First $\nu_\mu \rightarrow \nu_e$ Oscillation
Results from MiniBooNE

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Warwick Particle Physics Seminar
May 8, 2007
1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results
Motivation: Neutrino Oscillations

if neutrinos have mass, a neutrino that is produced as a $\nu_\mu$ (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$) has a non-zero probability to oscillate and some time later be detected as a $\nu_e$ (e.g. $\nu_e n \rightarrow e^- p$)

Pontecorvo, 1957
Motivation: Neutrino Oscillations

In a world with 2 neutrinos, if the weak eigenstates ($\nu_e$, $\nu_\mu$) are different from the mass eigenstates ($\nu_1$, $\nu_2$):

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
= 
\begin{pmatrix}
\cos\theta & \sin\theta \\
-sin\theta & \cos\theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
$$

The weak states are mixtures of the mass states:

$$
|\nu_\mu\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle \\
|\nu_\mu(t)\rangle = -\sin\theta (|\nu_1\rangle e^{-iE_1t}) + \cos\theta (|\nu_2\rangle e^{-iE_2t})
$$

The probability to find a $\nu_e$ when you started with a $\nu_\mu$ is:

$$
P_{\text{oscillation}}(\nu_\mu \rightarrow \nu_e) = | < \nu_e | \nu_\mu(t) > |^2
$$
Motivation: Neutrino Oscillations

In units that experimentalists like:

\[ P_{oscillation}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L(km)}{E_\nu (GeV)} \right) \]

Oscillation probability between 2 flavour states depends on:

1. fundamental parameters
   \[ \Delta m^2 = m_1^2 - m_2^2 = \text{mass squared difference between states} \]
   \[ \sin^2 2\theta = \text{mixing between } \nu \text{ flavours} \]

2. experimental parameters
   \[ L = \text{distance from } \nu \text{ source to detector} \]
   \[ E = \nu \text{ energy} \]
Motivation: Oscillation Signals

Solar $\nu$: measured by Homestake, ..., SNO confirmed by KamLAND

Atmospheric $\nu$: measured by K-II, ..., Super-K confirmed by Soudan2, MACRO, K2K, MINOS

Accelerator $\nu$: measured by LSND unconfirmed
Motivation: The Problem

\[ P_{\text{oscillation}}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L(km)}{E_\nu (GeV)} \right) \]

A standard 3 neutrino picture:

\[ \Delta m^2_{12} = m_1^2 - m_2^2 \]
\[ \Delta m^2_{23} = m_2^2 - m_3^2 \]
\[ \Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23} \]

The oscillation signals cannot be reconciled without introducing physics (even farther) beyond the Standard Model.
Motivation: LSND

MiniBooNE was proposed in 1997 to address the LSND result.

LSND observed a 4σ excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam: $87.9 \pm 22.4 \pm 6.0$ interpreted as 2-neutrino oscillations, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.26\%$

$$P = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L(km)}{E_\nu(GeV)} \right)$$

MiniBooNE strategy:

Keep $(L/E_\nu)$ same as LSND but change systematics, including event signature:

- Order of magnitude higher $E_\nu$ than LSND
- Order of magnitude longer baseline $L$ than LSND
- Search for excess of $\nu_e$ events above background

Simple $\nu_\mu \rightarrow \nu_e$ oscillation
The MiniBooNE Collaboration

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Motivation: MiniBooNE and LSND

If MiniBooNE observes LSND-type $\nu$ oscillations...

The simplest explanation is to add more $\nu$s, to allow more independent $\Delta m^2$ values.

The new $\nu$s would have to be **sterile**, otherwise they would have been seen already.

If MiniBooNE does not observe LSND-type oscillations...

The Standard Model wins again!

