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PHOTON-PHOTON COLLISIONS*

STANLEY J. BRODSKY
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

1. Introduction

Over the past decade the field of photon-photon collisions[1)] has emerged as an important laboratory for testing both perturbative and nonperturbative properties of quantum chromodynamics.

At this meeting a huge array of new and high quality experimental results for exclusive and inclusive two-photon channels has been reported, both at high and low transverse momentum and at high and low virtual photon mass.[2)] In many theoretical areas the precision of QCD predictions has now been sharpened, allowing quantitative measures of the running coupling constant, $\alpha_s(Q^2)$, determinations of basic features of hadronic wavefunctions, as well as tests of specific QCD scaling laws and spin selection rules. The striking resonance structure measured[3),4)] in the $\gamma\gamma \to \rho^0\rho^0$ cross section suggests an interpretation in terms of $(qq\overline{q}\overline{q})$ bound states, which if confirmed, represents a manifestation of novel degrees of freedom of QCD. In the case of the photon structure function, we are now beginning to understand the interplay between point-like and hadron-like interactions of on-shell photons and how to meaningfully extract a high precision value for the QCD scale $\Lambda_{\overline{MS}}$.

In photon-photon collisions one studies in e^+e^- storage rings the production of even charge conjugation states by two elementary probes of variable mass and polarization. (See Fig. 1a.) The conventional viewpoint until the early 1970's had been that photon interactions were mediated by intermediate vector meson states (current field identity, generalized vector mesons dominance, etc.). Our viewpoint from the perspective of QCD is just the reverse: even on-mass-shell

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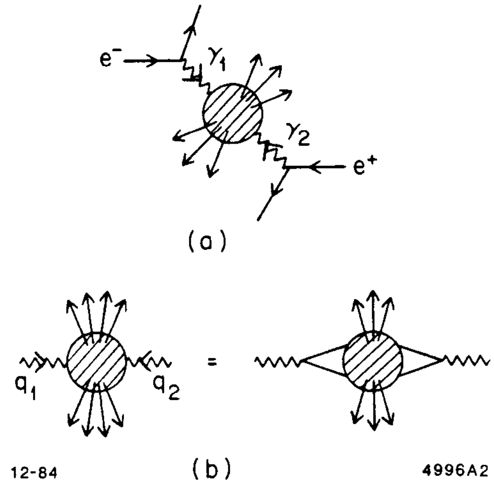


Fig. 1. (a) Photon-photon collisions in e^+e^- storage rings. (b) The direct coupling of photons to $q\bar{q}$ currents in QCD.

photons couple directly to local quark currents. (See Fig. 1b.) The observation[5] of two-jet events: $\gamma\gamma \to$ jet + jet at high p_T is in dramatic conflict with the VMD description since hadronic collisions nearly always produce four or more final state jets. At an even more basic level, the confirmation of the QCD scaling law[6]

$$F_{2\gamma}(x, Q^2) \cong f(x)\, \ell n \frac{Q^2}{\Lambda^2} \tag{1.1}$$

for deep inelastic scattering on a photon target ($e\gamma \to e'X$) over the range of $1 \lesssim Q^2 \lesssim 100$ GeV^2 is in striking contrast to the observed scaling pattern of hadron structure functions. In a related area of real photon physics, the charge asymmetry reported at this meeting by the MAC group[7] in the reaction $e^+e^- \to \gamma+$ jet automatically measures the direct coupling of a real photon to the outgoing quark jet currents[8] and agrees with the QCD fractional charge assignment for Σe_q^3.

The study of photon-photon collisions in the dynamical range accessible at e^+e^- storage rings such as PEP and PETRA is well matched to the basic energy scales of QCD: for processes in which the quarks and gluon propagator are far off-shell ($Q^2 \gg \Lambda^2_{\overline{MS}}$ and $Q^2 \gg \langle k_\perp^2 \rangle$), higher-twist power-law and non-perturbative corrections become small and perturbative calculations become justified. Experimentally, the specific QCD scaling of the photon structure function, the $p_T^{-4} f(x_T, \theta_{cm})$ scaling of the invariant jet production cross section, and the scaling of the $\gamma\gamma \to \pi^+\pi^-, K^+K^-$ cross sections at large momentum transfer confirm the basic validity of QCD perturbative predictions in this domain. Conversely, at lower momentum transfer one can study in the simplest channels non-perturbative dynamics, including multi-quark and gluon resonance formation, prebinding effects, and other fundamental aspects of hadronization. The total $\gamma\gamma$ cross section has now been measured over a large dynamic range—up to the maximum PEP and PETRA energies.[9] Here there is the outstanding theoretical question whether the box graph which is special to the $\gamma\gamma \to \gamma\gamma$ forward amplitude gives a local $1/W^2$ contibution separate from the conventional Reggeon parameterization.

In this summary, I shall discuss only a few of the many interesting topics presented at this workshop. My main emphasis will be on the use of photon-photon collisions as a primary tool for investigating QCD.

2. Two-body Production Processes

One of the most important areas where two-photon physics will have a critical impact in QCD is in the study of exclusive channels. The exclusive two-body processes $\gamma\gamma \to H\overline{H}$ at large $W^2_{\gamma\gamma} = (q_1 + q_2)^2$ and fixed $\theta^{\gamma\gamma}_{\rm c.m.}$ provide a particularly important laboratory for testing QCD, since the large momentum-transfer behavior, helicity structure, and often even the absolute normalization can be rigorously predicted.[10] Conversely, the angular dependence of $\gamma\gamma \to H\overline{H}$ cross sections can be used to determine the shape of the hadron distribution amplitudes[11] $\phi_H(x_i, Q)$—the process-independent probability amplitudes for finding valence quarks in the hadron, each carrying (light-cone) fraction x_i of the hadron's momentum collinear up to the momentum transfer scale Q of the process. The $\gamma_\lambda \gamma_{\lambda'} \to H\overline{H}$ amplitude can be written as a factorized form[10)]

