$\bar{\nu}_\mu$ CCQE at MiniBooNE

Joe Grange  
University of Florida  
NuInt '11  
Dehradun, India
Outline

1. Booster Neutrino Beam
2. CCQE events in MiniBooNE
3. MiniBooNE $\nu_\mu$ CCQE result review
4. $\nu_\mu$ flux in $\bar{\nu}_\mu$ beam measurements
5. RFG model comparisons to $\bar{\nu}_\mu$ CCQE data
6. Future BooNE CCQE measurements, conclusions
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Booster Neutrino Beam

8.9 GeV/c momentum protons extracted from Booster, steered toward a Beryllium target in bunches of \( 5 \times 10^{12} \) at a maximum rate of 5 Hz
Booster Neutrino Beam

Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons ("neutrino" vs "anti-neutrino" mode)

FNAL Booster target and horn
decay region absorber dirt detector

Booster

primary beam (protons)

secondary beam (mesons) tertiary beam (neutrinos)
MiniBooNE Flux

* Flux prediction based exclusively on external data - no in situ tuning

Dedicated pion production data taken by HARP experiment to predict neutrino flux at MiniBooNE

A spline fit to these data brings flux uncertainty to ~9% for pions produced in HARP-covered phase space
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CCQE Events in MiniBooNE

CCQE is the most prevalent interaction at MiniBooNE's energy range, accounting for ~40% of all events.

MiniBooNE: spherical Cherenkov detector, filled with 800 tons of undoped mineral oil (CH₂)

80% CCQE purity
25% efficiency

No nucleon reconstruction
CCQE Events in MiniBooNE

- MiniBooNE nuclear simulation: Relativistic Fermi Gas (RFG) model
  - [Nucl. Phys. B43 (1972) 605](http://dx.doi.org/10.1016/0550-3213(72)90503-3)

- Models nucleons as independent, quasi-free particles bound by a constant $E_B$

- All struck (outgoing) nucleons subject to Pauli blocking, enforced by a global Fermi momentum

- Dipole axial form factor, $F_A(Q^2) = 1.267(1 - Q^2/M_A^2)^{-2}$

- Non-dipole vector form factor
  - [Bodek et al., arxiv:hep-ex/0308005](http://arxiv.org/abs/hep-ex/0308005)
Only the muon from the primary interaction is observed, but we can reconstruct incident anti-neutrino energy and momentum transfer based on muon kinematics.

Under the assumption of a target proton at rest, 
($\theta_{\mu}$: muon angle wrt neutrino beam)

\[
E_{\tilde{\nu}}^{\text{QE}} = \frac{2(M_p - E_B)E_{\mu} - (E_B^2 - 2M_pE_B + m_{\mu}^2 + \Delta M^2)}{2\left[(M_p - E_B) - E_{\mu} + p_{\mu}\cos\theta_{\mu}\right]}
\]

\[
Q_{\text{QE}}^2 = 2E_{\tilde{\nu}}^{\text{QE}}\left(p_{\mu}\cos\theta_{\mu} - E_{\mu}\right) + m_{\mu}^2
\]
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MiniBooNE $\nu_\mu$ CCQE Review

* First presented NuInt09, T. Katori

* Measurements:
  * $d\sigma/dQ^2$
  * $\sigma(E_\nu)$
  * $d^2\sigma/dT_\mu d\cos \theta_\mu$
MiniBooNE $\nu_\mu$ CCQE Review

* First presented NuInt09, T. Katori

* Measurements:

  $d\sigma/dQ^2$

Using the RFG nuclear model, the axial mass $M_A$ and an empirical Pauli blocking scale was extracted from a shape-only fit to data
MiniBooNE $\nu_\mu$ CCQE Review

* First presented NuInt09, T. Katori

* Measurements:
  * $d\sigma/dQ^2$
  * $\sigma(E_\nu)$

More interesting, $\nu_\mu$ CCQE $\sigma > 30\%$ higher than expected!
MiniBooNE $\nu_\mu$ CCQE Review

