First Oscillation Results From MiniBooNE

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Double Beta Decay and Neutrinos Workshop 2007
Osaka, 2007
Outline

• Introduction
• MiniBooNE experiment.
• Oscillation analysis.
• First oscillation result.
• Conclusions.
**LSND Experiment**

**Liquid Scintillator Neutrino Detector** at Los Alamos Meson Physics Facility (LAMPF) accelerator

- Neutrino source: stopped pion and muon decays
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

- $L = 30$ m, $E = 30$-53 MeV

**Observed excess:**
- an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam, $87.9 \pm 22.4 \pm 6.0$ (3.8$\sigma$)
- which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:

**Points -- LSND data**
**Signal** (blue)
**Backgrounds** (red, green)
**LSND Oscillation Signal**

**LSND** observed excess in the context of two-neutrino oscillation:

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}
\]

Comparison with **KARMEN** and **Bugey** given the same oscillation model

Joint analysis with Karmen2:
64% compatible

*Church, et al., PRD 66, 013001*
Neutrino Oscillations – Pre MiniBooNE

In three neutrino model two $\Delta m^2$ constrain the third:

- $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta m^2$</th>
<th>Oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>$\Delta m^2 &gt; 0.1\text{eV}^2$</td>
<td>$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$</td>
</tr>
<tr>
<td>Atmos.</td>
<td>$\Delta m^2 \approx 2 \times 10^{-3}\text{eV}^2$</td>
<td>$\nu_\mu \leftrightarrow \nu_\tau$</td>
</tr>
<tr>
<td>Solar</td>
<td>$\Delta m^2 \approx 10^{-4}\text{eV}^2$</td>
<td>$\nu_\alpha \leftrightarrow \nu_\tau$</td>
</tr>
</tbody>
</table>

- 3 neutrino masses can not reconcile an order of magnitude difference in the 3 $\Delta m^2$.

Is there fourth neutrino?
- $Z^0$ boson resonance width measurements is consistent with only 3 weakly interacting neutrinos.

Possible solutions
- Sterile neutrino sector.
- Discover one of the three is not oscillations.
Test of LSND within the context of $\nu_\mu \rightarrow \nu_e$ appearance only is an essential first step:

- Keep the same L/E
- Higher energy and longer baseline – $E=0.5 – 1$ GeV; $L=500m$
- Different beam
- Different oscillation signature $\nu_\mu \rightarrow \nu_e$
- Different systematics
- Antineutrino-capable beam

MiniBooNE Experiment – E898 at Fermilab
MiniBooNE Collaboration


University of Alabama
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
MiniBooNE extracts beam from the 8 GeV Booster
• 4 ×10^{12} protons per 1.6 µs pulse delivered at up to 5 Hz.

6.3 ×10^{20} POT delivered.

Delivered to a 1.7λ Be target inserted into a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)
The MiniBooNE Detector

- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH₂)
  (Fiducial volume: 450 t)
- 1280 inner phototubes, 240 veto phototubes
Subevent: Multiple hits within a ~100 ns window form “subevents”

Most events are from $\nu_\mu$ CC interactions ($\nu + n \rightarrow \mu + p$) with characteristic two “subevent” structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

A 19.2 $\mu$s beam trigger window
- encompasses the 1.6 $\mu$s spill
- starts 4 $\mu$s before the beam

Timing and Subevents

Tank Hits

Hit Time (ns)
Event Topologies in MiniBooNE Detector

Electron/photon event – fuzzy ring
- short track, large scattering
- $\gamma$ converts and looks like electrons

Muon event
- long track, small scattering

$\pi^0$ event – two fuzzy rings
Oscillation Analysis

- Neutrino flux model.
- Neutrino cross sections model.
- Detector response model.
- Particle ID and reconstruction
- Systematic errors and checks
- Oscillation fit
Neutrino Flux Prediction

- GEANT4 based Monte Carlo simulates the neutrino flux in MiniBooNE beamline,
- high purity $\nu_\mu$ beam – 99%,
  small $\nu_e$ component – intrinsic $\nu_e$
  - background for $\nu_e$ appearance
  $\nu_\mu \rightarrow \nu_e$, $\nu_e / \nu_\mu = 0.5\%$
- “Intrinsic” $\nu_e + \bar{\nu}_e$ sources:
  $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (52%)  
  $K^+ \rightarrow \pi^0 e^+ \nu_e$ (29%)  
  $K^0 \rightarrow p e^- \nu_e$ (14%)  
  Other ( 5%)  
- Antineutrino content: 6%
\[ \pi^+ \text{ production cross section} \]

\[ \text{is parameterized from a fit to HARP } \pi^+ \text{ production cross section, using the standard Sanford-Wang parameterization.} \]