Today: MiniBooNE’s initial results on testing the LSND anomaly

- 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
1. Motivation & Introduction

2. Description of the Experiment
   - Beam
   - Detector

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MiniBooNE Overview: Beam and Detector

**Protons:** $4 \times 10^{12}$ protons per 1.6 $\mu$s pulse, at 3 - 4 Hz from Fermilab Booster accelerator, with $E_{\text{proton}} = 8.9$ GeV. *First result uses $(5.58 \pm 0.12) \times 10^{20}$ protons on target.*

**Mesons:** mostly $\pi^+$, some $K^+$, produced in p-Be collisions, + signs focused into 50 m decay region.

**Neutrinos:** traverse 450 m soil berm before the detector hall. Intrinsic $\nu_e$ flux $\sim$ 0.5% of $\nu_\mu$ flux.

**Detector:** 6 m radius, 250,000 gallons of mineral oil (CH$_2$), which emits Cherenkov and scintillation light. 1280 inner PMTs, 240 PMTs in outer veto region.
**Prediction** from a fit to $p\text{ Be} \rightarrow \pi^+ X$ production data from E910 and HARP experiments ($p_p = 6$-$12$ GeV/c, $\Theta_\pi = 0$ - $330$ mrad.)

**Fit** (shown at right) uses Sanford-Wang parametrisation

HARP has excellent phase space coverage for MiniBooNE

$\pi^-$ similarly parametrised

Kaons flux predictions use a Feynman Scaling parametrisation (no HARP data yet)
MiniBooNE is searching for an excess of $\nu_e$ in a $\nu_\mu$ beam

Modelled with a Geant4 Monte Carlo

“Intrinsic” $\nu_e + \bar{\nu}_e$ content: 0.5%

$\nu_e$ Sources:
- $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (42%)
- $K^+ \rightarrow \pi^0 e^+ \nu_e$ (28%)
- $K^0 \rightarrow \pi^+ e^- \nu_e$ (16%)
- $\pi^+ \rightarrow e^+ \nu_e$ (4%)

Antineutrino content: 6%
MiniBooNE Detector: Neutrino Cross Sections

Modelling what the neutrinos do in the detector

Use CCQE events for oscillation analysis signal channel:

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

Only need lepton direction and angle to find \( \nu \) energy!

MO Wascko, Warwick Particle Physics Seminar

May 8, 2007
MiniBooNE Detector: Optics

charged final state particles produce $\gamma$s

Cherenkov radiation

- Light emitted by oil if particle $v > c/n$
- forward and prompt in time

Scintillation

- Excited molecules emit de-excitation $\gamma$s
- isotropic and late in time

Extinction Rate for MiniBooNE Marcol 7 Mineral Oil

$\gamma$s are (possibly) detected by PMTs after undergoing absorption, reemission, scattering, fluorescence

“the optical model”
MiniBooNE Detector: Hits

First set of cuts based on simple hit clusters in time: “sub-events.”

Most events are from $\nu_\mu$ CC interactions, with characteristic two “sub-event” structure from stopped $\mu$ decay.

$\nu_e$ CC interactions have 1 “sub-event”.

Simple cuts eliminate cosmic ray events:
1. Require < 6 veto PMT hits,
2. Require > 200 tank PMT hits.
**MiniBooNE Detector: Reconstruction and Particle ID**

**Reconstruction:**
PMTs collect $\gamma$s, record $t$ and $q$, fit time and angular distributions to find tracks.

**Final State Particle Identification:**
- Muons have sharp Cherenkov rings and long tracks.
- Electrons have fuzzy rings, from multiple scattering, and short tracks.
- Neutral pions decay to 2 $\gamma$s, which convert and produce 2 fuzzy rings, *easily misidentified as electrons if one ring gets lost!*
MiniBooNE Beam & Detector: Stability

Neutrinos per proton on target throughout the neutrino run:

MiniBooNE observes ~1 neutrino interaction per 1E15 protons.
1. Motivation & Introduction
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3. Analysis Overview
   - Signal and Backgrounds
   - Strategy
4. Two Independent Oscillation Searches
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Analysis Overview: **Blind Analysis**

*To avoid bias, MiniBooNE has done a blind analysis.*

“Closed Box” Analysis

To study the data, we defined specific event sets with $< 1\sigma \nu_e$ signal for analysis.

