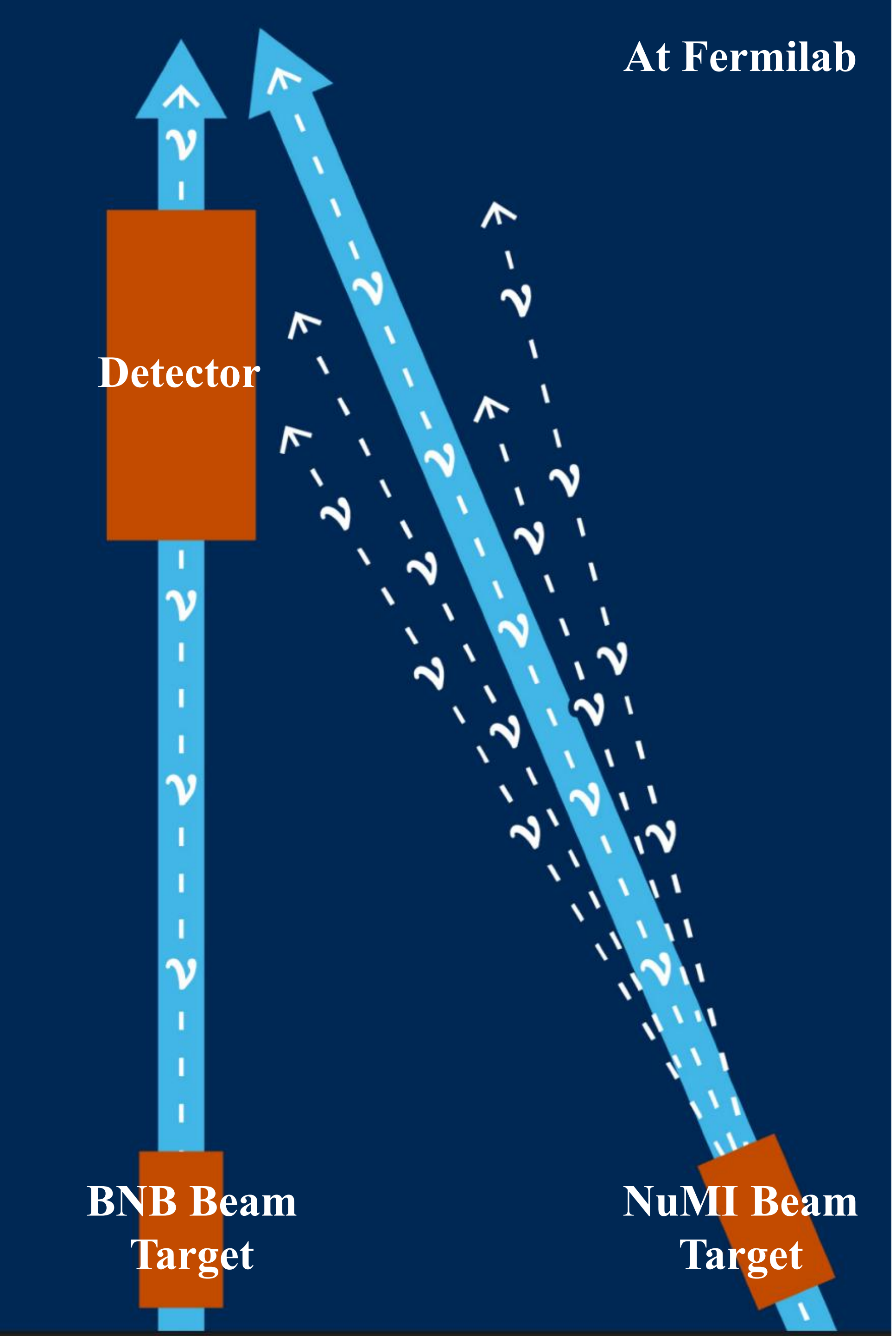


Two Beams, One Detector MicroBooNE’s Search for eV-scale Sterile Neutrinos

Based on Nature 648, 64–69 (2025 December)

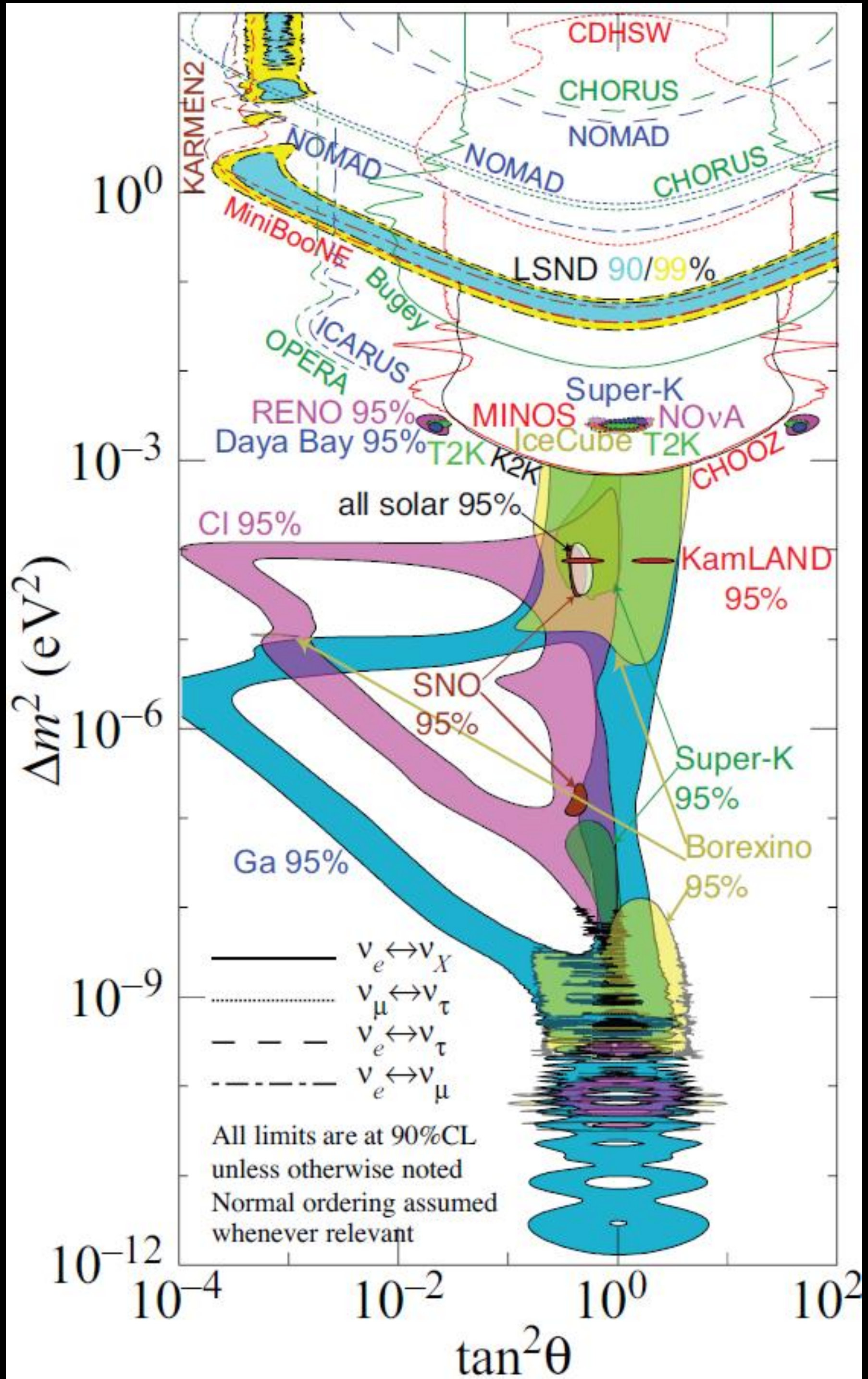
季向盼（南开大学）

中国物理学会高能物理分会

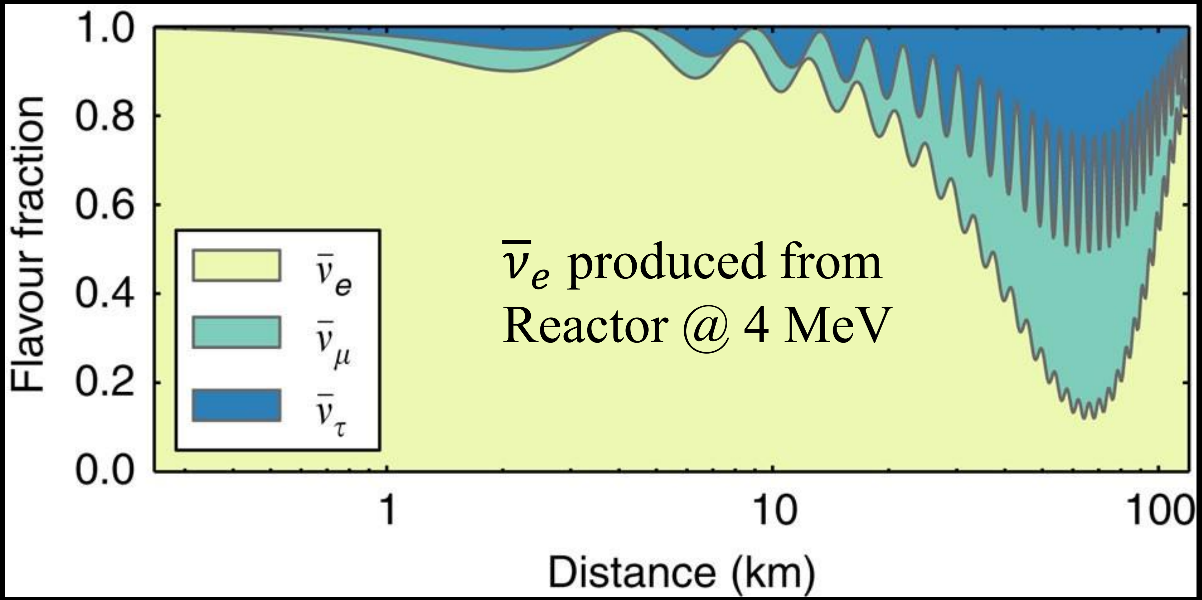
第十二届全国会员代表大会暨学术年会

2026年7月15日

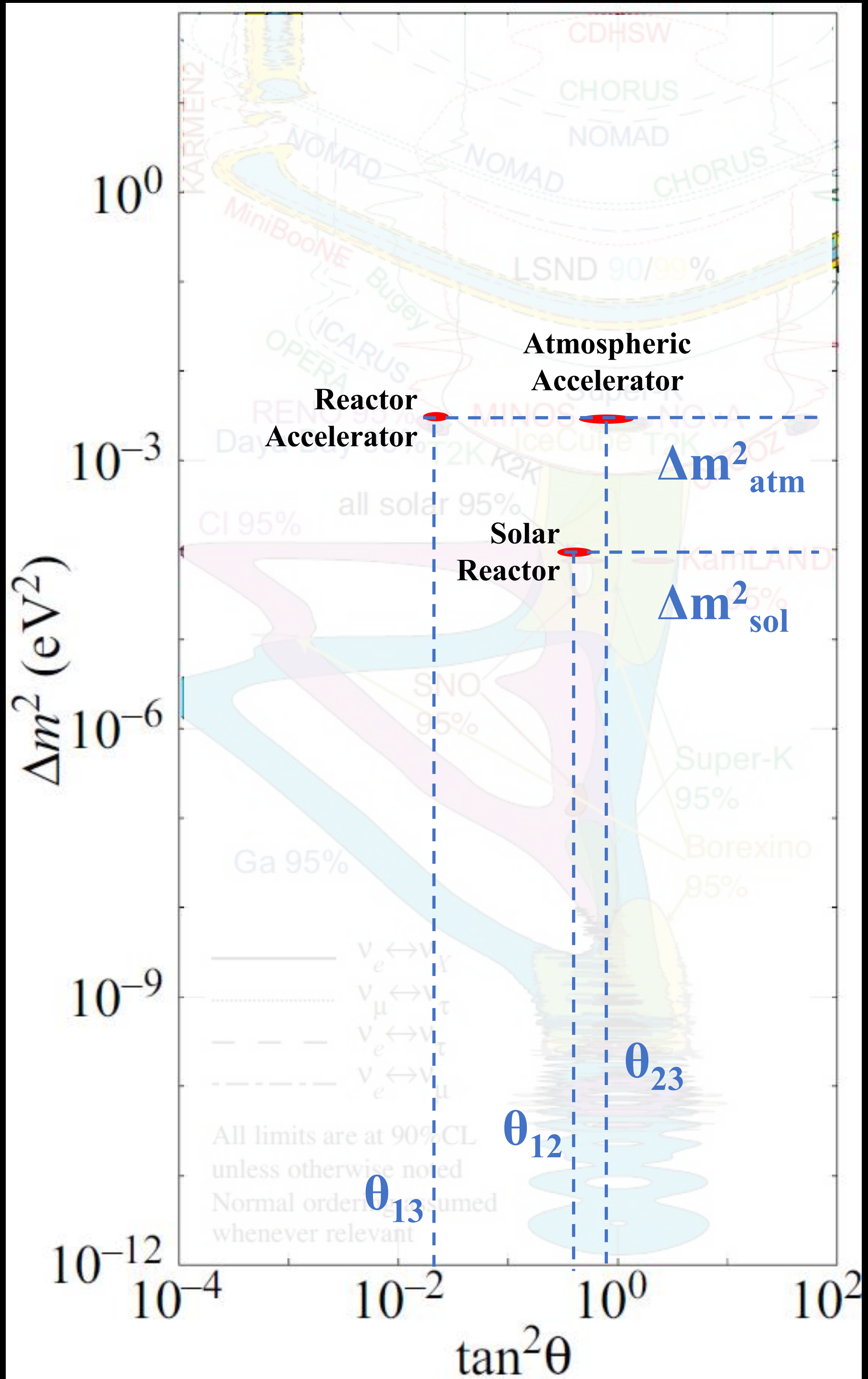
Neutrino Oscillation Experiments



- > 50 years
- > 30 experiments
- Phase space over tens of orders of magnitude



Credit: Hitoshi Murayama



Neutrino Oscillation Experiments

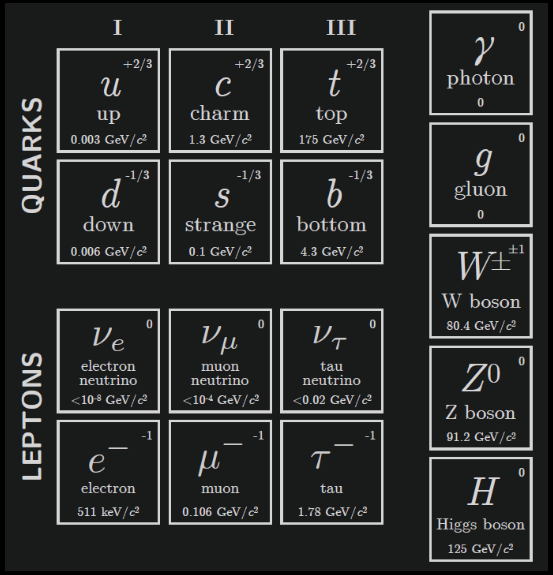
- > 50 years
- > 30 experiments
- Phase space over tens of orders of magnitude

Six Parameters for the Osc.

$$\theta_{12} \quad \theta_{23} \quad \theta_{13}$$

$$\Delta m^2_{21} \quad \Delta m^2_{31}$$

$$\delta^{CP}$$



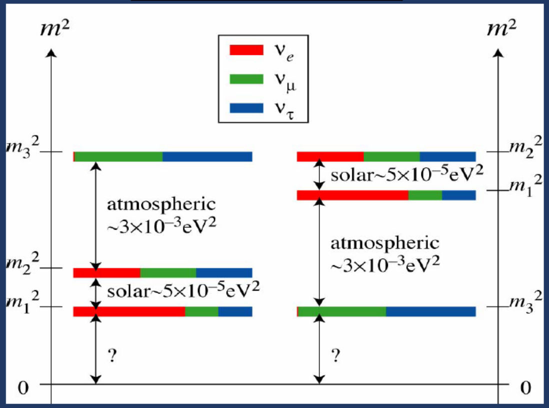
Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$ } Solar, Reactor

$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)
$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)
} Atmospheric,Accelerator

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$ } Reactor, Accelerator

Mass Hierarchies



Normal Inverted

Future objectives:

- δ_{CP}
- θ_{23} max?
- Hierarchy?

