Effects of the Hadronic Structure of the Photon at the DESY *ep* Collider HERA

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We investigate the production of hadronic jets with high transverse momenta p_T at the forthcoming DESY *ep* collider HERA. We find that events where the exchanged quasireal photon is resolved into quarks and gluons *dominate* the two-jet cross section for $p_T \lesssim 40$ GeV. We also find that this class of events contributes about 20% to the total $b\bar{b}$ and $c\bar{c}$ production. The possibility to use these processes to measure the gluon content of the photon is discussed.

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One of the first classes of events that will be studied at the forthcoming DESY *ep* collider HERA are events that contain two jets with high transverse momentum p_T. As a result of propagator effects the corresponding cross section is dominated by events where the exchanged photon is (almost) on shell, which means that the scattered electron will go in a forward direction and thus vanish in the beam pipe.

In lowest order in the electromagnetic coupling constant $\alpha_{\rm em}$ and the strong coupling constant α_s two distinct processes contribute to this inclusive two-jet cross section; see Fig. 1. In the first class [Fig. 1(b)], the photon couples directly to a quark or gluon within the proton, whereas in the second class [Fig. 1(a)] the photon is also resolved into quarks and gluons which then interact with the partons inside the proton. Henceforth we shall refer to the contributions from the first type of process as "direct contributions," and to those from the second type as "resolved-photon contributions." Note that both classes of contributions are of order $\alpha_{\rm em}^2\alpha_s$, since the parton distributions $\mathbf{q}^\gamma=(u^\gamma, d^\gamma, G^\gamma)$ inside the photon are[1] of order $\alpha_{\rm em}/\alpha_s$.

Up to now the only existing experimental information on $\mathbf{q}^\gamma$ comes from e^+e^- colliders where the electromagnetic photon structure function F_2^γ has been measured[2]; unfortunately these measurements suffer from a rather poor statistics, and the momentum scale with which the on-shell photon could be probed is limited to $Q^2 \lesssim 100$ GeV^2; finally, F_2^γ depends on G^γ only in higher order in QCD, which means that practically nothing is known experimentally about the gluon content of the photon.

The situation looks somewhat brighter on the theoretical side. It has been known[1,3] for more than ten years that $\mathbf{q}^\gamma$ can be predicted from QCD in the limit of large Q^2. Unfortunately these "asymptotic" predictions diverge as Bjorken x approaches zero, and it can be shown[4] that these divergences become worse in higher orders in α_s. Furthermore, it is not clear[5] how large Q^2 has to be in order to make the asymptotic predictions trustworthy even for medium and large values of x. Further experimental information is necessary before the ongoing[6] discussion about these questions can be settled. This information might come from the study of the resolved-photon contributions to two-jet events.

They are given by

$$\frac{d\sigma}{dp_T}=2p_T\int_{4p_T^2/s}^{1} dz\, f_{\gamma|e}(E,z)\int_{4p_T^2/\tilde{s}}^{1} dx_p\int_{4p_T^2/x_p\tilde{s}}^{1} dx_\gamma\, V_p(x_p,Q^2)V_\gamma(x_\gamma,Q^2)\left[\frac{d\hat{\sigma}}{dp_T^2}(\hat{s},\hat{t},\hat{u})+\frac{d\hat{\sigma}}{dp_T^2}(\hat{s},\hat{u},\hat{t})\right]. \quad (1)$$

Here, $\tilde{s}\equiv zs$ is the squared c.m.-system-energy of the photon-proton system, and $\hat{s}=x_p x_\gamma \tilde{s}$ the corresponding quantity in the parton-parton system; $\hat{t},\hat{u}$ are then determined by $\hat{s}$ and p_T. The relevant parton densities are labeled V_p for the proton and V_γ for the photon, and $\hat{\sigma}$ is the parton-parton cross section.[7] Furthermore, $f_{\gamma|e}$ describes the flux of (almost) real photons; in Weizsäcker-Williams (leading-logarithm) approximation it is given by[8]

$$f_{\gamma|e}(E,z)=\frac{\alpha}{2\pi}\,\frac{1+(1-z)^2}{z}\ln\frac{\bar{E}^2}{m_e^2}, \quad (2)$$

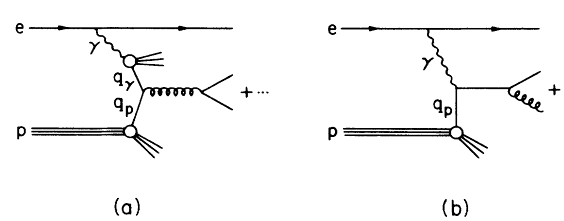

FIG. 1. Typical Feynman diagrams for (a) resolved and (b) direct contributions to two-jet production at HERA.

where we have used $\bar{E}^2 = s x_p z$ with $\sqrt{s} = 314$ GeV; this choice is somewhat arbitrary, but is known[9] to work quite well for heavy-quark production via photon-gluon fusion at HERA. Finally, we chose $Q^2 = \hat{s}$ for the momentum scale in Eq. (1). We used $N_f = 3$ flavors in $\alpha_s(Q^2)$ and $V_\gamma(Q^2)$ for $Q^2 < 50$ GeV^2; $N_f = 4$ for 50 GeV$^2 \leq Q^2 \leq 500$ GeV^2; and $N_f = 5$ for $Q^2 > 500$ GeV^2.

