Antineutrino Oscillation Results from MiniBooNE & Possible CP Violation in the Lepton Sector

W.C. Louis

Los Alamos National Laboratory

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Outline

- Introduction
- LSND $\nu_\mu \rightarrow \nu_e$ Oscillation Results
- MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Search
- Fits to the World Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments
- Conclusion
Neutrino Oscillations

Weak Eigenstates

\[ \nu_\mu \]
\[ \nu_e \]

Eigenstates of Propagation

\[ \cos \theta \nu_1 + \sin \theta \nu_2 \]
\[ -\sin \theta \nu_1 + \cos \theta \nu_2 \]

\[ P(\nu_\mu) \]
\[ P(\nu_e) \]

\[ P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L/E_\nu) \]

\[ \Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \ L \text{ in meters, } E_\nu \text{ in MeV} \]
Probability of Neutrino Oscillations

\[ P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_i \sum_j |U_{\alpha i} U^*_{\beta i} U_{\alpha j} U^*_{\beta j}| \sin^2(1.27\Delta m_{ij}^2 L/E_{\nu}) \]

As N increases, the formalism gets rapidly more complicated!

<table>
<thead>
<tr>
<th>N</th>
<th>#\Delta m_{ij}^2</th>
<th>#\theta_{ij}</th>
<th>#CP Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
T & CP & CPT Violation in the Lepton Sector

$\nu_\alpha \rightarrow \nu_\beta \neq \nu_\beta \rightarrow \nu_\alpha$  \hspace{1cm} T Violation

$\nu_\alpha \rightarrow \nu_\beta \neq \nu_\alpha \rightarrow \nu_\beta$  \hspace{1cm} CP Violation

$\nu_\alpha \rightarrow \nu_\beta \neq \nu_\beta \rightarrow \nu_\alpha$  \hspace{1cm} CPT Violation
LSND Signal

- LSND experiment
- Stopped pion beam
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
  \[ e^+ + \nu_\mu + \nu_e \]
- Excess of \( \nu_e \) in \( \nu_\mu \) beam
- \( \nu_e \) signature: Cherenkov light from \( e^+ \) with delayed \( \gamma \) from n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8\( \sigma \))
LSND Signal

- Assuming two neutrino oscillations

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 \ L \ \Delta m^2}{E} \right) = 0.245 \pm 0.067 \pm 0.045 \% \]

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings
Sterile Neutrinos

- 3+N models
- For N>1, model allows CP violation for short baseline
  - $\nu_{\mu} \rightarrow \nu_{e} \neq \nu_{\mu} \rightarrow \nu_{e}$
Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al. arXiv:1006.5276)

\[ 3 + N_s \]
\[ m_v = 0 \]

\[ 3 + N_s \]
\[ m_s = 0 \]
MiniBooNE Experiment

- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector
\( \nu_e \) Event Rate Predictions

\#Events = Flux x Cross-sections x Detector response

External measurements (HARP, etc)
\( \nu_\mu \) rate constrained by neutrino data

External and MiniBooNE measurements
- \( \pi^0 \), delta and dirt backgrounds constrained from data.

Detailed detector simulation checked with neutrino data and calibration sources.

**Neutrino**
- Green: Effective \( \pi^0 \)'s
- Blue: Dirt
- Pink: Delta's
- Yellow: Other
- Lt Blue: Nue (CCQE)

**Antineutrino**
- Green: Effective \( \pi^0 \)'s
- Blue: Dirt
- Pink: Delta's
- Yellow: Other
- Lt Blue: Nue (CCQE)
Modeling Production of Secondary Pions

- HARP (CERN)
  - 5% $\lambda$ Beryllium target
  - 8.9 GeV proton beam momentum
  - $\pi^+$ & $\pi^-$

Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024
Neutrino Flux from GEANT4 Simulation

Wrong-sign background is $\sim 6\%$ for Nu-Mode & $\sim 18\%$ for Antinu-Mode

Intrinsic $\nu_e$ background is $\sim 0.5\%$ for both Nu-Mode & Antinu-Mode
Neutrino Cross Sections

