RESONANCE FORMATION IN TWO-PHOTON COLLISIONS*

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Two-photon collisions at the e^+e^- colliders allow to investigate the formation and the properties of resonant states in a very clean experimental environment. A remarkable number of new results have been recently obtained giving important contributions to meson spectroscopy and glueball searches. The most recent results from the LEP collider at CERN and CESR at Cornell are reviewed here.

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1. Introduction

Two-photon collisions at electron positron storage rings are a good laboratory to investigate the properties of meson resonances and play a crucial role in glueball searches.

A resonant state R can be formed by the collision of two photons via the reaction $e^+e^- \to e^+e^-R$ (Fig. 1). The outgoing electron and positron are usually scattered at very small angles and are not detected (no-tag mode). In this case the two photons are quasi real and the resonant state R must be neutral and unflavoured with $C = 1$ and $J \neq 1$. If one of the two photons is highly virtual, the outgoing electron or positron can be detected at low angle and the spin of the resonant state is allowed to be one (single-tag mode). In both cases the two outgoing particles carry nearly the full beam energy and the mass of the resonant state is much smaller than the e^+e^- centre of mass energy. This fact allows a clean separation between the two-photon and the annihilation process by using a cut in the visible energy. Since there are no particles produced other than R, the reconstruction of the final state can be performed in a very clean experimental environment.

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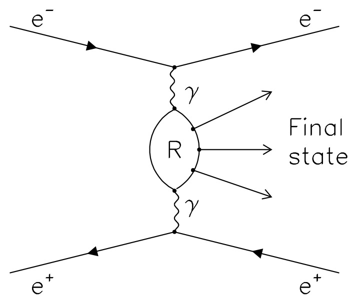

Fig. 1. Diagram of the formation of a resonant state in two-photon collisions at e^+e^- colliders.

The cross section for this process is given by the convolution of the QED calculable luminosity function $\mathcal{L}$, giving the flux of the virtual photons, with the two-photon cross section $\sigma(\gamma\gamma \to R)$ that is expressed by the Breit–Wigner function

$$\sigma(\gamma\gamma \to R) = 8\pi(2J+1)\frac{\Gamma_{\gamma\gamma}(R)\Gamma(R)}{(W_{\gamma\gamma}^2 - m_R^2)^2 + m_R^2\Gamma^2(R)}\,, \tag{1}$$

where $W_{\gamma\gamma}$ is the invariant mass of the two-photon system, $m_R, J, \Gamma_{\gamma\gamma}(R)$ and $\Gamma(R)$ are the mass, spin, two-photon partial width and total width of R, respectively. This leads to the proportionality relation

$$\sigma(e^+e^- \to e^+e^- R) = \mathcal{K} \cdot \Gamma_{\gamma\gamma}(R) \tag{2}$$

that allows to extract the two-photon width from the cross section. The proportionality factor $\mathcal{K}$ is evaluated by a Monte Carlo integration.

In the single tag-mode the high virtuality of one of the two photons is taken into account by multiplying the Breit–Wigner function by a VDM pole transition form factor

$$F^2(Q^2) = \left(\frac{1}{1 + Q^2/\Lambda^2}\right)^2\,, \tag{3}$$

where Q^2 is the four vector squared of the virtual photon and Λ is a parameter to be measured experimentally.

Since gluons do not couple directly to photons, the two photon width of a glueball is expected to be very small. A state that can be formed in a gluon rich environment but not in two photon fusion has the typical signature of a glueball. According to lattice QCD predictions [1], the ground state glueball has $J^{PC} = 0^{++}$ and a mass between 1400 and 1800 MeV. The 2^{++} tensor glueball is expected in the mass region around 2200 MeV while the 0^{-+}

pseudoscalar glueball is predicted to be heavier. Since several 0^{++} states have been observed in the 1400–1800 MeV mass region, the scalar ground state glueball can mix with nearby quarkonia, making the search for the scalar glueball and the interpretation of the scalar meson nonet a complex problem [2–4]. The results from two-photon formation represent therefore a fundamental piece of information for glueball searches.

