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To cite this article: Justin Evans and MINOS and MINOS+ collaborations 2017 J. Phys.: Conf. Ser. 888 012017

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New results from MINOS and MINOS+

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Abstract. The MINOS and MINOS+ experiment consists of two magnetised steel-scintillator tracking calorimeters, observing flavour change in the NuMI beam over 735 km. With eleven years of data from both $\nu_\mu$ and $\bar{\nu}_\mu$ beam modes, in configurations with peak energies at 3 GeV and 7 GeV, the experiment has made precision measurements of neutrino oscillation parameters and performed a number searches for new physics in the neutrino sector. These proceedings present a set of new results covering a range of topics. The largest neutrino mass-squared splitting is measured to be $(2.42 \pm 0.09) \times 10^{-3}\text{eV}^2$ assuming the normal mass hierarchy and $-(2.48^{+0.09}_{-0.11}) \times 10^{-3}\text{eV}^2$ assuming the inverted mass hierarchy. Searches for sterile neutrinos and antineutrinos are presented, setting limits on the mixing angle $\theta_{24}$ over six orders of magnitude in the mass-squared splitting $\Delta m^2_{41}$. The neutrino limits constrain $\sin^2 \theta_{24} < 0.022$ and $\sin^2 \theta_{34} < 0.28$ at $\Delta m^2_{41} = 0.5\text{eV}^2$, both at 95% CL. Limits are set on the possible size of a large extra dimension, $R < 0.17\mu$m (90% CL), assuming the lightest neutrino state has zero mass. Limits are set on the parameter $\epsilon_{e\tau}$ of a model of non-standard neutrino interactions. A search for non-standard appearance of electron neutrinos above 6 GeV observes 78 events, compared to an expectation of 56.7, and is interpreted as a limit on the PMNS matrix element combination $4|U_{\mu 4}|^2|U_{e4}|^2$ in a sterile neutrino model. Finally, a combination of the MINOS $\nu_\mu$ disappearance search with $\nu_e$ disappearance searches from Daya Bay and Bugey-3 excludes the parameter space allowed by LSND and MiniBooNE for $\Delta m^2_{41} < 0.8\text{eV}^2$ at 90% CL.

1. The MINOS and MINOS+ experiments

Since 2005, the NuMI beam [1] has been sending muon neutrinos and antineutrinos to the Soudan Underground Laboratory in the Vermilion Range, one of the Iron Ranges of northern Minnesota. After eleven years of running, the NuMI beam now regularly achieves a power of around 615 kW, with 700 kW having been achieved in a short test run [2]. Throughout that time, the NuMI neutrinos have been streaming through the two MINOS detectors [3]. At Soudan, 5,400 t of steel is instrumented with strips of scintillator, the patterns of scintillation light observed by Hamamatsu multi-anode photomultiplier tubes allowing the charged current interactions of both muon and electron neutrinos to be identified, along with neutral current interactions of all neutrino flavours. Observing the appearance or disappearance of these neutrino flavours has allowed MINOS to measure the parameters governing their oscillations; to provide a baseline against which to measure the appearance and disappearance, a smaller detector of the same design sits near the neutrino production point at Fermilab to characterise the NuMI beam as well as allowing measurements of neutrino cross sections [4].

The energy spectrum of neutrinos from the NuMI beam is tuneable; the distances between the proton target and meson-focusing horns can be altered, as can the current through those horns. Until 2012, NuMI ran primarily in low-energy mode, delivering $10.56 \times 10^{20}$ protons-on-target...
Figure 1. Left: the energy spectrum of charged-current $\nu_\mu$ interactions observed at the MINOS detector in the Soudan mine, compared to the expectation, derived from observations at a detector in Fermilab, both with and without oscillations. The two shaded histograms show the contributions of the low-energy MINOS-era data and the medium-energy MINOS+-era data to the total. Right: the ratio of the observed energy spectrum to the expectation without oscillations, along with the expectation with the best-fit oscillation parameters.

