Recent Single-Photon Searches in MicroBooNE to Explain the MiniBooNE Anomaly

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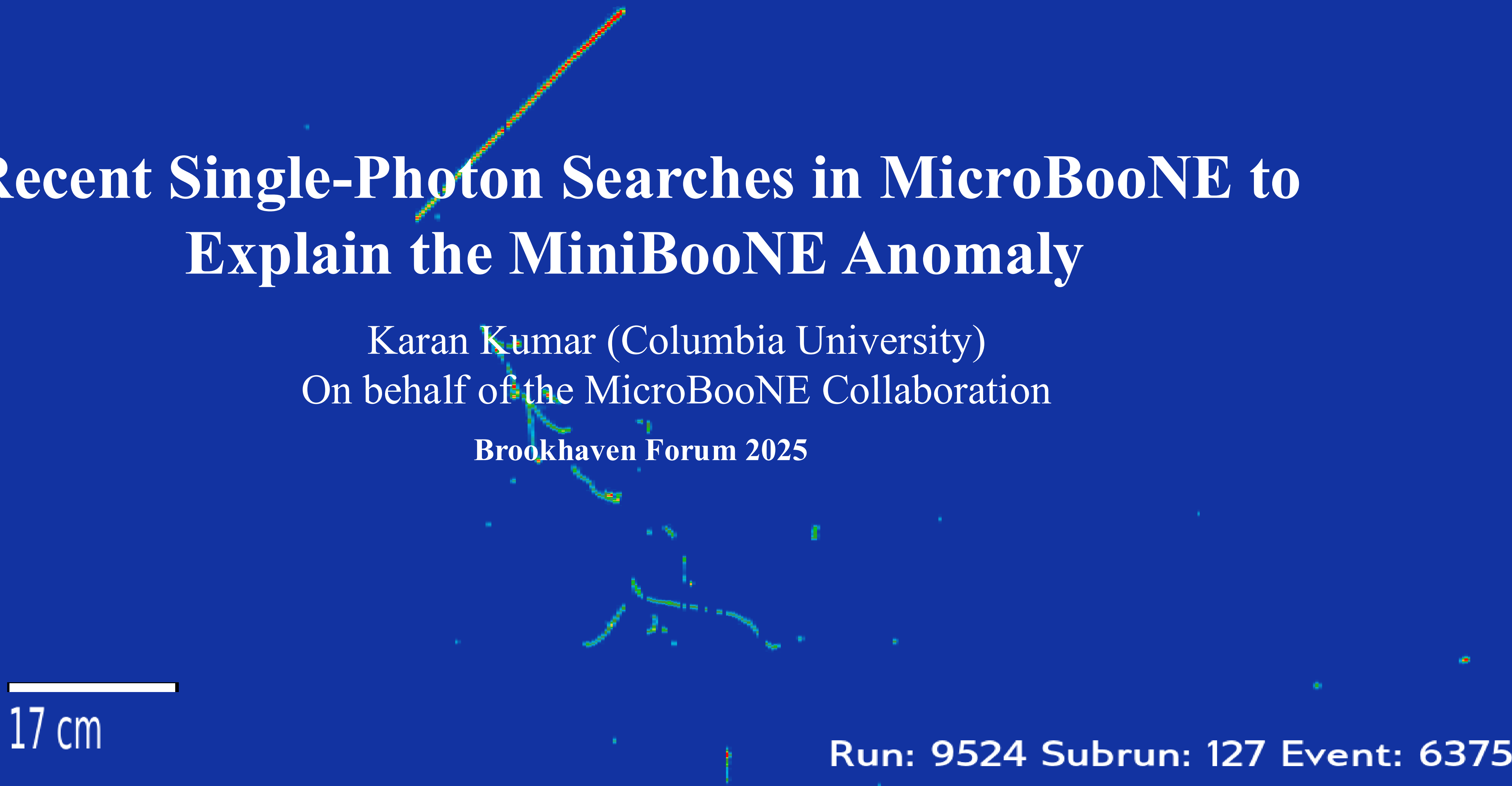
On behalf of the MicroBooNE Collaboration

Brookhaven Forum 2025

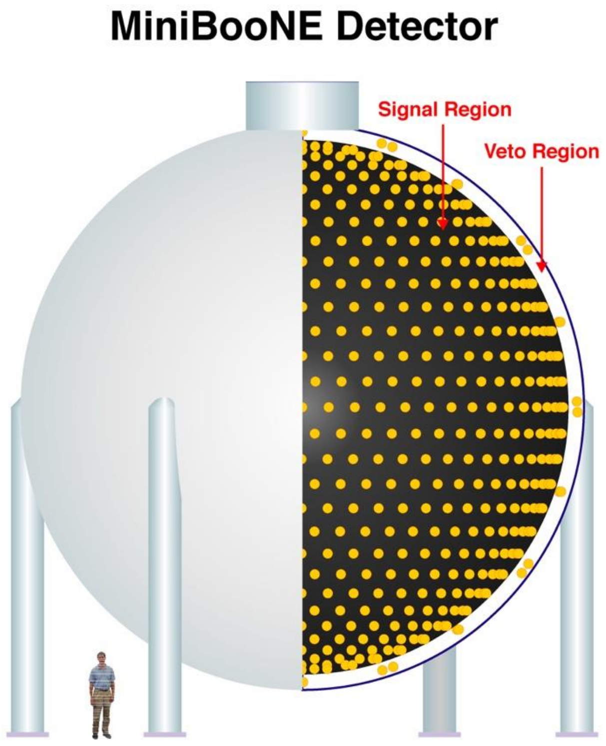


Overview

- Motivation for MicroBooNE
- MicroBooNE
- MicroBooNE Tests of Single-Photon LEE Interpretations
  - Standard Model Searches (NC $\boldsymbol{\Delta} \rightarrow N\gamma$, Coherent γ, Inclusive γ)
  - Heavy Neutral Leptons Searches for the LEE
- What's Next For MicroBooNE
- Summary

Motivation for MicroBooNE: MiniBooNE

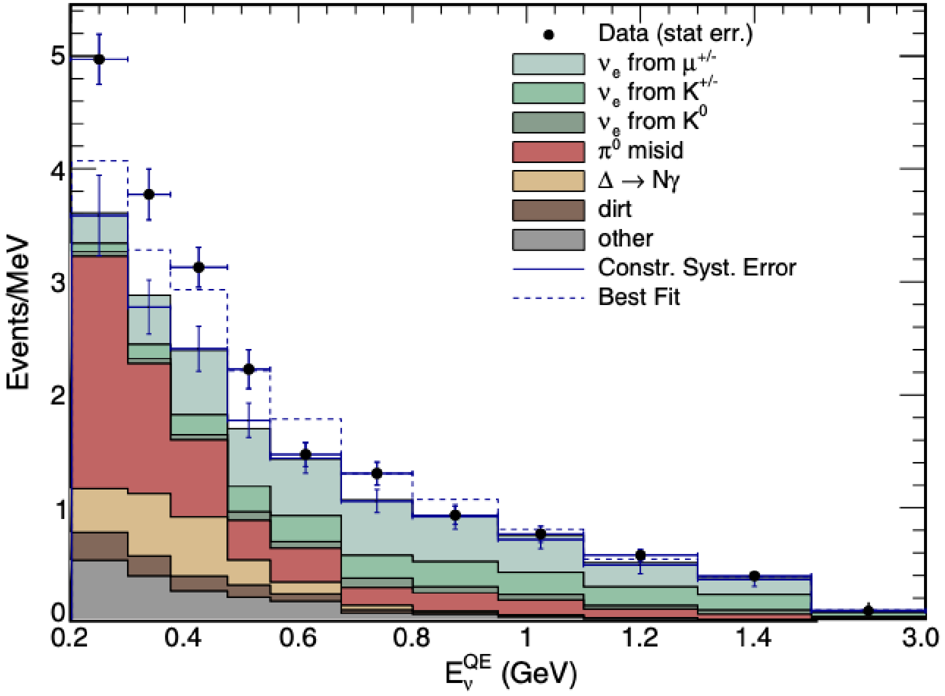
- Proton beam (8 GeV) from Fermilab Booster (ν_μ or $\overline{\nu_\mu}$ beam)
- Detector: 12 m diameter sphere filled with mineral oil (800 tons), instrumented with ~1500 PMTs
- Detects Cherenkov + scintillation light from neutrino interactions
- Baseline: L/E ≈ 1 m/MeV



Source: Fermilab

Motivation for MicroBooNE: MiniBooNE

- MiniBooNE's main goal was to test the Liquid Scintillator Neutrino Detector (LSND) anomaly.
- In the 1990s, the LSND experiment (at Los Alamos) observed more electron antineutrinos than expected when starting from a muon antineutrino beam.
- MiniBooNE saw more events than expected below ~0.6 GeV consistent with LSND anomaly — that's the famous "Low-Energy Excess (LEE)."
  It could indicate:
  - an unaccounted background (like photon mis-ID or nuclear effects).
  - a sterile neutrino oscillation



