

Enhancing DUNE's Solar Neutrino Capabilities with Neutral-Current Detection

Stephan A. Meighen-Berger^{1,2,*} Jayden L. Newstead^{1,3,†} John F. Beacom^{1,2,4,5,‡}

Nicole F. Bell^{1,3,§} and Matthew J. Dolan^{1,3,||}

¹*School of Physics, The University of Melbourne, Victoria 3010, Australia*

²*Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210, USA*

³*ARC Centre of Excellence for Dark Matter Particle Physics, School of Physics, The University of Melbourne, Victoria 3010, Australia*

⁴*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*

⁵*Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*

 (Received 8 October 2024; revised 29 May 2025; accepted 2 June 2025; published 2 July 2025)

We show that the Deep Underground Neutrino Experiment (DUNE) has the potential to make a precise measurement of the total active flux of ^8B solar neutrinos via neutral-current (NC) interactions with argon. This would complement proposed precise measurements of solar-neutrino fluxes in DUNE via charged-current (CC) interactions with argon and mixed CC/NC interactions with electrons. Together, these would enable DUNE to make a Sudbury Neutrino Observatory (SNO)-like comparison of rates and thus to make the most precise measurements of $\sin^2 \theta_{12}$ and Δm_{21}^2 using solar neutrinos. Realizing this potential requires dedicated but realistic efforts to improve DUNE's low-energy capabilities and separately to reduce neutrino-argon cross-section uncertainties. Comparison of mixing-parameter results obtained using solar neutrinos in DUNE and reactor antineutrinos in the Jiangmen Underground Neutrino Observatory (JUNO) would allow for unprecedented tests of new physics.

DOI: [10.1103/htfm-tbdq](https://doi.org/10.1103/htfm-tbdq)

An era of radically improved precision is beginning in neutrino physics. At present, the neutrino mixing parameters are known to ~ 3 – 10% precision [1]. In 2025, the Jiangmen Underground Neutrino Observatory (JUNO) will begin its measurements of reactor antineutrinos, achieving subpercent level precision for Δm_{21}^2 , $\sin^2 \theta_{12}$, and Δm_{31}^2 [2,3]. In 2027, the Hyper-Kamiokande experiment will begin several measurements, improving the present Δm_{32}^2 and $\sin^2 \theta_{23}$ uncertainties by a factor of ~ 3 [4,5]. Then, beginning about 2030, the long-baseline program at the Deep Underground Neutrino Experiment (DUNE) will provide even greater precision [6,7].

With these huge leaps in precision come huge opportunities to test for new physics in the neutrino sector, i.e., anything beyond simple three-flavor mixing. The “solar” mixing parameters, $\sin^2 \theta_{12}$ and Δm_{21}^2 , can be measured in two independent ways: with solar neutrinos or reactor

antineutrinos. With the former, we have a long baseline, large matter effects, and large magnetic fields. With the latter, we have short baselines and effectively zero matter density and magnetic fields. To match the opportunity of JUNO's precision reactor neutrino measurements, significantly improved solar neutrino measurements are needed. With those, we could powerfully test a variety of new physics scenarios with solar neutrinos [8–17].

Capozzi *et al.* [18], building on prior work on solar-neutrino detection in liquid argon [19–23], showed that DUNE has the potential to make the world's most precise measurements of high-energy ($E_\nu > 5$ MeV) solar neutrinos. In their proposal, Δm_{21}^2 would be measured through the day-night effect, which is independent of the solar ^8B flux and the uncertainties on the neutrino-argon cross section, while $\sin^2 \theta_{12}$ would be determined by comparing the rates of two channels. The first is charged-current (CC) interactions with argon ($\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$, where $*$ indicates a nuclear excited state). The second is mixed CC

*Contact author: stephan.meighenberger@unimelb.edu.au

†Contact author: jnewstead@unimelb.edu.au

‡Contact author: beacom.7@osu.edu

§Contact author: n.bell@unimelb.edu.au

||Contact author: matthew.dolan@unimelb.edu.au

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

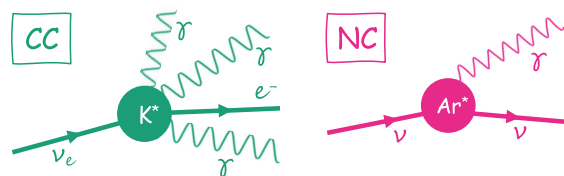


FIG. 1. Charged-current (left) and neutral-current (right) detection channels in DUNE.

and neutral-current (NC) elastic scattering (ES) interactions with electrons ($\nu + e^- \rightarrow \nu + e^-$). This approach breaks the degeneracy between the mixing angle and the ^8B flux because the high-energy rates depend on the fluxes as

$$\mathcal{R}^{\text{CC}} \propto \phi_{\nu_e} \quad (1)$$

$$\mathcal{R}^{\text{ES}} \propto \phi_{\nu_e} + \frac{1}{6}(\phi_{\nu_\mu} + \phi_{\nu_\tau}), \quad (2)$$

where the ϕ_α terms indicates the fluxes of the various flavors after neutrino mixing and ϕ_{tot} is the total active flux. Here, Eq. (1) depends on $\phi_{\text{tot}} \sin^2 \theta_{12}$, while Eq. (2) depends on $\phi_{\text{tot}} (\sin^2 \theta_{12} + \frac{1}{6} \cos^2 \theta_{12})$. This is not an ideal comparison due to the $\approx 1/6$ factor, but this can be partially overcome with the expected large statistics.

In this Letter, we show that DUNE has the potential to do even better by also using the pure NC channel ($\nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar}^*$), where the rate is

$$\mathcal{R}^{\text{NC}} \propto \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \equiv \phi_{\text{tot}}, \quad (3)$$

independent of the details of active-flavor mixing. Importantly, the ratio $\mathcal{R}^{\text{CC}}/\mathcal{R}^{\text{NC}}$ directly determines $\sin^2 \theta_{12}$, providing a conceptually cleaner way to measure the mixing angle. Moreover, by providing a third type of measurement, it provides a cross-check and improves the overall precision.

Figure 1 sketches how CC and NC events can be distinguished. Since earlier work, where the NC channel was only briefly discussed for solar neutrinos [18,19], there have been two key developments that make it seem much more promising. First, the experimental work in Refs. [24–26] have remeasured nuclear excitations in

argon, significantly improving the precision (and opening the door to further improvements), and showed that the cross section to a dominant state is about three times larger than previously thought. Second, there is increased optimism about the ability for liquid-argon detectors to register nuclear de-excitations through the emission of MeV-range gamma rays [27–31].

Figure 2 (details given below) shows the sensitivity to the solar neutrino fluxes in three stages: with current data, including the precise ES measurement by Super-Kamiokande [32] and the pioneering CC and NC measurements in heavy water in the Sudbury Neutrino Observatory (SNO) [33]; with the “DUNE Solar” capabilities proposed in Ref. [18]; and with the advances proposed here using the NC channel too. This final step would enable DUNE to improve upon SNO’s CC/NC comparison, which no other experiment can do. (While JUNO and current dark-matter experiments will make solar NC measurements, their projected uncertainties are larger [34–36]; the proposed Xenon LUX-ZEPLIN DARWIN (XLZD) experiment may reach a competitive exposure [37].) Our primary goal in this Letter is to demonstrate the physics potential of NC measurements in DUNE while pointing out key experimental challenges.

