EXCLUSIVE ρ^0 -PRODUCTION IN DEEP INELASTIC MUON PROTON SCATTERING

The European Muon Collaboration (EMC)

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Exclusive ρ^0 production has been measured in 120, 200 and 280 GeV muon proton interactions at high Q^2 ($1 \text{ GeV}^2 < Q^2 < 25 \text{ GeV}^2$) and W ($6 \text{ GeV} < W < 19 \text{ GeV}$). The photoproduction cross section decreases as $1/Q^4$. A shallow t distribution, typical of a hard scattering process is observed and the ρ^0 is found to be dominantly in the helicity zero spin state. The ρ^0 s are mainly produced by transverse photons and s channel helicity conservation seems to be invalid. The data cannot be described by the vector meson dominance model. These data show that at high Q^2 even exclusive ρ^0 muoproduction is a hard scattering process and that the soft hadron like properties of the photon have disappeared.

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Exclusive ρ^0 production has been studied extensively in photoproduction as well as in electro and muoproduction at small values of Q^2 in order to test the predictions of the vector meson dominance model (VDM) [1]. This paper presents the first measurements of exclusive ρ^0 muoproduction, i.e. of the process $\mu p \rightarrow \mu \rho^0 p$ at high Q^2 and W , but small x_{BJ} . This kinematic region is well suited to test the VDM [1]. The process $\mu p \rightarrow \mu \rho^0 p$ can be viewed as exclusive ρ^0 production by virtual photons, $\gamma^* p \rightarrow \rho^0 p$. At high Q^2 the virtual photon acts predominantly as a pointlike particle, therefore hard processes such as photon-gluon fusion which gives a good description of the production of heavy vector mesons e.g. J/ψ [2, 23] are likely to contribute. However, for lower mass vector mesons it is possible that the hadron-like properties of the photon remain and the VDM will still work [3]. The purpose of these measurements is to test these ideas by studying exclusive ρ^0 production at high Q^2 .

The experiment was performed in the M2 muon beam at the CERN SPS using a 6 metre long target of liquid hydrogen at incident muon energies of 120, 200 and 280 GeV. Events with two oppositely charged forward hadrons and the scattered muon were detected in the EMC forward spectrometer [4]. Exclusive and quasi-exclusive events were selected kinematically using energy balance as described below. The data were taken in 3 experimental runs corresponding to 7.6×10^{11} incident muons.

The standard kinematic variables for the description of the deep inelastic scattering process are used. These are $Q^2 = -q^2 = (k - k')^2$; $W^2 = (q + p)^2$; $v = (p \cdot q)/M$; $x = Q^2/2Mv$; $\epsilon = 1/(1 + 2(Q^2 + v^2)/(4EE' - Q^2))$; $z = (p \cdot v)/(p \cdot q)$ and $t = (v - q)^2$. Here, k (k') are the 4-momenta of the incident (scattered) muon, p and M are the 4-momentum, and mass of the target proton, respectively, $v = (p_{h+} + p_{h-})$ is the 4-momentum of the outgoing pair of oppositely charged hadrons assuming both tracks to be pions and ϵ describes the degree of polarisation of the virtual photon.

The cuts shown in table 1 were applied to the data to ensure good geometrical acceptance for the scattered muon and the decay pions from the ρ^0 . Selection of events and tracks was similar to that described in [5] and a complete description of the analysis is given in [6].

TABLE 1
Kinematic cuts applied to the data.

E_{beam} [GeV]	Q^2_{range} [GeV ²]	W^2_{range} [GeV ²]	θ_{min} [mrad]	$P_{\mu\text{min}}$ [GeV]	$P_{h\text{min}}$ [GeV]
120	1-18	36-150	10	20	2
200	2-25	36-280	9	30	3
280	3-25	36-360	8	40	3

In order to correct the observed data for apparatus effects, losses of the reconstruction and analysis and for QED bremsstrahlung effects, elastic ρ^0 events were simulated in a Monte-Carlo programme and then passed through the full data analysis chain. The simulation accounted for detector resolutions and inefficiencies and directly included the influence of QED bremsstrahlung [7] which is small in this kinematic region. As reinteractions of the decay pions inside the 6 metre long H₂ target are important, the Monte Carlo simulation included a detailed description of the target construction. The ρ^0 mass was generated according to a simple Breit-Wigner distribution. An exponential t-distribution was used with average t values adjusted to be consistent with the data. The ρ^0 s were initially assumed to be unpolarised. In a second stage the events were reweighted according to the observed Q^2 -dependences of the polarisation and the cross section. The acceptance was then calculated as the ratio of accepted to generated ρ^0 s in each individual bin. The mass dependence of the acceptance was explicitly considered for the determination of the ρ^0 cross section. This acceptance decreases almost linearly with mass, the slope depending on the selected kinematic range.