The corresponding expression for the direct contributions can be obtained from Eq. (1) by our setting $V_\gamma(x_\gamma, Q^2) = \delta(1 - x_\gamma)$ and inserting the relevant subcross sections.[10] Obviously it would be very hard to extract information on $\mathbf{q}^\gamma$ from the two-jet cross section if it were dominated by these direct contributions.[11]

In Fig. 2 we show the ratio R_σ of resolved to direct contributions to the total two-jet cross section as a function of the jet transverse momentum p_T. It is striking to note that the direct contributions dominate only for large values of p_T, $p_T \gtrsim 40$ GeV, whereas for $p_T \lesssim 10$ GeV the resolved-photon contributions are at least 4 times *bigger* than the direct ones. This means that the perturbative part of the total *ep* cross section at HERA energies will be *dominated* by events where the photon is resolved into quarks and gluons. These events will look very similar to minijet events at a $p\bar{p}$ collider.

The results of Fig. 2 have been derived from the second set of parametrizations given by Duke and Owens[12] for the proton structure functions. Note that the direct contributions probe smaller values of x_p than the resolved-photon contributions; therefore, R_σ does depend on the shape of the parton distribution functions inside the proton, especially at small x_p. Fortunately these can be measured at HERA in deep-inelastic *ep* scattering.

The two curves in Fig. 2 correspond to the two existing parametrizations of $q^\gamma(x, Q^2)$. The solid curve has been obtained from the parametrization of Drees and Grassie[13] (DG), which have been obtained by solving the evolution equations[14] starting from a finite $\mathbf{q}^\gamma(x, Q_0^2 = 1$ GeV$^2)$, and are thus free of $x \to 0$ divergences. For the dashed curve the parametrization given in Ref. 10 (DO) for the singular asymptotic prediction for $\mathbf{q}^\gamma$ has been used. Unfortunately, the difference between these two parametrizations becomes apparent only for $p_T \lesssim 6$ GeV; this region might be hard to explore with the planned HERA detectors.[15] On the other hand, at $p_T = 3$ GeV the $x \to 0$ divergence of the asymptotic solution becomes apparent, increasing the cross section by almost 50% compared with the prediction of the DG parametrization.

In Fig. 3(a) we show the resolved-photon contributions to the cross section, where we have used the DG parametrizations. The long-dashed, short-dashed, and long-short-dashed curves represent final states with two quarks (where "quark" means any type of quark or anti-

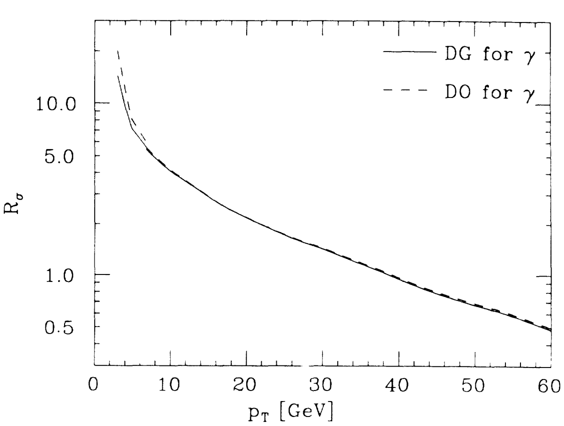

FIG. 2. The ratio R_σ of resolved-photon to direct contributions to the two-jet cross section at HERA ($\sqrt{s} = 314$ GeV), as a function of the jet transverse momentum p_T, where set 2 of Ref. 12 has been used for the proton structure functions. The solid and dashed lines are for two different parametrizations of $\mathbf{q}^\gamma$: DG, Ref. 13, and DO, Ref. 10.

