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# TWO-PHOTON PHYSICS AS A PROBE OF HADRON DYNAMICS*

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ABSTRACT

Two-photon collisions provide an ideal laboratory for testing many features of quantum chromodynamics, especially the interplay between the vector-meson-dominated and point-like hadronic interactions of the photon. A number of QCD applications are discussed, including: jet and single-particle production at large transverse momentum; the photon structure function and its relationship to the $\gamma \to q\bar{q}$ wave function; and the possible role of gluonium states in the $\gamma\gamma \to \rho^0\rho^0$ channel. We also discuss evidence that even low momentum transfer photon-hadron interactions are sensitive to the point-like $\gamma \to q\bar{q}$ coupling.

## I. INTRODUCTION

One of the most important aspects of photon-photon collisions[1)] is that it allows the study of hadron dynamics in processes in which the initial state is simple and controllable. In this talk I shall outline many of the special advantages of ee → ee + hadron reactions as a double-electromagnetic probe of the strong interactions. The photon plays a unique role in QCD because of its elementarity and its direct interactions with the hadronic constituents. QCD predicts asymptotically scale-free couplings of the photon with the quark current for high $Q^2$ virtual photon interactions and also for real on-shell photon interactions in large momentum transfer (short-distance) processes. On the other hand, at low momentum transfer many features of the photon-hadron interactions can be interpreted in terms of interpolating vector meson fields[2)]. In this talk I shall focus on this dual nature of photon interactions and the many critical tests of quantum chromodynamics possible in photon-photon collisions.

Photon-photon collisions provide a close analogue to meson-meson collisions. In the case where the scattered leptons are tagged, we can study exclusive or inclusive cross sections $\sigma_{\gamma\gamma}\left(Q_1^2, Q_2^2, s\right)$ as a

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function of the photon mass and polarization. For example, the angle $\phi$ between the lepton scattering planes provides a photon linear polarization correlation

$$\frac{d\sigma}{d\phi}\,(ee \to eeX) \propto \sigma_{\parallel}^{\gamma} + \sigma_{\perp}^{\gamma\gamma} + \cos 2\phi\left(\sigma_{\parallel}^{\gamma\gamma} - \sigma_{\perp}^{\gamma\gamma}\right) \qquad (1)$$

In addition, if the lepton beams are circularly polarized, then the photons also become circularly polarized (with 100% correlation at $x_\gamma = \frac{k^o + k^3}{p_e^o + p_e^3} \to 1.$)[3)]

## II. RESONANCE PRODUCTION IN TWO-PHOTON COLLISIONS

Two-photon physics allows the detailed exploration of even charge-conjugation hadronic systems channel by channel. This includes the study of C = + resonances, such as the f, $\eta$, $\eta'$, $\eta_c$, $S^*$,... and other quarkonium or gluonium systems as well as exclusive channels, such as $\gamma\gamma \to \tau^+\tau^-$ (tests of tau electrodynamics), $\gamma\gamma \to \pi\pi$, $K\bar{K}$, $\rho\bar{\rho}$, $p\bar{p}$ (determination of $\pi\pi \to \pi\pi$ phase shifts via Watson's theorem and tests of high momentum transfer QCD). The virtual photon mass-dependence for channels such as $\gamma^*\gamma \to \pi^o$, $\eta$, etc., allows the study of the anomaly structures and short-distance QCD effects. One can also probe QCD dynamics in the reaction $\gamma\gamma \to X$ where the hadronic system X has fixed mass, and $Q_1^2$, $Q_2^2$ become large. Detailed predictions for the spectrum for $\gamma\gamma \to$ charm particles have also been made[4)] (see Fig. 1).

Although many of the above tests await high luminosity experiments, data already exist for the $\gamma\gamma \to \pi^+\pi^-$ and $\rho^o\rho^o$ channels. (For a detailed report see Ref. 5.) The $\gamma\gamma \to \rho^o\rho^o$ cross section measured by the Tasso group at PETRA appears anomalously high (80 nb) at $W = \sqrt{s_{\gamma\gamma}} \sim 1.6$ GeV, and has led to a number of theoretical speculations. For example, an analysis by Goldberg and Weiler[6)] indicates a possible signal for a $2^{-+}$ isoscalar resonance at 1660 MeV. The most exciting possibility, as suggested by Layssac and Renard[7)], is that the Tasso cross section could be evidence for a gluonium resonance with $J^{PC} = 0^{-+}$ or $2^{++}$ at 1600 MeV, with a width $\Gamma \sim 100$ MeV. (Fits to the data are shown in Fig. 2.) This idea is obviously speculative, since the $\gamma\gamma$ coupling via a quark loop would be expected to suppress the

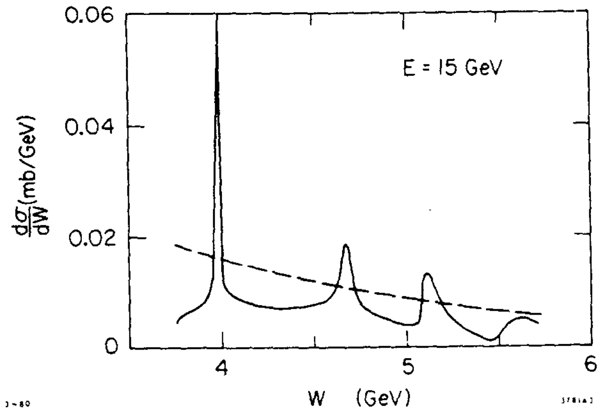


Fig. 1. Cross section $d\sigma/dW$ for charmed particle production $\gamma\gamma \to D\bar{D}$, $F\bar{F}$, $D\bar{D}^*$, etc. The dashed line is $d\sigma/d\bar{W}$ for $c\bar{c}$ pairs with no binding in the final state. (From Carlson and Suaya, Ref. 4, and Suaya, Proc. 1979 Internat. Conf. on Two-Photon Collisions, Ref. 2.)

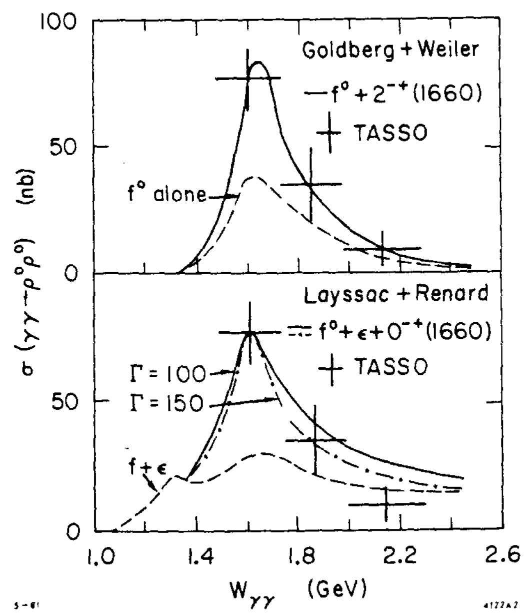


Fig. 2. Possible resonance fits to the $\gamma\gamma \to \rho^o\rho^o$ cross section.

