SLAC-PUB-2587
August 1980
(T/E)

EXCLUSIVE TWO-PHOTON PROCESSES IN QUANTUM CHROMODYNAMICS*

Stanley J. Brodsky
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

G. Peter Lepage†
Laboratory of Nuclear Studies
Cornell University, Ithaca, New York 14853

ABSTRACT

Leading order perturbative QCD predictions are given for the two-photon processes $\gamma\gamma \to \pi\pi$, $K\bar{K}$, and $\rho\bar{\rho}$ at large momentum transfer.

As we have shown in a series of recent papers,[1] the predictions of perturbative quantum chromodynamics can be extended to the whole domain of large momentum transfer exclusive processes. The results lead to a comprehensive new range of rigorous predictions of QCD which test both the scaling and spin properties of quark and gluon interactions at large momentum transfer as well as the detailed structure of hadronic wavefunctions at short distances. The two-photon reactions ($M = \pi, K, \rho, \omega, \ldots$)

$$\frac{d\sigma}{dt}(\gamma\gamma \to M\bar{M}) \qquad \begin{array}{l}\text{at large } s = (k_1 + k_2)^2 \\ \text{and fixed } \theta_{c.m.}\end{array}$$

provide a particularly important laboratory for testing QCD since these "Compton" processes are, by far, the simplest calculable large-angle exclusive hadronic scattering reactions. As we discuss below, the large-momentum-transfer scaling behavior, the helicity structure, and often even the absolute normalization can be rigorously computed for each two-photon channel.[2] Conversely, the angular dependence of the $\gamma\gamma \to M\bar{M}$ amplitudes can be used to determine the shape of the process-independent meson "distribution amplitudes," $\phi_M(x,Q)$, the basic short-distance wavefunctions which control the valence quark distributions in high momentum transfer exclusive reactions.[1]

A critically important feature of the $\gamma\gamma \to M\bar{M}$ amplitude is that the contributions of Landshoff pinch singularities are power-law suppressed at the Born level -- even before taking into account Sudakov form factor suppression. There are also no anomalous contributions from the $x \sim 1$ end-point integration region. Thus, as in the calculation of the meson form factors, each fixed-angle helicity amplitude can be written to leading order in $1/Q$ in the factorized form $[Q^2 = p_T^2 = tu/s;\ \tilde{Q}_x = \min(xQ, (1-x)Q)]$:

---

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

(Invited talk presented at the XXth International Conference on High Energy Physics, University of Wisconsin, Madison, July 17-23, 1980.)

$$\mathcal{M}_{\gamma\gamma\to M\bar{M}} = \int_0^1 dx \int_0^1 dy\ \phi_{\bar{M}}\left(y,\tilde{Q}_y\right) T_H\left(x,y,s,\theta_{c.m.}\right) \phi_M\left(x,\tilde{Q}_x\right) \qquad (1)$$

where T_H is the hard scattering amplitude $\gamma\gamma \to (q\bar{q})(q\bar{q})$ for the production of the valence quarks collinear with each meson (see Fig. 1), and $\phi_M(x,Q)$ is the (process-independent) distribution amplitude for finding the valence q and $\bar{q}$ with light-cone fractions of the meson's momentum, integrated over transverse momenta $k_\perp < Q$. The contributions of non-valence Fock states are power-law suppressed. Further, the spin-selection rules[1] of QCD predict that vector mesons M and $\bar{M}$ are produced with opposite helicities to leading order in $1/Q$ and all orders in $\alpha_s(Q^2)$.

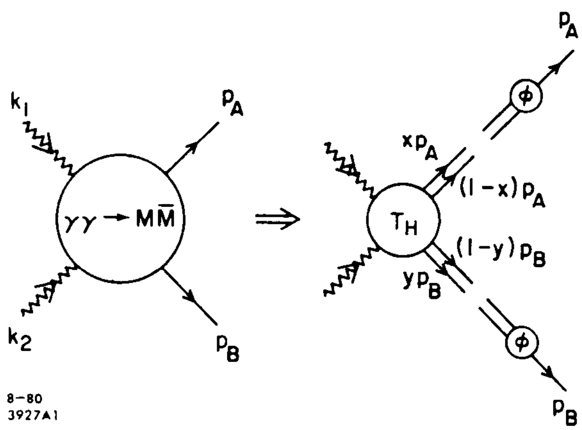

Fig. 1. Factorization of the $\gamma\gamma \to M\bar{M}$ amplitude.

