Sterile Neutrino Search with MicroBooNE's Electron Neutrino Disappearance Data

Peter B. Denton*

High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 12 November 2021; revised 17 May 2022; accepted 12 July 2022; published 2 August 2022)

A sterile neutrino is a well motivated minimal new physics model that leaves an imprint in neutrino oscillations. Over the last two decades, a number of hints pointing to a sterile neutrino have emerged, many of which are pointing near $m_4 \sim 1$ eV. Here, we show how MicroBooNE data can be used to search for electron neutrino disappearance using each of their four analysis channels. We find a hint for oscillations with the highest single channel significance of 2.4σ (using the Feldman-Cousins approach) coming from the Wire-Cell analysis and a simplified treatment of the experimental systematics. The preferred parameters are $\sin^2(2\theta_{14}) = 0.35^{+0.19}_{-0.16}$ and $\Delta m^2_{41} = 1.25^{+0.74}_{-0.39}$ eV^2. This region of parameter space is in good agreement with existing hints from source experiments, is at a similar frequency but higher mixing than indicated by reactor antineutrinos, and is at the edge of the region allowed by solar neutrino data. Existing unanalyzed data from MicroBooNE could increase the sensitivity to the $>3\sigma$ level.

DOI: 10.1103/PhysRevLett.129.061801

Introduction.—Sterile neutrino searches have formed a major part of new physics searches in the neutrino sector, and with good reason. It is anticipated that sterile neutrinos may exist with some mixing with the active neutrinos to explain why neutrinos have mass. This parameter space for the mixings and the masses for sterile neutrinos, however, spans many orders of magnitude [1] and no guaranteed prediction exists encouraging a broad search program.

Because of a variety of anomalies suggesting the existence of sterile neutrinos at the $m_4 \sim 1$ eV scale from the Liquid Scintillator Neutrino Detector (LSND), the reactor antineutrino anomaly, reactor spectral data, T2K, the gallium anomaly, and the MiniBooNE anomaly [2–8], an intense global effort to understand these hints has accelerated in recent years; for recent reviews see [9–11]. The various oscillation probes of $m_4 \sim 1$ eV sterile neutrinos can be generally classified into three dominant categories: (1) ν_e disappearance containing solar, reactor, and source calibration data, (2) ν_μ disappearance containing accelerator and atmospheric data, and (3) $\nu_\mu \to \nu_e$ appearance data containing accelerator data. Thus far, anomalies exist in ν_e disappearance [3,6,7] and $\nu_\mu \to \nu_e$ appearance [2,8] but no significant evidence for new oscillation frequencies has been seen in ν_μ disappearance [12,13]. Since $\nu_\mu \to \nu_e$ appearance requires both ν_e disappearance and ν_μ disappearance with the same frequency and partially constrained mixing angles, the evidence for $\nu_\mu \to \nu_e$ appearance has been considered to be in tension with the lack of evidence for steriles from ν_μ disappearance; see, e.g., [14]. Solar data and reactor spectral data disfavor the large mixing indicated by source data.

Strong constraints on additional neutrinos from cosmological measurements of the cosmic microwave background and baryon acoustic oscillations exist [15] although the Hubble tension [16,17] may be pointing to evidence for a new degree of freedom in the early Universe [18]. These constraints could also be partially alleviated in new physics models, typically with a new low scale interaction [19–27].

Recently, MicroBooNE reported their first search for ν_e events with 7×10^{20} POT in a dominantly ν_μ beam to test MiniBooNE's evidence for ν_e appearance. Their data was analyzed in four different analysis channels with different final state selections. They did not see electron neutrinos at the rate predicted by MiniBooNE [28–31] and disfavored ν_e templates compatible with MiniBooNE's excess best fit point at 3.75σ in the most sensitive analysis [31]; uncertainty in the best fit MiniBooNE spectrum will further weaken this constraint; see also [32].

There is more information in MicroBooNE data than just a constraint on $\nu_\mu \to \nu_e$ appearance and a test of MiniBooNE's low energy excess. (MicroBooNE can also search for ν_μ disappearance [32–35].) Because of the presence of intrinsic ν_e in the beam, we will show that MicroBooNE has not only modest sensitivity to ν_e disappearance searches [35], but also interesting hints for ν_e disappearance, compatible with many of the existing datasets in the literature, including some in the same regions of parameter space.

