

# Search for neutrino-induced charged coherent pion production with carbon in a 1.3 GeV wide band muon neutrino beam

E. Aliu,<sup>1</sup> S. Andringa,<sup>1</sup> S. Aoki,<sup>10</sup> J. Argyriades,<sup>3</sup> K. Asakura,<sup>10</sup> R. Ashie,<sup>30</sup> H. Berns,<sup>33</sup> H. Bhang,<sup>20</sup> A. Blondel,<sup>26</sup> S. Borghi,<sup>26</sup> J. Bouchez,<sup>3</sup> J. Burguet-Castell,<sup>32</sup> D. Casper,<sup>28</sup> C. Cavata,<sup>3</sup> A. Cervera,<sup>26</sup> K. O. Cho,<sup>4</sup> J. H. Choi,<sup>4</sup> U. Dore,<sup>19</sup> X. Espinal,<sup>1</sup> M. Fechner,<sup>3</sup> E. Fernandez,<sup>1</sup> Y. Fukuda,<sup>15</sup> J. Gomez-Cadenas,<sup>32</sup> R. Gran,<sup>33</sup> T. Hara,<sup>10</sup> M. Hasegawa,<sup>12</sup> T. Hasegawa,<sup>22</sup> K. Hayashi,<sup>12</sup> Y. Hayato,<sup>7</sup> R. L. Helmer,<sup>25</sup> J. Hill,<sup>23</sup> K. Hiraide,<sup>12</sup> J. Hosaka,<sup>30</sup> A. K. Ichikawa,<sup>7</sup> M. Iinuma,<sup>8</sup> A. Ikeda,<sup>17</sup> T. Inagaki,<sup>12</sup> T. Ishida,<sup>7</sup> K. Ishihara,<sup>30</sup> T. Ishii,<sup>7</sup> M. Ishitsuka,<sup>31</sup> Y. Itow,<sup>30</sup> T. Iwashita,<sup>7</sup> H. I. Jang,<sup>4</sup> E. J. Jeon,<sup>20</sup> I. S. Jeong,<sup>4</sup> K. Joo,<sup>20</sup> G. Jover,<sup>1</sup> C. K. Jung,<sup>23</sup> T. Kajita,<sup>31</sup> J. Kameda,<sup>30</sup> K. Kaneyuki,<sup>31</sup> I. Kato,<sup>12</sup> E. Kearns,<sup>2</sup> D. Kerr,<sup>23</sup> C. O. Kim,<sup>11</sup> M. Khabibullin,<sup>9</sup> A. Khotjantsev,<sup>9</sup> D. Kielczewska,<sup>34,21</sup> J. Y. Kim,<sup>4</sup> S. Kim,<sup>20</sup> P. Kitching,<sup>25</sup> K. Kobayashi,<sup>23</sup> T. Kobayashi,<sup>7</sup> A. Konaka,<sup>25</sup> Y. Koshio,<sup>30</sup> W. Kropp,<sup>28</sup> J. Kubota,<sup>12</sup> Yu. Kudenko,<sup>9</sup> Y. Kuno,<sup>18</sup> T. Kutter,<sup>13,27</sup> J. Learned,<sup>29</sup> S. Likhoded,<sup>2</sup> I. T. Lim,<sup>4</sup> P. F. Loverre,<sup>19</sup> L. Ludovici,<sup>19</sup> H. Maesaka,<sup