In the next section, we review the physics of neutrino-argon interactions and explain the new developments. We then present our main calculations for NC interactions in DUNE, the implications for solar neutrinos, and the required next steps. In End Matter, we provide further information.

Neutrino-argon NC interactions—We consider the NC interaction channel

$$\nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar}^*, \quad (4)$$

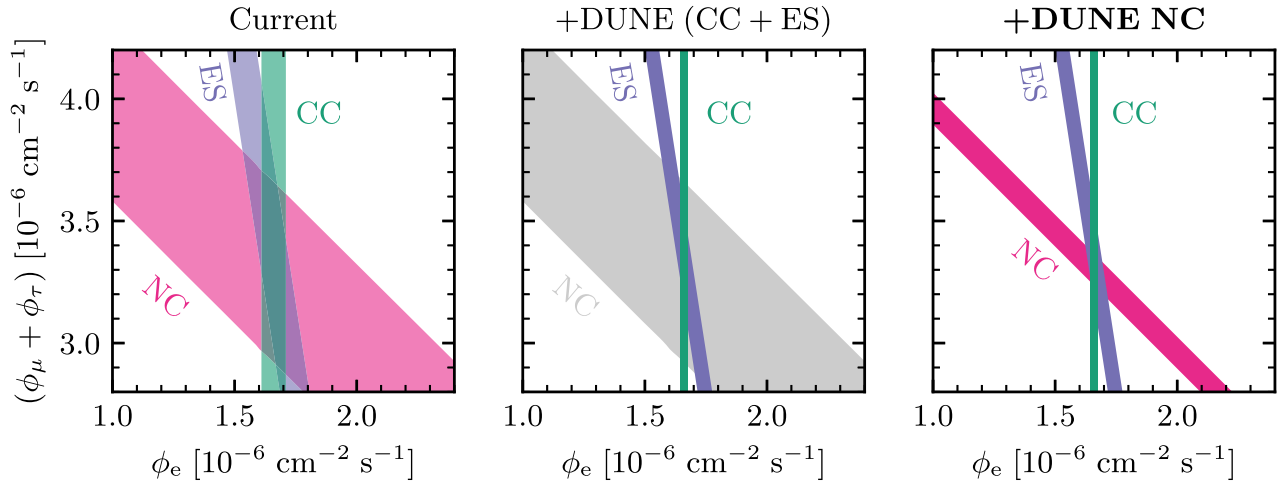


FIG. 2. The ν_e and $\nu_\mu + \nu_\tau$ content of the solar flux (statistical uncertainties only). Left: Current measurements from SNO (CC and NC) [33] and Super-Kamiokande (ES) [32,38]. Middle: Predictions for DUNE CC + ES from Ref. [18]. Right: Adding the DUNE NC measurement proposed here. Measurement of the NC rate in DUNE would have a major impact.

where * again indicates a nuclear excited state, ignoring subdominant final states where nucleons are ejected. We consider only the most detectable final states, which have excitation energies of 5–10 MeV and decay directly to the ground state by the emission of *single* gamma rays. Because of the high nuclear thresholds, the detection rate is sensitive to only the high-energy tail of the ^8B spectrum, where the electron neutrino survival probability is nearly energy independent. NC interactions are the same for all three neutrino flavors; they are somewhat different for neutrinos and antineutrinos, which could become important for exotic models of flavor change.

The total NC neutrino-nucleus cross section can be calculated from electroweak theory [39], which requires the nuclear matrix elements for the transitions of interest. These can be calculated from first principles, using the nuclear Hamiltonian and many-body theory. However, various theoretical approaches—for example, the shell model [40] or the continuum random phase approximation [41]—show discrepancies between each other and data [25]. Notably, the shell model overestimates the magnetic dipole strength by a factor of ~ 6 [26].

Therefore, we use a direct empirical approach where the nuclear matrix elements are extracted from data. This follows similar treatments of NC and CC cross sections for various nuclear targets for solar and supernova neutrinos, e.g., in Refs. [42–45]. While more detailed studies of the cross section will be needed to measure the absolute event rates, the formalism used here is adequate for establishing the prospects for DUNE.

In this empirical approach, one considers the long-wavelength ($q \rightarrow 0$) limit [40,44] and only the final states that dominate the reaction, which are picked out based on angular momentum selection rules [46]. Given that the ground state of ^{40}Ar is $J^P = 0^+$, the reaction is dominated by transitions to $J^P = 1^+$ excited states; these are all allowed Gamow-Teller (GT) transitions. In these limits, the cross section for the transition between the ground state and the j th nuclear excited state is

$$\sigma_j(E_\nu) = \frac{G_F^2}{\pi} (E_\nu - \omega_j)^2 B_j(\text{GT}). \quad (5)$$

Here E_ν is the neutrino energy, ω_j is the energy difference between the ground state and state j , G_F is the Fermi constant, and $B_j(\text{GT})$ is the Gamow-Teller strength. The axial-vector constant g_A and other factors are absorbed into $B_j(\text{GT})$ [26,44]. This approach has been shown to accurately reproduce the total all-orders cross section from shell model calculations in the energy range of solar neutrinos [26].

Computing the cross section now amounts to determining the Gamow-Teller strengths; in the long-wavelength limit, these are obtained via a simple scaling, $B_j(\text{GT}) = B(\text{M1})g_A^2/(2.2993\mu_N)^2$ [44], where $g_A = -1.267$ and the

magnetic dipole strengths, $B(\text{M1})$, can be obtained directly from experiment [26]. Because we use experimental data, we do not need to include quenching of the Gamow-Teller strength, which is used when relating theory (e.g., the shell model) to experiment [47]. To go beyond the empirical approach of using measurements of a related process, direct neutrino-nucleus measurements will ultimately be needed, as discussed in End Matter. The approach of Refs. [26,44] gives the following: (i) an excellent measurement of the excited-state energy, (ii) a value for the strength with well-controlled uncertainties, and (iii) a prescription for how the excited state decays.

A first recent key development is new measurements of the 1^+ states in ^{40}Ar up to 10 MeV using nuclear resonance fluorescence [24–26]. These measurements of the $B(\text{M1})$ strength found new states (and significantly increased strength near 10 MeV) while reducing the total uncertainty on transitions to these states from 40% to within 20%, which could be improved with new experiments. These measurements also established that these states dominantly decay directly to the ground state through the emission of single gamma rays. For the expected energy resolution of DUNE, some of these states are degenerate, though we calculate them separately. While higher-energy states may exist, they would only contribute minimally, due to the steeply falling solar-neutrino spectrum. In End Matter, we sketch the level diagram and show the relevant cross sections.

A second recent key development is that the prospects for detecting nuclear de-excitation gamma rays in liquid-argon detectors—conservatively neglected in Ref. [18]—have recently improved. In the energy range that we consider, gamma rays produce detectable signals primarily through Compton scattering and pair production. ArgoNeUT has shown experimentally that they can reconstruct MeV-range nuclear de-excitation gamma rays in liquid argon [27]. Further, Refs. [28–30] show that these gamma rays should also be detectable in DUNE.

Prospects for DUNE—DUNE will leverage the transformative power of its Liquid Argon Time Projection Chamber (LArTPC) to reconstruct events with sub-cm-scale position resolution, allowing for detailed tracking of individual particles [48–51]. Because this position resolution is much smaller than the radiation length (about 14 cm in liquid argon), it is possible to distinguish different event classes. For example, this is critical to DUNE’s ability to separate NC and CC neutrino-argon events (as sketched in Fig. 1). DUNE will initially have two modules, with two more planned to be added later, with each module having a fiducial mass of 10 kton. They will be located 1.5 km underground in the Sanford Underground Research Facility in South Dakota.

