Joint Search for $\nu_\mu$ Disappearance at $\Delta m^2 \sim 1 \text{ eV}^2$

Searching for sterile neutrinos with SciBooNE & MiniBooNE

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Outline

- Introduction
  - Neutrino oscillation
  - The LSND signal and sterile neutrinos
- Experiments: SciBooNE and MiniBooNE
- SciBooNE-MiniBooNE joint $\nu_\mu$ disappearance analysis
- Results
Introduction
Neutrino oscillation

- if neutrinos have mass...
  - a neutrino that is produced as a $\nu_\mu$
    - (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)
  - might some time later be observed as a $\nu_e$
    - (e.g. $\nu_e n \rightarrow e^- p$)

Source

Detector

Pontecorvo

*Sov.Phys.JETP*
6:429,1957
*Sov.Phys.JETP*
26:984-988,1968

Maki, Nakagawa, Sakata

Neutrino oscillation

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:

$$
|\nu_\mu> = -sin\theta |\nu_1> + cos\theta |\nu_2>
$$

$$
|\nu_\mu(t)> = -sin\theta (|\nu_1> e^{-iE_1 t}) + cos\theta (|\nu_2> e^{-iE_2 t})
$$

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

$$
P_{oscillation}(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2
$$
\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m_{12}^2 \frac{L}{E}) \]

- 2 fundamental parameters
  - \(\Delta m^2\) ↔ period
  - \(\theta_{12}\) ↔ magnitude

- 2 experimental parameters
  - \(L\) = distance travelled
  - \(E\) = neutrino energy

- Choose \(L\&E\) to target ranges of \(\Delta m^2\) and \(\theta\)

- Neutrinos disappear and appear
2 fundamental parameters
- $\Delta m^2 \leftrightarrow$ period
- $\theta_{12} \leftrightarrow$ magnitude

2 experimental parameters
- $L =$ distance travelled
- $E =$ neutrino energy

Choose $L&E$ to target ranges of $\Delta m^2$ and $\theta$

Neutrinos disappear and appear
\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m^2_{12} \frac{L}{E}) \]

- 2 fundamental parameters
  - \( \Delta m^2 \leftrightarrow \) period
  - \( \theta_{12} \leftrightarrow \) magnitude

- 2 experimental parameters
  - \( L = \) distance travelled
  - \( E = \) neutrino energy

- Choose \( L \& E \) to target ranges of \( \Delta m^2 \) and \( \theta \)
- Neutrinos disappear and appear

\( (\nu_\mu \rightarrow \nu_e) \)
$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$

- L and E determine $\Delta m^2$ sensitivity
- $\theta_{12}$ sensitivity determined by statistics, backgrounds, and uncertainties
- No signal: exclusion curve
- Signal: allowed region
Neutrino Interactions

CC interactions preserve neutrino flavor, but require enough energy to produce rest mass of charged lepton!

NC interactions can happen equally for all flavors because there is no energy requirement

Both interaction modes are useful for neutrino oscillation experiments!
Three flavors

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

where \( c_{ij} = \cos \theta_{ij} \), \( s_{ij} = \sin \theta_{ij} \)
Atmospheric Oscillation

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Super-K
  - Multi-GeV e-like
  - Multi-GeV $\mu$-like + PC

- MINOS
  - No oscillation
  - $\nu_\mu \rightarrow \nu_\tau$ oscillation


PhysRevLett.101.131802

Wednesday, 12 October 11
Solar Oscillation

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = 
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

with real reactor distribution

ideal oscillation pattern


Cross Mixing

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

Causes $\bar{\nu}_e$ disappearance in reactors and $\nu_e$ appearance in accelerator experiments.
Current picture

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13}e^{-i\delta} \\
    0 & 1 & 0 \\
    -s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

where \( c_{ij} = \cos \theta_{ij} \), \( s_{ij} = \sin \theta_{ij} \)

Mass (eV)

\begin{align*}
\nu_e & \quad \nu_\mu & \quad \nu_\tau \\
0.05 & \quad & 0.009 \\
? & \quad & ?
\end{align*}

Non-zero \( \delta \): matter vs antimatter

| \[ \Delta m^2_{23} \] | \[ 2.35E-03 \text{ (eV}^2) \] |
| \[ \Delta m^2_{12} \] | \[ 7.58E-05 \text{ (eV}^2) \] |
| \[ \sin^2 \theta_{12} \] | \[ 0.306 \] |
| \[ \sin^2 \theta_{23} \] | \[ 0.42 \] |
| \[ \sin^2 \theta_{13} \] | \[ 0.02 \] |
| \[ \delta \] | \[ ? \] |


Wednesday, 12 October 11
Open Questions

• What is the value of $\theta_{13}$? $\delta_{CP}$?
• What is the mass hierarchy?
• What is the absolute mass scale?
• What is the nature of neutrino mass?
  • Dirac or Majorana?
• Answers important for theories about origins of neutrino mass
  • Relations to flavor? GUTs?
• Cosmological and astrophysical implications
The LSND Signal
The LSND Signal

- The LSND experiment observed a small excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam.

