Study of charm production by neutrinos in nuclear emulsion
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Chapter 4

Deep inelastic charm production

Neutrino physics is largely an art of learning a great deal by observing nothing.
Haim Harari [72]

In this chapter the procedure for analyzing charm events produced in charged-current (CC) deep inelastic scattering (DIS) is described and the results are reported. First an introduction is given about the classification and signature of neutrino events in the CHORUS detector. Then the general procedure for the analysis chain of charm events found in the emulsion is described. In order to extract physics results it is necessary to model and understand the data in a Monte-Carlo (MC) simulation. The outcome of the comparison of MC simulation and data is shown and the description of the selection criteria for charm events is presented.

The observed event sample is summarized in terms of event topologies and kinematics. Furthermore, the charm production cross section, the charm quark mass, charm fragmentation, the strange sea component and the weak mixing angle $V_{cd}$ are extracted.

4.1 Analysis procedure

4.1.1 Classification of neutrino events

In CHORUS the recorded neutrino events are classified according to the number of muons seen in the spectrometer. In Figure 4.1 examples of zero muon ($0\mu$) (a), one muon ($1\mu$) (b) and dimuon ($2\mu$) (c) events in the detector are
Figure 4.1: Examples of zero, one and two muon events in the CHORUS detector (from top to bottom).
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4.1.1 Figure 4.2: A typical neutrino interaction in emulsion (a), and the result of a general tracking algorithm (b).

displayed. Neutrino interactions identified in the emulsion can be examined near the primary vertex down to micrometer level. A typical neutrino event in a single emulsion layer perpendicular to the neutrino beam is shown in Figure 4.2a. The clearly visible black tracks are mainly heavily ionizing fragments from nuclear breakup in the interaction emitted at large scattering angles. The particles resulting directly from the partonic neutrino interaction are usually minimum ionizing, and produced in the forward direction. Since Figure 4.2a is only a two dimensional thin emulsion slice, particles going into the forward direction manifest themselves in this projection only in single spots; thus they are not recognizable as tracks in this figure. To visualize those tracks, a series of parallel emulsion layers allowing recording in a third dimension is needed. An outcome of such a three dimensional reconstruction (general tracking) is displayed in Figure 4.2b.

4.1.2 Correcting the data

To locate a neutrino interaction and - in particular - a charmed particle decay in the emulsion, several analysis steps have to be made. If a neutrino has interacted in the emulsion the event is expected to also have triggered the data acquisition, and to have been reconstructed from the electronic detector data.
The reconstructed particle trajectories followed backwards predict tracks in the emulsion. The automatic microscopes have to locate and trace these tracks further backwards in the emulsion, from plate to plate until a primary vertex is found. Only then the emulsion plate and coordinates of the vertex position are known so that an operator (scanner) can examine such an event in detail.

In every step of the above procedure losses and smearing occur. These depend often on instrumental (and indirectly on kinematical) characteristics. They have to be taken into account, before an original 'physics true' distribution can be quantitatively associated with the corresponding measured distribution. Conversely, we want to design a procedure that - given a measured distribution - allows to reconstruct as closely as possible the corresponding 'physics true' distribution. For this purpose, we first describe in the following the flow diagram from a simulated 'physics truth' towards the final distribution of measured events (Figure 4.3) in more detail.

- **Detector reconstruction acceptance** $A_{\text{Rec}}$

  Neutrino events are triggered in the detector and reconstructed with a certain kinematic acceptance probability (short: acceptance) and (in)efficiency (e.g. due to dead time, misalignment, etc.). Similarly, it has to be taken
into account that also in the analysis, e.g. by selecting explicitly a kinematic region, the acceptance is affected. The trigger, reconstruction and explicit kinematic selection together are taken care of in $A_{\text{Rec}}(k)$, where $k$ stands for all kinematic variables. It is evaluated by using a MC simulation. Applying our current kinematic selections e.g. for dimuon charm events, $A_{\text{Rec}}$ amounts to typically 30%, when integrated over the kinematic variables.

• **Automatic scanning efficiency** $A^{AS}$

Once a measured event from the electronic detector has been reconstructed, the track exit points on the emulsion stack are predicted. An automatic microscope scanning system locates the predicted tracks, and follows them upstream through the emulsion plates until the primary vertex is found. Tracks and vertices can get lost due to wrong or inaccurate track predictions, as well as due to inefficiencies of the emulsion and/or of the scanning system.

The vertex location efficiency of the automatic scanning process ($A^{AS}(k)$) is evaluated from the analysis of a data sample composed of $2\mu$ events generated from charmed particle decays and pions decaying in flight showing an identical signature in the electronic detector.

In this sample 763 $2\mu$ events have been located in the emulsion with respect to an original sample of 2256 preselected $2\mu$ events in the detector. The scanning efficiency $A^{AS}$ integrated over the kinematic dependence is therefore 34%.

Unfortunately, the large number of $1\mu$ events scanned for the oscillation search could not be used for determining $A^{AS}$ due to a 30 GeV upper momentum cut that was applied on the $1\mu$ predictions. Such a cut is unacceptable for our work.

• **Manual scanning efficiency** $A^{MS}$

In the search for charm events, the located $2\mu$ events are examined manually for decay topologies. Here, for a given event topology the optical system and the human eye introduce an additional acceptance limitation. This function ($A^{MS}(k)$) has been estimated by a MC simulation and verified by a cross check with the charm events found in the data. Taking into account the limited focal depth of the microscopes and the grain density inside the emulsion, a shortest visible flightlength of 10 $\mu$m is expected
2.0.14 - Observed charm decays

Furthermore, in principle it is expected that inside the emulsion, the smallest visible decay angle increases with the track angle (polar angle with respect to the X-axis). This effect occurs because of the particular emulsion plate orientation with respect to the microscope optics.

