Charmonium Resonance Formation in $\gamma\gamma$ Collisions with the L3 Detector

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Measurements of the two-photon partial widths of the charmonium mesons χ_{c2} and η_c from data collected by the L3 detector are presented. The data comprises 140 pb^{-1} at $\sqrt{s} \approx 91$ GeV and 52 pb^{-1} at $\sqrt{s} \approx 183$ GeV. The Q^2 dependence of the η_c cross section is studied for $Q^2 < 9$ GeV^2. A J/ψ pole form factor in the VMD model is found to describe the data better than a ρ pole.

1. Introduction

Measurements of charmonium systems in $\gamma\gamma$ collisions are motivated by the definite predictions of cross sections and form factors made by perturbative calculations assuming charm quarks bound by a QCD potential.

At e^+e^- colliders, charmonium resonance formation is studied via $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R$ where R is a $C = +1$ meson such as η_c,χ_{c0} or χ_{c2}. The total production cross section is related to the two-photon cross section $\sigma(\gamma\gamma \to R)$ by the QED luminosity function $L_{\gamma\gamma}^{QED}$:

$$\sigma(e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R) \quad = \quad \int d^5 L_{\gamma\gamma}^{QED} \cdot \sigma(\gamma\gamma \to R) \tag{1}$$

The two-photon cross section depends on the characteristics of the resonance such as the 2-photon width $\Gamma_{\gamma\gamma}(R)$,

$$\sigma(\gamma\gamma \to R) \quad = \quad 8\pi(2J_R+1)\frac{\Gamma_{\gamma\gamma}(R)\Gamma_R}{(W^2-M_R^2)^2+M_R^2\Gamma_R^2} \times F^2(q_1^2,q_2^2) \tag{2}$$

and the transition form factor $F^2(q_1^2,q_2^2)$, which is expressed in pole form as:

$$F^2(q_1^2,q_2^2) \quad = \quad F^2(q_1^2)F^2(q_2^2) = \frac{1}{1-q_1^2/\Lambda^2}\cdot\frac{1}{1-q_2^2/\Lambda^2} \text{ in VMD } \Lambda = \mathrm{m}_\rho, \mathrm{m}_\omega, \mathrm{m}_{\mathrm{J}/\psi}, \ldots \tag{3}$$

Usually the electrons are not suffiently scattered to be “tagged” by the forward calorimeters, with small momentum transfers $q_1^2 \approx q_2^2 \approx 0$ corresponding to quasi-real photons, and the transition form factor approaches unity. Resulting in a linear relationship between the total cross section $\sigma(e^+e^- \to R)$ and the 2-photon width $\Gamma_{\gamma\gamma}(R)$.

When a scattered electron is detected $Q^2 = -q_1^2$, $q_2^2 \approx 0$ the θ_{tag} and E_{tag} allow the Q^2 dependence or transition form factor of the cross section to be measured.

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2. $\chi_{c2} \to J/\psi\,\gamma \to \ell^+\ell^-$ selection

This decay mode provides a clean final state signature of 2 muon or electron tracks of opposite charge and one photon. A selection is made by requiring the invariant mass of the leptons $M(\ell^+\ell^-)$ to be within 0.25 GeV of the J/ψ mass and the total transverse momentum imbalance $\Sigma\vec{p_t}^{\,2}$ to be less than 0.08 GeV^2, ensuring all significant decay particles are detected. The photon energy E_γ is required to be greater than 0.3 GeV as indicated in Figure 1a.

a) b)

