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February 1991

CM-P00063102

Inclusive $\rho^0(770)$ meson production
in νp and $\bar{\nu} p$ charged current interactions

Birmingham-CERN-Imperial College-München (MPI)-Oxford-
University College London Collaboration (WA21)

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(Submitted to *Zeitschrift für Physik C*)

Abstract. Using data obtained with the bubble chamber BEBC at CERN, the inclusive $\rho^0(770)$ meson production in νp and $\bar{\nu} p$ charged current reactions is studied. The average ρ^0 multiplicity is measured as a function of the event variables E_ν , W^2 , Q^2 , x_{Bj} , and the charged multiplicity. The differential x_F , y^* , z , and p_T^2 distributions of the ρ^0 are presented as well as the average p_T^2 as a function of W^2 and x_F . The ρ^0/π^0 ratio and the fractions of the $\pi^\pm$ originating from ρ^0 decays are given as functions of x_F . The results are compared to the predictions of fragmentation models. A particular version of the Lund model predicts ρ^0 multiplicities which are generally too high, although it qualitatively reproduces many aspects of the data. The ρ^0 multiplicities predicted by a semi-empirical model (Wells model) are in quantitative agreement with the measurements.

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1. Introduction

The study of resonance production in high-energy interactions is primarily motivated by our understanding that resonances are a more direct product of the collisions and, therefore, reflect more closely the dynamical mechanisms involved than the final particles, which to a large extent originate from resonance decays.

This paper presents an analysis of the inclusive $\rho^0(770)$ resonance production in νp and $\bar{\nu} p$ charged current interactions, i.e. of the processes

$$\begin{aligned}\nu p &\rightarrow \mu^- \rho^0 X \\ &\quad \hookrightarrow \pi^+ \pi^- \\ \bar{\nu} p &\rightarrow \mu^+ \rho^0 X' \\ &\quad \hookrightarrow \pi^+ \pi^-, \end{aligned}$$

where X and X' denote hadronic systems. The analysis is based on the complete charged current event samples of the BEBC WA21 experiment. The event statistics significantly exceed the statistics of previous analyses [1–4] of ρ^0 production in νp and $\bar{\nu} p$ interactions. The publications [3, 4] from the same experiment were based on only a part of the data now available. The aim of the present paper is to determine the properties of inclusive ρ^0 production as completely as possible and to compare them to the expectations of the quark-parton model and of fragmentation models. Some related results on inclusive $f_2(1270)$ production will be published separately [5].

The outline of the paper is as follows: Section 2 describes the main features of the experiment and the details of the analysis, including the procedures used to obtain the average ρ^0 multiplicities and to correct the results for instrumental effects. Section 3 presents the results of the analysis, i.e. the various properties of inclusive ρ^0 production together with comparisons to the model predictions. A summary is given in Sect. 4.

2. Details of the analysis

2.1 The data samples

The detector used in this experiment was the bubble chamber BEBC [6] at CERN. Its volume of approximately 32 m^3 was filled with liquid hydrogen and kept in a vertical magnetic field of 3.5 Tesla. BEBC was equipped with a two-plane external muon identifier (EMI) [7] and, for the later part of the experiment, with an “internal picket fence” (IPF) [8], which recorded position and time information for most of the charged particles entering or leaving BEBC. In several runs during the years 1977 to 1983, BEBC was exposed to the horn-focussed ν and $\bar{\nu}$ wide band beams at the CERN SPS. A total of 458 400 pictures with incident ν and 307 400 pictures with incident $\bar{\nu}$ were taken, each picture consisting of 4 stereoscopic photographs of the BEBC volume. The film was scanned for events with at least 3 charged particles, and the momenta of these charged particles were measured with high accuracy (average fractional momentum error below 2%). Muons were identified by means of the EMI. Only a small fraction of the protons, charged pions and charged kaons was recognized by the particle stopping or decaying in the chamber. The charged particles not identified by these means are, for the analysis described here, taken to be pions. Most of the neutral particles escape detection; in particular, due to the low photon detection efficiency of about 7%, π^0 mesons cannot be reconstructed.

Because of the missing energy due to undetected neutral particles, the energy E_ν of the incident (anti-)neutrino cannot, for most of the events, be directly inferred from the visible energy. E_ν is, therefore, estimated from the momenta of the observed particles by a method based on transverse momentum balance [9, 10]. On the average, E_ν is determined with a relative error of about 20%.

The present analysis is restricted to events which satisfy the following criteria: The event vertex lies within a fiducial volume of about 19 m^3 to ensure good measurement conditions. All the charged tracks of the event are measured with fractional momentum errors of less than 30%. The event contains at least 3 charged tracks, thus excluding the one-prong events $\bar{\nu}p \rightarrow \mu^+ + \text{neutrals}$. In order to select the charged current events, exactly one muon per event is required which has the right charge (μ^- for νp , μ^+ for $\bar{\nu}p$), a momentum greater than $3\text{ GeV}/c$, and is identified by the EMI. The estimated E_ν is required to have a value between 10 GeV and 200 GeV. The resulting samples consist of 17 750 νp and 10 452 $\bar{\nu}p$ charged current events. The average values of the variables E_ν , W , and Q^2 respectively (see

next section for the definitions) are 49 GeV, 5.0 GeV, and 8.0 GeV² for the νp sample and 40 GeV, 4.0 GeV, and 5.2 GeV² for the $\bar{\nu} p$ sample.

Most of the results presented in Sect. 3 refer to the data samples with an additional cut in the hadronic mass W : $W > 2$ GeV is chosen in order to select the events above the ρ^0 production threshold; $W > 3$ GeV enables direct comparisons to the Lund model.

2.2 Definitions of the kinematical variables

Table 1 defines the event variables in terms of the 4-momenta k of the (anti-)neutrino, k' of the muon, and $q = k - k'$ of the intermediate vector boson. The 4-momenta refer to the laboratory system, where the target proton is at rest.

The particle variables used to characterize individual hadrons are defined in Table 2. They are derived from the particle's energy E and transverse momentum $\vec{p}_T$ in the lab system, or its energy E^* and longitudinal momentum p_L^* in the hadronic center of mass system (CMS), where the longitudinal and transverse components are defined relative to the current direction (direction of the intermediate vector-boson).

2.3 The Monte Carlo simulation

Monte Carlo simulations of the experiment are used to test the applied methods, to correct the experimental results for systematic losses and errors, and to obtain the predictions of the Lund fragmentation model. Some details of the simulations performed are described in the following. For each Monte Carlo event, there are two data sets: one giving the “initial” information as observed in an ideal experiment, the other one containing the “modified” values as measured under the influence of the instrumental limitations and deficiencies.

Based on the standard model of electroweak interactions and the quark-parton model, and assuming standard sets of proton structure functions [11], νp and $\bar{\nu} p$ reactions are generated at the parton level. To simulate the subsequent formation of hadrons, either the Lund string fragmentation model or an LPS model is used (see below). After the decays of the produced resonances, all the “initial” values are defined.

These initial data are then modified according to the measurement process, taking into account the experimental momentum resolution, the limited ability to identify charged particles, and the low efficiencies for observing neutral particles.

The Lund string fragmentation model is implemented in its version LEPTO 4.3, JETSET 5.2 [12]. The parameter $P(s)/P(u)$ (= suppression of s quark pair production compared to u or d quark pair production) is set to 0.21, the parameter $E_{\min}$ (= energy threshold below which the fragmentation of a string is stopped) to 0.20 GeV. All other parameters are left at their default values. In particular, the ratio V/P of the probabilities for primary production of vector mesons and pseudoscalar mesons is 1. The mixing of the neutral vector mesons ρ^0 , ω , and ϕ is governed by several parameters such that a vector meson ($u\bar{u}$) or ($d\bar{d}$) is taken as either ρ^0 or ω with equal probabilities, whereas ($s\bar{s}$) always results in a ϕ . It was shown in previous analyses of the experiment [13, 14] that, with this choice of parameters, the experimental data are in many respects well described by the Lund simulation. Because the Lund Monte Carlo cannot be successfully applied at small values of the hadronic mass W , the simulation is restricted to events with $W > 3$ GeV.

