# Recent Results from MicroBooNE's Search

*for a Low-Energy-Excess Anomaly under the Electron Hypothesis and additional BSM Studies*

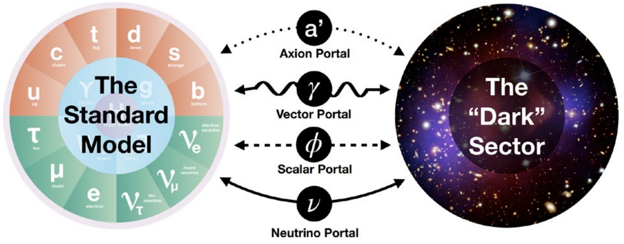

**Xiangpan Ji (Nankai University)**

*On behalf of the MicroBooNE Collaboration*


**TAUP 2025, August 25, Xichang**

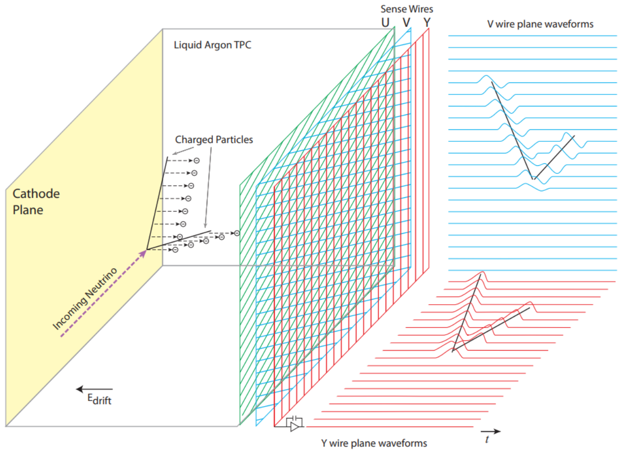
# MicroBooNE Scientific Goals

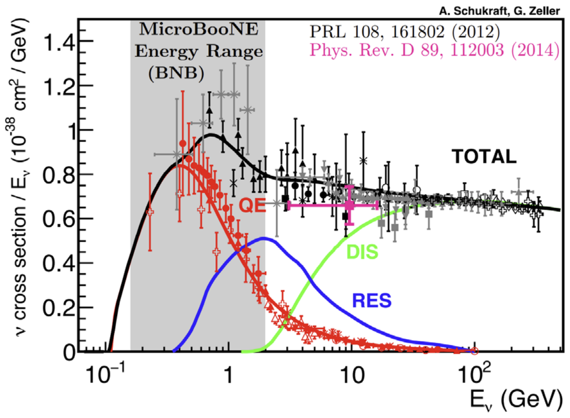
**Investigate MiniBooNE Low Energy Excess**
**Search for BSM physics**




**LArTPC hardware & software R&D**

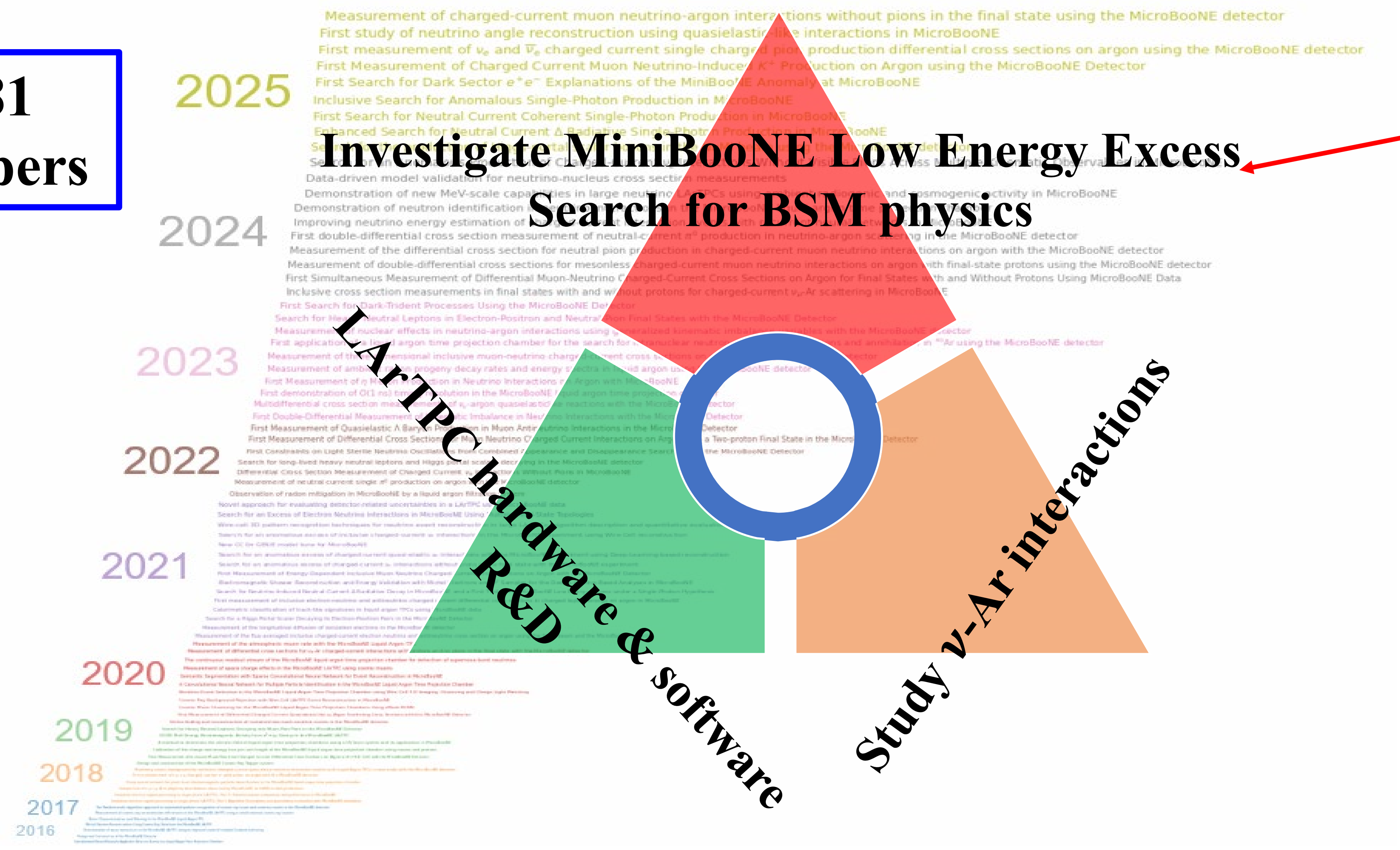
**Study ν-Ar interactions**



# MicroBooNE Scientific Goals

**81 papers**




**My talk today**

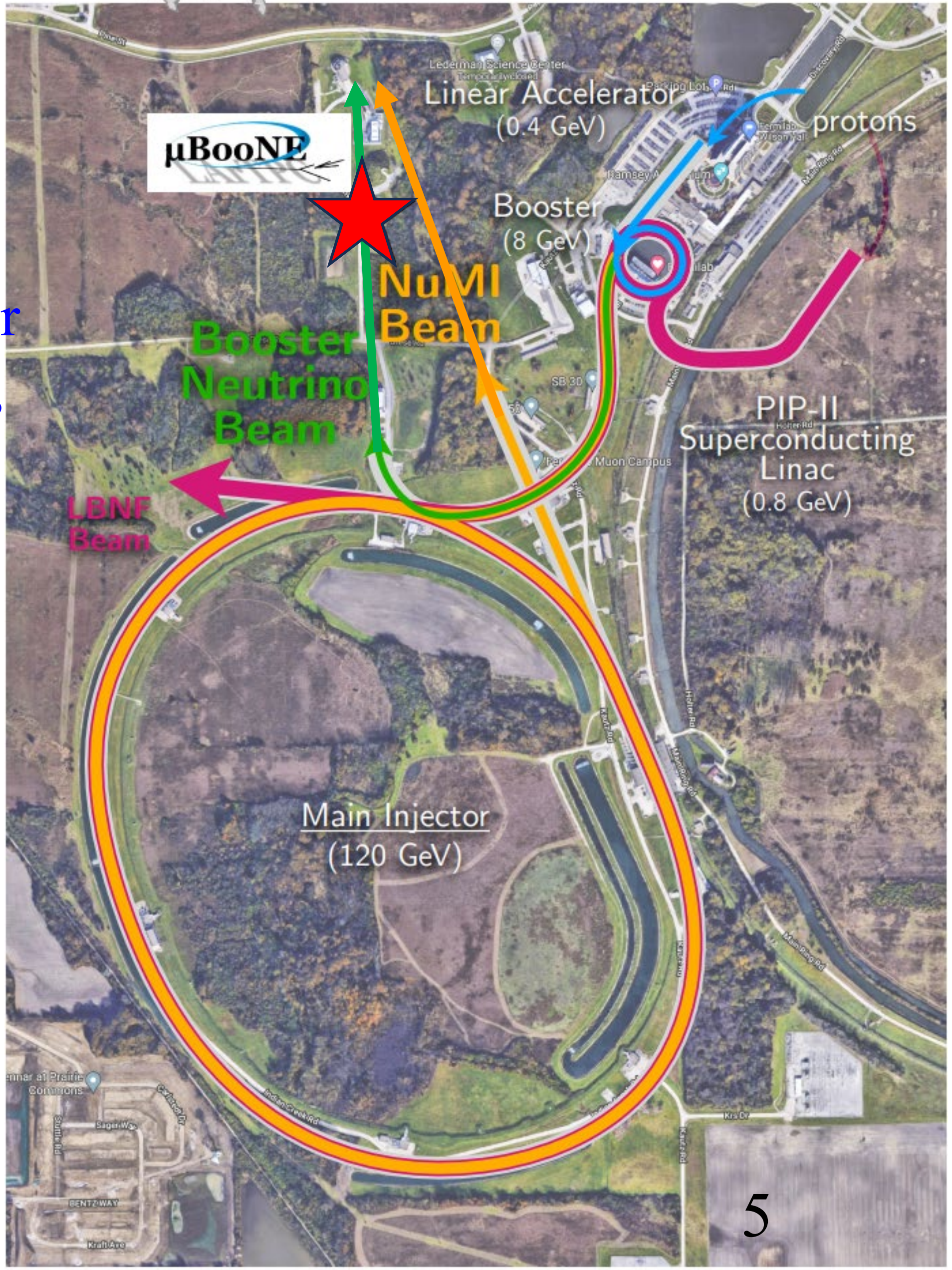

# the Micro Booster Neutrino Experiment (MicroBooNE)

*185 Collaborators*
*from 41 Institutions*

# MicroBooNE


- Located at Fermilab
- Sureface-level LArTPC detector
- 85 ton active liquid Argon mass
- Took data: 2015-2021
- Decommissioned now

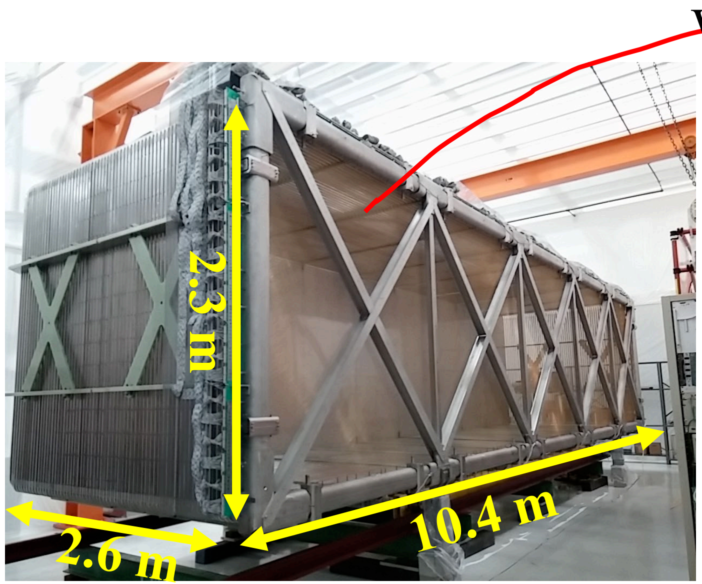
Fermilab

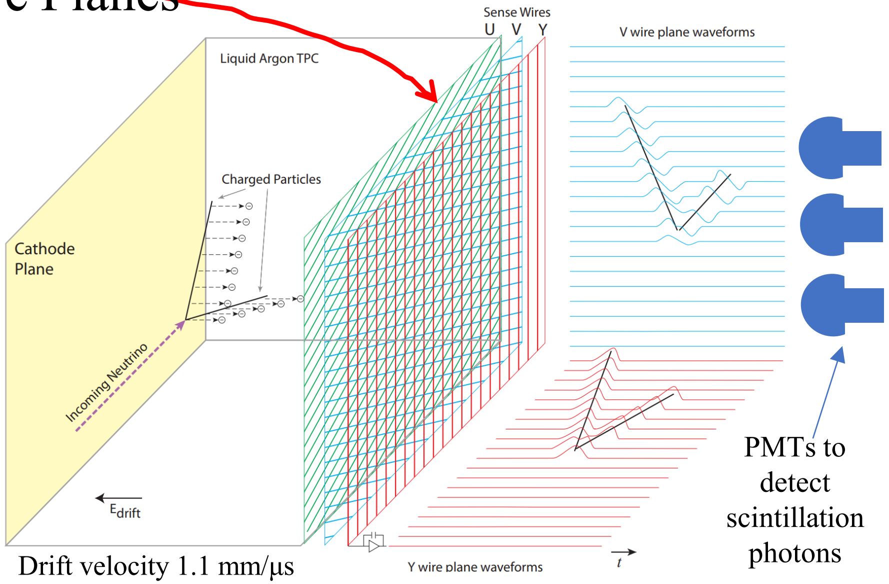



## Two Neutrino Beams

| On-axis beam: BNB | Off-axis ($8^o$) beam: NuMI |
|---|---|
| 8 GeV protons | 120 GeV protons |
| 470 meter baseline | ~680 meter baseline |
| 0.8 GeV mean neutrino E | 1.5 GeV mean neutrino E |
| Collected ~0.5M neutrino events | ~0.3M neutrino events |

