Three-jet production in deep-inelastic electron–proton scattering to order α_s^2

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We study three-jet production in deep-elastic electron–proton scattering in second-order QCD perturbation theory. Virtual and real corrections to the Born terms are calculated. Only the transverse photon exchange contribution is considered, and terms of the order of the jet cut are neglected. We present numerical results for thrust distributions and for integrated cross sections depending on the jet resolution cut.

The preparation of electron–proton scattering experiments at HERA offers the possibility of studying deep-inelastic processes with high accuracy over a wide range of the kinematical parameters. In the hadronic final state one expects well separated hadron jets [1]. In the standard model these processes are described on the parton level by QCD. To disentangle new physics phenomena from those expected within the framework of the standard model, accurate higher-order predictions for jet rates are necessary. The $O(\alpha_s)$ corrections have been calculated in refs. [2–4] and are used in Monte Carlo simulations [5]. These corrections contribute to three- as well as to two-jet events. In $O(\alpha_s^2)$, the four-jet cross section has been studied [6], and even five-jet events up to $O(\alpha_s^3)$ have been investigated [7]. Here, however, the jet rates are quite low. For a genuine test of QCD, also the second-order contributions to three- and two-jet events should be known. The aim of this paper is to present first results on the $O(\alpha_s^2)$ corrections to three-jet events. We restrict our study to one-photon exchange and to a certain linear combination of the longitudinal and unpolarised cross sections. Furthermore, we drop terms that vanish if the jet cut is set to zero and do not take into account hadronisation effects.

To $O(\alpha_s)$, the tree diagrams of fig. 1 contribute. To $O(\alpha_s^2)$, we have to consider virtual as well as real corrections. The virtual corrections are given by the products of the graphs of fig. 2 with the graphs of fig. 1. To obtain the real corrections, we calculated the four-jet cross section by taking into account the tree graphs of fig. 3. After partional fractioning to separate initial- and final-state IR and collinear divergences, we integrated over the singular region of phase space, where a four-jet event looks like a three-jet event. Two particles are combined into one cluster if their invariant mass squared is less than cW^2, where c is the jet cut and W^2 is the invariant mass of the hadronic final state. The integrations have been regularised dimensionally, so the singularities show up as single and double poles in the parameter $\varepsilon=2-$

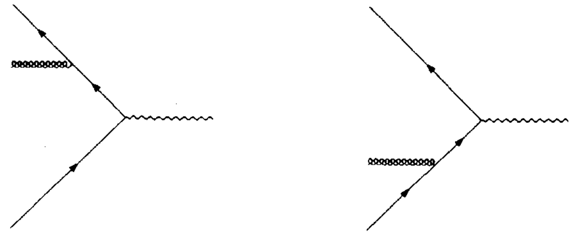

Fig. 1. Feynman diagrams $\gamma^*+\text{parton}\to 2$ partons, $O(g_s)$.

