Title: Results from the MiniBooNE Experiment

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Abstract: We present the results from the MiniBooNE neutrino oscillations search in which no significant excess of events is observed above background in the energy range from 475 MeV to 3000 MeV. For lower energies an excess of events that is not consistent with a two neutrino oscillation model is observed. We present recent advances in the understanding of this excess, including a study of muon and electron neutrinos from the nearby NuMI neutrino source. The techniques used in the first oscillation analysis are discussed as well the use of a recent analysis that combines two different electron neutrino candidate samples with a high statistics muon neutrino sample in the oscillations fit to reduce systematic uncertainties.
Outline

The experiment and the oscillations result
NC $\pi^0$ rate measurement
Combining analyses
Compatibility of high $\Delta m^2$ experiments
Event excess below oscillations analysis threshold
Data from the NuMI beam at MiniBooNE
Summary
The MiniBooNE Collaboration

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Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University

Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

Alexis A. Aguilar-Arevalo
Results from the MiniBooNE Experiment
PASCOS’08
June 3, 2008
The MiniBooNE Strategy

Test the LSND indication of anti-electron neutrino oscillations
keep same $L/E$, change beam energy and systematic errors

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)$$

Neutrino Energy (E):
- MiniBooNE: ~600 MeV
- LSND: ~30 MeV

Baseline (L):
- MiniBooNE: ~540 m
- LSND: ~30 m

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Integrated Fluxes: $\nu_\mu = 93.8\%$, $\nu_e = 0.5\%$, $\bar{\nu}_\mu = 5.7\%$, $\bar{\nu}_e = 0.08\%$
The MiniBooNE Detector

541 meters downstream of target
3 meter overburden of dirt
12 meter diameter sphere
Filled with 800 t of pure mineral oil
\[ (CH_2 \quad \text{density} \quad 0.845 \text{ gr/cm}^3, \quad n=1.47) \]

Fiducial volume 450 t
1280 inner 8” phototubes – 10% coverage
240 veto phototubes
Less than 2% tubes failed during run
Neutrino Interactions

MiniBooNE typical $\nu$ energy

- $5.6 \times 10^{20}$ POT in neutrino mode (10/02-12/05).
- 193,709 $\nu_\mu$ CCQE interaction candidates

\( \nu \) events in the detector

- Cosmic \( \mu \) rejected with low veto activity cut.
- Exponential decay: \( e \) from \( \mu \) decay:
  Rejected with minimum tank hits cut.

Sub-events:

- \( \mu \) from \( \nu_e \) CCQE interactions have typically two sub-events.
- \( \nu_e \) CCQE interactions, typically one sub-event.
Oscillation analysis structure

Two algorithms used:

(1) Track Based Likelihood (TBL*)

Uses direct reconstruction of particle types and likelihood ratios for PID.

(2) Boosted Decision Tree (BDT)

Uses less detailed reconstruction, and a set of "low level" variables combined in BDT algorithm into a PID score.

The TBL analysis had higher sensitivity to oscillations, hence was chosen for primary results.
MiniBooNE First Results (April, 2007)

Data consistent with expected background
⇒ Inconsistent with a $\nu_\mu \to \nu_e$ oscillations

Exclude region in parameter space:

Oscillation Search Region
$475 < E_\nu < 1250$ MeV

- data: $380 \pm 19$ (stat) events
- expectation: $358 \pm 35$ (sys) events
- significance: $0.55 \sigma$

Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)$

Probability of Null Fit: 93%
Probability of Best Fit: 99%

Oscillation Signal

⇒ An Excess of “ν_e” Events over Expectation

All the major backgrounds for the oscillation search can be constrained directly from measurements using MiniBooNE data

- **NC π^0** production: (arXiv:0803.3423, accepted for publication by Phys. Rev. Lett.)
  Largest mis-ID background, where one of the decay photons is missed.
  MiniBooNE cannot distinguish electrons from single gammas.
  Rate constrained from dedicated NC π^0 sample. Also constrains radiative Δ decays:
  \[ \Delta \rightarrow N\gamma \]  

- **External events (Dirt):**
  Backgrounds from interactions with material outside of the detector. Rate constrained from dedicated sample.

