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TESTS OF PERTURBATIVE QUANTUM CHROMODYNAMICS IN PHOTON-PHOTON COLLISIONS*

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ABSTRACT

The production of hadrons in the collision of two photons via the process[1] $e^+e^- \to e^+e^-X$ (see Fig. 1) can provide an ideal laboratory for testing many of the features of the photon's hadronic interactions, especially its short distance aspects. We will review here that part of two-photon physics which is particularly relevant to tests of perturbative QCD.

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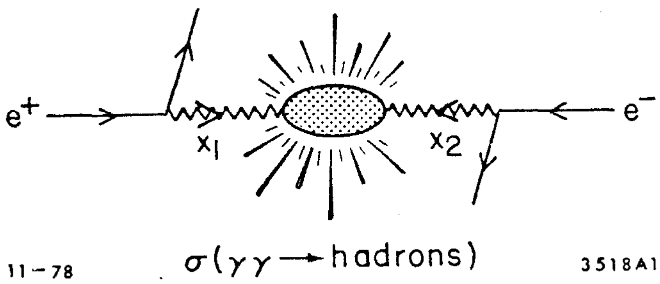

Fig. 1. Two-photon annihilation into hadrons in e^+e^- collisions.

Large p_T jet production[2-7]

Perhaps the most interesting application of two photon physics to QCD is the production of hadrons and hadronic jets at large p_T. The elementary reaction $\gamma\gamma \to q\bar{q} \to$ hadrons yields an asymptotically scale-invariant two-jet cross section at large p_T proportional to the fourth power of the quark charge. The $\gamma\gamma \to q\bar{q}$ subprocess[7] implies the production of two non-collinear, roughly coplanar high p_T (SPEAR-like) jets, with a cross section nearly flat in rapidity. Such "short jets" will be readily distinguishable from $e^+e^- \to q\bar{q}$ events due to missing visible energy, even without tagging the forward leptons. It is most useful to determine the ratio,

$$R_{\gamma\gamma} \equiv \frac{d\sigma(e^+e^- \to e^+e^-q\bar{q} \to e^+e^- + \text{jets})}{d\sigma(e^+e^- \to e^+e^-\mu^+\mu^-)} \tag{1}$$

since experimental uncertainties due to tagging efficiency tend to cancel.[8] In QCD, with 3-colors, one predicts[2-4]

$$R_{\gamma\gamma} = 3 \sum_{q=u,d,s,c,\ldots} e_q^4 \left(1 + O\left[\frac{\alpha_s(p_T^2)}{\pi}\right]\right) \tag{2}$$

where p_T is the total transverse momentum of the jet (or muon) and $\alpha_s(Q^2) \to 4\pi/(\beta \log Q^2/\Lambda^2)$, $\beta = 11 - 2/3n_f$ for n_f flavors. Measurements of the two-jet cross section and $R_{\gamma\gamma}$ will directly test the scaling of the quark propagator $\not{p}^{-1}$ at large momentum transfer, check the color factor and the quark fractional charge. The QCD radiative corrections are expected to depend on the jet production angle and acceptance. Such corrections are of order $\alpha_s(p_T^2)$ since there are neither infrared singularities in the inclusive cross section, nor quark mass singularities at large p_T which could give compensating logarithmic factors. The onset of charm and other quark thresholds can be studied once again from the perspective of $\gamma\gamma$-induced processes. The cross section for the production of jets with total hadronic transverse momentum ($p_T > p_{Tmin}$) from the $\gamma\gamma \to q\bar{q}$ subprocess alone can be estimated from the convenient formula,[2,4]

$$\sigma_{e^+e^- \to e^+e^- \,\mathrm{Jet}+X}\left(s, p_T^{jet} > p_T^{min}\right) \equiv R_{\gamma\gamma}\, \sigma_{e^+e^- \to e^+e^-\mu^\pm\mu^\mp}\left(s, p_T^{\mu\pm} > p_T^{min}\right)$$

