DPF-PHENO 2024

Recent MicroBooNE Cross Section Results

London Cooper-Troendle
on behalf of the MicroBooNE Collaboration
May 14th, 2024

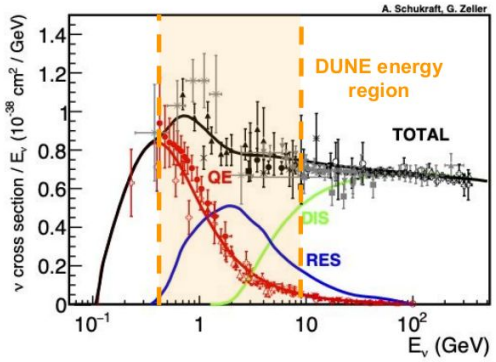
μBooNE

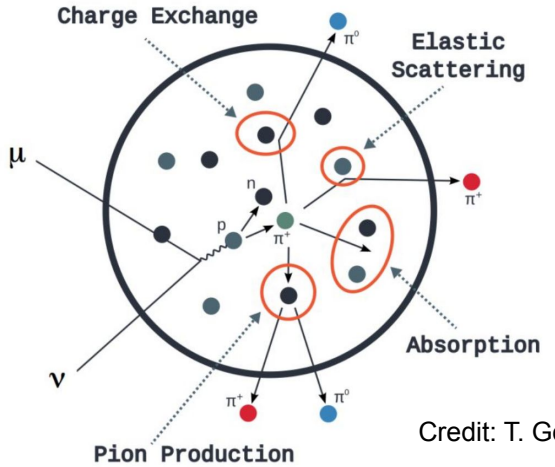
Challenges in Neutrino Interaction Modeling

RevModPhys.84.1307

Need high precision for oscillation measurements, however:

- Wide range of energies
  - Spans QE, RES, DIS
- Range of nuclear targets across experiments
  - Hydrogen, Deuterium, Carbon, Argon, Iron, Lead
- Complex QCD physics inside nucleus
  - Nuclear initial state
  - Nucleon-nucleon correlations
  - Final state interactions

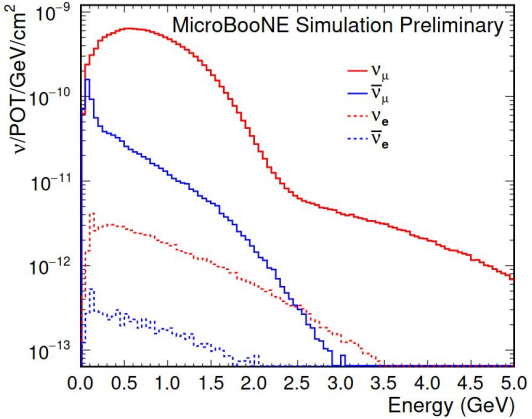




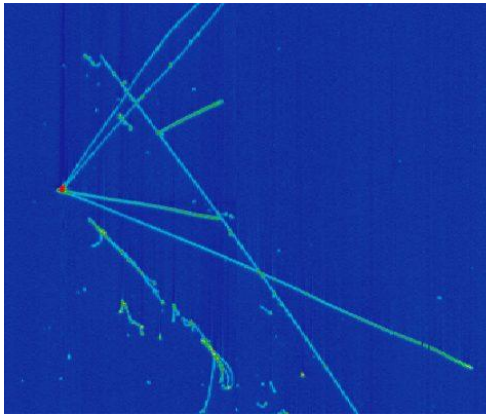
Credit: T. Golan

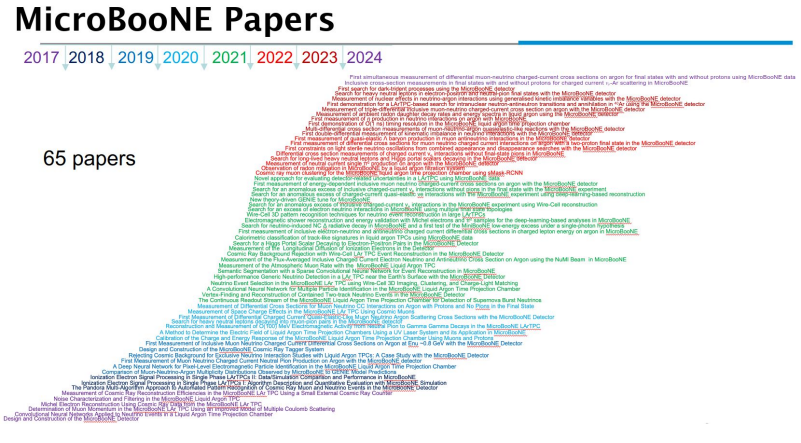
About MicroBooNE

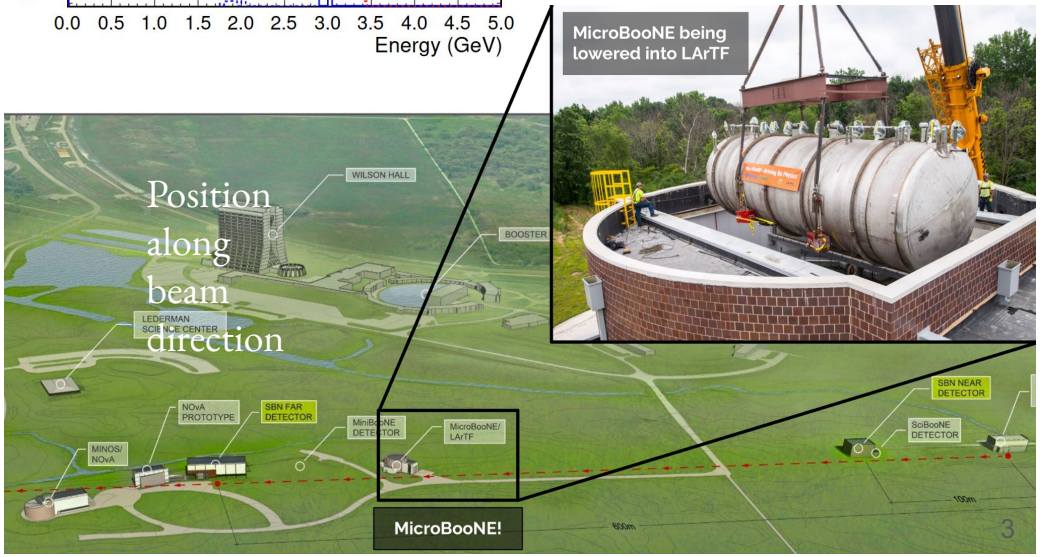
- 85 tonne liquid argon time projection chamber
  - Low detection thresholds
  - Precise spatial resolution and calorimetry
  - Powerful particle identification
- 0.8 GeV peak neutrino energy