It has been found that the (presumed) smallest visible decay angle as a function of the track angle depicted in Figure 4.4 is in good agreement with the observed decays and with our MC studies. The flat behaviour in the range \(0 < \theta < 100 \text{ mrad}\) follows from the limited accuracy of the manually measured angles (see Figure 3.14). The linear trend towards zero as described in the CHORUS proposal (see Figure 4.4) may thus be too optimistic for our present data set.

For part of the data, additional selection criteria have been applied in order to decrease the manual scanning load. For 1996-1997 data, candidate events have only been scanned manually, if a) the \(\mu^+\) and the \(\mu^-\) stop in different emulsion plates, or b) \(\mu^+\) and \(\mu^-\) stop in the same plate but have a minimum distance of more than 5 \(\mu\text{m}\). These criteria have been included.
4.1. ANALYSIS PROCEDURE

in the MC simulation and \( A^{MS} \) integrated over kinematics is estimated to be typically 82%.

In the following sections distributions of various kinematic variables are studied. The observed distributions can be corrected for the kinematic acceptances, cuts and (deduced or estimated) inefficiencies to obtain the corresponding 'true' distributions

\[
N_{\text{true}}(k_j) = \frac{N_{\text{obs}}(k_j)}{A(k_j)},
\]

where \( N_{\text{obs}}(k_j) \) is the observed distribution and \( A(k_j) \) the acceptance, both as a function of the kinematic variable \( k_j \) and integrated over all other kinematic variables. For charm events, the acceptance function is

\[
A(k_j) = A^{\text{Rec}}(k_j) A^{A}(k_j) A^{MS}(k_j).
\]

In the determination of the charm production cross section described in section 4.2.3 we normalize with respect to the cross section for the CC event sample. However, this CC event sample and the charm sample cannot be compared on the 'emulsion level' without introducing additional biases, because of the unfortunate upper muon momentum cut in the CC sample. Therefore, the corresponding 'true' distributions of CC events observed and reconstructed in the detector are used for the normalization. The 'true' CC data distributions are obtained from the observed distributions according to Equation 4.1 with the acceptance function

\[
A(k_j) = A^{\text{Rec}}(k_j).
\]

In summary, the corrections are evaluated by MC simulations and - where possible - by data, taking into account all relevant hardware and software aspects. To get confidence in this procedure, in the following section the physics input coming from CC event generators is compared—as a consistency check—with the deduced 'true' experimental distributions.

4.1.3 Event generation and detector response

For the various topics studied in this thesis, different MC generators have been used. For simulating deep inelastic neutrino interactions, the standard CHORUS event generator JETTA [73] has been employed. It is based on the LEPTO [74] package to simulate \( \nu_\mu \) and \( \nu_\tau \) CC interactions, and JETSET [32]
for hadronization and decays. The structure functions are parameterized according to GRV94LO [75]. In the JETTA generator heavy quark effects are not implemented (see slow rescaling model Equation 2.8).

For extracting physics parameters of charmed hadron production, a new fast and flexible simulation has been developed, based on the event generator MICKEY used for the structure function analysis in the CHORUS calorimeter [44]. This simulation uses also the GRV94LO structure function set and includes heavy quark effects according to the slow rescaling model. The Peterson model (see Equation 2.13) is implemented for the charm fragmentation and particle decays are realized with the JETSET package. For the search of diffractively produced charmed mesons, a new event generator (ASTRA) has been written. The output of the generators has been interfaced to the GEANT [76] based CHORUS detector simulation EFICASS including all details of the detector and providing the appropriate detector response for the MC-generated events.

In the following, some CC distributions obtained with the deep inelastic MC generators are compared with the 'true' data obtained with the correction procedure described in the previous subsection. A kinematic region that is dominated by deep inelastic production is selected. The selection criteria for the data versus MC comparison are $\nu > 2.3$ GeV, $Q^2 > 5$ GeV$^2$ and $W^2 > 2$ GeV$^2$.

In Figure 4.5 the one-dimensional projections for the neutrino energy $E_{\nu}$ (a), the momentum of the negatively charged muon $p_{\mu^-}$ (b), the Bjorken $x$ (c), the inelasticity $y$ (d), the square of the transferred four-momentum $Q^2$ (e) and the square of the invariant mass of the hadronic final state $W^2$ are displayed. The data (1994 - 1995) have been corrected according to Equation 4.1 for instrumental acceptances and inefficiencies and they are compared with the JETTA MC (squares) and MICKEY MC (triangles) simulations. The data and MC distributions are normalized to the same number of entries.

For the $E_{\nu}$ (Figure 4.5a) distribution, data and MC clearly reproduce the shoulder of high energy (>70 GeV) neutrinos that originates mainly from the kaon contribution in the CERN primary meson beam. The two MC simulations agree with each other, however they deviate from the data points in the low part of the spectrum $120 < E_{\nu} < 160$ GeV. This deviation can be understood in terms of a not fully realistic estimate of horn and reflector current in the neutrino beam simulation [44], of which an output sample serves as input to our physics MC event generation. The deviation which is minor in terms of the integrated
4.1. ANALYSIS PROCEDURE

Figure 4.5: Data and MC comparison in 1D projections for various kinematic variables. The black dots represent the - for acceptance - corrected ('true') data, the squares the JETTA MC and the triangles the MICKEY MC ( (a) $E_\nu$, (b) $E_{\mu^-}$, (c) $x$, (d) $y$, (e) $Q^2$, (f) $W^2$).
beam, anyhow largely cancels in the ratio of charm event distributions and CC event distributions.

For $E_{\mu^-}$ (Figure 4.5b) both MC distributions agree with the data. Good agreement also exists for Bjorken $x$ (Figure 4.5c).

