MiniBooNE PAC Presentation
Continued AntiNeutrino Running in 2007

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Richard Van de Water
for the MiniBooNE Collaboration
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Outline

• Motivation for antineutrino running.
• Overview of experiment
• Status of current antineutrino running.
• Physics potential of requested $2 \times 10^{20}$ POT in antineutrinos.
• Conclusions.
Motivation for Antineutrino Running

- Antineutrino cross section measurements at \(~1\) GeV are sparse.
- Next generation long baseline experiments need these for oscillation and CP violation searches.
  - Specific issues related to pion/electron mis-identification rates.
- Extend $\overline{\nu}_\mu$ disappearance oscillation measurement by a few orders of magnitude in $\Delta m^2$. 
Motivations for Antineutrino running: Cross Sections are essential.
Motivation for Antineutrino Running: Input to Future Experiments

- Energy overlap makes MiniBooNE ideal place to measure $\nu_\mu$ and $\bar{\nu}_\mu$ cross sections for future long baseline experiments.
Overview of Experiment

- Primary mission to confirm or refute the LSND oscillation measurement.
  - Different systematics, same L/E.

8 GeV protons on Be target
Magnetic focusing horn (polarity reversible)

800 tons CH$_2$
1280 inner PMTs
240 veto PMTs
Key Features of MiniBooNE

1. Our beam:
   a) The secondary production is well-understood from HARP
   b) The design is simple and therefore systematics from design are low (e.g. only one horn, beamline is only 50 m, etc.)
   c) $\sim 1$ GeV is an important energy range for study.

2. Our detector:
   a) Carbon-based measurements are valuable for any future experiment using scintillator or oil-base
   b) Cerenkov detectors are good at isolating CCQE and single $\pi$ event types in the $\sim 1$ GeV range

Opportunity:
- We can do antineutrino measurements now, without upgrades.
- No other experiment will have our antineutrino event rates for many years!
Overview of Experiment

- Successfully took $7.0 \times 10^{20}$ POT in neutrino mode from Aug 2002 to Jan 2006.
  - Enough data to perform osc analysis.
- Jan 2006 switched to antineutrino running.
- E898 Phase I running and analysis
  - Spokespersons J. Conrad and W. Louis (update talk tomorrow).
- E944 Phase II running and analysis
  - Spokespersons S. Brice and R. Van de Water.
State of The MiniBooNE Collaboration in FY07


Currently 65 collaboration members: 25 lab, 20 faculty, 11 postdocs, 9 students

5 new graduate students earmarked for antineutrino analysis
- 1 Columbia student working on $\pi^0$ analysis
- 1 Columbia student working on 3+2 osc analysis
- 2 Yale students
- 1 Virginia tech

The collaborators are committed to FY07 running and analysis
Status of Antineutrino Running

- Early January 2006 switched horn power supply polarity.
  - Two weeks installing new supplies and power bus reconfiguration.
  - Next switch would take only one week.
  - Successful switchover, now running at -174kA.

First neutrino candidate in antineutrino mode
Weekly Run Statistics

Start anti-neutrino running

**Number of Horn Pulses**
- To date: 198.69 million
- Largest week: 2.46 million
- Latest week: 0.92 million

**Number of Protons on Target**
- To date: 8.0715 E20
- Largest week: 0.1085 E20
- Latest week: 0.0351 E20

**Number of Neutrino Events**
- To date: 737721
- Largest week: 11447
- Latest week: 586
Weekly Run Statistics

Start anti-neutrino running

POT per Horn Pulse
- Largest week: 4.85 E12
- Latest week: 3.81 E12

Horn Rate
(for time periods with beam)
- Largest week: 4.48 Hz
- Latest week: 1.91 Hz

Beam Uptime Fraction
(fraction of time with beam)
- Largest week: 97.4 %
- Latest week: 79.1 %
Antineutrino rates about a factor x5 less than neutrino rates (flux and cross sections).

Detector uptime over 99%.

Current (2\textsuperscript{nd}) horn collected over 100 million pulses, broke world record set by first horn!
- Have third spare horn ready to go.

Many improvements/upgrades to Booster during March 2006 shutdown
- Steadily increasing beam intensity
Integrated Protons During Antineutrino Running

Linux GxPA 1 Booster Charge History

Prot sums: event 1D at 34->34ms.