} Accelerator,Reactor, Atmospheric

- Majorana ν?
- Absolute mass

} 0νββ, Cosmology, Electron spectrometers,

- Sterile ν? } Accelerator,Reactor, Atmospheric

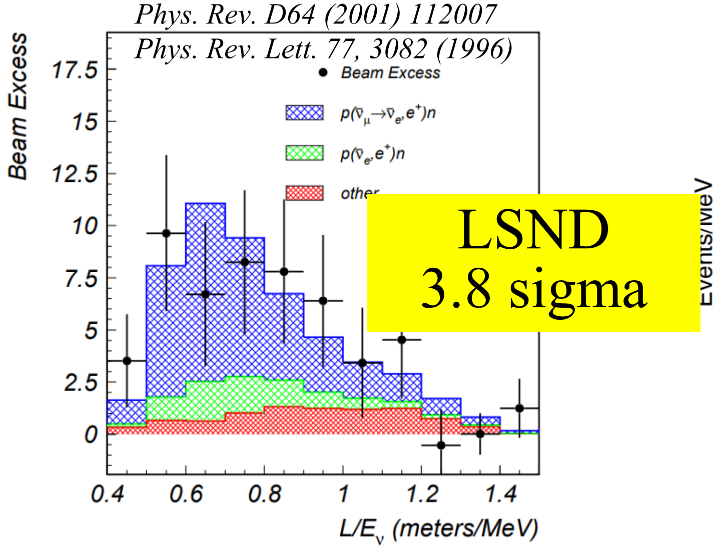
惰性中微子
存不存在？

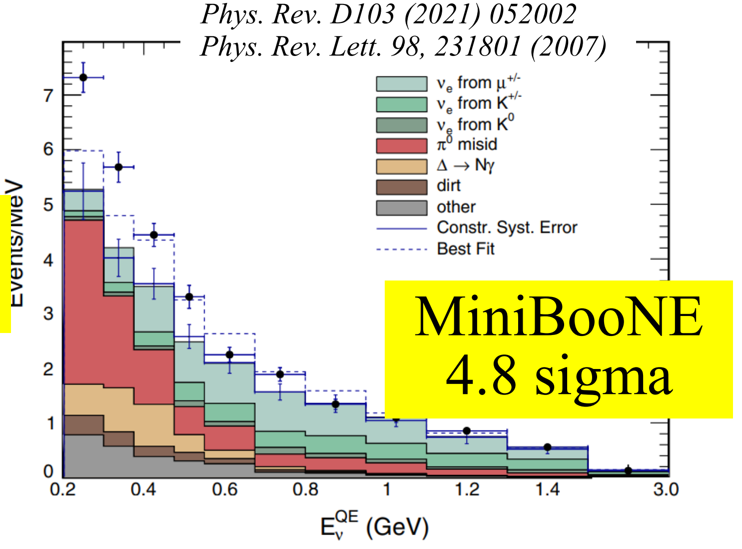
Short-Baseline Neutrino Anomalies

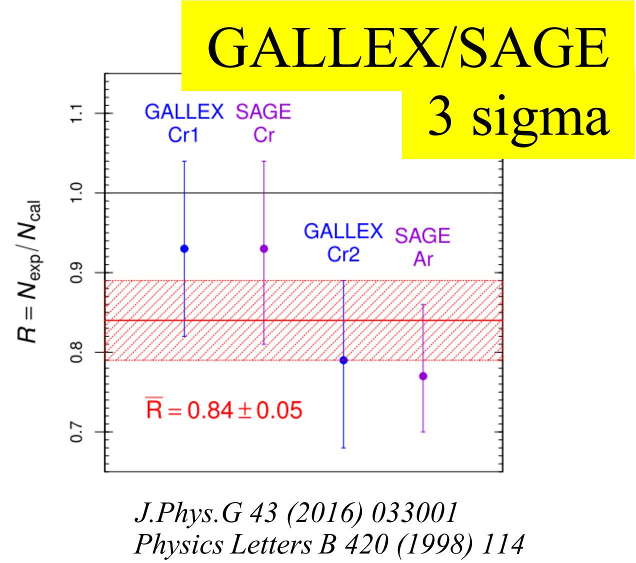
Experiment	Channel
LSND anomaly	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
MiniBooNE anomaly	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ $\nu_\mu \rightarrow \nu_e$
GALLEX/SAGE, BEST (radioactive source), Gallium anomaly	$\nu_e \rightarrow \nu_e$
Neutrino-4 reactor expt.	$\overline{\nu}_e \rightarrow \overline{\nu}_e$

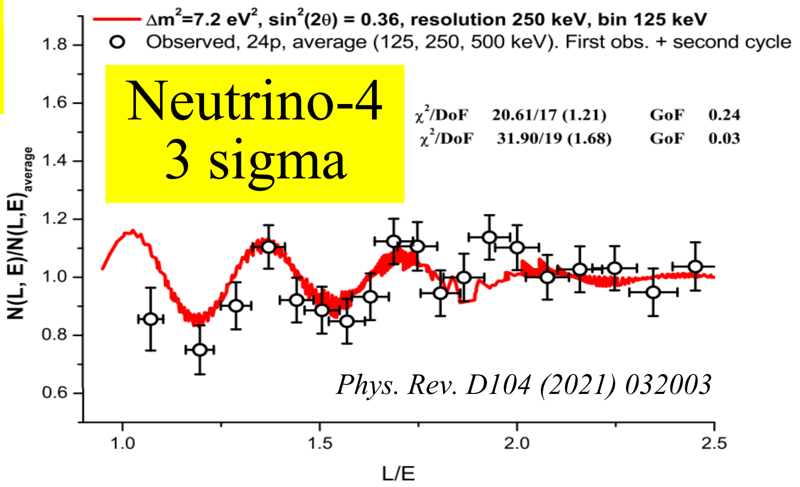
Anomalies:

- Neutrino appearance expts: **<u>excess than expectation</u>**
- Neutrino disappearance expts: **<u>deficit than expectation</u>**









Short-Baseline Neutrino Anomalies

Experiment	Channel
LSND anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$
MiniBooNE anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_e$
GALLEX/SAGE, BEST (radioactive source), Gallium anomaly	$\nu_e \to \nu_e$
Neutrino-4 reactor expt.	$\bar{\nu}_e \to \bar{\nu}_e$

Anomalies:

- Neutrino appearance expts: **excess than expectation**
- Neutrino disappearance expts: **deficit than expectation**

3(active)+1(sterile) Neutrino Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}}\sin^2 2\theta_{\alpha\beta}\sin^2\Delta_{41}$$

$$\Delta_{41} = 1.267\cdot\frac{\Delta m^2_{41}\cdot L}{E}\cdot\frac{\mathrm{MeV}}{\mathrm{eV}^2\cdot\mathrm{m}}$$

All these experiments $\frac{L}{E}\sim 1$

Hints of eV-scale sterile neutrino

Short-Baseline Neutrino Anomalies

Experiment	Channel
LSND anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$
MiniBooNE anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_e$
GALLEX/SAGE, BEST (radioactive source), Gallium anomaly	$\nu_e \to \nu_e$
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Anomalies:

- Neutrino appearance expts: **excess than expectation**
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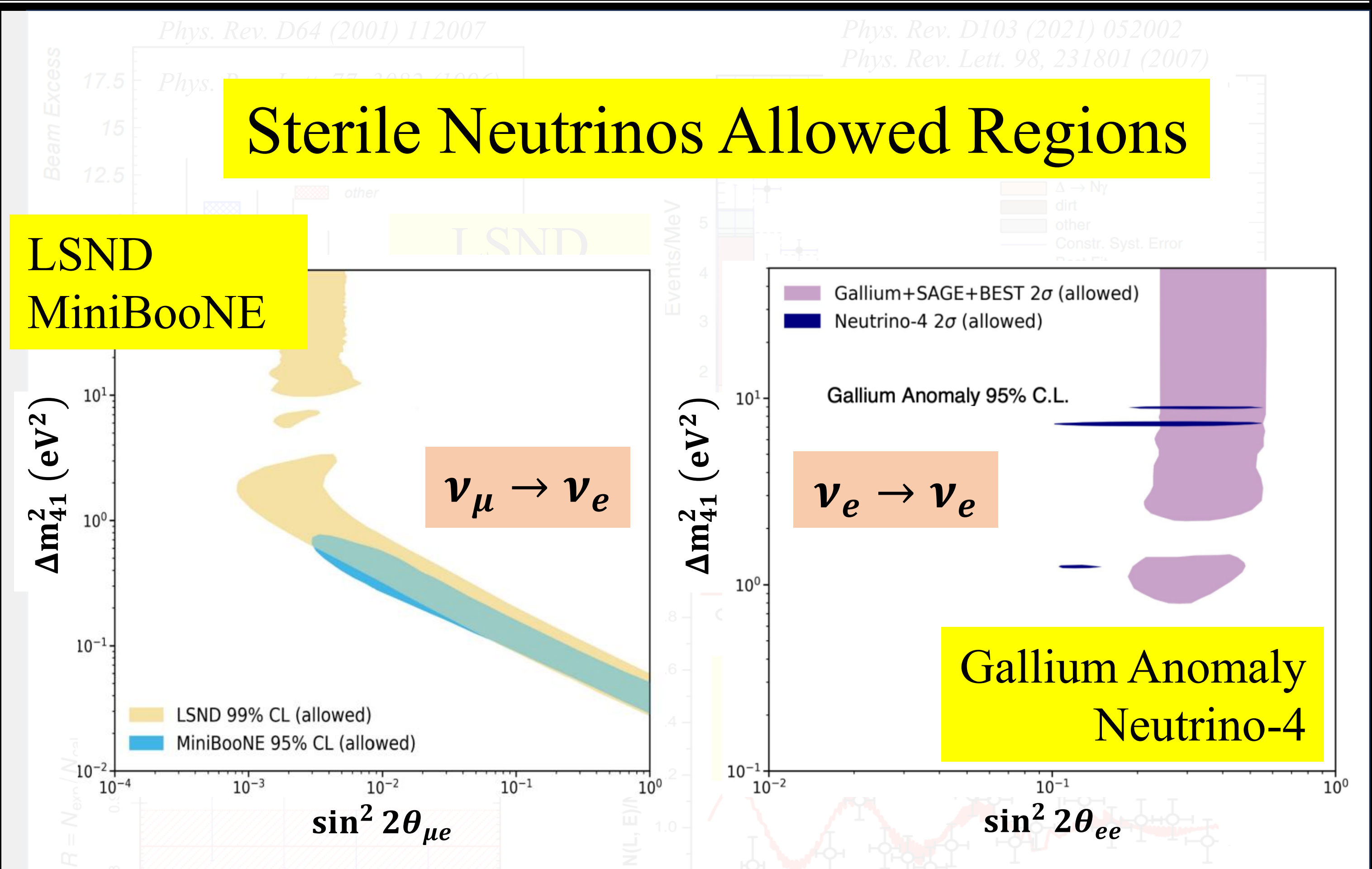
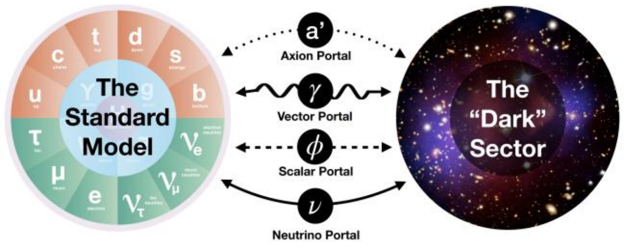


$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \sin^2 2\theta_{\alpha\beta} \sin^2 \Delta_{41}$$

the Micro Booster Neutrino Experiment (MicroBooNE)

186 Collaborators
from 41 Institutions

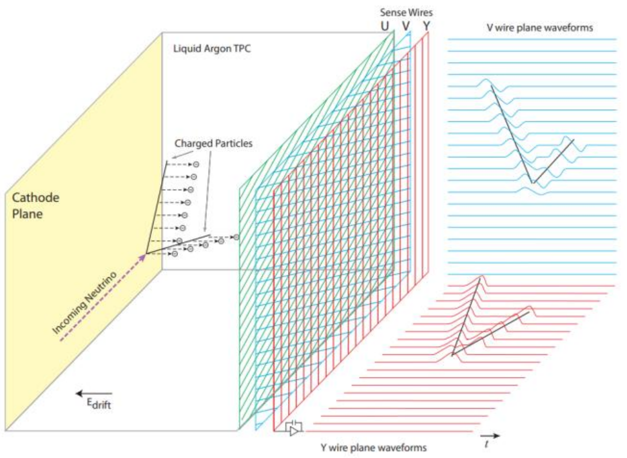
MicroBooNE Scientific Goals

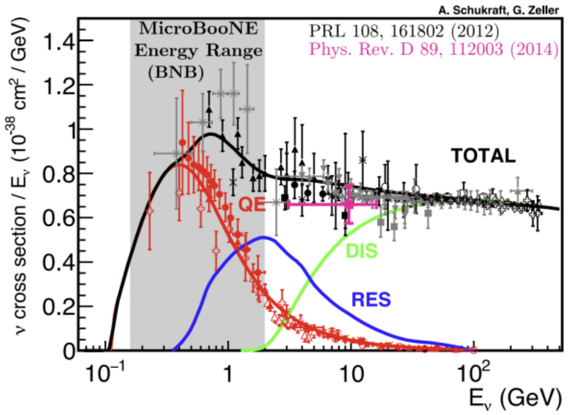


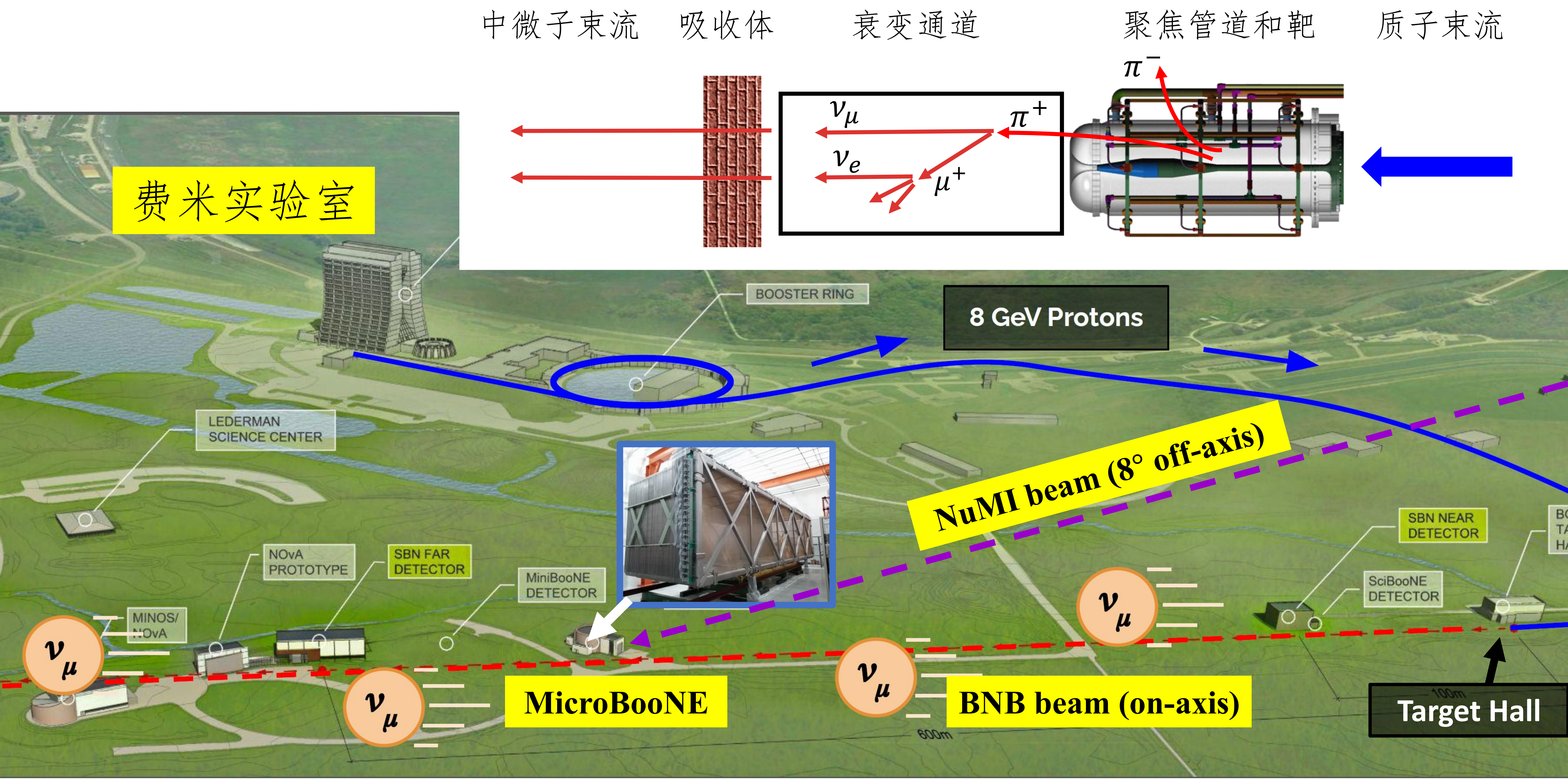
Investigate MiniBooNE Low Energy Excess
Search for Sterile ν and other BSM physics