MiniBooNE also sat in the same accelerator beam and thus one could imagine looking for evidence of ν_e

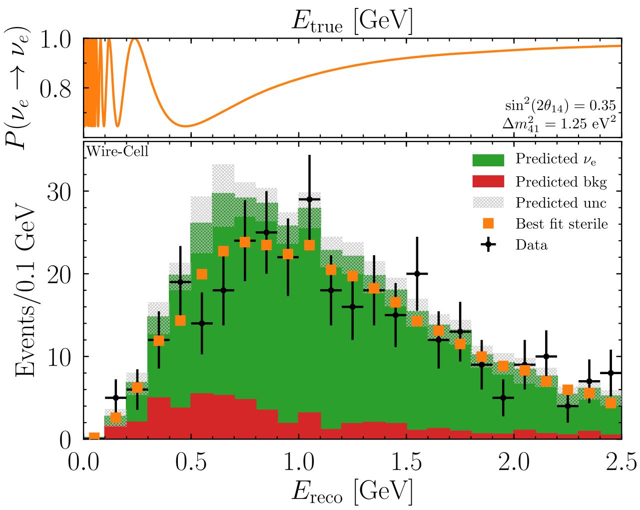

FIG. 1. Top: The disappearance probability in true energy for the best fit set of sterile oscillation parameters, $\Delta m^2_{41} = 1.25$ eV^2 and $\sin^2(2\theta_{14}) = 0.35$, for the Wire-Cell data. Bottom: The expected event rate at MicroBooNE in the Wire-Cell analysis in reconstructed neutrino energy [31], including contributions from backgrounds (red) and ν_e events (green) along with the systematic uncertainty (gray hatched). The actual data is shown in black and the expected data, assuming the best fit sterile hypothesis, is shown in orange.

disappearance in their data. However, their backgrounds from π^0 misidentification, $\Delta \to N\gamma$, and others dominated over ν_e events, while the opposite is true for MicroBooNE due to the awesome reconstruction power of Liquid Argon Time Projection Chambers. In addition, MiniBooNE has reported an excess of electron neutrino candidate events [8] that seem to require an explanation beyond a $m_4 \sim 1$ eV sterile neutrino due to constraints from MicroBooNE, MINOS+, IceCube, and cosmology [12,13,15,28–31], some of which could potentially be evaded in more complicated models [18–27,36,37]. It is still to be determined if existing explanations of MiniBooNE without a $m_4 \sim 1$ eV sterile neutrino [38–48] are also consistent with MicroBooNE's new results; until this story is better understood it does not make statistical sense to analyze the MiniBooNE data for ν_e disappearance.

In this Letter, we will present a ν_e disappearance sterile oscillation analysis of the MicroBooNE data focusing on the Wire-Cell analysis, compare the result to others in the literature, and discuss the results. The analysis of the other three channels can be found in the Supplemental Material [49]. All the data files associated the parameter scans shown in Fig. 2 and the Supplemental Material [49] can be found at https://peterdenton.github.io/Data/Micro_Dis/index.html.

Analysis.—MicroBooNE has reported four ν_e analyses dubbed Wire-Cell [31], which is sensitive to final states with one electron and anything else including both fully and partially contained events; Pandora [30], which is sensitive to final states with one electron, zero pions, and either zero protons or 1+ protons; and Deep Learning [29], which is sensitive to final states with one electron and one proton, primarily from charged-current quasielastic interactions. Each of these four analyses has different strengths and weaknesses in terms of statistics, purity, and calibration data, summarized in [28]. As the Wire-Cell analysis has the highest ν_e statistics, we take it as our fiducial analysis, but we also investigate the other channels for completeness; see the Supplemental Material [49].

To analyze the MicroBooNE data in terms of a sterile neutrino, we consider a two parameter model where the sterile neutrino mixes dominantly with electron neutrinos. Thus, the expected ν_e events will be reduced by the disappearance probability

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{14}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \quad (1)$$

where $L = 470$ m is MicroBooNE baseline [33], $\Delta m^2_{41} \equiv m^2_4 - m^2_1$ is the new oscillation frequency, and θ_{14} gives the amplitude of the oscillations. This is equivalent to setting $\theta_{24} = \theta_{34} = 0$, or to small enough values to be irrelevant.

While a full analysis including a combination of all channels, a full treatment of energy reconstruction, backgrounds, and other systematics is necessary to robustly quantify the statistical significance of these sterile oscillations, we can still get a good estimate of the parameters of interest preferred in a simplified analysis. In order to quantify the significance we define a test statistic,

$$\Delta\chi^2 = 2\sum_i \left[N_{th,i} - N_{d,i} + N_{d,i} \log\left(\frac{N_{d,i}}{N_{th,i}}\right)\right], \quad (2)$$

