Resonant Pion Production – Recent Measurements

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Resonant Pion Production – Recent Measurements

- Introduction.
- Experiments Review.
- Recent results.
- Future experiments.
- Summary.
Introduction

A new interest in neutrino interactions in the few-GeV region started with the discovery of neutrino oscillations.

Neutrino charged-current quasi elastic (CCQE) is the golden mode for neutrino oscillation searches, while the resonant pion production is a major background and a source of large uncertainty.

Neutrino resonant pion production:

\[ \nu + N \rightarrow \Delta + \pi \]

\[ \downarrow \]

N’ + mesons (usually pions at these energies)

Resonant pion production mainly comes from \( \Delta(1232) \) with small contributions from higher resonances and non-resonant background for the energy range of the reviewed experiments.

Detailed theory - covered by L. Alvarez-Ruso.
Review of the Experiments

All experiments that have published/presented results on resonant pion production in the last 5 years.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$\langle E_\nu \rangle$ GeV</th>
<th>Main goal</th>
<th>Detector</th>
<th>$\nu$ target</th>
<th>$\nu$ MC</th>
<th>Cross section results</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>1.3</td>
<td>$\theta_{23}$, $\Delta m_{23}$</td>
<td>Fine Grained, Water Cher</td>
<td>CH, H$_2$O</td>
<td>NEUT</td>
<td>Pub: NC$\pi^0$, CC$\pi^+$ Prelim: CC$\pi^0$</td>
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<td>MiniBooNE</td>
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<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>Oil Cher</td>
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- two oscillation experiments + a dedicated cross section experiment,
- nuclear targets,
- resonant single pion production results.
Challenges – Nuclear Targets

- Nuclear target – re-interactions in the nucleus.
- Different primary neutrino interactions become indistinguishable experimentally.
- Final State Interactions (FSI) model is needed to extract nucleon cross section – large uncertainties.

Nuclear model details - covered by O. Benhar.
Measuring Cross Sections for Nuclear Targets

Signal definition:
- observable signal - all events experimentally indistinguishable at nuclear level – least model dependent - no FSI correction.
- nucleon level signal – needs correction for FSI - model dependent, large uncertainties due to large FSI model uncertainty.

Backgrounds:
- data constrained backgrounds. No models involved.
- better hadron interaction models are needed. Current uncertainty for $\pi^+$ charge exchange in carbon is 50% and for $\pi^+$ absorption is 35% for ~300MeV pions.

Measured quantity:
- cross section ratio – many systematic effects cancel (especially beam related).
- absolute observable cross sections - requires good understanding of the flux and control of flux uncertainties. Flux prediction difficulties and \textit{in-situ} flux techniques covered by M. Bishai and S. Kopp.
Resonant $\nu_\mu$ NC $\pi^0$

$$\nu + n(p) \rightarrow \Delta^0 (\Delta^+) + \nu$$

$$\downarrow$$

$$n(p) + \pi^0 \rightarrow n(p) + \gamma + \gamma$$

**Neutrino oscillation:**
- very important for $\nu_e$ appearance searches
  - if one of the $\gamma$'s is lost or below threshold.

**Neutrino cross section:**
- important for understanding coherent and resonant production.
- no data below 2GeV.

World data consists of several measurements of cross section ratios.
\( \nu_\mu \) NC \( \pi^0 \) Cross Section Ratio

K2K measurement - 1kt water Cherenkov

Reconstruction – 2 \( \gamma \) rings
\[ \sigma^{\text{NC} \pi^0}/\sigma^{\text{CC}} = 0.064 \pm 0.001 \text{(stat.)} \pm 0.007 \text{(sys.)} \]
MC prediction is 0.065.

Very good \( \pi^0 \) reconstruction.


SciBooNE measurement

Reconstruction:
- 2 \( \gamma \) reconstructed with SciBar and EC

\[ \sigma^{\text{NC} \pi^0}/\sigma^{\text{CC}} = (7.7 \pm 0.5 \text{(stat.)} \pm 0.5 \text{(sys.)}) \times 10^{-2} \]
MC prediction 6.8x10\(^{-2}\)

MiniBooNE $\nu_\mu$ NC $\pi^0$ Measurement

Excellent $\pi^0$ containment (4\pi). Signal definition – observable.

Reconstruction:
• 2\gamma rings
• fully reconstructed $\pi^0$ sample – 21,542 events, 73% purity, 36% efficiency

First inclusive differential cross sections for this channel for both $\nu$ and $\bar{\nu}$:
$$d\sigma/dp_{\pi^0}, d\sigma/d\cos\theta_{\pi^0}$$

---

Resonant $\nu_\mu$ CC $\pi^+$

$\nu + n(p) \rightarrow \Delta^+(\Delta^{++}) + \mu$

↓

$n(p) + \pi^+$

Important for neutrino oscillation:

- major background for $\nu_\mu$ disappearance
  - modifies $\nu_\mu$QE energy spectrum.
- need to know $\nu_\mu$CC$\pi^+/\nu_\mu$CCQE($E_\nu$) to better than 5%.

Existing data from bubble chamber experiments:

- $D_2$, $H_2$ targets.
$\nu_\mu$ CC $\pi^+$ Cross Section Ratio

K2K measured the ratio to the $\nu_\mu$ CCQE events.

*K2K Collaboration, Phys. Rev. D78:032003, 2008*

MiniBooNE measured the ratio to the $\nu_\mu$ CCQE events.


