HADRON MULTIPLICITY VARIATION WITH Q^2 AND SCALE
BREAKING OF THE HADRON DISTRIBUTIONS IN DEEP INELASTIC
MUON-PROTON SCATTERING

The European Muon Collaboration

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Abstract

Measurements are presented of the variation with Q^2 (scaling violation) of the hadron multiplicity in deep inelastic muon-proton scattering. An increase in the average multiplicity of both the charged hadrons and K^0 mesons is observed with increasing Q^2 or x_{Bj} for fixed centre-of-mass energy W . The study of the shape of the effective fragmentation function $D^h(z, W, Q^2)$ shows that the increase of the particle yield with Q^2 takes place for low z particles. The variation of the hadron distributions with Q^2 is also studied in the current fragmentation region where a decrease in multiplicity is observed. Such effects are expected from QCD.

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In Quantum Chromodynamics (QCD), the evolution of the quark fragmentation functions with Q^2 , the four momentum transfer squared between the incident and scattered leptons, is a natural consequence of gluon emission [1,2]. For deep inelastic scattering processes the gluon emission from the struck quark completes the standard picture provided by the simple Quark Parton Model, which contains Feynman scaling [3]. The question whether the Q^2 dependence of the hadron multiplicity is calculable in perturbative QCD has been widely debated in the past few years [4,5,6] and a faster than logarithmic rise with Q^2 of the average multiplicity in the jet has been predicted [4]. The dependence of the charged hadron multiplicity on the hadronic c.m. energy W has been measured both in neutrino [7] and muon scattering [8]. In both reactions the average hadron multiplicity was observed to grow logarithmically with energy and the fragmentation functions were observed to shrink at high z with increasing W [9,10]. In order to study the Q^2 dependence it is thus essential to be independent of the c.m. energy and related kinematic effects. In contrast to e^+e^- annihilation where phase space and QCD contributions depend on the same variable W , in deep inelastic lepton scattering one may fix W and vary Q^2 . In this letter we present the first observation of a Q^2 dependence of the average hadron multiplicity and of the hadron distributions at fixed W . The data come from the muon proton scattering experiments performed by the European Muon Collaboration at CERN.

The deep inelastic muon scattering variables used in this analysis are: the hadronic c.m. energy W , the four momentum transfer squared $-Q^2$, the laboratory energy ν of the virtual photon and the fraction of proton momentum carried by the struck quark, $x_{Bj} = Q^2/2M\nu$, where M is the proton mass. The variables W , Q^2 and x_{Bj} are related by:

$$W^2 = M^2 + Q^2 \left(\frac{1}{x_{Bj}} - 1 \right). \quad (1)$$

The two independent event variables used here are W and Q^2 . The hadron variable used in this analysis is the fraction of the total laboratory energy of the virtual photon carried by a hadron, defined as $z = E^h/\nu$. The production of hadrons in deep inelastic muon proton scattering is characterised by an effective fragmentation function defined as:

$$D^h(z, W, Q^2) = \frac{1}{N_{ev}(W, Q^2)} \frac{dN^h}{dz}(z, W, Q^2) , \quad (2)$$

where $N_{ev}(W, Q^2)$ is the number of events in the W, Q^2 bin. With this definition the function D^h is the differential average hadron multiplicity.

The data sample consisted of 25000 complete events measured by the NA9 apparatus which detected hadrons of momentum greater than 0.2 GeV giving essentially 4π solid angle coverage in the c.m. frame. The current fragmentation region ($z \gtrsim 0.15$) has been studied using 143000 events from the NA2 experiment where the fast forward going particles only were detected. Detailed descriptions of each apparatus can be found elsewhere [11,12]. In order to reduce the corrections for acceptance, smearing and radiative effects the following selection criteria were applied:

$$\begin{aligned} Q^2 &> 4 \text{ GeV}^2, \\ 4 \text{ GeV} &< W < 20 \text{ GeV}, \\ y = \frac{\nu}{E} &< 0.9, \\ E' &> 20 \text{ GeV}, \\ \theta_\mu &> 0.75^\circ, \end{aligned}$$

where E, E' are the laboratory energies of the incident and scattered muons, respectively, and θ_μ is the laboratory angle between these muons. For the K^0 analysis the cut on θ_μ was reduced to 0.5° to increase the number of events (1390 K_S^0 observed in total).