MiniBooNE Collaboration, Phys. Rev. D 103, 052002

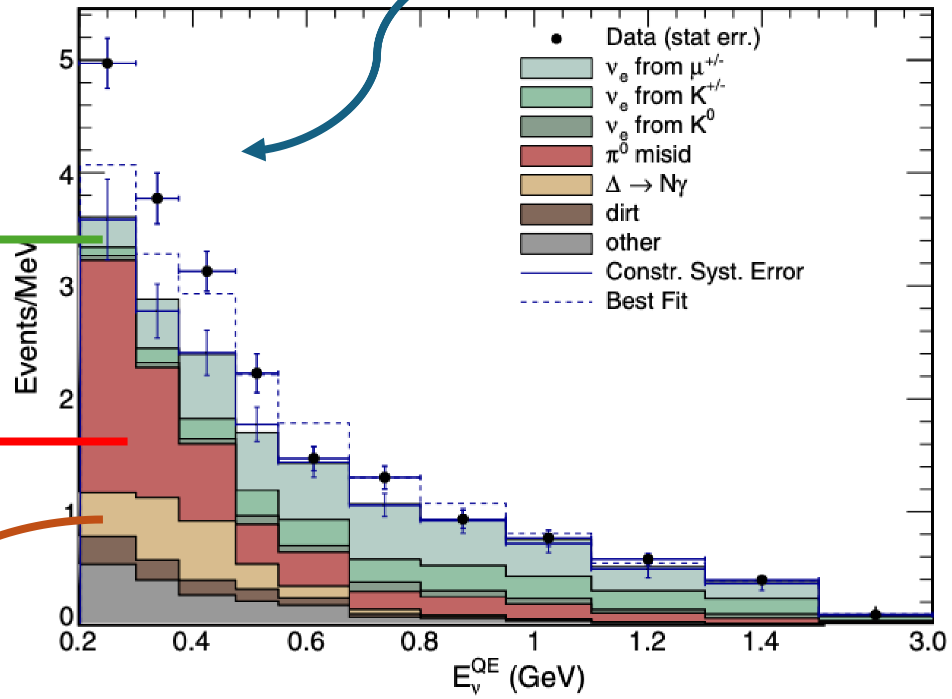
Motivation for MicroBooNE: MiniBooNE

4.8 σ excess of electron-like events

Intrinsic ν_e (from μ, $K^{+/-}$, K^0 decays) — beam contamination

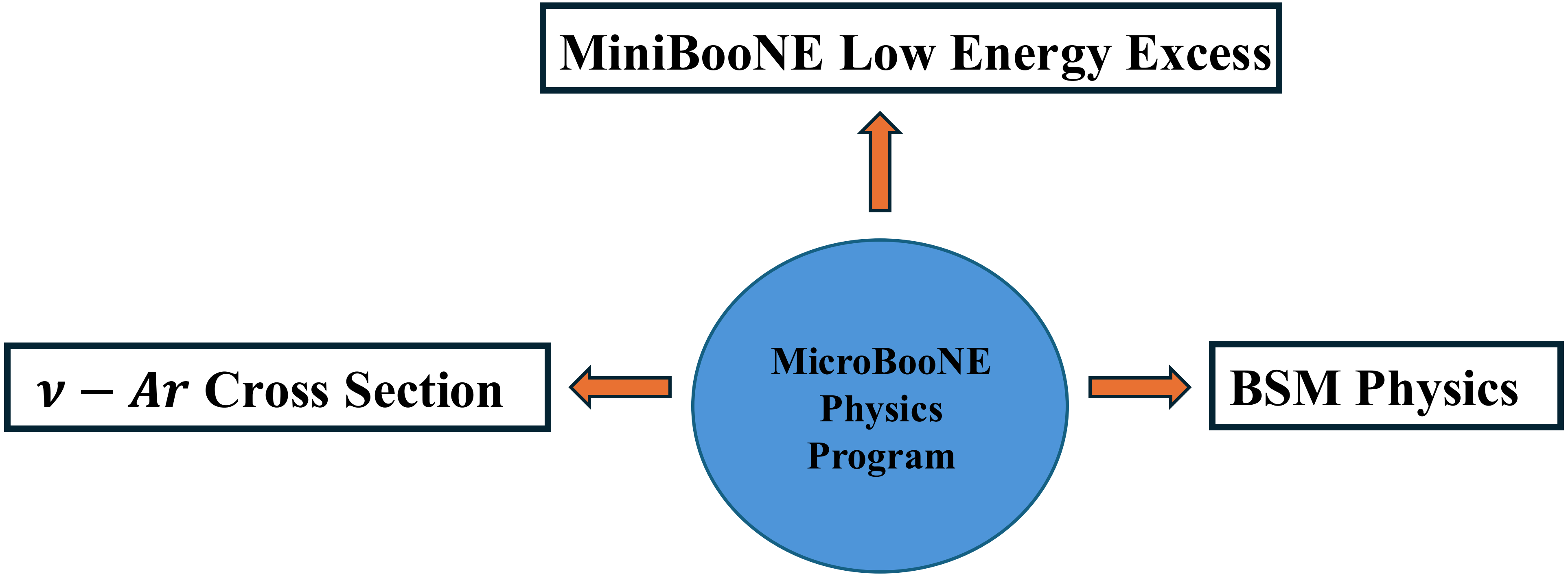
Photons from neutral pions misidentified as electrons (major low-energy background)

Radiative decays of the Δ resonance



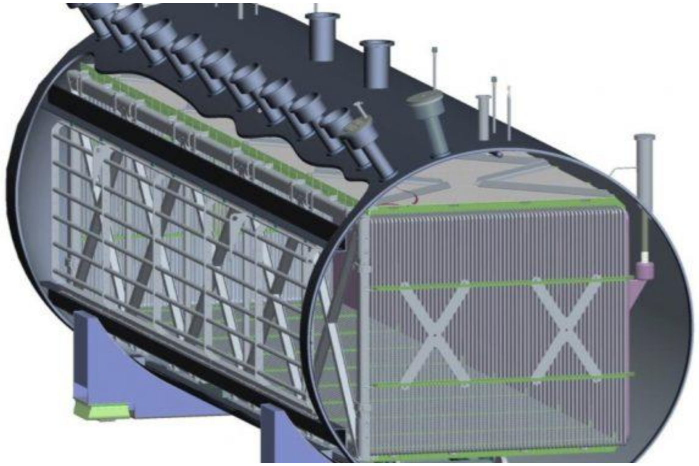
MiniBooNE Collaboration, Phys. Rev. D 103, 052002

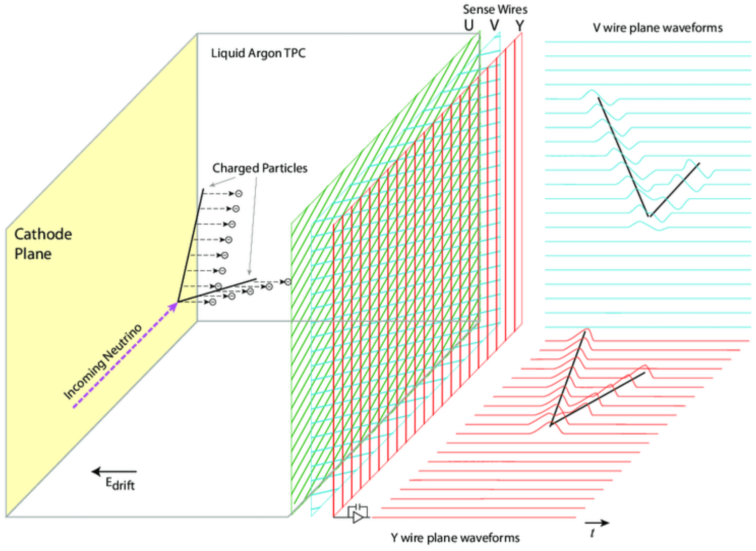
MicroBooNE


MiniBooNE Low Energy Excess
$\nu - Ar$ Cross Section
MicroBooNE Physics Program
BSM Physics

MicroBooNE

- **LArTPC Technology**: ~85-tonne active mass (170-ton total).
- **Wire Planes & Photodetectors**: 3 wire planes and 32 PMTs.
- **High Precision**: Enables 3D charged-particle tracking and accurate energy measurements.

