

Sterile Neutrino Searches with MINOS/MINOS+

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The MINOS and MINOS+ experiment ran from 2005 until 2016 with two detectors at baselines of 1 km and 735 km exposed by the NuMI beam from Fermilab. The NuMI beam neutrino flux peaked at an energy of 3 GeV during the MINOS era in both ν_μ and $\bar{\nu}_\mu$ modes. The MINOS+ data were taken entirely in ν_μ mode with a peak energy of 7 GeV. A study of three-flavour oscillations with the full MINOS sample and the first two years of data from MINOS+ measured $\Delta m_{32}^2 = (2.42 \pm 0.09) \times 10^{-3} \text{ eV}^2$ assuming the Normal Hierarchy, and $\Delta m_{32}^2 = -(2.48_{-0.11}^{+0.09}) \times 10^{-3} \text{ eV}^2$ in the Inverted Hierarchy. Searches for both sterile neutrinos and sterile antineutrinos were performed with no significant evidence of a signal, hence exclusion limits were placed over six orders of magnitude of the sterile neutrino mass-splitting Δm_{41}^2 . A joint analysis of the MINOS ν_μ disappearance sample and the Daya Bay and Bugey-3 $\bar{\nu}_e$ disappearance samples excludes the LSND and MiniBooNE allowed regions for $\Delta m_{41}^2 < 0.8 \text{ eV}^2$ at 95% C.L.. Finally, an analysis searching for anomalous ν_e appearance above 6 GeV in MINOS+ was used to set a limit on the allowed sterile neutrino parameter space.

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1. Introduction

The MINOS/MINOS+ experiment [1] consists of two functionally equivalent magnetised tracking calorimeters formed from alternating layers of scintillator and steel. The two detectors are at baselines of 1 km and 735 km from the target that produces the NuMI beam [2] at Fermilab. MINOS ran from 2005 until 2012 in the low-energy (LE) beam configuration of the NuMI beam, with a peak energy of 3 GeV. The NuMI beam ran mostly in the ν_μ -dominated mode whereby positively charged mesons emergent from the target were focused using two magnetic horns to produce a ν_μ beam. The polarity of the magnetic horns could also be reversed to generate a $\bar{\nu}_\mu$ -enhanced beam with a significantly larger $\bar{\nu}_\mu$ component. The total LE exposure for MINOS was 10.56×10^{20} protons-on-target (POT) in ν_μ -dominated mode and 3.36×10^{20} POT in $\bar{\nu}_\mu$ -enhanced mode. The experiment was designed to measure the atmospheric scale oscillations, governed by the parameters θ_{23} , θ_{13} and Δm_{32}^2 .

In 2013, the experiment became MINOS+ and ran in the upgraded NuMI beam in medium-energy (ME) mode until June 2016, with a peak energy of 7 GeV. The results presented here consider exposures of 2.99×10^{20} POT and 5.80×10^{20} POT in ν_μ -dominated mode corresponding to one and two years of MINOS+ data, respectively. The ME configuration for MINOS+ motivates searches beyond the standard model, since many non-standard effects become most evident in the high energy tail of the neutrino spectrum, away from the main three-flavour oscillation peak.

In particular, the 3+1 sterile neutrino model will be considered. This is the minimal extension to include a fourth neutrino state, which must be sterile based on the results from LEP [3] showing there are only three neutrino species that couple to the Z boson with $m_\nu < 0.5m_Z$. This extension adds three new mixing angles (θ_{14} , θ_{24} and θ_{34}) as part of an expanded 4×4 mixing matrix and three additional mass-splittings, of which one, Δm_{41}^2 , is independent. MINOS/MINOS+ has sensitivity to θ_{24} through searching for disappearance of both charged-current (CC) ν_μ and neutral-current (NC) ν interactions, and small sensitivity to θ_{34} from the NC sample. The CC ν_e appearance analysis has sensitivity to a combination of θ_{14} and θ_{24} .