>12</sup> J. Mallet,<sup>3</sup> C. Mariani,<sup>19</sup> T. Maruyama,<sup>7</sup> S. Matsuno,<sup>29</sup> V. Matveev,<sup>9</sup> C. Mauger,<sup>21</sup> K. McConnel,<sup>14</sup> C. McGrew,<sup>23</sup> S. Mikheyev,<sup>9</sup> A. Minamino,<sup>30</sup> S. Mine,<sup>28</sup> O. Mineev,<sup>9</sup> C. Mitsuda,<sup>30</sup> M. Miura,<sup>30</sup> Y. Moriguchi,<sup>10</sup> T. Morita,<sup>12</sup> S. Moriyama,<sup>30</sup> T. Nakadaira,<sup>12</sup> M. Nakahata,<sup>30</sup> K. Nakamura,<sup>7</sup> I. Nakano,<sup>17</sup> T. Nakaya,<sup>12</sup> S. Nakayama,<sup>31</sup> T. Namba,<sup>30</sup> R. Nambu,<sup>30</sup> S. Nawang,<sup>8</sup> K. Nishikawa,<sup>12</sup> K. Nitta,<sup>7</sup> F. Nova,<sup>1</sup> P. Novella,<sup>32</sup> Y. Obayashi,<sup>30</sup> A. Okada,<sup>31</sup> K. Okumura,<sup>31</sup> S. M. Oser,<sup>27</sup> Y. Oyama,<sup>7</sup> M. Y. Pac,<sup>5</sup> F. Pierre,<sup>3</sup> A. Rodriguez,<sup>1</sup> C. Saji,<sup>31</sup> M. Sakuda,<sup>7,17</sup> F. Sanchez,<sup>1</sup> A. Sarrat,<sup>23</sup> T. Sasaki,<sup>12</sup> K. Scholberg,<sup>6,14</sup> R. Schroeter,<sup>26</sup> M. Sekiguchi,<sup>10</sup> E. Sharkey,<sup>23</sup> M. Shiozawa,<sup>30</sup> K. Shiraishi,<sup>33</sup> G. Sitjes,<sup>32</sup> M. Smy,<sup>28</sup> H. Sobel,<sup>28</sup> J. Stone,<sup>2</sup> L. Sulak,<sup>2</sup> A. Suzuki,<sup>10</sup> Y. Suzuki,<sup>30</sup> T. Takahashi,<sup>8</sup> Y. Takenaga,<sup>31</sup> Y. Takeuchi,<sup>30</sup> K. Taki,<sup>30</sup> Y. Takubo,<sup>18</sup> N. Tamura,<sup>16</sup> M. Tanaka,<sup>7</sup> R. Terri,<sup>23</sup> S. T'Jampens,<sup>3</sup> A. Tornero-Lopez,<sup>32</sup> Y. Totsuka,<sup>7</sup> S. Ueda,<sup>12</sup> M. Vagins,<sup>28</sup> C.W. Walter,<sup>6</sup> W. Wang,<sup>2</sup> R.J. Wilkes,<sup>33</sup> S. Yamada,<sup>9</sup> S. Yamamoto,<sup>12</sup> C. Yanagisawa,<sup>23</sup> N. Yershov,<sup>9</sup> H. Yokoyama,<sup>24</sup> M. Yokoyama,<sup>12</sup> J. Yoo,<sup>20</sup> M. Yoshida,<sup>18</sup> and J. Zalipska<sup>21</sup>

