Charmonium resonance production in $\gamma\gamma$ collisions with the L3 detector

Begoña de la Cruz[a]
on behalf of the L3 Collaboration

[a]CIEMAT, Avda. Complutense 22, 28040 Madrid, Spain

The production of $c\bar{c}$ states in two-photon collisions has been studied with the L3 detector at LEP. We present results on the two-photon partial widths for the resonances η_c and χ_{c2}, measured at $\sqrt{s} \simeq 91$ GeV with an integrated luminosity of 140 pb^{-1} and at $\sqrt{s} \simeq 183$ GeV with an integrated luminosity of 50 pb^{-1}. The studied decay channels are $\eta_c \to 4\pi, K^+K^-\pi^+\pi^-, \phi\phi, K^0K^\mp\pi^\pm, \pi^0K^+K^-, \eta\pi^+\pi^-, \eta'\pi^+\pi^-, \rho\rho$ and $\chi_{c2} \to J/\Psi\gamma$.

1. INTRODUCTION

The process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R$, where R is a resonant C=+1 meson, provides valuable information on the meson constituents. The scattered e^+e^- usually go undetected along the beam pipe, allowing the photons to be considered as quasi-real and the resonances to be produced isolated in the detector. If an electron is detected in the very forward electromagnetic calorimeters the event is said to be *tagged*.

The cross section for two-photon resonance production is given by [1]

$$\sigma(e^+e^- \to e^+e^-R) = \int \sigma_{\gamma\gamma\to R} d\mathcal{L}_{\gamma\gamma}(W^2) \qquad (1)$$

with the Breit-Wigner cross section

$$\sigma_{\gamma\gamma\to R}(W^2) = 8\pi(2J+1)F^2(q_1^2,q_2^2) \times \frac{\Gamma_{\gamma\gamma}\Gamma}{(W^2-M^2)^2+M^2\Gamma^2} \qquad (2)$$

Here W is the two-photon center of mass energy, q_1^2, q_2^2 the square of the photon four-momenta, $\mathcal{L}_{\gamma\gamma}(W^2)$ the two photon luminosity function. The resonance parameters are $M, J, \Gamma_{\gamma\gamma}$ and Γ, its mass, spin, two-photon partial width and total width, respectively. The two-photon width $\Gamma_{\gamma\gamma}$ is, thus, linearly proportional to the total cross section:

$$\sigma(e^+e^- \to e^+e^-R) = \kappa\,\Gamma_{\gamma\gamma} \qquad (3)$$

The transition form factor $F^2(q_1^2,q_2^2)$ contains the cross section dependence on the square of the momentum transferred to the photons and it is equal to unity for quasi-real photons. In the Vector Dominance Model it is parametrized by a pole form

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

with $\Lambda = m_V, V = \rho, \omega, \phi, J/\Psi...$

In the case of charmonium $c\bar{c}$ mesons, the J^{PC} states accessible in quasi-real two-photon reactions are 0^{-+}, 0^{++} and 2^{++}, corresponding to $\eta_c(2980)$, $\chi_{c0}(3415)$ and $\chi_{c2}(3555)$.

We report results from the whole statistics obtained by the L3 detector at $\sqrt{s} \simeq 91$ GeV, during the years 1991 through 1995, corresponding to a total integrated luminosity of 140 pb^{-1}, both for the η_c and the χ_{c2} resonance, and from data collected at a $\sqrt{s} \simeq 183$ GeV, corresponding to an integrated luminosity of 52.4 pb^{-1} for χ_{c2}.

To measure the two-photon partial width several decay modes of the charmonium resonances have been combined and the accuracy of the measurement is limited by the present accuracy on the resonance width and branching ratios. The χ_{c2} is detected through its dominant radiative decay to J/Ψ and the subsequent leptonic decay $\chi_{c2} \to \gamma J/\Psi \to \gamma e^+e^-, \gamma\mu^+\mu^-$. The η_c does not have a dominant decay mode and ten channels, listed in Table 1, have been analyzed. The χ_{c0} has a very small branching ratio into radiative J/Ψ decay and at the present level of statistics we have no evidence of signal in the χ_{c0} mass region.

