# Recent Results from MicroBooNE
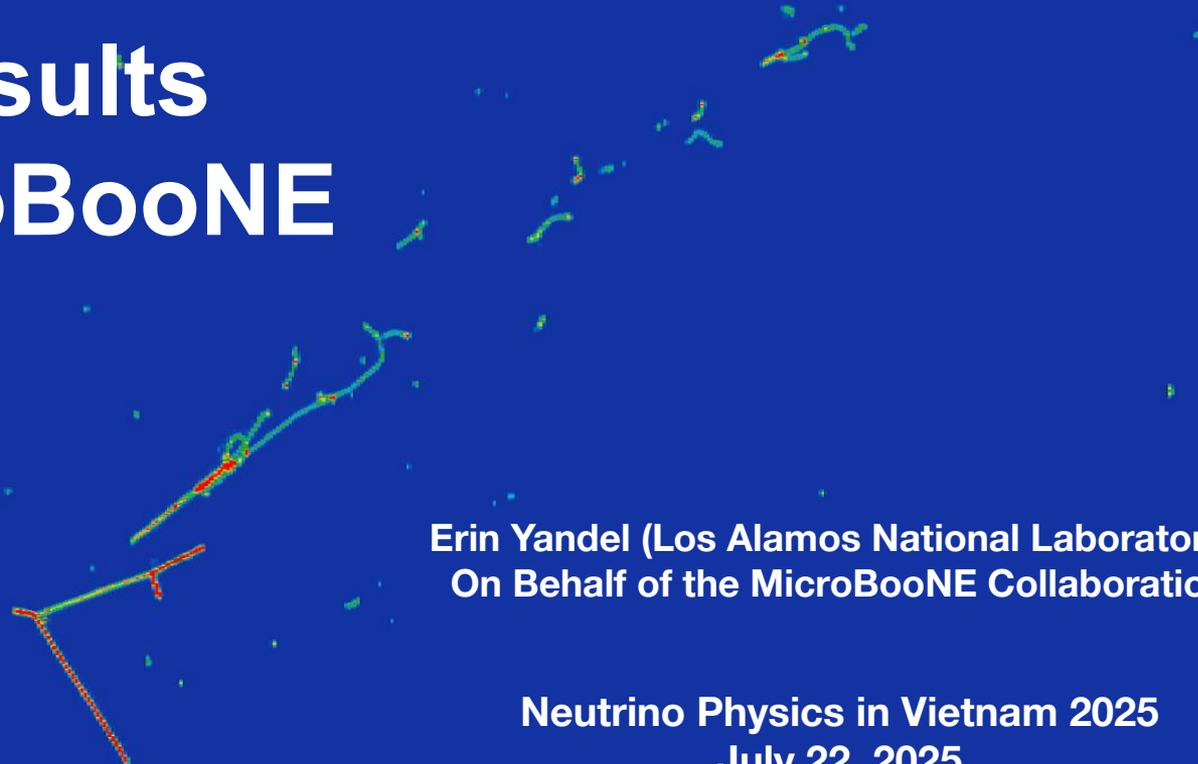
Erin Yandel (Los Alamos National Laboratory)
On Behalf of the MicroBooNE Collaboration

Neutrino Physics in Vietnam 2025
July 22, 2025

MicroBooNE

- Surface-level, 85 tonne Liquid Argon Time Projection Chamber (LArTPC) neutrino experiment at Fermilab

- Collected data 2015 - 2021 (now decommissioned)

- ~0.5M neutrino events across two beams

- 195 collaborators from 38 institutions

- 82 papers and counting

MicroBooNE Science Goals
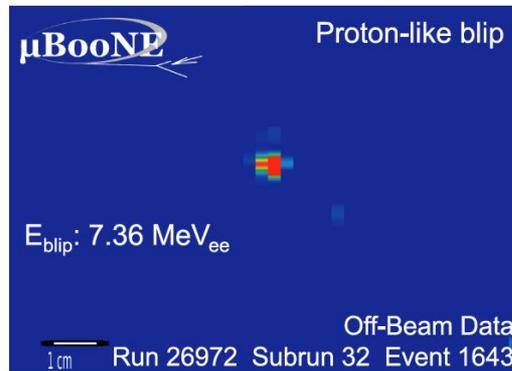
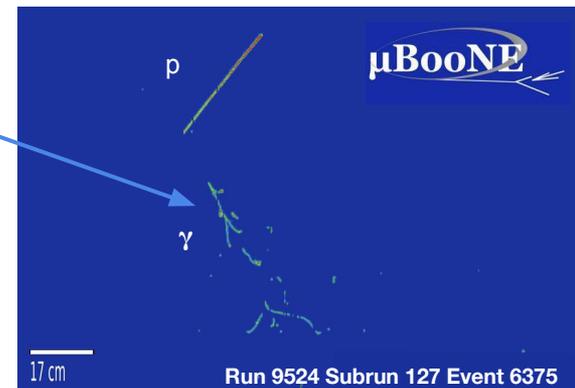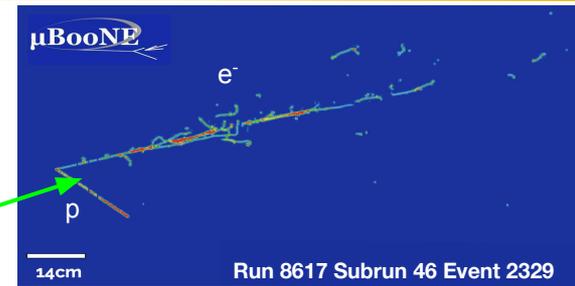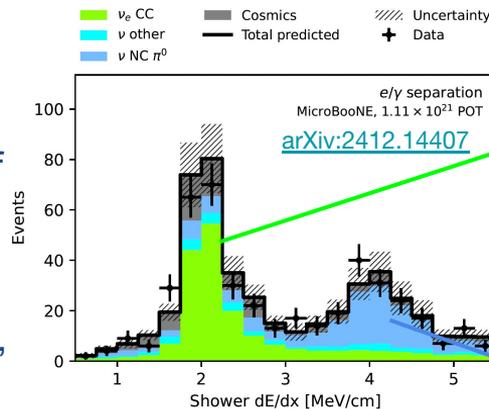Investigate the MiniBooNE Low Energy Excess (LEE) and search for BSM physics
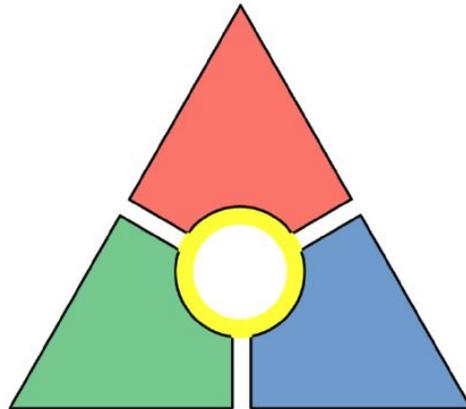
LArTPC detector hardware and software R&D

