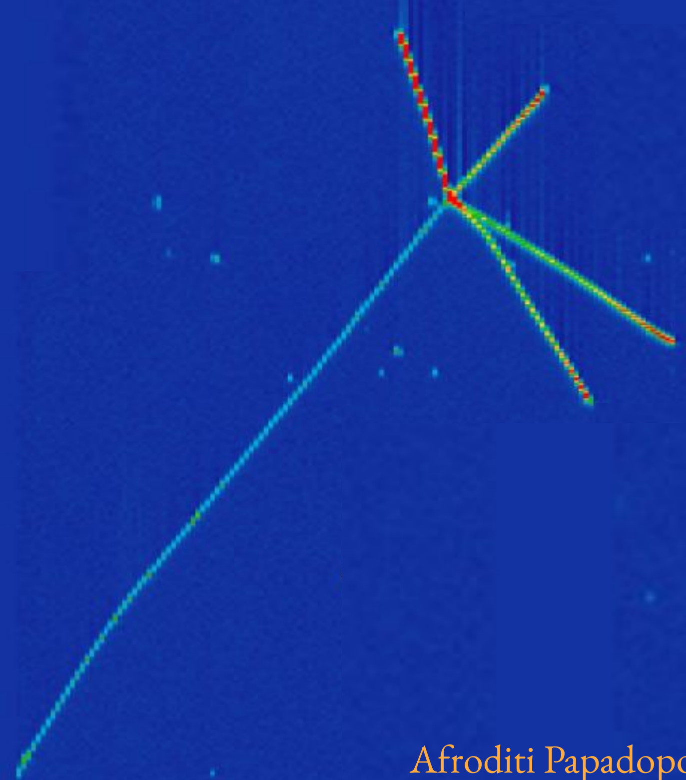
High-precision neutrino interaction measurements with MicroBooNE



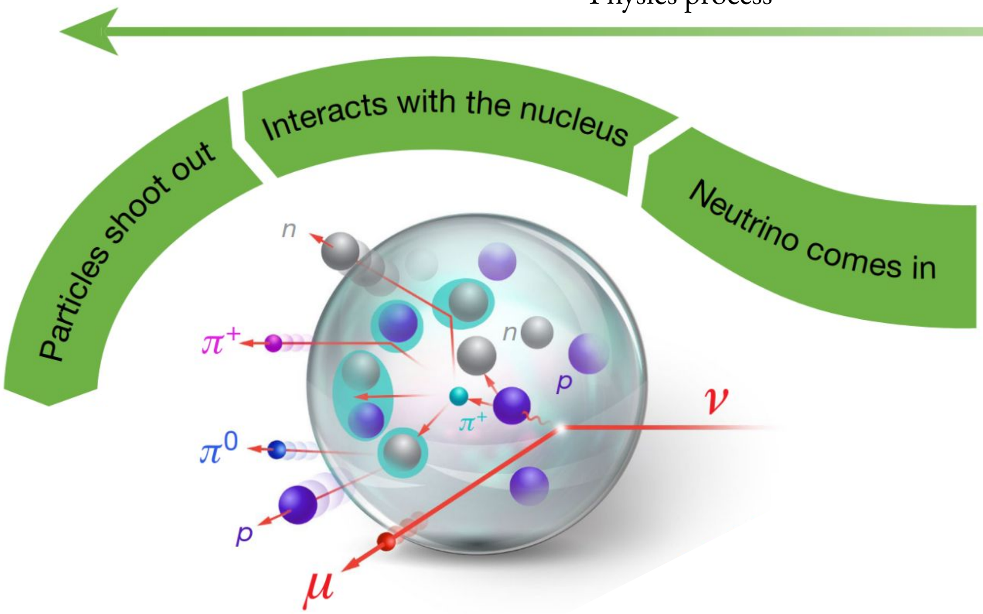
µBooNE

Afroditi Papadopoulou, Argonne National Laboratory
on behalf of the MicroBooNE collaboration

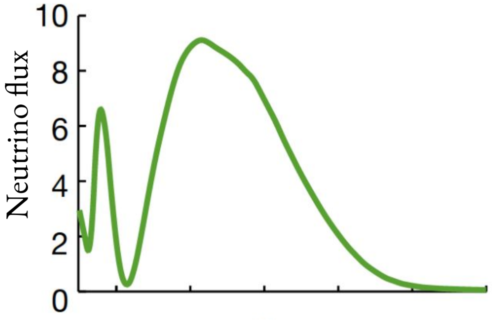
XXXI International Conference on Neutrino Physics And Astrophysics, 21st June 2024

High-precision neutrino era

Physics process

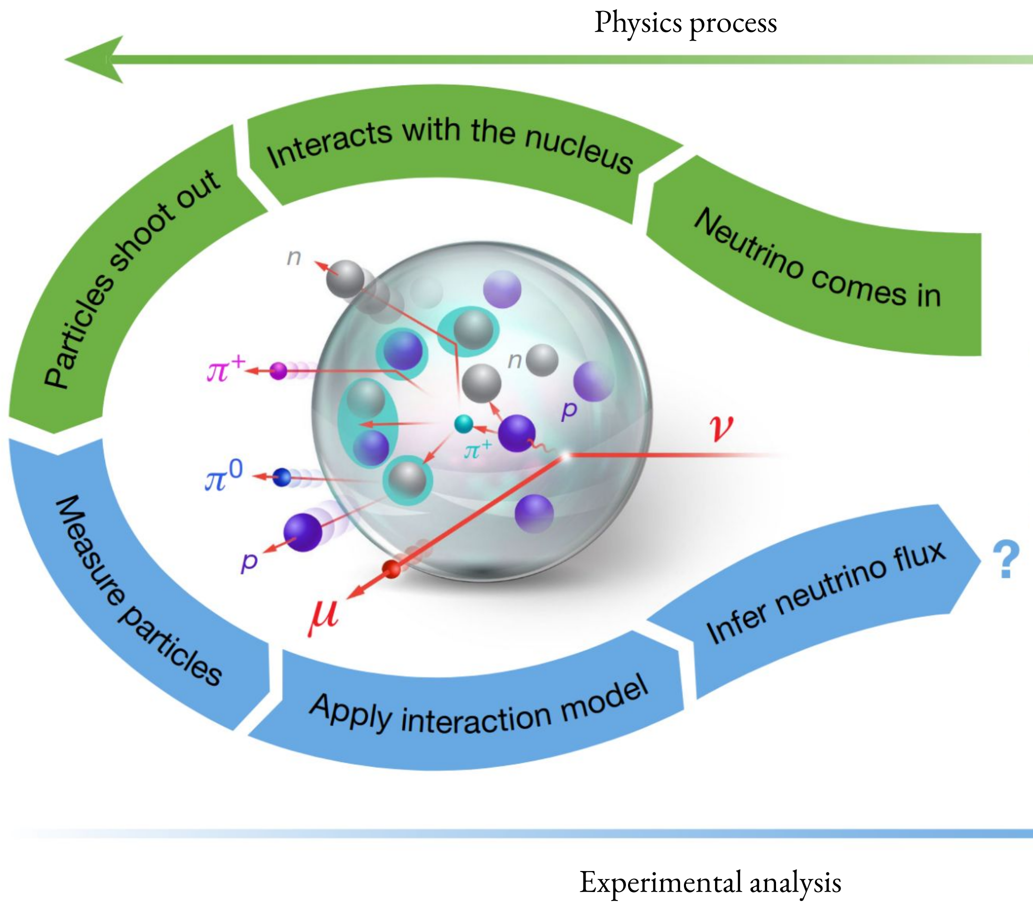


Input to neutrino oscillation studies

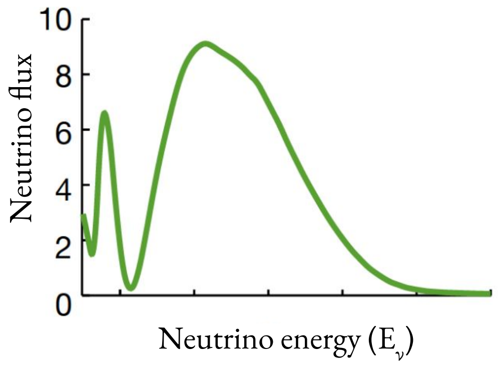


Nature 599, 565–570 (2021)

High-precision neutrino era

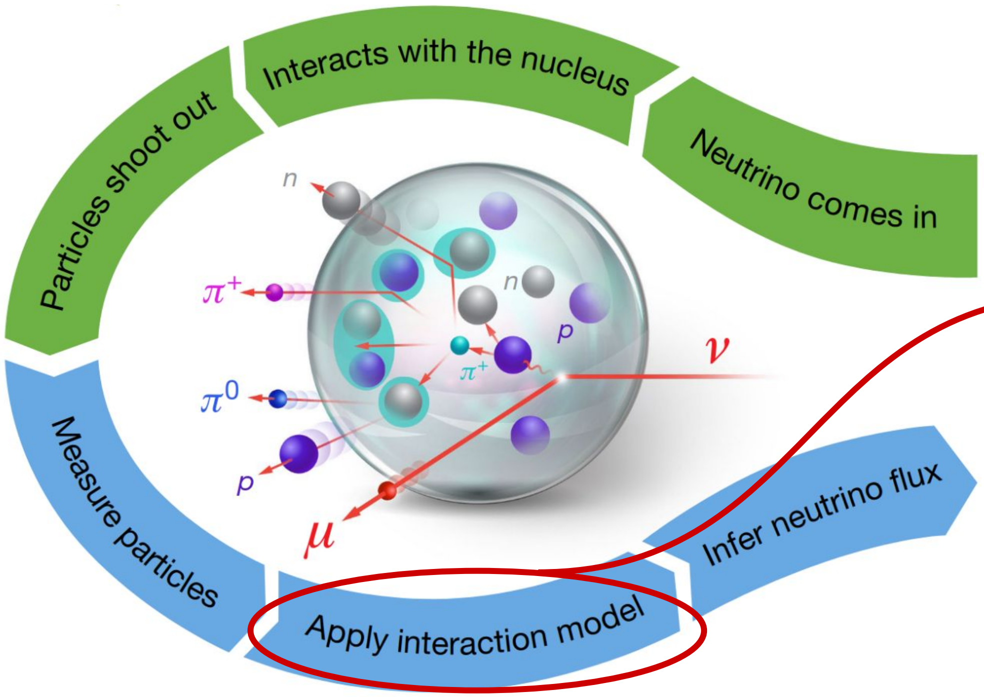


Input to neutrino oscillation studies



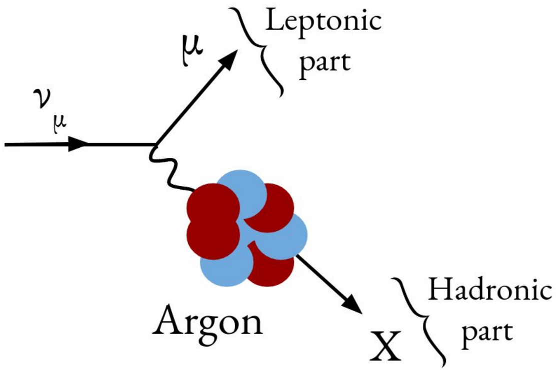
Nature 599, 565–570 (2021)

High-precision neutrino era



Discovery science requires unprecedented understanding of neutrino-nucleus interactions

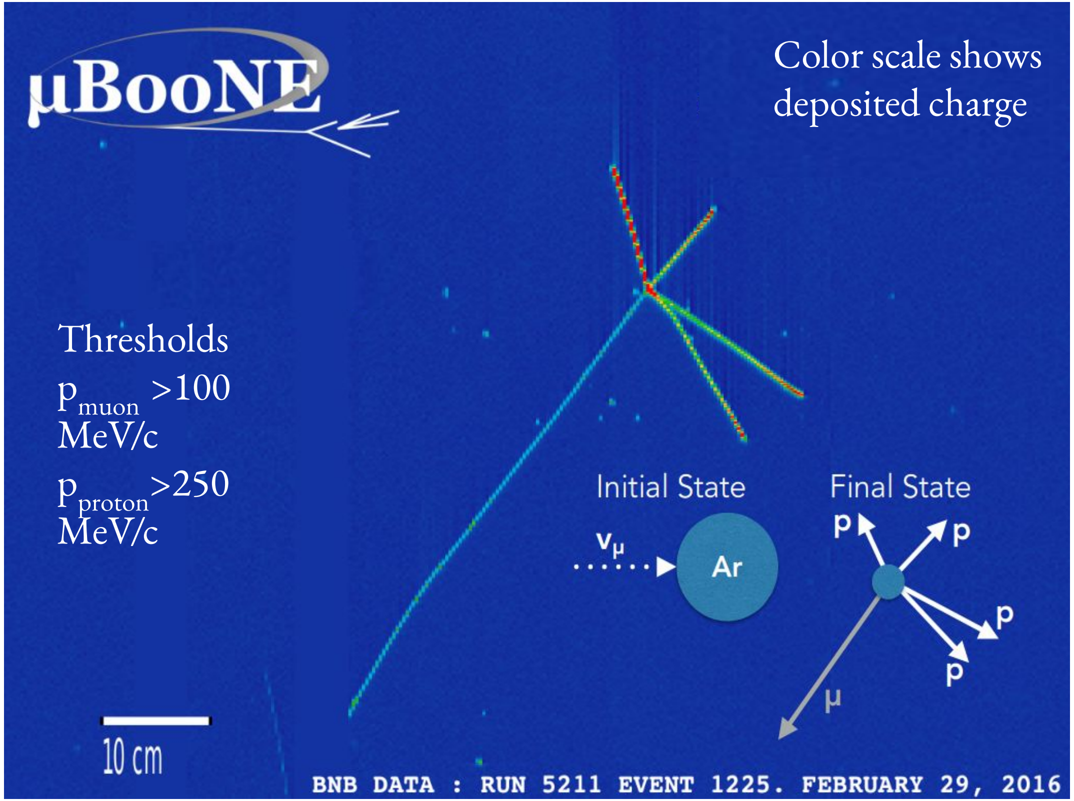
Extremely challenging given
- broad neutrino spectra*
- various complex interaction mechanisms



Nature 599, 565–570 (2021)

*Also see Julia's e4ν talk

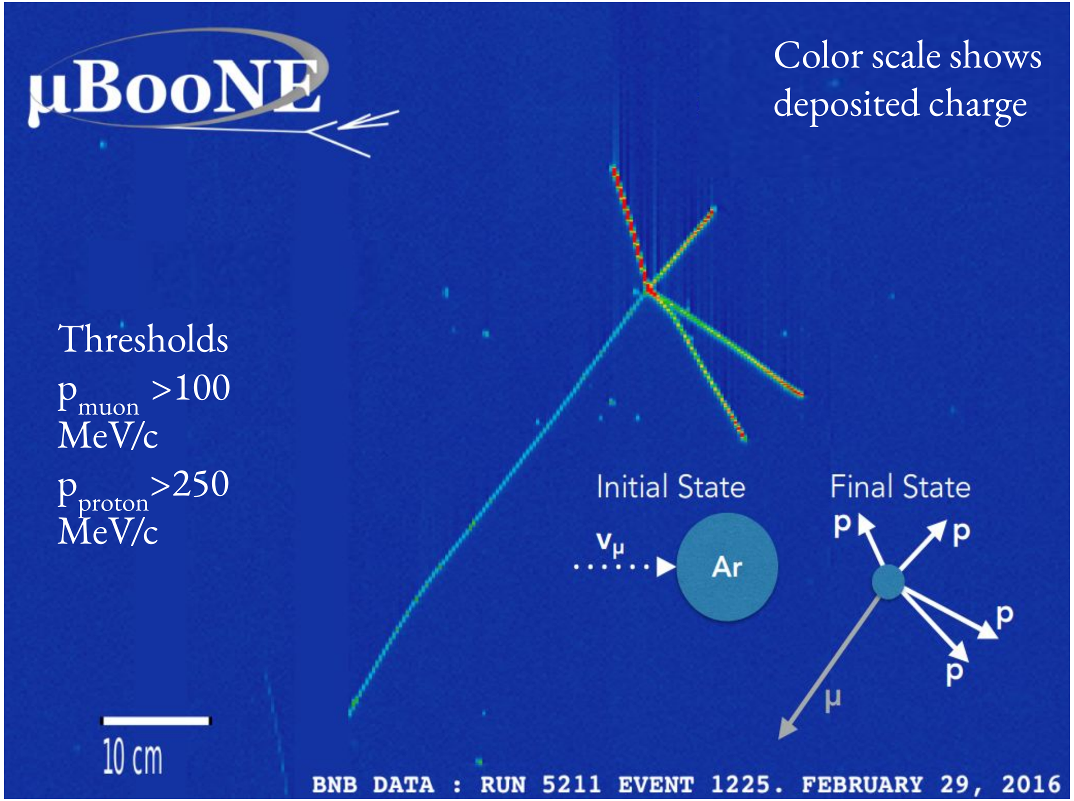
Crucial input from MicroBooNE cross-section program



- Liquid argon time projection chamber (LArTPC) at Fermilab
- Same detector technology as Short Baseline Neutrino (SBN) experiments and Deep Underground Neutrino Experiment (DUNE)
- Low detection thresholds and fully active tracking calorimeter
- Largest neutrino-argon data set to date with ~500k recorded neutrino events in 5y
- Already more than 20 published cross sections

Also see David's talk

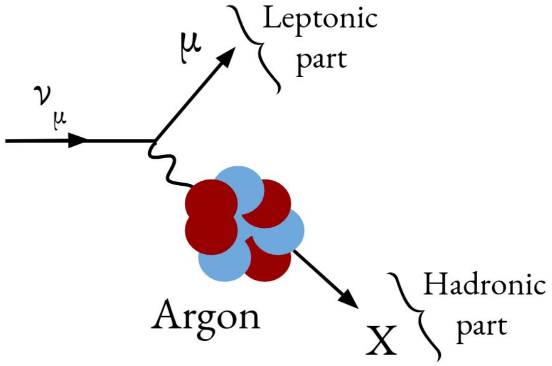
Crucial input from MicroBooNE cross-section program



- Liquid argon time projection chamber (LArTPC) at FNAL
- Same detector technology as Short Baseline Neutrino (SBN) experiments and Deep Underground Neutrino Experiment (DUNE)
- Low detection thresholds and fully active tracking calorimeter
- Largest neutrino-argon data set to date with ~500k recorded neutrino events in 5y
- Already more than 20 published cross sections

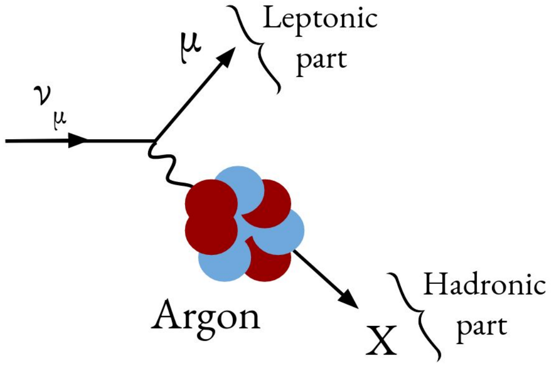
Also see David's talk

Addressing key modeling issues



Addressing key modeling issues

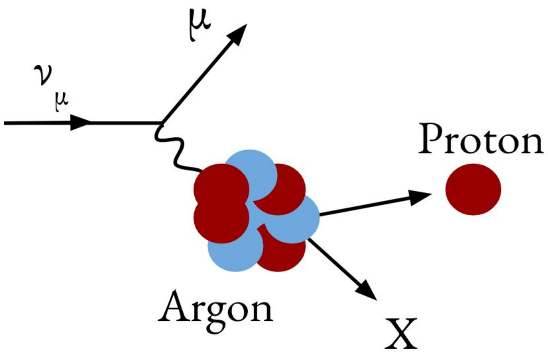
- Leptonic and hadronic system modeling to accurately reconstruct neutrino energy

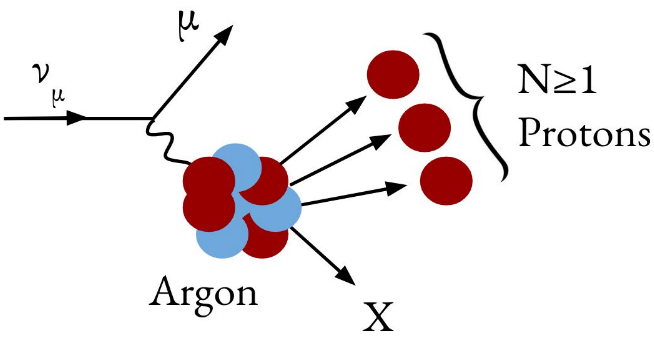


Addressing key modeling issues

- Leptonic and hadronic system modeling to accurately reconstruct neutrino energy

