Neutrino Scattering Results from MiniBooNE

Outline:
- introduction, motivation
- MiniBooNE experiment
- MiniBooNE measurements, results
- interpretations
- further work
- conclusions
Neutrino scattering measurements

In order to understand $\nu$ oscillations, it is crucial to understand the detailed physics of $\nu$ scattering (at 1-10 GeV)
- for current and future oscillation experiments:
  MINOS, MiniBooNE, T2K, NOvA, LBNE
- especially for precision (e.g. 1%) measurements and/or small oscillation probabilities (e.g. 0.1%)

Requires: Precise measurements to enable a complete theory valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)

A significant challenge with neutrino experiments:
- non-monoenergetic and poorly-known beams
- large backgrounds
- nuclear scattering (bound nucleons)

....
Neutrino scattering measurements

No one said it would be easy...

for example:

$\nu$ CCQE total cross section measurement from MiniBooNE, SciBooNE, NOMAD

Also,
Revealing some interesting new and/or underappreciated physics.
MiniBooNE experiment, overview

- Built to test the LSND observation of $\nu$ oscillations via $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance.
- ~20 papers published (so far, on oscillations, scattering, details)
  See  http://www-boone.fnal.gov/publications/  (All MB theses available there also)
MiniBooNE experiment, ν flux

- Prediction of ν flux is absolute necessity to produce absolute cross sections

- Determined from π prod measurements plus detailed MC (GEANT4) simulations of target+horn ([PRD79(2009)072002])

- There was no tuning of flux based on MB data

- Crucial π production measurements from HARP at 8.9 GeV/c beam momentum (as MB), on 5% int. length Be target ([Eur.Phys.J.C52(2007)29])

- Error on HARP data (7%) is dominant contribution to flux uncertainty

- Overall 9% flux uncertainty, dominates cross section normalization (“scale”) error

---

**FIG. 2:** (color online) Predicted νμ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is $5.16 \times 10^{-10} \nu_\mu / \text{POT/cm}^2$ ($0 < E_\nu < 3 \text{ GeV}$) with a mean energy of 788 MeV. Numerical values corresponding to the top plot are provided in Table V in the Appendix.
MiniBooNE experiment, ν detector

- 541 meters from target
- 12 meter diameter sphere
- 800 tons mineral oil (CH$_2$)
- 3 m overburden
- includes 35 cm veto region
- viewed by 1280 8” PMTs (10% coverage) + 240 veto
- Simulated with GEANT3
- (detector NIM paper ref here)
**ν scattering channels in MiniBooNE**

- ν charged-current (CC) quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial formfactor
- ν neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions to form factors (possibly strange quarks)
- ν CC production of π⁺, π⁰
  - background (and perhaps signal) for oscillations
  - insight into models of neutrino pion production via nucleon resonances and via coherent production
- ν CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details
- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
- ν NC production of photons
  - a possible oscillation background

---

**Diagram: MB ν events composition**

- CCQE 42%
- NC π⁺ 22%
- NC π⁰ 6%
- DIS/Nπ 4%
- NC elastic 18%
- CC π⁺ 3%

---

"CC": charged-current

"NC": neutral-current
MiniBooNE experiment, event reconstruction

- Charged particles in MB create cherenkov and small amount of scintillation light

- Tracks reconstructed (energy, direction, position) with likelihood method utilizing time, charge of PMT hits *(NIM, A 608 (2009), pp. 206-224)*

- In addition, muon, pion decays are seen by recording PMT info for 20μs around 2μs beam spill

- In CCQE analysis, all observables are formed from muon energy (E_μ ) and muon scattering angle (θ_μ)

- E_ν^{QE} and Q^2_{QE} reconstructed from E_μ , θ_μ with assumption of interaction with bound neutron at rest (“QE assumption”)