The exclusive ρ^0 -events were selected by demanding only 2 measured hadron tracks with opposite charge fulfilling the condition $-0.1 < I < 0.08$ where I is the inelasticity defined as $I = [(q+p-v)^2 - p^2]/W^2$. $I = 0$ corresponds to elastic scattering neglecting the energy of the recoil proton. To reduce backgrounds from e^+e^- pairs from photon conversions and K^+K^- pairs from ϕ decay, events were rejected if the mass of the pair is consistent with 0 or the ϕ mass when assigning the electron or kaon mass to the tracks, respectively.

Fig. 1a presents the distribution of the quantity I which shows a significant enhancement at $I \approx 0$. The smooth curve shown in Fig. 1a is an estimate of the inelastic background, normalized to the data, calculated from the LUND model [8] which did not contain elastic ρ^0 production. Fig. 1b shows the remaining signal after subtraction of this background estimate compared to a Monte-Carlo simulation of elastic ρ^0 production. The width and position of the enhancement in the data are well represented by the Monte-Carlo simulation of the process $\mu p \rightarrow \mu \rho^0 p$, which indicates that the selected events should be exclusive.

This was further checked using data taken at 280 GeV incident muon energy with the EMC vertex spectrometer [9] which gave full acceptance of the hadronic final states for hadrons of momenta > 200 MeV. Events with two forward hadrons were selected with the same kinematic cuts as described above. The sample selected in the ρ^0 mass region contained 28 events of which 4 were observed to contain extra charged hadrons. From this we conclude that the final event sample contained only a small background of quasi exclusive events which was neglected.

Fig. 1c shows the dipion mass distribution for all events after cuts. A clear ρ^0 signal is visible above a small background. Fig 1d shows the acceptance corrected mass spectrum. The smooth curve in Fig. 1d shows a fit to the data of a p wave Breit-Wigner shape [10] skewed by a Q^2 dependent factor [11] and a smooth background parameterisation as used for the inclusive ρ^0 analysis [12]. The fit gave $m_\rho = 765.0 \pm 6.5$ MeV and $\Gamma_\rho = 155 \pm 25$ MeV for the mass and width of the ρ^0 meson in excellent agreement with the values of 769 MeV and 154 MeV in the Particle Data Table [13]. The mass resolution at the ρ^0 mass was ~ 20 MeV FWHM.

To extract the cross sections the data in each Q^2 bin were fitted in the same manner fixing the mass and width of the ρ^0 to the values given by the Particle Data Table. The χ^2 per degree of freedom for all fits is in the range $0.5 < \chi^2/\text{NDF} < 1.7$, with an average value of 0.9. The results of the fit were insensitive to the inclusion of the mass skewing factor. In contrast to photoproduction and low Q^2 electroproduction almost no skewing of the mass distribution is observed at the Q^2 values of these data.

The most important potential source of systematic error is the large ($\approx 50\%$) correction for pion reinteractions in the target. Due to the quoted selection of exclusive events, events with one or both of the decay pions reinteracting are unlikely to be present in the selected sample. The reinteraction correction therefore relies only on the well known total πN cross section and can be calculated accurately. The final systematic error of the ρ^0 cross section was estimated to be 25% and includes the following less important sources of error: reconstruction efficiency, fit procedure, Monte-Carlo simulation, radiative corrections and normalisation.

