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Resonance Production in $\gamma\gamma$ Collisions

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1. Introduction

The first motivation[1] for $\gamma\gamma$ collisions was indeed the study of $C = +1$ resonances. After the pioneer works listed in Ref. 1, one can trace back from the four preceeding $\gamma\gamma$ workshops[2–5] and other high energy physics conferences[6] how the subject developed since this time. The theoretical concern progressively evolved from kinematical considerations (properties of the $e^+e^- \to e^+e^-X$ processes) to dynamical ones, namely resonances, soft hadronic processes, current algebra constraints, sum rules, duality relations and more recently hard (point-like) processes and QCD tests. Several phenomenological studies on the possible production of exotic particles (like technihadrons, Higgs bosons, supersymmetric particles, excited fermions, ...) have also been made but this is outside the scope of our review.

The processes $\gamma\gamma \to$ hadrons can be depicted as follows. One photon creates a $q\bar{q}$ pair which starts to evolve; the other photon can either (A) make its own $q\bar{q}$ pair and the $(q\bar{q}q\bar{q})$ system continue to evolve or (B) interact with the quarks of the first pair and lead to a modified $(q\bar{q})$ system in interaction with $C = +1$ quantum numbers. The main lines of evolution are, in case (A):

- each $q\bar{q}$ pair forms a vector meson V and both V's interact like in hadronic collisions with formation of resonances at low energy and with diffractive and peripheral scattering at high energy.
- the $q\bar{q}$ pairs make a quark rearrangement and hadronize (this can be described by perturbative QCD when the arrangement is due to hard gluons, i.e., when one has a large momentum transfer).

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in case (B):

— the $q\bar{q}$ pair has some probability of making a bound quarkonium,

— it can quasi-freely evolve and make independent quark jets if the momentum transfer between the two photons (or the two quarks) is large enough.

— it can also hadronize into a small number of hadrons (this can again be described by QCD if the momentum transfer is large).

— it can annihilate into two or more gluons and make glueballs or gluon jets.

The theoretical challenge is the computation of the probabilities of each of these possibilities. I am supposed to review the recent theoretical activity concerning resonance production and related problems. I think that since the last (1981) $\gamma\gamma$ workshop the new aspect of the theoretical works precisely concerns the resonance spectroscopy and the description of exclusive processes. In particular a special attention has been paid to the unusual states like four quark, mixed quark and gluon bound states and glueballs. As a consequence we organize our review as follows:

Sec. 2: Hadronic $C = +1$ spectroscopy ($q\bar{q}$, $qq\bar{q}\bar{q}$, $q\bar{q}g$, gg, ggg bound states and mixing effects).

Sec. 3: Exclusive $\gamma\gamma$ processes (generalities, unitarized Born method, VDM and QCD).

Sec. 4: Total cross section (soft and hard contributions).

Sec. 5: q^2 dependence of soft processes (soft/hard separation, $1^{\pm+}$ resonances).

Sec. 6: Polarization effects.

Sec. 7: Conclusion.

2. Hadronic $C = +1$ Spectroscopy

2.1 STANDARD $q\bar{q}$ BOUND STATES

The low lying $C = +1$ states are $0^{-+}(^1S_0)$, $0^{++}(^3P_0)$, $1^{++}(^3P_1)$ and $2^{++}(^3P_2)$. Predictions for the $\gamma\gamma$ decay rates of the light quark bound states have been given a long time ago[1–8]. It is striking how many of the recent experimental results tend to favor the simplest picture based on the non-relativistic quark model. In this short section we just want to quote the recent calculations concerning light and heavy quark bound states and the new assignments for the 0^{++} nonet. The case of the 1^{++} states which cannot couple to two real photons will be discussed in Sec. 5.

0^{-+} states: $\pi^0, \eta, \eta', \eta_c, \eta_b \ldots$ Theoretical and experimental values of $\Gamma_{\gamma\gamma}$ are given in Table 1. $\Gamma_{\pi\to\gamma\gamma}$ is computed from the triangle anomaly in terms of f_π.[7] $\Gamma_{\eta\to\gamma\gamma}$ and $\Gamma_{\eta'\to\gamma\gamma}$ are then obtained by nonet symmetry ($f_\pi = f_{\eta_1} = f_{\eta_8}$).[8] Heavy quarkonia decay widths have been computed using the relativistic corrections calculated in Ref. 9 who give a factor 0.5 for η_c and 0.6 for η_b with respect to the non-relativistic case.[12]

0^{++} states. In Table 2 we tentatively assign $\epsilon(1425)$, $X^0(1770)$, $\vec{X}(1300)$ to the light scalar nonet[10,13] instead of the old choice $\sigma(700)$, $S^*(980)$, $\vec{\delta}(980)$. θ is the unknown mixing angle in this nonet. The $\Gamma_{\gamma\gamma}$ normalization has been fixed applying the factor $\frac{15}{4}$ to the quark model prediction for the 2^{++} nonet (see below). The heavy quarkonia decay widths have also been computed according to the results of Ref. 9 who give a correction factor 0.4 for $\chi_0(c\bar{c})$ and 0.6 for $\chi_0(b\bar{b})$ with respect to the non-relativistic case.

For completeness we want to quote old computations giving[8] 6.0 to 22.0 keV for $\sigma(700)$ and[11] 12.8 $(sin\theta - \frac{cos\theta}{2\sqrt{2}})^2$ keV for $S^*(980)$ and 4.8 keV for $\delta^0(980)$. However see Sec.2.2 for the four quark interpretation of these states.

2^{++} states: $f, f', A_2^0, \chi_2(c\bar{c}), \chi_2(b\bar{b}), \ldots$. Many different predictions have been given for the f meson (using tensor dominance of the energy-momentum tensor, finite energy or superconvergence sum rules, quark models ...)[8] which range from 1.0 to 12.0 keV. In Table 3 we took for reference the expressions of Ref. 11. With a mixing angle $\theta = 24^o$ or 35.3^o one would get 2.4 or 2.3 keV and 0.014 or 0.18 keV for $\Gamma_{f\to\gamma\gamma}$ and $\Gamma_{f'\to\gamma\gamma}$ respectively. There is also a recent calculation[14] on the basis of a Veneziano-type dual meson-meson amplitude which gives $\Gamma_{f\to\gamma\gamma} = 2.66 \pm 0.45$, $\Gamma_{f'\to\gamma\gamma}B_{f'\to KK} = 0.141 \pm 0.039$, $\Gamma_{A_2\to\gamma\gamma} = 0.90 \pm 0.36$ keV in good agreement with experiments. However a precise comparison with experimental results in the case of the f has to face the problems of mass and width shifts (see Sec. 3.2).

Heavy quarkonia predictions also come from Ref. 9, the relativistic correction factors being now 0.45 for $\chi_2(c\bar{c})$ and 0.75 for $\chi_2(b\bar{b})$.

