MiniBooNE at First Physics

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NBI 2003
KEK, Tsukuba
November 7, 2003
MiniBooNE at First Physics

- Physics motivation: LSND
- MiniBooNE overview
  - Beam
  - Detector
  - Reconstruction and particle ID
- First physics results
- Status and near future
LSND decay-at-rest neutrino source

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search

Decay-at-rest $E_\nu < 53$ MeV

Baseline 30 meters
Energy $E < 53$ MeV

$L/E \sim 1-1.5 \text{ km/GeV}$
**LSND DETECTOR:**
- 167 TONS CH₂ (mineral oil, doped)
- 1220 PMTs (8° Hamamatsu)
- ACTIVE VETO SHIELD
- PASSIVE SHIELDING TOO

**LAMPF beam:**
- 800 MeV/c protons
- 6% duty factor
- 28,998 Coulombs on target
- 1993-98
Neutrino Fluxes

DAR Flux (96) at the Center of LSND

DECAYs AT REST

DIF Flux (96) at the Center of LSND

DECAYs IN FLIGHT

LSND Neutrino Physics
LSND oscillation signature

From $\mu^+$ decay at rest:

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$T = 186\mu$s

$$n + p \rightarrow d + \gamma$$

Reconstruct $e^+$ and $\gamma$ with appropriate delayed coincidence
## Event selection criteria at LSND

<table>
<thead>
<tr>
<th>Targeted Background</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-electron</td>
<td>Particle ID using Cerenkov cone shape and timing distribution</td>
</tr>
<tr>
<td>Cosmic ray muon</td>
<td>VETO SHIELD</td>
</tr>
<tr>
<td>Cosmic ray neutron</td>
<td>ONLY ONE T RECONSTRUCTS</td>
</tr>
<tr>
<td>Positron from $\pi$ decay</td>
<td>NO MUON-LIKE ACTIVITY IN 15 ms BEFORE EVENT</td>
</tr>
<tr>
<td>Accidental $\gamma$ coincidence</td>
<td>Cuts on likelihood ratio $R$ (incorporates spatial, temporal proximity)</td>
</tr>
<tr>
<td>Remaining beam-unrelated backgrounds</td>
<td>MEASURE using beam-off data (94% of live time) and SUBTRACT.</td>
</tr>
</tbody>
</table>

$R > 10 = \text{“golden mode”}$
LSND

20 MeV ≤ $E_{\text{visible}}$ ≤ 60 MeV data

- From $R>10$ sample (lowest background):

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Events</td>
<td>83</td>
</tr>
<tr>
<td>Beam-unrelated background</td>
<td>(-) 33.7</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ background (mostly from $\mu$ in beam dump)</td>
<td>(-) 8.5</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ background ($\mu^+$ decay in detector)</td>
<td>(-) 3.5</td>
</tr>
<tr>
<td>Other $\nu$ backgrounds (with no neutron)</td>
<td>(-) 4.6</td>
</tr>
</tbody>
</table>

| Unexplained Excess                           | 32.7 ± 9.2 |

- From fit to $R$ distribution:

| Oscillation Excess                          | 83.5 ± 21.2 |

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Probability

$(2.5 \pm 0.6 \pm 0.4) \times 10^{-3}$
LSND

$R > 10$ data

Energy distribution consistent with oscillations

$\Delta m^2 \sim 0.2$-$10 \text{ eV}^2$
KARMEN2: similar expt in England, no evidence for oscillations.

FIG. 14. Comparison of oscillation searches performed by different short baseline experiments.

These examples based on expected additional $\bar{\nu}_e$ events from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ demonstrate that at smaller values of $\Delta m^2$ there is a restricted parameter region statistically compatible with both experimental results. At high $\Delta m^2$ values, the LSND solutions are in clear contradiction with the KARMEN upper limit.

VIII. CONCLUSION

Results based on the entire KARMEN2 data set collected from 1997 through 2001 have been presented. The extracted candidate events for $\bar{\nu}_e$ are in excellent agreement with background expectations showing no signal for $\nu_\mu \rightarrow \bar{\nu}_e$ oscillations. A detailed likelihood analysis of the data leads to upper limits on the oscillation parameters $\sin^2(2\theta)$ and $\Delta m^2$ excluding parameter regions not explored analyzed by other experiments.