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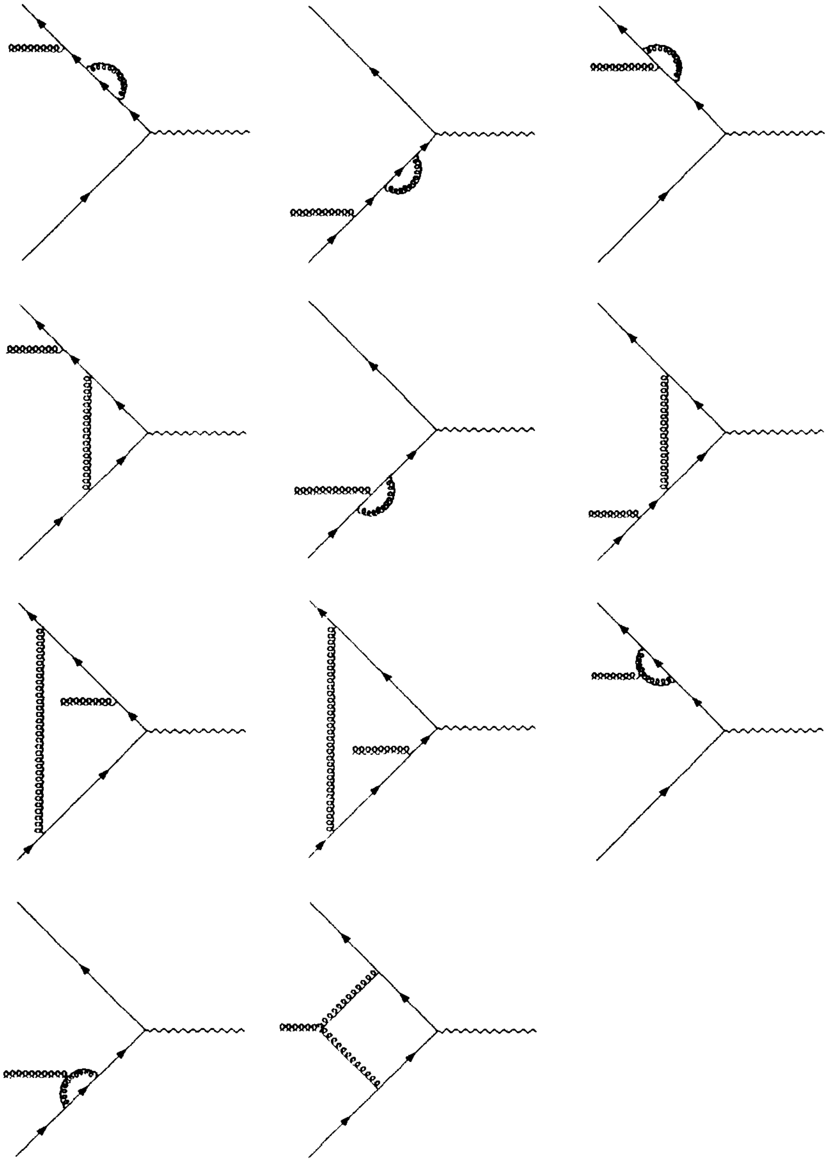

Fig. 2. Feynman diagrams $\gamma^* + \text{parton} \to 2$ partons, $O(g_s^3)$.

$d/2$, where d is the space–time dimension. The poles partially cancel against similar poles of the virtual corrections, which is a consequence of the Kinoshita, Lee and Nauenberg theorem [8]. However, contrary to e^+e^- annihilation, some poles remain. They can be factorised and then be absorbed into the renormalised parton densities [9]. Finally we obtained a finite three-jet cross section that we evaluated numerically by the adaptive Monte Carlo integration routine VEGAS [10].

The differential cross section may be decomposed into several helicity cross sections that reflect the angular correlations of the orientation of the hadronic final state relative to the outgoing lepton. A complete decomposition is given in refs. [3,4]. Here we only consider the contribution proportional to $d\sigma_U -$

