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Measurement of D^{*+} production in charged-current neutrino 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 of the CERN SPS of 27 GeV average neutrino energy. In total about 100 000 charged-current neutrino interactions were located in the nuclear emulsion target and fully reconstructed. A high-statistics sample of neutrino interactions with a D^0 in the final state was collected. Using the decay mode $D^{*+} \to D^0\pi^+$ a production cross-section measurement of the D^{*+} in neutrino–nucleon charged-current interactions was performed. The low Q-value of the decay was used to isolate a sample of candidate events containing a positive hadron with a small p_T with respect to the D^0 direction. A signal of 22.1 ± 5.5 D^{*+} events was obtained. The D^{*+} production cross-section relative to the D^0 production cross-section, $\sigma(D^{*+})/\sigma(D^0)$, was estimated to be $0.38 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$. From this result, the fraction of D^0's produced via the decay of a D^* was deduced to be 0.63 ± 0.17. The D^{*+} production cross-section relative to the ν_μ charged-current interaction, $\sigma(D^{*+})/\sigma(\text{CC})$, was estimated to be $[1.02 \pm 0.25(\text{stat}) \pm 0.15(\text{syst})]\%$.

1. Introduction

The measurement of the D^{*+} production cross-section and its comparison with the total D^0 production cross-section gives some insight into the charm production mechanism. In particular, the ratio of charmed vector meson and scalar meson production in deep-inelastic scattering can be obtained.

Several experimental groups have performed a study of D^{*+} production in neutrino charged current interactions [1–3]. In these experiments the identification of charmed particles relied mainly on reconstructing the invariant mass of the assumed decay products.

In emulsion experiments charm production can be observed without the need to reconstruct the invariant mass. The tracking in emulsion has enough spatial resolution to clearly separate the charm decay vertex from the primary neutrino interaction vertex. In hybrid experiments, combining the emulsion technique with electronic detectors, the high spatial resolution at the neutrino and decay vertices can be coupled with kine-

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matical measurements of the outgoing particles. This technique has been applied in a neutrino beam by the E531 experiment at FNAL [4]. However, the number of events accumulated was limited.

Recent improvements in automatic emulsion scanning systems made it possible to measure orders of magnitude larger volumes of emulsion. In the CHORUS experiment large-volume data taking around neutrino interactions in the emulsion target was performed and a high statistics of charm decays was collected. In particular, a large sample of neutral charmed-particle (D^0) decays was identified.

In this Letter, a measurement of the D^{*+} production rate in charged-current neutrino interactions is reported. Contrary to the previous experiments which use the reaction $D^{*+} \to D^0\pi^+$ to tag the D^0, in this measurement the D^0 is directly recognized by its decay topology, independently of the presence of the D^{*+} parent. Therefore, the D^{*+} sample is obtained through the recognition of the above reaction as a subset of an already very pure sample of D^0 events. This offers the unique opportunity to measure the D^{*+} production rate relative to the D^0 production cross-section without the need for an external normalization.

2. The experimental set-up

The primary aim of the CHORUS experiment is to search for $\nu_\mu \to \nu_\tau$ oscillation by detecting the characteristic decay topology of the τ lepton produced in ν_τ charged-current interaction. The apparatus was exposed to the CERN SPS wide-band neutrino beam during the years 1994–1997. The accumulated neutrino interactions in the emulsion were analysed by fully automatic scanning systems. Since charmed particles have a lifetime similar to that of the τ lepton, the experiment is also well suited to study charm production.

The CHORUS detector [5] is a hybrid set-up that combines a nuclear emulsion target with various electronic detectors. The emulsion target with a total mass of 770 kg is segmented into four stacks where each stack consists of eight modules of 36 plates with a size of 36 cm × 72 cm. Each stack is followed by an interface emulsion sheet and by a set of scintillating-fibre tracker planes [6]. The high spatial resolution of the nuclear emulsion target makes it possible to perform a three-dimensional reconstruction of neutrino interaction vertices and the decays of short-lived particles such as τ leptons and charmed hadrons.