These limits exclude large regions of the parameter area favored by the LSND experiment. A more quantitative statistical statement on the compatibility between KARMEN and LSND has to be based on a combined statistical analysis of both likelihood functions [65]. Such a detailed joint statistical analysis has been performed [66].

The negative search for $\bar{\nu}_e$ from muon decay at rest presented here sets also stringent limits on other potential processes of $\bar{\nu}_e$ production such as lepton family number violating decays $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ or neutrino oscillations $\nu_e \rightarrow \bar{\nu}_e$ which will be discussed in a separate paper. Future experiments such as the MiniBooNE experiment at Fermilab [67] aim at investigating the LSND evidence and the oscillation parameters not yet excluded by the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search presented here.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support from the German Bundesministerium für Bildung und Forschung (BMBF), the Particle Physics and Astronomy Research Council (PPARC), and the Council for the Central Laboratory of the Research Councils (CCLRC). In particular, we thank the Rutherford Appleton Laboratory and the ISIS neutron facility for hospitality and steady support during years of data taking.
Joint KARMEN-LSND analysis:

- No disagreement between experiments
- Narrows allowed parameter range
Too many $\Delta m^2$'s:

- Only 3 light, weakly interacting neutrinos (LEP, SLD)
- Solar/KAMLAND $\Delta m^2$: $7 \times 10^{-5}$ eV$^2$ (mostly $\nu_e \rightarrow \nu_{\mu,\tau}$)
- Atmospheric $\Delta m^2$: $2 \times 10^{-3}$ eV$^2$ (mostly $\nu_{\mu} \rightarrow \nu_{\tau}$)
- LSND $\Delta m^2$: $0.2-10$ eV$^2$ (mostly $\nu_{\mu} \rightarrow \nu_e$)
- $\Delta m^2_3 = \Delta m^2_1 + \Delta m^2_2$

What's going on?

- One set of experiments is not seeing oscillations
- The neutrino sector contains nonstandard physics beyond oscillations
New Physics I: Sterile Neutrinos

An Experimentally Allowed Model

- Bimaximal mixing in 3 + 1 models
  - W. Krolakowski HEP-PH/0106350

\[ V_4 \]

\[ \Delta m^2 \text{ LSND} \]

\[ V_3 \]

\[ \Delta m^2 \text{ Atm.} \]

\[ V_2 \]

\[ \Delta m^2 \text{ Solar} \]

\[ V_1 \]

\[ \text{New "sterile" neutrino - has no normal weak interactions} \]

Solve "too many \( \Delta m^2 \)" problem by adding extra neutrino mass states.
New Physics II: Maximal CPT violation
(Barenboim, Borissov, and Lykken, hep ph/0212116)

- Independent mass hierarchies for $v$ and $\bar{v}$.

- Proposed in 2001, but accommodates KamLAND

- Side benefit: heavier antineutrinos allow early universe leptogenesis in thermal equilibrium

- Compatibility with SuperK data may be a stretch.
BooNE

- BooNE will test the LSND result with:
  - x10 statistics
  - Different beam
  - Different energy
  - Different oscillation signature
  - Different systematics
- Primary beam: 8 GeV protons from Fermilab Booster
- Horn-focused secondary $\pi$, $K$ decay in flight to neutrinos
- 500 meter oscillation baseline
- 800 ton mineral oil/Čerenkov detector
The BooNE Collaboration

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(with summer students)
Summer 2002
Oscillation signature at BoONE:

\[ \nu_e N \rightarrow e^- N' \] quasielastic scattering

Neutrino energy \( 0.5 - 1 \) GeV

Normalize to \( \nu_m N \rightarrow \mu^- N' \) (several \( \times 10^5 \) interactions)

Particle ID by Čerenkov ring shape.

Backgrounds to oscillation:

Intrinsic \( \nu_e \) in beam:

from \( \pi \rightarrow \mu \rightarrow \nu \) decay in secondary beam

from \( K_{e3} \) decays (\( K^+ \rightarrow \pi^0 e^+ \nu_e \), \( K^0 \rightarrow \pi^- e^- \bar{\nu}_e \))

Particle mis-id in detector:

\( \mu \) decays to \( e \), \( \mu \) not observed

\( \mu \) mis-id as \( e \), decay not seen

\( \tau e^0 \) produced in neutral currents, mis-id as \( e \)
WHAT IS
"MINI-BOONE?"