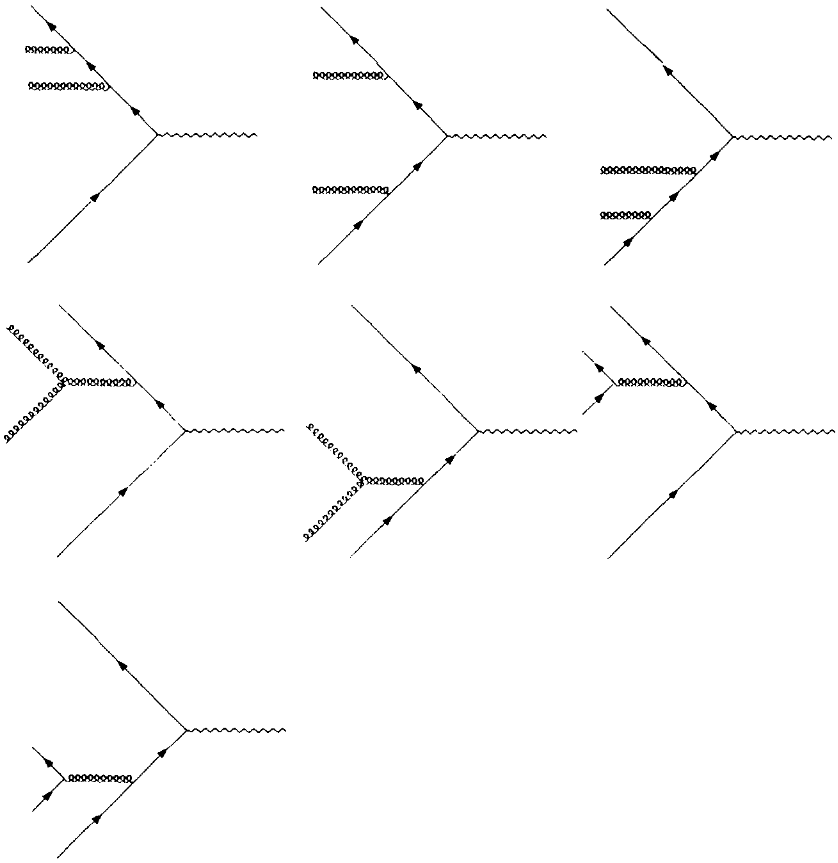

Fig. 3. Feynman diagrams $\gamma^* + \text{parton} \to 3$ partons, $O(g_s^2)$.

$d\sigma_L/2$ that is obtained by taking the trace of the hadron tensor. On the tree graph level, the angular integrated cross section is dominated by this contribution [4]. The region of deep-inelastic scattering is defined by $Q^2 \geqslant 4$ GeV^2, $W^2 \geqslant 12$ GeV^2 [3,6]. We used the parton density parametrisation of ref. [11], mode 1, with $\Lambda_{QCD} = 100$ MeV. For simplicity, Q^2 is used both as renormalisation and factorisation scale.

Fig. 4 shows the jet cut dependence of the cross section integrated over the deep-inelastic scattering region defined above for a CM energy of $\sqrt{s_H} = 314$ GeV. For small values of the jet cut, the Born cross section increases fast, as is expected. In comparison, the cross section up to order α_s^2 increases up to a cut value of $c \approx 0.01$, and then, for smaller cuts, decreases to become eventually negative, which means that perturbation theory and the scheme used to renormalise the parton densities break down. For reasonable cut value $c = 0.015$–0.04, the $O(\alpha_s^2)$ corrections are in the range of -26% to $+7\%$. We wish to stress that we neglected non-singular terms in our factorisation. These contributions vanish for $c = 0$, but they may modify the integrated cross section.

Of course, the question arises if there is a region for c in which the calculation is reliable, that means where terms $O(c)$ may be neglected, and where the terms $O(\ln^\alpha c)$ are small enough not te spoil the fixed-order calculation. The situation in deep-inelastic scattering can be compared with e^+e^- annihilation, where the same problem arises. In ref. [12], energy–energy correlation has been studied for different values of the jet cut. Here, terms O(cut) have been neglected, too. After adding 3-jet and 4-jet contributions, the leading logarithms in the jet cut cancel, and the result ap-

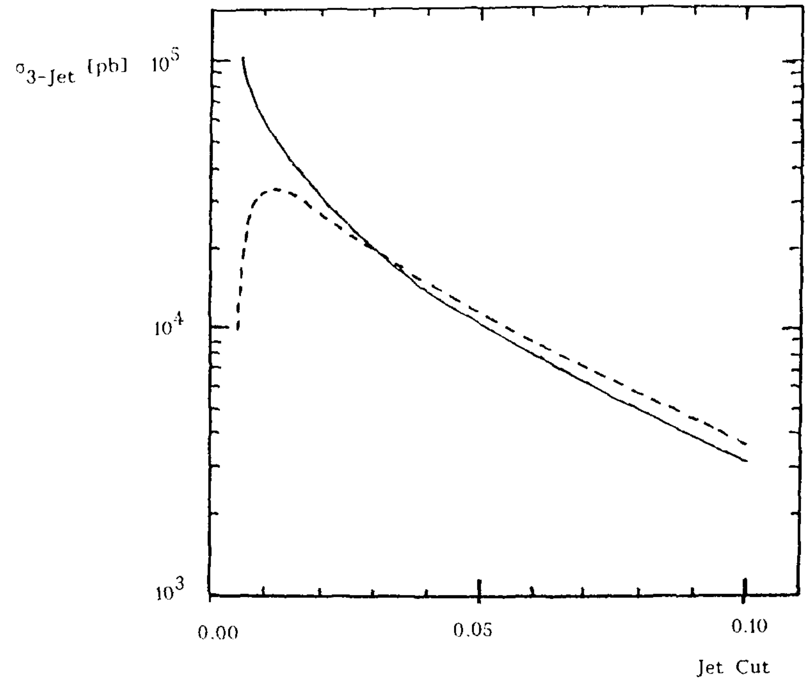

Fig. 4. Cut dependence of the integrated cross section. $O(\alpha_s)$ contribution: full line, $O(\alpha_s)+O(\alpha_s^2)$ contribution: dashed line.

