Azimuthal asymmetries in deep inelastic scattering at HERA

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Abstract. The distribution of the azimuthal angle of charged and neutral hadrons has been studied in the hadronic centre-of-mass system for neutral current deep inelastic *ep* scattering with the ZEUS detector at HERA using an integrated luminosity of 45.21 pb^{-1}. Measurements of the dependence of the moments of the azimuthal distribution on the pseudorapidity and minimum transverse energy of the final state hadrons are presented using the energy flow method.

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INTRODUCTION

The investigation of the semi-inclusive process $ep \to ehX$ in deep inelastic scattering (DIS), where h is an observed hadron, addresses an important prediction of perturbative Quantum Chromodynamics (pQCD) in the description of hadron production. It is of interest to investigate the distribution of the azimuthal angle of the detected hadrons around the virtual photon direction in the hadronic centre-of-mass frame (HCM). The azimuthal angle ϕ, is defined as the angle between the hadron production plane and the lepton scattering plane (Figure 1a).

The azimuthal dependence of hadron production has the form [1, 2, 3] as

$$\frac{d\sigma}{d\phi} = \mathscr{A} + \mathscr{B}\cos\phi + \mathscr{C}\cos 2\phi \tag{1}$$

where the azimuthal asymmetries, defined as parameters $\mathscr{B}$ and $\mathscr{C}$, can be evaluated experimentally. They are extracted from experimental data by calculating statistical moments for experimental distributions of the respective trigonometrical functions of ϕ:

$$\langle\cos\phi\rangle = \frac{\mathscr{B}}{2\mathscr{A}} \qquad \langle\cos 2\phi)\rangle = \frac{\mathscr{C}}{2\mathscr{A}} \tag{2}$$

For neutral current deep inelastic scattering interactions NC DIS with an unpolarised lepton beam the $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ values are of the order of a few percent [4, 5].

Azimuthal asymmetries, (2) exist only if the the final state hadron has transverse momentum. The higher order QCD processes such as QCD-Compton QCDC and boson-gluon fusion BGF are the main source of these hadrons. These two processes have a different ϕ behaviour as described in [6] as well as a different rapidity dependence. The rapidity or pseudorapidity η^{HCM} is defined here w.r.t. the incoming proton direction. Hadrons from BGF and QCDC dominate over hadrons from the zeroth order DIS process in the region $-4 < \eta^{\text{HCM}} < 0$. In addition the gluons and quarks from the QCD Compton process populate different region of rapidity. The coefficient $\mathscr{B}$ has an opposite sign for gluons and quarks, thus motivating a study of the azimuthal asymmetry as a function of rapidity η^{HCM}.

Chay, Ellis and Stirling [2] proposed analysing the asymmetry as a function of the detected hadron's transverse momentum cutoff $p_{\text{T cut}}$. This is equivalent to removal of the zeroth order QCD processes and a selection of leading hadrons produced directly from the scattered partons. Consequently at higher $p_{\text{T cut}}$ values a better agreement should be obtained with the perturbative QCD predictions that suggest the coefficient $\mathscr{C}$ to be always positive and larger for higher $p_{\text{T cut}}$ values.

Asymmetries in the ϕ distribution arise whenever a non-zero transverse momentum is presented in the scattering process in the HCM frame. Thus the perturbative azimuthal asymmetry originates in the first and higher order QCD processes and is observable in single particle production because the high-energy hadrons are produced close to the direction of the scattered hard partons. The transverse momenta arising from parton hadronisation does not contribute to the asymmetry but smears the observed distribution. The energy flow method enhances the contribution of the hard hadrons and is used here to calculate the mean values (2). In this method the direction of each particle h in the final state is weighted with its transverse energy. The range of the investigated phase space is increased with respect to the previous studies [4, 5].

DATA SAMPLE

The experimental results are based on the data collected in 1995-97 with the ZEUS detector at the HERA collider with protons of energy 820 GeV. Electrons of energy 27.5 GeV are longitudinally unpolarised. Neutral current deep inelastic scattering events have been selected from the data corresponding to an integrated luminosity of 45.21 pb^{-1}. ZEUS is a multipurpose detector described in detail elsewhere [7].

Particles in the final state were reconstructed by combining information from tracking and calorimeter in the ZEUS detector, as energy flow objects [8]. The selection criteria were based on the earlier ZEUS investigation [4]. The main cuts were:

- the event had an identified scattered positron with energy $E_{e'} > 10$ GeV;
- in order to define the phase space of the measurement, the event was required to have $100 < Q^2 < 8000$ GeV^2, $0.2 < y < 0.8$ and $0.01 < x < 0.1$. The double angle method was used to reconstruct these variables [9];
- the reconstructed hadrons (charged and neutral particles) were required to have their transverse momenta $p_{\text{T}}^{\text{LAB}} > 150$ MeV. These cuts excluded hadrons contained within the beam pipe or failing to traverse sufficient layers of the tracker to ensure good reconstruction.

CORRECTION PROCEDURE

Monte Carlo (MC) events were used to correct the data for detector inefficiences. The detector simulation is based on the GEANT 3.13 program [10]. Neutral current

(NC) events with electroweak radiative corrections came from the LEPTO 6.5.1 code interfaced to HERACLES 4.6.1 [11] via the DJANGOH 1.1 code [12]. High order QCD processes were simulated using the MEPS option of LEPTO.
A second sample of NC DIS Monte Carlo events was generated with ARIADNE 4.10 [13] where the QCD cascade came from the colour-dipole model. In all cases, the events have been generated using the CTEQ4D next-to-leading order parton density parametrization of the proton. The final state parton system was hadronised using the LUND string model as implemented in JETSET 7.4.10 [14].