In order to distinguish ordinary quarkonia from glueballs, a parameter called stickiness has been introduced [5]. The stickiness is an estimate of the ratio $|\langle R|gg\rangle|^2/|\langle R|\gamma\gamma\rangle|^2$ evaluated from the the ratio $\Gamma(J/\psi\to\gamma R)/\Gamma(R\to\gamma\gamma)$ corrected by a phase space factor. The $s\bar{s}$ mesons have the largest stickiness among quarkonia (14.7 for the $f_2'(1525)$) while much larger values are expected for glueballs.

Because of the large mass of the charm quark, the study of the formation of charmonium states allows to test non-relativistic perturbative QCD calculations and to measure α_s at the charm scale.

Two e^+e^- colliders have collected a large amount of data in the last few years. The four LEP experiments ALEPH, DELPHI, L3 and OPAL at CERN have collected approximately 150, 55, 175, 240 pb^{-1} each at $\sqrt{s}\sim 91$, 183, 189, 191-202 GeV respectively. The CLEO experiment at CESR (Cornell) has collected about 3000 pb^{-1} at $\sqrt{s}\sim 10.6$ GeV. Since the luminosity function $\mathcal{L}$ increases with the beam energy, the higher energy allows LEP to partially compensate the smaller luminosity by a larger cross section.

In this paper the most recent results on resonance formation and glueball searches obtained at LEP and CESR are reviewed.

2. The $\pi^+\pi^-\pi^0$ final state

A study of the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0$ is performed by L3 [6, 7] using only untagged events. The mass spectrum (Fig. 2) is dominated by the formation of the $a_2(1320)$ tensor meson. A clear enhancement is visible around 1750 MeV where the study of the total transverse momentum distribution shows evidence for an exclusive process. The study of the angular distributions shows that the a_2 formation is dominated by a $J^{PC}{=}2^{++}$ helicity 2 wave. measured to be $0.92\pm0.05\pm0.05$. The radiative width is found to be $\Gamma_{\gamma\gamma}(a_2)=0.98\pm0.05\pm0.09$ keV. A spin-parity analysis in the mass region above the $a_2(1320)$ shows that also this region is dominated by a $J^{PC}{=}2^{++}$ helicity 2 wave, confirming the observation of the CERN-IHEP collaboration [8] and in contradiction with CELLO [9] and Crystal Ball [10] measurements. This can be interpreted as the formation of a radial recurrence of the a_2 for which $\Gamma_{\gamma\gamma}(a_2'(1765))\times\mathrm{BR}(a_2'(1765)\to\pi^+\pi^-\pi^0)=0.29\pm0.04\pm0.02$ keV in agreement with theoretical predictions [11]. The $J^{PC}{=}2^{-+}$ wave contribution is found compatible with zero.

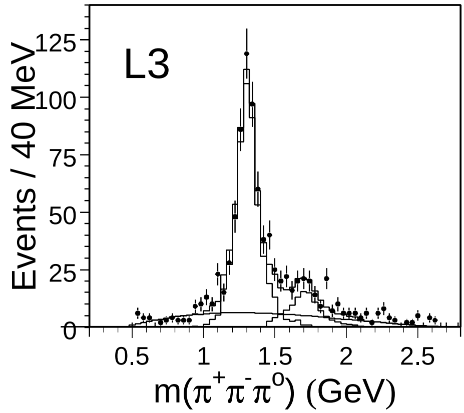

Fig. 2. The $\pi^+\pi^-\pi^0$ mass spectrum.

3. Pseudoscalar mesons and their form factors

The reaction $\gamma\gamma \to \eta' \to \pi^+\pi^-\gamma$ is studied by L3 [12] in both the no-tag and single-tag mode. The $\pi^+\pi^-\gamma$ mass spectrum (Fig. 3) shows a prominent peak due to the formation of the $\eta'(958)$ while the enhancement around 1250 MeV is due to the process $\gamma\gamma \to$a$_2$(1320)$\to \pi^+\pi^-\pi^0$ when one photon from the π^0 goes undetected. For the two-photon width, $\Gamma_{\gamma\gamma}(\eta') = 4.17 \pm 0.10 \pm 0.27$ keV is measured. The electromagnetic form factor of the η' is studied using tagged and untagged events. For the untagged events Q^2 can be measured as $(\Sigma p_{\rm t})^2$, as demonstrated by a Monte Carlo study. A low gluonic component in the $\eta'(958)$ is found by comparing the data with the

