First Results from MiniBooNE

April 11, 2007
William Louis, Janet Conrad

for the MiniBooNE Collaboration
The 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
• Introduction
• The Neutrino Beam
• Events in the Detector
• Two Independent Analyses
• Errors, Constraints and Sensitivity
• Initial Results
MiniBooNE was approved in 1998, with the goal of addressing the LSND anomaly:

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 Collab, PRD 64, 112007*
Within a $\nu_\mu \rightarrow \nu_e$ appearance model,

$$P_{osc} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

This model allows comparison to other experiments:

- Karmen2
- Bugey

Joint analysis with Karmen2:

64% compatible

*Church, et al., PRD 66, 013001*
This is a simplistic interpretation.

\[ P_{osc} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]

A 3 neutrino picture requires

\[ \Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2 \]

\[ \Delta m_{23}^2 = m_2^2 - m_3^2 \]

\[ \Delta m_{12}^2 = m_1^2 - m_2^2 \]

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics.
However a test of LSND within the context of $\nu_\mu \rightarrow \nu_e$ appearance (no disappearance) is an essential first step:

- This is the simplest model which explains LSND.

- This model allows cross comparison with published oscillation results from LSND and other relevant past experiments (e.g. Karmen)
MiniBooNE’s Design Strategy...

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

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

Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

Order of magnitude longer baseline (~500 m) than LSND (~30 m)
Today we report MiniBooNE’s initial results on testing the LSND anomaly:

• A generic search for a ν_e excess in our ν_μ beam,

• An analysis of the data within a ν_μ → ν_e appearance context

This was a blind analysis.
The box was opened on March 26, 2007

Two independent analyses were performed.
The primary analysis was chosen based on ν_μ → ν_e sensitivity, prior to unblinding.
The Neutrino Beam
4 \times 10^{12} \text{ protons per 1.6 \mu s pulse delivered at up to 5 Hz.}

6.3 \times 10^{20} \text{ POT delivered.}

Results correspond to (5.58 \pm 0.12) \times 10^{20} \text{ POT}

MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 \lambda \text{ Be target}

within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by \times 6)
Modeling Production of Secondary Pions

- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum

Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024
Modeling Production of Secondary Kaons

K$^+$ Data from 10 - 24 GeV.
Uses a Feynman Scaling Parameterization.

data -- points
dash -- total error
(fit $\oplus$ parameterization)

K$^0$ data are also parameterized.

*In situ measurement of K$^+$ from LMC agrees within errors with parameterization*
Neutrino Flux from GEANT4 Simulation

“Intrinsic” $\nu_e + \bar{\nu}_e$ sources:
- $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (52%)
- $K^+ \rightarrow \pi^0 e^+ \nu_e$ (29%)
- $K^0 \rightarrow \pi e \nu_e$ (14%)
- Other (5%)

$\nu_e/\nu_\mu = 0.5$

Antineutrino content: 6%
Stability of running:

Observed and expected events per minute

Full v Run
Events in the Detector
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 (CH$_2$)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
  240 veto phototubes
- Simulated with a GEANT3 Monte Carlo
10% Photocathode coverage

Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

Time Resolution: 1.7 ns, 1.1 ns
Detected photons from
• Prompt light (Cherenkov)
• Late light (scintillation, fluorescence) in a 3:1 ratio for $\beta \sim 1$

Attenuation length: $>20$ m @ 400 nm

We have developed a 39-parameter “Optical Model” based on internal calibration and external measurement.
A 19.2 μs beam trigger window encompasses the 1.6 μs spill

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 $\mu \rightarrow \nu_\mu \nu_e e$
Progressively introducing cuts on the time window:

Raw data

Veto<6 removes through-going cosmics

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

Tank Hits > 200 (equivalent to energy) removes Michel electrons, which have 52 MeV endpoint
Predicted event rates before cuts
(NUANCE Monte Carlo)
D. Casper, NPS, 112 (2002) 161

Event neutrino energy (GeV)

Multi $\pi$
- NC $\pi^0$ 8%
- NC $\pi^\pm$ 4%
- CC $\pi^0$ 4%
- CC $\pi^\pm$ 25%
- CC QE 39%
- NC EL 16%

antineutrino background
CCQE
(Charged Current Quasi-Elastic)

39% of total

• Events are “clean” (few particles)
• Energy of the neutrino can be reconstructed

\[
E_{\nu}^{QE} = \frac{1}{2} \frac{2M_p E_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)\cos\theta_\ell}}
\]

Reconstructed from:
Scattering angle
Visible energy (E_{\text{visible}})

An oscillation signal is an excess of \(\nu_e\) events as a function of \(E_{\nu}^{QE}\)
Model describes CCQE $\nu_\mu$ data well

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

From electron scattering data:
- $E_b$ -- binding energy
- $p_f$ -- Fermi momentum

NUANCE Parameters:

data/MC~1 across all angle vs.energy after fit
The $\pi^0$ decays to 2 photons, which can look “electron-like” mimicking the signal...

