Neutrino Interaction Measurement in 1kton Water Cherenkov Detector in K2K Experiment

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Abstract

I report about the neutrino spectrum measurement and neutrino interaction study in 1kton water Cherenkov detector (1KT) in K2K experiment. Neutrino spectrum measurement is one of the key issues in K2K experiment. 1KT detector accumulates a huge number of good ν_μ interaction data. This paper, I present about neutral current π^0 production measurement. This interaction is a good probe for NC interaction rate, and will be a good probe to test the neutrino oscillation to sterile neutrinos.

1. Introduction

The KEK to Kamioka long-baseline neutrino experiment (K2K) [1][2] is the first accecelator based experiment to investigate the neutrino oscillation observed in atmospheric neutrinos [5]. K2K experiment intended to confirm the ν_μ disappearance by observing a deficit of total ν_μ events and a distortion of the neutrino energy spectrum, and to search for the appearance of ν_e.

The K2K experiment uses almost pure (98%) ν_μ beam, which is produced by 12 GeV protons from the KEK proton synchrotoron. The 12 GeV proton beam is extracted in a 1.1μsec spill every 2.2seconds. The proton beam is bent to Kamioka direction, and hits an aluminum target. The produced charged particles, mainly π^+, are focused by a pair of magnet horn and then decay to produce a neutrino beam. A pion monitor (PIMON) is occasionally put downstream of the 2nd horn in order to measure the direction and momentum of the pions [7]. The beam direction is monitored every beam spill by measuring the profile of the muons from the pion decays. The mean of the produced neutrino beam is 1.3 GeV.

The experiment had front detectors located at 300m from the target to measure neutrino beam energy spectrum and profile. The front detectors consist of two detector sets: a 1 kiroton water Cherenkov detector (1KT) and a fine

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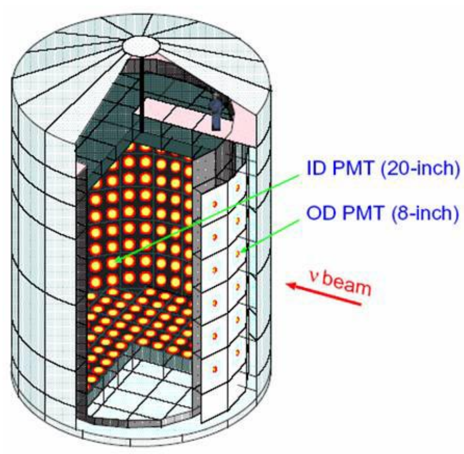

Fig 1. Schematic view of 1kton water Cherenkov Detector

grained detector system. The detectors are also used for the study of neutrino interactions.

2. 1kton water Cherenkov detector

1kton water Cherenkov detector (1KT) is one of a neutrino detector located at 300m from the pion production target. The primal purpose of the near detector is measurement of the neutrino energy spectrum and neutrino interaction rate. Also, 1KT provides a good measurement of neutrino interactions with high statistics. 1KT uses same instruments as Super-Kamiokande, and is a smaller version of Super-Kamiokande which is used as a far neutrino detector. 1KT detector consists of the cylindrical tank of 10.8m diameter and 10.8m height, and filled with 1000 ton pure water. The inside of the tank is separated for an inner volume of 8.6 m diameter and 8.6 m height, and an outer detector. Inner volume is viewd by 680 photo-multiplier tubes (PMTs) of 50 cm diameter, facing inward to detect Cherenkov light from neutrino events. The PMTs are uniformly arranged on a lattice with 70.7 cm interval. Coverage of the photocathode is 40%, and the other surface is covered with a opaque black sheet made of phyethylene therephthalate. Fig. 1 shows the schematic view of 1kton detector. The neutrino target is water which is same as Super-Kamiokande, and the systematic uncertainty of the neutrino interaction will be largely cancelled in neutrino oscillation study.

Physical quantity of an event such as the vertex position, the number of Cherenkov rings, particle types and momentum are determined by the same algorithms as used in Super-Kamiokande [6].

3. Measurement of neutrino spectrum in 1KT

Primal purpose of the 1kton detector is measure the neutrino spectrum. The method of the neutrino spectrum measurement is explained below. Here I show the results based on January 2000 to February 2004 data, which is corresponding to 8.9×10^{19} POT.