Another option, alternative to the Lund model, is a longitudinal phase-space (LPS) Monte Carlo, which was also tuned to reproduce various properties of the experimental data [10]. It does not contain resonances like the ρ . Here, it is mainly used to simulate the events with $W < 3$ GeV.

2.4 The determination of the ρ^0 signal

Since the ρ^0 is a resonance decaying into $\pi^+\pi^-$, its analysis is based on the quantitative determination of the corresponding resonance signal in the invariant mass distribution of $\pi^+\pi^-$ combinations. This is achieved by fitting the following expression, containing a relativistic Breit-Wigner function $BW_\rho(m)$ for the ρ^0 signal, and a parameterisation $BG(m)$ for the background, to the $\pi^+\pi^-$ invariant mass (m) distribution:

$$\frac{dN}{dm} = [1 + \alpha_1 BW_\rho(m)] BG(m) \quad (1)$$

$$\text{where} \quad BW_\rho(m) = \frac{m}{p} \frac{\Gamma(m)}{(m_\rho^2 - m^2)^2 + m_\rho^2 \Gamma(m)^2} \quad (2)$$

$$\Gamma(m) = \Gamma_\rho \left(\frac{p}{p_\rho} \right)^{2l+1} \quad (3)$$

$$BG(m) = \alpha_2 (m - 2m_\pi)^{\alpha_3} e^{\alpha_4 m + \alpha_5 m^2}. \quad (4)$$

N is the number of $\pi^+\pi^-$ combinations. m_ρ and Γ_ρ are the central mass and the width of the ρ resonance, assumed to be 770 MeV and 153 MeV* respectively [15]. $p = \sqrt{m^2/4 - m_\pi^2}$ is the pion momentum in the two-pion rest frame, and $p_\rho = p(m_\rho)$ its value at the ρ^0 central mass. m_π is the charged pion mass. $l = 1$ is the relative orbital angular momentum of the two pions from the (p -wave) ρ^0 decay. α_1 to α_5 are free parameters which are determined from a χ^2 -fit. The fit is performed in the mass range $0.3 \text{ GeV} < m < 1.8 \text{ GeV}$. In eq. (1), the Breit-Wigner function is multiplied by BG in order to account for the available phase-space [16]. It is assumed that the background distribution reflects the variation of phase-space.

The number of ρ^0 mesons contained in the signal is given by

$$N_{\rho^0} = \int_{2m_\pi}^{m_{\max}} \alpha_1 BW_\rho(m) BG(m) dm, \quad (5)$$

with $m_{\max}$ set to the upper limit of the fitted mass range. The statistical error of N_{ρ^0} is determined from the error matrix of the parameters α_i , which is obtained from the behaviour of χ^2 near the minimum.

For some of the fits of this analysis, an extra term $\alpha_6 BW_f(m) BG(m)$ for the $f_2(1270)$ resonance, containing another free parameter α_6 , is added to expression (1). This leads to a slightly better description of $m_{\pi^+\pi^-}$ distributions with relatively high statistics (e.g. from the complete samples of $\pi^+\pi^-$ combinations without cuts, Fig. 1a and b), therefore indicating f_2 production, but has little influence on N_{ρ^0} . Details and results of the analysis concerning f_2 meson production are given in [5].

As examples, Fig. 1 shows the $\pi^+\pi^-$ mass spectra of the ν and $\bar{\nu}$ data samples, without cuts and with the cut $x_F > 0.5$. It can be seen that the distributions are well described by the ansatz (1-4) and that there are clear ρ^0 signals.

Various tests using both the experimental data and the Lund Monte Carlo simulation have been performed in order to probe the reliability and to estimate the systematic uncertainties of the described method to determine N_{ρ^0} . For the tests using the experimental data, the distributions shown in Fig. 1 were chosen, together with the corresponding distributions of the combined ν and $\bar{\nu}$ data, and of halves of the data samples, to investigate the influence of the size of the data set.

As one check, the mass and width of the ρ^0 resonance were treated as free parameters and, together with the α_i , determined from the fit. Taking into account the statistical errors, the results agreed in all cases with the PDG values, 770 MeV and 153 MeV respectively.

*The experimental resolution of about 9 MeV in m is negligible compared to the natural width.

For a quantitative study of the systematic error on N_{ρ^0} due to the fit method, several variations of the method, e.g. changing the bin width, changing the fitted mass range, fixing the parameter α_5 at zero, and including the extra term for the f_2 resonance, were tried and the results obtained for N_{ρ^0} were compared to each other. Although the observed variations of N_{ρ^0} were at most of the order of the statistical errors, some of the variations appeared to be systematic because they preferred one direction of change and were roughly independent of the statistical size of the sample. Averaged over the tested distributions, the results for N_{ρ^0} varied within a range of 12% (relative variation $\Delta N_{\rho^0}/N_{\rho^0}$), which is taken as one estimate of the systematic error.

The Lund Monte Carlo makes more direct tests of the fit method possible since, for every sample of Lund events, the number of ρ^0 mesons is known a priori. In addition, systematic effects due to other resonances can be studied in detail. Figure 2 shows a typical $\pi^+\pi^-$ mass spectrum of modified Lund events, where the contributions of several resonances are indicated. Besides $\rho^0 \rightarrow \pi^+\pi^-$, the following resonance decays are taken into account:

$$\begin{aligned}\eta &\rightarrow \pi^+\pi^-\pi^0 \\ &\rightarrow \pi^+\pi^-\gamma \\ \eta'(958) &\rightarrow \pi^+\pi^-\eta \\ \omega &\rightarrow \pi^+\pi^-\pi^0 \\ K^{*0} &\rightarrow K^+\pi^- \\ \overline{K^{*0}} &\rightarrow K^-\pi^+.\end{aligned}$$

The signals of these decays appear as “reflections” in the $\pi^+\pi^-$ mass distribution (for the K^{*0} and $\overline{K^{*0}}$ due to wrong interpretation of the final state). Some other reflections, e.g. from $\phi \rightarrow K^+K^-$ or $\Delta^0 \rightarrow p\pi^-$, contribute only very little to the distribution. The $f_2(1270)$ resonance is not implemented in this version of the Lund model.

As can be seen from Fig. 2, the shape of the $\pi^+\pi^-$ mass distribution is strongly influenced by the reflections of η , η' , ω and K^* . Attempts to include one, or several, of these reflections explicitly in the fitted function showed that they are too close to each other and to the ρ^0 signal to have their contributions independently determined by the fit. On the other hand, it was found that the parameterization (4) is flexible enough to describe the background distribution, including all the reflections, with sufficient accuracy. Of course, there arise systematic deviations of the fitted function from the mass distribution, but the resulting systematic errors on N_{ρ^0} are of moderate size (see below).

Quantitative checks on whether the N_{ρ^0} obtained from the fit agrees with the known number of ρ^0 mesons were performed in several test series, each series using an independent Lund event sample of the size of the experimental ν data sample. For each event sample, the sample of $\pi^+\pi^-$ combinations was subdivided into several bins in several kinematical variables (W , Q^2 , x_{Bj} , charged hadron multiplicity, x_F , z , p_T^2), and for each bin a fit was performed to extract N_{ρ^0} , as was done with the experimental data in order to study the dependence of ρ^0 production on these variables (see Sect. 3). Thus, each series consists of a number of test fits which are statistically nearly independent and differ widely in characteristic properties, like the size of the ρ^0 signal or the shape of the background distribution.

The results of such a test series are displayed in Fig. 3. Evidently, the N_{ρ^0} obtained from the fit agree very well with the correct N_{ρ^0} , taking into account the statistical errors. Furthermore, over a wide range of values, the reliability of the fit method depends neither on the absolute size of the ρ^0 signal (Fig. 3a) nor on the signal/background ratio (Fig. 3b). Nevertheless, there is a small systematic offset; averaged over the test fits shown in Fig. 3, N_{ρ^0} is underestimated by 8.4 %. Similar offsets in the range $-(8 \pm 1) \%$ were observed in all the test series using Lund distributions with the default resonance multiplicities.