In the $y$-distribution (Figure 4.5d) the MC distributions agree, except at $y < 0.25$ where the data are higher than MC, and at $y > 0.9$ where they are lower. These deviations could be avoided by applying more stringent cuts. However, the systematic error originating from this deviation is small in comparison to the statistical error of the charm data sample. In favour of keeping more charm events in the sample this deviation has been accepted.

For $Q^2$ (Figure 4.5e) and $W^2$ (Figure 4.5 (f)) the agreement of both generators and the data is again within the error bars.

In conclusion both simulation methods, JETTA and MICKEY, are in overall agreement with our CC data. Hence, both generators can model the observed CC data including all detector effects and they can be used in the analysis of the charm data sample.

4.1.4 Charm event selection

For our study of CC deep inelastic charm production, events with two muons of opposite charge in the final state are preselected (see Sections 2.2 and 2.4). Identification and reconstruction of the $\mu^+$ and $\mu^-$ momenta in the muon spectrometer is required.

Furthermore, only those events are used in this analysis where the vertex is reconstructed in the emulsion. The emulsion plates are distributed for scanning over several laboratories. However, for the CHORUS Phase I analysis and scanning (used in our work), it is only the Nagoya University laboratory - who pioneered automatic scanning - that really counts in terms of scanning capacity. Therefore, we concentrate on events with a vertex position predicted in emulsion plates that have been scanned at Nagoya University.

Using the electronic prediction, the dimuon events are scanned by automatic scanning systems, and after the location of the primary vertex, each event is examined by an operator for a charm-type decay topology. The outcome of this selection is our raw charm data sample.

The CC $(1\mu)$ event sample selected for our analysis has one identified muon in the spectrometer with negative charge and a reconstructed vertex in the emulsion. The selected kinematic region is $\nu > 2.3$ GeV, $Q^2 > 5$ GeV$^2$ and
$W^2 > 2 \text{ GeV}^2$.

In Table 4.1 the year-by-year event samples with a reconstructed vertex in the emulsion and the events with a vertex located by the automatic scanning system are summarized.

In 1995 and 1997 there are less events with a located vertex in the emulsion target than expected from the number of recorded CC events. The reason is that in 1995 a set of emulsion plates was not usable for scanning because of a damaged surface. The fraction of located vertices in 1997 data is smaller because internal scanning criteria have been changed to decrease the scanning load. This has been taken into account in the analysis.

After the manual scanning, the number of found charm events also reflects in the year-by-year statistics of the automatically scanned and located events as depicted in Figure 4.6. In total a sample of 132 charm decays has been obtained.

<table>
<thead>
<tr>
<th>Year</th>
<th>1994</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\mu$ events predicted in the emulsion</td>
<td>38014</td>
<td>54141</td>
<td>68508</td>
<td>80973</td>
<td>241636</td>
</tr>
<tr>
<td>$2\mu$ events predicted in the emulsion</td>
<td>378</td>
<td>540</td>
<td>610</td>
<td>724</td>
<td>2252</td>
</tr>
<tr>
<td>Events tried for scanning</td>
<td>355</td>
<td>371</td>
<td>583</td>
<td>662</td>
<td>1971</td>
</tr>
<tr>
<td>$\mu^+$ tried for scanning</td>
<td>320</td>
<td>311</td>
<td>567</td>
<td>647</td>
<td>1845</td>
</tr>
<tr>
<td>Event found on CS</td>
<td>211</td>
<td>216</td>
<td>422</td>
<td>568</td>
<td>1417</td>
</tr>
<tr>
<td>Event found on SS</td>
<td>199</td>
<td>198</td>
<td>366</td>
<td>329</td>
<td>1092</td>
</tr>
<tr>
<td>Vertex in bulk plate 3-36</td>
<td>137</td>
<td>123</td>
<td>270</td>
<td>233</td>
<td>763</td>
</tr>
</tbody>
</table>

Table 4.1: Raw data event samples for our analysis.

Figure 4.6: Number of charm events found, split into neutral charm and charged charm decays.
4.2 Results

Apart from E531, CHORUS is the only experiment where charmed particles can be directly observed in emulsion, both at the production and at the decay vertex. At the time of this analysis only a limited event sample of muonic charm decays was available (Phase I scanning). In view of the Phase II event sample, being scanned presently, which includes hadronic decay channels and which is expected to be more than an order of magnitude larger, our analysis can serve as a basis for upcoming studies. In this perspective it is attempted to find an appropriate level of detail in presenting the results.

4.2.1 Charm topologies

In the observed charm decays, contributions from $D^0$, $D^+$, $D_s^+$ and $\Lambda_c^+$ are expected. In the emulsion, neutral charmed particles can be distinguished from charged charmed particles. However, the particle type ($D^+$, $D_s^+$ or $\Lambda_c^+$) cannot be identified on a single event basis.\(^1\) The type of information that can be extracted from charm events in emulsion can be judged from Figure 4.7. Only charged particles are visible (solid lines), the neutral particles (dotted lines) can not be seen as tracks in the emulsion. At the primary vertex and at the secondary decay vertex, the number of charged particles can be counted. Furthermore flight lengths and angles of the charmed particles can be measured.

\(^1\)It might be possible in the Phase II analysis to reconstruct the invariant mass of the charmed particles with hadronic decays.

![Figure 4.7: Topology of charm events where charged particles are visible in the emulsion (solid lines), and neutral particles (dashed and dotted lines) are invisible. Neutral charmed hadrons (dashed line) can usually be identified by the kinematics and topology of the visible parts of the event.](image-url)
Figure 4.8: Corrected ('true') number of charged decay products $N_{\text{prong}}$ for charged charm (a) and neutral charm data (b). The integral is normalized to unity. The data (crosses) are compared with MC (histogram).

