

Toward a Robust Confirmation or Refutation of the Sterile-Neutrino Explanation of Short-Baseline Anomalies

Ohana Benevides Rodrigues^{1,*}, Matheus Hostert^{2,†}, Kevin J. Kelly^{3,‡}, Bryce Littlejohn^{1,§},
 Pedro A. N. Machado^{4,||}, Ibrahim Safa^{5,¶} and Tao Zhou^{3,**}

¹*Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616, USA*

²*Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts 02138, USA*

³*Department of Physics and Astronomy, Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*

⁴*Theoretical Physics Department, Fermilab, P.O. Box 500, Batavia, Illinois 60510, USA*

⁵*Columbia University, New York, New York 10027, USA*



(Received 25 March 2025; accepted 1 August 2025; published 19 August 2025)

The sterile neutrino interpretation of the LSND and MiniBooNE neutrino anomalies is currently being tested at three liquid argon detectors: MicroBooNE, SBND, and ICARUS. It has been argued that a degeneracy between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_e$ oscillations significantly degrades their sensitivity to sterile neutrinos. Through an independent study, we show two methods to eliminate this concern. First, we resolve this degeneracy by including external constraints on ν_e disappearance from the PROSPECT reactor experiment. Second, by properly analyzing the full three-dimensional parameter space, we demonstrate that the stronger-than-sensitivity exclusion from MicroBooNE alone already covers the entire 2σ preferred regions of MiniBooNE at the level of $2 - 3\sigma$. We show that upcoming searches at SBND and ICARUS can improve on this beyond the 4σ level, thereby providing a rigorous test of short-baseline anomalies.

DOI: [10.1103/4fn7-svnh](https://doi.org/10.1103/4fn7-svnh)

Introduction—For decades, some neutrino experiments have hinted at the incompleteness of the three-neutrino paradigm. In one case, the MiniBooNE experiment (MB) observed a significant, 4.8σ , excess of electron-neutrino-like events at low energies [1], still unresolved [2–5]. This unexplained excess has prompted extensive theoretical and experimental investigations [6] and bears significant implications for particle physics and cosmology. The simplest interpretation of MB involves eV-scale sterile neutrinos—gauge-singlet fermions that mix with active neutrinos driving short-baseline oscillations. This interpretation connects MB to a previously observed anomaly at the Liquid Scintillator Neutrino Detector (LSND) experiment [7], a

3.8σ excess of $\bar{\nu}_e$ events in a neutrino source from μ^+ decays at rest. While global fits have established a tension between these anomalies and several other neutrino experiments [8–10], direct tests of MB using similar neutrino beams can still provide valuable insights.

The MicroBooNE experiment (μB) was specifically designed to test MB using the superior particle identification capabilities of liquid argon time projection chamber (LArTPC) technology [11]. Operating in the same neutrino beam as MB, the Booster Neutrino Beam (BNB), μB can distinguish electronlike events from other backgrounds (e.g., γ/π^0 signatures) with unprecedented precision [12–16]. This enhanced background discrimination significantly reduces systematic uncertainties associated with photon-related backgrounds, an important source of uncertainty for MB [3,17].

Recent sterile-neutrino analyses have supported the idea that μB data remain compatible with MB’s allowed region [18–20]. Three sterile-neutrino parameters govern oscillations relevant to MB and μB : two mixing angles and a mass-squared splitting Δm_{41}^2 . The mixing elements U_{e4} and $U_{\mu 4}$ individually control ν_e and ν_μ disappearance, while their product determines the appearance probability through $\sin^2(2\theta_{\mu e}) \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$. The copious ν_μ events are often used as a control sample to mitigate flux and cross section uncertainties. However, the Booster Neutrino Beam contains an intrinsic component of ν_e (0.5%),

* Contact author: obenevidesrodrigues@iit.edu

† Contact author: mhostert@g.harvard.edu

‡ Contact author: kjkelly@tamu.edu

§ Contact author: blittlej@iit.edu

|| Contact author: pmachado@fnal.gov

¶ Contact author: isafa94@gmail.com

** Contact author: taozhou@tamu.edu

providing significant background to appearance searches. This introduces an inescapable degeneracy between $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_e \rightarrow \nu_\mu$ disappearance signals for some combination of mixing parameters.

We show here that, when profiling over a multidimensional parameter space and showing allowed regions in $\sin^2(2\theta_{\mu e})$ versus Δm_{41}^2 , comparisons between different experiments can be misleading. Difficulties arise from the fact that, for a single value of $\sin^2(2\theta_{\mu e})$, two experiments' underlying best-fit parameters $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ need not be the same. Global-fit sterile-neutrino analyses are sensitive to clarifying this when the datasets considered are mutually consistent; however, this relies on phenomenological combinations of numerous experiments. In this work, we focus only on μ B as it provides a direct test, and we show that μ B *alone* is already able to probe the $3 + 1$ -oscillation at a meaningful level (see the End Matter for a description of the datasets and simulations used here).

We demonstrate that μ B demonstrates stronger tensions with MB than previously recognized by examining the full three-dimensional parameter space ($|U_{e4}|^2$, $|U_{\mu 4}|^2$, Δm_{41}^2). Our analysis accounts for how these parameters influence the control sample and background predictions in MB and μ B. We observe that μ B disfavors MB's entire 2σ preferred region at more than 95% confidence level (CL) when properly accounting for all parameter correlations. We also examine how sterile-neutrino exclusion is improved when considering electron-flavor disappearance data from the reactor-based PROSPECT constraints and future data from the short baseline neutrino (SBN) program—both in terms of profiled $\sin^2(2\theta_{\mu e})$ - Δm_{41}^2 space and the full parameter space.

Short-baseline oscillations and degeneracies—The sterile neutrino interpretation of MB requires extending the three-neutrino framework to include a fourth state. At short baselines, the oscillation probabilities in this framework are simple; the appearance probability is

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right), \quad (1)$$

while for disappearance it is

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right), \quad (2)$$

where $\sin^2(2\theta_{\alpha\alpha}) \equiv 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$ for $\alpha = e, \mu$.