Fig. 2 shows the Q^2 dependence of the cross section for virtual photoproduction of elastic ρ^0 mesons, obtained by normalising the observed number of ρ^0 s to the measured deep inelastic differential cross section [14]. The systematic error which to a large extent is an overall normalization uncertainty is not included in the error bars. As the cross sections from the 200 GeV and the 280 GeV data agreed within errors, the data sets were combined. At small Q^2 the data agree well with the high energy points of earlier μp and $e p$ scattering experiments [15,16,17] which are also shown in fig. 2. The smooth curves show the predictions of the VDM (described below). The Q^2 dependence of our data is proportional to $1/Q^4$. A fit of the form $1/Q^\alpha$ gives $\alpha = 3.96 \pm 0.36$. An indication of such a $1/Q^4$ behaviour can already be seen in an earlier result for $Q^2 > 1 \text{ GeV}^2$ [16].

Comparison of the different data sets in fig. 2 suggests an increase of the cross section with the photon energy. Assuming a dependence of the cross section of the form $(1+Q^2/m_\rho^2)^{-2}$ which is well supported by the data [1] (dashed curve in fig. 2) the cross sections were extrapolated to $Q^2 = 2 \text{ GeV}^2$ separately for the 120 GeV and the 200/280 GeV data sets. The results together with the mean values of Q^2 , ν , ϵ and x_{BJ} for each data set are given in table 2. The relative systematic uncertainty between the data sets is 15%. We stress that the observed ν dependence cannot be distorted by an additional ϵ dependence as the ϵ distributions for the two data sets are similar and the mean values of ϵ are almost equal (see table 2).

TABLE 2

Cross sections and kinematic mean values
for 120 and 200/280 GeV data.

E_{beam} [GeV]	$\langle Q^2 \rangle$ [GeV ²]	$\langle \nu \rangle$ [GeV]	$\langle x_{\text{BJ}} \rangle$	$\langle \epsilon \rangle$	Total event sample	No. of ρ^0 's	$\sigma (\gamma^*p \rightarrow \rho^0 p)$ ($Q^2=2\text{GeV}^2$) [nb]
120	4.9	58	0.067	0.83	124438	220	270 ± 33
200/280	11.4	97	0.072	0.85	94475	170	396 ± 51

The ratio R of the cross sections for longitudinally and transversely polarised photons for exclusive ρ^0 production was estimated by comparing the data from the CHIO group [15] taken at $\langle \epsilon \rangle = 0.39$ and that presented here at $\langle \epsilon \rangle = 0.84$. The virtual photoproduction cross section, $\sigma_Y = \sigma_T + \epsilon \sigma_L$, was extrapolated to $Q^2 = 2 \text{ GeV}^2$ using the form $(1 + Q^2/m_\rho^2)^{-2}$. It was also extrapolated to $\nu = 90 \text{ GeV}$ assuming a linear rise with ν with a slope determined from the data in Table 2. This gives average values of $\sigma_Y = 468 \pm 25(\text{stat.}) \pm 41(\text{syst.}) \text{ nb}$ for the CHIO data at $\langle \epsilon \rangle = 0.39$ and $373 \pm 32 \pm 93 \text{ nb}$ for these data at $\langle \epsilon \rangle = 0.84$. Errors of 11% and 10% were added to the systematic error to account for the uncertainty in the rise of the cross section with ν and in the extrapolation to $Q^2 = 2 \text{ GeV}^2$, respectively. From these values of the cross sections the ratio, $R = \sigma_L / \sigma_T$, is $-0.38 \pm 0.13(\text{stat.})^{+0.9}_{-0.4}(\text{syst.})$ in the region of Q^2 where the two data sets overlap. This value is compatible with zero within errors and implies that elastic ρ^0 's are mainly produced by transverse photons.

The small background under the ρ^0 signal allows the analysis of the t -dependence and the ρ^0 angular distribution without fitting bin by bin. By restricting the mass interval to $692 < m_{\pi\pi} < 846 \text{ MeV}$, we assure that the minimum signal to noise ratio for the data used in the analysis is > 4 . The systematic error for both measurements is mainly influenced by the background events. Increasing the mass interval to $615 \text{ MeV} < m_{\pi\pi} < 923 \text{ MeV}$, which increases the background by a factor ~ 1.5 , produced changes which were much less than the statistical errors.

Fig. 3a shows the t' -distribution ($t'=t-t_{\min}$) for all pairs within the mass range $692 < m_{\pi\pi} < 846$ MeV. The distributions are consistent with exponentials of the form $d\sigma/dt' \approx e^{bt'}$ with smaller slopes for the data at higher beam energy, i.e. higher Q^2 or W . Fig. 3b shows the slope parameter $b = - \langle t \rangle^{-1}$ as a function of Q^2 . The systematic error of b is estimated to be 0.8 GeV^{-2} .