**Initial Open Boxes**
- all non-beam-trigger data
- 0.25% random sample
- $\nu_\mu$ CCQE
- $\nu_\mu$ NC1$\pi^0$
- “dirt”
- all events with $E_\nu > 1.4$ GeV
- $\nu_\mu$ CC1$\pi^+$
- $\nu_\mu$ -e elastic

**Second Step:**
One closed signal box

Use calibration and MC tuning
- an unbiased data set
- measure flux, $E_\nu^{QE}$, oscillation fit
- measure rate for MC
- check MC rate
- check MC rate
- check MC rate

explicitly sequester the signal,
- 99% of data open
For robustness, MiniBooNE has performed two independent oscillation analyses.
Analysis Overview: Signal and Backgrounds

what we predict for the full ν data set (5.6E20 protons on target):

stacked signal and backgrounds after νₑ event selection

Oscillation νₑ

Example oscillation signal
- \(\Delta m^2 = 1.2 \text{ eV}^2\)
- \(\sin^2 2\theta = 0.003\)

Fit for excess as a function of reconstructed νₑ energy
Analysis Overview: Signal and Backgrounds

what we predict for the full $\nu$ data set (5.6E20 protons on target):


$\nu_e$ from $K^+$ and $K^0$

Use high energy $\nu_e$ and $\nu_\mu$ in-situ data for normalisation cross-check

Use fit to kaon production data for shape
Analysis Overview: Signal and Backgrounds

what we predict for the full $\nu$ data set (5.6E20 protons on target):

stacked signal and backgrounds after $\nu_e$ event selection

$\nu_e$ from $\mu^+$

$p+Be \rightarrow \pi^+ \rightarrow \nu_\mu \rightarrow \nu_e$  

- Measured with in-situ $\nu_\mu$ CCQE sample
- Same ancestor $\pi^+$ kinematics
- Most important background
  - Constrained to a few %
Analysis Overview: Signal and Backgrounds

what we predict for the full ν data set (5.6E20 protons on target):

stacked signal and backgrounds after ν_e event selection

MisID ν_µ

- ~46% π^0
  - Determined by clean π^0 measurement
- ~14% “dirt”
  - Measure rate to normalise and use MC for shape
- ~16% Δ γ decay
  - π^0 measurement constrains
- ~24% other
  - Use ν_µ CCQE rate to normalise and MC for shape
Analysis Overview: Strategy

recurring theme: good data/MC agreement

in-situ data are incorporated wherever possible...

(i) MC tuning with calibration data
   - energy scale
   - PMT response
   - optical model of light in the detector

(ii) MC fine-tuning with neutrino data
   - cross section nuclear model parameters
   - $\pi^0$ rate constraint

(iii) constraining systematic errors with neutrino data
   - ratio method example: $\nu_e$ from $\mu$ decay background
   - combined oscillation fit to $\nu_\mu$ and $\nu_e$ data

"I think you should be more explicit here in step two."
Analysis Overview: MC Tuning

MC tuning with calibration data

![Graphs showing data and MC tuning results](image)
Analysis Overview: Strategy

**in-situ data are incorporated wherever possible...**

(i) MC tuning with calibration data
- energy scale
- PMT response
- optical model of light in the detector

(ii) MC fine-tuning with neutrino data
- cross section nuclear model parameters
- $\pi^0$ rate constraint

(iii) Constraining systematic errors with neutrino data
- ratio method example: $\nu_e$ from $\mu$ decay background
- combined oscillation fit to $\nu_\mu$ and $\nu_e$ data
Analysis Strategy: $\nu_\mu$ CCQE Events

used to measure the $\nu_\mu$ flux and check $E_{\nu\,QE}$ reconstruction

1. tag muons by requiring 2 sub-events in time
2. require reconstructed distance between sub-events < 1m

$\sim$74% CCQE purity, $\sim$190k events

$U_Z = \cos \theta_z$

$E_{\nu\,QE} = \frac{1}{2} \left( \frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)} \cos \theta_\mu} \right)$
Incorporating $\nu_\mu$ Data: CCQE Cross Section

The $\nu_\mu$ CCQE data $Q^2$ distribution is fit to tune empirical parameters of the nuclear model ($^{12}\text{C}$ target) this results in good data-MC agreement for variables not used in tuning

the tuned model is used for both $\nu_\mu$ and $\nu_e$ CCQE
Analysis Strategy: $\pi^0$ Mis-ID Background

clean $\pi^0$ events are used to tune the MC rate vs. $\pi^0$ momentum

$\pi^0$ events can reconstruct outside of the mass peak when:

1. asymmetric decays fake 1 ring
2. 1 of the 2 photons exits the detector
3. high momentum $\pi^0$ decays produce overlapping rings

$\nu_\mu$
Analysis Strategy: $\pi^0$ Mis-ID Background

The MC $\pi^0$ rate ($\text{flux} \times \text{xsec}$) is re-weighted to match the measurement in $p_\pi$ bins.

