Short-Baseline Neutrino Experiments with Beams: Status and Prospects



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Brookhaven National Laboratory

Disclaimer

- this talk covers 4 experiments: MicroBooNE, SBND, ICARUS, and JSNS^2
- I am a collaborator on MicroBooNE
  - but I'm <u>not</u> a collaborator on SBND/ICARUS, fairly familiar with their status, progress, and recent results
    - newest results from SBND will be discussed in the next talk from Ornella
  - and I'm <u>not</u> a collaborator on JSNS^2, and relatively less familiar with its detailed status
  - many plots are adopted from Neutrino2026 slides for these experiments, so they may be slightly outdated by now
- all the experiments have broad physics programs; but in this talk I'll primarily focus on their <u>neutrino oscillation studies</u>

Outline

1 **short-baseline anomalies**

appearance and disappearance hints at L/E ~ 1 m/MeV

2 **SBN at Fermilab: MicroBooNE, ICARUS, and SBND**

Recent results from LArTPC experiments at Fermilab

3 **JSNS2 at JPARC**

Direct test of LSND

4 **outlook**

what comes next for the field

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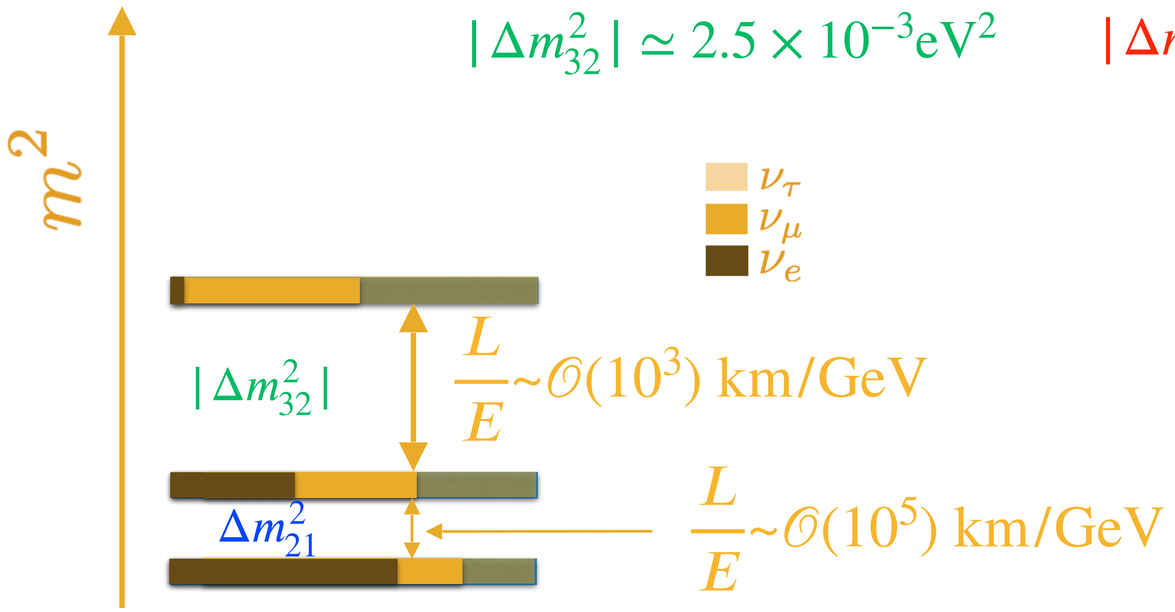
Three-flavor neutrino oscillations

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric, Accelerator
θ_{23}~48°
$|\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$

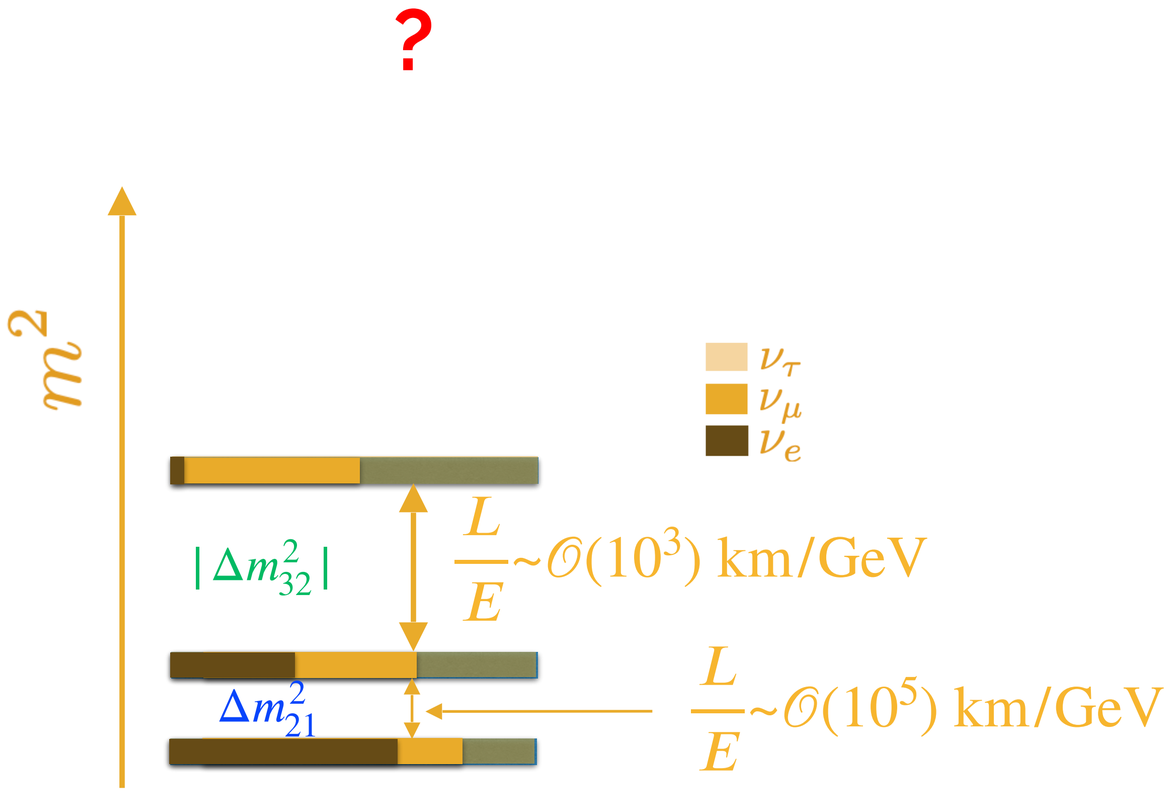
Reactor
θ_{13}~9°
$|\Delta m^2_{31(2)}| \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$

Solar, KamLAND, JUNO
θ_{12}~34°
$\Delta m^2_{21} \simeq 7 \times 10^{-5}\mathrm{eV}^2$



Experimental Anomalies

majority of the experimental results align with the “standard” three-active-flavor scenario, but several “anomalies” do exist **at much smaller L/E** than expected

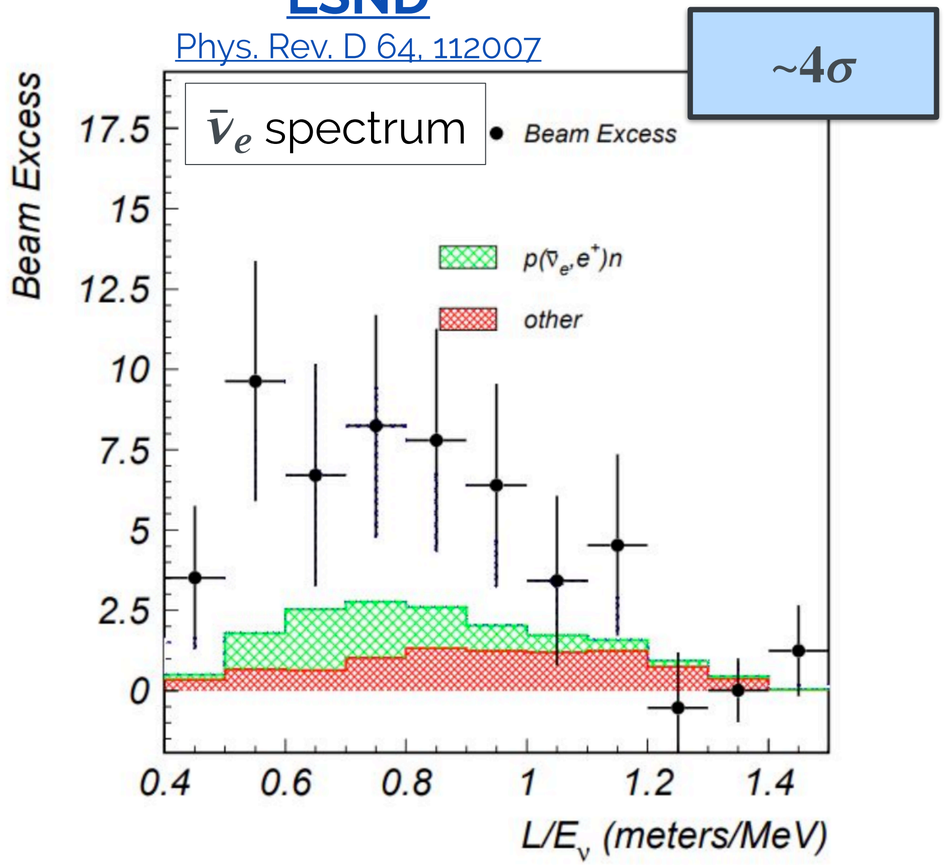


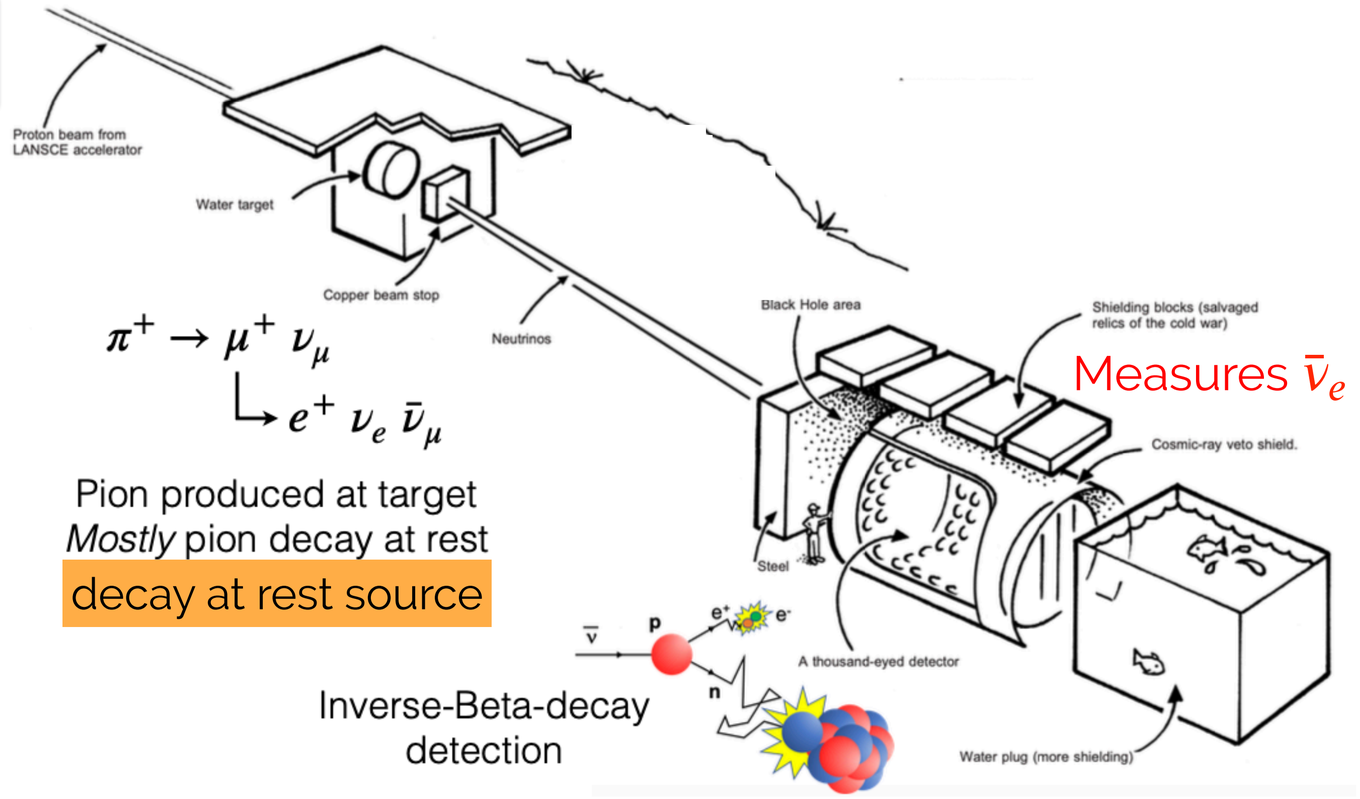
LSND and MiniBooNE ν_e appearance anomalies

LSND

Phys. Rev. D 64, 112007

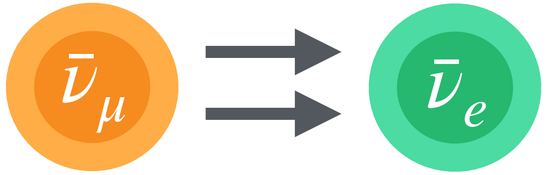
~4σ





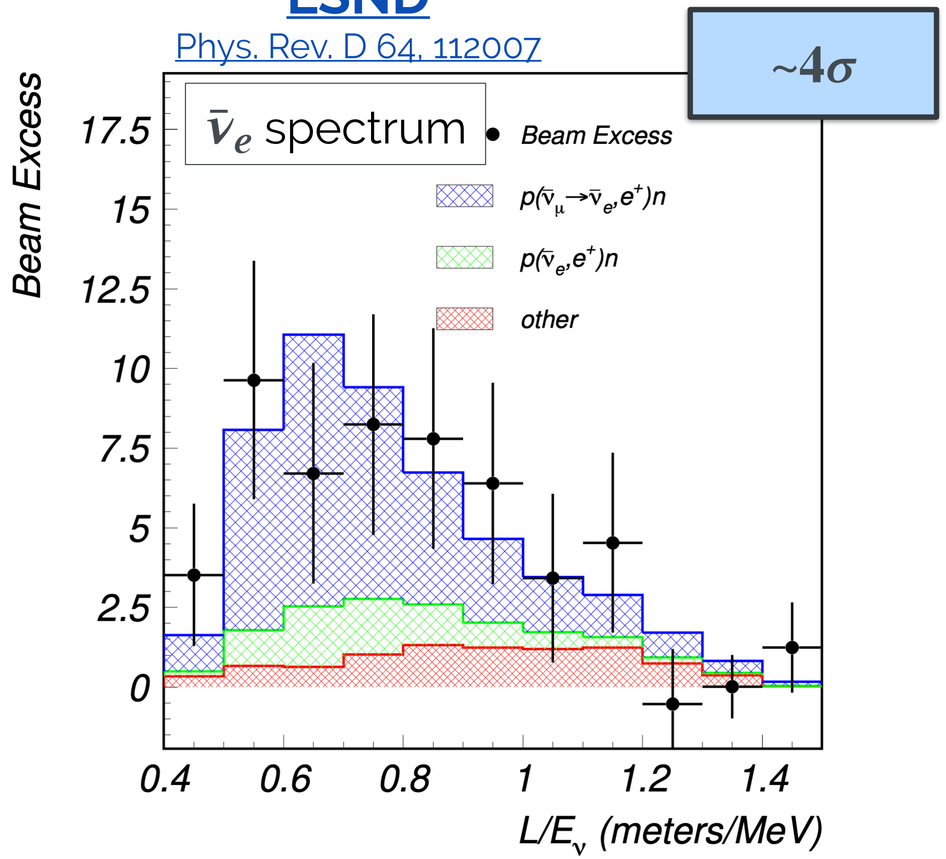
- LSND observed a significant excess of 20-60 MeV $\bar{\nu}_e$ from a $\nu_e/\bar{\nu}_\mu$-dominated μ^+ DAR source

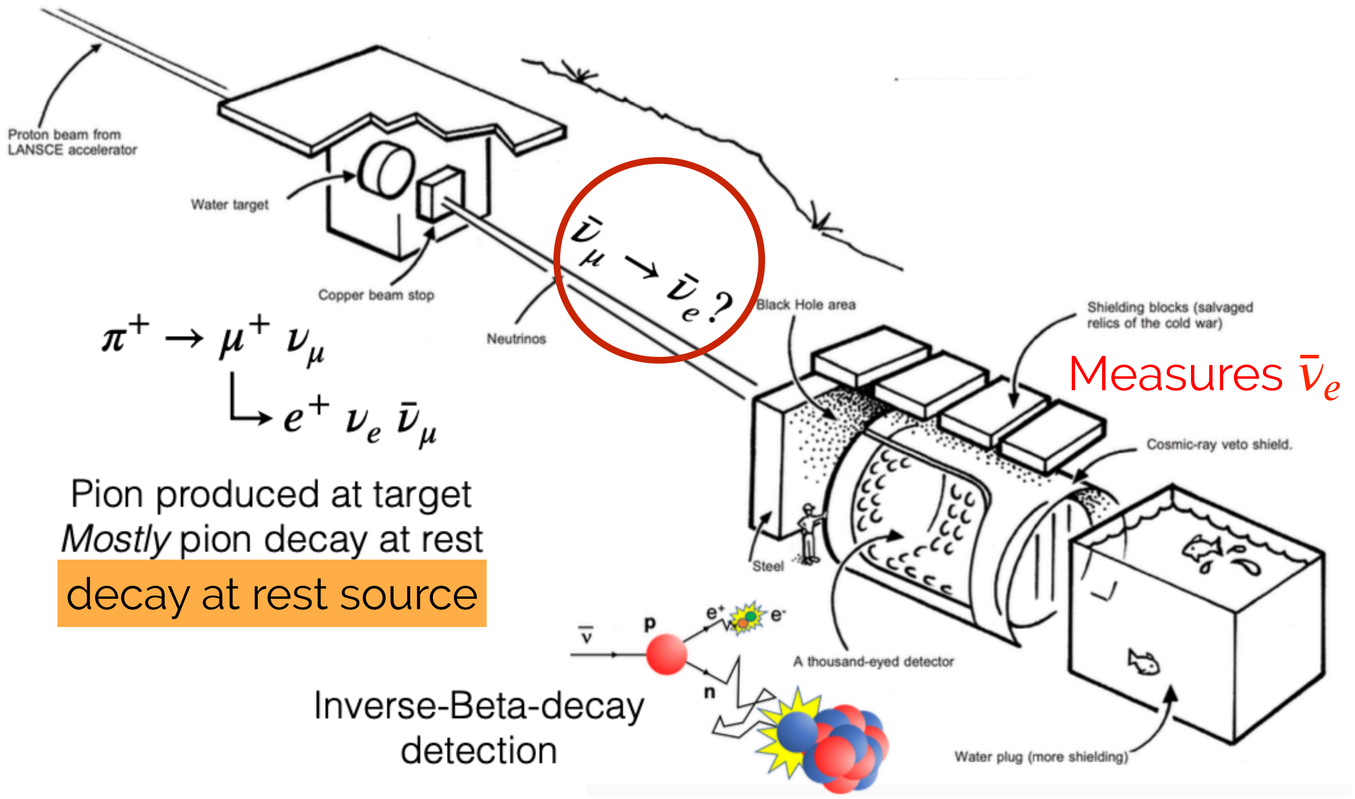
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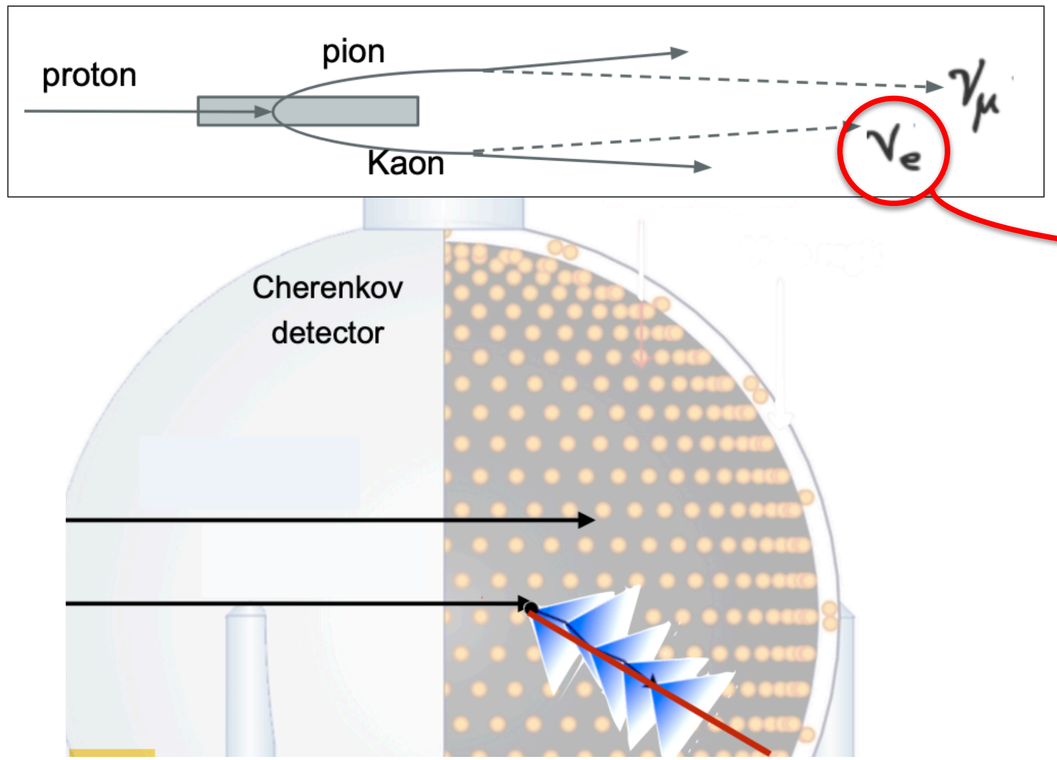


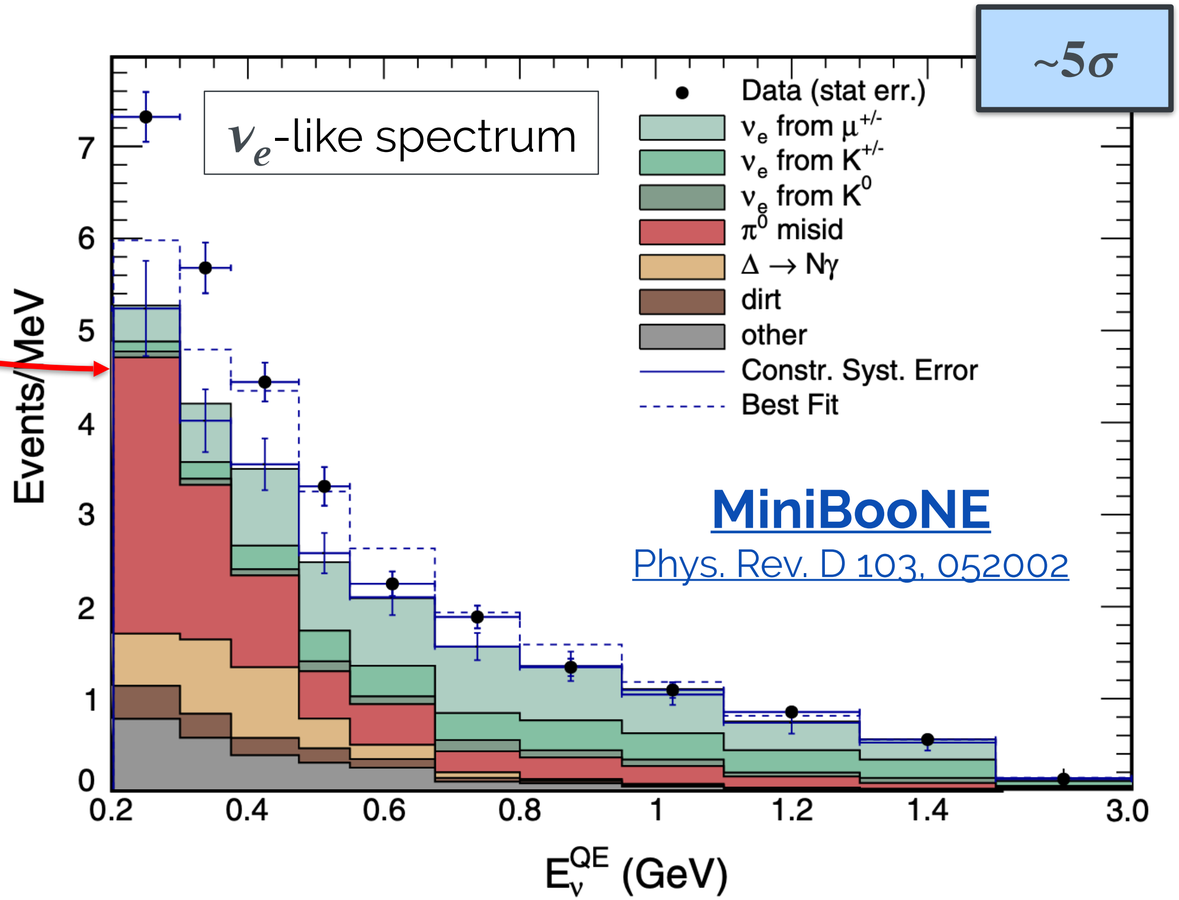


- LSND observed a significant excess of 20-60 MeV $\bar{\nu}_e$ from a $\nu_e/\bar{\nu}_\mu$-dominated μ^+ DAR source
- the excess can be interpreted as a $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation
- the excess covers L/E from 0.4-1.4 $\mathrm{m/MeV}$

LSND and MiniBooNE ν_e appearance anomalies

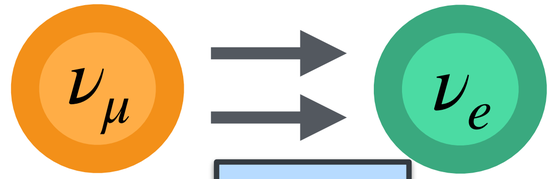
decay in flight source



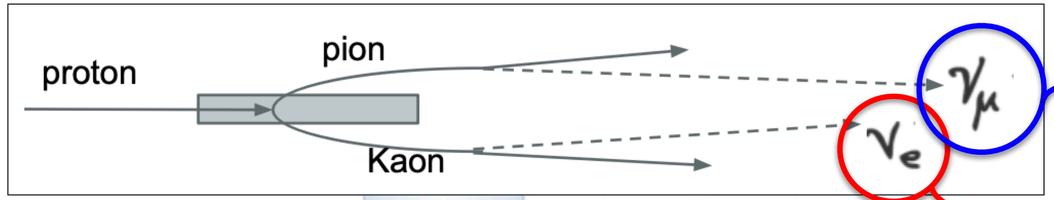


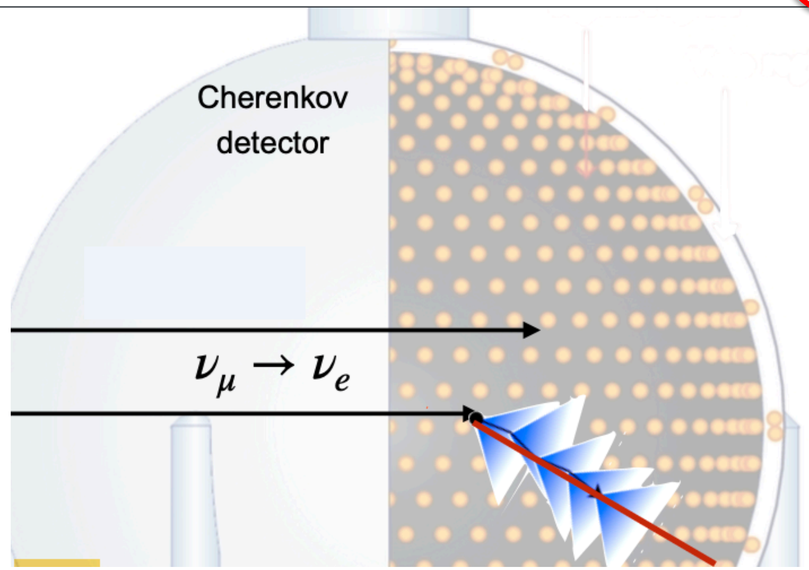
- MiniBooNE, motivated by the LSND anomaly, observed a significant excess of 200-600 MeV neutrinos from a typical accelerator neutrino beam
- the excess covers L/E from 0.2-2 $\mathrm{m/MeV}$ (or km/GeV), similar to the LSND anomaly

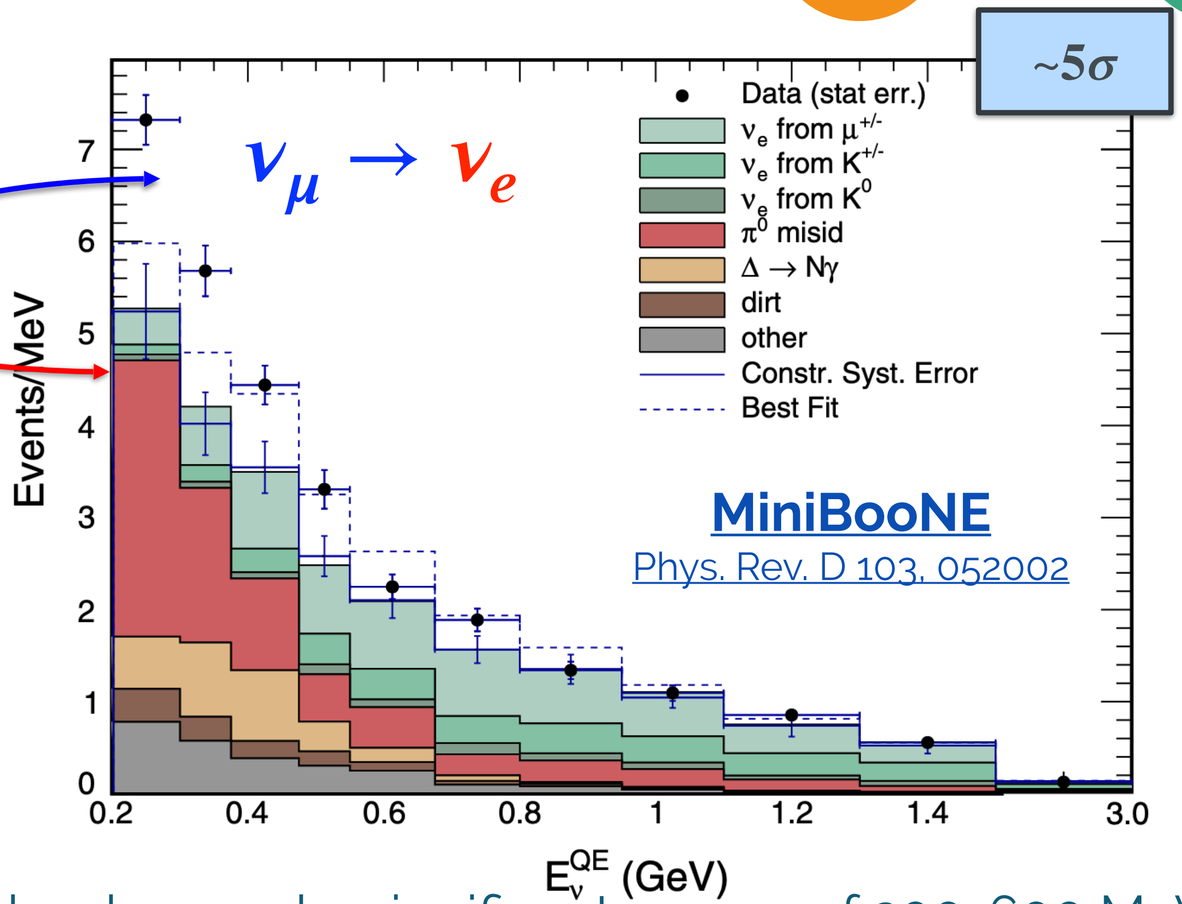
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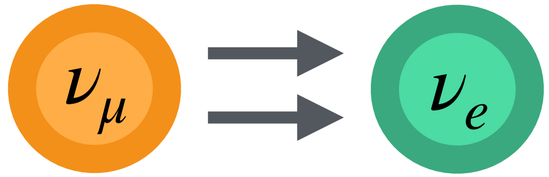




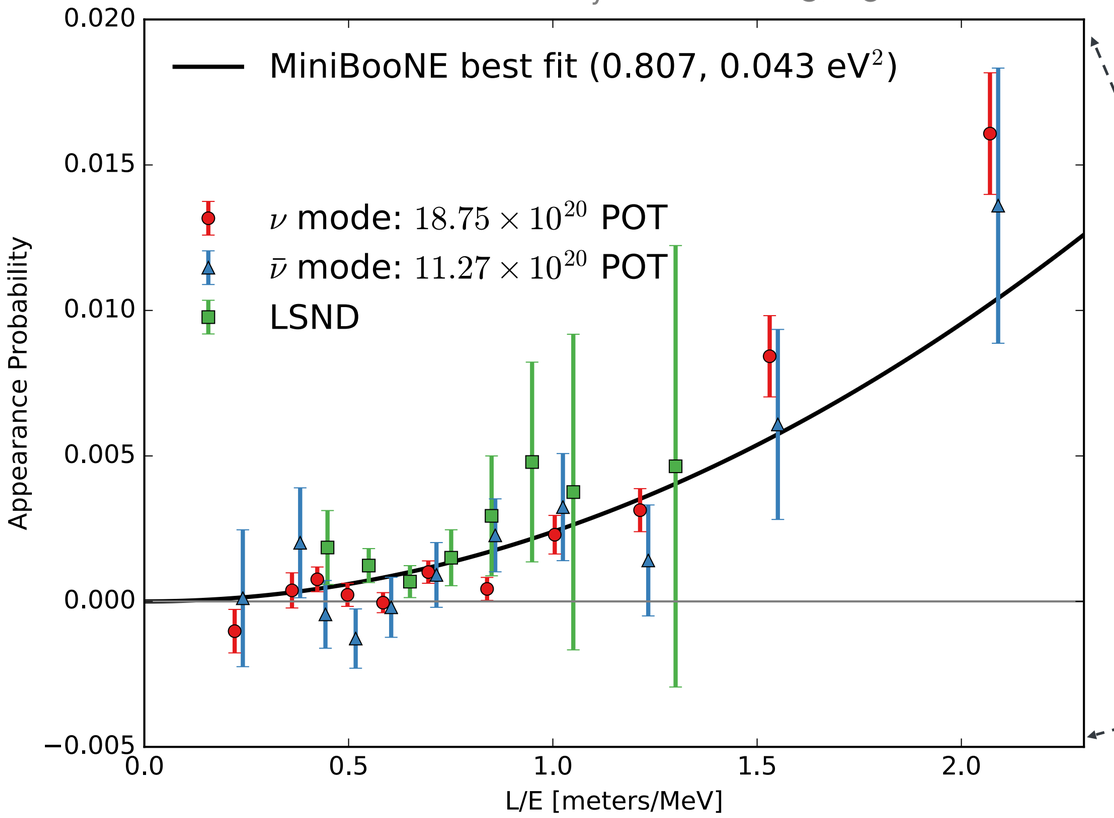


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- the excess covers L/E from 0.2-2 $\mathrm{m/MeV}$ (or km/GeV), similar to the LSND anomaly
- this excess can be interpreted as a beam ν_μ to ν_e oscillation

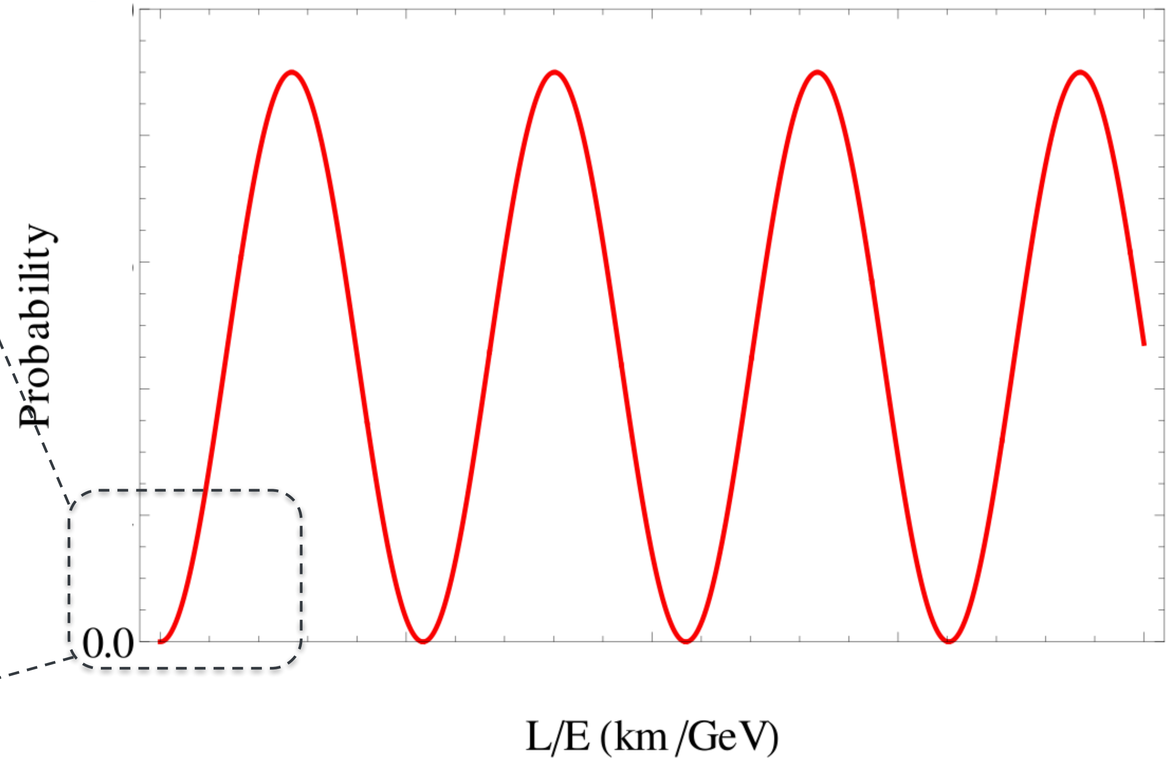
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Phys. Rev. D 103, 052002 (2021)

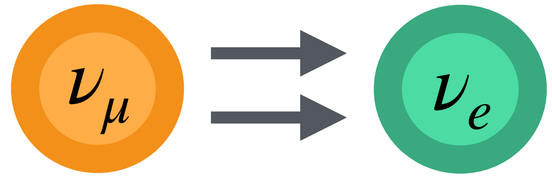


$\nu_\mu \rightarrow \nu_e$ Two neutrino approximation

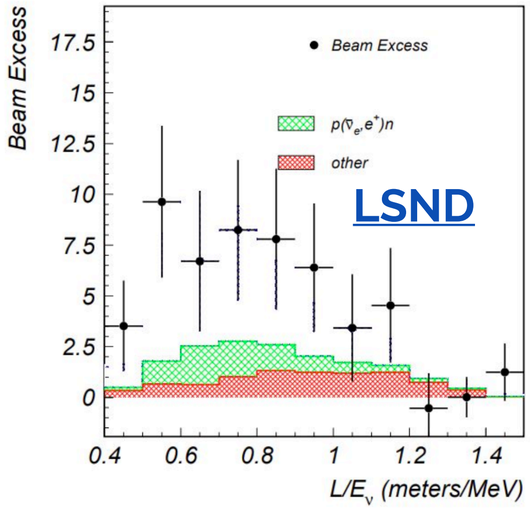


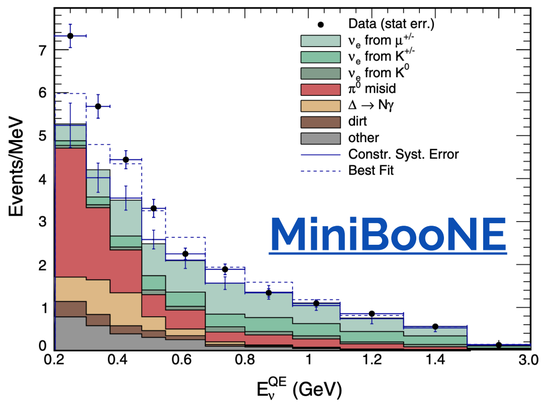
$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\mu e}) \cdot \sin^2(\frac{\Delta m^2 L}{4E})$$

