The NOνA Experiment

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Abstract. The NOνA Project will construct a 15 kt Far Detector 835 km from Fermilab at Ash River Minnesota, a 220 ton Near Detector on the Fermilab site and upgrade the existing NuMI beamline from 400 kW to 700 kW. The detector technology is liquid scintillator captured in reflective rigid PVC cells. The light is captured using WLS fibre and routed to avalanche photo diodes. NOνA is designed to observe the appearance of electron neutrinos, determine the value of $\sin^2(2\theta_{13})$ and begin the study of CP violation in the neutrino sector. NOνA is the only currently approved experiment with the ability to determine the neutrino mass ordering. The NOνA physics program and projected sensitivities are described in this report.

1. Introduction

NOνA plans to split its running time equally between neutrino running and antineutrino running. Even though the rates are higher for neutrino running than antineutrino running, there are two reasons for this strategy. First, it makes the sensitivity to seeing a signal less dependent on the value of δ and the sign of Δm^2_{atm}. Second, without antineutrino running, NOνA would have no ability to measure δ or the sign of Δm^2_{atm}.

In the following, we will show the capabilities of the NOνA experiment assuming a 15 kT detector with both 36×10^{20}, 60×10^{20}, and 120×10^{20} protons on target (pot). The first corresponds to 6 full years (44 weeks per year) of running at 700 kW beam power, assuming the NuMI and accelerator upgrades included in the NOνA project. The last two corresponds to 6 full years of running at 1.2 MW and 2.3 MW beam power with the conceptual SNuMI and Project X upgrades. These latter beam powers are included to illustrate the potential of the NOνA experiment if either of these projects were to be accomplished. The sensitivity calculations have been done using results of simulations assuming a systematic uncertainty in the background extrapolation from the near to far detector of 10%. These calculations take into account the antineutrinos in the neutrino running (1.5%) and the neutrinos in the antineutrino running (3.8%).

2. Sensitivity to $\sin^2(2\theta_{13})$

Figure 1 shows the sensitivity to $\theta_{13} \neq 0$ at the three standard deviation level as a function of δ for each of the mass orderings. A way of comparing the difference between 700 kW, 1.2 MW, and 2.3 MW beam power is to note the fraction of the parameter space for which the NOνA three-standard deviation sensitivity is more than an order of magnitude greater than the Chooz experiment 90% upper limit. The 2.3 MW and 1.2 MW sensitivities meet this criterion for 64% and 22% of the parameter space, respectively, while the 700 kW sensitivities meet it for only 9.5% of the parameter space.

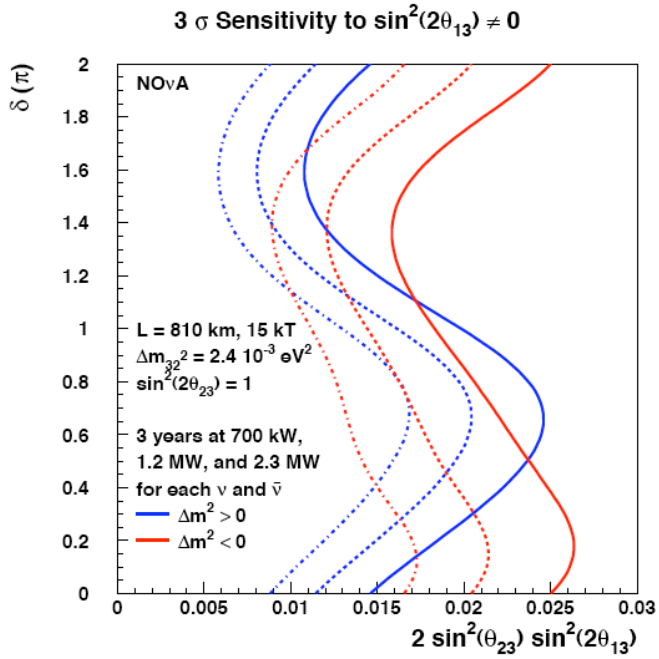

Figure 1. Three standard deviation sensitivity to $\theta_{13} \neq 0$ as a function of the CP-violating phase δ for a 6-years of NOνA running split evenly between neutrino and antineutrino running. The solid curves are for 700 kW beam power, the dashed curves are for 1.2 MW beam power, and the dot-dashed curves are for 2.3 MW beam power. The blue (more S-shaped) curves are for the normal mass ordering and the red curves are for the inverted mass ordering.