Tracks found in the scintillating-fibre tracker planes are used to predict the position of neutrino interactions in the target. In particular, for charged-current events, the track of the primary muon is used to predict with high precision the point where it traversed the interface emulsion sheet. The interaction vertex is located by following the track upstream from plate to plate. The emulsion scanning is performed by computer-controlled, fully automatic microscopes equipped with CCD cameras [7,8]. The track-finding efficiency of the scanning system is higher than 98% for track slopes less than 400 mrad with respect to the direction perpendicular to the emulsion plates [9]. In a volume around the located interaction point full data-taking is performed using the 'NetScan' method first used for the DONUT experiment [10]. The procedure used for this study has been described in detail in a previous publication [11].

The target region is followed by a hadron spectrometer, an electromagnetic and hadronic calorimeter, and a muon spectrometer, respectively. The hadron spectrometer is composed of diamond-shaped scintillating-fibre planes [6] upstream and downstream of a hexagonal air-core magnet [12]. The diamond-shaped scintillating-fibre planes are complemented by a 'honeycomb' tracking system [13] at the downstream side, and by the tracker planes in the target region to measure the magnetic deflection. The resolution of the hadron spectrometer is $\Delta p/p \approx 30\%$ for low momenta in the momentum range relevant for this study. Muons are identified by their range in the calorimeter and the muon spectrometer. The muon spectrometer consists of magnetized iron toroids interspersed with drift chambers, streamer tubes, and scintillator planes. It is used to determine the charge and momentum of muons.

3. Event reconstruction and selection of decay topologies

The identification of D^{*+} in this experiment is based on its decay into D^0 and π^+

$$D^{*+} \to D^0\pi^+. \tag{1}$$

The reconstruction of the invariant mass of the D^{*+} would require to measure momenta of at least three

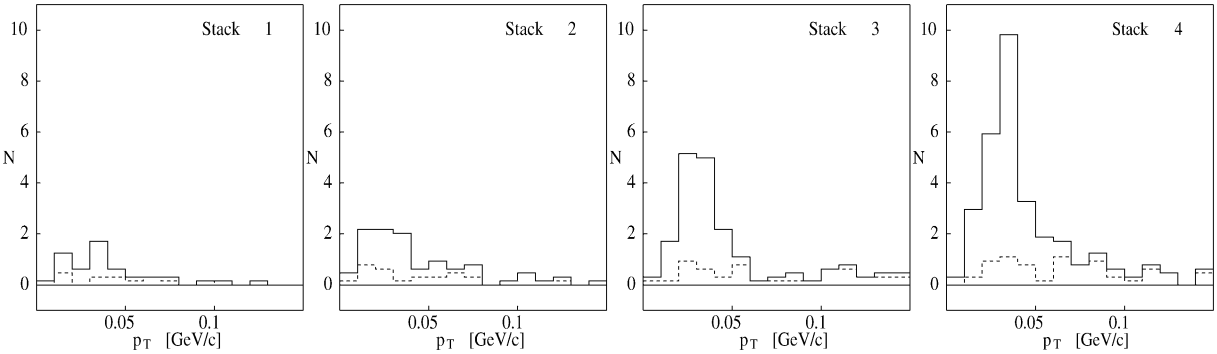

Fig. 1. Simulated transverse-momentum distribution of charged hadrons from the primary vertex with respect to the D^0 direction. The meaning of the histograms is explained in the text. The four panels show the simulation for the four emulsion stacks, stack one being the most upstream stack.

charged hadrons (the π^+ from the D^{*+} decay and two charged decay daughters of the D^0 for the most favourable decay mode, $D^0 \to K^-\pi^+$ with a branching ratio of $(3.80 \pm 0.09)\%$ [14]). Such a strategy would introduce a very small efficiency and has therefore not been followed.

The procedure used relies on the high purity of the sample of D^0 events recognized by the decay topology and by the low Q-value of the D^{*+} decay (corresponding to a maximum p_T of 39 MeV$/c$ [14]). As a consequence, the π^+ from the D^{*+} decay has a relatively low momentum (< 4 GeV$/c$) and small angle with respect to the D^0 direction. In this two-body decay, the transverse momentum spectrum of the π^+ with respect to the D^0 direction shows a Jacobian peak below 40 MeV$/c$.