<1% of $\pi^0$ contribute to background.

Events producing pions

**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”
- (also decays to a single photon with 0.56% probability)

(also decays to a single photon with 0.56% probability)
The types of particles these events produce:

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

$\pi^0$s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.
Two Independent Analyses
The goal of both analyses:

minimize background & maximize signal efficiency.

“Signal range” is approximately $300 \text{ MeV} < E_{\nu}^{\text{QE}} < 1500 \text{ MeV}$

One can then either:
- look for a total excess (“counting expt”)
- fit for both an excess and energy dependence (“energy fit”)

MiniBooNE signal examples:
- $\Delta m^2 = 0.4 \text{ eV}^2$
- $\Delta m^2 = 0.7 \text{ eV}^2$
- $\Delta m^2 = 1.0 \text{ eV}^2$
MiniBooNE is searching for a small but distinctive event signature.

In order to maintain blindness, Electron-like events were sequestered, Leaving ~99% of the in-beam events available for study.

Rule for cuts to sequester events: $<1\sigma$ signal outside of the box

Low level information which did not allow particle-id was available for all events.
Both Algorithms and all analyses presented here share “hit-level pre-cuts”:

Only 1 subevent
Veto hits < 6
Tank hits > 200

And a radius precut:
R<500 cm
(where reconstructed R is algorithm-dependent)
Analysis 1: “Track-Based” (TB) Analysis

Philosophy:

Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

This algorithm was found to have the better sensitivity to \( \nu_\mu \rightarrow \nu_e \) appearance. Therefore, before unblinding, this was the algorithm chosen for the “primary result”
Each event is characterized by 7 reconstructed variables: vertex \((x,y,z)\), time, energy, and direction \((\theta,\phi)\leftrightarrow(U_x, U_y, U_z)\).

Resolutions:
- vertex: 22 cm
- direction: 2.8°
- energy: 11%

\(\nu_\mu\) CCQE events

2 subevents
Veto Hits<6
Tank Hits>200
Rejecting “muon-like” events
Using $\log(L_e/L_\mu)$

$log(L_e/L_\mu)>0$ 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
Rejecting “$\pi^0$-like” events

Using a mass cut

Using log($L_e/L_\pi$)

Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity
Testing $e-\pi^0$ separation using data

1 subevent

log($L_e/L_\mu$)>0 (e-like)

log($L_e/L_\pi$)<0 (π-like)

mass>50 (high mass)
χ² Prob for mass<50 MeV (”most signal-like”): 69%

Next: look here....

1 subevent
\[ \log(L_{e}/L_{\mu}) > 0 \] (e-like)
\[ \log(L_{e}/L_{\pi}) < 0 \] (π-like)
mass<200 (low mass)
Summary of Track Based cuts

“Precuts” +

\[ \log \left( \frac{L_e}{L_{\mu}} \right) + \log \left( \frac{L_e}{L_{\pi}} \right) + \text{invariant mass} \]

Efficiency:

Backgrounds after cuts

Stacked backgrounds:
- $\nu^K_e$
- $\nu^K_{\mu}$
- $\nu^K_\pi$
- $\pi^0$
- dirt events
- $\Delta \rightarrow N \gamma$
- other
Analysis 2: Boosted Decision Trees (BDT)

Philosophy:

Construct a set of low-level analysis variables which are used to make a series of cuts to classify the events.

