

# MiniBooNE: first results on the muon-to-electron neutrino oscillation search

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**Abstract.** MiniBooNE's first results on a search for an electron neutrino excess in a muon neutrino beam are presented, together with an analysis of the data within a two neutrino  $\nu_\mu \rightarrow \nu_e$  appearance-only oscillation context. MiniBooNE finds excellent agreement between data and Standard Model predictions in the oscillation analysis energy region. If neutrino and antineutrino oscillations are the same, MiniBooNE excludes at  $\sim 98\%$  confidence level the two neutrino  $\nu_\mu \rightarrow \nu_e$  appearance-only oscillation interpretation of the LSND anomaly. MiniBooNE also finds a discrepancy at energies below the oscillation analysis range, which is currently not understood and under investigation.

## 1. Introduction

Solar [1] and atmospheric [2] neutrino oscillations, recently confirmed by reactor [3] and accelerator-based [4] experiments, are now well established. On the other hand, the interpretation of the LSND  $\bar{\nu}_e$  excess [5] as  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations at the  $\Delta m^2 \sim 1 \text{ eV}^2$  scale lacked for many years experimental confirmation or refutation. The primary goal of the MiniBooNE experiment [6] is to address this anomaly in an unambiguous and independent way.

The MiniBooNE flux is obtained via a high-intensity, conventional neutrino beam. Secondary hadrons, mostly pions and kaons, are produced via the interactions of 8 GeV protons from the Fermilab Booster accelerator with a thick beryllium target, and are focused by a horn. The switchable horn polarity allows for both neutrino and antineutrino running modes. The neutrino beam is produced via the decay of secondary mesons and muons in a 50 m long decay region. Overall, about  $9.5 \cdot 10^{20}$  protons on target have been accumulated over the five years of beamline operation,  $5.6 \cdot 10^{20}$  of which are used in this oscillation analysis, based on the neutrino running mode sample only.

The MiniBooNE detector is located 540 m away from the beryllium target. The detector is a 12 m in diameter sphere filled with 800 t of undoped mineral oil, whose inner region is instrumented with 1280 photomultiplier tubes (PMTs). Neutrino interactions produce prompt, ring-distributed Cherenkov light, and delayed, isotropic scintillation light. Light transmission is affected by fluorescence, scattering, absorption and reflections. The outer detector region is used to reject cosmic ray activity or uncontained neutrino interactions. About  $7.7 \cdot 10^5$  neutrino interactions have been collected at MiniBooNE.

Specifically, the purpose of the first MiniBooNE electron appearance analysis is two-fold: perform a model-independent search for a  $\nu_e$  excess (or deficit), and interpret the data within

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a two neutrino, appearance-only  $\nu_\mu \rightarrow \nu_e$  oscillation context, to test this interpretation of the LSND anomaly. Two independent analyses have been developed to this end, having complementary merits: a track-based (TB) analysis, less sensitive to systematic uncertainties, and a boosted decision tree (BDT) analysis, providing a better oscillation signal-to-background ratio expectation [6]. In the following, almost exclusively the TB analysis will be discussed, as this was chosen as the primary analysis because of a slightly better  $\nu_\mu \rightarrow \nu_e$  oscillation sensitivity. This was a blind analysis. The closed box was opened on March 26, 2007, and results were first released to the public on April 11, 2007 [7].

## 2. The closed electron neutrino box era

A detailed model of extended-track light production and propagation is used to reconstruct neutrino interactions [6, 7]. A first event selection for the appearance analysis is performed via hit multiplicity, fiducial volume, and energy threshold requirements. A higher-level selection based on particle identification is applied next, to reject final state muons and  $\pi^0$ 's, and enhance the charged current quasi-elastic (CCQE) fraction in the  $\nu_e$  sample,  $\nu_e n \rightarrow e^- p$ . For this purpose, each event is reconstructed under four hypotheses: single muon track, single electron track, two track with invariant mass fixed to the  $\pi^0$  mass, and unconstrained two track hypothesis, returning  $L_\mu$ ,  $L_e$ ,  $L_\pi$  likelihood fit values and a  $m_{\gamma\gamma}$  invariant mass value, respectively. The cut values in  $L_e/L_\mu$ ,  $L_e/L_\pi$  and  $m_{\gamma\gamma}$  are energy-dependent, and chosen to optimize the  $\nu_\mu \rightarrow \nu_e$  sensitivity.