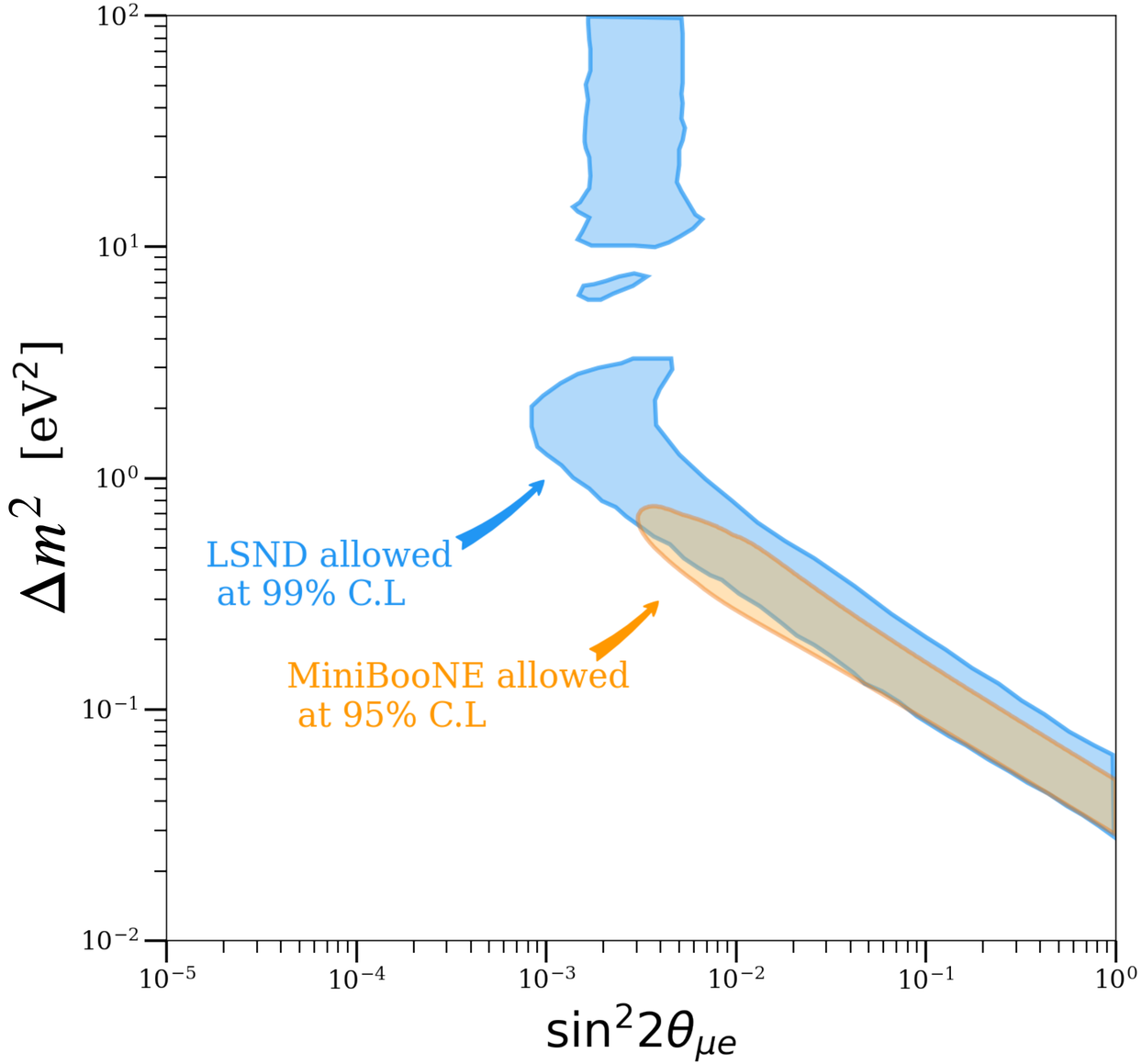
ν_e Appearance Allowed Regions



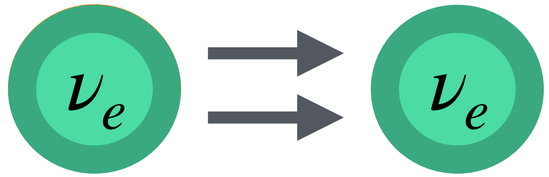
$$P_{\nu_\mu \to \nu_e} = \sin^2(2\theta_{\mu e}) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$







Gallium and Reactor ν_e disappearance anomalies



Gallium Anomaly

PRC 105 (2022) 065502

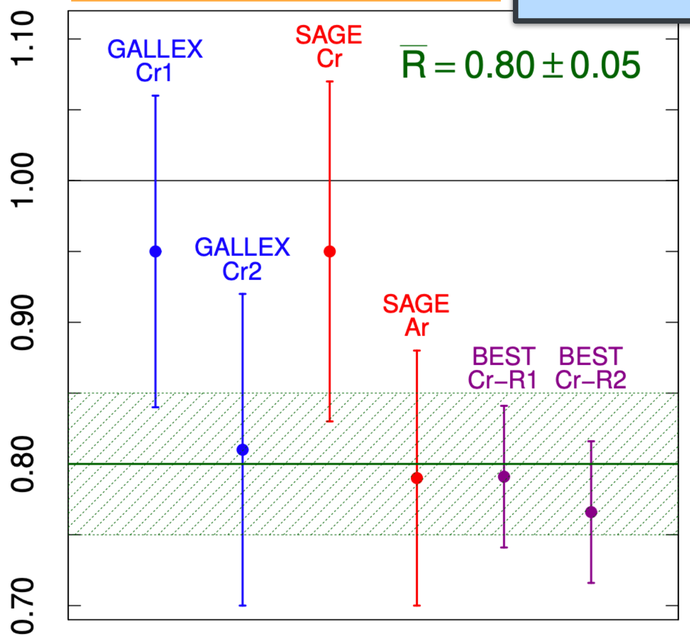
radioactive source
discrete sub-MeV $\bar{\nu}_e$

~4σ

$\nu_e \rightarrow \nu_e$

$R = N_{exp}/N_{cal}$

$\sin^2(2\theta_{ee}) \cdot \sum \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

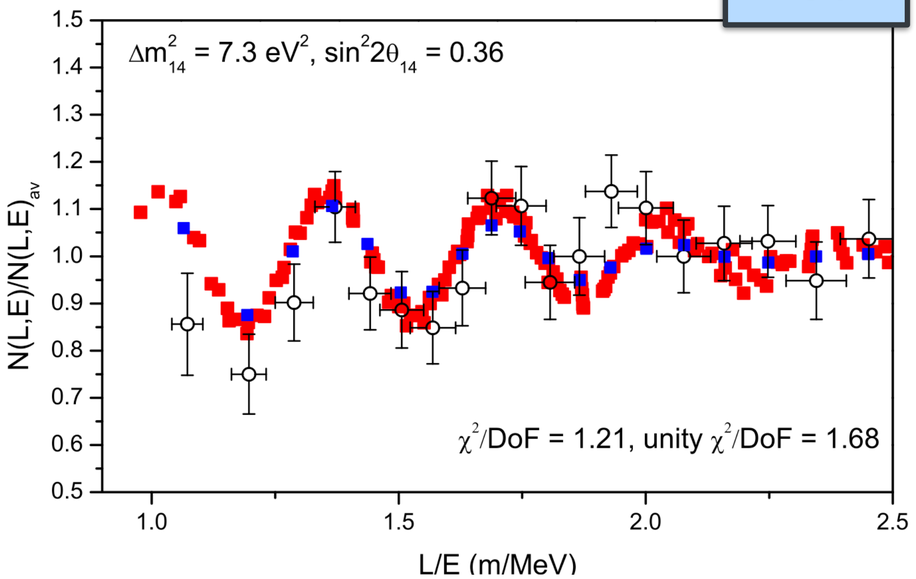


Neutrino-4

PRD 104 032003 (2021)

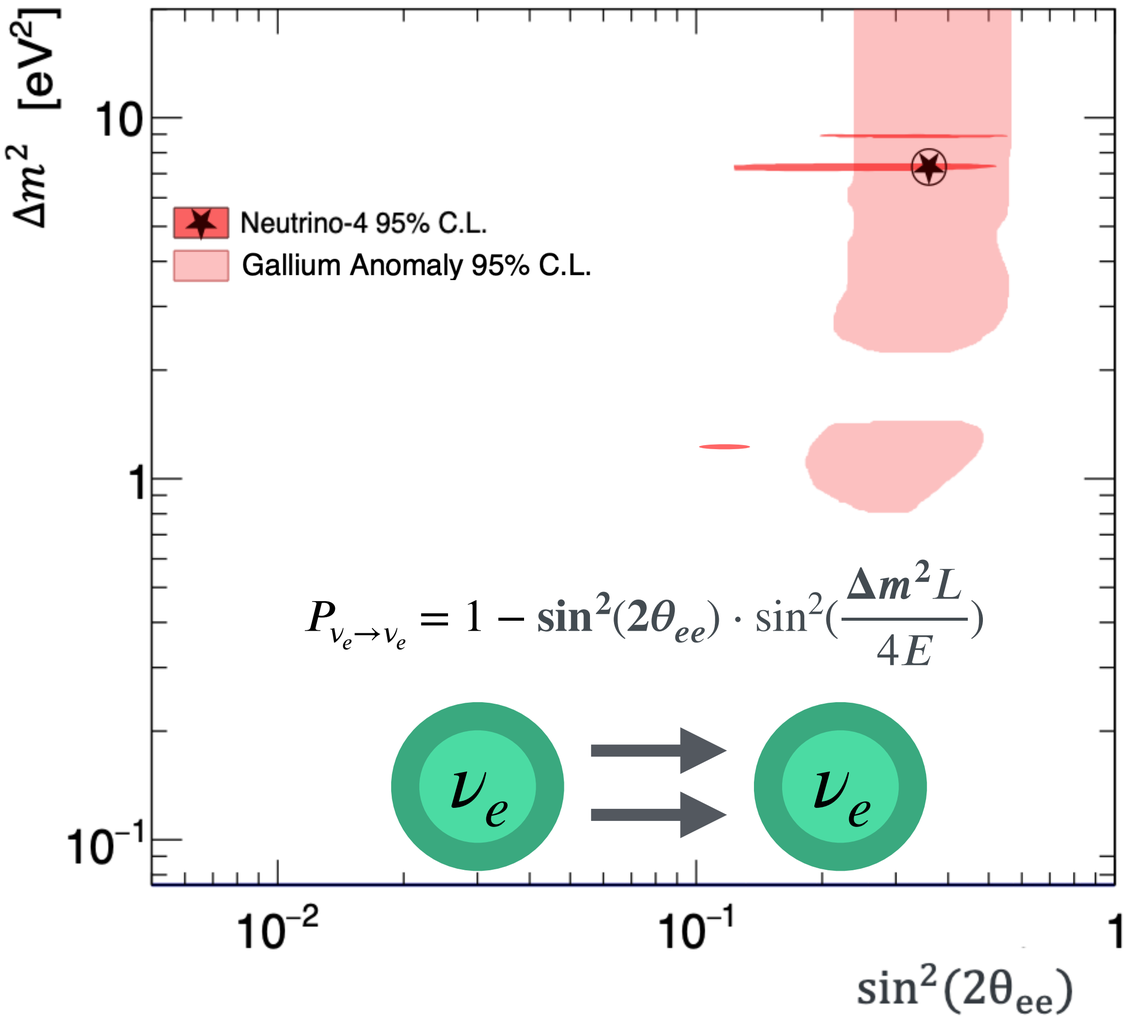
Reactor source
1-8 MeV $\bar{\nu}_e$

~3σ

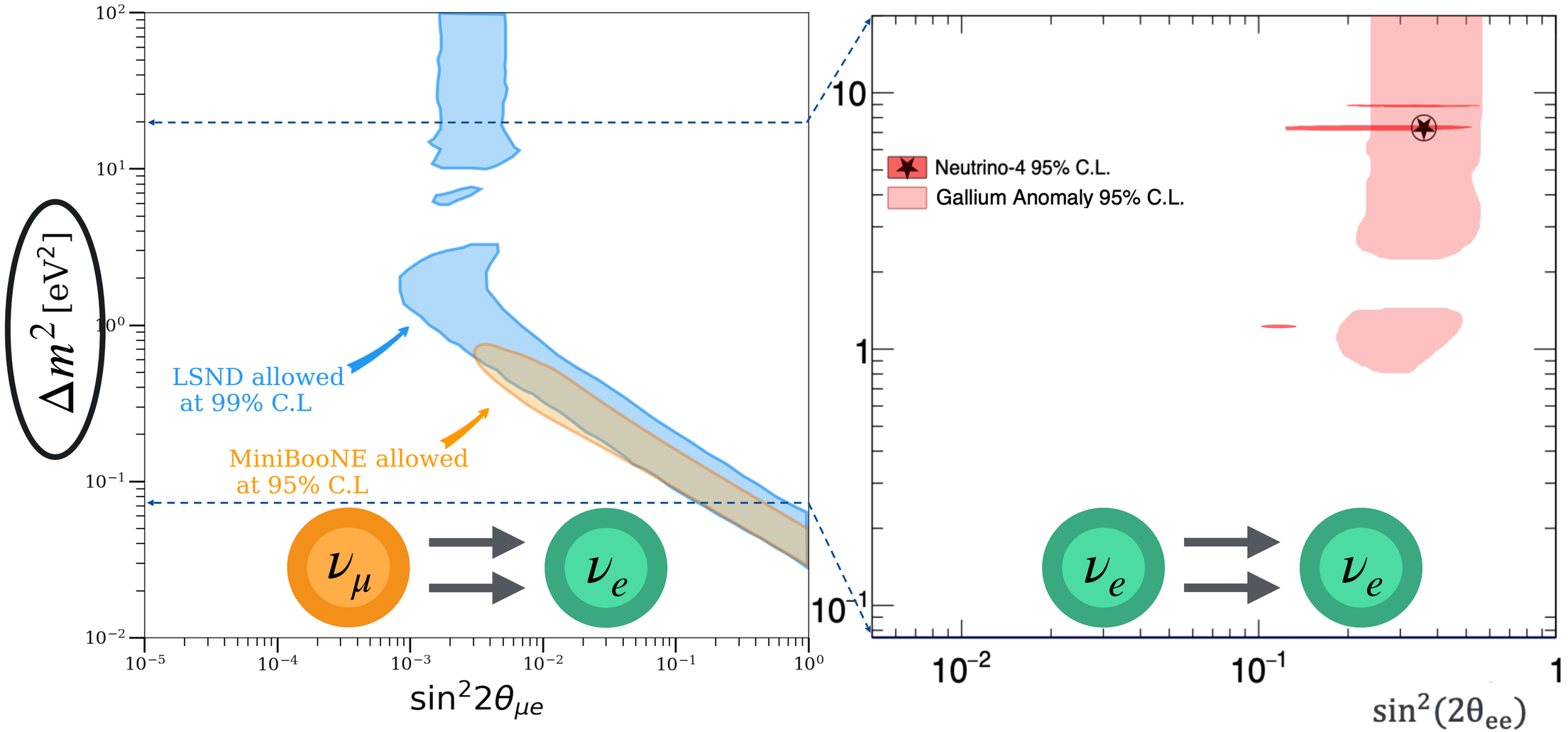


- radiochemical gallium detectors observed a deficit in the integrated event rate
- the deficit can be interpreted as a disappearance oscillation effect, with discrete L/E values ranging from 0.5-2.5 $\mathrm{m/MeV}$
- the Neutrino-4 experiment also observed a possible oscillation pattern in a similar L/E range

Experimental Anomalies Allowed Regions



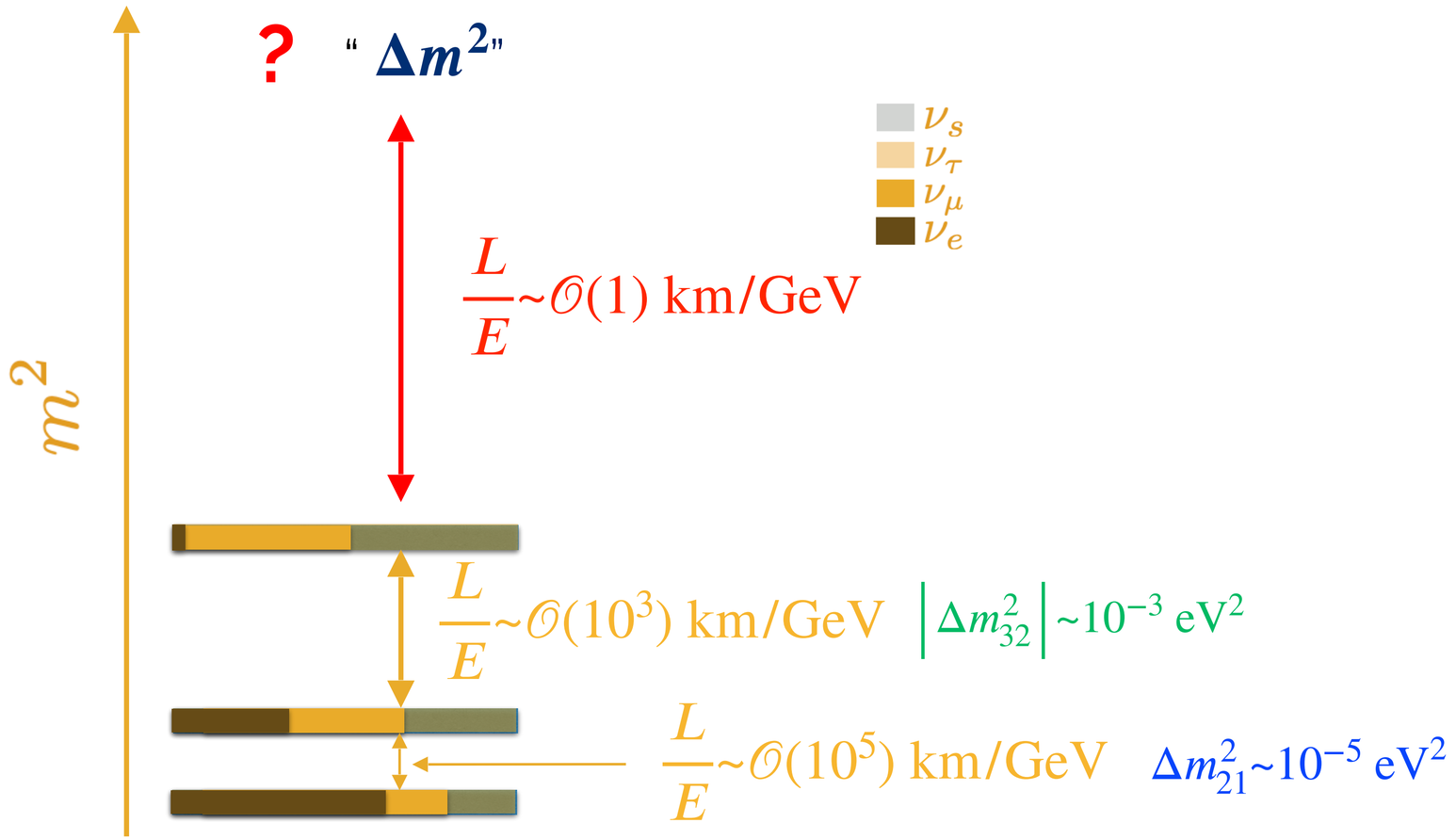
Experimental Anomalies Allowed Regions



the appearance and disappearance anomalies point to a similar Δm^2 scale, and the oscillation hypothesis provides a plausible explanation for all of them

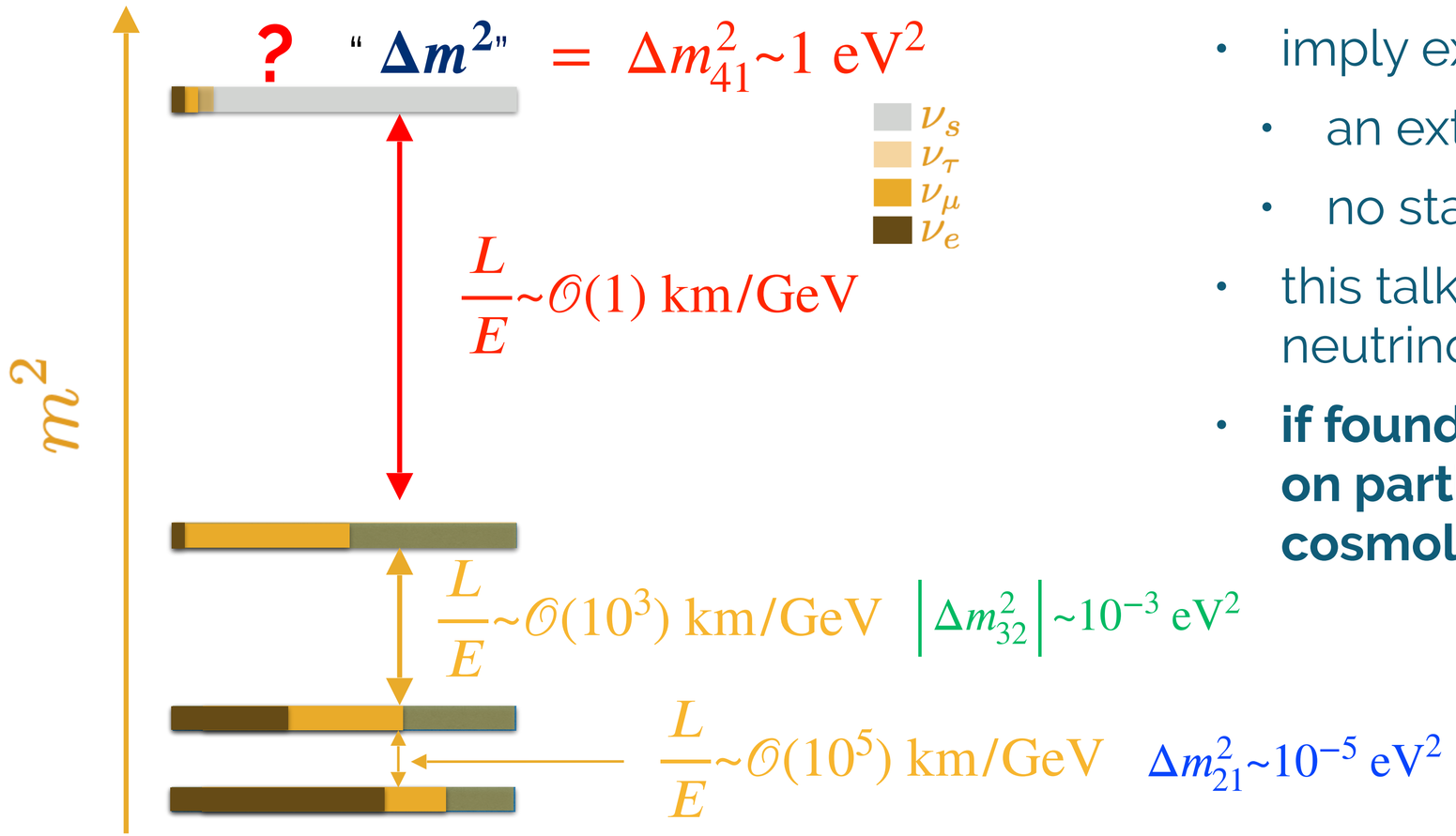
Experimental Anomalies

majority of the experimental results align with the "standard" three-active-flavor scenario, but several "anomalies" do exist at a much smaller L/E → an oscillation at high Δm^2, inconsistent with the two known mass splittings



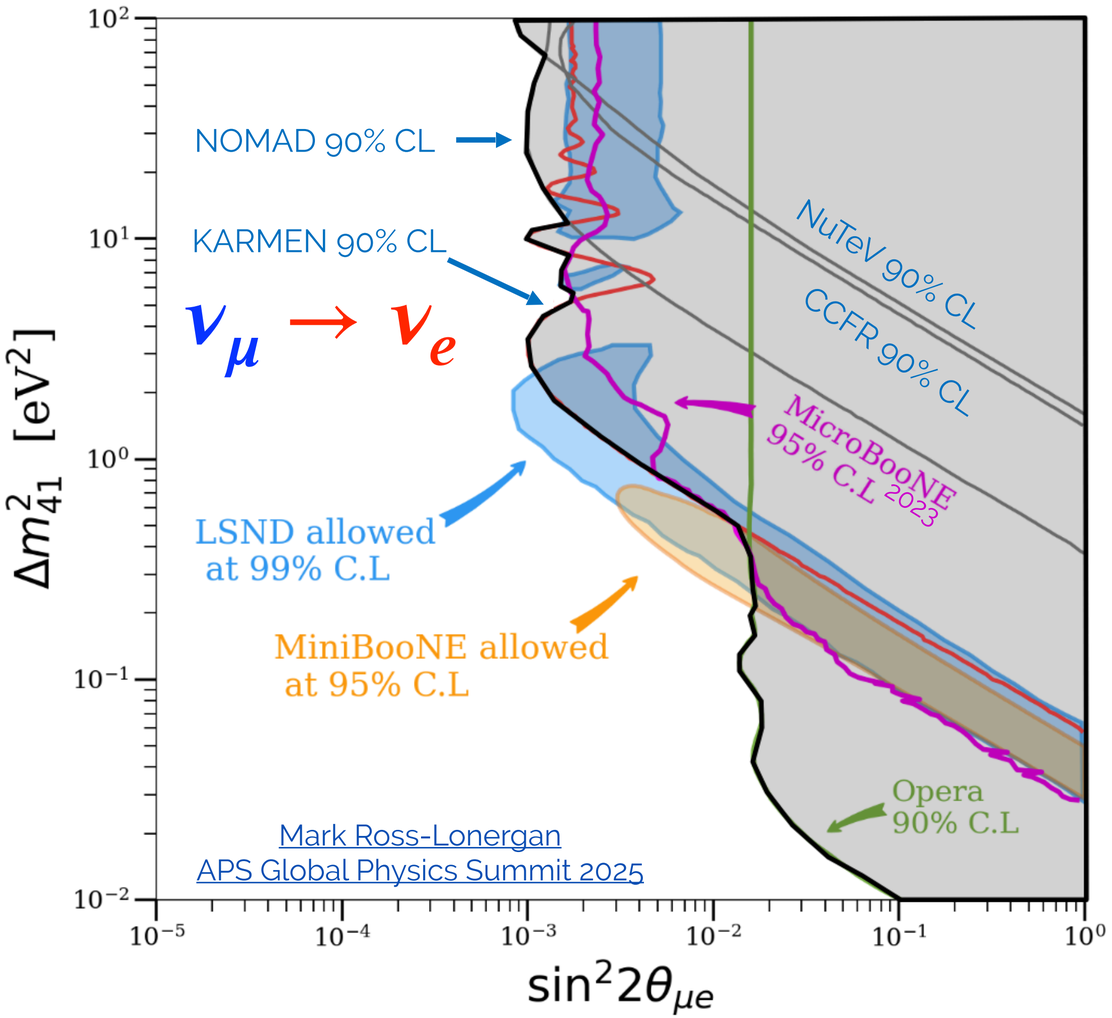
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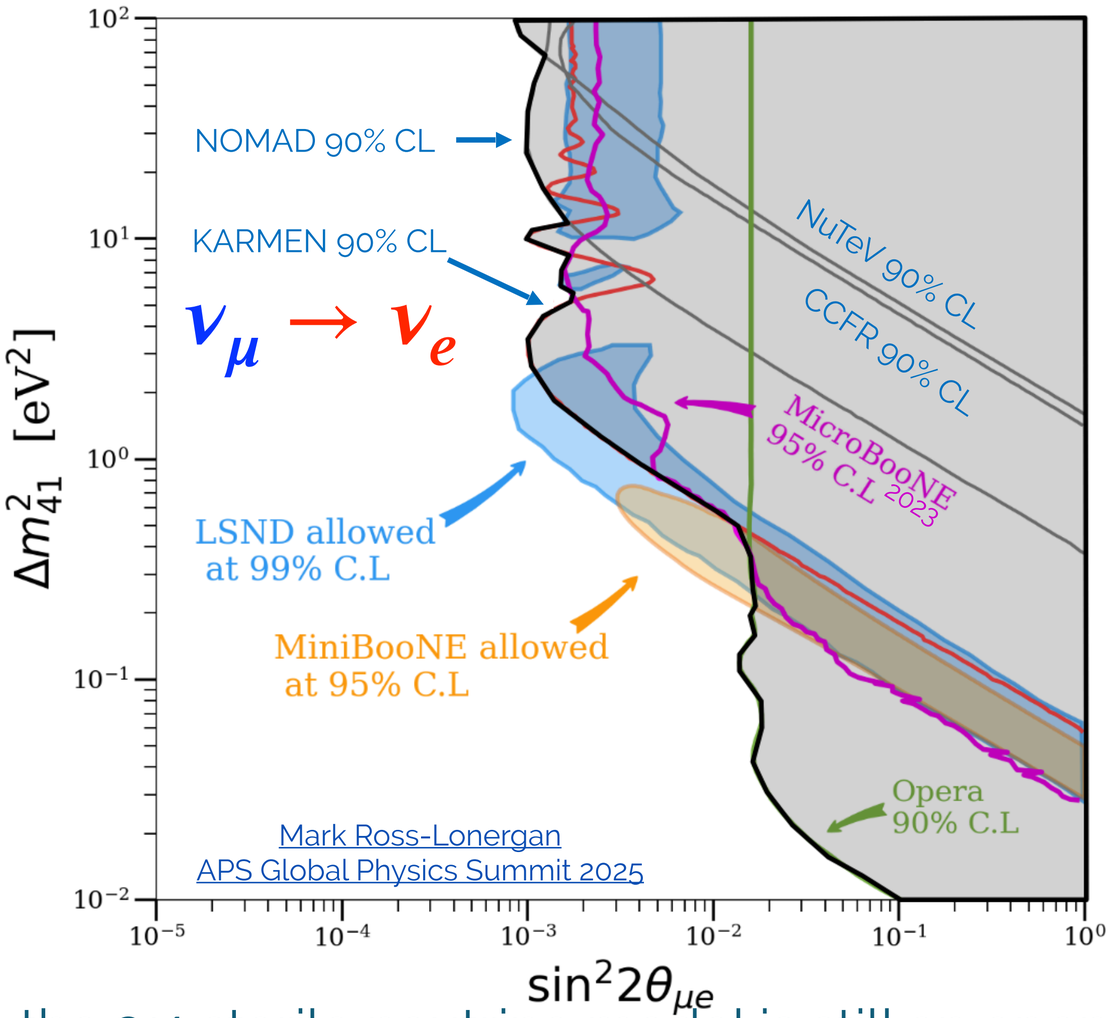
- imply existence of a ***sterile*** neutrino
  - an extra heavier flavor/mass eigenstate
  - no standard model interactions
- this talk focuses on **eV-scale "light" sterile** neutrinos
- **if found, a BSM particle; profound impact on particle /astro-particle physics and cosmology**

Previous Constraints on Experimental Anomalies

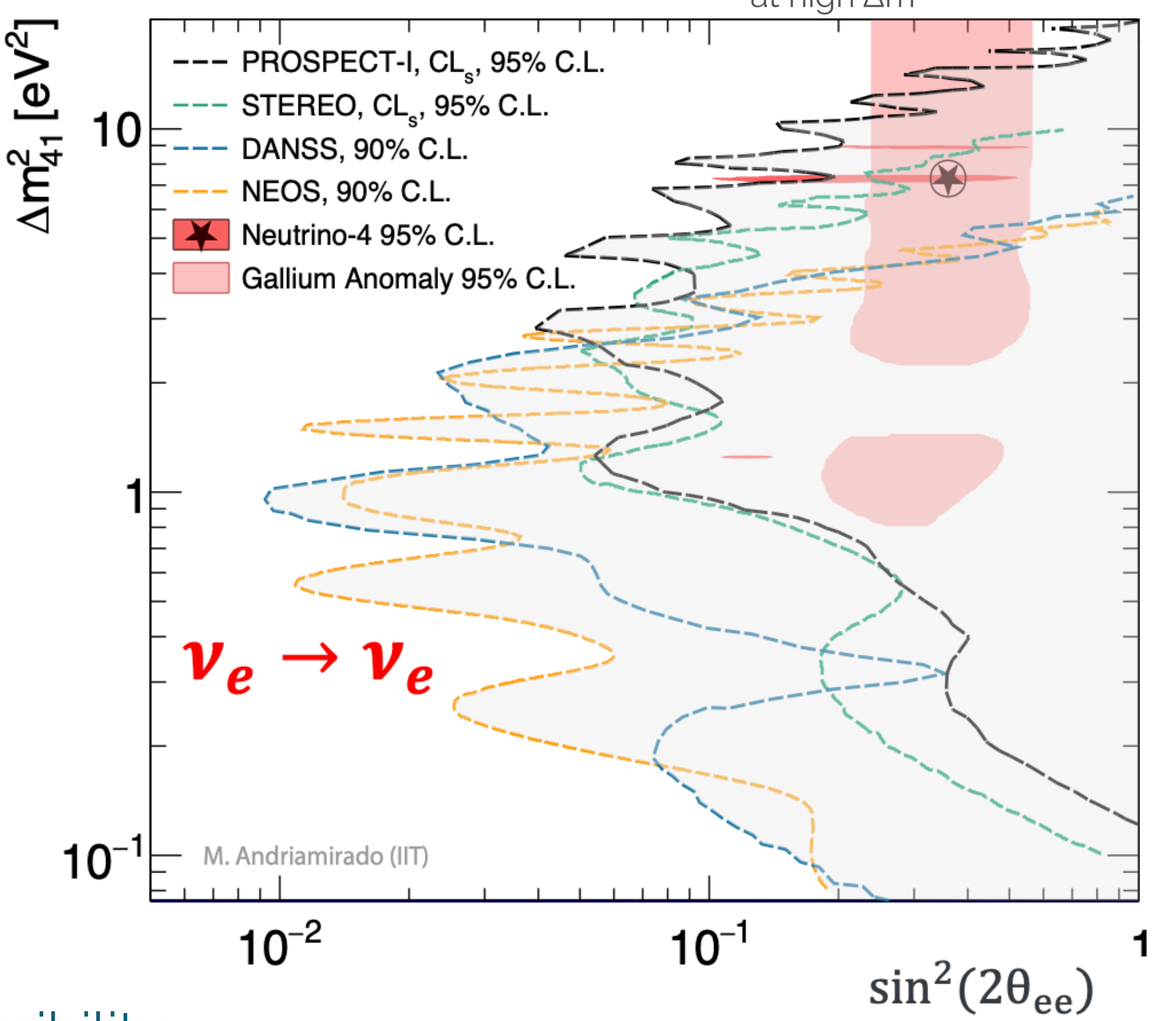


the 3+1 sterile neutrino model is still an open possibility

Previous Constraints on Experimental Anomalies



(NOT included)
KATRIN exclusion
at high Δm^2



- the 3+1 sterile neutrino model is still an open possibility
- an interesting situation in the ν_e disappearance channel with most recent PROSPECT and KATRIN results

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Recent results from LArTPC experiments at Fermilab

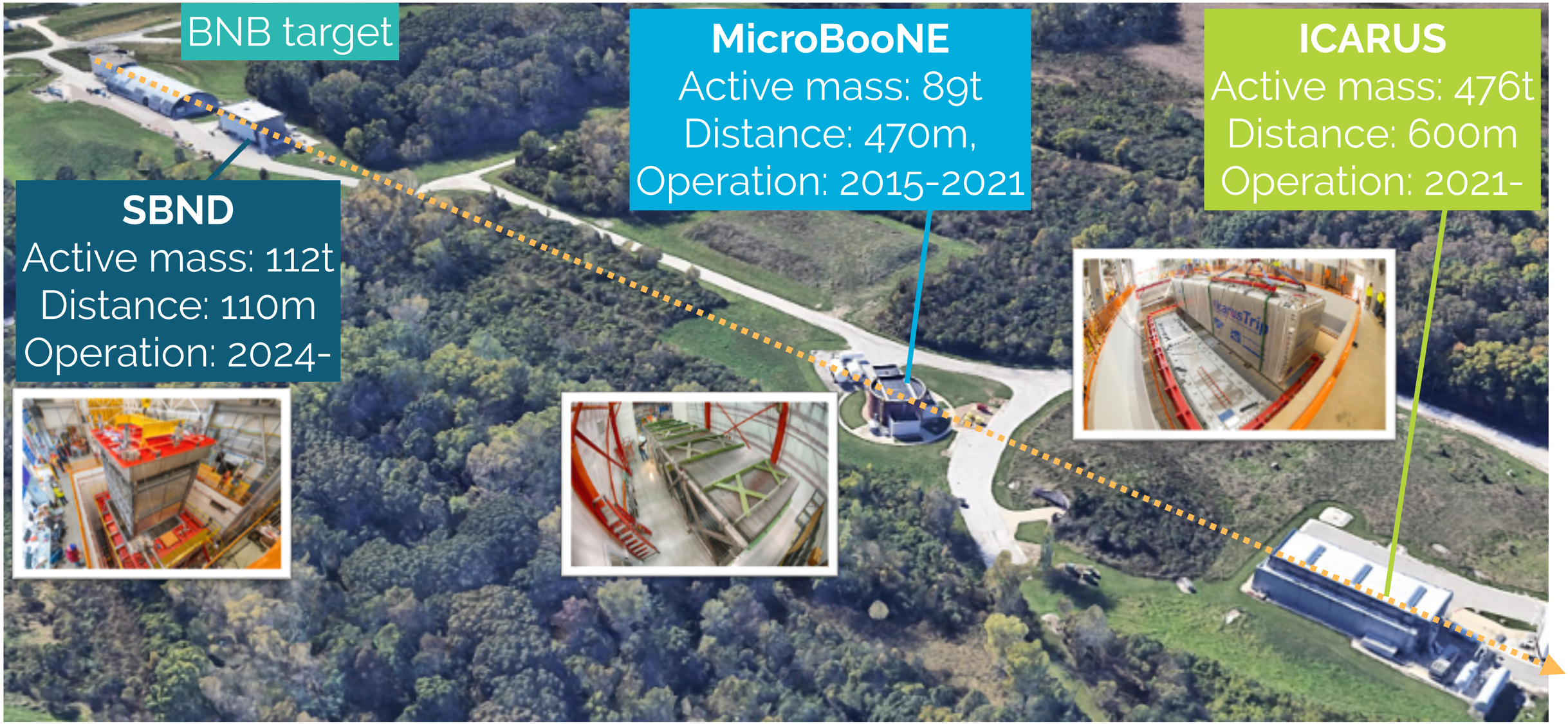
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Direct test of LSND

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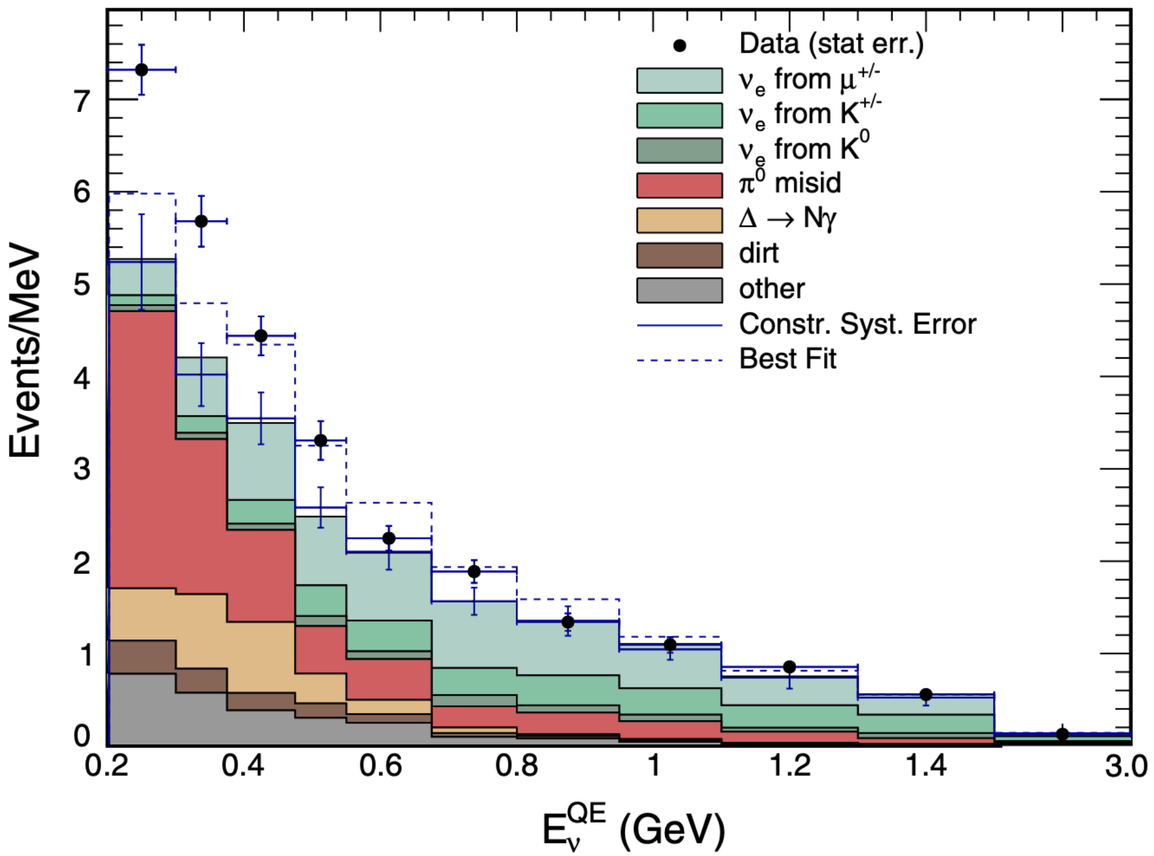
what comes next for the field

SBN Program at Fermilab



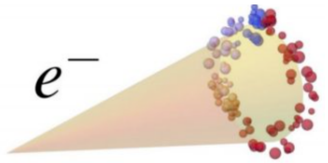
Why LArTPC? Electron or Photon?