Table 1

$\gamma\gamma$ Decay Widths of 0^{-+} Mesons

	π^0	η	η'	η_c	η_b
TH	7.6 eV	0.39 keV	6 keV	3 keV	0.25 keV
EXP	7.95 ± 0.55	$\begin{cases} 0.324 \pm 0.046 \\ 0.56 \pm 0.12 \end{cases}$	5.3 ± 0.6		

Table 2

$\gamma\gamma$ Decay Widths of 0^{++} Mesons

	$\epsilon(1425)$	$X^0(1770)$	$X^0(1300)$	$\chi_0(c\bar{c})$	$\chi_0(b\bar{b})$
TH	$(sin\theta + 2\sqrt{2}\,cos\theta)^2$ keV	$(cos\theta - 2\sqrt{2}\,sin\theta)^2$ keV	3 keV	1.4 kev	25 eV
EXP	$\Gamma_{\gamma\gamma}B_{\pi\pi} < 1.5$ keV				

Table 3

$\gamma\gamma$ Decay Widths of 2^{++} Mesons

	$f(1270)$	$f'(1515)$	$A_2^0(1320)$	$\chi_2(c\bar{c})$	$\chi_2(b\bar{b})$
TH	$0.28(sin\theta + 2\sqrt{2}\,cos\theta)^2$ keV	$0.28(cos\theta - 2\sqrt{2}\,cos\theta)^2$ keV	0.83 keV	0.5 keV	8.0 eV
EXP	2.8 ± 0.2	$\Gamma_{\gamma\gamma}B_{KK} = 0.11^{\pm 0.02}_{\pm 0.04}$ keV	0.82 ± 0.30		

Excited states: In the light quark spectroscopy there are several candidates for orbital excitations:

$$2^{-+} : A_3(1680)\ ,\ X(1820)$$

$$4^{++} : A_2(2000)\ ,\ h(2040)$$

and for radial excitations:

$$0^{-+} : \pi'(1270)\ ,\ \xi(1275)$$

$$2^{++} : (\pi f)_{1700}$$

$$2^{-+} : A_3^1(2100)\ .$$

No estimation of the $\gamma\gamma$ widths of these kinds of states has been given. One can expect that they will decrease with the degree of radial excitation like $\Gamma_{V\to e^+e^-}$ (one could for example use the ratios $\frac{\Gamma_{\rho'\to e^+e^-}}{\Gamma_{\rho\to e^+e^-}}$ and $\frac{\Gamma_{\phi'\to e^+e^-}}{\Gamma_{\phi\to e^+e^-}}$).

There are well-known $(\chi', \chi'', \ldots)$ excitations in the $c\,\bar{c}$ and $b\,\bar{b}$ spectroscopy. Predictions for their $\gamma\gamma$ decay widths have been given in Ref. 9.

2.2 $(qq\,\bar{q}\,\bar{q})$ STATES

The classification of these four quark states has been given by Jaffe.[13] Low lying (S-wave) states are obtained by coupling color and spin taking into account the exclusion principle and the mass shifts due to gluon exchanges. A distinction is made between exotic states $E(J^{PC},\ \underline{n})$ and cryptoexotic states $C(J^{PC},\ \underline{n})$. The first ones have Y, I_3 values which cannot be obtained in a $(q\,\bar{q})$ nonet; they necessarily pertain to flavor $SU(3)$ representations $\underline{n} > \underline{9}$ (i.e., $\underline{18}$, $\underline{18}^*$, $\underline{36}$, ...). The second ones pertain to any $\underline{n}$ but have $Y,\ I_3$ values that one can find in a nonet. The lowest states are the cryptoexotic nonets because they are the states which maximize the negative mass shifts due to gluon exchanges.

The lowest one is $(0^{++}, \underline{9})$ whose contents are: $u\,\bar{u}\,d\,\bar{d}$; $\frac{1}{\sqrt{2}}s\,\bar{s}\,(u\,\bar{u}+d\,\bar{d})$; $s\,\bar{s}\,d\,\bar{u}$, $\frac{1}{\sqrt{2}}s\,\bar{s}\,(u\,\bar{u}-d\,\bar{d})$, $s\,\bar{s}\,u\,\bar{d}$; $d\,\bar{s}\,u\,\bar{u}$, $u\,\bar{s}\,d\,\bar{d}$; $s\,\bar{d}\,u\,\bar{u}$, $s\,\bar{u}\,d\,\bar{d}$. Candidates are $\sigma(650)$, $S^*(980)$, $\delta(980)$ and $\kappa(900)$. These states should decay by fall-apart (quark rearrangement) in Pseudoscalar-Pseudoscalar channels and very little in Vector-Vector channels (see Table 4). This is why one gets large widths for $\sigma \to \pi\pi$ and $\kappa \to K\pi$; S^* and δ widths are limited $K\,\bar{K}$ phase space.

The second $(0^{++},\ \underline{9}^*)$ nonet should be higher in mass (1450-1800 MeV) because of different recouplings of the four quark states which also favor VV decays with respect to PP (see Table 4).

There is also a $(2^{++},\ \underline{9})$ nonet in the range (1650-1950 MeV) which should only decay into VV channels (Table 4).

Table 4

$qq\bar{q}\bar{q}$ States and $\gamma\gamma$ Widths[17,18]

	M(GeV)	Γ (GeV)	Recoupling PP	Recoupling VV	$\Gamma_{\gamma\gamma}$ (keV)
$(0^{++}, \underline{9})$	$\sigma(0.65)$ $S^*(0.98)$ $\delta(0.98)$	0.6 0.04 0.05	0.743	−0.041	8.? 0.27 0.27
$(0^{++}, \underline{9}^*)$	1.45 1.8 1.8	0.07 0.23 0.18	−0.177	0.644	1.7 0.8 0.1
$(2^{++}, \underline{9})$	1.65 1.8 1.95	0.04 0.57 0.58	0	$\sqrt{2/3}$	1.7 0.04 0.35
$(2^{++}, \underline{36})$	1.65 1.65 1.65 1.95 1.95 2.25	0.2 0.2 0.19 0.29 0.29 0.36	0	$\sqrt{1/3}$	1.26 1.23 0.3 0.02 0.17 0.02
$(0^{++}, \underline{36}^*)$	1.8 1.8 1.8 2.1 2.1 2.35	> 2 GeV	0.041	0.743	> 2 keV

Next higher representations with exotic and cryptoexotic states are $(0^{++}, \underline{36})$, $(0^{++}, \underline{36}^*)$ and $(2^{++}, \underline{36})$. There are also several 1^+ states: $(1^{+-}, \underline{9})$ and $(1^{+-}, \underline{36})$ which cannot couple to 2 photons because of $C = -1$ and $(1^+, \underline{18})$, $(1^+, \overline{18})$, $(1^+, \underline{18}^*)$, $(1^+, \overline{18}^*)$ which can mix into $C = \pm 1$ states; the $C = +1$ states could appear in the case of virtual photons.[15] States with high values of orbital momentum have been discussed in the framework of dual models and in connection with possible baryonium states.[16]

The $\gamma\gamma$ decay widths of these various four quark states have been computed[17,18] using VDM and their strong VV fall-apart decays. Results are summarized in Table 4. The first $(0^{++}, \underline{9})$ nonet is only weakly coupled to $\gamma\gamma$ because of its small VV fall-apart. This may explain why S^* and δ^0 are only weakly or not at all observed in present experiments. The case of the $\sigma(650)$ is not yet clear (see Sec. 3.2). The other cryptoexotic states get larger $\gamma\gamma$ widths because of their strong VV fall-apart. However simultaneously their large total width may render their identification difficult. The $\rho\rho$ enhancement may be partly due to such states.[17,18] Predictions for other VV channels have also been given. The $\theta(1640)$ could be tentatively assigned to a 4-quark state although its copious production by the 2-gluon channel in $\psi \rightarrow \gamma X$ would not be likely.