Neutrino interaction measurements on argon

LArTPC

- Use ionization charge and scintillation light to get 3D image of event
- Excellent particle identification
- Can distinguish electrons, photons, muons, protons, pions, etc.
  - topological information
  - energy deposition per length (dE/dx)
- Separate complicated topologies
- Explore inclusive and exclusive channels in detail
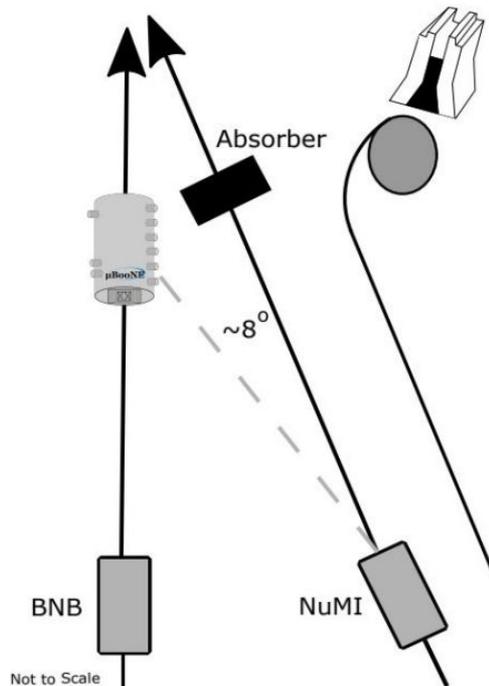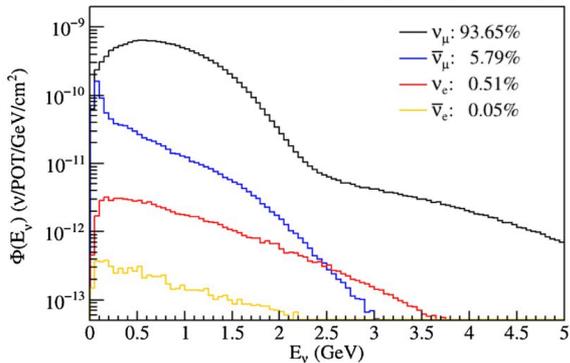- MeV-level detection thresholds

e/γ separation
MicroBooNE, 1.11×10^{21} POT
arXiv:2412.14407

Legend: ν_e CC, ν other, ν NC π^0, Cosmics, Total predicted, Uncertainty, Data

Events vs Shower dE/dx [MeV/cm]

μBooNE — e⁻, p
14cm — Run 8617 Subrun 46 Event 2329

μBooNE — p, γ
17 cm — Run 9524 Subrun 127 Event 6375

μBooNE — Proton-like blip
E_{blip}: 7.36 MeV_{ee}
Off-Beam Data
1 cm — Run 26972 Subrun 32 Event 1643

Neutrino Beams

On-axis to Booster Neutrino Beam (BNB)

1.3E21 POT

Off-axis to Neutrinos at the Main Injector (NuMI) beam

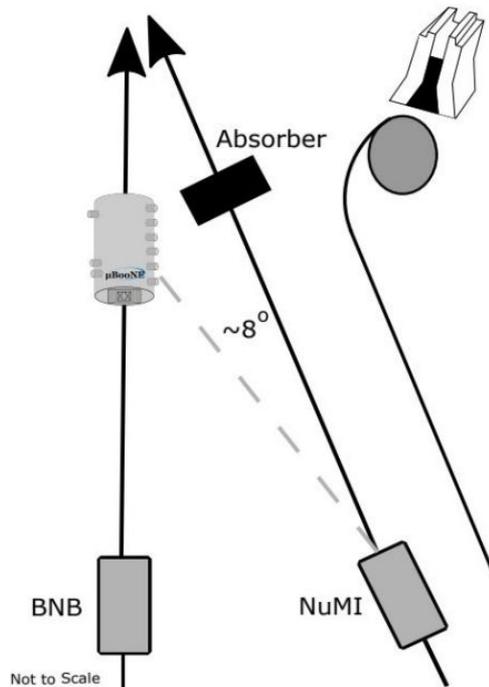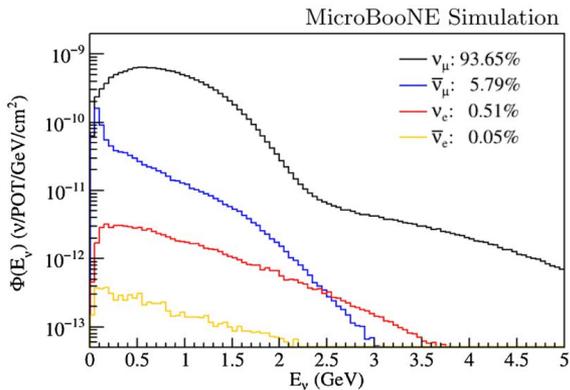**2.0E21 POT**

- Off-axis: 8° (target), 120° (absorber)
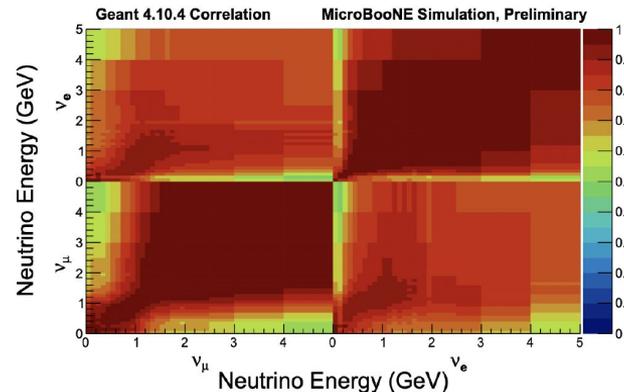- Higher energy and v_e content than the BNB
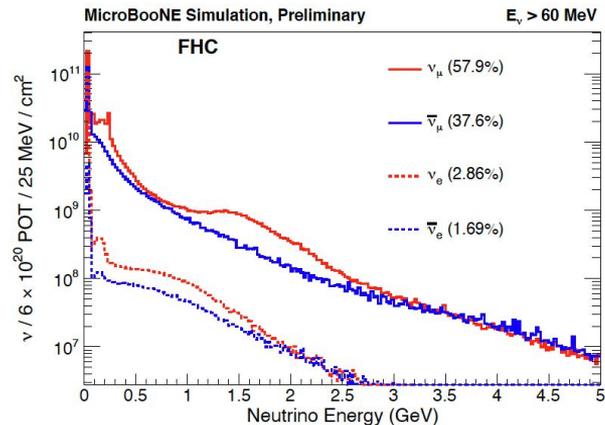
Neutrino Beams

On-axis to Booster Neutrino Beam (BNB)

MicroBooNE Simulation
ν_μ: 93.65%
$\bar{\nu}_\mu$: 5.79%
ν_e: 0.51%
$\bar{\nu}_e$: 0.05%

Off-axis to Neutrinos at the Main Injector (NuMI) beam

- Reevaluated the NuMI neutrino flux prediction for it's off-axis position
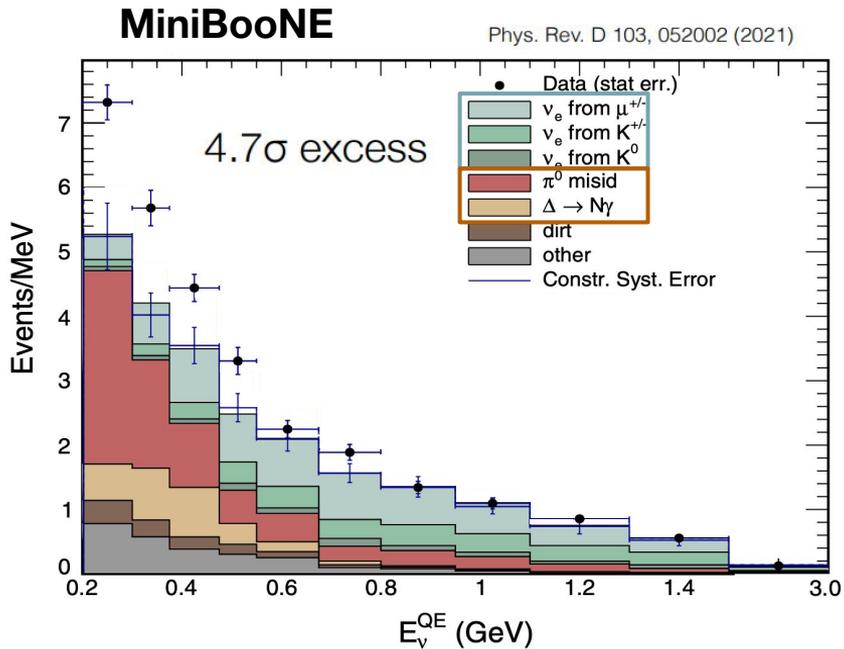- New base model (G4.10.4) : better agreement with π, K production data from NA49

