FERMILAB-CONF-11-524-E

Improved statistics in the search for $\bar{\nu}_e$ appearing in an $\bar{\nu}_\mu$ beam in the MiniBooNE detector

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The MiniBooNE experiment at Fermi National Accelerator Laboratory recently updated a search for $\bar{\nu}_e$ appearing in an $\bar{\nu}_\mu$ beam to include higher statistics. Previous results were published with a total of 3.39×10^{20} protons on target (POT) [1], while these results have been expanded to include a total of 5.66×10^{20} POT [2]. An excess of 20.9 ± 14.0 events is observed in the energy range from $475 < E_\nu^{QE} < 1250$ MeV, with the statistical significance of the excess peaking at 25.7 ± 7.2 in the lowest two energy bins $475 - 675 MeV$. The consistency with the background-only hypothesis in the $475-1250$ MeV region is 0.5%, after constraints from the measured $\bar{\nu}_\mu$ spectrum have been applied. A fit to a 2ν-mixing hypothesis yields a best-fit point at $(\Delta m^2, \sin^2 2\theta) = (0.064\text{eV}^2, 0.96)$, although the 1σ allowed region encompasses a range of Δm^2 values up to 1eV^2 at reduced values of $\sin^2 2\theta$. After Feldman-Cousins corrections [3], it is found that the best-fit is preferred at a 99.4% C.L. over a background-only hypothesis, with an absolute goodness-of-fit of 8.7%

1. Background Information

The MiniBooNE experiment was constructed to explore short-baseline (anti) neutrino oscillations at an $L[\text{m}]/E[\text{MeV}] \sim 1$. The LSND experiment previously explored this region of parameter space with an $\bar{\nu}_\mu$ beam produced from a stopped pion source, and found a 3.8σ excess of $\bar{\nu}_e$ candidates [4]. Prior to MiniBooNE, several other experiments [5,6] were able to rule out portions of the LSND allowed region, but none had the sensitivity to exclude the entire parameter space.

Prior to the results presented here, MiniBooNE has published several oscillation results. Due to the higher flux and cross-section, the experiment started out probing $\nu_\mu \to \nu_e$ oscillations [7]. The final analysis, based on 5.46×10^{20} POT with a neutrino beam, found no evidence for ν_e signal candidates for $E_\nu^{QE} > 475$ MeV. In fact, the data in this region were found to be consistent with the background hypothesis at a 40% compatibility. At lower energies, $200 < E_\nu^{QE} < 475$ MeV, a 3.0σ excess was observed that remains unexplained [8]. Initial results from a lower statistics search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations were previously reported [1], but were found to be inconclusive with respect to LSND's preferred region of $(\Delta m^2, \sin^2 2\theta)$.

2. Experiment and Analysis Overview

The MiniBooNE experiment impacts 8GeV/c protons from the Fermilab Booster onto a Be target at the center of a 174 kA pulsed, electromagnetic horn. A secondary meson beam consisting primarily of pions with a small kaon component, is allowed to decay in a 50 m decay tunnel. The meson production is determined via a dedicated measurement by the HARP collaboration [9], along with some E910 data [10]. Details of the MiniBooNE (anti) neutrino flux prediction may be found elsewhere [12].

The MiniBooNE detector is a 12 m diameter, spherical tank filled with pure mineral oil (CH_2). The tank is divided optically into an outer veto region with a 35 cm thickness and 240 back-to-back 8" photomultiplier tubes (PMTs), and an inner region with 1280 equally-spaced, inward-facing 8" PMTs that provide $\sim 10\%$ photocathode coverage. Details of the detector may be found here [13].

Neutrino interactions are ($\sim 60\%$) quasi-elastic or elastic, with a large number of events ($\sim 35\%$) containing a single pion in the final state. Higher-multiplicity events, multi-pion and DIS, make up $< 5\%$ of the data sample. The v3 NUANCE [14]

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

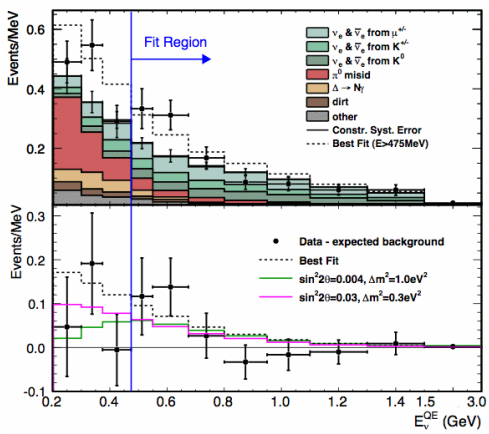

Figure 1. Predicted event backgrounds, data, and signal corresponding to the best-fit for $E_\nu^{QE} >$ 475 MeV (above). Event excess plotted relative to best-fit and point two other oscillation scenarios within the LSND/MB allowed regions.

event generator with some modifications [15–19] is used to predict the various (anti) neutrino cross-sections.