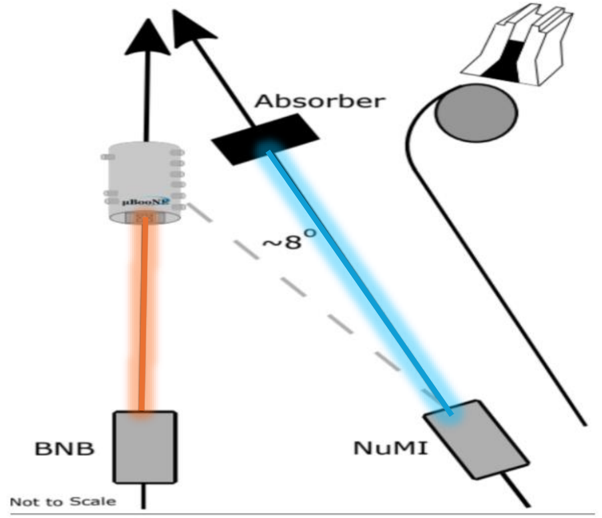




Source: MicroBooNE

MicroBooNE

Broad Energy Range: Access to neutrinos from multiple beams (BNB on-axis, NuMI off-axis). Differences in flux and energy shapes enable complementary measurements, such as cross-sections studies and new physics searches.



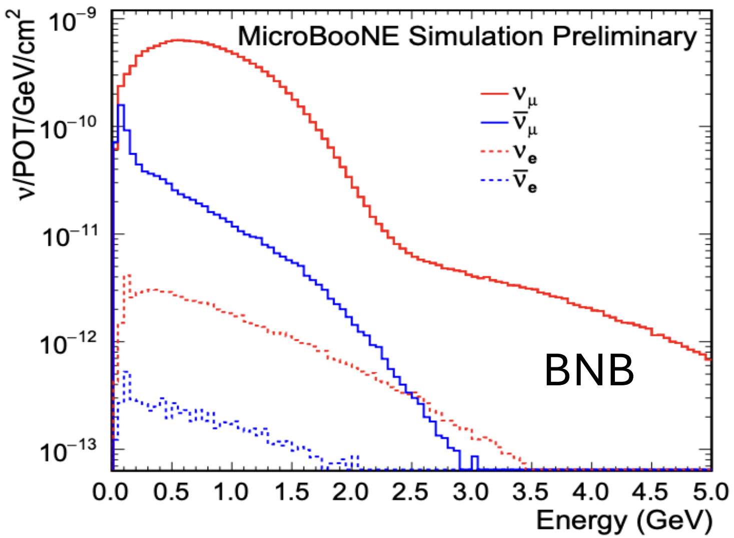
Booster Neutrino Beam

- ~0.8 GeV mean neutrino energy
- On-axis

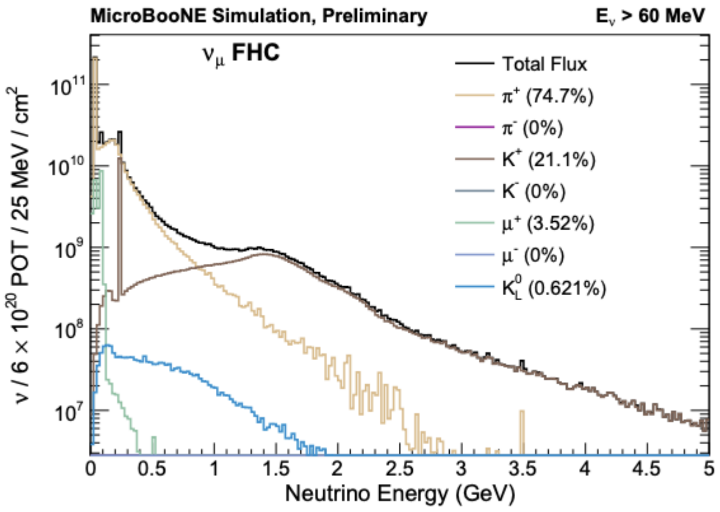
NuMI Beam

- ~1.5 GeV mean neutrino energy
- ~8° off axis

MicroBooNE, https://doi.org/10.2172/1573216

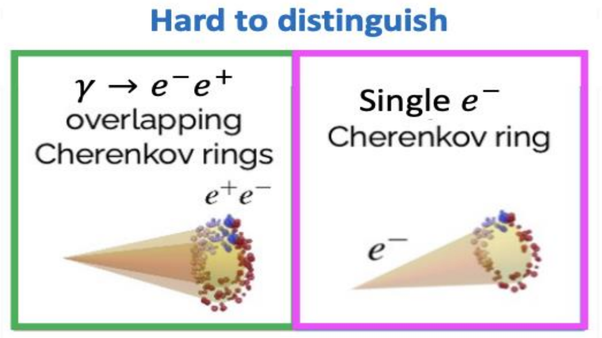


MicroBooNE-NOTE-1129-PUB

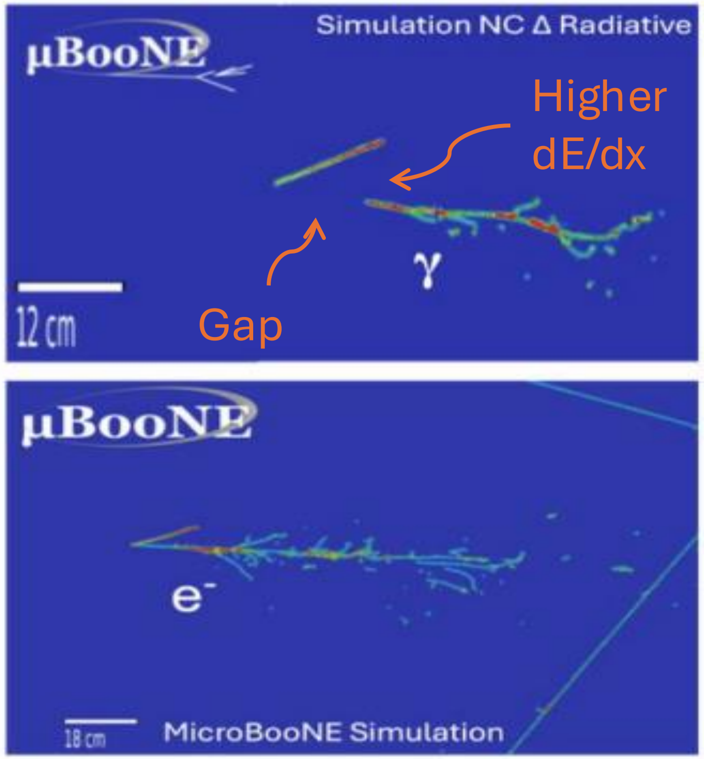


MiniBooNE Low-Energy Excess (LEE)

- MiniBooNE couldn't distinguish electrons from photons because its oil Cherenkov detector produced similar light rings for both, causing photon backgrounds to mimic electron-like events.



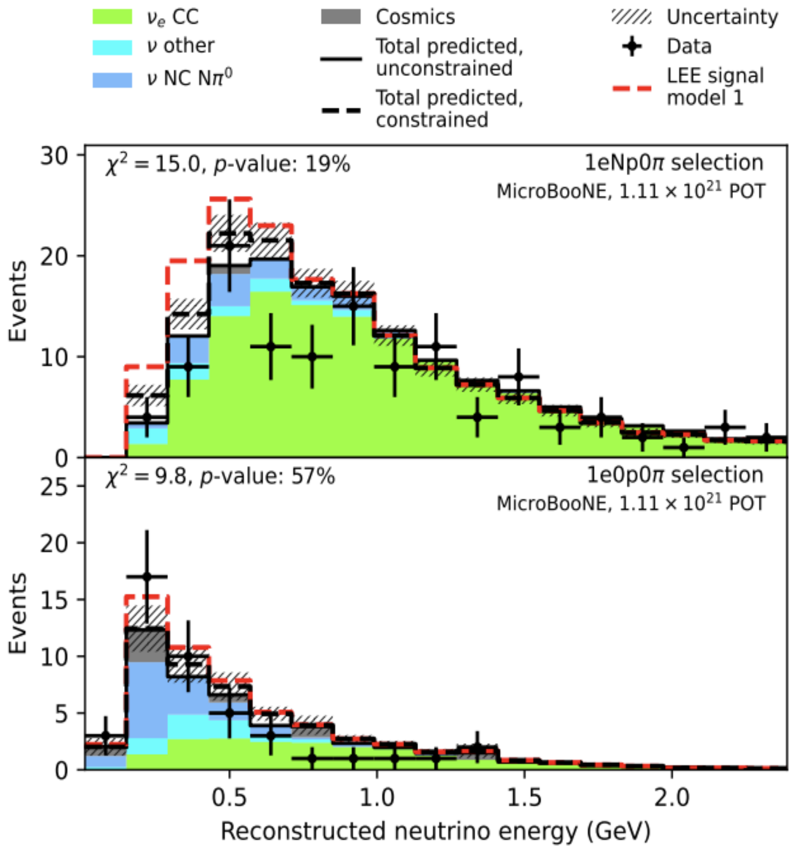
- MicroBooNE is in the same BNB beam using new detector technology with much better e/γ separation capabilities.



