Title: MiniBooNE Cross Section Measurement

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MiniBooNE Cross Section Measurement

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Outline

• Booster Neutrino Beamline & MiniBooNE detector
• Cross section measurements with MiniBooNE
• New results
  – Anti neutrino CCQE (J. Grange)
• Forthcoming results
  – NC Elastic (R. Dharmapalan)
  – CC inclusive (M. Tzanov)
• Conclusion
Booster Neutrino Beam

- Designed to study LSND anomaly - similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- Mineral oil Cherenkov detector
Hadron production in BNB target

- Major uncertainty in the neutrino flux prediction due to pion production in p+Be interactions
- Need to know neutrino flux for precise cross section measurements
- Used external pi+ & pi- production data (HARP, BNL E910)
- HARP measured production on Be target using 8.9GeV protons
- Covers phase space contributing to 78% of neutrino flux from pi+ (76% from pi- in antineutrino mode)
- Overall 9% flux uncertainty – dominant error in cross section measurement

Predicted flux

Neutrino mode

$\nu_{\mu}$ 93.6%
$\overline{\nu}_{\mu}$ 5.8%
$\nu_e + \overline{\nu}_e$ 0.6%

Anti-neutrino mode

$\nu_{\mu}$ 15.7%
$\overline{\nu}_{\mu}$ 83.7%
$\nu_e + \overline{\nu}_e$ 0.6%
Predicted flux

Neutrino mode
\[ \nu_\mu \quad 93.6\% \]
\[ \bar{\nu}_\mu \quad 5.8\% \]
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Anti-neutrino mode
\[ \nu_\mu \quad 15.7\% \]
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\[ \nu_e + \bar{\nu}_e \quad 0.6\% \]

Wrong signs
MiniBooNE Detector

- 6.1m radius sphere filled with 800t of pure mineral oil – interactions on \( \text{CH}_2 \)
- 1280 PMTs inner region and 240 PMTs in outer veto region
- 10% photo cathode coverage
- 4pi detector – covers entire angular space
- Event reconstruction primarily based on Cherenkov light – best at reconstructing leptons
- Timing and topology
- Scintillation light enables measurement of NC elastic events

Neutrino mode cross sections

- Collected data corresponding to $6.5 \times 10^{20}$ POT
- $\sim 1000000$ interactions in fiducial volume
- MiniBooNE has published $\sim 90\%$ of the total neutrino mode rate

Event rates

Wrong sign: $\bar{\nu}_\mu$ in $\nu_\mu$ beam $\sim 2\%$
Anti neutrino mode cross sections

- Collected data corresponding to more than $10^{21}$ POT
- Unprecedented $\bar{\nu}$ statistics
- Large background from wrong-sign $\nu_\mu$
  - has been addressed

Event rates

Wrong sign: $\nu_\mu$ in $\bar{\nu}_\mu$ beam $\sim 40\%$!
Wrong sign background

- Pion parents contributing to wrong sign flux in antineutrino mode not covered by HARP measurement
- Have to measure this background
- No magnetic field to distinguish $\mu^+$ vs $\mu^-$
WS background (cont’d)

• Three methods yield consistent results
  – CC1pi⁺ - direct rate measurement of wrong signs
  – μ⁻ capture – due to nuclear capture \( ν_μ \) CC events less likely to produce decay electrons compared to \( \bar{ν}_μ \)
  – CCQE – angular distribution (not actually used since it depends on \( \bar{ν}_μ \) cross section)

• Predicted \( ν_μ \) flux in antineutrino mode constrained to better than 15% - not a dominant uncertainty anymore

Phys. Rev. D84, 072005 (2011)
CCQE results

- 71k $\bar{\nu}_\mu$ CCQE candidates (30% efficiency/60% purity)
- Largest background from wrong signs (measured)
- Main result is the double differential on $\text{CH}_2$ - least model-dependent measurement possible with MiniBooNE data
- Many other cross sections available in the paper (hydrogen subtracted CCQE, Total $\sigma(E_\nu)$, ...)

