PHYSICAL REVIEW D **84**, 034036 (2011)

$\eta(1475)$ and $f_1(1420)$ resonances in $\gamma\gamma^*$ collisions and $J/\psi \to \gamma(\rho\rho, \gamma\rho^0, \gamma\phi)$ decays

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(Received 4 May 2011; published 19 August 2011)

The available data on the Q^2 dependence of the $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ reaction cross section in the energy region 1.35–1.55 GeV is explained by the $\eta(1475)$ resonance production in contrast to their conventional interpretation with the use of the $f_1(1420)$ resonance. It resolves theoretically the contradiction between the suppression of the $\eta(1475) \to \gamma\gamma$ decay width and the strong couplings of the $\eta(1475)$ to the $\rho\rho$, $\omega\omega$, and $\gamma\rho^0$ channels. The experimental check of our explanation requires definition of the spin-parity of the resonance contributions, R, in $\gamma\gamma^*(Q^2) \to R \to K\bar{K}\pi$ and in $J/\psi \to \gamma R \to \gamma\gamma(\rho^0, \phi)$. This will help to solve difficulties accumulated in understanding properties of the $\eta(1475)$ state and its nearest partners.

DOI: 10.1103/PhysRevD.84.034036 PACS numbers: 13.20.Jf, 13.40.−f, 13.60.Le

I. INTRODUCTION

The family of the pseudoscalar states $\pi(1300)$, $\eta(1295)$, $\eta(1405)$, $\eta(1475)$, and $K(1460)$ [1] has very mysterious properties; see for review [2–11]. The $\eta(1475)$ can be also confused with the $f_1(1420)$ [1] in the $K\bar{K}\pi$ decay channel, without carrying out a partial wave analysis.

Recall that in 2004 the long-known state $E/\iota(1440)/\eta(1440)$ was officially split into two components [7,9], $\eta(1405)$ and $\eta(1475)$, decaying mainly into $a_0(980)\pi$ and $K^*(892)\bar{K}$, respectively [1,8,11]. The splitting of the $\eta(1440)$ significantly complicates the classification of the above-mentioned pseudoscalar states [1,8–11]. An "odd" member of this family with putative glueball properties is often associated with the $\eta(1405)$ state [1,8,11]. Notice that this state has not been seen in $\gamma\gamma$ or in $\gamma\gamma^*$ collisions even in its main decay channel into $\eta\pi\pi$ [1,8,11–13]. The available data on the $J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0$ and $J/\psi \to \gamma\eta(1440) \to \gamma\rho^0\rho^0$ decays are quoted in the later Particle Data Group (PDG) reviews [1,7,9], in the $J/\psi(1S)$ section, as the data for the unresolved $\eta(1405/1475)$ state. At the same time, the even data on $J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0$ are assigned to the $\eta(1405)$ state in the $\eta(1405)$ section [1]. To clarify the existing uncertain situation, we attribute the data on $J/\psi \to \gamma\eta(1440) \to \gamma(\gamma\rho^0, \rho^0\rho^0)$ decays to the $\eta(1475)$. (If we were to attribute these decays to $\eta(1405)$, then our scenario would not change.) Experimental verification of our scenario will automatically resolve the question of the role of the $\eta(1405)$ in the problem under discussion. We emphasize that, if the L3 Collaboration is right when they assert that the $\eta(1405)$ signal is absent in $\gamma\gamma$ and $\gamma\gamma^*$ collisions [12,13], then most likely the data on the $\gamma\rho^0$ decay cannot be attributed to the $\eta(1405)$.

In this paper we concentrate on the manifestations of the $\eta(1475)$ and $f_1(1420)$ resonances in $\gamma\gamma$ and $\gamma\gamma^*(Q^2)$ collisions (where Q^2 is a photon virtuality) and in $J/\psi \to \gamma\gamma(\rho^0, \phi)$ decays. Section II describes the history of the search for the $\eta(1475)$ meson production in $\gamma\gamma$ collisions. In Sec. III, the paradox related to the suppression of the $\eta(1475) \to \gamma\gamma$ decay width and the strong couplings of the $\eta(1475)$ to the $\rho\rho$, $\omega\omega$, and $\gamma\rho^0$ channels is presented. In Sec. IV, a scenario resolving the problem with the $\eta(1475) \to \gamma\gamma$ decay is considered, and on its basis we obtain the alternative explanation of the existing data on the Q^2 dependence of the $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ reaction cross section in the region of the $\eta(1475)$ and $f_1(1420)$ resonances. The relations between the data on the $f_1(1420) \to \gamma(\rho^0, \phi)$ and $f_1(1420) \to \gamma\gamma^*$ decays are discussed in Sec. V. The measurements required to solve accumulated difficulties in understanding properties of the $\eta(1475)$ state and to check our explanation are briefly listed in Sec. VI. Several technical details are relegated to the Appendix.

II. THE $\eta(1475) \to \gamma\gamma$ DECAY

The history of the search for the $\eta(1475)$ meson production in $\gamma\gamma$ collisions in the $K\bar{K}\pi$ and $\eta\pi\pi$ final states is represented in Table I [12–19]. The first successful experiment was performed by the L3 Collaboration [12], in which 37 ± 9 $\gamma\gamma \to \eta(1475) \to K^0_S K^\pm\pi^\mp$ events were selected in the region of the resonance peak with the mass $M = 1481 \pm 12$ MeV. Then the CLEO II Collaboration [18] investigated the reaction $\gamma\gamma \to K^0_S K^\pm\pi^\mp$ with a data sample that exceeds the L3 statistics by a factor of 5 and did not find any signal in this region. As a result, they obtained the strongest upper limit on the product of the $\eta(1475) \to \gamma\gamma$ decay width, $\Gamma(\eta(1475) \to \gamma\gamma)$, and the $\eta(1475) \to K\bar{K}\pi$ decay branching ratio, $B(\eta(1475) \to K\bar{K}\pi)$; see Table I. Later on, the L3 Collaboration treated all collected statistics (which is 50% higher than that used previously [12])) and confirmed the result of their own experiment, $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi) = 0.23 \pm 0.05 \pm 0.05$ keV [13,20]. As noted in Ref. [13], if the world average width of $\eta(1475)$ is used, the CLEO II upper limit increases from 0.089 keV to 0.140 keV, that is consistent with the L3 result within two errors.

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TABLE I. Information about the $\eta(1475) \to \gamma\gamma$ decay.