where the sum goes over the energy bins in the analysis, $N_{d,i}$ is the number of recorded events in bin i, and $N_{th,i}$ is the number of expected events in bin i, including backgrounds as a function of the oscillation parameters. Systematic uncertainties are handled by replacing $N_{th,i} \to N_{th,i}(1 + \xi_i)$ and the addition of $\sum_i (\xi_i/\sigma_i)^2$ to the test statistic, which is then conservatively minimized over all the ξ_i treated independently. In addition, Eq. (2) is calculated in reconstructed energy while the oscillation probability is applied to the spectrum in true energy (determined by unfolding) and then the $N_{th,i}$ are calculated by integrating over the smearing function and the width of the bin. For some results we assume Wilks' theorem but for the primary sensitivity we perform Monte Carlo studies as described by Feldman and Cousins (FC) [53], including systematic effects as described in [54–57]. See the Supplemental Material [49] for more details on the statistical analysis. For the Wire-Cell (Pandora-Np) analysis we start with the [0.1, 0.2] ([0.14, 0.28]) GeV bin as the statistics in the lowest energy bin are essentially zero in

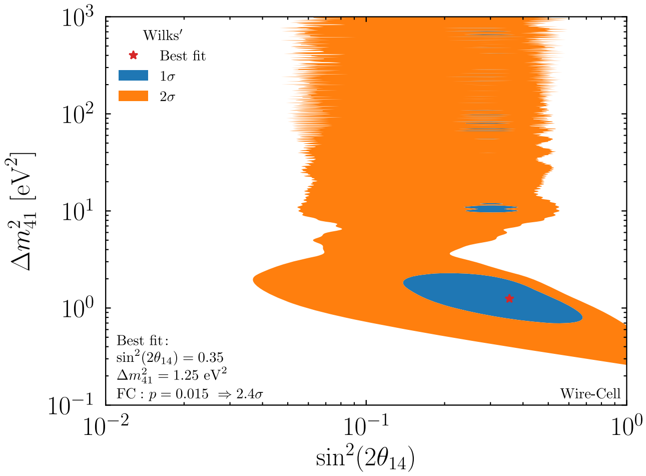

FIG. 2. The preferred regions in Δm^2_{41}-$\sin^2(2\theta_{14})$ parameter space using data from MicroBooNE's Wire-Cell analysis [31]. The blue (orange) contours are at 1σ (2σ) as determined by Wilks' theorem; the Feldman-Cousins significance of the best fit compared to no oscillations is 2.4σ with a simplified treatment of systematics.

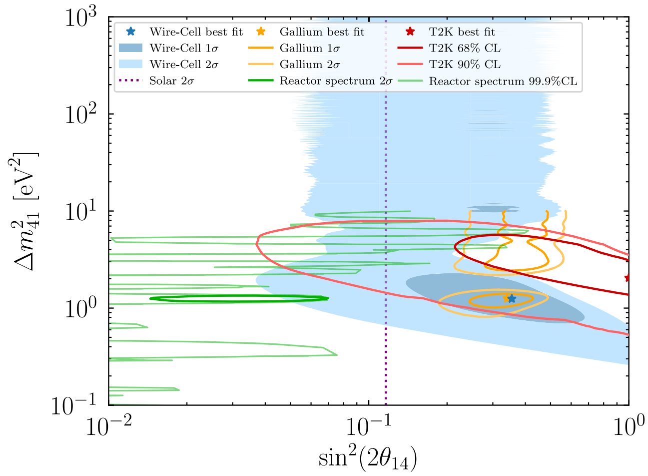

FIG. 3. The preferred regions (Wilks') from MicroBooNE's Wire-Cell analysis [31] as calculated in this Letter (blue), from BEST [7] combined with other gallium data from SAGE [59] and GALLEX [60] (orange), from T2K [5] (red), and a global analysis of modern reactor antineutrino spectral data [4] (green). Additionally, solar (purple) [58] and reactor (light green) neutrinos disfavor large mixing angles.

these analyses. Note that we do not include correlations in the systematic uncertainties that could modify these results.

In Fig. 1 we show the contributions to the predicted spectra and its systematic uncertainty, the data, and the expected data given the best fit sterile neutrino point, along with the sterile neutrino oscillation probability at the best fit point. To determine the best fit point in sterile neutrino parameter space, we performed a scan, shown in Fig. 2, showing contours of the test statistic that correspond to $1, 2\sigma$ assuming Wilks' theorem. We have explicitly confirmed that the preferred regions shown in Fig. 2 are quite similar using FC. We find a best fit point of $\Delta m^2_{41} = 1.25^{+0.74}_{-0.39}$ eV^2 and $\sin^2(2\theta_{14}) = 0.35^{+0.19}_{-0.16}$, which is in mild tension with the no oscillation hypothesis at the 2.4σ level using Monte Carlo methods as described by FC and a simplified treatment of experimental systematics. The results for the other three analysis channels are shown in the Supplemental Material [49] and are generally compatible with significances 1.8–2.4σ.