In short-baseline oscillation experiments, such as MB and μ B, intrinsic ν_e backgrounds are affected by the same mixing parameters that control appearance. The ν_e disappearance probability scales with U_{e4} , partially compensating any appearance signal. Additionally, the ν_μ flux used to predict the appearance signal is inferred from ν_μ measurements, which themselves can be depleted by oscillations from nonzero $U_{\mu 4}$. This interplay between appearance, disappearance, and flux determination introduces degeneracies with

(potentially) different manifestations in each experiment's parameter space.

A detector's technology can also lead to different background compositions. MB's Cherenkov detector cannot distinguish electrons from single photons that convert to e^+e^- pairs inside the fiducial volume, making $\pi^0 \rightarrow \gamma\gamma$ and $\Delta(1232) \rightarrow \gamma N$ significant backgrounds. The LArTPC technology of μ B distinguishes electrons from photons using the presence of a gap between the event vertex and the electromagnetic shower, and the ionization yield in the first few centimeters of the shower, substantially reducing photon-related backgrounds. These different background compositions translate into different degeneracies in the sterile neutrino parameter space, which is crucial for estimating the compatibility between these two experiments.

Pitfalls of projection—Traditional sterile neutrino searches for anomalous $\nu_\mu \rightarrow \nu_e$ appearance—particularly LSND, MB, and μ B—present their results in the $\sin^2(2\theta_{\mu e})$ – Δm_{41}^2 plane (e.g., see Fig. 1). While optimal for experiments that are sensitive almost exclusively to $\nu_\mu \rightarrow \nu_e$ appearance signals (e.g., LSND), this projection obscures important physical effects in experiments with significant neutrino-related backgrounds (MB/ μ B). The latter are sensitive not just to the appearance product $4|U_{e4}|^2|U_{\mu 4}|^2$ but also to individual mixing elements through ν_μ disappearance in flux-normalizing control samples and ν_e disappearance in backgrounds. Because of this scaling, a small appearance signal is

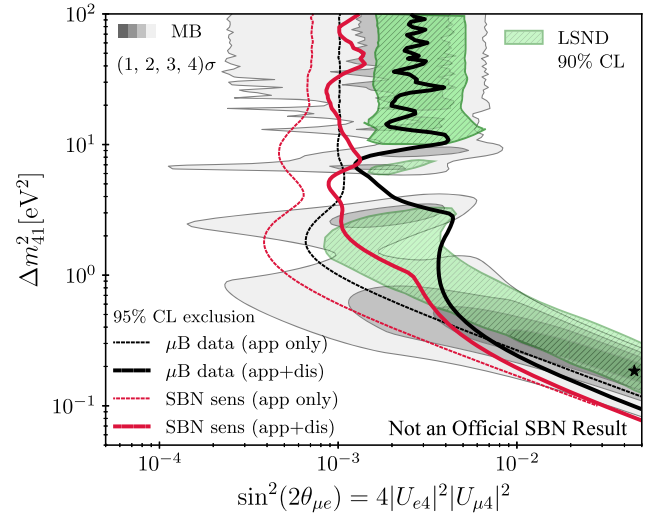


FIG. 1. Sterile neutrino parameter space and $1 - 4\sigma$ preferred regions of MiniBooNE (gray) and 90% CL region of LSND (green) along with 95% CL MicroBooNE exclusion (black lines) and SBN sensitivity (red lines), assuming Wilks' theorem. Solid lines show the result of a full $3 + 1$ oscillation model and dashed lines of the common, but physically inconsistent, appearance-only model. The MiniBooNE fit is shown for the full oscillation model. For LSND, they are approximately the same. Apparent compatibility between experiments is a potential artifact of the projection into the appearance mixing angle.

typically accompanied by much larger disappearance effects. This leads to a nontrivial degeneracy among the mixing elements and the appearance amplitude.

Figure 1 illustrates the impact of the above degeneracy: μ B and SBN sensitivities assuming the unphysical scenario of appearance-only oscillations are significantly stronger than in the full $3 + 1$ model, which accounts for oscillations in the backgrounds and control sample. Within the consistent treatment of oscillations, this result naively suggests that there currently is a large parameter space where concordance between MB and μ B can be found and that SBN may not be able to cover the entire 3σ region of the MB parameter space at more than 95% CL. However, as we show below, this conclusion is incorrect.

One avenue to avoid such degeneracy is including data from a neutrino source with a different ν_e/ν_μ flavor ratio composition. This is present in the neutrinos at the main injector (NuMI) beam and is currently being pursued by the μ B collaboration [21,22]. The measurement of this flux at MiniBooNE [23] has even already been used to constrain oscillations in Ref. [9]. With a larger ν_e/ν_μ flavor ratio, appearance and disappearance signals can be directly constrained, and parameters for which ν_e disappearance can accommodate a greater amount of $\nu_\mu \rightarrow \nu_e$ appearance in the BNB flux without leading to an observable excess would not necessarily do so for the NuMI dataset, thereby reducing the impact of the degeneracy shown in Fig. 1.

The flavor-pure flux of $\bar{\nu}_e$ emanating from a nuclear reactor also offers an opportunity for reducing this degeneracy. In Fig. 2 (top) we present the μ B exclusion in this parameter space with and without PROSPECT data. PROSPECT provides direct constraints on $|U_{e4}|^2$ through searches for short-baseline $\bar{\nu}_e$ disappearance. The combination of appearance and disappearance experiments naturally resolves the degeneracy in the $3 + 1$ framework by directly imposing a limit on the amount of ν_e disappearance that is permissible in the intrinsic background, effectively removing the possibility of hiding appearance signals. Combined with PROSPECT, the BNB experimental searches recover their constraining power in the traditional profiled parameter space of Figs. 1 and 2.