Expectations for  $\nu_e$  candidate events are formed by simulating neutrino fluxes, neutrino interactions, and detector response [6, 7]. About half of the backgrounds to the oscillation signal in the final sample are expected to be due to the  $\nu_e$  contamination in the  $\nu_\mu$  beam, with roughly the other half due to mis-identified  $\nu_\mu$  interactions. One of the strengths of the MiniBooNE appearance analysis is that all relevant backgrounds can be directly constrained or cross-checked via MiniBooNE data samples other than the  $\nu_e$  candidate sample. The main mis-identification background is due to  $\nu_\mu N \rightarrow \nu_\mu N \pi^0$  interactions where one of the two photons from the  $\pi^0$  decay is not seen. In order to constrain this background, a high (>90%) purity sample of neutral current  $\pi^0$  production interactions is selected to correct the expected  $\pi^0$  production rate as a function of  $\pi^0$  momentum. The same reweighting scheme is then applied to correct the rate of  $\nu_\mu N \rightarrow \nu_\mu N \pi^0$  interactions that can be mis-identified. Furthermore, the ability to isolate the resonant and coherent mechanisms of  $\pi^0$  production allows to correct also for the interactions proceeding via radiative  $\Delta$  decay that can be mis-identified. Another important background arises because of interactions of the neutrino beam with material surrounding the detector, creating 100-300 MeV photons that penetrate the detector unvetoes, thus producing electron-like events. Using a sample of high detector radius, inward-pointing events, this background expectation was confirmed directly with data with an accuracy of about 15%. The most important intrinsic  $\nu_e$  background is due to  $\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+$  decays occurring in the decay region. This background is accurately constrained by measuring the muon neutrino flux via the MiniBooNE  $\nu_\mu$  charged current quasi-elastic sample. For this type of interactions, the known decay kinematics allows to infer the parent  $\pi^+$  flux and momentum distribution from the observed  $\nu_\mu$  interactions. Once the parent pion flux is known, the  $\pi^+ \rightarrow \mu^+ \nu_e$  decay chain is well constrained. Also, this same  $\nu_\mu$  charged current quasi-elastic sample is used to determine the normalization of the predicted oscillation signal. Finally, for what concerns the intrinsic  $\nu_e$  background due to kaon decay, the fact that both the  $\nu_\mu$  and  $\nu_e$  candidate samples at high neutrino energies are largely due to kaon decay can be used as a constraint. In this case, the kaon-induced flux is directly measured at high energies, where no significant oscillation events are expected, and then extrapolated to lower energies in the oscillation signal energy region.

Systematic errors in predicting  $\nu_e$  candidate events, due to uncertainties in the modeling of the beam, neutrino interactions, and detector response, have been thoroughly evaluated. A first estimate is obtained from “first principles” uncertainties from simulation models and external

measurements. Better estimates are obtained via MiniBooNE calibration and neutrino data fits. Extensive cross-checks on a variety of distributions and open data samples insensitive to oscillations have been performed prior to box opening, to quantitatively verify the good level of agreement between data and predictions.

### 3. The open electron neutrino box era

Box opening proceeded as follows. First, a neutrino oscillation fit of the neutrino energy distribution for  $\nu_e$ -like events in the  $300 < E_\nu < 3000$  MeV energy range is performed, retaining blindness to the best-fit oscillation signal component added to background predictions. Goodness-of-fit information from the comparison of data with Monte Carlo (MC) predictions in several diagnostic variables is disclosed. Second, data and MC histogram contents for the same diagnostic variables is disclosed. Third, goodness-of-fit information from the neutrino energy distribution data/MC comparison is disclosed. Fourth, full information on  $\nu_e$  candidate events and oscillation fit results is disclosed. This scheme allowed to progress in a step-wise fashion, with ability to iterate if necessary. All event selection and oscillation fit procedures were determined before full box opening.