HARP (CERN) measured the \[ \pi^+ \] production cross section
- 5% \( \lambda \) Beryllium target
- 8.9 GeV proton beam momentum

HARP collaboration, hep-ex/0702024
K Production Cross Section

- K\(^+\) production cross section is parameterized from a fit to external data with beam momentum from 10-24 GeV.
- Feynman Scaling function is used parameterization.
- SW parameterization was also used and it’s completely covered by the FS uncertainty.

\( \sigma_k \) production cross section is also parameterized from external data using SW.

\( K^0 \) cross section is also parameterized from external data using SW.
**K⁺ Production Limit from LMC**

LMC - off-axis muon spectrometer viewing the decay pipe at 7°.

- High-$p_T$ $\mu$'s come from $K^+$ decays; Low-$p_T$ $\mu$'s come from $\pi^+$ decays

- Effective $|p|$ separation at this angle.

Constraint on the $K^+$ flux normalization:

- MC simulates $p$ and $K$ decays.
- No hadronic interaction backgrounds simulated.
- Plot shows data vs MC for well-identified muons in a region where we expect low backgrounds.

The upper limit on the $K^+$ flux normalization is 1.32.
Predicted event type fractions.

Predicted neutrino energy spectrum
Golden mode for oscillation search
\[ \nu_i n \rightarrow l^- p \]

- Clean signature in the detector.
- Neutrino energy is reconstructed from the reconstructed momentum and angle of the charged lepton.

\[
E^\text{CCQE}_\nu = \frac{m_N E_i - \frac{1}{2} m_i^2}{m_N - E_i + p_i \cos \theta_i}
\]

\[
Q^2 = -2E_\nu(E_i - p_i \cos \theta_i) + m_i^2
\]

- Nuclear target
- Nucleon is not excited
Default NUANCE model QE $Q^2$ distr. shows discrepancy with data.
  • reported by K2K (1kt) as well

From $Q^2$ fits to MB $\nu_\mu$ CCQE data:
  • $M_A^{\text{eff}}$ -- effective axial mass
  • $E_{\text{lo}}^{\text{SF}}$ -- Pauli Blocking parameter

From electron scattering data:
  • $E_B$ -- binding energy
  • $p_F$ -- Fermi momentum

Submitted for publication to PRL:
e-Print: arXiv:0706.0926

The $\pi^0$ decays to 2 photons, which can look “electron-like” mimicking the signal. <1% of $\pi^0$ contribute to background.

(CC $\pi^+$)
Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.

(NC $\pi^0$)
The $\pi^0$ decays to 2 photons, which can look “electron-like” mimicking the signal. (also decays to a single photon with 0.56% probability)
Constraining NC $\Delta$ Resonance

- Fully reconstructed $\pi^0$ events sample constrains the total NC $\Delta$ rate.

- Re-weight the MC $\pi^0$ using the measured momentum distribution and total rate.

- Reduces the uncertainty of the $\pi^0$ mis-ID/misreconstructed background.

- It constrains also $\Delta\rightarrow N\gamma$

Reweighting improves agreement in other variables, e.g.⇒
“Dirt” Events
ν interactions outside of the detector $N_{\text{data}}/N_{\text{MC}} = 0.99 \pm 0.15$

Event Type of Dirt after PID cuts

Cosmic Rays: Measured from out-of-beam data: $2.1 \pm 0.5$ events
We have developed a 39-parameter "Optical Model" based on internal calibration and external measurement.

**Primary light sources**

- **Cherenkov**
  - Emitted promptly, in cone known wavelength distribution
- **Scintillation**
  - Emitted isotropically
  - Several lifetimes, emission modes
- Studied oil samples using Indiana Cyclotron test beam
- Particles below Cherenkov threshold still scintillate

**Optical properties of oil, detectors:**

- **Absorption** (attenuation length >20m at 400 nm)
- Rayleigh and Raman scattering
- Fluorescence
- Reflections
Detector “Optical” Model

Timing distribution for PMT hits
- Calibration laser source inside tank
- Monte Carlo with full optical model describes most of the timing structure
Detector Callibration

Tracker system

15% E resolution at 53 MeV

δm~20%

Michel electrons

π^0 photon energies

Tracker & Cubes

Through-going cosmics

Visible energy range of oscillation signal
Events Reconstruction and Particle ID

Two parallel approaches to PID analysis:

Track/likelihood-based (TB)

PID is based on log-likelihood ratios of different particle hypotheses.

