This is a repository copy of *Measurement of Coherent π+ Production in Low Energy Neutrino-Carbon Scattering*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/108577/

Version: Accepted Version

**Article:**

https://doi.org/10.1103/PhysRevLett.117.192501

---

**Reuse**
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher’s website.

**Takedown**
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.
Measurement of coherent $\pi^+ \text{ production in low energy neutrino-Carbon scattering}$

University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan

C. Andreopoulos
STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom and University of Liverpool, Department of Physics, Liverpool, United Kingdom

M. Antonova, I. Karpikov, M. Khabibullin, A. Khotjantsev, A. Kopylov, Y. Kudenko

V. Matveev, A. Mefodiev, O. Mineev, T. Ovsyannikova, A. Shaikhiev, S. Suvorov, and N. Yershov
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

S. Aoki, T. Hara, A. Suzuki, and T. Yano
Kobe University, Kobe, Japan

A. Ariga, A. Ereditato, M. Hierholzer, M. Nirkko, C. Pistillo, A. Redij, and C. Wilkinson
University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), Bern, Switzerland

Colorado State University, Department of Physics, Fort Collins, Colorado, U.S.A.

D. Autiero, V. Galymov, and J. Marteau
Université de Lyon, Université Claude Bernard Lyon 1, IPN Lyon (IN2P3), Villeurbanne, France

Kyoto University, Department of Physics, Kyoto, Japan

M. Barbi, S.G. Giffin, and N.C. Hastings
University of Regina, Department of Physics, Regina, Saskatchewan, Canada

University of Warwick, Department of Physics, Coventry, United Kingdom

G. Barr, D. Coplowe, D. Dewhurst, S. Dolan, K.E. Duffy, A. Jacob, X. Lu, and A. Vacheret
Oxford University, Department of Physics, Oxford, United Kingdom

P. Bartet-Friburg, J. Dumarchez, C. Giganti, M. Pavin, and B. Popov
UPMC, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Paris, France

M. Batkiewicz, A. Dabrowska, T. Wachala, and A. Zalewska
H. Niewodniczanski Institute of Nuclear Physics PAN, Cracow, Poland

F. Bay, S. Di Luise, S. Horikawa, S. Murphy, and A. Rubbia
ETH Zurich, Institute for Particle Physics, Zurich, Switzerland

V. Berardi, M.G. Catanesi, R.A. Intonti, L. Magaletti, and E. Radicioni
INFN Sezione di Bari and Università e Politecnico di Bari, Dipartimento Interuniversitario di Fisica, Bari, Italy

University of British Columbia, Department of Physics and Astronomy, Vancouver, British Columbia, Canada
Warsaw University of Technology, Institute of Radiophysics, Warsaw, Poland


High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan

D. Fukuda, Y. Koshio, and T. Shirahige
Okayama University, Department of Physics, Okayama, Japan

Y. Fukuda
Miyagi University of Education, Department of Physics, Sendai, Japan

P. Hamilton, P. Jonsson, R.P. Litchfield, W.Y. Ma, L. Pickering, and Y. Uchida
Imperial College London, Department of Physics, London, United Kingdom

J. Harada, H. Kim, T. Okusawa, Y. Seiya, K. Wakamatsu, and K. Yamamoto
Osaka City University, Department of Physics, Osaka, Japan

M. Hartz
Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan and TRIUMF, Vancouver, British Columbia, Canada

Y. Hayato, M. Nakahata, H. Sekiya, and M. Shiozawa
University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan and Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan

TRIUMF, Vancouver, British Columbia, Canada

A. Hillairet and J. Myslik
University of Victoria, Department of Physics and Astronomy, Victoria, British Columbia, Canada

A. Himmel, K. Scholberg, and C.W. Walter
Duke University, Department of Physics, Durham, North Carolina, U.S.A.

J. Holeczek and J. Kisiel
University of Silesia, Institute of Physics, Katowice, Poland

J. Insler, T. Kutter, T. Thakore, M. Tzanov, and J. Yoo
Louisiana State University, Department of Physics and Astronomy, Baton Rouge, Louisiana, U.S.A.

