MEASUREMENT OF HADRONIC AZIMUTHAL DISTRIBUTIONS IN
DEEP INELASTIC MUON PROTON SCATTERING

The European Muon Collaboration

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ABSTRACT

Results on moments of the azimuthal angle φ of final state hadrons from 120 GeV and 280 GeV μp scattering are presented. A φ asymmetry is observed and its W^2 , Q^2 , z and p_T dependences compared with model calculations which include intrinsic transverse momentum and first order QCD corrections. These studies indicate that the observed asymmetry is mainly due to intrinsic transverse momentum k_T .

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A measurement of the azimuthal asymmetry of final state hadrons in deep inelastic lepton scattering offers, in principle, the possibility of testing perturbative QCD predictions [1]. However, direct experimental tests are difficult because of non-perturbative effects such as intrinsic transverse momentum k_T [2,3] and fragmentation. Previously published results on the azimuthal asymmetry as measured by neutrino scattering [4] and muon proton scattering [5] do not have the statistical significance of this experiment. The data reported here consist of about 100,000 events obtained by scattering 280 GeV and 120 GeV muons on a liquid hydrogen target.

The normalised multiplicity $\frac{1}{N_\mu} \frac{dN^{h^\pm}}{d\varphi}$ where φ is the azimuthal angle of a charged hadron around the virtual photon direction can be described by the following formula:

$$\begin{aligned} \frac{1}{N_\mu} \frac{dN^{h^\pm}}{d\varphi} &= \frac{1}{d\sigma/(dx dy)} \frac{d\sigma^{h^\pm}}{dx dy d\varphi} \\ &= a + f_1(y)b \cos\varphi + f_2(y)c \cos 2\varphi - f_3(y)d P \sin\varphi. \end{aligned}$$

$$\cos\varphi = \frac{\vec{p}_\mu \times \vec{q}}{|\vec{p}_\mu \times \vec{q}|} \cdot \frac{\vec{p}_h \times \vec{q}}{|\vec{p}_h \times \vec{q}|} \quad \text{with } \vec{p}_\mu, \vec{p}_h \text{ and } \vec{q} \text{ being}$$

the three-momenta of the incident muon, the produced hadron, and the exchanged photon respectively. The definition of the other variables is the same as for example in [6].

The last term reflects the fact that the positive muon beam has a longitudinal polarization P , which is about -0.8 at 280 GeV. The functions $f_1(y)$ to $f_3(y)$ describe the kinematic dependences on y , the energy fraction of the virtual photon

$$f_1(y) = \frac{(2-y)\sqrt{1-y}}{1 + (1-y)^2}, \quad f_2(y) = \frac{1-y}{1 + (1-y)^2}, \quad f_3(y) = \frac{y\sqrt{1-y}}{1 + (1-y)^2}.$$

The quantities a to d depend on the muon and hadron variables and describe the absorption cross sections of transverse unpolarized and longitudinal polarized virtual photons (a), the interference between the two transverse polarizations of the photon (c), and the interference between linear polarized transverse

and longitudinal photons (b is the real part and d the imaginary part). The first moments of $\cos\varphi$, $\cos 2\varphi$ and $\sin \varphi$ are connected with a, b and c by

$$\langle \cos\varphi \rangle = \frac{b}{2a} f_1(y),$$

$$\langle \cos 2\varphi \rangle = \frac{c}{2a} f_2(y), \text{ and}$$

$$\langle \sin\varphi \rangle = \frac{d}{2a} P f_3(y).$$

The apparatus used consisted of a large open dipole spectrometer with proportional and drift chambers and has been fully described elsewhere [7]. It is important for the measurements described here to note that the momenta and directions of both incident and scattered muons were well measured giving accurate knowledge of the virtual photon direction.