MicroBooNE Science Goals

Investigate the MiniBooNE Low Energy Excess (LEE) and search for BSM physics

MiniBooNE Low Energy Excess (LEE)

MiniBooNE

Phys. Rev. D 103, 052002 (2021)

4.7σ excess
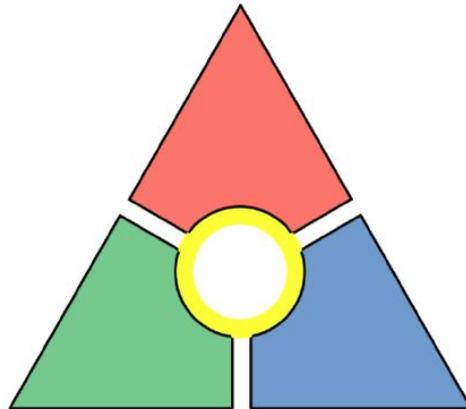
- Cherenkov detector at Fermilab
- Sits in the BNB just downstream of MicroBooNE
- Sees a 4.7σ excess
- Still unexplained after many years
- Consists of single electromagnetic showers
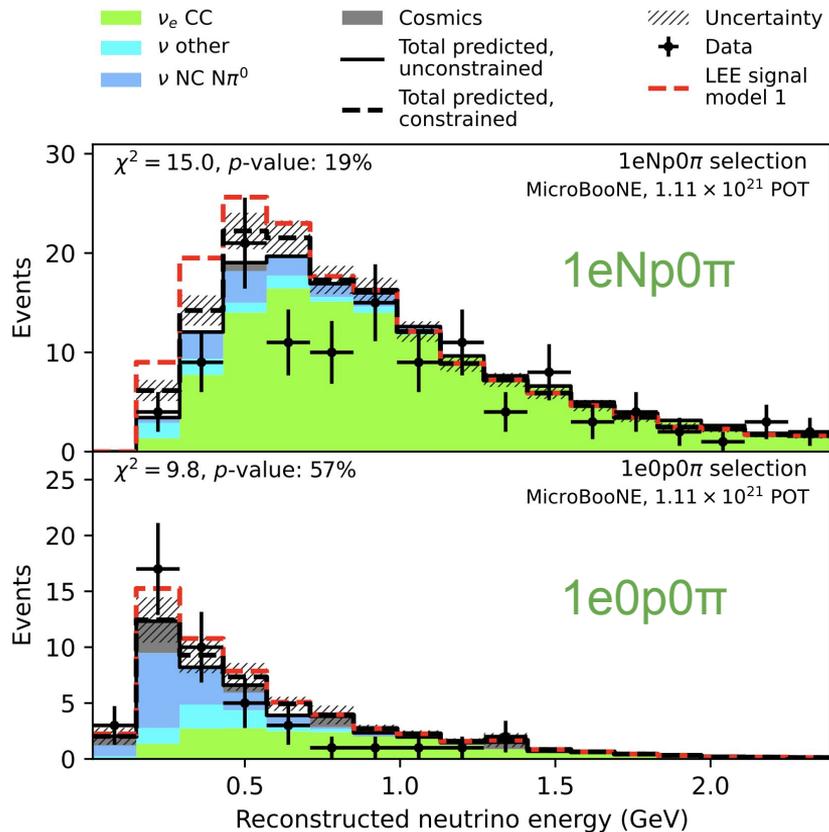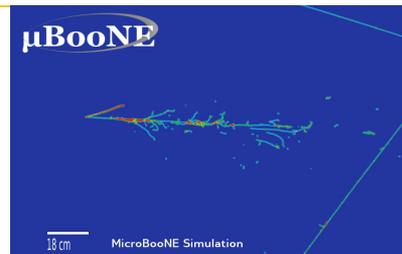- MiniBooNE can not distinguish between e^- and γ
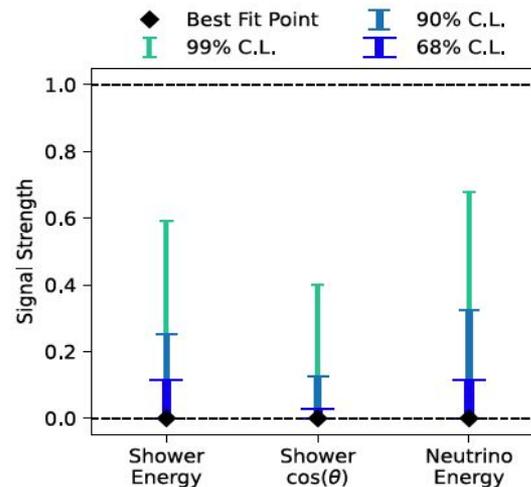
MiniBooNE   **MicroBooNE**
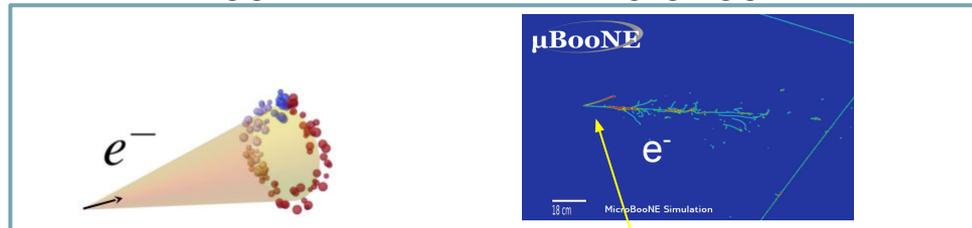
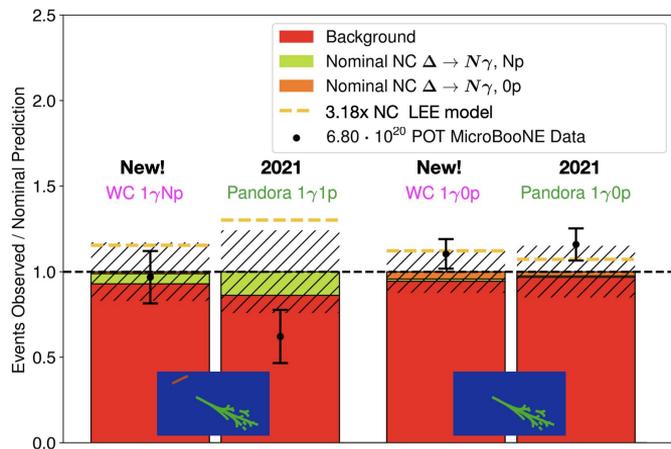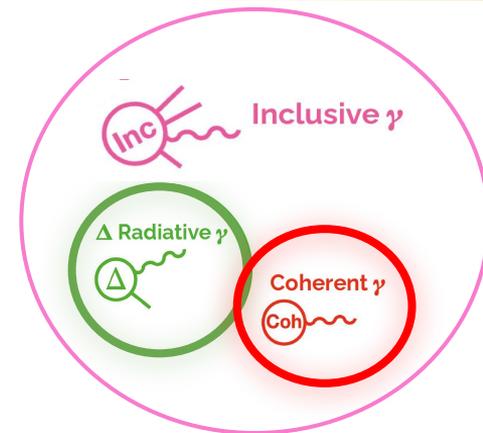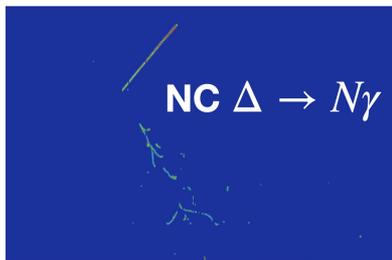# Electron-like Search

arXiv:2412.14407

- Recently, investigated ν_e CC with no pions in the full MicroBooNE BNB dataset with more LEE models
- See no sign of a MiniBooNE-like excess

