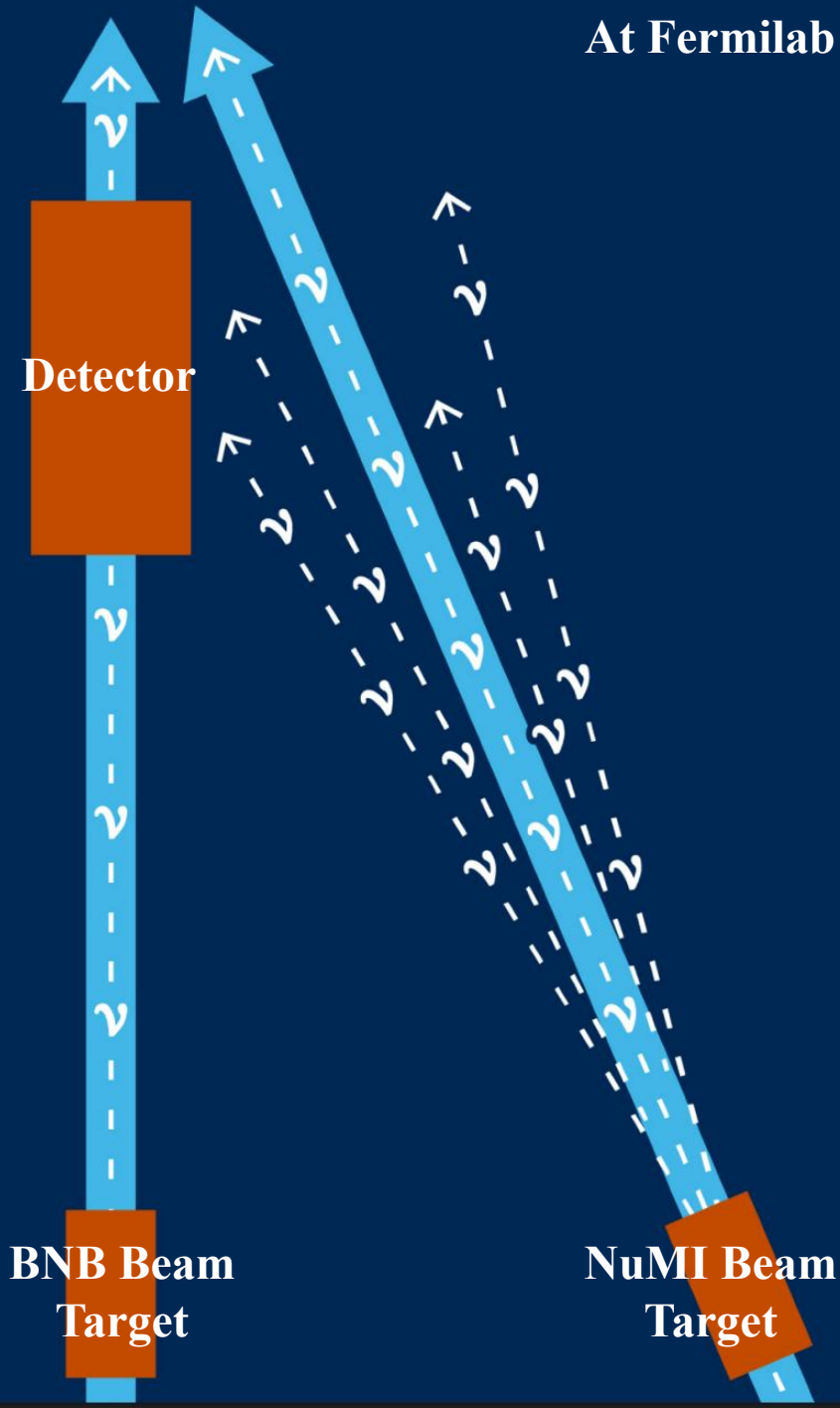


At Fermilab



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

*Based on Nature 648, 64–69 (2025)*

季向盼（南开大学）

第十八届粒子物理、核物理和宇宙学  
交叉学科前沿问题研讨会

2026年4月11日

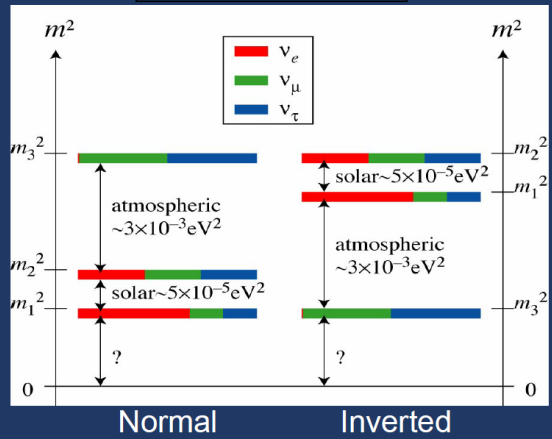
	I	II	III	
QUARKS	$u$ up 0.003 GeV/c <sup>2</sup>	$c$ charm 1.3 GeV/c <sup>2</sup>	$t$ top 175 GeV/c <sup>2</sup>	$\gamma$ photon 0
	$d$ down 0.006 GeV/c <sup>2</sup>	$s$ strange 0.1 GeV/c <sup>2</sup>	$b$ bottom 4.3 GeV/c <sup>2</sup>	$g$ gluon 0
	$\nu_e$ electron neutrino <10 <sup>-8</sup> GeV/c <sup>2</sup>	$\nu_\mu$ muon neutrino <10 <sup>-4</sup> GeV/c <sup>2</sup>	$\nu_\tau$ tau neutrino <0.02 GeV/c <sup>2</sup>	$W^{\pm}$ W boson 80.4 GeV/c <sup>2</sup>
	$e^-$ electron 511 keV/c <sup>2</sup>	$\mu^-$ muon 0.106 GeV/c <sup>2</sup>	$\tau^-$ tau 1.78 GeV/c <sup>2</sup>	$Z^0$ Z boson 91.2 GeV/c <sup>2</sup>
				$H$ Higgs boson 125 GeV/c <sup>2</sup>
	LEPTONS			

Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$   
 $\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$   
 $\sin^2(\theta_{23}) = 0.539 \pm 0.022$  (S = 1.1) (Inverted order)  
 $\sin^2(\theta_{23}) = 0.546 \pm 0.021$  (Normal order)  
 $\Delta m_{32}^2 = (-2.536 \pm 0.034) \times 10^{-3} \text{ eV}^2$  (Inverted order)  
 $\Delta m_{32}^2 = (2.453 \pm 0.033) \times 10^{-3} \text{ eV}^2$  (Normal order)  
 $\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

- Solar, Reactor
- Atmospheric, Accelerator
- Reactor, Accelerator

Mass Hierarchies



Future objectives:

- $\delta_{CP}$
  - $\theta_{23} \text{ max?}$
  - Hierarchy?
  - Majorana  $\nu$ ?
  - Absolute mass
  - Sterile  $\nu$ ?**
- Accelerator, Reactor, Atmospheric  
 $0\nu\beta\beta$ , Cosmology, Electron spectrometers,  
 Accelerator, Reactor, Atmospheric

Neutrino 2024

Opening Talk: Where are we?

Art McDonald  
Queen's University, Canada

Milan, Italy  
June 17, 2024

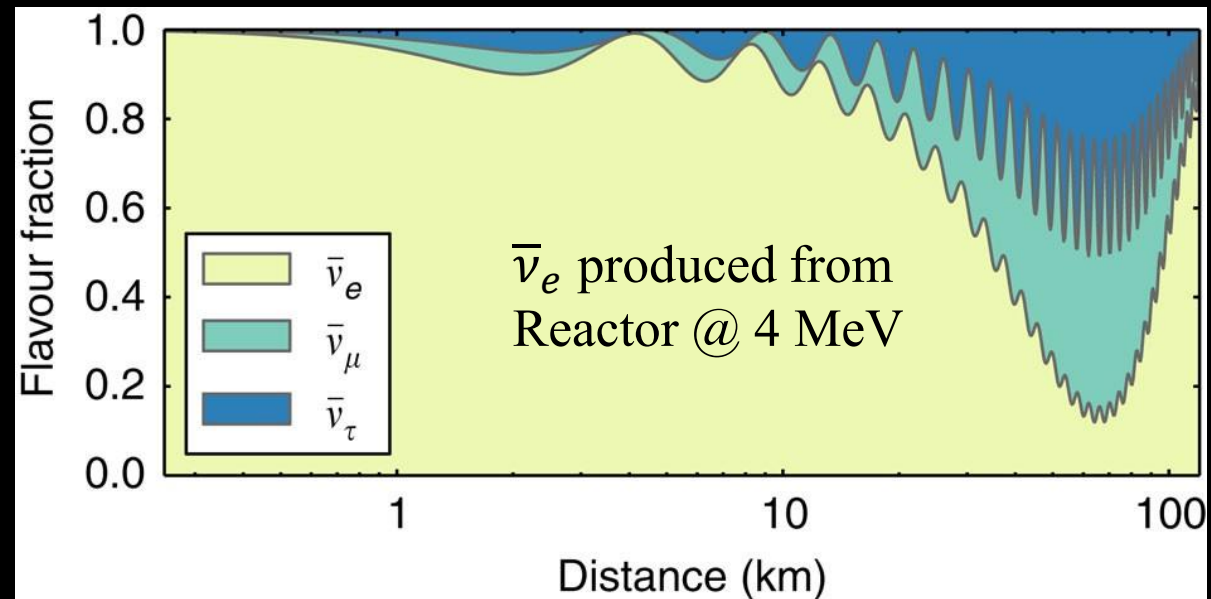
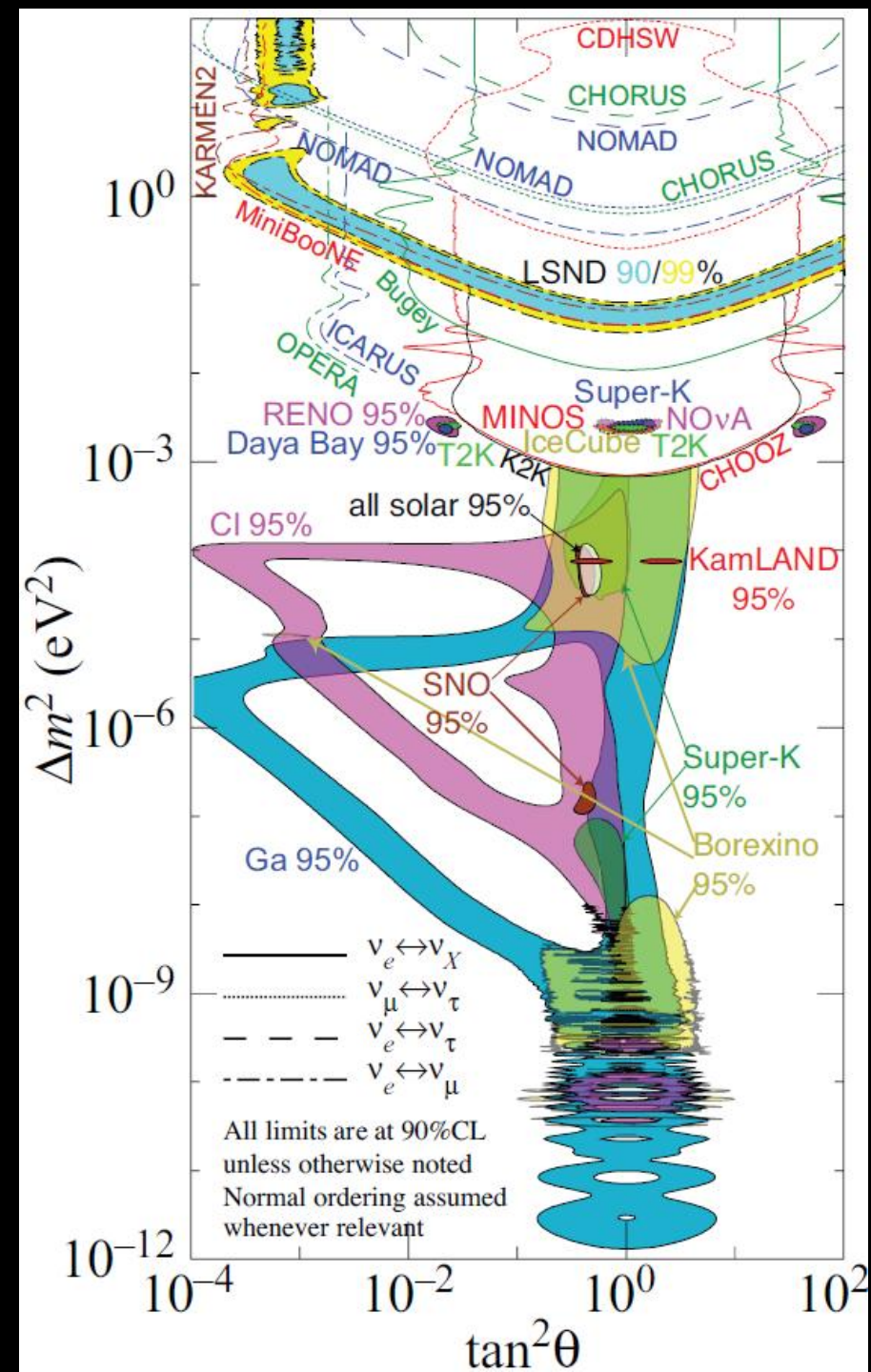
阿瑟 麦克唐纳

梶田隆章

惰性中微子 存不存在?

