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TWO PHOTON COUPLINGS OF SCALAR AND TENSOR MESONS *

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ABSTRACT

Experimental data on exclusive two photon reactions are investigated with respect to formation of tensor and scalar mesons. Theoretical and experimental status and progress is reviewed. Furthermore, new CELLO results on $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \rho^0\rho^0$ are presented. Clear evidence for a large scalar contribution is found in both reactions. The implications of these new results are discussed.

INTRODUCTION

Whereas the ground state tensor mesons f_2, a_2 and f_2' are well understood, this is not the case for scalars. There are lots of scalar meson candidates, most of them with large widths. Since both sectors are strongly interrelated both theoretically (differing only by the relative orientation of L and S in the quark model) and experimentally (appearing mainly in the same reactions), we discuss them simultaneously. This review is organized as follows: We first give a short overview of our present knowledge about tensor and scalar mesons. Then the merits and difficulties of $\gamma\gamma$ experiments are discussed, followed by some notes about the helicity structure in tensor meson formation. The main part consists of a critical review of experimental results on the reactions $\gamma\gamma \to \pi\pi$, $\to \eta\pi$, $\to K\bar{K}$, to other pseudoscalar pairs and $\to \rho^0\rho^0$. The emphasis is put on new experimental findings and their phenomenological interpretation. In particular, we present new, yet unpublished CELLO partial wave cross sections on the processes $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \rho^0\rho^0$, both of which show a large scalar contribution. Finally we summarize our results and give some conclusions.

WHAT DO WE CURRENTLY KNOW ABOUT TENSOR MESONS?

The ground state tensor mesons are quite well known: there are the nearly mass degenerate $I = 0$ and $I = 1$ $f_2(1270)$ and $a_2(1320)$ consisting of mainly u and d quarks, and the somewhat heavier mainly $s\bar{s}$ state $f_2'(1530)$. All these are well understood, including their coupling to two photons (at the $\pm 20\%$ level). Apart from these there are a few candidates for radial excitations, glueballs ($\Theta/f_2(1720)$, g_T states), and multiquark states ($AX/f_2(1565)$). None of these is seen in two-photon interactions. There is however a large, conventionally unexplained cross section in $\gamma\gamma \to \rho^0\rho^0$ at threshold, at least partly 2^{-+}, which could be due to 4 quark dynamics. The isospin related process $\gamma\gamma \to \rho^+\rho^-$ has a too small cross section for a single resonance interpretation.

WHAT DO WE CURRENTLY KNOW ABOUT SCALAR MESONS?

One of the most important and controversal topics in current meson spectroscopy is the situation in the scalar sector. It is not clear how many scalar states exist and what their parameters are [1, 5]; even more controversial and speculative is their interpretation in QCD. The major problem is the large width of 0^{++} mesons due to their strong decays into a pair of pseudoscalars, which occur without angular momentum barrier (in S-wave) and have a large phase space available. Simple Breit-Wigner fits are inadequate in such a case, and many complicated effects (coupled channel effects, threshold enhancements, resonance mixings etc., see e.g. [6]) obscure a straight forward identification of peaks in the cross section with resonances. There are more candidate states than needed

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in the $q\bar{q}$ quark model. Those two states whose existence is without doubt – the narrow S^* and δ with masses just below the $K\bar{K}$ threshold – are now perhaps the best candidates for non-$q\bar{q}$ states. We prefer to use the old name convention here because the new names imply a classification in the quark model which is not at all settled. They have been considered being $4q$ states as predicted in the MIT bag model [7], these seem to appear largely in a configuration containing two colour singlets with kaon quantum numbers spatially separated in the bag [8]. The need to describe resonances in an analytical and unitary way has repeatedly been stressed at this conference [5, 9 – 12]. This introduces not only widths (imaginary parts of the mass), but also real mass shifts (of the bare poles) and a strong "mixing" with the $S-$ wave two-particle continuum and other resonances with the same quantum numbers. In this way a resonance (the definition of which is not unambiguous) is a pole in a nonlinear coupled channel T matrix equation and corresponds to a superposition of different (one and two) particle states. In Weinstein's coupled channel ansatz [12] the S^* wave function thus consists of mainly $K\bar{K}$ (bound state or "molecule") and relatively small admixtures of $f_0(1300)$, $f_0'(1530)$, $\eta\eta$ and other two particle continua. It is not clear whether the other ($q\bar{q}$) poles still have to appear as separate poles (as in Weinstein and Isgur's model, where a "quark exchange potential" is the driving force to create the bound state), or whether at least one of them is the origin of the S^* pole [9, 10]. As Törnqvist [11] pointed out, a narrowing at the S- wave $K\bar{K}$ threshold occurs in almost every model. Thus the search for possible "normal" $q\bar{q}$ states is of great importance to clarify this point.

The analysis of Au, Morgan and Pennington has resulted in *two* narrow structures in the vicinity of the $K\bar{K}$ threshold [13], probably one $K\bar{K}$ bound state and one extra conventional pole which thwy interprete as a glueball candidate.

The situation of the broad scalars is even worse: There seems to be one very broad isoscalar at a mass of about 1 GeV which drives the $\pi\pi$ phase, with the narrow S^* on top of it [5, 13]. Evidence for a low mass (400 or 700 MeV) and for a high mass (1200-1400 MeV) scalar is weak. Although the latter is listed in the Particle Data Group [1] tables, its existence must be questioned. Both instead seem to be the low and high mass side of one very broad resonance. Note that due to kinematics in the $K\bar{K}$ and $\eta\eta$ final states only the upper part of this very broad structure can be excited, with some phase motion (however only about 90°). Controversial resonance parameters in different experiments are then easily understandable.

In the isospin 1 sector there is weak evidence for a scalar $a_0(1300)$ with mass and width degenerate to that of the $a_2(1320)$. This has been seen by GAMS [14] in a partial wave analysis of the reaction $\pi^- p \rightarrow \eta\pi n$. However, only being a 2% effect directly under the dominating a_2, doubts about possible systematic uncertainties cannot easily be destroyed.

Also, there is an indication of an $f_0'(1530)$ mainly coupling to $K\bar{K}$ from a partial wave analysis by LASS [15]. Here we have the same situation: the signal just appears at the same mass as the dominant tensor $f_2'(1530)$. Certainly, in the quark model (see e.g. [16, 17]) this is just what one expects, the only difference between the $q\bar{q}$ spin triplet states 0^{++}, 1^{++} and 2^{++} being the relative orientation of $L = 1$ and $S = 1$. Provided the $L - S$ interaction being small, mass splittings are indeed expected to be small – for *bare* states - not necessarily for observed resonances! Note that the tensor mesons do not have a large S-wave decay channel: only into vector meson pairs, which kinemetically are highly suppressed due to the high ρ masses and only allowed through the large ρ width. The third spin parity combination in the quark spin triplet, the axial vector 1^{++}, has an S-wave decay into a vector and a pseudoscalar meson. Due to the antisymmetric $F-$coupling [18], only the isovector (the a_1) has a large width into $\rho\pi$ (leading in fact to unitarity effects [19, 20]), isoscalars can only couple to K^*K and are thus expected to be reasonably narrow. This makes it clear why mainly the scalars are so hard to understand. We also want to test the currently most popular hypothesis about scalar mesons. Are S^* and δ really four quark states or $K\bar{K}$ states? Is it true that there are scalar $q\bar{q}$ mesons mass degenerate to every known tensor meson? For this purpose we first summarize theoretical expectations for relevant two-photon experiments. We then collect the experimental information with emphasis on recent developments by going through the most important channels (mainly two pseudoscalar final states). The standard interpretation of the $\pi\pi$ final state is shown to need dramatic changes. Relevant (i.e. as far as possible model independent and statistically significant) numerical data are summarized in tables.