Since this result depends strongly on the multiplicities of the various resonances affecting the $\pi^+\pi^-$ distribution, and since it cannot be assumed that these multiplicities are perfectly simulated by the Lund model, additional tests were performed where the contributions of the η (η'), ω and K^* reflections were changed. Varying these contributions independently of each other within plausible limits, systematic shifts of $\pm 9 \%$ were observed in addition to the -8% offset. Because of the uncertainty as to what extent these results apply to the experimental data, they were only taken as order-of-magnitude estimates of the systematic effects. By adding the two numbers (8 % and 9 %) in quadrature, one arrives at a total systematic uncertainty for N_{ρ^0} of $\pm 12 \%$. This result is in good agreement with the estimate derived (independently) from the experimental data, and it will be used in the following.

2.5 Corrections

In addition to the systematic uncertainties of the fitting method, there are instrumental effects, which can be studied and corrected for with the help of the Monte Carlo simulation (see Sect. 2.3). The most important effects are the “smearing” caused by the imperfect knowledge of the kinematical variables, and event losses due to the experimental limitations and cuts.

2.5.1 Smearing correction

In order to correct a differential distribution dN/dx for the smearing in the variable x , a matrix method is applied, where the matrix is determined in the Monte Carlo (MC) simulation. Let L_{ij} denote the number of ρ^0 mesons which are in the i th bin of the initial MC set and in the j th bin of the modified MC set. Then the matrix M , defined as

$$M_{ij} = \frac{L_{ij}}{\sum_k L_{kj}} = \frac{L_{ij}}{N_j^{\text{mod}}}, \quad (6)$$

transforms the modified into the initial MC distribution:

$$N_i^{\text{init}} = \sum_j M_{ij} N_j^{\text{mod}}. \quad (7)$$

This transformation, which represents a perfect correction for the MC data, is not necessarily an ideal correction for the experimental data, in particular if the experimental distribution differs significantly from the MC distribution (see Sect. 3). In order to reduce the dependence of M_{ij} on the MC distribution, the initial MC distribution (N_i^{init}) is modified to agree with the experimentally measured distribution (N_i^{meas}) before an improved transformation matrix $\widetilde{M}_{ij}$ is calculated:

$$\widetilde{L}_{ij} = \frac{L_{ij}}{N_i^{\text{init}}} N_i^{\text{meas}} = \frac{L_{ij}}{\sum_k L_{ik}} N_i^{\text{meas}} \quad (8)$$

$$\widetilde{M}_{ij} = \frac{\widetilde{L}_{ij}}{\sum_l \widetilde{L}_{lj}}. \quad (9)$$

The application of this matrix leads to an approximate solution which is close to the perfect correction in the limit of small corrections. The exact solution could be reached by an iteration of this method⁺. However, it can be shown that this exact solution is highly unstable against small fluctuations of the input data [17].

⁺An alternative approach to find the exact solution would be to determine from the MC data the matrix which transforms the initial into the modified distribution and to apply the inverse of this matrix to the experimentally observed distribution.

Therefore, the results shown in Sect. 3 are corrected with the approximate method*. This choice is supported by the fact that, in almost all cases, the condition of small corrections is found to be fulfilled (mean absolute value of the correction: 8.7 % of N_{ρ^0}). Furthermore, various tests performed with the Monte Carlo simulations demonstrated the reliability of the method [18]. A systematic undercorrection was found in the cases where the corrections are large. To account for this behaviour, a systematic error of 50% of the correction was introduced.

2.5.2 Event losses

Event losses arise from unidentified or low momentum muons, from badly measured tracks, or from events missed during the scanning of the film. The investigation of these losses with the help of the Monte Carlo leads to the conclusion that most of these effects are negligible (on the order of 1%) for the ρ^0 results presented in this paper, which are relative quantities, normalized to the number of events or to the number of pions.

The only effect that cannot be neglected is caused by the 1-prong events $\bar{\nu}p \rightarrow \mu^+ + \text{neutrals}$. Although these events do not contribute to the ρ^0 production, they affect the average ρ^0 multiplicity via the total event number. The 1-prong events were systematically scanned and measured for only a part of the $\bar{\nu}$ data. From these measurements, the 1-prong rate was determined as a function of E_ν [19] and as a function of W [20]. In the present analysis, these results are used to calculate 1-prong corrections for the $\bar{\nu}$ event numbers.

For the complete $\bar{\nu}$ data sample as described in Sect. 2.1, the 1-prong rate $R_{1\text{-prong}}$, defined as the number of 1-prong events divided by the number of all charged current events including the 1-prong events, is 0.27 ± 0.04 . This corresponds to a correction on the number of observed events (with ≥ 2 charged hadrons) of $1/(1 - R_{1\text{-prong}}) = 1.37 \pm 0.07$. Restricting to the event sample with $W > 2 \text{ GeV}$ or $W > 3 \text{ GeV}$ reduces the 1-prong correction to 1.12 ± 0.03 or 1.05 ± 0.02 respectively. For each subsample of the $\bar{\nu}$ data, the 1-prong correction is calculated from the E_ν and W spectra of the events. Sizeable corrections occur mainly in the regions of small W or small E_ν (see Table 3).

*The method is described here for the case of a differential distribution of the ρ^0 mesons. The ρ^0 multiplicity as a function of an event variable is corrected in an analogous way for the smearing of events in that variable.

2.5.3 Pion numbers

For the cases where the ρ^0 multiplicities are compared to the multiplicities of charged pions, these are derived from the observed numbers of all charged particles for which the pion hypothesis is not excluded. A Monte Carlo correction is applied to take into account the fraction of protons and kaons. This is done by multiplying the experimental numbers with the ratio $N_{\pi}^{\text{init}}/N_{\pi}^{\text{mod}}$ of the corresponding initial and modified Monte Carlo numbers. Correction factors of 0.75 and 0.90 respectively are obtained for the complete π^+ and π^- samples. If kinematical distributions of the pions are considered, the correction is applied separately for each bin, which takes care not only of the p and K fractions but also of smearing effects. To allow for possible systematic differences between the data and the Monte Carlo, a systematic error of $\pm 10\%$ is assumed for all pion numbers.

3. Results

This section contains the experimental results obtained and corrected by the methods described above. In the cases where only one error is quoted, the statistical and the systematic errors are added in quadrature. This applies also for the error bars drawn in the figures. In order to study the ρ^0 production as a function of a kinematical variable, the set of $\pi^+\pi^-$ combinations in the data sample is divided into several bins in that variable, and the ρ^0 number in each bin is extracted by a fit to the corresponding $\pi^+\pi^-$ mass distribution.

Most of the results are presented together with the predictions of the Lund fragmentation model, which are obtained from a Monte Carlo simulation (see Sect. 2.3). In addition, comparisons to a semi-empirical model developed by J. Wells [21] are made where the model is applicable. This model, the parameters of which were determined from hadron interaction data, gives absolute predictions for the average multiplicities of various resonances, including the ρ^0 , as a function of W . The relative multiplicities of particles with different spin are, in the Wells model, assumed to follow from spin-statistics (corresponding to $V/P=3$, for example). While the Lund model, in the version used here, takes into account only the production of the $J^P = 0^-$ and 1^- mesons (where the quark and antiquark are in a state with orbital angular momentum $l = 0$), the Wells model includes also the $J^P = 0^+$, $1_{a_1}^+$, 2^+ , and $1_{b_1}^+$ multiplets (with $l = 1$). It should be emphasized that the two models describe the fragmentation at completely different levels; the Lund model is an explicit simulation of the fragmentation process, whereas the Wells model gives a global description of the average particle multiplicities in different reactions.

3.1 The average ρ^0 multiplicity

The global ρ^0 multiplicities observed in the data samples with $W > 2 \text{ GeV}$ or $W > 3 \text{ GeV}$ respectively are listed in Table 4. The average ρ^0 multiplicity $\langle n_{\rho^0} \rangle$ is defined as the ratio of the number of ρ^0 mesons (N_{ρ^0}) to the number of events (N_{ev}). The ratios N_{ρ^0}/N_{π} , which are also given in Table 4, compare the ρ^0 multiplicity to the pion multiplicities. The charged pion numbers N_{π^+} and N_{π^-} were obtained from the numbers of charged hadrons by applying a Monte Carlo correction (see Sect. 2.5.3). Note that N_{π^+} and N_{π^-} include the pions from ρ^0 decays. π^0 mesons are not observed in the present experiment; it is, however, known from ν and $\bar{\nu}$ Neon scattering [22] that the number of π^0 mesons is described in good approximation by the quantity $N_{\pi^0} = (N_{\pi^+} + N_{\pi^-})/2$.

