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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6. Conclusion
MiniBooNE extracts 8.9 GeV/c momentum proton beam from the Booster.
1. Booster Neutrino Beamline

Protons are delivered to a beryllium target in a magnetic horn (flux increase ~6 times)

FNAL Booster | target and horn | decay region | absorber | dirt | detector

Booster

primary beam (protons) secondary beam (mesons) tertiary beam (neutrinos)

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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


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

Booster neutrino beamline pion kinematic space

HARP experiment (CERN)

HARP kinematic coverage
1. Booster Neutrino Beamline

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 data with 8.9 GeV/c proton beam momentum

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

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

MiniBooNE collaboration, PRD79(2009)072002
1. Booster neutrino beamline

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3. CC1π background constraint

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

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

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

MiniBooNE detector
(spherical Cherenkov detector)

MiniBooNE collaboration, NIM.A599(2009)28

muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

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

$\nu_\mu$ CCQE interactions ($\nu+n \rightarrow \mu+p$) has characteristic two “subevent” structure from muon decay

$$\nu_\mu + n \rightarrow \mu^- + p \rightarrow \nu_\mu + \bar{\nu}_e + e^- + p$$

- 26.5% efficiency
- 75.8% purity
- 146,070 events with 5.58E20POT

Muon high hits

Michel electron low hits
2. CCQE event measurement in MiniBooNE

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 $Q^2_{QE}$ can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest (“QE assumption”)

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

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos \theta_\mu)$$
1. Booster neutrino beamline

2. CCQE events in MiniBooNE

3. CC$1\pi$ background constraint

4. CCQE $M_A$-$\kappa$ shape-only fit

5. CCQE absolute cross section

6. Conclusion
3. CC\(1\pi\) 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 CC\(1\pi\) without pion (CCQE-like). We need a background prediction with an absolute scale.

MiniBooNE collaboration, PRL100(2008)032301
3. CC1π background constraint, introduction

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

Problem 2

CC1π sample is worse situation, data and MC do not agree in shape nor normalization.

Under this situation, we cannot use CC1π prediction for background subtraction for CCQE absolute cross section measurement.

recent development of prediction in CC1π, see J. Novak’s talk, May 22 (Fri.),

pion measurement in CC1π, 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. CC1$\pi$ background constraint

data-MC comparison, after CC1$\pi$ constraint (absolute scale)

Now we have an absolute prediction of CC1$\pi$ background in CCQE sample.

We are ready to measure the absolute CCQE cross section!
1. Booster neutrino beamline
2. CCQE events in MiniBooNE
3. CC1π 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.

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

\[ k \quad k+q \]

Pauli blocked phase space

Initial nucleon phase space

final nucleon phase space

Pauli blocking is enhanced

05/19/2009

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

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

$M_A^{\text{eff}} = 1.35 \pm 0.17 \text{ GeV (stat+sys)}$

$\kappa = 1.007^{+0.007}_{-\infty} \text{ (stat+sys)}$

$\chi^2/\text{ndf} = 47.0/38$

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

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

Fit parameter space

05/19/2009  Teppei Katori, MIT  21
4. $M_A^{\text{eff}}$-κ shape-only fit

$M_A^{\text{eff}}$ - κ shape-only fit result

$M_A^{\text{eff}} = 1.35 \pm 0.17$ GeV (stat+sys)

$\kappa = 1.007 \pm 0.007$ (stat+sys)

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.
1. Booster neutrino beamline
2. CCQE events in MiniBooNE
3. CC1$\pi$ background constraint
4. CCQE $M_A$-$\kappa$ 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 ($E_{\nu}^{\text{RFG}}$)

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 ($E_{\nu}^{\text{RFG}}$)

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 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 double differential cross section

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

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
Embry 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 Grácies!