Boosted decision trees (BDT)

PID is based on algorithm extracting collective information from a large number of low level variables.
MiniBooNE is searching for a small but distinctive event signature.

Blind region:
- Electron-like events were sequestered - about 1% of the in-beam events.

The rest 99% of in beam events
- At the beginning highly restrictive.

- Rule for cuts to sequester events: $<1\sigma$ signal outside of the box
- Look closer and closer to the box as the PID and MC became more and more trustworthy.

Finally box was opened in series of steps.
Eliminating Cosmic Background

Progressively introducing cuts on the time window:

Raw data

Veto<6 removes through-going cosmics

This leaves “Michel electrons” $(\mu \rightarrow \nu_\mu \nu_e e)$ from cosmics

Tank Hits > 200 (effective energy cut) removes Michel electrons, which have 52 MeV endpoint.
Precuts:

- Only 1 subevent
- Veto hits $< 6$
- Tank hits $> 200$

And a radius precut:
- $R < 500$ cm
  (where reconstructed $R$ is algorithm-dependent)
Track-Based Analysis
Track Reconstruction

Predicts the probability for each tube to be “hit” based on the average number photo electrons (PE).

- detailed calculation of the PE, given the optical properties of the detector and the particle parameters (parameters in the fit), accounting for:
  - Non-uniform light source.
  - Prompt light
  - Delayed light
  - Indirect light
  - Angular profile of the produced light.

Several track hypothesis:
- a single track ($\mu, e$) is parameterized with 7 parameters –
  ($x^0, y^0, z^0, T^0, E^0, \theta^0, \phi^0$)

- two track fit to $\pi^0$ hypothesis includes additionally $\gamma_1, \gamma_2$ conversion lengths, energy and direction of $\gamma_2$ $\pi^0$ mass.

Perform likelihood fits to each event with different particle hypothesis ($\mu, e, \pi^0 \rightarrow 2 \gamma$ with and without $\pi^0$ mass constraint).
• Single track fit to muon and electron hypothesis

• \( \log(\frac{L_e}{L_\mu}) > 0 \) selects electron hypothesis.

• The cut is a quadratic function with energy, optimizing oscillation sensitivity.

• Separation is clean at high energies where muon-like events are long.
Track-Based Analysis Test of $e/\pi^0$ Separation

1 subevent
log($L_e/L_\mu$) > 0 (e-like)
log($L_e/L_\pi$) < 0 (\pi-like)
mass > 50 (high mass)
Track-Based Analysis
Checking the Sidebands

\( \chi^2 \) Prob for mass<50 MeV ("most signal-like"): 69%

1 subevent
\( \log(\frac{L_e}{L_\mu}) > 0 \) (e-like)
\( \log(\frac{L_e}{L_\pi}) < 0 \) (\( \pi \)-like)
mass<200 (low mass)
Track-Based Analysis
Predicted Background and Signal Efficiency

Efficiency:

“Precuts” + 
\( \log(L_e/L_\mu) + \)
\( \log(L_e/L_\pi) + \)
Invariant mass
**Boosted Decision Tree Analysis (BDT)**

- An algorithm optimized to combine many weakly discriminating variables into one that provides powerful separation
  
  \[ \text{B. Roe et al., Nucl. Inst. Meth. A543 577 (2005)} \]

- Procedure for building a “decision tree”:
  
  - Find the variable separating signal and background best.
  
  - for each of the two subsets repeat the process.
  
  - final nodes are called leaves (can not be further separated).
This tree is one of many possibilities...
A set of decision trees can be developed, each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees (“boosting”).

For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.

The total for all trees is combined into a “score”
Background and Signal Efficiency of BDT

Analysis cuts on PID score as a function of Energy

Monte Carlo Prediction - $\nu_e$

- $\nu_e$ from $\mu$
- $\nu_e$ from $K^+$
- $\nu_e$ from $K^0$
- $\pi^0$ misid
- delta
- dirt
- other

Efficiency after precuts

signal

background
Uncertainties, Constraints and Sensitivity
We have two categories of backgrounds:

Predictions of the backgrounds are among the nine sources of significant error in the analysis.
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty On $\nu_e$ background</th>
<th>Track Based /Boosted Decision Tree error in %</th>
<th>Checked or Constrained by MB data</th>
<th>Further reduced by tying $\nu_e$ to $\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux from $\pi^+/\mu^+$ decay</td>
<td>6.2 / 4.3</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Flux from $K^+$ decay</td>
<td>3.3 / 1.0</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Flux from $K^0$ decay</td>
<td>1.5 / 0.4</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>2.8 / 1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu$-cross section</td>
<td>12.3 / 10.5</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>NC $\pi^0$ yield</td>
<td>1.8 / 1.5</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>External interactions (“Dirt”)</td>
<td>0.8 / 3.4</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Optical model</td>
<td>6.1 / 10.5</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>DAQ electronics model</td>
<td>7.5 / 10.8</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>
Cross Section Uncertainties

(Many are common to $\nu_\mu$ and $\nu_e$ and cancel in the fit)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error/Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$, $E_{lo}^{SF}$, $\sigma$ norm QE</td>
<td>6%, 2% (stat+bkg), 10%</td>
<td>MB $\nu_\mu$ CCQE, MB $\nu_\mu$ CCQE</td>
</tr>
<tr>
<td>NC $\pi^0$ rate $\Delta \rightarrow N\gamma$ rate</td>
<td>few % (depends on $p_{\pi}$), ~10%</td>
<td>MB NC $\pi^0$ data, MB NC $\pi^0$ data, BR</td>
</tr>
<tr>
<td>$E_B$, $p_F$, $\sigma$ DIS</td>
<td>9 MeV, 30 MeV, 25%</td>
<td>External data, External data</td>
</tr>
</tbody>
</table>
Error Propagation

Use “Multisim” technique for error propagation:
- vary the parameters according to a full covariance matrix and obtain MC for each parameter set (ensemble of MC experiments).

Optical model:
- depends on 39 parameters such as absorption, scintillation, etc.
- ensemble of 70 full GEANT MC “experiments” to map the space of detector responses to the parameters.

Other:
- Flux and neutrino cross-section parameter variations do not affect the hit distributions for a given event, only the probability of that event occurring in the first place
- ensemble of 1000 MC by reweighting the same MC events: reduced MC statistics error and greatly reduced CPU usage.

Example of multisim outputs in a single osc. bin:

# of multisims  # events passing signal cuts in bin 500<E_{\nu}<600 MeV
**Error Matrix Calculation**

\[
E_{ij} \approx \frac{1}{M} \sum_{\alpha=1}^{M} \left( N_i^{\alpha} - N_i^{MC} \right) \left( N_j^{\alpha} - N_j^{MC} \right)
\]

- \(N\) is number of events passing cuts
- \(MC\) is standard monte carlo
- \(\alpha\) represents a given multisim
- \(M\) is the total number of multisims
- \(i,j\) are \(E_{\nu}^{QE}\) bins

Total error matrix is sum from each source.

TB: \(\nu_e\)-only total error matrix
BDT: \(\nu_\mu\)-\(\nu_e\) total error matrix

Correlations between \(E_{\nu}^{QE}\) bins from the optical model:
## Predicted Background Content (TB)

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>Miscellaneous $\nu_\mu$ Events</td>
<td>13 ± 5</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>NC Coherent &amp; Radiative $\gamma$</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Dirt Events</td>
<td>17 ± 3</td>
</tr>
<tr>
<td>$\nu_e$ from $\mu$ Decay</td>
<td>132 ± 10</td>
</tr>
<tr>
<td>$\nu_e$ from $K^+$ Decay</td>
<td>71 ± 26</td>
</tr>
<tr>
<td>$\nu_e$ from $K^0_L$ Decay</td>
<td>23 ± 7</td>
</tr>
<tr>
<td>$\nu_e$ from $\pi$ Decay</td>
<td>3 ± 1</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td><strong>358 ± 35</strong></td>
</tr>
<tr>
<td><strong>LSND signal</strong></td>
<td><strong>0.26% $\nu_\mu \rightarrow \nu_e$</strong></td>
</tr>
</tbody>
</table>
Set using $\Delta \chi^2 = 1.64$ @ 90% CL

MiniBooNE Sensitivity

- Track-based analysis has slightly better sensitivity to 2-neutrino oscillations.
- Therefore it’s the PRIMARY MiniBooNE result.

This is the culmination of the analysis

Next step: UNBLINDING Procedure in steps.
First Oscillation Results
Unblinding Steps

After applying all analysis cuts:

1. Fit sequestered data to an oscillation hypothesis, returning no fit parameters. Return the $\chi^2$ of the data/MC comparison for a set of diagnostic variables.