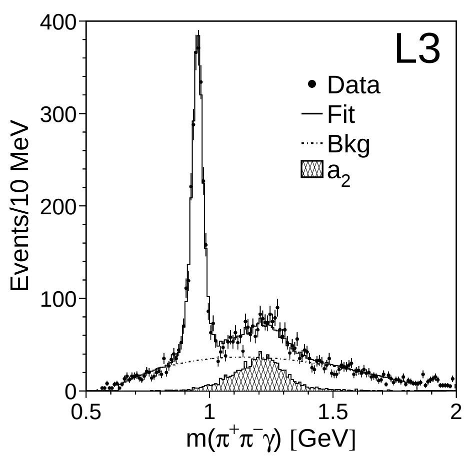

Fig. 3. The $\pi^+\pi^-\gamma$ mass spectrum for $Q^2 < 0.01$ GeV^2.

theoretical predictions [13]. The value $0.900 \pm 0.046 \pm 0.022$ GeV is obtained for the parameter Λ.

The transition form factors for the three pseudoscalar mesons π^0, η and η' are studied by CLEO [14] using only the single-tag mode. The values Λ_{π^0}=0.776±0.010±0.012±0.016 GeV, Λ_{η}=0.774±0.011±0.016±0.022 GeV, $\Lambda_{\eta'}$=0.859±0.009±0.018±0.020 GeV are measured. Data are consistent with a similar wave function for the π^0 and η. The non-perturbative properties of the $\eta'(958)$ are found to be different from those of the π^0 and η. According to Feldmann [15], another interpretation of these results leads to the conclusion that π^0, η' and η' mesons behave similarly in hard exclusive reactions.

Interesting new preliminary results on the $K^0_{\mathrm{S}}K^{\pm}\pi^{\mp}$ and the $\eta\pi^+\pi^-$ final states are obtained by L3 [16]. The $K^0_{\mathrm{S}}K^{\pm}\pi^{\mp}$ mass spectrum is studied as a function of Q^2 (Fig. 4). A prominent signal is present at 1470 MeV at low and at high Q^2. At very high Q^2 another signal appears around 1300 MeV due to the formation of the $f_1(1285)$. The study of the cross section as a function of Q^2 in the 1470 MeV region reveals that both the 0^{-+} and 1^{++} waves are needed to fit the data. The 0^{-+} wave is due to the formation of the $\eta(1440)$ and largely dominates at low Q^2 while at high Q^2 the formation of the $f_1(1420)$ is found to be dominant. The value $\Gamma_{\gamma\gamma}(\eta(1440)) \times \mathrm{BR}(\eta(1440) \rightarrow$

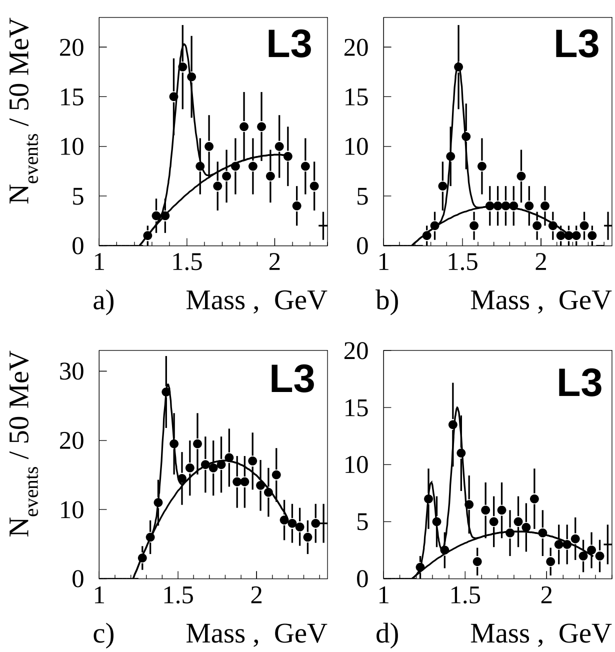

Fig. 4. The $K^0_{\mathrm{S}}K^{\pm}\pi^{\mp}$ mass spectrum for $Q^2 < 0.02$ GeV^2 (a), $0.02 < Q^2 < 0.2$ GeV^2 (b), $0.2 < Q^2 < 1.0$ GeV^2 (c) and $1.0 < Q^2 < 7.0$ GeV^2 (d).

