Measurement of associated charm production in neutrino-nucleon interactions

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Abstract.
In the CHORUS experiment, a search for associated charm production has been performed in the sample of 130,000 \( \nu \) interactions. Four events consistent with associated charm production have been found. In the neutral-current sample, three events with associated charm decay topology have been observed with an estimated background of 0.18\(^{+0.05}_{-0.04}\). The relative rate of the associated charm cross-section in deep inelastic \( \nu \) DIS interactions, \( \frac{\sigma(\bar{c}c)}{\sigma_{\text{DIS}}} \), has been measured. In charged-current \( \nu \) DIS interactions, one event has a decay topology which is consistent with associated charm production. Based on one event with the estimated background of 0.18\(^{+0.06}_{-0.06}\), we obtained the upper limit on associated charm production in charged-current interactions at 90% C.L. to be \( \frac{\sigma(\bar{c}c)}{\sigma_{\text{CC}}} < 9.69 \times 10^{-4} \).

1. Introduction
Associated charm production in neutrino-nucleon interaction is very rare process therefore difficult to observe. The production of charm pairs in neutral-current (NC) neutrino interactions occurs through boson-gluon fusion and gluon bremsstrahlung mechanisms while in charged-current (CC) interactions, charm pairs (\( c\bar{c} \)) is produced through only gluon bremsstrahlung process.

The first measurement of \( c\bar{c} \) production in CC neutrino interactions was based on study of prompt trimuons [1] and like-sign dimuons ([2],[3]) in neutrino experiments at the CERN SPS and Fermilab. However, experiments of this kind suffer a significant background of non prompt muons. In previous paper the CHORUS collaboration has published the first evidence for this process [4] through the observation of one event.

The first evidence for \( c\bar{c} \) production in NC neutrino interaction was found in the E531 experiment. One event with neutral decay topology was reported by the E531 collaboration. Based on the single event a relative rate was measured as \( \frac{\sigma(\nu_{\mu} \rightarrow \bar{c}\bar{c} \nu_{\mu})}{\sigma(\nu_{\mu} \rightarrow \nu_{\mu})} = (1.3^{+3.1}_{-1.1}) \times 10^{-3} \) [5] at the average neutrino beam energy of 22 GeV.

A recent measurement on \( c\bar{c} \) production in NC neutrino interactions was obtained through the detection of events with wrong sign muon final states by the NuteV collaboration [6]. After subtracting backgrounds and correcting for efficiencies, a production cross section \( \frac{\sigma(\nu_{\mu} \rightarrow c\bar{c} \nu_{\mu})}{\sigma(\nu_{\mu} \rightarrow \nu_{\mu})} = (6.4^{+5.5}_{-4.6}) \times 10^{-3} \) is obtained.

A search was performed for \( c\bar{c} \) production in both NC and CC neutrino interactions in the CHORUS experiment. It was based on direct observation of \( c\bar{c} \) decay vertices in the nuclear emulsion target which provides sub-micron spatial resolution therefore very suitable for the
detection of short-lived particles like charm. The search was resulted in observation of four events (one in CC and three in NC interactions) with double charm decays. Here, we give a measurement of the cross-section, both for NC and CC processes.

2. The CHORUS experiment
A wide band neutrino beam at average energy of 27 GeV, exposed to the CHORUS detector, was provided by the West Area Neutrino Facility (WANF) at CERN. It consists mainly of $\nu_\mu$, with a contamination of 5.1% $\bar{\nu}_\mu$, 0.8% $\nu_e$ and 0.2% $\bar{\nu}_e$.

The CHORUS detector as described in Ref. [7] is a hybrid setup that combines a nuclear emulsion target with various electronic detectors.

The emulsion target is made of four stacks with an overall mass of 770 kg. Each of the stacks consists of eight modules of 36 plates of 36 cm $\times$ 72 cm size. Each plate has 350 $\mu$m layers of emulsion on either side of a 90 $\mu$m plastic base. Three emulsion sheets, acting as an interface to a set of scintillating fibre tracker planes, were located at the downstream of each stack.

Based on the electronic detector information, the data was classified as the 1 and 0 samples. The 1 sample contains one reconstructed muon of negative charge which was reconstructed in the muon spectrometer. Event belonging to the 0 sample has no reconstructed muon. It mainly consists of NC $\nu_\mu$ interactions with a contamination of mis-identified CC $\nu_\mu$ interactions and interactions generated by neutrinos other than $\nu_\mu$.

