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RESULTS AND IMPLICATIONS FROM MINIBOONE: NEUTRINO OSCILLATIONS

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*Abstract.*The MiniBooNE experiment at Fermilab reported an excess of electron antineutrino-like events in a muon antineutrino beam, consistent with evidence for antineutrino oscillations in the 0.1 to 1.0 $eV^2\Delta m^2$ range from the Liquid Scintillator Neutrino Detector experiment at Los Alamos National Laboratory. Results from an updated $\bar{\nu}_e$ appearance analysis, based on 50% more data taken in antineutrino mode, will be discussed. Models involving sterile neutrinos have been proposed to explain these observations, with some models predicting large muon antineutrino disappearance. Joint analyses using data from the MiniBooNE and SciBooNE detectors to extend the sensitivity to muon neutrino and antineutrino disappearance will be discussed.

1 The MiniBooNE Experiment

The MiniBooNE experiment [1] was built at Fermi National Accelerator Laboratory to test evidence for neutrino oscillations at the $\Delta m^2 \approx 1\text{eV}^2$ scale seen in the LSND experiment at Los Alamos National Laboratory [2]. MiniBooNE uses the booster neutrino beamline at FNAL; 8 GeV protons strike a beryllium target, positive or negative pions and kaons are then either focused or defocused as determined by the polarity of a focusing horn, resulting in a beam with an enhanced flux of either muon neutrinos or antineutrinos. Neutrino interactions are then detected in a 12 m diameter, mineral oil Cherenkov detector at a distance of 540 m from the target. The detector is instrumented with 1280 8 inch PMTs in the active region, and 240 8 inch PMTs in an outer, veto region. The MiniBooNE oscillation search has the same $L/E \approx 1$ as LSND, but independent systematic uncertainties.

2 Updated Electron Antineutrino Appearance Measurement

MiniBooNE neutrino mode results, based on 6.5×10^{20} protons on target (POT), were reported in Ref. [3]. Above 475 MeV, the neutrino mode results showed good agreement with the background-only hypothesis and, assuming CP conservation, were inconsistent with LSND-type oscillations at the 98% confidence level (CL). Below 475 MeV, however, the data showed a 3σ excess over background. The shape of this excess, as a function of reconstructed neutrino energy, was not consistent with a simple two neutrino oscillation model. The neutrino mode low energy excess is further discussed in [4].

Figure 1 shows the updated $\bar{\nu}_e$ event distribution, using data taken in antineutrino mode through May, 2011. This data included 8.58×10^{20} POT,

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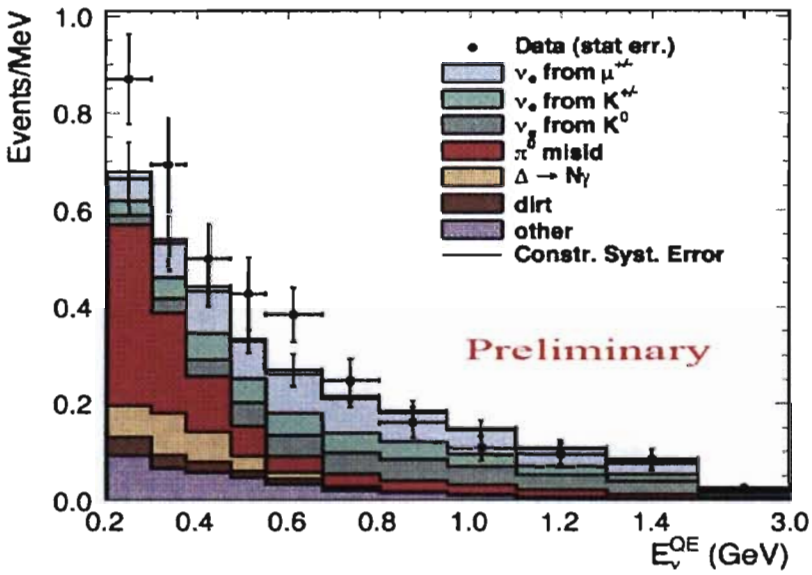

Figure 1: Data, with statistical uncertainty, versus reconstructed neutrino energy for updated $\bar{\nu}_e$ analysis. Also shown are the predicted backgrounds with systematic uncertainty.

about 50% more data than that used in the previously published $\bar{\nu}_e$ appearance results [5]. The reconstructed neutrino energy is computed assuming that all events in the final event sample are charged current quasi-elastic (CCQE), $\nu N \rightarrow eN'$. Figure 2 shows the observed event excess, relative to expected backgrounds, as a function of energy. This data shows an excess of 38 $\pm$ 18.5 events in the low energy region, below 475 MeV. With the addition of the new data, the low energy excess in antineutrino mode looks more similar to the low energy excess in the ν_e event sample in neutrino mode [3,4]. However, the origin of the low energy excess, whether it is due to a more complicated oscillation signal, misunderstood background, or new physics, remains unresolved and is one of the physics motivations for the MicroBooNE detector [6].

