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# Search for muon neutrino disappearance due to sterile neutrino oscillations with the MINOS/MINOS+ experiment

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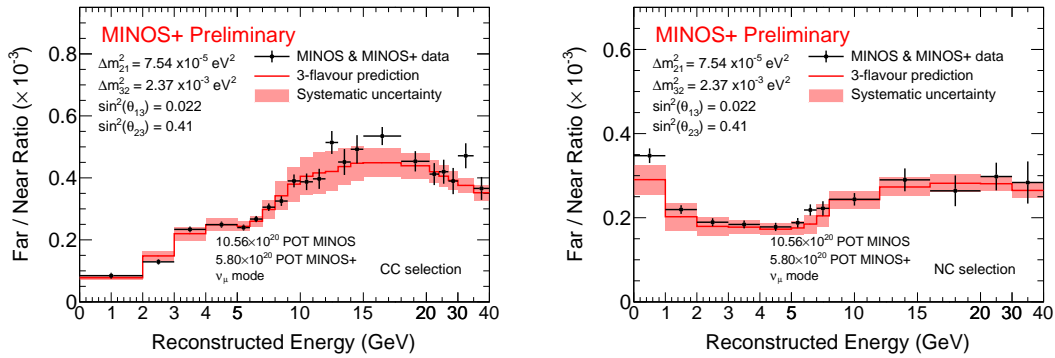
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**Abstract.** Three-flavour neutrino oscillations have successfully explained a wide range of neutrino oscillation data. However, anomalous results, such as the electron antineutrino appearance excesses seen by LSND and MiniBooNE, can be explained by the addition of a sterile neutrino at a larger mass scale than the existing three neutrino mass states. MINOS is a two-detector, long-baseline neutrino oscillation experiment optimized to measure muon neutrino disappearance in the NuMI neutrino beam. MINOS+ is the continuation of the MINOS experiment with the NuMI beam in a medium energy configuration. In the model with one sterile neutrino flavor added to the three active neutrino flavors, a sterile neutrino causing electron antineutrino appearance at LSND and MiniBooNE would also cause muon neutrino disappearance at MINOS. The sterile neutrino signature would be seen as modulations at high energy in the charged-current muon neutrino spectrum and a depletion of events in the neutral current spectrum. These proceedings show new results from fitting neutral-current and charged-current energy spectra from MINOS and MINOS+ data to a neutrino oscillation model assuming one sterile neutrino.

The MINOS/MINOS+ experiment consists of functionally identical steel-scintillator tracking calorimeters located on the axis of the NuMI neutrino beam [1] at baselines of 1.04 km and 735 km for the 0.98 kton Near Detector (ND) and 5.4 kton Far Detector (FD), respectively. The MINOS era, with the NuMI beam in the low-energy configuration, included the years 2005-2012 and was followed by the MINOS+ era, with the NuMI beam in a medium-energy configuration, which included the years 2013-2016. This analysis utilizes the full  $10.56 \times 10^{20}$  protons-on-target (POT) exposure in MINOS data and an additional  $5.80 \times 10^{20}$  POT exposure from the first two years of MINOS+ data.

LSND [2] and MiniBooNE [3] results have shown evidence of electron antineutrino appearance consistent with oscillations driven by a mass eigenstate different from the standard three-flavour paradigm. However, measurements of the  $Z^0$  boson decay width by ALEPH, DELPHI, OPAL, and L3 at the Large Electron-Positron Collider (LEP) provide high precision evidence for exactly three weakly interacting flavours of light neutrinos. The apparent inconsistency between these





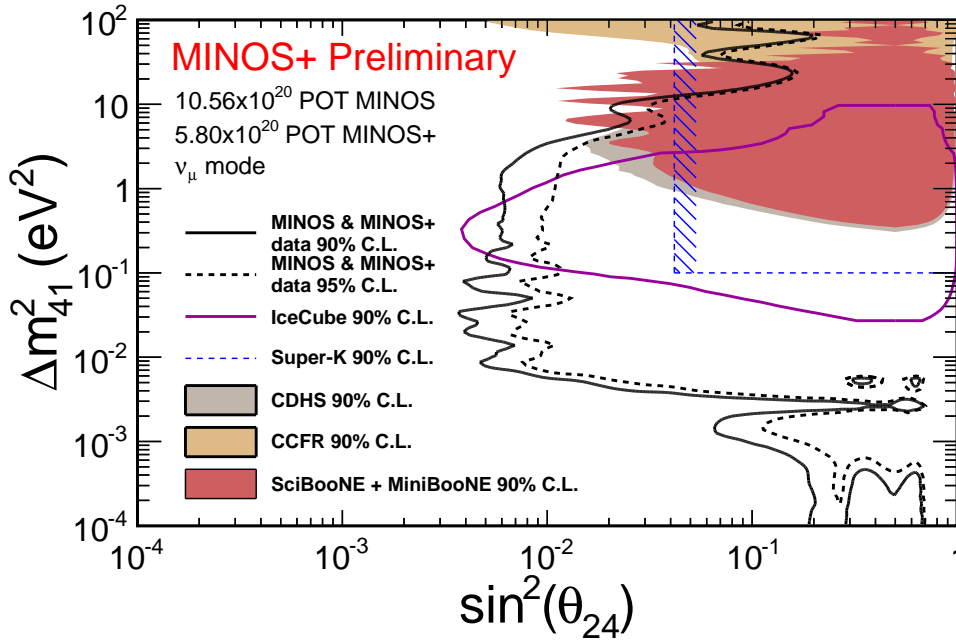
**Figure 1.** The combined MINOS and MINOS+ FD/ND ratio of observed (left)  $\nu_\mu$  charged current and (right) neutral current events. These distributions are fit to determine the oscillation parameters.

