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# Study of the azimuthal asymmetry of jets in neutral current deep inelastic scattering at HERA

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## Abstract

The azimuthal distribution of jets produced in the Breit frame in high-$Q^2$ deep inelastic $e^+p$ scattering has been studied with the ZEUS detector at HERA using an integrated luminosity of 38.6 pb$^{-1}$. The measured azimuthal distribution shows a structure that is well described by next-to-leading-order QCD predictions over the $Q^2$ range considered, $Q^2 > 125$ GeV$^2$.

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## 1. Introduction

Jet production in neutral current (NC) deep inelastic scattering (DIS) at high $Q^2$ (where $Q^2$ is the negative of the virtuality of the exchanged boson) provides a testing ground for the theory of the strong interaction between quarks and gluons, namely, quantum chromodynamics (QCD). An observable of interest is $\phi^{\rm B}_{\rm jet}$, the azimuthal angle in the Breit frame [1] between the lepton scattering plane, defined by the incoming and outgoing lepton momenta, and the jets produced with high transverse energy ($E^{\rm B}_{T,\rm jet}$) in that frame.

In the Standard Model, azimuthal asymmetries arising from perturbative QCD effects [2–4] are expected in the $\phi^{\rm B}_{\rm jet}$ distribution. At leading order (LO), the azimuthal dependence for unpolarised NC DIS at $Q^2 \ll M_Z^2$ has the form

$$\frac{d\sigma}{d\phi^{\rm B}_{\rm jet}} = A + B\cos\bigl(\phi^{\rm B}_{\rm jet}\bigr) + C\cos\bigl(2\phi^{\rm B}_{\rm jet}\bigr). \qquad (1)$$

The current–current form of the electromagnetic interactions makes the cross section linear in $\cos(\phi^{\rm B}_{\rm jet})$, $\cos(2\phi^{\rm B}_{\rm jet})$, $\sin(\phi^{\rm B}_{\rm jet})$ and $\sin(2\phi^{\rm B}_{\rm jet})$. However, the coefficients of the terms in $\sin(\phi^{\rm B}_{\rm jet})$ and $\sin(2\phi^{\rm B}_{\rm jet})$ vanish due to time-reversal invariance and the absence of final-state interactions at the quark–gluon level at LO. The coefficients $A$, $B$ and $C$ result from the convolution of the matrix elements for the partonic processes with the parton distribution functions (PDFs) of the proton [3,4]. The $\cos(2\phi^{\rm B}_{\rm jet})$ term is expected from the interference of amplitudes arising from the $+1$ and $-1$ helicity components of the transversely polarised part of the exchanged photon, whereas the interference between the transverse and longitudinal components gives rise to the $\cos(\phi^{\rm B}_{\rm jet})$ term. In addition, a non-perturbative contribution to the asymmetry arises from the intrinsic transverse momentum of partons in the proton. Since such intrinsic transverse momenta are small [5], this contribution is expected to be negligible for jet production at high $E^{\rm B}_{T,\rm jet}$ [6].

Previous studies of single hadron production in NC DIS observed a $\cos\phi$ term that was attributed to non-perturbative effects [7]. However, more recently, a ZEUS measurement of the azimuthal dependence of charged hadrons with high transverse momentum in the centre-of-mass system gave evidence for perturbative contributions to the azimuthal asymmetry [8]. This Letter presents the first study of the azimuthal distribution of jets with high transverse energy in the Breit frame and the comparison with LO and next-to-leading-order (NLO) QCD predictions.

## 2. Experimental details

These results are based on data collected in 1996–1997 with the ZEUS detector at HERA, corresponding to an integrated luminosity of $38.6 \pm 0.6$ pb$^{-1}$. The HERA rings were operated with protons of energy $E_p = 820$ GeV and positrons of energy $E_e = 27.5$ GeV. The ZEUS detector is described elsewhere [9,10]. The main components used in the present analysis are the central tracking detector [11], positioned in a 1.43 T solenoidal magnetic field, and the uranium-scintillator sampling calorimeter (CAL) [12]. The tracking detector was used to establish an interaction vertex. The CAL covers 99.7% of the total solid angle. It is divided into three parts with

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a corresponding division in the polar angle,[53] $\theta$, as viewed from the nominal interaction point: forward (FCAL, $2.6^\circ < \theta < 36.7^\circ$), barrel (BCAL, $36.7^\circ < \theta < 129.1^\circ$), and rear (RCAL, $129.1^\circ < \theta < 176.2^\circ$). The smallest subdivision of the CAL is called a cell. Under test-beam conditions, the CAL relative energy resolution is $18\%/\sqrt{E(\mathrm{GeV})}$ for electrons and $35\%/\sqrt{E(\mathrm{GeV})}$ for hadrons. A three-level trigger was used to select the events online [10].

As the analysis follows very closely that of the inclusive jet cross sections in the Breit frame [13], details about the event selection, jet finding, systematic uncertainties and theoretical predictions are not repeated here.