- For NCel, observables from new proton fitter, no E_ν^{QE} possible and Q^2_{QE} = 2m_p T_p

\[
E_ν^{QE} = \frac{2(M'_n)E_μ - ((M'_n)^2 + m_μ^2 - M_p^2)}{2 \cdot [(M'_n) - E_μ + \sqrt{E_μ^2 - m_μ^2 \cos θ_μ}]}, \quad (1)
\]

\[
Q^2_{QE} = -m_μ^2 + 2E_ν^{QE}(E_μ - \sqrt{E_μ^2 - m_μ^2 \cos θ_μ}), \quad (2)
\]
CCQE scattering

- $\nu_\mu$ charged-current (CC) quasielastic (CCQE)
  - most fundamental scattering process in ~1GeV range
  - detection and normalization signal for oscillations
  - charged-current axial formfactor

- Historically, “quasielastic” in “CCQE” comes from high-energy $\nu$ experiments where muon mass is negligible.

- But has evolved to mean quasielastic scattering from bare nucleons (lightly?) bound in nucleus. How true is this?

- Careful! Can also imply a final state selection for experiments. Important to consider.
  - eg: in MiniBooNE, QE = muon and no pions, no selection on outgoing nucleons
  - in K2K, QE=muon + proton with QE kinematics

Can result in different measurements.
**MiniBooNE $\nu$ CCQE analysis**

- CCQE experimental definition: $1\, \mu^-$, no $\pi$
- Requires id of stopping $\mu^-$ and 1 decay $e^-$ (2 “subevents”)
  \[ \nu_\mu + n \rightarrow \mu^- + p \]
  \[ \rightarrow \nu_\mu + \nu_e + e^- \quad (\tau \sim 2\mu s) \]
- (No selection on (and $\sim$ no sensitivity to) f.s. nucleon)
- CC$\pi$ produces 2 decay electrons (3 subevents)
  \[ \nu_\mu + N \rightarrow \mu^- + N + \pi^+ \]
  \[ \rightarrow \mu^+ \rightarrow \nu_\mu + \nu_e + e^+ \quad (\tau \sim 2\mu s) \]
  \[ \rightarrow \nu_\mu + \nu_e + e^- \quad (\tau \sim 2\mu s) \]
- CC$\pi^+$ is (largest) background,
  ($e^+$ missed because of $\pi$ absorption, $\mu^-$ capture)
- Important detail:
  - MiniBooNE data used to measure this background
  - $\sim 1/2$ of CC$\pi$ background is “irreducible” or “CCQE-like” (no $\pi$ in final state)

**Final CCQE sample:**
- 146k CCQE candidates
- 27% efficiency
- 77% purity

---

T, Katori, Ph.D, Indiana U
PRD 81, 092005 (2010),
PRL 100, 032301 (2008)
MiniBooNE CCQE analysis

- At this stage, fit (shape-only) for $M_A$, $\kappa$
  (but, not main result of analysis and has no effect on cross section results).

$$M_A^{\text{eff}} = 1.35 \pm 0.17 \text{ GeV (stat+sys)}$$
$$\kappa = 1.007 \pm 0.007 \text{ (stat+sys)}$$
$$\chi^2/\text{ndf} = 47.0/38$$

- Compared to prev result, best fit values change somewhat with new background (CC$\pi$) measurement and subtraction.

- data compared to world-average $M_A$
  and $\kappa = 1.0$ (no PB correction):

$$\chi^2/\text{ndf} = 67.5/40 \text{ (0.5\% prob)}$$

- $M_A^{\text{eff}}$ only fit:

$$M_A^{\text{eff}} = 1.37 \pm 0.12 \text{ GeV}$$
$$\chi^2/\text{ndf} = 48.6/39$$

These fit parameters can now be used within MB RFG model for good description of data (modulo possible cross section normalization factors).

... then on to cross section extraction...
MiniBooNE CCQE results

Double-differential cross section:

- Maximum information measurable on CCQE process from MB (which uses muon only)

- Most model-independent result possible

- Normalization (scale) error is 10.7% (not shown)

- Error bars show remaining (shape) error

Flux-integrated double differential cross section ($T_\mu - \cos \theta$):

PRD 81, 092005 (2010)
MiniBooNE CCQE results

Single-differential cross section:

- data is compared (absolutely) with CCQE (RFG) model with various parameter values

- Compared to the world-averaged CCQE model (red), MB CCQE data is 30% high

- RFG model with MB CCQE parameters (extracted from shape-only fit) agrees well with data over to within normalization error.