<table>
<thead>
<tr>
<th>Uncertainty type</th>
<th>Normalization uncertainty (%)</th>
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<tbody>
<tr>
<td>$\bar{\nu}_\mu$ flux</td>
<td>9.6</td>
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<tr>
<td>Detector</td>
<td>3.9</td>
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<tr>
<td>Unfolding</td>
<td>0.5</td>
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<tr>
<td>Statistics</td>
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<tr>
<td>$\nu_\mu$ background</td>
<td>3.9</td>
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<tr>
<td>CC1$\pi^-$ background</td>
<td>4.0</td>
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<tr>
<td>All backgrounds</td>
<td>6.4</td>
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<tr>
<td>Total</td>
<td>13.0</td>
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</table>
Bit of history

• In the early days saw discrepancy between neutrino data & prediction (Relativistic Fermi Gas (RFG) +\(M_A=1.0\text{GeV}\))

• No model at the time, so tuned \(M_A\) for oscillation analysis

• Good fit with \(M_A=1.35\text{GeV}\), however suspected this is just effective parameter covering for nuclear effects
  – Published double differential \(\sigma(T_\mu, \theta_\mu)\)
  – independent of interaction assumptions (unlike total cross section \(\sigma(E_\nu)\))
Why $M_A$ worked well for MiniBooNE?

- Recent Minerva results prefer strongly $M_A=1\text{GeV}+$Tranverse Enhancement Model (TEM) over $RFG+M_A=1.35\text{GeV}$


*Phys. Rev. Lett. 111, 022502 (2013)*

See talks by:
Chris Marshal (Tuesday WG2 10:30)
David Schmitz (Friday Plenary 10 8:30)
Why $M_A$ worked well for MiniBooNE?

- Recent Minerva results prefer strongly $M_A = 1\text{GeV} + \text{Tranverse Enhancement Model (TEM)}$ over $RFG + M_A = 1.35\text{GeV}$

- At BNB energies two models degenerate (above $Q^2 > 0.2\text{GeV}^2$)
Forthcoming cross sections

- CC inclusive
- NC elastic
CC inclusive

- Very important to measure inclusive cross section as well as exclusive channels to build models
- Can’t just add CCQE, CCpi+ and CCpi0, complicated correlated systematics
  - Each channel is a background for the others through FSI model
New reconstruction

• Developed for CC inclusive measurement
• Muon kinematics from 2-track likelihood fit; second fitted track absorbs the bias due to second most prominent ring
• Significant improvement of muon kinetic energy – resolution is about 5% (angle resolution as before better than 1deg)
CC inclusive results

- Selected 344k events with 96% purity
- Coming soon $d\sigma/dT_\mu \, d(\cos\theta_\mu)$, and a whole suite of other cross sections
- Full lepton reconstruction without any assumptions about nuclear target, no dependence on FSI
NC elastic

- Use scintillation light from mineral oil
- Measure n & p NC elastic interactions – some separation above Cherenkov threshold (350 MeV)
- 61k event candidates (32% efficiency, 40% purity)
NC results

- Main result is $d\sigma/dQ^2$
- Normalization agrees well with MC prediction (tuned to $\nu_\mu$ CCQE data)
- $Q^2$ calculated using nucleon energy assuming interaction with an independent, at-rest target – complementary to CCQE

<table>
<thead>
<tr>
<th>Error source</th>
<th>Normalization uncertainty (%)</th>
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<tbody>
<tr>
<td>anti-$\nu$ flux</td>
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<tr>
<td>Backgrounds</td>
<td>6</td>
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<tr>
<td>Detector</td>
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<td>Unfolding</td>
<td>7</td>
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<tr>
<td>Total (includes correlations)</td>
<td>21</td>
</tr>
</tbody>
</table>
Conclusion

• 10 years of MiniBooNE running (2002-2012)
• Extremely stable:
  – Neutrino rate/POT at 2% level
  – Energy scale stable within 1%
  – $6.5 \times 10^{20}$ POT in neutrino and $11.3 \times 10^{20}$ POT in antineutrino mode
• MiniBooNE measured cross sections for 90% of events in neutrino mode and 83% in antineutrino mode (when new antineutrino CCQE cross sections & NC elastic are included)
• Coming soon CC inclusive and antineutrino NC elastic cross sections
• Important measurements to fully understand the cross sections and nuclear models
Backup
10 years of running

- Detector and beam extremely stable
- Neutrino/POT within 2%
- Detector calibration stable at 1% level
- 6.5e20 POT in neutrino and 11.3e20 POT in antineutrino mode