# Neutrino Oscillation Experiments

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



# Neutrino Oscillation Experiments

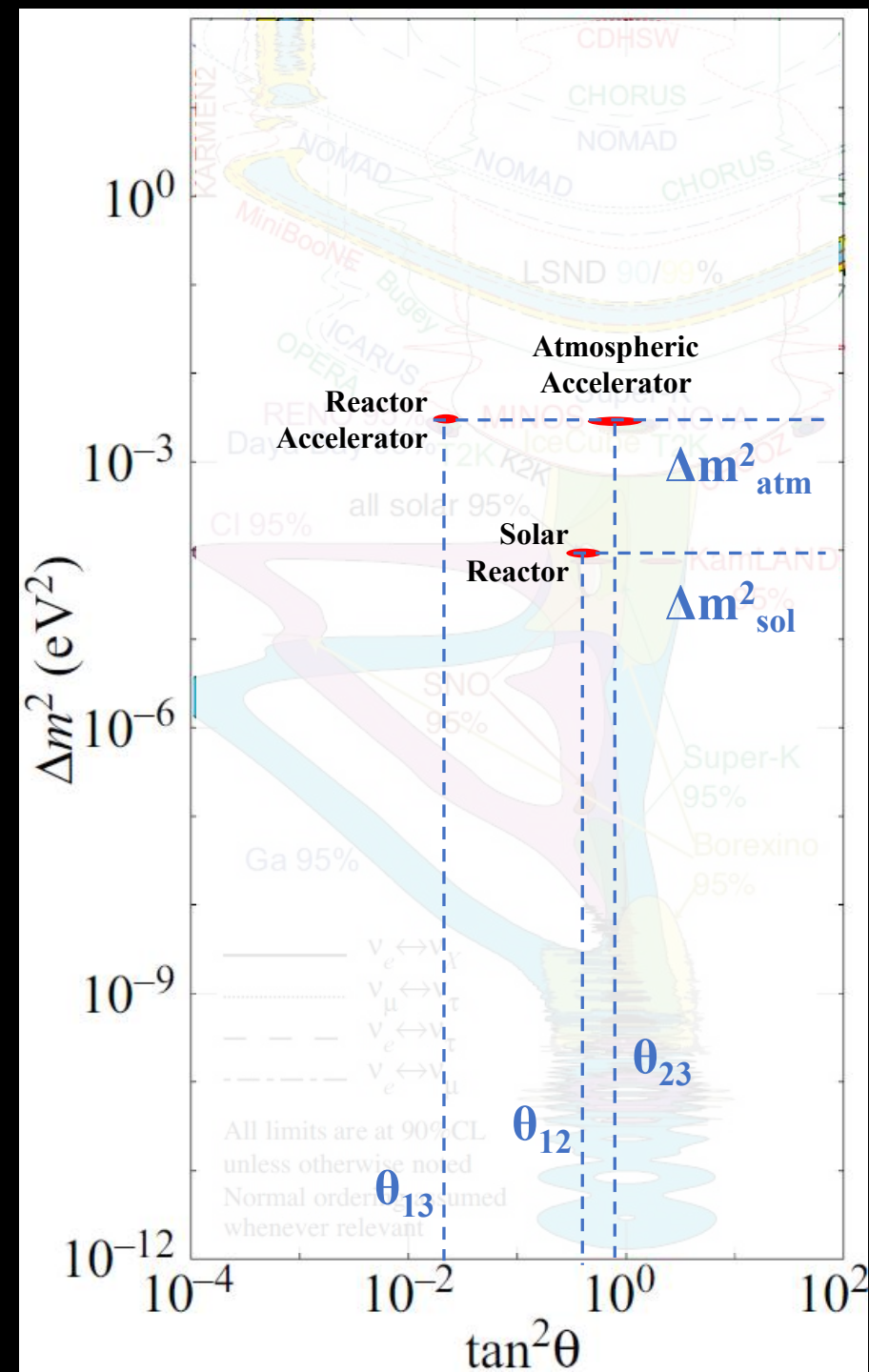
- > 50 years
- > 30 experiments
- Phase space over tens of orders of magnitude

## Six Parameters for the Osc.

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

$$\Delta m_{21}^2 \quad \Delta m_{31}^2$$

$$\delta^{CP}$$

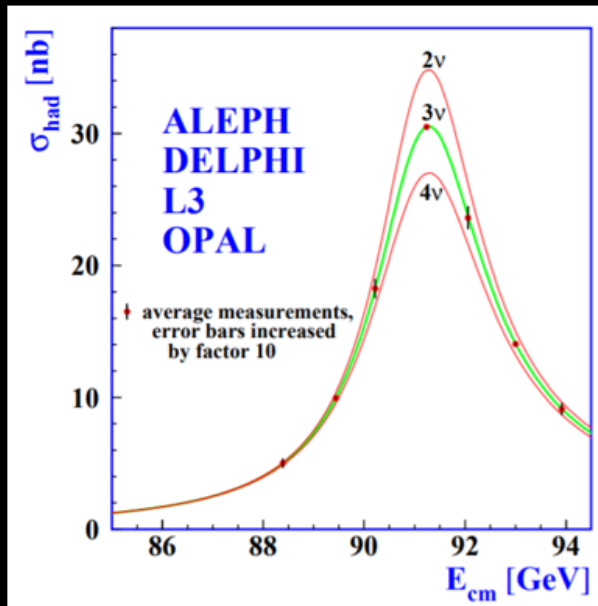


# Standard Three Neutrino Paradigm?

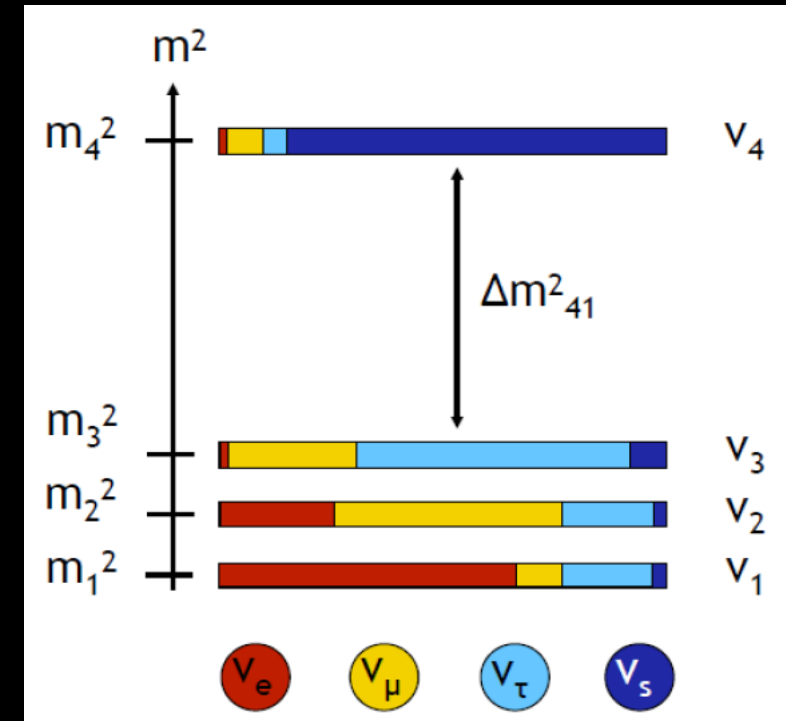
## Experiment Anomalies

Additional neutrinos beyond three, they just don't participate in weak interactions (i.e., sterile neutrino)?

Z-boson decay measurements  
 $N_\nu = 2.9840 \pm 0.0082$

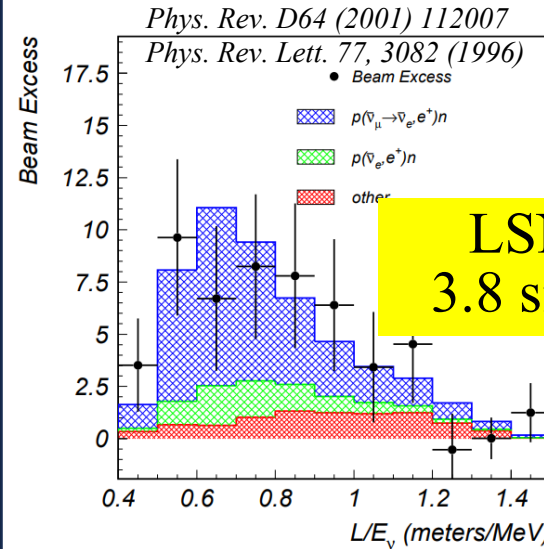


*Phys. Rept.* 427, 257 (2006)

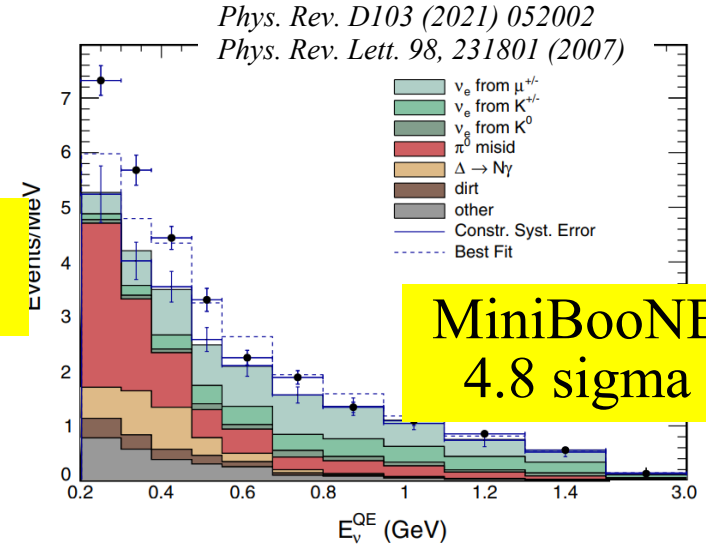


# Short-Baseline Neutrino Anomalies

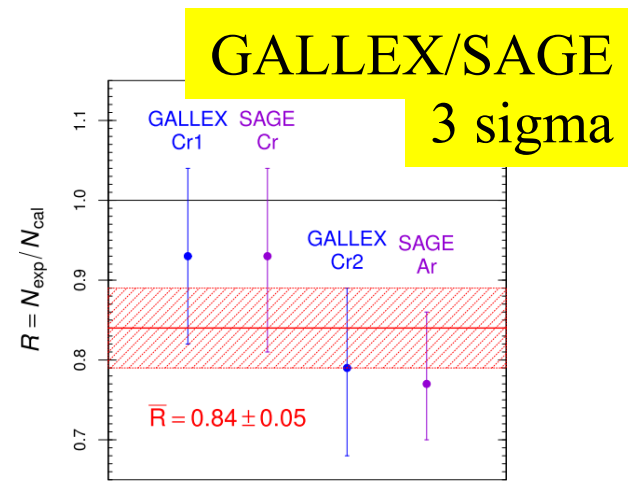
Experiment	Channel
LSND anomaly	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
MiniBooNE anomaly	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$
GALLEX/SAGE, BEST (radioactive source), Gallium anomaly	$\nu_e \rightarrow \nu_e$
Neutrino-4 reactor expt.	$\bar{\nu}_e \rightarrow \bar{\nu}_e$



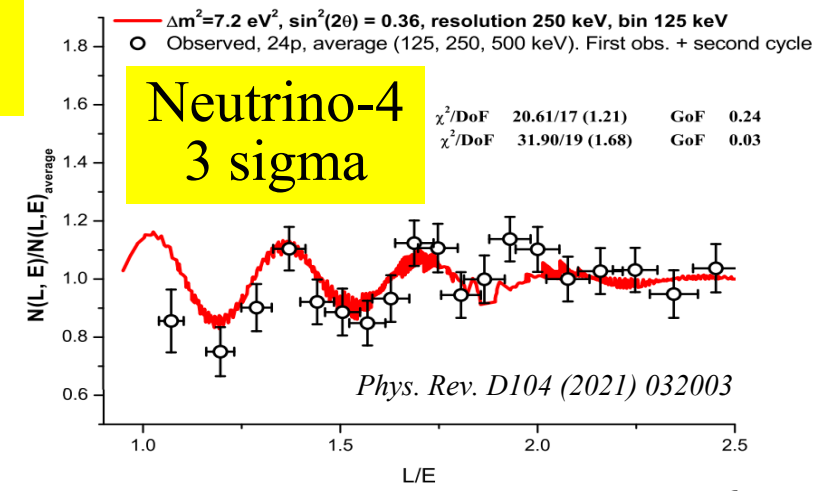
**LSND  
3.8 sigma**



**MiniBooNE  
4.8 sigma**



J.Phys.G 43 (2016) 033001  
Physics Letters B 420 (1998) 114



Anomalies:

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

# Short-Baseline Neutrino Anomalies

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

Anomalies:

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

3(active)+1(sterile) Neutrino Oscillation

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

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

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

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

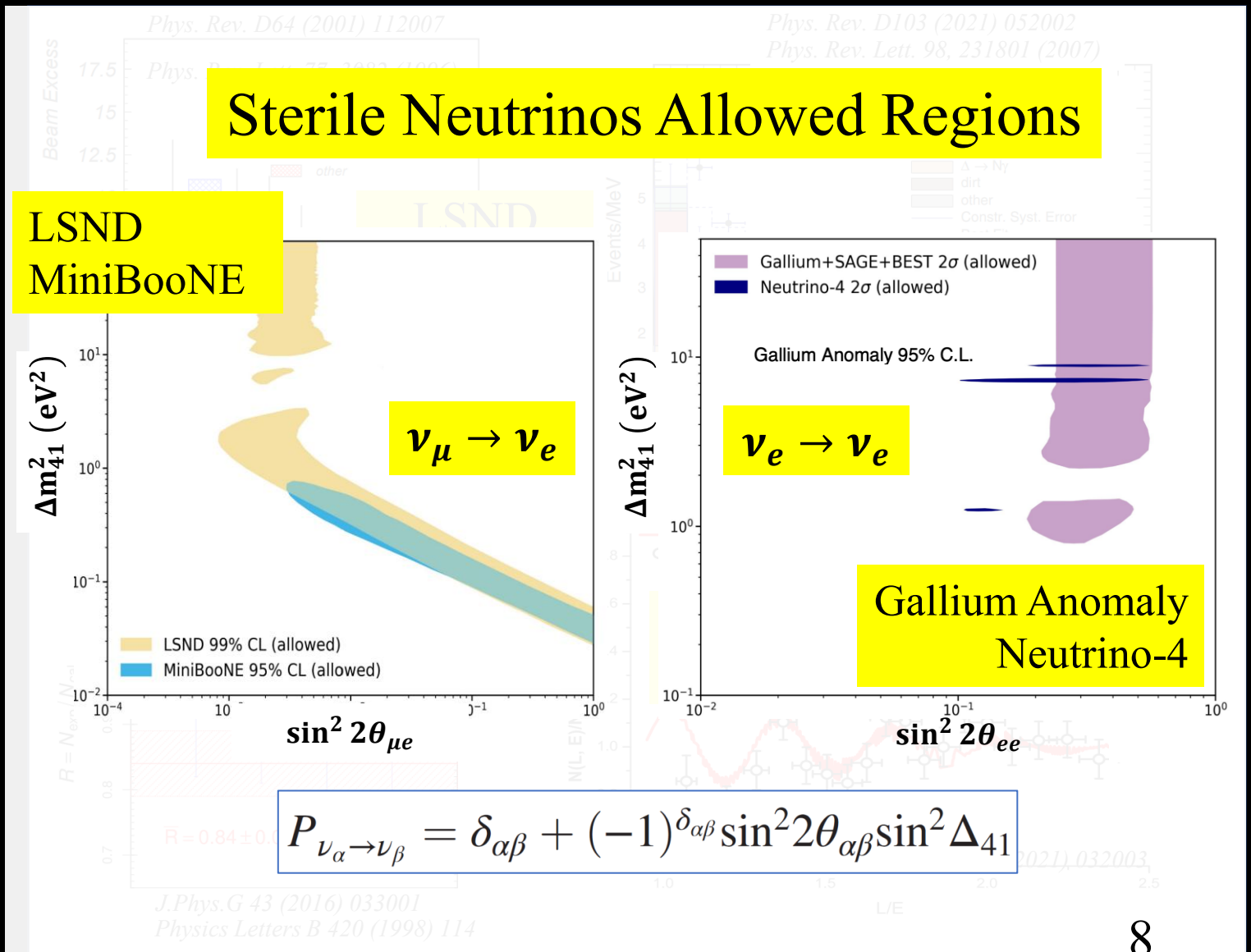
Hints of eV-scale sterile neutrino

# Short-Baseline Neutrino Anomalies

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

Anomalies:

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



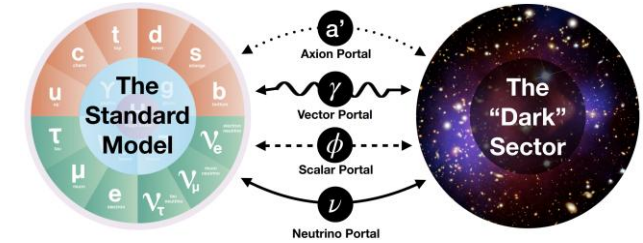


# **the Micro Booster Neutrino Experiment (MicroBooNE)**

*186 Collaborators  
from 41 Institutions*

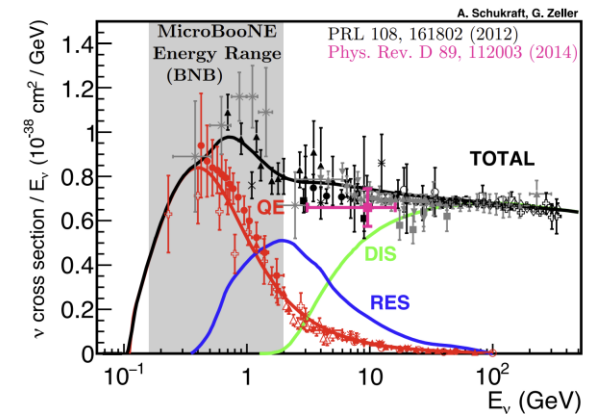
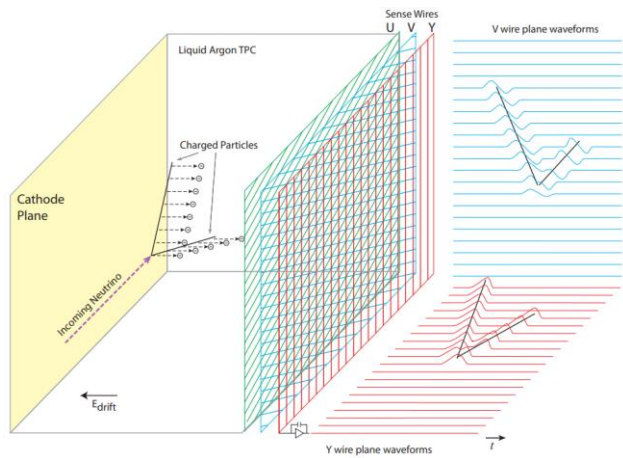
# MicroBooNE Scientific Goals

Investigate MiniBooNE Low Energy Excess  
Search for Sterile  $\nu$  and other BSM physics



LArTPC hardware & software R&D

Study  $\nu$ -Ar interactions



中微子束流

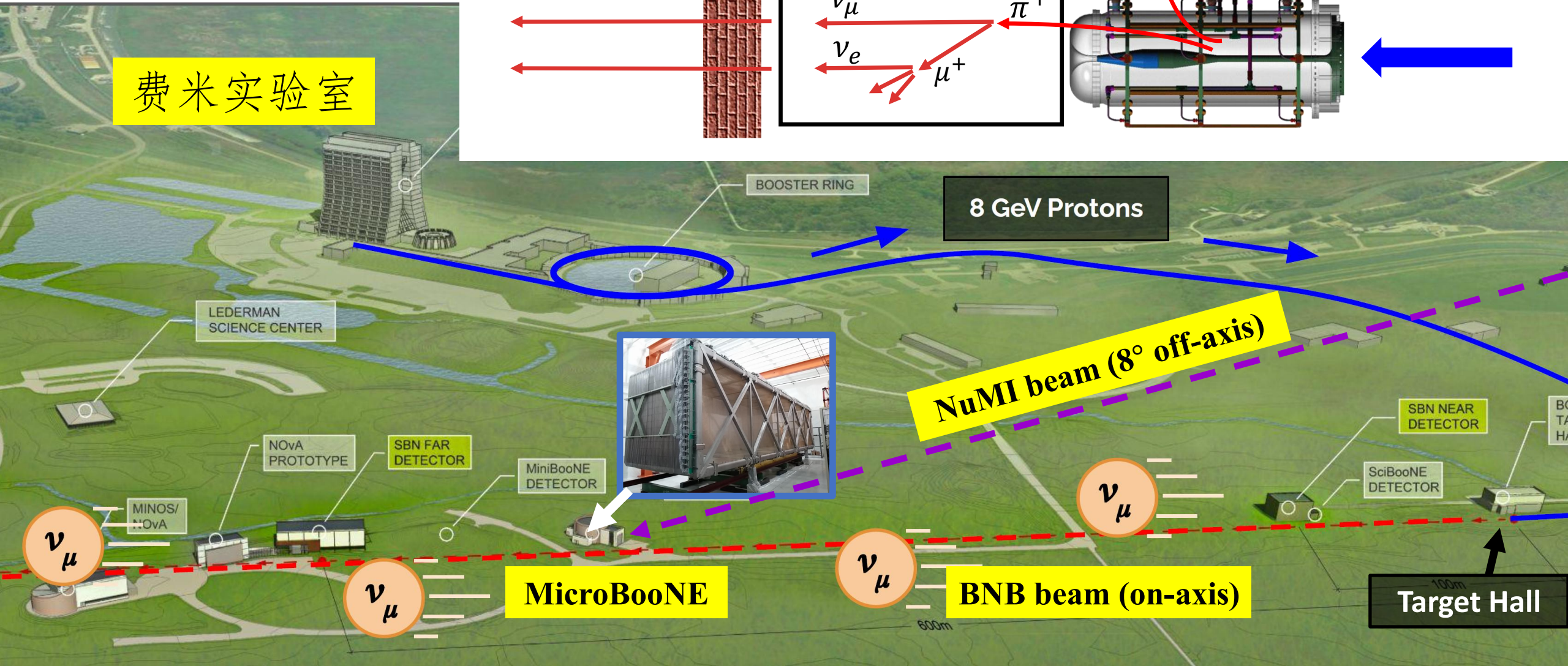
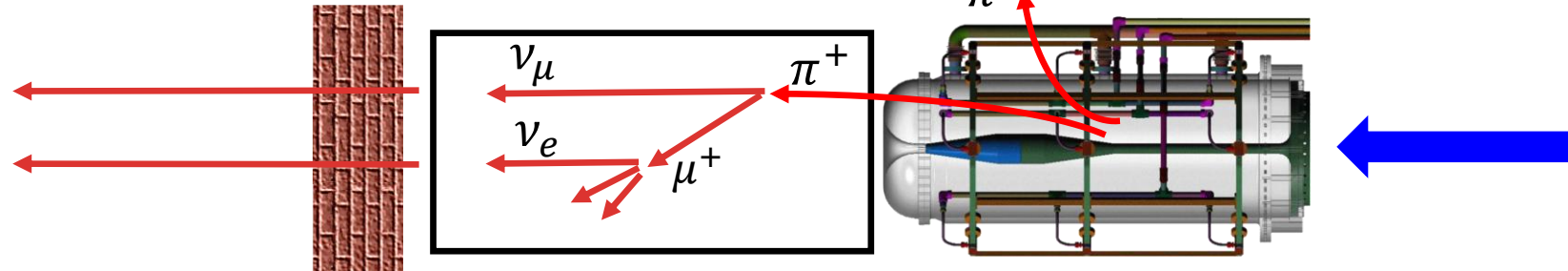
吸收体

衰变通道

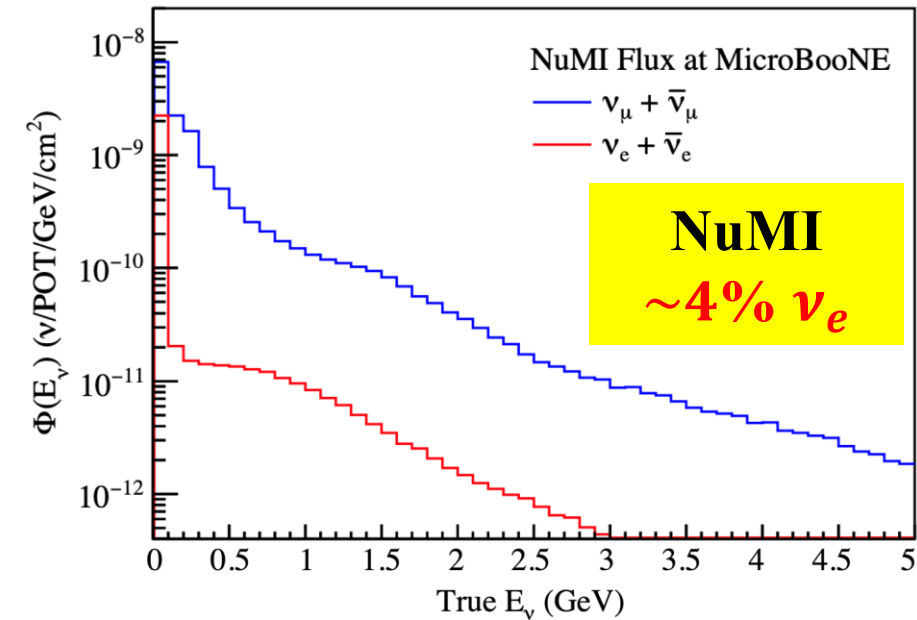
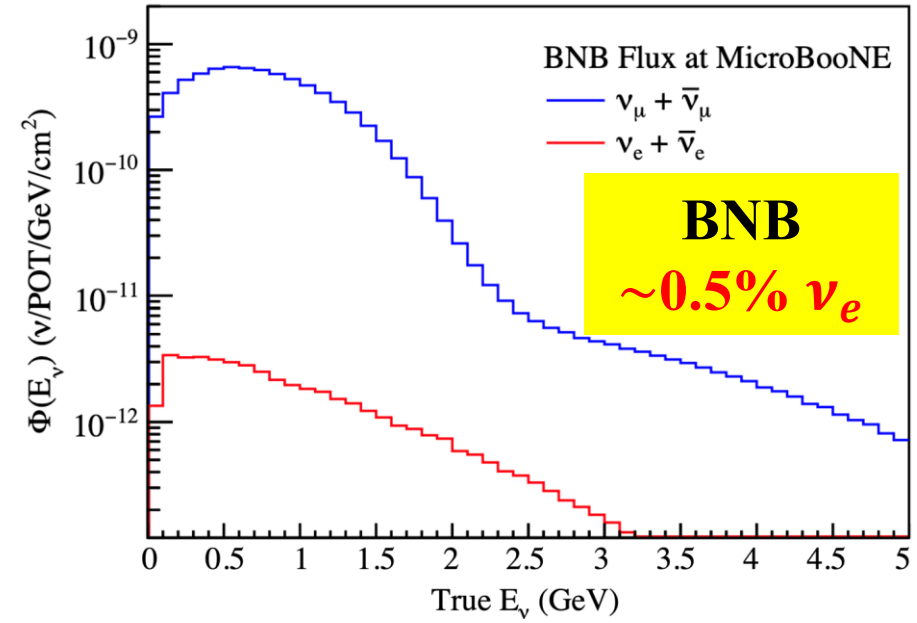
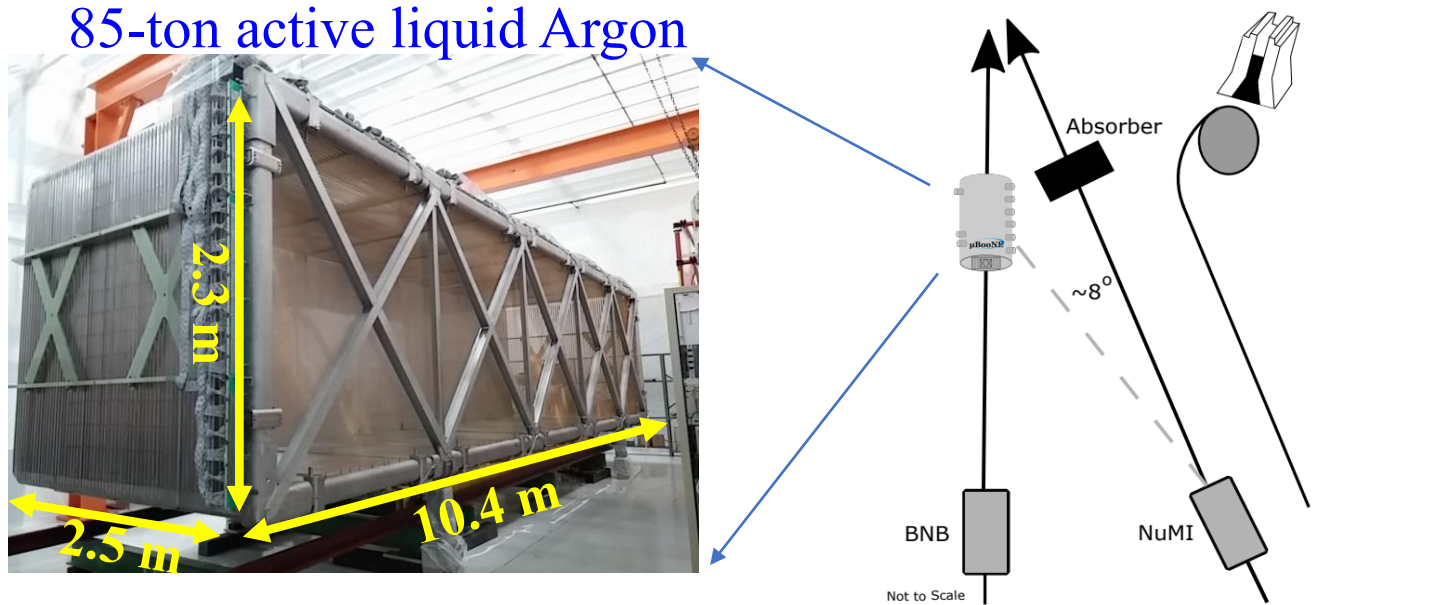
聚焦管道和靶

质子束流

费米实验室



# Two Beams



## Two Neutrino Beams

On-axis beam: BNB	Off-axis (8°) 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