LArTPC hardware & software R&D

Study ν-Ar interactions

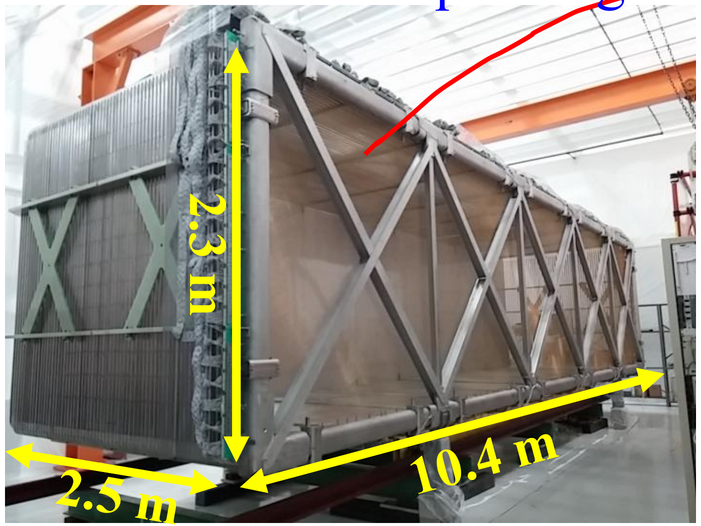




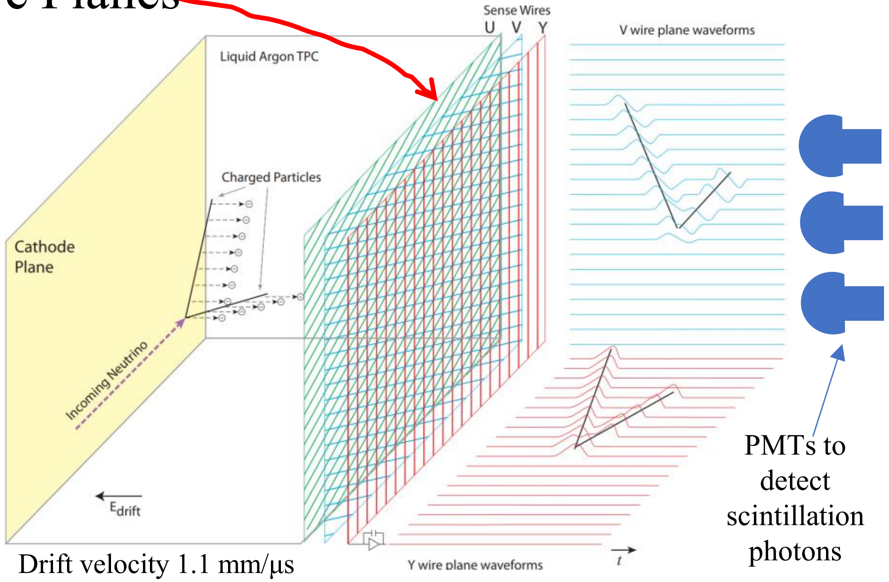

中微子束流
吸收体
衰变通道
聚焦管道和靶
质子束流
π^-
ν_μ
π^+
ν_e
μ^+
费米实验室
BOOSTER RING
8 GeV Protons
LEDERMAN SCIENCE CENTER
NuMI beam (8° off-axis)
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MINOS/
SBN NEAR DETECTOR
SciBooNE DETECTOR
ν_μ
MicroBooNE
BNB beam (on-axis)
Target Hall
100m
600m

Detector: Liquid Argon Time Projection Chamber (LArTPC)

85-ton active liquid Argon



Wire Planes



Drift velocity 1.1 mm/μs

PMTs to detect scintillation photons

Full-Active Tracking Calorimeter

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

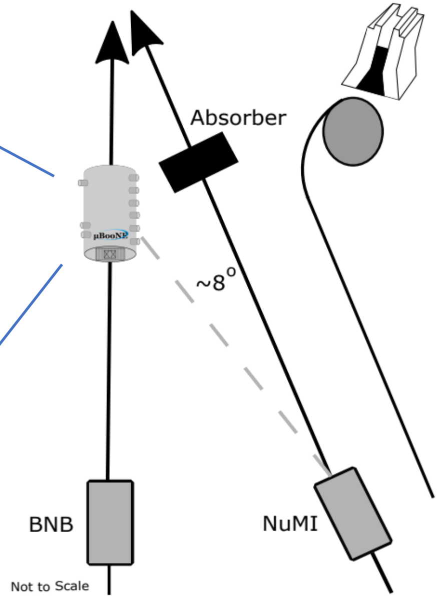
Excellent Particle Identification

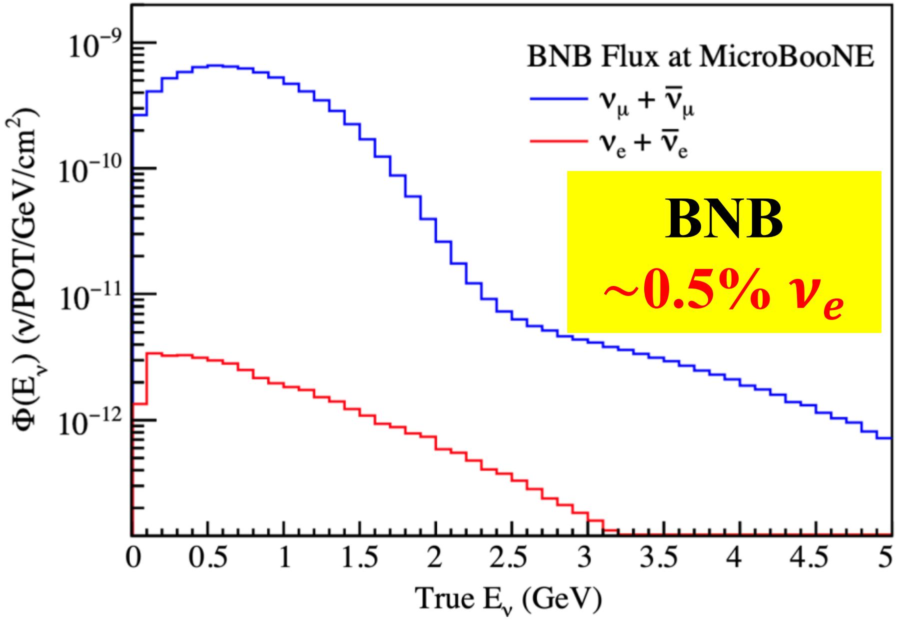
- Final states topological and calorimetric
- Track and shower identification
- Electron and photon shower separation
- Distinguish muons, protons, pions

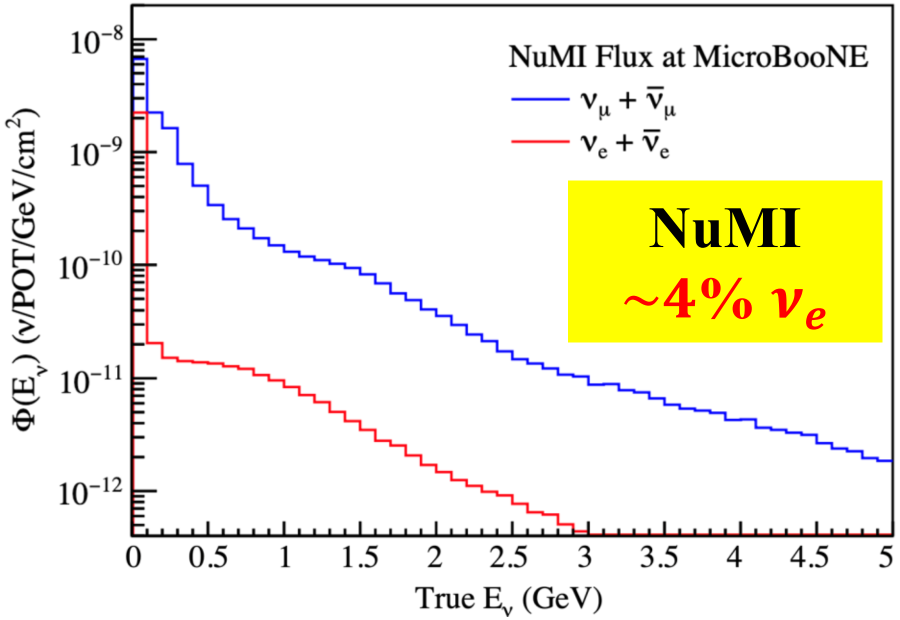
https://microboone.fnal.gov/documents-publications/

Two Beams

85-ton active liquid Argon



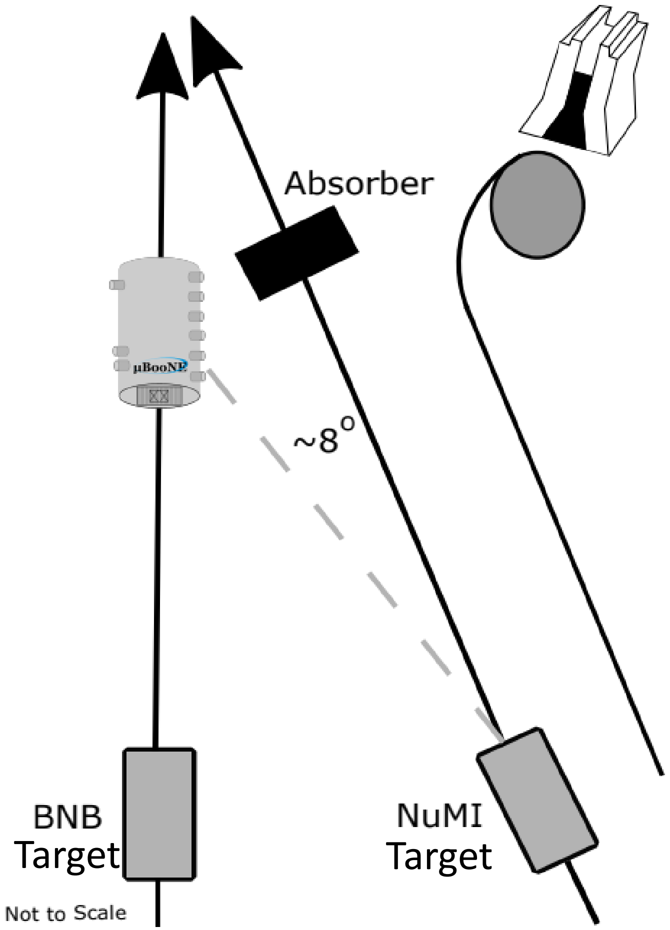




Two Neutrino Beams

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

One Detector with Two Beams
Breaking the Cancellation of ν_e App. and Disapp.

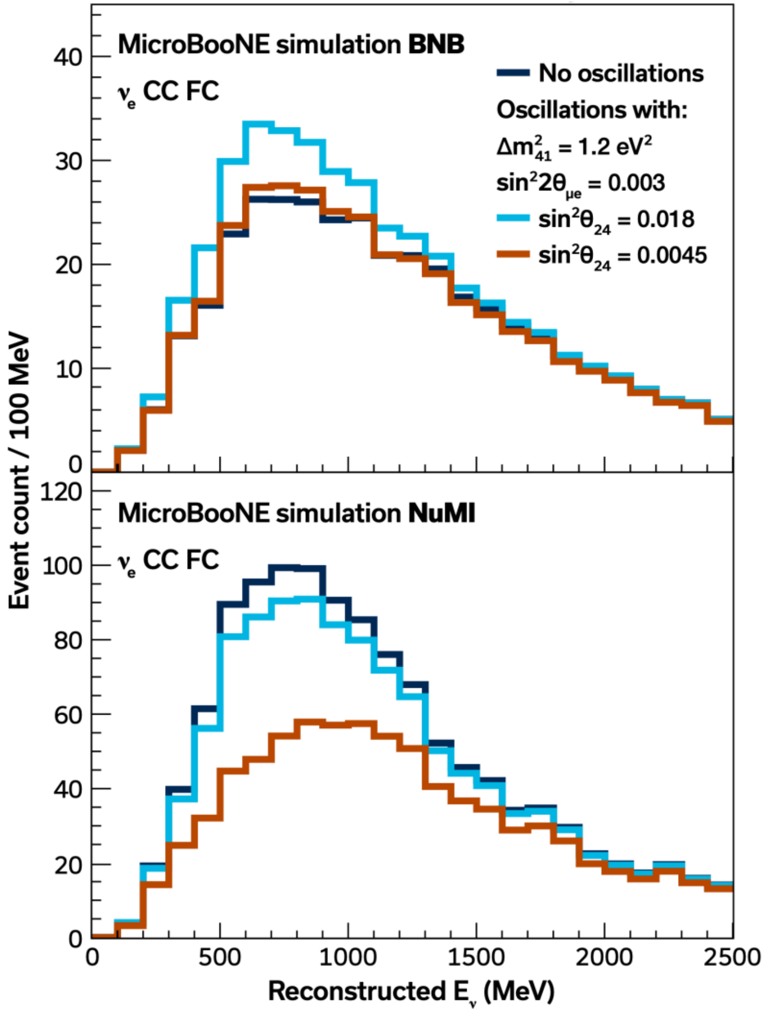


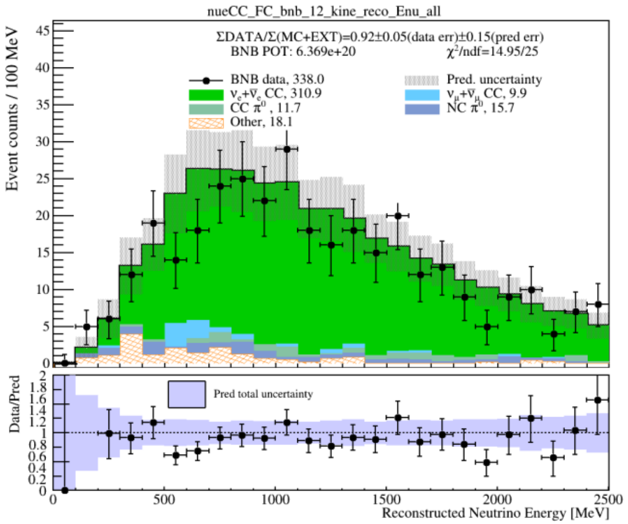
$$N_{\nu_e} = \boxed{N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e}} + \boxed{N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \boxed{(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1)} \cdot \sin^2 2\theta_{14} \cdot \sin^2\Delta_{41}\right]$$

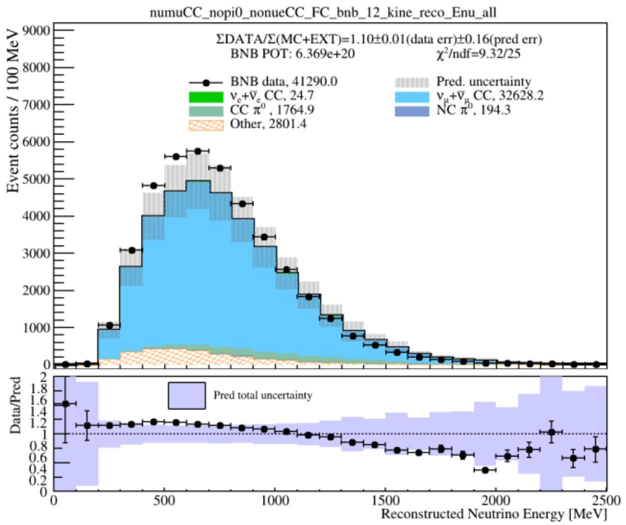
- Degeneracy when $\sin^2\theta_{24}$ approaches R_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)

At MicroBooNE	R_{ν_e/ν_μ} Average
BNB beam	~0.005
NuMI beam	~0.04

Significant difference in the ν_μ/ν_e flux ratio in BNB and NuMI
→ mitigate the degeneracy







ν_eCC Fully Contained

ν_eCC Partially Contained

ν_μCC Fully Contained

Simultaneous Fit of 14 channels (2x beams)

ν_μCC Partially Contained

CCπ^0 Fully Contained

CCπ^0 Partially Contained

NCπ^0

All Selection Channels: BNB (7) + NuMI (7) = 14 Channels

Constraint Power for Total Systematics

Systematics of ν_e CC channels

	BNB FC	BNB PC	NuMI FC	NuMI PC
Systematic uncertainties on CC ν_e signal samples				
Neutrino flux prediction	5.9%	6.1%	19.6%	19.7%
Neutrino interaction uncertainties	14.7%	14.0%	17.5%	15.1%
Detector uncertainties	3.3%	3.2%	2.0%	3.9%
Monte Carlo statistics	1.57%	1.95%	1.16%	1.67%
Total unconstrained uncertainty	16.3%	15.8%	26.4%	25.2%
Total constrained uncertainty	4.5%	5.5%	5.8%	5.9%