3. Analysis
In total about 130,000 $\nu$ events have been located in the emulsion target with a procedure described in Ref. [8]. In order to identify decay topologies, a volume of 1.5 mm $\times$ 1.5 mm $\times$ 6.3 mm around the located vertex position is scanned. The parameters of all track segments with angles below 400 mrad found in this volume are stored in a database. This scanning method is called "Netscan" [9]. A description of the procedure and of the algorithms used to reconstruct the event topology are given in Ref. [10, 11]. In order to reconstruct the complete event topology, low-energy tracks are filtered out as well as track originating from outside the volume. The remaining track segments, about 40 tracks, are combined into one or more vertices using the minimum distance search. After performing the event reconstruction, a set of criteria is applied in order to select the potentially interesting event topologies. The selection criteria select 717 and 2816 events in the samples of 26,621 0$\mu$ and 99,245 1$\mu$ events respectively. In order to confirm the decay topology, the selected events are further inspected visually using the semi-automatic microscope system. A secondary vertex is accepted as decay if the number of prongs is consistent with charge conservation and there is no evidence for hadronic interaction, e.g. Auger electron, nuclear recoil or break up. The observable decay topologies are classified according to their numbers of charged decay products into C1, C3 or C5 for the charged and V2, V4 or V6 for neutral decaying particles. The result of the visual inspection can be found in Ref. [12].

After topological confirmation of the decays, further kinematical selections are applied in order to eliminate the background coming from strange particle decays and from hadronic interactions. In case of a C1 topology, the requirement $p_T > 0.25$ GeV/$c$ on the transverse momentum of the daughter particle with respect to the parent direction is applied. This cut also reduces significantly the background caused by “white kinks”, i.e. single prong hadronic interaction without emission of any heavily ionizing particle, Auger electron or other evidence for nuclear recoil or break up. The selection criterion applied to V2 decays is $\phi > 10$ mrad, where the angle $\phi$ measures the acoplanarity between the parent direction and the plane formed by the charged decay products. This cut eliminates mainly the two-body decays of neutral strange particles.

Four events (three candidates in NC and one in CC) satisfied the above selection criteria. A detail description of each event can be found in Ref [12]. The general features of candidate
events are given in Table 1.

**Table 1.** General features of the associated charm candidates. Ns(Ns*) and Nh stand for number of shower (reconstructed in the electronic detector) and heavily ionizing tracks at the neutrino interaction vertex. $E_{sh}$ is the hadronic shower energy, $p_\mu$ the muon momentum and $\theta_\mu(y,z)$ the angle between the muon and the beam directions, respectively in the horizontal and vertical planes. No correction was made for the energy of the two neutrinos from the charm decays.

| Event Id   | Ns (Ns*) | Nh | $E_{sh}$ (GeV) | $p_\mu$ (GeV/c) | $\theta_\mu(y,z)$ (rad) |
|------------|----------|----|---------------|-----------------|-------------------------|
| 8132-12312 | 1(1)     | 2  | 38.2          |                 |                         |
| NC         | 7692-5575| 2(1)| 0             | 47.1            |                         |
| 7739-3952  | 6(1)     | 1  | 45.9          |                 |                         |
| CC         | 7904-4944| 4(2)| 0             | 42.5            | 17.6 (-0.164,0.080)     |

In summary, one event which has $c\bar{c}$ decay topology is found in a sample of 99,245 $1\mu$ events. After subtracting the background and correcting for efficiencies, we obtain for the relative rate an upper limit at 90% C.L. of

$$\frac{\sigma(c\bar{c}\mu^-)}{\sigma_{cc}} < 9.69 \times 10^{-4},$$

In the sample of 26,621 $0\mu$ events, three events showed decay topologies that are consistent with $c\bar{c}$ production. The total background in the NC sample is estimated to be $0.18 \pm 0.05$. The relative rate of NC $c\bar{c}$ production of

$$\frac{\sigma(c\bar{c}\nu)}{\sigma_{DIS}^{DIS}} = (3.62^{+2.95}_{-2.42}(stat) \pm 0.54(syst)) \times 10^{-3}.$$ 

is obtained after subtracting the background and correcting for efficiencies. The statistical error is derived using a 68% confidence interval in the unified approach for the analysis of small signals in the presence of background [13]. We have accounted for a systematic uncertainty of 15% coming from the efficiency estimation by Monte Carlo modeling.

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