T.J. Irvine, T. Kajita, and Y. Nishimura
University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, Kashiwa, Japan

K. Iwamoto, S. Manly, and K.S. McFarland
University of Rochester, Department of Physics and Astronomy, Rochester, New York, U.S.A.

A. Izmaylov
IFIC (CSIC & University of Valencia), Valencia, Spain and Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

B. Jamieson and F. Shaker
University of Winnipeg, Department of Physics, Winnipeg, Manitoba, Canada
We report the first measurement of the flux-averaged cross section for charged current coherent $\pi^+$ production on carbon for neutrino energies less than 1.5 GeV and with a restriction on the final state phase space volume in the T2K near detector, ND280. Comparisons are made with predictions from the Rein-Sehgal coherent production model and the model by Alvarez-Ruso et al., the latter representing the first implementation of an instance of the new class of microscopic coherent models in a neutrino interaction Monte Carlo event generator. We observe a clear event excess above background, disagreeing with the null results reported by K2K and SciBooNE in a similar neutrino energy region. The measured flux-averaged cross sections are below those predicted by both the Rein-Sehgal and the Alvarez-Ruso et al. models.

PACS numbers: 14.60.Lm, 25.30.Pt, 25.40.Ve

Introduction—Charged current coherent pion production in neutrino-nucleus scattering, $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$, is a process in which the neutrino scatters coherently from an entire nucleus, leaving the nucleus unchanged. No quantum numbers are exchanged and there is little four-momentum transfer to any nucleon. Due to these restrictions the outgoing lepton and pion are aligned with the beam direction and no other hadrons are produced.
where $y = E_\pi/E_\nu$ with $E_\pi$ and $E_\nu$ being the energy of the pion and neutrino respectively, $f_\pi$ is the pion decay constant and $|t| = |(q-p_\pi)|^2$ is the magnitude of the square of the four-momentum transferred by the exchange boson to the nucleus. Different models \[2, 3\] choose different methods for extension to $Q^2 > 0$ and implementations of the $\pi A$ elastic scattering cross-section. The validity of these models below neutrino energies of roughly 2 GeV is limited \[6–9\].

The second class, known as the microscopic models, was developed specifically for neutrino energies less than 2 GeV \[8, 10–12\]. These models are based on the single nucleon process $\nu N \rightarrow l^- N \pi^+$, which is dominated by $\Delta$ production at low energies as shown in the right diagram in Fig. 1(b). The total cross section is derived from the coherent sum of the contribution of all nucleons within the individual nuclei. Effects of the nuclear medium on the $\Delta$ and on the pion wavefunction are taken into account. These models have not been tested against data. Only recently has one instance of this class, the model from Alvarez-Ruso et al. \[11\], been implemented in a neutrino event generator.

The charged current coherent production cross section has been measured at neutrino energies above 7 GeV by several experiments \[14, 15\] and has been found to agree with the standard coherent model developed by Rein and Sehgal. More recent model dependent searches by K2K \[19\] and SciBooNE \[20\] at neutrino energies of 0.5 - 2 GeV suffer from low statistics and reported null results. Recently the MINERνA experiment published a measurement of this cross section for neutrino energies between 1.5 GeV and 20.0 GeV \[21\].

This letter presents the first measurement of the charged current coherent pion production cross section below a neutrino energy of 1.5 GeV. The analysis conducts a model independent search for an excess of events at low $|t|$. The flux averaged charged current coherent pion production cross section is presented for two regions of the final state phase space. The restricted final state phase space region is limited to $p_{\mu,\pi} > 0.18$ GeV/c, $\theta_{\mu,\pi} < 70^\circ$, which removes areas of low detector acceptance, and $p_\pi < 1.6$ GeV/c, which removes an area outside the range of validity of the microscopic model. The angles of the muon and pion, $\theta_{\mu,\pi}$, are measured with respect to the average direction of the incoming neutrino beam.

