PROCEEDINGS OF SCIENCE

Sterile Neutrino searches with MINOS and MINOS+

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A search for sterile neutrinos was performed by looking for muon neutrino disappearance using the MINOS/MINOS+ detectors. The two detectors are at baselines of 1.04 km and 735 km from the neutrino production target of the NuMI neutrino beam at Fermilab. The data exposure consists of 10.56×10^{20} protons-on-target from a beam configuration with a neutrino energy distribution peaked at 3 GeV and a further 5.8×10^{20} protons-on-target in a higher energy configuration with a beam peak energy of 7 GeV. A simultaneous analysis of the ν_μ charged-current and neutral-current neutrino energy spectra in the two detectors, using a 3+1 sterile neutrino model, yields no evidence of sterile neutrino mixing. A world-leading limit on the sterile mixing angle $\sin^2\theta_{24}$ is set for many values of the sterile neutrino mass-splitting $\Delta m^2_{41} > 10^{-4}\,\mathrm{eV}^2$.

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1. Introduction

The MINOS experiment collected data in a Near Detector (ND) and a Far Detector (FD) [1] from Fermilab's muon neutrino NuMI beam [2], with a neutrino energy distribution peaked at 3 GeV, between 2005 and 2012. The ND is located at Fermilab, 1.04 km upstream of the neutrino production target and the FD was at a distance of 735 km located in the Soudan Underground Laboratory in northern Minnesota. The detectors are functionally equivalent magnetised tracking sampling calorimeters formed by alternating planes of scintillator strips oriented at $\pm 45^\circ$ to the vertical, interleaved by layers of 2.54 cm-thick iron. From 2013 to 2016 the experiment continued as MINOS+ collecting further data in the upgraded NuMI beam with the peak neutrino energy increased to 7 GeV. The neutrinos are the decay products of mesons, predominantly π and K, produced by the interaction of 120 GeV protons from the Main Injector proton accelerator at Fermilab and a graphite target. The energy of the beam is tuned using two magnetic horns that focus the charged mesons produced in the target into a 625 m decay pipe. The current in the magnetic horns is also reversible, converting the beam from a predominantly ν_μ beam to a beam with a significantly enhanced $\overline{\nu}_\mu$ component.

The exposure in the MINOS era totals 10.56×10^{20} protons-on-target (POT) in neutrino mode and 3.36×10^{20} POT in antineutrino mode, and the first two years of MINOS+ data correspond to 5.80×10^{20} POT. The MINOS FD also collected 37.88 kiloton-years of atmospheric neutrinos, with an additional 10.79 kiloton-years processed from MINOS+. The detectors are sensitive to ν_μ charged-current (CC) interactions, ν_e CC interactions and neutral-current (NC) interactions of all neutrino flavours. The three-flavour oscillation analysis, described in Sec. 2, considers interactions reconstructed as either ν_μ CC or ν_e CC (and the corresponding antineutrinos), whereas the sterile neutrino analysis was performed using the ν_μ CC and NC event samples and is detailed in Sec. 3.

2. Three-flavour oscillations

A previous MINOS analysis [3] of the ν_μ disappearance oscillation parameters θ_{23} and Δm^2_{32} was performed using the full MINOS exposure from the neutrino and antineutrino beam modes, as well as the ν_e CC and $\overline{\nu}_e$ CC appearance sample [4] plus the MINOS era atmospheric neutrino exposure [5]. This analysis adds the first two years of MINOS+ beam data and the MINOS+ atmospheric neutrino data. A simultaneous fit to all of the listed samples was performed to find the best-fit values of Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$ and δ_{CP}.

The left panel in Fig. 1 shows the combined beam ν_μ CC and beam $\overline{\nu}_\mu$ CC reconstructed energy spectrum, the pink and blue hashed regions show the individual contributions from the MINOS and MINOS+ exposures, respectively. The high statistics of the MINOS+ sample, especially in the higher energy region away from the main oscillation maximum, provides an excellent test of the three-flavour paradigm in the regime where more exotic phenomena could be seen, and it is demonstrated that three-flavour oscillations provide a very good description of the MINOS and MINOS+ data, and hence the effect of any exotic phenomena must be relatively small. The right panel shows the MINOS/MINOS+ 68% confidence level (C.L.) and 90% C.L. contours in the $\Delta\chi^2$ surface as a function of θ_{23} and Δm^2_{32} compared to preliminary results from other experiments. The