05/19/2009
Tepper, Nathan, MIT
¡Muchas Gracias!
Back up
1. CCQE event measurement in MiniBooNE

CC inclusive cut

1. veto hits <6 for all subevents
2. 1\textsuperscript{st} subevent is within beam window, 4400<T(ns)<6400
3. fiducial cut, muon vertex <500cm from tank center
4. visible energy cut, muon kinetic energy >200MeV
5. \(\mu\) to e log likelihood cut
6. 2 and only 2 subevent
7. \(\mu\)-e vertex distance cut

This cut is not designed to remove CC\(1\pi\) events, but trying to remove “others”. This is an important step for CC\(1\pi\) background fit.
1. CCQE event measurement in MiniBooNE

CC inclusive cut

→ CCQE cut

1. veto hits <6 for all subevents
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7. $\mu$-$e$ vertex distance cut

$\nu_\mu$ CCQE interactions ($\nu+n \rightarrow \mu+p$) has characteristic two “subevent” structure from muon decay

$\nu_\mu + n \rightarrow [\mu] + p$  \hspace{1cm} $\mu \rightarrow \nu_\mu + \nu_e + e$
1. CCQE event measurement in MiniBooNE

CC inclusive cut
→ CCQE cut

1. veto hits <6 for all subevents
2. 1st subevent is within beam window, 4400<T(ns)<6400
3. fiducial cut, muon vertex <500cm from tank center
4. visible energy cut, muon kinetic energy >200MeV
5. $\mu$ to $e$ log likelihood cut
6. 2 and only 2 subevent
7. $\mu$-e vertex distance cut

This cut is not designed to remove CC1$\pi$, but trying to remove “mis-reconstructed CC1$\pi$” and “others”. This is an important step for CC1$\pi$ background fit.
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. 1\textsuperscript{st} subevent time T is in beam window</td>
<td>44.7</td>
</tr>
<tr>
<td>3. 1\textsuperscript{st} subevent reconstructed vertex &lt; 500 cm</td>
<td>37.5</td>
</tr>
<tr>
<td>4. 1\textsuperscript{st} 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
2. CC1π background fit

data-MC $Q^2$ ratio in 3subevent after fit with various assumption

Since we can fit with any assumptions, $Q^2$ ratio is always flat.
2. CC1\pi background fit

data-MC $T_\mu$-$\cos\theta$ plane ratio in 3subevent after fit with various assumption

However, we can differentiate them by 2 dimensional kinematic plane.

15% increase of piabs and 0% of coherent fraction gives the best fit.

We chose 15% for piabs, and 50% for cohfrac as new cv MC which will be used to estimate background from all kinematic distribution.

The rest of models go to make a new error matrix

05/19/2009

Teppei Katori, MIT
2. CC1\(\pi\) background fit

**MC \(T_\mu - \cos \theta\) plane**

CC1\(\pi\) kinematics has different shape from CCQE kinematics.

The background cross section error is maximum at the bins where CC1\(\pi\) has larger number of event comparing with CCQE.
2. Energy scale of MiniBooNE

Mis-calibration of the detector can mimic large $M_A$ value. Roughly, 2% of energy shift correspond to 0.1GeV change of $M_A$.

To bring $M_A=1.0\text{GeV}$, 7% energy shift is required, but this is highly disfavored from the data.

Question is what is the possible maximum mis-calibration? (without using muon tracker data)

05/19/2009
2. Energy scale of MiniBooNE

Energy resolution is very good. Typical resolution is <10%, and the error is 20-80MeV.
2. Energy scale of MiniBooNE

Range is the independent measure of muon energy. So range-$T_\mu$ difference for data and MC can be used to measure the possible mis-calibration.

This variable agrees in all energy regions within 1.5%.

Range - $T_\mu \times 0.5 + 100$
4. Kappa and (e,e’) experiments

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q²)

Data and predicted xs difference for $^{12}\text{C}$

Butkevich and Mikheyev
4. Kappa and (e,e') experiments

In low \(|q|\), the RFG model systematically over predicts cross section for electron scattering experiments at low \(|q|\) (~low \(Q^2\)).

We had investigated the effect of Pauli blocking parameter “\(\kappa\)” in (e,e’) data. \(\kappa\) cannot fix the shape mismatching of (e,e’) data for each angle and energy, but it can fix integral of each cross section data, which is the observables for neutrino experiments. We conclude \(\kappa\) is consistent with (e,e’) data.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Angle</th>
<th>(Q^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=240MeV</td>
<td>(\theta=60) degree</td>
<td>0.102GeV(^2)</td>
</tr>
<tr>
<td>E=730MeV</td>
<td>(\theta=37.1) degree</td>
<td>0.182GeV(^2)</td>
</tr>
</tbody>
</table>

black: (e,e’) energy transfer data
red: RFG model with kappa (=1.019)
blue: RFG model without kappa
4. Kappa and (e,e’) experiments

In low $|q|$, the RFG model systematically over predicts cross section for electron scattering experiments at low $|q|$ ($\sim$ low $Q^2$)

We had investigated the effect of Pauli blocking parameter $\kappa$ in (e,e’) data. $\kappa$ cannot fix the shape mismatching of (e,e’) data for each angle and energy, but it can fix integral of each cross section data, which is the observables for neutrino experiments. We conclude $\kappa$ is consistent with (e,e’) data.

