Solar cycle effects in future measurements of low-energy atmospheric neutrinos

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(Received 17 April 2023; accepted 19 October 2023; published 13 December 2023)

We study the impact of time-dependent solar cycles in the atmospheric neutrino rate at DUNE, Hyper-Kamiokande (HK), and JUNO, focusing in particular on the flux below 1 GeV. Including the effect of neutrino oscillations for the upward-going component that travels through the Earth, we find that across the solar cycle the amplitude of time variation is about $\pm5\%$ at DUNE, $\pm4\%$ at JUNO, and $\pm1\%$ at HK. We find significant variance in the ratio of upward-going events to downward-going ones in all three experiments, though the overall event rates vary significantly across the three. Over the 11-year solar cycle, we find that the estimated statistical significance for observing time modulation of atmospheric neutrinos is 4.8σ for DUNE and 2.0σ for HK and JUNO. Flux measurements at all three experiments will be important for understanding systematics in the low-energy atmospheric flux as well as for understanding the effect of oscillations in low-energy atmospheric neutrinos.

DOI: 10.1103/PhysRevD.108.123019

I. INTRODUCTION

While one of the oldest sources of neutrinos studied in high energy physics, atmospheric neutrinos continue to be an active area of research, significantly contributing to the determination of oscillation parameters [1–7]. Atmospheric neutrinos are produced when cosmic rays (CRs) collide with the Earth's atmosphere, resulting in the production of charged mesons which, through a series of decays, ultimately leading to a large flux of electron, muon, and even tau neutrinos. The neutrinos are produced ranging from sub-MeV to greater than PeV energies, and have been studied by many experiments [8].

The lowest energy component of the atmospheric neutrino flux arises from CR with energies of $\lesssim 10$ GeV, see Fig. 1. At these energies, two distinct physical mechanisms affect the CR flux at Earth. First, CRs diffuse through the solar wind [9], so there is an expected modulation from the solar cycle [10]. This CR modulation due to solar activity has been measured by PAMELA [11] and BESS [12]. The solar cycle itself has been measured for centuries (e.g., Ref. [13]) through observations of sunspots, yet the impact on the atmospheric neutrino flux has yet to be observed. The Super-Kamiokande (SK) experiment searched for such a correlation in the atmospheric neutrino flux over

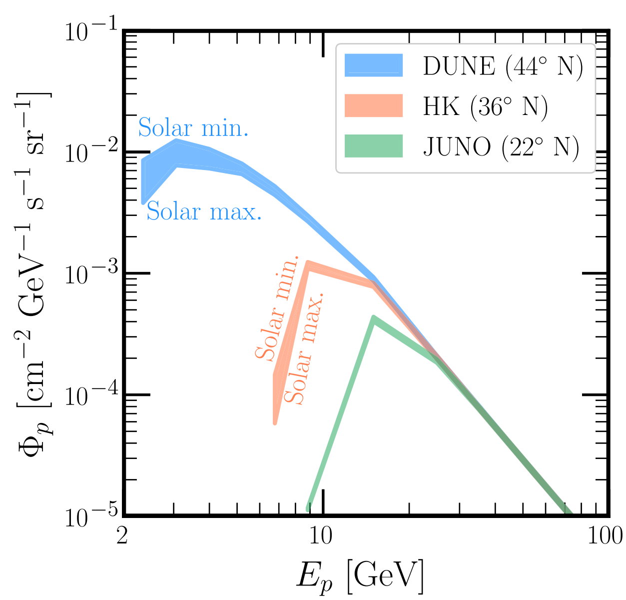

FIG. 1. Cosmic ray protons producing neutrinos $E_\nu > 100$ MeV. For each spectrum (latitudes indicated), the shaded band represents the differences between solar min and solar max.

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20-year-long periods, but reported a detection with a statistical significance of only 1.1σ [4]. One of the challenges in measuring this effect is that it is largest at low energies, particularly below the GeV scale, and it depends on the incoming direction of the neutrinos. Reconstructing energy and direction of sub-GeV atmospheric neutrinos is a challenge for large Cherenkov detectors since low energy protons do not emit Cherenkov light.

A second mechanism that affects the low-energy atmospheric neutrino flux is the rigidity (momentum/charge) cutoff which results from the geomagnetic field. This rigidity cutoff is different for each location on Earth, so that the low-energy CR spectrum is different for different locations on Earth. This cutoff ultimately induces an asymmetry in the low-energy atmospheric flux [14]. This effect has also been studied by SK [4], which identified an east-west asymmetry due to the geomagnetic field.

