STUDIES OF QUARK AND DIQUARK FRAGMENTATION INTO IDENTIFIED HADRONS
IN DEEP INELASTIC MUON-PROTON SCATTERING

The European Muon Collaboration

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Abstract

Data on identified hadrons produced in deep inelastic muon-proton scattering are presented. Results on the normalized x_F distributions of charged pions, kaons, protons and antiprotons are given. The negative x_F region below $x_F < -0.5$ is found to be dominated by protons and this shows little W^2 dependence. Lambdas show a similar fragmentation behaviour to protons. Significant production of antibaryons is observed in the current fragmentation region ($x_F > 0$). The relative fraction of kaons and protons is found to increase in the forward direction. The mean multiplicities of identified hadrons are observed to rise logarithmically with W^2 , the rise of the pion multiplicity being much faster than that for kaons and protons. The $\langle p_{\perp}^2 \rangle$ in the central x_F region is larger for charged kaons and protons than for pions. The measurements are compared to the predictions of the Lund string model.

1. Introduction

In this paper identified hadron distributions are presented from the hadrons produced in muon-proton scattering at 280 GeV. The experiment reported here is the first lepton-nucleon-scattering experiment which allows a study of the complete final state including identification of charged hadrons and the reconstruction of neutral kaons and lambdas up to high centre of mass energies. Studies of the hadrons produced in different reactions, such as hadron-hadron, lepton-hadron or e^+e^- interactions have contributed greatly to the present understanding of the physics underlying the fragmentation process.

In the quark parton model (QPM), deep inelastic muon scattering is described by the interaction of the exchanged virtual photon with the constituents of the target nucleon resulting in a struck quark and a target remnant system. At sufficiently high energies confining forces cause the struck quark and the target remnant to fragment into hadrons. In the virtual-photon proton centre of momentum system (CMS) this leads to forward and backward going jets of particles. The study of the production of pions, strange particles and baryons contributes to the further understanding of the fragmentation process.

Baryon production in muon-proton scattering is thought to originate from two different sources. First one expects to find a baryon in the jet from the target remnants. In addition baryons and antibaryons can be produced in the fragmentation of the struck quark as shown in previous experiments [1,2].

The virtual photon axis is completely defined by the muon kinematics. The 4-momentum of the virtual photon is the 4-momentum difference of the incoming (μ) and scattered muon (μ'), $q=(v, k-k')$. The variables describing the event kinematics are the energy transfer to the hadrons in the laboratory system, $v=E_\mu-E_{\mu'}$, the negative 4-momentum squared of the virtual photon, $Q^2=-q^2$, the scattering angle Θ_μ , the Bjorken variable, $x_{Bj}=Q^2/2m_p v$ and the invariant mass of the hadronic final state with $W^2=-Q^2+m_p^2+2m_p v$. The final state hadrons are described in the CMS by the longitudinal Feynman x variable $x_F=2p_{||}/W$ and the transverse momentum $p_\perp$. In this system $p_{||}$ and $p_\perp$ are momenta measured parallel and transverse to the virtual photon direction.

To describe the hadronisation of quarks into the observed hadrons, various fragmentation models such as the Field-Feynman [3] or the Lund [4] model have been developed. We will compare the data with the Lund string model. First order QCD matrix elements, i.e. hard gluon emission and photon gluon fusion, leading to three-jet events are included. The model also includes contributions from 'soft' gluon emission, the predicted effects of which are compatible with those observed in the data [5,6]. The production of strange hadrons in the fragmentation is controlled by the ratio of $\gamma_s/\gamma_u=0.3$ of the probabilities to create the heavier strange quark (s) in proportion to that for the lighter up (u) or down (d) quarks ($\gamma_u=\gamma_d$). Furthermore a parameter $\gamma_{qq}=0.075$ expresses the relative probability that a diquark-antidiquark pair is created in the hadronisation cascade of the struck quark. The antidiquark acts as the source of antibaryons.

2. Experimental Conditions and Data Analysis

The data presented here were taken with the EMC-NA9 experiment in the M2 muon beam at CERN, at an incident muon energy of 280 GeV. The apparatus consists of a double magnetic spectrometer [7,8]. A vertex spectrometer magnet (VSM) contains a 1 metre long liquid hydrogen target inside a streamer chamber. Tracks leaving the streamer chamber are detected in a set of proportional chambers and drift tubes. The scattered muon and fast hadrons enter the forward spectrometer magnet having a bending sense opposite to the VSM. A hodoscope trigger system allows selection of the scattered muons with angles greater than 0.5° . An arrangement of proportional and drift chambers provides the track detection for fast forward particles. This apparatus gives almost complete acceptance for the detection of final state hadrons over the full solid angle and for momenta larger than 200 MeV/c.