2. Open up the plots from step 1. The Monte Carlo has unreported signal. Plots chosen to be useful diagnostics, without indicating if signal was added.

3. Report the $\chi^2$ for a fit to $E_{\nu}^{QE}$, without returning fit parameters.

4. Compare $E_{\nu}^{QE}$ in data and Monte Carlo, returning the fit parameters. At this point, the box is open (March 26, 2007)
We re-examined our background estimates using sideband studies. We found no evidence of a problem.

However, knowing that backgrounds rise at low energy, we tightened the cuts for the oscillation fit (TB only):

\[ E_{\nu_{QE}} > 475 \text{ MeV} \]

We agreed to report events over the original full range:

\[ E_{\nu_{QE}} > 300 \text{ MeV} \]
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:

Counting Experiment: $475 < E_{\nu}^{QE} < 1250$ MeV

data: 380 events
expectation: $358 \pm 19$ (stat) $\pm 35$ (sys) events

significance: $0.55 \sigma$

No evidence of oscillations
Track Based energy dependent fit results:

- Data are in good agreement with background prediction.
- Best Fit (dashed): \((\sin^22\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)\)

Error bars are diagonals of error matrix.

Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%
Oscillation Limit

- The result of the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis is a limit on oscillations.
- $\chi^2$ probability, null hypothesis: 93%

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV
96 ± 17 ± 20 events above background, for $300 < E_n^{QE} < 3000$ MeV

Deviation: $3.7\sigma$

Full energy range:
- $300 < E_n^{QE} < 3000$ MeV
- $300 < E_\nu^{QE} < 475$ MeV
Energy Fit to Full Spectrum

Fit to the > 300 MeV range:

Best Fit (dashed): \((\sin^2 2\theta, \Delta m^2) = (1.0, 0.03 \text{ eV}^2)\)

\(\chi^2\) Probability: 18%

Examples in LSND allowed range
Counting Experiment: $300 < E_v^{QE} < 1600$ MeV

data: 971 events

expectation: $1070 \pm 33$ (stat) $\pm 225$ (sys) events

significance: $-0.38 \sigma$
Boosted Decision Tree $E_{\nu}^{QE}$ data/MC comparison:

Error bars are stat and sys (diagonals of matrix)

(sidebands used for constraint not shown)
Comparison of the Limits

- Energy-fit analysis:
  solid: TB
  dashed: BDT

- Independent analyses are in good agreement.

TB is still the primary analysis
1) There are various ways to present limits:
• Single sided raster scan (historically used, presented here)
• Global scan
• Unified approach (most recent method)

2) This result must be folded into an LSND-Karmen joint analysis.

Church, et al., PRD 66, 013001

We will present a full joint analysis soon.
MiniBooNE-LSND Compatibility Test

- For each $\Delta m^2$, determine the MB and LSND measurement:
  
  $$z_{MB} \pm \delta z_{MB}, \quad z_{LSND} \pm \delta z_{LSND}$$

  where $z = \sin^2(2\theta)$ and $\delta z$ is the $1\sigma$ error

- For each $\Delta m^2$, form $\chi^2$ between MB and LSND measurement

  $$\chi^2 = \frac{(Z_{MB} - Z_0)^2}{\sigma_{MB}^2} + \frac{(Z_{LSND} - Z_0)^2}{\sigma_{LSND}^2}$$

- Find $z_0$ that minimizes $\chi^2$
  
  (weighted average of two measurements) and this gives $\chi^2_{min}$

- Find probability of $\chi^2_{min}$ for 1 dof;
  
  this is the joint compatibility probability for this $\Delta m^2$
MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL
More papers supporting this analysis will follow, in the near future:

- NC$\pi^0$ production
- MiniBooNE-LSND-Karmen joint analysis

Further analyses of the neutrino data,
- Combined TB and BDT analysis,
- more exotic models for the LSND effect,
- Neutrino cross sections.

MiniBooNE is presently taking data in antineutrino mode.
Conclusions

• The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model.
• Therefore we set a limit on $\nu_\mu \rightarrow \nu_e$ appearance.

• Data show discrepancy vs. background at low energies, but spectrum is inconsistent with two-neutrino oscillation.

Accepted for publication in PRL:

e-Print: arXiv:0704.1500

A Search for electron neutrino appearance at the $\Delta m^2 \sim 1 \text{ eV}^2$ scale.
Acknowledgements

Our thanks to DOE, NSF and Fermilab