Photon-like Searches: Exclusive

Expanded search for NC $\Delta \to N\gamma$ arxiv:2502.05750

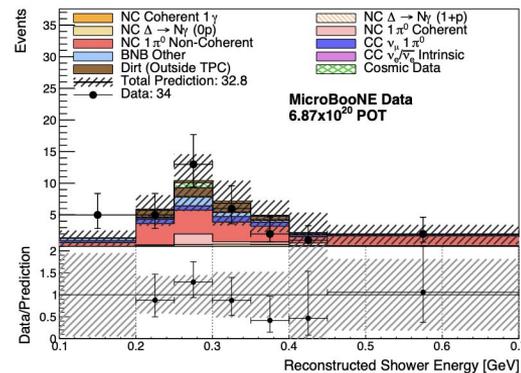- New selection added to 2021 result using a different reconstruction paradigm

- ~Double the statistics of 2021 result and increased 0p sensitivity

- No NC Δ excess at 94.4% CL

NC $\Delta \to N\gamma$

First-ever search for NC Coherent 1γ arxiv:2502.06091

NC Coherent
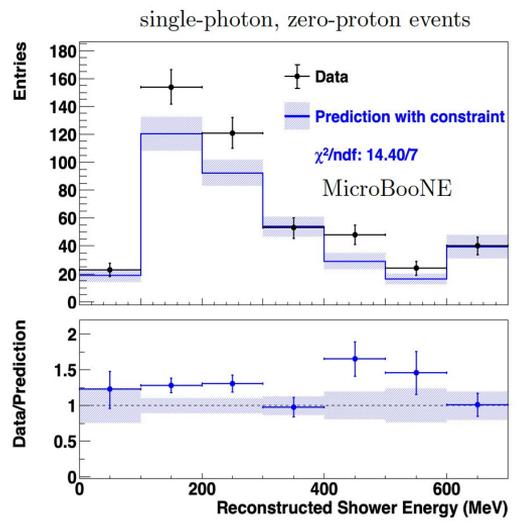
- Very rare process

- Sees no excess

- $\sigma < 1.49\times10^{-41}$ cm^2 at 90% CL

MicroBooNE Data 6.87x10^{20} POT

Photon-like Searches: Inclusive

arXiv:2502.06064
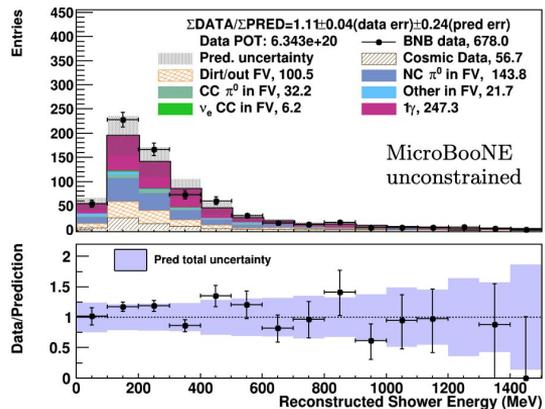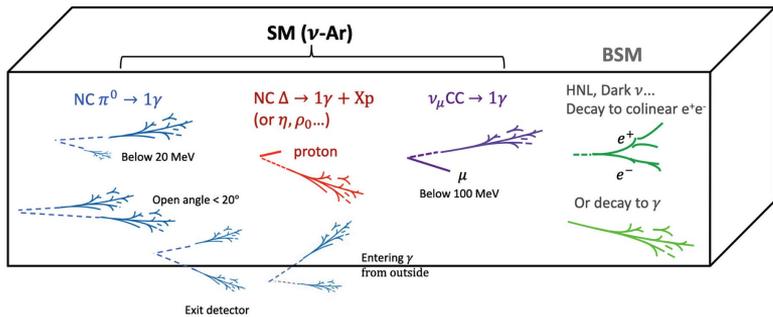
- Overall result in full energy range agrees well with prediction at under 2σ

- See hint of excess (2.2σ) in 0p subsample, below 600 MeV photon energy

- Further studies and investigations underway
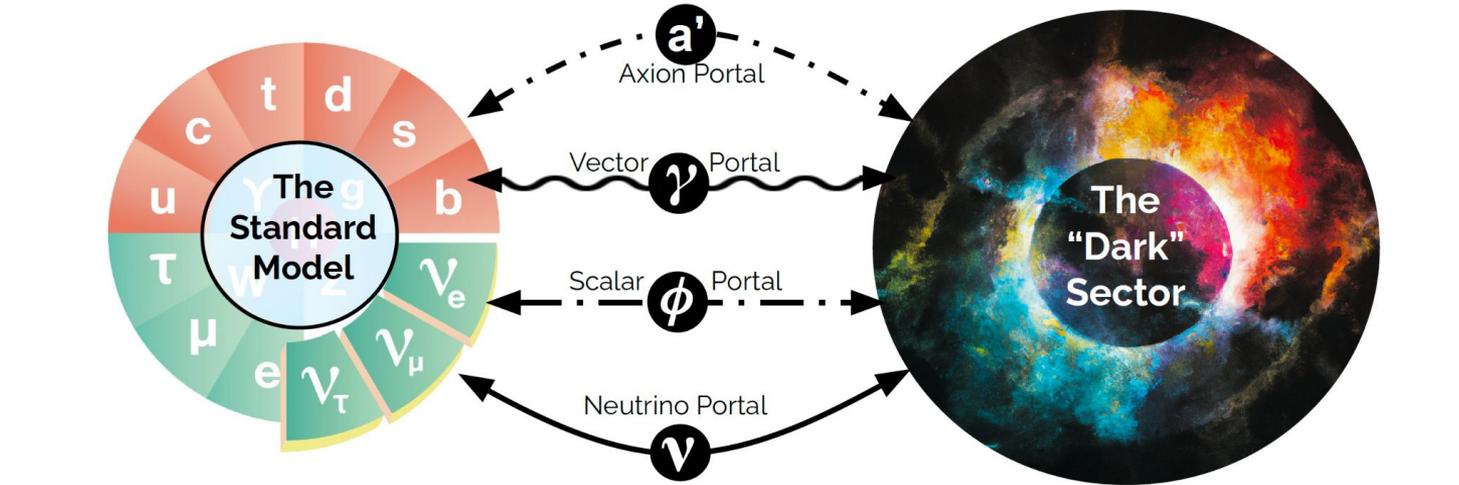
Inclusive

Dark Sector Portals

Neutrino Portal ν

$$\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

Scalar Portal φ

$$\mathcal{L} \supset (A S + \lambda S^2) H^{\dagger} H$$

- Higgs Portal Scalars

Vector Portal γ

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

- Light Dark Matter
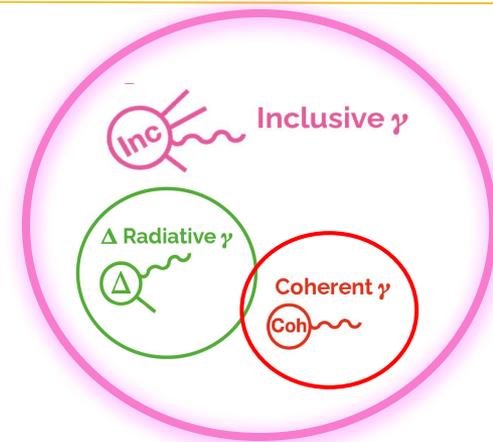- Millicharged Particles

Axion Portal a'

