FORWARD PRODUCED PROTONS AND ANTIPROTONS IN DEEP INELASTIC
MUON PROTON SCATTERING

The European Muon Collaboration

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Abstract

A significant rate of forward proton and antiproton production has been observed in 120 and 280 GeV muon proton scattering. The z and p_T^2 distributions are presented. The dependence of the normalized production cross section on the muon variables x and Q^2 is studied.

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The Quark-Parton Model describes the deep inelastic scattering of a muon on a proton as the interaction of a virtual photon with a quasi-free quark which then fragments into hadrons in a cascade process. For the description of this process we use the following kinematic quantities:

Q^2	negative four momentum squared of the virtual photon
ν	the energy of the virtual photon
x	$= \frac{Q^2}{2M\nu}$, M being the proton mass
W^2	$= Q^2 \left(\frac{1}{x} - 1 \right) + M^2$, the hadronic centre of mass energy squared
z	$= \frac{E_h}{\nu}$, E_h being the laboratory energy of a final hadron
p_T	the momentum component of this hadron perpendicular to the direction of the virtual photon.

In conventional fragmentation models based on the ideas of Field and Feynman [1], baryon production in the current fragmentation region has always been neglected. In fact, very low energy data ($W = 2$ to 3 GeV) from ep scattering [2,3,4] show a strong decrease of the forward proton production with W . Such a behavior would be expected if the protons were target fragments. The experiment of Martin et al. [5] at W around 4.5 GeV however yielded a result slightly higher than that expected from the trend of the lower energy proton data and furthermore observed antiproton production. The results from the experiment reported here cover the range of $3 < W < 21$ GeV and are presented in terms of x , Q^2 , z and p_T^2 to investigate the production mechanism.

The data were taken with 120 and 280 GeV muons incident on a liquid hydrogen target. The scattered muon and charged hadron tracks were detected and measured in a large magnetic spectrometer [6]. Transverse and longitudinal distributions of hadrons without particle identification from the higher energy data have been reported previously [7,8].

The selection of events was similar to that for the overall hadron distributions [7,8]. The hadron tracks were required to be fitted from the target up to the drift chambers in front of the hadron absorber and to be fitted to the muon interaction vertex or to pass within 2 cm of it. This track selection was studied in detail for the 280 GeV data, and it was checked that the effect of different selection criteria gave an error in absolute normalization of less than 20% and internal systematic uncertainties of less than 10% for all the data.

To avoid the dead regions of the chambers near the beam, the hadrons were required to be outside a 20 cm radius of the beam axis in the last chamber.

The identification of hadrons was performed by a large threshold Cerenkov counter [6,9] with 78 cells. With one Cerenkov counter protons can be identified in a limited momentum region for each gas filling, nitrogen or neon. The inefficiency of the counter was measured with muons in these momentum ranges. It was checked that the inefficiency was uniformly distributed in time and position. The observed proton yields were corrected for misidentified pions and kaons, using inefficiencies deduced from these muon measurements. The uncertainty of the efficiency correction and the effect of occasionally observing more than one track in a cell lead to a systematic error in the absolute normalization of less than 10%. The acceptance was determined by a Monte Carlo simulation of the apparatus.

The systematic errors arising from the above treatment are less than 25% in absolute scale and less than 10% in internal variation. The errors plotted in the figures are statistical only. Table 1 summarizes the kinematics of the 3 data samples used for this analysis.

Table 1

	data set 1	data set 2	data set 3
Beam energy (GeV)	280	280	120
$Q_{\min}^2$ (GeV) ²	2	2	2
$v_{\min}$ (GeV)	20	20	10
$v_{\max}$ (GeV)	240	240	100
$W_{\min}^2$ (GeV ²)	50	50	10
Fiducial target length (m)	2	2	2
Number of events after cuts	3.3K	16.3K	50.6K
Cerenkov gas	N ₂	Ne	N ₂
Momentum range for proton identification (GeV)	25-40	50-80	25-40
Observed number of protons and antiprotons	47	170	239
Efficiency of the Cerenkov counter for μ in proton momentum range	>99.9%	97.2%	99.8%

Fig. 1a shows the normalized differential cross section $\frac{1}{N_\mu} \frac{dN^P}{dz}$ for protons (black symbols) and antiprotons (open symbols) as a function of z averaged over the accessible range of x and Q^2 . Fig. 1b shows the ratios N^P/N^{h^+} and $N^{\bar{P}}/N^{h^-}$ as a function of z , where N^{h^+} and N^{h^-} are the numbers of all positive and negative hadrons in the momentum range of proton identification. It is important to notice that due to the limited momentum range of identification the hadron and muon kinematics are correlated so that the mean x of each point in the plot changes from about $\langle x \rangle = 0.05$ at $z = 0.2$ to $\langle x \rangle = 0.2$ at $z = 0.8$ at about constant $\langle Q^2 \rangle = 15 \text{ (GeV)}^2$. The shaded band in Fig. 1a is an extrapolation of data at $W \leq 3.5 \text{ GeV}$ based on parameterisations [2,3] of those data to the $\langle W \rangle$ values of the data of this experiment at each z . It is clear that our proton data lie much above this band, especially at high z , implying that the strong decrease with energy observed for $W < 3.5 \text{ GeV}$ does not persist to higher energies. From the data of Martin et al. [5] we deduced values for $1/N_\mu \cdot dN^P/dz$ which are compatible with our data from protons but which are about a factor of three lower for antiprotons for $0.3 \leq z < 0.6$.

