1. Introduction

Over the past few years the field of photon-photon collisions 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 \( \gamma \gamma \rightarrow HH \) at large \( W_h^2 = (q_1 + q_2)^2 \) and fixed \( \phi_{Hh}^0 \) 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. The angular dependence of \( \gamma \gamma \rightarrow HH \) cross sections can be used to determine the shape of the hadron distribution amplitudes \( \phi_h(x,Q) \) — the process-independent probability amplitudes for finding valence quarks in the hadrons, each carrying (light-cone) fraction \( x \), of the hadron's momentum transferred up to the momentum transfer scale \( Q \) of the process. The hard-scattering helicity amplitude for \( \gamma \gamma \rightarrow HH \) can be written as a factorised form:

\[
M_{Hh}(W_{\gamma\gamma},\phi_{Hh}) = \sum_{\lambda_1} \delta_{\lambda_1} \phi_{\lambda_1}(x_{123} Q) T_{Hh}(\lambda_1,\lambda_2;W_{\gamma\gamma},\phi_{Hh})
\]

where \( T_{Hh} \) is the hard scattering helicity amplitude for scattering the clusters of valence quarks in each hadron. \( T_{Hh} \) can be computed in perturbation theory and scales according to the dimensional counting rules to leading order \( T \propto \alpha(\alpha/2W_{\gamma\gamma})^{1/2} \) and \( d \phi_{\lambda} \propto W_{\gamma\gamma}^{-2}\phi_{\lambda}(\phi_{Hh}) \) for meson and baryon pairs, respectively. The distributions amplitudes \( \phi_h(x,Q) \) 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 \( 1/W_{\gamma\gamma} \). The QCD predictions have now been extended to mesons containing \( (gg) \) Fock states by Atkinson, Sucher and Taekum, to \( \gamma \gamma \rightarrow \pi \pi \) by Damgaard, and to all \( HH \) octet and decuplet states by Farar, Maine and Nesi. The normalisation of the \( \gamma \gamma \rightarrow \pi \pi \) amplitude is determined by the \( \gamma \gamma \rightarrow \pi \pi \) rate. The accurate calculation of 280 \( \gamma \gamma \rightarrow \pi \pi \pi \pi \) diagrams in \( T_{Hh} \) required for calculating \( \gamma \gamma \rightarrow HH \) is greatly simplified by using two-component spinor techniques. Since there is a disagreement between the calculations of Ref. 2 and 7, a third calculation is necessary. It is also important to repeat the \( \gamma \gamma \rightarrow \pi \pi \) calculations assuming the asymptotic form of the proton distribution amplitude derived from the ITEP sum rules by Chernyavsky and Zheltukh. 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 and by Lagur and Llewellyn Smith concerning the magnitude of \( G_A^p(Q^2) \) at large \( Q^2 \) is removed if one assumes a nucleon distribution amplitude broader than the asymptotic form \( G_A^p(Q^2) \) and/or by assuming a small radius for the \( qq \) valence Fock state.

The normalisation and angular dependence of the \( \gamma \gamma \rightarrow \pi^+\pi^- \) 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. Recent Mark II data for \( \pi^+\pi^- \) and \( K^+K^- \) production in the range \( 1.6 < W_{\gamma\gamma} < 2.4 \text{ GeV} \) near \( M^2 \) are in excellent agreement with the normalisation and energy dependence predicted by QCD (see Fig. 1). The onset of scaling at this range of momentum transfer for meson production is reasonable since the off-shell quark propagators in the diagrams for \( T_{Hh} \) carry momenta large compared to the relevant QCD scales: quark masses, intrinsic transverse momentum, and \( 1/Q^2 \). However, just as in \( e^+e^- \rightarrow HH \), 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 the Coulomb interactions between attractive charged particles which, in the non-relativistic regime, give singular distortion factors of the form \( \sqrt{1 - c^2} \).
The data\textsuperscript{14,15} for $\gamma \gamma \rightarrow p\bar{p}$ 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 signal in $p^* p^*$ 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.\textsuperscript{16} and Li and Liu\textsuperscript{17} in terms of two interfering $J = 0$ and $J = 2, J^{PC} = 2^{+}$, $\pi\pi\pi\pi$ resonances with masses 1.3 and 1.6 GeV, respectively. Two photons couple naturally to such "mesonium" $S$-wave states. Since $A(\gamma\gamma \rightarrow p\bar{p}) = \frac{1}{2} A(0) + \frac{1}{2} A(2)$ and $A(\gamma\gamma \rightarrow p^* p^*) = \frac{1}{2} A(0) - \frac{1}{2} A(2)$, if the $J = 0$ and $J = 2$ amplitudes add constructively in $p^* p^*$, they interfere destructively\textsuperscript{18} for $p^* p^*$. Identification of these resonances with the predicted couplings in $\gamma \gamma$ as well as other $\gamma\gamma \rightarrow VV$ channels is crucial for a check of this hypothesis. At the high end of the experimental range, $W_{\gamma \gamma} \geq 2$ GeV, the data seem to approach the perturbative predictions.\textsuperscript{2}

In general, QCD predicts a large array of exotic resonances $\rho \rho, \rho \rho', \rho \rho''$, etc., which can be prominent in the threshold region of the appropriate $\gamma\gamma$ production channel. In the case of $\gamma\gamma \rightarrow pp$, the cross section $\langle d\sigma/dcos\theta = 3 \pm 1.6 \rangle$ measured by TASSO\textsuperscript{18} in the threshold region $2 < W_{\gamma\gamma} < 2.4$ GeV is roughly 60 times larger than the prediction of Farrar et al.,\textsuperscript{2} although $\gamma\gamma \rightarrow A^* A^*$ may be close to the predicted normalization. Again, this suggests distortions due to resonance production, e.g., $\pi\pi\pi\pi$ baryonium states. The perturbative predictions for $\gamma\gamma \rightarrow BB$ cannot become valid unless all of the quark and gluon propagators in $T_B$ are reasonably off-shell, i.e., $W_{\gamma\gamma} \geq 5$ GeV and large $\delta_{\text{CA}}$. 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\textsuperscript{19} from effective Lagrangian models with point-like $\rho, \omega, \Delta$, and $\gamma$ couplings.