It is important to notice that with a recent non-relativistic potential model Weinstein and Isgur concluded[19] that only the lowest 4-quark states could exist and in fact as meson-meson bound states. Because of strong color mixing forces no other resonance state should be observed. The interpretation of $S^*(980)$ and $\delta(980)$ as $K\bar{K}$ bound states also came out from analyses of $\pi\pi$ and $K\bar{K}$ scattering amplitudes.[20]

2.3 $(q\bar{q}g)$ STATES

The existence of valence gluons is controversial. So far the description of these kinds of states has mainly been attempted with the bag model.[21] Such states get various names such as hermaphrodite,[22] hybrid[23] or meikton.[24] One expects them to be rather stable because of large color magnetic forces between the $(q\bar{q})$ octet and the gluon octet. The lowest gluon states in the bag correspond to transverse electric $TE(J^{PC} = 1^{+-})$ and transverse magnetic $TM(1^{--})$ radiations. Masses are computed by minimizing the total energy contribution to the bag. A recent overall fit of $(q\bar{q})$, $(q\bar{q}g)$ and (gg) states has been done by Chanowitz and Sharpe[24] including the important effects of gluon self-energy and interpreting the $\iota(1440)$ as a 0^{-+} glueball.

The low lying spectrum is obtained with $(q\bar{q})$ in S-wave ($^1S_0$ and $^3S_1$) and either a $TE(1^{+-})$ gluon giving 1^{--}, 0^{-+}, 1^{-+}, 2^{-+} states or a $TM(1^{--})$ gluon giving 1^{+-}, 0^{++}, 1^{++}, 2^{++} states (see Table 5). Decays should proceed in a first step by $g \rightarrow q\bar{q}$ and in a second step by $(q\bar{q}q\bar{q})$ hadronization.[23] A distinction is expected[23] between TE and TM states. The first ones should have smaller widths because in the non-relativistic limit the $q\bar{q}$ state issued from the gluon is in a P-wave and leads to small overlap integrals. The second ones should have normal hadronic widths because they are in S-wave.

$\gamma\gamma$ decays can be estimated with *VDM* and the strong *VV* channels in the case of 0^{++} and 2^{++} *TM* states (Table 5).

These $(q\bar{q}g)$ states could also be reasonably produced in $\psi \to \gamma X$ decays. The rates should be half way between those of $(q\bar{q})$ states and those of (gg) glueballs. $\iota(1440)$ and $\theta(1640)$ do not fit with $(q\bar{q}g)$ states because of their too large experimental widths.

The appearance of exotic states (1^{-+}) in the $(q\bar{q}g)$ spectrum has been especially advertised[22] but they are not easily producible in $\gamma\gamma$ collisions (see Sec. 5 and Ref. 15).

Table 5

$(q\bar{q}g)$ States and $\gamma\gamma$ Widths[23,24]

	M(GeV)	Γ (GeV)	Modes	$\Gamma_{\gamma\gamma}$
1^{--}	1.83	?	*PP*	–
0^{-+}	1.41	0.015	*PS*	small
1^{-+}	1.61	0.003	*PA*, *PB*	(virtual γ's) small
2^{-+}	1.97	0.002	*PT*	small
1^{+-}	2.0	?	*PP*, *PS*, *PA*, *PT*	–
0^{++}	1.6	0.2	*PP*, *VV*, *PB*	$\simeq 0.4$ keV
1^{++}	1.8	0.06	*PV*, *PS*, *PA*, *PT*	(virtual γ's) small
2^{++}	2.2	0.15	*VV*	$\simeq 1.2$ keV

Each state appears in a nonet of flavor-like ρ, ω, ϕ, K^* with mass differences due to strange quarks. In this table we give the mass value for the ρ, ω-like states. Chanowitz and Sharpe[24] described the *TE* states. We placed the *TM* states about 0.2 GeV higher in mass because of the higher magnetic gluon radiation energy.

2.4 (gg) AND (ggg) GLUEBALLS

Pure gluonic bound states are predicted in QCD by lattice calculations and have been studied phenomenologically in bag models and in non-relativistic potential models. Results have also been obtained by ITEP sum rules.

Progress in lattice calculations has for example been reviewed by Berg.[25] There are still many quantitative uncertainties however the mass of the lowest state (0^{++}) generally falls around or below 1 GeV and the next states $(0^{-+}$, 1^{+-}, $2^{++})$ come out between 1 and 2 GeV.

ITEP sum rules[26] give quite different results with the 2^{++} at 1.5 GeV but the 0^{-+} around $2 \div 2.5$ GeV and the 0^{++} around 4 GeV.

A systematic classification of glueballs has been attempted with the bag model.[27-29] With the TE and TM gluon radiation states (defined in Sec. 2.3) and Bose statistics one gets the lowest states:

$$TE \times TE \ : \ 0^{++},\ 2^{++} \qquad\qquad TE \times TM \ : \ 0^{-+},\ 2^{-+} \ .$$

Identifying the 0^{-+} with $\iota(1440)$ Chanowitz and Sharpe[24] obtained the spectrum: $0^{++}(1.2 \pm 0.5)$, $2^{++}(2.15 \pm 0.4)$ and $2^{-+}(2.30)$. Three gluon states were predicted with 0^{++}, 1^{+-}, 3^{+-} around 1.45 GeV and 0^{-+}, 1^{-+}, 2^{-+}, 2^{--}, 1^{--}, 3^{--}, 3^{-+} around 1.8 GeV[29] when gluon-self energy effects are neglected.

Confining potential models predict additional states formed with longitudinal components for massive (effective) valence gluons; for example there are now 1^{-+}, 2^{-+} and 3^{-+} states for (gg) glueballs and many others for (ggg) glueballs.[30] It was noticed that the level ordering is much dependent upon the type of potential which is used (and equivalently upon the boundary conditions used in the bag model).[31]

With an effective gluon mass $m_g = 500$ MeV Cornwall and Soni[32] obtained the following (gg) spectrum: $m(0^{++}) \simeq 1200$ MeV, $m(0^{-+}) \simeq 1400$ MeV, $m(2^{++}) \simeq 1900$ MeV, $m(1^{-+}) \simeq 1500$ MeV, $m(2^{-+}) \simeq 1800$ MeV and a (ggg) 0^{-+} bound state at 2400 MeV.

The decay process of glueballs is still controversial. A somewhat standard claim is that because $gg \to q\bar{q}$ involve an α_s factor the corresponding width should be halfway between an *OZI* forbidden decay and a normal hadronic decay, i.e., a few tens of MeV for a 1.5 GeV glueball. This is not obvious because it is not clear what value of Q^2 and then what value of $\alpha_s(Q^2)$ will control these decays. Cornwall and Soni[32] claim that the process $(gg) \to g + g$ is perfectly allowed. If gluons then hadronize non-perturbatively (for example, $gg \to q\bar{q}q\bar{q}$) one can get a normal hadronic decay width (50-200 MeV). There are also possibilities of strong mixing with other hadronic states which could drive these decays. Decay modes should a priori be flavor singlet but large quark mass effects in the basic amplitude and in hadronization as well as phase space effects will spoil this property. Lipkin[33] argues for a similarity with $\psi \to 3g \to$ hadrons; however with a lower mass the effects quoted above could be more important than for the ψ. Also mixing with nearby non-singlet states will completely modify the basic pattern.[34,40]

Consequently $\gamma\gamma$ decays of glueballs are very model dependent and variable from one state to the other; widths can lie between the two extreme values $\sqrt{\frac{\Gamma_{OZI}}{\Gamma_{allowed}}}\ \Gamma_{(q\bar{q})\to\gamma\gamma}$ and $\Gamma_{(q\bar{q})\to\gamma\gamma}$. If the decay of a glueball into two vector mesons is known obviously VDM can be applied in order to get the $\gamma\gamma$ decay.

