Probing *CP* Violation with Neutrino Disappearance Alone

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The best way to probe *CP* violation in the lepton sector is with long-baseline accelerator neutrino experiments in the appearance mode: the appearance of ν_e in predominantly ν_μ beams. Here we show that it is possible to discover *CP* violation with disappearance experiments only, by combining JUNO for electron neutrinos and DUNE or Hyper-Kamiokande for muon neutrinos. While the maximum sensitivity to discover *CP* is quite modest (1.6σ with 6 years of JUNO and 13 years of DUNE), some values of δ may be disfavored by $> 3\sigma$ depending on the true value of δ.

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Introduction—There are three free parameters in our current model of particle physics that control the size of *CP* violation in their respective sector: the $\bar{\theta}$ term in the QCD sector which seems to be either zero or very small [1], the CKM matrix [2,3] describing quark mixing which is known to have some *CP* violation [4,5], and the PMNS matrix [6,7] describing lepton mixing. It is unknown if there is *CP* violation in the lepton mixing matrix [8–11] and thus determining if *CP* is violated in the lepton sector is of the utmost priority in particle physics.

The best way to probe *CP* violation in the leptonic sector is by an appearance measurement of an oscillation maximum [12–19]. To date only NOvA [20] and T2K [21] have strong evidence for the detection of appearance by detecting electron neutrinos in predominantly muon neutrino sources, but do not yet significantly probe *CP* violation past the 2σ level [22,23]. Atmospheric neutrinos, which are mostly muon neutrinos, also have some evidence for appearance [24–26]. Since there is significant electron neutrino contribution at the source, the appearance information is thus somewhat scrambled.

We will show how it is also possible to probe *CP* violation, via neutrino disappearance measurements only, in three different ways: counting parameters using a specific parametrization, direct analytic calculation in a parametrization independent framework, and numerical computation. The key physics effect that makes this possible is unitarity [27] and thus if there is new physics in the neutrino sector this story may get more complicated. It is also possible to relate the amount of *CP* violation directly to the measured parameters from disappearance. Given the sizable expected improvements in disappearance measurements in the ν_e channel with the Jiangmen Underground Neutrino Observatory (JUNO) and the ν_μ channel with the Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (HK), such a study is quite timely. Moreover, disappearance has a different dependence on the oscillation parameters as well as different (and often cleaner) systematics than appearance measurements which means that this can be a valuable cross check of *CP* violation probes in the appearance channel. See also [28] for a very early study discussing some related oscillation physics and [29] for some numerical studies.

In this Letter, we will briefly review the standard *CP* violation picture. We will then develop the theory for where there is information about *CP* violation in disappearance measurements. Finally, we will perform numerical studies indicating the sensitivity to measure δ, and thus determine if *CP* is violated or not, via disappearance measurements only.

Conventional CP violation picture—It is true that, consistent with conventional wisdom in the literature, disappearance channels are *CP* invariant, see, e.g., [12,14,17,30–32], under the assumption that *CPT* is conserved. That is, by *CPT* conservation

$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha), \tag{1}$$

in vacuum [33]. Thus neutrinos and antineutrinos act the same in vacuum disappearance experiments.

The *CP* asymmetry, on the other hand, is only nonzero for appearance and is proportional to the Jarlskog invariant $J \equiv s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$ [46]. The difference in probabilities for neutrinos and antineutrinos is

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \simeq \pm 8\pi J \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \tag{2}$$

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in vacuum near the first oscillation maximum with $\alpha \neq \beta$ where the sign depends on α and β. Thus a determination of J, which requires measuring all four parameters of the PMNS matrix, indicates how neutrinos and antineutrinos behave differently in appearance oscillation measurements [47]. Since the Jarlskog invariant shows up in both neutrino mode and antineutrino mode, a measurement of both is not necessary to measure $\sin\delta$, but may help with systematic uncertainties.

New physics such as sterile neutrinos [48], nonstandard neutrino interactions [34,49,50], or unitarity violation [51] could also modify this picture in nontrivial ways by making fully CP conserving scenarios appear CP violating or other such nightmare scenarios. It may be possible to avoid these scenarios via a combination of experiments at different baselines and energies; see, e.g., [11,52,53].

