MiniBooNE Oscillation Searches

Steve Brice (Fermilab) for the MiniBooNE Collaboration
Neutrino 2008
Outline

• **Electron Neutrino Appearance**
  – Oscillation Result
  – $\pi^0$ Rate Measurement
  – Combining Analyses
  – Compatibility of High $\Delta m^2$ Measurements
  – Low Energy Electron Candidate Excess
  – Data from NuMI Beam

• **Muon Neutrino Disappearance**

• **Anti-Electron Neutrino Appearance**

• **Summary**
The MiniBooNE Collaboration


2 National Laboratories, 14 Universities, 80 Researchers

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry-Riddle Aeronautical University
Fermi National Accelerator Laboratory
University of Florida

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

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The MiniBooNE Strategy

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

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

neutrino energy (E):

MiniBooNE: ~500 MeV
LSND: ~30 MeV

baseline (L):

MiniBooNE: ~500 m
LSND: ~30 m

Event rates:

$$\nu_\mu = 98.1\%, \ \nu_e = 0.6\%, \ \bar{\nu}_\mu = 1.2\%, \ \bar{\nu}_e = 0.03\%$$
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
  \((\text{CH}_2-\text{density 0.86, } n=1.47)\)
- Fiducial volume: 450 t
- 1280 inner 8” phototubes-10% coverage,
- 240 veto phototubes
  (Less than 2% channels failed during run)
Oscillation Analysis Results: April 2007

track-based analysis:
Counting Experiment: $475 < E_\nu < 1250$ MeV
data: 380 events
expectation: $358 \pm 19$ (stat) $\pm 35$ (sys)
significance: $0.55 \sigma$

No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region
Measuring $\nu_\mu$ NC $\pi^0$ and Constraining $\nu_e$ MisIDs

- largest $\nu_\mu$ NC $\pi^0$ sample ever collected!

$28,600 \pi^0$ events
$\Delta m_\pi \sim 20 \text{ MeV/c}^2$

$\pi^0$ rate measured to a few percent
Critical input to oscillation result → without it, $\pi^0$ background errors would be $\sim 25$

Oscillation Analysis Strategy

Two algorithms were used:

- “track-based likelihood” (TBL)
  Uses direct reconstruction of particle types and likelihood ratios for particle-ID

- “boosted decision trees” (BDT)
  Set of low-level variables combined with BDT algorithm -> PID “score”

- In the end, the TB analysis had slightly better sensitivity, so was used for primary results.
Combining $\nu_e$ BDT + $\nu_e$ TBL Samples

The combination of the two $\nu_e$ samples gives an increase in coverage in the region $\Delta m^2 < 1$ eV$^2$.

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

The combination yields a consistent result.

10%-30% improvement in 90% C.L. limit below $\sim 1$eV$^2$. 
Global Data Analysis

• Combine results from several experiments -- LSND, MiniBooNE, Karmen and Bugey

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

• Allowed regions
  – Indicate where oscillation parameters would lie, at a given CL, assuming all expt. results can arise in a framework of 2-ν osc.
  – The compatibility is the metric for the validity of this assumption.

Global Fits to Experiments

<table>
<thead>
<tr>
<th>LSND</th>
<th>KARMEN2</th>
<th>MB</th>
<th>Bugey</th>
<th>Max. Compat %</th>
<th>$\Delta m^2$</th>
<th>$\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>25.36</td>
<td>0.072</td>
<td>0.256</td>
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<tr>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>3.94</td>
<td>0.242</td>
<td>0.023</td>
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<tr>
<td>X</td>
<td>X</td>
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<td></td>
<td>16.00</td>
<td>0.072</td>
<td>0.256</td>
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<tr>
<td>X</td>
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<td>0.253</td>
<td>0.023</td>
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<td></td>
<td></td>
<td>73.44</td>
<td>0.052</td>
<td>0.147</td>
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<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>27.37</td>
<td>0.221</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Global Fit Results-2D Fits

Colors represent $\Delta \chi^2$

- **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$^2$, $\sin^2 2\theta = 0.023$
Low Energy $\nu_e$ Candidate Excess

- No significant excess at higher E, where $\nu_e$ bkgd dominates.