3.1. Event selection

The events are selected by requiring following conditions: (1) An event is triggered within 1.2μsec beam spill gate. (2) There is no detector activity within a 1.2μsec window preceding a beam spill. (3) Only a single event is observed in the spill by a peak search on the recorded analog sum of all 680 PMTs' signal. (4) The reconstructed vertex is in the 25ton fiducial volume, which is defined as 4m diameter and 2m long cylindrical region along the beam axis. (5) The visible energy (Evis) is greater than 30 MeV. (6) Total p.e.s is greater than 1000 p.e.s. (7) Maximum number of photoelectrons in a single PMT is less than 200 p.e.s. The condition (7) is to require is all visible particles are inside the detector. This sample is called fully contained (FC) sample. If maximum number of photoelectrons is a single PMT is greater than 200 p.e.s, the event is categorized as partially contained (PC) events. For neutrino energy spectrum analysis, we require further conditions to enrich the ν_μ quasi-elastic scattering (QE) fraction: (8) Single Cherenkov ring is observed (1R event). (9) Particle type is muon (μ-like). This sample is called FC 1-ring μ-like (FC1Rμ) events. The fraction of QE is about 60%. Fig 2 shows the paremt neutrino energy distribution. The mean of neutrino energy is about 1.1GeV.

Figs. 3 show muon momentum distribution and angle distribution with respect to the neutrino beam direction. The muon momentum is agree with the data, but we found a clear deficit in a forward region. This deficit is also observed in other neutrino detectors. We suspect that this deficit is related to the neutrino interaction, and intensively studied in near neutrino detectors. At this time we don't show turther discussions.

3.2. χ^2 fitting and result

Both data and Monte Carlo are binned into 2-dimensional distributions of the muon momentum versus scattered angles. Figs 4 shows the schematic view of the binning. The Monte Carlo events separatedly filled in the histogram according to the parent neutrino energy and the interaction mode: Neutrino energy is divided into 8bins, 0-0.5GeV, 0.5GeV-0.75GeV,0.75GeV-1.0GeV, 1.0GeV-1.5GeV,1.5GeV-2.0GeV,2.0GeV-2.5GeV,2.5GeV-3.0GeV, and over 3.0GeV. We

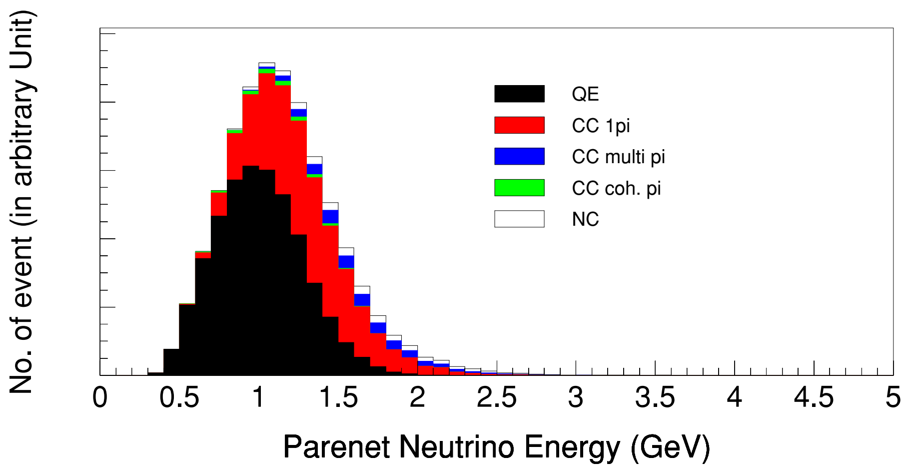

Fig 2. Parent neutrino energy distribution for FC1Rμ events. Histograms show the Monte Carlo for QE, CC single pion production (CC1pi), CC DIS scatterng (CC-multipi),CC coherent pion productin (CCcoh), and NC interactions.

