# Exploring BSM Physics and Neutrino Interactions with MicroBooNE

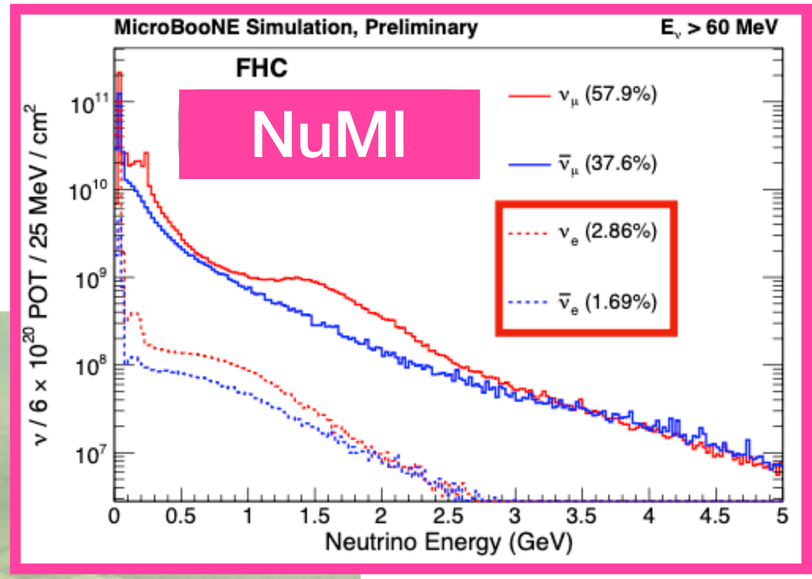
**Sergey Martynenko (Brookhaven National Laboratory)**
**On behalf of MicroBooNE collaboration**

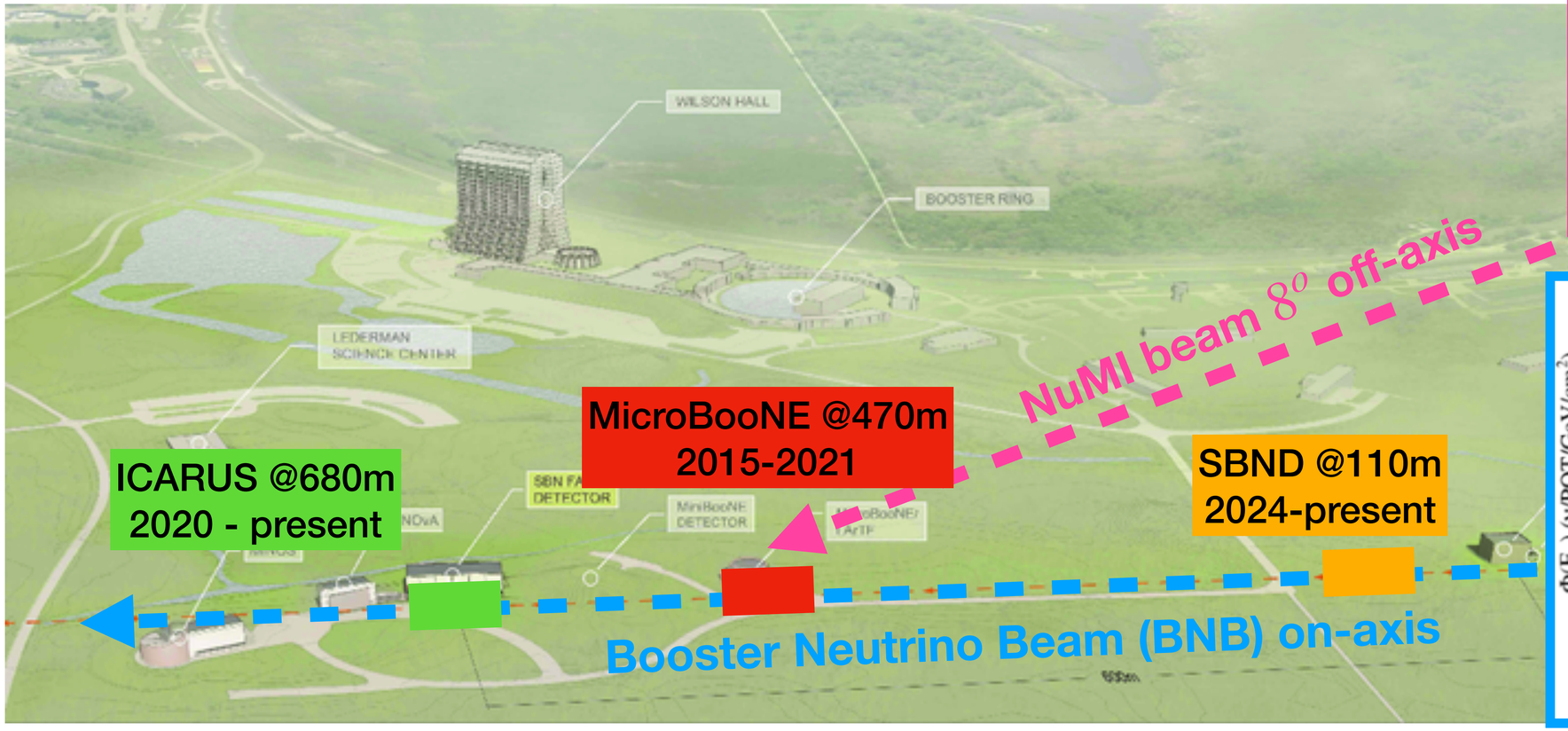

# MicroBooNE Experiment

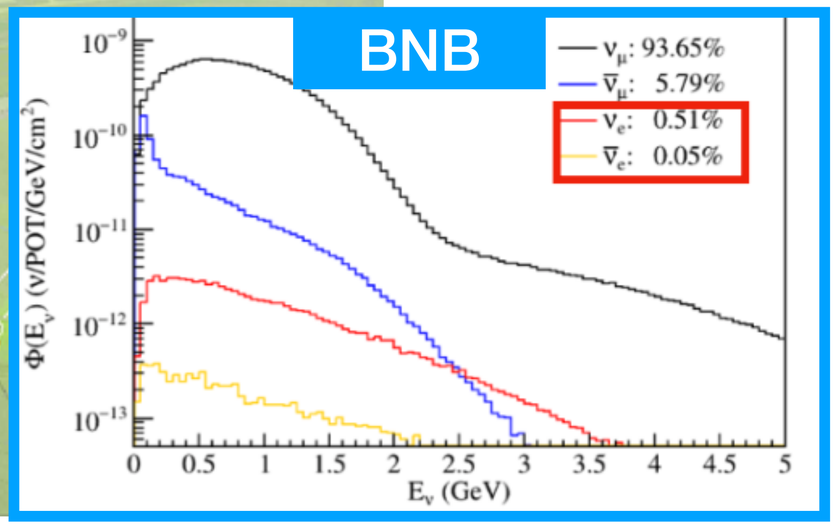
PRD 104, 052002 (2021)

PRD 105, 112005 (2022)

- Part of the Fermilab Short-Baseline Neutrino (SBN: SBND, MicroBooNE, and ICARUS) Program
- $O(500K)$ interaction in 5 year running period with two beams :
  - Booster Neutrino Beam (BNB): On-axis, 470m baseline , $99.5\,\%\,\nu_\mu(\bar{\nu}_\mu)/0.5\,\%\,\nu_e(\bar{\nu}_e)$
  - Neutrinos at the Main Injector (NuMI): $8^o$ off-axis, 680m baseline, $95.5\,\%\,\nu_\mu(\bar{\nu}_\mu)/4.5\,\%\,\nu_e(\bar{\nu}_e)$



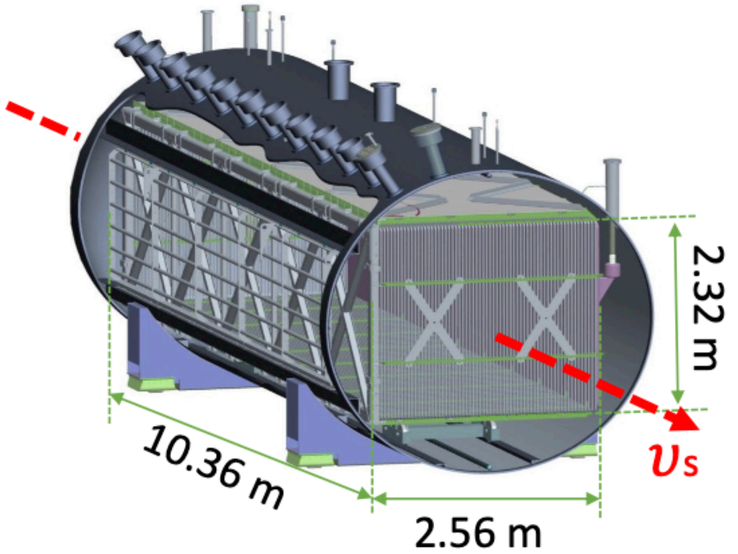



# MicroBooNE Detector

MicroBooNE Detector is a Liquid Argon Time Projection Chamber (LArTPC) with:

- 85 tonne active volume
- 3 planes of wires (vertical, +60° , -60°), 3 mm spacing
- 32 PMTs to detect scintillation photons



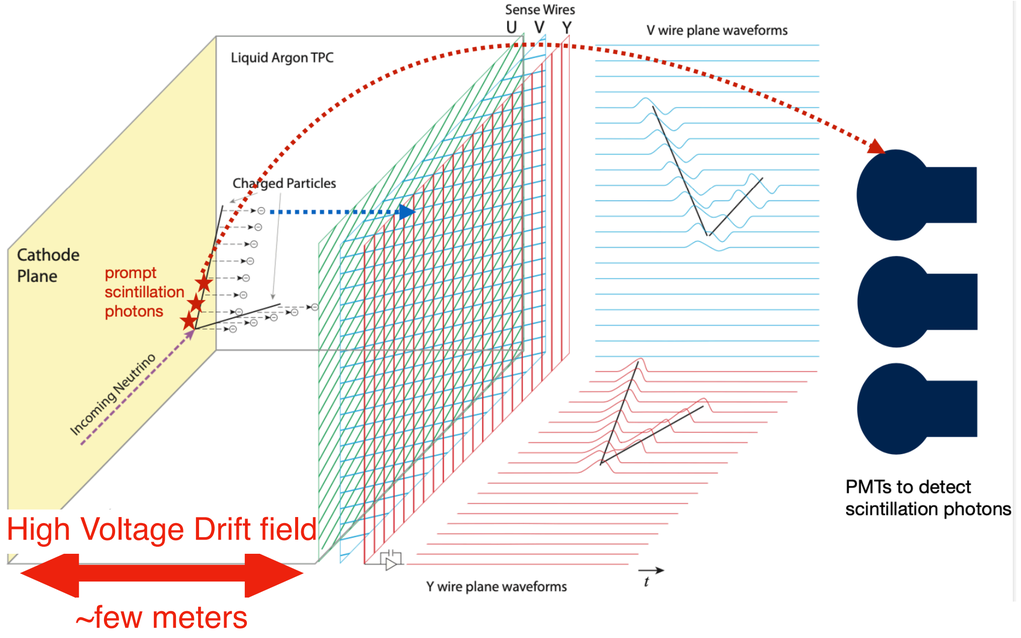

JINST 12 (2017) 02, P020

**LArTPC concept**

Charged particle generated in the detector

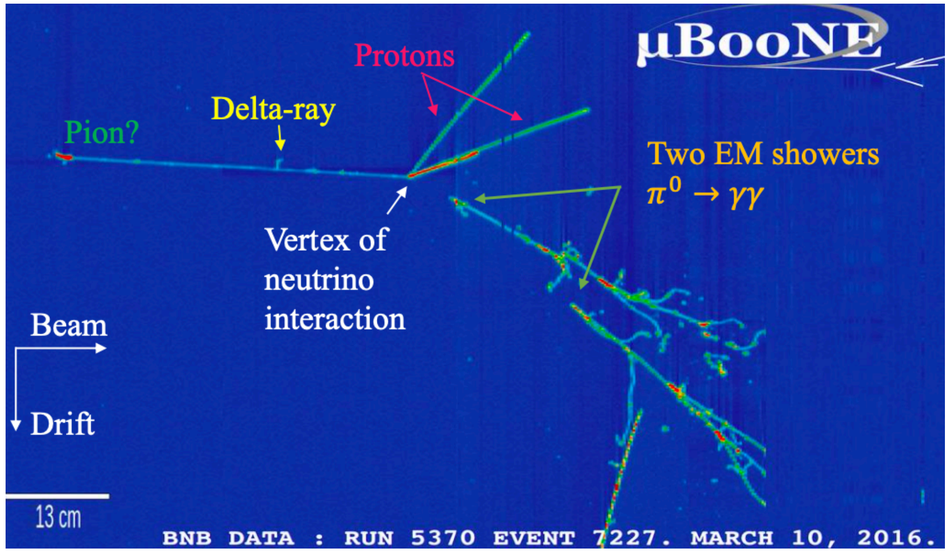
Scintillation light emitted by excited Ar, detected by PMTs

Ionization electrons drift to anode plane [2 induction wire planes and 1 collection]



# Liquid Argon Time Projection Chamber (LArTPC)

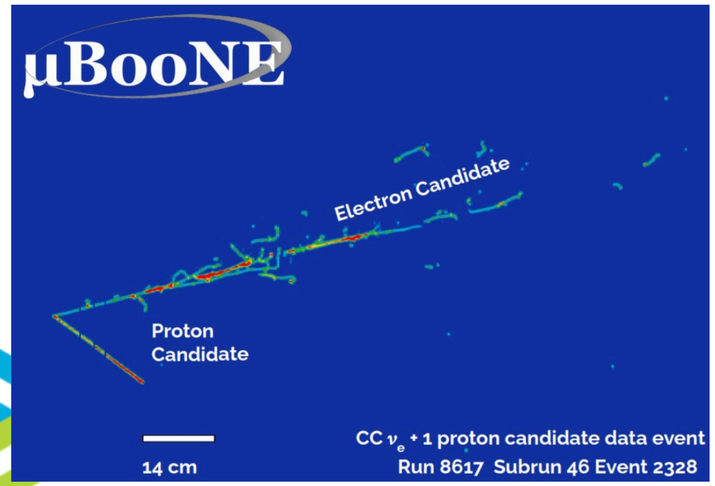
- Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

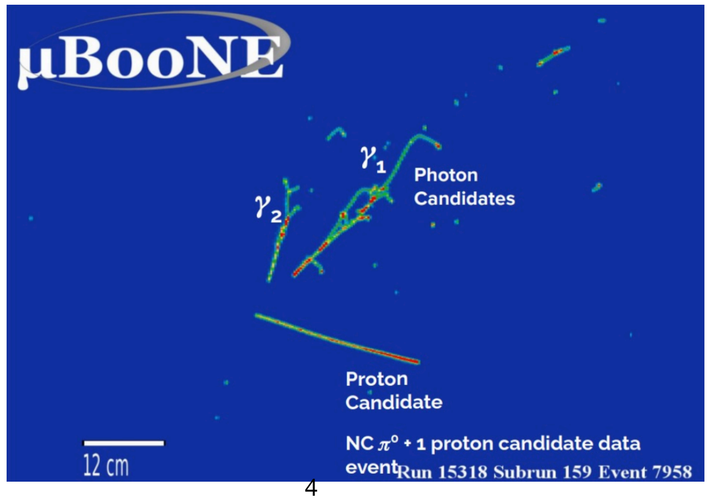


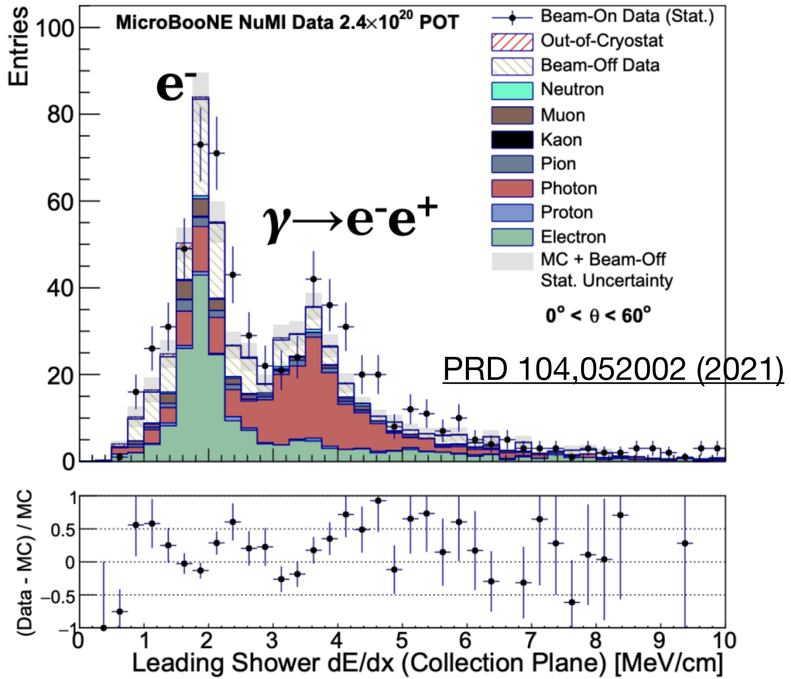

- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track ($\mu$, $\pi$, $p$ etc.) vs shower (e, γ EM cascade)
- $e$ / $\gamma$ (e+e– pair production) separation

Important for $\nu_\mu \rightarrow \nu_e$

1. Gap between shower start point and $\nu$ vertex
2. dE/dx two times difference (1 MIP vs 2 MIPs)




PRD 104,052002 (2021)

# MicroBooNE Physics Program

Investigate MiniBooNE Low Energy Excess (LEE) & Search for BSM

Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)


Study $\nu$-Ar scattering using one of the largest $\nu$-Ar data collected to date!