The scattered-positron candidate was identified from the pattern of energy deposits in the CAL [14]. The kinematic region of the analysis was selected by the requirements $Q^2 > 125\ \mathrm{GeV}^2$ and $-0.7 < \cos\gamma < 0.5$, where $\gamma$ is the angle of the scattered quark in the quark–parton model. Cuts on this angle restrict the phase-space selection in Bjorken $x$ and the inelasticity $y$ due to the relation

$$\cos\gamma = \frac{(1-y)xE_p - yE_e}{(1-y)xE_p + yE_e}.$$

The longitudinally invariant $k_T$ cluster algorithm [15] was used in the inclusive mode [16] to reconstruct the jets in the hadronic final state both in data and in events simulated by Monte Carlo (MC) techniques. In data, the algorithm was applied to the energy deposits measured in the CAL cells after excluding those associated with the scattered-positron candidate. The jet search was performed in the pseudorapidity ($\eta^{\mathrm{B}}$)–azimuth ($\phi^{\mathrm{B}}$) plane of the Breit frame, where $\phi^{\mathrm{B}} = 0$ corresponds to the direction of the scattered positron. The transverse energy of the jets in the Breit frame, $E^{\mathrm{B}}_{T,\mathrm{jet}}$, was required to be larger than 8 GeV and the pseudorapidity range was restricted to $-2 < \eta^{\mathrm{B}}_{\mathrm{jet}} < 1.8$. The data sample contained 8523 events, 5073 of which were one-jet, 3262 two-jet, 182 three-jet and 6 four-jet events. The $Q^2$ range covered by the data sample extended up to $Q^2 \sim 16\,000\ \mathrm{GeV}^2$; measurements of the azimuthal distribution are presented up to a mean $Q^2$ value of $\sim 2300\ \mathrm{GeV}^2$.

## 3. Monte Carlo studies and systematic uncertainties

Samples of events were generated to determine the response of the detector to jets of hadrons and to calculate the correction factors necessary to obtain the hadron-level jet cross sections. The generated events were passed through the GEANT 3.13-based [17] ZEUS detector- and trigger-simulation programs [10] and were reconstructed and analysed by the same program chain as the data. The NC DIS events were generated using the LEPTO 6.5 program [18] interfaced to HERACLES 4.6.1 [19] via DJANGOH 1.1 [20]. The HERACLES program includes photon and $Z$ exchanges and first-order electroweak radiative corrections. The QCD cascade was modelled with the ARIADNE 4.08 program [21]. The CTEQ4D [22] parameterisations of the proton PDFs were used. As an alternative, samples of events were generated using the model of LEPTO based on first-order QCD matrix elements plus parton showers (MEPS). In both cases, fragmentation into hadrons was performed using the JETSET 7.4 program [23]. In these programs, the azimuthal distribution was generated according to the LO QCD calculation.

The jet search was performed on the MC events using the energy measured in the CAL cells in the same way as for the data. The same jet algorithm was also applied to the hadrons in simulated events. The comparison of the reconstructed jet variables for the hadronic and the calorimetric jets in simulated events showed that no correction was necessary for $\phi^{\mathrm{B}}_{\mathrm{jet}}$ and that the average resolution was 0.09 radians. The sample of events generated with either ARIADNE or LEPTO-MEPS, after applying the same offline selection as for the data, gave a good description of the measured distributions for both the event and jet variables [13,24]. However, a MC sample of events generated with a uniform azimuthal distribution did not describe the observed $\phi^{\mathrm{B}}_{\mathrm{jet}}$ distribution at detector level. These comparisons establish the presence of an azimuthal modulation in the data.

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[53] The ZEUS coordinate system is a right-handed Cartesian system, with the $Z$ axis pointing in the proton beam direction, referred to as the "forward direction", and the $X$ axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point. The pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, where the polar angle $\theta$ is taken with respect to the proton beam direction.

The cross sections presented here were corrected to the hadron level by applying bin-by-bin corrections to the measured distributions. The correction factors had some dependence on $\phi^{\mathrm{B}}_{\mathrm{jet}}$ due to the cuts applied to remove the effects of QED radiation that lead to a radiated photon from the positron being misidentified as a hadronic jet. The observed $\phi^{\mathrm{B}}_{\mathrm{jet}}$ dependence of the correction factor was not sensitive to the assumed azimuthal distribution in the generator; this was confirmed by the observation that the correction factors based on the MC sample generated with a uniform azimuthal distribution had the same dependence on $\phi^{\mathrm{B}}_{\mathrm{jet}}$. The MC programs were also used to evaluate the corrections for QED radiative effects, which were negligible for the normalised cross sections.

A detailed study of the systematic uncertainties was carried out. Those that had an effect on the shape of the azimuthal distribution were:

- the uncertainty in the absolute energy scale of the jets;
- the uncertainty in the MC modelling of the hadronic final state, which was estimated from the differences between ARIADNE and LEPTO-MEPS in correcting the data for detector effects;
- the uncertainty in the positron identification, which was estimated by repeating the analysis using an alternative technique [25] to select the scattered-positron candidate.