Glueball candidates are $\iota(1440)$ and $\theta(1640)$, the 0^{-+} and 2^{++} states observed in $\psi \to \gamma X$.[35] They are not (yet) observed in $\gamma\gamma$ experiments which only give upper limits:[6,36]

$$\Gamma_{\gamma\gamma} B_{\iota \to K\bar{K}\pi} < 8\,\text{keV}$$

$$\Gamma_{\gamma\gamma} B_{\iota \to \rho\rho} < 1.0\,\text{keV}$$

$$\Gamma_{\gamma\gamma} B_{\theta \to \eta\eta} < 5\,\text{keV}$$

$$\Gamma_{\gamma\gamma} B_{\theta \to \rho\rho} < 1.2\,\text{keV}$$

$$\Gamma_{\gamma\gamma} B_{\theta \to K\bar{K}} < 0.3\,\text{keV}$$

The very different pattern of $\psi \to \gamma X$ and of $\gamma\gamma \to X$ certainly is an important hint for the glueball interpretation. Broad enhancements have been observed in $\pi^- p \to (\phi\phi) + n$ just above the $\phi\phi$ threshold. It has been proposed to interpret[37] them as due to the presence of 2^{++} states $g_t(2160)$, $g_t'(2310)$ which could be glueballs.

In addition the problems associated with the $f(1270)$ production in $\gamma\gamma$ collisions (mass and width shifts, small $\gamma\gamma$ width) and the strong $\rho\rho$ production is suggestive for the mixing of the f with a nearby state which could be a glueball.[27,28,40]

2.5 Mixing Effects

The $\gamma\gamma$ landscape corresponding to the $q\bar{q}$, $qq\bar{q}\bar{q}$, $q\bar{q}g$, gg and ggg spectroscopy is depicted in Fig. 1. It appears to be rather rich but also rather intricate especially because of the large widths of the $qq\bar{q}\bar{q}$ states. In addition the basic states described in the previous sections do not necessarily correspond to the physical states because of mixing effects. Basic mixing terms are:

— quarkonia mixing ($q\bar{q} \leftrightarrow q'\bar{q}'$); for example the ones responsible for the deviation to ideal structure (strange/non-strange mixing).

— $q\bar{q} \leftrightarrow gg$ mixing. Such a term is important for hadronic decay of glueballs. It has also been invoked for explaining anomalous properties of isosinglet pseudoscalar mesons (η, η', η_c) by giving them some pure glue component.

— $qq\bar{q}\bar{q} \leftrightarrow gg$ mixing. This is another possibility for hadronic decay of glueballs.

— $q\bar{q}g \leftrightarrow q\bar{q}q\bar{q}$. It is the basic term for hadronic decays of ($q\bar{q}g$) mesons.

The mixing amplitudes may be due to simple point-like couplings between quarks and gluons (the so-called annihilation diagrams) or to intermediate single or multi-body hadronic states (the so-called unitary corrections with complex amplitudes). The second case can always "accidently" happen when two nearby states have the same quantum numbers and some common decay channels which induce these "unitary" terms. The rich spectroscopy expected between 1 and 2 GeV certainly offers many such possibilities.

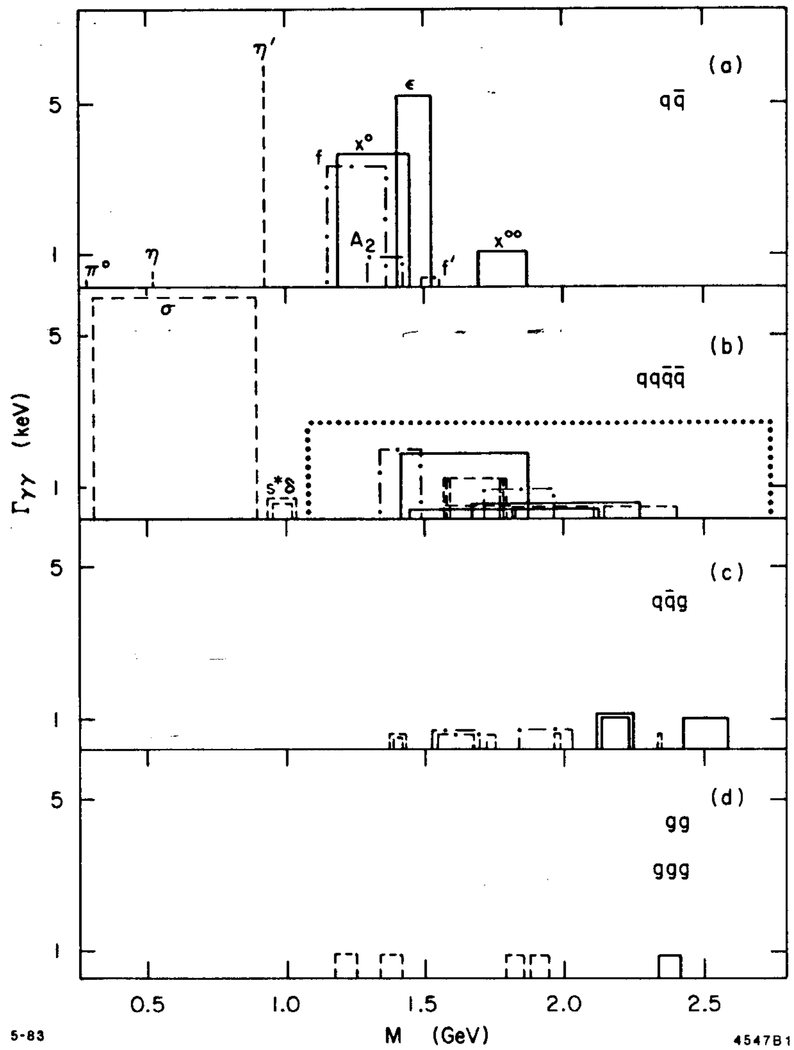


Fig. 1. Predictions for $\gamma\gamma$ widths of: a) $q\bar{q}$ states, b) $qq\bar{q}\bar{q}$ states, c) $q\bar{q}g$ states, d) gg and ggg states.

Fundamental aspects of mixing are on the one hand to allow couplings a priori forbidden for one of the states (i.e., $s\bar{s} \to$ non-strange hadrons; $(gg) \to$ hadrons, ...) and on the other hand to forbid some couplings by destructive interference between components. This last property can always be accidental for a particular channel but it is systematic for the dominant channels of mixed degenerate states (decoupling theorem[28,38] well known in quantum mechanics and particle physics).

Applications have been done for glueballs by several groups. An $\eta-\eta'-G$ mixing was tried for explaining the η, η' anomalies in ψ decays and recently G was identified with $\iota(1440)$. Fishbane et al.,[39] recently showed that this does not work with a 3×3 orthogonal mass mixing, the minimal value for the 0^- glueballs mass being 2 GeV. An $f - f' - G$ mixing was also used because of the problems in f, f' production in ψ decay; here the 2^+ G state was taken as the $\theta(1640)$. This also fails to work as recently explained by Rosner and Tuan.[40–42] The modes $f' \to \pi\pi$, $K\bar{K}$, $\gamma\gamma$ are inconsistent with the smallness of the mode $\theta \to \pi\pi$ as being due to a destructive interference between $q\bar{q}$ and gg components. It was observed that an ad-hoc $f-\theta$ mixing could work while the f' is left unmixed; it is however difficult to understand why a non-strange $q\bar{q} \leftrightarrow gg$ term would exist whereas a strange $s\bar{s} \leftrightarrow gg$ would not.

It may well be that these applications are oversimplified again because of the rich spectroscopy in this energy range. The mixing formalism could be improved by considering s-dependence and imaginary parts[38,43] but at least a qualitative understanding should appear before going into very technical and perhaps artificial solutions. It is possible that the θ is not a glueball (it could be a $q\bar{q}g$ or a $qq\bar{q}\bar{q}$ state) or is not the glueball which mixes with f and f'. Other narrower states could both or separately mix with them. It is also possible that the spectroscopy in the θ region is more complex; new results coming from ψ decays and from $\gamma\gamma$ processes could clarify this situation.