$K\bar{K}\pi) = 234 \pm 55 \pm 17$ eV is obtained by using data at low Q^2. This first observation of the $\eta(1440)$ in untagged two-photon collisions disfavours its interpretation as the 0^{-+} glueball in agreement with the lattice QCD calculations. The $\eta(1440)$ can therefore be interpreted as a radial excitation [17]. The $\eta\pi^+\pi^-$ final state shows no evidence for the formation of the $\eta(1440)$ at low and at high Q^2 (Fig. 5). A prominent signal due to the formation of the $\eta'(958)$ is present in the two spectra while the $f_1(1285)$ is visible only at high Q^2. The upper limits $\Gamma_{\gamma\gamma}(\eta(1440)) \times \mathrm{BR}(\eta(1440) \to \eta\pi\pi) < 88$ eV and $\Gamma_{\gamma\gamma}(\eta(1295)) \times \mathrm{BR}(\eta(1295) \to \eta\pi\pi) < 61$ eV at 90% C.L. are obtained.

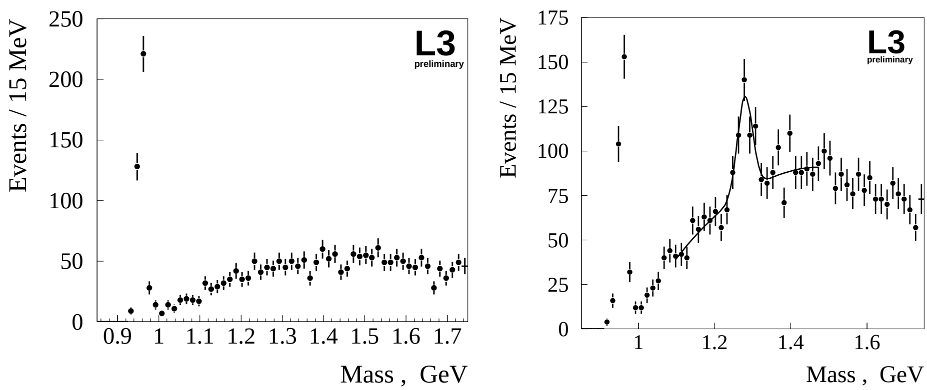

Fig. 5. The $\eta\pi^+\pi^-$ mass spectrum for $Q^2 < 0.02$ GeV^2 (left) and $Q^2 > 0.02$ GeV^2 (right).

4. Glueball searches in the $K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ and $\pi^+\pi^-$ final states

A study of the reaction $\gamma\gamma \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ is performed by L3 [7, 18]. The mass spectrum is shown in Fig. 6 (left). The 1100–1400 MeV mass region shows destructive $f_2(1270)$–$a_2(1320)$ interference in agreement with theoretical predictions [19]. The spectrum is dominated by the formation of the $f_2'(1525)$ tensor meson in helicity 2 state as clearly shown by the angular distribution in the $K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ center of mass. The preliminary value $\Gamma_{\gamma\gamma}(f_2'(1525)) \times \mathrm{BR}(f_2'(1525) \to K\bar{K}) = 0.076 \pm 0.006 \pm 0.011$ keV is obtained. A clear signal is present in the 1750 MeV mass region due to the formation of the $f_J(1710)$. The presence of a 0^{++} $s\bar{s}$ meson would support the glueball interpretation of the $f_0(1500)$ [2]. The study of the angular distribution in the 1750 MeV mass region favours the presence of a 2^{++}, helicity 2 wave. This is consistent with the interpretation of the $f_J(1710)$ as a radial recurrence of the $f_2'(1525)$ [11]. The presence of a 0^{++} wave cannot however be excluded. The BES Collaboration [20] reported the