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

This procedure results in good data-MC agreement for variables not used in tuning.
**Analysis Overview: Strategy**

*in-situ data is incorporated wherever possible...*

(i) MC tuning with calibration data  
- energy scale  
- PMT response  
- optical model of light in the detector

(ii) MC fine-tuning with neutrino data  
- cross section nuclear model parameters  
- $\pi^0$ rate constraint

(iii) constraining systematic errors with neutrino data  
- ratio method example: $\nu_e$ from $\mu$ decay background  
- combined oscillation fit to $\nu_\mu$ and $\nu_e$ data

"I think you should be more explicit here in step two."
Analysis Strategy 1: Ratio Method

Example: $\nu_\mu$ CCQE events measure $\pi^+$ spectrum, constrain $\mu^+$-decay $\nu_e$ flux

Ratio Method Constraint:

1. MC based on external data predicts a central value and a range of possible $\nu_\mu(\pi)$ fluxes
2. make Data/MC ratio vs. $E_{\nu}^{\text{QE}}$ for $\nu_\mu$ CCQE data
3. re-weight each possible MC parent-$\pi^+$ flux by the ratio (2), including sister $\mu^+$ & niece $\nu_e$

Can use ratio method to constrain most BG sources
Analysis Strategy 2: Combined Fit

Fit the $E_{\nu}^{QE}$ distributions of $\nu_e$ and $\nu_\mu$ events for oscillations, together

Raster scan in $\Delta m^2$, and $\sin^2 2\theta_{\mu e}$ ($\sin^2 2\theta_{\mu x} = 0$),
calculate $\chi^2$ value over $\nu_e$ and $\nu_\mu$ bins

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)$$

In this case, systematic error matrix $M_{ij}$ includes predicted uncertainties for $\nu_e$ and $\nu_\mu$ bins

$$M_{ij} = \begin{pmatrix} \nu_e & \nu_e \nu_\mu \\ \nu_\mu \nu_e & \nu_\mu \end{pmatrix}$$

Left: example, $m_i = "fake data" = MC with no oscillations

Correlations between $E_{\nu}^{QE}$ bins from the optical model:

A combined fit constrains uncertainties in common
Analysis Strategy: Error Matrix

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

- \( N \) is number of events passing cuts
- \( MC \) is standard Monte Carlo
- \( \alpha \) represents a different MC draw (called a “multisim”)
- \( M \) is the total number of MC draws
- \( i, j \) are \( E^Q_\nu \) bins

Total error matrix is sum from each source.

Primary (TB): \( \nu_e \)-only total error matrix
Cross-check (BDT): \( \nu_\mu - \nu_e \) total error matrix
Analysis Overview: Systematic Errors

A long list of systematic uncertainties are estimated using Monte Carlo:

**neutrino flux predictions**
- \( \pi^+, \pi^-, K^+, K^-, K^0, n, \) and p total and differential cross sections
- secondary interactions of mesons
- focusing horn current
- target + horn system alignment

**neutrino interaction cross section predictions**
- nuclear model
- rates and kinematics for relevant exclusive processes
- resonance width and branching fractions

**detector modelling**
- optical model of light propagation in oil (39 parameters!)
- PMT charge and time response
- electronics response
- neutrino interactions in dirt surrounding detector hall

✓ Most are constrained or checked using in-situ MiniBooNE data.
1. Motivation & Introduction
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4. Two Independent Oscillation Searches
   - Reconstruction and Event Selection
   - Systematic Uncertainties
5. First Results
Two Independent Oscillation Searches: **Methods**

**Method 1: Track-Based Analysis**

- *Use careful reconstruction of particle tracks*
- *Identify particle type by likelihood ratio*
- *Use ratio method to constrain backgrounds*

**Strengths:**
- Relatively insensitive to optical model
- Simple cut-based approach with likelihoods

**Method 2: Boosted Decision Trees**

- *Classify events using “boosted decision trees”*
- *Apply cuts on output variables to improve separation of event types*
- *Use combined fit to constrain backgrounds*

**Strengths:**
- Combination of many weak variables form strong classifier
- Better constraints on background events
Method 1: Track-Based Analysis

Reconstruction fits an extended light source with 7 parameters: vertex, direction (\(\theta, \phi\)), time, energy