The selection starts from the sample of D^0 events, characterized by the decay topology into two or four charged particles and is described in Ref. [11]. In total, the sample contains 1048 D^0 events. 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. The kinematical quantities needed for this approach are the direction of the π^+, the direction of the D^0, and the momentum of the positive pion. In the CHORUS experiment, the track reconstruction in the nuclear emulsion target determines the slope of the charged particles with high precision (resolution of the order of 1 mrad). The measurement of the position of the primary neutrino interaction vertex and the decay vertex of the charmed particle determines the direction of the D^0. The precision depends on the decay length and, for this measurement, only decays more than 100 µm downstream of the interaction are used to ensure good resolution.

The momentum measurement of the particles reconstructed in the emulsion is performed by extrapolating the tracks from the emulsion to the fibre trackers installed downstream of the target and to the tracking detectors located upstream and downstream of the hexagonal magnet. In order to select the tracks with a reliable momentum determination, strict requirements are applied on these measurements. Only tracks with a hit in all six diamond-shaped fibre trackers or with track segments in the honeycomb chambers and a smaller number of hits in the fibre trackers were retained. Of the 1116 tracks reconstructed at the primary vertex, the momentum of 377 particles was measured. The inefficiency can be attributed in about equal parts to secondary interactions in the target material and to the limited geometrical acceptance of the air-core spectrometer.

In order to study the potential separation power between signal and background, the p_T distribution was simulated for the events originating in the four stacks of the emulsion target separately. Fig. 1 shows the p_T distribution of the simulated D^0 candidates (including events where the D^0 was produced from the decay of the D^{*+}), selected by the same charm selection algorithm as used for the data. The drawn histogram is the prediction for combinations of D^0's with positively charged hadrons including the expected signal. The dashed one is the same for the sample of D^0's which do not originate from the reaction $D^{*+} \to D^0\pi^+$. The data for the four stacks are based on the same sim-

Table 1
Number of events and tracks used in the analysis

	In all stacks	In stacks 3 and 4
Number of ν_μ CC events	93 807	
With a visually confirmed D^0 decay	1048	527
D^0 decays selected for analysis (flight length ⩾100 µm)		488
Hadron tracks at the primary vertex		1116
Hadrons from the primary vertex with a measured momentum		377
Charge	Positive	Negative
	248	129
Within angular range	62	26
Within momentum window	47	12
In p_T signal region	27	4

ulated sample and thus predict the relative weight of the signal to be observed in the four stacks. The separation between signal and background is possible only for interactions originating in stacks three and four. Therefore only the events originating in these two most downstream stacks were considered in the analysis. The signal-to-background ratio is most favourable in the p_T region from 10 to 50 MeV/c. This region is used as 'signal region' in the analysis.

The loss of efficiency for the upstream stacks is easy to understand, since the average momentum of the π^+ is low ($\approx 1\ \text{GeV}/c$) in reaction (1). Multiple scattering plays a large role together with re-interaction in the downstream stacks. Thus the matching of the track seen in the emulsion with the hits in the hadron spectrometer has a low efficiency when a large amount of material has been traversed by the particle.

The candidate events were searched within the sample of 488 D^0 events in stacks three and four with a D^0 flight length exceeding 100 µm. After removing tracks identified as muons, 1116 tracks originating from the primary vertex were found in these events. To obtain an enriched sample of candidate events within this sample, the set of kinematical criteria described below was applied.

Since the typical momentum of the π^+ from D^{*+} decay is smaller than 4 GeV/c, hadrons with a momentum greater than this value were not considered. In addition, tracks having a measured momentum smaller than 400 MeV/c were rejected in order to reduce background. These tracks are more likely to come from secondary hadrons and from random coincidences of hits in the tracking system of the hadron spectrometer. A selection on the angle between the hadron and the D^0 smaller than 60 mrad was applied. The simulation showed that the signal does not populate the region of larger angles. For the remaining tracks a separation between positive and negative charges was made and the p_T spectra were further analysed. The result of the event and track selection is given in Table 1.

Fig. 2 shows the p_T distribution of positively charged hadrons and negatively charged hadrons originating from the primary vertex in the D^0 data sample and in a sample of charged charm production events separately. In the figure, the points with error bars show the number of candidates with their statistical error. The dashed histogram shows the background prediction. In the distribution for the D^0 with positive hadrons the drawn histogram represents the expected shape of the candidates (including the background simulation) normalized to the observed events. In the other panels the drawn curve shows the prediction for the shape normalized to the total number of D^0's and charged charm events, respectively. An excess which can be attributed to the signal is visible in the range between 10 to 50 MeV/c in the p_T distribution of positive hadrons in the D^0 sample, while in the p_T distribution of negative hadrons no such excess is seen. In addition, if one makes the same comparison between the p_T spectra of positive and negative hadrons with respect to charged charm particles found in the same stacks and with the same kinematical cuts, no such signal can be seen. This behaviour is a clear indication of a signal of D^{*+} decays. The background and the efficiency for this reaction have to be determined before any quantitative statement can be made.