3. Exclusive $\gamma\gamma$ Processes

3.1 GENERALITIES

Although in both cases one deals with a non-hadronic initial state there is a great difference between $\gamma\gamma \to$ hadrons and $e^+e^- \to \gamma^* \to$ hadrons. Not only are the J^{PC} different but the general analytic structures of the amplitudes are completely different. For example, a two-body amplitude $\gamma\gamma \to A+B$ has both left-hand cuts (due to t- or u-channel exchanges like Born terms) and right-hand cuts (final state interactions including possible resonances). Any reliable analysis of a particular $\gamma\gamma \to$ hadrons process should consider these various contributions. Resonances may come from rescattering in the final state or may also have a direct coupling to $\gamma\gamma$. A multi-channel analysis (K-matrix type) can disentangle these possibilities. A very important related question is the role of threshold effects. They may be more important than in $e^+e^- \to$ hadrons because of enhancements due to light particle exchanges (for example pions) in the crossed channels. Again analyticity should tell us how to separate a threshold enhancement from a true resonance. An example of such analysis has been recently given by Mennessier[44] for $\gamma\gamma \to \pi\pi$ at low energy. Earlier works in this domain can be found in Brodsky's review at the Paris colloquium in 1973.[2] It would be interesting to try similar studies for other simple channels like $\gamma\gamma \to VP$ and $\gamma\gamma \to VV$ where there are many new states to look for. At least we would like to ask for a minimal caution when fitting experimental cross-sections with broad resonances especially near below or above a threshold (for example $\gamma\gamma \to \rho\rho$). Modified Breit-Wigner forms including finite width effects consistent with analyticity and unitarity should be used.[38,45] The output parameters should be very sensitive to the correctness of the treatment. In these cases a comparison of the resonance effects in different channels (with different threshold locations, like $\rho\rho$ and $\rho\gamma$) should be very instructive.[46]

In the soft domain there are several properties to check. There are low energy theorems coming from gauge invariance, current algebra and soft pions. For example, there exist precise predictions for the $\gamma\gamma \to n$ pion amplitudes just above the thresholds.[47] Cross sections are rather high in the case of even n but low for odd n. Contact terms like $\gamma\gamma\rho\pi$, $\gamma\gamma\rho\pi\pi$, $\gamma\gamma A_2\pi$ should give some threshold enhancements.[48] $\gamma\gamma$ amplitudes should agree with VDM and the hadron-like behavior of the photons. Tests can be done either in the resonance region (when $VV-R$ couplings are known) or outside (when VV scattering amplitudes are known).

When the momentum transfer Q between the two photons increases these "soft" contributions should decrease like powers of $\frac{m^2}{Q^2}$ where m is an hadronic mass. One enters in the "hard domain" defined by large W <u>and</u> Q where point-like contributions should dominate. QCD results are reviewed elsewhere at this conference.[49] Here we only want to quote a few contributions for exclusive channels $\gamma\gamma \to M\bar{M}$[50] and $\gamma\gamma \to B\bar{B}$[51] in order to compare the behaviors of the cross sections in soft and hard domains. We want to underline the fact that the transition between these two domains is not well understood.

3.2 $\gamma\gamma \to M\bar{M}$ AT LOW ENERGY; UNITARIZED BORN METHOD

Mennessier[44] proposed a method for treating the strong interaction effects in the $M\bar{M}$ channel according to analyticity and unitarity constraints. The model for $\gamma\gamma \to M\bar{M}$ consists in:

— "Born terms": gauge invariant (P, V) meson exchanges and contact terms.

— final $M\bar{M}$ scattering in agreement with $\pi\pi$, πK and $K\bar{K}$ phase shifts.

— possible direct couplings of resonant states to $\gamma\gamma$.

This method allows a very interesting discussion of the respective role of background (Born terms), of resonances in the final state and of states directly coupled to $\gamma\gamma$. A first application [44] to $\gamma\gamma \to \pi\pi$ in the DCI-SPEAR-PEP-PETRA energy range $W \leq 1.4$ GeV led to the following conclusions:

— A state with $M \simeq \Gamma \simeq 600$ MeV (the $\sigma(600)$?) is required with a direct coupling corresponding roughly to $\Gamma_{\gamma\gamma} \simeq 8$ keV.

— Only a weak $S^*\gamma\gamma$ coupling is necessary (this would agree with the interpretations for the S^* to be either a $(qq\bar{q}\bar{q})$ or a $(K\bar{K})$ bound state).

— The $f^0\gamma\gamma$ direct coupling is approximately the standard one. An apparent mass shift appears from the interference with the non-resonant amplitudes. However this mass shift is always larger (by -30 MeV) in the $\pi^+\pi^-$ channel than in $\pi^0\pi^0$. If the disagreement with experiment would persist it would be a signal for the need of another nearby state.

3.3 VDM DESCRIPTIONS

For real photons the VDM hypothesis consists in replacing the photon state $|\gamma>$ by the series $\sum_V \frac{eg_{V\gamma}}{m_V^2}|V>$ where the summation extends to ρ, ω, ϕ in the "restricted" version and to series ρ, ρ', ρ'', ... in the "extended" version. For any $\gamma\gamma$ process we would write:

$$R(\gamma\gamma \to F) = \sum_{V,V'} \frac{e^2 g_{V\gamma} g_{V'\gamma}}{m_V^2 m_{V'}^2} R(VV' \to F) \quad .$$

Such a formula supposes an extrapolation procedure from $q^2 = m_V^2$, $q'^2 = m_{V'}^2$ to $q^2 = q'^2 = 0$. The "VDM assumption" generally consists in taking a gauge invariant amplitude which coincides for onshell vector mesons with the strong $VV' \to F$ amplitude and which has the weakest q^2, q'^2 dependence. There may nevertheless be some ambiguities. There are also constraints from Bose statistics; for recent applications see for example Refs. 15 and 18. Clear VDM predictions and tests correspond to cases where the $VV' \to F$ amplitudes are well known either from experiment or from a reliable model. The usually quoted results concern the asymptotic behavior of $\gamma\gamma \to VV$. Using either additive quark model relations for cross sections or factorization properties for diffractive scattering one gets the relation:

$$\sigma(\gamma\gamma \to VV) = \frac{[\sigma(\gamma p \to Vp)]^2}{\sigma(pp \to pp)} \quad .$$

It is not satisfied by experiment in the case of $\gamma\gamma \to \rho^0\rho^0$ for $W < 2$ GeV. This is not so surprising. Its use at low energy is not reasonable for two kinds of reasons, kinematical and dynamical ones. Firstly the t-channel exchange processes are strongly dependent on the mass extrapolations from m_V, $m_{V'}$ to $m_\gamma = 0$ for example through t_{min} effects. Alexander et al.,[52] proposed to use the above relation at fixed $p_{c.m.}$ (instead of fixed $c.m.$ energy) in order to reduce the kinematical effects. Because of flux corrections this has the result of enhancing largely the predictions for $\sigma(\gamma\gamma \to VV)$ at low energy. Secondly, there may exist typical $VV' \to F$ resonances (for example the states discussed in Sec. 2) which locally enhance $\gamma\gamma \to F$ and which are not reproduced by the above relation. In other words as long as we do not know the low energy behavior of $VV' \to F$ we cannot make a reliable prediction for $\gamma\gamma \to F$ by VDM.