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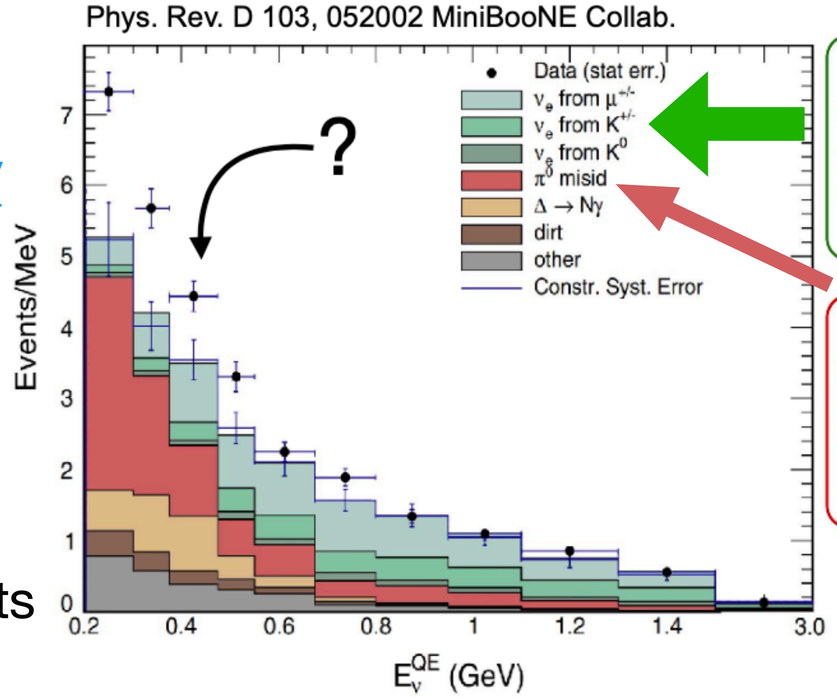
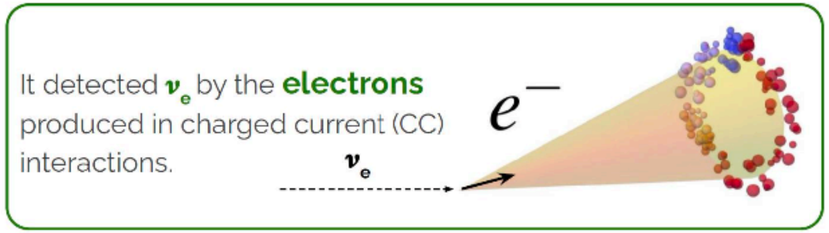
# Short-baseline Neutrino Anomalies

- Anomalous results observed at short baselines using various neutrino sources (LSND, MiniBooNE, GALLEX/SAGE, etc.)
  - Inconsistent with the standard $3\nu$ framework if attributed to oscillations
- MiniBooNE observed the Low Energy Excess (LEE) of electromagnetic events with 4.8σ significance





## MiniBooNE

- Cherenkov detector
- Unable to distinguish between electrons and photons
- Unable to detect hadronic final-state particles below Cherenkov threshold

Same BNB beam
Almost same baseline

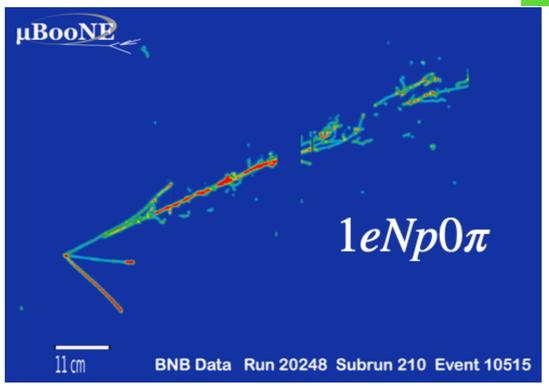
## MicroBooNE

- LAr TPC detector
- Much better $e/\gamma$ separation capabilities

# Low Energy Excess (LEE) Search : $\nu_e$ - like

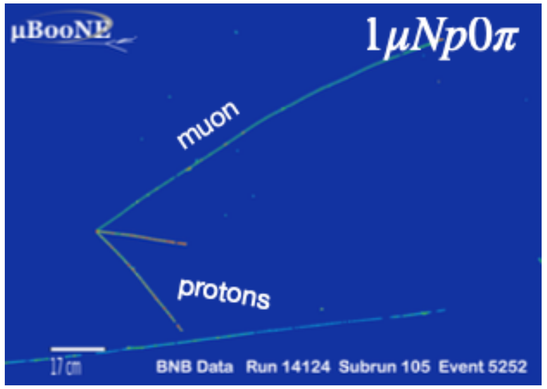
**Electron Hypothesis**

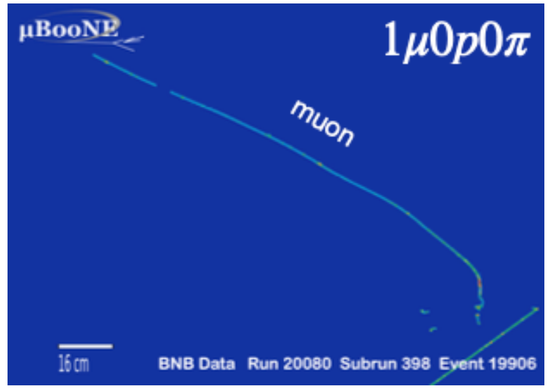
- **Is LEE coming from electron neutrinos?**
- Pionless $\nu_e$ LEE analysis ⇒ Same topology as MiniBooNE LEE ($\nu_e CC0\pi$)
- 1st generation saw no evidence of $\nu_e$- like excess (>97% CL exclusion) [Phys. Rev. Lett. 128,241801]
- Update analysis :
  - First analysis to use full MicroBooNE dataset (BNB) ⇒ 60% POT increase
  - New background constraint ⇒ $\nu_\mu CC$ (divided between Np and 0p) and $NC\ \pi^0$ rich sidebands




MICROBOONE- Note-1127-PUB

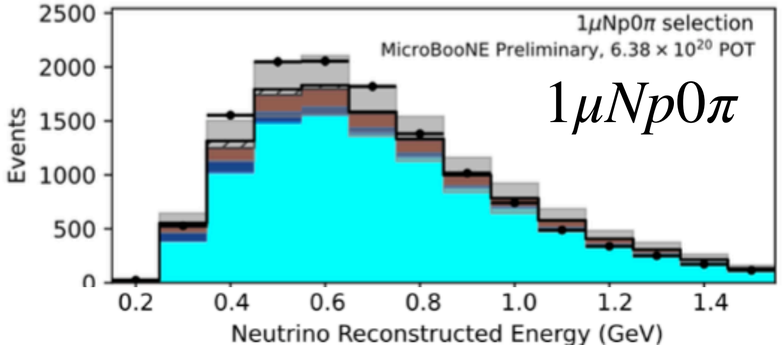

Phys. Rev. Lett. 135, 081802 (2025)

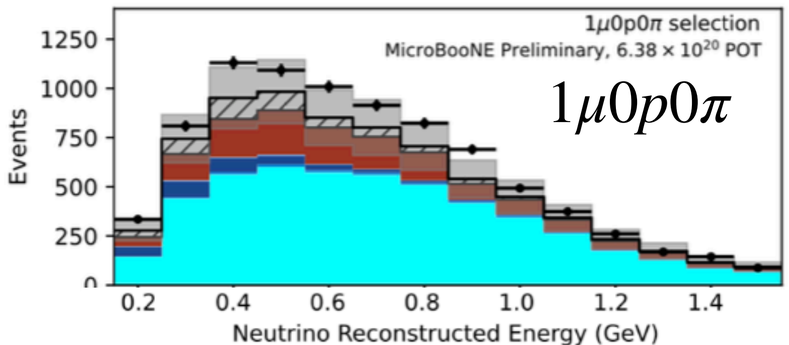


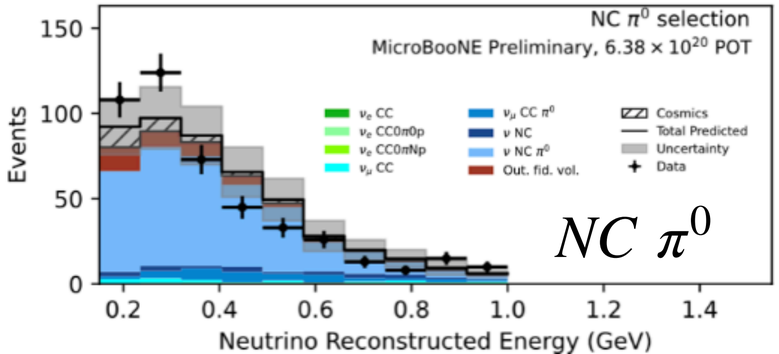




match hadronic final states of $\nu_e$ signal channel

constrain dominant $\pi^0$ background



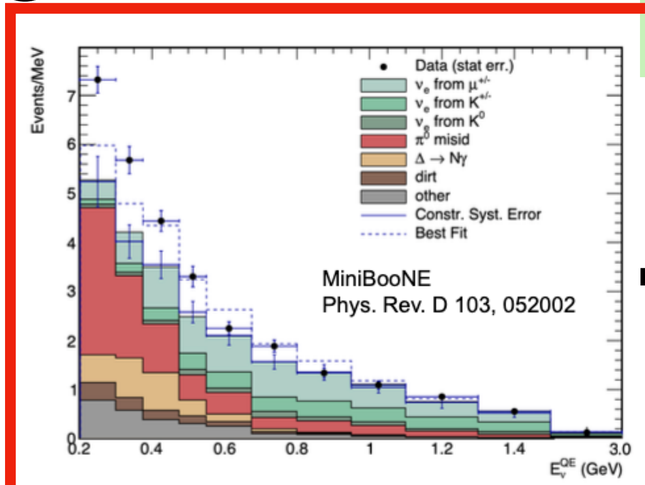
# LEE Search : $\nu_e$ - like

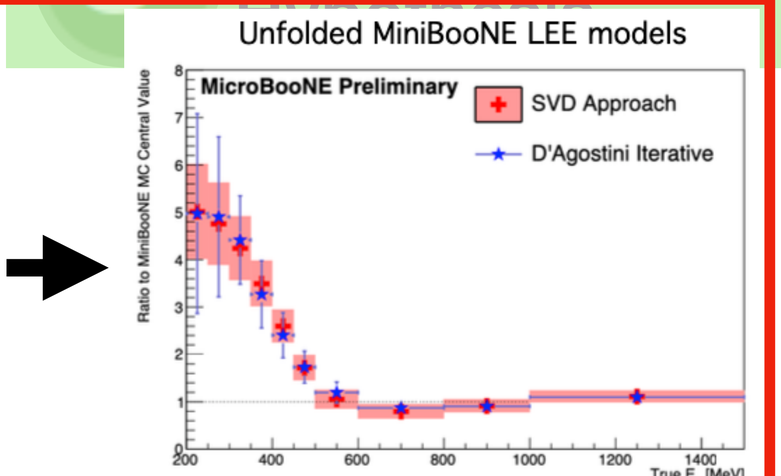
- New signal model ⇒ address electron kinematic variables

- Initial Model:
  - MiniBoone-like excess based on true $E_\nu$

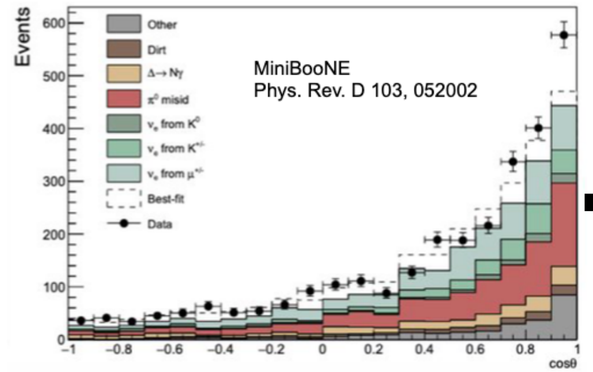
- New Model:
  - Enchantment in true $E_e$, $cos\theta_e$ (shower kinematics)
  - More Comprehensive MiniBooNE LEE hypothesis for $\nu_e$-like

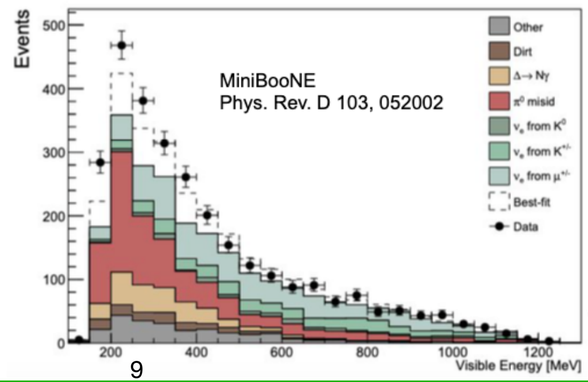
**Initial Model**

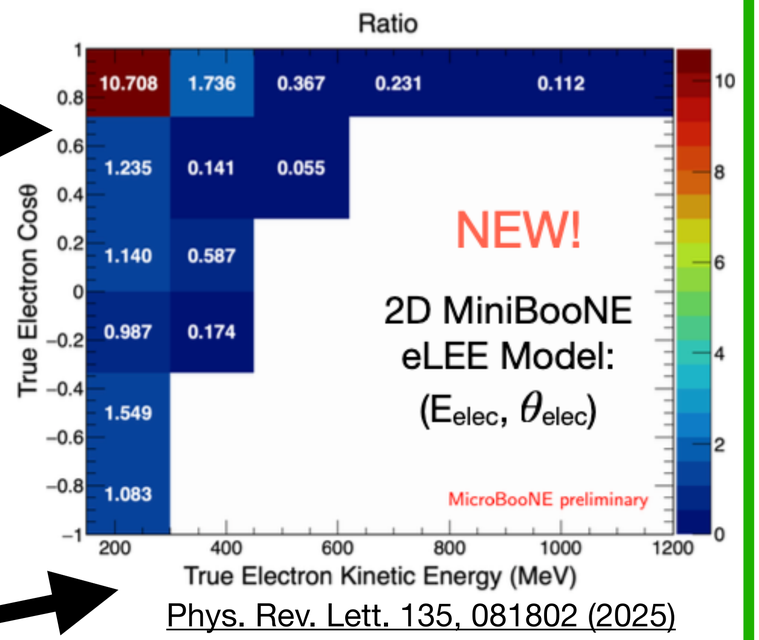



**New Model**




Phys. Rev. Lett. 135, 081802 (2025)

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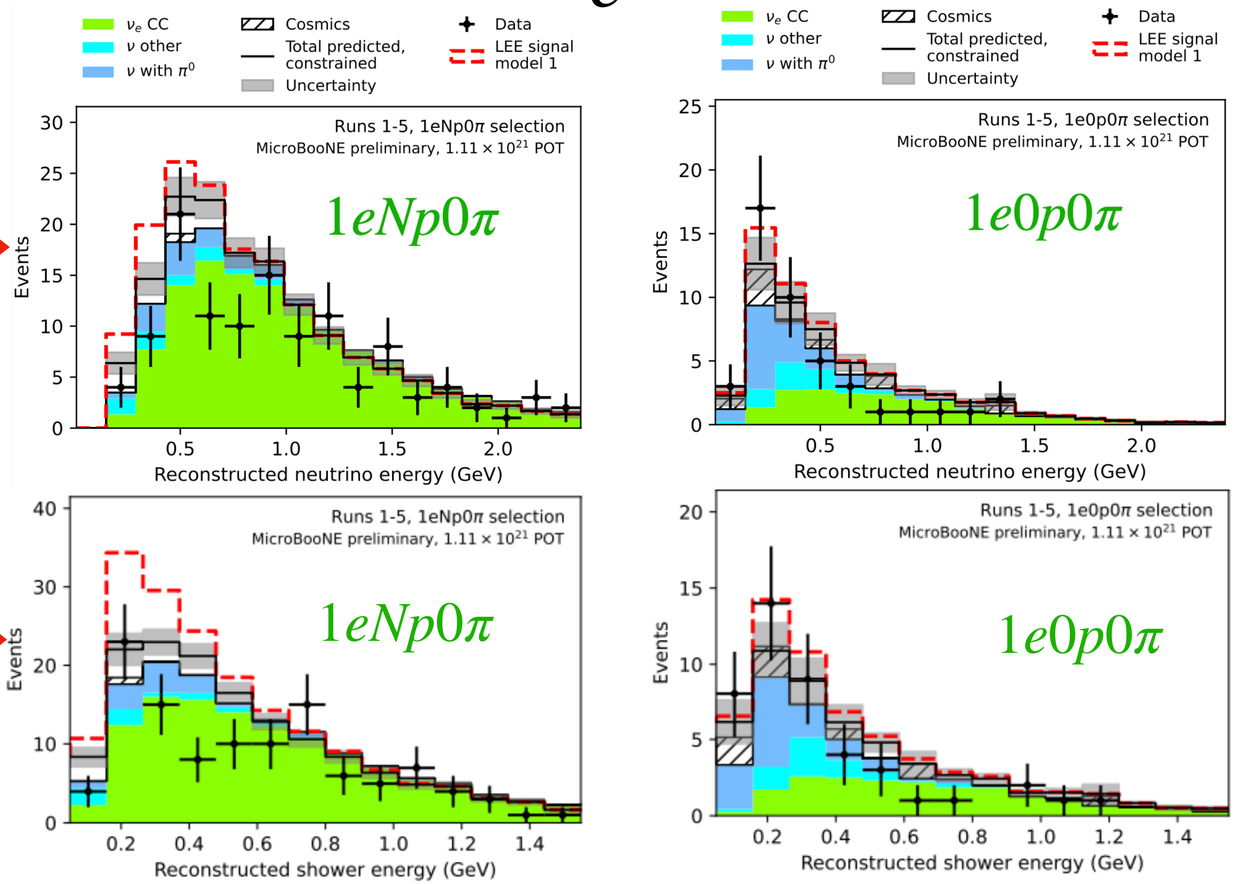
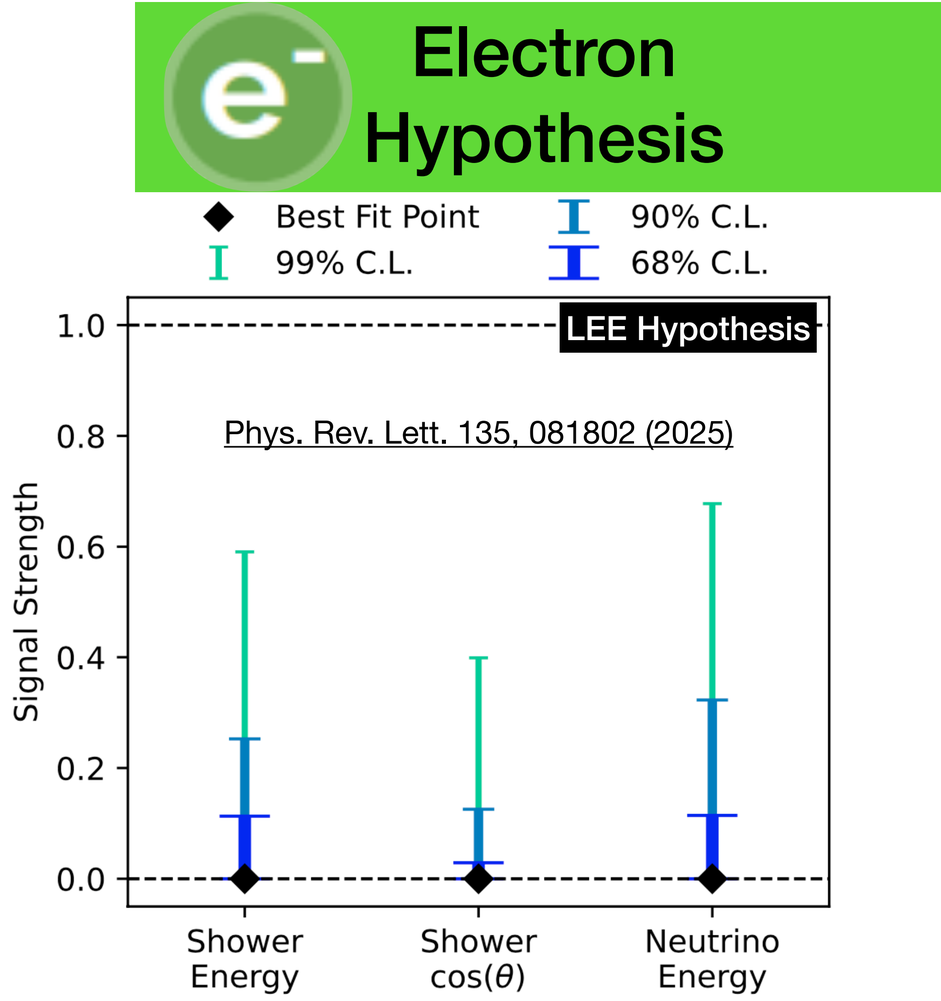
# LEE Search : $\nu_e$ - like

$E_\nu$ model

$E_e, cos\theta_e$ model




- With ~65% more stats and new sideband constraints => able to provide strong limits on the MiniBooNE LEE $\nu_e$-like
- **Inconsistent with $\nu_e$-like excess at > 99% CL!**
- **Consistent results across all kinematic observables**

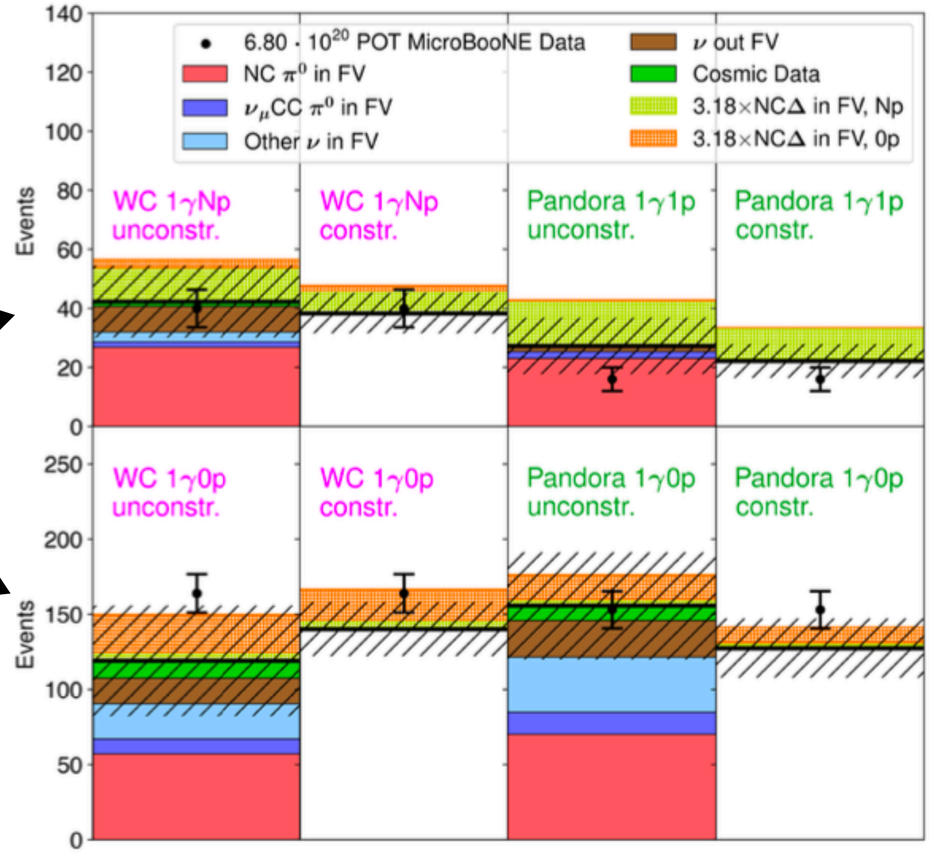
**Previous $CC\nu_e$ analysis also shows no evidence of excess**