3. Sensitivity to the Mass Ordering

Figure 2 shows the sensitivity to the mass ordering at the 95% confidence level as a function of δ for each of the mass orderings. The dot-dashed and dashed lines show the sensitivity for 2.3 MW and 1.2 MW running, respectively, and the solid lines show the sensitivity for 700 kW running. The mass ordering can only be resolved by NOνA alone for the portion of the parameter space in which the matter effect and CP violation affect the oscillation in the same manner. For the remainder of the parameter space, a third measurement is required to resolve the mass ordering. One possibility is to combine NOνA data with data from T2K, which has a much shorter baseline. Figure 3 shows the effect of combining NOνA results with those from a 6-year neutrino run from the T2K experiment. It is assumed that the T2K beam power will upgrade in a similar way to the possible NOνA beam upgrades [8].

4. Sensitivity to the CP-Violating Phase

Figure 4 shows one standard deviation contours in the $\sin^2(2\theta_{13})$-δ plane for a sample point, $\sin^2(2\theta_{13}) = 0.06$ and δ = 3π/2, for 2.3 MW, 1.2 MW and 700 kW running. There is not enough statistical power to demonstrate CP-violation at three standard deviation level, but there is enough sensitivity to give an indication of the type of future experiments that will be necessary. For cases in which the mass ordering is not determined, there will also be contours for the alternative mass ordering hypothesis.

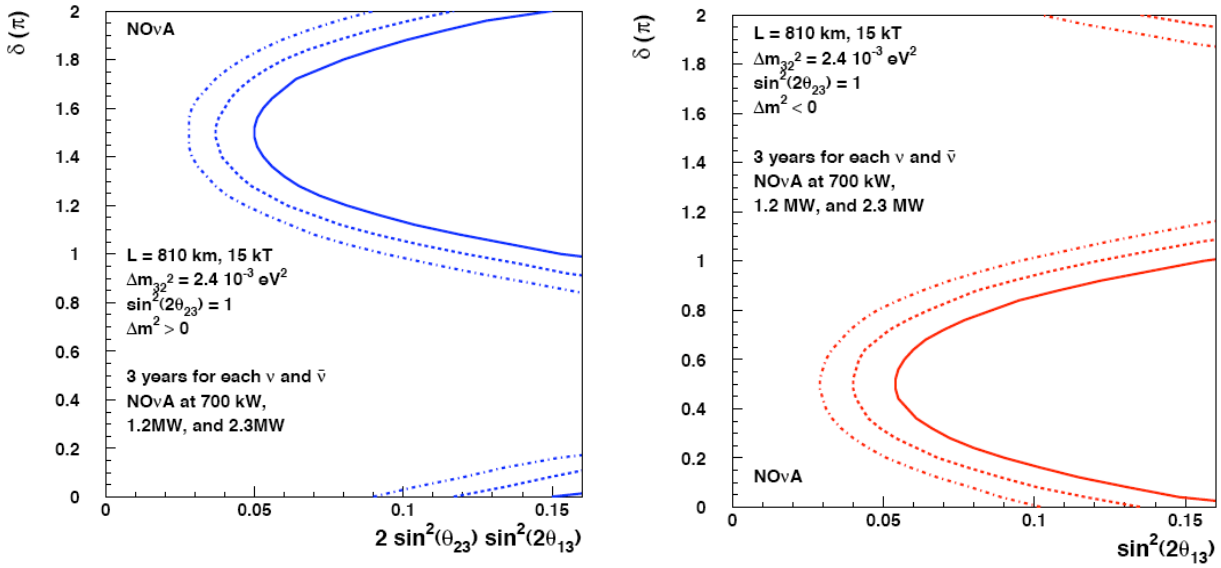

Figure 2. 95% resolution of the mass ordering as a function of the CP-violating phase δ for 6-years of NOνA running split evenly between neutrino and antineutrino running. The dot-dashed and dashed curves are for 2.3 MW and 1.2 MW beam power, respectively, and the solid curves are for 700 kW beam power. The left graph is for the normal mass ordering and the right graph is for the inverted mass ordering.