WHAT CAN WE LEARN FROM TWO PHOTON EXPERIMENTS?

Two photon formation of neutral meson resonances is considered an important source of information about their internal structure. In particular. $q\bar{q}$ mesons couple to two photons via a valence quark loop with $M_{\gamma\gamma R} \propto \sum_q e_q^2$. Thus it is possible to establish relations between the three neutral members of a given J^{PC} nonet. The same relations hold true in a vector meson dominance model applying Zweig's rule at the RVV vertex [18]. It occurs that for the 0^{-+} and 2^{++} ground state multiplets nonet symmetry is satisfied and the octet singlet mixing angles [21 – 23] are well in accord with independent measurements from e.g. radiative and hadronic J/ψ decays [1].

Glueballs are expected to couple only weakly to two photons since their valence constituents are not electrically charged. This has lead to the concept of "stickiness" [24], and strong experimental limits on the classical glueball candidates $\iota/\eta(1440)$ and $\Theta/f_2(1720)$ have been obtained [25]. (In the light of new spin parity analyses of radiative J/ψ decays into $\eta\pi\pi$ and $K\bar{K}\pi$ however the ι might in fact be three states (two of which probably have changed spin parity to 1^{++})[26, 27]. This has three important consequences: numerical stickiness values are lower again, the branching ratio to the surviving 0^{-+} state is not the largest exclusive radiative any more, it might just be a radial excitation; and spin 1 states being excited at comparable levels the picture of radiative J/ψ decays proceeding via two massless gluons has to be revised since the latter would forbid spin 1 formation by means of the Landau-Yang theorem based on Bose symmetry [28]. The situation has to be compared with two photon formation of spin 1 particles which indeed has been observed in cases where one photon is appreciably virtual [29, 25, 30]. Reanalysis of the Θ region indicates that at least part of the signal is 0^{++} [26].)

The non-relativistic quark model (NRQM) predicts $\Gamma_{\gamma\gamma}^{0^+}/\Gamma_{\gamma\gamma}^{2^+} = 15/4 = 3.75$ for mass degenerate scalar and tensor resonances with equal quark flavour content (see e.g. [31] and references therein, also for phase space corrections in case of non-equal masses), i.e. one expects large numbers in the order of $3 - 10\,keV$ for the non-$s\bar{s}$ states.

S^* and δ being four quark states are believed to have a much smaller radiative decay width in the order of $0.27\,keV$ [7], and as $K\bar{K}$ molecules of $0.6\,keV$ [31]. Note that the latter calculation used the K^+K^- Born term as an input for the non-resonant $\gamma\gamma \to K^+K^-$ cross section near threshold. In view of the recently measured (see below) cross section being much smaller than the Born term, one would like to reduce this number considerably.

The $\gamma\gamma$ cross section is connected to the radiative width by

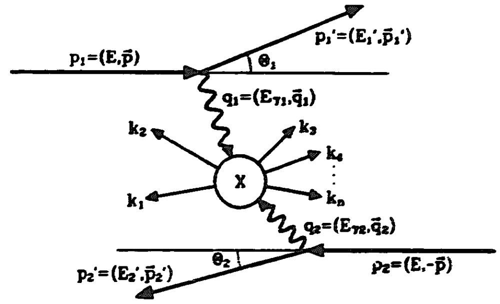

Figure 1: Feynman graph for $\gamma\gamma$ reactions at e^+e^- colliders

$$\sigma_{\gamma\gamma} = 8\pi(2J+1)\frac{m^2}{W^2}\frac{\Gamma_{\gamma\gamma}\Gamma_{tot}}{(m^2 - W^2)^2 - m^2\Gamma^2}$$

thus suppressing scalar formation relative to tensors by a spin multiplicity factor of 5. Altogether we thus expect spin 0 and 2 signals in the same order of magnitude. Tensor mesons can be excited in the helicity states ± 2 and 0, which do not interfere in the present day *no tag* experiments due to the non-observation of the scattered beam electrons which emit the slightly virtual photons in the overall reaction $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R$ (see Fig. 1). A consequence of the implicit azimuthal angular integration which leads to the incoherence is that the spin helicity contents of the data cannot uniquely be determined from the angular distribution of a two pseudoscalars final state, since $\int Y_2^2 d\phi \propto \int (Y_2^0 - \sqrt{5}Y_0^0)d\phi$ [32 – 35]. A pure $(J,\lambda) = (2,2)$ distribution of $|cos\theta$ (which is compatible with all measurements of tensor meson formation) can thus also be achieved by a suitable linear combination of (2,0) and (0,0) in case the relative phase is π. Taking this into account the span of possible solutions is much larger than previously thought: both hard limits for scalar states and for the helicity 0 component of spin 2 states which had been obtained in simple incoherent fits had to be questioned [33 – 36].

HELICITY STRUCTURE IN TENSOR MESON FORMATION

Now however there is some evidence that such naive incoherent fits were not too bad and may in fact be justified. The first piece of evidence is experimental and comes from the reaction $\gamma\gamma \to a_2 \to \rho\pi$, for which CELLO [37] has observed a pure helicity 2 formation and derived a strong upper limit for the helicity 0 amplitude using the correlation of two Euler angles. Interference cannot spoil the results in this final state, since the decay of a scalar into $\rho\pi$ (or more generally into 3 pseudoscalars) is forbidden by parity conservation. New ARGUS results on the same reaction presented at this workshop [38] confirm the suppression of the helicity 0 mode. From SU(3) symmetry then it is very probable that this also holds for f_2 and f_2'.

The other argument in this direction is of theoretical nature: The NRQM and all other sensible models predict a helicity 0/2 ratio of zero or much less than 1/6; no single model predicts more than 1/6 (see e.g. the compilation in [37]). New calculations by Close, Li and Barnes [39] presented at this conference [40] made clear that this ratio stays very small also if relativistic corrections are applied. This is true in field theoretic as well as vector meson dominance approaches, whose Close connection has been understood. In contrast, the spin 0 / spin 2 ratio may be reduced considerably from it's nonrelativistic value. However, the old Babcock and Rosner prediction [41] that the $0^{+-} q\bar{q}$ two photon coupling vanishes altogether because of symmetry arguments is found not to hold true [40].

Strong signals of the ground state tensor mesons are seen in $\gamma\gamma$ reactions with up to now only marginal evidence for scalars. We now investigate the single channels. Closely linked to theoretical uncertainties, the experimental situation is also confused, and using the same input data, different authors come to different conclusions. Instead of listing all the controversial numbers, we give some conservative estimates of the reasonable ranges in the tables.