- **Intrinsic kaon decay ν_e’s:**
  Partially constrained by observed ν_e events at high energy where there are no oscillation events.

- **Intrinsic muon decay ν_e’s:**
  Largest intrinsic ν_e background. Highly constrained by the observed ν_μ events. The constraint can applied by using the combined ν_e/ ν_μ oscillation fit.
Measurement of $\nu_e \text{ NC } \pi^0$ Rate and constraint of $\nu_e$ of Mis-IDs

Largest NC $\pi^0$ sample ever collected (28,600 $\pi^0$ events)

- $\pi^0$ rate measured to a few percent.
- Critical to oscillation analysis → without $\pi^0$ rate errors would be ~25%
- First measurement of coherent NC $\pi^0$ production off $^{12}$C below 2 GeV (19.5±2.7 %).

TBL Analysis: expected events

\( \nu_e \) candidate sample composition shown below:

**Stacked backgrounds:**
- \( \nu_e^K \)
- \( \nu_e^\mu \)
- \( \nu_e^\tau \)
- \( \pi^0 \)
- dirt events
- \( \Delta \rightarrow N \gamma \)
- Other

**475 MeV – 1250 MeV**

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e^K )</td>
<td>94 ± 27</td>
</tr>
<tr>
<td>( \nu_e^\mu )</td>
<td>132 ± 10</td>
</tr>
<tr>
<td>NC ( \pi^0 )</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>Dirt</td>
<td>17 ± 3</td>
</tr>
<tr>
<td>( \Delta \rightarrow N \gamma )</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>Other</td>
<td>33 ± 6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>358 ± 35</td>
</tr>
<tr>
<td><strong>LSND best fit ( \nu_\mu \rightarrow \nu_e )</strong></td>
<td>126 ± 21</td>
</tr>
</tbody>
</table>

**Sig/\sqrt{Bkgd} = 6.8**

\[
E_N^{QE} = \frac{1}{2} \frac{2M_P E_\ell - m_\ell^2}{M_P - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)\cos^2 \theta}}
\]
A Combined $\nu_e$ BDT, $\nu_e$ TBL, $\nu_\mu$ CCQE Oscillations Fit

Do oscillation fit to the observed and $\nu_e$ BDT, $\nu_e$ TBL, and $\nu_\mu$ CCQE energy distributions by minimizing the following $\chi^2$ statistic:

$$
\chi^2 = \sum \left( \begin{array}{c}
\Delta_{i}^{\nu_e \text{BDT/TBL}} \\
\Delta_{i}^{\nu_e \text{BDT/TBL}} \\
\Delta_{i}^{\nu_\mu \text{CCQE}} \\
\end{array} \right) \left( \begin{array}{ccc}
M_{ij}^{\nu_e \text{BDT/TBL}} & M_{ij}^{\nu_e \text{BDT/TBL}} & M_{ij}^{\nu_e \text{BDT/TBL}} \\
M_{ij}^{\nu_e \text{BDT/TBL}} & M_{ij}^{\nu_e \text{BDT/TBL}} & M_{ij}^{\nu_e \text{BDT/TBL}} \\
M_{ij}^{\nu_\mu \text{CCQE}} & M_{ij}^{\nu_\mu \text{CCQE}} & M_{ij}^{\nu_\mu \text{CCQE}} \\
\end{array} \right)^{-1} \left( \begin{array}{c}
\Delta_{i}^{\nu_e \text{BDT/TBL}} \\
\Delta_{i}^{\nu_e \text{BDT/TBL}} \\
\Delta_{i}^{\nu_\mu \text{CCQE}} \\
\end{array} \right).
$$

where $\Delta_{i}^{\nu_e \text{BDT/TBL}} = \text{Data}_{i}^{\nu_e \text{BDT/TBL}} - \text{Pred}_{i}^{\nu_e \text{BDT/TBL}}$, $\Delta_{i}^{\nu_\mu \text{CCQE}} = \text{Data}_{i}^{\nu_\mu \text{CCQE}} - \text{Pred}_{i}^{\nu_\mu \text{CCQE}}$.