- First presented NuInt09, T. Katori

- Measurements:
  - $d\sigma/dQ^2$
  - $\sigma(E_\nu)$
  - $d^2\sigma/dT_\mu d\cos\theta_\mu$

- Primary result - extraction based on observables only
  - Independent of interaction model assumptions
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Wrong-sign Background

- “Wrong signs”: anti-neutrinos in the neutrino beam and vice versa
- MiniBooNE detector unmagnetized, cannot separate contributions based on CC interactions
- Wrong-sign background far more serious in anti-neutrino mode due to both flux and cross section effects
Wrong-sign Background

* Cross section: at MiniBooNE energies ($E_{\nu} \sim 1$ GeV), neutrino cross section $\sim 3x$ higher than anti-neutrino

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_{\nu}^2} \left[ A(Q^2) \right] \left[ B(Q^2) \left( \frac{s - u}{M^2} \right) + C(Q^2) \left( \frac{s - u}{M^2} \right)^2 \right]$$

* Flux: leading particle effect creates $\sim 2x$ as many $\pi^+$ as $\pi^-$
How wrong signs contribute to flux

- Wrong-sign pions escape magnetic deflection and contribute to the anti-neutrino beam via low angle production.

- In anti-neutrino mode low-angle production is a crucial flux region and we do not have a reliable prediction.

This motivates a dedicated study of $\nu_\mu$ content of the beam.
Wrong-sign measurements

Three independent and complementary measurements of the wrong-sign background:

1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the CCπ⁺ sample
3. Measuring how often muon decay electrons are produced (exploits μ⁻ nuclear capture)
Wrong-sign measurements

Three independent and complementary measurements of the wrong-sign background:

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First measurement of the $\nu_\mu$ content of a $\bar{\nu}_\mu$ beam using a non-magnetized detector.

arxiv:1102.1964
Wrong-sign measurements

* General strategy: isolate samples sensitive to the $\nu_\mu$ beam content, apply the measured cross sections from neutrino mode (CCQE, CC$\pi^+$)
  * Crucial application of BooNE-measured $\nu_\mu \sigma$'s

* The level of data-simulation agreement then reflects the accuracy of the $\nu_\mu$ flux prediction
Wrong-sign measurements

- Three independent and complementary measurements of the wrong-sign background:
  1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
  2. Comparing predicted to observed event rates in the $\text{CC}\pi^+$ sample
  3. Measuring how often muon decay electrons are produced (exploits $\mu^-$ nuclear capture)
In the RFG, due to the interference term the CCQE $\nu_\mu \sigma \gg \bar{\nu}_\mu \sigma$ for backward-going $\mu$
Results indicate the $\nu_\mu$ flux is over-predicted by $\sim 30\%$

Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled

<table>
<thead>
<tr>
<th>$E^{QE}_\nu$ (MeV)</th>
<th>$\alpha_\nu$</th>
<th>$\alpha_\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 600</td>
<td>0.65 ± 0.22</td>
<td>0.98 ± 0.18</td>
</tr>
<tr>
<td>600 - 900</td>
<td>0.61 ± 0.20</td>
<td>1.05 ± 0.19</td>
</tr>
<tr>
<td>&gt; 900</td>
<td>0.64 ± 0.20</td>
<td>1.18 ± 0.21</td>
</tr>
<tr>
<td>Inclusive</td>
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Wrong-sign measurements

* Three independent and complementary measurements of the wrong-sign background:

1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the $\text{CC}\pi^+$ sample
3. Measuring how often muon decay electrons are produced (exploits $\mu^-$ nuclear capture)
The neutrino induced resonance channel leads to three leptons above Cherenkov threshold:

1. Primary muon
2. Decay electron
3. Decay positron
Due to nuclear $\pi^-$ capture, the corresponding anti-neutrino interaction has only two:

1. Primary muon
2. Decay positron
With the simple requirement of two decay electrons subsequent to the primary muon, we isolate a sample that is ~80% neutrino-induced.

Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is over-predicted in normalization, while the spectrum shape is consistent with the prediction.

<table>
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<th>$E_{\nu}^\Delta$ (MeV)</th>
<th>$\nu_\mu \Phi$ scale “$\alpha_\nu$”</th>
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<tr>
<td>600 - 700</td>
<td>$0.65 \pm 0.10$</td>
</tr>
<tr>
<td>700 - 800</td>
<td>$0.79 \pm 0.10$</td>
</tr>
<tr>
<td>800 - 900</td>
<td>$0.81 \pm 0.10$</td>
</tr>
<tr>
<td>900 - 1000</td>
<td>$0.88 \pm 0.11$</td>
</tr>
<tr>
<td>1000 - 1200</td>
<td>$0.74 \pm 0.10$</td>
</tr>
<tr>
<td>1200 - 2400</td>
<td>$0.73 \pm 0.15$</td>
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**CCπ⁺ ν_μ flux measurement**

- With the simple requirement of two decay electrons subsequent to the primary muon, we isolate a sample that is ~80% neutrino-induced.

- Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is overpredicted in normalization, while the spectrum shape is consistent with the prediction.

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Model-independent measurement, employed by both CCQE, NCE anti-neutrino analyses.
Wrong-sign measurements

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1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the CC$\pi^+$ sample
3. Measuring how often muon decay electrons are produced (exploits $\mu^-$ nuclear capture)
μ⁻ capture measurement

- We isolate a > 90% CC sample for both μ-only and μ+e samples

- CC events typically observe both μ+e - two reasons why we may not observe the decay electron:
  1. Decay electron detection efficiency
  2. μ⁻ nuclear capture (νμ CC events only)
\( \mu^- \) capture measurement

By requiring \((\mu\text{-only}/\mu+e)^{\text{data}} = (\mu\text{-only}/\mu+e)^{\text{MC}}\) and normalization to agree in the \(\mu+e\) sample we can calculate a \(\nu_\mu\) flux scale \(\alpha_{\nu}\) and a rate scale \(\alpha_{\nu^c}\)

\[
\frac{\mu}{\mu + e}^{\text{data}} = \left( \frac{\alpha_{\nu} \nu^\mu + \alpha_{\nu^c} \nu^\mu}{\alpha_{\nu} \nu^{\mu+e} + \alpha_{\nu^c} \nu^\mu + e} \right)^{\text{MC}}
\]

Predicted neutrino content in the \(\mu+e\) sample, for example
**μ− capture measurement**

* By requiring \((\mu\text{-only}/\mu+e)^{\text{data}} = (\mu\text{-only}/\mu+e)^{\text{MC}}\) and normalization to agree in the \(\mu+e\) sample we can calculate a \(\nu_\mu\) flux scale \(\alpha_\nu\) and a rate scale \(\alpha_{\nu\nu}\)

\[
\frac{\mu}{\mu + e} \text{ data} = \left( \frac{\alpha_\nu \nu^\mu + \alpha_{\nu\nu} \bar{\nu}^\mu}{\alpha_\nu \nu^{\mu+e} + \alpha_{\nu\nu} \bar{\nu}^{\mu+e}} \right) \text{ MC}
\]

Results:

\[
\alpha_\nu = 0.86 \pm 0.14
\]
\[
\alpha_{\nu\nu} = 1.09 \pm 0.23
\]

PRELIMINARY
Neutrino flux measurement summary

Discrepancy with prediction appears to be in normalization only - flux shape is well modeled
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RFG model comparisons

- Will show \textit{bkg-subtracted data}
- Purity: 64%.
- Data not corrected for reconstruction biases

