Neutrino Interaction Physics at MicroBooNE

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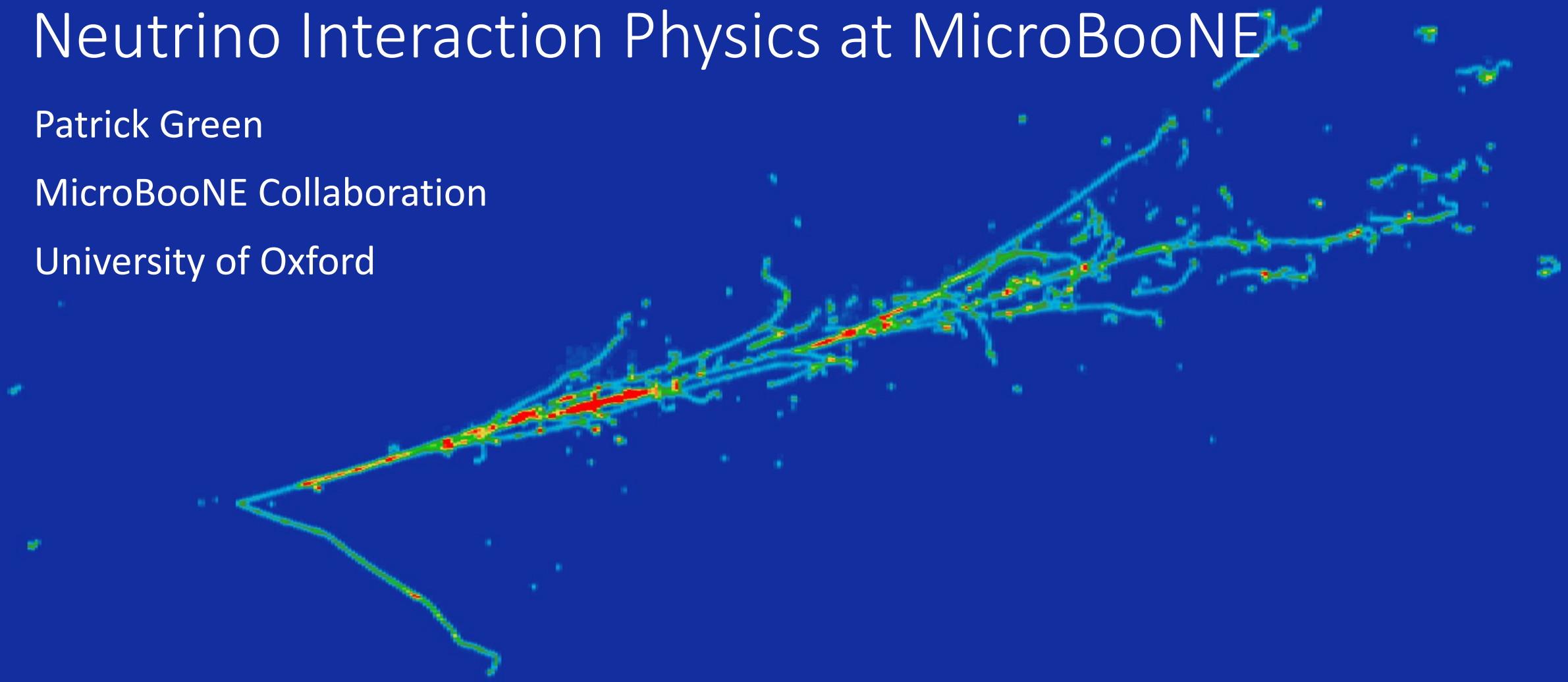
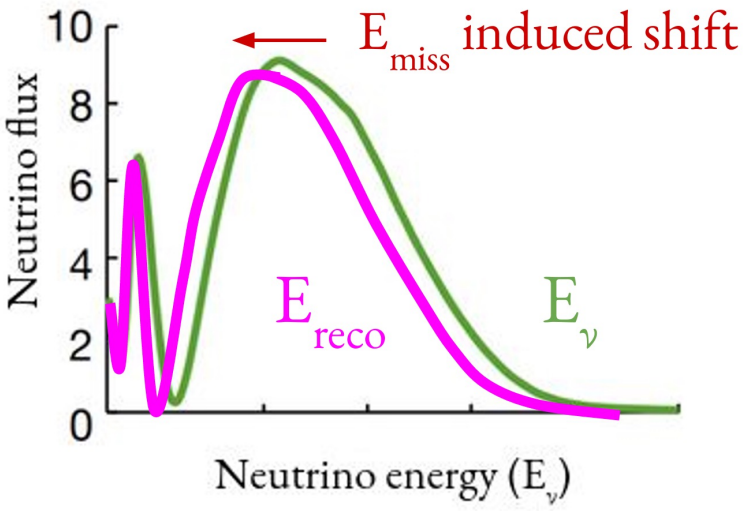


Entering era of precision neutrino oscillation physics

Precision neutrino physics requires precision understanding of neutrino interactions

- highly complex: broad neutrino energy spectrums, multiple interaction modes, final state interactions
  - and getting it wrong has the potential to bias our oscillation measurements

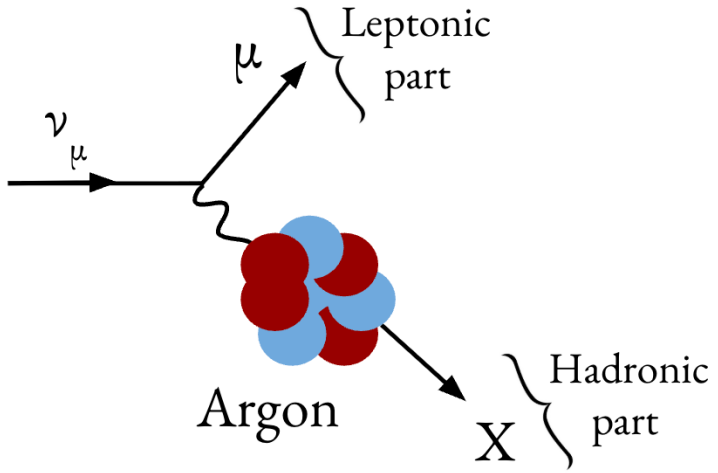
Input to neutrino oscillation measurements



"Easy" Hard

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

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



MicroBooNE providing crucial measurements on Argon

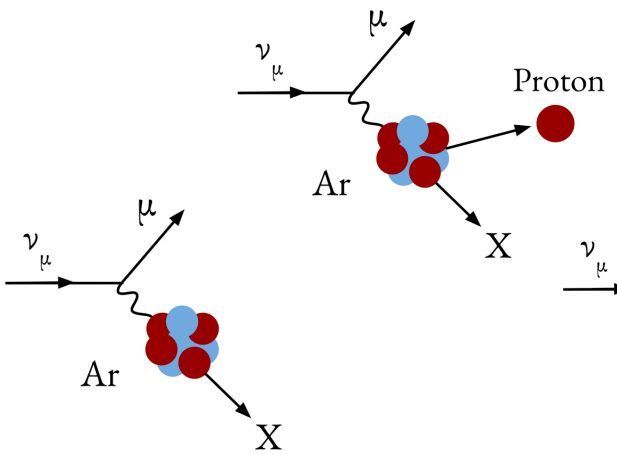
Expansive ν-Ar interaction measurement programme – **35 neutrino interaction papers to-date**

- probe modelling essential for DUNE, across numerous final state topologies and interaction modes

This talk: high-level overview of our 10 most recent results

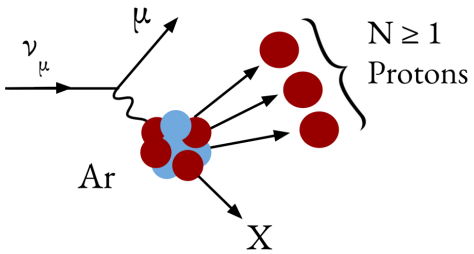
See dedicated posters for details!

(Quasi-elastic) neutrino direction

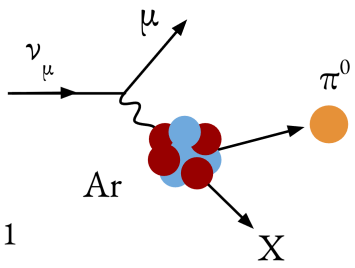


Leptonic modelling

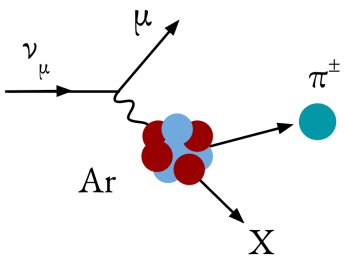
Proton multiplicity



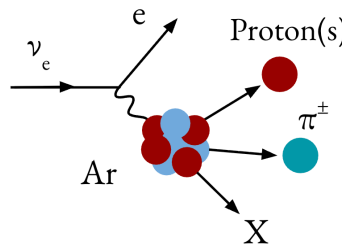
Neutral pions



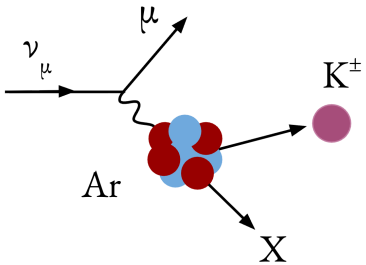
Charged pions



Electron neutrinos



Kaons



MicroBooNE providing crucial measurements on Argon

MicroBooNE 85-tonne LArTPC:

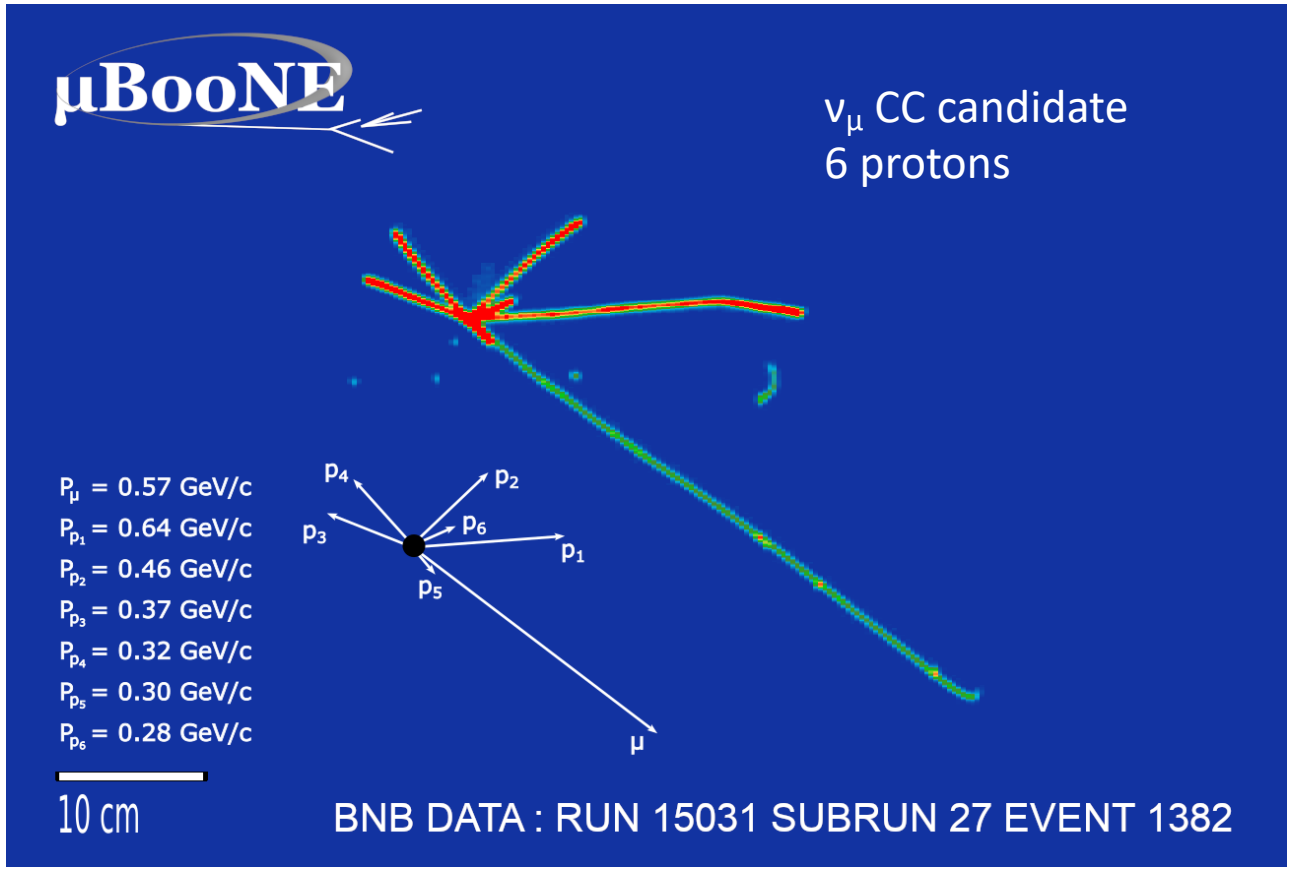
- mm resolution, ns timing, MeV thresholds
- fully active, 4π geometric acceptance

Two neutrino beams, 800k neutrinos:

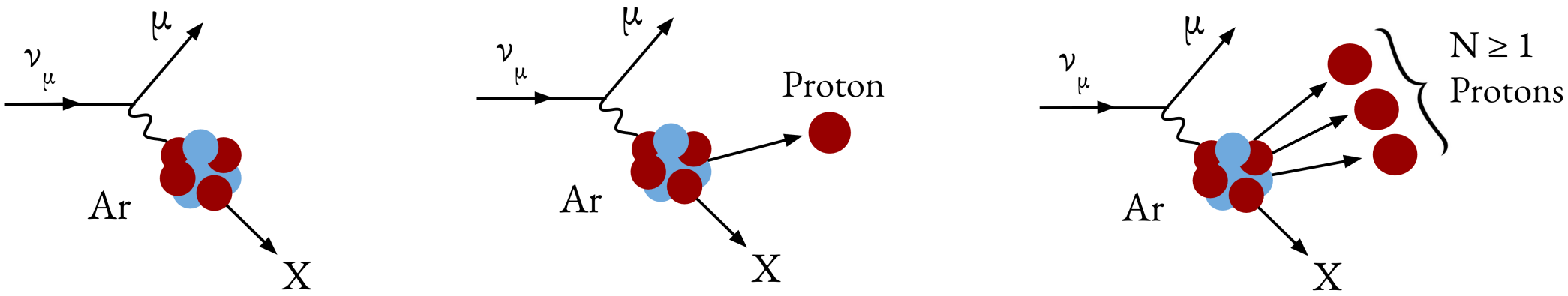
- BNB and NuMI @ Fermilab
- well-understood dataset

Leveraging our full dataset for the first time

- doubled data statistics compared with previous generation of measurements

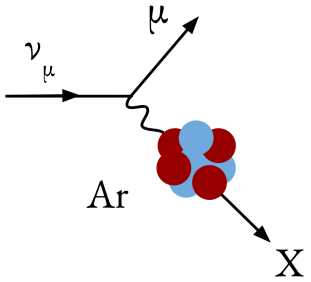


Meson-less Measurements



Lepton kinematics: ν_μ CC 0π Xp

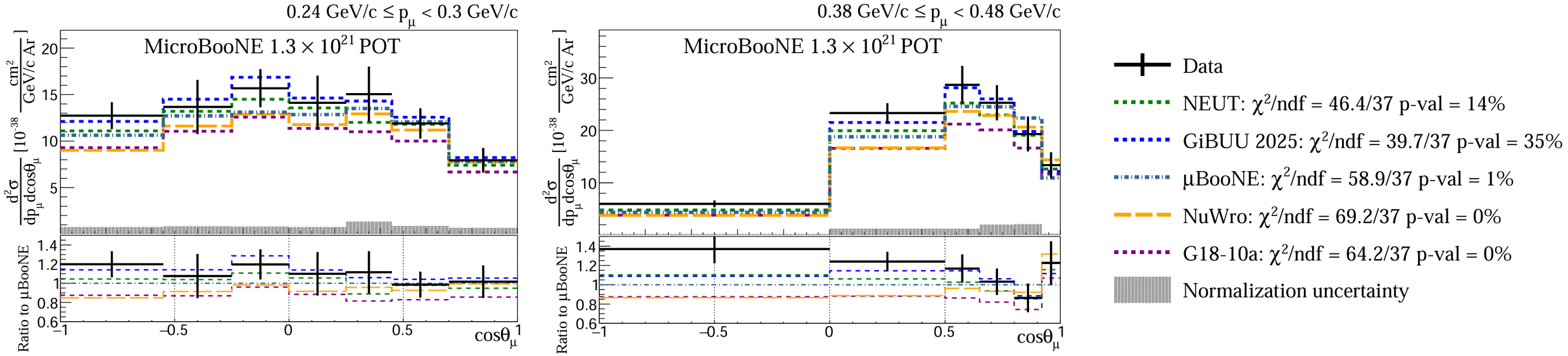
PRD **112** 072007 (2025)
Poster #285



New CC 0π measurement, using our full BNB dataset

Strong tensions seen in 2D lepton kinematics:

- current **DUNE base model** (as benchmark): **Genie AR23 χ^2/ndf = 65.9/37, p = 0.002**



Lepton kinematics: ν_μ CC 0π Xp

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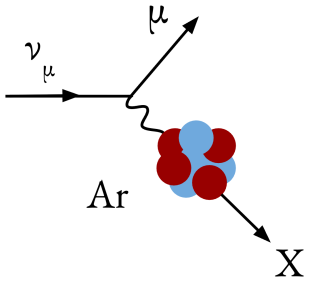
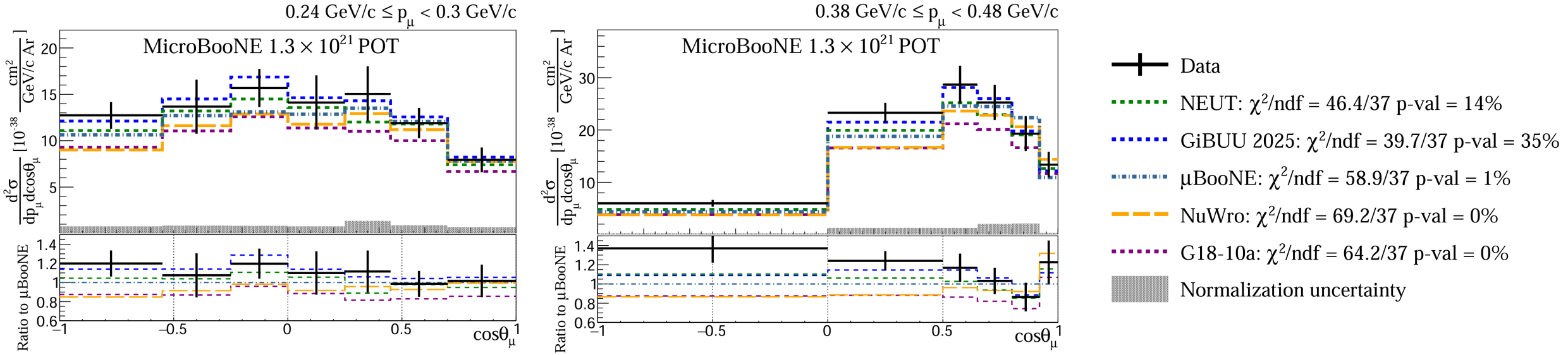


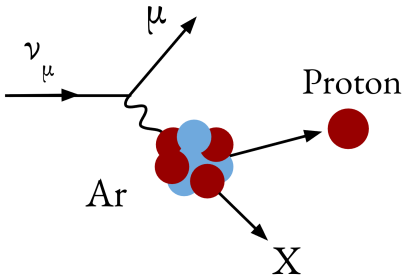
First step towards joint measurement with ANNIE:

- Ar / H_2O XSec in same beam
- coming later this year!



Neutrino direction: QE-like 1p

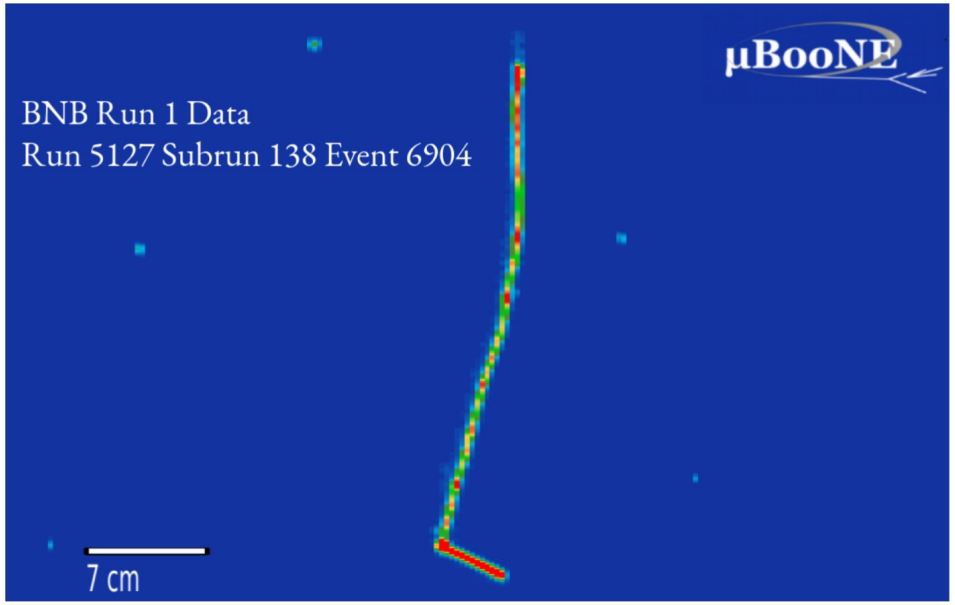
PRD **111** 113007 (2025)
Poster #110

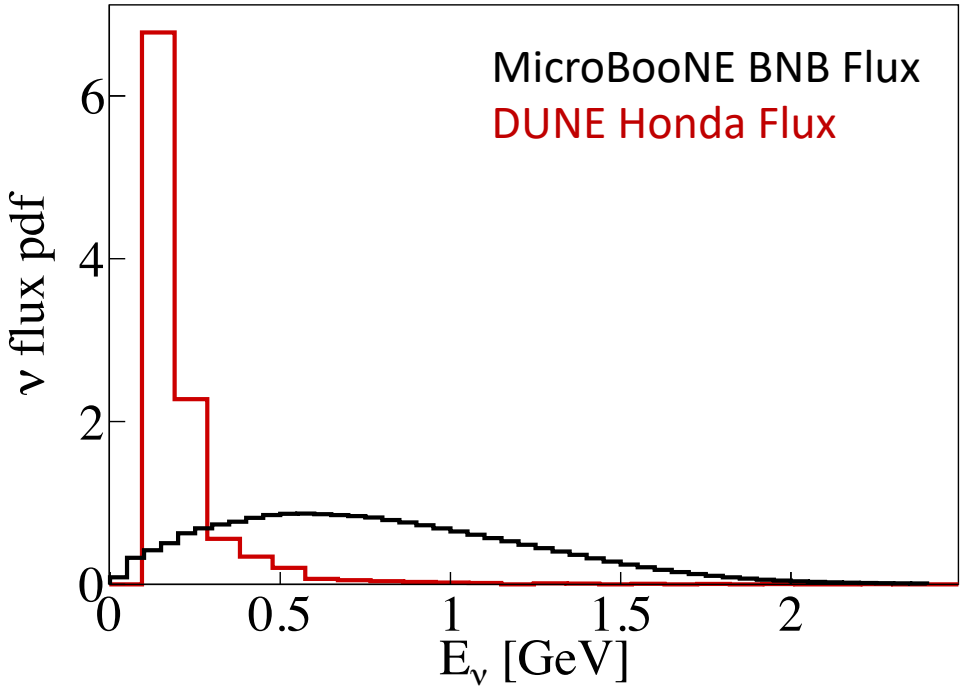


Neutrino direction reconstruction essential for DUNE atmospheric neutrino measurements

BNB flux overlaps Honda DUNE atmospheric flux:

- test angular reconstruction and modeling in MicroBooNE with known neutrino direction





Neutrino direction: QE-like 1p

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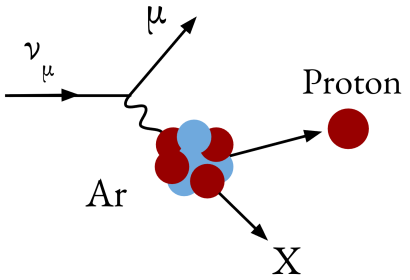
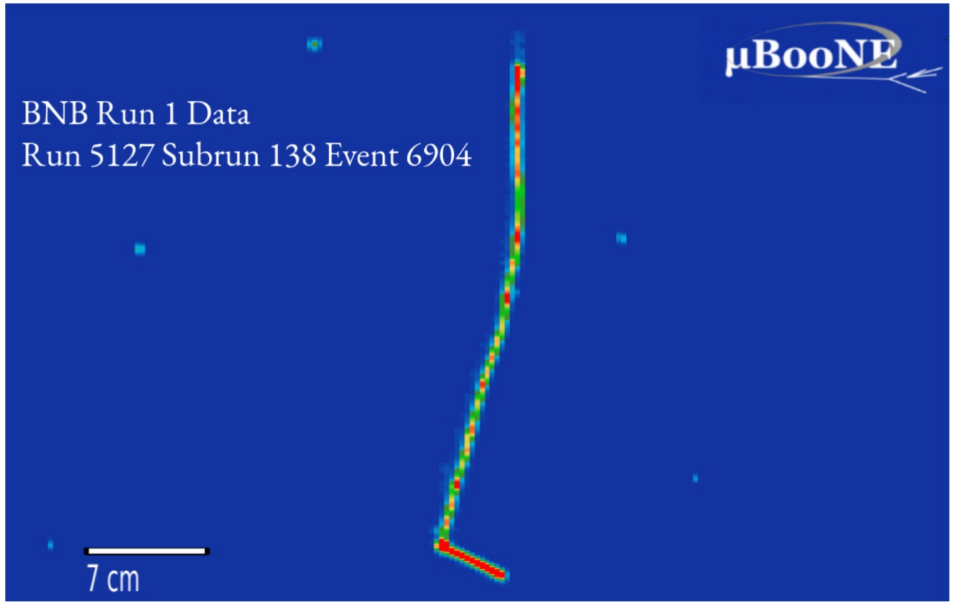
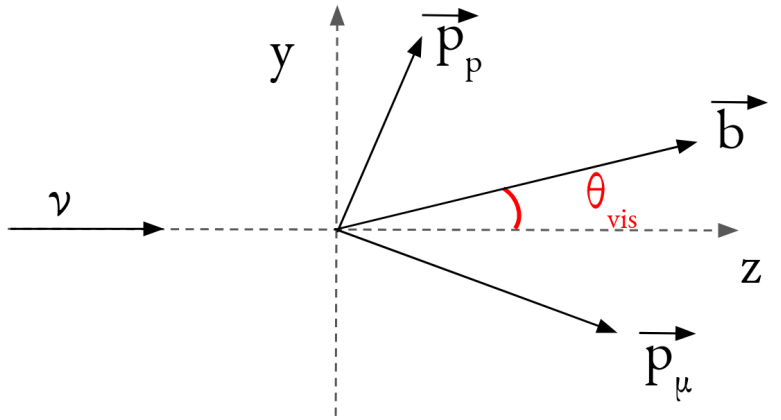


