Results of MiniBooNE Experiment

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Outline

• MiniBooNE Experiment Description
• MiniBooNE’s Neutrino Oscillation Search Results with Neutrinos
• MiniBooNE’s Neutrino Oscillation Search Results with Anti-neutrinos
• Summary
Oscillation Status After LSND

This signal looks very different from the others...

- Much higher $\Delta m^2 = 0.1 - 10 \text{ eV}^2$
- Much smaller mixing angle
- Only one experiment!

- Three distinct neutrino oscillation signals, with $\Delta m^2_{\text{solar}} + \Delta m^2_{\text{atm}} \neq \Delta m^2_{\text{LSND}}$

- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics
This signal looks very different from the others...
- Much higher $\Delta m^2 = 0.1 - 10 \text{ eV}^2$
- Much smaller mixing angle
- Only one experiment!

In SM there are only 3 neutrinos

$\Delta m_{23}$

$\Delta m_{13}$

$\Delta m_{12}$

$\bar{v}_\mu \rightarrow \bar{v}_e$

$\nu_e \rightarrow \nu_X$

Atmospheric

$\nu_\mu \rightarrow \nu_X$

Solar MSW

Oscillation Status After LSND?
Oscillation explanation of LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 \( \nu' \) s.

Models developed with 1 or more sterile \( \nu' \)s (or other new physics models).

Simplified 3+2 Models for \( \nu_\mu \rightarrow \nu_e \):
- 2 independent \( \Delta m^2 \)
- 3 mixing parameters
- 1 Dirac CP phase
It was important to check LSND what was left to MiniBooNE

(Boo\textcolor{red}{\textit{ster}} Neutrino Experiment)
MiniBooNE Setup

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

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

<table>
<thead>
<tr>
<th>LSND:</th>
<th>MiniBooNE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>E \sim 30,\text{MeV}</td>
<td>E \sim 500,\text{MeV}</td>
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<tr>
<td>L \sim 30,\text{m}</td>
<td>L \sim 500,\text{m}</td>
</tr>
<tr>
<td>L/E \sim 1</td>
<td>L/E \sim 1</td>
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Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with $6.5\times10^{20}$ POT → assumes CP/CPT conservation

Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with $11.3\times10^{20}$ POT → direct test of LSND
MiniBooNE Detector:
- 12m diameter sphere
- 950000 liters of oil (CH$_2$)
- 1280 inner PMTs
- 240 veto PMTs

Detector Requirements:
- Detect and Measure Events: Vertex, E$_\nu$
- Separate $\nu_\mu$ events from $\nu_e$ events.
MiniBooNE Data

- Data taking: 2002-2012.
- Total POT collected $19.8 \times 10^{20}$.
- Neutrino mode: $6.5 \times 10^{20}$ POT.
- Antineutrino mode: $11.3 \times 10^{20}$ POT.
MiniBooNE Data

- Beam and Detector low level stability checks:
  - beam (neutrino/POT) stable to 2%
  - detector energy response to 1%.

\[ \nu/POT = (102.1 \pm 0.1) \times 10^{-17} \]
\[ \chi^2/ndf = 840.35/862 \]

\[ \bar{\nu}/POT = (20.79 \pm 0.05) \times 10^{-17} \]
\[ \chi^2/ndf = 815.44/782 \]
Čerenkov rings provide primary means of identifying products of $\nu$ interactions in the detector.

- $\nu_\mu n \rightarrow \mu^- p$
- $\nu_e n \rightarrow e^- p$
- $\nu_\mu p \rightarrow \nu_\mu p \pi^0$
- $\pi^0 \rightarrow \gamma\gamma$

**Particle Identification**

Beam $\mu$ candidate

$\mu$-decay $e$-candidate

Beam $\pi^0$ candidate
Energy Calibration

Tracker system

15% E resolution at 53 MeV

Michel electrons

δm ~ 20%

![Graphs and diagrams illustrating energy calibration and resolution](image)
Booster Flux at MiniBooNE

Neutrino-Mode Flux

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad E_{\text{avg}} \approx 0.8 \text{ GeV} \]
\[ K^+ \rightarrow \mu^+ \nu_\mu \]

\[ \sim 6\% \overline{\nu} \]

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

neutrino mode: \( \nu_\mu \rightarrow \nu_e \) oscillation search

antineutrino mode: \( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \) oscillation search

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

Antineutrino-Mode Flux

\[ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad E_{\text{avg}} \approx 0.6 \text{ GeV} \]
\[ K^- \rightarrow \mu^- \bar{\nu}_\mu \]

\[ \sim 18\% \nu \]
\( \nu_e, \bar{\nu}_e \) Event Rate Predictions

Events Rate = Flux \( \times \) Cross-sections \( \times \) Detector response

- External measurements (HARP, etc)
- \( \nu_\mu \) rate constrained by neutrino data
- External and MiniBooNE Measurements
  - \( \pi^0, \Delta \rightarrow N\gamma \), dirt, and intrinsic
  - \( \nu_e \) constrained from data.

- Detailed detector simulation and PID
  - Checked with neutrino data and calibration sources.