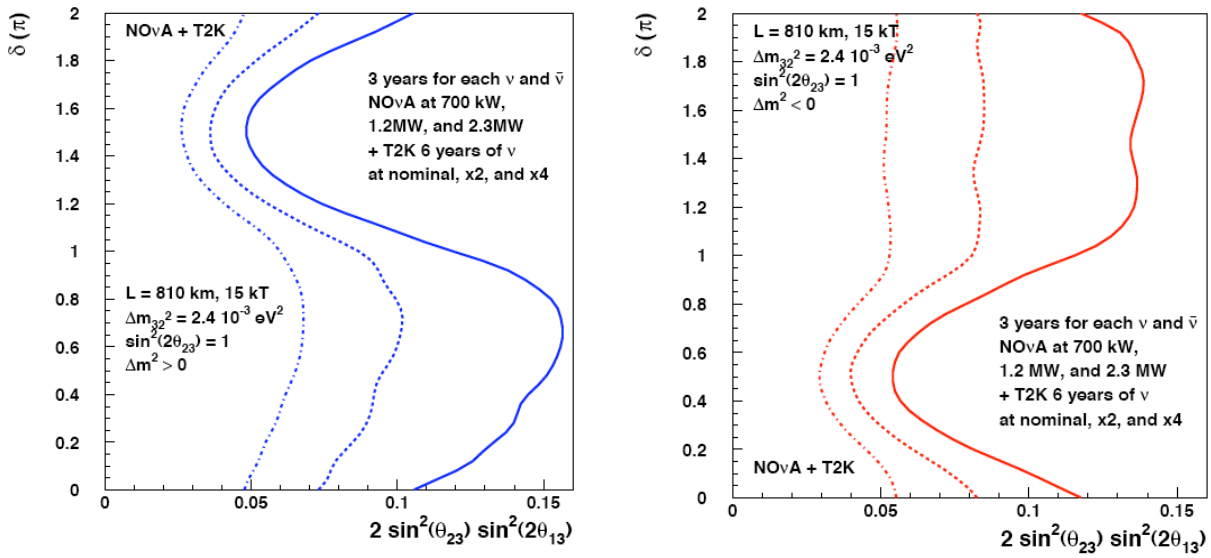

Figure 3. 95% resolution of the mass ordering as a function of the CP-violating phase δ for 6 years of NOνA running split evenly between neutrino and antineutrino running combined with 6 years of T2K running on neutrinos. The dot-dashed and dashed curves are for 2.3 MW and 1.2 MW beam power, respectively, and the solid curves are for 700 kW beam power for NOνA. It is assumed that T2K will upgrade it beam power in parallel with NOνA. The left graph is for the normal mass ordering and the right graph is for the inverted mass ordering.

