Single $\pi$ production in MiniBooNE and K2K

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(Thanks to the MiniBooNE collaboration especially, M. Wascko and S. Zeller for providing the MiniBooNE plots.)
Introduction

Neutrino interactions around 1GeV region

- Charged current quasi-elastic scattering (CCQE) \( \nu_\mu + n \rightarrow \mu^- + p \)
- Neutral current elastic scattering \( \nu_\mu + N \rightarrow \nu + N \)
- Single \( \pi, \eta, K \) resonance productions
- Coherent pion productions
- Deep inelastic scattering

\[ \nu_\mu + N \rightarrow l + N' + \pi (\eta, K) \]
\[ \nu_\mu + X \rightarrow l + X' + \pi \]
\[ \nu_\mu + N \rightarrow l + N' + m\pi (\eta, K) \]

\( l \) : lepton, \( N, N' \) : nucleon, \( m \) : integer

Cross-sections

To study neutrino interactions, it is also important to take into account nuclear effects. Mesons (especially \( \pi \)) and protons interactions in target nucleus. (Oxygen, Carbon ..)
Importance of neutrino interaction studies

• To search for the $\nu_e$ appearance in the $\nu$ oscillation experiments, $\pi^0$ productions will be one of the major backgrounds. Asymmetric $\pi^0$ decay event looks like $\nu_e$ appearance signal. (Energetic $\gamma$ looks like $e$ from $\nu_e$ charged current interaction.)

• Charged Current Quasi-Elastic scattering ($\nu_\mu + n \rightarrow \mu^- + p$) is very useful to measure the neutrino energy spectrum. However, $\pi$ interacts in nucleus. Because of this, some of the single $\pi$ production events looks like CC quasi-elastic events.

It is important to understand the neutrino induced $\pi$ productions and $\pi$ interactions in nucleus.
Study of neutral current single $\pi^0$ production at K2K (with water Cherenkov detector)
K2K neutrino beamline

Front (Near) Detector direction ($\nu$) spectrum, rate
$\mu$-monitor
direction ($\pi \rightarrow \mu$)

12 GeV PS
fast extraction
every 2.2 sec
beam spill width
1.1 $\mu$s (9 bunches)
~6x$10^{12}$ protons/spill

North Counter Hall

Target station

AI target

Decay section
($\pi \rightarrow \mu \nu \mu$)
200m

Double Horn (250kA) ~20 x flux

Pion monitor
($P_{\pi}, \theta_{\pi}$ after Horn)

Near to Far flux ratio $R_{FN}$
The K2K near detectors

$E_\nu \sim 1\text{GeV}$

Almost pure $\nu_\mu$ beam (~98%)

It is possible to investigate various neutrino interactions with the K2K near detectors.

**Target material**

- Water (H$_2$O)
- Scintillator (CH)
- Iron

**Detection technologies**

SciFi detector

SciBar detector

Muons range detector

1kt water Cherenkov detector

MRD

$\nu_\mu$ energy spectrum @ K2K near detector

$E_\nu$ (GeV)
NC $\pi^0$ measurements in 1kt detector
Neutral current single $\pi^0$ production

$\nu + N \rightarrow \nu + N + \pi^0$

Observable in 1kt: $\pi^0$
(Cherenkov threshold of proton $> 1$GeV/c)

2 $\gamma$s from $\pi^0$ are identified as 2 electron like rings

$\rightarrow$ reconstruct invariant mass
NC $\pi^0$ measurements in 1kt detector

1kt water Cherenkov detector
high efficiency in finding low energy $\pi^0$

$\pi^0$ sample selection criteria
\begin{align*}
\{ & \text{2 e-like rings} \\
& \text{reconstructed mass 85~215MeV/c}^2
\end{align*}

$\rightarrow$ detection efficiency of $\pi^0 \sim 49\%$
86\% from NC interactions

Contamination from charged current
$\rightarrow$ low momentum $\mu$ ($P_\mu < 200\text{MeV/c}$) can not be identified.

Pions generated in Oxygen interacts with nucleons.

(Inelastic scatterings, charge exchange and absorption in Oxygen are considered in Monte-Carlo simulation program)
NC $\pi^0$ measurements in 1kt detector

momentum and direction of $\pi^0$

There still remains interactions other than the neutral current $\pi^0$ production

Estimate the efficiency and the purity by using Monte-Carlo simulation.
NC $\pi^0$ measurements in 1kt detector

Background subtraction (shaded area in Fig. a)
Efficiency correction (Use detection efficiency curve)

$\pi^0$ momentun
(before correction (a)
& BG subtraction)

$\pi^0$ detection efficiency (b)

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NC $\pi^0$ measurements in 1kt detector

Cross-section of NC $\pi^0$ production

Use single ring $\mu$-like events as a reference.