NC EL

QE

NC \pi^0

CC \pi^0
NuInt07, final results soon

CC \pi^+
(PAC (Mar 2008))

multi-\pi

NUANCE
Antineutrino Cross Sections

NUANCE
Calibration Sources

Tracker system

15% E resolution at 53 MeV

Michel electrons

$\delta m \sim 20\%$

$\pi^0$

Visible Tank Energy (MeV)

Cosmic Muon Energy

Tracker & Cubes

Visible energy range of oscillation signal
NC$\pi^0$ Scattering


coherent fraction = 19.5\% ± 1.1\% ± 2.5\%
Fermi Gas Model describes CCQE $\nu_\mu$ data well

$M_A = 1.23^{+0.20}_{-0.20} \text{ GeV}$

$\kappa = 1.019^{+0.011}_{-0.011}$

Also used to model $\nu_e$ and $\bar{\nu}_e$ interactions

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

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

186,000 muon neutrino events

14,000 anti-muon neutrinos

PRELIMINARY
Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}\text{C})>6\sigma_{\nu\mu}(n)$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

MiniBooNE Neutrino Oscillation Results
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

- 6.5e20 POT
- No excess of events in signal region (E>475 MeV)
- Ruled out simple $2\nu$ oscillations as LSND explanation (assuming no CP or CPT violation)

$\Delta m^2$ vs $\sin^2(2\theta)$

**SIGNAL REGION**

- Data
- $\nu_e$ from $\mu$
- $\nu_e$ from $K^+$
- $\nu_e$ from $K^0$
- $\pi^\circ$ misid
- $\Delta \rightarrow N_y$
- dirt
- other
- Const. Syst. Error

MiniBooNE Neutrino Oscillation Results
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess of events observed at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)
Shape not consistent with simple 2ν oscillations
Magnitude consistent with LSND


Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009


MiniBooNE Data Show a Low-Energy Excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess from 200-475 MeV = 128.8+-20.4+-38.3 events

6.46E20 POT
# Number of Excess Events

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Data</th>
<th>Background</th>
<th>Excess</th>
<th>#σ_{tot} (#σ_{stat})</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-300</td>
<td>232</td>
<td>186.8+-26.0</td>
<td>45.2+-13.7+-22.1</td>
<td>1.7 (3.3)</td>
</tr>
<tr>
<td>300-475</td>
<td>312</td>
<td>228.3+-24.5</td>
<td>83.7+-15.1+-19.3</td>
<td>3.4 (5.5)</td>
</tr>
<tr>
<td>200-475</td>
<td>544</td>
<td>415.2+-43.4</td>
<td>128.8+-20.4+-38.3</td>
<td>3.0 (6.3)</td>
</tr>
<tr>
<td>475-1250</td>
<td>408</td>
<td>385.9+-35.7</td>
<td>22.1+-19.6+-29.8</td>
<td>0.6 (1.1)</td>
</tr>
<tr>
<td>200-1250</td>
<td>952</td>
<td>801.0+-58.1</td>
<td>151.0+-28.3+-50.7</td>
<td>2.6 (5.3)</td>
</tr>
</tbody>
</table>
Low-Energy Excess vs $\cos\theta$
Backgrounds: Order \((G^2\alpha\alpha_s)\), single \(\gamma\) FS?

Dominant process accounted for in MC!

Axial Anomaly

Radiative Delta Decay

Other PCAC

So far no one has found a \(N\bar{N}\) process to account for the \(\nu,\bar{\nu}\) difference & the \(\nu\) low-energy excess. Work is in progress:

R. Hill, arXiv:0905.0291
Jenkins & Goldman, arXiv:0906.0984
Sterile $\nu$ Decay?

- The decay of a $\sim$50 MeV sterile $\nu$ has been shown to accommodate the LSND & MiniBooNE excesses
  - Gninenko, PRL 103, 241802 (2009)
  - arXiv:1009.5536
More Complicated $\nu$ Oscillations?

