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MEASUREMENT OF D^0 PRODUCTION IN NEUTRINO CHARGED-CURRENT INTERACTIONS

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Abstract

During the years 1994–1997, the emulsion target of the CHORUS detector was exposed to the Wide Band Neutrino Beam from the CERN-SPS. About 170,000 neutrino interactions were successfully located in the emulsion. Improvements in the automatic emulsion scanning systems and application of different criteria allowed the sample of located events to be used for studies of charm production. We present a measurement of the production rate of D^0 mesons based on a sample of 25693 located ν_μ charged-current (CC) interactions analysed so far. After reconstruction of the event topology in the vertex region, 283 D^0 decays were observed with an estimated background of 9.2 K^0 and Λ decays. The ratio of cross-section of D^0 production and ν_μ CC interactions is found to be (1.99±0.13(*stat.*)±0.17 (*syst.*))$\times 10^{-2}$ at 27 GeV average ν_μ energy.

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1 Introduction

Charm production in neutrino charged-current (CC) interactions has been studied in several experiments, in particular, CDHS [1], CCFR [2], CHARM [3], CHARM-II [4], NOMAD [5] and NuTeV[6] by means of electronic detectors and through the analysis of dimuon events. In those events, the leading muon is interpreted as originating from the neutrino vertex and the other, of opposite charge, as the product of the charmed particle semileptonic decay. Experiments of this type, however, suffer from significant background ($\sim 30\%$) in which the second muon originates from an undetected decay in flight of a pion or a kaon rather than from a charm decay. Moreover, the type of charmed particle and its decay topology can not be identified in these experiments. Nevertheless, they have provided measurements of the strange quark content of the nucleon as well as an estimate of the charm quark mass.

A much lower level of background can be achieved using an emulsion target which provides a sub-micron spatial resolution, and hence, the topological identification of charmed hadron decays. However, the statistics accumulated in this way, in particular in the E531 experiment at FNAL [7], was limited. Only recently, with the development of automatic scanning devices of much higher speed within CHORUS have studies of charm production with high statistics become possible.

In this paper the first results on D^0 production obtained from a sample of the CHORUS data are reported.

2 The experimental apparatus

The CHORUS detector [8] is a hybrid setup that combines a nuclear emulsion target with various electronic detectors. The nuclear emulsion is used as target for neutrino interactions, allowing three-dimensional reconstruction of short-lived particles like the τ lepton and any charmed hadron. The emulsion target, which is segmented into four stacks, has an overall mass of 770 kg, each of the stacks consisting of eight modules of 36 plates of size 36 $\times$ 72 cm^2. Each plate has a 90 μm plastic support coated on both sides with a 350 μm emulsion layer [9]. Each stack is followed by three interface emulsion sheets with a 90 μm emulsion layer on both sides of an 800 μm thick plastic base and by a set of scintillating fibre tracker planes. The interface sheets and the fibre trackers provide accurate predictions of particle trajectories into the emulsion stack for the location of the vertex positions. The accuracy of the fibre tracker prediction is about 150 μm in position and 2 mrad in the track angle.

The emulsion scanning has been performed by fully automatic microscopes equipped with CCD cameras and a read-out system, called *Track Selector* [10]. In order to recognize track segments in an emulsion, a series of tomographic images are taken by focusing at different depths in the emulsion thickness. The digitized images are shifted according to the predicted track angle and then added. The presence of aligned grains forming a track is detected as a local peak of the grey level of the summed image. The track finding efficiency of the track selector is higher than 98% for track slopes less than 400 mrad.

The electronic detectors downstream of the emulsion target include a hadron spectrometer which measures the bending of charged particles in an air-core magnet, a calorimeter where the energy and direction of showers are measured and a muon spectrometer which determines the charge and momentum of muons.

3 Data collection

The West Area Neutrino Facility (WANF) at CERN provides a beam of 27 GeV average energy consisting mainly of ν_μ with a 5% $\bar{\nu}_\mu$ contamination. During the four years of operation the emulsion target was exposed to the beam with an integrated intensity which corresponds to

5.06×10^{19} protons on target. The data from the electronic detectors were analysed and the set of events possibly originating from the emulsion stacks was identified.