Define visible direction θ_{vis}: difference between beam direction and muon–proton system

- construct variables to sensitive to the impact of nuclear effects, e.g. missing momentum p_{miss}



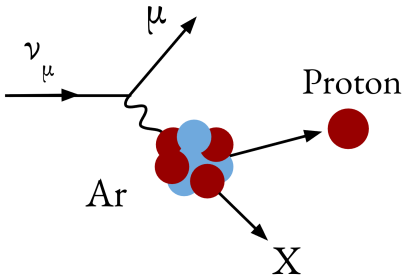


$$\theta_{\text{vis}} = \text{acos}(\frac{\vec{b} \cdot \hat{z}}{|\vec{b}|}), \quad \text{with } \vec{b} = \vec{p}_\mu + \vec{p}_p,$$

$$p_{\text{miss}} = E_{\text{reco}} - b,$$

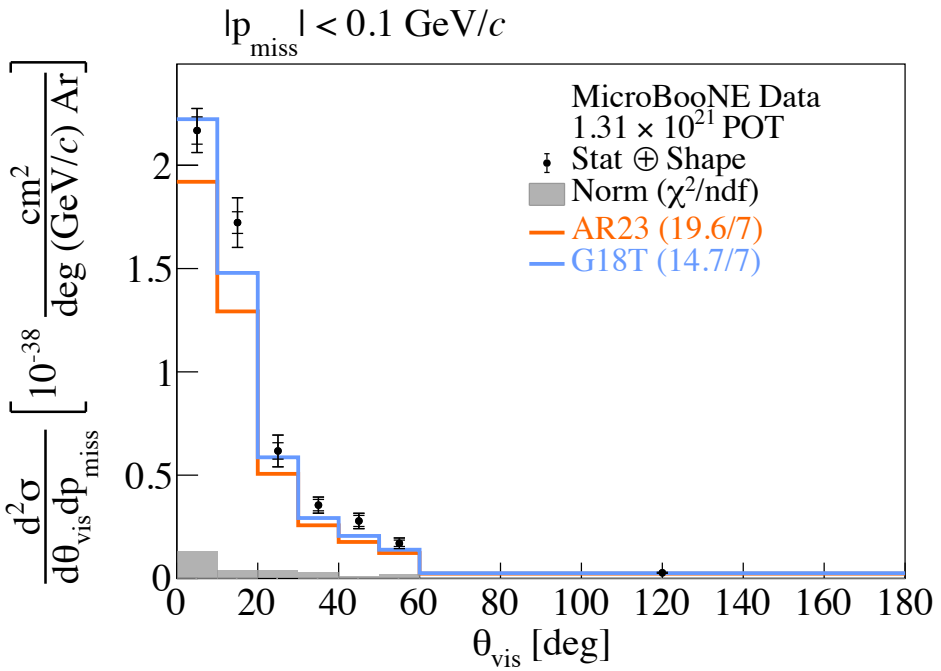
Neutrino direction: QE-like 1p

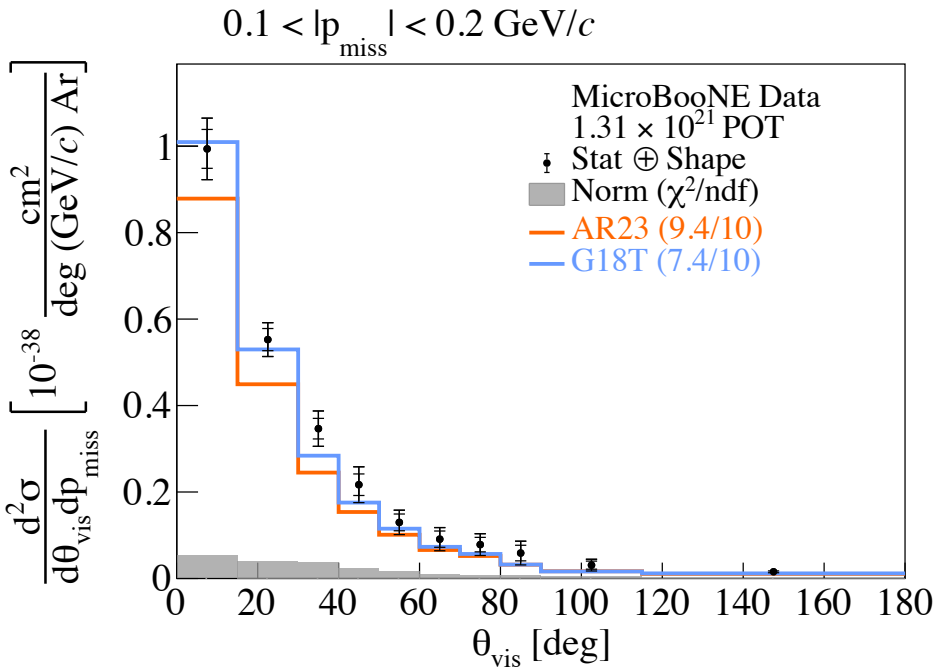
PRD **111** 113007 (2025)
Poster #110



Double differential cross section measurements:

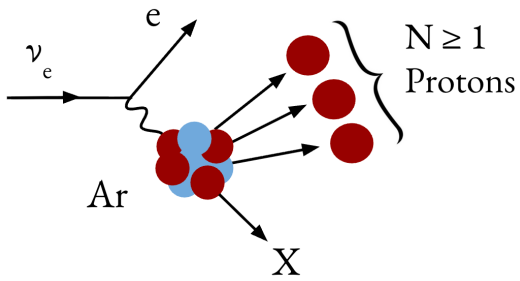
- generally, see satisfactory angular modelling across most of phase space
- but, significant tensions observed at low $|p_{miss}|$ for Genie Ar23: χ^2/ndf = 19.6/7, p = 0.007





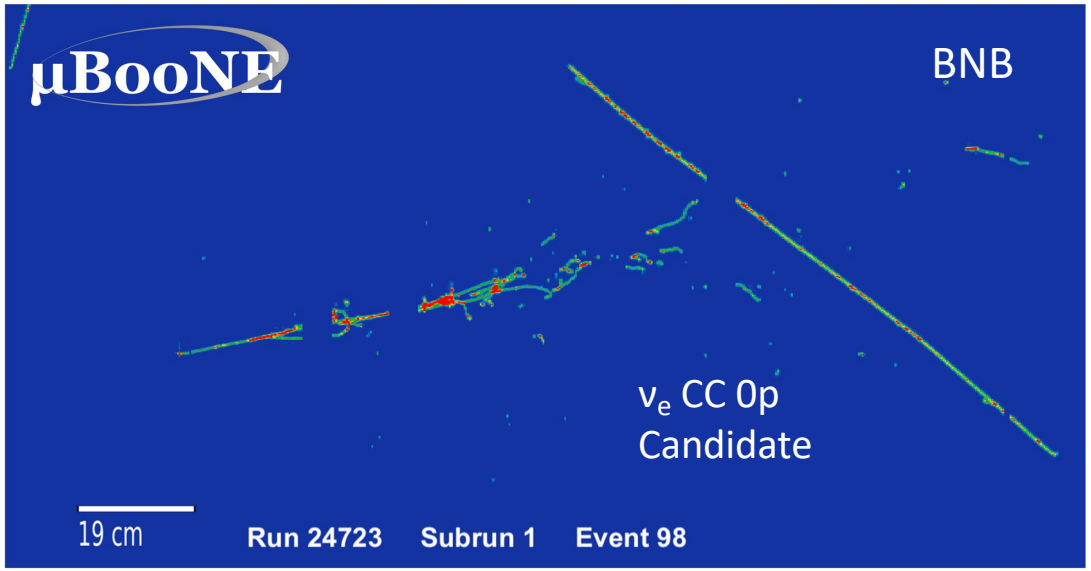
Electron neutrinos: ν_e CC 0π Np

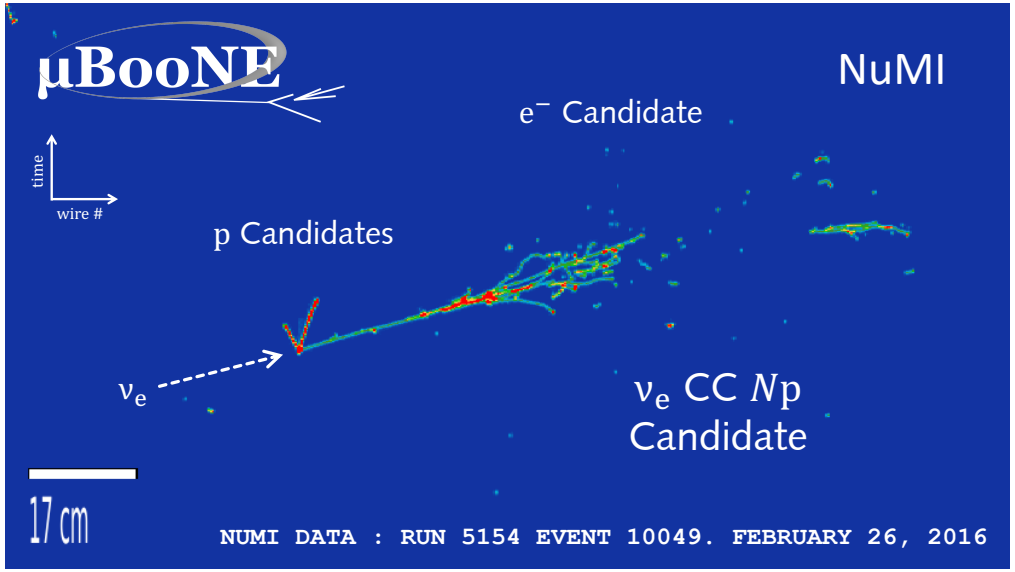
arXiv:2511.17342 (NuMI)
arXiv:2603:13593 (BNB)
Poster #139



Pionless ν_e measurements using two neutrino beams: BNB and NuMI (off-axis)

- similar but distinct fluxes, provide complementary information





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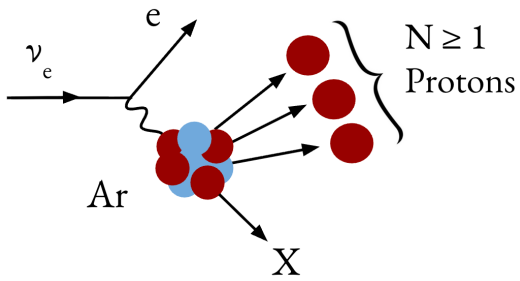


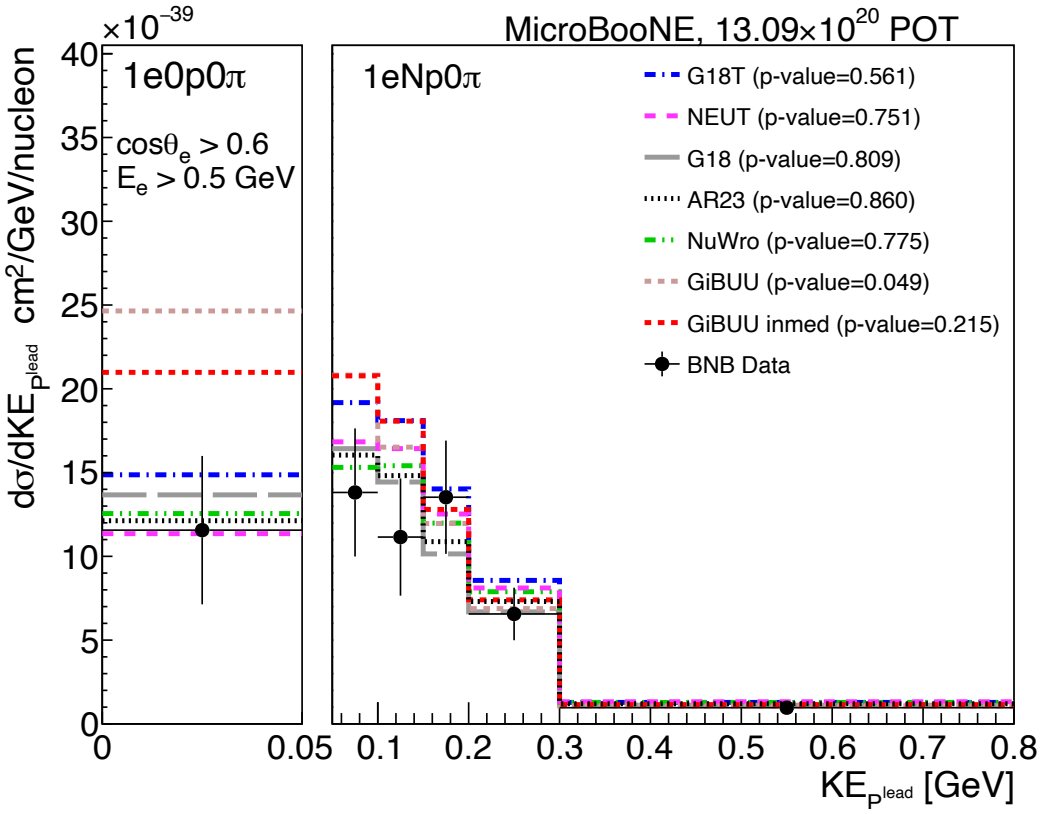
Simultaneous ν_e 0p / Np measurement (BNB):

- significant tension with higher prediction of GiBUU

Opposite effect to equivalent ν_μ 0p / Np:

- PRL 133 (2024) 4, 041801
- but hard to interpret, different signal definitions (inclusive vs. pionless, etc.)