Source: MicroBooNE

MicroBooNE Single-Electron Searches

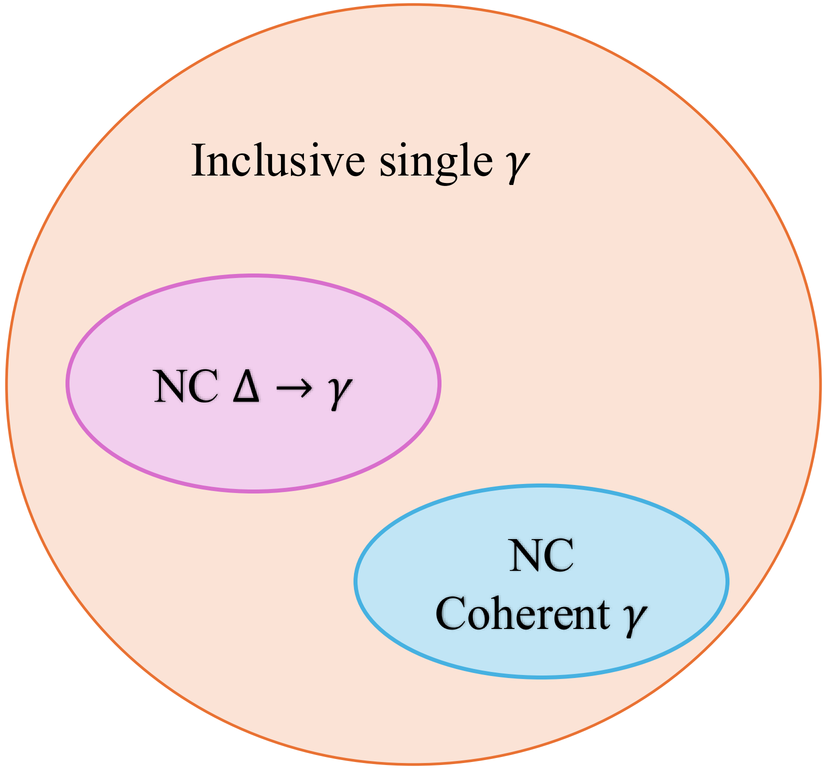
- MicroBooNE studied multiple topologies with a single electron in the final state.
- The 1eNp0π channel selects CC ν_e events with at least one proton near the interaction vertex and no pion (top plot), while the 1e0p0π channel selects CC ν_e events with no visible protons or pions (bottom plot).
- This measurement shows that MicroBooNE's data exclude an electron-like interpretation of the MiniBooNE low-energy excess based on the tested models at greater than 99% confidence level.



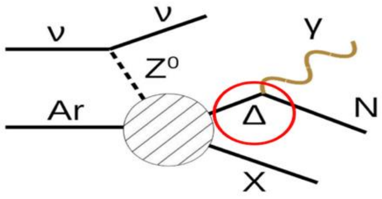
First results in 2022: PhysRevLett.128.241801

Updated MicroBooNE results in fall 2024 arXiv:2412.14407

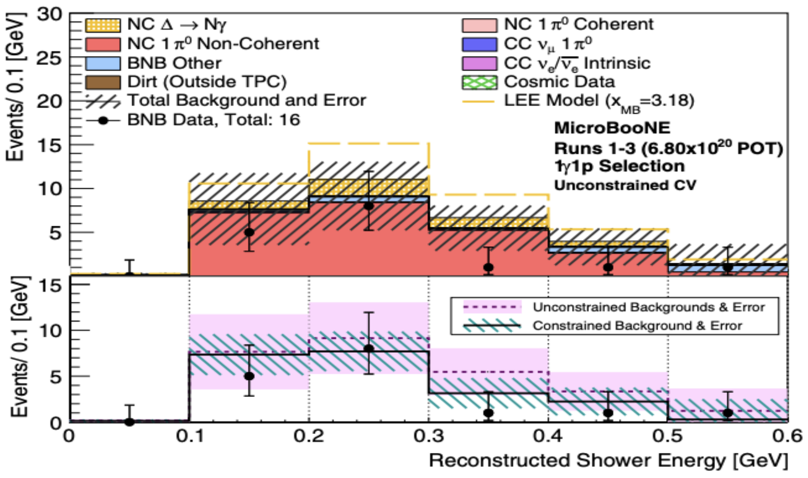
What if the LEE is an Excess of Single Photons?



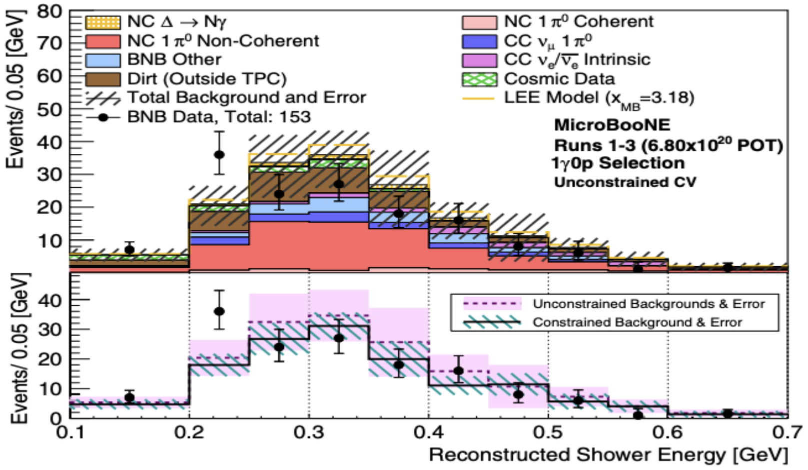
Neutral Current (NC) Δ Radiative Decay Search in MicroBooNE



- MiniBooNE reported that a 3.18x enhanced rate of NC $\Delta \rightarrow N\gamma$ events would explain the excess well.
- First results in 2021: MicroBooNE analyzed the 1γ1p and 1γ0p topologies.
- Used Pandora Reconstruction, with multiple BDTs trained to reject cosmic, π⁰, and CC backgrounds.
- Rules out a photon-based explanation of the MiniBooNE excess (×3.18 scaling) at 94.8% C.L.
- The selection was more sensitive to 1γ1p events and less sensitive to 1γ0p events due to larger background contamination; therefore, 0p-like topologies are still possible in alternative models.



(a)

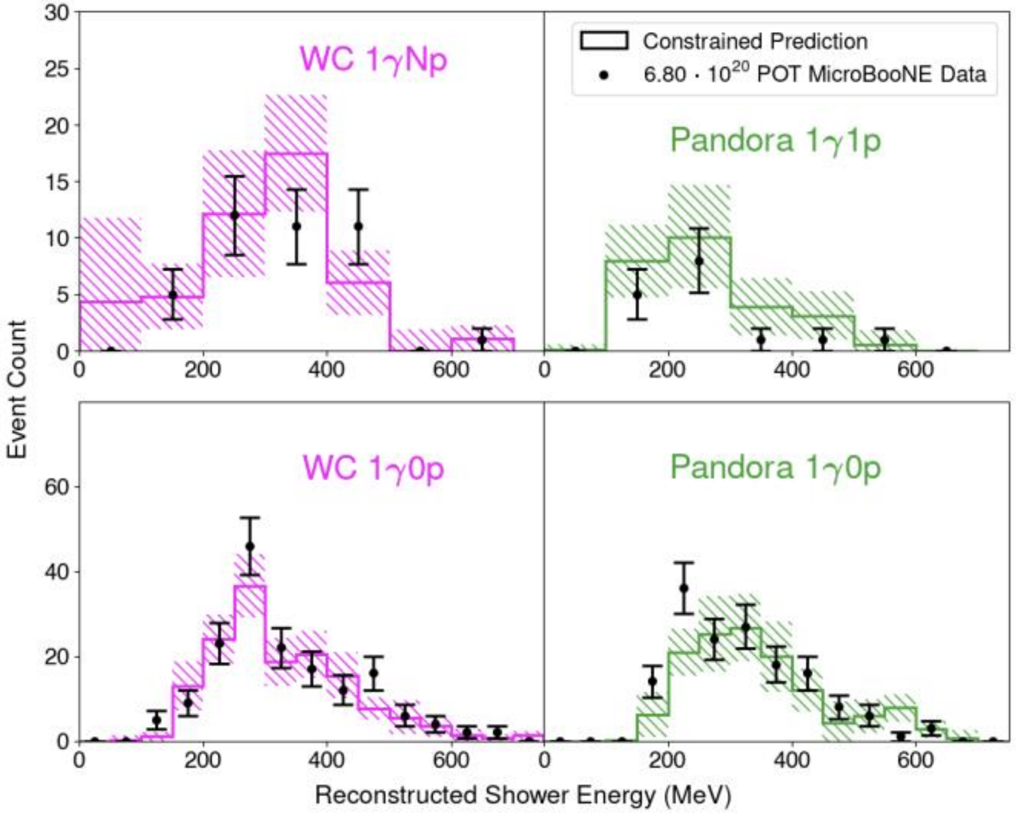


(b)

PhysRevLett.128.111801

Enhanced Neutral Current (NC) Δ Radiative Decay Search in MicroBooNE

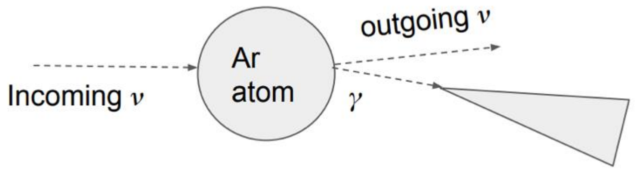
- Expanded the previous analysis by combining Pandora-based reconstruction and Wire-Cell (WC) reconstruction.
- Treated the 1γNp and 1γ0p channels independently, allowing different scaling factors to test for photon-like excesses without assuming $\Delta \rightarrow N\gamma$ isospin symmetry.
- No significant excess observed; data remain consistent with Standard Model predictions and the previous analysis.
- The Wire-Cell 1γ0p channel achieved better sensitivity to photon-like events without protons but was not sufficient to exclude all models with 0p topologies.