MicroBooNE Event Display





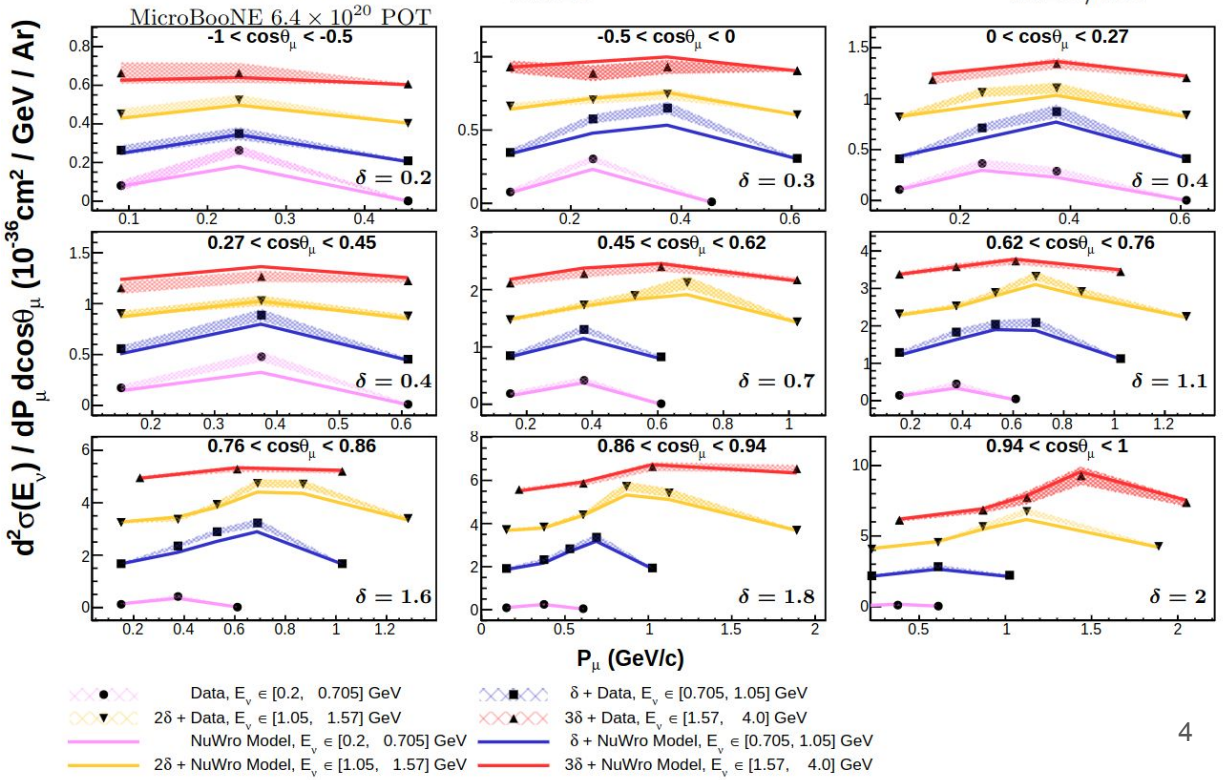


ν_μ CC Inclusive 3D

- First triple-differential cross section on argon
- Measurement of E_ν is crucial for model development and osc measurements
- Data-driven validation and fake data studies
- Disagreement with all models examined

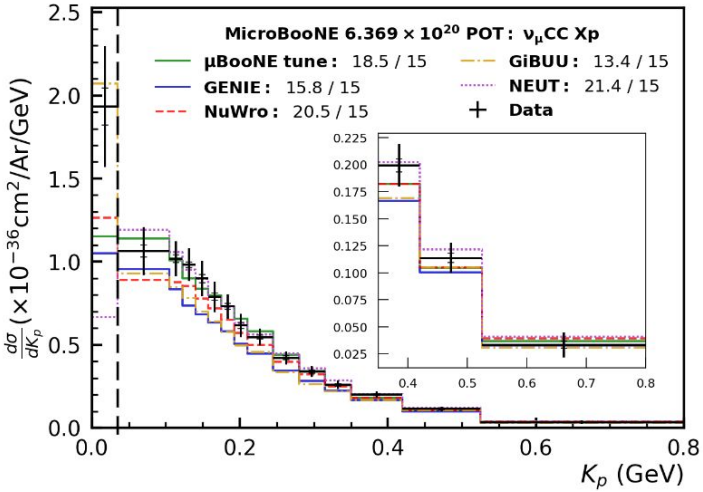
arXiv:2307.06413

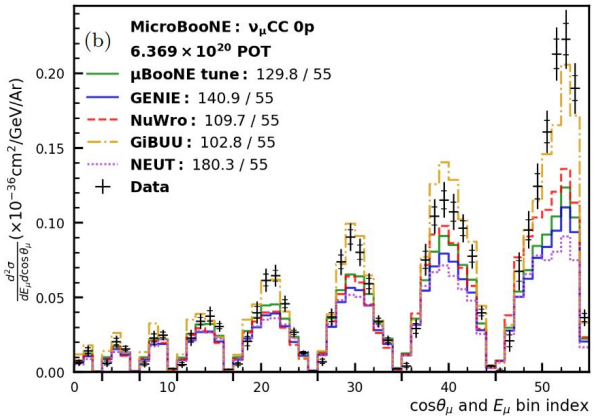
Model Name	χ^2/ndf
GENIE v2	741.1/138
MicroBooNE model	326.1/138
GENIE v3 untuned	322.2/138
GiBUU	269.9/138
NEUT	243.4/138
NuWro	212.1/138