Figure 4.9: Corrected ('true') distribution of the charged track multiplicity $N_s$ at the primary vertex for charm data (crosses) and MC (histogram).
Due to charge conservation, the charged charmed particles decay into an odd number of charged daughter particles ($\mu^+$ included), whereas a neutral charmed particle decay involves two or four charged daughter particles.

In Figure 4.8 the number of events in each decay category is compared with the MC estimate from the JETTA program. The events are corrected according to Equation 4.1 and hence reflect the 'true' distribution. The integrals over the corrected data and over the MC are normalized to unity and the error on the data points is statistical (also in forthcoming figures).

In the charged charmed particle decays (Figure 4.8a) we see slightly more 1-prong decays and less 3-prong decays than the MC results, whereas the neutral 2-prong and 4-prong decays (Figure 4.8b) agree with the MC values. The analysis of the particular production ratio of neutral and charged charmed particles is presented in detail in Section 4.2.4.

![Graphs showing corrected flight length distribution for data and MC](image)

Figure 4.10: Corrected ('true') flight length ($L$) distribution for data (crosses) and MC (histogram).
An interesting observation here is that the JETTA MC modeling of the fragmentation and jet development at a primary neutrino vertex is rather well described by the string fragmentation model. The observed multiplicity of charged particles $N_s$ (number of 'shower tracks') that emerge from the primary charm production vertex in the forward direction is displayed in Figure 4.9. The overall shape with a biased production of an even number of charged particles is reproduced in the MC distribution. For charge conservation at the primary vertex, the nuclear fragments have to be taken into account. However, the complex nuclear dynamics leading to the emission of heavy nuclear fragments is not modeled in the MC.

The flight length distribution of the charm events is shown in Figure 4.10. While the neutral charm events agree well with MC, at short flight lengths there is a slight excess of the charged charm events compared with the MC estimate. We studied whether this excess hints at a higher $\Lambda_c^+$ contribution than modeled in the MC simulation. However, within the limited statistics of the sample this could not be found in other kinematic projections.

The azimuthal angle at the primary vertex between the primary $\mu^-$ trajectory and the charmed hadron trajectory, projected on the plane transverse to
the neutrino beam direction, is displayed in Figure 4.11. The charmed particle is produced preferentially in the $\nu_\mu - \mu^-$ DIS CC scattering plane. This is expected, because in DIS the charm quark is produced back-to-back with respect to the muon in the neutrino-quark CM frame. In the laboratory system this is reflected - with $p_T$ smearing - in coplanarity of the corresponding momenta.

4.2.2 Charm kinematics

To get an overview not only of the topological properties - but also the kinematics - of the events, the 'true' distributions in terms of various kinematic variables are presented in this section. The data are also here corrected according to Equation 4.1 and have their integral normalized to unity. The error on the data points is statistical.

Figure 4.12 shows the 'true' distributions for $E_{\mu^-}$, $E_{\mu^+}$, $E_\nu$ and $Q^2$, whereas Figure 4.13 shows them for $W^2$, Bjorken-$x$, $y$ and $z_\mu$.

The overall agreement with the MC distributions is good. In $W^2$ there is perhaps an excess in the data at low $W^2$. The $y$-distribution shows for the data large bin-by-bin statistical fluctuations.

The secondary muon is identified by its positive charge. As expected, it is usually less energetic than the primary (negatively charged) muon from the CC interaction. The average energy of the interacting neutrinos producing a charmed particle ($< E_{\nu}^{\text{charm}} > = 56.4$ GeV) is higher than in a CC interaction ($< E_{\nu}^{\text{CC}} > = 49.3$ GeV), also as expected.

In the following subsection we use the shape of distributions to extract certain parameters for modeling the production process of charmed particles by neutrinos. In particular, we use the energy distribution to extract the charm quark mass, the $x$-distribution to get information on the strange sea component, and the $z_\mu$-distribution to derive a fragmentation parameter.

4.2.3 Charm cross section

The charmed particle cross section at different neutrino energies has been a controversial topic for many years. Charm quark mass effects are expected to manifest themselves as a threshold effect in the energy distribution. The big advantage of the CHORUS experiment is that the charmed particles can be directly observed and tagged, whereas in most of the previous experiments it was only possible to observe the final state particles. It was neither possible to see the primary vertex nor the charmed particle decay giving substantial
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Figure 4.12: Corrected ('true') event distributions for kinematic variables (a) $E_{\mu-}$, (b) $E_{\mu+}$, (c) $E_{\nu}$ and (d) $Q^2$. The data (crosses) are compared with MC (histogram).
Figure 4.13: Corrected ('true') event distributions for kinematic variables (a) $W^2$, (b) $x$, (c) $y$ and (d) $z_\mu$. The data (crosses) are compared with MC (histogram).
uncertainties. Furthermore, in CHORUS the charm production cross section can be separated into charged and neutral contributions. Until now only in E531 this distinction could be made.

The charm cross section is here calculated per CC interaction. To obtain the 'true' distributions, both the full CC distributions and the kinematically corresponding charm distributions have to be corrected - separately but consistently - for detector and emulsion acceptances and inefficiencies. Because the energy dependence of the cross section is studied, we show the behaviour of the correction functions against the variable \( E_{\nu} \). The CC events are corrected for detector effects using \( A^{Rec}(E_{\nu}) \) according to Equation 4.1 (Figure 4.14a). The charm distributions are corrected for detector effects \( A^{Rec}(E_{\nu}) \), automatic scanning system inefficiencies \( A^{AS}(E_{\nu}) \) and manual scanning inefficiencies \( A^{MS}(E_{\nu}) \) according to Equation 4.1 (Figure 4.14b-d).

