Physics of the NOνA Experiment

(Prepared for the DOE Office of Science)

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1 Introduction

The NOνA experiment is the second-generation experiment on the NuMI beamline. Before we get into the quantitative physics sensitivities of the NOνA experiment, it is useful to point out that NOνA will addresses seven of the eight questions about neutrinos that the 2008 HEPAP P5 subpanel raised in its report.[1] (P5 questions are in italics.)

1. *What is the value of θ_{13}, the mixing angle between first- and third-generation neutrinos ... ? Determining the size of θ_{13} has critical importance not only because it is a fundamental parameter, but because its value will determine the tactics to best address many other questions in neutrino physics.*

   NOνA will measure θ_{13}, but the measurement from the reactor experiments will be somewhat more precise, so the NOνA measurement will be an important consistency check on the model of neutrino oscillations.

2. *Do neutrino oscillations violate CP? If so, how can neutrino CP violation drive a matter-antimatter asymmetry among leptons in the early universe (leptogenesis)? What is the value of the CP violating phase, which is so far completely unknown? Is CP violation among neutrinos related to CP violation in the quark sector?*

   NOνA will acquire significant information on the CP-violating phase δ.

3. *What are the relative masses of the three known neutrinos? Are they "normal," analogous to the quark sector, ($m_3 > m_2 > m_1$) or do they have a so-called "inverted" hierarchy ($m_2 > m_1 > m_3$)? ... The ordering has important consequences for interpreting the results of neutrinoless double beta decay experiments and for understanding the origin and pattern of masses in a more fundamental way, restricting possible theoretical models.*

   Due to its long baseline, NOνA will be able to gain information on the mass ordering and possibly resolve it through a "matter effect," which will be explained below. An additional reason to resolve the mass ordering is that it is necessary to measure CP violation in neutrinos. This is because the matter effect acts like a CP violation, due to the existence of electrons but not positrons in the earth, and thus could confuse the measurement of CP violation, as will be discussed below.

4. *Is θ_{23} maximal (45 degrees)? if so, why? Will the pattern of neutrino mixing provide insights regarding unification of the fundamental forces? Will it indicate new symmetries or new selection rules?*

   NOνA will provide a more sensitive measurement of θ_{23} than is currently available. If θ_{23} is not maximal, determining whether it is greater than or less than 45 degrees will contribute to our understanding of the relationship between neutrino mass states and flavor states, as will be discussed below.

5. *Are neutrinos their own antiparticles? Do they give rise to lepton number violation, or leptogenesis, in the early universe? ...*

   The only practical way to determine whether neutrinos are their own antiparticles is through neutrinoless double beta decay experiments. However, by measuring the neutrino mass ordering, NOνA can make an essential contribution to interpreting neutrinoless double beta decay experiments. If the mass ordering is inverted, then the next generation of neutrinoless double beta decay experiments will be able to determine if the neutrino is a Majorana particle, that is, that the neutrino is its own antiparticle. However, if the mass ordering is normal, then a negative result from neutrinoless double beta decay experiments will be inconclusive. It is necessary that the neutrino be a Majorana particle for leptogenesis to explain the existence of matter in the universe.[2]

6. *What can we learn from observation of the intense flux of neutrinos from a supernova within our galaxy?...*

   Of order 10,000 supernova neutrinos will interact in the NOνA far detector in a ten-second interval with half the neutrino interactions occurring in the first second. Fast timing in the NOνA detector will allow for vetoing background signals from cosmic rays, and the NOνA data acquisition system is designed to be able to trigger on a supernova burst.

7. *What can neutrinos reveal about other astrophysical phenomena? Will we find localized cosmic sources of very high-energy neutrinos?*

   Since the NOνA far detector is on the surface, it will not be able to contribute to the study of very-high-energy cosmic ray events.

8. *What can neutrinos tell us about new physics beyond the Standard Model, dark energy, extra dimensions? Do sterile neutrinos exist?*

   NOνA will be able to search for sterile neutrinos by looking for a discrepancy between the rate of neutral current events in the near and far detectors.