One can see from Table 4 that, while the ν and the $\bar{\nu}$ data differ significantly in $\langle n_{\rho^0} \rangle$, they agree within the errors in the ratio N_{ρ^0}/N_{π^0} , (see also Table 6). The large differences in N_{ρ^0}/N_{π^+} and N_{ρ^0}/N_{π^-} between the ν and the $\bar{\nu}$ data, on the other hand, can be qualitatively explained by the total charge of the hadronic system (+2 in the νp , 0 in the $\bar{\nu} p$ reaction).

Regarding the model predictions for $\langle n_{\rho^0} \rangle$ and N_{ρ^0}/N_{π} listed in Table 4, one finds good agreement of the Wells expectations (given only for $\langle n_{\rho^0} \rangle$) with the experimental results, whereas the Lund model predicts numbers which are significantly too high in all cases. The Lund predictions for $\langle n_{\rho^0} \rangle$ are $(57 \pm 24)\%$ higher in the νp reaction and $(114 \pm 43)\%$ higher in the $\bar{\nu} p$ reaction than the experimental measurements. By varying the model parameters, it was found that any improvement in the predicted ρ^0 multiplicity is accompanied by a detuning in other properties like the charged particle multiplicities. It appears that a quantitatively correct description of both ρ^0 and pion production is not possible within the given version of the Lund model. This might be caused by the fact that, in this version, the model contains only the pseudoscalar and vector mesons and neglects the higher states which, through their decays, influence the experimentally observed ρ/π ratios. The good agreement between the Wells model predictions and the data seems to confirm this view; the Wells model includes the production of the higher scalar, axial-vector, and tensor mesons.

In Table 5, the average ρ^0 multiplicities measured in this experiment are compared to the results of other measurements. All the previous results, with the exception of the Neon experiment [23], were obtained with significantly smaller data samples than those used here. This is also true for the previous WA21 results [3, 4], which were based on part of the data used here and did not take the systematic errors into account.

The ν scattering results listed in Table 5 are in reasonable agreement with each other, even when reactions on different target nuclei are compared. The deviation of [27] from the other measurements can be explained by the different W regions. Comparing the results of the $\bar{\nu}$ experiments to each other, one finds larger differences, which do not appear to be correlated to the W range. These differences may be due to the fact that the background parameterisation used in [2] and [24] differs from the function (4) assumed in [4] and [23] as well as in this analysis.

3.2 The dependence on event variables

The average ρ^0 multiplicity as a function of the (anti-)neutrino energy E_ν is shown in Fig. 4 for the ν and $\bar{\nu}$ data without a W cut. In the ν data, one observes a significant increase of $\langle n_{\rho^0} \rangle$ with E_ν . In the $\bar{\nu}$ data, $\langle n_{\rho^0} \rangle$ seems to be roughly independent of E_ν . However, in this case, the event numbers are small and the statistical errors are, therefore, large at larger E_ν . At small E_ν ($E_\nu \lesssim 60$ GeV), the ν and the $\bar{\nu}$ results approximately agree. Note that the $\bar{\nu}$ results incorporate large 1-prong corrections (see Table 3).

The average multiplicity $\langle n_{\rho^0} \rangle$ for a fixed E_ν is related to the cross section of inclusive ρ^0 production, which can be obtained by multiplying by the total event cross-section: $\sigma_{\rho^0} = \langle n_{\rho^0} \rangle \sigma_{\text{tot}}$. The total νp and $\bar{\nu} p$ charged current cross-sections have been measured to be $\sigma_{\text{tot}}^{\nu p}/E_\nu = (0.474 \pm 0.029) \cdot 10^{-38} \text{ cm}^2/\text{GeV}$ and $\sigma_{\text{tot}}^{\bar{\nu} p}/E_\nu = (0.500 \pm 0.032) \cdot 10^{-38} \text{ cm}^2/\text{GeV}$ respectively [28].

The dependence of the average ρ^0 multiplicity on W^2 , the hadronic invariant mass squared, is displayed in Fig. 5. In addition to $\langle n_{\rho^0} \rangle$, the multiplicities $\langle n_{\rho^0} \rangle_{\text{forw.}}$ and $\langle n_{\rho^0} \rangle_{\text{backw.}}$ of the ρ^0 mesons produced in the forward ($x_F > 0$) or backward ($x_F < 0$) hemisphere of the hadronic system are shown.

In the ν data, one clearly observes the expected logarithmic rise of $\langle n_{\rho^0} \rangle$ with W^2 . A χ^2 -fit of the expression $\langle n_{\rho^0} \rangle = a + b \ln(W^2/\text{GeV}^2)$ to the data points in Fig. 5a results in $a = -0.155 \pm 0.074$ and $b = 0.099 \pm 0.025$, with a χ^2 of 1.1 for 3 degrees of freedom. The solid line in Fig. 5a indicates the fitted function. No clear W^2 dependence is seen in the case of the $\bar{\nu}$ data (Fig. 5b), where the measurement conditions are poor at higher W^2 values because of the unfavourable W distribution of the $\bar{\nu}$ event sample (see [4]).

The Lund model predictions (dashed lines in Fig. 5) are generally higher than the data, as already observed in Sect. 3.1. The difference is most prominent in the backward multiplicity $\langle n_{\rho^0} \rangle_{\text{backw.}}$. The logarithmic rise of $\langle n_{\rho^0} \rangle$ in the ν data is qualitatively reproduced by the Lund model.

The Wells model predictions (dotted lines in Fig. 5) are in good agreement with the ν data and at least consistent with the $\bar{\nu}$ measurements. The separate predictions of the forward and backward multiplicities reflect the division of the total multiplicity into several “components”, which is one of the basic assumptions of the Wells model. The good agreement between the model and the data found in Fig. 5 confirms this assumption as well as the underlying ideas of the quark-parton model. Some deviations at small W are not surprising since, in this region, one cannot expect a perfect separation of the different components. Furthermore, the

application of the Wells model at small W is perhaps inappropriate as phase-space threshold effects are not taken into account.

The results of an attempt to determine the dependence of $\langle n_{\rho^0} \rangle$ on W and Q^2 simultaneously are shown in Fig. 6. The ν data were divided into bins both in W and in Q^2 . Obviously, the W dependence is the dominant effect. However, in each of the three W bins, there is a slight increase of $\langle n_{\rho^0} \rangle$ with Q^2 . This might be an indication of a Q^2 dependence at fixed W , as was observed in [20] for the charged hadron multiplicities of the present experiment. (Within each W bin, the dependence of the mean W on Q^2 is negligible.) For a quantitative analysis, following [20], the function $\langle n_{\rho^0} \rangle = a + b \ln(W^2/\text{GeV}^2) + c \ln(Q^2/\text{GeV}^2)$ was fitted to the data points in the region $3 \text{ GeV} < W < 15 \text{ GeV}$, $1 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$, resulting in $a = -0.125 \pm 0.113$, $b = 0.086 \pm 0.038$, $c = 0.018 \pm 0.026$. The value of c indicates a Q^2 dependence which is, compared to the experimental errors, not significant. The dotted curves in Fig. 6 show the fitted function calculated at the average $\ln W^2$ value of each W bin.

Figure 7 presents the x_{Bj} dependence of $\langle n_{\rho^0} \rangle$. The observed decrease with x_{Bj} can be explained as a reflection of the dominant W dependence of $\langle n_{\rho^0} \rangle$, mediated by the x_{Bj} dependence of $\langle W \rangle$. This is demonstrated by the dotted histogram in Fig. 7a, which indicates the expected $\langle n_{\rho^0} \rangle$ values calculated from the result $\langle n_{\rho^0} \rangle = -0.155 + 0.099 \ln(W^2/\text{GeV}^2)$ obtained above and the $\langle \ln W^2 \rangle$ value in each x_{Bj} bin. The Lund predictions (dashed curves in Fig. 7) show again qualitative but not quantitative agreement with the measurements.