- Largest backgrounds at lower E are $\nu_\mu$-induced, in particular:
  - NC $\pi^0$
  - NC $\Delta \rightarrow N\gamma$
  - Dirt

<table>
<thead>
<tr>
<th>reconstructed neutrino energy bin (MeV)</th>
<th>200-300</th>
<th>300-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>375±19</td>
<td>369±19</td>
<td>380±19</td>
</tr>
<tr>
<td>total background</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>
</tbody>
</table>
Updates to Low Energy $\nu_e$ Prediction

Nearing the end of a comprehensive review of the $\nu_e$ appearance backgrounds and their uncertainties

$\rightarrow$ Not Quite Ready for Release Yet
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Arrows indicate whether effect is to increase or decrease the low energy data excess
The effects have different magnitudes despite the arrows all being the same size

• Included photonuclear effect

• Photonuclear absorption removes one of the gammas from a $\nu_\mu$-induced NC $\pi^0 \rightarrow \gamma\gamma$
  – Photonuclear absorption was missing from our GEANT3 detector Monte Carlo
  – Reduces size of excess
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  – e.g. uncertainties in final state following photonuclear interaction
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   – Errors propagated in model-independent way
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- **Incorporation of MiniBooNE $\pi^0$ coherent/resonant measurement**
  - No longer need to rely on more uncertain past results

- **Better handling of the radiative decay of the $\Delta$ resonance**
  - Comprehensive review of how the $\Delta^{0,+}$ radiative decay rate is inferred from the measured $\pi^0$ rate
Updates to Low Energy $\nu_e$ Cuts

Removing dirt events

In low energy region there is a significant background from neutrino interactions in the dirt outside the tank.

Dirt events tend to be at large radius, heading inward.

Add a new cut on “Distance to Wall backward” to reduce these.
Removing Dirt Events

“Distance to Wall Backwards” cut:

- Reduces dirt events by ~80%
- Reduces $\nu_e$ events by ~20%

MC upgrades and new cuts have no appreciable effect above 475 MeV
NuMI Events in MiniBooNE

The beam at MiniBooNE from NuMI is significantly enhanced in $\nu_e$ from K decay because of the 110 mrad off-axis position. MiniBooNE is 745m from NuMI target.

**NuMI event rates:**
- $\nu_\mu$: 81%
- $\nu_e$: 5%
- $\bar{\nu}_\mu$: 13%
- $\bar{\nu}_e$: 1%
**NuMI $\nu_\mu$ and $\nu_e$ Data**

Good agreement between data and Monte Carlo: the MC is tuned well.

Very different backgrounds compared to MB (Kaons vs Pions)

Ongoing effort to reduce $\nu_e$ CCQE sample systematics

1.26$\sigma$ excess < 900 MeV
MiniBooNE $\nu_\mu$ Disappearance Sensitivity

- MiniBooNE data 90% CL sensitivity (NOT limit from data)
- CDHS CCFR 90% CL
- Combined analysis with SciBooNE data will significantly improve this sensitivity
MiniBooNE Present and Future

• Taken ~6.6 x 10^{20} POT in neutrino mode
  – Making suite of cross-section measurements
  – Searching for various neutrino oscillations
  – Publications coming out

• Taken ~2.5 x 10^{20} POT in anti-neutrino mode
  – Making suite of cross-section measurements
  – Searching for anti-neutrino disappearance

• In Nov 2007 request granted for extra running for an anti-nue appearance search
  – LSND result was an indication of anti-nue appearance
  – Extra ~2.5 x 10^{20} POT (making grand total of ~5 x 10^{20} POT)
  – Should take FY2008 and FY2009 running
Anti-nue Appearance Sensitivity

Region allowed at 90% C.L. by joint analysis of LSND and KARMEN

Only anti-neutrinos allowed to oscillate

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Summary

• **Electron Neutrino Appearance**
  – Combining Analyses
    • Sets a tighter limit
  – Compatibility of High $\Delta m^2$ Measurements
    • High $\Delta m^2$ experiments compatible with 2v osc. at only 3.94% level
  – Low Energy Electron Candidate Excess
    • Full update coming this summer
  – Data from NuMI Beam
    • Sample complementary to MB flux, only small significance LE excess seen with current uncertainties

• **Muon Neutrino Disappearance**
  – Result this summer

• **Anti-Electron Neutrino Appearance**
  – Doubling current POT for result
Backups
Broad Range of Analyses

