RECENT DEVELOPMENTS IN THE THEORY OF PHOTON-PHOTON COLLISIONS*

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1. Introduction

Over the past few years the field of photon-photon collisions[1] has emerged as one of the best testing grounds for QCD, particularly in the area of exclusive and inclusive hard scattering processes, exotic resonance production, and detailed tests of the coupling of real and virtual photons to the quark current. In this summary of contributed papers, I will briefly review recent theoretical progress in the analysis of two-photon reactions and possible directions for future work.

2. Two-body Production Processes

Exclusive two-photon processes $\gamma\gamma \to H\bar{H}$ at large $W^2_{\gamma\gamma} = (q_1+q_2)^2$ and fixed $\theta^{\gamma\gamma}_{c.m.}$ 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.[2] Conversely, the angular dependence of $\gamma\gamma \to H\bar{H}$ cross sections can be used to determine the shape of the hadron distribution amplitudes[3] $\phi_H(x_i, Q)$—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 $\gamma_\lambda\gamma_{\lambda'} \to H\bar{H}$ amplitude can be written as a factorized form[2]

$$M_{\lambda\lambda'}(W_{\gamma\gamma}, \theta_{c.m.}) = \int_0^1 [dy_i]\, \phi^*_{\bar{H}}(x_i, Q)\, \phi^*_H(y_i, Q)\, T_{\lambda\lambda'}(x, y; W_{\gamma\gamma}, \theta_{c.m.}) \qquad (1)$$

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:[4] to leading order $T \propto \alpha(\alpha_s/W^2_{\gamma\gamma})^{1,2}$ and $d\sigma/dt \sim W^{-6,-8}_{\gamma\gamma} f(\theta_{c.m.})$ 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. Detailed predictions for pseudo-scalar and vector-meson pairs for each helicity amplitude are given in Ref. 2. The helicities of the vector-meson pairs are 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,[5] to $\gamma\gamma \to p\bar{p}$ by Damgaard,[6] and to all $B\bar{B}$ octet and decouplet states by Farrar, Maina and Neri.[7] The normalization of the $\gamma\gamma \to p\bar{p}$ amplitude is determined by the $\psi \to p\bar{p}$ rate.[2] The arduous calculation of 280 $\gamma\gamma \to qqq\bar{q}\bar{q}\bar{q}$ diagrams in T_B required for calculating $\gamma\gamma \to B\bar{B}$ is greatly simplified by using two-component spinor techniques.[7] Since there is a disagreement between the calculations of Ref. 6 and 7, a third calculation is necessary. It is also important to repeat the $\gamma\gamma \to p\bar{p}$ calculations assuming the asymmetric form of the proton distribution amplitude derived from the ITEP QCD sum rules by Chernyak and Zhnitskii,[8] since their model can readily account for the magnitude and sign of the proton and neutron form factors. The difficulty noted by Belyaev and Ioffe[9] and by Isgur and Llewellyn Smith[10] concerning the magnitude of $G^p_M(Q^2)$ at large Q^2 is resolved if one assumes a nucleon distribution amplitude broader than the asymptotic form $x_1x_2x_3$ and/or by assuming a small radius[11] for the qqq valence Fock state.

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 can be written directly in terms of the pion form factor taken from experiment. Recent Mark II data[12] 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. 1). The onset of scaling

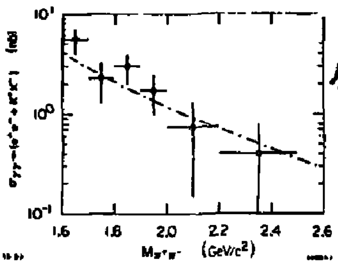

Fig. 1. Measured cross section for $\gamma\gamma \to \pi^+\pi^-$ plus $\gamma\gamma \to K^+K^-$ integrated over the angular region $|\cos\theta_{c.m.}| < 0.3$ (from Ref. 12). The curve is the perturbative-QCD prediction from Ref. 2.

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 $\Lambda^{\overline{MS}}_{QCD}$. However, just as in $e^+e^- \to H\bar{H}$, the scaling behavior of the Born cross sections can be distorted by resonance production; the perturbative predictions could 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[13] of the form $\zeta/(1-e^{-\zeta})$ where $\zeta = 2\pi\alpha/v$ ($\Rightarrow 8\pi\alpha_s/3v$ in QCD).]