An extensive particle identification system, in the vertex detector, consists of a set of two gas Cerenkov counters filled with neopentane and nitrogen, two Aerogel Cerenkov counters and a time of flight hodoscope system for low momentum particles. A large Cerenkov counter filled with neon is used to identify fast particles in the forward spectrometer. This set-up allows the identification of roughly 50% of all charged hadrons.

In order to restrict the data to a region where the acceptance is good and radiative corrections are small the following conditions were used:

$$\begin{array}{ll} Q^2 > 4 \text{ GeV}^2 & x_{Bj} > .02 \\ 20 < \nu < 260 \text{ GeV} & 16 < W^2 < 400 \text{ GeV}^2 \\ \nu < .9 E_\mu & \Theta_{\mu'} > 0.5^\circ \end{array}$$

This leads to a data sample of about 12000 events with the mean values of the event variables being: $\langle Q^2 \rangle = 12 \text{ GeV}^2$, $\langle \nu \rangle = 76 \text{ GeV}$, $\langle W^2 \rangle = 130 \text{ GeV}^2$ and $\langle x_{Bj} \rangle = 0.11$.

Particle identification using the Cerenkov and time of flight information is performed as follows [9,10]. For each detector conditional probabilities that a given particle hypothesis (e, π , K, p) would produce the observed signal in the detector, are computed, taking possible background contributions into account. The muon hypothesis is excluded, as forward

muons are identified behind the hadron absorber in the forward spectrometer. In the vertex system alone muons cannot be distinguished from pions. Products of the conditional probabilities from the various detectors are formed for each mass hypothesis, serving as a basis for the mass assignment. These products are required to be above certain values to avoid misidentification of tracks where the difference between two or more hypotheses is small. The identification procedure and the requirements are described in detail in ref. [10]. The remaining contaminations of the pion sample by other hadrons is less than 10% and less than 20% for kaons and protons. Losses and contaminations in this procedure are corrected for by the Monte Carlo simulation described below.

All the experimental results are corrected for apparatus acceptance, smearing due to measurement errors, and the inefficiencies of the detectors and of the various off-line pattern recognition, fitting and vertex finding algorithms. These corrections are obtained by a detailed Monte Carlo simulation of the experiment. Muon scattering events are generated according to the measured structure functions [11] incorporating radiative effects [12]. Hadrons are then generated using the Lund string model [4]. Secondary interactions are generated in the target. Particle decays are generated according to the measured lifetimes and branching ratios and photon conversions are taken into account. A simulation of the raw data using the measured chamber efficiencies, and the known dead regions in the apparatus is performed. In addition a simulation of the various Cerenkov counters and the streamer chamber film measurement is made. These Monte Carlo events are then passed through the same analysis chain as the measured events.

The total correction to a measured distribution is obtained by comparing the corresponding generated Monte Carlo distribution with the distribution obtained after processing the Monte Carlo events through the analysis chain. The corrected distributions labeled as "pion", "kaon" or "proton" are produced with identified hadrons only. There are some regions in the momentum distribution where particles cannot be identified. These "holes" disappear in the x_F distributions due to the integration over all other kinematical variables. Identified electrons are removed from the data.

In all distributions presented below the error bars represent the statistical errors only. Systematic effects have been investigated resulting in an error of $\pm 20\%$. This error includes normalisation uncertainties due

to the event and track selections and uncertainties in the hadron identification procedure mainly due to uncertainties in the simulation of background, overlapping Cerenkov light cones and multiple hits in the time of flight hodoscopes and Cerenkov counters.

3. Results

The mean multiplicity of charged pions, kaons and protons plus antiprotons in the forward and backward hemispheres are plotted versus W^2 in fig. 1 a) and b). The data are consistent with a logarithmic rise with W^2 . Only the proton yield in the backward direction is not strongly W dependent and is around 0.5 protons per event as one would expect, if the stable baryon from the target fragmentation is a neutron in half of the events. The rise is much faster for pions than for heavier particles. A higher particle yield in the forward compared to that in the backward hemisphere is observed for pions and kaons whereas the opposite is true for protons.

Figs. 2 a), b) and c) show the normalized x_F distributions of hadrons produced in the semi-inclusive reaction $\mu + p \rightarrow \mu + h + X$, where h symbolizes π, K, p or Λ and X the remaining final state hadrons. Positive and negative charges are plotted separately. Neutral kaons and Λ 's measured in this experiment [13] are compared to charged kaons and protons. The curves are the predictions of the Lund model.

The $(K^0 + \bar{K}^0)/2$ distribution is similar to that of K^- in both the forward and backward hemisphere. This is to be expected in the QPM as neither K^0 ($\bar{K}^0$) nor K^- contains a u valence quark, which is favoured since the virtual-photon coupling is proportional to the charge squared of the struck quark. The comparison of the x_F distributions for Λ 's ($\bar{\Lambda}$'s) and p ($\bar{p}$'s) in the forward direction suggests a similar production mechanism for both. The Λ 's show a similar behaviour in the backward hemisphere to that observed for the protons. Λ 's ($\bar{\Lambda}$'s) are suppressed by roughly a factor of 5 in both the backward and forward region. The Lund model describes the data rather well.