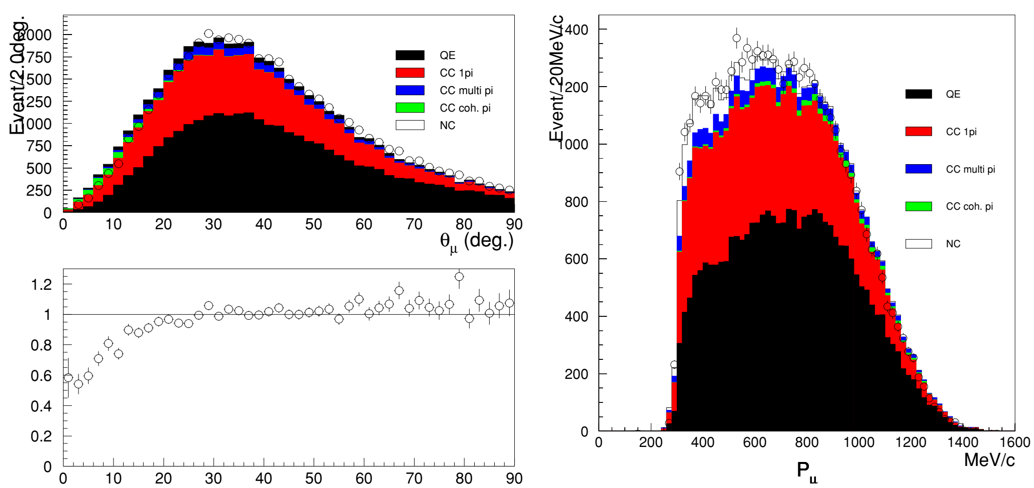

Fig 3. Muon momentum distribution (Right) and muon angular distribution with respect to neutrino beam direction (Left upper) and Data/MC ratio (Left lower) for FC1Rμ events. Circles show the data, histograms show the Monte Carlo. In angluar distribution, deficit in foward region is observed.

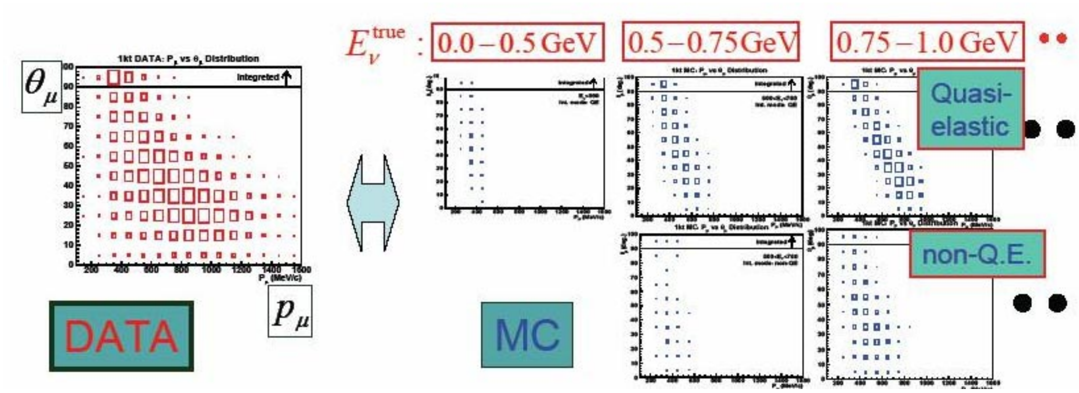

Fig 4. Schematic view of the binning of the data and Monte Carlo events.

divide the MC events to QE and the other interaction modes (nQE).

The neutrino spectrum is derived by comparing the observed data and weighted sum of Monte Carlo expectations using a χ^2 test. The χ^2 is defined as below:

$$\chi^2 \;=\; \sum_{m,n} \frac{\left(N^{\rm data}_{m,n} - N^{\rm MC}_{m,n}\right)}{\sigma^2_{m,n}} + \frac{(1-\epsilon)}{\sigma^2_{energy}} + \chi^2_{PIMON} \tag{1}$$

$$N^{\rm MC}_{m,n} \;=\; \alpha \cdot \sum_{i=1}^{8} f_i \cdot \left(N^{\rm MC(QE)}_{m,n,i} - R_{\rm nqe} \cdot N^{\rm MC(nQE)}_{m,n,i}\right) \tag{2}$$

where $N^{\rm data}_{m,n}$ is the number of events for data for (m,n)-th bin, $N^{\rm MC(QE)}_{m,n,i}$ and $N^{\rm MC(nQE)}_{m,n,i}$ are the number of events for (m,n)-th bin for both QE and nQE Monte Carlo events for i-th neutrino enery bin, ϵ is the fitting parameter for energy scale ($\epsilon = 1$ is a nominal value) which scales muon momentum, $\sigma_{m,n}$ is the error including statistical and systematic errors, σ_{energy} is the estimated uncertainty of the energy scale (+2-3%), f_i is the weighting factor for i-th energy bin, $R_{\rm nqe}$ is the weighting factor for nQE events, α is the overall normalization factor, χ^2_{PIMON} is a constraint term from the measurement of PIMON, respectively. The sources of the systematic errors are vertex reconstruction, Cherenkov ring finding, particle identification, angular resolution, FC/PC separation, and energy scale.