NuMI off periods

Shutdown
Integrated Protons

- Have collected $1.1 \times 10^{20}$ POT in six months of running (halfway to goal).
- Booster running well, reached Champagne goal of $9 \times 10^{16}$ p/hr for one hour, and integrated $1.1 \times 10^{19}$ POT/week (8/23/2006)!
- With NuMI on, recently averaging $0.35 \times 10^{19}$ POT/week.
  - Can expect to maintain this rate for duration of MiniBooNE antineutrino running.
  - By January 2007, expect total $1.5 \times 10^{20}$ POT.
  - By June 2007, expect total $2.2 \times 10^{20}$ POT.
Data Quality Checks

- Simple neutrino selection demonstrates good data ($0.7 \times 10^{20}$ POT).
  - TankHits > 200, cuts michel electrons.
  - VetoHits < 6, cuts cosmic rays.
Data Quality Checks

- Full neutrino reconstruction with $0.05 \times 10^{20}$ POT
  - Data/MC comparison looks reasonable.
Antineutrino Scale Factor

- Absolute normalization of data to MC antineutrino rates
  - data/MC approximately the same for $0.7 \times 10^{20}$ POT.
- Since data/MC inclusive rates agree, gives us confidence in MC to predict number of neutrinos for $2 \times 10^{20}$ POT.
Event Rates for $2 \times 10^{20}$ POT:

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>32,500</td>
</tr>
<tr>
<td>NC elastic</td>
<td>13,300</td>
</tr>
<tr>
<td>CC $\pi^-$</td>
<td>11,900</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>6,500</td>
</tr>
</tbody>
</table>

Reconstruction with $R < 550\text{cm}$

Antineutrino events:
To date all anti-neutrino beams suffer from neutrino (aka "wrong-sign") background.

At MiniBooNE:

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>$\bar{\nu}$</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>32,500</td>
<td>11,200</td>
</tr>
<tr>
<td>NC elastic</td>
<td>13,300</td>
<td>4,700</td>
</tr>
<tr>
<td>CC $\pi^-$</td>
<td>11,900</td>
<td>0</td>
</tr>
<tr>
<td>CC $\pi^+$</td>
<td>0</td>
<td>7700</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>6,500</td>
<td>2,200</td>
</tr>
</tbody>
</table>

(Reconstruction with $R<550\text{cm}$)

Compare to $\sim2\%$ WS contamination in neutrino mode.

- Have developed a method to reduce WS error on xsec to 2% - THIS IS CRUCIAL TO OUR PHYSICS GOALS

- Applicable for T2K/NoVA CP violation searches

Why?
Because the leading + charged particle is hard to defocus.
Three Independent Methods of Understanding WS Background.

1. Angular distribution of the CCQE scatters:
   - Fitting the angular distribution:
     - 7% measure of WS (2% error on xsec)

2. Muon Lifetime measurement:
   - 8% of $\mu^-$ capture but 0% of $\mu^+$ capture
   - Affecting the measured lifetime of stopped $\mu$
   - 30% measure of WS (9% error on xsec)

3. CC $\pi^+$ analysis
   - 15% measure of WS
     - (5% error on xsec)
Measuring WS and RS flux shapes

Angular distribution of the CCQE Events:

- Fitting the angular distribution: 7% measure of WS rate using full sample
- Want to repeat fit in Energy bins to extract WS and RS flux shapes.

Fit Errors:

- With $2 \times 10^{20}$ POT estimate 19k events after CCQE cuts:
  - For 16 energy bins, expect 28% fit errors per bin.
- Fit errors increase to 40% per bin for $1 \times 10^{20}$ POT.
Three examples of physics measurements that can be completed:

- 2 Interesting Cross Section Measurements
- Antineutrino Disappearance

... other ideas are in development
Cross Sections: CCQE

- Existing world data set is <1000 events (zero in MB energy range).
- Scattering from free protons should be well understood.
- Scattering from Carbon is not, due to nuclear effects.

![CC νμ̅bar Quasi-Elastic Cross Section](image)

- MiniBooNE range should be well predicted.
- Is prediction ~20% high?

**Free Nucleon**

**Bound Nucleon**
Planned CCQE Analysis with \(2 \times 10^{20}\) POT:

Start with 40k \((\nu + \overline{\nu})\) full MC events. Apply the \(\nu\) reconstruction...

Goals:

1. Obtain the cross section vs. energy -- 20% normalization error.
   - currently systematics limited.
   - needed for our antineutrino oscillation analyses!

2. Study nuclear effects and form factors with \(d\sigma/dQ^2\).

<table>
<thead>
<tr>
<th>Event type</th>
<th># events passing CC QE selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE (\bar{\nu}_\mu) (RS)</td>
<td>10,893</td>
</tr>
<tr>
<td>CC QE (\nu_\mu) (WS)</td>
<td>3,332</td>
</tr>
<tr>
<td>1(\pi) (\bar{\nu}_\mu) backgrounds</td>
<td>3,341</td>
</tr>
<tr>
<td>1(\pi) (\nu_\mu) backgrounds</td>
<td>1,032</td>
</tr>
<tr>
<td>QE (\bar{\nu}_\mu) hyperon production</td>
<td>329</td>
</tr>
<tr>
<td>total</td>
<td>18,927</td>
</tr>
</tbody>
</table>

Do we see larger/different effect?

Study suppression in \(\bar{\nu}\) also
Cross Sections: NC\(\pi^0\)

Existing data set:

There are \textbf{NO} published \(\bar{\nu}\) measurements in our range (one published measurement of a single data point at 2 GeV)

Antineutrinos isolate the coherent contribution:

Range of \(\nu\)-mode predictions (compared to resonance):

\[50\% \text{ (shown)} \rightarrow 5\%\]
Mis-ID $\pi^0$ Analysis

Points:
- Major background to oscillation measurements (MB, T2K, NoVA).
- Need accurate determination of $\pi^0$ momentum spectrum to correct MC --> softens distribution.
- Mis-ID rates enhanced at higher momentum
- Analysis is very sensitive to statistics at high momentum!

