La Primera Medida de la Sección Eficaz Doble Diferencial en la Dispersión Quasi-elastica de la Corriente Cargada del Neutrino Muónico

Teppei Katori for the MiniBooNE collaboration
Massachusetts Institute of Technology
NuInt 09, Sitges, May, 19, 09

Work based on PhD thesis at Indiana University
First Measurement of Muon Neutrino Charged Current Quasielastic (CCQE) Double Differential Cross Section

Outline

1. Booster neutrino beamline
2. CCQE events in MiniBooNE
3. CC1π background constraint
4. CCQE $M_A^{\text{eff}}$-$\kappa$ shape-only fit
5. CCQE absolute cross section
6. Conclusion

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5. CCQE absolute cross section

6. Conclusion
MiniBooNE extracts 8.9 GeV/c momentum proton beam from the Booster.
Protons are delivered to a beryllium target in a magnetic horn (flux increase \(\sim 6\) times).
Modeling of meson production is based on the measurement done by HARP collaboration:
- Identical, but 5% Beryllium target
- 8.9 GeV/c proton beam momentum


Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)

1. Booster Neutrino Beamline

HARP experiment (CERN)
Modeling of meson production is based on the measurement done by HARP collaboration
- Identical, but 5% \( \lambda \) Beryllium target
- 8.9 GeV/c proton beam momentum

HARP collaboration,

The error on the HARP data (~7%) directly propagates. The neutrino flux error is the dominant source of normalization error for an absolute cross section in MiniBooNE.
The decay of mesons make the neutrino beam. The neutrino beam is dominated by $\nu_\mu$ (93.6%), of this, 96.7% is made by $\pi^+$-decay.

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

1. Booster Neutrino Beamline

Predicted $\nu_\mu$-flux in MiniBooNE

MiniBooNE collaboration, PRD79(2009)072002

05/19/2009 Teppei Katori, MIT

FNAL Booster target and horn decay region absorber dirt detector

Booster

primary beam (protons) secondary beam (mesons) tertiary beam (neutrinos)
1. Booster neutrino beamline

2. CCQE events in MiniBooNE

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4. CCQE $M_A^{\text{eff}}$ shape-only fit

5. CCQE absolute cross section

6. Conclusion
2. CCQE event measurement in MiniBooNE

$\nu_\mu$ charged current quasi-elastic ($\nu_\mu$ CCQE) interaction is an important channel for the neutrino oscillation physics and the most abundant (~40%) interaction type in MiniBooNE detector.

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

$$\nu_\mu + ^{12}C \rightarrow X + \mu^-$$

MiniBooNE detector
(spherical Cherenkov detector)

MiniBooNE collaboration, NIM.A599(2009)28
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MiniBooNE collaboration, NIM.A599(2009)28

proton measurement in neutral current elastic, see D. Perevalov and R. Tayloe’s talk, May 20 (Wed.)

muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event
2. CCQE event measurement in MiniBooNE

\[ \nu_{\mu} \text{ CCQE interactions (}\nu+n \rightarrow \mu+p) \text{ has characteristic two}
\]

“subevent” structure from muon decay

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

26.5% efficiency
75.8% purity
146,070 events
with 5.58E20POT
All kinematics are specified from 2 observables, muon energy $E_\mu$ and muon scattering angle $\theta_\mu$

Energy of the neutrino $E_\nu^{QE}$ and 4-momentum transfer $Q_{QE}^2$ can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest ("QE assumption")

$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos \theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos \theta_\mu)$$
1. Booster neutrino beamline
2. CCQE events in MiniBooNE
3. CC1\(\pi\) background constraint
4. CCQE \(M_A^{-K}\) shape-only fit
5. CCQE absolute cross section
6. Conclusion
3. CC1\(\pi\) background constraint, introduction

data-MC comparison, in 2 subevent sample (absolute scale)

Problem 1

CCQE sample shows good agreement in shape, because we tuned relativistic Fermi gas (RFG) parameters.