MiniBooNE, PRD 103, 052002 (2021)



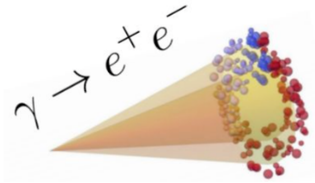
in a Cherenkov detector, an electron and a photon both leave a single fuzzy ring: the MiniBooNE excess could be either

electron?



→ ν_e appearance, the 3+1 oscillation picture

single photon?

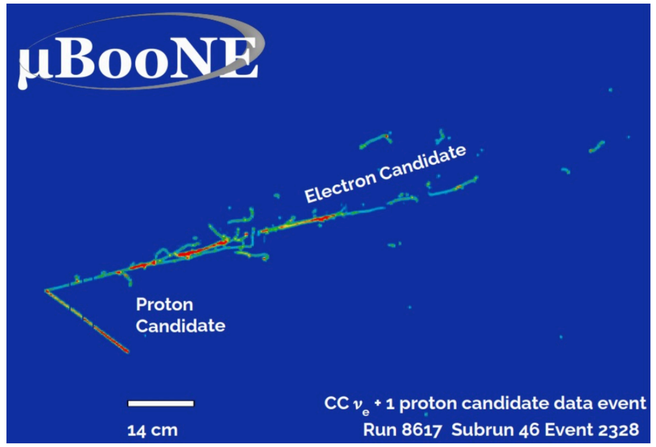


→ mis-modeled background (e.g. Δ → Nγ), or new physics (e.g. dark-sector e^+e^- pairs)

a LArTPC images each event in 3D and can tell electrons from photons:
can address both questions

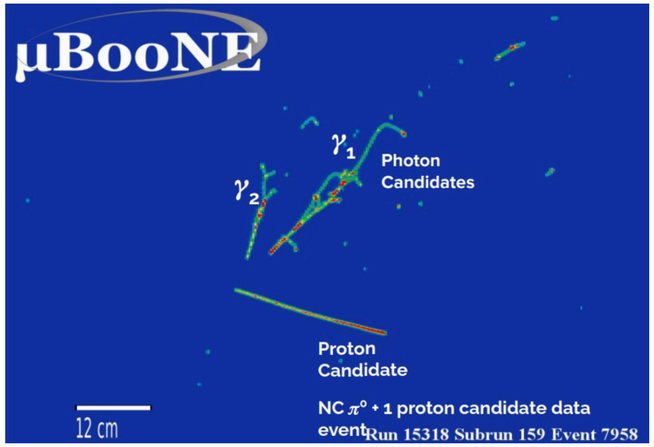
Telling Electrons from Photons

electron (ν_e CC)

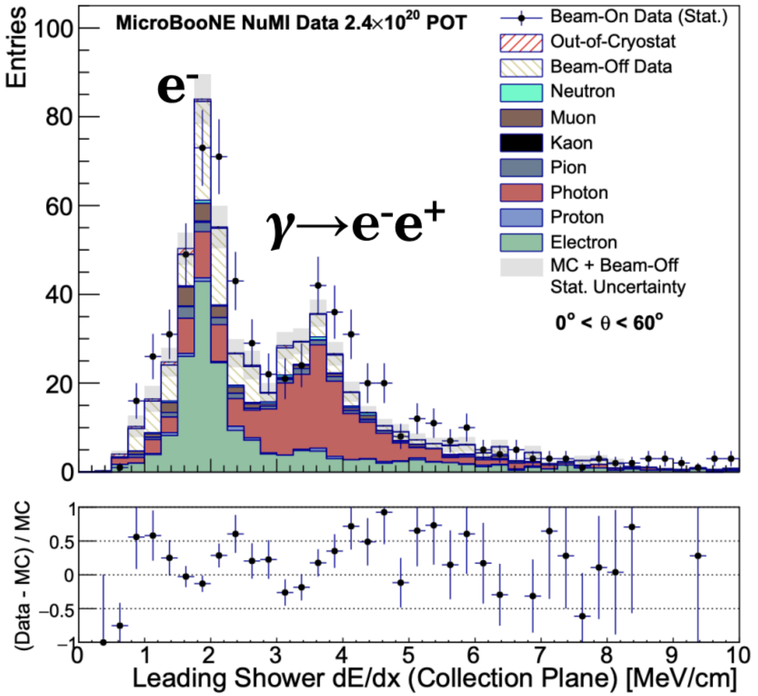


dE/dx at shower start ≈ 2 MeV/cm (**1 MIP**)

photon (e.g. $\pi^0 \rightarrow \gamma\gamma$)



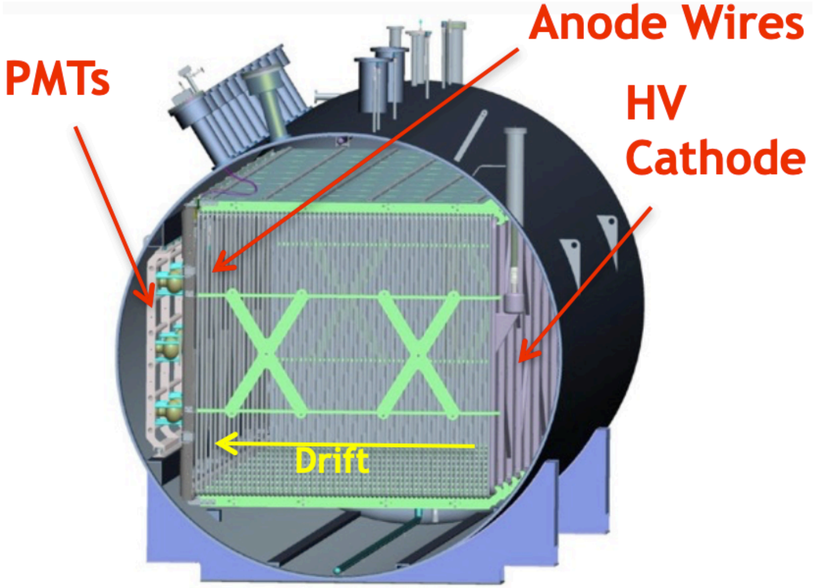
dE/dx at shower start ≈ 4 MeV/cm (**2 MIP**)

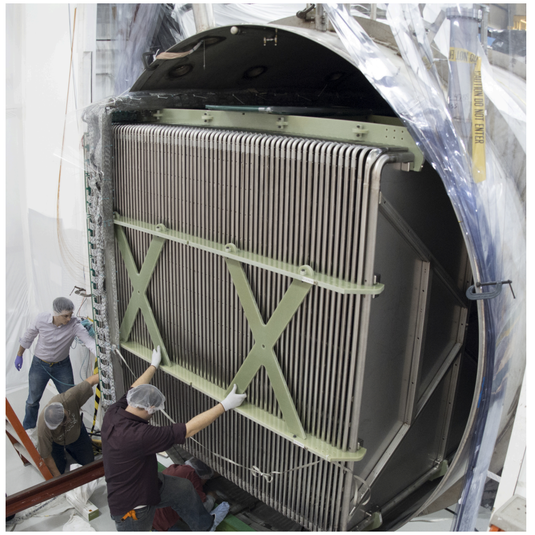


- **energy at the shower start**: one electron vs an e^+e^- pair
- **gap** between vertex and shower: a photon travels ~18 cm on average in LAr before converting

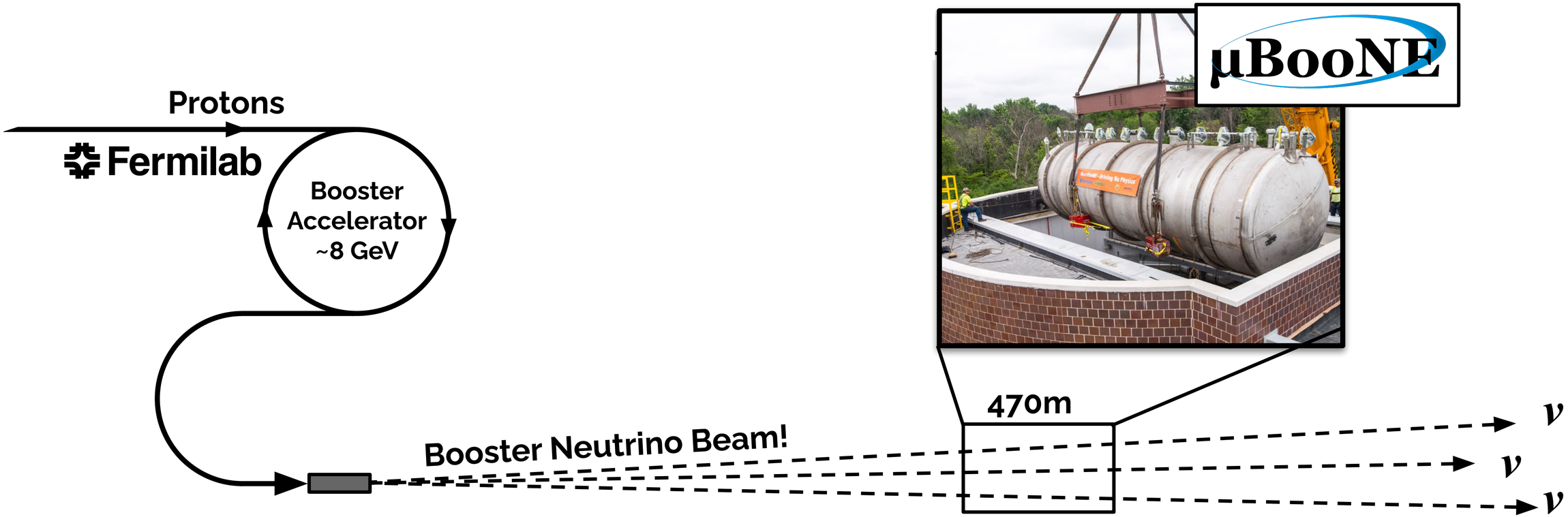
MicroBooNE experiment

- LArTPC Detector
  - 89 tons of LAr active volume
  - TPC: 8256 anode sense wires in 3 planes
    PMT: 32 8-inch PMTs
  - CRT (cosmic ray tagger) is installed around TPC
  - operated 2015-2021, total POT collected 1.5 x 10^{21} for BNB and 2.2 x 10^{21} for NuMI

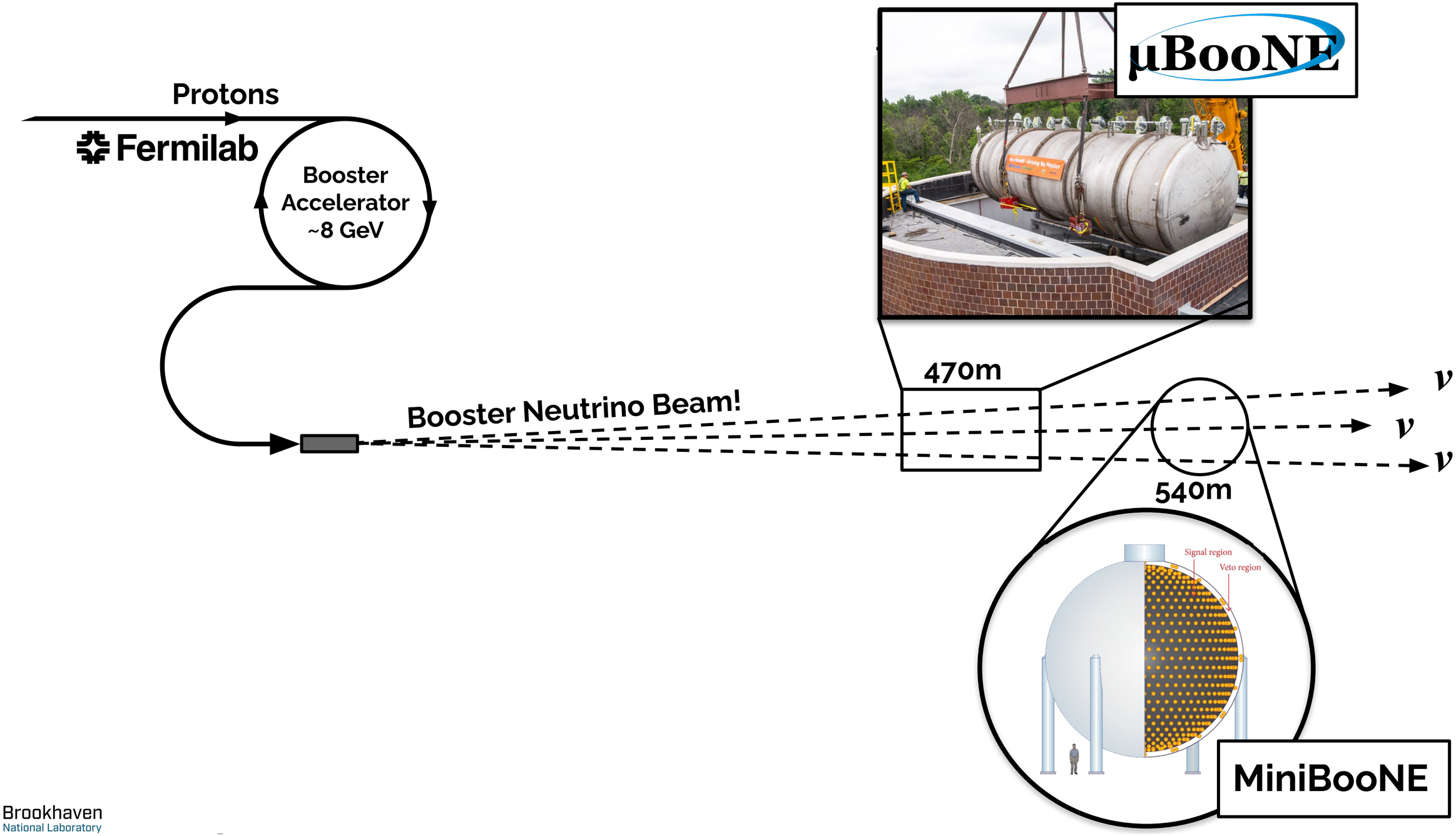




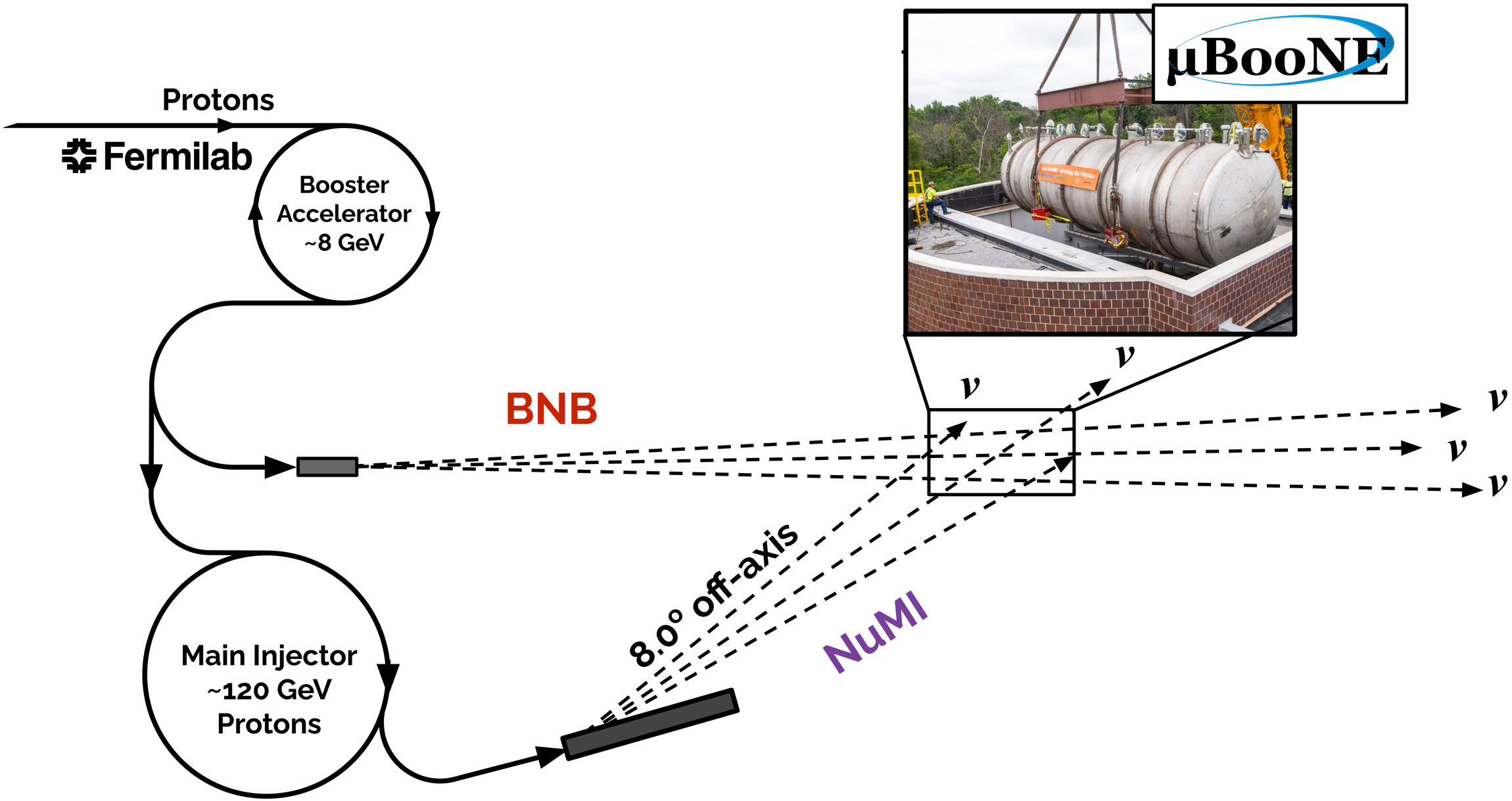
3+1 Sterile Neutrino Search: Two beam lines



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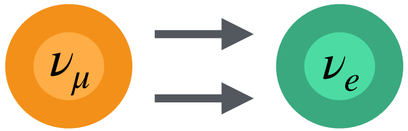


3+1 Sterile Neutrino Search: Two beam lines



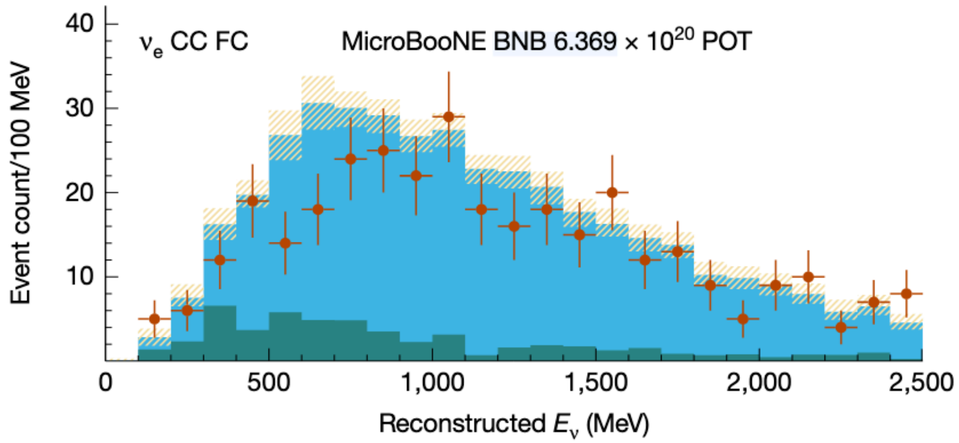
3+1 Sterile Neutrino Search: ν_e appearance search

Nature 648 64-69 (2025)

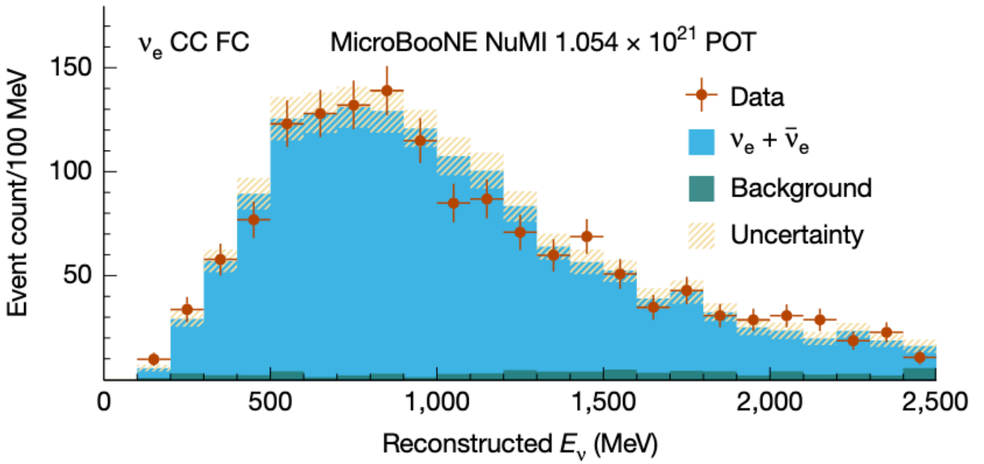


- after updating our information using larger statistic sideband data (ν_μ and π^0) to reduce uncertainties, **we look for an excess in the ν_e**
- no excess observed over the expected background, both in BNB and NuMI
- *but why do we need both beams?*

BNB CC ν_e



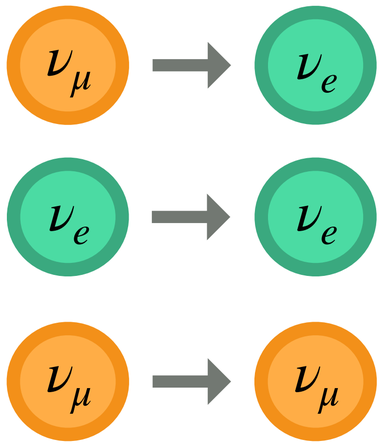
NuMI CC ν_e



3+1 Sterile Neutrino Search: degeneracy

- we consider three main oscillation channels

beam detector



appearance

disappearance

} …and these two effects can *cancel each other* at certain oscillation parameters

disappearance

- BNB and NuMI have different amount of intrinsic ν_e: BNB with **0.6%** and NuMI with **4%**

- **using both beams simultaneously breaks this degeneracy!**

3+1 Sterile Neutrino Search: degeneracy

- we consider three main oscillation channels

beam detector

$\nu_\mu \rightarrow \nu_e$ appearance

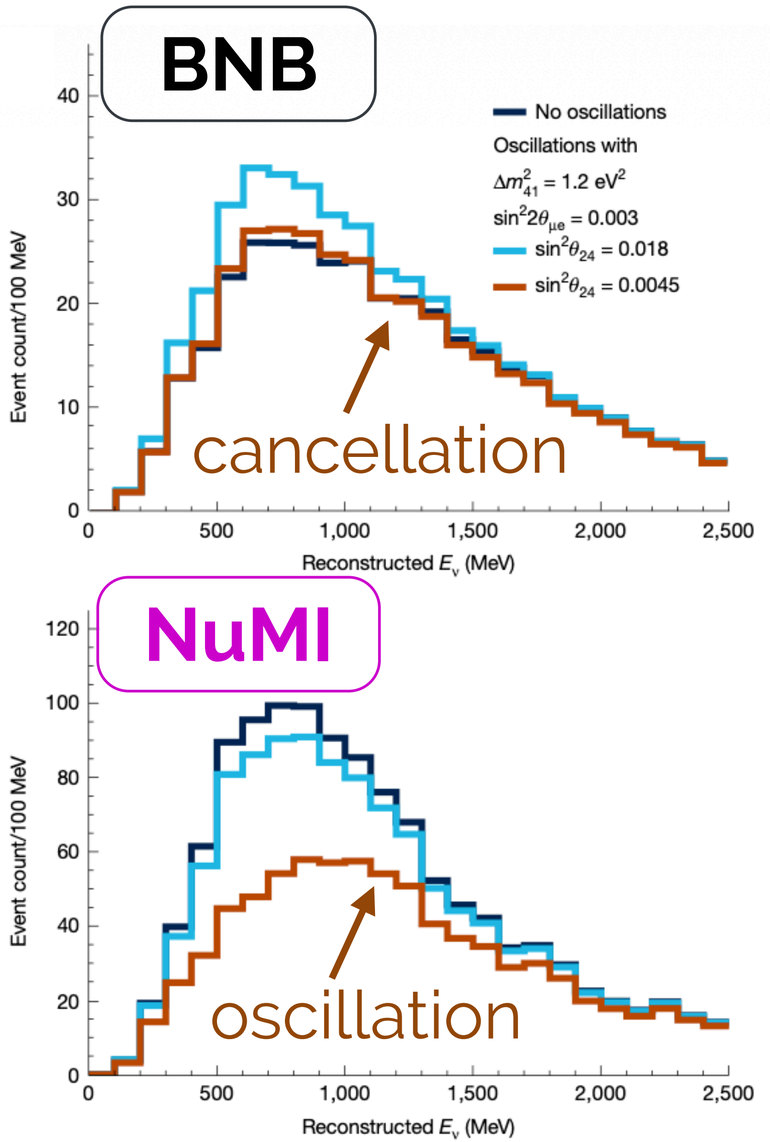
$\nu_e \rightarrow \nu_e$ disappearance

$\nu_\mu \rightarrow \nu_\mu$ disappearance

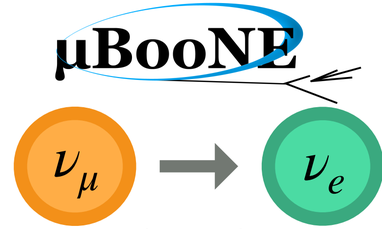
- BNB and NuMI have different amount of intrinsic ν_e: BNB with **0.6%** and NuMI with **4%**

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Nature 648 64-69 (2025)



3+1 Sterile Neutrino Search: BNB-only result (2023)

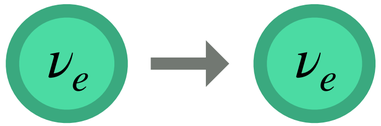


PRL 130 011801 (2023)

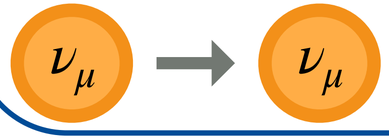
BNB-only Result (2023)



appearance

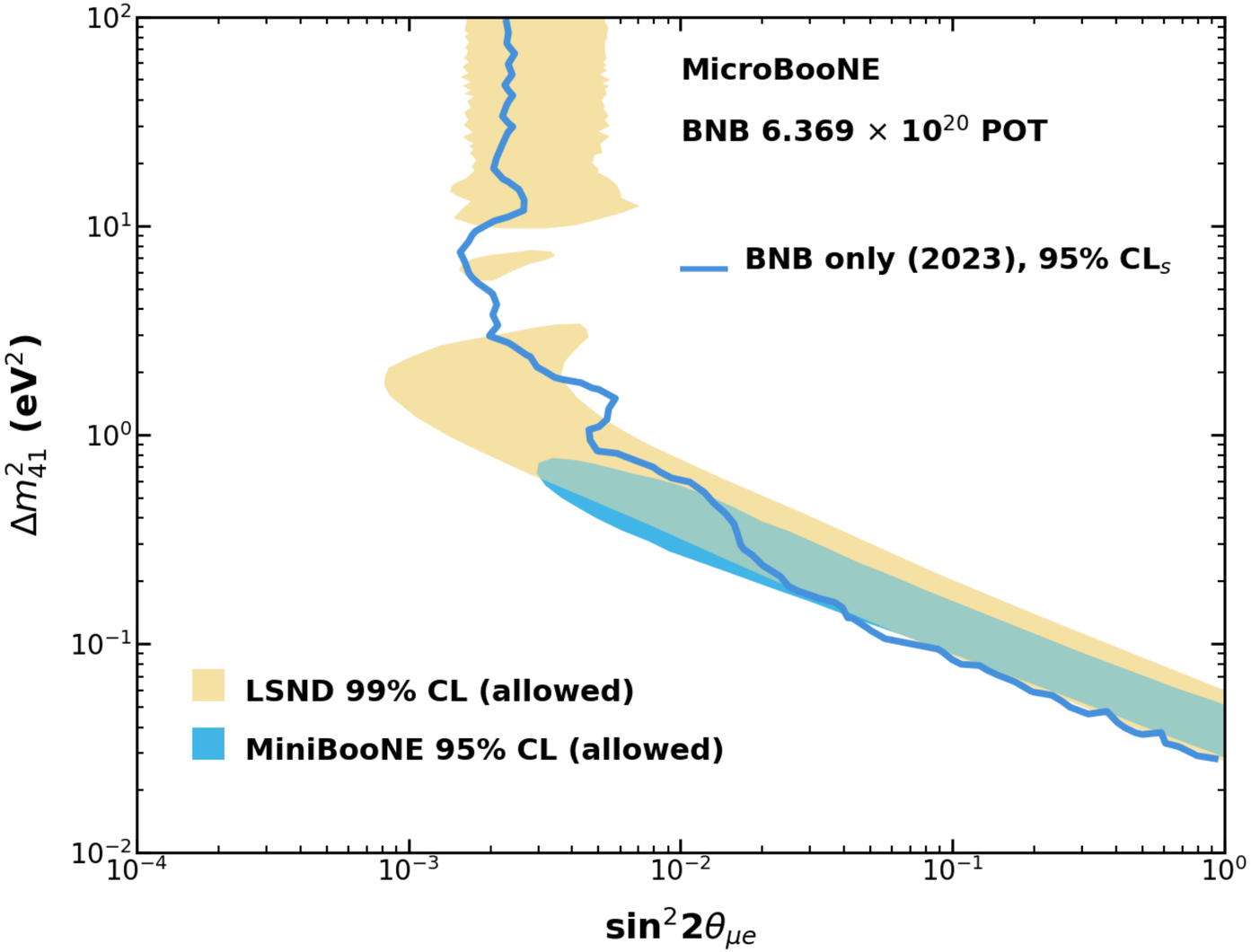


disappearance



disappearance

2023 result is not strong enough to exclude the allowed regions *due to the degeneracy*



3+1 Sterile Neutrino Search: BNB+NuMI result

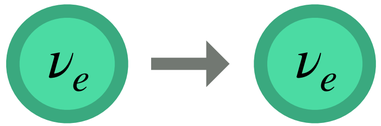


Nature 648 64-69 (2025)

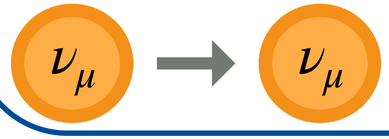
BNB+NuMI Result



appearance

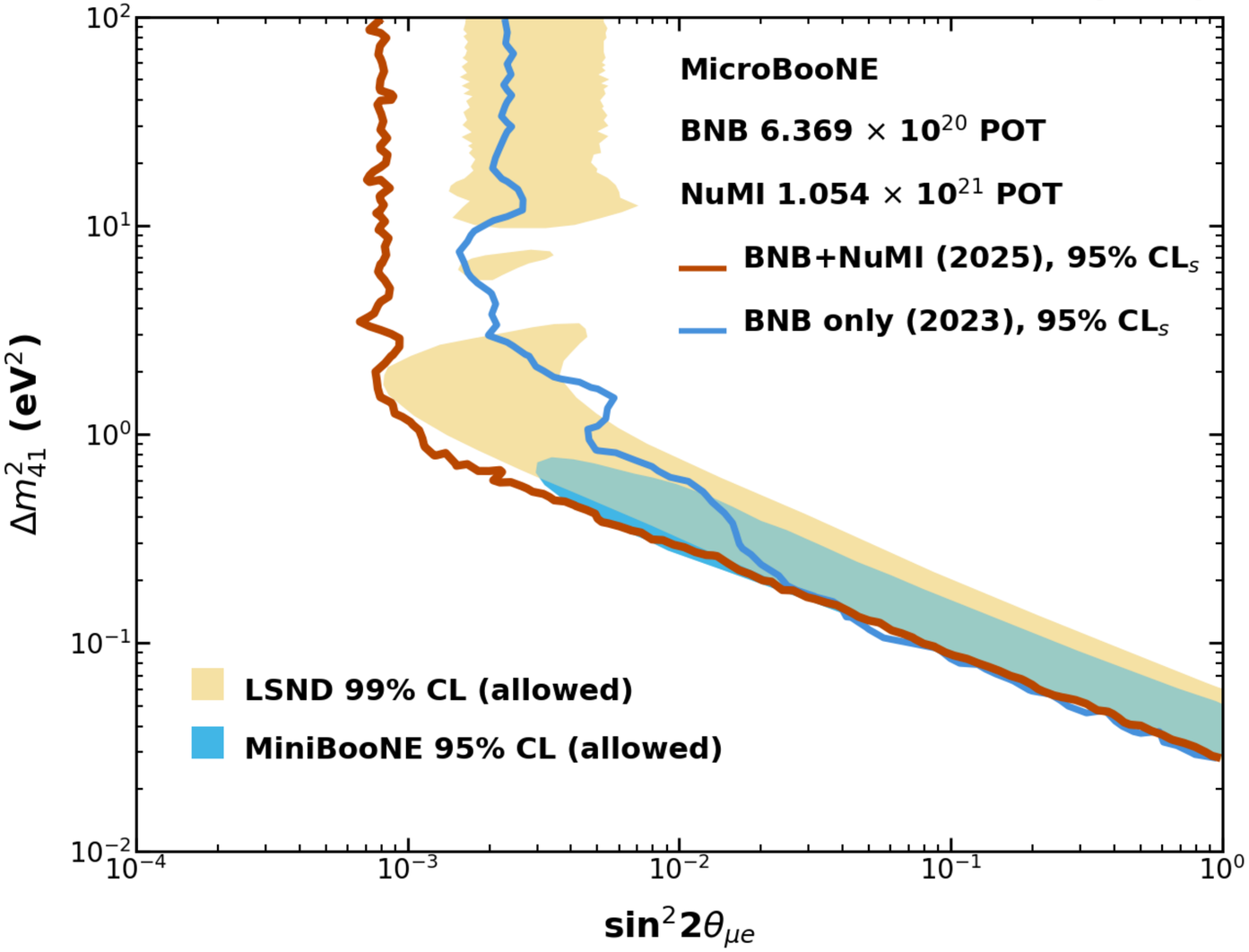


disappearance

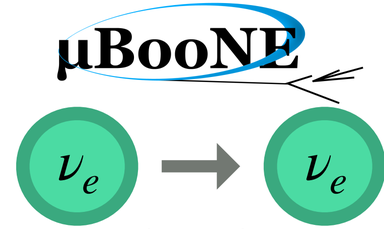


disappearance

in ν_e appearance channel, MicroBooNE excludes LSND and MiniBooNE allowed region at the 95% CL by mitigating degeneracy



3+1 Sterile Neutrino Search: BNB-only result (2023)

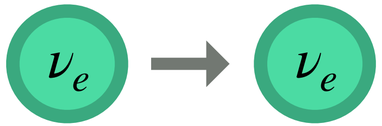


PRL 130 011801 (2023)

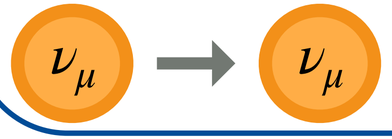
BNB-only Result (2023)



appearance

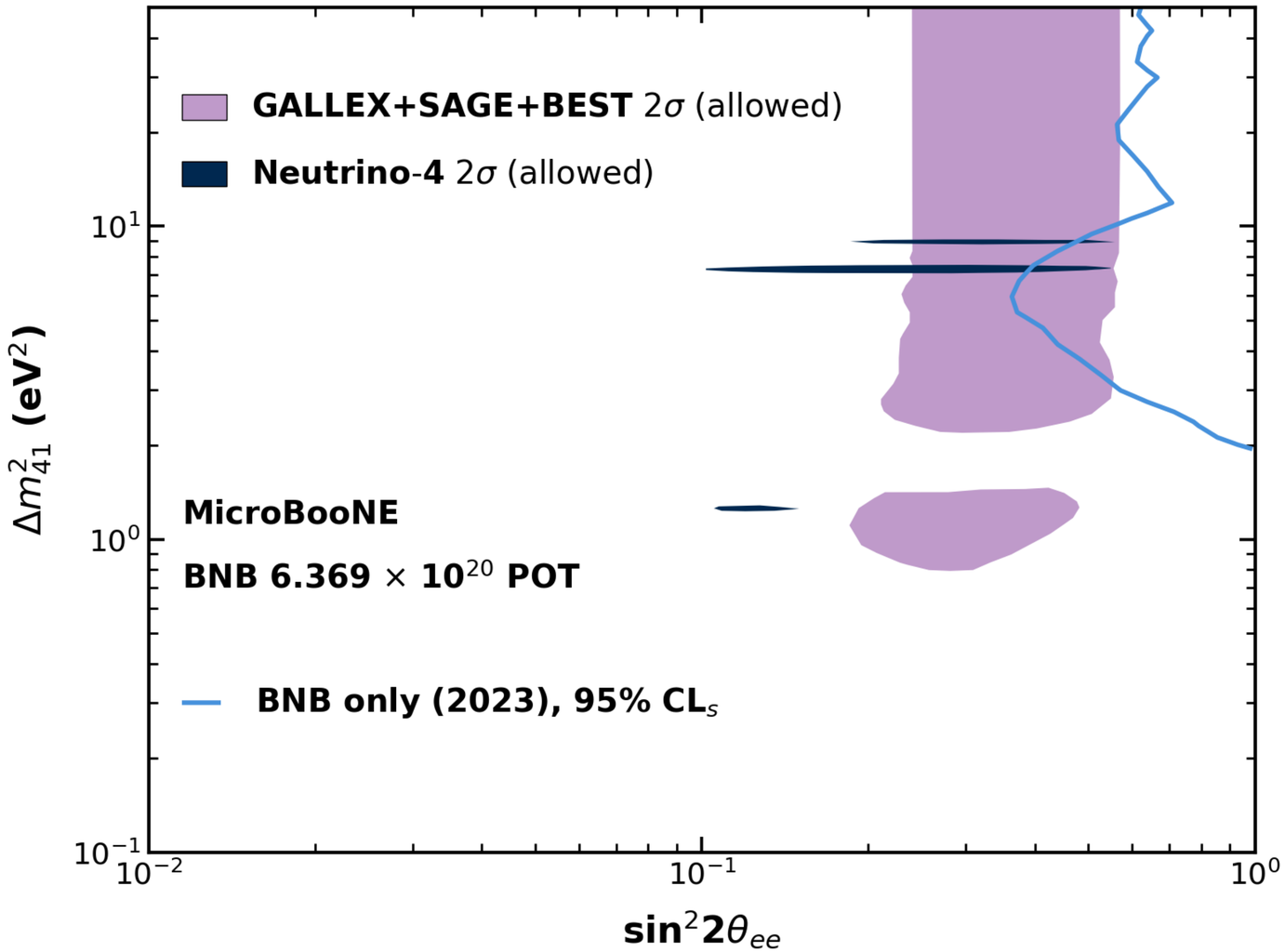


disappearance



disappearance

2023 result is not strong enough to exclude the allowed regions *due to the degeneracy*