Experiment	Ref.	Data (in keV)
		$\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi)$
MARK II, 1983	[14]	<8
TASSO, 1985	[15]	<2.2
TPC/2γ, 1986	[16]	<1.6
CELLO, 1989	[17]	<1.2
L3, 2001	[12]	$0.212 \pm 0.050 \pm 0.023$
CLEO II, 2005	[18]	<0.089 (90% C.L.)
L3, 2007	[13]	$0.23 \pm 0.05 \pm 0.05$
		$\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to \eta\pi\pi)$ (keV)
Crystal Ball, 1987	[19]	<0.3
L3, 2001	[12]	<0.095 (95% C.L.)

III. PARADOX OF THE $\eta(1475) \to \rho^0\rho^0$, $\eta(1475) \to \gamma\rho^0$, AND $\eta(1475) \to \gamma\gamma$ DECAYS

The J/ψ meson radiative decays, such as $J/\psi \to \gamma K\bar{K}\pi$, $J/\psi \to \gamma\rho\rho$, $J/\psi \to \gamma\omega\omega$, and $J/\psi \to \gamma\gamma\rho^0$, are a very important tool of the $\eta(1475)$ meson investigation [1–3,8,21–36].

In the mid 1980s, we showed [26] that pseudoscalar ($J^P = 0^-$) structures discovered by MARK III [21,24,25] in the $\rho\rho$ and $\omega\omega$ mass spectra near their thresholds in the $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\omega\omega$ decays can be explained by decays $\eta(1440) \to \rho\rho$ and $\eta(1440) \to \omega\omega$ at the resonance tail. This explanation was supported by subsequent results from MARK III [2,27–29], DM2 [30,31], and BES [34] on the $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\omega\omega$ decays. In the work [26], we also showed that the strong coupling of $\eta(1440)$ to $\rho^0\rho^0$ leads within the usual vector dominance model (VDM) to the large decay widths $\eta(1440) \to \gamma\gamma$ and $\eta(1440) \to \gamma\rho^0$: $\Gamma(\eta(1440) \to \rho^0\rho^0 \to \gamma\gamma) \approx 6.6$ keV and $\Gamma(\eta(1440) \to \gamma\rho^0) \approx 1.3$ MeV. Note that these values should be doubled at present because the branching ratio $B(J/\psi \to \gamma\eta(1405/1475) \to \gamma\rho^0\rho^0) = (1.7 \pm 0.4) \times 10^{-3}$ [1] has since increased approximately 2 times. Such an estimate for the width $\Gamma(\eta(1440) \to \gamma\gamma)$ is in apparent contradiction with the results of its direct measurements presented in Table I. The recent experiments performed by L3 [12,13] and CLEO II [18] Collaborations essentially sharpened this contradiction when compared to its first manifestations which were discussed more than 20 years ago [2,3,22,26,37–42].

Let us consider the data on the $J/\psi \to \gamma\gamma\rho^0$ decay [1,2,22,23,25,27,32,33,36], revealing the coupling of the $\eta(1475)$ to the $\gamma\rho^0$ decay channel. Notice that the first Crystal Ball and MARK III measurements [2,23,27,32] did not clarify the question about the spin-parity of the resonance enhancement observable in the $\gamma\rho^0$ system near 1.44 GeV. The $\gamma\rho^0$ angular distributions agree with the $J^P = 0^-$ resonance production, but spin-parity $J^P = 1^+$ was not excluded. However, not so long ago, the BES Collaboration [36] obtained some indirect indication in favor of the $\eta(1440)$ meson production in the $J/\psi \to \gamma R \to \gamma\gamma\rho^0$ decay. To determine whether R is more likely to be the $f_1(1420)$ or the $\eta(1440)$, they used the measurement by the WA102 Collaboration [43],

$$B(f_1(1420) \to \gamma\rho^0)/B(f_1(1420) \to K\bar{K}\pi) < 0.02, \quad (1)$$

together with the PDG result [5],

$$B(J/\psi \to \gamma f_1(1420) \to \gamma K\bar{K}\pi) = (7.9 \pm 1.3) \times 10^{-4},$$

and obtained

$$B(J/\psi \to \gamma f_1(1420) \to \gamma\gamma\rho^0) < 1.7 \times 10^{-5} \quad (2)$$

(with 95% C.L.). Comparing this restriction with their own measurement of

$$B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0) = (1.07 \pm 0.17 \pm 0.11) \times 10^{-4}$$

(see Table II), they concluded that R in the $J/\psi \to \gamma R \to \gamma\gamma\rho^0$ channel should be predominantly $\eta(1440)$. Note that in Sec. V we shall obtain a stronger restriction for $B(f_1(1420) \to \gamma\rho^0)/B(f_1(1420) \to K\bar{K}\pi)$ in comparison with Eq. (1), with the help of the quark model and the data on the $f_1(1420) \to \gamma\phi$ decay.

The $\eta(1475) \to \gamma\rho^0$ decay width can be estimated from the relation

$$\Gamma(\eta(1475) \to \gamma\rho^0) = \Gamma^{tot}_{\eta(1475)} B(\eta(1475) \to K\bar{K}\pi) \times \frac{B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\rho^0)}{B(J/\psi \to \gamma\eta(1475) \to \gamma K\bar{K}\pi)}. \quad (3)$$

If we put $\Gamma^{tot}_{\eta(1475)} = 85$ MeV [1], $B(\eta(1475) \to K\bar{K}\pi) = 0.6$ [44] and use the last BES data [35,36] for $B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\rho^0)$ and $B(J/\psi \to \gamma\eta(1475) \to \gamma K\bar{K}\pi)$ (see Table II), we find that $\Gamma(\eta(1475) \to \gamma\rho^0) \approx 3.3$ MeV. If we use for $B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\rho^0)$ and $B(J/\psi \to \gamma\eta(1475) \to \gamma K\bar{K}\pi)$ the PDG averages [1,9] (also indicated in Table II), then we have

TABLE II. Information about the $\eta(1475/1440) \to K\bar{K}\pi$, $\gamma\rho^0$, $\gamma\omega$, and $\gamma\phi$ decays.

Experiment	Ref.	Data
BES, 2000	[35]	$B(J/\psi \to \gamma\eta(1440) \to \gamma K\bar{K}\pi) = (1.66 \pm 0.10 \pm 0.58) \times 10^{-3}$
BES, 2004	[36]	$B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0) = (1.07 \pm 0.17 \pm 0.11) \times 10^{-4}$
BES, 2004	[36]	$B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\phi) = (0.31 \pm 0.30) \times 10^{-4}$, or $<0.82 \times 10^{-4}$ (95% C.L.)
PDG, 2006, 2010	[1,9]	$B(J/\psi \to \gamma\eta(1475) \to \gamma K\bar{K}\pi) = (2.8 \pm 0.6) \times 10^{-3}$
PDG, 2006, 2010	[1,9]	$B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\rho^0) = (0.78 \pm 0.2) \times 10^{-4}$
MARK III, 1985	[2,25]	$B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\omega) < 2.3 \times 10^{-4}$ (90% C.L.)

