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The search for CP violation and the determination of the neutrino mass hierarchy in NOνA and LBNE

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With the recent discovery of a non-zero value of the neutrino mixing angle θ_{13}, the NuMI Off-Axis ν_e Appearance (NOνA) long baseline neutrino oscillation experiment, currently under construction, has unique sensitivity to both the CP-violating neutrino mixing phase and the neutrino mass-hierarchy. Beyond NOνA, the proposed Long Baseline Neutrino Experiment (LBNE) is designed for much greater sensitivity to the CP-violating phase while providing a very rich physics program. I will review the design, capabilities and schedule of both experiments.

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1. Introduction

The discovery of a non-zero value of the neutrino mixing angle θ_{13} by reactor-based neutrino oscillation experiments [1, 2, 3] was one of the great accomplishments of 2012 in the field of particle physics. Indeed, the size of $\theta_{13} \simeq 9^\circ$ is large compared to the sensitivity of current experiments, meaning that this mixing angle which has been elusive for so long will very soon be one of the most precisely measured neutrino oscillation parameter.

The size of the angle of θ_{13} implies that current long-baseline neutrino oscillation experiments may be capable of determining the neutrino mass hierarchy and the octant of the θ_{23} mixing angle. Future long-baseline experiments will determine both of these parameter and will also have significant sensitivity to the neutrino oscillation CP-violating phase, δ_{CP}. In this paper I discuss the status and prospects for the NuMI Off-Axis ν_e Appearance (NOνA) experiment and the Long Baseline Neutrino Experiment (LBNE).

The ability of long-baseline neutrino oscillation experiments to measure all of these quantities arises from the measurements of muon-neutrino to electron-neutrino probabilities for both neutrinos and antineutrinos since

$$P(\nu_\mu \to \nu_e) = f\left(\sin^2\theta_{23}\sin^2 2\theta_{13}, \frac{\Delta_{31}}{(\Delta_{31} \mp aL)}\sin(\Delta_{31} \mp aL), \sin\delta_{\mathrm{CP}}\right) \tag{1.1}$$

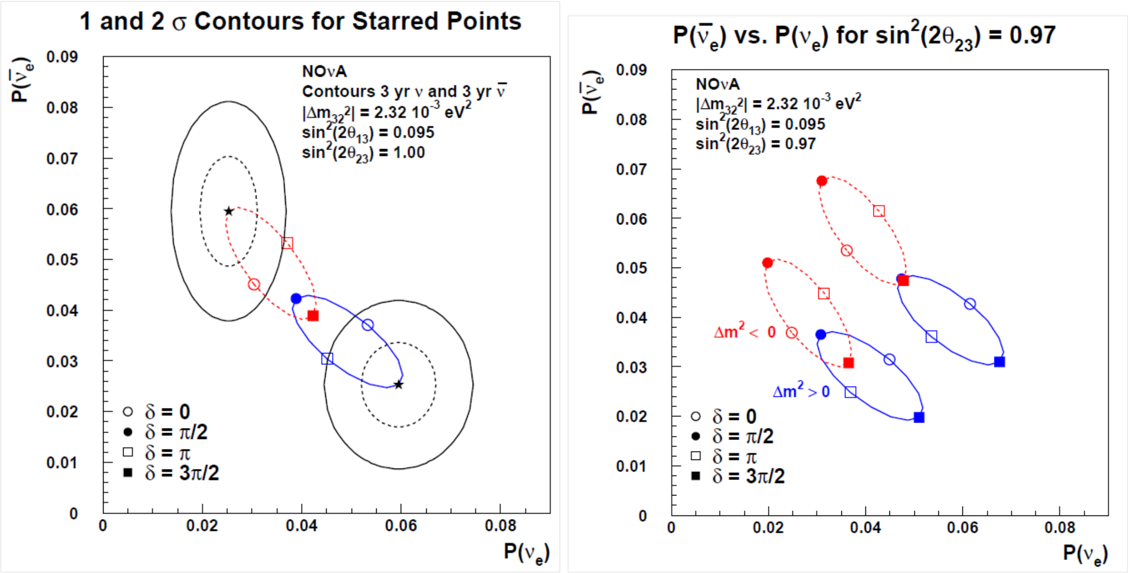
where $\Delta_{ij} = \Delta m^2_{ij}L/(4E)$ and $a = G_F N_e\sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$. The negative signs in Eqn. 1.1 are for neutrinos, positives for antineutrinos. The sign of δ_{CP} also flips between neutrinos and antineutrinos. The aL in Eqn. 1.1 arises due to coherent forward scattering of electron neutrinos and allows for the determination of the neutrino mass hierarchy. A larger L used in an experiment results in a larger matter effect. For comparison, the value of aL in NOνA is ~ 0.23, and 0.37 in LBNE.