- A. A. Aguilar-Arevalo et al., “Measurement of \( \nu_u \) and \( \nu_\mu \) induced neutral current single \( \pi^0 \) production cross sections on mineral oil at \( E_\nu \sim 1 \) GeV”, Phys. Rev. D81, 013005 (2010).
Background Prediction

-Similar backgrounds in neutrino and anti-neutrino mode.

\[ \nu_\mu \rightarrow \nu_e \]

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
Background Prediction

- Intrinsic $\nu_e$
  - External measurements
  - HARP p+Be for $\pi^\pm$
  - Sanford-Wang fits to world $K^+/K^0$ data
  - MiniBooNE data constrained
  - SciBooNE data constraint.

Published PRD 79, 072002 (2009)
Published PRD 84, 012009 (2011)
Background Prediction

Neutral Current $\pi^0$

MiniBooNE NC $\pi^0$ measurement

Published PRD 81, 013005 (2010)

Constrains radiative $\Delta$ decays as well
Background Prediction

Neutral Current $\pi^0$

Published PLB 664, 41 (2008)

Measured Coherent/Resonant Ratio
Background Prediction

\[ \Delta \rightarrow N \gamma \]

Use MiniBooNE NC $\pi^0$ measurement to constrain...
Background Prediction

Dirt Events

- Events at high radius pointing toward center
- Low energy depositions

MiniBooNE measurement
Updates and news

• Updated neutrino results.
• Full anti-neutrino mode results: $11.3 \times 10^{20}$ POT compared to previous $5.7 \times 10^{20}$ POT (Phys.Rev.Lett.105:181801, 2010.).
Analysis improvements since last publication

- In situ measurement of wrong-size contamination in $\bar{\nu}$ beam (PRD84, 072005 (2011)):
  - $\nu_\mu$ CCQE angular fit and,
  - $\pi^+$ rate constraint.

- New SciBooNE constraint on intrinsic $\nu_e$ from $K^+$:
  - found $K^+$ production to be $0.85\pm0.12$ relative to prediction, consistent with original MiniBooNE assessment of $1.00\pm0.30$.
- Combined with world $K^+$ production data, reduces error on $K^+$ flux to 9% in MiniBooNE energy range.
- Leading error on $K^+$ background becomes $\sim20\%$ error on cross-section.
Analysis improvements since last publication

- CC $\pi^+$ events (bkg for $\nu_\mu$ CCQE sample when $\pi^+$ is absorbed) $Q^2$ reweighting applied based on internal MiniBooNE measurement).
- See PRD83, 052007 (2011) for details.
• $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.

• Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics (doubled) in control samples:
  - Dirt neutrino background.
  - Neutral-current $\pi^0$ production.
Oscillation Fit Method

- Identical to previous result
- Maximum likelihood fit:
  \[
  -2 \ln(L) = (x_1 - \mu_1, ... x_n - \mu_n) M^{-1} (x_1 - \mu_1, ... x_n - \mu_n)^T + \ln(|M|)
  \]
  
  \[M = M_{om} + M_{xsec} + M_{flux} + M_{\pi 0} + M_{dirt} + M_{K0} + ...\]

- Simultaneously fit
  - $\nu_e$ CCQE sample
  - High statistics $\nu_\mu$ CCQE sample

- $\nu_\mu$ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties
  - Cross section uncertainties (CCQE process)
The following three distinct samples are used in the oscillation fits:

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

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

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

logL calculated using both datasets ($\nu_e$ and $\nu_\mu$ CCQE), and corresponding covariance matrix
Updated Neutrino Appearance Results

- Excess (200-1250 MeV): $146.3 \pm 28.4 \pm 40.2$.
- Some tension between 3+1 model fits in two energy regions (1.4% probability to see $3.73 \rightarrow 13.24$ when including low E).

<table>
<thead>
<tr>
<th>ν mode</th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>22.81</td>
<td>6.35</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>0.5%</td>
<td>36.6%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>13.24</td>
<td>3.73</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>6.12%</td>
<td>42.0%</td>
</tr>
</tbody>
</table>
Low Energy Excess

- What can we say about the low energy excess?
  - Not a statistical fluctuation, statistical significance is 6σ.
  - Unlikely to be intrinsic $\nu_e$, small background at low E.
  - NC $\pi^0$ background dominates.
    - Reduces significance to 3σ.
    - Heavily constrained by NC $\pi^0$ in situ measurement.
  - Region where single $\gamma$ can contribute.
    - MB ties $\Delta \rightarrow N \gamma$ expected rate to be 1% of measured NC $\pi^0$ rate.
    - Number of theory calculations exist for various single $\gamma$ processes; all find total cross-section within 20% of MB $\sim 5 \times 10^{-42}$ cm$^2$/N.
    - Would require nearly 300% change to account for 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-ph0705.0107; G. K., NuFACT 07 conference]
– Anomaly mediated photon production
  [Harvey, Hill, and Hill, hep-ph0708.1281]
– New light gauge boson
– Neutrino decay
  [hep-ph/0602083]
– Extra dimensions
  [hep-ph/0504096]
– CPT/Lorentz violation
  [PRD(2006)105009]
– …

