MiniBooNE's First Neutrino Oscillation Result

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Abstract.
The MiniBooNE Collaboration has performed a search for ν_e appearance in a ν_μ beam. No significant excess of events above background was observed in the analysis region. The data are consistent with no oscillation.

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INTRODUCTION

The discovery of neutrino flavour oscillation, and the associated discovery of neutrino mass, is the first confirmed observation not allowed by the Standard Model of particle physics. Although the Standard Model has been remarkably successful in describing the interactions of matter at low energies, we know it must break down at higher energies. The study of neutrino oscillation, which was first postulated in 1962 [1] but not conclusively observed until 2003 [2], promises to point the way toward the next theory beyond the Standard Model.

For two neutrinos, the probability for a neutrino created as an eigenstate of flavour *a* to later be observed as flavour *b* is given by:

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E}), \tag{1}$$

where the two mass states are m_1 and m_2, θ_{12} is the mixing angle, $\Delta m^2_{12} = m_1^2 - m_2^2$, L is the distance the neutrino has travelled in km and E is the neutrino energy in GeV.

To date, we have observed three distinct neutrino oscillation signals. Atmospheric ν_μ disappearance was first observed by the Super-Kamiokande experiment in 1998, indicating $\Delta m^2 \sim 10^{-3}\text{eV}^2$ [3] with maximal mixing betwenthe states. Oscillation on this scale was confirmed with long-baseline accelerator beams of neutrinos [4, 5]. Neutrinos from the sun were found to oscillate with a large mixing angle and $\Delta m^2 \sim 10^{-5}\text{eV}^2$ [6]. Flavour oscillation at this mass scale was also observed with reactor neutrinos [2]. The third indication of neutrino oscillation comes a from short baseline accelerator neutrino beam experiment, LSND [7], which saw an excess of $\overline{\nu}_e$ in a $\overline{\nu}_\mu$ beam with $\Delta m^2 \sim \text{eV}^2$. The LSND oscillation probability is extremely small, 0.26%.

The LSND signal was interpreted in the context of a simple two neutrino oscillation, which is justified because the mass scale is clearly independent from the other two mass scales. Other experiments, notably KARMEN and BUGEY, were sensitive to oscillation in the LSND allowed mass region but with lower sensitivities; their lack of oscillation signals are thus not able to completely rule out the LSND oscillation hypothesis.

Because $\Delta m^2_{LSND} >> \Delta m^2_{atmos} + \Delta m^2_{solar}$, the confirmation of LSND would require at least one more neutrino mass state. The spectacular implications of additional neutrino states made it imperative that the LSND result be checked. MiniBooNE was designed to do exactly that.

MINIBOONE DESCRIPTION

MiniBooNE creates a ν_μ beam at Fermilab which travels 541 m to the MiniBooNE detector. The neutrino beam is comprised of 95% ν_μ, 4.4% $\overline{\nu}_\mu$, 0.6% ν_e and trace amounts of $\overline{\nu}_e$, and has a mean energy of 0.8 GeV. The beamline can also be run in a configuration which produces a beam of antineutrinos. The detector is a 610 cm radius steel sphere filled with $\sim$ 800 tonnes of pure mineral oil. The detector is divided into two regions: a sperical shell *veto* region, 35 cm thick, surrounds the optically isolated *main* detector volume which contains the $\sim$510 cm fiducial volume. Charged particles from the neutrino interactions in the detector cause emission of Cherenkov and scintillation light in the oil, which is detected by 8" photomultiplier tubes (PMTs). The PMT hit patterns are used to reconstruct the particle tracks under the hypotheses that they were created by an e, μ, or two γs from neutral pion decay. Likelihood ratios from these three hypotheses are used to distinguish the ν_e candidate events from the more numerous ν_μ events.

MiniBooNE collected data from February 2002 until January 2005. In total 5.58×10^{20} protons on target (POT) were collected for the neutrino oscillation analysis, yielding 1.7 million neutrino interactions in the detector.

ν_e APPEARANCE SEARCH

The MiniBooNE oscillation search [11] had two aspects: a counting experiment for ν_e appearance in a ν_μ beam and an energy fit for simple two-neutrino appearance-only oscillation. Because the experiment used only one neutrino detector, many consistency checks were applied to the Monte Carlo prediction of the signal and background rates using calibration and neutrino data samples. Systematic uncertainties from neutrino beam prodcution, neutrino interactions in the detector, and the detector modelling were considered. The experiment employed a "closed-box" blind analysis. Before unblinding the data set, the energy limits on the analysis region for the counting experiment and energy fit were set at 475 MeV and 1250 MeV because they maximised the sensitivity of the ν_e appearance search.

If the LSND oscillation hypothesis were correct, MiniBooNE would expect $\sim$163$\pm$21 ν_e events after all analysis cuts. These would appear above a background of 358$\pm$35$\pm$19: 229 from intrinsic ν_es in the beam and 129 from misidentified ν_μ events.