Neutrino Analysis: Pion misidentification rates with corrected momentum

<table>
<thead>
<tr>
<th>$\pi^0$ Momentum bin (GeV/c)</th>
<th>Neutrino mode $5.7 \times 10^{20}$ POT</th>
<th>Antineutrino mode $2.0 \times 10^{20}$ POT</th>
<th>Antineutrino mode $1.0 \times 10^{20}$ POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; p ≤ 0.1</td>
<td>1525 ± 150 (9.8%)</td>
<td>184 ± 14</td>
<td>91 ± 10</td>
</tr>
<tr>
<td>0.1 &lt; p ≤ 0.2</td>
<td>10380 ± 197 (1.9%)</td>
<td>1171 ± 34</td>
<td>586 ± 24</td>
</tr>
<tr>
<td>0.2 &lt; p ≤ 0.3</td>
<td>3303 ± 195 (2.1%)</td>
<td>878 ± 30</td>
<td>439 ± 21</td>
</tr>
<tr>
<td>0.3 &lt; p ≤ 0.4</td>
<td>5902 ± 177 (3.0%)</td>
<td>549 ± 23</td>
<td>275 ± 17</td>
</tr>
<tr>
<td>0.4 &lt; p ≤ 0.5</td>
<td>2420 ± 138 (5.7%)</td>
<td>220 ± 15</td>
<td>110 ± 11</td>
</tr>
<tr>
<td>0.5 &lt; p ≤ 0.6</td>
<td>1249 ± 110 (8.8%)</td>
<td>148 ± 12</td>
<td>74 ± 9</td>
</tr>
<tr>
<td>0.6 &lt; p ≤ 0.8</td>
<td>913 ± 90 (9.8%)</td>
<td>72 ± 9</td>
<td>36 ± 6</td>
</tr>
<tr>
<td>0.8 &lt; p ≤ 1.0</td>
<td>265 ± 65 (24%)</td>
<td>36 ± 6</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>1.0 &lt; p ≤ 1.5</td>
<td>180 ± 67 (37%)</td>
<td>30 ± 6</td>
<td>15 ± 4</td>
</tr>
<tr>
<td>Total</td>
<td>32139 ± 422 (1.3%)</td>
<td>3288 ± 57</td>
<td>1644 ± 41</td>
</tr>
</tbody>
</table>
Disappearance in antineutrino mode has not been explored in our range at all....

If we don't see a signal in neutrino mode this is a search for CPT violation (See Barger, et al, hep-ph/0308399)

\[ P(\bar{\nu}_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \]

implies CPT violation!
CP Violation (3+2) Models:

$$P_{\text{osc}}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{\text{osc}}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

The same mechanism as for 3-generation CP violation.

MiniBooNE can have a small signal in neutrino-mode (which could easily fluctuate to a null signal!) and a $\times 2$ larger signal in antineutrino mode.

Future possibility with more data, current estimates $\sim 6 \times 10^{20}$ POT.
Impact of MiniBooNE Running

- **Accelerator Division (AD)**
  - MiniBooNE gets whatever protons are available without adversely affecting other programs.
  - Minimal technical support required.
  - $12/hour cost to operate the beam (electricity).

- **Computing Division (CD)**
  - Is able to continue current level of support.

- **Particle Physics Division (PPD)**
  - Is able to continue current level of support.

- **AD costs common to SciBooNE and MiniBooNE.**
Our Request to the PAC

- We currently have successfully collected $1.1 \times 10^{20}$ POT in antineutrino mode.
- We request running to collect another $1 \times 10^{20}$ POT, for a total of $2 \times 10^{20}$ POT.
  - Requires running to June 2007 (~next shutdown).
- We thank the AD for outstanding efforts delivering POT, and encourage continued pushes to increases POT.
- Expect to develop a new run plan after the neutrino oscillation analysis results.
Reasons for Reduced Antineutrino Rates

1. The antineutrino beam, produced by $\pi^-$, has **lower intensity** and is **softer** ($<E_{\bar{\nu}}>=650$ MeV compared to $<E_{\nu}>=750$ MeV)

2. **Spin suppresses the cross section** for $\bar{\nu}$ interactions (RH) because at our energies we only hit valence quarks (LH)

Compare:

<table>
<thead>
<tr>
<th>LH neutrino + LH quark</th>
<th>RH antinu + LH quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_z=0$</td>
<td>$J_z=1$</td>
</tr>
<tr>
<td>easily scatters into:</td>
<td>cannot scatter into:</td>
</tr>
<tr>
<td>$J_z=0$</td>
<td>$J_z=-1$</td>
</tr>
</tbody>
</table>

Overall Result: About 5 times less antineutrino than neutrino events...