I =0 and I =2 in $\gamma\gamma \to \pi\pi$

Figs. 2 - 6 summarize the recent high statistics data on $\gamma\gamma \to \pi^+\pi^-$ from MARK II [43] and CELLO [34] (for a preliminary version see [35]) and $\gamma\gamma \to \pi^0\pi^0$ from Crystal Ball [42] and JADE [32]. The new CELLO results have been obtained using two different methods [44, 43] of particle identification exploiting detailed calorimeter information. The two orthogonal samples yield consistent results, whose weighted mean is shown here [34]. The charged pion cross sections can be understood in terms of a final state interaction modified One Pion Exchange Born term dominating at small masses and a $f_2(1270)$ Breit- Wigner. There is no need for a very low mass $\sigma(400)$ or $\varepsilon(700)$, whose existence had been suggested from former, low statistics results. It is interesting to note that the Born term - which above 0.7 GeV is dominated by the spin 2, helicity 2 partial wave - overestimates the data above about 1 GeV, especi-

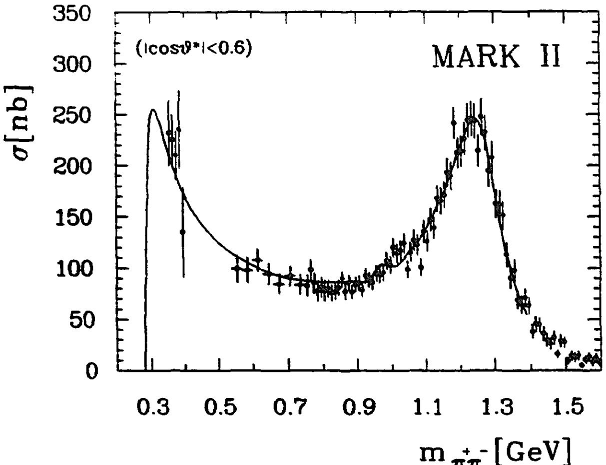

Figure 2: MARK II cross section for $\gamma\gamma \to \pi^+\pi^-$. Line: Morgan/Pennington fit.

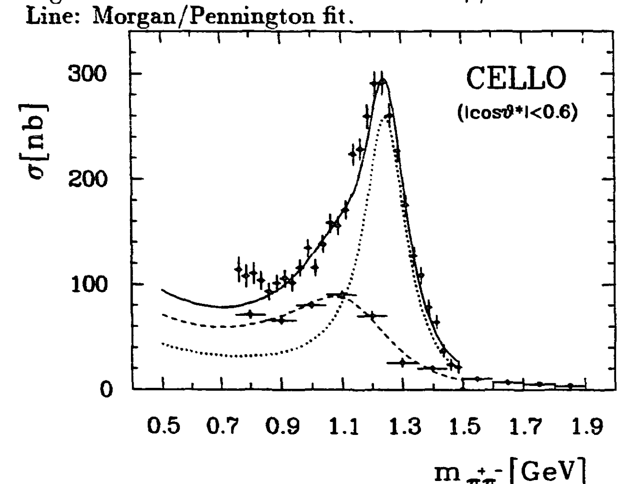

Figure 3: CELLO cross section for $\gamma\gamma \to \pi^+\pi^-$. Dotted line: unitarized damped Born + standard f_2 BW, dashed: BW fit to (0,0) partial wave (lower data points). Solid: sum of both contributions. See text.

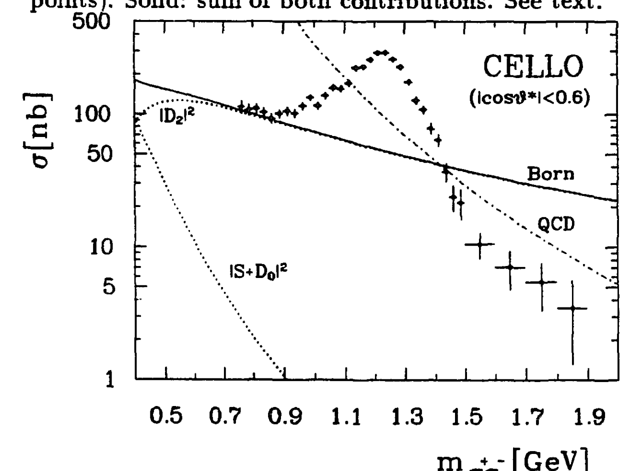

Figure 4: $\sigma(\gamma\gamma \to \pi^+\pi^-)$ in the range $|cos\theta^*| < 0.6$ (CELLO) compared to the OPE Born term (dashed line) and the QCD prediction of Brodsky and Lepage.

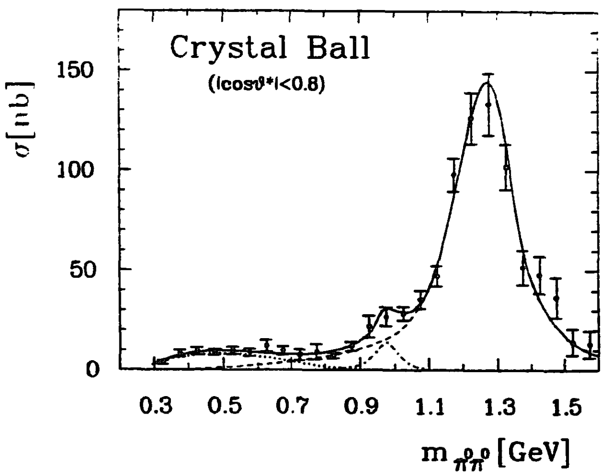

Figure 5: Crystal Ball cross section for $\gamma\gamma \to \pi^0\pi^0$

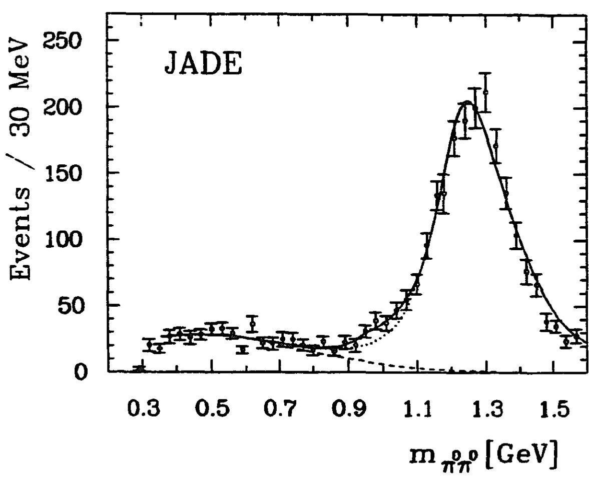

Figure 6: $\gamma\gamma \to \pi^0\pi^0$ event spectrum (JADE). Curves in Figs.5 and 6: Fits to standard f_2 BW, an S^* BW and phenomenological background (assumed to stem from final state interactions from the Born term).