The $\bar{\nu}_e$ appearance analysis of Ref. [5] was repeated using additional data taken in antineutrino mode through May, 2011. In addition to reduced statistical uncertainties in the internally constrained backgrounds, the results of a recent SciBooNE measurement of K^+ production in the beam [7] were included in background predictions. The results are shown in Fig. 3. Consistent with the analysis reported in [5], the region above 475 MeV was fit to a two-neutrino oscilaltion model. Above 475 MeV, there is an excess of 16 $\pm$ 19 events with an expected background of 152 events. The two-neutrino oscillation hypothesis is

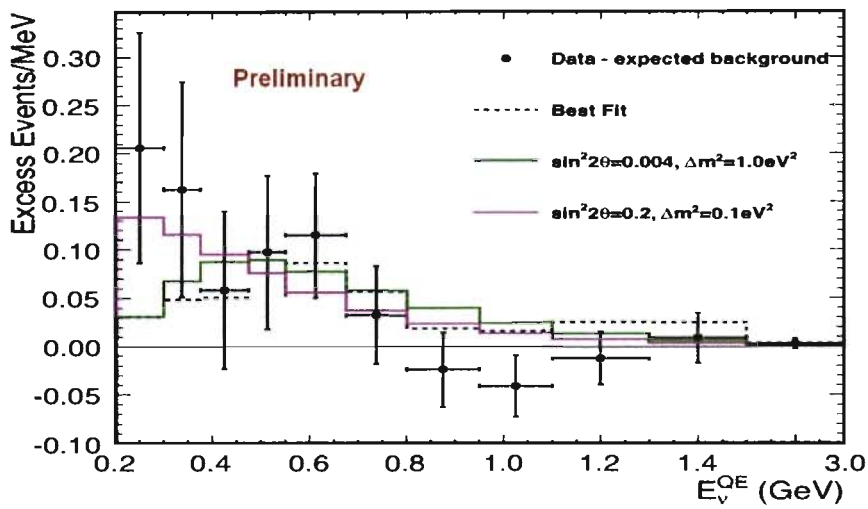

Figure 2: $\bar{\nu}_e$ appearance data minus expected background. Error bars include statistical and systematic uncertainties. The best fit to the two-neutrino oscillation model and two other oscillation hypotheses consistent with the LSND result are shown.

favored over the null (background only) hypothesis at a 91.1% CL. Although significance relative to the null hypothesis is lower than the 99.4% CL reported for the earlier $\bar{\nu}_e$ appearance result [5], compatibility with neutrino oscillations is improved. The χ^2 probability is 35.5% for the oscillation fit and 14.9% for the null fit. For the previous result, the χ^2 probability was 8.7% for the oscillation fit and 0.5% for the null fit. If the entire region above 200 MeV is used in the updated analysis, then LSND-like oscillations are favored at the 97.6% CL, with a χ^2 probability of 50.7% for the oscillation fit.

3 Joint MiniBooNE/SciBooNE Disappearance Analysis

Sterile neutrino models have been invoked to explain the short baseline appearance results of MiniBooNE and LSND [8]. If these models are correct, then the appearance of $\nu_e(\bar{\nu}_e)$ in a $\nu_\mu(\bar{\nu}_\mu)$ beam is the result of one or more sterile neutrinos acting as an intermediary. Hence, observation of the short baseline disappearance of $\nu_\mu(\bar{\nu}_\mu)$ in an experiment such as MiniBooNE would be the "smoking gun" to confirm or exclude these models. Such a search was performed in MiniBooNE [9], and no evidence for ν_μ or $\bar{\nu}_\mu$ disappearance was found. However, the sensitivity of the analyses was limited by neutrino flux and cross section uncertainties. The search for ν_μ disappearance was recently revisited with the inclusion of data from the SciBooNE detector [10]. SciBooNE

