Neutrino and Antineutrino Cross Sections at MiniBooNE

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- our 1st $\nu$ cross section results (CC $\pi^+/\text{QE}$)
- future directions in MiniBooNE $\sigma_\nu$ program
MiniBooNE is a $\nu$ Oscillation Experiment

- main goal: confirm or rule out $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ LSND results
- search for $\nu_\mu \rightarrow \nu_e$ oscillations

- not going to be showing oscillation results
- working hard on performing a very careful $\nu_e$ appearance analysis …
- you’ll have to stay tuned
MiniBooNE On the Way

- while designed for $\nu_\mu \rightarrow \nu_e$ oscillation search …
  
  * well-suited for low $E$ $\nu$ cross section physics
    
    - useful to the community
    - important for oscillation analysis
    - will tell you about

* plus some new opportunities (mention at end)
  
  - antineutrino data! (big change for us)
Previous Measurements

• most of present low energy $\nu \sigma$ knowledge comes from bubble chamber exps

• early experiments at ANL, BNL, FNAL, CERN, Serpukhov, etc.

• 20-100% errors due to:
  - low statistics (100’s of events)
  - uncertainties in $\nu$ flux

• in addition to large errors, results often conflicting (some care in interpreting)

• data useful to constrain our MCs

• idea of caliber of past data …
Low Energy $\nu$ Cross Sections

predictions from NUANCE

- MC which MBooNE uses
- open source code
- supported & maintained by D. Casper (UC Irvine)

- standard inputs
  (common ingredients - osc exps)
  - Smith-Moniz Fermi Gas
  - Rein-Sehgal $1\pi$
  - Bodek-Yang DIS

Super-K atmospheric $\nu$

MINOS, NuMI
K2K, NOvA
MiniBooNE, T2K
Low Energy $\nu$ Cross Sections

- imperative to precisely predict signal & bkgd rates for future oscillation exps
  - will be more sensitive to sources of syst error
  - nuclear targets!
    (most past data on $H_2, D_2$)

- further motivates need for new measurements

- new data adding new info; revealing interesting features
  K2K, NOMAD, MiniBooNE
MiniBooNE Beamline

- >700,000 contained $\nu$ events
- providing a valuable sample to study low $E \nu$ cross sections

decay region: $\pi \rightarrow \mu \nu$, $K \rightarrow \mu \nu$

“LMC” measure $K$ flux in-situ

MiniBooNE detector ($CH_2$)

magnetic focusing horn

450 m earth berm: $\nu$

movable absorber: stops muons, undecayed mesons

magnetic horn: meson focusing

FNAL 8 GeV Booster
νμ Flux at MiniBooNE Detector

- incident on detector: high purity beam (>99% νμ flavor)

- νμ mainly from π+ → μ+ νμ

- π production constrained by global π data & E910 …

- eventually HARP

- really advance knowledge of low E hadroproduction (see Gibin’s talk)

MC predicted ν energy spectrum
\(\nu_{\mu}\) Flux at MiniBooNE Detector

- \(<E_{\nu}>^{\text{MB}oo\text{NE}} \approx 0.7 \text{ GeV}\)
- well-suited for low energy \(\nu\) cross section studies
  - small tail; enjoy smaller backgrounds from higher multiplicity \(\nu\) interactions
- complementary to other \(\sigma_{\nu}\) experiments
  \(<E_{\nu}^{\text{K2K}} > \approx 1.3 \text{ GeV}\)
  \(<E_{\nu}^{\text{NuMI}} > \approx 10 \text{ GeV}\)
  \(<E_{\nu}^{\text{NOMAD}} > \approx 24 \text{ GeV}\)

MC predicted \(\nu\) energy spectrum
Event Fractions at MiniBooNE

MiniBooNE flux-averaged event compositions
(N_{TANK}>200, N_{VETO}<6)

- 48% CC QE
- 31% CC $\pi^+$
- 8% NC $\pi^0$
- 5% CC $\pi^0$
- 3% NC $\pi^{+/-}$
- 4% multi-$\pi$
- 1% NC elastic

this flux spectrum dictates what type of $\nu$ interactions we see …

demonstrate understanding of 79% of events before analyzing $\nu_e$ (<1% of total)
Quasi-Elastic Scattering

Why important?