(The K2K Collaboration)

<sup>1</sup>*Institut de Fisica d'Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra (Barcelona), Spain*

<sup>2</sup>*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*

<sup>3</sup>*DAPNIA, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France*

<sup>4</sup>*Department of Physics, Chonnam National University, Kwangju 500-757, Korea*

<sup>5</sup>*Department of Physics, Dongshin University, Naju 520-714, Korea*

<sup>6</sup>*Department of Physics, Duke University, Durham, North Carolina 27708, USA*

<sup>7</sup>*High Energy Accelerator Research Organization(KEK), Tsukuba, Ibaraki 305-0801, Japan*

<sup>8</sup>*Graduate School of Advanced Sciences of Matter, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8530, Japan*

<sup>9</sup>*Institute for Nuclear Research, Moscow 117312, Russia*

<sup>10</sup>*Kobe University, Kobe, Hyogo 657-8501, Japan*

<sup>11</sup>*Department of Physics, Korea University, Seoul 136-701, Korea*

<sup>12</sup>*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

<sup>13</sup>*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803-4001, USA*

<sup>14</sup>*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

<sup>15</sup>*Department of Physics, Miyagi University of Education, Sendai 980-0845, Japan*

<sup>16</sup>*Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan*

<sup>17</sup>*Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan*

<sup>18</sup>*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*

<sup>19</sup>*University of Rome La Sapienza and INFN, I-000185 Rome, Italy*

<sup>20</sup>*Department of Physics, Seoul National University, Seoul 151-747, Korea*

<sup>21</sup>*A. Soltan Institute for Nuclear Studies, 00-681 Warsaw, Poland*

<sup>22</sup>*Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi 980-8578, Japan*

<sup>23</sup>*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA*

<sup>24</sup>*Department of Physics, Tokyo University of Science, Noda, Chiba 278-0022, Japan*

<sup>25</sup>*TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*

<sup>26</sup>*DPNC, Section de Physique, University of Geneva, CH1211, Geneva 4, Switzerland*

<sup>27</sup>*Department of Physics & Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*

<sup>28</sup>*Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697-4575, USA*

<sup>29</sup>*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*

<sup>30</sup>*Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan*

<sup>31</sup>*Research Center for Cosmic Neutrinos, Institute for Cosmic Ray*

*Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*

<sup>32</sup>*Instituto de Fisica Corpuscular, E-46071 Valencia, Spain*

<sup>33</sup>*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*

We report the result from a search for charged-current coherent pion production induced by neutrinos with a mean energy of 1.3 GeV. The data are collected with a fully active scintillator detector in the K2K long-baseline neutrino oscillation experiment. No evidence is observed and an upper limit of  $0.60 \times 10^{-2}$  is set on the cross section ratio of coherent pion production to the total charged-current interaction at the 90% confidence level. This is the first experimental limit for the charged current coherent pion production in the energy region of a few GeV.

PACS numbers: 13.15.+g, 25.30.Pt, 95.55.Vj

**1** This Letter presents the result from a search for charged current (CC) coherent pion production by neutrinos with energies of a few GeV using the accelerator-produced  $\nu_\mu$  beam in the KEK to Kamioka long-baseline neutrino oscillation experiment (K2K). The CC coherent pion production in neutrino-nucleus scattering,  $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$ , is a process in which the neutrino scatters coherently off the entire nucleus with a small energy transfer. It has been measured in a number of experiments [1–5], providing a test of the partially conserved axial-vector current (PCAC) hypothesis [6]. The existing data agree with the Rein and Sehgal model [7] based on the PCAC hypothesis in the neutrino energy region from 7 to 100 GeV, while there is no measurement available around 1 GeV. The recent discovery of neutrino oscillations has renewed interest in the neutrino-nucleus interaction in the sub to few GeV region. Many atmospheric and accelerator-based neutrino oscillation experiments use interactions of neutrinos in this energy region. Therefore, precise knowledge of them is indispensable to improve the accuracy of the measurements. In this Letter, we compare our result with the Rein and Sehgal model [7] because it is the only model that provides the kinematics of pions and is commonly used in neutrino oscillation experiments.

**2** In the K2K experiment, protons are extracted in a  $1.1\mu\text{s}$  spill every 2.2 seconds from the KEK 12 GeV proton synchrotron and collide with an aluminum target. Positively charged secondary particles, mainly pions, are focused by a magnetic horn system and decay to produce an almost pure (98%)  $\nu_\mu$  beam with a mean energy of 1.3 GeV [8, 9]. The neutrino beam energy spectrum and profile are measured through neutrino interactions by the near neutrino detectors located 300m downstream from the target. An estimation of the absolute flux has large ambiguity due to uncertainties in the primary proton beam intensity, the proton targeting efficiency, and hadron production cross section. Therefore, instead of deriving the absolute cross section for CC coherent pion production, the cross section ratio to the total CC interaction is measured. The data are collected with one of the near detectors, namely SciBar [10], from October 2003 to February 2004, corresponding to  $1.7 \times 10^{19}$  protons on target (POT).