$\Gamma(\eta(1475) \to \gamma\rho^0) \approx 1.4$ MeV. These values agree with the first results for $\Gamma(\eta(1440) \to \gamma\rho^0)$ [2,22,23,25–27,37,42] obtained over 20 years ago. We accept as a conservative estimate

$$\Gamma(\eta(1475) \to \gamma\rho^0) = 1 \text{ MeV}. \tag{4}$$

To estimate the width of the $\eta(1475) \to \gamma\gamma$ decay caused by the transitions $\eta(1475) \to \gamma V$ (where $V = \rho^0$, ω, and ϕ), we apply VDM and $SU(3)$ symmetry, together with the nonet symmetry assumption for the V meson interactions and the ideal $\omega - \phi$ mixing. Hereafter, for short, the $\eta(1475)$ will be denoted in the indices by ι. Thus, for the coupling constants $g_{\iota\gamma\gamma}$ and $g_{\iota\gamma\rho}$, one can write the following relation [26,37]:

$$g_{\iota\gamma\gamma} = \frac{e}{f_\rho} g_{\iota\gamma\rho}\left(1 + \frac{1}{9} + \frac{2}{9}H(x)\right), \tag{5}$$

where the three terms correspond to a transition via $\gamma\rho$, $\gamma\omega$, and $\gamma\phi$, respectively, $f_\rho^2/(4\pi) = \alpha^2 m_\rho/[3\Gamma(\rho^0 \to e^+e^-)] = 1.96$ [1], $H(x) = (1 - 2x)/(1 + x)$, the parameter $x = r\tan\theta_\iota/\sqrt{2}$, where $\tan\theta_\iota$ defines the ratio of the octet and singlet components in the $\eta(1475)$ wave function, and $r/\sqrt{2}$ is the ratio of the octet and singlet coupling constants of the $\eta(1475)$ with $\gamma\rho^0$.

Equation (5) is correct for the $\eta(1475)$ wave function of the general form, that is, for the mixing of the $SU(3)$ octet (quark-antiquark) and $SU(3)$ singlet (quark-antiquark and glueball) components. This is evidenced by the presence of three parameters in Eq. (5), $g_{\iota\gamma\rho}$, $\tan\theta_\iota$, and r.

The coupling constants, for which we apply the VDM and symmetries, enter into expressions for the decay widths $\eta(1475) \to \gamma\gamma$ and $\eta(1475) \to \gamma V$ in the following ways:

$$\Gamma(\eta(1475) \to \gamma\gamma) = m_\iota^3 g_{\iota\gamma\gamma}^2/64\pi, \tag{6}$$

$$\Gamma(\eta(1475) \to \gamma V) = C_V[(m_\iota^2 - m_V^2)/m_\iota]^3 g_{\iota\gamma\rho}^2/32\pi, \tag{7}$$

where $C_\rho = 0.832$ (this factor taking into account the finite width of the ρ^0 resonance in the $\eta(1475) \to \gamma\rho^0 \to \gamma\pi^+\pi^-$ decay [26]; for the stable ρ^0, $C_\rho = 1$), $C_\omega = 1/9$, and $C_\phi = (2/9)H^2(x)$.

Owing to the $\eta(1475) \to \gamma\rho^0$ transition only, $\Gamma(\eta(1475) \to \gamma\rho^0 \to \gamma\gamma) \approx 5.9$ keV. Owing to the $\eta(1475) \to \gamma\rho^0$ and $\eta(1475) \to \gamma\omega$ transitions, $\Gamma(\eta(1475) \to (\gamma\rho^0 + \gamma\omega) \to \gamma\gamma) \approx 7.3$ keV. If the $\eta(1475)$ is an $SU(3)$ singlet, then $x = 0$, $H(x = 0) = 1$, and $\Gamma(\eta(1475) \to (\gamma\rho^0 + \gamma\omega + \gamma\phi) \to \gamma\gamma) \approx 10.5$ keV. Some restriction on $|H(x)|$ can be obtained from the relation

$$\frac{\Gamma(\eta(1475) \to \gamma\phi)}{\Gamma(\eta(1475) \to \gamma\rho^0)} = 0.1 \times H^2(x) = \xi = \frac{B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\phi)}{B(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\rho^0)}. \tag{8}$$

According to the BES experiment [36], in which the $\gamma\rho^0$ and $\gamma\phi$ channels were investigated simultaneously, $B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0) = (1.07 \pm 0.17 \pm 0.11) \times 10^{-4}$ and $B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\phi) = (0.31 \pm 0.30) \times 10^{-4}$, which corresponds to a 95% C.L. upper limit $B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\phi) < 0.82 \times 10^{-4}$ (see Table II). Hence, $\xi < 0.77$ [45]. Let, for example, $\xi = 0$, 0.29, 0.77. Then we get from Eq. (8) $H(x) = -2.77$, -1.7, 0, 1.7, 2.77, and from Eqs. (4)–(7), $\Gamma(\eta(1475) \to \gamma\gamma) = 1.45$, 3.2, 7.3, 13.1, 17.6 keV, respectively. (See also endnote [46].)

Thus, using the data on the $J/\psi \to \gamma\eta(1475) \to \gamma\gamma(\rho^0, \phi)$ decays, we estimate

$$\Gamma(\eta(1475) \to \gamma\gamma) > 1.45 \text{ keV}, \tag{9}$$

which is in conflict with the L3 [12,13] and CLEO II [18] results on the reaction $\gamma\gamma \to \eta(1475) \to K\bar{K}\pi$ unambiguously indicative of the suppression of the $\eta(1475) \to \gamma\gamma$ decay (see Table I).

The above analysis allows us to conclude that the contradiction with the results of the direct measurements of the $\eta(1475) \to \gamma\gamma$ decay width is a real challenge.

