First Measurements of Differential Cross Sections in Kinematic Imbalance Variables with the MicroBooNE Detector

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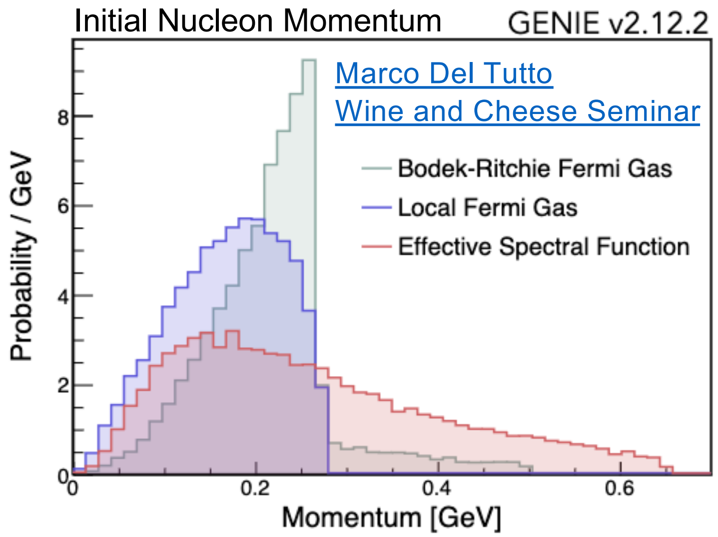
On behalf of the MicroBooNE Collaboration

New Perspectives - 8th July 2024

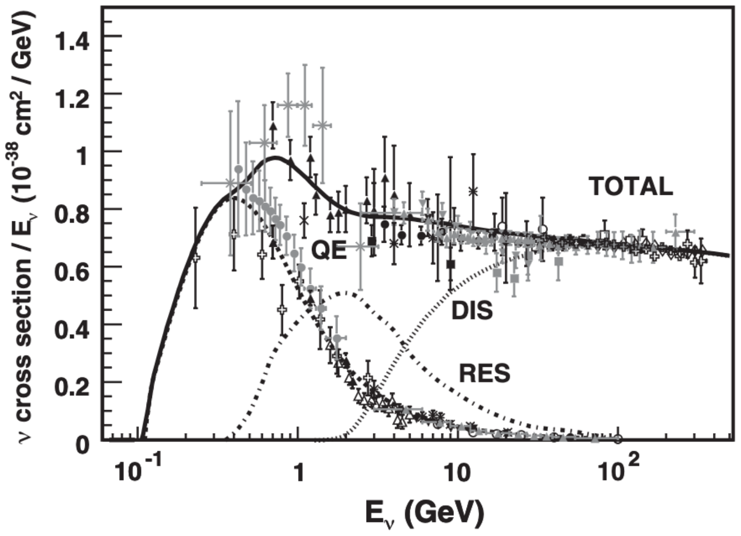
FERMILAB-SLIDES-24-0144-PPD

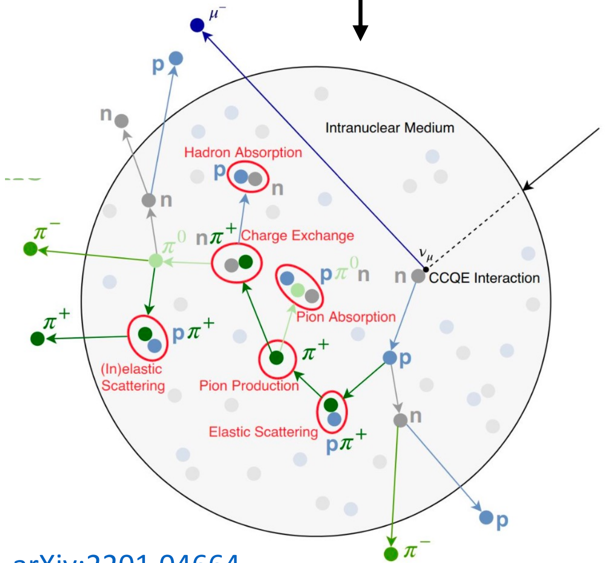
Neutrino Interaction Modeling Challenge

- Broad range of neutrino fluxes
- Many known unknowns that must be accurately simulated:
  - Ground states, Fermi motion
  - Neutrino interaction mechanisms
  - Final state interactions (FSI)
  - …

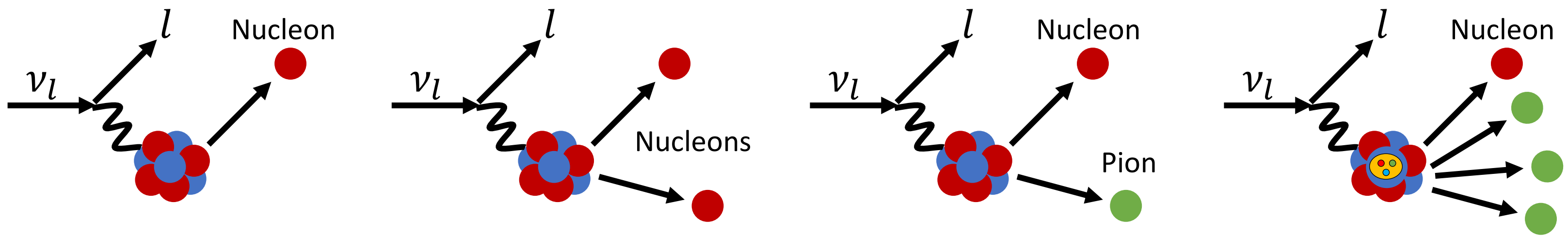


[Rev. Mod. Phys. 84, 1307 (2012)](#)





[arXiv:2201.04664](#)



Quasi-elastic (QE)

Meson Exchange Current (MEC)

Resonance (RES)

Deep Inelastic Scattering (DIS)

E_ν

Double-Differential Single-Proton Xsec

- Mismodeling can limit experimental sensitivity.
  → Issue for future flagship experiments like DUNE.
- Can use the MicroBooNE detector to set constraints:
  - First double-differential single-proton cross section measurement on argon.
  - 1μ1p final state – Charged Current Quasi-elastic (CCQE) interactions.
  - Dominant at MicroBooNE energies.
  - Uses ~ 50% of available dataset and the Booster Neutrino Beam (BNB) at Fermilab.
  - Regions of phase-space identified that are sensitive to nuclear effects (Fermi motion & FSI) using kinematic imbalance variables.