Flux-integrated single differential cross section ($Q^2_{QE}$):

PRD 81, 092005 (2010)
MiniBooNE CCQE results

Single-differential cross section (again):

- same plot as previous but with “irreducible” (CCπ with π intra-nuc absorption) background shown.

- this background is subtracted, but may be undone (if desired) to produce “CCQE-like” sample

- also reported for double-diff xsection

Flux-integrated single differential cross section ($Q_{QE}^2$):

PRD 81, 092005 (2010)
MiniBooNE CCQE results

Total cross section:
- Total cross section is extracted by binning in “true” neutrino energy bins. “$E_{\nu}^{\text{QE,RFG}}$”
- Caution, model dependent, but conventional. -Opinion: better way to report is $d\sigma/dE_{\nu}^{\text{QE}}$
- Again, total cross section value well-reproduced from extracted CCQE model parameters
- Fractional errors (as function of neutrino energy) and overall normalization errors reported
- Note how frac errors grow “off-peak” of flux. Important to consider for extracting energy-dependence
MiniBooNE CCQE results

MiniBooNE CCQE total cross section:

- ~30% larger than expected with world-average $M_A$

- ~10% larger than free-nuc (world-average $M_A$) value

- However, $M_A \sim 1.35$ GeV describes data in both $Q^2$ shape and total cross section (within RFG model), coincidence?

Flux-unfolded total cross section ($E^{QE,RFG}_\nu$)

PRD 81, 092005 (2010)
MiniBooNE CCQE results

- MB results are consistent with SciBooNE, a highly segmented scibar in Booster ν beam at FNAL (as MiniBooNE) (arXiv:0909.5647)

- NOMAD:
  - wire chamber detector at CERN, mostly carbon target, 3-100 GeV
  - in agreement with “world-average” $M_A$, $M_A = 1.05 \pm 0.02 \pm 0.06$ GeV
  - EPJ C63, 355 (2009)

- MINOS:
  - Fe target, ~5GeV
  - yields larger $M_A$ (1.2 ± 0.1 ± 0.1 GeV) consistent with MiniBooNE, SciBooNE, K2K
ν NC elastic scattering from MiniBooNE

- The most fundamental NC probe of the nucleus/nucleon.

- Does our knowledge of CCQE (usually measured via muon) completely predict NCel (measured via recoil nucleon) for nuclear targets?

- Unlike CC quasielastic, sensitive to isoscalar component of nucleon (strange quarks) via isoscalar or “strange” axial-vector formfactor, $G_{A}^{s}(Q^{2})$ and $\Delta s = G_{A}^{s}(Q^{2} = 0)$

\[
\langle N|A_{\mu}^{Z}|N\rangle = \left[\frac{G_{F}}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\left\{ \bar{u}\gamma_{\mu}\gamma_{5}u - \bar{d}\gamma_{\mu}\gamma_{5}d - \bar{s}\gamma_{\mu}\gamma_{5}s\right\}|N\rangle \\
= \left[\frac{G_{F}}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\left\{ \Delta u \Delta d \Delta s \right\}|N\rangle \\
= \langle N|\frac{1}{2}\left\{ -G_{A}(Q^{2})\gamma_{\mu}\gamma_{5}\tau_{z} + G_{A}^{s}(Q^{2})\gamma_{\mu}\gamma_{5}\right\}|N\rangle
\]

- Experimental sensitivity to isoscalar effects best via ratios:

  - NC(p)/NC(n), NC(p)/NC(p+n), NC(p)/CCQE

as many systematics (flux, nuc. effects) should cancel. Requires separation of protons/neutrons.
MiniBooNE NC elastic analysis

- NCell experimental definition: 1 p/n, no µ⁻, π

- below Cerenkov threshold, p/n separation not possible, p/n recon'd via small amount of scintillation