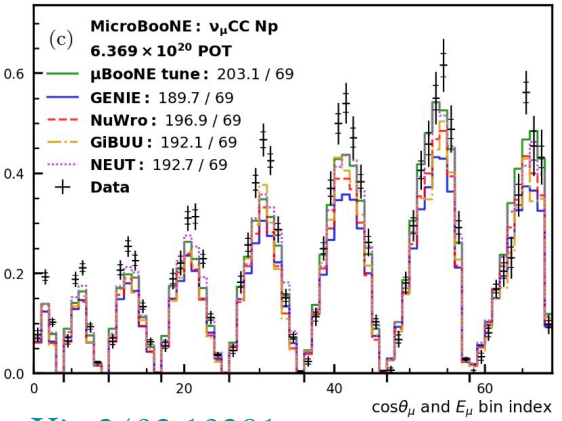


ν_μ CC0pNp Inclusive 3D

- Separates final state by number of protons
- Many cross sections measured in 1D, 2D, 3D with correlations between each reported
- GIBUU describes K_p 0p/Np split well, perhaps because of more realistic FSI model







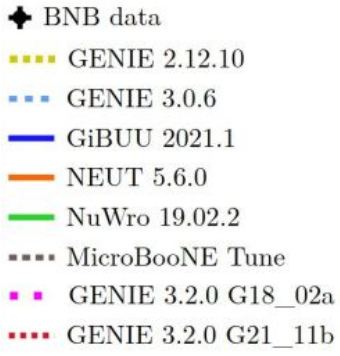
arXiv:2402.19216 arXiv:2402.19281

ν_μ CCNp0π

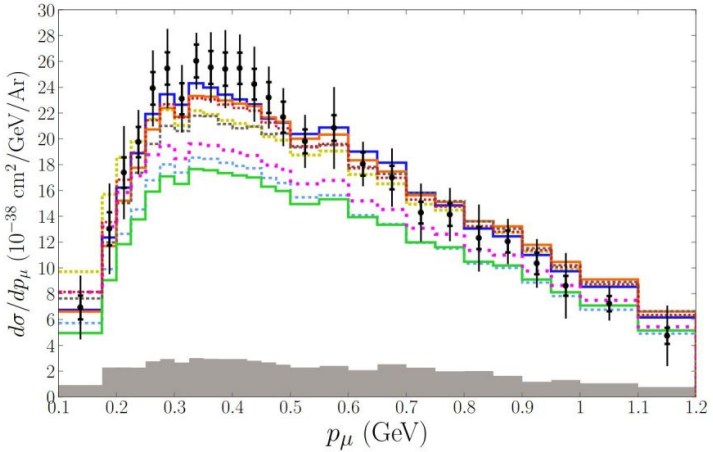
arXiv:2403.19574

- 10 observables, 14 distributions, 359 bins
  - Covariance between all bins reported
- Underprediction at low p_μ / overprediction at high p_μ
- Muon-Proton angle shape disagreement: **GiBUU** and **NEUT** perform best

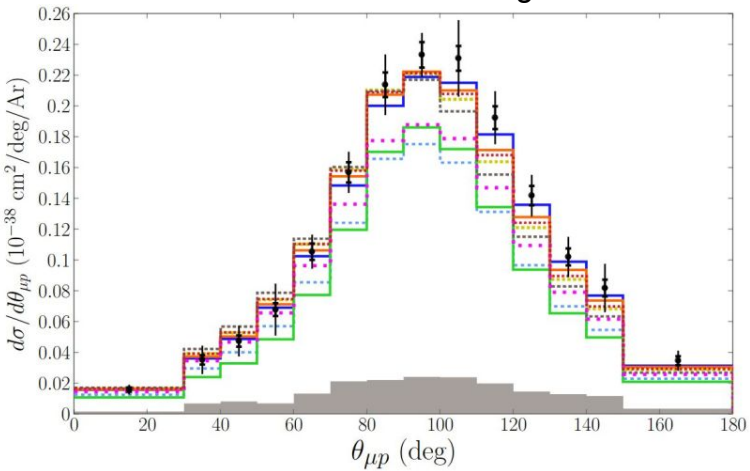
Model	χ^2 / 359 bins
GENIE 3.0.6	1859
NEUT 5.6.0	2582
MicroBooNE Tune	2673
GENIE 3.2.0 G21_11b	2947
GiBUU 2021.1	4836
NuWro 19.02.1	5315
GENIE 3.2.0 G18_02a	5724
GENIE 2.12.10	7799



