MiniBooNE Oscillation Results and Implications

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Abstract. The MiniBooNE Collaboration has reported first results of a search for ν_e appearance in a ν_μ beam. With two largely independent analyses, no significant excess was observed of events above background for reconstructed neutrino energies above 475 MeV and the data are consistent with no oscillations within a two neutrino appearance-only oscillation model. An excess of events ($186 \pm 27 \pm 33$ events) is observed below the 475 MeV oscillation search cut. This low-energy excess cannot be explained by a two-neutrino oscillation model. This report presents an overview of the MiniBooNE first result and decribes some initial cross checks and investigations associated with the low energy excess.

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1. Introduction

MiniBooNE was motivated by the result from the Liquid Scintillator Neutrino Detector (LSND) experiment [1], which has presented evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at the $\Delta m^2 \sim 1$ eV^2 scale. LSND observed an approximate 3.8 σ excess of electron antineutrinos which would correspond to a $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probability of 0.26 ± 0.08 %. When combined with the positive solar and atmospheric oscillation observations, LSND would require for explanation the addition of one or more sterile neutrinos[2] or further extensions of the Standard Model (*e.g.,* Lorentz Violations[3]). The MiniBooNE experiment is designed to have the same "L/E" as LSND but at higher neutrino energy in order to probe neutrino oscillations with similar oscillation parameter sensitivity but with different systematic uncertainties. The initial MiniBooNE oscillation analysis is performed within a two neutrino appearance-only $\nu_\mu \to \nu_e$ oscillation model where the ν_μ events are used to constrain the predicted ν_e rate. Other than oscillations between these two species, no effects beyond the Standard Model are assumed.

2. The MiniBooNE Experiment

The MiniBooNE experiment was proposed in the summer of 1997 and has been operating since 2002. The experiment uses the Fermilab Booster neutrino beam where 8 GeV protons (typically, 4×10^{12} protons within a ~ 1.6 μs beam spill at a rate of 4 Hz) are incident on a 71 cm long beryllium target which is inside a toroidal magnetic focusing horn. Positively charged pion and kaons are focused into a 50 m long decay region which is 91 cm in radius (See Fig. 1). The data used in the first oscillation result corresponds to 5.579×10^{20} protons on target. The main flux of neutrinos is from pion and kaon decay to muon neutrinos but there is also an intrinsic component of electron neutrino flux from kaon and muon decay with a flux ratio of $\nu_e/\nu_\mu \approx 0.5\%$. Neutrino interactions in the data sample are mostly charged-current quasi-elastic

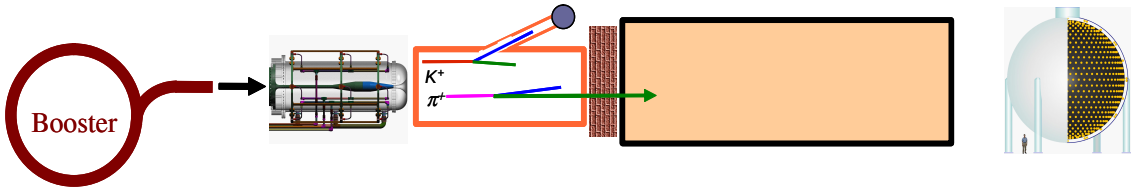

Figure 1. Schematic layout (not to scale) of the MiniBooNE beamline and detector. Protons from the 8 GeV Fermilab booster are directed onto a Be target inside a magnetic focusing horn. Pion and kaons are focused into a 50 m decay region that ends in a steel beam dump. The MiniBooNE neutrino detector is then located after $\sim$ 500 m of dirt shielding.

(CCQE) scattering (39%), neutral-current (NC) elastic scattering (16%), charged-current (CC) single pion production (29%), and NC single pion production (12%).

