K2K Cross Section Measurements

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For the K2K collaboration

1. NC single $\pi^0/(\text{All CC})$ in 1KT Cherenkov detector
2. CC-Coherent Pion Production in SciBar detector
3. MA-QE from shape fit to SciFi detector data
(4. Final results from mu-disappearance and e-appearance)
Motivations

Improve knowledge of Cross Sections

Cross Sections and Nuclear Effects are important for extracting oscillation parameters from nu-mu disappearance nu-e appearance experiments.
98% pure $\nu_\mu$ beam target materials: H$_2$O, HC, Fe

$\nu_\mu$ energies at the K2K near detectors
NC single $\pi^0$ in the water Cherenkov detector

\[ \nu + N \rightarrow \nu + N + \pi^0 \]

Neutral Current (no muon),
recoil proton below 1 GeV/c threshold (no proton)

Typical $\pi^0$ candidate
has two electron-like rings

Reconstructed invariant mass (MeV)
NC single $\pi^0$ signal and backgrounds

Signal (70%) is from NC resonant and NC coherent pizero production
AFTER pion-nucleus reinteractions such as charge exchange
(and includes a small amount from non-resonant “DIS” pion production)

Background from multiple (below threshold) pion production
And from Charged Current pion product with muon below threshold

Direction $\cos \theta_\pi$

$\pi^0$ momentum (MeV/c)
NC single $\pi^0$ fraction result

After efficiency and background corrections
Create ratio with single-ring muon-like events as the reference.

Signal in 25 ton fiducial volume
$(3.61 \pm 0.07 \text{ stat} \pm 0.36 \text{ syst}) \times 10^3$

All muon-like in 25t fiducial volume
$(5.65 \pm 0.03 \text{ stat} \pm 0.26 \text{ syst}) \times 10^4$

NC$1\pi^0/\mu$ ratio at $<E_{\nu}> \sim 1.3$ GeV
$= 0.064 \pm 0.001 \text{ stat} \pm 0.007 \text{ syst.}$
(Prediction from our MC = 0.065)

Major sources of systematic error:
- DIS model dependence 5.6%
- NC/CC cross section 3.2%
- Ring counting 5.4%
- e-like ring particle ID 4.2%
  (In mu-like denominator only: vertex reconstruction 4%)

CC coherent pion in SciBar detector

Fully active scintillator detector (neutrino target HC)

Low thresholds for protons and pions

and proton vs pion particle ID via \(dE/dx\)
CC coherent pion selection

Resonant pion production is scattering from nucleon

Coherent pion scatters from entire nucleus.

No recoil nucleon (see only $\mu^-$ and $\pi^+$)
Very low momentum transfer (low $Q^2$, low angle).

Several recent experiments see disagreement between data and expectation in very low $Q^2$ region.

Does CC coherent pion contribute to disagreement?
Reconstruct $Q^2$ from the muon in CC samples

1. Assume CCQE kinematics, get $E_ν$ and $Q^2$ from $p_μ$ and $θ_μ$
get the “wrong answer” (too low) for non quasi-elastic events but this treat data and MC same

$$E_ν = \frac{m_N E_μ - m_μ^2 / 2}{m_N - E_μ + p_μ \cos θ_μ}$$

$$Q^2 = -2 E_ν (E_μ - p_μ \cos θ_μ) + m_μ^2$$

2. Still using CCQE kinematics
Divide into QE enhanced and nonQE enhanced subsamples

3. Apply SciBar PID ability to the non muon track to separate protons and pions
CC coherent pion results

Reconstructed $Q^2$ for four sub-samples

- (d) non-QE Pion
- (c) non-QE Proton
- (b) QE

Further purify expected CC coherent pion
reject events with a lot of vertex activity

2-track nonQE pion-like

Normalized by total CC events

2trk CC QE
as a control sample.
CC coherent pion results

Select the 113 events with $Q^2_{\text{rec}} < 0.1$ (GeV/c)$^2$

Coherent Pion content expected
21.1% efficiency 47.1% purity

Mesurement relative to all CC events
\[
\frac{\sigma_{\text{CCcoh}\pi}}{\sigma_{\text{All CC}}} = (0.04 \pm 0.29 \text{ stat } +0.32 \text{ -0.35 syst}) \times 10^{-2}
\]

