New Observations in the MiniBooNE Experiment

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Abstract. The MiniBooNE neutrino oscillation search experiment at Fermilab has recently reported results from a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, using a data sample corresponding to 5.66×10^{20} protons on target in anti-neutrino mode. The experiment is now sensitive to the excess of $\bar{\nu}_\mu \to \bar{\nu}_e$ events observed by Los Alamos Liquid Scintillator Neutrino Detector (LSND). MiniBooNE data are consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the Δm^2 range of 0.1 to 1.0 eV^2 and with the evidence for antineutrino oscillations from LSND.

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INTRODUCTION

Motivated by the LSND observation of an excess of observed $\bar{\nu}_e$ events above background prediction in a $\bar{\nu}_\mu$ beam [1], the MiniBooNE experiment was designed to test the neutrino oscillation interpretation of the LSND signal in both neutrino and anti-neutrino modes. The MiniBooNE collaboration has performed a search for $\nu_\mu \to \nu_e$ oscillations with 6.486×10^{20} protons on target (POT), the results of which showed no evidence of an excess of ν_e events for neutrino energies above 475 MeV [2]. Despite having observed no evidence for oscillations above 475 MeV, the MiniBooNE $\nu_\mu \to \nu_e$ search observed an excess of 128.8±43.4 events at low energy, between 200-475 MeV [3]. Although the excess is incompatible with LSND-type oscillations within the simple two neutrino oscillation framework, several hypotheses, including sterile neutrino oscillations with CP violation, anomaly-mediated neutrino-photon coupling, and many others, have been proposed that provide a possible explanation for the excess itself [4]. In some cases, these theories offer the possibility of reconciling the MiniBooNE ν_e excess with the LSND $\bar{\nu}_e$ excess. A search in antineutrino mode provides a more direct test of the LSND signal, which was observed with antineutrinos. In this report I describe new results that the MiniBooNE collaboration published from a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, using a data sample corresponding to 5.66×10^{20} POT exposure.

NEW $\bar{\nu}_\mu \to \bar{\nu}_e$ RESULT

The analysis technique used here was already described [3, 5] and assumes only $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with no $\bar{\nu}_\mu$ disappearance and no ν_μ oscillations. The signature of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations is an excess of $\bar{\nu}_e$-induced charged-current quasi-elastic (CCQE) events.

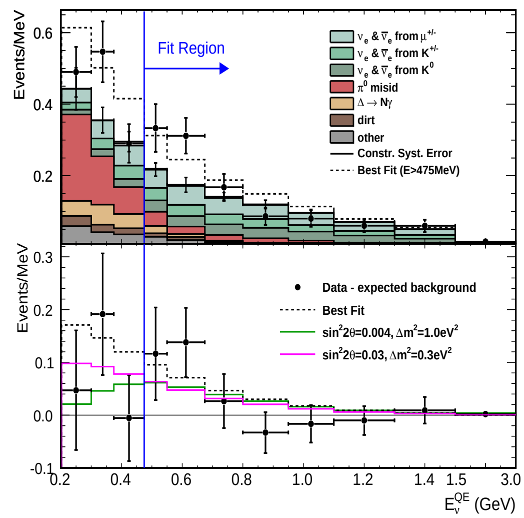

FIGURE 1. Top: Reconstructed E_ν distribution of $\bar{\nu}_e$ CCQE candidates in MiniBooNE anti-neutrino running. Bottom: The difference between the data and predicted backgrounds as a function of reconstructed neutrino energy. The error bars include both statistical and systematic components. Also shown in the figure are expectations from the best oscillation fit with $E_\nu > 475$ MeV, $(\Delta m^2, \sin^2 2\theta)$ = (0.064 eV^2, 0.96) where the fit is extrapolated below 475 MeV and from other neutrino oscillation parameter sets in the LSND allowed region.

