EXPERIMENTAL STUDY OF DIFFERENTIAL CROSS-SECTIONS IN
CHARGED-CURRENT NEUTRINO AND ANTINEUTRINO INTERACTIONS

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ABSTRACT

Inclusive neutrino and antineutrino charged-current interactions were studied using the electronic detector of the CHARM Collaboration exposed to the narrow-band beam of the CERN SPS. The relative contributions of quarks and antiquarks to the neutrino cross-sections were deduced from the differential cross-sections $d\sigma/dy$. The x and Q^2 dependence of the structure functions F_2 and xF_3 were measured. Scaling violations were observed, in qualitative agreement with QCD. A value of the mass scale parameter of QCD, $\Lambda = [0.29 \pm 0.12 \text{ (stat.)} \pm 0.10 \text{ (syst.)}] \text{ GeV}$, was deduced in a leading-order approximation, following the method of Buras and Gaemers.

In this letter we report on a study of the differential cross-sections $d\sigma/dy$ of neutrinos and antineutrinos on nucleons, and on the nucleon structure functions F_2 and xF_3 measured as a function of x and Q^2 . As is well known, the y -distribution reveals the relative contributions of quarks and antiquarks to the cross-section, whereas combining the x -distributions measured by neutrino and antineutrino scattering provides the possibility to study the structure functions of the nucleon, which are interpreted in the quark-parton model as momentum distribution functions of quarks and antiquarks in nucleons. In addition, the study of the Q^2 -dependence of these structure functions can be used to test theoretical predictions of quantum chromodynamics (QCD).

The data presented here were obtained using the CHARM electronic neutrino detector in the CERN 200 GeV/c narrow-band neutrino beam. The narrow-band beam (NBB) selects and focuses pions and kaons, produced at 0° by the interactions of 400 GeV protons on a beryllium target, into a nearly parallel beam with well-defined momentum [1]. Neutrinos are produced by decays of pions and kaons in a 300 m long decay tunnel. At the detector, the energy of the neutrinos is correlated with the radial distance of the interaction from the beam axis. This property of the NBB is a result of the small momentum spread and the small divergence of the secondary beam, together with the two-body nature of the dominant decay processes. An ambiguity of the relation between energy and radius is caused by the presence of neutrinos from both pion and kaon decay. The neutrino energy spectrum and the method used for normalizing neutrino and antineutrino fluxes have been described elsewhere [2,3].

Details of the apparatus and of its performance may be found in ref. [4]. The target calorimeter consists of 78 equal subunits of marble plates, scintillators and proportional drift tubes [5], surrounded by an iron frame magnet which serves as a calorimeter and muon spectrometer. It is followed by a forward muon spectrometer consisting of iron disks with a toroidal magnetic field. The frame magnets and the end magnets are instrumented with proportional drift tubes.

Measurements with the following resolutions are obtained with this detector:

- i) hadronic energy: $\sigma(E_H)/E_H \approx 0.53/\sqrt{E_H}/\text{GeV}$;

- ii) muon momentum: $\sigma(p_\mu)/p_\mu \approx 15\%$ to 20% on the average;
- iii) hadronic shower angle: $\sigma(\theta_H)_{\text{proj}} \approx \left[0.16/\sqrt{E_H/\text{GeV}} + 0.20/(E_H/\text{GeV}) \right]$ (for charged-current events);
- iv) muon angle: $\sigma(\theta_\mu)_{\text{proj}} \approx 5$ mrad for 50 GeV muons and 2 mrad for 150 GeV muons on the average;
- v) neutrino energy from beam properties: $\sigma(E_\nu)/E_\nu \approx 10\%$ to 20% .

With these measurements it is possible to perform a kinematical fit with three constraints.

The electronic trigger of the experiment required that at least four scintillator planes were hit and that the total ionization energy was larger than the energy corresponding to a 1.0 GeV shower. This trigger accepted, with full efficiency, events satisfying the following off-line criteria for the selection of charged-current (CC) neutrino candidates:

- i) The interaction vertex lies within a fiducial volume covering an area of 120 cm radius around the beam axis, and extending between target subunits 7 to 60, corresponding to a target mass of 65 tons.
- ii) The event contains no charged track entering the front or the sides of the detector.
- iii) The event has a track identified as a muon associated with the interaction vertex. A track is defined to be a muon if it is non-interacting, and has a range corresponding to more than 1.0 GeV/c, of which 0.67 GeV/c is clearly visible outside the shower.
- iv) The total energy of the event measured in the detector is larger than 30 GeV.

