THREE-JET PRODUCTION IN DEEP-INELASTIC SCATTERING AT HERA*

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Three-jet production has been studied in deep-inelastic positron-proton scattering. The measurement carried out with the H1 detector at HERA covers a large range of four-momentum transfer squared $5 < Q^2 < 5\,000\,\mathrm{GeV}^2$ and invariant three-jet masses $25 < M_{3\mathrm{jet}} \lesssim 140\,\mathrm{GeV}$. Jets are defined by the inclusive $k_\perp$ algorithm in the Breit frame. The size of the three-jet cross section and the ratio of the three-jet to the dijet cross section $R_{3/2}$ are described over the whole phase space by the predictions of perturbative QCD in next-to-leading order. The shapes of angular jet distributions deviate significantly from a uniform population of the available phase space but are well described by the QCD calculation.

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1. Introduction

Multi-jet production in deep-inelastic scattering (DIS) has been successfully used at HERA to test the predictions of perturbative QCD (pQCD) over a large range of four-momentum transfer squared Q^2. Recently the H1 collaboration has determined the strong coupling α_s and the gluon density in the proton [1] from the inclusive jet and the dijet cross sections measured in the Breit frame. While these cross sections are directly sensitive to QCD effects of $\mathcal{O}(\alpha_\mathrm{s})$, the three-jet cross section in DIS is already proportional to α_s^2 in leading order (LO) in pQCD. The higher sensitivity to α_s and the greater number of degrees of freedom of the three-jet final state thus allow

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the QCD predictions to be tested in more detail. Here we present differential measurements of the three-jet cross section in neutral current DIS and measurements of shapes of angular jet distributions which are sensitive to dynamic effects of the interaction [2]. The present analysis includes the first comparison of three-jet distributions measured in hadron induced reactions with a pQCD calculation in next-to-leading order (NLO) *i.e.* $\mathcal{O}(\alpha_s^3)$ [3].

2. Measured observables

In neutral current DIS the lepton interacts with a parton in the proton via the exchange of a boson (γ, Z). At a fixed center-of-mass energy the kinematics of the lepton inclusive reaction (for unpolarized lepton and proton beams) is given by two variables which are here chosen to be the four-momentum transfer squared Q^2 and the Bjorken scaling variable $x_{\rm Bj}$. The subprocess $1+2 \rightarrow 3+4+5$ in which three massless jets emerge from the boson-parton reaction is fully described by six further variables which can be constructed from the energies E_i and the momenta $\vec{p}_i$ of the jets in the three-jet center-of-mass (CM) frame. It is convenient to label the three jets ($i = 3,4,5$) in the order of decreasing energies in the three-jet CM frame. Two of these variables are the angles θ_3 and ψ_3 that specify the relative orientation of the jets,

$$\cos\theta_3 \equiv \frac{\vec{p}_{\rm B}\cdot\vec{p}_3}{|\vec{p}_{\rm B}|\,|\vec{p}_3|}\,, \qquad \cos\psi_3 \equiv \frac{(\vec{p}_3\times\vec{p}_{\rm B})\cdot(\vec{p}_4\times\vec{p}_5)}{|\vec{p}_3\times\vec{p}_{\rm B}|\quad|\vec{p}_4\times\vec{p}_5|}\,, \tag{1}$$

where $\vec{p}_{\rm B}$ denotes the direction of the proton beam. θ_3 is the angle of the highest energy jet with respect to the proton beam direction. ψ_3 is the angle between the plane spanned by the highest energy jet and the proton beam and the plane containing the three jets. The angle ψ_3 indicates whether the third jet (*i.e.* the lowest energy jet) is radiated within ($\psi_3 \rightarrow 0$ or $\psi_3 \rightarrow \pi$) or perpendicular ($\psi_3 \rightarrow \pi/2$) to the plane containing the highest energy jet and the proton beam.

The observable $R_{3/2}$, defined by the ratio of the inclusive three-jet cross section and the inclusive two-jet cross section, is of interest especially for quantitative studies, since in this ratio both experimental and some theoretical uncertainties cancel to a large extent.

This contribution presents measurements of the inclusive three-jet cross section in DIS as a function of Q^2. Distributions of three-jet events are measured in the variables $\cos\theta_3$ and ψ_3. The ratio $R_{3/2}$ is measured as a function of Q^2. Measurements of further observables can be found in [2].

3. Results

The analysis is based on data taken in positron-proton collisions with the H1 detector in the years 1995–1997 with a positron beam energy of $E_e = 27.5\,\mathrm{GeV}$ and a proton beam energy of $E_p = 820\,\mathrm{GeV}$, leading to a center-of-mass energy $\sqrt{s} = 300\,\mathrm{GeV}$.