The flux averaged cross section for production to the complete phase space is also presented. In addition, for each choice of final state phase space coverage, we present results using two different models: the Rein-Sehgal model \[6\] as implemented in the GENIE 2.6.4 neutrino event generator (which uses a more sophisticated parameterisation of the pion-nucleus elastic scattering than outlined in the original Rein-Sehgal paper \[22\]) and an implementation of the microscopic model constructed by Alvarez-Ruso et al. \[11\]. Previous null results \[13, 20\] used the Rein-Sehgal coherent model to devise and tune kinematic cuts and were, thus, not model independent.

**T2K Experiment—T2K** \[23\] is an off-axis long-baseline neutrino oscillation experiment sited at the J-PARC facility in Tokai, Japan. A complete description of the experiment may be found in Ref. \[23\]. The experiment views an off-axis neutrino beam flux that is composed of 92.6% $\nu_\mu$ with a peak $\nu_\mu$ energy of 0.6 GeV. Details of the neutrino beam are described in detail in references \[23\] and \[24\]. The data used in this analysis corresponds to $5.54 \times 10^{20}$ protons on target (POT).

ND280 \[23\] is the off-axis magnetized tracking near detector designed to measure interactions of both $\nu_\mu$ and $\nu_e$ from the T2K beam before oscillations. The detector rests within the refurbished UA1/NOMAD magnet, which provides a magnetic field of 0.2 T, and is split into two regions: the upstream $\pi^0$ detector \[22\] and the tracker. The tracker region contains two plastic scintillator detectors \[20\] (FGDs or Fine Grained Detectors), used as targets for neutrino interactions, sandwiched between three argon-gas TPCs \[27\]. The first, most upstream, FGD (FGD1), only has layers of plastic (CH) scintillator bars whilst the second FGD (FGD2) also contains water layers. Surrounding these inner subdetectors is a set of electromagnetic calorimeters \[28\]. The magnet yokes are instrumented with scintillator-based side muon range detectors \[29\] to track high angle muons.

Neutrino interactions are simulated using the default GENIE 2.6.4 neutrino event generator package \[3\]. Quasielastic scattering is modelled using the Llewellyn-Smith \[30\] model with an axial mass, $m_A$, set to 0.99 GeV/c$^2$. The initial state nuclear model is the

![FIG. 1. (a) the diagram for coherent charged pion production model based on Adler’s Theorem. The $\Pi$ represents the transfer of a Pomeron to the nuclear system. (b) Dominant diagram for the microscopic class of coherent charged pion production models.](image-url)
Bodek-Ritchie relativistic Fermi gas model (RFG) with a Fermi momentum of 221 MeV/c, extended to include short range nucleon-nucleon correlations. Inelastic single pion production from resonances is simulated using the Rein-Sehgal model. Interference between the resonance states and lepton mass effects are ignored, although the effect of lepton masses on phase space boundaries is taken into account. Non-resonant pion production is modelled using an extension of the Bodek-Yang model to low energies. Interference between the resonant and non-resonant interaction modes is not taken into account. The relative contributions were tuned by GENIE against available single pion production cross section data. The transition to non-resonant inelastic scattering is simulated using the same Bodek-Yang model. Hadronisation is described using the AGKY model. Hadronic interactions in the nuclear medium are modelled using the INTRANUKE package.

