Energy Flow and Leading Neutron Production at HERA

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Abstract. The azimuthal asymmetry of hadrons in the semi-inclusive process e+p $\rightarrow$ e+h+X is studied in deep inelastic scattering at HERA. A measurement of the dijet cross section with a leading neutron is also reported, the P_T^2 distribution of the leading neutron is investigated.

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INTRODUCTION

The semi-inclusive process e+p $\rightarrow$ e+h+X in deep inelastic scattering (DIS), where h is an observed hadron, provides an important test of pQCD in hadron production. An interesting variable is the distribution of the azimuthal angle ϕ of the hadron (measured in the hadronic centre-of-mass frame HCM), between the lepton plane, defined by the incoming and outgoing lepton, and the hadron plane, defined by the outgoing hadron and the virtual boson. The azimuthal asymmetry in the ϕ distribution is due to the non-zero transverse momentum of the hadron. The contribution from the intrinsic momentum of a quark in the proton is small at high momentum transfer Q^2 [1]. The contribution from higher order QCD processes such as the QCD Compton and boson-gluon fusion processes weakly depends on Q^2 and persists at high Q^2. In this paper, we use the energy flow method to investigate the azimuthal asymmetry, where the range of investigated phase space is increased with respect to previous publications [2]. We compare experimental data with Monte Carlo (MC) predictions incorporating leading order (LO) and parton showers and with a next-to-leading-order (NLO) pQCD calculations.

There is a significant fraction of events with a baryon in the hadronic final state carrying a large fraction of incoming proton energy in ep collisions. It is interesting to investigate the production mechanism for low transverse momentum baryons. In this paper, we study leading neutron production e+p $\rightarrow$ e+n+X. The leading neutron can result from fragmentation of the proton remnant or one pion exchange. In the one pion exchange model, the virtual photon interacts with a pion from the proton, i.e. $\sigma_{ep\rightarrow enX} = f_{\pi/p}(x_L,t) \times \sigma(e\pi \rightarrow e'X)$, where t is the square of the four-momentum of the exchanged pion. The outgoing neutron of energy E_B carries a fraction $x_L = E_B/E_p$ of the incoming proton energy. $f_{\pi/p}$ is the flux of virtual pions emitted by the proton. One feature of the exchange model is vertex factorization, which predicts that the cross section on baryon vertex variables will be independent of lepton vertex variables. We test vertex factorization by comparing events in photoproduction ($Q^2 \sim 0$ GeV^2) and

DIS ($Q^2 \geq 1$ GeV^2) events. In this paper, we study the p_T^2 of the leading neutron, and report the dijet cross section in leading neutron production. We compare experimental results with Monte Carlo and pQCD calculations.

AZIMUTHAL ASYMMETRY IN ϕ DISTRIBUTION

The semi-inclusive DIS cross section $d\sigma/d\phi$ in the HCM frame is

$$\frac{d\sigma^{ep\to ehX}}{d\phi} = A + B\cos(\phi) + C\cos(2\phi) + D\sin(\phi) + E\sin(s\phi) \quad (1)$$

where the azimuthal asymmetry is denoted by parameters B, C, D and E. The parameters can be determined by first moments, i.e.

$$\langle\cos(\phi)\rangle = \frac{B}{2A} \quad \langle\cos(2\phi)\rangle = \frac{C}{2A} \quad \langle\sin(\phi)\rangle = \frac{D}{2A} \quad \langle\sin(2\phi)\rangle = \frac{E}{2A} \quad (2)$$

The mean values $\langle\cos(n\phi)\rangle$ and $\langle\sin(n\phi)\rangle$ (n=1,2) are measured by the ZEUS Collaboration [3] in neutral current DIS events. The kinematic region is defined by $100 < Q^2 < 8000$ GeV^2 and $0.01 < x < 0.1$. The measured azimuthal asymmetry in terms of $\langle\cos(\phi)\rangle$, $\langle\cos(2\phi)\rangle$, $\langle\sin(\phi)\rangle$ and $\langle\sin(2\phi)\rangle$ determined by the energy flow method are presented in figure 1 as a function of pseudorapidity η of the hadron with transverse momenta $P_T^{LAB} > 150$ MeV. The mean values $\langle\sin(\phi)\rangle$ and $\langle\sin(2\phi)\rangle$ are small and consistent with zero, this is consistent with predictions of LO MC programs LEPTO and ARIADNE. The measured $\langle\cos 2\phi\rangle$ is about zero for $\eta^{HCM} < -2.0$ and positive for higher η^{HCM}. LEPTO and ARIADNE provide a good description of the data. The mean value $\langle\cos\phi\rangle$ is negative for $\eta^{HCM} < -2.0$ and positive for higher η^{HCM}, while the LEPTO and ARIADNE predictions are always negative in the whole η^{HCM} range. The NLO predictions, made using DISENT [4] and corrected for hadronization effects and Z^0 exchange effects, describe the data points better than LEPTO and ARIADNE.