Detailed predictions for each $\gamma\gamma \to M\bar{M}$ helicity amplitude can be worked out to leading order in $\alpha_s(Q^2)$ from the seven diagrams for T_H shown in Fig. 2. The general result is

$$\mathcal{M}_{\gamma\gamma\to M\bar{M}}\left(s,\theta_{c.m.}\right) = \frac{\alpha\alpha_s(Q^2)}{Q^2} \sum_{n,m} a_{nm}\left(\theta_{c.m.}\right) \left[\ell n\ Q^2/\Lambda^2\right]^{-\gamma_n-\gamma_m}$$

$$\times \left[1 + \mathcal{O}\left(\alpha_s(Q^2),\ m/Q\right)\right] \qquad (2)$$

where the first factor follows from the fixed angle scaling of T_H. The γ_n are the universal logarithm anomalous dimensions for helicity 0 or helicity 1 mesons as derived from the operator product expansion at short distances,[3] or equivalently, the QCD evolution equation[1] for $\phi_M(x,Q)$. Modulo logarithmic corrections, Eq. (2) implies $s^4\, d\sigma/dt\ (\gamma\gamma \to M\bar{M})$ scaling at fixed $\theta_{c.m.}$.

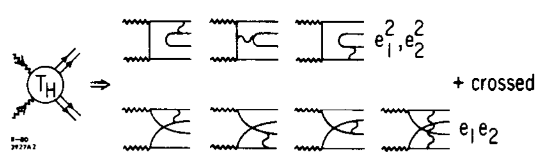

Fig. 2. Leading order contributions to the hard scattering amplitude T_H.

The QCD predictions for $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^o\pi^o$ to leading order in $\alpha_s(Q^2)$ are shown in Fig. 3. For asymptotic Q^2, $\phi_\pi(x,Q) \Longrightarrow \sqrt{3}\, f_\pi\, x(1-x)$ and the predictions [curve (a)] become exact and parameter-free. For subasymptotic Q^2, $\phi_\pi(x,Q)$ depends on the details of hadronic binding. Curves (b) and (c) correspond to the extreme examples $\phi \propto [x(1-x)]^{\frac{1}{4}}$ and $\phi \propto \delta(x-\frac{1}{2})$, respectively. In each case it is convenient to rescale the results in terms of the measured pion form factor.

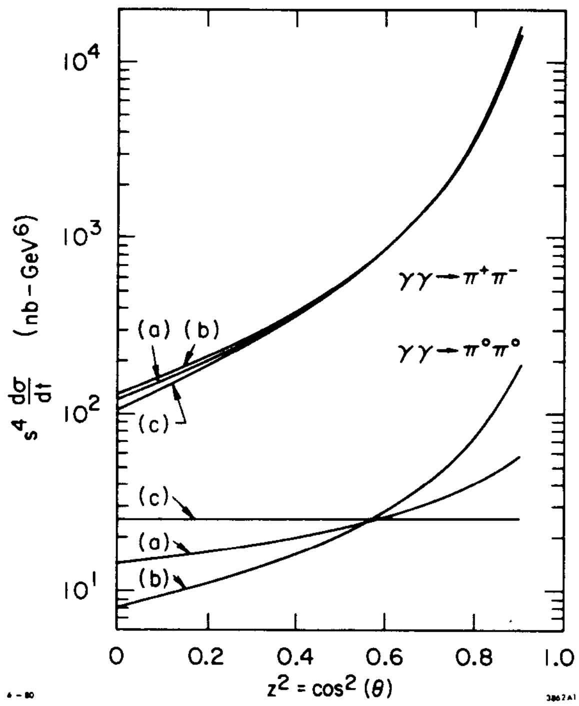

Fig. 3. Perturbative QCD predictions for $\gamma\gamma \to \pi\pi$ at large momentum transfer. Predictions for other helicity-zero mesons only differ in normalization. The curves (a),(b) and (c) correspond to the three distribution amplitudes described in the text.

The prediction for other helicity-zero mesons are identical up to overall normalization factors:

$$\mathcal{M}_{\gamma\gamma \to \pi\pi} : \mathcal{M}_{\gamma\gamma \to K\bar{K}} : \mathcal{M}_{\gamma\gamma \to \rho_L \bar{\rho}_L}$$

$$\propto \quad f_\pi^2 \quad : \quad f_K^2 \quad : \quad 2f_\rho^2$$

$$\propto \quad 1 \quad : \quad \sim 1.5 \quad : \quad \sim 2.5$$

For comparison, $s^2\, d\sigma/dt \cdot (\gamma\gamma \to \mu^+\mu^-) \cong 4\pi\alpha^2(1+z^2)/(1-z^2) \cong 260$ nb GeV^4 at $z \equiv \cos\theta_{c.m.} = 0$.

