TRANSVERSE MOMENTUM AND ITS COMPENSATION IN CURRENT AND
TARGET JETS IN DEEP INELASTIC MUON-PROTON SCATTERING

The European Muon Collaboration

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Abstract

Results are presented on the transverse momentum distributions of charged hadrons in 280 GeV muon-proton deep inelastic interactions. The transverse momenta are defined relative to the accurately measured virtual photon direction and the experiment has almost complete angular acceptance for the final state hadrons. Significantly larger values of the average transverse momentum squared are found for the forward going hadrons than for the target remnants. This result, combined with a study of the rapidity region over which the transverse momentum is compensated, can be explained by a significant contribution from soft gluon radiation, but not by a large value of the primordial transverse momentum of the struck quark.

In this paper results are presented from a study of the transverse momentum distributions of the charged particles produced in 280 GeV muon-proton scattering. The experiment combines, for the first time, both the high centre of mass energies necessary for good separation of current and target fragments [1] and the almost complete angular acceptance [2] needed to study the final state hadrons. Studies of both single particle transverse momentum distributions and correlations in the transverse momenta of final state hadrons in hadron-hadron, lepton-hadron and e^+e^- interactions have contributed a great deal to the understanding of the underlying physics in these processes. The various results can be described in terms of the framework provided by the quark parton model (QPM) as modified by the effects of perturbative and non-perturbative Quantum Chromodynamics (QCD).

The data presented here come from the EMC (NA9) experiment which consists of a double magnetic spectrometer. This comprises a vertex magnet containing a streamer chamber, which itself contains a 1-metre long liquid hydrogen target, and a forward spectrometer magnet which is used in the detection and measurement of the scattered muon and fast charged hadrons. The complete system [2] can detect tracks with momentum of more than 280 GeV down to less than 200 MeV and thus gives essentially 4π coverage in the hadronic centre of mass system (cms). In addition, time-of-flight hodoscopes plus four threshold Cerenkov counters give good particle identification over a wide range of momentum. More details of the experimental set-up and analysis procedures can be found in refs. [1] and [2].

The analysis presented here uses a sample which constitutes about half of the total number of events taken with a hydrogen target. The selection criteria used are defined in terms of the usual kinematic variables in deep inelastic scattering and are $Q^2 > 4 \text{ GeV}^2$, $40 < W^2 < 400 \text{ GeV}^2$,

$20 < \nu < 260$ GeV, $E'_\mu > 20$ GeV, $y < 0.9$, where Q^2 is the square of the 4-momentum transferred between the leptons, ν is the corresponding energy transferred in the laboratory system, W is the total cms energy of the final state hadrons, E'_μ is the energy of the scattered muon in the lab. system and $y = \nu/E_\mu$, with E_μ the lab. energy of the incident muon. In addition it is required that the angle between the incident and scattered muons is greater than 0.75° . These cuts are applied in order to avoid regions where corrections for the acceptance, radiative effects or smearing are large ($\geq 10\%$). The number of events remaining after these cuts is 11,000. The variables used to describe the final state hadron momentum in the hadronic cms are p_T , the momentum transverse to the current direction, $x_F = 2p_L/W$ where p_L is the momentum along the current direction and $y^* = 0.5 \ln((E+p_L)/(E-p_L))$, where E is the cms energy.

In these deep inelastic muon-proton scattering events the direction of the virtual photon, that is the momentum difference between the incident and scattered muons, is accurately measured. This direction provides a natural axis with respect to which the various contributions to the transverse momentum of hadrons can be studied. Thus leptonproduction offers a unique possibility to study the various contributions to the transverse momentum. In terms of the Quark Parton Model and QCD these are

- i) The intrinsic (or primordial) transverse momentum of the struck quark or antiquark, k_T .
- ii) Multiple soft gluon radiation from the struck quark.
- iii) Hard QCD processes. To first order in α_s there are two possible final states in terms of the partons:
 - a) quark plus gluon
 - b) quark plus antiquark. In both a) and b) the remaining quarks, antiquarks and gluons are assumed to act as spectators in the collision (target remnants).