3+1 Global Fit to World Neutrino Data Only


Best 3+1 Fit:
$\Delta m_{41}^2 = 0.19$ eV$^2$
$\sin^2 2\theta_{\mu e} = 0.031$
$\chi^2 = 90.5/90$ DOF
Prob. = 46%

Predicts $\nu_\mu$ & $\nu_e$
disappearance of
$\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and
$\sin^2 2\theta_{ee} \sim 3.4\%$
MiniBooNE Antineutrino Oscillation Results

- $5.66 \times 10^{20}$ POT
MiniBooNE Antineutrino Null Probability

- Absolute $\chi^2$ probability of null point (background only) - model independent
- Frequentist approach

<table>
<thead>
<tr>
<th>Energy Range (MeV)</th>
<th>chi2/NDF</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>6.1/6</td>
<td>40%</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>18.5/6</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
## Number of Excess Events

<table>
<thead>
<tr>
<th>Energy (MeV) Data</th>
<th>Data</th>
<th>Background</th>
<th>Excess</th>
<th>$#\sigma_{\text{tot}}$ ($#\sigma_{\text{stat}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-475</td>
<td>119</td>
<td>100.5+-14.3</td>
<td>18.5+-10.0+-10.2</td>
<td>1.3 (1.9)</td>
</tr>
<tr>
<td>475-675</td>
<td>64</td>
<td>38.3+-7.2</td>
<td>25.7+-6.2+-3.7</td>
<td>3.6 (4.1)</td>
</tr>
<tr>
<td>475-1250</td>
<td>120</td>
<td>99.1+-14.0</td>
<td>20.9+-10.0+-9.8</td>
<td>1.5 (2.1)</td>
</tr>
<tr>
<td>475-3000</td>
<td>158</td>
<td>133.3+-18.0</td>
<td>24.7+-11.5+-13.8</td>
<td>1.4 (2.1)</td>
</tr>
<tr>
<td>200-3000</td>
<td>277</td>
<td>233.8+-22.5</td>
<td>43.2+-15.3+-16.5</td>
<td>1.9 (2.8)</td>
</tr>
</tbody>
</table>
MiniBooNE Oscillation Fit

E>475

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit \((\sin^2 2\theta, \Delta m^2) = (0.9584, 0.064 \text{ eV}^2)\)
  \[\chi^2/\text{NDF} = 8.0/4; \text{Prob.} = 8.7\% \text{ (475-1250 MeV)}\]
$\Delta \chi^2$ vs $\Delta m^2$
$E > 200\text{MeV}$

- $5.66E20$ POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta, \Delta m^2$) = (0.0066, 4.42 eV$^2$) $\chi^2/NDF = 11.6/7$; Prob.$=10.9\%$
E > 200 MeV

- Subtract excess produced by neutrinos in $\nu$ mode (11.6 events)
- Best fit $(\sin^2 2\theta, \Delta m^2) = (0.0061, 4.42 \text{ eV}^2)$
  $\chi^2/\text{NDF} = 12.6/7$; Prob. = 7.5%
MiniBooNE Oscillation Fit

\( E > 475 \text{ MeV} \)

\( \nu_\mu \rightarrow \nu_e \) oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed.
MiniBooNE
Oscillation Fit

$\nu_\mu \rightarrow \nu_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed.
LSND/MiniBooNE Data Compared to 3+N Global Fits

(3+1) $\bar{\nu}_\mu$, Model Antineutrino Appearance

(3+2) $\bar{\nu}_b$, Model Antineutrino Appearance
3+1 Global Fit to World Antineutrino Data (with new MiniBooNE data set)

Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:
$\Delta m_{41}^2 = 0.92 \text{ eV}^2$
$\sin^2 2\theta_{\mu e} = 0.0045$
$\chi^2 = 85.0/103 \text{ DOF}$
Prob. = 90%

