DUNE as the Next-Generation Solar Neutrino Experiment

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We show that the Deep Underground Neutrino Experiment (DUNE), with significant but feasible new efforts, has the potential to deliver world-leading results in solar neutrinos. With a 100 kton-yr exposure, DUNE could detect $\gtrsim 10^5$ signal events above 5 MeV electron energy. Separate precision measurements of neutrino-mixing parameters and the ^{8}B flux could be made using two detection channels ($\nu_e + {}^{40}$Ar and $\nu_{e,\mu,\tau} + e^-$) and the day-night effect ($>10\sigma$). New particle physics may be revealed through the comparison of solar neutrinos (with matter effects) and reactor neutrinos (without), which is discrepant by $\sim 2\sigma$ (and could become 5.6σ). New astrophysics may be revealed through the most precise measurement of the ^{8}B flux (to 2.5%) and the first detection of the hep flux (to 11%). DUNE is required: No other experiment, even proposed, has been shown capable of fully realizing these discovery opportunities.

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Introduction.—Tremendous scientific opportunities remain in solar neutrinos. What are the particle properties of neutrinos? What are the nuclear processes that power our Sun and other stars? Although the basics are known [1–6], there are multiple unknowns and discrepancies. To progress, we need precise measurements of all neutrino-producing processes, plus ways to isolate new physics from new astrophysics. Here we focus on high energies (>5 MeV electron energy).

For particle physics, the primary opportunity is to test for new physics through a precision comparison of neutrino-mixing parameters [7–14] measured in solar versus reactor experiments. Figures 1 and 2 preview this. There is a $\sim 2\sigma$ discrepancy for Δm^2_{21} [6,15–17]. The reactor measurement will soon be greatly improved by the Jiangmen Underground Neutrino Observatory (JUNO) experiment [18], but testing new physics depends on improving the solar measurement, too. The contrast in physical conditions is striking: neutrinos versus antineutrinos, matter versus vacuum mixing, plus a much larger distance, giving sensitivity to *CPT* violation [7,8], nonstandard neutrino interactions [9,19], neutrino decay [20,21], and more.

For astrophysics, the primary opportunity is to make an independent precise measurement of the ^{8}B flux, which is extremely sensitive to the solar core temperature ($\sim T_c^{25}$ [23]) and which is an important ingredient for resolving the solar-metallicity discrepancy (requiring also progress on the ^{7}Be and CNO fluxes) [24–28]. Discovery of the hep flux [24–30], the highest-energy neutrino process, would probe physical conditions far from the solar center while still having large matter effects.

How can these opportunities be realized, especially simultaneously? This requires a new multi-10-kton-scale experiment, plus breakthroughs in detection strategy.

We propose that the Deep Underground Neutrino Experiment (DUNE)—intended to make transformative studies of GeV long-baseline neutrino mixing, proton decay, and supernova neutrino bursts [31–33]—has the potential to do the same for solar neutrinos. The budgeted plans for DUNE provide a large active volume, a huge overburden, and excellent technical capabilities, including at MeV energies (for supernovae) [31–33]. For solar neutrinos, DUNE would need new investments, detailed below, that would also enhance its planned programs. Building on prior work on solar neutrino detection in liquid argon [34–37], our Letter goes much further.

We review the challenges in solar neutrinos, outline our proposed strategy for DUNE, calculate the signals and backgrounds, calculate the physics reach, define technical requirements, and conclude. To show what DUNE could achieve, we calculate our main results under optimistic but feasible assumptions; we also discuss the impact of varying these assumptions. In Supplemental Material [38] and a separate paper on backgrounds [39], we provide further details. Further technical studies will be needed.

