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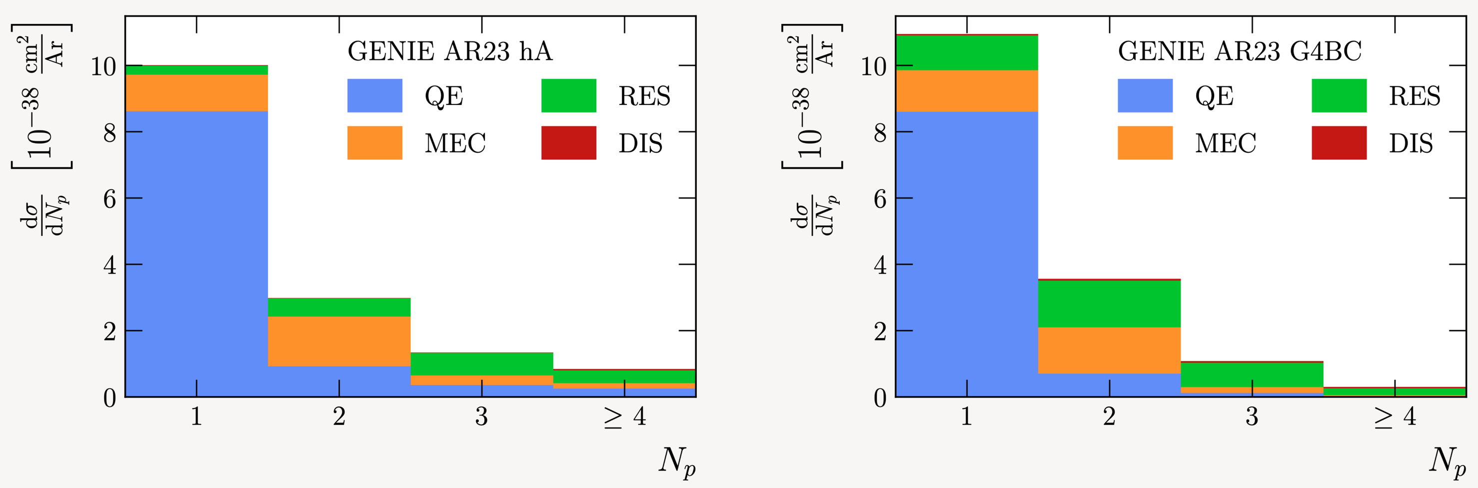
Mesonless Muon Neutrino Charged-Current Cross Section Measurements on Argon Across Proton Multiplicities with MicroBooNE

Francisco Martínez López and Tanaz Mohayai on behalf of the MicroBooNE Collaboration

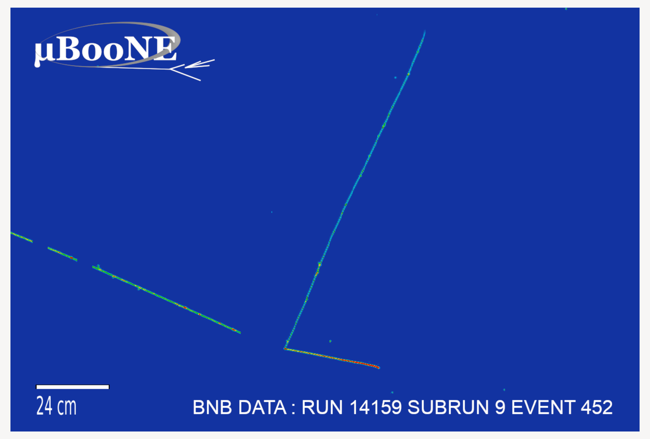
MICROBOONE-NOTE-1135-PUB

Why proton multiplicity?

- Proton multiplicity is directly shaped by FSI — sensitive probe of nuclear models
- Proton counting helps disentangle MEC from single-nucleon processes
- Proton mis-modeling biases neutrino energy reconstruction in oscillation experiments

