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CHARMONIA IN PHOTON–PHOTON COLLISIONS*

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Measurements on χ_{c2}-formation are reported by the OPAL and L3 collaborations. 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.

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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^- collider, the reaction $e^+e^- \to e^+e^-X$ is measured. In the case of resonance formation, the two-photon cross section is

$$\sigma(\gamma\gamma \to R) = 8\pi(2J_R + 1)\frac{\Gamma_{\gamma\gamma}(R)\Gamma(R)}{(s - m_R^2)^2 + m_R^2\Gamma(R)^2}F(q_1^2, q_2^2). \tag{1}$$

Here, J_R, m_R and $\Gamma(R)$ are the spin, the mass and the total width of the resonance R, respectively; s is the c.m. energy squared of the colliding photons. 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, 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 $Q^2 = -\max(q_1^2, q_2^2) = 2E_{\text{beam}}E_{\text{tag}}(1 - \cos\theta_{\text{tag}})$.

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

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The OPAL and L3 experiments have measured [1] 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 $\Delta M = M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)$, where $\ell^+\ell^-$ is the electron pair or the muon pair whose invariant mass is compatible with that of a J/ψ meson. For the χ_{c2}, ΔM then has a unique value of 459 MeV.

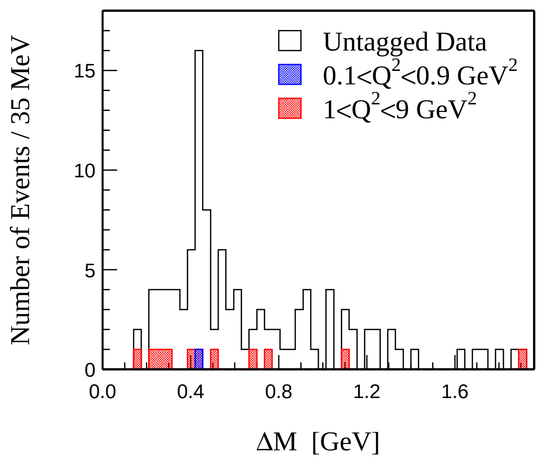

Fig. 1. The ΔM spectrum of L3. Tagged events are hatched.

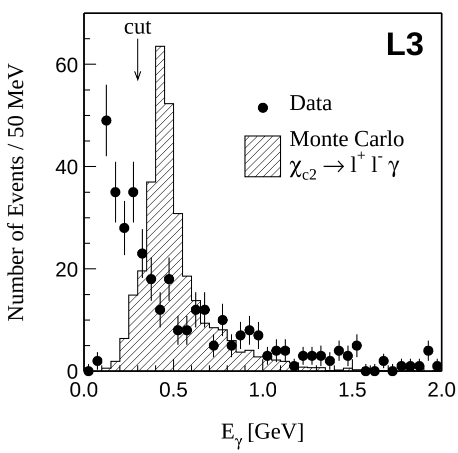

Fig. 2. The distribution of E_γ in the χ_{c2} selection, after all other cuts.

Figure 1 shows the distribution of events as a function of ΔM for L3. A clear peak is visible. L3 has observed events also in the tagged mode, but not sufficiently many to draw any conclusions yet. The resulting values of

$\Gamma_{\gamma\gamma}(\chi_{c2})$ are listed in Table I, together with earlier results from CLEO at Cornell and the TPC/2γ experiment at PEP in Stanford [1]. The average of the four experiments is $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.23 \pm 0.26$, with $\chi^2/Ndf = 0.8$.

TABLE I

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

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	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.0\ ^{+0.9}_{-0.7} \pm 0.3$

The experiment E835 at Fermilab measures directly the decay $\chi_{c2} \to \gamma\gamma$ in the reaction $p\bar{p} \to \chi_{c2}$ and finds a significantly lower value: $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.31 \pm 0.05 \pm 0.04$ keV [2]. In the light of this discrepancy, I make the following comments: *(i)* he background estimate by the OPAL experiment seems to be on the low side; *(ii)* 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 2. Systematic problems with this cut affect all experiments in the same way, and one cannot therefore simply average their results; *(iii)* 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.

