EVIDENCE FOR PLANAR EVENTS AND A FORWARD DOUBLE JET STRUCTURE
IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration

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Abstract

The final states of charged hadrons produced in 280 GeV μp scattering are analysed with respect to their planarity and jet structure. Distributions of $p_{\perp in}^2$ and $p_{\perp out}^2$ are presented. A two jet structure in the forward hemisphere is observed for events with high $p_{\perp}$ tracks as predicted by QCD models.

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We reported recently on measurements of transverse momentum distributions of charged hadrons observed in deep inelastic μp scattering¹⁾. We showed that the observed rise of $\langle p_{\perp}^2 \rangle$ with $W^2 = s$ could be interpreted as being due to gluon emission as predicted by QCD²⁾. This interpretation of our data has also been suggested by theoretical work of Andersson et al.³⁾ and Dechantreiter et al.⁴⁾. The widening with W^2 of $p_{\perp}$ distributions of hadrons produced in deep inelastic lepton scattering has also been observed by neutrino scattering experiments^{5,6)}.

So far, however, no direct experimental evidence exists that the hadrons with high $p_{\perp}$, observed in deep inelastic scattering, are indeed associated to multi jet production. In the framework of perturbative QCD two forward hadron jets are to be expected due to either quark and gluon (fig. 1a,b) or quark and antiquark (fig. 1c) emission.

It is the purpose of this paper to investigate whether the events with high $p_{\perp}$ hadrons are indeed planar, as expected if the observed hadrons of the forward hemisphere are due to two forward going jets, and further whether this two jet structure manifests itself in the momentum flow observed. Similar phenomena have been observed in e^+e^- interactions⁷⁾. Although the acceptance is limited in the present experiment to the forward hemisphere, muon scattering allows the study of high $p_{\perp}$ phenomena in detail as high luminosities can be reached and the current direction is measured precisely by the primary and secondary muon and need not be reconstructed from the observed hadrons.

The experiment was performed in the muon beam of the SPS at CERN with a mean energy of 280 GeV. The muons, scattered in a 6m long hydrogen target, and the hadrons produced were measured in the EMC forward spectrometer⁸⁾. The apparatus, trigger and the track reconstruction criteria used are the same as described in 1). To reduce the contamination of the hadron sample by secondary interactions within the target, we required, as in 1), the event vertex to be in the downstream two metres of the target.

If p_{μ} , p_{μ}' are the four vectors of the primary and secondary muon and p_i and p_f those of the target proton and a final state hadron the following standard variables can be defined:

$$\begin{aligned}
 q &= p_\mu - p_\mu' \\
 -Q^2 &= q^2 = (p_\mu - p_\mu')^2 \\
 v &= (p_i \cdot q)/M = (E_\mu - E_\mu')_{\text{lab}} \\
 W^2 &= s = 2Mv + M^2 - Q^2 \\
 x &= Q^2/2Mv \\
 z &= (p_f \cdot p_i)/(q \cdot p_i) = E_h/v
 \end{aligned}$$

The transverse momentum $p_\perp$ of the hadrons is measured relative to the virtual photon or current direction $\vec{q}$.

For each event we define an event plane with normal $\vec{n}$, using the measured current direction $\vec{q}$ and the reconstructed hadron momenta by demanding that:

- (a) the plane contains the current direction $\vec{q}$,
- (b) the sum of the squares of the momentum components of all hadrons transverse to this plane, i.e.

$$\sum_h (\vec{p}_f \cdot \vec{n})^2 \equiv \sum_h p_{\perp \text{out}}^2$$

is minimised and hence $\sum_h p_{\perp \text{in}}^2$ is maximised, where the transverse momentum $\vec{p}_\perp$ of each hadron is decomposed in components $p_{\perp \text{out}}$ and $p_{\perp \text{in}}$ normal and parallel to this plane.

