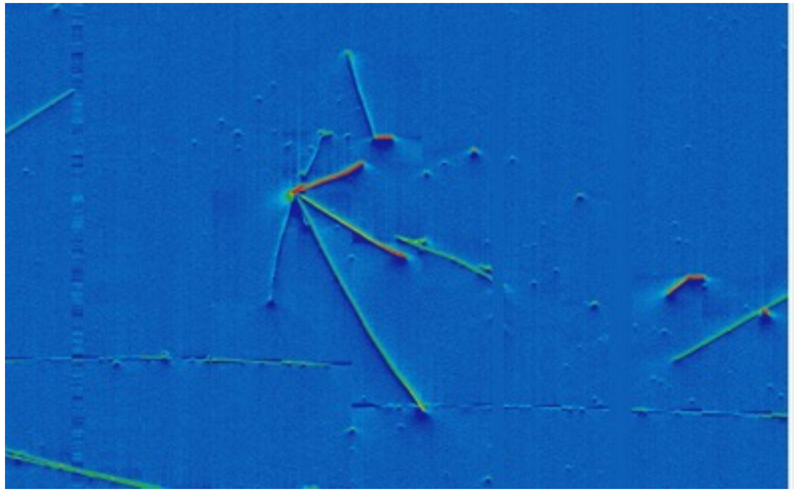
MicroBooNE



Sophie Berkman
Michigan State University
Fermilab User's Meeting
July 11, 2024

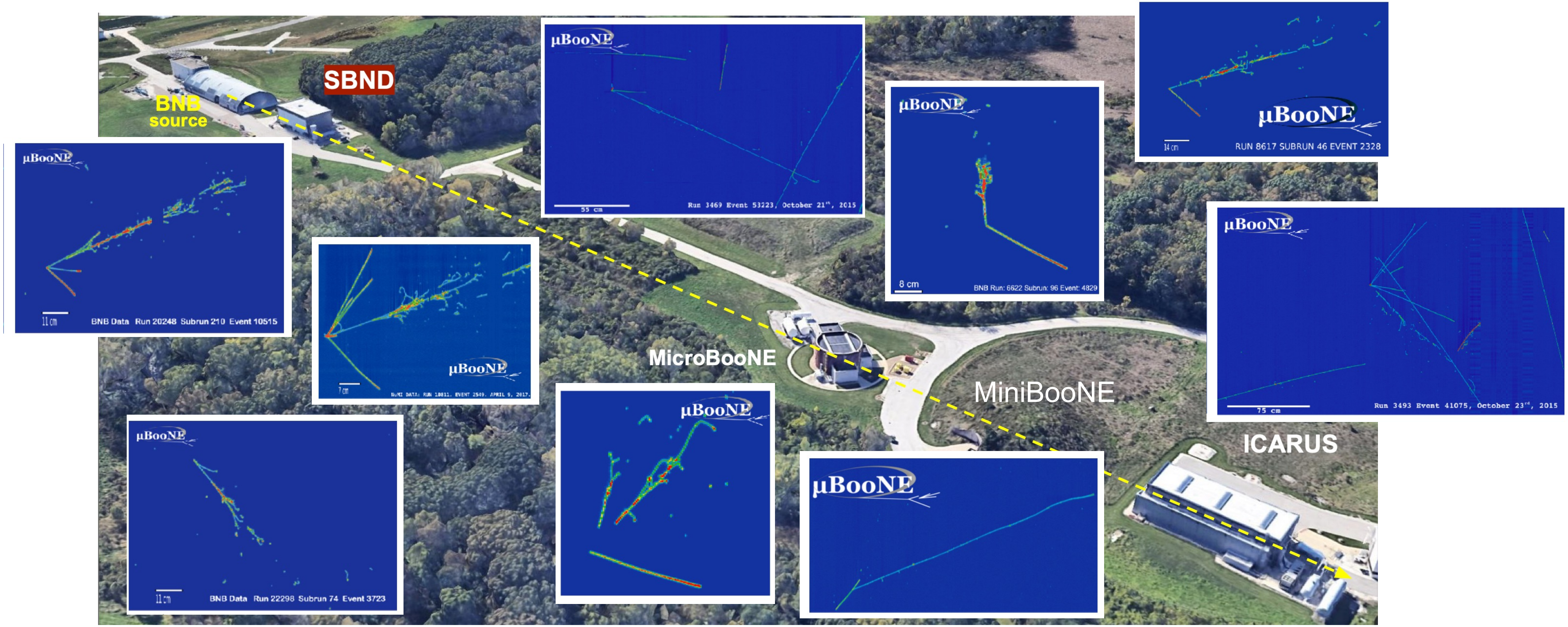
MicroBooNE

- Longest operating LArTPC detector, with world's largest data set of neutrino-argon interactions

- Collect data from the BNB and NuMI beamlines at Fermilab

MicroBooNE

- Longest operating LArTPC detector, with world's largest data set of neutrino-argon interactions

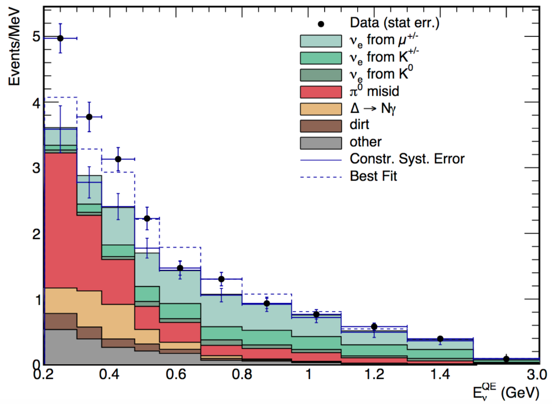


- Thank you to everyone at Fermilab who has made this possible!

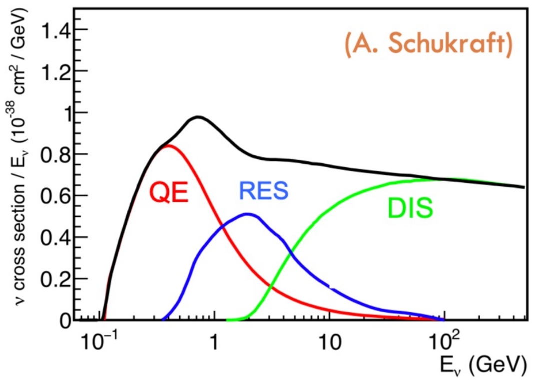
ACCELERATOR DIVISION CYRO ENGINEERS OPERATIONS COMPUTING

Why MicroBooNE?

1. Exploring anomalies and new physics



2. Providing input for the future with
   neutrino interaction cross sections



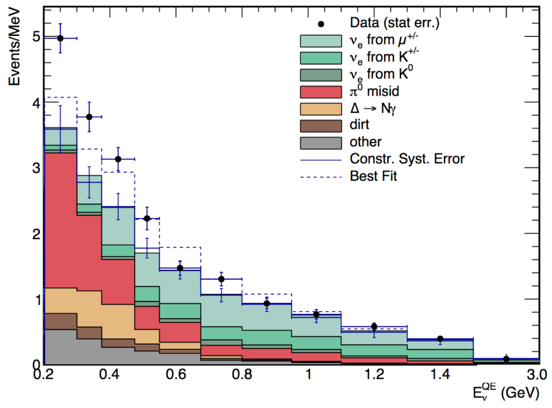
3. Expanding the reach of LArTPC detectors

Why MicroBooNE?

Today:

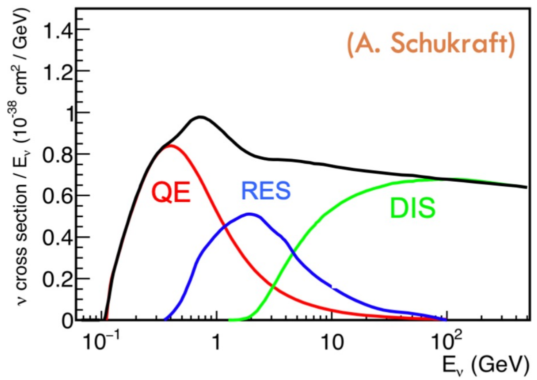
1. Exploring anomalies and new physics

   New results using full 5 years of data for the first time!



2. Providing input for the future with neutrino interaction cross sections

   New measurements taking advantage of detailed topological information available in LArTPCs

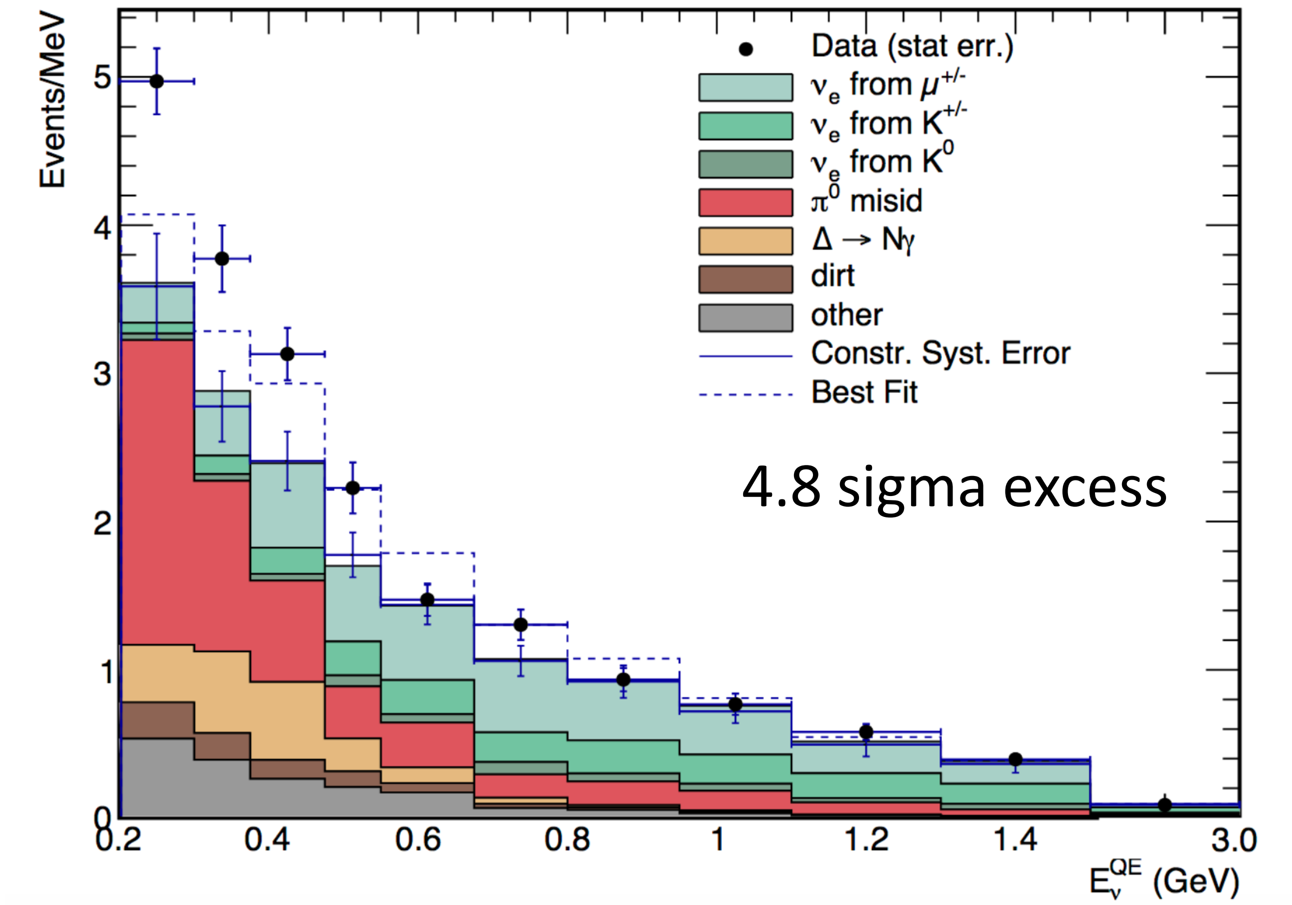


3. Expanding the reach of LArTPC detectors

   Continuing to innovate and develop new methods to use LArTPC data to its full capacity with detector R&D

Exploring Anomalies and New Physics

Outstanding anomaly for >10 years



Why MicroBooNE for Anomaly Exploration?