Before constraints

After constraints

Systematics are reduced by 3~4 factor

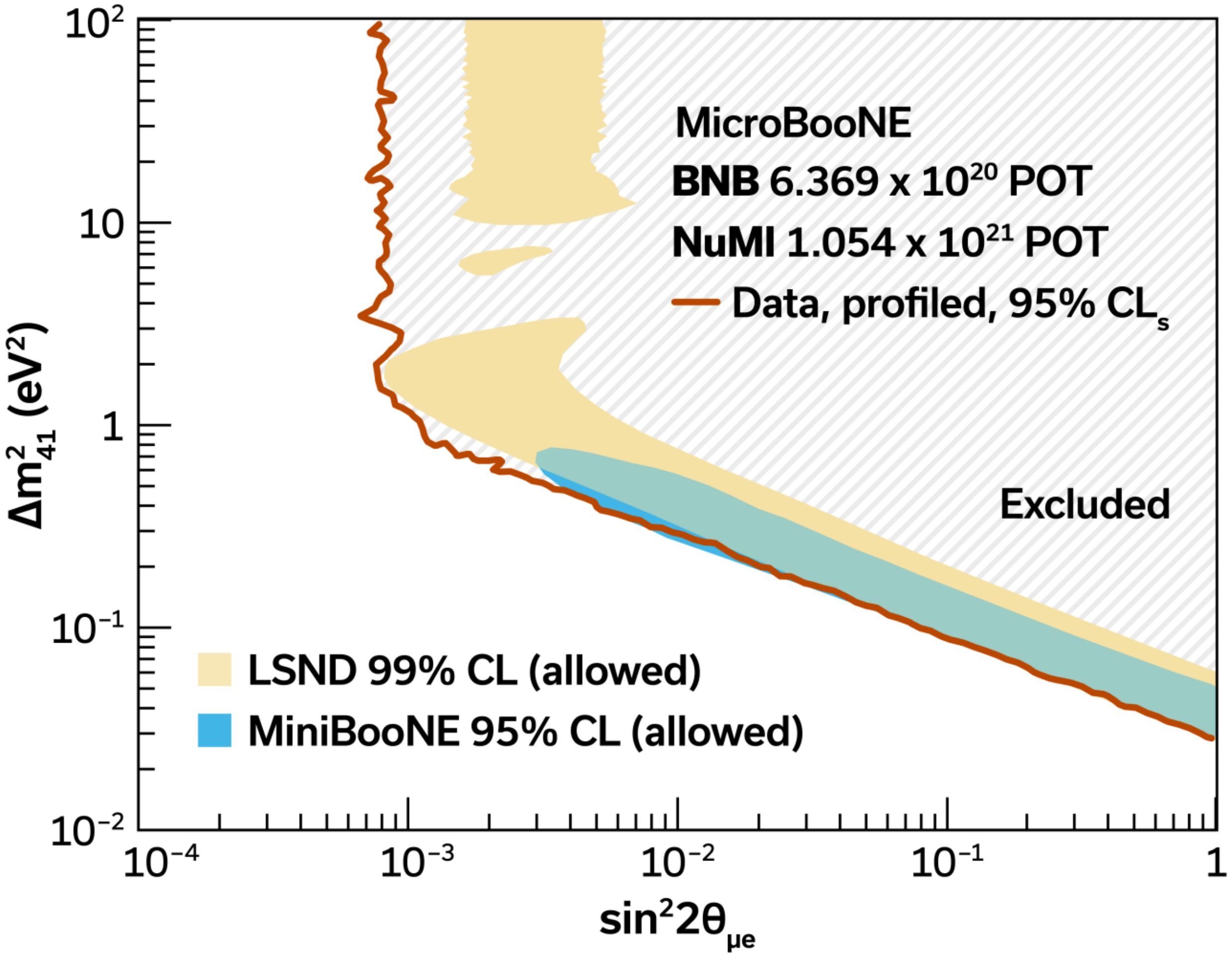
Two Beams: ν_e Appearance Result ($\nu_\mu \rightarrow \nu_e$)

MicroBooNE data at 95% CL

- **Excludes LSND 99% allowed region**
- **Excludes vast majority of MiniBooNE 95% allowed region**

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\mu e}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$

$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$



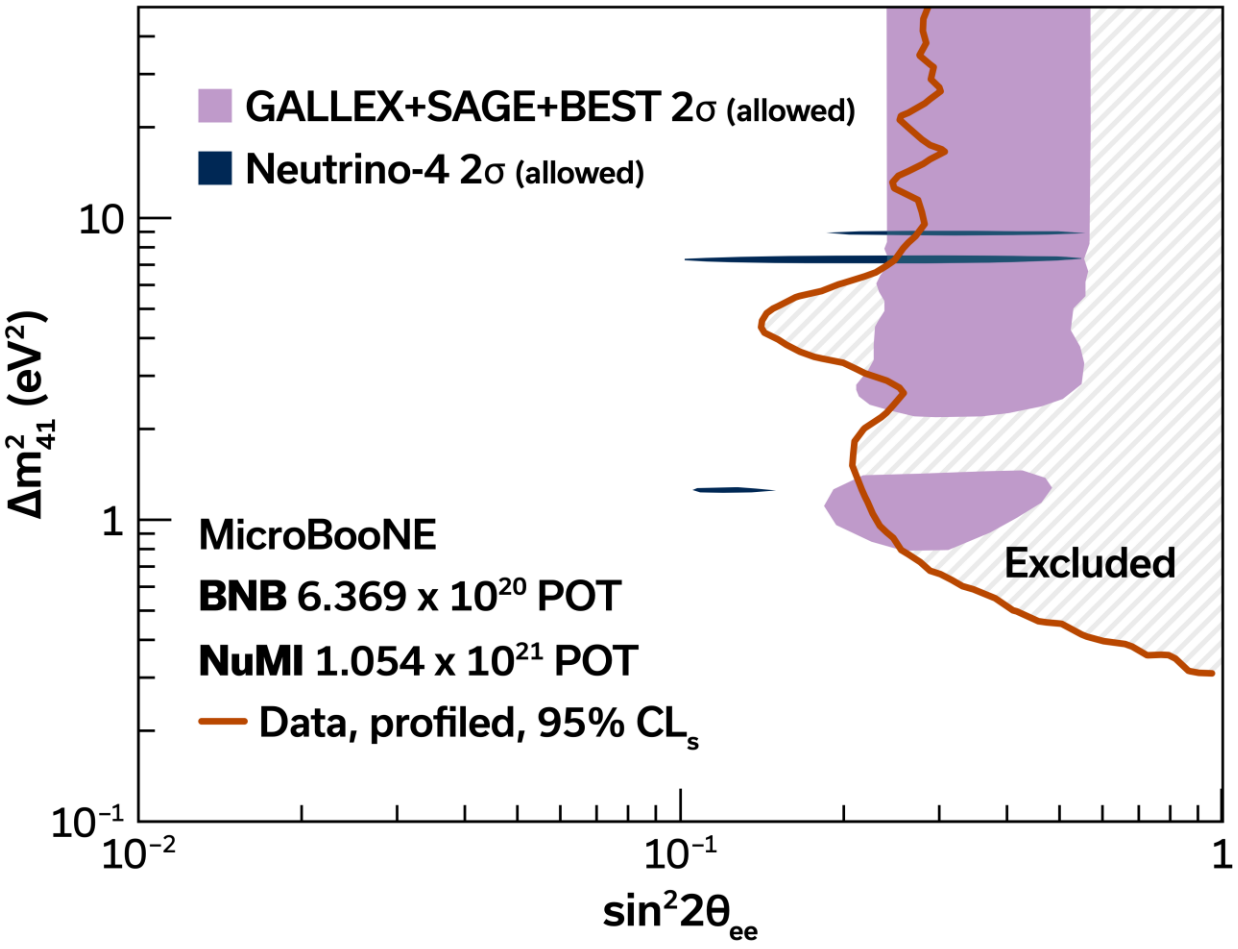
Two Beams: ν_e Disappearance Result ($\nu_e \rightarrow \nu_e$)

MicroBooNE data at 95% CL

- **Excludes most of the Gallium allowed region**
- **Excludes part of the Neutrino-4 allowed region**

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2(2\theta_{ee}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$

$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$$



Two Beams: ν_μ Disappearance Result $(\nu_\mu \rightarrow \nu_\mu)$

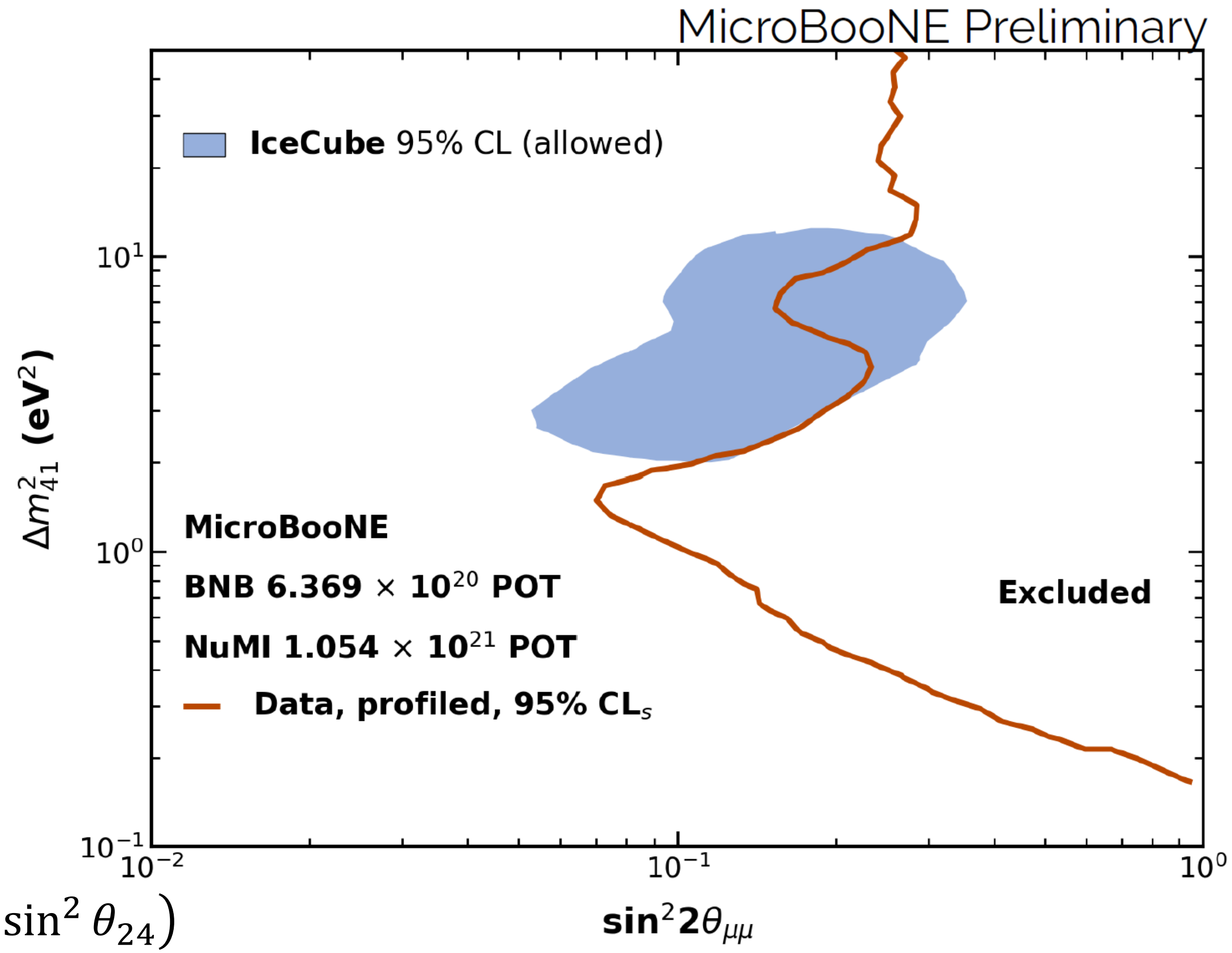
New!

MicroBooNE data at 95% CL

- **Excludes part of the IceCube allowed region**
- **The date results are largely impacted by conservative detector systematics.**

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2(2\theta_{\mu\mu}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$

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

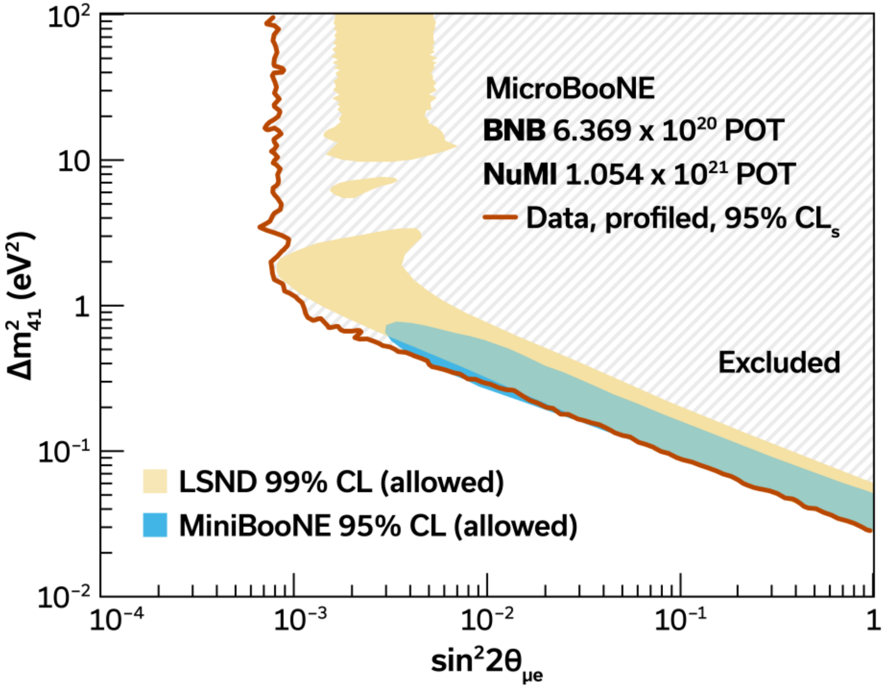


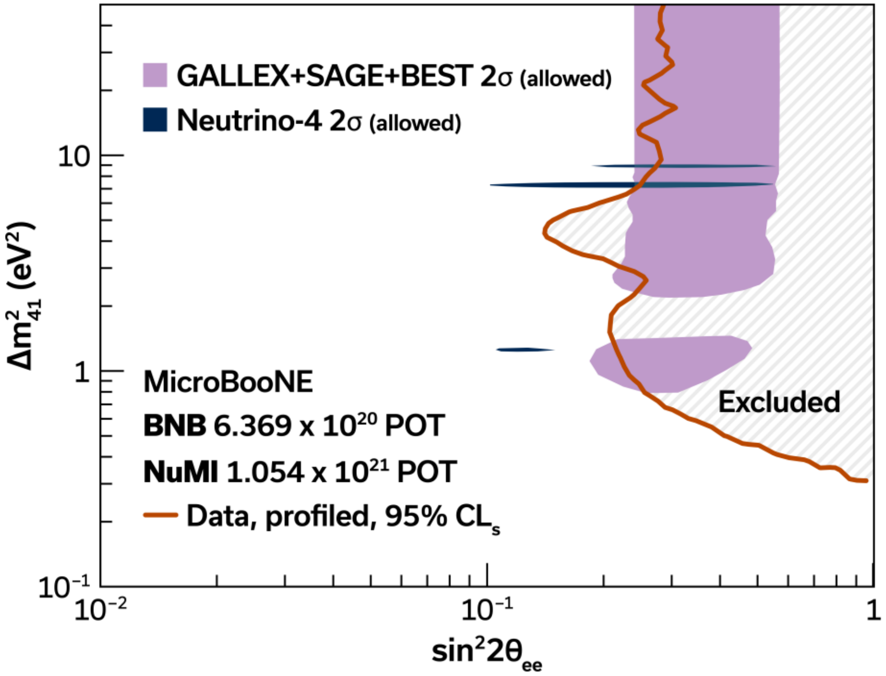
Summary

Nature 648, 64–69 (2025, December)

- In the **first analysis of its kind**, MicroBooNE has tested the 3+1 sterile neutrino model
  - **Two beams, One detector**
  - Neutrino appearance and disappearance **simultaneous search** in one experiment

- MicroBooNE sees **no sign** of 3+1 sterile-neutrino-induced oscillations that would explain the MiniBooNE and LSND anomalies, **closing the window on the 3+1 explanation.**



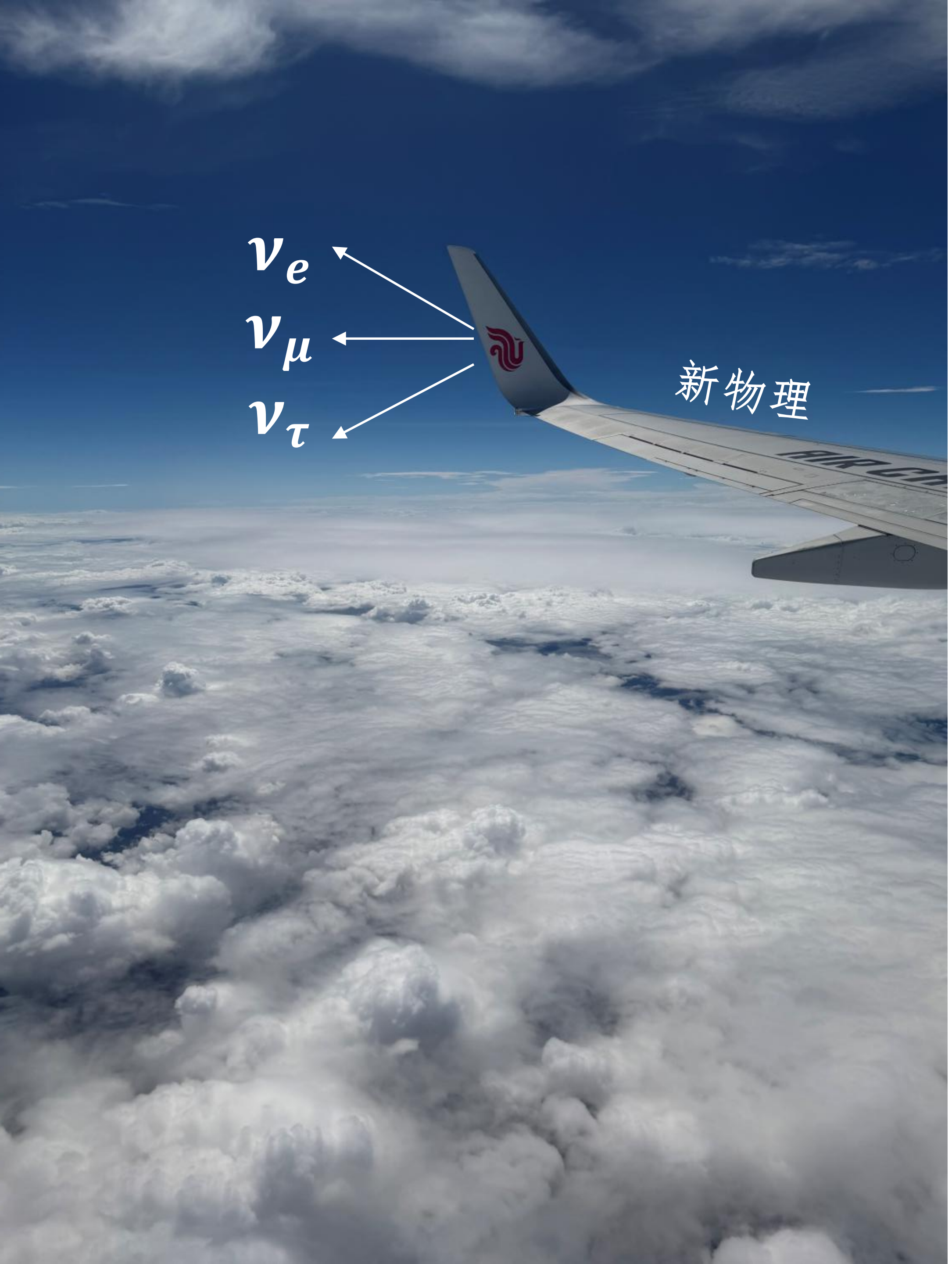


Although the 3+1 framework no longer provides a viable explanation,
the LSND and MiniBooNE anomalies themselves haven't gone away.