As can be seen from Table 6, the average ρ^0 multiplicity is strongly correlated with the multiplicity $n_{\text{ch.had.}}$ of charged hadrons (including the pions from the ρ^0 decays). If, however, the number of ρ^0 is normalized to $N_{\pi^0} = (N_{\pi^+} + N_{\pi^-})/2$, the dependence on $n_{\text{ch.had.}}$ is apparently removed. The results of the ν and the $\bar{\nu}$ data at fixed $n_{\text{ch.had.}}$ seem to agree both in $\langle n_{\rho^0} \rangle$ and in N_{ρ^0}/N_{π^0} , although there is only a limited region ($n_{\text{ch.had.}} = 4, 6$) where the comparison can be made. At $n_{\text{ch.had.}} > 6$, the statistics in the $\bar{\nu}$ data are too small to allow the determination of N_{ρ^0} .

3.3 Longitudinal properties

The longitudinal properties of the ρ^0 mesons are investigated using the variables x_F , y^* , and z (see Table 2 for the definitions). Figure 8 shows the normalized differential distributions in these variables. As can be seen, the great majority of the ρ^0 are produced in the forward hemisphere ($x_F > 0$ or, equivalently, $y^* > 0$). This indicates—using the language of the quark-parton model—that most of the ρ^0 are current fragments, i.e. originate from the fragmentation of the primarily struck quark. Differences between the ν and $\bar{\nu}$ data sets show up mainly in the intermediate region $0 \lesssim x_F \lesssim 0.2$ (or $0 \lesssim y^* \lesssim 0.75$, or $0.2 \lesssim z \lesssim 0.4$), where the ρ^0 multiplicity is higher in the ν than in the $\bar{\nu}$ data.

The distributions of Fig. 8 are not reproduced by the Lund model. The Lund calculations clearly overestimate the ρ^0 multiplicities in the backward region, but agree within the errors with the experimental results in the forward region (in the case of $\bar{\nu}$ for $x_F \gtrsim 0.2$).

The large differences between the ρ^0 multiplicities in the two hemispheres are also evident from Table 7, which contains the average forward and backward ρ^0 multiplicities, $\langle n_{\rho^0} \rangle_{\text{forw.}}$ and $\langle n_{\rho^0} \rangle_{\text{backw.}}$ (see also Fig. 5), and the forward-backward-asymmetry

$$A_{\text{fb}} = \frac{\langle n_{\rho^0} \rangle_{\text{forw.}} - \langle n_{\rho^0} \rangle_{\text{backw.}}}{\langle n_{\rho^0} \rangle_{\text{forw.}} + \langle n_{\rho^0} \rangle_{\text{backw.}}} . \quad (10)$$

The ν and the $\bar{\nu}$ data agree in A_{fb} . The Lund model predicts too high ρ^0 multiplicities in both hemispheres and too small values of A_{fb} . The Wells model, on the other hand, matches the data very well in all these quantities.

3.4 Comparison to pion production

Since ρ mesons and pions are states of identical quark composition, it is of special interest to compare their x_F distributions. The primary production properties of ρ^0 and π^0 , for example, are expected to be essentially similar apart from effects due to the mass difference and the spin degree of freedom. Most important are the mesons at high values of x_F , where the primary particles are concentrated and the influence of the V/P ratio should be most directly observable.

The ratio of the differential x_F distributions of the ρ^0 and ‘ π^0 ’ mesons ($N_{\pi^0} = (N_{\pi^+} + N_{\pi^-})/2$, see Sect. 3.1) is shown in Fig. 9. The ν and $\bar{\nu}$ measurements approximately agree. In the central region ($x_F \approx 0$), where the products of resonance decays accumulate, pions are much more frequent than ρ^0 . At higher absolute values

of x_F , in both the forward and backward hemispheres, the ρ^0 and π multiplicities are comparable to each other. At $x_F \rightarrow 1$, the observed ratio N_{ρ^0}/N_{π^0} is close to unity.

The Lund model calculations clearly disagree with the experimental results for N_{ρ^0}/N_{π^0} in the central region, which may be due to the higher meson resonances not included in the applied version of the model. The decays of these higher resonances will enhance the pion numbers in the central region. At higher $|x_F|$, the Lund predictions (with $V/P = 1$) seem to agree approximately with the experiment.

The ratios N_{ρ^0}/N_{π^+} , N_{ρ^0}/N_{π^-} , and N_{ρ^0}/N_{π^0} , as observed in the region $x_F > 0.5$ are listed in Table 8. These results can be used for a definite test of the quark-parton model, which predicts certain relations between the values obtained in νp and $\bar{\nu} p$ scattering: From the isospin and charge conjugation symmetries of the strong interaction, one deduces the following identities of fragmentation functions:

$$\begin{aligned} D_u^{\pi^+} &= D_d^{\pi^-} = D_{\bar{d}}^{\pi^+} = D_{\bar{u}}^{\pi^-} \\ D_u^{\pi^-} &= D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^+} \\ D_u^{\rho^0} &= D_d^{\rho^0} = D_{\bar{d}}^{\rho^0} = D_{\bar{u}}^{\rho^0} . \end{aligned} \quad (11)$$

D_q^H describes the fragmentation of a quark of type q into hadrons of type H (as a function of e.g. x_F). According to the quark-parton model, the hadrons in the forward region are the fragments of the current quark, which, neglecting strange and heavier quarks, is a u or $\bar{d}$ in the νp , and a d or $\bar{u}$ in the $\bar{\nu} p$ reaction. Therefore, in the forward direction, the following relations are expected to hold approximately:

$$\left(\frac{N_{\rho^0}}{N_{\pi^+}} \right)_{\nu p} = \left(\frac{N_{\rho^0}}{N_{\pi^-}} \right)_{\bar{\nu} p} \quad (12)$$

$$\left(\frac{N_{\rho^0}}{N_{\pi^-}} \right)_{\nu p} = \left(\frac{N_{\rho^0}}{N_{\pi^+}} \right)_{\bar{\nu} p} . \quad (13)$$

The definition $N_{\pi^0} = (N_{\pi^+} + N_{\pi^-})/2$ then implies:

$$\left(\frac{N_{\rho^0}}{N_{\pi^0}} \right)_{\nu p} = \left(\frac{N_{\rho^0}}{N_{\pi^0}} \right)_{\bar{\nu} p} . \quad (14)$$

One sees from Table 8 that the experimental results obey, within the errors, all these relations and are thus in complete agreement with the quark-parton model.

The differences observed between the numbers related to π^+ and π^- can be qualitatively explained within the quark-parton model: The π^+ in νp (π^- in $\bar{\nu} p$)

scattering can be the leading particle containing the current quark, whereas the oppositely charged pion contains only quarks created later on in the fragmentation process and is, therefore, unfavoured. In either case, there can be a leading ρ^0 . This leads to the following expectations (for the forward hemisphere):

$$\left(\frac{N_{\rho^0}}{N_{\pi^+}}\right)_{\nu p} < \left(\frac{N_{\rho^0}}{N_{\pi^-}}\right)_{\nu p} \quad (15)$$

$$\left(\frac{N_{\rho^0}}{N_{\pi^+}}\right)_{\bar{\nu} p} > \left(\frac{N_{\rho^0}}{N_{\pi^-}}\right)_{\bar{\nu} p} \quad (16)$$

The Lund model predictions, which are also listed in Table 8, clearly fulfill the relations (12–16). The Lund numbers are, however, in all cases somewhat lower than the measurements. This may be an indication that the value $V/P = 1$ assumed in the Monte Carlo is not in accord with reality. However, due to the fact that the Lund calculation does not contain higher resonances (see above), definite conclusions cannot be drawn.

The ratios N_{ρ^0}/N_{π^+} and N_{ρ^0}/N_{π^-} (in a given pion sample) can also be interpreted as the fractions of the charged pions which originate from ρ^0 decays. In Fig. 10, these fractions are plotted as functions of the pion x_F variable. In addition, the values found in the region $x_F > 0.5$ are listed in Table 8. Again, the symmetry relating, in the forward region, the π^+ (π^-) from νp to the π^- (π^+) from $\bar{\nu} p$ scattering becomes apparent. The fraction of ρ^0 decay products among the pions which cannot contain the current quark (π^- in νp , π^+ in $\bar{\nu} p$) is impressively large in this region and is underestimated by the Lund model (see Table 8). In the central region, on the other hand, the Lund model overestimates all fractions by a factor of about two.