Data excess: $87.9 \pm 22.4 \pm 6.0$ (3.8 $\sigma$)

Best fit: $\Delta m^2 \sim 1$ eV$^2$, $\sin^2 2\theta \sim 0.003$

Phys. Rev. D 64, 112007 (2001)
Sterile Neutrinos

• LEP experiments measured the number of light neutrinos: 3

• Only two independent $\Delta m^2$ values for 3 neutrinos
  • $2.5 \times 10^{-3} + 7.6 \times 10^{-5} \neq 1$

• LSND signal involves sterile neutrinos, if it is due to neutrino oscillation
  ➡ They do not interact via the weak force

Active-sterile Neutrino Oscillation?

- Sterile neutrinos could still mix with active neutrinos!

A simple realisation of the sterile neutrino is a right-handed neutrino $\nu_R$, which can be mixed with active $\nu_L$.

$$
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\
U_{s11} & U_{s12} & U_{s13} & U_{s14} & \cdots \\
& \cdots & \cdots & \cdots & \cdots \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\cdots \\
\end{pmatrix}
$$

3+1 sterile neutrino scheme

$\Delta m^2_{LSND}$

$\Delta m^2_{23}$

$\Delta m^2_{12}$
MiniBooNE $\nu_e$ Results

- MiniBooNE recently tested the LSND signal.
- Ruled out most of LSND region in $\nu_\mu \rightarrow \nu_e$ search.
- However, observed (small) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess.
- Consistent with LSND???
- We want to test this with disappearance measurements!
Appearance vs. Disappearance

Testing appearance signals with disappearance measurements

\[ P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \left[ 1.27 \Delta m_{41}^2 \frac{L}{E} \right] \]

\[ P(\nu_e \rightarrow \nu_x) = 1 - 4|U_{e4}|^2 (1 - |U_{e4}|^2) \sin^2 \left[ 1.27 \Delta m_{41}^2 \frac{L}{E} \right] \]

\[ P(\nu_\mu \rightarrow \nu_x) = 1 - 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \left[ 1.27 \Delta m_{41}^2 \frac{L}{E} \right] \]

\( \nu_\mu \rightarrow \nu_e \) appearance probability can be constrained by \( \nu_e \) and \( \nu_\mu \) disappearance measurements!
Figure 1. Compatibility of the existing measurements in (3+1) model

- LSND region is incompatible with disappearance results.
- Disappearance measurement is a powerful tool!
Other Scenarios

- 3+2 sterile neutrino mixing
  PRD 76, 093005 (2007)
  PRD 80, 073001 (2009)
  arXiv:1103.4570

- Sterile neutrinos in extra dimensions
  PRD 72, 095017 (2005)

- Decaying sterile neutrino
  JHEP 09, 048 (2005)

- CPT violation
  PRD 77, 033001 (2008)

Disappearance measurements can constrain these models.
$\nu_\mu$ Disappearance Measurements

- Important to independently test $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance.
- Testing CPT-invariance.
- Recently, MiniBooNE searched for $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance with MiniBooNE data only (PRL 103, 0611802)
- That analysis used the flux shape only, and suffered from large flux and cross section uncertainties.
- Improve with near detector constraints!

![Graph showing $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance measurements]
Experiments
Overview

SciBooNE (2007-8)

Target/Horn

MiniBooNE (2002-present)

8GeV Booster

Fermilab visual media service

Fermilab

SciBooNE (2007-8)

Target/Horn

Decay region

50 m

100 m

440 m
Overview

- MiniBooNE is designed to test the LSND signal
  - LSND L/E: $20\text{m}/30\text{MeV} \sim 0.7\text{ meter}/\text{MeV}$
  - MiniBooNE L/E: $540\text{m} / 0.8\text{ GeV} \sim 0.7\text{ m}/\text{MeV}$
- SciBooNE (2007-2008) has two purposes
  - Precise measurement of neutrino cross section for future oscillation experiments (T2K, etc)
  - MiniBooNE near detector

Common beamline + Common neutrino target (both carbon) → Significant reduction of systematic errors
Fermilab Booster $\nu$ Beam