$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$

- Heavy QCD Axions

ν γ **Combined and Non-Minimal Portals**

Dark Sector Portals
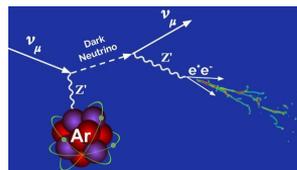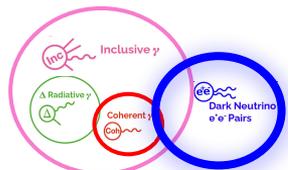
Dark Neutrino e⁺e⁻-like LEE Search

e^+e^- — arxiv:2502.10900

- First search for an e^+e^--like explanation to the LEE
  - Purely BSM hypothesis
- Dark neutrino decaying produced via a new dark Z'
  - Decays to neutrino + e^+e^- pair
- 95 events seen; 69.7 (17.3) predicted
  - Agreement at 1.5σ
- Bounds placed on wide range of Z' mass values
  - Majority of phased spaced ruled out

MiniBooNE 95% Allowed Regions
Example $M_{Z'}$ values:
- 0.03 GeV
- 0.1 GeV
- 0.2 GeV
- 0.5 GeV
- 0.8 GeV
- 1.25 GeV

MicroBooNE 95% CL Exclusion Regions
Prior Model Independent Bounds

$|U_{\mu 4}|^2$ vs m_4 [GeV]

MicroBooNE Data 6.87×10^{20} POT
Constrained Backgrounds and Uncertainty
Single Dark Neutrino Signal
$m_{Z'}: 30$ MeV, $m_4 : 106$ MeV, $|U_{\mu 4}|^2 : 2 \times 10^{-10}, \epsilon : 8 \times 10^{-4}$

Events vs Total Reconstructed Visible Energy [MeV]

Heavy Neutral Leptons (NuMI)

PRL 132, 041801 (2024)

- New limits on HNL production from searches across two final states in the NuMI beam

$|U_{\mu 4}|^2$ limit at 90% C.L. vs HNL mass [MeV]

$N \rightarrow \nu e^+ e^-$

$N \rightarrow \nu \pi^0$

- SIN
- PIENU
- E949
- KEK E89
- KEK E89/E104
- PS191 $\nu e \mu$
- NA62
- MicroBooNE

Neutrino Portal
$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$
- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

Scalar Portal
$$\mathcal{L} \supset (AS + \lambda S^2) H^\dagger H$$
- Higgs Portal Scalars

Vector Portal
$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$
- Light Dark Matter
- Millicharged Particles

Axion Portal
$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$
- Heavy QCD Axions
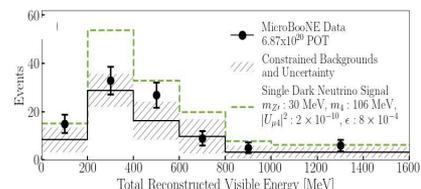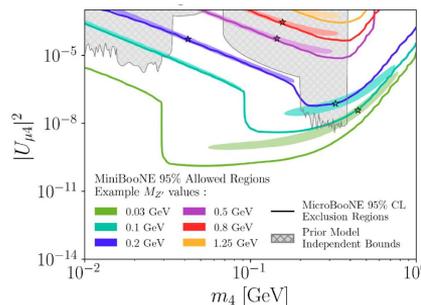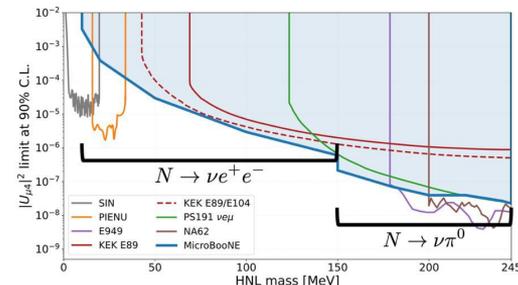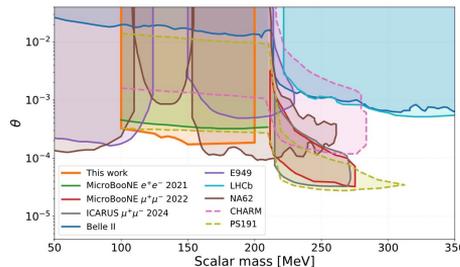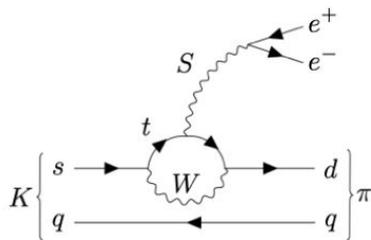
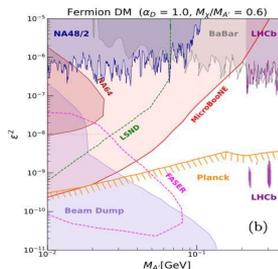### Combined and Non-Minimal Portals

Dark Sector Portals

Higgs Portal Scalar (NuMI) arXiv:2501.08052

- Search for S→e⁺e⁻ from kaons in NuMI
- ID'd by angle
- Strongest limits to date

This work
MicroBooNE e⁺e⁻ 2021
MicroBooNE μ⁺μ⁻ 2022
ICARUS μ⁺μ⁻ 2024
Belle II
E949
LHCb
NA62
CHARM
PS191

μBooNE

cosmic muon
detector axis
decays to e⁺e⁻
Scalar from KDIF
24 cm
MicroBooNE Simulation

Dark Tridents (NuMI) PRL 132, 241801 (2024)

- First search for dark-trident scattering in a neutrino beam
- Constrains parameter space for the production of fermion and scalar DM particles

μBooNE
Signal score: 0.940
Dark Trident Simulation

Fermion DM ($\alpha_D = 1.0$, $M_\chi/M_{A'} = 0.6$)
NA48/2
BaBar
LHCb
LSND
MiniBooNE
E137
Planck
Beam Dump
$M_{A'}$ [GeV]

ν Neutrino Portal

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

φ Scalar Portal

$$\mathcal{L} \supset (A S + \lambda S^2) H^\dagger H$$

- Higgs Portal Scalars

γ Vector Portal

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

- Light Dark Matter
- Millicharged Particles

a' Axion Portal

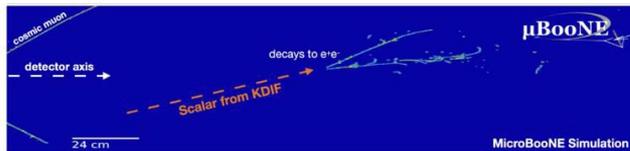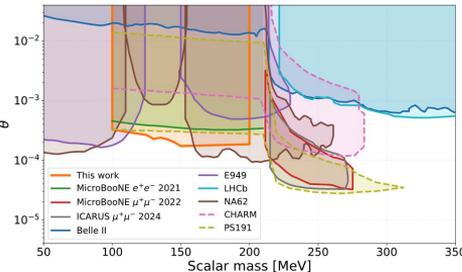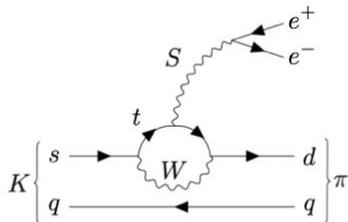$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$

- Heavy QCD Axions

ν γ Combined and Non-Minimal Portals

Dark Sector Portals

Higgs Portal Scalar (NuMI) arXiv:2501.08052

- Search for S→e⁺e⁻ from kaons in NuMI
- ID'd by angle
- ⅓ of available MicroBooNE NuMI data
- Strongest limits to date

Dark Tridents (NuMI) PRL 132, 241801 (2024)

- First search for dark-trident scattering in a neutrino beam
- Constrains parameter space for the production of fermion and scalar DM particles

