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A Seacrch for Sterile Neutrinos at MINOS and MINOS+

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MINOS+ is a long-baseline neutrino oscillations experiment designed to perform high-precision measurement of Δm^2_{32} and θ_{23} in the three-flavor neutrino oscillations model and to probe potential anomalous oscillations beyond the standard paradigm. MINOS+ utilizes the identical 1 kt Near and 5.4 kt Far Detectors used in the already successful MINOS experiment in order to sample the neutrino beam originating at the NuMI beam facility at baselines of 1 km and 735 km downstream, respectively. The comparison between observations of both charged-current and neutral-current weak interactions in the Near and Far Detectors permits searches for muon neutrino survival and for active neutrino disappearance consistent with the existence of sterile neutrino flavor states. Here we present a measurement of anomalous disappearance of muon neutrinos interpreted using a (3+1)-flavor neutrino oscillations model, and using an improved two-detector simultaneous fit technique we find no evidence consistent with the existence of sterile neutrinos. We set the most constraining limit at present on the sterile neutrino mixing parameter $\sin^2\theta_{24}$ for a wide range of values of the sterile neutrino mass-splitting $10^3 > \Delta m^2_{41} > 10^{-4}$ eV^2.

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1. Introduction

The standard three-flavor neutrino paradigm has been measured to high precision using solar, atmospheric, nuclear reactor, and accelerator neutrino sources [1]. The measurement by LEP of the invisible decay width of the Z boson strongly constrains the number of light, active neutrino species to agreement with this standard three-flavor model [2].

Contrasting with the otherwise strong evidence for the standard three-flavors, a particular subset of both past and present neutrino oscillation measurements indicate potential anomalous behavior in the electron neutrino sector. Deficits with respect to theoretical prediction have been observed in ν_e production from radioactive calibration sources used for gallium neutrino experiments [3] and in the $\bar{\nu}_e$ neutrino flux from nuclear reactor sources [4]. In addition, the short-baseline accelerator neutrino experiments LSND [5] and MiniBooNE [6] have observed excess ν_e and $\bar{\nu}_e$ appearance in a predominantly muon neutrino beam. These anomalous oscillations can be reconciled with the three-flavor LEP constraint through the introduction of additional neutrino states that are sterile with respect to the weak interaction.

The neutrino oscillation phenomenon is due to the non-correspondence of mass and weak flavor eigenstates, and the rotational transformation between these bases is customarily parameterized in the form of the unitary 3×3 PMNS mixing matrix [7, 8]. The PMNS matrix can be described by three mixing angles, θ_{12}, θ_{13}, and θ_{23}, and a single CP-violating phase, δ_{CP}. The frequency of the neutrino oscillations is governed by the squared mass differences, Δm^2_{21}, Δm^2_{31} and Δm^2_{32}, which are defined by the relation $\Delta m^2_{kj} \equiv m^2_k - m^2_j$. The simplest extension of the standard three-flavor model to include a sterile neutrino state is a (3+1)-flavor model, which requires an additional mass eigenstate and the expansion of the PMNS matrix to a 4×4 unitary matrix. The extension of the mixing matrix introduces three additional mixing angles, θ_{14}, θ_{24}, and θ_{34}, and two additional CP-violating phases, δ_{14} and δ_{24}. Further, a new independent mass-splitting, Δm^2_{41}, defines the frequency of sterile neutrino-mediated oscillations that may be observed through mixing with the active neutrino species.

2. MINOS and MINOS+

The MINOS (Main Injector Neutrino Oscillation Search) experiment was designed to study neutrino oscillations over a long-baseline using two functionally identical steel-scintillator tracking calorimeters. Magnetization of the detectors allowed for the determination of particle charges in addition to more precise energy estimation. The identical construction of the detectors also allows for the effects of many systematic uncertainties to be mitigated when comparing the neutrino energy spectra observed in each detector. MINOS sampled the Fermilab based NuMI beam on-axis at baselines of 1 km for the Near Detector (ND), which is also located at Fermilab, and 735 km for the Far Detector (FD), which was located in the Soudan Underground Laboratory in Northern Minnesota.

MINOS sampled the NuMI beam in the low energy configuration, which has a peak energy of approximately 3 GeV and was optimized for observing oscillations at the atmospheric frequency. MINOS+ sampled the beam in the medium energy configuration, the same configuration used for the NOvA experiment, which has an on-axis peak energy of approximately 7 GeV and is suitable for constraining deviations from the three-flavor paradigm. MINOS collected data for approximately seven years with total exposures of 10.56×10^{20} proton-on-target (POT) in neutrino mode and 3.36×10^{20} POT in antineutrino mode. MINOS+ collected data for three years with a total of 9.69×10^{20} POT in neutrino mode, though only the first two years, with an exposure of 5.80×10^{20} POT, of MINOS+ data are included in the analysis presented here.

MINOS and MINOS+ detect predominantly three event types of interest to this analysis, namely ν_μ charged current (CC), neutral current (NC), and ν_e-CC events. The ν_μ-CC events produce long tracks due to the production of an outgoing muon, the charge of which can be determined by curvature leading to an identification of neutrino versus antineutrino events. NC events are defined by a dispersed hadronic shower topology in the detector. Finally, ν_e charged current events are observed and can be identified by short electromagnetic showers, and these events represent a background to both the CC and NC samples used in the sterile neutrino search.