- Intense $\nu_\mu$ beam with the mean energy of ~0.8 GeV
- 93% pure $\nu_\mu$ beam.
- $\bar{\nu}_\mu$ beam is also produced by inverting horn polarity.
SciBooNE Collaboration

63 physicists
5 countries 18 institutions

SciBooNE, 2008

Spokespersons:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

Universitat Autonoma de Barcelona
University of Cincinnati
University of Colorado, Boulder
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London
Indiana University
Institute for Cosmic Ray Research (ICRR)
Kyoto University
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
Purdue University Calumet
Universita degli Studi di Roma "La Sapienza" and INFN
Saint Mary's University of Minnesota
Tokyo Institute of Technology
Universidad de Valencia
SciBooNE detector

- Located 100 m from target.
- SciBar:
  - Fully active scintillator tracker (~14000 strips)
  - Neutrino target (~10 ton)
  - Main component: CH
- Muon Range Detector (MRD)
  - Sandwich type detector of steel + plastic scintillator.
  - Reconstruct muon energy from path-length

SciBar

Muon Range Detector (MRD)

Sci BooNE Detector

MiniBooNE Detector

MiniBooNE Collaboration


1 University of Alabama, Tuscaloosa, AL 35487
2 Bucknell University, Lewisburg, PA 17837
3 University of Cincinnati, Cincinnati, OH 45221
4 University of Colorado, Boulder, CO 80309
5 Columbia University, New York, NY 10027
6 Embry Riddle Aeronautical University, Prescott, AZ 86301
7 Fermi National Accelerator Laboratory, Batavia, IL 60510
8 Indiana University, Bloomington, IN 47405
9 Los Alamos National Laboratory, Los Alamos, NM 87545
10 Louisiana State University, Baton Rouge, LA 70803
11 University of Michigan, Ann Arbor, MI 48109
12 Princeton University, Princeton, NJ 08544
13 Saint Mary's University of Minnesota, Winona, MN 55987
14 Virginia Polytechnic Institute & State University, Blacksburg, VA 24061
15 Western Illinois University, Macomb, IL 61455
16 Yale University, New Haven, CT 06520
MiniBooNE detector

- Located 540 m from target
- Mineral oil Cherenkov detector
  - $n = 1.47$
  - Select $\nu_\mu$ with single muon and decay electron signal.
  - Total mass: 800 ton
  - Main component: $\text{CH}_2$
- Taking beam data since 2002
### Data sets

<table>
<thead>
<tr>
<th>Period</th>
<th>BNB Mode</th>
<th>SciBooNE POT</th>
<th>MiniBooNE POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 2006 - Aug. 2007</td>
<td>Antineutrino</td>
<td>0.52 x 10^20 (from Jun. 2007)</td>
<td>1.71 x 10^20</td>
</tr>
<tr>
<td>Oct. 2007 - Apr. 2008</td>
<td>Neutrino</td>
<td>0.99 x 10^20</td>
<td>0.83 x 10^20</td>
</tr>
<tr>
<td>Apr. 2008 - present</td>
<td>Antineutrino</td>
<td>1.01 x 10^20 (until Aug. 2008)</td>
<td>ongoing</td>
</tr>
</tbody>
</table>

Analysis of the full neutrino data sets is presented today:
- SciBooNE: 0.99 x 10^20 POT
- MiniBooNE: (5.58 + 0.83) x 10^20 POT
Analysis
Analysis Overview

**Two independent analyses**

**Spectrum fit**

- SciBooNE data
- CC interaction rate measurement
- MiniBooNE rec. $E_{\nu}$ prediction
- MiniBooNE rec. $E_{\nu}$ data

**Simultaneous fit**

- SB + MB Rec. $E_{\nu}$ Data
- SB + MB Rec. $E_{\nu}$ Prediction

**Advantage:**
Decouple oscillation fit from constraint. Observe the effects of the constraint.

Direct fit for disappearance in SciBooNE and MiniBooNE. Correlation between the two constrain systematic error.
SciBooNE event selection

- Select MIP-like energetic tracks ($P_\mu > 0.25 \text{ GeV}$)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped ($P_\mu, \theta_\mu$)
  - MRD-stopped ($P_\mu, \theta_\mu$)
  - MRD-penetrated ($\theta_\mu$)