Follow up measurement will explore further



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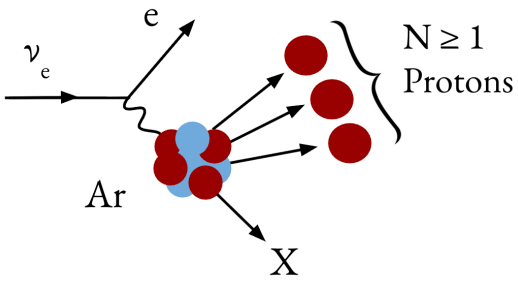
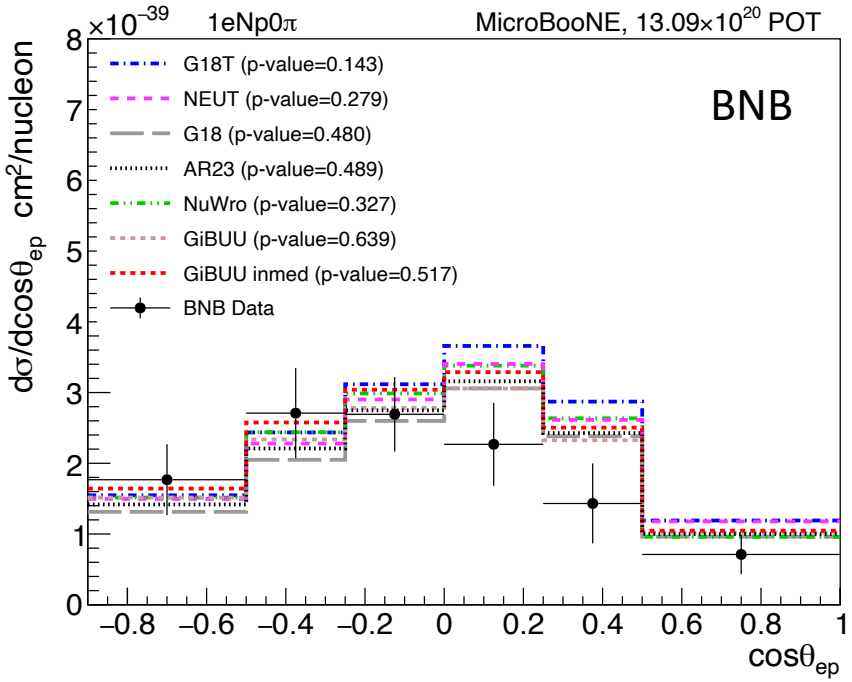
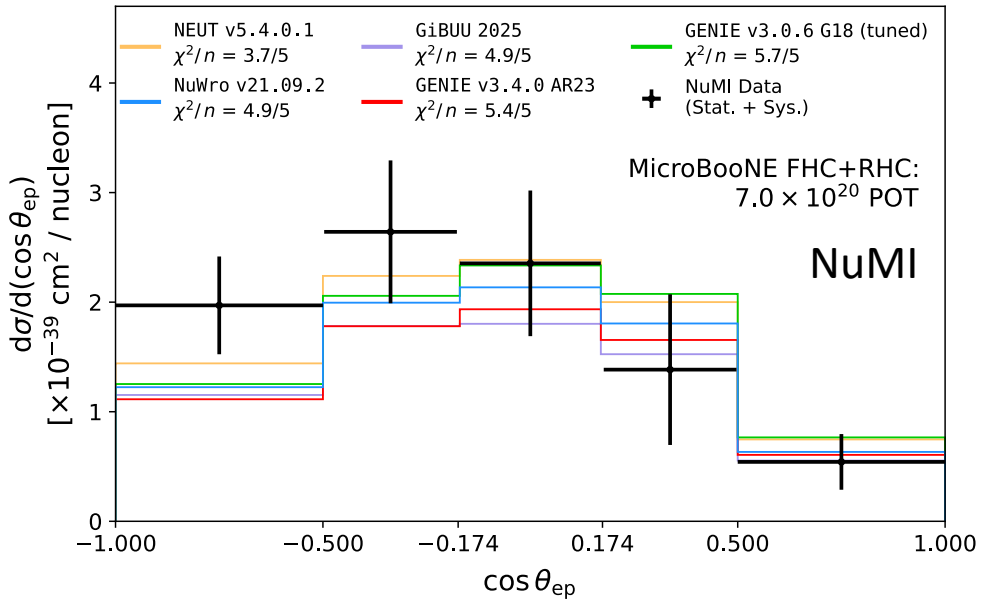


Pionless ν_e measurements using two neutrino beams: BNB and NuMI

- similar features across two different fluxes, hints of shape tension lepton-proton opening angle – effect also seen in similar ν_μ 0π Np measurement (PRD 112 (2025), 112004)

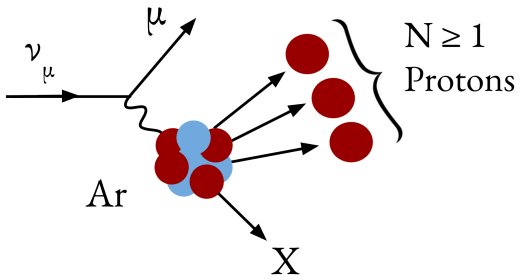




Proton multiplicity: ν_μ CC 0π Np

MICROBOONE-NOTE-1135-PUB

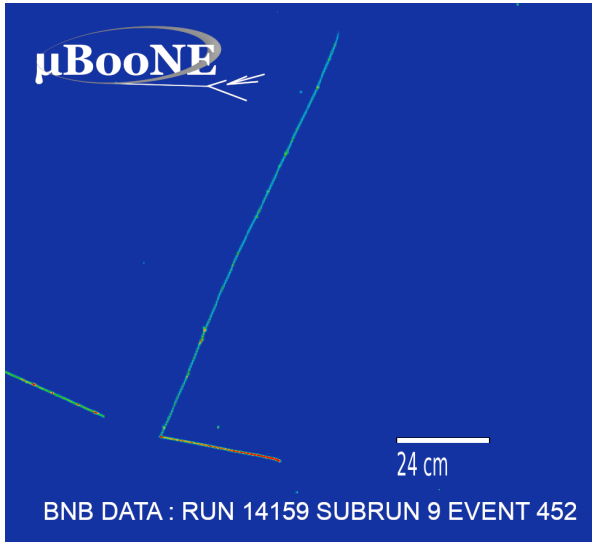
Poster #393



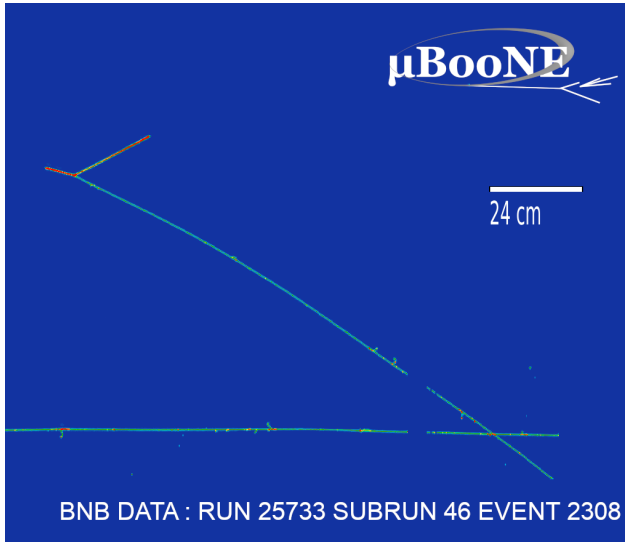
First double-differential cross section measurements in proton multiplicity on Argon

- slices in 1 proton, 2 protons, 3 protons and 4 or more protons final state topologies
- measure kinematics of sub-leading protons for the first time, all the way up to 4th proton

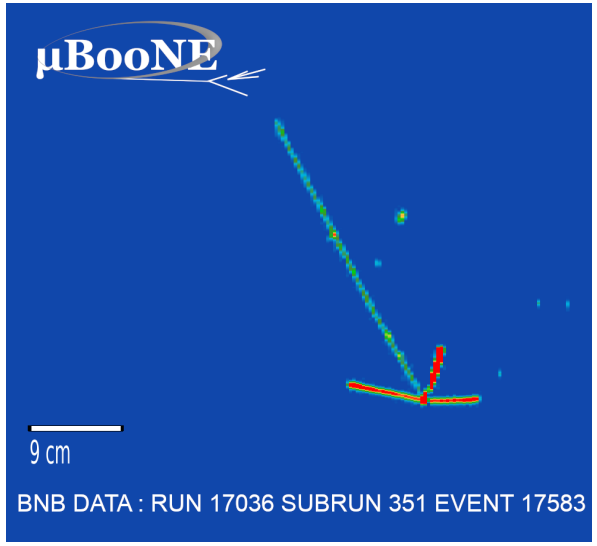
1p (QE-like)
55740 data events



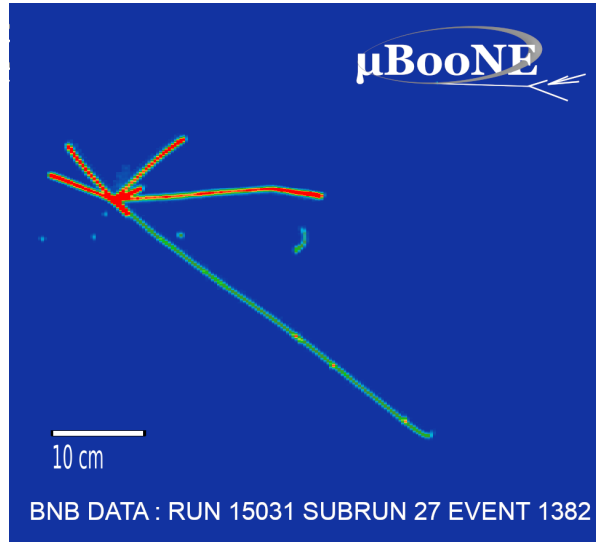
2p (2p2h-like)
14087 data events



3p (3p3h-like)
2732 data events



4p+
499 data events



Proton multiplicity: ν_μ CC 0π Np

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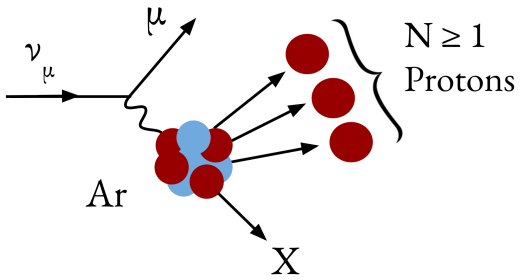
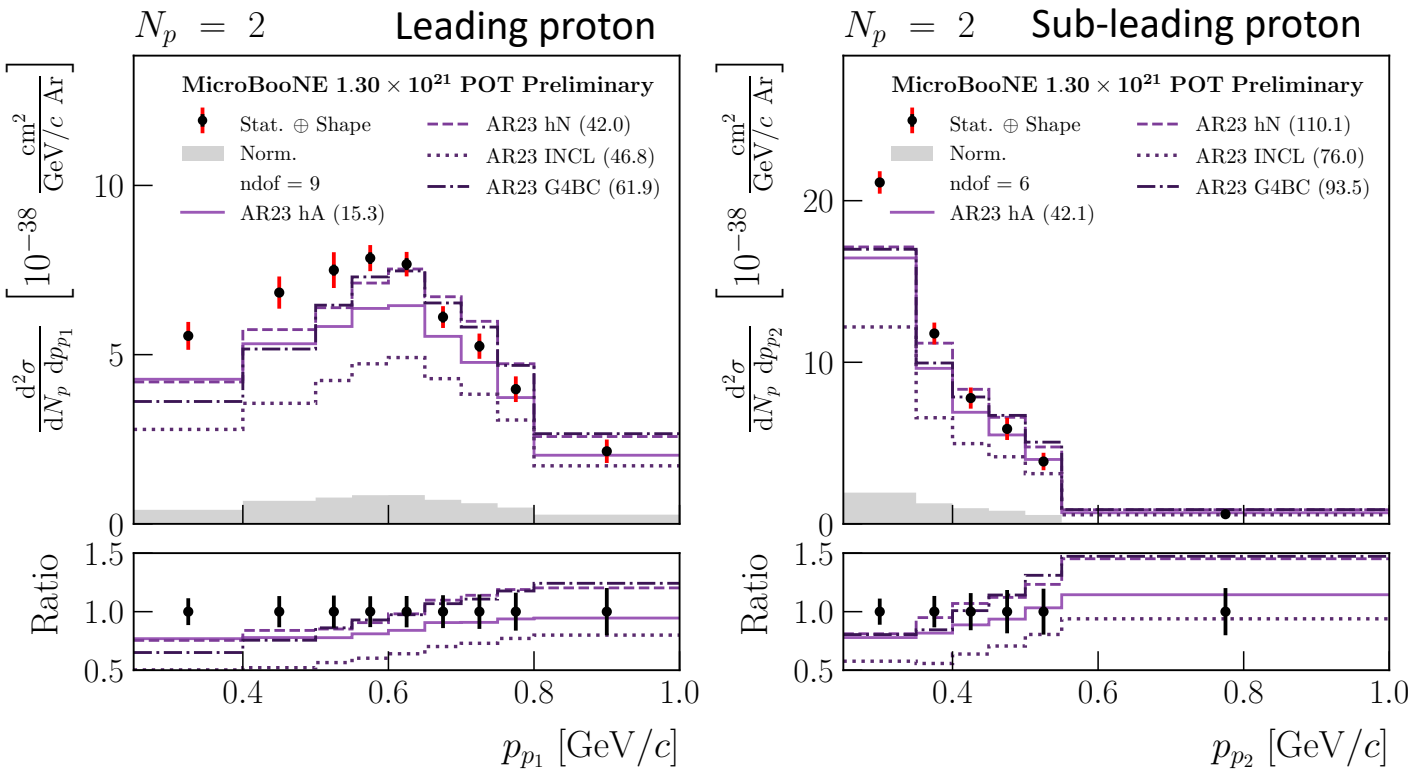