The relative changes in the normalised differential cross section induced by the variations mentioned

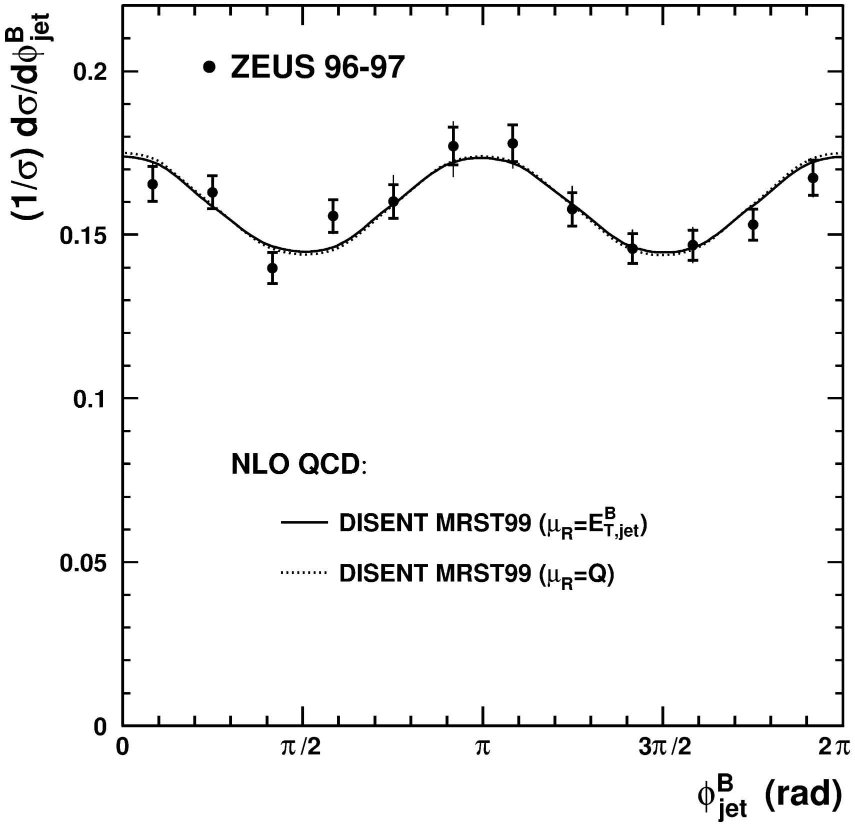

Fig. 1. The normalised differential cross section $(1/\sigma)\, d\sigma/d\phi^{\mathrm{B}}_{\mathrm{jet}}$ for inclusive jet production with $E^{\mathrm{B}}_{T,\mathrm{jet}} > 8$ GeV and $-2 < \eta^{\mathrm{B}}_{\mathrm{jet}} < 1.8$ (points). The inner error bars represent the statistical uncertainty. The outer error bars show the statistical and systematic uncertainties added in quadrature. The NLO QCD calculations using DISENT and the MRST99 parameterisations of the proton PDFs are shown for two choices of the renormalisation scale.

above were typically smaller than the statistical uncertainties, which ranged from $\sim 2\%$ at $Q^2 \sim 125\ \mathrm{GeV}^2$ up to 6% at $Q^2 \sim 1000\ \mathrm{GeV}^2$.

## 4. Perturbative QCD calculations

The LO and NLO QCD predictions were obtained using the program DISENT [26]. The number of flavours was set to five and the renormalisation ($\mu_\mathrm{R}$) and factorisation ($\mu_\mathrm{F}$) scales were chosen to be $\mu_\mathrm{R} = E^\mathrm{B}_{T,\mathrm{jet}}$ and $\mu_\mathrm{F} = Q$, respectively. The strong coupling constant, $\alpha_s$, was calculated at two loops with $\Lambda^{(5)}_{\overline{\mathrm{MS}}} = 220$ MeV, corresponding to $\alpha_s(M_Z) = 0.1175$. The calculations were performed using the MRST99 [27] parameterisations of the proton PDFs. The results obtained with DISENT were cross-checked by using the program DISASTER++ [28]. The differences were always smaller than 1%.

The perturbative QCD contribution to the terms $B$ and $C$ in Eq. (1) is large. At LO in $\alpha_s$, two processes contribute to jet production in the Breit frame: QCD-Compton scattering (QCDC, $\gamma^* q \to qg$) and photon-gluon fusion (PGF, $\gamma^* g \to q\bar{q}$). For the former, the scattered gluon (quark) preferentially appears at $\phi^\mathrm{B}_\mathrm{jet} = 0\ (\pi)$, whilst for the PGF process, the $\phi^\mathrm{B}_\mathrm{jet}$ dependence is dominated by the $\cos(2\phi^\mathrm{B}_\mathrm{jet})$ term and is very similar for quarks and antiquarks. Thus, the different contributions to the $\cos(\phi^\mathrm{B}_\mathrm{jet})$ term from quarks and gluons tend to cancel in the $\cos(\phi^\mathrm{B}_\mathrm{jet})$ asymmetry and the predicted azimuthal distribution is very close to $A + C\cos(2\phi^\mathrm{B}_\mathrm{jet})$. The NLO QCD correction mainly modifies the normalisation and slightly affects the shape of this prediction. In order to test the QCD prediction for the azimuthal distribution, it is desirable that no cut be applied to the jets in the laboratory frame; otherwise, the azimuthal distribution can be strongly distorted by kinematic effects [4]. For this reason, no such cut was used in the definition of the cross sections.