Muon Momentum

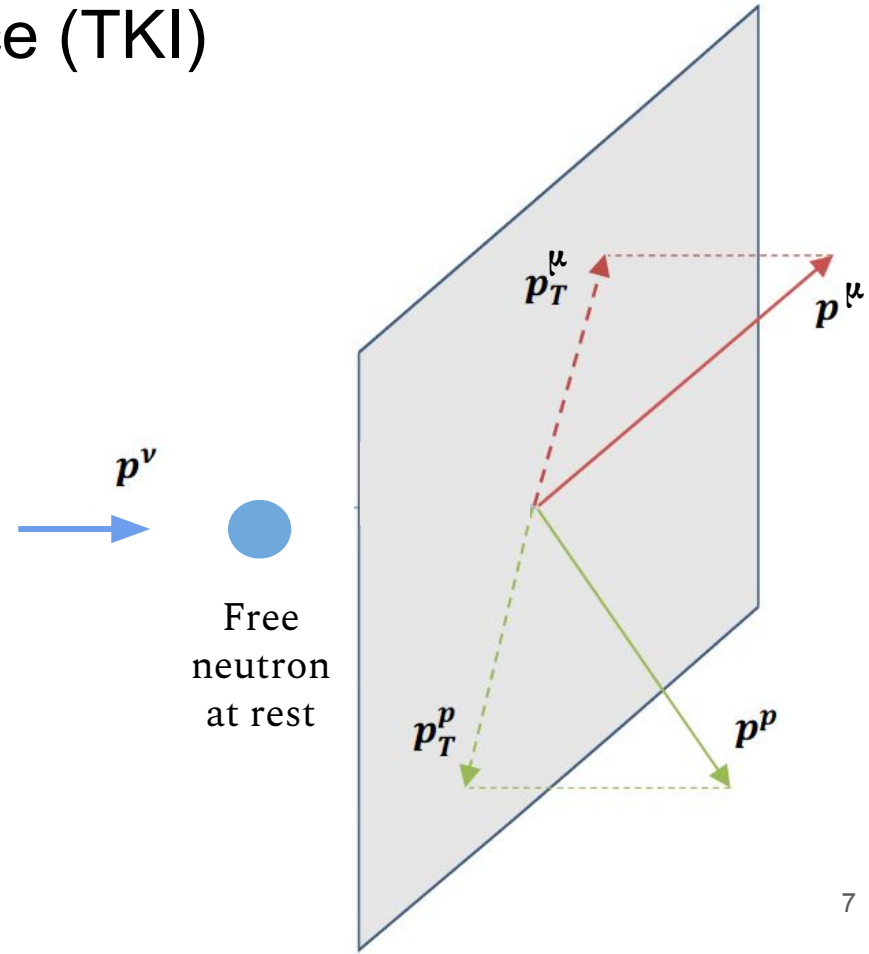


Muon-Proton Angle



Transverse Kinematic Imbalance (TKI)

- Consider interaction: ν -> μ + p
- Transverse kinematics insensitive to E_ν
- Total transverse momentum μ + p conserved before nuclear initial state and final state interactions



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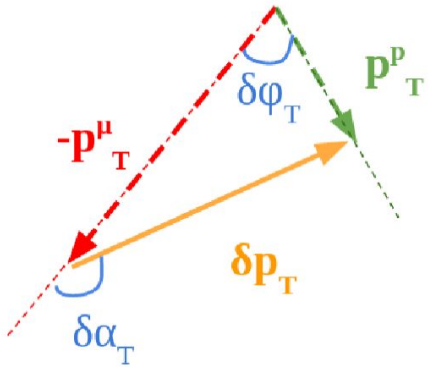
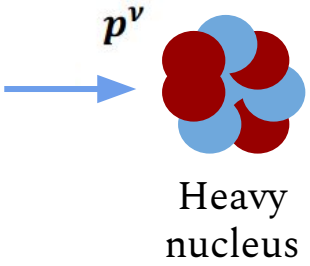
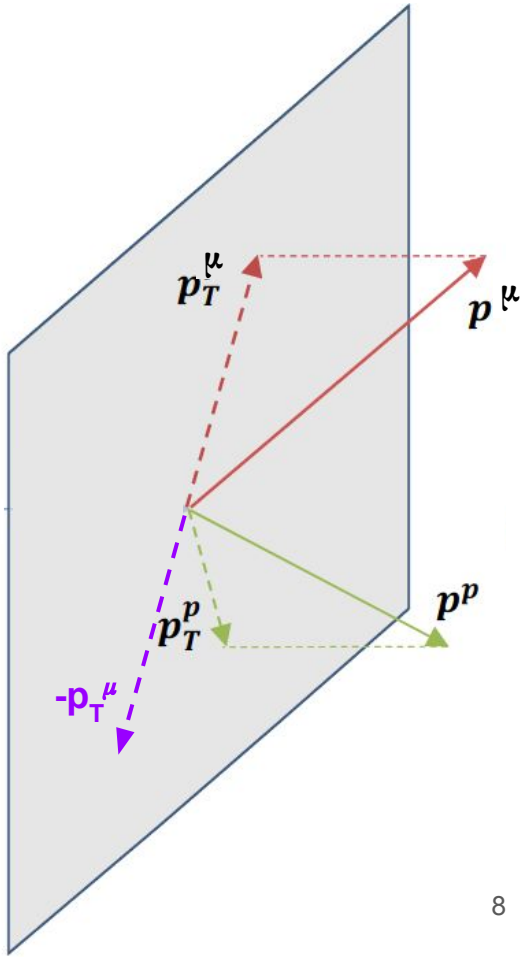
- $\delta \mathbf{p_T} = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} |$

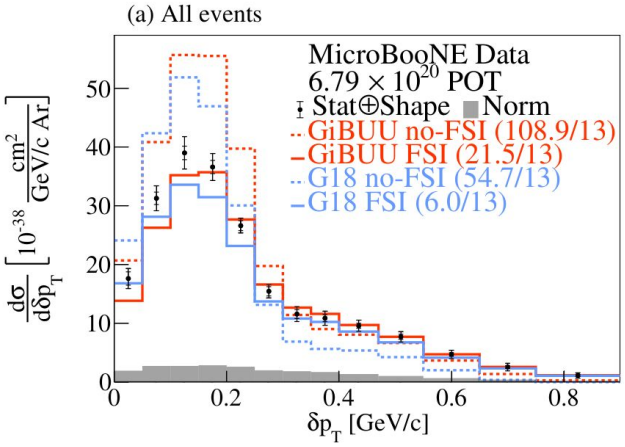


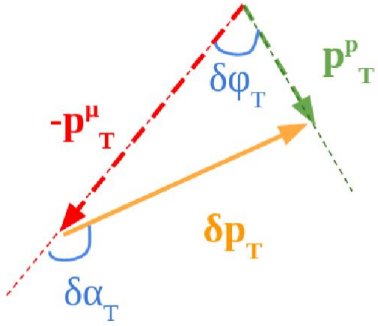




Transverse Kinematic Imbalance (TKI)

Phys. Rev. Lett. 131, 101802 (2023)
Phys. Rev. D 105, 072001 (2022)