N_p = 2 slice – cross section in leading and sub-leading proton kinematics

- significant tension seen with DUNE base model, Genie AR23 hA – especially for sub-leading proton



Explore alternative FSI models:

- hN, INCL, G4 Bertini Cascade
- no model satisfactorily describes the data

Proton multiplicity: ν_μ CC 0π Np

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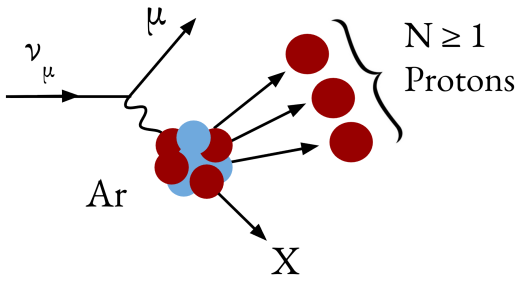
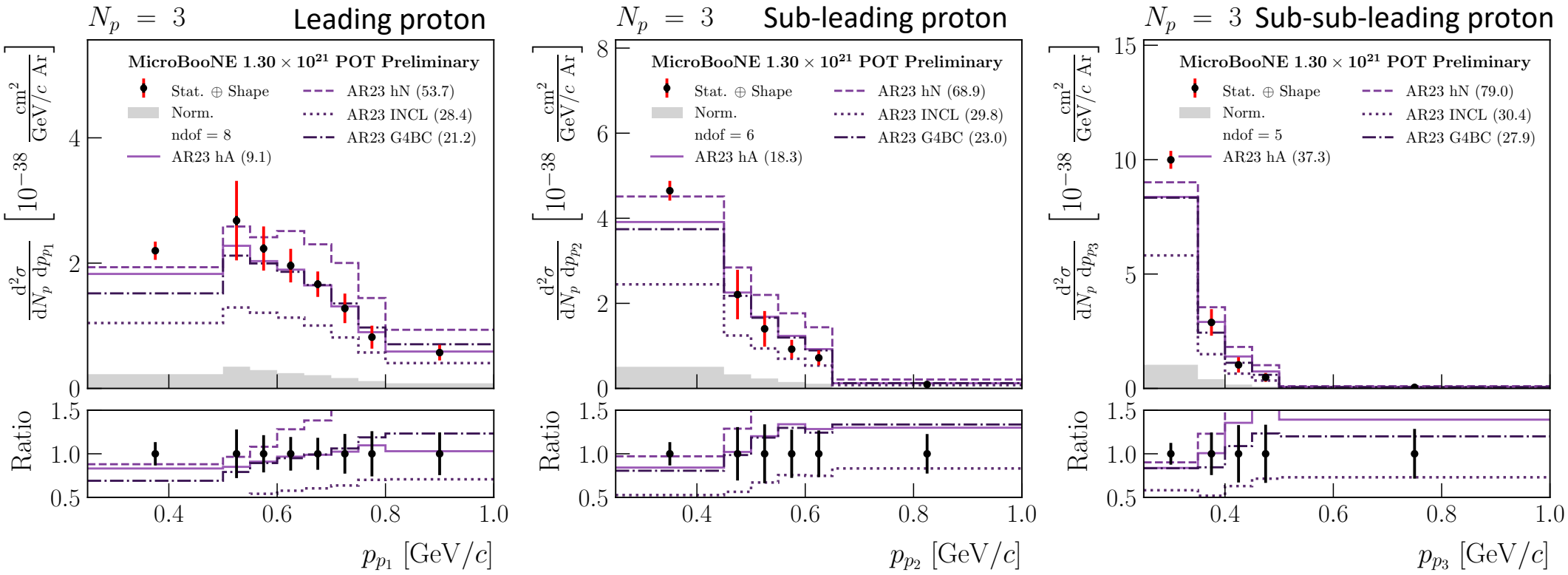


N_p = 3 slice – cross section in leading, sub-leading and sub-sub-leading proton kinematics

- AR23 hA models leading proton reasonably well, but strong tensions for sub-leading protons



Proton multiplicity: ν_μ CC 0π Np

MICROBOONE-NOTE-1135-PUB

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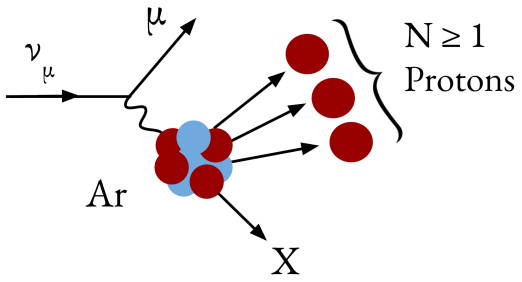
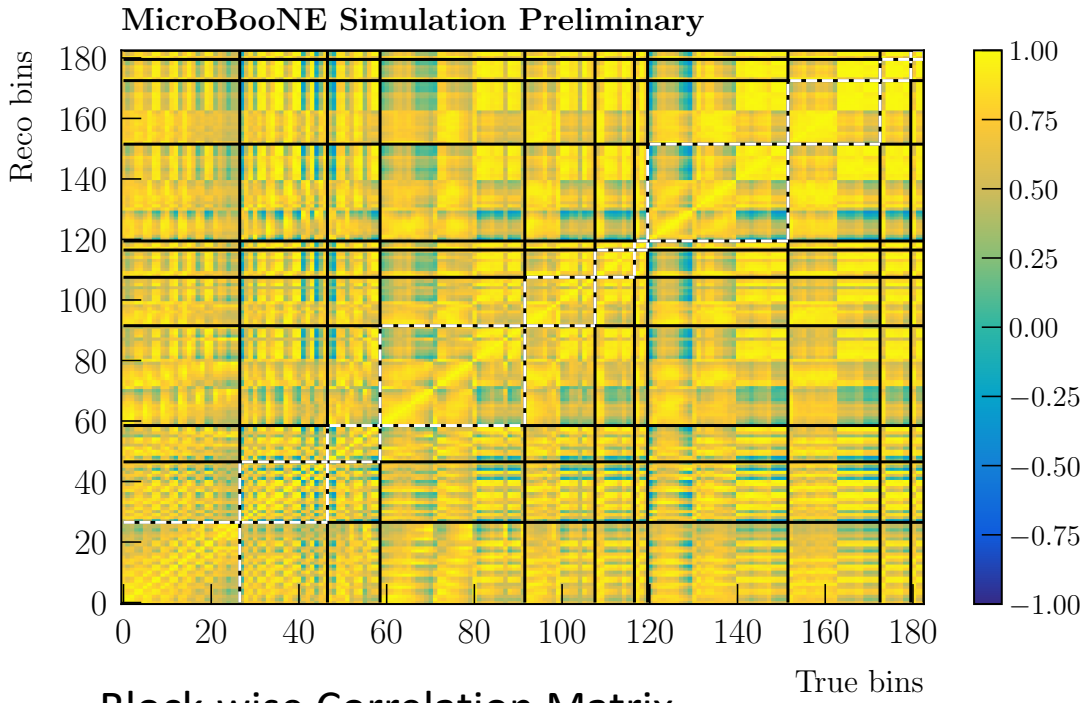


Extract global χ^2 accounting for correlations across all 183 bins

- no generator gets even close to satisfactorily describing full correlated phase space

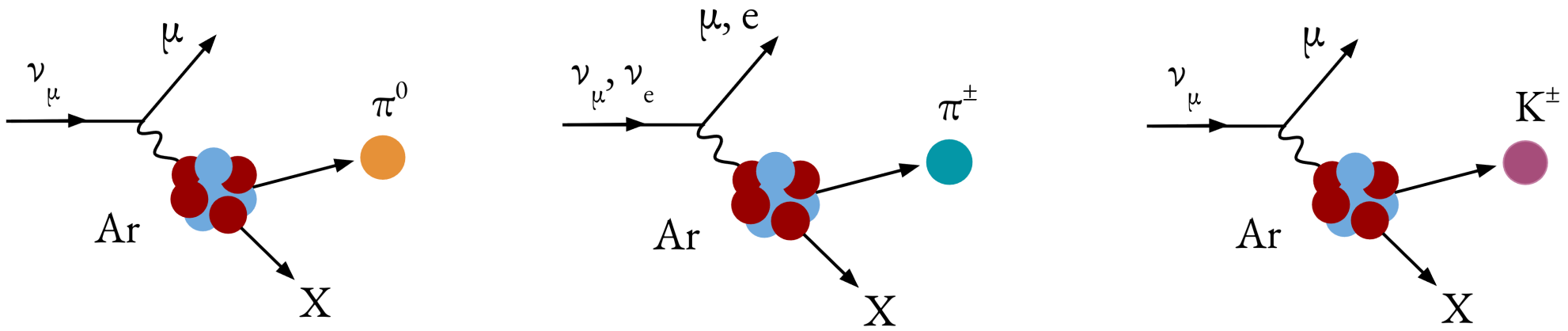


Block-wise Correlation Matrix

	Global χ^2 – 145 dof
Genie 3.6.2 Ar23	488.1
NEUT 5.6.2	1132.0
NuWro 25.11	692.5
GiBUU 2025	480.9

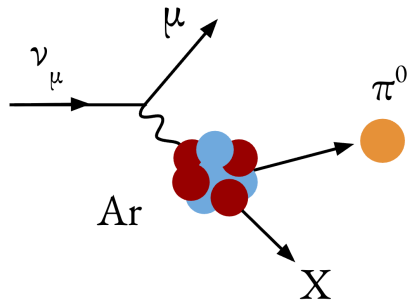
Using block-wise unfolding:
arXiv:2401.04065

Meson Production Measurements



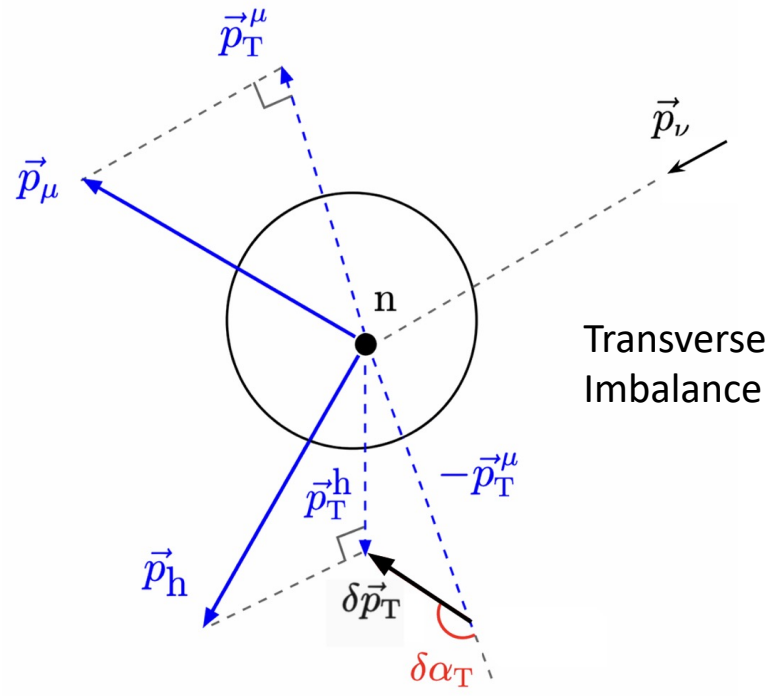
Neutral pions: ν_μ CC $1\pi^0$ TKI

arXiv:2606.23559
Poster #145

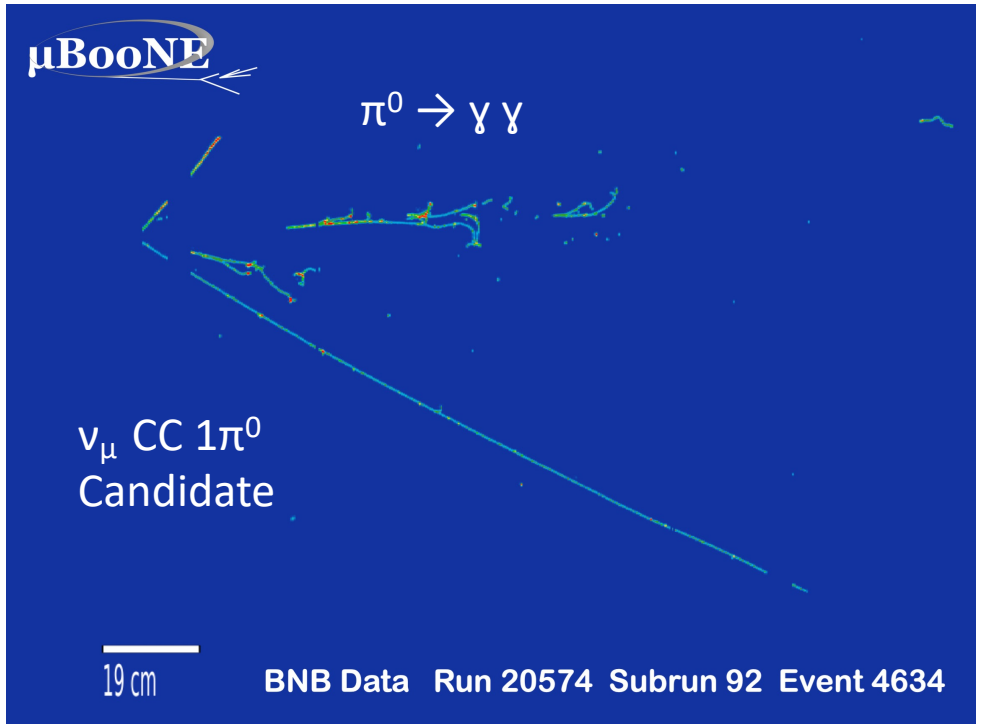


New CC π^0 measurement exploring kinematic imbalance variables

- identify missing momentum from nuclear effects, powerful probe of FSI
- + doubled data statistics and improved MCS momentum reconstruction (arXiv:2605.03048)