**3** The SciBar detector consists of 14,848 extruded plas-

tic scintillator strips read out by wavelength shifting fibers and multi-anode PMTs. Each layer consists of two planes to measure horizontal and vertical position. The scintillator also acts as the neutrino interaction target; it is a fully active detector and has high efficiency for low momentum particles. Scintillator strips with dimensions of  $1.3 \times 2.5 \times 300 \text{ cm}^3$  are arranged in 64 layers. The size of the detector is  $300 \times 300 \times 170 \text{ cm}^3$  providing total mass of 15 tons, while a volume of  $260 \times 260 \times 135.2 \text{ cm}^3$  (9.38 tons) is used as a fiducial volume in this analysis. Due to the fine segmentation, the minimum reconstructable track length is 8cm. A track finding efficiency of more than 99% is achieved for a single track with a track length of more than 10cm. The track finding efficiency for a second, shorter track is lower than that for the single track due to overlap with the primary track. This efficiency increases with track length and reaches 90% at a track length of 30cm. In SciBar, the experimental signature of CC coherent pion production is the existence of exactly two tracks, both consistent with minimum ionizing particles, and low momentum transfer defined as  $q^2 \equiv (p_\mu - p_\nu)$ , where  $p_\mu$  and  $p_\nu$  are muon and neutrino momentum, respectively.

**4** The NEUT program library [11] is used to simulate the neutrino interactions with the nucleus. CC coherent pion production is simulated based on the Rein and Sehgal model [7]. The cross section averaged over the K2K neutrino energy spectrum is  $2.85 \times 10^{-40} \text{ cm}^2/\text{nucleon}$  for carbon. The Lewellyn Smith model [12] and the Rein and Sehgal model [13] are employed for quasi-elastic (QE) scattering ( $\nu_\mu + n \rightarrow \mu + p$ ) and charged current single pion (CC1 $\pi$ ) production ( $\nu_\mu + N \rightarrow \mu + N + \pi$ ), where  $N$  is a nucleon. The axial vector mass in the dipole formula of the nucleon form factor is set to be  $1.1 \text{ GeV}/c^2$  for both QE and CC1 $\pi$  interactions [14–16]. For deep inelastic scattering (DIS), we use GRV94 nucleon structure functions [17] with a cross section correction by Bodek and Yang [18], which reduces the cross section on average by 25% for the K2K neutrino energy spectrum. Nuclear effects are taken into account in  $\nu$ -C scattering. As for the pions originating from neutrino interactions, absorption, elastic scattering and charge exchange inside the target nucleus are considered. Pion cross sections are calculated using the model by Salcedo et al. [19] which is based on past experimental data [20].

5 Charged current (CC) events are selected by requiring that at least one reconstructed track starting in the fiducial volume of SciBar is matched with a track or hits in the muon range detector (MRD) [21] located just behind SciBar. With this criterion, the threshold for  $p_\mu$  is 450 MeV/c. According to the Monte Carlo (MC) simulation, 98% of the events selected by the requirement are CC induced events, and the rest are neutral current (NC) interactions accompanied by a charged pion or proton track which penetrates into the MRD. The background contamination from non-neutrino induced events in the sample is at the 0.01% level as verified by a timing distribution. The momentum of the muon is reconstructed from its range through SciBar and MRD. The resolutions for  $p_\mu$  and angle with respect to the neutrino beam direction  $\theta_\mu$  are 80 MeV/c and 1.6 degrees. The CC events with one or two reconstructed tracks are selected. The sample of two track events is divided into two categories of QE sample and non-QE sample by using kinematic information [22]. The second track in the non-QE sample is then classified as proton-like (non-QE-proton) or pion-like (non-QE-pion) based on  $dE/dx$  information. The particle identification capability is verified using cosmic ray muons and the second tracks in the QE sample, where the latter provides a proton sample with a purity of more than 90%. The probability to mis-identify a muon track as proton-like is 1.7% with a proton efficiency of 90%.