# 3+1 Sterile Neutrino Results

## Limited by the Cancellation of $\nu_e$ Appearance and Disappearance

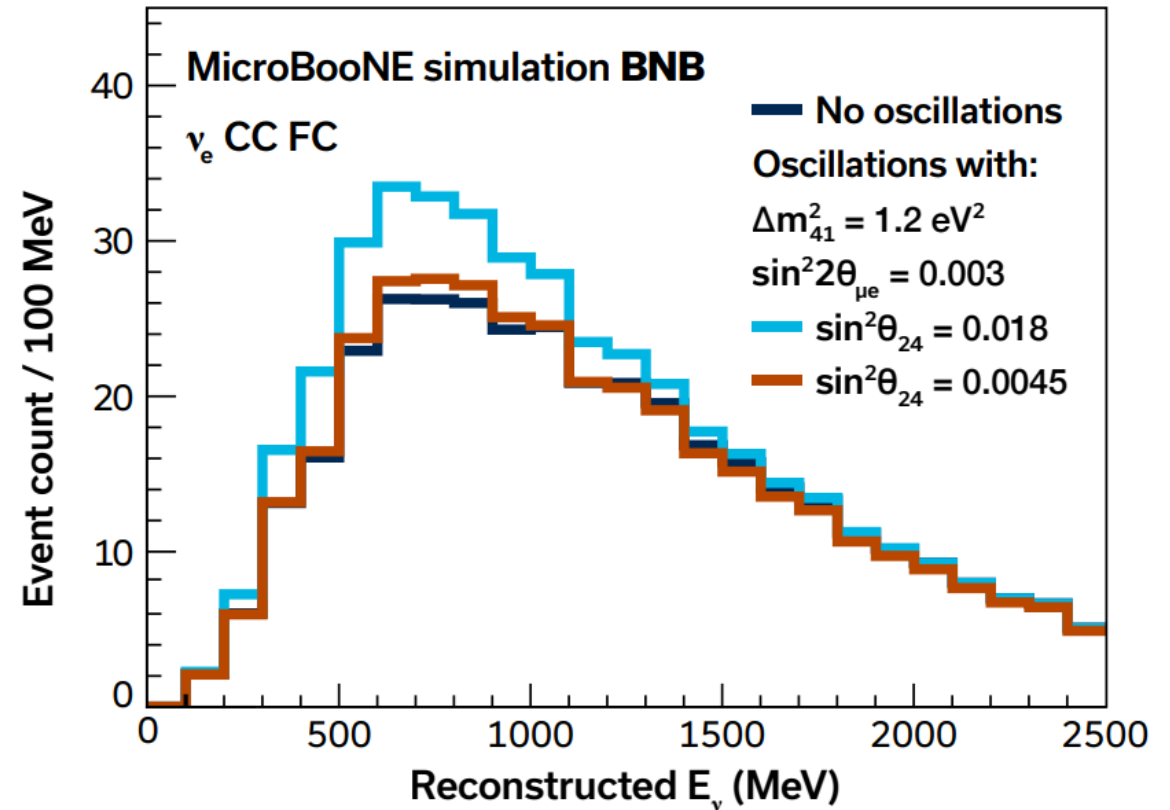
- Observed  $\nu_e$  events are a combination result of  $\nu_e$  appearance and disappearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \rightarrow \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \rightarrow \nu_e}$$

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

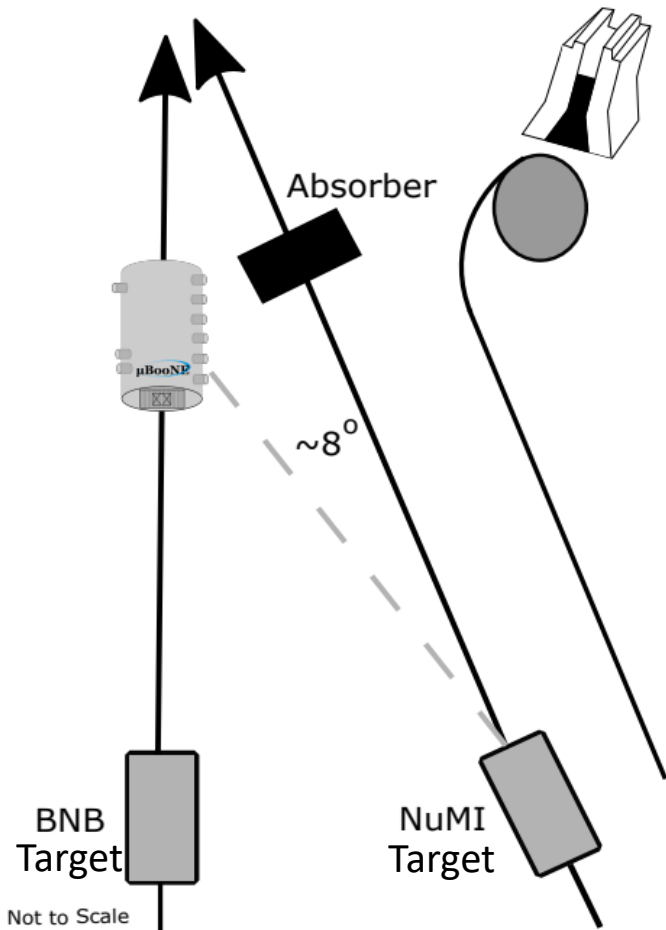
- Degeneracy when  $\sin^2 \theta_{24}$  approaches  $R_{\nu_e/\nu_\mu}$  (the ratio of beam intrinsic  $\nu_e$  and  $\nu_\mu$  flux)

At MicroBooNE	$R_{\nu_e/\nu_\mu}$ Average
BNB beam	$\sim 0.005$



# One Detector with Two Beams

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



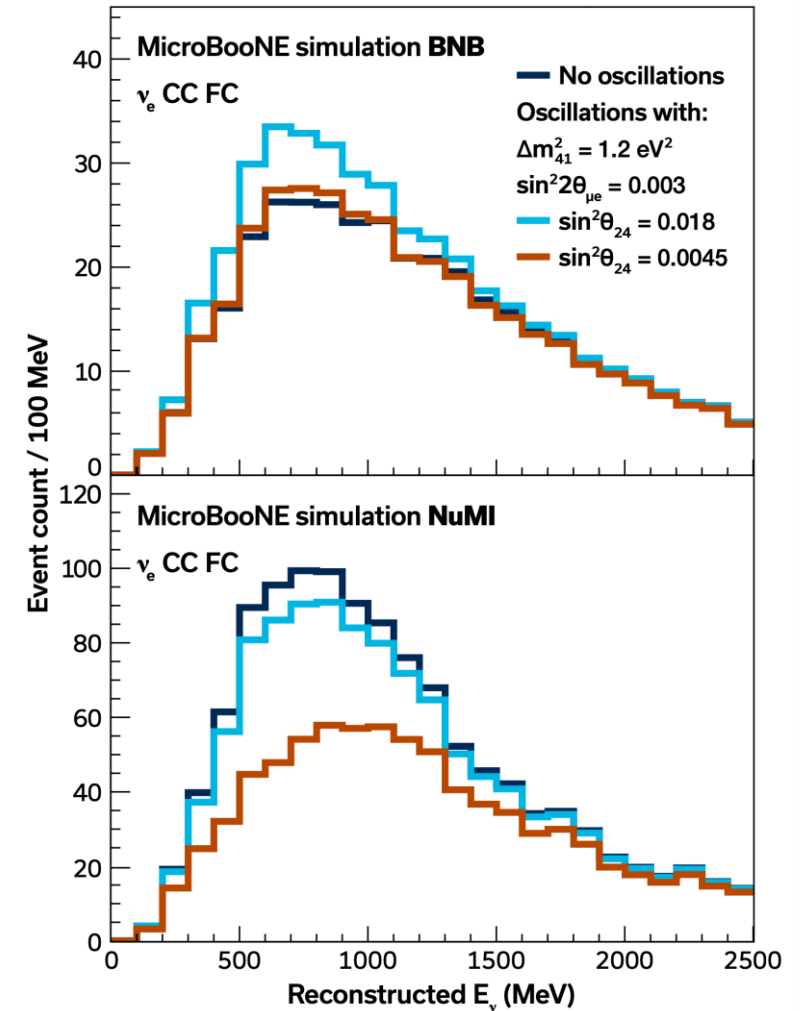
$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \rightarrow \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \rightarrow \nu_e}$$

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

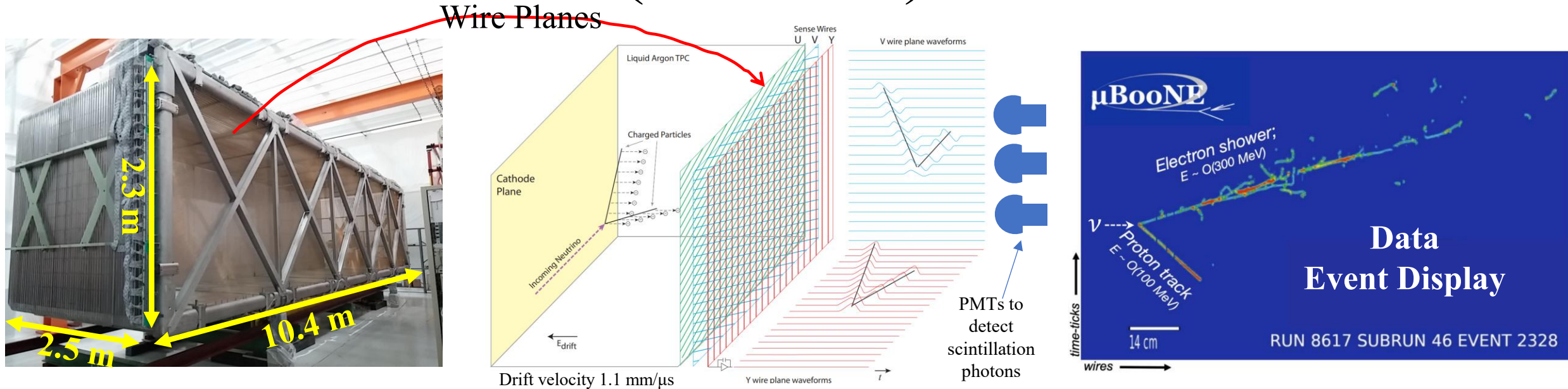
- Degeneracy when  $\sin^2 \theta_{24}$  approaches  $R_{\nu_e/\nu_\mu}$  (the ratio of beam intrinsic  $\nu_e$  and  $\nu_\mu$  flux)

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

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



# Detector: Liquid Argon Time Projection Chamber (LArTPC)



## Full-Active Tracking Calorimeter

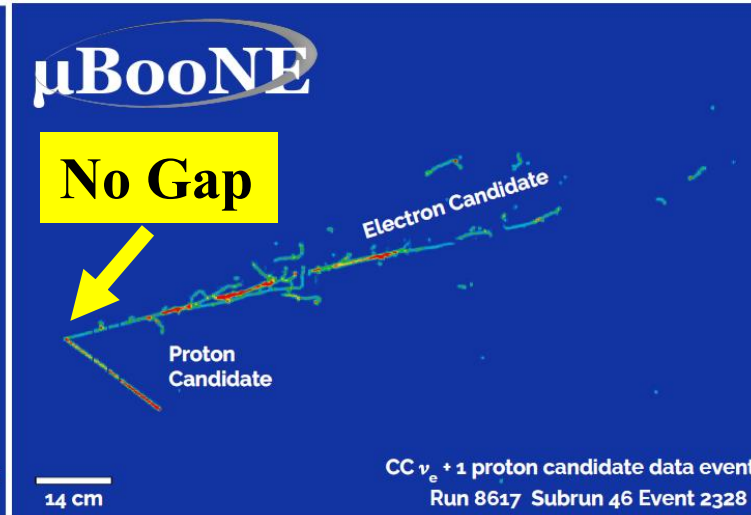
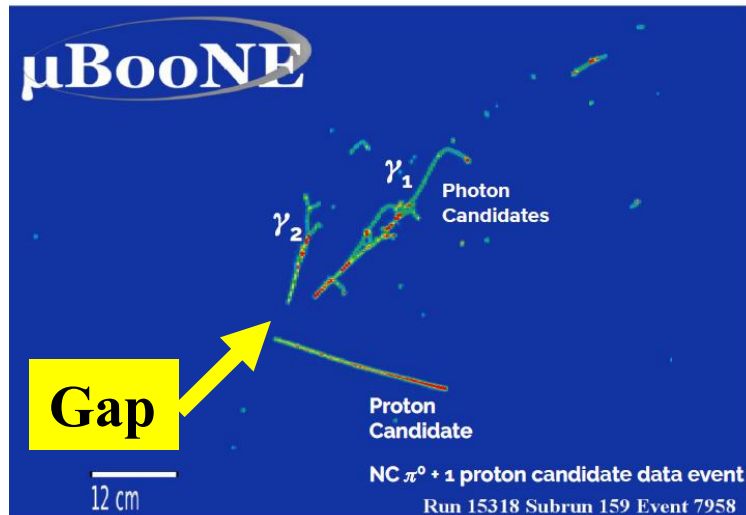
- mm-level position resolution
- MeV-level detection energy threshold
- ns-scale neutrino interaction time resolution
- 3D reconstruction of position

## Excellent Particle Identification

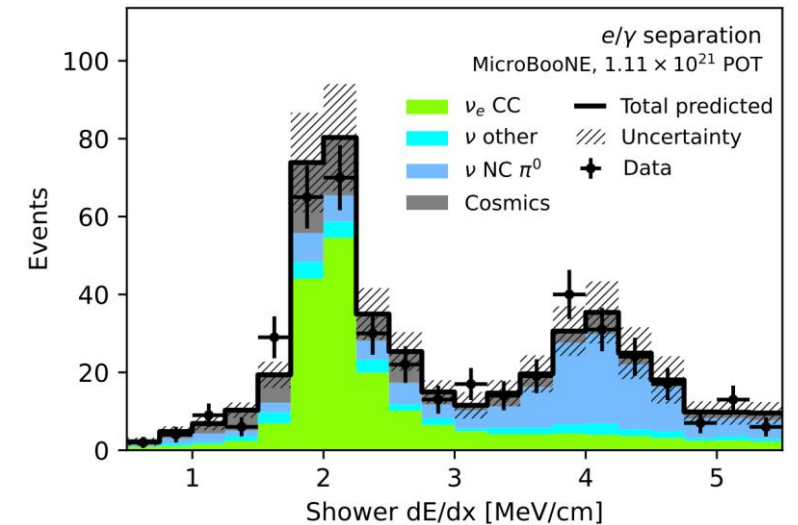
- Final states topological and calorimetric
- Track and shower identification
- Electron and photon shower separation
- Distinguish muons, protons, pions