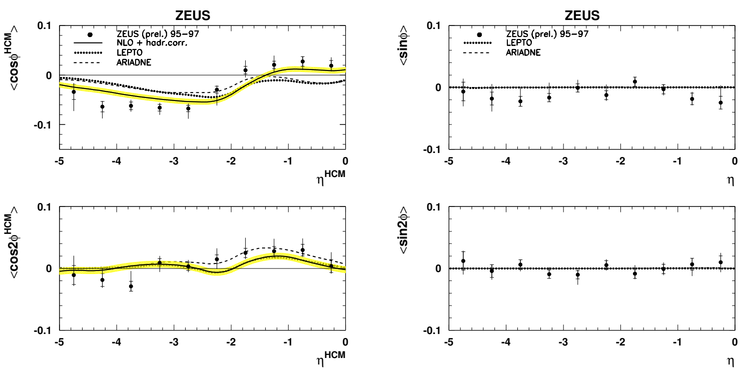

FIGURE 1. The measured $\langle\cos(n\phi)\rangle$ and $\langle\sin(n\phi)\rangle$ (n=1,2) as a function of η of hadrons. The NLO DISENT prediction and LO MC predictions by LEPTO and ARIADNE are also shown.

The azimuthal asymmetry is also analyzed as a function of the detected hadron's minimum transverse energy $E_T^{HCM}(\text{min})$. In this case, the lowest order contribution come

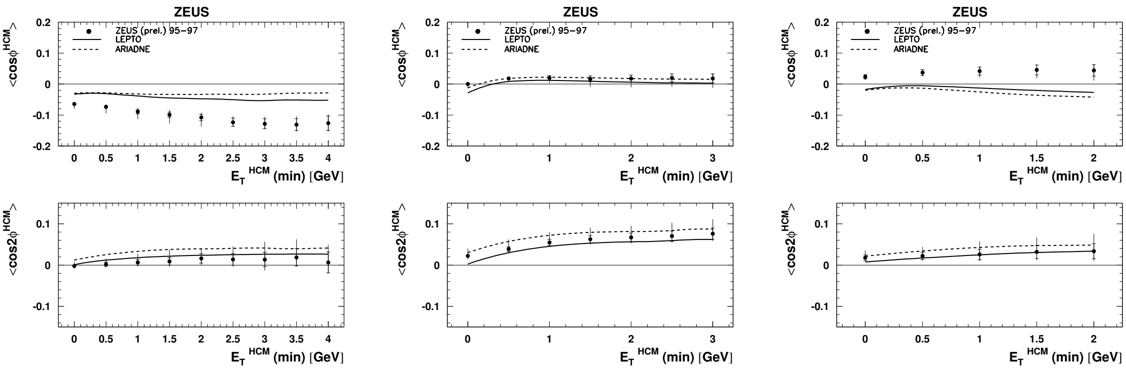

FIGURE 2. The measured $\langle\cos(n\phi)\rangle$ (n=1,2) as a function of hadron's minimum transverse energy E_T^{HCM}(min) in three regions of η^{HCM}: $-5.0 < \eta^{HCM} < -2.5$ (left), $-2.5 < \eta^{HCM} < -1.0$ and $-1.0 < \eta^{HCM} < 0.0$ (right). The lines are LEPTO (solid line) and ARIADNE (dashed line) predictions.

from QCDC and BGF processes, and the contributions from Born level are suppressed. The experimental results are shown in figure 2 in three regions of η^{HCM}: $-5.0 < \eta^{HCM} < -2.5$ (left), $-2.5 < \eta^{HCM} < -1.0$ and $-1.0 < \eta^{HCM} < 0.0$ (right). The same trends are seen as a function of E_T^{HCM}(min) as in the inclusive case.

P_T^2 DISTRIBUTION OF LEADING NEUTRON

The ZEUS Collaboration has measured the p_T^2 distribution of the leading neutron in photoproduction ($Q^2 < 0.02$ GeV^2) and DIS ($Q^2 > 2$ GeV^2) [5]. The p_T^2 distribution for different x_L bins in photoproduction and DIS, normalized to unity at $p_T^2 = 0$, is shown in figure 3 (left). The photoproduction distribution is clearly steeper in the range $0.6 < x_L < 0.9$. The line on each plot is a fit to a function of form $\exp(-bp_T^2)$, which gives a good description of experimental data. The fitted b in DIS as a function of x_L is in figure 3 (middle). Fitted b is consistent with zero below $x_L = 0.3$; and b rises linearly in the range $0.30 < x_L < 0.85$, and then decrease slightly at higher x_L. The pion flux $f_{\pi/p}$ is not an exponential in p_T^2, but, the different models of $f_{\pi/p}$ can be fitted with $\exp(-bp_T^2)$ at fixed x_L, where the resulting b is a model prediction. The figure 3 (middle) shows that there is no model which describes the data over the whole x_L range. As we know, one pion exchange is expected to dominate for $0.6 < x_L < 0.9$. Hence one can use the measured b to critical test models.