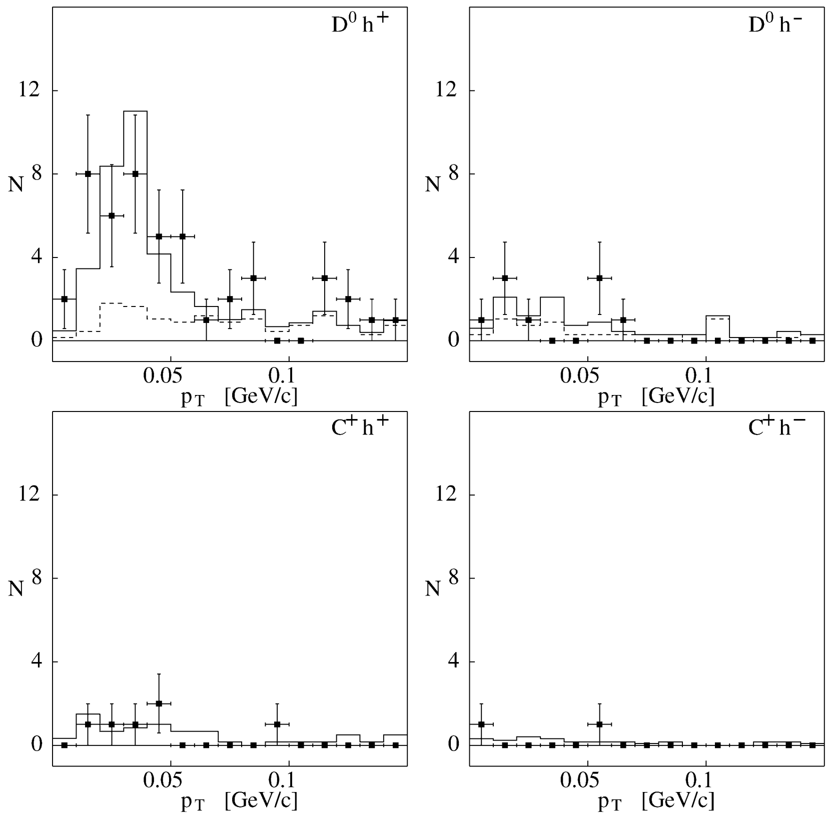

Fig. 2. Transverse-momentum distribution of charged hadron tracks from the primary vertex with respect to the direction of charmed particles. The panel in the left (right) upper corner shows the p_T of positively (negatively) charged hadrons with respect to D^0's and the panel in the lower left-hand (right-hand) corner shows the p_T for positively (negatively) charged hadrons with positively charged charm particles.

4. Efficiency and background evaluation

The detection efficiencies and expected background contamination were evaluated with a detailed Monte Carlo simulation of the experiment based on GEANT3 [15]. GEANT3 was also used for the modelling of the neutrino beam. A large number of deep-inelastic neutrino interactions were generated according to the beam spectrum by the JETTA [16] generator developed from LEPTO [17] and JETSET [18]. The simulated response of the CHORUS electronic detectors was processed through the standard chain of reconstruction programs. The efficiency of the event location and reconstruction in the emulsion was obtained by a detailed simulation of the efficiency and resolution of the NetScan procedure. In order to simulate realistic conditions of background grains in the emulsion, the data of 'empty volumes', i.e., NetScan volumes where no neutrino interaction is present, were overlaid on the simulated events. The main source of background is formed by π^+ tracks from the primary vertex in events with a D^0 which have a p_T with respect to the D^0 in the signal region as defined in Section 3. The number of background events in the signal region was estimated using Monte Carlo D^0 events excluding the events coming from D^{*+} production. The simulated p_T distribution in the π^+–D^0 channel was normalized by comparing the number of events observed in the region $p_T < 0.1\ \mathrm{GeV}/c$ in the π^-–D^0 channel with the data in that channel. The total background is calculated to be $4.9 \pm 1.6(\mathrm{stat}) \pm 1.0(\mathrm{syst})$, where the statistical error comes mainly from the normalization with respect to the events with a π^- (or other negative hadron) and the systematic error is an estimate of the precision of the simulation.

