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Sterile Neutrino Search via Neutral-Current Disappearance with NOvA

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Observations of neutrino oscillations from the majority of neutrino oscillation experiments are consistent with a three-flavor framework. However, the excess of events seen by LSND and MiniBooNE are incompatible with this model and can be explained by an additional, sterile, neutrino. These intriguing results are not conclusive and are in tension with findings from other short-baseline and long-baseline experiments.

The NOvA experiment, which uses a long baseline of 809 km between its functionally identical liquid scintillator near and far detectors at Fermilab and Minnesota, has the potential to set world-leading limits on the parameters governing sterile neutrino oscillations by searching for a deficit of neutral-current interactions compared to that predicted at the two detectors. An updated analysis with the NOvA neutrino dataset will be presented along with the first results from a long-baseline sterile search in an antineutrino beam. Limits on the sterile neutrino mixing parameters will be shown and plans for future analyses, including a two-detector joint fit utilizing a covariance matrix to constrain systematics, will be discussed.

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1. Introduction

There have been a couple of anomalous results from short-baseline neutrino experiments, with both LSND [1] and MiniBooNE [2] reporting an excess of ν_e-like events in $\nu_\mu/\bar{\nu}_\mu$ beams. These results may be explained by introducing a fourth neutrino flavor state, with a mass-square splitting $\Delta m^2 \sim 1$ eV^2. However, measurements of the Z-boson decay width by experiments at the LEP collider placed strict limits on the number of light ($< M_W/2$) neutrinos to be three [3], so any additional neutrinos must not interact with the weak force.

The simplest way to incorporate a 'sterile' neutrino is known as the 3+1 model and adds a new neutrino mass state with a new mass-squared splitting, thereby increasing the PMNS matrix from a 3×3 to a 4×4 matrix. In addition to the new mass splitting Δm^2_{41}, this introduces three new mixing angles (θ_{14}, θ_{24} and θ_{34}) and two potential CP-violating phases (δ_{14} and δ_{24}).

The rate of neutral-current (NC) events in a long-baseline neutrino oscillation experiment may be used to search for existence of sterile neutrinos; this rate is unaffected by 3-flavor oscillations so if any depletion is observed this may be indicative of neutrinos oscillating into a sterile flavor state. Assuming a small θ_{14} (consistent with solar and reactor constraints), this measurement is sensitive to θ_{24}, θ_{34}, Δm^2_{41} and δ_{24}. The analysis presented here is only valid for $0.05 < \Delta m^2_{41}$ (eV^2) < 0.5, corresponding to oscillations at the NOvA near detector which are small enough to be ignored.

2. The NOvA Experiment

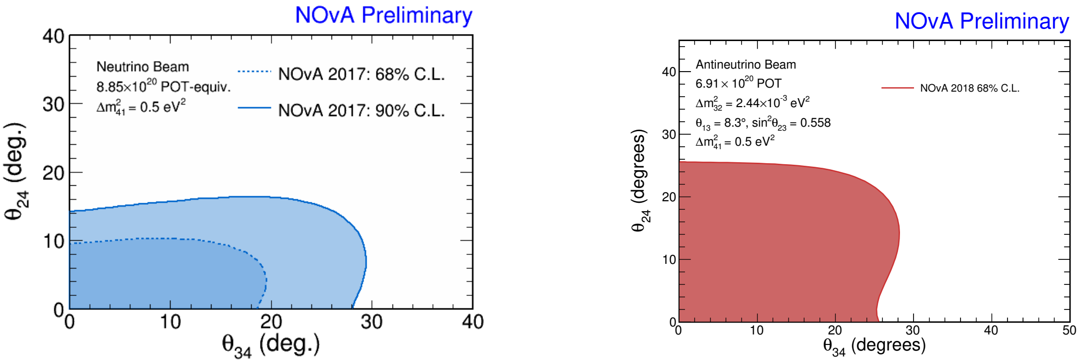
The NOvA experiment is a long-baseline neutrino oscillation experiment based at Fermi National Accelerator Laboratory (Fermilab). It comprises two detectors, a near detector at 1 km from the neutrino source and a far detector, in Ash River, northern Minnesota, at 810 km. The experiment is located 14.6 mrad off-axis of Fermilab's NuMI beamline [4], resulting in a neutrino energy spectrum peaked sharply at around 2 GeV. Both detectors are functionally identical, low-Z tracking calorimeters composed of alternating horizontal and vertical planes of PVC containing liquid scintillator, instrumented with wavelength-shifting fibers and read out using avalanche photodiodes.