25t fiducial ($r<2m$, $-2m<z<0m$)
2 ring FC events, both e-like
$M_{\gamma\gamma} = 85 - 215$ MeV/c$^2$

(3.61$\pm$0.07$\pm$0.36)$\times 10^3$ events

Major sources of the systematic error
- DIS model dependence (5.6%)
- NC/CC $\sigma$ uncertainty (3.2%)
- Ring counting (5.4%)
- Particle ID (4.2%)

$\pi^0/\mu$ ratio @ $<E_{\nu}>$~1.3GeV

0.064$\pm$0.001(stat.)$\pm$0.007(sys.)

(Prediction from our Monte-Carlo simulation : 0.065)

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(5.65$\pm$0.03$\pm$0.26)$\times 10^4$ events

Major source of the systematic error
- vertex reconstruction (4%)

$\pi^0$ fiducial ($r<2m$, $-2m<z<0m$)
25t fiducial ($r<2m$, $-2m<z<0m$)
Fully contained $\mu$-like events
and Partially contained events

(*)Flux averaged charged current total cross-section
(used in Monte-Carlo simulation program)

1.1 $\times$ 10$^{-38}$cm$^2$
Study of charged current coherent $\pi$ production at K2K
(with SciBar detector)
The SciBar detector

*Installed in the summer 2003*

- Full Active tracking detector
  - Extruded scintillator with WLS fiber readout
    - Cell size: 2.5 x 1.3 x 300cm³
    - Light yield: 7~20p.e. /MIP/cm (2 MeV)
  - Extruded scintillator (15t)
  - Multi-anode PMT (64 ch.)
  - Wave-length shifting fiber

- High efficiency
  - Even for the short tracks
- Can detect
  - Low momentum protons down to \( \sim 350 \) MeV/c.
- PID \((p/\pi)\)
  - & momentum measurement by \(dE/dx\).

- Reconstruct vertex
- Identify the interaction

- Installed in the summer 2003

- Cell size: 2.5 x 1.3 x 300cm³
- Light yield: 7~20p.e. /MIP/cm (2 MeV)
- Extruded scintillator (15t)
- Multi-anode PMT (64 ch.)
- Wave-length shifting fiber
Some distributions from K2K

In K2K, number of forward going particles was smaller than expected. If we assume quasi-elastic scattering and reconstruct $q^2$, deficits were observed in the small $q^2$ region.

Disagreement of single $\pi$ production or coherent $\pi$ production?

Reconstructed $q^2$ distributions from SciBar

$q^2_{\text{rec}}$: from $p_\mu/\theta_\mu$, assuming CCQE kinematics

\[
q^2_{\text{rec}} = 2E^\text{rec}_\nu (E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2
\]

\[
E^\text{rec}_\nu = \frac{m_n E_\mu - m_\mu^2 / 2}{m_n - E_\mu + p_\mu \cos \theta_\mu}
\]
In the **coherent π production**, the neutrino scatters off the nucleus with small energy transfer and **there is no nucleon in the final state**.

The model used in the Monte-Carlo simulation (Rein & Sehgal’s model) has been checked in the higher energy region.

In the **resonance π production**, proton or neutron exists in the final state.

**Signature of charged current coherent π production**
- a $\mu^-$ and a $\pi^+$ in the final state.
- No activity in the area of the vertex.
Charged current coherent $\pi$ analysis with the SciBar detector

The SciBar detector is possible to find $\mu$, $\pi$, $p$ tracks.

How to identify type of interaction (2 track events)

• For CC quasi-elastic (CCQE) events, expected direction of proton can be derived from $p_\mu$ and $\theta_\mu$.
  (Direction of $\nu$ is well defined.)

• To identify CCQE events, compare the observed direction of $p$ with expectation.
  a) CCQE-like : $|\theta_p - \theta_{\text{expected}}| < 25^\circ$
  b) CC non-QE like : $|\theta_p - \theta_{\text{expected}}| > 25^\circ$
Charged current coherent $\pi$ analysis with the SciBar detector

Use $dE/dx$ to identify particle type (proton or pion/muon).

85% efficiency, 80% purity for protons (estimated by Monte-Carlo simulation).
Charged current coherent $\pi$ analysis
with the SciBar detector

Reconstructed $q^2$ distributions (SciBar)

?? Indication of the much smaller cross-section of coherent $\pi$ ??
Charged current coherent $\pi$ analysis

- **Vertex activity rejection**
  
  Cut by the energy deposit around the vertex.