CP violation in disappearance—An understanding via parameter counting: While it is not directly possible to determine if nature prefers neutrinos or antineutrinos via disappearance measurements alone, it is possible to determine if nature treats neutrinos and antineutrinos the same or differently via measurements of these CP conserving disappearance channels [54]. That is, disappearance measurements cannot provide information on $\mathrm{sign}(\sin\delta)$ or, equivalently, on $\mathrm{sign}J$, but can constrain $\cos\delta$ and thus potentially rule out CP conserving values of $|\cos\delta| = 1$.

The disappearance probability in vacuum for flavor α is

$$\begin{aligned} P(\nu_\alpha \to \nu_\alpha) = 1 &- 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2\sin^2\Delta_{21} \\ &- 4|U_{\alpha 1}|^2|U_{\alpha 3}|^2\sin^2\Delta_{31} \\ &- 4|U_{\alpha 2}|^2|U_{\alpha 3}|^2\sin^2\Delta_{32}, \end{aligned} \tag{3}$$

where $\Delta_{ij} = \Delta m_{ij}^2 L/4E$ is the kinematic term.

To understand how one can determine if CP is conserved or not, we focus on the four parameters that describe the mixing matrix [56]. We begin by examining the PMNS mixing matrix U in the usual parametrization [4,57,58]:

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}. \tag{4}$$

Since disappearance measurements only constrain absolute values of elements of the PMNS matrix, we notice that the measurements of the first row, the ν_e row, provide no information about δ. It would seem that measurements of either the ν_μ or ν_τ row would provide information about δ, specifically $\cos\delta$, implying that ν_e's are somehow special and different from the other two flavors [59]. In reality, any one row (and any one column) can be made to be "simple": only a product of sines, cosines, and $e^{\pm i\delta}$, see, e.g., [58]. The remaining four elements must always be "complicated": the sum or difference of the products of such terms, one of which always contains $e^{\pm i\delta}$. This provides one means of understanding why two separate disappearance measurements are required to probe CP violation. That is, if, for example, we had an excellent measurement of ν_μ disappearance but not ν_e or ν_τ disappearance, since we could choose to make the ν_μ row simple then therefore we cannot learn anything about CP violation.

The absolute value of the complicated elements contains a $\cos\delta$ contribution, which is our means of getting at CP violation.

A perfect measurement of a disappearance channel allows for the determination of the coefficients of all three terms, but provides only two constraints on the mixing matrix due to unitarity. That is, one can always define away one of the $|U_{\alpha i}|^2$ in terms of the other two by $|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2 = 1$. Thus a perfect measurement of the ν_e disappearance probability can constrain two parameters which, given how we typically parametrize the mixing matrix, the measurements map onto the parameters θ_{13} and θ_{12}. To date, Daya Bay [61] and RENO [62] provide excellent constraints on θ_{13} while KamLAND [63], SNO [64], Super-Kamiokande [65], and Borexino [66] provide good constraints on θ_{12}. In the future JUNO [67] will measure θ_{12} with excellent precision. Thus the ν_e row is or will be in excellent shape.

For the ν_μ row, disappearance measurements provide up to two independent fundamental measurements that map onto four parameters: θ_{23}, θ_{13}, θ_{12}, and $\cos\delta$. But since θ_{13} and θ_{12} are or will be well known, then similar measurements of ν_μ disappearance will provide information about θ_{23} and $\cos\delta$.

Getting directly at the Δ_{21} oscillations in ν_μ disappearance in the same fashion that JUNO does for ν_e disappearance is extremely challenging given realistic constraints; see the Supplemental Material [68], which includes Refs. [69–74], for a discussion of this hypothetical scenario.

We instead focus on leveraging data in planned experiments such as DUNE and HK and a careful spectral measurement to provide information about the beginning of the Δ_{21} oscillations in a Δ_{31} and Δ_{32} dominated regime. This is similar to the discussed plan for measuring the solar parameters Δm_{21}^2 and θ_{12} with Daya Bay data [75]. The effect of CP violation thus begins to show up at the low energy side of the ν_μ disappearance spectrum, and thus DUNE has an advantage: ν_μ experience more oscillations before the ν_μ charged-current cross section hits the muon threshold. While event rates and reconstructions are challenging at lower energies, the effect will impact the rate at which the oscillation maximum decreases where the probability is near one, so there is no probability suppression, which helps the rate.