IV. SOLUTION OF THE $\eta(1475) \to \gamma\gamma$ DECAY PROBLEM AND EXPLANATION OF THE $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ DATA

In our early work [42], we showed that taking into account the heavy vector mesons V' ($V' = \rho'^0$, ω', ϕ') in the VDM framework, along with the usual ρ^0, ω, and ϕ

mesons, permits one to easily solve the problem with $\Gamma(\eta(1475) \to \gamma\gamma)$ owing to the strong destructive interference between the V and V' contributions in the $\eta(1475) \to (\gamma V + \gamma V') \to \gamma\gamma)$ transition amplitude. Here, we discuss this solution in more detail. It is important that the proposed explanation of a number of the experimental facts results in the nontrivial prediction [42]: there must arise the resonance peak caused by the $\eta(1475)$ meson production in the $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ reaction cross section for $Q^2 \neq 0$. Indeed, if the almost total compensation between the V and V' contributions takes place at $Q^2 = 0$ in $\Gamma(\eta(1475) \to \gamma\gamma) \equiv \Gamma(\eta(1475) \to \gamma\gamma^*(Q^2 = 0))$, then it is broken with increasing Q^2 because of the considerable V-V' mass difference, and $\Gamma(\eta(1475) \to \gamma\gamma^*(Q^2))$ sharply increases. It is very likely that only the above phenomenon has been observed in single-tagged two-photon interactions by the TPC/2γ, MARK II, JADE, CELLO, CLEO II, and L3 Collaborations.

The reactions $\gamma\gamma^*(Q^2) \to K^0_S K^\pm \pi^\mp$ [12,13,17,18,47–51] have been investigated parallel with the reactions $\gamma\gamma \to K^0_S K^\pm \pi^\mp$ [12–18]. A clear resonance signal in their cross sections has been found in the $K^0_S K^\pm \pi^\mp$ invariant mass range $1.35\ \text{GeV} < W < 1.55\ \text{GeV}$ for $Q^2 \neq 0$ (in the region $0.04\ \text{GeV}^2 < Q^2 < (1\text{–}8)\ \text{GeV}^2$) in the experiments performed by TPC/2γ [47,49], MARK II [48], JADE [51], CELLO [17], and CLEO II [18]. The absence of the resonance signal in $\sigma(\gamma\gamma \to K^0_S K^\pm \pi^\mp)$ and its appearance in $\sigma(\gamma\gamma^*(Q^2) \to K^0_S K^\pm \pi^\mp)$ has led naturally to the hypothesis of the $J^P = 1^+ f_1(1420)$ resonance production [1,17,18,47–52], which is forbidden in two real photon collisions [53]. For small Q^2, the $\gamma\gamma^*(Q^2) \to f_1(1420)$ transition amplitude is proportional to $\sqrt{Q^2}$ [13,17,47–57]. However, this can in no way eliminate the contradiction connected with the $\eta(1475) \to \gamma\gamma$, $\gamma\rho^0$, $\rho^0\rho^0$ decays.

Poor statistics in the TPC/2γ (12 useful events) [49], MARK II (13 events) [48], JADE (16 events) [51], and CELLO (17 events) [17] experiments did not allow a determination of the spin-parity of the resonance structure directly with the angular distributions. The L3 [12,13] and CLEO II [18] conclusions about the quantum numbers of the enhancement discovered in the region 1.35–1.55 GeV are also based only on the data for the Q^2 dependence of $\sigma(\gamma\gamma^*(Q^2) \to K^0_S K^\pm \pi^\mp)$. In the last L3 experiment [13], 193 ± 20 events have been selected in the resonance region. They were about evenly distributed among five Q^2 intervals: 0–0.01, 0.01–0.12, 0.12–0.4, 0.4–0.9, and 0.9–7 GeV^2. The presence of events in the first Q^2 interval was naturally associated with the production of the $\eta(1475)$ [58], and, to describe the data for higher Q^2, the contribution of the $f_1(1420)$ resonance was recruited [59]. As already noted above, the resonance signal at $Q^2 \approx 0$ has not been observed in the CLEO II experiment [18], and, therefore, the enhancement discovered for intermediate Q^2 ($0.04\ \text{GeV}^2 < Q^2 < 0.36\ \text{GeV}^2$ and $Q^2 \gtrsim 1\ \text{GeV}^2$) was attributed without any provisos to the $f_1(1420)$ production [18].

The possibility that we outlined permits one to explain the available data on the reaction $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ in the $f_1(1420)/\eta(1475)$ region by the $\eta(1475)$ resonance production only (see Fig. 1). Let us explain the experimental points and theoretical curves shown in this figure.

The cross section for the production of a resonance R with $J^P = 0^-$ or 1^+ in $\gamma\gamma^*$ collisions can be written in the form:

$$\sigma(\gamma\gamma^*(Q^2) \to R \to K\bar{K}\pi) = 8\pi(2J+1)N_J\left(1 + \frac{Q^2}{m_R^2}\right) \times \frac{\tilde{\Gamma}(R \to \gamma\gamma^*(Q^2))B(R \to K\bar{K}\pi)\Gamma_R^{\text{tot}}}{(m_R^2 - W^2)^2 + (m_R\Gamma_R^{\text{tot}})^2}, \quad (10)$$

where $N_0 = 1$, $N_1 = 2$, m_R is the mass, Γ_R^{tot} the total width, and $\tilde{\Gamma}(R \to \gamma\gamma^*(Q^2))$ the reduced $\gamma\gamma^*$ width of the resonance. Detailed discussions of the parametrizations and normalizations of the $\gamma\gamma^*$ decay widths for the resonances with spin $J = 0$ and 1 may be found in Refs. [13,17,42,47–52,60]. Necessary information is briefly presented in the Appendix.

The data on the Q^2 dependence of $\tilde{\Gamma}(R \to \gamma\gamma^*(Q^2))$ are the matter of theoretical fits. The TPC/2γ [49], CELLO

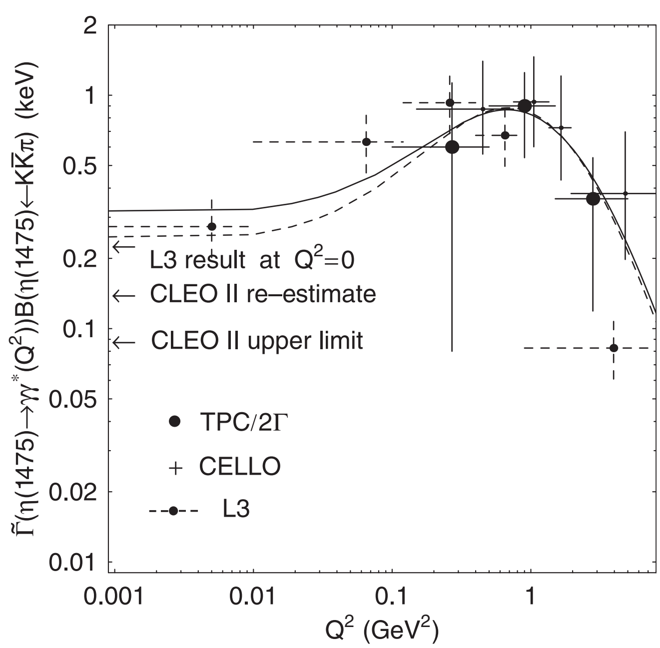

FIG. 1. $\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))B(\eta(1475) \to K\bar{K}\pi)$ as a function of Q^2. The points with the error bars were obtained from data from TPC/2γ [49], CELLO [17], and L3 [13]. The arrows point to the L3 result at $Q^2 = 0$ [13] and the CLEO II upper limit [18], presented in Table I, as well as the CLEO II upper limit re-estimated by L3 [13], equal to 0.14 keV. The fitted curves are described in the text.

