The MicroBooNE Cross Section Program

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For the MicroBooNE Collaboration

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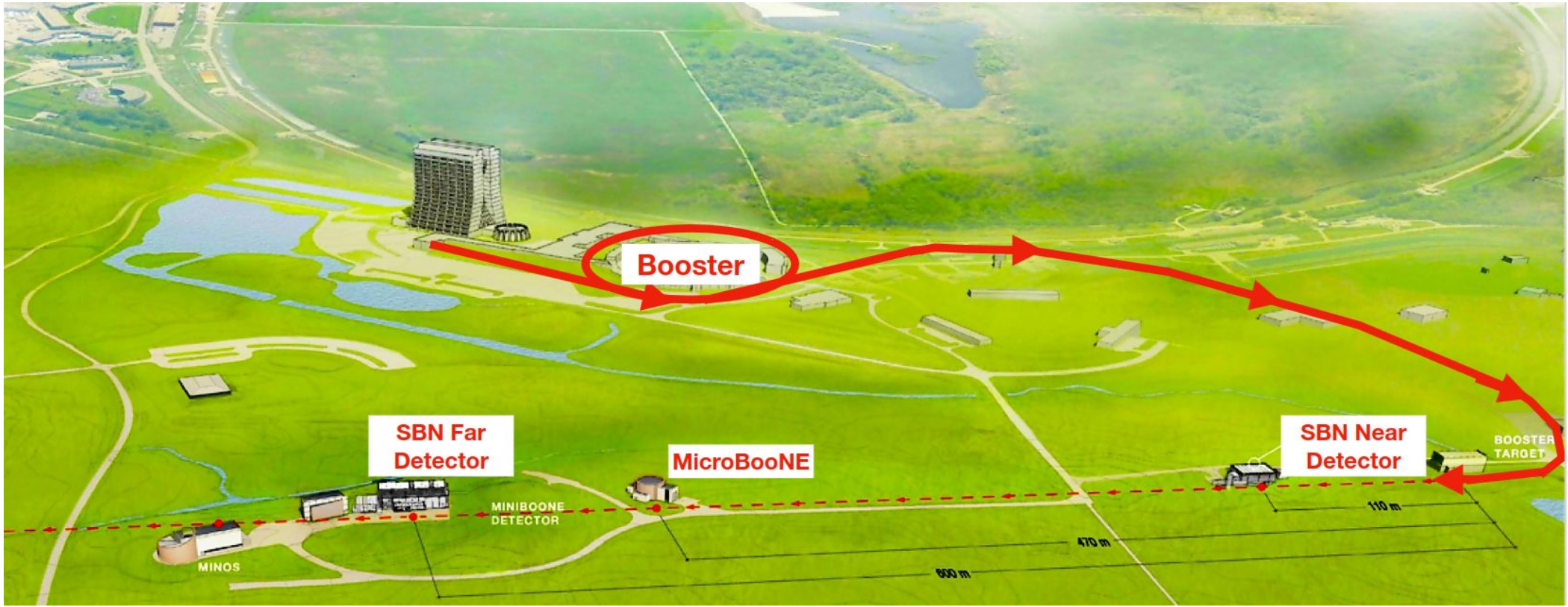
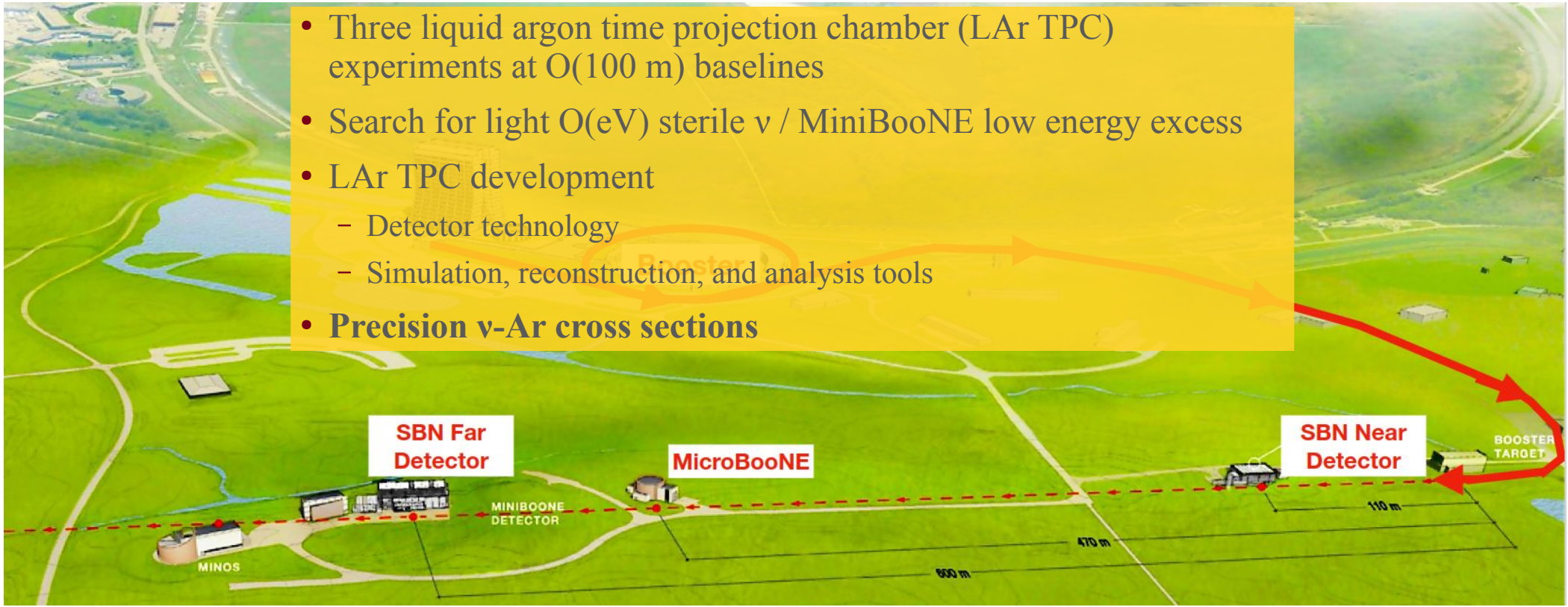
UNIVERSITY OF MINNESOTA