Previous ν_e disappearance probes.—Existing probes of light sterile neutrinos mixing with ν_e's exist from gallium, T2K near detector, reactor, and solar data. We show the preferred regions (disfavored region in the case of solar) for all of these data from [4,5,7,58] in Fig. 3. Existing hints for a sterile neutrino from gallium data collected by SAGE, GALLEX, and BEST [7,59,60] show a high significance ($> 5\sigma$ [61]) preference for sterile parameters consistent with that from MicroBooNE. There exist various interpretations of the gallium anomalies with different theory estimates and, while the significances vary from $\sim$2.3 to $> 3\sigma$ with the latest BEST data, the central values and thus preferred regions remain similar in the analyses [7,62,63]. T2K performed a search for ν_e disappearance using their near detector and found weak evidence, $< 2\sigma$, for ν_e disappearance [5]. Solar data has been analyzed a number of times in the context of sterile neutrinos; one such analysis using all relevant solar data [59,60,64–70] found $|U_{e4}|^2 < 0.03$ at 95% C.L. [58].

A recent analysis of modern reactor antineutrino data [4] finds a preference for oscillations at $\Delta m^2_{41} = 1.26$ eV^2, quite consistent with this MicroBooNE analysis, but with a significantly smaller mixing angle; their analysis also disfavors mixing angles larger than 10^{-2}–10^{-1} with considerable variation due to oscillation effects. The significance of the reactor data is under intense scrutiny with different estimates of the significance for oscillations varying from $\lesssim 1$ to 3.2σ and the impact of fuel evolution studies may partially weaken the evidence for sterile neutrinos in reactor data but seems to not remove it completely [4,71–84]. In addition, while some reactor flux predictions, in particular [85–87] are compatible with the MicroBooNE hint, others such as [81,88,89] provide a constraint slightly weaker than that from solar for $\Delta m^2_{41} \gtrsim 1$ eV^2 in slight tension with the MicroBooNE and gallium hints; see [81] for a comparison of the different reactor predictions. Neutrino-4 has also searched for light sterile neutrinos and has reported modest evidence for oscillations around $\Delta m^2_{41} \sim 7$ eV^2 and $\sin^2(2\theta_{14}) \sim 0.4$ [90], although multiple aspects of their analysis have been criticized in the literature [91–94] and are in considerable tension with other reactor data [4].

It is also possible to probe the existence of a sterile neutrino through an analysis looking for evidence of unitary violation of the lepton mixing matrix. Various analyses have drawn rather tight constraints on such mixing from observing that the three dominant terms in the electron row $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2$ seem to sum close to one at the few $\times$ 10^{-2}–few $\times$ 10^{-3} level [95–97]. Care is required as these analyses avoid datasets that show evidence for unitary violation from, e.g., LSND, MiniBooNE, the reactor antineutrino anomaly, or gallium experiments.

Discussion.—A combined analysis of the four different channels could increase the significance further for a sterile neutrino as the two datasets with the most statistics, Wire-Cell and Pandora-Np, are fairly consistent. Moreover, due to many shared systematics with regards to flux, cross sections, and detector performance, there should be a partial cancellation of the systematic uncertainties. Considerable care is required in such a combined analysis due to some shared events and would require intimate knowledge of the experiment, as well as all of the individual analyses, which is beyond the scope of this Letter. Nonetheless, we see that there is general agreement that the data indicate oscillations at $\Delta m^2_{41} \sim 1$–5 eV^2 and $\sin^2(2\theta_{14}) \gtrsim 0.1$, although we note that two of the analyses, Deep Learning and Pandora-0p, are consistent with the no oscillation hypothesis at $< 2\sigma$.

In this analysis, we assumed that the backgrounds would be unmodified by the presence of a sterile neutrino but neutral current (NC) events provide a considerable contribution to the backgrounds in the Wire-Cell analysis and a sterile neutrino would deplete this contribution. This contribution is safely ignored in this analysis since (a) the backgrounds are quite small compared to the neutrino signal in the Wire-Cell data and the NC events are a subset of those implying a modification due to sterile neutrinos would be quite minor and (b) the neutrino flux at MicroBooNE is dominantly ν_μ, and thus the ν_e contribution to the NC flux should be quite small.