Since the CHORUS experiment was designed primarily to search for $\nu_\mu \rightarrow \nu_\tau$ oscillation, the data selection for the first phase of the analysis was optimized for the detection of a τ decaying into a single charged particle. The selection criteria are described in [11]. It should be noted that among the events containing one reconstructed muon track of negative charge ('one-mu' sample), only those with a muon momentum less than 30 GeV/*c* were selected for emulsion scanning. This cut has a marginal effect on the τ signal but plays a more important role in the present study of charm production. In order to correct for the effect of this cut, about 3000 ν_μ CC events with a muon momentum greater than 30 GeV/*c* were located and analysed.

The emulsion scanning of a one-mu event starts at the impact point position of the reconstructed muon track in the interface sheets. The track segments found in these sheets are then used to predict with high accuracy the position and angle of the muon track at the exit of the emulsion stack. The track is then followed from one plate to the next using the segments in the most upstream 100 μm part of each plate. The interaction vertex is assumed to be located if the track is not observed in two consecutive plates, the first of which is defined as the 'vertex plate'. This plate may contain the primary or the decay vertex, or both. The efficiency of this scan-back procedure has only a weak dependence on the momentum and angle (up to 400 mrad) of the particle.

The data flow of the one-mu sample is summarized in Table 1.

Table 1: Data flow of the one-mu sample.

	number of events
vertex predicted in emulsion	713,000
$p_\mu < 30$ GeV/*c* and angular selections	477,600
scanned	355,395
located	143,742
analysed with netscan	22,415 + $3,278^\dagger$

† muon momentum larger than 30 GeV/*c*.

To perform the search for charm decays, a new method called 'netscan' is applied. This method originally developed for the DONUT experiment [12] consists in recording all track segments within a large angular acceptance in a volume surrounding the located vertex position. In our application, the scan volume is 1.5 mm wide in each transverse direction and 6.3 mm long, corresponding to eight plates, i.e. the vertex plate, one plate upstream and six downstream (see Figure 1). The parameters (positions, slopes, pulse heights, etc.) of all track segments with angles below 400 mrad found in this volume are stored in a database. Typically, five thousand track segments are recorded per event. With the scanning systems used, the netscan of one event takes about 11 min. The results presented here are based on a sample of 25,693 events analysed with this method.

4 Reconstruction and selection of decay topologies

The offline reconstruction program first aims to select from the large number of recorded track segments only those belonging to the neutrino interaction under study. It consists of the following steps:

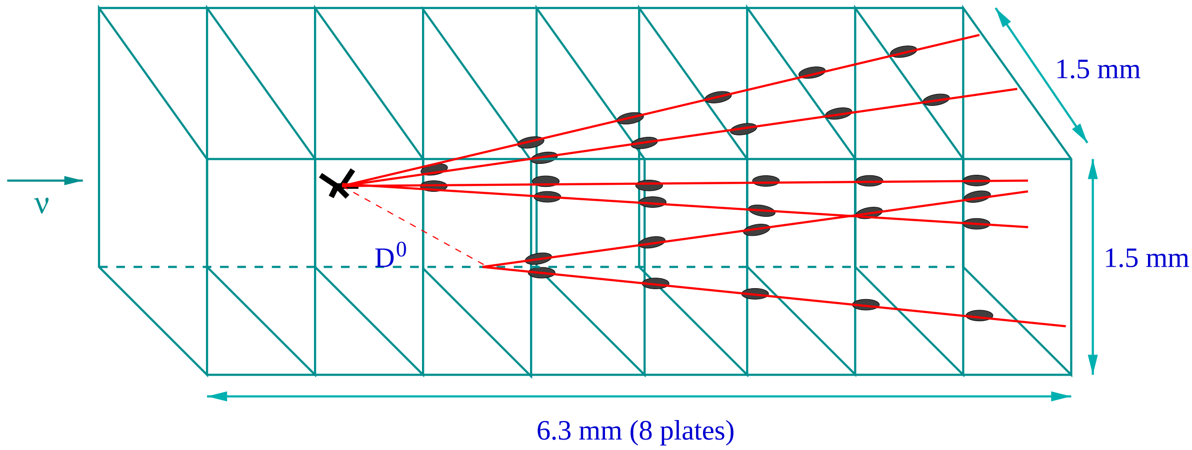

Figure 1: The netscan volume with a sketch of a D^0 decay. The ellipses represent track segments in 100 μm emulsion layers in which automatic scanning is performed. Offline programs reconstruct the tracks and associate them to common vertices.