However absolute normalization does not agree.

The background is dominated with CC1\(\pi\) without pion (CCQE-like). We need a background prediction with an absolute scale.
3. CC1\(\pi\) background constraint, introduction

data-MC comparison, in 3 subevent sample (absolute scale)

Problem 2

CC1\(\pi\) sample is worse situation, data and MC do not agree in shape nor normalization.

Under this situation, we cannot use CC1\(\pi\) prediction for background subtraction for CCQE absolute cross section measurement.

recent development of prediction in CC1\(\pi\), see J. Novak’s talk, May 22 (Fri.),
pion measurement in CC1\(\pi\), see M. Wilking’s talk, May 22 (Fri.),
3. CC1π background constraint

data-MC comparison, before CC1π constraint (absolute scale)

Solution

Use data-MC $Q^2$ ratio in CC1π sample to correct all CC1π events in MC.

Then, this “new” MC is used to predicts CC1π background in CCQE sample.

This correction gives both CC1π background normalization and shape in CCQE sample.
3. CC$1\pi$ background constraint

data-MC comparison, after CC$1\pi$ constraint (absolute scale)

Now we have an absolute prediction of CC$1\pi$ background in CCQE sample.

We are ready to measure the absolute CCQE cross section!
1. Booster neutrino beamline

2. CCQE events in MiniBooNE

3. CC$1\pi$ background constraint

4. CCQE $M_A^{\text{eff-}\kappa}$ shape-only fit

5. CCQE absolute cross section

6. Conclusion
4. Pauli blocking parameter “kappa”, $\kappa$

We performed shape-only fit for $Q^2$ distribution to fix CCQE shape within RFG model, by tuning $M_A^{\text{eff}}$ (effective axial mass) and $\kappa$.

Pauli blocking parameter "kappa", $\kappa$

To enhance the Pauli blocking at low $Q^2$, we introduced a new parameter $\kappa$, which is the energy scale factor of lower bound of nucleon sea in RFG model in Smith-Moniz formalism, and controls the size of nucleon phase space.

\[
E_{\text{lo}} = \kappa \left( \sqrt{(p_F^2 + M^2)} - w + E_B \right)
\]

Smith and Moniz, Nucl., Phys., B43(1972)605
4. $M_{A}^{\text{eff}}-\kappa$ shape-only fit

$M_{A}^{\text{eff}} - \kappa$ shape-only fit result

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

$M_{A}^{\text{eff}}$ goes even up, this is related to our new background subtraction.

$\kappa$ goes down due to the shape change of the background. Now $\kappa$ is consistent with 1.
$\kappa$ doesn’t affects cross section below $\sim 0.995$.

$M_{A}^{\text{eff}}$ only fit ($M_{A}^{\text{eff}} = 1.37 \pm 0.12$ GeV, $\chi^{2}/\text{ndf} = 48.6/39$)

data-MC $Q^{2}$ comparison before and after fit

Fit parameter space

$\chi^{2} = 47.0/38$
$M_{A}^{\text{eff}}$ (GeV) = 1.35
$\kappa = 1.007$
4. $M_A^\text{eff}-\kappa$ shape-only fit

Data-MC agreement in $T_\mu$-$\cos\theta$ kinematic plane is good.

World averaged RFG model

$M_A^\text{eff} = 1.03$, $\kappa = 1.000$

This new CCQE model doesn't affect our cross section result.

MiniBooNE anti-neutrino CCQE data
J. Grange poster, May 19 (Tue.)
1. Booster neutrino beamline

2. CCQE events in MiniBooNE

3. CC1π background constraint

4. CCQE $M_A-K$ shape-only fit

5. CCQE absolute cross section

6. Conclusion
5. CCQE absolute cross section

Flux-averaged single differential cross section \( (Q^2_{QE}) \)

The data is compared with various RFG model with neutrino flux averaged.

Compared to the world averaged CCQE model (red), our CCQE data is 35% high.