To predict the number of NC events at DUNE, we convolve the arriving neutrino flux with the NC cross section. We use the unoscillated (because this is a NC

interaction) neutrino spectrum, $d\phi_{\text{tot}}/dE_\nu$, from the BS05 (OP) solar model [52–55]. For a given Gamow-Teller transition (j), the number of NC events is

$$\mathcal{N}_{\text{NC}}^j = N_t \Delta t \int_{\omega_j} dE_\nu \frac{d\phi_{\text{tot}}}{dE_\nu}(E_\nu) \sigma_j(E_\nu), \quad (6)$$

where N_t is the number of target argon atoms and Δt is the detector live time. For the exposure, we assume 100 kton-year, equivalent to five years of live time for the initial two-module configuration.

The nuclear excitations that we consider decay predominantly via isotropic emission of a single high-energy gamma ray, corresponding to the nuclear energy level. For a particular excitation, the yield is the only observable, i.e., the only information accessible is the *integral* in Eq. (6). This means that only the ${}^8\text{B}$ flux matters as it is much larger than the *hep* flux (and the atmospheric-neutrino flux). Information about the *integrand* can be obtained by comparing the NC yields for different nuclear excitations or, more directly, via CC interactions.

Reducing backgrounds to the NC signal in DUNE will require dedicated but realistic work by experimentalists, as overviewed in Refs. [18,56–58]. We focus our attention on backgrounds that are present in the fiducial volume and thus not shielded by the outer layers of liquid argon. First, the experimentalists must reduce the large background from the radiative capture of thermal neutrons on argon (releasing 6.1 MeV in ~ 3 gamma rays [59]). This can be accomplished with at least 50 cm of hydrogenous shielding outside the detector [18,60]; this shielding need not be perfectly hermetic because the elastic scattering of neutrons in nonhydrogenous regions will often cause them to pass through (and stop) in hydrogenous regions. Second, they must reduce the large background from the (α, γ) process on argon, where the α particles arise from dissolved ${}^{222}\text{Rn}$ and where the gamma-ray energies are up to 15 MeV [58,61,62]. This can be accomplished through standard radon-mitigation techniques, which have reduced the concentrations in, e.g., Super-Kamiokande, SNO, and MicroBooNE, by several orders of magnitude [63–66]. Third, they must reduce the spallation background to the estimates of Ref. [56] by employing the ideas noted there.

With the steps above, the dominant background would be that induced by solar-neutrino CC + ES interactions. For this, we follow Ref. [18], including taking into account neutrino mixing in the Sun and Earth, which gives an energy-independent suppression during the day and an energy-dependent change during the night. The CC interactions predominantly result in an electron and a ${}^{40}\text{K}$ nucleus in a nuclear excited state, with a subleading ($< 1\%$) component with a final-state neutron and ${}^{39}\text{K}$ [29]. The excited states have energies up to 8 MeV and de-excite via the isotropic emission of *multiple* gamma rays whose

energies range between 30 keV and 2 MeV [67,68]. These low energies make the CC de-excitation gamma rays harder to detect as they produce “blips” within the detector, corresponding to low-energy Compton-scattered electrons [28,29]. This is in contrast to higher energy *single* ${}^{40}\text{Ar}$ de-excitation gamma rays from NC interactions, which are easier to detect because they produce longer electron tracks. The ES interactions result in just a single electron, which is scattered forward.

To suppress CC + ES backgrounds, we first use particle identification (PID) techniques developed to distinguish gamma rays from electrons [28–31,49,69]. Next, we apply an angular cut to remove most of the ES background [18]. In combination, these two cuts retain 80% of the signal but only 10% of the background. With dedicated studies—including using topological classifications [28,29] and tagging a specific long-lived state of ${}^{40}\text{K}$ [68]—we expect that the cuts could be much improved. Further details about PID are given in End Matter. With this approach, the signal would be smaller than the background but larger than its uncertainty. Further background reduction would be helpful but not essential.

Figure 3 shows the expected spectra in DUNE for an exposure of 100 kton-year, where we require detected energies to be above 4.5 MeV. For the x axis, we follow Ref. [70] and define the detectable energy as $E_{\text{det}} = E_e + \Sigma E_\gamma$, where only tracks that have an energy deposit above 300 keV at a single point are included, though DUNE may be able to do better [28,29]. (In contrast, Ref. [18] conservatively assumed that gamma

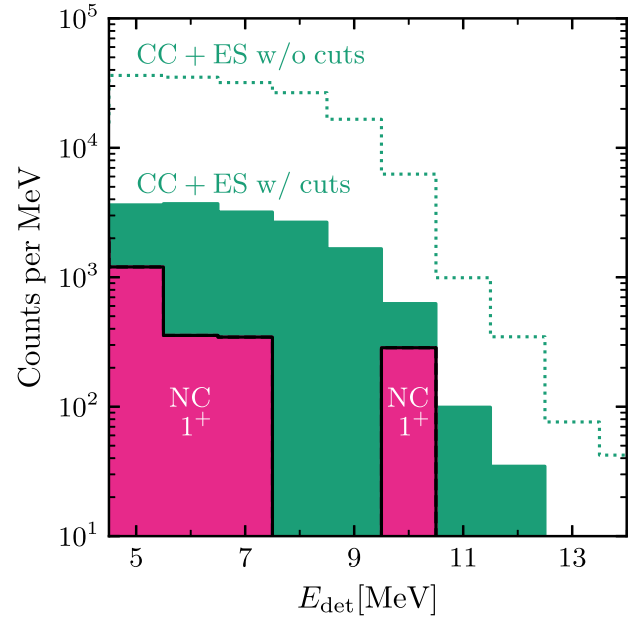


FIG. 3. Expected spectra for NC (fuschia) and CC + ES events (green) for a DUNE exposure of 100-kton-year. The solid regions show our predictions after PID and an angular cut, while the dotted line shows the CC + ES spectrum before cuts.

rays were undetectable.) *After cuts*, we predict $\simeq 2200$ NC events in total above 4.5 MeV and $\simeq 15\,000$ CC + ES events above 4.5 MeV. While 2200 is much less than 15000, it is much greater than $\sqrt{15\,000} \simeq 122$, allowing for a precise measurement of the NC signal (magenta). It helps that the NC signal near 10 MeV is narrow; it also helps that the background of residual CC + ES events (green solid, after cuts) will be independently measured with high statistics (green dotted, before cuts), which itself improves solar-neutrino measurements.

In Fig. 3, the small peak at 6 MeV in the CC + ES spectrum after cuts is caused by $\simeq 240$ captured neutrons from the rare branch of CC events with a final-state neutron. Other sources, such as the *hep*, diffuse supernova neutrino background [71], and atmospheric fluxes, are contributing in the CC (NC) channel 20 (4), 1 (0), and 0 (1) events, respectively (after cuts). Due to their low counts, we ignore them here.

To estimate DUNE's sensitivity to the solar mixing parameters, we take both statistical and systematic uncertainties into account and perform a χ^2 fit for ϕ_{tot} and $\sin^2 \theta_{12}$ because Δm_{21}^2 will be determined independently via the day-night effect in the CC + ES data [18]. Without PID and the angular cut, the dataset is dominated by CC + ES events, which allow for a high-precision measurement of the product $\phi_{\text{tot}} \sin^2 \theta_{12}$. With PID and the angular cut, the dataset has an enhanced NC fraction that allows us to break the degeneracy between those two factors.