[17], and L3 [13] data, attributed to the resonance with $J^P = 1^+$, are easily recalculated in the case of the resonance with $J^P = 0^-$ having approximately the same mass. (See the Appendix for details.) The corresponding values for $\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))B(\eta(1475) \to K\bar{K}\pi)$ are shown in Fig. 1 [61].

To describe $\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))B(\eta(1475) \to K\bar{K}\pi)$, we use the following parametrization:

$$\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))B(\eta(1475) \to K\bar{K}\pi) = \Bigg| A\left(\frac{10}{9}\frac{1}{1+Q^2/m_\rho^2} + \frac{2}{9}\frac{h}{1+Q^2/m_\phi^2}\right) + A'\left(\frac{10}{9}\frac{1}{1+Q^2/m_{\rho'}^2} + \frac{2}{9}\frac{h}{1+Q^2/m_{\phi'}^2}\right)\Bigg|^2, \quad (11)$$

where $m_{\rho'} = 1.45$ GeV [1], $m_{\phi'} = 1.68$ GeV [1], a parameter $h = H(x)$ [see Eq. (5)],

$$A^2 = \Gamma(\eta(1475) \to \gamma\rho^0 \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi),$$

and

$$A' = -A - 9\frac{\sqrt{\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi)}}{(10+2h)};$$

$\Gamma(\eta(1475) \to \gamma\gamma) = \tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2 = 0))$. In Eq. (11), we assume for simplicity that the V' meson family has the ideal nonet structure, too. If we fix the value of $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi)$, then Eq. (11) will contain only two free parameters: A and h. For example, if we put (according to L3 [13]) $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi) = 0.23$ keV, then the fitting to the data gives $A = 2.44\ \text{keV}^{1/2}$ and $h = -1.7$ ($\chi^2 = 5$ for 9 degrees of freedom; see the Appendix), and, at $r = 1$, $\theta_\iota \approx 85.5°$. The result of the fit is shown in Fig. 1 by the dashed curve. It is interesting to note that $h = -1.7$ from the fit is in agreement with the estimate $|H(x)| < 2.77$ obtained above from the BES data [36] and that the value of A^2, at $B(\eta(1475) \to K\bar{K}\pi) \approx 1$, corresponds to $\Gamma(\eta(1475) \to \gamma\rho^0) \approx 1$ MeV, i.e., it is in agreement with the estimate in Eq. (4). If $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi)$ is not fixed, i.e., if A' is considered as a free parameter, then the fit, shown in Fig. 1 by the solid curve, gives $A = 1.88\ \text{keV}^{1/2}$, $A' = 2.48\ \text{keV}^{1/2}$, and $h = -0.9$ ($\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi) = 0.3$ keV, $\chi^2 = 3.9$ for 8 degrees of freedom); and at $r = 1$, $\theta_\iota \approx 68°$. In this case, the value of A^2 corresponds to $\Gamma(\eta(1475) \to \gamma\rho^0) \approx 1$ MeV, if $B(\eta(1475) \to K\bar{K}\pi) \approx 0.6$.

Let us consider two more variants different in normalization at $Q^2 = 0$. Take $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi) = 0.14$ keV or $= 0.089$ keV, which is equal to the CLEO II upper limit re-estimated by L3 [13] (see Sec. II) or the CLEO II upper limit [18] (see Table I), respectively. The fits obtained for these variants are shown in Fig. 2 by the solid curve ($A = 3.22\ \text{keV}^{1/2}$, $h = -2.36$; at $r = 1$, $\theta_\iota \approx -86°$) and the dashed curve ($A = 3.75\ \text{keV}^{1/2}$, $h = -2.66$; at $r = 1$, $\theta_\iota \approx -83°$), respectively. For $\Gamma(\eta(1475) \to \gamma\gamma)B(\eta(1475) \to K\bar{K}\pi) = 0.14$ keV, the L3 points in the region $Q^2 < 0.1\ \text{GeV}^2$ are described within 2 standard deviations. The description of the higher Q^2 region is quite satisfactory for both normalizations.

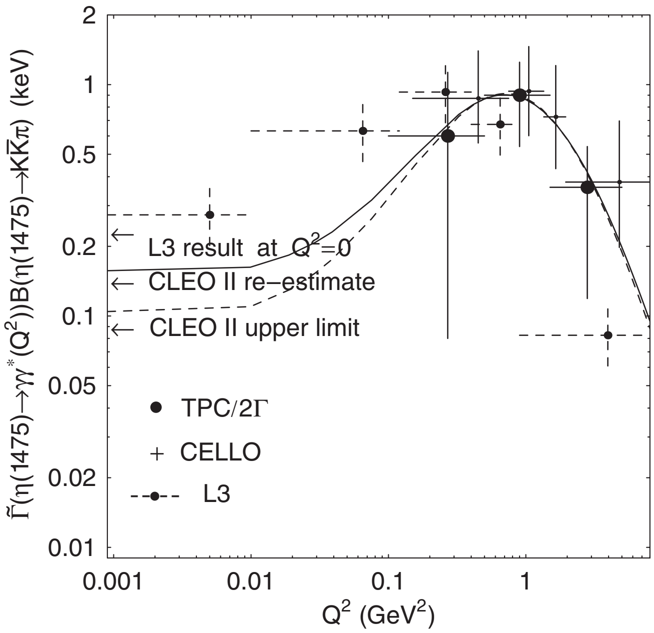

FIG. 2. The same as in Fig. 1 but with different fitting variants as described in the text.

When accurate data on the $\eta(1475)$ in $\gamma\gamma^*$ collisions appears, the model for the Q^2 dependence on $\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))$ can be refined. For example, the masses $m_{\rho'}$ and $m_{\phi'}$ could be considered as free parameters, and their values might be defined from a fit. Theoretically, high-quality data can allow us to consider even heavier vector meson contributions.