Our model extracted from shape-only fit has better agreement (within our total normalization error).
5. CCQE absolute cross section

Flux-unfolded total cross section ($E_v^{RFG}$)

New CCQE model is tuned from shape-only fit in $Q^2$, and it also describes total cross section well.
5. CCQE errors

Error summary (systematic error dominant)

Flux error dominates the total normalization error.

Cross section error is small because of high purity and in situ background measurement.

Detector error dominates shape error, because this is related with energy scale.

Unfolding error is the systematic error associated to unfolding.
5. QE cross section comparison with NOMAD

Flux-unfolded total cross section ($E_{\nu}^{\text{RFG}}$)

New CCQE model is tuned from shape-only fit in $Q^2$, and it also describes total cross section well.

Comparing with NOMAD, MiniBooNE cross section is 35% higher, but these 2 experiments leave a gap in energy to allow some interesting physics.
5. CCQE total cross section model dependence

Flux-unfolded total cross section ($E_{\nu}^{RFG}$)

Unfortunately, flux unfolded cross section is model dependent.

Reconstruction bias due to QE assumption is corrected under “RFG” model assumption.

One should be careful when comparing flux-unfolded data from different experiments.
5. CCQE total cross section model dependence

Flux-unfolded total cross section \( (E_{\nu}^{\text{RFG}}) \)

Unfortunately, flux unfolded cross section is model dependent.

Reconstruction bias due to QE assumption is corrected under “RFG” model assumption.

One should be careful when comparing flux-unfolded data from different experiments.
5. CCQE double differential cross section

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

This is the most complete information about neutrino cross section based on muon kinematic measurement.

The error shown here is shape error, a total normalization error ($\delta N_T = 10.8\%$) is separated.
5. CCQE double differential cross section

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

This is the most complete information about neutrino cross section based on muon kinematic measurement.

The error shown here is shape error, a total normalization error ($\delta N_T=10.8\%$) is separated.
6. Conclusions

Using the high statistics and high purity MiniBooNE $\nu_\mu$ CCQE data sample (146,070 events, 26.5% efficiency, and 75.8% purity), the absolute cross section is measured. We especially emphasize the measurement of flux-averaged double differential cross section, because this is the most complete set of information for muon kinematics based neutrino interaction measurement. The double differential cross section is the model independent result.

We measured 35% higher cross section than RFG model with the world averaged nuclear parameter. Interesting to note, our total cross section is consistent with RFG model with nuclear parameters extracted from shape-only fit in our $Q^2$ data.
BooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Emory Riddle Aeronautical University
Fermi National Accelerator Laboratory
Indiana University
University of Florida
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

Moltes Gràcies!
¡Muchas Gracias!

05/19/2009 Teppei Katori, MIT 33
Back up
1. CCQE event measurement in MiniBooNE

<table>
<thead>
<tr>
<th>cut type</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. veto hits &lt; 6 for all subevents</td>
<td>45.1</td>
</tr>
<tr>
<td>2. 1st subevent time T is in beam window</td>
<td>44.7</td>
</tr>
<tr>
<td>3. 1st subevent reconstructed vertex &lt; 500 cm</td>
<td>37.5</td>
</tr>
<tr>
<td>4. 1st subevent kinetic energy &gt; 200MeV</td>
<td>32.7</td>
</tr>
<tr>
<td>5. $\mu$ to e log likelihood cut</td>
<td>31.3</td>
</tr>
<tr>
<td>6. 2 subevent total</td>
<td>29.0</td>
</tr>
<tr>
<td>7. $\mu$-e vertex distance cut</td>
<td>26.5</td>
</tr>
</tbody>
</table>

26.5% cut efficiency  
75.8% purity  
146,070 events with  
5.58E20POT
4. CCQE absolute cross section

Absolute flux-averaged differential cross section formula

\[ \sigma_i = \frac{\sum_j U_{ij} (d_j - b_j)}{\varepsilon_i (\Phi T)} \]

- \( i \): true index
- \( j \): reconstructed index
- \( U_{ij} \): unsmearing matrix
- \( d_j \): data vector
- \( b_j \): predicted background
- \( \Phi \): integrated target number
- \( \varepsilon_i \): efficiency
- \( \sigma_i \): cross section

The cross section is a function of true value, for example, \( d\sigma^2/T_{\mu}/\cos\theta_\mu \), \( d\sigma/dQ^2_{QE} \), etc.