The MiniBooNE neutrino detector is located 541 m downstream of the beryllium target and 1.9 m above the center of the beam line. The detector is a spherical tank of inner radius 610 cm and filled with 800 tons of pure mineral oil (CH_2) with a density of 0.86 g/cm^3 and an index of refraction of 1.47. Charged particles produce both prompt directional Cherenkov light and longer time constant isotropic scintillation light in a ratio of about 3 to 1 for $\beta \approx 1$ particles. The detector consists of an inner spherical target region of radius 575 cm with 1280 equally-spaced inward-facing 8-inch phototubes (PMT) providing a 10% photocathode coverage; there is also an optically isolated outer veto shield region 35 cm thick with 240 8-inch phototubes. The detector has been designed to detect and measure neutrino events in the energy range from 100 MeV to a few GeV. The system is used to determine the event vertex, outgoing particle angles, and incident neutrino energy as well as separate electron neutrino from muon neutrino induced events.

3. Data Analysis

In the analysis of the data, PMT charge and time information in the 19.2 μs beam window is used to reconstruct neutrino interactions and identify the product particles. The reconstruction uses a detailed model of extended-track light production and propagation in the tank to predict the charge and time of hits in each PMT. Event parameters are varied to maximize the likelihood of the observed hits, yielding the vertex position and time of the event and the direction, energy, and, for photons, the conversion distance of the Cherenkov ring(s). For ν_e events, the event vertex, direction, and energy are reconstructed on average with resolutions of 22 cm, 2.8°, and 11%, respectively, while NC π^0 events are reconstructed with a π^0 mass resolution of 20 MeV/c^2.

The energy calibration for observed muon and electron tracks is accomplished over an energy range from 50 to 1000 MeV using a combination of techniques including muon-decay electrons, gammas from π^0 decay, and stopping and through-going cosmic ray muons. The E_ν^{QE} resolution is about 10% at 800 MeV for both muon and electron neutrino events.

Within the beam window, the data is divided into "subevents", collections of PMT hits clustered in time within $\sim$100 ns. Electron neutrino candidates are selected by requiring one subevent (as expected for ν_e CCQE events) with fewer than 6 hits in the veto and more than 200 hits in the main tank (above the muon-decay electron endpoint). This very effectively removes entering cosmic-ray muons and their associated decay electrons

The types of outgoing particles can be identified by their time structure and hit patterns. Muons have a sharp outer Cherenkov ring that is filled in by the muon travel distance, NC π^0 events have two Cherenkov rings, and signal electrons have one ring that is not sharp due to multiple scattering and the electromagnetic shower process. Thus, the PMT hit patterns can be

used to identify candidate electron neutrino events.

The final analysis cuts are designed to isolate a sample of ν_e-induced events that are primarily CCQE. Two particle identification algorithms were used for the analysis; one, a likelihood based analysis, is the baseline for the first result and the other a "boosted decision tree" (BDT)[4][5] method is used as a secondary complementary analysis.

For the likelihood based particle identification analysis, the PMT hit patterns in the events are reconstructed under four hypotheses: a single electron-like Cherenkov ring, a single muon-like ring, two photon-like rings with unconstrained kinematics, and two photon-like rings with $M_{\gamma\gamma} = m_{\pi^0}$. To identify ν_e events and reject muon and π^0 events, E_{vis}-dependent cuts are applied on $\log(L_e/L_\mu)$, $\log(L_e/L_{\pi^0})$, and $M_{\gamma\gamma}$, where L_e, L_μ, and L_{π^0} are the likelihoods for each event maximized under the muon 1-ring, electron 1-ring, and fixed-mass 2-ring fits, and $M_{\gamma\gamma}$ is from the unconstrained two-ring fit.

The BDT reconstruction uses a simpler model of light emission and propagation. The particle identification uses 172 quantities such as charge and time likelihoods in angular bins, $M_{\gamma\gamma}$, and likelihood ratios (electron/ pion and electron/muon) as inputs to boosted decision tree algorithms [4] that are trained on sets of simulated signal events and background events with a cascade-training technique [5].