- iv) The hadronisation process by which the partons are converted into hadrons.

Results on the transverse momentum distributions of charged particles in high energy lepton-proton scattering have been obtained in previous studies using both incident muon and neutrino beams. However the muon studies [3-6] have been restricted in acceptance to charged hadrons which are forward going in the cms and the neutrino results [7,8], which have almost complete angular acceptance for charged hadrons, are mostly at low values of W , where there is a significant overlap of current and target fragments. These experiments have shown that $\langle p_T^2 \rangle$ increases as a function of W [3,7]. For the values of W previously explored (mostly $W \leq 10$ GeV), this increase is most pronounced for hadrons with $x_F > 0$ [7]. At higher values of W large values of $\langle p_T^2 \rangle$ are obtained for large positive x_F [3]. These latter results can be reproduced by either a large (and somewhat unphysical) value of $\langle k_T^2 \rangle \sim (0.8 \text{ GeV})^2$ or by a smaller $\langle k_T^2 \rangle \sim (0.4 \text{ GeV})^2$ and the inclusion of soft gluon effects. A previous study of the p_T balancing that of the large x_F particle [5] did not exclude either of these possibilities due to the limited range in rapidity accessible.

All of the above mentioned contributions i) to iv) to p_T are included in the Lund string fragmentation model [9]*. Final states with either 2 or 3 partons (jets) are produced. The struck quark or antiquark is chosen from the density distributions of Gluck, Hoffmann and Reya

* The version of the Lund Model used is based on Jetset version 4.3. The following values of the parameters were used: width of fragmentation p_T distribution $\sigma_q = 0.44 \text{ GeV}$, $\langle k_T^2 \rangle = (0.44 \text{ GeV})^2$, strange quark suppression $\gamma_s/\gamma_u = 0.3$, diquark to quark suppression $P_{qq}/P_q = 0.065$. Equal amounts of vector and pseudoscalar mesons were generated.

[10]. The 3-parton final states are produced using the first order QCD matrix element, with $\alpha_s = 12\pi/(25\ln(Q^2/\Lambda^2))$ and $\Lambda = 0.3$ GeV. The primordial transverse momentum, k_T , is effected essentially by a rotation of the direction of the struck quark and remnant target system with respect to the current. The probability of soft gluon radiation is assumed for a given event to be constant throughout the accessible rapidity range, with the recoil p_T going to the struck quark from which the gluons are emitted. A detailed comparison of the data and the predictions of the Lund model is presented below.

The various distributions presented below have all been corrected for the effects of acceptance, smearing introduced by the resolution of the apparatus, radiative corrections and the efficiency of the various off-line pattern recognition, fitting and vertex finding programs. This is performed by a detailed Monte Carlo simulation as described in ref. [1]. All distributions have been corrected to correspond to those that would be obtained with complete particle identification of all charged particles and are given in the hadronic cms. Specific mass assignments are necessary in order to make the Lorentz transformation to the cms from the laboratory system. Particle identification is not used directly in this analysis. However, as shown in ref. [1], good agreement is found between the cms distributions obtained using identified particles and those obtained using this Monte Carlo correction method.

The measured values of $\langle p_T^2 \rangle$ as a function of x_F are shown in fig. 1. Possible systematic effects on $\langle p_T^2 \rangle$ from a variety of sources have been investigated. In the backward hemisphere the estimated systematic effects are similar in magnitude to the statistical errors; the main contribution arises from uncertainty in the correction factor for the mass assignment. In the forward hemisphere the estimated systematic errors are less than the statistical errors except for $x_F > 0.5$, where they

