MEASUREMENT OF THE Q^2 , x AND W^2 DEPENDENCE OF SINGLE HADRON PRODUCTION
IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration

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ABSTRACT

Measurements are presented of the distributions in scaled energy of the hadrons produced in high energy muon scattering. The observed dependence on x (non-factorisation) and Q^2 (scaling violation) is similar to that expected from next to leading order QCD calculations. These variations in the data can be equivalently represented by a dependence on the single variable W^2 .

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Scale breaking in the quark distribution functions is well known but the non-scaling of hadron production by charged leptons has not yet been established [1,2,3,4]. The low energy ($W^2 \lesssim 16 \text{ GeV}^2$) e-p data from Drews et al. [3], however, may indicate some factorization breaking. Neutrino scattering experiments have reported both scale breaking and factorization breaking at low W^2 [5]. In this letter we present data on muoproduction of hadrons at high W^2 which shows factorisation breaking and indicates scaling violation.

The kinematic variables relevant for inclusive single hadron production in deep inelastic muon scattering are defined by:

$$\begin{aligned} -Q^2 &= q^2 = (p_\mu - p_{\mu'})^2 & v &= \frac{(p_i \cdot q)}{M} \\ x &= \frac{Q^2}{2Mv} & z &= \frac{(p_f \cdot p_i)}{(q \cdot p_i)} \\ W^2 &= Q^2 \left(\frac{1}{x} - 1 \right) + M^2 & y &= \frac{(q \cdot p_i)}{(p_\mu \cdot p_i)} \end{aligned}$$

where p_μ , $p_{\mu'}$ are the momenta of the incident and scattered muons, respectively, p_i and p_f are the momenta of the target proton and a final state hadron and M is the proton mass.

In the Quark-Parton Model (QPM) the cross-section for the production of single hadrons can be expressed in the form

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

where the sum runs over all quark and antiquark flavours. N_h is the number of hadrons h observed in N_μ scatters, $\sigma(x, Q^2)$ and $\sigma^h(z, x, Q^2)$ are respectively the total and inclusive hadron production cross-sections by virtual photons. The e_i^2 are the quark charges squared, $q_i(x)$ are the quark distribution functions of the target and $D_i^h(z)$ is the fragmentation function of quark i into a hadron h . The product structure of (1) is known as factorization and the independence of Q^2 as scaling.

The data reported here consist of $\sim 75,000$ events obtained by scattering 120 GeV (25,000 events) and 280 GeV (50,000 events) muons on a liquid hydrogen target. The apparatus used consisted of a large open dipole spectrometer with numerous proportional and drift chamber planes and has been fully described elsewhere [6]. Several aspects of this data set have already been published [7].

In the data analysis the charged tracks found by the pattern recognition program were subjected to a geometrical fit to obtain their charges and momenta. A vertex between a fully measured incident muon and the scattered muon was then reconstructed. This vertex was required to be in the downstream part of the target (3m for the 280 GeV data and 2m for the 120 GeV data) to reduce the contamination of the hadron sample by reinteractions. Reconstructed hadrons were selected and associated with the vertex according to a set of criteria on the quality of both the track reconstruction and the vertex association. A more complete description of the analysis procedures used is given in Ref. [8].

The acceptance of the apparatus was determined by a Monte Carlo calculation. The complete apparatus including chamber efficiencies, hodoscope efficiencies and measurement errors was simulated. The effects of higher order electromagnetic processes (i.e., radiation by the muons), which introduce a small systematic error in the reconstructed 4 momentum of the virtual photon, q , were included directly in the Monte Carlo calculation. The correction is at maximum 20% at the highest z and at the highest y , and less than 5% for most of the data. Although the physics model [9] in the Monte Carlo represented the data well, it was checked that the acceptances were insensitive to the details of the model. At high values of the scattered muon momentum the systematic error on its measurement is $\sim 1\%$ and leads to a large relative error in v and hence z . Given the strong z dependence ($\sim e^{-6z}$) of $\frac{1}{N_\mu} \frac{dN^h}{dz}$ there is then a large systematic error in the measurement of this quantity at very low v . At high y the radiative corrections are large and at low muon angle or low hadron momentum the acceptance corrections are large. In order to maintain the combined systematic error from these sources at less than 10% for all presented points, the cuts shown in Table 1 were applied. The correlations between these errors could lead to up to 12% change in $\frac{1}{N_\mu} \frac{dN^h}{dz}$ from lowest to highest v . There is an additional overall normalisation uncertainty of about 10% which comes mainly from the track selection.