Integrated flux is removed, so it is called flux-averaged cross section.
4. CCQE absolute cross section

Absolute flux-unfolded total cross section formula

\[ \sigma_i = \frac{\sum_j U_{ij} (d_j - b_j)}{\varepsilon_i (\Phi T)} \]

- \( U_{ij} \): unsmearing matrix
- \( d_j \): data vector
- \( b_j \): predicted background
- \( \varepsilon_i \): efficiency
- \( \Phi_i \): \( \nu \)-flux vector
- \( T \): integrated target number

The cross section is a function of true neutrino energy, \( \sigma[E_{\nu QE}] \).

Flux shape is removed bin by bin, so it is called flux-unfolded cross section.
5. CCQE flux error

Flux error

The flux error dominates total normalization error.

The shape error is weak, except high energy region, where HARP measurement has large error and skin effect of horn has large error.
5. CCQE background cross section error

The background cross section error is small, because of high purity and in situ background constraint.

The large error comes from pion absorption, so the kinematic space of CC1$\pi$ events has large error.
5. CCQE detector error

Detector error

The detector error has the largest contribution to the shape error because it is related with the energy scale of muon.

However the contribution to the total normalization error is not so large.
They didn't even try to determine their \( \nu \) flux from pion production and beam dynamics.


The distribution of events in neutrino energy for the 3C \( \nu d \rightarrow \mu^- p p_s \) events is shown in Fig. 4 together with the quasielastic cross section \( \sigma(\nu n \rightarrow \mu^- p) \) calculated using the standard \( V - A \) theory with \( M_A = 1.05 \pm 0.05 \) GeV and \( M_V = 0.84 \) GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.
Neutrino Flux and Total Charged-Current Cross Sections
in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguchi, K. Tamai,
T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

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.

Again, they use QE events and theoretical cross section to calculate the $\nu$.

When they try to get the flux from meson ($\pi$ and $K$) production and decay kinematics they fail miserably for $E_\nu < 30$ GeV.
The Procedure

• Pion production cross sections in some low momentum bins are scaled up by 18 to 79%.

• The $K^+$ to $\pi^+$ ratio is increased by 25%.

• Overall neutrino (anti-neutrino) flux is increased by 10% (30%).

All driven by the neutrino events observed in the detector!
Flux derived from pion production data. Were able to test assumptions about the form of the cross section using absolute rate and shape information.

<table>
<thead>
<tr>
<th>Likelihood function</th>
<th>$M_A^{Dipole}$ (GeV)</th>
<th>$M_A^{Monopole}$ (GeV)</th>
<th>$M_A^{Tripole}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>0.75^{+0.13}_{-0.11}</td>
<td>0.45^{+0.11}_{-0.07}</td>
<td>0.96^{+0.17}_{-0.14}</td>
</tr>
<tr>
<td>Shape</td>
<td>1.010 ± 0.09</td>
<td>0.56 ± 0.08</td>
<td>1.32 ± 0.11</td>
</tr>
<tr>
<td>Rate and shape</td>
<td>0.95 ± 0.09</td>
<td>0.52 ± 0.08</td>
<td>1.25 ± 0.11</td>
</tr>
<tr>
<td>Flux independent</td>
<td>0.95 ± 0.09</td>
<td>0.53 ± 0.08</td>
<td>1.25 ± 0.11</td>
</tr>
</tbody>
</table>

- Pion production measured in ZGS beams were used in this analysis.
- A very careful job was done to normalize the beam.
- Yet they have a 25% inconsistency between the axial mass they measure considering only rate information verses considering only spectral information.

Interpretation: Their normalization is wrong.