- Use charged current inclusive sample

- SciBar
- EC
- MRD

**SciBar stopped**

**MRD stopped**

**MRD penetrated**

$\nu_\mu$ event selection

Use charged current inclusive sample

- Select MIP-like energetic tracks ($P_\mu > 0.25 \text{ GeV}$)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped ($P_\mu, \theta_\mu$)
  - MRD-stopped ($P_\mu, \theta_\mu$)
  - MRD-penetrated ($\theta_\mu$)

- Use charged current inclusive sample

- SciBar
- EC
- MRD

**SciBar stopped**

**MRD stopped**

**MRD penetrated**

$\nu_\mu$ event selection

- Select MIP-like energetic tracks ($P_\mu > 0.25 \text{ GeV}$)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped ($P_\mu, \theta_\mu$)
  - MRD-stopped ($P_\mu, \theta_\mu$)
  - MRD-penetrated ($\theta_\mu$)

- Use charged current inclusive sample

- SciBar
- EC
- MRD

**SciBar stopped**

**MRD stopped**

**MRD penetrated**
Neutrino event selection

- Booster provides pulsed beam with 1.6 µsec width.
- Require the event time to be within the 2 µsec beam window.
  - Less than 0.5% cosmic ray contamination.
- ~14K SciBar-stopped events.
- ~20K MRD-stopped events.
- ~4K MRD-penetrated events.
Muon distributions

- We use two neutrino interaction generators

<table>
<thead>
<tr>
<th>NEUT: SK, K2K, T2K, etc</th>
<th>(+ all other cross section measurements in SciBooNE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUANCE: MiniBooNE, etc</td>
<td>(Use NUANCE for this joint oscillation analysis)</td>
</tr>
</tbody>
</table>

Both tuned to explain data, but predict different cross sections.

→ Testing these in a single experiment (SciBooNE) is an important topic!

**muon momentum** ($p_\mu$)

**muon angle** ($\theta_\mu$)

MC reproduces data within the (large) systematic error
Spectrum fit

- Tune MC prediction by re-weighting as a function of true neutrino energy.
- Determine the rate normalisation factor which best fits the $p_\mu$ vs. $\theta_\mu$ 2D distributions.
- All three samples (SciBar-stop, MRD-stop and MRD-penetrated samples) are used simultaneously.

MC template (MRD-stop)

![Reconstructed $p_\mu$ vs. $\theta_\mu$ distributions for MRD-stopped sample. From the top-left, template for -0.5, 0.5-0.75, ...., 1.5-1.75 and 1.75- (GeV).]
CC interaction rate

- Extract CC interaction rate normalisation factor

\[
R_i = \frac{f_i \cdot N_i^{\text{pred}} \cdot P_i}{\epsilon_i}
\]

- This is the product of (flux) x (cross-section)

Direct input for this joint $\nu_\mu$ disappearance analysis


<table>
<thead>
<tr>
<th>Parameter</th>
<th>$f_0$</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
<th>$f_4$</th>
<th>$f_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\nu$ range (GeV)</td>
<td>0.25 - 0.5</td>
<td>0.5 - 0.75</td>
<td>0.75 - 1.0</td>
<td>1.0 - 1.25</td>
<td>1.25 - 1.75</td>
<td>1.75+</td>
</tr>
</tbody>
</table>
Distributions after fit

- Apply obtained rate normalisation factors.
- Confirmed that the MC distributions reproduce the data, and the errors are much smaller after fit.
CC inclusive cross section

\[ \sigma_i = f_i \cdot <\sigma_{CC}^{\text{pred}}>_i = \frac{f_i \cdot N_i^{\text{pred}} \cdot P_i}{\epsilon_i \cdot T \cdot \Phi_i} \]

- First measurement of CC-inclusive cross section on carbon in the 1 GeV region
- NEUT & NUANCE based measured xsecs consistent.
- Consistent with MINOS, NOMAD and old BNL bubble chamber (deuterium) measurements
- Used to tune MC for T2K.
Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

CC interaction rate measurement

MiniBooNE rec. $E_\nu$ prediction

MiniBooNE rec. $E_\nu$ data

Simultaneous fit

SB + MB Rec. $E_\nu$ Data

Oscillation Fit

SB + MB Rec. $E_\nu$ Prediction

Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

Advantage:
Decouple oscillation fit from constraint.
Observe the amount of constraint.
MiniBooNE reconstruction

- Employ same selection/reconstruction as used in previous MiniBooNE-only analysis ([PRL 103, 061802 (2009)]).
- Select CC quasi-elastic (QE) ($\nu n \rightarrow \mu p$) like events by requiring hits from muon and its decay electron.
- Reconstruct muon kinematics from the Cherenkov light yield.
- Reconstruct neutrino energy from muon kinematics.
- >150k events!

$$E_{\nu}^{rec} = \frac{m_{p}^{2} - (m_{n} - E_{B})^{2} - m_{\mu}^{2} + 2(m_{n} - E_{B})E_{\mu}}{2(m_{n} - E_{B} - E_{\mu} + p_{\mu} \cos \theta_{\mu})}$$
MiniBooNE prediction

• Apply the rate normalisation factor obtained by SciBooNE analysis to MiniBooNE.

