Current Status of LSND & BooNE

- **LSND**
  
Preliminary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results from 1993–1998
  
  Published $\nu_\mu \rightarrow \nu_e$ results from 1993–1995
  
  Final global analysis results ($\nu$ oscillations, $\nu C, \nu e, \nu p$) by the end of 1999

- **BooNE**
  
  Definitive test of the LSND signal
  
  Construction begins in October, 1999
  
  Data taking begins in December, 2001
\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
Particle Identification
\[ \bar{\nu}_e \text{C} \rightarrow e^- \text{N}_{g.s.} \]

**Electron Energy (MeV)**

- **Data MC**
- **Events**
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80
  - 90
  - 100

**Positron Energy (MeV)**

- **Data MC**
- **Events**
  - 0
  - 5
  - 10
  - 15
  - 20

**Table**

- $\chi^2$/ndf: 15.49 / 13
- $P_1$: 110.3 ± 7.643
- $P_2$: 14.39 ± 0.8861

- $\tau_{\text{Data}} = 14.4 \pm 0.9 \text{ msec}$
- $\tau_{\text{Theory}} = 15.9 \text{ msec}$

**Graph**

- Δt between electron - positron (msec)

**σ** = \((9.1 \pm 0.4 \pm 0.9) \times 10^{-42} \text{ cm}^2\) (LSND)
\((9.4 \pm 0.5 \pm 0.8) \times 10^{-42} \text{ cm}^2\) (KARMEN)
\((9.3 - 9.4) \times 10^{-42} \text{ cm}^2\) (theory)
Cross section of $\nu_e C \rightarrow e^- N_{g.s.}$
$\nu_\mu C \rightarrow \mu^{-}N_{g.s.}$

- **Data**
  - Electron energy (MeV)
  - Positron energy (MeV)

- **$\nu_\mu C$ Data**
  - Number of events

- **$\mu X$ Data**
  - Number of events

- **MC**
  - Number of events

- **$\Delta t$ between $\mu-e^+$ (msec)**

\[ \sigma = (6.5 \pm 1.0 \pm 1.0) \times 10^{-41} \text{ cm}^2 \ (LSND) \]

\[ (6.3 - 6.6) \times 10^{-41} \text{ cm}^2 \ (\text{theory}) \]
Cross section of $\nu_\mu C \rightarrow \mu^- N_{g.s.}$
ν Oscillation Events Signature

\[ \overline{\nu}_\mu \xrightarrow{\text{oscillation}} \overline{\nu}_e + p \rightarrow e^+ + n \]
\[ \tau = 186 \mu s \]
\[ n \ p \rightarrow d^+ \gamma(2.2 \text{MeV}) \]

- \( e^+ \) selection
  
  Particle ID : cut cosmic neutrons
  \( d_{PMT} > 35 \text{cm} : \) fiducial volume
  \( \Delta t_{\text{previous}} > 20 \mu s : \) cut cosmics
  \( \Delta t_{\text{next}} > 8 \mu s : \) cut muons
  \( n_{\gamma} < 2 : \) cut cosmic neutrons
  < 4 veto hits : cut cosmics
  \( S > 0.5 : \) cut cosmics
  Efficiency : 0.37

- \( \gamma \) selection : Likelihood ratio, R method
Correlated $\gamma$ ID

- define $L = P(\Delta t) \cdot P(\text{# hits}) \cdot P(\Delta r)$

- for $R = L(\text{correlated})/L(\text{accidental})$
$^{12}\text{C}(\nu_e,e^-)^{12}\text{N}_e$. Sample (94–97)

Correlated Component = ($-0.6 \pm 1.1$)%
$^{12}\text{C}(\nu_{\mu}, \mu^-) \times \text{Sample}(94-97)$

Correlated Component = (10.2 ± 1.1%)
Preliminary LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Results for 1993–1998