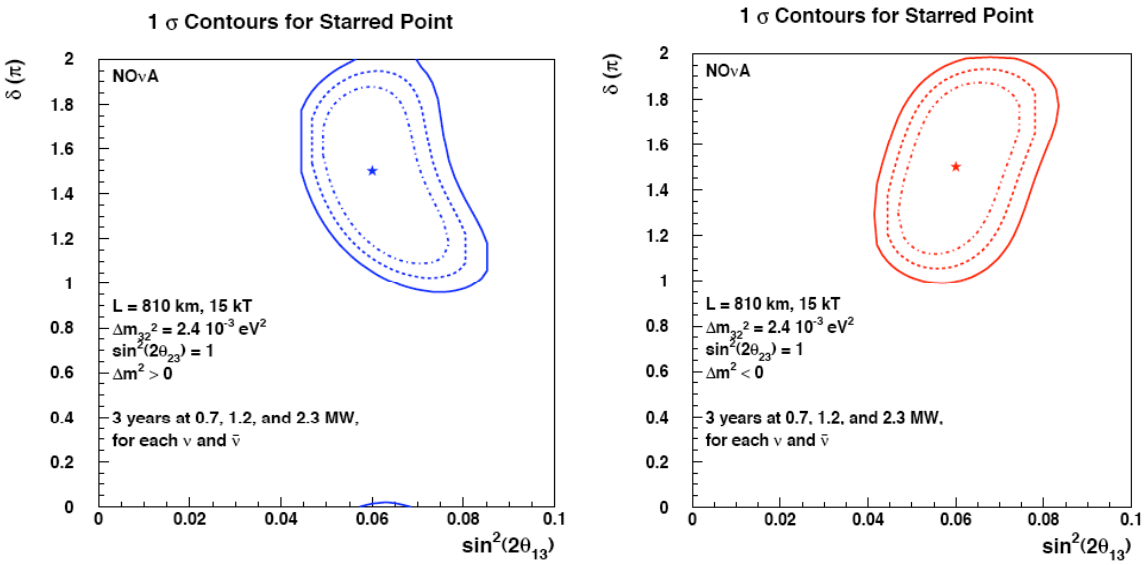

Figure 4. Expected 1-standard deviation contour for a sample point, $\sin^2(2\theta_{13}) = 0.06$, $\delta = 3\pi/2$, for 6-years of NOνA running split evenly between neutrino and antineutrino running. The solid contour is for 0.7 MW beam power, the dashed contour is for 1.2 MW beam power, and the dot-dashed cure is for 2.3 MW beam power. The left graph is for the normal beam ordering and the right graph is for the inverted mass ordering.

5. Measurement of the Dominant Mode Oscillation Parameters via ν_μ Disappearance

Although the primary NOνA physics goal is the study of $\nu_\mu \rightarrow \nu_e$ oscillations, NOνA will also be able to make significant measurements of the dominant mode oscillation parameters, $\sin^2(2\theta_{23})$ and Δm^2_{32}. The best current measurement of $\sin^2(2\theta_{23})$ comes from the Super Kamiokande study of atmospherically produced neutrinos [7]. This measurement is consistent with maximal mixing, $\sin^2(2\theta_{23}) = 1$, but with a considerable uncertainty. At the 90% confidence level, $\sin^2(2\theta_{23}) > 0.92$, which translates into a large range of possible values of $\sin^2(2\theta_{23})$, namely $0.36 < \sin^2(2\theta_{23}) < 0.64$.

There are three reasons why determining $\sin^2(2\theta_{23})$ is of high interest:

1. If the mixing is maximal, it might be due to some currently unknown symmetry.
2. The $\nu_\mu \rightarrow \nu_e$ oscillation is mostly proportional to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$ while $\bar{\nu}_e$ disappearance, measured by reactor experiments, is proportional to $\sin^2(2\theta_{13})$. Thus, if the mixing is not maximal, there is an ambiguity in comparing accelerator and reactor experiments.
3. Conversely, whether θ_{23} is greater than or less than $\pi/4$, which measures whether the third neutrino mass eigenstate couples more strongly to ν_μ's or ν_τ's, can best be measured by comparing precise accelerator and reactor measurements.

The deviation of $\sin^2(2\theta_{23})$ from unity is measured by the depth of the oscillation dip in the ν_μ disappearance spectrum. Thus, precision in this quantity requires good statistics in this region, excellent neutrino energy resolution, and good control of systematics. NOνA offers the possibility of satisfying all of these requirements.

It appears that the best way to meet these requirements is to limit the analysis to totally contained quasielastic events, i.e., those events in which the geometrical pattern of energy deposition is consistent with the presence of only an energetic muon and a possible recoil proton.

We have performed a preliminary study of how well NOνA can use these events to measure $\sin^2(2\theta_{23})$ and Δm^2_{32} using a parametric representation of the energy. This procedure is justified by the nature of these events, which are extremely clean.

The calculated one and two standard deviation contours are displayed in Figure 5 for assumed values of $\sin^2(2\theta_{23})$ of 0.95, 0.98, and 1.00 and a six-year run equally divided between neutrinos and antineutrinos for beam powers of 700 kW, 1.2 MW, and 2.3 MW. The energy resolution has been assumed to be 2%, but the contours do not change markedly as one increases the resolution to 4%.

Note that the precision of the $\sin^2(2\theta_{23})$ measurement increases as the value of $\sin^2(2\theta_{23})$ approaches unity. For maximal mixing, the error on the measurement of $\sin^2(2\theta_{23})$ is about 0.003 for 700 kW power and somewhat smaller for the other beam powers.