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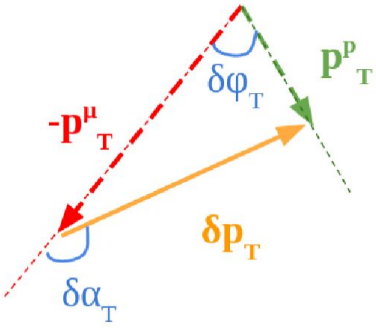
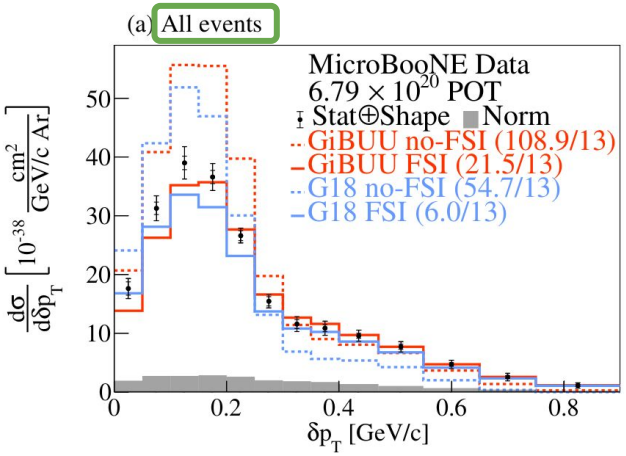
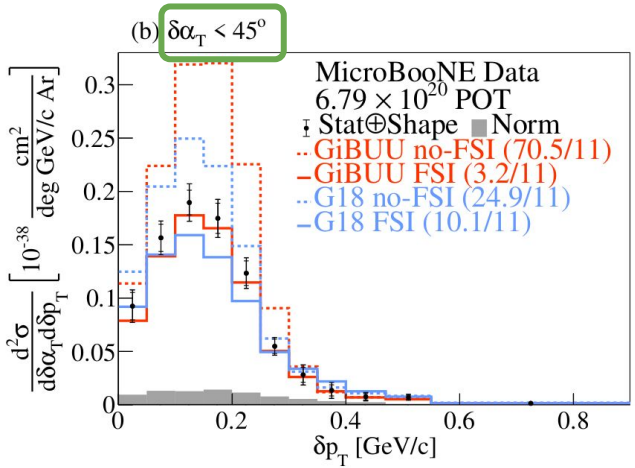
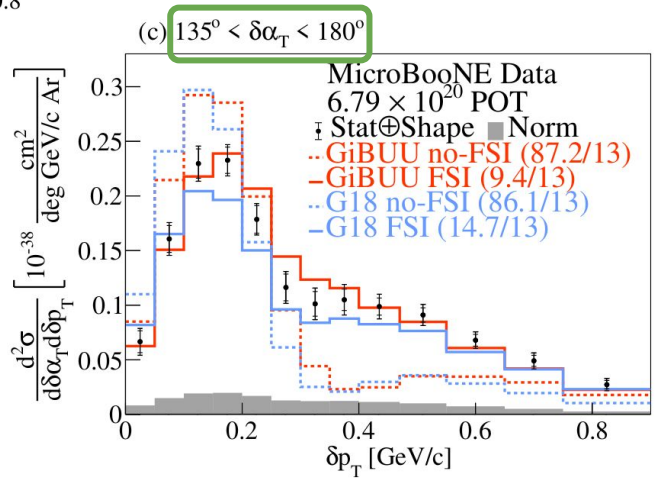


QE-dominated

MEC/RES/FSI-dominated







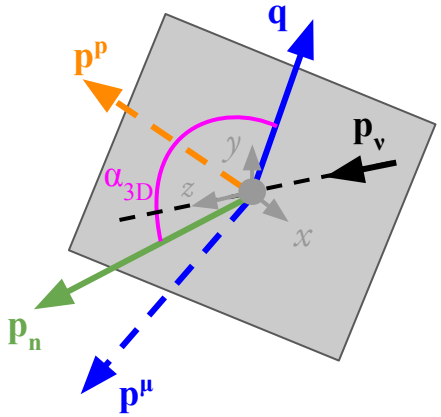
Global Kinematic Imbalance (GKI)

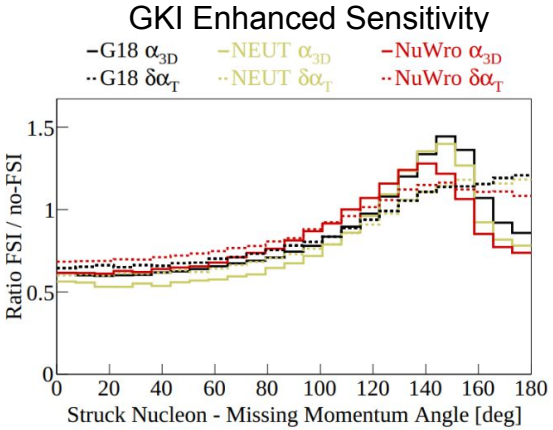
Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

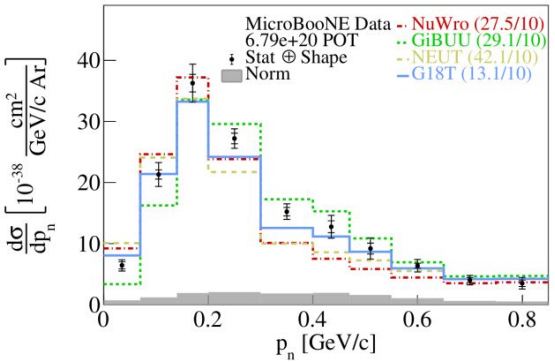
$$\vec{p}_N = \vec{p}_\mu + \vec{p}_p - E_{cal}\hat{\nu}$$

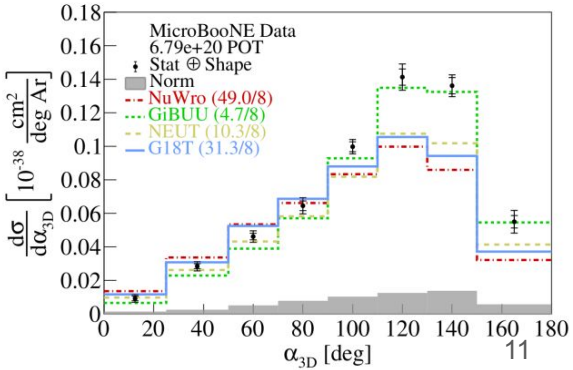
$$\alpha_{3D} = \cos^{-1}\left(\vec{q}\cdot\vec{p}_N / |q|\cdot|p_N| \right)$$