Fit events under 3 possible hypotheses: 
\(\mu\)-like, e-like, two track (\(\pi^0\)-like)

Fitter resolution

- Vertex: 22 cm
- Direction: 2.8\(^\circ\)
- Energy: 11\%

Particle ID relies on likelihood ratio cuts to select \(\nu_e\), cuts chosen to maximise sensitivity to \(\nu_\mu \rightarrow \nu_e\) oscillation
Test $\mu$-$e$ separation on data:

$\nu_\mu$ CCQE data sample
- Pre-selection cuts
- Fiducial volume: (R < 500 cm)
- 2 subevents: muon + decay electron

"All-but-signal" data sample
- Pre-selection cuts
- Fiducial volume: (R < 500 cm)
- 1 subevent: 8% of muons capture on $^{12}$C

Events with $\log(L_e/L_\mu) > 0$ (e-like) undergo additional fit with two-track hypothesis.
Track-Based Analysis: $e/\pi^0$ Likelihood

Test $e-\pi^0$ separation on data:

“All-but-signal” data sample

- Pre-selection cuts
- Fiducial volume cut ($R < 500$ cm)
- 1 subevent
- Invariant mass $> 50$ MeV/c$^2$
- $\log(\frac{L_e}{L_\pi}) < 0$ ($\pi$-like)

Tighter selection cuts:
- Invariant mass $< 200$ MeV/c$^2$
- $\log(\frac{L_e}{L_\mu}) > 0$ (e-like)
- $\log(\frac{L_e}{L_\pi}) < 0$ ($\pi$-like)

BLINDED REGION

Data

Monte Carlo

Monte Carlo $\pi^0$ only

Events/5 MeV/c$^2$

Signal Region

Events/0.01

BLINDED REGION

BLINDED REGION

BLINDED REGION

Events/10.0 (MeV/c$^2$)

Mass (MeV/c$^2$)

- $10^2$
- $10^3$
- $\chi^2$/ndf =
- Mass $< 50$ MeV/c$^2$: $\chi^2$/ndf =

Invariant Mass (MeV/c$^2$)
**Method 2: Boosted Decision Trees**

**Decision Trees:** A machine-learning technique which tries to recover signal events that would be eliminated in cut-based analyses.

*Training a decision tree:*

For a set of N variables, determine the cut value for each variable that gives best S/B separation.

Cut on the best variable (i.e. highest S/B) and repeat.

*Final score:* For each leaf,
- 1 for correct events (signal event on a signal leaf, etc.)
- +1 for incorrect events

**Boosting:** Increase weight of misclassified events.
Re-training with newly weighted events improves performance.
**Boosted Decision Trees: Reconstruction and Particle ID**

*Reconstruction fits a point-like light source:*
vertex, direction \((\theta, \phi)\), time, energy

Particle ID “input variables” for the boosted decision trees are created from basic quantities in each bin: e.g., charge, number of hits...

To select events, a particle ID cut is made on the Boosting output score.
Boosted Decision Trees: Particle ID

A *sideband* region is selected to validate MC in region near signal.

Sideband contains mostly mis-identified $\pi^0$ background events.

$\chi^2$ is calculated using the full systematic error matrix, data and MC are consistent.
Comparison: Efficiencies

The two analyses have different event selection efficiency vs. energy trends,

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

and different reconstructed \( E_{\nu} \) regions for the oscillation analyses.
Comparison: Backgrounds

The two analyses have somewhat different background compositions.

<table>
<thead>
<tr>
<th>Source</th>
<th>T-B</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ from $\mu$ decay</td>
<td>0.37</td>
<td>0.32</td>
</tr>
<tr>
<td>$\nu_e$ from $K$ decay</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>$\pi^0$ mis -- ID</td>
<td>0.17</td>
<td>0.21</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Dirt</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Other</td>
<td>0.09</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Comparison: Systematic Errors

Both analyses construct error matrices for the oscillation fit, binned in $E_{\nu}$, to estimate the uncertainty on the expected number of $\nu_e$ background events.

