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Total and jet photoproduction cross sections at DESY HERA and Fermilab energies

Raj Gandhi and Ina Sarcevic
Physics Department, University of Arizona, Tucson, Arizona 85721
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We present results of calculations of the total and jet photon-proton cross sections at energies of relevance to the Fermilab E683 experiment and the ZEUS and H-1 experiments at the DESY *ep* collider HERA. The calculations take into account the high-energy QCD structure of the photon and are performed for two different photon structure functions. We discuss how these forthcoming experiments may be able to provide important information on two major uncertainties inherent to the calculation of photoproduction cross sections in particular and, in a more general context, to the nature of strong interactions. If the total photoproduction cross section is measured at E683 energies ($\sqrt{s}=16$–28 GeV), it will provide a firmer value for $p_T^{\min}$, the lower bound on the transverse momentum of outgoing jets, which signals the onset of hard scattering. At HERA energies ($\sqrt{s}$ up to 300 GeV), the total and jet cross sections will help determine the photon structure function better at low x (the fractional parton momentum) values, currently a region where there are large uncertainties due to a lack of data.

Measurements up to $\sqrt{s}=18$ GeV [1–4] of the total hadronic photoproduction cross section $\sigma_T(\gamma\text{-}p)$ point towards a hadronlike behavior for the photon. In this range the cross section first decreases with energy to a minimum and then increases, as observed in hadron-hadron collisions [5]. If the photon continues to mimic hadronic behavior, the rise in the total cross section should continue at higher energies, presumably due to the dominance of hard-scattering partonic processes over higher-order nonperturbative ones. In p-p and p-$\bar{p}$ collisions, the rise of the cross section has been effectively modeled [6–11] by

$$\sigma_T=\sigma_{\rm soft}+\sigma_{\rm jet}\,. \tag{1}$$

Here $\sigma_{\rm soft}$ is the nonperturbative contribution to the total, and is taken to be constant at all but the lowest energies. $\sigma_{\rm jet}$, on the other hand, is the perturbative contribution from QCD jet processes, which rises rapidly with energy. One of the important inputs in the calculation of the total cross section is a cutoff for the transverse jet momentum, $p_T^{\min}$, which signals the onset of hard scattering. By appropriately fixing this at the relevant energy, one can obtain agreement with CERN ISR, CERN collider, and cosmic-ray data [11–13]. The actual value of $p_T^{\min}$, however, below which nonperturbative processes make important contributions, is impossible to pin down theoretically using perturbative techniques.

In what follows, we shall assume that the above features of hadron-hadron collisions carry over to γ-p interactions. The physical picture underlying this conceptual extension is that the photon, with increasing probability at higher energy, produces a q-$\bar{q}$ pair, and the subsequent QCD evolution fills up the confinement volume with quarks and gluons with a density akin to that of a pion or nucleon. The ensuing γ-p interactions thus mimic the general features of p-p collisions up to a photon structure function, which essentially parametrizes the quark and gluon content of the photon. Although it was shown that in the limit of very high momentum transfers (Q^2) these distributions are completely calculable [14], there are unphysical divergences associated with these solutions as $x\rightarrow 0$ [15,16]. A more extensive discussion of this important theoretical issue can be found, for instance, in [17] and references therein. The two existing parametrizations of the photon structure function which we shall use here are those of Duke and Owens [18] (DO) and Drees and Grassie [19] (DG). Although good agreement with existing low-energy data is obtained using both these distributions, they differ dramatically in their predictions at higher energy (and low x), as has been shown recently by their application to high-energy cosmic-ray photons interacting with the atmosphere [20,21]. Recently it has been emphasized by Drees and Godbole [17] and by Baer, Ohnemus, and Owens [22] that the measurement of inclusive multijet photoproduction cross sections at the DESY *ep* collider HERA over a range of p_T will yield important information on the hadronic content of the photon. In this Rapid Communication we discuss how measurements of the *total* inelastic photoproduction cross section σ_T, and the total jet cross section $\sigma_{\rm jet}$ [as defined in Eq. (1) above] both at HERA and the Fermilab E683 experiment, can also help resolve uncertainties about the low-x behavior of the photon structure function and pin down the value of $p_T^{\min}$ used to determine the onset of hard-scattering processes.