For the fits, we generate 10^6 simulated datasets, each corresponding to an exposure of 100 kton-year, including the additional backgrounds discussed above. We assume a standard ^8B spectrum shape [72], require that the received flux be compatible with the 2% uncertainty on Super-K's

apparent ν_e flux [38], and include an energy reconstruction uncertainty of $\sigma/E \sim 10\%/\sqrt{E[\text{MeV}]} \oplus 2\%$ [28,66,73]. (Our results are not very sensitive to the assumed energy, angular, or position resolutions of DUNE.) We then perform a χ^2 fit on the datasets without and with PID and the angular cut. We use the resulting distributions of the best-fit values to calculate the mean and confidence intervals of the fit parameters. The final uncertainty is statistics dominated due to the relatively low counts of the NC events.

We assume that the neutrino-argon NC cross sections could eventually be measured to 1% precision, which is ambitious but not out of reach, given the extremely high scientific payoff (in End Matter, we show that reaching a precision of even 5% would be valuable). An eventual precision of 1% is the same that Ref. [18] assumed for the neutrino-argon CC cross section. To fully address the CC and NC cross-section uncertainties, a dedicated program of studies will be needed, ultimately including direct neutrino-nucleus measurements, as discussed in Refs. [18,74–76] and End Matter.

Figure 4 shows how the precision of the solar mixing parameters improves at successive steps, starting with the current allowed regions, then with the predictions of Ref. [18], and finally with our results. For the central values, we use the current best fits of Super-Kamiokande [38] and KamLAND [77]. The primary benefit of including the NC events is that this improves the uncertainty on $\sin^2 \theta_{12}$ from 4.5% to 1.7%. Additionally, it improves the uncertainty on the total ^8B solar neutrino flux from 5% [33] to 1.6%. For Δm_{21}^2 , the day-night effect used in Ref. [18] remains the best approach. Importantly, using CC, ES, and NC measurements in DUNE would make its solar-neutrino uncertainties much more comparable to JUNO's reactor-antineutrino

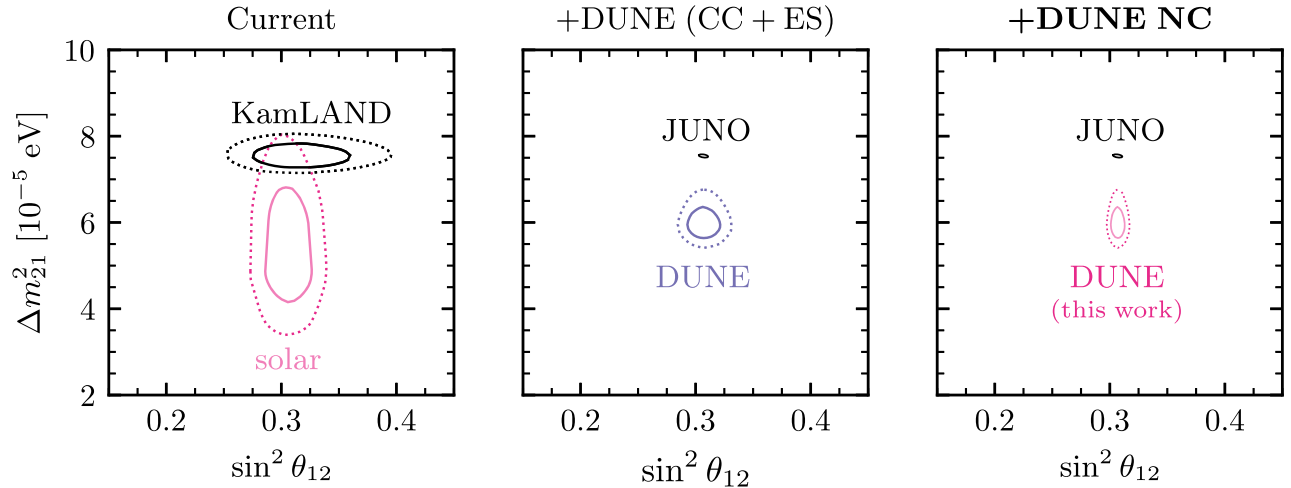


FIG. 4. Uncertainty contours (1- and 2-sigma) for the solar mixing parameters. Left panel: Current results using the combined solar neutrino data (depending mostly on Super-Kamiokande and SNO) [78] and the reactor antineutrino data of KamLAND [77]. Middle panel: Predictions for DUNE using CC + ES events [18] and for the JUNO reactor data [79]. Right panel: Our predictions for DUNE based on using the solar NC events in addition to the CC + ES events. The middle and right panels assume eventual cross-section uncertainties of 1%.

uncertainties, allowing for unprecedented tests of new physics. At present, there is a slight tension between the solar and reactor Δm_{21}^2 values. Visually, this makes the Δm_{21}^2 comparison more noticeable, but it is important to compare precision measurements of *both* $\sin^2 \theta_{12}$ and Δm_{21}^2 .

The qualitative understanding of why DUNE's NC results would be so powerful for improving the precision on $\sin^2 \theta_{12}$ is given in Fig. 2 and the text near Eqs. (1)–(3). How well one can determine the mixing angle is set by how well one can determine where the bands overlap. The overlap region is much smaller in Fig. 2(c) (after DUNE CC, ES, and NC) than it is in Fig. 2(a) (with present data). The progression in the three panels of Fig. 2 is mirrored in the three panels of Fig. 4.

We restricted our analysis to excitations in the range of 5–10 MeV. Extending this range would improve our results. Known transitions below 4.5 MeV [26] would enable the NC dataset to be approximately doubled; plus theory predicts another strong transition at 11 MeV. Additionally, since the projected uncertainty is statistics limited, additional modules would help.

Conclusions and outlook—We have shown that DUNE can measure the total active-flavor flux of ^8B solar neutrinos using NC interactions with argon. Because DUNE can also measure the surviving ν_e flux using CC interactions with argon, they would thus improve the precision of $\sin \theta_{12}$ over all previous solar measurements. No other experiment has been shown capable of doing this. Further, through the day-night effect in the CC data, DUNE would also improve the precision of Δm_{21}^2 over all previous solar measurements. As neutrino mixing physics moves into a precision era, it is crucial to have multiple independent measurements.

Comparison of the neutrino mixing parameters measured with DUNE and JUNO would allow for unprecedented tests of new physics in solar neutrinos, such as nonstandard neutrino-matter interactions [8–10], new neutrino flavors [11,80], CPT violation [12,13], neutrino decay [14,15], neutrino self-interactions [16,81], and leptonic forces [17,82,83]. Separately, improving the precision on the total ^8B flux would help better probe the temperature of the solar core [84,85]. More generally, it would help test solar models, for which there are persistent discrepancies with helioseismology and metallicity data [86–90].

Realizing DUNE's potential for these solar-neutrino measurements is challenging but realistic. It will require investments in background reduction [18,29,56,60], argon cross-section measurements [74,91–96], and event-selection studies [28,29,97]. The costs of these are very likely far below the cost of DUNE, but would substantially increase its scientific impact.

Acknowledgments—We are grateful for helpful discussions with Francesco Capozzi, David Caratelli, Shirley Li, Bryce Littlejohn, Vishvas Pandey, and Austin Schneider.

