Title: Results and Implications from MiniBooNE: Neutrino Oscillations and Cross Sections

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Intended for: Presentation of recent results from the MiniBooNE neutrino experiment (operating at FNAL); for the 15th Lomonosov Conference on Elementary Particle Physics at Moscow State University.
RESULTS AND IMPLICATIONS FROM MINIBOONE:
NEUTRINO OSCILLATIONS AND CROSS SECTIONS

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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/Δm^2 range from the Liquid Scintillator Neutrino Detector experiment at Los Alamos National Laboratory. Oscillations at this mass scale are not compatible with the conventional neutrino oscillation model based on the interference of just three mass eigenstates. Models involving sterile neutrinos, and possibly CP or CPT violation, have been proposed to explain these observations. Models in which the mixing is occurring with one or more sterile neutrinos acting as an intermediary predict large muon antineutrino disappearance. In addition to a review of previous appearance and disappearance analyses in MiniBooNE, joint analyses using data from MiniBooNE and SciBooNE to extend the sensitivity for neutrino and antineutrino disappearance will be discussed. The SciBooNE detector was located along the Booster Neutrino Beamline, nearer to the target than MiniBooNE, and can be used to further constrain flux and cross section uncertainties. Implications from neutrino-nucleon cross section measurements in MiniBooNE will be briefly discussed.

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Results and Implications from MiniBooNE: Neutrino Oscillations and Cross Sections

15th Lomonosov Conference, 19 Aug 2011
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Outline

- Electron Neutrino and Antineutrino Appearance
  - Review of previous results
  - Updated antineutrino appearance results

- Muon Neutrino and Antineutrino Disappearance
  - Review of previous results
  - New MiniBooNE/SciBooNE joint analysis

- Neutrino and Antineutrino Cross Section Measurements from MiniBooNE
LSND Saw an excess of $\bar{\nu}_e$: $87.9 \pm 22.4 \pm 6.0$ events.

With an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$.

3.8 $\sigma$ evidence for oscillation.

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics!
MiniBooNE was designed to test the LSND signal

Keep L/E same as LSND while changing systematics, energy & event signature

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 L/E \right) \rightarrow \text{Two neutrino fits} \]

LSND: \[ E \sim 30 \text{ MeV} \quad L \sim 30 \text{ m} \quad L/E \sim 1 \]

MiniBooNE: \[ E \sim 500 \text{ MeV} \quad L \sim 500 \text{ m} \quad L/E \sim 1 \]

Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with $6.5 \times 10^{20}$ POT \( \Rightarrow \) assumes CP/CPT conservation

Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with $8.58 \times 10^{20}$ POT \( \Rightarrow \) direct test of LSND

FNAL has done a great job delivering beam!
**Particle Identification**

- Identify events using timing and hit topology
- Use primarily Cherenkov light
- Can’t distinguish electron from photon

Interactions in MiniBooNE (neutrino mode):

- $\nu_e, \bar{\nu}_e \rightarrow e^+, e^-$
- $p, n \rightarrow \pi^+$
- $n, p \rightarrow \mu^-$, $\nu_\mu, n \rightarrow e^-, p$
- Multi-ring (e.g. $\pi^0 \rightarrow \gamma\gamma$)

(similar mix for antineutrino mode, except rate down by factor of 5)
Calibration Sources

Tracker system

15% E resolution at 53 MeV

δm \sim 20%

Michel electrons

Visible energy range of oscillation signal

\pi^0 photon energies

Through-going cosmics

\begin{align*}
\text{Visible Tank Energy (MeV)} & \quad \text{Cosmic Muon Energy} \\
\text{Cube Range Energy (MeV)} & \quad \text{Tracker & Cubes}
\end{align*}
Booster Flux at MiniBooNE

Neutrino-Mode Flux

\[ \pi^+ \to \mu^+ \nu_\mu \quad E_{\text{avg}} \sim 0.8 \text{ GeV} \]

\[ K^+ \to \mu^+ \nu_\mu \]

Subsequent decay of the \( \mu^+ (\mu^-) \) produces \( \bar{\nu}_e (\nu_e) \) intrinsics \( \sim 0.5\% \)

Neutrino mode: \( \nu_\mu \to \nu_e \) oscillation search

Antineutrino mode: \( \bar{\nu}_\mu \to \bar{\nu}_e \) oscillation search

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam
Constrained Fit

The following three distinct samples are used in the oscillation fits:

1. **Background** to $\nu_e$ oscillations
2. $\nu_e$ **Signal** prediction (dependent on $\Delta m^2$, $\sin^2\theta$)
3. $\nu_\mu$ **CCQE** sample, used to constrain $\nu_e$ prediction (signal+background)

\[
-2 \ln(L) = (x_1 - \mu_1, ... x_n - \mu_n)^T M^{-1} (x_1 - \mu_1, ... x_n - \mu_n) + \ln(|M|)
\]

$M_{ij} = \text{full syst+stat covariance matrix at best fit prediction}$

$\log L$ calculated using both datasets ($\nu_e$ and $\nu_\mu$ CCQE), and corresponding covariance matrix
**In situ** background constraints:

Reconstruct majority of $\pi^0$ events; extrapolate into kinematic region where 1 photon is missed due to kinematics or escaping the tank.