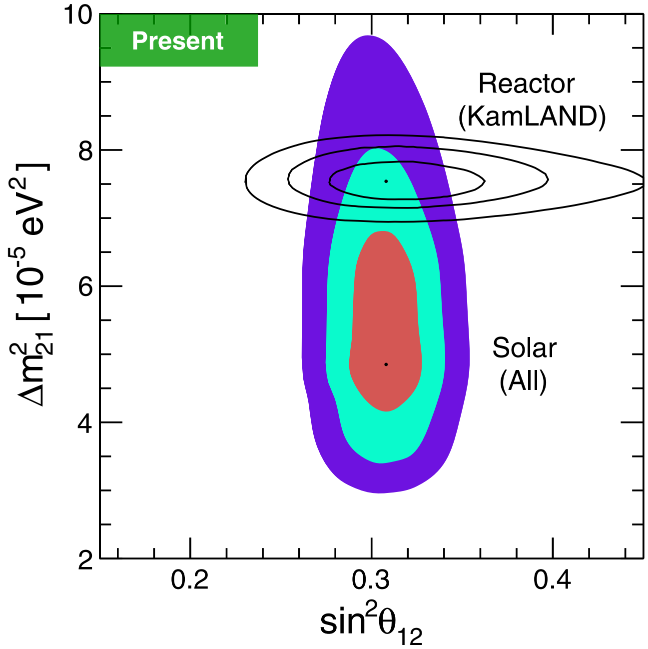

FIG. 1. Present measurements (1, 2, and 3σ) of neutrino mixing with solar [1–6] and reactor [15] neutrinos.

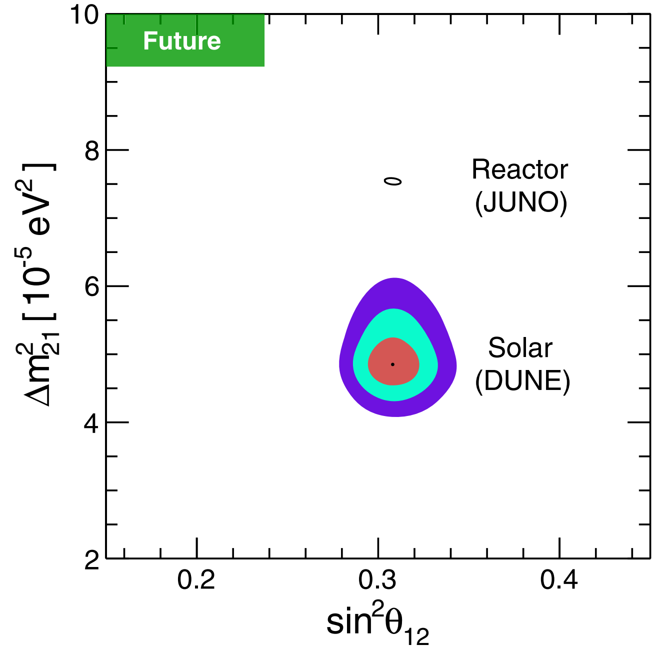

FIG. 2. Future precision of neutrino mixing with solar (DUNE alone; 1, 2, and 3σ) and reactor (JUNO alone; 3σ [18,22]) neutrinos, using present best-fit points and 100 kton-yr for each.

Solar neutrinos: Status and obstacles.—The fundamental challenge in solar neutrinos is disentangling neutrino-mixing effects and source properties. Super-Kamiokande (Super-K) and Sudbury Neutrino Observatory (SNO) measurements of ^{8}B neutrinos dominate the precision of solar determinations of $\sin^2\theta_{12}$ and Δm^2_{21}, as well as $\phi(^8\mathrm{B})$, the total ^{8}B flux [5,6,12,40,41]. The hep flux, $\phi(\mathrm{hep}) \sim 10^{-3}\phi(^8\mathrm{B})$, has not been detected [42,43].

Super-K and SNO measurements are consistent with an energy-independent ν_e survival probability $P_{ee} \simeq \sin^2\theta_{12}$; the lack of an observed upturn in P_{ee} at low energies sets a weak upper limit on Δm^2_{21} [5,6]. Within the theoretical framework of matter-affected neutrino mixing [44–49], these results are consistent with lower-energy solar neutrino data [1–4]. Two other results were key.