(PoT) of $\nu_\mu$-dominated beam and $3.36 \times 10^{20}$ PoT of $\nu_\mu$-enhanced beam with peak energies near 3 GeV. From 2013, in a phase called MINOS+, the NuMI beam has run in a higher-energy mode, delivering a $\nu_\mu$-dominated beam with a peak energy near 7 GeV. These proceedings report results using the first two of three MINOS+ data-taking periods; this corresponds to an exposure of $5.80 \times 10^{20}$ PoT of the higher-energy data, around half of the total exposure available.

2. Three-flavour oscillation parameters
Oscillations driven by the mass-squared splitting $\Delta m^2_{32}$ and the mixing angle $\theta_{23}$ cause a disappearance of muon neutrinos and antineutrinos that is maximal near 1.5 GeV. Using the energy spectrum of charged current $\nu_\mu$ and $\bar{\nu}_\mu$ interactions observed at the Fermilab detector, the spectrum expected at Soudan can be predicted. The data shows an energy-dependent deficit when compared to this expectation, as shown in Fig. 1, that can be fit to extract values of the mass-squared splitting and mixing angle,

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

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

Figure 2 shows the 90% CL allowed regions for these parameters, along with the corresponding allowed regions from the NO$\nu$A [5] and T2K [6] experiments that were released at the Neutrino 2016 conference, as described elsewhere in these proceedings.

3. Beyond three flavours, and into a new analysis paradigm
The large number of high-energy neutrinos collected by MINOS+ allows the Collaboration to go beyond measurements of the three-flavour oscillation parameters, and to search for new physics. This new physics could manifest itself as appearance or disappearance of muon and electron neutrinos and antineutrinos, but at length scales and energies much different from those at
2.5
3.0
Normal hierarchy
MINOS+ Preliminary
MINOS, MINOS+
combined analysis
68% C.L. 90% C.L.

Inverted hierarchy
MINOS+ best fit
Neutrino 2016

Figure 2. The 90% CL allowed regions for
the mass-squared splitting and mixing angle
that govern $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance in
MINOS. Also shown are the measurements
released at the Neutrino 2016 conference by
NO\nu\nu A [5] and T2K [6] that are described
elsewhere in these proceedings.

which standard oscillations are seen. Most importantly, this means that neutrino flavour change
could impact the energy spectra seen at the Fermilab detector, meaning that this detector no
longer provides a characterisation of the NuMI beam independent of the physics for which an
analysis is searching. To surmount this problem, searches for new physics no longer use the
observations of Fermilab detector to predict what will be seen at Soudan; instead, the searches
use the ratio of what is seen at Soudan to what is seen at Fermilab—the ‘Far-over-Near ratio’—
which would be altered by any new physics that changes the neutrino energy spectra in one of
the detectors differently from how it affects the spectra in the other detector. Figure 3 shows
the Far-over-Near ratios for charged-current $\nu_\mu$ interactions and for neutral-current neutrino interactions of all active neutrino flavours. The ratio from the data matches the ratio from the simulation
well, indicating that no signals for new physics have been seen. The challenge lies in using this
observation to express limits on the parameters of new physics models.

4. Sterile neutrinos
The search for sterile neutrinos has been ongoing since the late 1990s when the LSND experiment
saw evidence for $\nu_\mu \rightarrow \nu_e$ transitions happening much faster than could be explained through
oscillations driven by only three neutrino flavours [7]. The mass splitting driving these anomalous
oscillations would be in the region of $\mathcal{O}(\Delta m^2_{41} = 1 \text{ eV}^2)$; in MINOS, such a mass splitting
could cause disappearance of muon neutrinos right across the energy spectrum. For such disappearance
neutrino mass state. In such a model, this mixing would be governed by an angle to happen, the muon flavour must, in a model with one sterile neutrino, be mixed into the fourth mass state. We set the constraint $|U_{\mu 4}|^2 < 0.022$ (95% CL). At the same value of $\Delta m^2_{41}$, we can also set a constraint on the angle $\theta_{34}$ that governs how much tau flavour mixes into the fourth mass state. We set the constraint $\sin^2 \theta_{34} < 0.28$ (95% CL). With the assumption $\theta_{14} = \theta_{24} = 0$, this is also a constraint on the PMNS matrix element $|U_{\tau 4}|$.