Within the statistical accuracy, the simulated background agrees well with the events observed in the combination of a D^0 with a negative hadron, and for events with charged charm particles combined with positive and negative hadrons, respectively. Only in the channel with a D^0 and a positive hadron, is a clear excess of events above the predicted background observed. The p_T distribution of the excess is compatible with the simulated detector response.

The background to the sample of D^0 events coming from neutral strange particle decays such as Λ^0 and K^0_s is negligible owing to the much longer decay length of these particles. Their number has been evaluated for the four emulsion stacks to be 11.5 ± 1.9 Λ^0's and 25.1 ± 2.9 K^0_s's in the full D^0 sample [19], respectively. Since the calculation of the background coming from randomly associated positive hadrons from the primary vertex in combination with a D^0 has been normalized to the number of negative hadrons with the same kinematic properties, also random associations of a neutral strange particle with a π^+ have been taken into account implicitly. Their number can be estimated to give approximately 0.3×10^{-3} events in the signal region. A potentially larger background is caused by K^* decays into a K^0_s and a π^+. With the assumption that all K^0_s's originate from K^* decay, 0.3 ± 0.1 events would pass the selection criteria. This estimate can thus be regarded as an upper limit for this background.

Since we consider only the ratio of D^{*+} events with respect to the D^0 events, only the efficiency associated with the detection of the π^+ has to be considered. Any energy-dependent effect distinguishing the D^0 from D^{*+} decay from other D^0's, which would spoil the cancellation of the efficiency is very small and is included in the simulation. The efficiencies in locating events of the two types in the emulsion are expected to be equal to a high accuracy.

The important issues related to the π^+ detection are the efficiency in attaching the π^+ to the primary vertex in the reconstruction, in measuring its momentum and the ability of the Monte Carlo chain to simulate the p and p_T resolution correctly. The combined systematic uncertainty in the product of the efficiency to find the π^+ and in the efficiency in measuring its momentum was estimated to be 7%. Such a value is obtained by observing the differences in the fraction of tracks with a measured momentum predicted by the simulation and observed in the data for different track samples. The samples compared were the tracks from primary neutrino vertices with those from D^0 decays. The efficiency in finding the π^+ track at the primary vertex is well reproduced by the simulation, and the uncertainty in this calculation contributes to a smaller extent to the systematic error.

A study of the effects governing the p_T resolution shows that the most critical ingredient is the measurement of the angle of the D^0. From a comparison of measurements using the vertex reconstruction with the tracks found in the NetScan procedure and the vertex measurement in the manual scanning process, an angular resolution of 10 mrad is deduced at short flight paths and 5 mrad at large flight lengths. Using these numbers a 5% uncertainty in the efficiency of the cut in p_T is evaluated.

The overall uncertainty in the efficiency is 11%, which includes the systematic uncertainty in the efficiency in measuring the π^+ momentum, the uncertainty in the effect of the p_T cut and the statistical error of the simulation.

5. Results and conclusion

There are 27 events with a positive hadron in the signal region in the D^0 sample. Using the evaluation of the background as described in Section 4 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 in charged-current neutrino interactions. This ratio can be expressed as

$$\frac{\sigma(D^{*+})}{\sigma(D^0)} = \frac{N(D^{*+} \to D^0\pi^+)}{N(D^0)} \frac{\epsilon(D^0)}{\epsilon(D^{*+} \to D^0\pi^+)} \times \frac{1}{B(D^{*+} \to D^0\pi^+)}, \tag{2}$$

where $N(D^{*+} \to D^0\pi^+)$ and $N(D^0)$ are the number of D^{*+} and D^0 events observed, respectively, and $\epsilon(D^{*+} \to D^0\pi^+)$ and $\epsilon(D^0)$ their relative detection efficiencies. The ratio of these efficiencies is 0.176 ± 0.020. The branching ratio $B(D^{*+} \to D^0\pi^+)$ is 0.677 ± 0.005 [14]. Substituting the numerical values, one obtains

$$\frac{\sigma(D^{*+})}{\sigma(D^0)} = 0.38 \pm 0.09(\text{stat}) \pm 0.05(\text{syst}). \tag{3}$$