Short-Baseline Neutrino Program at Fermilab

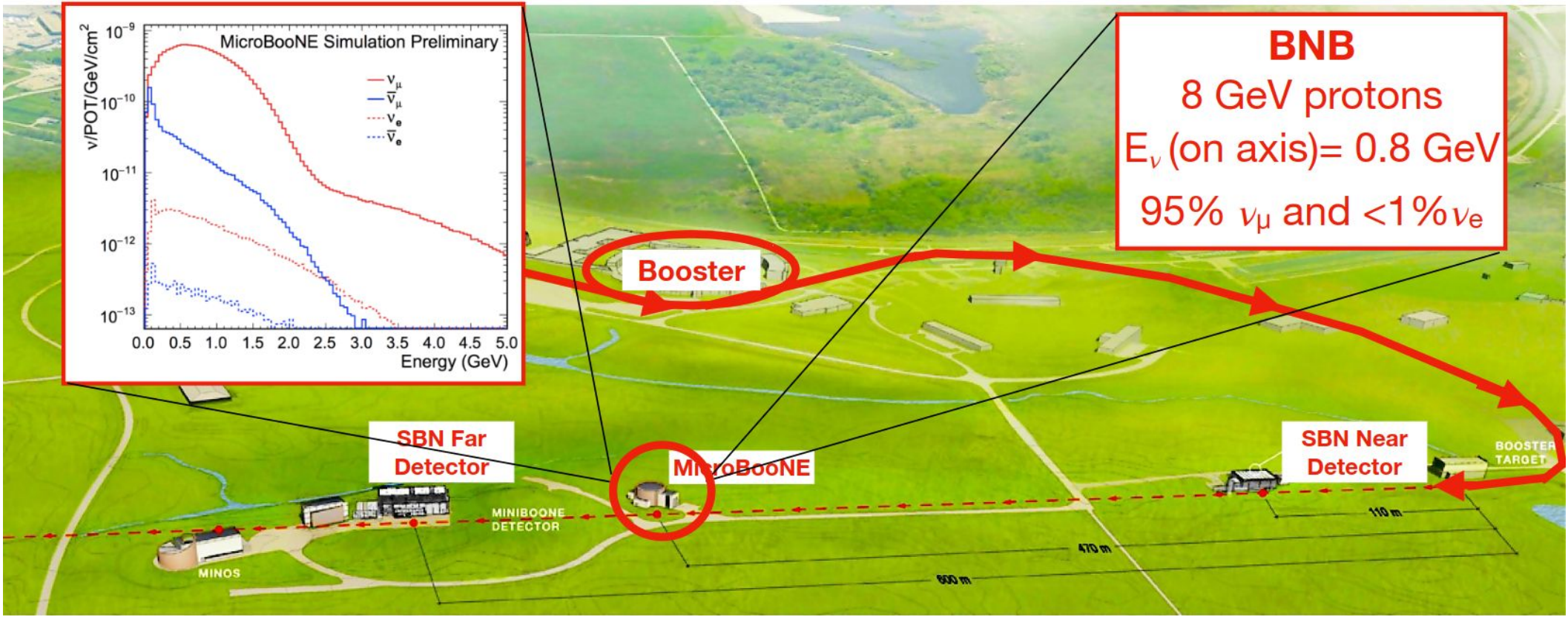


Short-Baseline Neutrino Program at Fermilab

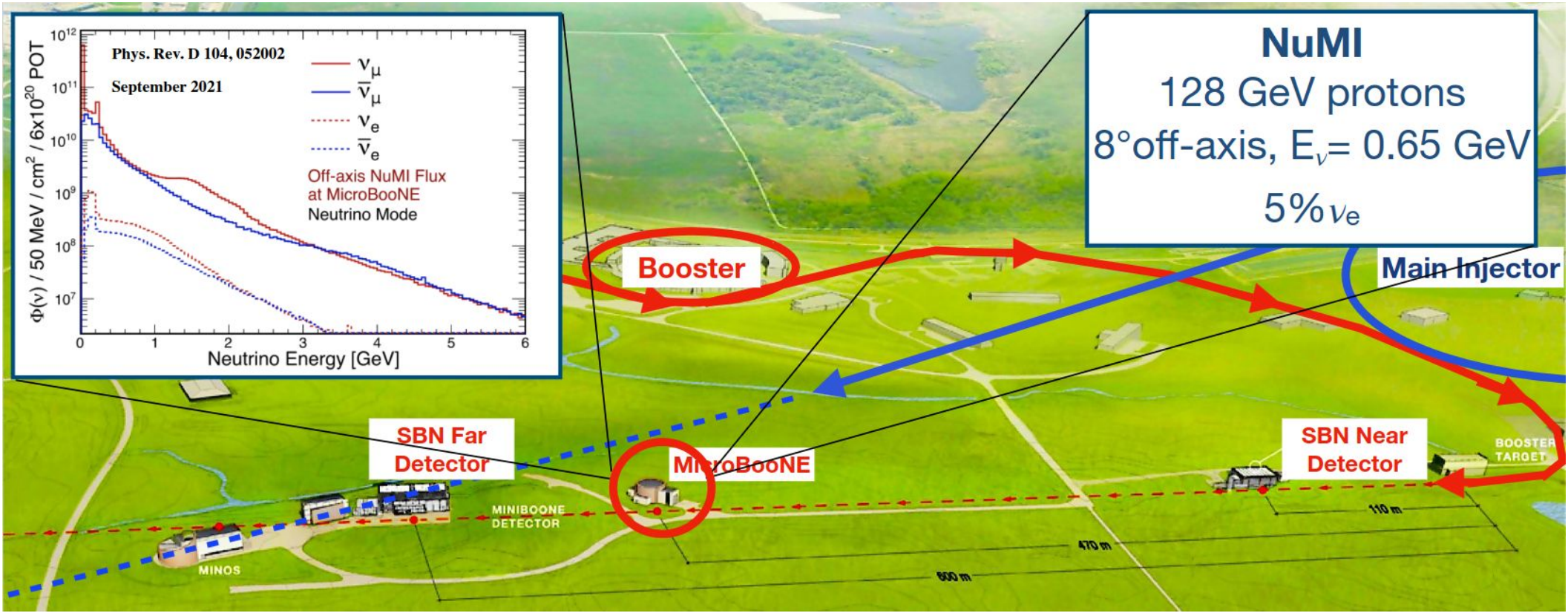
- Three liquid argon time projection chamber (LAr TPC) experiments at O(100 m) baselines
- Search for light O(eV) sterile ν / MiniBooNE low energy excess
- LAr TPC development
  - Detector technology
  - Simulation, reconstruction, and analysis tools
- **Precision ν-Ar cross sections**



Short-Baseline Neutrino Program at Fermilab

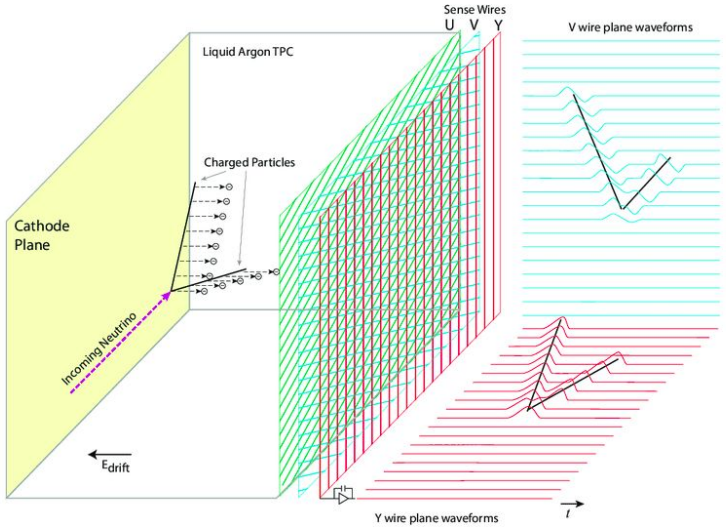


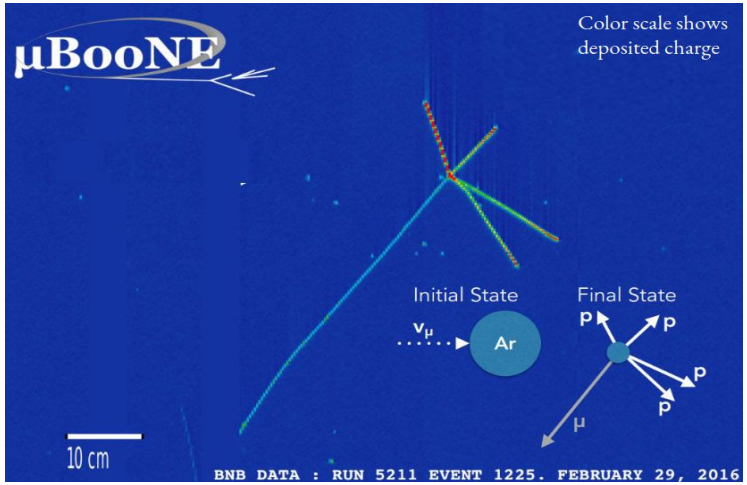
Short-Baseline Neutrino Program at Fermilab