<table>
<thead>
<tr>
<th>Selection</th>
<th>Beam On</th>
<th>Beam-Off</th>
<th>$\nu$ Background</th>
<th>Total Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&gt;30 20&lt;E&lt;60</td>
<td>70</td>
<td>17.7±1.0</td>
<td>12.8±1.7</td>
<td>39.5±8.8</td>
</tr>
<tr>
<td>R&gt;30 36&lt;E&lt;60</td>
<td>33</td>
<td>6.2±0.6</td>
<td>3.3±0.7</td>
<td>23.5±5.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>20–36 MeV</th>
<th>36–60 MeV</th>
<th>20–60 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993–1995 (low, high $\Delta m^2$)</td>
<td>3.7±4.2 (11.0,7.1)</td>
<td>17.4±4.7 (14.1,16.6)</td>
</tr>
<tr>
<td>1996–1998 (low, high $\Delta m^2$)</td>
<td>12.3±5.1 (6.7,4.7)</td>
<td>6.1±3.4 (7.7,11.0)</td>
</tr>
<tr>
<td>1993–1998 (low, high $\Delta m^2$)</td>
<td>16.0±6.6 (17.7,11.9)</td>
<td>23.5±5.8 (21.8,27.6)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Fitted Excess</th>
<th>Total Excess</th>
<th>Oscillation Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993–1995</td>
<td>63.5±20.0</td>
<td>51.0±20.2</td>
<td>(0.31±0.12±0.05)%</td>
</tr>
<tr>
<td>1993–1998</td>
<td>111.8±25.6</td>
<td>90.9±26.1</td>
<td>(0.33±0.09±0.05)%</td>
</tr>
</tbody>
</table>

N.B.: The absolute electron efficiency, energy calibration, duty factor, and neutrino flux have been estimated for the 1996 through 1998 data and are subject to change. A global analysis of all of the data (DAR and DIF) is underway.
Events with Multiple Gammas

I. \((20<E<60) \& (R>30)\)

\[\#\gamma = 1 \Rightarrow\] 70 on, 308 off, 52.3+8.4 excess

\[\#\gamma > 1 \Rightarrow\] 6 on, 99 off, 0.3+2.5 excess

Ratio => 0.09 0.32 0.01+0.05

II. \((36<E<60) \& (R>30)\)

\[\#\gamma = 1 \Rightarrow\] 33 on, 113 off, 26.8+5.8 excess

\[\#\gamma > 1 \Rightarrow\] 1 on, 41 off, -1.4+1.1 excess

Ratio => 0.03 0.36 -0.05+0.04

We expect that for primary neutrons, the events would have multiple gammas with Ratio = 0.60. Therefore, our signal is NOT due to primary neutrons!
FIG. 32. The total number of hit PMTs in the detector tank for the extra events that occur 0 - 3μs and 3 - 6μs prior to oscillation candidate events. The candidates are in the 25 < E_e < 60 MeV energy range with (a) R ≥ 0 and (b) R > 30. The data points are the beam-on events, while the solid curve is what is expected from random PMT hits as determined from the sample of laser calibration events.
\( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) Checklist

**OK** 1. Spatial Distribution

**OK** 2. Energy Distribution

**OK** 3. Correlated \( \gamma \) Distribution

**OK** 4. Angular Distribution

**OK** 5. Veto Distribution

**OK** 6. Events with Multiple \( \gamma \)s

**OK** 7. Hit PMTs in Lookback

**OK** 8. \( \text{H}_2\text{O} \) Target vs High z Target
The diagram shows the relationship between \( \Delta m^2 \) [eV\(^2\)] and \( \sin^2 2\Theta \) for different experiments:

- **CCFR**
- **NOMAD**
- **KARMEN**
- **Bugey**

The highlighted region represents the 90% and 95% CL regions following the approach of Feldman and Cousins for the **LSND** experiment from 1993-98.
$\Delta m^2$ [eV$^2$] vs. $\sin^2 2\Theta$ graph showing data from CCFR, KARMEN, LSND, and Bugey. The combined 90% confidence region is the overlap of the 95% confidence levels.
$\nu_\mu \rightarrow \nu_e$ DIF Oscillation Search

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

$\nu_e C \rightarrow e^- N$

- Different systematics than DAR
- Different backgrounds than DAR
  $\mu \rightarrow e \nu_\mu \nu_e$ and $\pi \rightarrow e \nu_e$
- Different coverage of $\Delta m^2$ and $\sin^2 2\theta$
- However, only a single signature
$18.1 \pm 6.6$ excess events
The BooNE Collaboration