# Liquid Argon Time Projection Chamber (LArTPC)





**Full-Active Tracking Calorimeter**

- mm-level position resolution
- MeV-level detection energy threshold
- ns-scale neutrino interaction time resolution
- 3D reconstruction of position

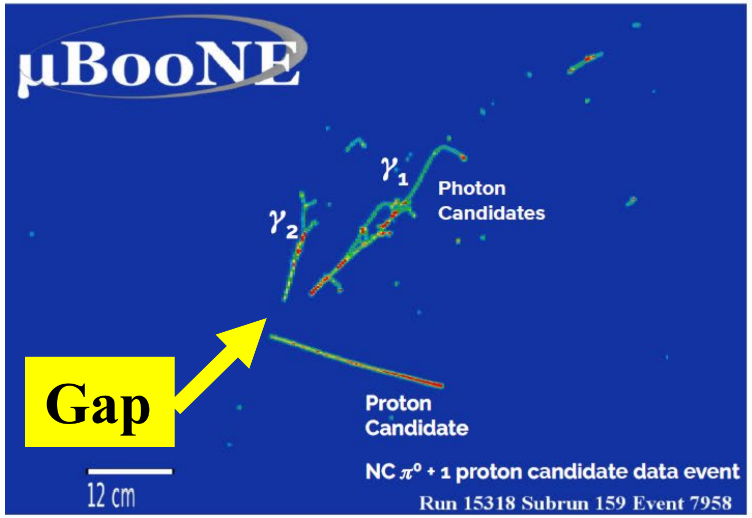
**Excellent Particle Identification**

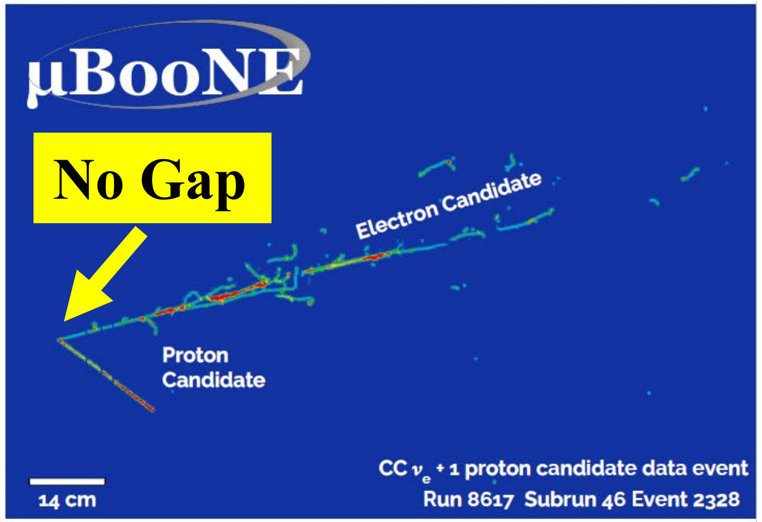
- Final states topological and calorimetric
- Track and shower identification
- Electron and photon shower separation
- Distinguish muons, protons, pions

https://microboone.fnal.gov/documents-publications/

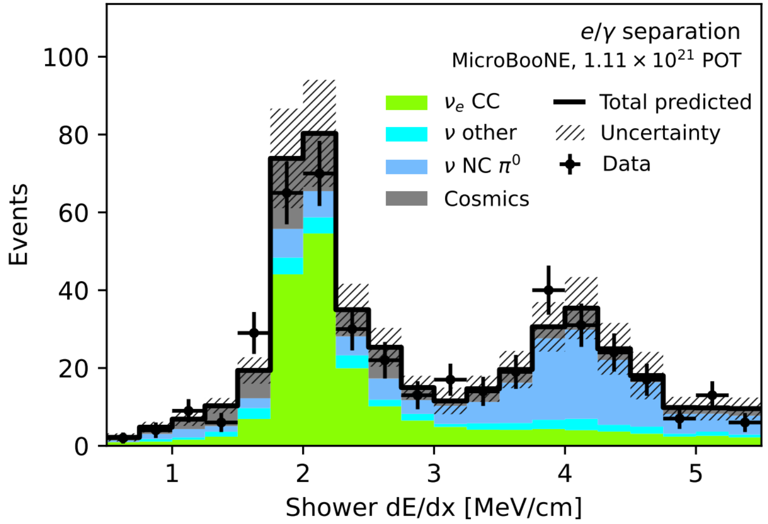
# Electron and Photon shower Separation

**Gap between shower start point and ν vertex**




**Electron 1-MIP vs. photon 2-MIPs**




## Full-Active Tracking Calorimeter

- mm-level position resolution
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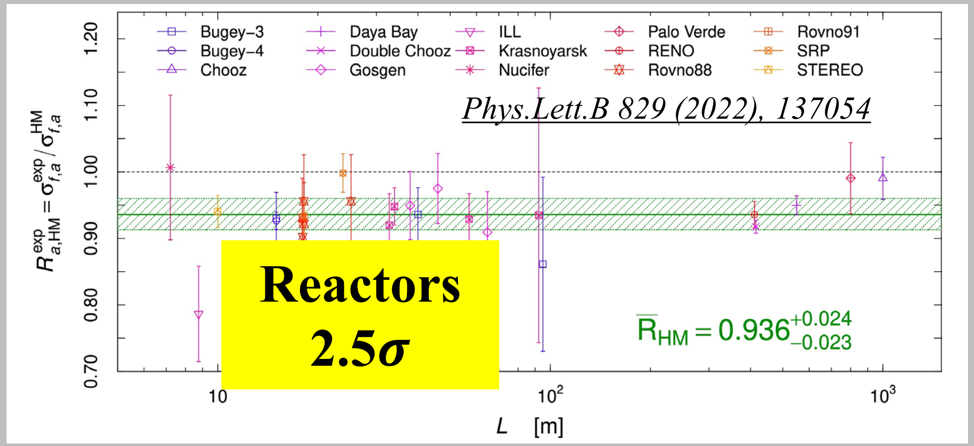
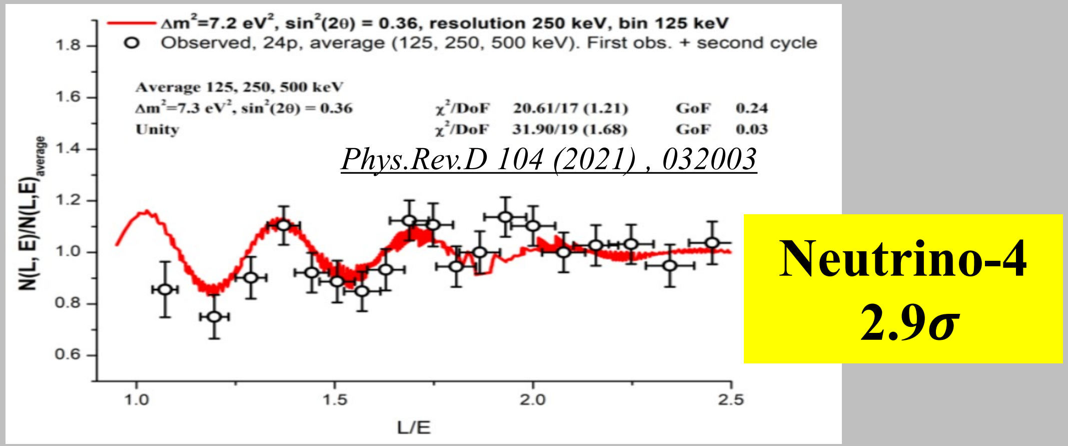
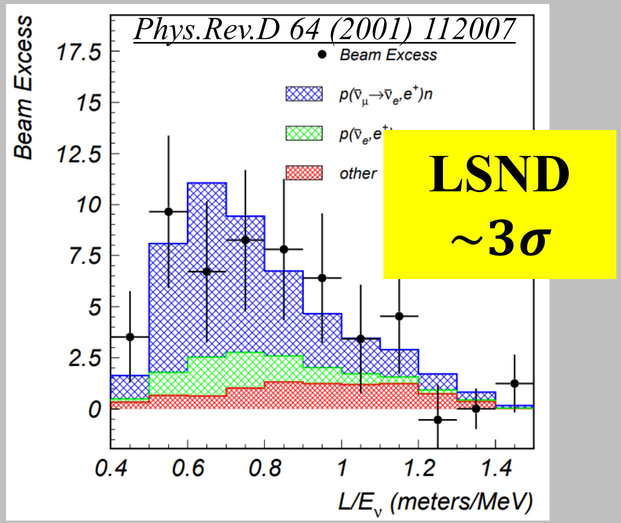
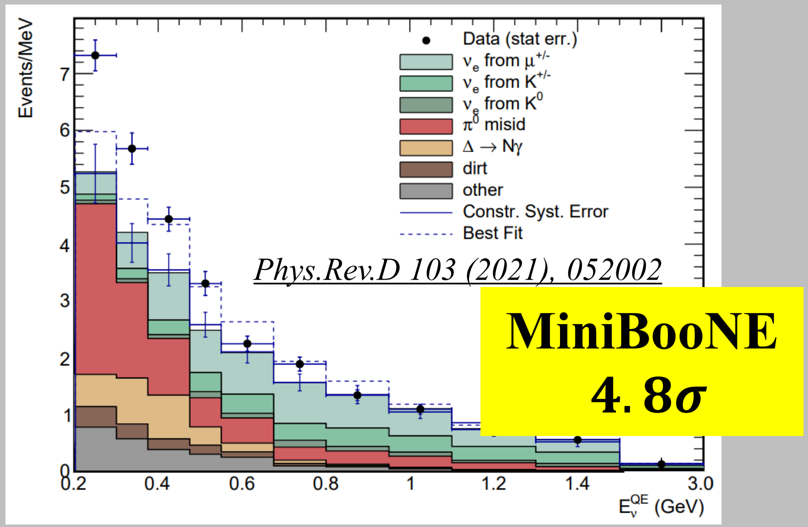
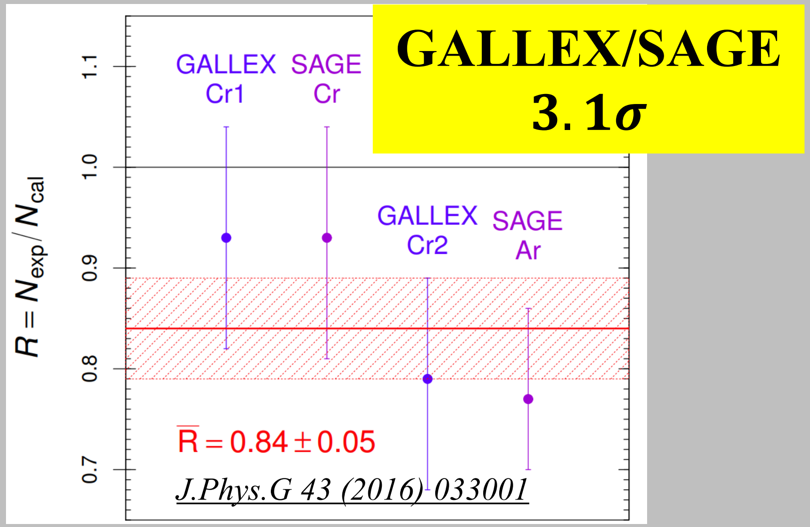