**Figure 4.** The 90% CL and 95% CL exclusion regions, obtained from a search for $\nu_\mu$ disappearance, for a model with one sterile neutrino. This result uses all MINOS-era data from a $\nu_\mu$-dominated beam, and the first two years of MINOS+ running. Regions to the right of the lines are excluded. The MINOS+ limits are compared to 90% CL exclusion regions from $\nu_\mu$-disappearance searches by IceCube [10], CDHS [11], CCFR [12], and SciBooNE and MiniBooNE [13].

**Figure 5.** The 90% CL and 95% CL exclusion regions, obtained from a search for $\bar{\nu}_\mu$ disappearance, for a model with one sterile neutrino. This result uses all MINOS-era running with a $\nu_\mu$-enhanced beam, plus the $\bar{\nu}_\mu$ background component in the MINOS-era data from a $\nu_\mu$-dominated beam. (No MINOS+ data is used.) Regions to the right of the lines are excluded. The MINOS limits are compared to 90% CL exclusion regions from $\bar{\nu}_\mu$ disappearance searches by CCFR [14] and SciBooNE and MiniBooNE [15].
5. Sterile antineutrinos

The MINOS detectors are magnetised, allowing charged current $\nu_\mu$ and $\bar{\nu}_\mu$ interactions to be separated on an event-by-event basis by looking at the directions of curvature of the muons produced. There are two samples of antineutrinos available in the MINOS data. The $3.36 \times 10^{20}$ PoT of data from a $\nu_\mu$-dominated beam provides a sample of antineutrinos peaking at around 3 GeV [16, 17]. Additionally, in the $10.56 \times 10^{20}$ PoT of data from a $\nu_\mu$-enhanced beam, around 7% of charged current interactions are from a $\bar{\nu}_\mu$ background that peaks at 7 GeV [18]. (A similar, much smaller sample exists in the MINOS+ $\nu_\mu$-dominated running, but is not used in this analysis.) These two samples have been put through an analysis procedure identical in concept to the procedure discussed for neutrinos in the previous section, to produce a limit on sterile antineutrinos. The limit on the antineutrino mixing angle $\theta_{24}$ is shown in Fig. 5, as a function of the antineutrino mass-squared difference $\Delta m^2_{41}$.

6. Large extra dimensions

A single additional sterile neutrino is not the only new physics that MINOS+ is sensitive to. The existence of large extra dimensions is a promising hypothesis that could explain such puzzles as the lightness of the neutrino and the weakness of gravity [19, 20]. In some theories of such extra dimensions, a sterile neutrino can propagate into those dimensions [20, 21, 22]. From our point of view, in only three dimensions, this would look like a tower of sterile neutrino mass states, all of which could take part in oscillations with the three active neutrinos, altering the $\nu_\mu$ disappearance probability observed by MINOS+, as shown in Fig. 6. The size of such an effect is dependent on the mass of the lightest neutrino mass state, $m_0$, and the length of the extra dimension into which the neutrino propagates, $R$ [23]. MINOS+ is therefore able to set limits on the size of the extra dimension as a function of $m_0$, as shown in Fig. 7. For $m_0 \to 0$, MINOS+ sets a limit of $R < 0.17 \mu m$ (90% CL).

7. Non-standard interactions

The oscillation probability observed by MINOS would also be altered by the presence of any non-standard interactions between neutrinos and the Earth as they travel from Fermilab to

**Figure 6.** The $\nu_\mu$ disappearance probability at the MINOS detector in Soudan, shown for the standard neutrino oscillation model, and for two cases of a large extra dimension with size $R$ and lightest neutrino mass $m_0 = 0$.

**Figure 7.** The large extra dimension size excluded by MINOS alone, and by a combination of MINOS and MINOS+ data, at 90% CL, as a function of the lightest neutrino mass. Regions to the right of the lines are excluded.
Minnesota. In models of such non-standard interactions [24, 25, 26, 27], a set of additional $\epsilon_{\alpha \beta}$ parameters that quantify the sizes of the non-standard interactions, where $\alpha$ and $\beta$ being the lepton flavours, are added to the Hamiltonian through the new term $H_{\text{NSI}}$:

$$H_{\text{NSI}} = \sqrt{2} G_F N_e \left( \begin{array}{ccc} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{array} \right),$$

(1)

where $G_F$ is the Fermi coupling constant and $N_e$ the electron density through which the neutrinos are passing. Three additional phases, $\delta_{e\tau}$, $\delta_{e\mu}$ and $\delta_{\mu\tau}$, also arise in this model. By searching for non-standard appearance of electron neutrinos when the beam reaches Soudan, MINOS has set limits on $|\epsilon_{e\tau}|$ as a function of the quantity $(\delta_{CP} + \delta_{e\tau})$ as shown in Fig. 8 [28], where $\delta_{CP}$ is the CP-violating phase of the standard three-flavour neutrino oscillation model.