In the data analysis chain, reconstructed hadrons were selected and associated with the muon vertex according to the same criteria as in [6]. The acceptance of the apparatus was determined by a Monte Carlo calculation including also radiative corrections, which introduce a systematic change of the four-momentum of the virtual photon q , and therefore also of the φ measurement. To avoid the large corrections at high y the region $y > 0.8$ was excluded. For a good φ definition only hadrons with a transverse momentum $p_T > 200$ MeV were used. The systematic errors were estimated by determining the φ moments in different parts of the apparatus. These errors include also effects of measurement errors which have been simulated by Monte Carlo calculations. The combined systematic errors were kept to a tolerable level by applying cuts which are summarized in table 1 for the 280 GeV (120 GeV) data.

Table 1

$Q_{\min}^2$ [GeV ²]	5 (2)	$y_{\max}$	0.8
$Q_{\max}^2$ [GeV ²]	100 (60)	$w_{\min}^2$ [GeV ²]	160 (60)
$p_{\mu', \min}$ [GeV]	40 (20)	$z_{\min}$	0.15
$\theta_{\mu', \min}$ [mrad]	10 (10)	$p_{T \min}$ [GeV]	0.2

A typical φ distribution for 280 GeV is shown in fig. 1. Since these distributions have been measured over the whole range of the azimuthal angle we are able to determine the three φ moments mentioned above. In order to compare these moments for different muon kinematics, the y dependences have been taken out, i.e. results are given for $\langle \cos\varphi \rangle / f_1(y)$, $\langle \cos 2\varphi \rangle / f_2(y)$, and $\langle \sin\varphi \rangle / f_3(y)$. Figs. 2(a-c) show the Q^2 dependence of the moments $\langle \cos\varphi \rangle / f_1(y)$ and $\langle \cos 2\varphi \rangle / f_2(y)$ for 3 bins of W^2 for $z > 0.2$. The lowest bin $60 \leq W^2 < 160 \text{ GeV}^2$ is a result of the analysis of the 120 GeV data. The higher bins $160 \leq W^2 < 260 \text{ GeV}^2$ and $260 \leq W^2 < 460 \text{ GeV}^2$ are from 280 GeV muons.

Taking into account the systematic uncertainties of this moments analysis, which are approximately ± 0.06 for the lowest Q^2 bin and ± 0.04 for the other Q^2 -bins, there is no significant Q^2 dependence in the moments. The $\cos\varphi$ moments are clearly negative, the $\cos 2\varphi$ and $\sin\varphi$ moments (not shown in the figures) are zero within the errors. Integrating over Q^2 for $z > 0.2$ and $p_T > 200 \text{ MeV}$ one obtains the results given in Table 2.

Table 2

$\langle W^2 \rangle$	$\langle \cos\varphi \rangle / f_1(y)$	$\langle \cos 2\varphi \rangle / f_2(y)$	$\langle \sin\varphi \rangle / f_3(y)$
100 GeV^2	-0.11 ± 0.02	$+0.03 \pm 0.03$	0.00 ± 0.04
205 GeV^2	-0.09 ± 0.02	$+0.06 \pm 0.03$	$+0.02 \pm 0.05$
325 GeV^2	-0.18 ± 0.02	$+0.01 \pm 0.04$	$+0.03 \pm 0.05$

In addition the systematic error is about ± 0.05 for the moments in the above table.

In fig. 3 the $\cos\varphi$ and $\cos 2\varphi$ moments are shown as a function of z for $Q^2 > 2 \text{ GeV}^2$ in the W^2 range $60 \leq W^2 < 160 \text{ GeV}^2$ from 120 GeV data and for $Q^2 > 10 \text{ GeV}^2$ in the W^2 range $160 \leq W^2 < 360 \text{ GeV}^2$ from 280 GeV data. From these data we see that the magnitude of $\langle \cos\varphi \rangle$ increases with z . This cannot be explained by systematic uncertainties.