3.5 Transverse properties

The differential p_T^2 distributions of the ρ^0 in the data samples with $W > 3$ GeV are shown in Fig. 11. Within the errors, the observed distributions are well described by exponential functions $a e^{-b p_T^2}$ (see solid lines in Fig. 11). The parameters a and b resulting from χ^2 -fits are $a = (0.54 \pm 0.10) \text{ GeV}^{-2}/\text{c}^{-2}$, $b = (2.72 \pm 0.31) \text{ GeV}^{-2}/\text{c}^{-2}$ for the ν data, and $a = (0.54 \pm 0.16) \text{ GeV}^{-2}/\text{c}^{-2}$, $b = (3.82 \pm 0.79) \text{ GeV}^{-2}/\text{c}^{-2}$ for the $\bar{\nu}$ data. The exponential fall seems to be steepest at smaller values of p_T^2 ; restricting the fits to the region $p_T^2 < 0.6 \text{ GeV}^2/\text{c}^2$ results in $b = (3.78 \pm 0.88) \text{ GeV}^{-2}/\text{c}^{-2}$ and $(4.71 \pm 1.33) \text{ GeV}^{-2}/\text{c}^{-2}$ for the ν and $\bar{\nu}$ data respectively.

The average transverse momentum squared, $\langle p_T^2 \rangle$, of the ρ^0 can be determined from the integrated ρ^0 signal in a $\pi^+\pi^-$ mass histogram where each entry is weighted by p_T^2 (of the $\pi^+\pi^-$ pair). $\langle p_T^2 \rangle$ is obtained by dividing this signal by N_{ρ^0} , the integrated signal in the unweighted histogram. In the ν and $\bar{\nu}$ data samples with $W > 3$ GeV, $\langle p_T^2 \rangle$ is found to be $(0.37 \pm 0.07) \text{ GeV}^2/c^2$ and $(0.30 \pm 0.10) \text{ GeV}^2/c^2$ respectively. These results agree with the inverse values of the slope b obtained above. In the ν and $\bar{\nu}$ event samples without a W cut, one measures $\langle p_T^2 \rangle$ of $(0.35 \pm 0.07) \text{ GeV}^2/c^2$ and $(0.28 \pm 0.08) \text{ GeV}^2/c^2$ respectively. The differences between the ν and $\bar{\nu}$ data observed in $\langle p_T^2 \rangle$ as well as in the slope b are probably due to the different W distributions of the two data sets and a W dependence of $\langle p_T^2 \rangle$ (see below).

In Fig. 12, the average p_T^2 of the ρ^0 is plotted as a function of the variables W^2 and x_F . By exploiting the fit results concerning the background distributions, one can also determine $\langle p_T^2 \rangle$ of the background $\pi^+\pi^-$ combinations in the ρ^0 mass region. For comparison, these results are also shown in Fig. 12, as are the $\langle p_T^2 \rangle$ values of the charged pions, which are, with a Monte Carlo correction, determined from the charged particle $\langle p_T^2 \rangle$. Only the measurements of the ν data are presented here, since the $\bar{\nu}$ measurements have too large errors to be meaningful.

Figure 12a shows that the $\langle p_T^2 \rangle$ of the ρ^0 increases with W . Such an increase of $\langle p_T^2 \rangle$ is known for other types of hadron, where it is explained mainly by kinematics and partly by gluon emission [13, 29]. In addition, Fig. 12a reveals characteristic differences in the behaviour of the ρ^0 and the pions; the $\langle p_T^2 \rangle$ values are larger and the increase with $\ln W^2$ is steeper for the ρ^0 than for the pions. Even the background $\pi^+\pi^-$ combinations differ from the ρ^0 , although, in this case, no kinematical differences are expected. A possible explanation is given below.

The measurements of the average p_T^2 as a function of x_F (“seagull plot”), presented in Fig. 12b, show again clear differences between the different particle types or combinations; whereas the $\langle p_T^2 \rangle$ of the pions and of the background $\pi^+\pi^-$ have a strong dependence on x_F (“seagull effect”), one observes only a weak (insignificant compared to the errors) variation with x_F in the case of the ρ^0 . This difference in the behaviour of the resonances and the background combinations has been reported for hadronically produced ρ^0 and K^{*0} mesons [30], and is confirmed here.

The effects seen in Fig. 12 are qualitatively reproduced by the Lund model (see Fig. 13). The Lund Monte Carlo can thus be used to investigate the reasons for the differences observed in the behaviour of the ρ^0 resonance and the pions. As can be seen from Fig. 13, similar differences are found when the primarily produced pions are compared to the set of all pions, the majority of which originate from resonance decays. Evidently, the decay products have a much lower average p_T^2 and show

a more pronounced seagull effect than the primary particles. This is because the momentum of a decaying particle is divided among the daughter particles. Compared to the differences between primary and secondary particles, mass effects are of minor importance, as is demonstrated by the comparison of primary pions, ρ^0 mesons (which are all primary in the Lund Monte Carlo), and primary protons. The qualitative agreement between the Lund predictions and the experimental data can be taken as an indication that a large fraction of the experimentally produced ρ^0 mesons are indeed primary particles.

4. Summary and conclusions

The properties of the inclusive $\rho^0(770)$ meson production in νp and $\bar{\nu} p$ charged current interactions have been studied and compared to the predictions of theoretical models. The results can be summarized as follows:

The average ρ^0 multiplicity, $\langle n_{\rho^0} \rangle$, in the νp and $\bar{\nu} p$ event samples with $W > 3 \text{ GeV}$ is $0.20 \pm 0.02 \pm 0.02$ and $0.14 \pm 0.02 \pm 0.02$ respectively. At fixed charged hadron multiplicity, $\langle n_{\rho^0} \rangle$ is comparable in νp and $\bar{\nu} p$ scattering.

$\langle n_{\rho^0} \rangle$ rises approximately linearly with $\ln W^2$. A slight increase of $\langle n_{\rho^0} \rangle$ with Q^2 at fixed W , as observed for the charged hadron multiplicities [20], is compatible with the data.

The great majority of the ρ^0 mesons are produced in the forward region ($x_F > 0$).

The average p_T^2 of the ρ^0 mesons increases with increasing W^2 . It is about 25% larger than that of the nonresonant $\pi^+\pi^-$ pairs in the ρ^0 mass region, and about 100% larger than that of the charged pions. It seems to be approximately independent of x_F , again in contrast to the nonresonant $\pi^+\pi^-$ pairs and to the charged pions. By analogy with the Lund Monte Carlo, this behaviour is interpreted as an indication that the ρ^0 mesons are to a large extent primarily produced particles.

The ρ^0/π^0 ratio increases strongly with increasing $|x_F|$ and tends to 1 for $x_F \rightarrow 1$. The charged pions with $x_F > 0.5$ originate in about 10% (π^+ in νp and π^- in $\bar{\nu} p$) or 60% (π^- in νp and π^+ in $\bar{\nu} p$) of the cases from ρ^0 decays.

The Lund fragmentation model (implemented in the version LEPTO 4.3, JET-SET 5.2) predicts ρ^0 multiplicities which are generally too large. This is most pronounced in the backward hemisphere ($x_F < 0$), where the Lund predictions exceed the experimental results by about a factor of 3. In the forward region (at $x_F > 0$ in νp and $x_F > 0.2$ in $\bar{\nu} p$ scattering), the Lund calculations are in approximate agreement with the measured ρ^0 multiplicities. The Lund predictions for the quantities N_{ρ^0}/N_{π^0} , $N_{\pi^+ \text{ from } \rho^0}/N_{\pi^+ \text{ all}}$, and $N_{\pi^- \text{ from } \rho^0}/N_{\pi^- \text{ all}}$ are about a factor of 2 too high in the central region ($-0.2 < x_F < 0.2$), but somewhat too low in the extreme forward region ($x_F > 0.5$). Many other aspects of the inclusive ρ^0 production are qualitatively reproduced by the Lund model. The discrepancies between the data and the model may be related to the fact that, in the tested version, the Lund model includes only the pseudoscalar and vector mesons and neglects the higher meson states. More advanced versions of the Lund model, which include the mesons up to tensor states, may provide a better description of resonance production.