Intrinsic $v_e$ from $\mu^+$ originate from same $\pi^+$ as the $v_\mu$ CCQE sample; measuring $v_\mu$ CCQE channel constrains intrinsic $v_e$ from $\pi^+$.

At high energy, $v_\mu$ flux is dominated by kaon production at the target; measuring $v_\mu$ CCQE at high energy constrains kaon production, and thus intrinsic $v_e$ from $K^+$.

### 475 MeV - 1250 MeV

- $v^K_e$ 94
- $v^\mu_e$ 132
- $\pi^0$ 62
- dirt 17
- $\Delta \to N\gamma$ 20
- other 33
- total 358

![Graph showing expected backgrounds](image)

- Neutrino mode
  - $v_e$ from $\mu^+$
  - $v_e$ from $K^+$
  - $v_e$ from $K^0$
  - $\pi^0$ misid
  - $\Delta \to N\gamma$
  - dirt
  - other

- Syst. Error 475 MeV - 1250 MeV

$p + Be \to \pi^+ \rightarrow \nu\mu \rightarrow v_\mu e^+$
**In situ** background constraints:

About 80% of NC π₀ events come from resonant Δ production; constrain Δ→Nγ by measuring the resonant NC π₀ rate, apply known branching fraction to N, including nuclear corrections.

Dirt events come from neutrinos interacting in surrounding dirt and structure; fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty.

In the end, every major source of background can be internally constrained by MB.
Neutrino Mode MiniBooNE Results (2009)

- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - Energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - Reduced to 3σ after systematics. Shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

Published PRL 102,101802 (2009)
Neutrino Mode MiniBooNE Results (2009): Limit

Neutrino Exclusion Limits: 6.5E20 POT

\[
\sin^2(2\theta) \leq 0.004, \quad \Delta m^2 = 1.0 \text{eV}^2
\]

\[
\sin^2(2\theta) \leq 0.02, \quad \Delta m^2 = 0.1 \text{eV}^2
\]

\[
\sin^2(2\theta) \leq 0.2, \quad \Delta m^2 = 0.1 \text{eV}^2
\]
Range of possible explanations for observed excess

Several possible explanations have been put forth by the physics community, attempting to reconcile the MiniBooNE neutrino mode result with LSND and other appearance experiments...

- **3+2 with CP violation**
  [Maltoni and Schwetz, hep-ph/0705.0107; G. K., NeFAC'T 07 conference]
- **Anomaly mediated photon production**
  [Harvey, Hill, and Hill, hep-ph/0708.1281]
- **New light gauge boson**
- **Neutrino decay**
  [hep-ph/0602083]
- **Extra dimensions**
  [hep-ph/0504096]
- **CPT/Lorentz violation**
  [PRD(2006)105009]
- ...
Reminder of Some Pre-unblinding Choices

We are using energy range $E_\nu > 475$ MeV in oscillation analysis.

Why is the 200-475 MeV region unimportant for oscillation search?
- Large backgrounds from mis-ids reduce S/B.
- Many systematics grow at lower energies.
- Most importantly, not a region of L/E where LSND observed a significant signal
Previous Anti-neutrino Mode Results (2010): 5.66E20 POT

- Results for 5.66E20 POT collected in anti-neutrino mode
- Only antineutrinos allowed to oscillate in fit
- In E < 475 MeV: A small 1.3σ electron-like excess.
- E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.

Published
Previous Anti-neutrino Mode Results (2010): 5.66E20 POT

Null excluded at 99.4% with respect to the two neutrino oscillation fit.

Best Fit Point
\((\Delta m^2, \sin^2 2\theta) = (0.064 \text{ eV}^2, 0.96)\)

\(\chi^2/\text{NDF} = 16.4/12.6\)

\(P(\chi^2) = 20.5\%\)
New Anti-neutrino mode results: 8.58E20 POT
(50% more data)
Data Checks

- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
Data Checks

- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.

- New SciBooNE constraint on $K^+$ component of the Booster beam: Reduces this component of background by 3% and error by factor of 3 (e-print 1105.2871 [hep-ex]).

- Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics in control samples:
  - $\pi$-decay neutrino normalization factors
  - Dirt neutrino background
  - Neutral-current $\pi^0$ production.
New Anti-neutrino mode results: 8.58E20 POT

475MeV<E<1250MeV:
• Expected events: 151.7±15.0 (syst) after fit constraints
• Observed events: 168.
• Observed Excess: 16.3±19.4 (total) →0.84σ
• Excess in oscillation serch region is reduced somewhat with new data.
• Low-energy excess is more significant and resembles neutrino-mode data.
Oscillation Fit

- Results for 8.58E20 POT
- Maximum likelihood fit.
- For the original osc energy region above 475 MeV, oscillations favored over background only (null) hypothesis at the 91.1% CL.
- Best Fit Point
  \((\Delta m^2, \sin^2 2\theta) = (4.6 \text{ eV}^2, 0.0045)\)
  
  \(\chi^2_{\text{BF}}/\text{NDF} = 4.3/3.9 \text{ with } P(\chi^2) = 35.5\%\)
  
  \(\chi^2_{\text{NULL}}/\text{NDF} = 9.3/5.9 \text{ with } P(\chi^2) = 14.9\%\)
- Consistent with LSND, though evidence for LSND-type oscillations less strong than previous published 5.66E20 result
- Previous result (5.66E20 POT):
  Oscillation favored over null at 99.4%CL
  \(\chi^2_{\text{BF}}/\text{NDF} = 8.0/6 \text{ with } P(\chi^2) = 8.7\%\)
  
  \(\chi^2_{\text{NULL}}/\text{NDF} = 18.5/4 \text{ with } P(\chi^2) = 0.5\%.\)
Oscillation Fit with $E_\nu > 200$ MeV

- Results for $8.58e20$ POT.
- Use full energy range $200 < E_\nu < 2000$ MeV in the fit.
- Does not include effects (subtraction) of neutrino low energy excess.
- For $E < 475$ MeV, excess = $38.6 \pm 18.5$ (For all energies, excess = $57.7 \pm 28.5$).
- Maximum likelihood fit method.
- Null excluded at 97.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point ($\Delta m^2, \sin^2 2\theta$) = $(4.6$ eV$^2, 0.0038)$
  $\chi^2_{BF}/NDF = 6.1/6.9, \ P(\chi^2) = 50.7\%$
  $\chi^2_{NULL}/NDF = 14.5/8.9, \ P(\chi^2) = 10.1\%$
Oscillation Fit with $E_\nu > 200$ MeV  
(include low $E_\nu$ v-mode effects)

- Results for $8.58 \times 10^{20}$ POT.
- Assume simple scaling of neutrino low energy excess; subtract 17 events from low energy region (200-475 MeV).
- Maximum likelihood fit method.
- Best Fit Point ($\Delta m^2$, $\sin^2 2\theta$) = (4.6 eV$^2$, 0.0037) 
$P(\chi^2, \text{BF})= 76.5\%$ 
$P(\chi^2, \text{NULL})= 28.3\%$
L/E Plot

- Data used for LSND and MiniBooNE correspond to 20<E<60 MeV and 200<E<3000 MeV, respectively.
- Oscillation probability is event excess divided by the number of events expected for 100% $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ transformation.
- $L$ is reconstructed distance travelled by the antineutrino from the mean neutrino production point to the interaction vertex; $E_\nu$ is the reconstructed antineutrino energy.

The data points include both statistical and systematic errors.
Comparison of $\nu_e$ and $\bar{\nu}_e$ Appearance Results

Neutrino $\nu_e$ Appearance Results (6.5E20POT)

Antineutrino $\bar{\nu}_e$ Appearance Results (8.58E20POT)
Low Energy Excess: How does it scale?

- Excess above background in 200<E<475 MeV is 38.6±18.5 events.
- Scaling from what is observed in neutrino mode we may test various hypotheses.
- Expected number of events in anti-neutrino mode assuming particular background as the source of low-E excess in neutrino mode:
  - Total background: 50
  - Neutrino contamination only: 17
  - $\Delta\rightarrow N\gamma$ decays: 39
  - Dirt: 46
  - Protons on target (neutrals in secondary beam): 165
  - $K^+$ in secondary beam: 67
  - NC $\pi^0$: 48
  - Inclusive CC: 59
Conclusions

• Significant $\nu_e$ and $\bar{\nu}_e$ excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE
• With new data update excess is indicated at low energy, as with neutrinos.
• Antineutrino data are consistent with LSND; significance of oscillation signal is reduced.
• Antineutrino results are statistics-limited: MiniBooNE requested $\sim 15 \times 10^{20}$ POT to complete the run.
Future MiniBooNE Running

MiniBooNE Collaboration requested 15x10^{20} POT to complete the run in current configuration.