Since the measurements refer to jets of hadrons, whereas the perturbative QCD calculations refer to partons, the hadronisation effects were investigated by using the models of ARIADNE, LEPTO-MEPS and HERWIG [29]. These effects were negligible [24]. The effects of an intrinsic transverse momentum of partons in the proton, which were modelled according to a two-dimensional Gaussian of width $k_0$ in ARIADNE, were estimated by varying $k_0$ in the range between 0 and 3 GeV. The relative changes in the normalised differential cross sections induced by such a variation were smaller than 0.2%.

## 5. Results

The cross sections presented here include every jet of hadrons in an event with $E^\mathrm{B}_{T,\mathrm{jet}} > 8$ GeV and $-2 < \eta^\mathrm{B}_\mathrm{jet} < 1.8$. A detailed comparison of the differential cross sections as functions of $Q^2$, $E^\mathrm{B}_{T,\mathrm{jet}}$ and $\eta^\mathrm{B}_\mathrm{jet}$ for inclusive jet production in the same kinematic region as used here was presented in a previous publication [13]. At low $Q^2$ and low $E^\mathrm{B}_{T,\mathrm{jet}}$, the NLO QCD calculations fall below the data by $\sim 10\%$. Nonetheless, the differences between the measurements and calculations are of the same size as the theoretical uncertainties [13]. The comparison of the shape of interest in this publication is facilitated by normalising the predicted cross section and the data to unity.

The normalised differential cross section $(1/\sigma) \times d\sigma/d\phi^\mathrm{B}_\mathrm{jet}$ for inclusive jet production as a function of $\phi^\mathrm{B}_\mathrm{jet}$ is shown in Fig. 1 and in Table 1. This distribution

Table 1
Normalised differential cross section $(1/\sigma)\, d\sigma/d\phi^\mathrm{B}_\mathrm{jet}$ for inclusive jet production with $E^\mathrm{B}_{T,\mathrm{jet}} > 8$ GeV and $-2 < \eta^\mathrm{B}_\mathrm{jet} < 1.8$. The statistical and systematic uncertainties are shown separately

| $\phi^\mathrm{B}_\mathrm{jet}$ interval (rad) | $(1/\sigma)\, d\sigma/d\phi^\mathrm{B}_\mathrm{jet}$ | $\Delta_\mathrm{stat}$ | $\Delta_\mathrm{syst}$ |
|---|---|---|---|
| $0$–$\frac{\pi}{6}$ | 0.1655 | ±0.0054 | $^{+0.0042}_{-0.0015}$ |
| $\frac{\pi}{6}$–$\frac{\pi}{3}$ | 0.1630 | ±0.0051 | $^{+0.0011}_{-0.0014}$ |
| $\frac{\pi}{3}$–$\frac{\pi}{2}$ | 0.1398 | ±0.0047 | $^{+0.0020}_{-0.0008}$ |
| $\frac{\pi}{2}$–$\frac{2\pi}{3}$ | 0.1557 | ±0.0050 | $^{+0.0000}_{-0.0022}$ |
| $\frac{2\pi}{3}$–$\frac{5\pi}{6}$ | 0.1601 | ±0.0051 | $^{+0.0062}_{-0.0013}$ |
| $\frac{5\pi}{6}$–$\pi$ | 0.1771 | ±0.0057 | $^{+0.0050}_{-0.0075}$ |
| $\pi$–$\frac{7\pi}{6}$ | 0.1779 | ±0.0056 | $^{+0.0016}_{-0.0052}$ |
| $\frac{7\pi}{6}$–$\frac{4\pi}{3}$ | 0.1577 | ±0.0050 | $^{+0.0051}_{-0.0015}$ |
| $\frac{4\pi}{3}$–$\frac{3\pi}{2}$ | 0.1458 | ±0.0046 | $^{+0.0035}_{-0.0008}$ |
| $\frac{3\pi}{2}$–$\frac{5\pi}{3}$ | 0.1468 | ±0.0047 | $^{+0.0032}_{-0.0028}$ |
| $\frac{5\pi}{3}$–$\frac{11\pi}{6}$ | 0.1531 | ±0.0047 | $^{+0.0017}_{-0.0014}$ |
| $\frac{11\pi}{6}$–$2\pi$ | 0.1674 | ±0.0054 | $^{+0.0018}_{-0.0027}$ |

has clear enhancements at $\phi^{\mathrm{B}}_{\mathrm{jet}} = 0$ and $\phi^{\mathrm{B}}_{\mathrm{jet}} = \pi$. This observation complements the ZEUS measurement of the azimuthal dependence of charged hadrons with high transverse momentum in NC DIS [8]. The NLO QCD calculations with either $\mu_{\mathrm{R}} = E^{\mathrm{B}}_{T,\mathrm{jet}}$ or $Q$ reproduce the asymmetry. This comparison constitutes a precise test of the perturbative QCD prediction for the azimuthal distribution since the theoretical uncertainties are small. The dominant theoretical uncertainty arose from terms beyond NLO and was estimated by varying $\mu_{\mathrm{R}}$ between $E^{\mathrm{B}}_{T,\mathrm{jet}}/2$ and $2E^{\mathrm{B}}_{T,\mathrm{jet}}$; the effect on the amplitude of the modulation of the distribution was $\sim \pm 1\%$. Other sources of theoretical uncertainty, such as the effect of varying $\mu_{\mathrm{F}}$ between $Q/2$ and $2Q$, the experimental uncertainties on the proton PDFs and the theoretical uncertainties affecting the extraction of the proton PDFs, were estimated to be small in comparison.