- Constrain nuclear modeling uncertainties with pionless analyses

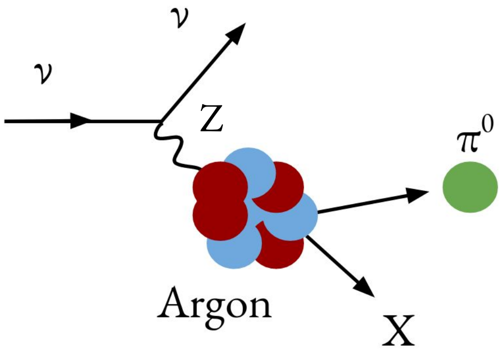




Addressing key modeling issues

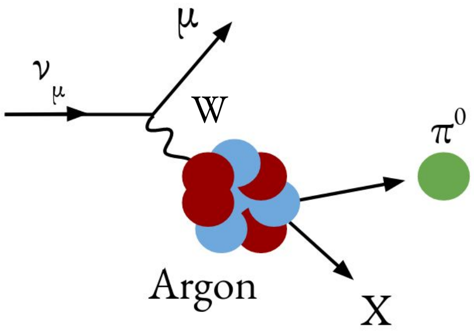
Apply interaction model

- Leptonic and hadronic system modeling to accurately reconstruct neutrino energy



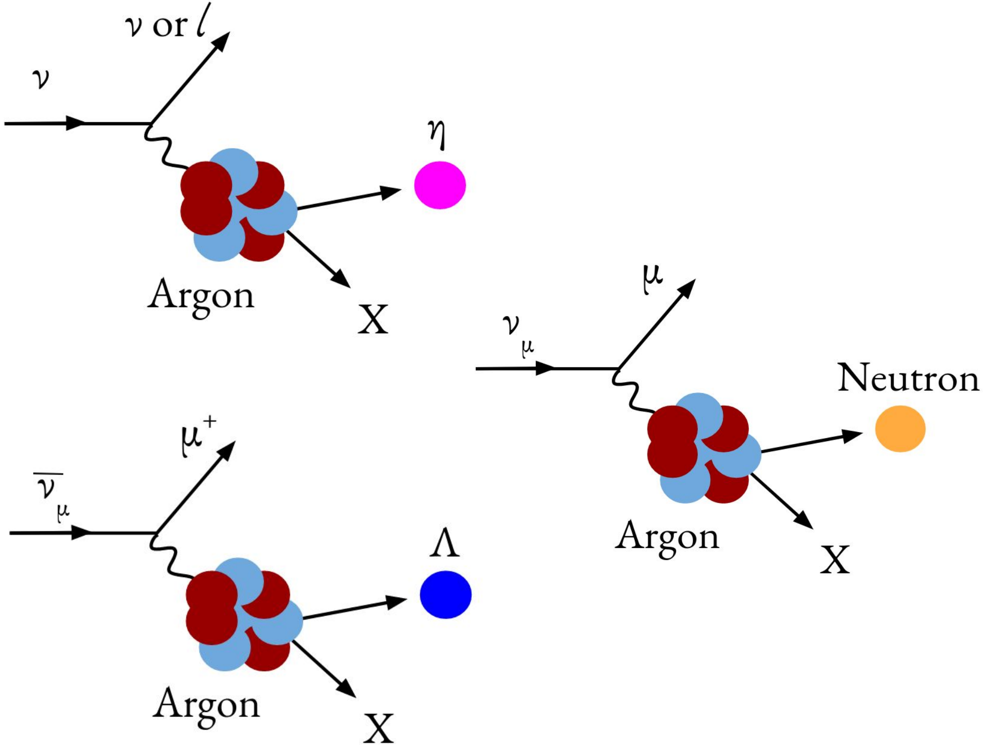
- Constrain nuclear modeling uncertainties with pionless analyses

- π^0 production as background to ν_e appearance and Beyond Standard Model searches



Addressing key modeling issues

- Leptonic and hadronic system modeling to accurately reconstruct neutrino energy
- Constrain nuclear modeling uncertainties with pionless analyses
- π^0 production as background to ν_e appearance and Beyond Standard Model searches
- Novel identification techniques for rare searches and challenging topologies



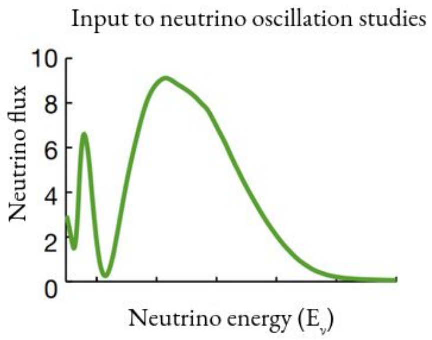
Leptonic and hadronic system modeling

- Oscillation measurements require accurate energy reconstruction of both lepton and hadron kinematics

"Easier" Lepton | "Harder" Hadrons

$$E_\nu = E_\ell + \omega$$

- Leverage LArTPC reconstruction and particle identification tools to obtain $E_{reco} \simeq E_\nu$



Leptonic and hadronic system modeling

- Oscillation measurements require accurate energy reconstruction of both lepton and hadron kinematics

"Easier" Lepton — "Harder" Hadrons

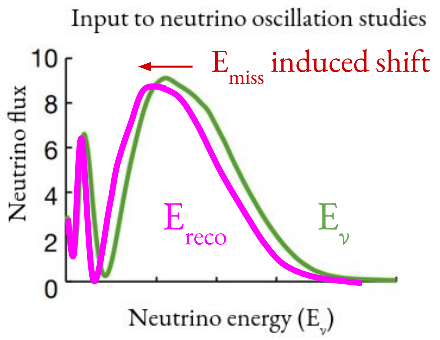
$$E_\nu = E_\ell + \omega$$

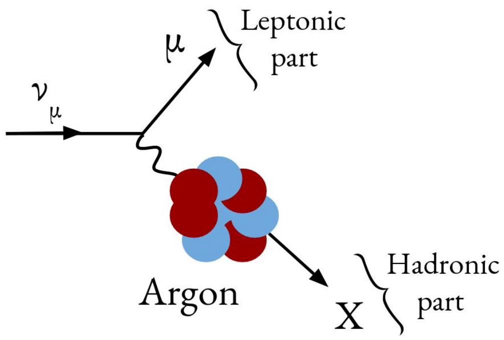
- Leverage LArTPC reconstruction and particle identification tools to obtain $E_{reco} \simeq E_\nu$

- Still need to correct for missing energy (E_{miss}) which might be large fraction of total energy balance

$$\omega = E_{had} + E_{miss}$$

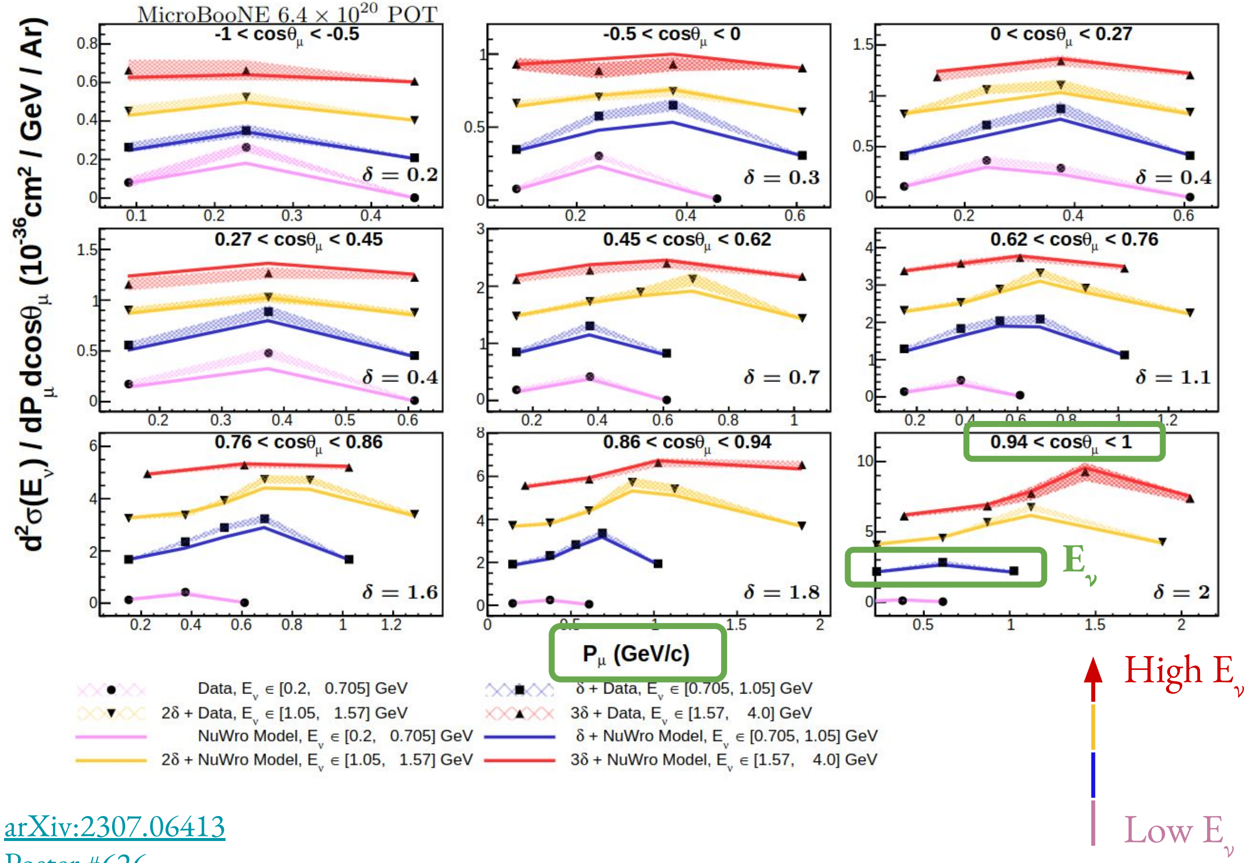
- Dedicated analyses developed to investigate both parts

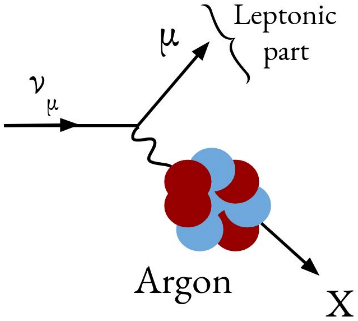




Leptonic system modeling

$\chi^2/\mathrm{ndf} = 212.1/138$

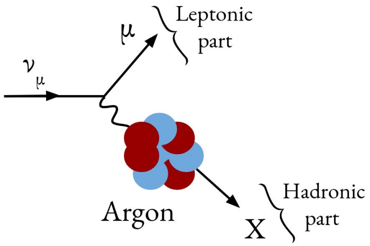


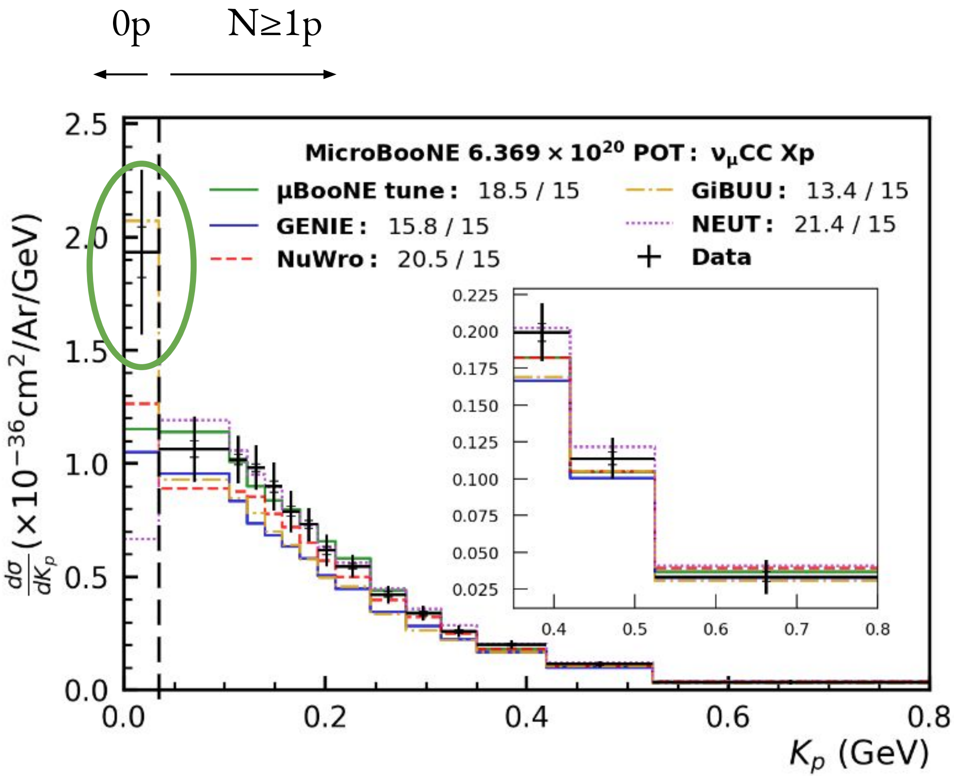


- First three-dimensional cross-section result on argon
- Novel data-driven validation to detect potential missing energy mismodeling
- New paradigm of cross sections as a function of the neutrino energy (E_ν)

arXiv:2307.06413
Poster #626

Hadronic system modeling



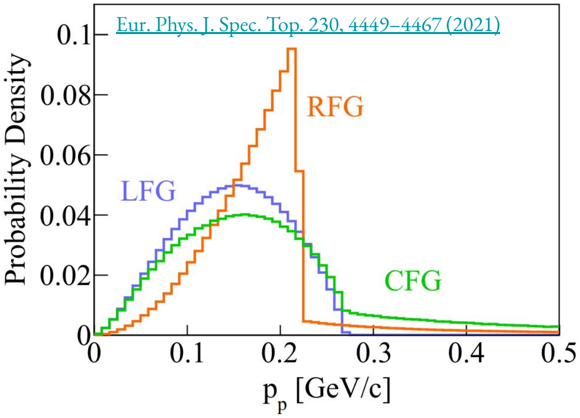


- Leveraging low proton detection threshold to investigate events with and without detected protons
- Extensive data-driven model validation to detect potential biases
- Stressed need for sophisticated treatment of low energy hadron reinteractions

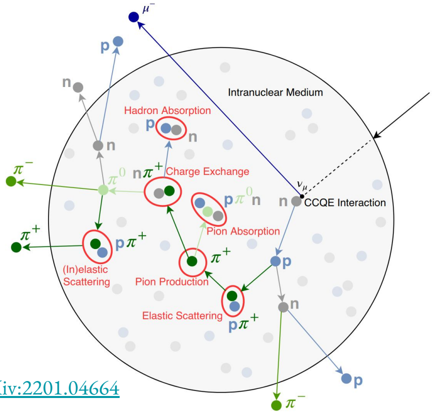
arXiv:2402.19216 accepted to PRD
arXiv:2402.19281 accepted to PRL
Poster #626

Nuclear effects with pionless analyses

Nuclear ground-state distributions

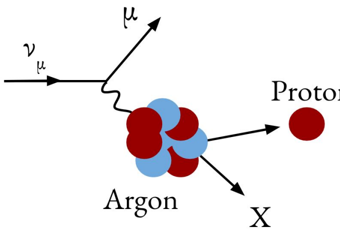


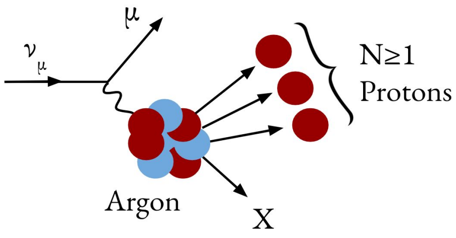
Hadron reinteractions



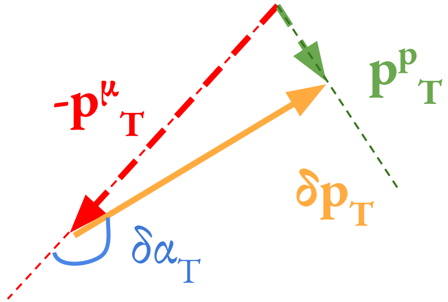
arXiv:2201.04664

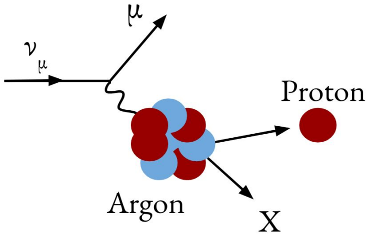
- Leverage high-quality LArTPC proton reconstruction and low proton detection thresholds (250 MeV/c)
- Probing nuclear ground-state distributions and hadron reinteractions on heavy argon nuclei
- Dedicated analyses investigating nuclear effects using transverse and generalized kinematic imbalance

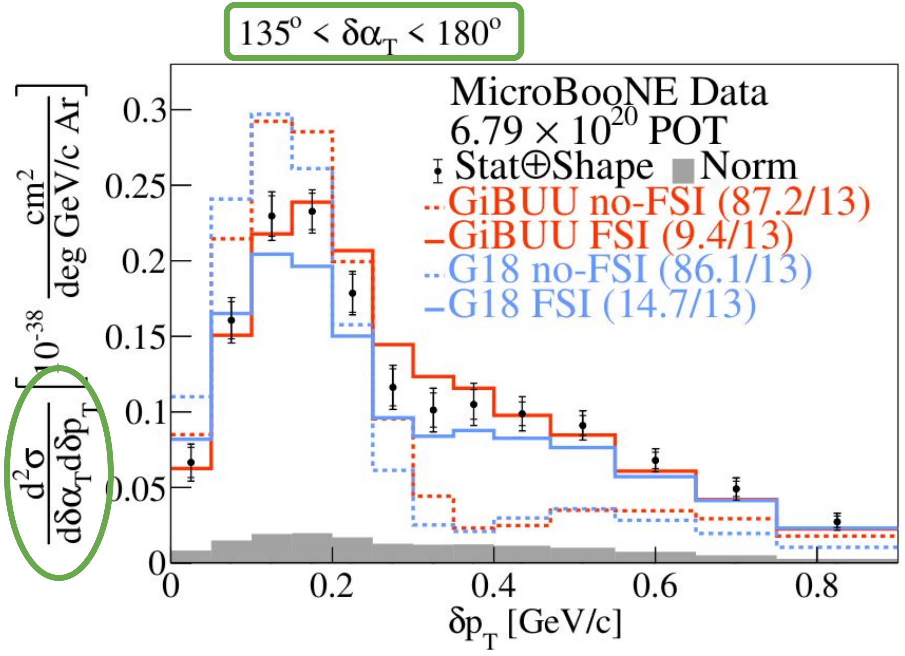




Transverse kinematic imbalance



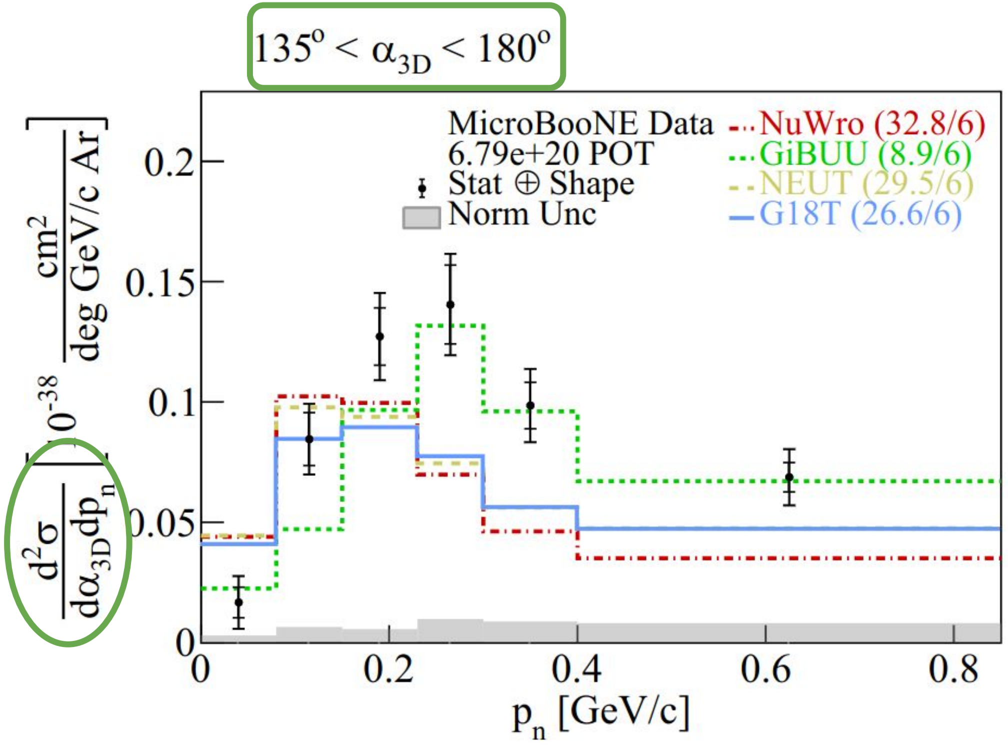


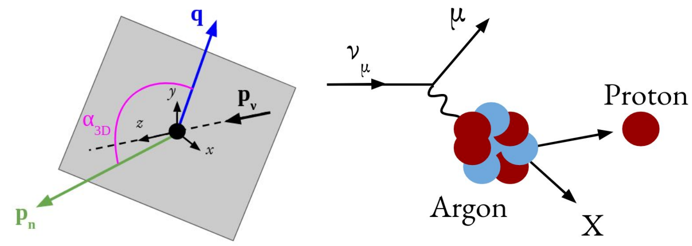


- First investigation of nuclear effects in two transverse kinematic imbalance variables simultaneously on argon
- Enables isolation of nuclear effects more completely than previous measurements in one variable
- Identification of phase space regions with sensitivity to nuclear ground-state distributions and hadron reinteractions