There is a remarkable exception to this assertion in the case of a broad resonance which decays dominantly into VV' channels such that it saturates unitarity for this partial wave. In this case one gets

$$\sigma(\gamma\gamma \to VV') \simeq \frac{8\pi(2J+1)}{W^2} B_{\gamma\gamma} \qquad \text{for } W^2 \simeq M^2 \ ,$$

with $B_{\gamma\gamma}$ just given by the VDM couplings:

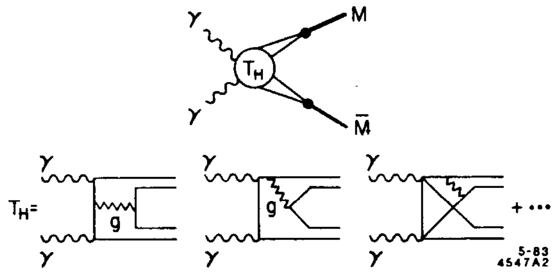
$$B_{\gamma\gamma} \simeq \frac{e^4 g^2_{V\gamma} g^2_{V'\gamma}}{m^4_V m^4_{V'}} \ .$$

This limiting case gives a VDM test independently of the hadronic VV'-Resonance coupling. Such broad resonances can be found in $q\bar{q}$ or $qq\bar{q}\bar{q}$ spectroscopy (see Sec. 2) and this prediction can apply to $\gamma\gamma \to \rho\rho$. The experimental amplitude analysis[53] suggests a peak around 1.2-1.3 GeV with possible additional contributions at 1.45 and 1.65 GeV. These contributions should interfere constructively below 1.6 GeV but destructively above in the case of $\rho^0\rho^0$. $I = 0$ and $I = 2$ contributions are required in order to explain the $\frac{\rho^+\rho^-}{\rho^0\rho^0}$ ratio. A multi-state structure ($q\bar{q}$, $qq\bar{q}\bar{q}$, ...) could give such features.[18] Tests of this picture can be obtained by looking to related processes (VV' and $V\gamma$: $\rho\gamma$, $\omega\gamma$, $\phi\gamma$, $\rho\omega$, $\omega\omega$, $\phi\phi$, $\phi\rho, \ldots$).[18,46] By the way the comparison of $\gamma\gamma \to W + M$ with $\gamma\gamma \to \gamma + M$ gives a good VDM test. One can also use the few experimental results existing in $p\bar{p} \to \rho\rho$, $\rho\omega$ at low energy to predict $\gamma\gamma \to p\bar{p}$ and compare with TASSO results. The order of magnitude turns out to be good.[54]

3.4 Exclusive $\gamma\gamma$ Processes in QCD

At large W and large momentum transfer (i.e., fixed angle above the $C = +1$ resonance region) it is expected[50] that exclusive processes will be dominated by the QCD diagrams of Fig. 2. The amplitude is expressed in terms of an hadronic distribution amplitude $\phi(x_i, Q)$ for each final hadron and a hard scattering amplitude T_H for $\gamma\gamma \to$ valence quarks. Such a factorized form reproduces the results of dimensional counting[55] $R_{fi} \simeq (Q^2)^{\frac{4-n}{2}} f(\theta)$, up to $log\ \frac{Q}{\Lambda}$ factors, where n is the total number of valence constituents in the initial and final states. Q is the typical

Fig. 2. QCD description of the exclusive process $\gamma\gamma \rightarrow M\bar{M}$.



momentum transfer in the process. The detailed properties of $f(\theta)$ depend upon the unknown form of $\phi(x_i,\ Q)$ which come from non-perturbative effects. However the normalization is fixed by the meson leptonic decay constant $\int_0^1 dx\phi_M(x,\ Q) = \frac{f_M}{2\sqrt{3}}$. Using a similar analysis of the meson form factors Brodsky and Lepage[50] were able to reabsorb all $\alpha_s(Q^2)$ factors in the expression:

$$\frac{d\sigma}{dt}\ (\gamma\gamma \rightarrow M\bar{M}) = 16\pi^2\alpha^2 \left|\frac{F_M(W^2)}{W^2}\right|^2\ G_M(\theta)\ .$$

$G_M(\theta)$ depends upon $\phi(x_i,\ Q)$ and has a different expression for helicity zero and for helicity $\pm$ 1 mesons. Several extreme choices for the amplitudes $\phi(x_i,\ Q)$ have been tried.[50] The normalization condition and the known values of f_M (i.e., $f_\pi = 93$ MeV, $f_K = 112$ MeV, $f_\rho = 154$ MeV, $f_\omega =$ 158 MeV, $f_\phi = 161$ MeV) already give interesting predictions for the asymptotic magnitudes of the cross section. See Table 1 of Ref. 50 for a comparison of $\gamma\gamma \rightarrow \pi\pi,\ K\bar{K}\ ,\ \pi\eta,\ \eta\eta,\ \rho\rho,\ \rho\omega,\ \omega\omega,\ \phi\phi$ and $\mu^+\mu^-$. For example:

$$\frac{d\sigma}{dt}\ (\gamma\gamma \rightarrow \rho_\perp^+\rho_\perp^-) \simeq 8\ \frac{d\sigma}{dt}\ (\gamma\gamma \rightarrow \pi^+\pi^-) \simeq \frac{5\,\mathrm{GeV}^4}{W^4}\cdot \frac{d\sigma}{dt}\ (\gamma\gamma \rightarrow \mu^+\mu^-)$$

for $\theta \simeq \frac{\pi}{2}$. The same method has been applied to $\gamma\gamma \rightarrow B\bar{B}$ by Damgaard.[51] In this case the normalization has been fixed by the known decay rate $\psi \rightarrow 3g \rightarrow p\bar{p}$ which involve the same $\phi_B(x_i,\ Q)$ amplitude. The cross section $\frac{d\sigma}{dt}$ $(\gamma\gamma \rightarrow p\bar{p})$ which behaves for large W and θ like $\frac{1}{W^{12}}$ $f(\theta)$ (up to $\alpha_s(Q^2)$ factors) has tentatively been compared to the preliminary TASSO results between $2 \leq W \leq 3$ GeV. Although a detailed comparison should not be valuable so close to the threshold the right order of magnitude seems to be obtained.

On another hand attention has been driven to possible enhancements of exclusive processes involving both light and heavy quarks. Ecclestone and Scott[56] pursuing an idea laready used for Z^0 decays considered the processes $\gamma\gamma \rightarrow M(Q\bar{q}) + M(\bar{Q}q)$ where M is a charmed or bottomed or topped meson. From diagrams of Fig. 3 they expected a strong enhancement (governed by the $\frac{m_Q}{m_q}$ ratio) due to the light quark propagator. However it is merely possible that this effect is completely washed out by strong final state interactions.

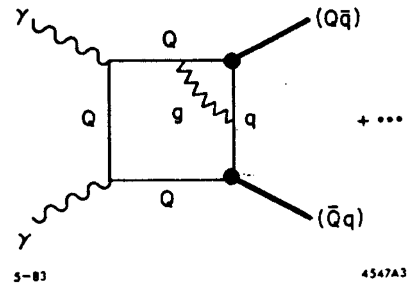


Fig. 3. QCD diagrams for heavy mesons production.