Unlike some of the other evidence for and probes of light sterile neutrinos, MicroBooNE's hint is in the central region of their spectrum showing signs of an oscillation minimum, although in a region where the efficiencies are not flat. Other probes depend on a total rate measurement (medium-baseline reactor, solar, and source experiments) or the only signal that is seen is at the edge of the energy spectrum (short-baseline accelerator appearance searches at LSND, MiniBooNE, and T2K). (Three exceptions are short-baseline reactor experiments, MINOS+ [12], and IceCube [13]. MINOS and IceCube, however, are not sensitive to sterile neutrinos mixing with ν_e's.) For example, for the best fit oscillation parameters in the Wire-Cell analysis, the oscillation minimum is at $E \sim 0.5$ GeV. While somewhat on the lower energy end of their spectrum, there are still modest statistics below that point. Similar results are true for the other analysis channels although the statistics in the Pandora-0p analysis are quite low. This can be seen in that the preferred regions from the two most sensitive MicroBooNE analyses, Wire-Cell and Pandora-Np, have closed islands for the smallest preferred Δm^2_{41} value before entering the oscillation averaged regime at higher Δm^2_{41} values; see the Supplemental Material [49].

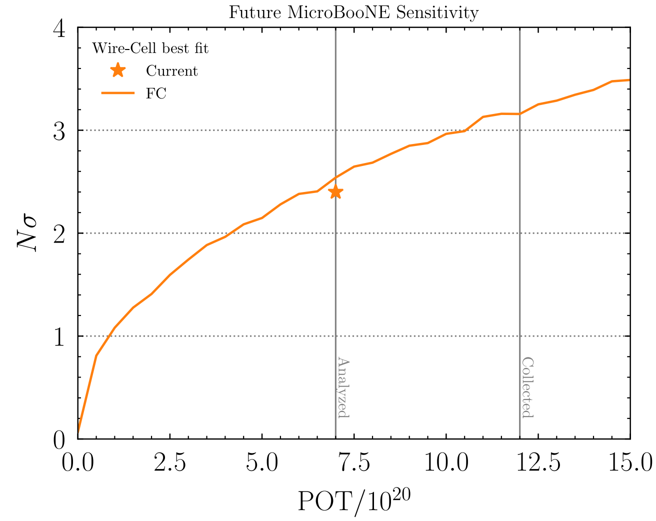

FIG. 4. The projected sensitivity in numbers of standard deviations as a function of POT when calculated with Feldman-Cousins in orange. The orange star shows the results from this analysis indicating that the data is experiencing mild fluctuations relative to the best fit sterile hypothesis.

In the future, this sterile neutrino hint can be tested at a range of experiments, including MicroBooNE, as more data is processed. In fact, MicroBooNE has already accumulated 12×10^{20} POT. The expected sensitivity for the best fit point in this analysis and a benchmark point from reactor neutrinos is shown in Fig. 4, which shows that with existing data the significance would be at the 2.5σ level using a simplified treatment of systematics. That is, for the best fit oscillation parameters, we actually expect slightly more sensitivity than was achieved; this is consistent within expectations from fluctuations in the data that

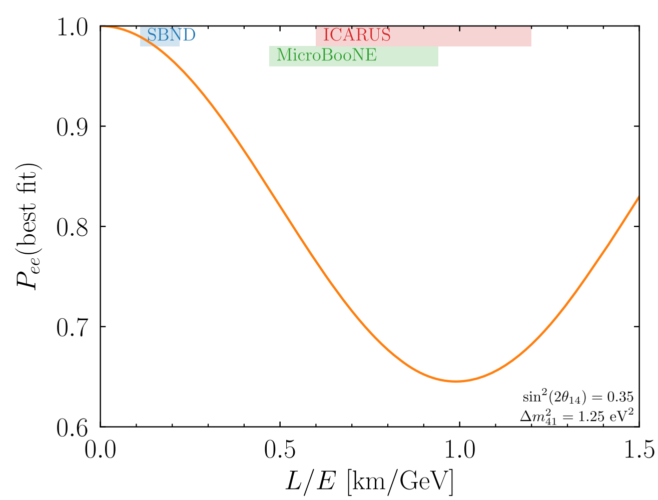

FIG. 5. The disappearance probability for the best fit oscillation parameters along with the primary kinematic range of each of the three detectors in the short baseline neutrino program at Fermilab.

are accounted for in the Monte Carlo approach. Future analyses of MicroBooNE's Wire-Cell data alone can reach $>3\sigma$ with existing systematic uncertainties.

In addition, the short baseline neutrino program at Fermilab with three Liquid Argon Time Projection Chamber detectors at different baselines in the same neutrino beam [33] can test this scenario with cancellation of some systematics. The best fit oscillation probability and the kinematic range probed by the three detectors are shown in Fig. 5. If a sterile neutrino exists with these parameters, the short baseline near detector will see a nearly unoscillated flux, while ICARUS will see a dip in the higher energy part of their spectrum that may be less affected by detector efficiencies.

