Measurement of coherent π^+ production in low energy neutrino-Carbon scattering

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We report the first measurement of the flux-averaged cross section for charged current coherent π^+ production on carbon for neutrino energies less than 1.5 GeV to a restricted final state phase space region 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. This results contradicts the null results reported by K2K and SciBooNE in a similar neutrino energy region.

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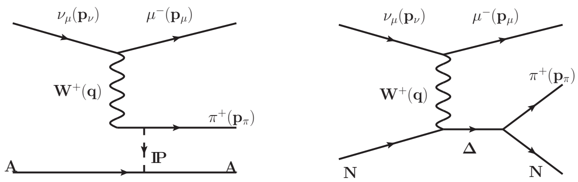
Introduction—Charged current coherent pion production in neutrino-nucleus scattering, $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$, is a process in which the neutrino scatters coherently from an entire nucleus, leaving the nucleus unchanged in its ground state. Preservation of nuclear coherence requires that no nucleon be singled out in the interaction. Thus, no quantum numbers can be exchanged nor can the four-momentum transfer to any one nucleon be large. Due to these restrictions the outgoing lepton and pion are aligned with the beam direction and no other hadrons are produced.

Two classes of models have been developed to describe



(a) (b)

FIG. 1. (a) the diagram for coherent charged pion production model based on Adler's Theorem. The IP represents the transfer of a Pomeron to the nuclear system. (b) Dominant diagram for the microscopic class of coherent charged pion production models.

this process. The first class of models uses Adler's theorem [1] to relate the coherent scattering cross section at $Q^2 = -q^2 = 0$ with the pion-nucleus elastic scattering cross section. Described by the diagram shown in Fig. 1(a), the differential cross-section is

$$\left.\frac{d\sigma_{coh}}{dQ^2 dy d|t|}\right|_{Q^2=0} = \frac{G_F^2}{2\pi^2} f_\pi^2 \frac{1-y}{y} \frac{d\sigma(\pi A \to \pi A)}{d|t|}, \qquad (1)$$

where $y = E_\pi/E_\nu$ with E_π and E_ν being the energy of the pion and neutrino respectively, f_π is the pion decay constant and $|t|$ is the magnitude of the square of the four-momentum transferred by the exchange boson to the nucleus. Different models [2–5] choose different methods for extension to $Q^2 > 0$ and implementations of the πA elastic scattering cross-section. The most common model currently used by neutrino event generators [5–7] is the Rein-Sehgal model [8]. There may be limited validity of these models below neutrino energies of roughly 2 GeV [8–11].

The second class, known as the *microscopic* models, was developed specifically for neutrino energies less than 2 GeV [10, 12–15]. These models are based on the single nucleon process $\nu_l N \to l^- N \pi^+$, which is dominated by Δ production at low energies as shown in the right diagram in Fig. 1(b). The total cross section is then derived from the coherent sum of the contribution of all nucleons within the individual nuclei. Effects of the nuclear medium on the Δ and on the pion wavefunction must also be taken into account. These models have not been tested against data. Only recently has one instance of this class of model, the model from Alvarez-Ruso *et al.* [13], 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 [16–19] and has been found to agree with the standard coherent model developed by Rein and Sehgal. More recent searches by K2K [20] and SciBooNE [21] at neutrino energies around 0.5 - 2 GeV suffer from low statistics and signals that were consistent with large backgrounds at the 90% confidence level. Recently the MINERνA experiment published a measurement of this cross section for neutrino energies between 1.5 GeV and 20.0 GeV [22].

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 searches for an excess of events with low four-momentum transfer to the nucleus. 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, $\theta_{\mu,\pi} < 70°$, 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. This restriction ensures that the result is less sensitive to the details of the signal model and to the simulation of kinematic thresholds in the detector response model.