3. Two-Detector Sterile Neutrino Search

The selection of ν_μ-CC and NC candidate events follows a two-step approach in order to prevent events from being included in both samples. Events are first passed through the NC selection, which consists of a cut-based method that requires events have compact topology with no extended tracks. Events rejected by the NC selection are then passed through the CC selection, which uses a 4 variable kNN to identify events with muon-like tracks and the proper charge associated with either neutrino or antineutrino events depending on the beam mode. Using Monte Carlo (MC) simulations, we estimate an NC selection efficiency in the MINOS+ era of 79.9% in the FD and 86.5% in the ND with corresponding sample purities of 60.3% and 64.9% for the ND and FD, respectively. Similar simulation of the CC selection yields expected efficiency of 56.4% in the ND and 85.1% in the FD with corresponding sample purities of 99.1% and 99.3% for the ND and FD, respectively [9].

The sterile neutrino search strategy employed here focuses on the coequal treatment of the two detectors in a simultaneous fit. The two-detector technique allows for the utilization of the the very high event rate in the ND in order to avoid FD statistical uncertainties in a search for ND oscillations. The beam neutrino flux model used for the sterile neutrino search differs from the standard oscillations analysis as it is not possible to assume null oscillations in the ND. Therefore, we use the PPFX method developed by the MINERνA Collaboration [16], which relies upon only hadron production experimental data. Systematic uncertainties are incorporated into the two-detector fit via covariance matrices, which encode the correlation of systematic effects amongst bins of reconstructed energy in both detectors. The effects of these systematic uncertainties are mitigated by the cancellation of correlated systematics due to large off-diagonal covariance matrix elements. The best fit is determined by minimizing a joint ν_μ-CC and NC chi-squared statistic computed using the covariance matrices and constructed by summing the individual χ^2 contributions of the independent samples.

We observe no evidence for sterile neutrino oscillations, and therefore, we set an upper limit in the Δm^2_{41} versus $\sin^2\theta_{24}$ parameter space as shown by the solid black line in both panels of Fig. 1. In order to compute the expected sensitivity of the simultaneous two-detector search technique and to quantify the expected variations from that sensitivity, we simulated a large sample of pseudo-

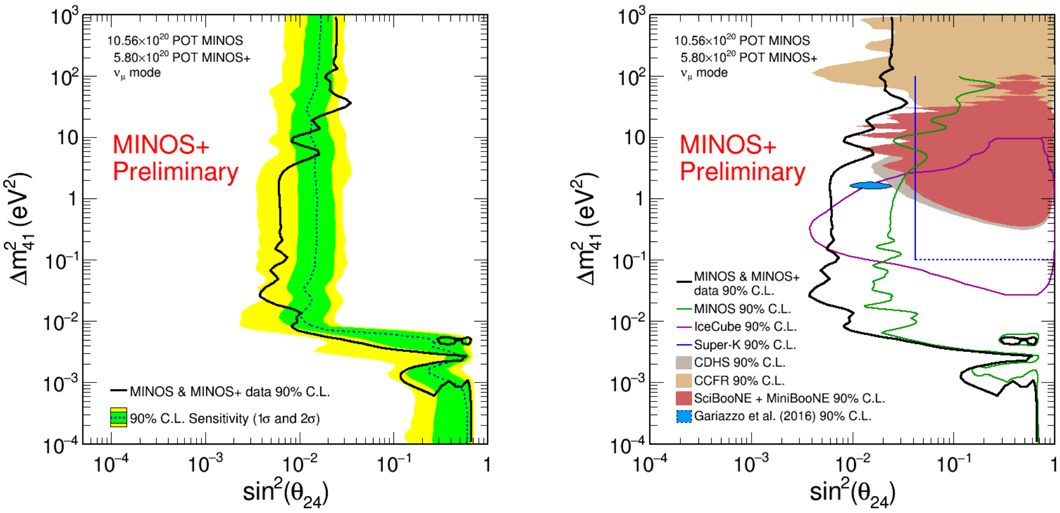

Figure 1: Left: The MINOS and MINOS+ two-detector search upper limit (black) and median fluctuated sensitivity (blue dashed) at 90% C.L. with regions containing 68% (green) and 95% (yellow) of fluctuated pseudoexperiment sensitivity contours in the Δm^2_{41} versus $\sin^2\theta_{24}$ parameter space resulting from the simultaneous Two-Detector fit after the FC correction. Right: Comparison of the two-detector upper limit at 90% C.L. (black) with previous results from IceCube [10], Super-K [11], CDHS [12], CCFR [13], and SciBooNE/MiniBooNE [14] constraining this parameter space. The Gariazzo et al. region is the result of a fit using a (3+1)-flavor model to global neutrino oscillation data [15].

experiments taking into account both systematic and statistical fluctuations. The median expected sensitivity from these pseudoexperiments is shown by the blue dashed line in the left panel of Fig. 1 with the green and yellow bands indicating the region containing the limit contours from 68% and 95% of the pseudoexperiments. Both the sensitivity simulations and the data limit were corrected by the Unified Approach of Feldman and Cousins [17] in order to ensure proper frequentist intervals. Our data exclusion limit does not appear statistically unlikely given the expected sensitivity of the experiment as determined by MC simulation.

MINOS and MINOS+ set a strong upper limit on the mixing parameter $\sin^2\theta_{24}$ over much of the range of $10^{-4} < \Delta m^2_{41} < 10^3$ eV^2, and in many regions, we set the most stringent limit at present. The improvement of the current limit over that previously demonstrated by MINOS alone [18] can be attributed to the increased statistical power of the ND in a simultaneous two-detector search, the cancellation of systematic uncertainties in the covariance matrix method, and an improvement in the binning scheme of the FD to maximize the precision measurement of the atmospheric oscillations. The new MINOS and MINOS+ limit presented here increases the existing tension with global fits, such as the example from Gariazzo et al. [15], which is shown in the right panel of Fig. 1 for comparison. A final year of MINOS+ data remains to be analyzed for the sterile neutrino search, which represents 50% more data for the MINOS+ spectrum and may represent continued improvement in the sensitivity of MINOS and MINOS+ to sterile-mediated neutrino oscillations.

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