4. Total Hadronic Production at Low W

The asymptotic behavior of $\sigma(\gamma\gamma \to \text{hadron})$ is generally thought to be dominated by the hadronic component of the photon.[1–8] VDM and Pomeron exchange with factorization or quark model relations[1–8] give:

$$\sigma \to \sigma_0 \simeq 0.24\mu b \ .$$

The same assumptions for $\alpha = \frac{1}{2}$ Regge trajectory exchanges give the W dependence:

$$\sigma \to \sigma_0 + \sigma_1 = 0.24\mu b + \frac{0.27\mu b\,\text{GeV}}{W} \ .$$

On the experimental side estimations of the total cross section have been given by the PLUTO and TASSO groups.[57,58] Both agree for $W \geq 2.5$ GeV and give larger values than the above relations. For $1.7 \leq W \leq 2.5$ GeV the results disagree. PLUTO results are especially high and can be represented by the expression:

$$\sigma = 0.97\left(0.24\mu b + \frac{0.27\mu b\,\text{GeV}}{W}\right) + \frac{2.25\mu b\,\text{GeV}^2}{W^2} \ .$$

However the TASSO group[59] has shown that experimental estimations are very dependent upon the model used for event topology. Nevertheless several theoretical explanations for high values of σ can be found. Low lying Regge trajectories like pion exchange may not satisfy the factorization assumption. For example π exchange seems to be more important in electromagnetic interactions (photo-production) than in purely hadronic interactions. A better description would then be obtained with:[52]

$$\sigma \to \sigma_0 + \sigma_1 + \sigma_2 \qquad \text{with } \sigma_2 = \frac{A^\pi}{W^2} \ .$$

EVDM descriptions also predict higher values of σ_0 and σ_1. For example with a series (Veneziano-type) of vector mesons with masses $m_n^2 = m_0^2(1+2n)$, photon couplings $g_{\gamma n}^2 = g_{\gamma 0}^2$ and cross sections satisfying the relations $\sigma_{\gamma n}(W)/\sigma_{\gamma 0}(W) = (m_0^2/m_n^2)^\alpha$ with $\alpha = 1$ for Pomeron (i.e., σ_0) and $\alpha = \frac{1}{2}$ for other Regge exchanges (i.e., σ_1) one obtains:[60]

$$\sigma \to 0.29\mu b + \frac{0.46\mu b\,\text{GeV}}{W} \ .$$

Point-like contributions may also give additional terms. Greco and Srivastava suggested many years ago[61] on the basis of duality relations (Regge-Resonances) that an additional term is needed and proposed the contribution of the Box diagram $\gamma\gamma \to q\,\bar{q}$:

$$\sigma_{\gamma\gamma}^{box} \simeq \frac{4\pi\alpha^2}{W^2} \sum_q e_q^4 \, log \, \frac{W^2}{m_q^2} \quad .$$

Such a term is similar to the above other $\frac{1}{W^2}$ terms in the low W region.

In the low W region, i.e., for $W \leq 2$ GeV where there are large resonance effects, the above formulae can only be considered as giving averaged descriptions. Also one should probably not add all the above contributions. For example EVDM is an alternative to QCD (point-like contributions). There probably is fewer overlap between other "hadronic" and "point-like" components which should respectively correspond to two different domains when one integrates over transverse momenta inside photon structure: $\int_0^{\mu^2} dp_T^2$ for the hadronic part and $\int_{\mu^2}^{\infty} dp_T^2$ for the point-like part where μ is of the order of hundreds of MeV.[62]

A way to disentangle the various components of the total cross section is to look to the q^2-dependences with slightly virtual photons. It should be steeper for hadron-like parts than for point-like parts (or equivalently for low mass vector mesons than for high mass vector mesons in EVDM series). At low W the contributions to the cross section can also be separated into exclusive processes where threshold effects (Born terms, contact terms), standard $q\,\bar{q}$ resonances and unusual resonances ($qq\,\bar{q}\,\bar{q}$, $q\,\bar{q}\,g$, gg, ggg) contribute. It would be interesting to reconstruct their respective averaged W and q^2 behaviors and to compare them to the above formulae. In Fig. 4 we draw a very tentative sum of resonance contributions from the results of Sec. 2. This at least shows that the so-called unusual part may be as important as the usual one.

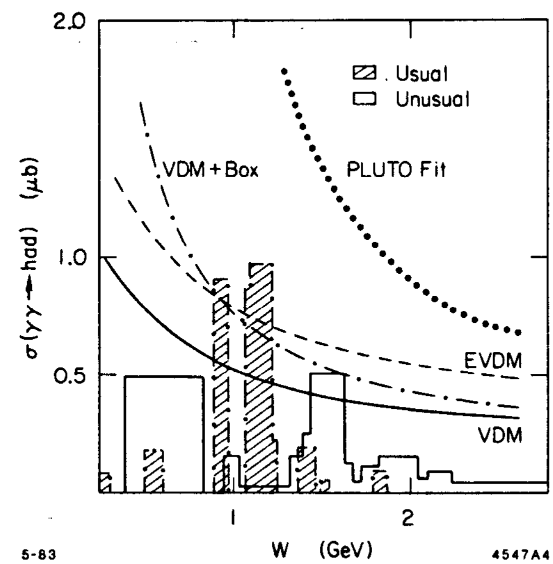


Fig. 4. Total $\gamma\gamma \to$ hadrons cross-section at low energies. Usual contribution refers to standard $q\,\bar{q}$ resonances and unusual to $(qq\,\bar{q}\,\bar{q})$, $(q\,\bar{q}\,g)$ and glueball states discussed in Sec. 2.

5. q^2 Behavior of Soft Processes

When one or both photons becomes slightly virtual soft processes should evolve according to VDM:

$$R(\gamma\gamma^* \to F) = \sum_V \frac{eg_{V\gamma}}{m_V^2 - q^2} R(\gamma V \to F) \ .$$

This should be applicable both to non-resonant and to resonant processes (as long as longitudinal γ^* amplitudes can be neglected). For example, when one vector meson (like ρ) is dominant one expects for the resonance decay width:

$$\Gamma_{R\to\gamma\gamma^*} \simeq \left(\frac{m_V^2}{m_V^2 - q^2}\right)^2 \Gamma_{R\to\gamma\gamma} \ .$$

This behavior should reflect in the total cross section (because ρ and ω with $m_V^2 \simeq 0.6$ GeV^2 give the same effect) and this seems to be the case up to $-q^2 \simeq 1$ GeV^2. For higher q^2 either point-like processes (QCD) or higher vector meson states (EVDM) begin to contribute and lead to a less decreasing cross section. In fact this transition from soft to hard processes is a difficult theoretical problem. Its experimental and phenomenological approach through the q^2 dependence is certainly most interesting. First it has been shown[50] that both VDM and QCD predict that the resonance contribution to $\gamma\gamma^*$ should fall off like $(1+q^2/0.68\,\text{GeV}^2)^{-1}$. A change in the dominant helicity amplitudes when passing from low $q^2(R \to \gamma\gamma)$ to high $q^2(R \to \gamma\gamma^*$ or $R \to \gamma^*\gamma^*)$ is also expected on the basis of the point-like behavior.[63] For example in f^0 case, $\lambda = 0$ should dominate instead of $\lambda = 2$ for real photons.

On the other hand in the hard domain (high momentum transfer) $\gamma\gamma^* \to M\bar{M}$ or $B\bar{B}$ should be rather insensitive to q^2 provided that $q^2 \ll W^2$.[50] These properties could be well illustrated by the behavior of the real photon structure functions in the low q^2 domain and especially in the exclusive limit.