are roughly equal to the statistical errors. The main contribution in the region $x_F > 0.5$ arises from uncertainties in correctly simulating the error distributions. It should be noted that, as shown in ref. [1], good separation of current and target fragments is achieved, for the first time in lepton-proton scattering due to the much larger values of W^2 explored in this experiment. It can be seen in fig. 1 that, in addition to the pronounced dip around $x_F = 0$ (seagull effect), the values of $\langle p_T^2 \rangle$ in the forward direction, for $x_F > 0.2$, are significantly larger than in the backward direction. Also shown in fig. 1 are several curves computed using the Lund model. The solid line is produced using the standard settings of the Lund model including hard QCD effects, the effects of soft gluon radiation and $\langle k_T^2 \rangle = (0.44 \text{ GeV})^2$. This model reproduces the data reasonably well. Also shown in fig. 1 are the model predictions with the standard settings of the parameters except that for the dashed line hard QCD processes are removed, for the dot-dashed line soft gluon processes are removed and for the dotted line soft-gluon processes are also removed but a value of $\langle k_T^2 \rangle = (0.88 \text{ GeV})^2$ is used. It can be seen that high $\langle k_T^2 \rangle$ alone does not reproduce the forward-backward asymmetry and that the main contribution to this asymmetry is, according to the Lund model, due to the effects of soft gluon radiation.

The differential distributions of p_T^2 for different regions of x_F , both positive and negative, are shown in fig. 2. In fig. 2a the p_T^2 distribution for the x_F interval $-0.6 < x_F < -0.4$ can be seen to fall off much more rapidly with p_T^2 than for the corresponding interval in the forward direction, $0.4 < x_F < 0.6$. The same effect is seen for the x_F intervals $-0.4 < x_F < -0.2$ and $0.2 < x_F < 0.4$, however the difference between the forward and backward directions is less pronounced. The Lund model predictions, which are also shown in fig. 2, adequately reproduce these trends.

The dependence of $\langle p_T^2 \rangle$ on the kinematic variables x , W^2 and Q^2 is shown in figs. 3a,b and c respectively. The Bjorken variable $x = Q^2/(2M\nu)$, where M is the nucleon mass, represents in the QPM the fraction of the nucleon's momentum carried by the struck quark. In the backward hemisphere there is little dependence of $\langle p_T^2 \rangle$ on any of these variables. However in the forward direction the values of $\langle p_T^2 \rangle$ at high W^2 ($W^2 > 256 \text{ GeV}^2$) and low x ($x < 0.05$) are significantly larger than those at low W^2 ($W^2 < 144 \text{ GeV}^2$) and high x ($x > 0.2$). There is little dependence on Q^2 . However the kinematic variables are related by $W^2 = M^2 + Q^2(\frac{1}{x} - 1)$, so some care must be taken in the interpretation of these trends. However all the observed trends are consistent with being mainly attributable to a dependence on W^2 alone with the x dependence and the small dependence on Q^2 being reflections of the W^2 dependence over the kinematic regions spanned by the data. The Lund model again reproduces the trends of the data as can be seen from the curves in fig. 3.

A sensitive method of determining the various sources contributing to the transverse momentum distributions is the study of correlations between the transverse momenta of the final state hadrons. In particular more detailed insight into the presence of any intrinsic transverse momentum, or of any soft gluon effects, may be found by studying the regions of rapidity over which the p_T of the leading particle, i.e. the one most likely to contain the struck quark, is compensated. Fig. 4a shows the rapidity distribution dP_T^{trig}/dy^* for trigger particles with $x_F > 0.5$, where dP_T^{trig}/dy^* is defined as

$$\frac{dP_T^{\text{trig}}}{dy^*} = \frac{1}{N_{\text{ev}}} \int P_T \frac{dN^{\text{trig}}}{dp_T dy^*} dp_T$$

where N^{trig} is the number of trigger particles. The sample containing such a trigger particle consists of 668 events. Fig. 4c shows a similar distribution for trigger particles with $-0.5 < x_F < -0.2$ (1934 events), that

is selecting trigger particles from the target fragments.