3+1 Sterile Neutrino Search: BNB+NuMI result

μBooNE

$\nu_e \rightarrow \nu_e$

Nature 648 64-69 (2025)

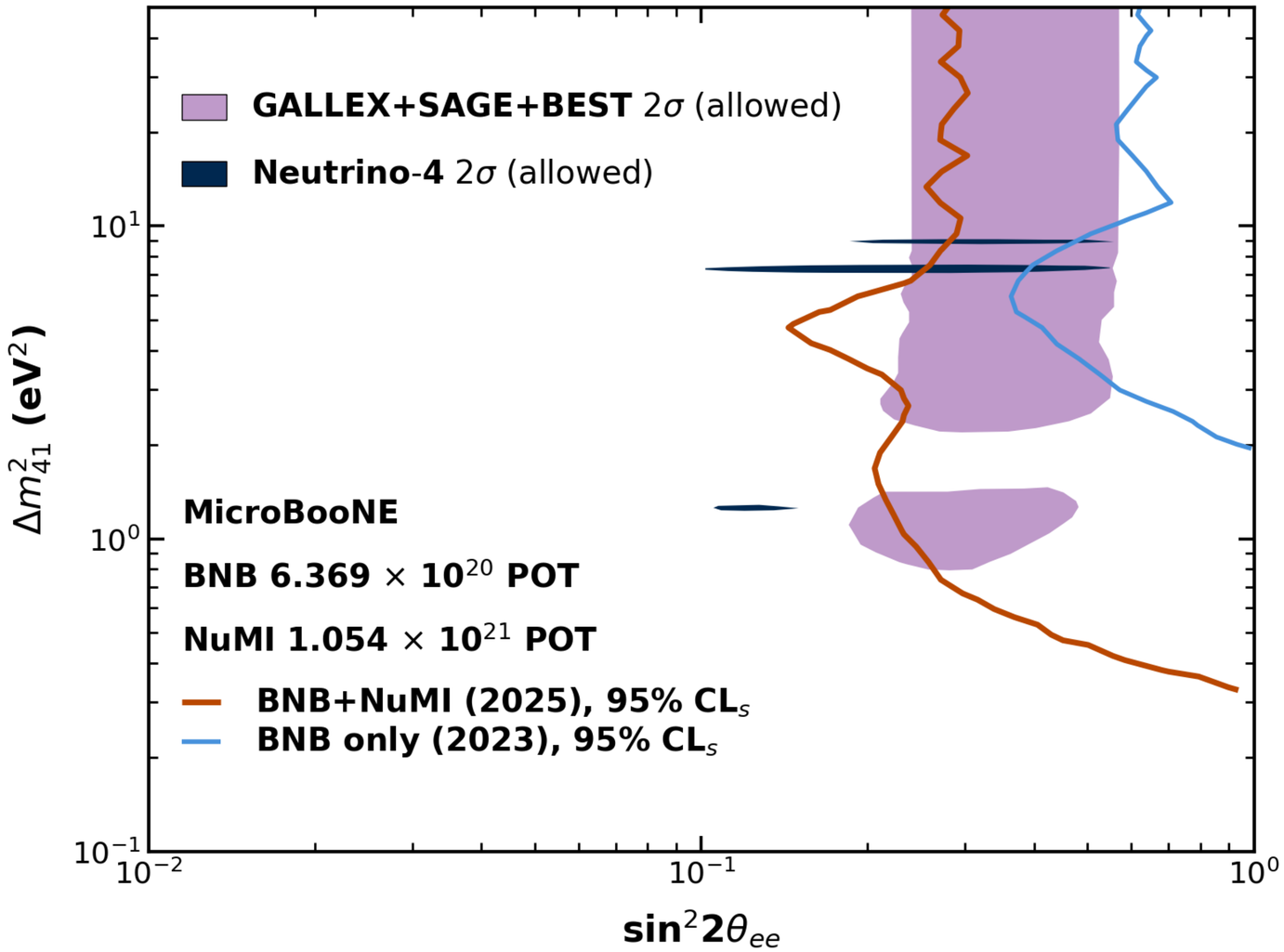
BNB+NuMI Result

$\nu_\mu \rightarrow \nu_e$ appearance

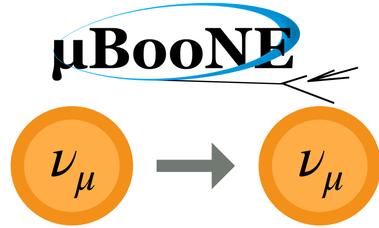
$\nu_e \rightarrow \nu_e$ **disappearance**

$\nu_\mu \rightarrow \nu_\mu$ disappearance

in ν_e disappearance channel, MicroBooNE excludes most of Gallium allowed region and part of Neutrino-4 allowed region



3+1 Sterile Neutrino Search: BNB+NuMI result



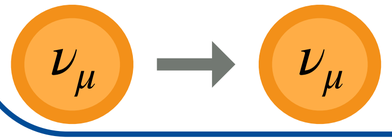
BNB+NuMI Result



appearance

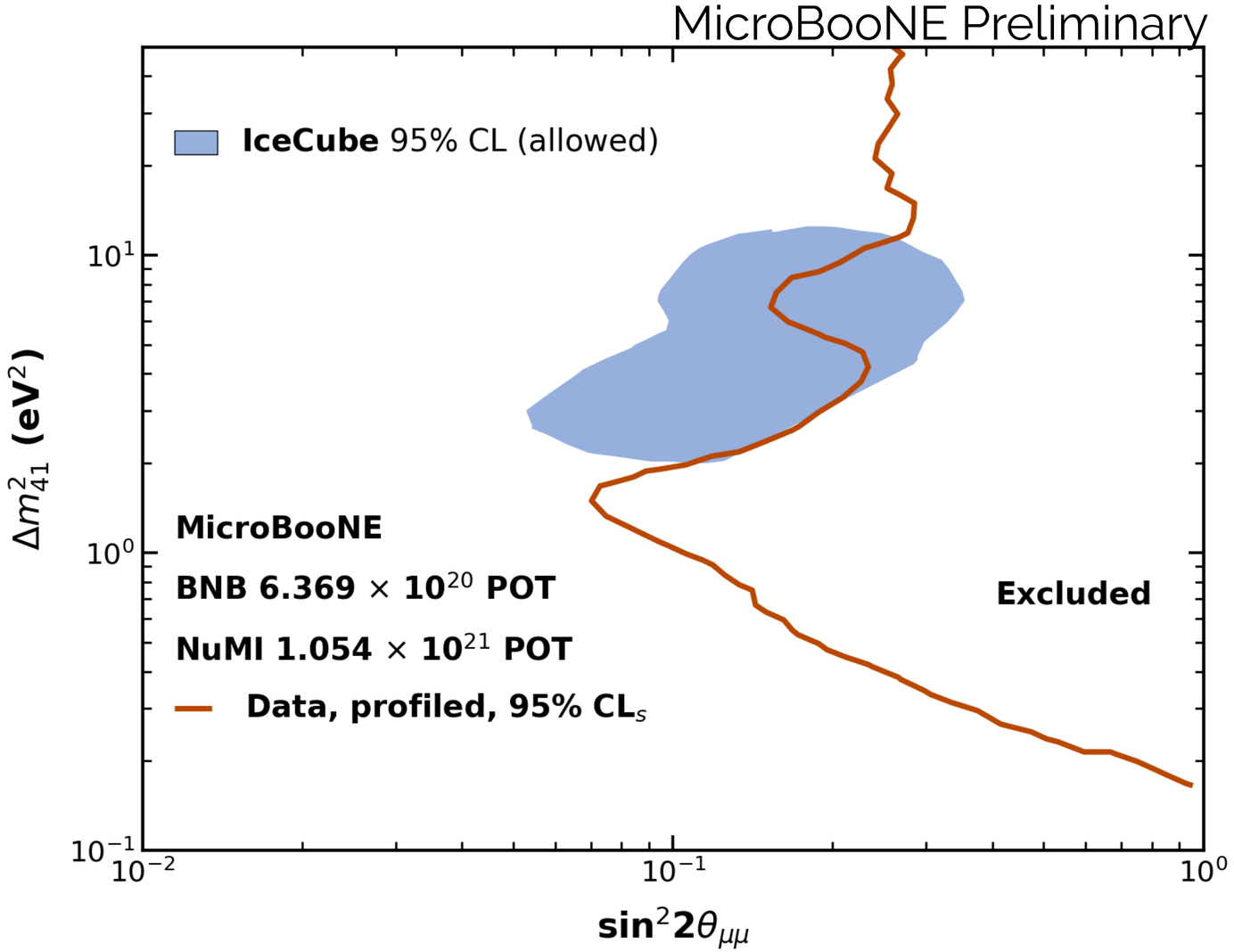


disappearance

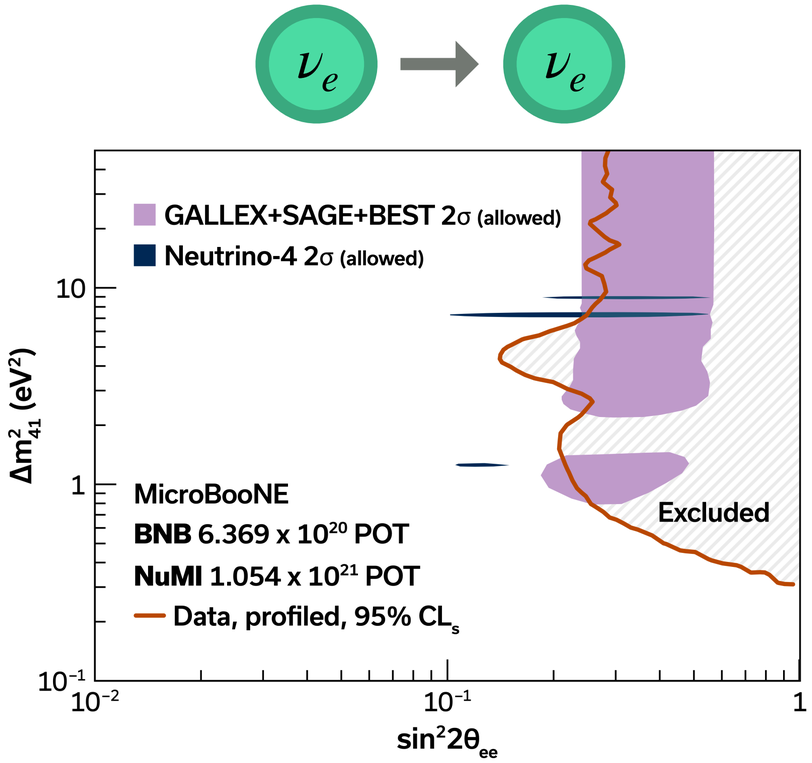


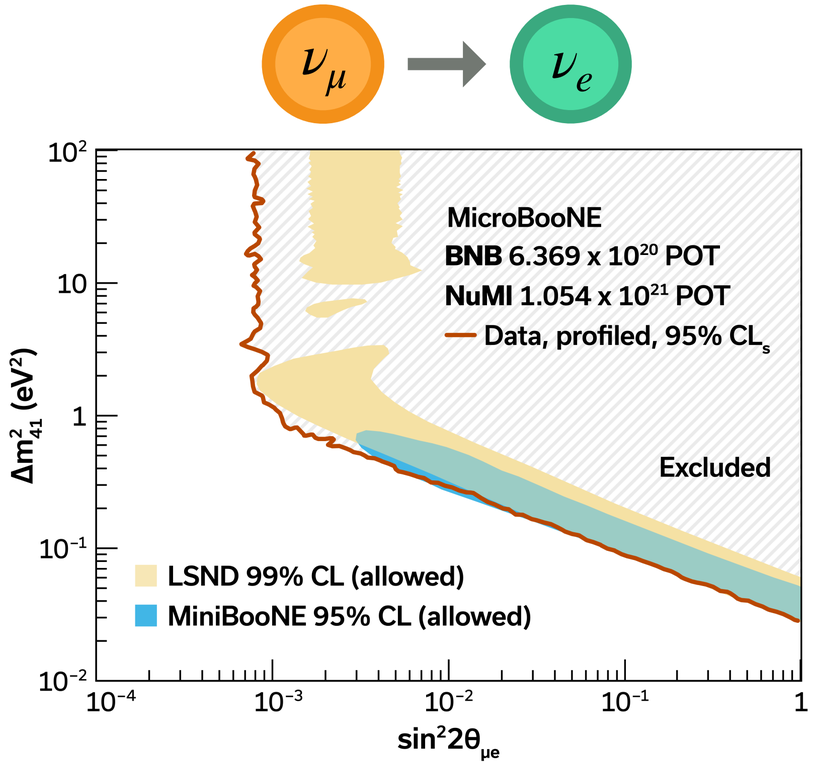
disappearance

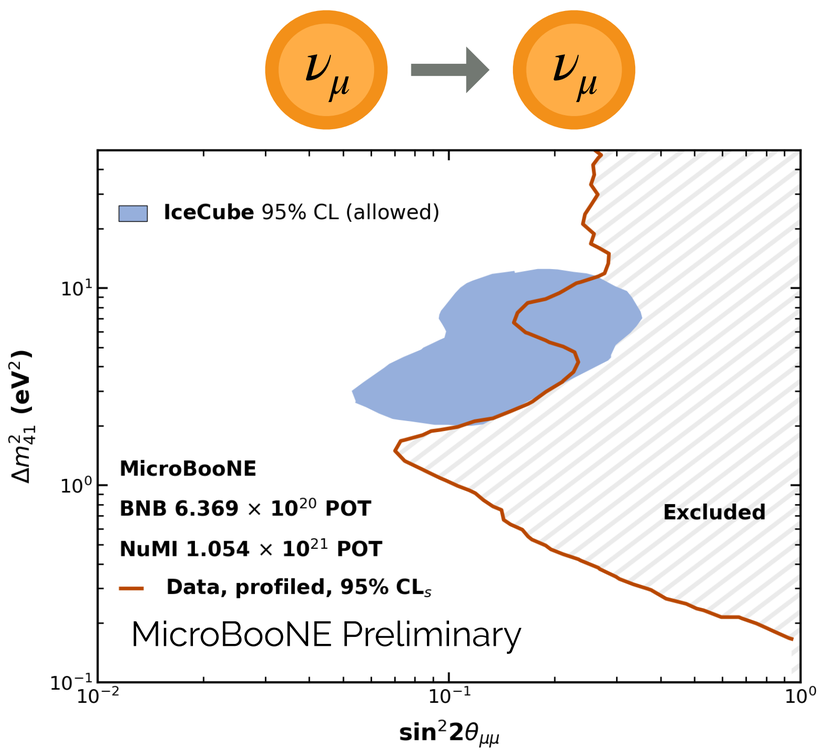
MicroBooNE excludes part of IceCube allowed region



3+1 Sterile Neutrino Search: BNB+NuMI result





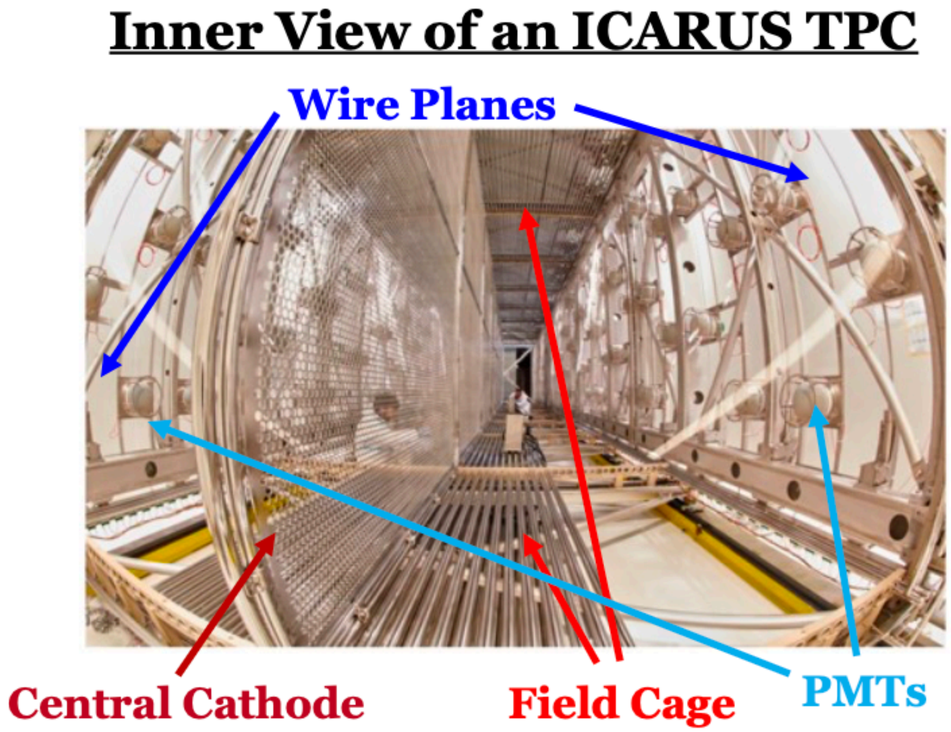


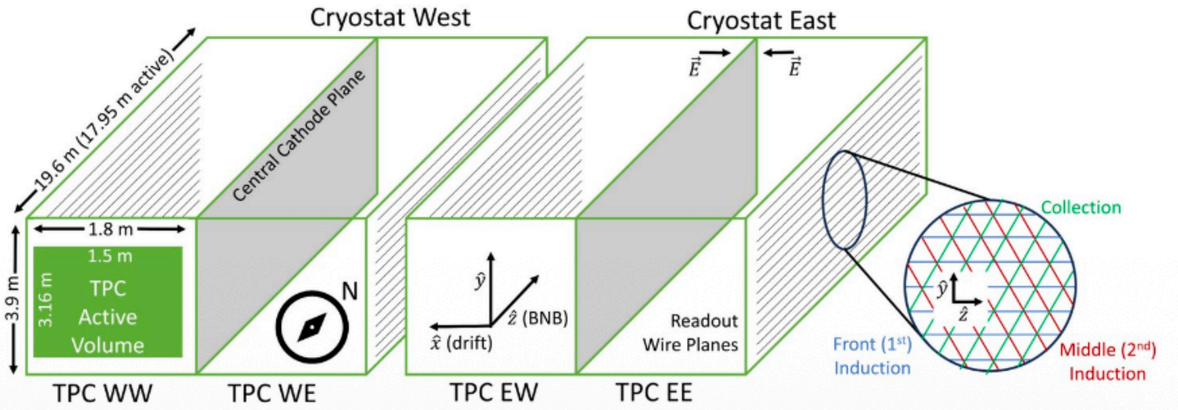
- MicroBooNE has now completed the full 3+1 program, all three oscillation channels measured in one detector
- all consistent with no sterile neutrino, with limited sensitivity in certain channels

ICARUS Detector

slide credit: M. Mooney (Nu2026)

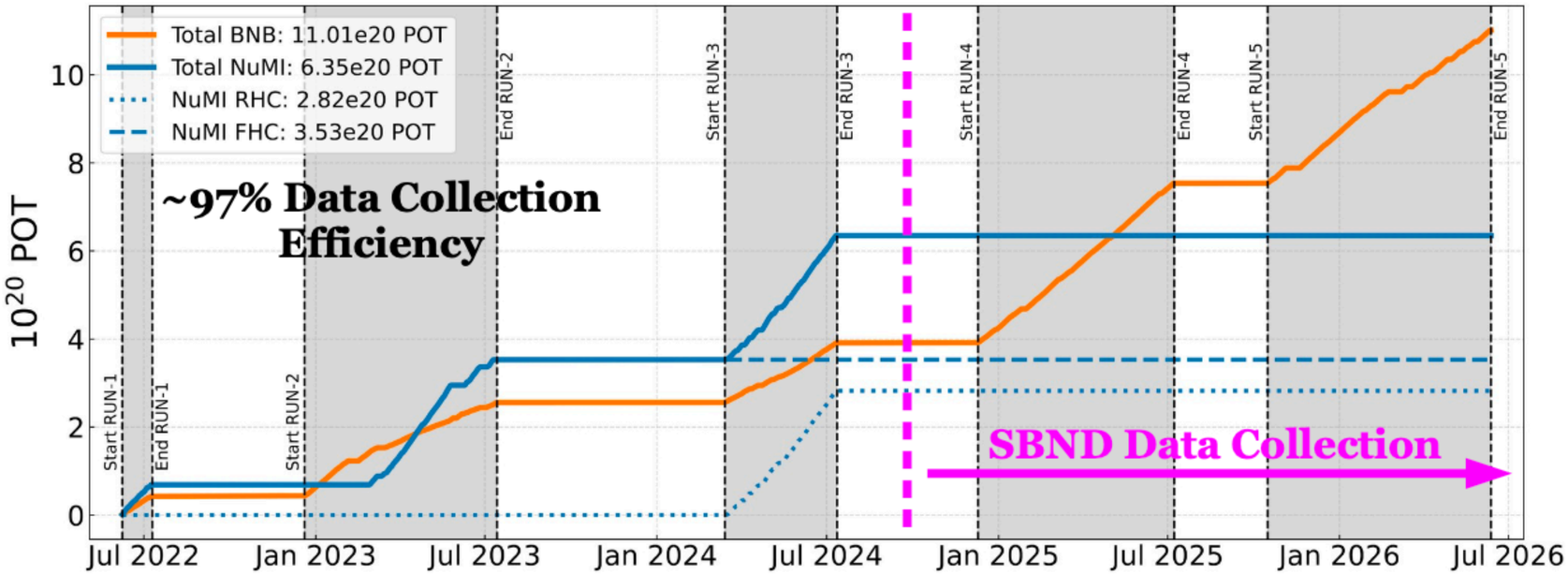
- **TPC:** wire-based LArTPCs with ~54,000 channels across two cryostats (four drift volumes) for imaging neutrino interactions
- **PDS:** 360 PMTs behind anode wire planes (90 per anode) for event triggering/timing using scintillation light
- **CRT:** top/side cosmic ray tagger panels (scintillator + SiPM readout) for tagging cosmics





ICARUS Data Collection

slide credit: M. Mooney (Nu2026)



ICARUS Total Projected POT (Depending on Accelerator Operations)

BNB: $13\text{-}16\times10^{20}$

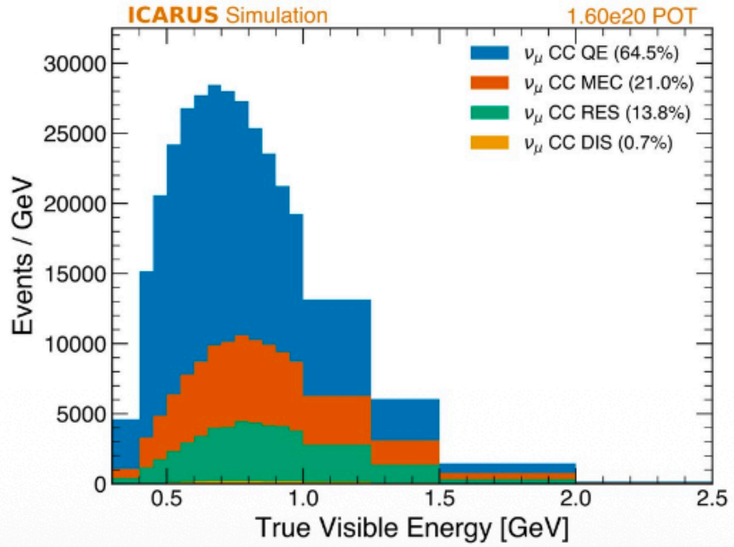
NuMI: $8\text{-}10\times10^{20}$

- Cold commissioning initiated in September 2020
- Started taking physics data in June 2022; still collecting data from BNB
  - Roughly 7×10^{20} POT of overlapping BNB data-taking w/ SBND (Runs 4 and 5)
  - NuMI beamline under maintenance since 2024

Oscillation Physics Overview

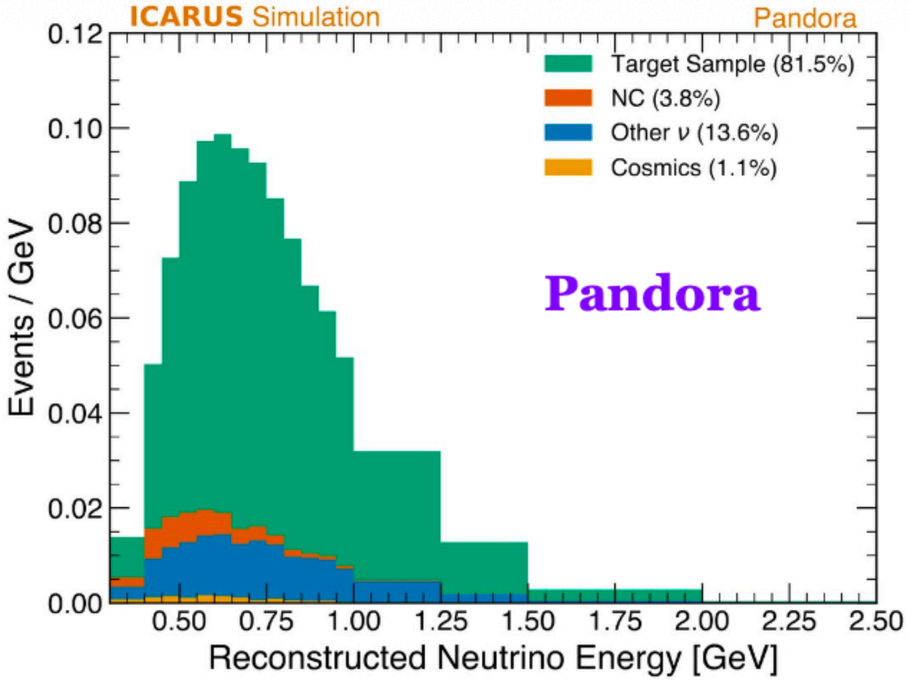
slide credit: M. Mooney (Nu2026)

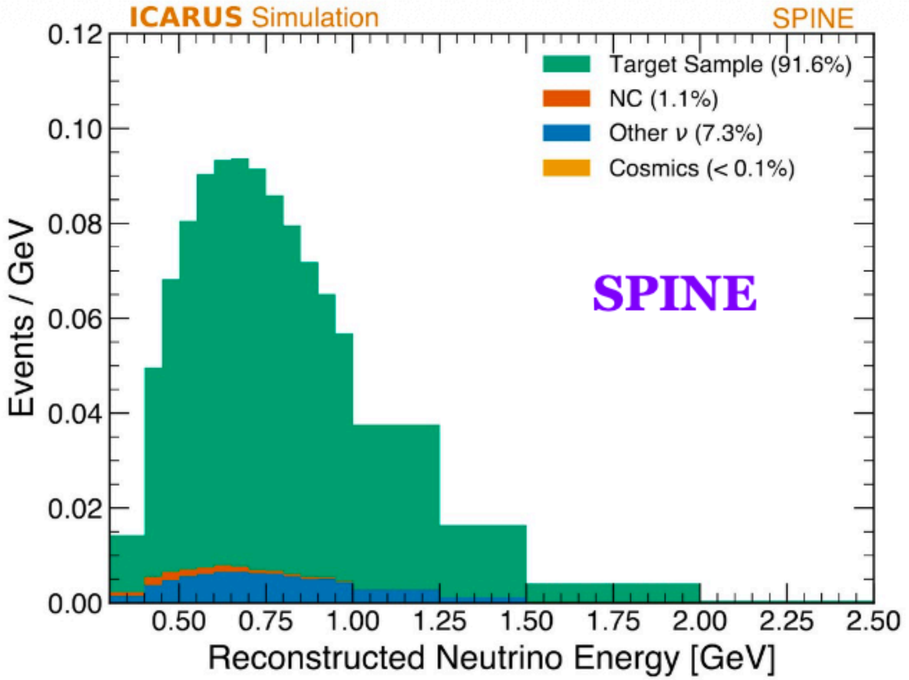
- Ultimate oscillation physics goal for ICARUS is to provide oscillated neutrino spectrum as far detector of SBN Program
  - Measure ν_μ disappearance + ν_e appearance (and disappearance) w/ two detectors
- During SBND commissioning, ICARUS has pursued **single-detector** neutrino oscillation physics probing **muon neutrino disappearance**
  - Pathway for tool developments (e.g. fitter, systematics) in preparation for eventual two-detector measurements of full SBN Program
- Use 1μNp0π BNB final states and two reconstruction approaches: **Pandora-based** and **SPINE ML**
  - Enables important cross-check between results



Event Selection Performance

slide credit: M. Mooney (Nu2026)

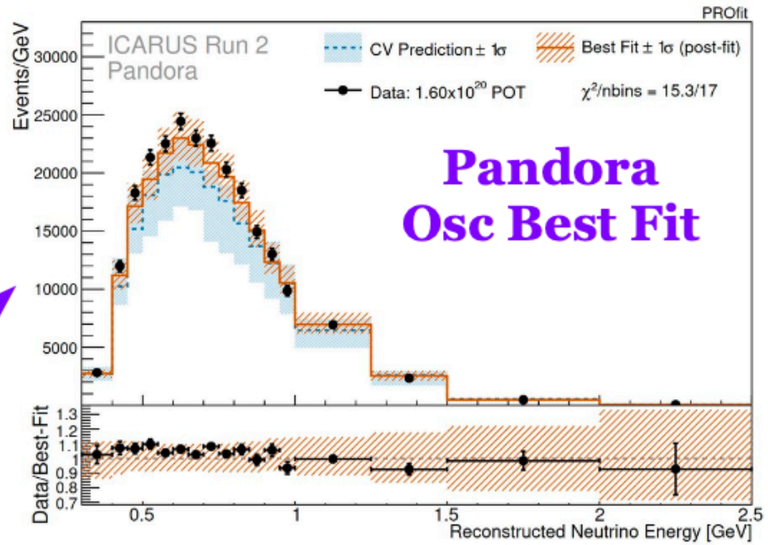


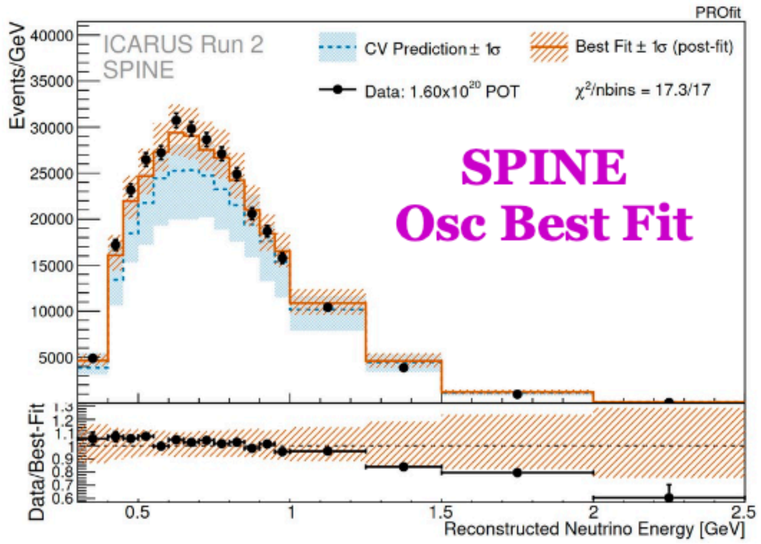


- Performant 1μNp0π selections:
  - **Pandora:** ~48% selection efficiency, ~82% selection purity
  - **SPINE:** ~77% selection efficiency, ~92% selection purity

Oscillation Fit Results

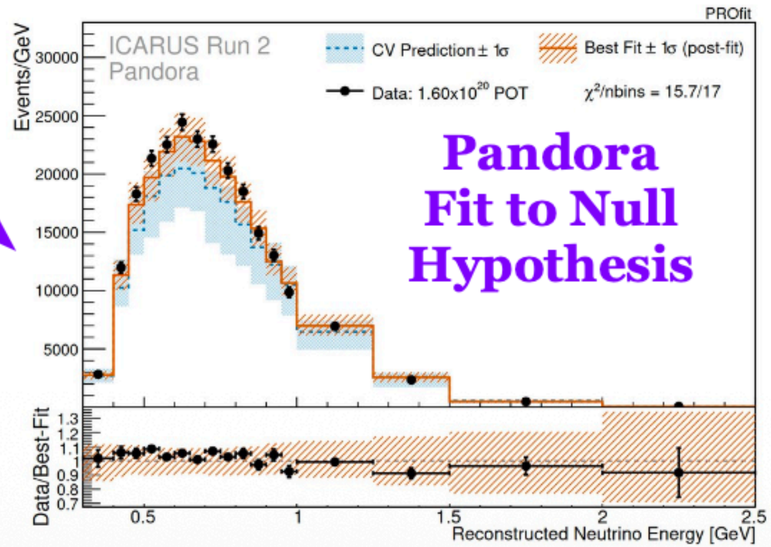
slide credit: M. Mooney (Nu2026)

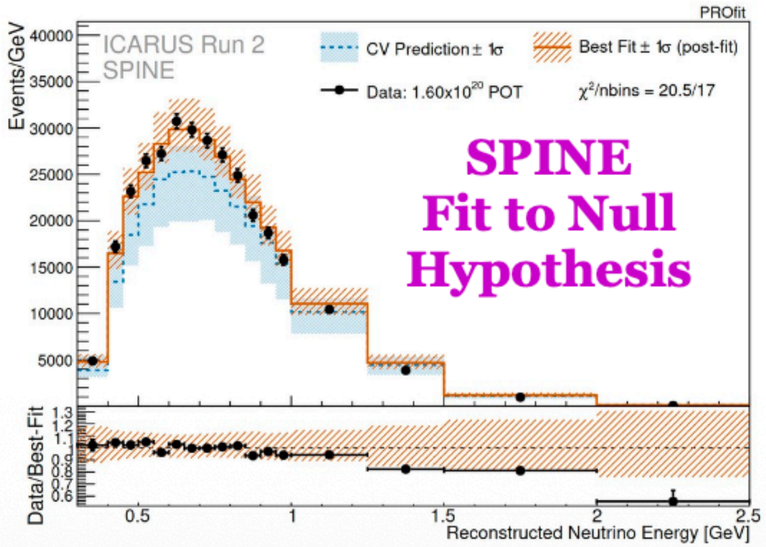




$\Delta\chi^2 \sim 0.4$

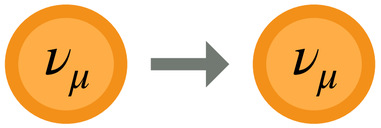
$\Delta\chi^2 \sim 3.2$



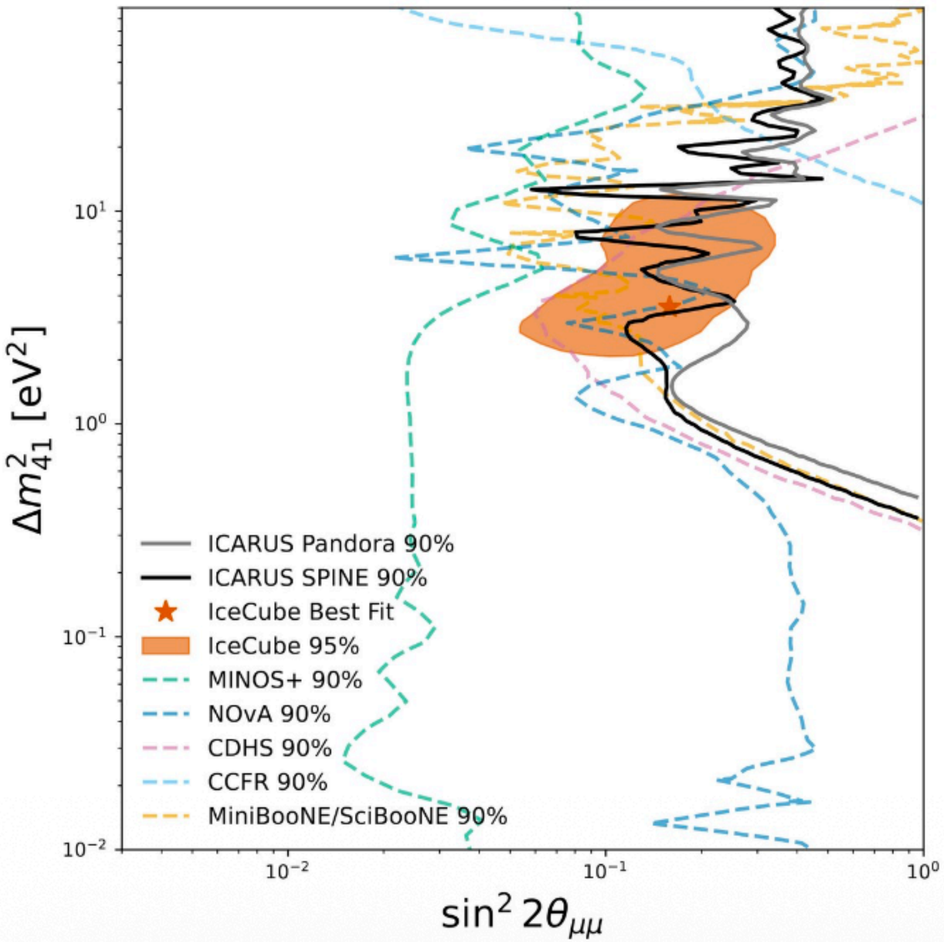


Oscillation Exclusion Contours

slide credit: M. Mooney (Nu2026)



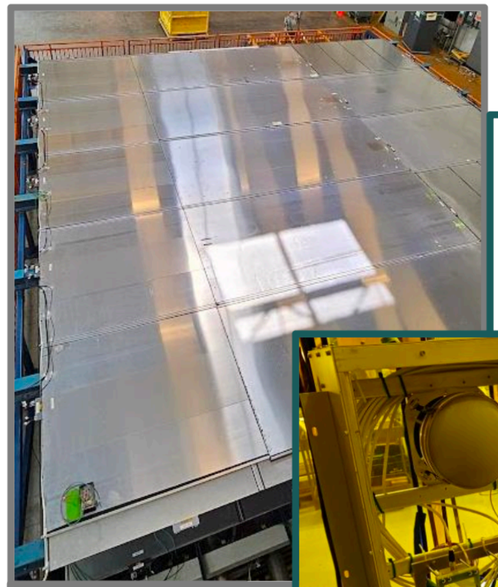
arXiv:2603.22557
Submitted to *PRD*



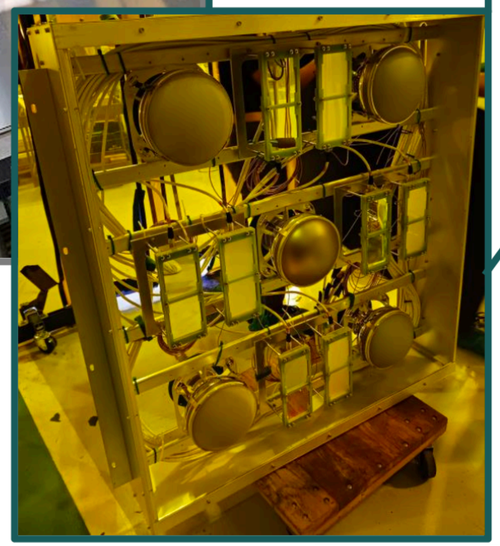
- No signs of significant neutrino oscillations from either analysis → set exclusion contours
  - Exclusion contours include Feldman-Cousins corrections
- First ICARUS ν_μ disappearance results are *systematics limited* (both Pandora and SPINE analyses)
  - Forthcoming SBN Program oscillation physics measurements will reduce all major source of systematic uncertainties, by design

The SBND Detector

slide credit: L. Wan (Nu2026)