(1) SNO separately measured $\phi(^8\mathrm{B})$ and $\sin^2\theta_{12}$ using two channels: $\nu_{e,\mu,\tau} + d \to \nu_{e,\mu,\tau} + p + n$, which is equally sensitive to all active flavors and, hence, measures the total flux, and $\nu_e + d \to e^- + p + p$, from which they can then extract the mixing angle. Progress on $\sin^2\theta_{12}$ is limited primarily by SNO's final precision for $\phi(^8\mathrm{B})$ of $\simeq$4% ($\simeq$3% statistical) and partially by the 1.7% systematic uncertainty on the elastic-scattering channel in Super-K [5,6,12,40].

(2) Super-K best constrains Δm^2_{21} by measuring the day-night flux asymmetry (at $\simeq 3\sigma$) [6] with the $\nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^-$ channel, where P_{ee} at night is increased by several percent due to the matter effect in Earth [49–52]. Progress is limited by the slow increase in statistics after 20 years of exposure.

Unique advantages of DUNE.—DUNE will be in the Homestake mine in South Dakota (4300 m.w.e.). Each of two liquid-argon (LAr) modules (eventually four) will have a fiducial mass of 10 kton, surrounded by ~1 m LAr shielding (details depend on single or dual phase). Readout is by the time-projection technique—here, drifting charge deposited in the volume onto wire planes at the boundaries—plus prompt detection of scintillation light [31–33,53].

DUNE can simultaneously measure neutrino-mixing parameters and solar neutrino fluxes. Here, we first state our underlying ideas and simple estimates.

(a) The degeneracy between $\sin^2\theta_{12}$ and $\phi(^8\mathrm{B})$ can be broken using two detection channels:

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*, \tag{1}$$

where the rate $R_{\mathrm{Ar}} \propto \phi(^8\mathrm{B}) \sin^2\theta_{12}$, and

$$\nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^-, \tag{2}$$

where $R_e \propto \phi(^8\mathrm{B})(\sin^2\theta_{12} + \frac{1}{6}\cos^2\theta_{12})$. These channels can be adequately separated with a crude angular cut. Though the dependence on the $\nu_{\mu,\tau}$ content is weak, DUNE can improve on SNO due to its huge statistics. Figure 3 illustrates this.

(b) Δm^2_{21} can be isolated through the day-night flux asymmetry, $A_{D-N} = (D-N)/\frac{1}{2}(D+N)$, which scales as $\propto E_\nu/\Delta m^2_{21}$. For the solar Δm^2_{21}, an exposure of 100 kton-yr, and using only events above 6 MeV electron energy (effective threshold; see below) and outside the

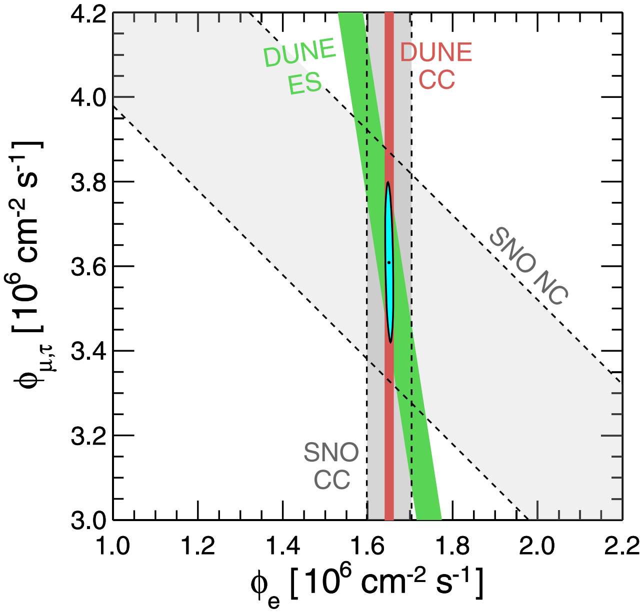

FIG. 3. Estimated precision of the ν_e and $\nu_{\mu,\tau}$ content of the ^{8}B flux, present (SNO [5,54]) and future (DUNE), with the ellipse for DUNE alone. Based on a simplified analysis, with only statistical uncertainties (1σ) but assuming 2 d.o.f., and with SNO fluxes slightly rescaled to match their global-fit ^{8}B flux. Note the small axis ranges. Full analysis in the text.

