The Formation of charmonium states in photon-photon collisions at LEP

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This presentation reviews the progress made since the Photon '97 conference on the measurements of charmonium states in photon-photon collisions at LEP. New measurements on χ_{c2}-formation are reported by the OPAL and L3 collaborations. New results on η_c formation, in particular a first measurement of the form factor are presented by L3. The DELPHI and L3 experiments give new limits on η_c' formation.

1. Introduction

The study of charmonium systems in photon-photon collisions is interesting because definite predictions of cross sections and form factors can be made. These predictions are usually based on perturbative calculations on a non-relativistic heavy quark system.

In an e^+e^- experiment, measurements are made of the reaction $e^+e^- \to e^+e^-X$ with a cross section for the production of the final state X given by

$$\sigma(e^+e^- \to e^+e^-X) = \int d^5\mathcal{L}_{\gamma\gamma}(\alpha_i)\sigma(\gamma\gamma \to X). \quad (1)$$

Here, $\mathcal{L}_{\gamma\gamma}(\alpha_i)$ is is the luminosity function expressed in the variables α_i, for example the four-momenta of the outgoing leptons. In the case of resonance formation, the two-photon cross section is given by

$$\begin{aligned}\sigma(\gamma\gamma \to R) &= 8\pi\frac{(2J_R+1)}{M_R}\Gamma_{\gamma\gamma}(R) \times \qquad (2)\\ &\times \frac{M_R\Gamma_R}{(s-M_R^2)^2+M_R^2\Gamma_R^2}F(q_1^2,q_2^2).\end{aligned}$$

Here, J_R, M_R and Γ_R are the spin, the mass and the total width of the resonance R, respectively. s is the center-of-mass energy of the colliding photon system. The interesting quantity is $\Gamma_{\gamma\gamma}(R)$, the two-photon width of the resonance. The factor $F(q_1^2,q_2^2)$ describes the Q^2 evolution of the cross section. It is sometimes absorbed into the two-photon width. q_1 and q_2 are the four-vectors of the two (virtual) photons. Usually, only one photon is virtual enough to be tagged by the corresponding lepton, in that case we define $Q^2 = -\max(q_1^2,q_2^2)$.

In this talk, I present the status of measurements of the charmonium states χ_{c2}, η_c and η_c'.

2. Formation of χ_{c2}

Since the Photon '97 conference, new results on the χ_{c2} have been published by OPAL[1] and L3[2], multi purpose experiments at the e^+e^- collider LEP at CERN. LEP is operated at c.m. energies corresponding to the Z mass, and more recently, at twice that energy. Both experiments measured the decay chain $\chi_{c2} \to J/\psi\,\gamma$, with subsequent decays $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$. In both cases, the results are presented as a plot of the mass difference ΔM:

$$\Delta M = M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-), \quad (3)$$

where $\ell^+\ell^-$ is the electron pair or the muon pair, selected in such a way that its invariant mass is compatible with that of a J/ψ meson. For the χ_{c2}, ΔM then has a unique value of 459 MeV. Figures 1 and 2 show the distributions of events as functions of ΔM for the two experiments. In both cases, a clear peak is visible. L3 has observed events also in the tagged mode, but not sufficiently many to draw any conclusions yet.

The efficiencies for observing the χ_{c2} decays were obtained by Monte Carlo techniques, which include the luminosity functions, the proper decay ratios and angular distributions of the χ_{c2} and

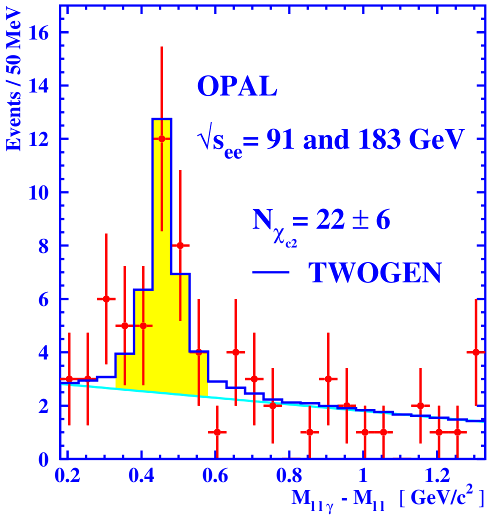

Figure 1. The ΔM spectrum of OPAL. TWOGEN refers to the Monte Carlo simulation[3].