<table>
<thead>
<tr>
<th>Contribution</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{\nu}_\mu$ CCQE</td>
<td>64</td>
</tr>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>14</td>
</tr>
<tr>
<td>CC$\pi^-$</td>
<td>14</td>
</tr>
<tr>
<td>CC$\pi^+$</td>
<td>4</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
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</table>
RFG model comparisons

* Will compare data to **absolutely-normalized** simulation under two CCQE model hypotheses:

"M_A^H": axial mass for hydrogen scattering, "M_A^C": carbon

1. \( M_A^C = 1.35 \text{ GeV}, \kappa = 1.007, M_A^H = 1.02 \text{ GeV} \)
2. \( M_A^C = M_A^H = 1.02 \text{ GeV} \quad \kappa = 1.000 \)

\( M_A = 1.35 \text{ GeV}, \kappa = 1.007 \) consistent with BooNE \( \nu_\mu \) data

\( M_A = 1.02 \text{ GeV} \) consistent with light target data

$Q^2_{\text{QE}}$: shape comparison to data

$\nubar_{\mu}$ CCQE

- $M^C_A = M^H_A = 1.02$ GeV, $\kappa = 1.000$
- $M^C_A (M^H_A) = 1.35 (1.02)$ GeV, $\kappa = 1.007$

Normalized to data

$M_A = 1.02$ GeV, $\kappa = 1$ inconsistent with data shape
$Q^2_{QE}$: absolute comparison with

**Data/MC integrated ratio:** $1.21 \pm 0.12$
$Q^2_{QE}$: absolute comparison with

$\bar{\nu}_\mu$ CCQE

- Data - Bkg, Stat Error
- $\bar{\nu}_\mu$ CCQE Prediction, Syst Error
- Bnd Target $M^C_\Lambda = 1.02$ GeV, $\kappa = 1.000$
- Free Target $M^H_\Lambda = 1.02$ GeV

PRELIMINARY

data/MC integrated ratio: $1.39 \pm 0.14$
$E_{\nu}^{QE}$: shape comparison to data

$E_{\nu}^{QE}$ shape insensitive to CCQE model parameters
$E_{\nu}^{QE}$: absolute comparison with

- Data - Bkg, Stat Error
- $\bar{\nu}_\mu$ CCQE Prediction, Syst Error
- Bnd Target $M_A^c = 1.35$ GeV, $\kappa = 1.007$
- Free Target $M_A^h = 1.02$ GeV

data/MC integrated ratio: $1.21 \pm 0.12$
$E_{\nu}^{QE}$: absolute comparison with $\bar{\nu}_\mu$ CCQE

Data/MC integrated ratio: $1.39 \pm 0.14$
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Future $\bar{\nu}_\mu$ CCQE measurements

* Absolute and differential cross section measurements, including the model-independent double differential cross section

$$\sigma(E_{\bar{\nu}})$$

$$d\sigma/dQ^2$$

$$d^2\sigma/dT_\mu d\cos\theta_\mu$$
Future $\overline{\nu}_\mu$ CCQE measurements

* Absolute and differential cross section measurements, including the model-independent double differential cross section

$$\sigma(E_{\overline{\nu}})$$

$$\frac{d\sigma}{dQ^2}$$

$$\frac{d^2\sigma}{dT_\mu \, d\cos \theta_\mu}$$

$$\frac{d\sigma}{dQ^2}^\nu - \frac{d\sigma}{dQ^2}^{\overline{\nu}} \propto F_A$$

Taking the difference between $\nu_\mu$ and $\overline{\nu}_\mu$ data in the $Q^2$ distribution gives direct sensitivity to the axial form factor
Conclusions

* Though MiniBooNE is unmagnetized, a model-independent statistical technique measures the $\nu_\mu$ content in the $\overline{\nu}_\mu$ beam to $\sim 15\%$ uncertainty

* Shape comparisons to data show consistency with RFG model parameters extracted from BooNE $\nu_\mu$ data, while $M_A = 1.02$ GeV remains inconsistent with BooNE data.