The correction factor for ϕ was defined as the ratio of energy flow of hadrons, $E(\phi^{MC}_{had})$, to energy flow detected, $E(\phi^{MC}_{det})$, i.e. $F^{MC}(\phi) = \frac{E(\phi^{MC}_{had})}{E(\phi^{MC}_{det})}$. The corrected integrated energy flow $E(\phi)$ was determined separately bin-by-bin for each region in the η-ϕ plane as $E(\phi^{DATA}) = F^{MC}(\phi) \cdot E(\phi^{DATA}_{det})$.

RESULTS

The measured azimuthal asymmetries in terms of the mean values of the trigonometrical functions which appear in the functional form (1) for the differential cross section for $ep \to ehX$ are presented in Figure 1b as a function of pseudorapidity η^{HCM} and in Figure 2 as the minimum transverse energy $\mathrm{E}_{\mathrm{T}}^{\mathrm{HCM}}$ (min) into three regions of η^{HCM}: $-5 < \eta^{\mathrm{HCM}} < -2.5$, $-2.5 < \eta^{\mathrm{HCM}} < -1$ and $-1 < \eta^{\mathrm{HCM}} < 0$.

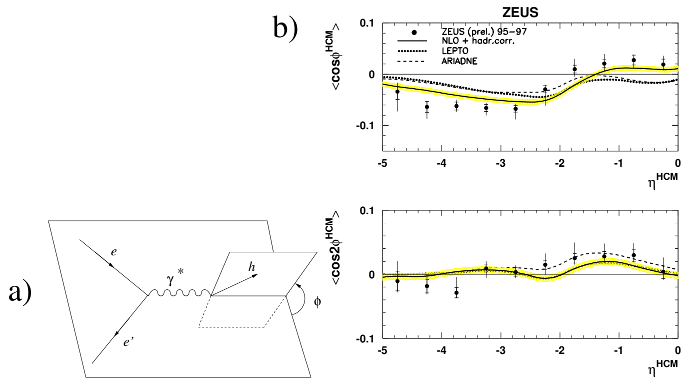

FIGURE 1. a) The definition of the azimuthal angle ϕ; b) The values of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ and $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ are shown as a function of hadron η^{HCM} obtained using the energy flow method.

Figure 1b shows that the mean value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ is negative for $\eta^{\mathrm{HCM}} < -2$ and becomes positive for larger η^{HCM}. This is in disagreement with the LO predictions that are negative throughout the measured η^{HCM} range. The measured $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are consistent with zero for for $\eta^{\mathrm{HCM}} < -2$ and are positive for higher values of η^{HCM}. This is consistent with the LO expectations from both LEPTO and ARIADNE.

In region $-5 < \eta^{\mathrm{HCM}} < -2.5$ (Figure 2a) the main contribution to azimuthal asymmetry comes from QCD Compton $\gamma q \to gq$ and arises from hadrons coming from quark fragmentation. This analysis confirms that the value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ is more negative than expected from the LO predictions. The $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are small and in agreement with both LEPTO and ARIADNE.

The region $-2.5 < \eta^{\mathrm{HCM}} < -1$ (Figure 2b) is that with an increasing contribution from boson-gluon fusion. The results presented here confirm a small value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ and positive values for $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ for all $\mathrm{E}_{\mathrm{T}}^{\mathrm{HCM}}(\mathrm{min})$. The LO predictions of LEPTO and ARIADNE are in good agreement with data.

The third region $-1 < \eta^{\mathrm{HCM}} < 0$ (Figure 2c) is populated equally by hadrons from QCD Compton and from boson-gluon fusion processes. The $\langle\cos\phi^{\mathrm{HCM}}\rangle$ values are positive, contrary to LO predictions, whereas the $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are positive and in agreement with LO predictions.

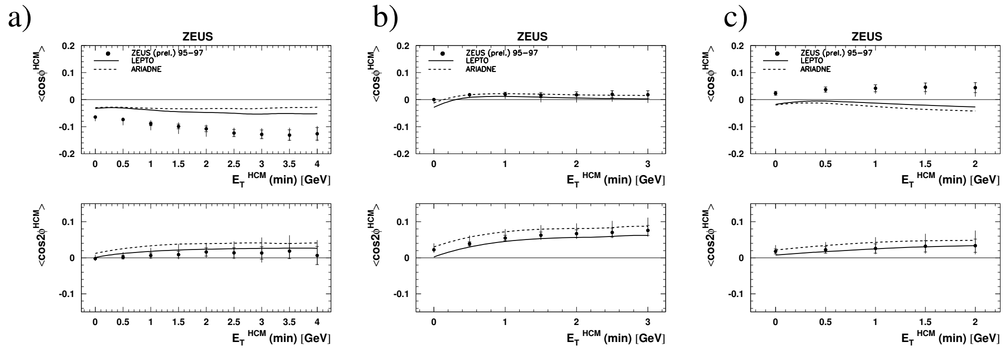

FIGURE 2. The values of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ and $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ are shown as a function of hadron minimum transverse energy $\mathrm{E}_{\mathrm{T}}^{\mathrm{HCM}}$ (min) in the HCM for a) $-5 < \eta^{\mathrm{HCM}} \leq -2.5$; b) $-2.5 < \eta^{\mathrm{HCM}} \leq -1$; c) $-1 < \eta^{\mathrm{HCM}} \leq 0$

CONCLUSIONS

Azimuthal asymmetries are investigated as a function of hadron pseudorapidity in the hadronic centre-of-mass frame. The $\langle\cos\phi^{\mathrm{HCM}}\rangle$ values are not described by LO predictions. The $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are only significant in the region $\eta^{\mathrm{HCM}} > -2.5$ when high minimum transverse momentum is selected for hadrons.

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