- Even larger FSI impact and model separation
- Different models preferred at different phase space regions
  - Can select for/against FSI, QE, MEC depending on region used
  - Genie does best in low-FSI regions
  - GiBUU does best in high-FSI regions





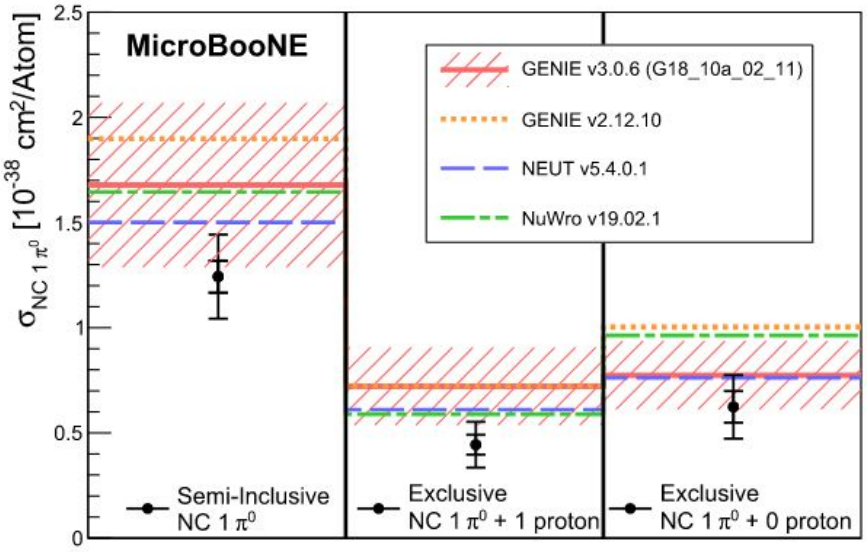




ν_μ NCπ^0 and CCπ^0

- Significant source of background
  - If one photon is missed, will enter photon and e^+e^- searches as bkg
  - Can also mimic ν_e interactions
- CCπ^0 have μ track to aid event selection and ν vertex reconstruction
- First NCπ^0 measurement on argon last year
  - NEUT model gives best prediction (χ^2/ndf = 2.4/2)
  - NuWro does well at 1p but overpredicts 0p channel (χ^2/ndf = 5.1/2)

Phys. Rev. D 107, 012004

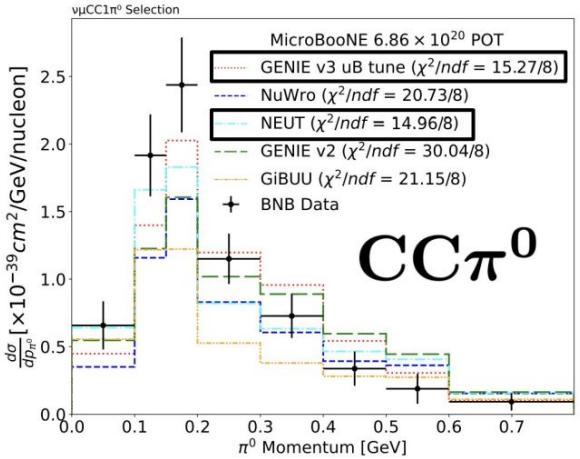


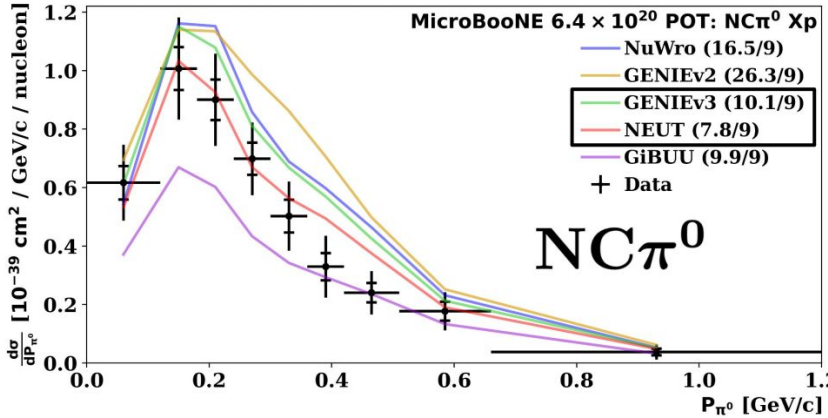
First measurement on argon!

ν_μ NCπ^0 and CCπ^0

arXiv:2404.09949
arXiv:2404.10948

- New differential measurements on NC and CC channels
  - Consistent model hierarchy between p_π measurements
  - NEUT and GENIEv3 perform best
- FSI impacts demonstrated
  - Charge exchange boosts CCπ^0 (from dominant CCπ^+)
  - Charge exchange reduces NCπ^0 (to sub-dominant NCπ^+)
  - Shifts 0p to Np





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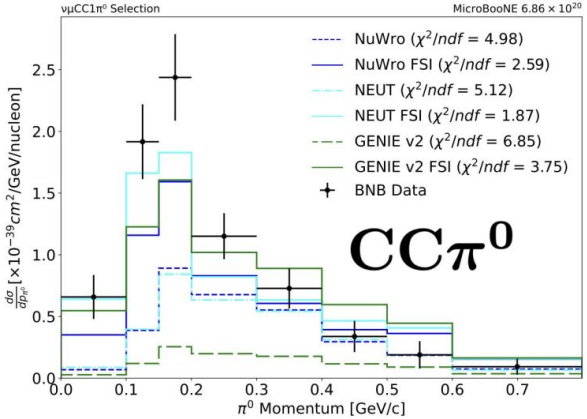

