

SLAC - PUB - 4129
October 1986
T/E

HADRON PRODUCTION NEAR THRESHOLD
IN PHOTON-PHOTON COLLISIONS*

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ABSTRACT

A dual picture between perturbative QCD and resonance production is exploited to describe non-diffractive meson pair production near threshold in $\gamma\gamma$ annihilation.

Submitted to *Physical Review Letters*

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

In quantum chromodynamics, hadron production in $\gamma\gamma$ annihilation is initiated by the coupling of the incident photons to either one or two quark pairs. At high momentum transfer, both inclusive and exclusive reactions can be computed in terms of underlying elementary quark and gluon scattering subprocesses.¹ A large body of data from PEP and PETRA gives good support to the validity of this perturbative QCD description. At low momentum transfer, the processes which convert the quarks into hadrons are generally nonperturbative, coherent, complex, and thus, at this point, not calculable.

There are, however, exceptional low momentum processes where perturbative QCD predictions should be reliable even at threshold energies if Coulombic rescattering corrections are properly taken into account; e.g., those rare $\gamma\gamma$ annihilation processes in which only hadrons containing heavy quarks are produced. As an example, we illustrate the leading order minimally-connected QCD diagrams for heavy meson pair production in Fig. 1. Since the exchanged gluon momenta and the effective renormalization scale are of order of the heavy quark mass a perturbative QCD analysis can be justified. Unfortunately, the predicted rate is small, and tests of this basic feature of QCD appear remote.

Nevertheless, we shall argue here, that given the validity of a dual picture between the perturbative amplitudes and suitably-averaged resonant contributions, one can obtain reasonable estimates of relatively light meson pair production $\gamma\gamma$ cross sections even near threshold.

Let us recall the situation for heavy quark-pair production in e^+e^- annihilation. In this case the cross section is well under control in QCD not only at high energies but also near threshold where only a minimal number of hadrons

can be produced. Close to threshold, the familiar one-gluon exchange vertex correction [α_s/π at high energies] transforms into a nonrelativistic Coulombic scattering correction $4\pi\alpha_s/3v_{rel}$.² In fact this QCD Schwinger correction appears to describe resonance production very well³ if properly smeared over level spacings.⁴ The dynamical reason for the validity of this dual picture is the Coulombic form of the heavy quark potential with a strength given by the running strong coupling constant at a distance of the order of the heavy quark Compton wavelength.

While the dual picture appears to be well understood for heavy quarks, it turns out to be applicable empirically even for light quarks – at least approximately.⁵ In this note we shall apply this extended duality picture to a class of $\gamma\gamma$ reactions which have recently attracted experimental attention. Typical examples are $\gamma\gamma \rightarrow \rho^+\rho^-$, $K^{*+}K^{*-}$, and $K^{*0}\bar{K}^{*0}$ in which the vector mesons cannot be produced diffractively,⁶ and the quarks created by the two photons must be interchanged to form the final state resonances. The various mechanisms are again described by the generic diagrams shown in Fig. 1. Before discussing these examples in detail, we first develop the basic formalism for the production of two heavy quark pairs to which perturbative QCD—including final state corrections—should safely be applicable in analogy with the results for e^+e^- annihilation.

We can conveniently describe the production of two heavy quark pairs of type q and $Q \neq q$ in $\gamma\gamma$ collisions,

$$\gamma\gamma \rightarrow q\bar{q} Q\bar{Q} \quad (1)$$

in terms of photon helicity amplitudes. We choose the flight axis of the γ 's

in the CM frame as the quantization axis of the quark spins. The following expressions can be derived for the helicity amplitudes and spin-averaged matrix-element squared, corresponding to the three mechanisms shown in Fig. 1(a-c).

(a) Constituent interchange:

$$\tau(++)=\tau(--)= -\frac{8g_s^2}{3} \frac{e_q e_Q}{m_q m_Q} (-)^{s_1} (-)^{s_3} \delta_{s_1 n_2} \delta_{s_3 n_4} \quad (2a)$$

$$\tau(+-)=\tau(-+)=0 \quad (2b)$$

$$\frac{1}{4} \sum |\tau|^2 = \frac{128}{9} \frac{g_s^4 e_q^2 e_Q^2}{m_q^2 m_Q^2} \quad (2c)$$

(b) Formation:

$$\tau(++)=\tau(--)=0 \quad (3a)$$

$$\tau(\pm\mp) = -\frac{4g_s^2}{3} \frac{[e_q^2 + e_Q^2]}{m_q m_Q} [1 \mp (-)^{s_1}] [1 \mp (-)^{s_3}] \delta_{s_1 s_2} \delta_{s_3 s_4} \quad (3b)$$

$$\frac{1}{4} \sum |\tau|^2 = \frac{128}{9} \frac{g_s^4 [e_q^2 + e_Q^2]^2}{m_q^2 m_Q^2} \quad (3c)$$