Another interesting feature of $q^2 \neq 0$ $\gamma\gamma^*$ collisions is the possibility of exciting $1^{\pm+}$ states forbidden for two real photons by Bose statistics. For one real photon and one virtual photon one in general has two independent couplings corresponding to $(\pm, \pm)$ and $(\pm, 0)$ helicity amplitudes.[15,63] The first ones vanish like q^2 for $q^2 \to 0$ because of (Bose) symmetrization effects. The second ones vanish like $\sqrt{-q^2}$ as expected for longitudinal amplitudes. 1^{++} states exist in $(q\bar{q})$, $(qq\bar{q}\bar{q})$, $(q\bar{q}g)$, (gg) and (ggg) spectroscopy. 1^{-+} states are exotic and exist in $(q\bar{q}g)$, (gg) and (ggg) spectroscopy. Predictions have been given recently for these various kinds of states.[15] On the basis of VDM one can expect that for low q^2 the decay widths will be of the order of:

$$\Gamma_{\gamma\gamma^*} \simeq \frac{|q^2|}{m^2} \Gamma^R_{\gamma\gamma^*}$$

where m is an hadronic mass and $\Gamma^R_{\gamma\gamma^*}$ stands for the decay width of a state (like $0^{\pm+}$, $2^{\pm+}$) normally allowed to decay into two real photons and whose q^2 dependence is only the one due to

VDM poles. For example $D(1285)$ and several $(qq\bar{q}\bar{q})$ predicted 1^{++} states are expected to have especially large decay widths. In $e^+e^- \to e^+e^- + X$ this additional $\frac{|q^2|}{m^2}$ factor will cancel the $\frac{1}{q^2}$ factor coming from the photon propagator so that one will lose one $log\frac{s}{m_e^2}$ enhancement in the non-tagged cross section. However tagged experiments with $|q^2| \geq m_V^2$ should allow to observe these resonances. Looking to specific channels like $P+V$ or $P+A$ could also help. For 1^{-+} exotic states the channels $\pi\eta$, $\pi\eta'$, $\eta\eta'$ were especially noticed in Ref. 24. Polarization (see the next section) could also help to disentangle the new helicity components.

In the whole the $1^{\pm+}$ contributions to the γ structure functions for $|q^2| \geq m_V^2$ are expected to be comparable to those of other partial waves.

6. Polarization Effects

The cross section for $e^+e^- \to e^+e^- + X$ with polarized $e^\pm$ beams has been given in the most general case in Ref. 64. When T and P invariance hold, this form reduces to the expressions more frequently written.[65,69] Let us consider the final $e^\pm$ distributions which like in the unpolarized case are expressed in terms of $\gamma\gamma$ luminosity coefficients times $\gamma\gamma$ cross sections for various helicity combinations. In the quasi-real $\gamma\gamma$ limit one gets:[64]

$$\frac{\ell_1^0\ell_2^0 d\sigma}{d_3\ell_1 d_3\ell_2} = \frac{\alpha^2}{2\pi^4}\cdot\frac{|\vec{q}\,|W}{sq_1^2q_2^2}$$

$$\left\{K_{TT}\sigma_{TT} + K'_{TT}Re\tau_T - Q'_{TT}Im\tau_T + P_LP'_LK''_{TT}\tilde{\sigma}_{TT} + P_L\tilde{V}_{TT}\sigma_T^1 + P'_LV_{TT}\sigma_T^2\right\} .$$

The kinematical coefficients are explicitly given in Ref. 64. We just notice that K'_{TT} and Q'_{TT} are proportional to $cos2\phi$ (the azimuthal angle between e^+e^- and $\gamma\gamma$ planes). When T-invariance holds $Im\tau_T = 0$ and when P-invariance holds $\sigma_T^1 \equiv \sigma_T^2 \equiv 0$ (there is no P_L or P'_L dependence in the cross section). Hence we are left with:

$\sigma_{TT} = \frac{1}{2}(\sigma_{\parallel} + \sigma_{\perp}) = \frac{1}{2}(\sigma_0 + \sigma_2)$, the unpolarized $\gamma\gamma$ cross section,

$\tilde{\sigma}_{TT} = \frac{1}{2}(\sigma_0 - \sigma_2)$ which will appear with longitudinally polarized $e^\pm$ beams,

$Re\tau_T = \sigma_{\parallel} - \sigma_{\perp}$, the linear correlation which will appear in the azimuthal ($cos2\phi$) distribution without $e^\pm$ polarization.

Measurements of these three quantities give interesting independent informations about the dynamics. In resonance physics they allow to separate the contributions of the different couplings. For a $2^\pm$ resonance one can separate $\lambda = 0$ from $\lambda = 2$ contributions[65,66]; (for $0^\pm$ resonances $\sigma_2 \equiv 0$ and $\sigma_{TT} \equiv \tilde{\sigma}_{TT} \equiv \pm\frac{1}{2}Re\tau_T$). For high W soft (hadron-like) processes one can separate various Regge terms.[66] $Re\tau_T$ and $\tilde{\sigma}_{TT}$ are given by unnatural parity exchanges which should decrease faster with W than σ_{TT}. This fact has been used in Ref. 67 for studying the sum rules

$$\int Re\tau_T(W^2)dW^2 = \int \tilde{\sigma}_{TT}(W^2)dW^2 = 0 \quad ,$$

their resonance saturation and the possibility of fixed j-plane singularities associated to point-like processes. For example the $\gamma\gamma \rightarrow f\bar{f}$ contributions are:

$$\sigma_{TT} = \frac{4\pi\alpha^2}{W^2} R_{\gamma\gamma}\left[\left(1+\frac{4m^2}{W^2}-\frac{8m^4}{W^4}\right)L-\left(1+\frac{4m^2}{W^2}\right)\sqrt{1-\frac{4m^2}{W^2}}\right]$$

$$\tilde{\sigma}_{TT} = -\frac{4\pi\alpha^2}{W^2} R_{\gamma\gamma}\left(L-3\sqrt{1-\frac{4m^2}{W^2}}\right)$$

$$Re\tau_T = -\frac{16\pi\alpha^2}{W^2} R_{\gamma\gamma}\frac{m^2}{W^4}\left(2m^2L+W^2\sqrt{1-\frac{4m^2}{W^2}}\right)$$

with

$$L \equiv 2\ log\left(\frac{W}{2m}+\sqrt{\frac{W^2}{4m^2}-1}\right)$$

and

$$R_{\gamma\gamma} = Q_f^4 \quad .$$

Notice that $\frac{\sigma_2}{\sigma_0} \simeq log\ \frac{W}{m}$.

It has also been pointed out[68] that the very interesting process $\gamma\gamma \rightarrow gg$ which gives $\sigma_2 \simeq \sigma_0$ could be separated from the $f\bar{f}$ background by using longitudinally polarized $e^{\pm}$ beams.

The advent of unusual contributions ($qq\bar{q}\bar{q}$, $q\bar{q}g$, gg, ggg) could give further motivations for polarization. If these contributions turned out to be important they should play a role in these various duality sum rules.

7. Conclusion

Photon-photon collisions offer another example of the power of electromagnetic interactions for studying hadronic structure. Owing to important experimental progress during these last years it is now a major field in particle physics. It can be compared to e^+e^- annihilation, lepton-hadron deep inelastic scattering and quarkonia physics. $\gamma\gamma$ collisions have genuine features which make them complementary to these other fields. The presence of two photons leads to a greater sensitivity to the point-like structure. One also has the possibility of tuning the q^2 value and in this way we can look at the soft and hard components with variable weights. The soft/hard transition actually is an unsolved theoretical problem. The present descriptions still need a lot of phenomenological inputs like vector meson properties, mesonic wave functions, which interfer with quark and gluon properties at short distances (i.e., VDM versus QCD). Not only the high energy scattering processes but also the formation of standard and unusual $C = +1$ states appear to be very sensitive to this double aspect of the strong interactions. Already it would be an important contribution from $\gamma\gamma$ collisions if this unusual spectroscopy could be confirmed and at least if the old problems of the 0^{++} mesons were clarified. The 1983 $\gamma\gamma$ Workshop is certainly a step on this way.

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