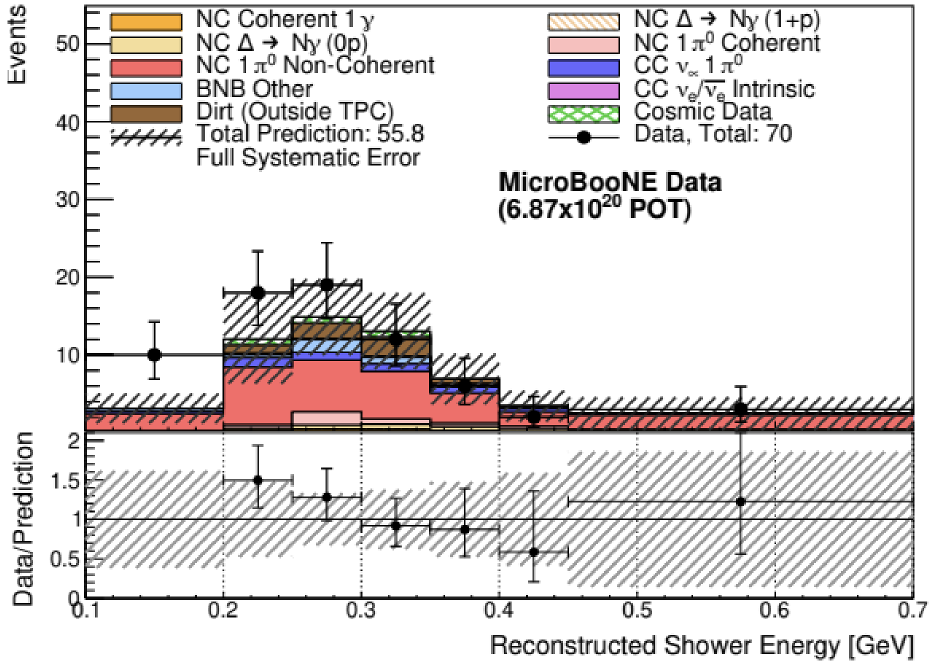


arXiv:2502.05750

Neutral Current (NC) Coherent single-photon production

- World's first search for neutrino-induced coherent single-photon production, where the neutrino interacts with the entire argon nucleus and emits a single forward photon.
- Built on previous single-photon selections, adding a proton stub veto (PSV) BDT to reject small hadronic activity near the vertex.
- PSV increases the single-photon purity.
- No evidence was found for enhanced coherent single-photon production to explain the MiniBooNE anomaly, and an upper limit of $\sigma < 1.49\times10^{-41}$ cm² (90% C.L.) was set on the cross section on argon as predicted by the Alvarez-Ruso et al model.



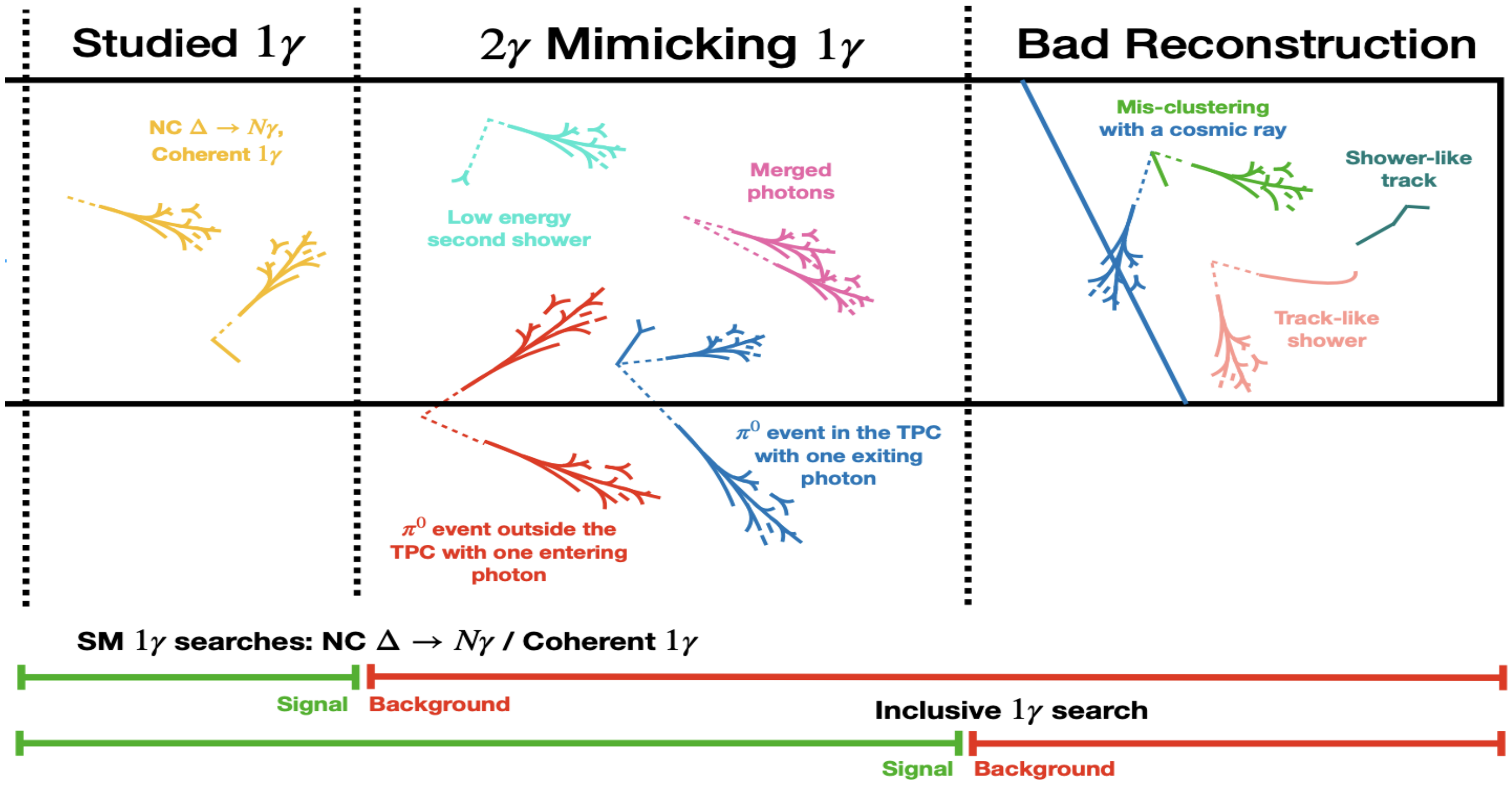


arXiv:2502.06091

Inclusive Photon Search

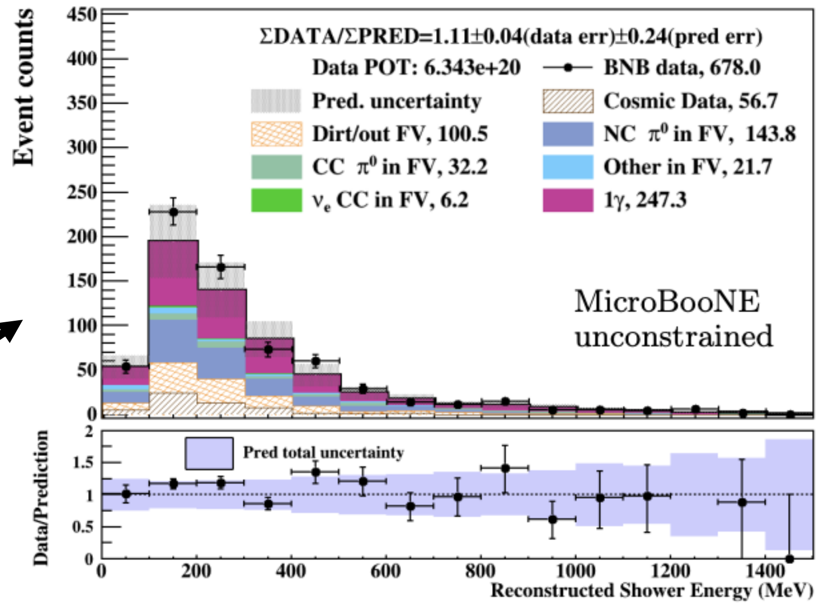
In this search, an inclusive single-photon topology was studied, defined as a neutrino-argon interaction producing one reconstructable photon-induced electromagnetic shower and no reconstructable muon or electron.