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 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-Seghal paper[23]) and implementation of the microscopic model constructed by Alvarez-Ruso *et al.* [13]. Neither of these models have been tested against data at the low neutrino energies accessible at the T2K off-axis near detector. Previous null results [20, 21] used the Rein-Seghal coherent model to devise and tune kinematic cuts and were, thus, not model independent. This analysis represents the first measurement of a low-$|t|$ event excess at neutrino energies less than 1.5 GeV.

T2K Experiment—T2K [24] is an accelerator-based long-baseline neutrino oscillation experiment based at the J-PARC facility in Tokai, Japan. A ν_μ beam (described in detail in Ref. [24]) illuminates an on-axis near detector (INGRID) and an off-axis near detector (ND280) which is positioned at an angle of 2.5° relative to the beam axis direction. The off-axis near detector is located 280 meters from the target and is used to measure neutrino cross sections and to determine the characteristics of the neutrino beam before the beam traverses the 295 km distance to Super-Kamiokande [25], the off-axis far detector.

The neutrino beam flux [26] at the near detector is predicted by modelling the interaction of the primary proton beam in the graphite target using FLUKA2008 [27]. Hadronic interactions outside the target are simulated using GEANT3 [28]. The simulated chain of hadronic interactions is then tuned to external hadron production data, primarily from the CERN NA61/SHINE experiment [29–31]. The off-axis neutrino flux peaks at a ν_μ energy of 0.6 GeV and is composed of 92.6% ν_μ. The data used in this analysis corresponds to 5.54×10^{20} protons on target (POT).

ND280 [24] is a magnetized tracking detector designed to measure interactions of both ν_μ and ν_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 π^0 detector [32] (P0D) and the tracker. The tracker region contains two plastic scintillator detectors [33] (FGDs or Fine Grained Detectors), used as targets for neutrino interactions, sandwiched between three argon-gas TPCs [34]. 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 [35] (ECals) which increase the hermeticity of the detector and tag outgoing particles. The magnet yokes themselves are instrumented with scintillator-based side muon range detectors [36] (SMRDs) to track high angle muons.

Neutrino interactions are simulated using the default GENIE 2.6.4 neutrino event generator package [5]. Before applying the coherent event selection, the event sample is dominated by charged current quasi-elastic (CCQE) and charged current resonance single pion production (CCRES). Quasielastic scattering is modelled using the Llewellyn-Smith [37] model with an axial mass, m_A, set to $0.99\,\mathrm{GeV/c^2}$. The initial state nuclear model is the Bodek-Ritchie relativistic Fermi gas model (RFG) with a Fermi momentum of $221\,\mathrm{MeV/c}$, extended to include short range nucleon-nucleon correlations [38]. Inelastic single pion production from resonances is simulated using the Rein-Sehgal model [39]. This cross section is calculated by summing over 16 intermediate resonances with hadronic invariant mass $W < 2\,\mathrm{GeV/c^2}$. Interference between the resonance states is ignored as are lepton mass effects in the differential cross section, 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 [40] to low energies. Interference between the resonant and non-resonant interaction modes is not taken into account, however the relative contributions were tuned by GENIE against available single pion production cross section data. Finally, the transition to non-resonant inelastic scattering is simulated using the same Bodek-Yang model. Hadronisation is described using the AGKY model [41]. Final state interactions, in which hadrons interact as they traverse the nucleus, are modelled using the INTRANUKE package [5].

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. Interactions in FGD2 are not considered here as they would include a significant contribution from interactions on oxygen. The first step is to select ν_μ CC inclusive events in FGD1 using the event selection criteria reported in detail in Ref. [42]. Events passing this selection are in-time with the beam and contain at least one negatively charged track in TPC2 consistent with a minimally ionising particle. Particle identification is achieved using dE/dx along the particle track in the TPC. The interaction vertex is defined to be the most upstream point of the muon candidate track. This must lie within the fiducial volume of FGD1, which excludes the two most upstream and downstream layers, and the outer-most 5 bars in each layer. The restriction in the downstream fiducial definition arises from the vertex activity cut, which considers all energy deposited in a cubic region around the vertex. Previously published results which do not use the vertex activity do not impose such a constraint on the fiducial volume. These requirements define a fiducial region containing 0.74 tonnes of carbon[43].

