of missing momentum:



- $\delta P_T \rightarrow p_n$
- $\delta\alpha_T \rightarrow \alpha_{3D}$

We know the neutrino mass is (nearly) zero:

- Energy and momentum should be equal

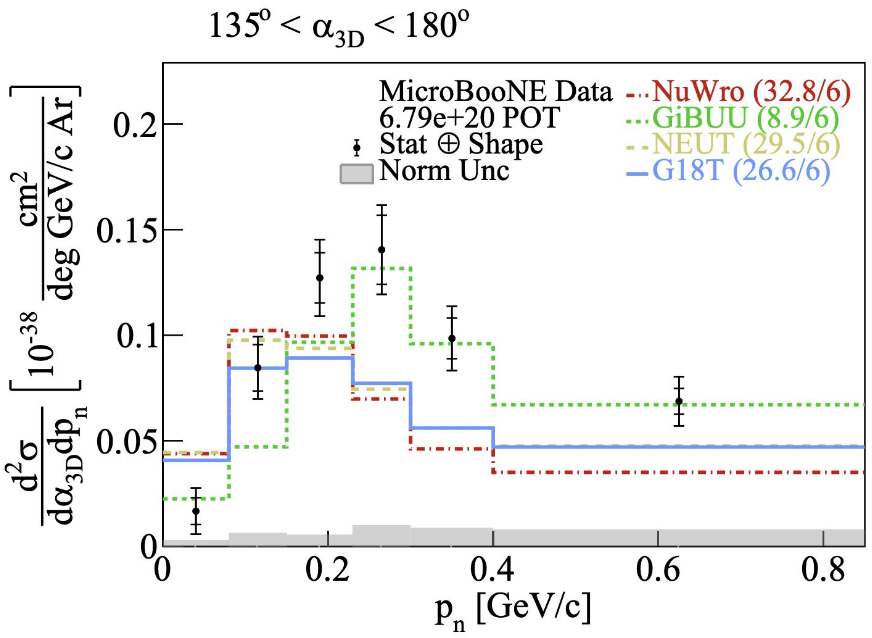
$$E_\nu = E_\mu + K_P + B = p_L^\mu + p_L^P$$

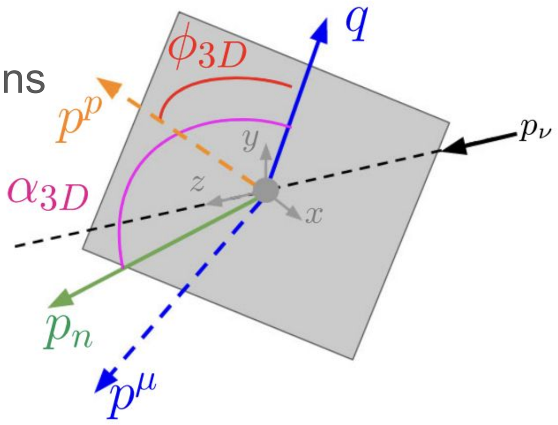
Define the longitudinal missing momentum:

$$p_L = p_L^\mu + p_L^P - (E_\mu + K_P + B)$$

CC1p0π Selection - GKI

Generalise kinematic imbalance (GKI) variables to three dimensions by considering longitudinal component of missing momentum:





- $\delta P_T \rightarrow p_n$
- $\delta\alpha_T \rightarrow \alpha_{3D}$

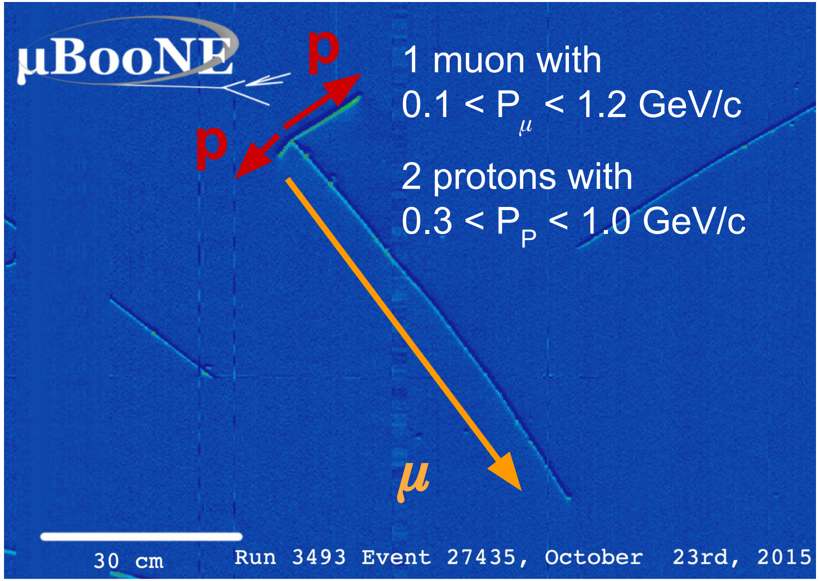
First measurement using novel GKI variables:
- Enhanced sensitivity to ground state modeling and hadron re-interactions