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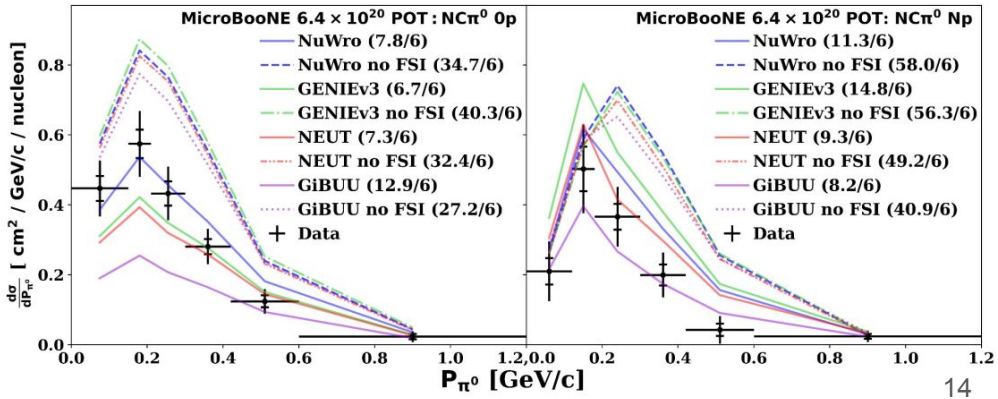
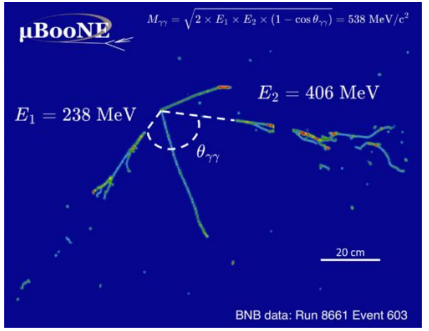
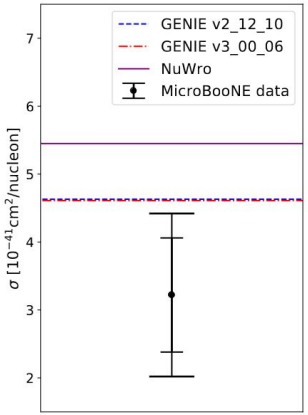


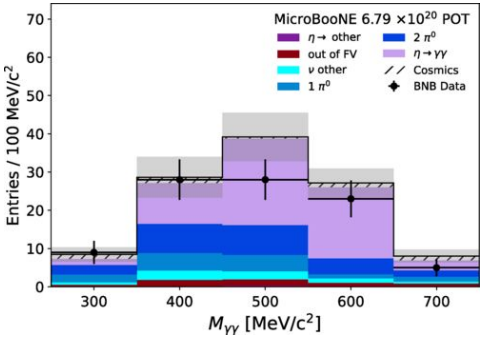
η Resonance Production

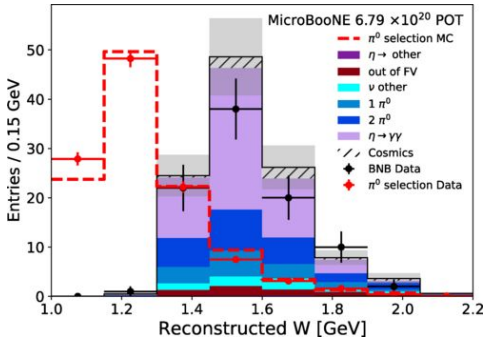
- Background to ν_e and and BSM processes
- 1-2% of DUNE ν will have η
  - 10% of RES include η
- First measurement on argon
- Calibrate EM shower reconstruction at high energies



Data deficit w.r.t. all model predictions. Genie is ~within uncertainties, NuWro is in some tension, and NEUT is rejected.



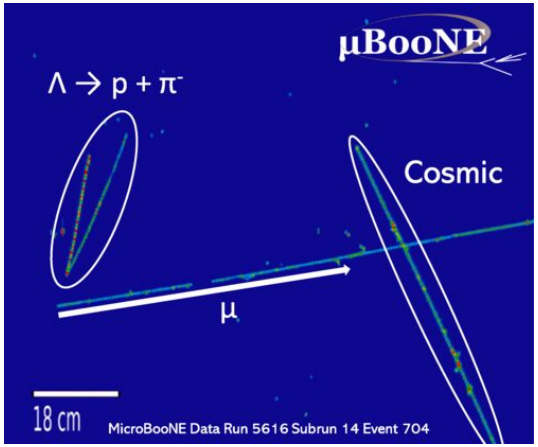




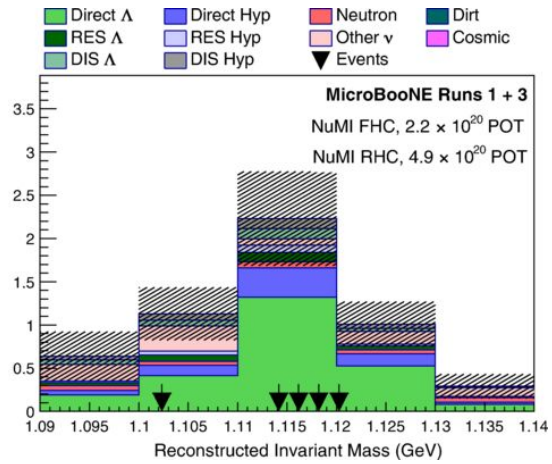
Phys. Rev. Lett. 132, 151801 (2024)

Λ Baryon Production

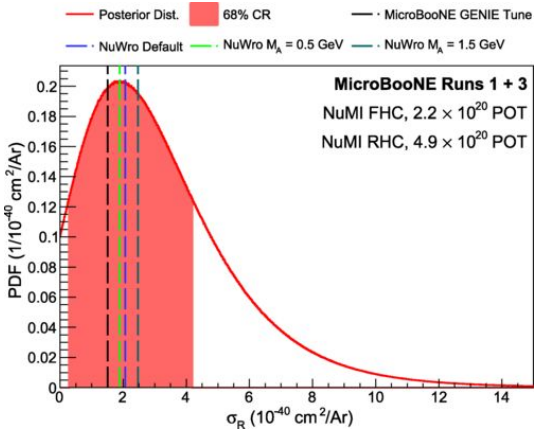
- Very rare process, 5 events observed
- Detected through Λ -> p + π^- decay (64% branch fraction)
- Measured cross section ($2^{+2.2}_{-1.7}$) consistent with Genie and NuWro predictions
- Statistics dominated, but 4x stats measurement underway