8. Electron neutrino appearance

The LSND anomaly was observed in the channel $\nu_\mu \rightarrow \nu_e$. Assuming no CP-violation effects, MINOS+ can make a direct comparison to the LSND signal by searching for non-standard appearance of electron neutrinos in the $\nu_\mu$ beam above 6 GeV where no standard $\theta_{13}$-driven appearance is expected. Figure 9 shows the spectrum of $\nu_e$ CC-like events observed at the Soudan detector, compared to the expectation in the absence of a sterile neutrino, which is predominantly non-$\nu_e$ background. The expectation is 56.7 events, compared to the 78 events observed—a 2.3$\sigma$ excess. The precision of this analysis will be significantly improved in the near future, with almost three times more data available than was used in the result shown here.

9. Comparing to the LSND and MiniBooNE excesses

In a model with one sterile neutrino, the LSND and MiniBooNE excesses would be driven by a combination of two mixing angles: the $\theta_{24}$ parameter on which MINOS+ has set limits, and also $\theta_{14}$, which governs how much electron flavour mixes into the fourth mass state. The magnitude of the LSND and MiniBooNE excesses would be given by the quantity

$$\sin^2 \theta_{24} \sin^2 (2 \theta_{14}) = 4 |U_{\mu 4}|^2 |U_{e 4}|^2 \equiv \sin^2 (2 \theta_{14}),$$

(2)
Figure 9. The spectrum of charged current $\nu_e$-like events observed at the Soudan detector.

where $U_{ij}$ are elements of the extended PMNS matrix, and $\theta_{\mu e}$ is an effective mixing angle often used to express these results.

The MINOS+ $\nu_\mu \rightarrow \nu_e$ search places a direct constraint on $\theta_{\mu e}$, which is shown in Fig. 10. To compare the MINOS $\nu_\mu$-disappearance limit on $\theta_{24}$ to the LSND and MiniBooNE allowed regions, a constraint on $\theta_{14}$ is required. A new $\theta_{14}$ constraint was shown at this conference by the Daya Bay Collaboration [29, 30]. The Daya Bay and MINOS collaborations have worked together on a combined analysis [31], which currently only uses MINOS-era data. This analysis also includes data from the Bugey-3 experiment [32], which sets stronger limits on $\theta_{14}$ than Daya Bay at higher values of $\Delta m_{41}^2$ (above approximately 0.2 eV$^2$). This leads to a strong exclusion of much of the LSND and MiniBooNE allowed regions, as shown in Fig. 10. The parameter space allowed by LSND and MiniBooNE is excluded for $\Delta m_{41}^2 < 0.8$ eV$^2$ at 95% CL.

10. Summary
The Neutrino 2016 conference provided an opportunity to mark the end of MINOS and MINOS+ data-taking. After eleven years of exposure to $2.61 \times 10^{20}$ PoT from the NuMI beam, the detectors were switched off on 29th June 2016. Analysis of data will continue for the next couple of years, rounding off more than a decade of precision neutrino oscillation measurements, cross section measurements, cosmic ray physics and searches for physics beyond the Standard Model.

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Figure 10. A summary of sterile neutrino results in the parameter space to which the LSND and MiniBooNE appearance signals are sensitive. The region to the right of the dashed brown line is excluded by the MINOS $\nu_\mu \rightarrow \nu_e$ search at 90% CL. The region to the right of the red line is excluded at 90% CL by a combination [31] of the MINOS $\nu_\mu$ disappearance search [8] and the Daya Bay [30] and Bugey-3 [32] $\tau_e$ disappearance searches.

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