a topic that we really haven’t talked about in a really long time and one that has gotten a lot more interesting over the past year
Introduction

- physicists have been scattering neutrinos off nuclei for decades

- so why so much interest in this topic now?

  - the study of $\nu$ oscillations over the past 15 years has certainly placed new demands on our understanding of $\nu$ interactions

  - the availability of modern, very intense $\nu$ sources has provided an excellent opportunity to revisit this physics, decades later

  - like any measurement, new data and higher statistics explorations can reveal previously hidden subtleties and raise new questions
Neutrino Physics

• looking forward, there are some big questions we will be trying to answer

• next generation of experiments will largely be focused on answering several key questions:

- what are the masses of neutrinos?
- are neutrinos their own anti-particles?
- is there a 4\textsuperscript{th} neutrino?
- is $\theta_{13}$ non-zero?
- what is the $\nu$ mass ordering?
- is CP violated in the $\nu$ sector?
Do you know what $\theta_{13}$ is yet?
The New $\theta_{13}$ Landscape

... looks something like this:

- $\theta_{13}$ is the gate-keeper
- It's large value opens up new windows of opportunity because it allows for measurable matter effects (MH) and opens the door for measuring CP violation in the $\nu$ sector
- “Signal is now guaranteed and measurement of $\delta_{CP}$ is guaranteed”

(M. Messier)
What Does Large $\theta_{13}$ Mean?

• we’ll enjoy larger signal samples
• can determine the MH more quickly
What Does Large $\theta_{13}$ Mean?

(S. Parke)

- we’ll enjoy larger signal samples
- can determine the MH more quickly
- but it doesn’t mean that the CP measurement is any easier
  - the $\nu/\bar{\nu}$ asymmetry is smaller as $\theta_{13}$ gets larger
  - systematics start to become increasingly important

• places even greater demands on our knowledge of $\nu$ ($\& \bar{\nu}$) interactions

S. Zeller, Penn seminar, 04/17/12
Neutrino Cross Sections

• to address MH and CP, are going to even longer baselines
  implies $E_\nu$’s of a few-GeV to be sensitive to these effects

• this region is dominated by poorly known $\nu$ cross sections

• this region is complex (lots of rich physics here)

• challenges:
  - sizable nuclear effects
  - multiple $\sigma$ contributions

(\sigma_\nu across 3 orders of magnitude)
Why Is This Complicated?

three basic reaction processes:
Why Is This Complicated?

three basic reaction processes:

CC Quasi-elastic
nucleon changes, but doesn't break up

\( \nu_\mu \rightarrow \mu^- \)
\( W \rightarrow n p \)

\[ \frac{\nu \text{ cross section}}{E_\nu (10^{-38} \text{ cm}^2 / \text{GeV})} \]

\( E_\nu (\text{GeV}) \)

T2K
NOvA
CNGS
LBNE

S. Zeller, Penn seminar, 04/17/12
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Why Is This Complicated?

three basic reaction processes:

CC Quasi-elastic
nucleon changes, but doesn’t break up

CC Single pion
nucleon excites to resonance state

CC Deep Inelastic
nucleon breaks up

(accel-based $\nu$ experiments all use broad band beams, so contain contribs from all of these reaction mechanisms)
• most of our information comes from data that is > 30 years old
(data you see on this plot, low stats but crucial for establishing overall size of $\sigma$, mostly $D_2$, $H_2$)

• good news: modern exps are making improved $\sigma_{\nu}$ measurements

• advantages of new data:
  - higher statistics
  - intense, well-known $\nu$ beams
  - nuclear targets (crucial!)