2. The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

The NOνA experiment consists of a 330 ton near detector located $\sim 90m$ underground at FNAL, 1 km from the NuMI target, and a 14 kton far detector located 810 km away on the surface at Ash River, MN. Both detectors are positioned 14 mrad off-axis of the NuMI beam. NOνA takes advantage of the existing NuMI beam at FNAL, however the beam is being upgraded to provide nearly twice the power (from ~ 400 kW to ~ 700 kW), and a new target and magnetic focusing horn configuration to produce a narrow-band neutrino energy spectrum peaked at the first maximum of $P(\nu_\mu \to \nu_e)$.

The near and far detectors are nearly identical, $\sim 70\%$ active, tracking calorimeters optimized for electron identification. Each plane of the detector consists of ~ 4 cm wide $\times \sim 6$ cm deep PVC cells filled with liquid scintillator and a wavelength shifting fiber routed to a single channel of a 32-pixel avalanche photo diode (APD). Each plane represents 0.18 radiation lengths (X_0). Planes are oriented in alternating orthogonal views (horizontal and vertical) allowing for three-dimensional reconstruction of neutrino-induced tracks and showers. The efficiency of identifying ν_e charged-current (CC) events in the NOνA far detector is 41-48%, while the neutral-current (NC) background rate is limited to 0.1%.

The plots in Fig. 1 demonstrate the principles by which a long-baseline neutrino oscillation experiment, such as NOνA, determines the mass hierarchy, measures the CP phase and determines



(a) The mass hierarchy may be determined depending on where the NOνA measurements (data, black stars) lie on the colored ellipses (prediction). This plot assumes $\theta_{23} = 45^\circ$.

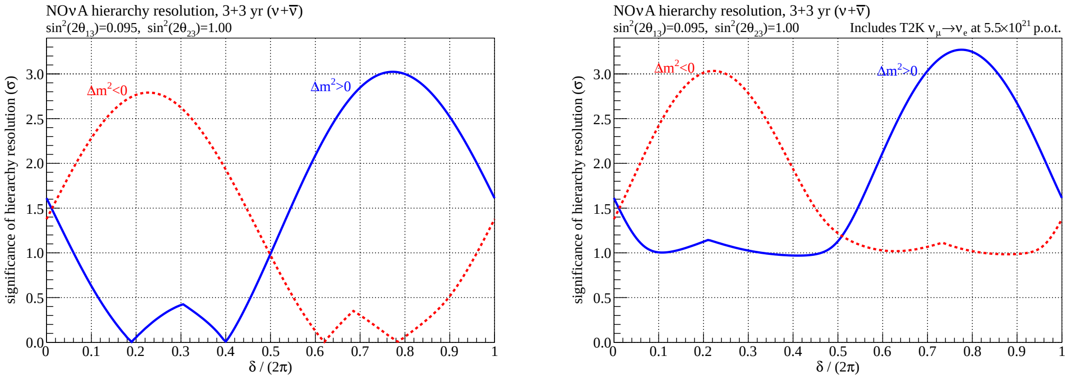
(b) The θ_{23} octant may be determined if $\sin^2 2\theta_{23}$ is non-maximal (in this case here it is 0.97). The ellipses with larger values are for $\theta_{23} > 45^\circ$, the ellipses with smaller values are for $\theta_{23} < 45^\circ$.

Figure 1: A schematic of the principles by which NOνA determines the mass hierarchy, measures the CP phase and determines the θ_{23} octant by measuring $P(\nu_\mu \rightarrow \nu_e)$ [x-axis] and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ [y-axis]. The blue and red ellipses show possible values of the oscillation probabilities for a fixed value of $\sin^2(2\theta_{13}) = 0.095$, the blue for the normal hierarchy and the red for the inverted hierarchy. On each colored ellipse, the choice of the δ_{CP} phase varies as one moves around the ellipse as indicated by the symbols.

the θ_{23} octant. The core of the approach is to measure the oscillation probabilities in neutrino mode (a point on the x-axis) and one in anti-neutrino mode (a point on the y-axis). The colored ellipses show the δ_{CP} values and choice of hierarchy (blue is the "normal" hierarchy ($m_3 > m_1$), red is the "inverted") that could yield from the oscillation probability measurements given a $\sin^2(2\theta_{13})$ value of 0.095.

NOνA plans to make a measurement of the oscillation probability in each neutrino mode (the default plan is 3 years of running in each mode). Fig. 1a shows the yield of two possibilities (best-case scenarios) represented by the starred points. The black dashed and solid contours are the 1- and 2-sigma statistical uncertainties of each measurement assuming maximal mixing for θ_{23} ($= 45^\circ$) and a value of $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2. In either of these best-case scenarios, the mass hierarchy is determined at nearly 3σ.