Figure 1 clearly shows both the effect of the time modulation and the rigidity cutoff. The time modulation is evident in the width of the different bands; the bands become wider at lower energies, showing that the time modulation effects are important for lower energy cosmic rays. The rigidity cutoff is evident in the turnover location of the spectrum for each location; for detectors at higher latitude, the spectrum cutoff occurs at lower CR energy.

The next generation of neutrino experiments will provide improved sensitivity to low-energy atmospheric neutrinos, allowing for better estimates of the solar modulation and geomagnetic field effects. The Deep Underground Neutrino Experiment (DUNE) [15], which uses liquid argon time projection chamber technology, is expected to measure sub-GeV atmospheric neutrinos and provide unparalleled reconstruction of both energy and direction of this sample [16]. The Hyper-Kamiokande (HK) experiment [17], a massive 200 kton water detector that is ten times larger than SK, is expected to have a large statistical sample that is sensitive to even percent-level time modulations of the atmospheric neutrino flux. The Jiangmen Underground Neutrino Observatory (JUNO) [18], a 20 kton liquid scintillator experiment designed to measure reactor neutrinos, is also expected to contribute to the observation of various other sources of neutrinos, including the sun, the atmosphere, and (along with DUNE and HK) the diffuse background of supernova neutrinos [19–21]. In addition to the above dedicated neutrino experiments, a future large scale dark matter detector will be somewhat sensitive to low energy atmospheric neutrinos [22].

In this paper, we examine the correlation between solar magnetic activity and the atmospheric neutrino flux, and the prospects for measuring this correlation at the aforementioned experiments. Despite being relatively well understood in theory, this effect has yet to be observed in neutrino experiments. We estimate the sensitivity of experiments to the correlation between solar magnetic activity and atmospheric neutrino flux using simulations of the atmospheric neutrino flux and detector responses in an event-by-event basis. By examining how the nature of the signal changes at different locations, we show that a measurement at DUNE, HK, and JUNO is necessary to best understand the systematic uncertainties in the flux.

II. LOW-ENERGY ATMOSPHERIC NEUTRINO FLUX

To calculate the low-energy atmospheric neutrino flux spectrum from the interactions of CRs, we follow the method of Ref. [23]. In Fig. 2, we show the ν_e and ν_μ fluxes at HK, DUNE, and JUNO for upgoing and downgoing neutrinos at the extrema of the solar cycles. In the following, we highlight relevant aspects of the calculation, and refer to Ref. [23] for further details on the simulations. We start from the CORSIKA code [24], which generates neutrinos from simulations of CR interactions and the subsequent air showers. Within CORSIKA, we use the FLUKA model to simulate low energy events, <80 GeV, and QGSJET 01C for higher energy

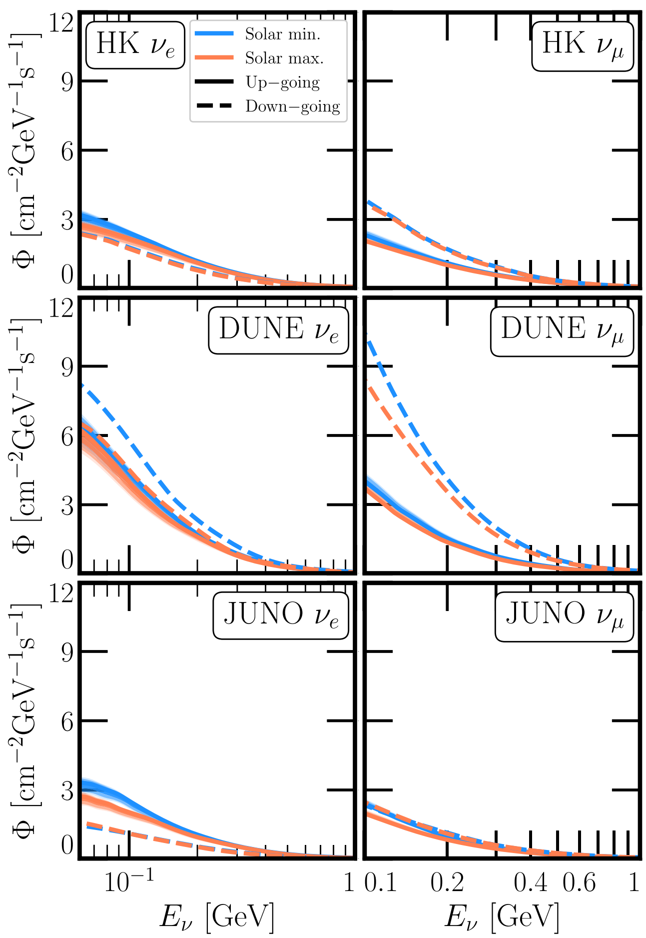

FIG. 2. Electron-neutrino (left) and muon-neutrino (right) fluxes at the Hyper-Kamiokande (top), DUNE (center), and JUNO (bottom) detectors at the extrema of the solar cycle: solar max. in blue and min. in orange. We divide the fluxes into the downgoing (dashed lines) and upgoing (solid bands, driven by uncertainty in neutrino oscillation parameters) components.

events.[1] For the input CR spectrum, we use the updated measurements of the CR spectrum on Earth at the different phases of the Solar cycle [11,12]. Upcoming measurements concurrent with DUNE, Hyper-Kamiokande, and JUNO may improve our understand of the CR spectrum (especially at low energies) leading to more robust predictions—we refer the reader to Ref. [26] for a thorough discussion of current and upcoming CR measurements.