$$\mathcal{M}_{\lambda\lambda'}(W_{\gamma\gamma}, \theta_{c.m.}) = \int_0^1 [dy_i]\, \phi_H^*(x_i, Q)\, \phi_{\overline{H}}^*(y_i, Q)\, T_{\lambda\lambda'}(x, y; W_{\gamma\gamma}, \theta_{c.m.}) \qquad (2.1)$$

where $T_{\lambda\lambda'}$ is the hard scattering helicity amplitude for scattering the clusters of valence quarks in each hadron. $T_{\lambda\lambda'}$ can be computed in perturbation theory and scales according to the dimensional counting rules:[12)] to leading order $T \propto \alpha(\alpha_S/W_{\gamma\gamma}^2)^{1,2}$ and $d\sigma/dt \sim W_{\gamma\gamma}^{-4,-6} f(\theta_{c.m.})$ for meson and baryon pairs, respectively. The distribution amplitudes $\phi_H(x_i, Q)$ require input from non-perturbative bound state physics, but their logarithmic dependence in Q^2 is determined by evolution equations.[11)] Detailed predictions for pseudo-scalar and vector-meson pairs for each helicity amplitude are given in Ref. 10. The helicities of the hadron pairs are predicted to be equal and opposite to leading order in $1/W^2$. The QCD predictions have now been extended to mesons containing $|gg\rangle$ Fock states by Atkinson, Sucher and Tsokos,[13)] to $\gamma\gamma \to p\overline{p}$ by Damgaard,[14)] and to all $B\overline{B}$ octet and decouplet states by Farrar, Maina and Neri.[15)] The normalization of the $\gamma\gamma \to p\overline{p}$ amplitude is constrained by the $\psi \to p\overline{p}$ rate.[11)] The arduous calculation of 280 $\gamma\gamma \to qqq\overline{qqq}$ diagrams in T_H required for calculating $\gamma\gamma \to B\overline{B}$ is greatly simplified by using two-component spinor techniques.[15)] However, since there is a disagreement between the calculations of Refs. 14 and 15, a third calculation is necessary.

The basic gauge-invariant measure of a hadron's wavefunction is the distribution amplitude $\phi_H(x_i, Q)$. Using the factorization theorem for exclusive scattering amplitudes, one can show that $\phi_H(x_i, Q)$ is the only non-perturbative input required to normalize and compute any exclusive hadronic scattering processes in QCD at high momentum transfer. Eventually one can hope to actually calculate distribution amplitudes from first principles in QCD, e.g. by solving the QCD light-cone equation of motion[10)] or from numerical constraints obtained from lattice gauge theory.[16)] At this point, we can utilize model distribution amplitudes for mesons and baryons as candidate forms for the nonperturbative dynamical input.

Candidate hadronic wavefunctions have been recently derived[17] using QCD sum rules which relate the first few x-moments of the meson and baryon distribution amplitudes to the QCD vacuum condensates $\langle 0| G^2_{\mu\nu} |0\rangle$ and $\langle 0| m\overline{\psi}\psi |0\rangle$. The resulting form for the nucleon distribution amplitude leads to a number of non-trivial predictions: the sign and magnitude of $G^P_M(Q^2)$ at high Q^2, the ratio G_{M_p}/G_{M_n} and the normalization of $\psi \to p\overline{p}$ are all correctly determined.[17] In the pion case, the normalization of the weak decay constant and high Q^2 form factor are consistent. All of this is contrary to the conclusions of Isgur and Llewellyn Smith[18] who had argued that QCD exclusive scattering formalism could not account for the normalization of the pion and nucleon form factors at presently available momentum transfer.[19]

Although there are a number of assumptions involved in applying QCD sum rules as wave function constraints, the distribution amplitudes derived by Chernyak and Zhnitskii serve as very useful Gedanken forms for making predictions for photon-photon exclusive cross sections.The postulated shapes differ significantly from the SU(6)-symmetric asymptotic solution to the distribution amplitude evolution equation: $\phi \propto x_1x_2x_3$, or the weak binding form $\phi \propto \delta(x_1 - \frac{1}{3})\delta(x_2 - \frac{1}{3})$. In particular, the proton quark distribution is strongly skewed: the u-quark with helicity parallel to that of the nucleon carries 65% of the nucleon's momentum. This asymmetry also implies that the hadron scattering amplitude is sensitive to the near-endpoint region of integration as well the dependence of the running coupling constant on the exchanged momentum in the hard scattering amplitude. Another special feature of the QCD sum-rule analysis is the strong sensitivity to the hadron helicity. This effect is induced due to the fact that the coupling of a pair of quarks through gluon exchange to the gluon condensate is strongest when the quark spins are antiparallel. The distribution amplitude for pions and rho-mesons with helicity zero is predicted to be double-humped, with a local minimum at $x = \frac{1}{2}$. The distribution amplitude of a rho-meson with helicity ± 1 is, however, peaked at equal momentum. This implies a strong dependence of the $\gamma\gamma \to \rho\rho$ amplitude on a non-perturbative vacuum condensate effect in the ρ wavefunction. In analogy one also expects that the Δ distribution amplitude has a very different shape for helicity $S_z = \frac{3}{2}$ and $S_z = \frac{1}{2}$ states. This dependence could have a striking effect on the relative normalization of the $\Delta\overline{\Delta}$ and $p\overline{p}$ production cross sections and could very possibly diminish the ratio of 60 predicted by Farrar *et al.* on the basis of symmetric helicity-independent nucleon and isobar wavefunctions. It is clearly important to repeat the $\gamma\gamma \to p\overline{p}$ calculations assuming the asymmetric form of the proton distribution amplitude derived from the ITEP QCD sum rules by Chernyak and Zhnitskii, since their model can readily account for the magnitude and sign of the proton and neutron form factors.