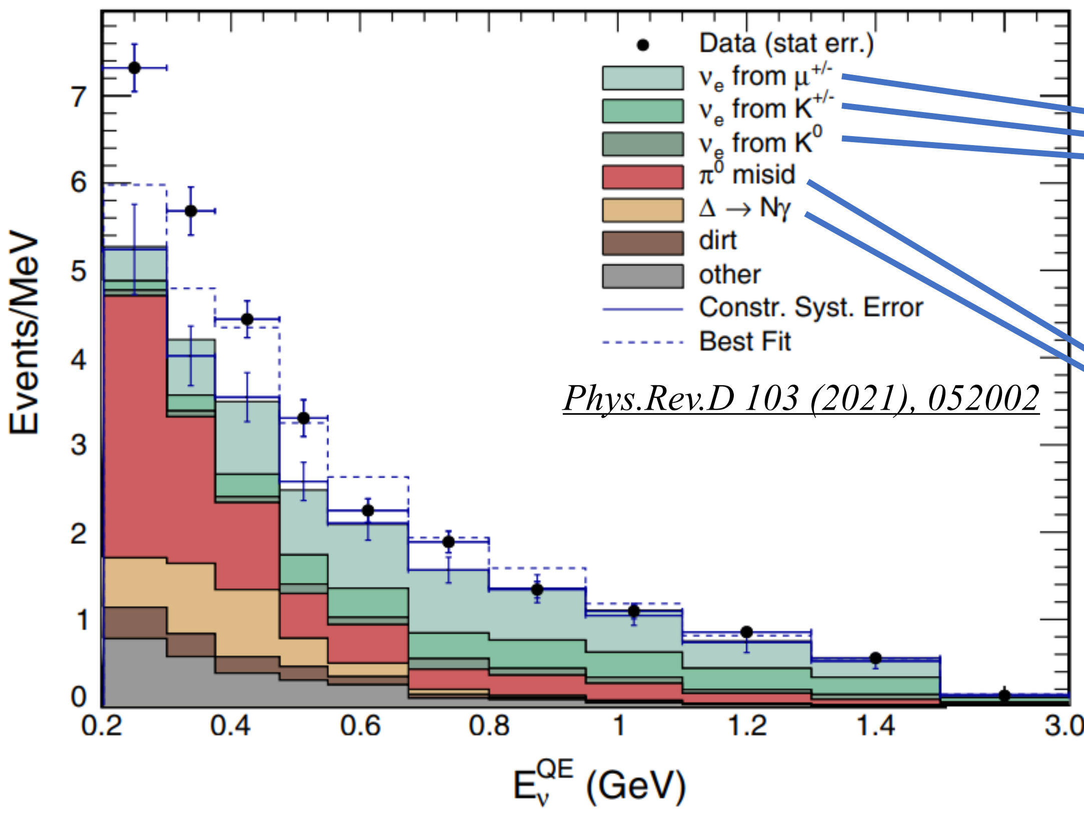




# Short-Baseline Neutrino Anomalies

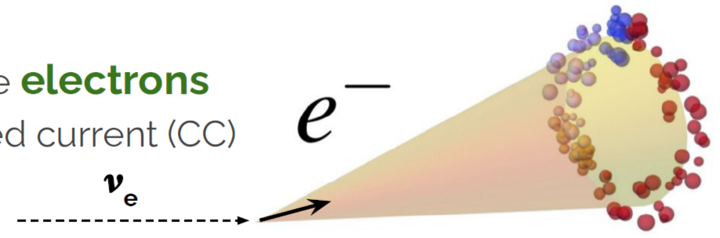
## -- Hints of eV-Scale Neutrinos

# MiniBooNE Anomaly: Low Energy Excess (LEE) eLEE or gLEE

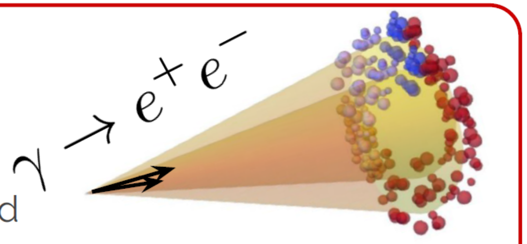



**MiniBooNE (2002-2019) observed the LEE of electromagnetic events with 4.8σ significance.**

It detected $\nu_e$ by the **electrons** produced in charged current (CC) interactions.




However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

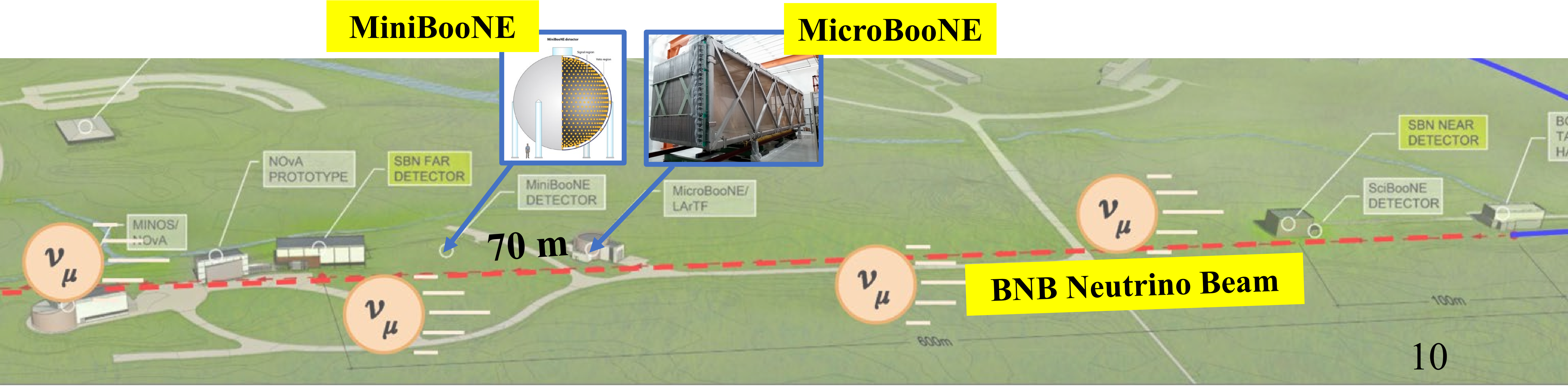



**MiniBooNE Cherenkov detector unable to distinguish photons and electrons, and unable to detect hadronic final-state particles below Cherenkov threshold.**

# MicroBooNE: eLEE Investigation

- First round results, data taken between 2016.2 – 2018.6 ***Phys. Rev. Lett. 128, 241801 (2022)***
  - $\nu_e$CC final states analysed: (1) 1e1p, (2) 1eNp0π and 1e0p0π, (3) inclusive 1eX
  - (1)(2)(3) with different reconstruction techniques

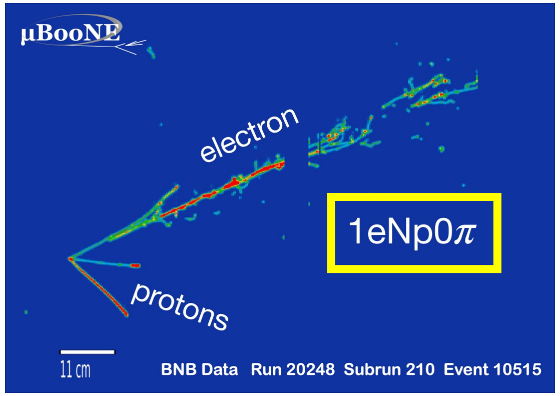
- Latest results, full five-year operation dataset 2016 – 2020 ***Phys. Rev. Lett. 135, 081802 (2025) 08/21/2025***
  - $\nu_e$CC final states analysed: 1eNp0π and 1e0p0π
  - Multiple LEE models tested: neutrino energy, shower kinematics