We present results from two event samples which correspond to integrated luminosities of $\mathcal{L}_{\mathrm{int}} = 21.1\,\mathrm{pb}^{-1}$ (low Q^2: $5 < Q^2 < 100\,\mathrm{GeV}^2$) and $\mathcal{L}_{\mathrm{int}} = 32.9\,\mathrm{pb}^{-1}$ (high Q^2: $150 < Q^2 < 5000\,\mathrm{GeV}^2$), respectively. Jets are selected in the Breit frame with $E_{\mathrm{T}} > 5\,\mathrm{GeV}$. The data are corrected for effects of detector resolution and acceptance, as well as for inefficiencies of the selection and for higher order QED effects.

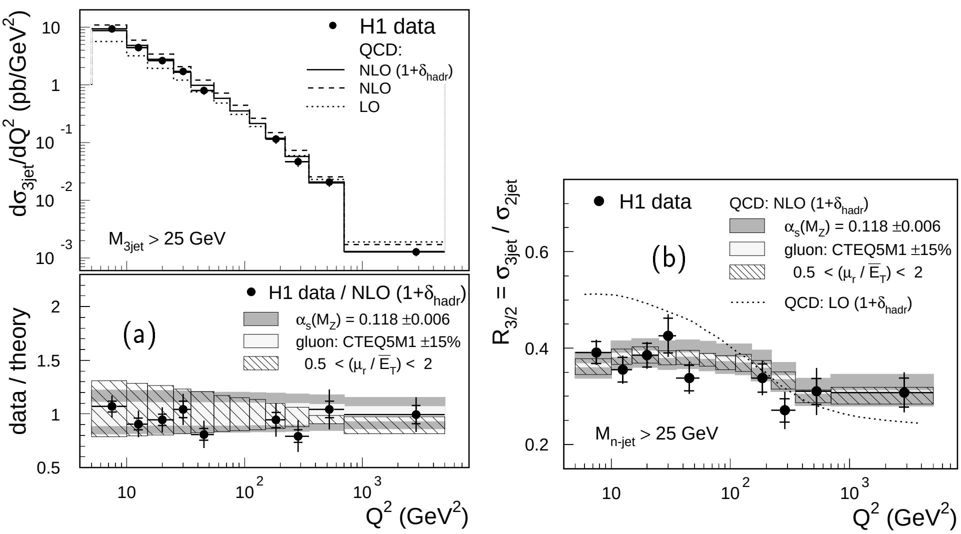

Fig. 1. The inclusive three-jet cross section (a) measured as a function of the four-momentum transfer squared Q^2. The predictions of perturbative QCD in LO (dotted line) and in NLO with (solid line) and without hadronization corrections (dashed line) are compared to the data. Also shown is the ratio of the measured cross section and the theoretical prediction, including the effects from variations of $\alpha_{\mathrm{s}}(M_Z)$, the renormalization scale μ_{r} and the gluon density in the proton. The ratio $R_{3/2}$ of the inclusive three-jet cross section to the inclusive dijet cross section (b) is compared to the LO (dotted line) and the NLO calculations (central value of the light band) including hadronization corrections. The sensitivity of the NLO calculation to parameter variations is indicated as in (a).

The measured three-jet distributions are presented in Figs. 1 and 2. The inner error bars represent the statistical uncertainties and the outer ones the quadratic sum of all uncertainties. The data are compared to pQCD predictions in LO and NLO with and without hadronization corrections. The LO and NLO calculations are carried out in the $\overline{\text{MS}}$-scheme for five massless quark flavors using the program NLOJET [3]. Renormalization and factorization scales (μ_r, μ_f) are set to the average transverse energy $\overline{E}_\text{T}$ of the three jets in the Breit frame. Hadronization corrections δ_hadr are determined using the Monte Carlo event generator LEPTO [4] as the relative change of an observable before and after hadronization.

Fig. 1(a) shows that over the whole range of Q^2 the NLO prediction (corrected for hadronization effects) gives a good description of the data — not only at high Q^2, where NLO corrections are small, but also at low Q^2, where the NLO prediction is a factor of two above the LO prediction. The theoretical prediction is subject to several uncertainties, the dominant sources being the value of the strong coupling, the parton density functions of the proton (especially the gluon density) and the renormalization scale dependence of the NLO calculation (see lower part of Fig. 1(a)). While for $Q^2 \gtrsim 50\,\text{GeV}^2$ the variation of α_s gives the largest effect, the renormalization scale dependence is the dominant source of uncertainty at lower values of Q^2, *i.e.* in the region where NLO corrections are also large. Over the whole Q^2 range the change of the cross section, induced by the variation of the gluon density is approximately half as large as the change induced by the α_s variation.