The normalization and angular dependence of the $\gamma\gamma \to \pi^+\pi^-$ predictions turn out to be insensitive to the precise form of the pion distribution amplitude since the results[10] can be written directly in terms of the pion form factor taken from experiment. The reason for this is that, for meson distribution amplitudes which are symmetric in x and $(1-x)$, the same quantity

$$\int_0^1 dx \, \frac{\phi_\pi(x,Q)}{(1-x)} \tag{2.2}$$

controls the x-integration for both $F_\pi(Q^2)$ and to high accuracy $M(\gamma\gamma \to \pi^+\pi^-)$. Thus we find the relation:

$$\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} \cong \frac{4|F_\pi(s)|^2}{1-\cos^4\theta_{cm}} \; . \tag{2.3}$$

The scaling behavior, angular behavior, and normalization of Eq. (2.3) are all non-trivial predictions of QCD. Recent Mark II data[20] for $\pi^+\pi^-$ and K^+K^- production in the range $1.6 < W_{\gamma\gamma} < 2.4$ GeV near 90° are in excellent agreement with the normalization and energy dependence predicted by QCD (see Fig. 2). As reported by Gidal[21] at this meeting, the Mark II results have now been extended to pair mass beyond 3 GeV, again in agreement with the QCD predictions. It is clearly very important to test the angular dependence of the

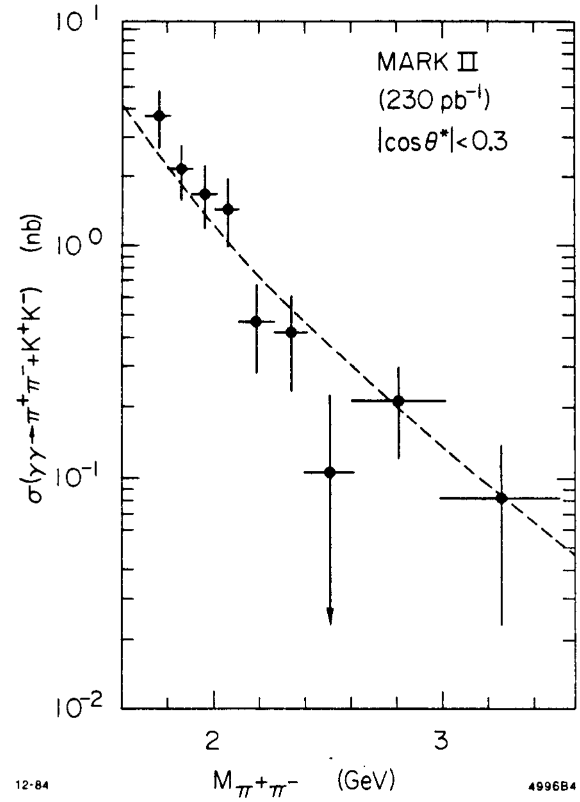
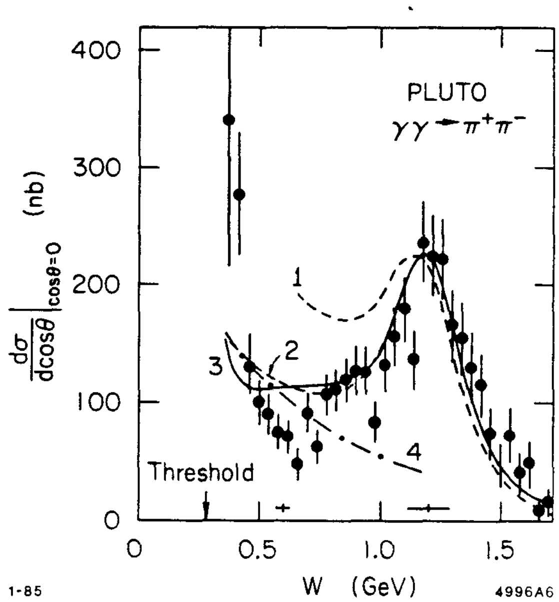


Fig. 2. Measured cross section for $\gamma\gamma \to \pi^+\pi^-$ plus $\gamma\gamma \to K^+K^-$ integrated over the angular region $|\cos\theta_{c.m.}| < 0.3$ (from Ref. 21). The curve is the perturbative-QCD prediction from Ref. 10.

cross sections and separate the $\pi^+\pi^-$ and K^+K^- contributions. The onset of scaling at this range of momentum transfer for meson pair production is reasonable since the off-shell quark propagators in the diagrams for T_H carry momenta large compared to the relevant QCD scales: quark masses, intrinsic transverse momentum, and $\Lambda_{QCD}^{\overline{MS}}$. However, just as in $e^+e^- \to H\overline{H}$, the scaling behavior of the Born cross sections can be distorted by resonance production; the leading order predictions are only be valid well above particle production thresholds and where low relative-velocity final-state corrections become unimportant. [Here we have in mind the QCD analogue of Coulomb interactions between attractive charged particles which, in the non-relativistic regime, give singular distortion factors[22)] of the form $\varsigma/(1-e^{-\varsigma})$ where $\varsigma = 2\pi\,\alpha/v$ ($\Rightarrow 8\pi\,\alpha_s/3v$ in QCD).]