* Normalization discrepancy ([data-bkg]/prediction):
  
  * $1.21 \pm 0.12$ for $M_A^C = 1.35$ GeV, $\kappa = 1.007$ $M_A^H = 1.02$ GeV
  * $1.39 \pm 0.14$ for $M_A^C = M_A^H = 1.02$ GeV $\kappa = 1.000$
  * $\nu_\mu$ CCQE data: $1.05 \pm 0.08$ for $M_A = 1.35$ GeV, $\kappa = 1.007$
Conclusions

- MiniBooNE will soon publish absolute and differential $\bar{\nu}_\mu$ CCQE cross sections, will also use $\nu_\mu$ CCQE measurement to measure interference term in $Q^2$ and $E_\nu$. 
More from MiniBooNE today

- For new results in the MiniBooNE anti-neutrino NCE channel please see the next talk by R Dharmaplan

- For a comprehensive review of MiniBooNE single pion production see R Nelson’s talk this afternoon
More from MiniBooNE today

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Thanks for your attention!
backup
RFG model comparisons: $Q^2$ shape

$\kappa$ suppresses low-$Q^2$ events  \hspace{1cm} M_A controls high-$Q^2$ tail

\[
Q^2_{QE} = 2E_{QE}^\mu (p_{\mu} \cos \theta_{\mu} - E_{\mu}) + m_{\mu}^2
\]
RFG model comparisons: $E_{\nu}^{QE}$ shape

Neutrino energy shape mostly insensitive to $M_A$, $\kappa$

\[
E_{\nu}^{QE} = \frac{2(M_p - E_B)E_{\mu} - (E_B^2 - 2M_pE_B + m_{\mu}^2 + \Delta M^2)}{2[(M_p - E_B) - E_{\mu} + p_{\mu} \cos \theta_{\mu}]}.
\]
How wrong would the $\nu_\mu$ $\Phi$ measurement have to be to account for observed enhancement?

Comparing to "#1": $M_A^C (M_A^H) = 1.35 (1.02)$ GeV, $\kappa = 1.007$
How wrong would the $\nu_\mu \Phi$ measurement have to be to account for observed enhancement?

$\alpha_\nu = 1.26$

$\alpha_\nu = 1.00$

$\mu$ scattering angle shape mismatched with $\nu_\mu \Phi \times 1.26$
How wrong would the $\nu_\mu \Phi$ measurement have to be to account for observed enhancement?

CC$\pi^+$ sample severely over-predicted
Wrong-sign Flux Prediction

- Not cross-section weighted
How Wrong Signs Contribute to Flux

D Schmitz

- Same low angle region not covered by HARP the most important for $\nu_\mu$ contamination
$Q^2$ - muon angle correlation

(z-axis: log scale)
CCQE Selection

1. Two subevents

2. Veto hits < 6, both subevents

3. Vertex, 1\textsuperscript{st} subevent < 500cm from tank center (fiducial volume)

4. 1\textsuperscript{st} subevent:
   \[4.4 < \text{cluster time (\mu s)} < 6.4\]

5. 1\textsuperscript{st} subevent: \(T_\mu > 200 \text{ MeV}\)

6. \(\mu\) range > \((500 \times T_\mu - 100)\) cm
   \(\mu\) range > 100 cm.

7. 1\textsuperscript{st} subevent \(\ln (\mu/e) > 0\)

8. \(\cos \theta_\mu > 0\)
CCQE Selection

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2. Veto hits < 6, both subevents
3. Vertex, 1\textsuperscript{st} subevent < 500 cm from tank center (fiducial volume)
4. 1\textsuperscript{st} subevent: 
   4.4 < cluster time (μ s) < 6.4
5. 1\textsuperscript{st} subevent: T_μ > 200 MeV
6. μ range > (500 * T_μ - 100) cm 
   μ range > 100 cm.
7. 1\textsuperscript{st} subevent ln (μ / e) > 0
8. cos θ_μ > 0
CCQE Selection

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2. Veto hits < 6, both subevents

3. Vertex, 1\textsuperscript{st} subevent < 500cm from tank center (fiducial volume)

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6. \( \mu \) range > (500 \* \( T_\mu \) - 100) cm
   \( \mu \) range > 100 cm.