An event sample with an enhanced coherent pion component is selected by refining the inclusive CC ν_μ selection. A second, positively charged, track originating from the interaction vertex is required. This second track is required to have a dE/dx profile consistent with a MIP traversing the TPC. Cuts to enforce this requirement remove proton tracks such that they make up less than 3% of the selected pion candidates.

Charged current coherent pion production leaves the nuclear target unchanged and in its ground state. Hence the only particles exiting the interaction are a charged lepton and an oppositely charged pion. Events with additional energy deposited around the vertex are removed by a cut on the vertex activity (VA), which is defined to be the sum of all energy deposits within a cubic volume with side length 5 cm centered on the vertex. No attempt is made to estimate and subtract the energy deposited by the muon and pion within this region. Simulated coherent events typically deposit 220 PEU (Photon Equivalent Unit[44]) with an RMS spread of 40 PEU. Sixty percent of the predicted background is removed by requiring the VA in the event to be less than 300 PEU with no loss of predicted signal.

Analysis strategy—Coherent interactions are characterised by the low transfer of four-momentum to the nucleus. Referring to the diagram in Fig. 1(a), this quantity is defined to be

$$|t| = |(q-p_\pi)^2| = \left(\sum_{i=\mu,\pi}(E_i - p_i^L)\right)^2 + \left(\sum_{i=\mu,\pi} p_i^T\right)^2 \tag{2}$$

where the approximation that negligible energy is transferred to the nucleus has been made, and p^T and p^L are the transverse and longitudinal components of the particle's momentum with respect to the direction of the neutrino beam. 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 arising from incoherent sources, ϵ is the coherent event selection efficiency, N_T is the number of target carbon nuclei and Φ 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 reinteractions 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 [26]. The uncertainties in the parameters of the background cross section models are constrained by previous measurements available in the literature as implemented in the default configuration of the GENIE generator [5, 45]. 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 [46].

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 in the charged current coherent π^+ background event sample. The former 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, [47, 48]). 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 MINERνA experiment reported a similar observation in a study of neutrino-nucleus quasi-elastic interactions [49]. The uncertainty in the simulation of energy produced at the vertex 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 π^+ signal.

Systematic Source	Fractional error on background	Fractional error on $\langle\sigma_{coh}^{rest}\rangle$
Flux model	0.05	0.10
Background model	0.14	0.25
Pion reinteractions	+0.05 -0.01	+0.14 -0.05
Vertex activity model	0.19	0.28
FGD Charge scale	0.06	0.15

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 ($\langle\sigma_{coh}^{rest}\rangle$).

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 $|t| < 0.15\,(\mathrm{GeV/c})^2$ and $VA < 300\,\mathrm{PEU}$; and two side-band regions. The first side-band is comprised of events which fail the VA cut ($|t| < 0.15\,(\mathrm{GeV/c})^2$ and $VA > 300\,\mathrm{PEU}$), while the second region contains events which fail the $|t|$ cut ($|t| > 0.15\,(\mathrm{GeV/c})^2$ and $VA < 300\,\mathrm{PEU}$). 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 fit to the side-bands yields a predicted number of background events of 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 π^+ production signal, while 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 efficiency for selecting coherent events in the restricted phase space ($p_{\mu,\pi} > 0.18\,\mathrm{GeV/c}$, $\theta_{\mu,\pi} < 70°$ and $p_\pi < 1.6\,\mathrm{GeV/c}$), dependent on the model used for its estimate, is 38% (42%) if the Rein-Sehgal (Alvarez-Ruso *et al.*) model is used. The difference between efficiency arises largely from the effect of the particle identification criterion applied to differing pion momentum and angular distributions in the models. The cross section for scattering to the restricted phase-space is $(3.2 \pm 0.8(stat)^{+1.3}_{-1.2}(sys)) \times$