A $\bar{\nu}_\mu/\nu_\mu$ sample is formed to constrain the $\bar{\nu}_e/\nu_e$ candidate events: the oscillation parameters are extracted from a combined fit to the $\bar{\nu}_e/\nu_e$ CCQE and $\bar{\nu}_\mu/\nu_\mu$ CCQE event distributions. Considering various sources of systematic uncertainty, a covariance matrix in bins of E_ν is constructed, which includes correlations between $\bar{\nu}_e/\nu_e$ CCQE (oscillation signal and background) and $\bar{\nu}_\mu/\nu_\mu$ CCQE samples. This covariance matrix is used in the χ^2 calculation of the oscillation fit parameters. The result is that the prediction is being constrained,

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i.e. tuned to the $\bar{\nu}_\mu/\nu_\mu$ data, and common systematic components in $\bar{\nu}_e/\nu_e$ and $\bar{\nu}_\mu/\nu_\mu$ CCQE samples cancel. The cancellation results from the fact that the majority of the events in both $\bar{\nu}_e/\nu_e$ and $\bar{\nu}_\mu/\nu_\mu$ CCQE samples originate from pure charged current interaction of neutrinos sharing same π decay chain at production, effectively sharing the same cross-section and beam systematic components. This procedure maximizes the sensitivity to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. The data show an excess of 43.2 ± 22.5 events: 277 electron-like events have been observed in $200 < E_\nu < 3000$ MeV reconstructed energy range, compared to an expectation of $233.8 \pm 15.3(stat) \pm 16.5(syst)$ events. Fig. 1 (top) shows the reconstructed E_ν distribution of observed $\bar{\nu}_e$ CCQE candidates and background expectation. In the energy range $475 < E_\nu < 1250$ MeV, the observed $\bar{\nu}_e$ events, when constrained by the $\bar{\nu}_\mu$ data events, have a $\chi^2/DF = 18.5/6$ and a probability of 0.5% for a background-only hypothesis. One may compare this to the 40% probability that is observed in neutrino mode [3] for the same energy range.

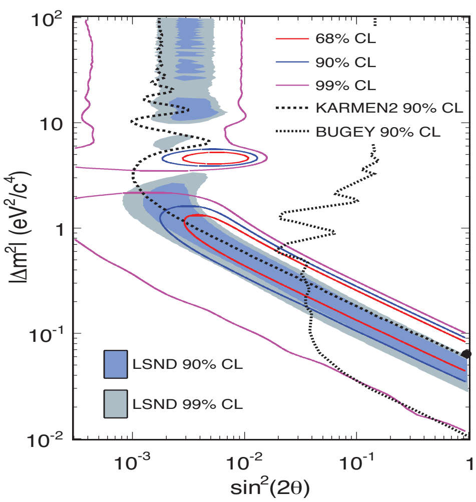

FIGURE 2. MiniBooNE 68%, 90%, and 99% C.L. allowed regions for events with $E_\nu > 475$ MeV within a two neutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation model. The shaded areas show the 90% and 99% C.L. LSND allowed regions. The black dot shows the best fit point.

Fig. 1 (bottom) shows the event excess as a function of E_ν. Using a likelihood-ratio technique, the best MiniBooNE oscillation fit for $475 < E_\nu < 3000$ MeV occurs at $(\Delta m^2, \sin^2 2\theta) = (0.064$ eV^2, $0.96)$. The energy range $E_\nu > 475$ MeV has been chosen for the fit as this is the energy range MiniBooNE used for searching for oscillations in neutrino mode. Also, this energy range avoids the region of the unexplained low-energy excess in neutrino mode [3]. The χ^2 for the best-fit point in the energy range of $475 < E_\nu < 1250$ MeV is 8.0 for 4 DF, corresponding to a χ^2-probability of 8.7%. The probability of the background-only fit relative to the best oscillation fit is 0.6%. Fig. 2 shows the MiniBooNE 68%, 90%, and 99% C.L. closed contours for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the $475 < E_\nu < 3000$ MeV energy range, where frequentist studies were performed to determine the C.L. regions. The allowed regions are in agreement with the LSND allowed region. With the oscillation fit region extended down to 200 MeV, the MiniBooNE closed contours for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations are similar [6].

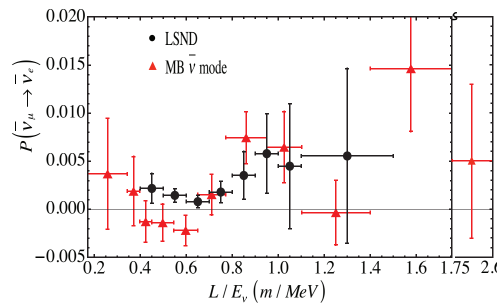

FIGURE 3. The oscillation probability as a function of L/E_ν for $\bar{\nu}_\mu \to \bar{\nu}_e$ candidate events from MiniBooNE and LSND. The data points include both statistical and systematic errors.