(c) Bremsstrahlung:

$$\tau(++)=\tau(--)= -\frac{4g_s^2}{3} \frac{m_q e_q^2 + m_Q e_Q^2}{m_q m_Q [m_q + m_Q]} \quad (4a)$$

$$\{ [1 - (-)^{s_1+s_3}] \delta_{s_1 s_2} \delta_{s_3 s_4} - \delta_{s_1 n_2} \delta_{s_3 n_4} \}$$

$$\tau(+-) = \tau(-+) = 0 \quad (4b)$$

$$\frac{1}{4} \sum |\tau|^2 = \frac{32 g_s^4 [m_q e_q^2 + m_Q e_Q^2]^2}{3 m_q^2 m_Q^2 [m_q + m_Q]^2} \quad (4c)$$

The masses and charges of the quarks are denoted by $m_{q,Q}$ and $e_{q,Q}$, respectively; g_s is the QCD coupling constant. The photon helicities are specified by the arguments of the helicity amplitudes. The quark spin indices are denoted by $s_i = 1, 2$ and $n_i = 2, 1$ for spin = up, down. The label $i = 1, \dots, 4$ corresponds to q, \bar{q}, Q, \bar{Q} , respectively.

It has been assumed in the derivation of the formulae that $(q\bar{Q})$ and $(\bar{q}Q)$ each form color singlets, resulting in a universal color factor $4/3$. As a consequence, the squared amplitudes of the three mechanisms summed over quark spins do not interfere with each other at threshold. Quarks and antiquarks in color singlet states attract each other, so that the production amplitude gets enhanced by the Coulombic rescattering corrections. In the octet state, by contrast, they repel each other and the production is de-enhanced.

We thus apply the Coulomb correction factor,²

$$C = \frac{8\pi\alpha_s m_{RED}}{3|p_{rel}|}, \quad (5)$$

to each quark pair in the final state, as indicated by the dashed blobs in Fig. 1. Here $m_{RED} = m_q m_Q / (m_q + m_Q)$ is the reduced quark mass and p_{rel} is the relative momentum of the quark-antiquark pair in its rest frame. The final state

correction factor is singular at zero relative momentum, strongly enhancing the threshold region $m(Q\bar{q}) \approx m_Q + m_q$. Since this singularity cancels part of the overall phase space suppression, we find fairly large threshold $\gamma\gamma$ cross sections.

By far the largest contribution is due to the formation mechanism. For equal quark charges, for example, and $m_Q \gg m_q$ or $m_Q = m_q$ the cross sections at threshold corresponding to constituent interchange, formation, and bremsstrahlung are in the ratio

$$\sigma_a : \sigma_b : \sigma_c = \frac{1}{4} : 1 : \frac{3}{16} \quad (6)$$

and similarly for other cases. Notice that the formation mechanism produces pairs of spin-one mesons only. Final states composed of charge 2/3 quarks are of course much more frequently created in $\gamma\gamma$ reactions than those of the down-type quarks.

There is a different rescattering mechanism that should contribute to four-quark final states in $\gamma-\gamma$ collisions: Two quarks attract each other in a di-quark 3^* state; the di-quark and di-antiquark may then form a $q\bar{q}q\bar{q}$ resonance. Such states would be expected to decay preferentially into many-particle final states since the color-neutral $q\bar{q}$ pairs are by assumption absent in the amplitude. We shall leave this very interesting problem aside in this paper.

As noted previously, the $\gamma\gamma$ cross sections for pairs of heavy quarks are too small to be readily accessible experimentally. However, by postulating the dual picture, we can at least tentatively extend the analysis to light quarks in order to obtain a semiquantitative understanding of the pair production cross section for meson resonances.

The parameters of the calculation are defined as follows. (i) We set the u and d quark masses to 300 MeV, the strange quark mass to 500 MeV, and the charmed quark mass to 1.5 GeV, corresponding to the familiar effective constituent quark mass values. The calculation is thus applicable to ρ and K^* production in the light-quark sector. The predicted rates for each resonance also include the corresponding $\pi\pi$ and $K\pi$ continuum of equivalent mass. One cannot expect these calculations to be applicable to $\gamma\gamma \rightarrow \pi\pi$ since the dual pion cannot be described in an additive quark picture in QCD, not even approximately. (ii) For the QCD coupling constant we have adopted $\Lambda = 200$ MeV and the argument of α_s is chosen as the geometric mean of all the quark energies involved in the process.