$$\cong R_{\gamma\gamma} \frac{32\pi\alpha^2}{3} \left(\frac{\alpha}{2\pi} \log \frac{s}{m_e^2}\right)^2 \frac{\left(\log \frac{s}{p_{Tmin}^2} - \frac{19}{6}\right)}{p_{Tmin}^2}$$

$$\cong \frac{0.5\,\mathrm{nb\,GeV}^2}{p_{Tmin}^2} \quad \text{at} \quad \sqrt{s} = 30\ \mathrm{GeV} \quad . \tag{3}$$

where we have taken $R_{\gamma\gamma} = 3\sum_q e_q^4 = 34/27$ above the charm threshold. For $p_{Tmin} = 4$ GeV, $\sqrt{s} = 30$ GeV, this is equivalent to 0.3 of unit of R; i.e., 0.3 times the $e^+e^- \to \mu^+\mu^-$ rate. We note that at $\sqrt{s} = 200$ GeV, the cross section from the $e^+e^- \to e^+e^-q\bar{q}$ subprocess with $p_{Tmin} = 10$ GeV is 0.02 nb, i.e., about 9 units of R! At such energies e^+e^- colliding beam machines are more nearly laboratories for $\gamma\gamma$ scattering then they are for e^+e^- annihilation! A useful graph[4] of the increase in R from the $\gamma\gamma \to q\bar{q}$ process for various $x_{Tmin} = 2p_{Tmin}/\sqrt{s}$ is shown in Fig. 2. The $\log s/p_{Tmin}^2 - 19/6$ in Eq. (3) arises from integration over the nearly flat rapidity distribution of the $\gamma\gamma$ system. The final state in high p_T $\gamma\gamma \to q\bar{q}$ events in the $\gamma\gamma$ center-of-mass should be similar in multiplicity and other hadronic properties as $e^+e^- \to \gamma^* \to q\bar{q}$, although