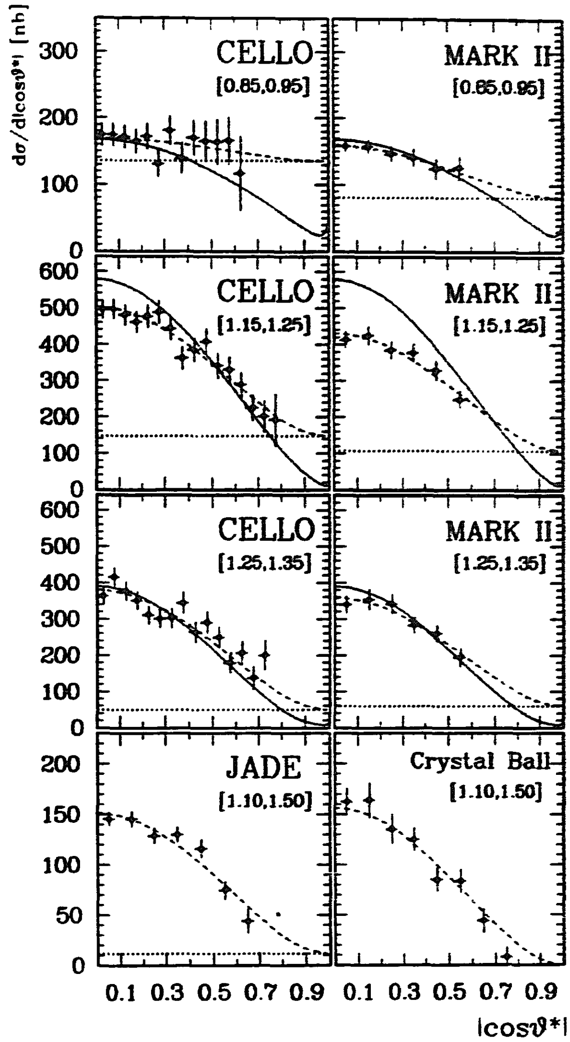

Figure 7: Differential cross section for $\gamma\gamma \to \pi^+\pi^-$ (left: CELLO, right: MARK II) in three mass ranges and $\gamma\gamma \to \pi^0\pi^0$ (left: JADE, right: Crystal Ball) in the mass range $1.1 < W < 1.5\,GeV$. Dashed line: result of incoherent spin 2, helicity 2 plus spin 0 fit; dotted line: spin 0 contribution. Solid lines: best (energy dependent) unitary model fit without scalar contribution.

ally through interference with the f_2, even if final state interactions [45 – 47] are taken into account. To fit the data quantitatively, it had to be phenomenologically damped or - physically not justifyable - the degree of coherence had to be reduced: Pions at this mass scale appear not pointlike any more! The QCD calculation of Brodsky and Lepage [48] (i.e. the $\gamma\gamma \to q\bar{q}$ "Born term" with a model calculation for the $q\bar{q} \to \pi$ transitions) describes or even overestimates the data already at $W > 1.5\,GeV$. A search for the tensor $AX(1530)$ seen in $p\bar{p}$ annihilation had negative results. Another important feature of this reaction is that the f_2 peak is observed to be shifted about $30\,MeV$ to lower values and somewhat broader in the $\pi^+\pi^-$ final state, but consistent with the PDG value [1] in $\pi^0\pi^0$. The new CELLO data agree with other high statistics data, needing a $\Gamma_{\gamma\gamma}(f_2)$ in excess of $3\,keV$, if a standard fit procedure is used.

Real progress in this field has become possible with the measurement of differential cross sections as function of $W_{\gamma\gamma}$. An analysis of the MARK II and Crystal Ball data by Morgan and Pennington using an elaborate unitary and analytic model has shown first evidence for the existence of a large broad scalar contribution hiding left and directly below the f_2 [33]. In addition to the data they used, now the new CELLO data [34] is available, and we have reconstructed the JADE differential cross section in a large mass bin around the f_2 from the published number of events spectrum and spin 0 (i.e. flat) expectation [32]. In Fig. 7 the differential cross sections are shown in some selected mass ranges.

In view of the evidence for strong spin 2- helicity 0 suppression as discussed above we have performed simple incoherent fits to the charged pion differential cross section, employing the two potentially important low lying waves, (0,0) and (2,2) (see Fig.7). In the usual Born term description one expects the angular distribution of the $\pi^+\pi^-$ final state in the mass range between 0.6 and 1.5 GeV to be (2,2). Obviously, the data are much flatter than expected in this ansatz and give rise to a large scalar (0,0) contribution around 1 GeV, which only vanishes slowly around the nominal f_2 mass. Both, the MARK II and CELLO data and thus also their weighted mean show this behaviour, the partial wave cross sections thus obtained are shown in Fig. 8. These results imply that the damping of the (2,2) Born term must be even stronger than previously thought. Checks have been performed whether interference with higher partial waves of the Born term can fake the scalar component: Using an ansatz very similar to that of Morgan and Pennington, we can show that this is not

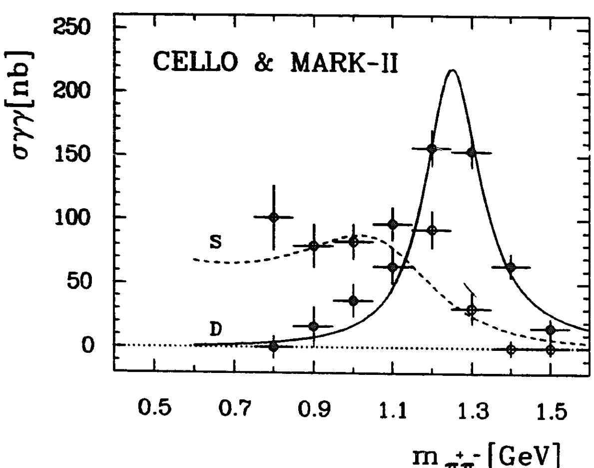

Figure 8: Spin 0 (light dots) and spin 2. helicity 2 (dark dots) partial wave cross sections (simple incoherent fit) for $\gamma\gamma \to \pi^+\pi^-$, combined fit to MARK II and CELLO)

the case: Good fits ($\chi^2/NDF \approx 1.5$) are obtained with a large scalar contribution (see e.g. the solution depicted in Fig. 3). Without a 0^{++} contribution the fit probability is dramatically worse ($\chi^2/NDF \approx 6.5$. see also solid lines in Fig. 7). We thus confirm Morgan and Pennington's conclusion in the fact that a large scalar is existing in $\gamma\gamma \to \pi^+\pi^-$. It is reassuring that this can already be seen using this very simple and energy-independent ansatz. Details however are much more difficult to settle. As an example, the spin 0 resonance mass we would derive is lower because we exclude a large helicity 0 coupling of the f_2, which through interference with the scalar contribution makes the differential cross section look like (2,2) in Morgan and Pennington's ansatz and thus could not be distinguished from ours by the fit. There are small hints for a narrow S^* in $\pi^0\pi^0$, but no obvious structure in $\pi^+\pi^-$. The way experimenters extracted radiative widths from the data (Breit Wigner fits on top of an incoherent background) was strongly criticized by Pennington [49], since constraints from unitarity and analyticity are violated. Thus it is hard to deduce values for radiative widths of the broad and narrow scalar states. Interference and mixing with narrow poles in the $K\bar{K}$ threshold region complicate a straight forward interpretation, and it may be necessary to determine the pole residues of a unitary and analytic model fit to the data [33]. On the other side, it also might be questioned whether Morgan and Pennington's approach is flexible enough to e.g. treat both of their proposed nearby narrow states [13] in full generality: what would be the differences if their direct $\gamma\gamma$ couplings had the same / opposite signs ?