- **Reconstructed $q^2$ cut**
  
  Select events with $q^2_{\text{rec}} < 0.10 \text{ (Gev/c)}^2$

  - # of events: 113
  - Efficiency: 21.1%
  - Purity: 47.1%
Charged current coherent $\pi$ analysis

In order to reduce the systematic uncertainties, take ratio to the charged current total cross-section.

$$\frac{\sigma(CC - Coh \, \pi)}{\sigma(\nu_{\mu}CC)} = (0.04 \pm 0.29(stat.)^{+0.32}_{-0.35}(syst.)) \times 10^{-2}$$

And the upper limit of this cross-section ratio is obtained to be

$$\frac{\sigma(CC - Coh \, \pi)}{\sigma(\nu_{\mu}CC)} < 0.60 \times 10^{-2} \text{ @ 90\% CL}$$

$\sim$30\% of Rein-Sehgal's model expectation

Major sources of systematic error
Uncertainty of
differential cross-section of resonant $\pi$ production
and $\pi$ interactions in carbon (from resonant $\pi$ production)

Study of charged current single $\pi^+$ production at MiniBooNE
Almost pure $\nu_\mu$ beam (>99%)
Mean neutrino energy ~0.7 GeV

decay region: $\pi \rightarrow \mu_\mu$, $K \rightarrow \nu_\mu$

Be target (1.7$\lambda$) magnetic horn for meson focusing

450 m earth berm: $\nu$
movable absorber: stops muons, undecayed mesons

FNAL 8 GeV Booster

MiniBooNE detector (CH$_2$)
MiniBooNE detector

800 ton CH$_2$ detector
Signal region
1280 8inch PMTs
Veto region
240 8inch PMTs

Use Cherenkov light and scintillation light

Typical $\mu$ event
Neutrino interactions at MiniBooNE

Monte-Carlo predicted $\nu_\mu$ flux

$<E_\nu> \sim 0.7$ GeV

Typical energy@MiniBooNE

Dominant interactions

CCQE & CC $1\pi$
Neutrino interactions at MiniBooNE

Dominant interactions

Charged current
quasi-elastic scattering
Charged & neutral current
single $\pi$ production

To study single $\pi$ production,
CCQE events are used for the normalization.
(In order to reduce systematic uncertainties.)

This Analysis:
$3.2 \times 10^{20}$ protons on target

60k CCQE events (after selection cuts)
40k CC1$\pi^+$ events (after selection cuts)
Charged current Quasi-Elastic scattering \( (\text{MiniBooNE}) \)

\[ \nu_\mu \ n \rightarrow \mu^- \ p \ \xrightarrow{\text{e}^-} \nu_\mu \ \bar{\nu}_e \]

Observed particles

- \( \mu^- \)
- decay electron

- Neutrino-Induced Event Selection Cuts
  (Mainly timing and VETO cuts)
- CC Selection Cut
  (Search for the delayed signal from decay electron)
- < 3 sub-events
  (No invisible \( \pi \)s in an event)

- event topology
- Fraction of on- vs. off- ring light
- PMT hit timing
- Fraction of prompt vs. late light
- \( \mu \)-like energy loss
- given \( E \), is track length consistent with \( \mu \)?
- 10 variable “Fisher discriminant”

Result: 86% CCQE purity
most of background from CC1\( \pi^+ \)
(due to \( \pi \) absorption in nucleus)
Charged current Quasi-Elastic scattering (MiniBooNE)

measured visible energy

\[ \cos(\theta) = 1 \sim \text{low } Q^2 \]

mostly Cherenkov from \( \mu^- \) + a little scintillation light from proton

Using Cherenkov light.

reconstructed direction of \( \mu \)

PRELIMINARY
Monte Carlo error bars from:
neutrino \( \sigma \),
light extinction,
& light scattering length uncertainties

\[ \text{Fraction of Events} /0.1 \text{GeV} \]

Reconstructed \( E_\mu \) (GeV) after CCQE Cuts

\[ \text{Fraction of Events} / (1/15) \text{ radians} \]

Reconstructed \( \cos(\theta_\mu) \) after CCQE Cuts
Charged current Quasi-Elastic scattering (MiniBooNE)

Using the obtained reconstructed energy and the direction of $\mu$, energy of neutrino is calculated as follows:

$$E_{v}^{QE} = \frac{1}{2} \frac{2M_{p}E_{\mu} - m_{\mu}^{2}}{M_{p} - E_{\mu} + \sqrt{(E_{\mu}^{2} - m_{\mu}^{2})}\cos\theta_{\mu}}$$