Since the appearance channel essentially constrains $\sin\delta$ [see Eq. (2)] while the disappearance channel constrains

$\cos\delta$, these two measurements provide key complementary information. In fact, there will be sign degeneracies in many regions of parameter space of δ with either only appearance or disappearance. Moreover, the precision on δ near $\pi/2$ or $3\pi/2$ is determined by the sensitivity to $\cos\delta$ which comes from this combination of disappearance measurements making this disappearance based measurement crucial for determining the exact value of δ if we are near $|\sin\delta| = 1$ as some data [23] may be indicating.

A direct analytic calculation: We now present a new direct analytic calculation of CP violation from disappearance measurements. We find that it is possible to relate the amount of CP violation given by J to the parameters measured in disappearance. We first note that CP violating effects are proportional to the Jarlskog invariant [46]

$$J \equiv \Im(U_{\alpha j}^* U_{\beta j} U_{\alpha i} U_{\beta i}^*) = |U_{\alpha j}||U_{\beta j}||U_{\alpha i}||U_{\beta i}| \sin(\phi_{\beta j} + \phi_{\alpha i} - \phi_{\alpha j} - \phi_{\beta i}), \quad (5)$$

up to an overall sign, for $\alpha \neq \beta$ and $i \neq j$, where $U_{\alpha i} = |U_{\alpha i}| e^{i\phi_{\alpha i}}$. Then, starting from a unitarity triangle closure condition along with the row normalization unitarity conditions and some algebra, one finds,

$$J^2 = |U_{e2}|^2 |U_{\mu 2}|^2 |U_{e3}|^2 |U_{\mu 3}|^2 - \frac{1}{4}(1 - |U_{e2}|^2 - |U_{\mu 2}|^2 - |U_{e3}|^2 - |U_{\mu 3}|^2 + |U_{e2}|^2 |U_{\mu 3}|^2 + |U_{e3}|^2 |U_{\mu 2}|^2)^2. \quad (6)$$

This provides an explicit relationship between the parameters measured in disappearance and the amount of CP violation; see the Supplemental Material [68] for more details.

We now leverage approximation techniques to theoretically investigate the size of the effect.

Analytic approximation: We now strive to understand exactly how $\cos\delta$, which can provide key information about CP violation, appears in the ν_μ disappearance probability in matter in the usual parametrization. We will see that the matter effect plays a key role in multiple terms of comparable size, making a simple approximation necessarily fairly challenging.

First, we note that the Δ_{31} and Δ_{32} terms in Eq. (3) can be approximately combined as mentioned above, see also [76]. Thus the $\cos\delta$ dependence in the magnitudes of these two terms will approximately cancel in vacuum, although the matter effect will somewhat change this, see the discussion later in this subsection. Second, we focus on the Δ_{21} term. In vacuum, to first order in s_{13}, the term is

$$-4c_{23}^2(c_{23}^2 s_{12}^2 c_{12}^2 + s_{23} c_{23} s_{13} \sin 2\theta_{12} \cos 2\theta_{12} \cos\delta) \sin^2\Delta_{21}, \quad (7)$$

where the $\cos\delta$ dependence is numerically $\approx -0.0005\cos\delta$ at $E_{\max} = 1.3$ GeV, the energy of the first nontrivial maximum for DUNE. Third, we include the correction due to the matter effect which significantly changes this. The matter effect has almost no impact on θ_{23} or δ below the atmospheric resonance at $E \simeq 11$ GeV [77,78]. In addition, while θ_{13}, Δm_{31}^2, and Δm_{32}^2 do evolve somewhat in matter, they change $\lesssim 10\%$ from their vacuum values and the effect can be safely ignored for the Δ_{21} term. The solar parameters, θ_{12} and Δm_{21}^2, on the other hand, evolve considerably in matter at these energies. To a sufficient approximation, the matter correction factor for the solar parameters is [77,79]

$$\mathcal{S}_\odot \simeq \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}, \quad (8)$$

where $a = 2\sqrt{2} G_F N_e E$ is the contribution from the matter effect. At $E_{\max} = 1.3$ GeV, $\mathcal{S}_\odot = 3.4$ and provides an excellent approximation to the rescaling of Δm_{21}^2 in matter. We note that past the solar resonance at $E = 0.13$ GeV, $\theta_{12} > \pi/4$ and thus $\cos 2\theta_{12} < 0$ flipping the sign on the $\cos\delta$ dependence. We can approximate the solar mixing angle in matter by

$$\cos 2\theta_{12} \to \frac{\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2}{\mathcal{S}_\odot} \approx -0.96, \quad (9)$$

which also agrees to excellent precision with the exact answer. Therefore the second term in the parentheses in Eq. (7) changes sign when the matter effect is considered, but the effect is only $0.004\cos\delta$, about half the true effect. We summarize all the effects comparing the vacuum result to that at HK and at DUNE in Table I.