6 The CC coherent pion candidates are extracted from the non-QE-pion sample. The major background is CC1 $\pi$  interaction,  $\nu_\mu + p(n) \rightarrow \mu^- + \pi^+ + p(n)$ , where the proton is below threshold or overlapping with other particle tracks. Even if the proton is not reconstructed as a track, it can be detected as a large energy deposit in the vertex strip or additional hits around the vertex. Figure 1 shows a distribution of energy deposit in the vertex strip for the non-QE pion sample. The MC prediction for the distribution of energy deposit in the vertex strip is verified with the QE sample, which has no contribution from non-visible protons. The events with the energy deposit less than 7 MeV and no additional hits around the vertex strip are selected. Furthermore, events are required to have two forward going tracks and reconstructed  $q^2$  less than 0.10 (GeV/c) $^2$ . We reconstruct  $q^2$  from  $p_\mu$  and  $\theta_\mu$ , where the neutrino momentum ( $p_\nu$ ) is calculated assuming QE interaction as

$$p_\nu = \frac{1}{2} \frac{(M_p^2 - m_\mu^2) + 2E_\mu(M_n - V) - (M_n - V)^2}{-E_\mu + (M_n - V) + p_\mu \cos \theta_\mu}$$

where  $M_{p(n)}$  is the proton (neutron) mass,  $m_\mu$  is the muon mass and  $V$  is the nuclear potential set at 27 MeV. Although QE interaction is assumed, the  $q^2$  for the CC coherent pion production is reconstructed with a resolution of 0.014 (GeV/c) $^2$  and shift of 0.008 (GeV/c) $^2$ .

7 The background contamination in the sample is estimated by the MC simulation. In order to reduce the uncertainty due to the neutrino interaction cross section,

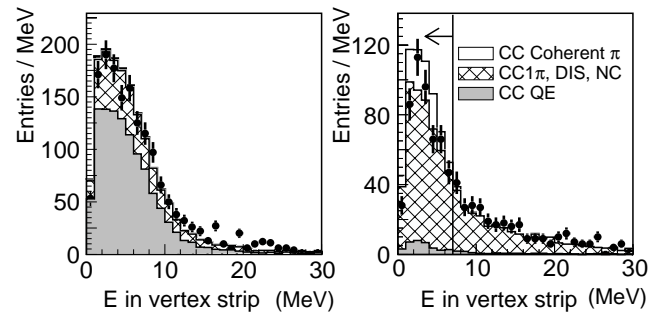


FIG. 1: Energy deposit distribution in the vertex cell for the QE (left) and non-QE pion (right) sample. Events with activity less than 7 MeV are selected.

nuclear effects, and the detector systematics, the reconstructed  $q^2$  ( $q_{\text{rec}}^2$ ) distributions of the events with  $q_{\text{rec}}^2$  more than 0.10 (GeV/c) $^2$  in the one track, QE, non-QE proton and non-QE pion samples are fitted simultaneously, treating the non-QE to QE relative cross section ratio, the magnitude of the nuclear effects and the momentum scale for muons as fitting parameters. Figure 2 shows the  $q_{\text{rec}}^2$  distributions of the data with the MC simulation after the fitting. The  $\chi^2$  value at the best fit in the regions with  $q_{\text{rec}}^2$  greater than 0.10 (GeV/c) $^2$  is 73.2 for 82 degrees of freedom (DOF).