Event selection—This analysis uses neutrino interactions which have occurred in the scintillator target of FGD1. Charged particles in the final state are analysed by the second TPC, which lies immediately downstream of FGD1. The first step is to select $\nu_\mu$ CC inclusive events in FGD1 using the event selection criteria reported in detail in Ref. This quantity is defined to be

$$|t| = \left| \sum_{i=\mu,\pi} \left( E_i - p_i^T \right) \right|^2 + \left( \sum_{i=\mu,\pi} p_i^T \right)^2$$  \hspace{1cm} (2)

where the approximation that negligible energy is transferred to the nucleus has been made, and $p_i^T$ and $p_i^L$ are the transverse and longitudinal components of the particle’s momentum with respect to the direction of the neutrino beam. The microscopic models also predict events clustering at low values of $|t|$. This experimental observable is well defined regardless of the class of model under consideration. This analysis searches for an excess of events above background at low $|t|$. No attempt is made to fit any particular model to the data.

Sources of systematic uncertainty—The flux averaged cross section is given by $\langle \sigma_{coh} \rangle = (N_{sel} - N_{bg})/\Phi N_T \epsilon$ where $N_{sel}$ is the number of selected events, $N_{bg}$ is the estimated number of background events, $\epsilon$ is the coherent event selection efficiency, $N_T$ is the number of target carbon nuclei and $\Phi$ is the integrated T2K neutrino flux incident on FGD1. The largest uncertainties on the flux-averaged cross section arise from: the flux model, the background interaction model, the model for final state pion interactions within the detector, and the model for the VA. Estimates of the uncertainty on the coherent cross section are determined by varying model parameters within their uncertainties, and propagating the changes to the result.

The flux systematic uncertainty is evaluated by varying the shape and normalisation of the T2K flux prediction. The uncertainties in the parameters of the background cross section models are constrained by previous measurements as implemented in the default configuration of the GENIE generator. The pion reinteraction uncertainty is evaluated by varying the total pion absorption and charge exchange cross sections within bounds defined by the difference between GEANT4 and published hadronic interaction data.

The VA uncertainty arises from two sources: the charge response of the FGD to energy deposition and the simulation of energy produced at the vertex. The charged current coherent $\pi^+$ background event sample was studied by comparing the charge response of the FGD to protons stopping in the FGD fiducial volume in data and Monte Carlo. The simulation was found to underestimate the average measured charge deposit by 10% and this was taken to be the systematic uncertainty in the FGD charge response.
The average VA of the simulated coherent background control sample was lower than that observed in the data. The issue of multi-nucleon knockout effects in neutrino scattering has recently received much attention (see, for example, [40, 41]). Such effects would eject low-momentum protons into the region around the vertex, increasing the average VA. Indeed, the simulated VA distribution can be made to agree better with background data by adding VA consistent with that deposited by a proton with kinetic energy distributed uniformly between 20 and 225 MeV to 25% of background events with a neutron target. The MINERvA experiment reported a similar observation in a study of neutrino-nucleus quasi-elastic interactions [42, 43]. The uncertainty in the vertex activity model was derived by switching this addition on and off. No correction is applied for this effect in deriving the cross section or significance of the signal. This is the dominant systematic uncertainty in the estimate of the background to the charged current coherent $\pi^+$ signal.

**Background estimate**—The estimated number of background interactions is constrained by fits to the data. The event sample was divided into a signal enriched sample, with $|t| < 0.15$ (GeV/c)$^2$ and VA < 300 PEU; and two side-band regions. The first side-band is comprised of events which fail the VA cut ($|t| < 0.15$ (GeV/c)$^2$ and VA > 300 PEU), while the second region contains events which fail the $|t|$ cut ($|t| > 0.15$ (GeV/c)$^2$ and VA < 300 PEU). The Monte Carlo predicts a $|t|$ resolution for signal events of less than 0.02 (GeV/c)$^2$. The signal enriched region was defined to include more than 99% of the coherent signal predicted by either model. Events in the side-band samples were then sorted into bins of reconstructed invariant mass, $W$. Template distributions of pion momenta were formed for each $W$ bin and scale factors estimated by fitting the normalisation of each $W$ bin to the data. The variation in $W$ was constrained by the covariance matrices encoding the effects of the variation in the systematic parameters described above.