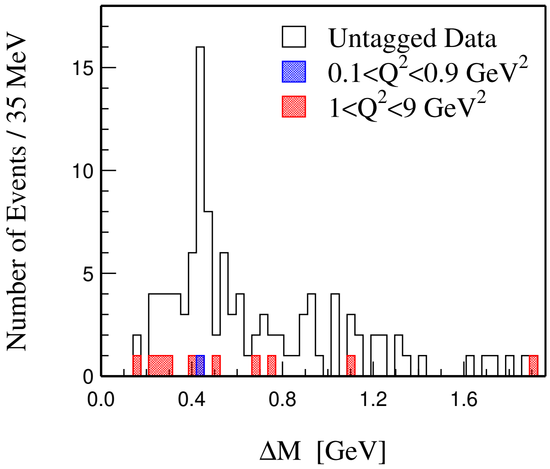

Figure 2. The ΔM spectrum of L3. The hatched area indicates tagged events.

the J/ψ and the effects of detector acceptance and resolution.

In the end, simulated events were subjected to the same selection criteria as the data. The resulting values of $\Gamma_{\gamma\gamma}(\chi_{c2})$ are listed in table 1, together with earlier results from CLEO at Cornell[7] and the TPC/2γ experiment at PEP in Stanford[4]. The average of the four experiments is $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.23 \pm 0.26$, with $\chi^2/Ndf = 0.8$, which is an acceptable chi-squared according to the Particle Data Group.

Interestingly, a completely different measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ has been reported at this conference by Michelle Stancari. Her experiment, E835 at Fermilab, measures directly the decay $\chi_{c2} \to \gamma\gamma$ in the reaction $p\bar{p} \to \chi_{c2}$. A significantly lower value is found: $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.31 \pm 0.05 \pm 0.04$ keV. This measurement is in agreement with an earlier measurement by the same group (E760).

In the light of this discrepancy, I make the following comments:

1. The background estimate by the OPAL experiment seems to be on the low side. Although the background was established from the J/ψ side bands, the number of 22 events observed seem to be on the high side.

2. Related to that, low statistics experiments always overestimate cross sections as a result of fine-tuning of cuts, wishful thinking, etc.

3. The systematic effects of the four e^+e^- experiments are similar. Consider for example the cut on the photon energy, which is at 300 MeV for both OPAL and L3. In both cases this cut is applied to a sharply decreasing spectrum of unknown origin, as shown in figure 3. Systematic problems with this cut affect all experiments in the same way, and one can therefore not simply average their results.

4. On the other hand, the $p\bar{p}$ measurement depends critically on the knowledge of the beam energy, and it is not completely obvious to me that the whole yield curve of the χ_{c2} has been observed by E760 and E835

Exp.	Production mechanism	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
CLEO	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.08 \pm 0.30 \pm 0.26$
TPC/2γ	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$3.4 \pm 1.7 \pm 0.9$
L3	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.02 \pm 0.40 \pm 0.15$
OPAL	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.76 \pm 0.47 \pm 0.37$
Average	$\chi^2/Ndf = 0.8$	1.23 ± 0.26
E760	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.32 \pm 0.08 \pm 0.05$
E835	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.31 \pm 0.05 \pm 0.04$
CLEO	$\gamma\gamma \to \chi_{c2} \to 4\pi$	$0.7 \pm 0.2 \pm 0.1$
R704	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.0\ ^{+0.9}_{-0.7} \pm 0.3$

Table 1
Reported values of $\Gamma_{\gamma\gamma}(\chi_{c2})$.

