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U.S. DEPARTMENT OF ENERGY

μBooNE

MicroBooNE cross section results from muon neutrinos with pions in the final state and rare processes

Michael Kirby (BNL) on behalf of the MicroBooNE Collaboration

42nd ICHEP 2024 - Prague, CZ

July 18, 2024

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Neutrino Interaction Model Investigations at MicroBooNE

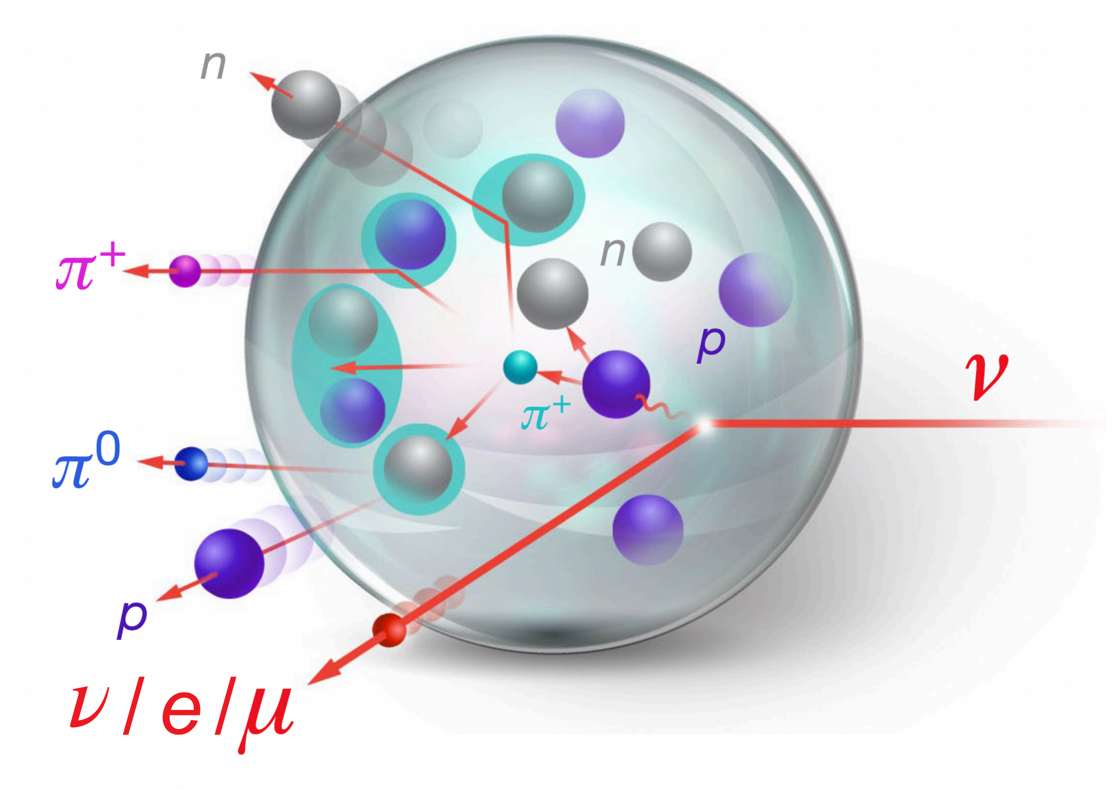
largest neutrino-argon dataset allows MicroBooNE to target specific aspects of neutrino interaction models

previous talks focused on ν_e-Ar and ν_μ-Ar inclusive and ν_μ-Ar pion-less measurements

Measurement of ν-Ar π topologies

- key background to ν_e appearance
- probes RES production

First measurements of rare production
- key component to exotic searches and future sensitivity studies



Nature 599, 565 (2021)

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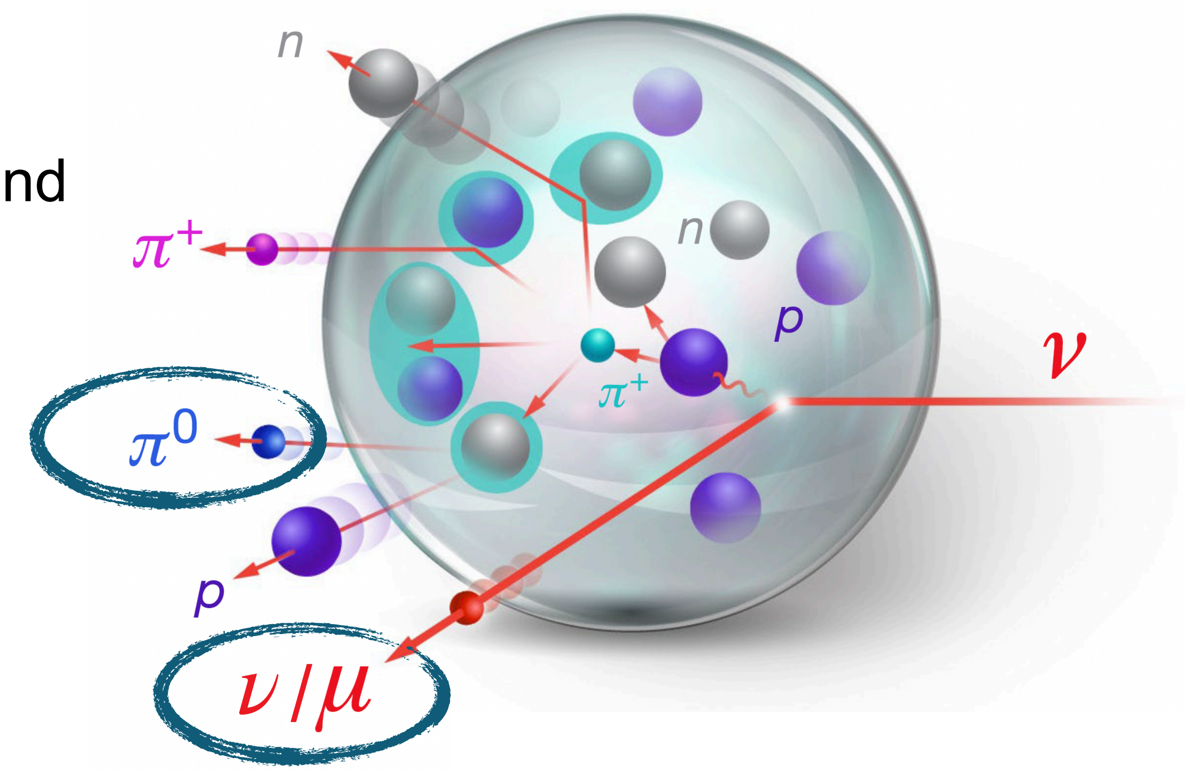

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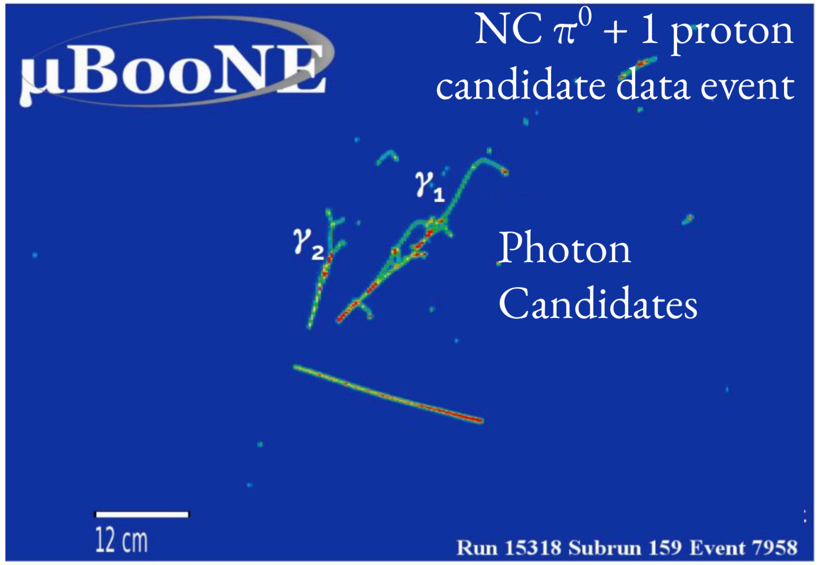
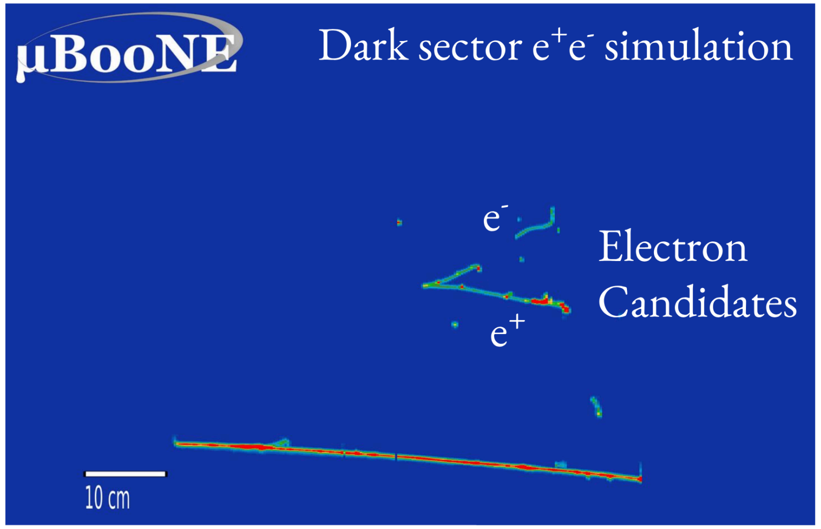
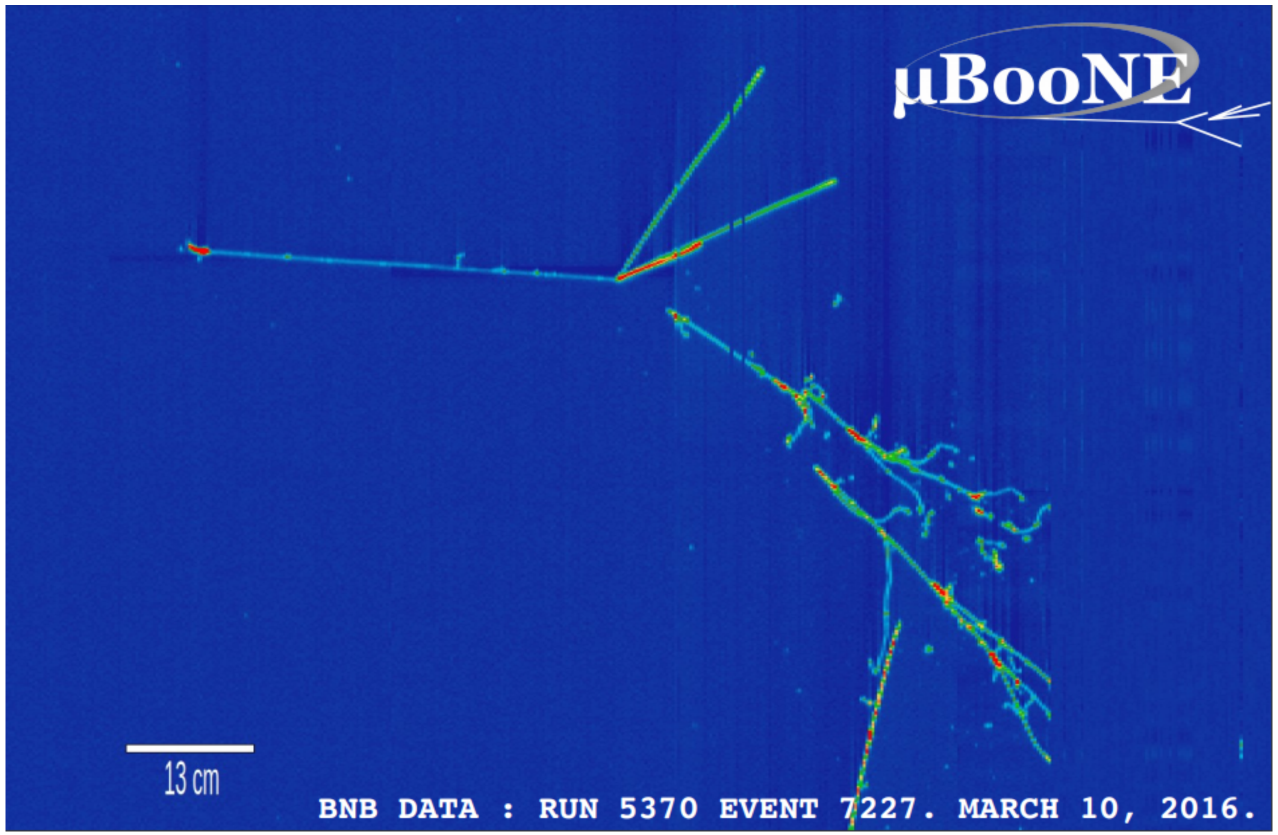
π^0 Production Measurements





