

MiniBooNE Oscillation Searches

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Abstract. The range of oscillation analyses being pursued by the MiniBooNE collaboration is described. Focus is given to the various searches for electron neutrino appearance, but the disappearance of muon neutrinos and the appearance search for electron anti-neutrinos are covered as well.

1. Introduction

The Mini-Booster Neutrino Experiment (MiniBooNE) was built to probe the oscillation interpretation of the LSND result [2]. It uses 8 GeV protons from the Fermilab Booster to produce a high purity beam of ~ 0.7 GeV ν_μ by running the protons into a Be target followed by a focusing horn. The detector is located 541m from the target and comprises a spherical tank of inner radius 610 cm filled with 800 tons of pure mineral oil (CH_2). The oil is viewed by 1280 8inch PMTs and surrounded by a veto region viewed by 280 PMTs. Using the pattern and timing of the Cerenkov and scintillation light hitting the tubes the experiment can distinguish electrons from other particles (in particular μ s and π^0 s) and so test for $\nu_\mu \rightarrow \nu_e$ oscillations.

2. Electron Neutrino Appearance

2.1. Oscillation Result

In April 2007 the experiment released it's first results [1]. The experiment found no evidence of neutrino oscillations in its analysis region above a neutrino energy of 475 MeV, though there was a excess of events found below this energy and this is currently under investigation. The exclusion plot that results from this measurement is shown in Fig. 1 along with the expected and measured reconstructed neutrino energy spectrum of the electron neutrino candidates.

2.2. π^0 Rate Measurement

A vital component of the ν_e appearance analysis that is not often highlighted is the analysis of Neutral Current (NC) π^0 events in the detector. By using a detailed two Cerenkov ring reconstruction and a simple set of cuts MiniBooNE is able to identify a high purity sample of NC π^0 events spanning the full range of π^0 kinematics. The reconstructed mass distribution of this sample is shown on the left in Fig. 2 and the clear peak at the π^0 mass indicates the high purity of the sample. On the right of Fig. 2 is shown the expected (red) and measured (blue) π^0 momentum distribution. The ratio of these two distributions as a function of π^0 momentum is used as a reweighting function to correct the predicted π^0 rate to that observed in the detector. This correction is vital to the ν_e appearance analysis as NC π^0 events misidentified as ν_e events

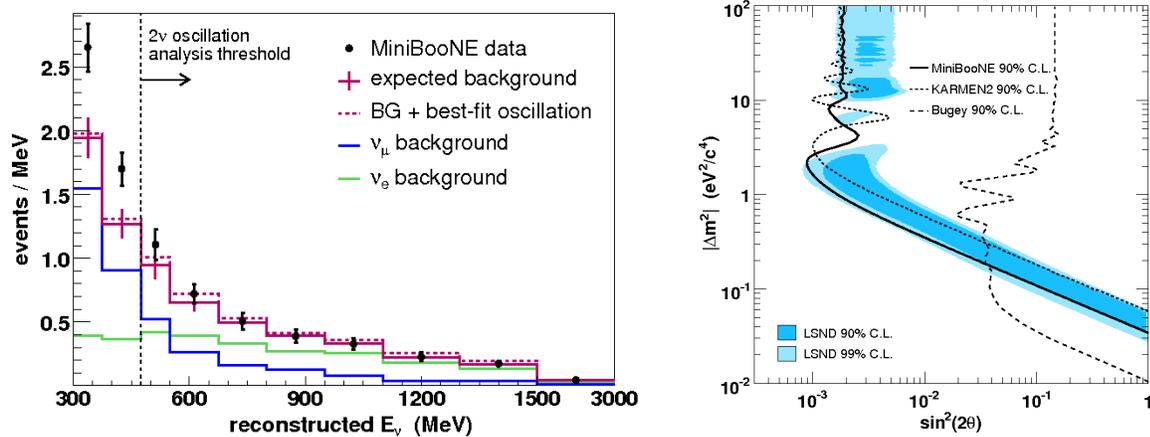


Figure 1. On the left is shown in red with systematic errors the spectrum of reconstructed neutrino energy for the electron neutrino candidate sample. The components expected from muon and electron neutrinos are shown in blue and green respectively. The data is overlaid in black with statistical error bars. On the right is shown the region of oscillation parameter space excluded at 90% C.L. by the MiniBooNE result [1]. Also shown are the regions allowed by the LSND result [2] at 90% C.L. (pale blue) and 95% C.L. (dark blue), and the 90% exclusion contours of the KARMEN2 [3] and Bugey [4] experiments.