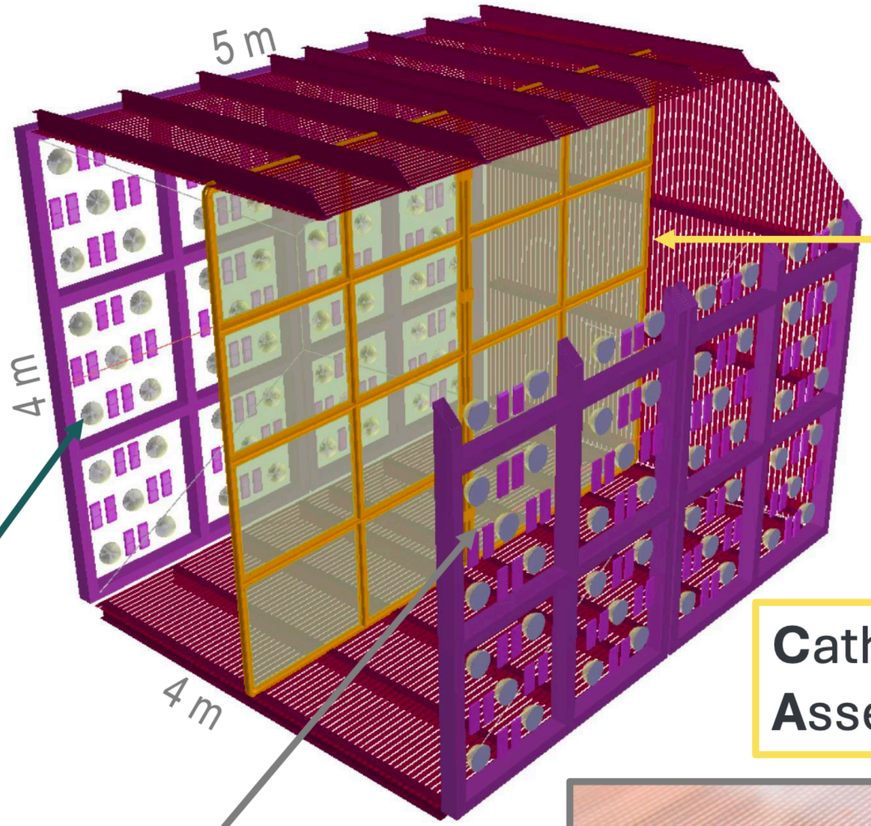


Cosmic Ray Tagger



Photon Detection System

Time Projection Chamber



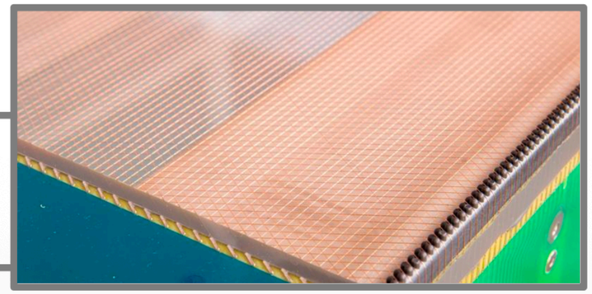


Cathode Plane Assembly at **-100 kV**

Inductions

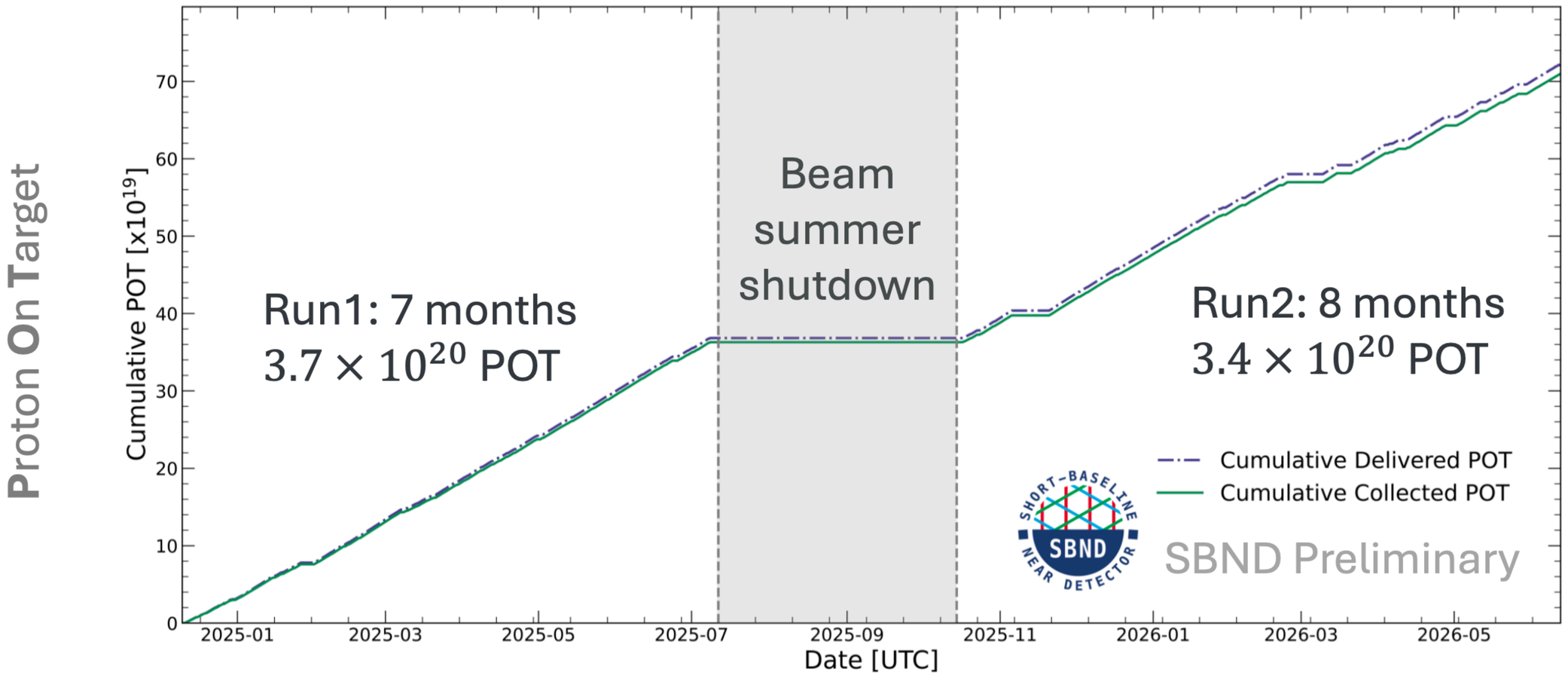
Collection

Anode Plane Assemblies connected to **cold electronics**



SBND Physics Data Taking

slide credit: L. Wan (Nu2026)

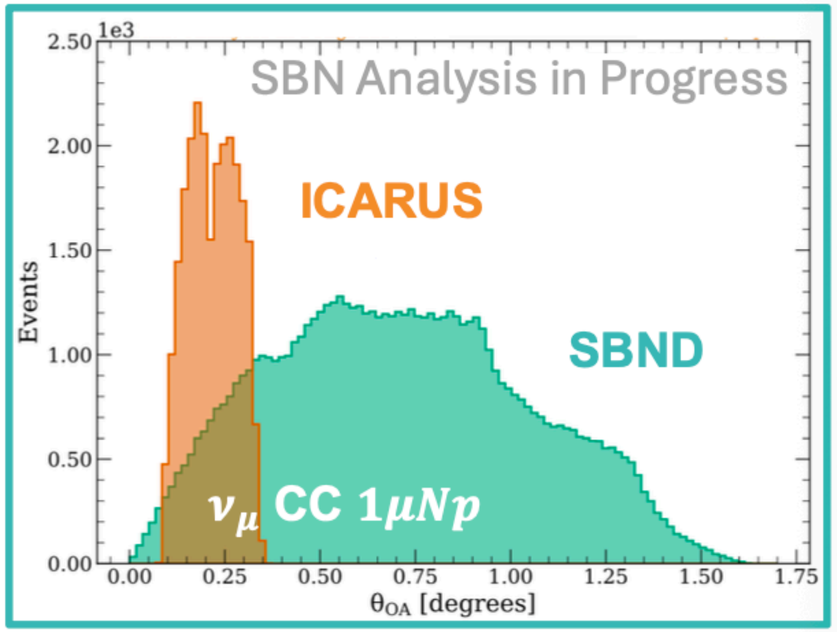


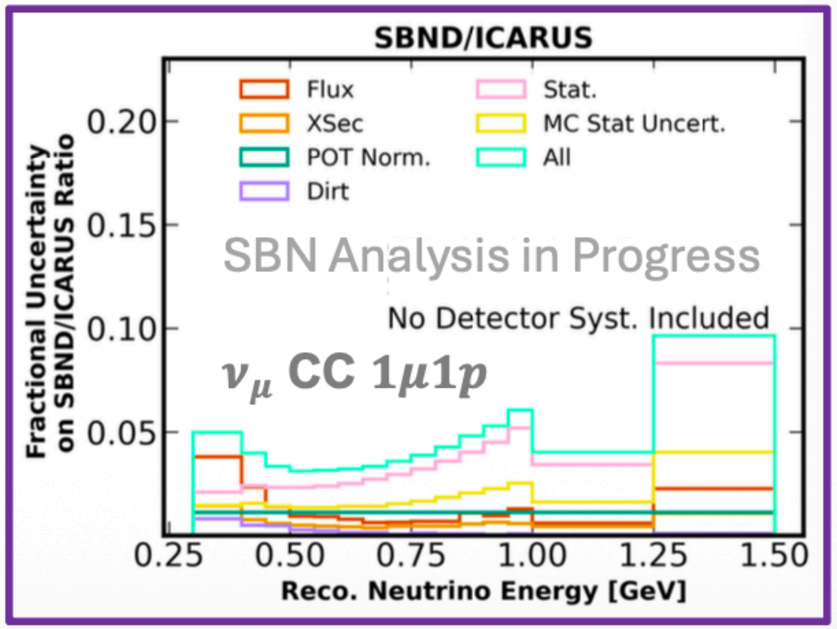
6 million neutrino interactions (4 million charged-current) collected, largest ν-Ar dataset ever!

SBN Sterile Neutrino Search

slide credit: L. Wan (Nu2026)

- SBND deepens the SBN sensitivity by more than an order of magnitude by constraining the event rate close to the source.
- The high statistics and unique features like SBND-PRISM allows binning the data to provide powerful handles on flux and cross-section.
- Using the same detector technology, target nucleus, and beamline, SBN can constrain systematic uncertainties to percent-level.





Outline

1 **short-baseline anomalies**

appearance and disappearance hints at L/E ~ 1 m/MeV

2 **SBN at Fermilab: MicroBooNE, ICARUS, and SBND**

Recent results from LArTPC experiments at Fermilab

3 **JSNS2 at JPARC**

Direct test of LSND

4 **outlook**

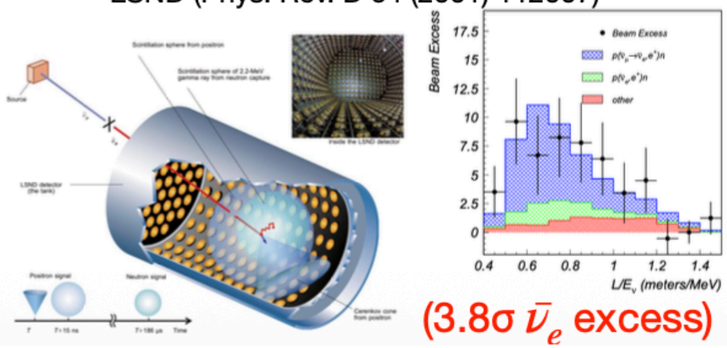
what comes next for the field

Direct Test of LSND Anomaly

slide credit: D. Lee (Nu2026)

	LSND	JSNS²/JSNS²-II
Target Mass	167 tons	17 tons (Near) , 32tons (Far)
Baseline	30 m	24 m (Near) , 48m (Far)
Beam Energy	0.8 GeV proton	3 GeV proton
# μ / p	0.079	**0.48 +- 0.17 (*)**
Beam duty factor	1/14 (by Linac)	**8/40000 (by Synchrotron)**
Energy Resolution	7% @ 45MeV	**3% @ 53MeV**
Liquid scintillator	Scintillation light	**Gd-loaded** Scintillation light + **DIN** is added
Delayed signal	E ~ 2.2MeV, Δt ~ 200μs	**E ~ 8MeV, Δt ~ 30μs**

LSND (Phys. Rev. D 64 (2001) 112007)



(3.8σ $\bar{\nu}_e$ excess)

(*) Phys. Rev. D 112, 032012 (2025)

- JSNS² / JSNS²-II use the same neutrino source (μ), target (H) and the detection principle (IBD) as the LSND.

=> **Direct test of the LSND anomaly**

- Advantages over LSND :

=> Larger #μ / proton (due to 3GeV proton beam)

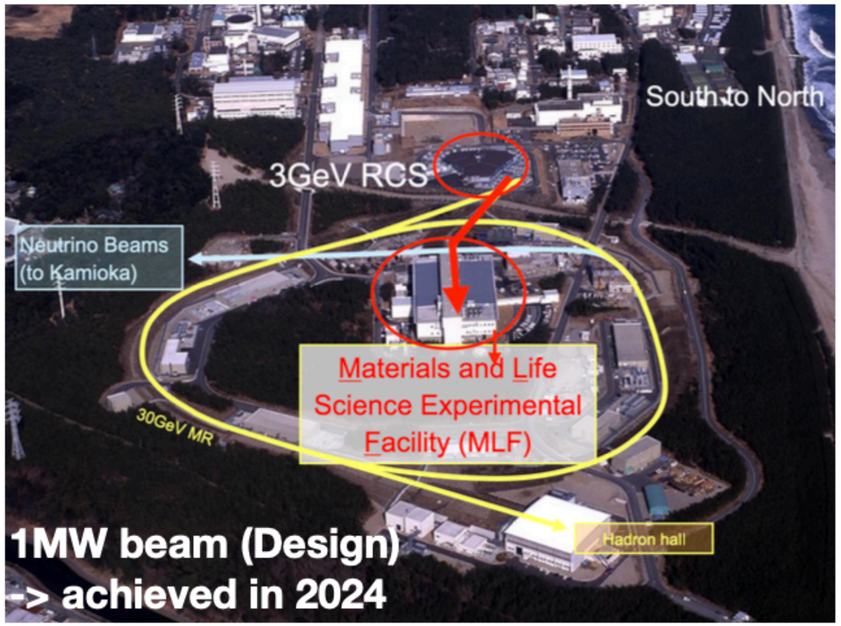
=> short-pulsed beam (much lower duty factor)

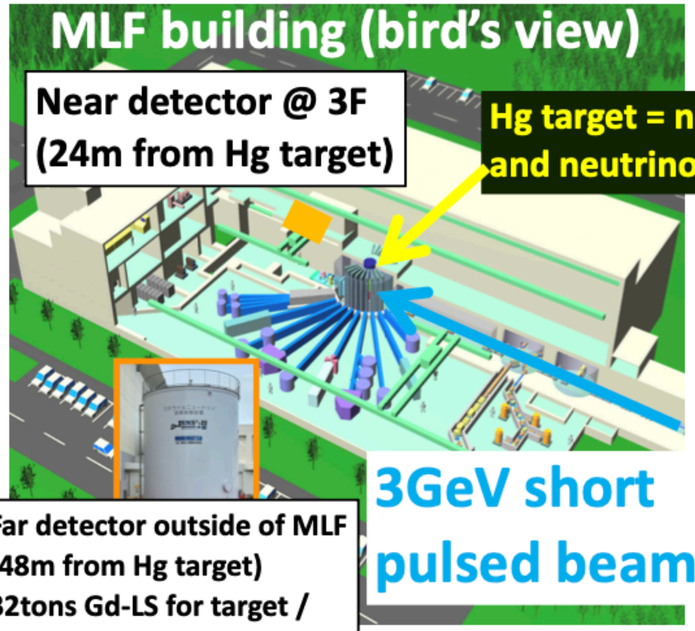
=> Gd-loaded liquid scintillator (suppress the accidental bkg.)

=> DIN + 500 MHz FADC DAQ (enhanced PSD capability)

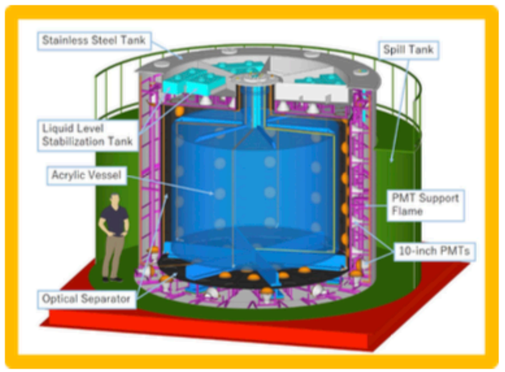
JSNS2 Experiment

slide credit: D. Lee (Nu2026)



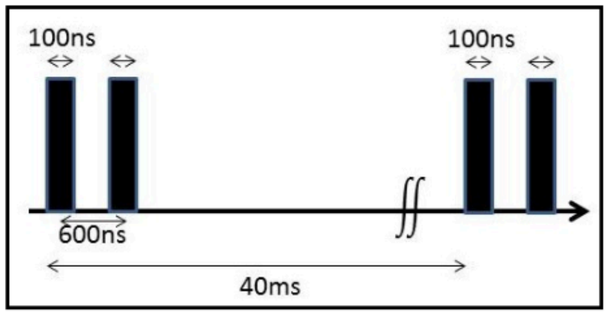


Near detector



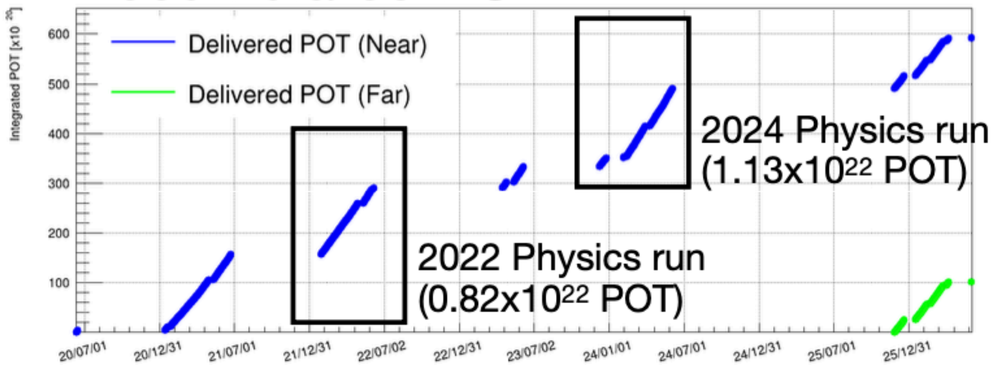
Nucl. Instrum. Methods A 1014 165742 (2021)

- **17tons** Gd-LS+DIN for target
- **96** 10" PMTs for the Inner Detector



- **Low duty factor beam**
(short pulse +
small repetition rate)
gives excellent S/N ratio.

Accumulated POT



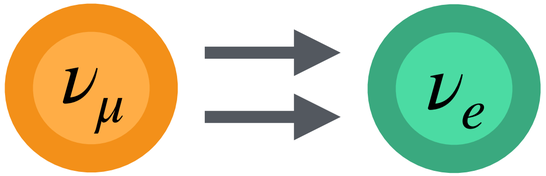
- Near Data taking
=> 5 long term physics runs (2021-2026)
=> 6.0x10²² POT so far (~53% of approved POT)

=> **2022 + 2024 Physics run (1.95x10²² POT) :**
Analysis results in this presentation

- Far Data taking
=> Commissioning (2025 Nov-)

How to detect $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal

slide credit: D. Lee (Nu2026)



- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ during 24m baseline.

IBD selections

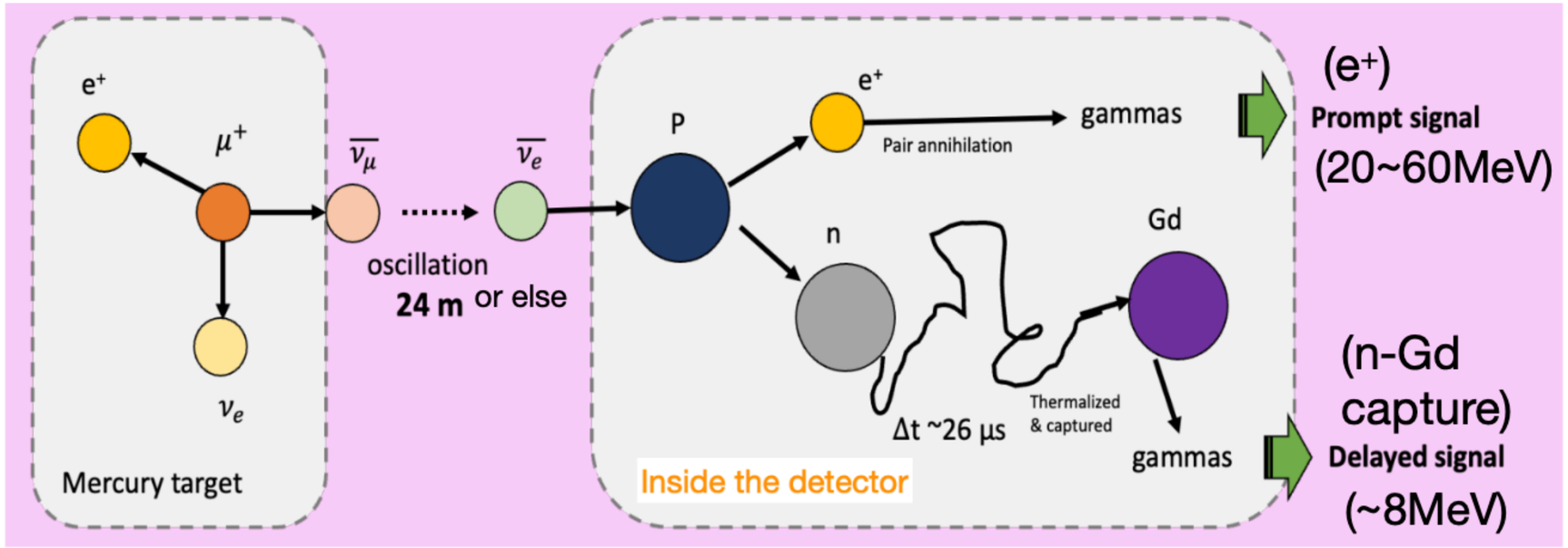
	Timing	Energy
Prompt	1.7 or 2<T_{beam}<10μs	20~60 MeV
Delayed	$\Delta T_{p\text{-}d}$ <100μs	7~12 MeV

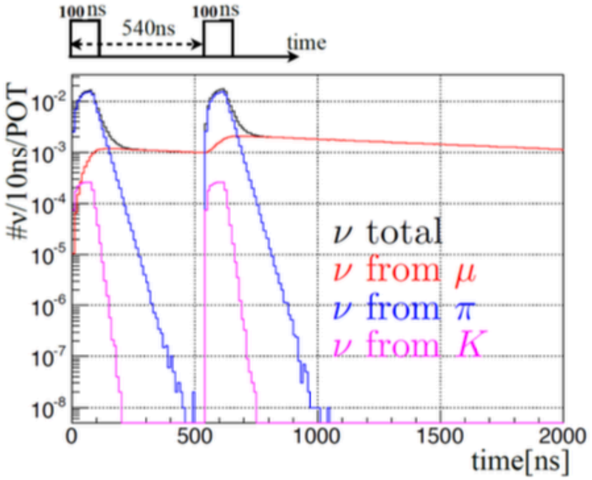
+ Spatial correlation cut
$\Delta VTX_{p\text{-}d}$ < 60cm

- Detection by coincidence of IBD (Inverse Beta Decay)

=> Prompt : e+ signal

=> Delayed : gammas from neutron capture on gadolinium (Gd)





Unblinded Results

slide credit: D. Lee (Nu2026)

- Observation vs Bkg. Prediction (signal region)

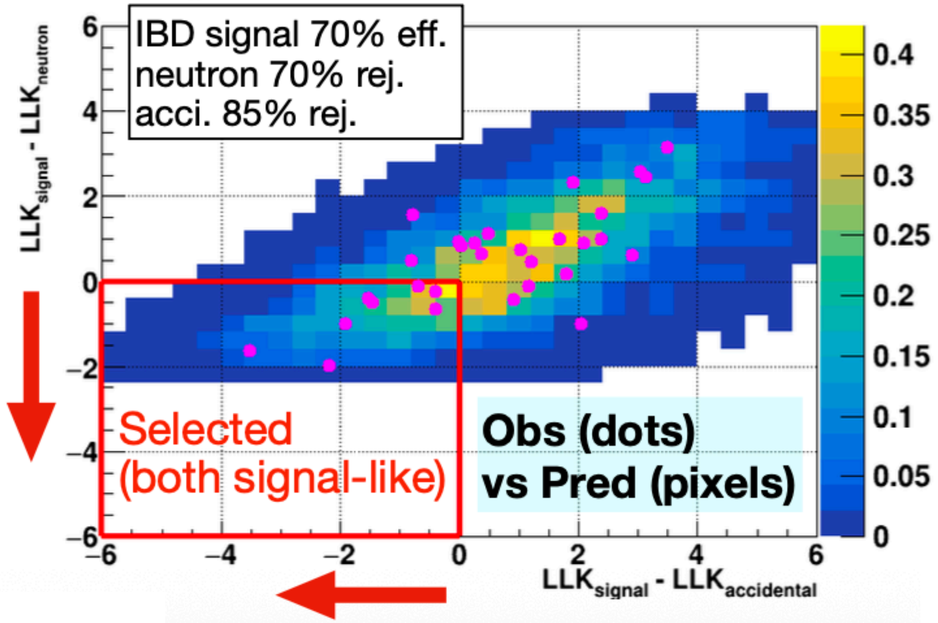
(syst. errors only)

cases	Observation	Prediction
w/o PSD w/o LLK	2195	2160.3 +- 128.6
w/o PSD w/ LLK	606	626.9 +- 37.0
w/ PSD w/o LLK	30	26.3 +- 1.6
w/ PSD w/ LLK	8	6.1 +- 1.0

Neutron 1.5±0.3
Acci 2.4±0.01
CNgs 0.20±0.06
Intrinsic Bkg ($\bar{\nu}_e$ from μ^-)
2.0±1.0

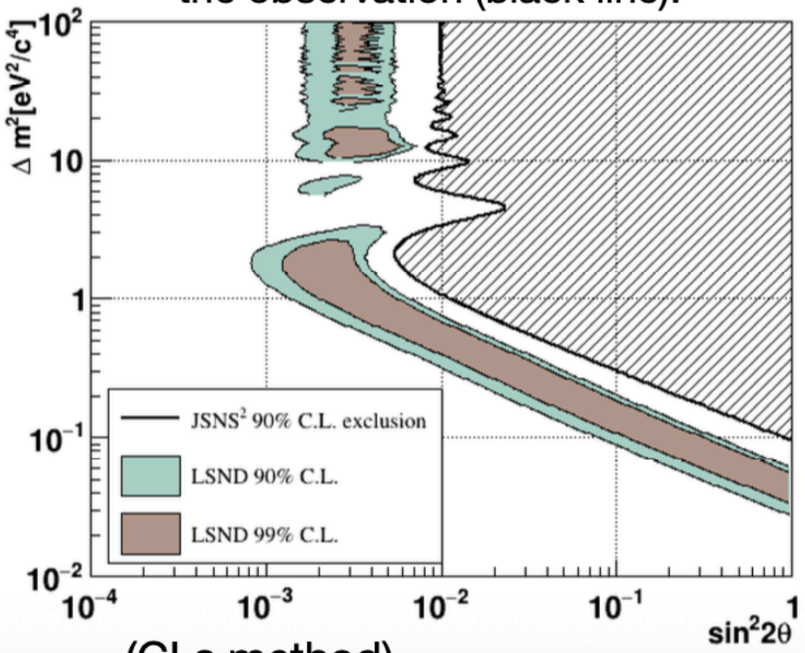
2022 + 2024 Physics run
(1.95x10²² POT)
JSNS² Preliminary

2D Log-Likelihood ratio score distribution



$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillation contour

90% CL exclusion limit derived from the observation (black line).



(CLs method)

Direct Comparison with the LSND Excess

$$N_{JSNS^2} = \frac{\Phi_{JSNS^2} \cdot \sigma_{IBD} \cdot N_{T,JSNS^2} \cdot \epsilon_{JSNS^2}}{\Phi_{LSND} \cdot \sigma_{IBD} \cdot N_{T,LSND} \cdot \epsilon_{LSND}} \times N_{LSND}$$

Expected number of events from the LSND anomaly

item	LSND	JSNS^2
ν flux ($\#\nu/cm^2$)	1.26×10^{14}	1.29×10^{14}
(POT	1.81×10^{23}	1.95×10^{22})
($\#\mu$/p	0.079	0.48 ± 0.17)
(baseline	30 m	24 m)
N_T	7.4×10^{30}	7.48×10^{29}
efficiency (%)	42.0 ± 3.0	12.9 ± 1.3
N_{eve}	87.9 ± 23.1	2.8 ± 1.3

• Fiducial volume : R < 140cm, |Z| < 100cm

2022 + 2024 Physics run (1.95x10^{22} POT) **JSNS^2 Preliminary**

	Observed events	Prediction events
Total	**8**	**8.9 +- 1.6**
JSNS^2 Bkg.		**6.1 +- 1.0**
LSND excess (scaled)		**2.8 +- 1.3**

- LSND $\bar{\nu}_e$ excess is normalized to compare with JSNS^2 data set

- Bkg only expectation (No LSND excess) : p-value (N>=8 | Bkg. = 6.1) = 0.27 (0.6σ)

- Bkg + LSND excess expectation : P (N<=8 | Bkg. + LSND = 8.9) = 0.47 (0.1σ)

- The observation is consistent with both the Bkg.-only and Bkg.+LSND expectations, so far.

Outline

1 **short-baseline anomalies**

appearance and disappearance hints at L/E ~ 1 m/MeV

2 **SBN at Fermilab: MicroBooNE, ICARUS, and SBND**

Recent results from LArTPC experiments at Fermilab

3 **JSNS2 at JPARC**

Direct test of LSND

4 **outlook**

what comes next for the field

Summary & Outlook

- short-baseline anomalies at L/E ~ 1 m/MeV remain unexplained
- **MicroBooNE**: two beams in one detector, all three 3+1 channels
  - ν_e appearance: LSND and MiniBooNE regions excluded at 95% CL
  - ν_e disappearance: most of the gallium region excluded
  - ν_μ disappearance (preliminary): part of the IceCube region excluded
- **ICARUS**: first ν_μ disappearance search, no significant oscillation, systematics-limited
- **SBND**: largest ν–Ar dataset to date (6M interactions); as the near detector, constrains SBN systematics to the percent level
- **JSNS^2**: 8 observed vs 6.1 ± 1.0 (bkg) and 8.9 ± 1.6 (bkg + LSND), consistent with both so far
- **outlook**: SBN two-detector oscillation analyses, MicroBooNE full dataset and extended models, JSNS^2 Phase 1 (~6× data) and a far detector at 48 m → independent tests of LSND/MiniBooNE in the next few years

Summary & Outlook

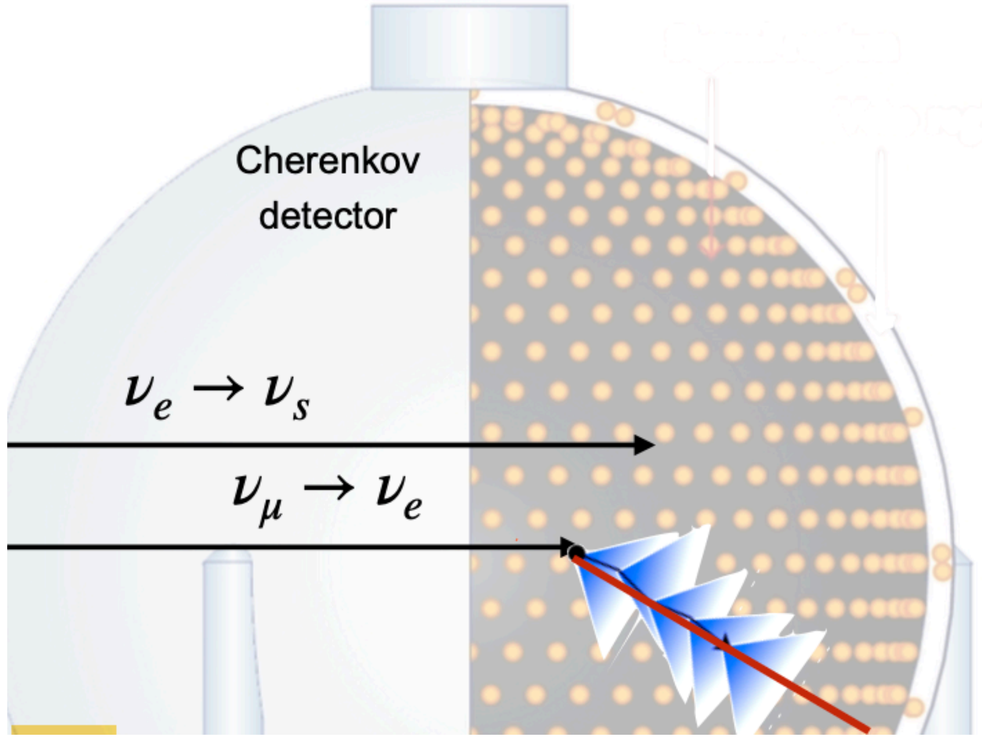
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Backup slides

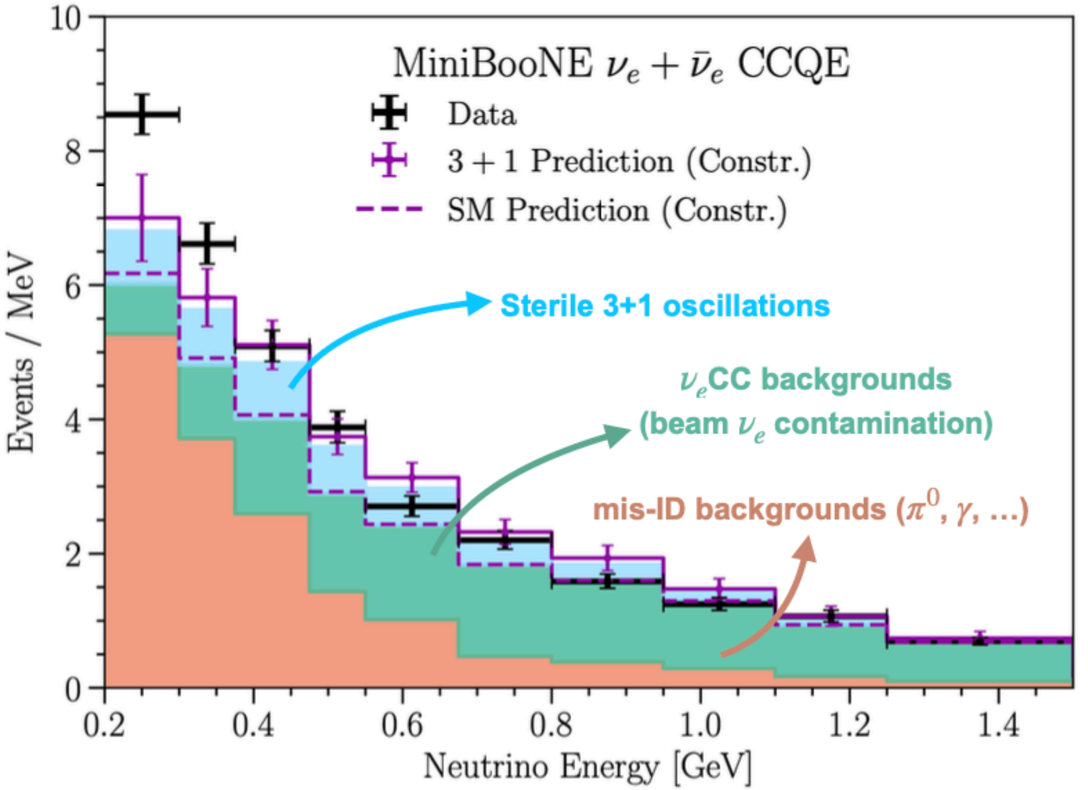
2000s: **MiniBooNE** and the ν_e-like Low-Energy Excess

Booster Neutrino Beam 8 GeV p^+
π and K decay in flight

- 18.75×10^{20} POT neutrino mode
- 11.27×10^{20} POT antineutrino mode



MiniBooNE coll., PRD 103, 052002 (2021)
Adapted from MiniBooNE coll., PRL129 (2022) 20, 201801

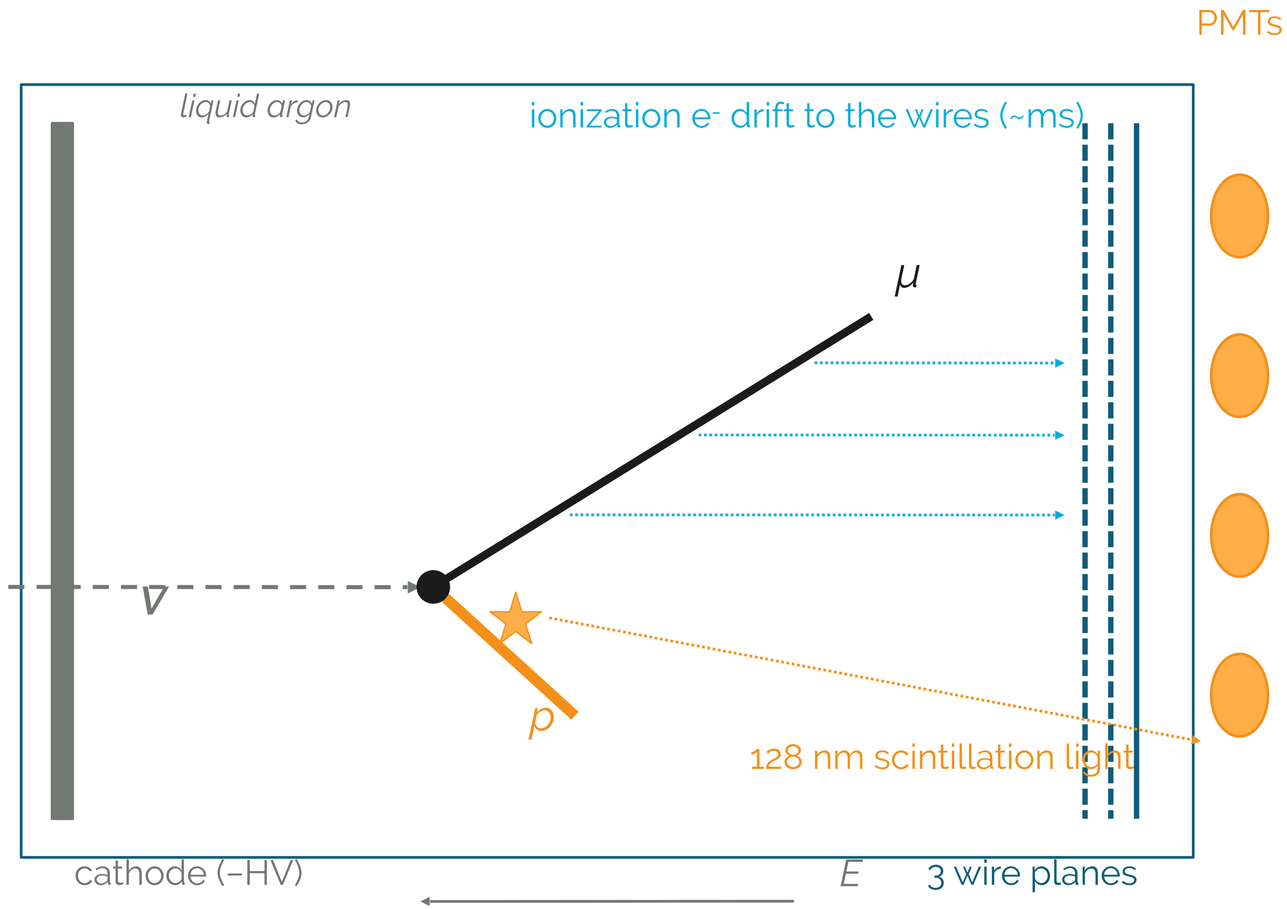


$638 \pm 52(\text{stat.}) \pm 122.2(\text{sys.})$

4.6σ preference of **full 3+1 oscillations**

over background-only hypothesis.