MC NCell event distribution

MiniBooNE NC elastic analysis

- requires dedicated reconstruction for protons (new to this analysis)

- proton fitter provides good separation between nucleons/electrons

- NCell sample:
  - 94.5K candidate evts
  - efficiency = 26%
  - purity = 65%

- NCell $\pi^{\pm}$ is (largest) background, ($\pi^+$ missed because of $\pi$ absorption)

- $\sim 1/3$ of background is NCell-like
MiniBooNE NC elastic results

- differential cross section:

- actually the wtd sum of 3 different processes:

\[
\frac{d\sigma_{\nu N \rightarrow \nu N}}{dQ^2} = \frac{1}{7} C_{\nu p, H}(Q^2) \frac{d\sigma_{\nu p \rightarrow \nu p, H}}{dQ^2} + \frac{3}{7} C_{\nu p, C}(Q^2) \frac{d\sigma_{\nu p \rightarrow \nu p, C}}{dQ^2} + \frac{3}{7} C_{\nu n, C}(Q^2) \frac{d\sigma_{\nu n \rightarrow \nu n, C}}{dQ^2},
\]

- ~1/3 of background is NCel-like (NCπ with π abs). This calc'd background is reported so NCel-like may be calculated.

MiniBooNE NC elastic results

- $M_A$ extraction:
  - from an absolute fit to proton KE distribution
    \[ M_A = 1.39 \pm 0.11 \text{ GeV} \]
    \[ \chi^2/\text{ndf} = 26.9/50 \]
  - small sensitivity to $\Delta s$, assume $\Delta s = 0$.
  - negligible sensitivity to $\kappa$
  - consistent with $M_A$ from CCQE (shape) fit

NCel proton KE distribution and $M_A$ comparison:

\[ \chi^2/\text{ndf} = 26.9/50 \]

MiniBooNE NC elastic results

- NCel to CCQE differential cross section ratio:

- flux error cancels between the 2 channels

- ratio is consistent with our RFG model. So no discrepancy in NCel compared to CCQE

MiniBooNE NC elastic results

- $\Delta s$ extraction:

- from NC(p)/NC(p+n) above proton cerenkov threshold where proton separation is possible

- $\Delta s = 0.08 \pm 0.26$

- limited by large errors but good demo of method

- consistent with expectations from deep-inelastic scattering meas:

$\Delta s \sim -0.10$

**CCπ production in MiniBooNE**

- ν CC production of π⁺, π⁰
  - background (and perhaps signal) for oscillations
  - insight into models of neutrino pion production via nucleon resonances and via coherent production
  - may also feed into “CCQE-like” events

- CCπ⁺/CCQE ratio measured in MiniBooNE

- CCπ⁺/CCQE ratio in agreement with model.

- So CCπ⁺ rate (cross section) is also larger than expected.

- In both FSI corrected/uncorrected samples

---

\[
\nu_\mu + p(n) \rightarrow \mu + \Delta^{(+)} \rightarrow \mu + p(n) + \pi^+
\]

\[
\nu_\mu + A \rightarrow \mu + A + \pi^+
\]

**CCπ⁺/CCQE ratio, no FSI corrections**

*FIG. 1: Observed CC1π⁺-like/CCQE-like cross section ratio on CH₂, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.*

---

S. Linden, PhD, Yale
**CCπ production**

CCπ⁺, π⁰ differential cross sections from MiniBooNE:
- in a variety of kinematic variables
- model independent, absolutely norm'd
- will guide models of pion production including coherent piece
- excess of data over model present in these channels also.

\[ \nu_\mu + p(n) \rightarrow \mu + \Lambda^{++} \rightarrow \mu + p(n) + \pi^+ \]

\[ \nu_\mu + A \rightarrow \mu + A + \pi^+ \]

**CCπ⁺ differential cross sections**

\[ \frac{\partial \sigma}{\partial Q^2} \text{ (cm}^2\text{MeV}^2) \]

