MiniBooNE First Oscillation Results
Bohr was ready to abandon Conservation of Energy to explain this missing energy phenomena until Pauli proposed this "desperate remedy": the neutrino.

1930: Pauli  
"...I have predicted something which shall never be detected experimentally!"

1956: Electron neutrino detected

2007: Continuously growing field of neutrino physics!
Neutrinos in the Standard Model

Quarks interact electromagnetically, strongly, weakly

Quark masses range from ~1 MeV to 170 GeV
Quarks mix between their flavors

The CKM Matrix

\[
\begin{bmatrix}
\begin{array}{c}
\theta \\
\phi \\
\end{array}
\end{bmatrix}
= 
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix}
\begin{bmatrix}
\theta \\
\phi
\end{bmatrix}
\]
Charged leptons interact electromagnetically and weakly. Charged leptons range in mass from 0.5 MeV to 1.7 GeV. Leptons are paired in doublets with neutrinos.
Neutrinos in the Standard Model

By comparison, we know relatively little about the neutrinos....

paired in doublets with electrons
no charge
until recently....no mass?
Why have we known so little?  
→ Took 26 years from Pauli just to see the neutrino

the weak force is **weak**!  
neutrinos interact  
\[100,000,000,000\]  
times less often than quarks

\[\nu\]  

A neutrino has a good chance of traveling through 200 earths before interacting at all!
Fortunately, there are many sources of neutrinos from all over the universe!

Unfortunately, they are so small, they don't make up much of the universe

Neutrino Beams made from Particle Accelerators

\[ \nu \]'s from cosmos:
- our sun
- supernovae
- relic neutrinos

Neutrino Beams made from Reactors

Created in particle decay:
Cosmic Ray Showers
Neutrino Mass:
Mass is a fundamental property of particles

Took many years to demonstrate neutrinos have mass
So small -> Can't measure mass in the usual way...

What other behavior is associated with mass?
A quantum mechanical effect called
Neutrino Oscillations

\[ \nu_\mu \rightarrow \nu_e \]
Neutrino Oscillations
indication of mass:

If we postulate:
- Neutrinos have (different) masses
- The Weak Eigenstate is a mixture of Mass Eigenstates:

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

Then a pure $\nu_\mu$ beam at $t = 0$, may evolve a $\nu_e$ component with time!

The Probability for Oscillations...

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

straightforward to extend to the 3 neutrino world...
Oscillation Probability depends on:

- Two fundamental parameters
  - $\Delta m^2$
  - $\sin^2 2\theta$
- Two experimental parameters
  - $L$: distance from source to detector
  - $E$: Neutrino energy

Probe different oscillation parameters by changing $L$ and $E$
Oscillation Landscape

Solar Neutrino Oscillations
- Deficit of $\nu_e$ observed from Sun Cl (Homestake), H$_2$O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\bar{\nu}_e$)

Atmospheric Neutrino Oscillations
- Zenith angle-dependent deficit of $\nu_\mu$:
  Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS

LSND Neutrino Oscillations
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam produced from $\mu^+$ decay-at-rest
- Unconfirmed by other experiments, but not excluded
LSND anomaly:

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,

$87.9 \pm 22.4 \pm 6.0$ (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:

Points -- LSND data
Signal (blue)
Backgrounds (red, green)
In a simple 3 neutrino picture:

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

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics.

There are too many signals!

\[ \nu_1 \xrightarrow{\Delta m_{12}^2} \nu_2 \]
\[ \nu_2 \xrightarrow{\Delta m_{23}^2} \nu_3 \]
\[ \Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2 \]

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics.
1) LSND is wrong?

2) There are sterile neutrinos
   -possible....as crazy an idea as Pauli's “desperate remedy”

3+1 and 3+2 models

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk, neutrino decay....

Too many signals...
MiniBooNE: address the LSND anomaly

- look for $\nu_e$ appearance in a $\nu_\mu$ beam at Fermilab

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
How Did the Universe Survive the Big Bang? In This Experiment, Clues Remain Elusive
• The Experimental Setup
• Two Independent Data Analyses
• Errors and Constraints
• First Results
8 GeV protons on Beryllium Target in a magnetically focusing horn
50 m decay region:

FNAL 8 GeV Booster

movable absorber: stops muons, undecayed mesons

$\pi, K$

$\nu_\mu$

$\mu$
Almost pure $\nu_\mu$ beam, peaked at 800 MeV

$\sim 0.5\%$ background “intrinsic” $\nu_e$s

$\nu_e$ intrinsics:

$\pi^+ \rightarrow \nu_\mu \mu$

$e^+ \nu_e \nu_\mu$

$k^+ \rightarrow \pi^0 \nu_e e^+$

$k_L \rightarrow \pi^- \nu_e e^+$
\( \nu_\mu \rightarrow \nu_e \) ???