The measurements folded about $\pi$, $|\phi^{\mathrm{B}}_{\mathrm{jet}}|$, in different regions of $Q^2$ are presented in Fig. 2 and in

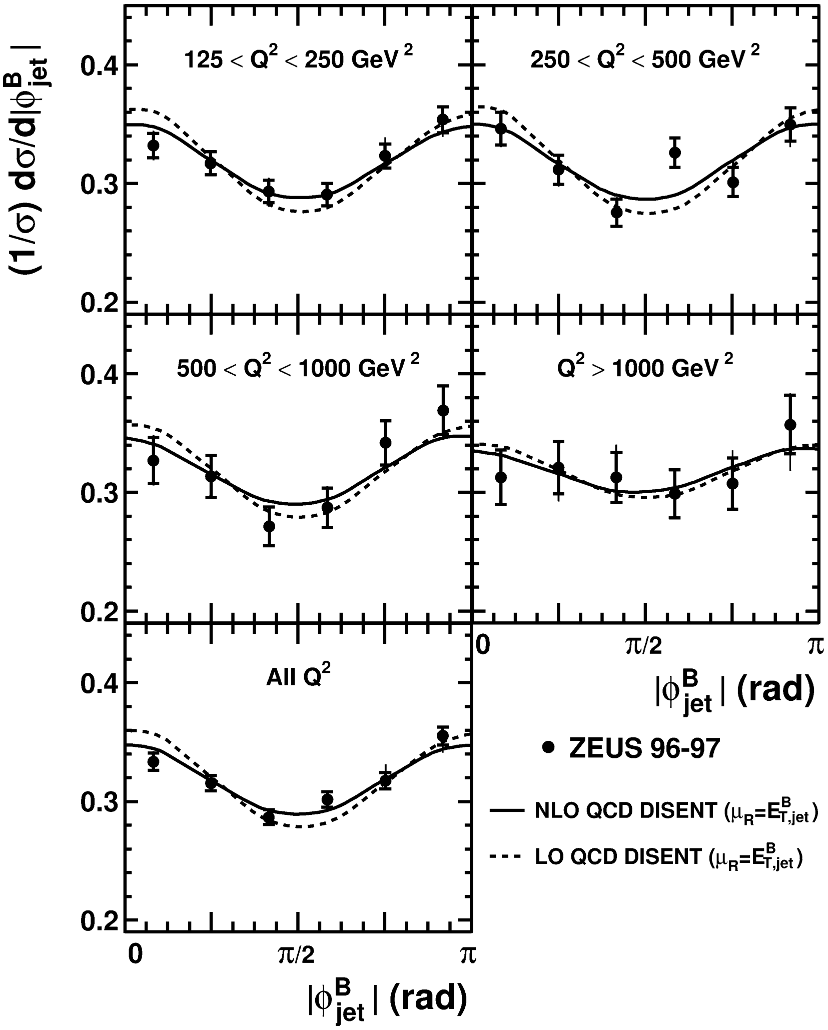

Fig. 2. The folded normalised differential cross section $(1/\sigma)\, d\sigma/d|\phi^{\mathrm{B}}_{\mathrm{jet}}|$ for inclusive jet production with $E^{\mathrm{B}}_{T,\mathrm{jet}} > 8$ GeV and $-2 < \eta^{\mathrm{B}}_{\mathrm{jet}} < 1.8$ in different $Q^2$ regions (points). The inner error bars represent the statistical uncertainty. The outer error bars show the statistical and systematic uncertainties added in quadrature. The LO and NLO QCD calculations using DISENT and the MRST99 parameterisations of the proton PDFs are also shown.

Table 2
Folded normalised differential cross section $(1/\sigma)\,d\sigma/d|\phi_{\text{jet}}^{\text{B}}|$ in different regions of $Q^2$ for inclusive jet production with $E_{T,\text{jet}}^{\text{B}} > 8$ GeV and $-2 < \eta_{\text{jet}}^{\text{B}} < 1.8$. For details, see the caption of Table 1