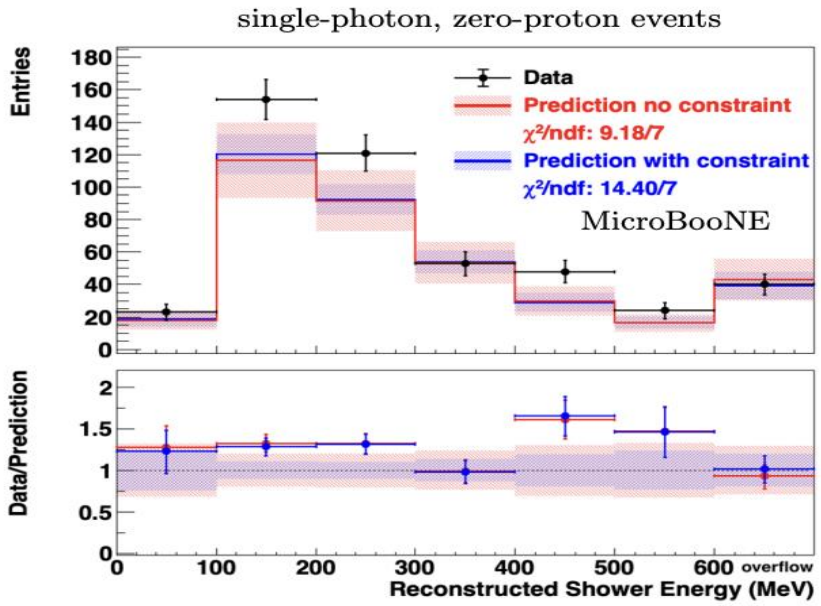
We cast a broad search for any single-photon events.



Inclusive Photon Search

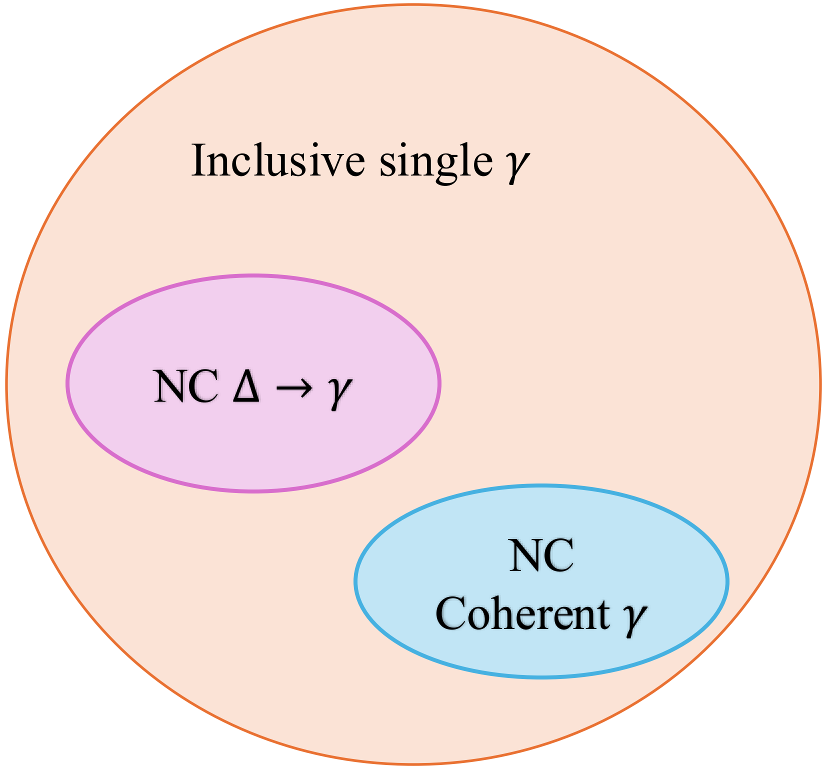
- Used Wire-Cell reconstruction with four BDTs to reject ν_μ CC, ν_e CC, NC π^0, and out-of-volume backgrounds.
- The inclusive single-photon data rate is consistent with the Standard Model predictions overall (at 1.6σ),
- We also investigate exclusive final state, and find localized 2σ excess in the 0p subsample below 600 MeV.
- The origin of the disagreement is unknown and requires further studies, in progress.





arxiv.org/pdf/2502.06064

What if the LEE is an Excess of Single Photons?



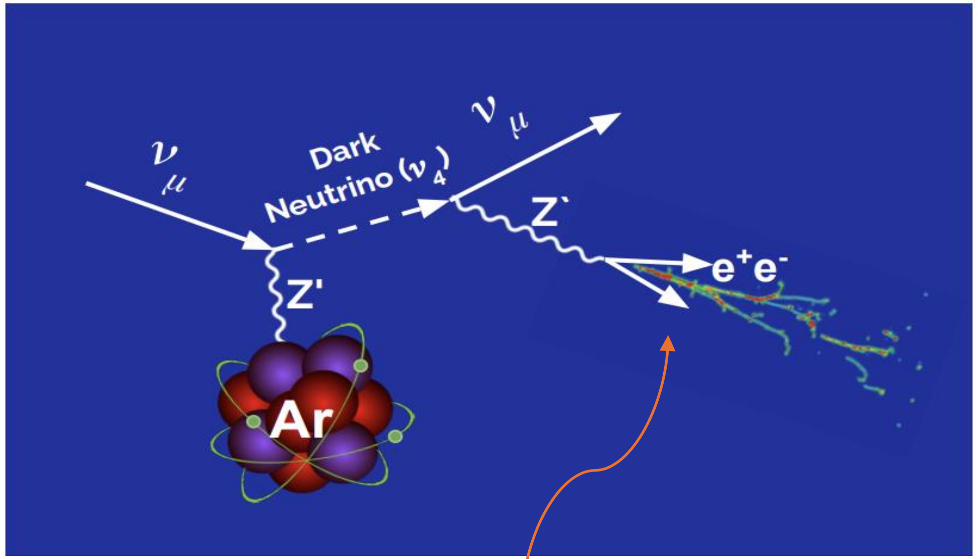
Beyond the Standard Model (BSM) ?

Heavy Neutral Lepton Searches for LEE

A Heavy Neutral Lepton (HNL) is a SM gauge singlet fermion that mixes with active neutrinos.

Portal Models

- A theoretical framework that describes how new particles or interactions beyond the Standard Model (BSM) communicate with SM particles.
- MicroBooNE tested one of such model which include dark neutrino(s) (HNL charged under $U(1)_D$) to explain the LEE.
- This is a renormalizable extension to the SM and doesn't require direct coupling through SM forces. Exciting and new ways to explore the dark sector.
- Dark neutrino produced in upscattering and decaying into an e^+e^-pair.



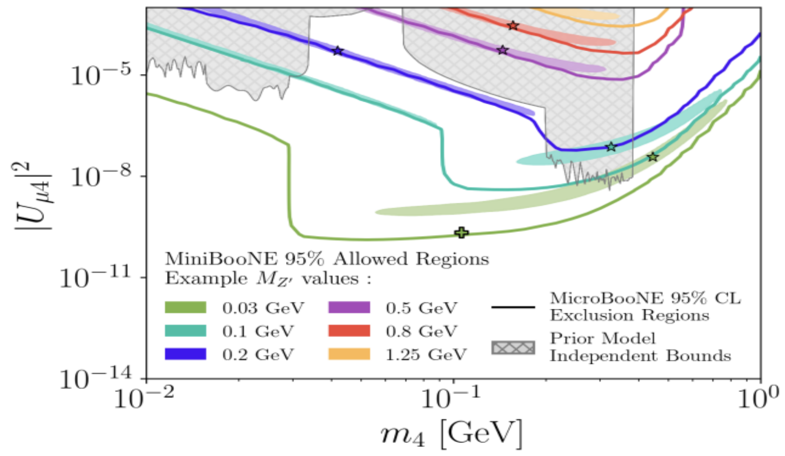
e^+e^-production often looks just like single photon production, if e^+e^- are sufficiently collimated

Heavy Neutral Lepton Searches for LEE

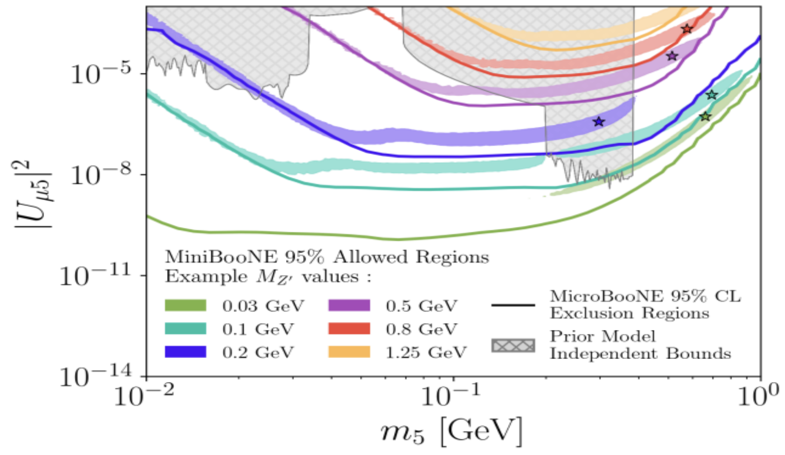
MicroBooNE observed 95 e^+e^- candidate events consistent with the constrained background of 69.7 ± 17.3 (a 1.5σ level).