All pre-cuts used to select the $\bar{\nu}_e$ signal sample are the same as detailed in the final $\nu_\mu \rightarrow \nu_e$ analysis [8]. Reconstruction is based on fitting events under three hypotheses, that the Cerenkov light observed is due to a single electron, muon, or π^0 propagating in the detector. Details of the reconstruction may be found elsewhere [20].

One complication specific to the anti-neutrino beam in MiniBooNE is the presence of a large wrong-sign (WS) background of ν_μ in the beam. An internal constraint on WS component has been obtained using two methods. The first method compares data to simulated event rates in a high purity ν_μ induced charged-current single π^+ sample while the second exploits the difference between the angular distributions of muons created in ν_μ and $\bar{\nu}_\mu$ charged-current quasi-elastic (CCQE) interactions. The WS component was found to be overestimated by about 30% relative to the native Monte Carlo prediction [21].

3. Results and Outlook

Data for the ν_e signal candidates for the full 5.66×10^{20} POT sample are shown in Figure 1,

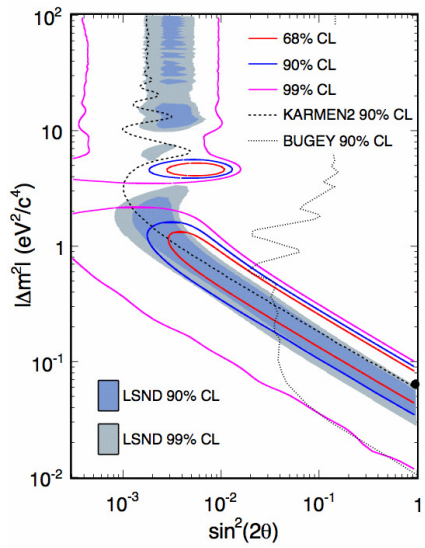

Figure 2. Limits obtained from a fit to a 2ν hypothesis where only $\bar{\nu}_\mu$ are assumed to oscillate. Limits from the Bugey and Karmen2 experiments are shown along with the LSND allowed regions.

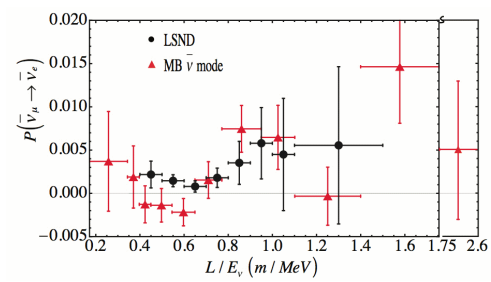

Figure 3. Oscillation probabilities as a function of L/E_ν inferred from the MiniBooNE anti-neutrino result and compared to LSND.

along with the background predictions. A small excess of 18.5 ± 14.3 is observed in the $200 < E_\nu^{QE} < 475$ MeV region. By comparison, if the low-energy excess observed in the $\nu_\mu \rightarrow \nu_e$ search were naively extrapolated (same cross-section) for all ν_μ and $\bar{\nu}_\mu$ events in the same energy range, then an excess of 67 events would have been expected. On the other hand if only the ν_μ component is responsible for the low-energy excess, then 11.6 excess events would be expected. Due to the uncertainty in the source, fits for the oscillation parameters are confined to the $E_\nu^{QE} > 475$ MeV range.

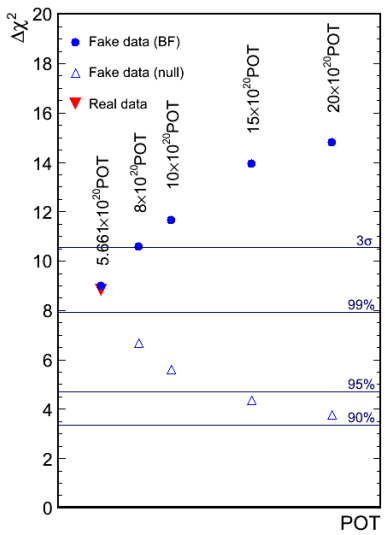

Figure 4. Projection of how strongly the null hypothesis will be excluded with additional data beyond 5.66×10^{20}, assuming the data is drawn from the current best-fit point (circles) versus background-only draws (open triangles).

The results of a fit to a 2ν mixing hypothesis in the region of $E_\nu^{QE} > 475$ MeV are shown in Figure 2. The allowed region of $(\Delta m^2, \sin^2 2\theta)$ parameter space is consistent with LSND, and the best-fit is preferred over the null hypothesis at the 99.4% CL. The overall fit quality after accounting for two fit parameters has a probability of 8.7%. The signal prediction at the best-fit point is shown in Figure 1 overlaid with the data and a couple of other oscillation hypotheses that are contained in the MiniBooNE/LSND allowed regions. A more model-independent comparison to LSND is plotted in Figure 3 where the inferred oscillation probability for both experiments has been plotted as a function of L/E_ν.

The MiniBooNE experiment continues to take data with an anti-neutrino beam and a total of $10-11 \times 10^{20}$ POT is expected by the long laboratory shutdown scheduled to begin in March 2012. An extrapolation of how strongly the null point will be excluded is shown in Figure 4. The extrapolation assumes the additional data is either drawn from the background only or has had signal corresponding to the current best-fit point added.

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