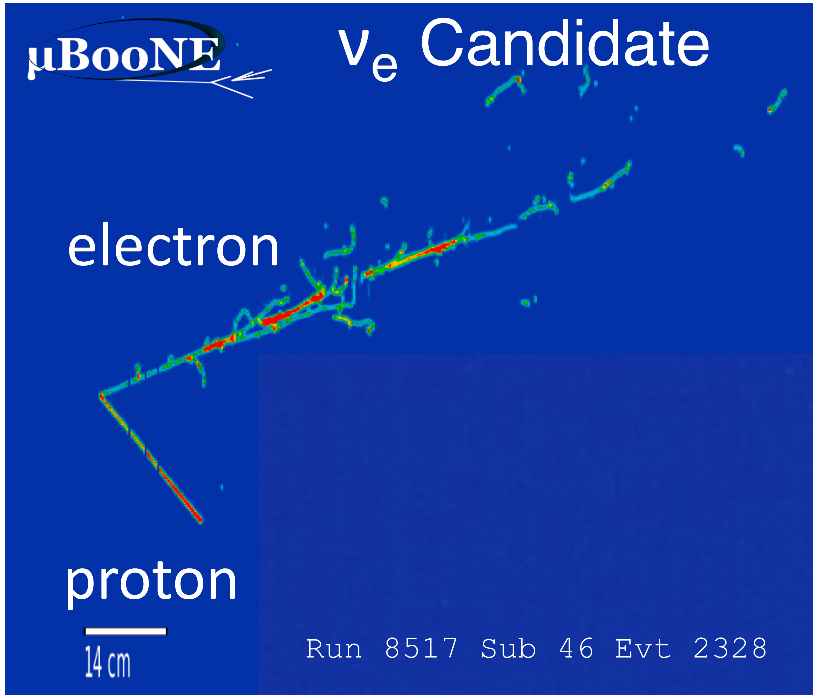
1. Collect data in the same neutrino beam at Fermilab and close to MiniBooNE

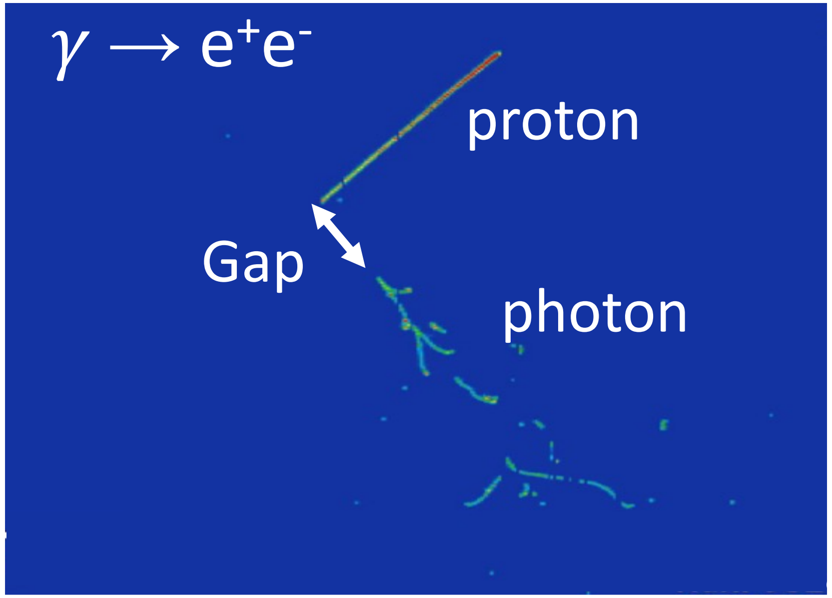
2. Different detector technology → additional information about neutrino interactions

Why MicroBooNE for Anomaly Exploration?

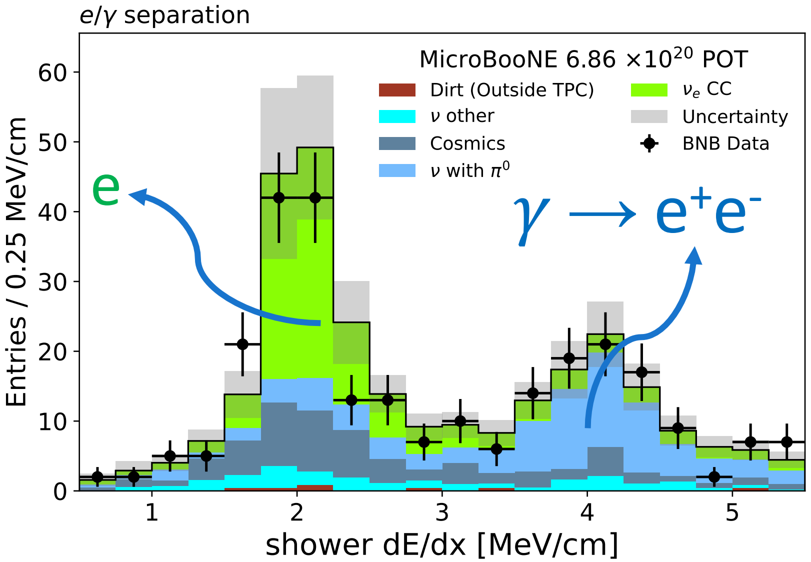
1. Separation of electrons and photons

Conversion Distance





Energy Deposited by Shower



Reconstructed Energy>0.65 GeV

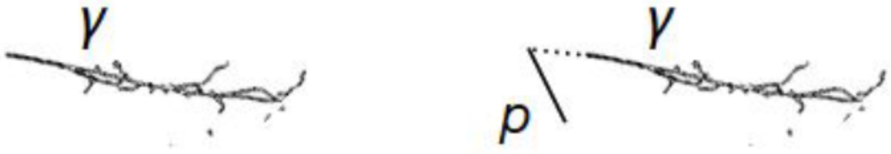
2. Visible protons: MiniBooNE limited by Cherenkov threshold of ~900 MeV/c for protons
arxiv:0806.4201

In MicroBooNE protons always ionize the argon and protons are visible down 10s of MeV KE

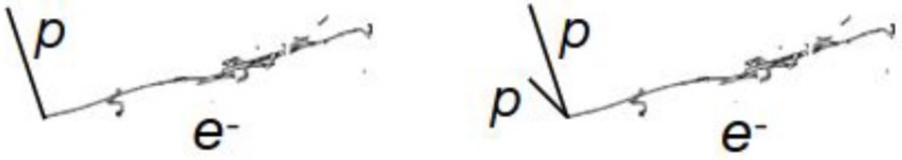
MiniBooNE Anomaly Exploration

- **What is the origin of the observed MiniBooNE excess?**
  - First results by MicroBooNE in 2021: no excess observed
  - Now in 2024:

Comprehensive Single Photon Measurements



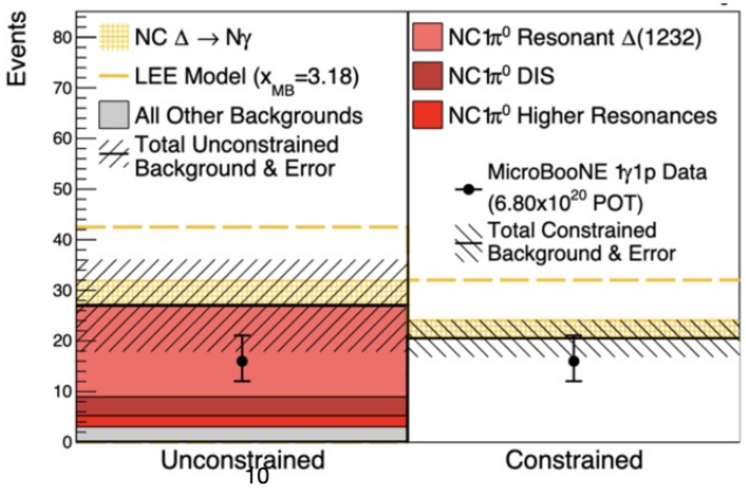
Expanded Electron Neutrino Search



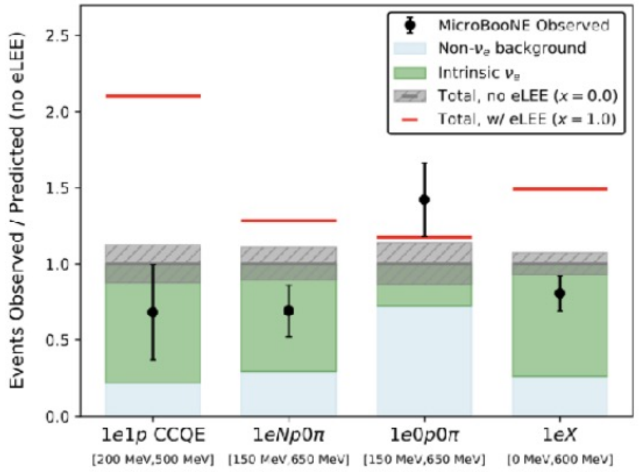
New e^+e^- Final States

Overlapping e+e- | Overlapping e+e- | Highly asymmetric e+e- | Highly asymmetric e+e-

PRL 128 (2022) 111801



PRL 128 (2022) 24, 241801

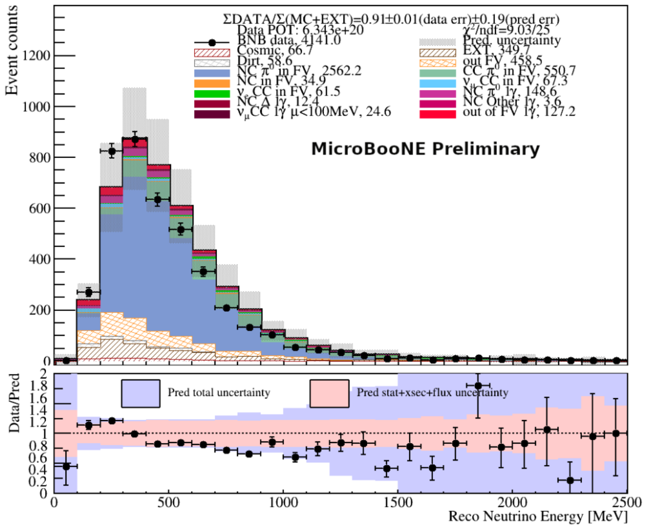


Comprehensive Single Photon Measurements

- **Previous results:** search for NCΔ radiative decay standard model process
- **Now:** search for variety of photon final states, independent of origin

NCπ^0 Background Sideband Samples for Each of these Searches

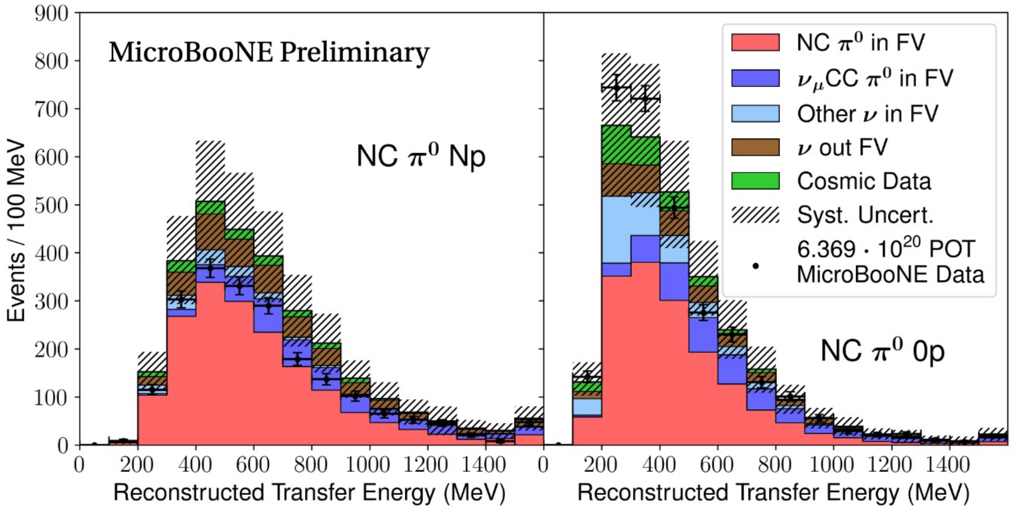
Inclusive single photon



MICROBOONE-NOTE-1125-PUB

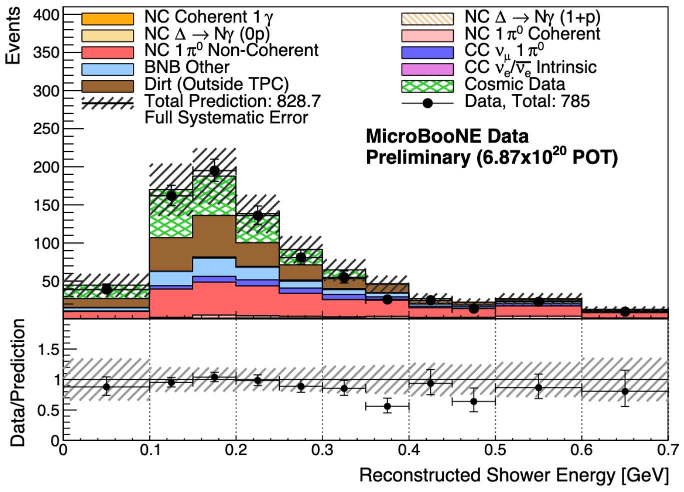
NCΔ → 1 photon

With a broader set of final states



MICROBOONE-NOTE-1126-PUB

NC Coherent



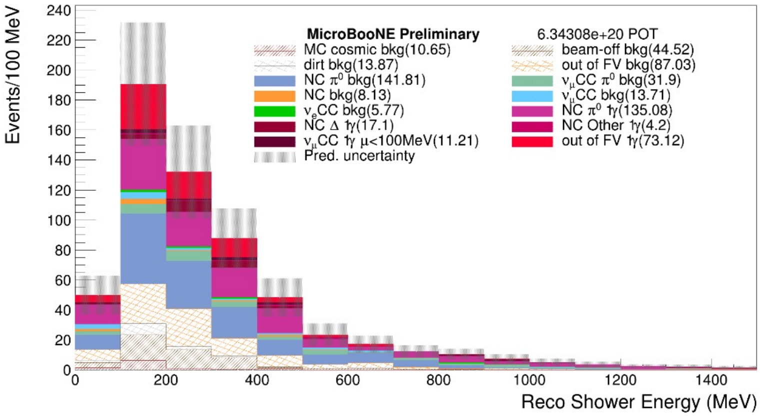
MICROBOONE-NOTE-1131-PUB

Comprehensive Single Photon Measurements

- **Previous results:** search for NC delta radiative decay standard model process
- **Now:** search for variety of photon final states, independent of origin