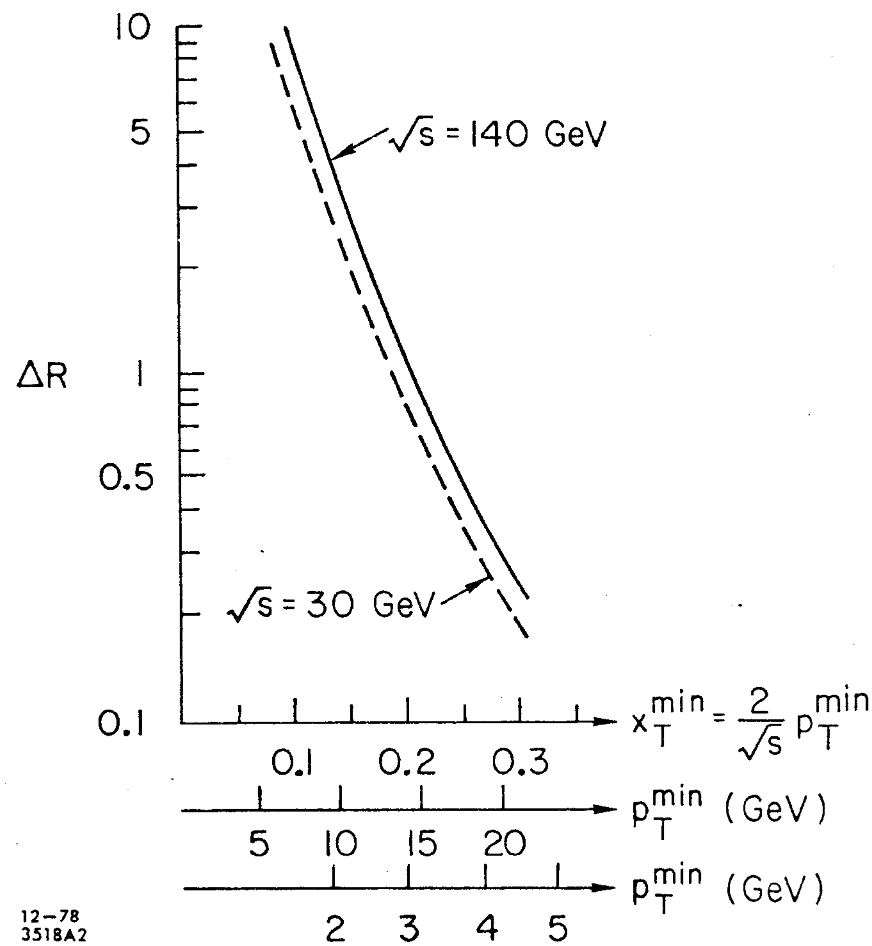

Fig. 2. The contribution to R from $\gamma\gamma \to q\bar{q}$ two jet processes at $\sqrt{s}$ = 30 and 140 GeV (from Ref. 4).

$u\bar{u}$ and $c\bar{c}$ events should be enhanced relative to $d\bar{d}$ and $s\bar{s}$ due to the e_q^4 dependence. Monte Carlo studies of SPEAR events at $s = 4p_T^2$ distributed uniformly in rapidity would be useful in order to learn how to identify and trigger $\gamma\gamma \to q\bar{q}$ events.

Although the above prediction for $R_{\gamma\gamma}$ is one of the most straightforward consequences of perturbative QCD, from the perspective of photon physics of 10 years ago, the occurrence of events with the structure $\gamma\gamma \to$ jet + jet at high p_T could only be regarded as revolutionary. From the VMD standpoint, a real photon acts essentially as a sum of vector mesons; however, it is difficult to imagine an inelastic collision of two hadrons producing two large p_T jets without hadronic energy remaining in the beam direction!

On the other hand, if the $\gamma\gamma \to$ two jet events are not seen at close to the predicted magnitude with an approximately scale invariant cross section, then it would be hard to understand how the perturbative structure of QCD could be applicable to hadronic physics. In particular, unless the pointlike couplings of real photons to quarks are confirmed, then the analogous predictions for perturbative high p_T processes, involving gluons such as $gg \to q\bar{q}$ are probably meaningless.

In fact, preliminary results from the Pluto group at PETRA give indications that high p_T jet events with a single electron tag do exist. "Triplicity" analyses seem to be well suited to finding the $q\bar{q}$ jet axes and total momenta.[9]

In addition to $\gamma\gamma \to q\bar{q}$ one also expects gluon jet production $\gamma\gamma \to gg$ at order $\alpha_s^2(p_T^2)$ via a quark loop box diagram.[10] Calculations predict the $gg/q\bar{q}$ ratio should be of order 20%.

Multi-jet processes and the photon structure function

In addition to the two-jet processes, QCD also predicts 3- and 4-jet events[2,3,4] from subprocesses such as $\gamma q \to gq$ (3 jet production where one photon interacts with the quark constituent of the other photon) as well as the conventional high p_T QCD subprocesses $qq \to qq$ and $q\bar{q} \to gg$ (which lead to jets down the beam direction plus jets at large p_T). The structrue of these events are very similar to that for hadron-hadron collisions. The cross section for $Ed\sigma/d^3p_J$ ($\gamma\gamma \to$ jet + X or ee $\to$ ee jet + X) can be computed in the standard way from the hard scattering expansion ($\hat{s} = x_a x_b s$, etc.)

$$E \frac{d\sigma}{d^3p} (AB \to CX) \cong \sum_{abd} \int_o^1 dx_a \int_o^1 dx_b \; G_{a/A}(x_a) \; G_{b/B}(x_b)$$

$$\frac{d\sigma}{d\hat{t}} (ab \to cd)\Bigg|_{\hat{s},\hat{t},\hat{u}} \frac{\hat{s}}{\pi} \; \delta(\hat{s} + \hat{t} + \hat{u}) \qquad (4)$$

where the hard scattering occurs in $ab \to cd$ and the fragmentation function $G_{a/A}(x_a)$ gives the probability of finding constituent a with light-cone fraction $x_a = (p_a^0 + p_a^3)/(p_A^0 + p_A^3)$. In general, $G_{a/A}$ has a scale-breaking dependence on $\log W^2$ which arises from the constituent transverse momentum integration when gluon bremsstrahlung or pair production is involved.