### Discussion of uncertainties

In the evaluation of the charm production cross section, several systematic errors shown in Table 4.2 are taken into account.

Because of the small size of the sample of observed muonic charm decays, the analysis is dominated by statistical errors. An additional statistical uncertainty arises from the limitation to 763 dimuon events located in the emulsion.

For the estimation of the systematic uncertainties affecting \( A^{Rec} \) two components have been taken into account. Uncertainties in the calibration parameters of the calorimeter and discrepancies in comparing MC and testbeam results lead to an estimated systematic error for the hadronic energy scale of 5%. Furthermore, the uncertainty on the muon momentum scale is estimated to be 2.5% [77].

For the estimation of the systematic uncertainty affecting \( A^{AS} \), we must be aware that the scanning is highly depending on the 'quality' of predictions. The scanning efficiency includes uncertainties in the scanning process itself, the fiducial volume, the reconstruction and the location of the events. The systematic error has been evaluated from results of different scanning strategies. On average, the systematic uncertainty in \( A^{AS} \) is estimated (conservatively) to be 15%. It is by far the largest uncertainty because it enters directly into the charm cross section.\(^2\) It has been tried [78] to simulate the entire scanning

\(^2\)This is one of the reasons, why for the CHORUS Phase II scanning the \( 1\mu \) events are scanned without cut on the muon momentum. This results in a CC sample for the automatic scanning correction that is about a factor 20 larger than the currently used sample. Hence, this contribution to the systematic uncertainty will be reduced drastically in the future by
Figure 4.14: Distributions of the various correction factors as a function of $E_\nu$ for the CC and charm samples.
### 4.2. RESULTS

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$\Delta \sigma_{\text{charm}}/\sigma_{\text{CC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic energy scale (5%)</td>
<td>0.14</td>
</tr>
<tr>
<td>Muon momentum scale (2.5%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Reconstruction and Scanning</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 4.2: Systematic uncertainties.

system and procedure, however, no consistent agreement with the data could be reached in sufficient detail.

**Charm cross section**

After having corrected the data leading to the corresponding 'true' distributions, it is possible to plot the charm production (with muonic decay) per CC interaction versus neutrino energy (Figure 4.15a). The overlayed histogram shows the expectation from MICKEY MC calculation using a charm quark mass $m_c = 1.3$ GeV and muonic branching ratios (see Equations 2.17 and 2.18) according to Table 2.2. The charm yield can be split into a charged (Figure 4.15b) and a neutral contribution (Figure 4.15c).

There is an overall agreement of the measured charm yield and the MC simulation. In the charged charm production the data overshoot the expectations in the second bin, whereas there are no entries in the first bin. This can be understood in terms of the rather steep rise in $A_{\text{Rec}}$ below 50 GeV (see Figure 4.14b). Therefore we can assume that the observed excess is of statistical nature.

Over the full energy range, the measured overall charm yield per CC interaction results in

$$\frac{\sigma_{\text{charm}} \cdot B_{e\to\mu}}{\sigma_{\text{CC}}} = (4.6 \pm 0.4 \pm 0.7) \times 10^{-3},$$

(4.4)

$$\frac{\sigma_{\text{charged charm}} \cdot B_{\Sigma \to h\to\mu}}{\sigma_{\text{CC}}} = (2.7 \pm 0.3 \pm 0.4) \times 10^{-3},$$

(4.5)

$$\frac{\sigma_{D^0} \cdot B_{D^0\to\mu}}{\sigma_{\text{CC}}} = (1.9 \pm 0.3 \pm 0.3) \times 10^{-3},$$

(4.6)

where the first error is statistical and the second systematic.

using Phase II data.
Figure 4.15: Corrected ('true') charmed hadron production with (semi-)muonic decay per CC interaction for all charm (a), charged charm (b) and neutral charm (c) as a function of neutrino energy.
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Comparison with results from other experiments

In Figure 4.16 the results of the cross section ratio for charmed hadron production per CC with a muonic decay as a function of neutrino energy is compared with results from previous experiments. Within the errors there is good agreement with NOMAD, CCFR and the emulsion experiment E531. The CDHS data tend to be slightly lower than those of the other experiments, including our results, particularly at low energy.

Figure 4.16: Corrected ('true') charm/CC cross section ratio (with muonic decay) from the present work compared with results of previous experiments.

4.2.4 Neutral charm versus charged charm

Having measured the charm/CC cross section ratio including the muonic branching ratio separately for charged and for neutral charm production, it is possible to examine the dependence of the neutral-charged ratio on the neutrino energy.

Assuming the muonic branching ratios $B_{D^0 \rightarrow \mu} = 6.6\%$ and $B_{\sum h_{\text{ch}} \rightarrow \mu} = 10.0\%$ (see Section 2.4), we can calculate the energy dependent ratio of neutral and charged charm production, and the result is shown in Figure 4.17. Also in this figure, the assumptions of a constant ratio (dotted line)
and a charged contribution increasing towards low energies [17] (solid line) are shown.

There is a slight tendency in the data that at low energies the charged particle component is higher than at high energies. If confirmed with higher statistics, this can support the hypothesis of a higher quasi-elastic $\Lambda_c$ contribution [17] at low energies, although no explicit excess of events with such characteristics could be identified in other kinematic projections.

![Neutral-over-charged ratio for charm production](image)

Figure 4.17: Neutral-over-charged ratio for charm production. The crosses correspond to the data; the dotted line represents the expectation for a flat behaviour and the solid line (histogram) for an increased charged charm contribution towards lower energies.