– A first plate-to-plate alignment is performed by comparing the pattern of segments in a plate with the corresponding pattern in the next upstream plate.
– Each segment of a plate is extrapolated to the next plate where a matching segment is looked for within about 4 μm (3σ of alignment resolution) in position and 20 mrad in angle. If none is found, the extrapolation is tried one plate further upstream.
– After connection of all matched segments, a second and more accurate alignment of the plates is performed using tracks passing through the entire volume, mainly from muons associated with the neutrino beam or charged particle beams in the same experimental area. After this alignment, the residual of the segment positions with respect to the fitted track is measured to be about 0.45 μm.
– At this stage, about 400 tracks remain in the fiducial volume. The majority of them can be recognized as due to low energy (typically less than 100 MeV) particles (mainly Compton electrons and δ rays) and can be discarded. Moreover, tracks are selected on the basis of the χ^2 of the fit to a straight line.
– The final step is the rejection of the tracks passing through the scanning volume. After this filtering, the mean number of tracks originating in the scan volume is about 40.

The program then tries to associate these tracks to common vertices. A detailed description of the algorithms to reconstruct the vertices is given in [13]. In short, a track is attached to a vertex if the distance of the vertex point to the track line (called hereafter impact parameter) is less than 10 μm. At the end of the procedure, one defines a primary vertex (and its associated tracks) and possibly one or more secondary vertices to which 'daughter' tracks are attached.

To select interesting decay topologies while preserving a good efficiency for D^0 detection, the following selection is applied:

– The primary muon track and at least one of the daughter tracks are detected in more than one plate and the direction measured in emulsion matches that reconstructed in the fibre tracker system.
– The impact parameter to the vertex of at least one of the daughter tracks is larger than a

value which is determined on the basis of the resolution. [1)]

– The impact parameter must also be smaller than 400 μm. This cut mainly rejects spurious tracks not related to the neutrino interaction.

From the present sample of 25,693 analysed events, these criteria select 851 events which are visually inspected (eye-scan) to confirm the decay topology. A secondary vertex is accepted as a decay if the number of prongs is consistent with charge conservation and no other activity (Auger electron or *blob*) is observed. The result of the visual inspection is given in Table 2. The purity of the automatic selection is found to be 63%.

Table 2: Results of visual inspection (eye-scan) of candidates.

Accepted events		Rejected events	
V2	226	low momentum	174
V4	57	hadron int.	68
C1	121	γ- conversion	42
C3	124	δ-ray	2
C5	7	other	30
Total	535		316

The observable decay topologies are classified as odd-prong decays of a charged particle (mainly D^+, D_s^+, Λ_c^+) or even-prong decays of a neutral particle (mainly D^0). These are denoted in Table 2 as V2 or V4 for neutral and C1, C3 or C5 for charged decays according to the multiplicity.

The rejected sample consists mainly of hadronic interactions, delta rays or gamma conversions ($\sim 35\%$) and of low momentum tracks which, due to multiple scattering, appear as tracks with a large impact parameter ($\sim 55\%$). The remaining 10% consists either of false vertices, being reconstructed using one or more background tracks, or of vertices with a parent track not connected to the primary vertex.

The confirmed D^0 sample (V2 and V4) contains 283 candidates. For 34 of these events (25 V2 and 9 V4) the muon momentum is greater than 30 GeV/*c*.

5 Reconstruction efficiency and background evaluation

Efficiencies and backgrounds were evaluated with a GEANT3 [14] based simulation of the experiment. Large samples of neutrino interactions were generated according to the beam spectrum using the JETTA [15] generator derived from LEPTO [16] and JETSET [17]. Quasi-elastic reactions were generated with the RESQUE [18] package with a rate of 8.5% relative to deep inelastic scattering reactions.

The simulated response of the CHORUS electronic detectors is processed through the same reconstruction program used for the data. The tracks in emulsion and the performance of the track selector are also simulated in order to evaluate the efficiency of the scanning procedure.

The ratio of reconstruction and location efficiency of events with a D^0 in the final state to that of all ν_μ CC events is found to be 0.87 ± 0.01. An additional 4% uncertainty on this ratio is estimated by varying the conditions of the simulation.

[1)] The impact parameter is required to be greater than $\sqrt{3^2 + (2\sigma dx)^2}$ μm; $\sigma = \sqrt{0.00305^2 + (0.0194\theta)^2}$ is a parametrization of the angular error and dx is the distance of the vertex to the most upstream daughter track segment.