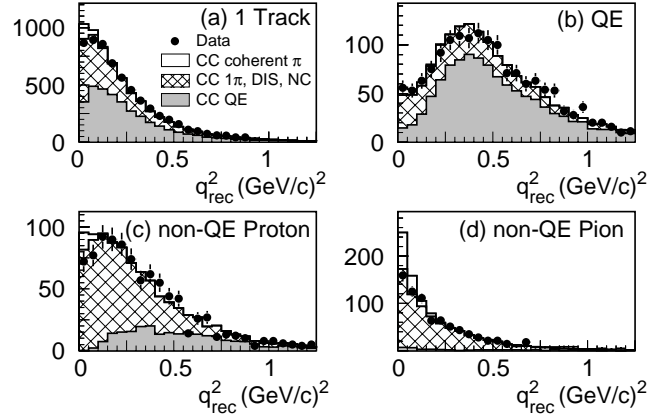


FIG. 2: The  $q_{\text{rec}}^2$  distributions for the (a) 1track, (b) QE, (c) non-QE-proton, and (d) non-QE-pion samples. Black circles show the observed data and open, hatched, and filled histograms show CC coherent pion production, CC-1 $\pi$ /DIS/NC, and QE events estimated by the MC simulation, respectively.

8 Figure 3 shows the  $q_{\text{rec}}^2$  distribution for the final CC coherent pion sample. The number of events in each selection step is summarized in Table I together with the efficiency and purity. In the signal region of  $q_{\text{rec}}^2$  less than 0.10 (GeV/c) $^2$ , 113 coherent pion candidates are found. The efficiency of CC coherent pion production as a function of the neutrino energy, estimated by the

MC simulation, is shown in Fig. 4. The total efficiency is 21.1%. The expected number of background events in the region is 111.4. After subtracting the background and correcting for the efficiency, the number of coherent pion events is measured to be  $7.64 \pm 50.40$  (stat.), while 470 events are expected by the MC simulation. No evidence of coherent pion production is found in the present data set.

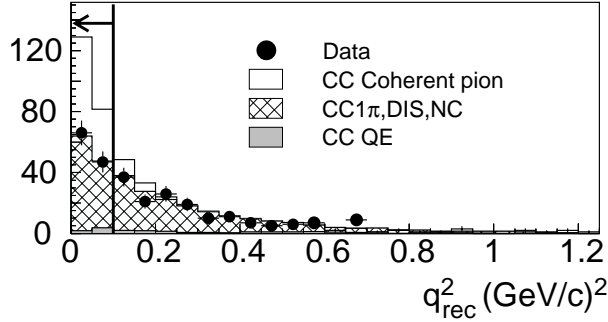


FIG. 3: The reconstructed  $q^2$  distribution in the final sample.

	Data	Efficiency	Purity
MRD	10049	77.9%	3.6%
Two track	3396	35.5%	5.1%
Non-QE pion	843	27.7%	14.8%
Track direction	773	27.3%	15.8%
No activity around the vertex	297	23.9%	28.2%
$q^2_{\text{rec}} \leq 0.10(\text{GeV}/c)^2$	113	21.1%	47.1%

TABLE I: The number of events, the MC efficiency and purity of coherent pion events after each selection.

**9** The total number of CC interactions is estimated by using the MRD matching sample. As shown in Table I, 10049 events are found in the MRD matching sample. The detection efficiency and purity for CC interaction in the sample are estimated to be 56.9% and 98.0%, respectively, by the MC simulation. By correcting for the efficiency and purity, the total number of CC events is obtained as  $(1.73 \pm 0.02(\text{stat.})) \times 10^4$ . The cross section ratio of CC coherent pion production to the total CC interaction is measured to be  $(0.04 \pm 0.29(\text{stat.})^{+0.32}_{-0.35}(\text{syst.})) \times 10^{-2}$ .