# Electron and Photon shower Separation

## Gap between shower start point and $\nu$ vertex



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

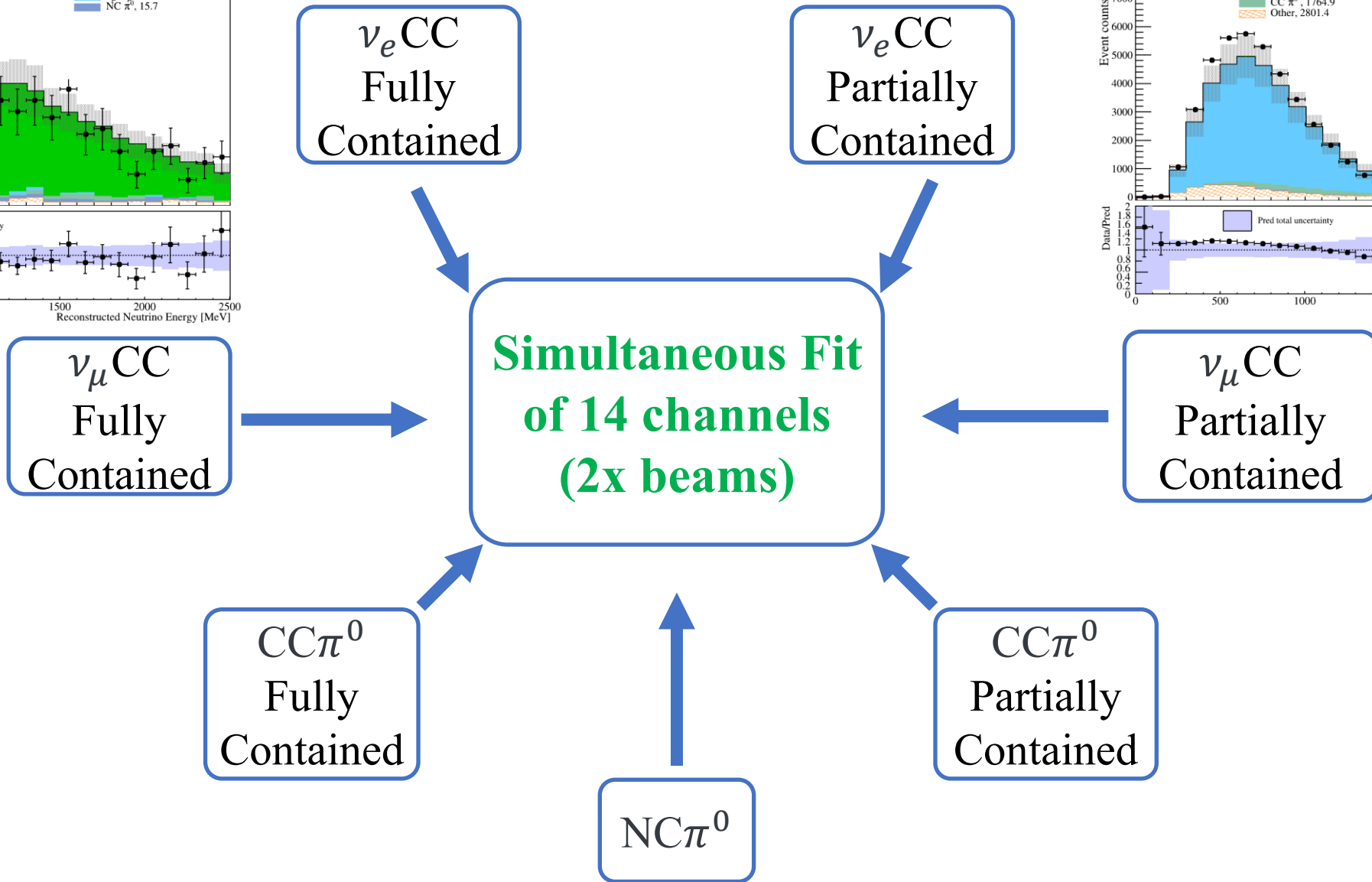
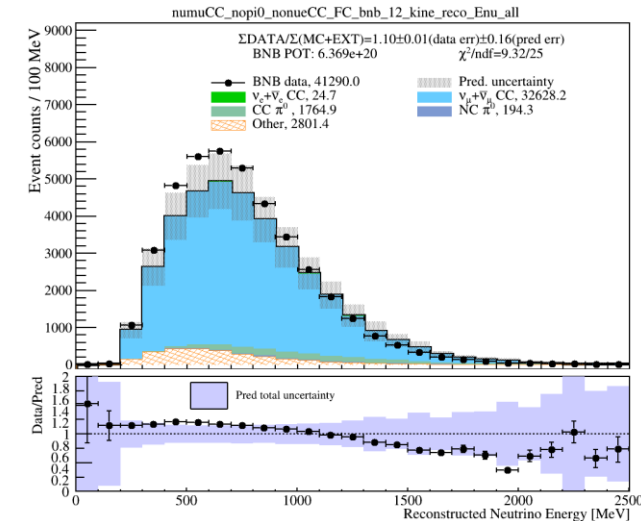
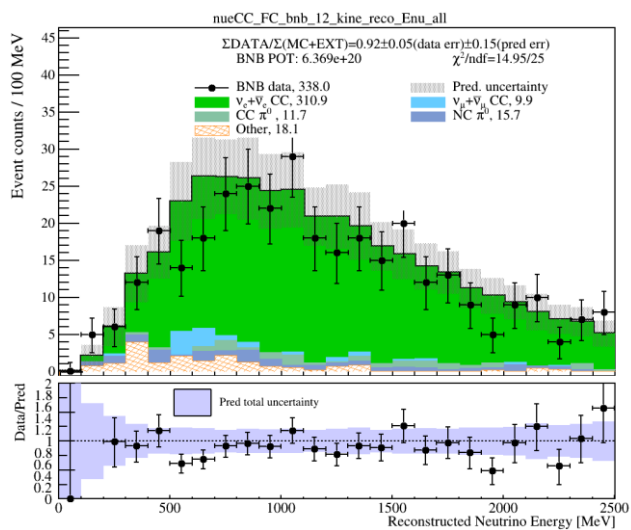


## Full-Active Tracking Calorimeter

- 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



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

# Constraint Power for Total Systematics

## Systematics of $\nu_e$ CC channels

	<b>BNB FC</b>	<b>BNB PC</b>	<b>NuMI FC</b>	<b>NuMI PC</b>
Systematic uncertainties on CC $\nu_e$ 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%
<b>Total unconstrained uncertainty</b>	<b>16.3%</b>	<b>15.8%</b>	<b>26.4%</b>	<b>25.2%</b>
<b>Total constrained uncertainty</b>	<b>4.5%</b>	<b>5.5%</b>	<b>5.8%</b>	<b>5.9%</b>

Before  
constraints

After  
constraints

Systematics are reduced by  
3~4 factor

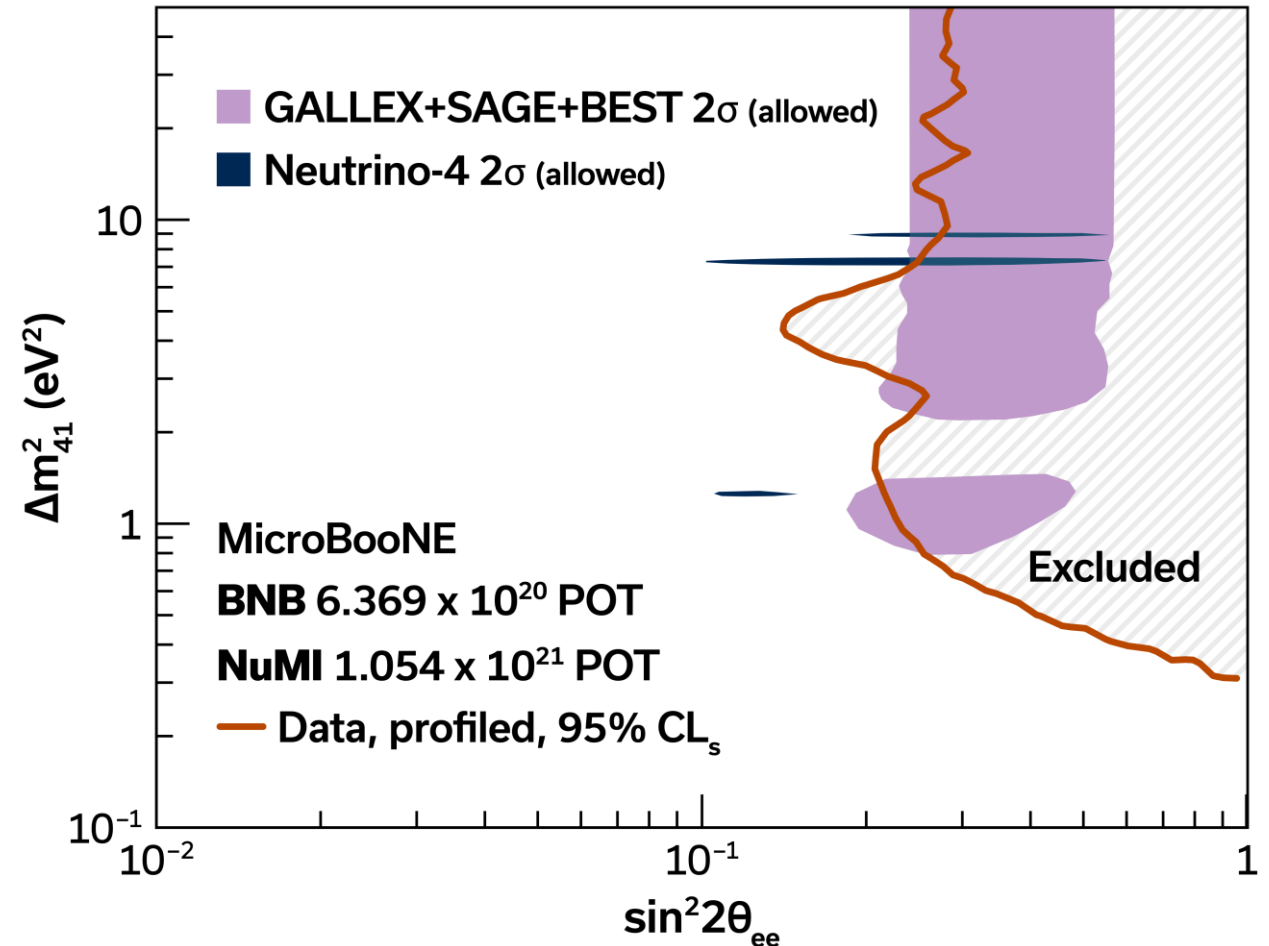
# Two Beams: $\nu_e$ Disappearance Result