MiniBooNE Detector

- 12m in diameter sphere
- 800 tons of ultra pure mineral oil
- sphere-within-a-sphere
- light tight signal region 1280 PMTs
- veto region 240 PMTs
See them interact by seeing remnants of the interaction....

Quasi-Elastic Scattering: Charged Current Interaction

$\nu_e$ see the recoil nucleon $e$ flavor tag

see the recoil nucleon
See them interact by seeing remnants of the interaction....

Quasi-Elastic Scattering: Charged Current Interaction

$V_\mu$

$\mu$

flavor tag

W

see the recoil nucleon
See them interact by seeing remnants of the interaction....

Single Pion Production to Deep Inelastic Scattering

$\nu_\mu$ see the outgoing particles $\pi^0$.
Neutrino interactions in MiniBooNE...

Event signature: First cluster of hits (first subevent) is the muon. Followed by smaller cluster of hits: decay electron

Predicted event rates before cuts (NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161
Muons:  
Produced in most CC events.

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

$\pi^0$s:  
Can form a background if one photon is weak or exits tank.
Example of Cerenkov Rings: A stopping cosmic ray

First the muon enters the tank and stops...
Later a the Michel electron is observed

Michel electrons provide muon tags and calibration
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 \( E_{\nu}^{QE} \)

\[ E_{\nu}^{QE} \text{ resolution} \sim 10\% \]
Model describes CCQE $\nu_\mu$ data well.

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

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

NUANCE Parameters:
The Experimental Setup

Two Independent Data Analyses

- Track Based Analysis
- Boosted Decision Trees

Errors and Constraints

First Results
Share
- GEANT 4 beam Monte Carlo
- NUANCE v3 event generator
- GEANT3 detector Monte Carlo
- Simple pre-cuts

removes low energy Michel electrons
(+ 1 subevent and R<500 cm)
Both were blind analyses:

- **data**
  - Filter: electron-like events were hidden from analysis
  - non-electron like (~99% of events) available for analysis

As well, for all events, low level information was available.
Each event is characterized by 7 reconstructed variables: vertex \((x,y,z)\), time, energy, and direction \((\theta, \varphi) \rightarrow (U_x, U_y, U_z)\).

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

\(\nu_\mu\) CCQE events

2 subevents
Veto Hits<6
Tank Hits>200
Each event is reconstructed under several different reconstruction hypotheses: electron-like ($L_e$), muon-like ($L_\mu$), $\pi^0$ like, ($L_{\pi^0}$).

$log(L_e/L_\mu)>0$ favors the electron-like hypothesis.

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.

Photon conversions are electron-like. These are not cut here.
Rejecting “π⁰-like” events

Using a mass cut

Using log($L_e/L_{π^0}$)

Cuts were chosen to maximize $ν_μ → ν_e$ sensitivity
Testing e-\(\pi^0\) separation using data

1 subevent
log(\(L_e/L_\mu\)) > 0 (e-like)
log(\(L_e/L_{\pi^0}\)) < 0 (\(\pi^0\)-like)
mass > 50 (high mass)
\[ \log \left( \frac{L_e}{L_\mu} \right) > 0 \] (e-like)

\[ \log \left( \frac{L_e}{L_{\pi^0}} \right) < 0 \] (\(\pi^0\)-like)

mass < 200 (high mass)

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

Next: look here....
Summary of TB cuts

Efficiency:

$\log \left( \frac{L_e}{L_{\mu}} \right)$

$\log \left( \frac{L_e}{L_{\pi^0}} \right)$

Invariant mass

Backgrounds after cuts
- The Experimental Setup
- Two Independent Data Analyses
- Errors and Constraints
- First Results
We have two categories of backgrounds:

- $\nu_\mu$ mis-id
- intrinsic $\nu_e$

Predictions of the backgrounds are among the nine sources of significant error in the analysis.
Summary of predicted backgrounds for the final MiniBooNE result (TB Analysis):

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Unrelated</td>
<td>2</td>
</tr>
<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>
<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 $E_v^{QE}$
- and information on the correlations between bins
Use “Multisims” To convert from errors on parameters to errors in $E_{\nu}^{QE}$ bins:

For each error source,

“Multisim” experiments are generated within the allowed variations by reweighting the standard Monte Carlo. In the case of the OM, hit-level simulations are used.

70 multisims for the Optical Model

From differences between central value and each Multisim, Form correlated Error Matrices

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

Error bars on plots are the diagonals of the error matrix, but the fully correlated matrix goes into oscillation fit
• The Experimental Setup
• Two Independent Data Analyses
• Errors and Constraints
• First Results
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: $0.55 \sigma$
TB energy dependent fit results:

Best Fit (dashed): \((\sin^22\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)\)

Error bars are diagonals of error matrix.

Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%
This places a limit on on oscillations for $\nu_\mu$ to $\nu_e$ appearance only oscillations

Energy fit: $475 < E_{\nu}^{QE} < 3000$ MeV

Boosted decision tree analysis is consistent (both as counting experiment and in energy fit) with this
Across a broader range of energies:
$300 < E_{\nu}^{\text{QE}} < 3000 \text{ MeV}$

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

Background-subtracted:

MiniBooNE investigating low energy events:
Need to understand these in any case:

- new physics
- background which must be understood for next class of experiments
What we already know about these events.....

- They are spread throughout the run,
- They show no bias in event timing
- They show no bias in spatial distribution (they are not from outside)
- The backgrounds in this region are large, but they are well constrained

**Likelihood Analysis**

300 MeV to 475 MeV
1) LSND is wrong?

Then these are the main mixing matrix elements

\[

\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s \\
\nu_s' \\
\vdots
\end{pmatrix}

= 

\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
U_{s1} & U_{s2} & U_{s3} \\
U_{s'1} & U_{s'2} & U_{s'3} \\
\vdots & \vdots & \vdots
\end{pmatrix}

\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\nu_5 \\
\vdots
\end{pmatrix}

\]

2) There are sterile neutrinos

3+1 and 3+2 models

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk, neutrino decay....
1) LSND is wrong?  
3+1 models are ruled out but 3+2 and 3+3 fit MiniBooNE + LSND well
...tension with SBL disappearance expts.
...tension for some configurations with cosmological constraints

2) There are sterile neutrinos

3+1 and 3+2 models

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s \\
\nu_s'
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & \cdots & U_{e4} & U_{e5} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu 4} & U_{\mu 5} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau 4} & U_{\tau 5} \\
U_{s 1} & U_{s 2} & U_{s 3} & \cdots & U_{s 4} & U_{s 5} \\
U_{s' 1} & U_{s' 2} & U_{s' 3} & \cdots & U_{s' 4} & U_{s' 5}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\nu_5
\end{pmatrix}
\]

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk, neutrino decay....
Are sterile neutrinos an asset for astrophysics?

**The R-process needs a large neutron imbalance**

How do you create a very large neutron-imbalance?  
First create an anti-electron neutrino rich environment.  
\[ \bar{\nu}_e + p \rightarrow e^+ + n, \quad \nu_e + n \rightarrow e^- + p \]

... which works if the conditions are right (high electron density, right oscillation parameters) to produce a $\nu_e \rightarrow \nu_s$ “resonance”

Allowed ranges for oscillation to enable sufficient U production

Beun, Surman, McLaughlin & Hix, preliminary

Are they a problem for cosmology?  
Cosmology constrains neutrino mass to $\sim$1-2 eV  
Depending on the sterile neutrino mass ordering, neutrino mass $\sim$2-10 eV. So some constraints are there.
1) LSND is wrong?

2) There are sterile neutrinos

3+1 and 3+2 models

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk, neutrino decay....

Then these are the main mixing matrix elements

- New physics? Possible
- Background? Well constrained but we're still looking!
- MiniBooNE, SciBooNE and follow-on experiments will look
MiniBooNE rules out a two neutrino interpretation of LSND

Discrepancy at low energy is under study
Fit to the > 300 MeV range:

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

\(\chi^2\) Probability: 18%
Boosted Decision Trees

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

Convert “Fundamental Variables” into “Analysis Variables” then develop trees to score events as signal or background.

This is an independent cross check of the Track Based Analysis.
Boosted Decision Trees

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

This is an independent cross check of the Track Based Analysis
Reduce Analysis Variables to a Single PID Variable

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

Boosting uses Decision Trees (sequential series of cuts)

Continue decision tree until each “leaf” is either very pure or statistically small.

Combine output of many trees → Boosting
Boosted Decisions Trees

A set of decision trees is created using Monte Carlo

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 then combined.

The resulting “score” for the event can be thought of as a probability that it is signal.
BDT cuts on PID score as a function of energy. We can define a “sideband” just outside of the signal region.
MiniBooNE data constrains uncertainties!

<table>
<thead>
<tr>
<th>Source of Uncertainty On $\bar{\nu}_e$ background</th>
<th>TB/BDT error in %</th>
<th>Checked or Constrained by MB data</th>
<th>Further reduced by tying $\bar{\nu}<em>e$ to $\nu</em>\mu$</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 ints. (“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>

Different analyses are sensitive to different uncertainties.