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A search for muon neutrino to electron neutrino oscillation mediated by sterile neutrinos in MINOS+

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Abstract. The MINOS experiment made precision measurements of the neutrino oscillation parameters that are governed by the atmospheric mass-squared splitting. These measurements were made with data that were collected while the NuMI muon neutrino beam operated in a low energy mode that peaks around 3 GeV. Today the NuMI beam is running with a higher energy mode that produces a neutrino energy spectrum that peaks around 7 GeV, allowing the MINOS+ experiment to probe neutrino oscillation phenomena that could potentially be governed by a fourth mass-squared splitting. If observed, the presence of a fourth mass-squared splitting would be compelling evidence for a sterile neutrino state. In this analysis, we will present the results of a search for $\nu_\mu \to \nu_e$ oscillation mediated by sterile neutrinos in MINOS+. The results will be contrasted against the measurements made by the LSND experiment.

1. Introduction

MINOS+ is the medium-energy NuMI beam [1] extension of MINOS, an on-axis, long-baseline experiment that studied neutrino and antineutrino oscillations in the low-energy NuMI beam mode. The MINOS/MINOS+ experiment consists of two functionally identical steel-scintillator tracking calorimeters. The 0.98 kton Near Detector (ND) and the 5.4 kton Far Detector (FD) are located 1.04 km and 735 km from the neutrino production target respectively.

The LSND [3] and MiniBooNE [4] experiments observed electron neutrino and antineutrino appearance inconsistent with standard three-flavour formalism, a possible explanation for these results is the existence of sterile neutrinos. The increased NuMI beam energy and power raises the opportunity to study $\nu_\mu \to \nu_e$ appearance searching for exotic oscillation phenomena by focusing on energies shifted from the oscillation maximum. We consider the 3+1 model in MINOS+, which adds additional oscillation parameters. This analysis is sensitive to both θ_{14} and θ_{24}, and there are additional dependencies to θ_{13}, θ_{23}, θ_{34}, δ_{13} and $\delta_{24} - \delta_{14}$.

We present preliminary results for the analysis performed on the first 2.97×10^{20} Protons-on-Target (POT) delivered to MINOS+, corresponding to the first year of data taking with two more years worth of data to be analysed.

2. Event selection

MINOS+ builds upon the vetted MINOS appearance [2] analysis to probe for new physics in the 6-12 GeV energy range. The selection method relies on the Library Event Matching

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(LEM) technique, which is based on a single discriminant (α_{LEM}) produced by comparing input candidates to a library of simulated signal and background events in the FD. The topology of input events is compared to that of simulated ν_e Charged Current (CC) and Neutral Current (NC) events. Four variables from the matching process are used as input to an artificial neural network that yields the discriminant:

- fraction of best 50 events that were signal matches;
- mean inelasticity of signal events in the best 50 matches;
- mean matched charge of signal events in the best 50;
- reconstructed energy of input candidate.

The selector provides a clear shape difference between background and signal events in 3+1 parameter space. The cut between 6-12 GeV significantly reduces background events and increases sensitivity to potential anomalous oscillation mechanisms. The signal-selected region corresponds to the LEM selector $\alpha_{\text{LEM}} > 0.6$.

3. Analysis crosschecks and results

Before looking at the signal-selected region, several crosschecks are performed to verify the LEM selection algorithm and the prediction method. The AntiPID crosscheck method compares the three-flavour FD prediction and data with $\alpha_{\text{LEM}} < 0.5$ where no ν_e CC excess is expected. We observe 62 AntiPID events in good agreement with a prediction of 64.5 ± 8.0 events (statistical error only). The handling of NC events in the analysis region ($\alpha_{\text{LEM}} > 0.6$) is assessed with the Muon Removed Charged Current (MRCC) sample, NC-like events created from well reconstructed ν_μ CC events in data and simulation, where the hits related to the muon are removed. We observe 59 MRCC events in the FD with a prediction of 51.6 ± 7.0 events.