The scale factors resulting from the fit to the side-bands were constant at 89% over the full $W$-range. The pre-fit incoherent background prediction was thereby reduced from 88 events to 78 ± 18. The fractional uncertainties in the background estimate from these sources of uncertainty are shown in Table I.

**Results**—The distribution of $|t|$ for the data and the predicted background, both after the VA cut is applied, is shown in Fig. 2. There is a clear excess of events in the data at low $|t|$ that is consistent with a charged current coherent $\pi^+$ production signal, while the shape of the high $|t|$ region is consistent with the background prediction. The total number of events observed in the signal region in the data is 123. After background subtraction, the number of coherent events in the data is 45 ± 18. The significance of observing such an excess of events is 2.2 $\sigma$ with a p-value of 0.014.

The model-dependent efficiency for selecting coherent events in the restricted phase space ($p_{\mu,\pi} > 0.18$ GeV/c, $\theta_{\mu,\pi} < 70^\circ$ and $p_\pi < 1.6$ GeV/c) is 38\% (42\%) if the Rein-Sehgal (Alvarez-Ruso et al.) model is used. The difference between efficiency arises from the effect of the particle identification criterion applied to differing pion kinematic distributions in the models. The cross section for scattering to the restricted phase-space is $(3.2 \pm 0.8(stat)^{+1.3}_{-1.2}(sys)) \times 10^{-40}$ cm$^2$/$^{12}C$ nucleus using the Rein-Sehgal model, and $(2.9 \pm 0.7(stat)^{+1.1}_{-1.1}(sys)) \times 10^{-40}$ cm$^2$/$^{12}C$ nucleus using the model from Alvarez-Ruso et al. These should be compared to the predictions of 5.3 $\times 10^{-40}$ cm$^2$/$^{12}C$ nucleus and 4.5 $\times 10^{-40}$ cm$^2$/$^{12}C$ nucleus from the models by Rein-Sehgal and Alvarez-Ruso et al., respectively. The fractional uncertainty on these estimates from each of the main sources of systematic error are shown in Table II. There is no guidance for the uncertainty of the coherent models in

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Fractional error on background</th>
<th>Fractional error on $\langle \sigma^{coh}_{\nu\ell}\rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux model</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Background model</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>Pion reinteractions</td>
<td>+0.05 -0.01</td>
<td>+0.14 -0.05</td>
</tr>
<tr>
<td>Vertex activity model</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>FGD Charge scale</td>
<td>0.06</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**TABLE I.** Summary of the fractional systematic uncertainties on the background estimate and on the phase space restricted charged current coherent flux averaged cross section ($\langle \sigma^{coh}_{\nu\ell}\rangle$).

![Fig. 2. The reconstructed $|t|$ distribution after the VA cut and the background tuning procedure have been applied. The errors on the data are statistical only, and the uncertainty on the tuned model is not shown. The model's prediction of the coherent contribution has been removed from the plot. The small external background component contains events that occur outside the FGD1 fiducial volume, such as interactions occurring in the surrounding magnet volume.](image-url)
the T2K neutrino energy regime and so we do not include a systematic uncertainty for the event selection efficiency in the cross section measurement. Fig. 3 shows the background subtracted reconstructed $Q^2$ distribution compared to the two models.

Total flux-averaged cross sections may be estimated by correcting these results by the fraction of the full phase space contained within the restricted phase space region predicted by the model. The total flux-averaged cross section is therefore inherently dependent on the signal model. The correction required for the two models is 1.20 for the Rein-Sehgal model and 1.17 for the Alvarez-Ruso et al. model, leading to the total flux-averaged charged current coherent scattering cross section of $(3.9 \pm 1.0 (stat) + 1.1 (sys)) \times 10^{-40}$ cm$^2$/12C nucleus for the Rein-Sehgal model and $(3.3 \pm 0.8 (stat) + 0.3 (sys)) \times 10^{-40}$ cm$^2$/12C nucleus in the context of the Alvarez-Ruso et al. model. These should be compared to the predictions of $6.4 \times 10^{-40}$ cm$^2$/12C nucleus and $5.3 \times 10^{-40}$ cm$^2$/12C nucleus from the Rein-Sehgal and Alvarez-Ruso et al. models, respectively.