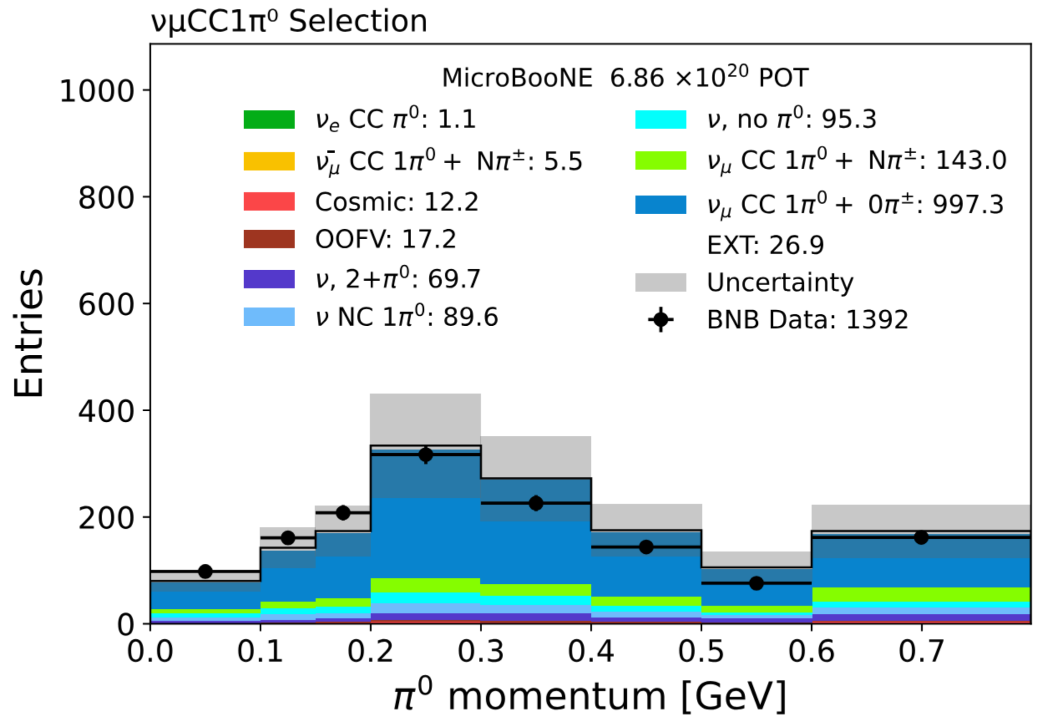
- significant role in ν_e appearance searches
- π^0 is dominant background in single photon and e^+e^-BSM searches
- Analyses that probe both neutral and charge current production

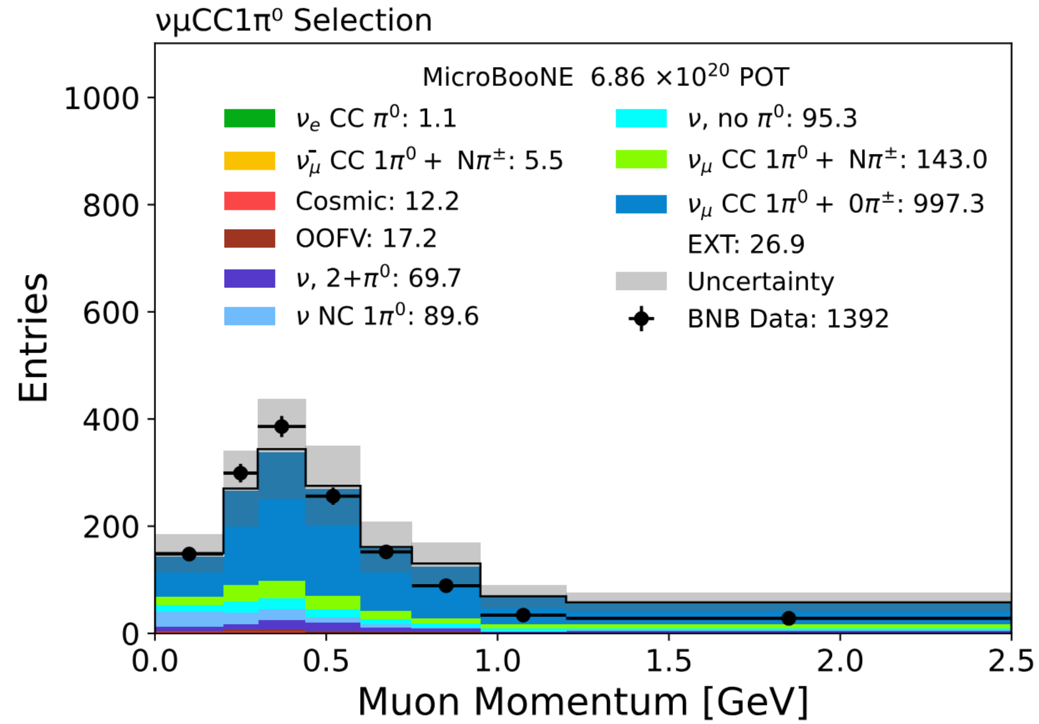
CC π^0 Event Selection



- ν_μ +Ar $\longrightarrow$ μ + π^0 + 0 $\pi^\pm$ + X
- reconstructed muon candidate (track, μ-like PID)
- two shower candidates
- reject charged pions
- no requirement on nucleons

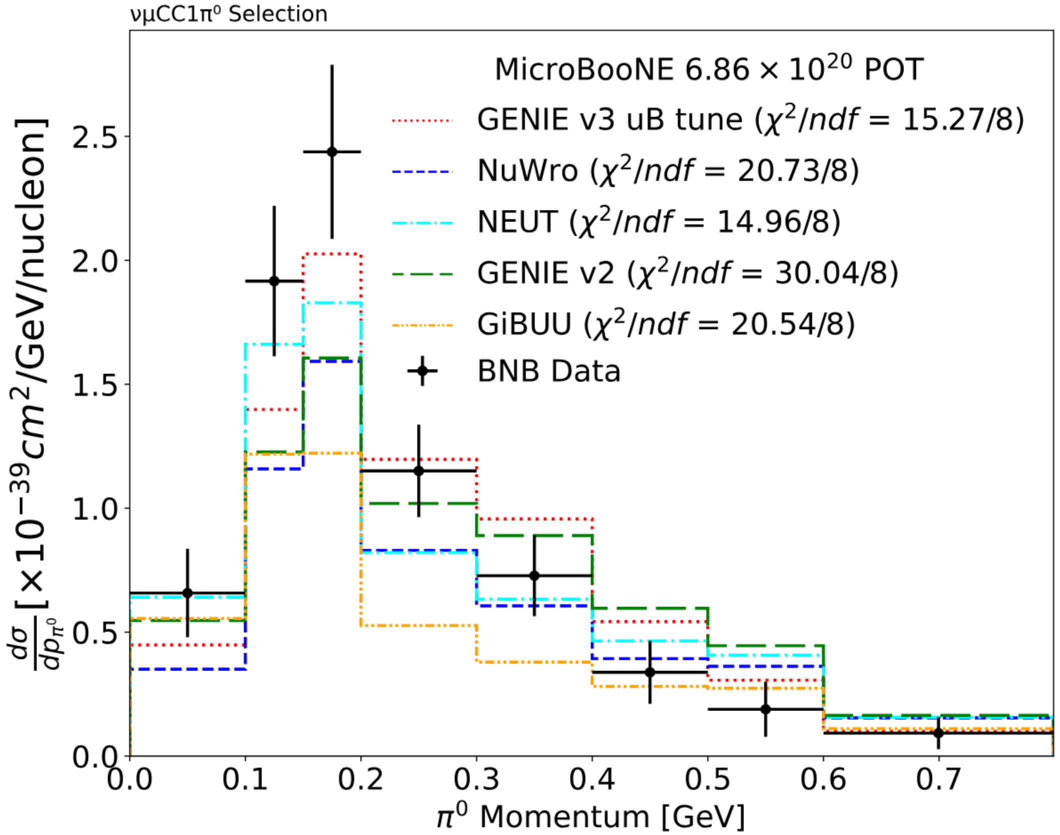
CC π^0 Event Yield





- Wiener-SVD unfolding technique to extract cross section
  - simulation - GENIE v3 MicroBooNE Tune using T2K data
- π^0 & μ mom and angle, opening angle between $\pi^0 - \mu$

Differential Cross Section CC π^0



arXiv:2404.09949

- production dominated by $\Delta(1232)$ resonance
- mis-modeling at low π^0 momentum region
- challenges from modeling low momentum transfer interactions, consistent with observations on other targets

