# Updated Search for Electron Antineutrino Appearance at MiniBooNE

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**Abstract.** The MiniBooNE experiment at Fermilab has updated its search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with data collected through May 2011. This represents a statistics increase of 52% over the result published in 2010. The data favor LSND-like oscillations over a background-only hypothesis at the 91.1% confidence level. While the new result remains equally consistent with LSND, the compatibility with the background-only hypothesis is improved. An excess of $38.6 \pm 18.5$ $\nu_e$-like events below 475 MeV is observed, consistent with the observation of such an excess in neutrino mode.

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## MINIBOONE

The MiniBooNE experiment (E898/944) at Fermi National Accelerator Laboratory is a short-baseline neutrino oscillation experiment whose main purpose is to test the LSND oscillation results [1]. MiniBooNE uses an 8 GeV proton beam from the Fermilab Booster to produce pions, which then decay in flight to produce a nearly pure $\nu_\mu$ flux at a mineral oil Cherenkov detector 500 m away. The detector uses Cherenkov ring shape information to distinguish charged-current $\nu_\mu(\bar{\nu}_\mu)$ from $\nu_e(\bar{\nu}_e)$ interactions, searching for an excess of $\nu_e$ which would indicate oscillations. Data collection began in late 2002 with the beam configured to produce neutrinos; since 2007 most operations have been with the focusing polarity reversed to produce antineutrinos. Antineutrino studies are important for a complete test of LSND, which was primarily a $\bar{\nu}_\mu \to \bar{\nu}_e$ search.

## OSCILLATION RESULTS FROM MINIBOONE

MiniBooNE has three previous appearance-mode oscillation results. The general technique is similar in all of them: events with a single electron-like Cherenkov ring are selected as charged-current quasielastic (CCQE) candidates. Cuts are designed to remove neutral-current $\pi^0$ events as well as fragments from neutrino interactions that occurred outside the detector ("dirt"). The reconstructed neutrino energy $E_\nu^{\mathrm{QE}}$ is computed assuming the process was $\nu N \to e N'$ with the nucleon unobserved and the neutrino originating from the beam direction. Significant backgrounds are intrinsic $\nu_e$ in the beam, neutral-current $\pi^0$ and $\Delta \to N\gamma$, and dirt. Neutrinos and antineutrinos cannot be distinguished on an event-by-event basis.

In 2007, the main search for LSND-like oscillations in neutrino mode was published [2] based on $5.7 \times 10^{20}$ protons on target (POT). This result excluded a *CP*-conserving two-neutrino oscillation explanation for LSND at the 98% confidence level. At the same time, an unexplained excess of $\nu_e$-like events below 475 MeV was seen; further studies of this low-energy excess were published in 2009 [3].

In 2010, a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ from $5.66 \times 10^{20}$ POT in antineutrino running mode was published [4]. That paper indicated an excess of $20.9 \pm 14.0$ $\nu_e/\bar{\nu}_e$ candidates in the 475-1250 MeV range where MiniBooNE is most sensitive to LSND-like oscillations and contributions from the neutrino-mode low-energy excess are minimized. However, a likelihood-ratio fit to the energy distributions of both the $\bar{\nu}_e$ and $\bar{\nu}_\mu$ candidates preferred the oscillation hypothesis over the background-only hypothesis with 99.4% probability. In the low-energy region of 200-475 MeV, the data excess over the background prediction was $18.5 \pm 14.3$ events. Scaling the neutrino-mode low-energy excess by the expected neutrino contamination in the antineutrino flux gives a predicted low-energy excess of 12 events.

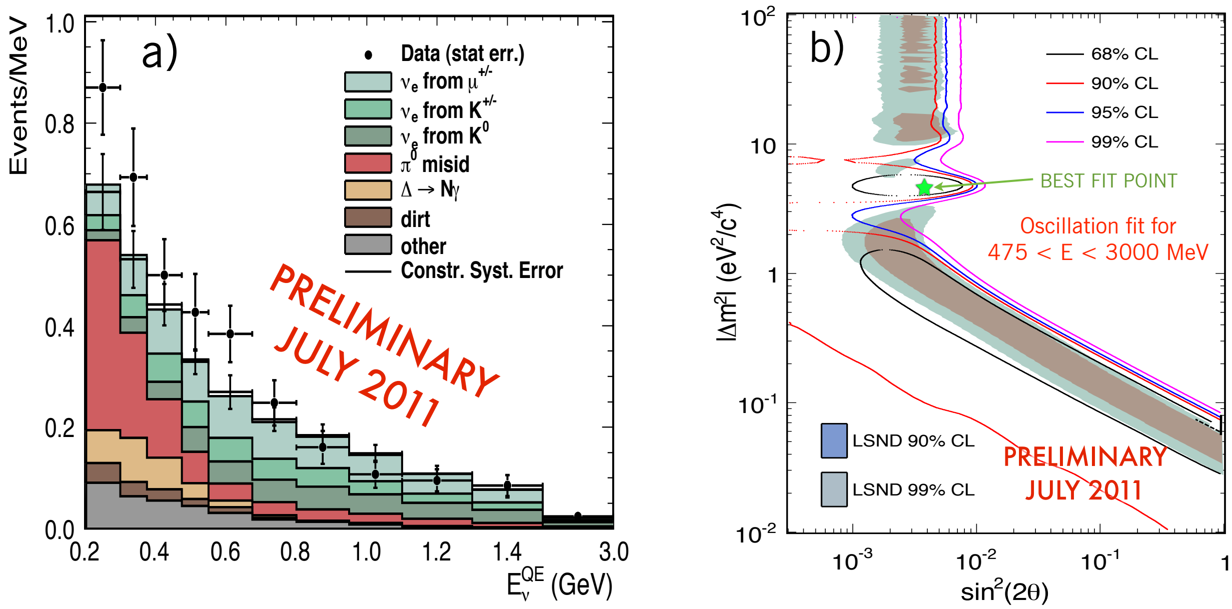


**FIGURE 1.** **a)** Reconstructed $E_\nu^{QE}$ distribution for $\bar{\nu}_e$ candidates with data collected in antineutrino mode through May 2011. **b)** Oscillation fit contours for updated $\bar{\nu}_e$ appearance analysis. Energy range of fit is $475 < E_\nu^{QE} < 3000$ MeV. Results are preliminary.