NOνA is designed to have an order of magnitude better neutrino oscillation physics sensitivity than MINOS, the first generation experiment on the NuMI beamline, particularly for $\nu_\mu \rightarrow \nu_e$ appearance measurements. The increased power comes from a combination of factors:

- Approximately three times more mass
- Approximately twice as much beam power
- Much better particle identification, particularly for electrons, as a "totally active," rather than a sandwich detector[1]
- Approximately eight times finer longitudinal sampling (in radiation lengths)
- Off-axis siting, yielding a narrow-band beam concentrated in the region of the oscillation, yielding more useful flux and less background

2 The NOνA Beam

2.1 The Off-Axis Beam

The NOνA detectors are sited 14 mrad off the center of the NuMI beam axis. The reason for this is shown in Figures 1 and 2. Figure 1 shows the relationship between a pion's energy and the

[1]NOνA is not literally totally active because the liquid scintillator is contained in plastic tubes, the walls of which are not active. However, the walls are much thinner than the liquid scintillator, making the detectors functionally totally active.

energy of its decay neutrino as a function of laboratory angle. For neutrinos emitted on-axis, the energy of the neutrino is proportional to the energy of the parent pion. However, for neutrinos emitted off-axis, the energy of the neutrino is largely independent of the parent pion energy, leading to the narrow-band beams shown in Figure 2

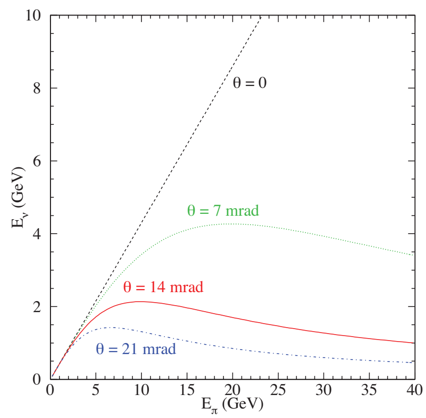

Figure 1. The energy of a neutrino vs. the energy of its parent pion for different laboratory angles.

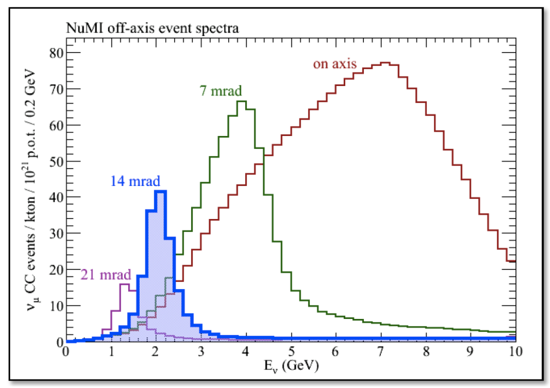

Figure 2. The energy spectrum of neutrino events for different off-axis angles for the NuMI medium-energy beam. The shaded distribution at 14 mrad corresponds to the NOνA beam.

2.2 NuMI Beam Power

The NOνA project includes an increase in the NuMI beam power from 400 kW to 700 kW. This is accomplished largely by storing the Booster batches in the Recycler, allowing the Main Injector to cycle in 1.33 s instead of 2.2 s.

3 The NOνA Detectors

The NOνA far detector will be located off the Ash River Trail in northern Minnesota, 810 km from the NuMI target. The Ash River Trail is the most northern road in the United States near the NuMI beam line. The NOνA near detector will be located on the Fermilab site about 1 km from the NuMI target. Neutrino oscillations are studied by comparing events in the near detector, where the neutrinos have not yet had time to oscillate, with those in the far detector. Using this comparison greatly reduces the systematic error, since uncertainties in the flux, cross sections, and hadronic interactions largely cancel in the comparison.

The NOνA detectors can be described as totally active, tracking, liquid scintillator calorimeters.[2] The basic cell of the far detector is a column or row of liquid scintillator with approximate transverse dimensions 4 cm by 15.6 m and longitudinal dimension 6 cm encased in a highly reflective polyvinyl chloride (PVC) container. A module of 32 cells is constructed from two 16-cell PVC extrusions glued together and fitted with appropriate end pieces. Twelve modules make up a plane, and the planes alternate in having their long dimension horizontal and vertical. The far detector will consist of a minimum of 928 planes, corresponding to a mass of 14

[2]See footnote 1.

kt. Additional planes are possible depending on available funds at the end of the project. The far detector enclosure was built to hold 18 kt.

The NOνA near detector is identical to the far detector except that it is smaller, 3 modules high by 3 modules wide, with 192 planes. Behind the near detector proper is a muon ranger, which is a sandwich of ten 10-cm iron plates, each followed by two planes of liquid scintillator detectors. NOνA has also constructed a near detector prototype called the NDOS (Near Detector On the Surface) which has been running since November 2010 on the surface at Fermilab, off axis to both the NuMI and Booster neutrino beams. Figure 3 contains a drawing of the NOνA detectors. Additional details of the NOνA detectors can be found in the Technical Design Report[3].