Systematic (and statistical) uncertainties are included in $(M_{ij})^{-1}$ matrix

- Covariance matrix includes correlations between $\nu_e$ and $\nu_\mu$ events.
- Statistical error component takes care of event overlap in $\nu_e$ samples.
- 68% of TBL $\nu_e$'s are also BDT $\nu_e$'s $\Rightarrow$ improvement is expected.

Need to define which $\nu_\mu$ CCQE sample to use. In this calculation we use the $\nu_\mu$ CCQE sample of the BDT analysis in the combination. This causes a loss of sensitivity in the TBL component (not identical to first result).
The $\nu_e$ BDT + $\nu_e$ TBL + $\nu_\mu$ CCQE results:

**Paper at draft stage**

The combination of the three samples gives a significant increase in coverage in the region $\Delta m^2 < 1 \text{ eV}^2$.

Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

3$\sigma$ and 5$\sigma$ limits improve significantly: 5$\sigma$ is comparable to previous 3$\sigma$ at low $\Delta m^2$.

The combination yields a consistent result.

**Preliminary**

10%-30% improvement in 90% C.L. limit below $\sim 1 \text{ eV}^2$. 

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Alexis A. Aguilar-Arevalo

Results from the MiniBooNE Experiment

PASCO'08

June 3, 2008
Global data analysis

Combine results of MiniBooNE, LSND, KARMEN2, and Bugey.

Compatibility:
- How probable is it that all experimental results come from the same underlying $2\nu$ oscillation hypothesis?
- Assessed by combining the $\Delta \chi^2$ surface of each experiment.

<table>
<thead>
<tr>
<th>LSND</th>
<th>KARMEN2</th>
<th>MB</th>
<th>Bugey</th>
<th>Max. Comp. (%)</th>
<th>$\Delta m^2$ (eV$^2$)</th>
<th>$\sin^2 2\theta$</th>
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<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>25.36</td>
<td>0.072</td>
<td>0.256</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>3.94</td>
<td>0.242</td>
<td>0.023</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>16.00</td>
<td>0.072</td>
<td>0.256</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>2.14</td>
<td>0.253</td>
<td>0.023</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>73.44</td>
<td>0.052</td>
<td>0.147</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>27.37</td>
<td>0.221</td>
<td>0.012</td>
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Global data analysis

Combine results of MiniBooNE, LSND, KARMEN2, and Bugey.

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</tr>
</tbody>
</table>

Global data analysis, Allowed regions

Allowed Regions:
- Indicate where oscillation parameters would lie, at a given CL, assuming all experimental results can arise in a framework of 2-ν oscillations.
- The compatibility is the measure of this assumption.

LSND, KARMEN2 & MiniBooNE:
- 25.36% compatibility at $\Delta m^2 = 0.072$ eV$^2$, $\sin^2 2\theta = 0.256$.

LSND, KARMEN2, MiniBooNE & Bugey:
- 3.94% compatibility at $\Delta m^2 = 0.242$ eV$^2$, $\sin^2 2\theta = 0.023$. 

Alexis A. Aguilar-Arevalo  Results from the MiniBooNE Experiment  PASCOS'08  June 3, 2008
We observe an excess of events below 475 MeV

- 96 ± 17 ± 20 evts. above background for 300 < E_\nu^{QE} < 475 MeV.
- Opened bin from 200-300 MeV.
- Calculated full systematic errors.
- Excess persists below 300 MeV

<table>
<thead>
<tr>
<th>Reconstructed ( \nu ) energy bin (MeV)</th>
<th>200-300</th>
<th>300-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>total BG</td>
<td>284±25</td>
<td>274±21</td>
<td>358±35</td>
</tr>
<tr>
<td>( \nu_e ) intrinsic</td>
<td>26</td>
<td>67</td>
<td>229</td>
</tr>
<tr>
<td>( \nu_{\mu} ) induced</td>
<td>258</td>
<td>207</td>
<td>129</td>
</tr>
<tr>
<td>NC ( \pi^0 )</td>
<td>115</td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td>NC ( \Delta \rightarrow N\gamma )</td>
<td>20</td>
<td>51</td>
<td>20</td>
</tr>
<tr>
<td>Dirt</td>
<td>99</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>other</td>
<td>24</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>DATA</td>
<td>375±19</td>
<td>369±19</td>
<td>380±19</td>
</tr>
</tbody>
</table>

- \( \nu_{\mu} \) mis-ID BG dominates the new bin even more.
Investigating the low E excess \((E_\nu < 475 \text{ MeV})\)

No Reconstruction problems found
All low-E electron candidate events have been examined via event displays, consistent with 1-ring events.