| $\lvert\phi_{\text{jet}}^{\text{B}}\rvert$ interval (rad) | $(1/\sigma)\,d\sigma/d\lvert\phi_{\text{jet}}^{\text{B}}\rvert$ | $\Delta_{\text{stat}}$ | $\Delta_{\text{syst}}$ | $(1/\sigma)\,d\sigma/d\lvert\phi_{\text{jet}}^{\text{B}}\rvert$ | $\Delta_{\text{stat}}$ | $\Delta_{\text{syst}}$ |
|---|---|---|---|---|---|---|
| | $125 < Q^2 < 250$ GeV$^2$ | | | $250 < Q^2 < 500$ GeV$^2$ | | |
| $0$–$\frac{\pi}{6}$ | 0.3319 | ±0.0103 | $^{+0.0068}_{-0.0069}$ | 0.3461 | ±0.0138 | $^{+0.0071}_{-0.0073}$ |
| $\frac{\pi}{6}$–$\frac{\pi}{3}$ | 0.3171 | ±0.0096 | $^{+0.0054}_{-0.0028}$ | 0.3116 | ±0.0122 | $^{+0.0054}_{-0.0072}$ |
| $\frac{\pi}{3}$–$\frac{\pi}{2}$ | 0.2932 | ±0.0095 | $^{+0.0066}_{-0.0085}$ | 0.2754 | ±0.0116 | $^{+0.0060}_{-0.0047}$ |
| $\frac{\pi}{2}$–$\frac{2\pi}{3}$ | 0.2907 | ±0.0093 | $^{+0.0038}_{-0.0018}$ | 0.3259 | ±0.0126 | $^{+0.0032}_{-0.0051}$ |
| $\frac{2\pi}{3}$–$\frac{5\pi}{6}$ | 0.3232 | ±0.0101 | $^{+0.0120}_{-0.0021}$ | 0.3011 | ±0.0122 | $^{+0.0129}_{-0.0033}$ |
| $\frac{5\pi}{6}$–$\pi$ | 0.3538 | ±0.0109 | $^{+0.0049}_{-0.0094}$ | 0.3497 | ±0.0141 | $^{+0.0059}_{-0.0126}$ |
| | $500 < Q^2 < 1000$ GeV$^2$ | | | $Q^2 > 1000$ GeV$^2$ | | |
| $0$–$\frac{\pi}{6}$ | 0.3268 | ±0.0192 | $^{+0.0100}_{-0.0085}$ | 0.3129 | ±0.0229 | $^{+0.0064}_{-0.0047}$ |
| $\frac{\pi}{6}$–$\frac{\pi}{3}$ | 0.3136 | ±0.0178 | $^{+0.0063}_{-0.0055}$ | 0.3210 | ±0.0220 | $^{+0.0068}_{-0.0182}$ |
| $\frac{\pi}{3}$–$\frac{\pi}{2}$ | 0.2713 | ±0.0164 | $^{+0.0053}_{-0.0052}$ | 0.3126 | ±0.0211 | $^{+0.0177}_{-0.0039}$ |
| $\frac{\pi}{2}$–$\frac{2\pi}{3}$ | 0.2871 | ±0.0167 | $^{+0.0079}_{-0.0062}$ | 0.2989 | ±0.0202 | $^{+0.0027}_{-0.0009}$ |
| $\frac{2\pi}{3}$–$\frac{5\pi}{6}$ | 0.3418 | ±0.0187 | $^{+0.0075}_{-0.0036}$ | 0.3074 | ±0.0215 | $^{+0.0178}_{-0.0048}$ |
| $\frac{5\pi}{6}$–$\pi$ | 0.3693 | ±0.0206 | $^{+0.0062}_{-0.0120}$ | 0.3571 | ±0.0247 | $^{+0.0105}_{-0.0299}$ |
| | $Q^2 > 125$ GeV$^2$ | | | | | |
| $0$–$\frac{\pi}{6}$ | 0.3334 | ±0.0072 | $^{+0.0053}_{-0.0043}$ | | | |
| $\frac{\pi}{6}$–$\frac{\pi}{3}$ | 0.3153 | ±0.0066 | $^{+0.0026}_{-0.0027}$ | | | |
| $\frac{\pi}{3}$–$\frac{\pi}{2}$ | 0.2867 | ±0.0064 | $^{+0.0035}_{-0.0019}$ | | | |
| $\frac{\pi}{2}$–$\frac{2\pi}{3}$ | 0.3016 | ±0.0065 | $^{+0.0017}_{-0.0014}$ | | | |
| $\frac{2\pi}{3}$–$\frac{5\pi}{6}$ | 0.3176 | ±0.0068 | $^{+0.0116}_{-0.0025}$ | | | |
| $\frac{5\pi}{6}$–$\pi$ | 0.3552 | ±0.0076 | $^{+0.0044}_{-0.0117}$ | | | |

Table 2. The LO and NLO QCD predictions are compared to the data. The NLO QCD prediction describes the data well, whereas the LO QCD calculations predict a larger asymmetry, particularly in the lower $Q^2$ intervals. In both cases, the asymmetry is predicted to decrease as $Q^2$ increases, as a result of the progressive decline of the contribution from the PGF process.