forward cone, we expect $D = 3.04 \times 10^4$ and $N = 3.29 \times 10^4$ signal $\nu_e + {}^{40}$Ar events, along with 0.83×10^4 background events in total (as detailed below, and conservatively including $\nu_{e,\mu,\tau} + e^-$ events). Considering for now only statistical uncertainties, we expect $A_{D-N} \simeq -(7.9 \pm 0.8)\%$ ($\sim 10\sigma$). DUNE can improve on Super-K, because the $\nu_e + {}^{40}$Ar channel has a larger cross section, emphasizes larger neutrino energies, and has a tighter relation between neutrino and electron energy.

Solar neutrinos in DUNE.—The MeV-range capabilities of DUNE [31–33] are designed for detecting supernova neutrinos. Above 5 MeV, we assume electrons can be detected with high efficiency and 7% energy-independent energy resolution [33]. For solar signals, electrons lose energy dominantly by ionization, as the critical energy of LAr is 32 MeV [55–57]. The angular resolution of DUNE is uncertain; we adopt 25°, based on ICARUS simulations [35]. Below, we discuss the impact of different assumptions.

We use neutrino spectra from Refs. [58,59] and radial distributions from the BS05(OP) model of Refs. [25,26]. As nominal fluxes, we use $\phi(^8\mathrm{B}) = 5.25 \times 10^6$ cm^{-2} s^{-1} (4% uncertainty, from SNO [5]) and $\phi(\mathrm{hep}) = 8.25 \times 10^3$ cm^{-2} s^{-1} (30% uncertainty, from theory [28,30]). The end point energies are $\simeq 15$ and $\simeq 19$ MeV.

For the charged-current (CC) channel $\nu_e + {}^{40}$Ar [60–74], the ground state threshold is $Q_{\mathrm{g.s.}} = 1.5$ MeV [75], but this transition is forbidden. The cross section is dominated by transitions to nuclear excited states in ^{40}K* (a super-allowed Fermi transition with $\Delta E_i = 4.4$ MeV, plus several Gamow-Teller transitions), which promptly produce gamma rays by nuclear deexcitation. Because of these nuclear thresholds, DUNE is most sensitive to $E_\nu \gtrsim 9$ MeV. We define the detectable energy of an event as the electron kinetic energy T_e, given by $T_e = E_\nu - Q$, where $Q = Q_{\mathrm{g.s.}} + \Delta E_i$, conservatively neglecting the detectability of the ΔE_i in gamma rays (if these gamma rays were detectable, that would dramatically improve event identification, background rejection, energy reconstruction, and sensitivity). The electrons are emitted near isotropically. Details, including cross section uncertainties, are discussed below and in Supplemental Material [38].

For the elastic-scattering (ES) channel $\nu_{e,\mu,\tau} + e^-$, there is no threshold, and the cross section is known with subpercent precision [76]. All flavors participate, but the sensitivity to the $\nu_{\mu,\tau}$ content is reduced, as these have only neutral-current couplings. DUNE is sensitive to $E_\nu \gtrsim 5$ MeV, though the broad differential cross section effectively raises that. The direction of the scattered electron is well correlated to the neutrino direction, with a maximum scattering angle of about 20°. We adequately separate $\nu_{e,\mu,\tau} + e^-$ and $\nu_e + {}^{40}$Ar events by defining a forward cone of half-angle 40°, maximizing the signal to background ratios for both event categories in the cone away from the Sun and its complement. Inside the cone, which includes 81% of $\nu_{e,\mu,\tau} + e^-$ events [35], they dominate; outside the cone, which includes 88% of $\nu_e + {}^{40}$Ar events, they dominate.