The compensation of the p_T of the trigger particle by the remaining charged particles in an event is studied using

$$\frac{dp_T^{bal}}{dy^*} = \frac{1}{N_{eV}} \int p_T' \frac{dN^{bal}}{dp_T' dy^*} dp_T'$$

where N^{bal} is the number of remaining charged particles and $p_T' = p_T \cos \phi_T$, where ϕ_T is the azimuthal angle about the virtual photon direction with $\phi_T = 0$ being defined by the trigger particle. Fig. 4b shows the distribution of dp_T^{bal}/dy^* when the trigger particle has $x_F > 0.5$. The corresponding distribution when the trigger particle has $-0.5 < x_F < -0.2$ is shown in fig. 4d. The estimated possible systematic effects are similar in magnitude to the statistical errors.

Also shown in fig. 4 are three curves computed using the Lund model with

- i) $\langle k_T^2 \rangle = (0.44 \text{ GeV})^2$, soft gluons included (solid line)
- ii) $\langle k_T^2 \rangle = (0.88 \text{ GeV})^2$, soft gluons excluded (dashed line)
- iii) $\langle k_T^2 \rangle = 0$, soft gluons included (dot-dashed line)

All of the three curves give an adequate description of the p_T behaviour of the trigger particle (figs. 4a and c). However, the large k_T^2 value alone (curve ii) gives a very poor description of the compensating p_T with the trigger particle in either the forward or backward directions (figs. 4b and d respectively). The conclusion that a large value of $\langle k_T^2 \rangle$ does not fit the data follows directly from QPM ideas without recourse to the Lund model because k_T represents a rotation of the event axis, thus leading to a compensating p_T in the opposite

hemisphere. However the inclusion of soft gluons, curves i) and iii), which give a compensation in the central rapidity region, provides a reasonable description of the data. The curve i), with $\langle k_T^2 \rangle = (0.44 \text{ GeV})^2$ reproduces the data somewhat better than curve iii) for which $\langle k_T^2 \rangle = 0$. Furthermore, the curve corresponding to the parameters of iii) fails to reproduce the behaviour of $\langle p_T^2 \rangle$ against x_F given in fig. 1 (not shown).

In conclusion a large asymmetry is observed in the values of $\langle p_T^2 \rangle$ between the forward (quark) and backward (target) hemispheres. The large $\langle p_T^2 \rangle$ in the forward direction is compensated mainly in the central rapidity region. The data cannot be explained by the large value of $\langle k_T^2 \rangle$ which, in the absence of soft gluons, is required to explain the values of $\langle p_T^2 \rangle$ in the forward direction. A lower, and physically more reasonable, value of $\langle k_T^2 \rangle$ plus soft gluon radiation effects describes the main features of the data found in the experiment. The existence of soft gluon radiation of this type further complicates the extraction of the QCD coupling constant α_s from the behaviour of the final state hadrons in leptonproduction and also, presumably, in e^+e^- annihilation.

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Figure Captions

Fig 1. Values of $\langle p_T^2 \rangle$ as a function of x_F for a) all charged hadrons, $h^\pm$ b) h^+ c) h^- . The errors shown are statistical only. The curves are computed using the Lund model [9] with the standard parameters (solid curve), with no 3-jet events (dashed curve), with no soft gluons (dot-dashed curve) and with no soft gluons but $\langle k_T^2 \rangle = (0.88 \text{ GeV})^2$ (dotted curve).

Fig 2. Distributions of $(1/N_{ev}) dN/dp_T^2$ for charged particles as a function of p_T^2 for different regions of x_F . The errors shown are statistical only. The curves are computed using the standard settings of the Lund model [9] with the solid curve being for negative x_F and the dashed curve for positive x_F .

Fig 3. $\langle p_T^2 \rangle$ versus x_F of charged hadrons for different intervals of a) x b) W^2 and c) Q^2 . The errors shown are statistical only. The curves are computed using the standard settings of the Lund model [9].

Fig 4. Distributions dP_T^{trig}/dy^* and dP_T^{bal}/dy^* when the trigger particle is in the range $x_F > 0.5$ ((a) and (b)) and $-0.5 < x_F < -0.2$ ((c) and (d)). The errors shown are statistical only. The curves are described in the text.

FIG. 1

FIG. 2

FIG. 3

FIG. 4 a,b

FIG. 4 c,d