Roughly 6500 neutrino events and 4500 antineutrino events were thus obtained.

These samples were corrected for background from the following sources:

- i) Events induced by interactions of neutrinos originating from π or K decays before the momentum slits in the beam line ("wide-band background"). This background amounts to 0.4% (3.2%) of the events in the neutrino (antineutrino) exposure.

- ii) Neutral-current (NC) events with a muon produced by π^- and K-decay in the shower faking a CC event. This background contributes 0.8% (0.4%) of the events in the neutrino (antineutrino) exposure [2].
- iii) Interactions of neutrinos produced by kaon decay modes other than $K_{\mu 2}$. The total contribution of this background is 1.6% (0.7%) for neutrino (antineutrino) exposures, and is dominated by $K_{\mu 3}$ decays.

The acceptance for primary muons of CC events was evaluated by means of a Monte Carlo simulation. According to this calculation, 1.8% (0.8%) of these muons are not recognized in the neutrino (antineutrino) exposure. The losses are mainly due to muons leaving the sides of the detector before being identified and, to a lesser extent, by muons obscured by the hadronic shower.

Each measured raw distribution was corrected for the effects of the experimental resolutions and the acceptance by means of an unfolding procedure, which consisted of finding that form of the differential cross-sections which yielded the best description of the measured distribution. Taking the y -distribution as an example, the assumption was made that $d\sigma/dy$ could be represented by a superposition of n bell-shaped functions (B-splines [6]) $b_i(y)$:

$$\frac{d\sigma}{dy} = \sum_{i=1}^n a_i b_i(y) , \quad (1)$$

with coefficients a_i to be determined.

This representation is fairly general; the limitation imposed on the unfolded differential cross-section implies that it varies smoothly over the width (knot-distance) of the bell-shaped functions, chosen to match the experimental resolution. The coefficients a_i were found by fitting expression (1), convoluted with the measurement errors and acceptance, to the observed event distribution in the measured variable y_m :

$$\frac{dN}{dy_m} = \sum_{i=1}^n a_i \int_0^1 b_i(y) r(y, y_m) dy ; \quad (2)$$

where $r(y, y_m)$ represents the resolution and acceptance function of the apparatus, which gives the probability that an event having a physical value is measured at y_m . The function $r(y, y_m)$ is obtained by numerical integration of the measurement resolution over the neutrino spectrum. The n integrals of eq. (2) are calculated by numerical integration. The unfolded distributions are presented by a histogram obtained by integrating eq. (1) over the width of the bins. The measurement uncertainties are given by the covariance (error) matrix of the bin contents, after a straightforward propagation of the covariance matrix of the coefficients a_i .

Corrections for Fermi motion were incorporated in the unfolding procedure. A Fermi momentum distribution of nucleons was used corresponding to an average nuclear potential in the target material, onto which tails were added corresponding to the deuteron wave function [7]. Radiative corrections were applied following a method of de Rújula et al. [8].

The y -distributions were obtained with an additional cut at 2 GeV shower energy, to suppress the contribution of quasi-elastic events. The acceptance of the detector is 100% in the region $0.1 < y < 0.8$, limited at low y by the shower energy cut, and at high y by the criteria used for the recognition of muons. The resolution in y is 0.035 on average. The unfolding of the experimental resolution was made using cubic B-splines with equidistant knots at a distance $\Delta y = 0.1$.