All the distributions presented below have been corrected for the effects of acceptance, resolution of the apparatus, radiative effects and inefficiencies of the various off-line pattern recognition and fitting and vertex finding algorithms. These corrections were determined using detailed Monte Carlo simulations of the experiments as described in [8,9,13] where the methods used to unfold the hadron multiplicities are described. The charged hadron multiplicities are corrected for the contributions from the decays of K_S^0 , Λ and $\bar{\Lambda}$ particles. The multiplicity distributions of K^0 and $\bar{K}^0$ mesons, which are corrected for the contributions of K_L^0 and the neutral decay modes of the K_S^0 , have been determined as in [14].

Figures 1a and b show the average multiplicities of charged hadrons and K^0 mesons respectively, as a function of W^2 for different Q^2 ranges. The corresponding values are presented in table 1. At fixed W , a systematic increase of the order of 8% is observed between the lowest and highest Q^2 for both types of particles, independent of the value of W . The same data for charged hadrons are plotted in fig. 2a as a function of Q^2 for different fixed W ranges. An approximately linear rise with $\ln Q^2$ is observed. A Q^2 variation at fixed W can also be interpreted as an x_{Bj} variation at fixed W due to the correlation in equation (1). Figure 2b shows the average charged hadron multiplicity as a function of x_{Bj} for fixed values of W . It can be seen that the increase observed with x_{Bj} is not limited to the region of low x_{Bj} ($x_{Bj} < 0.1$) where the contribution of the sea quarks to the interactions is important. The observed increase of the hadron multiplicity with Q^2 is not predicted by fragmentation models such as the Lund model [15] in which a decrease of particle yields with increasing Q^2 or x_{Bj} is expected at high W (dashed lines on figure 2b).

Fits of the form $\langle n \rangle = a + b \ln Q^2$ have been performed to the average charged hadron and K^0 multiplicities for different W ranges. The slope parameter b is positive in all W ranges for both types of particles. The mean values of the slope parameters have been obtained from a joint fit of the W and Q^2 dependences using the following formula:

$$\langle n \rangle = a_0 + a_1 \ln W^2/W_0^2 + a_2 \ln Q^2/Q_0^2 \quad (3)$$

where W_0^2 and Q_0^2 were taken to be 1 GeV^2 . The results of these fits for the total charged hadron and K^0 meson multiplicities and the χ^2/NDF ratios are given in table 2. A fit to the charged particle data without the $\ln Q^2$ term results in a significantly lower confidence level ($\chi^2/\text{NDF} = 35/23$). The addition of a correlation term of the form $(\ln W^2 \cdot \ln Q^2)$ between W^2 and Q^2 does not provide any further improvement of the fit.

The errors shown in the figures are statistical only. The normalisation systematic error on the average and partial multiplicities was $\pm 5\%$ as discussed in [8,13]. The systematic error on the coefficient a_2 of the $\ln Q^2$ term in

equation (3) was estimated to be 0.06 (second error in table 2). These were derived by studying different track selection criteria and different methods of correcting the data. For the K^0 multiplicity the systematic errors are estimated to be much smaller than the statistical errors.

Due to the large statistical errors, the K^0 data taken separately, do not provide conclusive evidence for a Q^2 dependence. However, the ratio between the slopes for K^0 mesons and charged hadrons tends to be larger for the $\ln Q^2$ term (0.35 ± 0.15) than for the $\ln W^2$ term (0.13 ± 0.02). This may be a hint that the origin of the effect is an increase of gluon radiation with Q^2 and that gluons fragment more readily to kaons.

The differential average multiplicities corresponding to the values of the effective fragmentation function $D^h(z, W, Q^2)$ for different z and W intervals are shown in figure 3 as a function of Q^2 . For each z range at fixed W , a dependence of the form $a + b \ln Q^2$ has been fitted. The mean values of the slope parameter b , defined as $dD^h(z, W, Q^2)/d \ln Q^2$ (averaged over the W bins), are shown as a function of z in figure 4a. The data show a clear rise with $\ln Q^2$ (i.e. positive b) for $z \lesssim 0.15$ for charged hadrons and K^0 mesons. This z range contains both the backward and central region. Figure 4a thus shows that the increase in multiplicity takes place predominantly for low z particles. For z values $\gtrsim 0.15$ a decrease of the differential multiplicity (i.e. negative b) is observed, which becomes small for $z \gtrsim 0.4$. Figure 4b shows the mean slope parameter for positive and negative hadrons separately. For negative particles the slopes are positive for $z \lesssim 0.05$ and become negative for $z \gtrsim 0.05$. The positive particle slope is positive or zero in the whole range of z . The differences in the slopes for $z > 0.10$ are expected from the Quark Parton Model where the production of positive hadrons is enhanced at high z and high x_{Bj} (i.e. high Q^2 at fixed W) by the effects of quark charge retention [16]. This x_{Bj} dependence cancels in the total charged hadron slopes. The observed residual Q^2 dependence in the total charged hadron slopes is qualitatively expected from leading order QCD.