K2K, MiniBooNE, MicroBooNE, SciBooNE, T2K
ArgoNeuT, ICARUS, MINER$\nu$A, MINOS, NOMAD, NO$\nu$A
• need to know all of this for antineutrinos too! *(will be important for CP)*

• existing measurements are even more sparse in this case

• recognizing that “every problem is an opportunity in disguise”, MiniBooNE launched a rather extensive neutrino cross section program
MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations \((\nu_\mu \rightarrow \nu_e \text{ at large } \Delta m^2 \text{ to address LSND})\)

small collaboration
~74 physicists, 18 institutions
MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations $(\nu_\mu \rightarrow \nu_e$ at large $\Delta m^2$ to address LSND)

- have been running for $\sim$10 yrs now

*A. Aguilar-Arevalo et al., PRL 105, 181801 (2010)*
MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations \((\nu_\mu \rightarrow \nu_e)\) at large \(\Delta m^2\) to address LSND

- have been running for \(~10\) yrs now

- over a million neutrino & antineutrino interactions!
  (world's largest data set in this E range; we quickly realized there were potentially some useful measurements to be made here)

- \(\sigma_\nu\) are a big part of our program

- have since measured \(\sigma\)'s for \(~90\%\) of \(\nu\) events in MB
  (high statistics, high quality data); turning out to be more interesting than we thought!

Aguilar-Arevalo et al., PRL 105, 181801 (2010)
MiniBooNE Detector

- 800 tons of mineral oil
- ν interactions on CH$_2$
- Čerenkov detector $\rightarrow$ ring imaging for event reconstruction and PID

Aguilar-Arevalo et al., NIM A599, 28 (2009)

(inside view of MB tank)
MiniBooNE Detector

Aguilar-Arevalo et al., NIM A599, 28 (2009)

- 800 tons of mineral oil
- $\nu$ interactions on CH$_2$
- Čerenkov detector $\rightarrow$ ring imaging

Based on Č ring topology, can differentiate different particle types

Muon candidate

Electron candidate
Neutrino Flux

- MB operates in the Booster ν beamline at Fermilab

- ν and $\bar{\nu}$ (currently $\bar{\nu}$)

- well-suited for low energy ν cross section studies

  \[<E_\nu> \sim 0.8 \text{ GeV}\]

  - enjoy small backgrounds from higher multiplicity ν interactions

    (perfect for QE + RES !)

- relevant to LBL ν oscillation experiments (T2K, NOνA, LBNE)

flux of neutrinos seen by the detector:

99% of flux predicted ν$_\mu$ energy spectrum

$E_\nu$ (GeV)

predicted $\nu_\mu$ energy spectrum

0

0.01

0.02

0.03

0.04

0.05

0 0.5 1 1.5 2 2.5 3 3.5 4
Flux Prediction

• made dedicated hadro-production measurements at CERN specifically for MiniBooNE
  - same beam energy
  - exact replica target

• need to know your $\nu$ flux to make $\nu$ cross section measurements

• comprehensive $\nu$ flux paper
  Aguilar-Arevalo et al., PRD 79, 072002 (2009)

• there was no tuning of flux based on MiniBooNE $\nu$ data!

(D. Schmitz, Columbia, Ph.D. thesis)
Flux Prediction

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- there was no tuning of flux based on MiniBooNE $\nu$ data!

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data and the cross section for reaction (2) derived from the $V-A$ theory.

Neutrino Interactions

- we’ll use this plot as our guide as we survey the landscape
- let’s start on the left and work our way up in energy …

- what have we learned in exploring this region again 30+ years later?
Why important?

• important for $\nu$ oscillation experiments
  - typically gives largest contribution to signal samples in many osc exps

  examples:
  $\nu_\mu \rightarrow \nu_e$ ($\nu_e$ appearance)
  $\nu_\mu \rightarrow \nu_\chi$ ($\nu_\mu$ disappearance)

- biggest piece of the $\sigma$ at $\sim 1$ GeV
  (lepton kinematics are used to infer $E_\nu$)

(one of the most basic $\nu$ interactions, single knock-out nucleon)

(heavily studied in 1970’s and 80’s, one of the 1st $\nu$ interactions measured)
Past Examples

- **BNL, D₂**
  - $M_A = 1.07 \pm 0.06$ GeV
  - 1,236 events

- **ANL, D₂**
  - $M_A = 1.00 \pm 0.05$ GeV
  - 1,737 events

- **FNAL, D₂**
  - $M_A = 1.05 \pm 0.16$ GeV
  - 362 events

- **Kitagaki, PRD 28, 436 (1983)**

- **Baker, PRD 23, 2499 (1981)**


- **νμ n → μ− p**

- **goal:** make more accurate predictions for NC, so measured the axial FF in CC scattering