## MicroBooNE data at 95% CL

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

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

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



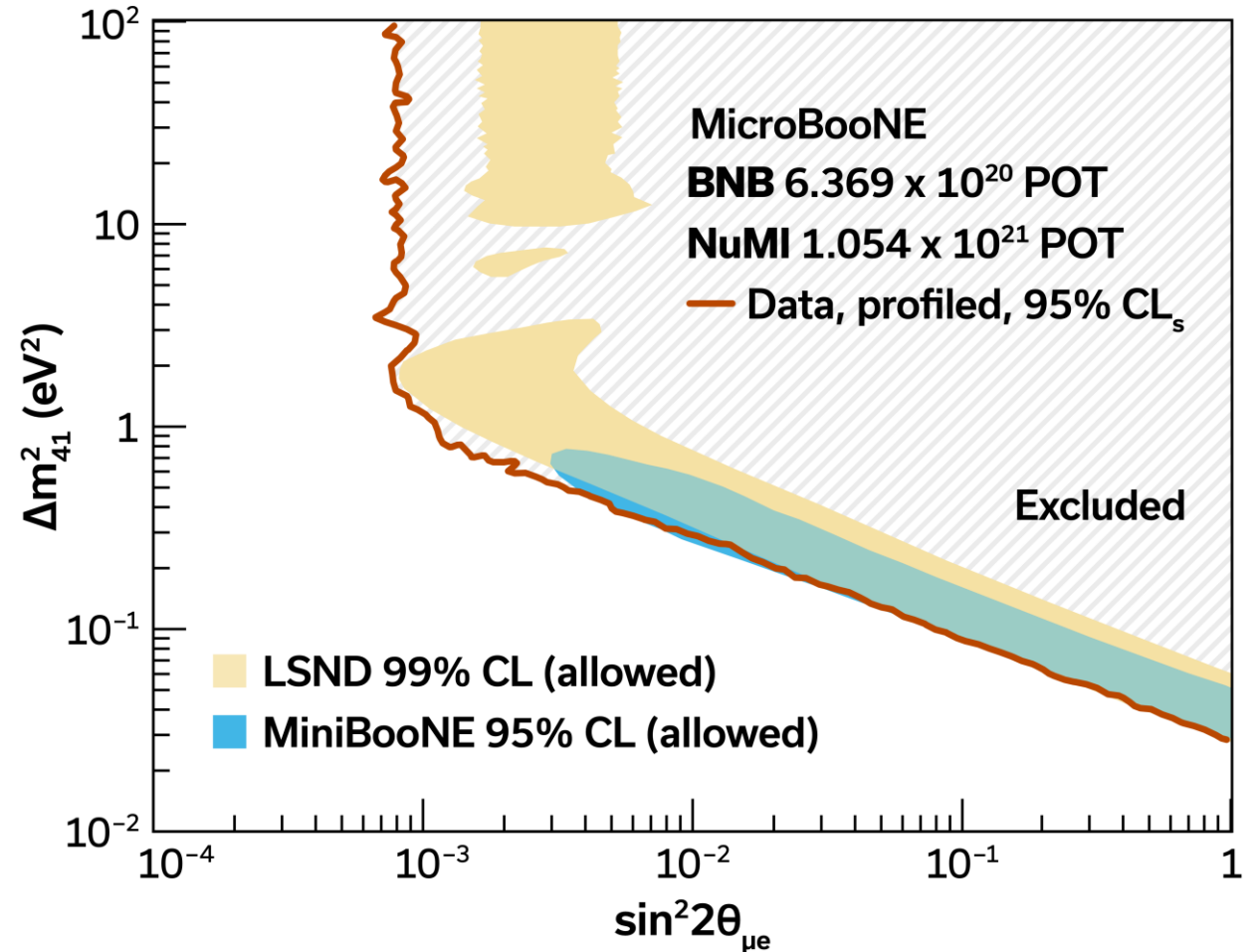
# Two Beams: $\nu_e$ Appearance Result

## MicroBooNE data at 95% CL

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

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

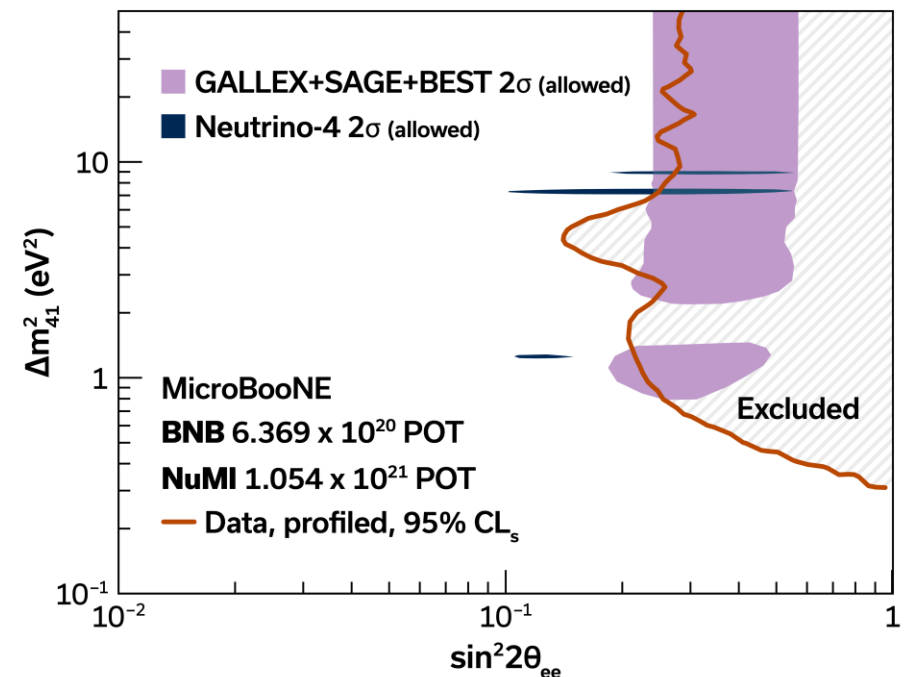
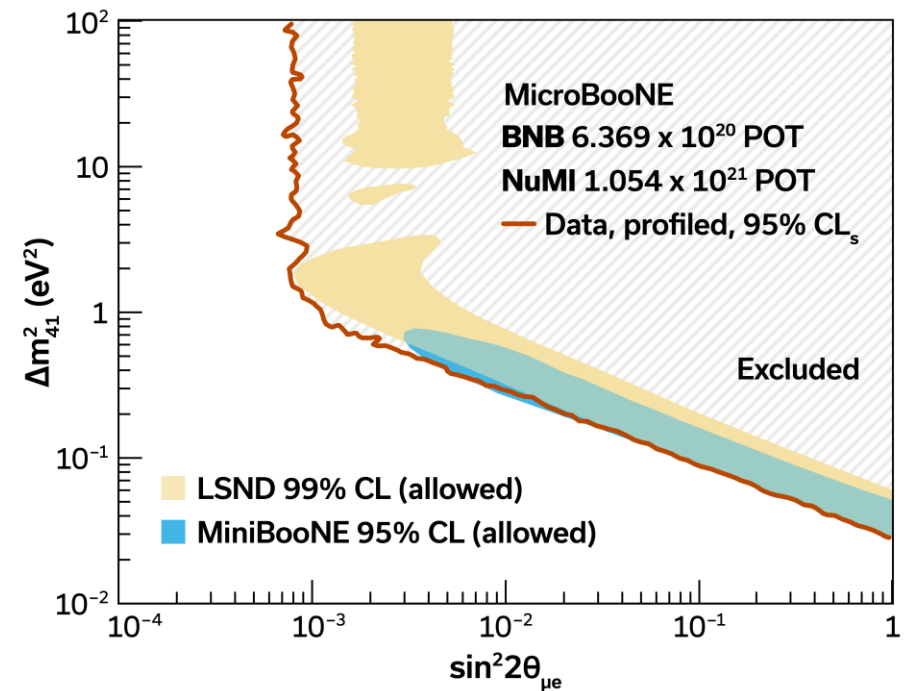
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$



# Summary

Nature 648, 64–69 (2025)

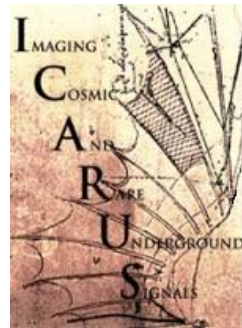
- In the **first analysis of its kind**, MicroBooNE has tested the 3+1 sterile neutrino model
  - **Two beams, single detector**
  - Neutrino appearance and disappearance **simultaneous search** in one experiment
- MicroBooNE sees **no sign** of 3+1 sterile-neutrino-induced oscillations that would explain 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)

# 回到起点

Neutrino 2024

Opening Talk: Where are we?

Art McDonald  
Queen's University, Canada

Milan, Italy  
June 17, 2024

Dear 梶君,

I hope you will have  
great result on neutrinos!

梶田隆章

Neutrino 2024

Opening Talk: Where are we?

Art McDonald  
Queen's University, Canada

Milan, Italy  
June 17, 2024



请各位专家批评指正

谢谢

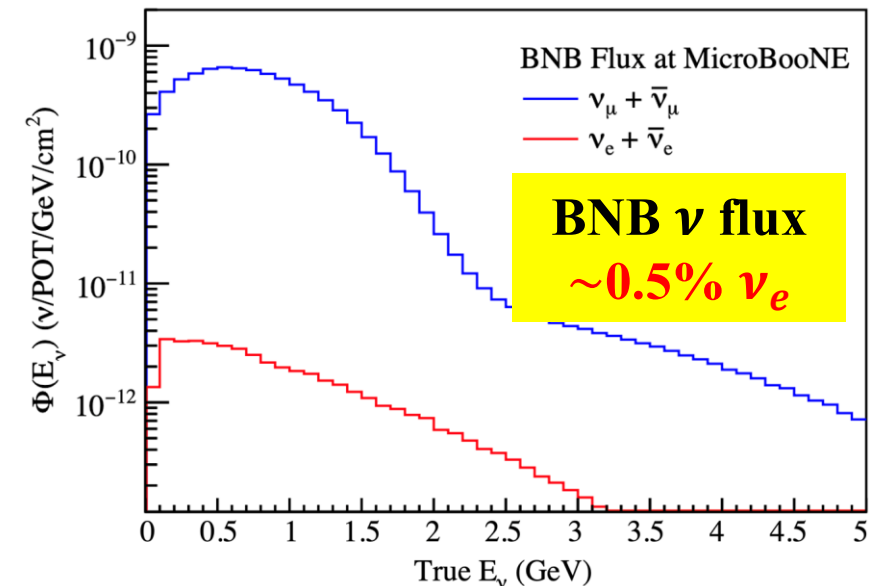
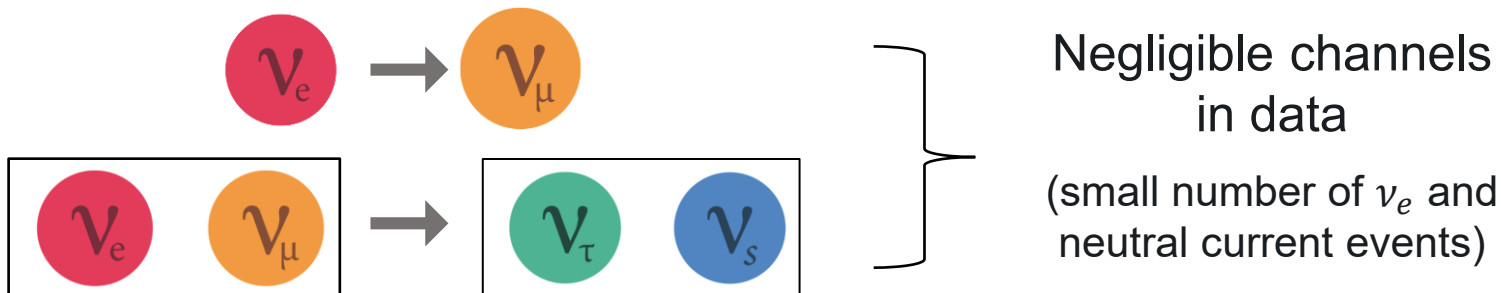
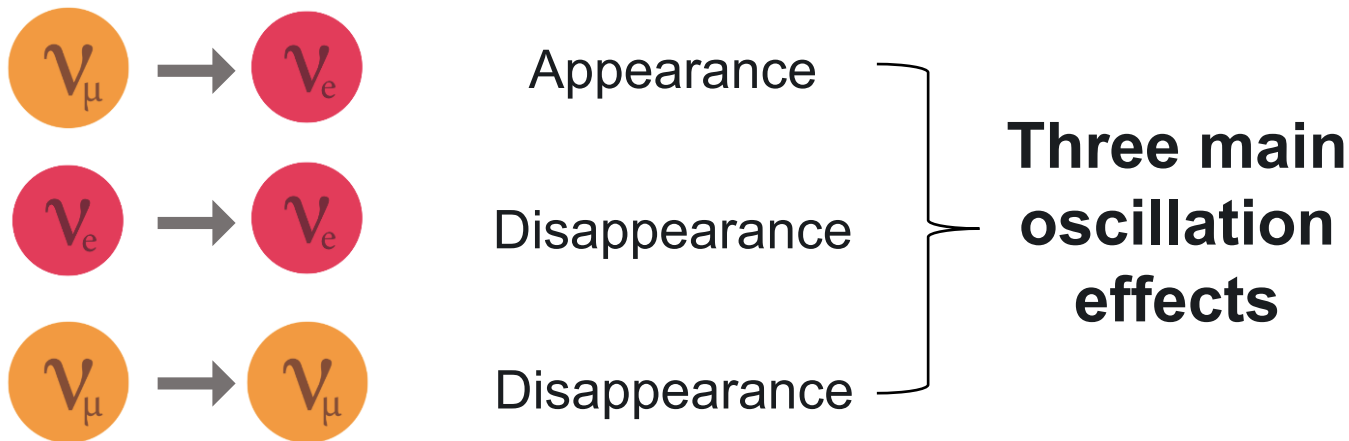




# 3+1 Sterile Neutrino Search at MicroBooNE



- Full “3+1” analysis – all detectable oscillation effects



# 3+1 Sterile Neutrino Search at MicroBooNE



- Full “3+1” analysis – all detectable oscillation effects



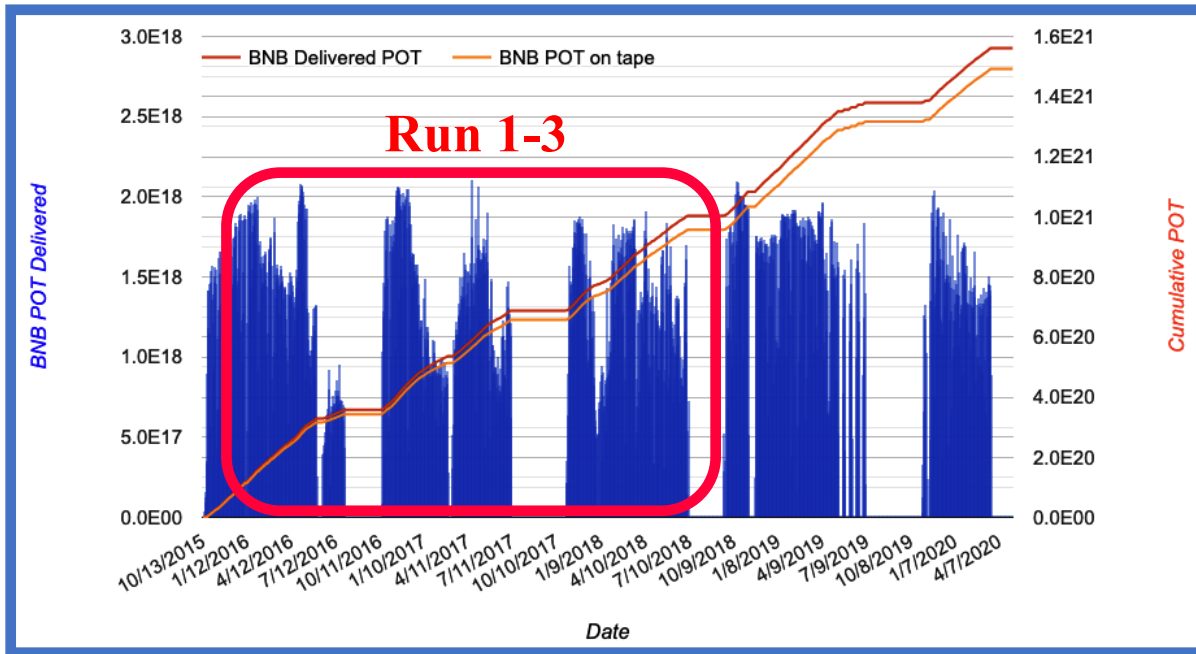
- However ...
- We only have one detector
- Because of  $\nu_e$  intrinsic contamination from beam:
- **Cancellation effect between  $\nu_\mu \rightarrow \nu_e$  and  $\nu_e \rightarrow \nu_e$**

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

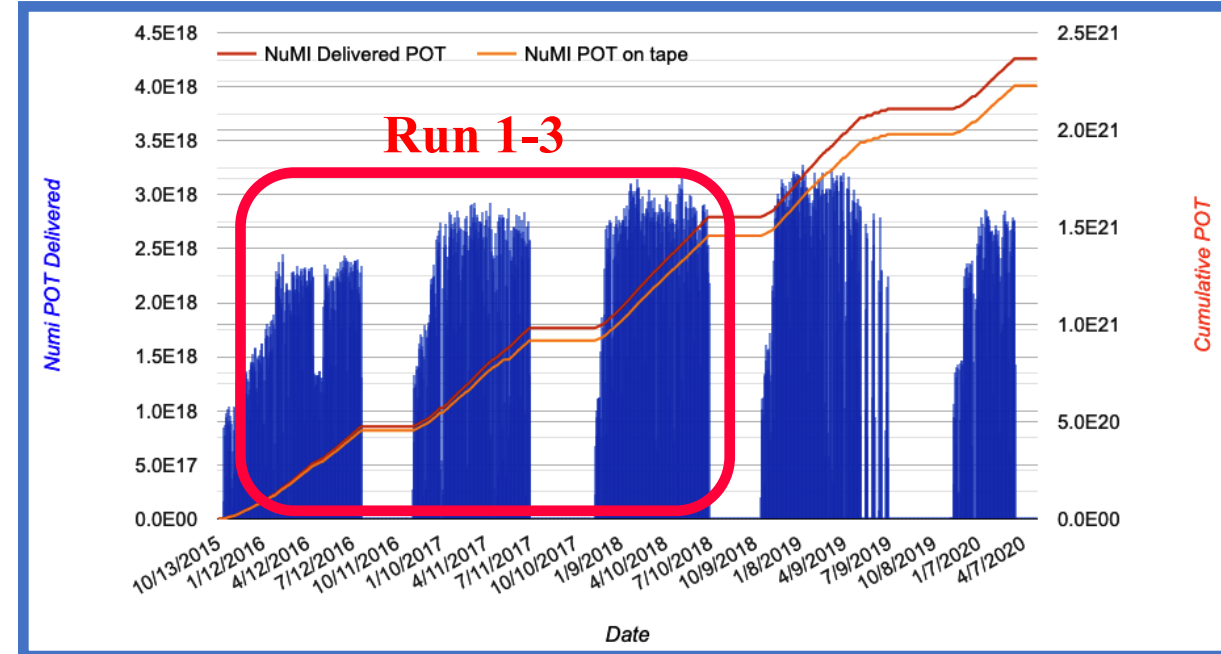
$\nu_e$  appearance ( $\nu_\mu \rightarrow \nu_e$ ):  $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$   
 $\nu_e$  disappearance ( $\nu_e \rightarrow \nu_e$ ):  $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$   
 $\nu_\mu$  disappearance ( $\nu_\mu \rightarrow \nu_\mu$ ):  $\sin^2 2\theta_{\mu\mu} = 4 \cos^2 \theta_{14} \sin^2 \theta_{24} (1 - \cos^2 \theta_{14} \sin^2 \theta_{24})$