It should be noted that T2K oscillation analyses utilise a version of the NEUT event generator which has undergone extensive tuning with non-T2K neutrino scattering data and then fitted to T2K near detector data [44]. This predicts a total charged current coherent scattering flux-averaged cross section of $6.7 \times 10^{-40}$ cm$^2$/12C nucleus, consistent with the measurement reported here. By contrast, the standard untuned NEUT predicts a total charged current coherent scattering flux-averaged cross section of $15.3 \times 10^{-40}$ cm$^2$/12C nucleus. The discrepancy with GENIE arises from the differing implementations of the pion-nucleus cross section.

**Conclusion**—T2K has made the first measurement of

the cross section for charged current coherent production of a pion from carbon nuclei for neutrino energies less than 1.5 GeV. This has been presented both in the restricted final state phase space ($p_{\mu,\pi} > 0.18$ GeV/c, $\theta_{\mu,\pi} < 70^\circ$ and $p_\pi < 1.6$ GeV/c) and the total final state phase space. This result disagrees with the null results reported previously by the K2K [19] and SciBooNE [20] experiments. These measurements have been compared to the standard Rein-Sehgal model and, for the first time, an instance of the class of microscopic models. While T2K observes a clear excess above background the measured flux-averaged cross sections are below those predicted by both the Rein-Sehgal and the Alvarez-Ruso et al. models. The statistical precision is insufficient to distinguish between the models.

We thank the J-PARC staff for superb accelerator performance and the CERN NA61 Collaboration for providing valuable particle production data. We acknowledge the support of MEXT, Japan; NSERC (Grant No. SAPPJ-2014-00031), NRC and CFI, Canada; CEA and CNRS/IN2P3, France; DFG, Germany; INFN, Italy; National Science Centre (NCN), Poland; RSF, RFBR and MES, Russia; MINECO and ERDF funds, Spain; SNSF and SERI, Switzerland; STFC, UK; and DOE, USA. We also thank CERN for the UA1/NOMAD magnet, DESY for the HERA-B magnet mover system, NII for SINET4, the WestGrid and SciNet consortia in Compute Canada, and GridPP in the United Kingdom. In addition, participation of individual researchers and institutions has been further supported by funds from ERC (FP7), H2020 Grant No. RISE-GA644294-JENNIFER, EU; JSPS, Japan; Royal Society, UK; and the DOE Early Career program, USA.

* affiliated member at Kavli IPMU (WPI), the University of Tokyo, Japan
† also at National Research Nuclear University ”MEAPhI” and Moscow Institute of Physics and Technology, Moscow, Russia
‡ also at JINR, Dubna, Russia
§ also at J-PARC, Tokai, Japan
¶ also at BMCC/CUNY, Science Department, New York, New York, U.S.A.
** deceased
†† also at Institute of Particle Physics, Canada
Note that the official version of GENIE 2.6.4 incorporates an error in the calculation of the pion-nucleus cross section. This error was fixed in GENIE versions 2.8.2 and beyond. The error has also been fixed for the version of GENIE 2.6.4 used in the current analysis.

References:


[14] FGD1 also contains hydrogen. Pure diffractive scattering from the protons can occur which, at low $Q^2$, may result in a similar final state to that produced by coherent interactions on nuclei. The contribution of diffractive scattering from hydrogen to the selected event sample was estimated to be less than 5%.

[15] A Photon Equivalent Unit is a measure of the response of the FGD to single photons. A single PEU corresponds to a deposited energy of 0.046 MeV.