$\gamma\gamma$ formation of pure gluonium states.

Bound states of gluons in the 1 to 3 GeV region are clearly an essential feature of QCD. Recently, Donoghue, Johnson, and Li[8] have made a number of predictions of the gluonium spectrum based on the MIT bag model. The lowest mass two-gluon state has $J^{PC} = 2^{++}$, with $0^{-+}$, $2^{-+}$ excited states; $0^{++}$ states do not appear since these mix with the vacuum. Three-gluon ground states with $J^{PC} = 1^{+-}$, $3^{+-}$ but not $1^{-+}$ are also predicted. The $2^{++}$ state is predicted to be nearly degenerate with the f, so that mixing of gluonia with flavor-singlet $|q\bar{q}\rangle$ and $|q\bar{q}q\bar{q}\rangle$ amplitudes becomes a serious complication. For example, in Rosner's[9] analysis, the f is identified as a coupled $|q\bar{q}\rangle$ and $|gg\rangle$ system. The orthogonal $2^{++}$ state $f^{\perp}$ has a larger $|gg\rangle$ content; the predicted mass is in the range $1.37 < m(f^{\perp}) < 1.55$ GeV. The $|q\bar{q}\rangle$ component of the $f^{\perp}$ allows a direct coupling to the $\gamma\gamma$ channel. It is clear that further experimental work, including a detailed partial-wave analysis, is required.

If the observed enhancement in $\gamma\gamma \to \rho^o\rho^o$ is indeed a $2^{\pm +}$ state with a predominant $|gg\rangle$ component, then an important question is why this state couples strongly to $\rho^o\rho^o$ but not to $\pi\pi$. A possible hint is provided in Fig. 3. The lowest order amplitude for $G \to \rho^o\rho^o$ is seen

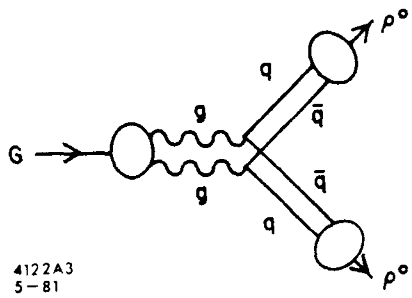


Fig. 3. Lowest order QCD amplitude for gluonium decay to two mesons. (For related calculations of quarkonium decay see S. J. Brodsky and G. P. Lepage, SLAC-PUB-2746 (1981).)

to involve the distribution amplitude[10)]

$$\phi_\rho(x,m_G) \propto \int^{k_\perp^2 < m_G^2} \psi_\rho(x,k_\perp)\, d^2k_\perp \quad . \tag{2}$$

We thus have

$$\Gamma_{G \to \rho\rho}/\Gamma_{G \to \pi\pi} \sim 3\left(\phi_\rho/\phi_\pi\right)^4 \sim 3\left(f_\rho/f_\pi\right)^4 \sim 20 \tag{3}$$

where the spin factor of 3 assumes equal parallel and antiparallel quark and anti-quark helicities.

It is likely that further analysis of the two-photon production channels and comparisons with $\psi \to \gamma X$ and $\Upsilon \to \gamma X$ data will lead to definitive results in this important area of QCD phenomenology.

## III. PHOTON INTERACTIONS IN QCD

The study of hadron production in two-photon collisions highlights another essential area of QCD dynamics: the dual aspect of hadronic photon interactions. On the one hand, low momentum transfer photon-initiated reactions can usually be described in terms of a traditional vector meson dominated (VMD) picture, whereas in QCD all photon interactions arise in the first instance from a direct $\gamma \to q\bar{q}$ coupling. This duality is an important and perhaps analyzable example of the interplay between nonperturbative and perturbative dynamics.

For large momentum transfer reactions, the point-like $\gamma \to q\bar{q}$ coupling of the photon is expected to be dominant. One (heuristic) way to see the transition between vector-meson-dominated and point-like-dominated photon interactions is to analyze the $\gamma \to q\bar{q}$ amplitude $\psi_\gamma(x,k_\perp)$ which describes the $|q\bar{q}\rangle$ Fock state of the photon ($\psi_\gamma$ is equivalent to the Bethe-Salpeter wave function defined at equal $\tau = z + t$ on the light cone). (See Fig. 4.) For example, the Born

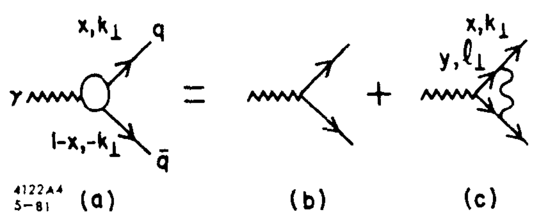


Fig. 4. QCD contributions to the $\gamma \to q\bar{q}$ wave function.

coupling gives (Fig. 4(b))[11]

$$\psi_\gamma^{(o)} = \frac{e_q}{\dfrac{k_\perp^2 + m^2}{x(1-x)}} \frac{\bar{u}_\uparrow(x,k_\perp)}{\sqrt{x}} \gamma\cdot\hat{\epsilon} \frac{v_\downarrow(1-x, -k_\perp)}{\sqrt{1-x}} \tag{4}$$

$$= \frac{e_q}{\dfrac{k_\perp^2 + m^2}{x(1-x)}} \begin{cases} \dfrac{ik_\perp}{x}\sqrt{2} & \hat{\epsilon} = \dfrac{\hat{x} + i\hat{y}}{\sqrt{2}} \\[2ex] \dfrac{k_\perp}{1-x}\sqrt{2} & \hat{\epsilon} = \dfrac{\hat{x} - i\hat{y}}{\sqrt{2}} \end{cases} \tag{5}$$

Thus the perturbative wave function has a $k_\perp^{-1}$ fall-off. Squaring, averaging over photon polarization, and summing over quark helicity, gives probability distributions

$$G^{(o)}\left(x,\vec{k}_\perp\right) \equiv \frac{dN_{q\bar{q}/\gamma}}{dx\,d^2k_\perp} = \frac{2e_q^2}{k_\perp^2 + m_q^2}\left[(1-x)^2 + x^2\right] \tag{6}$$

and

$$G^{(o)}(x,Q) \equiv \int^{k_\perp^2<Q^2} \frac{d^2k_\perp}{16\pi^3}\, G^{(o)}\left(x,\vec{k}_\perp\right) = \frac{\alpha e_q^2}{2\pi}\log\frac{Q^2}{m_q^2}\left[(1-x)^2+x^2\right] \tag{7}$$

This result gives a first approximation to the photon structure function in QCD (see Sect. V).