**Comparison with results from other experiments**

While for cross section measurements of overall neutrino-induced charm production various experiments contribute, before CHORUS experimental data for distinctly identified neutral and charged charm production are limited to the E531 emulsion experiment. Since in this experiment a full kinematic reconstruction of the hadronic charm decays could be performed, it was possible to identify the type of charmed particle on a single event basis. A reanalysis [17] gave production fractions for different charm types as shown in Figure 2.2. The data of Figure 2.2 are converted into the neutral-over-charged charm production ratio and overlayed with the CHORUS experimental results in Figure 4.18.

Within the error bars, the CHORUS data points agree with the E531 measurement, which is consistent with an enhanced fraction of $\Lambda_c$ events at low energy.
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Figure 4.18: Neutral-over-charged charm production. The hatched area corresponds to the E531 measurement.

4.2.5 Charm quark mass

Using the neutrino energy distribution of charm production per CC (Figure 4.15a), it is possible to compare the data with MICKEY MC calculations that include slow rescaling (see Equation 2.8) while varying the charm quark mass parameter ($m_c$). For every $m_c$ value a measure for the goodness of the fit ($\chi^2$) can be calculated [5]. The resulting $\chi^2$ distribution is shown in Figure 4.19. The $\chi^2$ at the minimum is 9.4 with 5 degrees of freedom. At very low values
(\(m_c \leq 0.5\) GeV) quark mass effects are suppressed in the MC. This is why the \(\chi^2\) distribution is fit by a parabola for \(0.6 \leq m_c \leq 3.0\) GeV. The result is

\[
m_c = 1.6 \pm 0.8\ \text{GeV},
\]

where the error is determined by the width of the \(\chi^2\) distribution one unit above the minimum.

**Comparison with results from other experiments**

In Table 4.3 the above deduced mass parameter is compared with other measurements. The central value of our measurement is larger than the central values obtained by CCFR and NOMAD and less than those from CHARM II and the CHORUS calorimeter analysis. Within the error bars there is a good overall agreement with the other measurements.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(m_c) (GeV)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARM II</td>
<td>1.8 ± 0.4</td>
<td>[79]</td>
</tr>
<tr>
<td>CCFR</td>
<td>1.3 ± 0.2</td>
<td>[80]</td>
</tr>
<tr>
<td>NOMAD</td>
<td>1.3 ± 0.4</td>
<td>[81]</td>
</tr>
<tr>
<td>CHORUS calo</td>
<td>2.1 ± 0.9</td>
<td>[82]</td>
</tr>
<tr>
<td>this analysis</td>
<td>1.6 ± 0.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of the obtained charm quark mass with values from various neutrino experiments.

**4.2.6 Charm fragmentation**

The charmed particle momentum fraction of the maximum available momentum \((z)\), often used as the main parameter to describe the fragmentation process, cannot be measured in the present case, since only charged decay products are observed (moreover with their momenta poorly measured). However, the positive muon from the decay can be identified and its momentum can be well measured. Since the momenta of parent and daughter particles in the decay are correlated, the measured value \(z_\mu\) (see Equation 2.15) can be used to obtain the charmed particle \(z\) value. In the following an unfolding procedure is introduced and then applied to our data.
Unfolding procedure

The problem of unfolding a measured (histogram) distribution $H_M$ to obtain the underlying true distribution $H_T$ can be expressed in general as $A H_M = H_T$, where $A$ is the response (folding) matrix. In the present case the distribution $(H_M)$ for $z_\mu$ should be converted into the one $(H_T)$ for $z$.

Following the argumentation in [83] a regularization of the response matrix has to be performed. The response matrix can be written as $A = USV^T$, where $U$ and $V$ are orthogonal matrices and where $S$ is a diagonal matrix with non-negative values. After this decomposition, the solution becomes $H_M = VS^{-1}U^T H_T$. The regularization of the solution is obtained by adding a term of the form $\sqrt{\tau}CH_M$ to the equation, where the matrix $C$ is chosen such as to minimize the second derivative of the unfolded distribution and where the parameter $\tau$ is the regularization parameter. A complete description of this method can be found in [83].

Extraction of the fragmentation parameter $\epsilon_p$

The response matrix $A$, necessary for the unfolding procedure has been extracted from MC simulations. Applying the unfolding method described above on the observed distribution for $z_\mu$ (Figure 4.13d) results in the distribution shown in Figure 4.20, which can be fit directly in a standard way by a parameterization for the fragmentation process. The solid curve in Figure 4.20 shows the best fit for the Peterson parameterization (Equation 2.13), with

$$\epsilon_p = 0.12 \pm 0.02 \pm 0.06. \quad (4.8)$$

Figure 4.20: Unfolded 'true' $z$-distribution of charm events with a Peterson fragmentation model fit.
The first error is the statistical error and the second error is attributed to systematic uncertainties in the unfolding procedure estimated by varying the input distributions in the evaluation of the response matrix.

Comparison with results from other experiments

In Table 4.4 the obtained result is compared with results from other neutrino experiments. While the results from CCFR and the CHORUS calorimeter analysis are not compatible with the results of CHARM II and E531, our result agrees with all other measurements of $\epsilon_P$ within the error bars.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\epsilon_P$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCFR</td>
<td>0.20 ± 0.04</td>
<td>[80]</td>
</tr>
<tr>
<td>CHARM II</td>
<td>0.072 ± 0.017</td>
<td>[84]</td>
</tr>
<tr>
<td>E531</td>
<td>0.076 ± 0.014</td>
<td>[85]</td>
</tr>
<tr>
<td>CHORUS calo</td>
<td>0.28 ± 0.11</td>
<td>[82]</td>
</tr>
<tr>
<td>this analysis</td>
<td>0.12 ± 0.06</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Comparison of the here obtained Peterson parameter ($\epsilon_P$) with values from other neutrino experiments.