ν Neutrino Portal

$$\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

φ Scalar Portal

$$\mathcal{L} \supset (A S + \lambda S^2) H^{\dagger} H$$

- Higgs Portal Scalars

γ Vector Portal

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

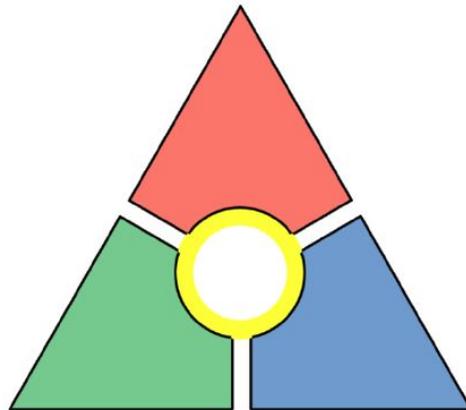- Light Dark Matter
- Millicharged Particles

a' Axion Portal

$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$
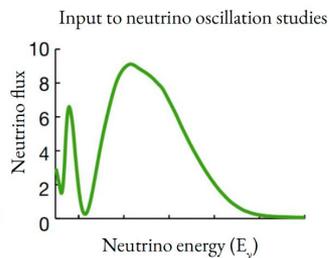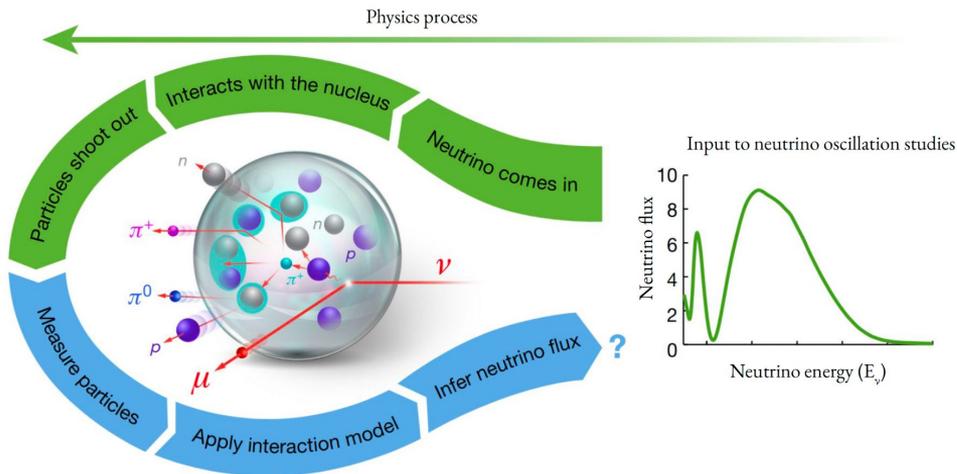
- Heavy QCD Axions

Work Ongoing!

ν γ Combined and Non-Minimal Portals

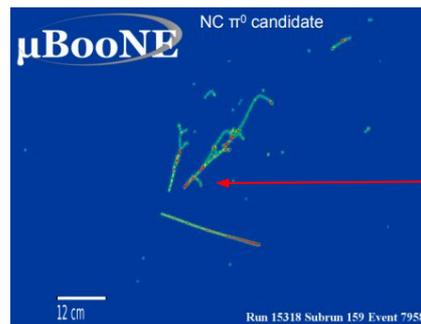# MicroBooNE Science Goals

Neutrino interaction measurements on argon

Interaction Modelling and Measurements

Physics process

Input to neutrino oscillation studies

Experimental analysis

Nature 599, 565–570 (2021)

- Many SM backgrounds in BSM searches that must be well-modelled and understood for new discoveries

- Interaction and flux modelling are inputs to oscillation studies

- Interactions on argon especially important for future neutrino program, e.g. DUNE

μBooNE   NC π⁰ candidate

12 cm   Run 15318 Subrun 159 Event 7958

μBooNE

E_{e+e-} ~210 MeV
θ_{sep} ~ 3°

17 cm   Dark Sector e+e- Simulation

MicroBooNE Cross Sections

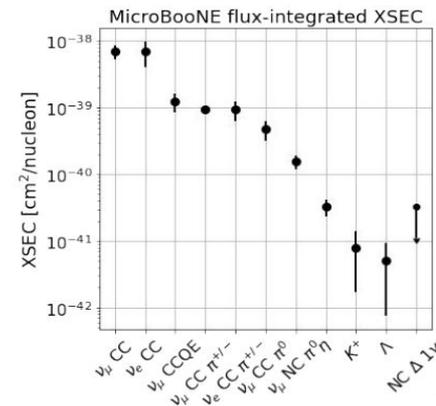| Published		Ongoing	
CC inclusive • 1D ν_μ CC inclusive @ BNB, PRL 123, 131801 • 1D ν_μ CC Ev @ BNB, PRL 128, 151801 • 3D CC E_ν @ BNB, arXiv:2307.06413 • 1D ν_e CC Inclusive @ NuMI, PRD 104 052002, PRD 105 L051102 • 2D ν_μ CC0pNp inclusive @ BNB, PRL 133, 041801, PRD 110, 013006 **Rare channels & novel techniques** • η production @ BNB, PRL 132, 151801 • Λ production @ NuMI, PRL 130, 231802 • K+ production @ BNB, arXiv:2503.00291 • Neutron identification, EPJC 84, 1052	**CC0π** • 1D ν_e CCNp0π @ BNB, PRD 106, L051102 • 1D & 2D ν_μ CC1p0π TKI @ BNB, PRL 131, 101802, PRD 108, 053002 • 1D & 2D ν_μ CC1p0π GKI @ BNB, PRD 109, 092007 • 1D ν_μ CC1p0π @ BNB, PRL 125, 201803 • 1D ν_μ CC2p @ BNB, arXiv:2211.03734 • 1D ν_μ CCNp0π @ BNB, Phys. Rev. D 102, 112013 • 2D ν_μ CCNp0π @ BNB, arXiv:2403.19574 **Pion production** • ν_μ NCπ^0 @ BNB, PRD 107, 012004 • 2D ν_μ NCπ^0 @ BNB, PRL 134, 161802 • ν_μ CCπ^0 @ BNB, PRD 110, 092014	**CC inclusive** • ν_μ CC inclusive @ NuMI • ν_e/ν_μ ratios @ BNB, NuMI • 3D E_ν, E_μ, E_{had} @ NuMI & BNB • anti-ν_e @ NuMI **Pion production** • ν_μ CC1π+ @ BNB & NuMI • ν_μ CCNπ @ NuMI • 1D ν_μ CCπ0 @BNB • 2D ν_μ CC/NC π0 @ BNB • 2D $\nu_{e,\mu}$ NCπ0 @ BNB	**CC/NC 0π** • 2D ν_μ CC1p0π GKI @ BNB • 1D & 2D ν_μ CC0π @ BNB • 2D ν_μ CCNp0π @ BNB • 1D ν_e CC0πNp @ NuMI • 1D ν_μ NC1p0π @ BNB **Rare channels & novel techniques** • MeV-scale physics • Low-energy neutrons @ BNB

MicroBooNE flux-integrated XSEC

ν_μ CC Kinematics

ν_μ CC Kinematics

BNB Inclusive 0p/Np PRL 133, 041801 (2024) PRD **110**, 013006 (2024)

- Probing **ν_μ** CC channel split by final state protons
- High statistics → differential (1D, 2D, 3D)
- Modeling better in Np
- Prefers strong FSI, in-medium corrections
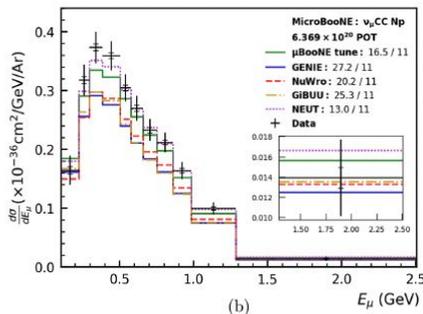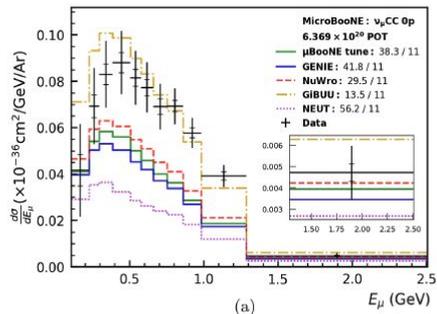
**1μ1p Neutrino Directional Resolution** PRD **111**. 113007 (2025) for DUNE Atmospherics