Predicts $\nu_\mu$ and $\nu_e$ disappearance of
$\sin^2 2\theta_{\mu\mu} \sim 37\%$ and
$\sin^2 2\theta_{ee} \sim 4.3\%$
3+N Models Requires Large $\nu_\mu$ Disappearance

In general, $P(\nu_\mu \rightarrow \nu_e) < \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Reactor Experiments: $P(\nu_e \rightarrow \nu_x) < 5\%$

LSND/MiniBooNE: $P(\nu_\mu \rightarrow \nu_e) \sim 0.25\%$

Therefore: $P(\nu_\mu \rightarrow \nu_x) > 20\%$
MiniBooNE Neutrino & Antineutrino Disappearance Limits

A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

Improved results soon from MiniBooNE/SciBooNE Joint Analysis!
Initial MINOS $\nu_\mu$ Disappearance Results in $\nu$ Mode

Expect $\overline{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.
Initial MINOS $\nu_\mu$ Disappearance Results in $\nu$ Mode

Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.
Future Experiments

- More MiniBooNE $\nu$ Data (15E20 POT)
- MicroBooNE
  - CD1 approved
  - Address low energy excess
- Few ideas under consideration:
  - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
  - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
  - Redoing a stopped pion source at ORNL (OscSNS - http://physics.calumet.purdue.edu/~oscsns/)
More MiniBooNE Antineutrino Running
MicroBooNE sensitivity to low energy excess:

(neutrino running, 70 ton fiducial volume, x2 higher PID efficiency than MiniBooNE, 3% mis-ID, 6.0e20 POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1σ stat. significance
BooNE: Near Detector at \(~200\) m

- 541 meters
- 200 meters
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
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- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation

Sensitivity (Antineutrinos)

10e20 Far + 1e20 Near POT

$\Delta m^2$ vs $\sin^2(2\theta)$
BooNE

- Much better sensitivity for $\nu_\mu$ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

6.5e20 Far/1e20 Near POT

1e21 Far/1e20 Near POT

$\nu_\mu$ Disappearance $\chi^2$

$\bar{\nu}_\mu$ Disappearance $\chi^2$

X Karagiorgi et al. Best Fit
ICARUS at the CERN PS

A new search for anomalous neutrino oscillations at the CERN-PS

B. Baibussinov, E. Calligarich, S. Centro, D. Gibin, A. Guglielmi, F. Pietropaolo, C. Rubbia, and P. Sala

Map of CERN-PS showing "Far position" and "Near position" with a "Neutrino beam" indicated.
ICARUS at the CERN PS

Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for $2.5 \times 10^{20}$ pot and $5.0 \times 10^{20}$ pot respectively. The LSND allowed region is fully enclosed in both cases.

Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

150 ton LAr at 127 m
OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos
OscSNS

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \ \Delta(L/E) \sim 3\% \ ; \ \bar{\nu}_e \ p \rightarrow e^+ \ n \]

\[ \nu_\mu \rightarrow \nu_e \ \Delta(L/E) \sim 3\% \ ; \ \nu_e \ C \rightarrow e^+ \ N_{gs} \]

\[ \nu_\mu \rightarrow \nu_s \ \Delta(L/E) < 1\% \ ; \ \textbf{Monoenergetic} \ \nu_\mu \ !; \ \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \]

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_s \ ; \ \bar{\nu}_\mu \ C \rightarrow \bar{\nu}_\mu \ C^*(15.11) \]

OscSNS would be capable of making precision measurements of \( \nu_e \) appearance & \( \nu_\mu \) disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)).
Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:
\[ \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \]


Neutral Current Disappearance Pattern in a Two Detector Setup

Muon Neutrino Source $E = 30\text{MeV}$

Diagram showing a neutrino source at 30 MeV, with detection areas at 10 m, 20 m, and 60 m, illustrating the disappearance pattern with $\sim 20\text{eV}^2$ and $\sim 1\text{eV}^2$.
OscSNS

- $\bar{\nu}_e$ appearance (left) and $\nu_\mu$ disappearance sensitivity (right) for 1 year of running (for 60m!)
Conclusions

• The MiniBooNE data are consistent with $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$ and consistent with the evidence for antineutrino oscillations from LSND.