  Systematic errors:

• Most flux and cross section errors cancel between SciBooNE and MiniBooNE.

• Remaining errors:
  • Relative flux difference
  • Efficiency variation due to cross section model uncertainties.
  • MiniBooNE detector response errors.

Carefully estimate these errors!
MiniBooNE prediction

Successfully reduced flux and cross section errors to the same level as the MiniBooNE detector response errors.
Miniboone prediction

Successfully reduced flux and cross section errors to the same level as the MiniBooNE detector response errors.
Systematic uncertainties (1)

Flux uncertainties

8 GeV Proton

• Use HARP p-Be interaction measurement uncertainty for the error analysis.
• Becomes negligible after taking ratio between SciBooNE and MiniBooNE

π⁺ production cross section

• Cross section used for MC production
• HARP data
• Spline interpolation of HARP data

![Graph](image_url)

**Figure 3.3:** Double differential π⁺/π⁻ production cross section from 8 GeV proton interactions. The red points show the HARP data, and the blue curve shows the best fit to the data with the Sanford-Wang function used to produce the MC central values. The black points show the profile of the spline curves produced by the HARP data points and their errors.
Systematic uncertainties (2)

Cross section uncertainties

- Variations of $Q^2$ (muon angle) distribution can change relative acceptance.
  - SciBooNE: (mostly) forward muons
  - MiniBooNE: isotropic acceptance.
  - The major source of the systematic error, together with the MB detector response error.
Predicting oscillation signal

- Mean $\nu$ path-length for SciBooNE events: $\sim 76m$
- Mean $\nu$ path-length for MiniBooNE events: $\sim 520m$
- Each has 50m spread due to the finite length of the decay volume
- We consider three effects:
  - Oscillation at SciBooNE
  - Oscillation at MiniBooNE
  - Smearing effect due to 50m spread
Oscillation probability

- Oscillation reaches maximum at the first oscillation peak,
- then washes out at high $\Delta m^2$ by integrating over neutrino energy.
- Since we compare the MB flux with SB, $P(\text{MB})/P(\text{SB})$ is the expected signal.
- Sensitive to oscillations in range $0.5 < \Delta m^2 < 30 \text{ eV}^2$.
Spectrum fit

- Test oscillation hypothesis for two flavors, and scan over \((\Delta m^2, \sin^2\theta)\) plane.

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27\Delta m^2[eV^2]L[km]}{E[GeV]}\right)
\]

- Evaluate

\[
\Delta \chi^2 = \chi^2(\text{each point}) - \chi^2(\text{best})
\]

\[
\chi^2 = \sum_{jk} (M_{j}^{\text{obs}} - M_{j}^{\text{pred}}) V^{-1}_{jk} (M_{k}^{\text{obs}} - M_{k}^{\text{pred}})
\]

- Use Feldman-Cousins for confidence level of \(\Delta \chi^2\) values.
Spectrum fit sensitivity

- Sensitivity reaches $\sin^2 2\theta \sim 0.1$ in $1 < \Delta m^2 < 20$ eV$^2$
- Significantly improved from MiniBooNE-only analysis.
- Achieved world’s best sensitivity at $0.5 < \Delta m^2 < 30$ eV$^2$
Results
Spectrum fit result

Fit both MiniBooNE new and old data

Best: $\Delta m^2 = 41.7 \text{ eV}^2$, $\sin^2 2\theta = 0.51$

$\chi^2 (\text{null}) = 41.5/32 (\text{DOF})$

$\chi^2 (\text{best}) = 35.6/30 (\text{DOF})$

$\Delta \chi^2 = \chi^2 (\text{null}) - \chi^2 (\text{best}) = 5.9$

$\Delta \chi^2 (90\% \text{CL, null}) = 8.4$

(estimated by simulation)

No significant oscillation signal observed.

Small data/MC discrepancy found, but doesn’t match oscillation signature.
The observed limits from both analyses are within the ±1σ band.

More support for null oscillation hypothesis.

World’s strongest limit at $10 < \Delta m^2 < 30 \text{ eV}^2$

arXiv:1106.5685[hep-ex]
Discuss!