Compute upper bound
\[
\frac{\sigma_{\text{CCcoh}\pi}}{\sigma_{\text{All CC}}} < 0.60 \times 10^{-2} \text{ (at 90\% CL)}
\]

This is ~30\% of Rein-Sehgal model

Largest systematics: $\sigma_{\text{Resonant Pion}}$ and pion reinteractions in carbon

Scintillating Fiber (SciFi) detector

~1 degree angle resolution

Require muon in the muon range detector

\[ P_\mu > 600 \text{ MeV} \]

Recoil proton threshold is three layers in SciFi

\[ P_p > 600 \text{ MeV} \]

(so proton not always seen)

Neutrino interaction

Target is Water in Aluminum tanks

(70% H2O, 22% Al, 8% HC)
Axial mass and shape of $Q^2$ distribution

Absolute Quasi-elastic Cross section (includes normalization)

This analysis: Shape Only

Measure $Q^2$ for each event still assuming QE interaction

$$E_\nu = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos \theta_\mu}$$

$$Q^2 = -2 E_\nu (E_\mu - p_\mu \cos \theta_\mu) + m_\mu^2$$
Other model effects that change the shape

Free neutron (no Pauli Blocking)

Pauli Blocking in (Fermi Gas) model
And CC Coherent Pion uncertainty contribute at low $Q^2$.

We exclude this region from the fit.

QE cross section calculation also depends on vector form factors.

We use updated form factors from fits to electron scattering data.

These, plus a second axial mass parameter (we take $MA1\pi=1.1$ GeV) affect the nonQE background.
Reconstructed $Q^2$ for subsamples (after fitting)

One-track events

Fit shape of signal

60% QE

Two-track QE

$\sim$85% nonQE
(mostly single-pion)

Constrains relative size of nonQE background

Subsample division
(as in slides 9 and 10 but no PID)
Results for effective Quasi-elastic $M_A$ on Oxygen

$M_A = 1.20\pm0.12$ GeV \hspace{1cm} (\chi^2 = 261/235 \text{ dof}) \hspace{1cm} \text{shape only}

Can be compared with Deuterium bubble chamber results (primarily also shape fits) with older vector form factors
K2K result $M_A = 1.23\pm0.12$  \hspace{1cm} Deuterium $M_A \sim 1.03\pm0.03$

Most significant errors:
- Muon momentum scale \hspace{1cm} 0.07
- Relative flux and normalization \hspace{1cm} 0.06
- $M_A 1\pi$ \hspace{1cm} 0.03
- relative nonQE fraction \hspace{1cm} 0.03
- Nuclear rescattering \hspace{1cm} 0.03
- Statistics only \hspace{1cm} 0.03

Our data has a flatter $Q^2$ spectrum than MC prediction

K2K default MC uses $M_A=1.1$ GeV dipole vector form factors

RG, Jeon, et al., submitted to PRD, hep-ex/0603034
Final neutrino oscillation results using the K2K data

HARP hadron measurements for new far/near extrapolation

Updated Super-Kamiokande reconstruction

Electron neutrino appearance analysis now uses entire data set.

(Other smaller refinements)
Final electron appearance result

one event observed
expected background 1.7 events
background consists of
1.32 from muon neutrinos
0.38 from beam electron neutrinos

Upper limit (90%CL) \( \sin^2 2\theta_{\mu e} < 0.13 \) at \( \Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2 \)
(Two-flavor analysis)

Final $\nu_\mu$ disappearance result

All neutrino events in SuperK
Observed 112, expected 158 $^{+9.2}_{-8.6}$

58 events
fully-contained
single-ring
muon-like
- no osc. shape
- best fit shape

Ahn, et al. sub. to PRD  hep-ex/0606032
Final $\nu_\mu$ disappearance result

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Maximal mixing 90% CL
$1.9 \times 10^{-3} < \Delta m^2 < 3.5 \times 10^{-3} \text{ eV}^2$
Best fit in physical region $2.8 \times 10^{-3}$

Ahn, et al. sub. to PRD hep-ex/0606032
Conclusions

Several cross section measurements:
Neutral Current single-pizero
Charged Current coherent pion
Shape of Quasi-elastic $Q^2$ spectrum

Still some ongoing cross section work

Oscillation analyses are final, papers available now.