Both E683 at Fermilab and the H-1 and ZEUS experiments at HERA will use tagged photons which are obtained from bremsstrahlung off electrons and are almost on mass shell. Precise measurement of the photon energy will be possible by measuring initial and final electron momenta. The range of photon energies probed at E683 is $\sqrt{s}=16$–28 GeV, while much higher energies are accessible at HERA, eventually up to $\sqrt{s}=400$ GeV. Keeping in mind the possible measurements for both experiments, we provide results both for σ_T and $\sigma_{\rm jet}$: the former for two values of $p_T^{\min}$, 1.4 and 2 GeV; and the latter for three different jet triggers, 3, 4, and 5 GeV, at fixed-target energies, and 5, 10, and 15 GeV at HERA energies.

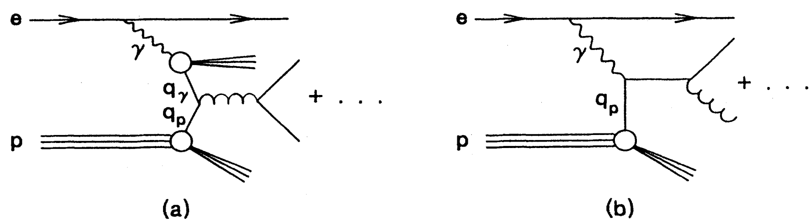

FIG. 1. Feynman diagrams depicting (a) a generic QCD anomalous process and (b) direct process relevant to two-jet production at HERA. q_γ and q_p are partons from the photon and proton, respectively.

We begin by giving the QCD jet cross section for photon-proton interactions,

$$\sigma_{\rm jet}(\gamma+p\to 2\ {\rm jets})=\sum_{ij}\frac{1}{1+\delta_{ij}}\int dx_\gamma dx_p\int_{p_{t,\min}}^{2} dp_t^2[f_i^{(\gamma)}(x_\gamma,\hat{Q}^2)f_j^{(p)}(x_p,\hat{Q}^2)+i\leftrightarrow j]\frac{d\hat{\sigma}_{ij}}{dp_t^2}(i+j\to 2\ {\rm jets})\,. \qquad (2)$$

Here, a caret denotes a parton-level quantity. The $\hat{\sigma}_{ij}$ are thus the appropriate parton-parton interaction cross sections for partons i and j, the expressions for which may be found, for instance, in [23]. $f_i^{(\gamma)}(x_\gamma,\hat{Q}^2)$ $[f_j^{(p)}(x_p,\hat{Q}^2)]$ is the probability that the photon [proton] contains a parton i [j] which carries a fraction x_γ [x_p] of its momentum. $\hat{Q}^2$ characterizes the scale of the parton-level process. We have used the choice $Q^2=p_T^2$ in all our calculations, a choice that appears to work well in hadronic minijet calculations [24]. We also note that the photon structure functions are proportional to $\alpha_{\rm em}/\alpha_s$, where $\alpha_{\rm em}$ is the electromagnetic coupling. The effective order of the above processes is therefore $\alpha_{\rm em}\alpha_s$, since the jet cross sections are of order α_s^2. Thus, they are of the same order as direct two-jet processes, in which the photon-parton vertex is electromagnetic and does not involve the photon's hadronic content (Fig. 1). These direct processes have been included in our calculations, and we show their contributions separately, although for the most part they are significant only at low energies. At all energies, however, the anomalous QCD processes dominate direct contributions to the total and jet cross sections, because the former increase sharply at low values of p_T and x. This sensitivity makes the measurement of these quantities an excellent testing ground for the hadronic structure of the photon. In all calculations, we have used the Eichten-Hinchcliffe-Lane-Quigg (EHLQ) parametrizations [25] of the proton structure function. The results are not appreciably sensitive to different choices of distribution functions for the proton.