In principle, DUNE could use the neutral-current (NC) channel $\nu_{e,\mu,\tau} + {}^{40}\mathrm{Ar} \to \nu_{e,\mu,\tau} + {}^{40}\mathrm{Ar}^*$, where the final state is detected through nuclear gamma rays [68,70,77]. We treat this as a background because the cross section seems small. If not, this could be an important new signal.

Backgrounds must be mitigated with standard MeV-detector techniques: defining a fiducial volume, removing U and Th from liquids and Rn from air, selecting low-background materials, applying dead time after high-energy events, etc. [1–6,15,18,78,79]. Three important backgrounds will remain (details in Supplemental Material [38] and Ref. [39]). First are neutron captures on ^{40}Ar, releasing a total of 6.1 MeV in several gamma rays [80–82]; these Compton scatter or pair-produce electrons. These neutrons, most less than a few MeV, are dominantly produced by (α, n) interactions in the rock following U- and Th-chain decays [35,83,84]; muon-induced neutrons are relatively negligible [39]. Once neutrons enter the detector, they fill the volume, due to their small cross section on argon. We assume a hermetic, passive water (or oil or plastic) shield of 40-cm thickness, reducing this background by $\sim 4 \times 10^3$. Below, we show that even no shielding is acceptable. Second, neutral-current $\nu_{e,\mu,\tau} + {}^{40}$Ar events cause a peak near 9 MeV [77]. Third, at the highest energies, are beta-decaying radioactivities