This work was supported by the Australian Research Council through Discovery Project No. DP220101727 and the University of Melbourne's Research Computing Services and the Petascale Campus Initiative. J. L. N was supported by the ARC Centre of Excellence for Dark Matter Particle Physics through CE200100008. J. F. B. was supported by U.S. National Science Foundation Grant No. PHY-2310018. J. F. B. speaks for himself as a theorist, not on behalf of the DUNE Collaboration. This work is based on the ideas and calculations of the authors, plus publicly available information.

-
- [1] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
 - [2] F. An *et al.* (JUNO Collaboration), Neutrino physics with JUNO, *J. Phys. G* **43**, 030401 (2016).
 - [3] A. Abusleme *et al.* (JUNO Collaboration), Sub-percent precision measurement of neutrino oscillation parameters with JUNO, *Chin. Phys. C* **46**, 123001 (2022).
 - [4] S. Fukasawa, M. Ghosh, and O. Yasuda, Complementarity between hyperkamiokande and DUNE in determining neutrino oscillation parameters, *Nucl. Phys.* **B918**, 337 (2017).
 - [5] K. Abe *et al.* (Hyper-Kamiokande Collaboration), Hyper-Kamiokande design report, [arXiv:1805.04163](https://arxiv.org/abs/1805.04163).
 - [6] B. Abi *et al.* (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment, *Eur. Phys. J. C* **80**, 978 (2020).
 - [7] M. Sajjad Athar *et al.*, Status and perspectives of neutrino physics, *Prog. Part. Nucl. Phys.* **124**, 103947 (2022).
 - [8] A. Friedland, C. Lunardini, and C. Pena-Garay, Solar neutrinos as probes of neutrino matter interactions, *Phys. Lett. B* **594**, 347 (2004).
 - [9] S. Abbaslu, M. Dehpour, Y. Farzan, and S. Safari, Searching for axial neutral current non-standard interactions of neutrinos by DUNE-like experiments, *J. High Energy Phys.* **04** (2024) 038.
 - [10] P. B. Denton, A. Giarnetti, and D. Meloni, Solar neutrinos and the strongest oscillation constraints on scalar NSI, *J. High Energy Phys.* **01** (2025) 097.
 - [11] A. Palazzo, Testing the very-short-baseline neutrino anomalies at the solar sector, *Phys. Rev. D* **83**, 113013 (2011).
 - [12] G. Barenboim, L. Borissov, J. D. Lykken, and A. Y. Smirnov, Neutrinos as the messengers of CPT violation, *J. High Energy Phys.* **10** (2002) 001.
 - [13] G. Barenboim, P. Martínez-Miravé, C. A. Ternes, and M. Tórtola, Neutrino CPT violation in the solar sector, *Phys. Rev. D* **108**, 035039 (2023).
 - [14] J. F. Beacom and N. F. Bell, Do solar neutrinos decay?, *Phys. Rev. D* **65**, 113009 (2002).
 - [15] A. de Gouvêa, J. Weill, and M. Sen, Solar neutrinos and ν_2 visible decays to ν_1 , *Phys. Rev. D* **109**, 013003 (2024).
 - [16] Q.-f. Wu and X.-J. Xu, Shedding light on neutrino self-interactions with solar antineutrino searches, *J. Cosmol. Astropart. Phys.* **02** (2024) 037.

- [17] S. Ansarifard, M. C. Gonzalez-Garcia, M. Maltoni, and J. P. Pinheiro, Solar neutrinos and leptonic spin forces, *J. High Energy Phys.* **07** (2024) 172.
- [18] F. Capozzi, S. W. Li, G. Zhu, and J. F. Beacom, DUNE as the next-generation solar neutrino experiment, *Phys. Rev. Lett.* **123**, 131803 (2019).
- [19] R. S. Raghavan, S. Pakvasa, and B. A. Brown, New tools for solving the solar neutrino problem, *Phys. Rev. Lett.* **57**, 1801 (1986).
- [20] J. N. Bahcall, M. Baldo-Ceolin, D. B. Cline, and C. Rubbia, Predictions for a liquid argon solar neutrino detector, *Phys. Lett. B* **178**, 324 (1986).
- [21] F. Arneodo *et al.*, Study of solar neutrinos with the 600-t liquid argon ICARUS detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **455**, 376 (2000).
- [22] D. Franco *et al.*, Solar neutrino detection in a large volume double-phase liquid argon experiment, *J. Cosmol. Astropart. Phys.* **08** (2016) 017.
- [23] A. N. Ioannisian, A. Y. Smirnov, and D. Wyler, Scanning the Earth with solar neutrinos and DUNE, *Phys. Rev. D* **96**, 036005 (2017).
- [24] T. C. Li, N. Pietralla, A. P. Tonchev, M. W. Ahmed, T. Ahn, C. Angell, M. A. Blackston, A. Costin, K. J. Keeter, J. Li, A. Lisetskiy, S. Mikhailov, Y. Parpottas, B. A. Perdue, G. Rainovski, W. Tornow, H. R. Weller, and Y. K. Wu, First evidence for spin-flip $m1$ strength in ^{40}Ar , *Phys. Rev. C* **73**, 054306 (2006).
- [25] U. Gayer, T. Beck, M. Bhihe, J. Isaak, N. Pietralla, P. C. Ries, D. Savran, M. Schilling, W. Tornow, and V. Werner, Experimental $M1$ response of ^{40}Ar as a benchmark for neutrino-nucleus scattering calculations, *Phys. Rev. C* **100**, 034305 (2019).
- [26] W. Tornow, A. P. Tonchev, S. W. Finch, Krishichayan, X. B. Wang, A. C. Hayes, H. G. D. Yeomans, and D. A. Newmark, Neutral-current neutrino cross section and expected supernova signals for ^{40}Ar from a three-fold increase in the magnetic dipole strength, *Phys. Lett. B* **835**, 137576 (2022).
- [27] R. Acciarri *et al.* (ArgoNeuT Collaboration), Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT, *Phys. Rev. D* **99**, 012002 (2019).
- [28] W. Castiglioni, W. Foreman, I. Lepetic, B. R. Littlejohn, M. Malaker, and A. Mastbaum, Benefits of MeV-scale reconstruction capabilities in large liquid argon time projection chambers, *Phys. Rev. D* **102**, 092010 (2020).
- [29] S. Gardiner, Nuclear de-excitations in low-energy charged-current ν_e scattering on ^{40}Ar , *Phys. Rev. C* **103**, 044604 (2021).
- [30] D. A. Newmark and A. Schneider, Sensitivity to supernovae average ν_x temperature with neutral current interactions in DUNE, *Phys. Rev. D* **108**, 043005 (2023).
- [31] P. Abratenko *et al.* (MicroBooNE Collaboration), Demonstration of new MeV-scale capabilities in large neutrino LArTPCs using ambient radiogenic and cosmogenic activity in MicroBooNE, *Phys. Rev. D* **111**, 032005 (2025).
- [32] K. Abe *et al.* (Super-Kamiokande Collaboration), Solar neutrino measurements in Super-Kamiokande-IV, *Phys. Rev. D* **94**, 052010 (2016).
- [33] B. Aharmim *et al.* (SNO Collaboration), Combined analysis of all three phases of solar neutrino data from the sudbury neutrino observatory, *Phys. Rev. C* **88**, 025501 (2013).
- [34] J. Zhao *et al.* (JUNO Collaboration), Model-independent approach of the JUNO ^8B solar neutrino program, *Astrophys. J.* **965**, 122 (2024).
- [35] Z. Bo *et al.* (PandaX Collaboration), First indication of solar ^8B neutrinos through coherent elastic neutrino-nucleus scattering in PandaX-4T, *Phys. Rev. Lett.* **133**, 191001 (2024).
- [36] E. Aprile *et al.* (XENON Collaboration), First indication of solar ^8B neutrinos via coherent elastic neutrino-nucleus scattering with XENONnT, *Phys. Rev. Lett.* **133**, 191002 (2024).
- [37] J. Aalbers *et al.* (XLZD Collaboration), The XLZD design book: Towards the next-generation liquid xenon observatory for dark matter and neutrino physics, [arXiv:2410.17137](https://arxiv.org/abs/2410.17137).
- [38] K. Abe *et al.* (Super-Kamiokande Collaboration), Solar neutrino measurements using the full data period of Super-Kamiokande-IV, *Phys. Rev. D* **109**, 092001 (2024).
- [39] J. S. O'Connell, T. W. Donnelly, and J. D. Walecka, Semileptonic weak interactions with C^{12} , *Phys. Rev. C* **6**, 719 (1972).
- [40] B. Dutta, W.-C. Huang, J. L. Newstead, and V. Pandey, Inelastic nuclear scattering from neutrinos and dark matter, *Phys. Rev. D* **106**, 113006 (2022).
- [41] N. Van Dessel, V. Pandey, H. Ray, and N. Jachowicz, Cross sections for coherent elastic and inelastic neutrino-nucleus scattering, *Universe* **9**, 207 (2023).
- [42] J. N. Bahcall and R. K. Ulrich, Solar models, neutrino experiments and helioseismology, *Rev. Mod. Phys.* **60**, 297 (1988).
- [43] W. Trinder *et al.*, ^{40}Ti beta decay and the neutrino capture cross-section of ^{40}Ar , *Phys. Lett. B* **415**, 211 (1997).
- [44] K. Langanke, G. Martinez-Pinedo, P. von Neumann-Cosel, and A. Richter, Supernova inelastic neutrino nucleus cross-sections from high resolution electron scattering experiments and shell model calculations, *Phys. Rev. Lett.* **93**, 202501 (2004).
- [45] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, Current unknowns in the three neutrino framework, *Prog. Part. Nucl. Phys.* **102**, 48 (2018).
- [46] E. Kolbe, K. Langanke, G. Martinez-Pinedo, and P. Vogel, Neutrino nucleus reactions and nuclear structure, *J. Phys. G* **29**, 2569 (2003).
- [47] J. Engel and J. Menéndez, Status and future of nuclear matrix elements for neutrinoless double-beta decay: A review, *Rep. Prog. Phys.* **80**, 046301 (2017).
- [48] B. Abi *et al.* (DUNE Collaboration), Deep underground neutrino experiment (DUNE), far detector technical design report, volume I introduction to DUNE, *J. Instrum.* **15**, T08008 (2020).
- [49] B. Abi *et al.* (DUNE Collaboration), Deep underground neutrino experiment (DUNE), far detector technical design report, volume II: DUNE physics, [arXiv:2002.03005](https://arxiv.org/abs/2002.03005).
- [50] B. Abi *et al.* (DUNE Collaboration), Deep underground neutrino experiment (DUNE), far detector technical design report, volume III: DUNE far detector technical coordination, *J. Instrum.* **15**, T08009 (2020).

