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Charm physics with the CHORUS detector

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Abstract. - During the years 1994–1998, the CHORUS experiment was taking data in the wide band neutrino beam of the CERN-SPS. The main goal of the experiment was the search for neutrino oscillation phenomena. In addition to the oscillation search, measurements of charm production have been performed. The CHORUS experiment was designed to search for the appearance of tau neutrinos by detecting the tau decay vertices in its nuclear emulsion target. The same technique was used to make a topological selection of charmed particles. Measurements of charmed particle production in neutrino interactions and charm decay properties were performed. The measurements in the emulsion target were complemented by the study of multi-muon production in the calorimeter. An overview of the charm physics results obtained with the CHORUS experiment will be given.

1. Introduction

In the CHORUS experiment it has become possible to study production of individual charm species with hundreds of events [1]. This type of analysis is enabled by the use of a massive emulsion target and by a steady increase in the speed of automatic microscope stages. About 2000 charm decays have been fully reconstructed, divided roughly equally between charged and neutral charmed particles. We review here mainly the analysis of this sample of events. In addition we compare the results obtained with the emulsion data with the analysis of di-muon events in the CHORUS calorimeter.

The CHORUS detector was exposed to the wide-band neutrino beam of the CERN SPS during the years 1994–98. The beam consisted mainly of ν_μ with a contamination of 5% $\overline{\nu}_\mu$ and about 1% ν_e. In total ≈94 000 ν_μ charged-current (CC) events with a negative primary muon were located and fully reconstructed in the emulsion target. The CHORUS detector is a hybrid set-up which combines a nuclear emulsion target with various electronic detectors such as trigger hodoscopes, a scintillating fibre tracker system, a hadron spectrometer, electromagnetic and hadronic calorimeters, and a muon spectrometer [2]. The emulsion scanning is performed by computer-controlled, fully automatic microscope stages equipped with a

Table 1: Charged-current data sample and charm subsample

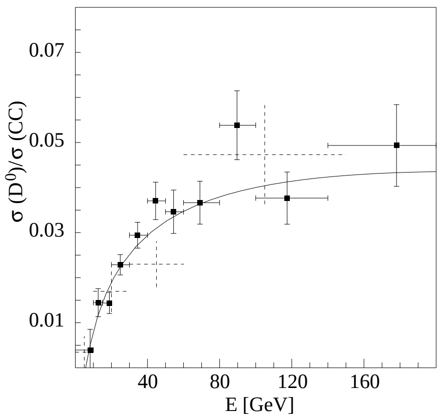
Located CC events	93 807
Charged charm candidates	965
C1	452
C3	491
C5	22
Neutral charm candidates	1048
V2	819
V4	226
V6	3
Total charm candidates	2013

CCD camera and a read-out system called 'track selector' [3, 4]. The track-finding efficiency of the automatic track recognition is higher than 98% for track slopes less than 400 mrad. This 'event location' process is described in detail in Refs. [5] and [6]. Once the vertex plate is identified, a very fast scanning system [7] is used to perform a detailed analysis of the emulsion volume around the vertex position, recording, for each event, all track segments within a given angular acceptance. We refer to this type of scanning, originally developed for the DONUT experiment [8], as 'NetScan' data taking [9].

Out of the sample of 93 807 scanned and analyzed neutrino-induced charged-current events, these criteria select 2752 events as having a decay topology. These have been visually inspected. The presence of a decay was confirmed for 2013 events. The purity of the automatic selection is 73.2%. The result of the visual inspection is given in Table 1 where according to the prong multiplicity the observable decay topologies are classified as even-prong decays V2, V4 or V6 for neutral particles (mainly D^0) and odd-prong decays C1, C3 or C5 for charged particles (mainly Λ_c^+, D^+, D_s^+).

