MiniBooNE and BooNE

1. MiniBooNE Appearance Results
2. Other Anomalies
3. Resolution: The BooNE Proposal
4. Conclusions
Synopsis:

- A number of anomalies are appearing in neutrino data in the region of \( \Delta m^2 \sim \text{an eV}^2 \)

- Predominantly from single detector experiments...

- There is some possibility that the effects are due to oscillations between sterile neutrinos and active neutrinos

- A definitive experiment is warranted

- BooNE would be such an experiment
Motivation....

Anomalies in Neutrino Data
Motivation....

Excess Events from LSND still remain:

- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Signature: Cerenkov light from $e^+$ with delayed n-capture (2.2 MeV)
- Excess: $87.9 \pm 22.4 \pm 6.0$ (3.8s)
- The data was analysed under a two neutrino mixing hypothesis*

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 \, L \, \Delta m^2}{E} \right)$$

$$= 0.245 \pm 0.067 \pm 0.045 \%$$

KARMEN at a distance of 17 meters saw no evidence for oscillations $\rightarrow$ low $\Delta m^2$
Reactor Anomaly in $\bar{\nu}_e$ Data

- Inclusion of new beta decay estimates in reactor flux calculations
- Increases expected flux
  
  Best fit: $0.943 \pm 0.023$
  $P_{\text{osc}} \sim 10\%$, $\Delta m^2 \sim 1$ eV$^2$
Gallium Source Anomaly in $\nu_e$ Data

- Observed too few $\nu_e$ interactions observed from an electron capture source
Can the anomalies be due to a more complicated oscillation picture?

Sterile neutrino models

- 3+2 \rightarrow \text{next minimal extension to 3+1 models}

- 2 \text{ independent } \Delta m^2
- 4 \text{ mixing parameters}
- 1 \text{ Dirac CP phase which allows difference between neutrinos and antineutrinos}

Oscillation probability:

\[ P\left( \nu_\mu \rightarrow \nu_e \right) = 4|U_{\mu 4}|^2|U_{e 4}|^2 \sin^2 \theta_{41} + 4|U_{\mu 5}|^2|U_{e 5}|^2 \sin^2 \theta_{51} + \]
\[ + 8 |U_{\mu 5}| |U_{e 5}| |U_{\mu 4}| |U_{e 4}| \sin \theta_{41} \sin \theta_{51} \cos (\theta_{54} \pm \phi_{45}) \]
Cosmology Fits for the Number of Sterile Neutrinos

**Motivation....**

\[ 3 + N_s \]

- **CMB + LSS + ΛCDM**

  \[ N_s = 1.6 \pm 0.9 \]

  Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301

- **BBN**:

  \[ N_s = 0.64 \pm 0.4 \]

Motivation....

MiniBooNE Data
MiniBooNE looks for an excess of electron neutrino events in a predominantly muon neutrino beam.

Neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

Antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search
Data stability

- Very stable throughout the run
Meson production at the Proton Target

Pions(+/−):

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:

- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed
Separating muon-like and electron-like events by using a likelihood ratio technique

$\log(L_e/L_m) > 0$ favors electron-like hypothesis

Note: photon conversions are electron-like.
This does not separate $e/\pi^0$.

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

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Reconstruction of NC π^0 events

Separating electrons from neutral current π^0s by using a likelihood ratio combined with the γγ invariant mass.
Data plotted vs L/E

5.66×10^{20} \text{ POT}  
(> 1×10^{21} \text{ to date})
Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data
Antineutrino mode MB results Full Energy Range

- Results for $5.66 \times 10^{20}$ POT

- Maximum likelihood fit in *simple 2 neutrino model*

- Null excluded at 99.5% with respect to the two neutrino oscillation fit
Conclusions (I)

Significant $\nu_e$ ($\sim 3\sigma$) and $\bar{\nu}_e$ ($\sim 2.75\sigma$) excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE.

Antineutrino mode: statistical errors dominate (more data?)

MiniBooNE plans has now accumulated $>10^{21}$ protons on target in anti-neutrino mode and we hope to release results this summer.

Difficulties remain:
- Cannot determine whether excesses are due to an oscillation phenomena because MiniBooNE has only one detector
- Need to vary $E$ and $L$
Long-Baseline News, May 2010:

“ *** LSND effect rises from the dead… “
A Letter of Intent to Build a MiniBooNE Near Detector: BooNE

October 12, 2009

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BooNE

- Cloning a MiniBooNE detector for ~200m


- Accumulate a sufficient data sample in < 1 year

- will dramatically reduce errors in neutrino mode, the 3σ low energy excess has a ~ 6σ significance with statistical errors only.

- Many short runs for checking systematic effects would be possible, as was done for MINOS (e.g. 25 meter absorber, different horn currents).