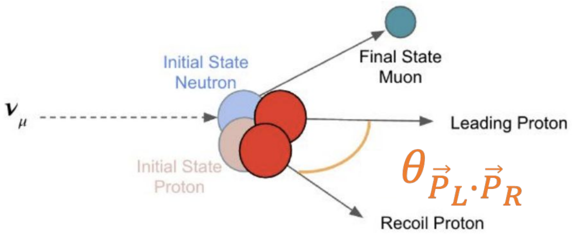
Region of α_{3D} > 135° contains large fraction of events which undergo FSI interactions

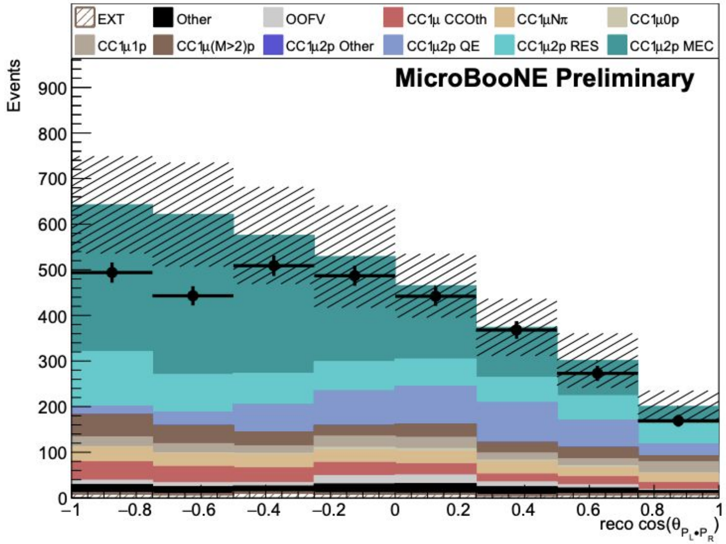
CC2p0π Selection

First two-proton final state differential cross-section measurement:

- Sensitive to modeling choices for meson exchange currents (MEC) and FSI





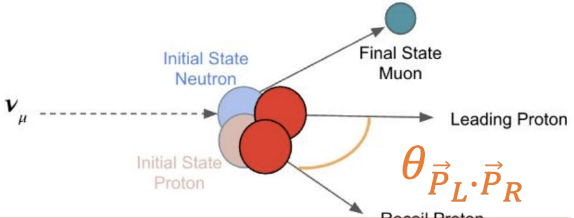


MICROBOONE-NOTE-1133

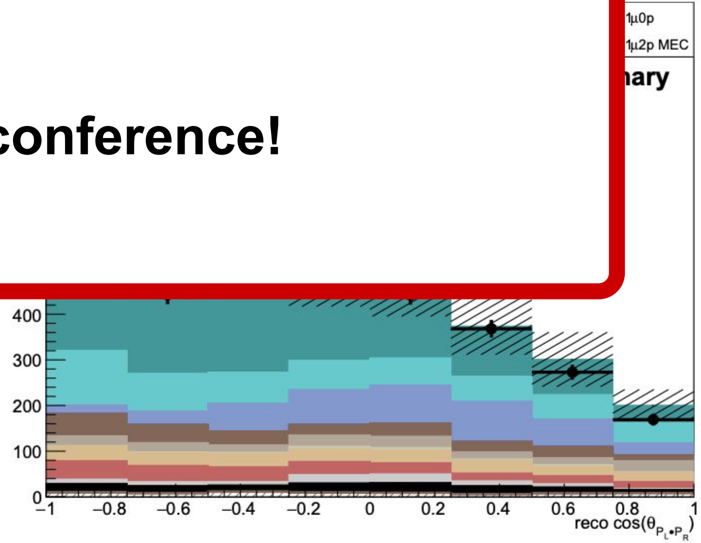
CC2p0π Selection

First two-proton final state differential cross-section measurement:

- Sensitive to modeling choices for meson exchange currents (MEC) and FSI



New results for <u>this</u> conference!