4. Oscillation Analysis

An oscillation signal in MiniBooNE would correspond to an excess of candidate electron neutrino events over expectation. Understanding the expected events is therefore the key to the oscillation search and the uncertainties in this expectation is a dominant factor in determining the sensitivity of the experiment. The primary uncertainties are associated with the ν fluxes, the ν cross sections, the modeling of the detection and identification efficiencies, and the rates of misidentifications. One needs to know the neutrino fluxes including the intrinsic ν_e flux from μ, K^+, and K^0 decay as well as the ν_μ flux which sets the scale of the signal and various misidentification backgrounds. These fluxes are used in conjunction with the neutrino cross sections and the detector simulation to predict the various types of event samples in the data. For MiniBooNE, the primary backgrounds to an oscillation ν_e signal are the intrinsic ν_e events along with misidentified neutral current ν_μ produced π^0, radiative $\Delta \to N\gamma$, and externally produced γ events. All of the important backgrounds can be directly constrained in both normalization and spectrum from observed non-background events in MiniBooNE; this procedure significantly reduces most of the systematic uncertainties.

The estimated number of background events with reconstructed neutrino energy, E_ν^{QE}, between 475 MeV and 1250 MeV after the complete event selection cuts is 358 ± 35. (The reconstructed energy, E_ν^{QE}, is determined from the reconstructed lepton energy and angle with respect to the known neutrino direction.) For comparison, the estimated number of ν_e CCQE signal events is 163 ± 21 for the LSND central expectation of 0.26% $\nu_\mu \to \nu_e$ transmutation. Studies of random triggers have established that no significant backgrounds survive the analysis cuts other than those due to beam related neutrinos (both ν and $\bar{\nu}$), which can be divided into either ν_μ-induced or ν_e-induced backgrounds. The small fraction of ν_e from μ, K, and π decay in the beamline gives a background that is indistinguishable from oscillations except for the energy spectrum. CC ν_μ events are distinguished from ν_e events by the distinct patterns of Cherenkov and scintillation light for muons and electrons, as well as by the observation of a delayed electron from the muon decay. NC π^0 events with only a single electromagnetic shower reconstructed are the main ν_μ-induced background, followed by radiative Δ decays giving a single photon, and then neutrino interactions in the dirt surrounding the detector, which can mimic a signal if a single photon penetrates the veto and converts in the fiducial volume.

The largest misidentification background is from NC π^0 production ($\nu_\mu + N \to \nu_\mu + N + \pi^0$) where one of the decay photons is undetected. For most of these events, both gammas from

the π^0 decay are detected. One can use these detected π^0 events to measure the production rate in bins of π^0 momentum. The Monte Carlo is used to correct the production rate for inefficiency, backgrounds, and resolution. The measured rate is then used to reweight the Monte Carlo and, thus, constrain the misidentified NC π^0 background. In a similar way, the background from gammas entering from outside the detector, "dirt" background, can be constrained from the sample of inward-pointing events at high radius that have a large component of this background.

The MiniBooNE oscillation analysis uses the combined information from both candidate ν_e and ν_μ events. Systematic and statistical uncertainties are included using a fully correlated covariance matrix in E_ν^{QE} bins. The systematic uncertainties come from the analyses of both MiniBooNE and external data. The neutrino flux systematic errors are determined from the uncertainties of particle production measurements, the detector model systematic errors are mostly determined from fits to MiniBooNE data, and the neutrino cross section systematic errors are determined from MiniBooNE data as well as from external sources, both experimental and theoretical. The uncertainties are propagated using the detector simulation Monte Carlo into a covariance matrix in terms of E_ν^{QE} for each group of systematic errors. These matrices are then summed including the statistical errors to form the final uncertainty covariance matrix. This matrix is used for perform a χ^2 fit of the observed data to a Monte Carlo prediction including backgrounds and possible oscillation signals in order to set limits and confidence intervals.