We consider the detection prospects of the low-energy atmospheric neutrino flux at two future, large neutrino detectors that will be coming online with particular strengths (and complementarity). DUNE [15] which is at a latitude $\sim 44°$ N and has a goal of 40 kt liquid argon fiducial mass, can detect charged-current electron-neutrino scattering down to $\mathcal{O}$(tens) of MeV thanks to its liquid argon time-projection-chamber technology, as well as charged-current muon-neutrino scattering above the $\mu^{\pm}$ production threshold. Hyper-Kamiokande [17], which is at latitude $\sim 36°$ N, offers a significantly larger detector volume (of water), however due to Cerenkov thresholds of charged particles, its low-energy capabilities are relatively weaker than that of DUNE. JUNO has a significantly smaller detector volume than DUNE and HK, yet (as we will show), the fact that it is in a more equatorial position (latitude $\sim 22°$ N), it provides interesting complementarity to the prospects of DUNE and HK. Such low-energy atmospheric neutrino prospects have been studied by the JUNO collaboration in detail [18,27], and we find consistent results in terms of overall event rates.

Measurements of how the atmospheric neutrino flux varies with time reinforces our understanding of the cosmic ray flux, especially at low energies. Such measurements can assist in reducing the many systematic uncertainties present in analyzing atmospheric neutrinos [28] that make precise neutrino-oscillation-parameter measurements in these environments challenging [5].

At any location on Earth, the neutrino flux is a sum of a downward-going component, $0 < \cos\theta_z < 1$, and an upward-going component, $-1 < \cos\theta_z < 0$, where θ_z is the zenith angle. The downgoing flux may be estimated from interactions of neutrinos in the atmosphere above the horizon. On the other hand, the upward flux requires information on the rigidity cutoff at all positions for all directions below the horizon. For this reason, estimating the upward-going flux presents a more substantial computational challenge. We therefore explicitly divide our simulations up into the downward and the upward flux components, and estimate the integrated neutrino fluxes over all angles for both directions.

To simulate the upward-going flux for each location, we divide the Earth into 20 zenith and 20 azimuthal patches. These upward-going samples are divided by different $\cos\theta_z$ and energy so that the effects of neutrino oscillations, as described below, may be properly included—our end result is the direction-integrated upward-going neutrino flux of each relevant neutrino flavor, ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$. To check our differential fluxes as a function of zenith angle, for a fixed zenith angle we integrate over azimuth, and ensure that the flux smoothly matches the fluxes from previous calculations at a zenith angle of $\cos\theta_z = 0.5$ [29] for neutrino energies >1 GeV.

Upward-going neutrinos additionally experience matter-induced oscillations as they travel through the Earth. We calculate the oscillation probabilities for $-1 \leq \cos\theta_z \leq 1$ and $100\ \mathrm{MeV} \leq E_\nu \leq 1$ GeV, assuming the PREM Earth density model [30]. Previously, it has been demonstrated that measurements of these oscillations can provide additional, complementary information on leptonic CP-violation, specifically at DUNE [31]. We additionally allow the six oscillation parameters to vary assuming current knowledge of their values[2] from Ref. [33]. Note that we focus on the current knowledge of oscillation parameters because, while DUNE and HK will greatly improve these measurements with beam neutrinos and JUNO with reactor ones, it will still be invaluable to perform independent measurements with atmospheric neutrinos. We find that varying $\sin^2\theta_{23}$ and δ_{CP} according to present-day uncertainty leads to the greatest variance in expected upward-going fluxes.

The time variation of the flux is manifest when examining the spectrum of CR protons that produce low-energy, >100 MeV neutrinos at each detector location. These spectra are shown in Fig. 1. As is apparent, DUNE is more sensitive to lower-energy CRs than any other detector, sampling CRs down to the limit of our calculation of ~ 2 GeV CR kinetic energy. For comparison, the CR spectra at HK and at JUNO cut off at higher energies, ~ 6 and ~ 9 GeV, respectively. Because of this lower energy cutoff, there is a larger variation in the CR proton flux in one solar cycle at DUNE.