Set world's first exclusion limits that rule out most of the dark neutrino parameter space which can explain the MiniBooNE LEE at 95% CL.

New Results on arXiv:2502.10900



(a) Single dark neutrino scenario, $\varepsilon = 8 \times 10^{-4}$.



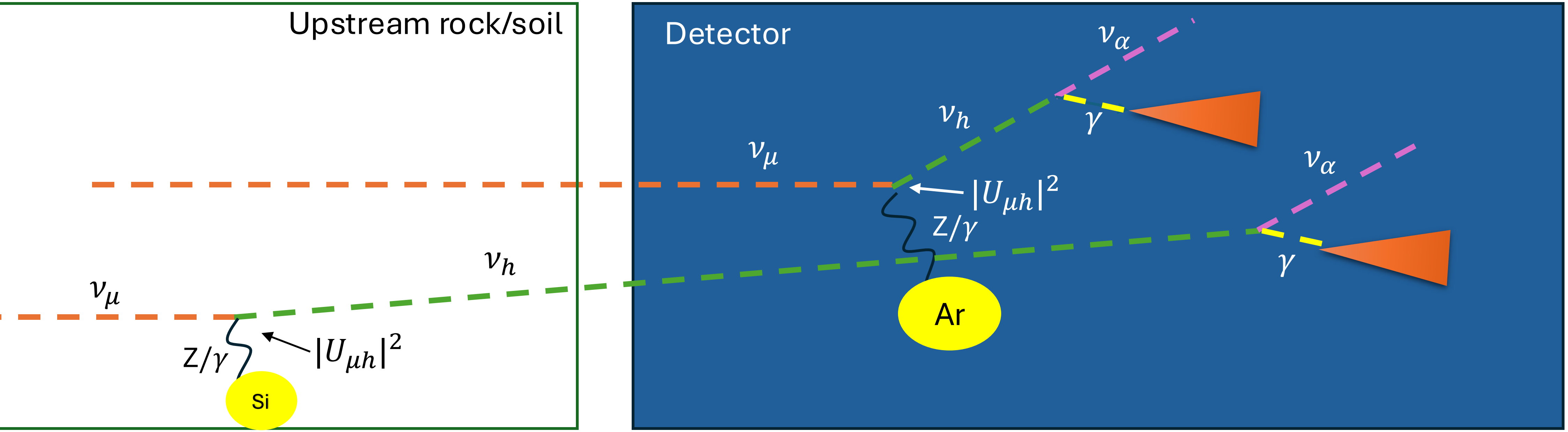
(b) Dual dark neutrino scenario, $\Delta = 1$, $\varepsilon = 8 \times 10^{-4}$.

Heavy Neutral Lepton Searches for LEE

Heavy Neutrino with Large Transition Magnetic Moment (TMM)

A transition magnetic moment, induced by quantum loops in a heavy neutrino, enables state-changing photon emission and offers a potential explanation for the MiniBooNE low-energy excess.

Phys. Rev. Lett. 103, 241802



Heavy Neutral Lepton Searches for LEE

Potential to explain MiniBooNE Low Energy Excess

- Previous study which combines low-energy excess as a combination of sterile neutrino oscillations and heavy neutrino decay, identifies a best-fit point at $m_{vh} = 0.48\ GeV, TMM = 2.5 \times 10^{-6}\ GeV^{-1}$, explaining the MiniBooNE low-energy excess.
- We aim to put new constraints on the parameter space using MicroBooNE data.
- Building onto single photon searches, e.g. NC coherent single photon search, where we look for a lone shower and no vertex activity associated with it, but retraining so we don't focus so much on the coherent signal.

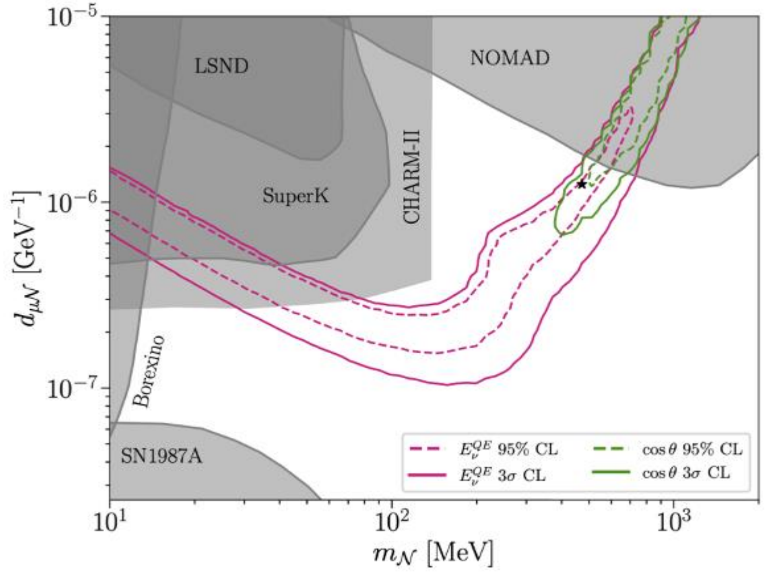


Figure 3: *Regions of parameter space allowed at 95% CL from fits of E_ν^{QE} and cosθ distributions (shaded regions represent regions ruled out by other neutrino experiments). The black star is located at m_N (m_{vh}) =480 MeV and $d_{\mu N} = 1.25 \times 10^{-6}$ GeV^{-1}.*

Phys. Rev. D 107, no.5, 055009 (2023)

Heavy Neutral Lepton Searches for LEE

Selection

Topological Requirements (1s0t)

→

Pre-cuts:
Cosmic muon decay electron & Fiducialization

→

Tailored background rejection BDTs

Cosmic BDT

BNB BDT

CC ν_e BDT

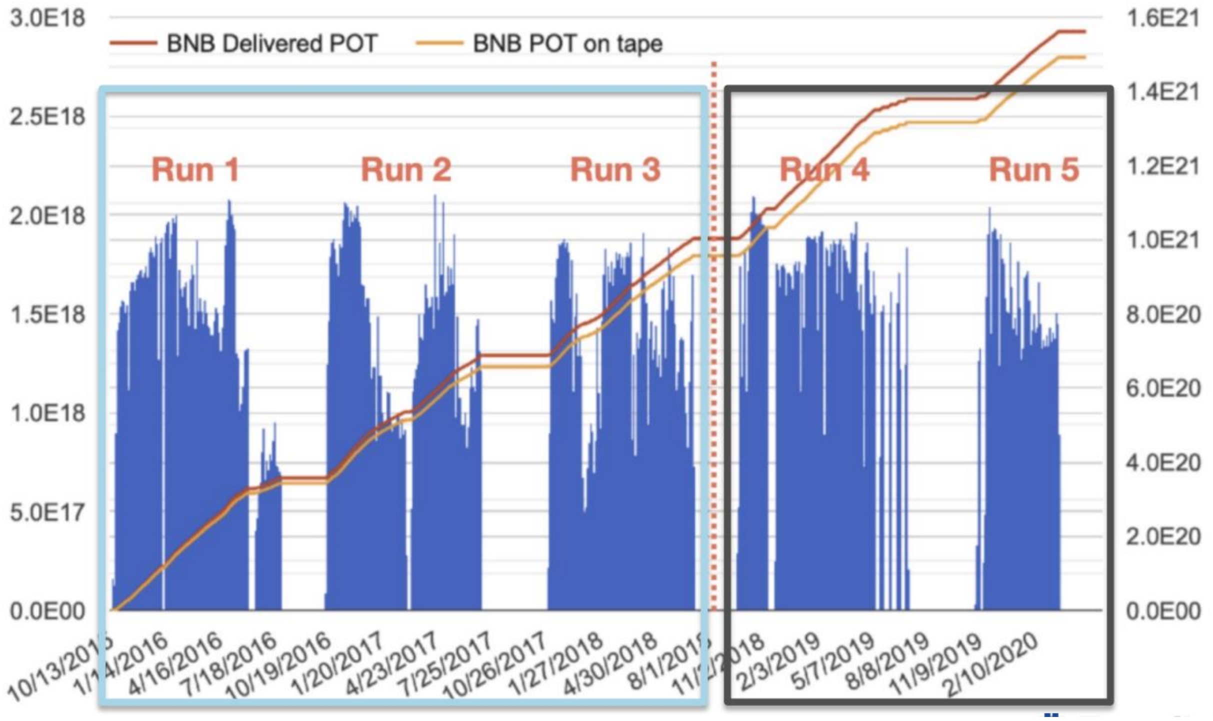
NC π^0 BDT

Analysis development is in progress

What's Next For MicroBooNE?