If the Born term is not the dominant contribution around 1 GeV, one has of course to ask why the $\pi^+\pi^-$ and $\pi^0\pi^0$ cross sections are so different, the latter mainly showing the narrow S^*, the former a large broad scalar. This can only be explained by interference of isospin 0 and 2, which in the Born term interpretation occurs naturally. (In terms of χ^2 however, a preliminary combined fit to $\pi^+\pi^-$ and $\pi^0\pi^0$ allowing for $I = 0$ and $I = 2$ scalar contributions is only marginally better ($\chi^2/NDF = 1.9$ compared to 2.0 without isospin 2 contribution)). If one nevertheless looks for an explanation, a possible candidate might be coupling to isospin 2 $qq\bar{q}\bar{q}$ states whose existence in this mass range has been predicted in the MIT bag model [50]. Similar interference patterns as in the $\rho^0\rho^0$ and $\rho^+\rho^-$ final states [51, 52] (see below) might also apply here.

An interesting idea has been put forward by Lipkin [53] at this workshop: If S^* and δ could mix, large isospin violation effects may occur. Especially in the vicinity of the $K\bar{K}$ threshold this could easily

channel	source	value $/keV$	assumptions
		$\Gamma_{\gamma\gamma}(f_2(1270))$	
$\pi^+\pi^-, \pi^0\pi^0$	PDG world average[1]	2.76 ± 0.14	mixture
$\pi^+\pi^-$	MARK II (prel.) [43]	$3.15 \pm 0.04 \pm 0.31$	unitarized damped Born + BW, no broad scalar
$\pi^0\pi^0$	Crystal Ball[42]	$3.19 \pm 0.16^{+0.29}_{-0.28}$	BW with small phenomen. bg., no broad scalar
$\pi^0\pi^0$	JADE[32]	$3.19 \pm 0.09^{+0.22}_{-0.38}$	BW with small phenomen. bg., no broad scalar
$\pi^0\pi^0, \pi^+\pi^-$	Morgan/Pennington[33]	$1.8 - 2.8$	different unitarized models, data from [43, 42]
$\pi^+\pi^-$	CELLO (prel.)[34], this work	$3.16 \pm 0.04 \pm 0.31$	diff. unitary parametrizations, no scalars
		$2.56 \pm 0.12 \pm 0.25$	diff. unitary parametrizations, including scalars
	Our suggestion	2.6 ± 0.4	scalar has to be included, uncertainty due to diff. unitarization schemes and isospin of scalar
		$\Gamma_{\gamma\gamma}(f_2(1270)) + 1/4 \cdot \Gamma_{\gamma\gamma}(f_0(1300))$	
$\pi^+\pi^-, \pi^0\pi^0$	Morgan/Pennington[33]	3.6 ± 0.3	different unitarized models, data from [43, 42]
		$f_0(\approx 1100)$ (broad I=0 scalar)	
$\pi^+\pi^-$	this work, data from [43, 34]	$\approx 5 - 10$	partial wave decomposition, different unitarized models
		$S^*/f_0(980)$ (narrow I=0 scalar)	
$\pi^0\pi^0$	Crystal Ball [42]	$0.31 \pm 0.14 \pm 0.09$	incoherent Breit Wigner fit
$\pi^0\pi^0$	JADE [32]	$< 0.6 (95\% c.l.)$	incoherent Breit Wigner fit
$\pi^0\pi^0, \pi^+\pi^-$	Morgan/Pennington[33]	0.63 ± 0.14	different unitarized models, data from [43, 42]
	Our suggestion	$< 1 keV$	exact number uncertain because of unitarity and mixing effects
		$\Gamma_{\gamma\gamma}(AX/f_2(1565)) \cdot B(AX \to \pi^+\pi^-)$ (multiquark candidate)	
$\pi^+\pi^-$	CELLO (prel.) [35, 34]	$< 0.016 (95\% c.l.)$	hel.2, constructive $AX - f_2$ interference
		$< 0.250 (95\% c.l.)$	hel.2, destructive $AX - f_2$ interference
		$< 0.167 (95\% c.l.)$	hel.0, any $AX - f_2$ interference

Table 1: Numerical data from the reaction $\gamma\gamma \to \pi\pi$

be possible because of the mass difference between charged and neutral kaons. It would be interesting to work out the consequences for the usual unitarization procedure which assumes exact separation of different isospins.

We propose that theorists should also check another possibility: We know the Born term not to describe the data well. The usual procedure is to perform a partial wave decomposition ((2,2) is the dominating wave above $\approx 700\,MeV$) and then to damp (at least) the low partial waves by some smooth function of energy. We propose the following alternative procedure, based on the fact that the Born term is computed from 3 Feynman diagrams, the two t- and u-channel pion exchange graphs, and the $\gamma\gamma\pi^+\pi^-$ contact (*seagull*) term. An interesting feature is observed if the partial wave decomposition is performed without including the contact term. This changes only the scalar wave, with the result that it looks exactly like the (2,2) contribution; the (0,0) suppression in the full Born term at higher energies thus is due to a cancellation of the pion exchange and the contact terms. If it were possible that (finite size) form factor damping affects the contact term stronger than the exchange graphs, the partial wave decomposition will change at higher energies and in particular will still contain a scalar (I=0 and I=2) contribution, which could help to explain the observed features.

I =1 in $\gamma\gamma \to \pi^0\eta$

There is data from Crystal Ball [54] (see Fig. 9) and (very similar) from JADE [32]. Both experiments show two narrow structures, interpreted as the scalar $\delta(980)$ and the tensor $a_2(1320)$, above a "continuum background". To extract the numbers, this background was taken to be incoherent to the narrow resonances. This probably is no good assumption, since it implies to be helicity 2 below the δ and helicity 0 below the a_2. Apart from being unexpected, such

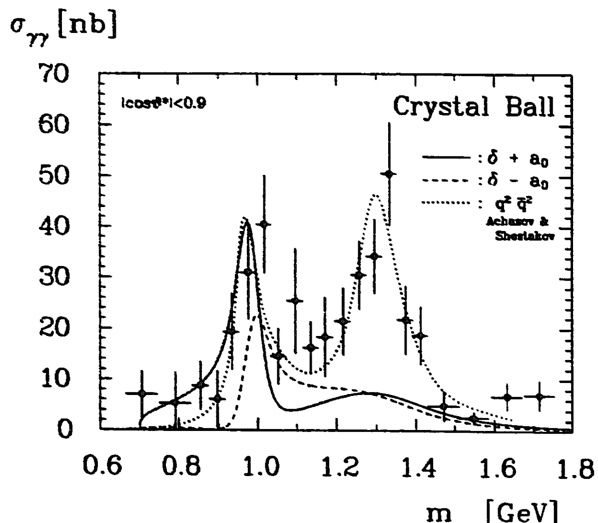

Figure 9: $\sigma(\gamma\gamma \to \eta\pi^{'})(W_{\gamma\gamma})$ for $|cos\theta^*| < 0.9$, Crystal Ball data [54]. Curves: dotted: Achasov's unitarized δ calculation (incl. a_2 contribution), solid: $\delta + a_0(1300)$; dashed: $\delta - a_0(1300)$ for broad $a_0(1300)$ with $\Gamma_{\gamma\gamma} \cdot B(\eta\pi) = 0.55\,keV$.

a behaviour is not supported by the measured angular distributions [54]. Furthermore, the existence of a large $\eta\pi$ continuum in $\gamma\gamma$ reactions is questionable since there is no obvious process which could create it: the final state particles being neutral, there is nothing like a Born term. There remains the possibility of final state interactions from the isospin 1 part of the K^+K^- Born term; however this is shown below to strongly overestimate the measured cross section and being no appropriate description of the observed features. Also experience on other neutral final states (e.g. $3\pi^0$) shows that they are completely resonance dominated. This is a strong argument for the "continuum" to stem from a broad resonance, which might be another state (quark model a_0 with $m \approx 1100 MeV$) or the δ itself, whose resonance shape then is strongly distorted due to the opening of the $K\bar{K}$ threshold. In both cases the experimental δ radiative width may well change; in the former case because one should add the two scalar resonances coherently. Fig. 9 shows that such an interpretation could describe the data with a radiative width of $3.75\,keV$, if the $\eta\pi$ branching ratio is only 14.5% as for the a_2 (probably a lower limit!) [36].