2. Measurements

We measure the *total* D^0 production rate in νN charged-current interactions and, using the energy dependence of this rate, obtain a value for m_c, the effective mass of the charm quark [10]. The ratios of topological D^0 branching fractions can be obtained by correcting the observed numbers of events with their corresponding efficiencies and background. For the ratio of four prongs, $B(\mathrm{D}^0 \to \mathrm{V4})$, to two prongs, $B(\mathrm{D}^0 \to \mathrm{V2})$, we find: $B(\mathrm{D}^0 \to \mathrm{V4})/B(\mathrm{D}^0 \to \mathrm{V2}) = 0.207 \pm 0.016 \pm 0.004$. The fraction of decays into four charged particles is obtained from an external measurement and found to be $B(\mathrm{D}^0 \to \mathrm{V4}) = 0.1339 \pm 0.0061$ [11]. The precision of this external measurement, together with the observed number of D^0 decays into four charged hadrons, can be exploited to yield the ratio of the cross-sections $\sigma(\mathrm{D}^0)/\sigma(\mathrm{CC})$. The topological branching fraction into two charged particles is obtained using this external measurement the ratio of $B(\mathrm{D}^0 \to \mathrm{V4})/B(\mathrm{D}^0 \to \mathrm{V2})$: $B(\mathrm{D}^0 \to \mathrm{V2}) = 0.647 \pm 0.049 \pm 0.031$.



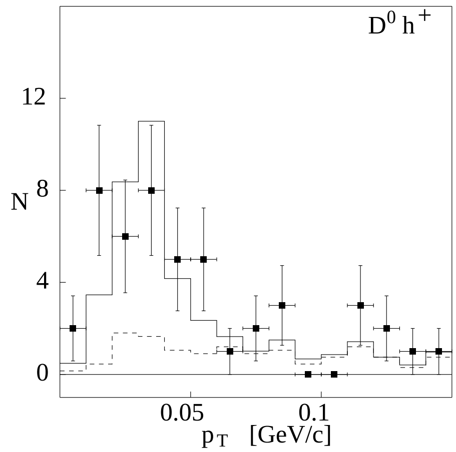


Figure 1: (left) Energy dependence of the cross-section ratio. The data points drawn as full lines show the measurements reported here. The curve through the data points shows the result of the model calculation. (right) Transverse-momentum distribution of positively charged hadron tracks from the primary vertex with respect to the direction of D^0.

Three events were observed with six charged daughter tracks; one obtains $B(\mathrm{D}^0 \rightarrow \mathrm{V6}) = (1.2^{+1.3}_{-0.9} \pm 0.2) \times 10^{-3}$.

From the branching fractions into visible decays, the branching ratio into final states with all neutral daughters can be deduced: $B(\mathrm{D}^0 \rightarrow \mathrm{V0}) = 0.218 \pm 0.049 \pm 0.036$. This result is significantly larger than the sum of measured neutral decay modes [11] ($\approx 5\%$). Wohl [12] predicted a result of $\approx 25\%$ in agreement with this measurement. The relative production cross-section of D^0's in CC interactions with respect to the inclusive CC cross-section can be obtained without making assumptions concerning the branching fractions of the D^0 by using the observed number of decays into four prongs and $B(\mathrm{D}^0 \rightarrow \mathrm{V4})$. With the statistics given in Table 1 a value of $\sigma(\mathrm{D}^0)/\sigma(\mathrm{CC}) = 0.0269 \pm 0.0018 \pm 0.0013$ for the relative rate compared to CC is found.

The measurement of the D^0 production rate relative to the CC interaction rate is shown as function of neutrino energy and compared with the measurements from E531 [13] (dashed errors) in Figure 1. From a fit of models (drawn curve in Fig. 1) to the energy dependence a value of the effective charm quark mass, m_c, can be obtained $m_\mathrm{c} = (1.42 \pm 0.08)$ GeV$/c^2$. An additional systematic error of ± 0.04 is deduced from variations of the assumptions.