- **focus of many early bubble chamber exps (D₂) \( \longrightarrow \) \( M_A \sim 1.0 \) GeV
QE Cross Section

- these same exps also measured $\sigma(E_{\nu})$

- conventional wisdom has always been that this $\sigma$ is well-known
  - it's a simple 2-body process
  - basic picture is that $\nu$ interacts with one nucleon at time

- this description has been quite successful
  - can predict size, shape of $\sigma$

- can consistently describe all the experimental data
  - most is on $D_2$
  - $M_A = 1.0$ GeV

with these ingredients, it looked straightforward to extend this to describe $\nu$ QE scattering on nuclei
QE Cross Section

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$\nu_\mu \ n \rightarrow \mu^- \ p$

Fermi Gas Model
(heavily used today)

scattering off a collection of independent nucleons in the nucleus
QE Cross Section on Carbon

- repeated 30 years later … this time on carbon
- two exps: different energy ranges, different detectors … different detection

MiniBooNE
PRD 81, 092005 (2010)

NOMAD
EPJ C63, 355 (2009)

MiniBooNE (FNAL)
2002-present
relies on μ reconstruction

NOMAD (CERN)
1995-1998
sees both μ and proton
QE Cross Section on Carbon

- MiniBooNE data is well above “standard” QE prediction (increasing $M_A$ can reproduce $\sigma$)
- NOMAD data consistent with “standard” QE prediction (with $M_A = 1.0$ GeV)

S. Zeller, Penn seminar, 04/17/12
• results of low & high E experiments appear to be inconsistent; cannot be described with a single prediction

• difference is not many $\sigma$, but leaves you in a quandary if want to predict # signal events expect to see in your oscillation experiment
QE Cross Section on Carbon

\[ \sigma \text{ (cm}^2\text{)} \]

- MiniBooNE
- T2K, NOvA, LBNE
- CNGS

\[ E_{\nu}^{QE,RFG} \text{ (GeV)} \]

30\%
**QE Cross Section on Carbon**

- Fermi Gas ($M_A = 1.35 \text{ GeV}$)
- Fermi Gas ($M_A = 1.03 \text{ GeV}$)

**T2K, NOvA, LBNE, CNGS, *NOMAD**

- good news is that new data will be weighing in on this soon that will exactly span this energy range

S. Zeller, Penn seminar, 04/17/12
MiniBooNE is the 1st time have measured the $\nu$ QE $\sigma$ on a nuclear target at these low energies ($< 2$ GeV)

- naturally, these results have garnered a lot of attention, largely because they were unexpected
  (increased QE rates also seen in K2K, SciBooNE, MINOS)

- naturally, attention focused on use of Fermi Gas model

- problem: adding nuclear effects decrease the $\sigma$

(O. Benhar, arXiv:0906.3144)
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• origin of this QE puzzle has been extensively debated (L. Alvarez-Ruso, NuFact11)
• a possible explanation has recently emerged …

• while traditional nuclear effects decrease the $\sigma$, there are processes that can increase the total yield

Martini et al., PRC 80, 065001 (2009)
Nuclear Effects to the Rescue?

• a possible explanation has recently emerged ...

• while traditional nuclear effects decrease the $\sigma$, there are processes that can increase the total yield

• there are add’l nuclear dynamics present

  (i.e., effects not included in the independent particle approaches we have been using for decades)

• $\nu$ can scatter off of a strongly correlated nucleon state; multi-nucleon correls produce an enhancement

  (most important distinction is that $E$ & $\bar{p}$ are absorbed by two or more nucleons, not a single nucleon)

---

Martini et al., PRC 80, 065001 (2009)
Nuclear Effects to the Rescue?