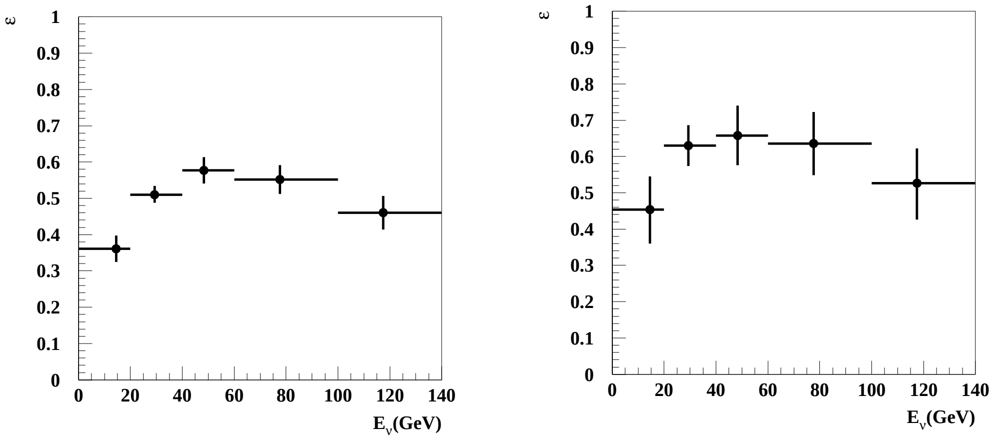

Figure 2: Detection efficiency as a function of E_ν for V2 (left) and V4 (right) topologies. The error bars are statistical uncertainties in the simulation.

In order to evaluate the netscan efficiency, realistic conditions of track densities need to be reproduced. This was achieved by merging the emulsion data of the simulated events with real netscan data which do not have a reconstructed vertex but contain tracks which stop or pass through the netscan fiducial volume, representing the real background. The combined data are passed through the same netscan reconstruction and selection programs used for real data.

The mean efficiencies of the different steps of the netscan analysis are presented in Table 3, separately for V2 and V4 D^0 decay topologies.

Table 3: Efficiencies of the netscan analysis for D^0 decays into V2 and V4 topologies. The errors quoted are statistical only.

	V2(%)	V4 (%)
ε_{geo}	96.6±0.2	96.3±0.5
ε_{net}	88.5±0.4	95.2±0.6
ε_{sel}	68.6±0.6	76.4±1.1
combined	58.6±0.7	70.1±1.3

In this table:

- ε_{geo} is the geometrical acceptance of the netscan volume.
- ε_{net} reflects the performance of the filtering and vertexing algorithms discussed in Section 4.
- ε_{sel} measures the efficiency of the specific selection criteria applied in this analysis. Among these criteria the most sensitive one is the requirement that at least one of the decay daughters matches the angles of a track reconstructed in the fibre tracker. This matching efficiency can be directly measured from the ratio of observed V2 events with one matched prong to those with two matched prongs and is found to be $(70.5 \pm 2.6)\%$, in good agreement with the simulation result $(70.7 \pm 2.0)\%$.

The systematic uncertainties of the netscan efficiencies arise mainly from the choice of the event generator and from variations in the emulsion data quality. By comparing the results obtained with samples generated with different structure functions (EHLQ [19], GRV [20]) and different charm fragmentation functions (Peterson model [21], Bowler model [22]), we estimate the first source of systematic error to be 4.6%. The second contribution is estimated to be 2% by merging the generated events with different sets of spurious netscan data corresponding to different track densities and different alignment accuracies. The average efficiency of the D^0 decay search is found to be $(58.6 \pm 5.1)\%$ for V2 and $(70.1 \pm 5.2)\%$ for V4, where the errors combine statistical and systematic uncertainties in quadrature. The combined detection efficiency (including the factor 0.87 quoted above) is shown in Figure 2 as a function of neutrino energy. By processing with the same chain of programs ν_μ CC interactions with no D^0 in the final state, the background rate is evaluated to be $(3.6 \pm 1.0) \times 10^{-4}$ per located CC event. In the present sample of 25,693 events this corresponds to 9.2 ± 2.6 background events, mainly K_s^0 and Λ^0 decays. No strong energy dependence of this background is observed.