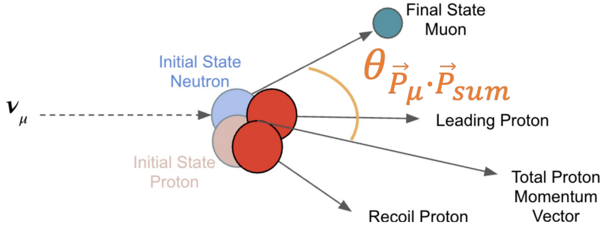


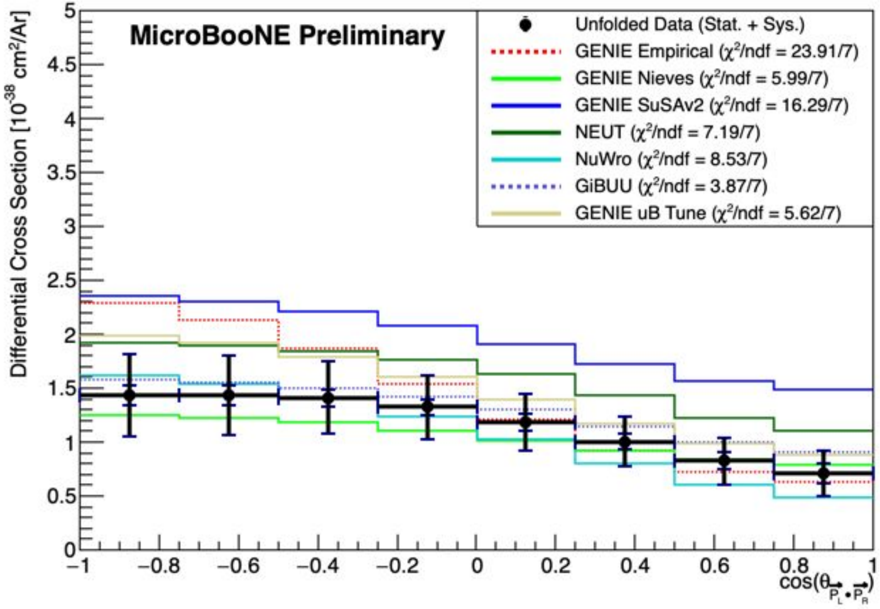
MICROBOONE-NOTE-1133

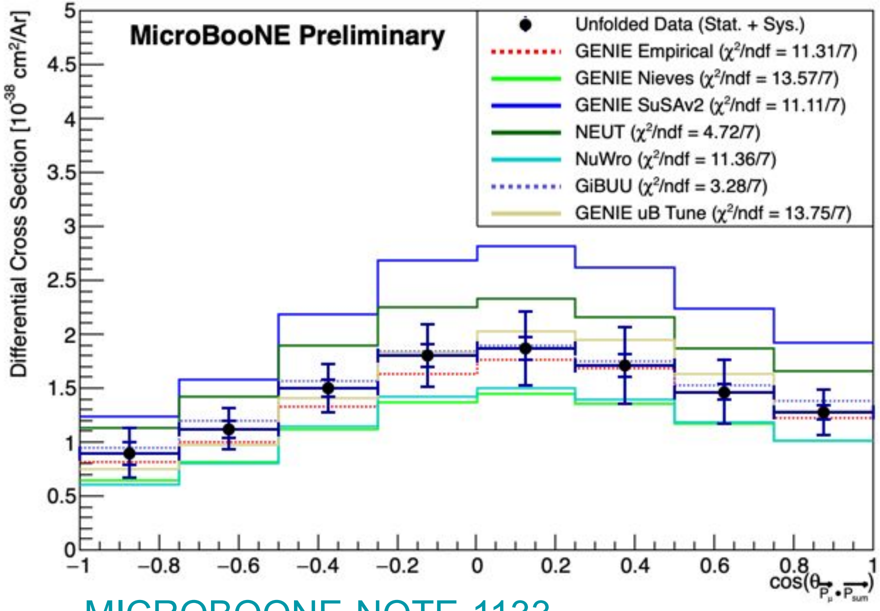
CC2p0π Selection - Proton Kinematics

Variety of variables investigated:

- Proton kinematics particularly sensitive to modeling choices







MICROBOONE-NOTE-1133

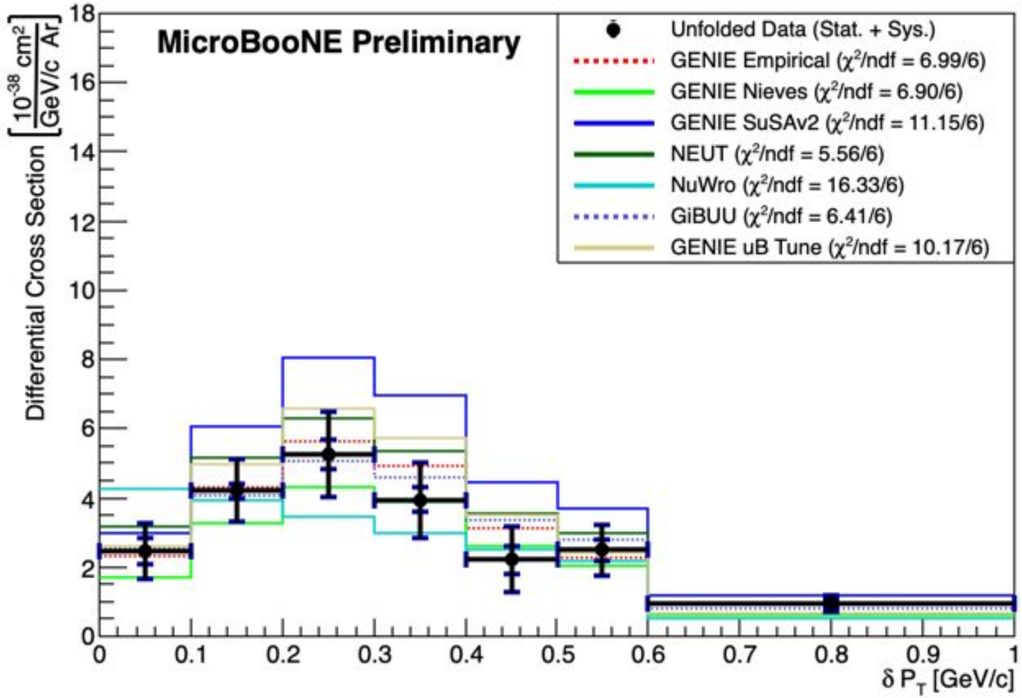
CC2p0π Selection - TKI

Results include differential measurements in TKI variables:

- Use the sum of the two proton momentum when calculating TKI variables

Conclusions:

- Observe model/data disagreements in shape and normalisation
- SuSAv2 normalisation is over-predicted
- NuWro peaks in lowest values of δP_T



MICROBOONE-NOTE-1133

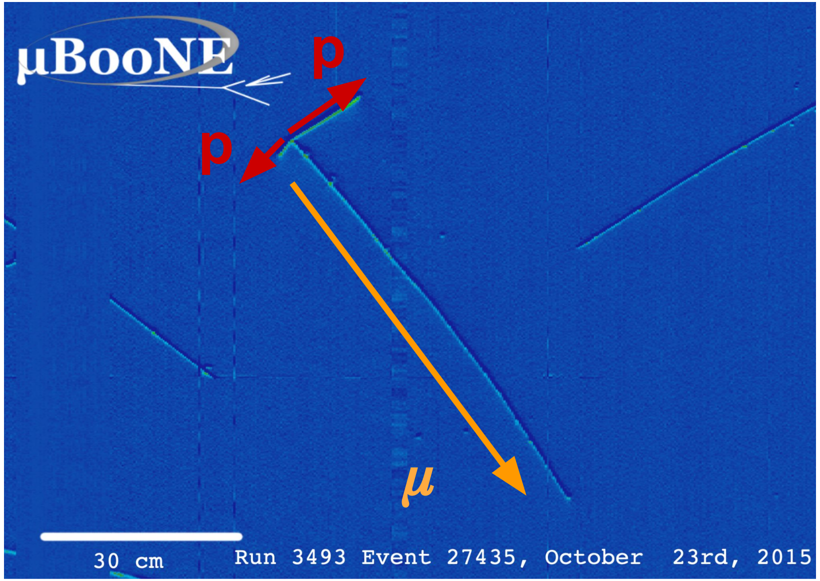
Conclusion

Strong MicroBooNE cross-section program with novel high-precision measurements:

- World's largest neutrino-Argon data set with 0.5 million events
- Inclusive, one-proton, and two-proton pionless final state selections
- Novel kinematic distributions and unfolding techniques utilised

Demonstrate sensitivity to expose interaction mis-modeling:

- Isolate regions of phase space particularly sensitive to hadron re-interactions or nuclear ground state



Results using full data set (x2 stats) to follow soon!

Watch out for other MicroBooNE talks/posters!

MicroBooNE Talks throughout NuFACT

N Nayak: Results from MicroBooNE
P Green: Pion Production Cross Sections
K Lin: MicroBooNE's BSM Physics Program
E Yandel: Searches for anomalous photon and dark-sector e+e- pairs
F Gao: MicroBooNE's electron neutrino Low Energy Excess Search
W Foreman: MeV-Scale Radon Measurements

Cross-section posters:
L Cooper-troendle: 95
D Barrow: 103
P Englezos: 118
B Bogart: 106
J Rondon: 127

BSM poster:
L Hagaman: 104

MeV Scale poster:
D Andrade: 115

Backup Slides

Conditional Constraint

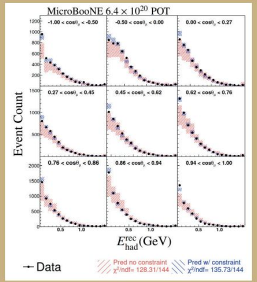
Poster - L Cooper-troendle: 95

Data-Driven Model Validation

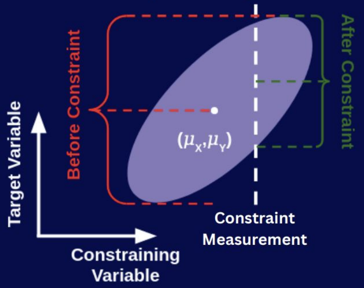
- Tests model w/ data before unfolding
- Increased sensitivity through conditional constraint procedure
  - Sensitive to modeling of missing energy
- Model describes data within uncertainties

Model Validation

$\{E_{had}, \theta_\mu\}$ Constrained by $\{P_\mu, \theta_\mu\}$



Conditional Constraint Example Diagram



NuWro 19.02.2 Fake Data Study

Xs and Stat Uncertainties Only:

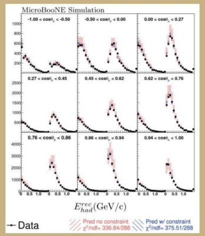
- Model validation detects mismodeling at 3.5 σ
- Unfolded cross section only biased by 1.1 σ

All Uncertainties:

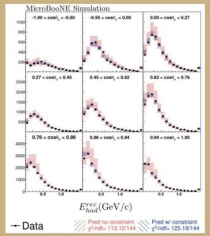
- Neither model validation (p=0.87) nor unfolded cross section (p=0.99) show significant bias

In all cases the model validation tests demonstrate a higher sensitivity to mismodeling than the unfolded cross section

Xs and Stat Uncertainties



All Uncertainties



Distribution over $\{E_{had}, \theta_\mu\}$ with and without constraint from $\{P_\mu, \theta_\mu\}$ for fully and partially contained events using Xs and stat uncertainties (left) and partially contained events using all uncertainties (right).

Conditional Constraint

Arxiv: 2307.06413v4

First, through conservation of energy the sensitivity to the modeling of $E_{\text{had}}^{\text{missing}}$ can be seen:

$$E_\nu = E_\mu + E_{\text{had}}^{\text{rec}} + E_{\text{had}}^{\text{missing}}. \tag{11}$$

$E_{\text{had}}^{\text{rec}}$ is directly measured, E_μ is determined through the measurement of P_μ^{rec}, and the distribution over E_ν is controlled by the flux prediction, which is constrained by the muon kinematics measurements. This leaves $E_{\text{had}}^{\text{missing}}$ as the only undetermined quantity, meaning that the constrained GoF test is sensitive to its mismodeling.