Phys. Rev. Lett. 131, 101802 (2023)
Phys. Rev. D 108, 053002 (2023)
Poster #626

Generalized kinematic imbalance

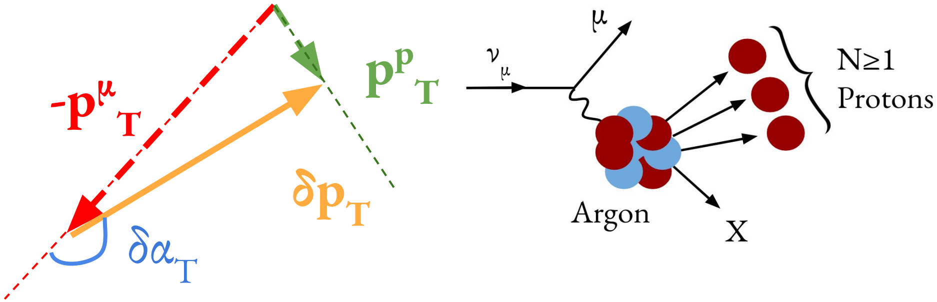


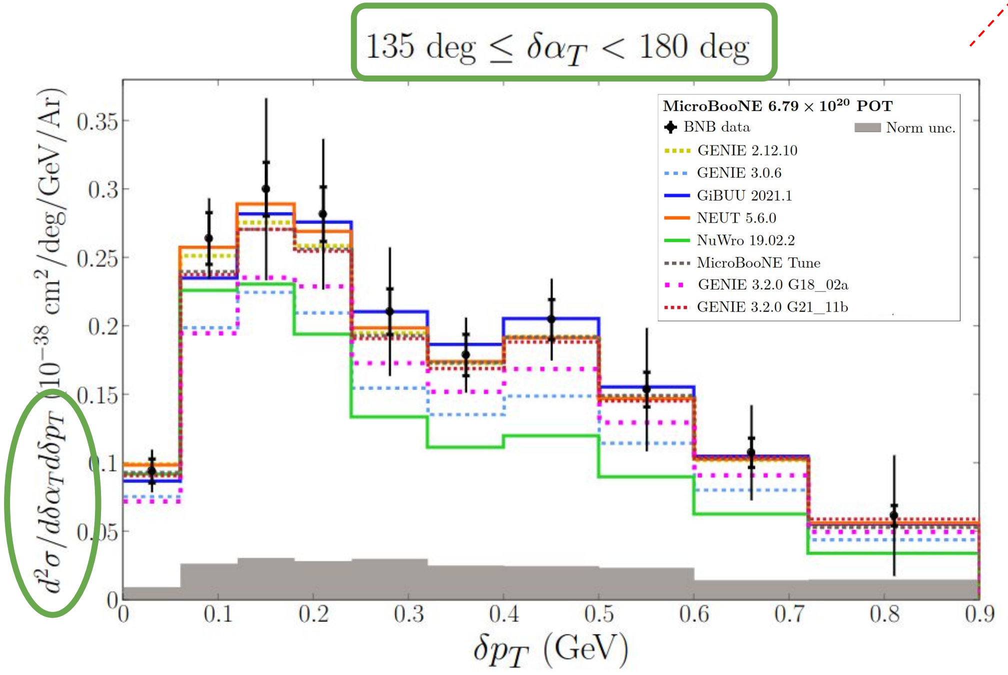


- Generalized to three dimensions by considering longitudinal component of missing momentum
- First-ever measurement reported on any nucleus in these novel variables
- Enhanced sensitivity to nuclear ground-state distributions and hadron reinteractions

Phys. Rev. C 95, 065501 (2017)
Phys. Rev. D 109, 092007 (2024)
Poster #626

Multi-proton kinematic imbalance



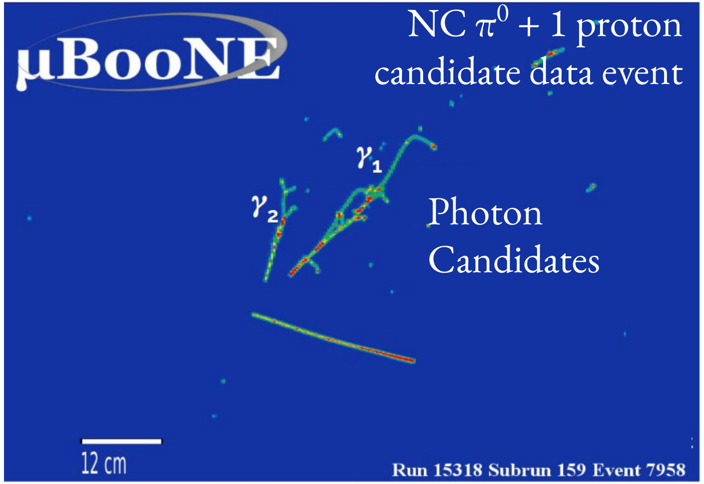


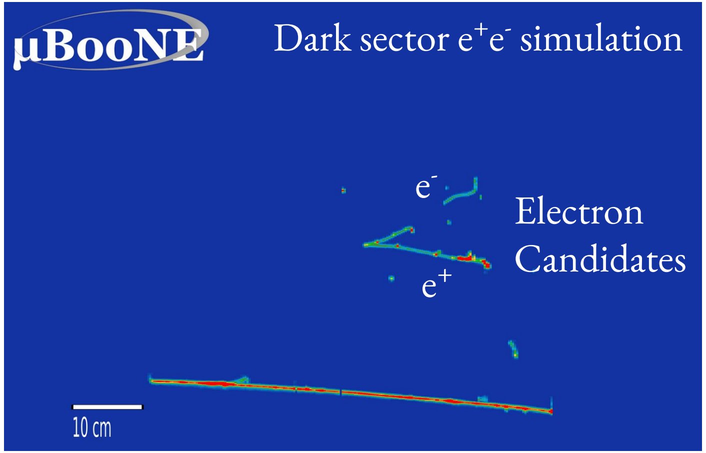
GENIE v3.0.6 χ^2/ndf = 1859/359

- Also studied transverse and generalized kinematic imbalance variables using the highest energy proton
- Novel full treatment of correlations across 359 kinematic bins describing different observables
- Poor agreement suggests that correlations between kinematic distributions are not well-modeled

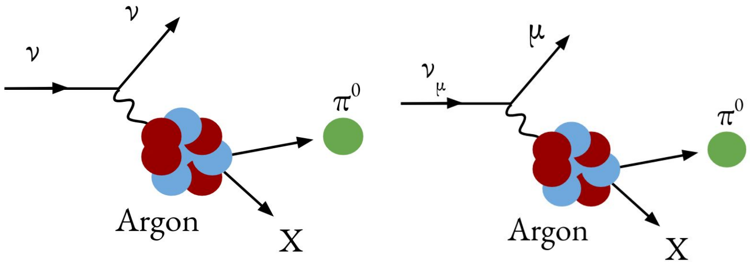
arXiv:2403.19574
Poster #626

π^0 production measurements

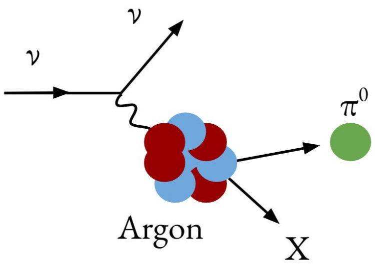


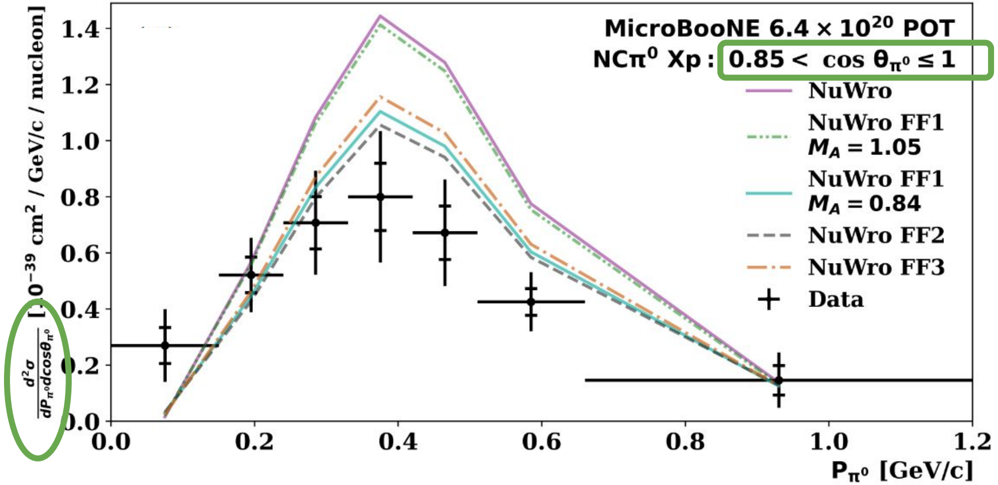


- Significant role in ν_e appearance studies
- π^0 events are the dominant background for single photon and e^+ e^- Beyond Standard Model searches
- Probed with neutral and charged current π^0 measurements



Neutral current π^0 production



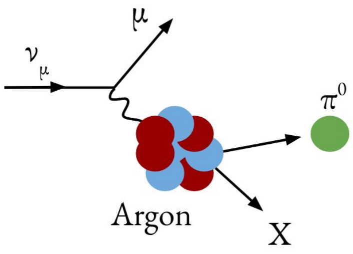


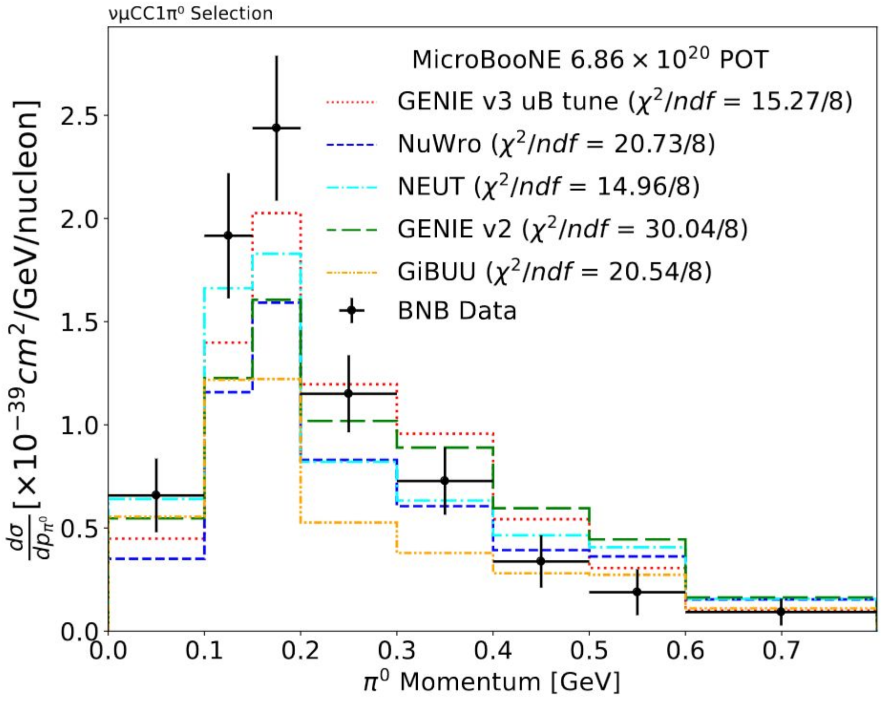
- Dominated by $\Delta(1232)$ resonances
- First measurement in two π^0 kinematic variables simultaneously
- Systematic overprediction when compared to data
- Demonstrated sensitivity to form factor modeling and hadron reinteractions

arXiv:2404.10948

Poster #627

Charged current π^0 production



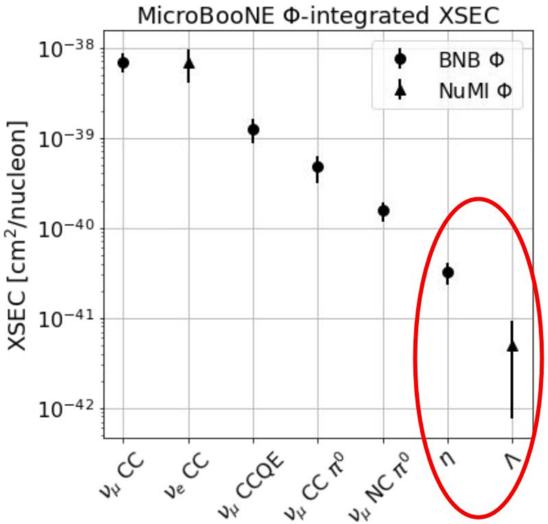


- Dominated by $\Delta(1232)$ resonances
- Mismodeling identified in π^0 momentum and muon forward angles
- Shortcomings associated with low momentum transfer, consistent with observations on other targets

arXiv:2404.09949

Poster #627

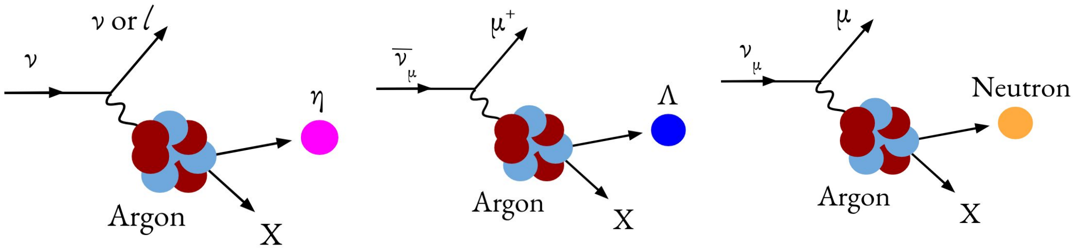
Novel identification techniques



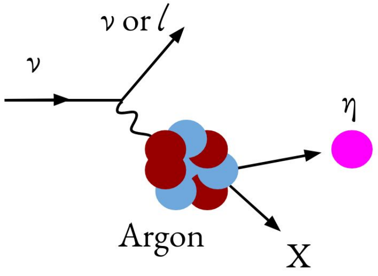
High-precision era requires

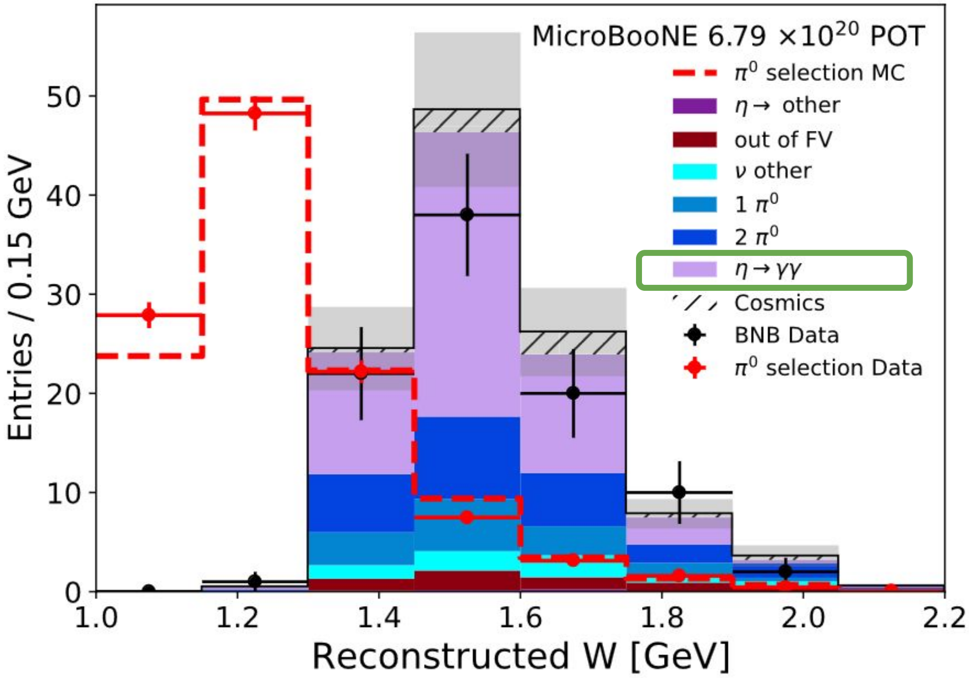
- accurate understanding of cross sections of even rarest processes
- novel reconstruction and identification techniques

Designed dedicated analyses to address these needs



η meson production



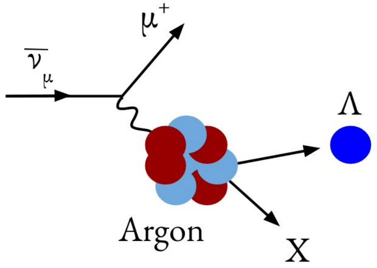


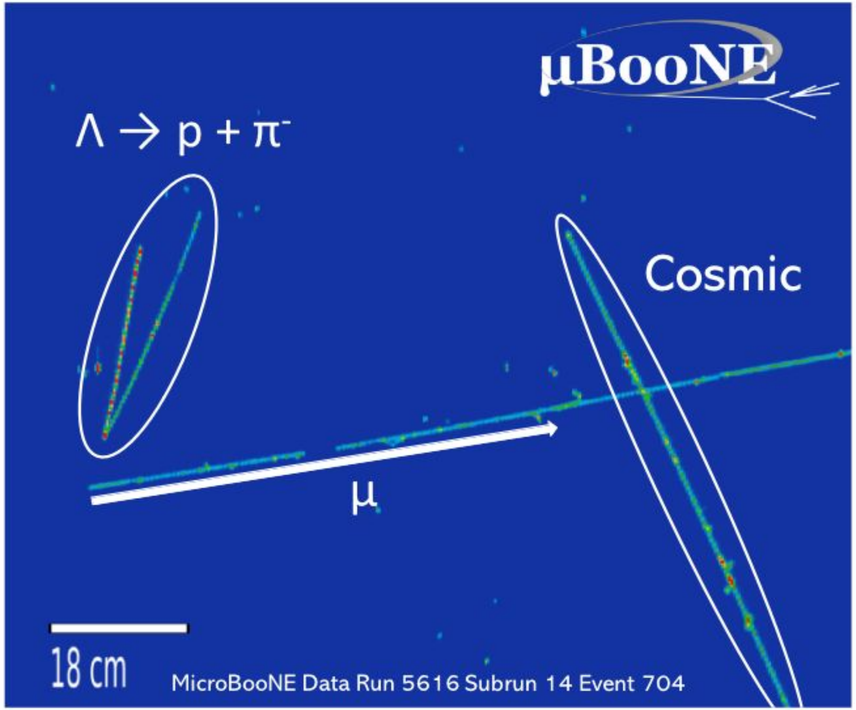
- Powerful new probe of resonances beyond Δ(1232)
- Enabled novel calibration source for electromagnetic showers in few-GeV region
- Invaluable input for proton decay channels ($p \rightarrow e^+\eta$ and $p \rightarrow \mu^+\eta$)

Phys. Rev. Lett. 132, 151801 (2024)