Neutrino energy resolution

Energy distribution used for the cross section measurement

PRELIMINARY, CCQE MC only

Monte Carlo error bars from:
- neutrino $\sigma$,
- light extinction,
- & light scattering length uncertainties
Charged current single $\pi^+$ production (MiniBooNE)

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

Observed particles
- $\mu^-$
- 2 decay electrons (from $\mu^-$ and $\pi^+$)

Event selection criteria
- Neutrino-Induced Event Selection Cuts
- CC Selection Cut (require decay electron)
- exactly 3 sub-events
- 2nd 2 sub-events consistent with Michel $e^-$ ($20 < N_{PMT} < 200$)

Purity: 84%

Main Backgrounds
- multi $\pi$ production and QE
- Inclusive final states
Charged current single $\pi^+$ production (MiniBooNE)

measured visible energy

reconstructed direction of $\mu$

Using Cherenkov light.

$\cos(\theta) = 1 \sim$ low $Q^2$

PRELIMINARY

Monte Carlo error bars from:
- neutrino $\sigma$,
- light extinction,
- light scattering length uncertainties
Charged current single $\pi^+$ production

*Neutrino Energy Reconstruction*

Assume 2 body kinematics (as in CCQE)
Assume $\Delta(1232)$ in final state
(instead of a proton in CCQE)

$$E_{\nu}^{QE} = \frac{1}{2} \frac{2M_p E_\mu - m_\mu^2 + (m_\Delta^2 - m_P^2)}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)\cos\theta_\mu}}$$

Energy resolution
$\sim 20\%$

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(MiniBooNE)

PRELIMINARY

Monte Carlo error bars from:
neutrino $\sigma$,
light extinction,
& light scattering length
uncertainties
CC single $\pi^+ / $ CC Quasi Elastic cross-section ratio

efficiency corrected $\sigma$ (CC $\pi^+$/ $\sigma$(CC QE)
measured on CH$_2$

current systematic errors
- light propagation in oil: $\sim$20%
- $\nu$ cross sections: $\sim$15%
- energy scale: $\sim$10%
- statistics: $\sim$5%

first measurement of this cross section ratio on a nuclear target at low energy!

(J. Monroe, M. Wascko)

(Sam Zeller @ NO-VE workshop 2006)
CC single $\pi^+$ production effective cross-section

(MiniBooNE)

- multiplying measured CC $\pi^+/\text{QE}$ ratio by QE $\sigma$ prediction ($\sigma_{\text{QE}}$ with $M_A=1.03$ GeV, BBA non-dipole vector form factors)
- $\sim 25\%$ lower than prediction, but within errors

(J. Monroe, M. Wascko)

- MC error band from external $\nu$ data constraints

(Sam Zeller @ NO-VE workshop 2006)
Plausible Interpretation

- since MiniBooNE 1\textsuperscript{st} meas on nuclear target at these E’s

- at 1\textsuperscript{st} glance, one might think this is pointing to a potential problem with nuclear corrs

- but free nucleon σ’s disagree!

- MC prediction splits difference

- MiniBooNE results more consistent with ANL than BNL
  - new data helping to decide between 2 disparate σ meas
  - once final, type of info that can feed back into open source MC

\hspace{2cm} (Sam Zeller @ NO-VE workshop 2006)
Summary

K2K neutral current $\pi^0$ production cross-section measurement
$\pi^0/\mu$ ratio @ $<E_\nu>$~1.3GeV

$0.064 \pm 0.001\text{(stat.)} \pm 0.007\text{(sys.)}$

(Prediction from our Monte-Carlo simulation : 0.065)
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K2K Charged current coherent $\pi^+$ production search

$$\frac{\sigma (CC - Coh \pi)}{\sigma (\nu_\mu CC)} < 0.60 \times 10^{-2} \text{ at } 90\% \text{ CL}$$

~30% of Rein-Sehgal’s model expectation

MiniBooNE charged current single $\pi^+$ production cross-section measurement

$E_\nu$ from 0.5 to 1.4 GeV

~25% smaller than the Monte-Carlo expectation.
But still within error.
One of the old experiments gives similar result(?)
(Near) Future prospects

• New NC $\pi^0$ results from MiniBooNE
  Some results with improved $\pi^0$ ID were presented recently.
  (cross-section was not presented.)

• SciBooNE (SciBar detector in the BooNE beamline)
  is expected to start soon.
  Study interactions with both $\nu$ and anti-$\nu$ beams.