External PROSPECT constraints accentuate the difference between μ B's sensitivity and exclusion: the constraint on $\sin^2(2\theta_{\mu e})$ for some values of Δm_{41}^2 is almost an order of magnitude stronger than the expected sensitivity. This is due to three contributing factors. First, the observed excess of ν_μ events at μ B disfavors ν_μ disappearance. Second (more importantly), the accompanying observed deficit of ν_e events leaves less room for $\nu_\mu \rightarrow \nu_e$ appearance. Finally, accounting for external constraints from PROSPECT, any amount of $\nu_\mu \rightarrow \nu_e$ appearance is strongly disfavored.

We choose to include the PROSPECT experiment in this way to demonstrate how, with only a single additional experiment, the “expected” constraining power in the traditional parameter space is recovered. At larger values

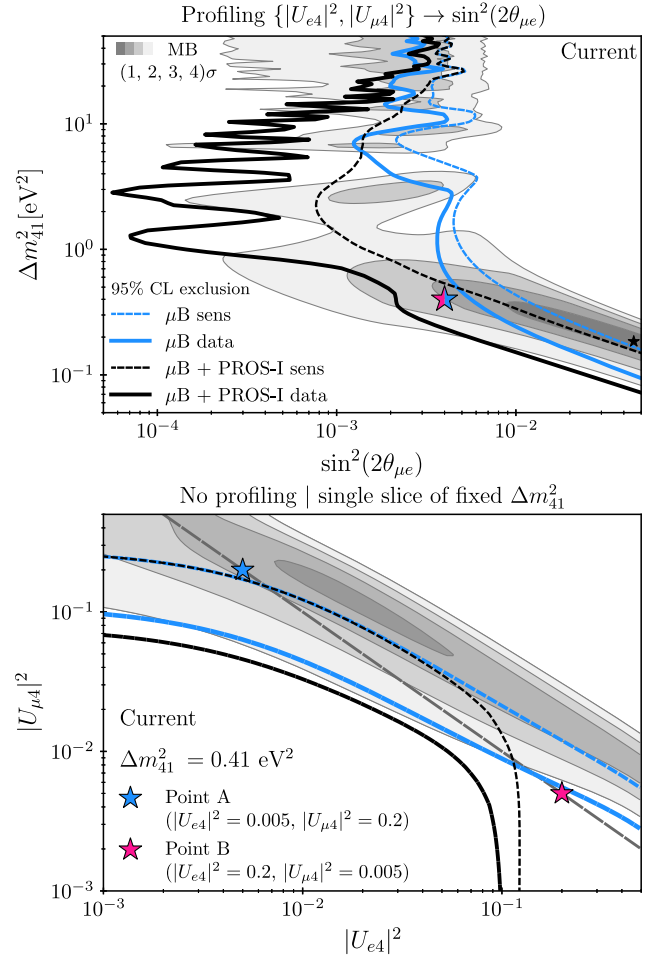


FIG. 2. Top: typical sterile-neutrino parameter space presentation, comparing the MiniBooNE-preferred regions (gray), with 95% CL sensitivity (exclusion) of MicroBooNE in blue (+ PROSPECT in black), assuming Wilks' theorem. Exclusions (data) are presented as thick, solid lines; sensitivities are with thin, dashed lines. Bottom: slice of $\Delta m_{41}^2 = 0.41 \text{ eV}^2$ parameter space, allowing $\{|U_{e4}|^2, |U_{\mu 4}|^2\}$ to vary independently *before* profiling. Blue point (A) and red point (B) stars both correspond to $\sin^2(2\theta_{\mu e}) = 4 \times 10^{-3}$ in the top panel. Despite this angle not being covered by μ B in the profiled space, top panel, the line that it represents in the bottom panel contains no points compatible with *both* MB and μ B.

of $\Delta m_{41}^2 \gtrsim 4 \text{ eV}^2$, leading constraints on $|U_{e4}|^2$ come from the KATRIN experiment [24–26] and could be included in a similar way. External constraints on $|U_{\mu 4}|^2$ from, e.g., MINOS and MINOS + [27] and NOvA [28], could also be included. However, our findings show that this is not required and that the large intrinsic ν_μ rate from the BNB already provides μ B with some sensitivity to ν_μ disappearance [18].

Apart from adding new datasets, another way to confront this degeneracy is to investigate the parameter space without relying on profiling. To illustrate this point, we take two benchmark points with the same appearance angle

$\sin^2(2\theta_{\mu e}) = 0.004$ and mass splitting $\Delta m_{41}^2 = 0.41 \text{ eV}^2$ but different mixing patterns: point (A) $|U_{e4}|^2 = 0.005$ and $|U_{\mu 4}|^2 = 0.2$ and point (B) $|U_{e4}|^2 = 0.2$ and $|U_{\mu 4}|^2 = 0.005$. In the top panel of Fig. 2, these two points appear as the half-blue-half-pink star, apparently compatible both with MB's preference for the existence of a sterile neutrino and with μB 's null result—according to the profiled parameter space, μB lacks the statistical power to meaningfully exclude this point. However, in the fixed- Δm_{41}^2 slice of the parameter space in the bottom panel, these two points are distinct, and neither of them is simultaneously compatible with MB and μB . The entire dashed gray line where $\sin^2(2\theta_{\mu e}) = 0.004$ in the slice panel collapses onto the star of the profiled plane, but nowhere along it can the preference regions of MB and μB be simultaneously satisfied.

While our benchmark points (A) and (B) yield identical $\sin^2(2\theta_{\mu e})$, they produce distinct event rates in the ν_μ and ν_e samples. This is explicitly shown in Fig. 5 of the End Matter, where we compare predicted event spectra for μB 's ν_e and ν_μ samples, as well as MB electronlike events. The relatively large $|U_{\mu 4}|^2$ of point (A) is disfavored by μB as it significantly affects the ν_μ channel. Point (B), conversely, has a smaller $|U_{\mu 4}|^2$, barely changing ν_μ disappearance, and is allowed by μB data. Nevertheless, the larger $|U_{e4}|^2$ leads to too much disappearance of the intrinsic ν_e background, not providing enough electronlike events to be favored by MB.