This algorithm represents an independent cross check of the Track Based Analysis
Step 1:
Convert the “Fundamental information” into “Analysis Variables”

<table>
<thead>
<tr>
<th>Analysis variables</th>
<th>Fundamental information from PMTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Hit Position</td>
</tr>
<tr>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Time sequence</td>
<td></td>
</tr>
<tr>
<td>Event shape</td>
<td>✓</td>
</tr>
<tr>
<td>Physics</td>
<td>✓</td>
</tr>
</tbody>
</table>

“Physics” = \( \pi^0 \) mass, \( E_{\nu}^{QE} \), etc.
Examples of “Analysis Variables”

Resolutions:
vertex: 24 cm
direction: 3.8°
energy 14%

Reconstructed quantities which are inputs to $E_{\nu}^{\text{QE}}$

$U_Z = \cos \theta_z$

$E_{\text{visible}}$

$\nu_{\mu} \text{ CCQE}$

$\nu_{\mu} \text{ CCQE} \cos \theta_{\mu}$

$\nu_{\mu} \text{ CCQE} \text{ muon kinetic energy (GeV)}$
Step 2: Reduce Analysis Variables to a Single PID Variable

Boosted Decision Trees
“A procedure that combines many weak classifiers to form a powerful committee”

A Decision Tree
(sequential series of cuts based on MC study)

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-like negative positive signal-like
BDT cuts on PID score as a function of energy.
We can define a “sideband” just outside of the signal region.
BDT cuts on PID score as a function of energy.
We can define a “sideband” just outside of the signal region.
BDT Efficiency and backgrounds after cuts:

Analysis cuts on PID score as a function of Energy

Efficiency after precuts

Monte Carlo Prediction - $\nu_e$

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

$E^\text{CCQE}_{\nu} (\text{GeV})$

$E^\text{QE}_{\nu} (\text{GeV})$
Errors, Constraints and Sensitivity
We have two categories of backgrounds:

\[ \nu_\mu \text{ mis-id} \]

- Intrinsic \( \nu_e \)
- Predictions of the backgrounds are among the nine sources of significant error in the analysis.
<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>
Tying the $\nu_e$ background and signal prediction to the $\nu_\mu$ flux constrains this analysis to a strict $\nu_\mu \rightarrow \nu_e$ appearance-only search.

Data/MC  Boosted Decision Tree: $1.22 \pm 0.29$
Track Based: $1.32 \pm 0.26$

Predict & energy dependence of both background and signal

From the $\nu_\mu$ CCQE events
$\nu_\mu$ constraint on intrinsic $\nu_e$ from $\pi^+$ decay chains

- Measure the $\nu_\mu$ flux
- Kinematics allows connection to the $\pi$ flux

Once the $\pi$ flux is known, the $\mu$ flux is determined
$K^+$ and $K^0$ decay backgrounds

At high energies, above “signal range” $\nu_\mu$ and “$\nu_e$ -like” events are largely due to kaon decay

Signal examples:
$\Delta m^2 = 0.4 \text{ eV}^2$
$\Delta m^2 = 0.7 \text{ eV}^2$
$\Delta m^2 = 1.0 \text{ eV}^2$

Predicted range of significant oscillation signal: $300 < E_{\nu QE} < 1500 \text{ MeV}$
In Boosted Decision Tree analysis:
Low energy bin 
\(200 < E_{\nu}^{\text{QE}} < 300 \text{ MeV}\)

... constraints \(\nu_\mu\) mis-ids:
\(\pi^0, \Delta \rightarrow N \gamma\), dirt ...
We constrain $\pi^0$ production using data from our detector. Because this constrains the $\Delta$ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$. Reweighting improves agreement in other variables, e.g.⇒. This reduces the error on predicted mis-identified $\pi^0$s.

Because this constrains the $\Delta$ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$. 

Other Single Photon Sources

Neutral Current: $\nu + N \rightarrow \nu + N + \gamma$ negligible
From Efrosinin, hep-ph/0609169,
calculation checked by Goldman, LANL

Charged Current $< 6$ events @ 95% CL
$\nu + N \rightarrow \mu + N' + \gamma$
where the presence of the $\gamma$ leads to mis-identification

Use events where the $\mu$ is tagged by the michel $e^{-}$
study misidentification using BDT algorithm.
External Sources of Background

“Dirt” Events
ν interactions outside of the detector $\frac{N_{\text{data}}}{N_{\text{MC}}} = 0.99 \pm 0.15$

Cosmic Rays: Measured from out-of-beam data: $2.1 \pm 0.5$ events
Summary of predicted backgrounds for the final MiniBooNE result (Track Based Analysis):

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>10</td>
</tr>
<tr>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>7</td>
</tr>
<tr>
<td>Miscellaneous $\nu_\mu$ Events</td>
<td>13</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>62</td>
</tr>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>20</td>
</tr>
<tr>
<td>NC Coherent &amp; Radiative $\gamma$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Dirt Events</td>
<td>17</td>
</tr>
<tr>
<td>$\nu_e$ from $\mu$ Decay</td>
<td>132</td>
</tr>
<tr>
<td>$\nu_e$ from $K^+$ Decay</td>
<td>71</td>
</tr>
<tr>
<td>$\nu_e$ from $K^0$ Decay</td>
<td>23</td>
</tr>
<tr>
<td>$\nu_e$ from $\pi$ Decay</td>
<td>3</td>
</tr>
<tr>
<td>Total Background</td>
<td>358</td>
</tr>
<tr>
<td>0.26% $\nu_\mu \rightarrow \nu_e$</td>
<td>163</td>
</tr>
</tbody>
</table>

(example signal)
Handling uncertainties in the analyses:

What we begin with...