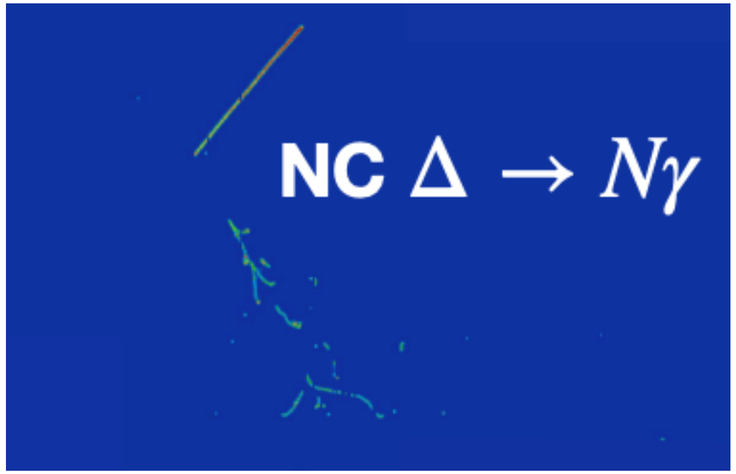
PRL 128, 241801 (2022)
PRD 105, 112004 (2022)
PRD 105, 112003 (2022)
PRD 105, 112005 (2022)

# LEE Search : single - $\gamma$ ($NC\Delta \rightarrow N\gamma$)

**Photon Hypothesis**

- **Is LEE coming from underestimated $NC\Delta$ background?**
- Past MicroBooNE results focused on $NC\ \Delta \rightarrow 1\gamma$ SM background
- Disfavor sole MiniBooNE explanation at 95% CL [PRL 128, 111801 (2022)]
- An expanded $NC\Delta \rightarrow N\gamma$ search confirmed **no NCΔ excess** at 94.4% CL
- Cannot rule out an interpretation of the MiniBooNE LEE as an enhancement of 0p $NC\Delta \rightarrow N\gamma$ events



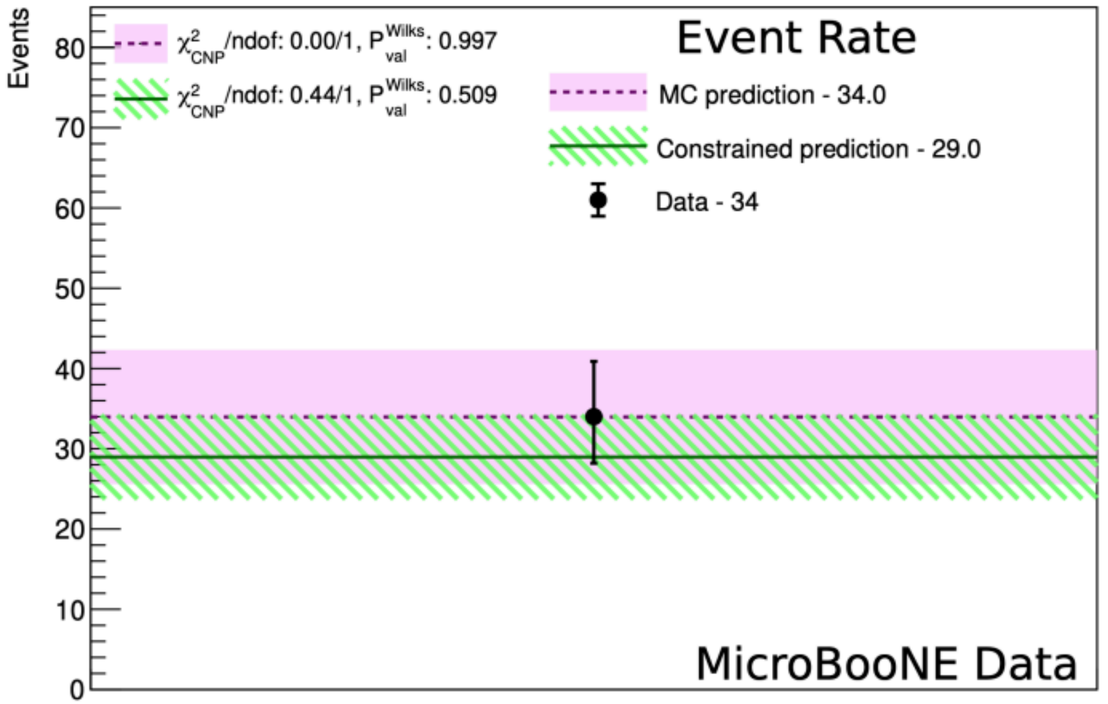

https://arxiv.org/abs/2502.05750

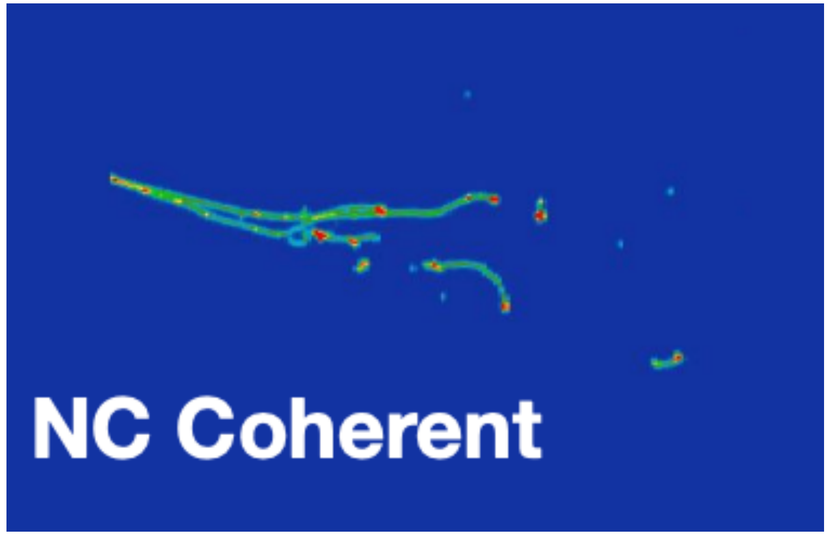
# LEE Search : single - $\gamma$ (NC Coherent Scattering)

**Photon Hypothesis**

$$\nu(\overline{\nu}) + \mathrm{Ar}_{gs} \rightarrow \nu(\overline{\nu}) + \mathrm{Ar}_{gs} + \gamma$$

- NC Coherent Scattering : Sub Dominant source of single $\gamma$ + 0p
- **No evidence** of any increased rate observed
- World's first upper limit on the cross section of the process of $1.49 \times 10^{-41} cm^2$ at 90% CL



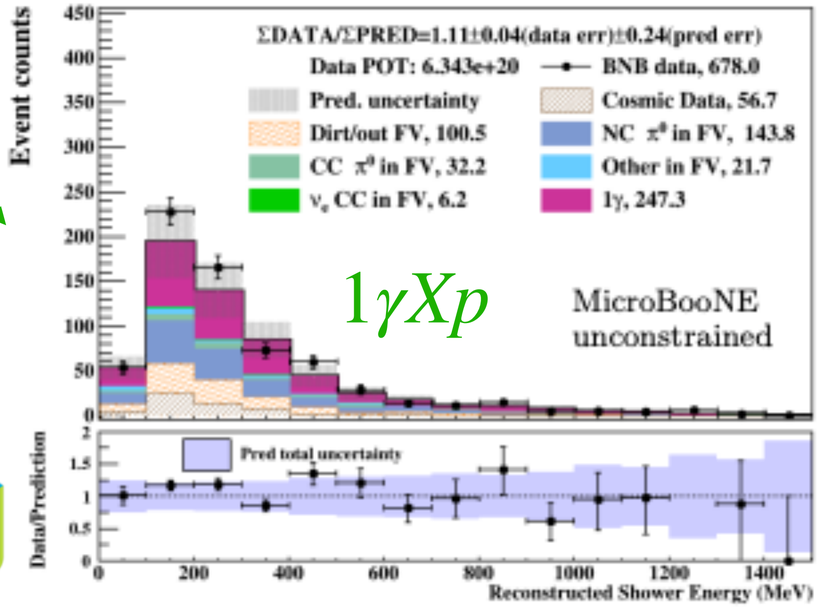

Hagaman & Yandel @ Fermilab 2025

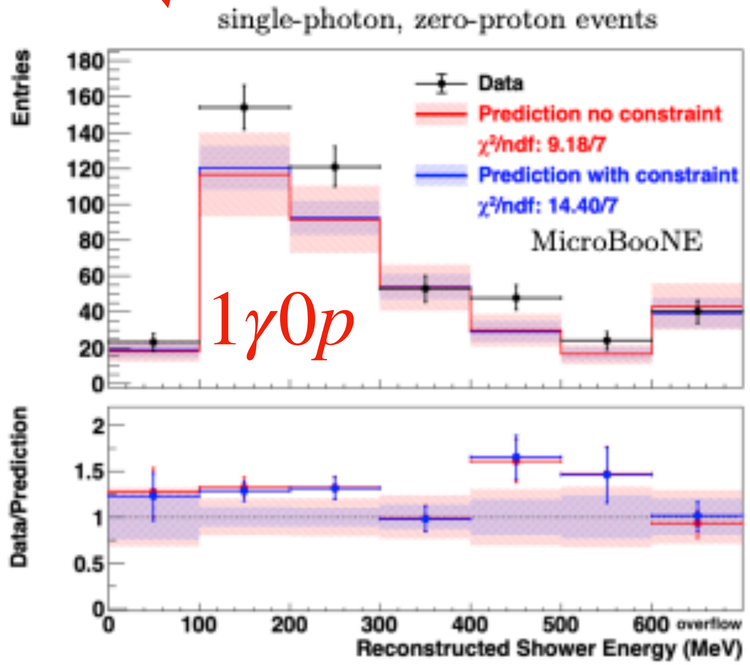
https://arxiv.org/abs/2502.06091

# LEE Search : single - $\gamma$ (Inclusive Single $\gamma$)

**Photon Hypothesis**

- Inclusive Single $\gamma$ : Any event that would look like a single $\gamma$ at MiniBooNE's threshold
- Good agreement with background observed in distributions where protons accompany the single-photons ($1\gamma Xp$)
- **Observed a $2\sigma$ excess** of single-photon events with no protons ($1\gamma 0p$) with shower energies below 600 MeV


Hagaman & Yandel @ Fermilab 2025

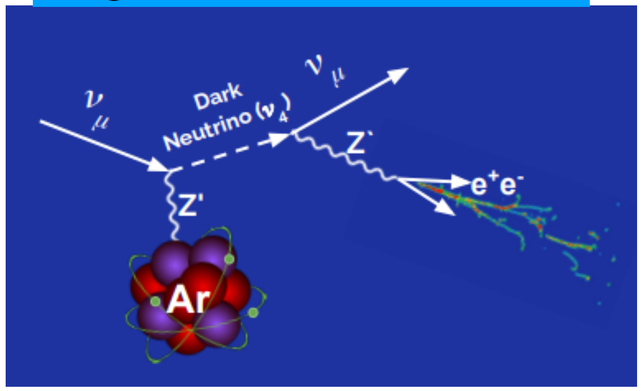
https://arxiv.org/abs/2502.06064

# LEE Search : BSM $e^+e^-$

**BSM $e^+e^-$ Hypothesis**

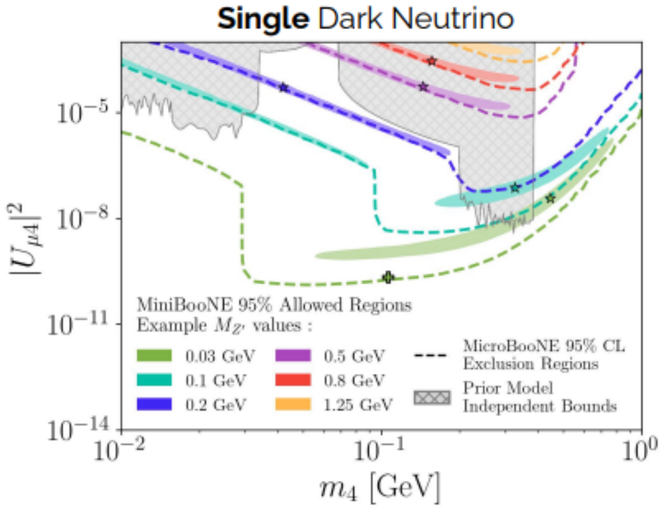
- **Is BSM physics producing $e^+e^-$ topology?**
- **Models:** SM neutrino upscatters via exchange of dark boson (Z') into sterile neutrino, which decays via Z' into an $e^+e^-$ pair
- **Result :**
  - No evidence for an $e^+e^-$signal consistent with a single or dual dark neutrino scenario
  - World's first direct test of these dark sector models as an explanation for the MiniBooNE low-energy excess
  - **Excludes the majority of the parameter space viable as a solution to the MiniBooNE anomaly** (especially for light Z' boson masses) at the 95% CL

**Single Dark Neutrino Model**

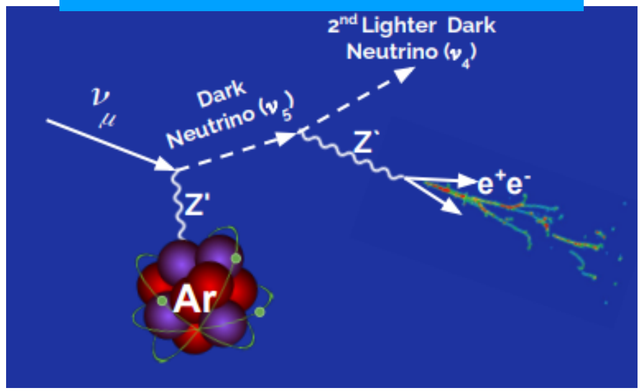



PRL 121 (2018) 24, 241801

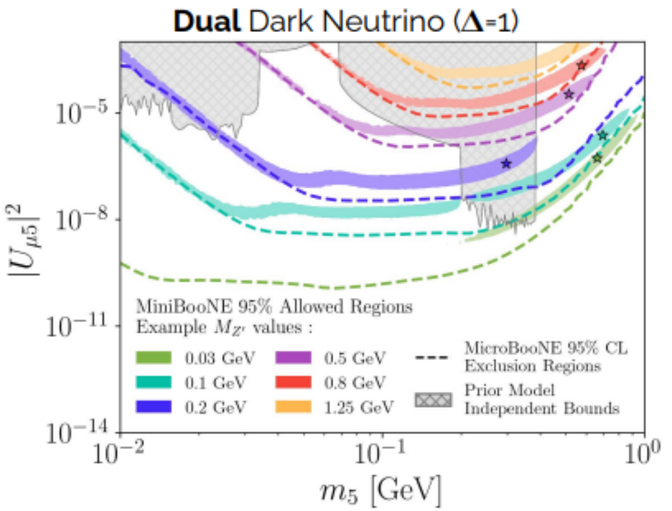
PRD 99 (2019) 071701



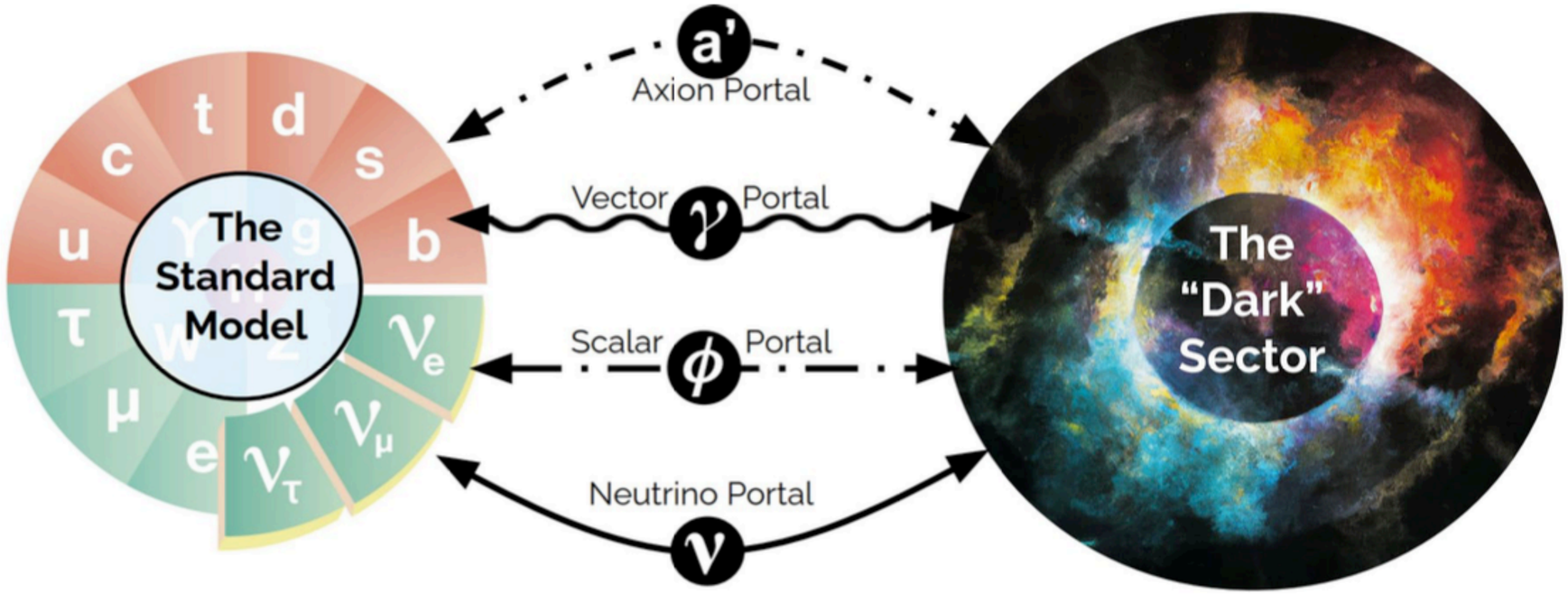

**Dual Dark Neutrino Model**




arXiv:2502.10900



# Portals to the Dark Sector




**Neutrino Portal**

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

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

**Scalar Portal**

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

- 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**

Results

Ongoing work

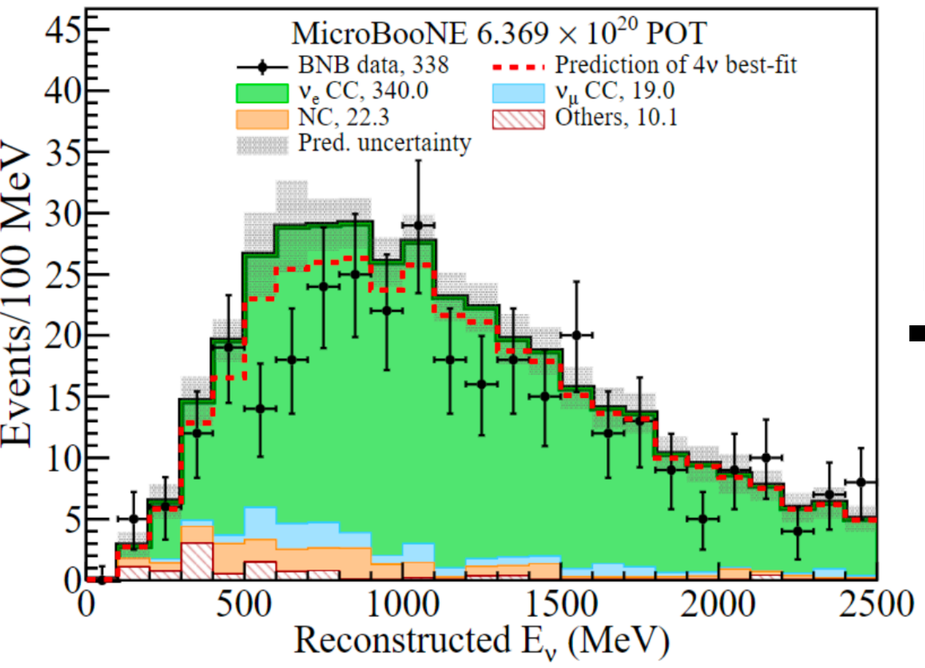
*Credit: Mark Ross-Lonergan*

# 3+1 Oscillation Analysis : BNB-only results

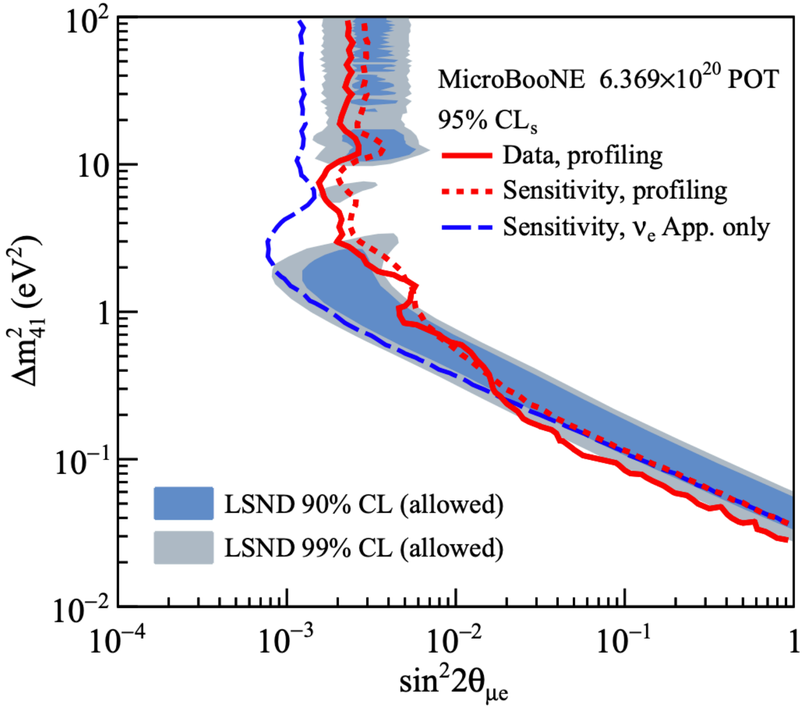
Neutrino Portal

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

PRL 130 (2023) 1, 01180




LEE $\nu_e$ search was reinterpreted under 3+1 sterile neutrino oscillation hypothesis