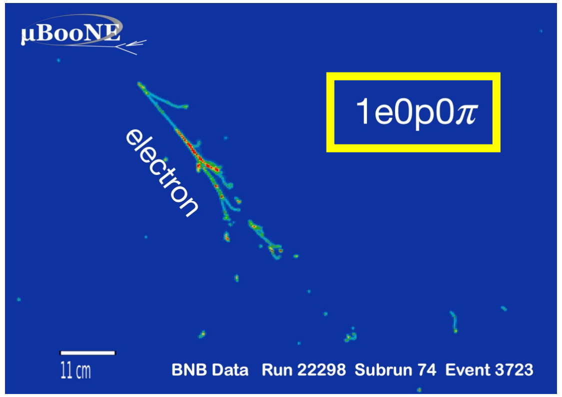


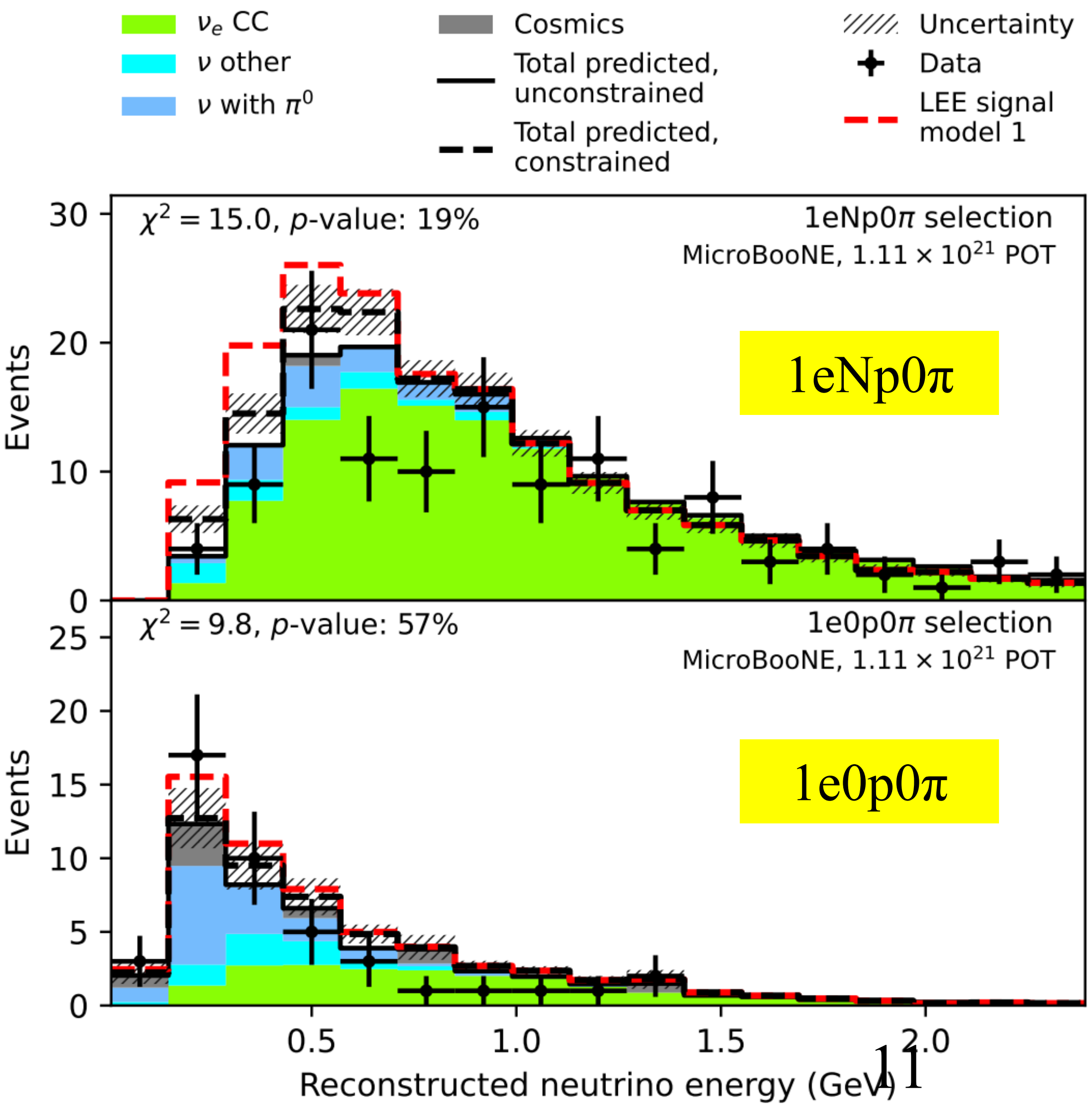
# MicroBooNE: eLEE Investigation

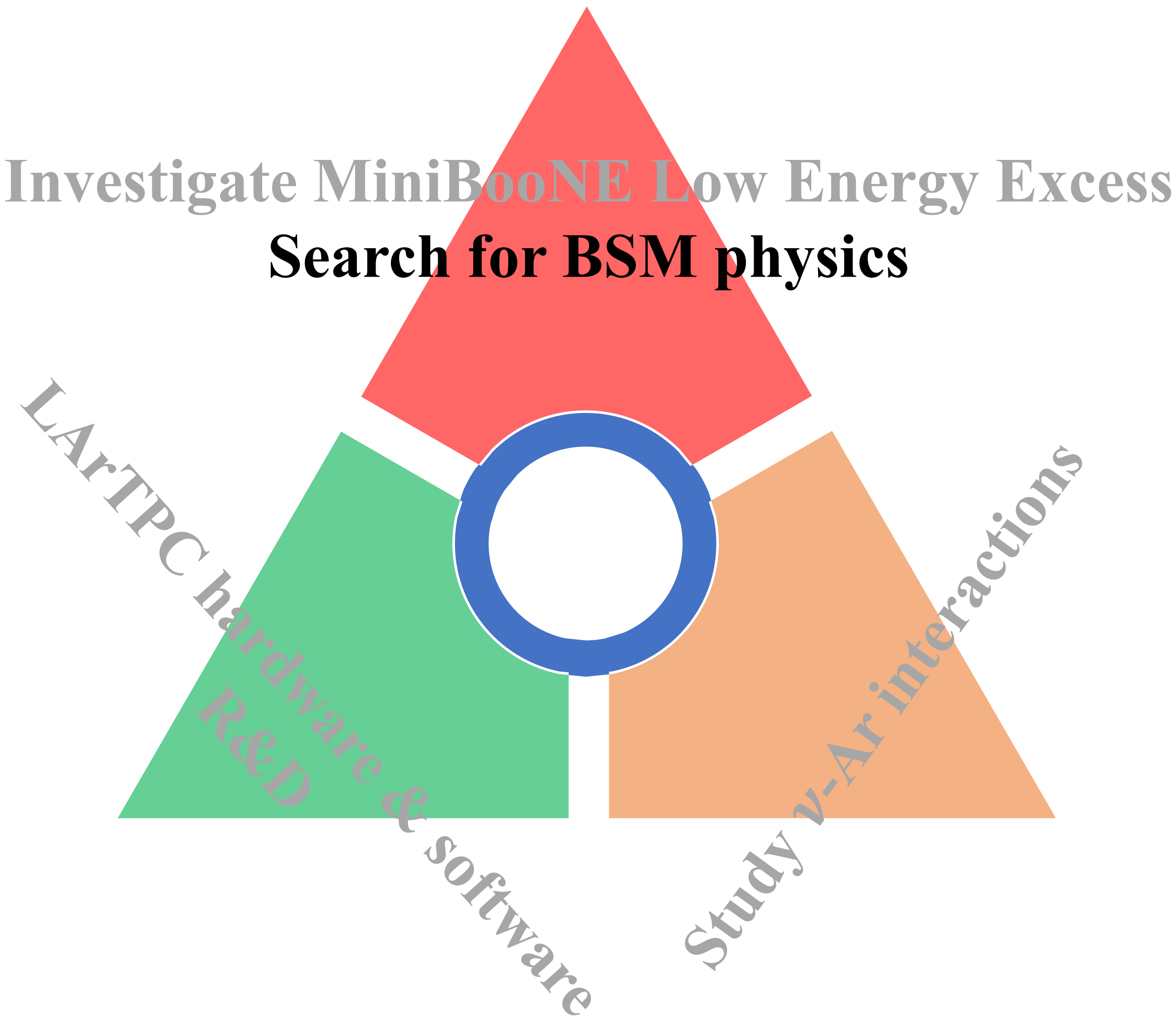
*Phys. Rev. Lett. 135, 081802 (2025)*

- Investigated $\nu_e$CC with no pions in the MicroBooNE full BNB dataset
- See no sign of MiniBooNE-like excess
- Exclude MiniBooNE LEE as $\nu_e$ at ≥ 99% CL
- Confirmed our previous eLEE search results




Investigate MiniBooNE Low Energy Excess
Search for BSM physics
LArTPC hardware & software R&D
Study ν-Ar interactions

# 3(active)+1(sterile) Neutrino Oscillation Framework

Look at 3+1 model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

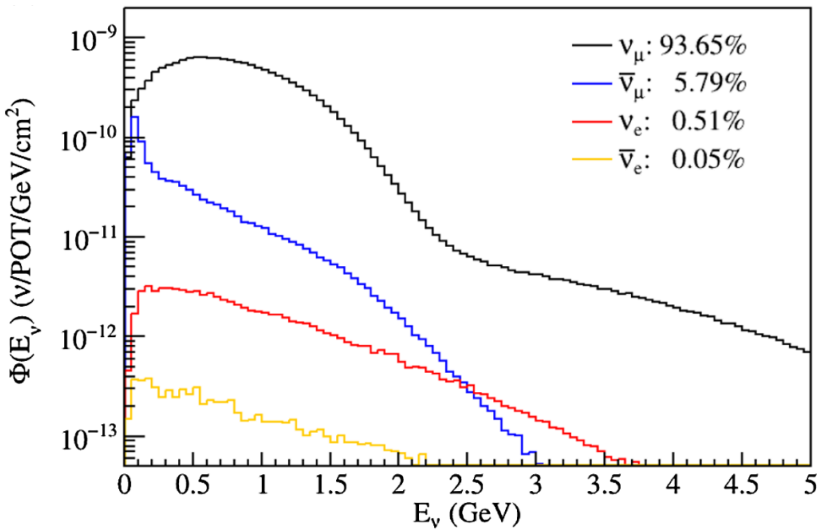
$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$

$\nu_e$ disappearance $(\nu_e \to \nu_e)$: $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

$\nu_e$ appearance $(\nu_\mu \to \nu_e)$: $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

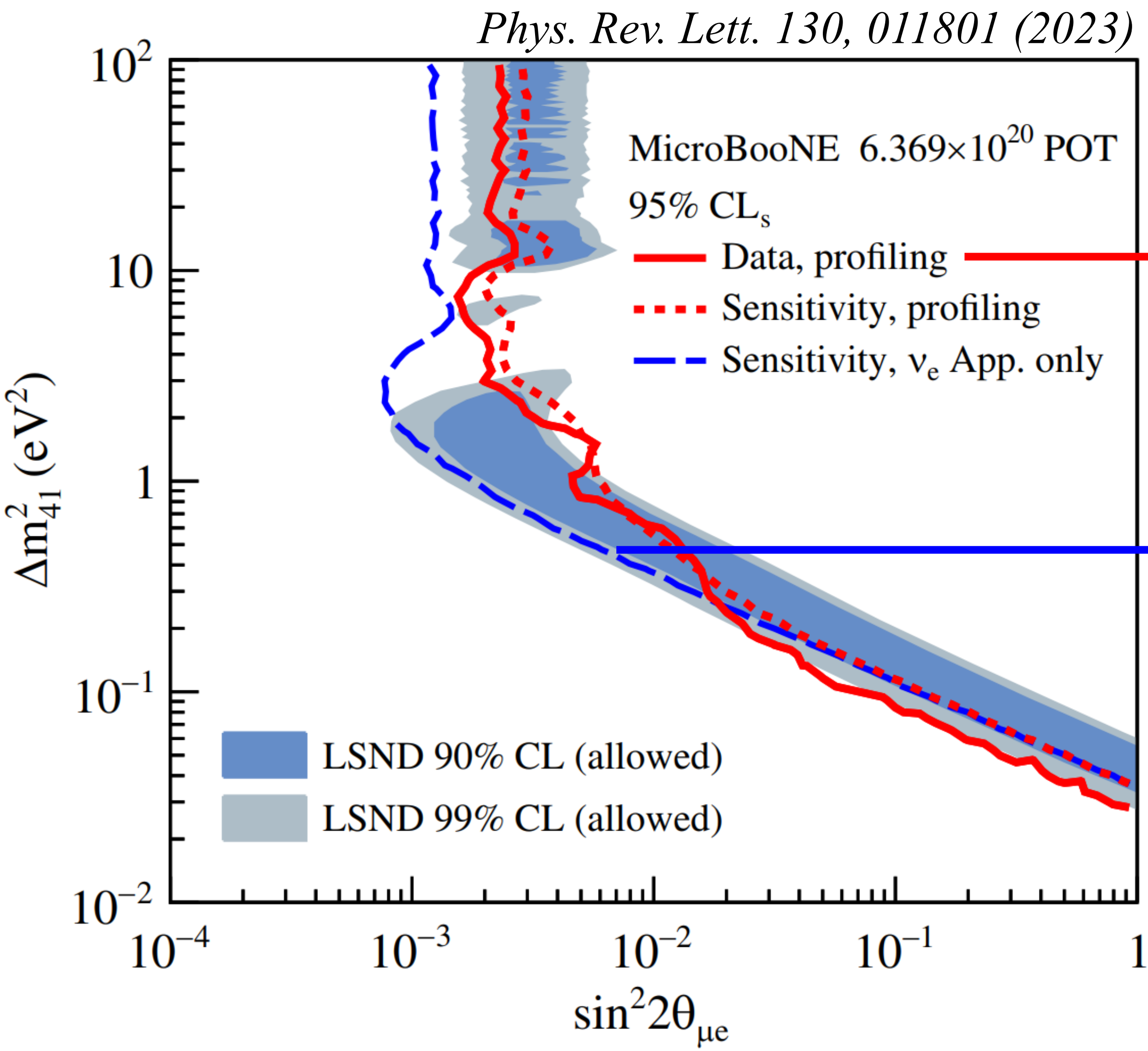
$\nu_\mu$ disappearance $(\nu_\mu \to \nu_\mu)$: $\sin^2 2\theta_{\mu\mu} = 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \left(1 - \cos^2 \theta_{14} \sin^2 \theta_{24}\right)$

**BNB beam @ MicroBooNE**
**Mean Neutrino Energy 0.8 GeV**
**99.44% $\nu_\mu/\bar{\nu}_\mu$**
**0.56% $\nu_e/\bar{\nu}_e$**




Quantitatively probes $\frac{L(\mathrm{m})}{E_\nu(\mathrm{MeV})} \sim \mathcal{O}(1)$ oscillation feature, and search for eV-scale sterile neutrinos.

# 3+1 Sterile Neutrino Oscillations Results by using BNB data




- 2D profiled result, full 3+1 analysis at each point in the parameter space.
- Oscillation effects considered:

$$\nu_\mu \rightarrow \nu_e$$
$$\nu_e \rightarrow \nu_e$$
$$\nu_\mu \rightarrow \nu_\mu$$

- $\nu_e$ appearance-only, more stringent limit However, it is physically not allowed in the 3+1 framework. (non-zero $\nu_e$ appearance requires both $\nu_e$ and $\nu_\mu$ disappearance )
- Oscillation effects considered:

$$\nu_\mu \rightarrow \nu_e$$

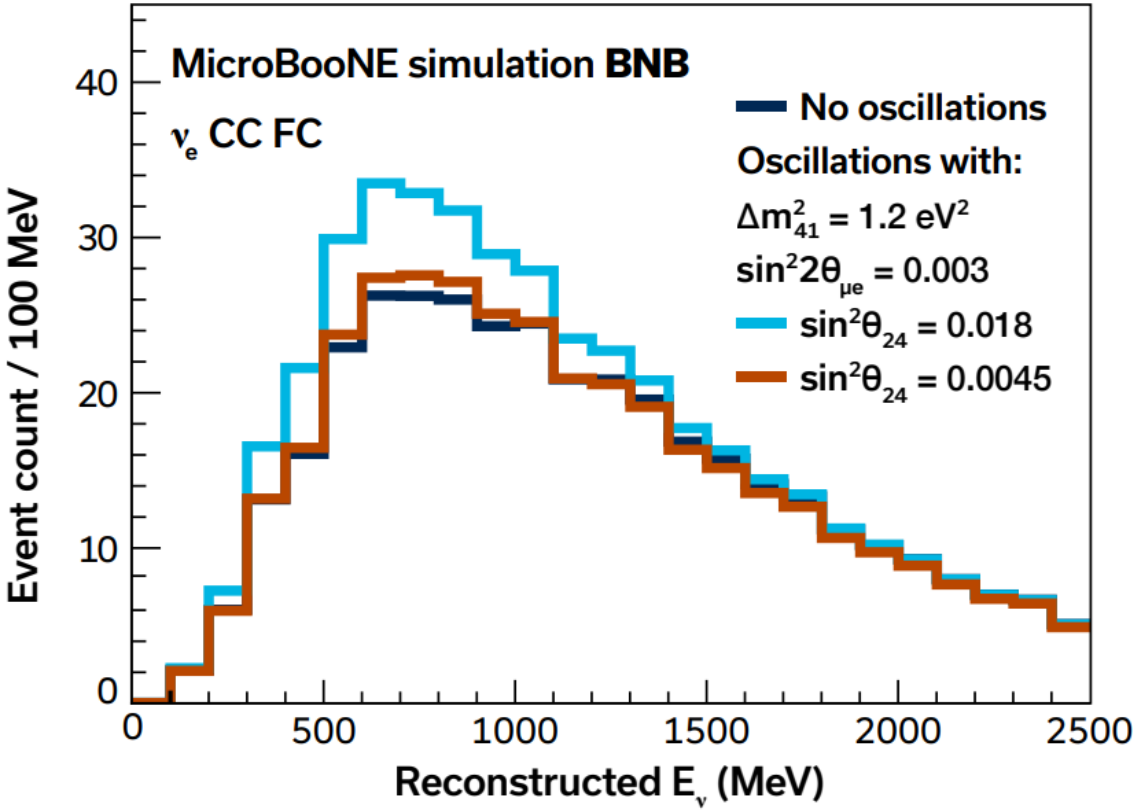
# 3+1 Sterile Neutrino Results
# Limited by the Cancellation of $\nu_e$ Appearance and Disappearance