- [51] B. Abi *et al.* (DUNE Collaboration), Deep underground neutrino experiment (DUNE), far detector technical design report, volume IV: Far detector single-phase technology, *J. Instrum.* **15**, T08010 (2020).
- [52] J. N. Bahcall, Gallium solar neutrino experiments: Absorption cross-sections, neutrino spectra, and predicted event rates, *Phys. Rev. C* **56**, 3391 (1997).
- [53] W. T. Winter, S. J. Freedman, K. E. Rehm, and J. P. Schiffer, The ^8B neutrino spectrum, *Phys. Rev. C* **73**, 025503 (2006).
- [54] J. N. Bahcall, A. M. Serenelli, and S. Basu, New solar opacities, abundances, helioseismology, and neutrino fluxes, *Astrophys. J. Lett.* **621**, L85 (2005).
- [55] BS05(OP) solar model, <https://www.sns.ias.edu/~jnb/SNdata/sndata.html#b8survival>, accessed: 2024-08-01.
- [56] G. Zhu, S. W. Li, and J. F. Beacom, Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds, *Phys. Rev. C* **99**, 055810 (2019).
- [57] S. Parsa *et al.*, SoLAr: Solar neutrinos in liquid argon, in *Snowmass 2021* (2022), [arXiv:2203.07501](https://arxiv.org/abs/2203.07501).
- [58] D. Caratelli *et al.*, Low-energy physics in neutrino LArTPCs, [arXiv:2203.00740](https://arxiv.org/abs/2203.00740).
- [59] H. Lycklama, N. P. Archer, and T. J. Kennett, The $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ reaction, *Nucl. Phys. A* **100**, 33 (1967).
- [60] L. Manzanillas and M. Martin, Shielding materials for neutron background reduction in DUNE (2024), https://indico.fnal.gov/event/65305/contributions/294859/attachments/179206/244579/DUNE_neutron_background_LE_2024_06_26.pdf.
- [61] J. Reichenbacher, J. Stock, and J. Haiston, External radioactive calibration sources in DUNE far detector (2018), https://indico.fnal.gov/event/16087/contributions/35748/attachments/22155/27520/DUNE_radioactiveSources_calibrationWorkshopFermilab_15Mar2018_JR.pptx.pdf.
- [62] S. Westerdale and J. Reichenbacher, Radiological backgrounds in DUNE far detectors (2024), https://indico.sanfordlab.org/event/68/contributions/1523/attachments/813/2044/cosurf24_westerdale.pdf.
- [63] Y. Takeuchi *et al.* (SuperKamiokade Collaboration), Measurement of radon concentrations at Super-Kamiokande, *Phys. Lett. B* **452**, 418 (1999).
- [64] I. Blevis *et al.*, Measurement of ^{222}Rn dissolved in water at the sudbury neutrino observatory, *Nucl. Instrum. Methods Phys. Res., Sect. A* **517**, 139 (2004).
- [65] P. Abratenko *et al.* (MicroBooNE Collaboration), Observation of radon mitigation in MicroBooNE by a liquid argon filtration system, *J. Instrum.* **17**, P11022 (2022).
- [66] P. Abratenko *et al.* (MicroBooNE Collaboration), Measurement of ambient radon progeny decay rates and energy spectra in liquid argon using the MicroBooNE detector, *Phys. Rev. D* **109**, 052007 (2024).
- [67] M.-K. Cheoun, E. Ha, and T. Kajino, Reactions on ^{40}Ar involving solar neutrinos and neutrinos from core-collapsing supernovae, *Phys. Rev. C* **83**, 028801 (2011).
- [68] Live Chart of Nuclides nuclear structure and decay data, <https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>, accessed: 2024-08-01.
- [69] R. Acciarri *et al.* (ArgoNeuT Collaboration), First observation of low energy electron neutrinos in a liquid argon time projection chamber, *Phys. Rev. D* **95**, 072005 (2017).
- [70] C. Anderson *et al.*, The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab, *J. Instrum.* **7**, P10019 (2012).
- [71] J. F. Beacom, The diffuse supernova neutrino background, *Annu. Rev. Nucl. Part. Sci.* **60**, 439 (2010).
- [72] C. E. Ortiz, A. Garcia, R. A. Waltz, M. Bhattacharya, and A. K. Komives, Shape of the ^8B alpha and neutrino spectra, *Phys. Rev. Lett.* **85**, 2909 (2000).
- [73] W. Foreman *et al.* (LArIAT Collaboration), Calorimetry for low-energy electrons using charge and light in liquid argon, *Phys. Rev. D* **101**, 012010 (2020).
- [74] P. S. Barbeau, Y. Efremenko, and K. Scholberg, COHERENT at the spallation neutron source, *Annu. Rev. Nucl. Part. Sci.* **73**, 41 (2023).
- [75] P. An *et al.* (COHERENT Collaboration), Measurement of $^{nat}\text{Pb}(\nu e, Xn)$ production with a stopped-pion neutrino source, *Phys. Rev. D* **108**, 072001 (2023).
- [76] P. An *et al.* (COHERENT Collaboration), Measurement of electron-neutrino charged-current cross sections on ^{127}I with the COHERENT NaI ν E Detector, *Phys. Rev. Lett.* **131**, 221801 (2023).
- [77] A. Gando *et al.* (KamLAND Collaboration), Constraints on θ_{13} from a three-flavor oscillation analysis of reactor anti-neutrinos at KamLAND, *Phys. Rev. D* **83**, 052002 (2011).
- [78] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola, and J. W. F. Valle, 2020 global reassessment of the neutrino oscillation picture, *J. High Energy Phys.* **02** (2021) 071.
- [79] F. Capozzi, E. Lisi, and A. Marrone, Neutrino mass hierarchy and precision physics with medium-baseline reactors: Impact of energy-scale and flux-shape uncertainties, *Phys. Rev. D* **92**, 093011 (2015).
- [80] K. Goldhagen, M. Maltoni, S. E. Reichard, and T. Schwetz, Testing sterile neutrino mixing with present and future solar neutrino data, *Eur. Phys. J. C* **82**, 116 (2022).
- [81] J. M. Berryman *et al.*, Neutrino self-interactions: A white paper, *Phys. Dark Universe* **42**, 101267 (2023).
- [82] J. A. Grifols and E. Masso, Neutrino oscillations in the sun probe long range leptonic forces, *Phys. Lett. B* **579**, 123 (2004).
- [83] M. C. Gonzalez-Garcia, P. C. de Holanda, E. Masso, and R. Zukanovich Funchal, Probing long-range leptonic forces with solar and reactor neutrinos, *J. Cosmol. Astropart. Phys.* **01** (2007) 005.
- [84] J. N. Bahcall and A. Ulmer, The temperature dependence of solar neutrino fluxes, *Phys. Rev. D* **53**, 4202 (1996).
- [85] M. Wurm, Solar neutrino spectroscopy, *Phys. Rep.* **685**, 1 (2017).
- [86] S. Basu and H. M. Antia, Helioseismology and solar abundances, *Phys. Rep.* **457**, 217 (2008).
- [87] J. L. van Saders and M. H. Pinsonneault, The sensitivity of convection zone depth to stellar abundances: An absolute stellar abundance scale from asteroseismology, *Astrophys. J.* **746**, 16 (2012).
- [88] M. Bergemann and A. Serenelli, Solar abundance problem, [arXiv:1403.3097](https://arxiv.org/abs/1403.3097).
- [89] J. Christensen-Dalsgaard, Solar structure and evolution, *Living Rev. Solar Phys.* **18**, 2 (2021).
- [90] G. D. O. Gann, K. Zuber, D. Bemmerer, and A. Serenelli, The future of solar neutrinos, *Annu. Rev. Nucl. Part. Sci.* **71**, 491 (2021).