The aforementioned degeneracy is effectively broken, and a fundamental tension between μB and MB is revealed in the full three-dimensional parameter space that would otherwise remain obscured in profiled comparisons. This point is demonstrated by Fig. 2 (bottom) for a specific choice of Δm_{41}^2 and is generalized for the broader parameter space in Fig. 4 of the End Matter, where we show more parameter-space slices. While the profiled space provides a picture of potential consonance between MB and μB at the chosen Δm_{41}^2 , the full space in Fig. 2 shows no overlap between the μB 95% CL allowed region and MB's 3σ allowed region. Adding PROSPECT excludes all of MB's 4σ allowed region at this Δm_{41}^2 . Across the full phase space, we observe that no single combination of mixing parameters in the $3+1$ scenario can simultaneously explain MB's excess at 2σ while remaining consistent with μB 's observations at the same CL.

Future projections—With future data from SBND and ICARUS, the capability to exclude MB -preferred parameter space is even stronger. To simulate these, we make the simplified assumption that SBND and ICARUS will have the same signal efficiency as μB , as well as the same number of backgrounds per neutrino per fiducial mass. This is a conservative estimate, as SBND and ICARUS are expected to improve upon detector performance, event reconstruction, and analysis techniques [29,30]. With our procedure, SBND

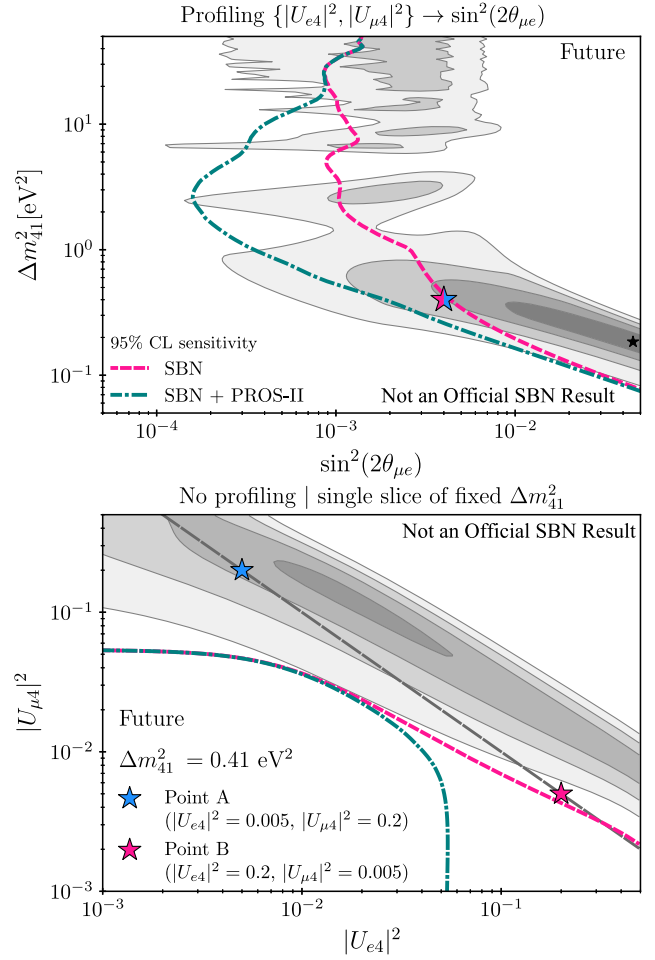


FIG. 3. Same as Fig. 2, focusing on future projections of SBN (pink) and SBN + PROSPECT-II (green) capabilities.

and ICARUS share the same energy binning and resolution as the μB analysis discussed above. We take the fiducial mass to be 112 and 476 t of liquid argon for SBND and ICARUS, respectively, with a total exposure of 6.6×10^{20} POT. The neutrino flux at the location of SBND and ICARUS is rescaled from the μB flux by an overall energy-independent factor of $(L_{\mu\text{B}}/L_{\text{SBND/ICARUS}})^2$, where $L_{\text{SBND}} = 110 \text{ m}$, $L_{\text{ICARUS}} = 600 \text{ m}$, and $L_{\mu\text{B}} = 470 \text{ m}$ are the approximate detector distances to the target. More details can be found in the End Matter. Projecting forward, we also consider future reactor antineutrino observations from PROSPECT-II. We use $\Delta\chi^2$ maps provided by the collaboration that describe the expected sensitivity of a two-year run at HFIR with an upgraded detector [31].

Figure 3 presents the same comparison of MB -preferred parameter space against future projections including SBN and additionally PROSPECT-II. In the top panel, the (misleading) profiling of $\{|U_{e4}|^2, |U_{\mu 4}|^2\} \rightarrow \sin^2(2\theta_{\mu e})$ portrays sensitivity that is not as impressive as one would hope—the SBN-only and SBN + PROSPECT-II projections only demonstrate modest improvement on the current

μB and $\mu\text{B} + \text{PROSPECT}$ results [32]. By contrast, when we focus on the sliced parameter space (bottom panel of Fig. 3 along with projections in Fig. 4 of the End Matter), future improvements are obvious. Across the three-dimensional parameter space, SBN and PROSPECT-II will thoroughly explore the MB -preferred parameter space.

An alternative metric to quantify the power of μB relative to the preferred parameter space of MB, as well as the future potential of SBN, is presented in Fig. 7 of the End Matter—we determine that μB excludes MB’s entire 2.3σ CL preferred region at more than the same confidence and that SBN has $> 3\sigma$ CL sensitivity to all of MB’s 3σ CL preferred parameter space.