The corresponding low-energy neutrino fluxes are shown in Fig. 2, for HK, DUNE, and JUNO. Analogous fluxes for antineutrinos are presented in the Appendix. The first interesting point to note from Fig. 2 is that the upward-going fluxes at all three locations are very similar. This is because the upgoing flux is integrated over a wide range of angular directions, so that the rigidity information in the CR spectrum is in essence averaged out. By similar reasoning, the impact of oscillations is similar for the three sets of fluxes (the thickness of the colored bands indicate $\pm 1/2/3\sigma$ uncertainty of the upward-going fluxes due to oscillation parameter uncertainty). The situation is different, however,

[1] In future studies, we plan on exploring the impact of different Monte Carlo simulations (see, e.g., Ref. [25]) on the resulting low-energy atmospheric neutrino flux and its variance within the solar cycle for these experiments. We expect that observables such as the ratio between solar minimum and maximum will be robust under various assumptions about the CR flux.

[2] Specifically, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, and Δm^2_{21} are drawn from their assumed-Gaussian distributions, and $\sin^2\theta_{23}$, Δm^2_{31}, and δ_{CP} are drawn with weights according to the χ^2 table (including Super-Kamiokande atmospheric data) provided from Ref. [32] to include proper parameter correlations.

for the downgoing fluxes. In comparison to the results from DUNE, the fluxes at HK are lower and have less variation when comparing the Solar cycle maximum and minimum—this comparison is even more obvious with JUNO.

A second interesting feature to note from Fig. 2 is the relationship between the upward-to-downward going fluxes at each location. Given the nature of the magnetic field nearer to the poles, the rigidity cutoff for CRs at DUNE's Homestake Mine location is lower than it is for detectors closer to the equator. This implies that the downgoing neutrino flux at Homestake at low energy is larger than it is for HK and JUNO, which results from the CR spectra shown in Fig. 1. However, for the upward going flux, the situation changes. Since Kamioka (and Jiangmen to an extent) is on the opposite hemisphere relative to the South Atlantic Anomaly, which is a region defined by a low rigidity cutoff, at this location the upward going flux is larger than the downgoing flux. On the other hand, at the Homestake location, the downward going flux is larger, since on average the upward flux arises from regions of higher rigidity. Since the upward/downward-going ratio is different for each location, a flux measurement at each is crucial for understanding the systematics that arise due to the solar modulation and the geomagnetic field.

III. MEASUREMENT CAPABILITIES

We now move on to estimating the prospects for measurement of the time variation of the atmospheric neutrino flux at the three detectors, DUNE/HK/JUNO. We use the NuWro [34,35] Monte Carlo event generator to determine charged-current-inclusive scattering cross sections of the different neutrino flavors on the different detector targets at these low energies and in turn, the expected event rate in a given time period. For simplicity, we first consider the total $e^{\pm}$ and $\mu^{\pm}$ event rates (assuming no particle mis-identification and no charge identification) during one complete solar cycle at HK with a 217 kt fiducial volume, DUNE with 40 kt, and JUNO with 20 kt. We make the simplifying assumption that the flux modulation over each solar cycle follows a sinusoidal pattern. We leave the possibility of detecting deviations from this assumption to future work.

The expected event rates for $E_\nu < 1$ GeV are displayed in Fig. 3 for $e^{\pm}$ (green) and $\mu^{\pm}$ (purple), where we take the median expected event rate subject to neutrino oscillation uncertainties and provide statistical error bars. The left panels show the total rate of events, and the right ones are broken down into up- and down-going components. The fact that these rates are not constant with respect to time is readily apparent. We can estimate the sensitivity to detect this modulation, for instance, by DUNE, by comparing fits to the green and purple data points in the left-center panel that are either (a) flat or (b) sinusoidal in nature. We find that, combining the $e^{\pm}$ and $\mu^{\pm}$ events, DUNE will favor (b), the varying scenario, at $\sim 4.8\sigma$ significance if it has 40 kt fiducial volume for one entire cycle. If DUNE only operates with two modules and a fiducial volume of 20 kt, this reduces to $\sim 3.4\sigma$.