5. First MiniBooNE Oscillation Result

MiniBooNE presented the first oscillation result in April, 2007.[6] The MiniBooNE analysis used a signal-blind analysis technique where candidate ν_e events ($\sim$ 5000) with conservative requirements were sequestered until the reconstruction software and analysis cuts were finalized; all other events (at the few 100,000 level) were available for examination and testing. After the analysis cuts were set and signal-blind tests of the data to MC agreement were performed, an oscillation analysis was performed in the $475 < E_\nu^{QE} < 1250$ MeV energy region. For the likelihood based analysis, $380 \pm 19(stat)$ data events were observed as compared to the no oscillation prediction of $358 \pm 35(syst)$ events; this agreement implies that there is no indication of an oscillation signal in the MiniBooNE data. The best fit oscillation parameters are $\left(\Delta m^2, \sin^2 2\theta\right) = (4.0\ \mathrm{eV}^2, 0.001)$ with a 99% probability as compared to a null oscillation hypothesis probability of 93%.

Fig. 2 shows candidate ν_e events as a function of E_ν^{QE}. The vertical dashed line indicates the minimum E_ν^{QE} used in the two-neutrino oscillation analysis. There is no significant excess of events ($22 \pm 19(stat) \pm 35(syst)$ events) for $475 < E_\nu^{QE} < 1250$ MeV; however, an excess of events ($186 \pm 27(stat) \pm 33(syst)$ events is observed below 475 MeV. This low-energy excess cannot be explained by a two-neutrino oscillation model; its source is under investigation and will be discussed more below .

A single-sided raster scan to a two neutrino appearance-only oscillation model is used in the energy range $475 < E_\nu^{QE} < 3000$ MeV to find the 90% CL limit corresponding to $\Delta\chi^2 = \chi^2_{limit} - \chi^2_{bestfit} = 1.64$. As shown in Fig. 3, the LSND 90% CL allowed region is excluded at the 90% CL. The plot also shows the results from the BDT analysis which has similar sensitivity. The two analyses are very complementary, with the BDT analysis having a better signal-to-background ratio, and the likelihood analysis having less sensitivity to systematic errors from detector properties.

6. Going Beyond the First Result

Investigations of the low energy excess are focusing on a broad range of possibilities from detector reconstruction issues to incorrect or new sources of background. Several new physics possibilities have also been proposed. Any explanation that involves extra backgrounds or signal sources could have important consequences for future oscillation experiments such at T2K or Nova. All

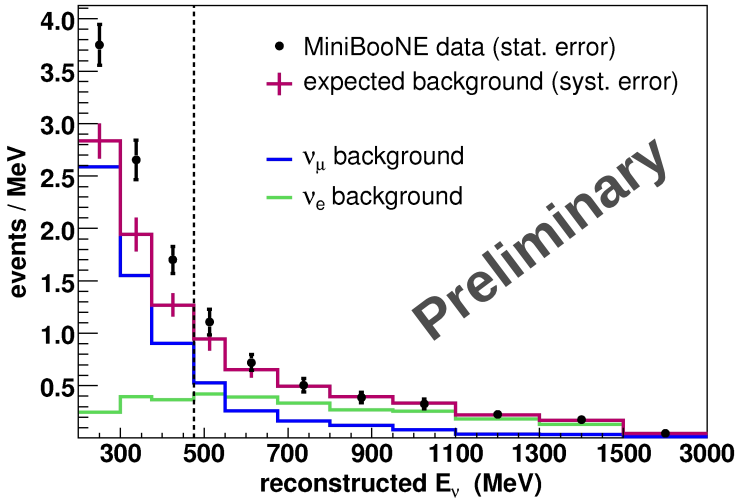

Figure 2. The number of candidate ν_e events as a function of E_ν^{QE}. The points represent the data with statistical error, while the histogram is the expected background with systematic errors from all sources. The vertical dashed line indicates the threshold used in the two-neutrino oscillation analysis. Also shown are the background contributions from ν_μ and ν_e induced events.