Discussion—We have presented two complementary arguments showing how MicroBooNE has and the SBN program will robustly cover the sterile neutrino interpretation of the LSND and MiniBooNE anomalies. This is the first time that the MicroBooNE exclusion and the SBN sensitivities are shown throughout the full $3 + 1$ -oscillation model without resorting to profiling. In this full oscillation model, the coexistence of a $\nu_\mu \rightarrow \nu_e$ appearance signal and the disappearance of ν_e backgrounds and ν_μ in the control sample leads to degeneracies and an apparent loss of sensitivity to the model in the plane of $\sin^2(2\theta_{\mu e})$ vs Δm_{41}^2 , after profiling. We conclude, however, that when comparing allowed experimental regions *before* profiling, this effect does not substantially diminish the exclusion power of μB data—we achieved this by generalizing the MiniBooNE, MicroBooNE, and SBN fits to slices of the full three-dimensional parameter space: $(|U_{e4}|^2, |U_{\mu 4}|^2, \Delta m_{41}^2)$. Exploring the full three-dimensional parameter space provides qualitatively different conclusions. For this reason, we urge all experiments that are sensitive to multiple oscillation parameters to make their full multidimensional χ^2 maps available, including MiniBooNE, to enable these compatibility comparisons in the future by the SBN program.

Even in the profiled case, we show that the degeneracy in μB data can be avoided altogether by incorporating strong constraints on ν_e disappearance from the flavor-pure PROSPECT reactor neutrino dataset. Besides PROSPECT, constraints on electron-flavor disappearance from μB ’s NuMI beam datasets [21,22] or other ν_e -dominant approaches [26,33–36], while not examined here, can play a complementary role. When examining the full three-dimensional oscillation phase space, PROSPECT data unsurprisingly serve as the strongest constraint on large $|U_{e4}|^2$ values. We note that this collection of results strongly disfavors a $3 + 1$ oscillation interpretation of the anomalous results of BEST [37] and other gallium experiments [38–41].

Acknowledgments—We thank Joachim Kopp for comments on this manuscript. The work of M. H. is supported by the Neutrino Theory Network Program Grant No. DE-AC02-07CH11359 and the U.S. DOE Award No. DE-SC0020250. K. J. K. and T. Z. are supported in part by

U.S. DOE Award No. DE-SC0010813. O. B. R. and B. R. L. are supported by U.S. DOE Award No. DE-SC0008347. The work of I. S. was supported by the National Science Foundation Award No. PHY-2310080. This manuscript has been authored by Fermi Forward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work was performed in part at Aspen Center for Physics, which is supported by National Science Foundation Grant No. PHY-2210452. This work is not an official MicroBooNE, SBND, or ICARUS result.

Data availability—The data that support the findings of this Letter are openly available [42].

-
- [1] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. D* **103**, 052002 (2021).
 - [2] R. J. Hill, *Phys. Rev. D* **81**, 013008 (2010).
 - [3] R. J. Hill, *Phys. Rev. D* **84**, 017501 (2011).
 - [4] V. Brdar and J. Kopp, *Phys. Rev. D* **105**, 115024 (2022).
 - [5] K. J. Kelly and J. Kopp, *J. High Energy Phys.* **05** (2023) 113.
 - [6] M. A. Acero *et al.*, *J. Phys. G* **51**, 120501 (2024).
 - [7] A. Aguilar *et al.* (LSND Collaboration), *Phys. Rev. D* **64**, 112007 (2001).
 - [8] M. Dentler, A. Hernández-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, and T. Schwetz, *J. High Energy Phys.* **08** (2018) 010.
 - [9] A. Diaz, C. A. Argüelles, G. H. Collin, J. M. Conrad, and M. H. Shaevitz, *Phys. Rep.* **884**, 1 (2020).
 - [10] S. Böser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens, A. Schukraft, and M. Wurm, *Prog. Part. Nucl. Phys.* **111**, 103736 (2020).
 - [11] R. Acciarri *et al.* (MicroBooNE, LAr1-ND, ICARUS-WA104 Collaborations), *arXiv:1503.01520*.
 - [12] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **128**, 111801 (2022).
 - [13] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **128**, 241801 (2022).
 - [14] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. D* **105**, 112005 (2022).
 - [15] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. D* **105**, 112003 (2022).
 - [16] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. D* **105**, 112004 (2022).
 - [17] E. Wang, L. Alvarez-Ruso, and J. Nieves, *Phys. Lett. B* **740**, 16 (2015).
 - [18] C. A. Argüelles, I. Esteban, M. Hostert, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez, *Phys. Rev. Lett.* **128**, 241802 (2022).
 - [19] P. B. Denton, *Phys. Rev. Lett.* **129**, 061801 (2022).
 - [20] P. Abratenko *et al.* (MicroBooNE Collaboration), *Phys. Rev. Lett.* **130**, 011801 (2023).
 - [21] MicroBooNE Collaboration, Updates to the NuMI flux simulation at MicroBooNE, Technical Report MICRO-BOONE-NOTE-1129-PUB, MicroBooNE, 2024.