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Invited talk presented at the 22nd International Conference on High Energy Physics
Leipzig, E. Germany, July 19-25, 1984

The data[14,15] 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 $M \sim 1.4$ GeV (see Fig. 2). The absence of a comparable

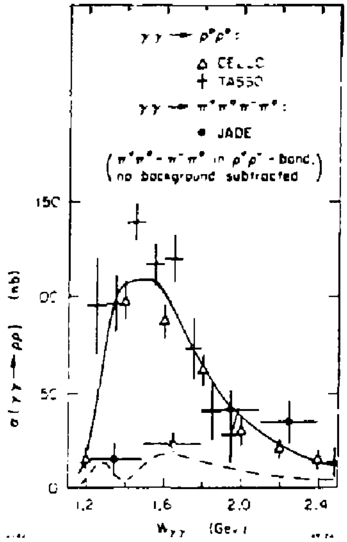

Fig. 2 Comparison of the $\gamma\gamma \to \rho^0\rho^0$ and $\rho^+\rho^-$ data[14,15] with the mesonium ($qq\bar{q}\bar{q}$) resonance model of Achasov *et al.*[16]

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.*,[16] and Li and and Liu[17] in terms of two interfering $I = 0$ and $I = 2$, $J^{PC} = 2^{++}$, $qq\bar{q}\bar{q}$ resonances with masses 1.3 and 1.6 GeV, respectively. Two photons couple naturally to such "mesonium" S-wave states. Since $A(\gamma\gamma \to \rho^0\rho^0) = \frac{1}{3}A(0) + \frac{2}{3}A(2)$ and $A(\gamma\gamma \to \rho^+\rho^-) = \frac{\sqrt{2}}{3}A(0) - \frac{\sqrt{2}}{3}A(2)$, if the $I = 0$ and $I = 2$ amplitudes add constructively in $\rho^0\rho^0$, they interfere destructively[16] for $\rho^+\rho^-$. Identification of these resonances with the predicted couplings in $\psi \to \gamma 4\pi$ as well as other $\gamma\gamma \to VV$ 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 seem to approach the perturbative predictions.[2]

In general, QCD predicts a large array of exotic resonances $q\bar{q}g$, gg, $q\bar{q}q\bar{q}$, $qqq\bar{q}\bar{q}\bar{q}$, etc., which can be prominent in the threshold region of the appropriate $\gamma\gamma$ production channel. In the case of $\gamma\gamma \to p\bar{p}$, the cross section ($d\sigma/d\cos\theta = 3 \pm 1\,nb$) measured by TASSO[18] in the threshold region $2 < W_{\gamma\gamma} < 2.4$ GeV is roughly 60 times larger than the prediction of Farrar *et al.*,[7] although $\gamma\gamma \to \Delta^{++}\bar{\Delta}^{++}$ may be close to the predicted normalization. Again this suggests distortions due to resonance production, *e.g.*, $qqq\bar{q}\bar{q}\bar{q}$ baryonium states. The perturbative predictions for $\gamma\gamma \to B\bar{B}$ cannot become valid unless all of the quark and gluon propagators in T_B are reasonably off-shell, *i.e.*, $W_{\gamma\gamma} \gtrsim 5$ GeV and large $\theta_{c.m.}$.

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[19] from effective Lagrangian models with *point-like* p, Δ, and γ couplings.

It is important to extend the QCD predictions for $\gamma\gamma \to B\bar{B}$ 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 $\theta_{c.m.}$, the q_1^2 and q_2^2 dependence of the $\gamma\gamma \to B\bar{B}$ amplitude for transversely polarised photons must be minimal[20] in QCD since the off-shell quark and gluon propagators in T_B 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 $\gamma\gamma \to c\bar{c}$ plus $\gamma\gamma \to c\bar{c}q\bar{q}$ contributions. The channels with maximal spin and charge such as $\gamma\gamma \to B_{3/2}(cuu)\,\bar{B}_{3/2}(\bar{c}\bar{u}\bar{u})$ are likely to be dominant due to charge coherence and multiple helicity states.