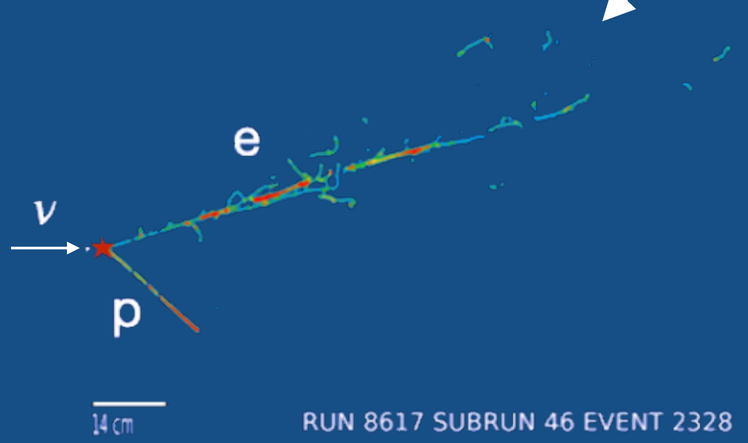
How a Liquid Argon TPC Works



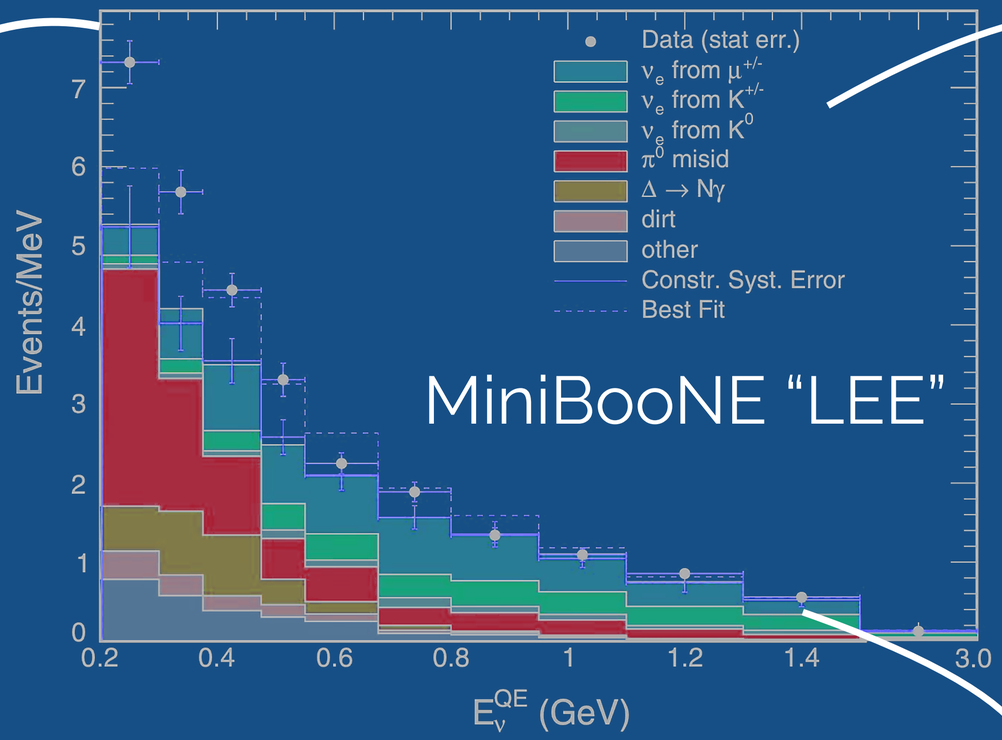
- charged particles **ionize** the argon and produce **scintillation light**
- ionization electrons **drift** in a uniform field to the anode wire planes
- three planes give three 2D views, combined into a **mm-scale 3D image**
- the light flash gives the **event time** (t_0) and the trigger

MicroBooNE's "Low Energy Excess" Search

electron?

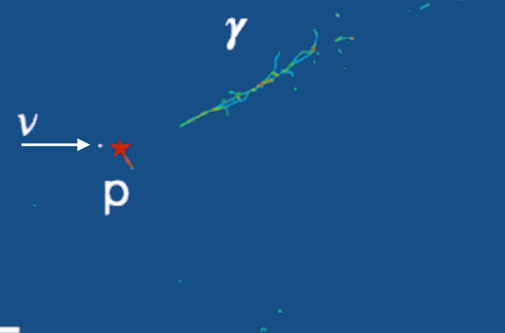


RUN 8617 SUBRUN 46 EVENT 2328



MiniBooNE "LEE"

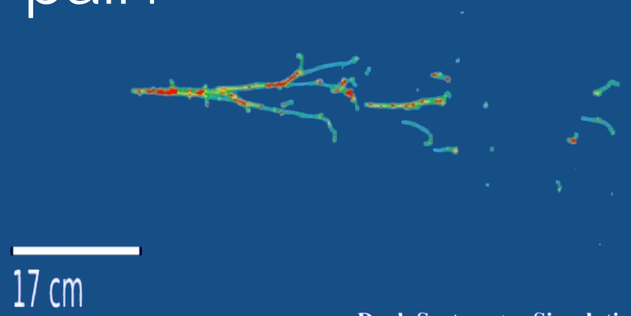
single photon?



MicroBooNE Data, Run 5462 Subrun 14 Event 732

e^+e^- opening angle 5.6°
e^+e^- energy 617 MeV

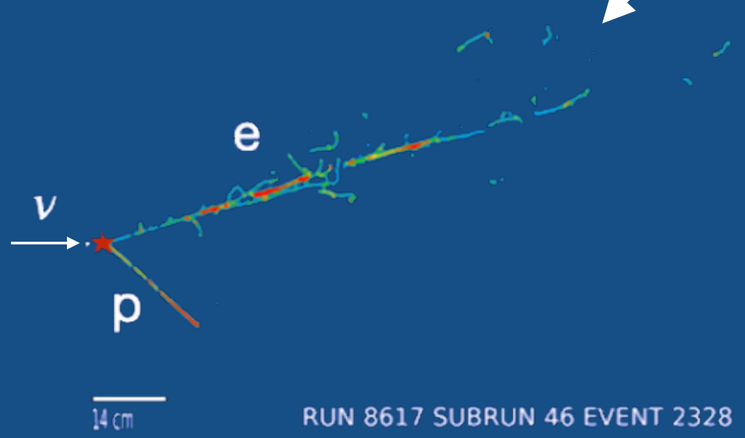
e^+e^- pair?



Dark Sector e^+e^- Simulation

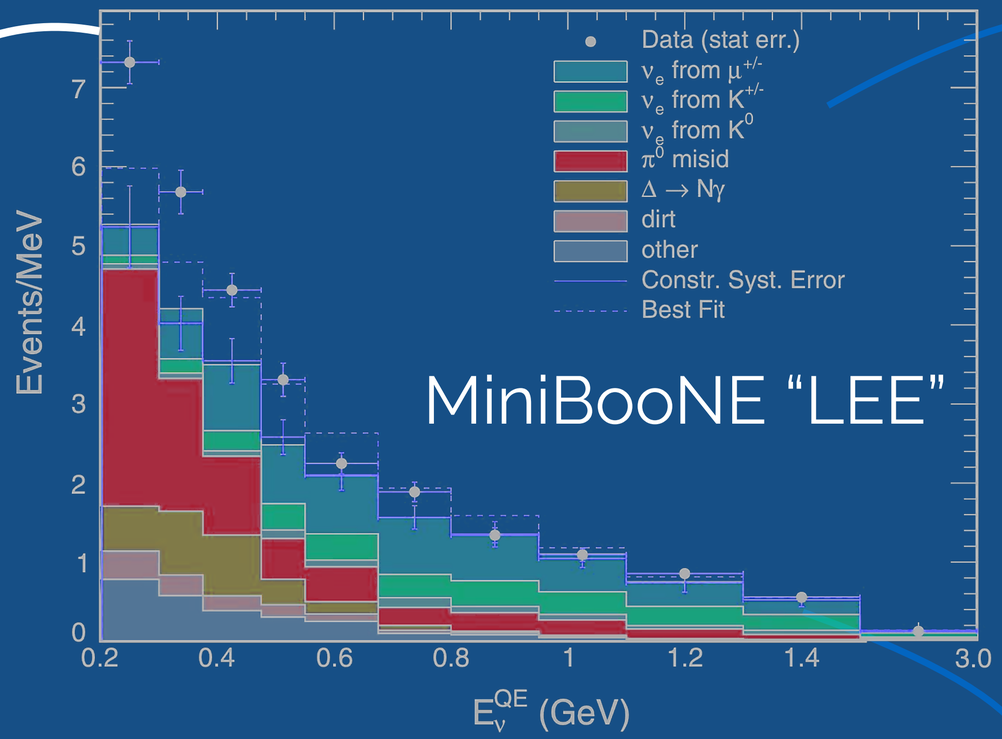
MicroBooNE's "Low Energy Excess" Search

electron?



RUN 8617 SUBRUN 46 EVENT 2328

disfavored!



single photon?



e^+e^- pair?



RD 105 112003 (2022)
RD 105 112004 (2022)
RD 105 112005 (2022)
RL 128 241801 (2022)
RL 135 081802 (2025)

RL 130 011801 (2023)
ture 648 64-69 (2025)

MicroBooNE's "Low Energy Excess" Search

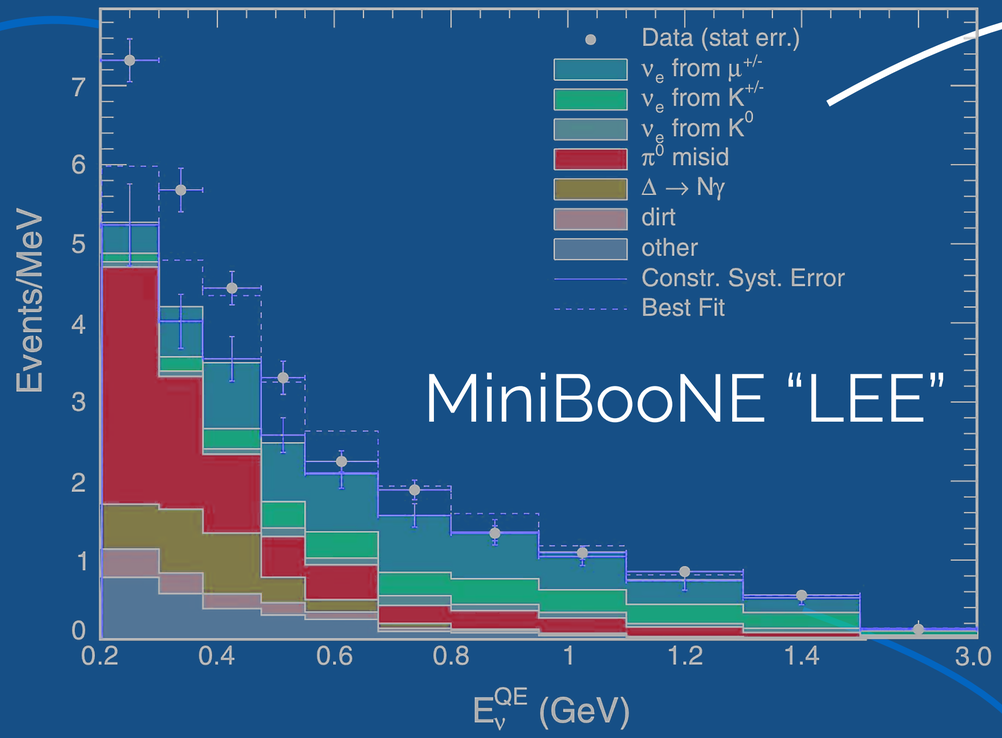
electron?



RUN 8617 SUBRUN 46 EVENT 2328

14 cm

disfavored!



single photon?



25 cm

MicroBooNE Data, Run 5462 Subrun 14 Event 732

disfavored most popular SM process explanations:

NC Δ → 1γ

PRL 128 111801 (2022)

NC coherent 1γ

arXiv:2502.06091

e^+e^- pair?



e^+e^- opening angle 5.6°
e^+e^- energy 617 MeV

17 cm

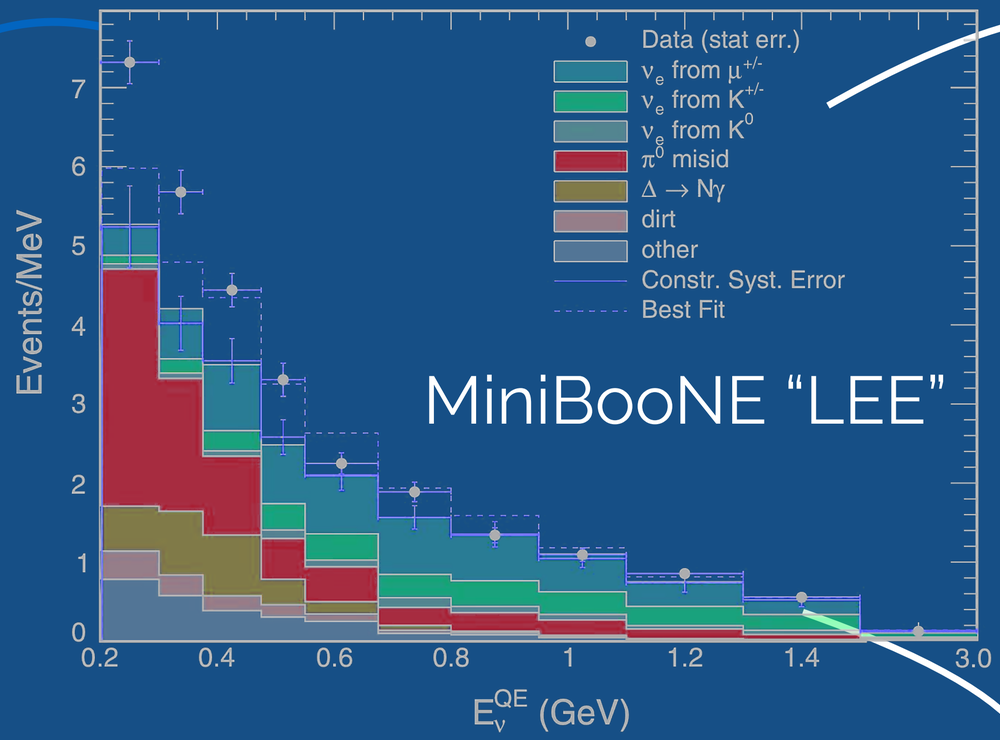
Dark Sector e^+e^- Simulation

MicroBooNE's "Low Energy Excess" Search

electron?

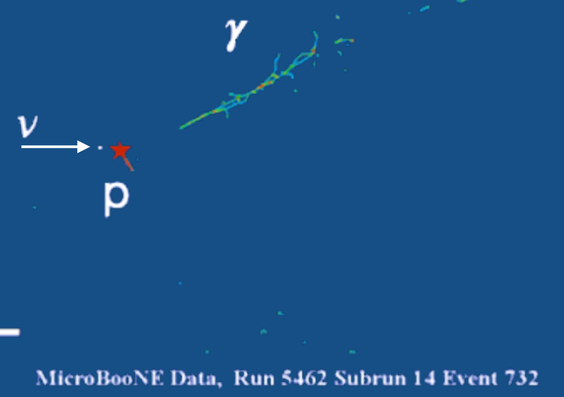


disfavored!



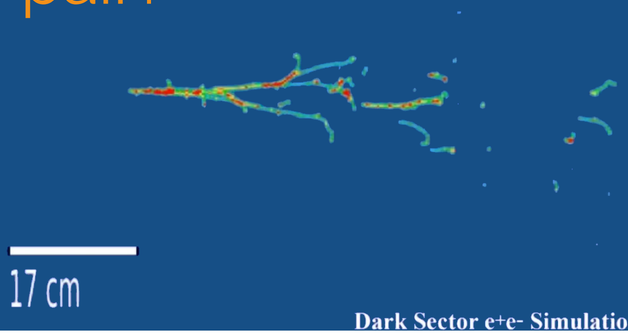
e^+e^- opening angle 5.6°
e^+e^- energy 617 MeV

single photon?



disfavored most popular SM process explanations

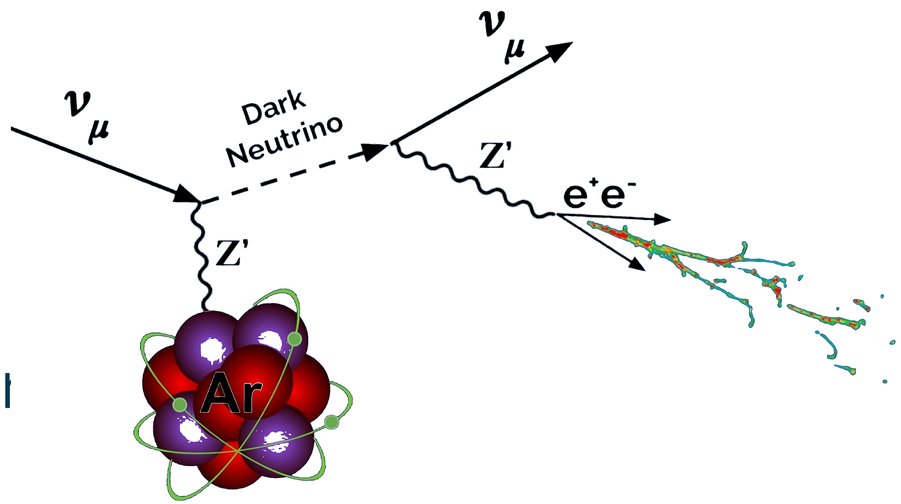
e^+e^- pair?

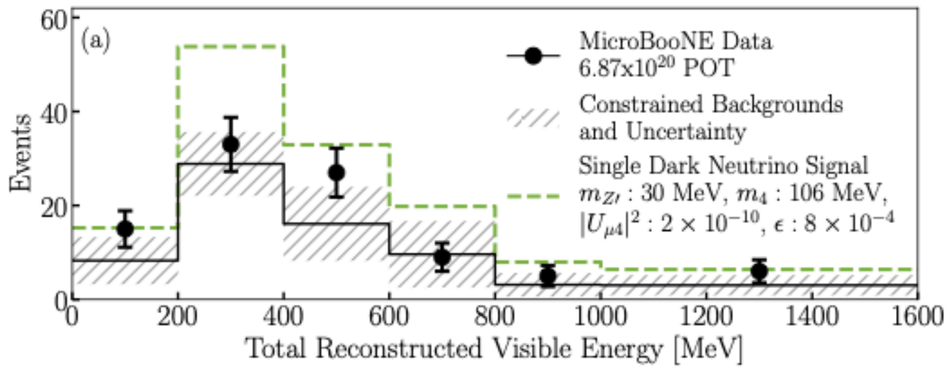


remaining signatures to probe: other **single photon** processes, or ***e+e-* pair** production with new physics

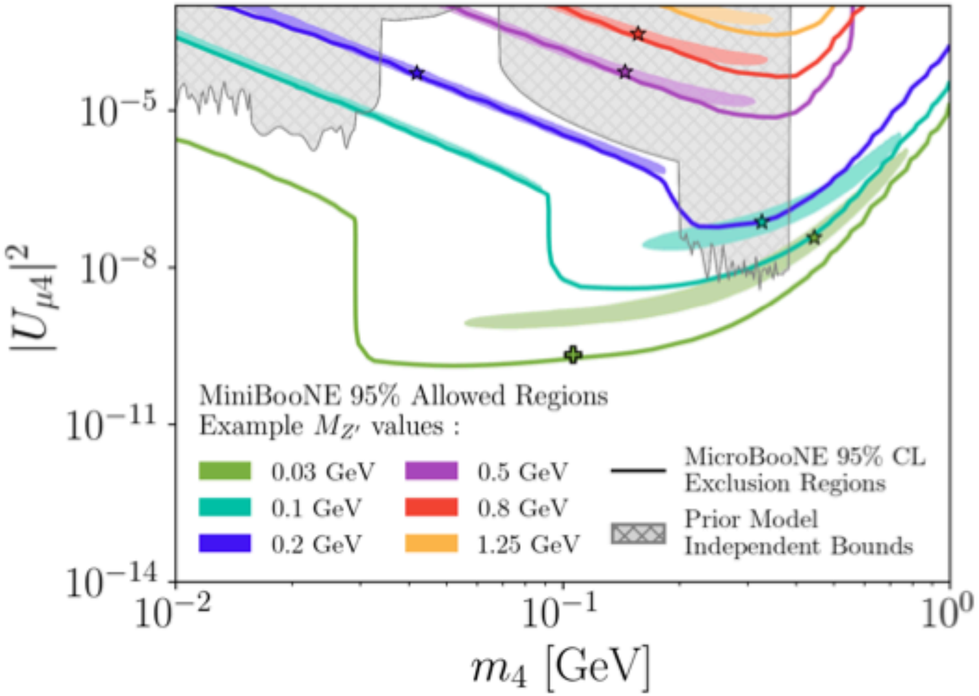
MicroBooNE's "Low Energy Excess" Search: BSM *e+e-*

PRL 136 121804 (2026)



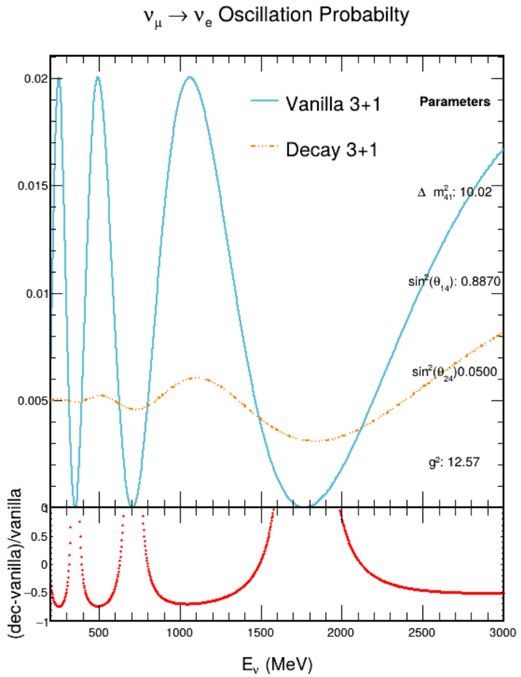


- sear[illegible]'s from uns[illegible]
- sensitive to MiniBooNE allowed region for th
- MicroBooNE places world leading exclusion [illegible] n of the MiniBooNE anomaly

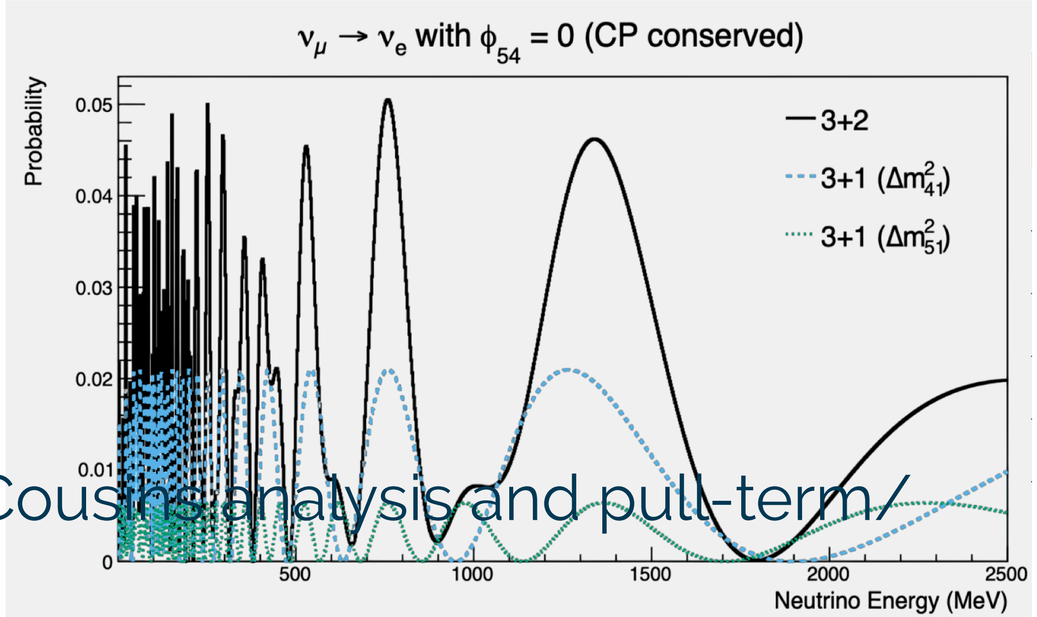


Expanded Sterile Neutrino Search

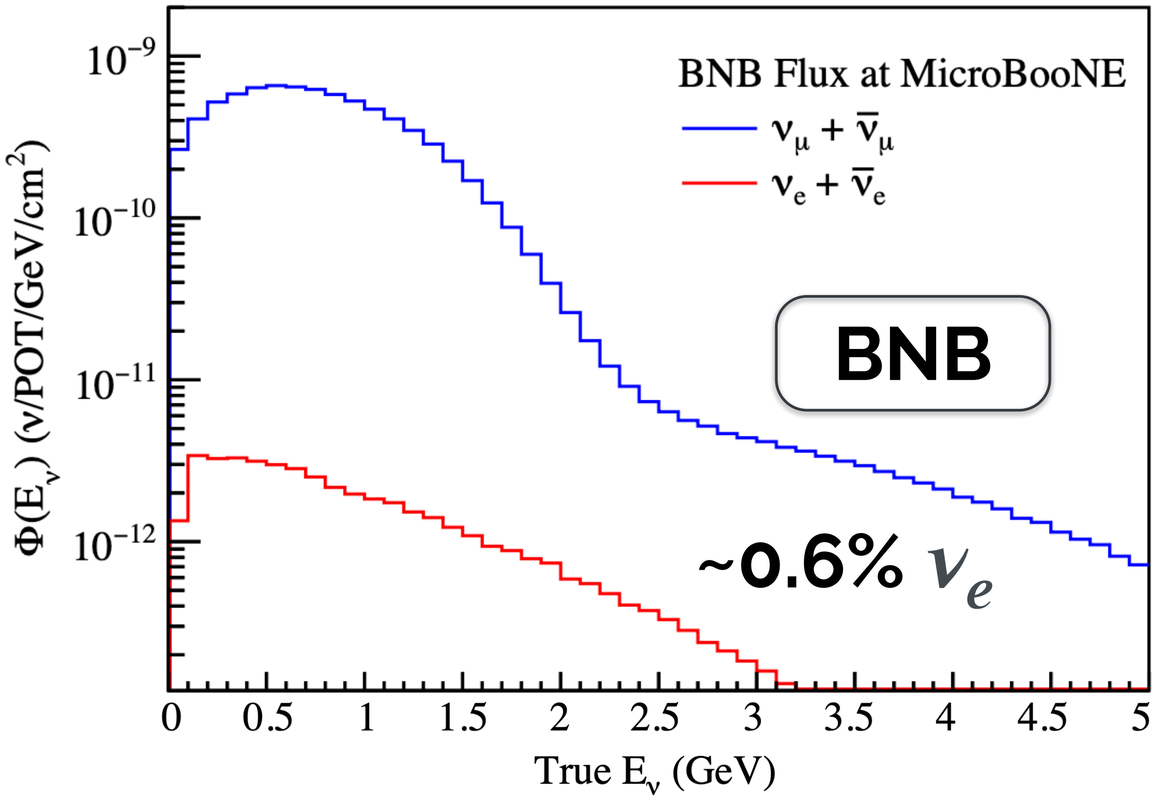
- **full-dataset 3+1 analysis**
  - almost double data in both BNB & NuMI
  - addition of external datasets (Prospect/KATRIN/ICAR
  - thorough investigation of 3D 3+1
- **additional models beyond vanilla 3+1**
  - 3+1+decay (invisible and visible)
  - 3+2 (includes CP violation)
- **expanding framework** to allow full Feldman-Cousins analysis and pull-term/ nuisance systematics

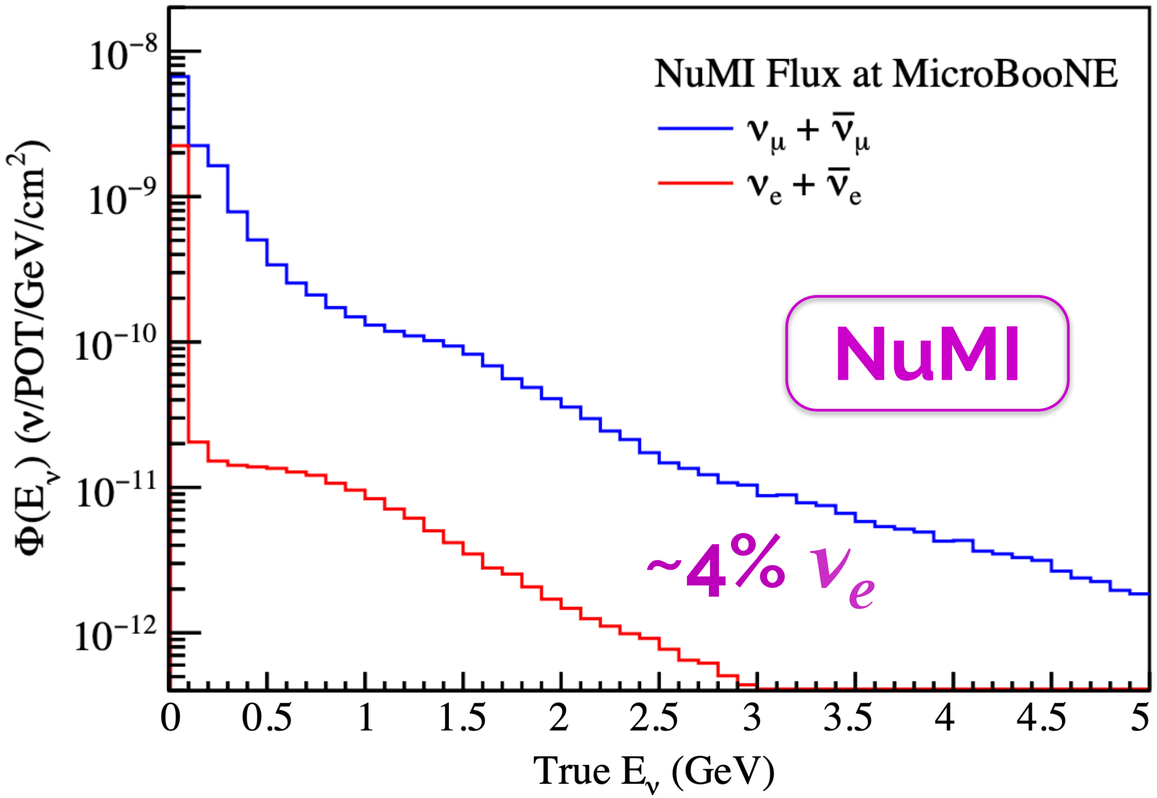


MicroBooNE Work In Progress



3+1 Sterile Neutrino Search: adding NuMI





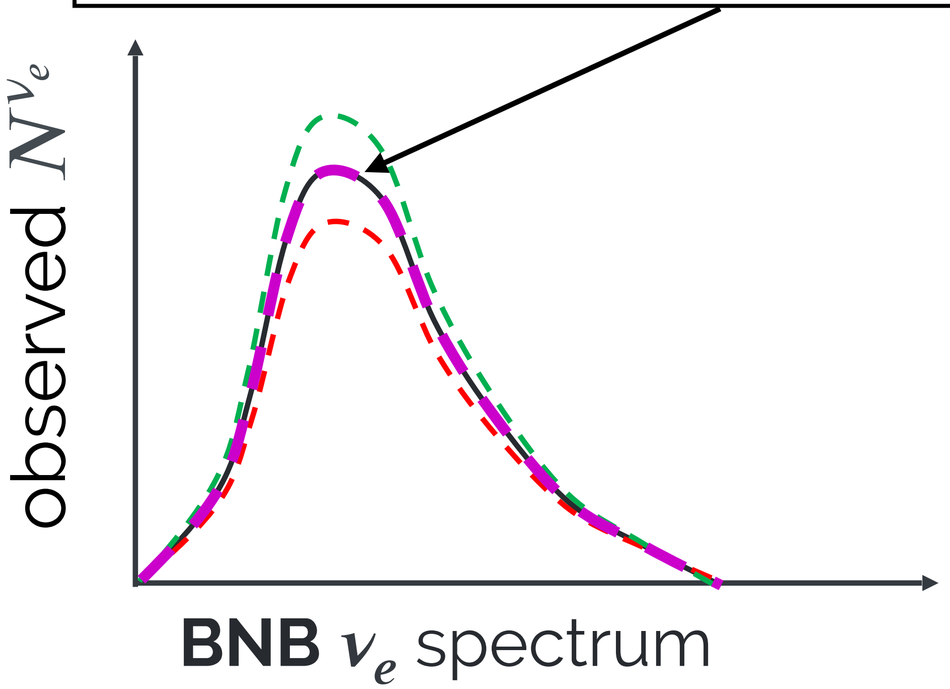
beam ν_μ-to-ν_e ratios: BNB~200 vs NuMI~25

they have quite different degeneracy points!

so we have two "handles" to lift the appearance-disappearance degeneracy

3+1 Sterile Neutrino Search: degeneracy

Cancellation of ν_e appearance and disappearance



No oscillation: N^{ν_e}

Disapp effect: $N^{\nu_e} \times P_{ee}$

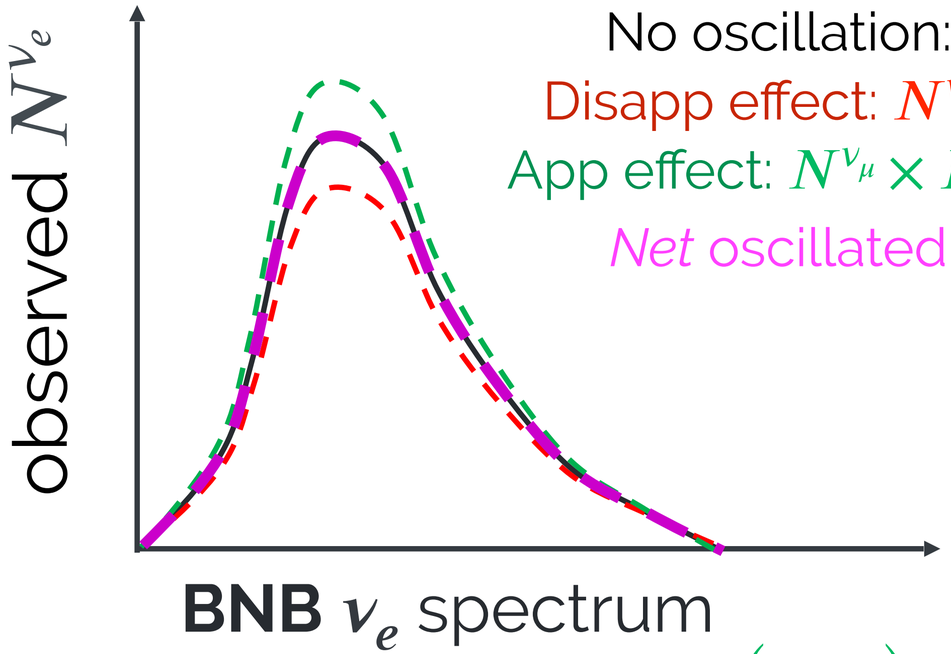
App effect: $N^{\nu_\mu} \times P_{\mu e} + N^{\nu_e}$

Net oscillated N^{ν_e}

degeneracy "point": $\frac{P_{\mu e}}{P_{ee}} = \frac{\sin^2\left(2\theta_{\mu e}\right)}{\sin^2\left(2\theta_{ee}\right)} = \frac{N^{\nu_e}}{N^{\nu_\mu}}$, fixed value for a given beam

3+1 Sterile Neutrino Search: adding NuMI

Cancellation of ν_e appearance and disappearance

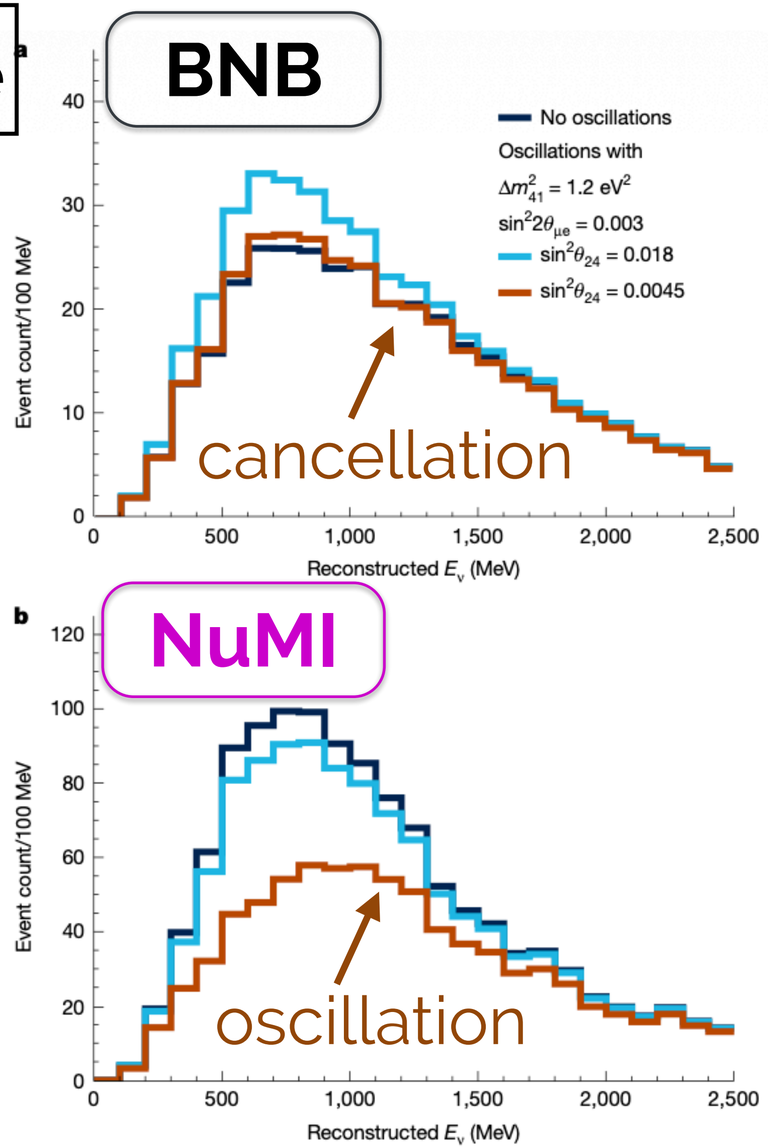


No oscillation: N^{ν_e}

Disapp effect: $N^{\nu_e} \times P_{ee}$

App effect: $N^{\nu_\mu} \times P_{\mu e} + N^{\nu_e}$

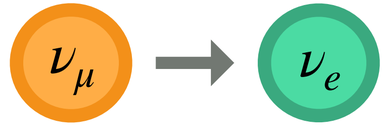
Net oscillated N^{ν_e}



now with different $\frac{P_{\mu e}}{P_{ee}} = \frac{\sin^2(2\theta_{\mu e})}{\sin^2(2\theta_{ee})} = \frac{N^{\nu_e}}{N^{\nu_\mu}}$ for BNB and NuMI,

even BNB (NuMI) has cancellation, NuMI (BNB) at the same oscillation parameters still show oscillation!