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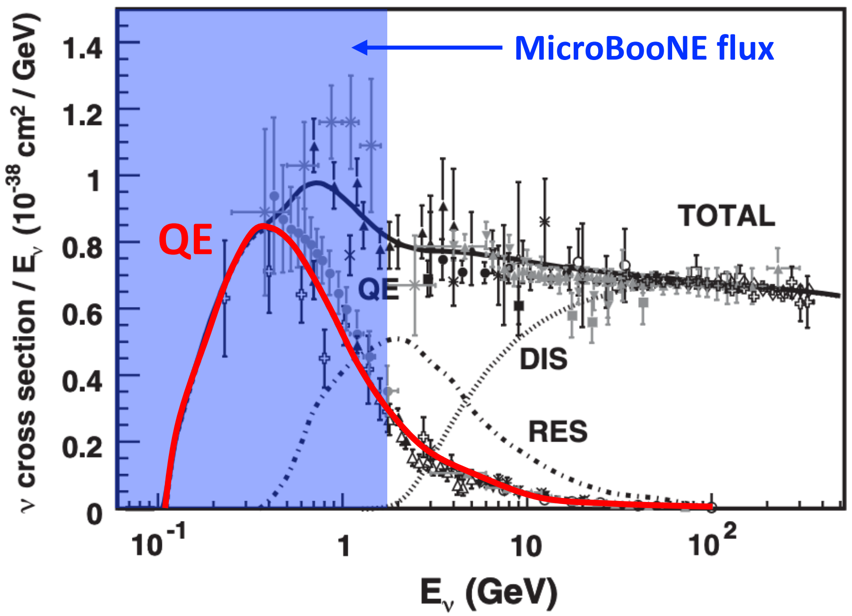
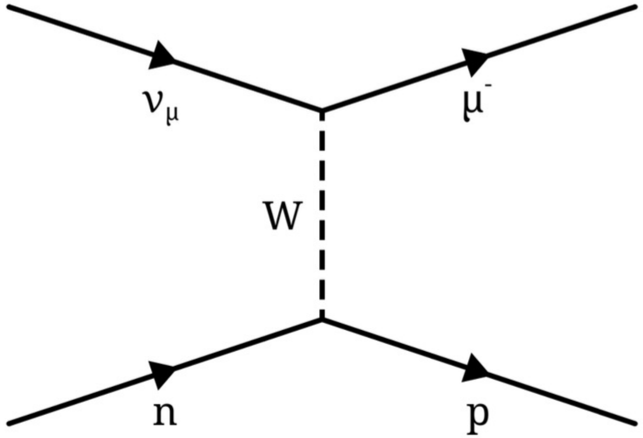




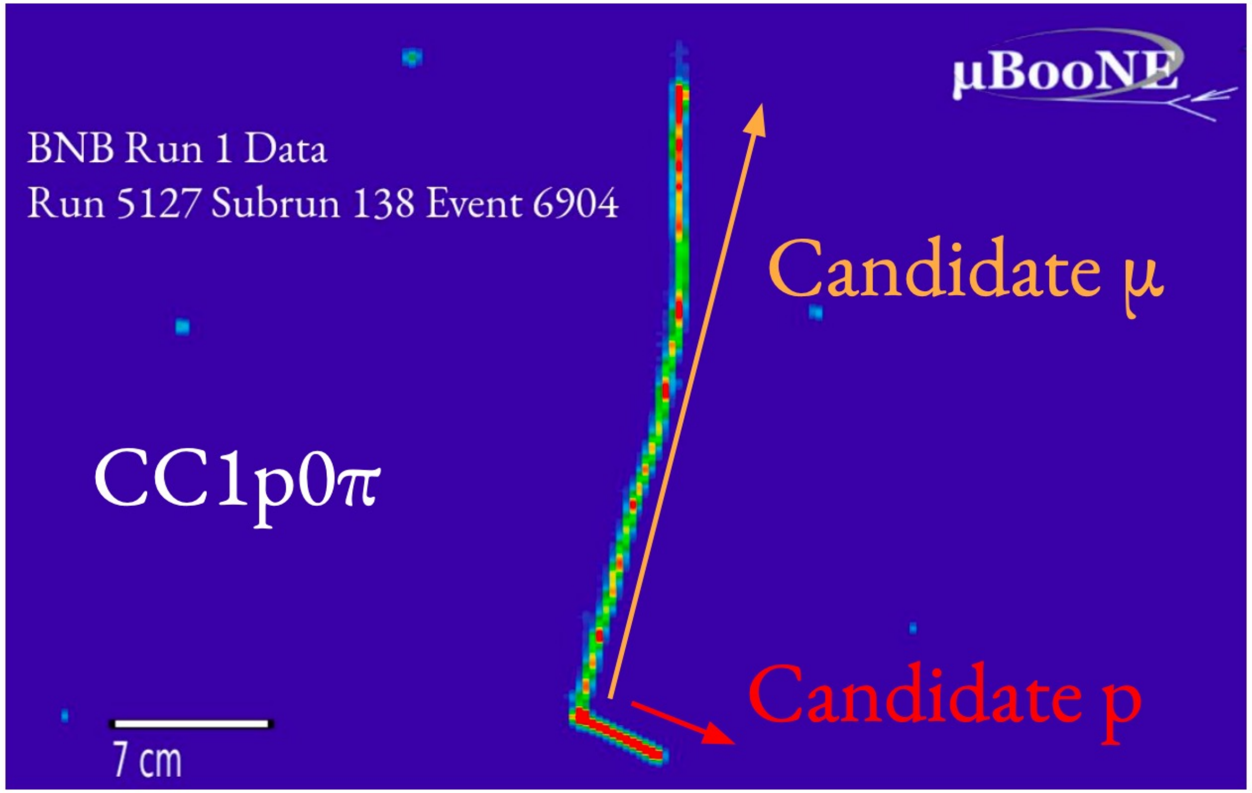
Phys. Rev. Lett. 131, 101802 (2023)
Phys. Rev. D 108, 053002 (2023)
Phys. Rev. D 109, 092007 (2024)

CC1μ1p0π QE-like Signal Definition

- 1 muon

  $1 < P_\mu < 1.2\ GeV/c$
- 1 proton

  $0.3 < P_p < 1\ GeV/c$
- No $\pi^\pm$ with momentum $P_\pi > 70\ MeV/c$
- No π^0 or heavier mesons
- Any number of neutrons