Table 1
Branching ratio for the different η_c decay channels considered. They have all been determined in the reaction J/$\Psi \to \gamma\eta_c$.

Channel	BR (%)
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	1.2 ± 0.4
$\eta_c \to K^+K^-\pi^+\pi^-$	2.0 ± 0.7
$\eta_c \to \Phi\Phi$	0.17 ± 0.07
$\eta_c \to K^0K^\pm\pi^\mp$	1.26 ± 0.39
$\eta_c \to \eta(\gamma\gamma)\pi^+\pi^-$	1.28 ± 0.47
$\eta_c \to \pi^0K^+K^-$	0.90 ± 0.28
$\eta_c \to \rho^+\rho^-$	1.73 ± 0.6
$\eta_c \to \eta(\pi\pi\pi)\pi^+\pi^-$	0.76 ± 0.28
$\eta_c \to \eta'(\eta\pi\pi)\pi^+\pi^-$	0.47 ± 0.20
$\eta_c \to \eta'(\rho\gamma)\pi^+\pi^-$	0.83 ± 0.34

2. L3 DETECTOR AND MONTECARLO

A detailed description of the L3 detector can be found in reference [2]. This analysis is mainly based on the central tracking system and the high resolution electromagnetic calorimeter. Particles scattered at small angles are measured by the luminosity monitor (LUMI) ($25 < \theta < 69$ mrad), and by a very small angle tagger (VSAT) ($5 < \theta < 10$ mrad).

For acceptance and efficiency purposes the PC MonteCarlo [3], based on the formalism of Budnev et al. [1], has been used. It generates the $e^+e^- \to e^+e^-R$ process for each individual decay channel of the resonance considered. The Q^2-dependence of the cross section is taken into account introducing a VDM form-factor with a J/Ψ-mass pole. For the χ_{c2} production it is assumed that only the helicity state λ=2 contributes to $\gamma\gamma \to \chi_{c2}$ formation [4].

3. χ_{c2} ANALYSIS

The χ_{c2} decays to γJ/Ψ, with the subsequent decay of the J/Ψ to e^+e^- or $\mu^+\mu^-$. Thus the final state consists of two oppositely charged leptons and a photon.

Candidates to χ_{c2} are recognized as events with a pair of leptons, with their mass within 250 MeV of the nominal J/Ψ mass, and a photon with an energy above 300 MeV. The excellent energy resolution of the electromagnetic calorimeter allows the detection of the χ_{c2} signal with the measurement of the mass difference $\Delta M = M(l^+l^-\gamma) - M(l^+l^-)$, with $l = e$ or μ (Figure 1a). In this spectrum the χ_{c2} signal appears at the expected value, $\Delta M = 0.459$ GeV, corresponding to the energy of the decay photon.

In order to subtract the background we fit the ΔM spectrum obtained from the J/Ψ sidebands ($2.5 < M(l^+l^-) < 2.8$ GeV and $3.4 < M(l^+l^-) < 3.7$ GeV) with a threshold function of the form $a_1 \frac{\exp(-x/a_2)}{1+\exp((a_3-x)/a_4)}$, as shown in Figure 1b.

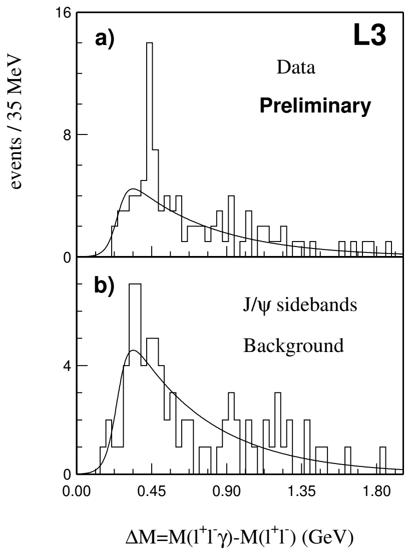

Figure 1. The mass difference $\Delta M = M(l^+l^-\gamma) - M(l^+l^-)$ for the selected sample (a) and the J/Ψ-sidebands sample (b). Both spectra are fitted with a threshold function, but for the signal sample, the region $0.38 < \Delta M < 0.52$ GeV is excluded.