Let us now consider the role of QCD radiative corrections as illustrated in Fig. 4(c). For $\ell_\perp \gg k_\perp$ this graph contributes to the usual renormalization of the point vertex. For the region $\ell_\perp \lesssim k_\perp$, however, we get a contribution $\Delta\psi_\gamma \sim \frac{1}{k_\perp^2}$ which is controlled by the gluon-exchange propagator and has the same fall-off as derived for a vector-meson bound state. For $\ell_\perp \lesssim \mathcal{O}\left(\Lambda_{QCD}\right)$ the radiative corrections are part of the nonperturbative dynamics where bound states influence the $q\bar{q} \to q\bar{q}$ amplitude. We thus expect (symbolically)

$$\psi_\gamma(x,k_\perp) \sim e\,\frac{k_\perp}{k_\perp^2 + m_q^2} + e\psi_{VMD}(x,k_\perp) \tag{8}$$

where the second term is similar to the $\psi_{q\bar{q}/\rho}$ wave function. We can then make the following ansatz consistent with the above picture:

1) For amplitudes which involve only small $k_\perp$, $\psi_\gamma(x,k_\perp)$ is dominated by the $\psi_{VMD}$ nonperturbative component.

2) For amplitudes sensitive to $k_\perp^2 \gg \Lambda_{QCD}^2$,

$$\psi_\gamma(x,k_\perp) \sim e\,\frac{k_\perp}{k_\perp^2 + m_q^2} + \mathcal{O}\left(\frac{1}{k_\perp^2}\right) \tag{9}$$

and the perturbative point-like coupling of the on-shell coupling is dominant. Notice, however, that this is only true for amplitudes with quark helicities $\lambda_q = -\lambda_{\bar{q}}$ . It is clear from the form of Eq. (8), that in general all photon amplitudes involve both VDM and point-like contributions.

## IV. JET AND SINGLE PARTICLE PRODUCTION IN $\gamma\gamma$ COLLISIONS

Perhaps the most dramatic examples of the dominance of point-like photon interactions at large momentum transfer are the QCD predictions for $\gamma\gamma \to$ jets.[12-15] In particular, the dominant subprocess $\gamma\gamma \to q\bar{q}$ leads to the formation of non-collinear coplanar jets in the $e^+e^-$ center of mass with kinematics identical to that for $\gamma\gamma \to \mu^+\mu^-$. The ratio of the $\gamma\gamma \to$ jet + jet and $\gamma\gamma \to \mu^+\mu^-$ cross sections at asymptotic transverse momentum is

$$R_{\gamma\gamma} \equiv \frac{d\sigma_{\gamma\gamma \to q\bar{q}}}{d\sigma_{\gamma\gamma \to \mu^+\mu^-}} = 3 \sum_q e_q^4 = \begin{cases} 2/3 & u,d,s \\ 34/27 & u,d,s,c \end{cases} \qquad (10)$$

with perturbative QCD corrections of the form $\left[1 + \mathcal{O}\left(\alpha_s(p_T^2)/\pi\right)\right]$. Aside from the flavor differences (enhancement of c and u jets) the jet distribution and hadronization for $\gamma\gamma \to q\bar{q}$ should be identical to the final state in $e^+e^- \to q\bar{q}$ at the same kinematics. The fact that the strong interaction corrections to $R_{\gamma\gamma}$ vanish at large transverse momentum is a critical and unique prediction of asymptotic freedom. Notice that the $\psi_{VMD}$ component of the photon wave function gives higher twist (power-law suppressed) contributions to the $\gamma\gamma \to q\bar{q}$ jet cross section.

The $\gamma\gamma \to$ jet + jet events are revolutionary from the point of view of traditional VMD since one would hardly expect the production of hadronic jets at large transverse momentum in meson-meson collisions without the production of hadronic energy in the forward direction. In fact, because of its point-like coupling, the photon, unlike a hadron, can directly participate in the short-distance "femtouniverse"[16] ($R < 10^{-15}$ cm) of quark and gluon scale-invariant subprocesses.

The integrated cross section for single jet production in $e^+e^-$ collisions with $p_T^{jet} > p_T^{min}$ from $\gamma\gamma \to q\bar{q}$ has been computed in some detail.[12,14,17] The result through order $\alpha_s$ is ($\rho = \log s/p^2_{Tmin}$)

$$\sigma\left(p_T^{jet} > p_T^{min}\right) = \frac{32\pi}{3}\,\alpha^2\,\frac{R_{\gamma\gamma}}{p^2_{Tmin}}\left(\frac{\alpha}{2\pi}\log\frac{s}{m_e^2}\right) f(\rho) \qquad (11)$$

where[17)]

$$f(\rho) = \rho - \frac{14}{3} + \frac{\left(p_T^{min}\right)^2}{2s}\left[\rho^3 + \left(\frac{51}{2} - \pi^2\right)\rho - 2.075\right] + \mathcal{O}\left(p^4_{Tmin}/s^2\right)$$
$$+ \frac{\alpha_s}{\pi}\left[-\,0.461\,\rho + 0.213 + \mathcal{O}\left(\frac{p^2_{Tmin}}{s}\right)\right] \quad . \qquad (12)$$

For $\alpha_s \cong .3$, the $\alpha_s/\pi$ correction obtained by Behrends, Kunszt, and Gastmans is $\cong -11\%$. The nominal size of the integrated cross section for $\sqrt{s} = 30$ GeV is $\mathcal{O}\left(p_T^{jet} > p_{Tmin}\right) \sim \frac{0.5\text{nb}}{p^2_{Tmin}}$, including a factor of 2 for detecting either jet. The $\gamma\gamma \to q\bar{q}$ cross section at $p_{Tmin} \sim 10$ GeV is equivalent to $\sim \frac{1}{2}$ unit of R at $\sqrt{s} = 100$ GeV.

In fact, events corresponding to the predicted QCD jet cross section have been reported by the Pluto, and Tasso groups.[18)] The preliminary results (see Fig. 5) appear to be in rough agreement in both magnitude and shape with the predictions of jet models based on the $\gamma\gamma \to q\bar{q}$ subprocess. More data and analysis will be required before definitive checks of the theory can be made. Confirmation of the predicted value for $R_{\gamma\gamma}$ [Eq. (10)] is one of the most critical tests of fractional quark charge in QCD.