Poster #627

Λ baryon production

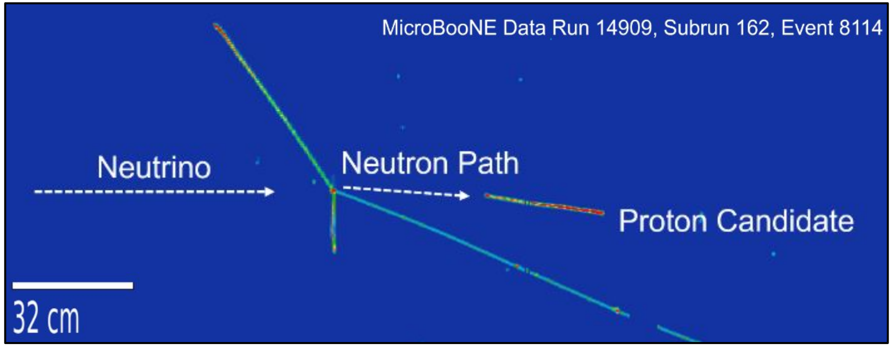


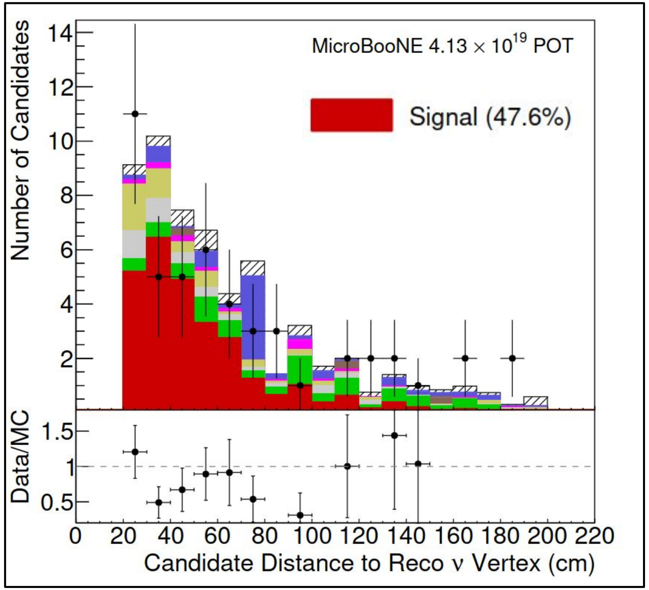


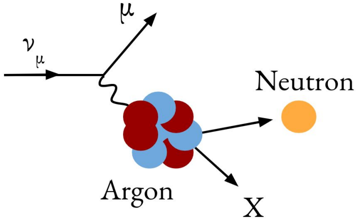
- First measurement with a LArTPC detector
- Very rare process due to Cabibbo suppression with only 5 observed events
- Invaluable input to hyperon interaction modeling and hyperon propagation in dense nuclear matter

Phys. Rev. Lett. 130, 231802
Poster #627

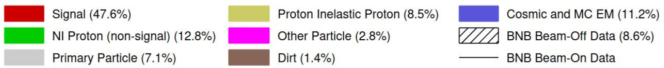
Neutron identification







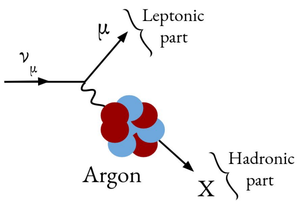
- Challenging identification since neutrons mostly escape the detector without any visible signature
- Novel detection capability demonstrated using secondary proton tracks, applicable to any LArTPC
- Accounting for missing energy due to neutrons can mitigate uncertainty due to biases in energy reconstruction

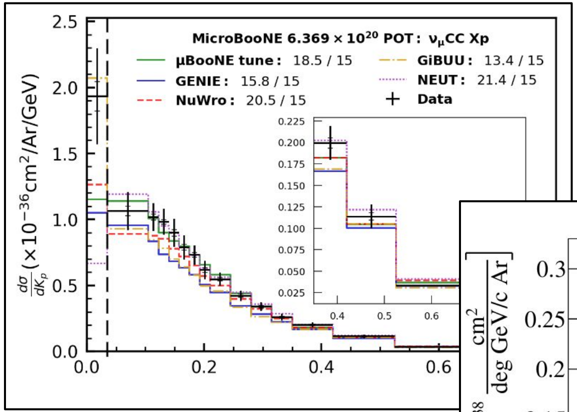


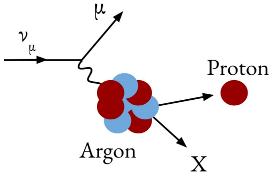
arXiv:2406.10583

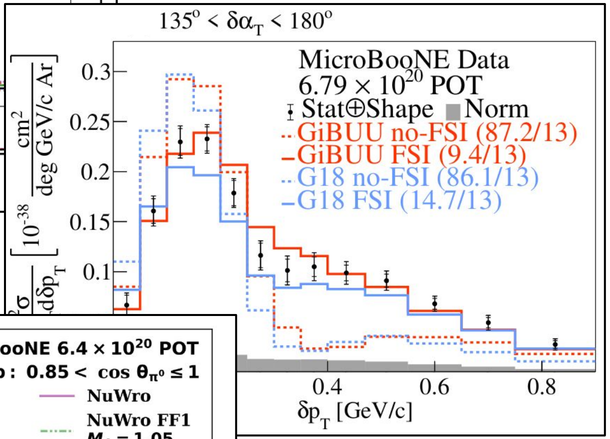
Poster #627

Summary

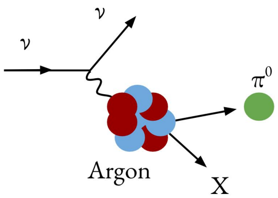


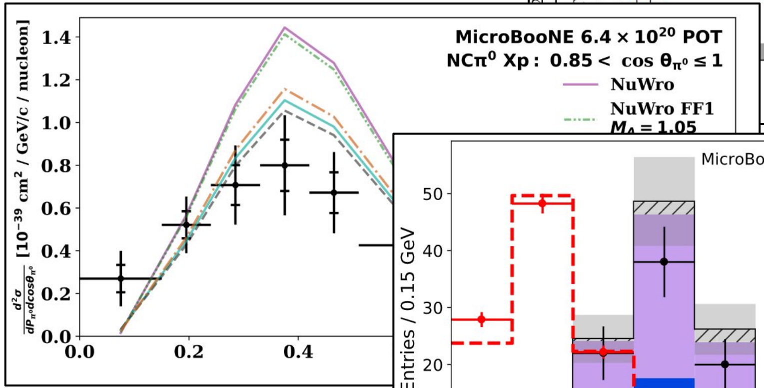


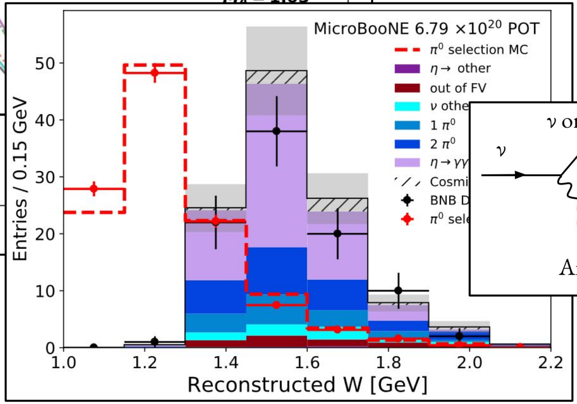


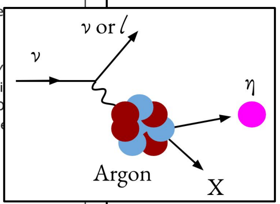


- Diverse MicroBooNE cross-section program with novel high-precision measurements
- Exploring variety of analysis techniques and demonstrating sensitivity to expose mismodeling effects
- Analyses using our full data set (2x stats), electron neutrinos, and charged pions to follow soon!









Already Public Results

μBooNE

CC inclusive

- 1D ν_μ CC inclusive @ BNB, Phys. Rev. Lett. 123, 131801
- 1D ν_μ CC E_ν @ BNB, Phys. Rev. Lett. 128, 151801
- 3D CC E_ν @ BNB, arXiv:2307.06413
- 1D ν_e CC inclusive @ NuMI, Phys. Rev. D104, 052002 Phys. Rev. D105, L051102
- 2D ν_μ CC0pNp inclusive @ BNB, arXiv:2402.19216, arXiv:2402.19281

Pion production

- ν_μ NCπ^0 @ BNB, Phys. Rev. D 107, 012004
- 2D ν_μ NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949

CC0π

- 1D ν_e CCNp0π @ BNB, Phys. Rev. D 106, L051102
- 1D & 2D ν_μ CC1p0π transverse imbalance @ BNB, Phys. Rev. Lett. 131, 101802 Phys. Rev. D 108, 053002
- 1D & 2D ν_μ CC1p0π generalized imbalance @ BNB, Phys. Rev. D 109, 092007
- 1D ν_μ CC1p0π @ BNB, Phys. Rev. Lett. 125, 201803
- 1D ν_μ CC2p @ BNB, arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB, Phys. Rev. D102, 112013
- 2D ν_μ CCNp0π @ BNB, arXiv:2403.19574

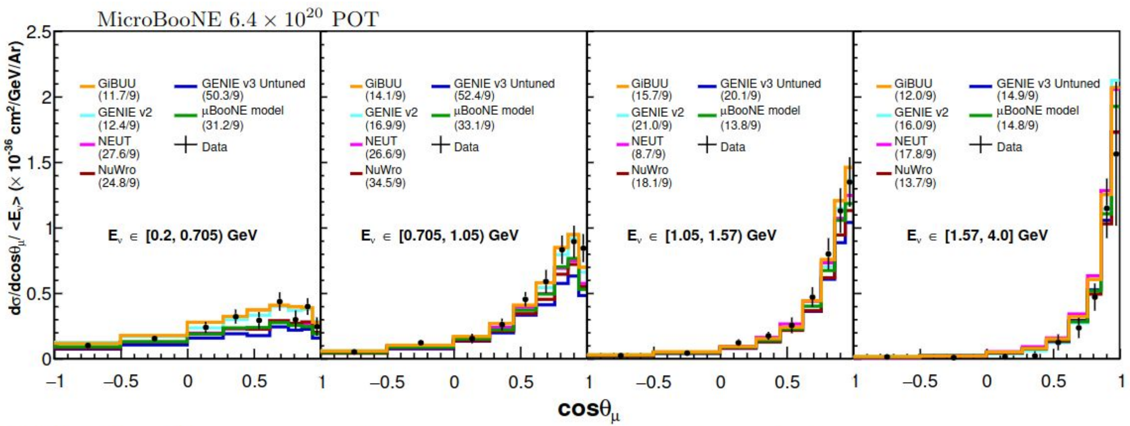
Rare channels & novel identification techniques

- η production @ BNB, Phys. Rev. Lett. 132, 151801
- Λ production @ NuMI, Phys. Rev. Lett. 130, 231802
- Neutron identification, arXiv:2406.10583

Thank you!

Backup Slides

Leptonic system modeling



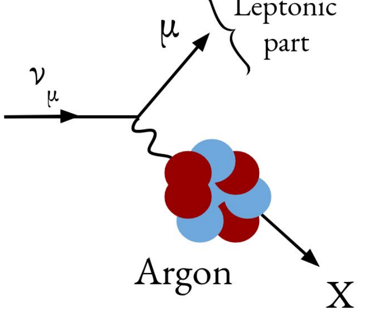
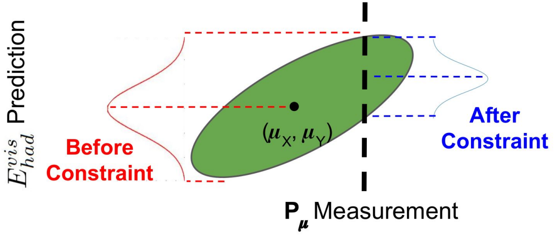
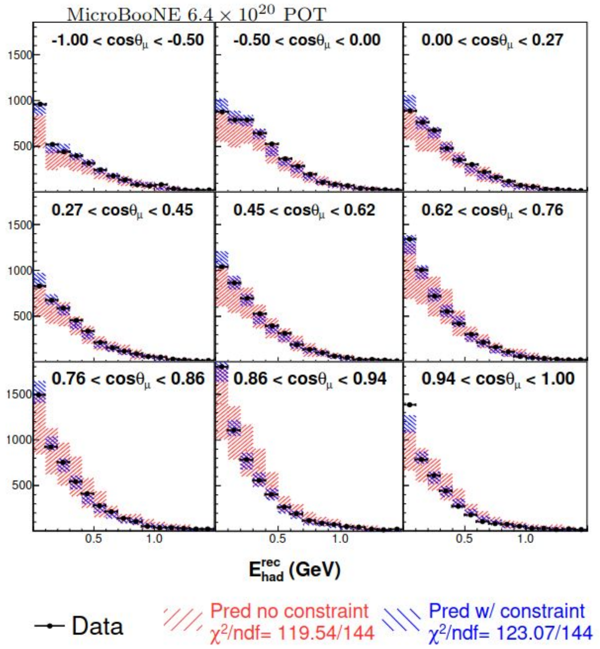


TABLE I. Comparisons between various models and the unfolded three-dimensional measurement.

Model Name	χ^2/ndf
GENIE v2	741.1/138
MicroBooNE model	326.1/138
GENIE v3 untuned	322.2/138
GiBUU	269.9/138
NEUT	243.4/138
NuWro	212.1/138

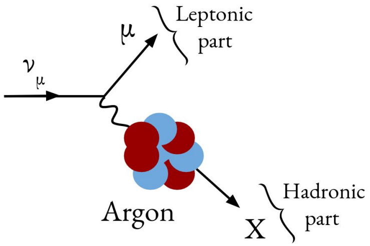


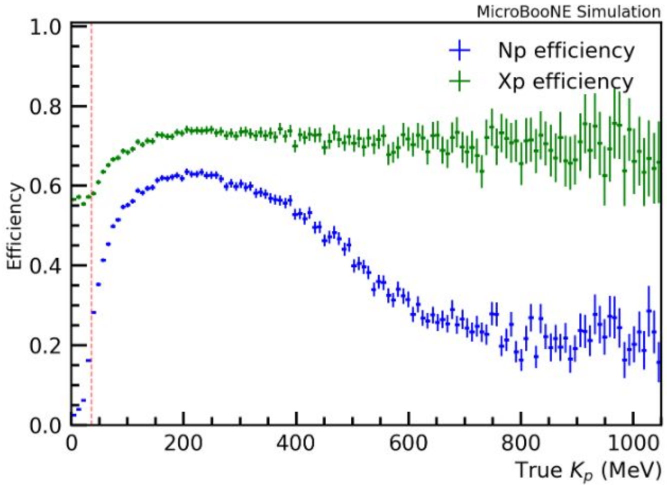
For Illustrative Purposes Only:

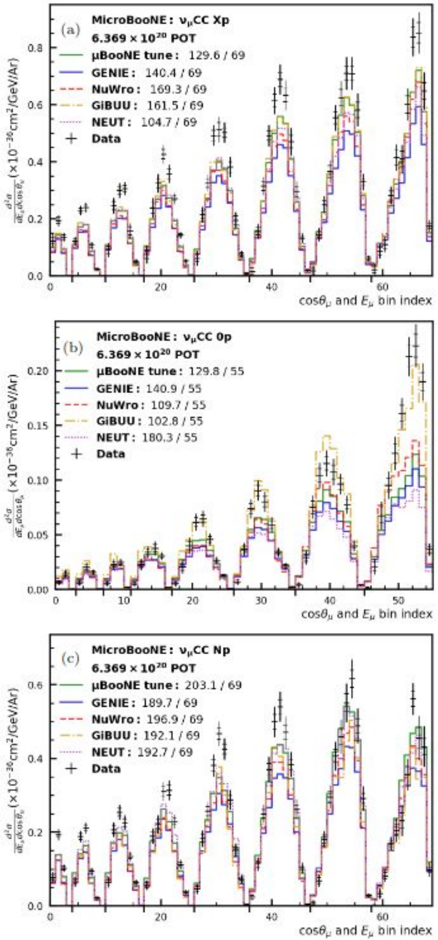


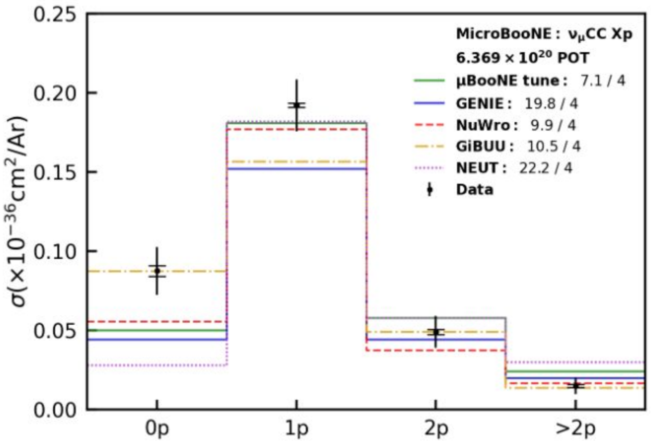
arXiv:2307.06413

Leptonic and hadronic system modeling



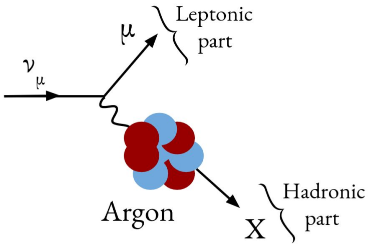




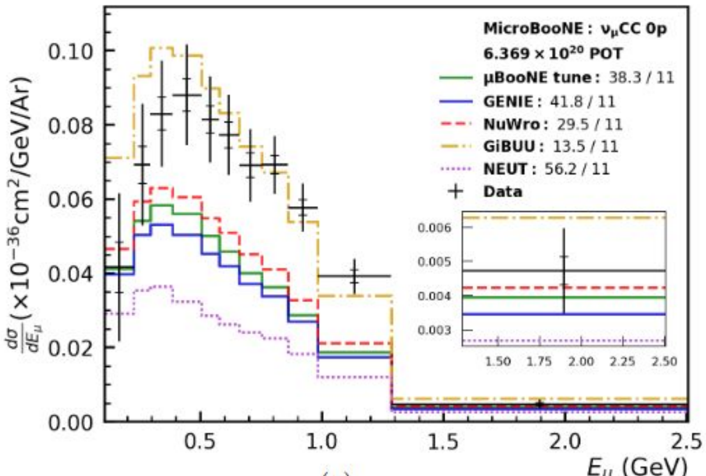


arXiv:2402.19216
arXiv:2402.19281

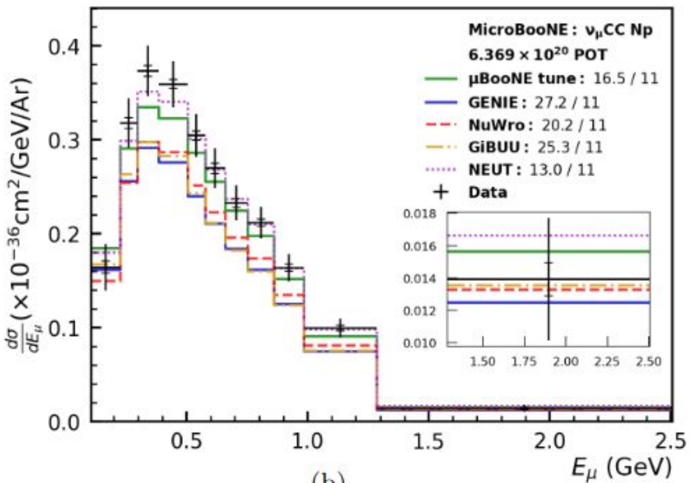
Leptonic and hadronic system modeling



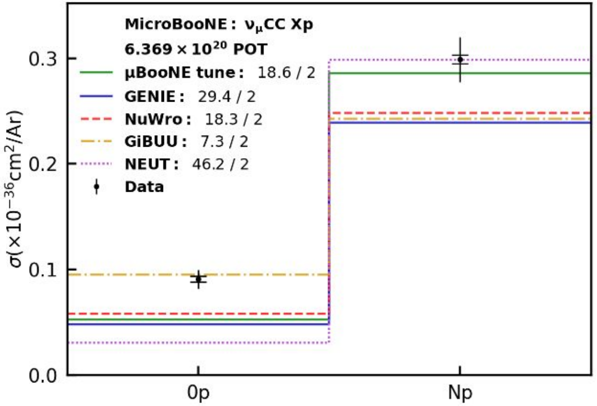
0pNp χ^2 (ndf = 22): μBooNE tune = 50.8, GENIE = 61.5, NuWro = 46.4, GiBUU= 37.6, NEUT = 65.7



(a)



(b)

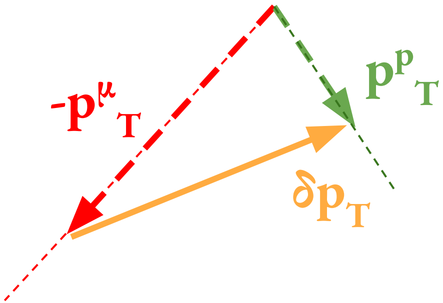


Generator	χ^2 all bins (ndf = 69):
μBooNE tune	129.6
GENIE	140.4
NuWro	169.3
NEUT	104.7
GiBUU	161.5