Liquid Argon Time Projection Chamber

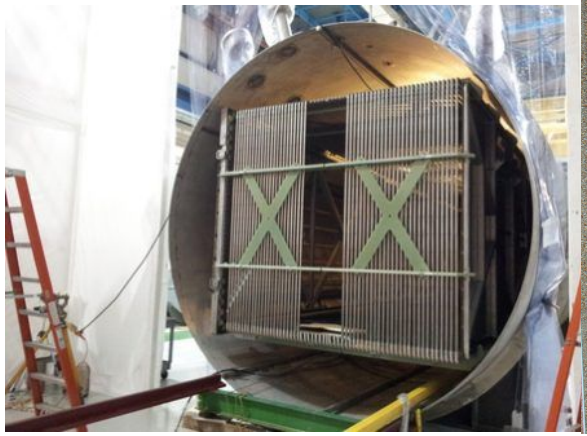
- Fully active tracker-calorimeter
- mm^3 / few ns resolution
- e/γ separation
- Low thresholds
  - p 250 MeV/c
  - e/μ/π 100 MeV/c
  - γ 30 MeV/c

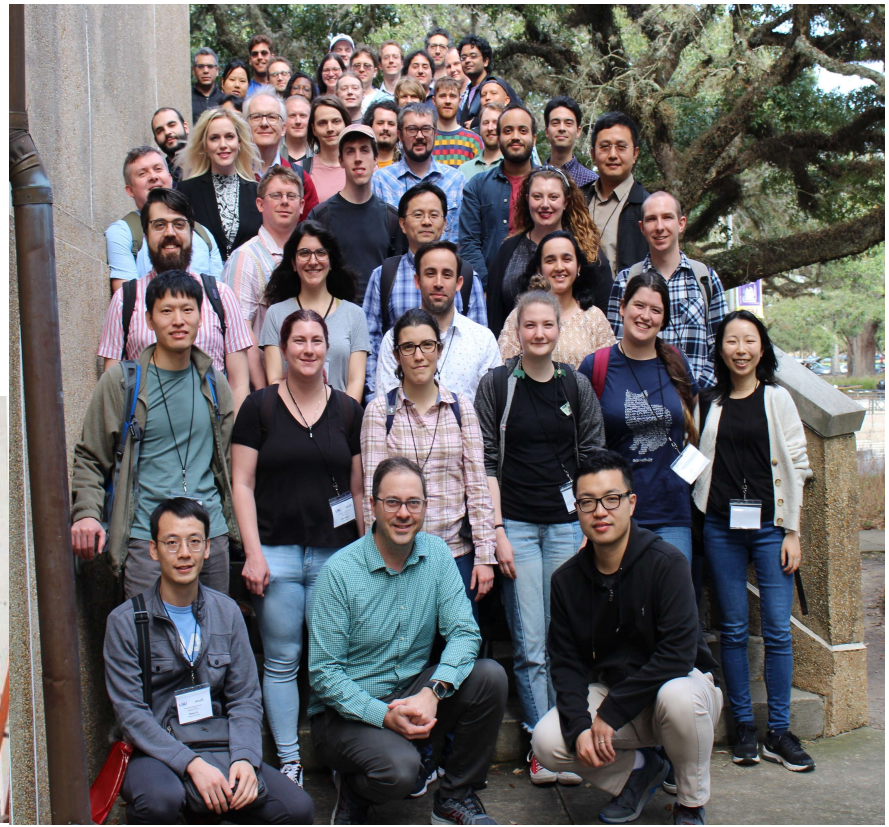




MicroBooNE (uB)

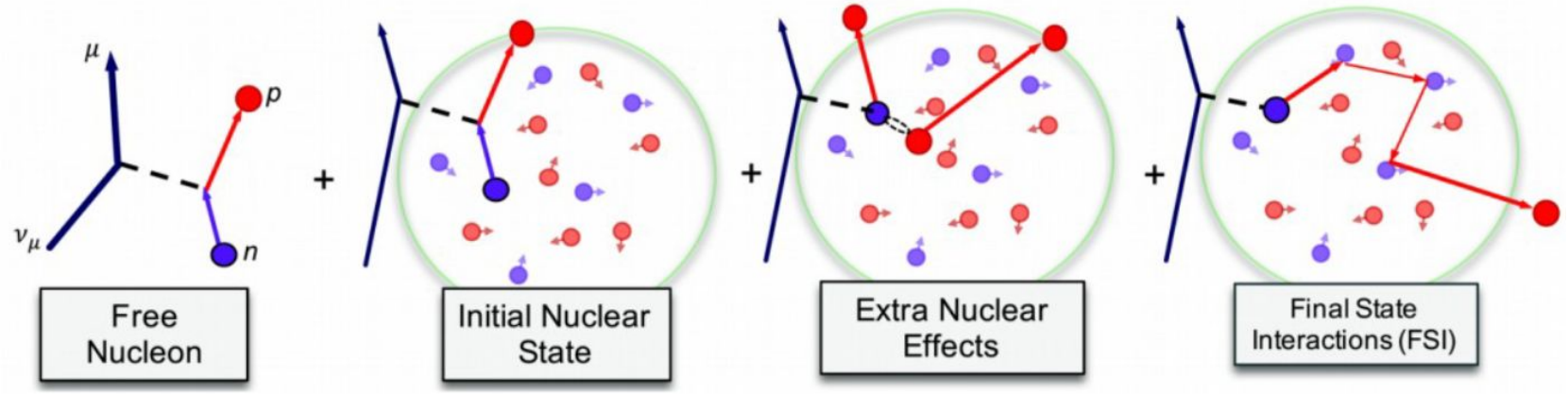
- 170 (85) tonnes (active) LAr
- Operated 2015-2021
- World's largest ν-Ar dataset (~500k interactions) to date



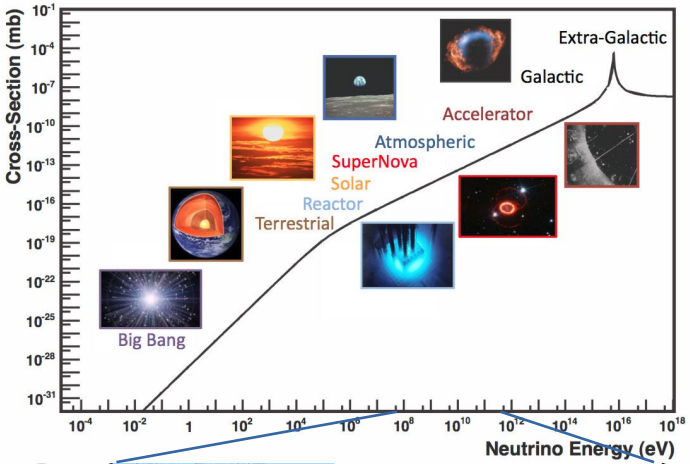


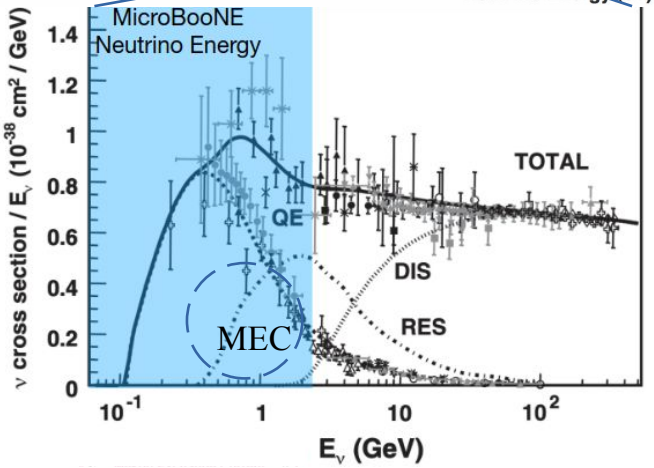
Neutrino Cross Section Measurements

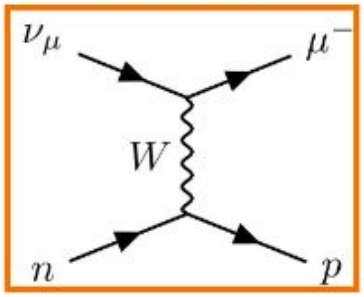
- Leading systematic in oscillation measurements
- ν-Ar measurements lacking (important for DUNE)
- Heavy targets → more stats but harder to model
- Popular generators: GENIE, NuWro, NEUT, GiBUU

