Hadron Structure of High-Energy Photons

M. Drees and F. Halzen
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
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We identify a new class of potentially large inclusive cross sections for the production of hadrons when high-energy photons interact with protons. Their origin is the abundant gluon content of very-high-energy photons. They can enhance the hadron (and also muon) content of high-energy electromagnetic showers as indicated by cosmic-ray observations and most dramatically illustrated by our failure to understand the muon content of photon showers from point sources. Experiments at the DESY *ep* collider HERA are in an ideal position to identify these contributions to photoproduction.

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The issue of the hadronic structure of high-energy photons has attracted renewed attention for a variety of reasons. The HERA electron-proton collider at DESY will soon study the photon structure function in an extended kinematic regime. Our knowledge of the hadron content of photon showers has also been recently challenged by a range of cosmic-ray experiments.[1] We here identify a mechanism for abundant photoproduction of hadrons associated with the large gluon content of high-energy photons. We foresee the possibility of photoproduction of hadron with inclusive cross sections in excess of the $\sim 10^2$-μb γp cross section observed with existing photon beams. These cross sections are rapidly rising in the $\sqrt{s} \simeq 0.5$ TeV energy range and could therefore be observed at HERA. Above incident energies of 10 TeV large photoproduction cross sections will increase the muon content of cosmic-ray photons by $\pi \to \mu$ decay, and our results could therefore have some relevance to our inability[1] to understand the muon content of showers initiated by photons emitted by point sources.

The basic point made in this Letter can be argued independently of the more detailed estimates which follow. The photoproduction of jets is an $O(\alpha\alpha_s)$ process. It is therefore $O(\alpha/\alpha_s)$ relative to hadronic jet production which is $O(\alpha_s^2)$, and photoproduction cross sections will therefore be intermediate between typical electromagnetic and hadronic cross sections. At energies where the hadron (gluon) content of the photon becomes significant, photoproduction of jets will exhibit rapid energy dependence to reach the expected $\sim$1-mb cross section. The rise is associated with the sampling of the gluon structure functions at decreased x values when collision energy is raised. The effect has been observed as "minijets" in $p\bar{p}$ collisions which reach values of $\sim \sigma_{\rm tot}$ as a result of the large number of soft gluons in high-energy hadrons.

We consider first the QCD calculation of high-p_T hadron jets in γp interactions; see Fig. 1. The diagrams are of the form[2]

$$\frac{d\sigma}{dx\,dx'\,dp_T^2} = f_i^\gamma(x,p_T^2) f_j^p(x',p_T^2) \frac{d\hat{\sigma}_{ij}}{dp_T^2}. \qquad (1)$$

Here f^γ (f^p) represents the photon (proton) quark and gluon structure functions and summation over all $q\bar{q}$, qg, and gg subprocesses $\hat{\sigma}$ is understood. The perturbative calculation should give a reliable estimate of the cross section for $p_T^2 \gg \Lambda^2$, in practice for $p_T^2 > (2\text{–}3\ \text{GeV})^2$ as illustrated by jet physics at $p\bar{p}$ colliders.[3] The total jet yield for $p_T^2 > p_{T\,\rm min}^2$, i.e.,

$$\sigma^{\gamma p}(\sqrt{s}) = \int_{p_{T\,\rm min}^2} dx\,dx'\,dp_T^2 \frac{d\sigma}{dx\,dx'\,dp_T^2}, \qquad (2)$$

is shown in Fig. 2 for three choices of $p_{T\,\rm min}$. We used the γ and p structure functions of Refs. 4 and 5, respectively. We have checked that the results do not change significantly for other choices of the proton structure function or of the evolution scale Q^2 taken to be p_T^2 in Eq. (1). They do, however, depend on the choice of photon structure function f_i^γ. The results for three choices[4,6,7] of photon structure functions are compared in Fig. 3.