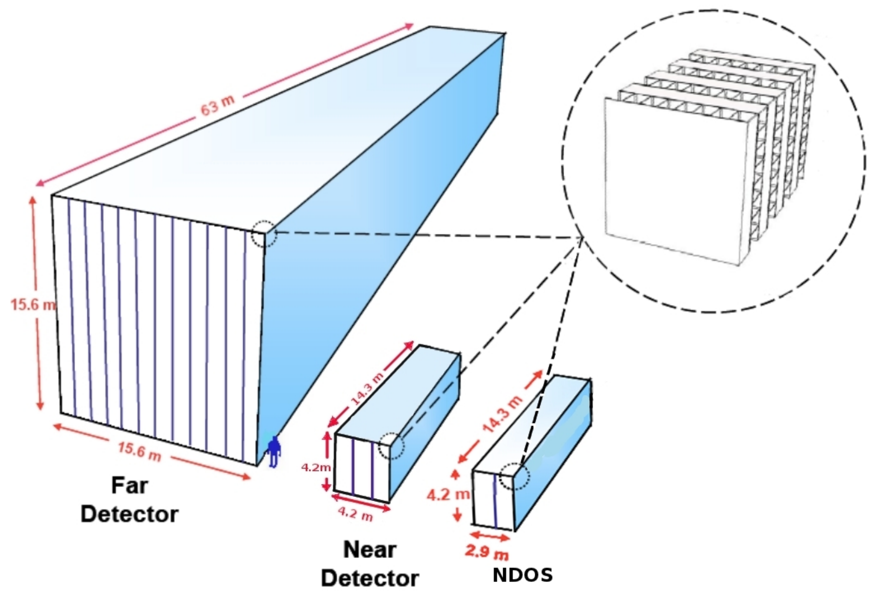

Figure 3. Drawings of the NOνA far and near detectors. The human figure at the base of the far detector is for scale.

4 The Basics of Neutrino Oscillations

In the "Nu Standard Model," as it is sometimes called, there are three neutrino mass states, ν_1, ν_2, and ν_3. Neutrino oscillations are sensitive to the differences in the squares of the neutrino masses, $\Delta m^2_{ij} = \Delta m^2_i - \Delta m^2_j$. With three neutrinos, there are two independent mass splittings. The so-called solar mass squared splitting, Δm^2_{21}, was first seen from a study of neutrinos emitted by the sun, but it has been best measured by the long-baseline KamLAND reactor experiment[4] and corresponds to an oscillation length of about 15,000 km/GeV. The so-called atmospheric mass squared splitting, an unresolved combination of Δm^2_{31} and Δm^2_{32}, was first seen from a study of neutrinos produced by cosmic rays hitting the earth's atmosphere. It has been best measured by the MINOS experiment[5] and corresponds to an oscillation length of about 500 km/GeV.

Neutrinos can be described as having either specific masses or specific flavors, but not both simultaneously. The three flavor states of neutrinos are ν_e, ν_μ, and ν_τ, which are produced by the weak interactions in conjunction with electrons, muons, and tau leptons, respectively. They are connected mathematically to the mass states through an abstract three-dimensional rotation, which is characterized by three mixing angles, $\theta_{12},\ \theta_{13}$, and θ_{23}, and a phase δ.

The angle θ_{12} controls the oscillations at the very long solar oscillation length. It is large but not maximal.

The angle θ_{23} controls the dominant oscillation at the atmospheric oscillation length, $\nu_\mu \rightarrow \nu_\tau$. This process is proportional to $\sin^2(2\theta_{23})$. Until very recently, all evidence was that this oscillation was maximal ($\theta_{23} = 45°$). However, the most recent results from both MINOS[5] and SuperKamiokande[6] indicate that it may not be maximal. If θ_{23} is not equal to unity, then it will be important to determine whether θ_{23} is greater or less than $\pi/4$, since this will determine whether ν_3 couples more strongly to ν_μ or to ν_τ, as can be seen in Figure 4. If the mass ordering turns out to be the normal ordering, then $\theta_{23} < \pi/4$ would be the most normal, since then ν_e would couple most strongly to ν_1, ν_μ would couple most strongly to ν_2, and ν_τ would couple most strongly to ν_3.