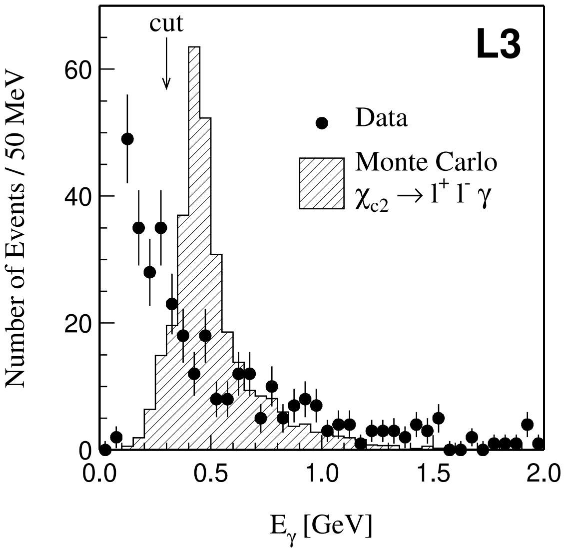

Figure 3. The distribution of E_γ in the χ_{c2} selection, after all other cuts were applied.

The theoretical predictions favour lower values of $\Gamma_{\gamma\gamma}(\chi_{c2})$ as well. In next-to-leading order, $\Gamma_{\gamma\gamma}(\chi_{c2})$ can be related to its decay width to two gluons by

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{gg}(\chi_{c2})} = \frac{9\alpha_s^2(m_c)}{8\alpha^2}\left(\frac{1-2.2\alpha_s/\pi}{1-16\alpha_s/3\pi}\right). \quad (4)$$

For the two-gluon width of the χ_{c2} one can take its total hadronic decay width. However, part of that decay goes through three gluons. That part is estimated by the hadronic decay of the χ_{c1}, which can only go through three gluons[5]. This yields $\Gamma_{\gamma\gamma}(\chi_{c2}) \simeq 0.82 \pm 0.30$ keV. Other calculations are listed in table 2, they are even lower.

Author[6]	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
T. Barnes	0.34 - 0.56
C.R. Münz	0.44 ± 0.14
H.-W. Huang *et al.*	0.39 - 0.50
G.A. Schuler *et al.*	0.28

Table 2
Theoretical predictions of $\Gamma_{\gamma\gamma}(\chi_{c2})$.

Finally, I would like to recall a report by CLEO[8] of the measurement of $\chi_{c2} \to 2\pi^+2\pi^-$ This yielded a lower $\Gamma_{\gamma\gamma}(\chi_{c2})$ value as well, be it with large errors (see table 1). In view of the problems mentioned above, it would be desirable to repeat that analysis with larger statistics.

3. Formation of η_c

Since the first, overly optimistic, claim by the PLUTO collaboration, the two-photon decay width of the η_c now seems to converge to around 7 keV. A new measurement is reported by L3[9], which observed the η_c in ten different decay channels. These channels are listed in table 3, adding up to a total of around 10% of the η_c decays. The signal observed by L3 is reproduced in figure 4.

From an unbinned likelihood fit to all decay channels simultaneously, a value of

$$\Gamma_{\gamma\gamma}(\eta_c) = 6.9 \pm 1.7_{\rm stat} \pm 0.8_{\rm sys} \pm 2.0_{\rm BR}\ \text{keV},$$

is derived. This is well in line with other measurements, as shown in table 4, and also with theoretical predictions[10], which vary between 3 and 11 keV.

Decay mode	Branching ratio (%)
$\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.)	1.2 ± 0.4
$K^+K^-\pi^+\pi^-$	2.0 ± 0.7
$K_S K^\pm \pi^\mp$, $K_S \to \pi^+\pi^-$	1.3 ± 0.4
$\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	1.3 ± 0.5
$\pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$	0.8 ± 0.3
$\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\gamma$	0.8 ± 0.3
$\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\eta$	0.5 ± 0.2
$K^+K^-\pi^0$	0.9 ± 0.3
$\rho^+\rho^-$, $\rho^\pm \to \pi^\pm\pi^0$	1.7 ± 0.6
total	10.5

Table 3
The η_c decay modes studied by L3.

Experiment	$\Gamma_{\gamma\gamma}(\eta_c)$ (keV)
E760	$6.7\ ^{+2.4}_{-1.7}\ \pm 2.3$
ARGUS	11.3 ± 4.2
CLEO	$5.9\ ^{+2.1}_{-1.8}\ \pm 1.9$
TPC/2γ	$6.4\ ^{+5.0}_{-3.4}$
L3	$6.9 \pm 1.7 \pm 0.8 \pm 2.0$

Table 4
Measured values of $\Gamma_{\gamma\gamma}(\eta_c)$.