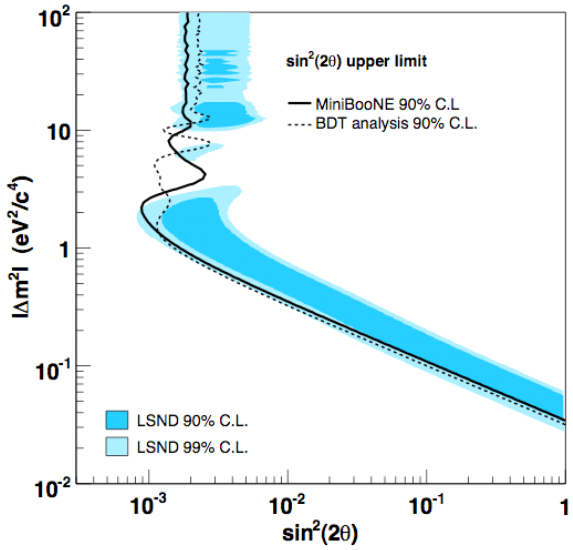

Figure 3. The MiniBooNE 90% CL limit (thick solid curve) from the TBT analysis for events with $475 < E_\nu^{QE} < 3000$ MeV within a two neutrino oscillation model. Also shown is the limit from the boosted decision tree analysis (dashed curve) for events with $300 < E_\nu^{QE} < 3000$ MeV. The shaded areas show the 90% and 99% CL allowed regions from the LSND experiment.

$\mathbf{E}_\nu^{QE}$ (MeV)	$200-300$	$300-475$	$475-1250$
Total Background	284 ± 25	274 ± 21	358 ± 35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^0	115	76	62
NC $\Delta \to N\gamma$	20	51	20
Dirt	99	50	17
other	24	30	30
Data	375 ± 19	369 ± 19	380 ± 19
Data - Background	91 ± 31	95 ± 28	22 ± 40

Table 1. Preliminary results for the predicted background and observed data event numbers in three E_ν^{QE} bins. The total background is broken down into the intinsic ν_e and ν_μ induced components and the ν_μ induced background is further broken down into its separate components. The indicated uncertainties are systematic for the total background, statistical for the data, and a quadrature combination for the data to Monte Carlo difference.

of the low energy candidate ν_e events have be visually scanned using computer event displays and have been found to be consistent with single-ring, electromagnetic-like events. MiniBooNE cannot distinguish outgoing electrons or photons so the low energy events could be of either type.

A significant excess is seen in all three bins below 475 MeV as shown in Fig. 2. Table 1 lists the event numbers in three E_ν^{QE} bins with the background separated into its various components. For the bin corresponding to the oscillation analysis, the main background is intrinsic ν_e events from muon and kaon decay. In contrast, the ν_e background becomes less important in the lower energy bins where ν_μ induced backgrounds from NC π^0 and Δ decay along with "Dirt" become more important. As described above, MiniBooNE constrains these low energy backgrounds using observed events so enhancements of these backgrounds to explain the excess would contradict these observations. On the other hand, these constraints do have systematic and statistical uncertainties which are quantified in the errors presented in Table 1.

Investigation of possible processes that might be improperly modeled or missing in the simulations is another possible change to the predicted background. Since MiniBooNE cannot tell the difference between a single outgoing electron or single outgoing gamma, the background or observed excess could be either. MiniBooNE has been investigating photonuclear processes that are not included in the current simulation. This process could absorb one of the gammas in a NC π^0 event giving a single gamma background. Initial estimates are at the 10-20% level in the two lowest energy bins and work is progressing on more refined calculations. Recently, another standard model process, anomaly-mediated,single-photon production by neutrinos, has been proposed by Harvey, Hill, and Hill[7] as a possible source of low energy events. This process has never been observed and the MiniBooNE excess could possibly be the first observation if the rates and kinematic distributions are shown to be consistent.