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- while traditional nuclear effects decrease the $\sigma$, there are processes that can increase the total yield

• idea is not new
  - Dekker et al., PLB 266, 249 (1991)
  - Singh, Oset, NP A542, 587 (1992)
  - Gil et al., NP A627, 543 (1997)
  - Nieves et al., PRC 70, 055503 (2004)

oldest models pre-date the experimental results

Martini et al., PRC 80, 065001 (2009)
Not a New Idea

• in 1999, recognized that may not be able to distinguish these two contributions

• warned that could see 20% more 1-ring events in Super-K

“QE” = true QE + nucleon-correls

(\(\mu+p\))   (\(\mu+p+p\))

we see an enhancement of the total yield with respect to the free quasi-elastic around 20\%.
This result points out the importance of a good evaluation of such neutrino induced \(np-nh\) excitations.

• idea is that there are two contributions present when we talk about $\nu$ QE scattering off of a nuclear target:

Martini et al., PRC 80, 065001 (2009) (single-nucleon knock-out; same as would get for free nucleon scattering)
Nuclear Effects to the Rescue?

- idea is that there are two contributions present when we talk about $\nu$ QE scattering off of a nuclear target:

scattering off of correlated nucleon states contributes up to 40% more $\sigma$ at these $\nu$ energies and produces a multi-nucleon final state ($\mu+p+p$)

Martini et al., PRC 80, 065001 (2009)

(would not have seen this large effect in $D_2$ so this would have been missed)
Nuclear Effects to the Rescue?

- idea is that there are two contributions present when we talk about ν QE scattering off of a nuclear target:

Martini et al., PRC 80, 065001 (2009)
Nuclear Effects to the Rescue?

- idea is that there are two contributions present when we talk about $\nu$ QE scattering off of a nuclear target:

- could this explain the difference between MiniBooNE & NOMAD?

  jury is still out on this

  need to be clear what we mean by “QE” when scattering off nuclear targets!

Martini et al., PRC 80, 065001 (2009)
Supporting Evidence from e⁻ QE Scattering

- while this is new to $\nu$ scattering, has been known for over 2 decades in e⁻ case (G. Garvey)

Carlson et al., PRC 65, 024002 (2002)
• while this is new to $\nu$ scattering, has been known for over 2 decades in e$^-$ case (G. Garvey)

• **longitudinal** part of $\sigma_{\text{QE}}$ can be described in terms of scattering off independent nucleons

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Carlson et al., PRC 65, 024002 (2002)
Supporting Evidence from $e^-$ QE Scattering

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• **longitudinal** part of $\sigma_{QE}$ can be described in terms of scattering off independent nucleons

• in contrast, see a very large enhancement in **transverse** part
  (can be explained by SRC and 2-body currents)

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• **longitudinal** part of $\sigma_{QE}$ can be described in terms of scattering off independent nucleons

• in contrast, see a very large enhancement in **transverse** part (can be explained by SRC and 2-body currents)

• implies that there should also be a corresponding transverse enhancement in $\nu$ QE scattering!

---

Carlson et al., PRC 65, 024002 (2002)

- took us awhile to realize that we may be seeing the same thing in $\nu$ scattering ... now widespread acceptance ...
Has Been a Focus in the Past Year

• over 50 theoretical papers on the topic of QE ν-nucleus scattering

• 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, arXiv:1203.3335, 1110.1004
• Paz, arXiv:1109.5708
• Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
• Bodek et al., arXiv:1106.0340
• Antonov, et al., arXiv:1104.0125
• Benhar, et al., arXiv:1012.2032, 1103.0987, 1110.1835
• Alvarez-Ruso, arXiv:1012.3871
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- Benhar, et al., arXiv:1012.2032, 1103.0987, 1110.1835
- Alvarez-Ruso, arXiv:1012.3871

(most of calcs have been focused on low $E$, but there has been new work to incorporate increased transverse response from $e^-$)

• however, need to do more
Moving Forward

- also new approaches on the experimental side ...

- double differential $\sigma$’s for the first time!
  \[ d^2\sigma / dT_\mu d\theta_\mu \]

- 146,000 $\nu_\mu$ “QE” events
  (currently world’s largest sample)

- historically, never had enough statistics to do this

- most model-independent result possible, provides richer info than $\sigma(E_\nu)$

- this data is getting heavily used by the community

(T. Katori, IU, Ph.D. thesis)

Aguilar-Arevalo et al., PRD 81, 092005 (2010)
Double Differential $\sigma$ Comparisons

- would be nice to have measurements at other $E_{\nu}$, $A$ and of the outgoing proton(s)!