Thus, with the help of the $\eta(1475)$, one can explain simultaneously the peak in the $\gamma\rho^0$ mass spectrum in the $J/\psi \to \gamma\gamma\rho^0$ decay, the pseudoscalar structures near thresholds in the $\rho\rho$ and $\omega\omega$ mass spectra in $J/\psi \to \gamma(\rho\rho, \omega\omega)$ decays [26], and the suppression of the $\eta(1475)$ signal in the reaction $\gamma\gamma \to K\bar{K}\pi$ and its appearance in $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ for $Q^2 \neq 0$. Our explanation might be rejected unambiguously by measuring the spin-parity of the signal in the region of 1475 MeV in the reaction $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$, together with the disavowal of the pseudoscalar structures in the $\rho\rho$ and $\gamma\rho^0$ mass spectra in the $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\gamma\rho^0$ decays.

V. $f_1(1420) \to \gamma(\rho^0, \phi)$ AND $\gamma\gamma^*$ DECAYS

Here we discuss the $f_1(1420)$ production in the reaction $\gamma\gamma^*(Q^2) \to f_1(1420) \to K\bar{K}\pi$ using the information about $f_1(1420) \to \gamma(\rho^0, \phi)$ decays as a guide.

We note, for short, $f_1(1420)$ ($f_1(1285)$) by f_1' (f_1) and write the $f_1' \to \gamma V$ decay width in the form

$$\Gamma(f_1' \to \gamma V) = C_V^{f_1'} \tilde{\Gamma}(f_1' \to \gamma V) \frac{m_V^2}{m_{f_1'}^2} \left(1 - \frac{m_V^2}{m_{f_1'}^2}\right)^3 \left(1 + \frac{m_V^2}{m_{f_1'}^2}\right), \quad (12)$$

where $C_\rho^{f_1'} = 0.74$ takes into account the finite width of the ρ^0 resonance in the $f_1' \to \gamma\rho^0 \to \gamma\pi^+\pi^-$ decay, $C_\omega^{f_1'} = C_\phi^{f_1'} = 1$, and the last factor includes the contributions from the longitudinal and transverse V meson production, respectively, as in the model [52]. Because the quantities $\tilde{\Gamma}(f_1' \to \gamma V)$ are free from the main kinematical factors, we shall assume that they are independent of m_V^2. Applying to them the naïve quark model, we have

$$\tilde{\Gamma}(f_1' \to \gamma\rho^0) = \frac{9}{4}\tilde{\Gamma}(f_1' \to \gamma\phi)\tan^2(\theta_i - \theta_A) \quad (13)$$

and $\tilde{\Gamma}(f_1' \to \gamma\omega) = \tilde{\Gamma}(f_1' \to \gamma\rho^0)/9$, where $\theta_i = 35.3°$ is the "ideal" mixing angle and θ_A is the mixing angle in the axial-vector nonet, the members of which are f_1' and f_1. To estimate $B(f_1' \to \gamma\rho^0)$, we use Eqs. (12) and (13), $B(f_1' \to \gamma\phi)/B(f_1' \to K\bar{K}\pi) = 0.003 \pm 0.001 \pm 0.001$ [43,62], and $\Gamma_{f_1'}^{\rm tot} = (54.9 \pm 2.6)$ MeV [1]. This gives $\Gamma(f_1' \to \gamma\phi) \approx (0.16 \pm 0.08)B(f_1' \to K\bar{K}\pi)$ MeV. The mixing angle θ_A can be found in a variety of ways, that is, from the different mass formulae as well as from suitable data (if they exist) on decays and production reactions. Every way is accompanied by some specific assumptions. For example, the Gell-Mann-Okubo-Sakurai mass formula [1,63]

$$m_{f_1'}^2\cos^2\theta_A + m_{f_1}^2\sin^2\theta_A = \frac{1}{3}(4m_{K_{1A}}^2 - m_{a_1}^2) \quad (14)$$

gives $\theta_A = 37.9° \pm 5°$, where the quark model considerations concerning the sign of θ_A [1] and the mass values from the PDG review [1] have been used. The error in θ_A has been estimated from the a_1 mass uncertainty. On the other hand, the model, in which the octet-singlet mixing is due to the symmetry breaking for the mass particles [1,64], gives

$$\tan\theta_A = \frac{4m_{K_{1A}}^2 - m_{a_1}^2 - 3m_{f_1'}^2}{2\sqrt{2}(m_{a_1}^2 - m_{K_{1A}}^2)} \quad (15)$$

and $\theta_A = 29.2° \pm 5.5°$. Then, from Eqs. (12) and (13) for the central values of $B(f_1' \to \gamma\phi)/B(f_1' \to K\bar{K}\pi) = 0.003$ and $\theta_A = 37.9°$ (29.2°), we get $B(f_1' \to \gamma\rho^0)/B(f_1' \to K\bar{K}\pi) = 1.6 \times 10^{-5}$ (8.4×10^{-5}) and, for $B(f_1' \to \gamma\phi)/B(f_1' \to K\bar{K}\pi) = 0.003 + 0.0014$, $\theta_A = 29.2° - 5.5°$,

$$B(f_1' \to \gamma\rho^0)/B(f_1' \to K\bar{K}\pi) = 4.6 \times 10^{-4}. \quad (16)$$

It is the maximal increase of the ratio within one error in every factor. This estimate should be compared with the available experimental restriction $B(f_1' \to \gamma\rho^0)/B(f_1' \to K\bar{K}\pi) < 0.02$ [43], which was discussed in Sec. III.

We now estimate the quantity $\tilde{\Gamma}(f_1' \to \gamma\gamma)$ (see Eq. (A4) in the Appendix), due to the $f_1' \to \gamma V$ transitions. (Note that, in contrast to the $\eta(1475)$, there has been no constructive idea that speculates about heavier vector meson contributions in the $f_1' \to \gamma\gamma^*$ decay for a while.) According to the VDM,

$$\tilde{\Gamma}(f_1' \to \gamma\gamma) = \frac{4\pi\alpha}{9f_\rho^2}\tilde{\Gamma}(f_1' \to \gamma\phi)\left(1 - \frac{5}{\sqrt{2}}\tan(\theta_i - \theta_A)\right)^2, \quad (17)$$

and, for the central value of $B(f_1' \to \gamma\phi)/B(f_1' \to K\bar{K}\pi) = 0.003$,

$$\tilde{\Gamma}(f_1' \to \gamma\gamma) \approx (1, 0.77, 0.3 \text{ keV})B(f_1' \to K\bar{K}\pi), \quad (18)$$

for $\theta_A = 37.9°$, $35.3°(= \theta_i)$, $29.2°$, respectively.

