Neutrino Scattering Results from MiniBooNE and SciBooNE

Outline:
- introduction, motivation
- MiniBooNE/SciBooNE experiments
- measurements, results
- interpretations
- future
- 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, etc
  - 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)

We are currently making progress...
Neutrino scattering measurements

No one said it would be easy... for example:

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

Revealing some interesting new and/or underappreciated physics.
MiniBooNE and SciBooNE experiments, overview

MiniBooNE
- Main Goal: Test the LSND observation of $\nu$ oscillations via $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance.
- Additional goal: Investigate $\nu$ cross sections and interactions

SciBooNE
- Goal: Measure $\nu$ cross sections and interactions with fine-grained detector for oscillation experiments (MiniBooNE, T2K)
- Ran: 2007-08 in $\nu_\mu$ and $\bar{\nu}_\mu$ modes.

Fermilab Booster Neutrino Beam

Fermilab Booster
- target and horn
- decay region
- absorber
- SciBooNE detector
- dirt
- MiniBooNE detector

primary beam (protons)
secondary beam (mesons)
tertiary beam (neutrinos)
pulsed beam @~5 Hz of width~1.5μs
 Booster neutrino beam, $\nu$ flux

- Prediction of $\nu$ flux is absolute necessity to produce absolute cross sections

- Determined from $\pi$ 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) and detailed MC (GEANT4) simulations of target+horn (PRD79(2009)072002)

- There was no tuning of flux based on MB data

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

- overall 9% flux uncertainty, dominates cross section normalization ("scale") error
MiniBooNE experiment, $\nu$ detector

- 541 meters from target
- 12 meter diameter sphere
- 800 tons mineral oil ($\text{CH}_2$)
- 3 m overburden
- includes 35 cm veto region
- viewed by 1280 8” PMTs (10% coverage) + 240 veto
- Simulated with GEANT3
SciBooNE experiment, $\nu$ detector

- 100 meters from target
- scintillator tracking detector (scibar)
  - 14,336 - 1.3 x 2.5 x 290 cm$^3$
  - scintillator bars (15 tons)
  - $p/\pi$ separation using $dE/dx$

- electron catcher (EC)
  - spaghetti calorimeter
  - 2 planes ($11 X_0$)
  - identify $\pi^0$ and $e$

- muon range detector (MRD)
  - 12 2”-thick steel + scintillator planes
  - measure muon momentum with range up to 1.2 GeV/c

- simulated with GEANT4
ν scattering channels in Booster Neutrino Beam

- ν CC quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial form factor

- ν 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

\[ \nu \rightarrow \nu \, W \rightarrow X \, Z \rightarrow X \]

"CC": charged-current

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

- Charged particles in MB create Cerenkov 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

- \( E_{\nu}^{QE} \) and \( Q_{QE}^2 \) reconstructed from \( E_{\mu}, \theta_{\mu} \) with assumption of interaction with bound neutron at rest (“QE assumption”)

\[
E_{\nu}^{QE} = \frac{2(M'_n)E_{\mu} - ((M'_n)^2 + m_{\mu}^2 - M_p^2)}{2 \cdot [(M'_n) - E_{\mu} + \sqrt{E_{\mu}^2 - m_{\mu}^2 \cos \theta_{\mu}}]}, \tag{1}
\]

\[
Q_{QE}^2 = -m_{\mu}^2 + 2E_{\nu}^{QE}(E_{\mu} - \sqrt{E_{\mu}^2 - m_{\mu}^2 \cos \theta_{\mu}}), \tag{2}
\]
SciBooNE experiment, event reconstruction

- Charged particles create scintillation light in scibar, EC, MRD

- Tracks reconstructed (energy, direction, position) from scibar hits

- MRD ranges out fraction of muons.