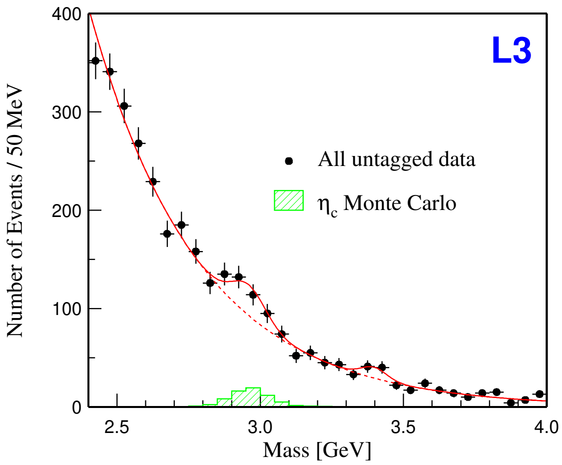

Figure 4. The L3 η_c signal.

In the same paper, L3 presents the first measurement of the form factor of the η_c. A dedicated small angle tagger (VSAT) and the luminosity monitor (LUMI) of the L3 experiment were used to tag the virtuality of one of the photons by measuring the angle and the energy of the tagging electron. The Q^2 is then derived as:

$$Q^2 = 2E_{\rm beam}E_{\rm tag}(1-\cos\theta_{\rm tag}). \qquad (5)$$

The VSAT covers tagging angles from 5 to 10 mrad, the LUMI from 30 to 65 mrad.

It has been shown in the case of the π^0, the η and the η' mesons, that a measurement of the form factor, i.e. the Q^2 dependence of $\Gamma_{\gamma\gamma}$ can be used to discriminate between different models of momentum distributions of the quarks inside these mesons[11]. In the case of the π^0 and the η, the asymptotic wave function $\phi_{AS}(x1,x2) = 6x_1x_2$ is clearly preferred over for example the Chernyak-Zhitnitsky function $\phi_{CZ} = 30x_1x_2(x_1-x_2)^2$. x_1 and x_2 are the momentum fractions of the two quarks in the meson.

The wave functions are translated to form factors using the Modified Hard Scattering Approach[11], and the result can then be parametrised by

$$F(Q^2) = F(0)\frac{1}{(1+Q^2/\Lambda^2)^2}. \qquad (6)$$

For some reason, unknown to me, the pole mass Λ corresponds exactly to the mass of the ρ-meson, at least for the π^0 and the η[12]. Therefore, the form factors are referred to as 'ρ-pole form factors'. For the η', the value of Λ is slightly higher.

Figure 5 shows the distribution of events with $Q^2 > 0$ as a function of their invariant mass. A peak at the η_c mass is clearly visible. The events in the peak are used to calculate the form factor in two bins of Q^2. This is shown in figure 6. Since the form factor is measured relative to the number of events with $Q^2 \simeq 0$, most of the systematic uncertainties cancel in the ratio. Figure 6 also shows the expected Q^2 development of the ρ-pole and the J/ψ pole form factors, as well as a form factor without any Q^2 dependence. From a

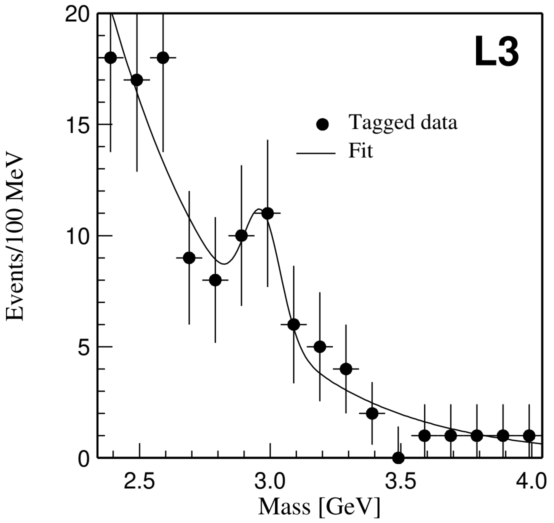

Figure 5. Mass distribution of tagged events.