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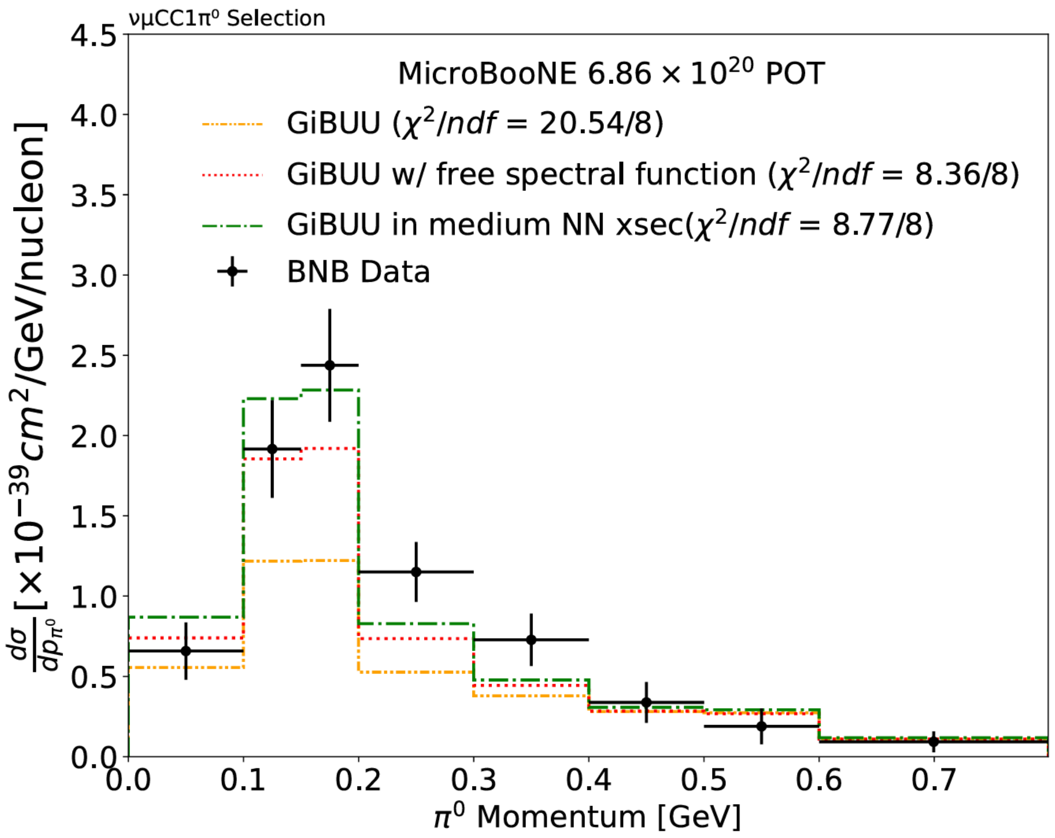
Differential Cross Section CC π^0



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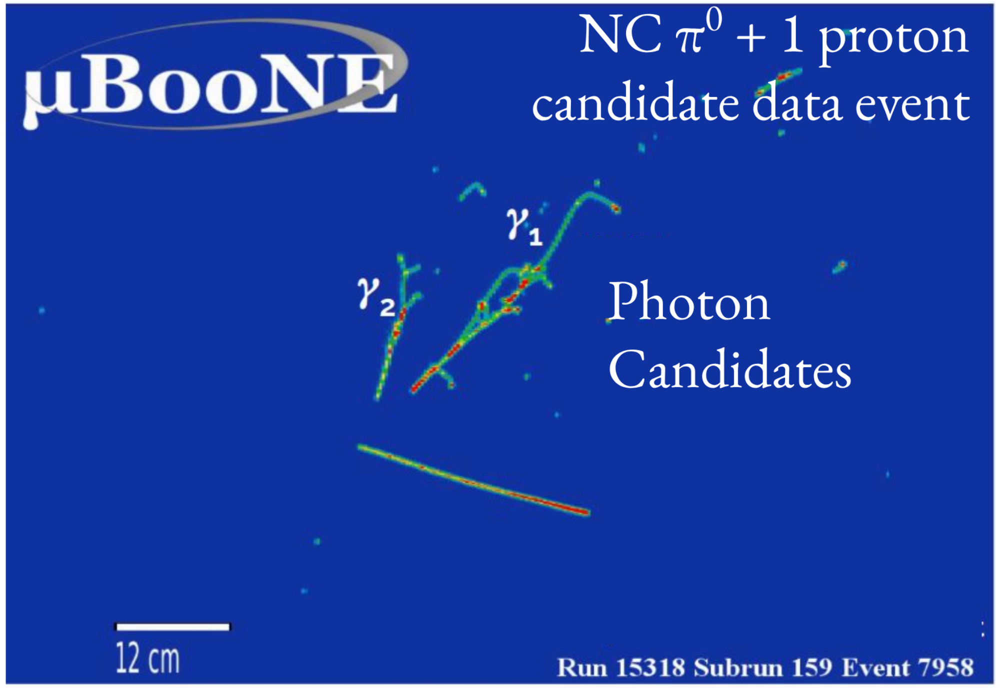
NC π^0 Event Selection



- WireCell* 3D pattern reconstruction followed by SparseConvNet** Selection
- π^0 reconstructed from leading two photon candidates
- candidate events separated into 0*p* and N*p* topologies
  - protons reconstructed with threshold of 35 MeV KE

*J. Instrum. 17 (01), P01037.

**10.1109/CVPR.2018.00961

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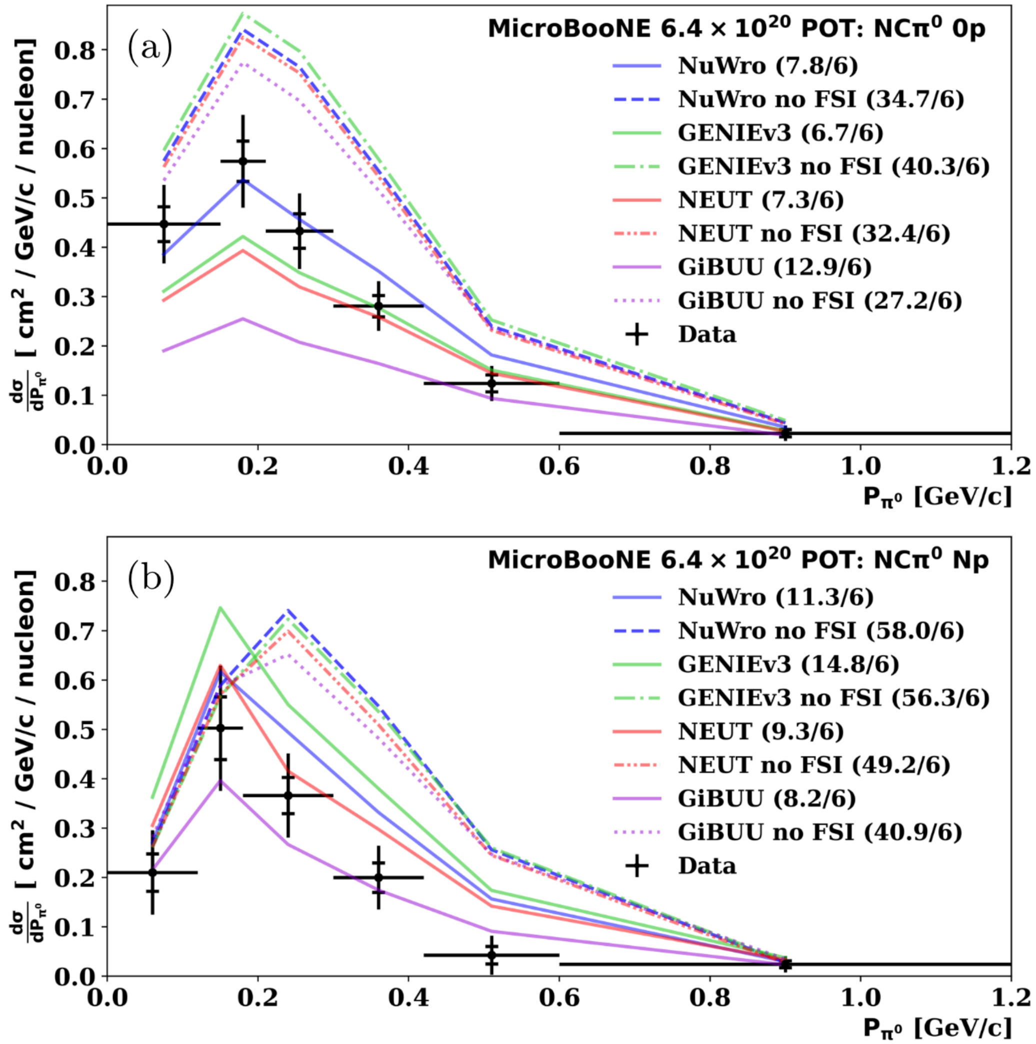
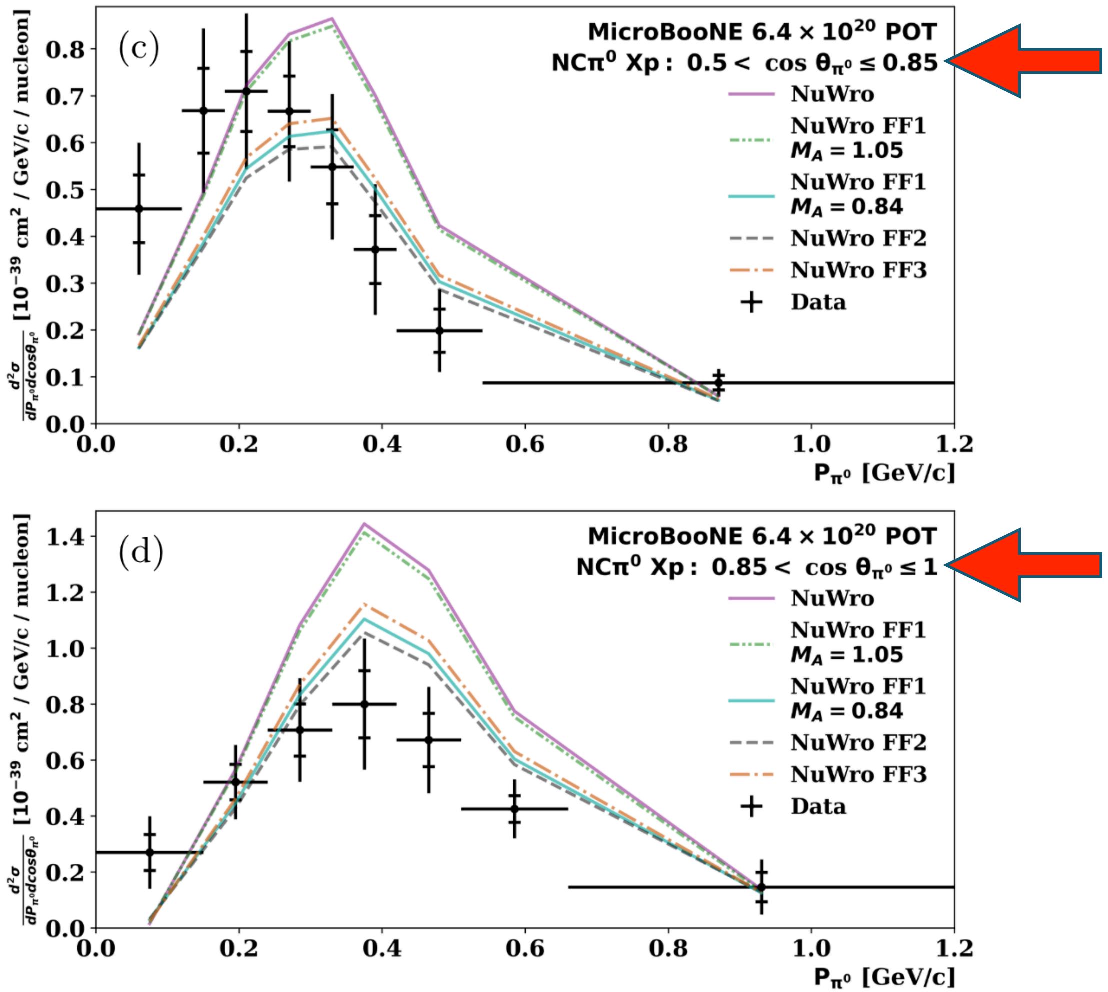
NC π^0 Differential Cross Section



arXiv:2404.10948

- cross section extracted using Wiener-SVD method
- separate single-differential measurements for 0*p* and N*p* samples
- clear over prediction without effects of FSI