# MicroBooNE Data Taking

On-axis BNB  $6.37 \times 10^{20}$  POT



Off-axis NuMI  $1.05 \times 10^{21}$  POT



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

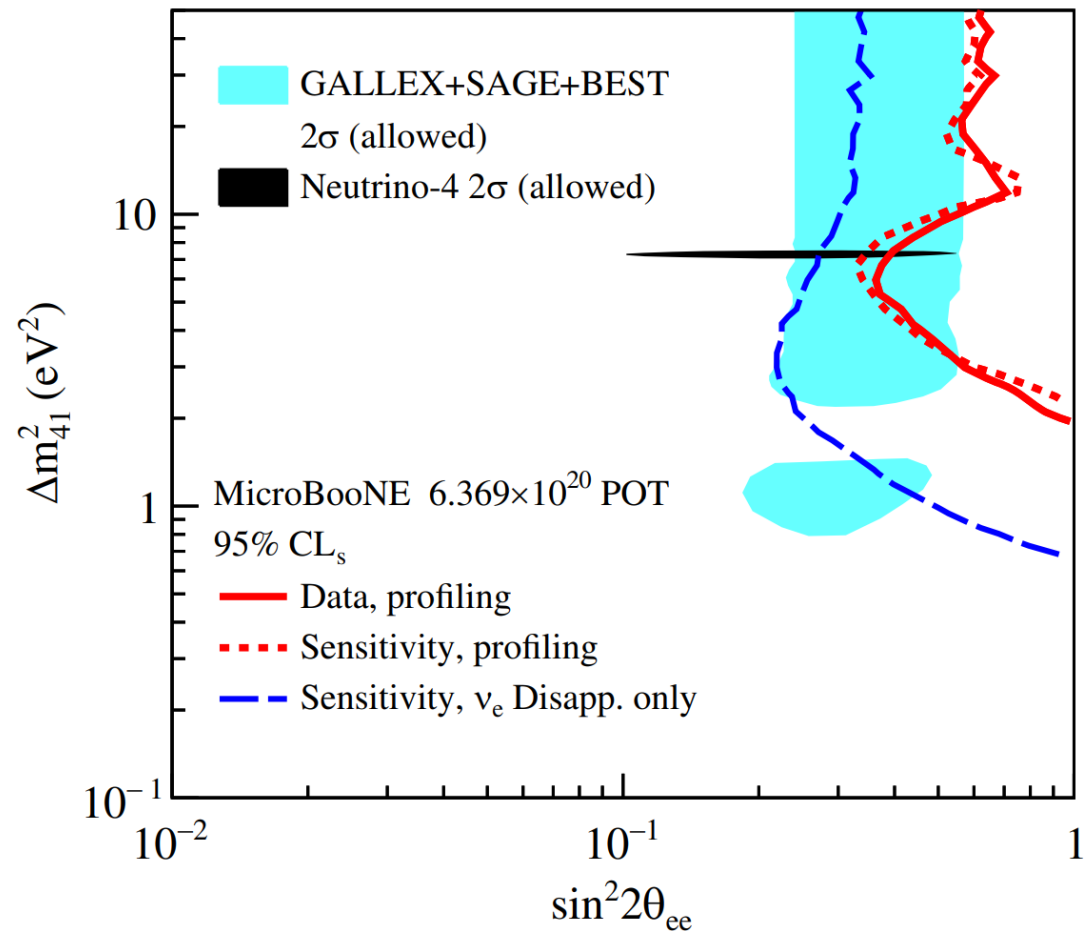
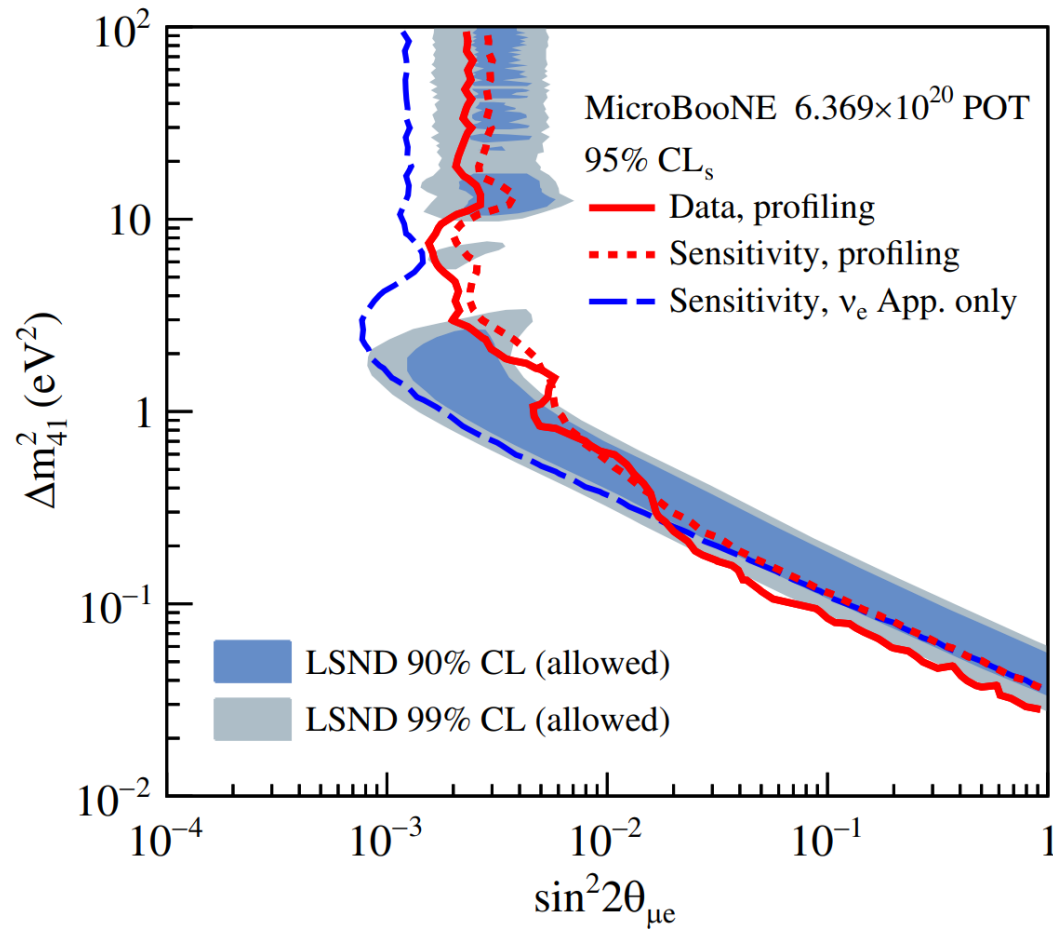
BNB [almost pure  $\nu_\mu$ ]  
very sensitive to  $\nu_e$  appearance!

NuMI [much larger  $\nu_e$  content]  
more sensitive to  $\nu_e$  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)

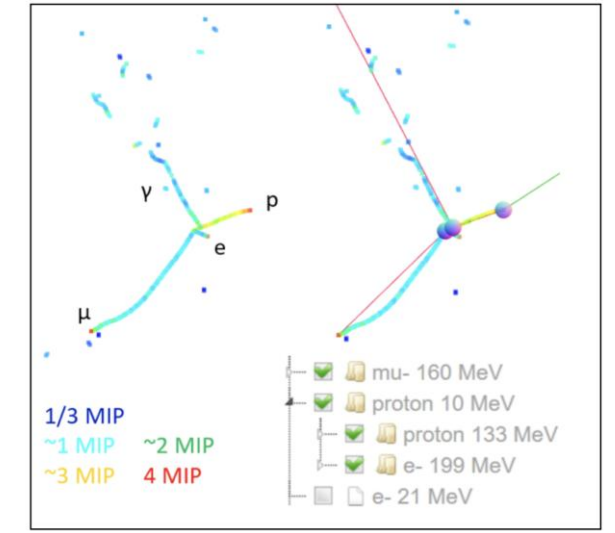
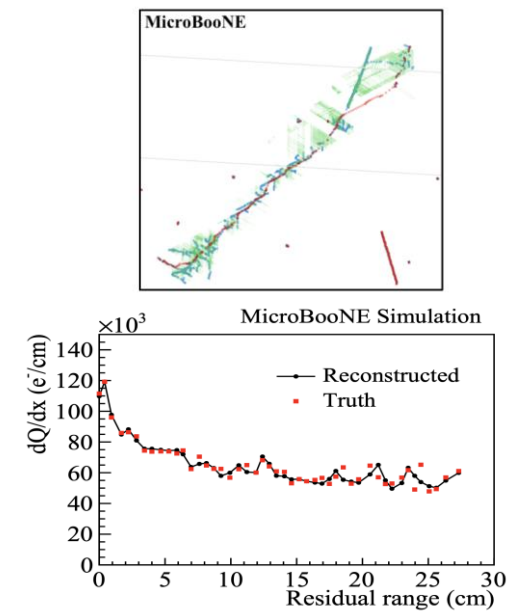
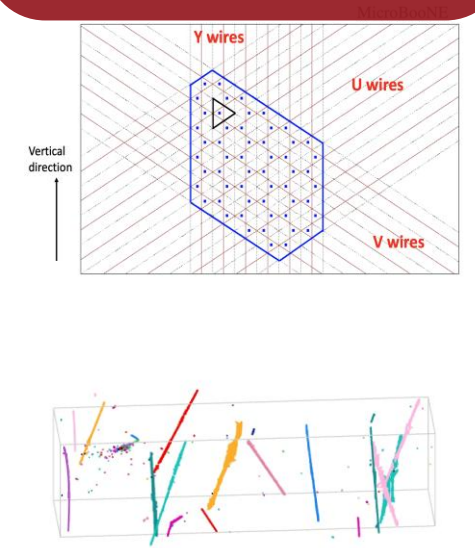
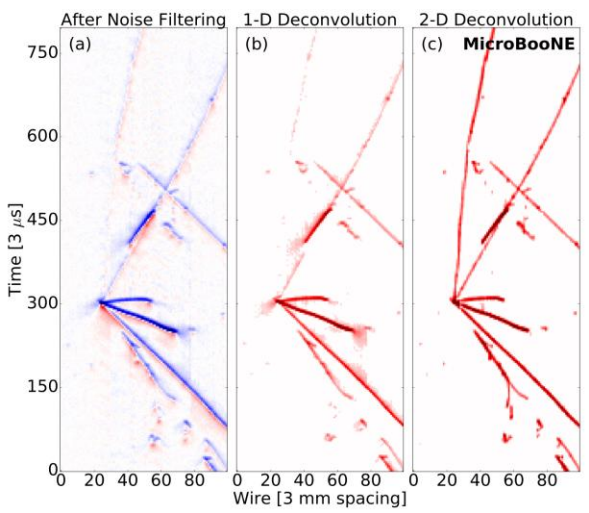


**Noise Filtering**  
**Signal Processing**

**3D imaging**  
**Clustering**  
**Charge-Light matching**

**3D trajectory & dQ/dx fitting**  
**Cosmic muon tagger**

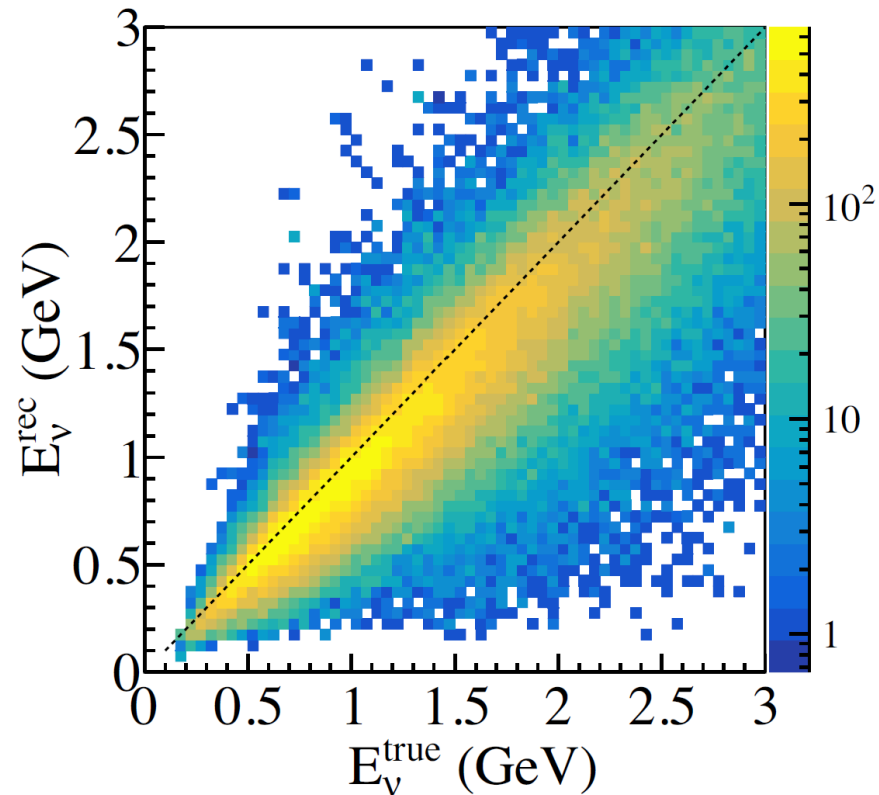
**Multi track fitting**  
**3D vertexing**  
**Particle identification**



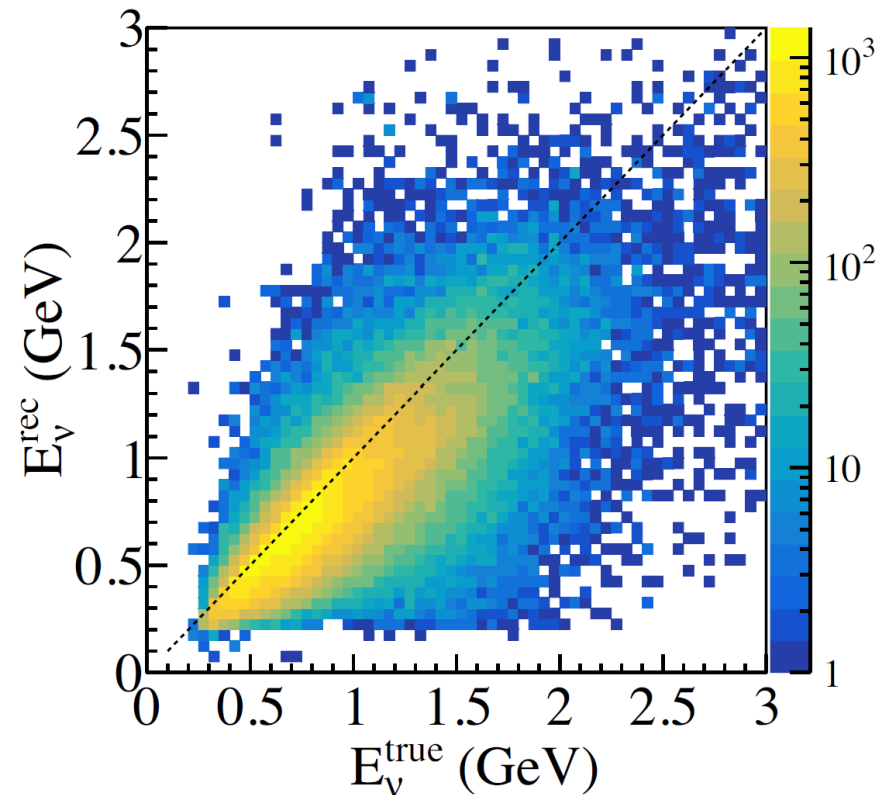
# Event Energy Resolution

- Reconstruction built upon Wire-cell, enabling superb performance
- Full inclusive  $\nu_e$  CC (charged-current) and  $\nu_\mu$  CC selections