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**RFG prediction-(e,e’) data ratio in $Q^2$ (GeV$^2$)**

- **red**: RFG prediction with $\kappa$ ($=0.019$)
- **blue**: RFG prediction without $\kappa$
4. CCQE normalization fit

data-MC comparison, after CCQE normalization fit

After the CC1π correction, normalization of CCQE is also found from CCQE sample.

We use limited $Q^2$ region to find CCQE normalization, so that this fit is insensitive with CCQE shape very much. 

Butkevich
arXiv:0904.1472

Now, CCQE normalization and CC1π normalization and CC1π shape looks good, except CCQE shape.

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4. $M_A$-$\kappa$ fit

Least $\chi^2$ fit for $Q^2$ distribution

$$\chi^2 = (\text{data} - \text{MC})^T (M_{\text{total}})^{-1} (\text{data} - \text{MC})$$

$\chi^2$ minimum is found by global scan of shape only fit with $0.0 < Q^2(\text{GeV}^2) < 1.0$

<table>
<thead>
<tr>
<th>Input error matrices</th>
<th>The total output error matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>keep the correlation of systematics</td>
<td>keep the correlation of $Q^2$ bins</td>
</tr>
<tr>
<td>$\pi^+$ production (8 parameters)</td>
<td>$M_{\text{total}} = M(\pi^+ \text{ production})$</td>
</tr>
<tr>
<td>$\pi^-$ production (8 parameters)</td>
<td>+ $M(\pi^- \text{ production})$</td>
</tr>
<tr>
<td>$K^+$ production (7 parameters)</td>
<td>+ $M(K^+ \text{ production})$</td>
</tr>
<tr>
<td>$K^0$ production (9 parameters)</td>
<td>+ $M(K^0 \text{ production})$</td>
</tr>
<tr>
<td>beam model (8 parameters)</td>
<td>+ $M(\text{beam model})$</td>
</tr>
<tr>
<td>cross section (20 parameters)</td>
<td>+ $M(\text{cross section model})$</td>
</tr>
<tr>
<td>detector model (39 parameters)</td>
<td>+ $M(\text{detector model})$</td>
</tr>
<tr>
<td></td>
<td>+ $M(\text{data statistics})$</td>
</tr>
</tbody>
</table>
4. CCQE absolute cross section

**Absolute flux-averaged differential cross section formula**

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

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

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

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

- \( U_{ij} \): 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 double differential cross section

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

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

The error shown here is total error.
5. CCQE double differential cross section

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

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

The error shown here is total error.
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 CC1π 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 $\nu d \rightarrow \mu^- pp_s$ 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.\(^4\)
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 IV. Results of axial-form-factor fits.**

<table>
<thead>
<tr>
<th>Likelihood function</th>
<th>$M_A^{\text{Dipole}}$ (GeV)</th>
<th>$M_A^{\text{Monopole}}$ (GeV)</th>
<th>$M_A^{\text{Tripole}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>$0.75_{-0.11}^{+0.13}$</td>
<td>$0.45_{-0.07}^{+0.11}$</td>
<td>$0.96_{-0.14}^{+0.17}$</td>
</tr>
<tr>
<td>Shape</td>
<td>$1.010 \pm 0.09$</td>
<td>$0.56 \pm 0.08$</td>
<td>$1.32 \pm 0.11$</td>
</tr>
<tr>
<td>Rate and shape</td>
<td>$0.95 \pm 0.09$</td>
<td>$0.52 \pm 0.08$</td>
<td>$1.25 \pm 0.11$</td>
</tr>
<tr>
<td>Flux independent</td>
<td>$0.95 \pm 0.09$</td>
<td>$0.53 \pm 0.08$</td>
<td>$1.25 \pm 0.11$</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.
First Measurement of Muon Neutrino Charged Current Quasielastic (CCQE) Double Differential Cross Section

Teppei Katori for the MiniBooNE collaboration
Massachusetts Institute of Technology
NuInt 09, Sitges, May, 18, 09