NC π^0 Differential Cross Section



arXiv:2404.10948

- first double-differential cross section measurement in π^0 kinematics
- additional sensitivity to regions of phase space
- demonstrates sensitivity to form factor modeling
- have additional data available for analysis in both CC and NC measurements

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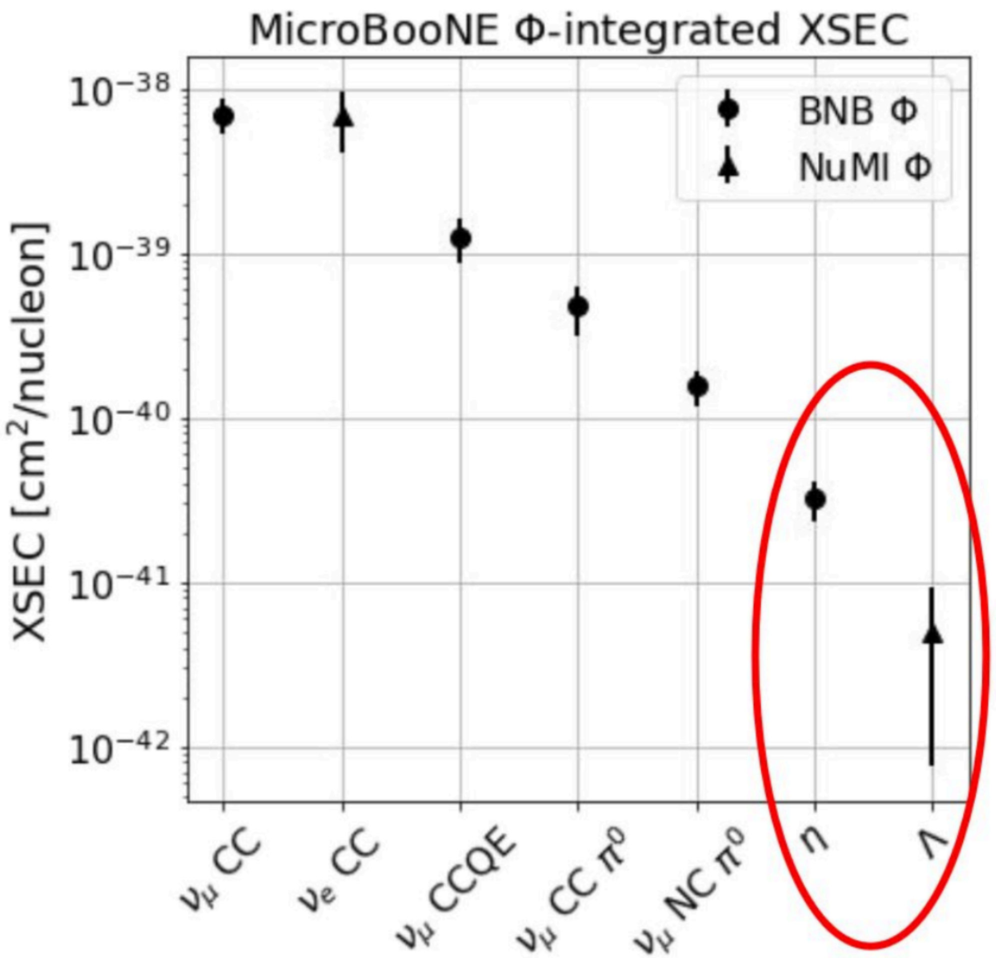
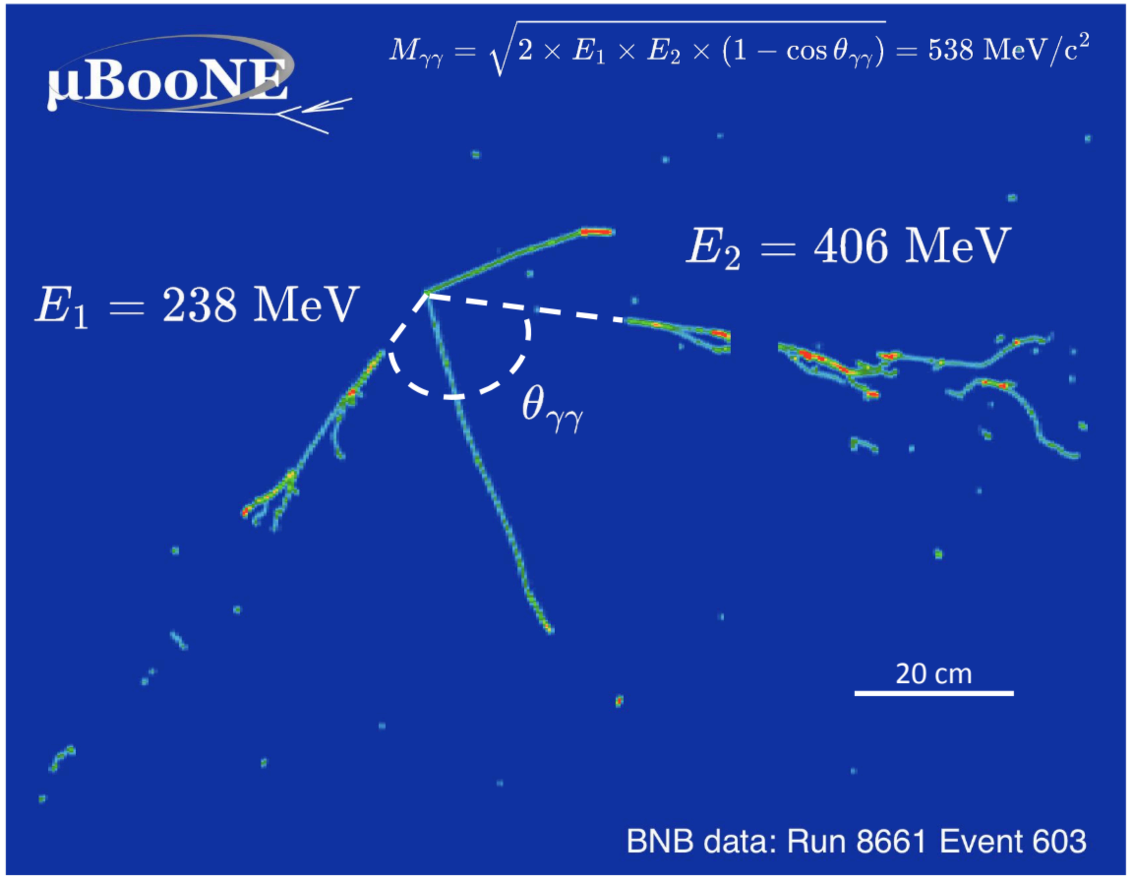
Rare Production Measurements



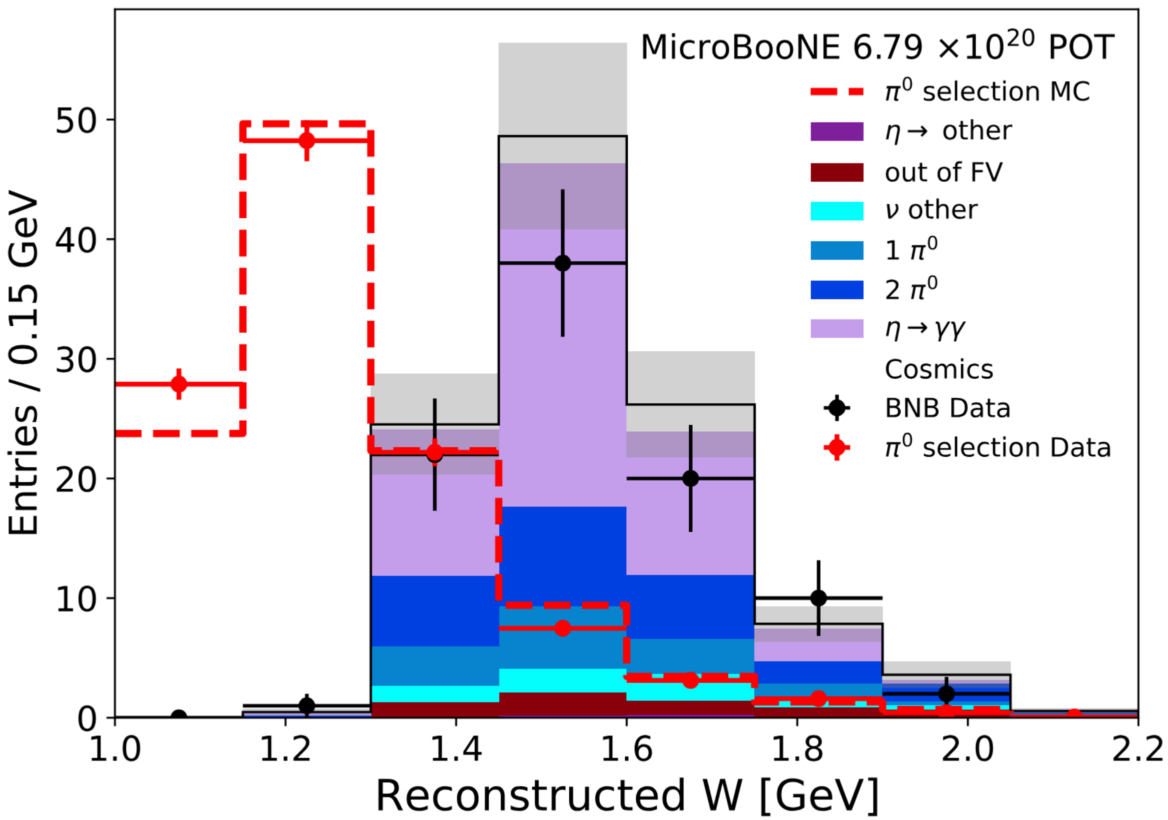
- orders of magnitude lower than previous cross section measurements
- provide unique opportunities as test of reconstruction and identification
- validation of models of rare processes that are backgrounds for searchs