2. Standard Oscillations

An update to the final MINOS three-flavour oscillations result [4] was performed using an additional 5.80×10^{20} POT from the first two years of MINOS+ exposure and an additional year of atmospheric neutrino data. The event selection uses a k-Nearest-Neighbour method to preferentially select the CC ν_μ and $\bar{\nu}_\mu$ interactions from a background of NC interactions from all neutrino flavours. The spectrum of CC ν_μ and $\bar{\nu}_\mu$ events selected from the MINOS and MINOS+ beam is shown in Fig. 1 compared to the null oscillations case and the best-fit simulation. The filled histograms show the relative contributions to the spectrum from the MINOS and MINOS+ run periods, illustrating the difference between the LE and ME tunes of the NuMI beam.

The 90% C.L. allowed region of the atmospheric oscillation parameters θ_{23} and Δm_{32}^2 as a result of the fit is shown in Fig. 2. It is compared to the latest results from the NOvA [5] and T2K [6] experiments. The limits in the individual parameters can also be extracted:

$$\Delta m_{32}^2 = \begin{cases} (2.42 \pm 0.09) \times 10^{-3} \text{ eV}^2 & \text{Normal Hierarchy} \\ -(2.48_{-0.11}^{+0.09}) \times 10^{-3} \text{ eV}^2 & \text{Inverted Hierarchy} \end{cases}$$

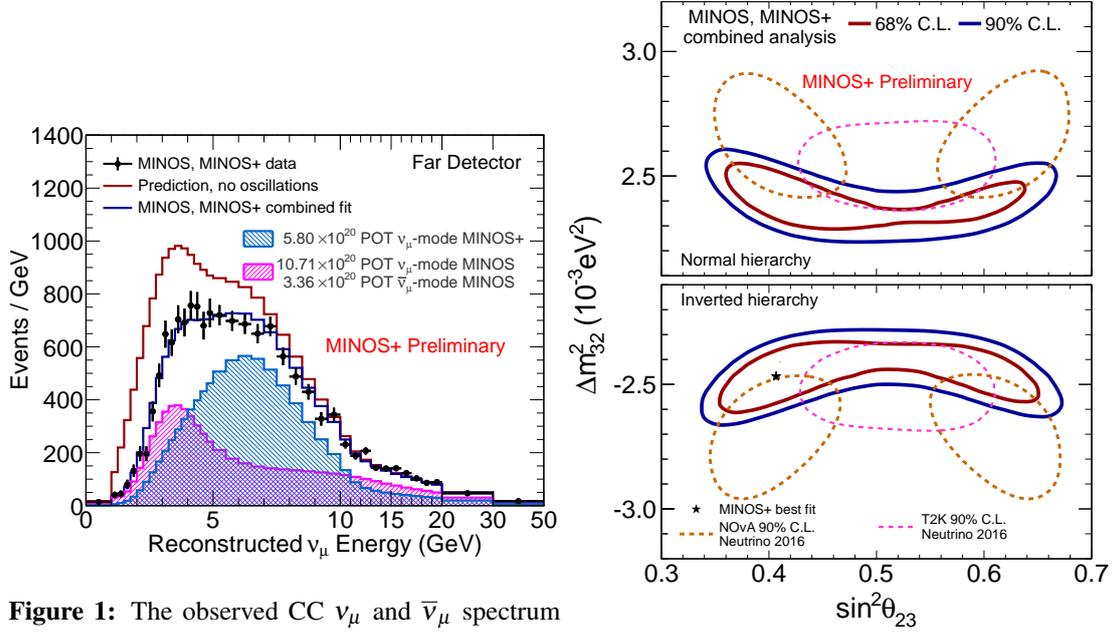


Figure 1: The observed CC ν_μ and $\bar{\nu}_\mu$ spectrum for MINOS and MINOS+ (black points) compared to the no oscillations (red) and best-fit (blue) simulation. Also shown are the individual MINOS atmospheric oscillation parameters measured by MINOS (pink) and MINOS+ (blue) contributions to the best-fit simulation.