Drees and Grassie[4] used $u^\gamma = (e_u/e_d)^2\, d^\gamma$ and estimated the gluons from bremsstrahlung off the quarks, i.e.,

$$g^\gamma(x,Q_0^2) = \frac{\alpha_s}{2\pi} \ln\frac{Q_0^2}{\Lambda^2} \int_x^1 \frac{dy}{y} P_{q\to g}\left(\frac{x}{y}\right) \sum_i [q_i^\gamma(y,Q_0^2) + \bar{q}_i^\gamma(y,Q_0^2)]. \qquad (3)$$

Consequently, $u^\gamma, d^\gamma, g^\gamma$ were properly evolved from $Q_0 = 1$ GeV. A similar estimate for f^p would considerably underestimate the gluon structure function of the nucleon. We therefore consider the calculation in Fig. 2 conservative. The input distributions do fit the photon structure function as shown in Ref. 4. In the kinematic region of the data[8] the measured quantity F_2^γ is, however, dominated by quarks. In contrast, Duke and Owens[6] parametrized the input-independent "asymptotic" prediction[9] for the photon structure function, which results from a summation of QCD corrections to the pointlike $\gamma q\bar{q}$ coupling. However, neglecting all "hadronic" contributions leads[9] to unphysical singu-

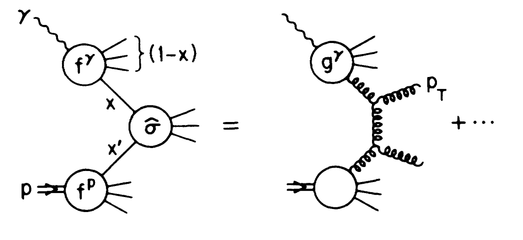

FIG. 1. Feynman diagram for those contributions to γp scattering where the photon is resolved into quarks and gluons.

larities in the small-x region; the parametrization of Ref. 5 therefore most probably overestimates the total γp cross section at $\sqrt{s} \gtrsim 500$ GeV. We finally show predictions for a vector-meson-dominance- (VMD) inspired *Ansatz*[7] for the photon structure functions. Here one assumes

$$F^\gamma(x,p_T^2) = (4\pi\alpha/f_\rho^2)\sum_i e_i^2 x q_i^\rho(x), \quad (4)$$

with

$$q^\rho = \tfrac{1}{2}(q^{\pi^+} + q^{\pi^-}). \quad (5)$$

Note that Eq. (4) falls short of existing data[8] on F_2^γ for $Q^2 \gtrsim 1$ GeV^2. Nevertheless, this *Ansatz* leads to predictions for the two-jet γp cross section similar to those obtained from the parameterizations of Ref. 4. The reason is that in the latter approach, *all* gluons are created dynamically, see Eq. (3), whereas the VMD-inspired parametrization assumes an intrinsically large gluon component of the photon.

We conclude from Figs. 2 and 3 that photoproduction cross sections associated with the quark-gluon structure of the photon exceed the familiar 100-μb values for $\sqrt{s} \simeq 0.5$ TeV. The values of the cross section are, however, determined by parton distributions at x values of order 10^{-3}. Here structure functions are unreliable and therefore our results depend crucially on the *Ansatz* in Eq. (3) as shown in Fig. 3.

At present, data on γp scattering only exist for $\sqrt{s} \lesssim 20$ GeV. Clearly, data at higher energies would help to sharpen our predictions for the ultrahigh energies relevant for cosmic-ray showers. HERA experiments studying the interactions of protons with "almost real" photons radiated by electrons might be able to study these phenomena up to $\sqrt{s}(\gamma p) \simeq 300$ GeV. Especially valuable for our purpose would be a measurement of the gluon content of the photon, and some information about the multiplicity and shape of the spectator jet that originates from the photon (see later). Since the gluon distribution inside the photon is presumably rather soft, and the photon spectrum itself peaks at small photon energies [flux$\sim -(\ln E/E)$], a measurement of g^γ necessitates the identification of jets with transverse momenta as low as 5 or even 3 GeV; these jets would be strongly boosted in the direction of the proton. In contrast, the quasi real