In addition to the $\gamma\gamma \to q\bar{q}$ subprocess, QCD also predicts gluon jet production $\gamma\gamma \to gg$ at order $\alpha_s^2(p_T^2)$ via a quark loop box diagram.[19)] This increases the 2-jet production cross section by about 10%. The theory also predicts 3-jet events from subprocesses such as $\gamma q \to gq$ (where one photon interacts with a quark constituent of the other proton) as well as 4-jet events from conventional high $p_T$ QCD subprocesses $qq \to qq$, $q\bar{q} \to gg$, $gq \to gq$, $gg \to gg$, etc.[12)]

The structure of the 4-jet events is similar in topology to jet production in hadron-hadron collisions.[15)] However, there are some remarkable differences:

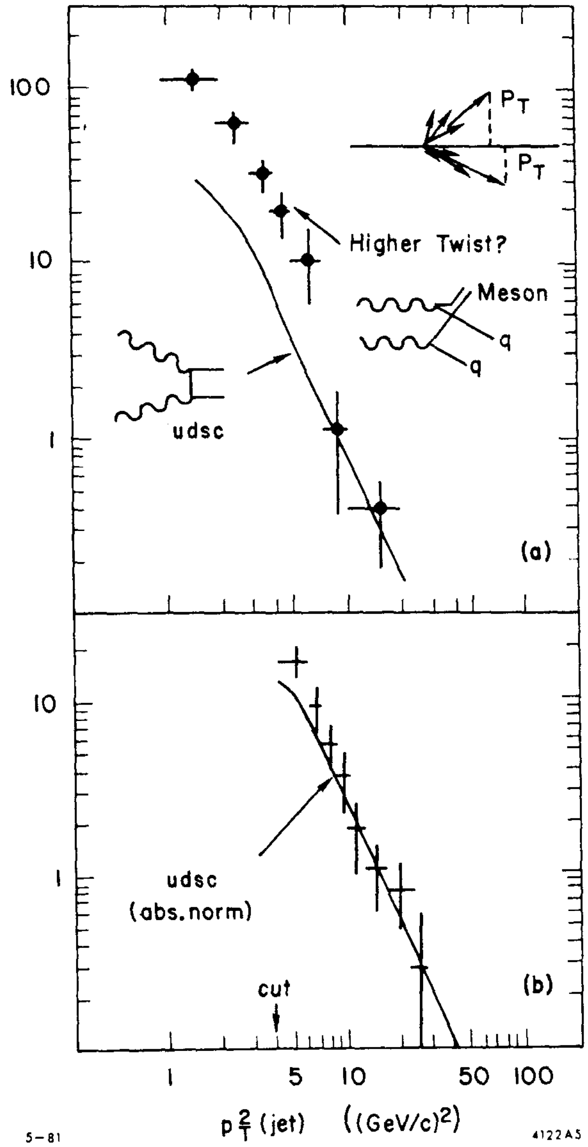


Fig. 5. Preliminary Pluto (a) and Tasso (b) data for large $p_T$ jet production in $\gamma\gamma$ collisions.

1) The predicted cross section $Ed\sigma/d^3p(\gamma\gamma \to \text{jet} + X)$ for each of the subprocesses $\gamma\gamma \to q\bar{q}$, $\gamma q \to gq$, $qq \to qq$, $q\bar{q} \to gg$, $q\bar{q} \to q\bar{q}$ is asymptotically scale-invariant $Ed\sigma/d^3p \to \alpha^4 \; p_T^{-4} \; f(p_T/\sqrt{s}, \theta_{c.m.})$. This is due to the fact that the leading contribution of the photon structure function $G_{q/\gamma}(x,Q) \sim \left[\alpha/\alpha_s(Q^2)\right] f(x)$ in QCD increases with the evolution scale (see Sect. V), precisely compensating[13,12] the $\alpha_s(Q^2)$ fall-off of the 3- and 4-jet subprocess cross sections (see Fig. 6).

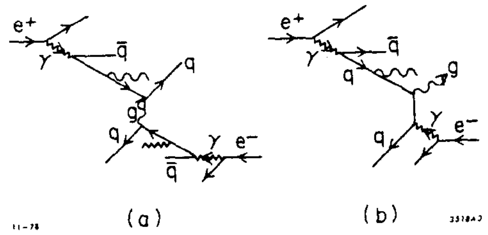


Fig. 6. Contributions from QCD subprocesses to (a) 4-jet and (b) 3-jet final states.

2) The asymptotic $\gamma\gamma \to$ jet + X cross section can thus be predicted from first principles in QCD without recourse to other measurements of the structure functions. Furthermore, unlike hadron-hadron collisions, there are no initial-state corrections from soft hadronic interactions. The cross sections fall very slowly in $(1 - x_T)$ at fixed $\theta_{c.m.}$ compared to hadron-induced reactions.

The various 2-, 3-, and 4-jet cross sections can in principle be separated by their different jet topology; in particular, by the flow of hadronic energy along the forward and backward directions. Detailed calculations are given in Ref. 12. The contribution of vector-meson dominated 3- and 4-jet photon induced cross sections falls rapidly with transverse momentum and can be neglected for $p_T^{jet} \gtrsim 2$ GeV. Some results of the calculations are shown in Fig. 7.

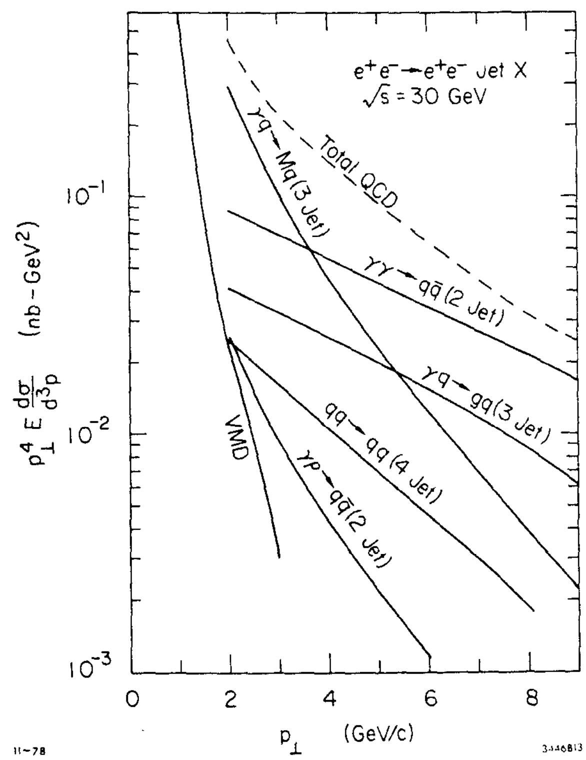


Fig. 7. QCD (and VMD) contributions to the ee $\to$ ee jet + X cross section. The 4-jet cross section includes the contributions for $qq \to qq$, $q\bar{q} \to q\bar{q}$, and $q\bar{q} \to gg$. (From Ref. 12.)