<table>
<thead>
<tr>
<th>source</th>
<th>track-based (%)</th>
<th>boosting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux from $\pi^+/\mu^+$ decay</td>
<td>6.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Flux from $K^+$ decay</td>
<td>3.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Flux from $K^0$ decay</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>2.8</td>
<td>1.3</td>
</tr>
<tr>
<td>$\nu$-cross section</td>
<td>12.3</td>
<td>10.5</td>
</tr>
<tr>
<td>NC $\pi^0$ yield</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>External interactions</td>
<td>0.8</td>
<td>3.4</td>
</tr>
<tr>
<td>Optical model</td>
<td>6.1</td>
<td>10.5</td>
</tr>
<tr>
<td>DAQ electronics model</td>
<td>7.5</td>
<td>10.8</td>
</tr>
<tr>
<td>constrained total</td>
<td>9.6</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Note: “total” is not the quadrature sum—errors are further reduced by fitting with $\nu_\mu$ data.
Comparison: Sensitivity

Since the track-based analysis achieved better sensitivity than the boosted decision tree analysis, we decided (before opening the box) that it would be used for the primary result.

Fit the Monte Carlo $E_{\nu}^{QE}$ event distributions for oscillations

Set using $\Delta \chi^2 = 1.64$ @ 90% CL

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)$$

$m_i$ = Number of measured data events in bin $i$
$t_i$ = Number of predicted events in bin $i$
$(t_i$ events are a function of $\Delta m^2$, $\sin^2 2\theta$, $M_{ij}^{-1}$ = Inverse of the covariance matrix

Raster scan in $\Delta m^2$, and $\sin^2 2\theta_{\mu e}$ (assume $\sin^2 2\theta_{\mu e} = 0$), calculate $\chi^2$ value over $E_{\nu}$ bins.
1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results
Results: Opening the Box

After applying all analysis cuts:

Step 1: Fit sequestered data to an oscillation hypothesis
   Fit does not return fit parameters
   Unreported fit parameters applied to MC; diagnostic variables compared to data
   Return only the $\chi^2$ of the data/MC comparisons (for diagnostic variables only)

Step 2: Open plots from Step 1 (Monte Carlo has unreported signal)
   Plots chosen to be useful diagnostics, without indicating if signal was added
   (reconstructed position, direction, visible energy...)

Step 3: Report only the $\chi^2$ for the fit to $E_{\nu}^{QE}$
   No fit parameters returned

Step 4: Compare $E_{\nu}^{QE}$ for data and Monte Carlo,
   Fit parameters are returned
   This step breaks blindness

Step 5: Present results within two weeks
We opened the box on March 26, 2007
The Box Opening
Results: Track Based Analysis

We observe no significant evidence for an excess of $\nu_e$ events in the energy range of the analysis.

NB: Errors bars=diagonals of error matrix

Best Fit (dashed):
$$(\sin^2 2\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)$$

Counting Experiment:

- 475 $< E_{\nu}^{QE} < 1250$ MeV
- Data: 380
- Expectation: 358 $\pm 19$ (stat) $\pm 35$ (sys)

$\chi^2$ probability of best-fit point: 99%
$\chi^2$ probability of null hypothesis: 93%
Results: Track Based Analysis, Lower Energy Threshold

Extending down to energies below the analysis range: $E_{\nu}^{QE} > 300$ MeV
(we agreed to report this before box opening)

Data deviation for $300 < E_{\nu}^{QE} < 475$ MeV: $3.7\sigma$

Oscillation fit to $E_{\nu}^{QE} > 300$ MeV:
Best Fit $(\sin^22\theta, \Delta m^2) = (1.0, 0.03 \text{ eV}^2)$

*Ruled out by Bugey*

$\chi^2$ prob. at best-fit point: 18%
No closed contour for 90%CL

Fit is inconsistent with $\nu_\mu \rightarrow \nu_e$ oscillations.
Results: Boosted Decision Tree Analysis

We observe no significant evidence for an excess of $\nu_e$ events in the energy range of the analysis.

Counting Experiment:
$300 < E_{\nu}^{\text{QE}} < 1500$ MeV

data: 971
expectation: $1070 \pm 33 \text{ (stat)} \pm 225 \text{(sys)}$

Best Fit Point (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 7 \text{ eV}^2)$

$\chi^2$ probability of best-fit point: 52%
$\chi^2$ probability of null hypothesis: 62%

significance: $-0.38 \sigma$
MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.

Results: Comparison

The two independent oscillation analyses are in agreement.