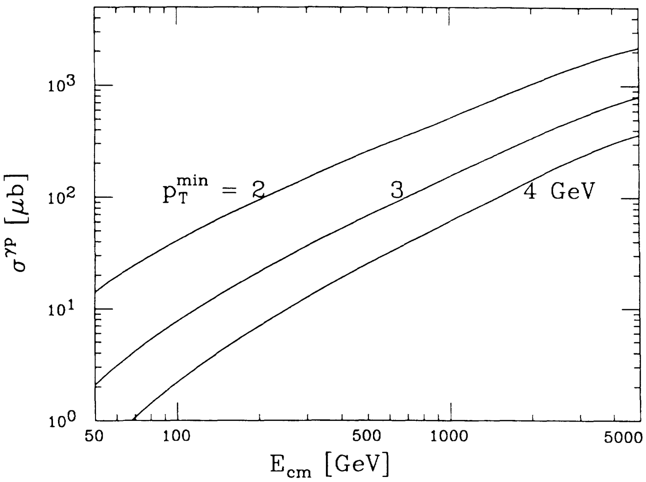

FIG. 2. Contribution of the processes depicted in Fig. 1 to the total γp cross section as a function of the proton-photon center-of-mass energy $E_{\text{c.m.}}$, where the transverse momentum of the partons produced in the hard scattering process has been required to be larger than $p_{T\min}$; see Eq. (2). The parton contents of the photon and proton are parametrized as given in Refs. 4 and 5.

photons and thus the spectator jets that emerge from them are more or less collinear with the electrons. An ideal detector for our purpose would therefore have to be able to see particles at small angles to the beam pipe in both the electron and the proton direction.

Do our observations have any relevance to calculations[10] of the hadron content of photon showers? The study of photon showers initiated by γ rays from point sources[1] and possibility other anomalies[11] observed in cosmic-ray interactions involving γ rays from π^0 decay exceeding 50-TeV energy have indicated a larger than expected hadron component of electromagnetic showers.

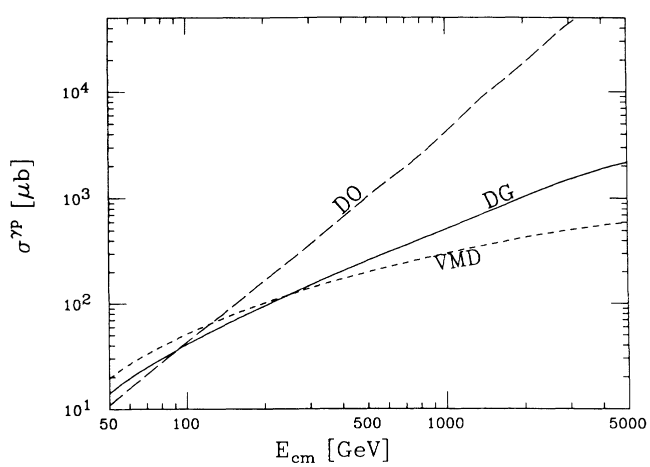

FIG. 3. Same as Fig. 2, with $p_{T\min} = 2$ GeV, but for three different parametrizations for the photon structure function f^γ: DG, Ref. 4; DO, Ref. 6; and VMD, set 1 of Ref. 7.