$\nu_e$  CC: resolution 10~15%, bias ~7%

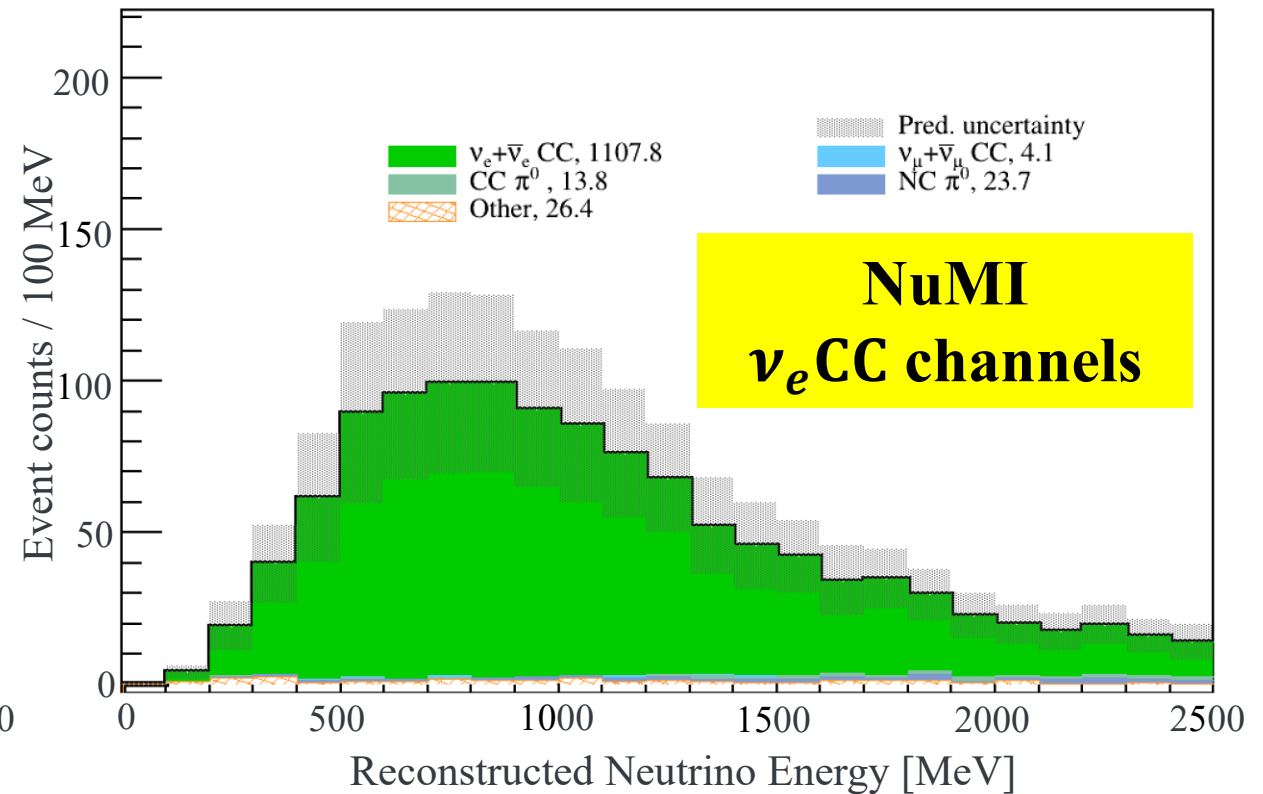
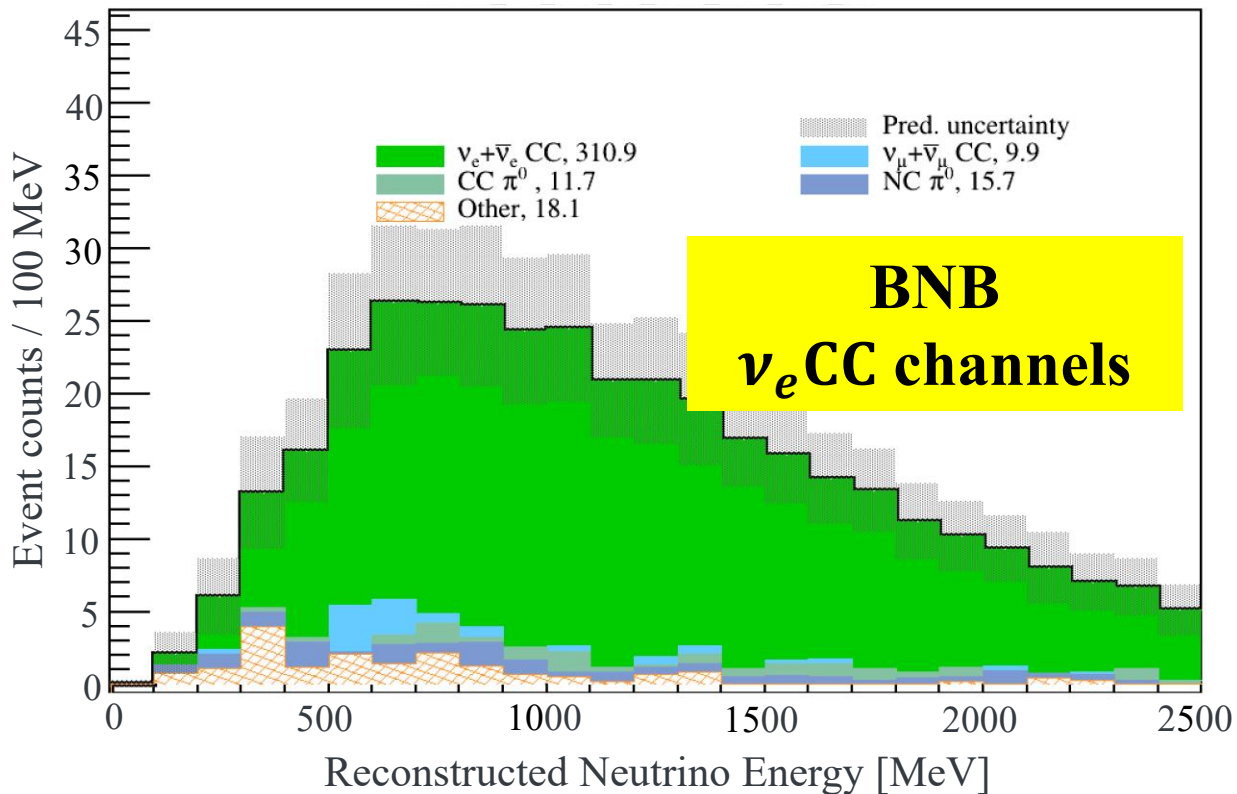


$\nu_\mu$  CC: resolution 15~20%, bias ~10%



# Target Channels: $\nu_e$ CC

- Reconstruction built upon Wire-cell, enabling superb performance
- Full inclusive  $\nu_e$  CC (charged-current) and  $\nu_\mu$  CC selections
- $\nu_e$  CC channels  $\sim 85\%$  purity, 50~60% efficiency
- $\nu_\mu$  CC channels  $\sim 90\%$  purity, 60~70% efficiency



# Constraint Power: Cross-Section Systematics

Leverage correlations to constrain the cross section model and its uncertainty

Constraint with BNB  $\nu_\mu$

BNB  $\nu_e$   
Only Cross Section Syst.

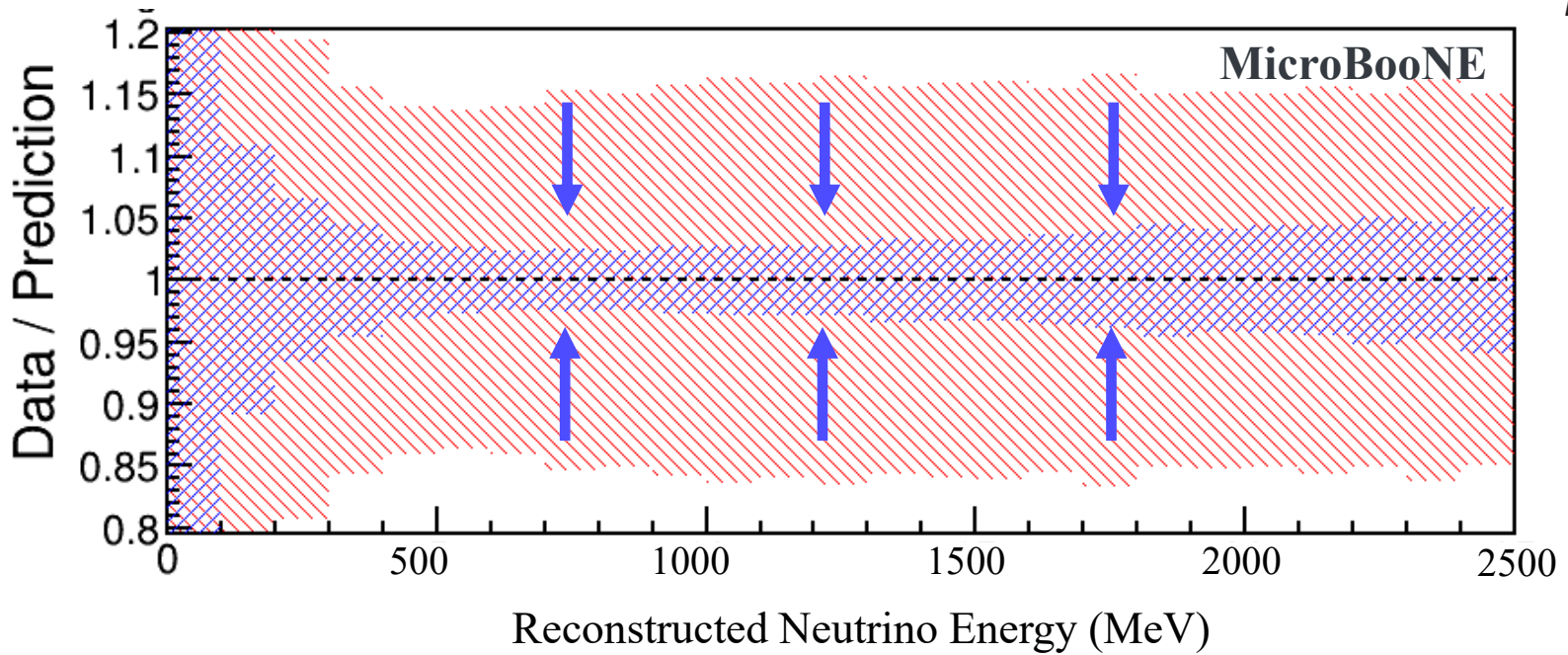
**Conditional expectation & covariance**

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

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

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

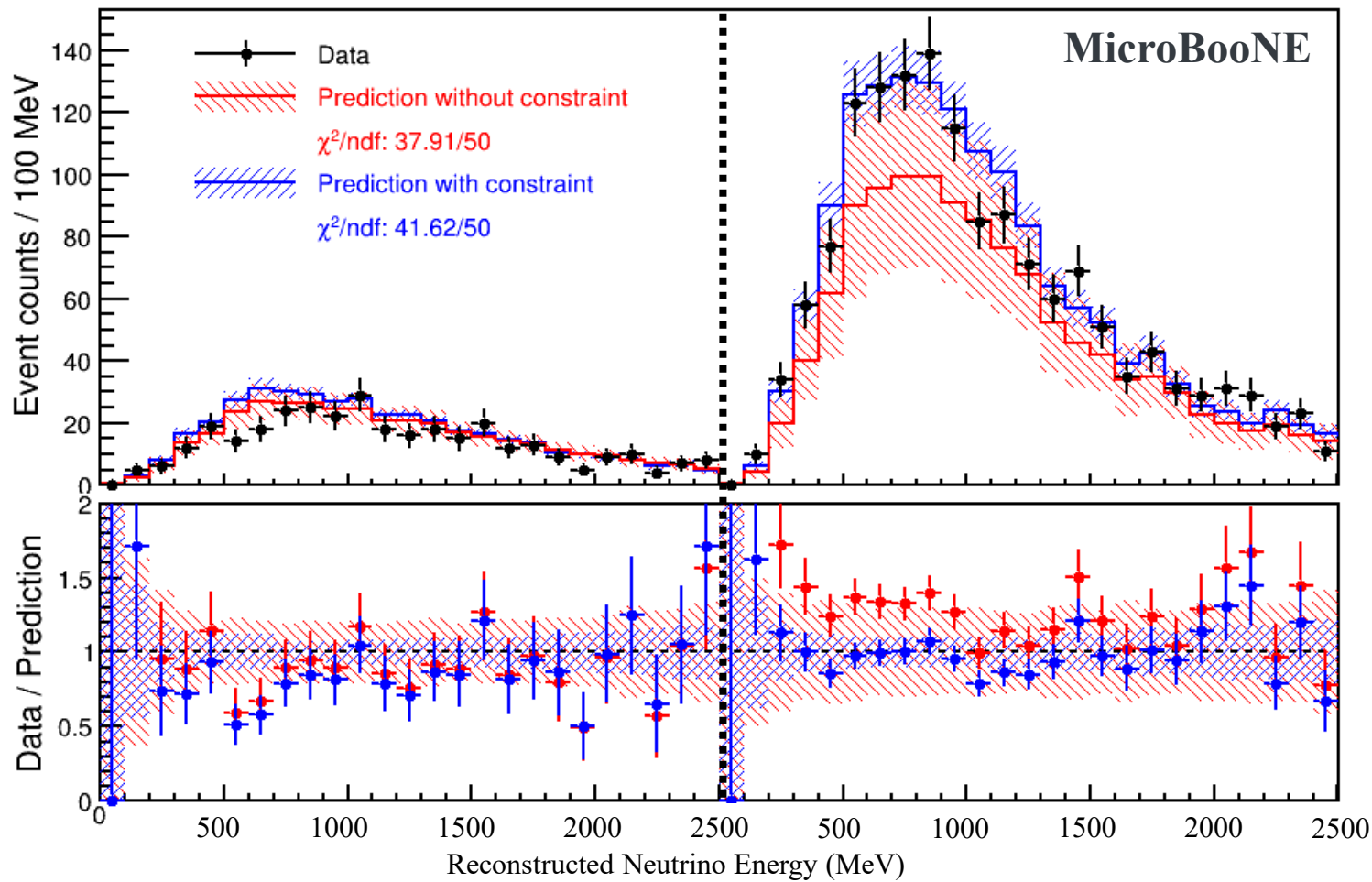
PRD 105, 112005 (2022)



# $\nu_e$ CC Channels with Constraints by All Non- $\nu_e$ 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)