**FIRST PHASE OF THE BOONE PROGRAM:**

- A SINGLE NEUTRINO DETECTOR, BASELINE 500 m
- GOAL IS DEFINITIVE TEST OF LSND SIGNAL
- SOME SENSITIVITY TO $\nu_e$ DISAPPEARANCE

THIS IS EXPERIMENT 898, OR "MINI-BOONE."
IT IS APPROVED, FUNDED, AND RUNNING.

**FUTURE PHASE OF THE PROGRAM:**
ASSUMING LSND CONFIRMED,

- BUILD A SECOND DETECTOR OF SIMILAR DESIGN
- NEW DETECTOR BASELINE OF 1000 m (IF LOW $\Delta m^2$)
  250 m (IF HIGH $\Delta m^2$)
- PRECISE MEASUREMENT OF OSCILLATION PARAMETERS
- MUCH BETTER SENSITIVITY TO $\nu_e$ DISAPPEARANCE.
BooNE Location on the Fermilab Site
BooNE's Neutrino Beam

- The Booster
- Horn and Target
- Decay Pipe
- Beam Absorbers
- Kaon Monitoring (LMC)
The Booster

- **8 GeV proton accelerator**
  - Built to inject protons into Main Ring
  - Now injects Main Injector
  - Has excess capacity
  - Magnets cycle at 15 Hz

- **Extraction**
  - All beam extracted in a single turn
  - Pulse is 1.6 $\mu$s long; consists of $\sim$82 bunches (“RF buckets”) spaced 19 ns apart
  - $10^{-5}$ duty factor -> eliminates non-beam backgrounds
  - New 8 GeV fixed target facility built for BooNE; can accommodate other users too in future
Demand on the Booster

Need record Booster performance for MiniBooNE to operate at satisfactory rate simultaneously with the rest of the FNAL program.

Beam losses are currently limiting the rate.
Booster Performance

- Must limit radiation levels and activation of Booster components
  - Increase proton rate
  - Decrease beam loss
- Steady improvements so far through
  - Careful tuning
  - Understanding optics
- Rate about a factor of 2 or 3 below what's needed for us to see $10^{21}$ p.o.t. before early 2005
- Further improvements:
  - Collimator project (completed in Autumn 2003 shutdown)
  - Lattice improvements
  - (later) larger aperture RF cavities

![Graph](image)

- red: Booster output (protons/minute)
- blue: energy loss per proton (W-min/proton)

- July 2002 - Sept 2003
• Achieved $1.5 \times 10^{20}$ protons on target before shutdown began September 2.
• Only 15% of goal. We are eagerly awaiting accelerator improvements!
Secondary beam overview
We considered “borrowing” a second horn from BNL to increase our flux, but...

...its condition was somewhat imperfect.
Target Pile

constructed of "Blue Blocks"
(modular steel shielding blocks)

Collimator
(Exit 35 in. dia, 5 m from target)

constructed of LAB E steel plates
Time structure of the beam

Each 2-second cycle:

10 Booster pulses at 15 Hz rep. rate

(many variations on this pattern depending on other experiments running, Booster losses, etc.)
Horn and Target Region

• Primary beam position monitor: air multiwire
• Target: 71 cm beryllium metal (1.7 $\lambda_0$), resides inside horn
• Horn:
  - Inner conductor thickness: 3 mm
  - Outer conductor thickness: 25 mm
  - Peak current: 170 kA
  - Pulse width: 140 $\mu$s
  - Voltage: $\sim$4 kV
Beryllium Target Assembly

End View

Side View
Horn welding and assembly
THE DECAY PIPE

- 6' dia. corrugated metal pipe, air-filled
- Surrounded by gravel shielding
- 50 m long, fixed dump at end
- Interrupted at 25 m for movable beam dump

Why a movable dump? Cross-check on backgrounds:

Intrinsic $\nu_e$ comes primarily from:
- Muons: $\pi^+ \rightarrow \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ → double decay $\propto L^2$; mostly downstream
- Kaons: $K^+ \rightarrow \pi^0 e^+ \nu_e$ → short lifetime; mostly upstream