While the LO calculation predicts a stronger Q^2 dependence of the ratio $R_{3/2}$ than observed in the data (Fig. 1(b)), the NLO calculation gives a good description of the data over the whole Q^2 range. Uncertainties in the theoretical prediction for $R_{3/2}(Q^2)$ are investigated in the same way as for the three-jet cross section. The NLO corrections for the three-jet and the dijet cross sections are of similar size. At low Q^2 this leads to a smaller NLO correction and renormalization scale dependence for the ratio $R_{3/2}$ than for the cross section. Furthermore, when measured in the same region of x_Bj and Q^2, with the same cut on the invariant multi-jet mass, the three-jet and the dijet cross sections probe the parton density functions of the proton in the same range of proton momentum fractions $\xi = x_\text{Bj}(1 + M^2_{\text{n-jet}}/Q^2)$. Since both jet cross sections are dominated by gluon induced processes, $R_{3/2}$ is almost insensitive to variations of the gluon density in the proton. For the central value of $\alpha_\text{s}(M_Z) \approx 0.118$ used in the calculations, the theoretical predictions are consistent with the data for the three-jet cross section and the ratio $R_{3/2}$.

The normalized distributions of the angular variables $\cos\theta_3$ and ψ_3 are shown in Fig. 2. The $\cos\theta_3$ distributions in both Q^2 regions (here only the low Q^2 region is shown) are peaked at the cut value of $\cos\theta_3 = \pm 0.8$, corresponding to angles close to the proton and the photon direction. The phase space prediction shows the opposite behavior, falling towards

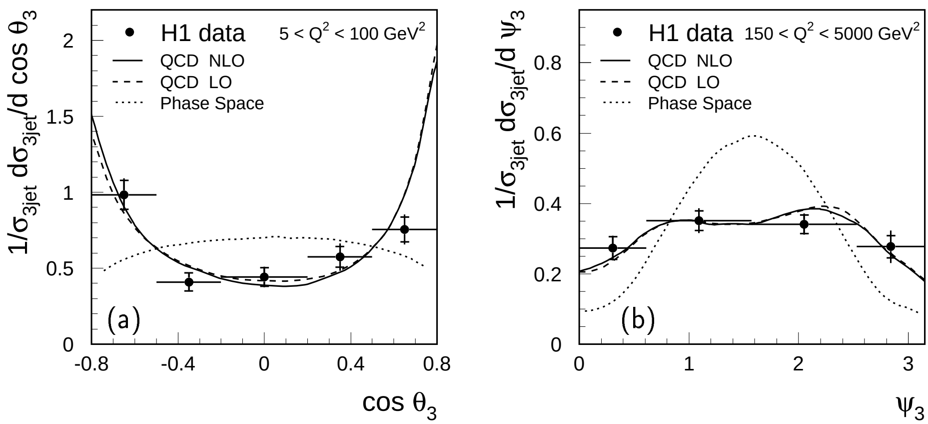

Fig. 2. Distributions of $\cos\theta_3$ at low Q^2 (a) and ψ_3 at high Q^2 (b). The data are compared to the predictions of perturbative QCD in NLO (solid line) and in LO (dashed line) and to a uniform population of the available three-jet phase space (dotted line).

$\cos\theta_3 \to \pm 0.8$. The QCD calculation in NLO gives a good description of the effects seen in the data. This is also the case for the measured ψ_3 distributions (here only the high Q^2 region is shown) which are relatively flat, while the underlying phase space is peaked at $\psi_3 = \pi/2$. Although at low Q^2 the NLO prediction is almost a factor of two higher than the LO prediction, the shapes of the angular jet distributions are almost unaffected by the NLO correction. QCD calculations, in contrast to the phase space predictions, indicate that, due to the bremsstrahlung nature of the process, configurations are preferred in which the plane containing the two lowest energy jets coincides with the plane spanned by the proton beam and the highest energy jet. This corresponds to values of $\psi_3 \to 0$ and $\psi_3 \to \pi$. The effects of cuts reduce this preference (Fig. 2(b)). These results are in qualitative agreement with measurements in $\bar{p}p$ collisions [5, 6] and in γp collisions [7].

4. Summary

The inclusive three-jet cross section and the ratio $R_{3/2}$ of the inclusive three-jet and the inclusive dijet cross section have been measured as a function of Q^2. The predictions of perturbative QCD in next-to-leading order give a good description of the three-jet cross section and the ratio $R_{3/2}$ over the whole range of Q^2 for values of the strong coupling close to the current world average of $\alpha_s(M_Z) \simeq 0.118$ [8]. Angular jet distributions have been measured in the three-jet center-of-mass frame. The angular orientation of the three-jet system follows the radiation pattern expected from perturbative QCD. While the angular distributions are not consistent with a uniform population of the available phase space, they are well described by the QCD predictions. This is the first — successful — test of $\mathcal{O}(\alpha_s^3)$ calculations at HERA.

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