It is also important to understand the $\gamma\gamma \to \pi^+\pi^-$ amplitude in the threshold region since this is the simplest two-body scattering amplitude in QCD. The amplitude is rigorously determined below threshold at $W = 0$ by the low energy

Fig. 3. Differential cross section for $\gamma\gamma \to \pi^+\pi^-$ at $\cos\theta = 0$ as a function of W = measured $\pi^+\pi^-$ mass. Curves 1-3 represent best fits to the data in the $f(1270)$ mass region using (1) Born amplitude + Breit-Wigner with fixed width; (2) Born amplitude + Breit-Wigner (variable width); (3) Mennessier model. Curve 4 represents the conventional Born cross-section alone. Above 1 GeV curve 2 is close to curve 3. The horizontal bars indicate the mean amount of smearing in W at 0.6 GeV and at 1.2 GeV. (From Ref. 24.)



theorem for Compton scattering and crossing. The phase of each $\gamma\gamma \to \pi^+\pi^-$ spherical wave is related by Watson's theorem to the phase of the corresponding $\pi^+\pi^- \to \pi^+\pi^-$ scattering amplitude. The most detailed predictions employing these constraints, which are obtained by modifying the $\gamma\gamma \to \pi^+\pi^-$ point-like Born approximation, have been given by Menessier.[23] As shown in Fig. 3, the Pluto data[24] appears to differ significantly from the model predictions at energies below the f^0 contribution. If these results are confirmed, this would signal a large threshold enhancement in the $\gamma\gamma \to \pi^+\pi^-$ amplitude, possibly indicating low velocity distortion effects[22] as discussed above or a new resonance near or below the $\pi^+\pi^-$ threshold. Either possibility has important implications for QCD.

The data[3),4)] for $\gamma\gamma \to \rho^0\rho^0$ from PETRA and PEP are much larger than predicted by QCD in the region $1.2 < W_{\gamma\gamma} < 2.4$ GeV and are clearly suggestive of resonance enhancement near $\mathcal{M} \sim 1.4$ GeV. (See Fig. 4.) The absence of a comparable signal in $\rho^+\rho^-$ precludes an explanation in terms of a single isoscalar resonance such as a glueball state. A possible, if not compelling, interpretation has been suggested by Achasov *et al.*,[25] and Li and Liu[26] in terms of two interfering $I = 0$ and $I = 2$, $J^{PC} = 2^{++}$, $qq\overline{qq}$ resonances with masses 1.3

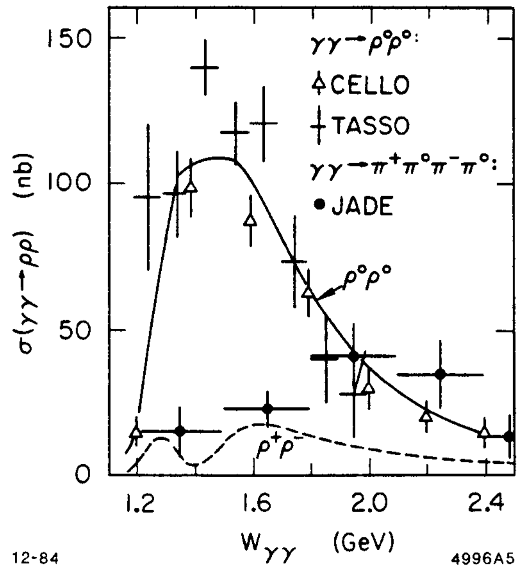


Fig. 4. Comparison of the $\gamma\gamma \to \rho^0\rho^0$ and $\rho^+\rho^-$ data[3),4)] with the mesonium ($qq\overline{q}\overline{q}$) resonance model of Achasov *et al.*[25)] See also Ref. 26.

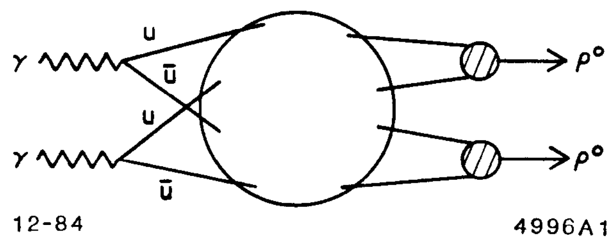


Fig. 5. Coupling of two photons to $q\overline{q}q\overline{q}$ systems decaying to the $\rho^0\rho^0$ final state. The $u\overline{u}u\overline{u}$ coupling is dominant.

and 1.6 GeV, respectively. Two photons couple naturally to such "mesonium" S-wave states since each photon is likely to produce a $q\overline{q}$ system. (See Fig. 5.) Since the $I = 0$ and $I = 2$ amplitudes add constructively in $\gamma\gamma \to \rho^0\rho^0$, they interfere destructively[25)] in $\gamma\gamma \to \rho^+\rho^-$. Identification of these resonances with the predicted couplings in $\psi \to \gamma\, 4\pi$ as well as other $\gamma\gamma \to V\overline{V}$ channels is crucial for a check of this hypothesis. At the high end of the experimental range, $W_{\gamma\gamma} \gtrsim 2$ GeV, the data could be approaching the magnitude predicted by perturbation theory.

In general, QCD predicts a large array of exotic resonances $q\overline{q}g$, gg, $q\overline{q}q\overline{q}$, $qqq\overline{q}\overline{q}\overline{q}$, *etc.*, which are expected to be prominent in the threshold region of the appropriate $\gamma\gamma$ production channel. In the case of $\gamma\gamma \to p\overline{p}$, the cross section ($d\sigma/d\cos\theta = 3 \pm 1\, nb$) measured by TASSO[27] in the threshold region $2 < W_{\gamma\gamma} < 2.4$ GeV is roughly 60 times larger than the prediction of Farrar *et al.*,[15] although $\gamma\gamma \to \Delta^{++}\overline{\Delta}^{++}$ may be close to the predicted normalization. Again this suggests distortions due to resonance production, *e.g.*, $qqq\overline{q}\overline{q}\overline{q}$ baryonium states or strongly helicity-dependent wavefunctions as we have discussed above. The perturbative predictions for $\gamma\gamma \to B\overline{B}$ would not be expected to become valid unless all of the quark and gluon propagators in T_H are reasonably off-shell, *i.e.*, $W_{\gamma\gamma} \gtrsim 5$ GeV and large $\theta_{\text{c.m.}}$.

An essential feature of the QCD predictions for baryon pair production is the fall-off of the cross section at large momentum transfer, reflecting the quark compositeness of the hadrons. One can compare these predictions with the large, rapidly increasing cross sections predicted[29] from effective Lagrangian models with *point-like* p, Δ, and γ couplings.