The identification of D^{*+} in this experiment is based on its decay into D^0 and π^+ [14]. For each particle track, recognized in the emulsion as originating from the primary vertex, a charge selection is made and the transverse momentum, p_T, with respect to the direction of the D^0 is measured. According to a MC calculation the separation between signal and background is possible only for interactions originating in stacks three and four. The signal-to-background ratio is most favourable in the p_T region from 10 MeV$/c$ to 50 MeV$/c$. Figure 1 shows the p_T distribution of positively charged hadrons originating from the primary vertex

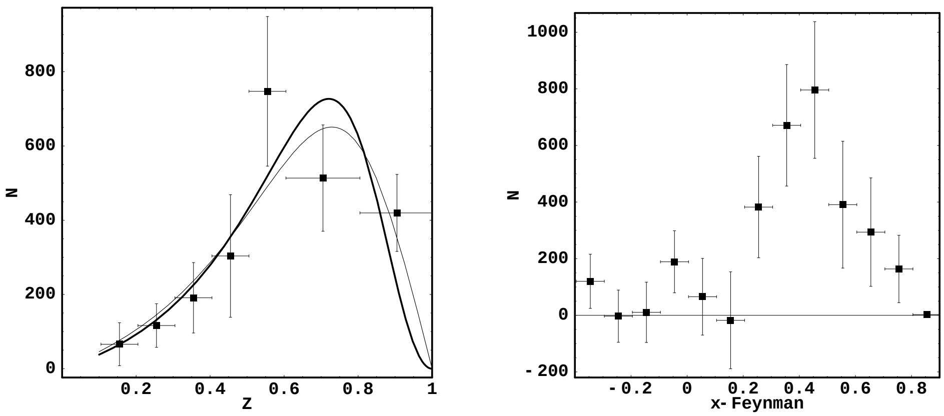


Figure 2: Measured distribution of z (left panel) and x_F (right panel) of the D^0. In the left panel the thicker curve represents the fit to the Peterson *et al.* model, while the thinner one shows the fit to the Collins–Spiller model.

in the D^0 data sample. The drawn histogram represents the expected shape of the candidates (including the background simulation) normalized to the observed events. In the other charge combinations no such signal is found. This behaviour is a clear indication of a signal of D^{*+} decays.

There are 27 events with a positive hadron in the signal region in the D^0 sample. Using the evaluation of the background amounting to 4.9 ± 1.9, a signal of 22.1 ± 5.5 events is obtained.

The most direct measurement which can be obtained is the ratio of D^{*+} and D^0 production; one gets $\sigma(\mathrm{D}^{*+})/\sigma(\mathrm{D}^0) = 0.38 \pm 0.09(\mathrm{stat}) \pm 0.05(\mathrm{syst})$. Under the assumption that the D^{*0} and D^{*+} production rates are equal and recalling that the D^{*0} always decays into a D^0, it can be concluded that most D^0's in neutrino interactions are produced through the decay of a D^* is 0.63 ± 0.17. The rate of D^{*+} meson production relative to the neutrino charged-current interaction cross-section can be obtained as: $\sigma(\mathrm{D}^{*+})/\sigma(\mathrm{CC}) = [1.02 \pm 0.25(\mathrm{stat}) \pm 0.15(\mathrm{syst})]\%$.

To study the fragmentation of charmed quarks into hadrons one usually defines the ratio z of the energy of the charmed particle E^D and the energy transfer to the hadronic system ν. The estimate of ν is obtained from the measurement of the total energy deposited in the calorimeter. The momentum of the D^0, required to define z, is not directly measured. Instead, one can exploit the correlation between the momentum and the angular distribution of the decay products [15] making use of an unfolding procedure [16].