**10** Systematic uncertainties for the cross section ratio are summarized in Table II. The major contributions come from uncertainties of nuclear effects and the neutrino interaction model. The uncertainty due to nuclear effects is estimated by varying the cross sections of pion absorption and elastic scattering by  $\pm 30\%$  based on the accuracy of reference data [20]. The uncertainties in QE and CC1 $\pi$  interactions are estimated by changing the axial vector mass by  $\pm 0.10 \text{ GeV}/c^2$ . For deep inelastic scattering, the effect of the Bodek and Yang correction

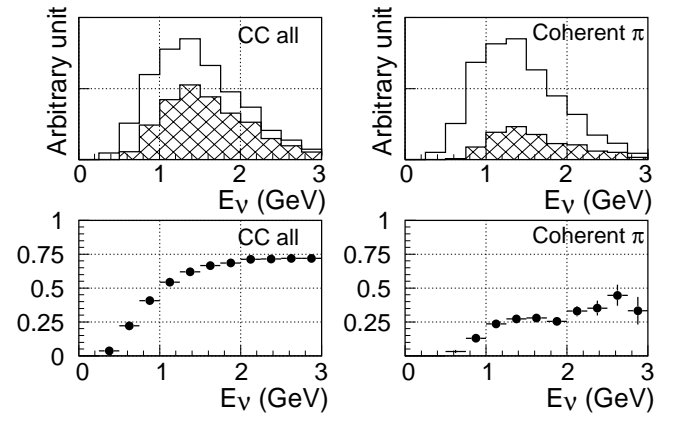


FIG. 4: Top: The neutrino energy spectrum for the total charged current events and the coherent pion events. In the figures, the hatched histograms show the detected events. Bottom: The efficiencies as a function of neutrino energy. Overall efficiencies are 56.9% and 21.1% for CC interaction and CC coherent pion production, respectively.

is evaluated by changing the correction by  $\pm 30\%$ . The  $q^2_{\text{rec}}$  distribution of the non-QE proton sample indicates an additional deficit of background events in the region  $q^2_{\text{rec}} < 0.10 \text{ GeV}/c^2$ . CC1 $\pi$  interaction dominates events in this region, while its cross section has significant uncertainty due to nuclear effects. We estimate the amount of possible deficit by fitting the  $q^2_{\text{rec}}$  distributions of the one track, QE and non-QE proton samples and find that a 20% suppression is allowed, which is treated conservatively as a systematic uncertainty. The uncertainty due to pion interaction outside the target nucleus is estimated by varying the cross section by  $\pm 10\%$  based on the accuracy of the reference data [23] and found to be negligible. We also consider the uncertainties of the event selection, where the dominant error comes from track counting, detector response such as scintillator quenching, and neutrino energy spectrum shape.

Error source	uncertainty( $\times 10^{-2}$ )	
Nuclear effects	+0.23	-0.24
Interaction model	+0.10	-0.09
CC1 $\pi$ suppression	+0.14	-
Event selection	+0.11	-0.17
Detector response	+0.09	-0.16
Energy spectrum	+0.03	-0.03
Total	+0.32	-0.35

TABLE II: The summary of systematic errors in the cross section ratio

**11** Our result is consistent with the non-existence of CC coherent pion production, and hence we set a frequentist upper limit on the cross section ratio as,

$$\sigma(\text{CC coherent } \pi)/\sigma(\nu_{\mu} \text{CC}) < 0.60 \times 10^{-2} \text{ (90\% CL)}.$$

The obtained upper limit is inconsistent with the prediction of the model by Rein and Sehgal,  $2.67 \times 10^{-2}$ . For reference, the total CC cross section is calculated as  $1.07 \times 10^{-38} \text{cm}^2/\text{nucleon}$  in the neutrino MC simulation by averaging over the K2K neutrino beam energy. There are other models predicting lower cross sections, but they do not provide the kinematics of pions and it is difficult to check them directly. Assuming the relation  $\sigma(\text{CC}) = 2\sigma(\text{NC})$  derived from isospin relation, the result is also inconsistent with the finite cross section of  $\sigma(\text{NC coherent } \pi) = (27 \pm 7) \times 10^{-40} \text{cm}^2/\text{Al nucleus}$  reported by the Aachen-Padra group [24] with an averaged beam energy of 2.0 GeV.

