Search for short-baseline oscillations at the NOvA Near Detector

Siva Prasad Kasetti\textsuperscript{1}, Adam Aurisano\textsuperscript{2}, Louise Suter\textsuperscript{3}, Alex Sousa\textsuperscript{2} and Bindu A Bambah\textsuperscript{1}

\textsuperscript{1}University of Hyderabad, Hyderabad, Telangana 500046, India
\textsuperscript{2}University of Cincinnati, 2600 Clifton Ave, Cincinnati, OH 45220, USA
\textsuperscript{3}Fermilab, Batavia, IL 60510, USA

E-mail: \textsuperscript{1}siva1987@fnal.gov, \textsuperscript{1}bbambah@fnal.gov, \textsuperscript{2}aurisano@fnal.gov, \textsuperscript{2}alex.sousa@uc.edu, \textsuperscript{3}lsuter@fnal.gov

Abstract. Anomalous results from past neutrino experiments have been interpreted as potential evidence for an additional sterile neutrino with a mass on order of 1 eV, but this evidence remains inconclusive. The NOvA Near Detector is a 300 ton almost fully-active fine-grained liquid scintillator detector, that was designed for electron-neutrino identification. The detector is placed along the Fermilab NuMI beam line 1 km from the target and 14.6 mrad off-axis. At this off-axis angle the detector is exposed to a narrow band beam peaked at 2 GeV. Therefore the NOvA Near Detector will see neutrinos with a L/E range that is sensitive to oscillations between active neutrinos and light sterile neutrinos. In this report we discuss NOvA sensitivity from the joint electron-neutrino appearance and muon-neutrino disappearance analysis search for short-baseline sterile neutrino mixing.

1. Introduction
Experiments, such as the Liquid Scintillator Neutrino Detector (LSND) \cite{1} and the Mini Booster Neutrino Experiment (MiniBooNE) \cite{2} which had a L/E $\approx 1$ km/eV, where L is the distance travelled by a neutrino with energy E, have reported anomalous results which can be explained by the existence of sterile neutrinos with the mass difference in the order of $\approx 1$ eV$^2$. Both LSND and MinBooNE have observed an excess of events above what was expected.

The NOvA \cite{3, 4} Near Detector is 0.3 kton fine-grained liquid scintillator detector with low-Z. It is placed $\approx 1$ km away from the target and uses the NuMI neutrino beam which peaks at 2 GeV \cite{5}, with a L/E $\approx 0.5$ km/eV, it will be sensitive to oscillations due to a 1 eV scale sterile neutrino. In this note, we will describe the NOvA potential for the short-baseline oscillations using a joint fit between muon neutrino disappearance and electron neutrino appearance.

2. Analysis Details
NOvA uses Fermilab’s NuMI neutrino beam which mainly consists of muon neutrinos ($\approx 98\%$) and a small fraction of electron neutrinos ($\approx 2\%$). If a sterile neutrino exists, one can expect to observe disappearance in muon neutrinos and appearance in electron neutrinos, due to oscillations with mass squared difference between the active and sterile neutrino, $\Delta m_{11}^2 > 1$ eV$^2$. In the (3+1) model, electron neutrino appearance can be expressed as

$$P_{\nu_{e} \rightarrow \nu_{\mu}} = 4|U_{\mu 4}|^2 |U_{e 4}|^2 \sin^2 \frac{\Delta m_{11}^2 L}{4E} = \ldots$$
\[ \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} \Delta L}{4E} \], where \( \sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 2\theta_{24} \) and muon neutrino disappearance can be expressed as 
\[
P_{SBL} = 1 - |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \frac{\Delta m^2_{41} \Delta L}{4E} = 1 - \sin^2 2\theta_{14} \sin^2 2\theta_{24} \] 
where \( \sin^2 2\theta_{14} = \cos^2 \theta_{14} \sin^2 \theta_{24} \) [6]. Since both \( \nu_e \) appearance and \( \nu_\mu \) disappearance probabilities are parameterized in \( \theta_{14} \) and \( \theta_{24} \), minimizing the total \( \chi^2 \) from both of them simultaneously with respect to \( \theta_{14} \) and \( \theta_{24} \) gives the potential to constrain both of these angles.

2.1. Event Selection
NOvA uses machine learning technology to identify particle interaction types using Convolutional Visual Networks (CVN) based on GoogLeNet convolutional neural network architecture [7]. For this analysis, the CVN algorithm was used for identifying both electron showers from electron neutrino interactions and muon tracks from muon neutrino interactions. This algorithm has impressive selection efficiency for electron showers at 49% and for muons at 58%. The primary backgrounds to electrons are \( \nu_\mu \) charged currents, neutral currents and beam electron neutrinos and neutral currents for \( \nu_\mu \) events. The energy distribution for the selected \( \nu_e \) 's and \( \nu_\mu \)'s is shown in Fig.1,2 along with the prediction for LSND best fit point in \( (\Delta m^2, \sin^2 2\theta) \approx (1.2 \text{ eV}^2, 0.03) \).

We can see that the \( \nu_e \) prediction at LSND best-fit point is higher due to appearing \( \nu_e \)'s and similarly \( \nu_\mu \) prediction has a smaller expected event rate as the \( \nu_\mu \) oscillate into sterile neutrinos.

2.2. Joint Fit Method
This analysis is performed by doing a joint fit between \( \nu_\mu \) disappearance and \( \nu_e \) appearance simultaneously. Both the MIGRAD and SIMPLEX [8] minimization algorithms have been used in the fitting procedure. The 3-flavor oscillation parameters are fixed at the values from Particle Data Group [9]. We use the profiling method to include the effect of flux and cross-section systematic uncertainties. For the \( \sin^2 2\theta_{24} \) sensitivity shown in Fig.3, we fix \( \theta_{14} \) at zero and profile over \( \theta_{34} \) to reduce the background oscillations considerably.

**Figure 1.** Reconstructed neutrino energy distribution for \( \nu_e \) selected sample with CVN > 0.95. Also shown is the \( \nu_e \) prediction at LSND best fit point.

**Figure 2.** Reconstructed neutrino energy distribution for \( \nu_\mu \) selected sample with CVN > 0.5. Also shown is the \( \nu_\mu \) prediction at LSND best fit point.
3. Results

The NOvA sensitivity at 90% C.L for short-baseline oscillations due to light sterile neutrinos is shown in Fig.[4] for a one year and three years of data taking. NOVAs one year 90% C.L sensitivity excludes LSND 90% and 99% C.L results at $\Delta m^2 > 1$ eV$^2$ region and is in tension at $\Delta m^2 < 1$ eV$^2$. The three year 90% C.L sensitivity completely excludes the LSND 90% and 99% C.L regions. In conclusion, NOvA has a strong sensitivity for light sterile neutrino oscillations and can put tight constraints on sterile mixing parameters.

![Figure 3.](image1.png)

**Figure 3.** 90% C.L sensitivity for $\theta_{24}$ at $\theta_{14} = 0$ rad while profiling over $\theta_{34}$. The regions excluded by CDHS, CCFR, MiniBooNE/SciBooNE are also shown.

![Figure 4.](image2.png)

**Figure 4.** Sensitivity for $\theta_{\mu e}$ while profiling over $\theta_{34}$ at 90% C.L. The regions excluded by LSND, MiniBooNE and KARMEN also shown.

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