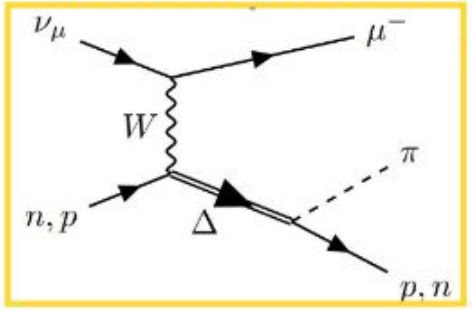


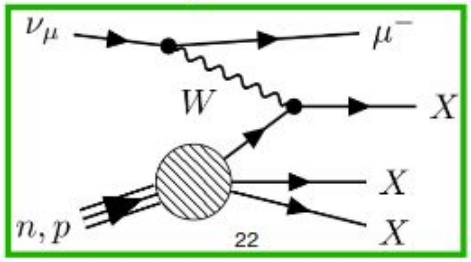
Neutrino Cross Section Measurements

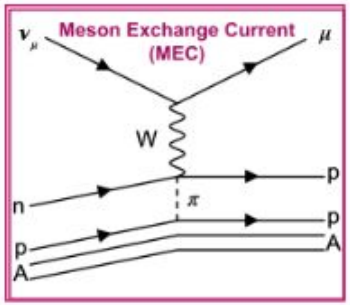












MicroBooNE Cross Section Results

- CC Inclusive
  - 1D & 2D ν_μ CC inclusive @ BNB
    Phys. Rev. Lett. 123, 131801 (2019)
  - 1D ν_μ CC E_ν @ BNB
    Phys. Rev. Lett. 128, 151801 (2022)
  - 3D CC E_ν @ BNB
    arXiv:2307.06413, submitted to PRL
  - 1D ν_e CC inclusive @ NuMI
    Phys. Rev. D105, L051102 (2022)
    Phys. Rev. D104, 052002 (2021)
- Pion production
  - ν_μ NCπ0 @ BNB
    Phys. Rev. D 107, 012004 (2023)
- Rare channels
  - Λ production @ NuMI
    Phys. Rev. Lett. 130, 231802 (2023)
  - η production @ BNB
    arXiv:2305.16249, submitted to PRL

- CC0π
  - 1D ν_e CCNp0π @ BNB
    Phys. Rev. D 106, L051102 (2022)
  - 1D & 2D ν_μ CC1p0π Kinematic Imbalance @ BNB
    Phys. Rev. Lett. 131, 101802 (2023)
    Phys. Rev. D 108, 053002 (2023)
    arxiv:2310.06082, submitted to PRD
  - 1D ν_μ CC1p0π @ BNB
    Phys. Rev. Lett. 125, 201803 (2020)
  - 1D ν_μ CC2p @ BNB
    arXiv:2211.03734
  - 1D ν_μ CCNp0π @ BNB
    Phys. Rev. D102, 112013 (2020)

15 publications and more than 30 active analyses

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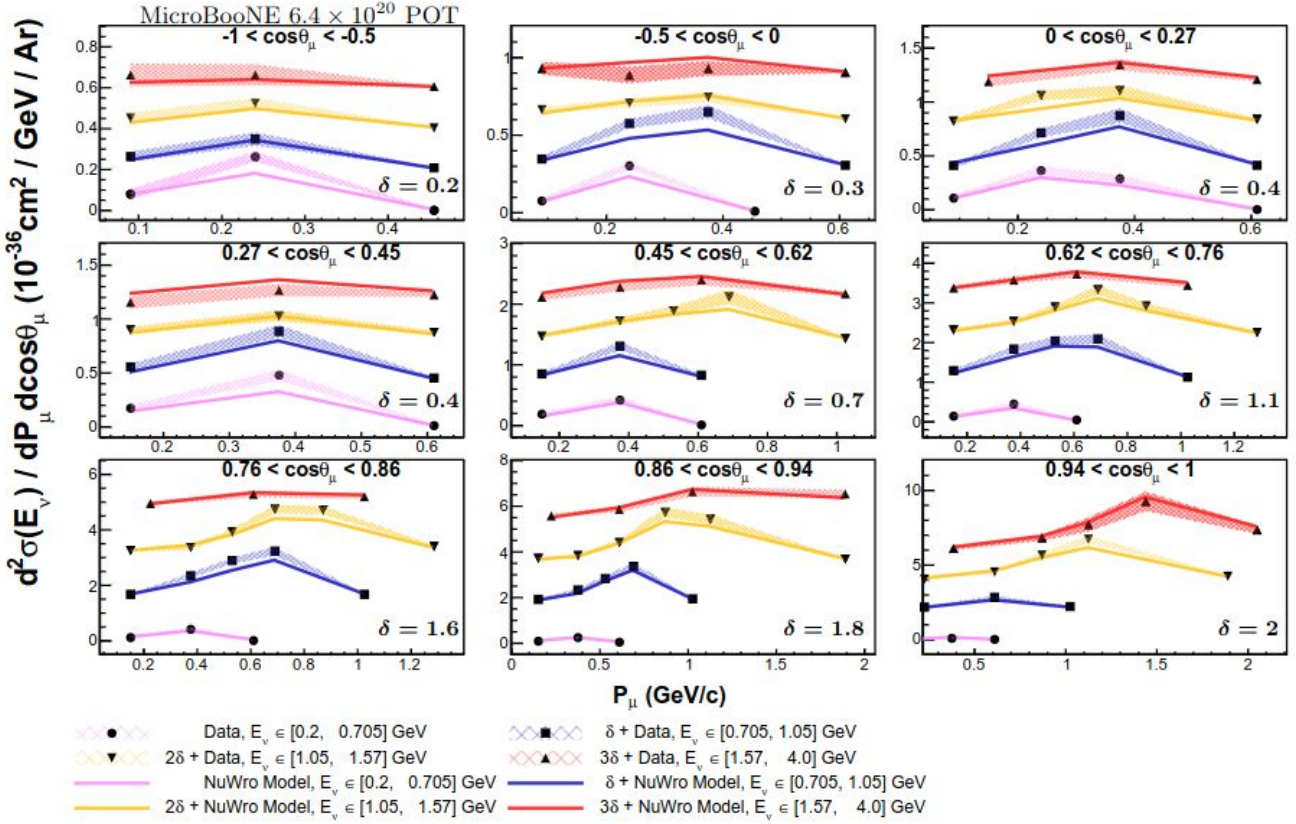
    Phys. Rev. D102, 112013 (2020)