Conclusions.—While hailed as a ν_e appearance experiment, MicroBooNE, due to the spectacular particle identification power of Liquid Argon Time Projection Chambers, can identify the intrinsic ν_e component of the flux. We have shown that it is possible to use this flux to probe neutrino oscillations and, in fact, we find hints for sterile oscillations at the 2.4σ level using a simplified treatment of the experimental systematics. Extremely interesting is the $>5\sigma$ hint for sterile neutrino oscillations from a combined analysis of SAGE, GALLEX, and BEST data for the same oscillation parameters.

A sterile neutrino with $m_4 \sim 1$ eV is in modest tension however, with reactor and solar data, and is in considerable tension with cosmological measurements. Cosmological constraints on light sterile neutrinos may be partially alleviated in more involved new physics scenarios such as those with neutrino decay [98] or new interactions that may partially resolve the Hubble tension [18]. The two upcoming detectors of Fermilab's short-baseline neutrino program, the short baseline near detector and ICARUS, are well positioned to further probe this hint.

We thank Xin Qian, Bryce Littlejohn, Georgia Karagiorgi, and all three anonymous referees for helpful comments. We acknowledge support from the U.S. Department of Energy under Grant Contract No. DE-SC0012704. The figures were done with PYTHON [99] and MATPLOTLIB [100].

*Corresponding author.
pdenton@bnl.gov

[1] P. D. Bolton, F. F. Deppisch, and P. S. Bhupal Dev, J. High Energy Phys. 03 (2020) 170.
[2] A. Aguilar-Arevalo, L. B. Auerbach, R. L. Burman, D. O. Caldwell, E. D. Church *et al.* (LSND Collaboration), Phys. Rev. D **64**, 112007 (2001).
[3] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D **83**, 073006 (2011).
[4] J. M. Berryman and P. Huber, J. High Energy Phys. 01 (2021) 167.
[5] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **91**, 051102 (2015).
[6] C. Giunti and M. Laveder, Phys. Rev. C **83**, 065504 (2011).
[7] V. V. Barinov *et al.*, Phys. Rev. Lett. **128**, 232501 (2022).
[8] A. A. Aguilar-Arevalo, B. C. Brown, J. M. Conrad, R. Dharmapalan, A. Diaz *et al.* (MiniBooNE Collaboration), Phys. Rev. D **103**, 052002 (2021).
[9] P. A. Machado, O. Palamara, and D. W. Schmitz, Annu. Rev. Nucl. Part. Sci. **69**, 363 (2019).
[10] A. Diaz, C. A. Argüelles, G. H. Collin, J. M. Conrad, and M. H. Shaevitz, Phys. Rep. **884**, 1 (2020).
[11] C. A. Argüelles *et al.*, Rep. Prog. Phys. **83**, 124201 (2020).
[12] P. Adamson *et al.* (MINOS+ Collaboration), Phys. Rev. Lett. **122**, 091803 (2019).
[13] M. G. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. Lett. **125**, 141801 (2020).
[14] 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.
[15] S. Hagstotz, P. F. de Salas, S. Gariazzo, S. Pastor, M. Gerbino, M. Lattanzi, S. Vagnozzi, and K. Freese, Phys. Rev. D **104**, 123524 (2021).
[16] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **641**, A6 (2020); **652**, C4(E) (2021).
[17] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, Astrophys. J. **876**, 85 (2019).
[18] C. D. Kreisch, F.-Y. Cyr-Racine, and O. Doré, Phys. Rev. D **101**, 123505 (2020).
[19] S. Hannestad, R. S. Hansen, and T. Tram, Phys. Rev. Lett. **112**, 031802 (2014).
[20] B. Dasgupta and J. Kopp, Phys. Rev. Lett. **112**, 031803 (2014).
[21] A. Mirizzi, G. Mangano, O. Pisanti, and N. Saviano, Phys. Rev. D **91**, 025019 (2015).
[22] N. Saviano, O. Pisanti, G. Mangano, and A. Mirizzi, Phys. Rev. D **90**, 113009 (2014).
[23] X. Chu, B. Dasgupta, and J. Kopp, J. Cosmol. Astropart. Phys. 10 (2015) 011.
[24] L. Vecchi, Phys. Rev. D **94**, 113015 (2016).
[25] F. Capozzi, I. M. Shoemaker, and L. Vecchi, J. Cosmol. Astropart. Phys. 07 (2017) 021.
[26] N. Song, M. C. Gonzalez-Garcia, and J. Salvado, J. Cosmol. Astropart. Phys. 10 (**2018**) 055.
[27] J. M. Cline, Phys. Lett. B **802**, 135182 (2020).
[28] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. Lett. **128**, 241801 (2022).
[29] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **105**, 112003 (2022).
[30] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **105**, 112004 (2022).
[31] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **105**, 112005 (2022).
[32] 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).
[33] M. Antonello *et al.* (MicroBooNE, LAr1-ND, ICARUS-WA104 Collaborations), arXiv:1503.01520.
[34] D. Cianci, A deep-learning-based muon neutrino CCQE selection for searches beyond the standard model with MicroBooNE, Ph.D. thesis, 2021.