Figure 2 shows the z distribution of all D^0's in the final state. The thicker curve represents the fit result with the value of the Peterson [17] parameter $\epsilon_{\mathrm{p}} = 0.108 \pm 0.017 \pm 0.013$. The fit to the data using the Collins–Spiller [18] approach with ϵ_{cs} as a free parameter, gave a

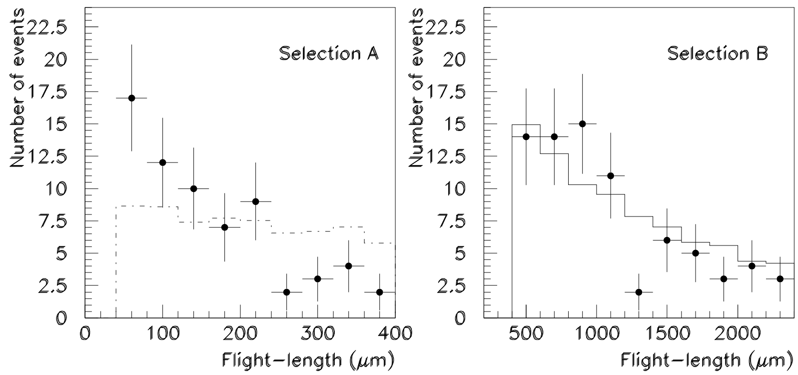


Figure 3: Flight-length distributions of charged charm candidates decaying into three particles. The histograms represent the flight-length distributions given by the Monte Carlo simulation for D^+ and D_s^+, normalized to the number of observed events.

value $\epsilon_{\rm cs} = 0.21^{+0.05}_{-0.04} \pm 0.04$.

It is also customary to describe the fragmentation process in terms of the Feynman x variable (x_F), which is defined as the longitudinal momentum of the charmed particle in the hadronic centre-of-momentum frame, divided by the maximum possible momentum for the particle. Figure 2 shows the x_F distribution of the D^0 production. For the average value we find $\langle x_F \rangle = 0.38 \pm 0.04 \pm 0.03$. The forward–backward asymmetry, A, is found to be $A = 0.79 \pm 0.14 \pm 0.05$ indicating once more that most charmed particles are produced in the forward region.

Charged charm decays in the CHORUS emulsion are coming from three types of parent particles: D^0, dspl and Λ_c^+. Since it is not possible to identify decays on an event-by-event basis, the separation among the different charmed particles is achieved in a statistical manner by exploiting their different lifetimes and hence flight-length distributions [19]. One sample enriched in Λ_c^+ decays (selection A) and another where D^+ and D_s^+ decays should dominate (selection B) have been defined. Figure 3 shows the flight-length distributions for decays into three charged particles for events in the two regions, compared with the expected distributions for the charged charm mesons D^+ and D_s^+ normalized to the observed number of events. A difference in shape and an excess of events is visible in the region of small flight lengths (below 200 μm) for selection A and it constitutes evidence for Λ_c^+ decays.

Normalizing to the number of CC events in the sample, a value of $(1.54 \pm 0.35(stat) \pm 0.18\ (\text{syst})) \times 10^{-2}$ is measured for $\sigma(\Lambda_c^+)/\sigma(\text{CC})$.

Charmed hadrons produced through quasi-elastic processes can be isolated by selecting events with a small number of charged particles at the interaction vertex with the additional constraint of the observed decay vertex [20]. A total of 72 decays were confirmed by a visual inspection. Figure 4 shows E_{EM}, the energy measured in the first sector of the calorimeter, for the candidate events. The distribution is compared with that expected for DIS production of charmed hadrons. An excess of events is visible in the energy region below 2 GeV. This region enhances the quasi-elastic charm signal, only events with $E_{EM} \leq 2$ GeV are considered for further analysis. In the plane perpendicular to the beam a Λ_c^+ produced in a quasi-elastic process is expected to be back-to-back with respect to the muon. In Fig. 4 the Φ distribution for events with $E_{EM} \leq 2$ GeV is compared with the Monte Carlo expectations. A signal of 17 events with a background of 1.7 events is found. Combining this result with the total production of Λ_c we can conclude that 0.15 ± 0.09 of all Λ_c baryons are produced through quasi-elastic processes.