The reactor and gallium anomalies also remain unresolved.

These anomalies continue to drive a global program of current and next-generation experiments aimed at resolving the remaining possibilities.

Baksan Experiment (BEST)



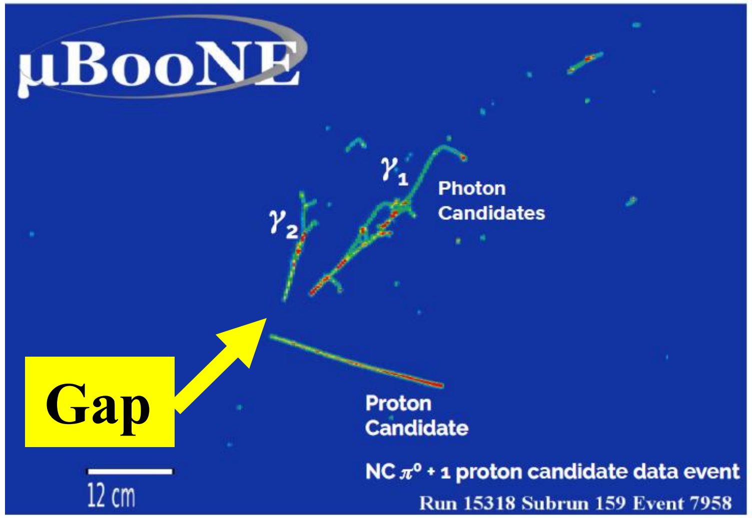
请各位专家批评指正

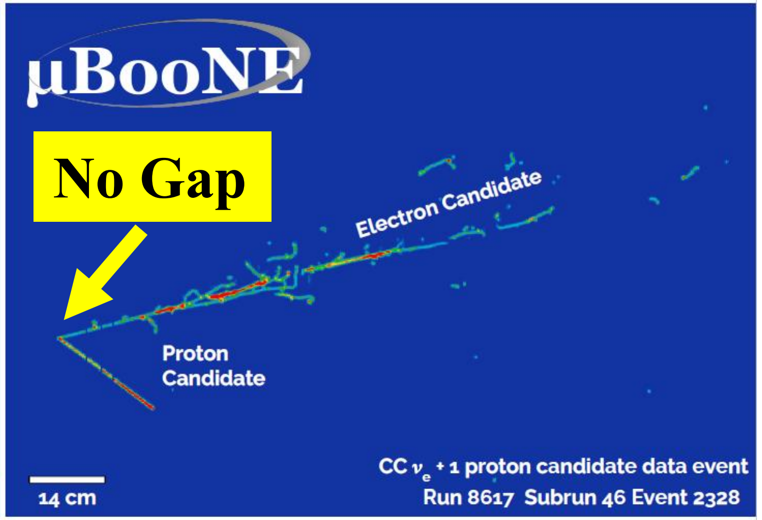
谢谢

Backup

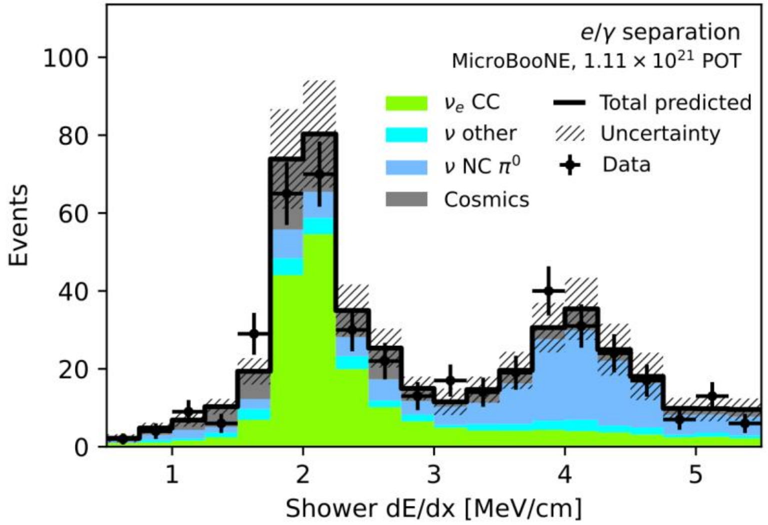
Electron and Photon shower Separation

Gap between shower start point and ν vertex





Electron 1-MIP vs. photon 2-MIPs



Full-Active Tracking Calorimeter

- mm-level position resolution
- 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/

3+1 Sterile Neutrino Search at MicroBooNE

- **"3+1"** ν_e electron neutrino, ν_μ muon neutrino, ν_τ tau neutrino, ν_s sterile neutrino

- **Full "3+1" analysis –** all <u>detectable</u> oscillation effects

$\nu_\mu \to \nu_e$ Appearance

$\nu_e \to \nu_e$ Disappearance

$\nu_\mu \to \nu_\mu$ Disappearance

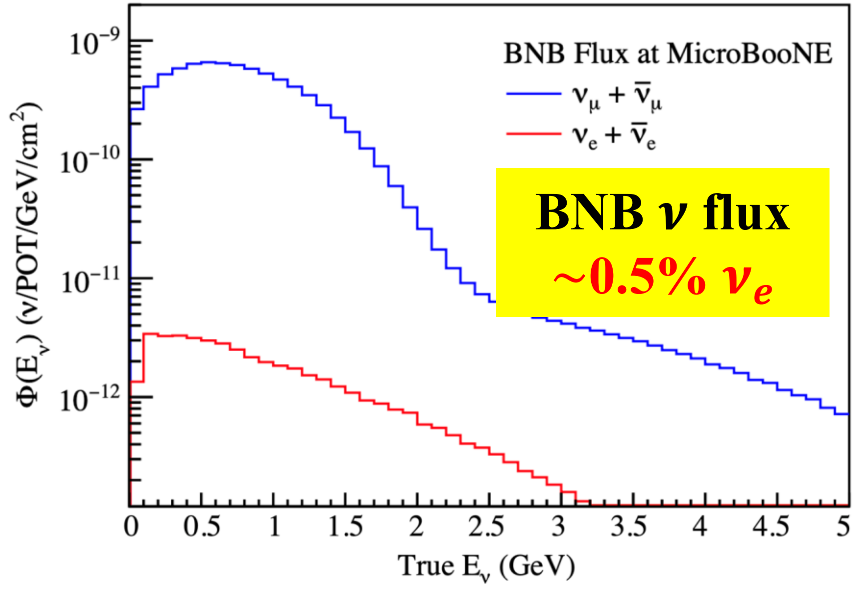
Three main oscillation effects

$\nu_e \to \nu_\mu$

$\boxed{\nu_e \quad \nu_\mu} \to \boxed{\nu_\tau \quad \nu_s}$

Negligible channels in data

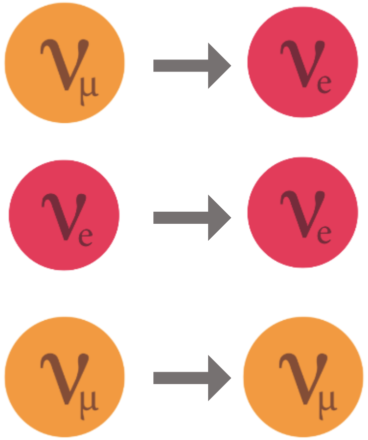
(small number of ν_e and neutral current events)



3+1 Sterile Neutrino Search at MicroBooNE

- **“3+1”**

- **Full “3+1” analysis –** all <u>detectable</u> oscillation effects



Appearance

Disappearance

Disappearance

- However …
- We only have one detector
- Because of ν_e intrinsic contamination from beam:
- **Cancellation effect between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_e$**

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

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

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

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

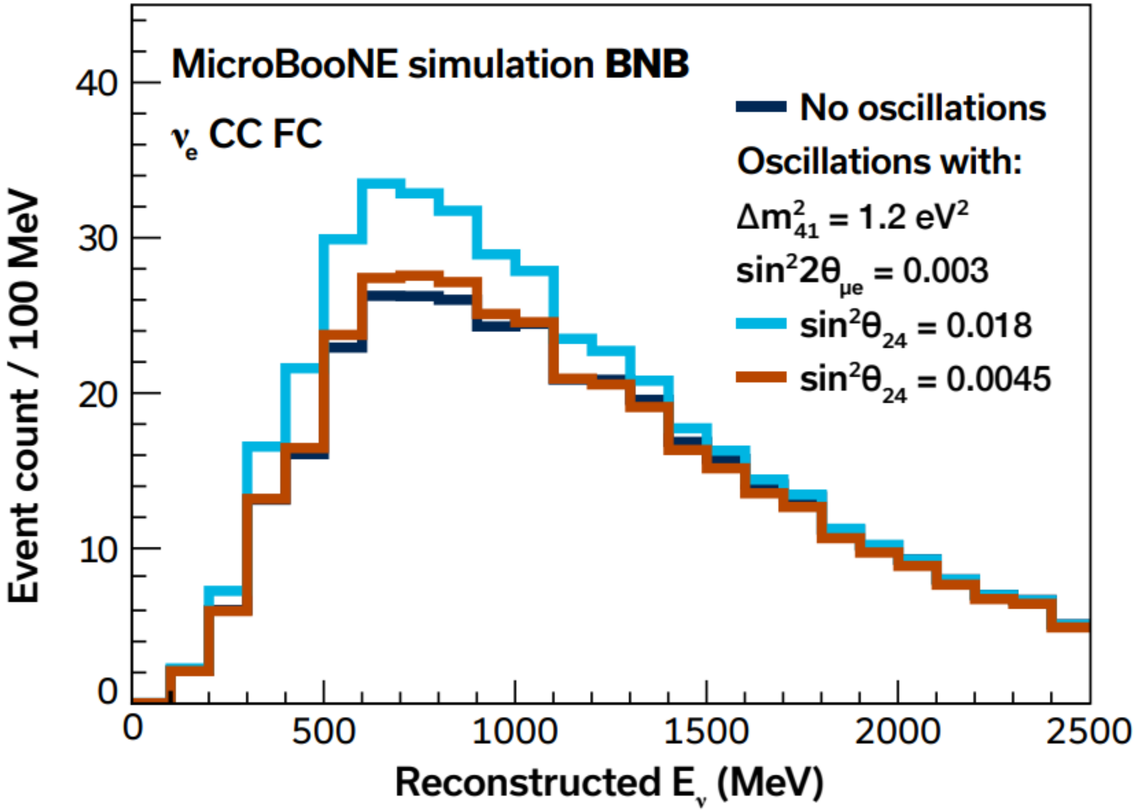
3+1 Sterile Neutrino Results
Limited by the Cancellation of ν_e Appearance and Disappearance

- Observed ν_e events are a combination result of ν_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_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)

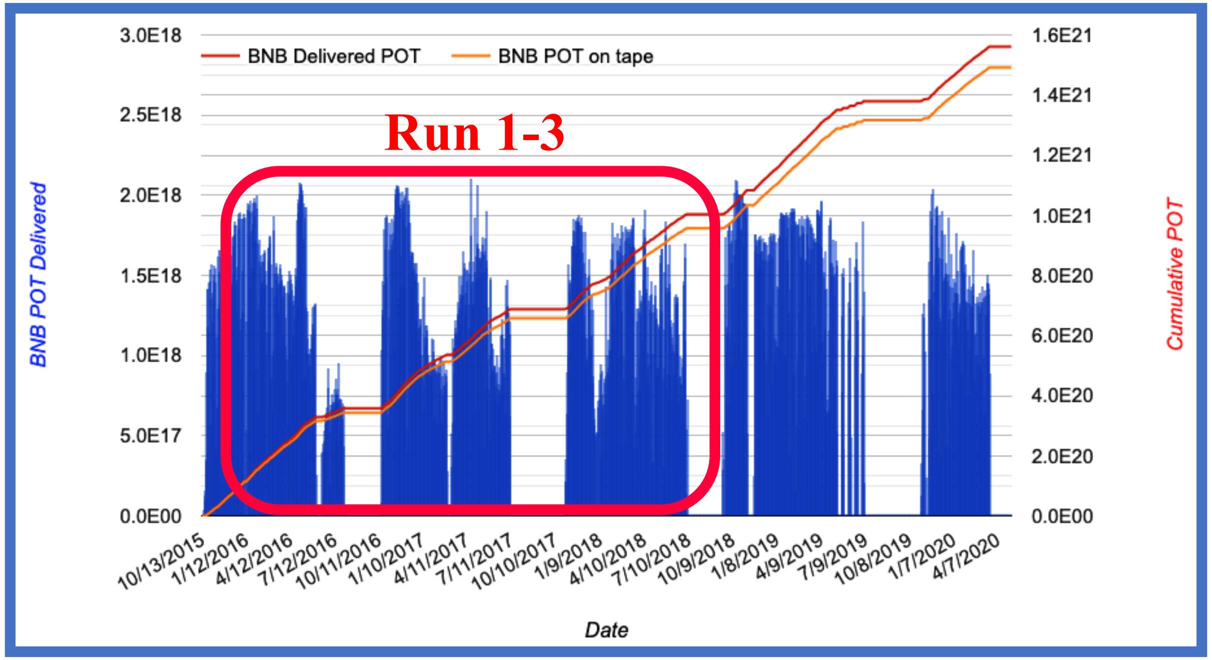
At MicroBooNE	R_{ν_e/ν_μ} Average
BNB beam	~0.005