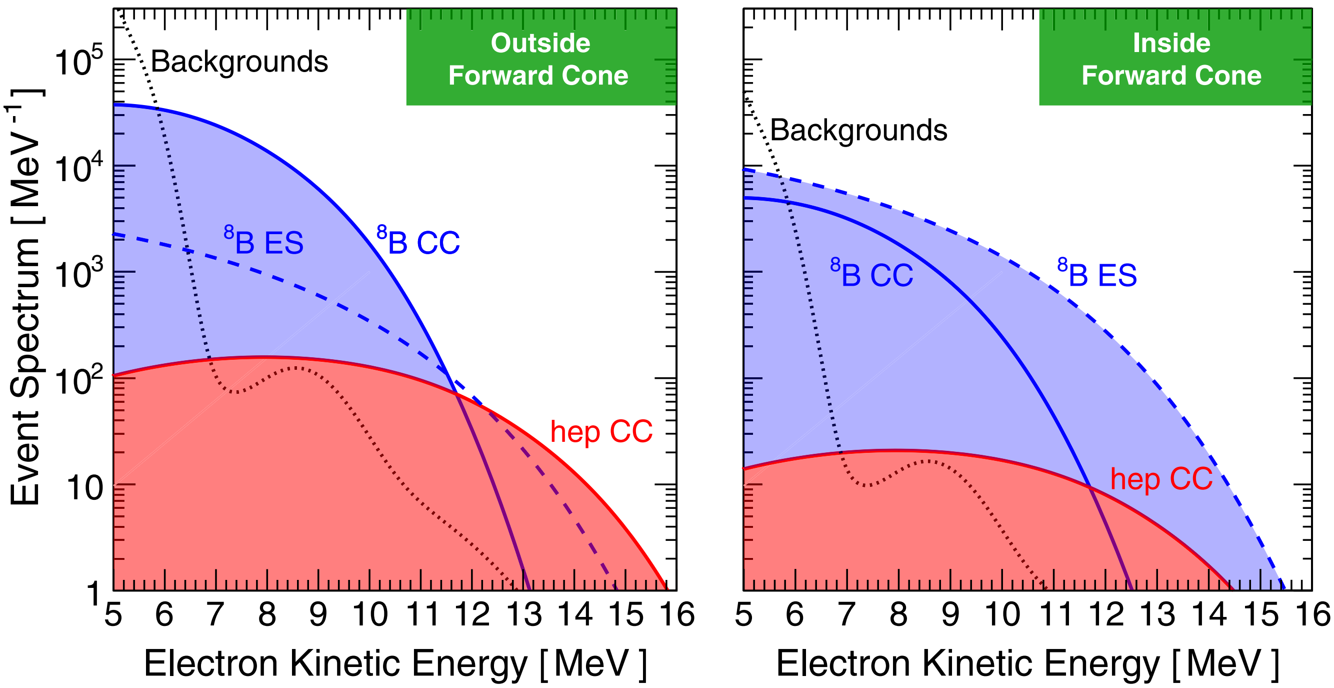

FIG. 4. Predicted solar neutrino signals and backgrounds in DUNE for 100 kton-yr, using a forward cone of half-angle 40° and (here only) combining day and night data. We include all factors discussed in the text.

induced by muons [39,85–87], for which we apply simple cuts. The pileup rates from these and other backgrounds (e.g., ^{39}Ar and ^{42}Ar decays) are negligible [39].

Figure 4 shows the solar neutrino signal and background spectra in DUNE. Our calculations include three-flavor neutrino mixing [44–51], realistic detection effects (differential cross sections [69,88–90], energy smearing, angular cuts [35], background reduction [75,91–104]), and a 100 kton-yr exposure.

For ^{8}B events, the two channels are well separated and have superb yields above 5 MeV electron energy. For $\nu_e + {}^{40}$Ar, there are 9.9×10^4 events outside the forward cone. For $\nu_{e,\mu,\tau} + e^-$, there are 2.6×10^4 events inside the forward cone. This channel provides better sensitivity to lower-energy neutrinos and the only sensitivity to $\nu_{\mu,\tau}$. For hep events, the $\nu_e + {}^{40}$Ar channel allows a clear separation at high electron energies, with 150 events above 11 MeV (the small $\nu_{e,\mu,\tau} + e^-$ channel is not shown).

DUNE physics reach.—DUNE can significantly improve the precision of solar neutrino observables. We jointly fit (without priors) four parameters: $\sin^2\theta_{12}$, Δm^2_{21}, $\phi(^8\mathrm{B})$, and $\phi(\mathrm{hep})$. When reporting projected uncertainties for n parameters, we marginalize over the others, adopting $\Delta\chi^2$ confidence levels for n d.o.f. We assume that new physics affecting solar neutrinos is reflected in mixing-parameter values that differ from the reactor values. We use the theoretically expected counts for signals and backgrounds, with Poisson uncertainties (below, we discuss systematics). We partition data into bins of energy, bins of Earth zenith angle (night only), and outside or inside the forward cone (as in Fig. 4). We use the total electron spectra, assuming only statistical separation of the components and not requiring neutrino-energy reconstruction.

Figure 2 shows the projected precision for DUNE's measurement of neutrino-mixing parameters, assuming the solar best-fit values ($\sin^2\theta_{12} = 0.308$ and $\Delta m^2_{21} = 4.85 \times 10^{-5}$ eV^2 [6]). The uncertainties are 3.0% and 5.9%, a factor of $\simeq 1.5$ and $\simeq 3$ better than from all solar experiments to date, respectively, as shown in Fig. 1. The sensitivity to Δm^2_{21} comes primarily from the day-night effect (10.4σ). The ^{8}B flux (marginalizing over other parameters) can be measured to 2.5%, a factor of $\simeq 1.6$ better than from SNO. DUNE can make a robust first detection of hep neutrinos, with a precision of 11%, a factor of $\simeq 3$ better than the current theoretical uncertainty.