- $\nu_\mu$ QE $\sigma$ necessary to accurately predict signal rates in oscillation experiments (including our own)
  
  * $\nu_e$ QE are main signal for $\nu_\mu \rightarrow \nu_e$ appearance searches; have similar kinematics & $\sigma$

- channel used as “golden mode” to normalize other cross section samples - lots of events, well known $\sigma$
  
  (common practice that we will also adopt for now)
Quasi-Elastic Scattering

\[ \nu_\mu \ n \rightarrow \mu^- \ p \]

- highest statistics
  \( \sim 2500 \) events
- low E data on \( D_2 \)
Quasi-Elastic Scattering

\[ \nu_\mu \ n \rightarrow \mu^- \ p \]

- new information already coming in (NOMAD, $^{12}\text{C}$)
Quasi-Elastic Scattering

\[ \nu_\mu \ n \rightarrow \mu^- \ p \]

- **MiniBooNE:**
  - \(^{12}\text{C}\) (valuable for osc exps)
  - this analysis: **60k events** (3.2x10\(^{20}\) POT)
    (already more data than all previous exps combined)
  - can select 86\% pure QE sample
MiniBooNE QE Data

- most copious events at MiniBooNE
- also simplest: two body kinematics

\[ \nu_{\mu} n \rightarrow \mu^- p \]

\[ \nu_{\mu} \quad l \quad \ell^- \quad W^+ \quad n \quad \mu^{-} \quad p \]

measure visible \( E \) and \( \theta_{\mu} \) from mostly Čerenkov (\( \mu \)) + some scintillation light (\( p \))

Forward muons corresponds to low \( Q^2 \) …
MiniBooNE QE Data

• similar effect seen by K2K

• working on understanding these features in our data …

• to improve data, MC agreement performing shape fits for:
  
  (J. Monroe)

  - axial form factor (M_A) &
  - nuclear model pars (E_B,p_F)

• incorporating new nuclear models (R. Tayloe)
  (that are constrained by modern electron scattering data)

\[ Q^2 = m_\mu^2 - 2E_\nu(E_\mu - p_\mu \cos \theta_\mu) \]
MiniBooNE QE Data

- making use of $E_\mu, \theta_\mu \ldots$

$$E_{\nu}^{QE} = \frac{2M_pE_\mu - m_\mu^2}{2(M_p - E_\mu + p_\mu \cos \theta_\mu)}$$

- energy distribution that will be used for CC $\pi^+$/QE cross section measurement

- next, numerator (CC $\pi^+$) \ldots

(J. Monroe)
CC $1\pi^+$ Production

resonant $\pi^+$ production (dominant)  coherent $\pi^+$ production

- forward emitted $\pi$
- low $Q^2$
CC $1\pi^+$ Production

resonant $\pi^+$ production (dominant)  coherent $\pi^+$ production
CC $1\pi^+$ Production

resonant $\pi^+$ production (dominant)  coherent $\pi^+$ production

- K2K: 1$^{\text{st}}$ search for coh $\pi^+$ prod at low E
- somewhat surprising results …
- see no evidence for coh $\pi^+$ production!
CC $1\pi^+$ Production

- resonant $\pi^+$ production (dominant)
- coherent $\pi^+$ production

**MiniBooNE:**
- inclusive measurement, CH$_2$
- this analysis: **40k events** (3.2x10$^{20}$ POT)
  (5x more than previous bubble chamber data combined)
CC $\pi^+$ Production

Why important?