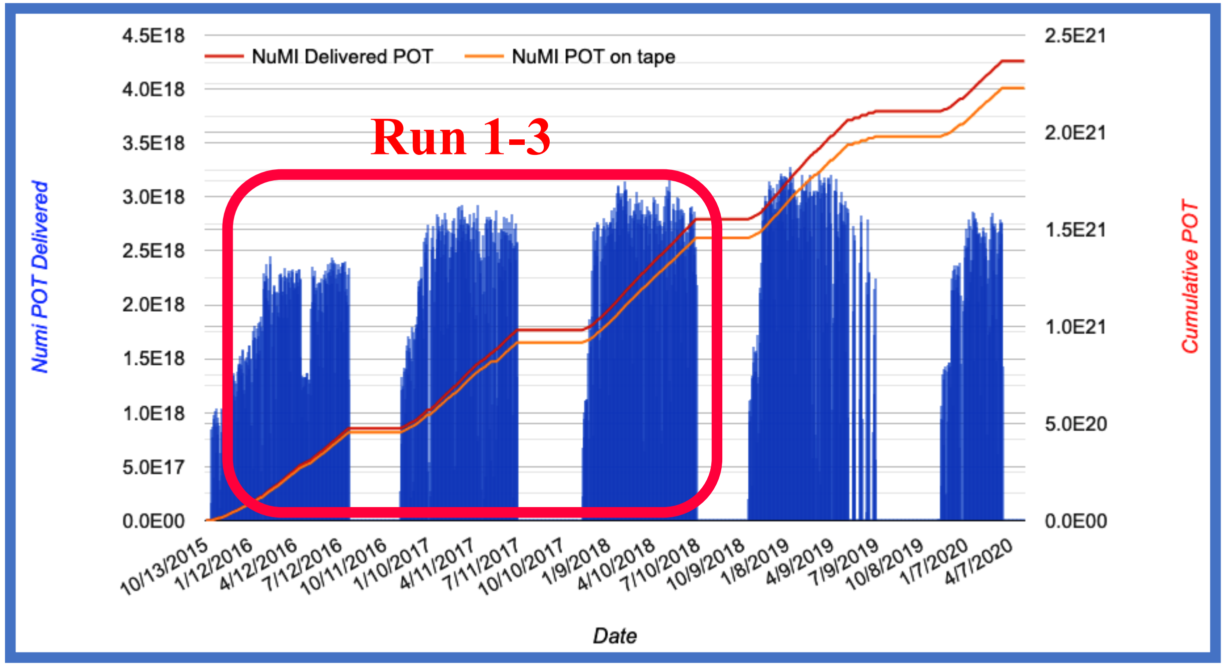


MicroBooNE Data Taking

On-axis BNB 6.37×10^{20} POT

Off-axis NuMI 1.05×10^{21} POT





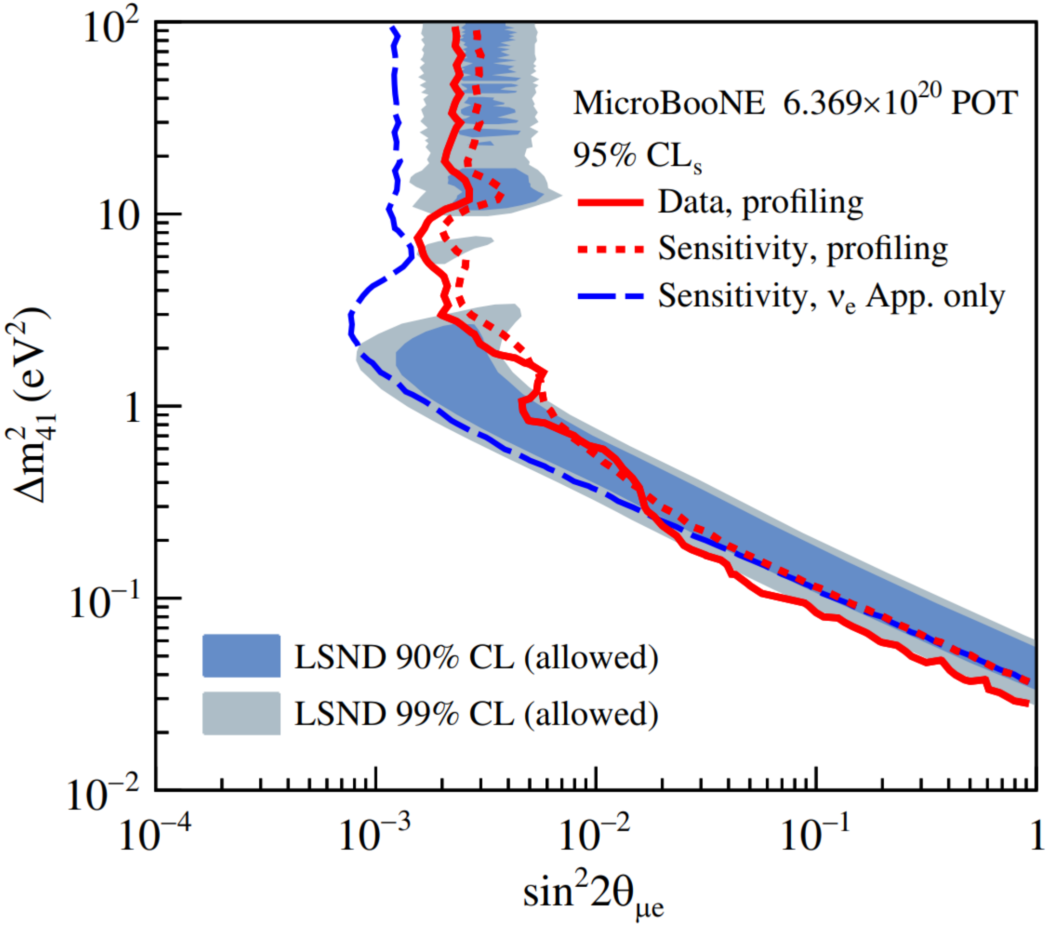
- Current Analysis uses ~half of full MicroBooNE data cross two beams
- BNB dataset same as previous published (2023 PRL), NuMI dataset added

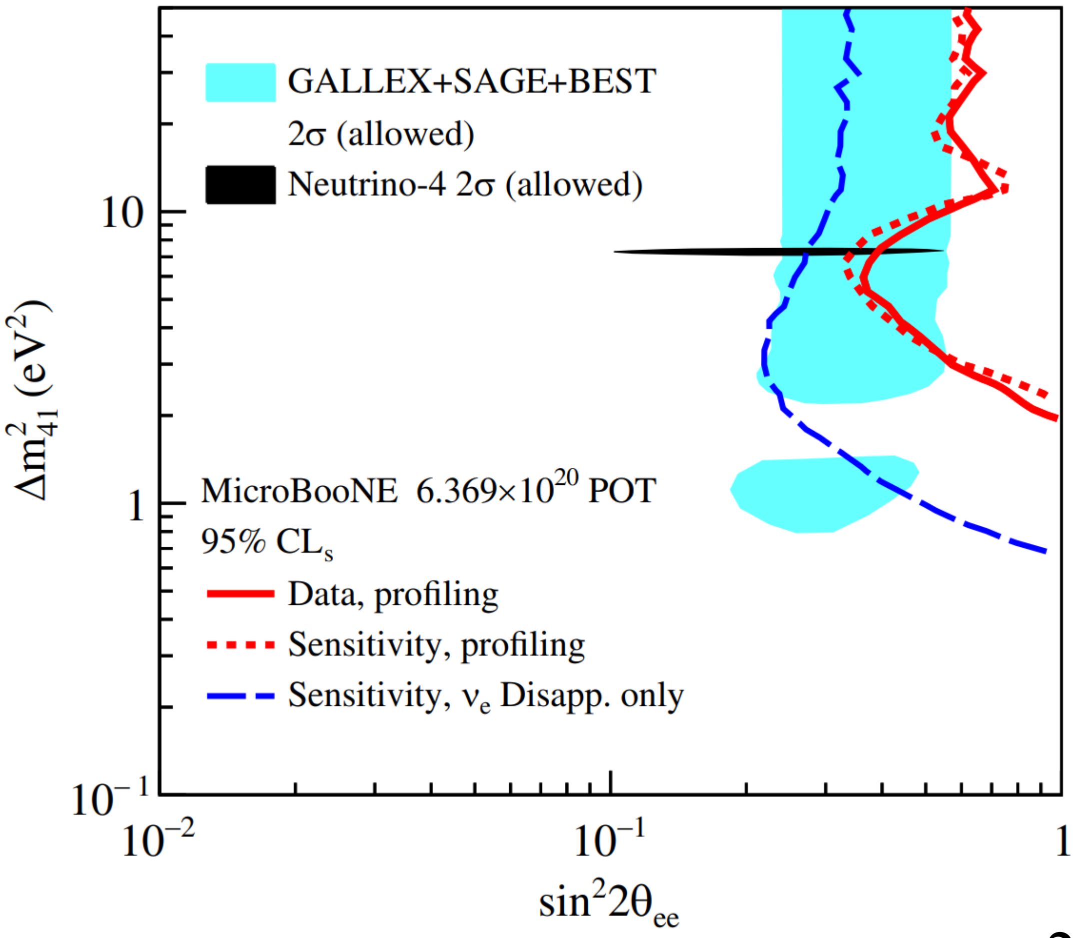
BNB [almost pure ν_μ]
very sensitive to ν_e appearance!

NuMI [much larger ν_e content]
more sensitive to ν_e disappearance!

3+1 Sterile Neutrino Oscillations Results by using BNB data

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





Event Reconstruction via Wire-Cell Package

JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)

JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

Phys. Rev. Applied 15 064071 (2021)

JINST 17 P01037 (2022)

Noise Filtering

Signal Processing

3D imaging

Clustering

Charge-Light matching

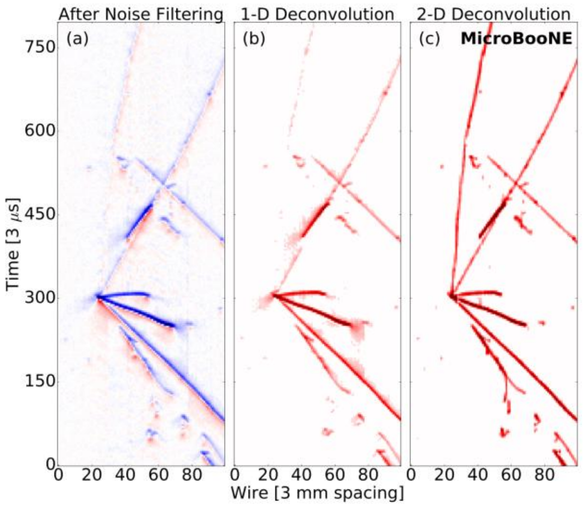
3D trajectory
&
dQ/dx fitting

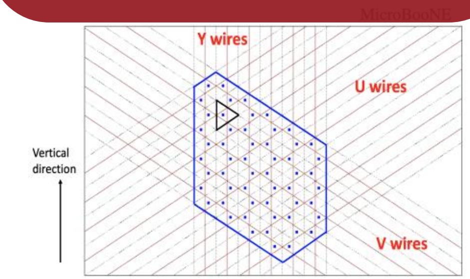
Cosmic muon tagger

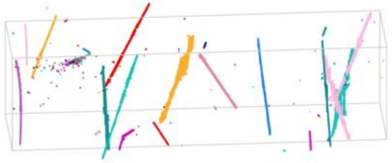
Multi track fitting

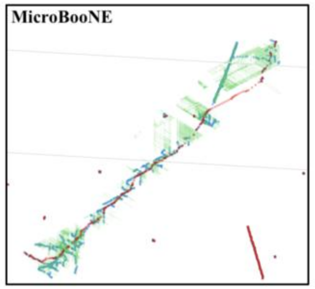
3D vertexing

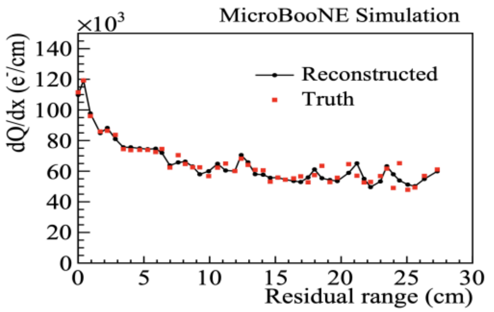
Particle identification

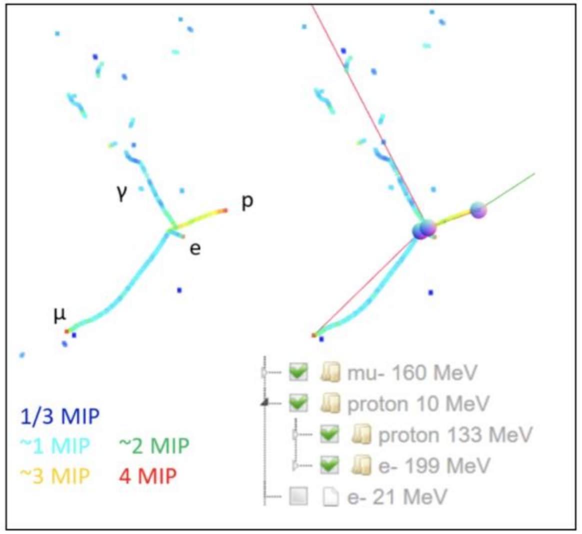








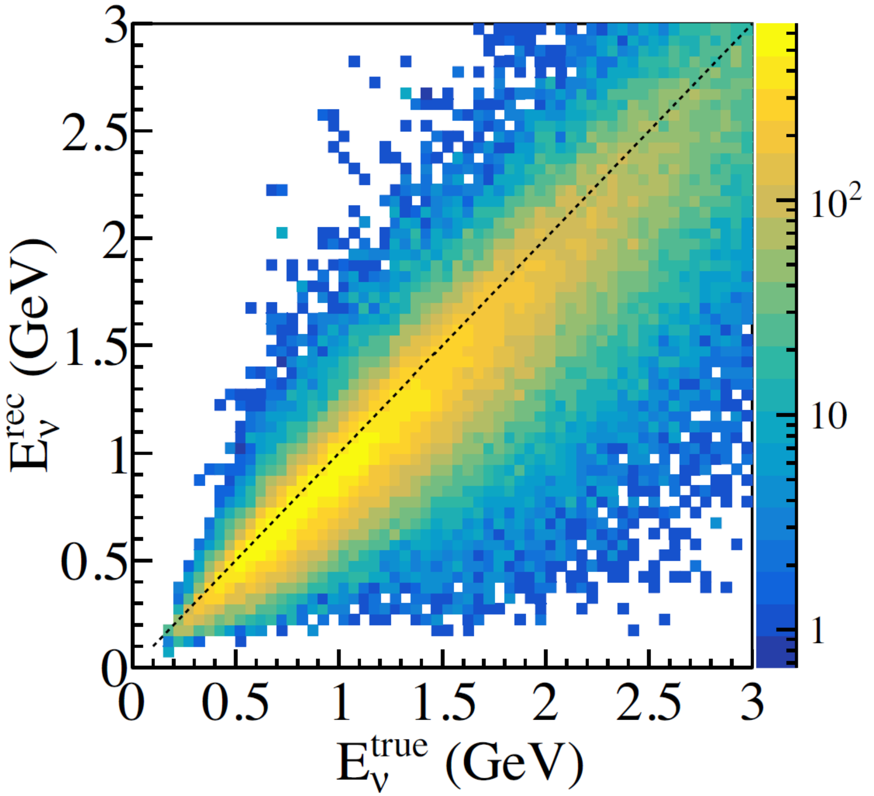




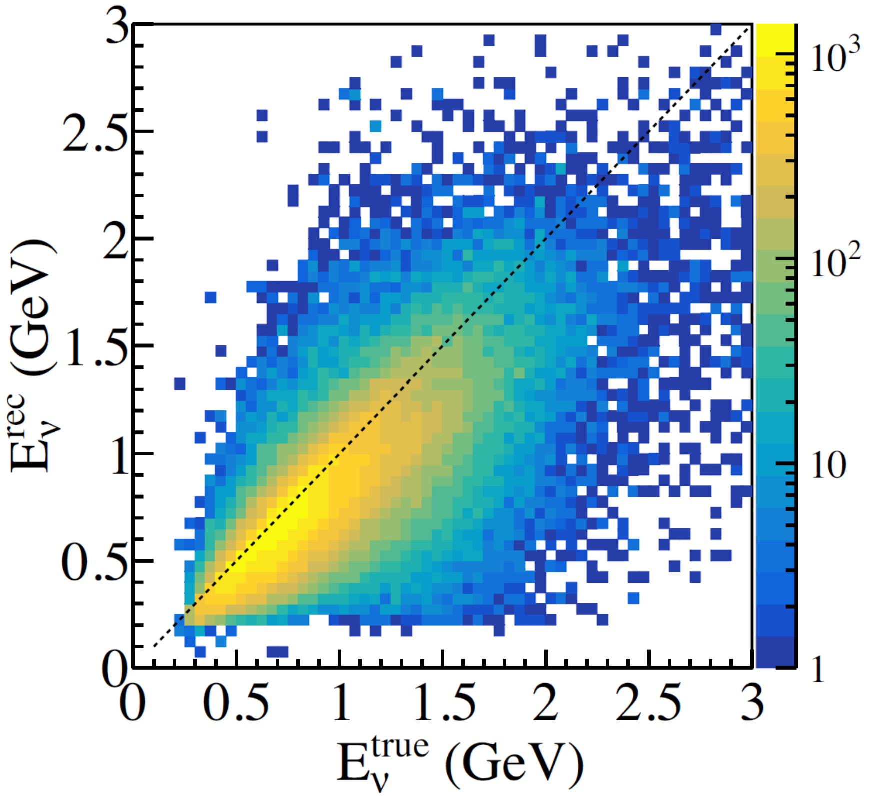
Event Energy Resolution

- Reconstruction built upon Wire-cell, enabling superb performance
- Full inclusive ν_eCC (charged-current) and ν_μCC selections