The corrected y -distributions averaged over the neutrino energy spectrum from 30 to 200 GeV are shown in Fig. 1. The curves correspond to the theoretical predictions whose parameters were obtained by fits performed as follows. Defining α to be the relative contribution of antiquarks to the neutrino cross-section compared to all quarks, and similarly $\bar{\alpha}$ for the antiquarks probed by antineutrinos, the differential CC cross-sections can be written within the context of the quark-parton model, and under the assumption that the weak CC contains only V-A terms, in the following way:

$$\frac{d\sigma^{\nu}}{dy} = A[(1-\alpha) + \alpha(1-y)^2] \quad (3)$$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \bar{A}[\bar{\alpha} + (1-\bar{\alpha})(1-y)^2] \quad (4)$$

The normalization constants A and $\bar{A}$ are equal if charge-symmetry holds. In eqs. (3) and (4) the Callan-Gross relation [9]

$$R = \frac{F_2 - 2xF_1}{F_2} = 0 \quad (5)$$

was assumed. A violation of this relation would add an extra term of the form

$$- \frac{R}{2} y^2 \quad (6)$$

inside the brackets of the right-hand sides of eqs. (3) and (4).

The simple form of this theoretical prediction makes it possible to obtain the free parameters by fits to the measured distributions. The distributions of the different terms in eqs. (3) and (4) were folded separately with the experimental resolutions and acceptance, in order to obtain histograms which can be compared with the measured distributions. The errors quoted in the following results contain both statistical errors and systematic uncertainties. The shape parameters, α and $\bar{\alpha}$, were obtained assuming $R = 0$ and charge symmetry ($A = \bar{A}$). The results of the fits incorporating the various corrections are given in table 1 for the full energy range and separately for two partial ranges. The value of $\bar{\alpha} - \alpha$, interpreted as the fractional momentum-weighted strange quark and antiquark content, is given separately. Radiative corrections are important, in particular in the neutrino case, while Fermi-motion corrections are small. No energy-dependence of the shape parameters is observed, although it has been argued that $\alpha(\bar{\alpha})$ should evolve with increasing E_ν . However, the result $\bar{\alpha} - \alpha$ is mainly determined by data at large y , a region of the data which is expected to be saturated first, whenever a threshold is crossed.

The Callan-Gross relation was tested by adding the value of R as defined in eq. (5) as an extra free parameter in the fit, assuming charge symmetry ($A = \bar{A}$). Including radiative and Fermi-motion corrections, the result

$$R = 0.04 \pm 0.10 \quad (7)$$

was obtained, showing agreement with the Callan-Gross relation.

A test of charge symmetry was performed, fitting both A and $\bar{A}$ as free parameters. Assuming $R = 0$ and including radiative and Fermi-motion corrections, the result

$$\frac{(\frac{d\sigma^{\bar{\nu}}}{dy})_{y=0}}{(\frac{d\sigma^{\nu}}{dy})_{y=0}} = 1.05 \pm 0.06 \quad (8)$$

was found, compatible with charge symmetry.

In principle, nucleon structure functions can be obtained by measuring the two-dimensional event distributions in x and Q^2 . However, in order to avoid problems due to the triangular shape of the physical region in the x - Q^2 plane, the unfolding of experimental resolutions was performed in terms of x and $\sqrt{\nu}$, where ν is the energy transfer to the hadron vertex. The physical region in these variables has a rectangular shape. Two-dimensional B-splines were defined in this rectangle as a product of two sets of one-dimensional B-splines, written in the form

$$\frac{d^2\sigma}{dx d\sqrt{\nu}} = \sum_i \sum_j a_{ij} b_i(x) \cdot \beta_j(\sqrt{\nu}) \quad (9)$$

where $b_i(x)$ and $\beta_j(\sqrt{\nu})$ were sets of B-splines. In order to provide a good description of the data, the functions $b_i(x)$ were chosen to be quartic splines and $\beta_j(\sqrt{\nu})$ to be cubic splines with knots according to the resolutions; the constant resolution in $\sqrt{\nu}$ suggested the use of equidistant knots in this variable, while non-equidistant knots were used in x , thus matching the good resolution for small x [$\sigma(x) = 0.01$ at $x = 0.05$] and the coarse resolution for large x [$\sigma(x) = 0.2$ at $x = 0.8$]. As another consequence of the coarse resolution near $x = 1$, extra assumptions were necessary in order to obtain stable results. The assumption was made that the differential cross-section and its first and second derivatives vanish at $x = 1$, as suggested by the results of high-energy electron scattering experiments [10], and following similar procedures used by other groups (see, for example, ref. [11]). Owing to these extra conditions the measurements near $x = 1$ do not contain independent information and are therefore not given.