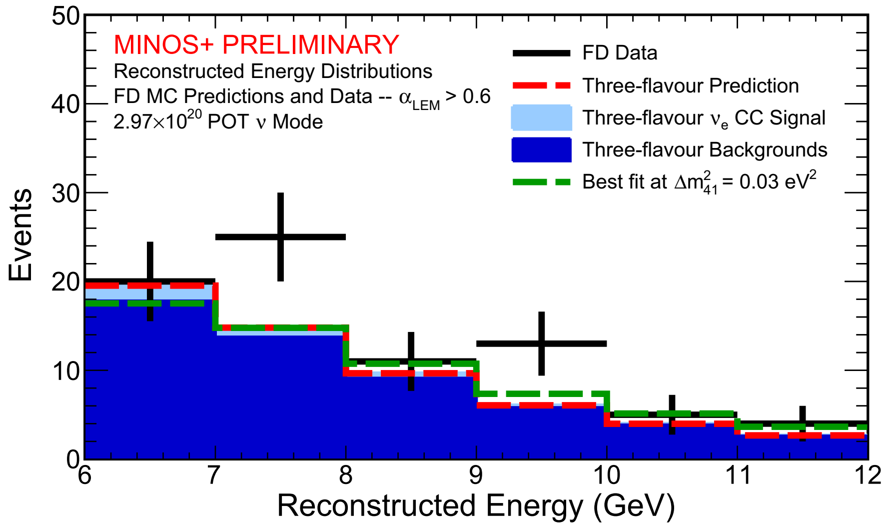

Figure 1. Far Detector energy spectrum for signal-selected events (6 GeV < Energy < 12 GeV and $0.6 < \alpha_{\text{LEM}} < 1.0$) with the total three-flavour prediction and the 3+1 model fit expectation.

Figure 1 shows the observed FD energy spectrum for the signal-selected events together with the three-flavour predictions based on global best values. The expected number of events in the FD based on the three-flavour oscillation prediction is 56.7 while we observe 78 events, corresponding to a 2.3 σ excess. The difference between the number of observed and predicted events is not significantly reduced considering the best fit to a 3+1 model, also shown in Figure 1, done in three bins of the LEM selector and six bins of reconstructed energy.

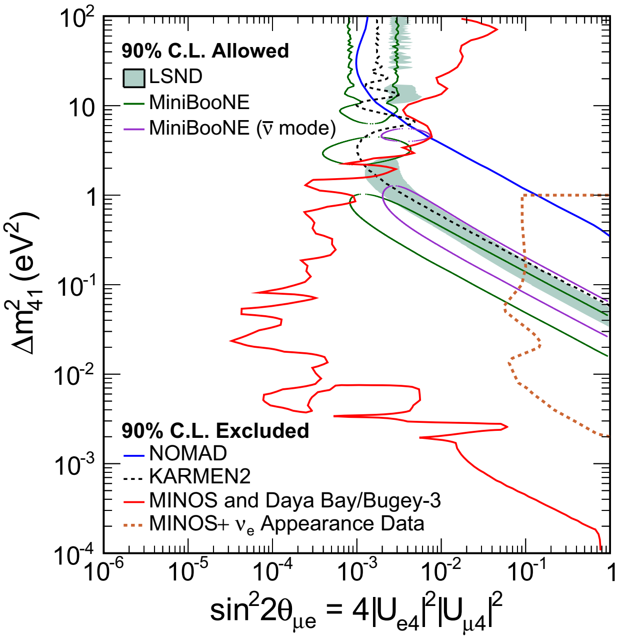

Figure 2. MINOS+ ν_e appearance exclusion limit at 90% C.L. in the $\sin^2 2\theta_{\mu e} - \Delta m^2_{41}$ phase space is compared to the LSND and MiniBooNE 90% C.L. allowed regions. The 90% C.L. exclusion limit by MINOS and Daya Bay/Bugey-3 combined [5], KARMEN2 [6] and NOMAD [7] are also shown. Regions of parameter space to the right of the exclusion contours are not allowed.

Likelihood surfaces spanning θ_{14} and θ_{24} are produced at various values of Δm^2_{41} to generate the 90% Confidence Level (C.L.) exclusion shown in Figure 2, where θ_{34}, δ_{13} and $\delta_{24} - \delta_{14}$ are profiled. Part of the LSND and MiniBooNE allowed regions are excluded by the present results at 90% confidence level.

This analysis complements MINOS disappearance result through a robust treatment of the 3+1 model parameters and offers immediate and independent comparison to LSND and MiniBooNE. The results presented here will be improved with two additional years of MINOS+ data.

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