Results shown used ~1/2 MicroBooNE dataset

ν_μCC Inclusive 3D

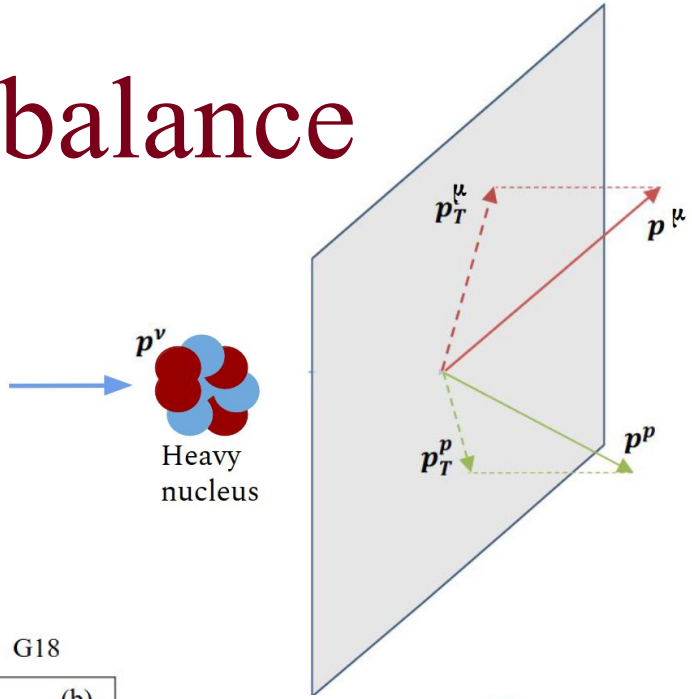
- First triple-differential cross section result on Ar covering broad phase space
- Extensive validation of missing energy model
- Neutrino energy dependence
- Disagreements in all generators in different parts of phase space

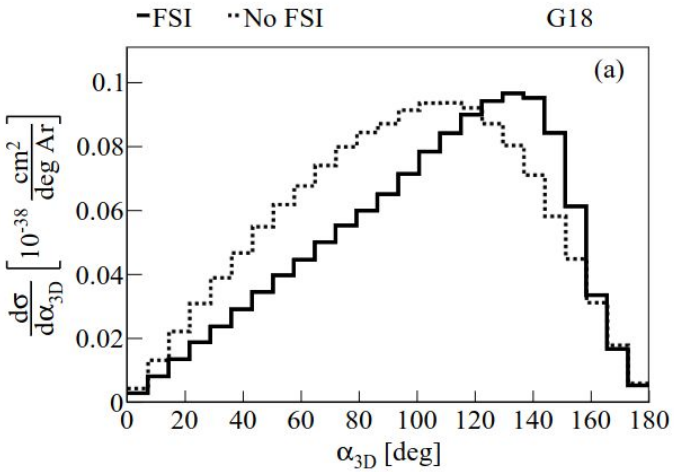


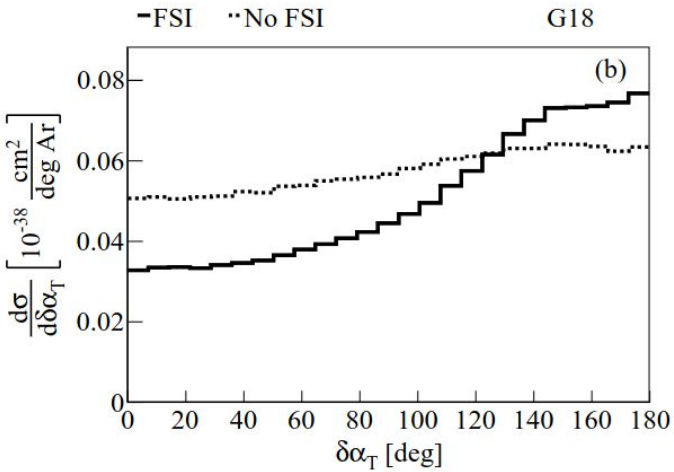
arxiv:2307.06413
Submitted to PRL

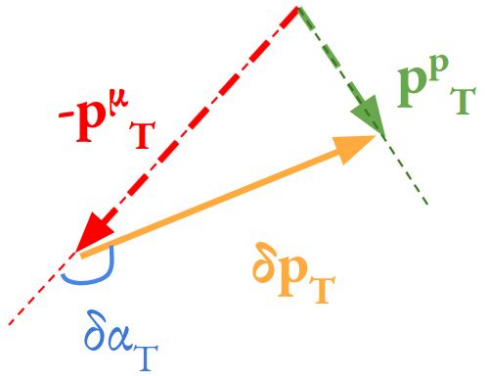
ν_μCC1p0π Kinematic Imbalance

- Assumptions about ν kinematics
  - Total transverse momentum (p_T) = 0, visible energy (E_{cal}) ~ p_ν
  - Deviations → FSI / nuclear effects
- 2D analysis in transverse plane (TKI)
- New method generalizes to 3D (GKI)
- Study magnitude (δp_T / p_n) and orientation of imbalance ($\delta\alpha_T$ / α_{3D})







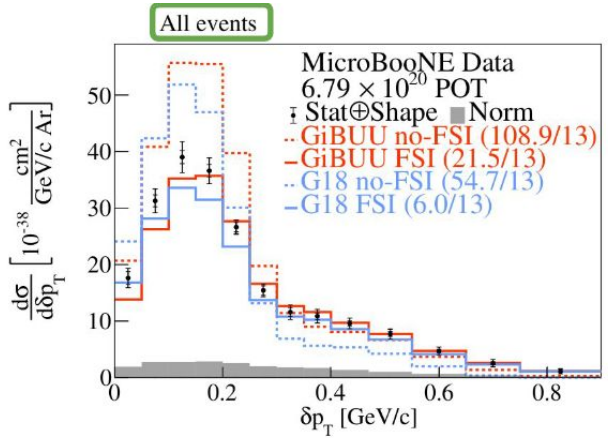


ν_μCC1p0π 2D TKI

- First 2D TKI analysis for Ar
- Greater model discrimination power
- Ability to target different aspects of FSI/nuclear effects

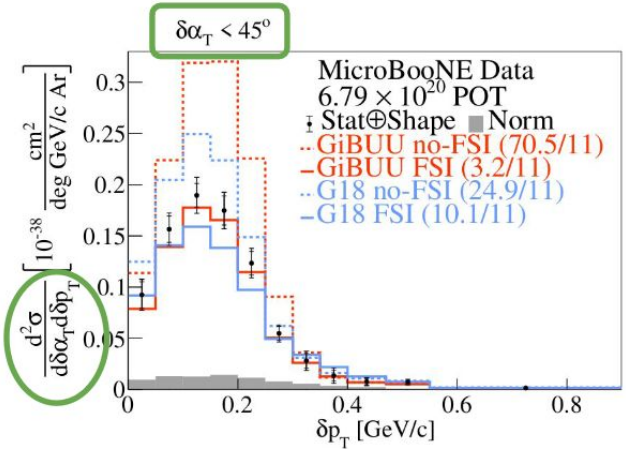
Phys. Rev. Lett. 131, 101802 (2023)

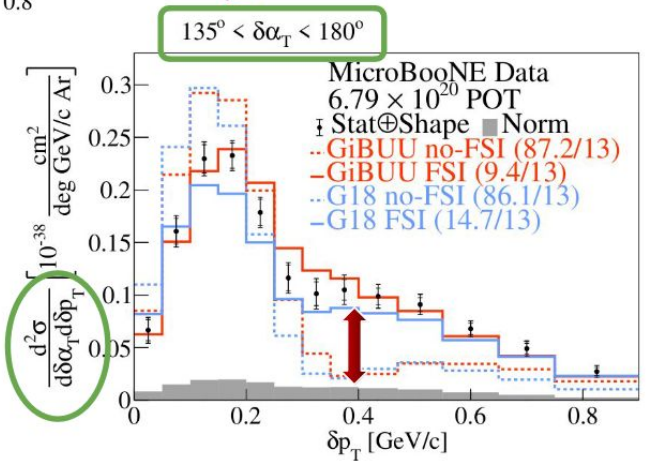
Phys. Rev. D 108, 053002 (2023)