data can be resolved by the addition of a neutrino mass eigenstate and a sterile flavour eigenstate to the standard three-flavour model. The resulting 3+1 flavour neutrino model would manifest itself in MINOS/MINOS+ as a perturbation on the charged current (CC) depletion in the FD, which is driven primarily by atmospheric mixing, in addition to a reduction in the number of observed neutral current (NC) events not observed in standard three-flavour oscillations.

The selection and separation of CC and NC events takes a two-tiered approach in order to prevent both the double counting of events with ambiguous characteristics and the reduction in sensitivity caused by cross contamination of the samples. The topology of the hadronic showers caused by NC events in MINOS/MINOS+ permits the selection of these events using elimination cuts based on the overall event length and the extension of any observed tracks in the detector associated with the event. The NC selection in this study achieved an efficiency of approximately 89% across all energies with a total sample purity of 61% [4]. Events which fail the NC selection cuts are then passed through a kNN CC selection consisting of four variables which are descriptive of the topology of the event and type of hits it registers in the detector. The CC selection results in a sample with 86% efficiency and 99% purity at the MINOS FD.

The search for sterile neutrino oscillations discussed here uses a FD/ND ratio method which allows for detection of the aforementioned spectral distortions while taking advantage of the cancellation or reduction of most effects from systematic uncertainty due to the similarities between the detectors. The observed FD/ND ratios for combined MINOS and MINOS+ data compared with the prediction from the MINOS standard oscillations best fit is shown in Figure 1. The observed data are consistent with the three-flavour oscillations picture within the statistical and systematic uncertainties. In order to quantify the agreement or disagreement between observed data and the prediction resulting from a given set of oscillation parameters, a  $\chi^2$  test statistic is computed using a covariance matrix to account for both the statistical and systematic uncertainties. The fit method also includes a penalty term to constrain the  $\Delta m^2_{32}$  parameter in order to reduce the potential for degeneracies between active and sterile mass-splitting effects.

Given the observed consistency between data and three-flavour oscillations, the unified approach of Feldman and Cousins [5] was used to establish an exclusion limit in the parameter space of the hypothesized additional mass splitting  $\Delta m^2_{41}$  and the most relevant mixing angle for MINOS/MINOS+,  $\theta_{24}$ , using a 3+1 flavour sterile neutrino model. The resulting MINOS/MINOS+ exclusion limits are shown in Figure 2 and are compared with other experiments of note. The new MINOS/MINOS+ excluded area extends over a range of approximately 6 orders of magnitude ( $10^{-4} \text{eV}^2$ - $10^2 \text{eV}^2$ ) in  $\Delta m^2_{41}$  and nearly 2.5 orders of



**Figure 2.** Plotted are the combined MINOS and MINOS+ FHC 90 and 95 % C.L. Feldman-Cousins corrected contours for data using  $\nu_\mu$  disappearance and searching for a deficit in NC events. The combined MINOS and MINOS+ contours are compared to other experiments. Note the axis is  $\sin^2(\theta_{24})$ . All experiments bar Super-K and MINOS(+) used a two-flavour approach and therefore have had their contours made symmetric when converting from  $\sin^2(2\theta_{24})$  to  $\sin^2(\theta_{24})$ .

magnitude in  $\sin^2(\theta_{24})$ . Furthermore, the new limit is the world's best for  $\Delta m_{41}^2 < 10^{-1} eV^2$  and  $0.7 eV^2 < \Delta m_{41}^2 < 5 eV^2$ , while still remaining competitive with other experiments for other ranges of  $\Delta m_{41}^2$ . Inclusion of NC and CC events in this analysis provides an approximately two-fold improvement in the exclusion area when compared to parameters excluded by the CC events alone. The combined limit represents a nearly three-fold improvement over the limit previously set by MINOS alone and reflects the significant contributions of the MINOS+ data both in the increase of overall data exposure, with corresponding reduction in statistical uncertainties, and the new energy ranges explored by the medium energy beam configuration. Future analysis will include twice the MINOS+ data and the limits shown are expected to improve.

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