However, there is an extraordinary difference between photon- and hardon-induced processes. In the case of proton-induced reactions, $G_{q/p}(x,Q^2)$ is determined from experiment, especially deep inelastic lepton scattering. In the case of the photon, the $G_{q/\gamma}$ structure function required in Eq. (4) has a perturbative component which can be predicted from first principles in QCD. This component, as first computed by Witten,[11] has the asymptotic form at large probe momentum Q^2

$$G_{q/\gamma}(x,Q^2) \Longrightarrow \frac{\alpha}{\alpha_s(Q^2)} f(x) + O(\alpha^2) \tag{5}$$

i.e., aside from an overall logarithmic factor, the $\gamma \to q$ distribution Bjorken scales; $f(x)$ is a known, calculable function. Unlike the proton structure function which contracts to $x = 0$ at infinite probe momentum $Q^2 \to \infty$, this component of the photon structure function <u>increases</u> as $\log Q^2$ independent of x. This striking fact is of course due to the direct $\gamma \to q\bar{q}$ perturbative component in the photon wave function. (The apparent violation of momentum conservation when $\alpha_s(Q^2) < \alpha$ should be cured when higher order terms in α are taken into account.) In addition to the perturbative component, one also expects a nominal hadronic component due to intermediate vector meson states.

Returning to the high p_T jet cross sections, we note the following striking fact: in each contribution to the four-jet cross section the two factors of $\alpha_s(p_T^2)$ from the subprocess cross section, e.g.,

$$\frac{d\sigma}{dt}(qq \to qq) \sim \frac{4\pi\left(\alpha_s(t)\right)^2}{t^2} \tag{6}$$

(see Fig. 3a) actually cancel (in the asymptotic limit) the two inverse powers of $\alpha_s(p_T^2)$ from the two $G_{q/\gamma}(x,p_T^2)$ structure functions.[2] Similarly the single power of $\alpha_s(p_T^2)$ in $d\sigma/dt\ (\gamma q \to gq)$ cancels the single inverse power of $\alpha_s(p_T^2)$ structure function in the 3-jet cross section (see Fig. 3b). Thus miraculously <u>all</u> of these jet trigger cross sections obey <u>exact</u> Bjorken scaling

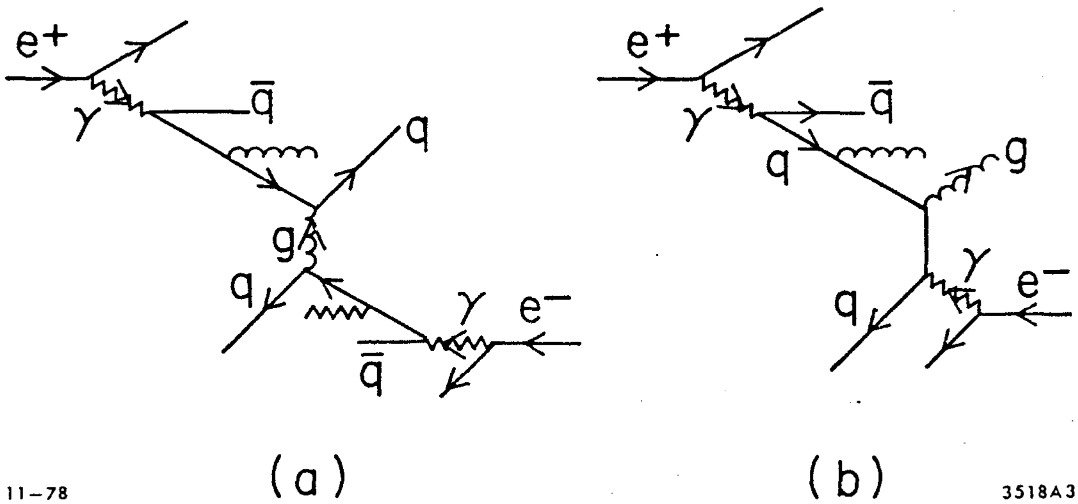

Fig. 3. Contributions from QCD subprocesses to (a) 4-jet and (b) 3-jet final states.