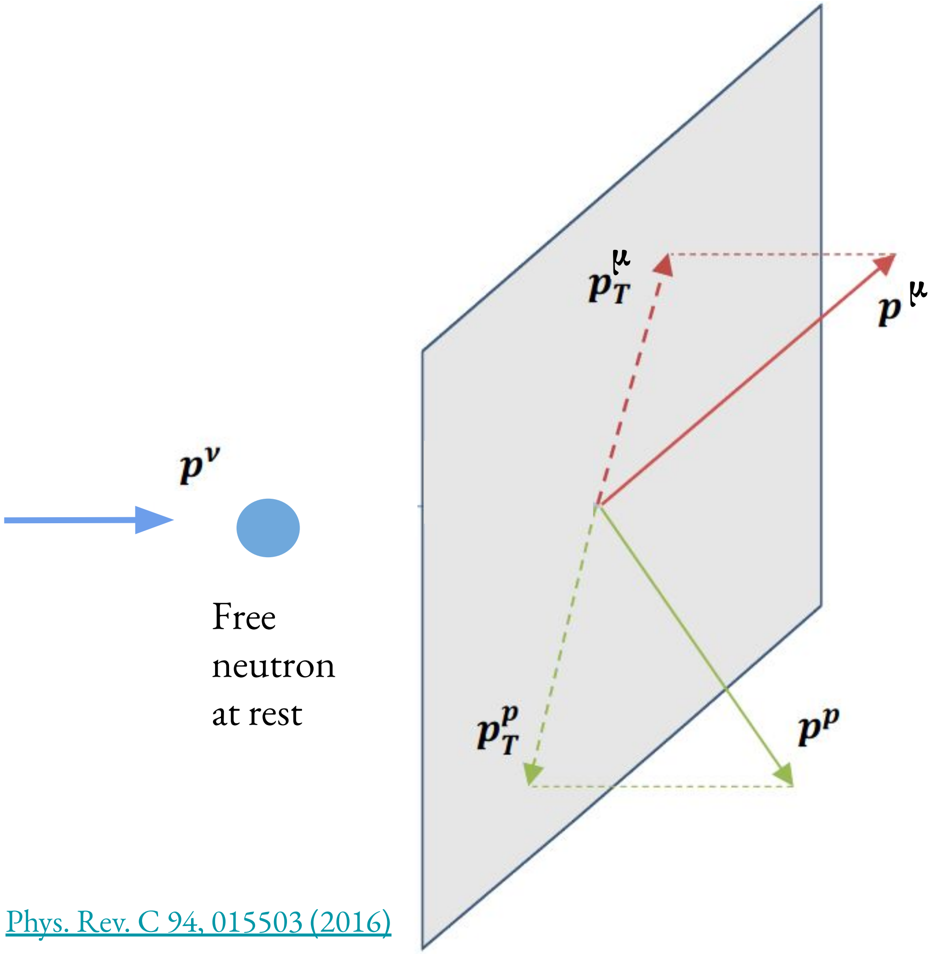
(i) The χ^2 values calculated for data and each generator prediction using all angular slices.

arXiv:2402.19216
arXiv:2402.19281

Transverse Kinematic Imbalance (TKI)



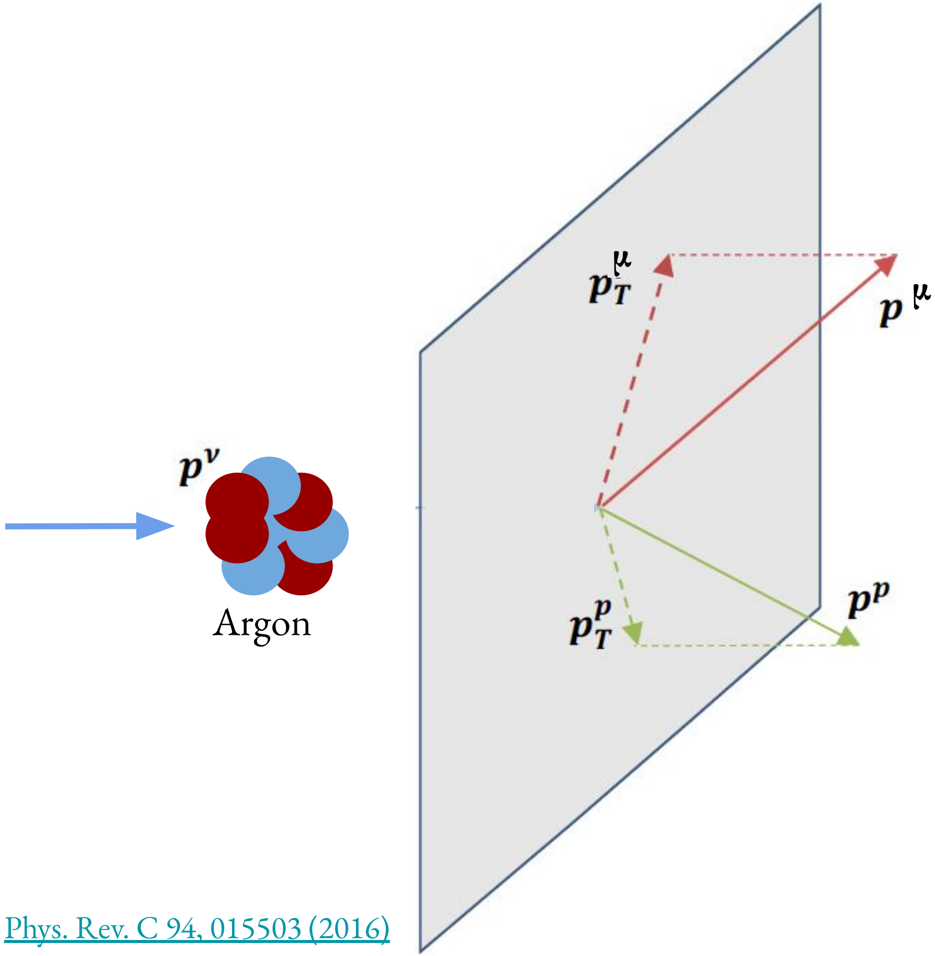
Transverse missing momentum
$\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | = 0$

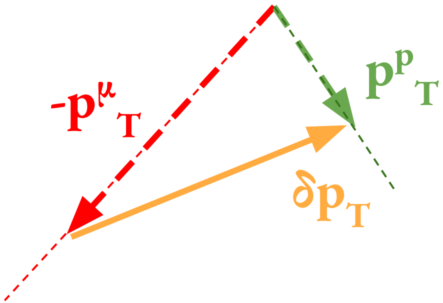


Free neutron at rest

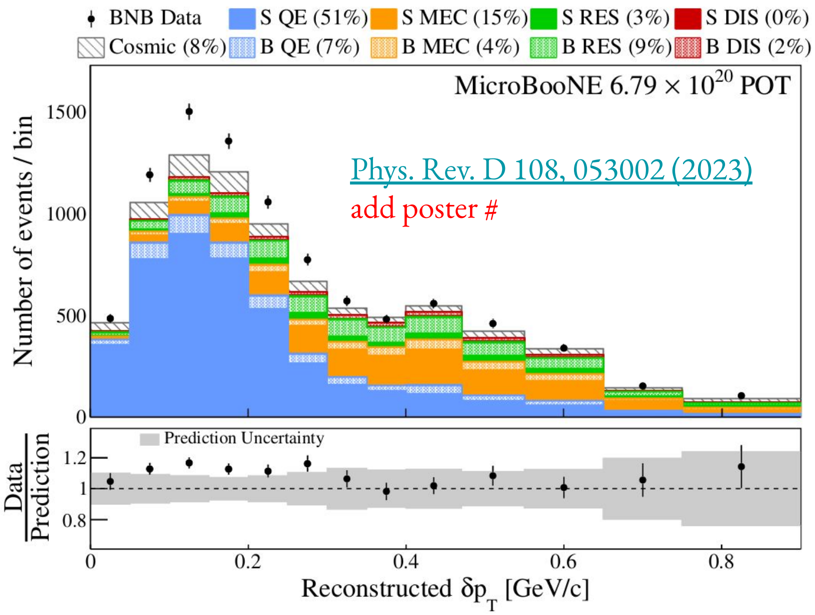
Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)





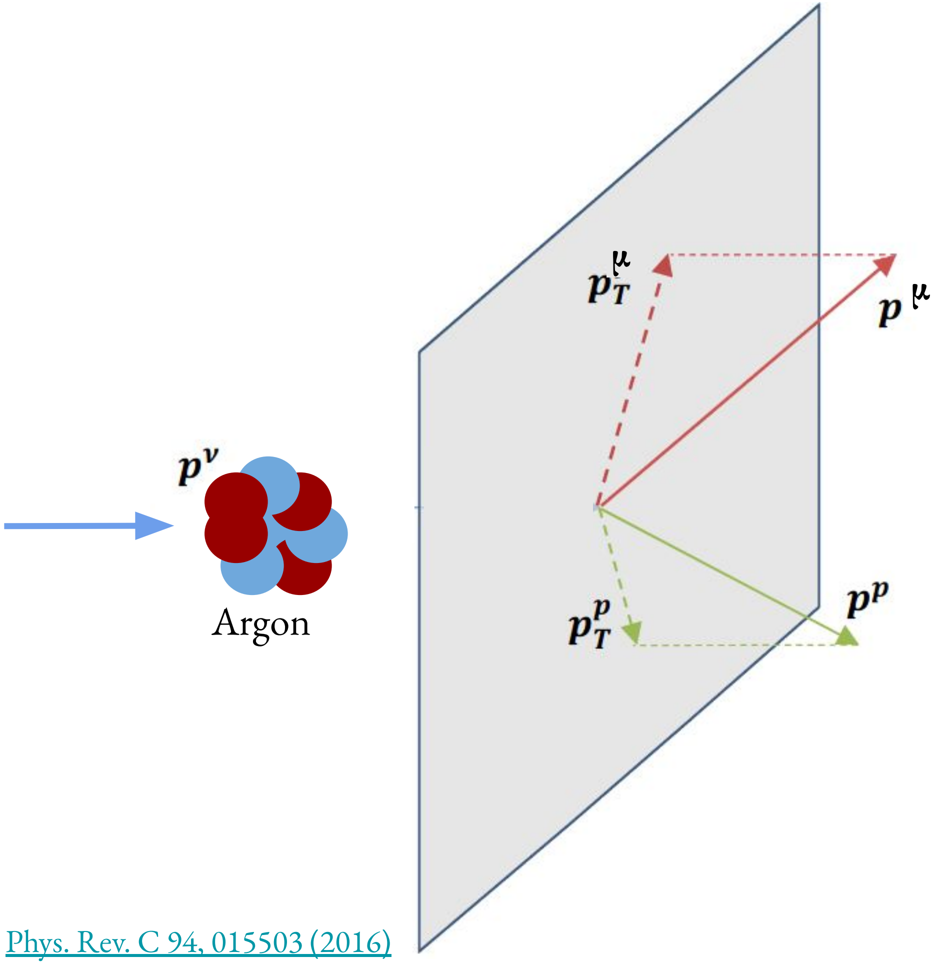
Transverse missing momentum
$\delta p_T = | \mathbf{p_T}^\mu + \mathbf{p_T}^p | > 0$

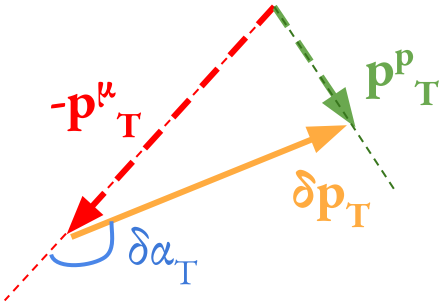


Phys. Rev. D 108, 053002 (2023)
add poster #

Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)

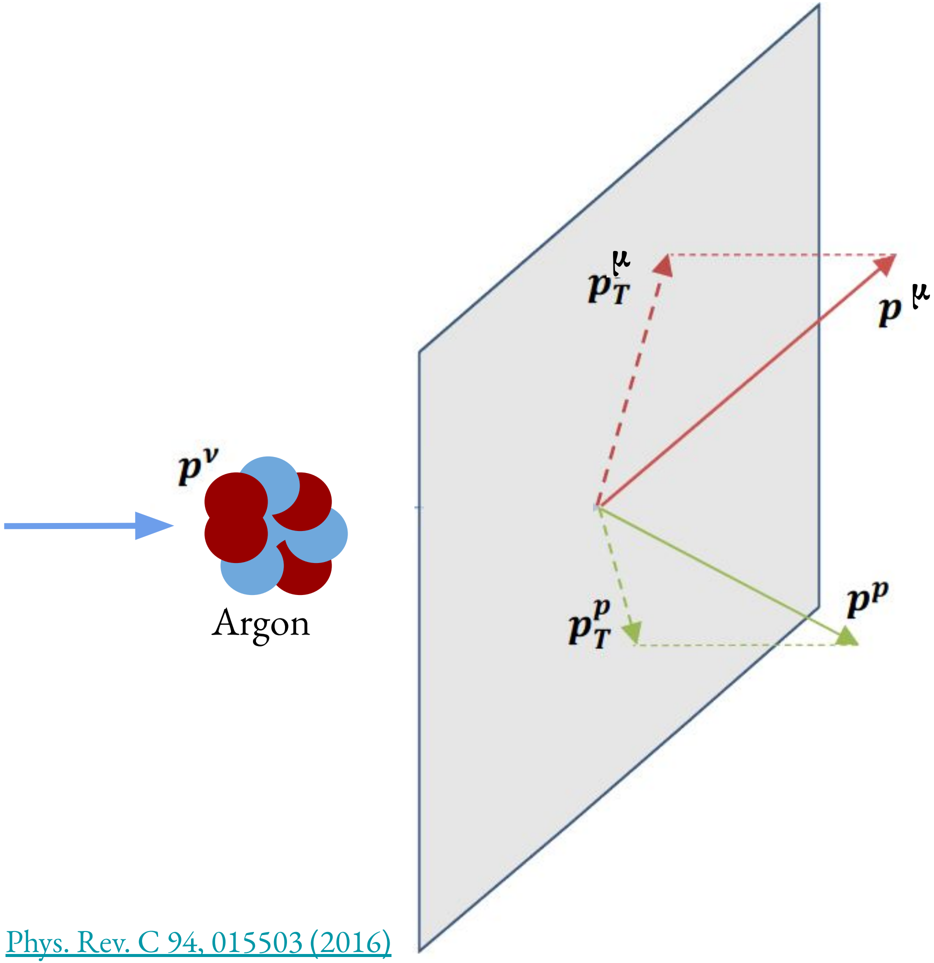


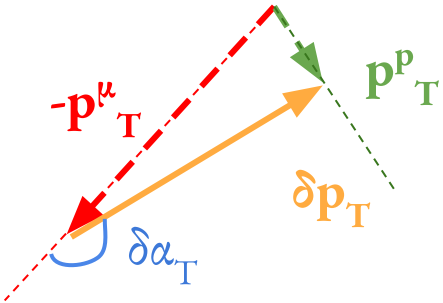


Orientation of the imbalance ($\delta\alpha_T$) also meaningful

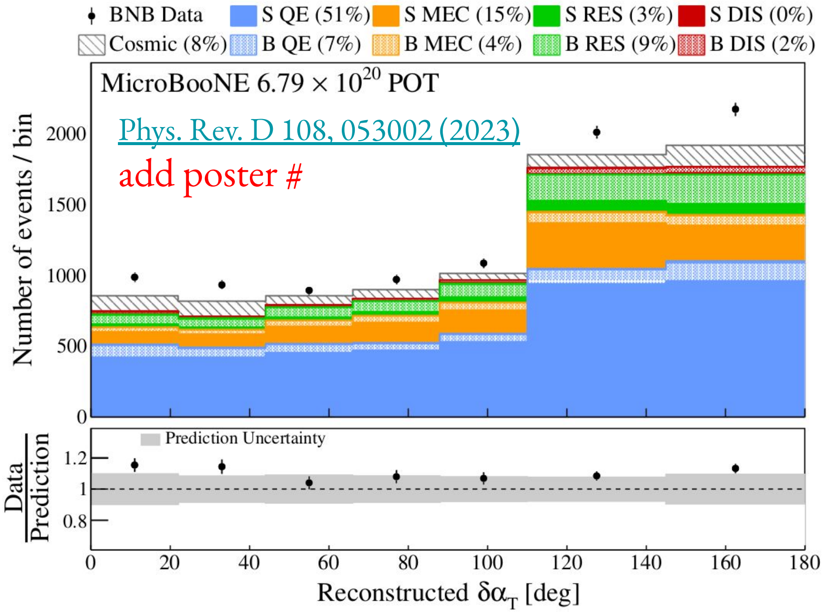
Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)





Sensitivity to hadron reinteractions



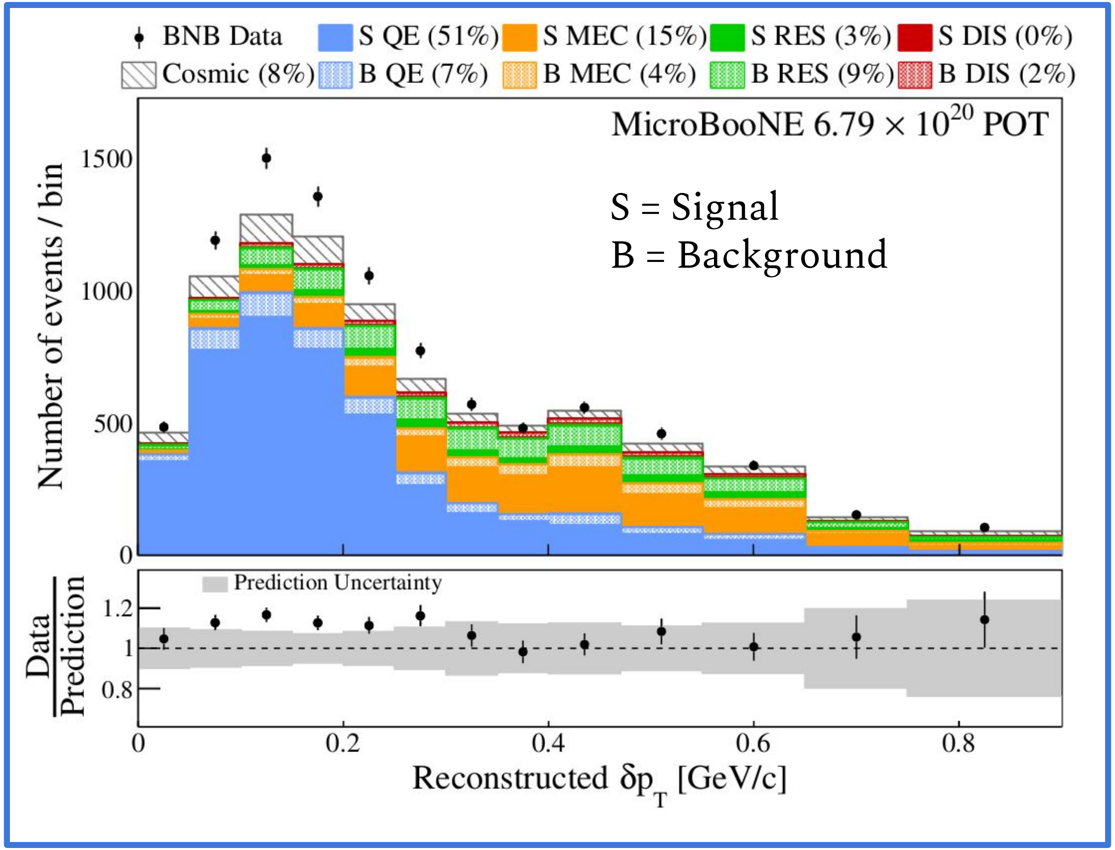
Phys. Rev. C 94, 015503 (2016)

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (Cosmics + MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