3+1 Sterile Neutrino Search: BNB+NuMI result



Unphysical

BNB-only Result (2023)



appearance

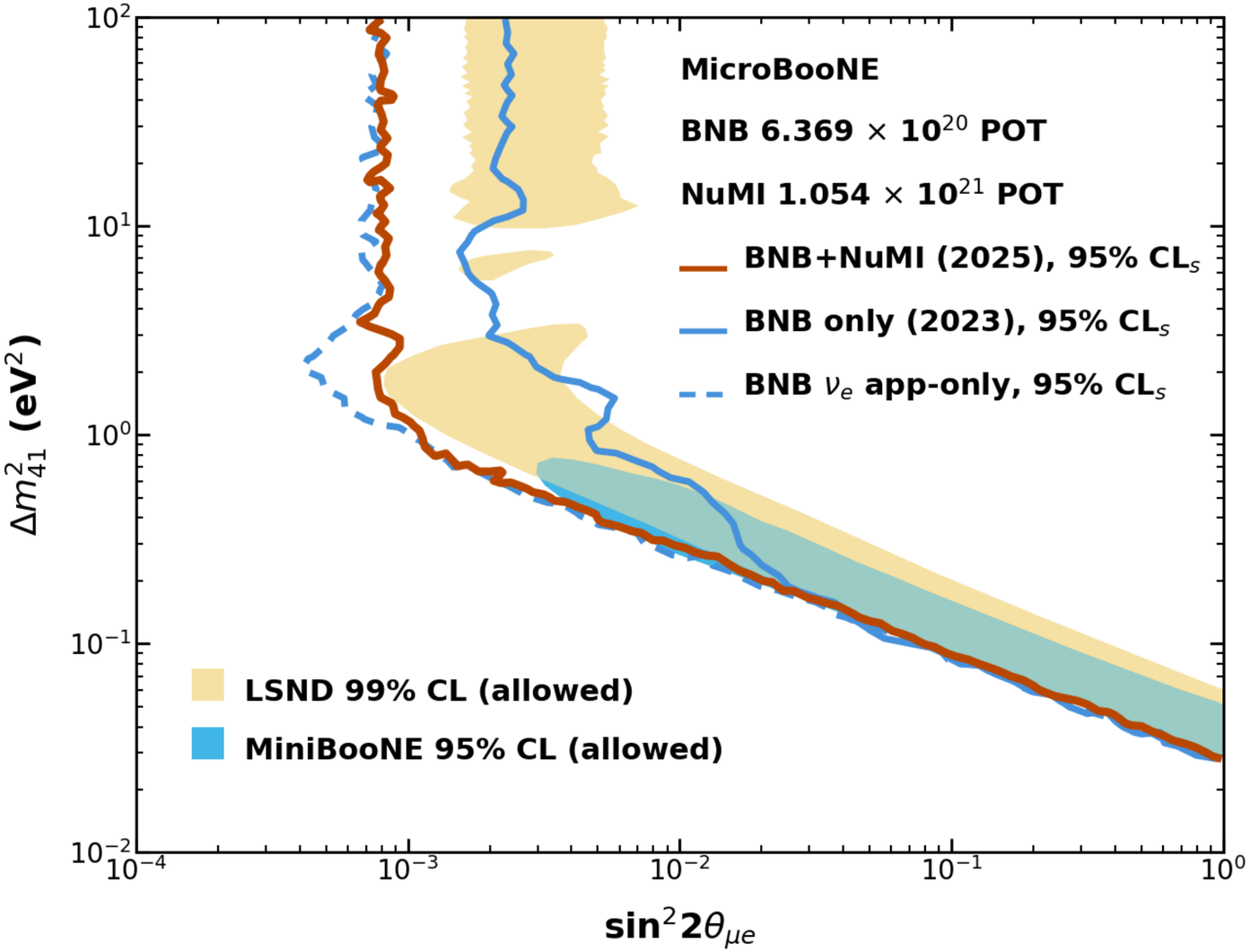


disappearance

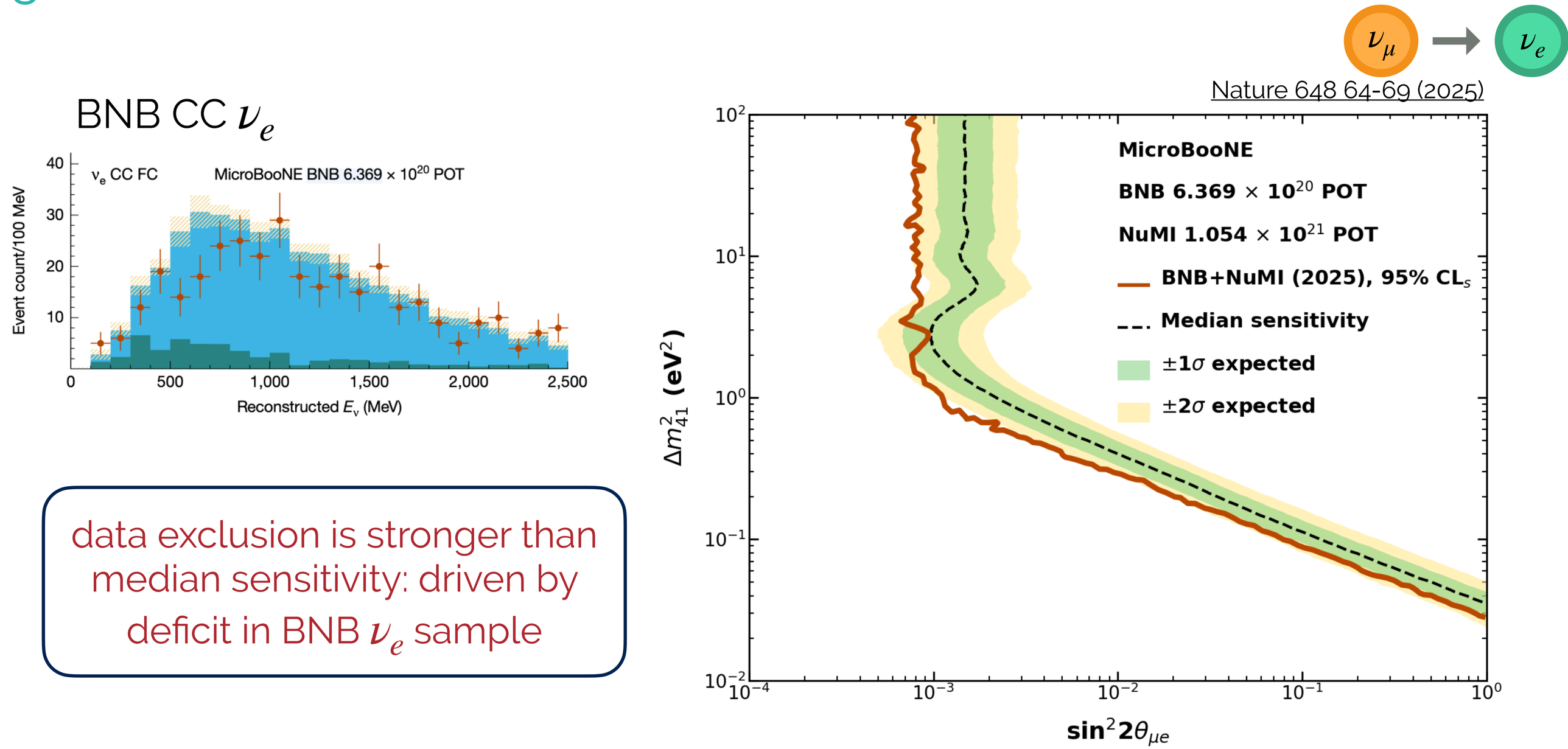


disappearance

addition of NuMI data lifts the degeneracy, significantly improving the sensitivity

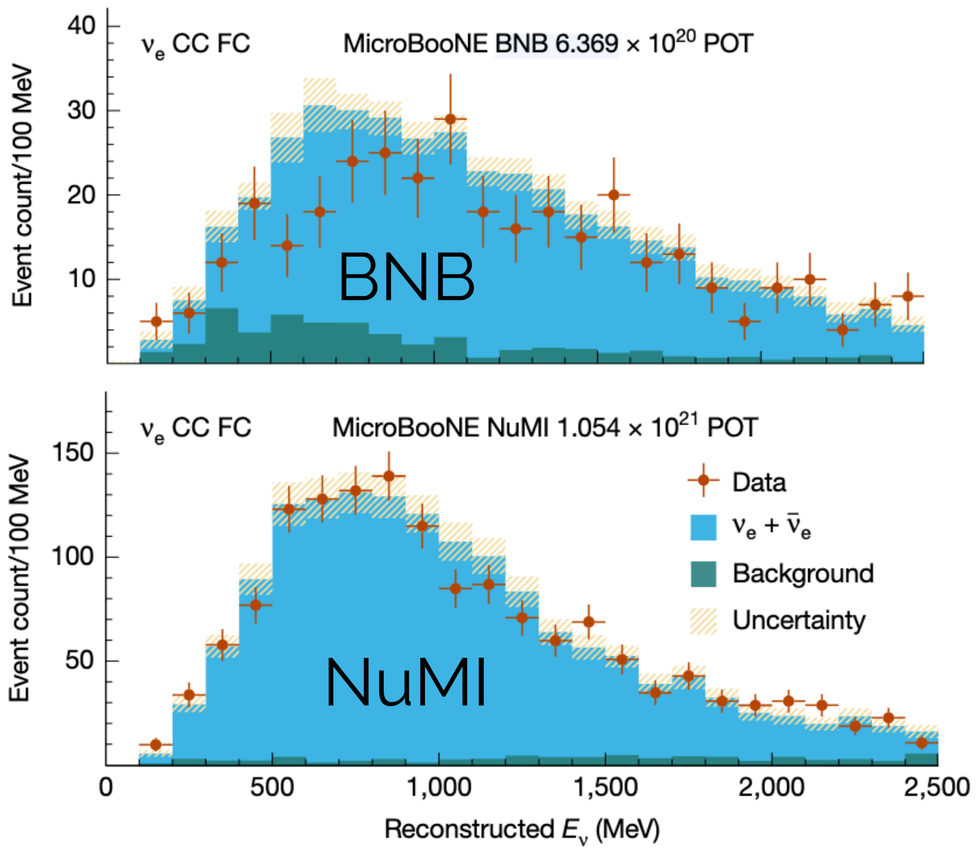


3+1 Sterile Neutrino Search: BNB+NuMI result



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

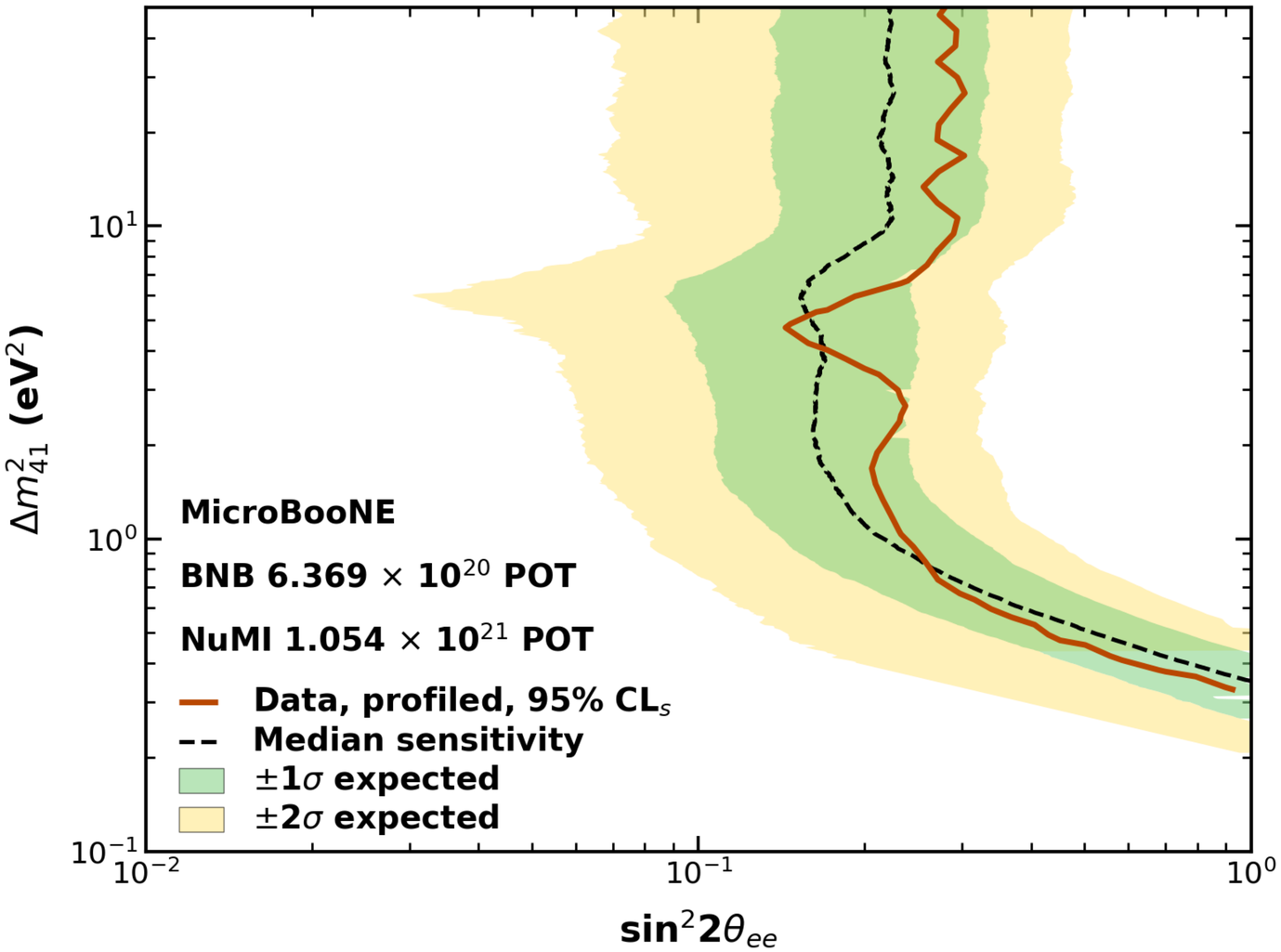
3+1 Sterile Neutrino Search: BNB+NuMI result



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

$\nu_e \rightarrow \nu_e$

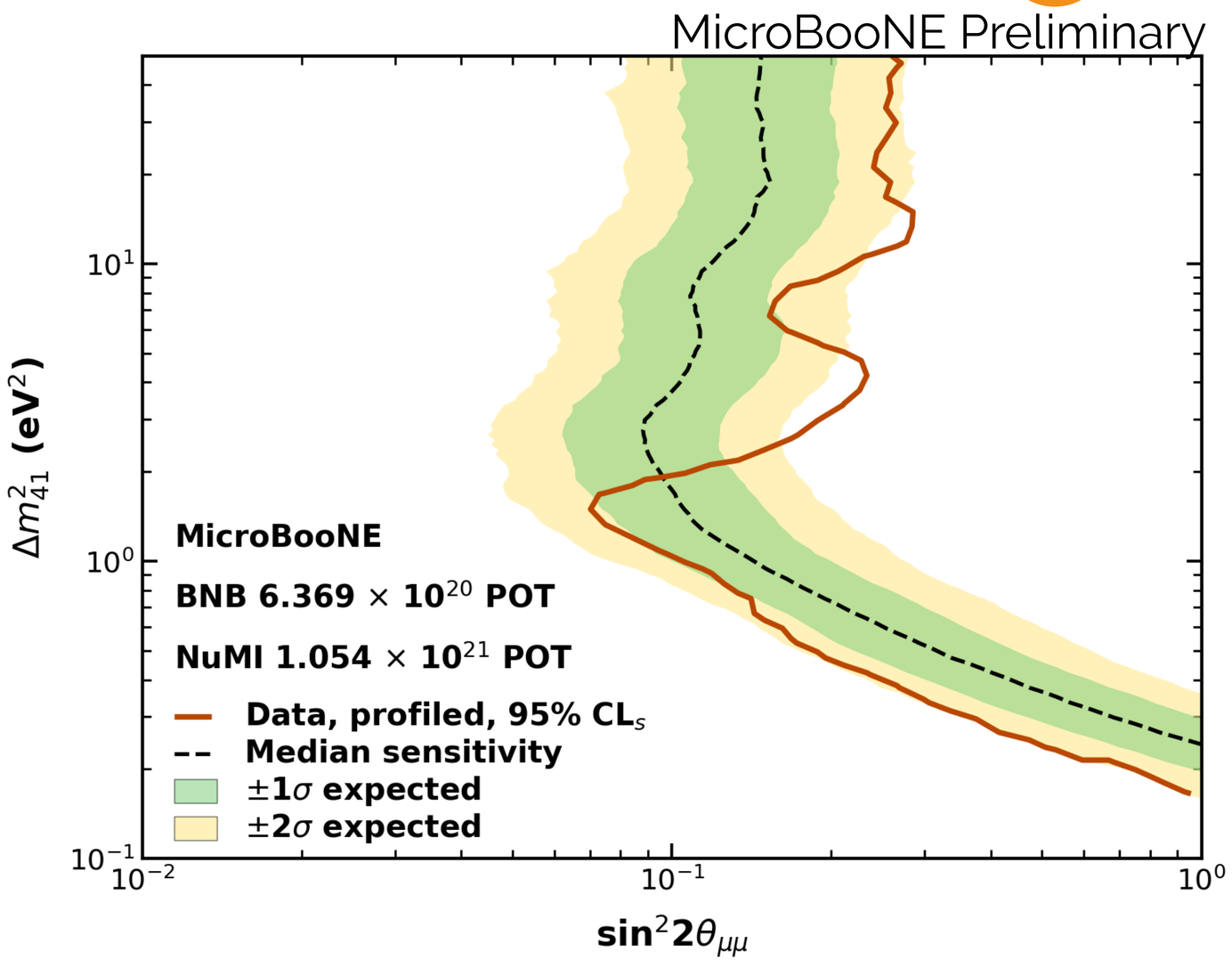
Nature 648 64-69 (2025)



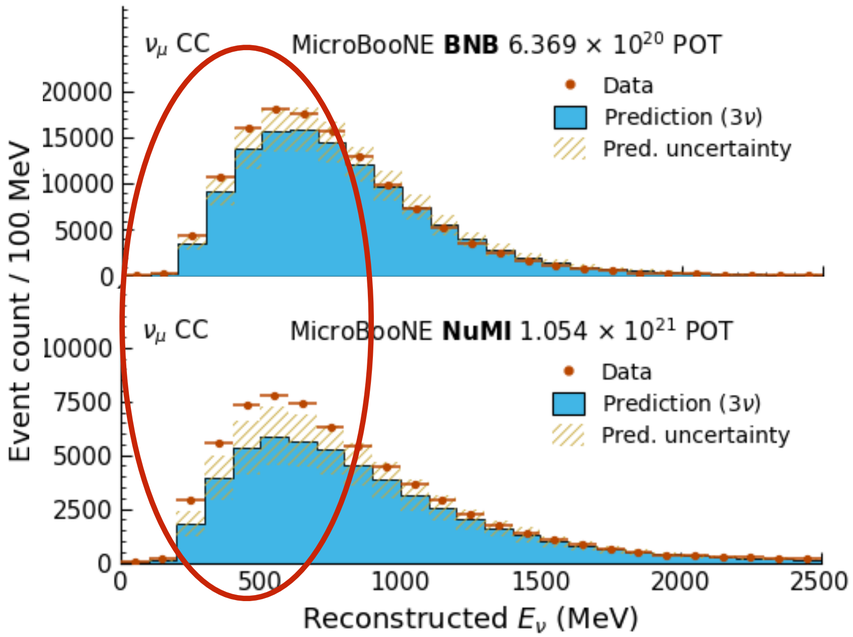
3+1 Sterile Neutrino Search: BNB+NuMI result

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

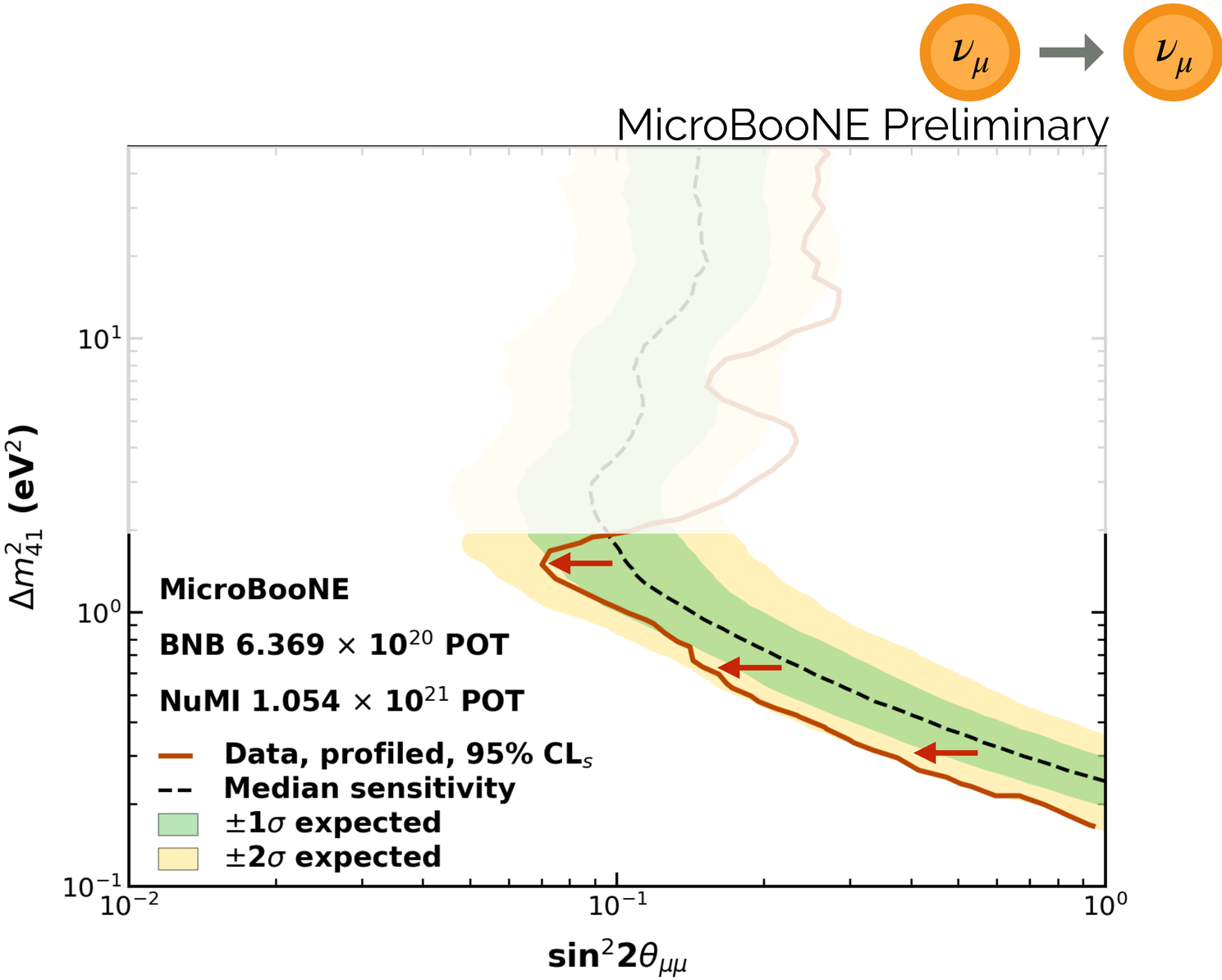
data exclusion is weaker than median sensitivity in high Δm^2 region, and slightly stronger in low Δm^2 region



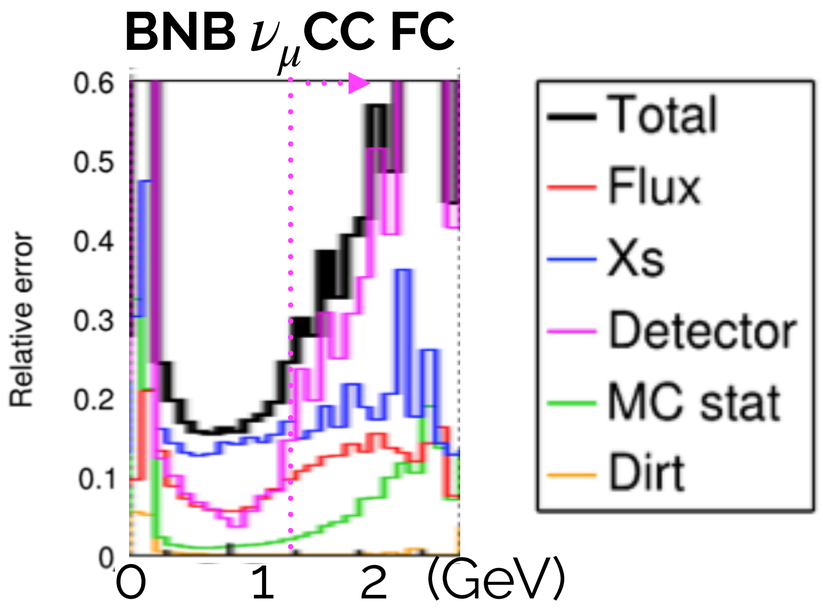
3+1 Sterile Neutrino Search: BNB+NuMI result



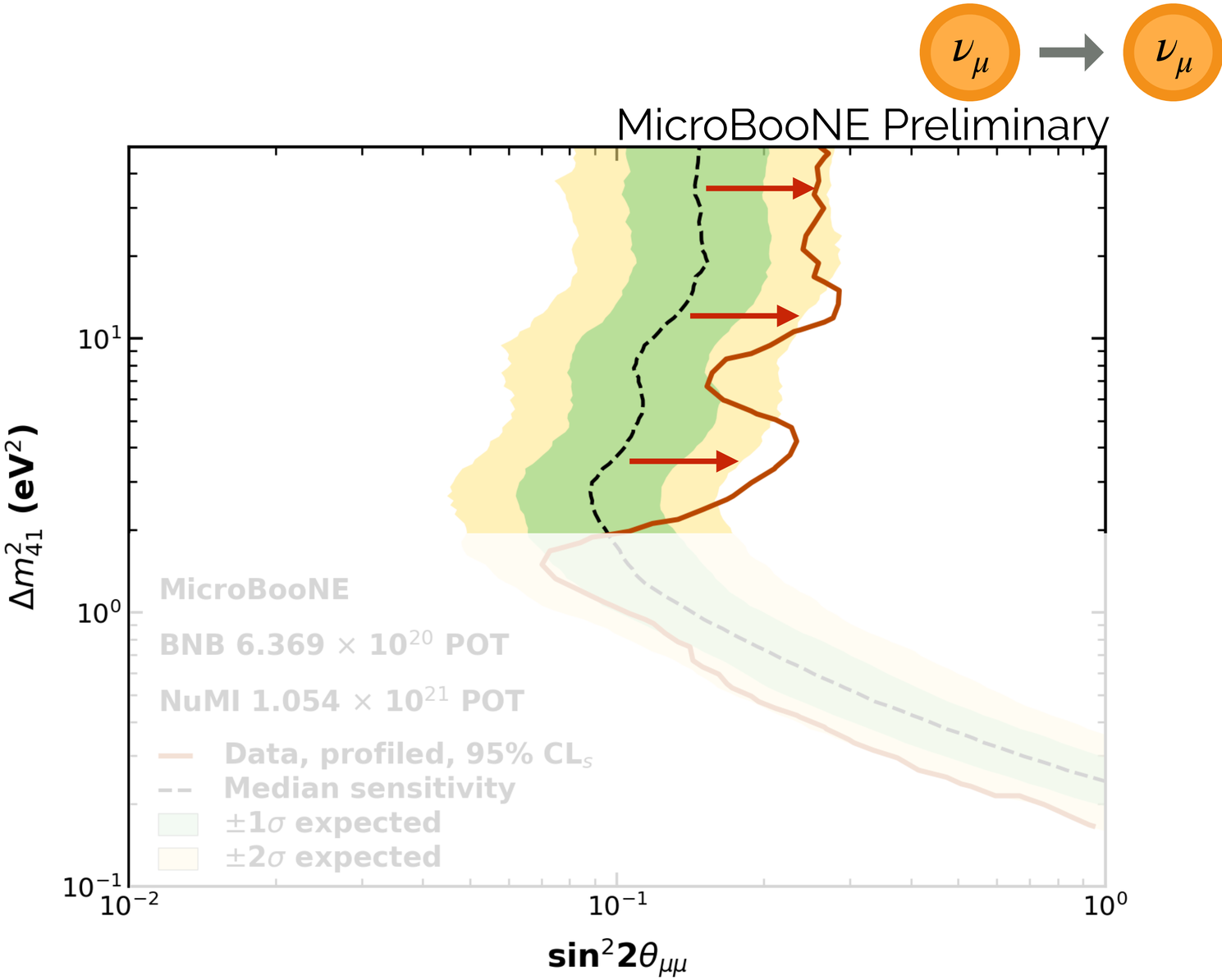
low Δm^2 region (<~1 eV^2) is where the oscillation maximum sits at lower energy portion of the ν_μ spectrum, where we have the data excess → stronger limit



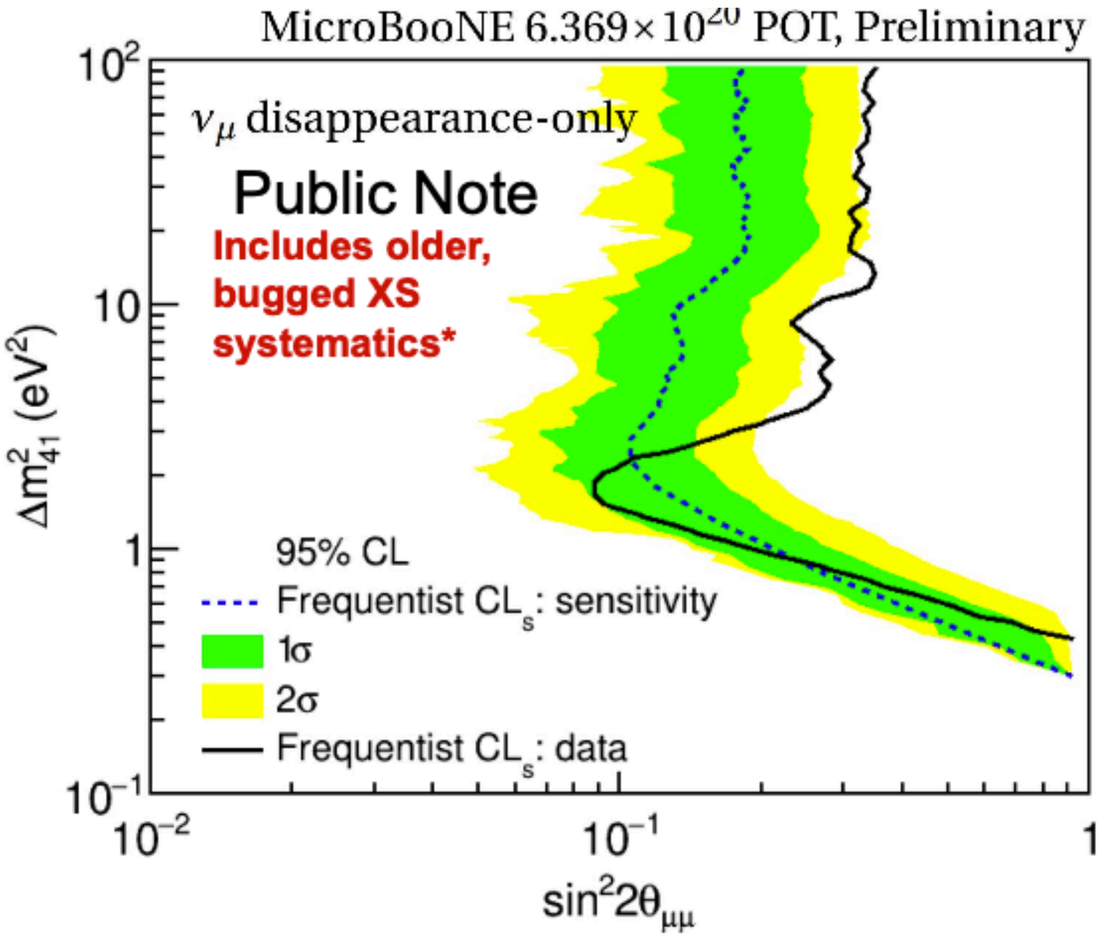
3+1 Sterile Neutrino Search: BNB+NuMI result

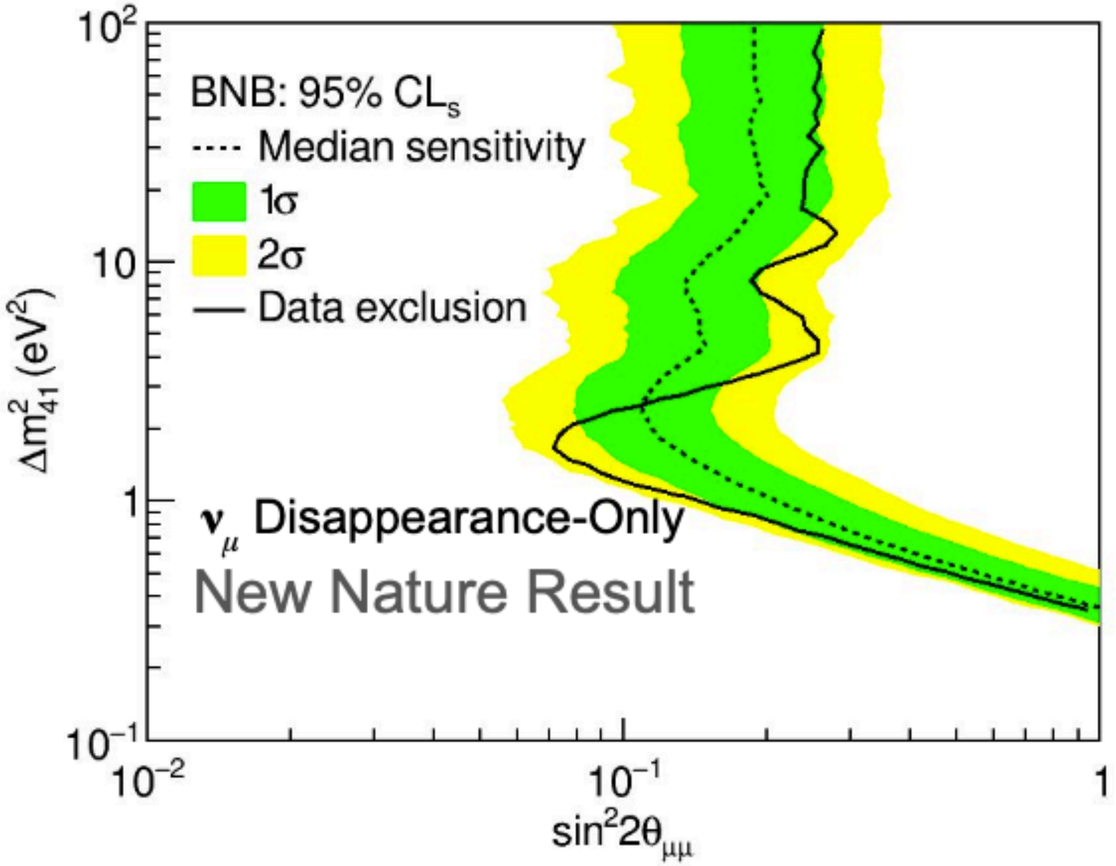


high Δm^2 region (>~1 eV²) is where oscillations reach higher energies and eventually average out as a pure rate effect, and our conservative detector systematics over-cover the data fluctuation



Comparison to Public Note: ν_μ disappearance-only result





The FSI bug fix is the main change

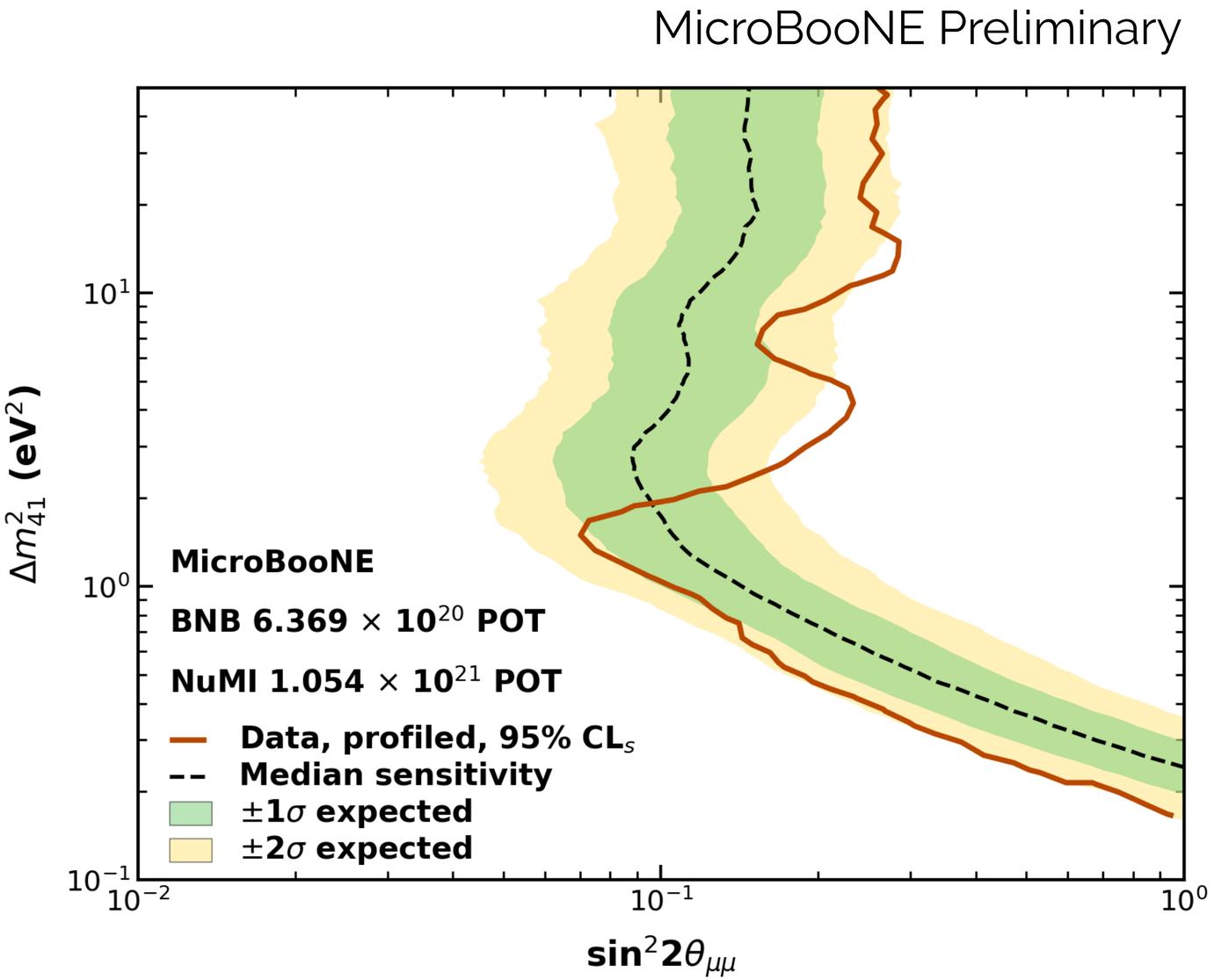
*Note these bugs were fixed long before our Nature result, but we never back ported to our Public Note until now

ν_μ disappearance result

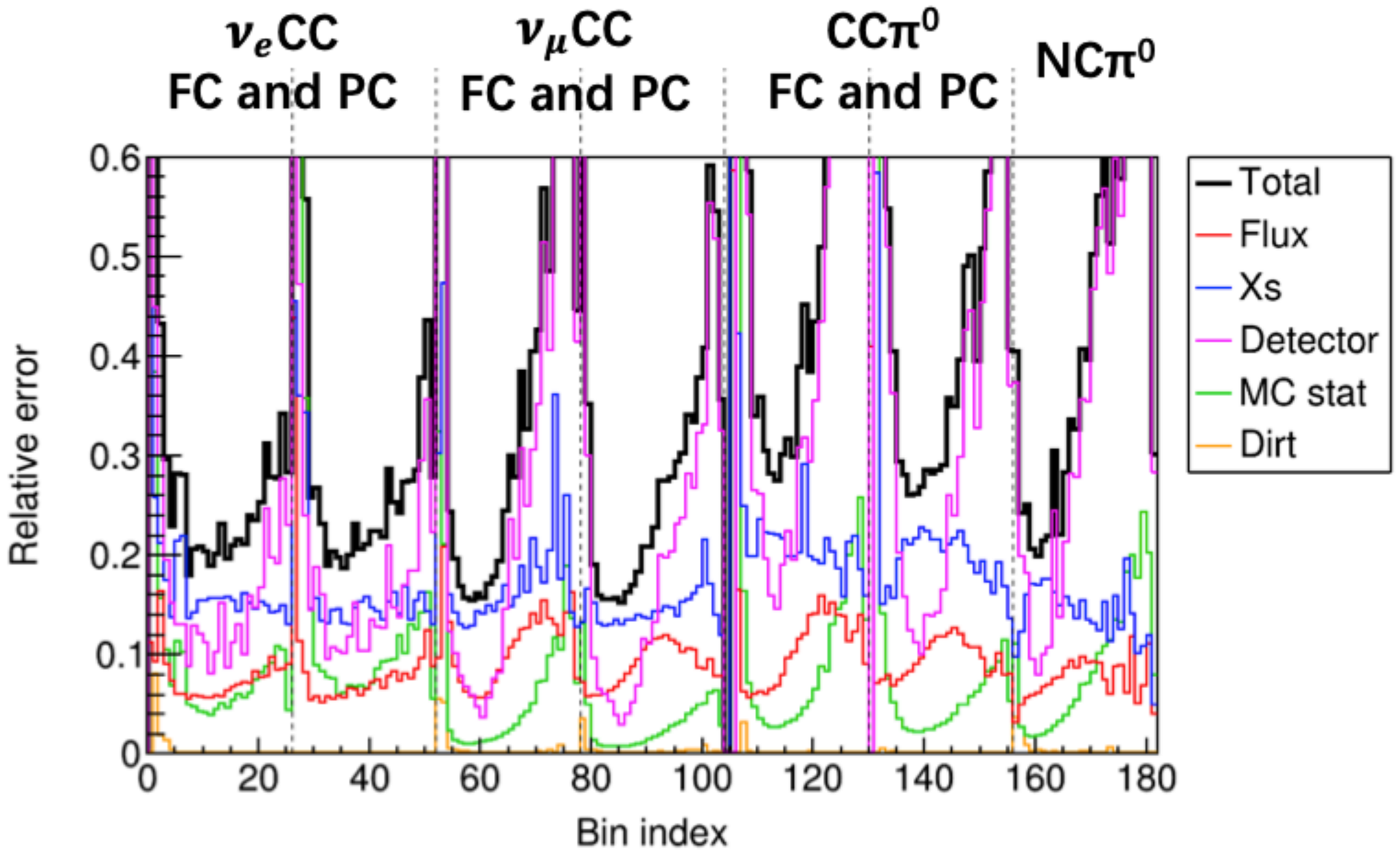
- why would large (detector) syst
exclusion limit? wouldn't such s
the data?