After background subtraction in the region $0.4 < M(l^+l^-\gamma) - M(l^+l^-) < 0.5$, we observe an enhancement of 7.0 signal events above a background of 6.0, at $\sqrt{s} = 91$ GeV, and 5.1 events above a background of 4.9 at $\sqrt{s} = 183$ GeV.

3.1. $\Gamma_{\gamma\gamma}(\chi_{c2})$

The two-photon width of the χ_{c2} is obtained maximizing the likelihood of a Poisson density function $\mathcal{L} = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$,where i runs over the two data sets corresponding to the two center of mass energies analyzed, n_i is the total number of events observed in the signal region and $\mu_i = \mu_S + \mu_B$, is the number of expected signal events (μ_S) plus the number of background events estimated from the J/Ψ sidebands (μ_B). The number of expected signal events is obtained from the integrated luminosity L, the branching ratio of the channel BR, the detector efficiency ϵ and the proportionality factor κ computed from the MonteCarlo events, and is given by

$$\mu_S = \kappa\, \epsilon\, BR\, L\, \Gamma_{\gamma\gamma}(\chi_{c2})$$

The value obtained maximizing the previous likelihood is

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.99^{+0.43}_{-0.37}(\text{stat}) \pm 0.36(\text{sys})\ \text{keV}$$

The systematic error includes the background subtraction (13%), the uncertainty in the total branching ratio (8%) and selection requirements (30%). Uncertainties in the MonteCarlo modelling (only transverse-transverse production, J/Ψ form factor and helicity corrections) amount to 12%. The error on trigger simulation is 2% for 1991-1995 data and 5% for 1997 data. These contributions result in a total systematic error of 36%.

The value obtained for $\Gamma_{\gamma\gamma}(\chi_{c2})$ is compared to other measurements in Table 2. It is compatible within the errors with values measured by other experiments [5], showing the best agreement with the CLEO result.

4. η_c ANALYSIS

Candidates to η_c are selected from events with either two or four charged tracks and zero or several photons, depending on the decay mode. In some channels, intermediate particles must be reconstructed, like π^0, η, as pairs of photons with their mass compatible with the neutral particle nominal mass. K^0_S are identified by the geometrical reconstruction of the secondary vertex $K^0_S \to \pi^+\pi^-$ and ρ, η from their decay to charged tracks, assumed to be pions.

The η_c signal in each channel has low statistics and the significance of the signal is estimated by the maximum likelihood ratio test [6,7]. This test consists in computing the ratio between the maximum value of two likelihood functions: one that fits data under the assumption of no signal (exponential background) and the other that fits data under the hypothesis of a Gaussian η_c signal of mass and width fixed to the MonteCarlo expected values. This ratio of the two likelihood values is small if the signal is statistically significant. In this case, the number of η_c events is computed from an unbinned maximum likelihood fit to the mass distribution. If, on the other hand, the probability that the observed signal is a background fluctuation is greater than 10%, we estimate an upper limit for the number of η_c events using Poisson statistics.

The mass distribution for all η_c decay channels added together, for tagged and untagged events, is presented in Figure 2. The distribution is fitted to an exponential background plus a Gaussian for the η_c signal, giving M(η_c)= 2.975 $\pm$ 0.008 GeV, in excellent agreement with the world average 2.979 $\pm$ 0.002 GeV [8]. The width of the gaussian is 0.061 $\pm$ 0.007 GeV.

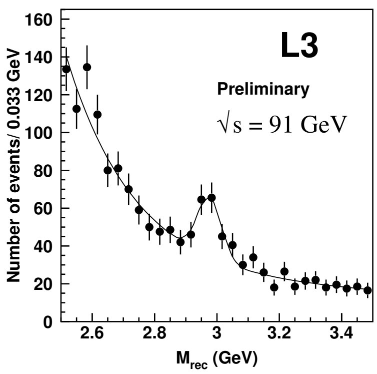

Figure 2. The mass spectrum for all η_c decay channels added together. The distribution has been fitted with an exponential for the background and a Gaussian for the signal.