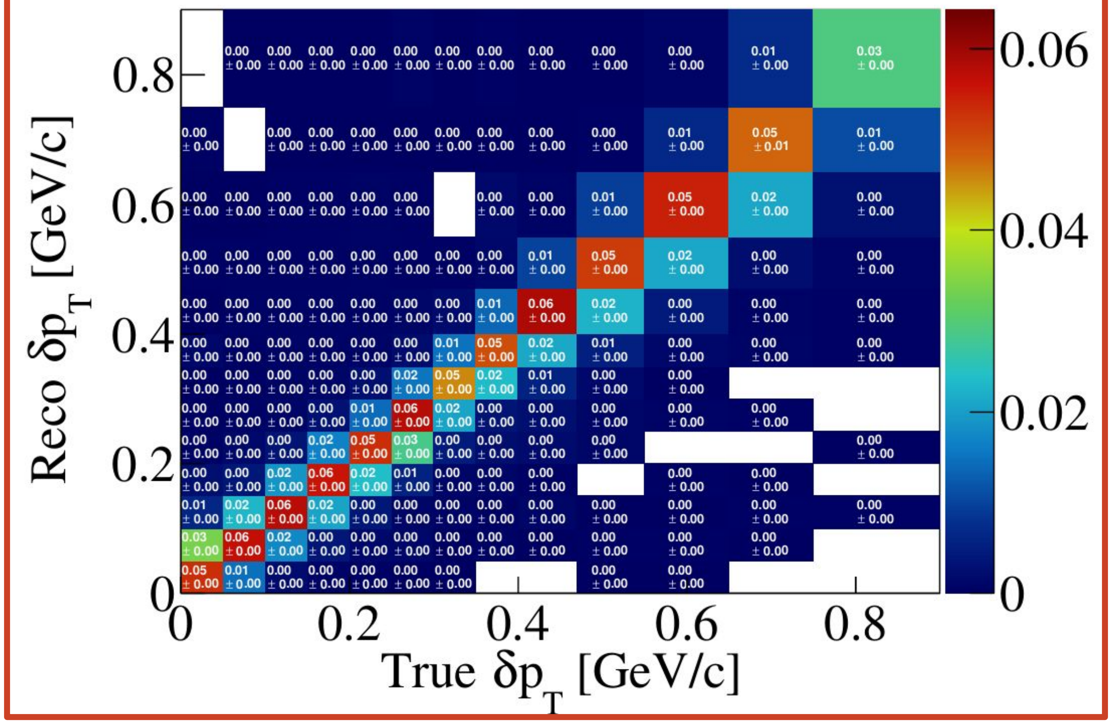
Phys. Rev. D 108, 053002 (2023)

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



Probability that a generated event is reconstructed and selected

Diagonal matrix with flat ~6% efficiency

Phys. Rev. D 108, 053002 (2023)

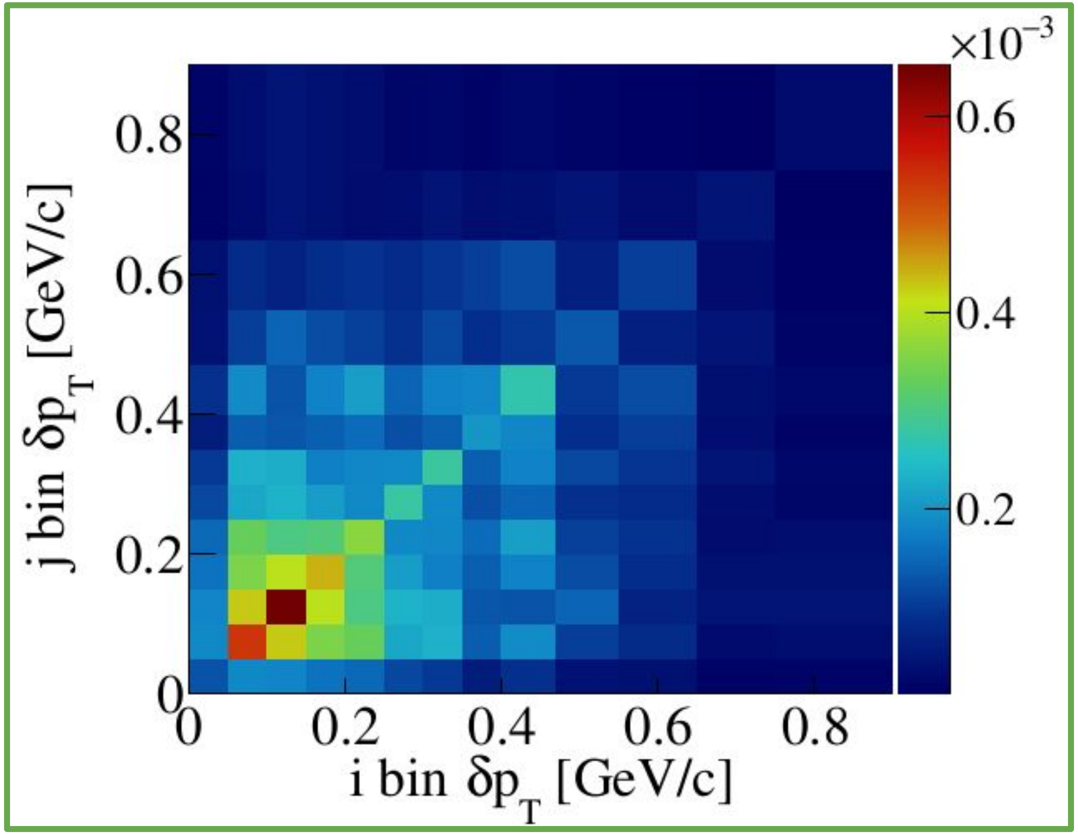
Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)

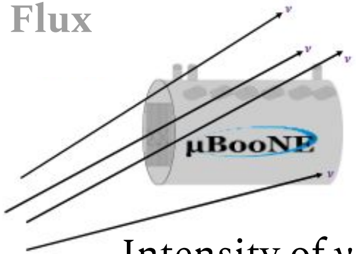
Includes information on statistical and systematic uncertainties



Phys. Rev. D 108, 053002 (2023)

Uncertainties

Flux



(7.3%)

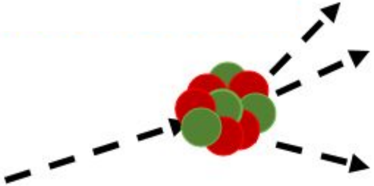
Intensity of ν source

Detector

(4.9%)

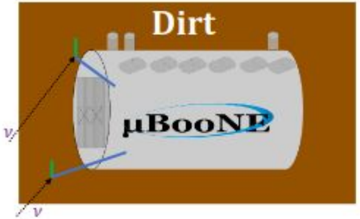
TPC & light variations

Cross section



(6%)

Modeling accuracy



(0.2%)

Out-of-cryostat ν interactions

Reinteractions

(1%)

Hadron rescattering

POT counting

(2%)

Protons-on-target precision

- \+ Statistical (1.5%)
- \+ Number of argon targets (1%)

Total (11%)

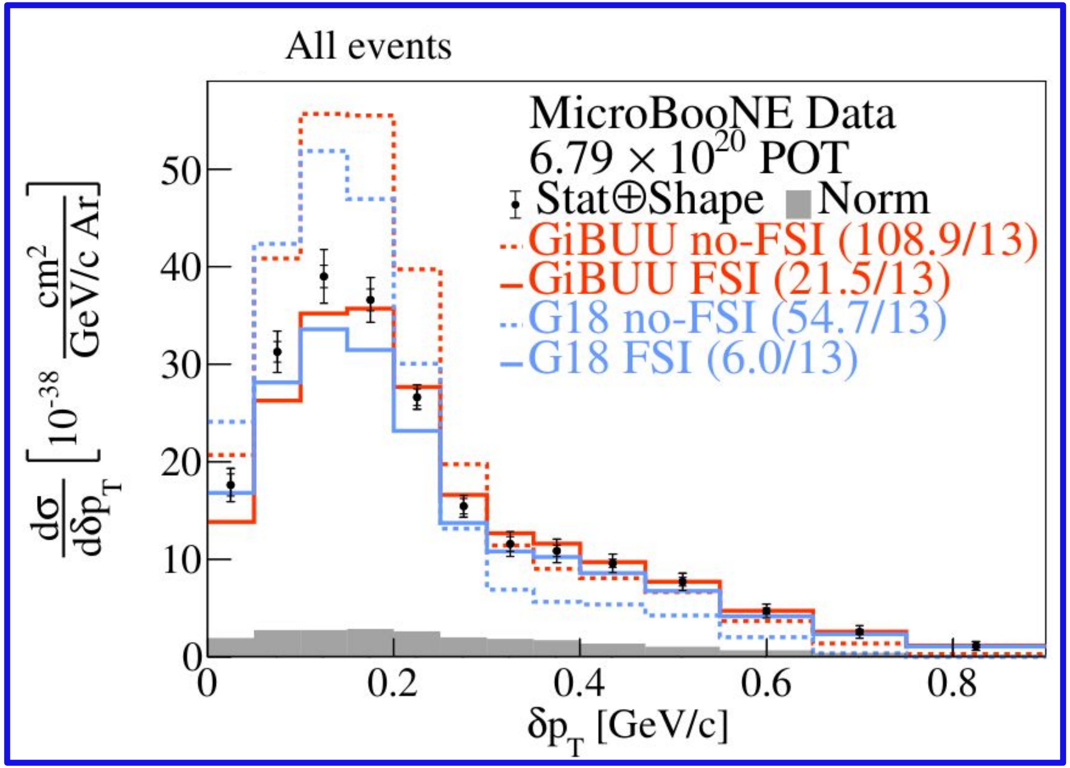
Systematics-dominated analysis

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Output quantities in regularized space

- Unfolded data spectrum
- Smearing Matrix A_C
  *Applied on theory predictions and included in data release



Phys. Rev. Lett. 131, 101802 (2023)

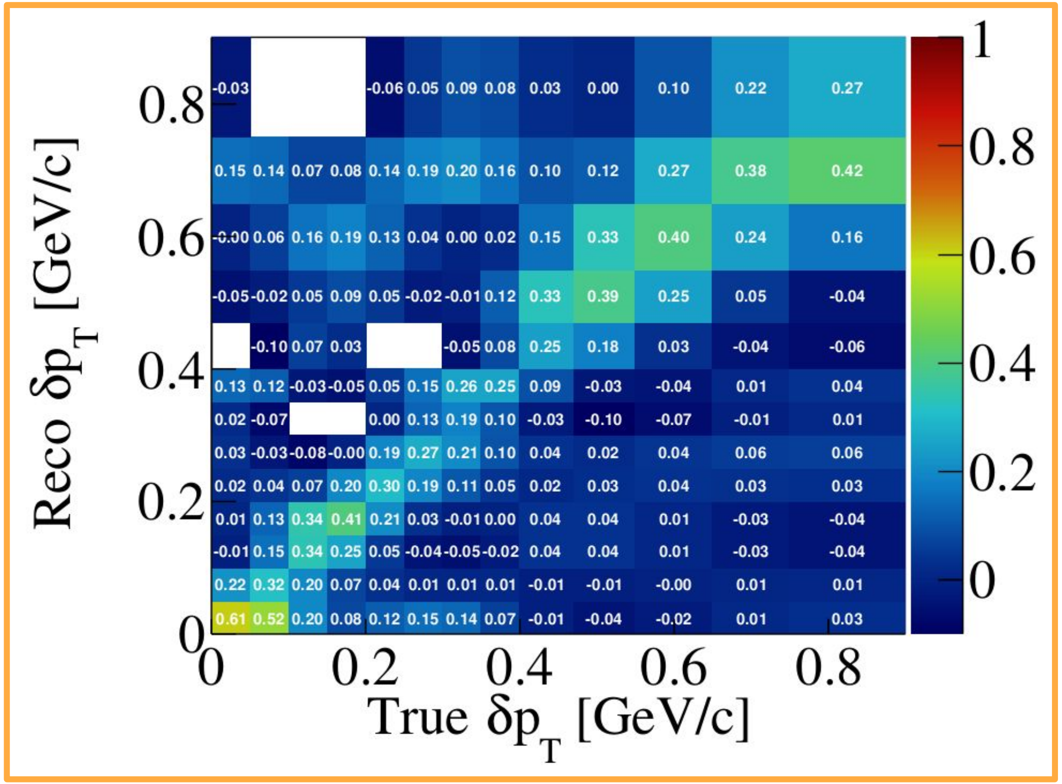
Cross Section Extraction with Wiener SVD Unfolding

[JINST **12** P10002 (2017)](#)

Output quantities in regularized space

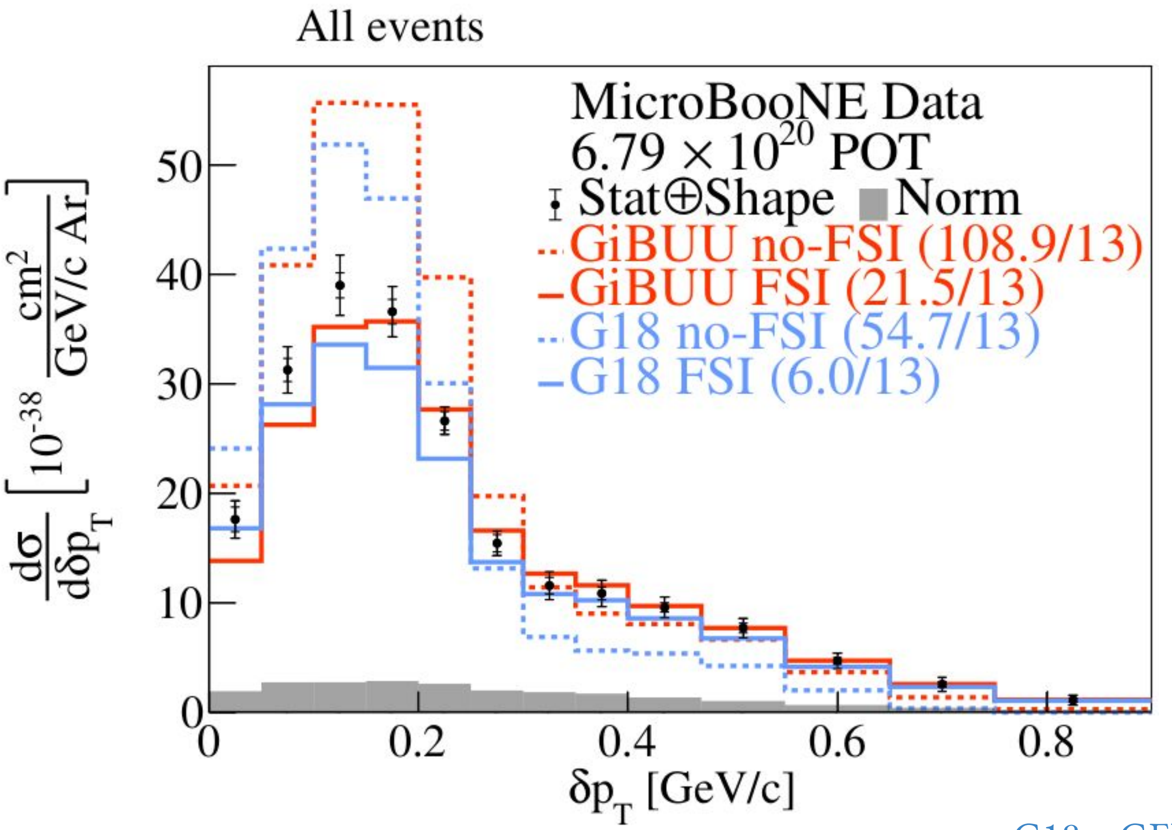
- Unfolded data spectrum
- Smearing Matrix A_C

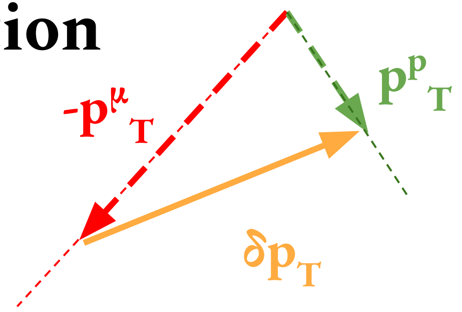
  *Applied on theory predictions and included in data release



[Phys. Rev. Lett. 131, 101802 (2023)](#)

Transverse Missing Momentum δp_T Cross Section





- First neutrino-argon differential cross section in δp_T
- FSI reduces strength of the peak
- Small changes in the tail
- Data favors FSI addition

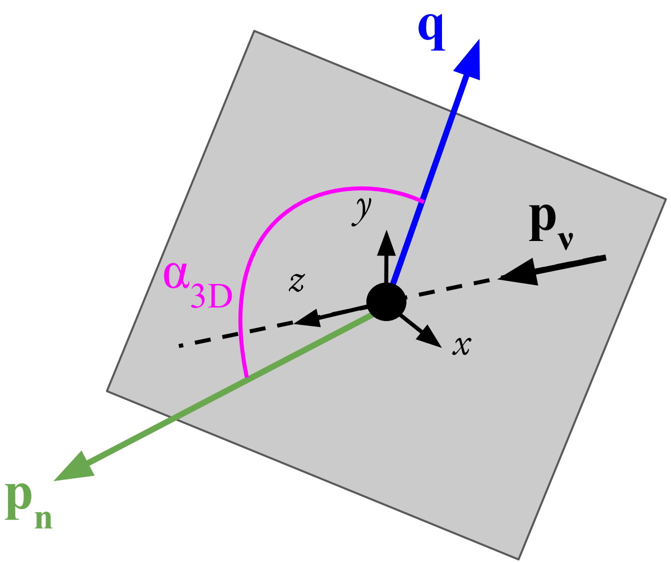
G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

Phys. Rev. Lett. 131, 101802 (2023)

* Phys. Rev. D 105, 072001 (2022)

Generalized Kinematic Imbalance (GKI)



- Extension to three dimensions by considering longitudinal component of missing momentum
- Leverage LArTPC calorimetric capabilities to reconstruct the incoming neutrino energy
- Demonstrated enhanced sensitivity to nuclear effects with simulation studies

p_n = total missing momentum vector
q = momentum transfer vector
α_{3D} = 3D orientation of missing momentum

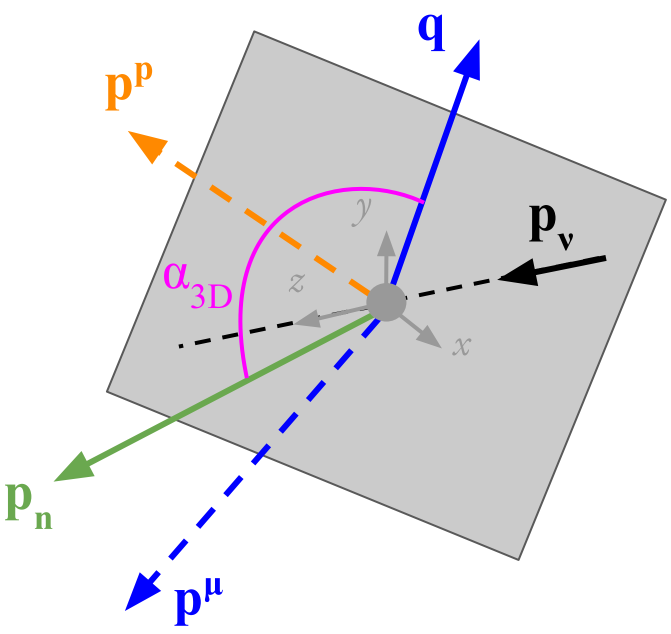
[Phys. Rev. C 95, 065501 (2017)]
[Phys. Rev. D 109, 092007 (2024)]
add poster #

Generalized Kinematic Imbalance (GKI)

Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy

B = 30.9 MeV



$$E_{\mathrm{cal}} = E_{\mu} + K_{p} + B$$

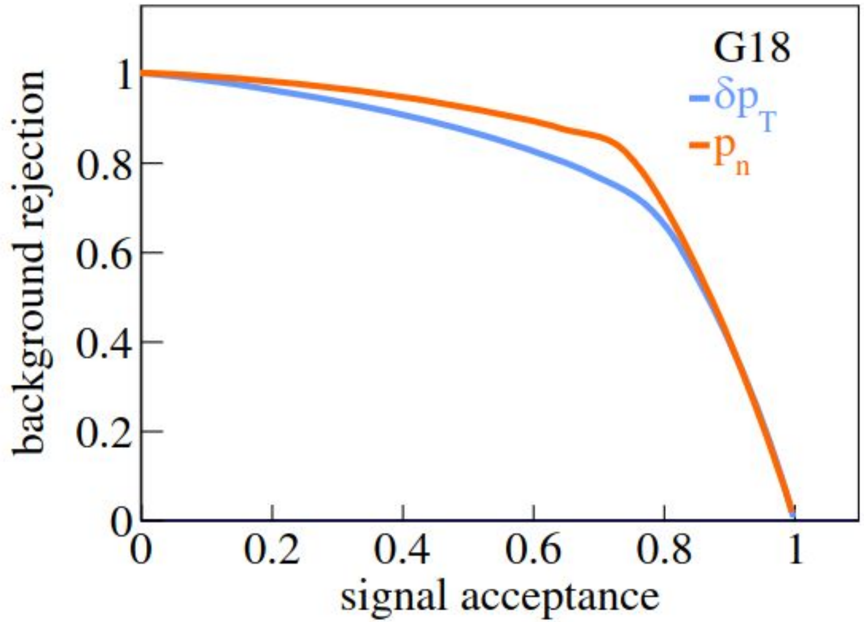
$$\vec{q} = E_{\mathrm{cal}}\hat{z} - \vec{p}_{\mu}$$