M. Wilking
PhD Colorado U,
PRD83, 052007 (2011)

**CCπ⁰ differential cross section**

\[ \frac{\partial \sigma}{\partial Q^2} \text{ (cm}^2\text{GeV}^2) \]

B. Nelson,
PhD Colorado U,
PRD 83, 052009 (2011)
CC inclusive from MB

- $\nu$ CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details

- MB measurement coming soon

- recent SciBooNE result
  (PRD 83, 012005, 2011)

![Graph showing $\nu$ CC inclusive cross section](image)
models for $\nu$ QE scattering

Much theoretical interest in results recently:

Nieves et al., arXiv:1106.5374 [hep-ph]
Bodek et al., arXiv:1106.0340 [hep-ph]
Amaro, et al., arXiv:1104.5446 [nucl-th]
Antonov, et al., arXiv:1104.0125
Benhar, et al., arXiv:1103.0987 [nucl-th]
Amaro, et al., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]

- for example
comparisons to double diff xsection

Meucci et al, arXiv:1107.5145v1 [nucl-th]
An interesting idea has emerged...
- Perhaps extra “strength” in CCQE from multi-nucleon correlations within carbon (Martini et al. PRC80, 065501, ’09)
- Related to neglected “transverse” response in noted in electron scattering? (Carlson et al., PRC65, 024002, ’02)
- Expected with nucleon correlations and 2-body exchange currents
- Note: may effect neutrino energy reconstruction in oscillation experiments!
- Perhaps related to different CCQE selections, eg:

**CCQE**

<table>
<thead>
<tr>
<th>e.g. NOMAD</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

**CCQE-like**

<table>
<thead>
<tr>
<th>e.g. MiniBooNE</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

---

CCQE total cross section

Martini et al., PRC80, 065501, ’09
models for $\nu$ QE scattering

However, not clear that simple QE-selection argument can explain NOMAD-MiniBooNE differences.

Courtesy: S. Mishra
CCQE scattering and 2-N correlations

- Recent results from e-scattering suggest 20% of nucleons in carbon are in a “SRC state” (R. Subedi et al, Science, 320, 1476 (2008))

- This effect should result in distinguishable final states of multiple recoil nucleons

- and have implications in interference terms (ν/ ¯ν) differences
upcoming MB results: $\bar{\nu}$ CCQE

- If multinucleon correlations are large contribution in CC-"QE" scattering,
- should result in different final states,
- interference terms not as in 1N model
- and prediction for $\bar{\nu}$ CCQE based on $\nu$ data should show that.

using simple L-S model:
- LS model with MB $M_A$
- LS with world ave $M_A$ and extra (non-interfering) term
- ratio

**L-S model:**

$$\frac{d\sigma}{dQ^2} \left( \nu_l + n \rightarrow l^- + p \right) = \frac{M^2 G_F^2 \cos^2 \theta_c}{8 \pi E_{\nu}^2} \left\{ A(Q^2) \pm B(Q^2) \frac{(s - u)}{M^2} + C(Q^2) \frac{(s - u)^2}{M^4} \right\}$$
upcoming MB results: $\bar{\nu}$ CCQE

Continuing with 2 different scenarios..

predicted $\nu - \bar{\nu}$ xsection diff:

predicted $\nu - \bar{\nu}$ xsection frac diff:

LS model:
- LS model with MB $M_A$
- LS with world ave $M_A$ and extra (non-interfering) term
upcoming MB results: $\bar{\nu}$ CCQE

Preliminary results: $\bar{\nu}$ CCQE

Final MiniBooNE $\bar{\nu}$ CCQE (J. Grange, Florida) and $\bar{\nu}$ NCel (R. Dharmapalan, Alabama) coming soon.
**NCπ^0 production**

- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
  - sizable coherent piece

- MiniBooNE has produced differential cross section on NCπ^0 production, used to constrain oscillation search background (NCπ^0 misID and NCγ)

- also SciBooNE results

---

C. Anderson PhD, Yale

PRD81, 013005 (2010)
**NC $\gamma$ production**

- $\nu$ NC production of photons
  - a possible oscillation background

- MiniBooNE low-energy excess has spurred work on a possible background: NC$\gamma$ production

- Important background for $\nu_e$ appearance searches


### Table I: Single photon and other backgrounds for MiniBooNE $\nu$-mode in ranges of $E_{QE}$. Ranges in square brackets are the result of applying a 20 – 30% efficiency correction.