It is more difficult to distinguish the D^+ and D_s^+. A separation among them is achieved in a statistical approach by exploiting the difference of lifetimes of Λ_c^+, D^+ and D_s^+. The momentum of the charmed hadrons can be estimated exploiting the correlation between the momentum and the angular distribution of the decay products. A likelihood function is constructed for each event using only the decay lifetime information. The one-prong and three-prong sample are fitted separately. Combining the result of the fit with the D^0 cross-section [1] we find the fractional contribution of charmed hadrons: $f_{D^0} = (45.7 \pm 3.0)\%$, $f_{\Lambda_c^+} = (18.5 \pm 3.6)\%$, $f_{D^+} = (24.5 \pm 3.8)\%$, $f_{D_s^+} = (11.3 \pm 4.7)\%$. Including also the result obtained for neutral charmed hadrons in Ref. [10], the inclusive charm production rate in neutrino charged-current interactions is $\sigma(\nu_\mu N \to \mu^- CX)/\sigma(\nu_\mu N \to \mu^- X) =$

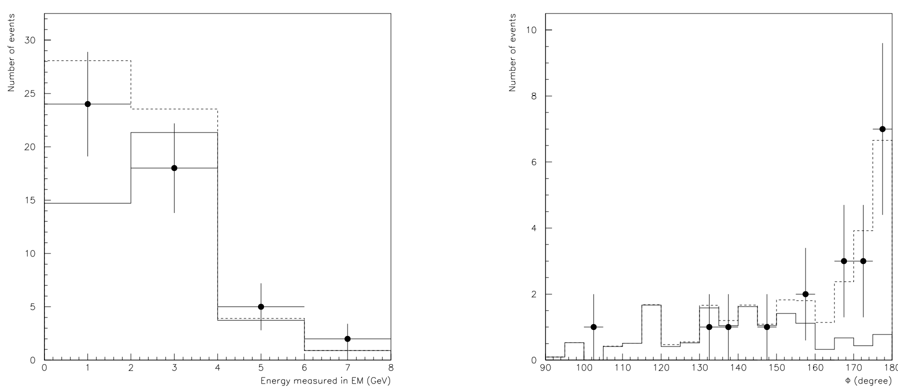


Figure 4: (left) Energy measured in the first sector of the calorimeter (EM) for charged charm candidates. The solid line shows the energy distribution given by Monte Carlo simulation for deep-inelastic charm production. The dashed line shows the effect of an additional 10% contribution from quasi-elastic charm production. (right) Azimuthal angle between the primary muon and the charmed particle trajectory in the transverse plane, for events with $E_{EM} \leq 2$ GeV. The solid and dashed lines are the expectations from deep-inelastic scattering and deep-inelastic scattering and quasi-elastic simulations, respectively.

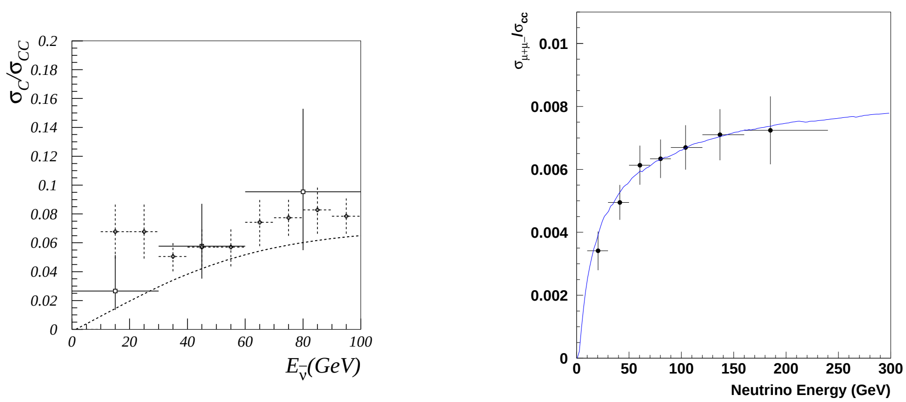


Figure 5: (left) Charm production rate in $\bar{\nu}_\mu$ CC interactions as a function of the anti-neutrino energy: measured in CHORUS (empty box) and derived from di-lepton data (dashed lines) using the muonic branching ratio B_μ given by Ref. [22]. The line shows the theoretical prediction obtained from a leading-order calculation with $m_c = 1.31$ GeV$/c^2$ [23]. (right) Opposite-sign di-muon production relative cross-section. The solid line represents the Monte-Carlo prediction obtained.