η Event Selection



- Neutrino candidate event based on TPC and photon detector signals
- require two photon showers
- reject events with π^0 $(250\ MeV/c^2 < m_{\gamma\gamma} < 750\ MeV/c^2)$

η Production



Phys. Rev. Lett. 132, 151801

- provides novel tool for calibration of GeV scale EM showers
- probes resonate production of higher mass states
  - $\Delta(1232)$ *vs* $\eta(1535)$
- opens the door to proton decay channels
  ($p \rightarrow e^{+}\eta$ & $p \rightarrow \mu^{+}\eta$)

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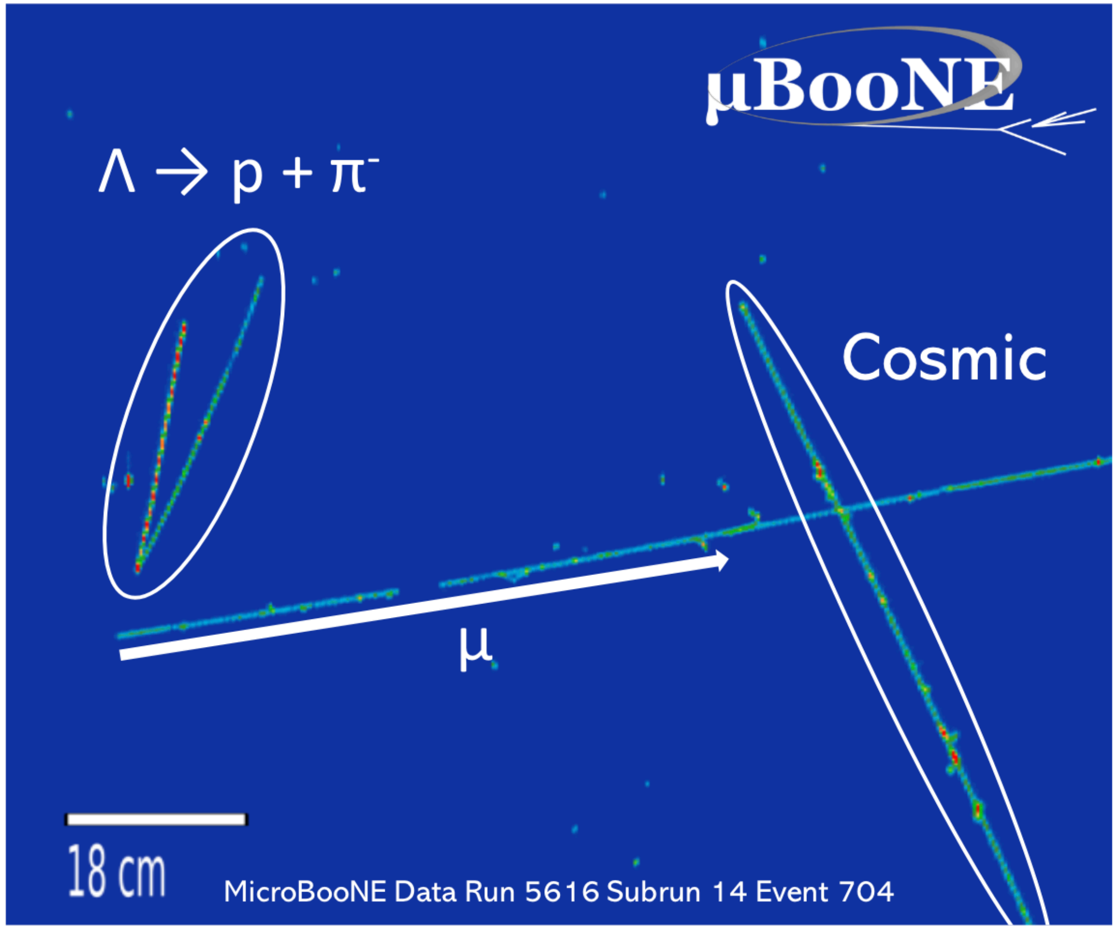
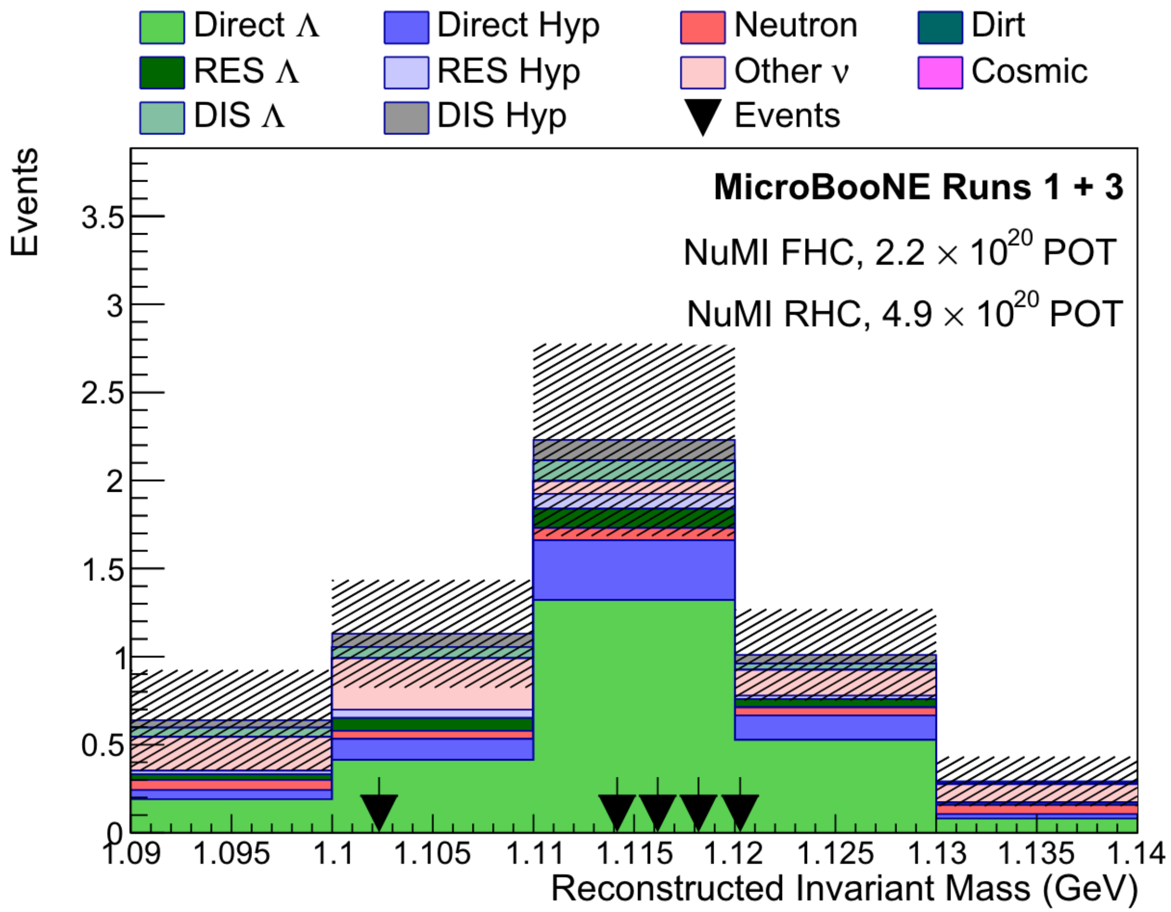
Λ production



- important input to hyperon interaction modeling and propagation in nuclear matter
- extremely rare process due to Cabibbo Suppression
- Event selection presented at ICHEP 2022

Λ production



Phys. Rev. Lett. 130, 231802 (2023)

- First measurement with a LArTPC detector
- $\sigma = 2.0^{+2.2}_{-1.7} \times 10^{-40} cm^2/Ar$
- Event distribution matches well with Λ expectation
- probes momentum resolution of protons and charged pions

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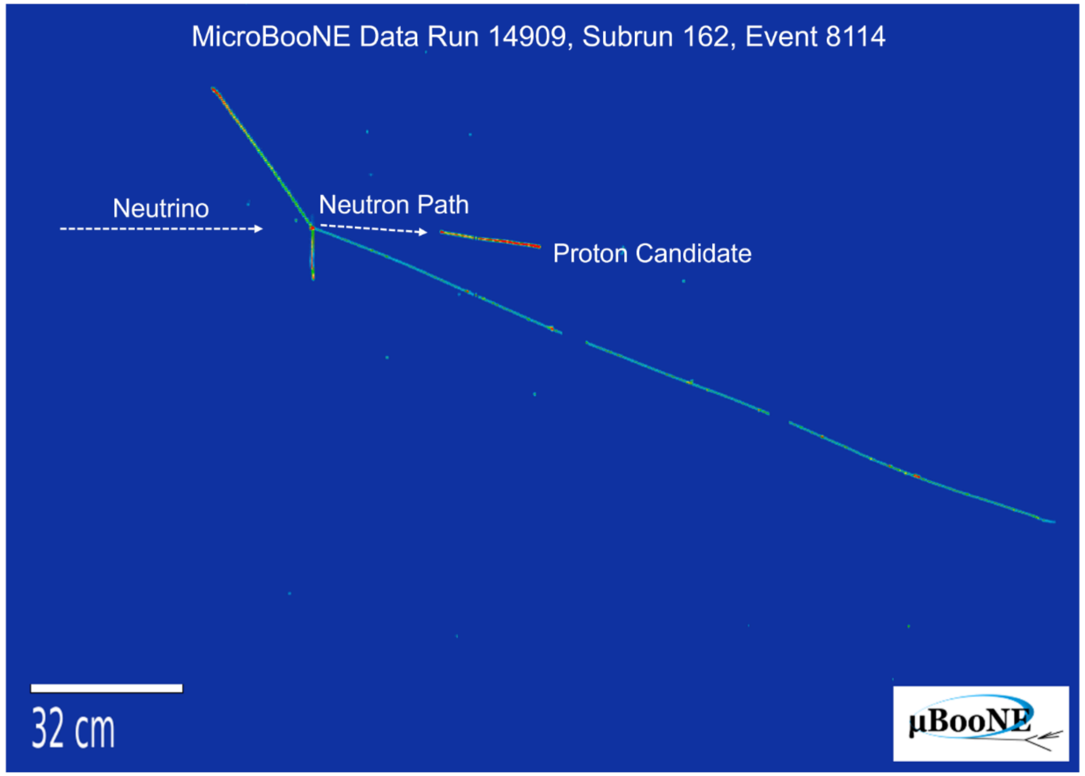
Neutron Identification in Neutrino Interactions



- very challenging reconstruction task since TPC designed around charged particle identification
- take advantage of secondary interactions generating protons
- mitigate uncertainty in energy reconstruction from "missing energy"