- Both measurements are consistent with previous measurements.
- Both measurements are consistent with Rein-Sehgal model.
MiniBooNE $\nu_\mu$ CC $\pi^+$ - Fully Reconstructed

Signal definition:
• observable – only $1\pi^+$ and $1\mu$ emerging from the target nucleus with no other mesons.

Reconstruction:
• $\pi^+$ undergoes hadron interactions results in kinked tracks.
• 3 rings - $\mu$ and kinked $\pi^+$
• events are tagged by two stopped muon decay electrons- ~90% purity, ~67,000 events.

First full reconstruction of CC$\pi^+$ events in Cherenkov detector.

First $\Delta$ peak from neutrino experiment in more than 20 years.

preliminary
MiniBooNE $\nu_\mu$ CC $\pi^+$ - Fully Reconstructed

First measurement of inclusive CC$\pi^+$ differential cross sections

Differential cross sections (flux averaged)
- $d\sigma/d(Q^2)$, $d\sigma/d(E_\mu)$, $d\sigma/d(\cos \theta_{\mu,\nu})$
- $d\sigma/d(E_\pi)$, $d\sigma/d(\cos \theta_{\pi,\nu})$

Double Differential Cross Sections
- $d^2\sigma/d(E_\mu)d(\cos \theta_{\mu,\nu})$, $d^2\sigma/d(E_\pi)d(\cos \theta_{\pi,\nu})$

- Data $Q^2$ shape differs from the model

Paper is in preparation.


M. Tzanov University of Colorado Neutrino 2010
\( \nu_\mu \) CC \( \pi^0 \) Cross Section

\[ \nu + n \rightarrow \Delta^+ + \mu \]
\[ \downarrow \]
\[ p + \pi^0 \rightarrow p + \gamma + \gamma \]

- Not a major concern as an oscillation background, BUT

- Resonant only—valuable for understanding the resonant production without coherent contamination.

- Existing data from bubble chamber experiments on \( H_2, D_2 \)
MiniBooNE $\nu_\mu$ CC $\pi^0$ Kinematics

Reconstruction:
- 3 rings – $\mu + 2\gamma$ - reconstruct entire event
- $\gamma\gamma$ invariant mass shows clear $\pi^0$ mass peak.
- Non-$\pi^0$ background doesn’t peak at the $\pi^0$ mass.

Background subtracted $m_{N\gamma\gamma}$. First reconstruction of CC$\pi^0$ events in Cherenkov detector.
MiniBooNE $\nu_\mu$ CC $\pi^0$ Cross Section

Signal definition: observable - $1\pi^0$ and $1\mu$ emerging from the target nucleus with no other mesons.

First measurement of inclusive CC$\pi^0$ differential cross sections:
- $\sigma(E)$, $d\sigma/dQ^2$, $d\sigma/dE_\mu$, $d\sigma/d\cos\theta_\mu$
- $d\sigma/dE_{\pi^0}$, $d\sigma/d\cos\theta_{\pi^0}$

Total fractional error is 18%.
Largest systematic error 12% is due to $\pi^+$ charge exchange model in the oil (background).


$\nu_\mu$ CC $\pi^0$ Cross Section

K2K ongoing analysis
Signal definition - observable - 1 or more $\pi^0$
Reconstruction:
• using SciBar + muon range detector (MRD)
• $\mu$ track in SciBar with a matched track in MRD.
• 2 electron showers in SciBar or EC.

Total cross section ratio to CCQE.
$$\sigma_{CC\pi^0}/\sigma_{CCQE} = 0.443 \pm 0.033\text{(stat.)} \pm 0.036\text{(syst.)}$$

Data is higher than MC.  
Mariani, NuInt09

SciBooNE ongoing analysis.
Signal definition – observable.
Reconstruction:
• similar to K2K - using SciBar + MRD
• no electron showers in SciBar or EC are required.

Goal is to calculate absolute cross section.  
J. Catala, NuInt09
Summary

Current measurements show discrepancies in both shape and normalization with the existing models.

Oscillation experiments need to predict the neutrino rate precisely for both signal and background, which requires:

- accurate neutrino cross section models describing data.
- good nuclear models.
- accurate prediction of the flux.

We need:

- more precise least model dependent measurements by dedicated experiments. MiniBooNE started this trend with a full suite of absolute observable differential cross section.
The Future is Here

T2K and MINERvA are taking data – results soon.

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<td>NA61</td>
<td>$\theta_{13}$, $\delta^{\text{CP}}$</td>
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<td>MINERvA</td>
<td>1-20</td>
<td>MIPP</td>
<td>$\sigma_\nu$</td>
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<td>C, Fe, Pb, He, D</td>
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MINERvA

- Both designed to measure cross sections.
- Overlapping energy range will allow measuring neutrino cross sections from 0.3 – 20 GeV. - map out CCQE and resonant $1\pi$ turn-on regions.
- Measurement of the A dependence.
Conclusions

There has been a major effort to measure the resonant pion cross sections:

- new results mainly from oscillation experiments.
- first complete sets of differential cross sections have been measured by MiniBooNE.

T2K and MINERVA have the potential to improve our understanding of the resonant pion production.
- high power neutrino beams – sufficient statistics.
- dedicated hadron production experiments – flux.
- various targets.

Both theoretical and experimental efforts are needed to understand neutrino resonant cross sections, which is crucial for precise measurement of all oscillation parameters.
Thank you!