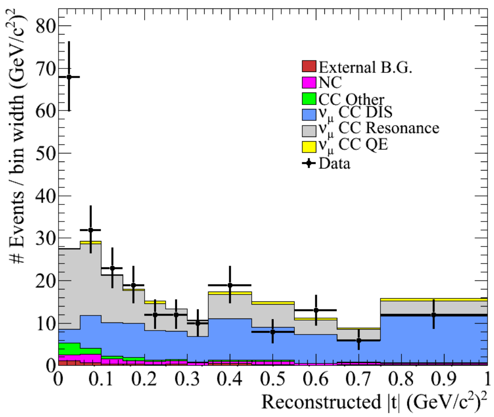


FIG. 2. The reconstructed $|t|$ distribution after the VA cut and the background tuning procedure have been applied. The model's prediction of the coherent contribution has been removed from the plot. The small external background component contains events that occur outside the FGD1 fiducial volume, such as interactions occurring in the surrounding magnet volume.

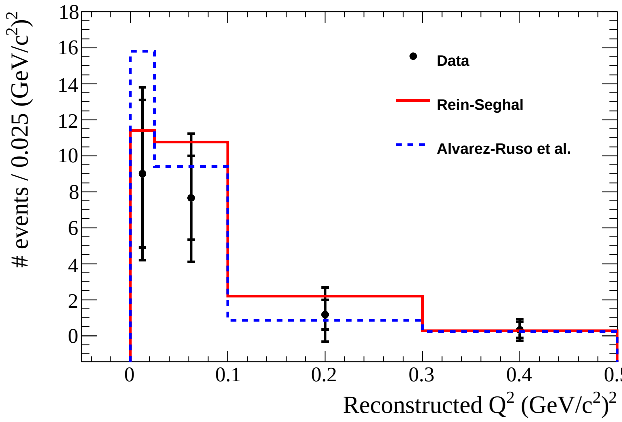


FIG. 3. The reconstructed Q^2 distribution after background subtraction. The inner error bars represent the statistical uncertainty on the data before background subtraction and the outer the total uncertainty which also includes systematic effects. Correlations between bins are not reflected in the uncertainty displayed on the figure. The last bin is an overflow bin, containing all events with reconstructed Q^2 greater than $0.3\,(\mathrm{GeV/c})^2$.

$10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus using the Rein-Sehgal model, and $(2.9 \pm 0.7(stat)^{+1.1}_{-1.1}(sys)) \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus using the model from Alvarez-Ruso *et al.* These should be compared to the predictions of $5.3 \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus and $4.5 \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ 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 I. There is no guidance for the uncertainty of the coherent models in the T2K neutrino energy regime and so we do not include a systematic uncertainty for the signal model in the cross section measurement.

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 $(3.9\pm1.0(stat)^{+1.5}_{-1.4}(sys))\times10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus for the Rein-Sehgal model and $(3.3\pm0.8(stat)^{+1.3}_{-1.2}(sys))\times 10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus in the context of the Alvarez-Ruso *et al.* model. These should be compared to the predictions of $6.4 \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus and $5.3 \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ nucleus from the Rein-Sehgal and Alvarez-Ruso *et al.* models, respectively. Fig. 3 shows the background subtracted reconstructed Q^2 distribution compared to the two models. 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 [50]. This predicts a total charged current coherent scattering flux-averaged cross section of $6.7 \times 10^{-40}\,\mathrm{cm}^2/^{12}C$ 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 $15.3\times10^{-40}\,\mathrm{cm}^2/^{12}C$ 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 ($p_{\mu,\pi} > 0.18\,\mathrm{GeV/c}$, $\theta_{\mu,\pi} < 70^\circ$ and $p_\pi < 1.6\,\mathrm{GeV/c}$) and the total final state phase space. This result contradicts the null results reported previously by the K2K [20] and SciBooNE [21] 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.

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