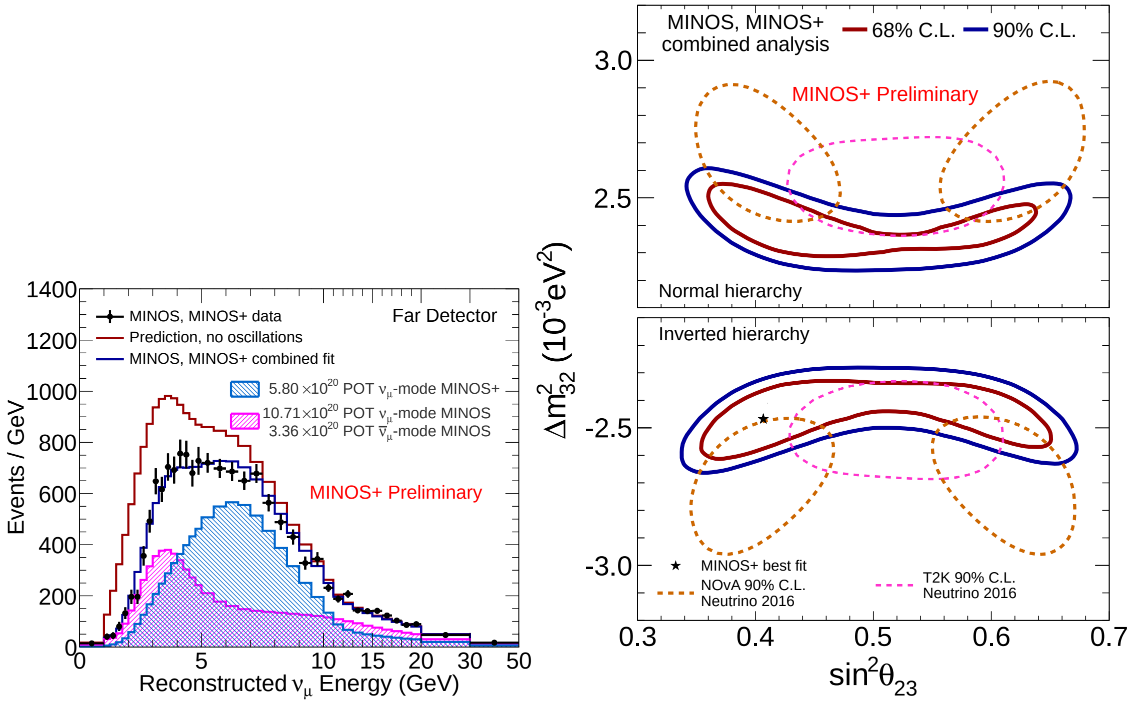

Figure 1: Left: The combined beam ν_μ CC and beam $\overline{\nu}_\mu$ CC reconstructed (anti)neutrino energy spectrum for MINOS and MINOS+. The individual contributions from MINOS and MINOS+ are shown in the pink and blue shaded regions, respectively. Right: the 68% C.L. and 90% C.L. contours in ($\sin^2\theta_{23}$, Δm^2_{32}) for MINOS/MINOS+ compared to results from NOvA [6] and T2K [7].

best-fit parameters for the Normal Hierarchy and Inverted Hierarchy cases are as follows:

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

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

3. Sterile neutrinos

The MINOS Collaboration recently published a sterile neutrino analysis based on the full MINOS neutrino-mode exposure [8], which was also combined with $\overline{\nu}_e$ disappearance data from the Daya Bay and Bugey-3 reactor neutrino experiments [9]. This previous analysis considered the ratio of the reconstructed neutrino energy spectra between the two detectors, referred to as the Far-over-Near method. The sensitivity of this method in the higher Δm^2_{41} region was limited by two different effects. Firstly, when the sterile neutrino mass-splitting is high enough that the sterile oscillations occur upstream of the ND then the effect cancels in the Far-over-Near ratio even though a clear deficit would be seen in each of the detectors individually. Secondly, the uncertainty on the

Far-over-Near ratio was dominated by the statistical uncertainty of the FD, limiting the statistical power of the very high statistics available in the ND. A two-detector fit method, whereby the reconstructed neutrino energy spectra for both the ν_μ CC and NC samples are fit simultaneously in both detectors, has been developed to give a significant improvement in sensitivity in the analysis presented here, in addition to the increased statistics obtained with the inclusion of the first two years of MINOS+ data.