- EC used for $\pi^0$ and e ID
**CCQE scattering**

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

- Our fits and event generator use a relativistic fermi gas (RFG) model with one free parameter, $M_A$, which controls axial formfactor:

\[
F_A(Q^2) = -\frac{gA}{\left(1 + \frac{Q^2}{M^2_A}\right)^2}
\]

- Expect, from $\nu$ H/D scattering and $\pi$ electroproduction, $M_A \sim 1.0 \text{ GeV}$

- (not quite one parameter, added a 2nd parameter needed to describe low-$Q^2$ behavior)

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Fig. 18. A summary of existing experimental data: the axial mass $M_A$ as measured in neutrino (left) and antineutrino (right) experiments. Points show results obtained both from deuterium filled BC (squares) and from heavy liquid BC and other experiments (circles). Dashed line corresponds to the so-called world average value $M_A = 1.026 \pm 0.021$ GeV (see review [23]).
MiniBooNE $\nu$ CCQE analysis

- CCQE experimental definition: 1 $\mu^-$, no $\pi$
- Requires id of stopping $\mu^-$ and 1 decay $e^-$ (2 "subevents")
  \[ \nu_\mu + n \rightarrow \mu^- + p \]
  \[ \rightarrow \nu_\mu + n + e^- (\tau \approx 2\mu s) \]

- No selection on (and ~no sensitivity to) f.s. nucleon

- CC$\pi$ produces 2 decay electrons (3 subevents)
  \[ \nu_\mu + N \rightarrow \mu^- + N + \pi^+ \]
  \[ \rightarrow \mu^+ \rightarrow \nu_\mu + n + e^+ (\tau \approx 2\mu s) \]
  \[ \rightarrow \nu_\mu + n + e^- (\tau \approx 2\mu s) \]

- CC$\pi^+$ is (largest) background
  ($e^+$ missed because of $\pi$ absorption, $\mu^-$ capture), but measured and

Final $\nu$ CCQE sample:
- 146k CCQE candidates
- 27% efficiency
- 77% purity
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).

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

- added 2nd fit parameter, $\kappa$, to get low $Q^2$
  shape just right

- This model describes data well in $\mu$ energy, angle and is used for other analyses.

... then on to cross section extraction...

PRD 81, 092005 (2010)
MiniBooNE CCQE results

Double-differential cross section:

- First measurement of this quantity
- 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” (CC$\pi$ with $\pi$ 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. “$E_{\nu}^{QE,RFG}$”

- Caution, model dependent, but conventional.

- 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

Flux-unfolded total cross section ($E_{\nu}^{QE,RFG}$)
SciBooNE CCQE results
- SciBooNE CCQE results are consistent with MiniBooNE

- NOMAD:
  - wire chamber detector at CERN, mostly carbon target, 3-100 GeV
  - in agreement with “world-average” $M_A$, $M_A = 1.05\pm0.02\pm0.06$ GeV
  - EPJ C63, 355 (2009)
**ν NC elastic scattering from MiniBooNE**

- ν neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions
to form factors (possibly strange quarks)

- 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 via isoscalar or “strange” axial-vector formfactor, $G_A^s(Q^2)$
and $\Delta s = G_A^s(Q^2 = 0)$

**axial nucleon weak neutral current**

$$
\langle N|A_{\mu}^Z|N\rangle = -\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N\left|\frac{1}{2}\{\bar{u}\gamma_\mu\gamma_5u-\bar{d}\gamma_\mu\gamma_5d-\bar{s}\gamma_\mu\gamma_5s\}\right|N\rangle
$$

$$=-\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N\left|\frac{1}{2}\{-G_A(Q^2)\gamma_\mu\gamma_5\tau_z+G_A^s(Q^2)\gamma_\mu\gamma_5\}\right|N\rangle
$$
MiniBooNE NC elastic analysis

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

- below Cerenkov threshold (~350MeV),
  - p/n ~same response, from scintillation light
- above Cerenkov threshold
  - p/n separation possible, but cross section small

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

- NCπ+/− is (largest) background,
  (π− missed because of π absorption)

D. Perevalov, Ph.D, Alabama U.
MiniBooNE NC elastic results

- differential cross section:

- actually the wtd sum of 3 different processes:

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

- ~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

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

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

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

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.