To conclude, this study provides evidence for scale breaking (Q^2 -dependence) of the hadron distributions in deep inelastic muon-proton scattering which is not predicted by the simple Quark Parton Model. The total average

multiplicity of both charged hadrons and K^0 mesons increases with Q^2 at fixed W . The study of the effective fragmentation function $D^h(z, W, Q^2)$ shows that the extra particles are produced predominantly in the low z region. A decrease of the multiplicities with increasing Q^2 is observed for $z \sim 0.2$. The softening of the z distributions and the possible enhancement of strange hadron production with Q^2 suggests that gluon bremsstrahlung could be the source of the effect.

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Table 1

Average hadron multiplicities as a function of W
for different Q^2 ranges (in GeV^2)

$\langle W \rangle$ [GeV]	$h^\pm$ $4 < Q^2 < 10$	$h^\pm$ $10 < Q^2 < 20$	$h^\pm$ $20 < Q^2 < 50$	$h^\pm$ $Q^2 > 50$	K^0 $4 < Q^2 < 10$	K^0 $10 < Q^2 < 20$	K^0 $20 < Q^2 < 50$
5.0	-	4.24 ± 0.09	4.39 ± 0.09	-	-	-	-
7.0	-	5.03 ± 0.07	5.23 ± 0.09	-	0.28 ± 0.10	0.28 ± 0.04	0.30 ± 0.06
9.0	-	5.52 ± 0.08	5.94 ± 0.09	6.16 ± 0.16	0.28 ± 0.08	0.33 ± 0.04	0.43 ± 0.05
11.0	-	6.16 ± 0.08	6.41 ± 0.07	6.35 ± 0.16	0.36 ± 0.08	0.56 ± 0.06	0.50 ± 0.07
13.0	6.38 ± 0.11	6.43 ± 0.07	6.74 ± 0.07	6.80 ± 0.15	0.48 ± 0.08	0.35 ± 0.05	0.55 ± 0.07
15.0	6.81 ± 0.08	6.81 ± 0.08	6.88 ± 0.07	6.90 ± 0.16	0.44 ± 0.06	0.61 ± 0.06	0.44 ± 0.07
17.0	7.04 ± 0.07	7.22 ± 0.08	7.38 ± 0.08	7.56 ± 0.16	0.51 ± 0.06	0.52 ± 0.06	0.66 ± 0.11
19.0	7.26 ± 0.07	7.42 ± 0.07	7.60 ± 0.08	-	0.53 ± 0.05	0.57 ± 0.07	0.78 ± 0.11

Table 2

Fit results of the function $\langle n \rangle = a_0 + a_1 \ln W^2/W_0^2 + a_2 \ln Q^2/Q_0^2$

$$(W_0^2 = Q_0^2 = 1 \text{ GeV}^2)$$

	a_0	a_1	a_2	χ^2/NDF
Charged hadrons	-0.30 ± 0.16	1.22 ± 0.03	$0.22 \pm 0.04 \pm 0.06$ stat. syst.	26.0/22
K^0 mesons	-0.55 ± 0.15	0.16 ± 0.02	0.077 ± 0.028	21.8/18

Figure Captions

1. Average multiplicity as a function of W^2 for different Q^2 ranges:
a) charged hadron multiplicity, b) K^0 multiplicity.
2. Average charged hadron multiplicity:
(a) as a function of Q^2 for fixed W bins. Full lines correspond to fits to the function $\langle n \rangle = a + b \ln Q^2$.
(b) as a function of x_{Bj} for fixed W bins. Dashed lines correspond to Lund model predictions [15].
3. Average differential multiplicity $D^h(z, W, Q^2)$ in different z and W ranges for charged hadrons as a function of Q^2 .
4. Mean values of the slope $dD^h/d(\ln Q^2)$ for the average differential multiplicity (mean over W) as a function of z :
a) charged hadrons and K^0 mesons,
b) positive and negative hadrons.

FIG. 1

FIG. 2a

FIG. 2b

FIG. 3

FIG. 4