- [22] MicroBooNE Collaboration, Search for a sterile neutrino in a $3 + 1$ framework using wire-cell inclusive charged-current ν_e selection with the BNB and NuMI beamlines in MicroBooNE, Technical Report MICROBOONE-NOTE-1132-PUB, MicroBooNE, 2024.
- [23] P. Adamson *et al.* (MiniBooNE, MINOS Collaborations), *Phys. Rev. Lett.* **102**, 211801 (2009).
- [24] M. Aker *et al.* (KATRIN Collaboration), *Phys. Rev. Lett.* **126**, 091803 (2021).
- [25] M. Aker *et al.* (KATRIN Collaboration), *Phys. Rev. D* **105**, 072004 (2022).
- [26] H. Acharya *et al.* (KATRIN Collaboration), *arXiv:2503.18667*.
- [27] P. Adamson *et al.* (MINOS + Collaboration), *Phys. Rev. Lett.* **122**, 091803 (2019).
- [28] M. A. Acero *et al.* (NOvA Collaboration), *Phys. Rev. Lett.* **134**, 081804 (2025).
- [29] P. Abratenko *et al.* (ICARUS Collaboration), *Eur. Phys. J. C* **83**, 467 (2023).
- [30] P. Abratenko *et al.* (SBND Collaboration), *Eur. Phys. J. C* **84**, 1046 (2024).
- [31] M. Andriamirado *et al.* (PROSPECT Collaboration), *J. Phys. G* **49**, 070501 (2022).
- [32] This may, however, be driven by the fluctuations present in μB data relative to its expectations.
- [33] K. Goldhagen, M. Maltoni, S. E. Reichard, and T. Schwetz, *Eur. Phys. J. C* **82**, 116 (2022).
- [34] F. P. An *et al.* (Daya Bay Collaboration), *Phys. Rev. Lett.* **113**, 141802 (2014).
- [35] J. M. Berryman and P. Huber, *J. High Energy Phys.* **01** (2021) 167.
- [36] C. Giunti, Y. F. Li, C. A. Ternes, and Z. Xin, *Phys. Lett. B* **829**, 137054 (2022).
- [37] V. V. Barinov *et al.*, *Phys. Rev. C* **105**, 065502 (2022).
- [38] J. N. Abdurashitov *et al.* (SAGE Collaboration), *Phys. Rev. C* **59**, 2246 (1999).
- [39] J. N. Abdurashitov *et al.*, *Phys. Rev. C* **73**, 045805 (2006).
- [40] M. Altmann *et al.* (GNO Collaboration), *Phys. Lett. B* **616**, 174 (2005).
- [41] F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, *Phys. Lett. B* **685**, 47 (2010).
- [42] GitHub repository: https://github.com/kjkellyphys/muB_oscillation (2025).
- [43] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *arXiv:2110.15055*.
- [44] M. Hostert, K. J. Kelly, and T. Zhou, *Phys. Rev. D* **110**, 075002 (2024).
- [45] J. Ashenfelter *et al.* (PROSPECT Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **922**, 287 (2019).
- [46] M. Andriamirado *et al.* (PROSPECT Collaboration), *Phys. Rev. D* **103**, 032001 (2021).
- [47] M. Andriamirado *et al.* (PROSPECT Collaboration), *Phys. Rev. Lett.* **131**, 021802 (2023).
- [48] M. Andriamirado *et al.* (PROSPECT Collaboration), *Phys. Rev. Lett.* **134**, 151802 (2025).
- [49] D. Cianci, A. Furmanski, G. Karagiorgi, and M. Ross-Lonergan, *Phys. Rev. D* **96**, 055001 (2017).
- [50] P. A. Machado, O. Palamara, and D. W. Schmitz, *Annu. Rev. Nucl. Part. Sci.* **69**, 363 (2019).
- [51] The addition of PROSPECT data for improving this exclusion is only modest: $\mu\text{B} + \text{PROSPECT}$ excludes MB's entire 2.4σ (98.5% CL) at greater than the same CL. By contrast, the Asimov-expected exclusion of $\mu\text{B} + \text{PROSPECT}$ was 1.7σ (91.3% CL).

End Matter

Datasets and simulations—We analyze MB and μB using their data releases [14,43], treating backgrounds consistently within the $3 + 1$ oscillation framework. To estimate the SBN program's sensitivity, we build on our existing μB framework [18,44]. Complementary electron neutrino disappearance constraints from the PROSPECT reactor neutrino experiment are also examined in this study. PROSPECT deployed a 4-ton segmented liquid-scintillator detector target a distance of 7-9 meters from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory [45], detecting over 60,000 inverse beta decay interactions ($\bar{\nu}_e + p \rightarrow e^+ + n$) while searching for short-baseline $\bar{\nu}_e$ disappearance [46,47]. Rather than reanalyzing PROSPECT neutrino and background datasets, we use maps of $\Delta\chi^2$ versus $\sin^2(2\theta_{ee})$ and Δm_{41}^2 provided by PROSPECT in their final oscillation analysis using the full dataset from the now-decommissioned PROSPECT-I detector [48]. We make all analysis tools and results fully public in [42].

Full slices of parameter space—In this appendix we expand on the point made in the main text by showing

more slices of the three-dimensional parameter space of sterile neutrinos. We compare the MiniBooNE-preferred regions with exclusions from MicroBooNE, PROSPECT, and the sensitivity of SBN with and without PROSPECT-II in Fig. 4 using the global $\Delta\chi^2$ with 3 degrees of freedom and assuming Wilks' theorem. The result of our coverage test is validated by noting that all MiniBooNE regions are already covered by MicroBooNE at the 95% CL level, even before including PROSPECT data.

In Fig. 5, we also show the event rates for MiniBooNE (top) and MicroBooNE (middle) ν_e sample and ν_μ sample (bottom), after subtraction of misidentification backgrounds. For reference, we present the theory predictions of a sterile neutrino model for the two benchmark points shown in Figs. 2 and 3.