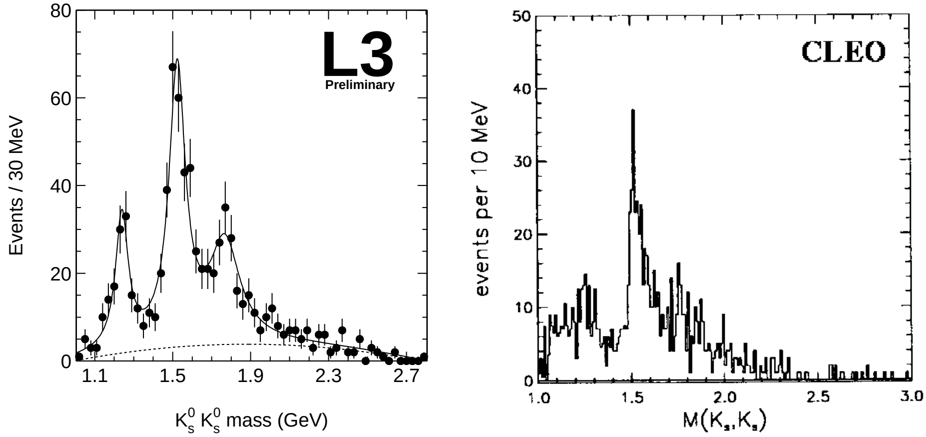

Fig. 6. The $K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ mass spectra measured by L3 (left) and CLEO (right).

presence of both 2^{++} and 0^{++} waves in the 1750 MeV region in K^+K^- in the reaction $e^+e^- \to J/\psi \to K^+K^-\gamma$. No signal for the formation of the $\xi(2230)$ [21] tensor glueball candidate is observed. The upper limit $\Gamma_{\gamma\gamma}(\xi(2230))\times\mathrm{BR}(\xi(2230) \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}) < 1.4$ eV at 95% C.L. is obtained. The stickiness is found to be $S_{\xi(2230)} > 73$ at 95% C.L.

The $\xi(2230)$ is searched by CLEO in the $K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ [22] and $\pi^+\pi^-$ [23] final states. The $K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ mass spectrum (Fig. 6 (right)) shows similar features respect to the L3 data. The upper limits $\Gamma_{\gamma\gamma}(\xi(2230)) \times \mathrm{BR}(\xi(2230) \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}) < 1.3$ eV and $\Gamma_{\gamma\gamma}(\xi(2230)) \times \mathrm{BR}(\xi(2230) \to \pi^+\pi^-) < 2.5$ eV at 95% C.L. are obtained. Combining these two results the stickiness is found to be $S_{\xi(2230)} > 102$ at 95% C.L. The very large lower limits for $S_{\xi(2230)}$ obtained by CLEO and L3 give a strong support to the interpretation of the $\xi(2230)$ as the tensor glueball. A confirmation of its existence in gluon rich environments becomes now very important.

The $\pi^+\pi^-$ final state is studied by ALEPH [24]. The mass spectrum (Fig. 7) shows a signal due to the formation of the $f_2(1270)$ tensor meson. No other signals are present. Assuming the $\mathrm{f}_0(1500)$ and the $f_J(1710)$ to be scalars, the upper limits $\Gamma_{\gamma\gamma}(f_0(1500)) \times \mathrm{BR}(f_0(1500) \to \pi^+\pi^-) < 310$ eV and $\Gamma_{\gamma\gamma}(f_J(1710)) \times \mathrm{BR}(f_J(1710) \to \pi^+\pi^-) < 550$ eV at 95% C.L. are obtained. Interference effects with the $\pi^+\pi^-$ continuum are not taken into account. According to Anisovitch *et al.* [25], interference with the $\pi^+\pi^-$ continuum should make the $f_0(1500)$ appear as a dip.

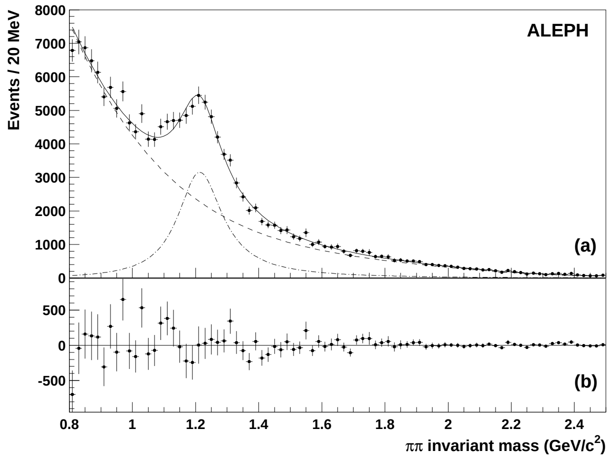

Fig. 7. The $\pi^+\pi^-$ mass spectrum: the only signal is due to the formation of the $f_2(1270)$.