For a given source of uncertainty,
Errors on a wide range of parameters in the underlying model

... what we need

For a given source of uncertainty,
Errors in bins of \( E_{\nu}^{QE} \) and information on the correlations between bins
How the constraints enter...

Two Approaches

TB: Reweight MC prediction to match measured $\nu_\mu$ result 
(accounting for systematic error correlations)

BDT: include the correlations of $\nu_\mu$ to $\nu_e$ in the error matrix:

$$
\chi^2 = \begin{pmatrix}
\Delta_i^{\nu_e} & \Delta_i^{\nu_\mu}
\end{pmatrix}
\begin{pmatrix}
M_{ij}^{e,e} & M_{ij}^{e,\mu} \\
M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu}
\end{pmatrix}^{-1}
\begin{pmatrix}
\Delta_j^{\nu_e} \\
\Delta_j^{\nu_\mu}
\end{pmatrix}
$$

where $\Delta_i^{\nu_e} = Data_i^{\nu_e} - Pred_i^{\nu_e}(\Delta m^2, \sin^2 2\theta)$ and $\Delta_i^{\nu_\mu} = Data_i^{\nu_\mu} - Pred_i^{\nu_\mu}$

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

$(i,j$ are bins of $E_\nu^{QE})$
Example: Cross Section Uncertainties

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

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$, $e_{lo}^{sf}$</td>
<td>6%, 2% (stat + bkg only)</td>
<td>determined from MiniBooNE $\nu_\mu$ QE data</td>
</tr>
<tr>
<td>QE $\sigma$ norm</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>QE $\sigma$ shape</td>
<td>function of $E_\nu$</td>
<td></td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$ QE $\sigma$</td>
<td>function of $E_\nu$</td>
<td></td>
</tr>
<tr>
<td>NC $\pi^0$ rate</td>
<td>function of $\pi^0$ mom</td>
<td>determined from MiniBooNE $\nu_\mu$ NC $\pi^0$ data</td>
</tr>
<tr>
<td>$M_A^{coh}$, coh $\sigma$</td>
<td>$\pm 25%$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$ rate</td>
<td>function of $\gamma$ mom + 7% BF</td>
<td></td>
</tr>
<tr>
<td>$E_B$, $p_F$</td>
<td>9 MeV, 30 MeV</td>
<td>determined from other experiments</td>
</tr>
<tr>
<td>$\Delta s$</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>$M_A^{1\pi}$</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>$M_A^{N\pi}$</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>DIS $\sigma$</td>
<td>25%</td>
<td></td>
</tr>
</tbody>
</table>
Example:

Optical Model Uncertainties

39 parameters must be varied

Allowed variations are set by the Michel calibration sample

To understand allowed variations, we ran 70 hit-level simulations, with differing parameters.

⇒ “Multisims”
Using Multisims to convert from errors on parameters to errors in $E_{\nu}^{QE}$ bins:

For each error source, “Multisims” are generated within the allowed variations by reweighting the standard Monte Carlo. In the case of the OM, hit-level simulations are used.

Number of multisims

1000 multisims for $K^+$ production

70 multisims for the Optical Model

Number of events passing cuts in bin $500 < E_{\nu}^{QE} < 600$ MeV
Error Matrix Elements:

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

- 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
As we show distributions in $E_{\nu}^{\text{QE}}$, keep in mind that error bars are the diagonals of the error matrix.

The effect of correlations between $E_{\nu}^{\text{QE}}$ bins is not shown,

however $E_{\nu}^{\text{QE}}$ bin-to-bin correlations improve the sensitivity to oscillations, which are based on an energy-dependent fit.
Sensitivity of the two analyses

The Track-based sensitivity is better, thus this becomes the pre-determined default algorithm

Set using $\Delta\chi^2=1.64$ @ 90% CL
Comparison to sensitivity goal for 5E20 POT determined by Fermilab PAC in 2003
The Initial Results
The Box Opening
Box Opening Procedure

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 $E_{\nu}^\text{QE}$, without returning fit parameters.