The parameters f_i, $R_{\rm nqe}$, α, and ϵ are the fitting parameters and the χ^2 is minimized by varying these parameters. In the minimization, MINUIT [8] program is used. As already mentioned, we found a mismatch in the forward region. The region ($\theta_\mu < 20$ deg.) are not used in this analysis. We did check the effect of the θ_μ cut for the spectrum-fitting using toy Monte Carlo events, and confirm that the the cut makes no large systematic biases.

Figs 5 shows the parent neutrino energy distribution after fitting. The

Table 1. Result of the spectrum fit. f4 is fixed because only the relative normalization of the parameters is important in this fitting. f8 is fixed to 1.0 because 1KT have no acceptance for this high energy neutrinos.

Parameter	fitted value
hline f1($E_\nu < 0.5$ GeV)	1.413 ± 0.416
f2(0.5GeV $< E_\nu < 0.75$ GeV	1.136 ± 0.103
f3(0.75GeV $< E_\nu < 1.0$ GeV	1.097 ± 0.008
f4(1.0GeV $< E_\nu < 1.5$ GeV	1.000 (fixed)
f5(1.5GeV $< E_\nu < 2.0$ GeV	0.856 ± 0.075
f6(2.0GeV $< E_\nu < 2.5$ GeV	0.936 ± 0.172
f7(2.5GeV $< E_\nu < 3.0$ GeV	0.776 ± 0.729
f8(3.0GeV $< E_\nu$	1.000 (fixed)
R_{nqe}	0.705 ± 0.113
E-scale	0.982 ± 0.005

results are shown in Table 1. Error bars shows the fitting errors. Obtained χ^2 is 51.8 for 60 degree of freedom. We obtained the neutrino spectrum using 1kton detector. For neutrino oscillation analysis, global fitting is carried out using 1kton detector and other front neutrino detectors [9].

4. Neutral Current π^0 production

A single π^0 event is a good signature of neutral current (NC) neutrino interactions in the GeV region. In water Cherenkov detector, a decay of the π^0 can be clearly identified as two electromagnetic-showering Cherenkov rings. The single π^0 production rate is a good probe to distinguish between the $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillation hypotheses. The NC rate is decreased in the case of transitions of ν_μ's into sterile neutrinos, while it does not change in the $\nu_\mu \leftrightarrow \nu_\tau$ scenario. An understanding of single π^0 production is also very important for a search for electron neutrino appearance in LBL experiments with a water Cherenkov detector, because the most serious background to single-ring ν_e signals is a single π^0 event with only one ring reconstructed due to highly asymmetric energies or small opening angle of two γ-rays in the π^0 decay [3]. There exist very little experimental data for NC single π^0 production and no reports on measurements with a water target, which is the target matter of a far detector in some of the LBL experiments [1, 4]. A good knowledge of NC single π^0 production cross section and π^0 momentum distribution is required for the above studies. 1KT provides a good measurement with high statistics.

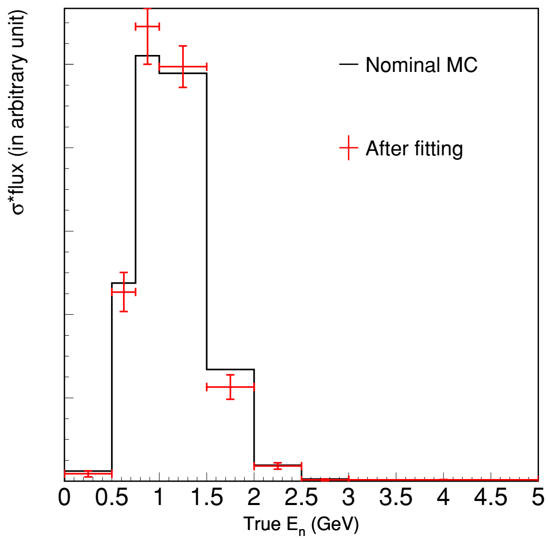

Fig 5. Neutrino energy spectrum after fitting. The histogram shows the nominal value, and crosses show the spectrum after fitting. Error bars show the fitting errors.