- Possible Improvements:
  - Dominant uncertainties: neutrino x-section and MiniBooNE detector response.
  - Further analysis of SciBooNE (and MiniBooNE) data could reduce the cross section errors if we had newer/better cross section models.
  - To reduce detector error, need identical detectors or $10^{-2}$ MeV $e^-$ calibration.
  - Muon antineutrino disappearance analysis \( \Leftarrow \text{Particularly interesting!} \)
  - These analysis methods are directly applicable to anti-neutrino analysis.

- $\nu$-mode result constrains $\nu$ BG, together with a direct measurement by MiniBooNE (arXiv:1102.1964) and event-by-event separation by SciBooNE.
Conclusions

• We have performed a joint search for muon neutrino disappearance at $\Delta m^2 \sim 1$eV$^2$ with SciBooNE and MiniBooNE.

• Two independent analyses performed; both showed consistent results.
  • Achieved world’s best sensitivity at $0.5 < \Delta m^2 < 30$ eV$^2$.
  • No significant signal found.
  • Set the best 90%CL limit at $10 < \Delta m^2 < 30$ eV$^2$.

• Paper on archive, submitted to Phys.Rev.D.
  
  arXiv:1106.5685[hep-ex]

• Stay tuned for a forthcoming joint muon anti-neutrino disappearance analysis!
Thanks!
Oscillation Observations

- Atmospheric region: $\Delta m^2 \sim 10^{-3} \text{ eV}^2$
  - Super-K, K2K, MINOS, etc
- Solar region: $\Delta m^2 \sim 10^{-5} \text{ eV}^2$
  - SNO, Super-K, KamLAND, etc

Only 2 $\Delta m^2$ regions are allowed in the current SM with 3 neutrino generations

However, there is one more region claimed by the LSND experiment at $\Delta m^2 \sim 1 \text{ eV}^2$
What does MiniBooNE claim?

1. No $\nu_e$ excess in $\nu_\mu$ beam above 475 MeV.
   ➡ Maximal oscillation sensitivity if LSND is L/E and CPT invariant.

2. $3\sigma$ excess $(128 \pm 43)$ of $\nu_e$ candidates in $\nu_\mu$ beam below 475 MeV.
   ➡ Does not fit well to a 2$\nu$ mixing hypothesis

3. Small excess $(18\pm14)$ below 475 MeV in $\bar{\nu}_\mu$ beam.
   ➡ Rules out some $\nu_\mu$ beam low-E excess explanations.

4. Small excess $(20.9 \pm 14)$ in $\bar{\nu}_\mu$ beam above 475 MeV.
   ➡ Null hypothesis in 475-1250 MeV region has p-value 0.005
   ➡ 2$\nu$ fit prefers LSND-like signal at 99.4% CL.
Comparing MB to LSND

Fit to 2ν mixing model


Model-independent plot of inferred oscillation probability
\( \nu_\mu \) Disappearance (cont’d)

- Large allowed region from global fit to world data with (3+1) model, if \( \nu_\mu \) and \( \bar{\nu}_\mu \) fit independently.

- Try to improve MiniBooNE results with a near detector (SciBooNE).

- Flux+shape analysis with reduced systematic error.

Analysis Overview

**Two independent analyses**

**Spectrum fit**

- SciBooNE data
  - CC interaction rate measurement
  - MiniBooNE rec. $E_{\nu}$ prediction
  - MiniBooNE rec. $E_{\nu}$ data

**Simultaneous fit**

- SB + MB Rec. $E_{\nu}$ Data
  - Oscillation Fit
  - SB + MB Rec. $E_{\nu}$ Prediction

**Advantage:**
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

**Advantage:**
Decouple oscillation fit from constraint.
Observe the amount of constraint.
Simultaneous Fit

- Fit reconstructed $E_\nu$ distributions from SciBar-stopped, MRD-stopped and MiniBooNE samples simultaneously.
- 16 bins/sample x 3 sample = 48 bins
- All bin-to-bin correlation is included into the fit.
- Off-diagonal elements are strongly correlated.

*MiniBooNE distribution is scaled by ~1/7*
Simultaneous Fit

• MC prediction is renormalised by the number of events in SciBooNE.