QE-dominated

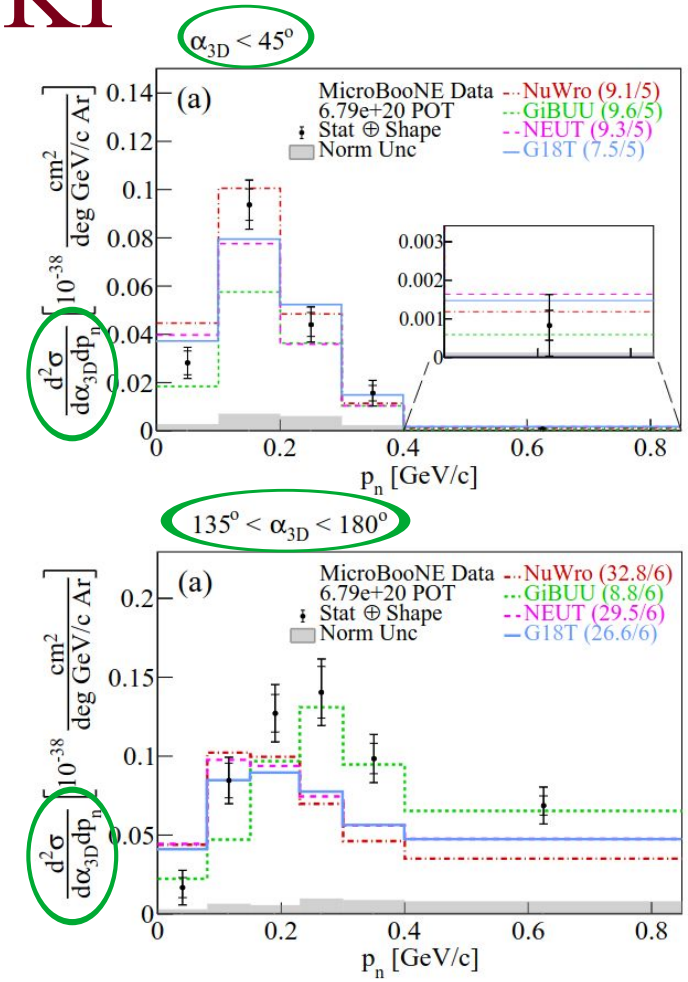
MEC/RES/FSI-dominated





ν_μCC1p0π 2D GKI

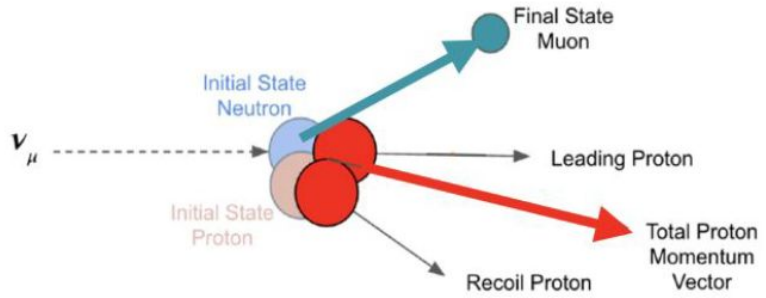
- Novel technique building on 2D TKI analysis
- More information → additional model discrimination power
- GiBUU has sophisticated nuclear transport model
- GENIE best when FSI non-dominant



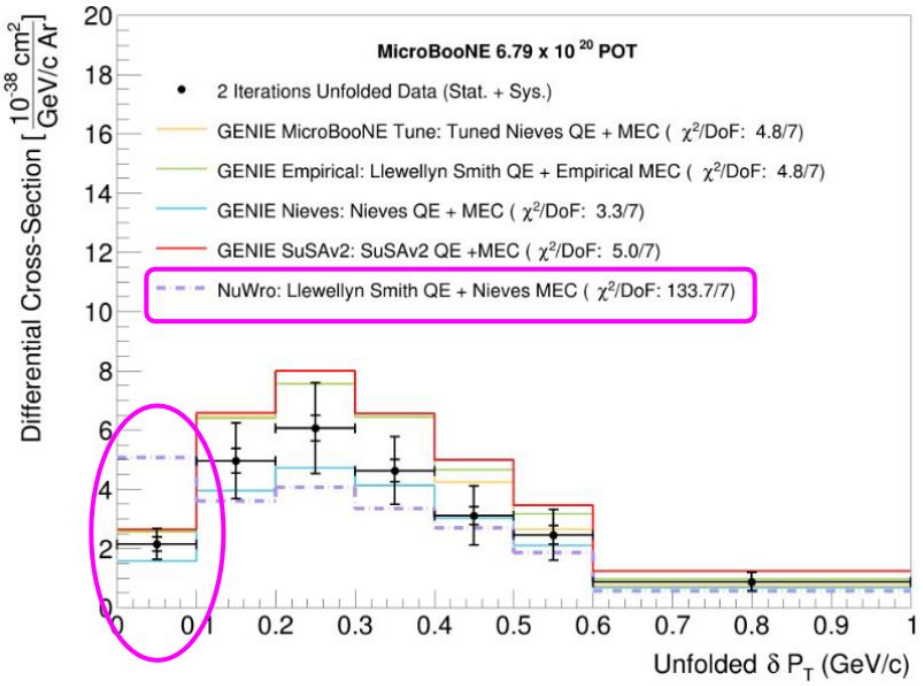
arxiv:2310.06082
Submitted to PRD

ν_μCC2p0π

- First differential cross section of this channel on Ar
- Dominated by meson exchange current (MEC)
- GENIE yields reasonable agreement
- NuWro overprediction at low δp_T



arXiv:2211.03734

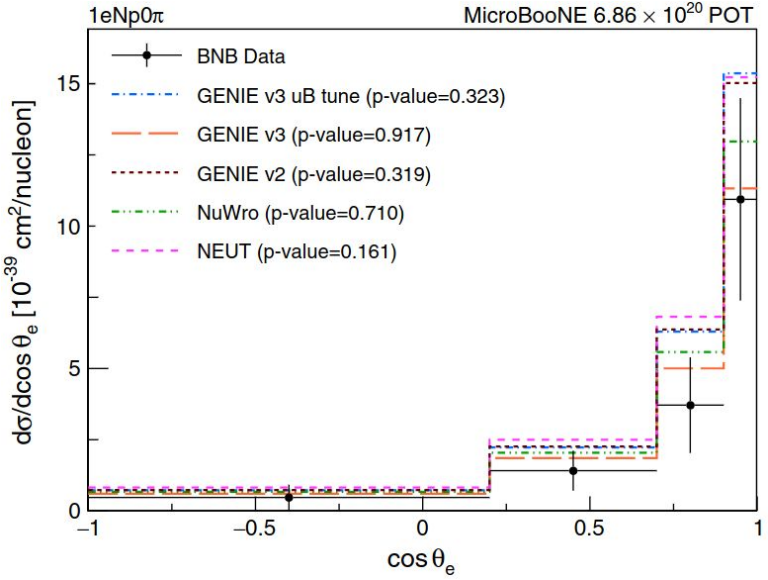


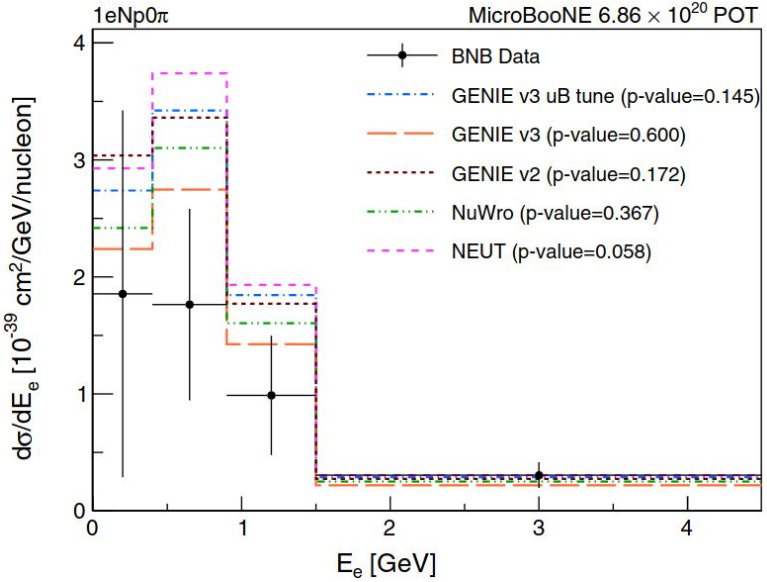
$$\delta\vec{P}_T = \vec{P}_T^{\mu} + \vec{P}_T^{L} + \vec{P}_T^{R}$$