$$E \frac{d\sigma}{d^3p} (\gamma\gamma \to \text{Jet} + X) \underset{p_T^2 \to \infty}{\Longrightarrow} \frac{1}{p_T^4} f(x_T, \theta_{cm}) \tag{7}$$

when the leading QCD perturbative corrections to all orders are taken into account. Furthermore, the asymptotic cross sections are even independent of $\alpha_s(p_T^2)$! The asymptotic prediction thus has essentially zero parameters.

To leading order in $\alpha_s(Q^2)$ the $G_{q/\gamma}$ structure function of the photon can be obtained via the convolution of the $G_{q/q}$ distribution with the Born term for the $\gamma \to q\bar{q}$ coupling (as schematically indicate in Fig. 4). In terms of the evolution equations, the direct $\gamma \to q\bar{q}$ coupling provides a driving term:[11,13]

$$\frac{\partial}{\partial \log Q^2} G_{q/\gamma}(x,Q^2) = e_q^2 \frac{\alpha_{em}}{2\pi} \left[x^2 + (1-x)^2\right] + \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} P_{q/q}(x/y)\, G_{q/\gamma}(y,Q^2) \ , \tag{8}$$

Taking moments, then leads to the the anti-scaling form (5). At large Q^2 and $x \sim 1$ one finds[14]

$$G_{q/\gamma}(x,Q^2) \underset{x \to 1}{=} \frac{3}{2\pi} e_q^2 \frac{\alpha}{\alpha_s(Q^2)} \frac{4}{\beta - (3 - 4\gamma_E)C_F + 4C_F \log \frac{1}{1-x}} \ , \tag{9}$$

much flatter than the power-law-damped meson structure functions. Here $C_F = 4/3$, $\beta = 11 - 2/3\, n_F$, and $\gamma_E = 0.577...$ is Euler's constant. An illustration of the photon structure function is shown in Fig. 5. Corrections to the next order in $\alpha_s(Q^2)$ have also been computed by Buras and Bardeen;[15] the main result is to increase the fall off at x close to 1. Measurements of the photon structure function, $F_{2\gamma}(x,Q^2) =$

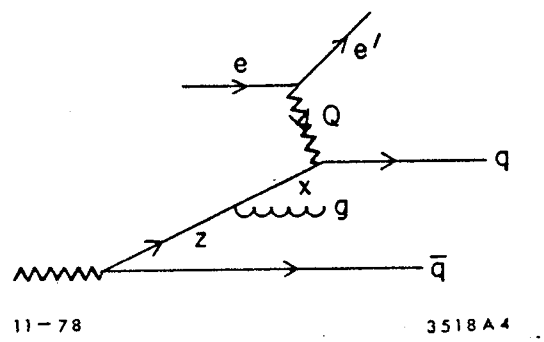

Fig. 4. Representation of the QCD photon structure function in deep inelastic scattering on a photon target. Real and virtual gluon corrections to all orders are included in the analytic results.