6. Measurement of the Sign of $\cos(2\theta_{23})$

If the dominant atmospheric oscillation is not maximal, it is interesting to determine whether θ_{23} is greater than or less than $\pi/4$, which measures whether ν_e's oscillate more strongly to ν_μ's or ν_τ's. This can be done most easily by comparing the results of the NOνA experiment with a reactor experiment, such as Daya Bay [9], since a reactor experiment will measure the oscillation of $\bar{\nu}_e$'s into the sum of $\bar{\nu}_\mu$'s and $\bar{\nu}_\tau$'s while an accelerator experiment will measure the oscillation of ν_μ's into ν_e's.

Figure 6 shows the region of $\sin^2(2\theta_{23})$ - $\sin^2(2\theta_{13})$ parameter space for which this measurement can be made at the 95% confidence level assuming that a reactor experiment can reach a one standard deviation precision of 0.005. The limits are functions of the CP-violating phase δ, the mass ordering, and the sign of $\cos(2\theta_{23})$; the values in Fig. 3.10 are averages over the parameter space.

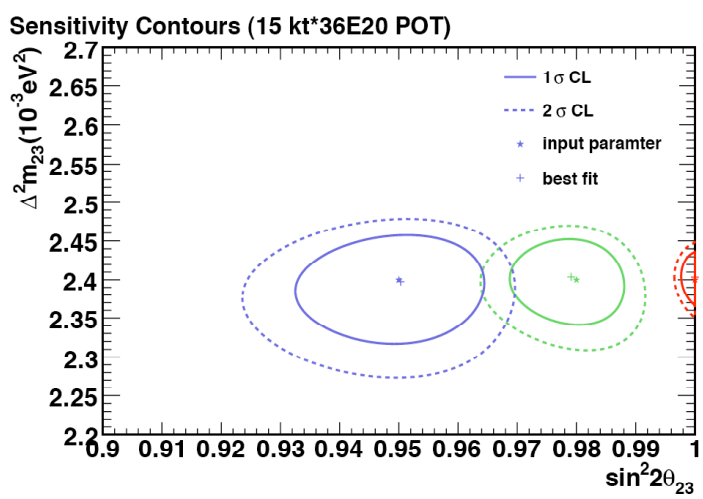

Figure 5. One and two standard deviation contours for a simultaneous measurement of Δm^2_{32} and $\sin^2(2\theta_{23})$ for a six-year run at equally divided between neutrinos and antineutrinos. The three input values are indicated by a star and the best fit for each is indicated by a plus sign. The top plot is for 700 kW beam power, the middle for 1.2 MW, and the bottom for 2.3 MW.

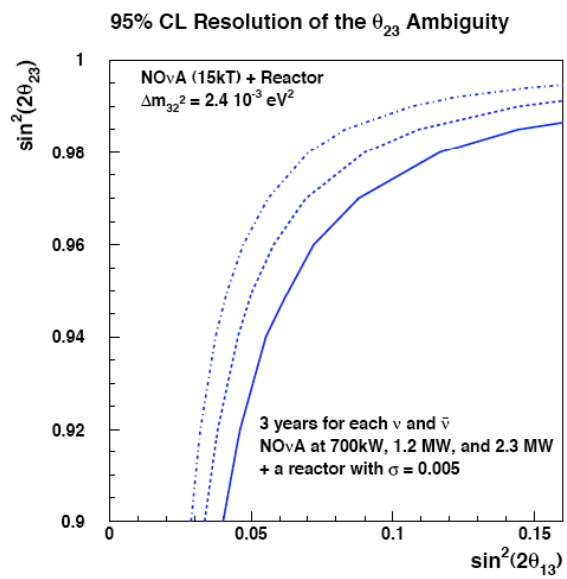

Figure 6. The $\sin^2(2\theta_{23})$ - $\sin^2(2\theta_{13})$ regions to the right of the curves are those in which the sign of $\cos(2\theta_{23})$ can be resolved at the 95% confidence level by a comparison of data from NOνA and a reactor experiment that can achieve a one standard deviation sensitivity of 0.005 in $\sin^2(2\theta_{13})$. The solid curve represents a 6-year NOνA run divided equally between neutrino and antineutrino running at 700 kW beam power and the dotted and dash-dotted curves represents the same run at 1.2 MW and 2.3 MW beam power, respectively. The regions are somewhat sensitive to δ, the mass ordering, and the sign of $\cos(2\theta_{23})$; the curves represent an average over the parameter space.

References

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