HK, in contrast, will only have sensitivity to this modulation at the $\sim 2.0\sigma$ level due to the smaller fractional modulation of its event rates, apparent in the top half of Fig. 3. JUNO has a larger fractional modulation than HK but a significantly smaller event rate, resulting in a $\sim 2.1\sigma$ statistics-only sensitivity. Further challenges exist, especially for HK, in measuring and reconstructing

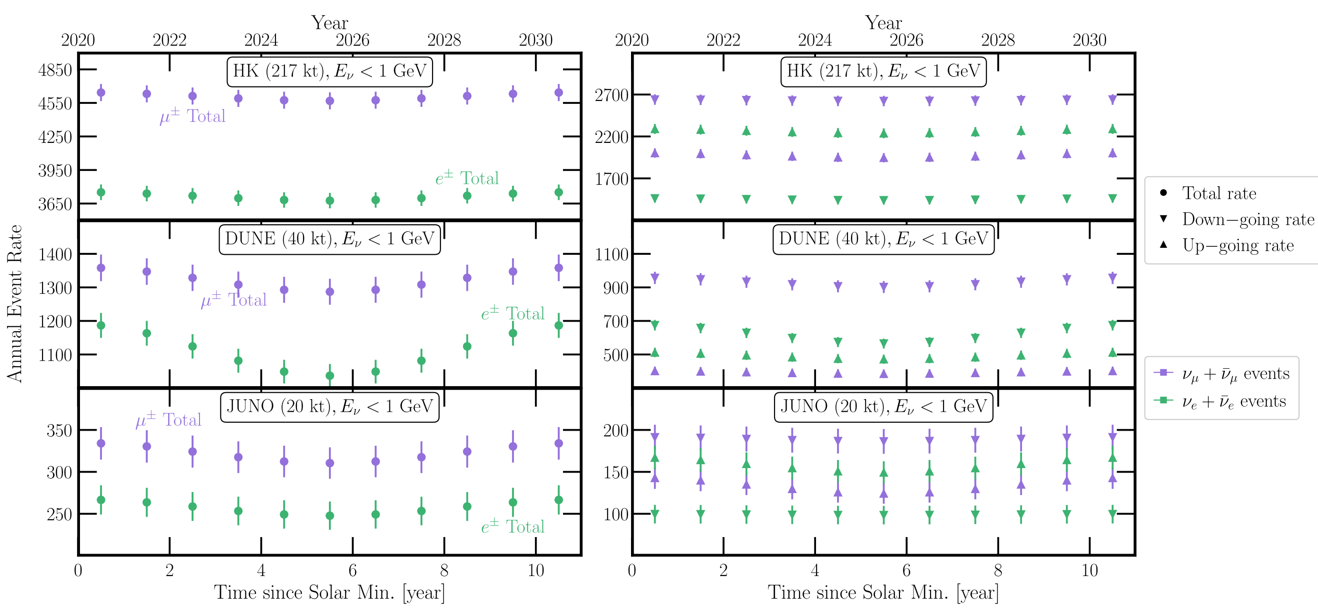

FIG. 3. Event rates per year at HK (top), DUNE (center), and JUNO (bottom) for $\mu^{\pm}$ (purple) and $e^{\pm}$ (green) event signatures. In the left panels, up-going and down-going event rates are added for simplicity, and shown separately in the right panels.

low-energy $e^{\pm}$ events due to Cherenkov thresholds. Realistic reconstruction of low-energy events will reduce HK's sensitivity to the solar cycle.

These significances could in principle rise if considering the up- and downgoing fluxes separately (assuming good enough angular resolution is available to sufficiently separate the samples, which we will investigate in future work). This is because the modulation is expected to be larger or smaller in one sample depending on which detector is considered—for instance the downgoing rates in DUNE (right-center panel) undergo larger fluctuations than the upgoing ones as we discussed above.

We can also revisit the assumption that the fluxes follow a sinusoidal pattern from the solar cycle here. For instance, Ref. [36] describes the variance of cosmic-ray fluxes on a more fine-grained timescale leading to more structure as a function of the 11-year solar cycle. If the future atmospheric neutrino detectors analyze their data with finer time-binning (e.g., monthly instead of yearly), then observing this structure in neutrino fluxes is possible. We expect that, as long as the overall variance from solar maximum to solar minimum is as dramatic as presented here, then these experiments (especially DUNE) will strongly favor the varying-flux hypothesis over the flat one. Our hope is that atmospheric neutrino experiments can further bolster our understanding of low-energy cosmic rays by precisely measuring the shape of this modulation over several solar cycles.

In comparing the three experiments' expected rates, we see a variance in the fractional modulation (from the ~2%–10% level) as well as in overall event rates (spanning an order of magnitude). However, since the year-to-year variance appears statistically significant, such modulations should be taken into account carefully for each experiment when measuring atmospheric neutrinos, especially as it pertains to oscillation analyses.