Table 2
Comparison of $\Gamma_{\gamma\gamma}(\chi_{c2})$ obtained in this analysis to other measurements.

Experiment	**Production mechanism**	$\mathbf{\Gamma_{\gamma\gamma}(\chi_{c2})}$ **(keV)**
R704	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.9\ ^{+1.3}_{-1.0} \pm 1.7$
E760	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.32 \pm 0.08 \pm 0.05$
TPC/2γ	$\gamma\gamma \to \chi_{c2} \to \gamma\ \mathrm{J}/\Psi$	$3.4 \pm 1.7 \pm 0.9$
CLEO	$\gamma\gamma \to \chi_{c2} \to \gamma\ \mathrm{J}/\Psi$	$1.08 \pm 0.30 \pm 0.26$
Avg PDG98		0.37 ± 0.17
L3 (this analysis)	$\gamma\gamma \to \chi_{c2} \to \gamma\ \mathrm{J}/\Psi$	$0.99^{+0.43}_{-0.37} \pm 0.36$
OPAL (prel.)	$\gamma\gamma \to \chi_{c2} \to \gamma\ \mathrm{J}/\Psi$	$1.76 \pm 0.47 \pm 0.37 \pm 0.15$

4.1. $\Gamma_{\gamma\gamma}(\eta_c)$

The two-photon width of the η_c is obtained from the combined information of all ten decay modes, searching for the value $\Gamma_{\gamma\gamma}(\eta_c)$ which maximizes the likelihood function

$$\mathcal{L}(\Gamma_{\gamma\gamma}) = \prod_{i=1}^{N_{decay}} \mathcal{P}_i(\Gamma_{\gamma\gamma}) \tag{4}$$

where $\mathcal{P}_i(\Gamma_{\gamma\gamma})$ is the probability distribution function with the expected number of events in each decay channel. For those channels with a significant signal, the probability distribution is an exponential plus a Gaussian shape, as obtained from the mass spectrum fit; for the channels with no apparent signal it is a Poissonian background distribution.

The $\Gamma_{\gamma\gamma}(\eta_c)$ value obtained from the fit, taking into account only statistical errors is $\Gamma_{\gamma\gamma}(\eta_c) = 9.3^{+1.8}_{-1.7}$ keV

Systematic errors are separated into errors common to all decay modes and errors particular to each channel. The common errors, due to MonteCarlo modelling and common selection requirements, are negligible in comparison to the uncertainty introduced by the poor knowledge of the branching ratio, $\mathrm{BR}(\mathrm{J}/\Psi \to \gamma\eta_c) = (1.27 \pm 0.36)$ % [8]. The systematic errors related to the individual channels take into account uncertainties in the efficiency, on the selection requirements and a residual uncertainty on the individual branching ratios.

Combining the ten channels with statistical and systematic errors we obtain $\Gamma_{\gamma\gamma}(\eta_c) =$
$= 9.5^{+2.1}_{-1.9}\,(\mathrm{stat+sys}) \pm 2.7\,(\mathrm{BR}(\mathrm{J}/\Psi))$ keV

Figure 3 shows a comparison of this result to previous $\Gamma_{\gamma\gamma}(\eta_c)$ measurements [9] and to the world average.

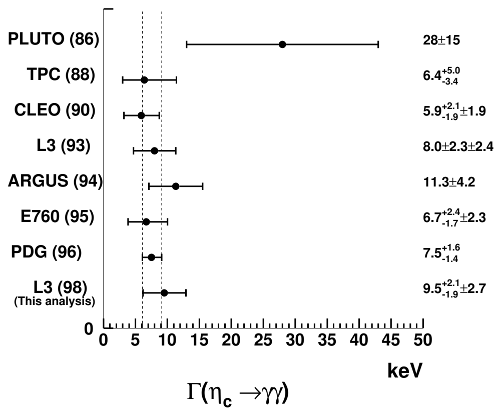

Figure 3. Comparison with previous measurements of $\Gamma_{\gamma\gamma}(\eta_c)$ performed by experiments at different colliders. The vertical dashed lines show the world average according to PDG [8].