Going forward.—New investments are needed to enhance the MeV capabilities of DUNE. At the trigger level, this includes enhancing data acquisition, storage, and processing for a steady rate of MeV events. Calibration at MeV energies across the detector volume will be crucial to controlling systematics. An enhanced light-detection system would enhance MeV detection.

Backgrounds must be controlled, and the biggest concern, after standard cuts [1–6,15,18,78,79], is neutron captures [39]. We see three possible strategies.

1. *40 cm of shielding, as assumed above.*—This allows a low threshold ($\simeq 5.8$ MeV) to test for shape distortions in the spectrum and to enhance particle-identification techniques.

2. *Additional run time.*—With less or no shielding, the effective analysis threshold would be higher. This can be

compensated by a larger exposure than 100 kton-yr. With 30, 20, 10, or 0 cm of shielding, the effective analysis threshold is $\simeq$6.2, 6.5, 6.9, or 7.2 MeV, and the exposure needed for comparable results increases at most of a factor of $\sim$2.

3. *Better particle-identification techniques.*—We assume that neutrino-interaction events and neutron-capture events with the same electron energy are indistinguishable. This is too conservative, because $\nu_{e,\mu,\tau} + e^-$, $\nu_e + {}^{40}\mathrm{Ar}$, and neutron-capture events would have one electron, an electron with γ rays, and multiple γ rays, respectively. For γ rays, the radiation length is 14 cm and Compton scattering dominates [55], so these event classes should be distinct.

The impact of varying the assumptions made above is detailed in Supplemental Material [38]. Here, we summarize some key points. The sensitivity to Δm^2_{21} is very robust, because it is determined from the day-night effect, which cancels many inputs. The uncertainty on the $\nu_e + {}^{40}\mathrm{Ar}$ cross section (presently 10%) and the detector systematics should be reduced to 1%. Without this, DUNE alone cannot break the degeneracy between $\sin^2\theta_{12}$ and $\phi({}^8\mathrm{B})$, though its measurement of Δm^2_{21} would be unaffected and its measurement of $\phi(\mathrm{hep})$ be only modestly affected. Importantly, the intended precision of $\sin^2\theta_{12}$ and $\phi({}^8\mathrm{B})$ could be largely restored by combining with existing solar data. If the energy resolution is 20%, the intended precision of $\phi(\mathrm{hep})$ would degrade to 18%, though that of $\sin^2\theta_{12}$, $\phi({}^8\mathrm{B})$, and Δm^2_{21} could be largely restored by increasing exposure by $\sim$2. DUNE's sensitivity would be lost if the energy resolution is poor *and* backgrounds are not reduced.

Concluding perspectives.—This is the first study to detail how DUNE, with a new, challenging but feasible solar neutrino program, would open substantial discovery space in both particle physics and astrophysics. With DUNE's precision measurements of $\sin^2\theta_{12}$ and Δm^2_{21}, the comparison to JUNO's may reveal new particle physics of neutrinos. Simultaneously, with DUNE's precision measurements of $\phi({}^8\mathrm{B})$ and $\phi(\mathrm{hep})$, it may reveal new astrophysics. Further studies are needed to evaluate our proposal and to optimize its sensitivity.

No other planned experiment has been shown potentially capable of meeting all of these goals. Of proposed experiments, Hyper-Kamiokande (Hyper-K) [105,106] stands out, and it can nicely complement DUNE. Hyper-K would have only one channel, $\nu_{e,\mu,\tau} + e^-$, but huge statistics. DUNE and Hyper-K would measure Δm^2_{21} (from the day-night asymmetry) comparably well. Hyper-K would have a significant advantage on measuring the upturn in the ν_e survival probability. DUNE would measure $\phi(\mathrm{hep})$ much better. Their combined impact would be significantly enhanced by new experiments for low-energy solar neutrinos [36,107,108].

Solar neutrino studies, begun long ago, are not done. DUNE can lead the next generation of discoveries.

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We speak for ourselves as theorists, not on behalf of the DUNE Collaboration. This work is based on our ideas, our calculations, and publicly available information.

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