Signal Region Prediction for Each of these Searches

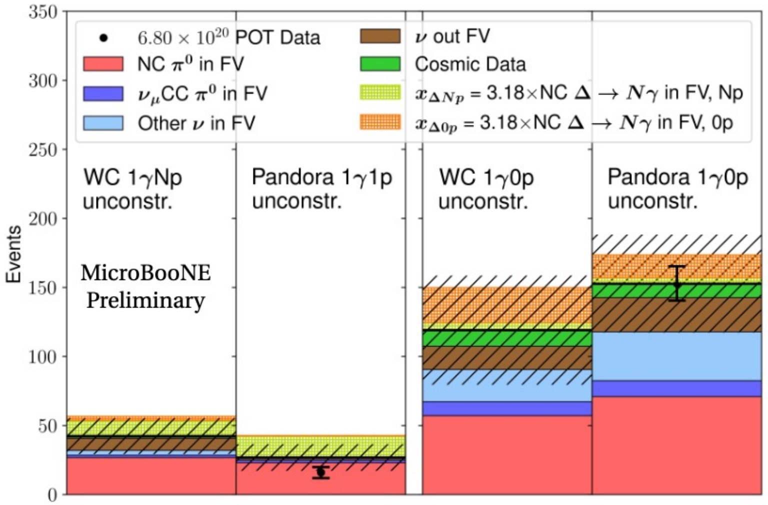
Inclusive single photon



MICROBOONE-NOTE-1125-PUB

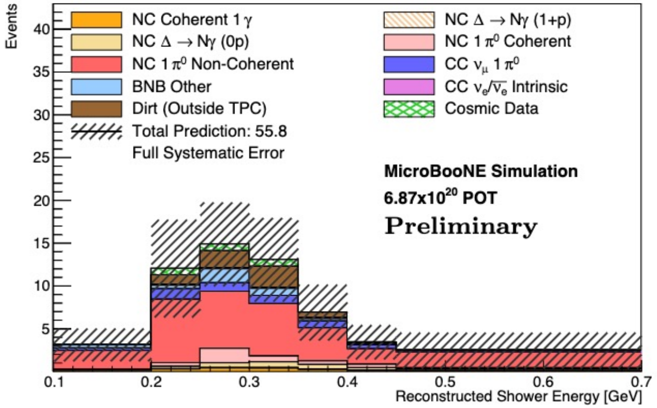
NCΔ → 1 photon

With a broader set of final states



MICROBOONE-NOTE-1126-PUB

NC Coherent



MICROBOONE-NOTE-1131-PUB

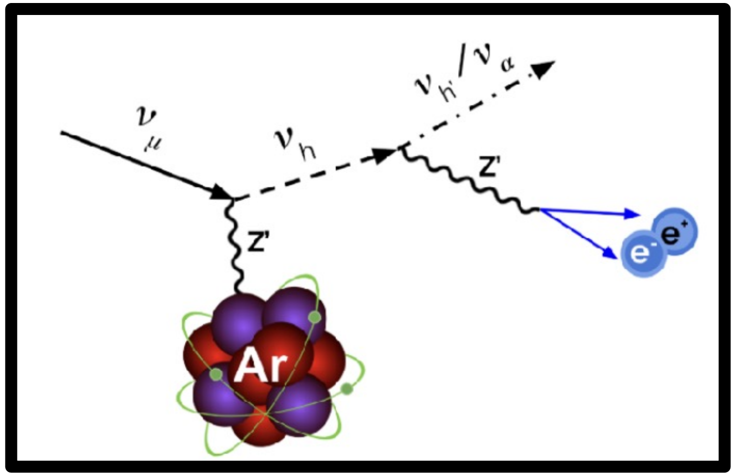
Stay tuned for these upcoming results!

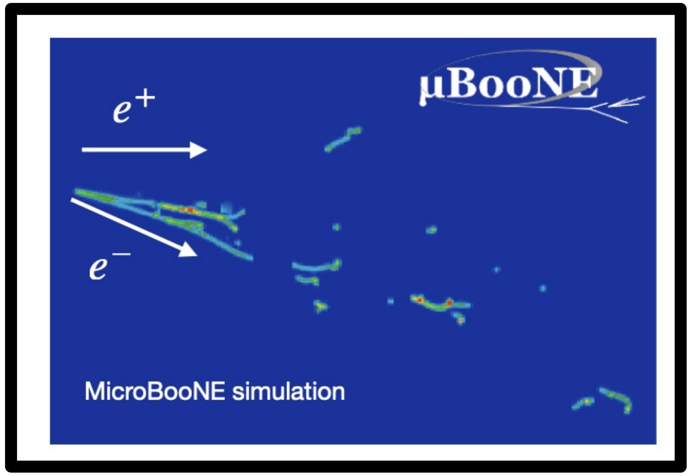
Dark Sector e+e- Final States

- Recent theoretical interest in dark neutrinos decaying to e^+e^- final states to explain MiniBooNE excess

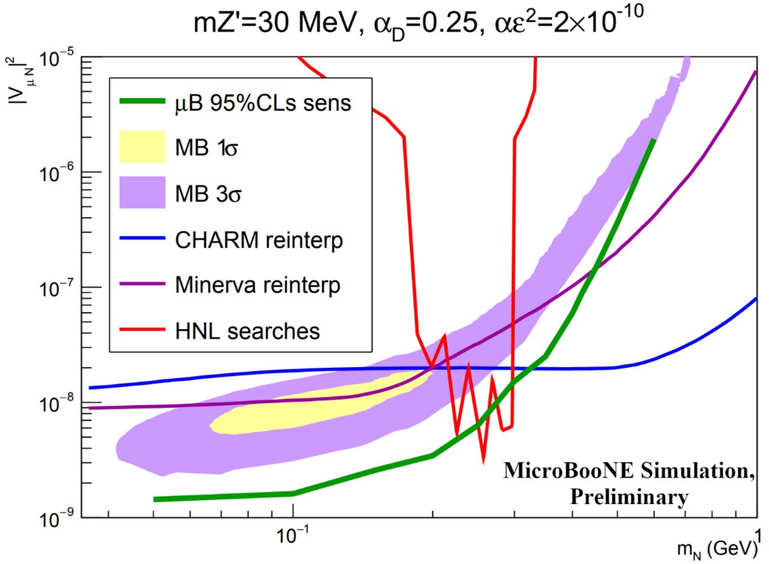
Ballet, Pascoli, Ross-Lonergan
PRD 99 (2019) 071701

Bertuzzo, Jana, Machado, Zukanovich Funchal
PRL 121 (2018) 24, 241801





- Developed new dedicated searches for this final state topology to test these models
  - Built from electron and photon analyses and result in higher overall efficiencies for this topology
  - Sensitive to MiniBooNE allowed region at 95% CL

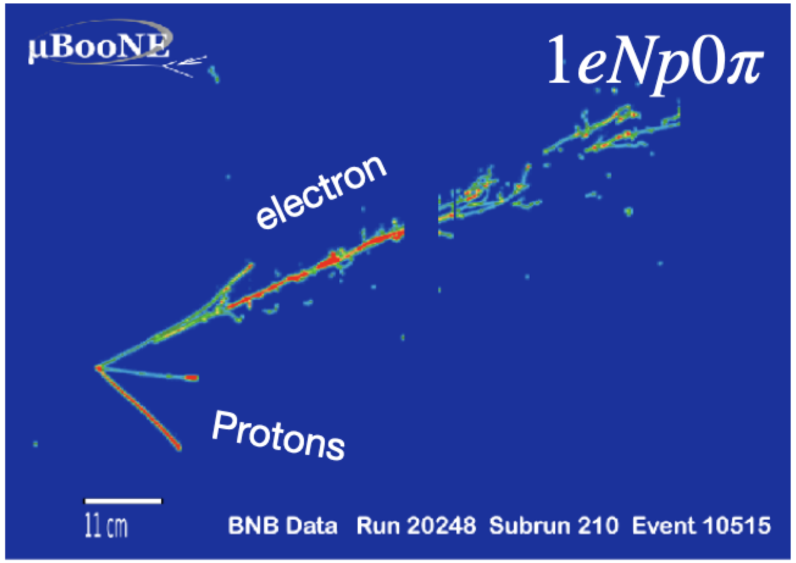


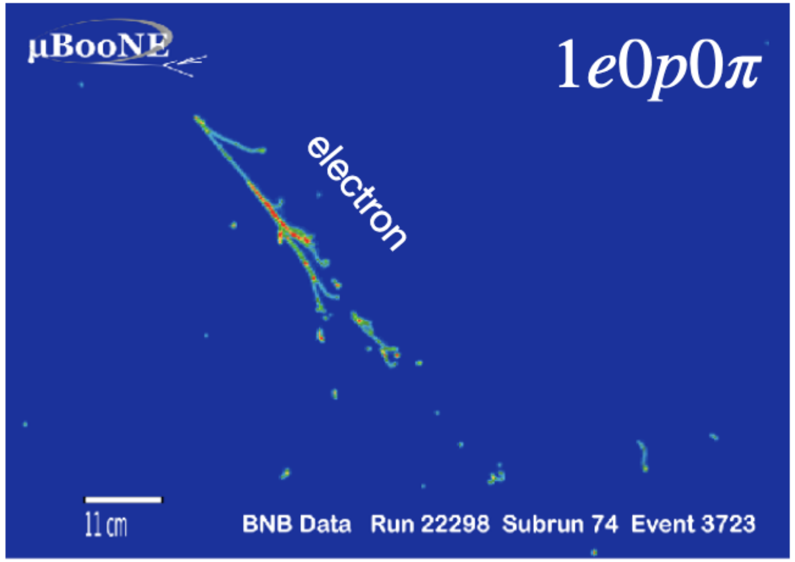
Stay tuned for the data results!

MICROBOONE-NOTE-1124-PUB

Expanded Electron Neutrino Search

- Search for electron neutrinos without visible pions in the final state
  - Same topology as MiniBooNE final state





First measurement to use five years of MicroBooNE data!

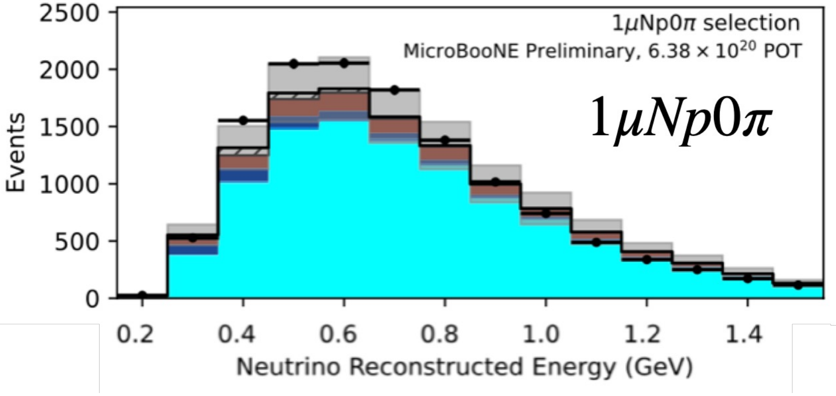
60% more data than previous analyses

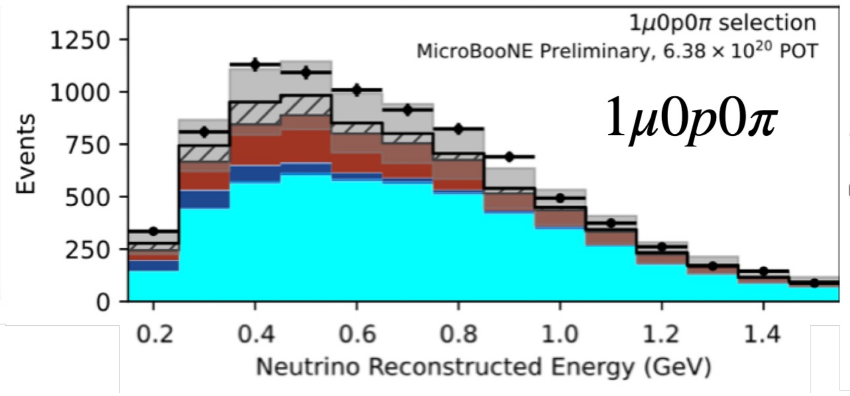
MICROBOONE-NOTE-1127-PUB

Expanded Electron Neutrino Search

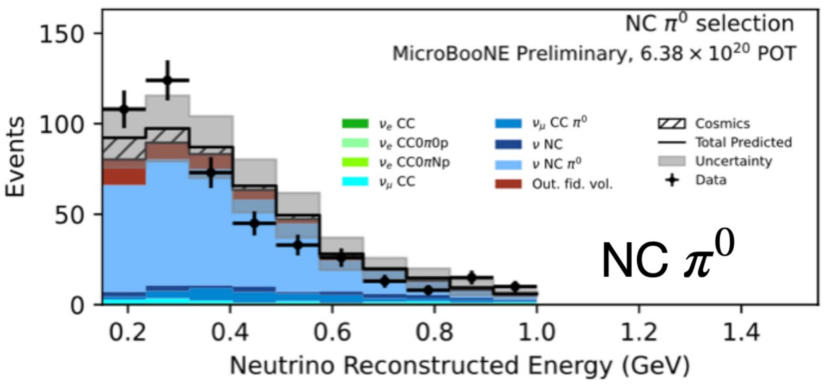
- Updated sideband constraint to match final state topologies and constrain π^0 background