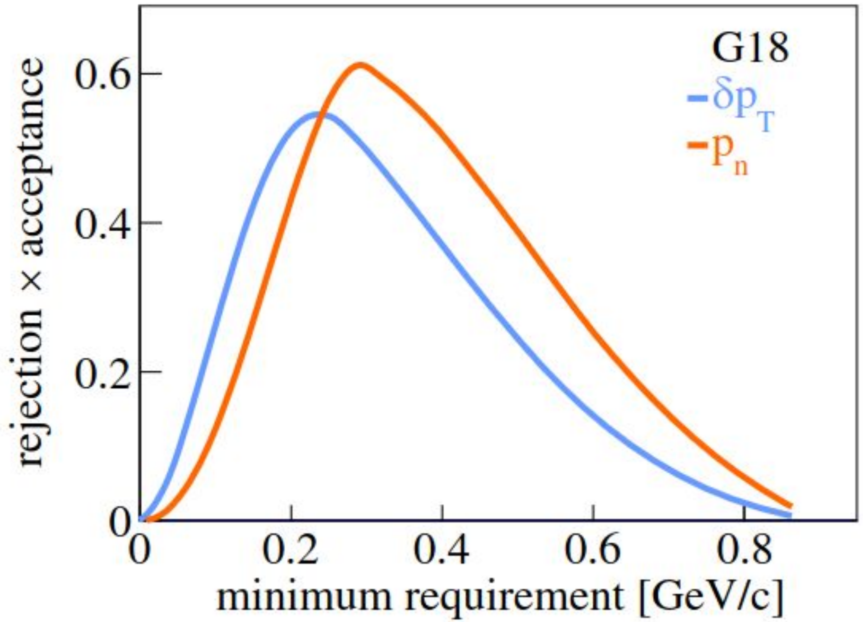
$$p_{L} = p_{L}^{\mu} + p_{L}^{p} - E_{\mathrm{cal}}$$

$$p_{n} = |\vec{p}_{n}| = \sqrt{p_{L}^{2} + \delta p_{T}^{2}}$$

$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_{n}}{|\vec{q}||\vec{p}_{n}|}\right)$$

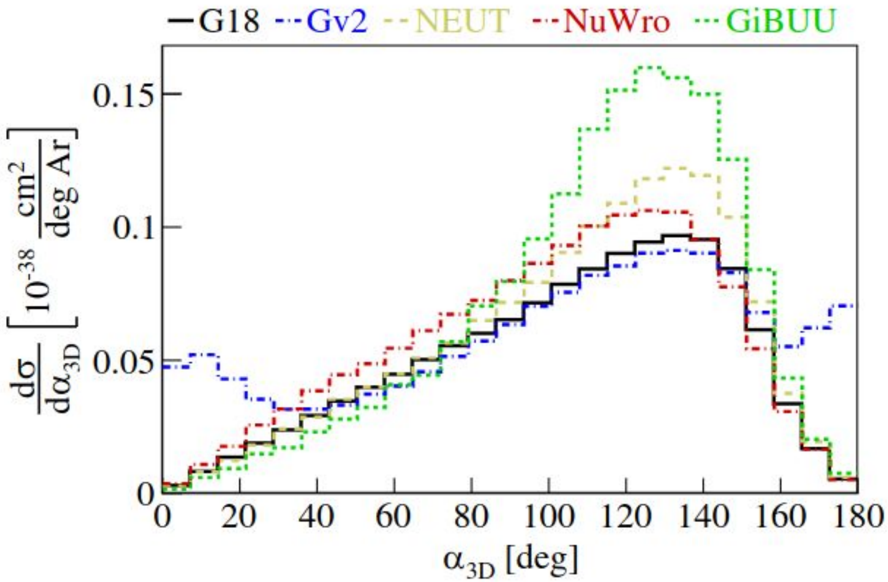
Generalized Kinematic Imbalance (GKI)

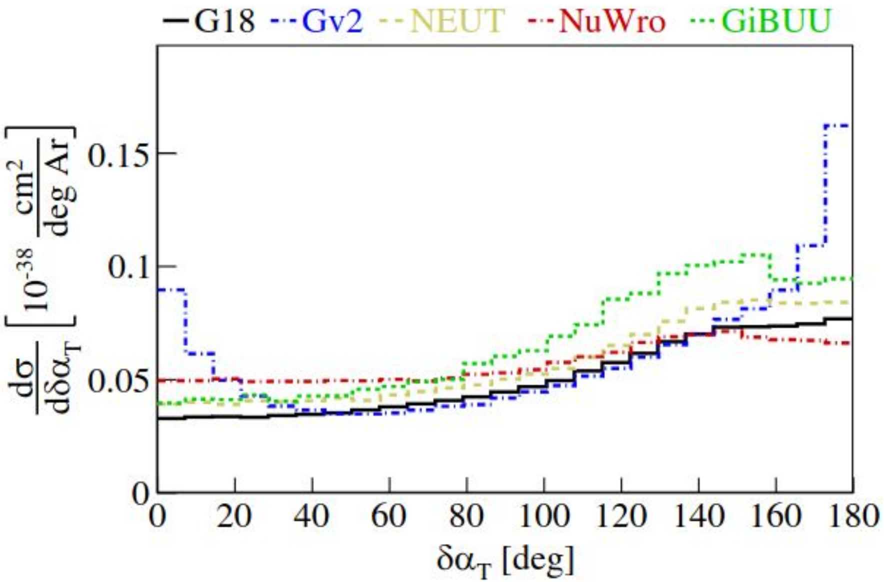




Phys. Rev. C 95, 065501 (2017)
Phys. Rev. D 109, 092007 (2024)

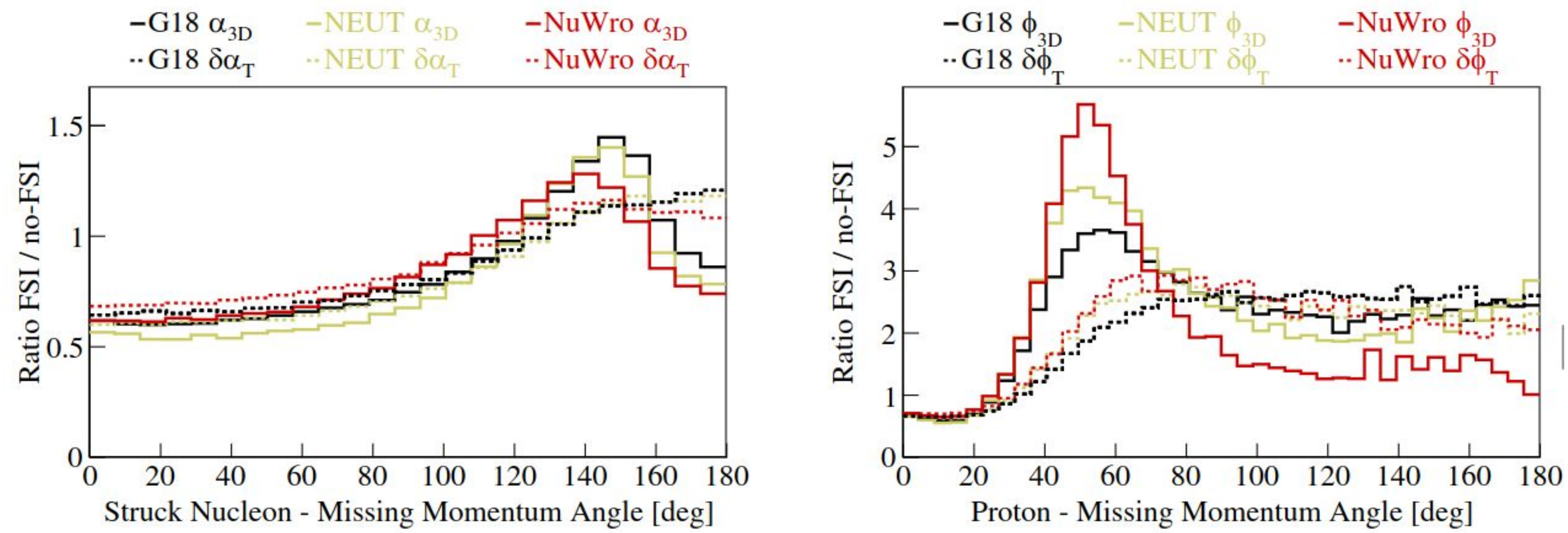
Generalized Kinematic Imbalance (GKI)





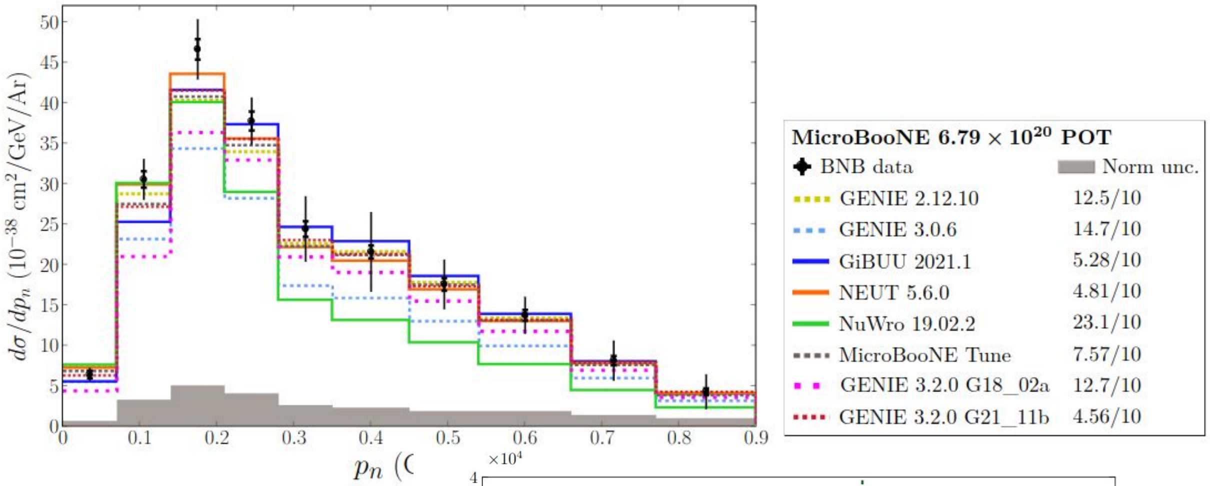
Phys. Rev. C 95, 065501 (2017)
Phys. Rev. D 109, 092007 (2024)

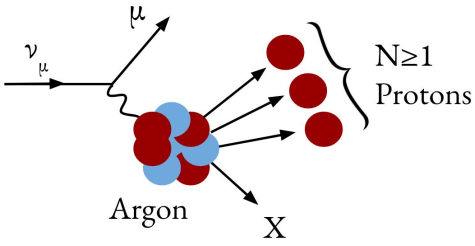
Generalized Kinematic Imbalance (GKI)



Phys. Rev. C 95, 065501 (2017)
Phys. Rev. D 109, 092007 (2024)

Multi-proton kinematic imbalance





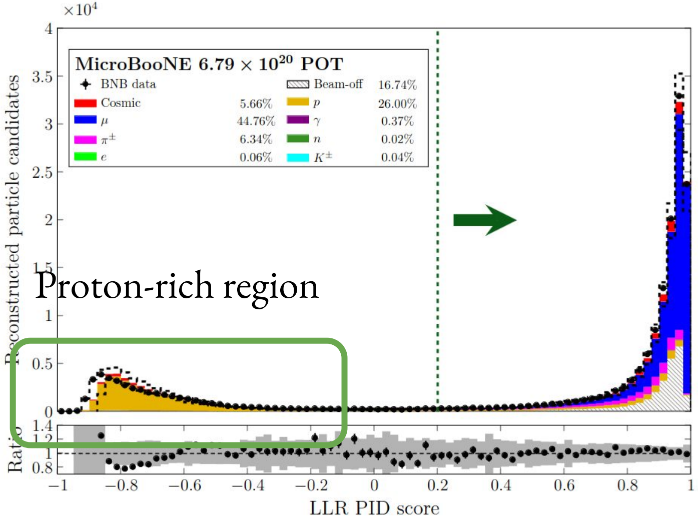
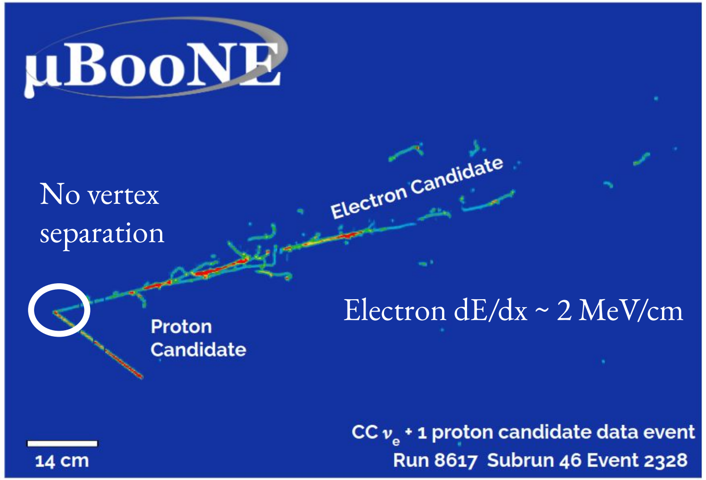


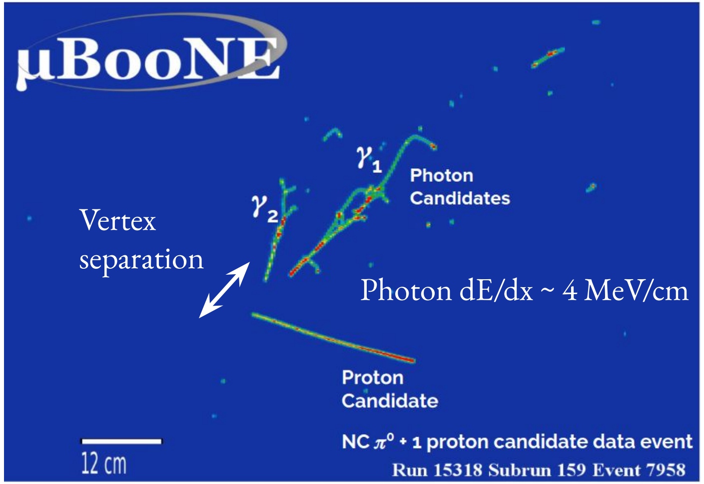
TABLE II. Overall χ^2 scores for each of the neutrino interaction models studied.

Model	χ^2 / 359 bins
GENIE 3.0.6	1859
NEUT 5.6.0	2582
MicroBooNE Tune	2673
GENIE 3.2.0 G21_11b	2947
GiBUU 2021.1	4836
NuWro 19.02.1	5315
GENIE 3.2.0 G18_02a	5724
GENIE 2.12.10	7799

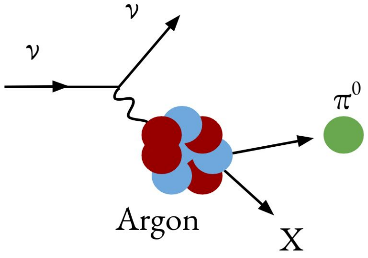
arXiv:2403.19574

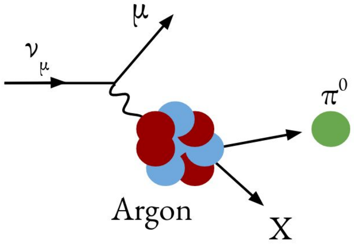
π^0 production measurements



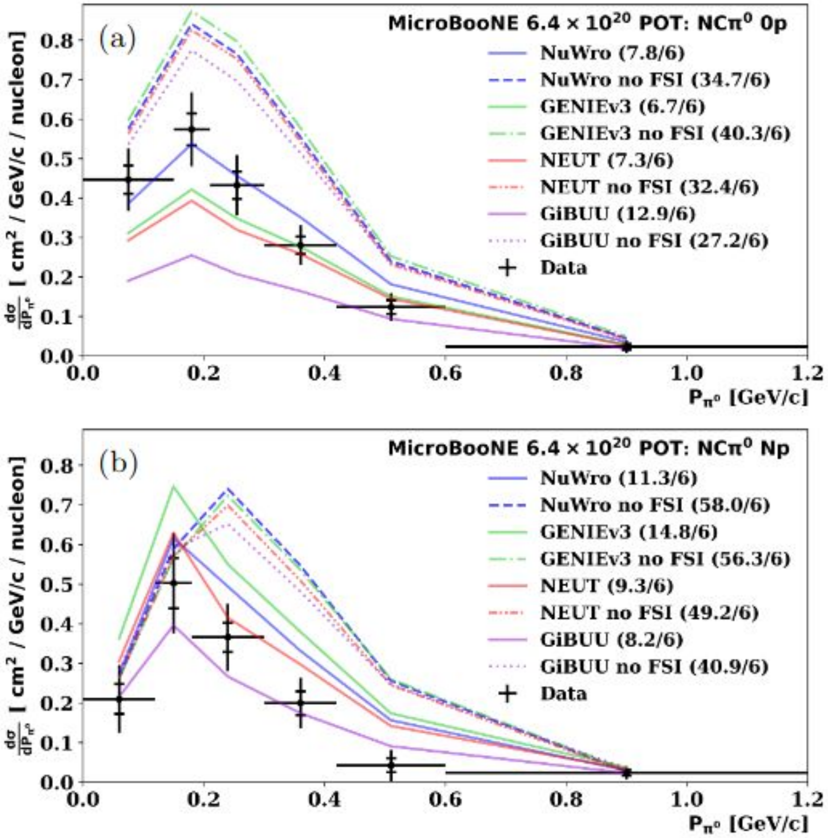


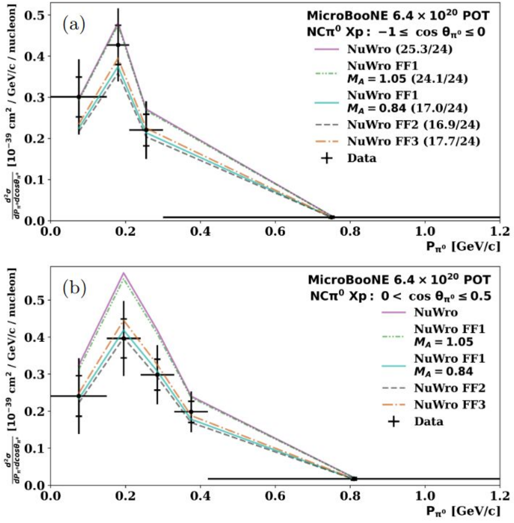
- π^0 events can mimic ν_e charged current events, but this is largely mitigated by dE/dx measurements and vertex separation
- Significant role in DUNE energy spectrum
- π^0 events form an irreducible background for single photon and $e^+ e^-$ Beyond Standard Model searches
- Need for extremely accurate modeling
- Tested with neutral and charged current π^0 measurements