Could be electrons or photons.

No Detector anomalies found
Example: rate of electron candidate events is constant (within errors) over course of run

\begin{figure}
\centering
\includegraphics[width=\textwidth]{event_POT_vs_day_300<E<475\text{ MeV}}
\end{figure}
Possible Sources of Single Gamma Backgrounds

MiniBooNE cannot tell an electron from a single gamma.

Processes that remove/absorb one of the gammas from a $\nu_\mu$ induced NC $\pi^0 \to \gamma\gamma$

- Should be in the GEANT detector Monte Carlo.
  Might be exceptions or inaccurate rates.
  - Example: photo-nuclear absorption

$\Rightarrow$ Under active investigation

$\nu$ processes that produce a final state single gamma:

- Example: Anomaly mediated photon production
  (Harvey, Hill, and Hill, arXiv:0708.1281[hep-ex])

$\Rightarrow$ Under active investigation
Advances in understanding the Low Energy excess:

- Included photo-nuclear effect (reduces excess)
  - Absent from GEANT3 – creates background from $\pi^0$'s

- More comprehensive hadronic errors.
  - e.g. uncertainties from final states in photo-nuclear interactions

- Better handling of beam $\pi^-$ production uncertainties
  - Errors propagated in a model-independent way

- Improved measurement of $\nu$ induced $\pi^0$'s (increases excess)
  - e.g. finer momentum binning

- Incorporation of MiniBooNE $\pi^0$ coherent/resonant measurement (increases excess)
  - No longer rely on more uncertain past results

- Better handling of radiative decay of $\Delta$ resonance (reduces excess)
  - As inferred from the measured $\pi^0$ rate.

Nearing the end of a comprehensive review of the $\nu_e$ appearance backgrounds and uncertainties. Not ready for release yet.
Check with neighboring neutrino source: \textbf{NuMI \rightarrow MINOS}

Test of principle of a horn-focused off-axis beam.


\textbf{NuMI flux composition:}
\[ \nu_\mu (66\%), \nu_\tau (2\%), \bar{\nu}_\mu (31\%), \bar{\nu}_e (1\%) \]

Enhanced in $\nu_\mu$ from $K$ decay because of the off-axis position (~111 mrad off axis).

\textbf{CCQE sample}

\textbf{CCQE sample}
MiniBooNE Present and Future

- Collected $\sim 6.6 \times 10^{20}$ POT in neutrino mode.
  - Making various cross section measurements.
  - Searching for various neutrino oscillations.
  - Publications being produced.

- Collected $\sim 2.5 \times 10^{20}$ POT in anti-neutrino mode.
  - Making various cross section measurements.
  - Searching for $\overline{\nu}_\mu$ disappearance.

- In Nov 2007 request for extra running in anti-neutrino mode granted.
  - LSND was an indication of $\overline{\nu}_\tau$ appearance.
  - Extra $\sim 2.5 \times 10^{20}$ for a grand total of $\sim 5 \times 10^{20}$ POT.
  - Will take data during FY2008 and FY2009.
Summary

- **MiniBooNE** observes no evidence for $\nu_\mu \rightarrow \nu_\tau \ 2\nu$ oscillations.

- Combined BDT and TBL analysis sets tighter limit below $\Delta m^2 < 1 \text{ eV}^2$.

- High $\Delta m^2$ experiments (LSND, KARMEN2, MB & Bugey) compatible only at the 3.94\% level.

- Low energy excess under active investigation. Expect full update this summer.

- NuMI beam data is complementary to MiniBooNE flux. Only a small significance excess in the $\nu_\tau$ sample is seen with current uncertainties (will constrain them using $\nu_\mu$ sample as done with booster beam data).

- More analysis of more data in progress.