It is important to extend the QCD predictions for $\gamma\gamma \rightarrow HH$ to the case of one or two virtual photons, since measurements can be performed with tagged leptons. In fact, for $W^2$ large and fixed $\xi$, $m$, the $q^2$ and $p^2$ dependence of the $\gamma\gamma \rightarrow HH$ amplitude for transversely polarized photons must be minimal,\textsuperscript{20} in QCD since the off-shell quark and gluon propagators in $T_B$ already transfer hard momenta; i.e., the $2\gamma$ coupling is effectively local for $|p_1^2|, |p_2^2| < p_0^2$.

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 $\gamma\gamma \rightarrow c\bar{c}$ plus $\gamma\gamma \rightarrow c\bar{c}$ contributions. The channels with maximal spin and charge such as $\gamma\gamma \rightarrow B_{D}^{+}(msu) \bar{B}_{D}^{-}(msu)$ are likely to be dominant due to charge coherence and multiple helicity states.

3. Forward Production

In the regime $s \gg p_0^2 \gg t_0^2$ the cross sections for $\gamma\gamma \rightarrow \gamma V$ and $\gamma\gamma \rightarrow \gamma V$ can be computed from $n \geq 2$ multiple gluon exchange diagrams by summing a series in $\alpha(s, t)$ with $p^2 = q^2 = W^2$ large, $k^2 = 0$. As shown by Ginzburg, Panfil, and Serbo,\textsuperscript{21} the exponentiation of this series leads to large enhancement factors of order 100 over Born contributions. The cross sections dominate over the lower-order quark exchange contributions at forward angles. Estimates are also given for $\gamma\gamma \rightarrow Vq\bar{q}$, 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\textsuperscript{22} measured in $e^- e^+ (q^2, k^2, W^2)$ with $p^2 = -q^2$ and $W^2$ large, $k^2 = 0$. As shown by DeWitt et al.,\textsuperscript{23} and Frazer and Guichon,\textsuperscript{24} the quark distributions in the photon obey (leading order) the extended evolution equations ($t = ln Q^2/k^2$)

$$\frac{dp_q(x,t)}{dt} = \frac{3\alpha_s Q^2}{2\pi} [x^2 + (1 - x)^2] + \frac{\alpha_s(t)}{2\pi} \int dy \frac{dy}{y}$$

$$ \left[ Q_{GL}(\frac{z}{x}) g_q(x,t) + Q_{CG}(\frac{z}{x}) G(y,t) \right]$$

(3.1)

$$\frac{dG(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi} \int dy \frac{dy}{y}$$

$$ \left[ Q_{GL}(\frac{z}{x}) \sum_i u_i(x,t) + Q_{CG}(\frac{z}{x}) \right] G(y,t)$$

(3.2)
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 $q_1^2(x, q^2) = |(a_1)/(a_0(q^2))|a_0(x) + \delta(x)$. However, in lowest order, this gives an artificial singularity in the photon structure function: $F_2 = a_0^2 x^{-\alpha_{QCD}}$ as $x \to 0$. In higher order, $\delta(x)$ at $x^{-2}$ 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,\(^\text{25}\) diagrammatically both horizontal and vertical gluon exchange corrections to the box diagram must be taken into account.\(^\text{26}\)

As emphasised by Glück et al.,\(^\text{28}\) rigorous QCD predictions can be made by construction of quark and gluon distributions in the photon to agree with experiment at a given scale $Q^2$, and then using the evolution Eq. (2) to make predictions at large $Q^2$. The different between higher and leading order predictions are found to be small. The fundamental prediction of QCD, $F_2(x, Q^2) \sim \log Q^2$ at fixed $x$ and large $Q^2$, remains. The disadvantage of this procedure is the possibility of determining $A_{Q^2}$ and making a priori predictions for the shape of the structure functions is lost. An alternative procedure, developed by Antoniadis and Grunberg,\(^\text{27}\) 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 $x \to 0$, where $z_0$ is set by the hadronic parameter.\(^\text{25}\)

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\(^\text{27}\) 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 $\gamma^- \to ct$ contribution including the final state radiation 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 $M^2_{\gamma\gamma}$. 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 $a_0$ and $A_{Q^2}$ from the $\gamma^- \gamma^- \to e^- e^+$ form factor and the photon structure function, as well as detailed checks of QCD, including determination of the shape of the hadron distribution amplitudes from $\gamma^- \gamma^- \to H^+$, reconstruction of $a_{H^+}$ 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 $\phi$ and $T$, 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 $cc$, $c\bar{c}$, $b\bar{b}$, etc. At higher energies (SLC, LEP, . . . ) electroweak effects and Higgs production due to "equivalent" $g^0$ and $W^\pm$ beams from $e^- e^+$ and $e^- W^-$ will become important.

All of these studies are severely limited by counting rate, which emphasises the necessity of increasing detector acceptance and the photon-photon luminosity $L_{\gamma\gamma}$. New accelerator developments,\(^\text{29}\) 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 $L_{\gamma\gamma}$. We note that may of the most interesting QCD tests require only modest photon energies $W_{\gamma\gamma} \leq 6$ to $10$ GeV, but high photon-photon luminosity.

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REFERENCES


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