It would be interesting to learn something about relative phases in such a process, or equivalently to have a mass spectrum prediction from unitarized quark models were the real δ is broad and the narrow structures observed are just cusp effects due to the opening of the $K\bar{K}$ threshold. If in these models the whole (broad + narrow) structure is due to the δ, then simple Breit Wigner fits to the narrow structure may underestimate the radiative width considerably, and much more sophisticated methods of determining the direct $\gamma\gamma$ coupling are necessary. Such a model has been constructed by Achasov and Shestakov [56], who interpret the whole non-a_2 part of the cross section as a wide $4q$ state with a cusp effect at the $K\bar{K}$ threshold. They do not need any $q\bar{q}$ scalar state, which might either be absent (coupling too small) or pushed to high masses by instanton effects [57]. Their total radiative width nevertheless is only $0.6\,keV$, which can be understood if the $\eta\pi$ branching ratio is large. They use the K^+K^- Born term without absorbtive corrections in their calculation, which according to the experimental results presented in the next chapter is not a good approximation. Another question related to this calculation is why they did not also use strong decays into vector meson pairs with subsequent VDM couplings to photons, as done in their calculation of the reactions $\gamma\gamma \to VV'$ (see below).

Quark model predictions usually do not consider any unitarity mixing etc. and might only correspond to the bare poles. It would be nice to have an estimate of the uncertainties due to these effects which are supposed to be especially important for scalar mesons.

From the Crystal Ball differential cross section [54] in the a_2 region a quite stringent upper limit on the $\gamma\gamma$ coupling of a hypothetical *narrow* a_0 à la GAMS [14] has been derived [36].

I =0 − I =1 INTERFERENCE in $\gamma\gamma \to KK$.

Interesting interference phenomena can be observed in the reaction $\gamma\gamma \to K\bar{K}$ [58,23]: isoscalar (f_J) and isovector (a_J) resonances interfere constructively

channel	source	value $/keV$	assumptions
		$\Gamma_{\gamma\gamma}(a_2(1320))$	
$\rho\pi,\eta\pi$	PDG world average [1]	0.90 ± 0.10	hel. 2
$\rho\pi$	CELLO [37]	$1.0 \pm 0.07 \pm 0.15$	
$\eta\pi$	JADE [32]	$1.01 \pm 0.14 \pm 0.22$	incoherent background, hel.2
$\rho\pi$	TPC/2γ [55]	$0.97 \pm 0.10 \pm 0.22$	hel.2
$\rho\pi$	ARGUS (prel.) [38]	$0.94 \pm 0.04 \pm 0.16$	
	Our suggestion	0.94 ± 0.07	stat.$\oplus$ syst. error
		$\Gamma_{\gamma\gamma}(\delta/a_0(980)) \cdot B(\delta \to \eta\pi)$	
$\eta\pi$	Crystal Ball [54]	$0.19 \pm 0.07^{+0.10}_{-0.07}$	narrow width, incoherent background
$\eta\pi$	JADE [32]	$0.28 \pm 0.04 \pm 0.10$	narrow width, incoherent background
	Our suggestion	< 0.8	even if broad with narrow cusp. and including interference with possible broad scalar
		$\Gamma_{\gamma\gamma}(S/a_0(1300)) \cdot B(a_0(1300) \to \eta\pi)$ (GAMS candidate. $\Gamma = 110\,MeV$)	
$\eta\pi$	Feindt [36], data from [54]	< 0.44 ($95\% c.l.$)	degenerate to a_2. limit from angular distribution
		$\Gamma_{\gamma\gamma}(S/a_0(1300)) \cdot B(a_0(1300) \to \eta\pi)$ (broad, $\Gamma \approx 350\,MeV$)	
	Our suggestion	< 1.0	limit from mass spectrum [54], a_2 contribution subtracted

Table 2: Numerical data for isospin 1 channels

in the reaction $\gamma\gamma \to K^+K^-$ and destructively in $\gamma\gamma \to K^0_S K^0_S$. This can be understood in the quark model applying Zweig's rule, and has been predicted [59] long before its observation [60 – 65]. Measured cross sections are shown in Fig. 10. The solid lines denote the expectations for the tensor resonances f_2, a_2 and f_2' using relative signs predicted in the quark model and $\gamma\gamma$ and $K\bar{K}$ couplings from the PDG for f_2 and a_2. Only the f_2' two photon coupling, which largely is known only from these data, is a free parameter. Note that this model almost saturates the measured cross section. The K^+K^- Born term (dashed line) does not give an appropriate description of the data, similar to the findings in the $\pi\pi$ final state there has to occur a strong damping (pions and kaons are not pointlike at $W_{\gamma\gamma} > 1\,GeV$). ARGUS [65] points out that a tiny coherent continuum is sufficient to make the data fit very well such that the small experimental excess over the tensor meson expectation can hardly be interpreted as evidence for scalar mesons (however, this also cannot be excluded). ARGUS has determined the radiative f_2' width times the $K\bar{K}$ branching ratio from this plot to be $0.0314 \pm 0.0050 \pm 0.0077\,keV$, much lower than the world average of almost $0.11\,keV$. The ARGUS result however strongly depends on their background model: a phenomenological smooth background with a constant phase, which leads to a better agreement in the region of the f_2, a_2 and mainly just below the f_2' mass. In this region the interference turns out to be constructive, thus only a small f_2' coupling constant is needed. An incoherent fit already increases the extracted value to $0.067\,keV$. This example again demonstrates the difficulty in extracting resonance parameters in a model independent way in the presence of background. The background model might be too simple, zeroes of the continuum as in the case of the reaction $\gamma\gamma \to \pi^+\pi^-$ might occur, at least the phase of the background should not be constant, e.g. due to unitarity. We do not know about theoretically guided ansatzes here, the Born term being terribly wrong and unitarization in this $I = 0$-$I = 1$ mixed channel anything but trivial. In our opinion the $K^0_S K^0_S$ analyses are more trustable for the determination of $\Gamma_{\gamma\gamma}(f_2')$ since they appear essentially background-free.