9051 CC1μ1p0π candidate data events

~ 10% efficiency

~ 70% purity

Phys. Rev. Lett. 131, 101802 (2023)
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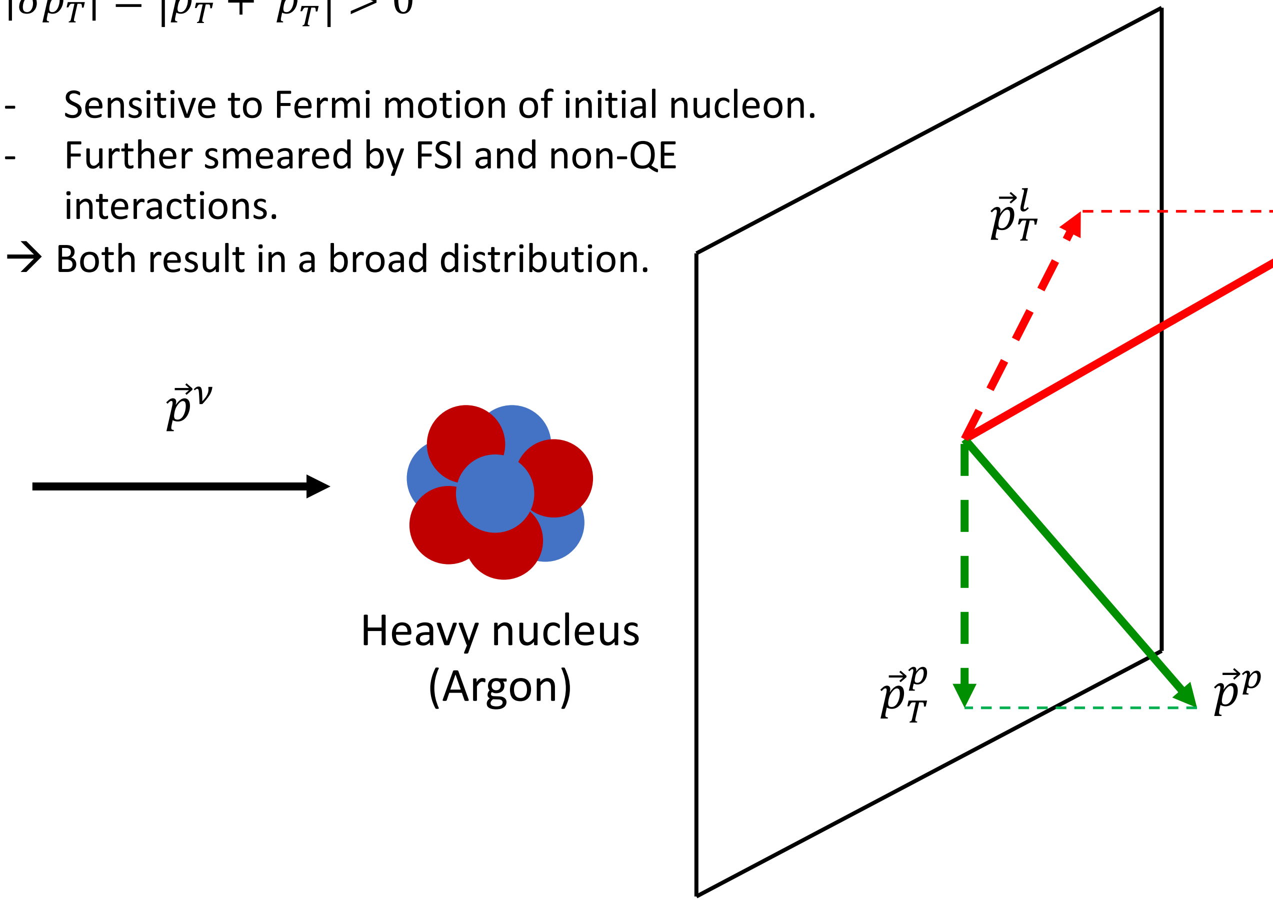
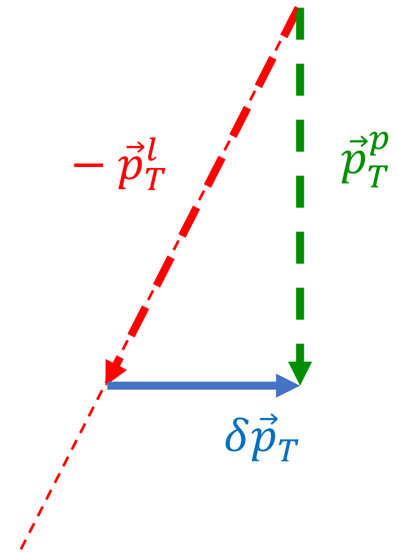
Transverse Kinematic Imbalance (TKI)

Transverse missing momentum
$|\delta\vec{p}_T| = |\vec{p}_T^{\,l} + \vec{p}_T^{\,p}| > 0$

- Sensitive to Fermi motion of initial nucleon.
- Further smeared by FSI and non-QE interactions.

→ Both result in a broad distribution.





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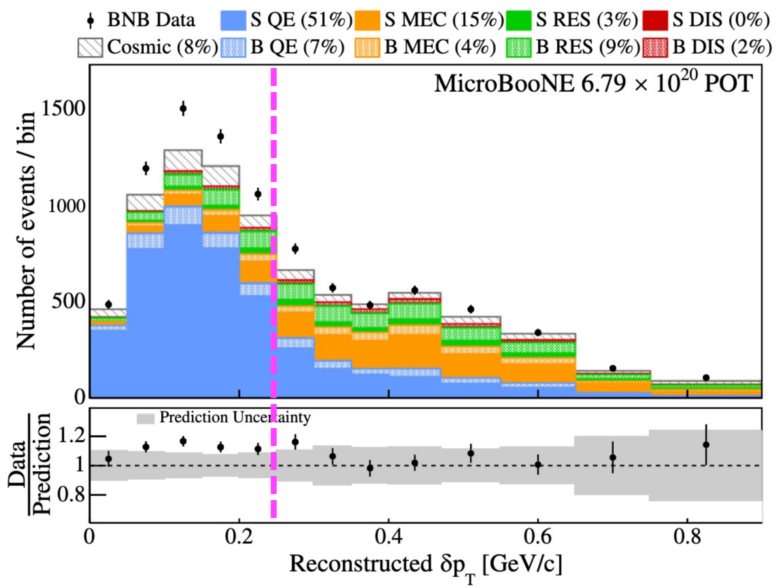


- S=Signal, B=Background
- QE dominance in peak below Fermi motion (~250 Mev/c).
- MEC/RES in high momentum tail.

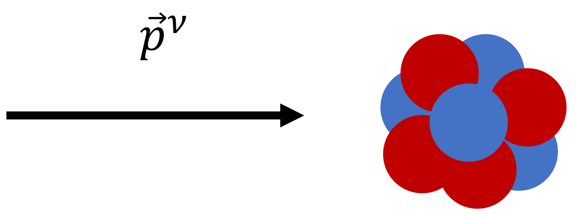
Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)

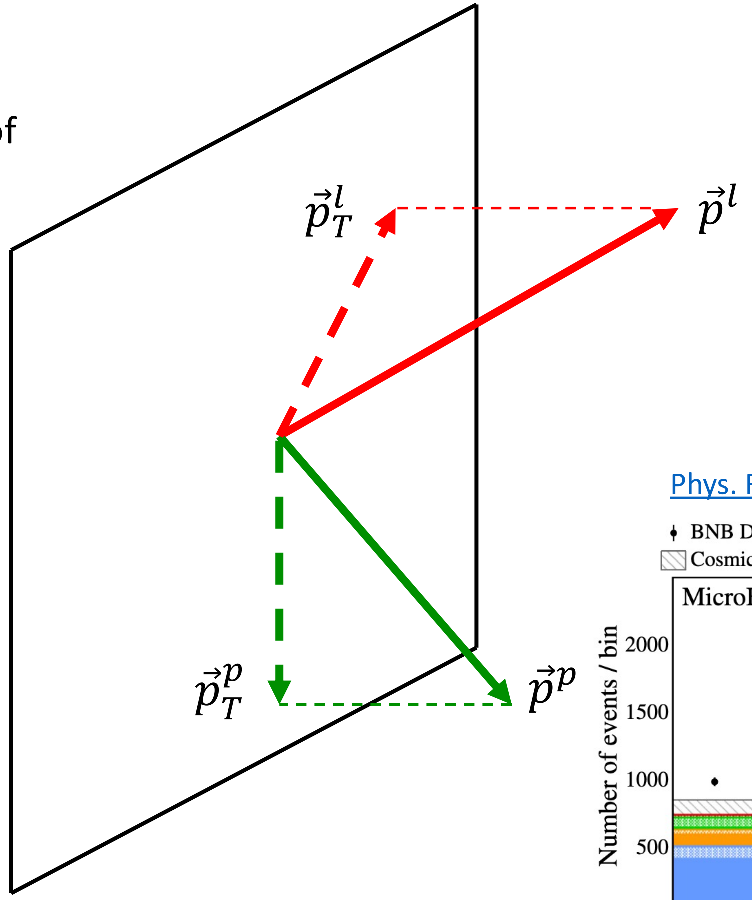
The direction of the imbalance is sensitive to FSI.