form a large, and in some energy regions the dominant, source of background. This analysis is detailed in [5]

2.3. Combining Analyses

In the original ν_e appearance analysis that led to the April 2007 result [1] two parallel approaches were taken to event reconstruction and particle ID. In the end the approach that yielded the best sensitivity (the “Track-Based Likelihood” (TBL)) was chosen over the alternative (the “Boosted Decision Tree” (BDT)). By combining the two data sets selected by the TBL and BDT approaches and by carefully handling the now correlated statistical and systematic errors one can improve upon the limit published in [1]. This improved limit is shown in Fig. 3 along with the original limit and the LSND allowed regions. The combined analysis produces noticeable improvement below about 1eV^2 . Above that mass the wiggles in the curve are caused by the details of statistical fluctuations and can, in places, make the combined limit actually worse than the original one.

2.4. Compatibility of High Δm^2 Measurements

MiniBooNE has also undertaken a study to see how compatible its ν_e appearance result is with the other experiments (LSND, Karmen2, and Bugey) sensitive to oscillations in the same region of parameter space. In this context compatibility is defined to be the probability that all experimental results come from the same underlying two neutrino oscillation hypothesis. Further details of this work can be found in [6]. MiniBooNE assesses the compatibility by first obtaining a $\Delta\chi^2$ surface for each experiment under a 2ν oscillation hypothesis and then simply adding these to form a global χ^2 surface. In such a way it is found that MiniBooNE, LSND, Karmen2, and Bugey are together compatible with a two neutrino oscillation hypothesis at only the 3.94% level.

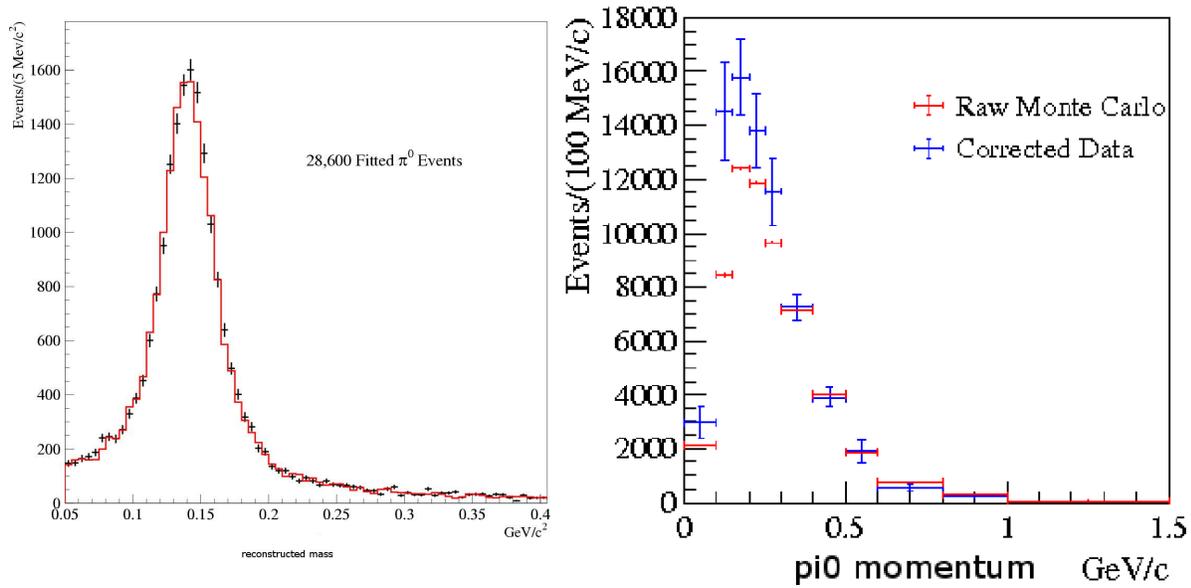


Figure 2. On the left is shown the reconstructed mass of the Neutral Current π^0 sample. The strong peak at the π^0 mass indicates the high purity of the sample. On the right is shown in red the Monte Carlo predicted π^0 momentum distribution of the sample and in blue the measured momentum distribution. The ratio of these two is used as a reweighting function to correct the simulation.