It is important to extend the QCD predictions for $\gamma\gamma \to H\overline{H}$ to the case of one or two virtual photons, since measurements can be performed with tagged electrons. In fact, for W^2 large and fixed $\theta_{\text{c.m.}}$, the q_1^2 and q_2^2 dependence of the $\gamma\gamma \to H\overline{H}$ amplitude for transversely polarized photons must be minimal.[29] in QCD since the off-shell quark and gluon propagators in T_H already transfer hard momenta; *i.e.*, the 2γ coupling is effectively local for $|q_1^2|$, $|q_2^2| \ll p_T^2$.

The study of resonance production in exclusive two-photon reactions is particularly advantageous because of the variety of new and exotic channels, the absence of complications from spectator hadrons, and the fact that the continuum can be computed or estimated from perturbative QCD. The onset of open charm is particularly interesting since the sum of the exclusive channel cross section should saturate the $\gamma\gamma \to c\overline{c}$ plus $\gamma\gamma \to c\overline{c}q\overline{q}$ contributions. The channels with maximal spin and charge such as $\gamma\gamma \to B_{3/2}(cuu)\, \overline{B}_{3/2}(\overline{c}\overline{u}\overline{u})$ are likely to be dominant due to charge coherence and multiple helicity states.

We also note that photon-photon collisions provide a way to measure the running coupling constant in an exclusive channel, independent of the form of hadronic distribution amplitudes. The photon-meson transition form factors $F_{\gamma\to M}(Q^2)$, $M = \pi^0, \eta^0, f$, etc. are measurable in tagged $e\gamma \to e'M$ reactions. QCD predicts[10]

$$\alpha_s(Q^2) = \frac{1}{4\pi} \frac{F_\pi(Q^2)}{Q^2|F_{\pi\gamma}(Q^2)|^2} \tag{2.4}$$

where to leading order the pion distribution amplitude enters both numerator and denominator in the same manner. The higher order corrections can be calculated using the methods of Ref. 30.

In the regime $s \gg p_T^2 \gg \mu^2$ the cross sections for $\gamma\gamma \to V\overline{V}$ and $\gamma\gamma \to \gamma V$ can be computed from $n \geq 2$ multiple gluon exchange diagrams by summing a series in $\alpha_S(p_T^2)\, \ell n\, s/p_T^2$. As shown by Ginzburg, Panfil, and Serbo,[31] the exponentiation of this series leads to large enhancement factors of order of 100 over Born contributions. The cross sections dominate over the lower-order quark exchange contributions at forward angles. Estimates are also given for $\gamma\gamma \to Vq\overline{q}$, although in this case soft gluon radiation needs to be included.

3. The Photon Structure Function

A key physical quantity in QCD is the set of photon structure functions[32] $F_i^\gamma(x, Q^2)$ measured in $e\gamma \to e'X$:

$$\frac{2\pi\, d\sigma}{dx\, dy\, d\phi} = \frac{4\pi\, \alpha^2 s_{e\gamma}}{Q^4} \left[(1-y)F_2 + y^2 xF_1 + \epsilon(1-y)\cos 2\phi F_3\right] \tag{3.1}$$

with $q^2 = -Q^2$, $x = Q^2/2k \cdot q$, $k^2 = 0$, $y = q \cdot k/q \cdot p_{e_1}$, and $\epsilon = 2(1-\varsigma)/(1+(1-\varsigma)^2)$, where $\varsigma = q \cdot k/q \cdot p_{e_2}$ is the energy fraction transferred from the lepton beam to the real photon. As first shown by Witten,[6] QCD predicts, unlike hadron structure functions, the normalization, shape, and evolution of the F_i^γ to second order in $\alpha_s(Q^2)$. The basic scaling behavior, $F_2^\gamma(x, Q^2) \sim \ell n\, Q^2 f(x)$

predicted by QCD has now been confirmed for $0.3 < x < 0.8$ by PLUTO, JADE, TASSO and PEP4-PEP9 measurements[2] for Q^2 below 2 GeV^2 to beyond 100 GeV^2. The quark and gluon distributions[33),34] in the photon obey (in leading order) the extended evolution equations ($t = \ell n\, Q^2/\Lambda^2$)

$$\frac{dq_i(x,t)}{dt} = \frac{3\alpha\, Q_i^2}{2\pi}\left[x^2 + (1-x)^2\right] + \frac{\alpha_S(t)}{2\pi}\int_x^1 \frac{dy}{y} \left[p_{qq}\left(\frac{x}{y}\right) q_i(x,t) + p_{qG}\left(\frac{x}{y}\right) G(y,t)\right] \tag{3.2}$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha_S(t)}{2\pi}\int_x^1 \frac{dy}{y} \left[p_{Gq}\left(\frac{x}{y}\right) \sum_i q_i(y,t) + p_{GG}\left(\frac{x}{y}\right) G(y,t)\right]. \tag{3.3}$$

where the inhomogeneous term is induced by the direct $\gamma\gamma \to q\bar{q}$ box diagram. It has been conventional to parametrize the QCD prediction in terms of a regular hadronic (vector meson dominance) piece plus the asymptotic solution to (Eq. (2)) of the form $q_i^\gamma(x_1 Q^2) = [(4\pi)/(\alpha_S(Q^2))]a_i(x) + b_i(x)$. However, in lowest order, this gives an artificial singularity in the photon structure function: $F_{2\gamma} = xq_2^\gamma \sim x^{-0.5964}$ at $x \to 0$. In higher order, $b_i(x) \propto x^{-2}$ implying a *negative* cross section for $x \to 0$ at fixed Q^2. These difficulties show that a straightforward separation of regular hadronic and pointlike contributions is *invalid*; diagrammatically both horizontal and vertical gluon exchange corrections to the box diagram must be taken into account.[35]