For scalar $q\bar{q}$ mesons we expect the same interference mechanism to work (as pointed out by

channel	source	value / keV	assumptions
		$\Gamma_{\gamma\gamma}(f_2'(1530)) \cdot B(f_2' \to K\bar{K})$	
$K_S^0K_S^0, K^+K^-$	PDG world average [1]	$0.108^{+0.023}_{-0.020}$	Note: "$\cdot B(K\bar{K})$" missing in [1]
$K_S^0K_S^0$	CELLO [63]	$0.11^{+0.03}_{-0.02} \pm 0.02$	
$K_S^0K_S^0$	PLUTO [62]	$0.10^{+0.04+0.03}_{-0.03-0.02}$	
K^+K^-	TPC/2γ [61]	$0.12 \pm 0.07 \pm 0.04$	
$K^+K^-, K_S^0K_S^0$	TASSO [60]	$0.11 \pm 0.02 \pm 0.04$	
$K_S^0K_S^0$	MARK II(prel.) [64]	0.10 ± 0.04	
K^+K^-	ARGUS [65]	$0.0314 \pm 0.0050 \pm 0.0077$	phenomenological coherent background
		$0.0673 \pm 0.0081 \pm 0.0151$	phenomenological incoherent background
	Our suggestion	0.0106 ± 0.018	neutral final states preferred due to absence of background
		$\Gamma_{\gamma\gamma}(f_0'(1530)) \cdot B(f_0' \to K\bar{K})$ (LASS scalar candidate)	
$K_S^0K_S^0$	Feindt [58]	$< 0.7\,(95\%c.l.)$	PLUTO [62] and CELLO [63] data
K^+K^-	this work (indirect)	$< 0.45\,(95\%c.l.)$	ARGUS [65] data
	Our suggestion	$< 0.4\,(95\%c.l.)$	combined data
		$\Gamma_{\gamma\gamma}(\Theta/f_2(1720)) \cdot B(f_2(1720) \to K\bar{K})$	
$K_S^0K_S^0$	Feindt [58]	$< 0.09\,(95\%c.l.)$	PLUTO [62] and CELLO [63] data, helicity 2, any $f_2' - \Theta$ interference
K^+K^-	ARGUS [65]	$< 0.058\,(95\%c.l.)$	helicity 2, any $f_2' - \Theta$ interference
		$\left(\sqrt{\Gamma_{\gamma\gamma}(f_0(1300)) \cdot B(f_0(1300) \to K\bar{K})} + \sqrt{\Gamma_{\gamma\gamma}(a_0(1300)) \cdot B(a_0(1300) \to K\bar{K})}\right)^2$ (300 MeV broad scalars)	
K^+K^-	this work	$< 0.95\,(95\%c.l.)$	ARGUS [65] data
		$\left(\sqrt{\Gamma_{\gamma\gamma}(f_0(1300)) \cdot B(f_0(1300) \to K\bar{K})} - \sqrt{\Gamma_{\gamma\gamma}(a_0(1300)) \cdot B(a_0(1300) \to K\bar{K})}\right)^2$ (300 MeV broad scalars)	
$K_S^0K_S^0$	this work	$< 0.47\,(95\%c.l.)$	PLUTO [62] and CELLO [63] data

Table 3: Numerical data from the reactions $\gamma\gamma \to K\bar{K}$

Lipkin at this conference, interference should also occur for S^* and δ, irrespective of their interpretation in the quark model). For mass degenerate states the K^+K^- ($K_S^0K_S^0$) cross section is proportional to $(\sqrt{\Gamma_{\gamma\gamma}(f_J)B(K\bar{K})} + (-)\sqrt{\Gamma_{\gamma\gamma}(a_J)B(K\bar{K})})^2$. From PLUTO and CELLO it is known that the f_2' region is well described by pure spin 2, helicity 2; and limits on a hypothetical scalar (the "LASS" f_0') have been derived [62, 63, 58] (ignoring a possible (2,0) contribution, as justified above). ARGUS has not published angular distributions or numbers on the spin content of their data. It is however possible to extract relevant information from their publication: They observe that spin 2, helicity 0 is not needed. To extract the K^+K^- cross section ARGUS has performed fits to the angular distribution in every $W_{\gamma\gamma}$ bin, to (2,2) and (0,0) because both have a different acceptance to correct for. From the published sensitivity curves for both spin hypotheses and the number of events-plot one can such reconstruct the cross sections which would be obtained for these models. Comparison of the published cross section points with the curves such obtained shows that their fit results must have been mostly consistent with spin 2 (see Fig. 12).

Putting all this information together, we obtain the limits listed in Table 3.

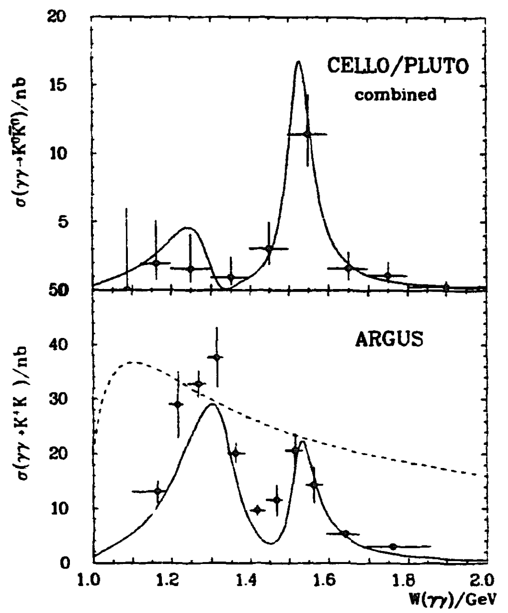

Figure 10: Cross section for $\gamma\gamma \to K^0\bar{K}^0$ (top) and $\gamma\gamma \to K^+K^-$ (bottom). Solid line: expectation for the tensor mesons f_2, a_2 and f_2' with world average $\gamma\gamma$ and $K\bar{K}$ couplings, and destructive and constructive $f_2 - a_2$ interference, resp. Dashed line: K^+K^- Born term prediction.

OTHER 0^-0^- FINAL STATES

Not much is known about other pseudoscalar pairs. Crystal Ball [66] has observed only a few events in the final states $\eta\eta$ (18 events), $\eta\eta'$ (1 event) and $\pi^0\eta'$ (4 events), all with "no structure", and derived an upper limit on the $f_0/G(1590)$.

state	$\Gamma_{\gamma\gamma} \cdot B(\eta\eta)/keV$	remarks
$G/f_0(1590)$	< 0.65	
$f_2(1720)$	< 0.07	hel. 2
$X_2(2220)$	< 0.04	hel. 2

Table 4: Crystal Ball [66] 90% upper limits on states in the $\eta\eta$ channel

TENSORS AND/OR SCALARS IN $\gamma\gamma \to \rho^0\rho^0$?

One of the most striking effects found in two photon reactions is the large cross section for $\gamma\gamma \to \rho^0\rho^0$ below threshold [67 – 72] (for reviews about $\gamma\gamma \to VV'$ see e.g. [73]). The much lower $\rho^+\rho^-$ cross section [74 – 76] rules out a single resonance interpretation;

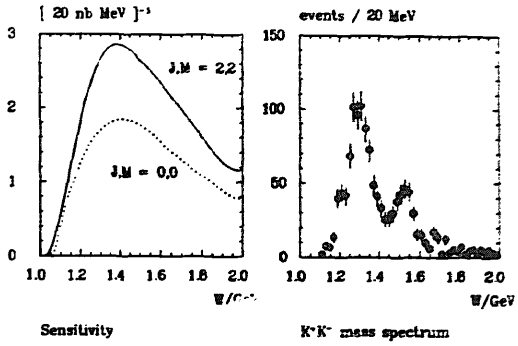

Figure 11: Reconstruction of ARGUS [65] spin fit results: Left: Sensitivity for spin 0 (dotted) and spin 2, helicity 2 (solid line). Right: K^+K^- event spectrum