• Evaluate

\[ \Delta \chi^2 = \chi^2(\text{each point}) - \chi^2(\text{best}) \]

\[ \chi^2 = \sum_{i,j} (d_i - Np_i)M_{ij}^{-1}(d_j - Np_j) \]

- \(d_i\): Data
- \(p_i\): Prediction (function of osc. parameter)
- \(M_{ij}\): 48x48 covariance matrix
- \(N\): Renormalization factor

• Again, Feldman-Cousins’s method is used to determine the CLs.
Simultaneous fit sensitivity

- Sensitivities of the two analysis method are (roughly) the same.
- Simultaneous fit sensitivity curve is smoother because of smaller binning effects than the spectrum fit analysis.
Simultaneous fit result

\[ \Delta \chi^2 (90\% CL, \text{null}) = 9.3 \]

(estimated by simulation)

No significant oscillation signal observed.

Best: \( \Delta m^2 = 43.7 \text{ eV}^2, \sin^2 2\theta = 0.60 \)

\( \chi^2(\text{null}) = 45.1/48(\text{DOF}) \)

\( \chi^2(\text{best}) = 39.5/46(\text{DOF}) \)

\( \Delta \chi^2 = \chi^2(\text{null}) - \chi^2(\text{best}) = 5.6 \)
90% CL limit from spectrum fit

• The observed limits are within the ±1σ band.
• Another support for null oscillation signal.
• World strongest limit at \(10 < \Delta m^2 < 30 \text{ eV}^2\)
• Constrain sterile neutrino mixing parameters.
90% CL limit from simultaneous fit

- The observed limits are within the ±1σ band.
- Another support for null oscillation signal.
- World strongest limit at $10 < \Delta m^2 < 30$ eV$^2$
- Constrain sterile neutrino mixing parameters.
systematic uncertainties

TABLE VIII. List of systematic uncertainties considered.

<table>
<thead>
<tr>
<th>Category</th>
<th>Error Source</th>
<th>Variation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺/π⁻ production from p-Be interaction</td>
<td>Spline fit to HARP data [19]</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>K⁺/K⁰ production from p-Be interaction</td>
<td>Tables VIII and IX in Ref. [21]</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>Flux</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) Nucleon and pion interaction in Be/Al</td>
<td>Table XIII in Ref. [21]</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>Horn current</td>
<td>±1 kA</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>Horn skin effect</td>
<td>Horn skin depth, ±1.4 mm</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>Number of POT</td>
<td>±2%</td>
<td>Sec. II B</td>
<td></td>
</tr>
<tr>
<td>(ii) Fermi surface momentum of carbon nucleus</td>
<td>±30 MeV</td>
<td>Sec. III B 1</td>
<td></td>
</tr>
<tr>
<td>Binding energy of carbon nucleus</td>
<td>±9 MeV</td>
<td>Sec. III B 1</td>
<td></td>
</tr>
<tr>
<td>Neutrino interaction</td>
<td>CC-QE $M_A$</td>
<td>±0.22 GeV</td>
<td>Sec. III B 1</td>
</tr>
<tr>
<td>CC-QE $\kappa$</td>
<td>±0.022</td>
<td>Sec. III B 1</td>
<td></td>
</tr>
<tr>
<td>CC-$1\pi$ $M_A$</td>
<td>±0.28 GeV</td>
<td>Sec. III B 2</td>
<td></td>
</tr>
<tr>
<td>CC-$1\pi$ $Q^2$ shape</td>
<td>Estimated from SciBooNE data</td>
<td>Sec. III B 2</td>
<td></td>
</tr>
<tr>
<td>CC-coherent-$\pi$ $M_A$</td>
<td>±0.28 GeV</td>
<td>Sec. III B 3</td>
<td></td>
</tr>
<tr>
<td>CC-multi-$\pi$ $M_A$</td>
<td>±0.52 GeV</td>
<td>Sec. III B 4</td>
<td></td>
</tr>
<tr>
<td>(iii) Intra-nuclear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction</td>
<td>Δ re-interaction in nucleus</td>
<td>±100 %</td>
<td>Sec. III B 2</td>
</tr>
<tr>
<td>Pion charge exchange in nucleus</td>
<td>±20 %</td>
<td>Sec. III B 5</td>
<td></td>
</tr>
<tr>
<td>Pion absorption in nucleus</td>
<td>±35 %</td>
<td>Sec. III B 5</td>
<td></td>
</tr>
<tr>
<td>Proton re-scattering in nucleus</td>
<td>±10 %</td>
<td>Sec. III B 5</td>
<td></td>
</tr>
<tr>
<td>NC/CC ratio</td>
<td>±20 %</td>
<td>Sec. III B 5</td>
<td></td>
</tr>
<tr>
<td>(iv) Detector response</td>
<td>PMT 1 p.e. resolution</td>
<td>±0.20</td>
<td>Sec. II D</td>
</tr>
<tr>
<td>Birk’s constant</td>
<td>±0.0023 cm/MeV</td>
<td>Sec. II D</td>
<td></td>
</tr>
<tr>
<td>PMT cross-talk</td>
<td>±0.004</td>
<td>Sec. II D</td>
<td></td>
</tr>
<tr>
<td>Pion interaction cross section in the detector material</td>
<td>±10 %</td>
<td>Sec. II D</td>
<td></td>
</tr>
<tr>
<td>dE/dx uncertainty</td>
<td>±3%(SciBar,MRD), ±10%(EC)</td>
<td>Sec. II D</td>
<td></td>
</tr>
<tr>
<td>Density of SciBar</td>
<td>±1 %</td>
<td>Sec. II C</td>
<td></td>
</tr>
<tr>
<td>Normalization of interaction rate at the EC/MRD</td>
<td>±20 %</td>
<td>Sec. III A</td>
<td></td>
</tr>
<tr>
<td>Normalization of interaction rate at the surrounding materials</td>
<td>±20 %</td>
<td>Sec. III A</td>
<td></td>
</tr>
</tbody>
</table>
Rate normalisation factors from SciBooNE spectrum fit