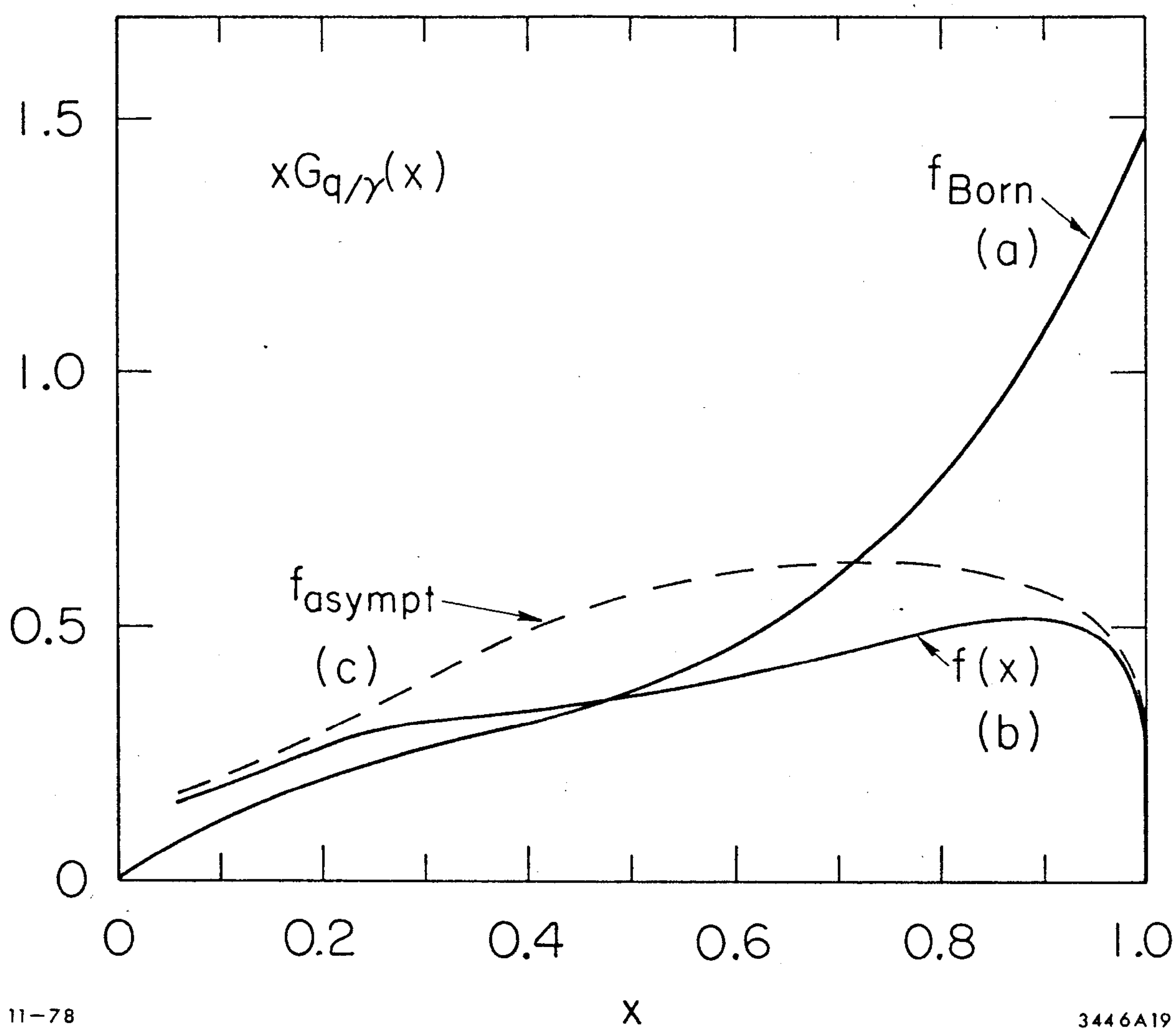

Fig. 5. The valence photon structure function $\bar{G}_{q/\gamma}(x)$ as calculated in (a) Born approximation, (b) to all orders in QCD, and (c) the $x\to 1$ limit (Eq. (9)). An overall factor proportional to $\log Q^2/\Lambda^2$ is factored out (from Ref. 2).

$\sum_q e_q^2\, xG_{q/\gamma}(x,Q^2)$ and the σ_L/σ_T ratio will clearly provide one of the most important tests of perturbative QCD. Detailed calculations are given in Ref. 11.

Figure 6 illustrates the magnitude of the QCD 2, 3, and 4 jet cross section at an e^+e^- center of mass energy of 30 GeV, compared to a simple vector meson dominance estimate.[2] The contrast between the scale-breaking hadron-induced jet production cross sections with scale-invariant p_T^{-4} two-photon induced jets is remarkable. In addition, one can estimate the single particle large p_T production cross sections for $\gamma\gamma \to \pi X$, etc. expected from QCD leading twist and high twist sub-processes such as $\gamma q \to \pi q$. Again, the analysis is much simpler and cleaner than the corresponding hadron induced reactions; measurements will lead to important constraints on the theory and the parametrization of the high twist terms p_T^{-6} which are expected to dominant at moderate p_T.