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

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

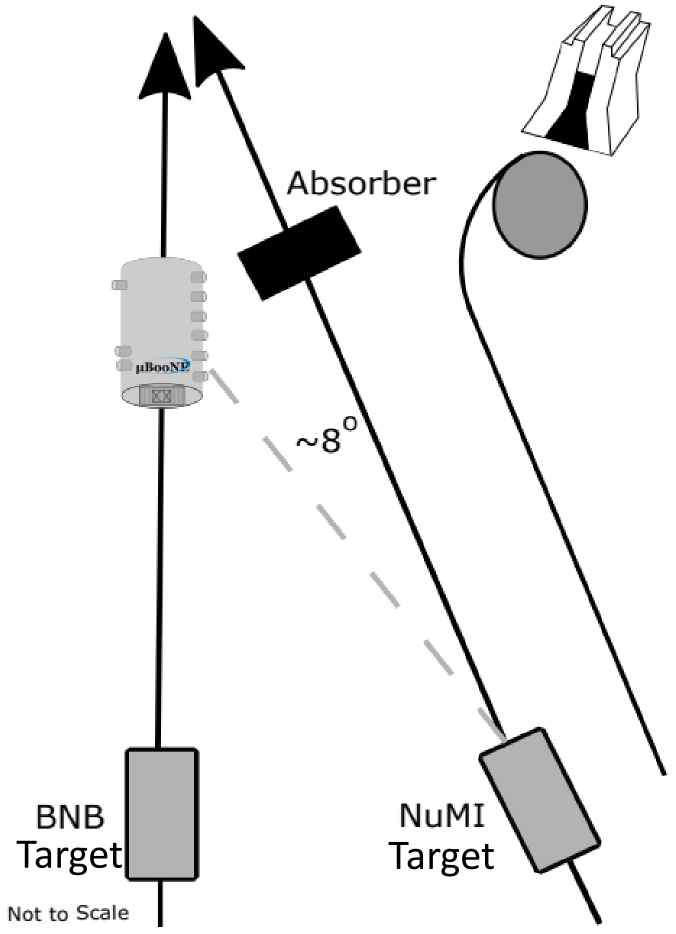
- Degeneracy when $\sin^2\theta_{24}$ approaches $R_{\nu_e/\nu_\mu}$ (the ratio of beam intrinsic $\nu_e$ and $\nu_\mu$ flux)

| At MicroBooNE | $R_{\nu_e/\nu_\mu}$ Average |
|---|---|
| BNB beam | ~0.005 |



# One Detector with Two Beams

## Breaking the Cancellation of $\nu_e$ App. and Disapp.

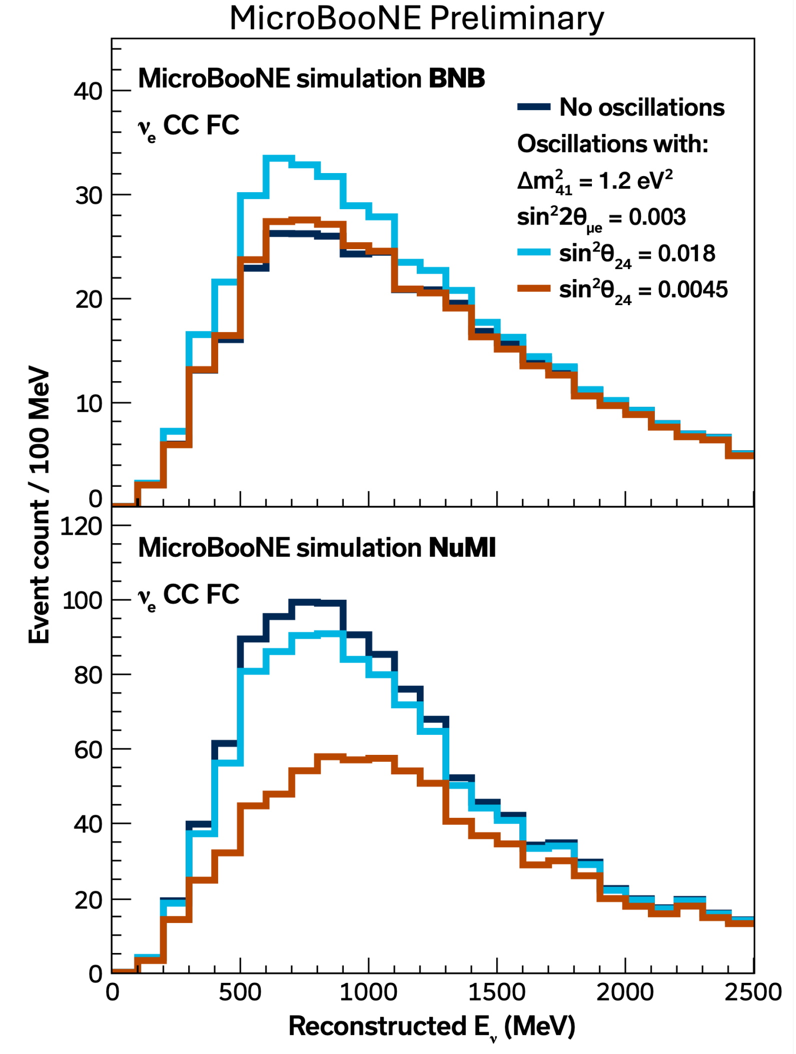



$$N_{\nu_e} = \boxed{N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e}} + \boxed{N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \boxed{(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1)} \cdot \sin^2 2\theta_{14} \cdot \sin^2\Delta_{41}\right]$$

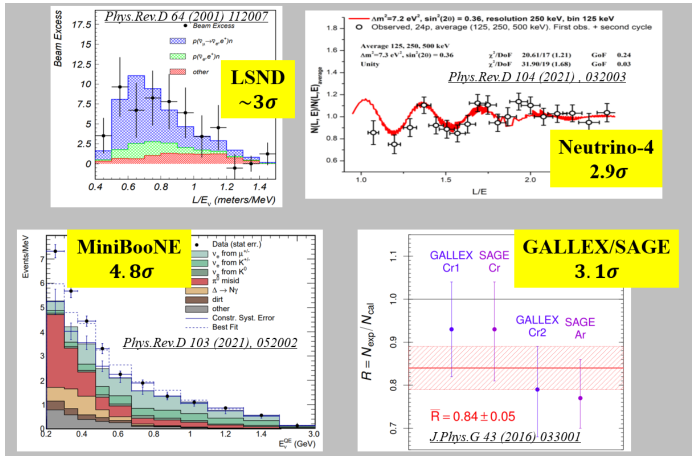
- Degeneracy when $\sin^2\theta_{24}$ approaches $R_{\nu_e/\nu_\mu}$ (the ratio of beam intrinsic $\nu_e$ and $\nu_\mu$ flux)

| At MicroBooNE | $R_{\nu_e/\nu_\mu}$ Average |
|---|---|
| BNB beam | ~0.005 |
| NuMI beam | ~0.04 |

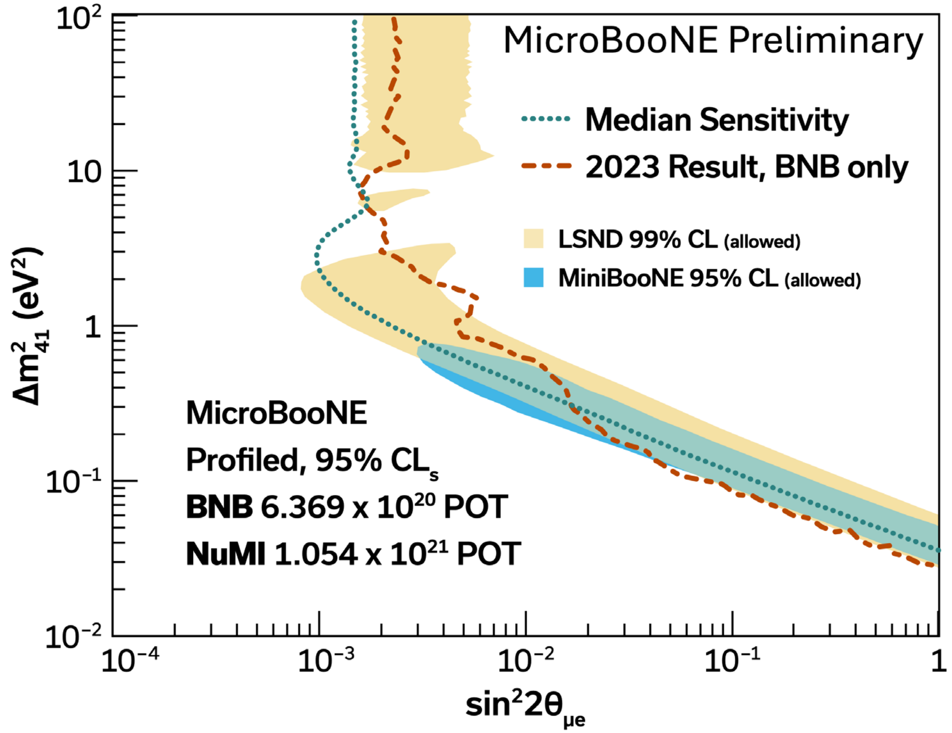
Significant difference in the $\nu_\mu/\nu_e$ flux ratio in BNB and NuMI → mitigate the degeneracy