For the observable $\Delta b = b(\gamma p) - b(DIS)$, some systematic uncertainties are cancelled. The measured Δb is in figure 3 (right) as a function of x_L, where $b(\gamma p)$ is clearly larger than $b(DIS)$ in the range $0.6 < x_L < 0.9$ with Δb between 0.5 and 1.0 GeV^{-2}. The depletion of neutrons at large p_T^2 is qualitatively described by absorption models. According to absorption models [6], the p_T^2 distribution is given by the $n-\pi$ separation whose size, which is inversely proportional to p_T^2. Rescattering processes remove neutron from small $n-\pi$ system hence with large p_T^2. Thus rescattering results in a depletion of neutron at high p_T^2 in photoproduction relative to DIS.

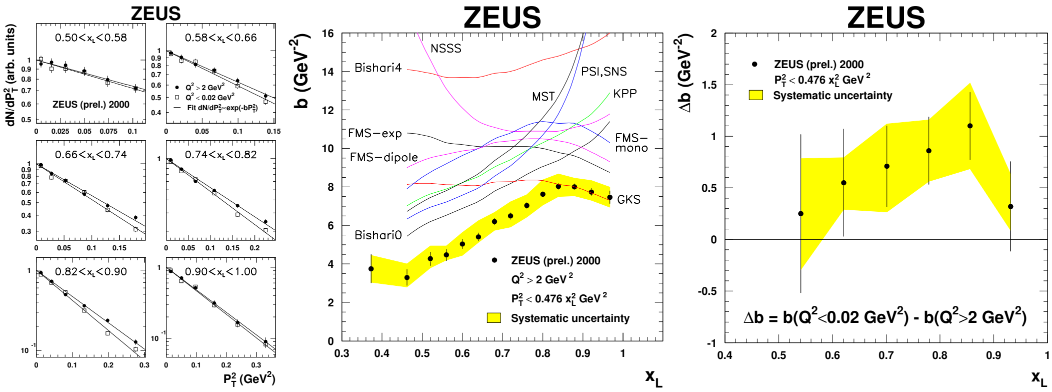

FIGURE 3. Left: p_T^2 distribution of the leading neutron for different x_L bins in photoproduction and DIS events. Middle: dependence of fitted b on x_L in DIS, Right: dependence of Δb on x_L.

DIJET CROSS SECTION WITH A LEADING NEUTRON

Leading neutron production is investigated further by requiring two jets with large transverse momenta e+p $\rightarrow$ e+n+jet+jet+X. This allows a more detailed comparison with MC predictions. We study the dependence of the cross section on jet related variables, such as $x_\gamma^{jet} = \sum_{i=1,2} E_{T,i}^{jet} \exp(-\eta_i^{jet})/(2yE_e)$ where E_T is the jet transverse energy, η^{jet} is the jet pseudorapidity, y is the inelasticity and E_e is the incoming electron energy.

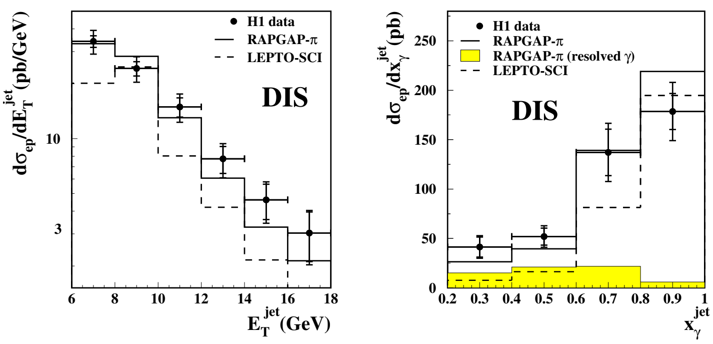

FIGURE 4. Dijet cross sections with a leading neutron as functions of E_T^{jet} and x_γ^{jet} in DIS.