- [91] C. Grant and B. Littlejohn, Opportunities with decay-at-rest neutrinos from decay-in-flight neutrino beams, *Proc. Sci. ICHEP2016* (2016) 483 [arXiv:1510.08431].
- [92] D. Baxter *et al.*, Coherent elastic neutrino-nucleus scattering at the European spallation source, *J. High Energy Phys.* **02** (2020) 123.
- [93] A. A. Aguilar-Arevalo *et al.* (CCM Collaboration), First dark matter search results from coherent CAPTAIN-Mills, *Phys. Rev. D* **106**, 012001 (2022).
- [94] S. Ajimura *et al.* (JSNS2 Collaboration), The JSNS2 detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1014**, 165742 (2021).
- [95] K. J. Kelly, P. A. N. Machado, A. Marchionni, and Y. F. Perez-Gonzalez, LEvEL: Low-energy neutrino experiment at the LHC, *J. High Energy Phys.* **08** (2021) 087.
- [96] A. Abed Abud *et al.* (DUNE Collaboration), Impact of cross-section uncertainties on supernova neutrino spectral parameter fitting in the deep underground neutrino experiment, *Phys. Rev. D* **107**, 112012 (2023).
- [97] C. Rott, D. Jeong, J. Kumar, and D. Yaylali, Neutrino topology reconstruction at DUNE and applications to searches for dark matter annihilation in the sun, *J. Cosmol. Astropart. Phys.* **07** (2019) 006.
- [98] S. Gardiner, Simulating low-energy neutrino interactions with MARLEY, *Comput. Phys. Commun.* **269**, 108123 (2021).
- [99] M. Bhattacharya, C. D. Goodman, and A. Garcia, Weak-interaction strength from charge-exchange reactions versus beta decay in the $A = 40$ isoquintet, *Phys. Rev. C* **80**, 055501 (2009).
- [100] M.-K. Cheoun, E. Ha, and T. Kajino, High-Lying excited states in Gamow Teller strength and their roles in neutrino reactions, *Eur. Phys. J. A* **48**, 137 (2012).
- [101] M. Bhattacharya, A. García, N. I. Kaloskamis, E. G. Adelberger, H. E. Swanson, R. Anne, M. Lewitowicz, M. G. Saint-Laurent, W. Trinder, C. Donzau, D. Guillemaud-Mueller, S. Leenhardt, A. C. Mueller, F. Pougheon, and O. Sorlin, Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti , *Phys. Rev. C* **58**, 3677 (1998).
- [102] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).

End Matter

Appendix—Here we provide additional details about (i) the NC neutrino-argon cross section; (ii) particle-identification techniques, and (iii) the dependence of our results on the NC cross-section uncertainty.

Neutrino-argon cross sections—Figure 5 sketches the basic nuclear physics of the NC interaction channel in argon. Figure 6 shows the NC cross section for 5–10 MeV 1^+ excitations compared to the NC cross section, including lower-energy 1^+ excitations that lead to lower-energy gamma rays. We also compare to the total CC cross section (for transitions to bound excited states in ^{40}K) from Refs. [29,98] (which build on Refs. [99,100]). The total CC cross section is much larger than the NC cross sections because the total strength for the CC nuclear transitions up

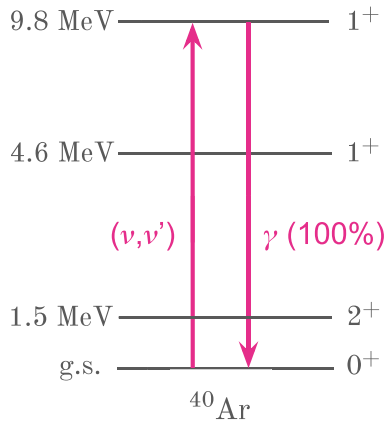


FIG. 5. Greatly simplified diagram of the nuclear states in ^{40}Ar , showing one example of NC excitation by neutrinos and de-excitation by single gamma-ray emission.

to 15 MeV is $B(\text{F} + \text{GT}) = 9.7$ [101], much larger than for the NC cases.