• poses largest background to $\nu_\mu$ QE samples (large $\sigma$ & $\pi^+$ can be absorbed in nucleus)

• useful for understanding $\Delta$ production in CH$_2$ ($\Delta \rightarrow N \gamma$ a background to $\nu_\mu \rightarrow \nu_e$ search)

• possibility for CC $\pi^+$ oscillation search

• useful in understanding our event reconstruction
MiniBooNE CC $\pi^+$ Selection

• very simple selection:
  - events with 2 decay electrons
  - unique, results in 84% purity

• expect $\mu^-$ to have shorter lifetime from $\mu^-$ capture (8% in $^{12}$C)
  - will also make use of this later

(M. Wascko)
MiniBooNE CC $\pi^+$ Reconstruction

measure Čerenkov light from muon (to avoid light from $\pi^+$)

see larger deficit in forward $\mu$ (low $Q^2$) than in QE data

(M. Wascko)
MiniBooNE CC $\pi^+$ Data

\[ 2M_p E_\mu - m_\mu^2 + (m_\Delta^2 - M_p^2) = \frac{E_{\nu\text{QE}}}{2(M_p - E_\mu + p_\mu \cos \Theta_\mu)} \]

- use 2 body (QE) kinematics
- assume $\Delta(1232)$ in final state (instead of $p$ in QE case)
- energy distribution that will be used for CC $\pi^+/\text{QE}$ cross section measurement
MiniBooNE CC $\pi^+$/QE Ratio

- efficiency corrected CC $\pi^+$/QE $\sigma$ ratio meas on CH$_2$
- eff corrections from MC
- ample statistics → can perform a binned measurement
- current systematics estimate:
  - light propagation in oil: ~20%
  - $\nu$ cross sections: ~15%
  - energy scale: ~10%
  - statistics: ~5%

(J. Monroe, M. Wascko)

first measurement of this cross section ratio on a nuclear target at low energy!
MiniBooNE CC $\pi^+$ Cross Section

- multiplying measured CC $\pi^+/\text{QE}$ ratio by QE $\sigma$ prediction ($\sigma_{\text{QE}}$ with $M_A = 1.03$ GeV, BBA non-dipole vector form factors)
- $\sim 25\%$ lower than prediction, but within errors

(J. Monroe, M. Wascko)  
- MC error band from external $\nu$ data constraints
Plausible Interpretation

- since MiniBooNE 1\textsuperscript{st} meas on nuclear target at these E’s
- at 1\textsuperscript{st} glance, one might think this is pointing to a potential problem with nuclear corrs
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- but free nucleon σ’s disagree!

- MC prediction splits difference

- MiniBooNE results more consistent with ANL than BNL
  - new data helping to decide between 2 disparate σ meas
  - once final, type of info that can feed back into open source MC
New $\sigma_\nu$ Directions at MiniBooNE

- new antineutrino data!
- observing $\nu$ events from NuMI
- coming soon: new fine-grained new detector to this beamline (comparisons to MiniBooNE will be interesting)
MiniBooNE Antineutrino Running

• just started antineutrino running (January 19th)
  - ~1,000 $\bar{\nu}$ events/week
  - will have world’s largest low $E$ $\bar{\nu}$ data set in a few weeks!

• goals are two-fold:
  - check LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal
    (longer program, not yet approved)
  - measure $\bar{\nu}$ cross sections
    - systematic check of $\nu$ analyses
    - low $Q^2$ investigations
    - coherent $\pi$ production
Need for $\bar{\nu} \sigma$ Measurements

- $\bar{\nu} \sigma$ data even less abundant
- MiniBooNE will make world’s 1st meas of $\bar{\nu} \sigma$ in this E range
  - expect $\sim$10k $\bar{\nu}_\mu$ QE in 1 year (after cuts)
- provide valuable input for future CP violation searches
  $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- prefer not to rely on extrapolation of models into regions where no data
Added Difficulty with $\bar{\nu}$ Beams

• contending with “wrong sign” backgrounds ($\nu$ in $\bar{\nu}$ beam)
  - MiniBooNE beam is no exception …

• in neutralino mode, antineutrinos are $\sim 2\%$ of total events
Added Difficulty with $\bar{\nu}$ Beams

- contending with “wrong sign” backgrounds ($\nu$ in $\bar{\nu}$ beam)
  - MiniBooNE beam is no exception …

- in antineutrino mode, neutrinos are $\sim$30% of total events
  - “$\bar{\nu}$-enhanced beam”