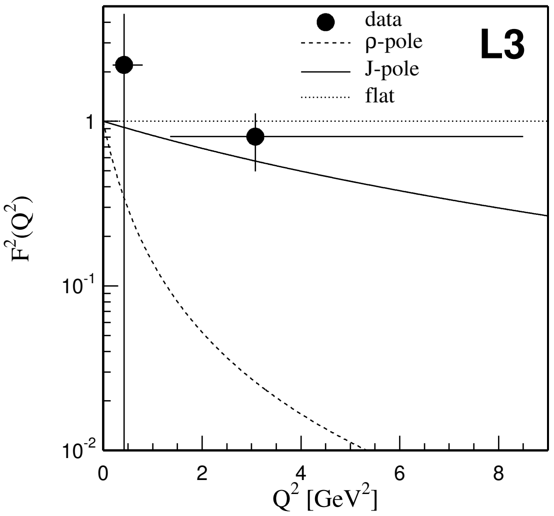

Figure 6. The η_c form factor as a function of Q^2.

detailed statistical analysis it follows that the J/ψ pole form factor is ten times more probable than the ρ pole form factor. Feldmann and Kroll have shown at the Photon '97 conference[13], that an asymptotic wave function would lead to exactly such a form factor.

4. Formation of η_c'

The L3 and DELPHI experiment have searched for signals of the η_c' in the invariant mass spectra where the η_c appears. This is motivated by an assumption that the η_c', whose observation by the Crystal Ball Collaboration in 1982[14] has not been confirmed yet, will have the same decay channels as the η_c. Barnes *et al.*[15] calculate that $\Gamma_{\gamma\gamma}(\eta_c') \simeq 0.75 \times \Gamma_{\gamma\gamma}(\eta_c)$. Similar calculations by the same authors give a rather accurate value of $\Gamma_{\gamma\gamma}(\eta_c) = 4.8$ keV, which adds credibility to their prediction for the η_c'. Figure 7 by the DELPHI collaboration[16] shows the mass distribution which clearly exhibits an η_c. An η_c' with $\Gamma_{\gamma\gamma}(\eta_c') = 3.5$ keV would appear as the solid histogram at $m = 3.5$ GeV. No such signal is discernable, which translates into an upper limit of $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) < 0.34$ keV at 90% c.l. The L3 experiment has performed a similar analysis, but quotes an absolute limit on the two-photon width: $\Gamma_{\gamma\gamma}(\eta_c') < 2$ keV at 95% c.l., of course still under the assumption that the decays of η_c and η_c' are identical. With this proviso, the limit of L3 is significantly below the prediction by Barnes *et al.*

5. Summary

New results of $\Gamma_{\gamma\gamma}(\chi_{c2})$ have been reported. The discrepancy between the $e^+e^- \to \chi_{c2}$ and the $p\bar{p} \to \chi_{c2}$ measurements persists. More data, in particular of the channel $\chi_{c2} \to 2\pi^+2\pi^-$ in $\gamma\gamma$ collisions are needed. The two-photon width of the η_c is converging to a value around 7 keV, in agreement with expectations. A first measurement of the form factor of the η_c clearly favours a J/ψ-pole mass. New limits on $\Gamma_{\gamma\gamma}(\eta_c')$ start to contradict predictions, at least under certain assumptions regarding the η_c' decay channels.

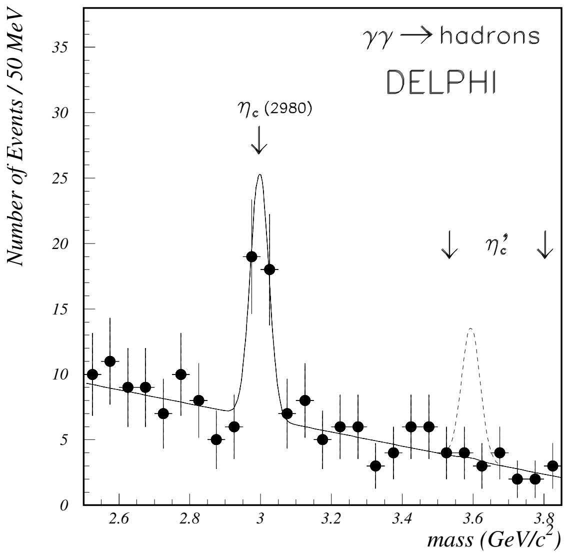

Figure 7. The invariant mass distribution in the η_c' range.

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