- over-coverage of the detector s
not see the same fluctuation in

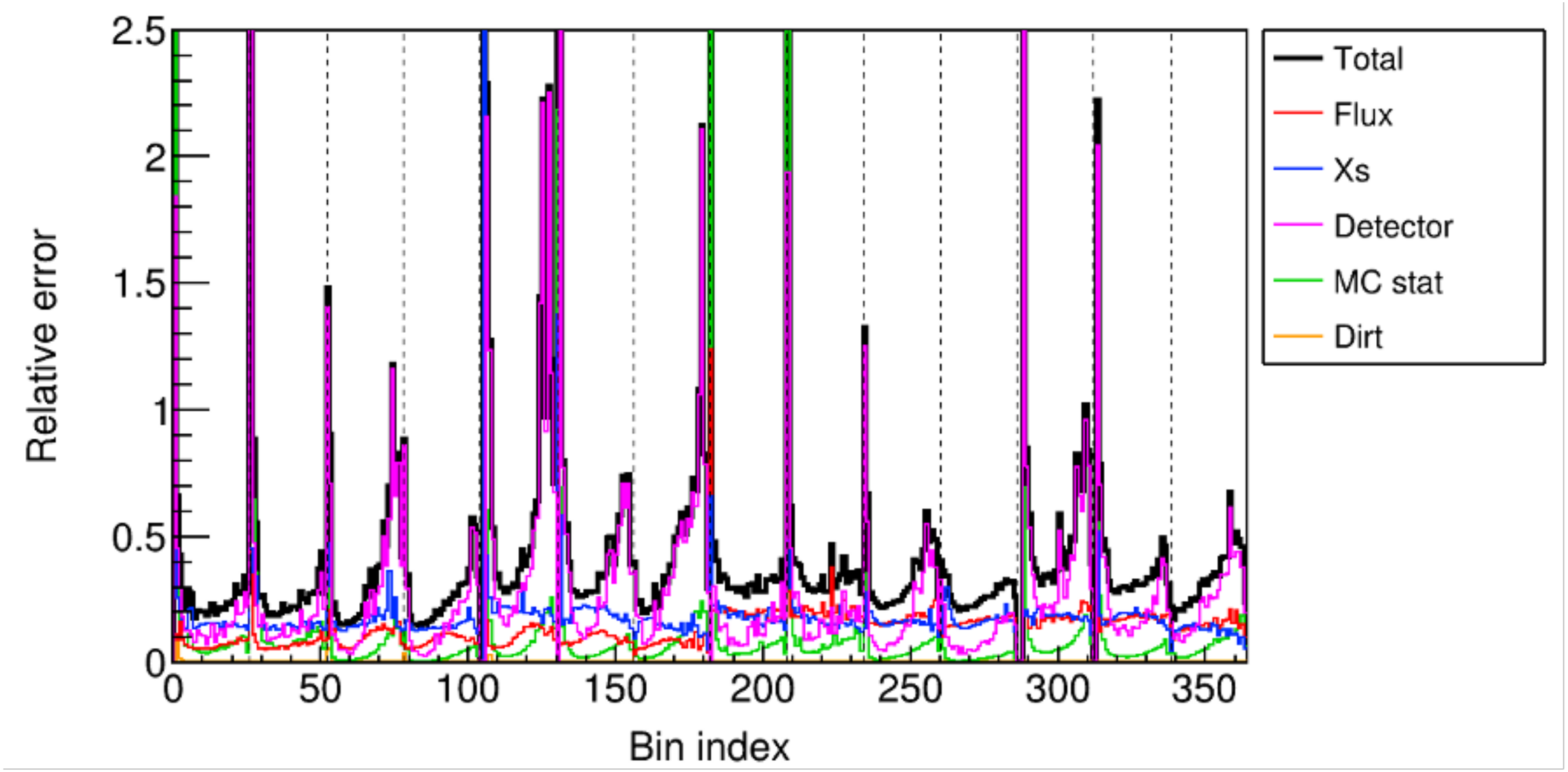
- this means our data is very simil
conservative covariance expect



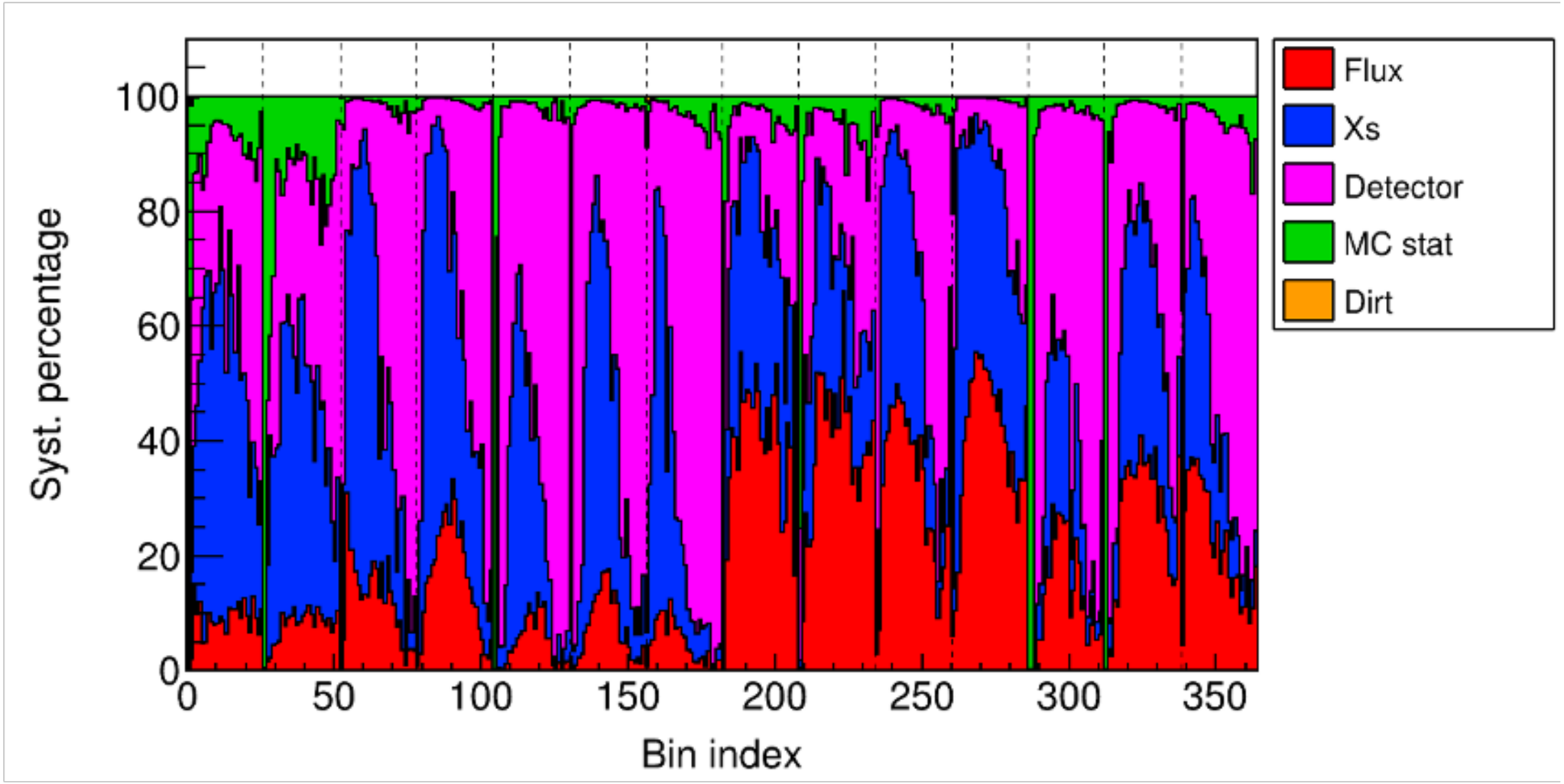
Systematics (BNB)



Systematics (BNB+NuMI)



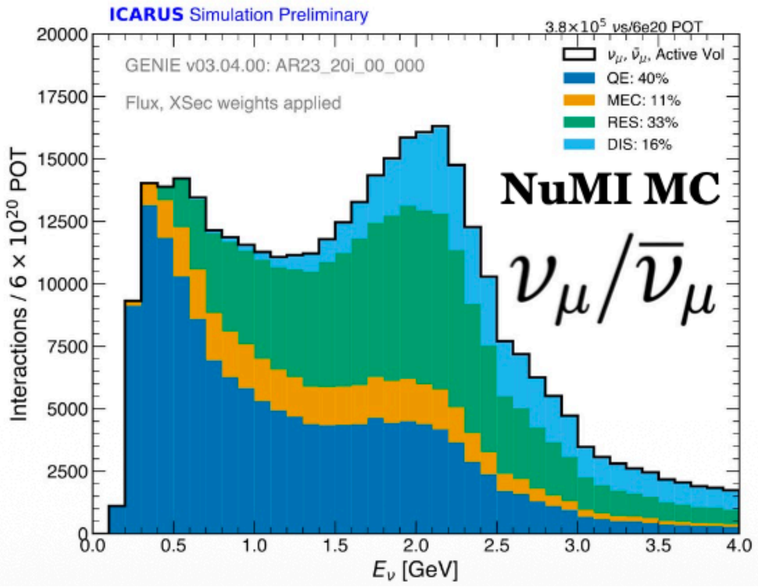
Error budget for BNB and NuMI

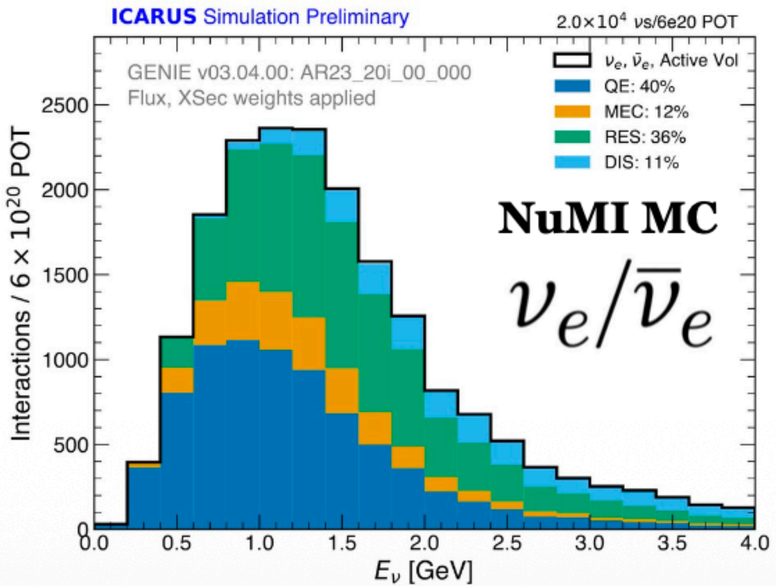


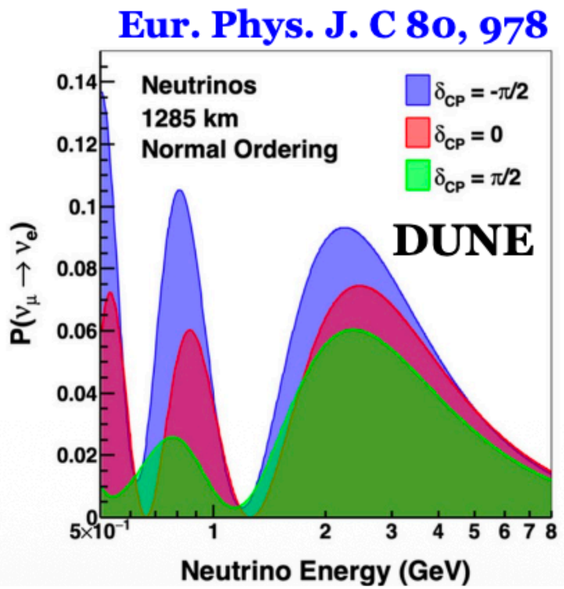
Cross Section Physics Overview

slide credit: M. Mooney (Nu2026)

- Large dataset from NuMI beam for cross section measurements:
  - Muon neutrinos/antineutrinos: **~380k** CC events for 6×10^{20} POT
  - Electron neutrinos/antineutrinos: **~20k** CC events for 6×10^{20} POT ← **~5% of NuMI**
- Relevant for first oscillation maximum of DUNE (high neutrino energy, low L/E)



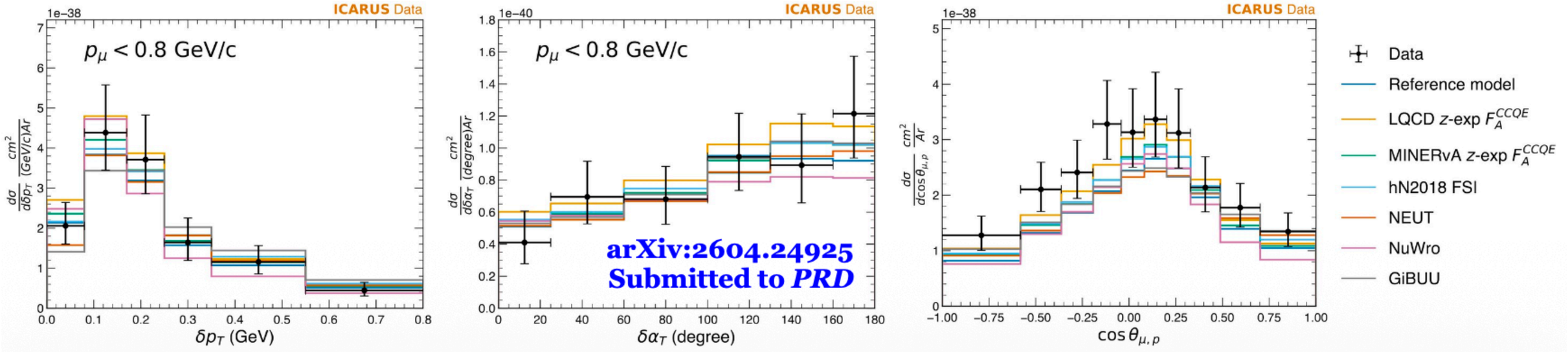




Cross Section Result: 1uNp0pi

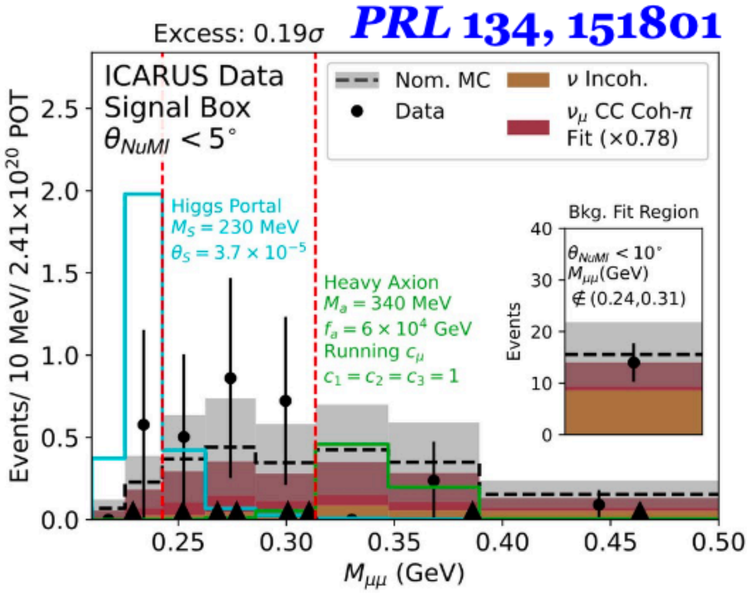
slide credit: M. Mooney (Nu2026)

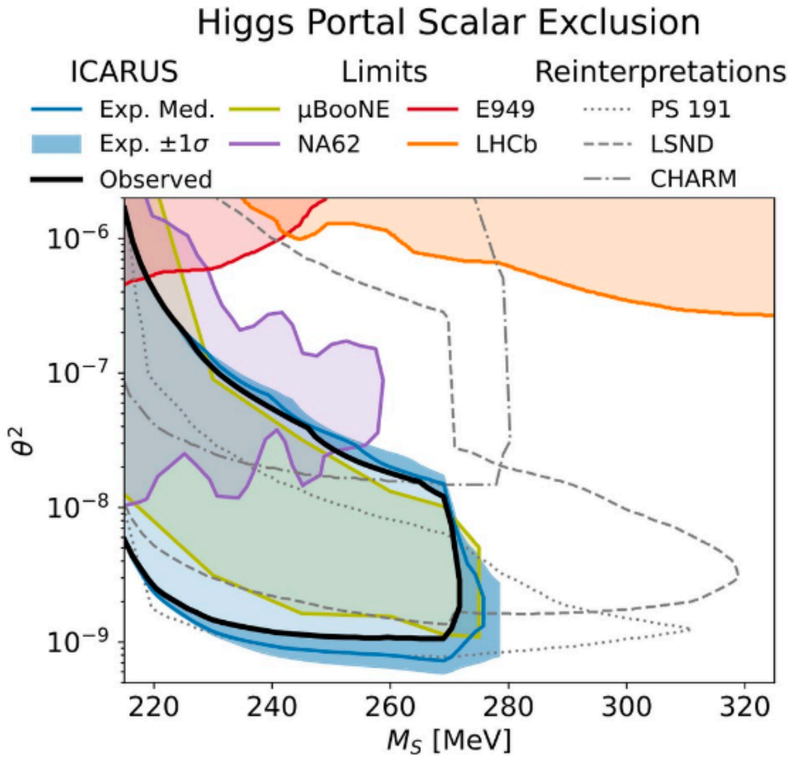
- First NuMI cross section measurement: **1μNp0π** final state (probes QE, 2p2h)
  - Require one muon (p_μ > 226 MeV/c), *at least* one proton (0.4 < p_p < 1.0 GeV/c)
- Probed observables include transverse kinematic variables, μ-p opening angle
- Reported cross sections are consistent with various modeling predictions
  - Follow-up analysis underway with improved detector systematics and more data

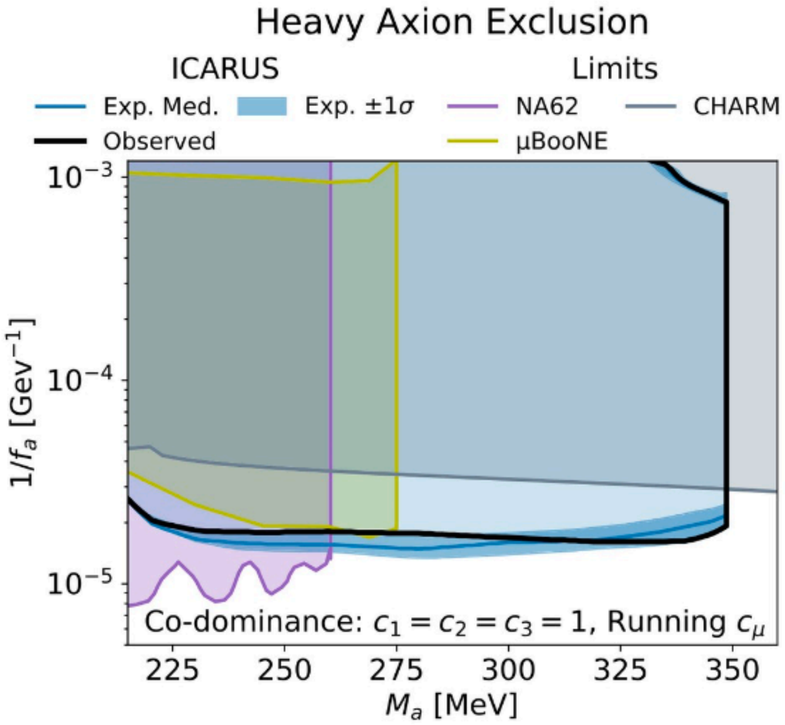


HPS/ALP Search Results

slide credit: M. Mooney (Nu2026)







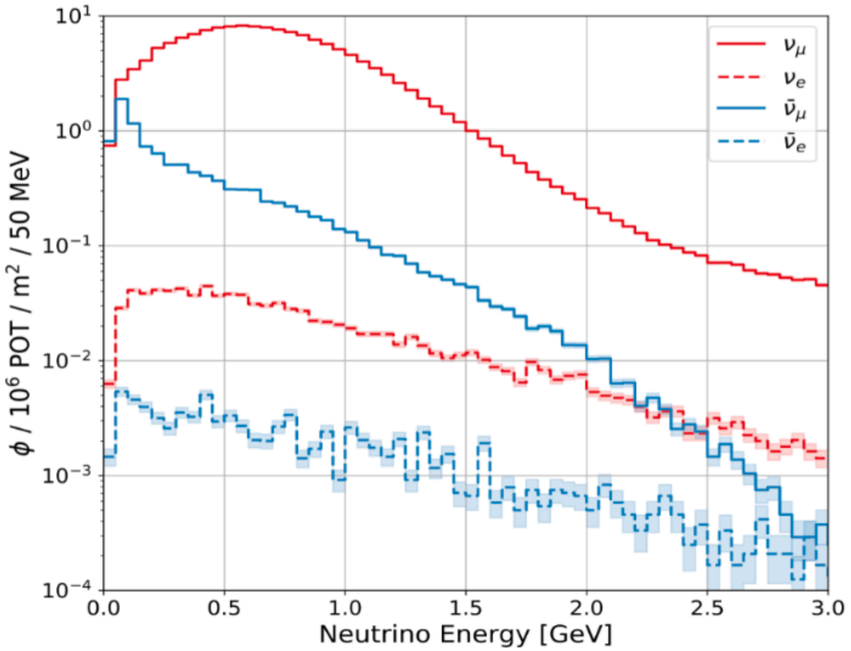
- Look for resonance at specific value of M(μμ) → **no BSM signal observed**
- **Additional analyses in pipeline:** non-contained μ+μ, μ+π, final states that involve showers (e/γ); use of SPINE ML to improve reconstruction efficiency

SBND: Short Baseline Neutrino Detector

slide credit: L. Wan (Nu2026)

Beam composition:

ν_μ (93.6%) $\bar{\nu}_\mu$ (5.9%) $\nu_e + \bar{\nu}_e$ (0.5%)

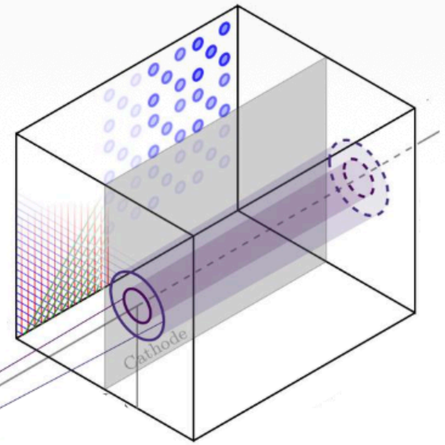


Detected mean ν_μ energy: ~0.8 GeV

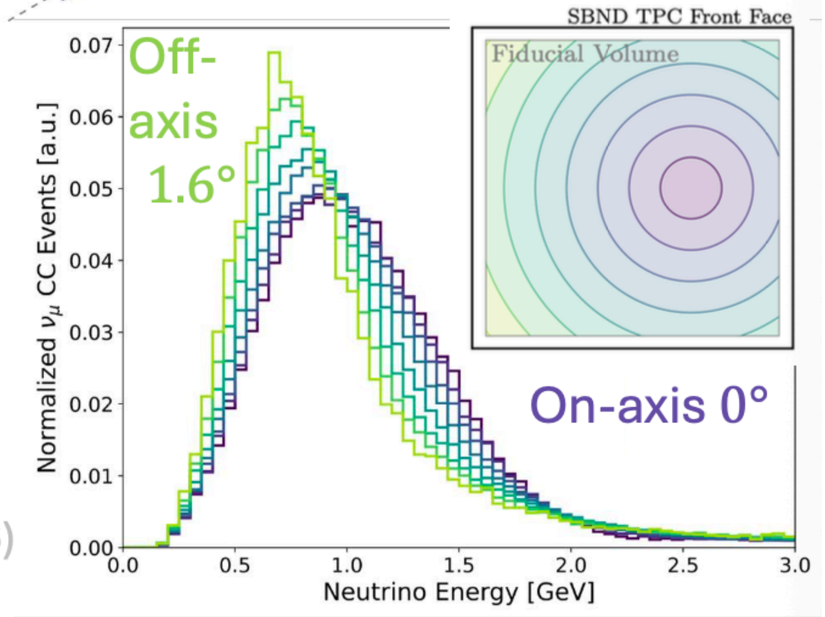
ν interactions per day: 12,000

PRISM

SBND's proximity to beam target provides a high neutrino flux and a range of flux angles to sample from.



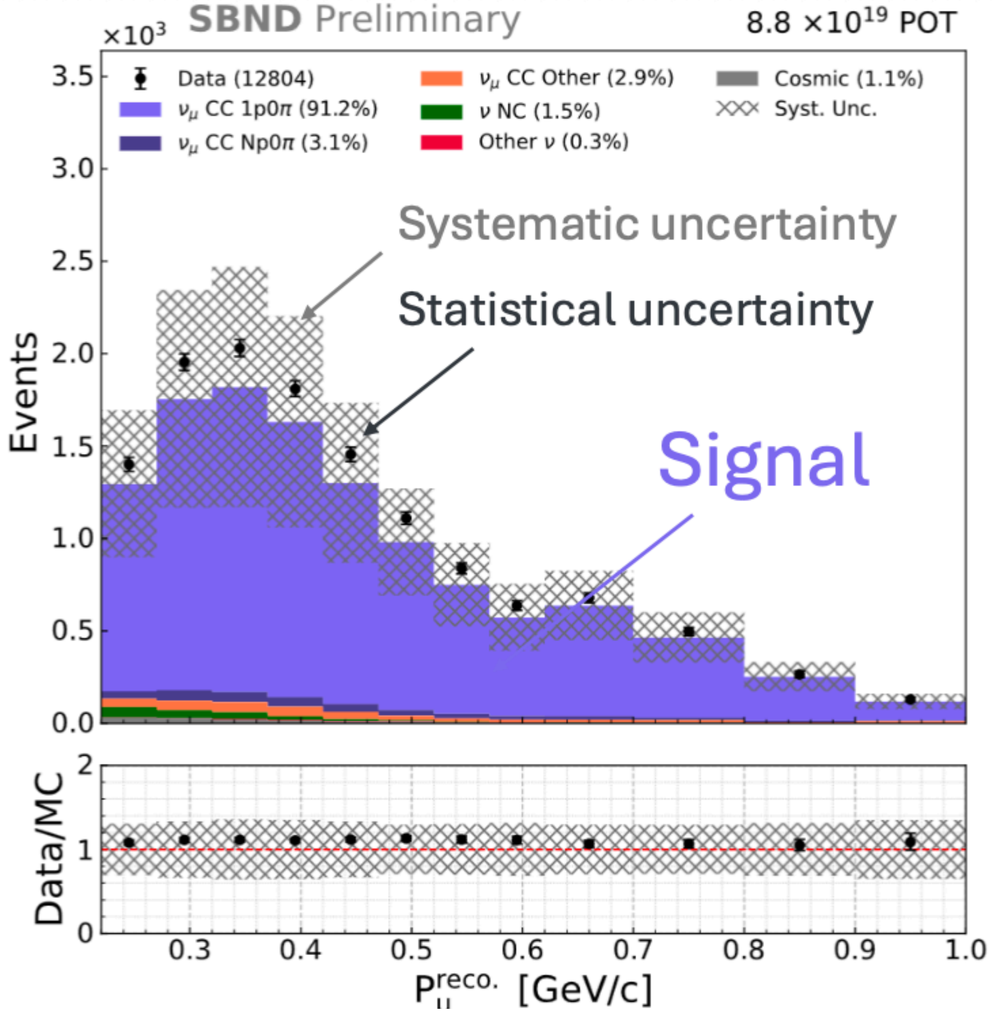
Beam direction



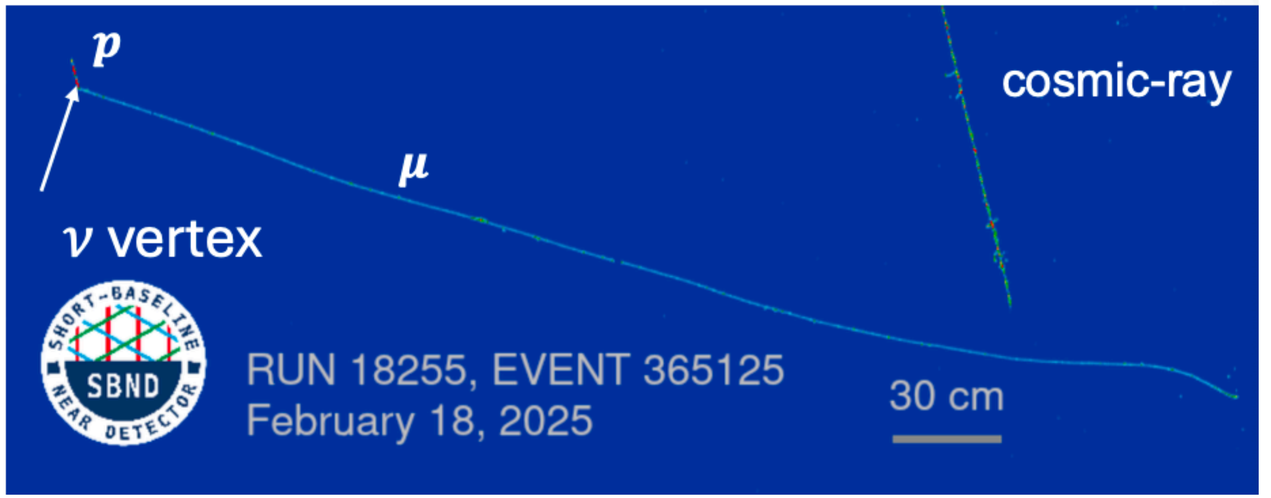
SBND PRISM
Phys.Rev.D 113 (2026) 7, 072007

ν_μ Charged Current 1u1p selection

slide credit: L. Wan (Nu2026)

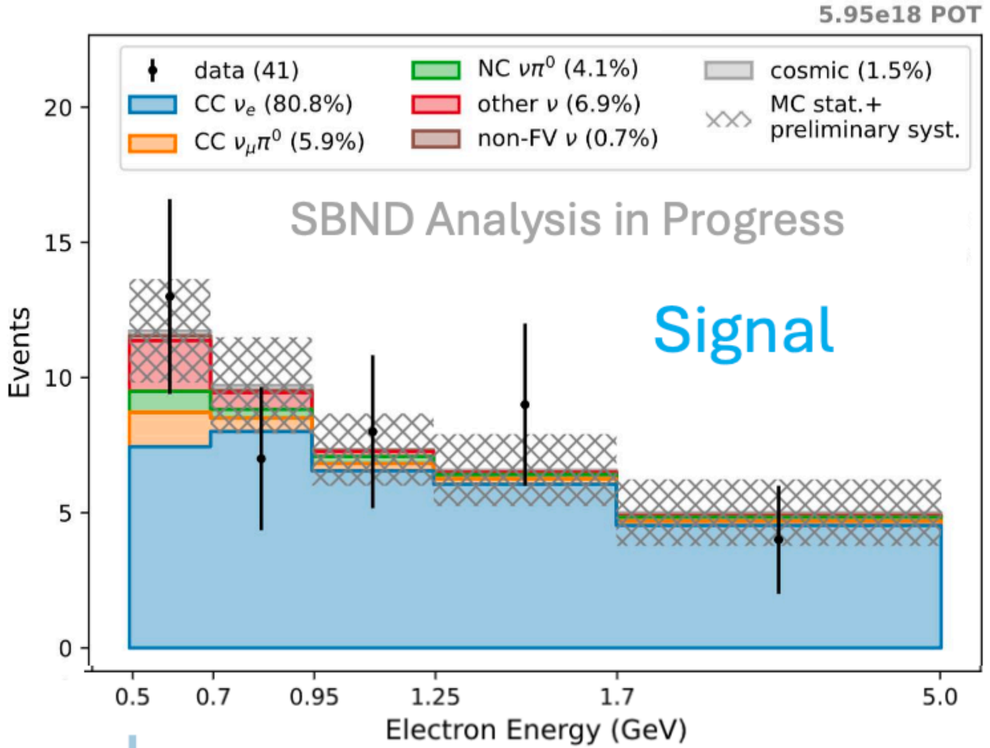


- Sample purity: 91%
- Selection efficiency: 38%
- 12k selected events collected in 2 months (15% of data collected so far)



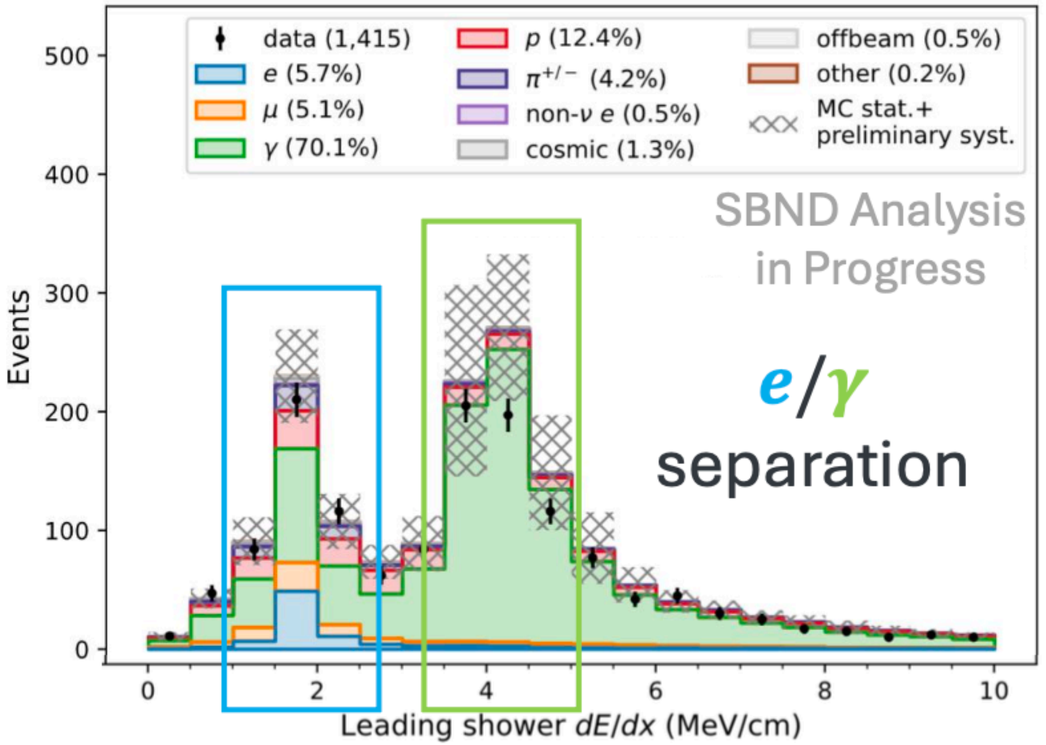
ν_e Inclusive Selection

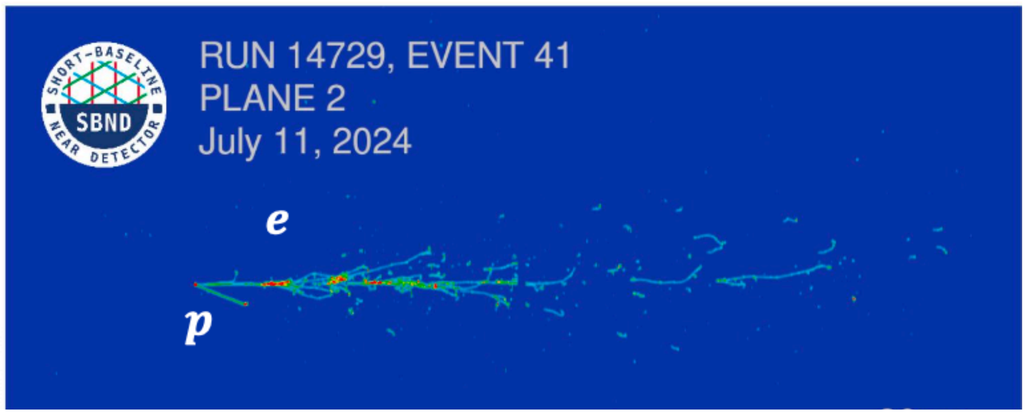
slide credit: L. Wan (Nu2026)



0.5 GeV threshold to avoid unblinding LEE

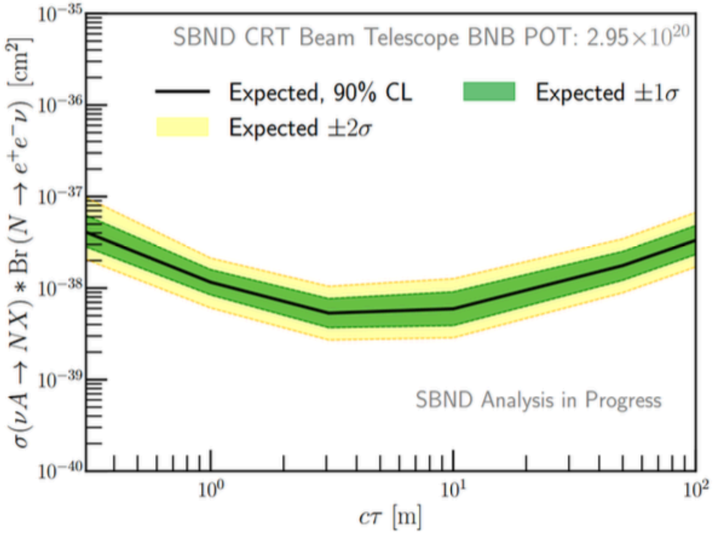
- Integrated purity: 81%
- Integrated efficiency: 26%
- Expect >10k events in 3-year SBND data



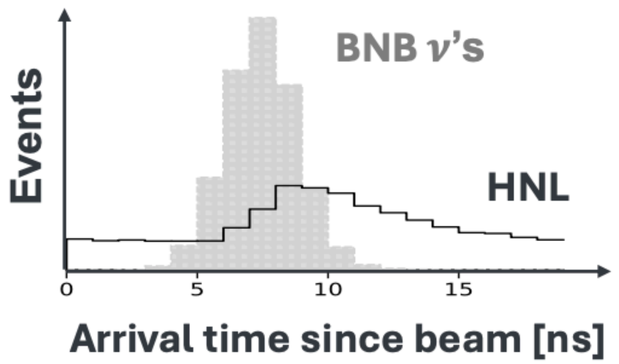


slide credit: L. Wan (Nu2026)

Searching for New Physics



SBND is sensitive to BSM physics such as **H**eavy **N**eutral **L**epton with the high-precision timing and high flux.



Prior to SBND data-taking, we conducted a search for **Long-Lived Particles** using SBND CRT with high sensitivities.
Data result coming soon!

MeVPrtl BSM generator arXiV: 2605.11321