Fig. 2 shows the Q^2 dependence for different x bins of $\int_{0.4}^{0.6} dz \frac{1}{N_\mu} \left(\frac{dN^P}{dz} + \frac{dN^{\bar{P}}}{dz} \right)$ for which z range the Q^2 and x covered by the data is most extensive. No strong Q^2 dependence is observed and this is also true if either protons or antiprotons are taken separately. At fixed x , W^2 is proportional to Q^2 , so this implies that the data show little W^2 dependence. Higher twist effects, as discussed recently by several authors [10,11], are potentially a source of forward going protons, however they are to be expected mainly at high x (> 0.5) and would show a strong $(1/Q^2)$ decrease with Q^2 . Since the data at the highest x values are at large Q^2 , such contributions to our proton sample are expected to be small.

As the observed Q^2 dependence is small, we show in Fig. 3a $\int_{0.4}^{0.6} dz \frac{1}{N_\mu} \frac{dN^{P,\bar{P}}}{dz}$ averaged over Q^2 as a function of x . The proton yield increases strongly with x , whereas the antiproton distribution is rather flat. Fig. 3b shows the corresponding ratios N^P/N^{h^+} and $N^{\bar{P}}/N^{h^-}$. There is an indication that the charge asymmetry increases with x somewhat more strongly for baryons than for mesons.

Using a factorisation ansatz [1] for the normalized cross section

$$\frac{1}{N_\mu} \frac{dN^h}{dz} = \frac{\sum_i e_i^2 q_i(x, Q^2) D_i^h(z)}{\sum_i e_i^2 q_i(x, Q^2)}$$

one may try to describe these x dependences. The sums are over all quarks with charges e_i , with momentum distributions $q_i(x, Q^2)$ and fragmentation functions $D_i^h(z)$. We use parameterizations [12] for $q_i(x, Q^2)$ which, for this purpose, adequately describe EMC structure function data [13]. Assuming strange and charm contributions to the denominator to be negligible and using charge conjugation invariance, one is left with the 4 fragmentation functions

$$D_u^P, D_d^P, D_{\bar{u}}^P, D_{\bar{d}}^P.$$

We further take $D_u^P = D_d^P$ and $D_{\bar{u}}^P = D_{\bar{d}}^P$, although the results are not sensitive to this, since the contributions from d ($\bar{d}$) quarks are small, and use a parameterization for the D_i^h describing the shape of the measured z distributions. The x dependences predicted by this factorisation ansatz are compared to the data in Fig. 3a. The trend of the data is reproduced, even though the quantitative agreement is not good.

The p_T^2 spectra for two different z bins were fitted with the form

$$\frac{1}{N_\mu} \frac{dN^h}{dp_T^2} = a e^{-bp_T^2}$$

for $p_T^2 < 2 \text{ (GeV)}^2$. The fits yielded $b = 3.1 \pm 0.6$ and $1.5 \pm 0.6 \text{ (GeV)}^{-2}$ in the ranges $0.2 \leq z < 0.4$ and $0.4 \leq z < 1.0$ respectively. The corresponding values for all the hadrons in the same kinematical range are 3.0 ± 0.1 and 1.8 ± 0.1 respectively. In Fig. 4 the p_T^2 spectra, integrated over the whole accessible range in x , Q^2 and z , are shown for protons plus antiprotons and for all hadrons. The distributions are again similar. The variation of slope with z contributes to the flattening with increasing p_T^2 .

To conclude, we see significant proton and antiproton signals in muon-proton scattering, which seem to have a different origin from those observed in very low energy electron-proton scattering [2,3,4]. Higher twist effects as a significant source of the observed protons can be excluded. The overall behaviour of protons and antiprotons is similar to that of all hadrons, although there is a larger charge asymmetry for medium z which tends to increase with x .

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FIGURE CAPTIONS

- Fig. 1 a) $\frac{1}{N_\mu} \frac{dN^{P,\bar{P}}}{dz}$, the normalized differential cross section, as a function of z ; the shaded band is an extrapolation of low energy proton data [2,3] to the $\langle W \rangle$ of the data ($\langle W \rangle \approx 17$ GeV at $z = 0.2$ and $\langle W \rangle \approx 8$ GeV² at $z = 0.8$).
- b) The ratios $\frac{N^P}{N^{h+}}$ and $\frac{N^{\bar{P}}}{N^{h-}}$ as a function of z .

- Fig. 2 The partial moments $\int_{0.4}^{0.6} dz \frac{1}{N_\mu} \frac{dN^{P+\bar{P}}}{dz}$ as a function of Q^2 for four different x bins.

- Fig. 3 a) The partial moments $\int_{0.4}^{0.6} dz \frac{1}{N_\mu} \frac{dN^{P,\bar{P}}}{dz}$ as a function of x . The curves represent the predictions of a factorisation ansatz.
- b) The ratios $\frac{N^P}{N^{h+}}$ and $\frac{N^{\bar{P}}}{N^{h-}}$ for $0.4 < z \leq 0.6$ as a function of x .

- Fig. 4 The p_T^2 distribution for protons plus antiprotons compared with that of all hadrons with the same kinematics.

Fig. 1

Fig. 2

Fig. 3

Fig. 4