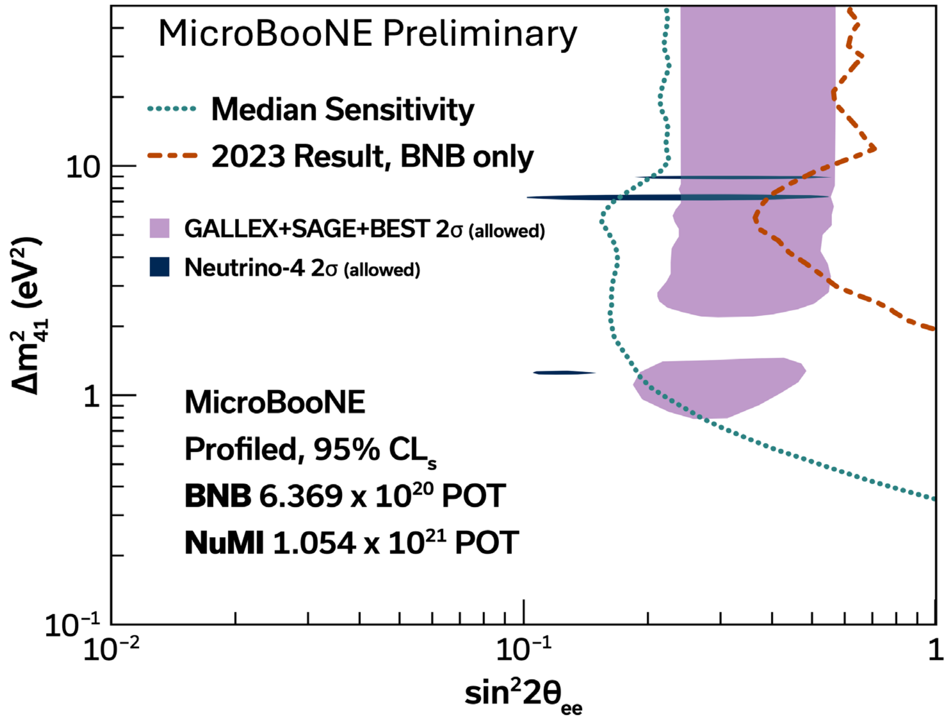


# 3+1 Sterile Neutrino Oscillations BNB+NuMI



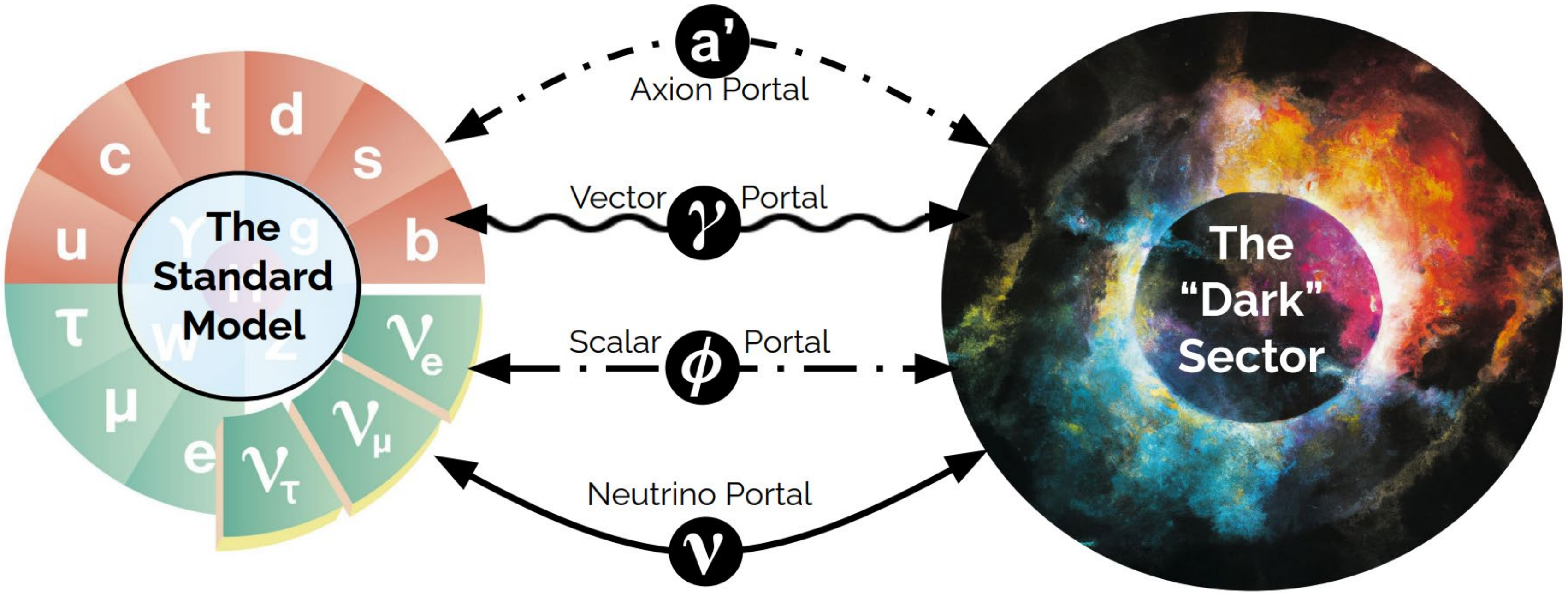

Adding second beam (NuMI) largely improves the sensitivities for both $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_e$ channels. Great coverage across LSND/MiniBooNE, GAA/Neutrino-4 allowed regions.




**Data Results Out Soon!**

# 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

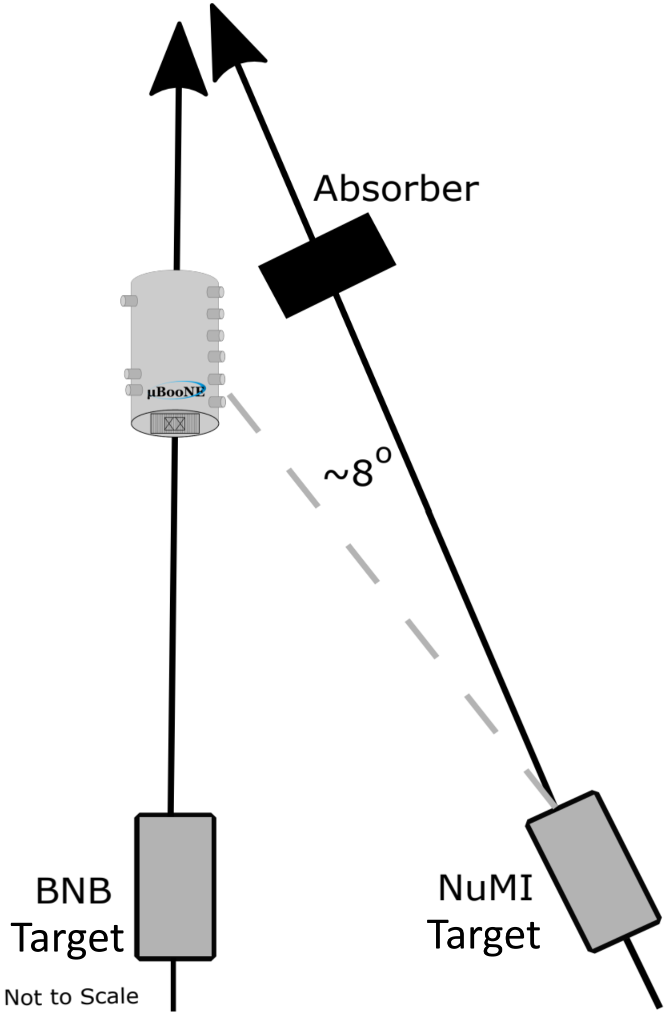
**Combined and Non-Minimal Portals**

*Credit: Mark Ross-Lonergan*

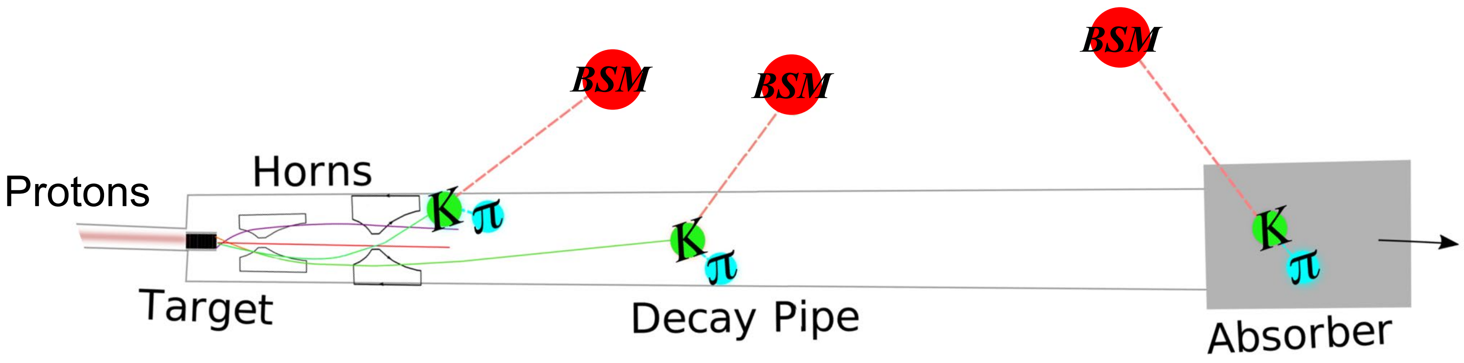
Results

Ongoing work

# A Source for BSM Particles



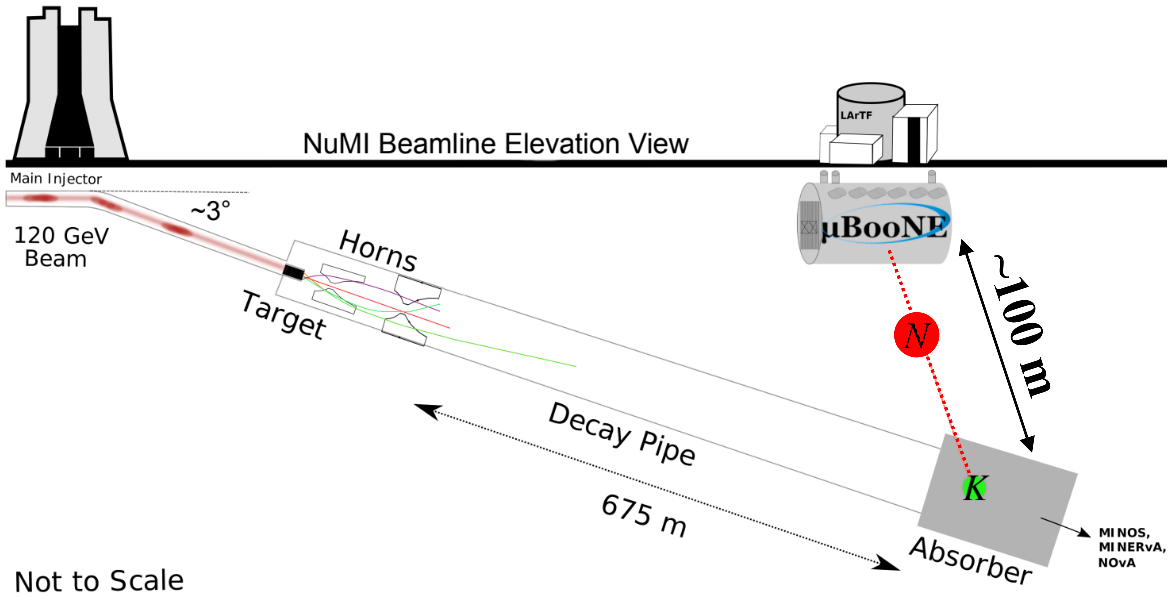

- Collisions with the target produce amounts of mesons
- Some models have mechanisms by which charged and neutral mesons can decay into BSM particles
  - Decay at rest in the target region
  - Decay in flight in the decay region
  - Decay at rest in the absorber region
- These BSM particles may survive long enough to reach MicroBooNE detector

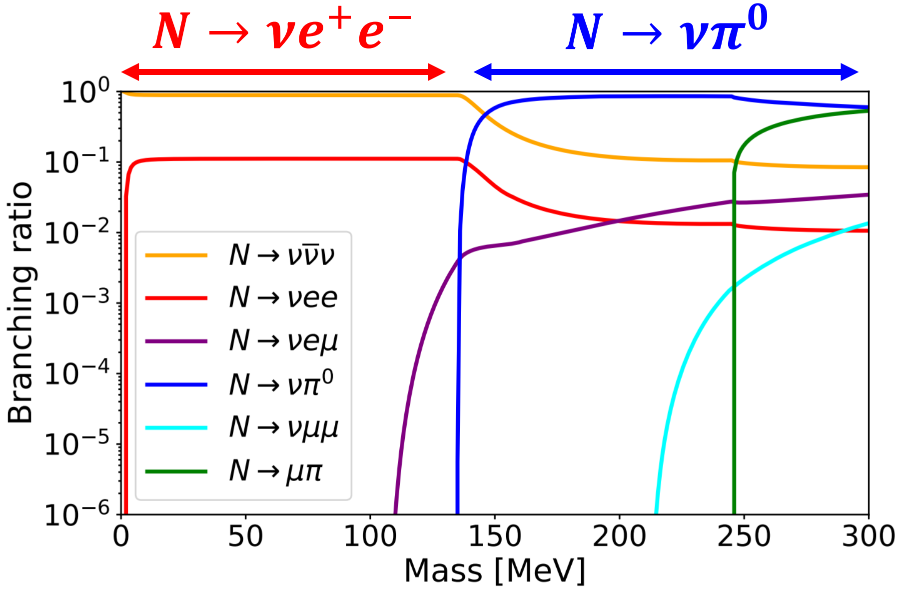


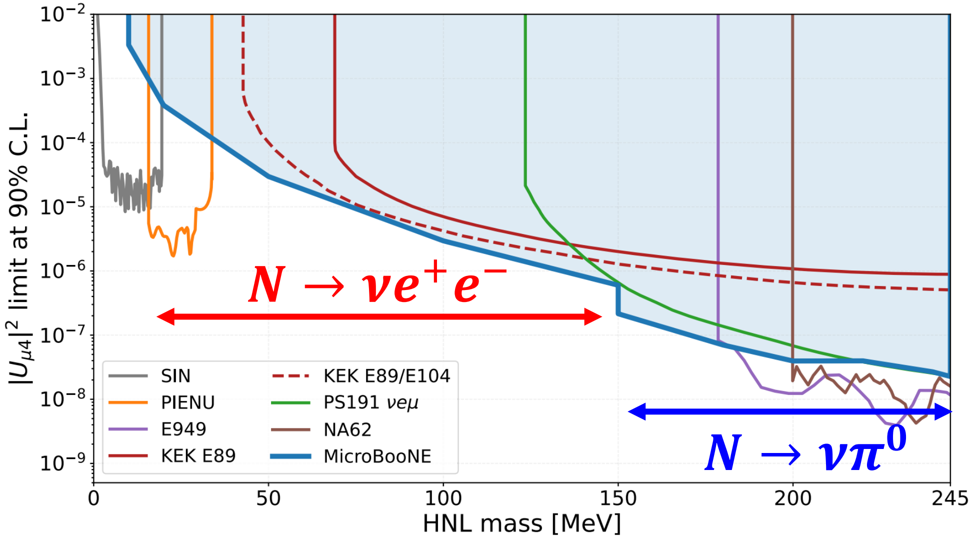
# Heavy Neutral Leptons (HNL)