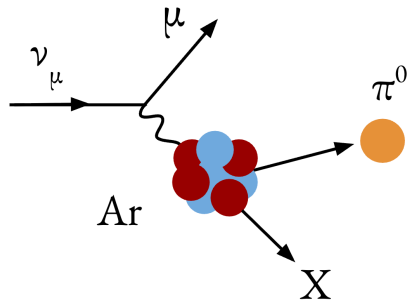


Transverse Kinematic Imbalance (TKI)



Neutral pions: ν_μ CC $1\pi^0$ TKI

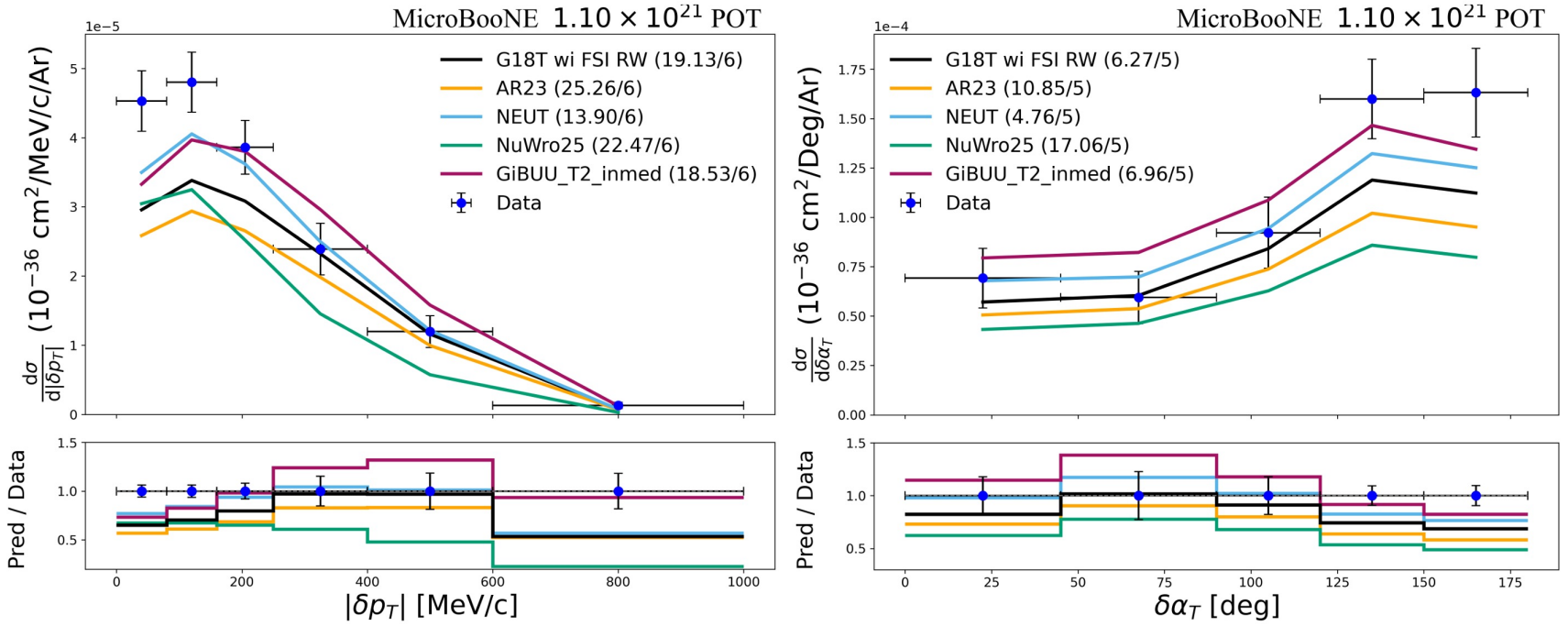
arXiv:2606.23559
Poster #145



See significant tension in kinematic imbalance variables:

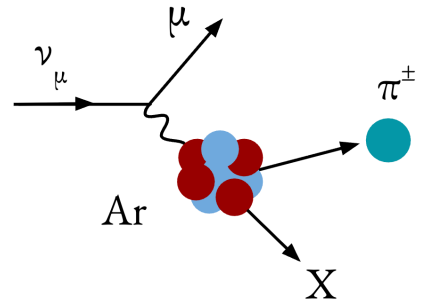
- strong tension seen at low $|\delta p_T|$ – could suggest overestimation of final state interactions
- tension also seen at high $\delta\alpha_T$ – could indicate deceleration of hadronic system, stronger FSI

Genie AR23:
$|\delta p_T|$ χ^2 = 25.26/6, p = 0.0003



Charged pions: ν_μ CC $1\pi^\pm$

PRD **113**, 032007 (2026)
Poster #137

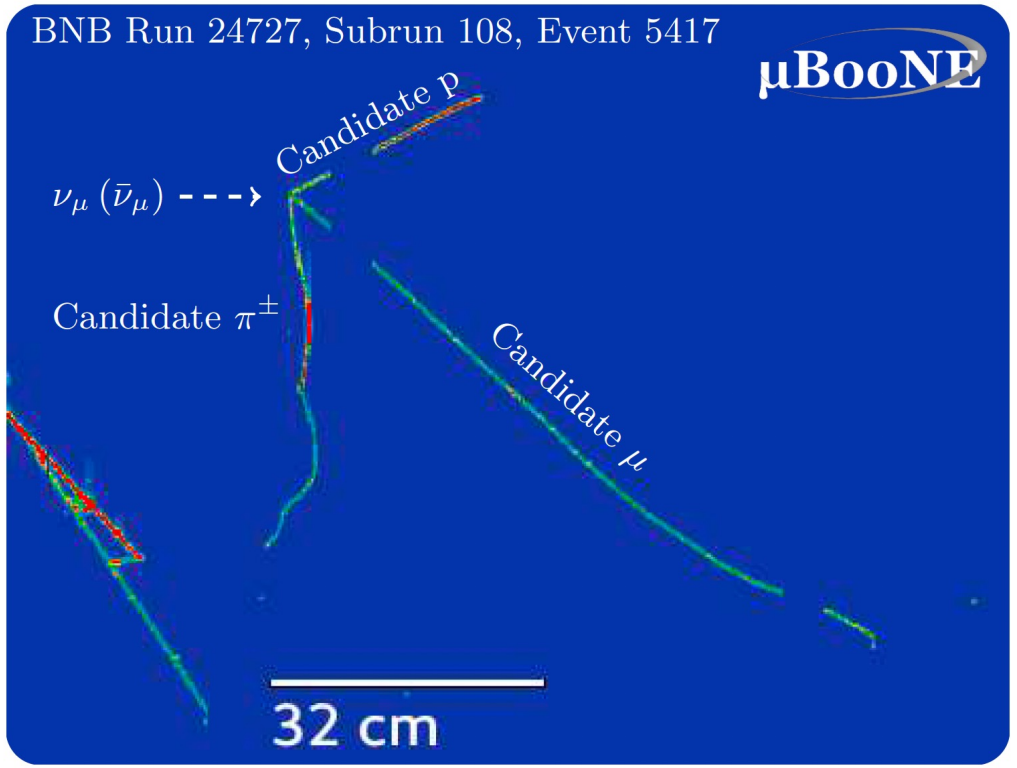


MicroBooNE recently released first set of $\pi^\pm$ production measurements

New measurement of resonant-like ν_μ CC $1\pi^\pm$

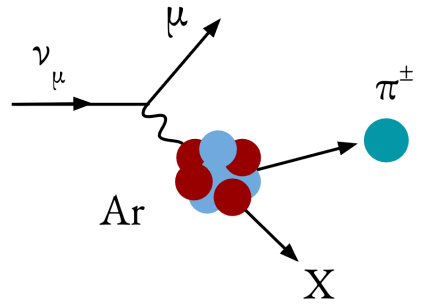
25 × increase in global data statistics on Argon

- ~6500 signal ν_μ CC $1\pi^\pm$ data events
- first differential measurement in $\pi^\pm$ momentum



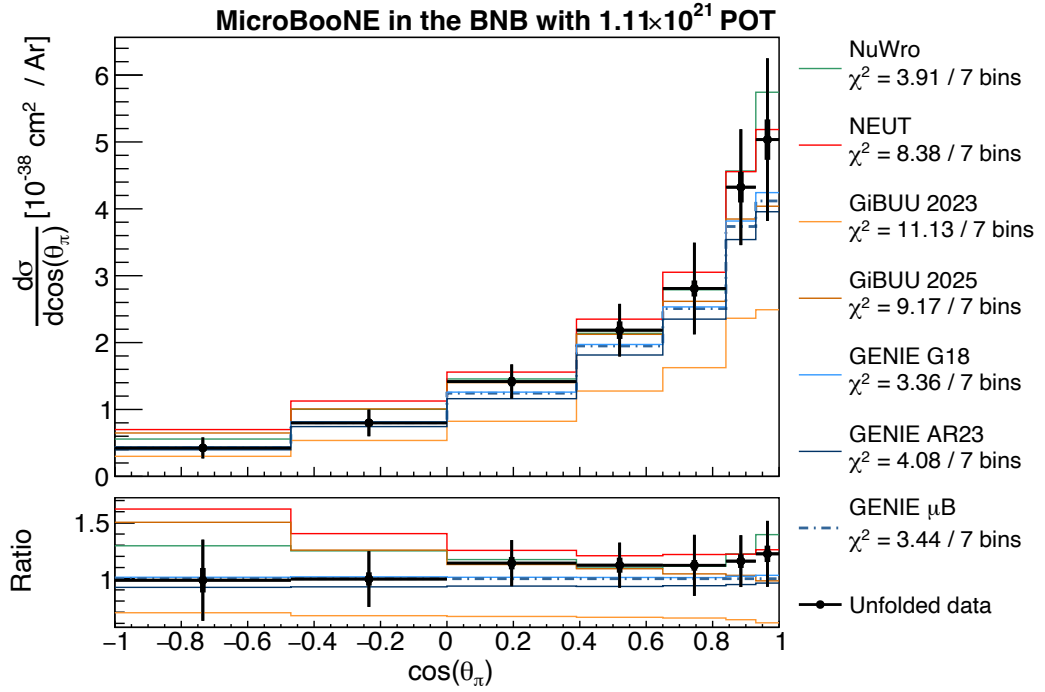
Charged pions: ν_μ CC $1\pi^\pm$

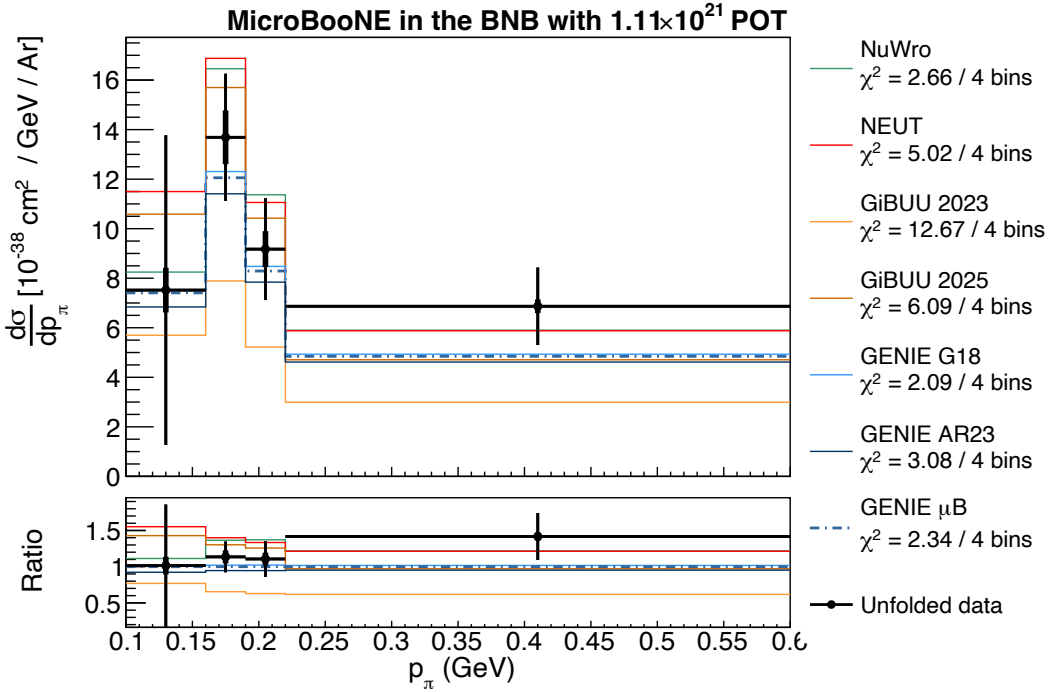
PRD **113**, 032007 (2026)
Poster #137



See possible hints of shape tension in pion kinematics, possibly driven by FSI

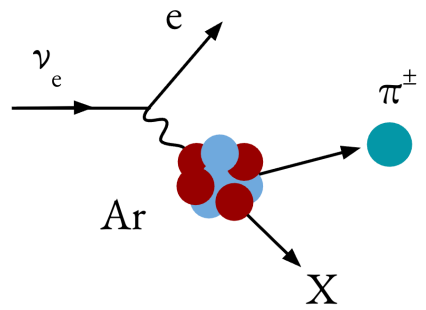
- follow up analysis exploring kinematic imbalance variables – coming later this summer