Figure 2: The 90% C.L. allowed region for the atmospheric oscillation parameters measured by MINOS and MINOS+ compared to the recent results from the NOvA [5] and T2K [6] experiments.

$$\sin^2 \theta_{23} = \begin{cases} 0.35 - 0.65 \text{ (90\% C.L.)} & \text{Normal Hierarchy} \\ 0.35 - 0.66 \text{ (90\% C.L.)} & \text{Inverted Hierarchy.} \end{cases}$$

3. Sterile Neutrinos

The MINOS collaboration recently published a sterile neutrino analysis based on the full LE MINOS exposure [7]. A sterile neutrino could cause oscillations at short baselines meaning that the standard assumption of no oscillations upstream of the Near Detector is no longer valid, and hence the extrapolation procedure used in the standard oscillations analysis cannot be used. In order to deal with potential oscillations in both detectors and maximise the range of Δm_{41}^2 that could be probed, the analysis considered the Far-over-Near ratio of event spectra. This analysis used both CC ν_μ disappearance and NC ν disappearance channels to search for a fourth neutrino state. The first two years of data from MINOS+ have also been analysed following the method developed for the MINOS analysis, and no significant evidence of a sterile neutrino was found. Figure 3 hence shows the 90% and 95% C.L. excluded regions in terms of Δm_{41}^2 and $\sin^2 \theta_{24}$ compared to a series of other experimental results, providing a strong exclusion over many orders of magnitude of Δm_{41}^2 .

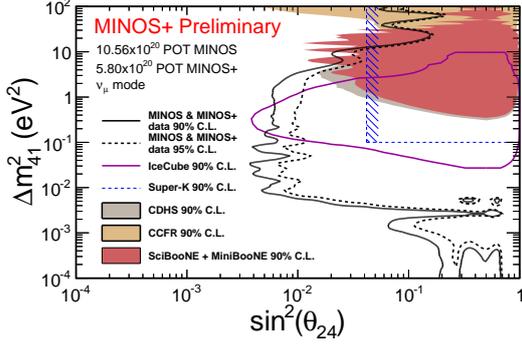


Figure 3: The 90% and 95% C.L. contours from the combined MINOS/MINOS+ sterile neutrino search compared to the recent result from IceCube [8], and further results from Super-K [9], CDHS [10], CCFR [11], and SciBooNE + MiniBooNE [12].

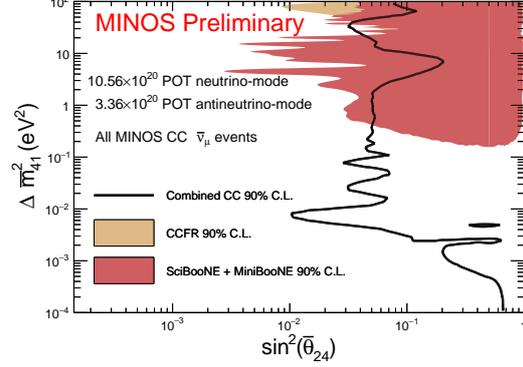


Figure 4: The 90% C.L. contour from the MINOS sterile antineutrino analysis compared results from CCFR [13] and SciBooNE + MiniBooNE [14].

4. Sterile Antineutrinos

The MINOS/MINOS+ detectors have the unique ability amongst long-baseline neutrino oscillation experiments to be able to select the charge of the muon outgoing from the CC interaction. This allows for the selection of a CC $\bar{\nu}_\mu$ sample to search for a sterile antineutrino. The sample of CC $\bar{\nu}_\mu$ interactions comprises two individual components, one from the $\bar{\nu}_\mu$ -enhanced beam and the other from the ν_μ -dominated beam. The small $\bar{\nu}_\mu$ component in the ν_μ -dominated beam has higher energy because the antineutrinos come from the decay of parent mesons that are highly boosted along the axis of the magnetic horn. This makes the two samples complimentary as they probe different regions of the energy spectrum. The analysis was performed in the same way as the neutrino-mode analysis [7] and no sterile antineutrino signal was observed. Figure 4 shows the 90% exclusion contour compared to results from CCFR [13] and SciBooNE + MiniBooNE [14].