ν_eCCNp0π

- First differential ν_e-Ar cross section in this channel
- Results in terms of electron and proton kinematics
- Reasonable agreement across generators
- Important result for future LAr based BSM searches

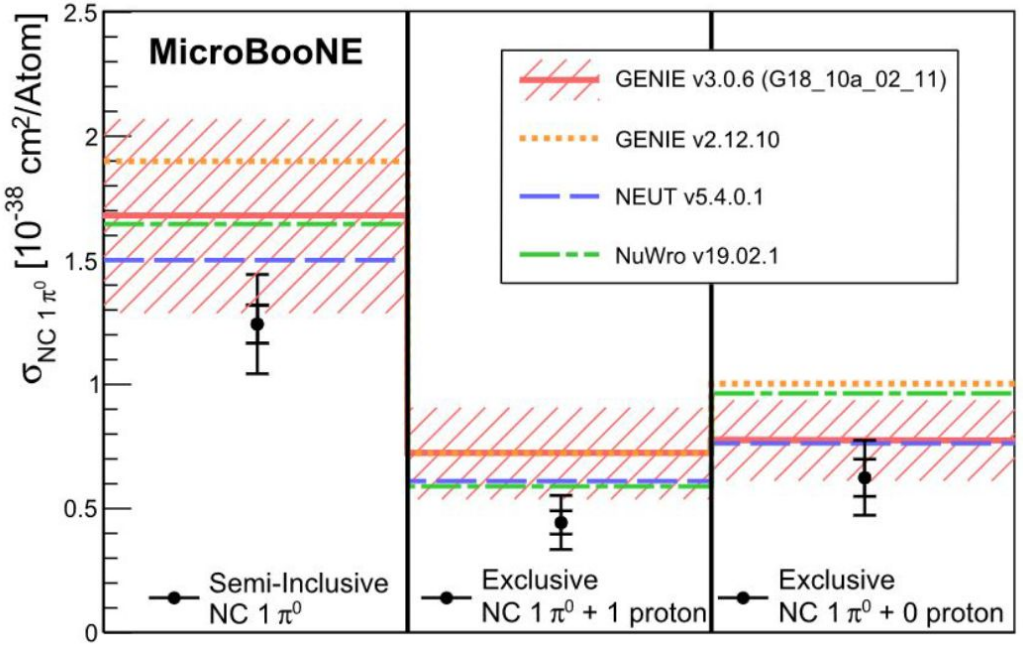
Phys. Rev. D 106, L051102 (2022)





$\nu NC\pi^0$

- First exclusive measurements on Ar
- 0p and 1p channels
- Background constraint for e/γ analyses
- NEUT yields overall best agreement



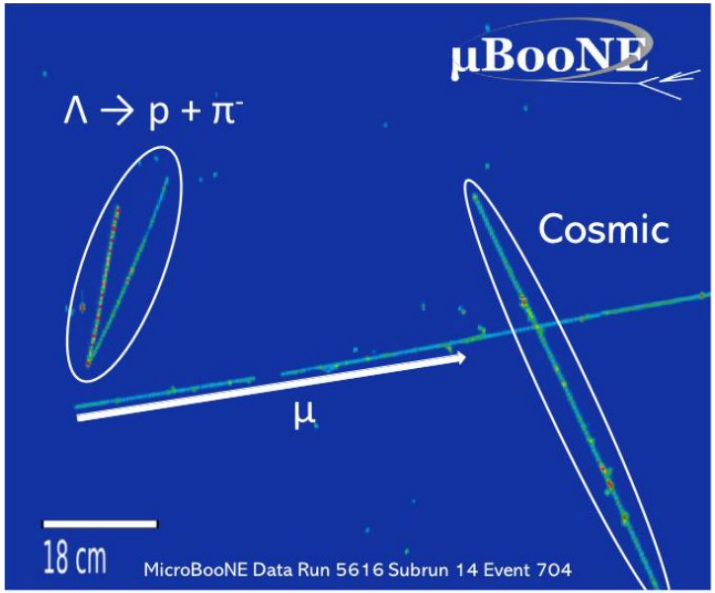
Phys. Rev. D 107, 012004

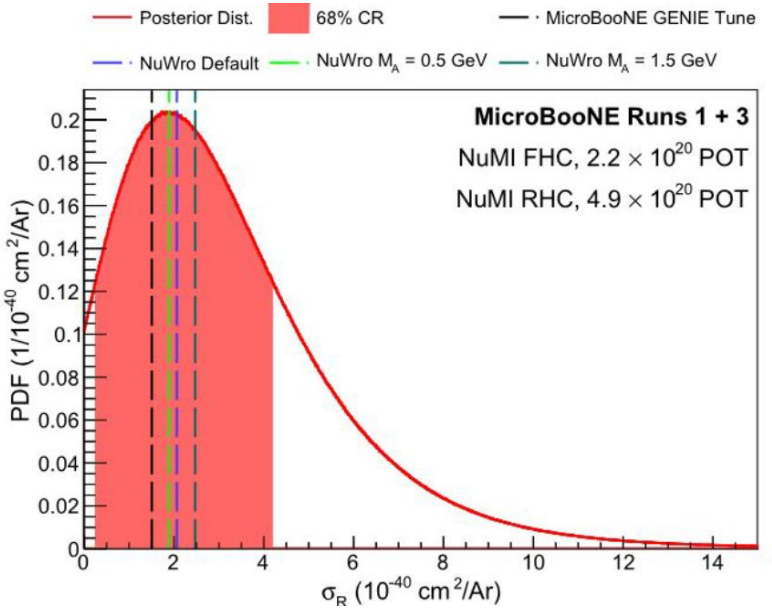
Λ Baryon Production

- First measurement w/modern detector
- Rare – 5 events observed
- Identified via invariant mass and vertex separation