Charged pions: ν_e CC $1\pi^{\pm}$

PRL **135** 061802 (2025)
Poster #137

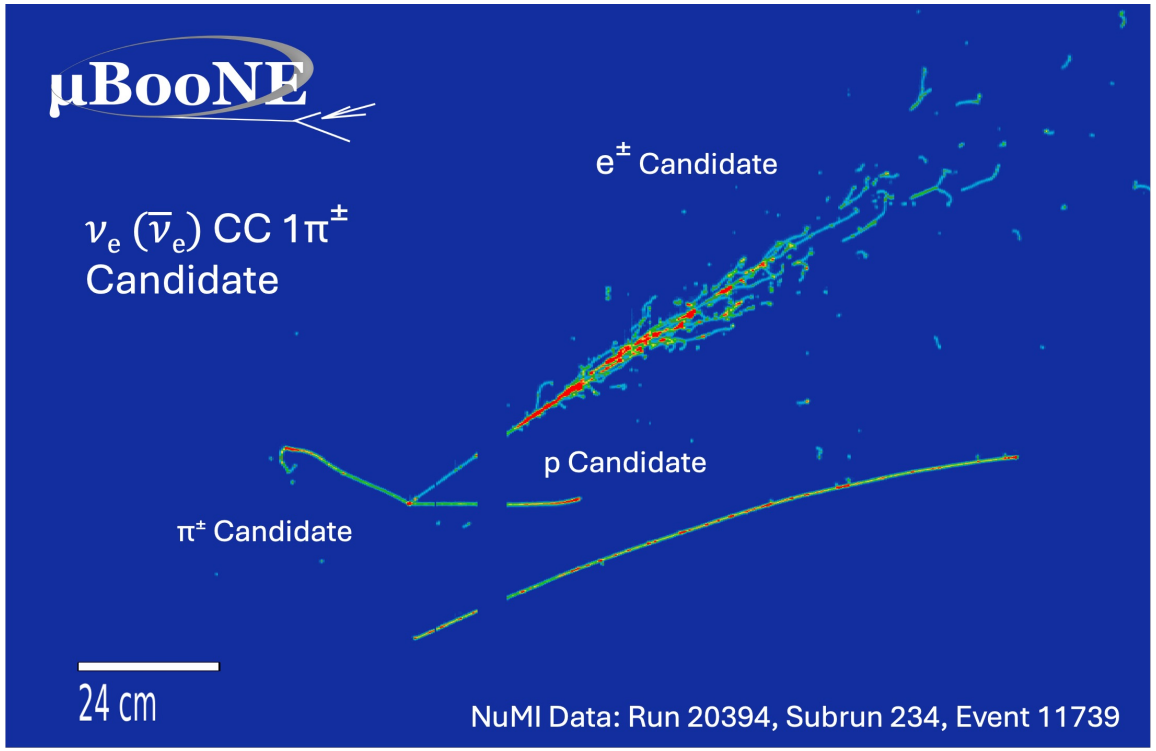


First ever measurement of ν_e resonant-like $\pi^{\pm}$ production on Argon

One of the leading signal processes in DUNE, but never measured before on Argon

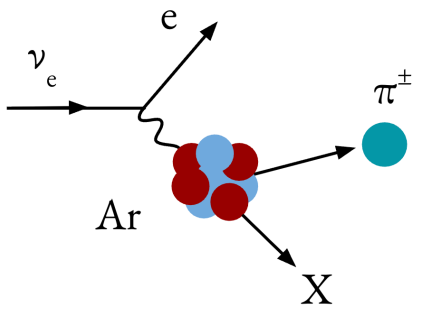
Challenging to reconstruct:

- complex electron and pion topology



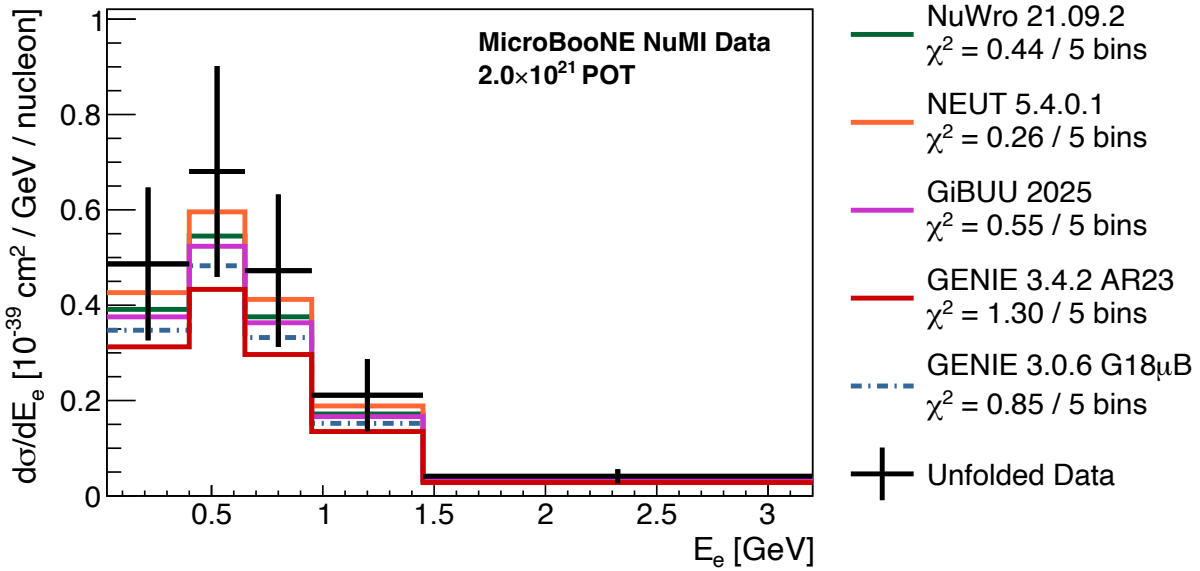
Charged pions: ν_e CC $1\pi^{\pm}$

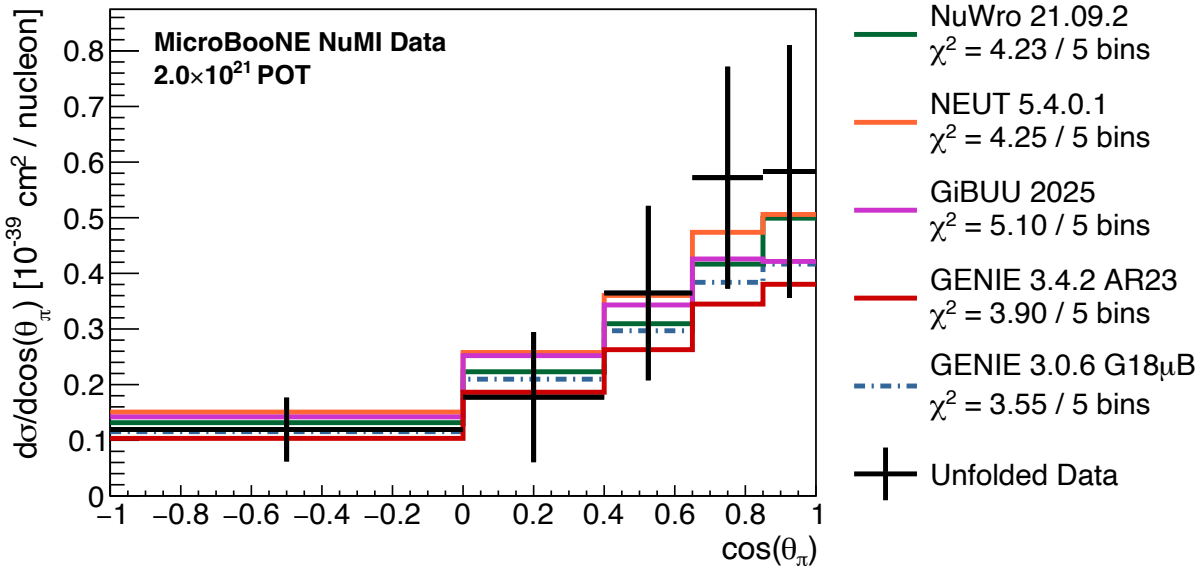
PRL **135** 061802 (2025)
Poster #137



See generally good agreement seen with generators

- statistically limited, large uncertainties from NuMI off-axis flux

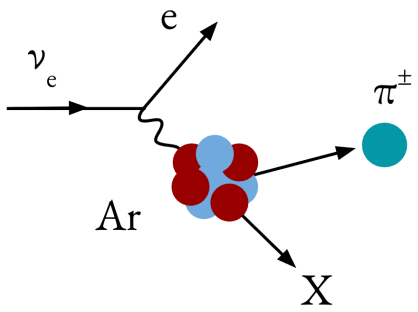




Charged pions: ν_e CC $1\pi^{\pm}$

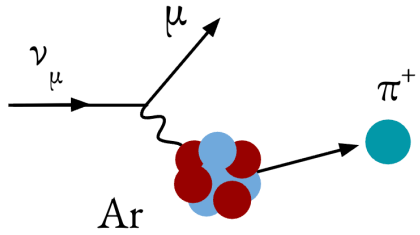
Highlighted on the front cover of PRL!