5. THE η_c FORM FACTOR

In Figure 4 the mass spectrum for single tagged η_c candidates from all the decay channels is shown. There are 8 events in the signal region and the number of background events, predicted from a fit to an exponential function at the sidebands of the η_c signal is 2.9.

By reweighting MonteCarlo events with different form factors, we calculate the number of expected signal events by different mass poles. Fig-

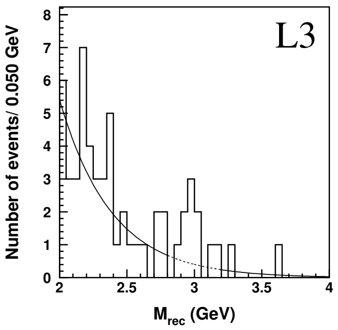

Figure 4. The invariant mass spectrum for the single tagged events from all η_c decay channels together. The line is an exponential fit to the η_c sidebands (2.0-2.8 and 3.2-4.0 GeV).

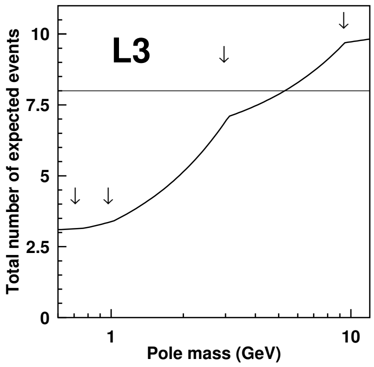

Figure 5. Number of expected η_c events as a function of the pole mass in the VDM form factor. The points for a $\rho(770)$, $\Phi(1020)$, $J/\Psi(3098)$, $\Upsilon(9460)$ and infinite pole (no form factor) are computed, while the other points are linear interpolations between them.

ure 5 shows the number of expected events plus the background as a function of the VDM pole mass. The points for $\rho(770)$, $\Phi(1020)$, $J/\Psi(3098)$, $\Upsilon(9460)$ and infinite pole (no form factor) are computed, while the other points are linear interpolations between them. It can be seen that the observed number of 8 events is compatible with a pole mass slightly above the J/Ψ mass.

From a log-likelihood fit of the number of observed events to the number of expected events, we can exclude, at 95 % CL, that the ρ-pole is the only pole in the VDM form factor for the η_c production and we establish the need for a J/Ψ-mass pole in the VDM form factor.

REFERENCES

1. V.M. Budnev *et al.*, Phys. Rev. **15** (1975) 181.
2. L3 Collab., B. Adeva *et al.*, Nucl. Inst. and Meth. **A289** (1990) 35;
   L3 Collab., M. Acciarri *et al.*, Nucl. Inst. and Meth. **A351** (1994) 300.
3. F.L. Linde, Ph.D Thesis, Rijksuniversiteit Leiden, 1988.
4. Z.P. Li, F.E. Close, T. Barnes, Phys. Rev. **D 43** (1993) 3037.
5. E760 Collab., T.A. Amstrong *et al.*, Phys. Rev. Lett. **70** (1993) 2988;
   TPC/2γ Collab., D.A. Bauer *et al.*, Phys. Lett. **B302** (1993) 345;
   CLEO Collab., J. Dominick *et al.*, Phys. Rev. **D50** (1994) 4265;
   R704 Collab., Baglin *et al.*. Phys. Lett. **B187** (1987) 191.
6. J.A. Rice, *Statistics and Data Analysis*, chapter 9.5.
7. F. James, 1980 CERN *School of Computing*, page 182. (1980).
8. Phys. Rev. **D 54** (1996) 1.
9. ARGUS Collab., H. Albrecht *et al.*, Phys. Lett. **B338** (1994) 390;
   E760 Collab., T.A. Amstrong *et al.*, Phys. Rev. **D52** (1995) 4839;
   PLUTO Collab., Ch. Berger *et al.*, Phys. Lett. **B167** (1986) 120;
   TPC/2γ Collab., H. Aihara *et al.*, Phys. Rev. Lett. **60** (1988) 2355;
   CLEO Collab., W.-Y. Chen *et al.*, Phys. Lett. **B243** (1990) 169;
   L3 Collab., O. Adriani *et al.*, Phys. Lett. **B318** (1993) 575.