There is an additional important issue when performing any analysis of atmospheric neutrino oscillations with these next-generation detectors that we highlight: implementing time-dependent fluxes for both upward- and downward-going neutrino components appropriately. This effect can be properly included by allowing for time-dependent neutrino fluxes (either fitting for the time-variance or using values from a simulation) instead of incorporating additional sources of uncertainty. Typically, the data are analyzed integrated over the entire lifetime of the experiment; if this is done without consideration of the flux modulation, a biased measurement of oscillation parameters (notably $\sin^2\theta_{23}$ and/or δ_{CP}) may be extracted from an analysis. Figure 4 demonstrates this with respect to the ratio of neutrino-scattering events from the upgoing flux to the downgoing flux for $e^{\pm}$ (top) and $\mu^{\pm}$ (bottom). The thick line in each panel presents the median-expected result when considering the possible values of neutrino oscillation parameters given current data [33], whereas the shaded regions portray uncertainty based on the current knowledge of oscillation parameters. These indicate the $\pm 1/2/3\sigma$ range allowed when oscillation parameters (notably, $\sin^2\theta_{23}$ and δ_{CP} have the largest impact) vary when using the information in Ref. [33]. Especially focusing on the DUNE panels (right), we see that the up/down ratio will vary at the several-percent level over one solar cycle. However, a few-percent change in the up/down event ratio is similarly produced by varying $\sin^2\theta_{23}$ or δ_{CP} within their current uncertainties.

We show an example of this in Fig. 5, where we estimate the upgoing event rates for ν_e (green) and ν_μ (purple) scattering in DUNE in the first four years of data collection where only 20 kt of fiducial detector mass will be available [37]. We perform this estimate assuming the fluxes vary according to the solar cycle (left) or are fixed to their median expectation (right). In the left panel, we assume that oscillations are driven by $\delta_{CP} = -\pi/2$ and $\sin^2\theta_{23} = 0.56$, wherein the right one (with the incorrect

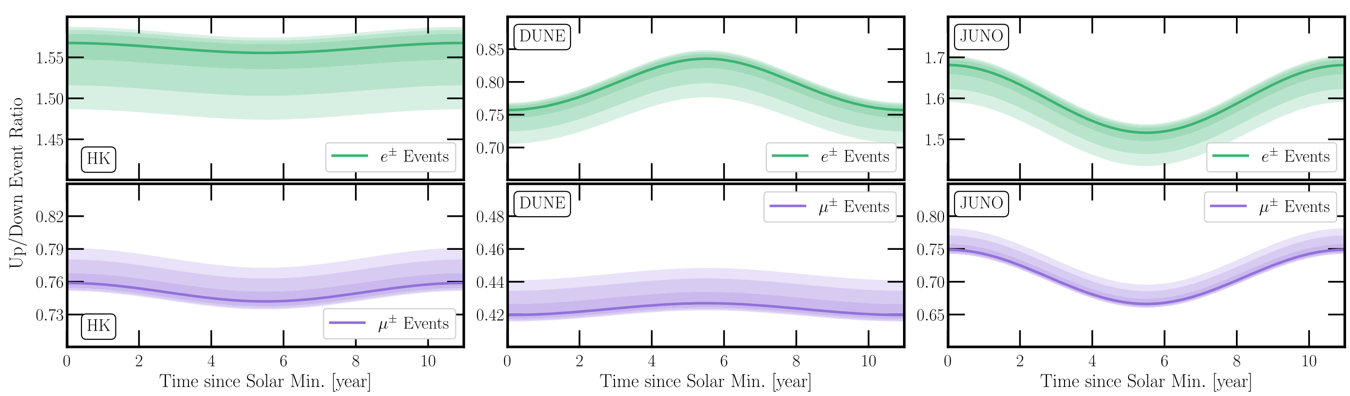

FIG. 4. Ratio of up-going events to down-going ones in HK (left), DUNE (center), and JUNO (right) over the course of one solar cycle—the top (bottom) panels demonstrate this ratio for $e^{\pm}$ ($\mu^{\pm}$) events. In each panel, the dark/medium/light shaded regions are the $\pm 1/2/3\sigma$ allowed regions of this prediction when we vary oscillation parameters consistent with current measurements [33], and the thick, solid line is the median expectation. The predicted solar-cycle dependence is highly correlated once a given set of oscillation parameters is assumed to be true.