PRL **135** 061802 (2025)
Poster #137



Coherent ν_μ CC $\pi^\pm$

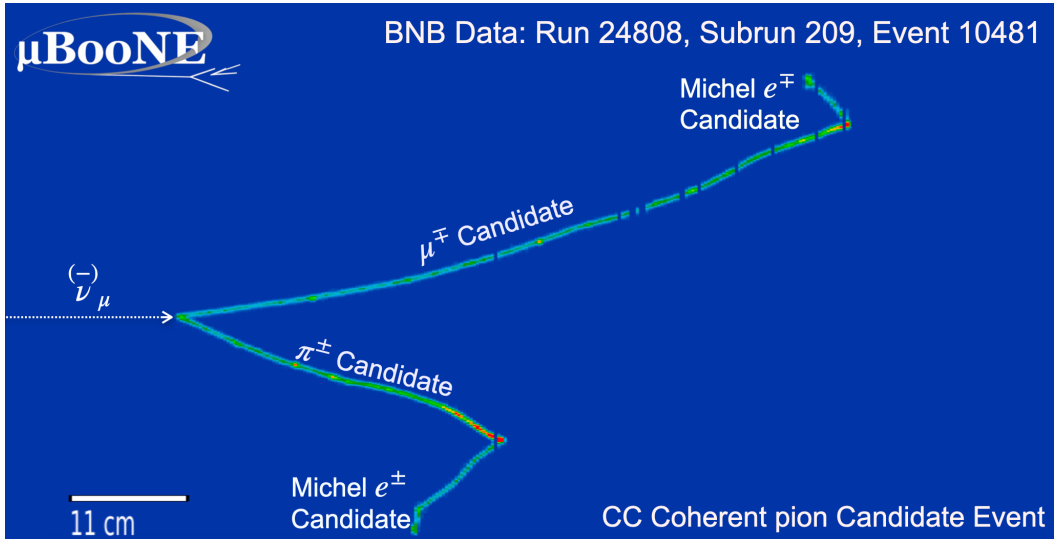
arXiv:2606:13613
Poster #211

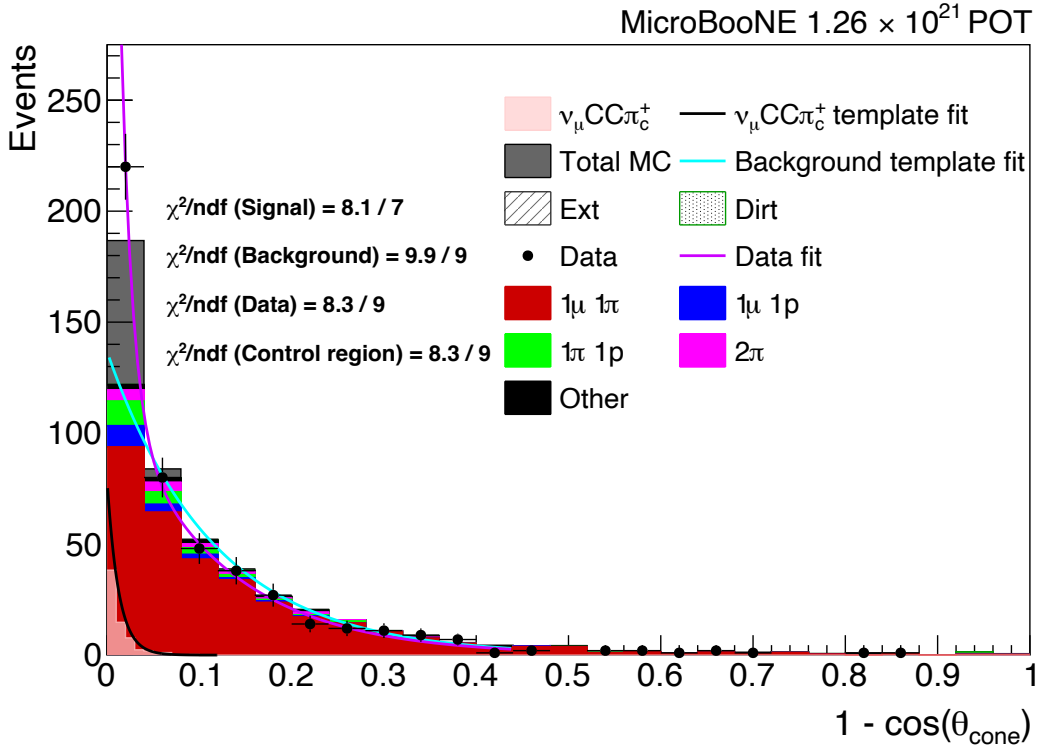


Neutrino interacts with whole nucleus, enables exact neutrino energy reconstruction

- has been proposed as a potential way to constrain neutrino fluxes

Isolate from irreducible resonant background through fitting angular distribution shape





Coherent ν_μ CC $\pi^\pm$

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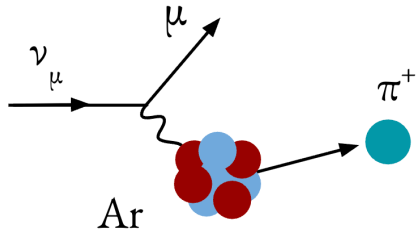
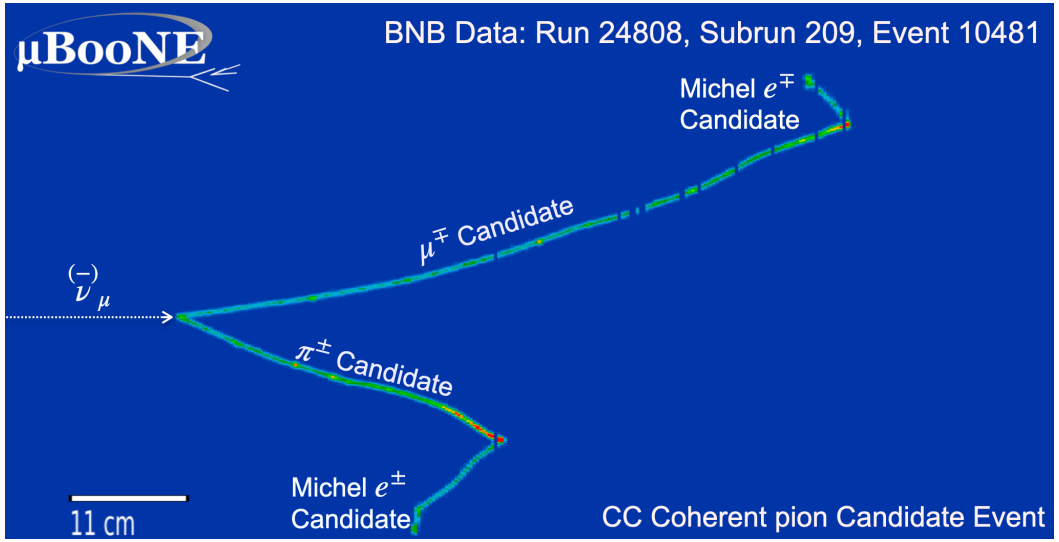


See significant disagreement between data and some of the generators

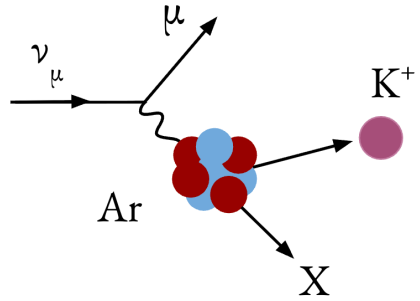
- further work needed to enable use as a flux constraint



	Cross section (10^{-40} cm^2 / Ar)
MicroBooNE	**9.1 ± 1.2 (stat.) ± 1.2 (syst.)**
Genie 3.0.6 G18	5.0
NEUT 6.1.4	10.7
NuWro 25.11	14.0

Kaon production

PRL **135** 251804 (2025)
Poster #181



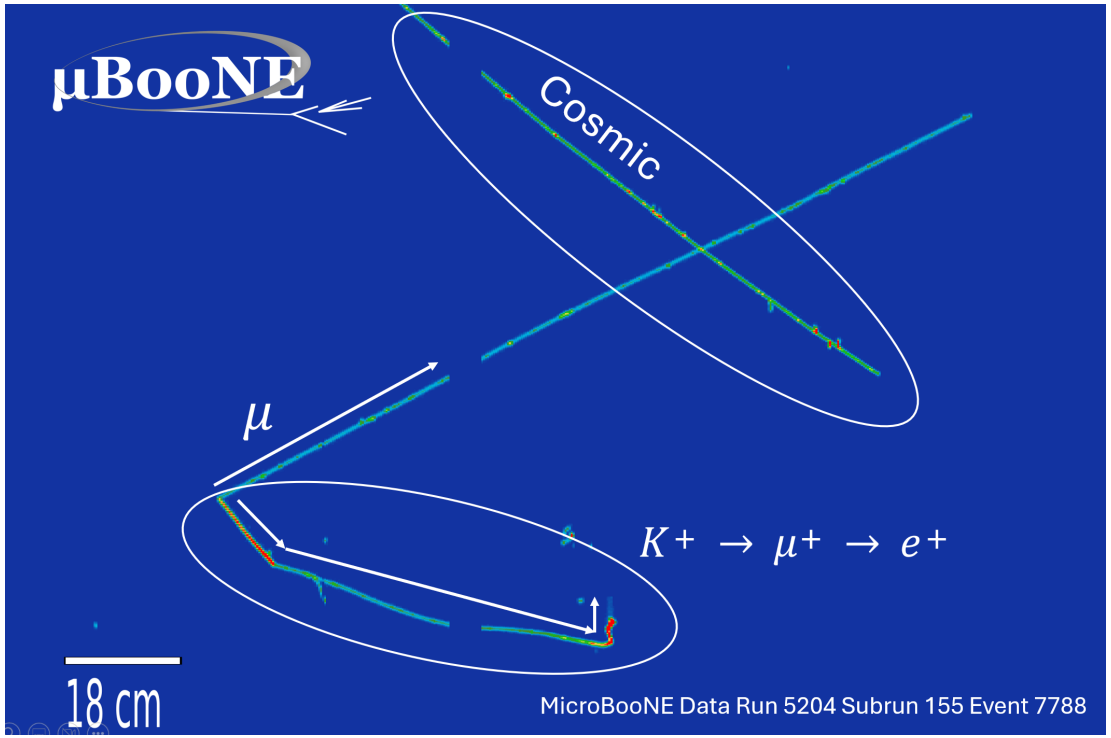
First measurement of ν_μ CC K^+ on Argon

Background for proton-decay searches p → ν K^+

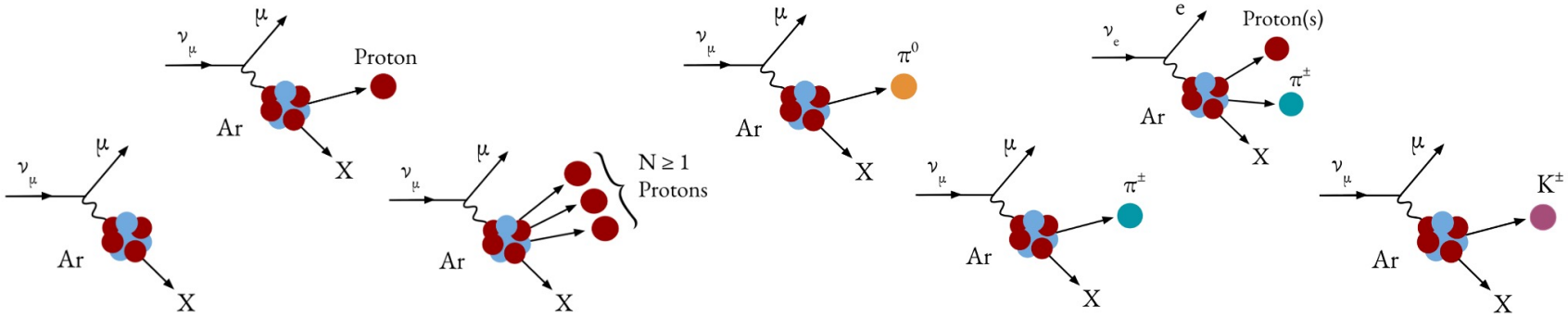
Demonstration of K^+ tagging in LArTPCs

- 10 candidates identified $K^+ \rightarrow \mu^+ \rightarrow e^+$

	Cross section (10^{-42} cm^2 / Nucleon)
MicroBooNE	**7.9 ± 3.2 (stat.) ± 2.8 (syst.)**
Genie 3.4.0 Ar23	9.9
NEUT 5.4.0.1	9.7
NuWro 19.02.1	10.9
GiBUU 2025	6.5



Summary



MicroBooNE has provided a wealth of ν–Ar scattering data for the first time ever

Essential inputs to guide improving our understanding of neutrino interactions on Argon in preparation for DUNE

Lots more to come from MicroBooNE

- many analyses in the pipeline
- recently deployed a suite of new improved reconstruction tools

Backups

MicroBooNE ν-Ar cross section publications

MicroBooNE Cross Section Publications

Inclusive Measurements

- ν_μ-Ar Multiplicity @ BNB: EPJC **79** 248 (2019)
- 1D ν_μ CC Inclusive @ BNB: PRL **123** 131801 (2019), PRL **128** 151801 (2022)
- 2D ν_μ CC Inclusive @ BNB: PRL **133** 041801 (2024), PRD **110** L013006 (2024)
- 3D ν_μ CC Inclusive @ BNB: PLB **870** 139939 (2025)
- 1D ν_e CC Inclusive @ NuMI: PRD **104** 052002 (2021), PRD **105** 051102 (2022)

Pionless Measurements

- 1D, 2D ν_μ CC 0π Np @ BNB: PRD **102** 112013 (2020), PRD **112** 072007 (2025), PRD **112** 112004 (2025)
- 1D ν_μ CC 0π 1p @ BNB: PRL **125** 201803 (2020)
- 1D, 2D ν_μ CC 0π 1p TKI @ BNB: PRL **131** 101802 (2023), PRD **108** 053002 (2023)
- 1D, 2D ν_μ CC 0π 1p GKI @ BNB: PRD **109** 092007 (2024)
- 1D, 2D ν_μ CC 0π 1p Neutrino Direction @ BNB: PRD **111** 113007 (2025)
- 1D ν_μ CC 0π 2p @ BNB: PLB **872** 140052 (2026)
- 2D ν_μ CC 0π Proton Multiplicity @ BNB: MICROBOONE-NOTE-1135-PUB
- 1D ν_e CC 0π Np @ BNB: PRD **106** L051102 (2022), arXiv:2603:13593 (acpt. PRD)
- 1D ν_e CC 0π Np @ NuMI: arXiv:2511.17342 (acpt. PRD)

Pion Production Measurements

- 1D ν_μ CC $1\pi^0$ @ BNB: PRD **99** 091102 (2019), PRD **110** 092014 (2024)
- 1D ν_μ CC $1\pi^0$ TKI @ BNB: arXiv:2606.23559
- 1D, 2D ν_μ NC $1\pi^0$ @ BNB: PRD **107** 012004 (2023), PRL **134** 161802 (2025)
- 1D ν_μ CC $1\pi^\pm$ @ BNB: PRD **113**, 032007 (2026)
- 1D ν_e CC $1\pi^\pm$ @ NuMI: PRL **135** 061802 (2025)
- Coherent ν_μ CC $1\pi^\pm$ @ BNB: arXiv:2606.13613

Rare Processes

- Λ Production @ NuMI: PRL **130** 231802 (2023)
- η Production @ BNB: PRL **132** 151801 (2024)
- K^+ Production @ BNB: PRL **135** 251804 (2025)

Novel Techniques

- MicroBooNE Genie Tune: PRD **105** 072001 (2022)
- Neutron Identification: EPJC **84** 1052 (2024)
- Model Validation: PRD **111** 092010 (2025)