We also note that there are a number of background processes from $e^+e^-$ collisions which must be separated from the $\gamma\gamma$-initiated events. These include $e^+e^-$ annihilation with hard-photon radiation from the initial lines, and hadronic bremsstrahlung events from $e^+e^- \to e^+e^-\gamma^* \to e^+e^-$ + hadrons. In some of these background processes the transverse momentum of the hadronic jet is balanced by a scattered lepton or a radiated photon.

In addition to jet production cross sections one can also predict[12] the rate for single-particle production at large transverse momentum, $Ed\sigma/d^3p(\gamma\gamma \to HX)$. The leading twist contributions have the usual QCD logarithmic scale violations associated with the quark and gluon fragmentation functions. In addition, one predicts higher twist QCD contributions which are suppressed by a power of $p_T^2$ but have a slower fall-off in $(1-x_T)$. (These higher twist processes are also numerically enhanced relative to leading twist due to the absence of trigger bias suppression.) For example, for $\gamma\gamma \to \pi X$ one predicts

$$Ed\sigma/d^3p(\gamma\gamma \to \pi X) \sim \frac{d\sigma}{dt}(\gamma\gamma \to q\bar{q})\, D_{\pi/q}\left(z,p_T^2\right) \tag{13}$$

where for large z[20]

$$D_{\pi/q}\left(z,p_T^2\right) \sim (1-z)^2 + C/p_T^2 \quad . \tag{14}$$

The $C/p_T^2$ term corresponds to the higher twist contribution in the longitudinal pion structure and fragmentation functions as recently observed in the $\pi p \to \mu^+\mu^- X$ and $\nu p \to \mu\pi X$ reactions. The $(1-z)^2$ term evolves in a standard way. It should also be noted that hard-scattering subprocesses such as $\gamma q \to \pi q$ produce pions at $z = 1$ directly. The cross section for this subprocess is absolutely normalized to the pion form factor[12,21]

$$\frac{d\sigma}{d\hat{t}}(\gamma u \to \pi^o u) = \frac{16\pi}{81}\,\alpha\alpha_s F_\pi(\hat{s})\,\frac{\hat{t}^2}{\hat{s}^2}\left[\frac{1}{\hat{s}^2} + \frac{1}{\hat{u}^2}\right] \quad . \tag{15}$$

As shown in Ref. 12, this subprocess can give an important contribution to the $\gamma\gamma \to \pi X$ single-particle production rate.

## V. THE PHOTON'S STRUCTURE FUNCTIONS

The classical test of QCD interactions of the photon is deep inelastic scattering on a photon target[22], which is measurable in $ee \to ee$ + hadrons if one lepton is tagged at large momentum transfer. In addition to the usual $F_1^\gamma(x,Q)$ and $F_2^\gamma(x,Q)$ structure functions, a third photon structure function $F_3^\gamma(x,Q)$ can be determined in double-tagged events from the angular ($\cos 2\phi$) correlation of the lepton scattering planes. The fourth photon structure function $F_4^\gamma(x,Q)$ can also be measured from the polarization symmetry if one has longitudinally polarized $e^+e^-$ beams. The relation between the structure functions and the absorptive part of the forward $\gamma^*\gamma \to \gamma^*\gamma$ helicity amplitudes is

$$\begin{aligned}
W_1 &\propto \frac{1}{2}\left[W(1,1\,;\,1,1) + W(1,-1\,;\,1,-1)\right] \\
W_4 &\propto \frac{1}{2}\left[W(1,1\,;\,1,1) - W(1,-1\,;\,1,-1)\right] \\
W_3 &\propto W(1,1\,;\,-1,-1) \\
W_2\,\frac{(k\cdot q)^2}{Q^2} - W_1 &\propto W(0,1\,;\,0,1) \qquad .
\end{aligned} \tag{16}$$

If we restrict ourselves to the point-like wave function $\psi_\gamma^0(k_\perp,x)$ in Eq. (4) then we obtain the "parton model" results[23]

$$\begin{aligned}
F_2^\gamma &= \nu W_2^\gamma = x\left[x^2 + (1-x)\right]\left\{\ell n\left[\frac{Q^2}{m_q^2}\left(\frac{1}{x} - 1\right)\right] - x + 8x^2(1-x)\right\} \\
F_L^\gamma &= \nu W_2^\gamma - 2xW_1^\gamma = 4x^2(1-x) \\
F_3^\gamma &= W_3^\gamma = -\,x^2 \\
F_4^\gamma &= W_4^\gamma = (2x-1)\left\{\ell n\left[\frac{Q^2}{m_q^2}\left(\frac{1}{x} - 1\right)\right] - 2\right\}
\end{aligned} \tag{17}$$

all multiplied by the color and charge factors $3 \frac{\alpha}{\pi} \sum_i e_i^4$. Since spin flip is required, the only contribution to $F_3^\gamma$ is from the crossed box graph[24]. The results [Eq. (17)] are of course also correct for $\gamma^* \gamma \to \mu^+ \mu^-$ with the charge factor $\alpha/\pi$. It is interesting to note that the preliminary Pluto measurements for both the hadronic and leptonic structure functions of the photon are consistent with these predictions for $F_2^\gamma$. (See Fig. 8.)

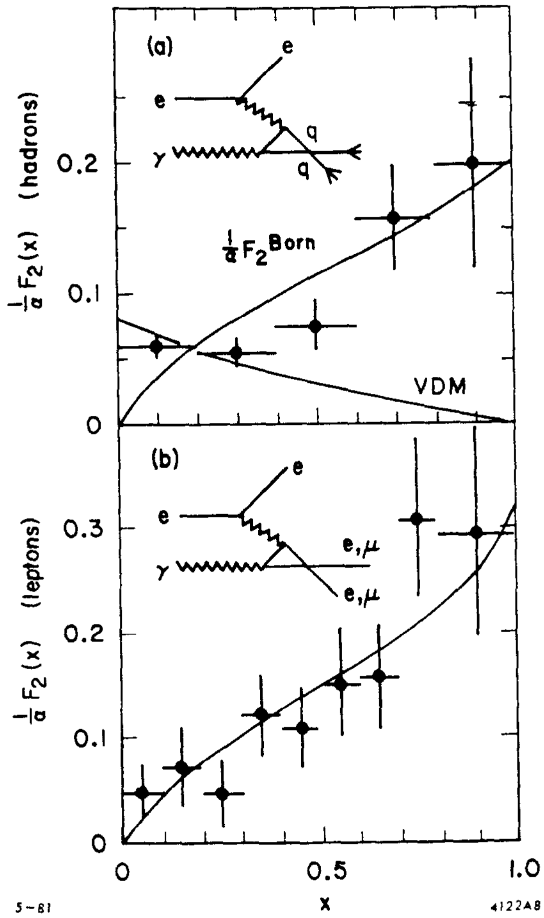


Fig. 8. Preliminary data for hadron (a) and lepton (b) final state contributions to the photon structure function. For comparison, the point-like contribution to $\frac{1}{\alpha} F_2^\gamma(x,Q)$ [Eq. (17)] is shown.