$(5.88 \pm 0.32)\%$, where the error is statistical only[1].

Charged-current interactions of the anti-neutrino contamination in the beam can be tagged using the outgoing muon charge [21]. For 2704 of the charged-current events reconstructed in the emulsion, the charge of the muon is found to be positive. A value of $\sigma(\bar{\nu}_\mu N \to \mu^+ \bar{c} X)/\sigma(\bar{\nu}_\mu N \to \mu^+ X) = (5.0^{+1.4}_{-0.9}(\text{stat}) \pm 0.7(\text{syst}))\%$ is obtained for the charm production rate in charged-current interactions induced by $\bar{\nu}_\mu$ normalized to the $\bar{\nu}_\mu$CC sample. Figure 5 displays the cross-section ratio as a function of the anti-neutrino energy (below 100 GeV), together with the corresponding results derived from di-lepton data and with the theoretical prediction.

Taking advantage of the manual measurement of the decay topology, the muonic branching ratio is determined separately on the basis of the number of charged daughters of the charmed particle [24]. The number of events is sufficient to determine the average muonic branching fraction directly from the number of charm events with a secondary muon in the final state, with an uncertainty comparable with that obtained by existing, indirect, measurements.

The result of applying the selection criteria for muons to tracks emerging from secondary vertices is shown in Table 1 for each decay topology separately. The measurement of the muonic decay branching ratio of the D^0 yields $B_\mu(\mathrm{D}^0) = [6.5 \pm 1.2\ (\text{stat}) \pm 0.3\ (\text{syst})] \times 10^{-2}$.

[1] This result is preliminary.

Table 1: Number of secondary tracks identified as muons in real data, background normalized to the number of selected tracks, and identification efficiency as obtained from simulation. The errors on the identification efficiencies are determined by the limited Monte Carlo statistics. The last column shows muonic branching ratios for different prong samples and their mixtures.

Number of prongs	**Selected**	**Background**	$\varepsilon_\mu^{\rm id}$,%	$\overline{B_\mu}$ (%)
C1	20	0.8	36.0 ± 3.4	10.8 ± 2.4 ± 0.5
V2	34	9.8	34.5 ± 1.9	8.3 ± 1.4 ± 0.4
C3	17	8.4	26.4 ± 2.6	6.1 ± 1.6 ± 0.6
C1+C3	37	9.2	31.7 ± 3.1	8.6 ± 1.4 ± 0.4
V2+V4	36	9.8	30.1 ± 1.5	8.1 ± 1.5 ± 0.3
Inclusive	73	19.0	30.4 ± 2.1	7.3 ± 0.7 ± 0.2

This result is in agreement with the value $(6.6 \pm 0.8) \times 10^{-2}$ quoted in Ref. [11]. The inclusive muonic branching ratio for the complete sample of charm hadrons is determined to be $\overline{B_\mu} = [7.3 \pm 0.8\ (\text{stat}) \pm 0.2\ (\text{syst})] \times 10^{-2}$.