- Analysis considered $\nu_e$ appearance and disappearance effects simultaneously
- The BNB data result is found to be consistent with the $3\nu$ hypothesis within $1\sigma$ following the Feldman-Cousins approach
- Excluded some region allowed by LSND at 95% CL

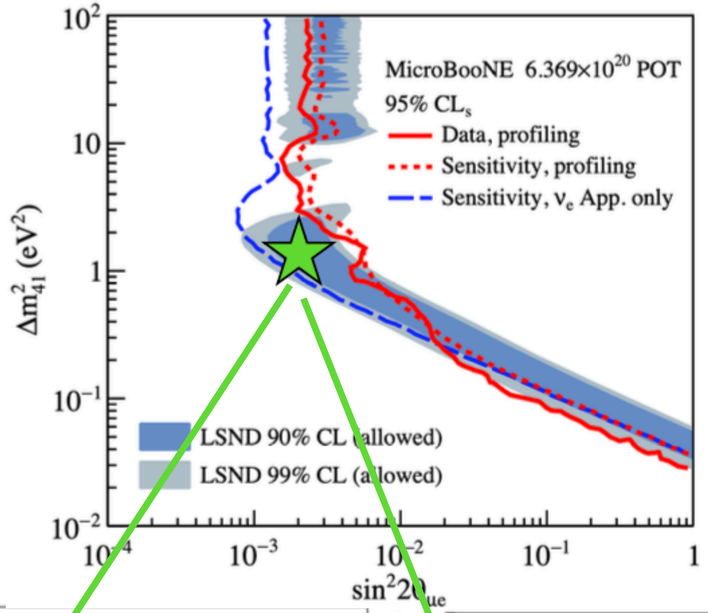
# 3+1 Oscillation Analysis : Degeneracy of Oscillation Parameters

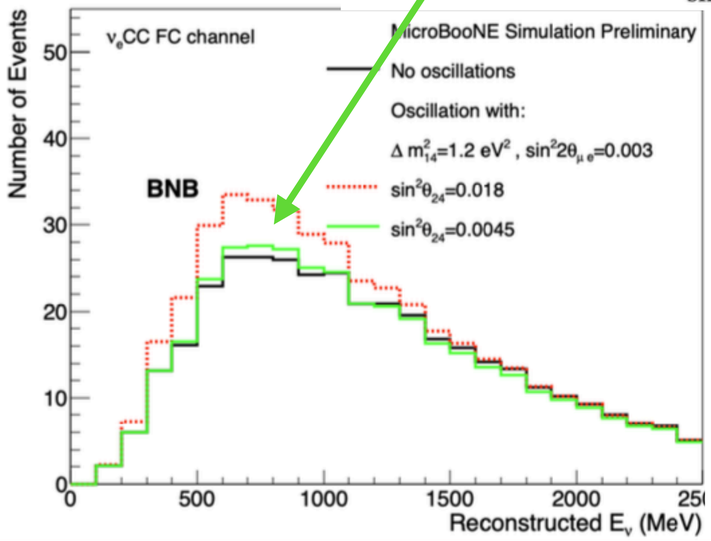
MICROBOONE-NOTE-1132-PUB

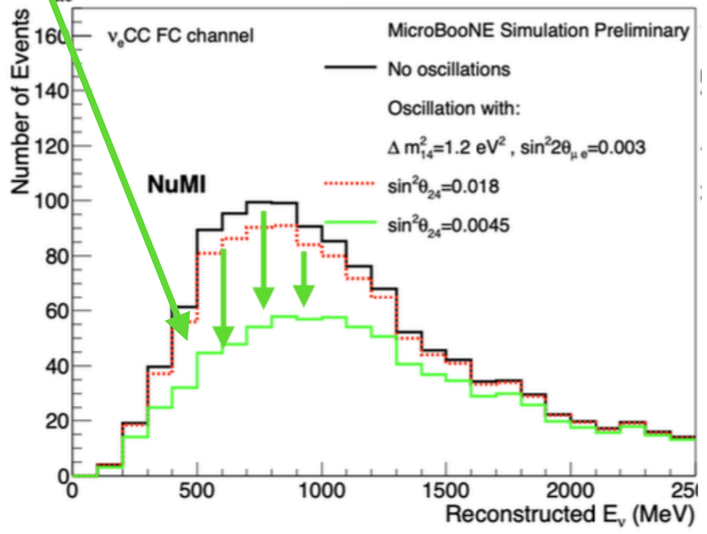
- Observed $\nu_e$ events are a combination result of $\nu_e$ appearance and disappearance:

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[ 1 + (R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41} \right]$$

- Degeneracy when $sin^2\theta_{24}$ approaches $R$ (the ratio of beam intrinsic $\nu_e$ and $\nu_\mu$ flux):
- BNB and NuMI beams have different degeneracy points:
  - ~0.005 for BNB [on-axis with baseline ~470m]
  - ~0.04 for NuMI [off-axis with baseline ~680m]



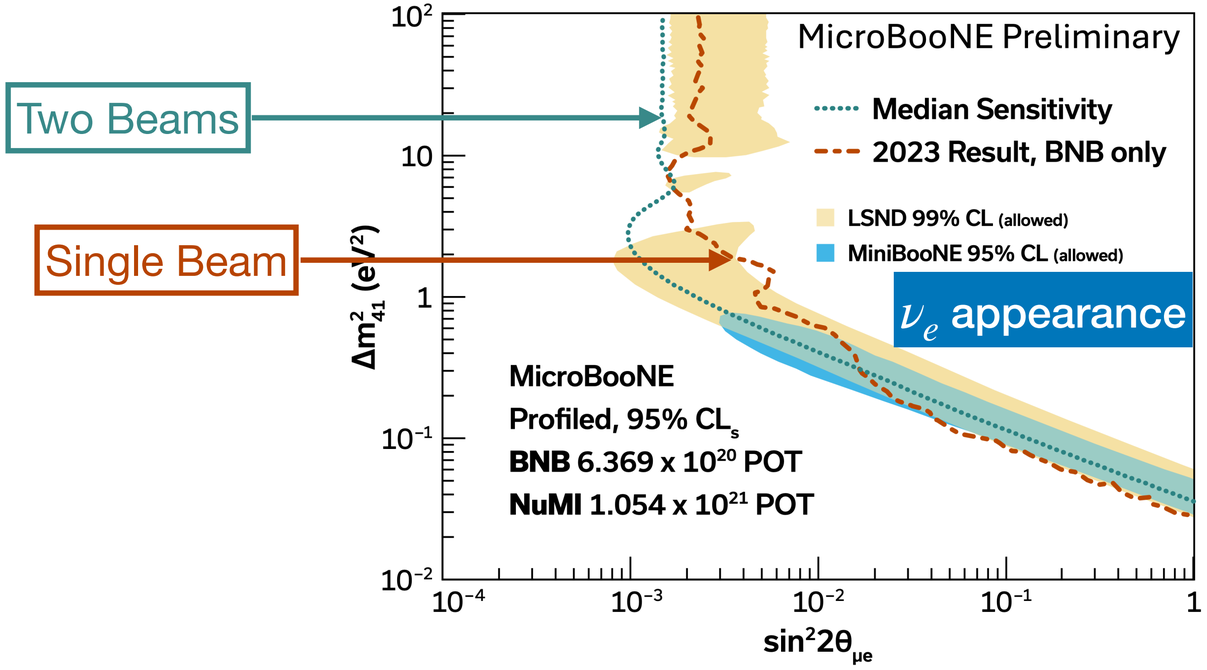

Combination of two beams can break degeneracy!

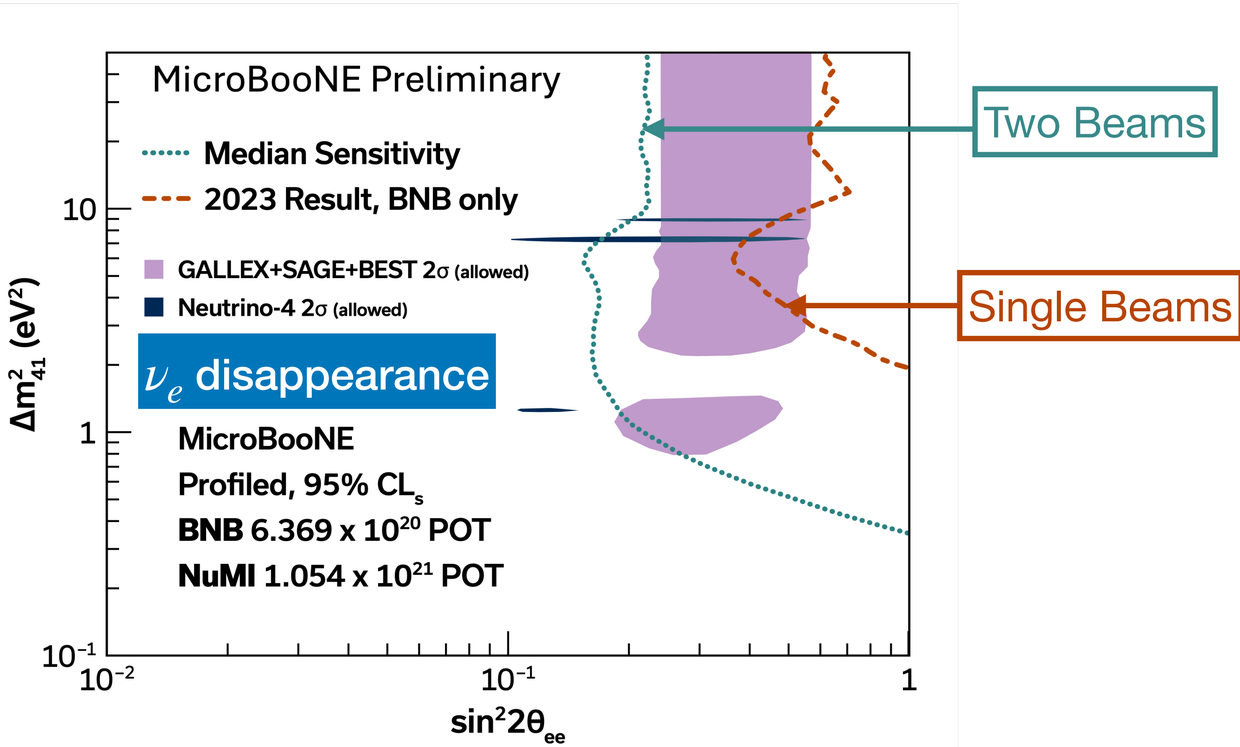
# 3+1 Oscillation Analysis : Sensitivities

- Joint 3+1 analyst with **BNB + NuMI** allows significant enhancement to sensitivity

- Results a coming very soon! **(~ a couple months)**

- More details in MICROBOONE-NOTE-1132-PUB



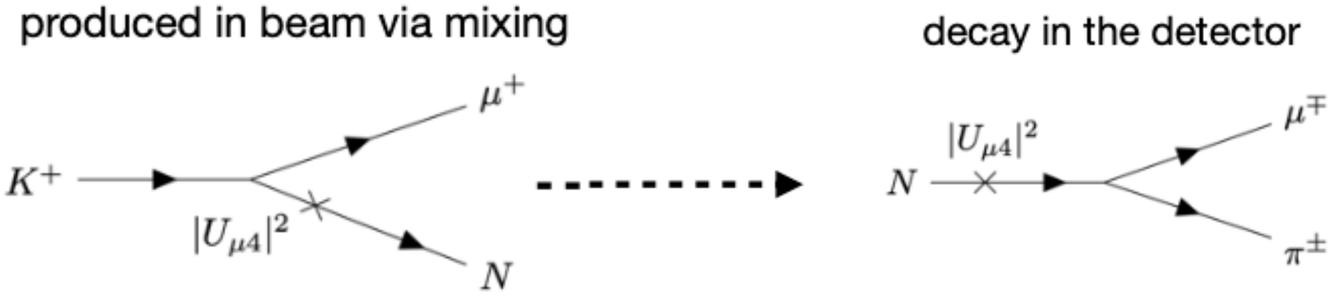



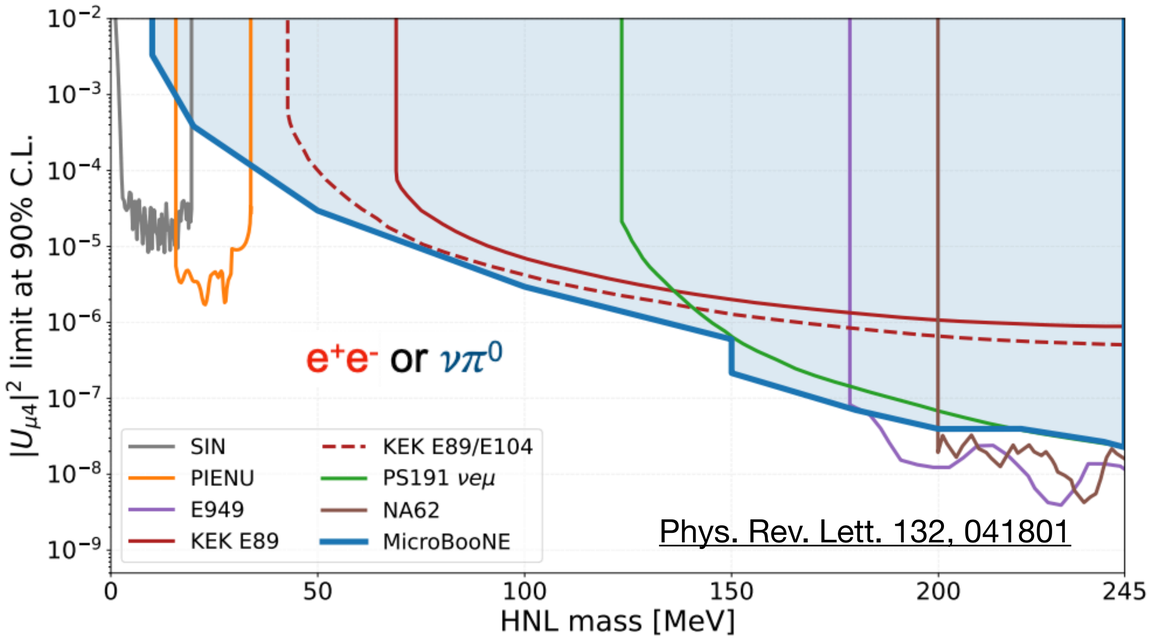
# Heavy Neutral Leptons

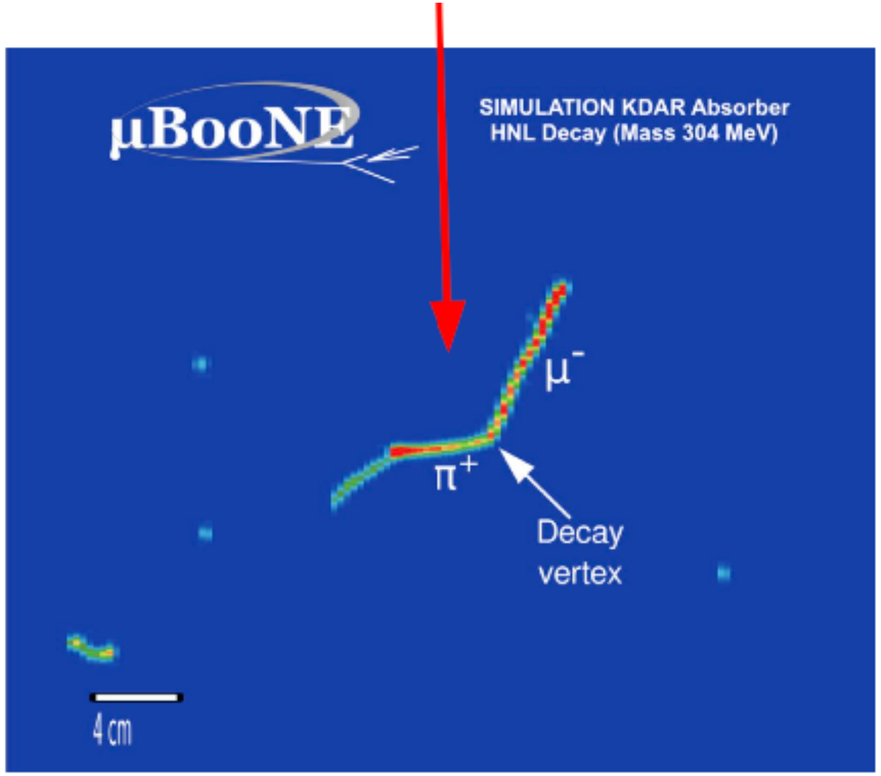
Neutrino Portal

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

- Heavy Neutral Lepton (HNL) relevant for neutrino mass (see-saw), Baryon asymmetry, and Dark matter
- Competitive limit across broad range of HNL mass, including <100MeV (multiple final states)