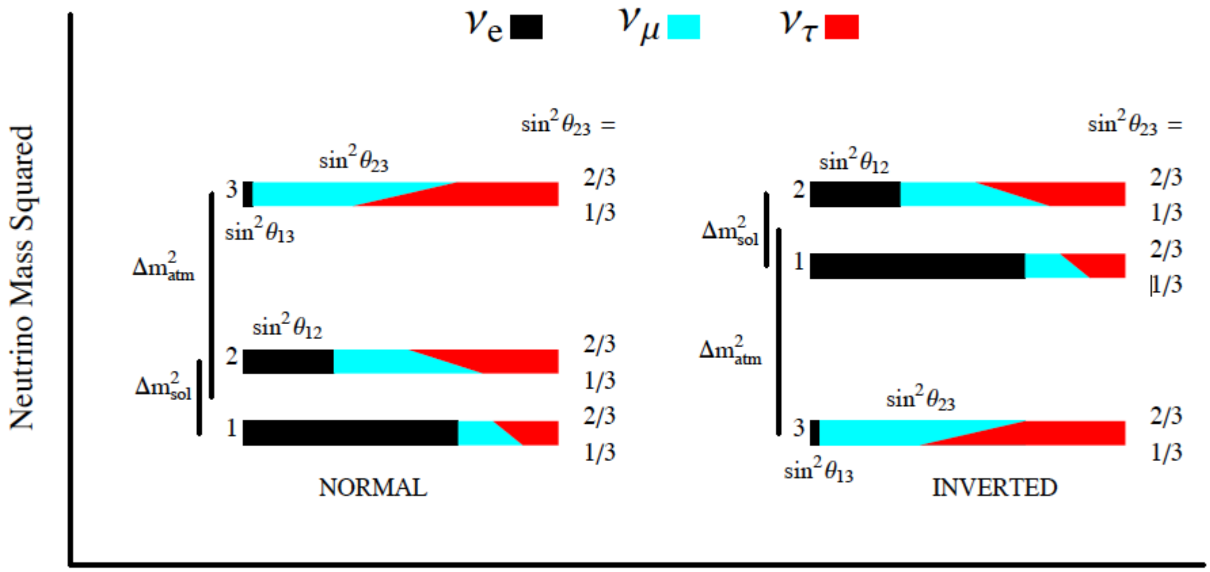

Figure 4. This figure shows the two possible mass orderings of the three neutrino mass states (not to scale) and the probability of each mass state materializing in a particular flavor state. The width of each bar represents a possible variation of $\sin^2(\theta_{23})$ from 2/3 to 1/3 corresponding to a variation of $\sin^2(2\theta_{23})$ over the range 0.89 to 1.00. The figure is from Mena and Parke[10].

The angle θ_{13} controls the crucial subdominant $\nu_\mu \rightarrow \nu_e$ oscillation at the atmospheric oscillation length. This angle is the smallest of the three, but recent measurements from three reactor experiments, Double Chooz[7], Daya Bay[8], and RENO[9], all indicate that it is near the previous upper limit and this will insure healthy $\nu_\mu \rightarrow \nu_e$ rates for all long-baseline accelerator experiments.

The phase δ produces CP violation if it is neither zero or π.

A further unknown is the mass ordering of the three neutrino states. This can be measured in long-baseline neutrino experiments by a "matter effect," the coherent forward scattering of ν_es off the electrons in matter. The forward scattering of ν_es in matter is different than that of ν_μs and ν_τs because the former have both neutral and charged current interactions with the electrons in matter, while the latter have only neutral current interactions. It is known from matter effects in the sun that between ν_1 and ν_2, ν_es couple more strongly to the lower of the two mass states, and that state is by convention called "ν_1." What is unknown at present is whether ν_3 lies higher or lower in mass than ν_1 and ν_2. This is illustrated in Figure 4.

5 NOνA Sensitivities

The sensitivities discussed below all assume that NOνA will run for three years in neutrino mode and three years in antineutrino mode. The sensitivities are largely based on analysis techniques that were used by the MINOS experiment. We expect to be able to achieve somewhat better sensitivities as we incorporate additional techniques allowed by NOνA's finer segmentation and greater active fraction.

5.1 ν_μ Disappearance

The disappearance of ν_μ charged current events measures $\sin^2(2\theta_{23})$. The latest MINOS measurement of this parameter is 0.96 ± 0.04.[5] For the reasons cited above, NOνA should be able to make a measurement that is about a factor of two to three more sensitive. Figure 5 shows the NOνA sensitivity for three possible values of $\sin^2(2\theta_{23})$. We will gain more information about θ_{23} from $\nu_\mu \to \nu_e$ oscillations, as discussed below.