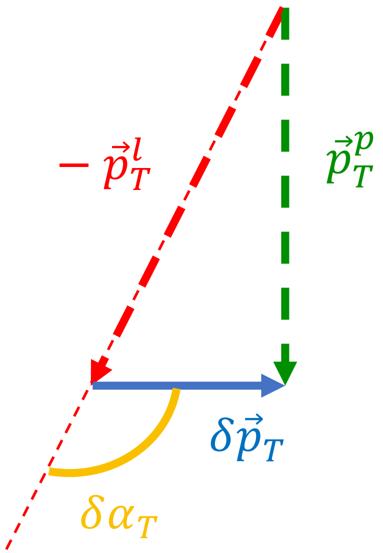
$\delta\alpha_T = \cos^{-1}\left(\frac{-\vec{p}_T^{\,l} \cdot \delta\vec{p}_T}{|\vec{p}_T^{\,l}||\delta\vec{p}_T|}\right)$

- Uniform distribution in the absence of FSI due to isotropic nature of Fermi motion.
- With FSI, proton momentum $\vec{p}_T^{\,p}$ reduces, so $\delta\alpha_T$ increases.

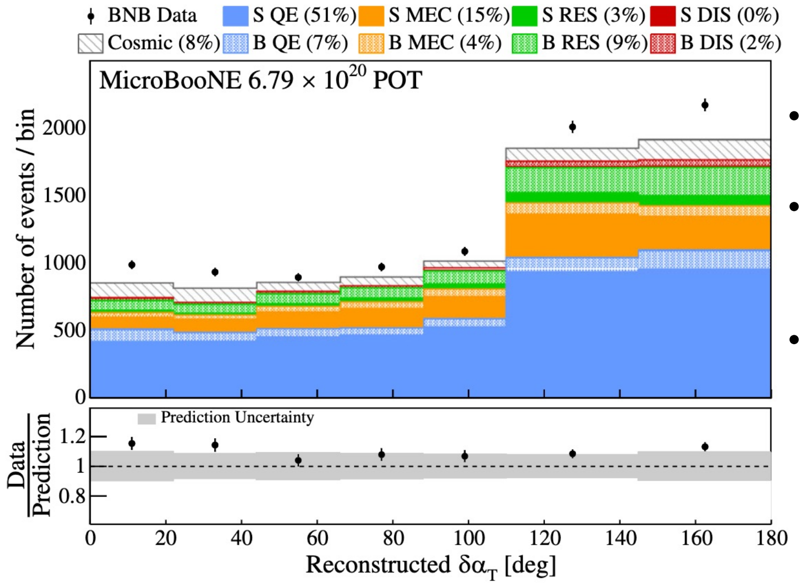


Heavy nucleus (Argon)





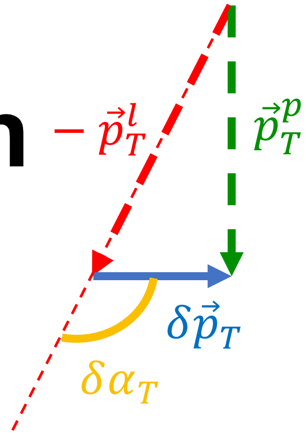
[Phys. Rev. D 108, 053002 (2023)]



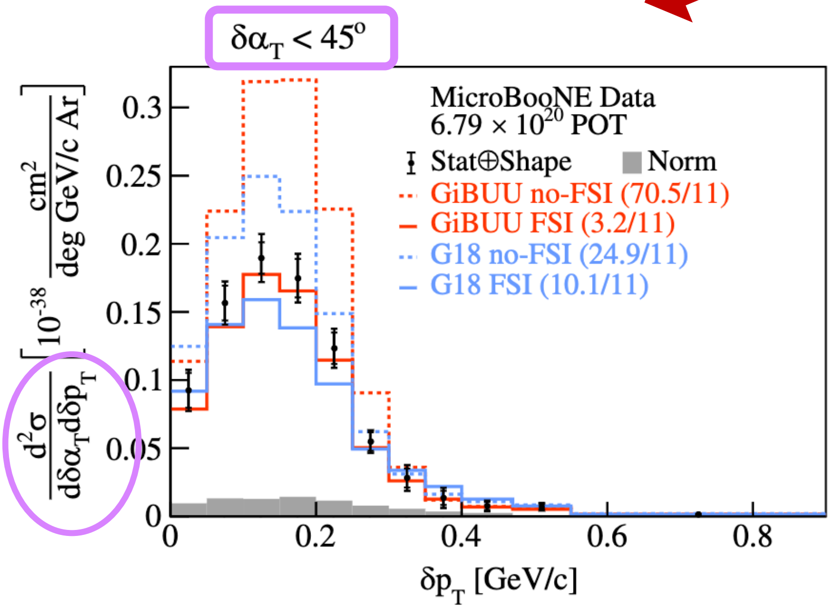
- S=Signal, B=Background
- Distribution is weighted towards 180° due to FSI.
- Increased fractional contribution from MEC/RES in ~180 ° region.

[Phys. Rev. C 94, 015503 (2016)]

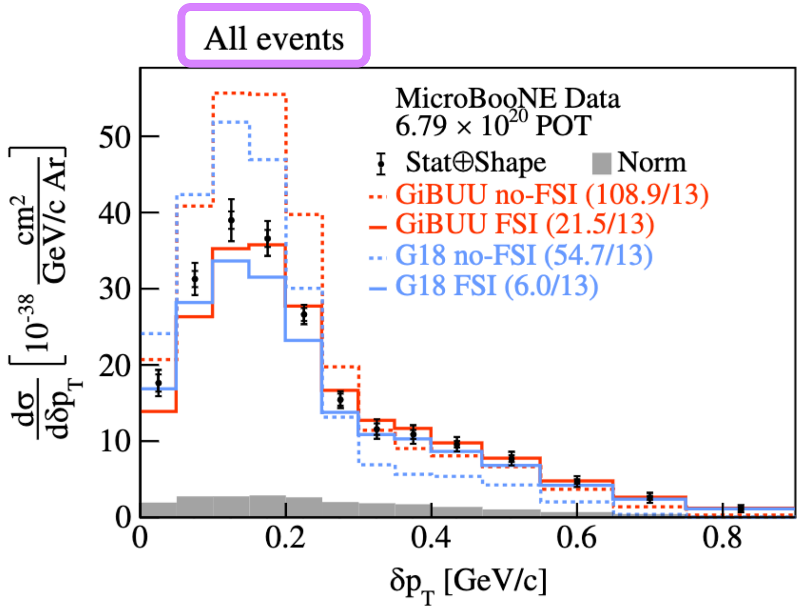
Double-Differential CC1μ1p0π Cross Section



QE-dominated



- No high $\delta\vec{p}_T$ tail – minimal FSI.
- Ideal region of phase-space to study Fermi motion.
- Results are consistent with the local Fermi gas distribution.



- FSI reduces the strength of the peak.
- Small changes in the tail.
- Data favours FSI predictions.