By switching the focusing horn current when producing the NuMI beam, both neutrino and antineutrino dominated data may be analyzed. The NOvA dataset currently comprises 8.85×10^{20} POT (protons-on-target) in neutrino mode and, new for this analysis, 6.91×10^{20} POT in antineutrino mode.

3. Neutral-Current Disappearance Analysis

In order to distinguish differing neutrino interaction topologies, NOvA utilizes a Convolution Neural Network [5]. This is the primary selector for NC events in both NOvA detectors and provides good separation between the NC signal and CC (charged-current) backgrounds. The NOvA far detector is located on the surface and is thus exposed to around 11 billion cosmic rays each day, which are removed using a selection of cuts. Full details of the selection may be found in Ref. [6]. The overall selection efficiency is 52% for the neutrino-dominated beam and 50% for antineutrino beam, with a purity of 77% and 78% respectively.

The FD data are compared to a prediction obtained using an extrapolation procedure, whereby the ND simulation is corrected using data before being convolved with the predicted ratios of the



(a) (b)

Figure 1: The 2D limits for non-excluded regions in $\theta_{24}-\theta_{34}$ parameter space for (a) neutrino dominated data [8] and (b) antineutrino dominated data.

FD and ND distributions whilst taking into account effects such as geometrical acceptances, beam dispersion and neutrino oscillations. The 3-flavor oscillation parameters used are taken from the PDG and recent NOvA results. This technique facilitates a partial cancellation of correlated systematic uncertainties between the two detectors. In neutrino mode, 191.2 ± 13.8(stat.)±22.0(syst.) events are predicted (148 NC, 35 CC, 8 cosmics) from simulation, with 214 events observed in the data. In antineutrino mode, 61 events are predicted from the data, with a prediction of 69 ± 8(stat.)±10(syst.) from simulation (53.4 NC, 10.2 CC, 5.3 cosmics). Both results are consistent with neutrino oscillations in a 3-flavor framework.

Performing a shape-based fit creates non-excluded regions in $\theta_{24}-\theta_{34}$ parameter space valid for low mass splittings ($0.05 < \Delta m^2_{41} < 0.5$), assuming $\theta_{14}, \delta_{14} = 0$ and profiling over θ_{23} (constrained by the NOvA best-fit and uncertainties [7]) and δ_{24}. These are shown in Figure 1. 1D C.L. are found to be $\theta_{24} < 16.2°$, $\theta_{34} < 29.8°$ (90% C.L.) in neutrino data and $\theta_{24} < 25.5°$, $\theta_{34} < 31.5°$ (68% C.L.) in antineutrino data.

The systematic uncertainties are dominated by the detector calibration, with cross-section and beam uncertainties also contributing highly. Additional sources of uncertainty considered include the kaon component of the beam, detector acceptances, neutron background interactions in the detectors and uncertainties on the 3-flavor oscillation parameters. A more complete description of the systematics is provided in Ref. [6].

4. Summary and Future Analyses

By searching for evidence of NC disappearance, NOvA has performed a probe for sterile neutrinos in both neutrino and antineutrino dominated data. Oscillations are consistent with neutrino mixing in a 3-flavor framework, and limits on any additional mixing parameters in a 3+1 model have been set.

Future analyses will feature an improved selection, incorporating improvements in the CVN classifier, and will utilize a joint-fit between both detectors via a Gaussian-based covariance framework to take into account ND oscillations and facilitate a search over a much wider range of parameter space. Additionally, the upcoming NOvA test beam program will improve understanding of detector effects and lead to a reduction in the systematic uncertainties present in the analysis.

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