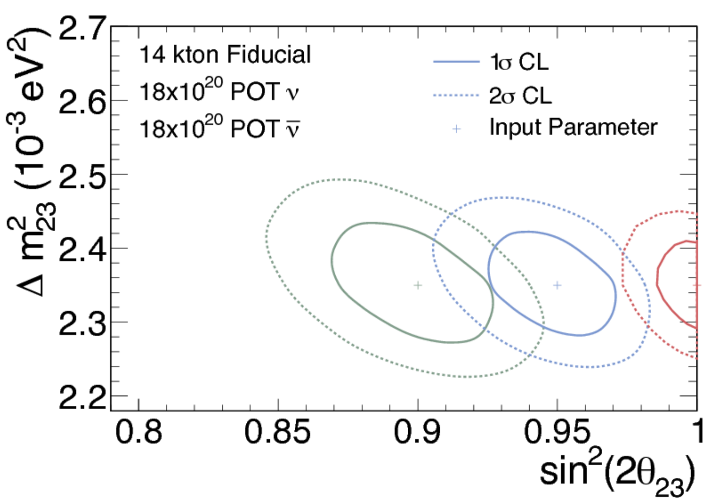

Figure 5. One and two standard deviation NOνA sensitivity contours for a joint measurement of Δm^2_{32} and $\sin^2(2\theta_{23})$ for three possible values of these parameters indicated by the crosses. The single parameter measurement of $\sin^2(2\theta_{23})$ will be somewhat more sensitive than the extreme limits of the displayed contours.

5.2 $\nu_\mu \to \nu_e$ Oscillations

The parameters for $\nu_\mu \to \nu_e$ oscillations are considerably more complex than for ν_μ disappearance. This process is largely proportional to both $\sin^2(2\theta_{13})$ and $\sin^2(\theta_{23})$, with large perturbations caused by the mass ordering (through the matter effect) and by CP violation. A convenient way to see the dependences is through bi-probability plots. These plots show the loci of possible NOνA measurements of $\nu_\mu \to \nu_e$ and $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillation probabilities, given a set of parameters. These parameters include $\sin^2(2\theta_{13})$, which is fixed at 0.095, a value consistent with the recent reactor measurements[7, 8, 9], and $\sin^2(2\theta_{23})$. Figures 6 and 7 show bi-probability plots for $\sin^2(2\theta_{23})$ = 1.00 and 0.97, respectively. The CP-violating phase δ traces out the ovals and the multiplicity of ovals represents the two possible mass orderings and, for Figure 7, the ambiguity of whether θ_{23} is larger or smaller than $\pi/4$.

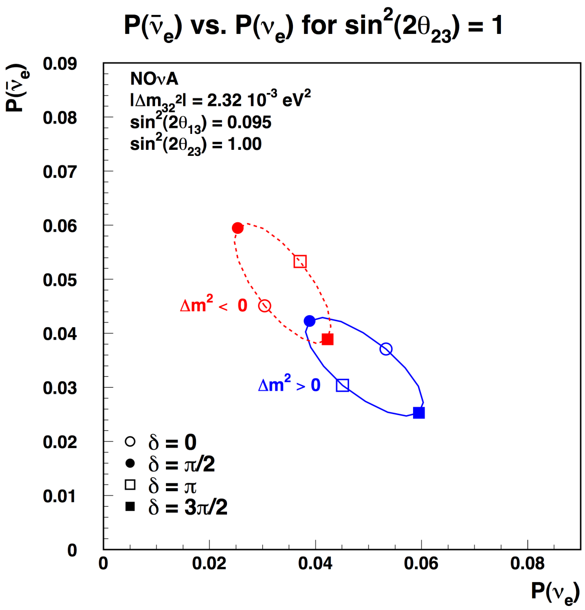

Figure 6. Bi-probability plot for $\sin^2(2\theta_{23})$ = 1.00. See text for explanation.

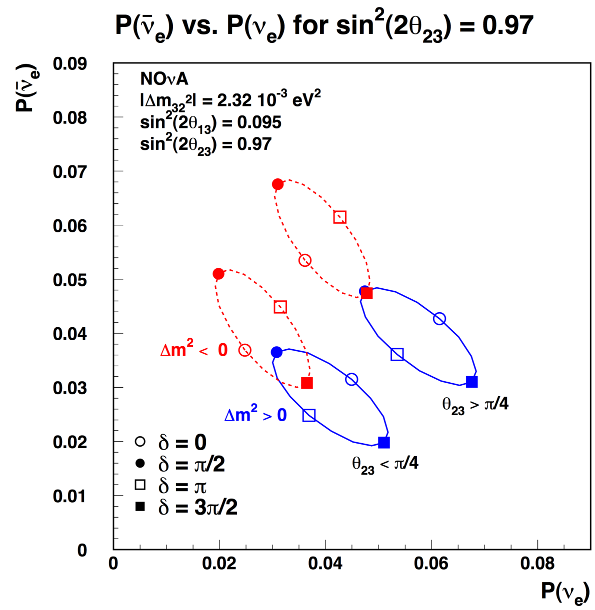

Figure 7. Bi-probability plot for $\sin^2(2\theta_{23})$ = 0.97. See text for explanation.