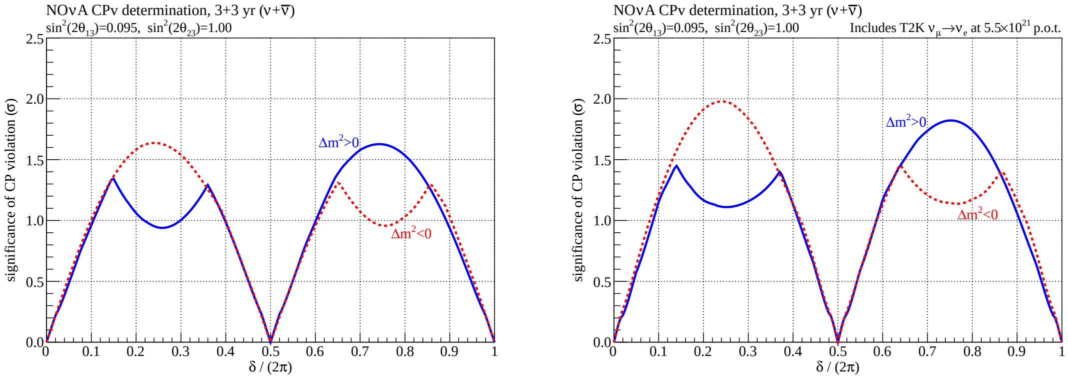
Fig. 1b shows how the θ_{23} octant may be determined. If θ_{23} is non-maximal, the colored ellipses shown in Fig. 1a split apart along the $y = x$ axis. The separation grows as $\sin^2 2\theta_{23}$ decreases, with the oscillation probabilities increasing for $\theta_{23} > 45^\circ$ and decreasing for $\theta_{23} < 45^\circ$. The positions of the ellipses will be determined by a precise measurement of $\sin^2 2\theta_{23}$ extracted from a



(a) Sensitivity of NOνA alone.

(b) NOνA combined with expected T2K sensitivity (numbers taken from [4]).

Figure 2: NOνA's sensitivity to the neutrino mass hierarchy as a function of $\delta_{\rm CP}$.



(a) Sensitivity of NOνA alone.

(b) NOνA combined with expected T2K sensitivity (numbers taken from [4]).

Figure 3: NOνA's sensitivity to CP violation ($\delta_{\rm CP} \neq 0, \pi$) as a function of $\delta_{\rm CP}$.

separate measurement of $P(\nu_\mu \to \nu_\mu)$, another goal of the NOνA experiment. Again, the location of the appearance measurements on these ellipses may allow one to determine the θ_{23} octant.

Figs. 2a and 3a give a sense of NOνA's sensitivity to the resolution of the neutrino mass hierarchy and the establishment of CP violation in the neutrino sector. CP violation is defined as $\delta_{\rm CP} \neq 0, \pi$. Statistical uncertainties and NC background rates are included in the calculations.

The T2K experiment, currently collecting data, will also be measuring $P(\nu_\mu \to \nu_e)$, but with a shorter baseline and is therefore relatively insensitive to matter effects. The T2K measurement is very complimentary to the NOνA measurement as it depends mostly on θ_{13} and $\delta_{\rm CP}$. Therefore adding in the expected sensitivities[4] with those of NOνA increases the sensitivity to the mass hierarchy, especially in the regions of $\delta_{\rm CP}$ where NOνA alone has little or no ability to resolve the mass hierarchy as seen in Fig. 2b. On the other hand, the combination of NOνA and T2K measurements does little to improve the regions of small or no sensitivity to CP violation, shown in Fig. 3b.

The NOνA far detector is currently under construction, and excavation of the near detector underground cavern and the NuMI upgrades are under way. NuMI beam operations are scheduled to resume by Spring of 2013, at which point approximately 1/3 of the far detector will be complete and collecting data. The far detector construction is expected to be completed by April, 2014, and the near detector construction is expected to be completed in late 2013. It is expected that NOνA will obtain a $\sim 5\sigma$ significance of ν_e appearance ($P(\nu_\mu \rightarrow \nu_e) > 0$) one year after NuMI operations resume.

3. The Long-Baseline Neutrino Experiment (LBNE)

The proposed LBNE is designed to absolutely determine the neutrino mass hierarchy for all values of δ_{CP}. In order to achieve this, the experiment is designed for a much longer baseline of $\sim$ 1300 km. Initially the configuration of LBNE consisted of a new 700 kW wide-band neutrino beam, upgradable to 2.2 MW, aimed at the Homestake Mine in Leed, South Dakota, USA, with a near detector at FNAL and a 34 kton liquid argon time projection chamber (LAr TPC) at the 4850-foot level of the Homestake Mine.

In March, 2012, the US Department of Energy (DOE) announced that it could not support the LBNE project as configured. Fermilab was tasked with developing "an affordable and phased approach that will enable important science results at each phase." [letter from W.F. Brinkman, DOE OSTP to Pier Odone, director of Fermilab]. Alternative options were also to be considered.