- Leverage known BNB beam direction to study angular distributions for the DUNE atmospheric flux
- Data-driven predictions for DUNE
- Sensitive to final state interactions (FSI) and hadron reinteractions
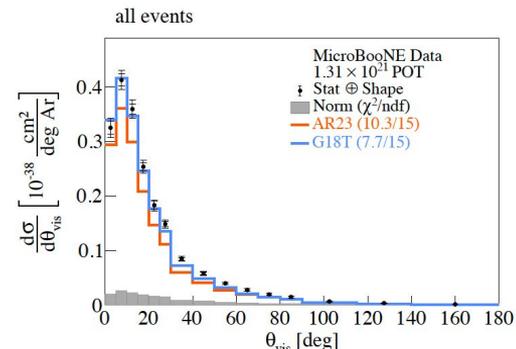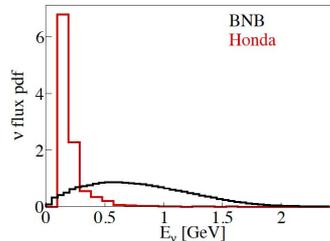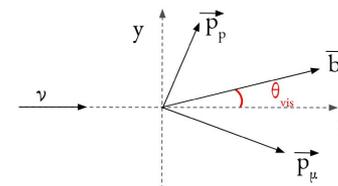
Nuclear Effect Studies

Using various **ν**_μ CC final states to probe nuclear modeling and final state interactions across models

- Transverse Kinematic Imbalance (TKI)
  - **1p:** PRL 131, 101802 (2023)
  - **1p:** PRD 108, 053002 (2023)
- Generalized Kinematic Imbalance (GKI)
  - **1p:** PRD 109, 092007 (2024)
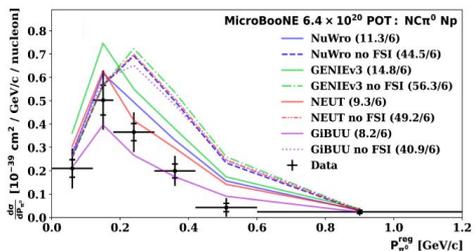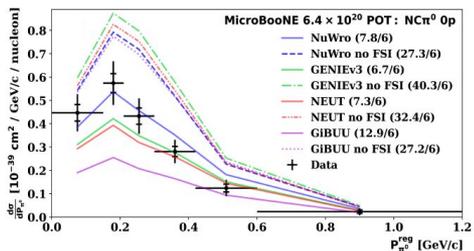- TKI and GKI
  - **Np:** arXiv:2403.19574
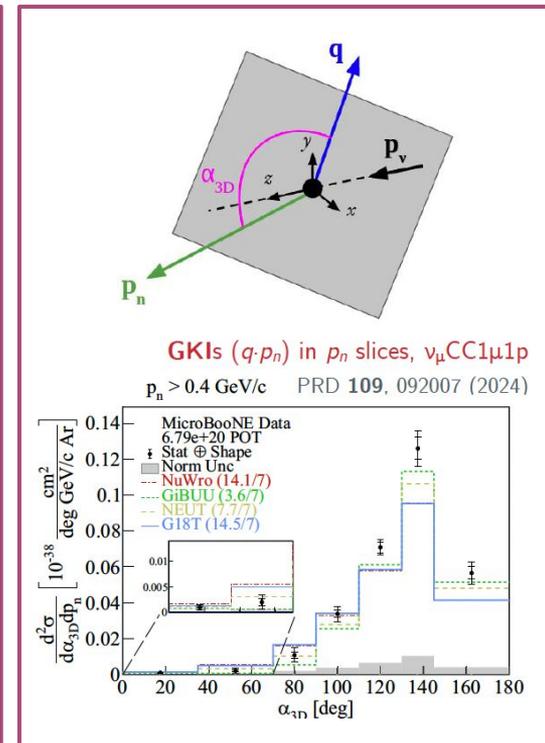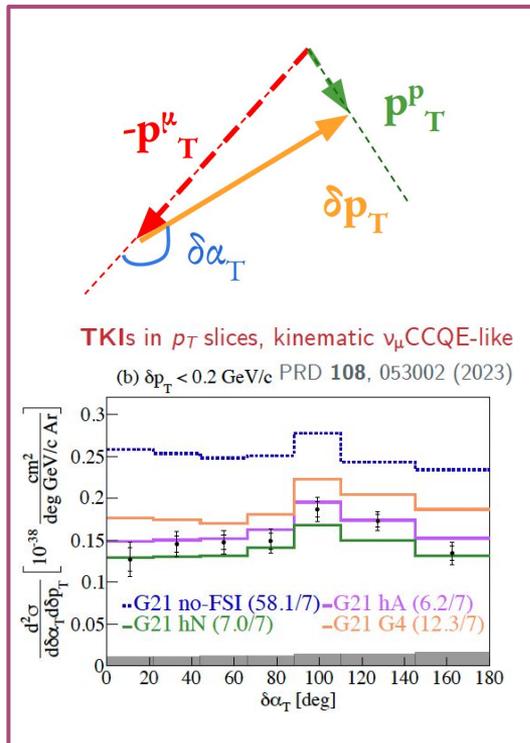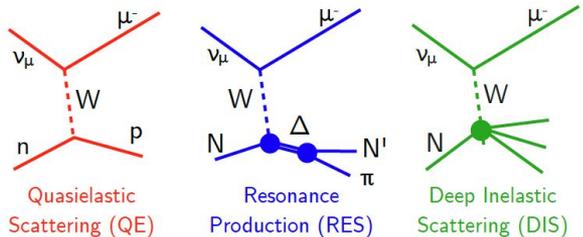
Pions

Major backgrounds for v_μ CC and v_e CC used in oscillation measurements as well as BSM searches (single photon, e^+e^-, $\mu\pi$)
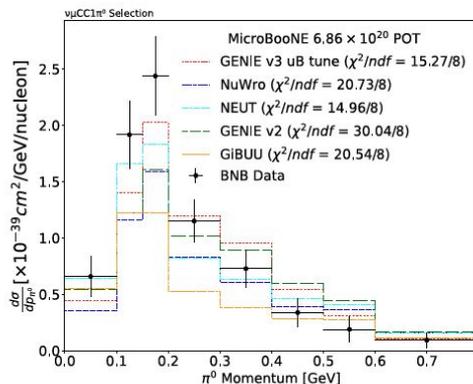
BNB 2D NC π^0 0p/Np PRL **134**, 161802 (2025)

- First 2D NC π^0 on Ar
- π^0 kinematics
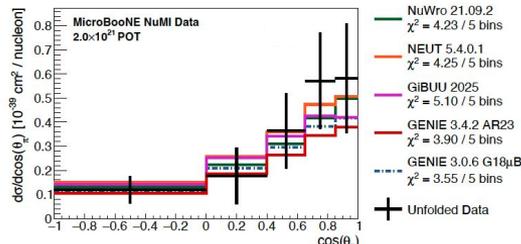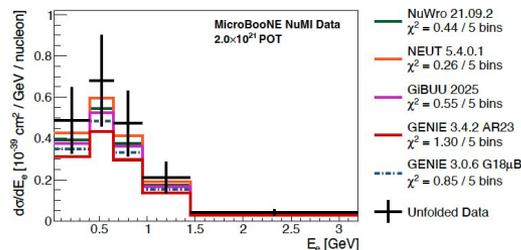- Split by final state protons
- Sensitive to FSI and form factors