<table>
<thead>
<tr>
<th>process</th>
<th>200-300</th>
<th>300-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\gamma$, non-$\Delta$</td>
<td>85[17 - 26]</td>
<td>151[30, 45]</td>
<td>159[32, 48]</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$</td>
<td>170[34 - 51]</td>
<td>394[79 - 118]</td>
<td>285[57 - 86]</td>
</tr>
<tr>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>14[2.7 - 4.1]</td>
<td>20[4.0 - 5.9]</td>
<td>40[7.9 - 12]</td>
</tr>
<tr>
<td>$\nu_e n \rightarrow ep$</td>
<td>100[20 - 30]</td>
<td>303[61 - 91]</td>
<td>1392[278 - 418]</td>
</tr>
<tr>
<td>MB excess</td>
<td>45.2 ± 26.0</td>
<td>83.7 ± 24.5</td>
<td>22.1 ± 35.7</td>
</tr>
<tr>
<td>MB $\Delta \rightarrow N\gamma$</td>
<td>19.5</td>
<td>47.5</td>
<td>19.4</td>
</tr>
<tr>
<td>MB $\nu_\mu e \rightarrow \nu_\mu e$</td>
<td>6.1</td>
<td>4.3</td>
<td>6.4</td>
</tr>
<tr>
<td>MB $\nu_e n \rightarrow ep$</td>
<td>19</td>
<td>62</td>
<td>249</td>
</tr>
</tbody>
</table>
NC $\gamma$ production

- more and recent work on this: "Weak Pion and Photon Production off Nucleons in a Chiral Effective Field Theory", B. Serot, X. Zhang, arXiv:1011.5913 [nucl-th]

- related to and constrained by $\pi$ production

- ultimately must understand this process together with pion production in all modes: resonant/non, coherent/non

- may be background for $\sim1\%$ oscillation probabilities

- should directly search for and/or measure this process.

---

**Tab.1: NC photon production event’s EQE distribution in MiniBooNE for neutrino scattering.**

<table>
<thead>
<tr>
<th>$E_{QE}$ (GeV)</th>
<th>[0.2, 0.3]</th>
<th>[0.3, 0.475]</th>
<th>[0.475, 1.25]</th>
</tr>
</thead>
<tbody>
<tr>
<td>coh</td>
<td>3.1</td>
<td>10.37</td>
<td>5.59</td>
</tr>
<tr>
<td>incoh</td>
<td>$6 \times (1.01 + 1.01)$</td>
<td>$6 \times (3.64 + 3.62)$</td>
<td>$6 \times (2.90 + 2.88)$</td>
</tr>
<tr>
<td>total</td>
<td>15.22</td>
<td>53.93</td>
<td>40.27</td>
</tr>
<tr>
<td>MiniBN</td>
<td>19.5</td>
<td>47.5</td>
<td>19.4</td>
</tr>
</tbody>
</table>
**Possible future effort: SciNOvA**

A “SciBar” detector using an existing and proven design (from KEK/SciBooNE), deployed in front of the NOvA near detector in the NuMI off-axis, 2 GeV, narrow-band beam.

A fine-grained SciBar detector in this location will provide:
- important and unique $\nu$ scattering measurements including:
  - A test of recent MiniBooNE results indicating anomalously large cross section in CCQE using a different $\nu$ source at slightly higher $E_\nu$
  - a search for 2N correlations
  - Neutral-current differential cross sections, $NC\pi^0$, $NC\gamma$ - crucial for $\nu_e$ appearance
- significant cross checks of NOvA $\nu$ oscillation backgrounds, esp $NC\pi^0$

Cost: $2.4M
SciNOvA: narrow band beam

- ~2 GeV mean energy,
- lower energy and smaller energy spread than on-axis flux
- complementary to the NUMI on-axis cross section program
SciNOvA: 2N correlations

- A search for 2 nucleon correlations with SciNoVA is experimentally feasible and would provide the most direct test for MiniBooNE results.