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S. Koutsoliotas
Bucknell University, Lewisburg, PA 17837

E. Church, I. Stancu, G. J. VanDalen
University of California, Riverside, CA 92521

R. A. Johnson, N. Suwonjandee
University of Cincinnati, Cincinnati, OH 45221

L. Bugel, J. M. Conrad, J. Formaggio, M. H. Shaevitz,
B. Tannminga, F. D. Zimmermann
Columbia University, Nevis Labs, Irvington, NY 10533

D. Smith
Embry Riddle Aeronautical University, Prescott, AZ 86301

C. Bhat, B. C. Brown, R. Ford, P. Kasper,
I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills,
C. Moore, A. Russell, R. Stefanski
Fermi National Accelerator Laboratory, Batavia, IL 60510

K. Eitel, G. T. Garvey, E. Hawker, W. C. Louis, G. B. Mills,
V. Sandberg, B. Sapp, R. Taylor, D. H. White
Los Alamos National Laboratory, Los Alamos, NM 87545

R. Inlay, H. J. Kim, A. Malik, W. Metcalf, M. Sung
Louisiana State University, Baton Rouge, LA 70803

R. Berbecu, B. P. Roe, N. Wadia, J. Yamamoto
University of Michigan, Ann Arbor, MI 48109

A. O. Bazarko, P. D. Meyers, F. C. Shoemaker
Princeton University, Princeton, NJ 08544
40-feet diameter sphere
1520 8-inch PMTs (1280 detector + 240 veto PMTs)
807 tons of mineral oil
445 ton fiducial volume
Oil vs Water

- More Cerenkov light \((x 1.45)\)
  - oil \(\rightarrow\) \(n = 1.47, \rho = 0.85\)
  - water \(\rightarrow\) \(n = 1.33, \rho = 1.00\)

- No need for a purification system

- No worry about liquid seeping into bases

- Oil has less multiple scattering
  - oil \(\rightarrow\) \(X_0 = 44.8 \text{ g/cm}^2\)
  - water \(\rightarrow\) \(X_0 = 36.1 \text{ g/cm}^2\)

- Oil has lower \(\mu^-\) capture rate
  - oil \(\rightarrow\) \(8\%\)
  - water \(\rightarrow\) \(18\%\)

- Pure mineral oil produces a little scintillation light
attenuation length of some oils, 2 runs with shift

- Shell Oil G 09
- ESSO Marcol 52
- Paraffin dünnflüssig
- Aral 96 / 6705
- BP 1998
- BP M 2520
- BP M 002
- Dea Pharma 5
- Dea Pharma 240
- Total Carnation
The electron time distribution in pure oil

Run 664 LSND data and Texas A&M cyclotron tests indicate that for pure oil:

(i) 75% Cerenkov light & 25% scintillation light
(ii) Scintillation time constant of ~ 35 ns
Full GEANT Monte Carlo Simulation

$\nu_e C \rightarrow e^- N$  Signal

$\nu_\mu C \rightarrow \mu^- N$  Background

$\nu_\mu C \rightarrow \nu_\mu \pi^0 X$  Background
Event Reconstruction & PID

1. electron event reconstruction
   \( \delta r \sim 21 \text{ cm} \)
   \( \delta t < 1 \text{ ns} \)
   \( \delta \theta \sim 3.6^0 \)
   \( \delta E/E \sim 10\% \)

2. muon event reconstruction
   mis-id background < 0.1\%
   \( \delta E/E \sim 29\% \)

3. \( \pi^0 \) event reconstruction
   mis-id background \sim 1\%
   \( \delta E/E \sim 10\% \)
The $\chi^2$ Particle ID Method
Systematic Errors from Particle Mis-id

$\mu^-$: <5\% systematic error
Use decay $\mu^-$ events to determine the mis-id rate:

- 92\% are tagged by the decay $e^-$
- 8\pm0.1\% are captured

$\pi^0$: \approx5\%
Use symmetric $\pi^0$ decays to determine the mis-id rate:

Angular distribution between 2 fitted rings
The BooNE $\nu$ beam  (*Full Geant Simulation*)

- Al target within 2-horn secondary focusing system

Solid – $\nu_\mu$ flux,  
Dashed – $\nu_e$ background

Sources of $\nu_e$ background (0.3% of beam):

- $\mu$ decays (75% of total $\nu_e$, 5% systematic error)
- $K$ decays (25% of total $\nu_e$, 10% systematic error)
- The $\nu_e$ beam background does not fit the energy shape for the oscillation hypothesis.
To know $\nu_e$'s from $\mu$ decays, we need the $\pi$ spectrum...