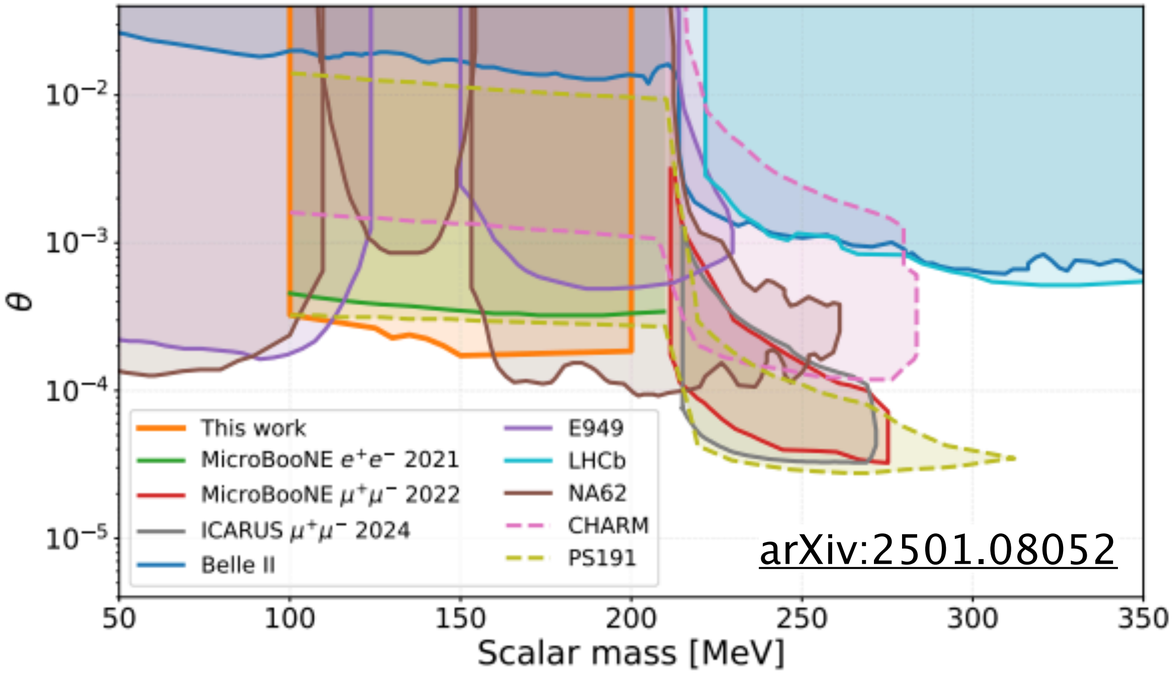



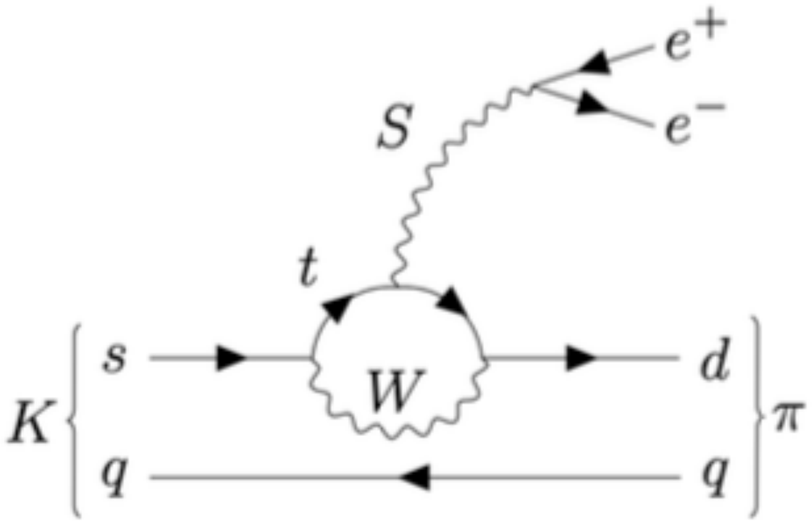
# Higgs Portal Scalar

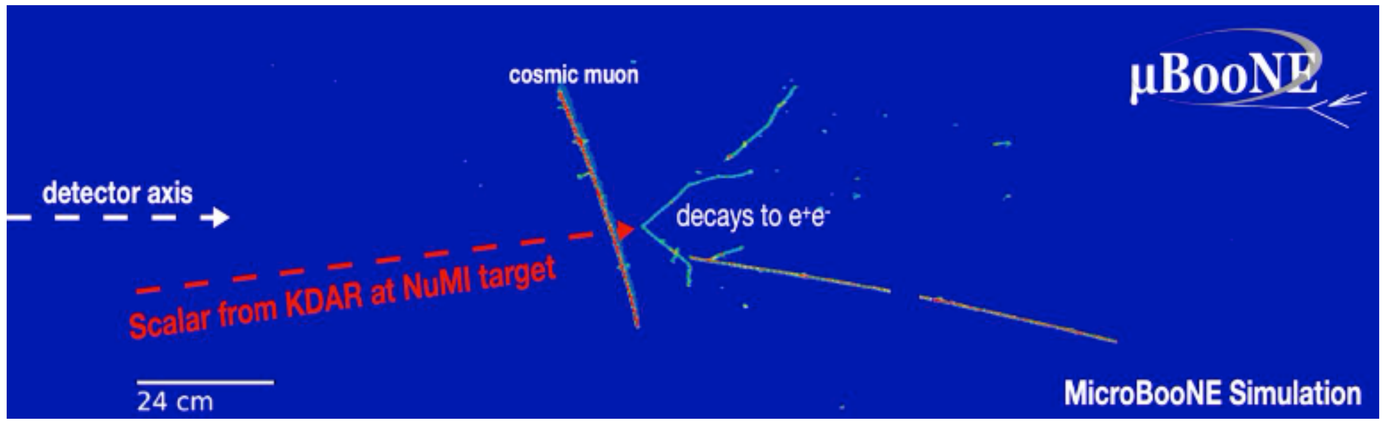
Scalar Portal

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

- Coupling to SM via neutral scalar singlet S, which mixes with Higgs boson via mixing angle $\theta$
- Production from kaon decay (At rest @NuMI target/absorber and Inflight @NuMI Decay Pipe)
- Strongest limit in 115 MeV to 155 MeV mass range



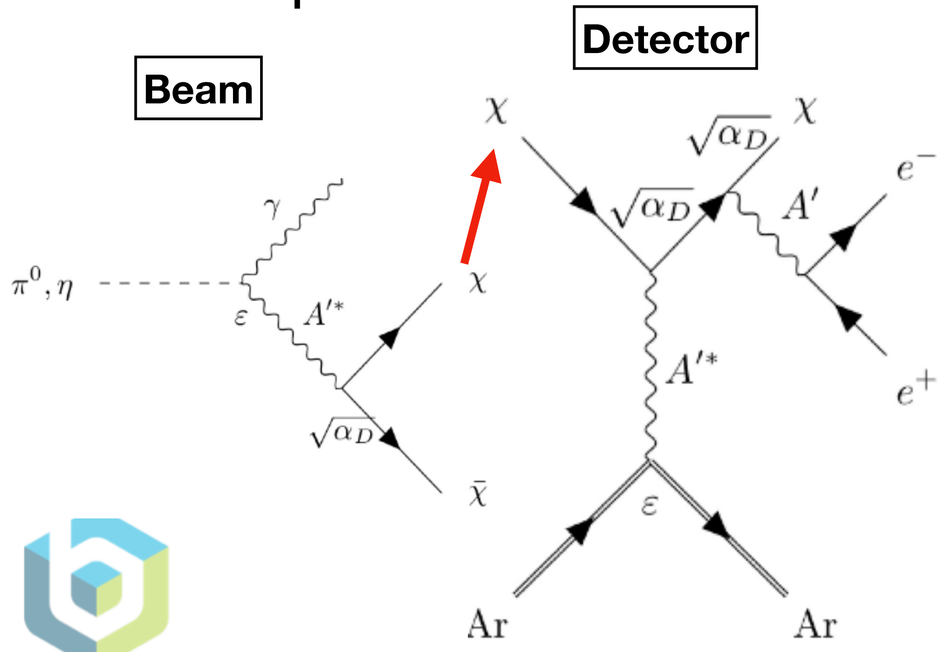



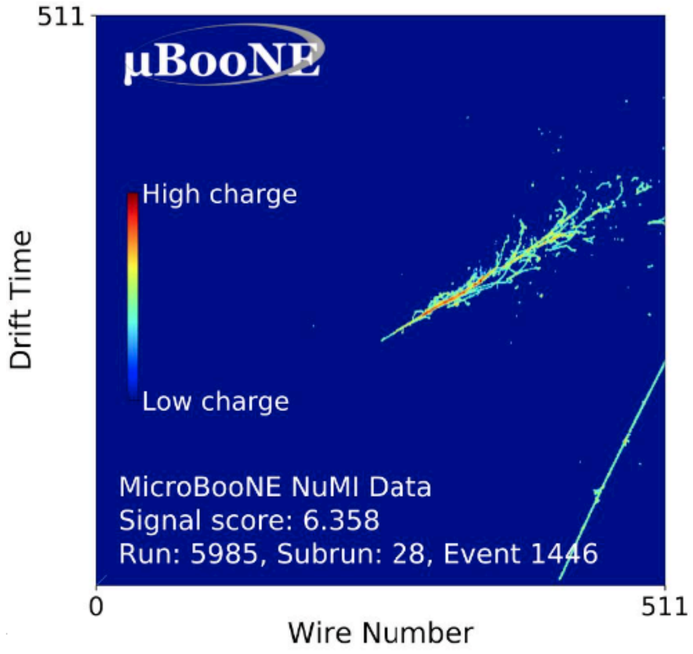
# Dark Tridents

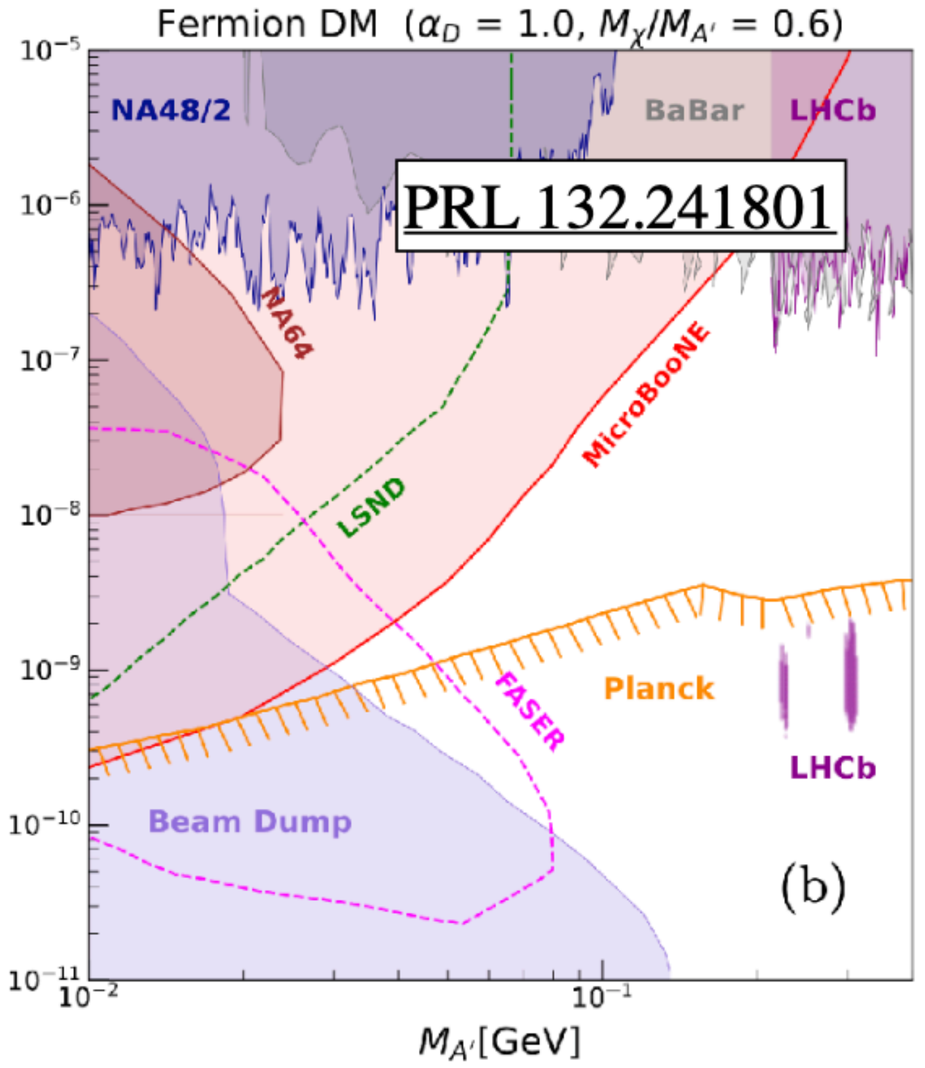
Vector Portal

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

- Dark tridents ⇒ light dark matter production via dark photon mediation resulting in $e^+e^-$ topology
- First search for dark-trident using a LArTPC
- Exploring new phase space and setting competitive limits



# MicroBooNE Physics Program

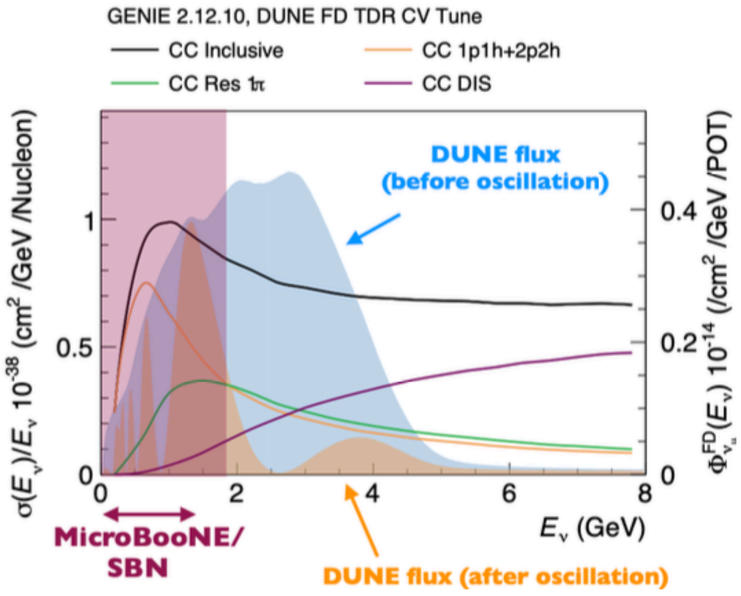
Investigate MiniBooNE Low Energy Excess (LEE) & Search for BSM

Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)


Study $\nu$-Ar scattering using one of the largest $\nu$-Ar data collected to date!

# MicroBooNE Cross Section Program

- One of the largest uncertainties in neutrino oscillation experiments!
- MicroBooNE possesses a **large comprehensive** neutrino-argon interaction dataset
- Probes nuclear effects at the GeV scale across multiple final state topologies
- MicroBooNE aims to support both our BSM program and future LArTPC experiments like DUNE and SBN




## MicroBooNE Cross Sections

### CC inclusive

- 1D $\nu_\mu CC$ inclusive @ BNB : PRL 123 131801 (2019), PRL 128 151801 (2022)
- 1D $\nu_\mu CC$ inclusive @ BNB : PRL 133 041801 (2024), PRD 110 L013006 (2024)
- 1D $\nu_\mu CC$ inclusive @ BNB : arXiv:2307.06413
- 1D $\nu_e CC$ inclusive @ NuMI : PRD 104 052002 (2021), PRD 105 051102 (2022)

### $CC0\pi$

- 1D, 2D $\nu_\mu CC0\pi Np$ @ BNB : PRD 102 112013 (2020), arXiv:2403.19574, arXiv:2507.00921
- 1D $\nu_\mu CC0\pi 1p$ @ BNB : PRL 125 201803 (2020)
- 1D, 2D $\nu_\mu CC0\pi 1p$ TKI @ BNB : PRL 131 101802 (2023), PRD 108 053002 (2023)
- 1D, 2D $\nu_\mu CC0\pi 1p$ GKI @ BNB : PRD 109 092007 (2024)
- 1D, 2D $\nu_\mu CC0\pi 1p$ AKI @ BNB : PRD 111 113007 (2025)
- 1D $\nu_\mu CC0\pi 2p$ @ BNB : arXiv:2211.03734
- 1D $\nu_e CC0\pi Np$ @ BNB : PRD 106 L051102 (2022)

### Pion Production

- 1D $\nu_\mu CC1\pi^0$ @ BNB : PRD 99 091102 (2019), PRD 110 092014 (2024)
- 1D, 2D $\nu_\mu NC1\pi^0$ @ BNB : PRD 107 012004 (2023), PRL 134 161802 (2025)
- 1D $\nu_\mu CC1\pi^\pm$ @ BNB : arXiv:2509.03628
- 1D $\nu_e CC1\pi^\pm$is @ NuMI : arXiv:2503:23384

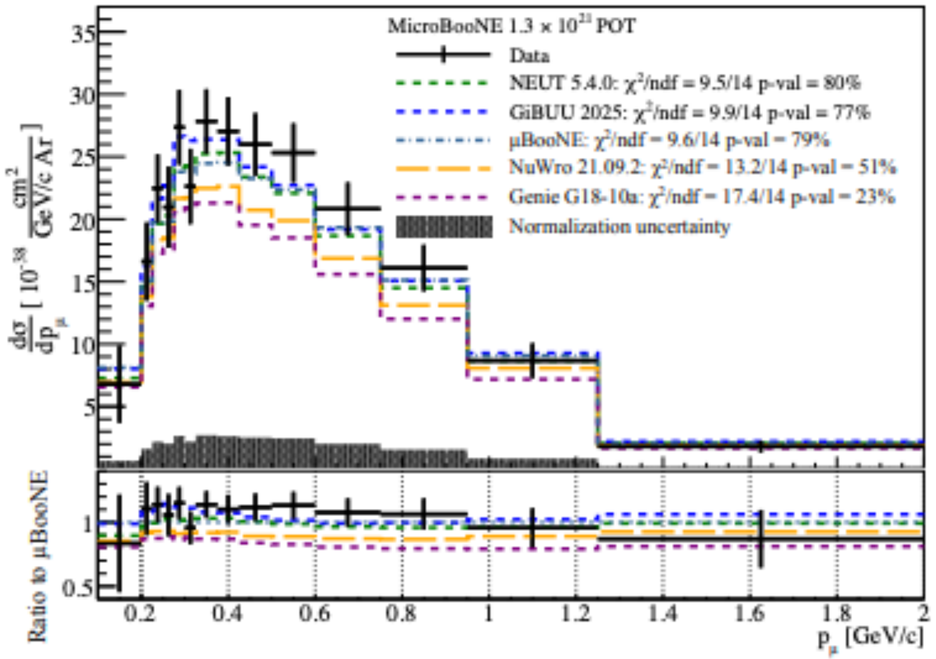
### Rare Channels and novel identification techniques

- $\Lambda$ production @ NuMI : PRL 130 231802 (2023)
- $\eta$ production @ BNB : PRL 132 151801 (2024)
- $K^+$ production @ BNB : arXiv:2503.00291
- Neutron Identification : EPJC 84 1052 (2024)
- Model Validation : PRD 111 092010 (2025)

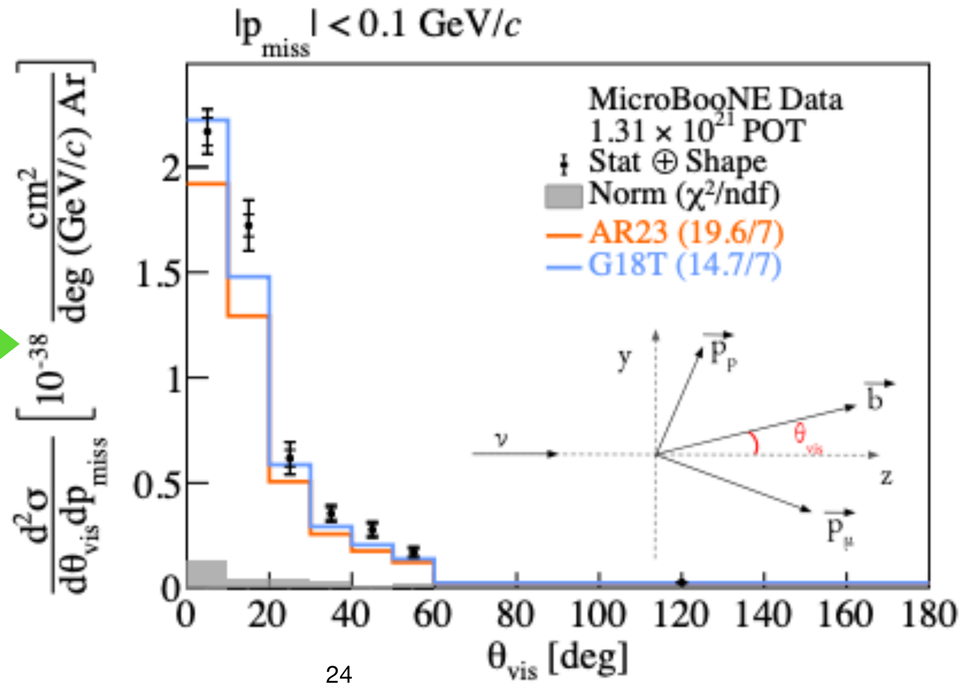
# $\nu_\mu CC$ + 0$\pi$ measurements

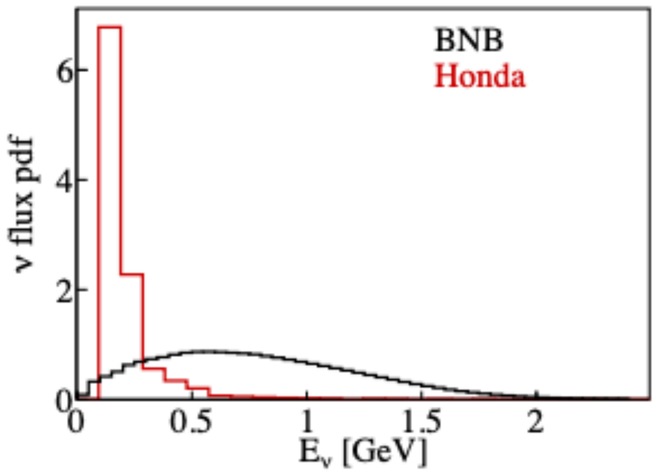
- High statistics $\nu_\mu CC$ pionless measurements: precision probes of nuclear modeling and final state interactions

- $\nu_\mu$**CC0**$\pi$ (arXiv: 2507.00921)
- Full data-set + 1D and 2D measurements
- Sparked joint analysis with ANNIE [on-going], water Cherenkov detector same beam




- $\nu_\mu$**CC0**$\pi$**1p , "AKI"** (Phys. Rev. D 111, 113007 (2025))
- Neutrino direction reconstruction resolution, key for DUNE atmospherics
- Prediction re-weighting to DUNE Honda atmospherics flux
- Angular kinematic imbalance, sensitive to nuclear effects impacting direction determination