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^*:

$$\sigma\left(D^* \to D^0\right)/\sigma\left(D^0\right) = 0.63 \pm 0.17. \tag{4}$$

Following Ref. [20], and defining R_2 as the fraction of D^0's coming from D^{*+} decays, we obtain $R_2 = 0.25 \pm 0.10$ where the statistical and systematic errors are combined. With the definition $f_V = V/(P+V)$, the ratio of the vector D meson production and the sum of vector and pseudoscalar production of D mesons as introduced in Ref. [20], we find $f_V = 0.51 \pm 0.18$. Within the precision, this determination is consistent with the value for the ratio of vector meson and pseudoscalar meson production (three to one) expected from simple spin arguments and with more precise measurements in e^+e^-, πN and γN experiments [21].

The rate of D^{*+} meson production relative to the neutrino charged-current interaction cross-section can be obtained by combining the result in Eq. (3) with the measurement $\sigma(D^0)/\sigma(CC) = 0.0269 \pm 0.0018 \pm 0.0013$ obtained using the same D^0 sample [11].[11] We then obtain

$$\frac{\sigma(D^{*+})}{\sigma(CC)} = \left[1.02 \pm 0.25(\text{stat}) \pm 0.15(\text{syst})\right]\%. \tag{5}$$

The NOMAD experiment [3] operating in the same neutrino beam as CHORUS has reported the rate of D^{*+} production per CC neutrino interaction to be $(0.79 \pm 0.17(\text{stat}) \pm 0.10(\text{syst}))\%$. The BEBC bubble chamber data [1] were reanalysed combining several datasets using a neutrino beam with energies similar to CHORUS. This group reported the rate of D^{*+} production per CC neutrino interaction to be $(1.22 \pm 0.25)\%$. Our result is consistent with these measurements. At the higher energies of the Tevatron beam a value of $(5.6 \pm 1.8)\%$ has been found [2].

[11] The D^0 production rate had been obtained using only the four-prong decay topology for which practically all decay modes are available in the literature. This procedure minimizes the systematic error due to the unmeasured decay modes in the two-prong topology and the decay modes into final states with neutral particles only.

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References

[1] A.E. Asratyan, et al., Z. Phys. C 68 (1995) 43.
[2] A.E. Asratyan, et al., Z. Phys. C 76 (1997) 647.
[3] P. Astier, et al., Phys. Lett. B 526 (2002) 278.
[4] N. Ushida, et al., Phys. Lett. B 206 (1988) 375.
[5] E. Eskut, et al., Nucl. Instrum. Methods A 401 (1997) 7.
[6] P. Annis, et al., Nucl. Instrum. Methods A 412 (1998) 412.
[7] S. Aoki, et al., Nucl. Instrum. Methods B 51 (1990) 466.
[8] T. Nakano, PhD thesis, Nagoya University, Japan, 1997.
[9] M. Güler, PhD thesis, METU, Ankara, Turkey, 2000.
[10] K. Kodama, et al., Nucl. Instrum. Methods A 493 (2002) 45.
[11] CHORUS Collaboration, G. Önengüt, et al., Phys. Lett. B 613 (2005) 105.
[12] F. Bergsma, et al., Nucl. Instrum. Methods A 357 (1995) 243.
[13] J.W.E. Uiterwijk, et al., Nucl. Instrum. Methods A 409 (1998) 682.
[14] Particle Data Group, Phys. Rev. D 66 (2002) 010001.
[15] GEANT 3.21, CERN program library long write up W5013.

[16] P. Zucchelli, PhD thesis, University of Ferrara, Italy, 1996.
[17] G. Ingelman, Preprint TSL/ISV 92-0065, Uppsala University, Sweden, 1992.
[18] T. Sjöstrand, Comput. Phys. Commun. 82 (1994) 74.
[19] M. Sorrentino, CHORUS internal note 2000027 (2004) http://choruswww.cern.ch/Publications/Notes/decaybackground.pdf.
[20] M.P. Alvarez, et al., Z. Phys. C 60 (1993) 53.
[21] G. De Lellis, et al., Phys. Lett. B 550 (2002) 16.