**TABLE 1.** Preliminary predicted low-energy excess from scaling neutrino-mode excess by various factors. The value observed in data is $38.6 \pm 18.5$.

| Scaling basis | Predicted excess | Scaling basis | Predicted excess |
|---|---|---|---|
| Total background | 50 | Neutrino contamination | 17 |
| $\Delta \rightarrow N\gamma$ decays | 39 | Dirt | 46 |
| Protons on target* | 165 | $K^+$ in secondary beam | 67 |
| Neutral-current $\pi^0$ | 48 | Inclusive charged-current | 59 |

* Excess would scale this way if due to neutral particles in secondary beam.

## UPDATED ANTINEUTRINO RESULTS

In this section we present preliminary updates to the antineutrino oscillation search reported in Ref. [4] using $8.58 \times 10^{20}$ POT, using a nearly unchanged analysis. The most significant change is an improved constraint on kaon-decay $\nu_e$ in the beam from the SciBooNE experiment [5], reducing the prediction for that background source by 3% and its error by a factor of three. Detector and beam monitoring have indicated no significant changes over the entire run period, and Kolmogorov-Smirnov tests of neutrino control samples are consistent with a constant event rate.

The reconstructed energy distribution of $\bar{\nu}_e$ candidates is shown in Fig. 1a. In the augmented data set, 168 events are observed in the 475-1250 MeV region, corresponding to an excess of $16.3 \pm 19.4$ over predicted background. The excess in this region is thus reduced when the new data are added.

In the low-energy region, the excess has grown to $38.6 \pm 18.5$ events. We can compare this excess to predictions from scaling the observed neutrino-mode low-energy excess by various factors (see Table 1). This can exclude some possible phenomena as primary sources of the low-energy excess, though it should be noted that none of these processes can be scaled by a large enough factor to explain the low-energy excess without disagreeing strongly with control samples.

The primary test of LSND's result is the simultaneous fit to the $\bar{\nu}_\mu$ and $\bar{\nu}_e$ candidates in the $475 < E_\nu^{QE} < 3000$ MeV range. The updated confidence-level contours are shown in Fig. 1b. The fit prefers the oscillation hypothesis to the background-only hypothesis at 91.1% confidence level. The best-fit point moved from the high-$\sin^2(2\theta)$, low-

$\Delta m^2$ region to the high-$\Delta m^2$ “island” solution, however the $\chi^2$ minimum is quite broad so this does not represent a significant change. In the signal bins, the $\chi^2$ probability is 14.9% for background-only and 35.5% for the oscillation fit. (These numbers were 0.5% and 10% before the statistics update.) The 68% confidence level contour still covers most of the LSND allowed region. This result is therefore still consistent with LSND, but the evidence for LSND-like oscillations is no longer as strong.

As in the published result, fits have been performed under other sets of assumptions. First, a fit to the entire energy range ($200 < E_\nu^{QE} < 3000$ MeV) yields similar contours, with oscillations preferred with 97.6% probability. The fit $\chi^2$ probabilities for background-only and the best oscillation fit are 10.1% and 50.7% respectively. However, it should be noted that there is a large known neutrino contamination in antineutrino running (22% of the $\bar{\nu}_\mu$ candidates and 44% of the total background to the $\bar{\nu}_e$ oscillation signal). A low-energy excess from neutrinos may be expected to contribute to the 200-475 MeV bins in this fit, but has not been subtracted because its origin and scaling are unknown. Therefore, this fit cannot be interpreted as a pure antineutrino physics result.

Another alternative fit is done with additional background subtraction, assuming that the low-energy excess contribution from neutrinos simply scales with the neutrino-induced event rate in each bin. This model’s validity may be poor, however, if the excess is due to feed-down from misreconstructed higher-energy neutrinos with unobserved particles in the final state (since the neutrino spectrum differs between neutrino and antineutrino running). The fit under this background subtraction model prefers oscillations with 94.2% probability. The fit $\chi^2$ probabilities for background-only and the best oscillation fit are 28.3% and 76.5% respectively.

The contours and best-fit points for the fits to the full energy spectrum are available in the slides from this presentation.

## CONCLUSION AND NEXT STEPS

MiniBooNE presents a preliminary update to its 2010 electron antineutrino appearance search with 52% more integrated flux. Adding the new data reduces the significance of the apparent LSND-like oscillation signal, and reveals a low-energy excess of $\bar{\nu}_e$ candidates similar to that observed in neutrino mode. In the higher-energy region, the new data are consistent with both LSND and a background-only hypothesis.

The experiment will continue to take data at least until the 2012 shutdown. The collaboration’s goal is a total of $1.5 \times 10^{21}$ POT – nearly doubling the current data set. This statistically-limited result should benefit greatly from the additional data. If either our best-fit value or LSND’s central value is correct, the expected exclusion of the background-only hypothesis (relative to the oscillation fit) with a data set that large is at the 98-99% confidence level.

## ACKNOWLEDGMENTS

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