*Phys. Rev. Lett. 132, 041801 (2024)*

- HNLs produced from
  $K^+ \to \mu^+ N$ at NuMI absorber
- Searches for
  $N \to \nu e^+ e^-$
  $N \to \nu \pi^0$
- Set limits on $|U_{\mu 4}|^2$ as a function of HNL mass



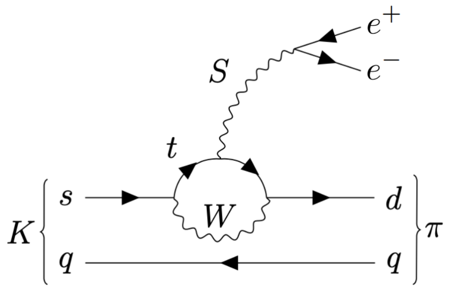



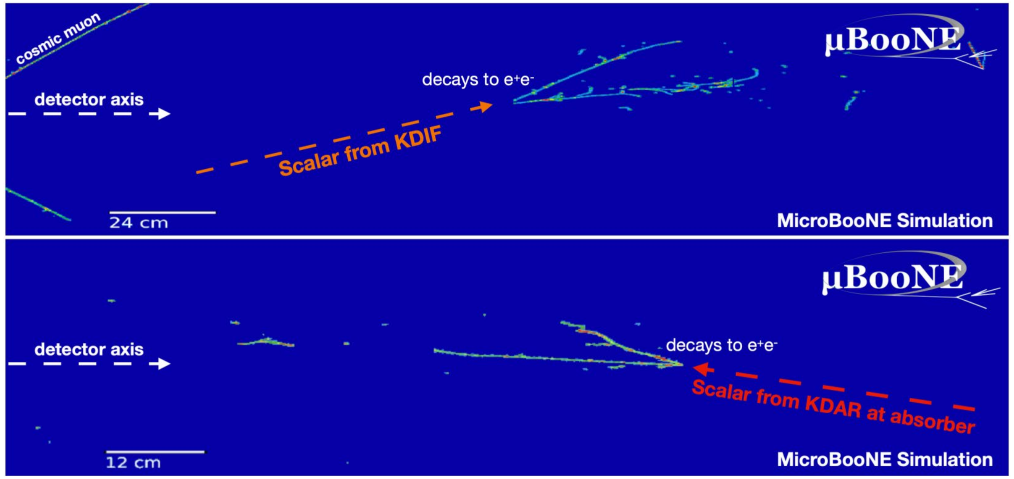



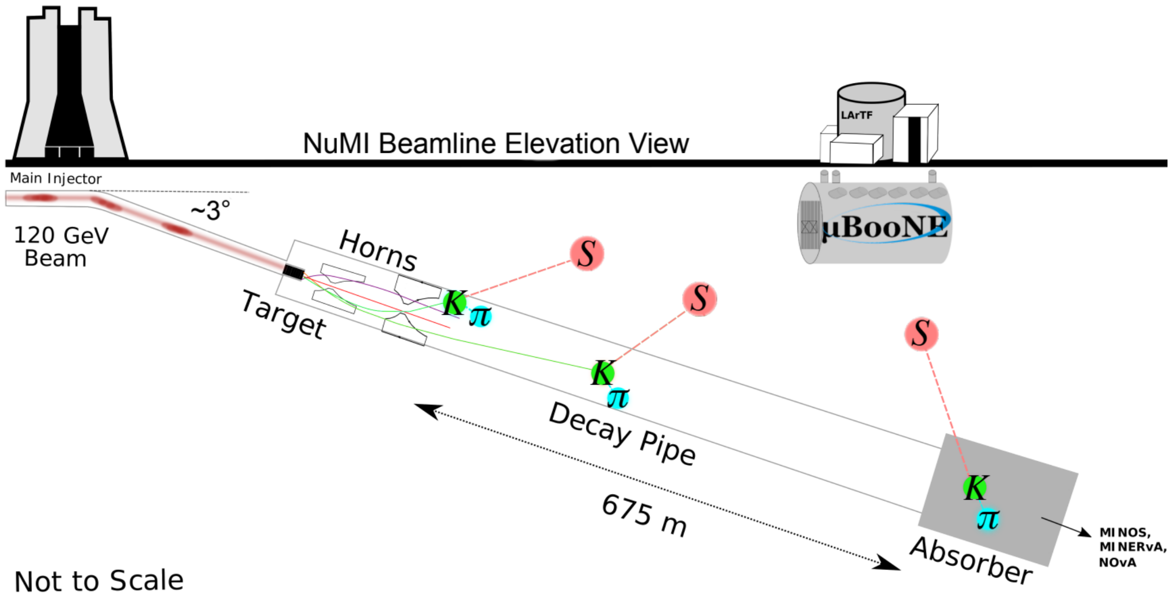
# Higgs-Portal Scalar Bosons

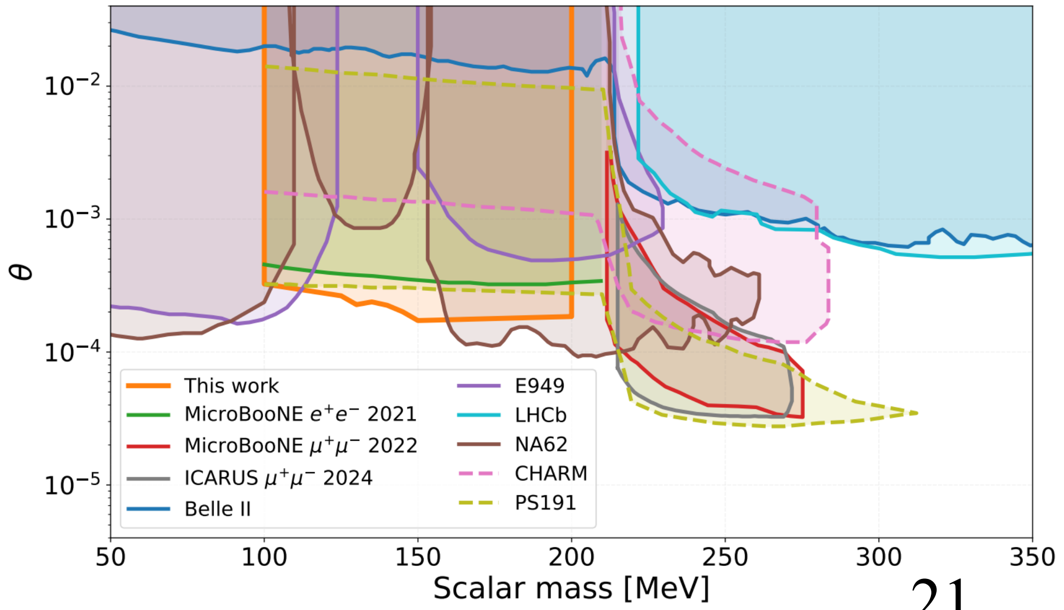
*arXiv:2501.08052*

- **Neutral scale singlet $S$**, mixing angle $\theta$ with Higgs boson
- Production from charged kaon decay
- Signature: $S \rightarrow e^{+}e^{-}$
- Set strongest limits on $\theta$ to date for $m_s$ at $(125, 150)$ MeV



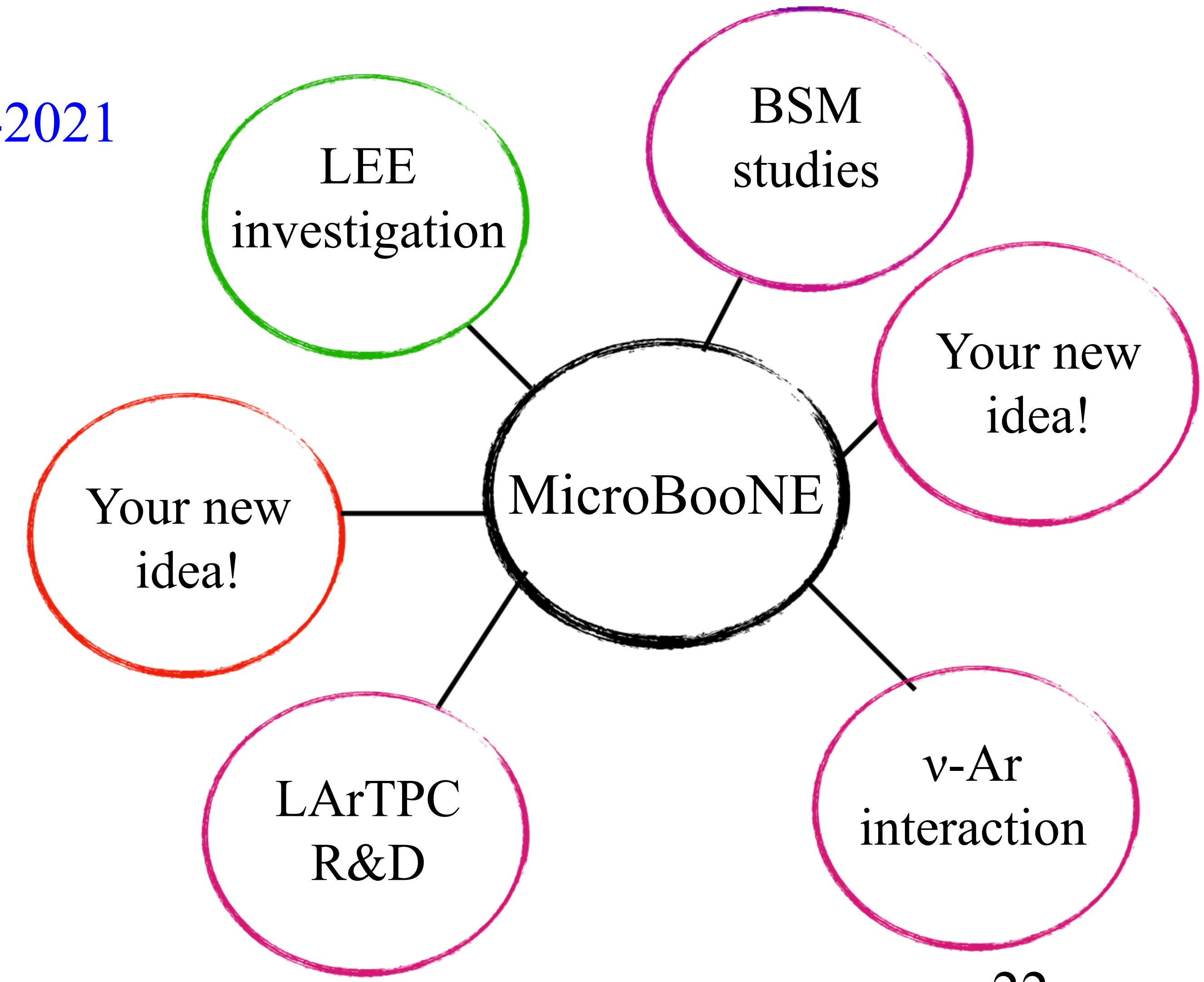



# Summary

- MicroBooNE completed data taking 2015-2021 BNB and NuMI neutrino beams
- Extensive inclusive physics programs
- Many new full dataset analyses upcoming!