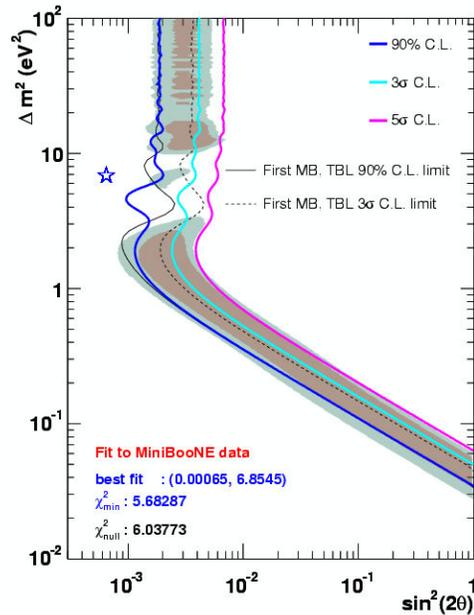


Figure 3. The 90%, 3σ , and 5σ limits that result from properly combining the two parallel approaches (“Track-Based Likelihood” and “Boosted Decision Tree”) to reconstruction and particle ID.

2.5. Low Energy Electron Candidate Excess

The April 2007 ν_e appearance result only considered events above a reconstructed neutrino energy of 475 MeV. Below that energy the data is significantly in excess of the background prediction, but with an energy shape that rises too steeply as energy is reduced to be accounted for by two flavor neutrino oscillations. Since that time MiniBooNE has been conducting a comprehensive review of all background predictions and uncertainty estimates with a particular emphasis on the low energy region. This review is not yet complete or ready for public release, but it has yielded a few changes that have needed to be made to our background and uncertainty predictions:-

- (i) Photo-nuclear absorption of gamma rays was absent from our GEANT3 simulation of the detector. Although a low probability process it is an important effect as it can take the two clean gammas from a π^0 decay and absorb one, leaving the other to mimic a single electron signal event. It is now included in the simulation and causes the background rate from π^0 s at very low energies to noticeably increase.
- (ii) The uncertainties in hadronic processes in the detector have been completely overhauled with particular attention paid to the final state that follows a photo-nuclear absorption. These uncertainties turn out to be minor and have little effect
- (iii) The way in which π^+ production uncertainties are propagated has been revamped to much more accurately reflect the uncertainties of the original measurements. Because the ν_e appearance analysis uses a ν_μ Charged Current Quasi-Elastic (CCQE) sample as calibration uncertainties in the neutrino flux from π^+ decay have very little influence on the final errors. This update will be important, however, for future neutrino cross-section measurements from MiniBooNE.
- (iv) Improvements to the measurement of NC π^0 events have been made. Finer binning and the removal of certain approximations has put the analysis described in Sec. 2.2 on an even surer footing.
- (v) The rate at which coherent and resonant NC π^0 events are misidentified as electron candidates is different, largely because the angular distribution of the π^0 s differs. Previously MiniBooNE used external measurements of the relative rate of the resonant and coherent processes, but this has now been replaced by the more accurate rates measured by MiniBooNE itself.
- (vi) The rate at which the Δ resonance is produced and decays radiatively is deduced from MiniBooNE's measurement of NC π^0 s (since most of these are produced via a Δ resonance). This process is important as its single gamma ray looks just like a single electron signal event in MiniBooNE. The process of inferring the radiative decay from our π^0 measurement has been comprehensively reviewed and its uncertainties adjusted as a result.

In addition to a complete review of the uncertainties and background estimates a cut has been added to the ν_e selection that removes low energy events originating from neutrino interactions in the dirt surrounding the MiniBooNE detector. Such events tend to be low energy, at large radius, and headed inward and so are efficiently removed by a simple topological cut. All studies so far indicate that the changed uncertainties, backgrounds, and cuts have essentially no impact above 475 MeV and so will not alter the conclusions of the already published ν_e appearance oscillation search.