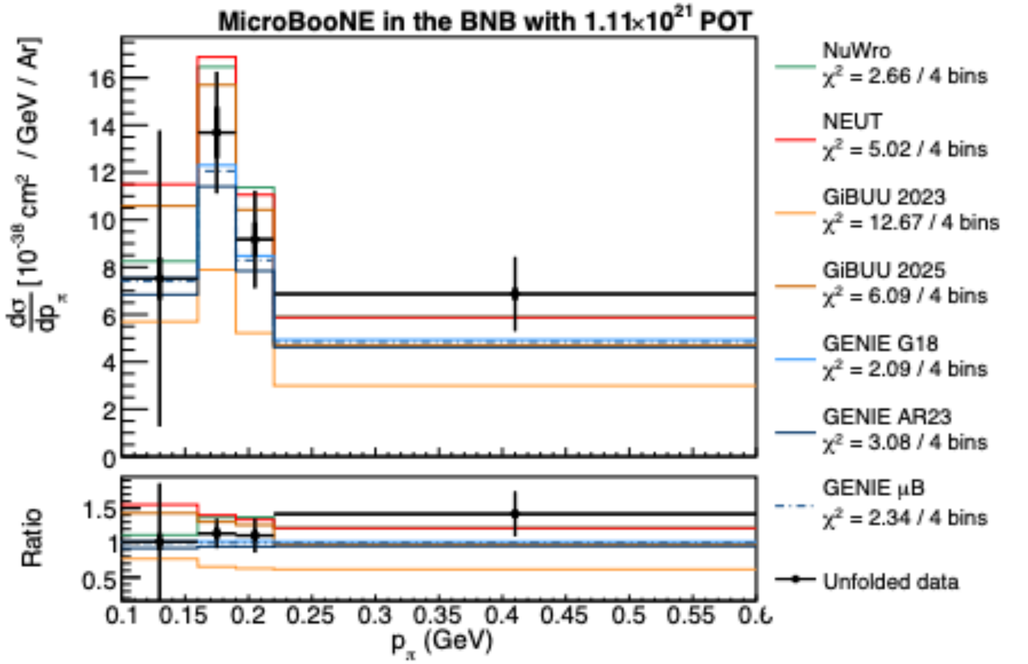


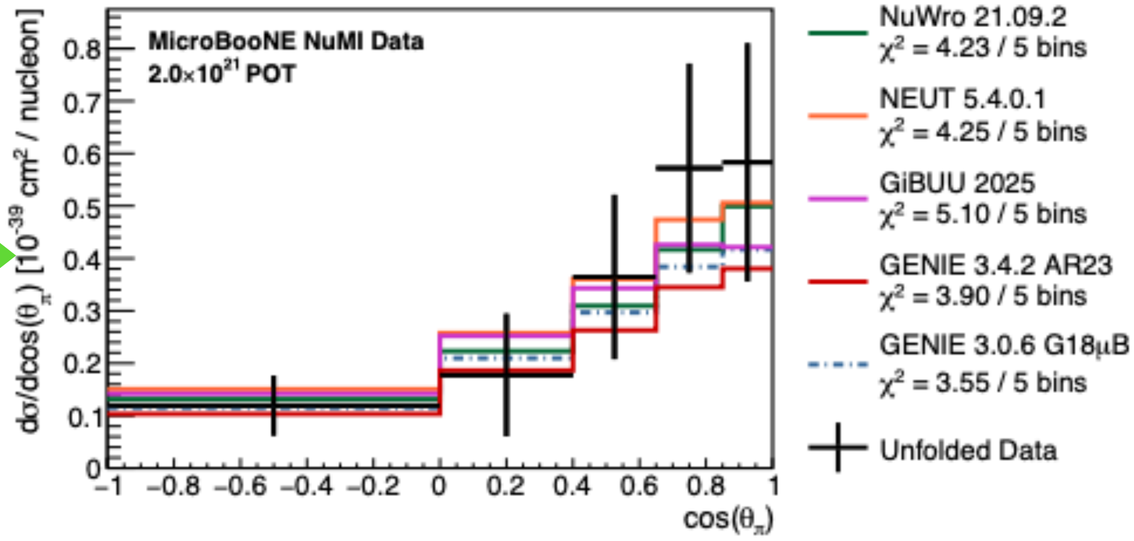
# Measurements with $\pi^{\pm}$

- First measurements of charged-pion production: one of the dominant interaction modes at energy of DUNE

- $\nu_\mu$**CC1**$\pi^{\pm}$ (arXiv:2509.03628)
- Full data-set, first measurement of pion momentum
- Signs of mis-modeling at low $Q^2$ and for high pion momenta driven by final state interactions

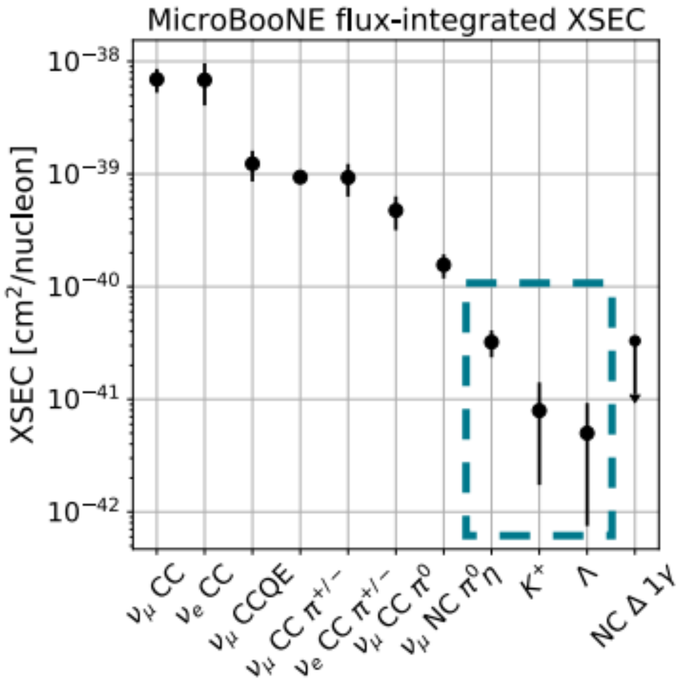


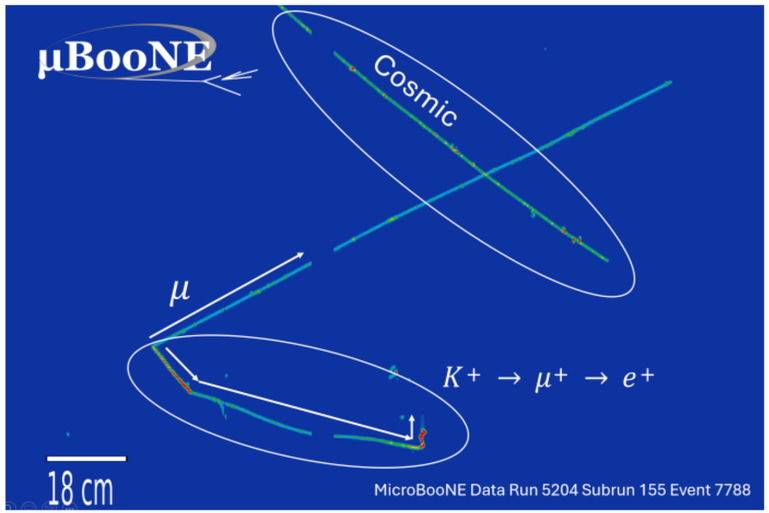

- $\nu_e$**CC1**$\pi^{\pm}$ (Phys. Rev. Lett. 135, 061802 (2025))
- First measurement of $\nu_e CC1\pi^{\pm}$ on argon
- Uses full NuMI dataset, higher $\nu_e$ content
- Good modeling seen within uncertainties

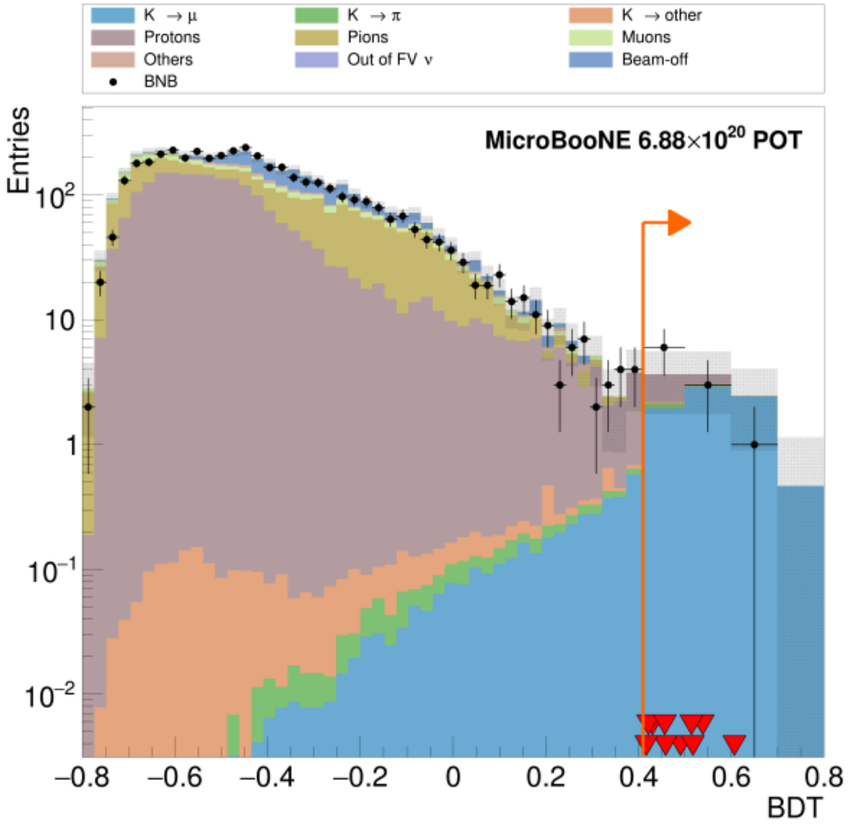


# Rare processes

- Provide insights into higher resonances and help with constraints of key backgrounds for nucleon decay
- Recent measurements: $\nu_\mu CC\Lambda$ (Phys. Rev. Lett. 130, 231802 (2023)) and $\nu_\mu CC\eta$ (Phys. Rev. Lett. 132, 151801 (2024))
- New $\nu_\mu CCK^+$ : first measurement of $K^+$ on argon (arXiv: 2503.00291)
- Background for proton decay $p \rightarrow K^+\nu$ in DUNE



# MicroBooNE Physics Program

Investigate MiniBooNE Low Energy Excess (LEE) & Search for BSM

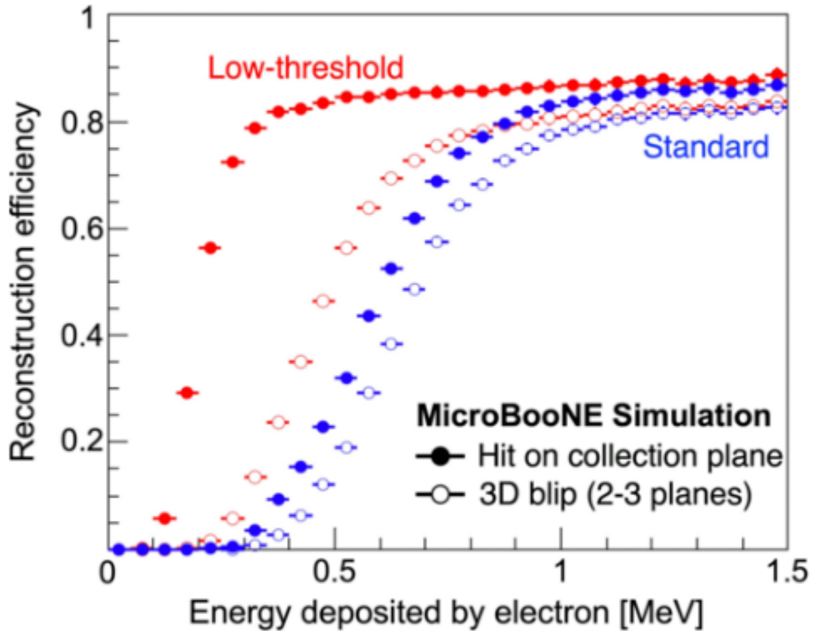
Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)

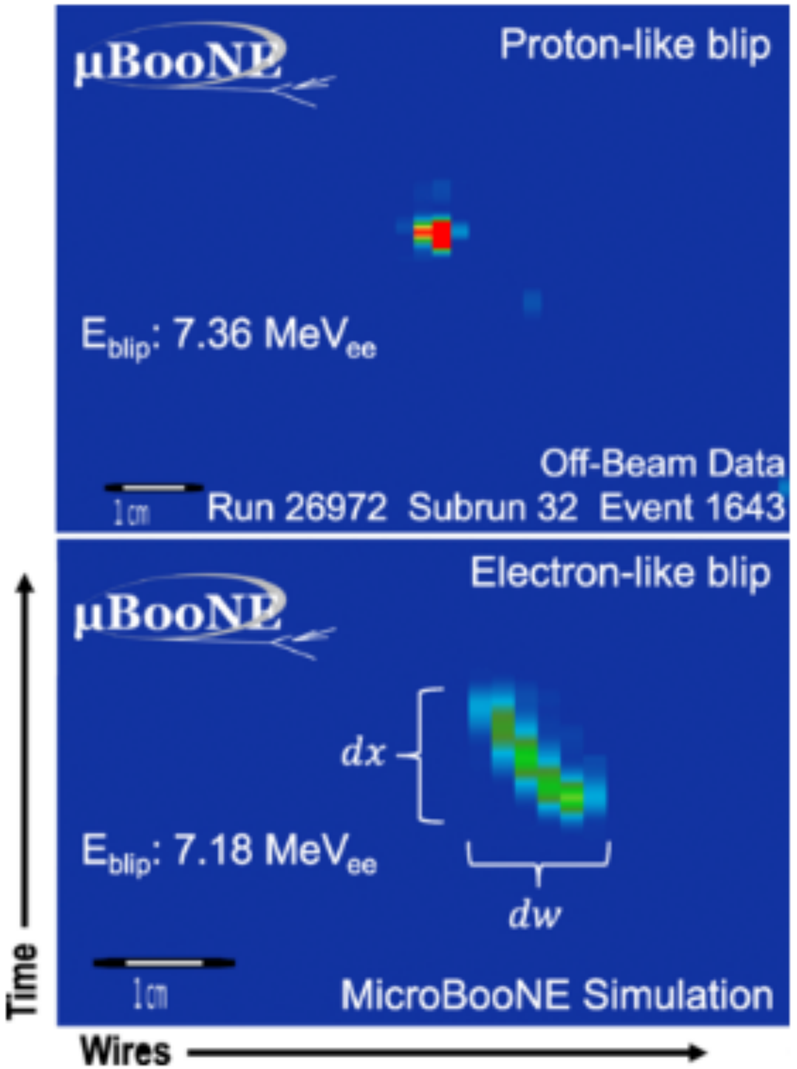

Study $\nu$-Ar scattering using one of the largest $\nu$-Ar data collected to date!

# MeV-scale physics

Phys. Rev. D 109, 052007 (2024)
Phys. Rev. D 111, 032005 (2025)

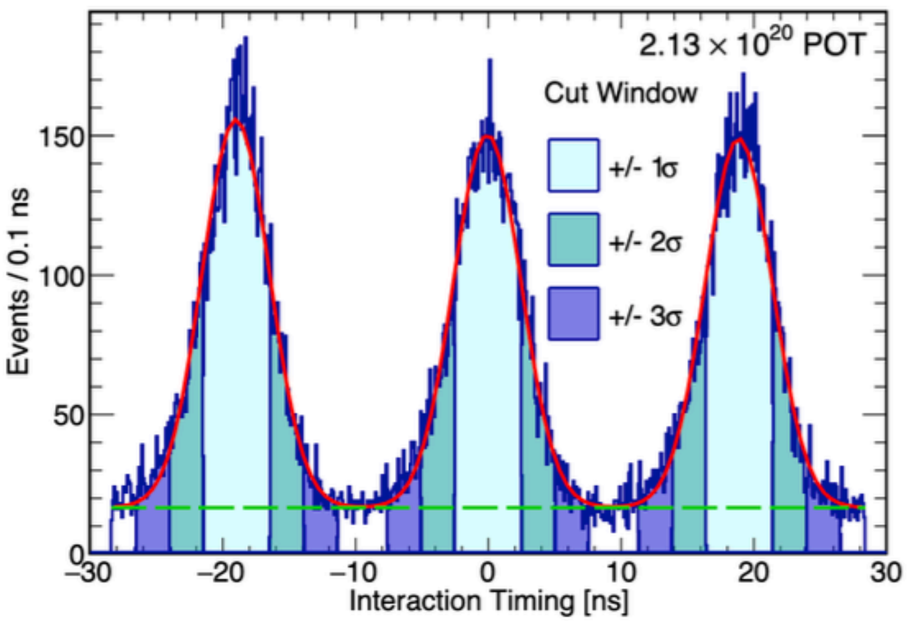
- Techniques to reconstruct “blips” (isolated O(MeV) energy depositions from various sources) pioneered at ArgoNeut ⇒ refined by MicroBooNE
- Achieved 150 keV detection threshold
- Vast range of applications: improved calorimetry, lower particle thresholds, BSM searches, muon/pion separation, neutron tagging, etc.



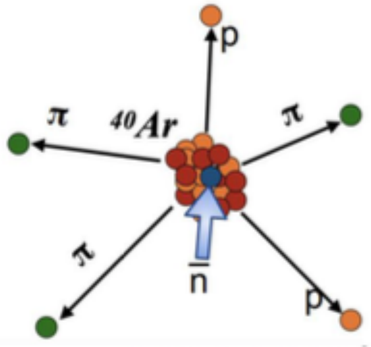



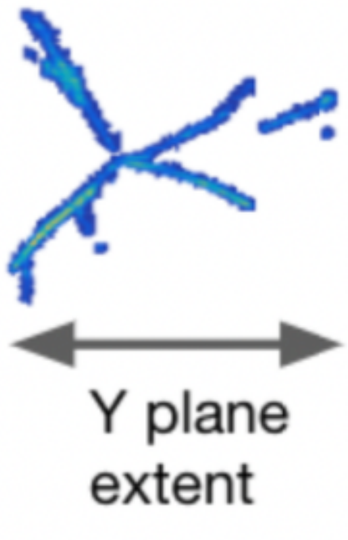
# LArTPC capabilities

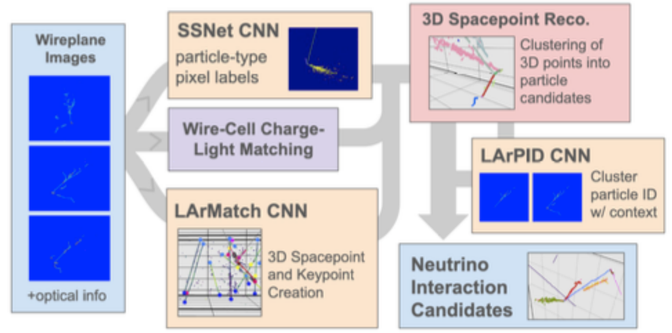
PRD 108 (2023) 5, 052010




JINST (2024) 19 P07032

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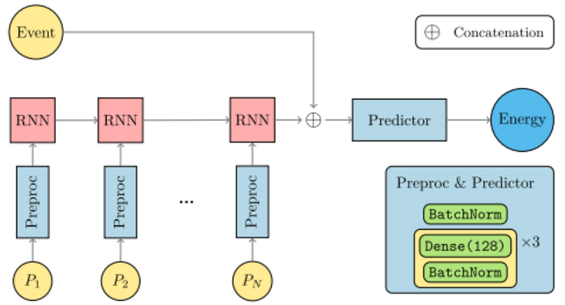



PhysRevD.110.092010

- Use fine-timing from PMTs and beam spill to extract $O(1ns)$-resolution
  - Enables long-lived BSM particle searches, better cosmic rejection
- Demonstrate new LArTPC reconstruction techniques for exotic topologies, deep-learning based methods for 3D reconstruction, neutrino energy estimation etc.