<table>
<thead>
<tr>
<th>Energy region (GeV)</th>
<th>( \nu_\mu ) CC rate normalization factor</th>
<th>NEUT</th>
<th>NUANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 - 0.50</td>
<td>1.04 ( \pm ) 0.20</td>
<td>1.65 ( \pm ) 0.22</td>
<td></td>
</tr>
<tr>
<td>0.50 - 0.75</td>
<td>1.03 ( \pm ) 0.11</td>
<td>1.31 ( \pm ) 0.11</td>
<td></td>
</tr>
<tr>
<td>0.75 - 1.00</td>
<td>1.23 ( \pm ) 0.08</td>
<td>1.36 ( \pm ) 0.08</td>
<td></td>
</tr>
<tr>
<td>1.00 - 1.25</td>
<td>1.29 ( \pm ) 0.10</td>
<td>1.38 ( \pm ) 0.09</td>
<td></td>
</tr>
<tr>
<td>1.25 - 1.75</td>
<td>1.19 ( \pm ) 0.11</td>
<td>1.36 ( \pm ) 0.12</td>
<td></td>
</tr>
<tr>
<td>1.75 -</td>
<td>0.79 ( \pm ) 0.08</td>
<td>0.90 ( \pm ) 0.09</td>
<td></td>
</tr>
</tbody>
</table>
Test of SB spectrum fit with oscillation effects

Black points: fit result

Red lines: input value

<table>
<thead>
<tr>
<th>$\Delta m^2$</th>
<th>$\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>3.4 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>5.5 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>8.9 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>14.5 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>23.4 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>36.0 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>61.7 eV$^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>100.0 eV$^2$</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Neutrino event displays

Real SciBooNE Data

vertex resolution \( \sim 5 \) mm

\[ \bar{\nu}_\mu \text{ CC-QE candidate} \]
\[ (\bar{\nu}_\mu + p \rightarrow \mu + n) \]

\[ \nu_\mu \text{ CC-QE candidate} \]
\[ (\nu_\mu + n \rightarrow \mu + p) \]
Growing Consensus

- We need broad coverage
  - Model independent measurements at many energies, nuclei
- Move away from process cross-sections
  - $\sigma$(QE), $\sigma$(res $\pi$), $\sigma$(coh $\pi$)
- Instead measure final state particle cross-sections
  - $\sigma$(CC), $\sigma$(\mu), $\sigma$(\mu+p), $\sigma$(\mu+\pi)

If $\theta_{13}$ is large, we need to understand these systematics in order to measure CP violation!

Same goes for NC...
Discuss!

- Possible Improvements:
  - Dominant uncertainties: neutrino x-section and MiniBooNE detector response.
  - Further analysis of SciBooNE (and MiniBooNE) data could reduce the cross section errors if we had newer/better cross section models.
  - To reduce detector error, need identical detectors or $10^{-2}$ MeV e$^-$ calibration.
  - Muon antineutrino disappearance analysis \( \Leftrightarrow \text{Particularly interesting!} \)
    - These analysis methods are directly applicable to anti-neutrino analysis.
  - $\nu$-mode result constrains $\nu$ BG, together with a direct measurement by MiniBooNE (arXiv:1102.1964) and event-by-event separation by SciBooNE.

- Size of errors at MB

- \( \nu \) (wrong sign)
  - \( \sim 90\% \bar{\nu} \) purity
  - \( \sim 90\% \nu \) purity

- 1-track w/o activity sample
- 2-track QE-like sample

- Preliminary