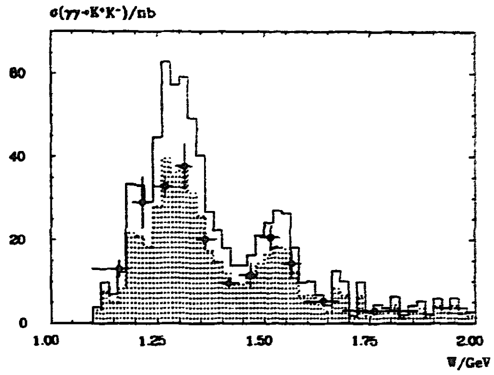

Figure 12: ARGUS fitted cross sections (points) of the reaction $\gamma\gamma \to K^+K^-$ together with the expectation for pure spin 0 (open histogram) and pure spin 2, helicity 2 (shaded histogram), calculated from Fig. 11.

both isospin 0 as well as 2 amplitudes and their interference must be present. This is of special importance since such a feature can naturally be explained by 4 quark states [51, 52] which have been predicted in this mass region in the MIT bag model [50]. In the ansatz of Achasov et al.[51] only spin 2 resonances are needed, whereas Li and Liu describe the data by spin 2 and spin 0 states. For further theoretical details see [77] and references therein.

Experimental spin parity analyses of the $\rho\rho$ enhancement are controversial, it may be 0^- and or 2^- [73]. Whereas a recent ARGUS analysis [78, 38] claims the dominance of the 2^+, helicity 2 amplitude, the preliminary result of CELLO as shown in Fig. 13 requires next to the 2^+ also a 0^- contribution in the same order of magnitude, in agreement with former analyses. Note that both, 0^+ and 2^- can couple to two 1^- (photons, ρ's) states in S-wave. A recent, not yet published ARGUS partial wave decomposition of the $\rho^+\rho^-$ cross section [79] shows the same qualitative

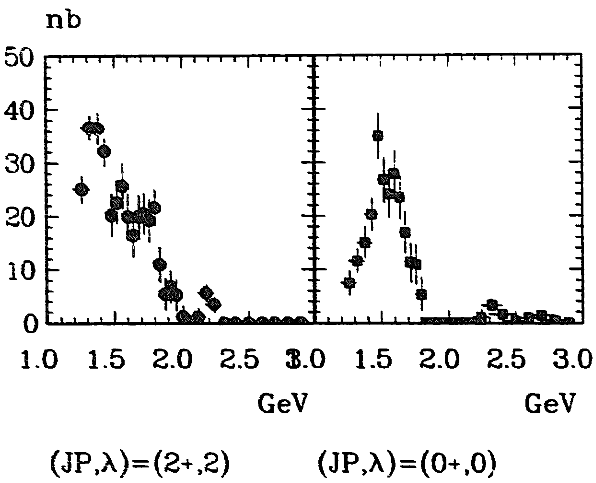

Figure 13: CELLO partial wave cross sections of the reaction $\gamma\gamma \rightarrow \rho^0\rho^0$. Left: $2^-, \lambda = 2$ contribution, right: 0^- contribution

features as Fig. 13: Both (2, 2) and (0, 0) components are needed, with a hint of a structure ($f_2(1270)$?) at low masses. A recent spin parity analysis of the reaction $\gamma\gamma \rightarrow \omega\rho$ by CELLO [80] also did not confirm a dominance of the (2, 2) wave. This final state is best described by a mixture of many different amplitudes.

SUMMARY AND CONCLUSION

We have presented a review of recent results concerning the two-photon coupling of tensor and scalar mesons. The difficulties in determining uniquely parameters of broad and overlapping resonances in the presence of background have been discussed. Nevertheless, some qualitative features have unambiguously been established:

1. Tensor mesons couple mainly via helicity 2 to two photons, the helicity 0 coupling is strongly suppressed.
2. The Born term largely overestimates data in $\pi^-\pi^-$ above $\approx 700\,MeV$ and in K^+K^- directly from threshold on. A sound theoretical description would be appreciated.
3. There is a large broad scalar in $\gamma\gamma \rightarrow \pi^+\pi^-$ with a mass of $\approx 1\,GeV$, a width of $\approx 450\,MeV$ and a radiative width of 5 - 10 keV, compatible with quark model expectations for a $q\bar{q}$ state. The absence of a correspondingly large signal in $\pi^0\pi^0$ needs further clarification.
4. The "continuum" observed in $\eta\pi$ probably is a broad $a_0(\approx 1100)$.
5. The narrow scalars S^* and δ have small two photon widths, qualitatively confirming $4q$ or $K\bar{K}$ molecule assignments. The somewhat dual description as bare $q\bar{q}$ states with large $K\bar{K}$ continuum admixture due to unitarity cannot be ruled out.
6. There is no evidence for the "usual" $q\bar{q}$ candidates $a_0(1300)$ seen by GAMS and $f_0'(1530)$ seen by LASS. However, with the present limits their existence cannot yet seriously be questioned.
7. There is no evidence for any of the glueball candidates $G/f_0(1590)$ and $\Theta/f_2(1720)$ (which in principle underlines this interpretation) or the multiquark state candidate $AX/f_2(1565)$ in $\gamma\gamma$ reactions. The latter might perhaps be connected with the $\rho\rho$ enhancement.
8. The large sub-threshold enhancement in $\gamma\gamma \rightarrow \rho^0\rho^0$ and the absence of a correspondingly large signal in $\rho^-\rho^-$ clearly need an exotic interpretation using isospin 0 and 2. 4-quark models may be the key to an understanding, however quantitative predictions do not hold in all VV' channels simultaneously. Spin-parity assignments still are controversial, the majority of experiments supports both spin 0 and spin 2 components.

Although we have reported some experimental progress, we cannot answer the question of the nature of the scalars. If the S^* and δ are interpreted largely as "molecules", it is still an open and controversial question what the binding potential is, whether the usual quark model scalars still have to exist at higher masses or whether they are the reason for the existence of the bound state. Also, if interpreted as broad states with threshold cusps, does this mean that one dynamical effect can produce two poles? Even if very broad, do 4 quark poles play a role? What happens if there are more scalar poles, e.g. $q\bar{q}$ and $4q$, when unitarized? Do both of them "run" towards the threshold? The situation is very complex, and much theoretical and experimental work is to be done. Because of these difficulties, a good cooperation between theorists and experimentalists seems extremely important. The latter should try to present their data in a as model independent as possible way - note that there are 12 (!) measurements of the $\pi\pi$ channel (bibliography see [35]) which are essentially useless since they did only show a number of events plot fitted to some model which today would not be accepted any more. Only three recent experiments presented total and especially differential cross sections, which also can be used as a basis for sophisticated theoretically guided interpretations. On the other hand, theorists are asked to supply experimenters with models and ideas in an understandable language.

Concerning point 3, we herewith claim rights for the Chanowitz Prize (type Berkeley) announced at the 1988 Shoresh $\gamma\gamma$ workshop [81] and recently readvocated [82]. In addition to the work of the first candidates Morgan and Pennington [33], we have provided independent experimental information, shown the existence of a large scalar using a very simple, energy independent partial wave decomposition, and also proved that the result does not change qualitatively if one includes sophisticated unitarity and analyticity constraints. Regarding the seemingly most important criterion, we officially declare that we have taken shifts for the CELLO data-taking in 1985 and 1986.

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