The data set will probe LSND signal at 2-3 $\sigma$ level.
MiniBooNE Neutrino & Antineutrino Disappearance Limits

A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

$V_{\mu} \rightarrow V_x$

$\Delta m^2 (eV^2)$

$\sin^2(2\theta)$

* best fit: $(31.30, 0.96)$ with $\chi^2$ of 5.43, $\chi^2$(null) of 10.29

- MiniBooNE 90% CL limit
- best fit: $(31.30, 0.96)$ with $\chi^2$ of 5.43, $\chi^2$(null) of 10.29
- 90% CL excluded, CDHS
- 90% CL excluded, CCFR

$\bar{V}_{\mu} \rightarrow \bar{V}_x$

$\Delta m^2 (eV^2)$

$\sin^2(2\theta)$

- MiniBooNE 90% CL sensitivity
- 90%CL excluded, CCFR
MiniBooNE/SciBooNE Joint $v_\mu$ Disappearance Search

MiniBooNE only error

Error for this joint analysis
MiniBooNE/SciBooNE Joint $\nu_\mu$ Disappearance Search

Use the CC rate measured at SciBooNE to constrain the MiniBooNE rate and test for disappearance

Two analysis methods:

**Simultaneous fit**
1) Fit SciBooNE and MiniBooNE data simultaneously for oscillation
2) Constraint applied within fit, effectively removes systematic uncertainties shared by both detectors

**Spectrum fit**
1) Extract neutrino energy spectrum from SciBooNE data  \cite{PhysRevD83:012005,2011}
2) Apply correction to MiniBooNE energy spectrum
3) Fit for oscillation at MiniBooNE
4) Systematics reduced by extraction process
BooNE: Near Detector at ~200 m
(LOI arXiv:0910.2698)

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation

![Diagram of sensitivity](image)

10$^{20}$ Far + 1$^{e20}$ Near POT

6.5$^{e20}$ Far + 1$^{e20}$ Near POT

Sensitivity (Antineutrinos)

Sensitivity (Neutrinos)
BooNE: Near Detector at ~200 m

- Much better sensitivity for $\nu_\mu$ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation

![Graphs showing $\nu_\mu$ Disappearance $\chi^2$](image1)

![Graphs showing $\nu_\mu$ Disappearance $\chi^2$](image2)
Neutrino Cross Sections

- 8 neutrino cross section publications

- have measured cross sections for 90% of $\nu$ interactions in MB

Diagram:
- NC EL
  - PRD 82, 092005 (2010)
- CC $\pi^+$
  - PRL 103, 081802 (2009)
  - PRD 83, 052007 (2011)
- multi-$\pi$
- CC $\pi^0$
- NC $\pi^-$
  - PRD 81, 013005 (2010)
• have measured cross for 90% of $\nu$ interaction
νμ CCQE Scattering


Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(n)$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

Nuclear Effects to the Rescue?

• possible explanation: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)

• large enhancement from short range correlations (SRC) and 2-body currents

• can predict MiniBooNE data without having to increase $M_A$ (here, $M_A=1.0$ GeV)

Martini et al., PRC 80, 065001 (2009)

From Sam Zeller
Nuclear Effects to the Rescue?

- possible explanation: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)
  J. Grange, NuInt11

R. Dharmapalan, NuInt11

- could this explain the difference between MiniBooNE & NOMAD?

NOMAD: \( \mu \) & \( \mu + p \)

MiniBooNE: \( \mu \) + no \( \pi \)'s + any \# p's

jury is still out on this

need to be clear what we mean by "QE"

From Sam Zeller
Is the Neutrino Energy Estimated Correctly in CCQE?

Meson Exchange Diags.

Electron Scattering
$^{56}$Fe, q=0.55GeV/c
Antineutrino Cross Sections

- 2 antineutrino cross section papers

- additional antineutrino analyses currently underway
neutralino CWZ

Preliminary
Neutrino Flux Revisited

- First measurement of neutrino contribution to anti-neutrino beam with non-magnetized detector

- **3 independent, complementary** measurements
  - $\mu^+/\mu^-$ angular distribution
  - $\pi^-$ capture
  - $\mu^-$ capture

- Demonstration of techniques for other non-magnetized detectors looking for $CP$
  - NOvA, T2K, LBNE, etc.
Conclusions

- MiniBooNE Neutrino Cross Sections are more interesting than expected!
- Theorists & Experimentalists must carefully specify what they mean by QE and what is assumed.
- Fermi Gas Model is inadequate for $\nu$-nucleus inclusive scattering.
- Realistic models are required and have to include initial and final state correlations and 2-body currents.
- Differences between neutrino & antineutrino cross sections and energy reconstruction must be better understood when searching for CP Violation.