Sketch of experimental method:
- Following method of JLab Hall A experiment:
  - Find CCQE scattering events with 2 high-momentum recoil nucleons.
  - Use transverse kinematics to eliminate neutrino energy unknown (all longitudinal)
  - Look for transverse momentum balance when both nucleons considered.
  - Separated from more mundane CCQE, CCπ events where energy should be shared with unobserved particles and recoil nucleus.
  - Modeled with assumed extra 30% 2N events.
Experimental search with SciNOvA (continued)

- look at $\cos \gamma$, angle between 2 nucleons

from JLAB experiment

- Resulting, signal/background ~ 3...
- a sensitive search for this process
- and an important experimental constraint.

<table>
<thead>
<tr>
<th>event type</th>
<th>events/10ton/6E20</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-nucleon signal</td>
<td>4119</td>
</tr>
<tr>
<td>CCQE 1-nucleon background</td>
<td>65</td>
</tr>
<tr>
<td>QElike background</td>
<td>1320</td>
</tr>
<tr>
<td>total background</td>
<td>1384</td>
</tr>
</tbody>
</table>
Summary/Conclusions/Outlook

- MiniBooNE $\nu$ scattering results have revealed interesting new insights.

- $\nu$ charged-current (CC) quasielastic (CCQE)
  - $\sigma$ anomalously high, 2N effects?
  - MB $\bar{\nu}$ measurement coming soon
  - MINERvA, perhaps SciNOvA
- $\nu$ neutral-current (NC) elastic (NCel)
  - consistent with CCQE
  - MB $\bar{\nu}$ measurement coming soon
- $\nu$ CC production of $\pi^+$, $\pi^0$
  - also large cross section consistent with CCQE
- $\nu$ CC inclusive scattering
  - MB results coming soon
- $\nu$ NC production of neutral pions
  - measurements constrain oscillation backgrounds
- $\nu$ NC production of photons
  - an interesting, important channel
  - should pursue further w/ theory and experiment
backup slides
modeling $\nu$ QE scattering

The canonical model for the $\nu$ QE process is fairly simple. Based on impulse-approximation (IA) together with rel Fermi gas (RFG).

- start with Llewellyn-Smith formalism for differential cross section:

$$\frac{d\sigma}{dQ^2} \left( \nu_l + n \rightarrow l^- + p \right) = \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_{\nu}^2} \left\{ A(Q^2) + B(Q^2) \frac{(s-u)}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right\}$$

  - lepton vertex well-known
  - nucleon vertex parameterized with 2 vector formfactors ($F_1$, $F_2$), and 1 axial-vector ($F_A$)
  - $F_1$, $F_2$, $F_A$ (inside of A,B,C) are functions of $Q^2 = 4$-momentum transfer

- To apply (for a nucleus, such as carbon)
  - assume bound but independent nucleons (IA)
  - use Rel. Fermi Gas (RFG) model (typically Smith-Moniz), with params from e-scattering
  - $F_1$, $F_2$ also from e-scattering measurements
  - $F_A$ is largest contribution, not well known from e scattering, but
  - $F_A(Q^2=0) = g_A$ known from beta-decay and
  - assume dipole form, same $M_A$ should cover all experiments.

- No unknown parameters (1 if you want to fit for $M_A$)

- can be used for prediction of CCQE rates and final state particle distributions.

- Until recently, this approach has appeared adequate and all common neutrino event generators use a model like this.
Summary of $M_A$ from CCQE scattering

- $M_A$ values extracted from various experiments
- Different targets/energies, fit strategies
- World average (as of 2002)
  \[ M_A = 1.026 \pm 0.021 \text{ GeV} \]
- Also, $M_A$ from $\pi$ electro-production similar
- However, recent data from some high-stats experiments (on nuclear targets) not well-described with this $M_A$. (Or perhaps... the physics model).