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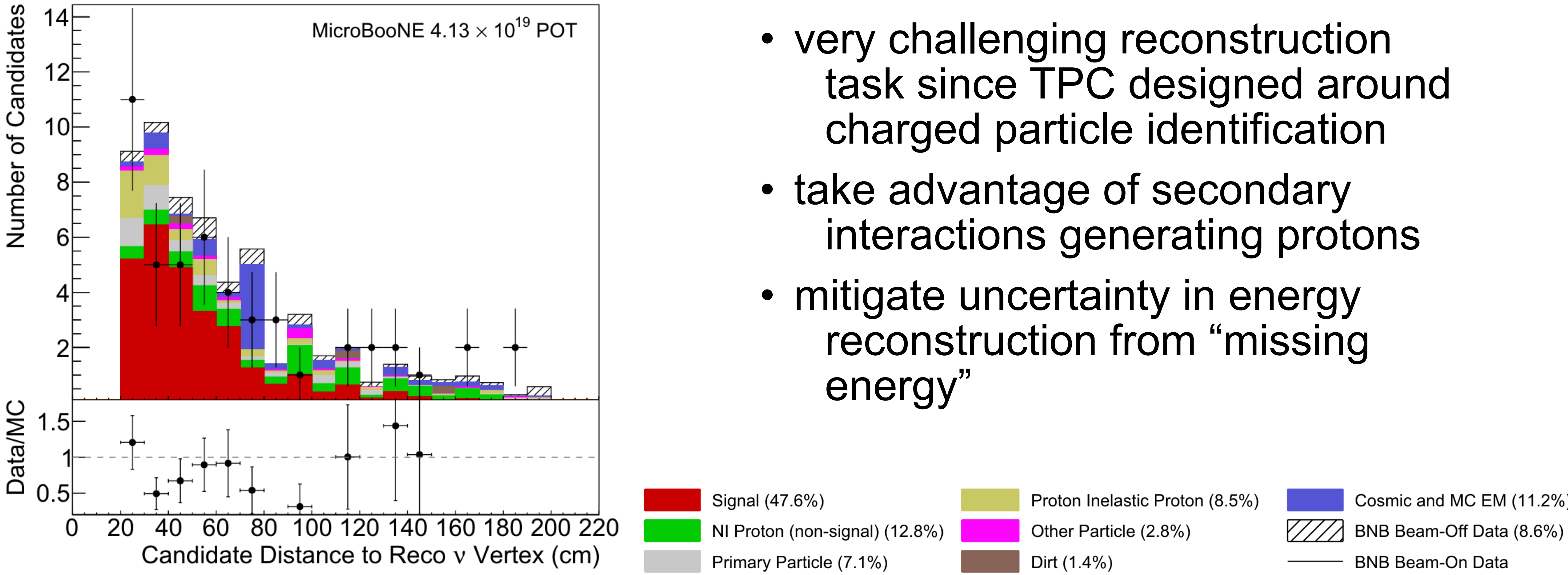
Neutron Identification in Neutrino Interactions



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arXiv:2406.10583

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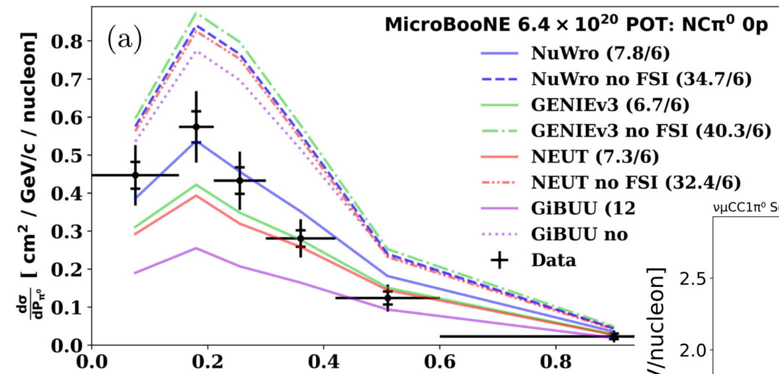
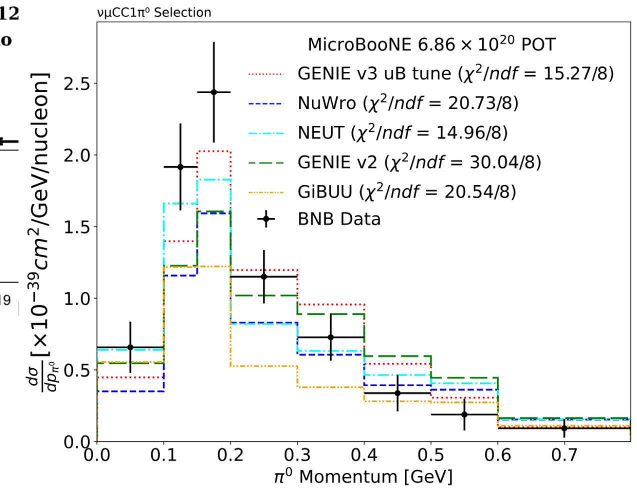
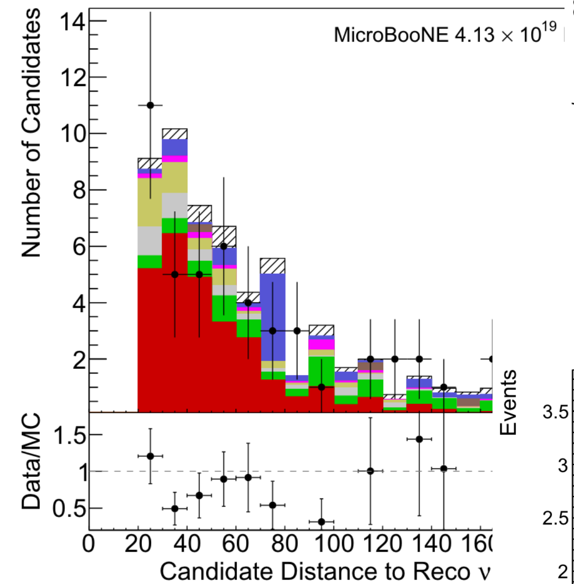
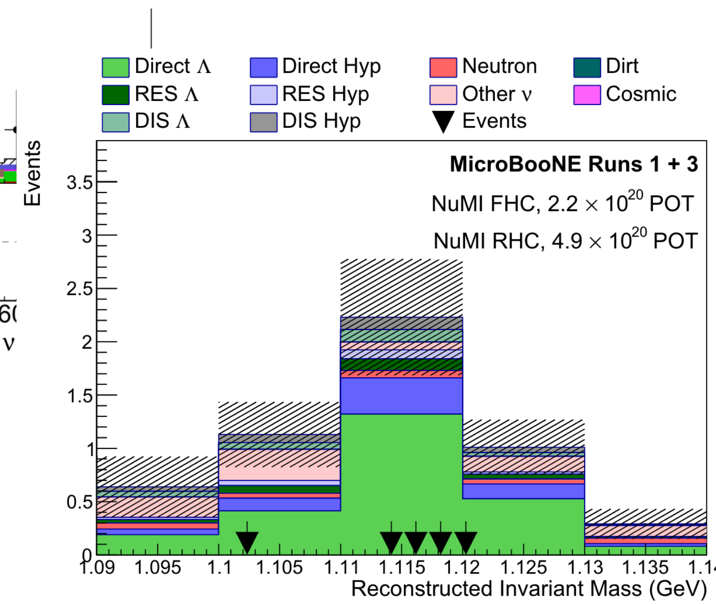
Summary

- **MicroBooNE has an extensive program of cross section and rare process analyses**
- **more than 25 publications so far with sensitivity to many model parameters and choices**
- **look forward to extending measurements in both statistics and dimensionality**









Thank you!

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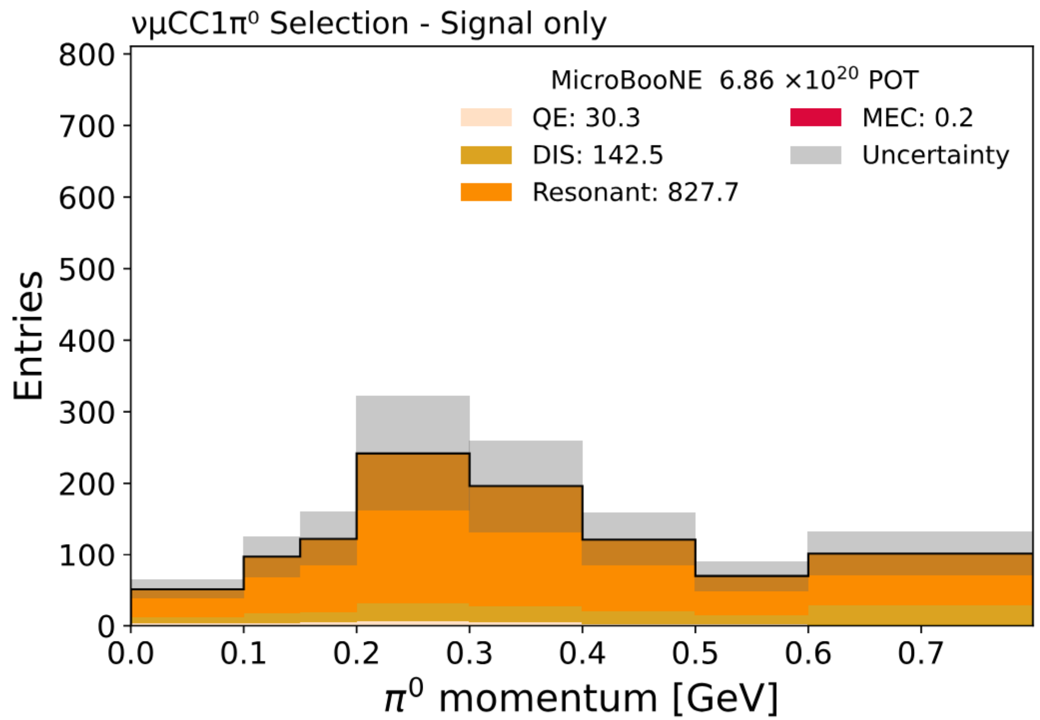
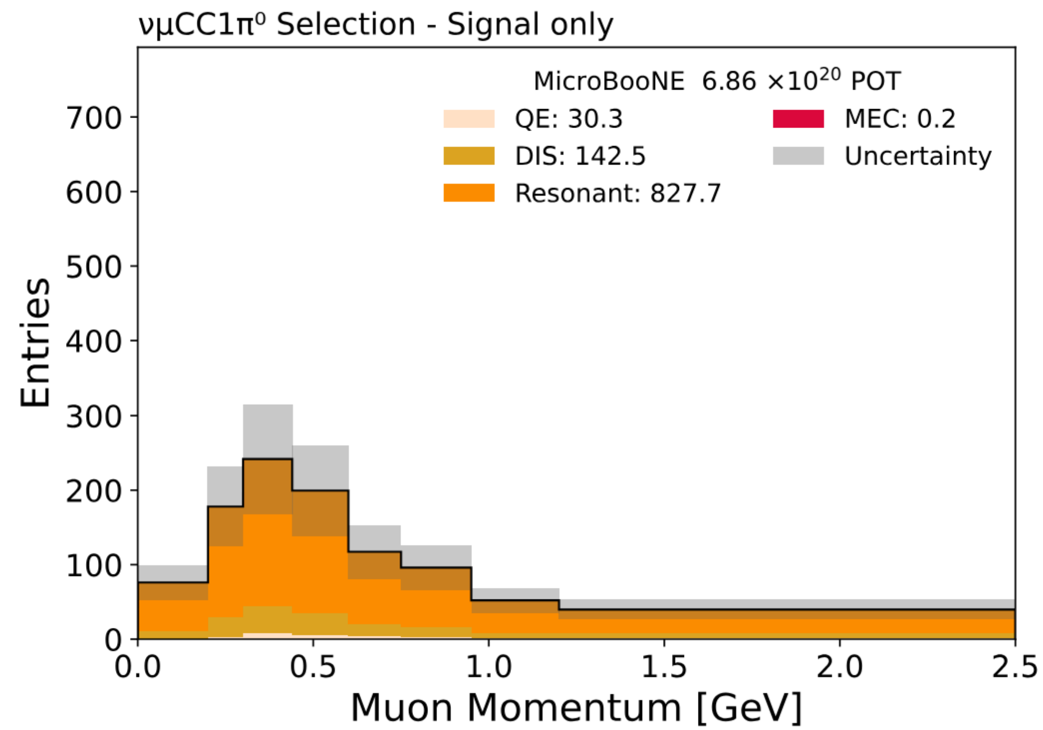
backup