5. Charmonium formation

The formation of the $\eta_c(2980)$ is studied by L3 [26]. Since the η_c decays in many different final states with small branching fractions, the simultaneous study of several decay channels is mandatory. The mass spectrum shown in Fig. 8 is obtained by summing nine different final states. The value $\Gamma_{\gamma\gamma}(\eta_c)$

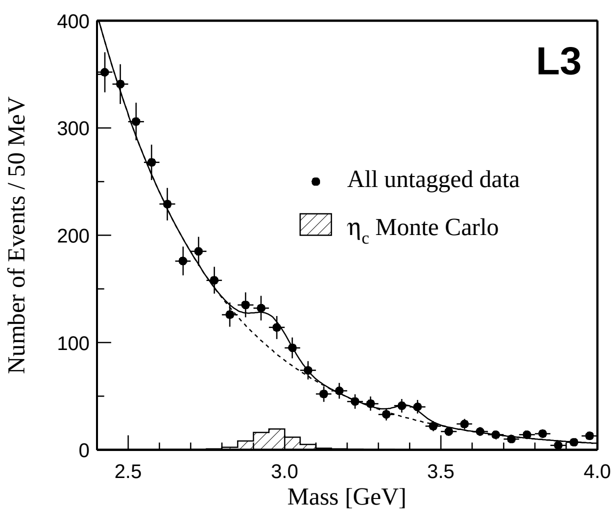

Fig. 8. The mass spectrum of the sum of nine different final states. The signals of the $\eta_c(2980)$ and the $\chi_{c0}(3415)$ are visible.

$= 6.9 \pm 1.7$ (stat.) $\pm$ 0.8 (sys.)$\pm$ 2.0 (BR) keV is measured. Despite the limited statistics, the study of the formation of the $\eta_c(2980)$ as a function of Q^2 allows to exclude a VDM ρ pole transition form factor. Data are consistent with a J/ψ VDM pole form factor, as expected. From the reaction $\gamma\gamma \to \chi_{c2}(3555) \to J/\psi\gamma \to l^+l^-\gamma$ with $l = e, \mu$, the two-photon width of the χ_{c2} is measured by OPAL [27]. The signal is seen in the distribution of the mass difference $m(l^+l^-\gamma)$–$m(l^+l^-)$ when $m(l^+l^-)$ is compatible with the mass of the J/ψ (Fig. 9). The value $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.76 \pm 0.47$ (stat.) $\pm$ 0.37 (sys.)$\pm$ 0.15 (BR) keV is obtained. The value $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.02 \pm 0.40$ (stat.) $\pm$ 0.15 (sys.)$\pm$ 0.09 (BR) keV is measured by L3 [28] using the same method.

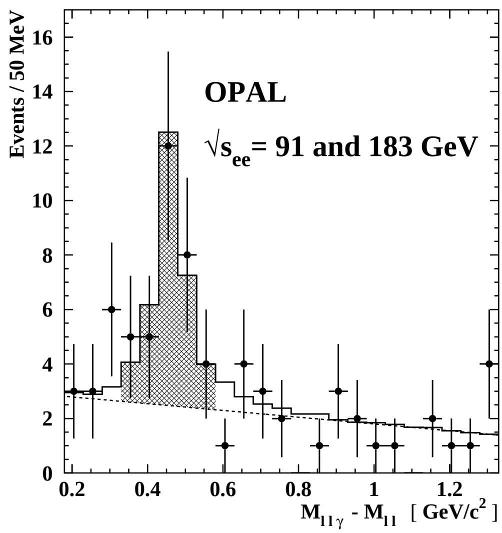

Fig. 9. The signal of the formation of the $\chi_{c2}(3555)$ from the mass difference $m(l^+l^-\gamma) - m(l^+l^-)$.

The measurements of the two-photon width of the η_c performed in two-photon collisions are in good agreement with the ones obtained in $p\bar{p}$ annihilations [29]. For the χ_{c2} the agreement is not good and the two-photon measurements are significantly higher than the value $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.31 \pm 0.05 \pm 0.04$ keV measured by E835 at Fermilab [30] in $p\bar{p}$ annihilations. This value is in agreement with a previous measurement by E760 [31]. The reason for this is not known but it is interesting to remark that all the two-photon measurements are performed by using the same final state and the same experimental method.