It should be noted that the kinematic quantity which controls the logarithmic growth of $F_2^\gamma$ and $F_4^\gamma$ is $W^2 = (k + q)^2 = Q^2\left(\frac{1}{x} - 1\right)$ since this sets the upper limit for the transverse momentum integrations. This fact is also essential when one takes into account QCD radiative corrections[25].

We can now include the $\psi^{\gamma}_{VMD}$ contribution to the photon $q\bar{q}$ wave function [Eq. (8)] and obtain additional leading twist contributions to $F^{\gamma}_{1}$ and $F^{\gamma}_{4}$ similar to those for a vector-meson target. Unlike the point-like case, this contribution to $F^{\gamma}_{L}$ and $F^{\gamma}_{3}$ is power-law suppressed in $Q^2$ because of the convergence of the quark transverse momentum integrations. There are no cross-term contributions from $\psi^{(o)}_{\gamma} \times \psi^{\gamma}_{VMD}$ because of quark helicity conservation. (The VMD helicity-one state has parallel $q,\bar{q}$ helicities.)

Finally, one can obtain the QCD evolution of the photon structure functions by allowing for quark bremsstrahlung and pair-production subprocesses. The $t = \ell n\, Q^2/\Lambda^2$ variation of the structure function comes from the upper limit of the quark and gluon transverse momentum integration. To leading logarithmic order, the quark distribution function for the photon, $q_i(x,t) = G_{q_i/\gamma}(x,Q)$, thus satisfies the evolution equation[26)]

$$dq_i(x,t)/dt = e_i^2 \frac{\alpha}{2\pi} P_{q\gamma}(x) + \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) q_i(y,t) + P_{qg}\left(\frac{x}{y}\right) g(y,t)\right] \qquad (18)$$

where $P_{q\gamma} = x^2 + (1-x)^2$ is the point-like "driving term". Since $\alpha_s(t) \sim 4\pi/(\beta \ell n t)$ we immediately see that the quark and gluon distributions have the form

$$q(x,t) = \frac{\alpha}{2\pi} h(x) t$$
$$g(x,t) = g(x) t \qquad (19)$$

where $h(x)$ and $g(x)$ are calculable in QCD. The prediction for $F^{\gamma}_{3}$ is unchanged from its parton model form to order $\alpha_s$. Equation (18) is equivalent to Witten's operator product expansion analysis[27)]. The important effect of the kinematic limits for the quark and gluon transverse momentum integration at $x \to 1$ is seen in the analysis of the order $\alpha_s$ corrections[28)]. Physically one expects the QCD corrections to become small in this phase-space limited region (see Ref. 29).

It is also interesting to analyze the relationship between contributions to the photon structure function at fixed $W^2$, and its $x \to 1$ limit. In particular, the channels $\gamma\gamma \to \pi^o$, etc., are analyzable in perturbative QCD[10].

## VI. POINT-LIKE CONTRIBUTIONS OF REAL PHOTONS

If we evaluate the parton model result of Eq. (17) in the $Q^2 = 0$ limit, one obtains

$$\sigma^{(o)}_{\gamma\gamma}(W) = 3 \sum_q e_q^2 \frac{4\pi\alpha^2}{W^2} \left( \log \frac{W^2}{m_q^2} - 1 \right) \tag{20}$$

which arises from the point-like part of the photon wave function $\psi^{(o)}_{\gamma}(x,k_\perp)$. The dependence on the quark mass in Eq. (20) obviously will be modified by nonperturbative effects. Nevertheless, the large $W^2$ dependence of this contribution, which arises from high quark transverse momentum, should give a reasonably reliable prediction. Thus, even when both photons are real, the point-like couplings give an additive correction to the VMD results. Evidence for a $W^{-2}$ contribution to $\sigma_{\gamma\gamma}$ has in fact been found by the Pluto group[18] (see Fig. 9), although this is not clear in the Tasso data. The photon-mass

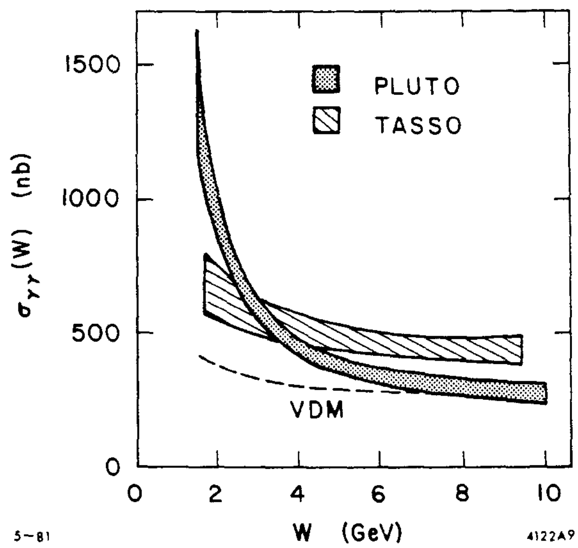


Fig. 9. Approximate fits to data for the total $\gamma\gamma \to$ hadron cross section (extrapolated to zero photon mass) obtained by the Pluto and Tasso groups. (From W. Wagner, Ref. 18.)

dependence of this cross section as well as its relationship to the $\gamma\gamma \to q\bar{q}$ jet processes, $\gamma\gamma \to Q\bar{Q}$ heavy quark thresholds, as well as to standard Regge and VDM contributions will be interesting to study in the future.

There is also evidence for the point-like interactions of real photons in low transverse momentum reactions. For example, an analysis[30] of the shadowing of the nuclear photo absorption cross section $\sigma_{\gamma A}(W^2)$ indicates that low mass vector mesons do not saturate the photon's hadronic interactions. Empirical evidence for the presence of J = 0 fixed Regge singularity[32] in the proton Compton amplitude also indicates a direct $\gamma q \to \gamma q$ coupling[33].