Within plausible uncertainties, a change in the *values* of the Gamow-Teller strengths that we use could be compensated by a plausible change in the required exposure (we conservatively assume five years and two modules). What is critical are the *uncertainties* of the strengths, which have

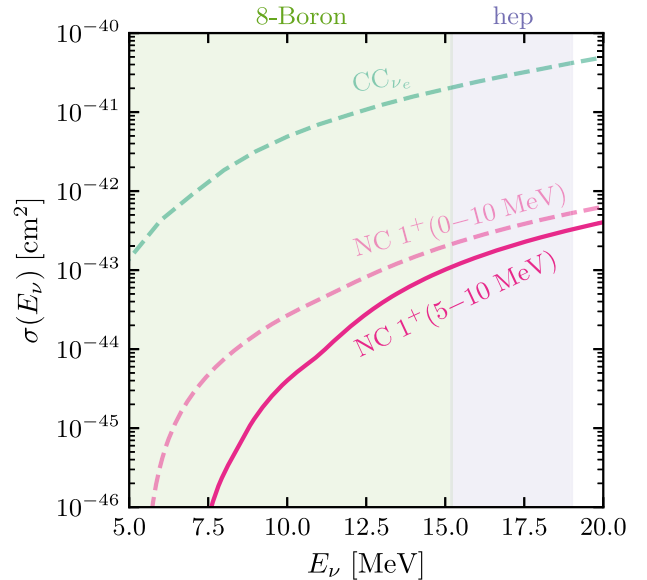


FIG. 6. NC neutrino-argon cross section for the 5–10 MeV 1^+ excitations that we consider. For comparison, we also show the NC cross section including lower-energy 1^+ excitations as well as the CC cross section. We note the energy ranges where different solar fluxes dominate in the parent neutrino spectra.

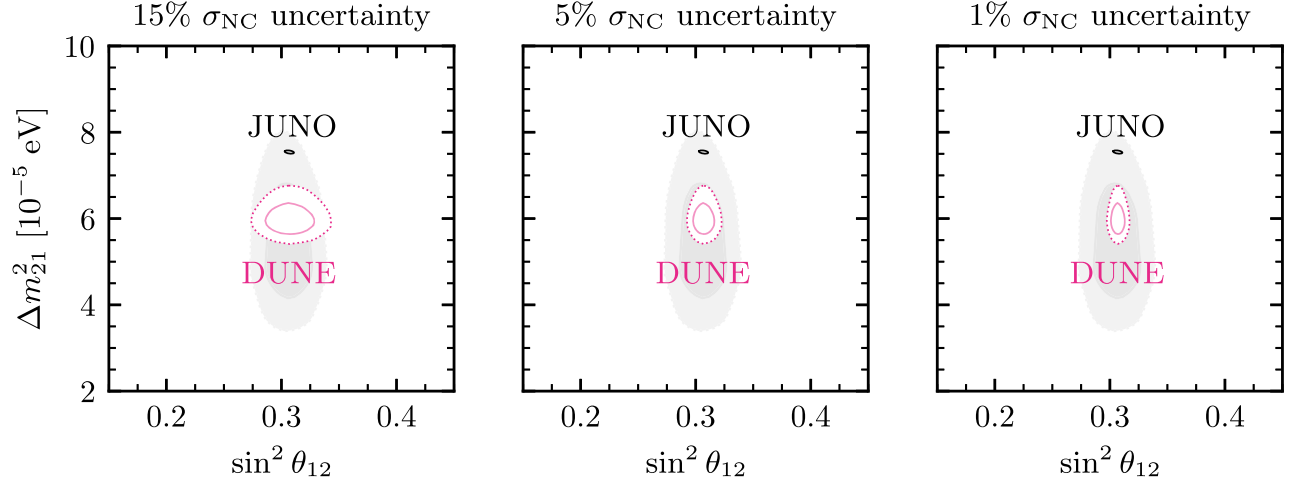


FIG. 7. Same as Fig. 4 right, with 15%, 5%, and 1% uncertainties on the NC neutrino-argon cross section (all assuming a 1% uncertainty on the CC neutrino-argon cross section, following Ref. [18]). In faint gray, we show the contours for the present solar mixing parameters.

to be small to realize DUNE’s unique potential to probe the mixing angle.

Ultimately, the precision of the CC and NC cross sections must be improved by a detailed program of experimental and theoretical work [18,74–76]. This will be challenging, but the payoff for DUNE would be huge, not just for solar neutrinos but also for extracting information from a supernova neutrino burst, one of DUNE’s three core goals. We expect that the opportunities for small- to medium-scale experimental and theoretical efforts on cross-section uncertainties to leverage the impact of the multi-\$1B investments in DUNE will therefore be very attractive.

Particle identification—We implement a basic form of particle identification to suppress backgrounds, expecting that it will be improved by the experimentalists. Using GEANT4 [102], we track the propagation of final-state particles from NC, CC, and ES interactions. The key task is to distinguish gamma rays from electrons, taking into account the excellent position resolution (sub-cm) of liquid-argon detectors. There are two relevant cases for particle identification: (i) where a gamma ray deposits all of its energy via Compton scattering and (ii) where a gamma ray converts to an electron-positron pair. The likelihood of pair conversion is $< 30\%$ at 5 MeV and rises to $> 80\%$ at 10 MeV [1].

Gamma rays that deposit energy purely via Compton scattering produce multiple low-energy electrons, which typically appear as multiple discrete short tracks, some of which are below the spatial resolution of DUNE [28,29]. This is unlike the spatially resolvable, multi-cm tracks generated by electrons produced in CC and ES events. It is also unlike the very short electron energy depositions caused by the low-energy gamma rays produced in CC interactions. In this case (Compton scattering), we assume a

100% separation efficiency between the high-energy gamma rays produced in NC interactions and the electron tracks produced in CC and ES interactions.

In some events, the gamma ray produces an electron-positron pair, which typically leads to recognizable multi-cm electron tracks. We follow Refs. [30,49,69], who showed that ionizing electron-positron pairs could be cleanly separated from single ionizing electrons by their $|dE/dx|$ values. The differences in $|dE/dx|$ arise from the number of minimally ionizing particles, each having an expected energy loss of 2 MeV/cm. Using GEANT4 but not a full detector simulation, we find that cutting at 3.1 MeV/cm retains 95% of the NC events with pair production and only 16% of the CC + ES events, consistent with Ref. [30], which considered the same Gamow-Teller NC transitions for supernovae neutrino detection. The true dE/dx -based separation at low energies is more challenging due to the discreteness of charge-collection elements, the temporal shaping of LArTPC waveforms, and the nonstraight trajectories of low-energy electrons. This can be improved by using topology and timing rather than relying solely on a dE/dx -based approach alone and can be a topic of future Letter.

Systematics—Figure 7 shows how the precision on $\sin^2 \theta_{12}$ depends on the assumed uncertainty on the NC neutrino-argon cross section. We show three cases, assuming 15% (close to the current uncertainty [25,26]), 5% (a reasonable improvement), and 1% (the ideal case). Once the cross-section uncertainty is below $\sim 3\%$, it is no longer a limiting factor compared to event statistics.

When aiming for 1% precision, other factors will become important, including the uncertainty on the size of the fiducial volume, which can be largely overcome by considering the ratios of the CC, ES, and NC rates.