As emphasized by Glück *et al.*,[36] rigorous QCD predictions can be made by construction of quark and gluon distributions in the photon to agree with experiment at a given scale Q_0^2, and then using the evolution Eq. (2) to make predictions at large Q^2. The differences between higher and leading order predictions are found to be small. The fundamental prediction of QCD, $F_{2\gamma}(x,Q^2) \sim \log Q^2$ at fixed x and large Q^2, remains. The disadvantage of this procedure is that the

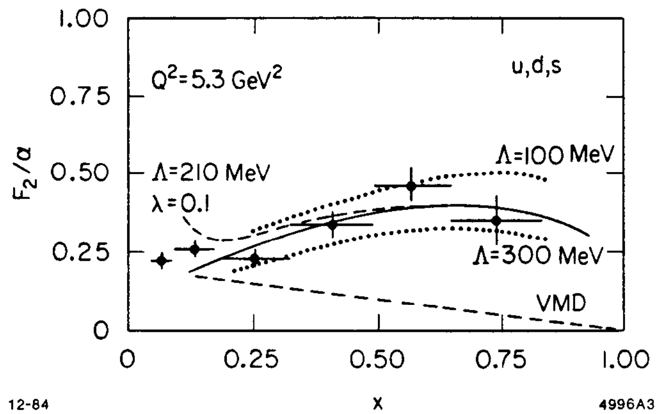


Fig. 6. Analysis of the photon structure function in the Antoniadis-Grunberg scheme.[37] See the reviews of A. Deuter and W. Wagner, these proceedings.

possibility of determining $\Lambda_{QCD}^{\overline{MS}}$ and making *a priori* predictions for the shape of the structure functions is lost.

A more convenient method has recently been proposed by Antoniadias and Grunberg.[37] They parametrize the photon structure moments in the form

$$\frac{4\pi}{\alpha} M_n^\gamma = \frac{4\pi}{\beta_0} \frac{a_n}{\alpha_s(Q^2)} + b_n^r + \frac{b}{n-2} \left[1 - (\lambda \alpha_s(Q^2))\right]^{d_n} + \ldots \tag{3.4}$$

The parameter $\lambda \neq 0$ represents hadronic contributions and eliminates the potential singularity at $n = 2$. Thus at the expense of one extra parameter, one can make detailed predictions for QCD; for $x > x_0 \cong 0.25$ there is apparently little sensitivity to the hadronic input. A PLUTO analysis based on this procedure gives $\Lambda_{\overline{MS}} = 160 \pm 45\ MeV$. (See Fig. 6.) Theoretical uncertainties still remain, however, concerning whether a background VMD contribution should still be included as in conventional fits and the manner in which charm quark contributions should be identified.

It clearly would be useful to test the accuracy of these methods in an example where the photon interactions and gluonic radiative corrections could be systematically computed. One such theoretical laboratory is the $\gamma^*\gamma \to Q\overline{Q}$ heavy quark contribution[38] to the photon structure function where, for $v^2/c^2 \ll 1$ and Coulomb gauge, only Coulomb gluons couple to the heavy quarks, and the radiative corrections to the spectator lines can be computed as an expansion in v/c. This model can also provide a guide to the $\gamma\gamma \rightarrow c\bar{c}$ contribution, including the effect of final state interactions at threshold.[22] In the case where one electron is untagged, the target photon can be appreciably off shell, thus obscuring the dependence of the photon structure function on $\Lambda^{\overline{MS}}_{\mathrm{QCD}}$. Heavy quark models could help settle this dynamical dependence, including the degree of quenching of the hadronic contribution as $|k^2|$ increases.

The photon structure function plays a pivotal role in perturbative QCD and further measurements are very much warranted. Higher luminosity measurements at PEP, PETRA, and higher energies possible at SLC, LEP and Tristan will allow more precise measurements at high $Q^2 \geq 100\ GeV^2$, the separation of F_1^γ, F_2^γ, F_3^γ and checks of specific QCD predictions for F_L^γ, separation of heavy quark contributions, checks on the jet topological structure, moment analyses, etc. We emphasize the need to check the photon-off-mass dependence and the need for real photon target measurements, since even at moderate k^2 the sensitivity of F_2^γ to $\Lambda_{\overline{MS}}$ drops out.

In the future, it may be possible to measure real photon structure functions in $e\gamma \rightarrow e'X$ reactions where the photon target is obtained from a laser or wiggler beam back-scattering on a linac beam.[39] In addition to potentially high luminosity, one also has the advantage that the photon beam is polarized and can have an energy spectrum peaked at high energy, reducing the need for reconstruction of the hadron production energy W.

4. High Transverse Momentum Inclusive Processes

One area of considerable theoretical and experimental uncertainty in photon photon collisions is jet and hadron production at high p_T. As reported by the JADE collaboration, the predicted QCD scaling law[40]

$$p_T^4\, E\, d\sigma/d^3p(\gamma\gamma \to Jet + X) = f(x_T, \theta_{cm})$$

appears to set in at p_T as low as 3 GeV. This is in remarkable contrast to the very high p_T ($p_T \gtrsim 20\, GeV$)) required before any semblance of scale-invariance is seen in pp collisions. The precocious scaling of $\gamma\gamma$ reactions could be due to a number of factors:

1. There are no logarithmic modifications predicted for the $\gamma\gamma \to 2$ jet, 3 jet and 4 jet processes in leading order. This is due to the fact that the scale-violation due to the running coupling constant in the $\gamma q \to gq$ and $qq \to qq$ subprocess contribution is compensated by the evolution of the quark distribution in the photon. The subprocess can be distinguished by the power of $(1 - x_T)^n$ at threshold $x_T = 2p_T/\sqrt{s_{\gamma\gamma}} \to 1$ or from jet topology.