4.2.7 Strange sea

In deep inelastic scattering (DIS), the Bjorken-$x$ value is a measure for the struck quark (longitudinal) momentum, where valence and sea quarks carry on average significantly different fractions of the nucleon momentum. In CC DIS charm production the interaction takes place either on a valence $d$ quark or on a sea ($s$ and $d$) quark. Following the CKM matrix, the c quark production on a $s$ quark is Cabibbo-favoured whereas the production on a $d$ quark is Cabibbo-suppressed.

Hence, because the Bjorken-$x$ distribution is sensitive to the $s$ and $d$ quark component, we describe in this section two methods to extract the integrated strangeness component with respect to the $d$ quark component.

E531 parameterization

To be able to compare our data with those of the other emulsion experiment E531, we follow their approach [85, 86, 87], where the valence $d$ quark distribution is parameterized as $xd(x) \propto \sqrt{x}(1 - x)^\alpha$ and the sea quark distribution as $xs(x) \propto (1 - x)^\beta$. Thus the total Bjorken-$x$ quark distribution can be written
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\[
\frac{dN}{dx} \propto N_d V_{cd}^2 \sqrt{x(1-x)}^\alpha + N_s V_{cs}^2 (1-x)^\beta \\
\propto \sqrt{x(1-x)}^\alpha + f(1-x)^\beta, \tag{4.9}
\]

with \(N_s\) and \(N_d\) as the fractional \(d\) quark and \(s\) quark normalizations and \(V_{cd}, V_{cs}\) the CKM matrix elements. The variable \(f\) summarizes \((N_s/N_d)(V_{cs}^2/V_{cd}^2)\). The exponents are taken as \(\alpha = 3.5 \pm 0.5\) and \(\beta = 7.0 \pm 1.0\) \cite{85, 86, 87, 88, 89}.

![Figure 4.21: The corrected ('true') x-distribution (crosses) with fitted contributions from \(d\) and \(s\) quarks. The solid line reflects the best fit to the data. Also shown are the fits assuming a strangeness contribution of 100% (dashed line) and 0% (dotted line).](image)

The best fit of Equation 4.9 to our data is shown in Figure 4.21 and compared with curves for the extreme cases where the \(s\) quark fraction is 0\% and 100\%. The best fit corresponds to

\[
f = 0.27 \pm 0.15 \pm 0.36, \tag{4.10}
\]

where the first error is statistical and the second systematic. Using this value
for $f$ the sea quark component results in the integrated strangeness-down ratio

$$\frac{s}{d} = 0.014 \pm 0.007^{+0.019}_{-0.010}. \quad (4.11)$$

In the systematic errors of $f$ and $s/d$ the various contributions as summarized in Table 4.5 are added in quadrature.

Varying the hadronic energy scale by 5% and the muon momentum scale by 2.5% results in systematic uncertainties in $A_{\text{Rec}}$ reflected in a variation of the fit result $\Delta f$. Systematic uncertainties in the reconstruction and scanning are evaluated by variations in the results for different scanning strategies. The dominant contribution in the systematic error results from the uncertainties in the exponents $\alpha$ and $\beta$ entering directly in the fit result.

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$+\Delta f$</th>
<th>$-\Delta f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic energy scale (5%)</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Muon momentum scale (2.5%)</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Reconstruction &amp; scanning</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Parameterization</td>
<td>0.34</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 4.5: Systematic uncertainties in the strangeness analysis using the E531 parameterization.

**GRV94LO parameterization**

We can also interpret our strangeness data in terms of a parameterization for a QCD analysis of various data sets. For this purpose we choose the parameterization of GRV94LO [75]. In this parameterization, the valence $d$ quark distribution is written as

$$x d(x, Q^2) = N x^a (1 + A x^b + B x + C x^{3/2})(1 - x)^D, \quad (4.12)$$

and the strange sea parameterization is written as

$$x s(x, Q^2) = \frac{s^\alpha}{(\ln(1/x))^a} (1 + A \sqrt{x} + B x)(1 - x)^D \cdot e^{-E + \sqrt{E' S \ln(1/x)}}, \quad (4.13)$$

where $a$, $b$, $\alpha$, $\beta$, $N$, $A$, $B$, $C$, $D$, $E$ and $E'$ are determined by a global fit to data, and where $S$ is defined as

$$S = \ln\left(\frac{\ln(Q^2/(0.232 \text{ GeV})^2)}{\ln(\mu_{LO}^2/(0.232 \text{ GeV})^2)}\right). \quad (4.14)$$

The distributions are evaluated at our $<Q^2> = 12 \text{ GeV}^2$ for $\mu_{LO}^2 = 0.232 \text{ GeV}^2$ [75].
Fitting the GRV94LO parameterization to our data results in

\[ f = 0.47 \pm 0.22^{+0.15}_{-0.13}, \]  

and thus

\[ \frac{s}{d} = 0.024 \pm 0.011^{+0.008}_{-0.007}. \]

The systematic errors summarized in Table 4.6 are added in quadrature. The systematic errors have been derived in a similar way as for the E531 parameterization, but no uncertainties in GRV94LO parameters are taken into account.

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>$\Delta f$</th>
<th>$-\Delta f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic energy scale (5%)</td>
<td>+0.06</td>
<td>-0.05</td>
</tr>
<tr>
<td>Muon momentum scale (2.5%)</td>
<td>+0.10</td>
<td>-0.08</td>
</tr>
<tr>
<td>Reconstruction &amp; scanning</td>
<td>+0.09</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

Table 4.6: Systematic uncertainties in the strangeness analysis using the GRV94LO parameterization.

Comparison with results from other experiments

The E531 result $s/d = 0.042 \pm 0.033$ is consistent with our result, based on the same method.