Say we have a 300 event $\nu_e$ excess: change decay length to 25 m:

<table>
<thead>
<tr>
<th>Decay Length</th>
<th>$\nu_\mu$ Events</th>
<th>$\nu_e$ Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 m</td>
<td>~400 000</td>
<td>300</td>
</tr>
<tr>
<td>25 m</td>
<td>~220 000</td>
<td>165</td>
</tr>
</tbody>
</table>

$\nu_\mu$ events • IF $\nu_\mu \rightarrow \nu_e$ oscillations • IF $\nu_e$ background misestimate

$\sim 250$ (if K mis-estimate), $\sim 80$ (if $\mu$)
Expected flux at MiniBooNE detector from GEANT4 Monte Carlo

- $\pi^+$ production: “JAM” fit to external data using Sanford-Wang parametrization.
- $K^+/K^-$ production: cross-section table derived from MARS production model
- $K^0$ production: MARS $K^+$ cross-section weighted by $K^0/K^+$ ratio from GFLUKA
K-decay $\nu_e$ background

- MiniBooNE will see $\sim$200-400 $\nu_e$ from $K^+$ and $K^0_L$ decays each year -- comparable to the yield from oscillation physics if LSND is correct.

- **Goal is a systematic error of <10% on K-decay $\nu_e$.**

- Information on these decays will come from:
  - Monte Carlo (GEANT4, MARS, GFLUKA)
  - Production measurements (BNL E910, HARP, plus other, older data)
  - In-situ measurement: LMC

50% disagreements!
K decays produce higher transverse-momentum muons than π decays

- LMC: off-axis (7°) muon spectrometer
- scintillating fiber tracker
- clean separation of muon parentage

- LMC: off-axis (7°) muon spectrometer

- temporary LMC detector (scintillator paddles):
  - shows that data acquisition is working
  - 53 MHz beam RF structure seen

Data from temporary LMC detector

Monte Carlo

μ from π

μ from K

Muon Spectrometer

Decay Channel

[Diagram of decay channel showing K and π decays]

Data from temporary LMC detector

[Graph showing muon momentum at 7° (GeV)]

[PMT5 hit time] - [beam-on-target time] (ns)
MINI-BOONE NEUTRINO DETECTOR

- Pure Mineral Oil - Total Mass 800 tons (20' radius)
- Fiducial Mass 445 tons (5m radius)
- Inner Volume has 1280 8'' PMTs (mostly from LSND)
- Outer (veto) Volume has 240 PMTs
Detector site, August 10, 1999
Tank assembly in place, May 4, 2000
PHOTOTUBE SUPPORT STRUCTURE (PARTIALLY ASSEMBLED VIEW)

- LAT SUPPORT STRUTS
- LATS
- PANEL MOUNTING
- VETO TUBES
- BARRIER PANEL

Support structure panels form opaque barrier between main volume (black) and veto volume (white)
TRIGGER AND READOUT

- Electronics reused from LSND
- Records time of first hit per tube and charge integral over 100 ns.
- Fully pipelined readout

TRIGGER:
- Record 20 μs about every beam pulse
- Trigger on certain patterns of detector activity off-spill to calibrate with cosmic rays and grab extra physics (may be able to see neutrinos from a galactic supernova!)
- Also trigger on calibration laser pulses
Selecting Neutrino Events

Beam window 1.6 µs

3 simple cuts give great rejection of non-ν events

No non-beam backgrounds unlike LSND
Particle ID

Event display key:
- Size: PMT charge
- Color: hit time (Red is early, Blue is late.)