5. Combination with Daya-Bay and Bugey-3

The MINOS ν_μ disappearance sterile neutrino result [7] was combined with the $\bar{\nu}_e$ disappearance results from Daya Bay [15] and Bugey-3 [16] in a joint analysis [17] with the Daya Bay collaboration. Disappearance of ν_μ in MINOS has sensitivity to θ_{24} and $\bar{\nu}_e$ disappearance in Daya Bay has sensitivity to θ_{14} . The mass-squared splitting Δm_{41}^2 is common between the two channels, meaning that the combination of results, performed using the CLs technique, can probe $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$. The effective mixing angle $\sin^2 2\theta_{\mu e}$ is the parameter measured by LSND [18] and MiniBooNE [19]. Figure 5 shows the 90% C.L. exclusion contour from MINOS and Daya Bay / Bugey-3 compared to allowed and excluded regions from other experiments, showing a very strong exclusion is set on the existence of the sterile neutrino for $\Delta m_{41}^2 < 0.8 \text{ eV}^2$.

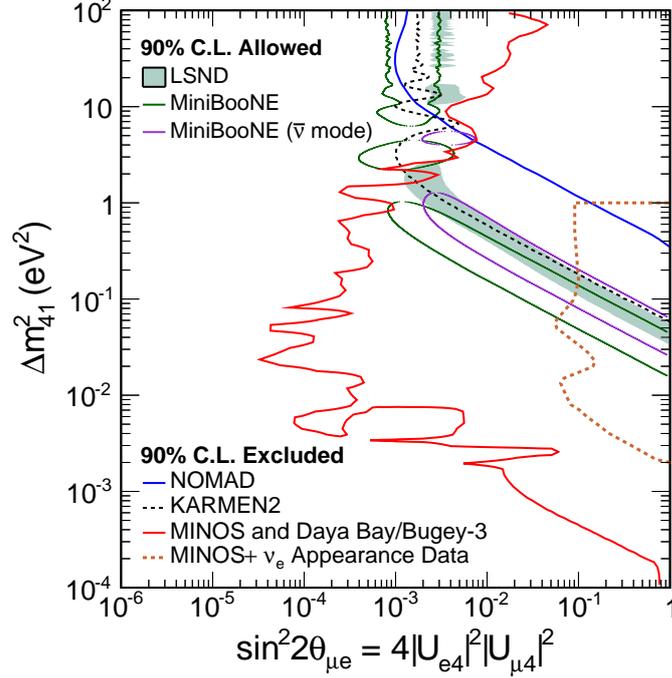


Figure 5: The 90% exclusion limits from the MINOS and Daya Bay/Bugey-3 [17] combined analysis (red) and the MINOS+ ν_e appearance result (dashed orange). These contours are compared to the LSND [18] and MiniBooNE [19] allowed regions, and the exclusion limits from KARMEN2 [20] and NOMAD [21].

6. Sterile-driven ν_e Appearance

The ME beam configuration used for MINOS+ provides an opportunity to directly probe the LSND/MiniBooNE phase-space by searching for anomalous appearance of electron neutrinos in the Far Detector. The analysis looks at the high energy part of the spectrum, above 6 GeV, away from the standard three-flavour oscillations and builds upon the framework developed for the MINOS three-flavour CC ν_e analyses [22]. A library-event-matching (LEM) algorithm is used to select the CC ν_e candidate events from the large background of NC interactions, and a detailed description of this analysis is provided elsewhere in these proceedings. A total of 78 events were observed in the first year of MINOS+ data, compared to an expectation of 56.7, corresponding to a 2.3σ excess. However, the 3+1 sterile neutrino hypothesis does not provide a significantly improved description of this excess. The 90% C.L. exclusion contour obtained from the analysis is shown by the orange dashed line in Fig. 5, in agreement with the disappearance-based analysis.

7. Conclusion

The MINOS/MINOS+ experiment continues to perform high-precision measurements of neutrino oscillations. The updated three-flavour oscillation result with the inclusion of the first two years of MINOS+ data provides a very accurate measurement of the mass-splitting Δm_{32}^2 . No evidence of a sterile neutrino was found across four analyses and strong limits spanning six orders of

magnitude in Δm_{41}^2 on the existence of the sterile neutrino and sterile antineutrino were obtained. The addition of the final year of data (approximately half of the total MINOS+ exposure) will further improve the sensitivity of the measurements from the MINOS+ experiment over the next year.

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