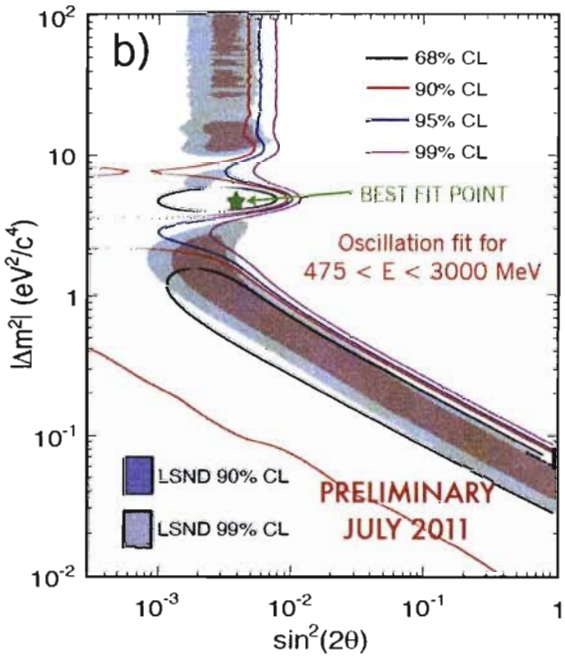

Figure 3: Preliminary results for the updated $\bar{\nu}_e$ oscillation analysis.

operated in the same beamline as MiniBooNE during 2007 and 2008, collecting data while the beam was operating in neutrino mode as well as antineutrino mode. SciBooNE was at a distance of 100 m from the target.

Two complimentary disappearance analyses were performed using the same data. In the simultaneous fit method, the data from both detectors were fit simulataneously to a two neutrino oscillation model. In the spectrum fit method, SciBooNE data were used to determine energy dependent scale factors that were then applied to the MiniBooNE simulation. The results can be seen in Fig. 3 of Ref. [11]. No evidence for ν_μ disappearance was found, however limits on $\sin^2 2\theta$ were improved, relative to previous results, in the region $10 \rightarrow 30$ eV^2. A joint search for $\bar{\nu}_\mu$ disappearance using data from MiniBooNE and SciBooNE is underway. This new analysis will take advantage of neutrino cross section measurements [12], background measurements [7, 12], and constraints on neutrino background in the antineutrino beam [13].

4 Summary and Future Plans

MiniBooNE's $\bar{\nu}_e$ appearance analysis has been updated using 50% more data. The result remains consistent with evidence from LSND for $\Delta m^2 \approx 1$ eV^2 oscillations, however with reduced significance but higher compatability with neutrino oscillations. The excess at low energy now appears more consistent between neutrino and antineutrino modes, however the origin is still unresolved. An analysis that will simultaneously fit MiniBooNE's ν_e and $\bar{\nu}_e$ appearance data is in progress, with and without allowing CP violation. A joint MiniBooNE/SciBooNE search for ν_μ disappearance has been completed and a search for $\bar{\nu}_\mu$ disappearance is underway. The MiniBooNE Collaboration anticipates running into the summer of 2012, increasing the current antineutrino data set by another 50%.

References

[1] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Nucl. Instrum. Meth.* **A**, 599:28-46 (2009).

[2] A. Aguilar *et al.*, (LSND Collaboration), *Phys. Rev.* **D** 64, 112007 (2001).

[3] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev. Lett.* 98, 231801 (2007).

[4] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev. Lett.* 102, 101802 (2009).

[5] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev. Lett.* 105, 181801 (2010).

[6] H. Chen *et al.*, (MicroBooNE Collaboration), Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines: MicroBooNE. FERMILAB-PROPOSAL-0974.

[7] G. Cheng *et al.*, (SciBooNE Collaboration), *Phys. Rev.* **D** 84, 012009 (2011).

[8] G. Karagiorgi, *et al.*, *Phys. Rev.* **D** 80, 073001 (2009); J. Kopp, M. Maltoni, and T. Schwetz, *Phys. Rev. Lett.* 107, 091801 (2011); C. Giunti and M. Laveder, arXiv: 1107.1452; G. Karagiorgi, arXiv: 1110:3735.

[9] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev. Lett.* 103, 061802 (2009).

[10] A.A. Aguilar-Arevalo *et al.*, (SciBooNE Collaboration), arXiv: hep-ex/0601022.

[11] K.B.M. Mahn *et al.*, (MiniBooNE and SciBooNE Collaborations), arXiv:.1106.5685, (submitted to Phys. Rev. Lett.).

[12] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev.* **D** 81, 092005 (2010).

[13] A.A. Aguilar-Arevalo *et al.*, (MiniBooNE Collaboration), *Phys. Rev.* **D** 84, 072005 (2011); J. Grange, arXiv: 1107.5327.