SBN sensitivities—To estimate the Asimov sensitivity of SBN, we use a χ^2 test statistic and model the systematic uncertainty on the BNB flux and neutrino-Argon cross sections via an approximate covariance matrix. We analyze the ν_μ and ν_e spectra of SBND and

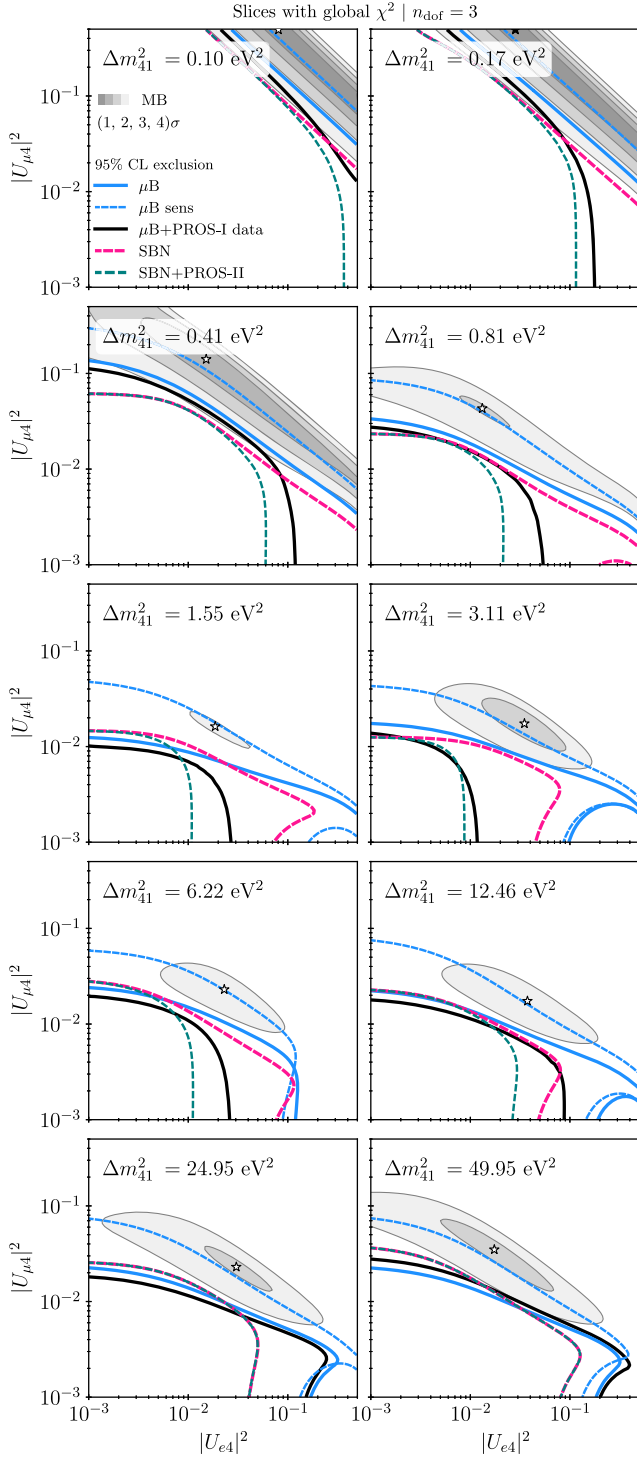


FIG. 4. MiniBooNE preferred regions, MicroBooNE exclusion, and SBN sensitivities in slices of fixed Δm_{41}^2 of the three-dimensional parameter space of sterile neutrinos for 3 degrees of freedom (global χ^2). Excluded regions are to the top right of each panel.

ICARUS together. We account for energy-dependent cross section uncertainties $\sigma_i^{\text{xs}} = 15\%$, fully correlated between ν_μ and ν_e and between SBND and ICARUS, but uncorrelated over all energies E_i . For flux

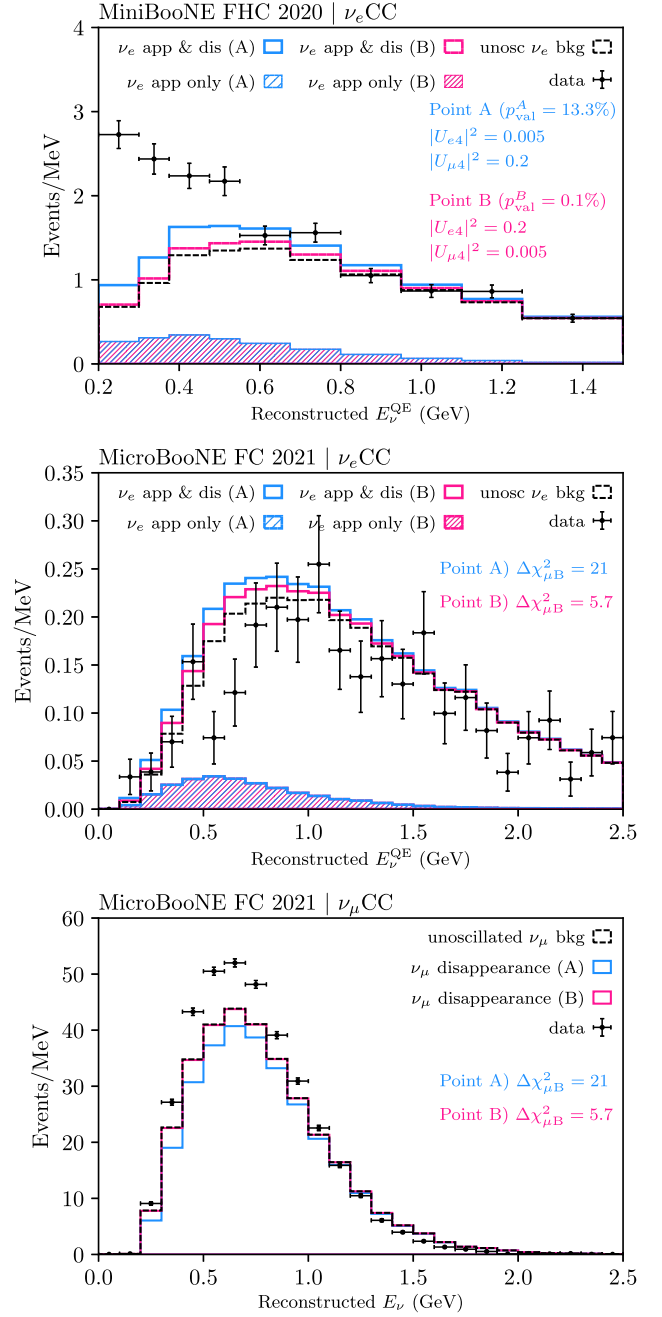


FIG. 5. ν_e event rate at MiniBooNE (top) and MicroBooNE (middle) and ν_μ event rate at MicroBooNE (bottom), after subtraction of misidentification backgrounds. We show the theory prediction of a sterile neutrino model for the two benchmark points discussed in Figs. 2 and 3, both with the same mass splitting $\Delta m_{41}^2 = 0.41$ eV². Point A shows a point excluded by μB at the $\Delta\chi_{\mu\text{B}}^2 = 21$ level, and point B shows a point with the ν_e appearance (disappearance) degeneracy that is compatible with μB at $\Delta\chi_{\mu\text{B}}^2 = 5.7$.