CC π^0 production GENIE v3 after signal selection - MicroBooNE Simulation





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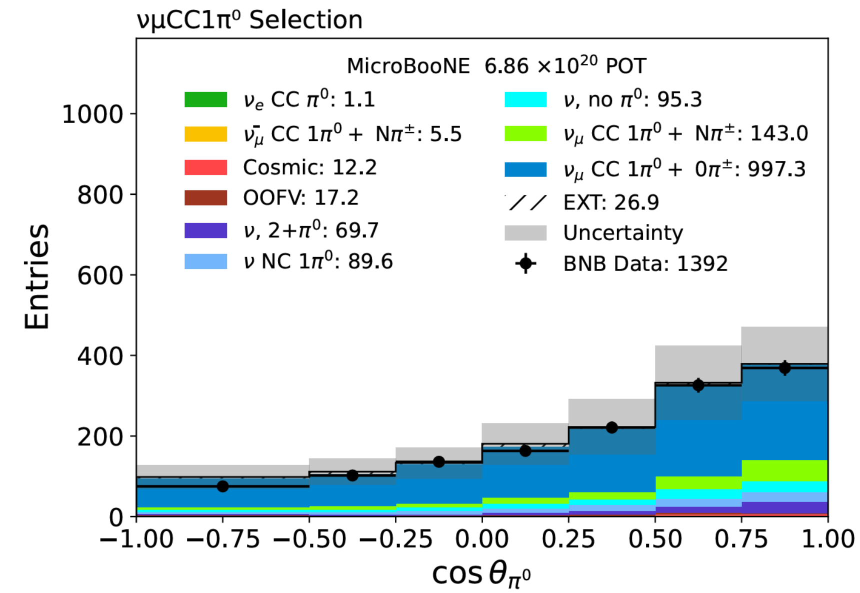
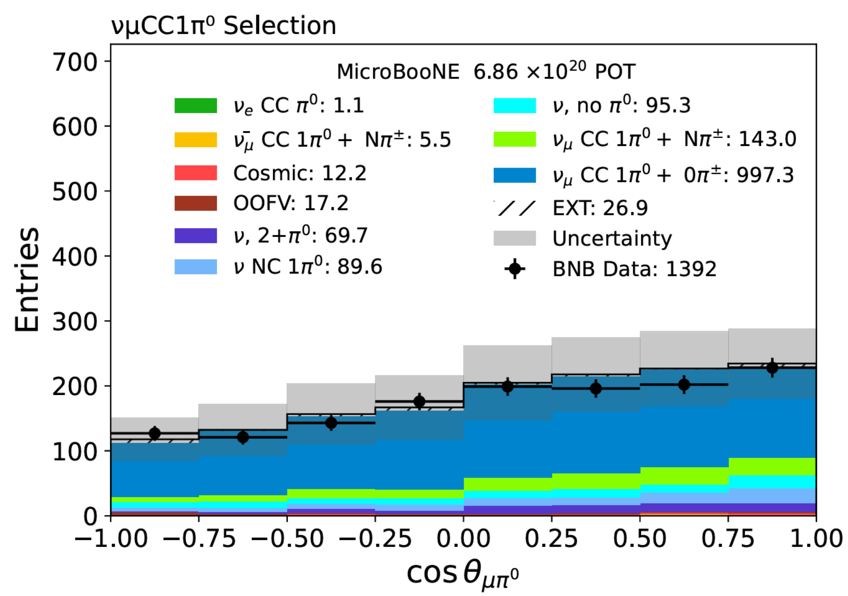
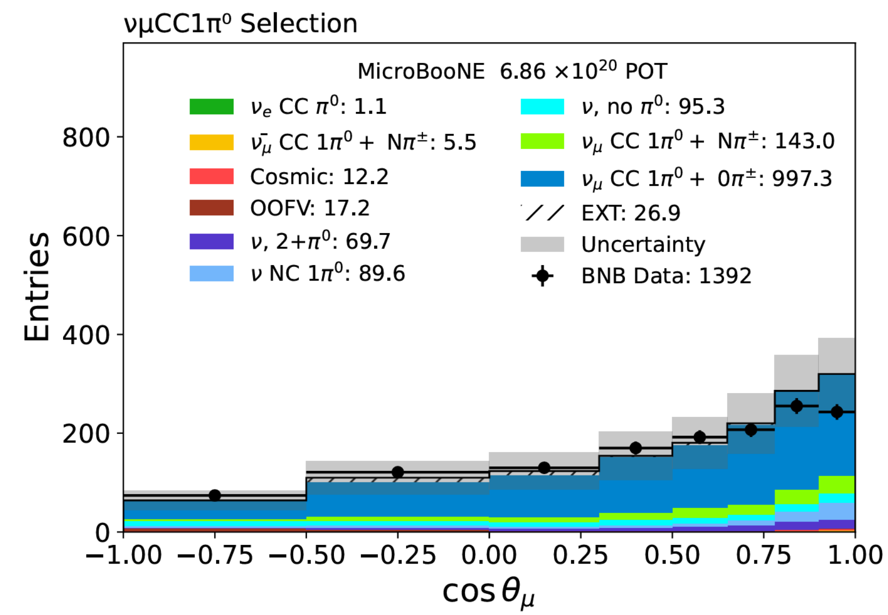
CC π^0 kinematics

Generator	p_{π^0}	$\cos(\theta_{\pi^0})$	p_μ	$\cos(\theta_\mu)$	$\cos(\theta_{\mu\pi^0})$
GENIE v3(tuned)	0.054	0.859	0.0063	0.246	0.922
NuWro	0.0079	0.748	0.0007	0.701	0.908
NEUT	0.059	0.788	0.0012	0.360	0.950
GENIE v2	0.0002	0.964	0.0046	0.218	0.874
GiBUU	0.008	0.465	0.0003	0.126	0.486

TABLE I. P-values comparing unfolded data and generator predictions given in Fig. 2.







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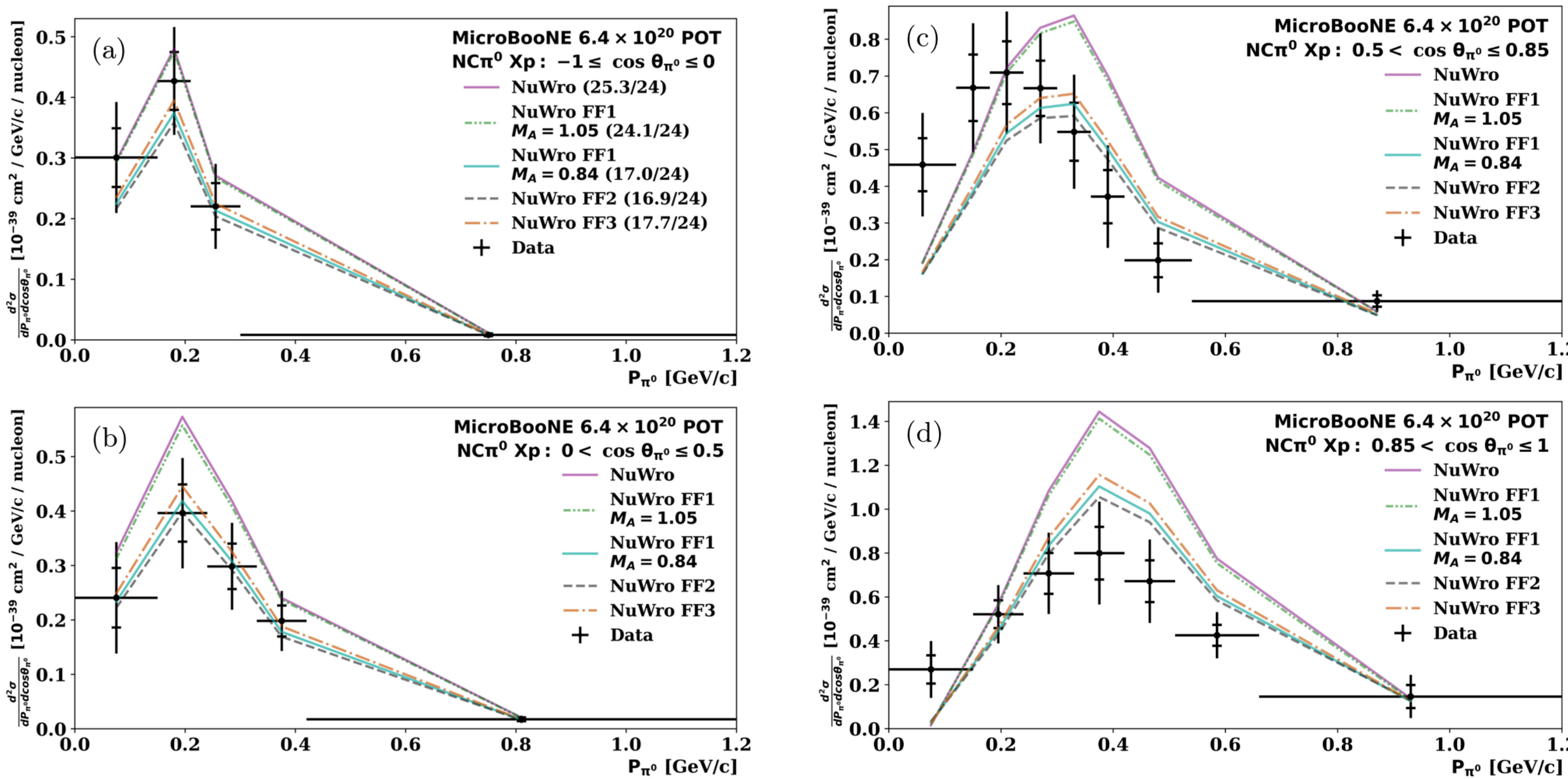
NC π^0 cross sections



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di-photon invariant mass in η sample