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New Location at 200 meters from BNB Target
Neutrino Fluxes at Near and Far Locations
Far to Near Neutrino Flux Ratios at 200 m

MiniBooNE Far/Near fluxes Scaled by $1/r^2$

Neutrino mode

Anti-neutrino mode

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$\nu_\mu$ Charged Current Event Rates Near and Far

Quasi elastic event rates
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Background prediction $\bar{\nu}$ mode

<table>
<thead>
<tr>
<th>5.66e20 Protons on Target</th>
<th>200-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>13.45</td>
<td>31.39</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>8.15</td>
<td>18.61</td>
</tr>
<tr>
<td>$K^0$</td>
<td>5.13</td>
<td>21.2</td>
</tr>
<tr>
<td>Other $\bar{\nu}_e$</td>
<td>1.26</td>
<td>2.05</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>41.58</td>
<td>12.57</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$</td>
<td>12.39</td>
<td>3.37</td>
</tr>
<tr>
<td>dirt</td>
<td>6.16</td>
<td>2.63</td>
</tr>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>4.3</td>
<td>2.04</td>
</tr>
<tr>
<td>Other $\nu_\mu$</td>
<td>7.03</td>
<td>4.22</td>
</tr>
<tr>
<td>Total</td>
<td>99.45</td>
<td>98.08</td>
</tr>
</tbody>
</table>
\[ \nu_e \] Background Uncertainties

- Unconstrained \( \nu_e \) background uncertainties
- Biggest contributors:
  - Detector response
  - Cross sections

<table>
<thead>
<tr>
<th>Uncertainty (%)</th>
<th>200-475MeV</th>
<th>475-1100MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ )</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>( \pi^- )</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>( K^+ )</td>
<td>2.2</td>
<td>4.7</td>
</tr>
<tr>
<td>( K^- )</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>( K^0 )</td>
<td>1.7</td>
<td>5.4</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>1.7</td>
<td>3</td>
</tr>
<tr>
<td>Cross sections</td>
<td>\textbf{6.5}</td>
<td>13</td>
</tr>
<tr>
<td>NC ( \pi^0 ) yield</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Hadronic interactions</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Dirt</td>
<td>1.6</td>
<td>0.7</td>
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<tr>
<td>Electronics &amp; DAQ model</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Optical Model</td>
<td>\textbf{8}</td>
<td>3.7</td>
</tr>
<tr>
<td>Total</td>
<td>13.4%</td>
<td>16.0%</td>
</tr>
</tbody>
</table>

(\( \bar{\nu}_\mu \) constrained error \( \sim 10\% \))
BooNE Performance

➢ Use full MiniBooNE sensitivity machinery

➢ Use identical detector response (fully correlated errors)

➢ $1 \times 10^{20}$ POT per mode ($2 \times 0.5$ years at current rates)

➢ Reweight MC events for fluxes at 200 meters

➢ Full oscillation analysis package applied
Sensitivity with Near/Far Comparison

• Near/Far comparison sensitivity
  ➢ Near location at 200 meter
    ✓ $1 \times 10^{20}$ pot $\sim 1$ yr of running
  ➢ Full systematic error analysis
    ✓ Flux, cross section, detector response

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Sensitivity with Near/Far Comparison Anti-nu Mode

- Near/Far comparison sensitivity
  - Near location at 200 meter
    - $1 \times 10^{20}$ pot $\sim$ 1 yr of running
  - Full systematic error analysis
    - Flux, cross section, detector response

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Neutrino Disappearance Sensitivity with Detector at 200 Meters
Antineutrino Disappearance Sensitivity with Detector at 200 Meters

\[ \nu_\mu \text{ Disappearance } \chi^2 \]

\[ \Delta m^2 (\text{eV}^2) \]

\[ \sin^2(2\theta_{\mu\tau}) \]

Preferred by some fits

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Conclusions and Outlook

Significant $\nu_e (3 \sigma)$ and $\bar{\nu}_e (2.75 \sigma)$ excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE

- The two modes do not appear to be consistent with a simple two flavor neutrino model
- Neutrino mode systematic errors dominate (near detector?)
- Antineutrino mode statistical errors dominate (more data?)
- MiniBooNE plans accumulate more data until the 2012 shutdown

BooNE proposal:

- Cloning or cannibalizing MiniBooNE at a near position following the $\bar{\nu}$ run
- Cost ~ 10M$ for new detector, 5M$ reusing the existing MiniBooNE detector.
- Data can be accumulated in < 1 yr at present proton delivery rates
BACKUP
We adjust the parameters of a Fermi Gas model to match our observed $Q^2$ Distribution.

Fermi Gas Model describes CCQE $n_m$ data well

$M_{A,\text{eff}} = 1.23 \pm 0.20 \text{ GeV}$

$\kappa = 1.019 \pm 0.011$

Also used to model $\nu_e$ and $\bar{\nu}_e$ interactions.
The most important types of neutrino events in the oscillation search:

Background Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents or exiting through veto.

Signal and Background
Electrons (or single photon):
Tag for \( \nu_\mu \rightarrow \nu_e \) CCQE signal.
1 subevent

Background \( \pi^0 \)s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.
Antineutrino mode MB results for $E>475$ MeV

($E>475$ avoids question of low energy excess in nu-mode)

- Results for 5.66E20 POT
- Maximum likelihood fit for *simple two neutrino model*
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $L / E_{\bar{\nu}}$ ($m / MeV$)

- LSND
- MB $\bar{\nu}$ mode $5.66 \times 10^{20}$ pot
Near/Far Sensitivity for Several Distances

- 150 m : $0.6 \times 10^{20}$ POT
- 200 m : $1.0 \times 10^{20}$ POT
- 250 m : $1.5 \times 10^{20}$ POT
- 300 m : $2.0 \times 10^{20}$ POT

Near/Far comparison relatively insensitive to detector distance for roughly the same number of events

- 200 meters gives similar flux shapes