7. 1\textsuperscript{st} subevent \( \ln(\mu/e) > 0 \)

8. \( \cos \theta_\mu > 0 \)
Event composition in $E_{\nu}^{QE}$
Event composition in $Q^2_{QE}$
Two dimensional muon kinematics - data/MC ratio, “#1”
$M_A^C = 1.35 \text{ GeV}$, $M_A^H = 1.02 \text{ GeV}$, $\kappa = 1.007$
Two dimensional muon kinematics - data/MC ratio, “#2”

$M_A^C = M_A^H = 1.02 \text{ GeV}, \kappa = 1.000$

(a) $E_\nu = 0.4 \text{ GeV}$
(b) $E_\nu = 0.8 \text{ GeV}$
(c) $E_\nu = 1.2 \text{ GeV}$
(d) $Q^2 = 0.2 \text{ GeV}^2$
(e) $Q^2 = 0.6 \text{ GeV}^2$
(f) $Q^2 = 1.0 \text{ GeV}^2$
Background simulation

- Sample is ~65% pure $\bar{\nu}_\mu$ CCQE.
- Of the remaining 35%, 30% are corrected based on MiniBooNE measurements
  - $\nu_\mu$ flux corrected by CC$\pi^+$-based measurement
  - Observed $\nu_\mu$ CCQE cross section implemented
  - All CC$\pi$ bkg events corrected based on kinematic measurements
MiniBooNE $\nu_\mu$ CCQE Review

$M_A = 1.35$ GeV comes in conflict with the previous $M_A$ measurements taken on mostly light nuclear targets.

Previous world average:

$M_A = 1.02 \pm 0.01$ GeV

However, other recent experiments have observed a larger axial mass as well.

Notable NOMAD measurement on a carbon nuclear target consistent with $M_A = 1.02$ GeV.

Crucial to recognize model dependence in interpretations: e.g. NOMAD makes some requirement of 1 µ, 1 p in FS; MiniBooNE makes no outgoing nucleon requirement.
Fitting the Outgoing Muon Angular Distribution

- We form a linear combination of the neutrino and anti-neutrino content to compare with CCQE data:

$$ T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}}) \equiv \alpha_\nu \nu^{MC} + \alpha_{\bar{\nu}} \bar{\nu}^{MC} $$

Rate scales to be extracted from data

All predicted neutrino, anti-neutrino events

- And minimize $\chi^2$:

$$ \chi^2 = \sum_{i,j} (T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_i - d_i) M^{-1}_{i,j} (T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_j - d_j) $$
Can we separate $H_2$ content?

Even in $T_\mu - \cos \theta_\mu$ space, $H_2$ content completely degenerate with $CC_\pi$ bkgs.
~9% errors only true for pions produced in HARP-covered phase space

Due to large proton background, pion production below 30 mrad not reported

While not a serious issue for neutrino mode, we’ll see later this is the dominant production region for a critical background to the anti-neutrino analyses

\[ p + \text{Be} \rightarrow \pi^- \rightarrow \bar{\nu}_\mu \]

HARP coverage

75.5%
Fitting the outgoing muon angular distribution

- Neutrino vs anti-neutrino CCQE cross sections differ exclusively by an interference term that changes sign between the two

\[
\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E^2_\nu} \left[ A (Q^2) \pm B (Q^2) \left( \frac{s - u}{M^2} \right) + C (Q^2) \left( \frac{s - u}{M^2} \right)^2 \right]
\]

- The divergence is more pronounced at higher $Q^2$, which is strongly correlated with backward scattering muons