In order to perform a more quantitative study of the asymmetry and its dependence on $Q^2$, a fit was performed to the values of $(1/\sigma)\,d\sigma/d|\phi_{\text{jet}}^{\text{B}}|$ both in the data and in the QCD predictions. The functional form

$$\frac{1}{\sigma}\frac{d\sigma}{d|\phi_{\text{jet}}^{\text{B}}|} = \frac{1}{\pi}\left[1 + f_1\cos\left(\phi_{\text{jet}}^{\text{B}}\right) + f_2\cos\left(2\phi_{\text{jet}}^{\text{B}}\right)\right]$$

was used. The parameter $f_1$ ($f_2$) represents the contribution of the $\cos\phi_{\text{jet}}^{\text{B}}$ ($\cos 2\phi_{\text{jet}}^{\text{B}}$) term to the total asymmetry. The fitted values of $f_1$ and $f_2$ as functions of $Q^2$ and for the entire sample with $Q^2 > 125$ GeV$^2$ are shown in Fig. 3 and listed in Table 3, together with the LO and NLO QCD predictions and their uncertainties. The fitted values are plotted at the weighted mean in

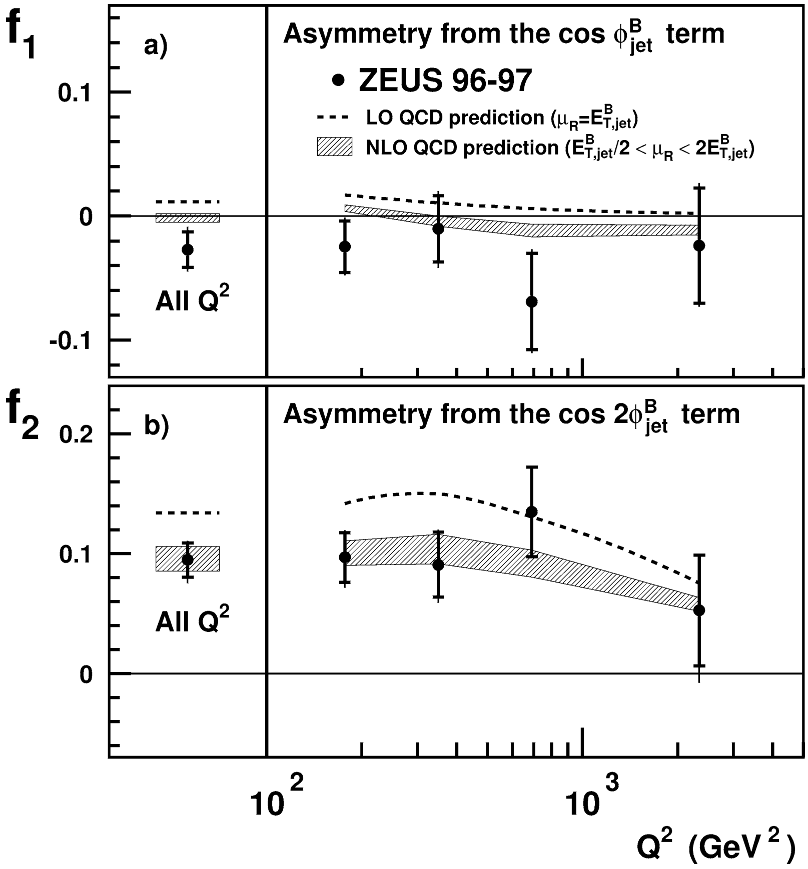

Fig. 3. The fitted values of (a) $f_1$ and (b) $f_2$ from the folded normalised differential cross section $(1/\sigma)\,d\sigma/d|\phi^{\mathrm{B}}_{\mathrm{jet}}|$ for inclusive jet production with $E^{\mathrm{B}}_{T,\mathrm{jet}} > 8$ GeV and $-2 < \eta^{\mathrm{B}}_{\mathrm{jet}} < 1.8$ as a function of $Q^2$ (points). The fitted values for the entire sample, $Q^2 > 125\ \mathrm{GeV}^2$, are shown on the left-hand side. The inner error bars represent the statistical uncertainty. The outer error bars show the statistical and systematic uncertainties added in quadrature. The results of the fits to the LO and NLO QCD predictions using DISENT and the MRST99 parameterisations of the proton PDFs are shown. The shaded bands represent the uncertainty of the calculations due to the dependence on the renormalisation scale.

each bin of $Q^2$. The comparison of the LO QCD calculations for the QCDC and PGF process shows that the asymmetry is predicted to arise mostly from the gluon-induced interactions. The LO QCD predictions do not reproduce the measurements. However, the uncertainty at LO is rather large. The difference between the LO and NLO calculations has been assigned as the theoretical uncertainty of the LO predictions and is $\sim \pm 0.04$ ($\pm 0.01$) for $f_2$ ($f_1$). At NLO, the dominant theoretical uncertainty on $f_2$ ($f_1$) was that due to terms beyond NLO and was estimated by fitting the predictions obtained with $\mu_{\mathrm{R}} = E^{\mathrm{B}}_{T,\mathrm{jet}}/2$ and $2E^{\mathrm{B}}_{T,\mathrm{jet}}$; it amounted to $\sim \pm 0.01$ ($\pm 0.005$). The NLO predictions for $f_1$ and $f_2$ based on calculations using $\mu_{\mathrm{R}} = Q$ differed from those using $\mu_{\mathrm{R}} = E^{\mathrm{B}}_{T,\mathrm{jet}}$ by as much as the estimated theoretical uncertainty. The NLO QCD predictions are in good agreement with the measured values of $f_2$. For $f_1$, the observed asymmetry tends to be slightly larger and more negative than that predicted by perturbative QCD. The measurements are consistent with the $Q^2$ dependence of $f_1$ and $f_2$ predicted by NLO QCD.