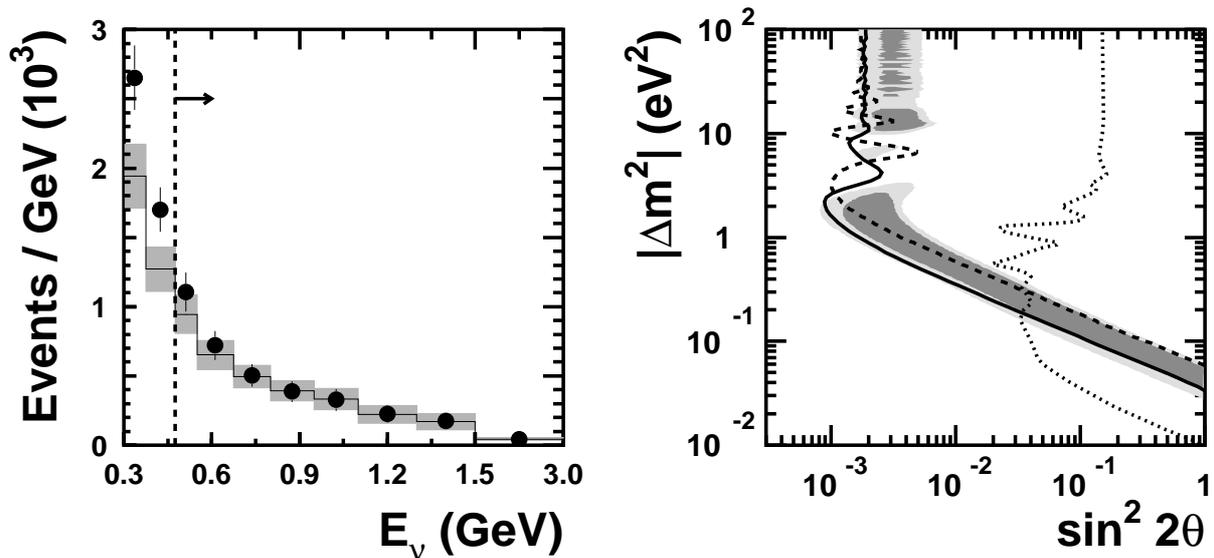
In a first iteration, comparisons between data and predictions were satisfactory in all diagnostic variables except for the visible energy, which returned a  $\chi^2$  probability of 1%, indicating a poor data/MC agreement beyond the ability of a two neutrino, appearance-only oscillation model to handle. This triggered further investigations of background estimates and associated uncertainties, but no evidence of a problem was found. However, given that backgrounds rise at low energies, that studies focused suspicions in the low-energy region, and that this choice has negligible impact on the oscillation sensitivity, the MiniBooNE Collaboration decided to look for an oscillation signal in the reduced  $475 < E_\nu < 3000$  MeV range, while reporting electron candidate events over the full  $300 < E_\nu < 3000$  MeV range. With the oscillation analysis energy threshold increased, a second box opening iteration indicated good data/MC agreement in all diagnostic variables. No oddities in any of the subsequent box opening steps were found, and electron candidate events became fully unblinded.

MiniBooNE observes 380 electron candidate events in the  $475 < E_\nu < 1250$  MeV energy range, to be compared with a no-oscillation background prediction of  $358 \pm 19 \pm 35$ . No evidence for neutrino oscillations is found. The same conclusion is reached by performing a fit to the neutrino energy distribution (see Fig.1) over the  $475 < E_\nu < 3000$  MeV range: the no-oscillation hypothesis describes the data well, with a goodness-of-fit  $\chi^2/\text{dof} \simeq 1.8/8$ , and no statistically significant differences in the description of the data are found assuming oscillations. Given the null result, an upper limit on neutrino oscillations is obtained. As shown in Fig. 1, no overlap in the 90% confidence level regions in oscillation parameter space allowed by MiniBooNE and LSND exists. MiniBooNE excludes two neutrino appearance-only oscillations as the explanation of the LSND anomaly at 98% confidence level. Very similar results are obtained with the second, largely independent, BDT analysis [7].

Upon investigation of electron candidate events over the full,  $300 < E_\nu < 3000$  MeV, energy range (see Fig. 1), it is found that low-energy data do not match expectations. A  $3.7 \sigma$  excess is seen in the data for  $300 < E_\nu < 475$  MeV. This discrepancy is currently not understood and under investigation. While this low-energy excess does not seem consistent with two neutrino appearance-only oscillations, more studies are needed to clarify its causes.

### 4. Conclusions and outlook

In conclusion, MiniBooNE finds excellent agreement between data and no-oscillation predictions in the oscillation analysis energy range. As a consequence, and if neutrino and antineutrino oscillations are the same, MiniBooNE excludes at 98% confidence level the two neutrino, appearance-only  $\nu_\mu \rightarrow \nu_e$  oscillations interpretation of the LSND anomaly. For energies below



**Figure 1.** Left:  $\nu_e$  candidate events versus reconstructed neutrino energy  $E_\nu$  [7]. Points indicate data with statistical-only error bars. The histogram shows the total background expectation, with systematic-only error rectangles. Right: allowed regions in oscillation parameter space ( $|\Delta m^2|, \sin^2 2\theta$ ). The filled regions indicate the region allowed by LSND [5] at 90 and 99% confidence level. The solid, dashed, and dotted curves indicate the 90% confidence level upper limits from the MiniBooNE [7], KARMEN [8], and Bugey [9] experiments, respectively.

the oscillation analysis range, MiniBooNE finds an excess of electron candidate events above expectations that is currently not understood and under investigation.

Apart from understanding this low-energy discrepancy, MiniBooNE's near-term goals include an improvement in oscillation sensitivity by combining the merits of the two analyses developed for this first result, additional searches addressing different models explaining the LSND anomaly, and neutrino cross section measurements. Results from the MiniBooNE's ongoing antineutrino running are expected after that.

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