2. Higher twist contributions receive less trigger bias in $\gamma\gamma$ compared to hadron-induced reactions.

The normalization of the JADE jet production cross section appears higher than QCD.[5] As discussed in this meeting, it seems unlikely that this discrepancy could be due to an integrally-charged quark model. Within the context of QCD, there are other possible explanations: anomalous K-factors for $\gamma\gamma \to q\bar{q}$, etc., anomalous threshold corrections for $\gamma\gamma \to c\bar{c}$; mis-estimate of higher jet nucleon contributions, etc. Measurements of $\gamma\gamma \to \pi X$, and $\gamma\gamma \to \gamma X$ at high p_T could help to resolve these questions. One is also interested in understanding the photon mass dependence of the inclusive cross sections, backgrounds due to $ee \to ee\gamma^*$ single photon radiation contributions, jet coherence effects[43] in 3-jet and 4-jet reactions, etc. On the theoretical side, we need to compute higher order corrections, relate the $\gamma\gamma \to Jet\, X$ cross sections to the measured photon structure function, analyse heavy quark production, etc. Aside from e^+e^- reactions, photon-photon collisions provide the simplest environment to understand jet production and hadronization.

5. Conclusions

The study of photon-photon collisions has progressed enormously, stimulated by new data and new calculational tools for QCD. In the future we can expect precise determinations of α_S and $\Lambda_{\rm QCD}^{\overline{MS}}$ from the $\gamma^*\gamma \to \pi^0$ form factor and the photon structure function, as well as detailed checks of QCD, determination of the shape of the hadron distribution amplitudes from $\gamma\gamma \to H\overline{H}$, reconstruction of $\sigma_{\gamma\gamma}$ from exclusive channels at low $W_{\gamma\gamma}$, definitive studies of high p_T hadron and jet production, and studies of threshold production of charmed systems. Photon-photon collisions, along with radiative decays of the ψ and Υ, are ideal for the study of multiquark and gluonic resonances. We have emphasized the potential for resonance formation near threshold in virtually every hadronic exclusive channel, including heavy quark states $c\bar{c}c\bar{c}$, $c\bar{c}u\bar{u}$, *etc.*

At higher energies (SLC, LEP, ...) parity-violating electroweak effects and Higgs production due to "equivalent" Z^0 and $W^\pm$ beams from $e \to eZ^0$ and $e \to \nu W$ will become important.[43] The basic form for the virtual (transversely polarized) Z^0 beam in an electron is $(x = (k_Z^0 + k_Z^z)/(p_e^0 + p_e^z))$

$$\frac{dN}{dx\, dk_\perp^2} = \frac{\alpha_Z}{2\pi} \frac{k_\perp^2}{(k_\perp^2 + M_Z^2)^2} \left[1 + (1-x)^2\right] .$$

Asymptotic $\log s/M_Z^2$ scaling for dN/dx becomes relevant at $s \gg M_Z^2$, where $k_\perp^2 \cong M_Z^2$.

Many of the most important $\gamma\gamma$ studies are severely limited by counting rate, emphasizing the need for increasing detector acceptance and photon-photon luminosity. New accelerator developments,[39] such as backscattered lasers on linear collider beams or other coherent methods[44] which can generate intense beams of photons, could lead to dramatic increases in $\mathcal{L}_{\gamma\gamma}$. We note that many of the most interesting QCD tests require only modest photon energies $W_{\gamma\gamma} \lesssim$ 5 to 10 GeV, but high photon-photon luminosity.

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REFERENCES

1. For recent reviews of photon-photon collisions, see H. Kolanoski, Bonn-HE-84-06 (1984), to be published in Springer Tracts in Modern Physics; J. H. Field, LPNHE 84-04 (1984); and the *Proceedings of the Vth International Colloquium on $\gamma\gamma$-Interactions, Aachen,* ed. Ch. Berger, in *Lecture Notes in Physics*, Vol. 191, Springer Verlag (1983).
2. See also the reviews of P. M. Zerwas and W. Ko, in these proceedings.
3. R. Brandelik *et al.*, (TASSO collaboration) Phys. Lett. 97B, 448 (1980); M. Althoff *et al.*, Z. Phys. C16, 13 (1982).
4. H.-J. Behrend *et al.*, (CELLO collaboration), Z. Phys. C21, 205 (1984). D. L. Burke *et al.*, (MARK II collaboration), Phys. Lett. 103B, 153 (1980). J. Dainton, (JADE collaboration), *Proc. of the European Physical Soc. Conf. 1983.*
5. See F. Foster, these proceedings.
6. E. Witten, Nucl. Phys. B120, 189 (1977). The experimental data are reviewed by W. Wagner, these proceedings.
7. R. Prepost, these proceedings; E. Fernandez *et al.*, SLAC-PUB-3410 (1984).

8. S. J. Brodsky, C. E. Carlson and R. Suaya, Phys. Rev. D14, 2264 (1976).

9. For a recent review see W. Ko, UCD-840915 (1984), to appear in the proceedings of the 22nd International Conference.

10. S. J. Brodsky and G. P. Lepage, Phys. Rev. D24, 1808 (1981); G. P. Lepage, S. J. Brodsky, T. Huang, P. B. Mackenzie, in *Particles and Fields 2*, eds. A. Z. Capri and A. N. Kamal (Plenum, New York, 1983), p 83; S. J. Brodsky, T. Huang, and G. P. Lepage, *ibid.*, p. 143.

11. G. P. Lepage and S. J. Brodsky, Phys. Rev. D22, 2157 (1980).

12. S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973). V. A. Matveev, R. M. Muradyan, A. V. Tavkheldize, Lett. Nuovo Cimento 7, 710 (1973).

13. G. W. Atkinson, J. Sucher, K. Tsokos, Phys. Lett. 137B, 407 (1984).

14. P. H. Damgaard, Nucl. Phys. B211, 435 (1983).

15. G. R. Farrar, E. Maina, F. Neri, Rutgers preprints RU-83-33 (1983), and RU-84-13 (1984), and G. Farrar, these proceedings.