**12** In summary, we report on a search for CC coherent pion production by muon neutrinos with a mean energy of 1.3 GeV. The data corresponding to  $1.7 \times 10^{19}$  POT are recorded with the K2K-SciBar detector. No evidence of CC coherent pion production is found and an upper limit on the cross section ratio of CC coherent pion production to the total charged current interaction is set to be  $\sigma(\text{coherent } \pi)/\sigma(\nu_\mu \text{CC}) < 0.60 \times 10^{-2}$  (90% CL). This result is the first experimental limit for charged current coherent pion production by neutrinos with energies of a few GeV.

We thank the KEK and ICRR directorates for their strong support and encouragement. K2K is made possible by the inventiveness and the diligent efforts of the KEK-PS machine group and beam channel group. We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. This work has been supported by the Ministry of Education, Culture, Sports, Science and Technology of the Government of Japan, the Japan Society for Promotion of Science, the U.S. Department of Energy, the Korea Research Foundation, the Korea Science and Engineering Foundation, NSERC Canada and Canada Foundation for Innovation, the Istituto Nazionale di Fisica Nucleare (Italy), the Spanish Ministry of Science and Technology, and Polish KBN

grants: 1P03B08227 and 1P03B03826.

- 
- [1] P. Vilain *et al.* [CHARM-II Collaboration], Phys. Lett. **B313**, 267 (1993).
  - [2] P. Marage *et al.* [BEBC WA59 Collaboration], Z. Phys. **C43**, 523 (1989).
  - [3] P. Marage *et al.* [BEBC WA59 Collaboration], Z. Phys. **C31**, 191 (1986).
  - [4] H. J. Grabosch *et al.* [SKAT Collaboration], Z. Phys. **C31**, 203 (1986).
  - [5] S. Willocq *et al.* [FNAL E632 Collaboration], Phys. Rev. D **47**, 2661 (1993).
  - [6] S. L. Adler, Phys. Rev. **135**, B963 (1964).
  - [7] D. Rein and L. M. Sehgal, Nucl. Phys. B **223**, 29 (1983).
  - [8] S. H. Ahn *et al.* [K2K Collaboration], Phys. Lett. B **511**, 178 (2001).
  - [9] S. Nakayama *et al.* [K2K Collaboration], [arXiv:hep-ex/0408134]
  - [10] K. Nitta *et al.*, Nucl. Instrum. Meth. A **535**, 147 (2004)
  - [11] Y. Hayato, Nucl. Phys. Proc. Suppl. **112**, 171(2002)
  - [12] C. H. Llewellyn Smith, Phys. Rept. **3**, 261 (1972)
  - [13] D. Rein and L. M. Sehgal, Ann. Phys. **133**, 79 (1981)
  - [14] V. Bernard, L. Elouadrhiri, and U. G. Meissner, J. Phys. G28, R1 (2002), hep-ph/0107088
  - [15] H. J. Grabosch *et al.* [SKAT Collaboration], Current Z. Phys. C **41**, 527 (1989).
  - [16] G. T. Jones *et al.* [WA21 Collaboration], Muon-Neutrino P Z. Phys. C **43**, 527 (1989).
  - [17] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C67**, 433 (1995)
  - [18] A. Bodek and U. K. Yang, Nucl. Phys. Proc. Suppl. **112**, 70 (2002)
  - [19] L. L. Salcedo *et al.* Nucl. Phys. **A484**, 557 (1988)
  - [20] C. H. Q. Ingram *et al.*, Phys. Rev. C **27**, 1578 (1983)
  - [21] T. Ishii *et al.* [K2K MRD Group], Nucl. Instrum. Meth. A **482**, 244 (2002) [Erratum-ibid. A **488**, 673 (2002)]
  - [22] E. Aliu *et al.* [K2K Collaboration], hep-ex/0411038
  - [23] A. S. Carroll *et al.*, Phys. Rev. C **14**, 635 (1976)
  - [24] H. Faissner *et al.*, Phys. Lett. **B125**, 230 (1983)