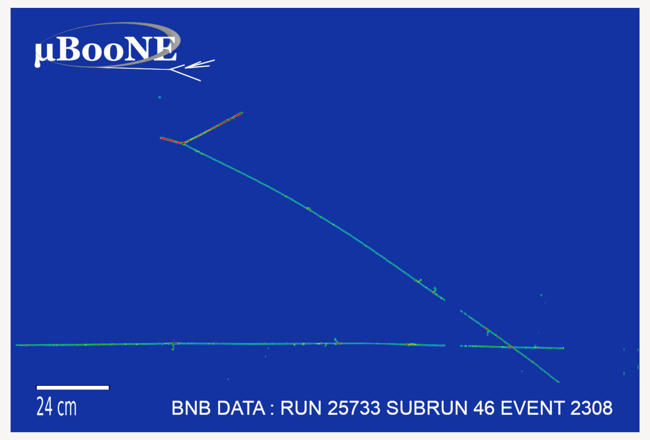


ν_μCC0π program @ MicroBooNE



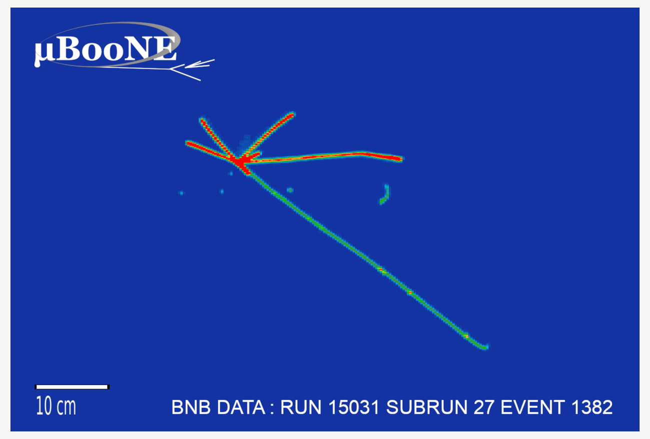
CC0π1p

- Transverse [1] and generalized [2] kinematic imbalance variable measurements
- Sensitive to nuclear effects



CC0π2p

- First 2p cross section measurements on Ar [3]
- Probes two-nucleon knockout through p-p correlations



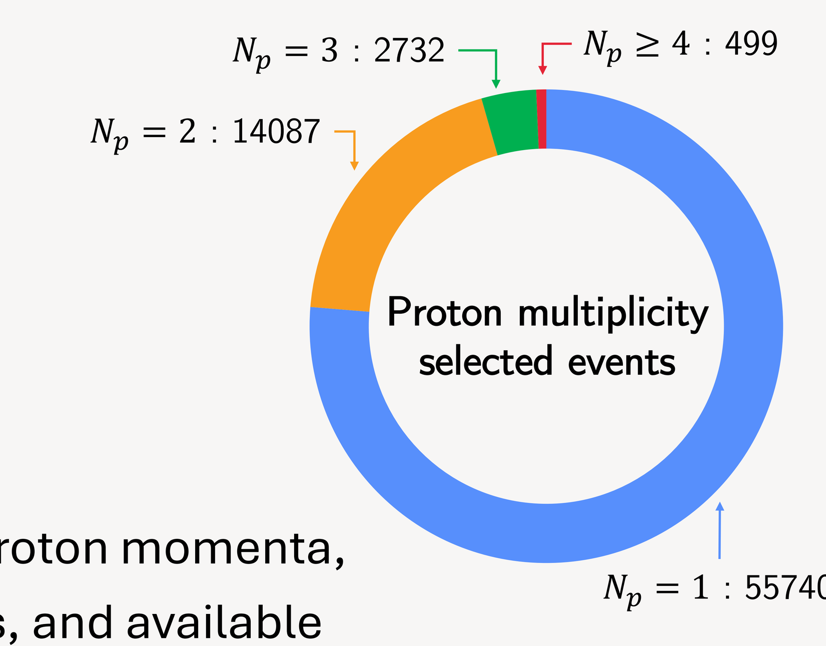
CC0πNp

- Double-differential cross sections probing muon-proton correlations
- Comprehensive measurement with 359 kinematic bins

This work: first measurement correlating cross sections across proton multiplicities