Our data, at small Q^2 , agree with the trend observed in an earlier μp scattering experiment [15] at a similar energy and some of the low energy measurements [17,18,19]. However the slope parameter measured in a low energy experiment [16] at high x is smaller. The W dependence observed by the latter experiment indicates an increase of b with W . Such a trend also seems to be present in our measurements at fixed Q^2 if the measured values of b at different incident beam energies are compared.

The data at small x ($x < 0.15$, see fig. 3b) show that the slope parameter b decreases as Q^2 increases. b decreases from $\sim 7 \text{ GeV}^{-2}$ at small Q^2 to $1-2 \text{ GeV}^{-2}$ at $Q^2 \sim 12 \text{ GeV}^2$. Thus, at small Q^2 the t dependence of exclusive ρ^0 muoproduction is similar to that in photoproduction [1,20] and diffractive meson proton scattering. The values of b at large Q^2 are comparable to those observed in inclusive ρ^0 or hadron p_t^2 spectra for $z > 0.4$ [12,21] i.e. they are similar to the typical p_t^2 behaviour observed in pointlike scattering processes. Thus exclusive ρ^0 production changes from a diffractive process at small Q^2 to a hard scattering process at larger Q^2 .

The ρ^0 decay angular distribution $W(\cos\theta, \phi, \Phi)$ can be used to analyse the ρ^0 spin state. Usually $W(\cos\theta, \phi, \Phi)$ is analysed in the s -channel helicity system [15,16,18,19,22], where the ρ^0 direction in the virtual photon proton centre of mass system (CMS) is taken as the quantisation axis. θ is the polar angle and ϕ the azimuthal angle of the π^+ in the ρ^0 CMS. Φ is the azimuthal angle of the ρ^0 production plane with respect to the μ scattering plane. At higher energies ϕ is difficult to determine, because the laboratory polar angle between the two decay pions is small. We therefore only present measurements of the $\cos\theta$ dependence. In this case the distribution becomes (integrating over ϕ and Φ):

$$W(\cos\theta) = \frac{3}{4} (1 - r_{00}^{04} + (3r_{00}^{04} - 1) \cos^2\theta) \quad (1)$$

and depends on only one measurable quantity r_{00}^{04} . This is one of the 23 independently measurable ρ^0 density matrix elements [22] and can be identified with the probability to produce a longitudinally polarised ρ^0 (i.e. helicity 0) by either transversely or longitudinally polarised photons.

Fig. 4a shows the $\cos\theta$ distributions, corrected for acceptance and normalised to unity, for all $\pi^+\pi^-$ pairs in the mass interval $692 < m_{\pi\pi} < 846$ MeV. For all three data sets a clear $\cos^2\theta$ dependence is observed, in contrast to the $\sin^2\theta$ dependence seen in real photoproduction [1,20]. The $\cos^2\theta$ behaviour indicates a dominantly longitudinal polarisation (helicity 0) of the produced ρ^0 which is more pronounced for the 280 and 200 GeV data than for the 120 GeV data.

To determine r_{00}^{04} the $\cos\theta$ distributions were fitted to equation (1) (fig. 4a). Fig. 4b shows r_{00}^{04} as a function of Q^2 . Again at small Q^2 our data agree with the trend from earlier experiments. A steep increase of r_{00}^{04} with Q^2 is visible and at high Q^2 the ρ^0 's become almost purely longitudinally polarised (helicity 0). The average value of r_{00}^{04} is $0.75 \pm 0.06(\text{stat}) \pm 0.08(\text{syst.})$ where the systematic error on r_{00}^{04} is dominated by the influence of background events.

Comparing figs. 3b and 4b shows that the increase of the longitudinal polarisation appears together with the decrease of the slope parameter b . Since small values of b are characteristic of hard scattering processes, it is likely that also the longitudinal polarisation is connected to hard scattering. A longitudinal ρ^0 polarisation for large b , i.e. small $\langle t \rangle$ is necessarily suppressed by helicity conservation at $t = 0$ for transversely polarised photons.