Several new physics interpretations of the excess have also been put forward in recent papers. Models with oscillations to sterile neutrinos have been considered (3+1 or 3+2)[8] but these models have trouble describing both the appearance and disappearance oscillation data. Prior to MiniBooNE's first result, it was proposed[9] that sterile neutrinos could take shortcuts in extra dimensions leading to $\nu_\mu \to \nu_e$ oscillations in MiniBooNE mainly at low energy. This model is currently being investigated with respect to the low energy excess. As indicated previously, Lorentz invariance violation[3] might lead to new phenomenology where the oscillation depends on $E \times L$ or possibly on the sidereal time.

Experimentally, new information related to the MiniBooNE excess should become available in the near future. MiniBooNE will run with antineutrinos during the next several years which will give new measurements of possible oscillations and checks on the systematic uncertainties. The SciBooNE detector is now taking data in the MiniBooNE beamline and will provide a cross check of electron neutrinos from kaon decay and be a near detector for a two-detector disappearance measurement. MiniBooNE also sees offaxis neutrinos from the NuMI/MINOS beam These events will provide an important cross check for the low energy excess since the energy and distance is similar to the Fermilab booster neutrino beam. In addition, the NuMI events are very different in background composition being dominated by ν_e backgrounds in the low energy region. Recently, a new experiment, MicroBooNE[10], has been proposed to put a 70 ton Liquid Argon detector near MiniBooNE to search for the low energy events with a fine-grained detection medium. This detector will have high ν_e efficiency, will be able to separate electron from gamma events, and be nearly free of backgrounds from misidentified particles. If the MiniBooNE low-energy excess is due to a new source of ν_e events, MicroBooNE would see a corresponding excess of 53 ± 9 events and establish a signal at the 9 σ level.

In summary, MiniBooNE has ruled out the LSND result interpreted as two neutrino $\nu_\mu \rightarrow \nu_e$ oscillations described by the standard L/E dependence. At low energies outside of the oscillation search region, MiniBooNE observes an excess of ν_e events; studies are currently underway to determine if these events are from unexpected backgrounds or possibly an indication of a new physics source.

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[1] C. Athanassopoulos *et al.*, Phys. Rev. Lett. 75, 2650 (1995); C. Athanassopoulos *et al.*, Phys. Rev. Lett. 77, 3082 (1996); C. Athanassopoulos *et al.*, Phys. Rev. Lett. 81, 1774 (1998); A. Aguilar *et al.*, Phys. Rev. D 64, 112007 (2001).
[2] M. Sorel, J. M. Conrad, and M. H. Shaevitz, Phys. Rev. D 70, 073004 (2004).
[3] T. Katori, A. Kostelecky and R. Tayloe, Phys. Rev. D 74, 105009 (2006).
[4] B. P. Roe *et al.*, Nucl. Instrum. Meth. A543, 577 (2005); H. J. Yang, B. P. Roe, and J. Zhu, Nucl. Instrum. Meth. A555, 370 (2005); H. J. Yang, B. P. Roe, and J. Zhu, Nucl. Instrum. Meth. A574, 342 (2007).
[5] Y. Liu and I. Stancu, Nucl.Instrum.Meth.A578:315-321,2007, arXiv:Physics/0611267.
[6] A. Aguilar *et al.*, Phys.Rev.Lett.98:231801,2007, arXiv:0704.1500 [hep-ex]
[7] J. Harvey, C. Hill, and R. Hill, "Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density", hep-ph0708.1281.
[8] M. Maltoni and T. Schwetz, "Sterile neutrino oscillaitons after the first MiniBooNE results", hep-ph0705.0107.; G. Karagiorgi, NuFACT07 conference proceedings.
[9] H. Pas, S. Pakvasa, and T. Weiler, Phys. Rev. D 72, 095017 (2005).
[10] http://www-microboone.fnal.gov/