Search for muon antineutrino disappearance due to sterile antineutrino oscillations with the MINOS experiment

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Abstract. Three-flavour neutrino mixing has successfully explained a wide range of neutrino oscillation data. However, results such as the electron antineutrino appearance excesses seen by LSND and MiniBooNE can be explained in terms of neutrino oscillations adding a sterile neutrino at a larger mass scale than the existing three flavour mass states. MINOS is a two-detector, long-baseline neutrino oscillation experiment that uses magnetized tracker-calorimeter detectors to measure the energy and composition of the NuMI neutrino beam. These magnetized detectors give MINOS a unique ability to be able to separate muon neutrino and antineutrino interactions. Using data taken with the NuMI beam configured in antineutrino mode, MINOS is able to search for sterile antineutrinos by looking for the disappearance of muon antineutrinos over its 734 km baseline. The sterile antineutrino signature would be seen as modulations at high energy in the charged-current muon antineutrino spectrum. We present the first MINOS results constraining 3+1 sterile antineutrino oscillations, using a combination of $3.36 \times 10^{20}$ protons-on-target (POT) of antineutrino-enhanced beam data, and $10.56 \times 10^{20}$ protons-on-target (POT) of neutrino-dominated beam data. These results are compared with existing constraints and future improvements to the searches are discussed.

Since the first observation of neutrino oscillations in 1998 [1, 2], a growing number of experiments have probed and greatly improved our understanding of the nature of neutrino flavour mixing [3]. These experiments use different sources of neutrinos to perform precision measurements of the parameters governing three-flavour neutrino oscillations. However, potential deviations from the three-flavour paradigm have been measured by experiments including the Liquid Scintillator Neutrino Detector (LSND) [4] and MiniBooNE [5]. These anomalies appear as excesses of electron antineutrino candidates in muon antineutrino beams. Interpreting these results in terms of neutrino oscillations requires the introduction of fourth neutrino flavour. This putative fourth neutrino is commonly called sterile because measurements of the width of the $Z^0$ boson decay into neutrinos performed at LEP are only consistent with three active neutrino flavours, implying that this new neutrino state does not couple to weak interactions or its associated mass is larger than half the $Z^0$ mass.

The Main Injector Neutrino Oscillation Search (MINOS) experiment is a long-baseline neutrino oscillation experiment using the Neutrinos at the Main Injector (NuMI) neutrino...
beam and two detectors separated by a distance of 735 km to make precise measurements of the neutrino oscillation parameters. The two functionally-equivalent detectors are steel-scintillator sampling calorimeters [6]. The NuMI beam is created at Fermilab and can be operated in neutrino-dominated or antineutrino-enhanced mode, by setting the polarity of the current in the focusing horns to focus \( \pi^+ \) or \( \pi^- \), respectively. The steel planes are magnetised along the beam axis, allowing for separation of neutrino and antineutrino CC interactions on an event-by-event basis through measurements of the curvature of tracks deposited by final-state \( \mu^- \) or \( \mu^+ \). The Near Detector (ND) is located 1.04 km downstream of the target at Fermilab. The Far Detector (FD) is located 735 km downstream of the target at the Soudan Underground Laboratory, MN. The two-detector setup allows for comprehensive cancellation of systematic effects arising from cross sections and beam flux uncertainties. MINOS has accumulated a total of \( 3.36 \times 10^{20} \) POT of antineutrino-enhanced data, and \( 10.56 \times 10^{20} \) POT of neutrino-dominated data. In antineutrino-enhanced mode, the NuMI beam contains 39.9\% of muon antineutrinos, whereas in neutrino-dominated mode the muon antineutrino fraction is 7.0\%. In this analysis, searches for active-to-sterile antineutrino mixing are carried out using these \( \bar{\nu}_\mu \) data.