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

**CCπ⁺ differential cross sections**

![CCπ⁺ differential cross sections graph]

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

**CCπ⁰ differential cross section**

![CCπ⁰ differential cross section graph]

B. Nelson, PhD Colorado U, PRD 83, 052009 (2011)
**CCπ production in SciBooNE**

SciBooNE coherent CCπ⁺ results:
- selected with forward-going low-Q2 pions

- No coherent production in CC channel observed, limit set.

- measured coherent
  CCπ⁰/NCπ⁰ ratio = 0.14±0.39
  Expected to be = 2 in most models.

- PRD78, 112004 (2008)
CC inclusive from SciBooNE

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

- SciBooNE result
  (PRD 83, 012005, 2011)

- larger rate than predicted (as expected from CCQE, CC$\pi$)
CC inclusive from MiniBooNE

- MiniBooNE preliminary results
- larger rate than predicted (as expected from CCQE, CC\(\pi\))
- differential cross section will also be reported
models for $\nu$ QE scattering

Much theoretical interest in results:

- Butkevich, arXiv:1204.3160
- Lalakulich et al., arXiv:1203.2935
- Mosel, arXiv:1204.2269, 1111.1732
- Barbaro et al., arXiv:1110.4739
- Giusti et al., arXiv:1110.4005
- Meloni et al., arXiv:1203.3335, 1110.1004
- Martini et al., arXiv:1202.4745, 1110.0221,
- Paz, arXiv:1109.5708
- Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
- Nieves et al., arXiv:1204.5404, 1106.5374,
- Bodek et al., arXiv:1106.0340
- Amaro, et al., arXiv:1112.2123, 1104.5446,
  1012.4265, Phys. Lett B696, 151 (2011)
- Antonov, et al., arXiv:1104.0125
- Benhar, et al., arXiv:1012.2032, 1103.0987, 1110.1835
- Alvarez-Ruso, arXiv:1012.3871

(disclaimer: this is not a complete list!)

with attention on the 40% excess over expectations
models for $\nu$ QE scattering

An interesting ideas have 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!
upcoming MiniBooNE results: $\bar{\nu}$ CCQE

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

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

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Preliminary results:
**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)

- SciBooNE has concentrated on coherent NCπ^0 and has measured non-zero value. In contrast to CCπ^0 coherent.

C. Anderson PhD, Yale

PRD81, 013005 (2010)
**NC γ production**

- MiniBooNE low-energy excess has spurred work on a possible background: NCγ production
- Important background for ν_e appearance searches
- Related to and constrained by π production
- Should directly search for and measure this process.

**Latest MiniBooNE oscillation candidate energy distribution**
Possible future plan for MiniBooNE: add scintillator

- Add scintillator (~30-50kg of butyl-PBD, as LSND) so that
  - n-capture (2.2 MeV) $\gamma$ and
  - $\beta$-decays (~15 MeV) are better measured.

- At low energy, if MB excess due to...
  - oscillation signal (charged current),
    then excess would contain $\sim$0 neutrons and a non-zero fraction of $^{12}\text{N}_{gs}$ events
  - neutral current background,
    then high yield of neutrons (~50%) and no $^{12}\text{N}_{gs}$... yielding a test of MB low-energy excess via CC/NC identification...

(Separates CC from NC components in this plot)

Other physics made possible with scintillator:
- NCn/NCp ratio, s-quark spin in nucleon and spin dependent dark-matter cross section
- neutron multiplicity in CCQE events provides info on multi-nucleon correlations in CCQE yield

Disclaimer: (this plan is not yet adapted by collaboration or approved by Fermilab)
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:
- 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, $\text{NC}\pi^0$, $\text{NC}\gamma$ - crucial for $\nu_e$ appearance
- important cross checks of NOvA $\nu$ oscillation backgrounds, esp $\text{NC}\pi^0$
Summary/Conclusions/Outlook

- MiniBooNE/SciBooNE $\nu$ scattering results have revealed interesting new insights on:

- $\nu$ charged-current (CC) quasielastic (CCQE)
  - cross section anomalously high, 2N effects?
  - MB $\bar{\nu}$ measurement coming soon
  - more from 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

- More results coming in from MINERvA, T2K, MiniBooNE, and (perhaps) SCINOvA.

- STAY TUNED!