Phys. Rev. Lett. 130, 231802

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

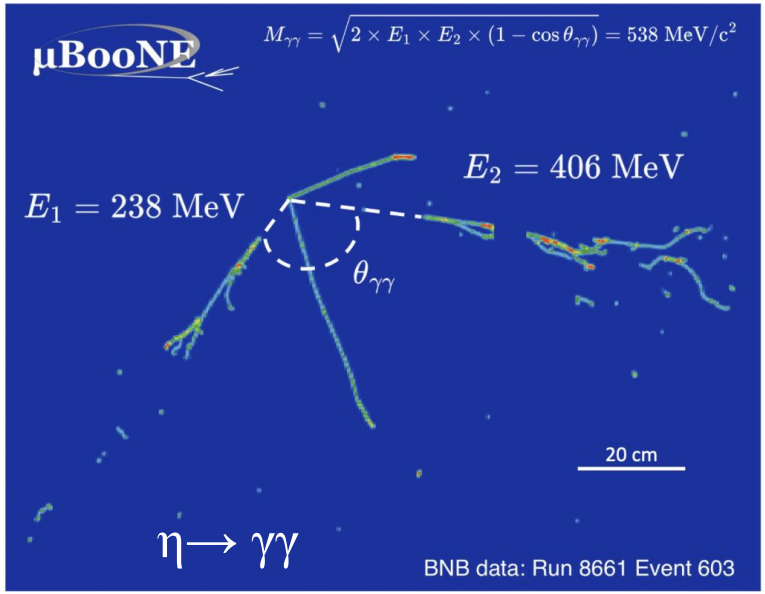


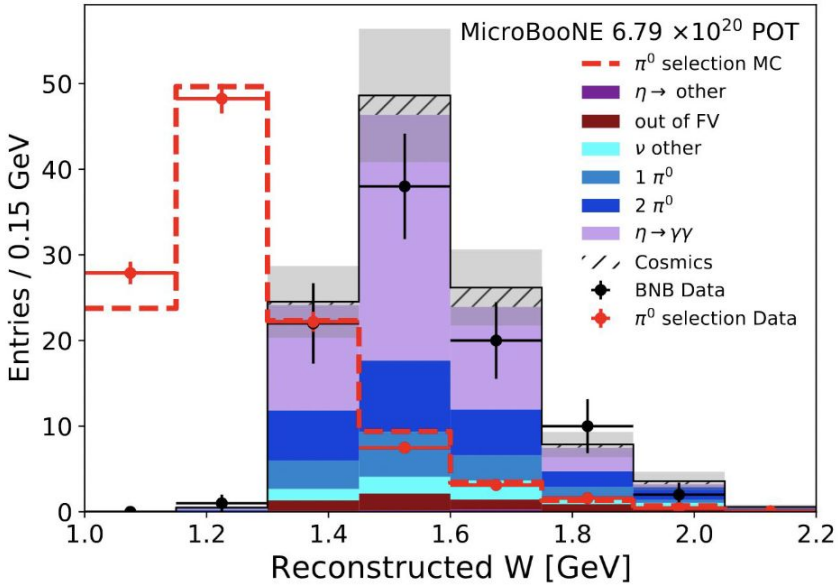


η Meson Production

- η production dominated by N(1535) resonance in uB
- Predicted proton decay mode
- New tool for studying higher order resonances
- Higher mass (548 MeV) standard candle for energy scale calibration

arXiv:2305.16249, submitted to PRL





Outlook

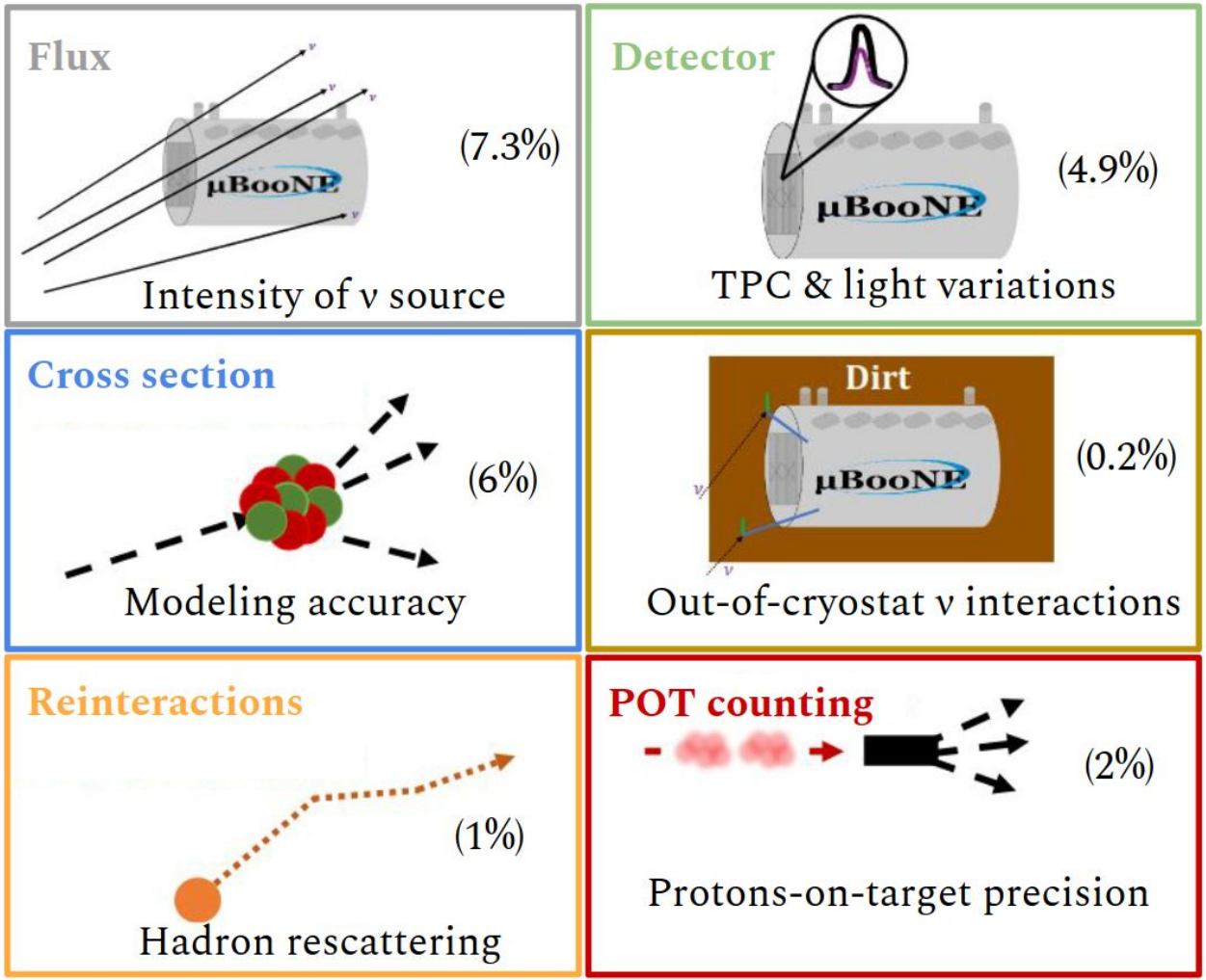
- CC inclusive
  - ν_μ CC inclusive @ NuMI
  - ν_e /ν_μ ratios @ BNB, NuMI
  - 3D E_ν, E_μ, hadronic energy @ NuMI & BNB
  - $\bar{\nu}_e$ @ NuMI
- Pion production
  - ν_μ CC1π^+ @ BNB, NuMI
  - ν_μ CCNπ @ NuMI
  - 1D ν_μ CCπ^0 @ BNB
  - 2D ν_μ CC/NC π^0 @ BNB
  - 2D $\nu_{e,\mu}$ NCπ^0 @ BNB
  - Kinematic imbalance
- CC0π
  - ν_μ CC0π inclusive @ BNB
  - 2D ν_μ CCNp0π @ BNB
  - 1D ν_e CC0πNp @ NuMI
  - 1D ν_μ NC1p0π @ BNB
- Rare & novel channels
  - ν_μ CC kaon @ BNB, NuMI
  - MeV-scale physics
  - Neutrons @ BNB

Summary

- Diverse, comprehensive cross section program
- Full dataset analyses (~2x stats) coming soon
- Stay tuned!

Backup

Uncertainties



A. Papadopoulou
(breakdown for 2D TKI analysis)

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

Total (11%)

Systematics-dominated analysis

Neutrino Event Generators at a Glance

- GENIE – version 2 and version 3
  - We have our own tune of v3
- NuWro – more theory focused generator, developed by University of Wrocław group
- NEUT – developed in-house by the SK/T2K collaboration
- GiBUU – more quantum mechanical, solves the Giessen-Boltzmann-Uehling-Uhlenbeck nuclear transport equations