# Summary

- New pionless $\nu_e$ LEE analysis, consistent with past results, disfavors a $\nu_e$-like MiniBooNE LEE, pointing to $\gamma/e^+e^-$ sources
- No evidence of BSM $\mathbf{e^+e^-}$ signal observed
- $NC\Delta \rightarrow N\gamma$ and coherent single-$\gamma$ analyses observed no excess
- Inclusive single-$\gamma$ search shows a $2\sigma$ excess in the region with low hadronic activity and below 600 MeV shower energy
  - Further study, including adding remainder of MicroBooNE's dataset, are planned
- New results on Higgs Portal, HNLs, and Dark tridents
- Upcoming 3+1 light sterile neutrino search with unique two-beam approach
- Wealth of neutrino-argon cross section measurements have been carried out
  - Important inputs for oscillation experiments
- Significant advancements in detector technology, with valuable implications for DUNE and our future analysis




# Thank you!

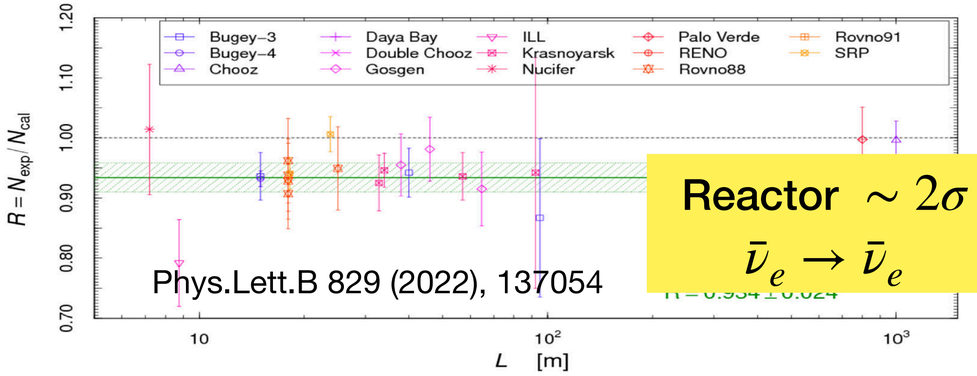
Brookhaven National Laboratory

µBooNE

# Back up

# Short-Baseline Anomalies

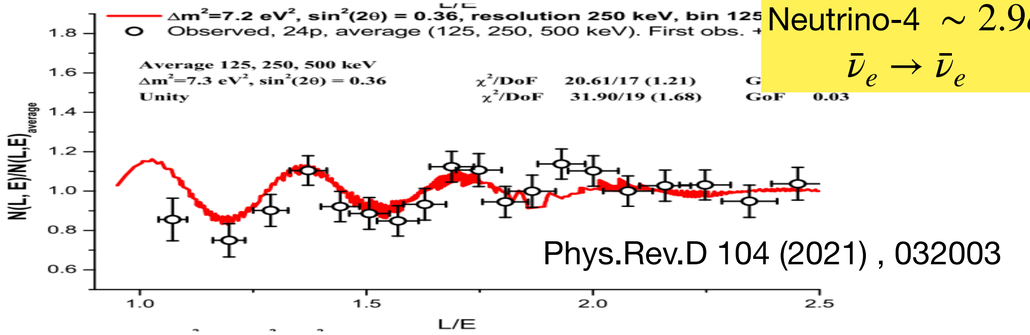
- ☑ **Reactor Neutrino Flux** → Initially found issue of theory by Daya Bay experiment / Resolved with new input data to flux calculation
- ☐ **Neutrino-4 Reactor Spectra** → In tension with other VSBL reactor $\nu$ experiments
- ☐ **The Gallium Anomaly** → BEST observed similar results
- ☐ **The LSND Anomaly** → JSNS² will perform direct test
- ☐ **MiniBooNE LEE** → Tested with MicroBooNE




Phys.Lett.B 829 (2022), 137054

Reactor $\sim 2\sigma$

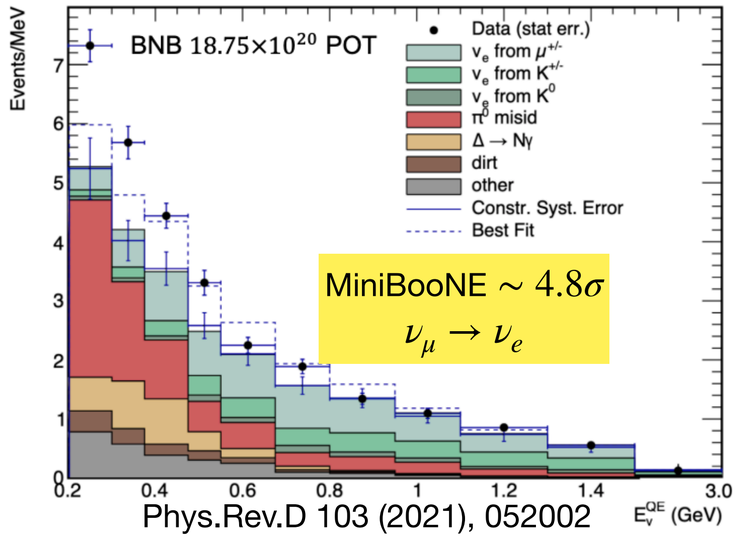
$\bar{\nu}_e \to \bar{\nu}_e$




Neutrino-4 $\sim 2.9\sigma$

$\bar{\nu}_e \to \bar{\nu}_e$

Phys.Rev.D 104 (2021) , 032003

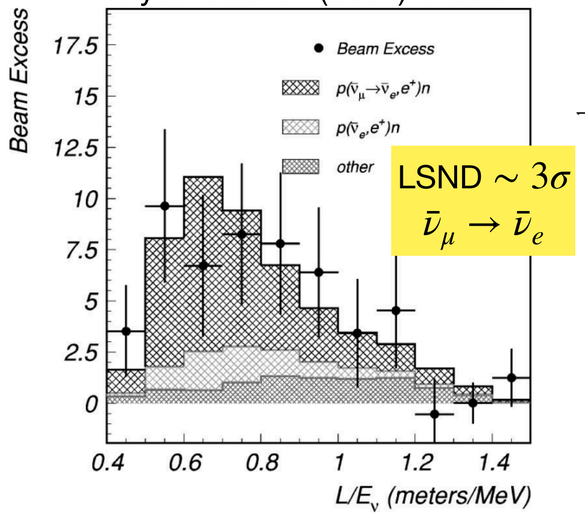



MiniBooNE $\sim 4.8\sigma$

$\nu_\mu \to \nu_e$

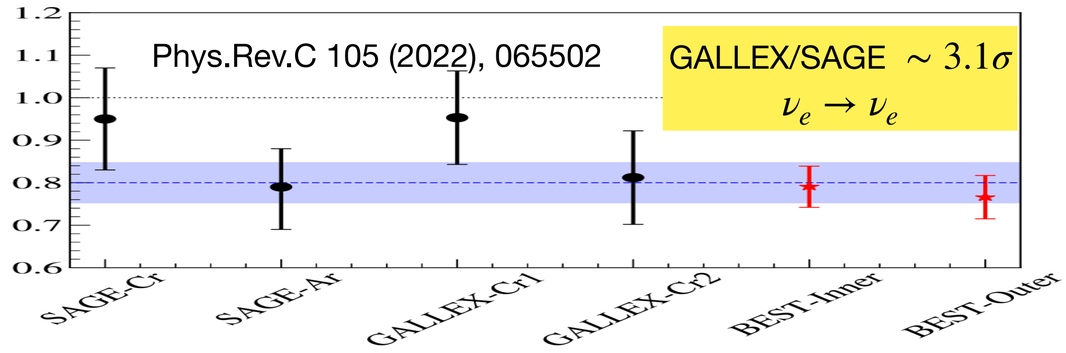
Phys.Rev.D 103 (2021), 052002

Phys.Rev.D 64 (2001) 112007




LSND $\sim 3\sigma$

$\bar{\nu}_\mu \to \bar{\nu}_e$



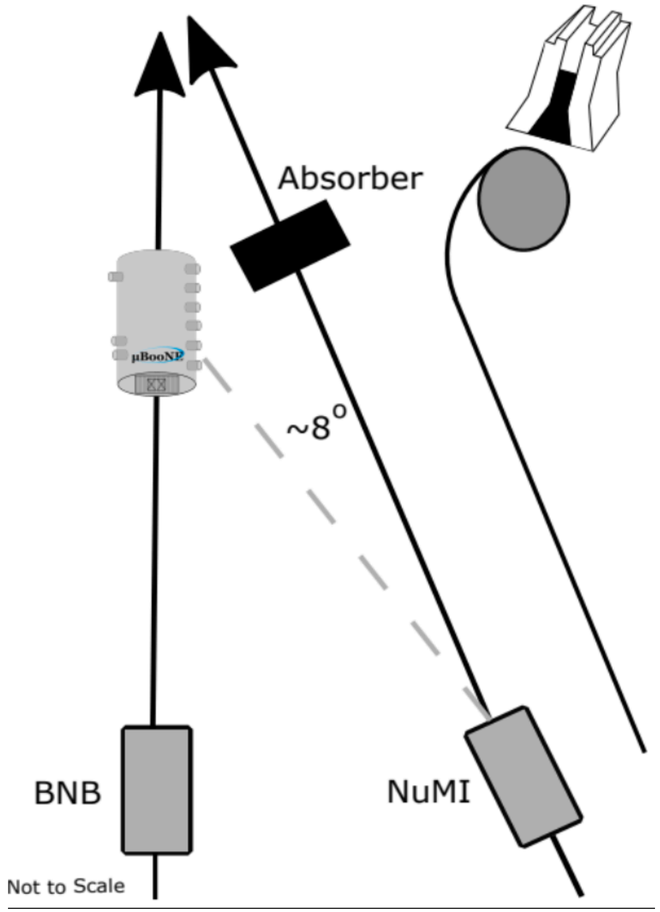

Phys.Rev.C 105 (2022), 065502

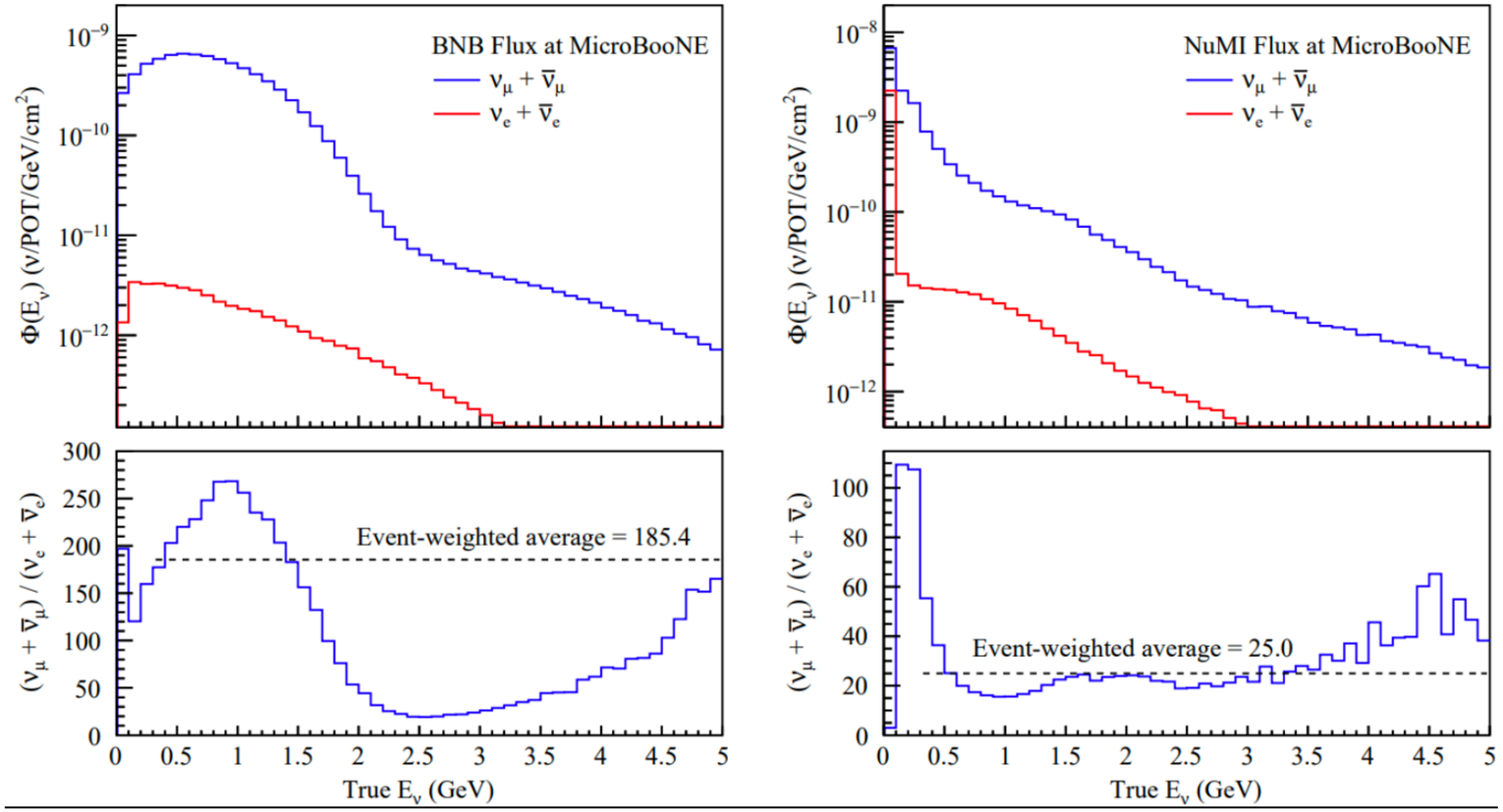
GALLEX/SAGE $\sim 3.1\sigma$

$\nu_e \to \nu_e$

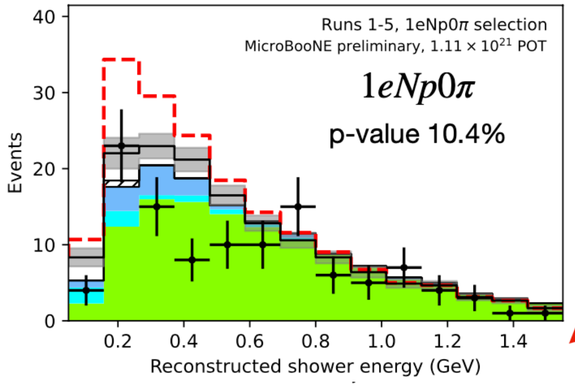
# BNB/NuMI fluxes

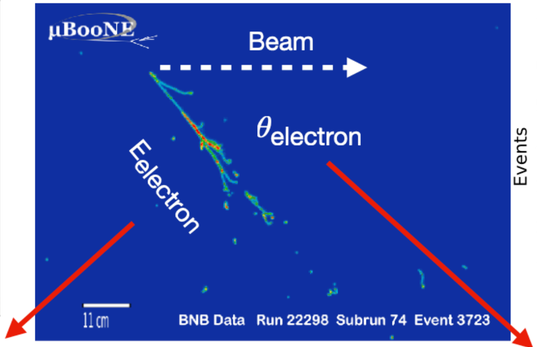
Phys. Rev. Lett. 130, 011801 (2023)

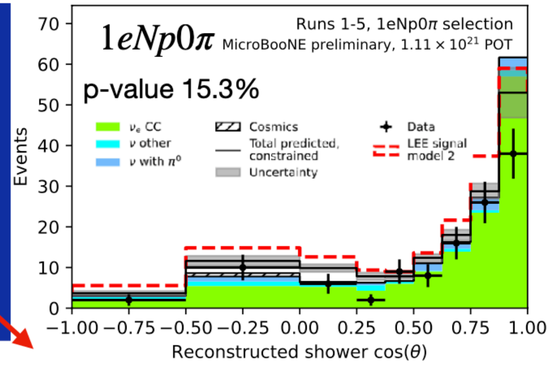


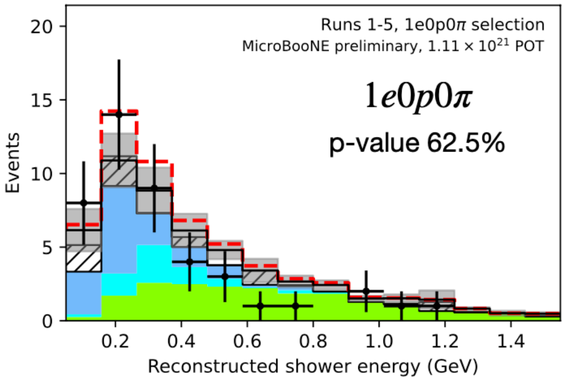



# $\nu_e$ - like LEE Search New



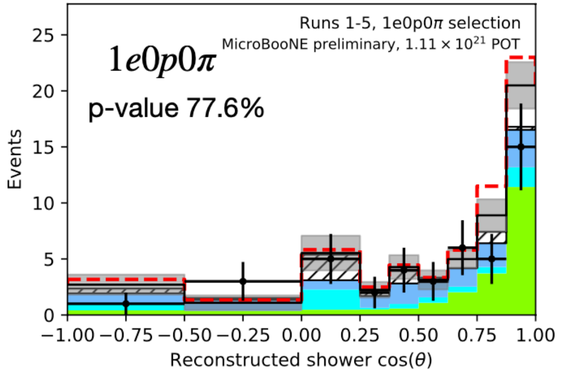



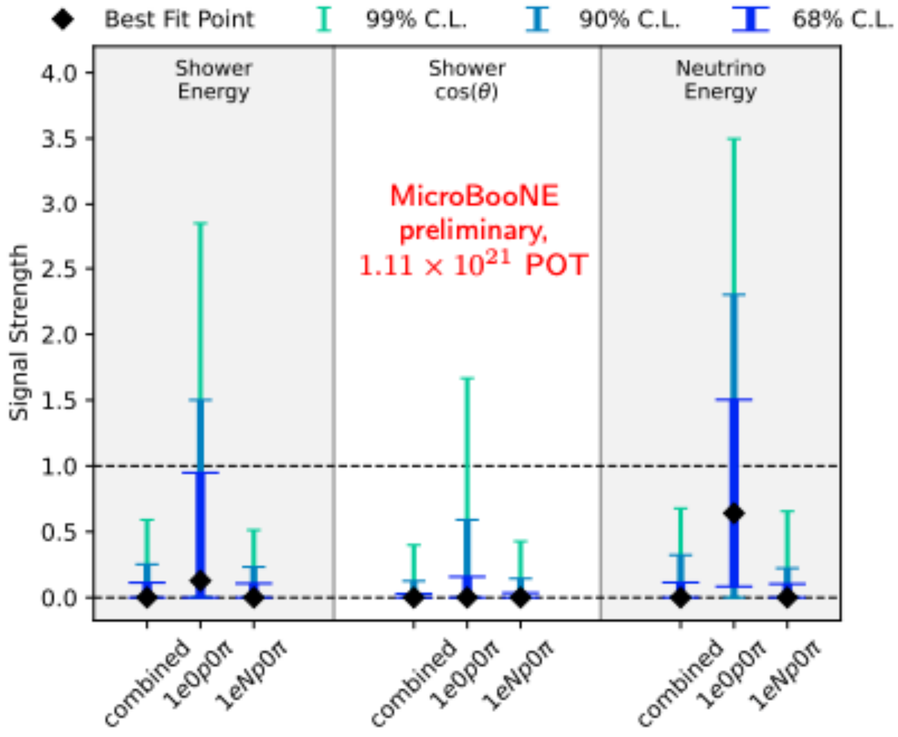




Shower kinematics-based model:

combined Np & 0p channels:

exclude model at > 99.9% CL

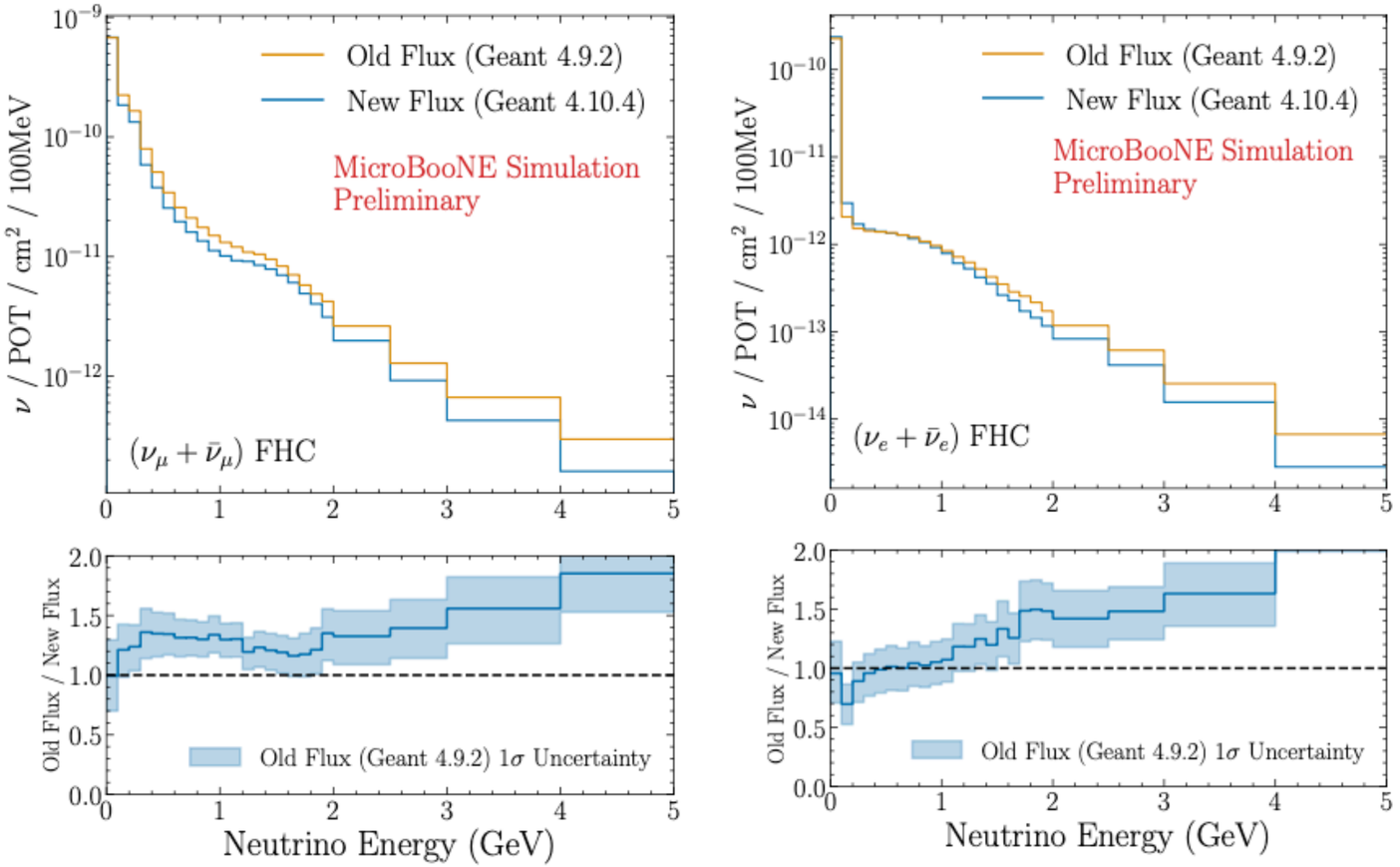


# 3+1 Oscillation Analysis : Updated NuMI Flux

- MicroBooNE sits highly off-axis ( $\sim 8^0$ degrees) to the NuMI beam:
  - flux dominated by hadron re-interactions with target hall material
  - phase space for hadron production not fully covered by world data
- Flux simulation upgrade:
  - Beam line geometry
  - Updated to a modern G4 version (4.10) for a better base model
  - Constraints from NA49 and others similar to NOvA, MINERvA
  - Conservative treatment of uncertainties outside data coverage