Experimental results for $\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi)$ are presented in Table III. The values of $\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi)$ found from the fits have the order of 1 keV. As can be seen from Table III, the values reveal a high sensitivity to the form assumed for the form factor $F(Q^2)$, although $\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi)$ is independent of $F(Q^2)$ by definition. [See Eq. (A4) in the Appendix]. Such a situation is due to limited statistics for the reaction $\gamma\gamma^*(Q^2) \to f_1(1420) \to K\bar{K}\pi$ at low Q^2. Note that the maximal value for $\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi) = (3.2 \pm 0.6 \pm 0.7)$ keV has been found in the most statistically significant experiment performed by the L3 Collaboration (see Table III).

A comparison of our tentative estimate (18) with highly model-dependent data from Table III does not allow conclusions about the $f_1(1420)$ dominance in the reaction $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$. It is impossible to exclude that there are two resonance contributions in this reaction, from the pseudoscalar $\eta(1475)$ and the axial-vector $f_1(1420)$,

TABLE III. The results for $\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi)$. (The TPC/$2\gamma$ convention [49,50] is used for normalization.) The results are dependent on the form factor, shown in the fourth column: $F(Q^2)$: $F(Q^2) = F_\rho = 1/(1 + Q^2/m_\rho^2)$, or $F(Q^2) = F_\phi = 1/(1 + Q^2/m_\phi^2)$, or $F(Q^2) = F_{L3} = 1/[(1 + Q^2/(0.926\text{ GeV})^2)^2(1 + Q^2/m_{f_1'}^2)^{1/2}]$.

Experiment	Ref.	$\tilde{\Gamma}(f_1' \to \gamma\gamma)B(f_1' \to K\bar{K}\pi)$ (keV)	$F(Q^2)$
MARK II, 1987	[48]	$1.6 \pm 0.7 \pm 0.3$	F_ρ
		$1.1 \pm 0.5 \pm 0.2$	F_ϕ
TPC/2γ, 1988	[49]	$1.3 \pm 0.5 \pm 0.3$	F_ρ
		$0.63 \pm 0.24 \pm 0.15$	F_ϕ
JADE, 1989	[51]	$2.3 \pm^{1.0}_{0.9} \pm 0.8$	F_ρ
		$1.5 \pm^{0.6}_{0.5} \pm 0.5$	F_ϕ
CELLO, 1989	[17]	$1.5 \pm 0.5 \pm 0.4$	F_ρ
		$0.7 \pm 0.2 \pm 0.2$	F_ϕ
L3, 2007	[13]	$3.2 \pm 0.6 \pm 0.7$	F_{L3}

whose separation requires substantial improvement of the data and obligatory determination of the spin-parity.

VI. CONCLUSION AND OUTLOOK

We resolved the contradiction between the suppression of the $\eta(1475) \to \gamma\gamma$ decay and the strong couplings of the $\eta(1475)$ to the $\rho\rho$, $\omega\omega$, and $\gamma\rho^0$ channels by taking into account the effect of the heavy vector mesons ρ'^0, ω', ϕ'. This led us to the explanation of the resonancelike Q^2 dependence on the $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ reaction cross section by $\eta(1475)$ production, which is an alternative to the conventional explanation of dependence by $f_1(1420)$ production.

To check our scenario and resolve the difficulties accumulated in understanding properties of the $\eta(1475)$, further experimental investigations are required:

(1) measurements of spin-parities of the intermediate states in the reaction $\gamma\gamma^*(Q^2) \to K\bar{K}\pi$ in the $\eta(1475)$ region for $0 \lesssim Q^2 \lesssim 3$ GeV^2 (which implies the separation of pseudoscalar and pseudovector contributions by using the angular distributions),

(2) further high-statistics measurements of the pseudoscalar structures in the $\rho\rho$ and $\omega\omega$ mass spectra near their thresholds in the $J/\psi \to \gamma\rho\rho$ and $J/\psi \to \gamma\omega\omega$ decays,

(3) a reliable determination of the spin of the $\gamma\rho^0$ system in the $J/\psi \to \gamma R \to \gamma\gamma\rho^0$ decay in the region of 1.475 GeV,

(4) acquisition of accurate data on the $\eta(1475)/f_1(1420) \to \gamma\phi$ decays.

High-statistics experiments necessary to solve these problems seem feasible at B and C/τ factories with the Belle, *BABAR*, CLEO II, and BES III detectors.

ACKNOWLEDGMENTS

This work was supported in part by RFFI Grant No. 10-02-00016 from the Russian Foundation for Basic Research.

APPENDIX

The formation of a 0^- state proceeds in collisions of two transverse photons. The $0^- \to \gamma\gamma^*$ decay width is

$$\Gamma(0^- \to \gamma\gamma^*(Q^2)) = (1 + Q^2/m^2_{0^-})^3 \tilde{\Gamma}(0^- \to \gamma\gamma^*(Q^2)). \quad \text{(A1)}$$

Here the factor $(1 + Q^2/m^2_{0^-})$ comes from the $\gamma\gamma^*$ phase space, and the factor $(1 + Q^2/m^2_{0^-})^2$ comes from the gauge-invariant Lorentz structure $\varepsilon_{\mu\nu\sigma\tau} q_\mu \epsilon_\nu(q) q^*_\sigma \epsilon_\tau(q^*)$ associated with the $0^-\gamma\gamma^*$ vertex, where $\epsilon_\nu(q)$ and $\epsilon_\tau(q^*)$ are the polarization four-vectors of the photons γ and γ^* with four-momenta q and q^*, respectively; $Q^2 = -q^{*2}$.

The 1^+ state can be produced either through collision of one longitudinal and one transverse (LT) or through two transverse (TT) photons. Thus, in the general case, the $1^+ \to \gamma\gamma^*$ decay width is expressed in the terms of two independent functions of Q^2:

$$\Gamma(1^+ \to \gamma\gamma^*(Q^2)) = (1 + Q^2/m^2_{1^+})^3 [\tilde{\Gamma}^{\rm LT}(Q^2) + \tilde{\Gamma}^{\rm TT}(Q^2)], \quad \text{(A2)}$$

where the factor $(1 + Q^2/m^2_{1^+})^3$ [17,50,52,54] has its origin similar to the 0^- case. The amplitude for the $1^+ \to \gamma\gamma^*$ transition can be written as

$$M = Q^2 \varepsilon_{\mu\nu\sigma\tau} q_\mu \epsilon_\nu(q) \epsilon_\tau(q^*) \times [\xi_\sigma(p) G_1(Q^2) + q^*_\sigma G_2(Q^2)(\xi(p), q - q^*)], \quad \text{(A3)}$$