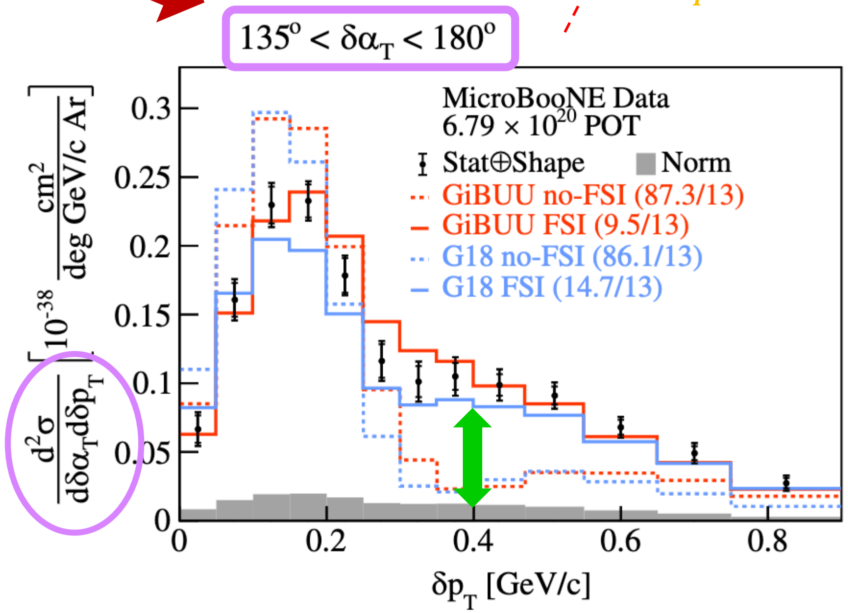
G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

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

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

MEC/RES/FSI - dominated



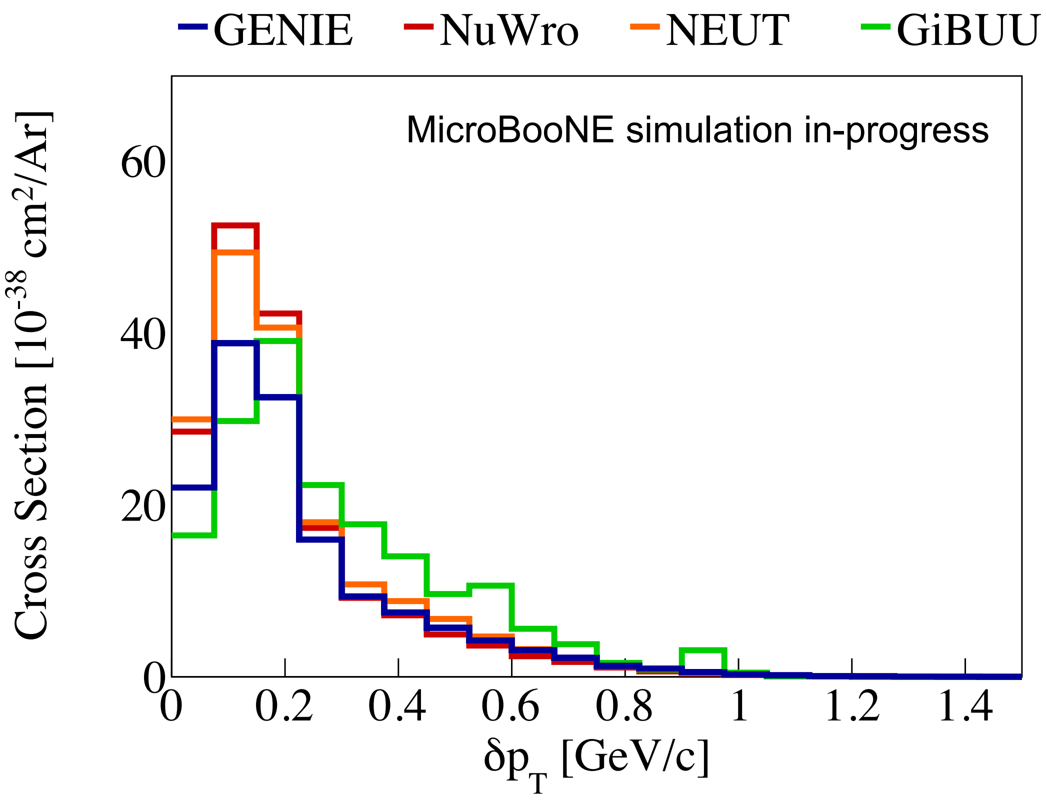
- FSI predictions in good agreement with data.
- The “no-FSI” predictions are minimal at high $\delta\vec{p}_T$.
- High $\delta\vec{p}_T$ and high $\delta\alpha_T$ phase-space is ideal to test FSI.

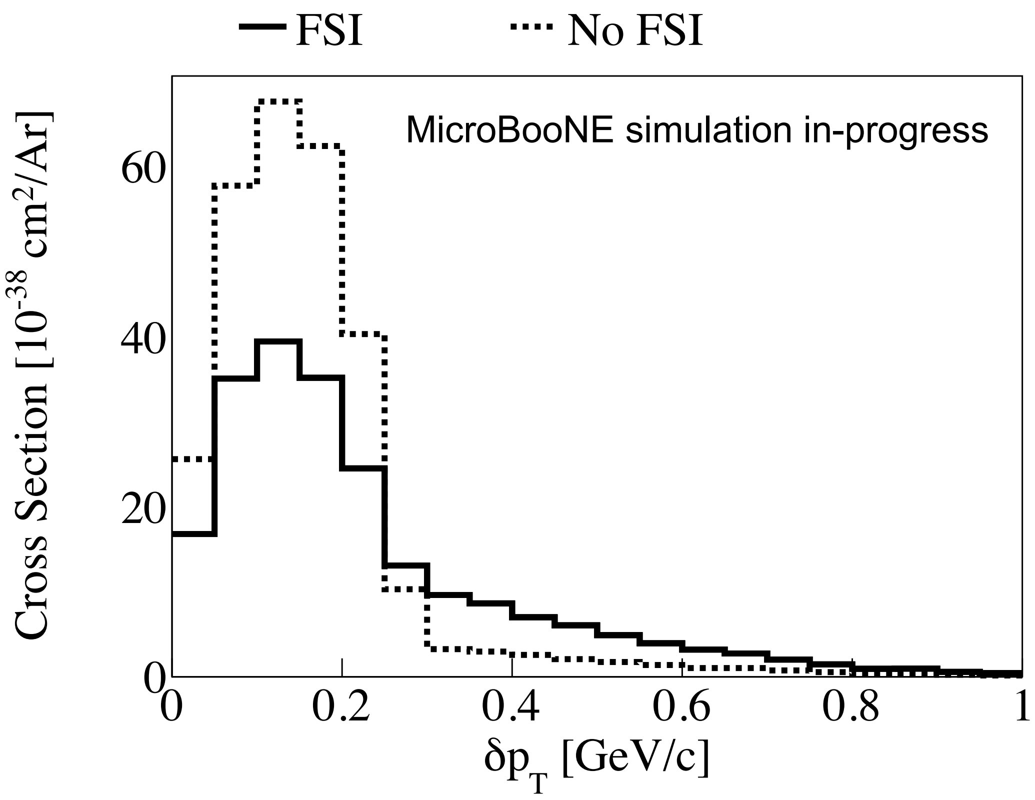
Complementary Ongoing Analysis: CC1e1p0π

- Similar ongoing cross section analysis with ν_e.

→ the appearance channel for oscillation studies!