Martini et al., arXiv:1110.0221

Lalakulich et al., arXiv:1203.2935

1$^{\text{st}}$ time we've had this sort of info available
Smoking Gun ...

- $e^-$ scattering experiments have already provided evidence for SRC
  

- direct measurement of multi-nucleon final states in a $\nu$ detector could play an important role in verifying scattering from such correlated nucleon states  
  
  (early attempts by NOMAD, Veltri et al., NP B609, 255 (2001))
Could We See This?

- If nucleon correlations are significant, this should produce a distinguishable final state ... this has be observable!
  
  (so not only the enhanced $\sigma$, but also multiple recoil nucleons)

- People are just starting to work out these details for $\nu$ scattering

- Recent paper suggests that this is promising

Promise of Liquid Argon TPCs

- perhaps one of our best chances to see this will be in a LAr TPC (can detect protons down to very low energy)

- \( \text{ArgoNeuT} = 175 \text{L LAr TPC} \)
  ran in the NuMI beam (2009-2010);
  there is also ICARUS and MicroBooNE!

- but need to disentangle from FSI!

What Does This All Mean?

- something as simple as QE scattering is not so simple
  - nuclear effects can significantly increase the cross section
  - idea that could be missing ~40% of $\sigma$ in our simulations is a big deal!

- good news: expect larger event yields
- bad news: need to understand the underlying physics
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1. impacts $E_\nu$ determination
   - Lalakulich, arXiv:1203.2935

2. effects will be different for $\nu$ vs. $\bar{\nu}$
   - (at worst, could produce a spurious $\mathcal{CP}$ effect)

Amaro et al., PRC **82**, 044601 (2010)
Neutrino/Antineutrino Ratio

- theory calculations currently disagree over the size of these effects for antineutrinos
- the situation is unclear and will need to get resolved
- for large $\theta_{13}$, the $\nu/\bar{\nu}$ asymmetry is small so will need a detailed understanding of these $\nu, \bar{\nu}$ differences!

we are currently working on a $\nu/\bar{\nu}$ $\sigma_{QE}$ ratio measurement in MB that should have some discriminating power (J. Grange)
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in the past year, have gone from a general complacency to having uncovered a host of rich nuclear effects... story will continue to evolve
Pion Production

• NC $\pi^0$ production
  (background for $\nu_e$ appearance)

  \[ \nu_\mu \rightarrow Z^0 \rightarrow \nu_\mu \]
  \[ n,p \rightarrow n,p \pi^0 \]

• CC $\pi^+$, $\pi^0$ production
  (a complication for $\nu_\mu$ disappearance)

  \[ \nu_\mu \rightarrow W^+ \rightarrow \mu^- \]
  \[ n,p \rightarrow n,p \pi^+ \]

• talked about QE (signal), what about bkgs?

  \[ \nu \text{ cross section} / E_\nu (10^{-38} \text{ cm}^2 / \text{GeV}) \]
  \[ n,p \rightarrow n,p \pi \]

• $\pi$ production also has important connections to $\nu$ osc measurements
Final State Effects Can Change the Picture

- a new appreciation for nuclear effects in this region as well

“final state interactions (FSI)”

- before they leave the nucleus, pions & nucleons can re-interact
- picture can be quite different from what happens at the primary vertex
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you will have to model final state effects
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“final state interactions (FSI)”

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- picture can be quite different from what happens at the primary vertex

• have to worry about these effects

• for $\nu$, is a subject that needs more attention

(U. Mosel,1108.1692 [nucl-th])
Final State Effects are Important

- **the distortions are large (>20%)**

(T. Leitner)

![Graph showing momentum of π's produced in MiniBooNE](image.png)

- leaves a big imprint on what you see in your detector

distribution that tends to be most affected by rescattering effects
Final State Effects are Important

- the distortions are large (>20%)
- and the predictions of their effects can vary

(T. Leitner)

http://regie2.phys.uregina.ca/neutrino/

- leaves a big imprint on what you see in your detector
- area where generators differ the most
- need \( \pi \) kinematic measurements!
  (has never been carefully studied in \( \nu \) scattering)