Match electron neutrino final state topologies

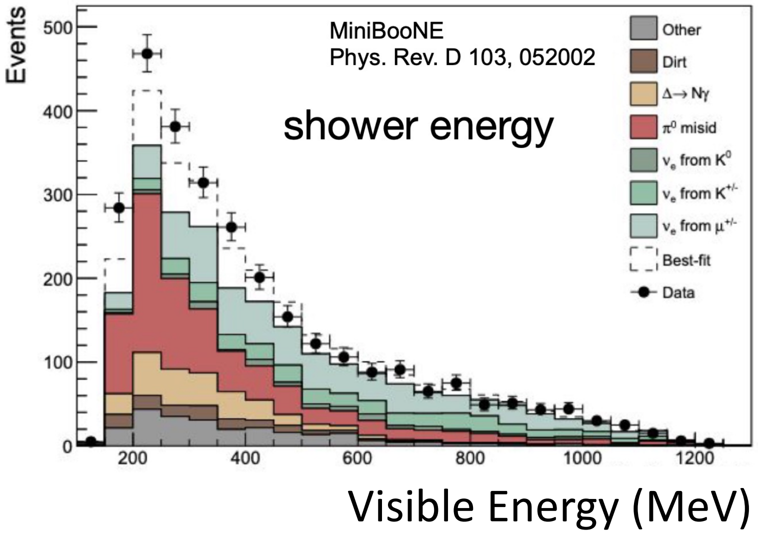


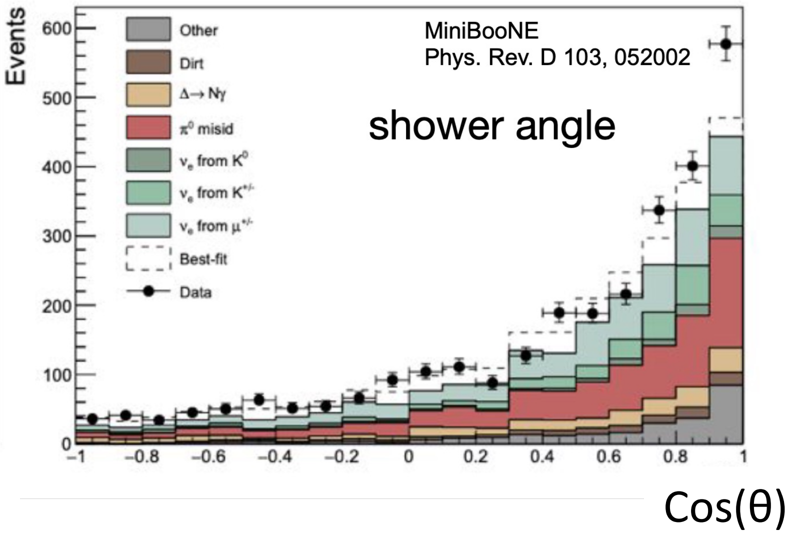


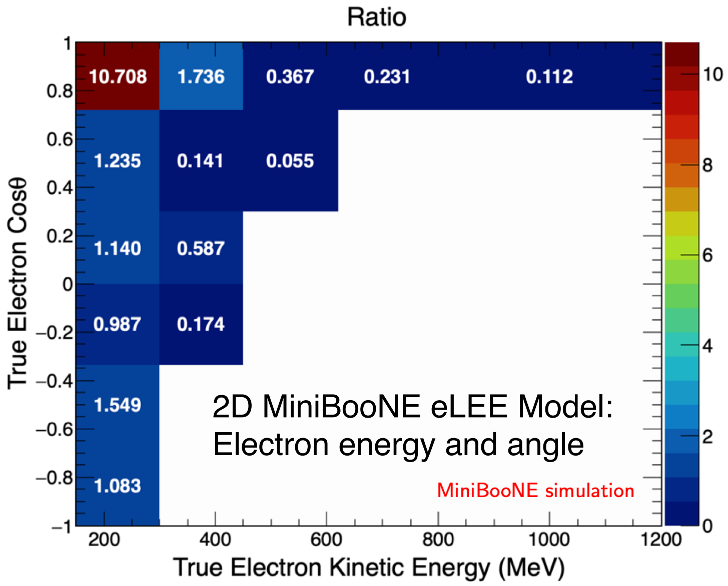
Constrain π^0 background



- Additional signal model in electron neutrino and energy

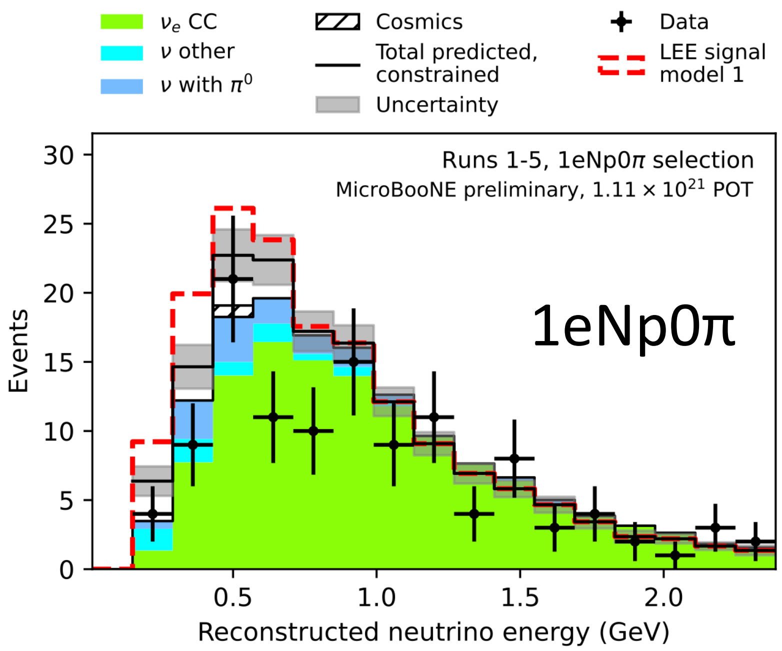


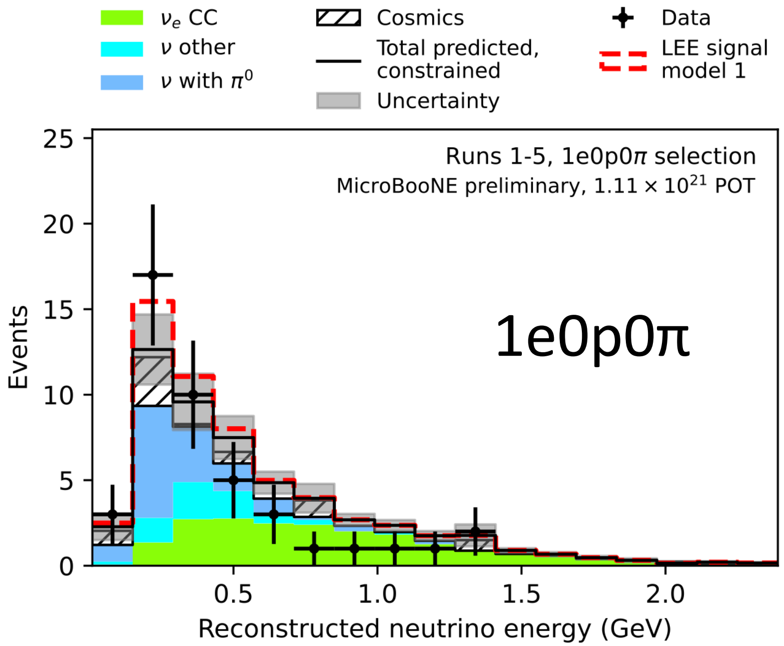




Expanded Electron Neutrino Search: Results

- Data compatible with background-only prediction

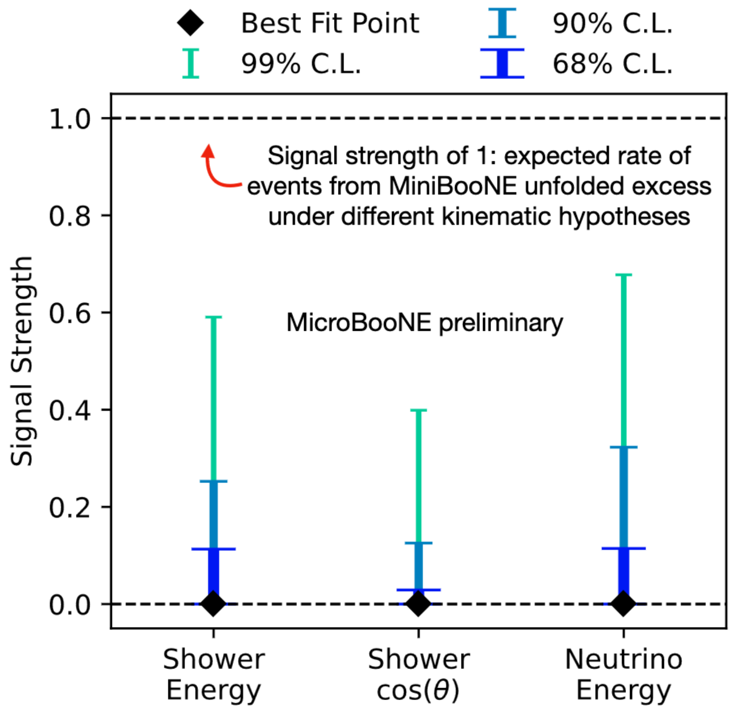




Background only p-values:

	1eNp0π	1e0p0π
Neutrino Energy	18.4%	56.1%
Shower Energy	10.4%	62.5%
Shower Angle	15.3%	77.6%

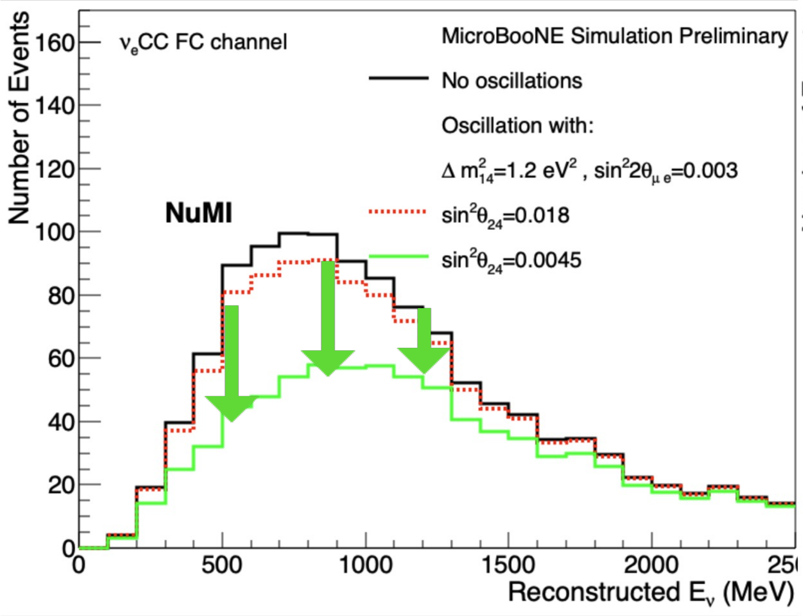
- Data incompatible with electron neutrino excess at >99% CL