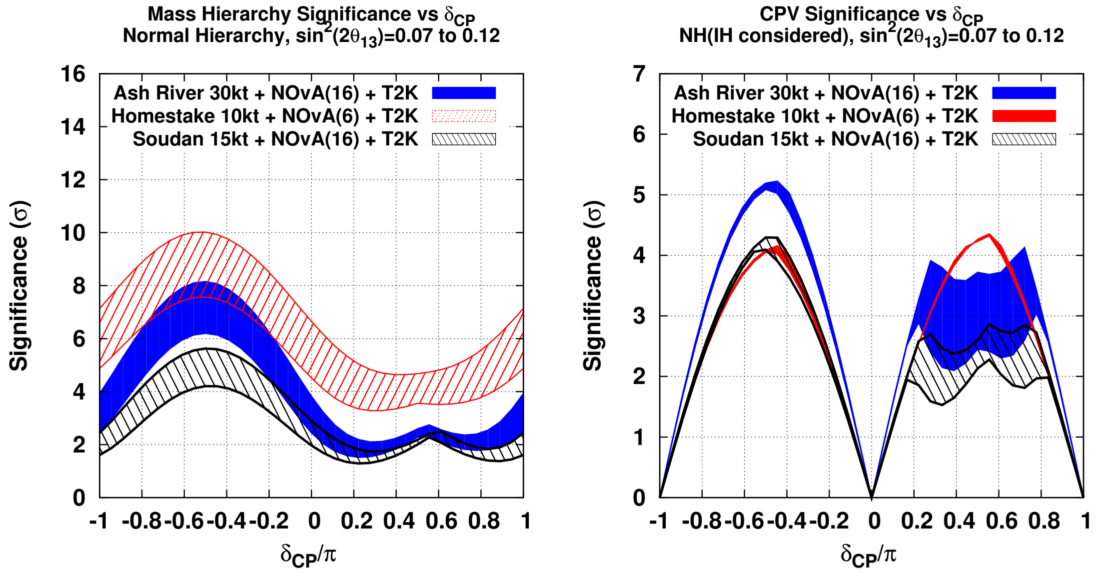
A steering committee was formed and considered the impact and capabilities of three options (all w/ 10 years of running): (a) 30 kton LAr TPC surface detector at Ash River, 810 km baseline, 14 mrad offaxis from 700 kW NuMI beam, (b) 15 kton LAr TPC underground detector at the 2340 ft. level in the Soudan Mine, 734 km baseline, on-axis along 700 kW NuMI beam, (c) 10 kton LAr TPC surface detector at the Homestake Mine, 1300 km baseline, on-axis along new beamline.

Fig. 4 shows the sensitivities of each option to the mass hierarchy and CP violation as a function of δ_{CP}. A range of values for $\sin^2 2\theta_{13}$ from 0.07 to 0.12 were used, resulting in the various thicknesses of the curves. These plots include expected information from both NOνA and T2K. In the case of the Ash River and Soudan options, it is assumed that NOνA would operate for an additional 10 years, whereas this is not possible for the Homestake option.

The steering committee "strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface" [5]. The LBNE Project management is therefore moving forward with the Steering Committee's preference, and LBNE was approved DOE Critical Decision-1 (CD-1) on December 10, 2012. The current schedule for LBNE to begin collecting beam neutrino data in the far detector by 2023.

4. Conclusions

The discovery of a larger-than-expected value for the θ_{13} neutrino mixing angle is a boon to the neutrino community. Long-baseline experiments are capable of measuring θ_{13} and the CP violating phase angle and determining the neutrino mass hierarchy and the θ_{23} octant, as well as provide a more precise measurement of θ_{23}. In the USA, NOνA is currently under construction; the first $\sim$



(a) Mass hierarchy sensitivity of LBNE combined with NOνA and T2K.

(b) CP violation sensitivity of LBNE combined with NOνA and T2K.

Figure 4: LBNE's sensitivity to the neutrino mass hierarchy (left) and CP violation (right) as a function of δ_{CP}.

1/3 of the far detector will be instrumented and commissioned by the time the NuMI beam resumes operations in Spring 2013, and the detector is expected to be completed by Spring 2014. LBNE is a proposed next-generation experiment with the first stage beginning data collection around 2023, designed to absolutely determine the mass hierarchy and have a considerable sensitivity to δ_{CP}. The future of long-baseline neutrino oscillation experiments is very bright, and the next two decades should be very exciting.

References

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[5] *LBNE Reconfiguration Steering Committee Report*, `http://www.fnal.gov/directorate/lbne_reconfiguration/files/LBNE-Reconfiguration-Steering-Committee-Report-August2012.pdf`, Aug. 6, 2012