Although ρ^0 muonproduction at large Q^2 appears to proceed by a hard scattering mechanism, the data were compared to the predictions of the VDM. In this model the Q^2 -dependence of the ρ^0 photo-production cross section [24], [1], for large W and small x , can be written:

$$\sigma_Y(Q^2) = \sigma_Y(Q^2=0) \frac{1}{(1 + \frac{Q^2}{m_\rho^2})^2} (1 + \epsilon \xi^2 \frac{Q^2}{m_\rho^2}) \quad (2)$$

where $\sigma_Y(Q^2=0)$ is the cross section for real photoproduction ($\sim 9.4 \mu\text{b}$ at high energies [20]). The term $\xi^2 Q^2/m_\rho^2$ in the model is the ratio of the ρ^0 production cross sections by longitudinal and transverse photons, i.e. R. Assuming s channel helicity conservation (SCHC) i.e. longitudinal (transverse) ρ^0 's are produced by longitudinal (transverse) photons only, the parameter ξ^2 is related to r_{00}^{04} by

$$r_{00}^{04}(Q^2) = \frac{1}{1 + \frac{m_\rho^2}{\epsilon \xi^2 Q^2}}. \quad (3)$$

Fitting the observed Q^2 dependence of r_{00}^{04} to this ansatz gives $\xi^2 = 0.40 \pm 0.13$. The VDM (see fig. 2), with this value of ξ^2 , predicts an asymptotic $1/Q^2$ behaviour and thus overestimates the cross section at high Q^2 . Using $\xi^2 = 0$ (implying transverse ρ polarisation, i.e. helicity ± 1), corresponding to $R = 0$, the Q^2 variation of the cross section predicted by the VDM is approximately correct. However, the observed longitudinal polarisation of the ρ^0 is then inconsistent with the model. Thus the VDM [25,1] with SCHC cannot describe the data. Furthermore, the small value of $R = \sigma_L/\sigma_T$ measured from the ϵ dependence at $Q^2 \sim 2 \text{ GeV}^2$ by combining CHIO and EMC data is consistent with the production by transverse photons. The observation of the longitudinal polarization of the ρ^0 thus indicates that SCHC is violated.

In conclusion, the first measurements of exclusive ρ^0 muoproduction in the deep inelastic region at high Q^2 and W are presented. A shallow t distribution of the produced ρ^0 s is observed leading to the conclusion that the production mechanism is a non diffractive hard scattering process. The polarisation of the produced ρ^0 is found to be mainly longitudinal (helicity 0) and the cross section decreases as $1/Q^4$ at high Q^2 . The data at such Q^2 values cannot be described by the vector meson dominance model with s channel helicity conservation. These data show that at high Q^2 even exclusive ρ^0 muoproduction is a hard scattering process. The soft hadron-like properties of the photon have disappeared so that the photon acts as a pure electromagnetic probe of the nucleon structure.

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FIGURE CAPTIONS

Fig. 1(a) Inelasticity distribution for events with only 2 measured hadrons of opposite charge. The dashed line is the distribution for inelastic events as calculated by the LUND-model [9] normalised to the data.

(b) Inelasticity distribution, LUND background subtracted. The dashed line is a Monte-Carlo calculation for exclusive events (normalised to the data).

(c) Uncorrected $\pi^+\pi^-$ mass distribution for all events after cuts.

(d) Corrected $\pi^+\pi^-$ mass distribution. The dashed line indicates the fit (see text), the dashed dotted line the background.

Fig. 2 ρ^0 photoproduction cross section as a function of Q^2 with comparison to previous measurements [15,16,17]. The lines represent a VDM-calculation [24] for different parameters ξ^2 .

Fig. 3(a) t' -distribution for all events ($615 \text{ MeV} < m_{\pi\pi} < 923 \text{ MeV}$) for the 3 data sets.

(b) slope parameter b for the 3 data sets as a function of Q^2 with comparison to previous measurements [15,16,17,18,19,20].

Fig. 4(a) $\cos \theta$ - distributions for the 3 data sets. The distributions are normalised to 1. The curves are the fitted decay angular distributions.

(b) ρ^0 density matrix elements r_{00}^{04} for the 3 data sets as a function of Q^2 with comparison to previous measurements [16,18,19,20].

FIG. 1

FIG. 2

FIG. 3

FIG. 4