In general, the point-like contributions to photon interactions will dominate the VMD contributions in exclusive or inclusive reactions at high $p_T$ or $x \to 1$ thus increasing the cross section in domains sensitive to short-distance phenomena. In particular:

1) For exclusive processes at large momentum transfer, the dimensional counting rule[34] is

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{1}{s^{n_{TOT}-2}} f(t/s) \tag{21}$$

where $n_{TOT} = n_A + n_B + n_C + n_D$ is the minimum total number of elementary fields entering or leaving the hard-scattering process. Since n = 1 for photons, n = 2 for mesons, and n = 3 for baryons, the point-like $\gamma$ contributions dominate the VMD contributions to $d\sigma/dt$ by a factor of s for each photon in the reaction. Experimental checks of this prediction for $\gamma p \to \pi p$ and $\gamma p \to \gamma p$ are discussed in Ref. 10.

2) Fragmentations and distribution functions $G_{q/\gamma}(x)$ and $D_{\gamma/q}(z)$ at the Born level are non-zero at $x \to 1$ and $z \to 1$ due to the point-like $\gamma \to q\bar{q}$ coupling. In contrast, $G_{q/M}(x)$ and $D_{M/q}(z)$ strongly vanish at the kinematic limit in the leading twist. The preliminary data for the photon structure function supports this (see Fig. 8).

3) Large transverse momentum inclusive cross sections involving photons in the initial or final state should approach nominal $p_T^{-4} f(x_T, \theta_{c.m.})$ scaling faster than the corresponding meson reactions since higher twist, initial- or final-state scattering corrections, and other scale-breaking effects should be considerably reduced for

photons[35]. For example, indications from the ISR[36] that the $\gamma/\pi$ ratio increases $\sim p_T^2$ at fixed $\theta_{c.m.}$ and $p_T/\sqrt{s}$ in pp collisions can be understood in terms of the dominance of higher twist subprocesses such as $gq \to \pi q$ for meson production. Other short-distance tests of direct photon reactions in QCD are reviewed in Ref. 36. It is also possible that the $\gamma\gamma \to$ jet + X cross section approaches scale invariant behavior at relatively low $p_T^{jet} \sim 4$ GeV, whereas the scaling of hadron-induced reactions is severely complicated by competing reactions and higher twist effects[37].

4) The photon structure function $F_2^\gamma$ increases upon QCD evolution, in contrast to shrinking hadronic structure functions.

Finally, we should remark that one of the most important areas of two-photon physics is the study of the exclusive processes $\gamma\gamma \to \pi\bar{\pi}$, $K\bar{K}$, $\rho\rho$, $p\bar{p}$, etc., at large momentum transfer. These real photon processes are by far the simplest calculable large-angle exclusive hadron scattering reactions. The scaling behavior, helicity structure, and sometimes even the normalization of the cross sections can be rigorously computed in leading twist for each $\gamma\gamma \to M\bar{M}$ channel. Conversely, the angular dependence of these cross sections can be used to determine the x-dependence of the process-independent distribution amplitudes $\phi_M(x,Q)$, the basic short-distance wave functions which control the valence quark distributions in high momentum transfer exclusive reactions. Unlike hadron-hadron scattering reactions, pinch singularities[39] in the $\gamma\gamma \to MM$ processes are power-law suppressed at the Born level[38]. The QCD predictions for $d\sigma/dt(\gamma\gamma \to M\bar{M})$ and a detailed discussion of the behavior of the $\gamma^*\gamma \to \pi^o$ amplitude are presented in Ref. 38.

In summary, it is evident that two-photon collisions can provide a clean and elegant testing ground for perturbative quantum chromodynamics. The occurrence of $\gamma\gamma$ reactions at an experimentally observable level implies that the entire range of hadronic physics which can be studied, for example, at the CERN-ISR can also be studied in parallel in $e^+e^-$ machines. Although low $p_T$ $\gamma\gamma$ reactions should resemble meson-meson collisions, the elementary field nature of the photon implies dramatic differences at large $p_T$. We have especially noted the sharp contrasts between hadron- and photon-included reactions due to the photon's point-like coupling to the quark current and the ability of a photon to give nearly all of its momentum to a quark. The large momentum transfer region can be a crucial testing ground for QCD since not only are a number of new subprocesses accessible ($\gamma\gamma \to q\bar{q}$, $\gamma q \to gq$, $\gamma q \to Mq$) with essentially no free parameters, but most important, one can make predictions for a major component of the photon structure function directly from QCD We also note that there are important questions in hadron-hadron collisions, e.g., whether nonperturbative effects[16] (instantons[40], soft gluon interactions[35]) are important for large $p_T$ reactions. Such effects are presumably absent for the perturbative, point-like interactions of the photon. We also emphasize that the interplay between vector-meson dominance and point-like contributions to the hadronic interactions of the photon is not completely understood in QCD, and $\gamma\gamma$ processes may illuminate these questions.

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## REFERENCES


1. See, e.g., S. J. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. D4, 1532 (1971). For reviews see V. M. Budnev et al., Phys. Rep. 15C, (1975); H. Terazawa, Rev. Mod. Phys. 45, 615 (1973); and the reports of S. J. Brodsky, H. Terazawa and T. Walsh in the Proc. of the Internat. Colloquium on Photon-Photon Collisions, published in Supplement au Journal de Physique, Vol. 35 (1974). See also G. Grammer and T. Kinoshita, Nucl. Phys. B80, 461 (1974); R. Bhattacharya, J. Smith and G. Grammer, Phys. Rev. D15, 3267 (1977); J. Smith, J. Vermaseren and G. Grammer, Phys. Rev. D15, 3280 (1977). For other reviews of $\gamma\gamma$ interactions, see the lectures of the 1979 International Conf. on Two-Photon Interactions, ed. by J. F. Gunion (Univ. of California, Davis), and in $\gamma\gamma$ collisions: International Workshop at Amiens, ed. by G. Cochard and P. Kessler (Springer-Verlag, Heidelberg, 1980), and also S. J. Brodsky, SLAC-PUB-2240 (1978), published in the Proc. of J. M. Weis Memorial Symposium on Strong Interactions (1978): 27.
2. For a detailed review of VMD see T. H. Bauer, R. D. Spital, D. R. Yennie, and F. M. Pipkin, Rev. Mod. Phys. 50, 261 (1979).
3. J. D. Bjorken, Phys. Rev. D1, 1376 (1970).
4. C. E. Carlson and R. Suaya, SLAC-PUB-2483 (1980).
5. E. Hilger, Bonn preprint HE-81-4 (1981), and these proceedings; D. Burke, these proceedings, and D. Burke et al., SLAC-PUB-2693 (1981). This reference includes the recent Mark II results for $\gamma\gamma \rightarrow \rho^o\rho^o$; and Tasso collaboration preprint DESY 80-77 (1980).
6. H. Goldberg and T. Weiler, Northeastern University preprint, NUB #2488 (1981).
7. J. Layssac and F. M. Renard, Montpellier University preprint PM/80/11 (1980).
8. J. F. Donoghue, K. Johnson, B. A. Li, Phys. Lett. 99B, 416 (1981).
9. J. L. Rosner, Univ. of Minnesota preprint (1981), and Kyoto University preprint RIFP-435 (1981).
10. G. P. Lepage and S. J. Brodsky, Phys. Lett. 87B, 359 (1979); Phys. Rev. D22, 2157 (1980); and S. J. Brodsky. Y. Frishman, G. P. Lepage and C. Sachradja, Phys. Lett. 91B, 239 (1980). See also S. J. Brodsky and G. P. Lepage, SLAC-PUB-2733 and 2746 (1981), and S. J. Brodsky, G. P. Lepage, and T. Huang, SLAC-PUB-2540 (1980).
11. For related calculations in light-cone perturbation theory, see J. Bjorken, J. Kogut, and D. Soper, Phys. Rev. D3, 1382 (1971); G. P. Lepage and S. J. Brodsky, Ref. 10, and S. J. Brodsky and S. D. Drell, Phys. Rev. D22, 2236 (1980).
12. S. J. Brodsky, T. A. DeGrand, J. F. Gunion and J. H. Weis, Phys. Rev. Lett. 41, 672 (1978); Phys. Rev. D19, 1418 (1979).
13. C. H. Llewellyn Smith, Phys. Lett. 79B, 83 (1978).
14. K. Kajantie, Phys. Scripta 29, 230 (1979); K. Kajantie and R. Raitio, Nucl. Phys. B159, 528 (1979); J. Field, E. Pietarinen, and K. Kajantie, Nucl. Phys. B171, 377 (1980). See also K. Kajantie, these proceedings.
15. See also J. D. Bjorken, S. Berman, and J. Kogut, Phys. Rev. D4, 3388 (1971).