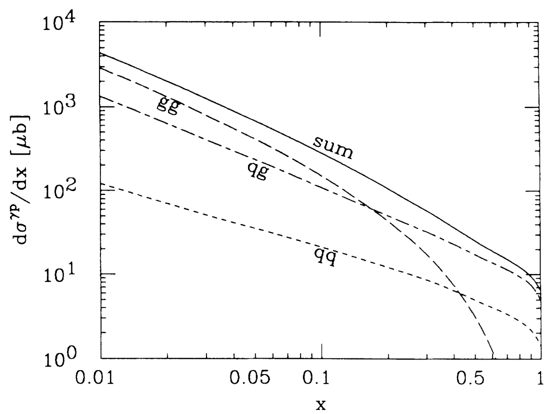

FIG. 4. Differential cross section $d\sigma^{\gamma p}/dx$, where x is the Bjorken variable for the parton in the photon. The contributions of final states containing two gluons, two quarks, or a quark and a gluon are shown separately. $E_{\text{c.m.}}=0.5$ TeV and $p_{T\min}=2$ GeV; f^{γ} and f^{p} are taken from Refs. 4 and 5.

Cosmic-ray experiments are by simple kinematics only sensitive to particles produced at very large rapidities, i.e., $p_L \simeq \sqrt{s}/2$. In this region photoproduction has conventionally been calculated *à la* VMD with $\gamma \rightarrow \rho \rightarrow \pi\pi$ and a cross section given by the total cross section at lower energies, $\sigma^{\gamma p} \simeq 10^2$ μb. The produced π's are often identified by a decay muon. On the other hand, we have shown that the cross section for the production of two jets with $p_T > 2$–3 GeV strongly increases with the photon energy and exceeds this "conventional" VMD cross section by more than an order of magnitude for $\sqrt{s} \gtrsim 1$ TeV. The cross sections shown in Fig. 1 are expected to produce many forward hadrons. The high-p_T jets are, of course, predominantly produced in the central region. The cross section is dominated by soft, small-Bjorken-x partons (mostly gluons) in the photon as shown in Fig. 4. This means that the spectator partons have very large ($\simeq 1-x$) Feynman x_F and will therefore be detected in cosmic-ray experiments.

In summary, we identified a contribution to hadron photoproduction sharply rising in the energy range required by the data. The forward inclusive cross section is $n\sigma$, with n the multiplicity of spectator hadrons in the photon and σ exceeding standard $\sim 10^2$-μb photoproduction cross sections. In air the relevant yield is $n\sigma A$ with $A=14.4$. With $n=1$–10, $\sigma=1$–10 mb, this yield can at high energy be competitive with Bethe-Heitler pair production which is about 500 mb. Further helped by a flatter energy spectrum, γ rays from point sources can be reasonably expected to yield hadrons (muons) resulting from ~ 10-mb photoproduction cross sections with abundances similar to those in cosmic-ray background showers. Quantitative results can unfortunately not be expected as we do not know how to determine $p_{T\min}$ in a perturbative calculation and as the multiplicity and momentum structure of the (crucial!) spectator partons also fall outside the scope of our approach. Some Monte Carlo modeling along the lines performed for minijets in hadron collisions[12] might, however, be attempted and prove to be revealing.

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[1]For reviews, see R. Protheroe, in *Proceedings of the Twentieth International Cosmic Ray Conference, Moscow, U.S.S.R., 1987,* edited by V. A. Kozyarivsky *et al.* (Nauka, Moscow, 1987); F. Halzen, in Proceedings of the SLAC Summer Institute on Particle Physics, Stanford, California, 1986, edited by E. Brennan (to be published).

[2]The photon can also couple directly to the partons in the proton. At the energies considered, this mechanism results in a cross section which is at most a 10% correction to our results.

[3]It is at present an open question whether the large increase with energy of the jet cross section defined by Eq. (2) is indeed the origin of the rise of the total cross section in hadron collisions. We calculated $\sigma^{\gamma p}$ as a total cross section corresponding to two high-p_T final-state jets. For a review, see C. S. Kim and F. Halzen, in *La Thuile Meeting on Results and Perspectives on Particle Physics, La Thuile, Aosta, Italy, 1987,* edited by M. Greco (Editions Frontieres, Gif-sur-Yvette, 1987).

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