Set using $\Delta \chi^2 = 1.64$ @ 90% CL

solid: track-based
$\Delta \chi^2 = \chi^2_{\text{best fit}} - \chi^2_{\text{null}} = 0.94$

dashed: boosting
$\Delta \chi^2 = \chi^2_{\text{best fit}} - \chi^2_{\text{null}} = 0.71$

Therefore, we set a limit.
Results: Compatibility with LSND

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 \( \Delta m^2 \), form \( \chi^2 \) between MB and LSND measurement
- Find \( z_0 (\sin^2 2\theta) \) that minimises \( \chi^2 \) (weighted average of 2 measurements), this gives \( \chi^2_{\text{min}} \)
- Find probability of \( \chi^2_{\text{min}} \) for 1 dof = joint compatibility probability for this \( \Delta m^2 \)

MiniBooNE is incompatible with a \( \nu_\mu \to \nu_e \) appearance-only interpretation of LSND at 98% CL

cf. LSND-KARMEN: 64% compatibility
A paper on this analysis is posted to the archive.

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

\[ \nu_\mu \text{ CCQE production} \]
\[ \pi^0 \text{ production} \]

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

an analysis which combines TB and BDT,

less simplistic models for the LSND effect.

MiniBooNE is presently taking data in antineutrino mode.

SciBooNE will start taking data in June!

Will improve constraints on \( \nu_e \) backgrounds

(intrinsic \( \nu_e \)s, improved \( \pi^0 \) kinematics)

Will provide important constraints on “wrong-sign” BGs for antineutrino oscillation analysis
Conclusions

1. Within the energy range of the analysis, MiniBooNE observes no statistically significant excess of $\nu_e$ events above background.

2. In two independent oscillation analyses, the observed $E_{\nu}$ distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model.

3. Therefore, we set a limit on $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$. The MiniBooNE - LSND joint probability is 2%.
Results: Interpreting Our Limit

There are various ways to present limits:

• Single sided raster scan  
  (historically used, presented here)

• Global scan

• Unified approach  
  (most recent method)

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.
Results: Event Overlap

Counting experiment numbers:
Track Based Algorithm finds 380 events
Boosting Algorithm finds 971 events

However, only 1131 events total, because 220 overlap
- chosen by both algorithms!
Results: Sensitivity Goal

Compared to our sensitivity goal for 5E20 protons on target from 2003 Run Plan

Set using $\Delta \chi^2=1.64$ @ 90% CL
MiniBooNE Detector: Cosmic Calibration

use cosmic muons and their decay electrons (Michels)

Angular Resolution
- data
- MC

Energy Resolution
- data
- MC

Cosmic muons which stop in cubes:
- test energy scale extrapolation up to 800 MeV
- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration
data continuously acquired at 1 Hz
MiniBooNE Detector: PMT Calibration

PMTs are calibrated with a laser + 4 flask system

PMT Charge Resolution: 1.4 PE, 0.5 PE
PMT Time Resolution: 1.7 ns, 1.1 ns

10% photo-cathode coverage

Two types of 8” Hamamatsu Tubes: R1408, R5912

Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants
MiniBooNE Detector: Cosmic Calibration

*use cosmic muons and their decay electrons (Michels)*

Michel electrons:
- set absolute energy scale and resolution at 53 MeV endpoint
- optical model tuning

![Graph showing Michel electrons](image)

**13% E resolution at 53 MeV**

Cosmic muons which stop in cubes:
- test energy scale extrapolation up to 800 MeV
- measure energy, angle resolution
- compare data and MC

**Muon tracker + cube calibration** data continuously acquired at 1 Hz
Incorporating $\nu_\mu$ Data: $\mu^+$-Decay $\nu_e$ Background

$\nu_\mu$ CCQE events measure the $\pi^+$ spectrum, this constrains the $\mu^+$-decay $\nu_e$ flux

**Ratio Method Constraint:**

1. MC based on external data predicts a central value and a range of possible $\nu_\mu(\pi)$ fluxes

2. make Data/MC ratio vs. $E_{\nu}^{QE}$ for $\nu_\mu$ CCQE data

3. re-weight each possible MC flux by the ratio (2) including the $\nu_\mu$, its parent $\pi^+$, sister $\mu^+$, and niece $\nu_e$

$E_\nu = 0.43 E_{\pi}$

This works well because the $\nu_\mu$ energy is highly correlated with the $\pi^+$ energy
Analysis Strategy: Delta Background