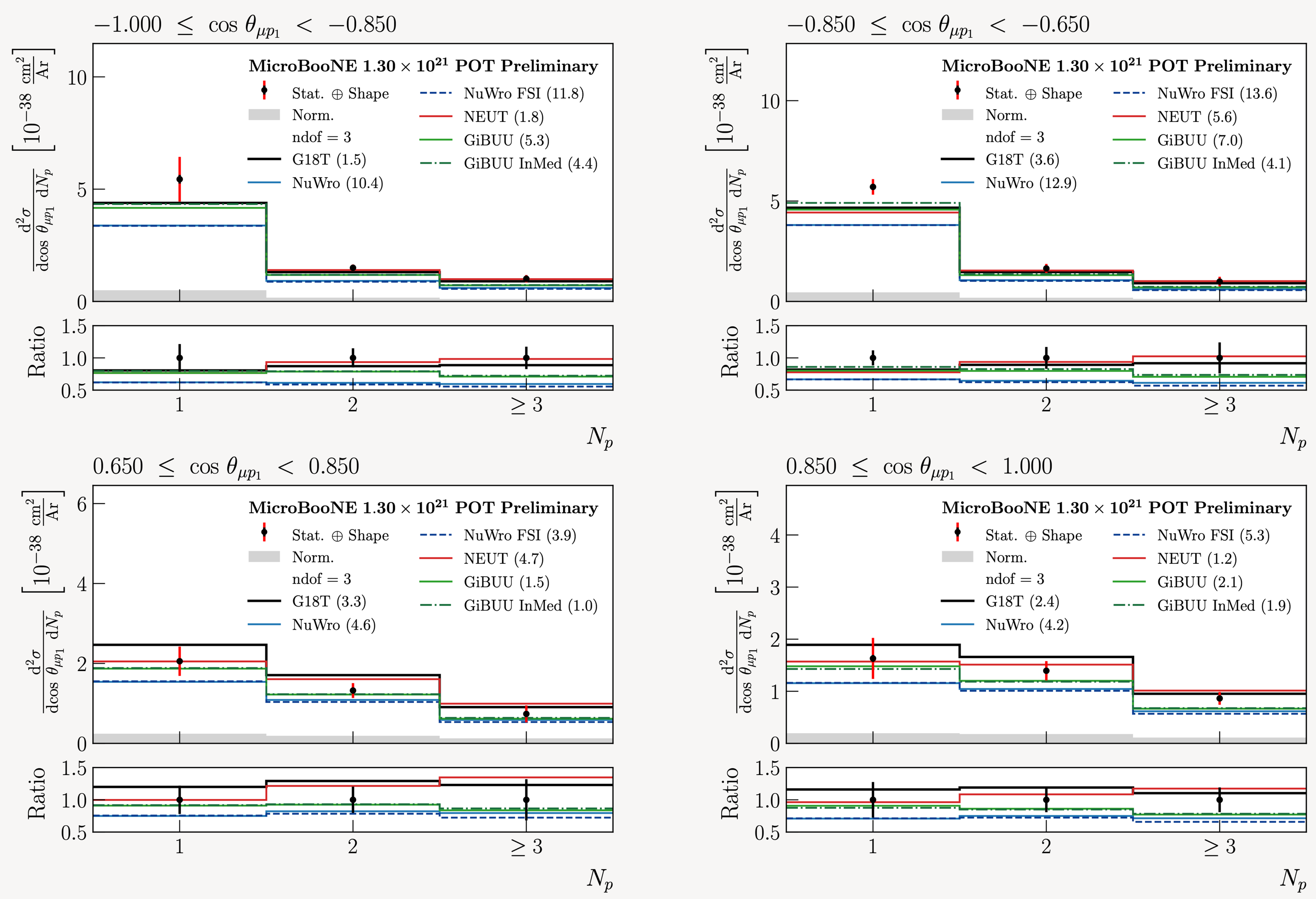
Measurement setup

- First double-differential cross section as a function of proton multiplicity and leading and subleading proton kinematics
- Full MicroBooNE dataset: 1.30×10^{21} POT
- Signal definition:
  - Single muon with $p_\mu \geq 0.10$ GeV/c
  - At least one proton with $0.25 \leq p_{p_1} < 1.00$ GeV/c
  - No mesons
- Multiplicity combined with proton momenta, muon-proton opening angles, and available energy
  - 183 bins across 11 2D distributions



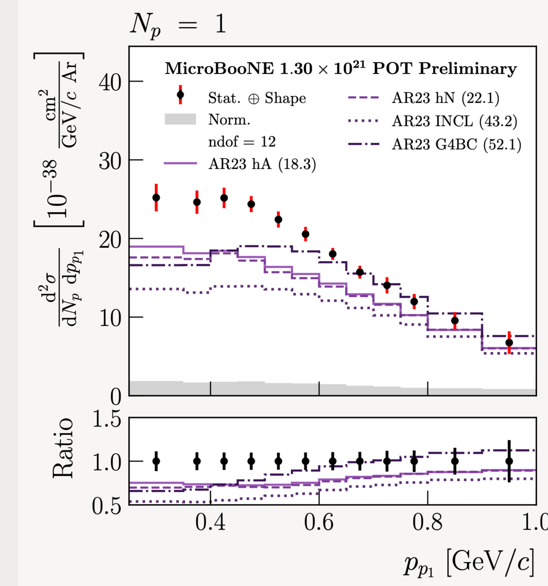
Results — opening angle vs multiplicity

- Backward-angle $N_p = 1$ deficit challenges all generators
  - GiBUU w/ in-medium corrections [5] partially recovers data
- Subleading proton angular isotropy well reproduced by all predictions