[35] D. Cianci, A. Furmanski, G. Karagiorgi, and M. Ross-Lonergan, Phys. Rev. D **96**, 055001 (2017).
[36] J. Liao and D. Marfatia, Phys. Rev. Lett. **117**, 071802 (2016).
[37] P. B. Denton, Y. Farzan, and I. M. Shoemaker, Phys. Rev. D **99**, 035003 (2019).
[38] S. N. Gninenko, Phys. Rev. D **83**, 015015 (2011).
[39] L. Alvarez-Ruso and E. Saul-Sala, in Prospects in Neutrino Physics (2017), arXiv:1705.00353.
[40] J. Asaadi, E. Church, R. Guenette, B. J. P. Jones, and A. M. Szelc, Phys. Rev. D **97**, 075021 (2018).
[41] P. Ballett, S. Pascoli, and M. Ross-Lonergan, Phys. Rev. D **99**, 071701(R) (2019).
[42] J. R. Jordan, Y. Kahn, G. Krnjaic, M. Moschella, and J. Spitz, Phys. Rev. Lett. **122**, 081801 (2019).
[43] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, Phys. Rev. Lett. **121**, 241801 (2018).
[44] O. Fischer, A. Hernández-Cabezudo, and T. Schwetz, Phys. Rev. D **101**, 075045 (2020).
[45] A. Abdullahi, M. Hostert, and S. Pascoli, Phys. Lett. B **820**, 136531 (2021).
[46] B. Dutta, S. Ghosh, and T. Li, Phys. Rev. D **102**, 055017 (2020).
[47] W. Abdallah, R. Gandhi, and S. Roy, Phys. Rev. D **104**, 055028 (2021).
[48] S. Vergani, N. W. Kamp, A. Diaz, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. A. Uchida, Phys. Rev. D **104**, 095005 (2021).
[49] See Supplemental Material, which includes Refs. [50–52], at http://link.aps.org/supplemental/10.1103/PhysRevLett.129.061801 for details on the statistical analysis and the results for the other experimental analyses.
[50] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, Phys. Rev. D **66**, 053010 (2002).
[51] M. Stanley, P. Patil, and M. Kuusela, arXiv:2111.01091.
[52] X. Qian (MicroBooNE Collaboration), Search for an anomalous excess in neutrino-induced interactions in the MicroBooNE liquid argon time projection chamber, BNL Colloquium, 2021.
[53] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[54] R. L. Berger and D. D. Boos, J. Am. Stat. Assoc. **89**, 1012 (1994).
[55] G. Feldman, Notes on the inclusion of nuisance parameters in the unified approach, NOVA-doc-15884, 2016.
[56] D. S. Pershey, A measurement of ν_e appearance and ν_μ disappearance neutrino oscillations with the NOvA experiment, Ph.D. thesis, Caltech, 2018.
[57] P. B. Denton and J. Gehrlein, J. High Energy Phys. 04 (2021) 266.
[58] K. Goldhagen, M. Maltoni, S. E. Reichard, and T. Schwetz, Eur. Phys. J. C **82**, 116 (2022).
[59] J. N. Abdurashitov, V. N. Gavrin, V. V. Gorbachev, P. P. Gurkina, T. V. Ibragimova *et al.* (SAGE Collaboration), Phys. Rev. C **80**, 015807 (2009).
[60] F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, Phys. Lett. B **685**, 47 (2010).
[61] J. M. Berryman, P. Coloma, P. Huber, T. Schwetz, and A. Zhou, J. High Energy Phys. 02 (2022) 055.
[62] C. Giunti, M. Laveder, Y. F. Li, Q. Y. Liu, and H. W. Long, Phys. Rev. D **86**, 113014 (2012).
[63] J. Kostensalo, J. Suhonen, C. Giunti, and P. C. Srivastava, Phys. Lett. B **795**, 542 (2019).
[64] B. Aharmim *et al.* (SNO Collaboration), Phys. Rev. C **88**, 025501 (2013).
[65] G. Bellini *et al.*, Phys. Rev. Lett. **107**, 141302 (2011).
[66] G. Bellini *et al.* (Borexino Collaboration), Phys. Rev. D **82**, 033006 (2010).
[67] G. Bellini *et al.* (BOREXINO Collaboration), Nature (London) **512**, 383 (2014).
[68] J. Hosaka *et al.* (Super-Kamiokande Collaboration), Phys. Rev. D **73**, 112001 (2006).
[69] J. P. Cravens *et al.* (Super-Kamiokande Collaboration), Phys. Rev. D **78**, 032002 (2008).
[70] K. Abe *et al.* (Super-Kamiokande Collaboration), Phys. Rev. D **83**, 052010 (2011).
[71] C. Giunti, X. P. Ji, M. Laveder, Y. F. Li, and B. R. Littlejohn, J. High Energy Phys. 10 (2017) 143.
[72] C. Giunti, Y. F. Li, B. R. Littlejohn, and P. T. Surukuchi, Phys. Rev. D **99**, 073005 (2019).
[73] Y. Declais *et al.*, Nucl. Phys. **B434**, 503 (1995).
[74] Y. J. Ko, B. R. Kim, J. Y. Kim, B. Y. Han, C. H. Jang *et al.* (NEOS Collaboration), Phys. Rev. Lett. **118**, 121802 (2017).
[75] D. Adey *et al.* (Daya Bay Collaboration), Phys. Rev. Lett. **121**, 241805 (2018).
[76] I. Alekseev *et al.* (DANSS Collaboration), Phys. Lett. B **787**, 56 (2018).
[77] G. Bak, J. H. Choi, H. I. Jang, J. S. Jang, S. H. Jeon, K. K. Joo *et al.* (RENO Collaboration), Phys. Rev. Lett. **122**, 232501 (2019).
[78] H. de Kerret *et al.* (Double Chooz Collaboration), Nat. Phys. **16**, 558 (2020).
[79] H. Almazán, L. Bernard, A. Blanchet, A. Bonhomme, C. Buck *et al.* (STEREO Collaboration), Phys. Rev. D **102**, 052002 (2020).
[80] M. Andriamirado *et al.* (PROSPECT Collaboration), Phys. Rev. D **103**, 032001 (2021).
[81] C. Giunti, Y. F. Li, C. A. Ternes, and Z. Xin, Phys. Lett. B **829**, 137054 (2022).
[82] F. P. An *et al.* (Daya Bay Collaboration), Phys. Rev. Lett. **118**, 251801 (2017).
[83] D. Adey *et al.* (Daya Bay Collaboration), Phys. Rev. Lett. **123**, 111801 (2019).
[84] F. P. An *et al.* (Daya Bay, PROSPECT Collaborations), Phys. Rev. Lett. **128**, 081801 (2022).
[85] T. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, and F. Yermia, Phys. Rev. C **83**, 054615 (2011).
[86] P. Huber, Phys. Rev. C **84**, 024617 (2011); **85**, 029901(E) (2012).
[87] L. Hayen, J. Kostensalo, N. Severijns, and J. Suhonen, Phys. Rev. C **100**, 054323 (2019).
[88] M. Estienne, M. Fallot, A. Algora, J. Briz-Monago, V. M. Bui *et al.*, Phys. Rev. Lett. **123**, 022502 (2019).
[89] V. Kopeikin, M. Skorokhvatov, and O. Titov, Phys. Rev. D **104**, L071301 (2021).