Fig. 3 a) gives the ratio of positive to negative yields for π, K and p . The measured ratio shows an excess of positive over negative for all three

particle types in the forward direction. In the QPM this is explained by the excess of valence u-quarks in the proton and the charge squared factor. The kaon and proton ratios increase even faster with increasing x_F than the pion ratio. In the backward region, where measured, the ratio π^+/π^- and K^+/K^- are the same within errors. The ratio of $p/\bar{p}$ is strongly increasing with decreasing x_F . As antiprotons are expected to be produced only in the fragmentation chain the large excess of protons over antiprotons can be attributed to the backward going target remnant, which often fragments into a proton.

Figs. 3 b) and c) show the fractions of pions, kaons and protons to all charged hadrons separately for positive and negative charges. The pions dominate in the central x_F region which could be due to the production from decays of heavier resonances. This pion excess produces a dip in the central region for the fractions of kaons and protons. The fraction of pions decreases in the forward region, whereas kaons and protons increase. In the very forward direction ($x_F > 0.5$) the data indicate a decrease of the fraction of kaons and protons. This decrease could be explained as follows: in the first breakup, where the leading hadron is produced, the probability of finding a diquark pair (γ_{qq}) or a strange quark (γ_s) counts only once, whereas a hadron produced in the fragmentation chain may have a diquark or strange quark coming from either side.

Fig. 4 shows the average transverse momentum squared $\langle p_{\perp}^2 \rangle$ as a function of x_F for the various hadrons. All three particle types indicate an increase of $\langle p_{\perp}^2 \rangle$ with x_F in the forward direction. An indication of a dip in the central x_F region (seagull effect) is seen in the pion and kaon data. QCD predicts a forward-backward asymmetry because of hard and soft-gluon bremsstrahlung from the struck quark which leads to an additional contribution to $p_{\perp}$ in the forward jet [5]. Comparing the $\langle p_{\perp}^2 \rangle$ distribution for heavier particle types shows in the central x_F region a somewhat larger $\langle p_{\perp}^2 \rangle$ for kaons and protons than for pions. For protons the $\langle p_{\perp}^2 \rangle$ distribution is rather flat. The data are compatible with the predictions of the Lund model.

4. Summary

Pion, kaon, proton and antiproton production has been studied in deep inelastic muon-proton scattering. The mean multiplicity of pions and kaons increases with W^2 in both the forward and the backward hemispheres. The proton multiplicity increases with W^2 in the forward region but there is little W^2 dependence in the backward hemisphere. The Feynman x_F distributions for p's and Λ 's have a similar shape with relatively large values in the negative x_F region. This can be interpreted as diquark fragmentation into baryons. The $\bar{p}$ and $\bar{\Lambda}$ distributions are similar in shape, but differ strongly from p and Λ , they decrease strongly in the backward hemisphere. This suggests a similar production mechanism in the fragmentation chain. Pions are found to be dominant in the central x_F region whereas the relative proportions of K and p are found to increase with x_F . The charge ratios π^+/π^- , K^+/K^- , $p/\bar{p}$ increase with x_F as expected from simple QPM arguments concerning the quark content of the target and the produced hadron. The K^0 ($\bar{K}^0$) and K^- , which do not contain a valence u quark, have x_F distributions which are similar in shape. The $\langle p_{\perp}^2 \rangle$ is found to increase with x_F as expected from QCD. There is a mass dependence of $\langle p_{\perp}^2 \rangle$ in the central x_F region where $\langle p_{\perp}^2 \rangle$ is larger for the heavier particles. The Lund model reproduces the main trends of the data.

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Fig. 1 Average multiplicity of pions, kaons and protons as a function of W^2

- a) backward multiplicity ($x_F < 0$)
- b) forward multiplicity ($x_F > 0$)

Fig. 2 Feynman x distributions normalized to the number of scattered muons (N_μ) for positive and negative hadrons

- a) π^+ , K^+ , p and Λ
- b) π^- , K^- , $\bar{p}$ and $\bar{\Lambda}$
- c) K^- and $(K^0 + \bar{K}^0)/2$

The curves represent the predictions of the Lund model

Fig. 3 Ratio of pions, kaons and protons as a function of Feynman x

- a) π^+ , K^+ , p normalized to π^- , K^- , $\bar{p}$
- b) π^+ , K^+ , p normalized to all positive hadrons
- c) π^- , K^- , $\bar{p}$ normalized to all negative hadrons

The curves represent the predictions of the Lund model

Fig. 4 Average transverse momentum squared $\langle p_\perp^2 \rangle$ versus Feynman x for pions, kaons and protons.

The curves represent the predictions of the Lund model

Fig. 1

Fig. 2

Fig. 3

Fig. 4