The additional correction comes from the Δm_{32}^2 term which, in matter, provides an additional $\cos\delta$ dependence of 0.004 which, when combined with the Δ_{21} term, adds to $0.008\cos\delta$, in agreement with the exact numerical result.

That is, we expect that the probability in matter should be highest for $\cos\delta = 1$ and lowest for $\cos\delta = -1$ varying a total of almost 2%, as is confirmed numerically in Fig. 1. We have also confirmed that the effect for HK is nearly identical to that in vacuum except for a shift $\cos\delta \to -\cos\delta$; this is because the relevant energy is approximately double the solar resonance in the Earth's crust. This measurement therefore also provides another

TABLE I. The impact of the matter effect on the $\cos\delta$ dependence of the Δ_{21} term at the first nontrivial oscillation maximum in vacuum, for HK, and for DUNE.

	Vacuum	HK	DUNE
E [GeV]	0	0.3	1.3
$\mathcal{S}_\odot$	1	1.01	3.4
s_{13}	0.148	0.152	0.166
$s_{212}c_{212}$	0.37	0.39	−0.26
Total:	−0.0005	0.0005	0.004

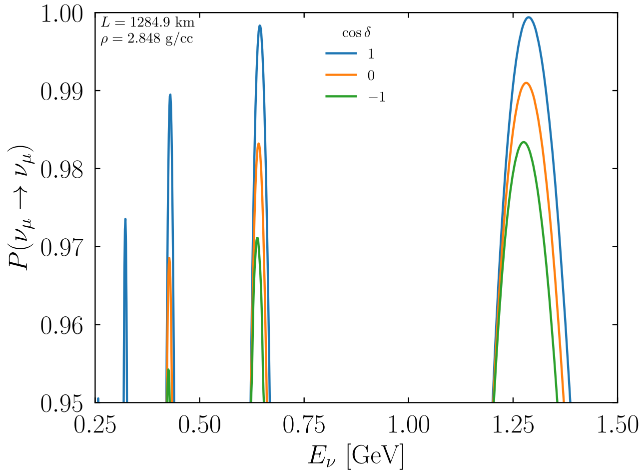

FIG. 1. The ν_μ disappearance probability for DUNE at different values of $\cos\delta$; see the Supplemental Material [68] for the same plot for HK.

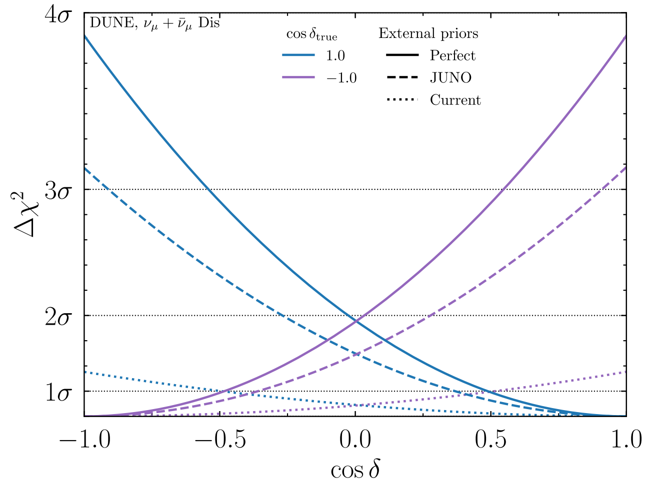

FIG. 2. The expected sensitivity to $\cos\delta$ using only ν_μ and $\bar{\nu}_\mu$ disappearance from DUNE along with external priors on the other five oscillation parameters from the current precision, the expected improvement with JUNO, or if the other oscillation parameters are known perfectly.

indirect test of the matter effect if one is able to compare measurements of δ between the appearance and the disappearance channels.

For antineutrinos the story is somewhat different. The value of $\cos\delta$ does not change as $\delta \to -\delta$, so it is the same as for neutrinos. In matter we note that while $\cos 2\widehat{\theta_{12}} < 0$ for neutrinos for DUNE and HK, it remains positive for antineutrinos, as in vacuum. Thus the impact on the oscillation maxima for antineutrinos is the same in matter as in vacuum and the probability is comparatively large for $\cos\delta = -1$ and small for $\cos\delta = +1$. Because of the lower statistics in $\bar{\nu}_\mu$ mode, however, this channel will not contribute as much as the neutrino channel to the total significance for probing $\cos\delta$ and CP violation.