[90] A. P. Serebrov *et al.* (NEUTRINO-4 Collaboration), Pis'ma Zh. Eksp. Teor. Fiz. **109**, 209 (2019).
[91] M. Danilov, J. Phys. Conf. Ser. **1390**, 012049 (2019).
[92] M. Andriamirado *et al.* (PROSPECT, STEREO Collaboration), arXiv:2006.13147.
[93] P. Coloma, P. Huber, and T. Schwetz, Eur. Phys. J. C **81**, 2 (2021).
[94] C. Giunti, Y. F. Li, C. A. Ternes, and Y. Y. Zhang, Phys. Lett. B **816**, 136214 (2021).
[95] S. Parke and M. Ross-Lonergan, Phys. Rev. D **93**, 113009 (2016).
[96] S. A. R. Ellis, K. J. Kelly, and S. W. Li, J. High Energy Phys. 12 (2020) 068.
[97] Z. Hu, J. Ling, J. Tang, and T. Wang, J. High Energy Phys. 01 (2021) 124.
[98] M. Escudero, J. Lopez-Pavon, N. Rius, and S. Sandner, J. High Energy Phys. 12 (**2020**) 119.
[99] G. Van Rossum and F. L. Drake, *PYTHON 3 Reference Manual* (CreateSpace, Scotts Valley, CA, 2009).
[100] J. D. Hunter, Comput. Sci. Eng. **9**, 90 (2007).