\( \nu \) induced interactions that produce single \( \gamma \)s in the final state

Radiative Delta Decay (NC)

(i) Use \( \pi^0 \) events to measure rate of NC \( \Delta \) production

(ii) Use PDG branching ratio for radiative decay
- 15% uncertainty on branching ratio

Inner Bremsstrahlung (CC)

(i) Hard photon released from neutrino interaction vertex

(ii) Use events where the \( \mu \) is tagged by the decay \( e^- \)
- study misidentification using BDT algorithm.
Analysis Strategy: External Backgrounds

Interactions outside the detector that deposit energy in the fiducial volume and pass the veto PMT hits cut

1. “Dirt” Events

\(\nu\) interactions outside of the detector are measured in the “dirt box:” \(N_{\text{data}} / N_{\text{MC}} = 0.99 \pm 0.15\)

Event Type of Dirt Events

2. Cosmic Ray Background Events

Measured from 126E6 strobe data triggers: \(2.1 \pm 0.5\) events.
# Analysis Overview: Background Summary

**Summary of predicted backgrounds for the primary 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 $K^0_L$ 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>
</tbody>
</table>

| $0.26\% \nu_\mu \rightarrow \nu_e$               | 163              |

*(example signal)*
MiniBooNE performed a *blind analysis* for the $\nu_\mu \rightarrow \nu_e$ appearance search

- Did not look at $\nu_e$ events while developing reconstruction, particle identification algorithms

- Final cuts made with no knowledge of the number of $\nu_e$ events in the box

Final sensitivity to $\nu_e$ appearance shown for two independent analyses

- “Primary” analysis chosen based on slightly better sensitivity
Results: Opening the Box

After applying all analysis cuts:

**Step 1:** *Fit sequestered data to an oscillation hypothesis*
Fit does not return fit parameters
Unreported fit parameters applied to MC; diagnostic variables compared to data
Return only the $\chi^2$ of the data/MC comparisons (for diagnostic variables only)

**Step 2:** *Open plots from Step 1 (Monte Carlo has unreported signal)*
Plots chosen to be useful diagnostics, without indicating if signal was added
(reconstructed position, direction, visible energy...)

**Step 3:** *Report only the $\chi^2$ for the fit to $E_{\nu}^{QE}$*
No fit parameters returned

**Step 4:** *Compare $E_{\nu}^{QE}$ for data and Monte Carlo,*
Fit parameters **are** returned
This step breaks blindness

**March 26:**
Track-Based
$\chi^2$ Probability: 99%
Boosting
$\chi^2$ Probability: 62%

**Step 5:** *Present results within two weeks*
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...

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

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

- We re-examined our background estimates using sideband studies.
  \[
  \Rightarrow \text{We found no evidence of a problem}
  \]

- However, knowing that backgrounds rise at low energy,
  \[
  \text{We tightened the cuts for the oscillation fit:}
  \]

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

We agreed to report events over the original full range:

\[
E_{\nu}^{\text{QE}} > 300 \text{ MeV}
\]
Step 1: again!

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

$\chi^2$ probabilities returned:

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

12 variables

46 variables

Parameters of the oscillation fit were not returned.
Step 2
Open up the plots from step 1 for approval.

Examples of what we saw:

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

BDT

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...
And the answer is...

Primary Analysis

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

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

Cross-check Analysis

Counting Experiment:
$300 < E_{\nu}^{QE} < 1500$ MeV

expectation: $1070 \pm 33$ (stat) $\pm 225$ (sys)
And the answer is...

Primary Analysis

Counting Experiment:
\[475 < E_{\nu}^{QE} < 1250 \text{ MeV}\]

expectation: \(358 \pm 19\) (stat) \(\pm 35\) (sys)

data: \(380\)

significance: \(0.55\ \sigma\)

Cross-check Analysis

Counting Experiment:
\[300 < E_{\nu}^{QE} < 1500 \text{ MeV}\]

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

data:

significance:
And the answer is...

Primary Analysis

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

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

data: 380

significance: $0.55 \sigma$

Cross-check Analysis

Counting Experiment: 
$300 < E_{v}^{QE} < 1500$ MeV

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

data: 971

significance: $-0.38 \sigma$
And the answer is...

*MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.*

The two independent oscillation analyses are in agreement!