BNB v_μ CC 1π^0 PRD **110**, 092014 (2024)

- 1D and 2D in μ and π^0 kinematics
- Shows a low-q suppression for resonant pion production and impact of pion FSI treatments
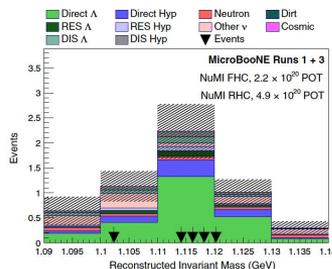

NuMI v_e CC 1$\pi^\pm$ arXiv:2503.23384

- First differential v_e 1$\pi^\pm$ on Ar
- e and π kinematics
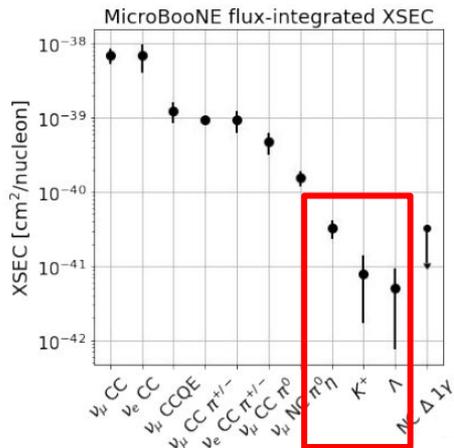- Showing good model agreement

Rare Channels

NuMI Λ Production PRL **130**, 231802 (2023)

- Inclusive ν_μ CC Λ + X production
- Sensitive to nucleon decay search backgrounds

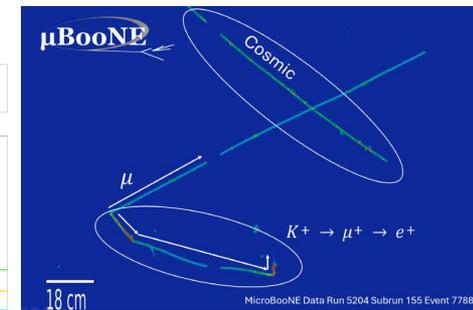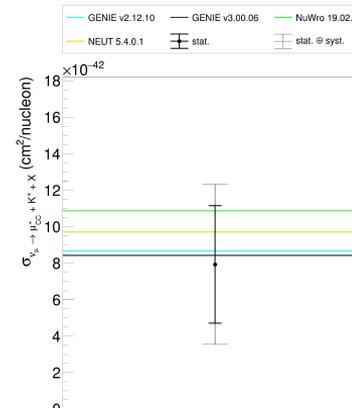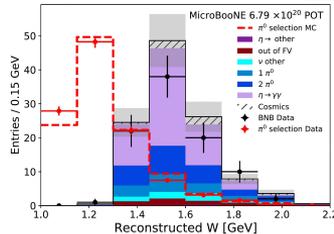## BNB ν_μ CC K$^+$ arXiv:2503.00291

- First ν K$^+$ production on Ar
- Probing strange production and nucleon decay backgrounds
- 10 candidate events
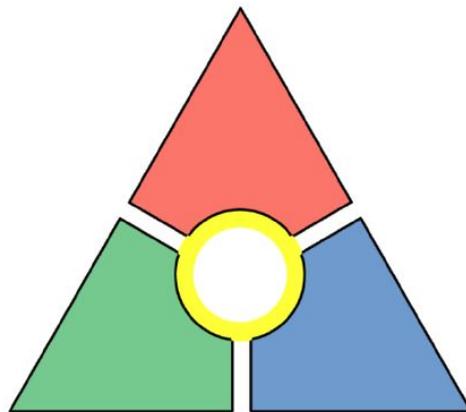

BNB η Production

PRL **132**, 151801 (2024)

- Inclusive CC+NC η production
- Probing resonances above the Δ(1232) mass

MicroBooNE Science Goals

LArTPC detector hardware and software R&D

Novel PID and Detector Physics

MeV-Scale "Blips" PRD **111**, 032005 (2025), PRD **109** 052007 (2024)

- Ability to reconstruct activity down to 150 keVee
- Applications: improved calorimetry, lower particle thresholding, BSM searches (e.g. millicharged particles), muon/pion charge sign tagging, gamma spectroscopy, neutron tagging, etc.
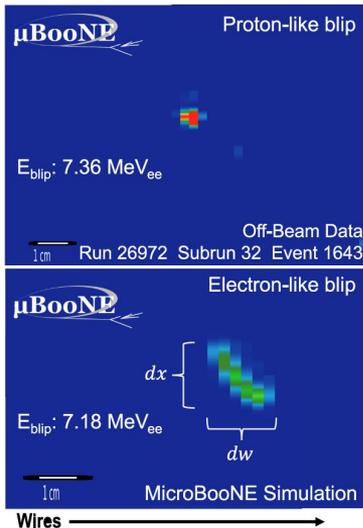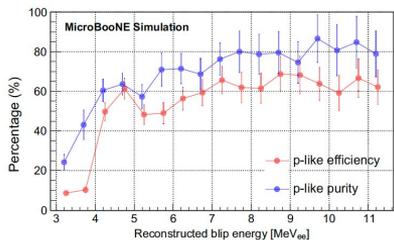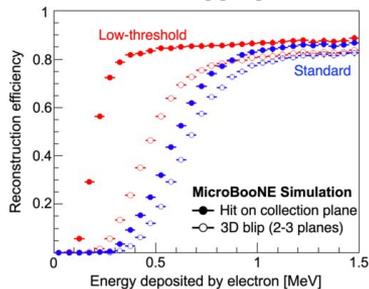

ns-level Timing Resolution PRD **108**, 052010 (2023)
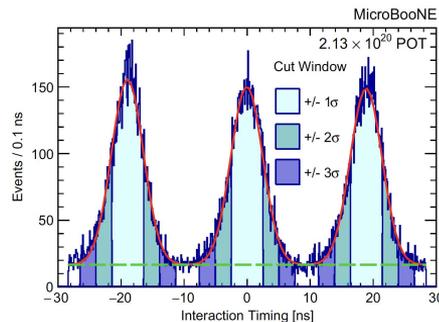
- Light propagation corrected to recover O(ns)-wide beam bunch structure
- σ < 2.5ns for Nph > 200
- Can use to reject cosmic BGs and enhance BSM searches for long-lived particles (HNLs)

Neutron-induced Protons EPJC **84**, 1052 (2024)

- Capability to identify and reconstruct neutrons > ~100 MeV via n-Ar inelastic single-proton production
- New insights into poorly-constrained neutral hadron production
- Work underway to combine with blips to extend toward low-energy neutrons
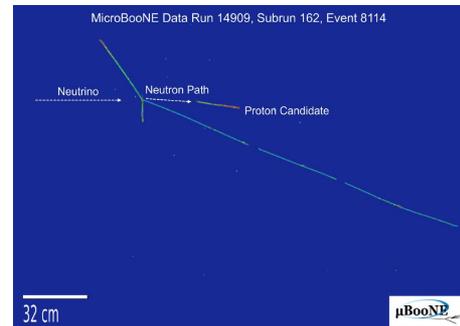
Summary

- MicroBooNE has finished it's 5 years of physics running and is now in "paper factory mode" — leveraging its existing dataset across two neutrino beams

- Extensive program across multiple areas of physics

  - New physics searches and LEE anomaly investigations

  - Neutrino interaction measurements on argon

  - Pioneering work in LArTPC calibrations, detector physics, and reconstruction tools

- Exciting new results out across all areas, with more in the works!

More Exciting Results Coming Soon!

Thank you!