Theoretical predictions favour lower values of $\Gamma_{\gamma\gamma}(\chi_{c2})$, too. In next-to-leading order, $\Gamma_{\gamma\gamma}(\chi_{c2})$ is related to its decay width to two gluons by

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

For the two-gluon width of the χ_{c2} one can take its total hadronic decay width, corrected for the color-octet contribution [4]. This yields $\Gamma_{\gamma\gamma}(\chi_{c2}) \simeq 0.82 \pm 0.30$ keV. Other calculations are listed in Table II, they are even lower.

TABLE II

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

Author [3]	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
Barnes	0.34 - 0.56
Münz	0.44 ± 0.14
Huang	0.39 - 0.50
Schuler	0.28

The CLEO [5] experiment measured $\chi_{c2} \to 2\pi^+2\pi^-$ and found a lower $\Gamma_{\gamma\gamma}(\chi_{c2})$ value, too, be it with large errors (see Table I). In view of the problems mentioned above, it would be desirable to repeat that analysis with larger statistics.

The two-photon decay width of the η_c now seems to converge to around 7 keV. The L3 [6] experiment observed the η_c in ten different decay channels. From an unbinned likelihood fit to all decay channels simultaneously, a value of $\Gamma_{\gamma\gamma}(\eta_c) = 6.9 \pm 1.7_{\rm stat} \pm 0.8_{\rm sys} \pm 2.0_{\rm BR}$ keV, is derived. This is well in line with other measurements, as shown in Table III, and also with theoretical predictions [7], which vary between 3 and 11 keV.

TABLE III

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

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	$6.9 \pm 1.7\ \pm 0.8\ \pm 2.0$

L3 also presented the first measurement of the η_c form factor of the η_c. In the case of the π^0, the η and the η' mesons, a measurement of the form factor, *i.e.* the Q^2 dependence of $\Gamma_{\gamma\gamma}$, discriminates between different models of momentum distributions of the quarks inside these mesons [8].

The momentum distributions are translated to form factors using the Modified Hard Scattering Approach [8], and the result can then be parametrised by $F(Q^2) = F(0)/(1+Q^2/\Lambda^2)^2$. The pole mass Λ corresponds to the mass of the ρ-meson, at least for the π^0 and the η, hence the name 'ρ-pole form factors'.

Figure 3 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. 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.

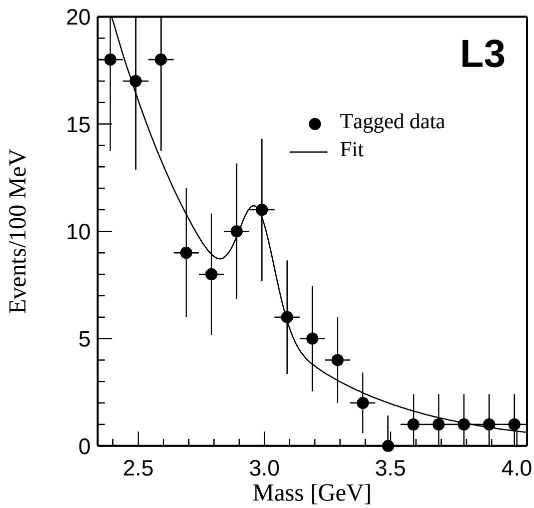

Fig. 3. Mass distribution of tagged events

From a 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 [9], that an asymptotic wave function would lead to exactly such a form factor.

The L3 and DELPHI experiments have searched for signals of the η_c' in the invariant mass spectra where the η_c appears, assuming that it will have the same decay channels as the η_c. Barnes *et al.* [10] 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'.

The DELPHI collaboration [11] published a mass distribution which exhibits a clear η_c, but no η_c', leading to an upper limit of $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) <$ 0.34 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., significantly below the prediction by Barnes *et al.* .

I wish to thank the organizers of the MESON 2000 Workshop, as well as my colleagues of L3, for allowing me to speak on a subject which has occupied me for a very long time [12].

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