A useful way to visualize what NOνA will be able to do is to superimpose one and two standard deviation contours on the bi-probability plots. For example, Figures 8 and 9 show these contours for a favorable set of parameters, normal mass ordering and $\delta = 3\pi/2$. The mass ordering is resolved to more than two standard deviations, the θ_{23} ambiguity is resolved to two standard deviations, and CP violation is established to almost two standard deviations. This occurred because the matter effect and the CP-violating effect went in the same direction, so there was no ambiguity.

An unfavorable set of parameters would be one in which the matter effect and the CP-violating effect go in opposite directions so that there is an ambiguity as to which direction each one went. An example of that is shown in Figure 10. The θ_{23} ambiguity is resolved, but the mass ordering is not, and therefore there is little information on the CP-violating phase. If nature gives us this situation, then the only way to resolve the mass ordering in the short term is to compare NOνA measurements of $\nu_\mu \to \nu_e$ oscillations with those from an experiment with a different baseline. The only experiment that meets that requirement is T2K experiment in Japan.[13], which has a 295 km baseline.

The algorithm for resolving the mass ordering is quite simple. If NOνA measures a higher probability of $\nu_\mu \to \nu_e$ oscillations than T2K, then the mass ordering is normal; if it is the opposite, it is inverted. That is because NOνA and T2K will see the identical CP-violation, but T2K will see a much smaller matter effect due to its shorter baseline. The only catch in this algorithm is that the comparison must be done at the same point in the oscillation phase, and the two experiments run at different average phases. Figures 11 and 12 show the bi-probability plots

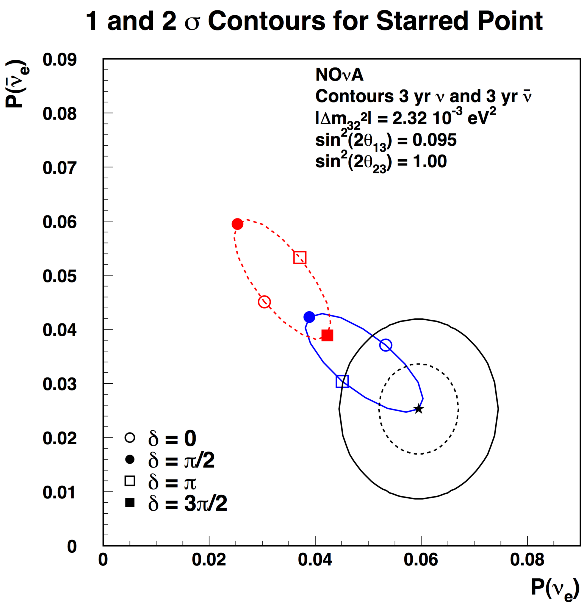

Figure 8. Bi-probability plot for $\sin^2(2\theta_{23})$ = 1.00 with NOνA expected 1 and 2 standard deviation contours superimposed on the starred point.

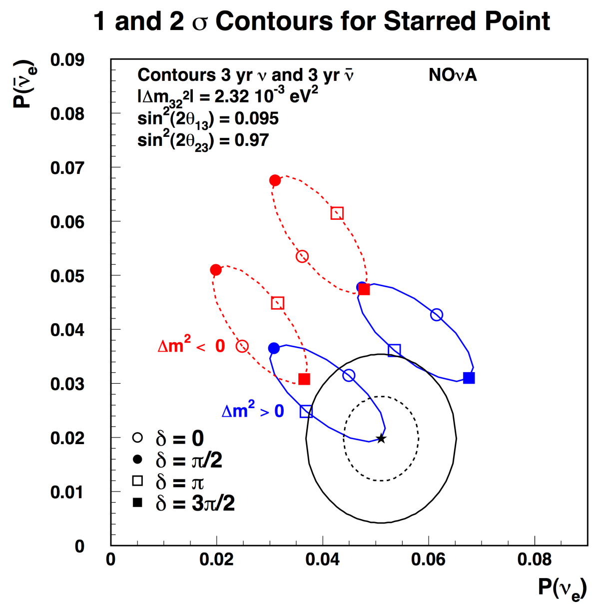

Figure 9. Bi-probability plot for $\sin^2(2\theta_{23})$ = 0.97 with NOνA expected 1 and 2 standard deviation contours superimposed on the starred point.