2.6. Data from NuMI Beam

MiniBooNE sees a very healthy rate of neutrino interactions from the NuMI beam at Fermilab. The MiniBooNE detector sits 745m from the NuMI target and at an off-axis angle of 110 mrad. Fig. 4 shows, on the left, how the events passing ν_μ CCQE cuts agree well with the prediction

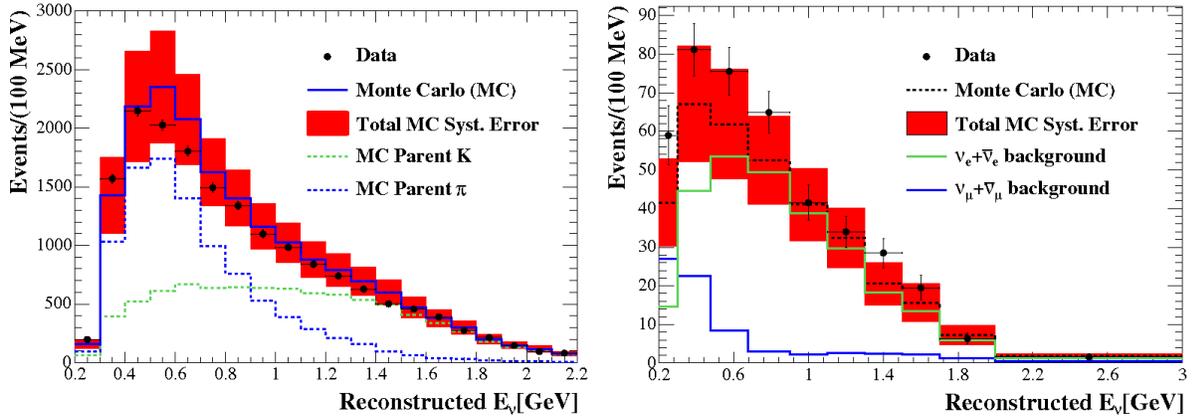


Figure 4. Comparing data and simulation for events passing ν_μ CCQE cuts (left) and those passing ν_e cuts (right). The data are shown as black dots with statistical errors. The MC prediction is shown with red systematic error band. For the ν_μ s the prediction is also broken into the components coming from kaon and from pion decay. For the ν_e s the prediction is broken into true ν_e interactions and ν_μ misIDs.

indicating that the simulation of the flux from NuMI is accurate. On the right of Fig. 4 the events passing ν_e selection cuts agree fairly well with the prediction. The ν_e sample is particularly interesting as the increased rate of neutrinos from kaon decay in the off-axis configuration means that the ν_e sample from NuMI is dominated by actual ν_e events even at low energy. This is completely different to the ν_e sample from the Booster Neutrino Beam which is dominated by mis-identified ν_μ events at low energies.

3. Muon Neutrino Disappearance

MiniBooNE has a very large sample of ν_μ Charged Current Quasi-Elastic interactions. Even after cuts the dataset consists of about 200,000 events. This data is being used to perform a search for ν_μ disappearance. Initially this search is being done with data from just the MiniBooNE detector. The left hand side of Fig. 5 shows the sensitivity to two neutrino oscillations in this mode. There is a good region of phase space that will be probed that has not been covered by any previous experiment. The SciBooNE experiment also ran in the same beam and took a good dataset in both neutrino and anti-neutrino modes of running. Despite being a very different technology the neutrino target in SciBooNE is still carbon and so it can act as a very effective near detector for MiniBooNE with much of the flux and cross-section uncertainty canceling.

4. Anti-Electron Neutrino Appearance

MiniBooNE started running in anti-neutrino mode in January of 2006. Since then the experiment has accumulated about 3×10^{20} protons on target (POT) in this mode. The right hand side of Fig. 5 shows the experiment's sensitivity to electron anti-neutrino appearance for three levels of data accumulation - 2, 5, and 10×10^{20} POT. Also shown is the region of phase space allowed by a combined analysis of LSND and Karmen2 [7]. MiniBooNE has approval to run until the end of FY2009 by which time it should have accumulated 5×10^{20} POT and will be sensitive to oscillations through most of the allowed region.