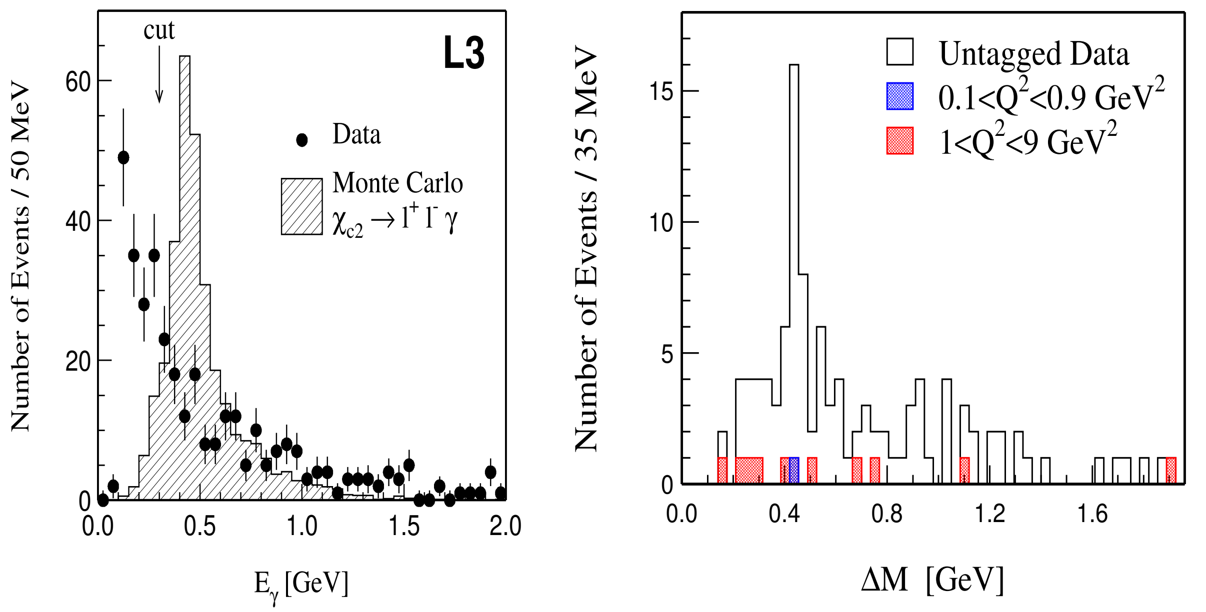

Figure 1. a) Photon energy distribution for data and arbitrarily normalised Monte Carlo, b) Mass difference, $\Delta M = M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)$, from the total data sample.

Within this selection the invariant mass difference $\Delta M = M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)$ of Figure 1b reveals a peak at the expected position. Modelling the ΔM spectrum with a gaussian and threshold function, an unbinned likelihood fit to the spectrum and the J/ψ sidebands yields 13.6 events corresponding to:

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.02 \pm 0.40_{\rm stat} \pm 0.15_{\rm sys} \pm 0.09_{\rm Br}\ \text{keV}$$

Comparing with other $\Gamma_{\gamma\gamma}(\chi_{c2})$ measurements in Table 1 shows consistency of the two-photon measurements, but a 3σ discrepancy with the more precise $p\bar{p}$ measurements. The $p\bar{p}$ measurements are at the low end of the range of theoretical predictions [1] of 0.3-0.6 keV.

Table 1

		$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
L3[2]	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	1.02 ±0.40 ±0.15
OPAL[3]	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	1.76 ±0.47 ±0.37
CLEO[4]	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	1.08 ±0.30 ±0.26
E760[5]	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	0.32 ±0.08 ±0.05
E835[6]	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	0.31 ±0.05 ±0.04

3. η_c formation

Table 2

Decay mode	Branching ratio (%)	Signature
$\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.)	1.2 ± 0.4	4 tracks
$K^+K^-\pi^+\pi^-$	2.0 ± 0.7	4 tracks
$K^0_S K^\pm\pi^\mp$, $K_S \to \pi^+\pi^-$	1.3 ± 0.4	2 tracks, sec. vertex
$\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	1.3 ± 0.5	2 tracks, 2 photons
$\pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$	0.8 ± 0.3	4 tracks, 2 photons
$\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\gamma$	0.8 ± 0.3	4 tracks, 1 photon
$\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\eta$	0.5 ± 0.2	4 tracks, 2 photons
$K^+K^-\pi^0$	0.9 ± 0.3	2 tracks, 2 photons
$\rho^+\rho^-$, $\rho^\pm \to \pi^\pm\pi^0$	1.7 ± 0.6	2 tracks, 4 photons

The η_c is observed using 9 hadronic decay modes, listed in Table 2, corresponding to a total branching ratio of 10.5%. The modes are selected using their different signatures and requiring invariant masses of groups of tracks to match these signaturess, as well as requiring a small momentum imbalance to ensure all significant particles are detected. Untagged events from all modes from both LEP1 and 2 samples, yield the η_c mass spectrum of Figure 2, with a signal at the expected mass. An unbinned likelihood fit to all modes simultaneously, accounting for the different efficiencies of each mode at each energy point, yields 76 ± 19 η_c events in a Gaussian peak above an exponential background. This corresponds to a two photon width of:

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

This value is consistent with other measurements and with the range of theoretical predictions, as shown in Table 3.