• The MiniBooNE $\nu_\mu \rightarrow \bar{\nu}_e$ oscillation allowed region appears to be different from the $\nu_\mu \rightarrow \nu_e$ oscillation allowed region. (CP or CPT Violation?)

• The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1 \text{ eV}^2$. This model predicts large $\bar{\nu}_\mu$ disappearance.

• BooNE at FNAL, ICARUS at CERN, or OscSNS at ORNL could measure neutrino oscillations with high significance ($>5\sigma$) and prove that sterile neutrinos exist!
Backup
3+1 Global Fit to World Antineutrino Data (with old MiniBooNE data set)

G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:
\( \Delta m_{41}^2 = 0.915 \text{ eV}^2 \)
\( \sin^2 2\theta_{\mu e} = 0.0043 \)
\( \chi^2 = 87.9/103 \text{ DOF} \)
Prob. = 86%

Predicts \( \bar{\nu}_\mu \) & \( \bar{\nu}_e \) disappearance of
\( \sin^2 2\theta_{\mu\mu} \sim 35\% \) and
\( \sin^2 2\theta_{ee} \sim 4.3\% \)
The MiniBooNE Detector

- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t
  of pure mineral oil (CH₂)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
  240 veto phototubes
- Simulated with a GEANT3 Monte Ca
10% Photocathode coverage

Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

Time Resolution 1.7 ns, 1.1 ns
Rejecting “muon-like” events

Using \( \log(L_e/L_\mu) \)

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

Note: photon conversions are electron-like. This does not separate \( e/\pi^0 \).

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the \( \nu_\mu \rightarrow \nu_e \) sensitivity
Testing $e$-$\pi^0$ separation using data

1 subevent
$log(L_e/L_\mu)>0$ (e-like)
$log(L_e/L_\pi)<0$ (\pi-like)
mass $>50$ (high mass)

![Diagram showing signal and invariant mass distribution]
The most important types of neutrino events in the oscillation search:

Background Muons (or charged pions):
Produced in most CC events. Usually 2 or more subevents or exiting through veto.

Signal and Background Electrons (or single photon):
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal. 1 subevent.

Background $\pi^0$s:
Can form a background if one photon is weak or exits tank. In NC case, 1 subevent.
Joint LSND/KARMEN Analysis

Joint analysis with Karmen2: 64% compatible

$E.\text{ Church, et al., PRD 66, 013001}$
LSND $\bar{\nu}_e$ Background Estimates

<table>
<thead>
<tr>
<th>Estimate</th>
<th>$\bar{\nu}<em>e/\nu</em>\mu$</th>
<th>$\bar{\nu}_e$ Bkgd</th>
<th>LSND Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND Paper</td>
<td>0.086%</td>
<td>19.5+-3.9</td>
<td>87.9+-22.4+-6.0</td>
</tr>
<tr>
<td>Zhemchugov Poster1</td>
<td>0.071%</td>
<td>16.1+-3.2</td>
<td>91.3+-22.4+-5.6</td>
</tr>
<tr>
<td>Zhemchugov Poster2</td>
<td>0.092%</td>
<td>20.9+-4.2</td>
<td>86.5+-22.4+-6.2</td>
</tr>
<tr>
<td>Zhemchugov Seminar</td>
<td>0.119%</td>
<td>27.0+-5.4</td>
<td>80.4+-22.4+-7.1</td>
</tr>
</tbody>
</table>

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\nu_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses MCNP)

Zhemchugov Poster1: FLUKA $\bar{\nu}_e/\nu_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: GEANT4 $\bar{\nu}_e/\nu_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: FLUKA $\bar{\nu}_e/\nu_\mu$ ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e/\nu_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p $\rightarrow$ $\mu^+$ n interactions, which confirms the $\pi^-$ production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!