In neutrino-nucleon deep-inelastic scattering, events that present two muons in the final state are mainly due to the muonic decay of a charmed hadron produced in a neutrino charged-current interaction. The sample of neutrino induced charged-current di-muon events produced in the lead-scintillating fibre calorimeter of the CHORUS detector represents the second largest data-set to date [25]. The primary muon and the decay muon have opposite electric charge. The number of observed di-muon events depends on the charm quark mass ($m_{\rm c}$) via the slow rescaling mechanism, the amount of strange quark sea (κ), the fragmentation parameter ($\epsilon_{\rm P}$) and on the branching ratio of charm into muon (B_μ). A total of 8910 ± 180 events with a leading μ^- and 430 ± 60 events with a leading μ^+ were selected. The result of this leading order analysis can be summarized as follows:

$$\begin{aligned} m_{\rm c} &= (1.26 \pm\ 0.16(\text{stat}) \pm\ 0.09(\text{syst}))\ \text{GeV}/c^2 \\ \kappa &= 0.33 \pm\ 0.05(\text{stat}) \pm\ 0.05(\text{syst}) \\ \epsilon_{\rm P} &= 0.065 \pm\ 0.005(\text{stat}) \pm\ 0.009(\text{syst}) \\ B_\mu &= 0.096 \pm\ 0.004(\text{stat}) \pm\ 0.008(\text{syst}) \end{aligned} \tag{1}$$

Results of this analysis compare well with earlier analyses of events originating in the nuclear emulsion target of the CHORUS experiment. The result is shown in Fig. 5 where statistical and systematic errors have been added in quadrature.

Among the multi-muon events produced in the calorimeter, 42 $\mu^-\mu^-\mu^+$ tri-muon events were selected and their kinematical properties investigated [26]. Detailed Monte Carlo simulations show that more than half of the tri-muon events can be attributed to the production and muonic decay of light neutral mesons and resonances. Muons from π^- and $\rm K^-$ decays in charm di-muon events are responsible for an additional ≈25% contribution to the total $\mu^-\mu^-\mu^+$ rate. The remaining 25% of events are likely to come from the internal bremsstrahlung of virtual photons into a muon pair. Associated-charm production with subsequent decays of both charmed particles into muons is a negligible component of this sample.

A search for associated charm production both in neutral and charged-current neutrino-nucleus interactions was performed using the data sample of confirmed charm events in the emulsion shown in Table 1 [27, 28]. Two processes can contribute to this reaction: boson-gluon fusion (only in NC interactions) and gluon bremsstrahlung (NC and CC). Four events were observed with two charm decays: three in NC and one in CC interactions. An overall background of 0.18 $\pm$ 0.06 events is expected in CC interactions, mainly from white interactions and a background of 0.18 $\pm$ 0.05 events is estimated in the 0μ sample. The main background source for the double charm production in NC interaction comes from charged lepton misidentification in CC double charm events.

The value obtained for rate of NC associated charm production relative to the total neutrino flux with 27 GeV average neutrino energy is $\sigma(c\bar{c}\nu)/\sigma_{\rm NC}^{\rm DIS} = (3.62^{+2.95}_{-2.42}(\text{stat})\pm 0.54(\text{syst}))\times 10^{-3}$. Our result is compatible with the prediction of the Z^0-gluon fusion model [29]. In the framework of this model, one obtains the relative rate of NC associated charm production as $\sim 4\times 10^{-3}$.

With the observation of one event for associated charm production in CC interactions, we obtain for the relative rate an upper limit at 90% C.L. [30] of $\sigma(c\bar{c}\mu^-)/\sigma_{\rm CC} < 9.69\times 10^{-4}$, normalizing to the total neutrino flux. The cross-section predicted by the QCD inspired parton model [31] has a strong energy dependence. Although the cross-section of this process at the average energy of the CHORUS ν_μ beam is low, the measured production rate is in agreement with the prediction of the QCD inspired parton model. The relative rate of CC associated charm production is calculated to be $\sim 2\times 10^{-4}$ within the framework of this model. The *a posteriori* probability that the background for the topology with two neutral decays gives one event is 0.016. Taking into account that this was not the only topology searched for, it is difficult to convert this into a uniquely defined confidence level. However, given the special topology, it is very likely that this event constitutes an observation of associated charm production in CC interactions.

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