We note that the $\gamma\gamma \to \pi^+\pi^-$ cross section is insensitive to the shape of $\phi_\pi(x,Q)$. However, because of its different charge structure, the $\gamma\gamma \to \pi^0\pi^0$ amplitude is strongly sensitive to the distribution amplitude: in fact, the $z = \cos\theta_{c.m.}$ dependence of $\mathcal{M}_{\gamma\gamma \to \pi^0\pi^0}$ resolves the x-dependence of $\phi_\pi(x,Q)$ in the same way that the x_{Bj}-dependence of the deep inelastic lepton scattering cross sections resolves the x_{Bj}-dependence of the structure functions. The strong coupling of the x, y, and $\cos\theta_{c.m.}$ variables in $\mathcal{M}_{\gamma\gamma \to M\bar{M}}$ can be traced to the gluon propagators in the last two diagrams for T_H shown in Fig. 2.

We have also computed the cross-section for transversely polarized vector mesons with opposite helicity, such as $\gamma\gamma \to \rho_T \bar{\rho}_T$. The predictions in Fig. 4 assume $\phi_\rho(x,Q) = \sqrt{2}(f_\rho/f_\pi)\phi_\pi(x,Q)$ independent of ρ-helicity (although this cannot be strictly true at asymptotic Q^2). The $\gamma\gamma \to \rho_T^0 \rho_T^0$ rate vanishes for $\phi_\rho \propto \delta(x - \frac{1}{2})$. We also note that the predicted cross section for $\gamma\gamma \to \rho^+\rho^-$ (summed over polarization) is quite large:

$$\frac{d\sigma/dt\ (\gamma\gamma \to \rho^+\rho^-)}{d\sigma/dt\ (\gamma\gamma \to \mu^+\mu^-)} \sim 7\ \mathrm{GeV}^4/s^2$$

at $\theta_{c.m.} = \pi/2$.

In summary, we note that $\gamma\gamma \to M\bar{M}$ processes can provide a detailed check of the basic Born structure of QCD: the scaling of quark and gluon propagators and interactions, as well as the constituent charges and spin. The form of the predictions are exact to leading order in $\alpha_s(Q^2)$. Power-law (m/Q) corrections can arise from mass insertions, higher Fock states, pinch singularities and non-perturbative effects.

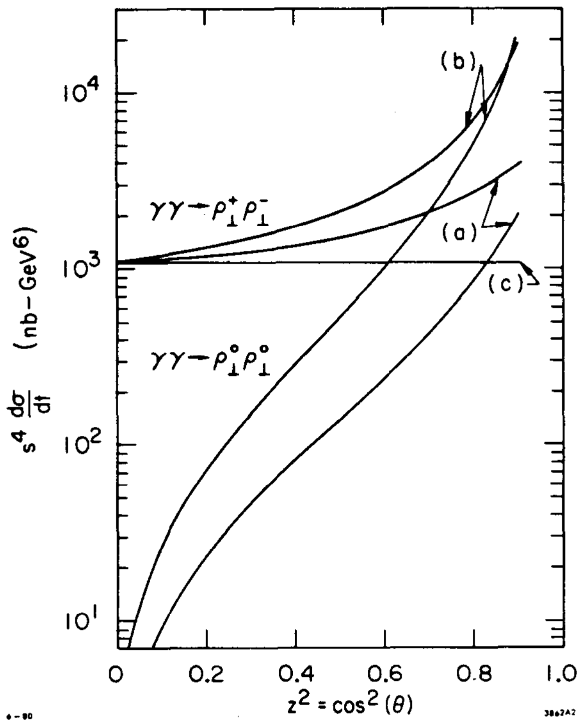

Fig. 4. Perturbative QCD prediction for $\gamma\gamma \to \rho_T\rho_T$ at large momentum transfer, corresponding to the normalization and choices of ϕ_ρ described in the text.

The most extraordinary feature of these results is the fact that the angular dependence of some of the two-photon reactions can directly determine the form of the hadronic wavefunctions at short distances. The determination of $\phi_M(x,Q)$ will remove a major ambiguity in the prediction of the meson form factors.[1] The extension of the results to the baryon channels $\gamma\gamma \to B\bar{B}$, and $\gamma B \to \gamma B$ is thus of obvious interest. The results presented here can also be used to study the occurrence of the fixed Regge singularity at $J = 0$, and the analytic connections to traditional hadronic phenomena: vector meson dominance, finite energy sum rules, and the low energy behavior of the $\gamma\gamma \to M\bar{M}$ amplitudes.

REFERENCES

1. See G. P. Lepage and S. J. Brodsky, SLAC-PUB-2478 (to be published in Phy. Rev. D) and references therein.
2. Complete results will be given in S. J. Brodsky and G. P. Lepage (in preparation).
3. S. J. Brodsky, Y. Frishman, G. P. Lepage and C. Sachrajda, Phys. Lett. 91B, 239 (1980).