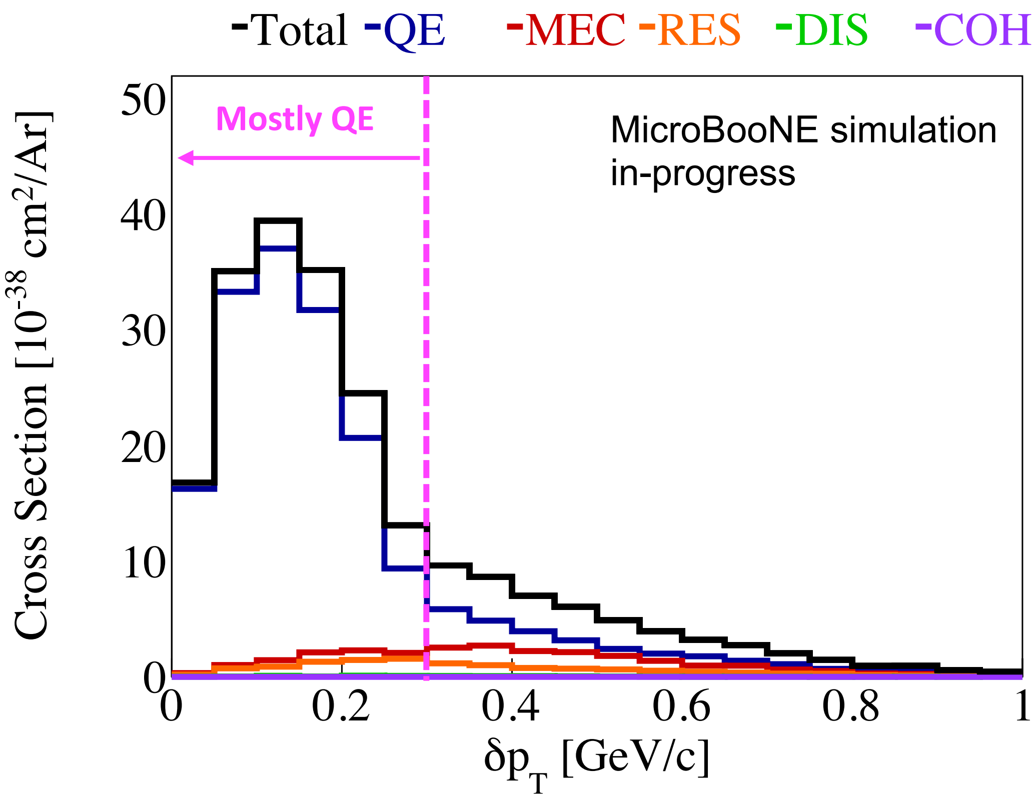
- Searching for 1e1p final states → QE-like interactions.

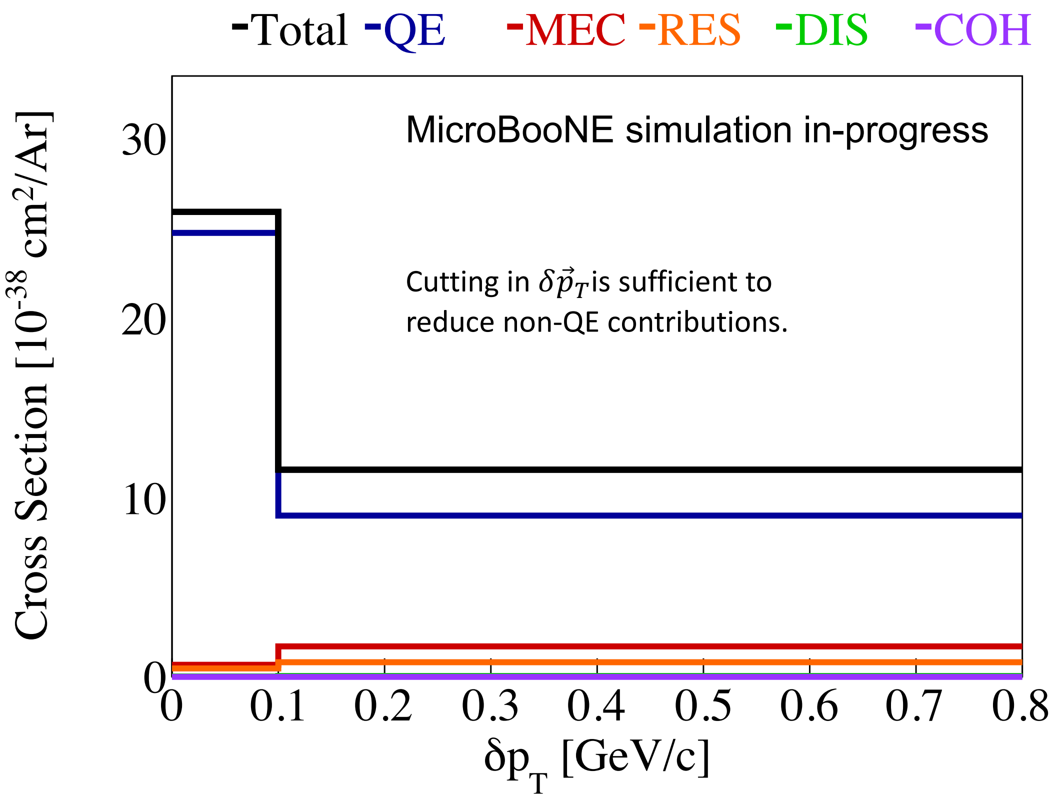




Complementary Ongoing Analysis: CC1e1p0π

- Interesting regions of QE-dominated phase-space identified using TKI truth variables:
  - Cross section measurement in such a “non-FSI region” is likely to yield small uncertainties.
  - Can we leverage this to perform an oscillation analysis and to reduce the overall systematic uncertainty?