Michel e candidate (e from \( \mu \) decay)
Beam \( \mu \) candidate
Beam \( \pi^0 \) candidate
Understanding the Detector

To calibrate PMT's, we measure:

- PMT charge
- Timing response
- Oil attenuation length

Laser Flasks:

- 397 nm laser light
- Four Ludox-filled flasks fed by optical fiber from laser

Timing Distribution for Laser Events (new tubes)
Stopping Muon Calibration System

Cosmic ray hodoscopes above the tank

Optically isolated scintillator cubes in tank:
- six 2-inch (5 cm) cubes
- one 3-inch cube

Calibration sample consists of muons up to 700 MeV
Michel Electron Measurements

- Michel electrons (from decays of stopped cosmic ray muons)

- Muon lifetime in oil:
  - measured: \( \tau = 2.15 \pm 0.02 \ \mu s \)
  - expected: \( \tau = 2.13 \ \mu s \)  
    (8% of \( \mu^- \) capture)

- Energy scale and resolution at Michel endpoint (53 MeV)
Data/MC Agreement in Vertex Reconstruction

Neutrino events:
- NHIT > 200
- NVETO < 6
- r < 450cm
- Timing
Initial Physics Measurements

• $\nu_\mu$ Quasielastic Scattering

• Neutral Current $\pi^0$ Production

• Neutral Current Elastic Scattering
Signatures of neutrino interactions in BooNE

Čerenkov ring (μ-like or e-like) plus small scintillation signal

1 or 2 Čerenkov rings plus larger scintillation signal

Mostly higher energies. A very ugly multi-ring event!

Two e-like rings plus larger scintillation signal from recoil nucleon

Same as above, but more forward-peaked

Recoil nucleon rarely above Čerenkov threshold; signal is almost entirely from scintillation. Very few PMT hits and low total charge.
CC $\nu_\mu$ Quasielastic Events

- Event selection
  - Topology
    - Ring sharpness
    - on- vs. off-ring hits
  - Timing
    - Single $\mu$-like ring
    - Prompt vs. late light
- Variables combined in a Fisher discriminant
- Data and MC normalized to unit area
- Yellow Band: MC with current uncertainties from
  - Flux prediction
  - $\sigma_{CCQE}$
  - Optical properties
$E_\mu$ reconstruction:
- Assume $\nu_\mu n \rightarrow \mu^- p$.
- Use $E_\mu$, $\theta_\mu$, to get $E_\nu$.

First look at neutrino flux:

**CC $\nu_\mu$ Quasielastic Events**

\[
\left( \frac{\Delta E}{E_{\text{Gen}}} \right)^2 = a^2 + \left( \frac{b}{E_{\text{Gen}}} \right)^2
\]

\begin{align*}
a &= 3.788008e-02 \\
b &= 8.364264e-02
\end{align*}

\(<10\% \text{ for } E_\nu > 800 \text{ MeV}\)
Preliminary $\nu_\mu$ Disappearance Sensitivity

Systematics dominated due to uncertainty in flux prediction.
NC $\pi^0$ Production

- $N_{\text{TANK}} > 200$, $N_{\text{VETO}} < 6$, no decay electron
- Perform two-ring fit on ALL events.
- Ring energies > 40 MeV
- Fit mass peak to extract signal yield including background shape from MC.

\[
\begin{align*}
\text{Mass} & = 0.1356 \pm 0.0009 \text{ GeV/c}^2 \\
\text{Width} & = 0.0209 \pm 0.0009 \text{ GeV/c}^2 \\
\text{Num. } \pi^0 & = 2425 \pm 107 \text{ Events}
\end{align*}
\]

note bkgd also peaking
NC $\pi^0$ Production Angle

- Production angle is sensitive to production mechanism: coherent is highly forward-peaked.

- Data and MC are normalized to unit area.

MC uses Rein-Sehgal cross-sections.
NC $\pi^0$ momentum and $E_\gamma$ asymmetry
NC Elastic Scattering

- Select $N_{\text{TANK}} < 150$, $N_{\text{VETO}} < 6$
- Use random triggers (Normalized Strobe Data) to subtract non-beam background.
- A cut on the fraction of late light in these events may help select NC elastic events.
\( \nu_e \) Appearance Status

- Blind analysis underway.

- Potential \( \nu_e \) candidates are not available for full analysis (particle ID, etc).

- All events are available for analyses which do not involve particle ID, for detector checks and Monte Carlo development.

- Sensitive to LSND region at 5 \( \sigma \).

- Updated estimates coming.

- Currently expect results in 2005.
Conclusions

• Beam and detector running well
• Still need more beam rate
• First physics plots are here

• $\leq 2$ years to $\nu_e$ oscillation results: Either we'll see oscillations and life will be very interesting, or we won't -- and phenomenology gets a lot easier.