In the analysis, $\alpha_s = g_s^2/4\pi$ was generally small, but in any event its value was frozen to $\alpha_s \leq 1$ where necessary. For the final numerical results the matrix elements for $\gamma\gamma \rightarrow \bar{q}q\bar{q}q$ were not approximated by threshold values but were evaluated numerically using the results of Ref. 7 so that the calculation should remain meaningful for light quark resonances with production energies up to $O(1\text{GeV})$ beyond threshold. Beyond this energy the dual representation of the vector mesons by the color neutral blobs presumably ceases to be valid.

The results of the calculations for nondiffractive vector meson pair production (plus the corresponding $\pi\pi, K\pi$ continua) are summarized in Fig. 2.

(a) $\gamma\gamma \rightarrow (u\bar{d}) + (\bar{u}d) \sim \rho^+\rho^-$ The cross section is shown in Fig. 2a where it is compared with the yield of $\gamma\gamma \rightarrow (\pi^+\pi^0) + (\pi^-\pi^0)$, the invariant $\pi\pi$ masses restricted to the ρ^\pm band, as measured by the JADE Collaboration,⁸ and presented in the summary of Ref. 9. The theoretical analysis appears compatible with the $\pi\pi$ yield in the ρ band. Note that no attempt has been made to adjust any parameters; they had been fixed on physical grounds before the numerical work

was started. Nonresonant 4π final states are also created by mechanisms not discussed in this note, such as $\gamma\gamma \rightarrow ugg\bar{u} \rightarrow (u\bar{d}) + (\bar{d}d) + (\bar{d}d) + (d\bar{u}) \sim \pi^+\pi^0\pi^0\pi^-$. These channels can spill into the $\rho\rho$ region.

(b) $\gamma\gamma \rightarrow (s\bar{u}) + (\bar{s}u) \sim K^{*-}K^{*+}$ and $(s\bar{d}) + (\bar{s}d) \sim \bar{K}^{*0}K^{*0}$: Due to the heavier s quark mass, we expect $\sigma(K^{*+}K^{*-})$ to be approximately a factor of ~ 3 smaller than $\sigma(\rho^+\rho^-)$. This is indeed born out by the detailed analysis shown in Fig. 2b. Furthermore, the ratio $\sigma(K^{*0}\bar{K}^{*0})/\sigma(K^{*+}K^{*-})$ is expected to be of the order of $2(e_d/e_u)^4 = 1/8$; see Fig. 2b. The neutral K^* sector has been analyzed by the TPC/Two-Gamma¹ 0 and Tasso¹ 1 collaborations. An upper limit of 5.7 nb has been reported for $K^{*0}\bar{K}^{*0}$ resonance production in Ref. 10, still much above our theoretical analysis. At the same time, a large ratio $\sigma(K^{*0}K\pi)/\sigma(K^{*0}\bar{K}^{*0}) \gg 1$ is observed. This is nicely compatible with general expectations: whereas an s or d quark has to be coupled to the photons to produce a $K^{*0}\bar{K}^{*0}$ final state, the formation of a nonresonant $K^+K^{*0}\pi^-$ final state can proceed via $\gamma\gamma \rightarrow ugg\bar{u} \rightarrow (u\bar{s}) + (s\bar{d}) + (d\bar{u})$ where a u -quark line is attached to both photons, thus resulting in a substantial increase of the cross section.

(c) $\gamma\gamma \rightarrow (c\bar{q}) + (\bar{c}q) \sim D\bar{D}, D^*\bar{D}^*$: Adding up all light-quark channels, the cross section is predicted to be of the order of $\sim 1/2\text{nb}$ in the threshold region. (See Fig. 2c.)

Even though the application of a perturbative QCD analysis in conjunction with duality arguments is a conjecture that can only be justified *a posteriori*, it is an attractive theoretical scheme since it is based solely on fundamental quark-gluon parameters: the quark masses, and the quark-gluon coupling constant. The picture is too crude to expect high accuracy; however, it offers a simple qualitative understanding of the magnitude of the cross sections and their ratios

for different final states. We hope that this analysis will be useful to describe the global features of $\gamma\gamma$ experiments now underway at DESY and the upgraded PEP at SLAC.