To be able to compare with other measurements that used neutrino and antineutrino data to evaluate the strangeness contribution, we follow the argumentation in Reference [85]. Our result can be converted to an other parameter value

\[ \eta_s = \frac{2s}{u + d}, \]  

by assuming equal up and down quark content. The result can also be expressed in the parameter

\[ \kappa = \frac{2s}{\bar{u} + \bar{d}}, \]  

by using the total quark/antiquark ratio measured by CCFR $q/\bar{q} = 0.153$ as in reference [90].

In Table 4.7 and Table 4.8 the various experimental results on $\eta_s$ and $\kappa$ are listed.

Within the error bars, our result generally agrees only with the E531 experiment that was based on similar assumptions. The central values that we
obtain for the strangeness parameter values are systematically below the other measurements.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\eta_s) ± Error (Ref)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDHS</td>
<td>0.061 ± 0.005 [79]</td>
</tr>
<tr>
<td>CHARM II</td>
<td>0.068 ± 0.014 [84]</td>
</tr>
<tr>
<td>CHARM</td>
<td>0.050 ± 0.015 [86]</td>
</tr>
<tr>
<td>CCFR</td>
<td>0.064 ± 0.015 [80]</td>
</tr>
<tr>
<td>E531</td>
<td>0.042 ± 0.033 [85]</td>
</tr>
<tr>
<td>NOMAD</td>
<td>0.071 ± 0.023 [81]</td>
</tr>
<tr>
<td>this analysis</td>
<td>0.024 ± 0.014</td>
</tr>
</tbody>
</table>

Table 4.7: Comparison of \(\eta_s\) values from different experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\kappa) ± Error (Ref)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDHS</td>
<td>0.47 ± 0.09 [79]</td>
</tr>
<tr>
<td>CHARM II</td>
<td>0.39 ± 0.10 [84]</td>
</tr>
<tr>
<td>CHARM</td>
<td>0.39 ± 0.12 [86]</td>
</tr>
<tr>
<td>CCFR</td>
<td>0.44 ± 0.11 [80]</td>
</tr>
<tr>
<td>E531</td>
<td>0.32 ± 0.25 [85]</td>
</tr>
<tr>
<td>NOMAD</td>
<td>0.48 ± 0.19 [81]</td>
</tr>
<tr>
<td>CHORUS calo</td>
<td>0.26 ± 0.11 [82]</td>
</tr>
<tr>
<td>this analysis</td>
<td>0.17 ± 0.11</td>
</tr>
</tbody>
</table>

Table 4.8: Comparison of \(\kappa\) values from different experiments.

### 4.2.8 Weak mixing \(V_{cd}\)

Combining the measurements on \(B_{c \rightarrow \mu} \mid V_{cd} \mid^2\) from CCFR [91] and CDHS [79] gives [17]

\[
B_{c \rightarrow \mu} \mid V_{cd} \mid^2 = (5.02^{+0.50}_{-0.69}) \times 10^{-3}. \tag{4.19}
\]

The average muonic decay branching ratio \((B_{c \rightarrow \mu})\) includes for every producible charmed particle type also the corresponding production fraction (ac-
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According to Equation 2.17)

\[ B_{c \rightarrow \mu} = P_{D^0} B_{D^0 \rightarrow \mu X} + P_{D^+} B_{D^+ \rightarrow \mu X} + P_{D_{s}^+} B_{D_{s}^+ \rightarrow \mu X} + P_{\Lambda_{c}^+} B_{\Lambda_{c}^+ \rightarrow \mu X}. \]  

(4.20)

Our present CHORUS data set does not allow to determine the charged charm composition independently. Only the charged-over-neutral charm ratio is measured. This quantity can be incorporated in Equations 4.19 and 4.20 to extract \( V_{cd} \).

Folding the E531 \( E_{\nu} \) dependent charged charm production fractions with the CHORUS neutrino beam spectrum results in contributions of \((42 \pm 10)\% D^+, (29 \pm 21)\% D_s^+, \) and \((29 \pm 16)\% \Lambda_c^+\) to the charged charmed hadron sample (see Section 2.2).

The total charged-over-neutral charm production ratio \( g_c \) as obtained in our analysis is

\[ g_c = 0.90 \pm 0.36. \]  

(4.21)

From this result, the \( D^0 \) contribution to the overall sample can be obtained:

\[ P_{D^0} = \frac{1}{1 + g_c} = 0.53 \pm 0.11. \]  

(4.22)

Using the branching ratios \( B_{D^0 \rightarrow \mu X} = (6.6 \pm 0.8)\% \) [29], \( B_{D^+ \rightarrow \mu X} = (17.2 \pm 1.9)\% \), \( B_{D_s^+ \rightarrow \mu X} = (5.0 \pm 5.4)\% \) [30] and \( B_{\Lambda_c^+ \rightarrow \mu X} = (4.5 \pm 1.7)\% \) [31] (see Table 2.1) in Equation 4.20, yields a muonic branching ratio of

\[ B_{c \rightarrow \mu} = 0.082 \pm 0.015, \]  

(4.23)

and in Equation 4.19 the CKM-element

\[ V_{cd} = 0.247 \pm 0.028. \]  

(4.24)

Comparison with results from other experiments

Our experimental value on \( V_{cd} \) has been evaluated from direct measurements (including the charged charm production fractions from E531), identifying explicitly the production and decay vertex. The direct measurement of \( V_{cd} \) from the E531 experiment yields \( V_{cd} = 0.232^{+0.017}_{-0.019} \) [17].

Our central value is like the E531 result (possibly due to the common use of the charged charm production fractions) slightly higher than the value \( V_{cd} = 0.221 \pm 0.003 \) derived from the unitarity requirement of the CKM matrix, but within the error bars all obtained values are in agreement.