The resolution unfolded function representing $d^2\sigma/dx d\sqrt{Q^2}$ was then integrated in square bins of x and Q^2 . By applying this procedure, the best estimates of the number of events in bins of x and Q^2 -- $N(x, Q^2)$ and $\bar{N}(x, Q^2)$ -- were obtained for neutrino and antineutrino exposures, respectively. From the measured numbers $N(x, Q^2)$ and $\bar{N}(x, Q^2)$, and the calculated neutrino and antineutrino flux spectra, the structure functions F_2 and xF_3 can be obtained (see, for example, ref. [12]) if an extra assumption is made on the Callan-Gross relation. In this analysis the Callan-Gross relation was assumed, i.e.

$$F_2 = 2xF_1 . \quad (10)$$

A correction was applied for the change of the average x -values in different bins of Q^2 ; the correction was made such that all values are defined at the centre of the bin.

The results of $F_2(x, Q^2)$ and $xF_3(x, Q^2)$ are shown in fig. 2. The error bars shown in this figure correspond to the diagonal elements of the covariance matrix. An additional scale uncertainty of $\approx \pm 5\%$ due to the flux normalization is not shown in the figure. In fits to the data, the non-diagonal elements of the covariance matrix were taken into account as well. The bin-to-bin correlations are positive for adjacent Q^2 -bins and negative for adjacent x -bins, the correlation coefficients being as large as 50% in some cases. The general trend of an increase with increasing Q^2 for small x and the opposite behaviour for large x is visible for F_2 . We note that the slope in the lowest x -bin ($0 < x < 0.05$) is smaller than the slope of the next to lowest bin ($0.05 < x < 0.1$), although this difference does not have large statistical significance. In the case of xF_3 the slopes as a function of Q^2 are not significantly different from zero.

The data were analysed in terms of leading-order QCD, following the method of Buras and Gaemers [13]. Only measurements for $Q^2 > 3 \text{ GeV}^2$ and $x < 0.65$ were used in this fit to F_2 and xF_3 . In this method the structure functions are parametrized by analytical functions, using an empirical parametrization of the x -dependence, not given by QCD, and a Q^2 -dependence consistent with leading order QCD predictions.

Here we briefly define the free parameters in the parametrization. The structure functions F_2 and xF_3 are built from valence and sea-quark distributions following the quark parton model. The valence-quark momentum distribution $x \cdot q_{\text{valence}}(x, s)$ is written in the form

$$x \cdot q_{\text{valence}}(x, s) = \frac{3}{\beta(\eta_1, \eta_2 + 1)} x^{\eta_1} (1-x)^{\eta_2}, \quad (11)$$

where

$$\eta_1 = \eta_{01} + \eta_{11} \cdot s \cdot (4/25)$$

$$\eta_2 = \eta_{02} + \eta_{12} \cdot s \cdot (4/25)$$

and

$$s = \log \left| \frac{\log(Q^2/\Lambda^2)}{\log(Q_0^2/\Lambda^2)} \right|.$$

The Euler beta-function β fixes the normalization. The free parameters are: Λ , defining the mass scale of QCD in the leading-order approximation, and η_{01} and η_{02} describing the x -dependence, while η_{11} and η_{12} follow from the QCD evolution equations once η_{01} and η_{02} are given; Q_0^2 is an arbitrary value of Q^2 , chosen to be 5 GeV^2 . The sea-quark distributions have the form

$$x \cdot q_{\text{sea}}(x, s) = A(s) \cdot (1-x)^{\eta_s(s)} \quad (12)$$

for up, down, strange, and charm-quarks. For the gluon distribution the same parametrization is chosen, i.e. the shape is the same: $\eta_{\text{gluons}} = \eta_{\text{sea}}$. The free parameter of the shape of the sea-distribution is $\eta_s(0)$ defined at Q_0^2 . The value of $A(s)$ at Q_0^2 for different quark flavours is given by the free parameters $\bar{q}/(q+\bar{q})$ for the up and down sea, and $\bar{s}/\bar{u}$ for the strange sea, while the charmed sea is fixed by the assumption that it vanishes for $Q^2 \leq 1.8 \text{ GeV}^2$. The gluon normalization is given by momentum conservation. The s -dependence of $A(s)$ and $\eta(s)$ is given by the QCD evolution equations. Threshold effects of charm production are taken into account using soft rescaling [14].