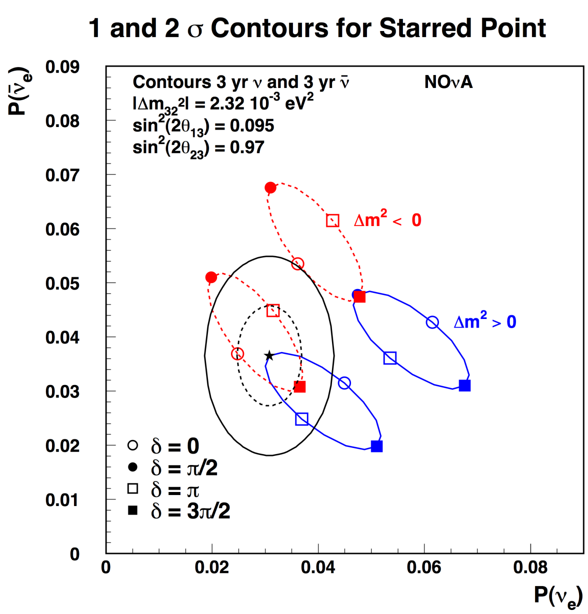

Figure 10. Bi-probability plot for $\sin^2(2\theta_{23})$ = 0.97 with NOνA expected 1 and 2 standard deviation contours superimposed on the starred point.

in which the NOνA measurements have been extrapolated to the same oscillation phase as the T2K measurements. A comparison of the two plots shows that the algorithm works for all values of δ.

Unfortunately, the combined statistical power of NOνA and T2K at the end of the nominal six-year NOνA run will be insufficient to resolve the mass ordering at the two standard deviation level using this strategy. However, it is unlikely that either the American or the Japanese neutrino program will end at that time. With anticipated improvements in both programs, in the worst case,

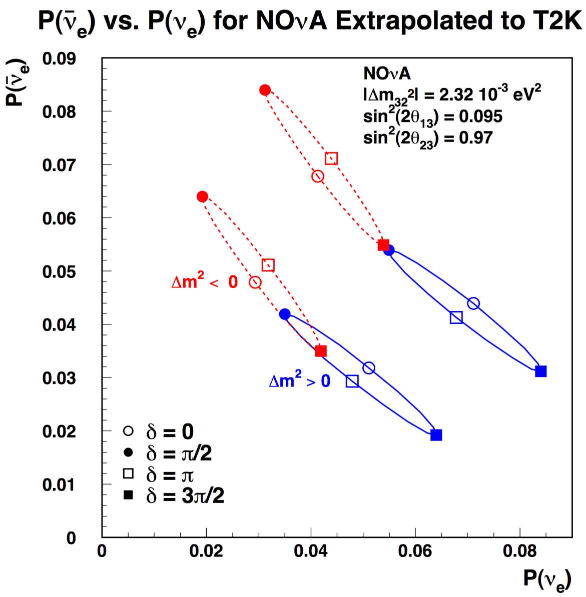

Figure 11. Bi-probability plot for $\sin^2(2\theta_{23})$ = 0.97 with for NOνA extrapolated to the average oscillation phase of T2K

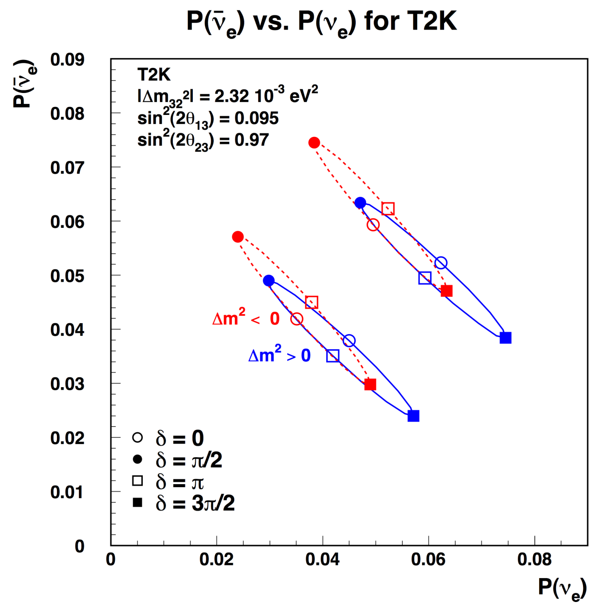

Figure 12. Bi-probability plot for $\sin^2(2\theta_{23})$ = 0.97 for T2K.

the mass ordering should be resolved in the next decade, regardless of which option is chosen for the reconfigured LBNE experiment.