We will further consider the differential scaled energy flow $\frac{d\Sigma}{d\psi}$ and particle flow $\frac{dN}{d\psi}$ in the hadronic centre of mass system, where

$$\frac{d\Sigma}{d\psi} = \frac{1}{\sigma} \int z \frac{d\sigma}{dzd\psi}(z, \psi) dz.$$

The angle ψ is the azimuth around the normal $\vec{n}$ with $\psi = 0$ corresponding to the current direction. The sense of ψ is defined for each event such that the track with the largest $p_\perp$ has $\psi < 0$.

All results presented below are corrected for acceptance losses, chamber inefficiencies and resolution effects by a Monte Carlo simulation of the whole experiment. This included also electromagnetic radiation from the muons⁹⁾. The hadrons were generated according to a model of lepton nucleon scattering of Andersson et al.³⁾ which includes QCD matrix elements²⁾ to first order in $\alpha_s(Q^2)$ as shown in fig. 1 and quark

and gluon fragmentation into hadrons. The chosen parton distributions followed those of Buras and Gaemers¹⁰⁾. The experimental yield of each bin of the resulting distributions, presented below, was corrected by the ratio of the yields for generated and accepted Monte Carlo events.

The results correspond to $\sim 5 \cdot 10^{11}$ incident muons and are derived from 25k muon scattering events satisfying the conditions $100 \leq W^2 \leq 460$ GeV², $Q^2 > 3$ GeV², $\theta_\mu > 0.8^\circ$, $\nu < 260$ GeV and $E_\mu' > 20$ GeV. Hadrons were only considered if they were produced in the forward hemisphere of the centre of mass system and if they had momenta $p_{lab} > 6$ GeV. Furthermore for this analysis only those events were used which had at least 4 charged hadrons satisfying these conditions leaving a sample of 2.7k events.

Distributions of $\sum p_{\perp in}^2$ and $\sum p_{\perp out}^2$ with respect to the plane defined above are presented in fig. 2. They are normalised to the number of events satisfying the above conditions. The errors given are statistical errors only. In contrast to the distribution of $\sum p_{\perp out}^2$, which is rather limited, $\sum p_{\perp in}^2$ has a long tail extending well beyond 5 GeV². We compare in fig. 2 the data with the model of Andersson et al.³⁾ mentioned above, and we also show for comparison the prediction of this model with the QCD matrix elements suppressed, i.e. only a quark jet without hard gluon radiation is considered. Any model will predict $\sum p_{\perp out}^2$ to be smaller than $\sum p_{\perp in}^2$ due to the finite number of particles per event and due to momentum conservation. However, already at $\sum p_{\perp in}^2 \approx 4$ GeV² the experimental yield is more than ten times larger than the expectation for a single quark jet. If the gluon graphs are included the model describes the general behaviour of the data reasonably well. On the other hand, keeping a single quark jet, but increasing the width of the $p_\perp$ distribution $dN/dp_\perp^2 \sim \exp(-p_\perp^2/2\sigma_q^2)$ of the quarks in the jet cascade from $\sigma_q = 310$ MeV³⁾ to $\sigma_q = 470$ MeV results in a very poor description of the data.

In figs 3a and 4a we show scaled energy and particle flow diagrams, as defined above, for the forward hemisphere in the hadronic centre of mass system. The selection criteria for the events and tracks are the same as for the $\sum p_{\perp in, out}^2$ distributions. Most of the hadrons and even

more clearly most of the energy is contained in a narrow forward cone around the current direction $\vec{q}$ ($\psi = 0$). If we select a subsample of events where at least one hadron has $p_{\perp}^2 > 2 \text{ GeV}^2$, 124 events remain, and we see a two jet structure in the forward hemisphere (figs 3b, 4b). The range $\psi < 0$ contains the hadron with largest $p_{\perp}$ as defined above. Whereas this side contains much more energy than the opposite side (fig. 3b), the number of particles is roughly equal on each side and substantial also in the forward direction. The QCD model reproduces the particle and energy flow of the total of the events quite well (figs 3a, 4a) and describes qualitatively the main features of the events with a high $p_{\perp}$ hadron (figs 3b, 4b). The actual structure depends on the details of the quark and gluon fragmentation. According to the model only around 10% of the events with $p_{\perp}^2 > 2 \text{ GeV}^2$ in figs 3, 4 are due to quark jet fragmentation not involving hard gluon radiation, 60% of the events are due to quark gluon bremsstrahlung (figs 1a,b), the remaining 30% contain a quark and an anti-quark jet in the final state due to photon gluon fusion (fig. 1c). Some dip structure in the forward region is to be expected by transverse momentum conservation. We therefore compare again with the single forward, but broadened, quark jet ($\sigma_q = 470 \text{ MeV}$). In this case there is an excess of energy opposite to the large $p_{\perp}$ particle which is not supported by the data.