ν_eCC: resolution 10~15%, bias ~7%

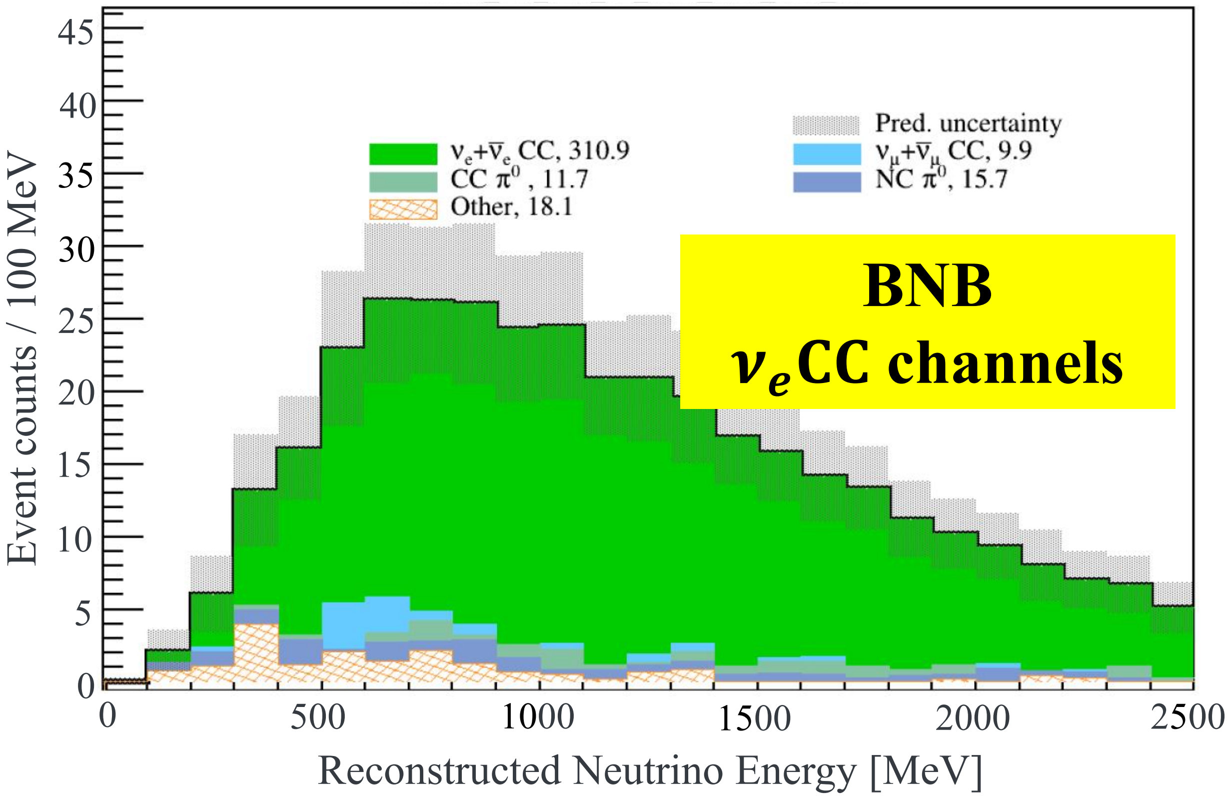


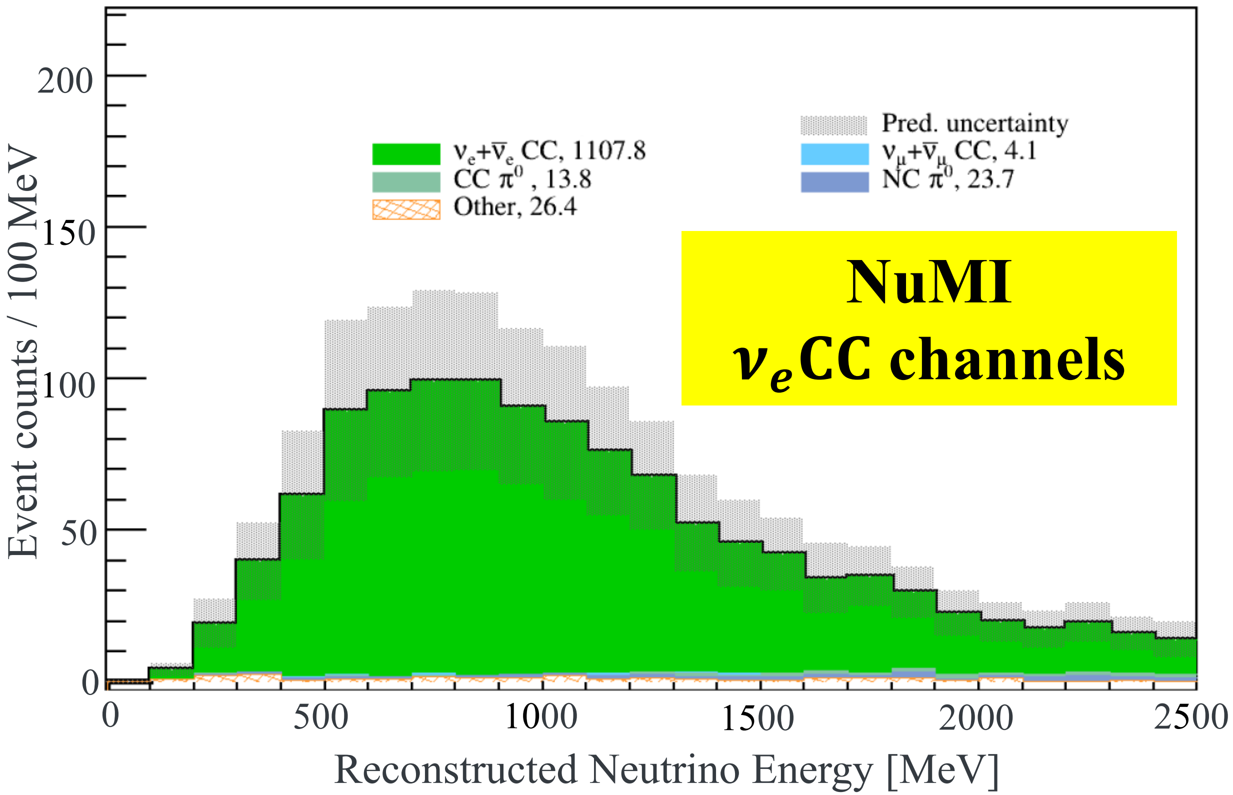
ν_μCC: resolution 15~20%, bias ~10%



Target Channels: ν_eCC

- Reconstruction built upon Wire-cell, enabling superb performance
- Full inclusive ν_eCC (charged-current) and ν_μCC selections
- ν_eCC channels ~85% purity, 50~60% efficiency
- ν_μCC channels ~90% purity, 60~70% efficiency





Constraint Power: Cross-Section Systematics

Leverage correlations to constrain the cross section model and its uncertainty

Constraint with BNB ν_μ

BNB ν_e
Only Cross Section Syst.

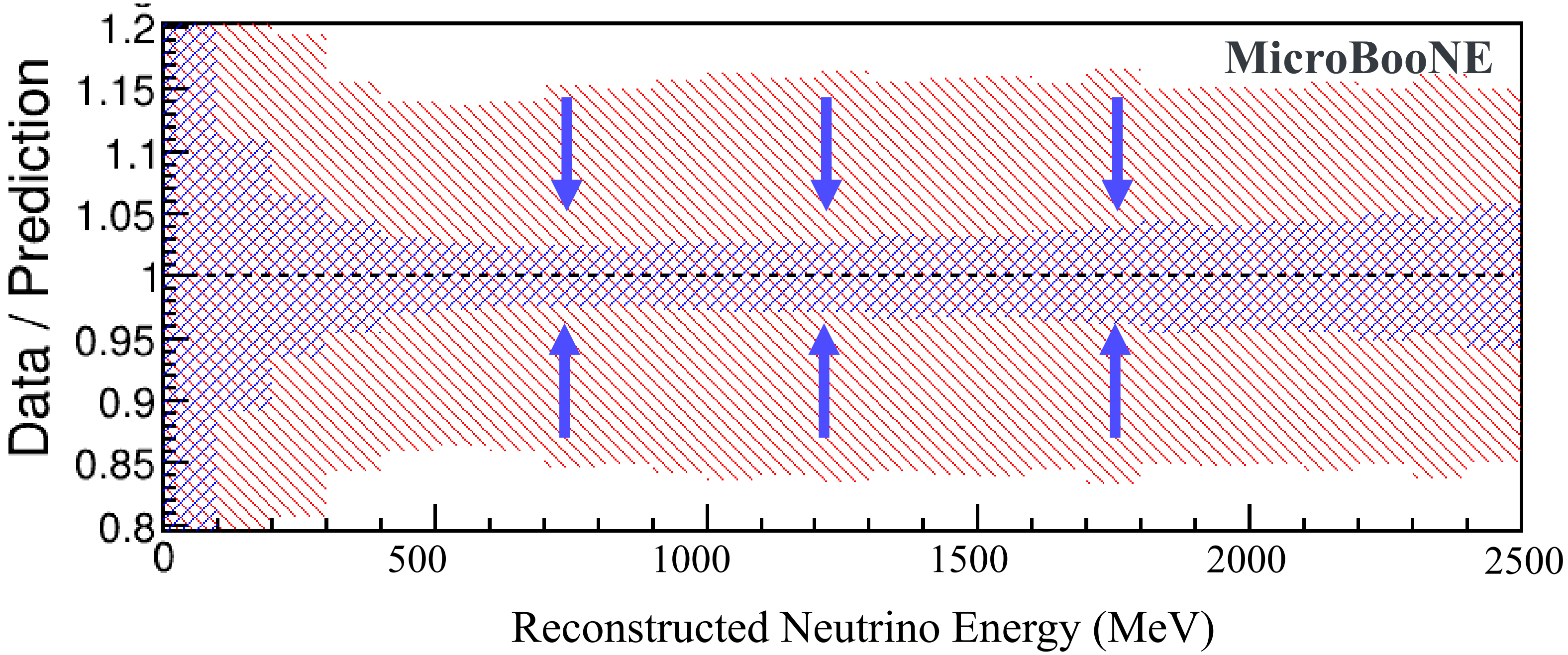
Conditional expectation & covariance

$$\mu_{X,Y} = \begin{pmatrix}\mu_X \\ \mu_Y\end{pmatrix}, \quad \Sigma_{X,Y} = \begin{pmatrix}\Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY}\end{pmatrix}$$

$$\mu_{Y|X} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X)$$

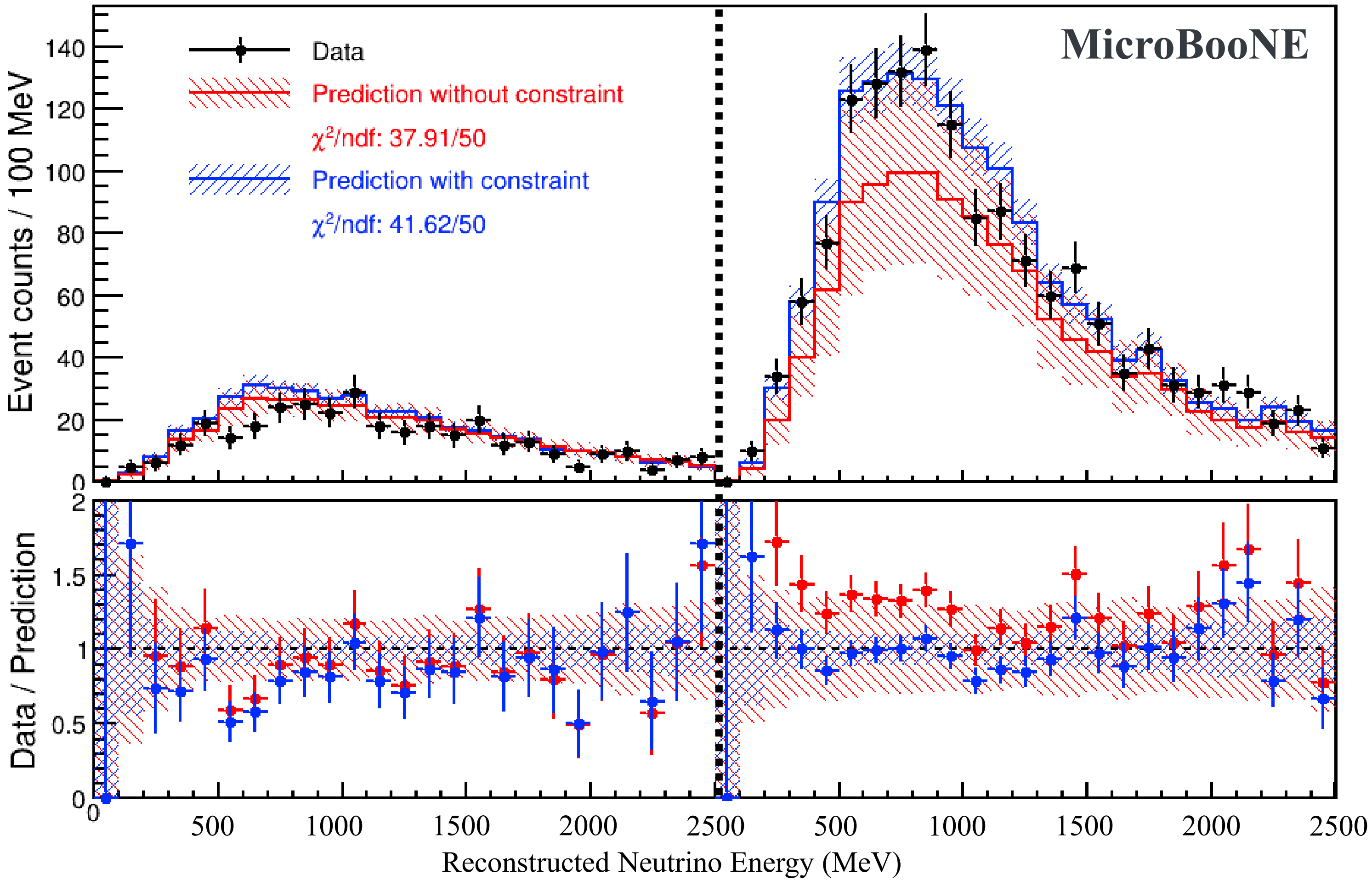
$$\boldsymbol{\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}}$$

PRD 105, 112005 (2022)



ν_eCC Channels with Constraints by All Non- ν_e Channels

BNB **NuMI**



Conditional expectation & covariance

$$\mu_{X,Y} = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \quad \Sigma_{X,Y} = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$$

$$\mu_{Y|X} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X)$$

$$\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}$$

PRD 105, 112005 (2022)

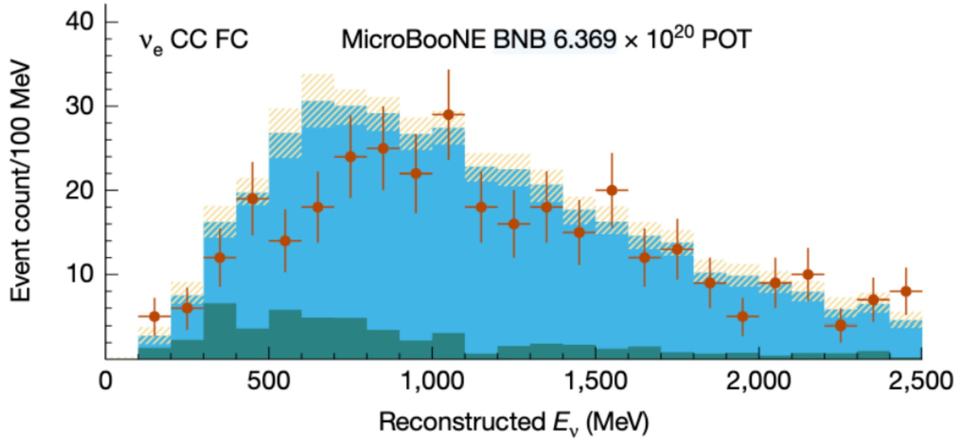
3+1 Sterile Neutrino Search: BNB+NuMI result

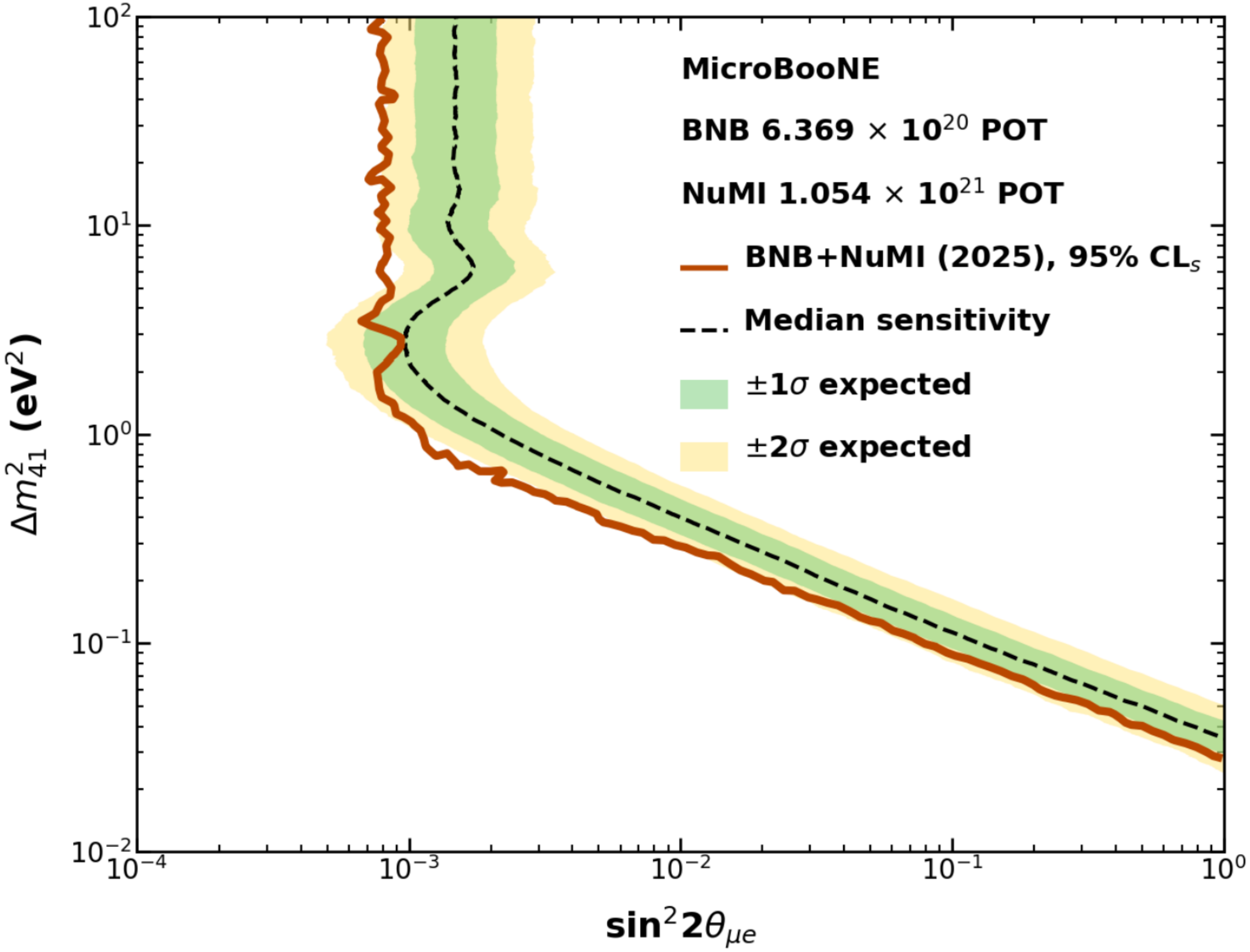
μBooNE

$\nu_\mu \rightarrow \nu_e$

Nature 648 64-69 (2025)