The dijet cross sections with a leading neutron measured by the H1 Collaboration [8] as a function of E_T^{jet} and x_γ^{jet} are presented in figure 4 (DIS: $2 < Q^2 < 80$ GeV^2) and figure 5 (photoproduction: $Q^2 < 0.01$ GeV^2). The data are well described by the pion exchange model in DIS and photoproduction taking into account a 20% normalization uncertainty in the data. LEPTO with soft color interactions is too low to describe the dijet cross sections with a leading neutron, however it describes well leading neutron production in inclusive DIS [7]. The contribution from resolved photons is important at low x_γ^{jet} in DIS events. PYTHIA without multi-parton interactions (MI) and pion

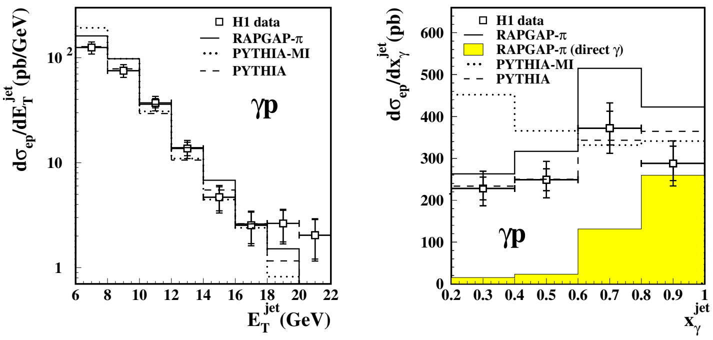

FIGURE 5. Dijet cross sections with a leading neutron as functions of E_T^{jet} and x_γ^{jet} in photoproduction.

exchange describes the data in photoproduction, but PYTHIA with MI is too high at low x_γ, while the MI is needed to describe inclusive dijet in the considered E_T^{jet} range.

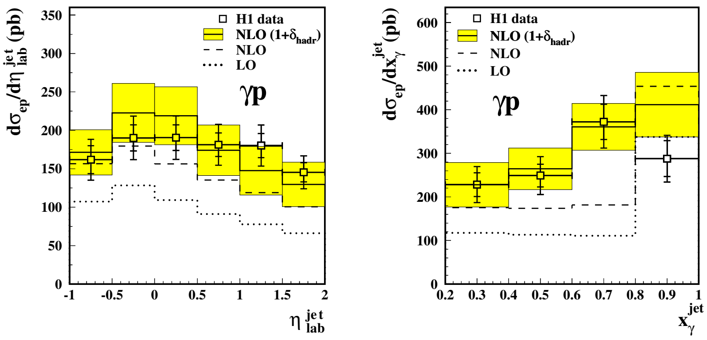

FIGURE 6. Dijet cross sections with a leading neutron as functions of η_{Lab}^{jet} and x_γ^{jet} in photoproduction.

NLO QCD predictions on the dijet cross sections with a leading neutron in photoproduction [9], corrected for hadronization effects, are shown in figure 6 with the measured cross section as functions of η_{Lab}^{jet} and x_γ^{jet}. There is good agreement between the NLO calculation and the measured data.

Figure 7 shows the ratio of the dijet cross section f_{ln} with and without the requirement of a leading neutron as functions of E_T^{jet} and x_γ^{jet} in photoproduction. If the hard interaction is independent of neutron production, f_{ln} should be independent of jet variables. f_{ln} is almost independent of E_T^{jet}, however f_{ln} shows a strong dependence on x_γ^{jet}, also on η^{jet} and x_p^{jet} (not shown). These dependences can only partly described by PYTHIA, which provides some estimates of possible phase space effects. If the leading neutron production is described by Rapgap-π and the inclusive dijet data by PYTHIA with multiparton interactions, this comparison suggests the dijet production with a leading neutron differs from inclusive dijet production.

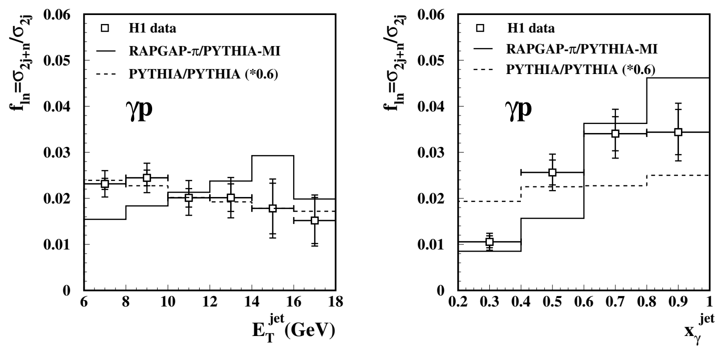

FIGURE 7. Ratio of dijet cross section with and without the requirement of a leading neutron, f_{ln}, as functions of E_T^{jet} and x_γ^{jet} in photoproduction.

SUMMARY

For the azimuthal asymmetry of hadrons in DIS, the NLO prediction shows better agreement with experimental data than LO MC programs, however some discrepancies are still visible. The form $\exp(-bp_T^2)$ describes well the p_T^2 distribution of leading neutron production in photoproduction and DIS. There is no model which describes the measured b over the whole range, and the measured b is different in photoproduction and in DIS. The dijet cross section with a leading neutron is described by pion exchange MC models. The NLO predictions describe the data in photoproduction. The dependence of f_{ln} on x_γ^{jet} and η^{jet} show the violation of factorization.

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