## 6. Summary

A study of the azimuthal asymmetry for inclusive jet production in neutral current deep inelastic $e^+p$

Table 3
Measured values of the parameters $f_1$ and $f_2$ in the different $Q^2$ regions. The LO and NLO QCD predicted values calculated using DISENT and the MRST99 parameterisation of the proton PDFs are shown for comparison. The quoted uncertainties in the theoretical predictions are described in the text

| | $Q^2$ region (GeV$^2$) | | $\Delta_{\rm stat}$ | $\Delta_{\rm syst}$ | LO QCD (PGF, QCDC) | NLO QCD |
|---|---|---|---|---|---|---|
| $f_1$ | All $Q^2$ ($Q^2 > 125$) | $-0.0273$ | $\pm 0.0144$ | $^{+0.0121}_{-0.0099}$ | $0.0115 \pm 0.0118$<br>$(0.0236, -0.0013)$ | $-0.0003\,^{+0.0025}_{-0.0044}$ |
| | $125 < Q^2 < 250$ | $-0.0248$ | $\pm 0.0208$ | $^{+0.0113}_{-0.0093}$ | $0.0171 \pm 0.0100$<br>$(0.0303, -0.0005)$ | $0.0071\,^{+0.0021}_{-0.0035}$ |
| | $250 < Q^2 < 500$ | $-0.0103$ | $\pm 0.0268$ | $^{+0.0144}_{-0.0166}$ | $0.0106 \pm 0.0136$<br>$(0.0210, -0.0015)$ | $-0.0030\,^{+0.0029}_{-0.0052}$ |
| | $500 < Q^2 < 1000$ | $-0.0690$ | $\pm 0.0388$ | $^{+0.0166}_{-0.0150}$ | $0.0060 \pm 0.0161$<br>$(0.0152, -0.0029)$ | $-0.0101\,^{+0.0036}_{-0.0067}$ |
| | $Q^2 > 1000$ | $-0.0238$ | $\pm 0.0465$ | $^{+0.0196}_{-0.0168}$ | $0.0022 \pm 0.0122$<br>$(0.0089, -0.0009)$ | $-0.0100\,^{+0.0028}_{-0.0052}$ |
| $f_2$ | All $Q^2$ ($Q^2 > 125$) | $0.0947$ | $\pm 0.0143$ | $^{+0.0068}_{-0.0133}$ | $0.1340 \pm 0.0356$<br>$(0.1999, 0.0452)$ | $0.0984\,^{+0.0074}_{-0.0131}$ |
| | $125 < Q^2 < 250$ | $0.0969$ | $\pm 0.0207$ | $^{+0.0095}_{-0.0151}$ | $0.1418 \pm 0.0388$<br>$(0.1880, 0.0410)$ | $0.1030\,^{+0.0074}_{-0.0127}$ |
| | $250 < Q^2 < 500$ | $0.0906$ | $\pm 0.0270$ | $^{+0.0112}_{-0.0164}$ | $0.1496 \pm 0.0424$<br>$(0.2262, 0.0632)$ | $0.1072\,^{+0.0088}_{-0.0158}$ |
| | $500 < Q^2 < 1000$ | $0.1348$ | $\pm 0.0374$ | $^{+0.0044}_{-0.0082}$ | $0.1306 \pm 0.0356$<br>$(0.1982, 0.0358)$ | $0.0950\,^{+0.0079}_{-0.0146}$ |
| | $Q^2 > 1000$ | $0.0526$ | $\pm 0.0462$ | $^{+0.0086}_{-0.0387}$ | $0.0754 \pm 0.0160$<br>$(0.1678, 0.0359)$ | $0.0594\,^{+0.0041}_{-0.0076}$ |

scattering in the Breit frame at a centre-of-mass energy of 300 GeV has been presented. Jets of hadrons were identified with the longitudinally invariant $k_T$ cluster algorithm in the Breit frame. The normalised cross sections as a function of the azimuthal angle of the jets in the Breit frame are given in the kinematic region $Q^2 > 125$ GeV$^2$ and $-0.7 < \cos\gamma < 0.5$. The cross sections include every jet of hadrons in the event with $E^{\rm B}_{T,\rm jet} > 8$ GeV and $-2 < \eta^{\rm B}_{\rm jet} < 1.8$.

The measured azimuthal distribution peaks in the directions along, and opposite to, that of the scattered positron in the Breit frame. The NLO QCD calculations give a good description of the observed azimuthal variation. The dependence of the azimuthal asymmetry on $Q^2$ is also compatible with NLO QCD.

These measurements constitute a precise test of the perturbative QCD prediction for the azimuthal distribution since the theoretical uncertainties are small.

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