BNB CC ν_e

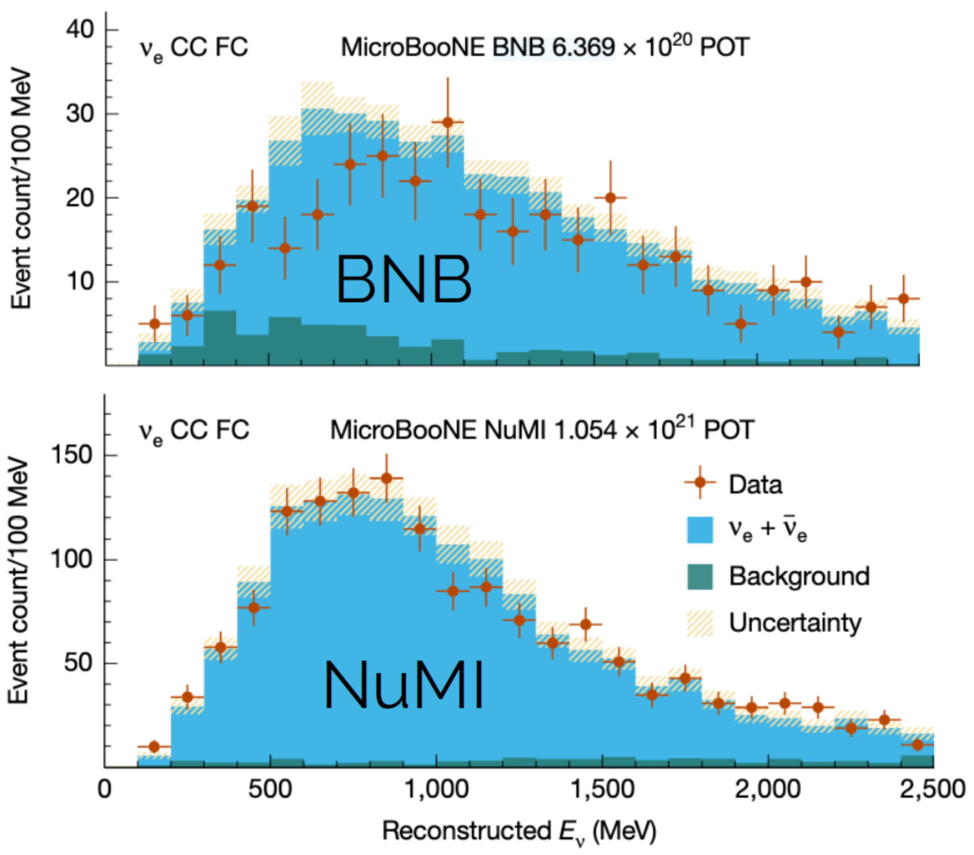




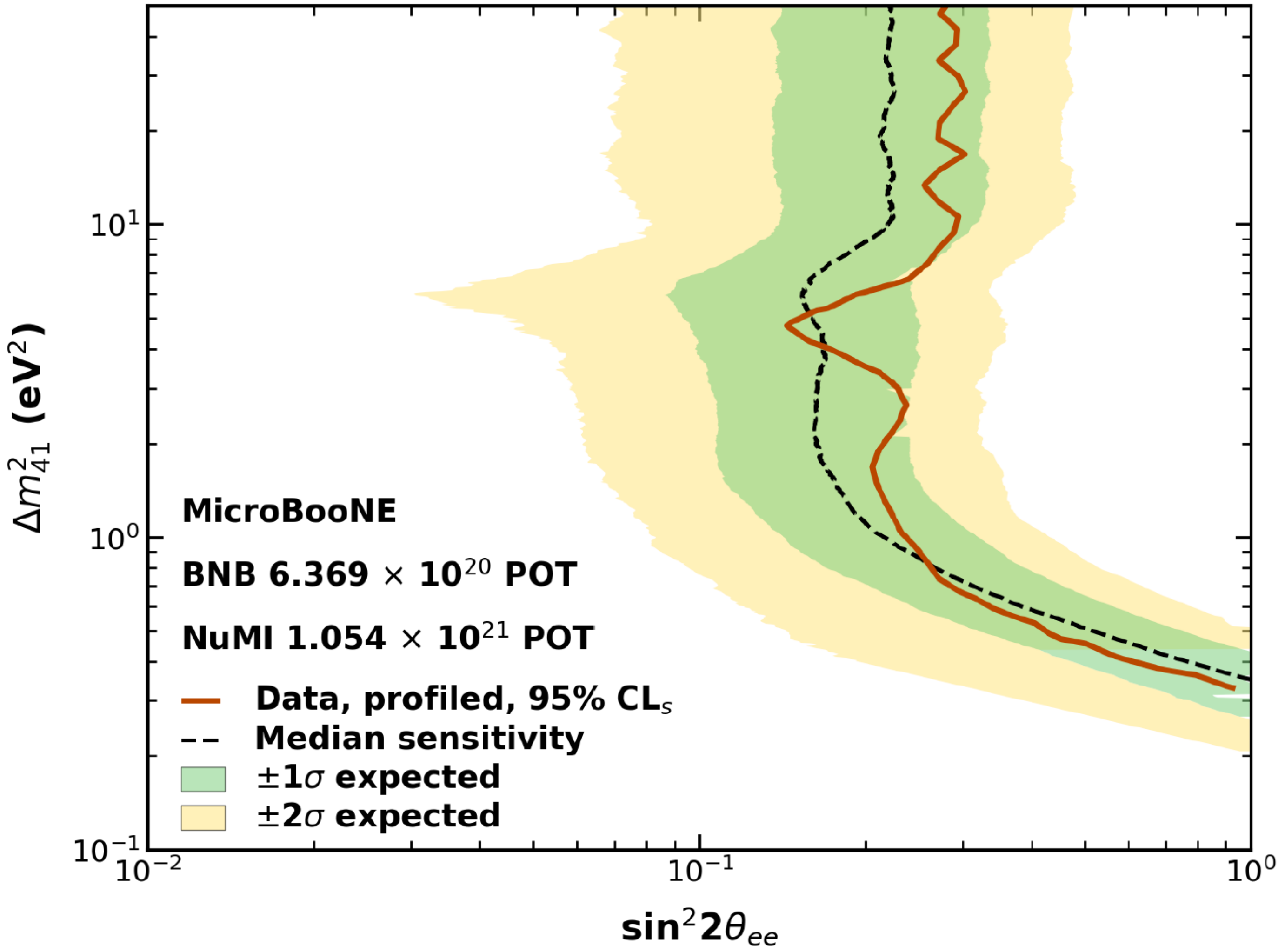
data exclusion is stronger than median sensitivity: driven by deficit in BNB ν_e sample

3+1 Sterile Neutrino Search: BNB+NuMI result

$\nu_e \rightarrow \nu_e$



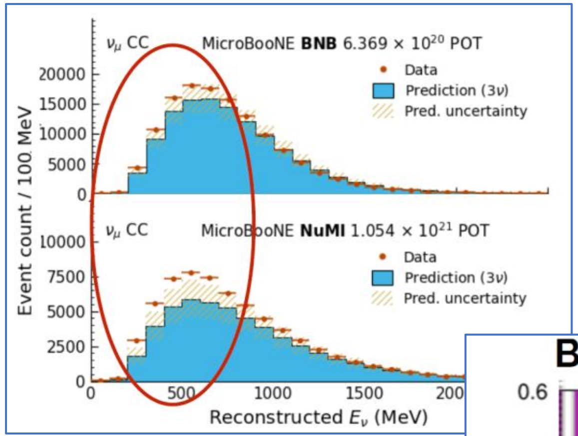
Nature 648 64-69 (2025)

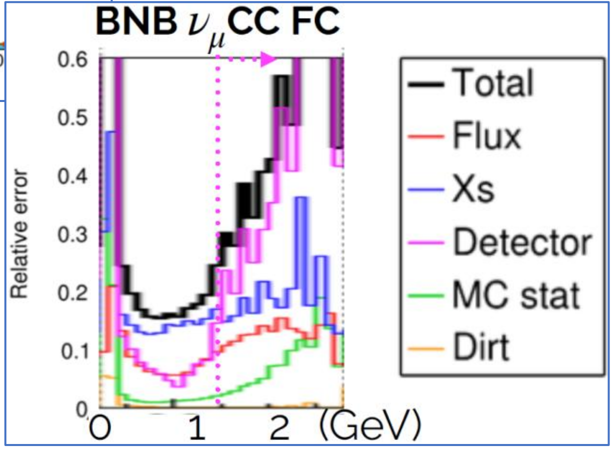


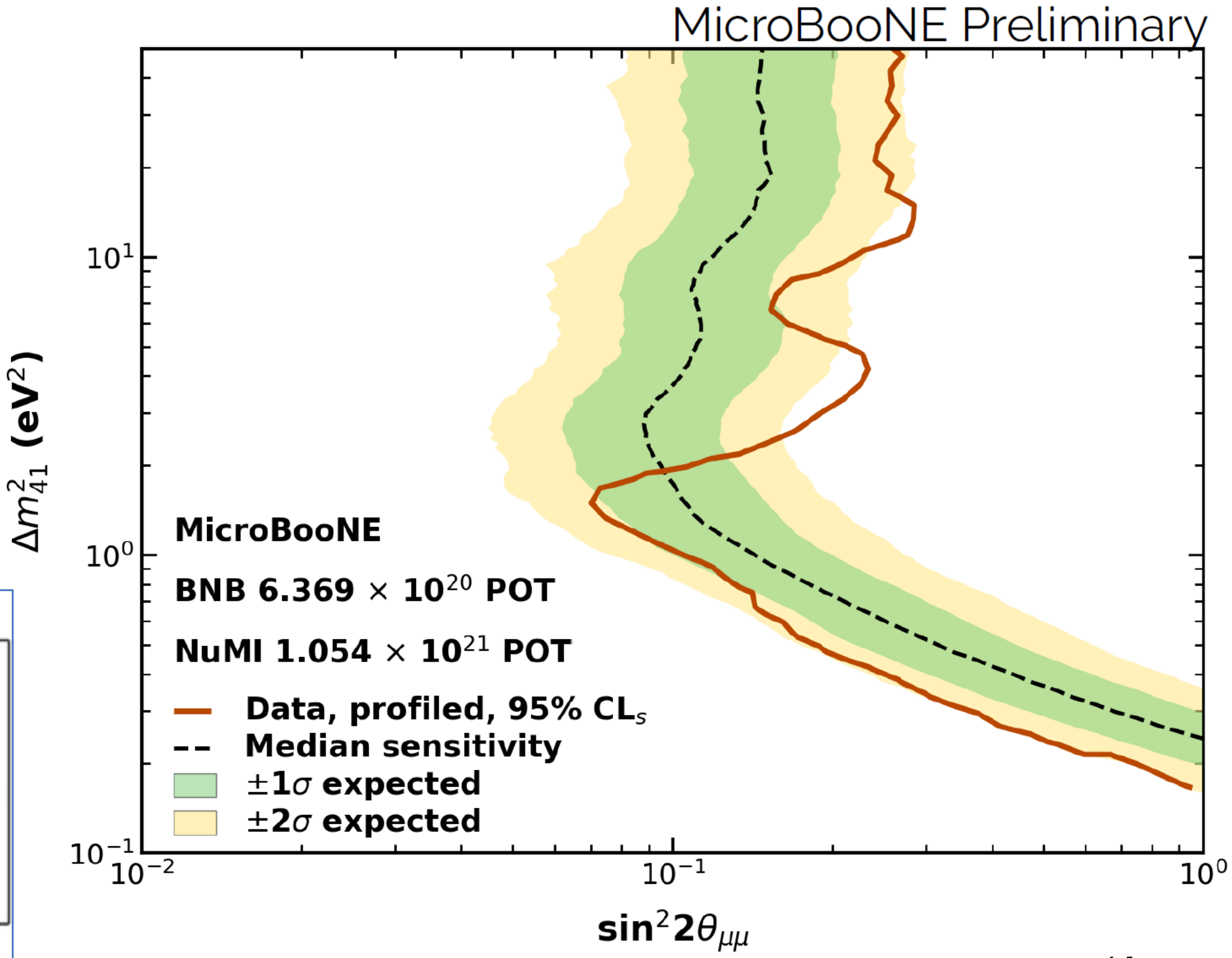
data exclusion is slightly weaker than median sensitivity: driven by deficit in BNB ν_e sample

3+1 Sterile Neutrino Search: BNB+NuMI result

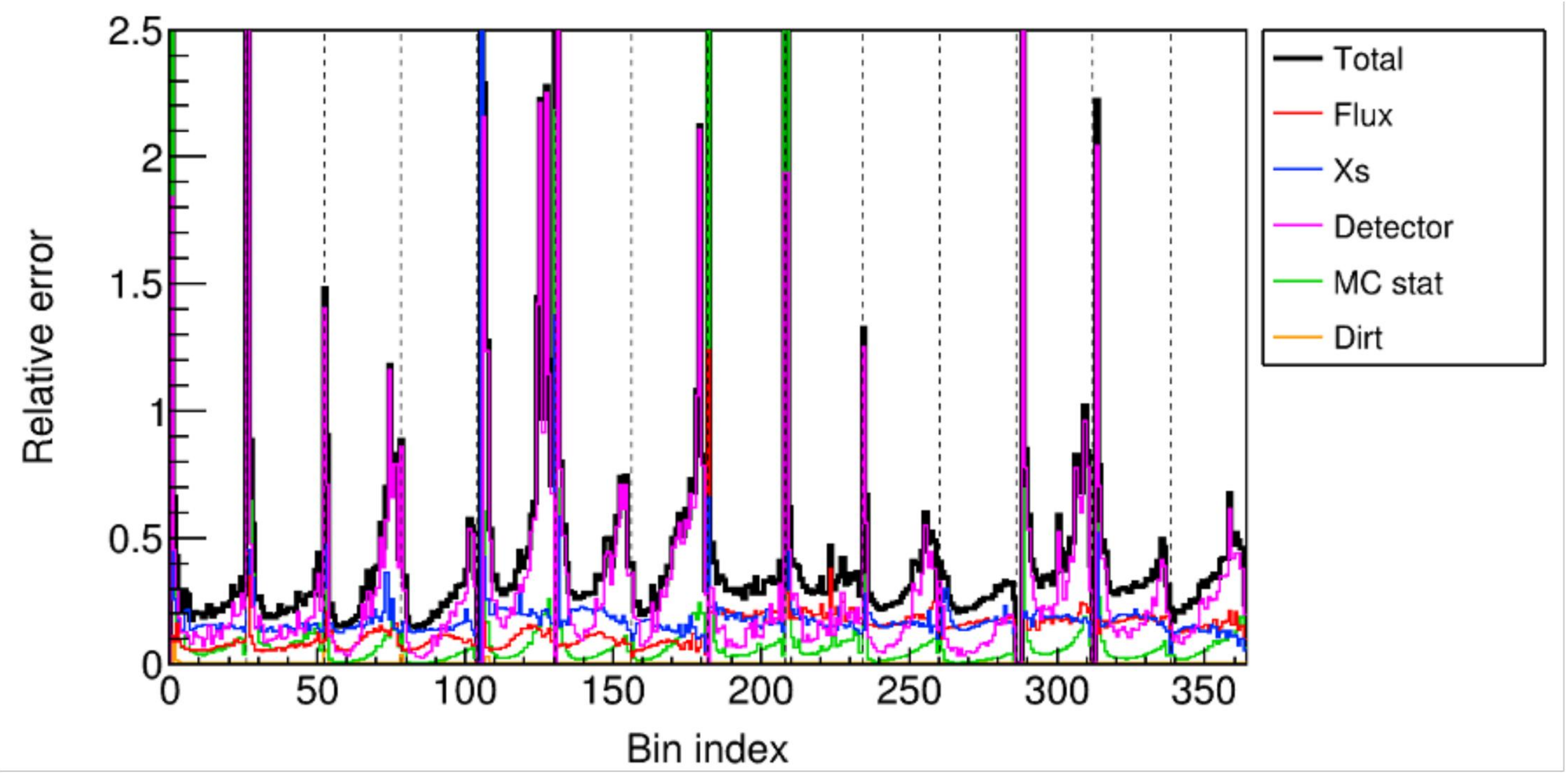
data exclusion is weaker than median sensitivity in high **Δ**m² region, and slightly stronger in low **Δ**m² region







Systematics (BNB+NuMI)



Error budget for BNB and NuMI