4. Compare $E_{\nu}^\text{QE}$ in data and Monte Carlo, returning the fit parameters. At this point, the box is open (March 26, 2007)

5. Present results two weeks later.
Step 1

Return the $\chi^2$ of the data/MC comparison for a set of diagnostic variables

12 variables are tested for TB
46 variables are tested for BDT

All analysis variables were returned with good probability except...

Track Based analysis $\chi^2$ Probability of $E_{\text{visible fit}}$: 1%

This probability was sufficiently low to merit further consideration
In the Track Based analysis

- We re-examined our background estimates using sideband studies.
  \( \Rightarrow \) We found no evidence of a problem

- However, knowing that backgrounds rise at low energy,
  We tightened the cuts for the oscillation fit:

\[
E_{\nu}^{QE} > 475 \text{ MeV}
\]

We agreed to report events over the original full range:
\[
E_{\nu}^{QE} > 300 \text{ MeV},
\]
Step 1: again!

Return the $\chi^2$ of the data/MC comparison for a set of diagnostic variables

$\chi^2$ probabilities returned:

TB ($E_{QE} > 475$ MeV)

- 12 variables

BDT

- 46 variables

Parameters of the oscillation fit were not returned.
Open up the plots from step 1 for approval.

Examples of what we saw:

TB ($E_{\nu}^{QE} > 475$ MeV)

MC contains fitted signal at unknown level
Step 3

Report the $\chi^2$ for a fit to $E_\nu^{QE}$ across full energy range

TB ($E_\nu^{QE} > 475$ MeV) $\chi^2$ Probability of fit: 99%
BDT analysis $\chi^2$ Probability of fit: 52%

Leading to...

Step 4

Open the box...
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 $\sigma$
Track Based energy dependent fit results:
Data are in good agreement with background prediction.

Best Fit (dashed): \((\sin^22\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)\)
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
As planned before opening the box....
Report the full range: $300 < E_{\nu}^{QE} < 3000$ MeV

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

Deviation: $3.7\sigma$

Background-subtracted:
Fit to the > 300 MeV range:

Best Fit (dashed): \((\sin^22\theta, \Delta m^2) = (1.0, 0.03 \text{ eV}^2)\)

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

Examples in LSND allowed range
This is interesting, but requires further investigation

⇒ A two-neutrino appearance-only model systematically disagrees with the shape as a function of energy.

⇒ We need to investigate non-oscillation explanations, including unexpected behavior of low energy cross sections. 
\textit{This will be relevant to future }\nu_{\mu} \rightarrow \nu_{e} \textit{ searches}

This will be addressed by MiniBooNE and SciBooNE
Boosted Decision Tree Analysis

Counting Experiment: \(300 < E_{\nu}^{QE} < 1600\) MeV
data: 971 events
expectation: 1070 ±33 (stat) ± 225 (sys) events
significance: \(-0.38\) \(\sigma\)

Counting Experiment
475 MeV < EnQE < 1250 MeV for TB
300 MeV < EnQE < 1600 MeV for BDT
Boosted Decision Tree  $E_{\nu}^{QE}$ data/MC comparison:

error bars are stat and sys (diagonals of matrix)

(sidebands used for constraint not shown)
Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.

Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.
Two points on interpreting our limit

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.
A MiniBooNE-LSND Compatibility Test

\[ \chi^2_0 = \frac{(z_{MB} - z_0)^2}{\sigma_{MB}^2} + \frac{(z_{LSND} - z_0)^2}{\sigma_{LSND}^2} \]

- 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

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

- Find probability of \( \chi^2_{\text{min}} \) 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
Plans:

A paper on this analysis will be posted to the “archive” and to the MiniBooNE webpage after 5 CT today.

Many more papers supporting this analysis will follow, in the very near future:

- $\nu_\mu$ CCQE production
- $\pi^0$ production
- MiniBooNE-LSND-Karmen joint analysis

We are pursuing further analyses of the neutrino data, including...

- an analysis which combines TB and BDT,
- more exotic models for the LSND effect.

MiniBooNE is presently taking data in antineutrino mode.
Conclusions
Our goals for this first analysis were:

• A generic search for a $\nu_e$ excess in our $\nu_\mu$ beam,

• An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance-only context
Within the energy range defined by this oscillation analysis, the event rate is consistent with background.

The observed low energy deviation is under investigation.
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.
We Thank:

DOE and NSF

The Fermilab Divisions and Staff