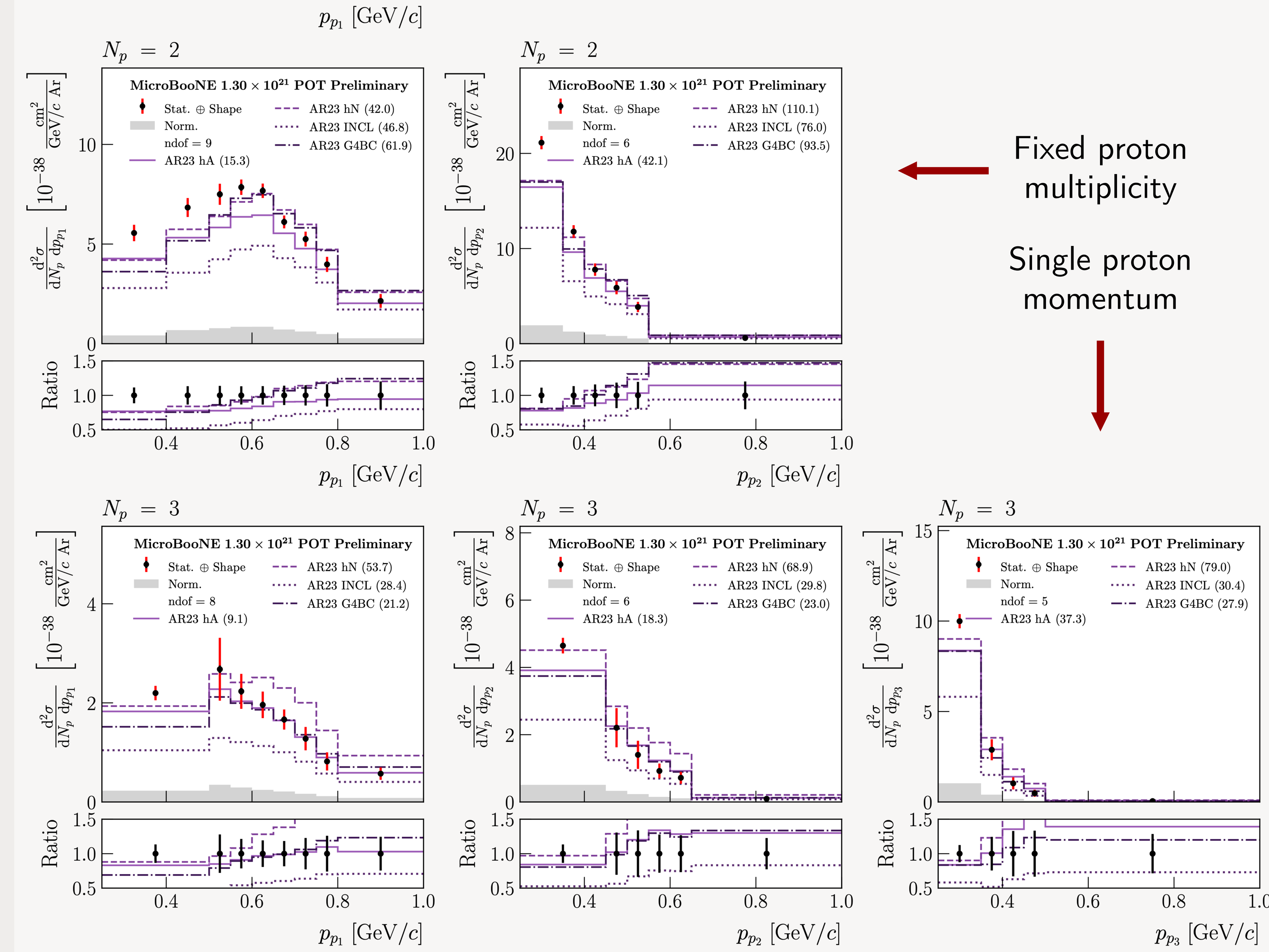


Results — multiplicity vs proton momenta

- Four GENIE AR23 FSI models compared: hA (empirical), hN, INCL, and G4BC (intranuclear cascade)



- FSI variants span wide χ^2 range
  - Strong cascade model sensitivity
- Significant tension for subleading proton kinematics
  - Underprediction at low momentum



Conclusions

- Global χ^2 accounts for correlations across all 183 bins using range-projected test statistic [6]
- GiBUU provides best description for most blocks and globally
- No generator achieves acceptable agreement with full dataset

Generator	MicroBooNE Tune	GiBUU InMed [5]	NuWro v25.11* [7]	GENIE AR23 hA	GENIE AR23 hN
Global χ^2/ndof	570 / 145	429 / 145	585 / 145	488 / 145	1200 / 145

References
[1] MicroBooNE Collaboration, Phys.Rev.D 108 (2023) 5, 053002
[2] MicroBooNE Collaboration, Phys.Rev.D 109 (2024) 9, 092007
[3] MicroBooNE Collaboration, Phys.Lett.B 872 (2026) 140052
[4] MicroBooNE Collaboration, Phys.Rev.D 112 (2025) 11, 112004
[5] B. Bogart, K. Gallmeister, and U. Mosel, Phys.Rev.C 110 (2024) 4, 044001
[6] L. Cooper-Troendle, S. Gardiner, P. Green, F. Martínez López, and T. Mohayai, in preparation
[7] H. Prasad et al., Phys.Rev.D 113 (2026) 9, 096023