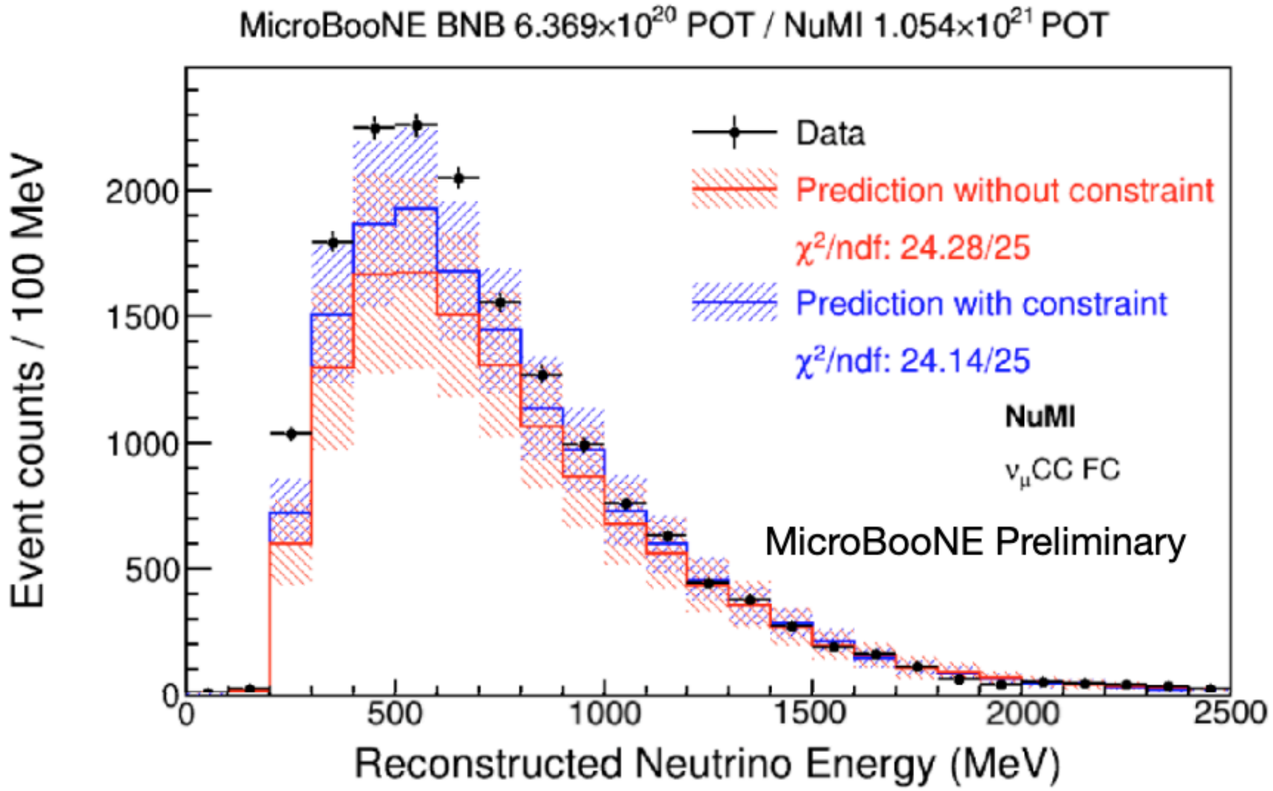
MICROBOONE-NOTE-1129-PUB



# 3+1 Oscillation Analysis : Updated NuMI Flux

MICROBOONE-NOTE-1132-PUB

- MicroBooNE's updated NuMI flux prediction vs. $\nu_\mu$ data
- Good data/MC agreement. Blue histogram shows NuMI $\nu_\mu$ prediction constrained by BNB $\nu_\mu$ which largely cancels out cross section and detector systematics.



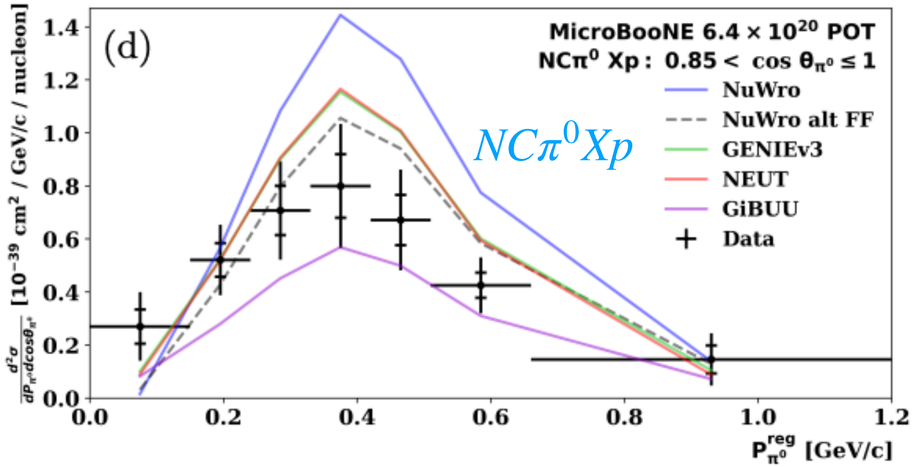
# Measurements with $\pi^0$

- Significant role in $\nu_e$ appearance studies
- $\pi^0$ events are the dominant background for single photon and BSM $e^+e^-$ searches

## $NC\pi^0Xp$

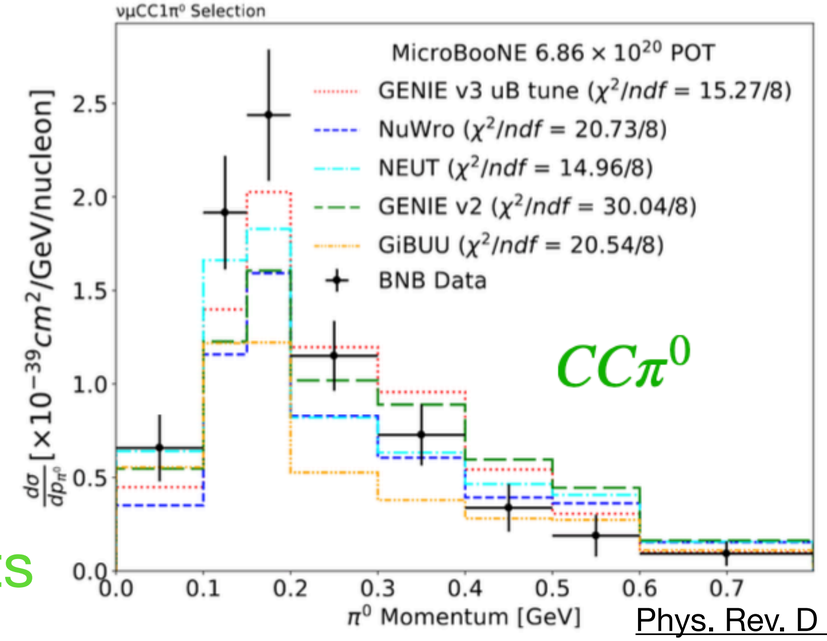
- First Double Differential cross section in $cos\theta_{\pi^0}$ and $P_{\pi^0}$ **simultaneously**
- Systematic over-prediction when compared to data
- Demonstrated sensitivity to form factor modeling and hadron reinteractions

arXiv:2404.10948




## $CC\pi^0$

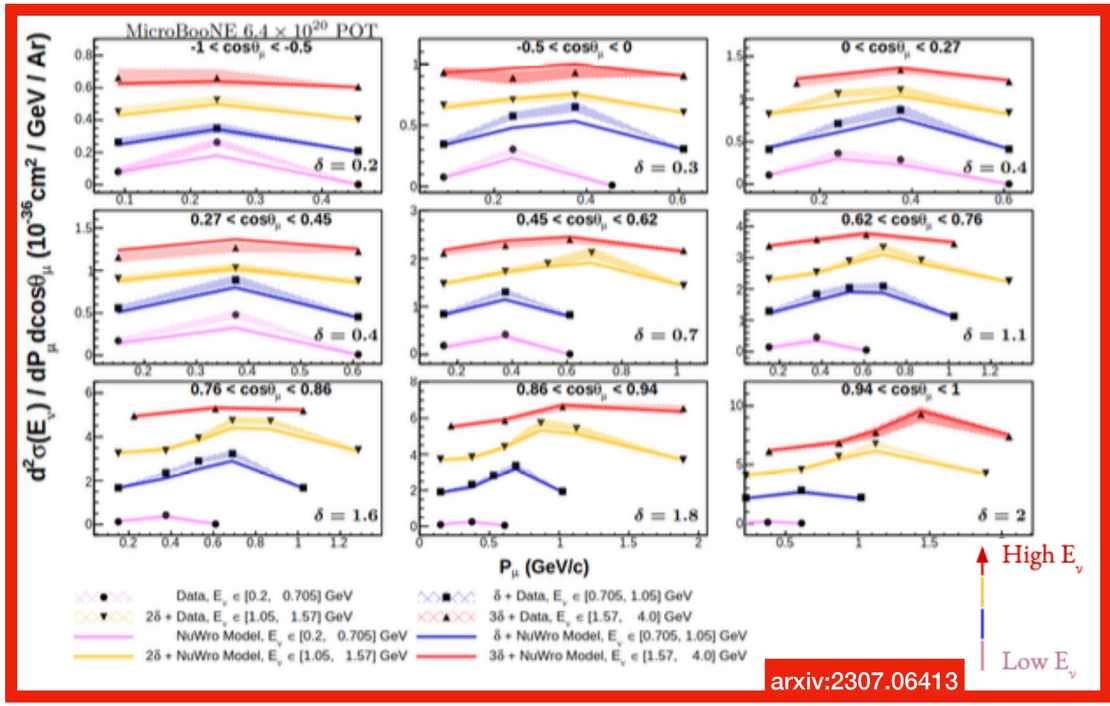
- Detailed description over $\pi^0$ kinematics
- Mismodeling identified in $\pi^0$ momentum and muon forward angles
- Shortcomings associated with low momentum transfer, consistent with observations on other targets

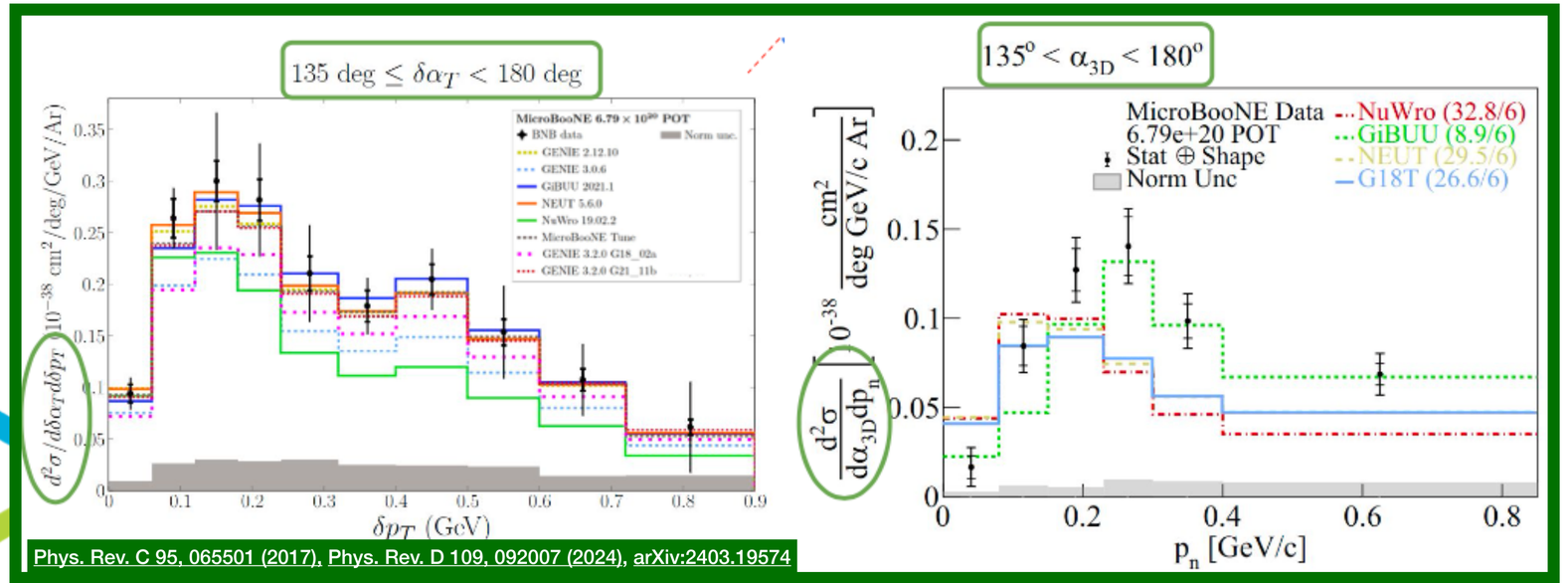



Phys. Rev. D 110, 092014

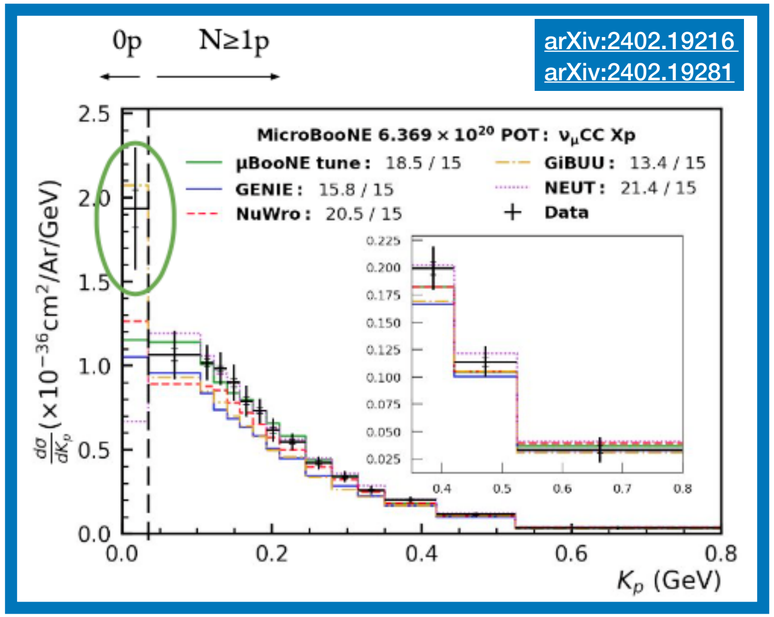
# Inclusive $\nu_\mu CC + 0\pi$

- First 3D cross-section result on argon $\sigma(E_\nu, P_\mu, cos\theta_\mu)$ -> New paradigm of cross sections as a function of the neutrino energy
- Pioneered data-driven model validation techniques! [arXiv:2411.03280]
- Leveraging low proton detection threshold to investigate $0p/Np$ topologies [**Important for single-$\gamma$ analysis!**]
- Measurement in kinematic imbalance variables (missing momentum etc.) to get sensitive probe into final-state interactions and other nuclear effects
- Achieving significant model discrimination power -> Will inform next generation improvements in interaction model



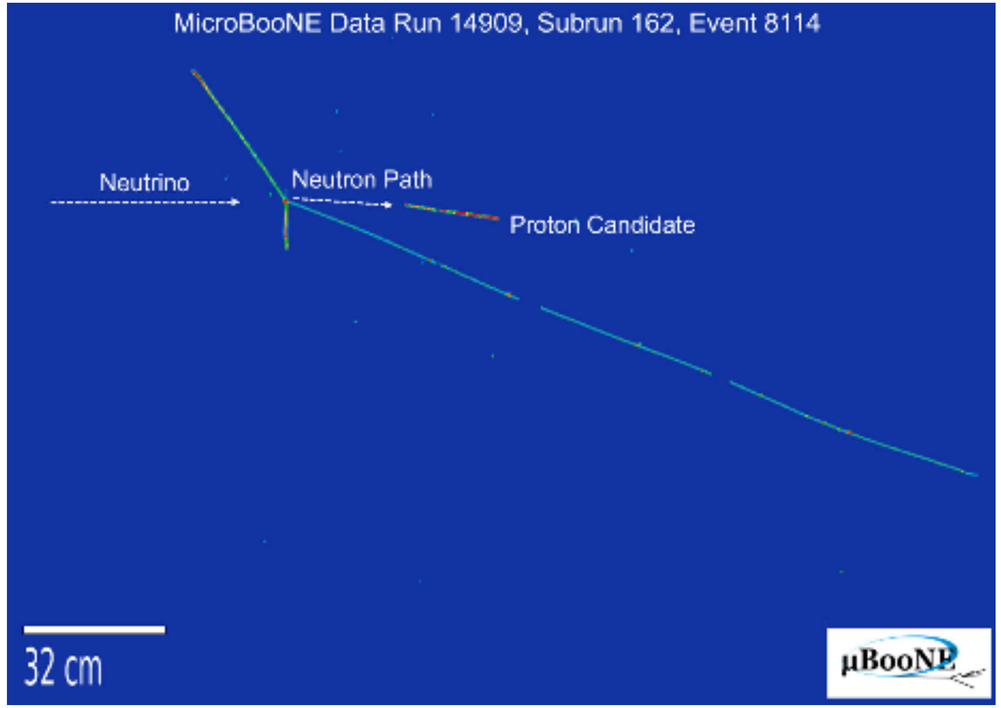



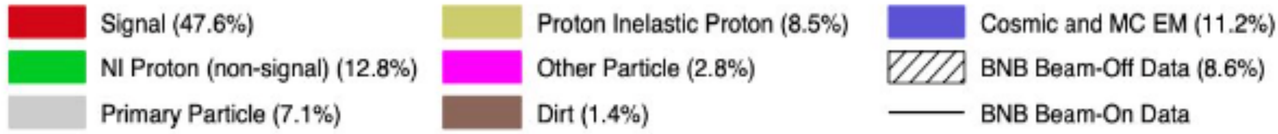

Phys. Rev. C 95, 065501 (2017), Phys. Rev. D 109, 092007 (2024), arXiv:2403.19574



# Neutron identification

- Significant source of missing energy in neutrino interactions
- Infer existence of neutron through interaction producing proton knockout

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