It also may be possible to measure two photon reactions with each of the initial photons virtual. As shown by Chase,[16] the $\gamma^* + \gamma^* \to$ Jet + Jet cross section and angular distribution can be predicted using perturbative QCD for the far-off-shell q_1^2, q_2^2 region with $s = (q_1 + q_2)^2$ fixed. The calculation to leading order in $\alpha_s(Q^2)$ involves the evolution equation[17] which determines the meson wave function at short distances.

Exclusive channels in two-photon reactions

Another very important area for testing QCD are large momentum exclusive $\gamma\gamma$ reactions. For example, the same techniques used to compute the pion form factor[17] can also be used to determine the large Q^2 $\gamma \to \pi^0$ transition form factor. We find, to leading order in $\alpha_s(Q^2)$,[17,18]

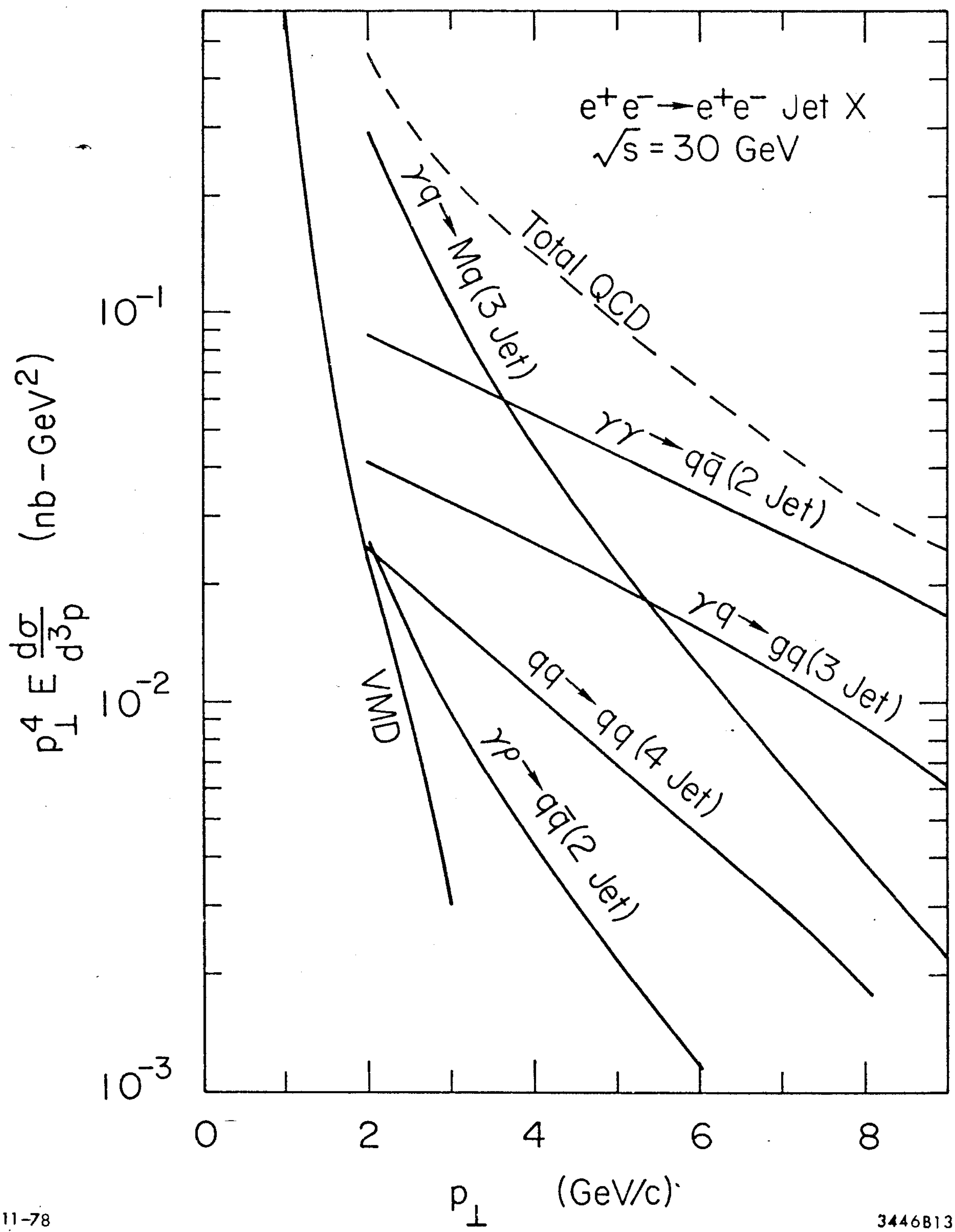

Fig. 6. QCD (and VMD) contributions to the $e^+e^- \to e^+e^-$ Jet + X. The 4-jet cross section includes the contributions from $qq \to qq$, $q\bar{q} \to q\bar{q}$, and $q\bar{q} \to gg$ (from Ref. 2).

$$F_{\pi\gamma}(Q^2) = \frac{2\left(e_u^2 - e_d^2\right)\sqrt{n_c}}{Q^2} \sum_{n=0}^{\infty} a_n\left(\log \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n}$$

$$= \frac{1}{Q^2}\; 2\left[\frac{Q^2\; F_\pi(Q^2)}{16\pi\; \alpha_s(Q^2)}\right]^{\frac{1}{2}}$$

$$\rightarrow 2\,\frac{f_\pi}{Q^2} \qquad \text{as} \qquad Q^2 \rightarrow \infty \tag{10}$$

where the $\gamma^*\gamma\pi^o$ vertex is defined as $ie^2F_{\pi\gamma}(Q^2)\,\epsilon_{\mu\nu\sigma\rho}\,p_\pi^\nu\, q^\rho\, \epsilon^\sigma$.

The two-photon process will also allow a detailed test of the application of perturbative QCD to large angle exclusive scattering. The processes $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow K^+K^-$ at fixed θ_{cm} and large $s_{\gamma\gamma}$ (with nearly on-mass-shell