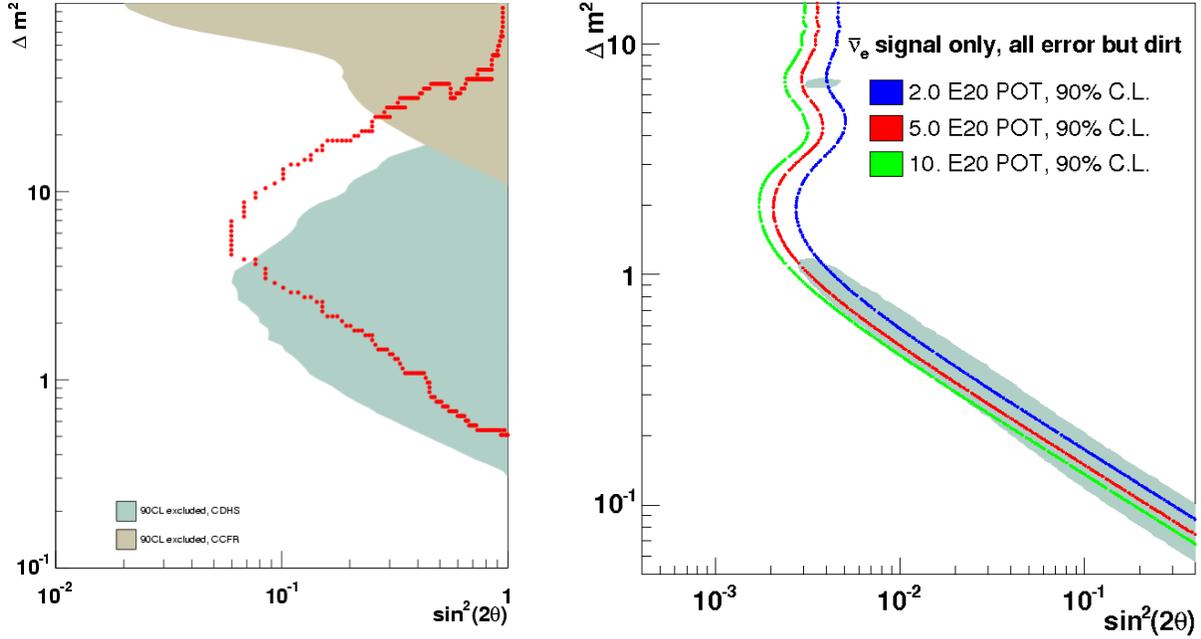


Figure 5. On the left is shown the 90% sensitivity to ν_μ disappearance using only the MiniBooNE detector. Also shown are the 90% confidence limits from the CDHS and CCFR experiments. A good portion of phase space unprobed by previous experiments is covered. On the right is shown the sensitivity at the 90% level to electron anti-neutrino appearance for three different data taking scenarios - 2, 5, and 10×10^{20} protons on target. Also shown is the region allowed at 90% by the combined analysis of the LSND and Karmen2 experiments [7].

5. Summary

MiniBooNE has accumulated 6.6×10^{20} POT in neutrino mode and is performing a suite of cross-section measurements as well as searches for electron neutrino appearance (published) and muon neutrino disappearance. In anti-neutrino mode with the horn polarity reversed the experiment has taken about 3×10^{20} POT and hopes to get to 5×10^{20} POT by the end of FY2009. With this data a suite of anti-neutrino cross-section measurements will be made as well as a search for electron anti-neutrino appearance. Recall that the LSND measurement was in anti-neutrinos.

References

- [1] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. Lett. **98**, 231801 (2007)
- [2] C. Athanassopoulos *et al.*, Phys. Rev. Lett. 75, 2650 (1995); 77, 3082 (1996); 81, 1774 (1998); A. Aguilar *et al.*, Phys. Rev. D 64, 112007 (2001).
- [3] B. Armbruster *et al.*, Phys. Rev. D 65, 112001 (2002).
- [4] B. Achkar *et al.*, Nucl. Phys. B434, 503 (1995).
- [5] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Lett. B. 664, 41 (2008).
- [6] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. D. 78, 012007 (2008).
- [7] E. Church *et al.*, Phys. Rev. D 66, 013001 (2002).