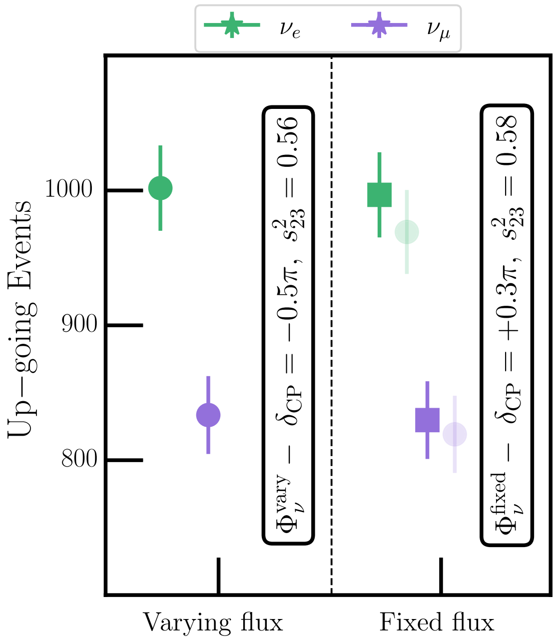

FIG. 5. The impact of assuming flat fluxes (right) vs varying ones (left) and the interplay with oscillation parameter effects. In the left (right) panel, we assume $\delta_{\rm CP} = -\pi/2$ and $\sin^2\theta_{23} = 0.56$ ($\delta_{\rm CP} = 0.3\pi$ and $\sin^2\theta_{23} = 0.58$). Faint data points show the rate estimate under the "incorrect" flux assumption with the same oscillation parameters as in the left panel.

flux assumption), we take $\delta_{CP} = +0.3\pi$ and $\sin^2\theta_{23} = 0.58$. The expected rates with $\delta_{\rm CP} = -\pi/2$ and $\sin^2\theta_{23} = 0.56$ are shown as faint data points, in contrast. This difference could result in an extracted atmospheric measurement at DUNE that is inconsistent with that extracted from DUNE's long-baseline ν_e appearance measurements, if these effects are not treated carefully. We take this example to serve as a proof-of-principle that such an impact can be present in an oscillation analysis, but note that this is a challenging measurement to perform, given the required direction reconstruction to separate upgoing and downgoing events [16]. We therefore leave dedicated studies of this and other experimental features to future work.

Finally, we also note that the modulating flux ratios between HK/JUNO and DUNE shown in Fig. 4 are out of phase—this is because DUNE sees modulations most significantly in its downgoing neutrino fluxes (see Fig. 2), whereas HK and JUNO have nearly constant downgoing neutrino fluxes and small variance in the upgoing ones. A combined analysis of DUNE, HK, and JUNO that reveals this out-of-phase dependence would provide further support for understanding of the CR flux, the varying rigidity cutoffs, and the modulation due to the solar cycle.

IV. DISCUSSION AND CONCLUSIONS

We have demonstrated that the time-variation of low-energy atmospheric neutrinos at next-generation experiments is a significant effect. This must be carefully accounted for to yield accurate predictions for neutrino-oscillation studies, and for them to be competitive with alternate methods of measuring parameters, such as the *CP*-violating phase in the lepton sector. This effect can be measured at DUNE and, to a lesser extent, HK and JUNO, over the course of 11 years of data collection.

Interestingly, the nature of the modulation is unique at each detector. DUNE sees a large modulation in its downward-going flux due to the low rigidity cutoff at its high latitude, whereas the downward-going flux at HK and JUNO is fairly stable at lower detector latitudes. All detectors, when viewing upward-going neutrinos, effectively sample the same profile of latitudes and longitudes. This, combined with the impact of neutrino oscillations in the upward-going fluxes, results in fairly similar upward-going modulation for each detector location. These effects together can predict nontrivial event modulations for both electronlike and muonlike events, for both upward- and downward-going neutrinos. The ratio of upward-to-downward-going events is a key indicator of these effects, and we have highlighted how the out-of-phase variation of this quantity, when comparing DUNE and Hyper-Kamiokande/JUNO, is a clear indicator of the solar cycle modulation. Further, this up-to-down-going ratio is important for the extraction of neutrino oscillation parameters and so care is required when performing these upcoming analyses.

We have presented results focused on generator-level information of incoming neutrinos at these two detector locations. On one hand, reconstructing the incoming direction of incoming sub-GeV atmospheric neutrinos is a nontrivial challenge. While LArTPCs may be able to achieve 20–30° directional reconstruction [16,31], water Cherenkov detectors have much worse directional capabilities due to the fact that low energy protons do not emit Cherenkov light, and liquid scintillator detectors present complementary challenges as well. Determining the feasibility of realistic measurements of these modulations and up-to-down ratios, as well as more in-depth statistical measures of these time-variations, is therefore left for future work.