photon) are the simplest non-trivial, 2-body scattering reactions which can be computed in QCD. The Landshoff-type pinch singularity contributions are power-law suppressed compared to the leading hard scattering amplitudes. One thus predicts the fixed angle scaling behavior[19]

$$R_{\gamma\gamma\rightarrow\pi^+\pi^-} = \frac{\frac{d\sigma}{dt}\,(\gamma\gamma \rightarrow \pi^+\pi^-)}{\frac{d\sigma}{dt}\,(\gamma\gamma \rightarrow \mu^+\mu^-)} \cong F_\pi^2(s)\; f(\theta_{cm}) \tag{11}$$

The absolute normalization and angular dependence of the $\pi^+\pi^-$ and K^+K^- cross sections also are predictable in QCD. We also note that the fixed angle $\gamma^* + \gamma \rightarrow \pi^+\pi^-$ QCD amplitude has negligible dependence[20] in q^2 if $s \ll |q^2|$, in strong contrast to what would be expected by vector meson dominance.[20]

In summary, it becomes 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 $e^{\pm}e^{-}$ machines. Although low p_T $\gamma\gamma$ reactions should strongly 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 pointlike 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 predicted ($\gamma\gamma \to q\bar{q}$, $\gamma q \to gq$, $\gamma q \to Mq$, deep inelastic scattering on a photon target) with essentially with 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 open questions in hadron-hadron collisions, e.g., whether non-perturbative effects (instantons, wee parton interactions) are important for large p_T reactions. Such effects are presumably absent for the perturbative, pointlike interactions of the photon. We also note that the interplay between vector-meson-dominance and pointlike contributions to the hadronic interactions of photon is not completely understood in QCD, and $\gamma\gamma$ processes may illuminate these questions.

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