In all the properties which are described by the Wells model, i.e. $\langle n_{\rho^0} \rangle$, $\langle n_{\rho^0} \rangle_{\text{forw.}}$, $\langle n_{\rho^0} \rangle_{\text{backw.}}$, and the W dependences of these quantities, there is excellent agreement between the Wells model predictions and the experiment. This supports the main ingredients of the Wells model, namely the relations between different reactions suggested by the quark parton model, the inclusion of the higher scalar, axial-vector, and tensor mesons in addition to the pseudoscalar and vector mesons, and the assumption that the primary production of the different mesons is governed by spin-statistics. Since the parameters of the Wells model are tuned to describe hadron collision data, the agreement found in this analysis means also that the average ρ^0 multiplicities observed in ν and $\bar{\nu}$ scattering are consistent (in the framework of the Wells model) with the results of hadronic experiments.

The results of this analysis confirm the quark-parton model. This follows in particular from the good description of the data by the Wells model and from the qualitative agreement with the Lund model observed in many quantities. Furthermore, there are direct predictions of the quark-parton model concerning the ratios N_{ρ^0}/N_{π^+} , N_{ρ^0}/N_{π^-} , and N_{ρ^0}/N_{π^0} in νp and $\bar{\nu} p$ scattering in the forward region, which are confirmed by the measurements.

Acknowledgements. It is a pleasure to acknowledge the careful work of the scanning and measuring teams at our laboratories, and to thank the staff at CERN for the operation of the SPS accelerator, neutrino beam, and BEBC with associated equipment. A correspondence with J. Wells was of great benefit.

References

- [1] J.P. Berge et al., Phys. Rev. **D22** (1980) 1043
- [2] M. Derrick et al., Phys. Lett. **91B** (1980) 307
- [3] P. Allen et al., Nucl. Phys. **B194** (1982) 373
- [4] H. Grässler et al., Nucl. Phys. **B272** (1986) 253
- [5] G.T. Jones et al., to be submitted to Z. Phys. C
- [6] G. Harigel, BEBC Users Handbook, CERN (1977)
- [7] C. Brand et al., Nucl. Instrum. Meth. **136** (1976) 485;
R. Beuselinck et al., Nucl. Instrum. Meth. **154** (1978) 445
- [8] H. Foeth, Nucl. Instrum. Meth. **176** (1980) 203;
H. Foeth et al., Nucl. Instrum. Meth. **A253** (1987) 245
- [9] H.G. Heilmann, internal WA21 report (1978)
- [10] U.F. Katz, Diplomarbeit, Max-Planck-Institut für Physik und Astrophysik, München (1986);
G.T. Jones et al., Z. Phys. **C37** (1987) 25
- [11] M. Glück, E. Hoffmann, E. Reya, Z. Phys. **C13** (1982) 119
- [12] G. Ingelman, Lund Monte Carlo for deep inelastic lepton-nucleon-scattering (1983);
T. Sjöstrand, Comput. Phys. Commun. **27** (1982) 243
- [13] G.T. Jones et al., Z. Phys. **C25** (1984) 121
- [14] G.T. Jones et al., Z. Phys. **C27** (1985) 43
- [15] G.P. Yost et al. (Particle Data Group), Phys. Lett. **204B** (1988)
- [16] J.D. Jackson, Nuovo Cim. **34** (1964) 1644
- [17] V. Blobel, Proc. CERN School of Computing, Aiguablava, Spain (1984), CERN 85-09, 88
- [18] J. Kern, Dissertation, Max-Planck-Institut für Physik und Astrophysik, München (1990)
- [19] P. Schmid, The WA21 one-prong story, internal WA21 report (1984)
- [20] G.T. Jones et al., Z. Phys. **C46** (1990) 25

- [21] J. Wells, Nuclear Physics Laboratory report 28/83, Oxford University (1983)
- [22] W. Wittek et al., Z. Phys. **C40** (1988) 231
- [23] W. Wittek et al., Z. Phys. **C44** (1989) 175
- [24] D. Allasia et al., Nucl. Phys. **B268** (1986) 1
- [25] C.C. Chang et al., Proc. 1981 Int. Conf. on Neutrino Physics and Astrophysics, Maui, Hawaii (1981), Vol. 2, 162
- [26] V.V. Ammosov et al., Sov. J. Nucl. Phys. **45** (1987) 457
- [27] V.V. Ammosov et al., Sov. J. Nucl. Phys. **46** (1987) 80
- [28] M. Aderholz et al., Phys. Lett. **173B** (1986) 211
- [29] G. Ingelman et al., Nucl. Phys. **B206** (1982) 239
- [30] M. Barth et al., Nucl. Phys. **B223** (1983) 296

Table 1. Definitions of the event variables. The 4-momenta (k of the (anti-)neutrino, k' of the muon, $q = k - k'$ of the intermediate vector boson) refer to the lab system. m_p is the proton mass

Variable	Definition	Description
E_ν	k_0	(Anti-)neutrino lab energy
E_μ	k'_0	Muon lab energy
ν	$q_0 = E_\nu - E_\mu$	Lab energy transfer
Q^2	$-q_\alpha q^\alpha$	4-momentum transfer squared
W	$\sqrt{m_p^2 + 2m_p\nu - Q^2}$	Hadronic invariant mass
x_{Bj}	$Q^2/2m_p\nu$	Bjorken scaling variable

Table 2. Definitions of the particle variables. The transverse and longitudinal components are with respect to the current direction

Variable	Definition	Description
p_T^2	—	Transverse lab momentum squared
p_L^*	—	Longitudinal CMS momentum
x_F	$2p_L^*/W$	Feynman x
y^*	$\frac{1}{2} \ln \frac{E^* + p_L^*}{E^* - p_L^*}$	CMS rapidity
z	E/ν	Lab energy fraction

Table 3. 1-prong corrections applied for the determination of the total event number as a function of E_ν or W^2 respectively, in the $\bar{\nu}$ data

E_ν interval (GeV)	1-prong correction	W^2 interval (GeV ²)	1-prong correction
10 – 30	1.57 ± 0.16	6.25 – 16	1.16 ± 0.05
30 – 60	1.23 ± 0.08	16 – 32	1.05 ± 0.02
60 – 90	1.09 ± 0.03	32 – 64	1.02 ± 0.01
90 – 140	1.06 ± 0.03	64 – 128	1.005 ± 0.002
140 – 200	1.04 ± 0.02		

Table 4. Numbers of ρ^0 mesons observed in the data samples with $W > 2 \text{ GeV}$ and $W > 3 \text{ GeV}$ in comparison to the event and the pion numbers. The errors on N_{ev} of the $\bar{\nu}$ data are due to the applied 1-prong corrections. Also listed are the Lund and the Wells model predictions for $\langle n_{\rho^0} \rangle$, and the Lund model predictions for the quantities N_{ρ^0}/N_{π}

	ν data		$\bar{\nu}$ data	
	$W > 2 \text{ GeV}$	$W > 3 \text{ GeV}$	$W > 2 \text{ GeV}$	$W > 3 \text{ GeV}$
N_{ev}	15752	13205	10229 ± 237	7034 ± 127
$\langle W \rangle$	5.5 GeV	6.1 GeV	4.4 GeV	5.1 GeV
N_{ρ^0}	2838 $\pm 245 \pm 340$	2668 $\pm 249 \pm 320$	1269 $\pm 166 \pm 152$	976 $\pm 155 \pm 117$
$\langle n_{\rho^0} \rangle$	0.180 $\pm 0.016 \pm 0.022$	0.202 $\pm 0.019 \pm 0.024$	0.124 $\pm 0.016 \pm 0.015$	0.139 $\pm 0.022 \pm 0.017$
Lund	—	0.318	—	0.298
Wells	0.188	0.200	0.157	0.169
N_{ρ^0}/N_{π^+}		0.081 ± 0.015		0.108 ± 0.024
Lund		0.130		0.216
N_{ρ^0}/N_{π^-}		0.156 ± 0.028		0.082 ± 0.018
Lund		0.234		0.169
N_{ρ^0}/N_{π^0}		0.107 ± 0.019		0.093 ± 0.021
Lund		0.167		0.190