The MINOS experiment is designed to measure the three-flavour parameters \( \theta_{23} \), and \( \Delta m_{32}^2 \) by measuring disappearance of muon neutrinos. The FD samples values of \( L/E \approx 500 \text{ km/GeV} \), which optimize the sensitivity to this measurement. For a 3+1 model including one sterile antineutrino, additional parameters are introduced, namely: the \( \theta_{14} \), \( \theta_{24} \), and \( \theta_{34} \) mixing angles; two additional CP phases \( \delta_{14} \) and \( \delta_{24} \); and a new independent mass splitting \( \Delta m_{41}^2 \). This analysis probes 3+1 CC muon antineutrino disappearance, approximately described by the survival probability:

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta m_{31}^2 - \sin^2 2\theta_{24} \sin^2 \Delta m_{41}^2,
\]

where \( \Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \), \( L \) is the distance traveled by the antineutrino, and \( E_\nu \) is the antineutrino energy. The sensitivity of MINOS to a wide range of \( L/E \) values afforded by a wide energy spectrum beam and a dual-detector setup enables searches for oscillations into sterile antineutrinos driven by values of \( \Delta m_{41}^2 \) spanning over 4 orders of magnitude.

The selection of \( \bar{\nu}_\mu \)-CC events in the two samples is carried out using a k-Nearest-Neighbours (kNN) algorithm [7, 8], with different parameter optimizations used for each sample. The main background in selecting \( \bar{\nu}_\mu \) in the antineutrino-enhanced sample arises from interactions by neutrinos originating from very forward unfocused \( \pi^+ \). These interactions occur at energies significantly higher than the peak of the antineutrino energy peak, resulting in a 95\% selection efficiency and 92\% selection purity at FD. In the case of the neutrino-dominated data, the selected signal is predominantly due to interactions by higher energy antineutrinos, this time resulting from decays of unfocused \( \pi^- \). A selection efficiency of 88\% with 94\% purity is achieved for this sample at the FD.

The systematic effects accounted for in this analysis arise from uncertainties associated with: detector acceptance; neutrino beam flux; neutrino cross sections; normalisation; neutrino energy scale; and selection backgrounds. Each systematic uncertainty is evaluated independently and incorporated in the analysis in covariance matrix form. The analysis fits the 3+1-oscillated Far/Near spectral ratio to its equivalent data measurement. Therefore, these systematic uncertainties largely cancel. The effects of systematic uncertainties on the MINOS sensitivity to sterile neutrino oscillations are shown in Figure 1.

The analysis follows the same approach adopted in other MINOS sterile neutrino searches [9], where the Far/Near spectral ratio is used for fitting the \( \nu_\mu \)-CC spectra selected in both samples. The \( \chi^2 \) value in this case is computed as:

\[
\chi^2 = (x - \mu)V^{-1}(x - \mu)^T - \frac{N_D - N_{MC}}{\sigma_{ND}^{-1}},
\]
where $x$ is a vector of Far/Near spectra calculated from the data measurement, $\mu$ is a vector of Far/Near spectra obtained from the MC simulation, and $V^{-1}$ is the inverted covariance matrix containing both statistical and systematic uncertainties. $N_D$ is the total number of observed ND events, and $N_{MC}$ is the total number of MC simulated ND events. The first term is used to compute the goodness of the Far/Near fit, while the second term is used to constrain the ND event rate. For this analysis, a conservative penalty term of 30% on the total ND event rate is applied to reflect knowledge of neutrino flux and cross sections at the ND.

Figure 1 shows the first MINOS limits on sterile antineutrino mixing. All the regions to the right of the black line are disfavored at the 90% C.L. For this analysis, $\Delta \bar{m}^2_{41}$ and $\bar{\theta}_{24}$ are varied along the parameter space, and $\Delta \bar{m}^2_{32}$, $\bar{\theta}_{23}$ and $\bar{\theta}_{34}$ are free parameters that are allowed to vary within physical constraints. All CP-violating phases and $\bar{\theta}_{14}$ are fixed to zero and all other parameters are fixed to global-fit values. The Feldman-Cousins ordering principle is also applied to remove biases in our limits [10].

MINOS has used its $\bar{\nu}_\mu$-CC samples to set the world’s strongest disappearance constraints on active-sterile antineutrino mixing for $\Delta \bar{m}^2_{41} \lesssim 0.5$ eV$^2$. The result is fully consistent with oscillations driven by three active antineutrinos. Further improvements to these results are expected from ongoing efforts to include $\bar{\nu}_\mu$-CC events selected in the MINOS+ sample ($9.7 \times 10^{20}$ POT), as well as NC events selected in the MINOS antineutrino-enhanced sample.

1. References
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