In addition to the direct and anomalous jet processes,

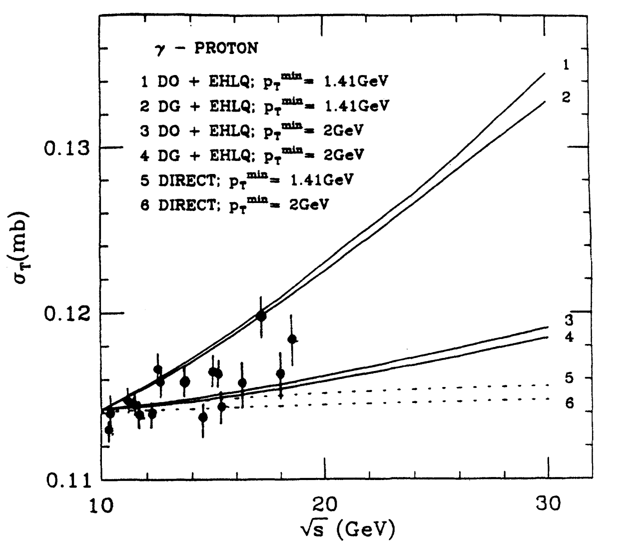

FIG. 2. Total inelastic cross section ($\sigma_{\rm jet}+\sigma_{\rm soft}$) predictions for low-energy fixed-target experiments (curves 1–4). The jet part includes contributions from direct processes. Results for two different choices of $p_T^{\min}$ and structure functions are shown. Also shown separately are contributions of direct processes, added to the constant soft part (curves 5 and 6). The value for $\sigma_{\rm soft}$ has been chosen to give the same total cross section for any choice of $p_T^{\min}$ and structure functions at $\sqrt{s}=10$ GeV.

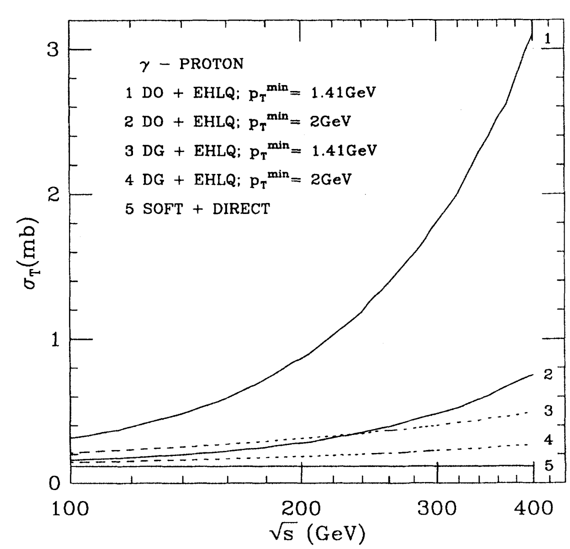

FIG. 3. Same quantities as in Fig. 2, but for HERA energies. The direct contribution to the total added to $\sigma_{\rm soft}$ (curve 5) is shown only for $p_T^{\min}=1.41$ GeV, since there is no appreciable difference between the results for the two different choices of this cutoff.

σ_T also has a contribution from nonperturbative processes ($Q^2 \approx 1$ GeV), which we have assumed to be constant with energy. From the data in [1], we find that $\sigma_{\rm soft} \approx 0.114$ mb, and this value has been used in our results. It acts as an effective threshold value above which QCD hard-scattering effects drive a steep increase in the jet and total cross sections.

Figure 2, plotted for E683 energies, shows our results for the total cross section [$\sigma_T = \sigma_{\rm soft} + \sigma_{\rm jet}$ (curves 1–4)]. Note that the jet part is the sum of the direct and anomalous contributions, as discussed above. The data points are from [1]. Both DG and DO give similar results in this range, but the dependence on the choice of $p_T^{\rm min}$ is dramatic. The two values of $p_T^{\rm min}$ chosen are motivated by the low-energy data shown, and it appears that the value of $p_T^{\rm min}$ marking the onset of hard scattering in photon-proton collisions is between 1.4 and 2 GeV. The low-energy data indicate that towards the upper end of the energy range probed by earlier experiments [1], a rise of about 3% is seen in the total cross section. This is presumably the tail of the expected increase due to QCD effects. Although the main emphasis at E683 will be on measuring jet effects using p_T triggers [26], we would encourage a measurement of the total cross section in view of the information on $p_T^{\rm min}$ that can be obtained. This is especially significant since, with this information, the measurement of the total cross section at HERA can increase our knowledge of the photon distribution functions, as we discuss below.