Full-Statistics Analyses:

- MicroBooNE completed 5 years of data running in 2021.
- Combine all data-taking periods for maximum statistics and sensitivity.

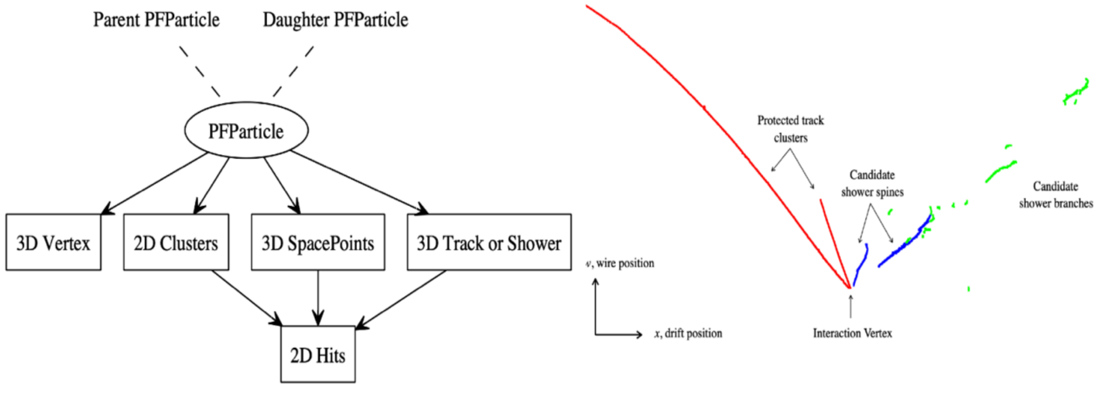


What's Next For MicroBooNE?

Combining Multiple Reconstructions

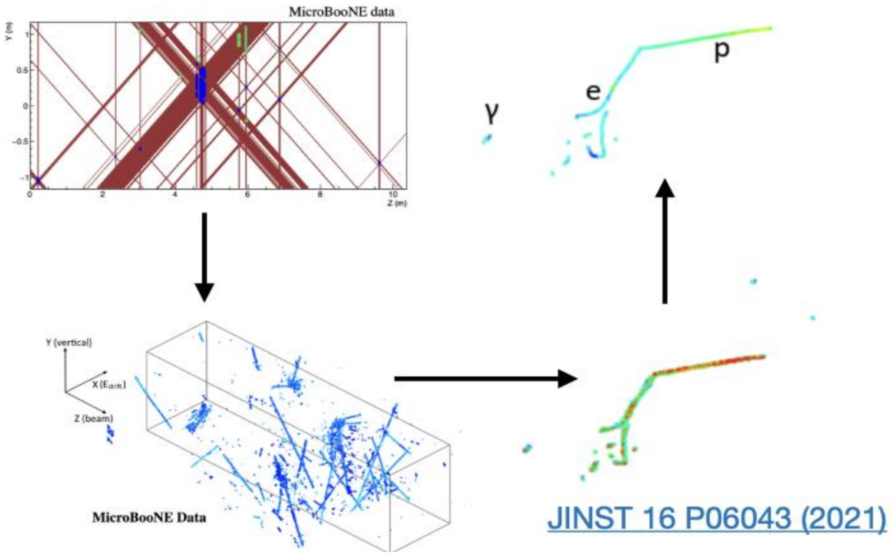
- MicroBooNE uses three reconstruction frameworks: Wire-Cell, Pandora, and Lantern each with unique capabilities.
- This combined approach improves event classification, and efficiency across analyses.

Pandora multi-algorithm reconstruction



Eur. Phys. J. C **78**, 82 (2018)

Wire-Cell pattern recognition procedure



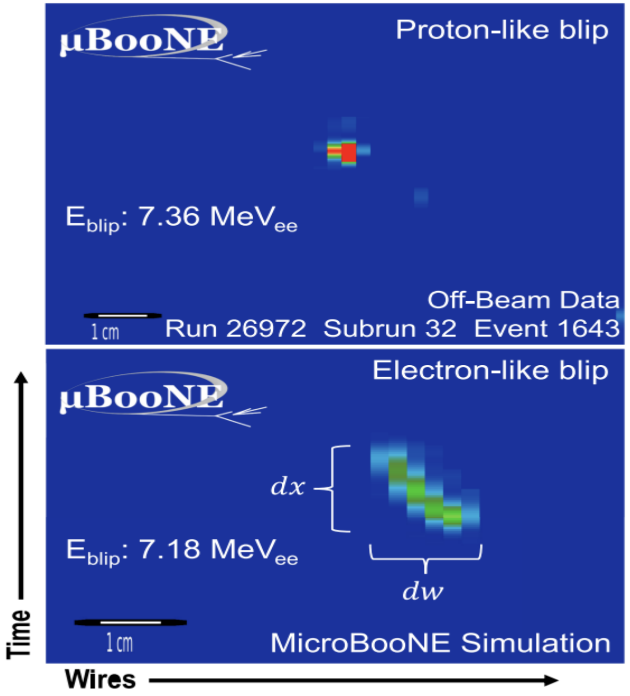
JINST 16 P06043 (2021)

JINST 17 P01037 (2022)

What's Next For MicroBooNE?

MeV Blips

LArTPCs mainly study GeV-scale events. MicroBooNE's MeV-scale program with improved MeV-blip reconstruction enhances low-energy sensitivity and single-photon purity.

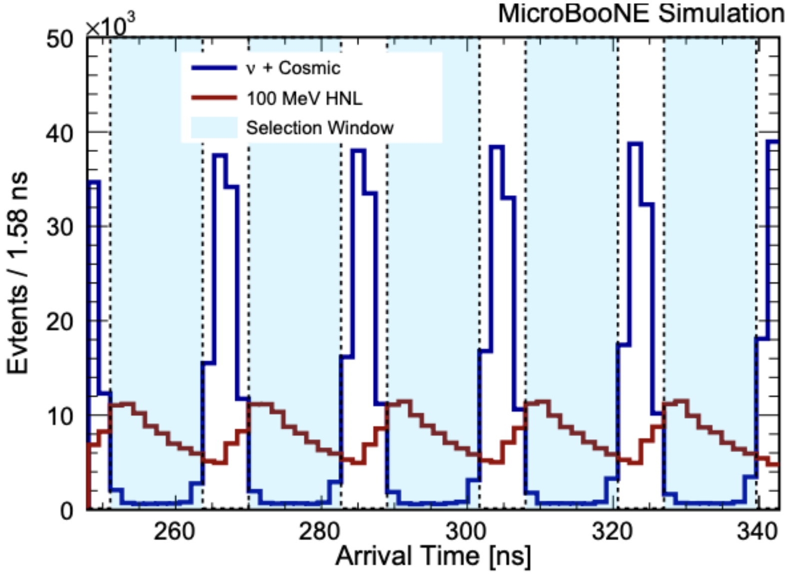


PhysRevD.111.032005

PhysRevD.109.052007

Nanosecond Timing

This precise nanosecond timing helps distinguish in-bunch neutrino interactions from out-of-bunch signals, improving searches for delayed BSM signatures and reducing background contamination.



arxiv.org/abs/2304.02076

Summary

- Microboone has had a very successful run of 5 years collecting neutrino data in the Fermilab BNB.
- Analyses carried out so far with Run 1-3 (50%) of data have shown no evidence of LEE, either electron- or photon-like.
  - **Single-electron searches** show no excess above the Standard Model expectation.
  - **Single-photon searches** ($\Delta \rightarrow \gamma$, coherent γ, inclusive γ) find no significant enhancement, though a localized 2σ excess in inclusive motivates continued study.
  - **Heavy Neutral Lepton (HNL) searches** set world-leading limits, ruling out most dark-neutrino parameter space explaining the MiniBooNE anomaly.

Continued efforts are focusing on**:**

- Full-statistics analyses with all data periods.
- Combine multiple reconstructions (Pandora, Wire-Cell, Lantern).
- Expand MeV-scale program (blips) and nanosecond-timing tools to boost single-photon purity and BSM sensitivity.

Thank you!