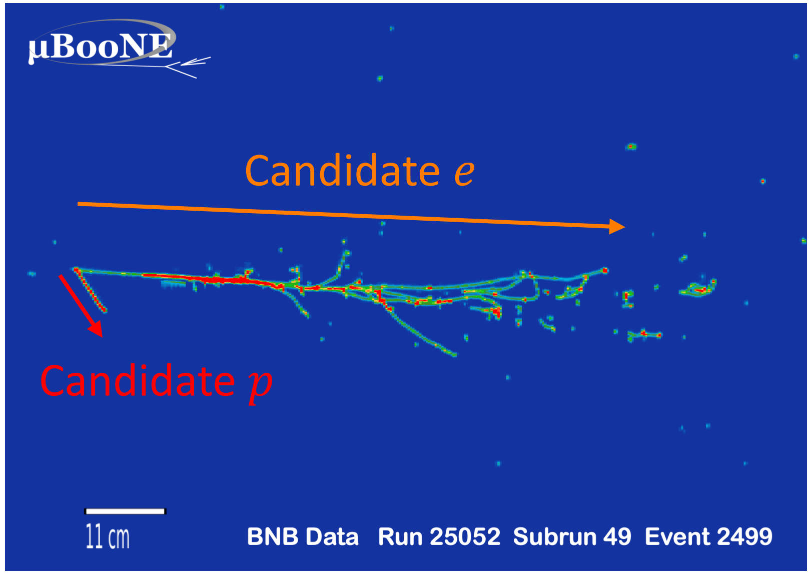




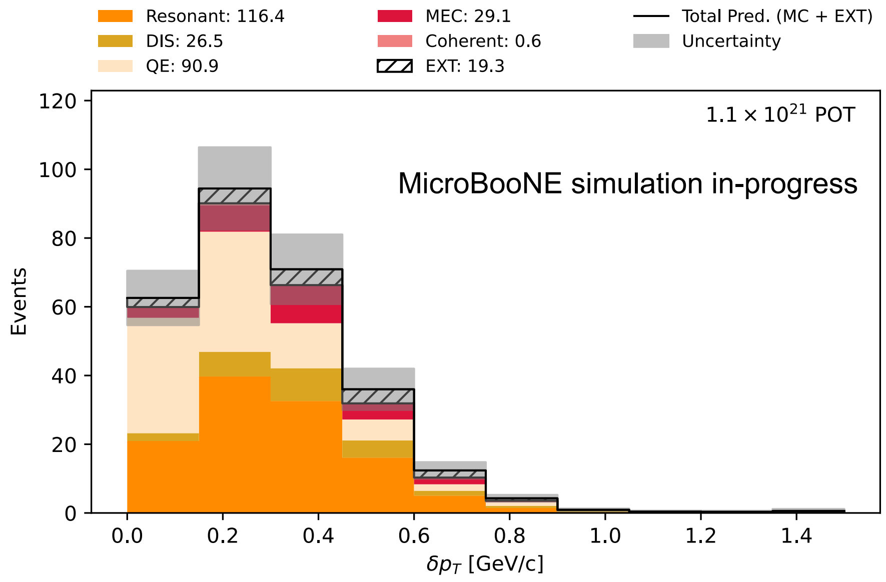
CC1e1p0π Signal Definition & Reco Selection

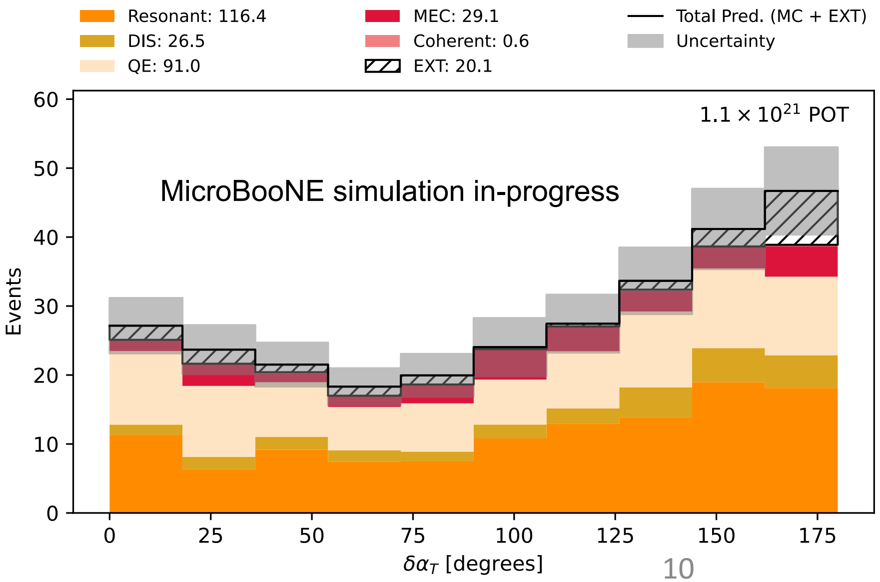
- 1 electron
- 1 proton

  $P_p > 0.3\ GeV/c$
- No $\pi^{\pm}$ with momentum $P_\pi > 70\ MeV/c$
- No π^0 or heavier mesons
- Any number of neutrons



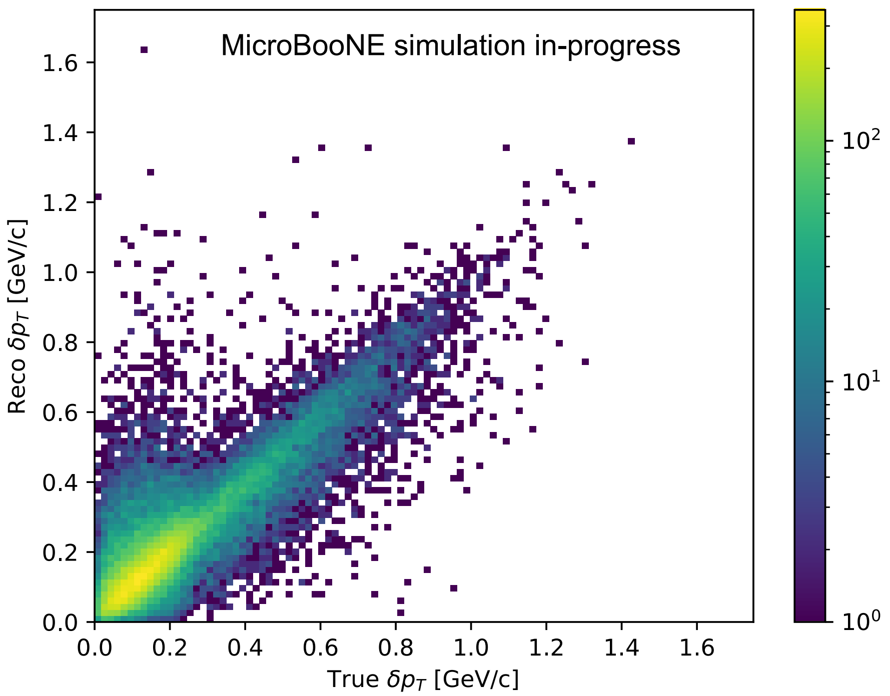
- More RES events passed the selection cuts than expected.
  → Still under investigation.
- The reco selections cuts are still being finalised.
- Purity ~ 28.12%
- Efficiency ~ 24.37%

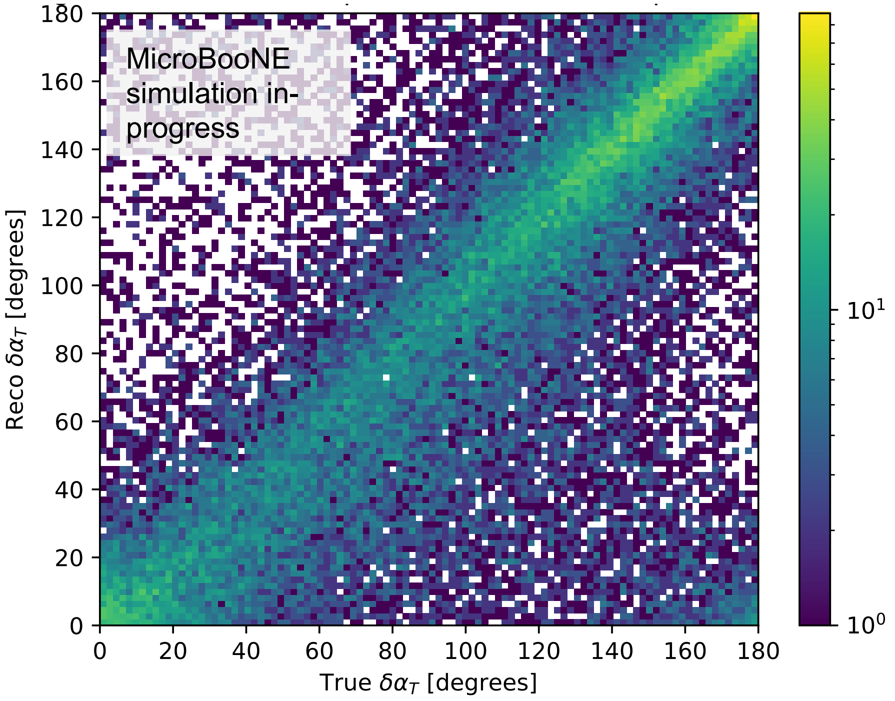




CC1e1p0π Resolution Study

- Need sufficient resolution (and enough statistics) to perform an oscillation measurement → especially for the electron showers (harder to reconstruct).
- The resolution plots below (using true CC1e1p0π events) for $\delta\vec{p}_T$ and $\delta\alpha_T$ look promising.
- Will change slightly once the reco selection is finalised.