Also shown in Fig. 2 are contributions of the direct processes, added to the constant soft contribution of 0.114 mb (curves 5 and 6). The direct part is significant mostly in

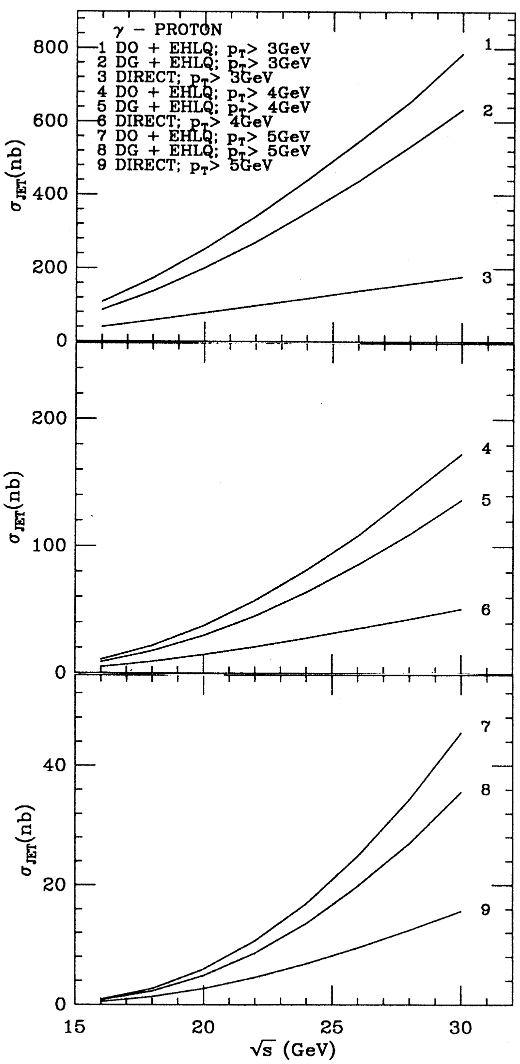

FIG. 4. Total jet cross sections $\sigma_{\rm jet}$ for low energies. As before, this includes both direct and anomalous contributions (curves 1, 2, 4, 5, 7, and 8) and the direct contributions alone (curves 3, 6, and 9). Results for three different jet triggers, $p_T = 3$, 4, and 5 GeV are shown, for both DG and DO structure functions.