S. Zeller, Penn seminar, 04/17/12
π Production in MiniBooNE

- trying to forge a new path here also
- extensive program to measure final state particle kinematics
  (after all of the nuclear effects have taken place)

score card:

<table>
<thead>
<tr>
<th>measurement</th>
<th>NC $\pi^0$</th>
<th>CC $\pi^0$</th>
<th>CC $\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(E_\nu)$</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$d\sigma/dQ^2$</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$d\sigma/dp_{\pi}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$d\sigma/d\cos\theta_{\pi}$</td>
<td>X</td>
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<tr>
<td>$d\sigma/dT_\mu$</td>
<td>X</td>
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<tr>
<td>$d\sigma/d\cos\theta_\mu$</td>
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<tr>
<td>$d^2\sigma/dT_\mu d\cos\theta_\mu$</td>
<td></td>
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<td>X</td>
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<tr>
<td>$d^2\sigma/dT_{\pi} d\cos\theta_{\pi}$</td>
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<td></td>
<td>X</td>
</tr>
</tbody>
</table>

• absolute $\sigma$'s for 3 channels, 14 diff'l $\sigma$'s
• all of this data available online
  http://www-boone.fnal.gov/for_physicists/data_release/

S. Zeller, Penn seminar, 04/17/12
NC $\pi^0$ Production

Why important?

• important for neutrino oscillation experiments
  
  - very important background for experiments looking for $\nu_\mu \rightarrow \nu_e (\theta_{13}, M_D, CP)$
  
  final state can mimic a $\nu_e$ interaction if $\pi^0 \rightarrow \gamma \gamma$

background for oscillation experiments
NC $\pi^0$ Production

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  final state can mimic a $\nu_e$ interaction if $\pi^0 \rightarrow \gamma \gamma$

  can be a sizable background

  goal: 5-10% level or better
Historically …

• interesting to go back through some of the history here too ….

• only two pre-existing NC $\pi^0$ $\sigma$ measurements (1978, 1983)

• both at $\sim$2 GeV

• historically:
  - $\sigma(E_\nu)$ at a single $E_\nu$ point
  - at the time, interest in studying neutral currents, not in understanding this as an oscillation bkg
Historically ...


- 240 NC $\pi^0$ events
- Gargamelle bubble chamber, propane-freon

\[
\pi^0 \rightarrow \gamma\gamma
\]

this is what oscillation exps have initially known about their NC $\pi^0$ backgrounds going in
NC $\pi^0$ at MiniBooNE

- coming back to this 30 years later …

- $21,542 \nu_\mu$ NC $\pi^0$ events
- $2,305 \bar{\nu}_\mu$ NC $\pi^0$ events

$\sim 100x$ more data than previously available!

1st time we’ve had a high statistics measurement of this process in $\nu$ scattering

$\pi^0 \rightarrow \gamma\gamma$

R.B. Patterson et al., NIM A608, 206 (2009)
• one thing we realized in going through the mechanics of the $\nu_\mu \rightarrow \nu_e$ analysis in MiniBooNE and looking for sub-1% signal, is that it’s not just an issue of adding another data point to this plot

• from MB experience, we quickly realized that this was not good enough! this will also be true for experiments like T2K, NOvA, LBNE
NC $\pi^0$ at MiniBooNE

Aguilar-Arevalo et al., PRD 81, 013005 (2010)

- one of our flagship meas

- what this is is the total $\sigma$ for a NC interaction to produce $\pi^0$ exiting the target nucleus
  (this is what we care about, “observed cross section”)

- have not corrected back to primary interaction vertex
  (this is something new!)