One may also inspect the oscillation probability as a function of L/E_ν for $\bar{\nu}_\mu \to \bar{\nu}_e$ candidate events, as a mean of comparison between the MiniBooNE and LSND antineutrino data sets. Fig. 3 shows the data used for LSND and MiniBooNE corresponding to $20 < E_\nu < 60$ MeV and $200 < E_\nu < 3000$ MeV, respectively. The oscillation probability is defined as the event excess divided by the number of events expected for the full $\bar{\nu}_\mu \to \bar{\nu}_e$ conversion, while L is the reconstructed distance travelled by the antineutrino from the mean neutrino production point to the interaction vertex and E_ν is the reconstructed antineutrino energy. The L/E_ν distributions for the two data sets are consistent.

In summary, the MiniBooNE experiment observes an excess of $\bar{\nu}_e$ events in the energy region above E_ν of 475 MeV for a data sample corresponding to 5.66×10^{20} POT. The allowed regions from the fit, shown in Fig. 2, are consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the 0.1 to 1 eV^2 Δm^2 range and consistent with the allowed region reported by the LSND experiment [1]. Additional running in antineutrino mode granted by the Fermilab PAC [7] is expected to significantly increase the current number of POT. In addition, several proposed short-baseline experiments [8] will be sensitive to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the 0.1 to 1 eV^2 Δm^2 range.

STATUS OF MINIBOONE NUMI RESULTS

Fermi National Accelerator Laboratory has two beam lines that produce neutrinos: the Booster Neutrino Beam (BNB) and the NuMI beam line. The BNB beam is designed for use by the MiniBooNE experiment. The NuMI beam produces neutrinos for the MINOS experiment and it will be supplying the NOνA experiment with neutrinos [9]. The MiniBooNE detector also observes neutrinos from the NuMI beamline, at an off-axis angle of 6.3 degrees. The first result of the analysis is already published [10]. Here we repeated the analysis with an updated beam Monte Carlo, used in MINOS [11] analysis and planned for use in NOνA. The result is shown in Figures 4 and 5. It shows that reliable predictions of the off-axis beam can be made. After the demonstration of the off-axis concept, the analysis is directed toward examing the low energy region and searching for oscillation. In this way it complements the analysis done at MiniBooNE using the BNB neutrino and anti-neutrino mode, but with different systematics. In addition, the current off-axis accelerator based long-baseline experiments, in particular the NOνA, would benefit from understanding and careful calibration of the off-axis beam components that may be extrapolated to NOνA 0.8^0 off-axis position. The analysis is in progress.

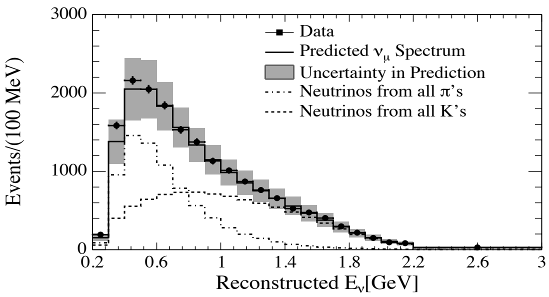

FIGURE 4. Reconstructed E_ν distribution of the NuMI off-axis ν_μ CCQE candidate events in MiniBooNE. The off-axis flux is separated into contributions from charged π and K parents. The error band indicate the total systematic uncertainty associated with the MC prediction.

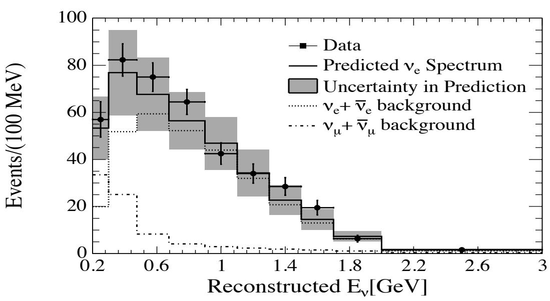

FIGURE 5. Reconstructed E_ν distribution of the NuMI off-axis ν_e CCQE candidate events in MiniBooNE. The prediction is separated into background contributions from ν_μ and ν_e neutrinos. The error band indicate the total systematic uncertainty associated with the MC prediction.

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