ACKNOWLEDGEMENTS

Discussions with H. Kolanoski and J. E. Olsson are gratefully acknowledged. We are particularly indebted to Z. Kunszt for providing us with a copy of his 4-parton computer program. P. M. Z. thanks M. Jacob for the warm hospitality extended to him by the CERN Theory Division. This research was begun at the Institute for Theoretical Physics at Santa Barbara, and was supported in part by the National Science Foundation under Grant No. PHY82-17853, supplemented by funds from the National Aeronautics and Space Administration, at the University of California at Santa Barbara.

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

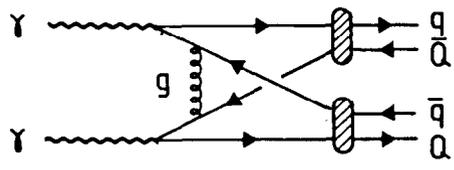
FIGURE CAPTIONS

1. Mechanisms for the non-diffractive production of color-neutral $q\bar{q}$ compounds in $\gamma\gamma$ annihilation. (a) Constituent interchange, (b) formation, and (c) bremsstrahlung.
2. Production cross sections for $q\bar{q}$ plus $q\bar{q}$ compounds in $\gamma\gamma$ annihilation near threshold. [The data points in (a) are upper limits for the $\rho^+\rho^-$ cross section.]

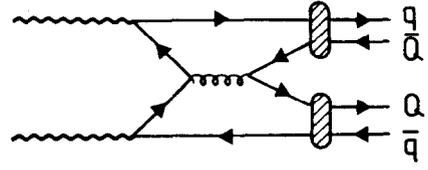
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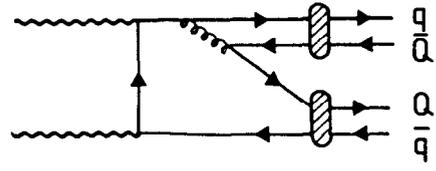
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(a)



(b)



(c)