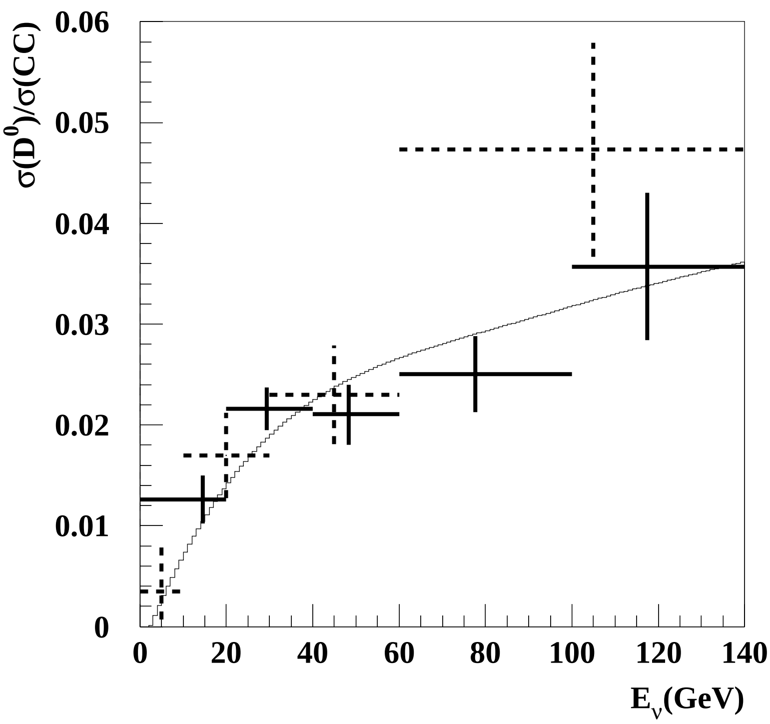

Figure 3: D^0 production rate as a function of neutrino energy. The results of this analysis are shown as solid lines and compared with those of the E531 experiment (dashed lines). The data points of E531 have been scaled with their measurement of the D^0 rate [7] compared to the total charm production rate. The curve shows a fit based on the slow rescaling model [24] to NOMAD charm data [5] multiplied by the (D^0/charm) cross-section ratio measured in the present experiment.

6 Results and conclusion

To estimate the D^0 production rate in ν_μ CC interactions, an additional weight factor needs to be applied to the 34 D^0 events (25 V2 and 9 V4) observed in the sample with $P_\mu >$ 30 GeV/*c*, since only a subset of this category of events has been analysed with the netscan procedure so far. This factor was found to be equal to 2.6 and was evaluated from the measured ratio of 0.381 ± 0.001 between CC events with $P_\mu >$ 30 GeV/*c* and $P_\mu <$ 30 GeV/*c* and the size of the samples (see Table 1) included in the current analysis.

Taking into account the estimated efficiencies and background described in Section 5, one obtains an average ratio of

$$\frac{\sigma(D^0)}{\sigma(\mathrm{CC})} = (1.99 \pm 0.13(stat.) \pm 0.17(syst.)) \times 10^{-2}.$$

This result is in good agreement with that of E531 [7] (dashed crosses in Figure 3) based on a statistically less significant sample. The topological ratio V4/V2 is found to be $(23.1 \pm 4.0) \times 10^{-2}$ in agreement with the world average value $(20.1^{+2.7}_{-1.9}) \times 10^{-2}$ [23].

In past years, analyses of events with opposite-sign dimuons in the final state in electronic detectors have provided a large amount of information. In particular, the charm (neutral and charged) production rate as a function of energy has been determined and a value for m_c, the effective mass of the charm quark, has been estimated within the formalism of slow rescaling [24].

Among the other experiments, NOMAD, which was exposed to the same neutrino beam as CHORUS, has given a measurement of charm production extending to low energies. Using the NOMAD [5] results on the total charm production and on the muonic branching ratio of charmed particles, $B_c = 0.095^{+0.007}_{-0.007}{}^{+0.014}_{-0.013}$, the value of 0.53 ± 0.11 has been obtained for the ratio $\sigma(D^0)/\sigma$(charm) in the energy range of the experiment ($\left\langle E_{\nu_\mu} \right\rangle = 27$ GeV).

The slow rescaling model with $m_c = 1.3\ \mathrm{GeV}/c^2$ which fits the NOMAD data is superimposed to the data points of Figure 3 and it agrees well with the energy behaviour of the cross-section ratio measured in emulsion experiments.

A second phase of analysis of the CHORUS data has started, with improved reconstruction codes and scanning systems. In about one year, a sample of 3000 charm events will be collected. A detailed and essentially background-free study of all the charm production processes will then become possible.

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