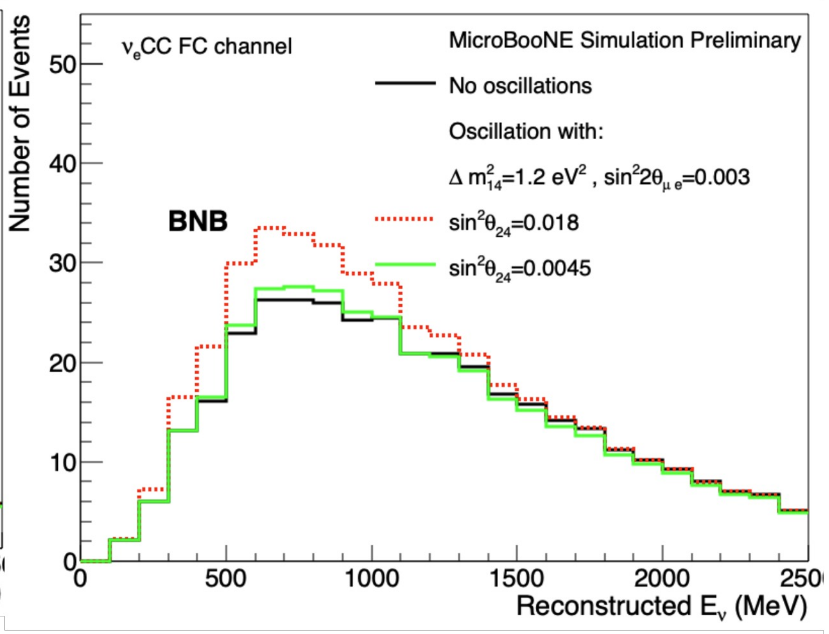


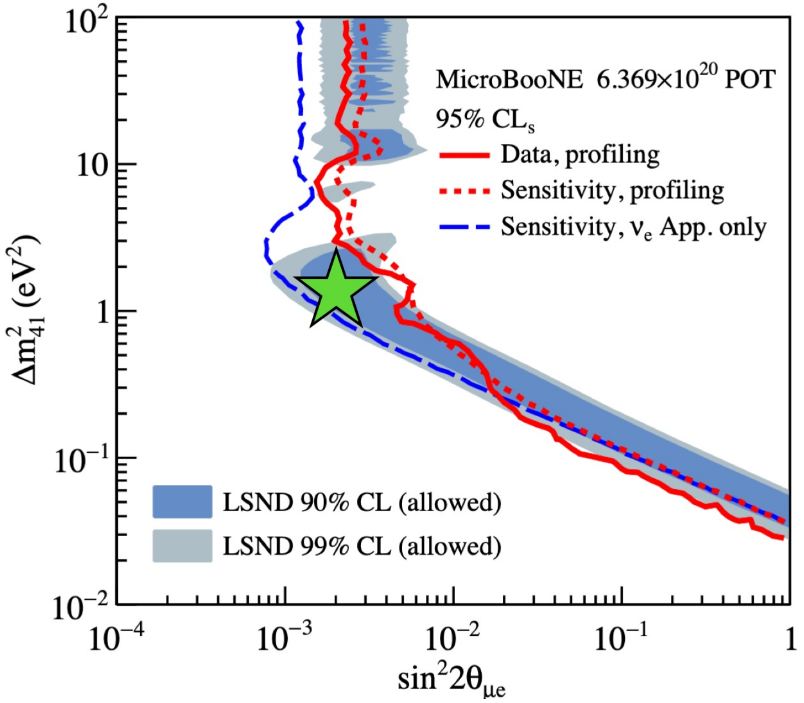
MICROBOONE-NOTE-1127-PUB

Sterile Neutrino Search

- Reinterpret electron neutrino excess search under 3+1 sterile neutrino hypothesis
- First MicroBooNE sterile 3+1 search in 2022 with inclusive electron neutrinos
- But, there is a degeneracy:
  - 3+1 electron neutrino appearance cancels out electron neutrino disappearance
  - NuMI beam makes it possible to cancel out this degeneracy due to different ratio between the number of electron neutrinos and muon neutrinos in the beam



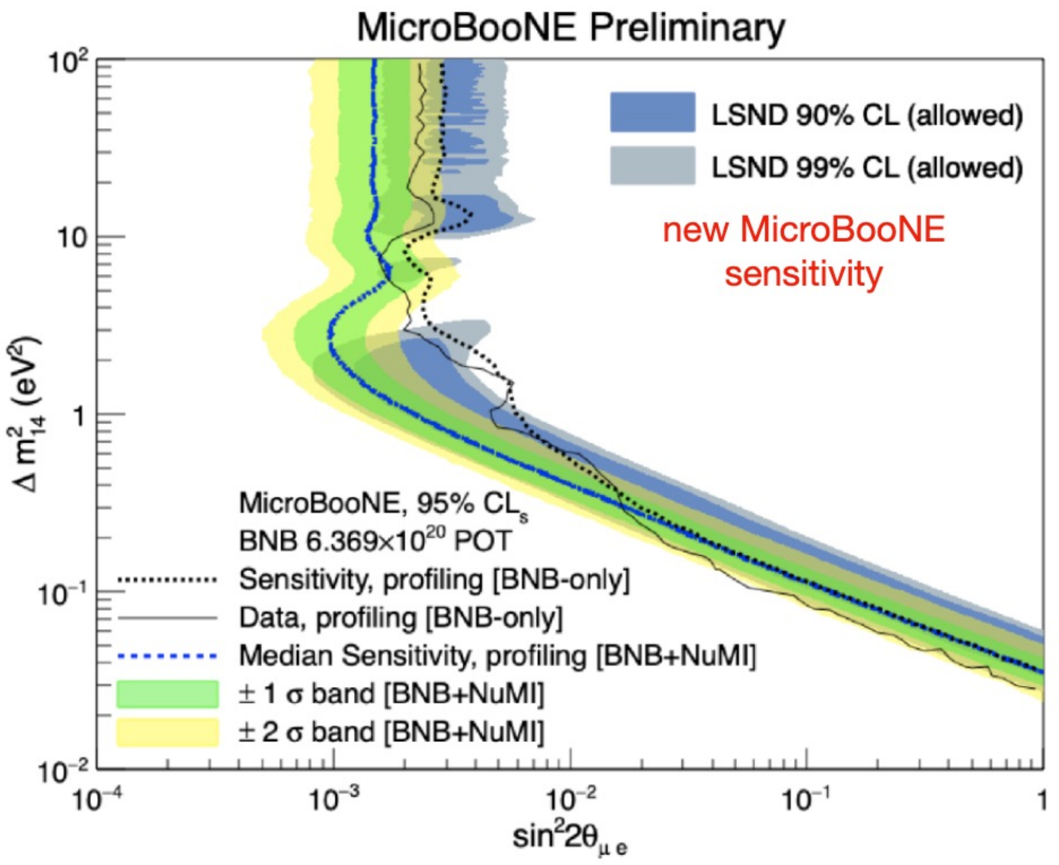




MICROBOONE-NOTE-1132-PUB

Sterile Neutrino Search

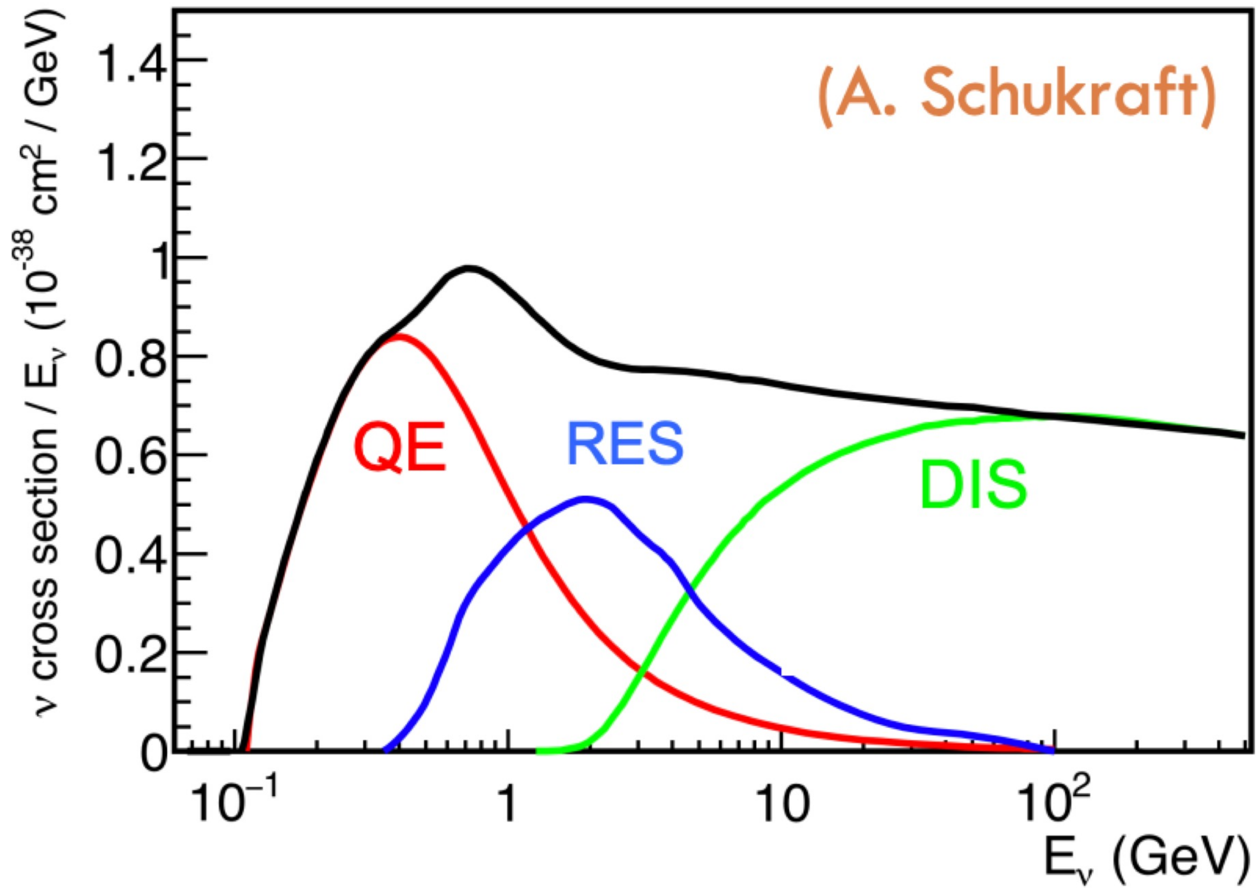
- Joint NuMI + BNB analysis allows for increased sensitivity relative to previous BNB only result



MICROBOONE-NOTE-1132-PUB

Stay tuned for these upcoming data results!

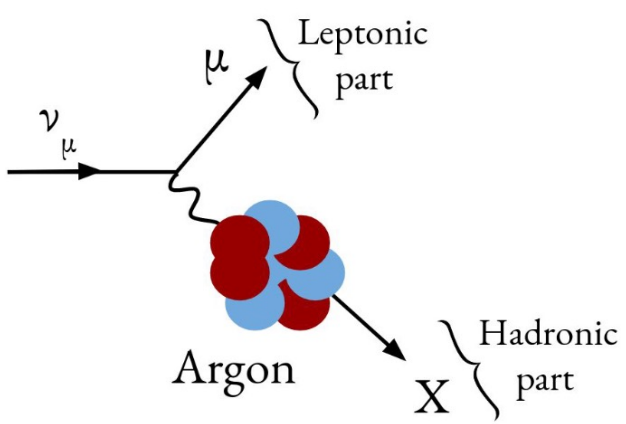
Looking Towards the Future: Interaction Cross Sections

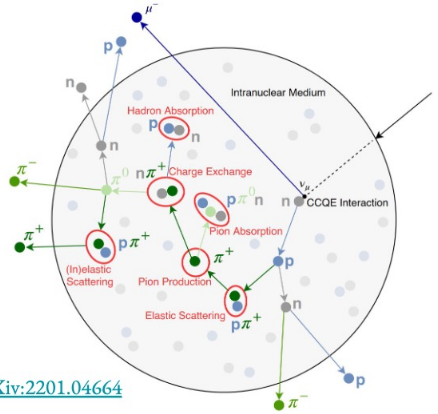


Looking Towards the Future: Interaction Cross Sections

- An understanding of neutrino interactions is required for discovery science, such as BSM and oscillation searches

General Components:





arXiv:2201.04664

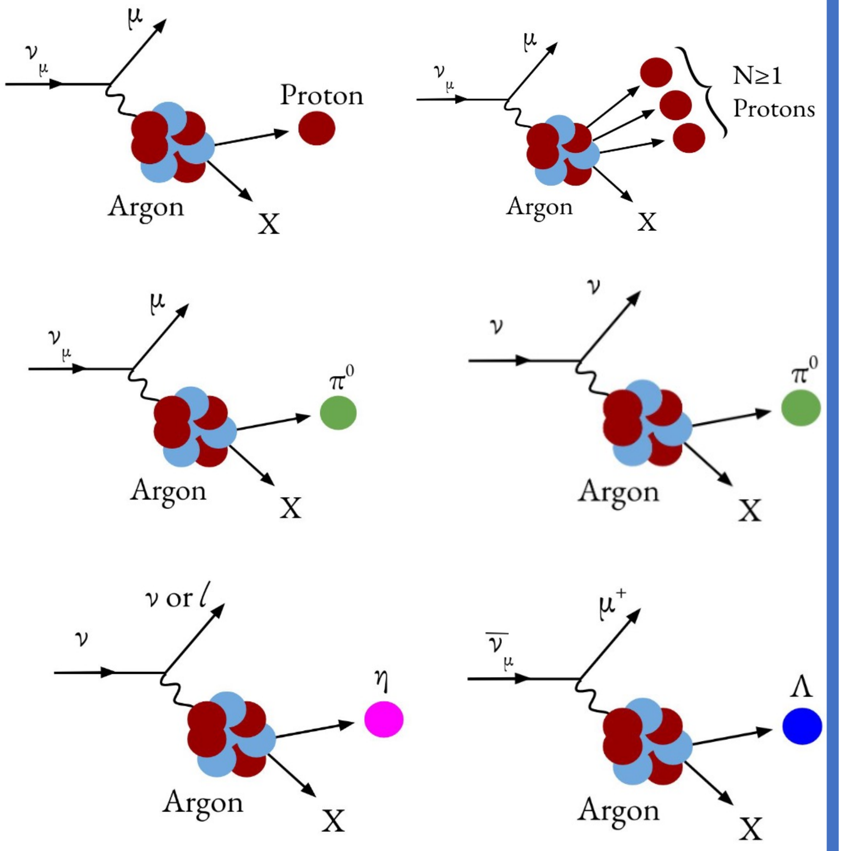
+ Hadronic Reinteractions

Many different final states:

Protons:

π^0 Production:

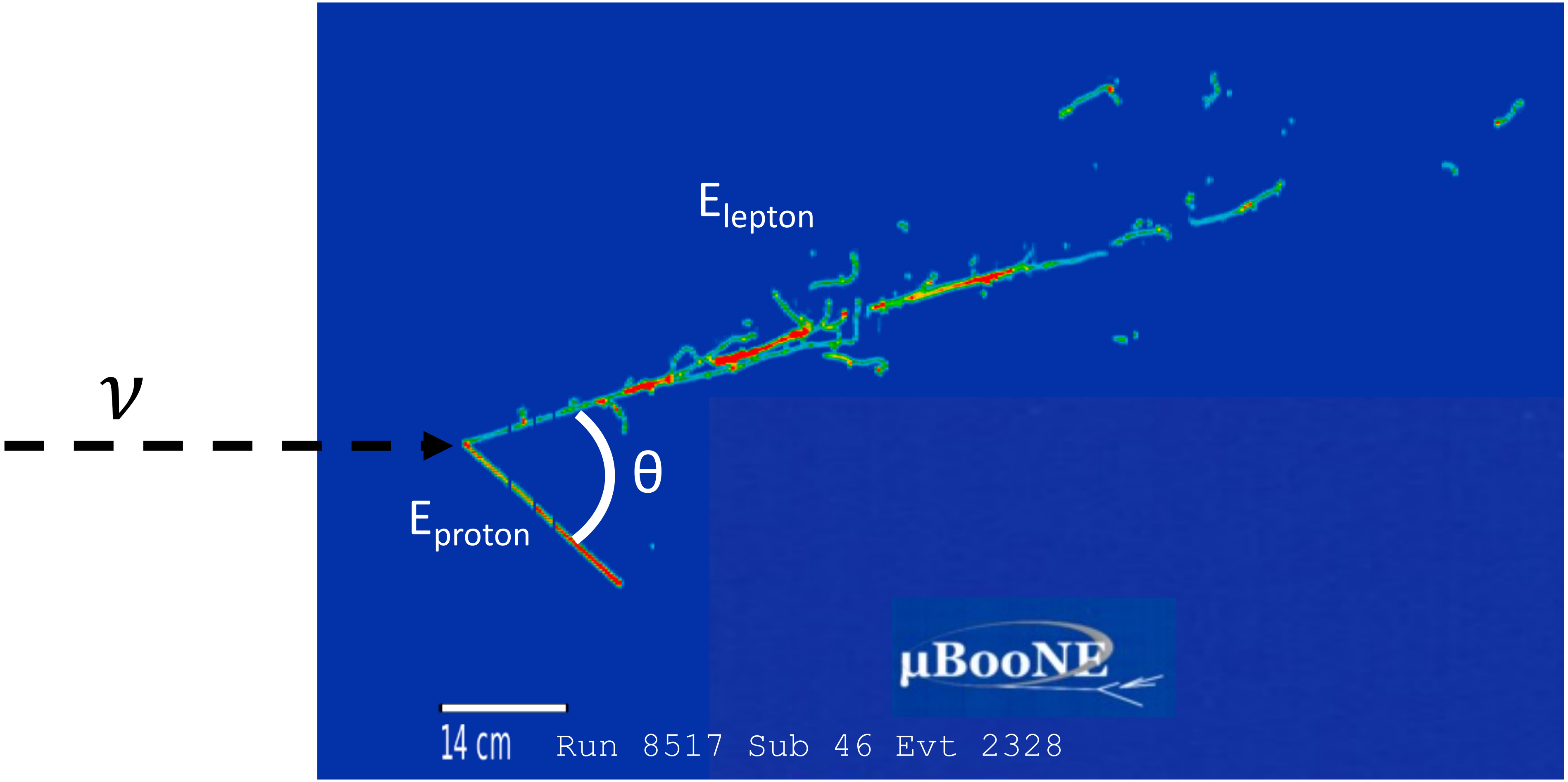
Rare particles:



- MicroBooNE currently has the largest recorded data set of neutrino-argon interactions

What Can We Measure?

1. Lepton properties: energy, angle relative to hadrons

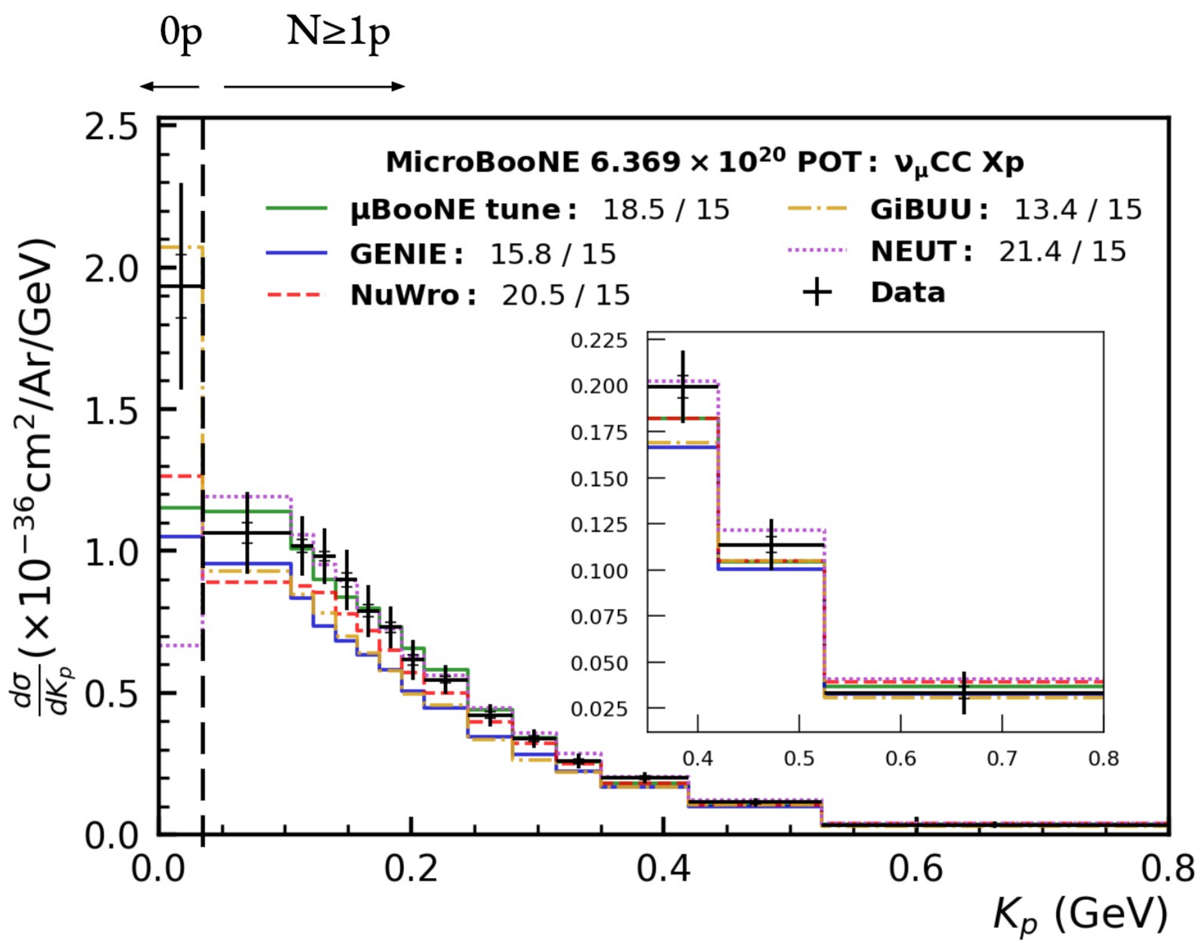


2. Hadronic System: energy and number of protons/pions

These kinematics are inputs to calculate neutrino energy

Hadronic System Modelling: Inclusive Measurement

- Starting to focus on understanding hadronic system and correlating with leptonic system
  - Already many MicroBooNE measurements on leptonic system

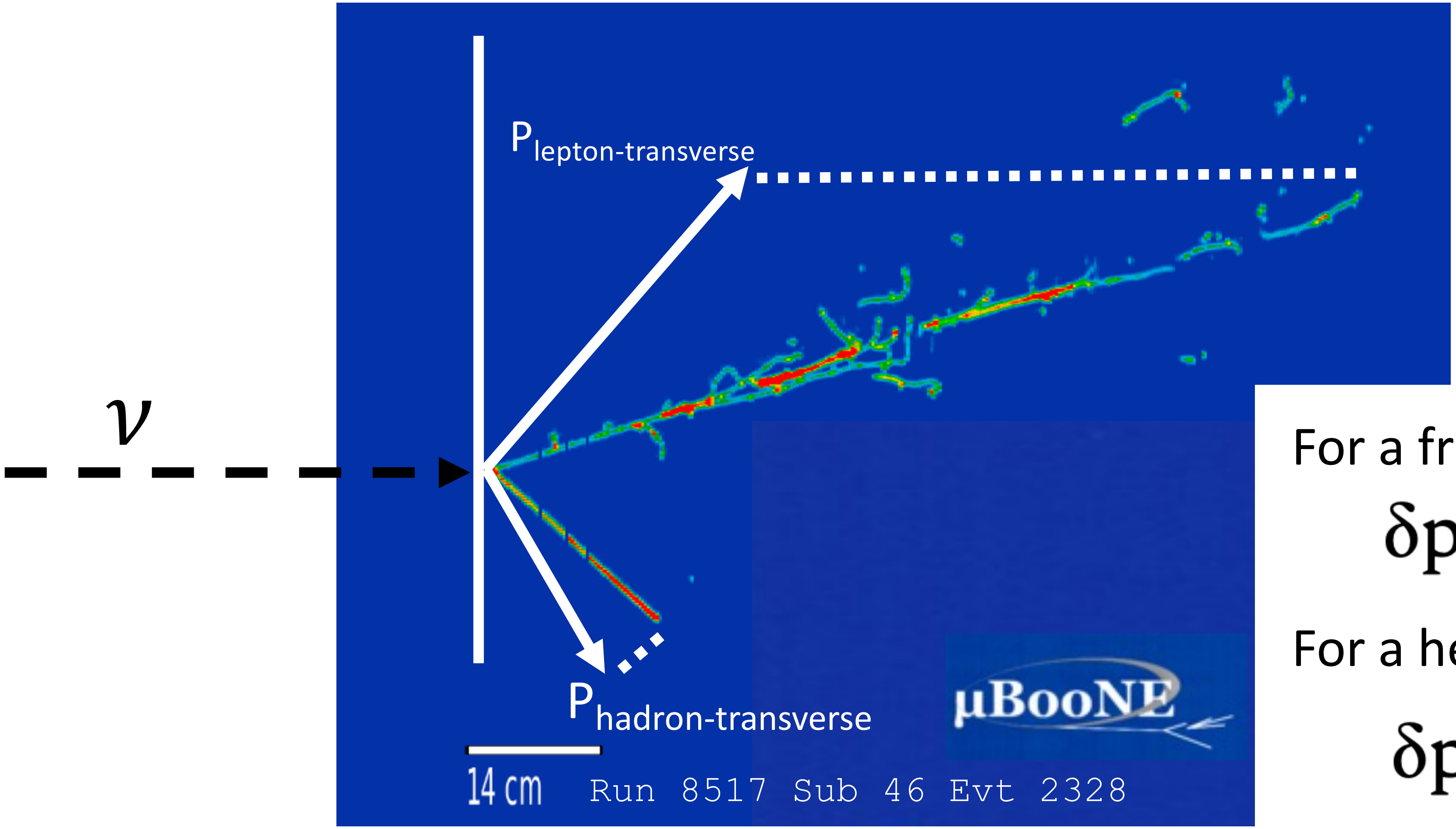


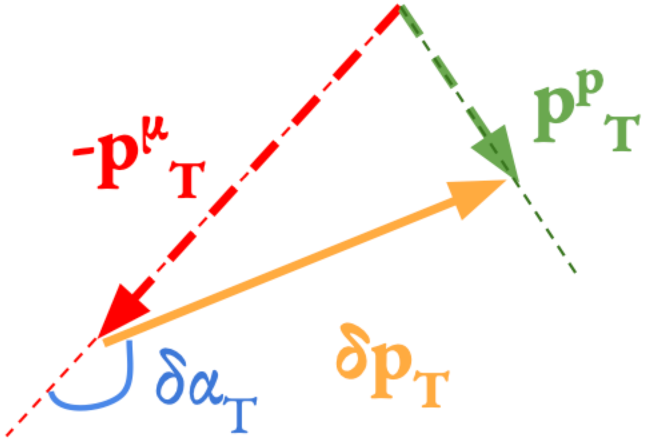
- Necessary for neutrino energy calculation
- Measure events with and without visible protons
- Demonstrates importance of modelling improvement for low energy protons

arXiv:2402.19216, accepted by PRD
arXiv:2402.19281, accepted by PRL

What Can We Measure?