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

The $\nu_\mu$ energy spectrum is highly correlated to the $\pi$ spectrum!

(Because the detector subtends a very small solid angle)

\[ E_\pi/E_\nu \approx 2.5 \text{ for all } E_\pi ! \]

This means we can...

1. Measure the $\nu_\mu$ flux
2. Apply a simple relation to convert $\nu_\mu$ flux to $\pi$ spectrum
3. Decay $\pi$ to $\mu$ to $\nu_e$ to get predicted $\nu_e$ flux

Investigating method using Monte Carlo:
We can constrain the $\nu_e$ from $\mu$ decay to 5%
## Estimated Number of Events after 1 year ($2 \times 10^7$ s)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \ C \rightarrow \mu^- N$</td>
<td>590,000</td>
</tr>
<tr>
<td>$\nu_\mu \ e \rightarrow \nu_\mu \ e$</td>
<td>130</td>
</tr>
<tr>
<td>$\nu_\mu \ C \rightarrow \mu^- \pi^0 X$</td>
<td>65,000</td>
</tr>
<tr>
<td>$\nu_\mu \ p,n \rightarrow \nu_\mu \ p,n$</td>
<td>72,000</td>
</tr>
<tr>
<td>$\nu_e \ C \rightarrow e^- N$</td>
<td>617,000</td>
</tr>
<tr>
<td>(100% transmutation)</td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2 = 0.4 \text{ eV}^2$, $\sin^2 2\theta = 0.02$</td>
<td>1200</td>
</tr>
<tr>
<td>Intrinsic $\nu_e$</td>
<td>1800</td>
</tr>
<tr>
<td>$\mu^-$ Misidentification</td>
<td>600</td>
</tr>
<tr>
<td>$\pi^0$ Misidentification</td>
<td>600</td>
</tr>
</tbody>
</table>
The background is low at low energies...

Points: $\Delta m^2 = 0.4 \text{ eV}^2$

$\sin^2 2\theta = 0.04$

colored bands show

systematic errors

note log scale $\rightarrow$

Signal after Bkgd Subtraction for Two Possible Osc. Parameters:

- Statistical uncertainty for signal is included in errors.
- Sys. and stat. uncertainty from background is included in errors.
- (Statistical fluctuations of data points not shown).

MiniBooNE can clearly establish a signal!

The signal indicates where to place the 2nd detector
A "Measurement" Experiment!

Two examples for MiniBooNE (1 detector) measurements:

<table>
<thead>
<tr>
<th>$\Delta m^2$ (eV$^2$)</th>
<th>$\sin^2 2\theta_0$</th>
<th>$\delta (\Delta m^2)$ (eV$^2$)</th>
<th>$\delta (\sin^2 2\theta)$</th>
<th>Signal Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.03</td>
<td>0.10</td>
<td>0.02</td>
<td>44 $\sigma$</td>
</tr>
<tr>
<td>2.0</td>
<td>0.002</td>
<td>0.10</td>
<td>0.0002</td>
<td>15 $\sigma$</td>
</tr>
</tbody>
</table>

Example BooNE (2 detector) measurement

And tests of CP violation with $\nu$ and $\bar{\nu}$ running
Conclusions

- Evidence for $\nu$ oscillations from LSND!
  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search yields $39.5^{+8.8}_{-8.8}$ events
  $\nu_\mu \rightarrow \nu_e$ search yields $18.1^{+6.6}_{-6.6}$ events
  $m_\nu > 0.4$ eV

- The BooNE experiment will make a definitive test of the LSND signal and will make precision measurements of $\Delta m^2$ and $\sin^2 2\theta$ if $\nu$ oscillations occur.

- BooNE construction begins 10/99
  Gain beneficial occupancy on 1/01
  Detector operational on 10/01
  Beam complete & taking data on 12/01