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Fig. 1

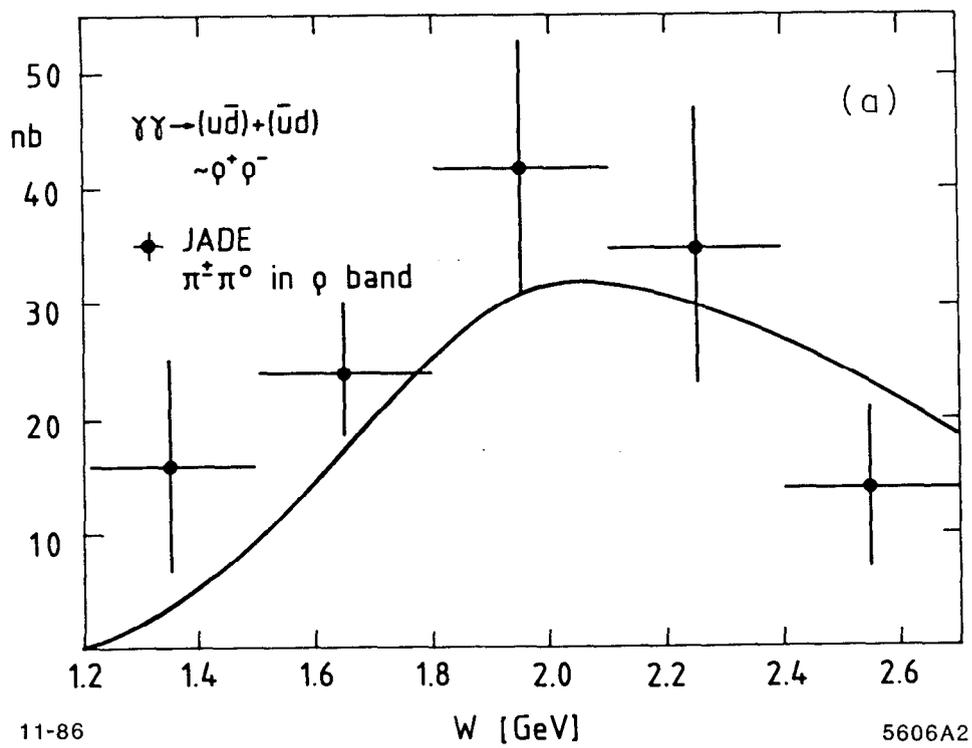


Fig. 2

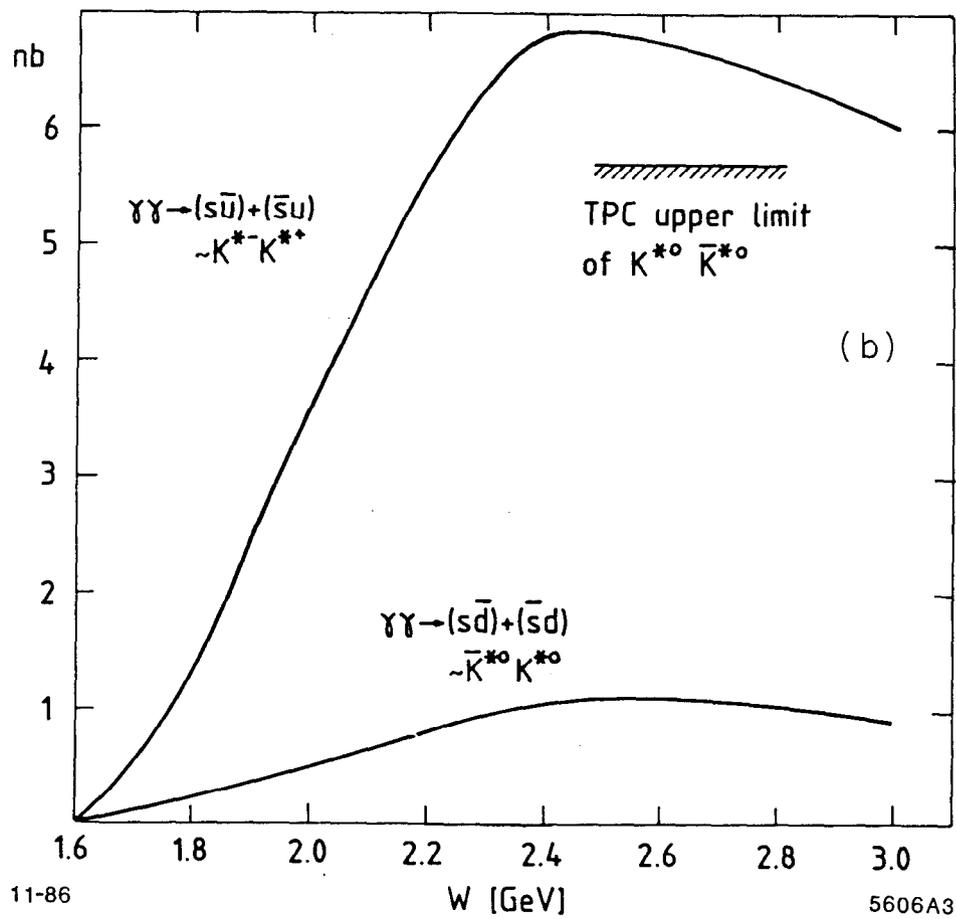


Fig. 2

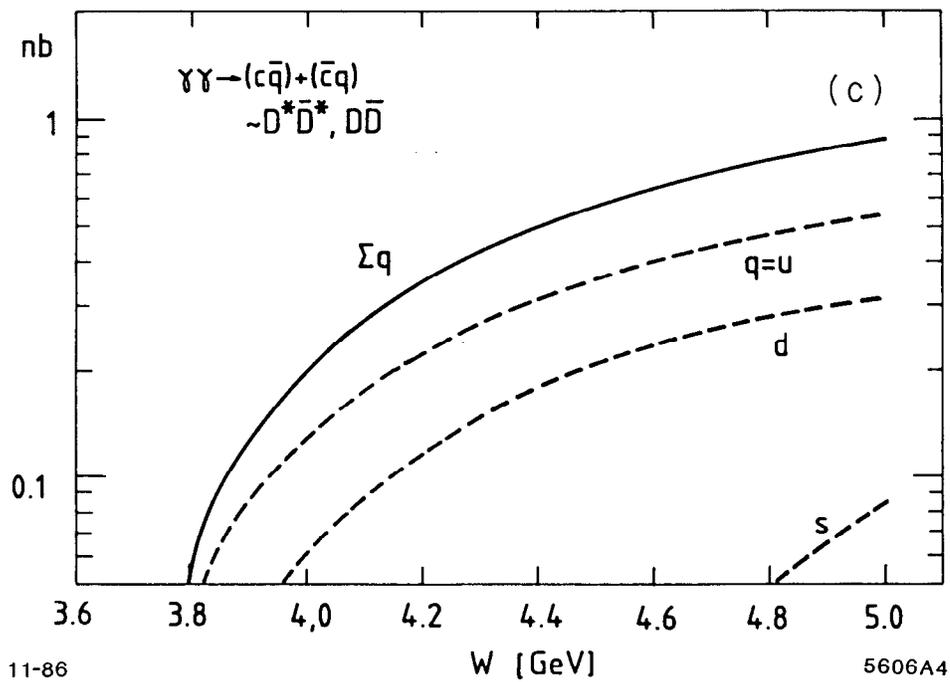


Fig. 2