No signal for the formation of the η_c' is observed at LEP. Five different decay channels are examined by DELPHI [32] as shown in Fig. 10. The formation of the $\eta_c(2980)$ is clearly observed while no signal is present in the η_c' mass region. The upper limit $\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)} < 0.34$ at 90% C.L. is obtained. The upper limit $\Gamma_{\gamma\gamma}(\eta_c') < 2.0$ keV at 95% C.L. is obtained by L3 [26] using nine different decay modes.

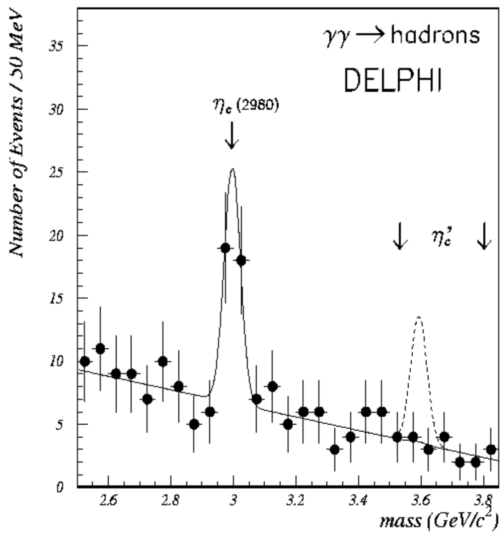

Fig. 10. The mass spectrum of the sum of five different decay channels.

6. Conclusions

A remarkable progress on the study of resonance formation in two-photon collisions has been achieved in the last few years. Data from the LEP collider at CERN and CESR at Cornell allowed to improve significantly the precision on the two-photon widths of several resonances, to study the transition form factors, to identify some radial excitations and to search for glueball candidates. All these results are summarised in Table I. They represent an important contribution to meson spectroscopy and glueball searches.

TABLE I

The most recent results on the two-photon width of mesons, charmonia, radial excitations and glueball candidates. († the value is given times the decay branching ratio.)

Resonance	Exp.	Final state	J^{PC}	$\Gamma_{\gamma\gamma}$	Ref.
$\eta'(958)$	L3	$\pi^+\pi^-\gamma$	0^{-+}	4.17±0.10±0.27 keV	[12]
$a_2(1320)$	L3	$\pi^+\pi^-\pi^0$	2^{++}	0.98±0.05±0.09 keV	[6]
$f_2^{'}(1525)$	L3	$K_s^0K_s^0$	2^{++}	0.085±0.007±0.012 keV	[18]
$\eta_c(2980)$	L3	9 chan.	0^{-+}	6.9±1.7.±0.8 keV	[26]
η_c'	L3	9 chan.	0^{-+}	< 2.0 keV	[26]
$\chi_{c2}(3555)$	L3	$l^+l^-\gamma$	2^{++}	1.02±0.40±0.15 keV	[28]
$\chi_{c2}(3555)$	OPAL	$l^+l^-\gamma$	2^{++}	1.76±0.47±0.37 keV	[27]
$\eta(1440)$	L3	$K_s^0K^\pm\pi^\mp$	0^{-+}	$234^\dagger$±55±17 eV	[16]
$f_J(1710)$	L3	$K_s^0K_s^0$	$(?)^{++}$		[18]
$a_2'(1752)$	L3	$\pi^+\pi^-\pi^0$	2^{++}	$0.29^\dagger$±0.04±0.02 keV	[6]
$f_0(1500)$	ALEPH	$\pi^+\pi^-$	0^{++}	< $310^\dagger$ eV	[24]
$f_0(1710)$	ALEPH	$\pi^+\pi^-$	0^{++}	< $550^\dagger$ eV	[24]
$\xi(2230)$	CLEO	$\pi^+\pi^-$	2^{++}	< $2.5^\dagger$ eV	[23]
$\xi(2230)$	CLEO	$K_s^0K_s^0$	2^{++}	< $1.3^\dagger$ eV	[22]
$\xi(2230)$	L3	$K_s^0K_s^0$	2^{++}	< $1.4^\dagger$ eV	[18]

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