Recent results from SciBooNE and MiniBooNE experiments

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Fermilab’s Booster Neutrino Beam

- Horn focused beam/8GeV protons from Booster
- Horn polarity -> Neutrino or Anti-neutrino mode
SciBooNE experiment

- Detector:
  - SciBar - Fully active scintillator tracker
  - Electron catcher – EM calorimeter
  - Muon Range Detector - Steel+plastic scinitillator

- Main goal to measure neutrino and anti-neutrino cross sections
- Neutrino oscillations with MiniBooNE
CCQE

• CCQE inclusive
  – First measurement on carbon in 1 GeV region
  – Consistent with MINOS, NOMAD and old BNL bubble chamber (deuterium) measurements

  \[ \text{Phys. Rev. D83, 012005 (2011)} \]

• CCQE (Preliminary)
  – Consistent with MiniBooNE
NC Coherent $\pi^0$

- Clear evidence of coherent production
- Cross section ratio

$$\frac{\sigma(\text{NC coh}\pi^0)}{\sigma(\text{CC})} = (1.16 \pm 0.24) \times 10^{-2}$$

consistent with Rein-Sehgal model

*Phys. Rev. D81, 111102 (2011)*
\( \bar{\nu} \) CC coherent \( \pi \)

- \( r = \text{ratio of } \nu \text{ and } \bar{\nu} \text{ fluxes in anti-neutrino mode} = 0.19 \)
- Previously measured cross section ratio in neutrino mode:

\[
\frac{\sigma(\nu \text{ CC coh-}\pi)}{\sigma(\nu \text{ CC})} = (0.16 \pm 0.17(\text{stat})(\text{sys})) \times 10^{-2}
\]
MiniBooNE experiment

• 800t mineral oil Cerenkov detector
• Main goal to study neutrino oscillations
  • Motivated by unexplained LSND signal (observed 3.8σ excess of nuebar events in numubar beam)
• Measure neutrino cross sections (measured cross sections using ~90% of neutrino events in detector)
NC elastic

- 17% of neutrino interactions
- Flux averaged cross section
- Best match to data with $M_A = 1.39 \pm 0.11$ GeV (agrees with shape only fits to MiniBooNE CCQE data)

- Sensitive to strange quark component
- Protons above Cerenkov threshold distinguished from neutrons
- Strange quark component contribution to axial form factor: $\Delta s = 0.08 \pm 0.26$
  (in agreement with BNL E734)

*Phys. Rev. D82, 092005 (2010)*
CC $\pi^+$

- 19% of neutrino interactions
- Important background to oscillation searches using CCQEs in few GeV range
- World largest sample of CC $\pi^+$ interactions (48322 candidates with 90% purity)
- Also measured flux averaged single and double-differential cross sections of the energy and direction of both final-state muon and pion

*arxiv: 1011.3572 [hep-ex]*
CC $\pi^0$

- 4% of neutrino interactions
- World largest sample at energies below 2 GeV
- Larger cross section than expected
- Also measured flux-averaged differential cross sections in terms of $\mu^-$ and $\pi^0$ kinematics

*arxiv: 1010.3264 [hep-ex]*
Neutrinos in Anti-neutrino mode

• In anti-neutrino mode neutrinos (wrong-signs) make ~30% of events
• Important for oscillation and cross section measurements in anti-neutrino mode
• Three independent and complementary measurements of the wrong-sign background
  – Angular distribution of CCQE events
  – Using CCpi+ sample
  – Using muon decay electrons

arxiv: 1102.1964 [hep-ex]
\( \nu_e \) appearance analysis

- **MiniBooNE Neutrino mode:**
  - no evidence of appearance in \( E > 475 \text{MeV} \) region (where LSND oscillation signal expected)
  - A 3\( \sigma \) excess of events in \( E < 475 \text{MeV} \) energy region (shape not consistent with 2\( \nu \) oscillations)