Early CCQE results

For example, BNL CCQE data:
- data on $D_2$
- 1,236 $\nu_\mu$ QE events
- $M_A = 1.07 \pm 0.06$ GeV

- curves with diff $M_A$ values, relatively norm'd, overlaid.

- $M_A$ extracted from the shape of this data in $Q^2$

$$F_A(Q^2) = -\frac{g_A}{(1 + \frac{Q^2}{M_A^2})^2}$$

from Sam Zeller
K2K CCQE results

- K2K results from scifi (in water) detector (PRD74, 052002, '06)
- $Q^2$ spectrum: more events at $Q^2 > 0.2$ GeV$^2$
- shape fit of $Q^2$ distribution yields $M_A = 1.20 \pm 0.12$

FIG. 2. A schematic diagram of the SciFi detector.

from Rik Gran, Nuint09
First MB CCQE results

- MiniBooNE results (from CH$_2$) (PRL100, 0323021, ’08)

- $Q^2$ spectrum of data, compared to world-average $M_A$ (dashed)
  shows substantial event excess at $Q^2 > 0.2$ GeV$^2$.
  ⇒ requires larger $M_A$

- Also event deficit at $Q^2 < 0.2$ GeV$^2$
  ⇒ requires new parameter, $\kappa$, to increases “Pauli-blocking” of FS nucleon

- shape-only fit of $Q^2$ distribution yielded:

$$M_A^{\text{eff}} = 1.23 \pm 0.20 \text{ GeV},$$

$$\kappa = 1.019 \pm 0.011.$$ 

- “eff” = effective to acknowledge possible nuc. effects.

- fit with $Q^2 > 0.2$ GeV$^2$ yields:
  $$M_A = 1.25 \pm 0.12 \text{ GeV}$$

![Graph showing $Q^2$ distribution with $M_A$, $\kappa$, and fit parameters.

FIG. 2. Reconstructed $Q^2$ for $\nu_\mu$ CCQE events including systematic errors. The simulation, before (dashed curve) and after (solid curve) the fit, is normalized to data. The dotted curve (dot-dashed curve) shows backgrounds that are not CCQE (not “CCQE-like”). The inset shows the 1$\sigma$ C.L. contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying the background shape (triangle).]
modeling $\nu$ QE scattering
SciNOvA CCQE scattering measurement

Estimated errors on SciNOvA CCQE total cross section measurement

- estimated with bootstrapping from MiniBooNE error analysis
- checked by predicting actual MiniBooNE errors
- dominant background is $CC\pi$ feeddown from high "true" $E_\nu$ to lower recon'd $E_\nu$ due to lost pion (in detector medium or nucleus)
- resulting error at 2 GeV (flux-peak of NOvA beam) is 12%
- will provide important points in CCQE total cross section data and most-directly check MiniBooNE results

all plots as function of reconstructed $E_\nu$ (GeV)
NC photon production

- should be possible (at higher rate experiments) and should be pursued
- SciNOvA event rates
- ~ equal to full MiniBooNE neutrino sample (but in 10 tons).
- NC$\gamma$ cross sections are calculated to be $O(10^{-3})$ that of CCQE (from Hill or Serot/Zhang)
- resulting in sample of $O(100)$ events in MB (same as 0.1% oscillations)
- SciNOvA will collect $O(100)$ events of this type if calculations are correct
- photon recon down to $\sim$100MeV and comparison with NC$\pi^0$ channel allows a measurement of NC$\gamma$
- together with NC$\pi^0$ channel will lend crucial info to $\nu_e$ appearance search (NOvA and others)
Measuring NC photon production
Final State interactions in nN

Might wonder about how FSI in nucleus of nucleons, pions may effect this story.

Good question... as they are not small...

in brief, they are modeled in state-art generators with guidance from theory, and constrained by nucleon, pion, scattering data, but had better also understand nu pion production channels.