These single π^0s in the GeV neutrino energy region are mainly produced via the Δ resonance as $\nu + N \to \nu + \Delta$, $\Delta \to N' + \pi^0$, where N and N' are nucleons. Because of nuclear effects such as Fermi motion, Pauli blocking, nuclear potential and final state interactions, Δ production and its decay could be different from a simple picture of neutrino-nucleon interactions. In addition, final state interactions of nucleons and mesons during a traversal of nuclear matter could largely modify the number, momenta, directions and charge states of produced particles. So, we measure the "NC π^0" events which is defined as neutral current neutrino interaction with just a single π^0 and no other mesons from nuclei, instead of the pure NC π^0 production.

4.1. Event Selection

We show the results based on the data from Jaunuary 2000 and July 2001, which is corresponding to 3.2×10^{19} POT. Event selection is as follows. (1) FC event (2) 2 Cherenkov ring (3) Both is electromaginetic shower (e-like) (4) The reconstructed invariant mass from the two rings are within 85 MeV/c^2 and 215 MeV/c^2. Fig. 6 shows the invariant mass distribution of the single π^0 events. The NCπ^0 fraction in the single π^0 sample is estimated to be 71%.

4.2. Number of NCπ^0 interaction

To derive the number of NCπ^0 interaction, we subtract non-NCπ^0 background from observed single π^0 sample, and apply fiducial volume correction and detection efficiency correction.

The data is binned in 10 π^0 momentum bins shown in Fig. 7 and the background subtraction is done in each bin. The background comes from NC

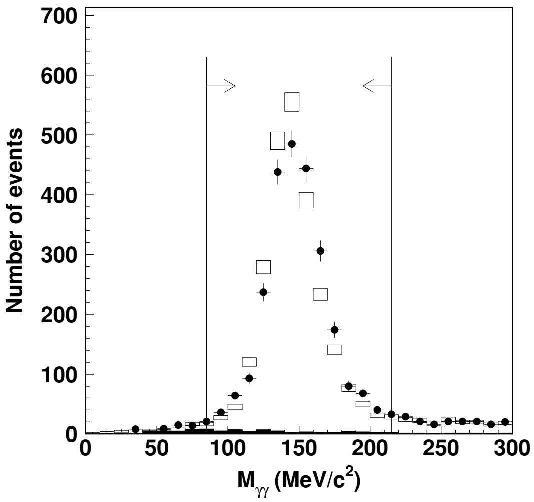

Fig 6. The invariant mass of two e-like ring events for the experimental data (black dots) and the neutrino Monte Carlo simulation (box histogram). The black portion in the Monte Carlo histogram shows the non-π^0 component.

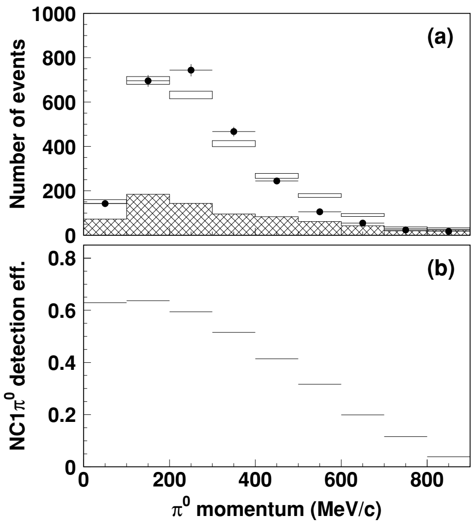

Fig 7. (a) The reconstructed π^0 momentum distribution for the single π^0 sample, comparing 1kt data (black dots) and the neutrino Monte Carlo (box histogram). The error bars are statistical only. The hatched portion in the Monte Carlo histogram shows the non-NC1π^0 component. (b) The detection efficiency for NC1π^0 interactions as a function of real π^0 momentum.