The observed ν_e events are shown as a function of neutrino energy in Figure 1, along with the predicted backgrounda and two representative signals allowed by the LSND result. In the analysis region, 380 ν_e events were observed, yielding an excess of 22$\pm$19$\pm$35 events and a significance of excess of 0.55 σ. The energy fit yielded no significant evidence for $\nu_\mu \rightarrow \nu_e$ oscillation in a simple two-neutrino context. Figure 2

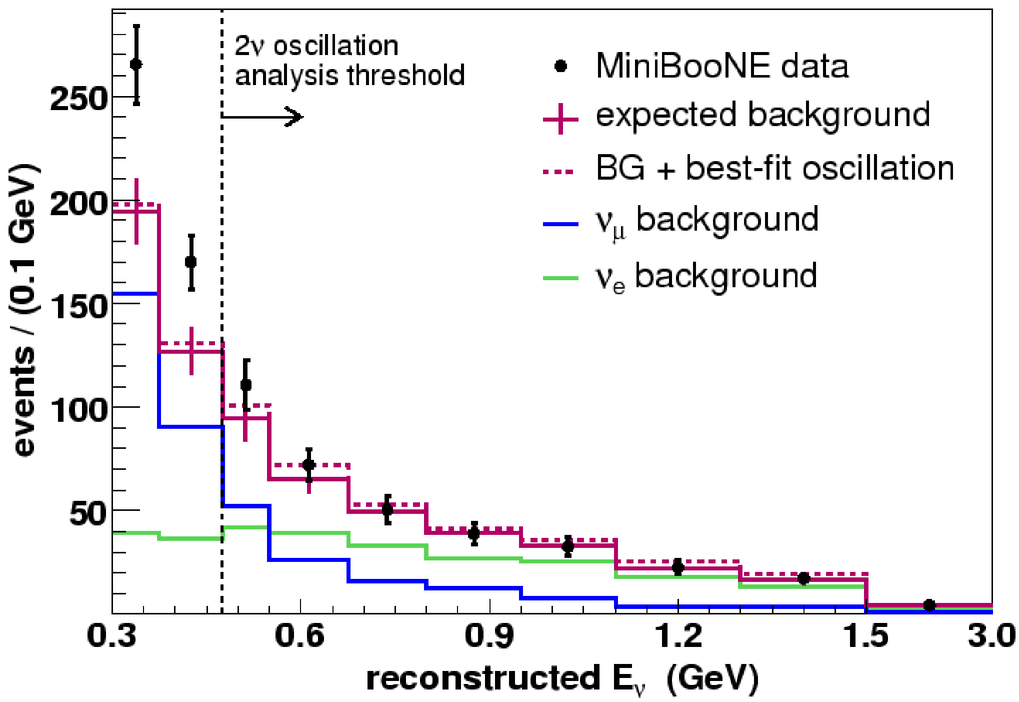

FIGURE 1. The number of candidate ν_e events as a function of neutrino energy . The points represent the data with statistical error, while the histogram is the expected background with systematic errors from all sources. The vertical dashed line indicates the threshold used in the two-neutrino oscillation analysis. Also shown are the best-fit oscillation spectrum (dashed histogram) and the background contributions from ν_μ and ν_e events.

shows the MiniBooNE 90% confidence level (CL) limit curve, which completely covers the LSND 90% CL allowed region. Assuming that neutrinos and antineutrinos oscillate with the same probability, this limit excludes two neutrino appearance-only oscillation as an explanation of the LSND anomaly at 98% CL.

Below 475 MeV, an excess of 96±17±20 ν_e events was observed. While this excess is intriguing, the shape of the excess as a function of energy is not consistent with a two-neutrino appearance signal; this is illustrated in Figure 1. The source of these events is currently under intense investigation.

CONCLUSIONS

Despite the presently unexplained excess of events at low energy, there is excellent agreement between data and Monte Carlo in the oscillation analysis region. If neutrinos and antineutrinos undergo oscillation in the same way, MiniBooNE excludes two neutrino appearance-only oscillation as an explanation of the LSND anomaly at 98%

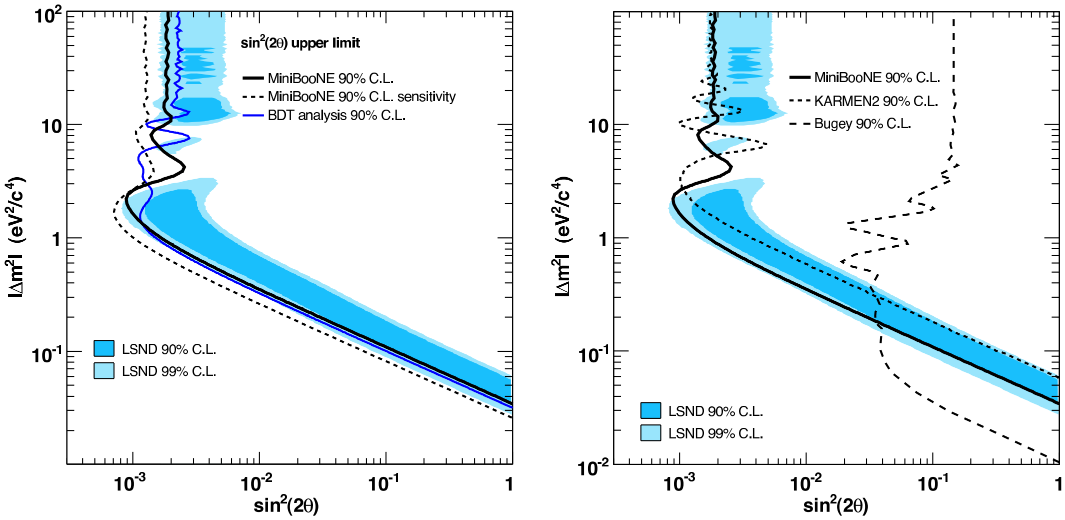

FIGURE 2. The left panel shows the MiniBooNE limit (thick solid curve) and sensitivity (dashed curve) for events in the analysis region within a two neutrino oscillation model. Also shown is the limit from the cross-check analysis (thin solid curve). The right panel compares the MiniBooNE limit with the limits from the KARMEN and Bugey experiments.

CL. MiniBooNE is currently taking data with the beam in antineutrino configuration.

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