3. Transverse kinematic imbalance: sensitivity to final state interactions and nuclear model





For a free nucleon target:

$$\delta p_T = |\, \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} \,| = 0$$

For a heavier target (like argon):

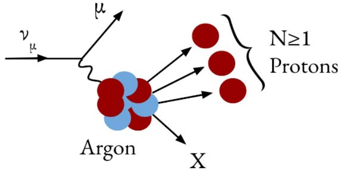
$$\delta p_T = |\, \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} \,| > 0$$

Orientation of imbalance: $\delta\alpha_T$

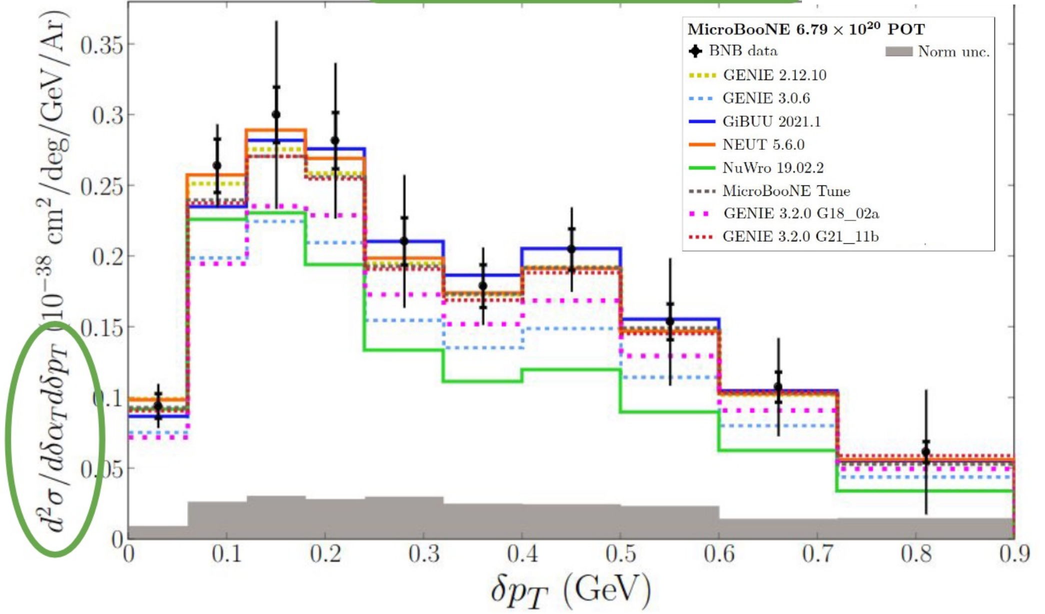
Nuclear Effects

Transverse Kinematic Imbalance

with 1μNp0pi events



$135 \text{ deg} \leq \delta\alpha_T < 180 \text{ deg}$

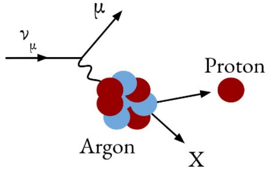


Generally poor agreement suggests correlations between kinematic variables are not well modelled

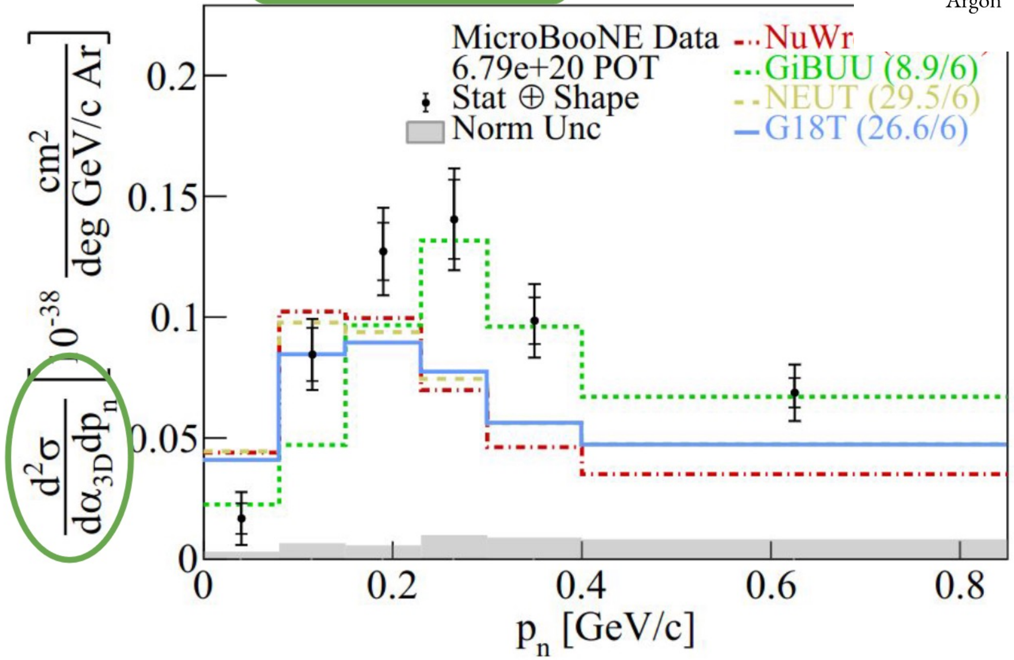
ie. GENIE v3.0.6 $\chi^2/ndf = 1859/359$

Generalized Kinematic Imbalance

with 1μ1p0pi events



$135^o < \alpha_{3D} < 180^o$

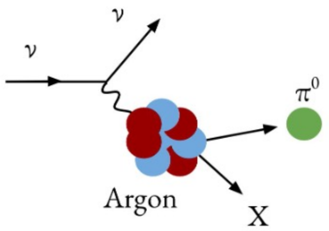


First measurement using novel variables that generalize transverse kinematic imbalance to 3D

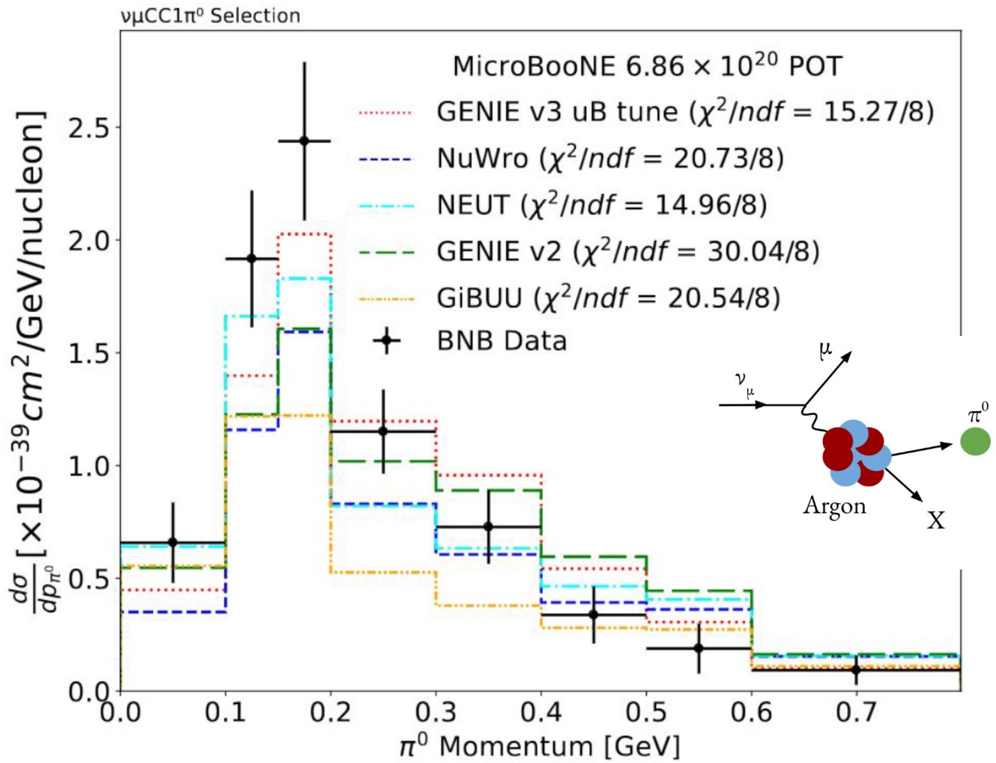
Enhanced sensitivity to nuclear reinteractions

More on these in an upcoming FNAL Wine and Cheese!

π^0 Production Measurements

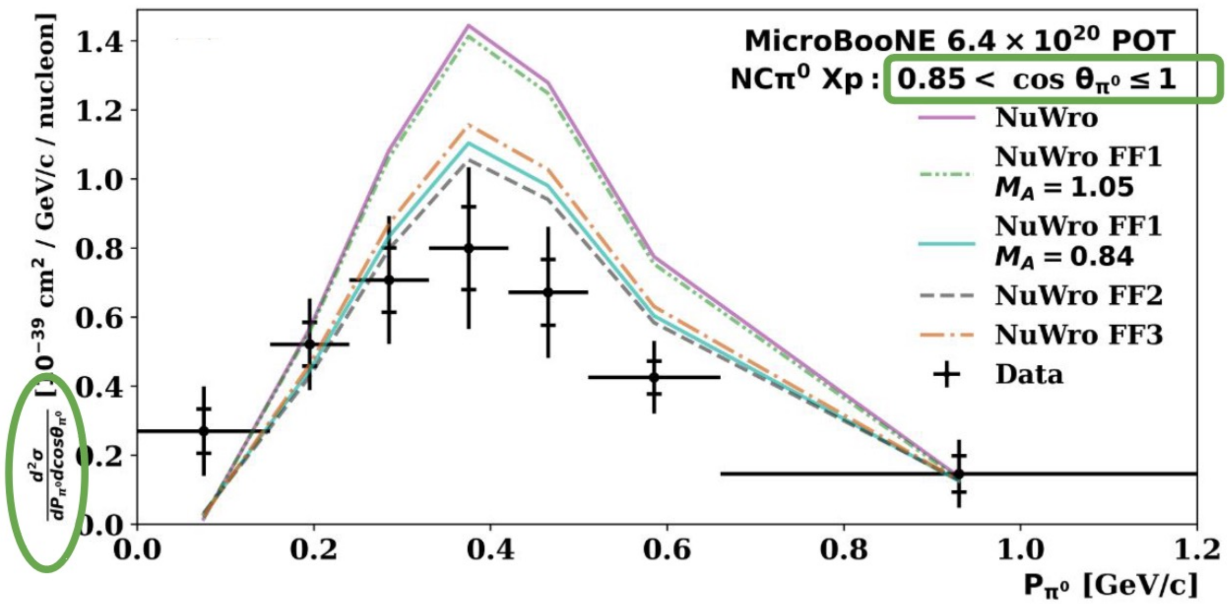


Muon Neutrino CCπ^0



- First differential CCπ^0 measurement
- Mismodelling in π^0 momentum and forward angles from low energy transfer region; consistent with measurements on other nuclei

NCπ^0



- First simultaneous measurement in two π^0 variables
- Sensitivity to form factor modeling and reinteractions
- Simulation consistently overpredicts the data

- More on these in an upcoming FNAL Wine and Cheese!

And many more!