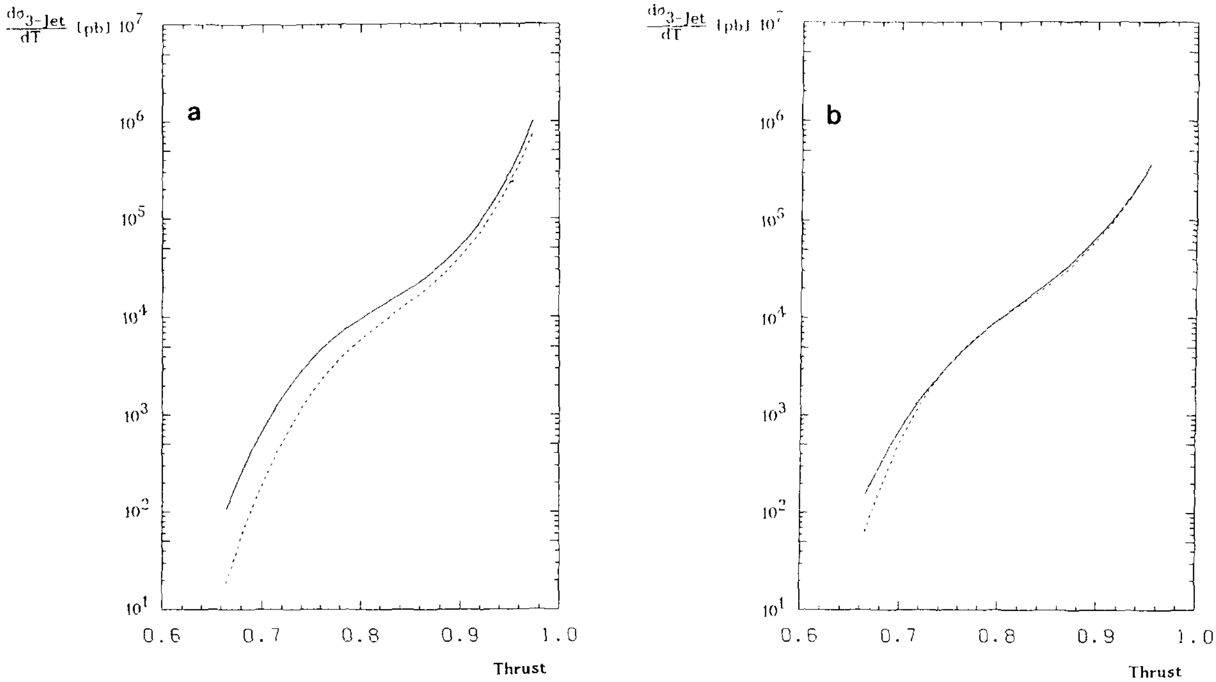

Fig. 5. Thrust distribution. $O(\alpha_s)$ contribution: full line, $O(\alpha_s)+O(\alpha_s^2)$ contribution: dashed line. (a) Cut=0.02, (b) cut=0.04.

proaches a limiting value for not too small values of the cut (see figs. 4 and 5 in ref. [12]). This means that in the calculation of ref. [12], it is a good approximation to neglect terms O(cut), if the cut is then chosen in a reasonable range. The situation in deep-inelastic scattering is analogous, at least for final state singularities.

In fig. 5 we show the thrust distribution [13] of the integrated cross section, again for $\sqrt{s_H}=314$ GeV. Qualitatively, the distributions for higher thrust values do not differ, if the Born terms are compared with the $O(\alpha_s^2)$ corrected cross sections. In magnitude, however, the corrections cannot be neglected

To summarise, we can say that for certain values of the jet cut the $O(\alpha_s^2)$ corrections to the three-jet cross section are substantial and should therefore definitely be included in future studies of jet cross sections.

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