μBooNE

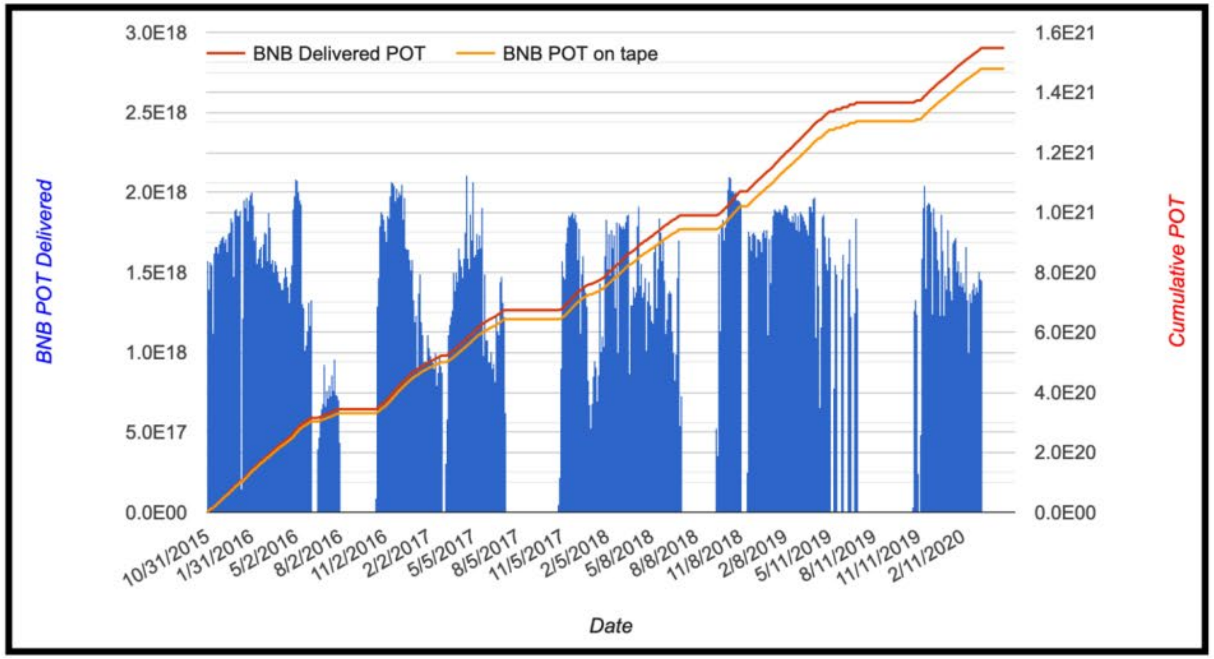
TAUP XICHANG

Thank you!

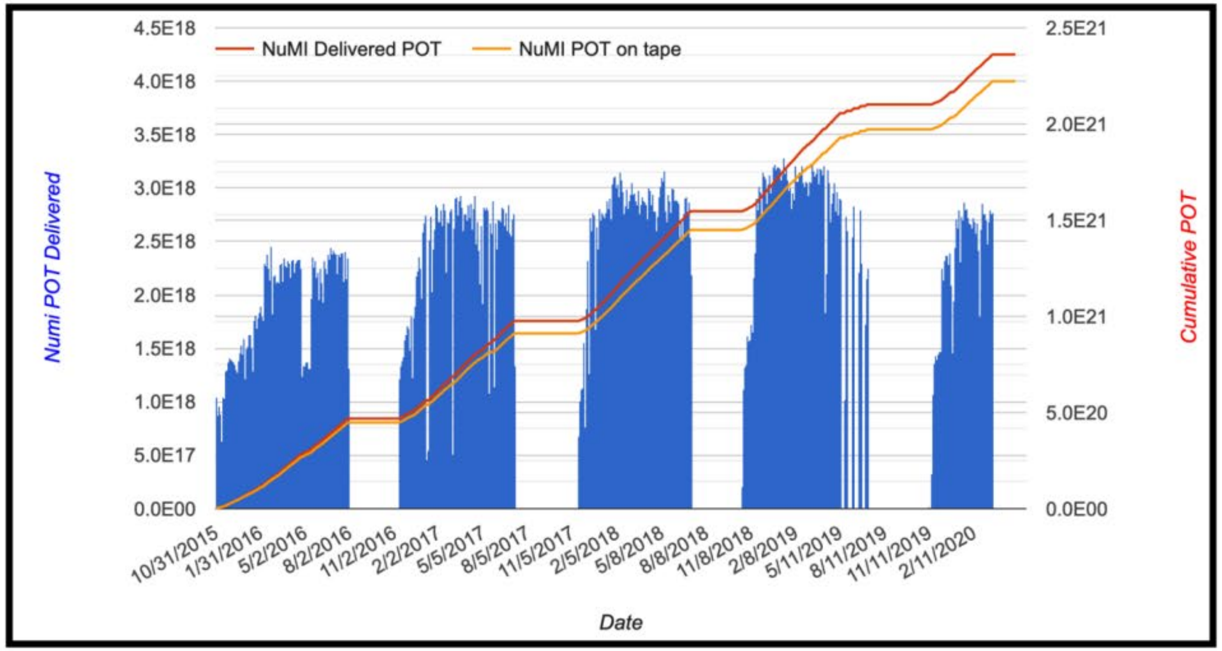
# Backup

# MicroBooNE Data Taking

On-axis BNB:
full dataset, $1.1 \times 10^{21}$ POT




On-axis BNB:
full dataset, $2.37 \times 10^{21}$ POT



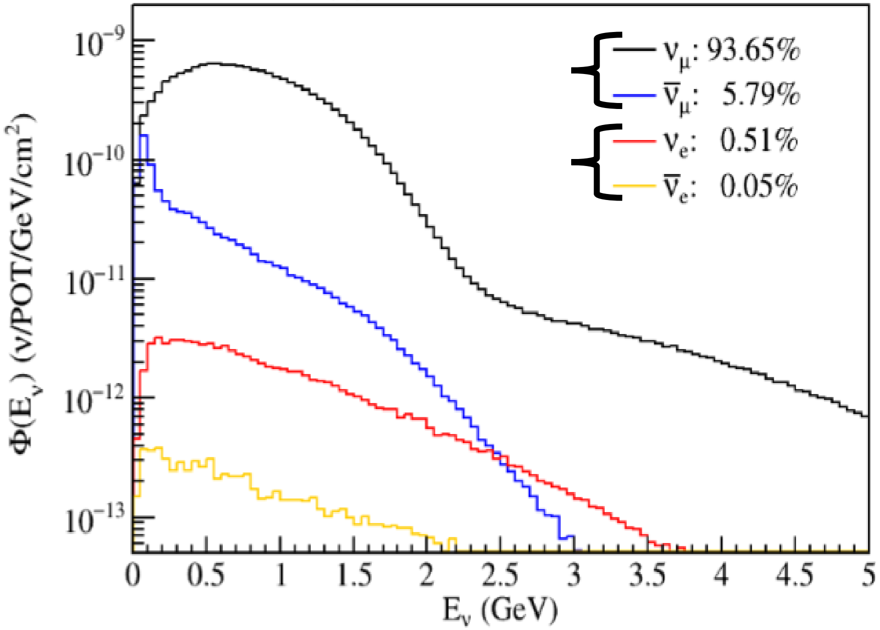

MicroBooNE collected data between 2015 and 2021 split into five runs.

# Challenging $\nu_e$ Selection

Cosmic-ray muon (5.5 kHz) @ MicroBooNE operating near-surface

- BNB beam spill triggers a 4.8 ms TPC window
- ~600 beam spills → 1 nu interaction

BNB neutrino flux
over 99% $\nu_\mu$ / $\bar{\nu}_\mu$
~0.5% $\nu_e$/ $\bar{\nu}_e$




A sensitive $\nu_e$ selection (CC interactions) requires

$\gtrsim$99.999% rejection of cosmic-ray muons and

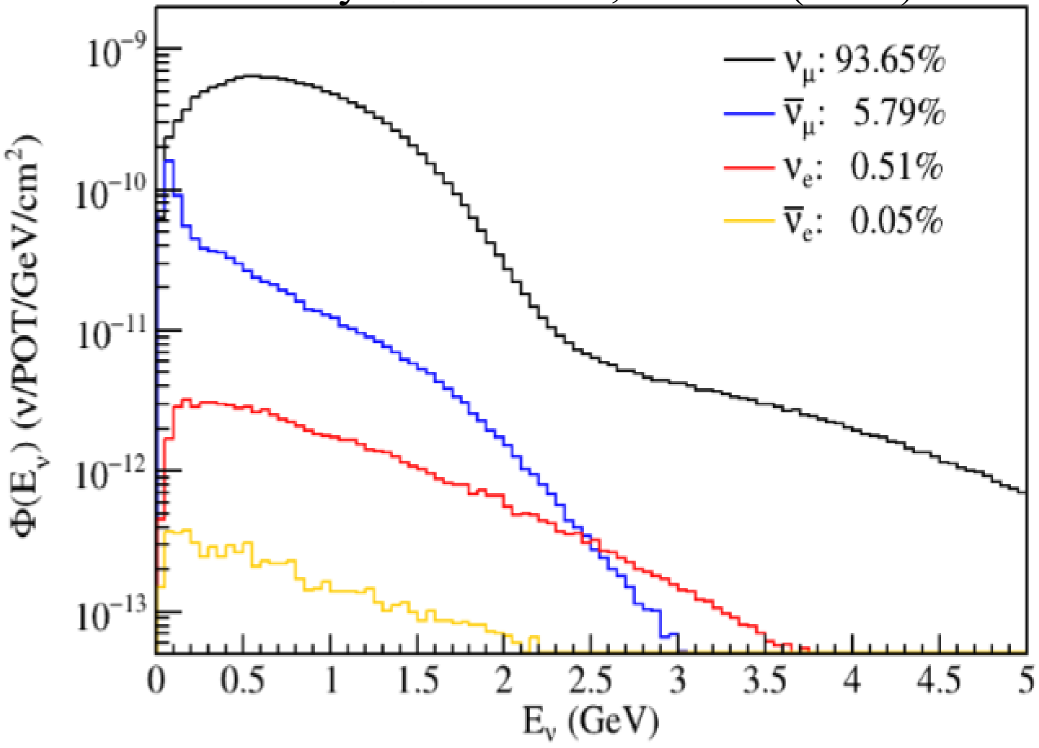
$\gtrsim$99.9% rejection of other $\nu$ background for nue analysis

**Developed advanced cosmic rejection techniques, event reconstruction and PID algorithms to exploit LArTPC capability to select $\nu_e$ events**

# BNB and NuMI Neutrino Flux @ MicroBooNE

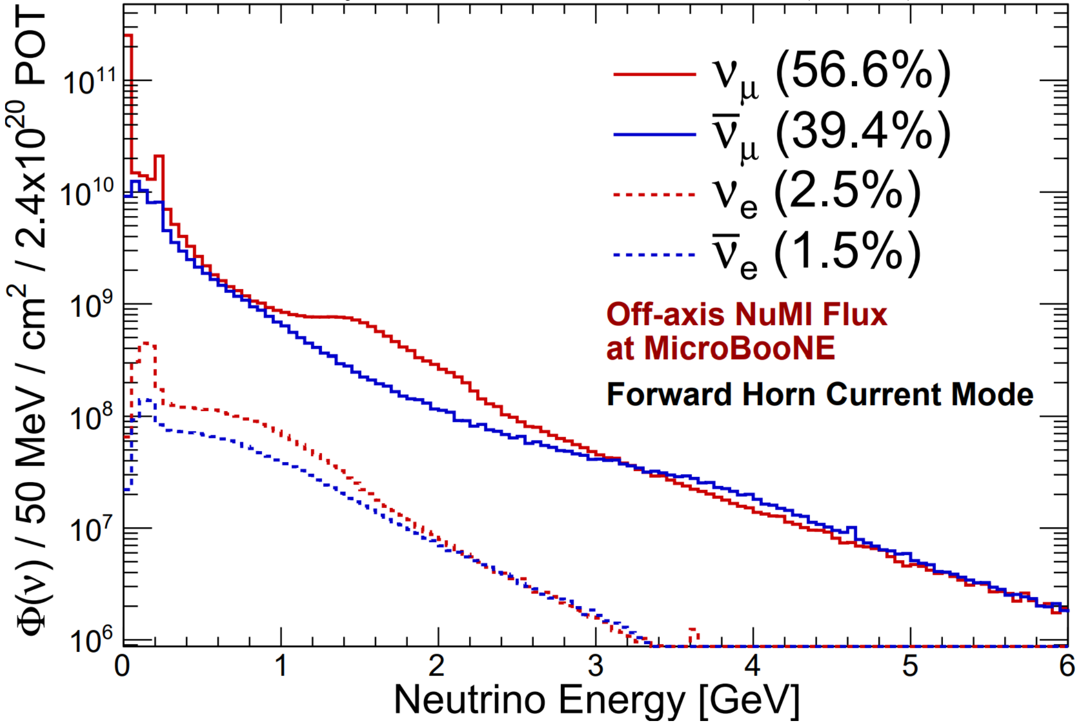
BNB

Phys. Rev. D105, 112005 (2022)




NuMI

Phys. Rev. D104, 052002 (2021)



# 3+1 Sterile Neutrino Oscillations Results by using BNB data

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