$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$



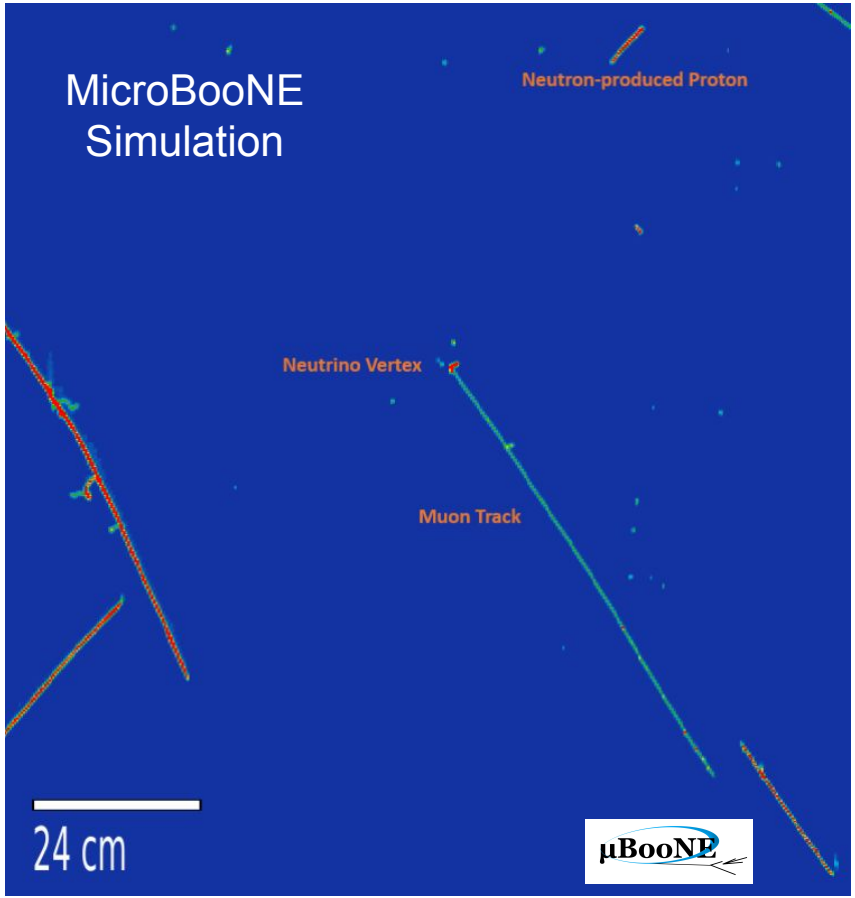
M_Λ = 1.116 GeV



Phys. Rev. Lett. 130, 231802

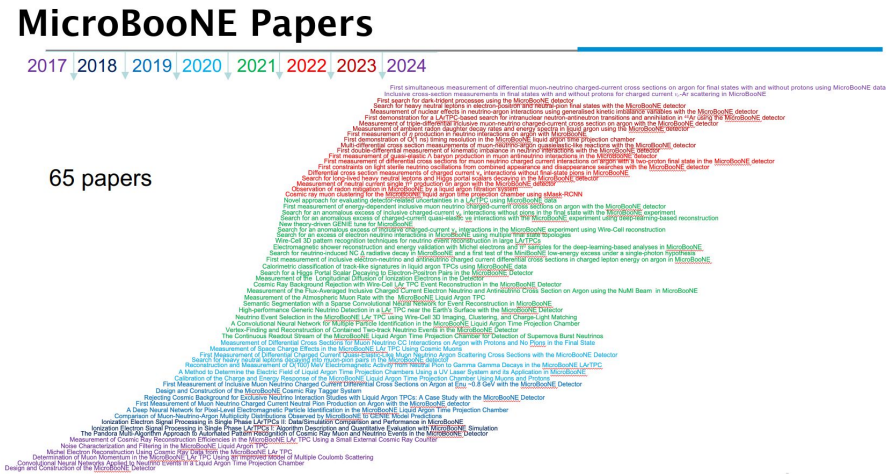
Neutron Tagging

- Neutrons contribute to missing energy, hampering E_ν reconstruction
- Detected through n + Ar -> p scattering in LAr
- First attempt at measurement on Ar
  - Most neutrons don't produce protons
  - Those that do are usually very low energy
  - Look for separated proton traveling outward from ν vertex



Summary

- MicroBooNE cross sections aid model development, especially for DUNE
- Inclusive measurements reconstruct E_ν and provide strong model discrimination
- TKI & GKI measurements give insight on final state modeling
- Neutral pion and rare process measurements help constrain background predictions
- Many more measurements in the works!



Backup

ν_μ CC Inclusive 3D

TABLE I. Comparisons between various models and the unfolded three-dimensional measurement within each E_ν slice.

Model Name	Total χ^2/ndf	[0.2, 0.705] GeV χ^2/ndf	[0.705, 1.05] GeV χ^2/ndf	[1.05, 1.57] GeV χ^2/ndf	[1.57, 4.0] GeV χ^2/ndf
GENIE v2	741.1/138	71.4/28	64.4/35	64.3/42	35.6/33
MicroBooNE model	326.1/138	85.0/28	77.8/35	44.6/42	31.9/33
GENIE v3 untuned	322.2/138	94.1/28	84.8/35	52.2/42	37.3/33
GiBUU	269.9/138	33.8/28	54.8/35	52.6/42	31.0/33
NEUT	243.3/138	58.5/28	59.9/35	43.1/42	38.2/33
NuWro	212.1/138	54.8/28	67.3/35	40.9/42	29.6/33