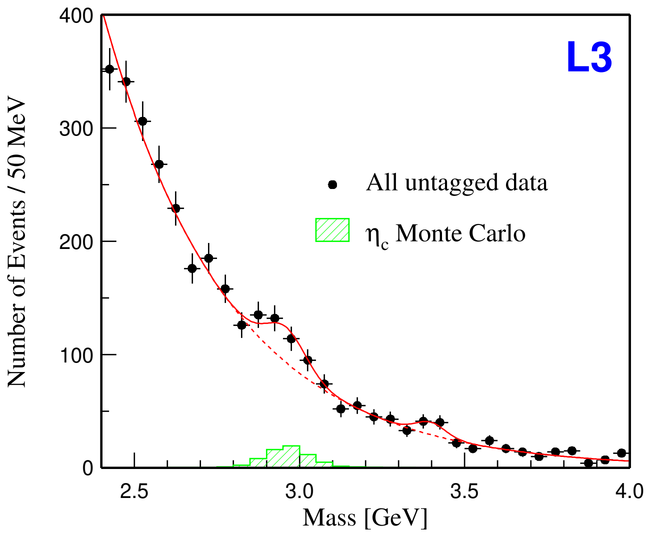

Figure 2. η_c mass spectrum.

Table 3

	$\Gamma_{\gamma\gamma}(\eta_c)$ (keV)
L3 [7]	$6.9 \pm 1.7 \pm 0.8$
PLUTO [8]	28 ± 15
E760 [9]	$6.7\ ^{+2.4}_{-1.7} \pm 2.3$
ARGUS [10]	11.3 ± 4.2
CLEO [11]	$5.9\ ^{+2.1}_{-1.8} \pm 1.9$
TPC/2γ [12]	$6.4\ ^{+5.0}_{-3.4}$
Theory [13]	3-9

4. η_c form factor

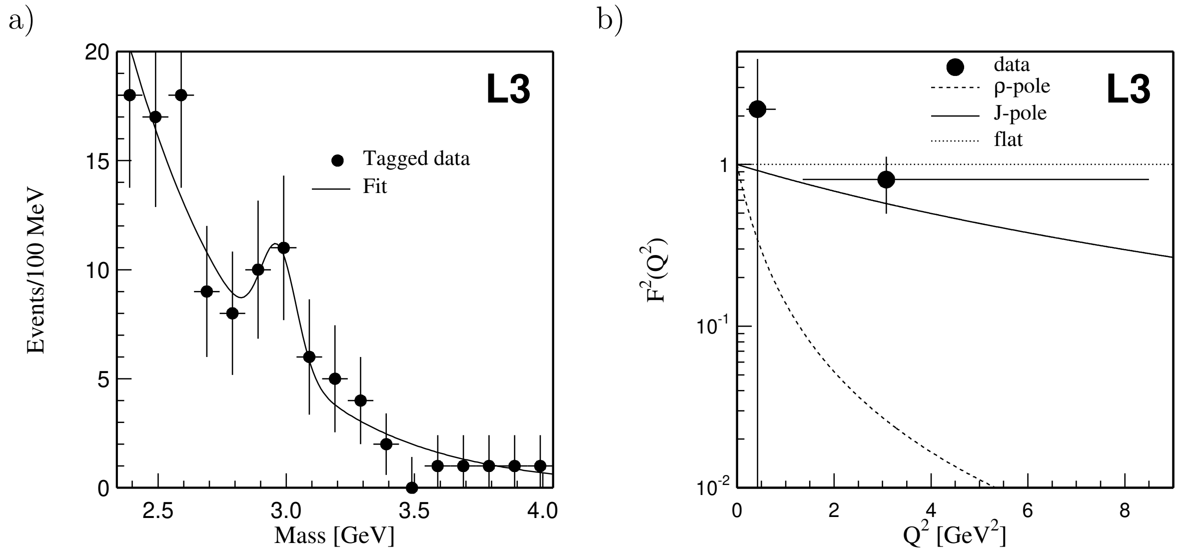

Figure 3. a) Mass distribution of tagged events. b) η_c form factor as a function of Q^2.

A first measurement of the Q^2 dependance of $\Gamma_{\gamma\gamma}(\eta_c)$ has been made using events tagged by the forward calorimeters of the L3 detector. Figure 3a shows the η_c mass spectrum for events tagged in the Very Small Angle Tagger at $\sqrt{s} \approx 183$ GeV ($Q^2 = 0.2 - 0.8$ GeV^2) or in the Luminosity monitor at $\sqrt{s} \approx 91$ GeV ($Q^2 = 1.3 - 8.5$ GeV^2). Separate unbinned likelihood fits for these Q^2 ranges yield 2.3 ± 2.3 and 7.7 ± 3.0 events respectively, corresponding to the η_c form factor of Figure 3b. A J/ψ-pole form factor is found to be 10 times more probable than a ρ-pole form factor.

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Table 3

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Theory [13]	3-9		