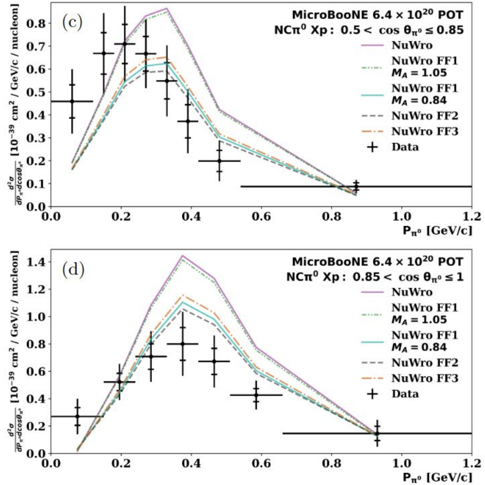


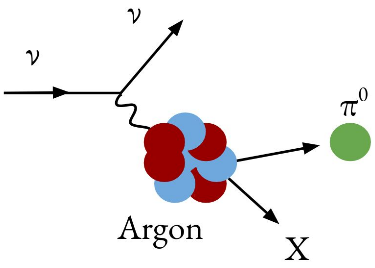


Neutral current π^0 production



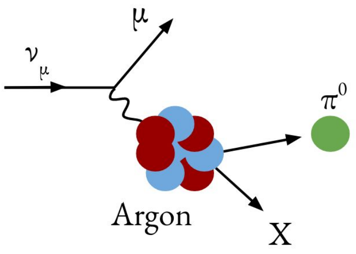


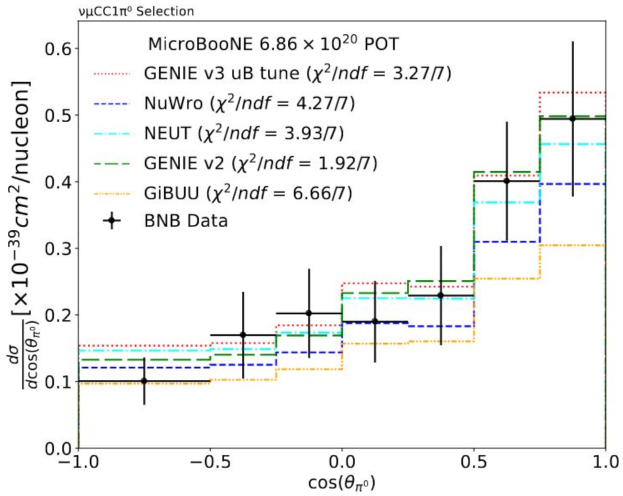


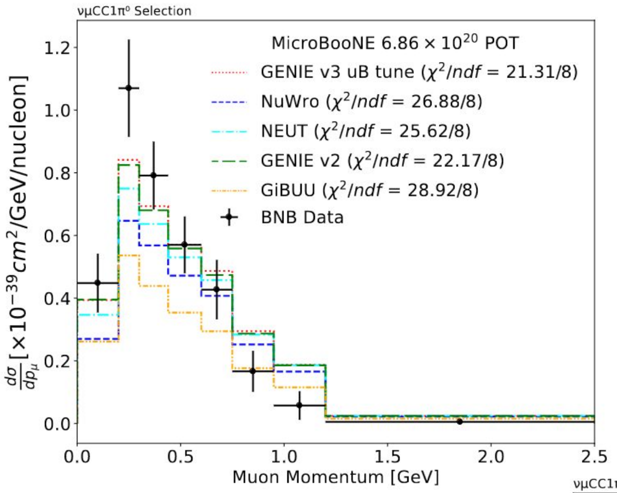


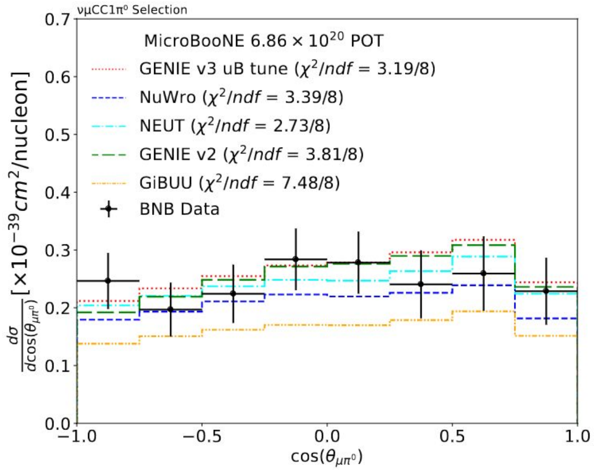
arXiv:2404.10948

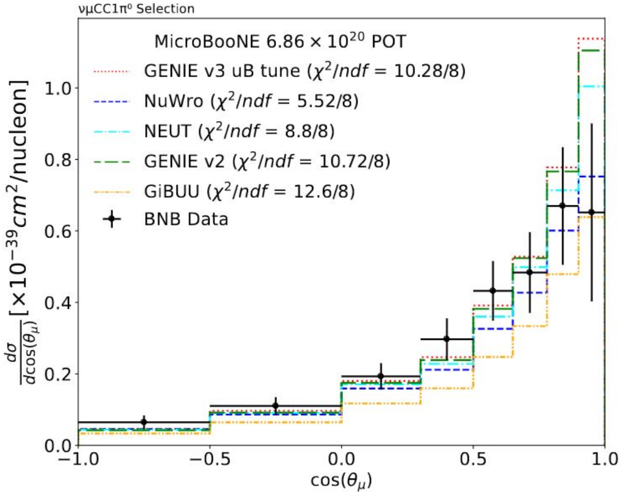
Charged current π^0 production





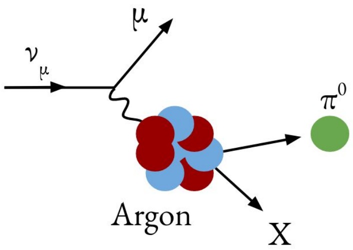


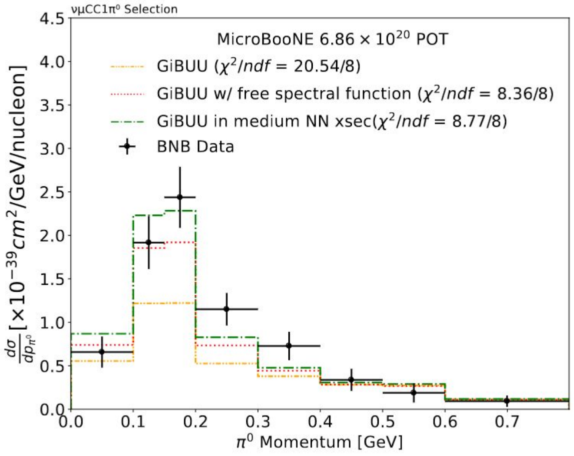


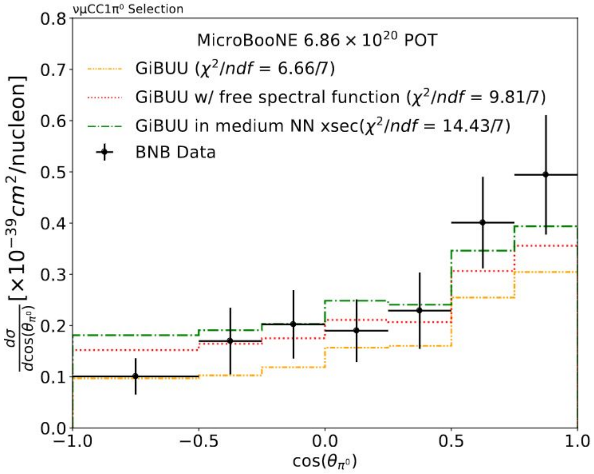


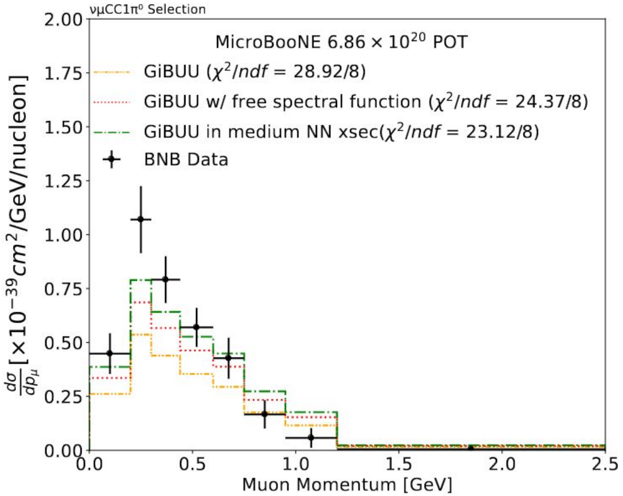
arXiv:2404.09949

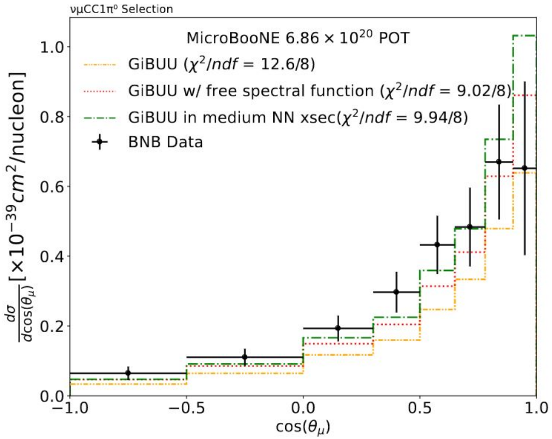
Charged current π^0 production

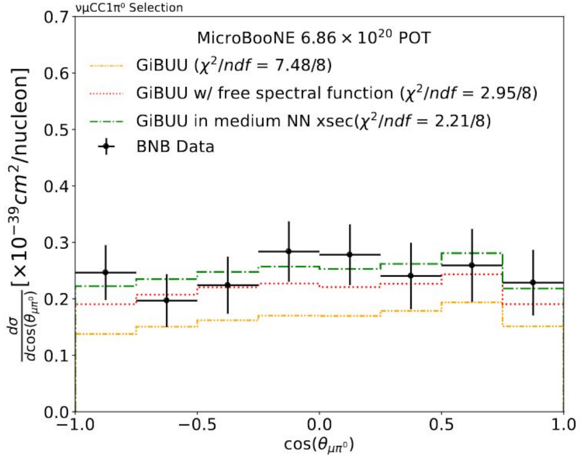






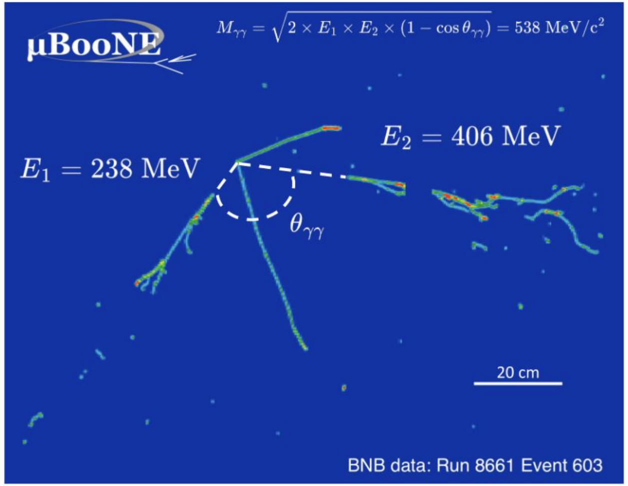


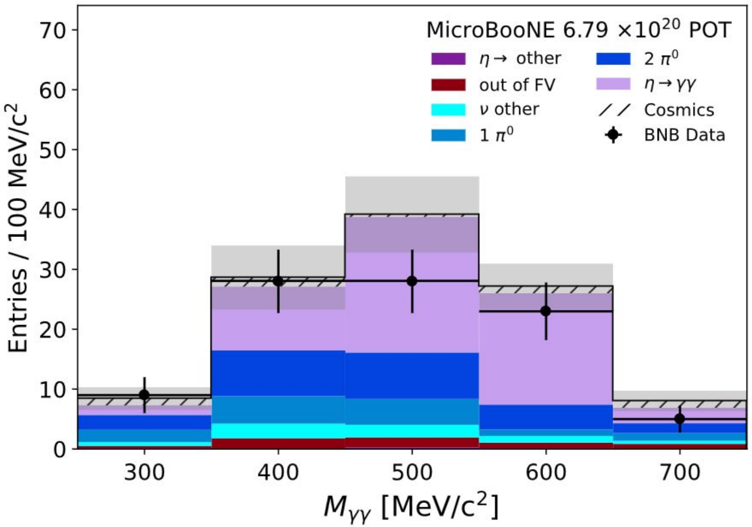


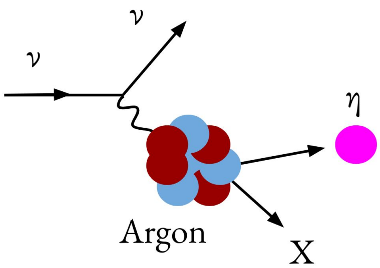


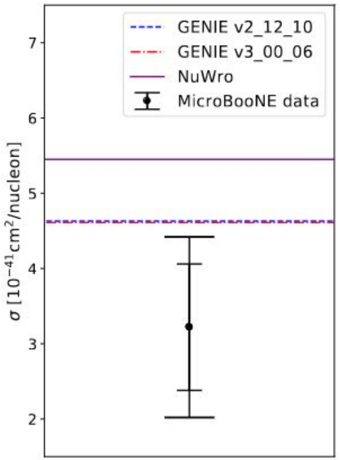
arXiv:2404.09949

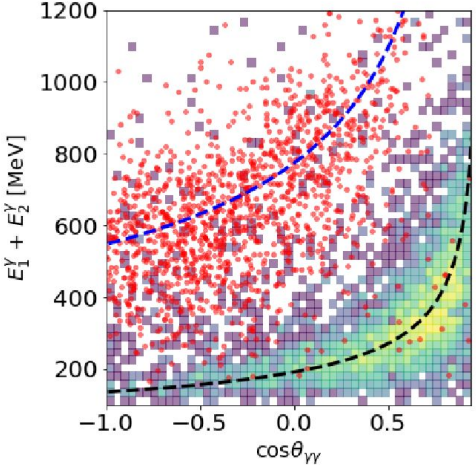
η meson production











[Phys. Rev. Lett. 132, 151801 (2024)](https://doi.org/)

Λ baryon production

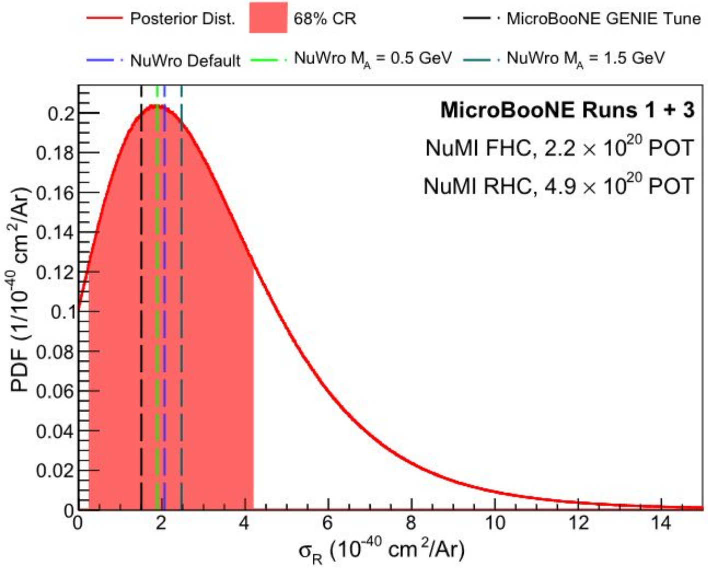
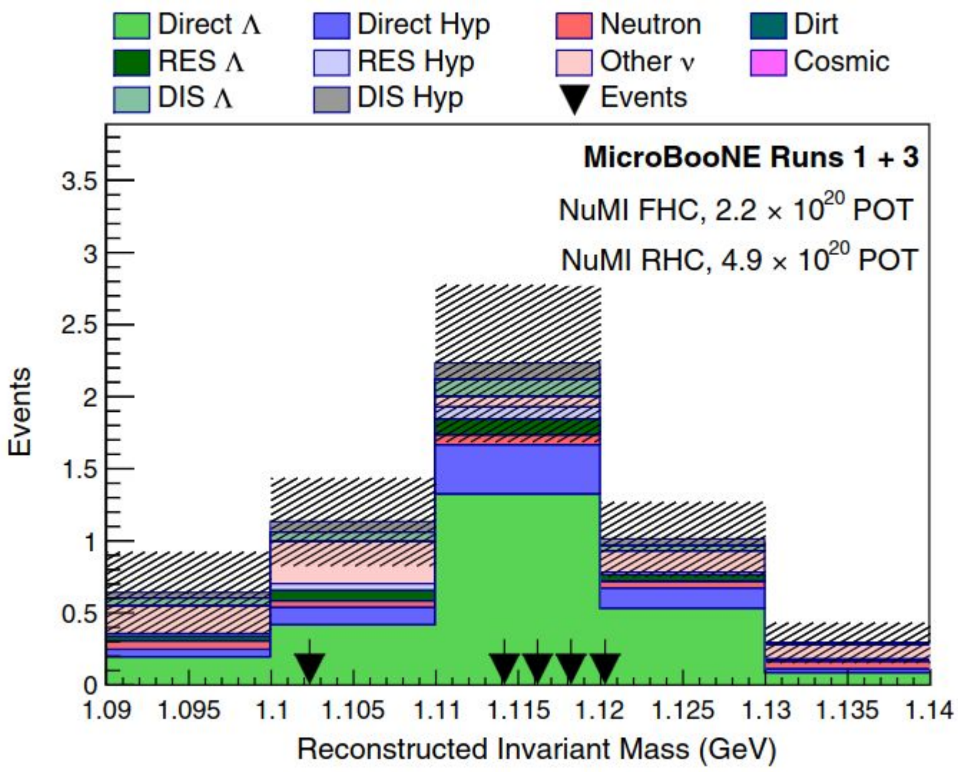


TABLE II. Fractional covariance matrix between the uncertainties on the selection efficiency ϵ, the $\bar{\nu}_\mu$ flux Φ, and the predicted number of background events B.

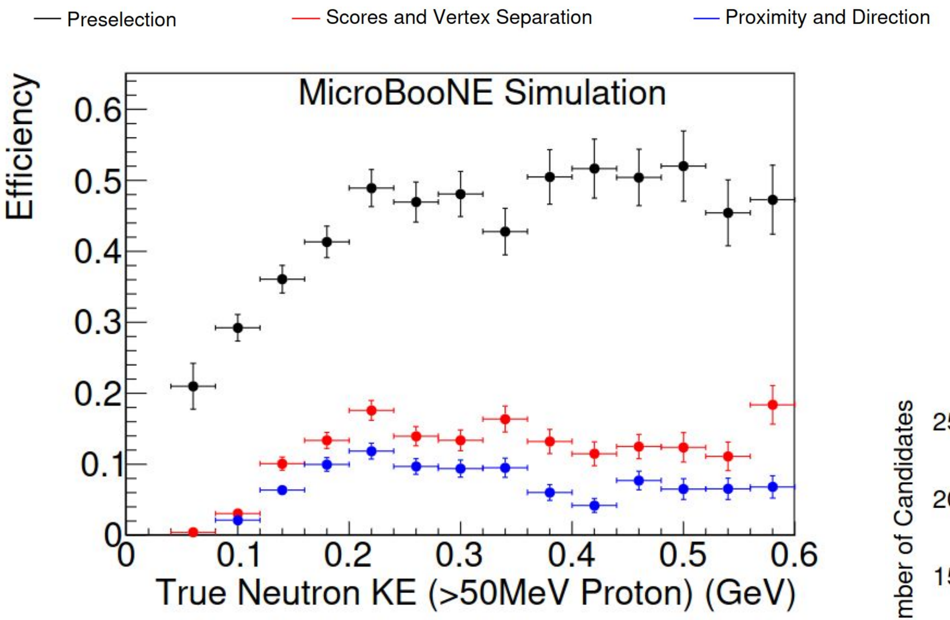
	ϵ	Φ	B
ϵ	0.04572	−0.00116	0.03237
Φ	−0.00116	0.05339	0.01887
B	0.03237	0.01887	0.33123



Phys. Rev. Lett. 130, 231802

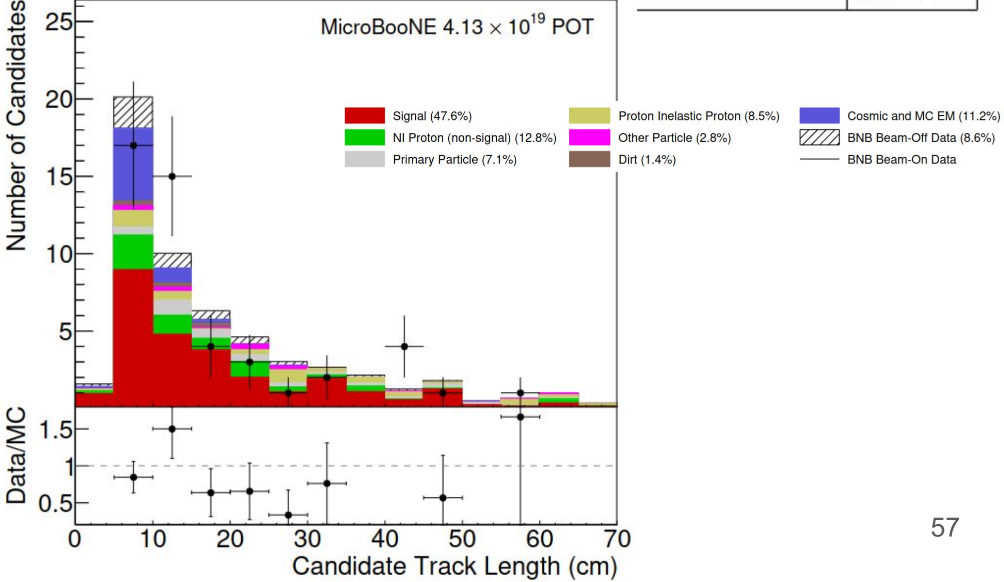
add poster #

Neutron identification



Neutron End Process	
Exit detector without inelastic scatter	24.63%
Exit detector after inelastic scatter	71.45%
Captured by argon	3.13%
Other	0.75%

Number of Inelastic Scatters	
0 Scatters	25.48%
1 Scatter	30.28%
2 Scatters	26.51%
3 Scatters	11.87%
4+ Scatters	5.87%



add arxiv/public note number here