$\nu_e$ appearance results

- 5.66E20 POT
- Excess of events in both 200-475MeV and 475-1250MeV region

<table>
<thead>
<tr>
<th></th>
<th>200-475MeV</th>
<th>475-1250MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>119</td>
<td>120</td>
</tr>
<tr>
<td>MC</td>
<td>100.5 ± 14.3</td>
<td>99.1 ± 14.0</td>
</tr>
<tr>
<td>Excess</td>
<td>18.5 ± 14.3</td>
<td>20.9 ± 14.0</td>
</tr>
<tr>
<td>LSND Best Fit</td>
<td>7.6</td>
<td>22</td>
</tr>
<tr>
<td>Expectation from $\nu$ Low E excess</td>
<td>11.6</td>
<td>0</td>
</tr>
<tr>
<td>LSND+Low E</td>
<td>19.2</td>
<td>22</td>
</tr>
</tbody>
</table>
$E_v^{QE} > 475$

- $5.66 \times 10^2$ POT
- $E > 475$ is signal region for LSND type osc.
- Null probability 0.5% (compared to 40% in neutrino mode)
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit $(\sin^2 2\theta, Dm^2) = (0.9584, 0.064 \text{ eV}^2)$
Conclusion

• Cross sections:
  • Important measurements from SciBooNE & MiniBooNE
  • Many 1\textsuperscript{st} measurements or first time full kinematics reported
  • Measurements with anti-neutrino beam under way

• Oscillations:
  • MiniBooNE $\bar{\nu}_e$ data prefers LSND signal over null hypothesis at 99.4%

• Future:
  • MiniBooNE oscillation analysis with more POT and analysis improvements
  • Joint SciBooNE/MiniBooNE numu disappearance analysis

MiniBooNE neutrino result

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

MiniBooNE neutrino result

Excess of events observed at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)

Shape not consistent with 2 ν oscillations

Magnitude consistent with LSND


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


E≥200MeV

- Subtract excess produced by neutrinos in $\nu$ mode (11.6 events)
- E<475MeV:
  - Large background
  - Not relevant for LSND type osc.
  - Big systematics
- Null $\chi^2=32.8$; $p=1.7\%$
- Best fit ($\sin^22\theta$, $\Delta m^2$) = (0.0061, 4.42 eV$^2$)
# LSND $\bar{\nu}_e$ Background Estimates

<table>
<thead>
<tr>
<th>Estimate</th>
<th>$\bar{\nu}<em>e/\bar{\nu}</em>\mu$</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 Poster</td>
<td>0.071%</td>
<td>16.1+-3.2</td>
<td>91.3+-22.4+-5.6</td>
</tr>
<tr>
<td>Dydak Seminar</td>
<td>0.116%</td>
<td>26.3+-5.3</td>
<td>81.1+-22.4+-7.0</td>
</tr>
</tbody>
</table>

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

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

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

Dydak Seminar: FLUKA $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at FNAL on January 14, 2011

Although the analysis of Zhemchugov, Dydak et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ 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 overestimate $\pi^-$ production at $\sim$800 MeV. Note that $N_{gs}$ events are included in the LSND background estimate.
GEANT4 Overestimates $\pi^-$ Production

$\sigma(\text{d}E/d\Omega, \text{MeV})$ vs Pion energy (MeV)

- Data (Cochran et al.)
- GEANT4 Bertini
- GEANT4 Binary Cascade

$p (730 \text{ MeV}) + C$: $45^\circ \pi^-$ spectrum

$p (730 \text{ MeV}) + C$: $60^\circ \pi^-$ spectrum
\( \nu_e \, C \rightarrow e^- \, N_{gs} \) Events Do Not Simulate
\( \bar{\nu}_e \, p \rightarrow e^+ \, n \) Events!

For \( N_{gs} \beta \) decay to be considered a 2.2 MeV \( \gamma \):
\[ \Delta r < 2 \text{m}, \Delta t < 500 \mu \text{s}, \ 19 < N_{\text{hits}} < 51 \]

The number of \( N_{gs} \) events with a \( \beta \) that satisfies this initial requirement is approximately:
\[ (600)(1)(1/31.8)(0.05) \sim 1 \text{ event}. \]

The number of \( N_{gs} \) events with \( R_{\gamma} > 10 \) \sim 0.1 \text{ events}.  

This background is included in the LSND background estimate.