In table 2 the values of the parameters obtained by the best fit, including all corrections, are summarized. The data are not sensitive to the value of $\bar{s}/\bar{u}$,

therefore this parameter was fixed at 0.5. The errors quoted in the table are only statistical. An estimate of the systematic uncertainty of the value of Λ was obtained by performing fits with different assumptions, e.g. when certain corrections are neglected, experimental uncertainties are varied, and some changes to the parametrization are made. In addition, different values of R [eq. (5)] were tried in order to obtain the structure functions:

- i) $R = 0.1$ as suggested by electron scattering experiments [10];
- ii) $R(x, Q^2) = 1.2 (\text{GeV}^2) \cdot (1-x)/Q^2$ as suggested by Gordon et al. [15].

The resulting changes of the value of Λ are summarized in table 3. From the variations in the resulting value of Λ , a systematic uncertainty of $\Delta\Lambda \approx 0.10$ was estimated, yielding the result:

$$\Lambda = [0.29 \pm 0.12 (\text{stat.}) \pm 0.10 (\text{syst.})] \text{ GeV} . \quad (13)$$

The value of η_2 (which governs the shape of the x -distributions at large x) found in this experiment is larger than the previously reported results of other experiments (e.g. ref. [11]), indicating a steeper decrease of the distribution towards $x = 1$. This fact causes the effect of the Fermi-motion corrections on the value of Λ found in this experiment to be large. The value of η_s indicates a slightly broader sea-distribution than has been found in previous experiments.

Investigating the possible influence of higher twist effects by adding $1/Q^2$ and $1/Q^4$ terms to the logarithmic Q^2 -dependence of QCD in the parametrization of the structure functions [16], we find that the value of Λ does not change significantly. The data are not sensitive to the existence of these higher twist terms.

The sum rule $\int F_3 dx$ due to Gross and Llewellyn Smith [17] is interpreted in the quark-parton model as the number of valence-quarks in the nucleon. The structure function xF_3 was obtained as a function of x averaging over all values of Q^2 . The integral of F_3 was calculated by numerical integration of the observed values of xF_3 weighted by x^{-1} over the interval $0.01 < x < 1.0$. The missing, unmeasured

fraction of the integral, i.e. over the interval $0 < x < 0.01$, was determined using a parametrization of xF_3 in this region, where the free parameters were fitted to the data in the region $0.01 < x < 1.0$. The total integral obtained by adding the two terms was

$$\int F_3 dx = 2.66 \pm 0.41, \quad (14)$$

where the error includes both the statistical and systematic uncertainties. This value is in agreement with the expectation of the quark-parton model.

In summary, from fits to the differential cross-sections $d\sigma/dy$ for neutrinos and antineutrinos, the relative contributions of antiquarks were determined and found to be in agreement with those deduced from the previously reported ratio of total cross-sections of neutrinos and antineutrinos [2]. The data show no deviation from the Callan-Gross relation and are consistent with charge-symmetry. The results agree with previous experiments [11,12,18,19]. The nucleon structure functions F_2 and xF_3 were measured over a large range of Q^2 -values and show a Q^2 -dependence in qualitative agreement with QCD predictions.

A value of the mass scale parameter Λ was obtained in a leading-order QCD approximation. Its value is consistent with previously reported results [11,20,21] within the large statistical and systematic uncertainties.

The Q^2 -dependence of the data is found to be in agreement with the results of other neutrino experiments, while some systematic differences in the x -dependence (especially at large x) among the different experiments were observed [11,12,19-21]. These differences may be explained by systematic uncertainties in the resolutions, which are large compared to the variation of the structure functions in the large- x region, for all neutrino experiments.

A quantitative analysis in terms of QCD is difficult because a significant part of the data is obtained below the value of Q^2 above which QCD is supposed to give reliable results. These difficulties are increased because a satisfactory theoretical description of the so-called higher twist effects is not available. For these reasons experiments with higher statistics and preferentially with higher energy beams are needed, in order to give precise and reliable measurements of Λ .