- σ = 3.22 ± 0.84 (stat.) ± 0.86 (syst.) x $10^{-41}cm^2$/nucleon
- 6.79 x 10^{20} POT -> 11.1 x 10^{20} POT

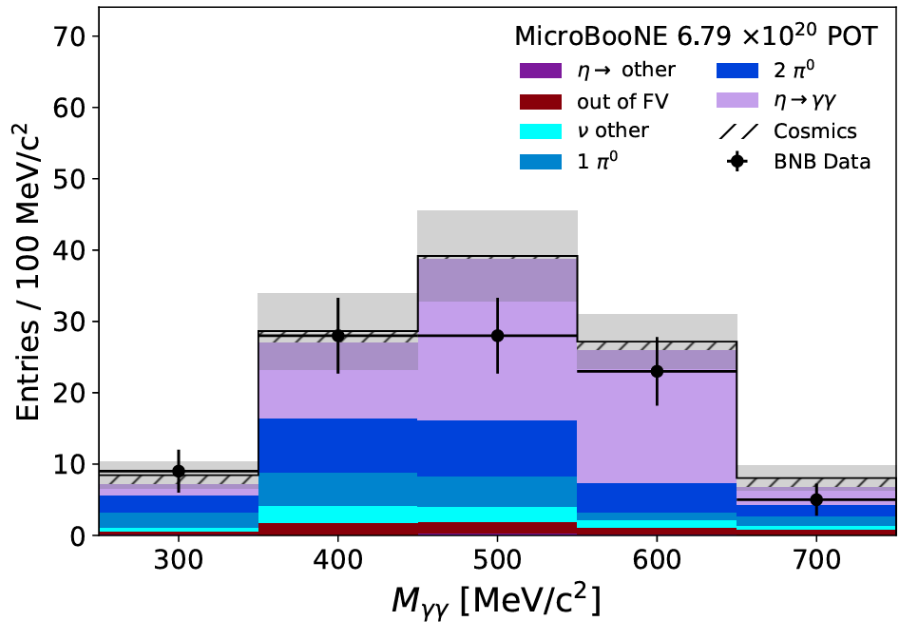

FIG. 2. Distribution of $M_{\gamma\gamma}$ for selected η candidates showing data (data points with statistical uncertainties denoted by the error bar) and the predicted event rate (stacked histogram). Different colors denote different topologies, as described in the legend. The gray error band denotes the systematic uncertainty on the predicted event rate.

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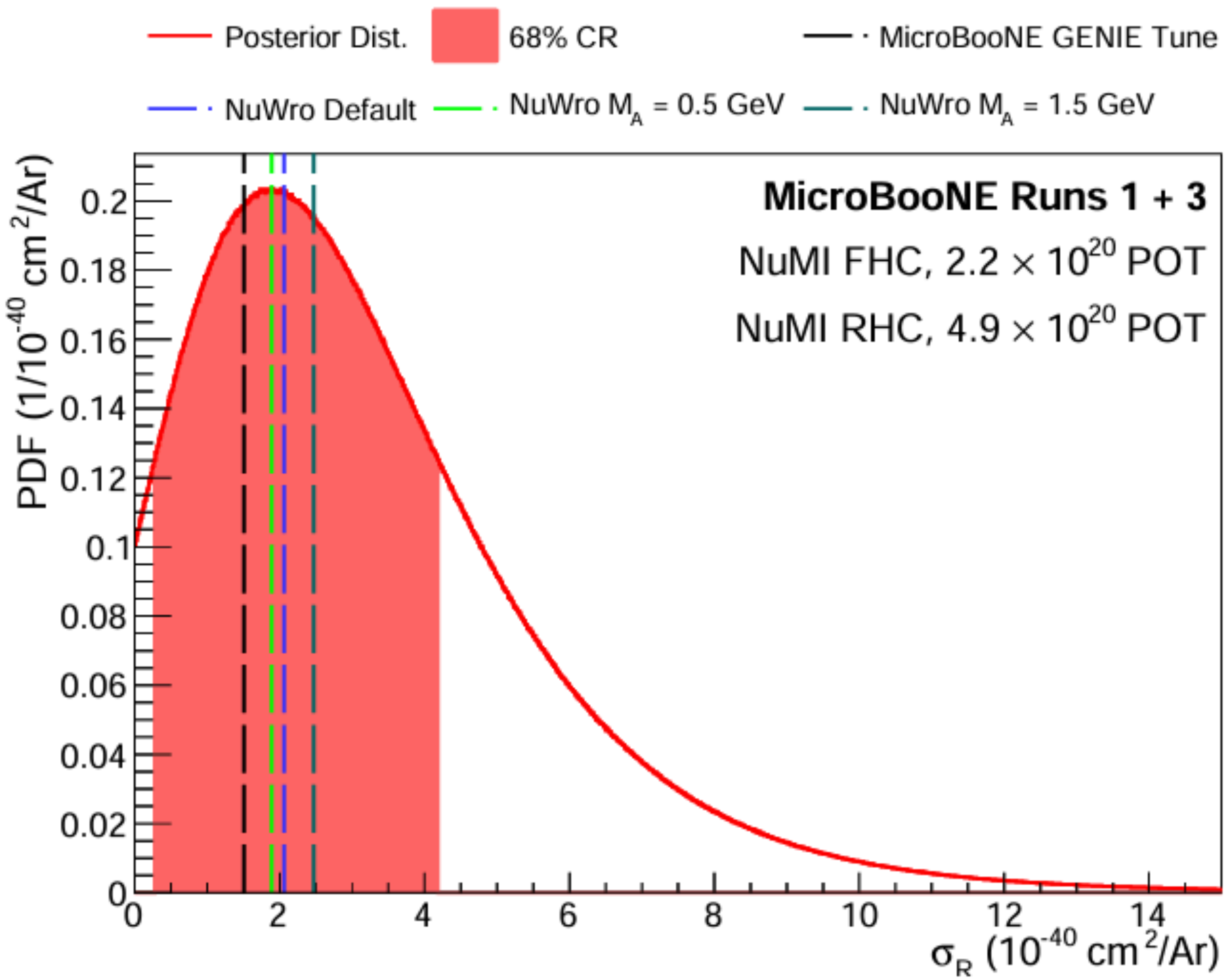
Λ cross section posterior



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Neutron identification via inelastic proton production efficiency

TABLE II: Number of times final state neutrons inelastically scatter.

Number of Inelastic Scatters	
0 scatters	25.48%
1 scatter	30.28%
2 scatters	26.51%
3 scatters	11.87%
4+ scatters	5.87%

TABLE III: Final state particles of neutron-argon inelastic scatters.

Final State of Scatter	
(1) Ar*	54.13%
(2) Ar* $+Nn$	30.86%
(3) $\mathrm{Cl}+Nn+1p$	6.60%
(4) $\mathrm{S}+Nn+2p$	1.37%
(5) $\mathrm{S}+Nn+\alpha$	2.14%
(6) Other proton final state	0.88%
(7) Other	4.03%

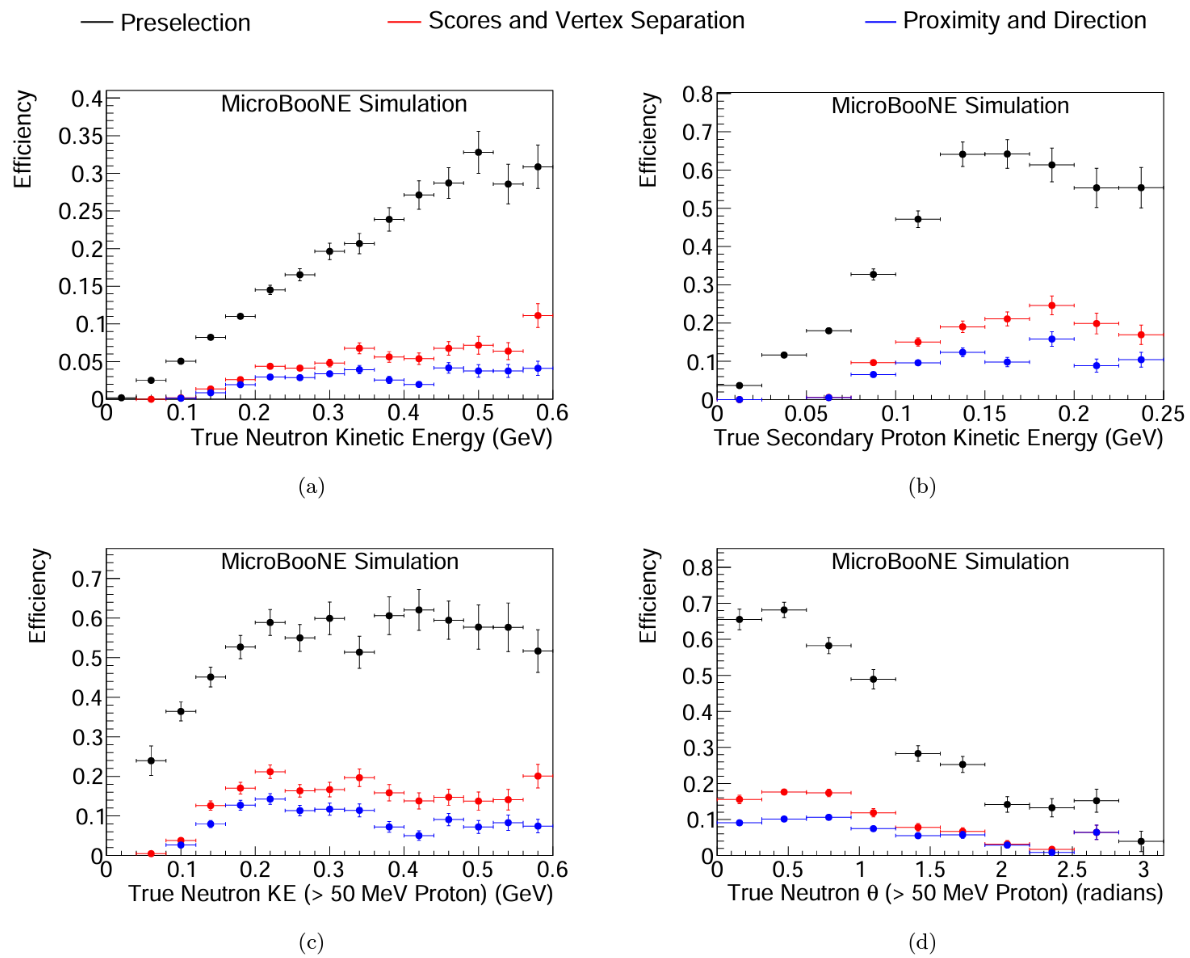

FIG. 10: (a) Neutron detection efficiency as a function of true neutron kinetic energy. (b) Secondary proton detection efficiency. (c) Neutron detection efficiency as a function of true neutron energy for neutrons that produce protons with kinetic energy 50 MeV or more. (d) Neutron detection efficiency as a function of neutron polar scattering angle for neutrons that produce protons with kinetic energy 50 MeV or more.

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arXiv:2406.10583