Summary

- First CC1μ1p0π single- and double- differential neutrino-argon cross section measurements in TKI.
- Results identified phase-space regions sensitive to Fermi motion and FSI, separating their effects.
- Many more single- and double- differential results in Phys. Rev. Lett. 131, 101802 (2023) and Phys. Rev. D 108, 053002 (2023)
- Presented an ongoing complementary analysis with ν_e: CC1e1p0π.
- Identified QE-dominated regions of phase-space in TKI variables for CC1e1p0π.
  - There is a possibility of extending this to using Generalized Kinematic Imbalance (GKI) variables, which have greater model discrimination power (Phys. Rev. D 109, 092007 (2024)). See backups.
- Resolution and reconstruction studies are underway to see if an oscillation measurement can be performed in these “non-FSI” regions and reduce the overall systematic uncertainty.

Thank you

The MicroBooNE Collaboration

Backup Slides

Purity and Efficiency Definitions

- $purity = \frac{S}{S+B}$, where:
  - S is no. of selected signal events
  - B is no. of selected background events

- $efficiency = \frac{S}{S_T}$, where:
  - S_T is total no. of signal events

Generalized Kinematic Imbalance Variables (GKI)

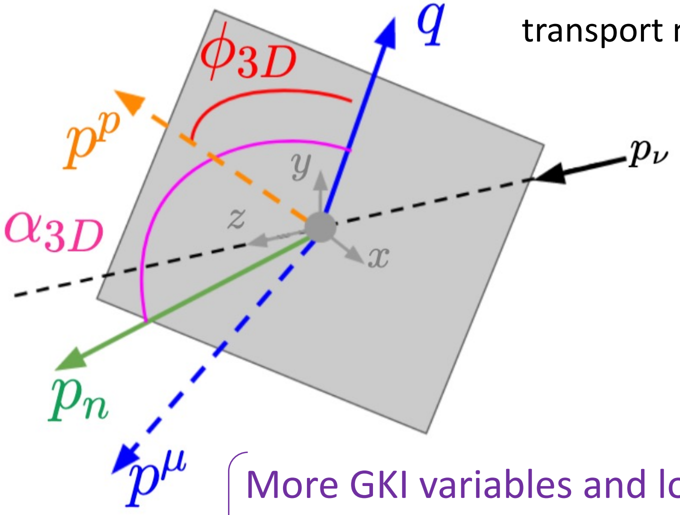
- arXiv:2310.06082 - Novel technique, which is an extension to 3D by considering the longitudinal component of missing momentum p_L and calorimetric assumption on the incoming energy E_{cal} (using the CC1μ1p0π channel).
- Assumptions on the incoming ν kinematics:
  1. $\vec{p}_T^{\,\nu} = 0$
  2. Visible energy $E_{cal} \approx |\vec{p}^{\,\nu}|$

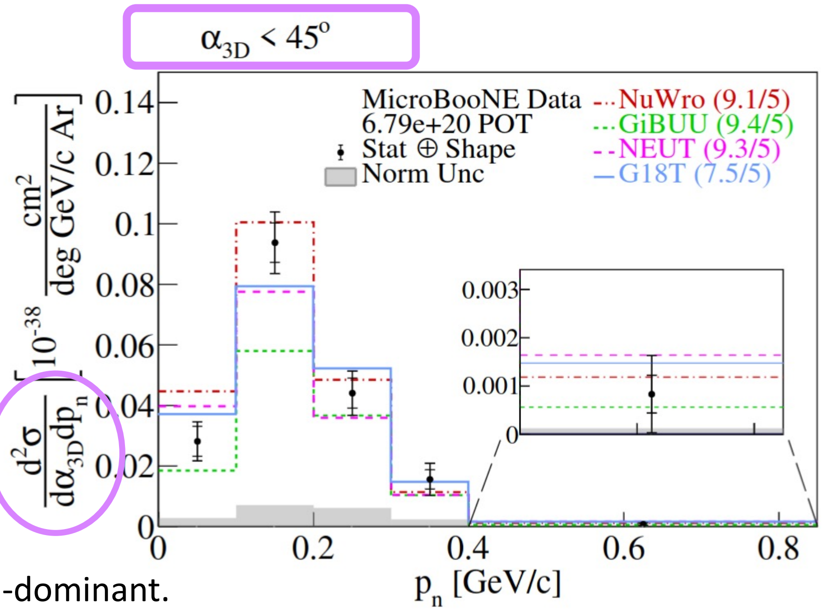
  } So any deviations are signs of nuclear effects/FSI.

$$E_{cal} = E_\mu + K_p + B$$
$$p_L = p_L^\mu + p_L^p - E_{cal}$$
$$\vec{q} = E_{cal}\hat{z} - \vec{p}^{\,\mu}$$

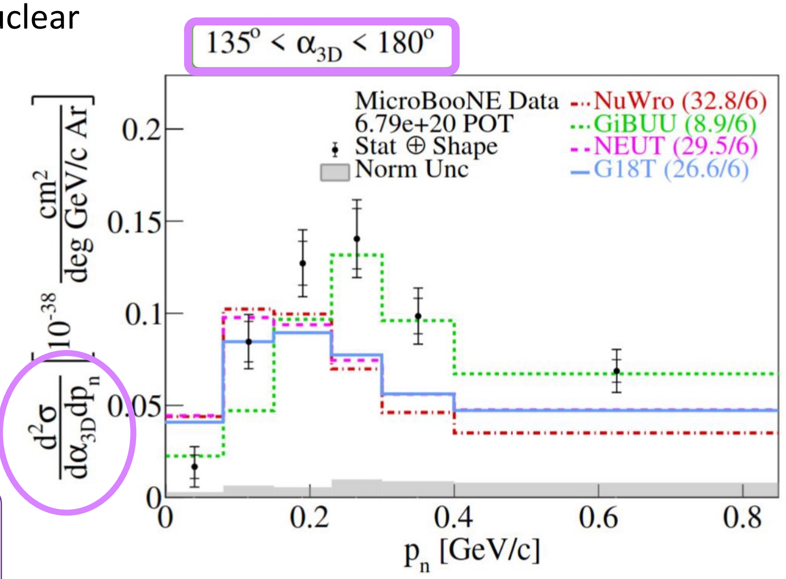
E_μ - total muon energy
K_p - proton kinetic energy
B – argon removal energy

$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2}$$
$$\phi_{3D} = \cos^{-1}\left(\frac{-\vec{q}\cdot\vec{p}_p}{|\vec{q}||\vec{p}_p|}\right)$$
$$\alpha_{3D} = \cos^{-1}\left(\frac{-\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right)$$





GENIE is best when FSI is non-dominant.
GiBUU has a sophisticated nuclear transport model.



GKI variables encode more information
→ Greater model discrimination power.

More GKI variables and lots more results in Phys. Rev. D 109, 092007 (2024).