where $\xi(p)$ is the polarization four-vectors of the 1^+ resonance state, $p = q + q^*$; $G_1(Q^2)$ and $G_2(Q^2)$ are the invariant functions. For $Q^2 \to 0$, $\tilde{\Gamma}^{\rm LT}(Q^2) \sim Q^2$ and $\tilde{\Gamma}^{\rm TT}(Q^2) \sim Q^4$. The measured cross section [see Eq. (10)] is defined by the combination $\tilde{\Gamma}(1^+ \to \gamma\gamma^*(Q^2)) = \tilde{\Gamma}^{\rm LT}(Q^2) + \frac{1}{2}\tilde{\Gamma}^{\rm TT}(Q^2)$, which is usually parametrized in the following way:

$$\tilde{\Gamma}(1^+ \to \gamma\gamma^*(Q^2)) = \frac{Q^2}{m^2_{1^+}} \tilde{\Gamma}(1^+ \to \gamma\gamma) \left[1 + \frac{Q^2}{2m^2_{1^+}}\right] F^2(Q^2), \quad \text{(A4)}$$

where $\tilde{\Gamma}(1^+ \to \gamma\gamma)$ is a parameter characterizing the strength of the coupling of the 1^+ resonance to the $\gamma\gamma$ system, and $F(Q^2)$ is some model form factor satisfying the normalization condition $F(0) = 1$; specific examples for $F(Q^2)$ are given in Table III. Such a representation corresponds to the model [52], in which $G_2(Q^2) = 0$ and $\tilde{\Gamma}^{\rm TT}(Q^2) = (Q^2/m^2_{1^+})\tilde{\Gamma}^{\rm LT}(Q^2)$.

As we mentioned in Sec. IV, the TPC/2γ [49] and CELLO [17] data, attributed to the resonance with $J^P = 1^+$, are easily recalculated in the case of the resonance with $J^P = 0^-$ having approximately the same mass. To do this, the TPC/2γ data (see Fig. 10(b) in the second paper from Ref. [49]) should be multiplied by 6, and the CELLO data (see Fig. 8 from Ref. [17]), taking into account a difference in normalization, should be multiplied by $3/(1 + Q^2/m^2_\iota)^3$. As for the L3 data [13], they have been presented for the Q^2 dependence of the number of $e^+e^- \to e^+e^- K^0_S K^\pm \pi^\mp$ events in the peak observed in the $f_1(1420)/\eta(1475)$ region. The two-photon width, or two-photon coupling parameter, $\Gamma_{\gamma\gamma}$, times the branching ratio for the $K\bar{K}\pi$ decay, BR$(K\bar{K}\pi)$ (in the notations of Ref. [13]), have been extracted from the fit for the 0^- and 1^+ resonances, together with parameters of the form factors $F^2_{0^-}(Q^2)$ and $F^2_{1^+}(Q^2)$ [58,59]. Let us use this information and make up the combination

$$([\Gamma_{\gamma\gamma}{\rm BR}(K\bar{K}\pi)]_{0^-} F^2_{0^-}(Q^2) + 6[\Gamma_{\gamma\gamma}{\rm BR}(K\bar{K}\pi)]_{1^+} F^2_{1^+}(Q^2))/(1 + Q^2/m^2_{0^-}).$$

(We ignore a small mass difference of the 0^- and 1^+

contributions.) Averaging this combination over the five Q^2 intervals considered in Ref. [13] (and listed in Sec. IV) and taking into account its $\approx 30\%$ error, we get putative "experimental points" from L3 for $\tilde{\Gamma}(\eta(1475) \to \gamma\gamma^*(Q^2))B(\eta(1475) \to K\bar{K}\pi)$. Notice that the log-scale for Q^2 is used in Fig. 1 to emphasize the small and moderate Q^2 regions. The rightmost point from L3 (0.082 ± 0.024 keV) relating to the Q^2 interval 0.9–7 GeV^2 is inconsistent with the other data. An average fitted to the data is equal to 0.52 ± 0.10 keV (see Fig. 1), and we exclude this point from our treatment. It is clear that the available data require further refinements.

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$$\Gamma(\eta(1295) \to \gamma\gamma) = \frac{25}{2}\left(\frac{M(\eta(1295))}{M(\eta(1475))}\right)^3 \Gamma(\eta(1475) \to \gamma\gamma) \geq (1.9 \pm 0.6)\ \text{keV}.$$

However, as yet the $\eta(1295) \to \gamma\gamma$ decay has not been observed: $\Gamma(\eta(1295) \to \gamma\gamma)[B(\eta(1295) \to \eta\pi\pi) + B(\eta(1295) \to K\bar{K}\pi)] < 0.08$ keV [1,12,18].

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[45] A very weak experimental restriction for $B(J/\psi \to \gamma\eta(1440) \to \gamma\gamma\omega)$ (see Table II) does not yield any additional information.

[46] For fixed $|H(x)|$, the width $\Gamma(\eta(1475) \to \gamma\gamma)$ possesses the minimal value for $H(x) < 0$; see Eqs. (5) and (6). Let us consider the simplest variant of the quark model in which the parameter $x = r\tan\theta_\iota/\sqrt{2} = \tan\theta_\iota/\sqrt{2}$, i.e., $r = 1$, which corresponds to the nonet symmetry assumption for the $\eta(1475)$ meson interaction. Then, with $H(x) = 0$, we have $x = 1/2$, $\tan\theta_\iota = 1/\sqrt{2}$, and the mixing angle $\theta_\iota = 35.3°$, i.e., equal to the so-called ideal mixing angle. If $H(x) = -1.7$ or -2.77, then $x = 9$, $\tan\theta_\iota \approx 12.7$, $\theta_\iota \approx 85.5°$ or $x \approx -4.9$, $\tan\theta_\iota \approx -6.9$, $\theta_\iota \approx -82°$, respectively. The octet component of the $\eta(1475)$ wave function is dominant in the two cases.

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[59] The form factor $F^2_{1^+}(Q^2) = (Q^2/m^2_{1^+})(1 + Q^2/2m^2_{1^+})/(1 + Q^2/(0.926\ \mathrm{GeV})^2)^4$ was used in Ref. [13] to fit the Q^2 dependence of the $f_1(1420)$ production cross section.

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[61] Notice that a single resonance peak has been observed in the $f_1(1420)/\eta(1475)$ region in all experiments on the reaction $\gamma\gamma^* \to K\bar{K}\pi$ [12,13,17,18,49,51]. Certainly, one must keep in mind poor statistics and wide steps in W in most experiments that made it impossible to resolve the overlapping peaks from the 0^- and 1^+ resonances in $\gamma\gamma^* \to K\bar{K}\pi$ (if they are produced simultaneously) owing to their small mass difference.

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