Though our analysis has focused on detection of neutrinos through charged-current interactions at DUNE, it is interesting to consider how this detection would be complementary to other detections of low-energy atmospheric neutrinos. For example, next generation dark matter detectors will be sensitive to atmospheric neutrinos via the neutral current CEνNS channel, though the rate of events is expected to be lower than the rates that we estimate at DUNE [23]. Because of this low event rate, the time variation will be more difficult to extract, though a measurement of the mean rate would provide a calibration to the results that we present. This is particularly important since dark matter detectors would be sensitive to even lower-energy neutrinos than we consider here. Additionally, neutrino oscillation effects are relevant for this study where they were not in Ref. [23] due to the neutral-current nature of the CEνNS process studied therein. Combined analyses of the two sets of experiments can also aide in understanding the relationships between the solar cycle and neutrino oscillation effects like those discussed in Fig. 4. Finally, we highlight again the interplay between low-energy atmospheric neutrinos in these detectors with the goal of detecting the diffuse background of supernova neutrinos [19–21]. Knowing that the low-energy atmospheric neutrino "background" to this search modulates with time will allow for better sensitivity to the DSNB and better characterization in the event of a detection.

The relatively large event rate and the detection of time variation at DUNE is due in large part to its high geographic latitude. It is interesting to consider whether detectors at locations event nearer to the poles would be provide better sensitivity to the low energy flux and to time variation that for DUNE. In the most extreme case, we can consider the IceCube detector. In this case, we find that the time modulation and the flux is similar to that of DUNE, so in this sense the sensitivity will not improve. However, IceCube would provide a distinct measurement, which may be sensitive to the flux in a different energy regime than we study. Since estimating the rate at IceCube requires a detailed analysis of their low-threshold sensitivities due to the complicated interplay of the Cerenkov radiation in ice and the sparse array of detectors, we leave this topic for future study.

Nevertheless, measurements of neutrino oscillations will improve between now and these experiments' data collections. These measurements will further inform our understanding of neutrino oscillations, and we have demonstrated the importance of understanding these modulations when using atmospheric neutrinos for oscillation measurements. Combined measurements of DUNE, Hyper-Kamiokande, and JUNO should meaningfully identify such solar-cycle effects and help for a better understanding of these low-energy cosmic ray fluxes as well.

ACKNOWLEDGMENTS

L. S., N. M., and Y. Z. are supported by the DOE Grant No. DE-SC0010813. Fermilab is managed by the Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

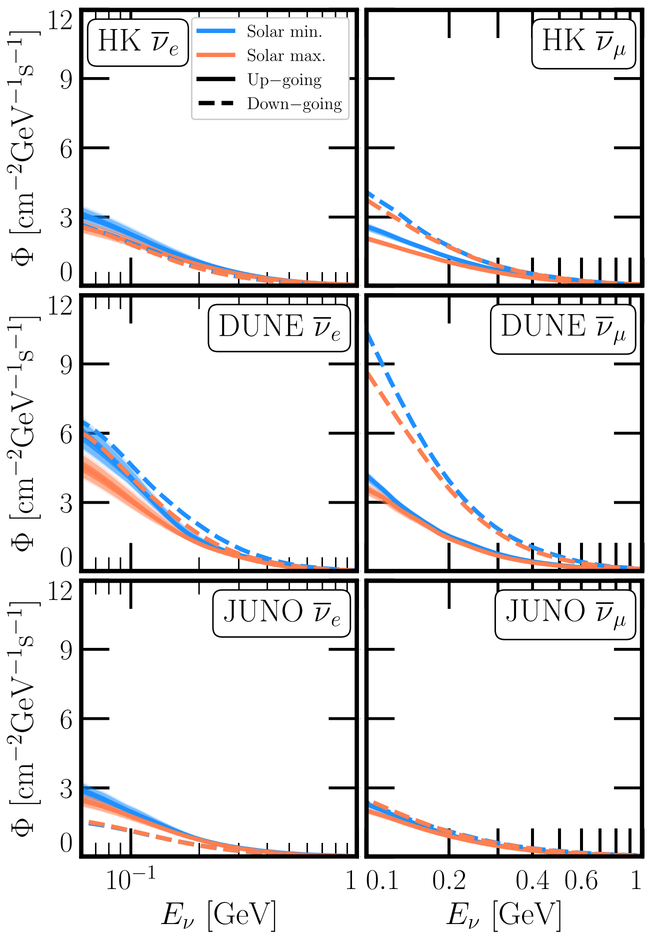

FIG. 6. Electron-antineutrino (left) and muon-antineutrino (right) fluxes at the Hyper-Kamiokande (top), DUNE (center), and JUNO (bottom) detectors at the extrema of the solar cycle: solar max. in blue and min. in orange. We divide the fluxes into the downgoing (dashed lines) and upgoing (solid bands, driven by uncertainty in neutrino oscillation parameters) components. See text for more detail.

APPENDIX: UPWARD- AND DOWNWARD-GOING ANTINEUTRINO FLUXES

For completeness, in Fig. 6, we show the $\bar{\nu}_e$ and $\bar{\nu}_\mu$ fluxes at HK, DUNE, and JUNO for upgoing and downgoing neutrinos at the extrema of the solar cycles.

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