The method used for the unfolding of experimental resolution functions in this analysis provides an estimate of the measurement uncertainties taking into account, in addition to the conventional statistical errors, the effect of finite experimental resolutions in a mathematically correct way. The latter effect turns out to be an important component of the final uncertainty in the measurements, which has been neglected by previous analyses.

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Figure Captions

- Fig. 1 : Differential cross-sections $d\sigma/dy$ for neutrinos and antineutrinos averaged over the neutrino energy spectrum from 30 to 200 GeV, corrected for resolution and acceptance. The curves are theoretical predictions with parameters determined by fits to the measured distributions.
- Fig. 2 : Observed Q^2 -dependence for a) F_2 and b) xF_3 in bins of x . The curves are QCD-fits, following the approach of Buras and Gaemers as discussed in the text.

Table 1

Shape parameters of y -distributions determined by fits to the data
[see eqs. (3) and (4)]

Corrections included	Energy (GeV)	α	$\bar{\alpha}$	$\bar{\alpha} - \alpha$
Radiative + Fermi motion	30-200	0.11 ± 0.04	0.16 ± 0.01	0.05 ± 0.05
Radiative		0.10 ± 0.04	0.16 ± 0.01	0.06 ± 0.04
None		0.06 ± 0.06	0.18 ± 0.01	0.12 ± 0.08
Radiative + Fermi motion	30-90	0.11 ± 0.04	0.16 ± 0.01	0.05 ± 0.05
Radiative + Fermi motion	90-200	0.12 ± 0.05	0.16 ± 0.02	0.05 ± 0.06

Table 2

Best values and statistical uncertainties*)
of the free parameters of the model of Buras and Gaemers [13]
as determined by fits to the data

η_{01}	0.53 ± 0.03	$(\eta_{11} = -0.81)$
η_{02}	3.08 ± 0.16	$(\eta_{12} = 5.56)$
η_s	4.55 ± 0.49	
$\bar{q}/(q+\bar{q})$	0.12 ± 0.01	
$\bar{s}/\bar{u}$	0.5 (fixed)	
Λ	$(0.29 \pm 0.12)\text{GeV}$	

*) The errors include the uncertainties
in the other parameters.

Table 3

Sensitivity of the mass scale parameter of QCD, Λ ,
to changes in the analysis

	Change in analysis	Effect on Λ (GeV)	Estimated uncertainty in Λ (GeV)
Experimental uncertainties	$\bar{\nu}/\nu$ flux ratio $\pm 1\sigma$	+0.012/-0.014	± 0.014
	Absolute scale of fluxes $\pm 1\sigma$	-0.008/+0.002	± 0.008
	Wide-band background $\pm 1\sigma$	0.008	± 0.008
	K/ π ratio uncertainties	0.030	± 0.030
	Resolution function uncertainty	0.025	± 0.025
Corrections	No Fermi-motion correction	-0.106	} ± 0.030 (FM)
	No Fermi-motion (FM), no radiative corrections (RC)	-0.167	
	No correction for changing centre of x-bin as a function of Q^2	+0.086	} ± 0.025 (RC)
	No correction for $F_2^\nu \neq F_2^{\bar{\nu}}$ and $xF_3^\nu \neq xF_3^{\bar{\nu}}$	-0.017	
Variations in the model	$\bar{s}/\bar{u} = 1.0$ (rather than $\bar{s}/\bar{u} = 0.5$)	+0.028	} ± 0.014
	$c = \bar{c} = 0$, no charmed sea	+0.021	
	No charmed sea, no charm production	-0.078	
	Cabibbo angle $\theta_C = 0$	-0.018	-
	$\eta_{\text{gluons}} = \eta_{\text{sea}}^{-1}$	+0.025	± 0.025
Callan-Gross relation	$R = 0.1$, see Ref. 10	-0.082	} ± 0.050
	$R = 1.2 \text{ (GeV}^2) \cdot (1-x)/Q^2$, see Ref. 15	-0.013

Fig. 1

Fig. 2