16. J. D. Bjorken, SLAC-PUB-2372 (1979), published in SLAC Summer Institute 1979, 219.
17. F. A. Berends, Z. Kunszt, and R. Gastmans, DESY preprint 80/89 (1980).
18. W. Wagner, DESY preprint 80/102; C. Berger, Aachen preprint (1980), presented at the International Workshop on $\gamma\gamma$ collisions, Amiens (1980); G. Knies, presented at the Vanderbilt Symposium on $e^+e^-$ interactions (1980).
19. R. Cahn and J. F. Gunion, Phys. Rev. D20, 2253 (1979); K. Kajantie and R. Ratio, Phys. Lett. 87B, 133 (1979).
20. See E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. 42, 940 (1979); E. L. Berger, Z. Phys. C4, 289 (1980), and references therein.
21. S. J. Brodsky, J. F. Gunion, and R. Rückl, Phys. Rev. D18, 2469 (1978); J. Bagger and J. F. Gunion, to be published. See also E. L. Berger, T. Gottschalk, and D. Sivers, Phys. Rev. D23, 99 (1981).
22. S. J. Brodsky, T. Kinoshita, and H. Terazawa, Phys. Rev. Lett. 27, 280 (1971); T. F. Walsh, Phys. Lett. 36B, 121 (1971).
23. C. Peterson, T. F. Walsh, and P. Zerwas, Nucl. Phys. B174, 424 (1980), and references therein.
24. K. Sasaki, SLAC-PUB-2712 (1981), and Phys. Rev. D22, 2143 (1980). For other related work see J. Kodaira, A. Higuchi, and S. Matsuda, SLAC-PUB-2695 (1981); J. A. Hassan and D. J. Pilling, Manchester University preprint M/C TH 80/23 (1981).
25. S. J. Brodsky and G. P. Lepage, SLAC-PUB-2447 (1975), published in the Proc. of the 1979 Summer Institute on Particle Physics at SLAC, Stanford, CA.
26. R. J. DeWitt, L. M. Jones, J. D. Sullivan, D. E. Willem, and H. W. Wyld, Phys. Rev. D19, 2046 (1979); D20, 1751 (E) (1979).
27. E. Witten, Nucl. Phys. B120, 189 (1977).
28. W. A. Bardeen and A. J. Buras, Phys. Rev. D20, 166 (1979); W. R. Frazer and J. F. Gunion, Phys. Rev. D20, 147 (1979); D. W. Duke and J. F. Owens, Phys. Rev. D22, 2280 (1980); see also W. R. Frazer, these proceedings.
29. M. Chase, Nucl. Phys. B167, 125 (1980); B174, 109 (1980); and Oxford preprint 97/80 (1980).
30. S. J. Brodsky and J. Pumplin, Phys. Rev. 182, 1794 (1969); S. J. Brodsky, F. E. Close, and J. F. Gunion, D6, 177 (1972).
31. M. Damashek and F. J. Gilman, Phys. Rev. D1, 1319 (1970).
32. M. J. Creutz, S. D. Drell, and E. A. Paschos, Phys. Rev. 178, 2300 (1969).
33. S. J. Brodsky, F. E. Close, and J. F. Gunion, Phys, Rev. D5, 1384 (1972).
34. S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973); Phys. Rev. D11, 1309 (1975); V. A. Matveev, R. M. Muradyan and A. V. Tavkheldize, Lett. Nuovo Cimento 7, 719 (1973). For discussions in QCD, see S. J. Brodsky and G. P. Lepage, SLAC-PUB-2746 (1981), and A. H. Mueller, Columbia preprint CU-TP-192.
35. For a discussion of initial state effects in hadron-hadron collisions, see G. Bodwin, S. J. Brodsky, and G. P. Lepage (in preparation).
For the case of $\gamma\gamma$ reactions initiated by hadron-hadron collisions, the initial state interactions lead to the exchange of finite transverse momenta, and thus would be expected to smear the transverse momentum of the $\gamma\gamma \to X$ system, without changing the

total production cross section.
See also the reports of C. Tao and A. Donnachie, these proceedings.

36. See the reports of W. Willis and P. Zerwas, these proceedings.
37. This includes multiple-jet collision processes, initial-state effects, as well as higher-particle number subprocesses. See, e.g., D. Sivers, R. Blankenbecler, and S. J. Brodsky, Phys. Reports 23C, 1 (1976).
38. G. P. Lepage, these proceedings; S. J. Brodsky and G. P. Lepage, SLAC-PUB-2733 (1981), and SLAC-PUB-2587 (1980), presented at the XXth International Conf. on High Energy Physics, Madison, WI.
39. P. V. Landshoff, Phys. Rev. D10, 1024 (1974); P. V. Landshoff and D. J. Pritchard, Z. Phys. C6, C9 (1980); and G. P. Lepage and S. J. Brodsky, Ref. 10.
40. J. Ellis, M. K. Gaillard, and W. J. Zakrzewski, Phys. Lett. 81B, 224 (1979).