3. Forward Production

In the regime $s \gg p_T^2 \gg \mu^2$ the cross sections for $\gamma\gamma \to VV$ 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,[21] 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 $\gamma\gamma \to Vq\bar{q}$, although in this case soft gluon radiation needs to be included.

4. The Photon Structure Function

One of the most important tests of QCD is the photon structure function[22] measured in $\sigma_{\gamma^*\gamma}(q^2, k^2, W^2)$ with $q^2 = -Q^2$ and W^2 large, $k^2 = 0$. As shown by DeWitt *et al.*,[23] and Frazer and Gunion,[24] the quark distributions in the photon obey (in leading order) the extended evolution equations ($t = \ell n\, Q^2/\Lambda^2$)

$$\frac{dq_i(x,t)}{dt} = \frac{3\alpha\, Q_i^2}{2\pi}\left[x^2 + (1-x)^2\right] + \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) q_i(x,t) + P_{qG}\left(\frac{x}{y}\right) G(y,t)\right] \qquad (2.a)$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} \left[P_{Gq}\left(\frac{x}{y}\right) \sum_i q_i(y,t) + P_{GG}\left(\frac{x}{y}\right) G(y,t)\right] \quad (2.b)$$

where the inhomogeneous term is induced by the direct $\gamma\gamma \to q\bar{q}$ box diagram. It has been conventional to parametrise the QCD prediction in terms of a regular hadronic (vector meson dominance) piece plus the asymptotic solution to (Eq. (2)) of the form $q_i^\gamma(x, Q^2) = [(4\pi)/(\alpha_s(Q^2))]a_i(x) + b_i(x)$. However, in lowest order, this gives an artificial singularity in the photon structure function: $F_{2\gamma} = xq_2^\gamma \sim x^{-0.5986}$ as $x \to 0$. In higher order, $b_i(x) \propto x^{-2}$ implying a *negative* cross section for $x \to 0$ at fixed Q^2. These difficulties[25] show that a straightforward separation of regular hadronic and pointlike contributions is *invalid*;[26] diagrammatically both horizontal and vertical gluon exchange corrections to the box diagram must be taken into account.[25]

As emphasized by Glück *et al.*,[26] 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 possibility of determining $\Lambda_{\rm QCD}^{\overline{MS}}$ and making *a priori* predictions for the shape of the structure functions is lost. An alternative procedure, developed by Antoniadis and Grunberg,[27] provides consistent, regular solutions to the evolution equation (through first order corrections) at the expense of a single parameter in the second moment of the photon structure functions which represent hadronic contributions. QCD predictions can then be made for the shape of the structure function for $x > x_0$, where x_0 is set by the hadronic parameter.

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 $\gamma^*\gamma \to Q\bar{Q}$ heavy quark contribution[28] 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 $\gamma\gamma \to c\bar{c}$ contribution including the final state distortion effects at threshold. 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 $\Lambda_{\rm QCD}^{\overline{MS}}$. The heavy quark model could help settle this dynamical dependence, including the degree of quenching of the hadronic contribution as $|k^2|$ increases.

5. Conclusions

The study of photon-photon collisions has progressed enormously in the last few years stimulated by new data and new calculational tools for QCD. In the future there are possibilities for precise determinations of α_s and $\Lambda_{\rm QCD}^{\overline{MS}}$ from the $\gamma^*\gamma \to \pi^0$ form factor[2] and the photon structure function, as well as detailed checks of QCD, including determinations of the shape of the hadron distribution amplitudes from $\gamma\gamma \to H\bar{H}$, 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....) 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.

All of these studies are severely limited by counting rate, which emphasizes the necessity of increasing detector acceptance and the photon-photon luminosity $\mathcal{L}_{\gamma\gamma}$. New accelerator developments,[29] such as backscattered lasers on linear collider beams or other coherent methods which can generate intense beams of photons, could lead to dramatic increases in the effective $\mathcal{L}_{\gamma\gamma}$. We note that may of the most interesting QCD tests require only modest photon energies $W_{\gamma\gamma} \lesssim 5$ to 10 GeV, but high photon-photon luminosity.

ACKNOWLEDGMENTS

I am grateful to Professor V. A. Sidorov, the organiser of this session, for helpful discussions and assistance.

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