The two-detector analysis method requires that the reconstructed neutrino energy spectra in the two detectors are fitted directly, and that the ND cannot be used to tune the simulation. For this reason, the a-priori NuMI flux prediction calculated by the MINERvA experiment is used [10]. Some cancellation of the systematic uncertainties is provided by the off-diagonal components of a covariance matrix that encodes the statistical and systematic uncertainties in both detectors. The fit is performed within the 3+1 sterile neutrino framework, and MINOS/MINOS+ have a primary sensitivity to $\sin^2\theta_{24}$ and Δm^2_{41} in addition to the three-flavour oscillation parameters.

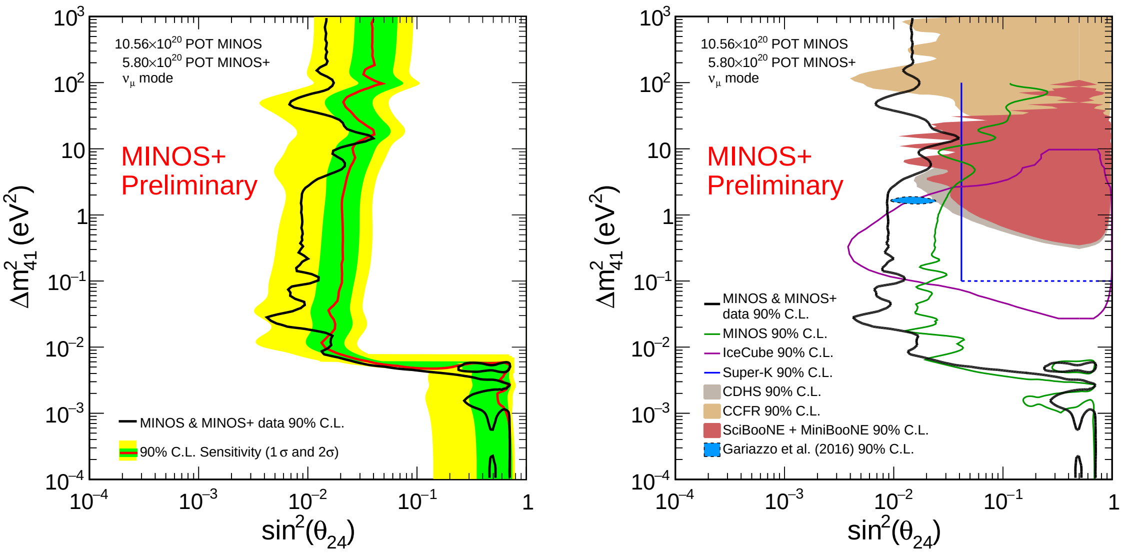

Figure 2: Left: the 90% C.L. contour in ($\sin^2\theta_{24}$, Δm^2_{41}) for the MINOS/MINOS+ data (black) compared to the MC simulation (red). The green and yellow bands represent the 1σ and 2σ regions from varying the simulation according to the statistical and systematic uncertainties. Right: the 90% C.L. MINOS/MINOS+ contour (black) compared to the previous MINOS result [8], those from other experiments [11, 12, 13, 14, 15] and the result of a global fit to neutrino oscillation data [16]. The MINOS/MINOS+ limits continue vertically upward for $\Delta m^2_{41} > 10^3\,\text{eV}^2$.

The results of the fit in the ($\sin^2\theta_{24}$, Δm^2_{41}) parameter space are shown in Fig. 2. The MINOS/MINOS+ 90% C.L. contour is shown in black and it is compared to: on the left, the Monte-Carlo (MC) simulation sensitivity and the 1σ and 2σ sensitivity bands obtained from a large sample of MC reconstructed neutrino energy spectra fluctuated using the statistical and systematics uncertainties covariance matrix; and on the right, results from other experiments, including the previously published MINOS result [8]. The difference in χ^2 between the best-fit 3+1 parameters and three-flavour oscillations is 0.12 units, and as such, no evidence is seen for a sterile neutrino.

A strong limit on $\sin^2\theta_{24}$ is set over a large range of Δm^2_{41} and falls within the 2σ expected region from the MC simulation.

4. Conclusions and Outlook

The MINOS/MINOS+ data have been shown to be well described by three-flavour neutrino oscillations. A search for sterile neutrinos, looking for the disappearance of ν_μ, using the 3+1 model yielded no evidence of a sterile neutrino and MINOS/MINOS+ sets a leading limit on $\sin^2\theta_{24}$ for much of the region with the sterile neutrino mass-splitting $\Delta m^2_{41} > 10^{-4}\,\mathrm{eV}^2$. The future addition of the final year of MINOS+ data, corresponding to 40% of the MINOS+ exposure, and on-going analysis improvements will further extend the sensitivity of the experiment.

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