Table 1

Data Selection Cuts

E_{μ}	[GeV]	280	120
$Q_{\min}^2$	[GeV ²]	5	2
$v_{\min}$	[GeV]	70	30
$P_{\mu',\min}$	[GeV]	40	20
$\theta_{\mu',\min}$	[mrad]	10	10
$P_{f\min}$	[GeV]	5	2.5

In Fig. 1 we display the differential multiplicities for the sum of positive and negative hadrons $\frac{1}{N_{\mu}} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$ as a function of Q^2 at fixed x and z values. Since, in the region of overlap, the results obtained with the two energies were in agreement, they have been combined. For $Q^2 > 10 \text{ GeV}^2$ the data show a weak but systematic tendency to decrease with Q^2 . The QPM predicts no Q^2 dependence for these data and a representative calculation based on the quark distribution functions given in ref. [10] and the fragmentation functions of ref. [11] is shown by the dashed lines in Fig. 1.

Fig. 2 shows the differential multiplicities, again with the two energies combined, as a function of x for bins of Q^2 and z . For the measured quantity the QPM factorisation property leads to approximate independence of x as shown by the dashed line. The data in contrast show a clear rise as a function of x . This rise cannot be accounted for by a reasonable variation of the contribution of strange and charm quarks in the nucleon as a function of x . It can therefore be concluded on the basis of both figures that the QPM does not provide a satisfactory description of the data.

QCD calculations in the leading logarithm approximation modify Eq. (1) by introducing a Q^2 dependence in the quark distribution and fragmentation functions [12,13] but do not modify the factorization structure [14]. The order α_s corrections to the leading logarithm approximation have been calculated by several authors [15,16,17,18] and lead to a breaking of factorisation. The full lines shown in Figs 1 and 2 are the results of one such calculation [15] in our

kinematic range. The quark and gluon fragmentation functions, derived solely from e^+e^- data for $z > 0.4$, were taken from ref. [19] and the parton distribution functions from ref. [20]. The value $\Lambda = 500$ MeV was used for the QCD scale parameter.

The calculation shows the same qualitative behaviour, a weak dependence on Q^2 and a rise with increasing x , exhibited by the data. The quantitative agreement is not good; however the large number of input functions prohibits an optimisation of the parameters with these data alone. The importance of a consistent determination of the distribution and fragmentation functions is emphasised in ref. [18].

Plotted as a function of W^2 the data show a decrease with increasing W^2 for all z intervals ($z > 0.2$) as shown in fig. 3. This decrease absorbs all the x and Q^2 dependence such that at fixed W^2 we observe no residual variation with these quantities. This simple representation of the data is also approximately reproduced by the next to leading order QCD calculation [15], shown as a solid line in Fig. 3.

In conclusion, the differential multiplicities $\frac{1}{N_\mu} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$ of hadrons produced in deep inelastic μp scattering show deviations from the scaling (Q^2 independence) and factorisation (x independence) predictions of the Quark Parton Model. The behaviour of the data is qualitatively reproduced by a QCD calculation including higher order effects. If the data are considered as a function of W^2 there is no need for an explicit x or Q^2 dependence.

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FIGURE CAPTIONS

Fig. 1 Q^2 dependence of $\frac{1}{N_\mu} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$ for different x and z .
The dashed line represents the QPM and the solid line is the QCD calculation [15].

Fig. 2 x dependence of $\frac{1}{N_\mu} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$ for different Q^2 and z .
The dashed line represents the QPM and the solid line is the QCD calculation [15].

Fig. 3 W^2 dependence of $\frac{1}{N_\mu} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$. The solid line is the QCD calculation [15].

Fig. 1

Fig. 2

Fig. 3