16. See, *e.g.,* B. Velikson and D. Weingarten, IBM/Brown University preprint (1984) and S. Gottlieb, P. B. Mackenzie, H. B. Thacker and D. Weingarten, Phys. Lett. 134B, 346-350 (1984).

17. V. L. Chernyak and A. R. Zhitnitskii, Novosibirsk preprint I4F-83-108 (1983); A. R. Zhitnitskii, I. R. Zhitnitskii and V. L. Chernyak, Yad. Fiz. 38, 1074-1086 (1983); V. L. Chernyak and A. R. Zhitnitskii, IYF-83-108, 1983, p. 37; T. Huang, private communication.

18. N. Isgur and C. H. Llewellyn Smith, Phys. Rev. Lett. 52, 1080 (1984).

19. See also V. M. Belyaev and B. L. Ioffe, Sov. Phys. JETP 56, 493 (1982). B. L. Ioffe, A. V. Smilga, Phys. Lett. 114B, 353 (1983); V. A. Nesterenko and A. V. Radyuskhin, Phys. Lett. 115B, 410 (1980); 123B, 439 (1983).

20. J. R. Smith *et al.*, (Mark II collaboration), Phys. Rev. D30, 851 (1984).

21. G. Gidal, these proceedings.

22. See, *e.g., Quantum Electrodynamics* by A. I. Akhiezev and V. B. Berestetski, National Tech. Trans. Service, Washington D.C. (1953). Applications to the threshold behavior of heavy quark production is given in S. J. Brodsky and J. F. Gunion, SLAC-PUB-3527 (1984).

23. C. Mennessier, Z. Phys. C16, 241 (1983).

24. Ch. Berger *et al.*, DESY 84-074 (1984).

25. N. N. Achasov, S. A. Devyanin, G. N. Shestakov, Phys. Lett. 108B, 134 (1982); Z. Phys. C16, 55 (1982), and Novosibirsk preprints, TF-65-141 (1984), TF-56-137 (1984).

26. Bing-an Li and K. F. Liu, Phys. Lett. 118B, 435 (1982), 124B, 550(E) (1983), Phys. Rev. Lett. 51, 1510 (1983).

27. R. Brandelik *et al.*, Phys. Lett. 108B, 67 (1982). M. Althoff *et al.*, Phys. Lett. 130B, 449 (1983).

28. E. Bagán, A. Bramon and F. Cornet, Barcelona preprint UAB-FT-99 (1983).

29. S. J. Brodsky and G. P. Lepage, Ref. 2. S. J. Brodsky, F. E. Close, J. F. Gunion, Phys. Rev. D6, 177 (1972).

30. M. H. Sarmadi, PITT-82-10, 1982, p. 10; F. M. Dittes and A. V. Radyushkin, Phys. Lett. 134B, 359-362 (1984); F. M. Dittes and A. V. Radyushkin, Yad. Fiz. 34, 529-540 (1981); S. J. Brodsky, P. Damgaard, Y. Frishman and G. P. Lepage, SLAC-PUB-3295 (1984).

31. I. F. Ginzburg, S. L. Panfil, V. G. Serbo, contributed to the 22nd International Conference, Leipzig; V. L. Chernyak and A. R. Zhitnitskii, Nucl. Phys. B222, 382-388 (1983), and Novosibirsk Inst. Nucl. Phys. Acad. Sci. 82-044, 1982, p. 14.

32. S. J. Brodsky, T. Kinoshita, H. Terazara, Phys. Rev. Lett. 27, 280 (1971). T. F. Walsh, Phys. Lett. 36B, 121 (1971). T. F. Walsh and P. M. Zerwas,

Phys. Lett. 44B, 195 (1973).

33. R. J. DeWitt, L. M. Jones, J. D. Sullivan, D. E. Willen, H. W. Wyld, Phys. Rev. D19, 2046 (1979), D20, 1751(E) (1979); W. A. Bardeen and A. J. Buras, Phys. Rev. D20, 166 (1979). S. Brodsky, SLAC-PUB-2447, *Proceedings of the SLAC Summer Institute (1979).* D. W. Duke and J. F. Owens, Phys. Rev. D22, 2280 (1980).

34. W. R. Frazer and J. F. Gunion, Phys. Rev. D20, 147 (1979).

35. G. Rossi, Phys. Lett. 130B, 105 (1983). W. Frazer, *Proceedings of the 4th International Colloquium on $\gamma\gamma$-Interactions, Paris (1981),* ed. G. W. London.

36. M. Glück and F. Reya, Phys. Rev. D28, 2749 (1983). M. Drees, M. Glück, K. Grassie, F. Reya, Dortmund preprint DO-TH-84/12 (1984), and contributions to this conference.

37. I. Antoniadis and G. Grunberg, Nucl. Phys. B213, 445 (1983); I. Antoniadis, these proceedings.

38. See T. Uematsu and T. F. Walsh, Phys. Lett. 101B, 263 (1981); Nucl. Phys. B199, 93 (1983).

39. See, *e.g.,* I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, V. I. Telnov, Nucl. Instr. Methods 219, 5 (1984); Yad. Fiz. 38, 372 (1983).

40. S. J. Brodsky, T. A. DeGrand, J. F. Gunion and J. H. Weis, Phys. Rev. D19, 1418 (1979) and Phys. Rev. Lett. 41, 672 (1978); C. H. Llewellyn Smith, Phys. Lett. 79B, 83 (1978).

41. See, *e.g.*, A. Janah, these proceedings; A. Janah, UMI 82-26472-mc (1982), Ph.D. Thesis.

42. S. J. Brodsky, SLAC-PUB-3429 (1984).

43. For a related idea in hadron collisions, see R. N. Cahn and S. Dawson, Phys. Lett. 136B, 196 (1984); Erratum-ibid 138B, 464 (1984).

44. J. Spencer, SLAC-PUB-2677 (1981), and private communication.