- need a way to constrain $\nu$ backgrounds in $\bar{\nu}$ data

- Čerenkov detectors cannot distinguish $\mu^-$, $\mu^+$ event-by-event (no magnetic field)
Constraining $\nu$ Backgrounds in $\bar{\nu}$ Data

• needed to be more clever
• developed several novel techniques to measure from data

• $1^{st}$ and most powerful ... 
• makes use of fact that QE $\nu$ & $\bar{\nu}$ have different angular distributions
• large angle QE’s as means of measuring $\nu$ content in $\bar{\nu}$ data 
  (“poor man’s sign-selection”)
Three Independent Constraints

1. QE angular distributions provide best “wrong-sign” constraint, but also …

2. add’l constraint from CC $\pi^+$ events in $\bar{\nu}$ mode data
   (come entirely from $\nu$ interactions as $\bar{\nu}$’s produce a $\pi^-$ in final state)
   - higher E constraint

3. also muon lifetimes ($\mu^-$ vs. $\mu^+$ to distinguish $\nu$ vs. $\bar{\nu}$)
   - $\mu^-$ and $\mu^+$ have different lifetimes due to $\mu^-$ capture probability in oil
   - not as precise a constraint, but indep of kinematics & recon

→ allows precise antineutrino $\sigma$ measurements
   (once have a handle on $\nu$ backgrounds)
Antineutrino $\sigma$ Measurements

- can add new info by mere fact that $\bar{\nu}$ scattering is different

\[ \frac{d\sigma}{dQ^2} \]

\[ \begin{align*}
\nu_\mu \text{ QE} & & \bar{\nu}_\mu \text{ QE} \\
\end{align*} \]

different shape & axial contribution

difference isolates interference term - directly $\alpha$ to axial FF
Antineutrino $\sigma$ Measurements

- can add new info by mere fact that $\bar{\nu}$ scattering is different

\[ \nu_\mu \text{ NC } \pi^0 \quad \bar{\nu}_\mu \text{ NC } \pi^0 \]

- $20\%$ is coherent production

- $40\%$ is coherent production

- “enhanced” coherent sample

latest K2K results say this peak will be missing: very apparent in $\bar{\nu}$ data
Can Detect $\nu$’s from NuMI!

- neighbor’s beam
- first off-axis neutrino beam!

(A. Aquilar-Arevalo)

~10,000 $\nu$ events so far
100’s of $\nu_e$ events (calibration)
also opened up possibility to use this sample for $\sigma_{\nu}$ meas
(slightly diff beam spectrum)

- MINOS also sees MiniBooNE neutrinos in their detector

NuMI $\nu$ events in MiniBooNE detector
SciBooNE (E954)

- new Int’l collaboration
- couple well-understood, fine-grained detector with high rate beam
- unique, low risk opportunity
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- excellent final state resolution

- improve on MiniBooNE $\nu$, $\bar{\nu}$, $\sigma$ studies
SciBooNE (E954)

- new Int’l collaboration
- couple well-understood, fine-grained detector with high rate beam
- unique, low risk opportunity
- excellent final state resolution
  - improve on MiniBooNE $\nu$, $\bar{\nu}$ studies
  - $\sigma_\nu$ measurements for T2K
- just received Stage 1 approval (Dec ‘05)
  rapid schedule: begin data taking this Fall
  - www-sciboone.fnal.gov
Conclusions

• collected > 700k neutrino (> 1k antineutrino) events (7 x 10^{20} POT)
  - amassed the world’s largest $\nu$ sample in 1 GeV range
  - already an order of magnitude more data than previous bubble chamber based measurements
  - part of effort to help improve our current understanding of low E $\sigma_\nu$
  - 1\textsuperscript{st} results on MiniBooNE CC $\pi^+/\text{QE}$ cross section

• coming soon …
  - $\nu_\mu$ CC QE cross section results
  - NC $\pi^0$ cross sections
  - HARP results (8 GeV, Be, thick target)

• stay tuned for $\nu_\mu \rightarrow \nu_e$ oscillation results