Estimated experimental sensitivities—To numerically quantify the magnitude of the effect given realistic experimental details, we simulate ν_μ and $\bar{\nu}_\mu$ disappearance in DUNE using DUNE's simulation files [80,81]. We consider 40 kt fiducial volume and 6.5 yr in each neutrino and antineutrino mode with 1.2 MW and 56% beam uptime. We consider priors on the five oscillation parameters other than δ from one of the following: (1) Our *current* knowledge of the oscillation parameters [9]. Since both DUNE and HK will provide better measurements of θ_{23} and Δm^2_{31} than existing data, this is equivalent to using Daya Bay, RENO, KamLAND, and Solar data (all disappearance experiments) to constrain θ_{13}, θ_{12}, and Δm^2_{21}. (2) The expected improvement on θ_{12}, Δm^2_{21}, and Δm^2_{31} from the inclusion of 6 yr of *JUNO*'s $\bar{\nu}_e$ disappearance data [67]. (3) The hypothetical scenario with *perfect* knowledge of all five other oscillation parameters. We now perform a statistical test to determine DUNE's capability to determine $\cos\delta$ including systematics, efficiency, smearing, and backgrounds as estimated by DUNE [80] and show our results in Fig. 2 for each of the three different choices of priors. For $\cos\delta = \pm 1$, the combination of DUNE and JUNO can disfavor $\cos\delta = \mp 1$ at $> 3\sigma$ and further improvements in JUNO's measurement could reach close to 4σ. In addition, for $\cos\delta = 0$ (CP violating), $|\cos\delta| = 1$ (CP conserving) can be disfavored at 1.6σ; see also the Appendix.

We have confirmed that there is information about $\cos\delta$ in each of neutrino and antineutrino modes individually, although neutrino mode contributes more to the information due to higher statistics from the larger cross section and lower wrong-sign lepton rates. In addition, as suggested by the theory discussion above, $\cos\delta$ can also be determined if DUNE was performed in vacuum, although the results would be modified. Numerous additional numerical results for DUNE as well as HK can be found in the Supplemental Material [68] including the impact of run-time.

We also checked the precision with which $\cos\delta$ can be determined. The 1σ uncertainty is essentially independent of the true value and is 0.63 and 0.51 given external information at the level associated with 6 yr of JUNO and perfect knowledge, respectively.

One could also consider ν_μ disappearance with atmospheric neutrinos at HK [82], IceCube [83], KM3NeT [84], or JUNO [85,86], however, the expected sensitivity is likely less than that presented here and depends strongly on systematics, see, e.g., [87] for a discussion including both disappearance and appearance in atmospherics. Nonetheless, due to the different systematics and timelines it may be useful to consider a fit including atmospheric neutrinos alongside state-of-the-art ν_e disappearance measurements.

In principle, one could probe $\cos\delta$ with existing disappearance data. The current status of the data is that the best ν_μ disappearance measurements come from

NOvA [22] and T2K [23] and the best ν_e disappearance measurements come from Daya Bay [61] and KamLAND [63]. The ν_e disappearance data is described by the "current" curves in Fig. 2 as well as those in the Supplemental Material [68], which show that even DUNE or HK can only provide at most $\sim 1.4\sigma$ sensitivity to $\cos\delta$; with existing NOvA and T2K data there would not be any significant $\cos\delta$ information at all.

Conclusion—Determining if CP is violated in the neutrino sector is one of the highest priorities in particle physics. The best way to do so is with neutrino oscillations in the appearance channels. As this measurement will face many significant systematic uncertainties, additional means of probing δ and CP violation will be crucial to ensure robustness. While disappearance channels are fundamentally CP conserving, we have shown both by counting information in parameters and a direct relationship between J and the $|U_{\alpha i}|^2$'s that disappearance measurements can still provide information about δ, specifically $\cos\delta$, which is sufficient to determine if CP is violated or not. Nonetheless, it cannot be done with any one disappearance measurement; we require good precision measurements of the disappearance probability of at least two different flavors.

The matter effect affects the details of this story somewhat, but CP violation can be determined in vacuum or matter. In addition, neutrinos and antineutrinos behave somewhat differently in disappearance due to the matter effect, but neutrino mode alone (or antineutrino mode alone) is sufficient to determine if CP is violated.