We compared our data also with the Monte Carlo program of Rumpf and Kramer¹¹⁾ which gives, also on the basis of QCD matrix elements to first order in α_s , very similar results to that of Andersson et al.³⁾.

We consider our results as support for the approach of perturbative QCD. The agreement with the models is not perfect, but no parameters of the Monte Carlo models have been fitted directly to the presented distributions. However, the surplus of energy flow for $\psi < 0$ from the Monte Carlo is sensitive to the distribution of primordial $k_{\perp}$, which has led us to choose a value of $\langle k_{\perp}^2 \rangle = 0.4 \text{ GeV}^2$. This is somewhat lower than the $\langle k_{\perp}^2 \rangle \approx 0.6 \text{ GeV}^2$ deduced from single particle spectra¹⁾ and may indicate an inadequacy in the models. The effective strong coupling constant α_s for the graphs in fig. 1 was chosen following the four flavour expression

$$\alpha_s(Q^2) = 12\pi/(25 \cdot \ln Q^2/\Lambda^2) \quad \text{with } \Lambda = 0.5 \text{ GeV}$$

leading to $\alpha_s = 0.34$ at $Q^2 = 20 \text{ GeV}^2$. A value of about this magnitude is

clearly needed to describe the distribution of $\sum p_{\perp i}^2$ in fig. 2. It is, to our knowledge, an open question to what extent the size of α_s needed for the first order description of high $p_{\perp}$ hadron jets, can be directly related to the value of Λ as determined from scaling violations of the structure function F_2 .

In conclusion, we observe in deep inelastic muon scattering planar events and patterns of energy and particle flow consistent with perturbative QCD.

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Figure Captions

Fig. 1 First order QCD graphs for muon nucleon scattering

- a), b) quark gluon bremsstrahlung,
- c) photon gluon fusion

Fig. 2 Distributions of $\sum p_{\perp in}^2$ and $\sum p_{\perp out}^2$ for events with > 4 charged hadrons with $p_{lab} > 6$ GeV.

Solid line: QCD-model of Andersson et al.³⁾

Dashed line: Single quark jet fragmentation, $\sigma_q = 310$ MeV

Dashed-dotted line: Single quark jet fragmentation, $\sigma_q = 470$ MeV.

Fig. 3 Scaled energy flow $d\Sigma/d\psi$.

Solid line: QCD-model of Andersson et al.³⁾

Broken line: Single quark jet fragmentation, $\sigma_q = 470$ MeV.

a) events with > 4 charged hadrons with $p_{lab} > 6$ GeV

b) subsample with > 1 charged hadron with $p_{\perp}^2 > 2$ GeV².

Fig. 4 As fig. 3 for particle flow $dN/d\psi$.

a

b

c

Fig.1

FIG. 2

$\mu p, 280 \text{ GeV}$

$100 \leq W^2 \leq 460 \text{ GeV}^2$

$Q^2 > 3 \text{ GeV}^2$

$\geq 4 \text{ charged hadrons}$

$P_{\text{lab}} \geq 6 \text{ GeV}$

FIG. 3

μp , 280 GeV

$100 \leq W^2 \leq 460 \text{ GeV}^2$

$Q^2 > 3 \text{ GeV}^2$

≥ 4 charged hadrons

$p_{\text{lab}} \geq 6 \text{ GeV}$

FIG. 4