The data in figs. 2 and 3 are compared with theoretical calculations of A. König and P. Kroll [8]. In this model, which is also similar to that of A.S. Joshipura and G. Kramer [9], the azimuthal asymmetry was calculated using first order QCD corrections to the quark parton model, including intrinsic transverse momentum k_T . The fragmentation was simulated by two different Monte Carlo models [10], which gave no significant difference in the z range covered by the data. The curves shown in the figures were calculated with a value of the strong interaction coupling $\alpha_s \approx 0.34$, and of $\langle k_T \rangle = 0.7 \text{ GeV}^{*})$ which describe well the p_T spectra of the EMC data [11], an average transverse momentum in the fragmentation cascade $\langle \sigma_q \rangle = 0.31 \text{ GeV}$, and a ratio of vector to scalar particles 1:1. The trend of the data is reproduced by the calculations.

As has been pointed out in [8], there is a large reduction of the asymmetry due to fragmentation. The (pure) first order QCD-effect does not provide a clean test of QCD in the present energy range. The calculated $\cos\phi$ asymmetry for the partons arising from these QCD effects is about -0.14 in the discussed kinematic region in agreement with previous calculations [13]. Fragmentation reduces this to -0.02 for the observed hadrons. Therefore changing α_s does not significantly change the result of the model. On the other hand varying $\langle k_T \rangle$ by $\pm 0.3 \text{ GeV}$ changes the prediction by about $\pm 50\%$. The model calculation therefore indicates that the observed asymmetries at present energies are mainly sensitive to an intrinsic transverse momentum as was suggested by Cahn [3].

The $\cos\phi$ moment is shown as a function of the transverse momentum of the observed hadrons in fig. 4. For very small p_T ($50 \text{ MeV} < p_T < 200 \text{ MeV}$) the asymmetry is small but increases for growing p_T . This effect, which is also reproduced by the model, is presumably due to dilution of the basic asymmetry at low p_T by fragmentation and provides an additional justification for the cut $p_T > 200 \text{ MeV}$ applied to the other distributions.

In conclusion a finite $\langle \cos\phi \rangle$ has been observed in deep inelastic muon scattering. The sign of the effect is negative and shows little Q^2

*) It may be that this value of $\langle k_T \rangle$ effectively includes soft gluon emission [12]. However, no explicit calculation of the ϕ dependence from this source exists.

or W^2 dependence. There is a significant increase of the asymmetry as a function of z and p_T . The general trend of the data is reproduced by a model containing a large effective intrinsic momentum. A contribution from leading order QCD cannot be excluded but is at present not required by the data.

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FIGURE CAPTIONS

Fig. 1 φ distribution from 280 GeV data for $p_T > 200$ MeV. The curve shows the result of the fit.

Fig. 2 Q^2 -dependence of φ moments for 3 different W^2 -bins for $z > 0.2$ and $p_T > 200$ MeV. The data are compared with model calculations described in [8] (statistical errors on model curves from Monte Carlo are ± 0.03 ; not shown).

- a) $60 \leq W^2 < 160 \text{ GeV}^2$ from 120 GeV data
- b) $160 \leq W^2 < 260 \text{ GeV}^2$ and
- c) $260 \leq W^2 < 460 \text{ GeV}^2$ from 280 GeV data.

Fig. 3 z -dependence of φ moments for 2 W^2 -bins and $p_T > 200$ MeV, compared with model calculations described in [8] (statistical errors on model curves from Monte Carlo ± 0.02 not shown).

- a) $60 \leq W^2 < 160 \text{ GeV}^2$ for $Q^2 > 2 \text{ GeV}^2$ from 120 GeV data
- b) $160 \leq W^2 < 360 \text{ GeV}^2$ for $Q^2 > 10 \text{ GeV}^2$ from 280 GeV data

Fig. 4 p_T -dependence ($p_T > 50$ MeV) of $\cos\varphi$ moment for $160 \leq W^2 < 360 \text{ GeV}^2$, $Q^2 > 10 \text{ GeV}^2$ and $z > 0.15$ compared with model calculations described in [8] (statistical errors on model curve from Monte Carlo ± 0.03 not shown).

Fig. 1

a)

b)

c)

Fig. 2

Fig. 3

Fig. 4