In the upcoming generation of experiments, JUNO will measure the $\bar{\nu}_e$ disappearance probability with unprecedented precision by directly observing all three oscillation frequencies. Long-baseline experiments like DUNE and HK will measure ν_μ disappearance primarily focused on the weighted average of the Δm^2_{31} and Δm^2_{32} frequencies, but will also detect at a subleading level the Δm^2_{21} frequency [88]. This is enough to provide some information about δ. In particular, we find that DUNE and JUNO combined will be able disfavor some values of $\cos\delta$ at up to $>3\sigma$ depending on the true value. Since ν_μ disappearance has somewhat cleaner and, more importantly, different, systematics from ν_e appearance in long-baseline measurements at DUNE and HK, this channel will provide a crucial robustness test of CP violation when combined with JUNO data.

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Data availability—Data files for the calculations in the Letter can be found at [89].

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End Matter

Appendix: CP violation discovery sensitivity—We now include, for completeness, several additional numerical results including both HK and DUNE. In Fig. 3, we quantify the expected sensitivity to discover *CP* violation (that is, ruling out $|\cos\delta| = 1$) as a function of the true value of δ for DUNE (left) and HK (right). We also consider different choices of external measurements of the other oscillation parameters as in Fig. 2. The different colors correspond to including both appearance and disappearance (the standard DUNE analysis), only appearance, and only disappearance. The different line styles correspond to external pulls from the current knowledge of the oscillation parameters, the expected improvements with JUNO, and hypothetical perfect knowledge. The blue dotted curve (both channels and current knowledge of the oscillation parameters) agrees with DUNE's curve very well.

For HK we assume 1.3 MW, 187 kton fiducial mass, 1:3 neutrino to antineutrino run time ratio, and 10 yr of running at 100% uptime to generally agree with the nominal HK prediction [82]. Note that we assume that the mass ordering is known which is relevant for HK and not for DUNE because DUNE will measure it directly at very high significance in the appearance channel. We find that HK is somewhat less sensitive to discovering *CP* violation in the disappearance channel than DUNE since the effect is smaller, but the larger statistics mostly compensate for the difference.

We note that the combined fit with both appearance and disappearance data yields more information than the naive sum of the $\Delta\chi^2$'s of each separately in the cases with the current or expected JUNO priors due to the fact that ν_μ disappearance will provide world leading measurements of Δm^2_{31} and θ_{23}, but with perfect knowledge of the other five oscillation parameters, the combined fit is the same as the naive sum of $\Delta\chi^2$'s.

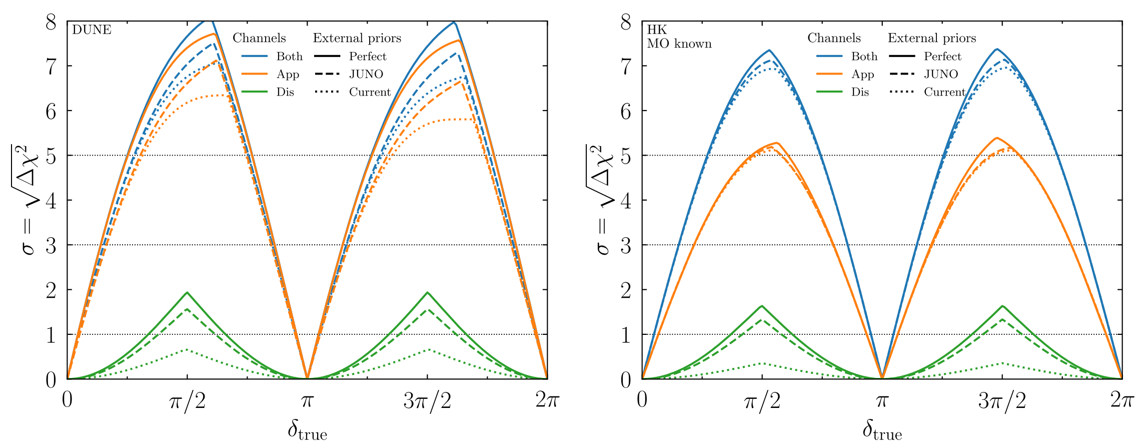

FIG. 3. The sensitivity of DUNE (left) and HK (right) to disfavor *CP* conservation, broken down by channel (colors) and the external priors (line styles).