π^0 production with low momentum invisible particles, CC π^0 production with low momentum invisible particles, π^0 production outside the target nucleus, and non-π^0 events. The systematic errors in background subtraction is estimated to be 7% from neutrino cross section uncertainty, and 1.6% from nuclear effects.

To calculate the number of interactions whose true vertices are inside in 25ton fiducial volume, a fiducial volume correction is applied. The number of NCπ^0 interactions in the Monte Carlo single π^0 sample is larger by 3% if we use the true vertex information. We multiply by 1.03 to data, and systematic uncertainty from this correction is estimated to be 2%. The detection efficiency have momentum dependence as shown in Fig. 7-(b). The inefficiency for higher momentum π^0 is due to an asymmetric decay of π^0 or small opening angle between the 2γs. The systematic error from this correction is estimated to be 4.2%, which is mainly from the systematic uncertainty of the Cherenkov ring finding and

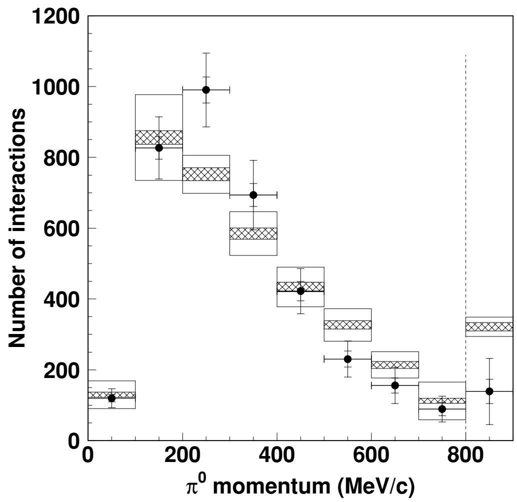

Fig 8. The momentum distribution of NC1π^0 events in the 25 ton fiducial volume (black dots). The inner and outer error bars attached to data points show statistical errors and total errors including systematic errors, respectively. The distribution predicted by the neutrino Monte Carlo simulation is also shown as a box histogram for comparison. The size of inner boxes represents Monte Carlo statistical errors. The size of outer boxes represents the uncertainty of the distribution shape due to neutrino interaction model ambiguity.

particle identification.

By a series of the corrections, the number of NCπ^0 is measured to be $(3.69 \pm 0.07 \pm 0.37) \times 10^3$) in the 25 ton fiducial volume. Fig. 8 shows the momentum distribution of NCπ^0 after all corrections. The hisgotramis normalized by the number of total events in fiducial volume.

To reduce the overall normalization uncertainty, we calculate the ratio of the cross section of NCπ^0 to total CC ν_μ interaction instead of deriving the absolute cross section for NCπ^0 interactions.

To make a CC ν_μ enriched sample, FC event and PC events are selected (see Section 3.1.). For FC events, we require additional conditions:(1) For FC1R events, the particle type is muon. (2) For FC multi-ring event, the particle type of the most energetic ring is muon. The fraction of CC ν_μ interaction is estimated to be 96%. The remaining background is mostly from NC interaction with energetic charged pions. We carried out same corrections as NCπ^0 events, background subtraction, fiducial volume correction, and detection efficiency correction. The measured CC ν_μ interaction is $(5.78 \pm 0.03 \pm 0.26) \times 10^4$ in the 25 ton fiducial volume in the same period. The estimated systematic error is 4% from vertex reconstruction, 1% from the uncertainty of neutrino interaction, 1% from particle identification, and 1% from the uncertainty of absolute energy scale.

By taking the ratio, the relative cross section for NCπ^0 interactions to the total CC ν_μ interaction is obtained to be $0.063 \pm 0.001 \pm 0.006$. The Monte Carlo prediction is 0.064, which is in good agreement with the measurement.

5. Summary

In this paper, I presented the neutrino spectrum measurement in 1kton water Cherenkov detector, and measurement of the relative cross section of NCπ^0 interaction at K2K neutrino beam energy region. 1KT has a good sensitivity below 1.0 GeV and it is a important region for neutrino oscillation analysis. By taking the ratio, the relative cross section for NCπ^0 interactions to the total CC ν_μ interaction is obtained to be $0.063 \pm 0.001 \pm 0.006$. The Monte Carlo prediction is 0.064, which is in good agreement with the measurement.

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