$\nu$ $\pi^0$ (CH$_2$, flux-averaged)

$d\sigma/dp_{\pi^0}$ ($10^{-39}$ cm$^2$/GeV/c/nucleon)
NC $\pi^0$ at MiniBooNE

Aguilar-Arevalo et al., PRD 81, 013005 (2010)

- this is the 1st time differential $\sigma$’s have been provided for such neutrino interactions

C. Anderson, Yale, Ph.D. thesis

*S. Zeller, Penn seminar, 04/17/12*
NC $\pi^0$ at MiniBooNE

- this data crucial for MB
  $\nu_\mu \to \nu_e$ oscillation search
  (dominant $\nu_\mu$-induced bkg to $\nu_e$ app search)

uncertainty in
NC $\pi^0$ backgrounds
reduced by a factor of 5
(full kinematic constraint)

- by providing diff’l $\sigma$’s, the data
  is now in a form others can use
- MiniBooNE $\pi$ production data has been in heavy use by FSI model builders (and T2K)

(U. Mosel)
**CC $\pi^0$ at MiniBooNE**

- as a cross-check, also decided to look at CC equivalent of this process
- these events have 3 Čerenkov rings, so developed a custom 3-ring fitter
  (B. Nelson, UC Boulder, Ph.D. thesis)
- most complex final state that attempt to reconstruct in MiniBooNE

\[
\begin{align*}
\nu_\mu & \rightarrow \mu^- \\
W^+ & \rightarrow \pi^0 \rightarrow \gamma \gamma \\
n & \rightarrow p
\end{align*}
\]

= 3 ring mess

- 5,800 events
  (>3x all previous data combined)
Historic CC $\pi^0$ Measurements

• this is what we’ve known on this reaction

\[ \sigma_{\nu n \rightarrow \mu^+\pi^0} \times 10^{-38} \text{ cm}^2 / \text{nucleon} \]

\[ E_\nu \text{ (GeV)} \]

... this is our starting point

• most of the focus was on measuring $\sigma(E_\nu)$
• models tend to underpredict the cross section at low $E_\nu$
• $x2$ difference between some of the measurements
• have measured a variety of kinematics for this process:

\[
\sigma(E_\nu), \frac{d\sigma}{dQ^2}, \frac{d\sigma}{dT_\mu}, \frac{d\sigma}{d\theta_\mu}, \frac{d\sigma}{d\rho_\pi}, \frac{d\sigma}{d\theta_\pi}
\]

reduced model-independence

• most comprehensive study of CC $\pi^0$ to date (B. Nelson, UC Boulder, Ph.D. thesis)

- excess of data/model also present in this channel too

- similar effects seen by K2K (higher $E_\nu$)

My Niece Asks ...

what about charged pions?
CC $\pi^+$ at MiniBooNE

- important background for disappearance experiments
  - if $\pi$ absorbed, impacts $E_\nu$ determination
  - introduces a systematic on $\Delta m^2_{23}$, $\theta_{23}$

- long-standing discrepancy between ANL & BNL ($D_2$)

(didn’t want to live with this for MB disapp)
CC $\pi^+$ at MiniBooNE

• want to measure more than $\sigma(E_\nu)$, but $\pi^+$ reconstruction in a $\bar{C}$ detector and $\mu/\pi^+$ separation are challenging - had never been done before

• $\pi$'s frequently interact hadronically, losing energy & changing direction sharply

• kinked track produces two rings $\rightarrow$ kinked track fitter

• algorithm developed to separately reconstruct muon & charged pion
  
  M. Wilking, UC Boulder, Ph.D. thesis

• 1$^{st}$ time has been done in a $\bar{C}$ detector (correct ID 88% of the time)
CC $\pi^+$ at MiniBooNE

- highest purity sample (90% CC $\pi^+$)
  Aguilar-Arevalo et al., PRD 83, 052007 (2011)

- again, measuring complete final state kinematics
  (not correcting for nuclear effects … to ensure that the results are less model dependent)

\[ \sigma(E_\nu), \frac{d\sigma}{dQ^2}, \frac{d^2\sigma}{dT_\mu d\theta_\mu}, \frac{d\sigma}{dT_\mu}, \frac{d\sigma}{d\theta_\mu}, \frac{d^2\sigma}{dT_\pi d\theta_\pi}, \frac{d\sigma}{dT_\pi}, \frac{d\sigma}{d\theta_\pi}, \frac{d^2\sigma}{dT_\pi d\theta_\pi} \] 8 dists