World neutrino argon cross section measurements:

ν_μ CC inclusive cross section

- ArgoNeuT: Single-differential cross section Phys. Rev. Lett. 108 161802 (2012)
- ArgoNeuT: Updated single-differential cross section Phys. Rev. D 89, 112003 (2014)
- μBooNE: Charged particle multiplicity Eur. Phys. J. C79, 248 (2019)
- μBooNE: Double-differential cross section Phys. Rev. Lett. 123, 131801 (2019)
- μBooNE: Single-differential cross section with updated detector and interaction models MICROBOONE-NOTE-1069-PUB
- μBooNE: Energy-dependent single-differential cross section Phys. Rev. Lett. 128, 151801 (2022)
- μBooNE: Triple-differential cross section arXiv:2307.06413 [hep-ex]
- μBooNE: Multi-differential with proton multiplicity arXiv:2402.19281 [hep-ex] arXiv:2402.19216 [hep-ex]

ν_μ exclusive channels

- μBooNE: ν_μ CCQE-like differential cross section Eur. Phys. J. C 79 673 (2019) Phys. Rev. Lett. 125, 201803 (2020)
- μBooNE: ν_μ CCπ1p double differential TKI cross section Phys. Rev. Lett. 131, 101802 (2023)
- μBooNE: ν_μ CC0pi1p multi-differential cross sections Phys. Rev. D 108, 053002 (2023)
- μBooNE: ν_μ CC0pi1p generalised kinematic imbalance Phys. Rev. D 109, 092007 (2024) (PRD Editor's suggestion)
- μBooNE: ν_μ CC0π≥1p differential cross section Phys. Rev. D 102, 112013 (2020)
- μBooNE: ν_μ CC0π≥1p double-differential cross section arXiv:2403.19574 [hep-ex]
- ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CC0π2p production measurement Phys. Rev. D 90, 012008 (2014)
- μBooNE: ν_μ CC0π2p differential cross section arXiv:2211.03734 [hep-ex]
- ArgoNeuT: ν_μ CCπ^0 total cross section Phys. Rev. D99, 091102(R) (2019)
- μBooNE: ν_μ CCπ^0 differential cross section arXiv:2404.09949 [hep-ex]
- ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ NCπ^0 production cross section Phys. Rev. D 96, 012006 (2017)
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- ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CCπ$^+$ production cross section Phys. Rev. D 98, 052002 (2018)
- ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ coherent CCπ$^+$ production Phys. Rev. Lett. 113, 261801 (2014)
- μBooNE: ν_μ CC kaon production search MICROBOONE-NOTE-1071-PUB
- μBooNE: ν_μ CC Λ^0 production cross section Phys. Rev. Lett. 130, 231802 (2023)
- μBooNE: ν_μ eta production cross section Phys. Rev. Lett. 132, 151801 (2024)
- μBooNE: ν_μ NC1p differential cross section MICROBOONE-NOTE-1067-PUB
- μBooNE: ν_μ NC elastic differential cross section MICROBOONE-NOTE-1101-PUB

Other measurements

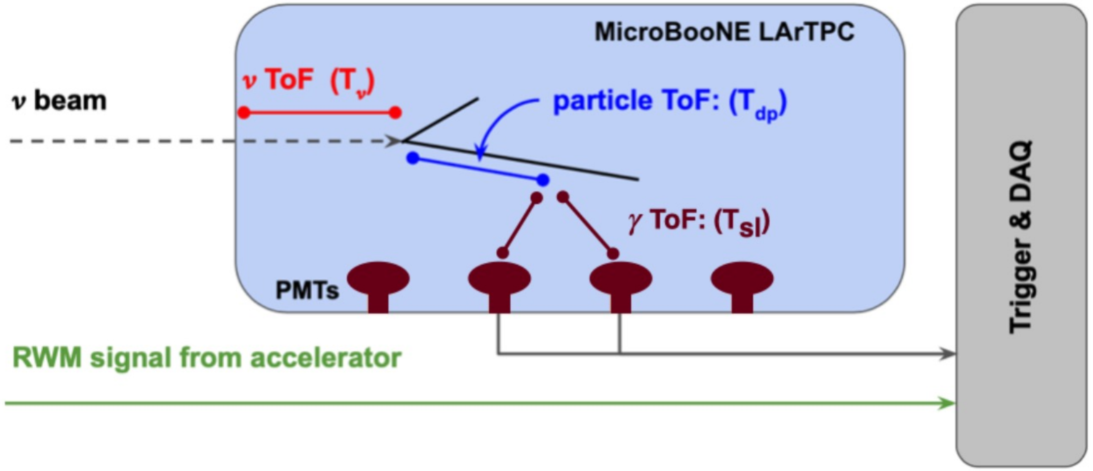
- ArgoNeuT: Inclusive differential ν_e+$\bar{\nu}_e$ cross section Phys. Rev. D 102, 011101(R) (2020)
- μBooNE: Total inclusive ν_e+$\bar{\nu}_e$ cross section Phys. Rev. D 104, 052002 (2021)
- μBooNE: Inclusive differential ν_e+$\bar{\nu}_e$ cross section Phys. Rev. D 105, L051102 (2022)
- μBooNE: Theory-driven tune of cross-section models Phys. Rev. D 105, 072001 (2022)
- μBooNE: Differential ν_e CC0π cross section Phys. Rev. D 106, L051102 (2022)

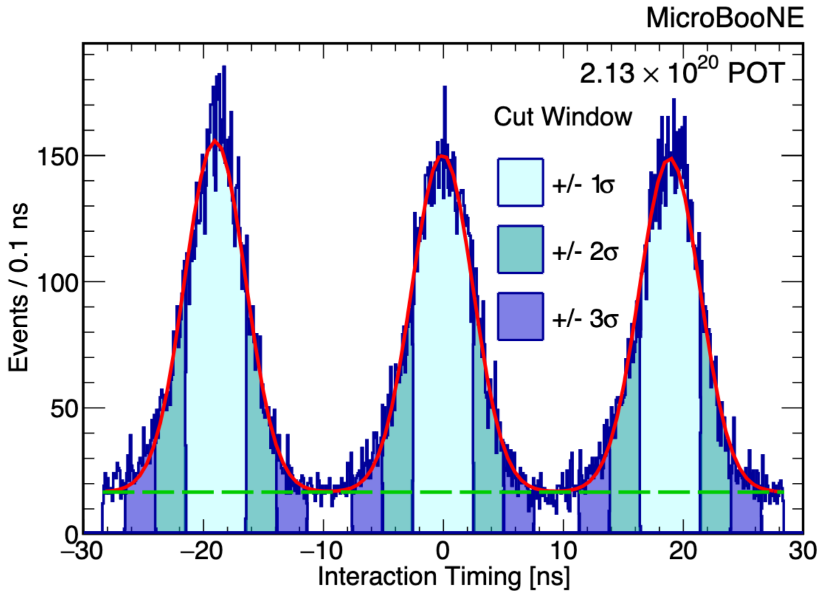
MicroBooNE is making significant contributions

Expanding the Reach of LArTPCs with Detector R&D

Neutrino Interaction Time with O(ns) Resolution

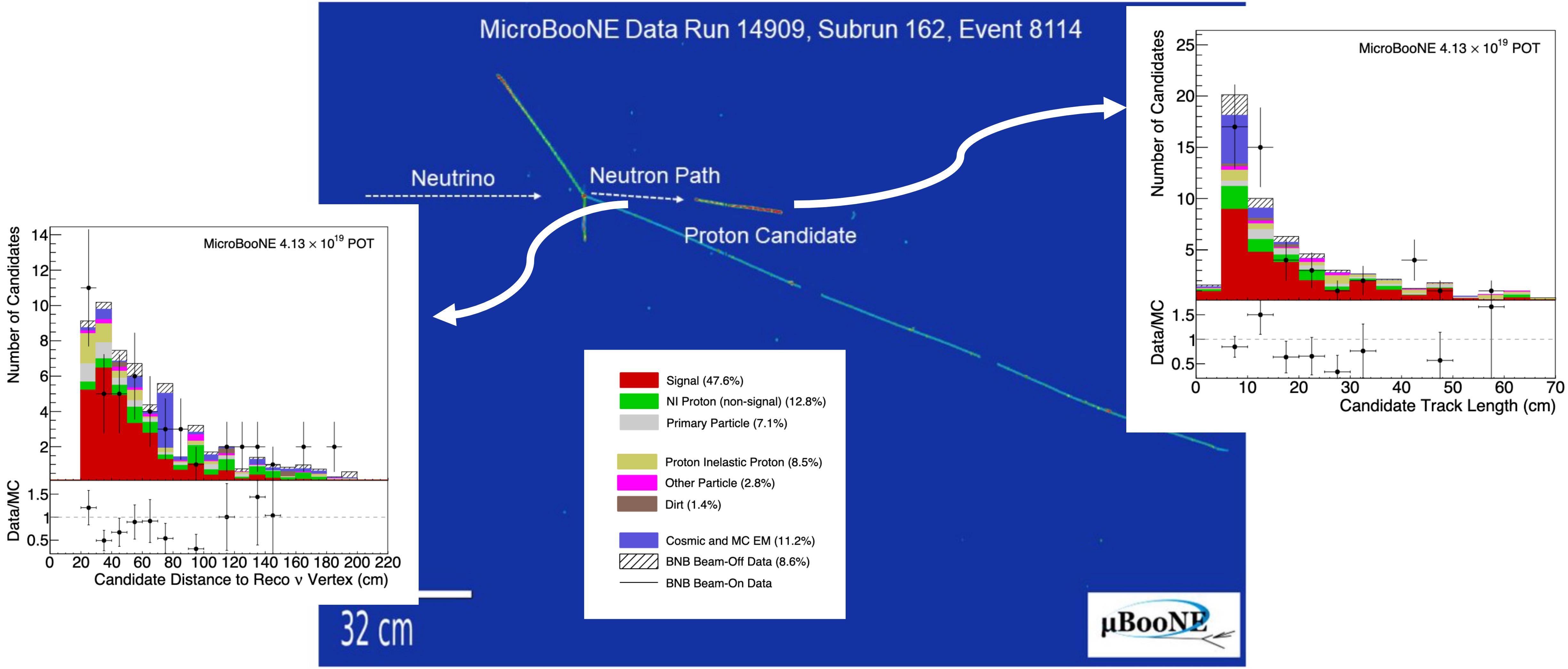
- Apply time of flight correction to resolve the BNB beam bunch structure
- **Improved cosmic rejection:** cosmics arrive uniformly in time, but the beam does not
- **Improved sensitivity to BSM physics, such as heavy neutral leptons:** Reduce neutrino background in these rare process searches by looking outside the beam window





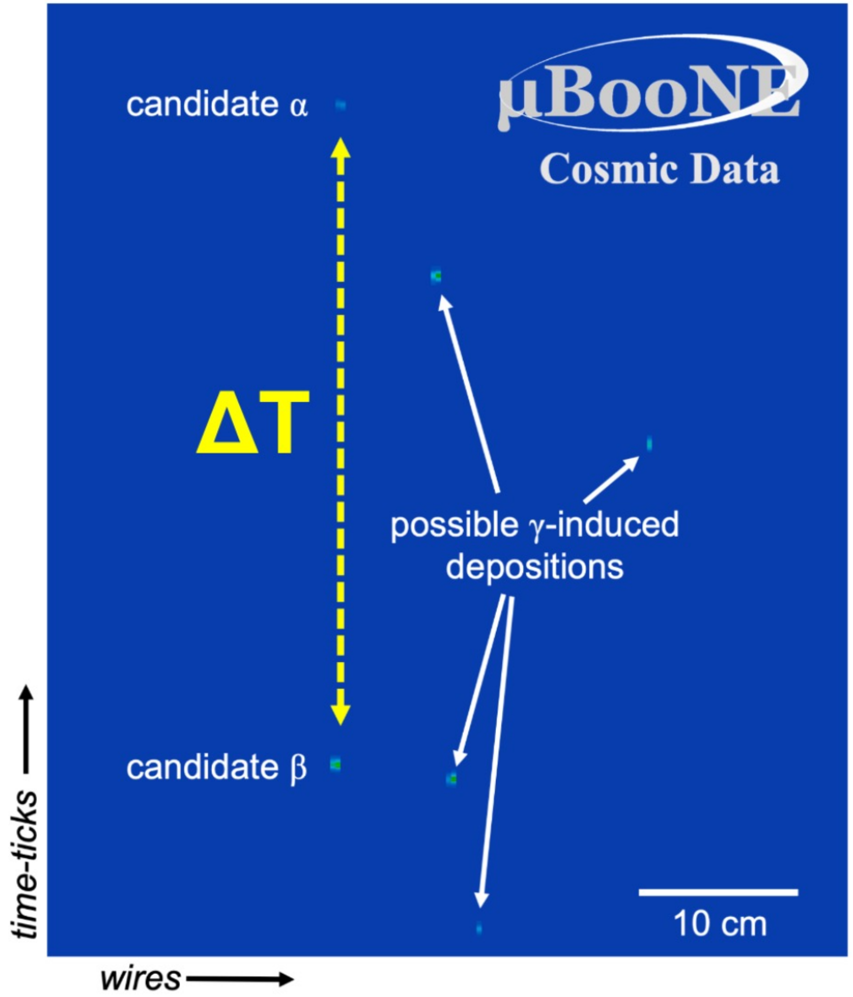
Neutron Identification

- Neutrons are one of the main sources of missing energy in LArTPCs
- Measured indirectly when they re-interact to produce protons in the detector



MeV Scale Physics Capabilities

- Reconstruct low energy deposits down to the MeV scale
- Provides additional physics capability:
  - Low energy neutron induced tracks
  - Coherent interactions
  - Neutral current interactions
  - Solar neutrinos
  - Supernova neutrinos
- Recently: Bi(214) radiopurity measurement in MicroBooNE demonstrates levels of Rn(222) that satisfy the requirements for DUNE



Conclusions

MicroBooNE is an active collaboration with a robust physics program that is:

- Exploring anomalies and BSM physics
- Looking towards the future with neutrino cross section measurements
- Expanding the reach of LArTPC detectors through detector physics and methods development