- **Oscillation**
  - Refined Nue appearance
  - Nuebar appearance
  - Numu and numubar disappearance
    - 1 PRL, ~3 further papers expected
- **Low Energy Excess**
  - Big effort
  - 2+ papers expected
- **Alternative Oscillations**
  - Phenomenology
  - CP violation, Lorentz violation, ...
  - 3+ papers expected
- **NuMI Events**
  - Large event rate from NuMI beam
  - Check on osc. and Low E
  - 1 paper being written
- **CCQE**
  - 1 PRL, 2 further papers expected
- **CC π+**
  - 2 papers expected
- **CC π0**
  - Reconstruction challenges overcome
  - 1 paper expected
- **NC π0**
  - 1 paper submitted PLB
  - Coherent/resonant in nu and anti-nu modes
  - Flux averaged cross-section measurement
  - 2 further papers expected
- **NC Elastic**
  - Flux averaged cross-section measurement
  - 1 paper expected
- **νμ-e Elastic**
  - Nu mag. Mom
  - 1 paper expected

- **No organizational separation between neutrino and anti-neutrino mode**
- **12 PhD Students + 6 graduated**

= PhD Student (6 already graduated)
\[ \nu_\mu \text{ NC Elastic} \]

Results (from 10% nu sample):

- NC elastic diff. cross section
  (per nucleon, n+p averaged, flux averaged)

- Flux Integrated Cross-Section
  \[ = 8.8 \pm 0.6\text{ (stat)} \pm 2.0\text{ (syst)} \times 10^{-40} \text{ cm}^2 \]

- Measured axial mass (NC)
  \[ = 1.34 \pm 0.38 - 0.25 \text{ GeV} \]

- work of Chris Cox, Indiana U., Ph.D. 2008
- further analysis on full nu data set and with goal of reducing systematic errors in progress
  (D. Perevalov, Alabama)
- eventual analysis goal:
  NC/CCQE ratio measurement and antinu data
Global Data Analysis

- Data provided as points on 2-D \( \Delta m^2 - \sin^2 2\theta \) grid
- Each pt = agreement between data & 2-\( \nu \) hypothesis at that point
- Data in \( \ln(L) \), \( \Delta \ln(L) \), \( \chi^2 \) grids
- Not able to obtain absolute \( \chi^2 \) (goodness of fit) from all experiments!
- Must use \( \Delta \chi^2 \) grids in this analysis
Two Methods

• Create $\Delta \chi^2$ grids in 2 ways

• 2-D grid uses global best fit point to calculate the $\Delta \chi^2$ at each point
  – Prob to observe all expt results if nature has 2-$\nu$ osc in this entire $\Delta m^2$ region

• 1-D (Raster Scan) uses local best fit point at each $\Delta m^2$ to produce $\Delta \chi^2$
  – Comp at each $\Delta m^2$, if nature truly had 2-$\nu$ osc at that specific $\Delta m^2$
Compatibility Calculation

• Construct a $\Delta \chi^2$ grid for each expt.
  – each pt = local value - best fit value

• Sum individual $\Delta \chi^2$ grids

• Compatibility = $\chi^2$ prob. of minimum of summed grid, using a reduced NDF
  – $\Sigma$(indep. $\alpha$) - (# indep $\alpha$ estimated from data)
  – ex: MB + LSND = 4 - 2 = 2 NDF

Allowed Region

• Each expt’s $\Delta \chi^2$ grid converted into $\Delta \chi^2$ prob grid using standard NDF (2, 1)
• Multiply $\Delta \chi^2$ prob grids together, produce $x$

$$P(x) = x \sum_{j=0}^{n-1} \frac{1}{j!} |\ln^{j}(x)|$$

• Allowed regions = closed contours in space
• Exclusion bands = non-closed contours
  – Values to R are excluded at a given CL

Roe, Probability and Statistics in Experimental Physics, (2001)
LSND, MB, Bugey, ± KAR2

- 2.14% vs 3.94%!
- Best fit point = 0.242 eV², 0.023 sin²2θ
- Including KARMEN2 increases the NDF used to calculate prob, but provides no increase in sensitivity!
Anomaly mediated neutrino-photon interactions at finite baryon density.

- Under active investigation, prediction of \( \sim 140 \left( \frac{g_o}{10} \right)^4 \) events, where \( g_o \) is 10 to 30.
- Can use photon energy and angle to check prediction.

(Harvey, Hill, and Hill, arXiv:0708.1281[hep-ph])