Figures 13 and 15 summarize the NOνA sensitivities for resolving the mass ordering and determining that there is CP violation in the leptonic sector, respectively. These figures are for NOνA alone and use only the total measured oscillation rate. There will be some gain in sensitivity in using the measured energy dependence and, as mentioned previously, improvements in the analysis. Figures 14 and 16 show the same information, but include the information from T2K that is expected to be available at the end of the nominal six-year NOνA run.

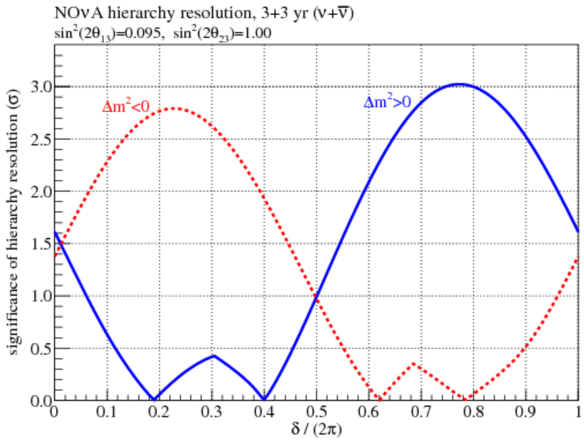

Figure 13. Significance of the resolution of the mass ordering as a function of δ in standard deviations. These sensitivities are for NOνA alone for the two possible orderings and $\sin^2(2\theta_{23})$ = 1.0. The zeros correspond to the crossing of the ovals in Figure 6.

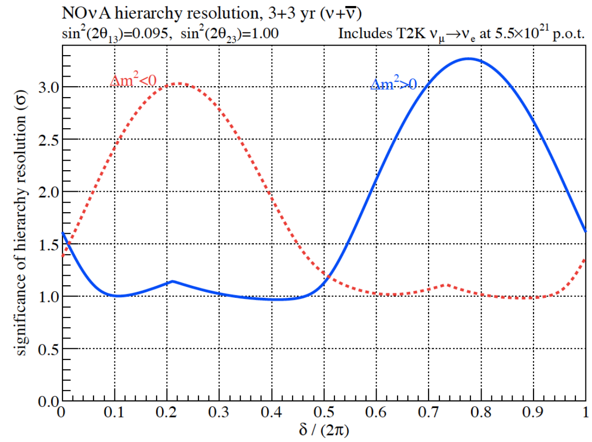

Figure 14. Same as the figure to the left except that information from the T2K experiment has been included.

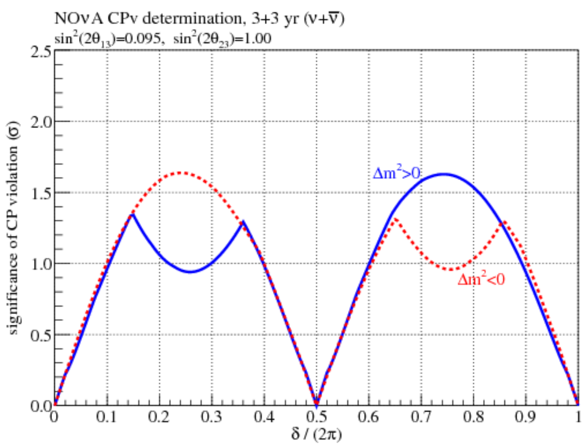

Figure 15. Significance of the determination that CP violation occurs in neutrino oscillations as a function of δ in standard deviations. These sensitivities are for NOνA alone for the two possible orderings and $\sin^2(2\theta_{23})$ = 1.0. The significance goes to zero at $\delta = 0$ and $\delta = \pi$ since there is no CP violation at those points. The dips in the peaks occur because the mass ordering has not been resolved for the ordering containing the dips.

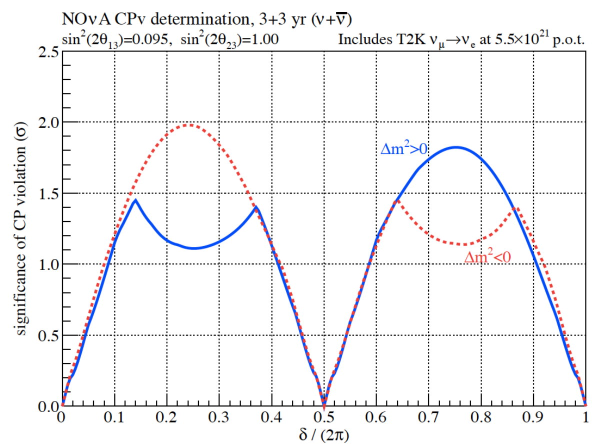

Figure 16. Same as the figure to the left except that information from the T2K experiment has been included.

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