Range of possible explanations for observed excess

\[ \Delta m_{45}^2 \sim 0.1 - 100 \text{ eV}^2 \]

\[ \Delta m_{34}^2 \sim 0.1 - 100 \text{ eV}^2 \]

\[ \nu_{\mu} \rightarrow \nu_e \neq \overline{\nu}_{\mu} \rightarrow \overline{\nu}_e ? \]
\( \bar{\nu}_e \) Event Rate Predictions in Appearance Analysis

- We have collected about \(~1/5\) the number of interactions as in neutrino mode when same POT considered.
- Neutrino mode: \(6.5 \times 10^{20}\) POT.
- Antineutrino mode: \(11.3 \times 10^{20}\) POT.
  \(\rightarrow\) expected number of candidates in anti-nu mode \(~1/3\) of nu-mode.

- The flux per proton on target is lower (\(~\times 1.5\) in \(\bar{\nu}\) mode
- The cross section is lower (\(~\times 3\) in \(\bar{\nu}\) mode
- Background types and relative rates are similar for neutrino and antineutrino mode.
  - except inclusion of \(~16\%\) wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.
Antineutrino Appearance Results $11.3\times10^{20}$ POT

- Wrong sign $\nu_\mu$ assumed not to oscillate.
- Excess (200-1250 MeV): $78.2\pm20.0\pm23.4$
- No tension between fits in two energy regions.

<table>
<thead>
<tr>
<th>anti-$\nu$ mode</th>
<th>$E &gt; 200$ MeV</th>
<th>$E &gt; 475$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2(null)$</td>
<td>16.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>5.4%</td>
<td>24.6%</td>
</tr>
<tr>
<td>$\chi^2(bf)$</td>
<td>4.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>67.1%</td>
<td>49.2%</td>
</tr>
</tbody>
</table>
Comparison of $\nu_e$ and $\bar{\nu}_e$ Appearance Results

![Comparison of $\nu_e$ and $\bar{\nu}_e$ Appearance Results](image-url)
Combined $\nu_e$ and $\bar{\nu}_e$ Analysis

- Simultaneous fit of electron neutrino and electron antineutrino appearance candidates.
- Full correlated systematic error matrix used.
- Excess (200-1250 MeV): $240\pm34.5\pm52.6$ (3.8 $\sigma$)
- Best fit preferred over null at 3.6 $\sigma$.

<table>
<thead>
<tr>
<th>combined</th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>42.53</td>
<td>12.87</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>0.1%</td>
<td>35.8%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>24.72</td>
<td>10.67</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>6.7%</td>
<td>35.8%</td>
</tr>
</tbody>
</table>
3 + 2 Model

- Allows CP-violation.
- Fits better the shape of MiniBooNE excess.
- Better fit to world data (see for example arXiv:1207.4765 for recent global fit.)
L/E dependence

- Model independent view of the results.
- Data used for LSND and MiniBooNE correspond to $20 < E_\nu < 60$ MeV and $200 < E_\nu < 3000$ MeV, respectively.
- Oscillation probability is event excess divided by the number of events expected for $100\% \ \nu_\mu \rightarrow \nu_e$ 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 excess as a function of $L/E$ in MiniBooNE neutrino, antineutrino and LSND data is consistent.
Conclusions and Future Prospects

• MiniBooNE observes an excess of nue candidates in the 200-1250 MeV range in neutrino mode ($3\sigma$) and in anti-neutrino mode ($2.5\sigma$).
• The combined excess is $240 \pm 34.5 \pm 52.6$ events ($3.8\sigma$).
• Some tensions in data within simple 2 neutrino oscillation model ($3 + 1$).
• Much better fit $3 + 2$ neutrino oscillation model.

• Running since 2002 in both neutrino and antineutrino mode, MiniBooNE has successfully accomplished primary goals and produced evidence that supports the claims of LSND oscillations.
• Being a one detector oscillations experiment, its systematic uncertainties now nearly dominate the total measurement error, therefore, more statistics in either neutrino or antineutrino mode do not significantly add new information to the question of oscillations.
• It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC $\gamma$ background, or something else.

• Collaboration considering benefits of future running: running under various configurations possible (detector capabilities enhanced with addition of scintillator, beam off-target mode and with beam absorber).
Thank you!
Backup Slides
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.
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

$\text{(E} \geq 475 \text{ MeV)}$
Previous Antineutrino Mode Results (2010): 5.66E20 POT

- Results for 5.66E20 POT collected in antineutrino mode
- Only antineutrino’s allowed to oscillate in fit
- In $E < 475$ MeV: A small $1.3\sigma$ 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.

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

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

$$\chi^2/\text{NDF} = 7.96/3.89$$

$P(\chi^2) = 8.7\%$$
No evidence for oscillations: Limit is better than other experiments in 10-30 eV² region.

MiniBooNE/SciBooNE Joint $\bar{\nu}_\mu$ Disappearance Search

- Significant improvement in sensitivity in muon antineutrino disappearance search.
- No evidence for oscillations.
- Results published: arXiv:1208.0322 [hep-ex], accepted by PRD.