uncertainties, we take the ν_e and ν_μ fluxes to be independent. We consider $\sigma_i^e = 10\%$, correlated among ν_e samples in both experiments but uncorrelated over all energies E_i , and similar for ν_μ .

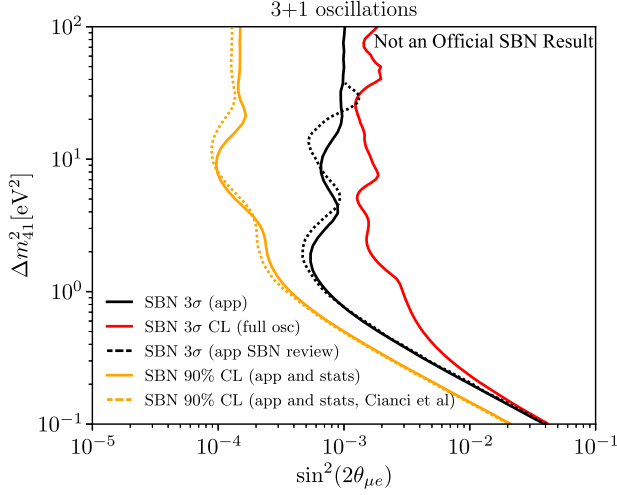


FIG. 6. Comparison of our SBN sensitivities with the literature for the case of a sterile model with $\nu_\mu \rightarrow \nu_e$ appearance only. We compare our sensitivity using statistical uncertainty only (solid orange) with that in Ref. [49] (dashed orange). We also compare the sensitivity including systematics (solid black) with that in Ref. [50]. Also shown is our sensitivity for a full oscillation model (solid red).

For validation, we also show the two-dimensional parameter space of Δm_{41}^2 vs $\sin^2(2\theta_{\mu e})$ in Fig. 6, comparing our result for the simpler, though unphysical, appearance-only model with that of Ref. [49] for the case of statistical uncertainties only and with the one in Ref. [50] for the appearance-only full systematics case. No previous SBN sensitivity curve could be found for the case of full oscillations.

Alternative metric: Compatibility chi-squared—To quantify the compatibility between any given null results and the MB -preferred multidimensional space, we construct a compatibility χ^2 . For a given value $\Delta\chi_0^2$, we obtain the 3D region in the sterile neutrino parameter space satisfying $\Delta\chi_{\text{MB}}^2 < \Delta\chi_0^2$. Then, scanning that entire region, we quantify the minimum $\Delta\chi_{\text{exp}}^2$ of another experiment within that region—determining the level at which that experiment excludes the entirety of the MB -preferred $\Delta\chi^2$ region.

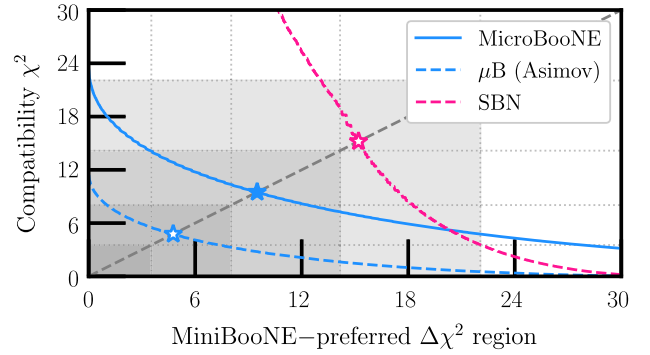


FIG. 7. Compatibility χ^2 of μB (blue) and SBN (pink) compared against MB -preferred parameter space. Gray regions contain the regions of compatibility, assuming Wilks' theorem, 1σ (darkest gray) to 4σ (lightest gray).

More precisely, given a region of the model parameter space defined by $\vartheta(\Delta\chi_0^2) = \{\vartheta | \Delta\chi_{\text{MB}}^2 < \Delta\chi_0^2\}$, the compatibility χ^2 for a given experiment or set of experiments is defined as $\chi_{\text{exp}}^2(\Delta\chi_0^2) = \min_{\vartheta(\Delta\chi_0^2)} \{\Delta\chi_{\text{exp}}^2\}$. The compatibility χ^2 is presented for μB and its Asimov sensitivity expectation, as well as for the projection for SBN in Fig. 7.

Each curve's intersection with the gray diagonal line addresses the following question: At what CL X can this experiment exclude MB's preference at the same CL? This corresponds to $\Delta\chi^2 = 9.5$ for μB alone (compared to $\Delta\chi^2 = 4.8$ for its sensitivity), which increases modestly by adding PROSPECT. With three degrees of freedom and assuming Wilks' theorem, this means that μB excludes MB's entire 2.3σ (97.6% CL) region at no less than the same CL. This should be contrasted with the compatibility calculated using the μB sensitivity, which yields 1.3σ (80.9% CL). This quantitative analysis confirms our parameter space exploration—no point in the full three-dimensional parameter space can simultaneously explain MB's excess while remaining consistent with μB 's observations at more than 2σ . [51] We also see that SBN will improve on this substantially, covering the entire 3σ region of MB at more than 3σ while excluding MB's most-favored $\sim 2\sigma$ parameter space with extremely high ($> 5\sigma$) confidence.