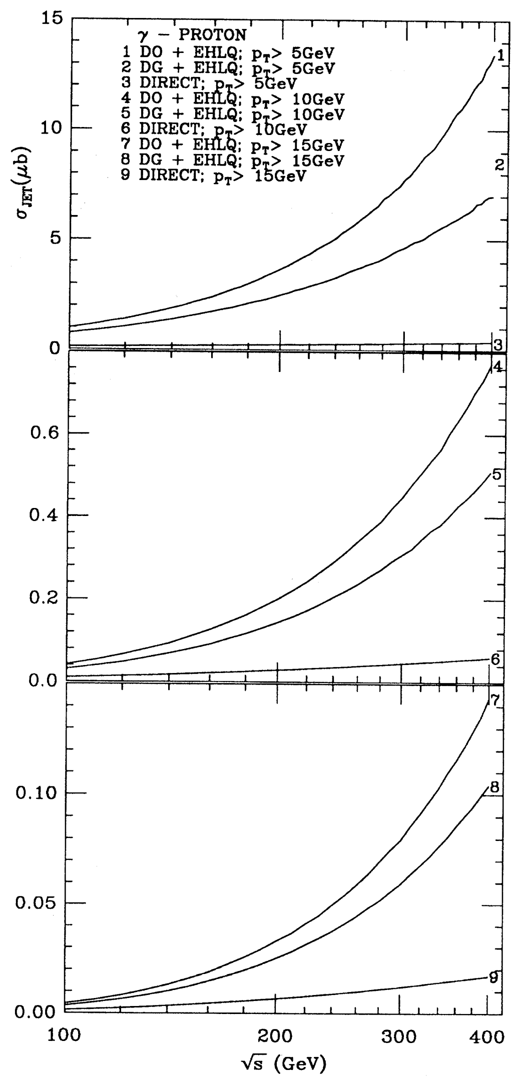

FIG. 5. Same quantities as in Fig. 4, but for HERA energies. As before, the two upper curves are $\sigma_{\rm jet}$, including direct contributions, while curves 3, 6, and 9 are direct contributions alone. Three different p_T triggers for jet discrimination relevant to HERA have been chosen, $p_T > 5$, 10, and 15 GeV.

the first half of the energy range, and should be small compared to jet contributions as QCD effects set in. These pointlike effects do make important contributions to inclusive photoproduction cross sections at higher values of p_T, as has been discussed in [17] and [22].

Figure 3 shows the same quantities as Fig. 2, but at HERA energies. The difference between results obtained using DO and DG (for the same $p_T^{\min}$) is large, especially for the lower cutoff of 1.41 GeV. Essentially the two parametrizations differ significantly for low values of $x \approx 4p_T^2/s$, which will be probed at the e-p collider for the first time. Obviously, if the $p_T^{\min}$ value is pinned down fairly well by low-energy data from fixed-target experiments, then the hadronic structure of the photon at low x can be understood better. We note that the DO results are much more sensitive to changes in the momentum cutoff than those obtained using DG. This results in different shapes with rising energy for the two structure functions, an important discriminating feature. The direct part, shown here only for one value of the cutoff, shows almost no increase with energy compared to QCD effects.

Figure 4 shows total jet cross sections (direct plus anomalous) contributions at E683 energies for jet transverse momenta greater than 3, 4, and 5 GeV. These cross sections will be measured at Fermilab in the immediate future. Differences of 15–20% exist between the predictions of DO and DG structure functions, especially as the energy rises, and these may be distinguishable in the measurements, even though experimental uncertainties would affect them somewhat. We note that as the transverse-momentum cutoff rises, the differences between the DG and DO predictions seem to increase, perhaps making such measurements easier. The direct contributions are also given separately, and manifestly have a less steeper change with rising energy.

Finally, Fig. 5 shows the same quantities as Fig. 4, but for HERA energies. The differences in structure functions are very much in evidence here, and the predictions differ approximately by a factor of 2 towards the upper end of the energy range. More than before, the pointlike contributions are negligible compared to the QCD ones.

In conclusion, we have used techniques confirmed in p-p collisions over a wide range of energies (Refs. [6–11]) to obtain a handle on total and jet cross sections for photoproduction. We stress that measurements of the total and jet photoproduction cross sections can provide important information both at HERA and at lower energies accessible to fixed-target experiments. First, they will provide important confirmation of the hadronlike nature of photon-proton interactions. Second, low-energy measurements of the total cross section can help fix a value for the transverse momentum marking the onset of hard-scattering contributions over soft, nonperturbative processes. We have shown that present data seem to indicate that this quantity lies between 1.4 and 2 GeV, but that still translates into a fairly large band of total cross sections at high energies. With this value pinned down better than it is currently, one can use the high-energy total and jet cross section data at HERA to obtain valuable information on the photon structure function. Specifically, the measurements can help determine the reliability of the existing parametrizations of the photon structure functions, and point to ways in which they may be extended and improved using data from hitherto unprobed regions of x. In this context, we note that parametrizations are only as good as the data on which they are based, and our use of the DO and DG functions is, in this respect, an extrapolation. This, however, does not discount the fact that measurements at HERA will be very important in determining whether the "true" structure of the photon is closer to the DO or to the DG predictions, since their behavior with rising energy is substantially different. In our view, the data will likely lie between the sharply increasing cross sections predicted by DO and the more conservative results obtained using DG functions.

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