Table 5. Measurements of the average ρ^0 multiplicity in ν and $\bar{\nu}$ charged current scattering experiments

Reaction	$\langle W \rangle$ (GeV)	$\langle n_{\rho^0} \rangle$	Reference
νp	5.5	$0.18 \pm 0.02 \pm 0.02$	this analysis
νp	($W > 2$ GeV)	$0.21 \pm 0.03 \pm 0.03$	[24]
νp	4.9	0.16 ± 0.02	[3]
νp	($W > 2$ GeV)	0.20 ± 0.05	[25]
νp	5.0	0.21 ± 0.04	[1]
νn	($W > 2$ GeV)	$0.21 \pm 0.02 \pm 0.03$	[24]
νn	—	0.17 ± 0.05	[25]
νNe	4.8	0.17 ± 0.04	[23]
νFreon	3.1	0.09 ± 0.02	[27]
$\bar{\nu} p$	4.4	$0.12 \pm 0.02 \pm 0.02$	this analysis
$\bar{\nu} p$	($W > 2$ GeV)	$0.20 \pm 0.02 \pm 0.03$	[24]
$\bar{\nu} p$	4.2	0.11 ± 0.02	[4]
$\bar{\nu} p$	3.4	0.21 ± 0.03	[2]
$\bar{\nu} n$	($W > 2$ GeV)	$0.18 \pm 0.03 \pm 0.03$	[24]
$\bar{\nu} \text{Ne}$	3.9	0.12 ± 0.02	[23]
$\bar{\nu} \text{Ne}$	4.3	0.13 ± 0.02	[26]

Table 6. Average ρ^0 multiplicity and ratio of ρ^0 and ' π^0 ' multiplicities in the data with $W > 3$ GeV as functions of the charged hadron multiplicity

$n_{\text{ch. had.}}$	ν data		$\bar{\nu}$ data	
	$\langle n_{\rho^0} \rangle$	N_{ρ^0}/N_{π^0}	$\langle n_{\rho^0} \rangle$	N_{ρ^0}/N_{π^0}
2	—	—	0.052 ± 0.018	0.077 ± 0.028
4	0.125 ± 0.026	0.087 ± 0.020	0.185 ± 0.040	0.119 ± 0.028
6	0.291 ± 0.055	0.122 ± 0.026	0.272 ± 0.077	0.109 ± 0.035
8	0.515 ± 0.111	0.155 ± 0.037	—	—
10	0.329 ± 0.202	0.078 ± 0.048	—	—
> 10	0.961 ± 0.438	0.180 ± 0.084	—	—

Table 7. Average ρ^0 multiplicities in the forward and backward hemispheres and forward-backward-asymmetry A_{fb} measured in the data with $W > 3$ GeV. The predictions of the Lund and the Wells model are also given

	$\langle n_{\rho^0} \rangle_{\text{forw.}}$	$\langle n_{\rho^0} \rangle_{\text{backw.}}$	A_{fb}
ν data	0.168 ± 0.025	0.033 ± 0.012	0.67 ± 0.11
Lund	0.207	0.110	0.31
Wells	0.165	0.034	0.66
$\bar{\nu}$ data	0.114 ± 0.023	0.026 ± 0.013	0.63 ± 0.16
Lund	0.195	0.104	0.30
Wells	0.149	0.020	0.76

Table 8. Ratios of ρ^0 and pion multiplicities in the region $x_F > 0.5$, and fractions of the charged pions with $x_F > 0.5$ originating from ρ^0 decays, measured in the data with $W > 3$ GeV. Also given are the Lund model predictions

	ν data	Lund	$\bar{\nu}$ data	Lund
$N_{\rho^0}^{x_F > 0.5} / N_{\pi^+}^{x_F > 0.5}$	0.53 ± 0.12	0.41	2.49 ± 0.59	1.19
$N_{\rho^0}^{x_F > 0.5} / N_{\pi^-}^{x_F > 0.5}$	1.99 ± 0.44	1.19	0.56 ± 0.13	0.41
$N_{\rho^0}^{x_F > 0.5} / N_{\pi^0}^{x_F > 0.5}$	0.84 ± 0.19	0.61	0.92 ± 0.22	0.61
$N_{\pi^+ \text{ from } \rho^0}^{x_F > 0.5} / N_{\pi^+ \text{ all}}^{x_F > 0.5}$	0.08 ± 0.04	0.08	0.68 ± 0.34	0.26
$N_{\pi^- \text{ from } \rho^0}^{x_F > 0.5} / N_{\pi^- \text{ all}}^{x_F > 0.5}$	0.59 ± 0.20	0.24	0.13 ± 0.06	0.09

Fig. 1. Distributions of the invariant $\pi^+\pi^-$ mass in the νp and $\bar{\nu} p$ data samples. a) and b) include all $\pi^+\pi^-$ combinations, c) and d) only the combinations with $x_F > 0.5$. The fits of expression (1) (in a) and b) with an additional term for the $f_2(1270)$ resonance) to the data points are indicated by solid curves, the background contributions (4) by dashed curves.

Fig. 2. $\pi^+\pi^-$ invariant mass distribution of modified νp Lund Monte Carlo events with $W > 3$ GeV. The areas due to the η , η' , ω , K^* , and ρ^0 resonances are indicated.

Fig. 3. Results of 34 test fits using a νp Lund event sample:

a) N_{ρ^0} from the fit versus correct N_{ρ^0} ;

b) relative deviation $\Delta N_{\rho^0} / N_{\rho^0}$ of the fit result from the correct ρ^0 number versus (correct) signal/background ratio (in the region $690 \text{ MeV} < m_{\pi^+\pi^-} < 850 \text{ MeV}$).

Only the statistical errors are shown. The location of perfectly correct fit results is indicated by dashed lines.

Fig. 4. Average ρ^0 multiplicity as a function of E_ν .

Fig. 5. Average ρ^0 multiplicity and average forward and backward ρ^0 multiplicities as functions of W^2 . The dashed and dotted lines are the predictions of the Lund and the Wells model, respectively. The solid line in a) represents a fitted function $\langle n_{\rho^0} \rangle = a + b \ln(W^2/\text{GeV}^2)$.

Fig. 6. Average ρ^0 multiplicity of the νp data as a function of Q^2 in three W intervals. The dotted curves show the Q^2 dependence of the fitted function (see text) at the three values of $\langle \ln W^2 \rangle$.

Fig. 7. Average ρ^0 multiplicity in events with $W > 3 \text{ GeV}$ as a function of x_{Bj} . The dotted histogram in a) shows the expectations following from $\langle \ln W^2 \rangle$ of each x_{Bj} bin. The dashed lines are the Lund model predictions.

Fig. 8. Normalized differential x_F , y^* , and z distributions of the ρ^0 mesons in events with $W > 3 \text{ GeV}$. The dashed lines are the Lund model predictions.

Fig. 9. Ratio of the differential x_F distributions of ρ^0 and π^0 mesons in events with $W > 3 \text{ GeV}$. The dashed lines are the Lund model predictions.

Fig. 10. Fractions of the π^+ and π^- mesons which originate from ρ^0 decays as functions of x_F (of the pion) in events with $W > 3 \text{ GeV}$. The dashed lines are the Lund model predictions.

Fig. 11. Normalized differential p_T^2 distribution of the ρ^0 mesons in events with $W > 3 \text{ GeV}$. The solid lines are fits of the function $a e^{-b p_T^2}$. The dashed lines are the Lund model predictions.

Fig. 12. Average p_T^2 of the ρ^0 mesons, the background $\pi^+\pi^-$ combinations (in the region $690 \text{ MeV} < m_{\pi^+\pi^-} < 850 \text{ MeV}$), and the charged pions as functions of a) W^2 and b) x_F in νp scattering.

Fig. 13. Average p_T^2 of various particle types as functions of a) W^2 and b) x_F in the Lund model ($W > 3 \text{ GeV}$).