(same as what we measured for QE)
CC $\pi^+$ at MiniBooNE

- highest purity sample (90% CC $\pi^+$)
- again, measuring complete final state kinematics
  (not correcting for nuclear effects ... to ensure that the results are less model dependent)

$$\sigma(E_{\nu}), \frac{d\sigma}{dQ^2}, \frac{d^2\sigma}{dT_{\mu}d\theta_{\mu}}, \frac{d\sigma}{dT_{\mu}}, \frac{d\sigma}{d\theta_{\mu}}, \frac{d\sigma}{dT_{\pi}}, \frac{d\sigma}{d\theta_{\pi}}, \frac{d^2\sigma}{dT_{\pi}d\theta_{\pi}}$$

8 dists
(many firsts!)

Aguilar-Arevalo et al., PRD 83, 052007 (2011)
Future Prospects

- MB has provided a wealth of new $\nu$ scattering data; in this process, we have really thought about how to provide the most information possible

- coming soon: several antineutrino $\sigma$’s and CC inclusive $\sigma$ to wrap-up our program

- don’t want to leave this open ended …

  - having cross-checks, confirmation, and more information is very important!

  - what does the future hold? a lot of exps are getting into this business
• **broad energy range** \((1-20+ \text{ GeV})\)
  (will help close the gap between the low and high energy results with a single apparatus)

• **multiple nuclear targets** \((\text{He-Pb})\)
  (1\(^{st}\) time this has been done; up to now much of the focus has been on O, C)

• starting data-taking with full detector in March 2010

• very large experimental program underway!

(example \(\nu\) event in finely-segmented tracking detector) (D. Schmitz)
Liquid Argon TPCs

ArgoNeuT

- small TPC that took data in NuMI beam (2009-2010)

- 1st publication
  arXiv:1111.0103, recently accepted by PRL
Liquid Argon TPCs

**ArgoNeuT**
- small TPC that took data in NuMI beam (2009-2010)
- 1st publication
  arXiv:1111.0103, recently accepted by PRL

**MicroBooNE**
- 170 ton TPC in BNB beam (~600x size of ArgoNeuT)
- ground-breaking for detector hall in January
- data-taking in 2014

LAr test facility
- will have $\sigma_{\nu}$ on Ar across a broad E range
Also, Near Detectors

**T2K ND**
- near detector at 280m (ND280)
  - very similar energy range as MiniBooNE
  - suite of fine-grained detector modules

**NOvA ND**
- near detector on surface (NDOS) taking data now
  - off-axis NuMI beam (NBB)

(J. Nowak, PANIC 2011)
New Ideas

- knowledge of incoming $\nu$ flux has always been a limiting factor in these cross section measurements

- very low energy neutrino factory (VLENF)

- muon storage ring to produce large samples of $\mu^+ \rightarrow \nu_e, \bar{\nu}_\mu$ and $\mu^- \rightarrow \bar{\nu}_e, \nu_\mu$

  goal: make the 1st measurements of $\nu_e$ and $\bar{\nu}_e$ cross sections at the few-% level in this energy range
• in the past couple years, there has been renewed appreciation for the complexities surrounding $\nu$-nucleus scattering in the few-GeV region

• this has been a very active area of investigation in MiniBooNE (9 publications, 5 channels, 24 differential $\sigma$ distributions)

  - probing nuclear effects with new precision
  - challenging assumptions about the size and source of nuclear effects at these energies

• MiniBooNE $\sigma_\nu$ publications have garnered over 400 citations over the past year or more

• look forward to additional data

• crucial to have this physics under control for future $\nu$ oscillation investigations ($\mathcal{M}H,\mathcal{CP}$)

Conclusions

stay tuned!
Further Reading

“Neutrino-Nucleus Interactions”,
(H. Gallagher, G. Garvey, G.P. Zeller)

“From eV to EeV: Neutrino Cross Sections Across Energy Scales”,
Rev. Mod. Phys., to be published (2012)
(J. Formaggio, G.P. Zeller)
Thank you!
Backups
MiniBooNE/NOMAD QE Selection

CCQE e.g. NOMAD

\[\mu + p\]

CCQE-like e.g. MiniBooNE

\[\mu + p + p\]