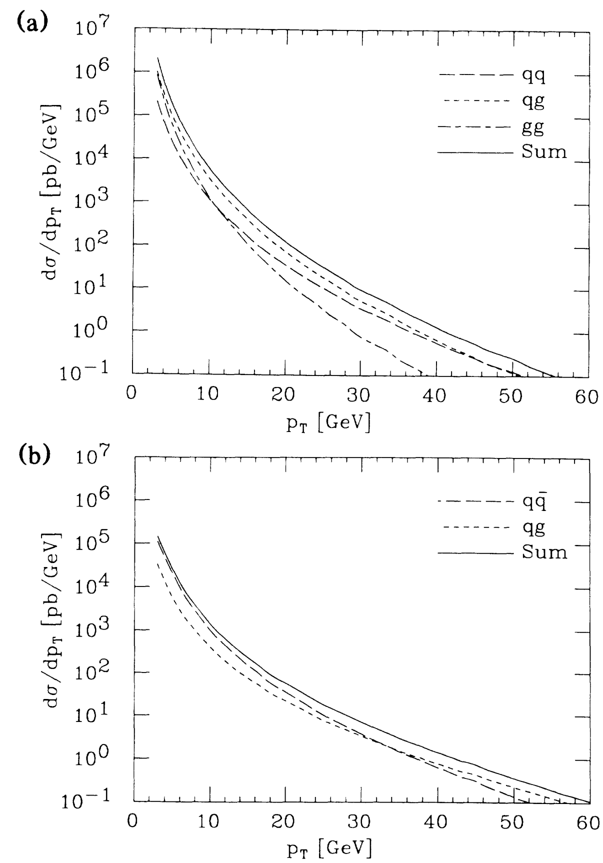

FIG. 3. Contributions of the (a) resolved-photon and (b) direct mechanism to the two-jet cross section at HERA. Contributions from final states of the hard scattering process containing two quarks, two gluons, or one quark and one gluon are shown separately, where "quark" means any quark or antiquark. In (a) the parametrization of Ref. 13 for $\mathbf{q}^\gamma$ has been used. The other parameters are as in Fig. 1.

TABLE I. Contribution to the total heavy-quark production cross section; the first three lines are for $c\bar{c}$ and the last three lines for $b\bar{b}$ production. The first three columns show the contributions from $q\bar{q}$ annihilation and gg fusion and the sum of both for the parton distributions inside the photon of Ref. 13. The fourth column shows the total resolved-photon contribution if the parametrization of Ref. 10 for $\mathbf{q}^\gamma$ is used, and the fifth column shows the direct contribution from γg fusion in the Weizsäcker-Williams approximation.

$m_{c,b}$ (GeV)	DG, from $q\bar{q}$ (nb)	DG, from gg (nb)	DG, sum (nb)	DO, sum (nb)	direct (nb)
1.2	20	190	210	530	940
1.5	10	88	98	190	610
1.8	5.7	45	51	85	410
4.5	0.3	1.2	1.5	1.7	7.0
5	0.21	0.73	0.94	1.05	4.9
5.5	0.16	0.47	0.63	0.67	3.6

quark), one quark and one gluon, and two gluons, respectively. In sharp contrast to corresponding predictions for $p\bar{p}$ scattering, the two-gluon final state dominates only at very small p_T, $p_T \lesssim 3$ GeV; this also explains why different *Ansätze* for $\mathbf{q}^\gamma$, which all agree with existing data on F_2^γ, can only be distinguished in the low-p_T region, since they mainly differ in G^γ, which has not yet been measured. Note that the qg final state is rather insensitive to G^γ since (for $p_T \gtrsim 10$ GeV and the DG parametrizations for $\mathbf{q}^\gamma$) more than 75% of this final state is initiated by a quark from the photon and a gluon from the proton. The reason is that the quark distributions inside the photon are very hard, i.e., peak around $x_\gamma \simeq 0.8$, which in turn allows for a rather small value of x_p, whereas the gluon distribution in the photon peaks at $x_\gamma = 0$. Finally, the two-quark final state is dominant only for $p_T \gtrsim 45$ GeV, where the total two-jet cross section is already dominated by the direct contributions. It is encouraging to note, however, that the total resolved-photon contribution at $p_T = 40$ GeV still exceeds 1 pb/GeV.

For comparison we show the predictions from the direct contributions in Fig. 3(b). We find that for $p_T > 40$ GeV it is dominated by the qg final state; in principle, it might therefore be possible to extract the resolved-photon contributions even at these large values of p_T by analysis of the final state, although the smallness of the cross section will make this impossible beyond $p_T \simeq 50$ GeV or so.

As mentioned earlier, the HERA detectors will probably not be able to identify jets with p_T less than 5 to 10 GeV; this makes it hard to extract G^γ from this measurement. However, the contributions proportional to G^γ can be enhanced by our studying specific final states. One obvious candidate is the production of a heavy-quark–antiquark pair. This has been studied in Ref. 13 for the case of the top quark, where it was found that the resolved-photon contributions are negligible.

In Table I we give the resolved-photon and direct contributions to the total $c\bar{c}$ and $b\bar{b}$ cross section at HERA. In case of the DG parametrization of $\mathbf{q}^\gamma$ we show the contributions from gluon fusion and $q\bar{q}$ annihilation separately; obviously heavy-quark production is sensitive to G^γ. On the other hand, the direct contributions[16] to both charm and bottom production are about 4 times bigger than the resolved-photon contributions; a measurement of G^γ is therefore only possible if the two contributions can be separated, either by detection of the spectator jet from the photon in the resolved-photon case, or by our looking at some differential cross sections. This will also be necessary if one wants to extract some information about the gluon distribution inside the *proton* from heavy-quark production.

We have thus found that contributions that originate from the quark and gluon content of the photon *dominate* the two-jet cross section at HERA for jet transverse momenta up to about 40 GeV, and contribute about 20% to the total $b\bar{b}$ and $c\bar{c}$ cross sections. This means that most hard scattering events at HERA look very similar to those at a hadron-hadron collider with unequal beam energies. On the other hand, the magnitude of these cross sections might provide us with an opportunity to measure[17] the gluon content of the photon about which at present very little is known experimentally.

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