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Study of η_c production in two-photon collisions

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Abstract. Production of the η_c meson in e^+e^- quasi-real two photon collisions has been looked for in three channels. The data were obtained from an integrated luminosity of $189\,\mathrm{pb}^{-1}$. An η_c signal is observed in two decay modes ($K_s^0K^\pm\pi^\mp$, $\pi^+\pi^-\pi^+\pi^-$) with a combined statistical significance of 3.5 standard deviations. Using the known η_c branching ratios to these channels and to $K^+K^-\pi^+\pi^-$, the combined partial η_c width to $\gamma\gamma$ is $\Gamma_{\gamma\gamma}(\eta_c)=19.9\pm6.1\pm8.6$ keV. The first error is statistical, and the second one includes the systematic and branching ratio errors. Calculated as an upper limit we obtain $\Gamma_{\gamma\gamma}(\eta_c)<36$ keV (95% C.L., including the systematic error).

1 Introduction

We have looked for η_c production by two-photon collisions in the reactions

$$e^+e^-\to e^+e^-K_s^0K^\pm\pi^\mp, \tag{1}$$

$$e^+e^-\to e^+e^-\pi^+\pi^-\pi^+\pi^-, \tag{2}$$

$$e^+e^-\to e^+e^-K^+K^-\pi^+\pi^- \tag{3}$$

where branching ratios of the η_c are available [1]. These reactions allow measurement of the two-photon partial width of the η_c, $\Gamma_{\gamma\gamma}(\eta_c)$, which is important for the understanding of the dynamics of the charmonium system. So far $\Gamma_{\gamma\gamma}(\eta_c)$ has been only poorly determined, with very large errors:

1. The PLUTO Collaboration [2] saw $7\eta_c$ events produced in reaction (1) at PETRA in a data sample corresponding to an integrated luminosity of $45\,\mathrm{pb}^{-1}$. They reported the product of $\Gamma_{\gamma\gamma}(\eta_c)B(\eta_c\to K_s^0K^\pm\pi^\mp)=0.5^{+0.2}_{-0.15}\pm0.1$ keV. Using the current value [1] of $B(\eta_c\to K\bar{K}\pi)=(5.4\pm1.8)\%$, and from I-spin and Clebsch-Gordan considerations, this value corresponds to $\Gamma_{\gamma\gamma}(\eta_c)=28\pm15$ keV.

2. The MARK II Collaboration [3] at PEP observed 4 events in the same channel, and obtained a preliminary result of $\Gamma_{\gamma\gamma}(\eta_c)=8.0\pm5.0\pm2.0$ keV.

3. An ISR experiment [4], intersecting a cooled coasting antiproton beam with a molecular hydrogen jet, found an enhancement in the excitation curve of the reaction $\bar{p}p\to\gamma\gamma$ at the η_c mass region. Using the published value [5] of $B(\eta_c\to\bar{p}p)$, they obtain the result $\Gamma_{\gamma\gamma}(\eta_c)=4.3^{+3.4}_{-3.7}\pm2.4$ keV.

4. Results of the TPC/Two Gamma Collaboration [6] searching for η_c in various four-prong final states in $\gamma\gamma$ collisions yielded for a data sample of $69\,\mathrm{pb}^{-1}$ $\Gamma_{\gamma\gamma}(\eta_c)=6.4^{+5.0}_{-3.4}$ keV or $1.7\text{ keV}<\Gamma_{\gamma\gamma}(\eta_c)<15.5$ keV (95% CL).

5. The MD-1 experiment at Novosibirsk has done a missing-mass measurement [7] in the reaction $e^+e^-\to e^+e^-+X$. With a data sample of $23.5\,\mathrm{pb}^{-1}$ they see no η_c, and give a preliminary result: $\Gamma_{\gamma\gamma}(\eta_c)<11$ keV (90% CL).

6. Similar preliminary results have been recently presented from the final state $K_s^0K^\pm\pi^\mp$ by the JADE Collaboration [8]: $\Gamma_{\gamma\gamma}(\eta_c)<11$ keV (95% CL) and by the CELLO Collaboration [9]: $\Gamma_{\gamma\gamma}(\eta_c)<12$ keV (95% CL).

Theoretical estimates of $\Gamma_{\gamma\gamma}(\eta_c)$ are generally obtained from a simple relation with the leptonic J/ψ decays, since both are proportional to the square of the wave function at the origin, and in the simplest approximation these wave functions are assumed to be the same for both cases [10], yielding $\Gamma_{\gamma\gamma}(\eta_c)=6$–7 keV. Corrections have been applied to account for relativistic effects [11–13], QCD corrections [13, 14], gluon condensates [14], and changes in the wave function due to spin-dependent forces [11] or hyperfine mass splitting [15], where the most recent calculations [13, 15] give values of 9–15 keV. The results are in a confused state, with different treatments differing not only in the magnitude but also in the direction of the correction to the simple model, and span the region between $\Gamma_{\gamma\gamma}(\eta_c)=3$–15 keV.

2 Data selection and analysis

In this experiment, a combined study of three known η_c decay channels has been performed. Our data sample consists of 2 run periods: An integrated luminosity of $83\,\mathrm{pb}^{-1}$ was taken at PETRA during 1979–1982 at various beam energies where most of the data is around $E_b=17$ GeV. An integrated luminosity of $106\,\mathrm{pb}^{-1}$ was taken in 1986 at a fixed beam energy of $E_b=17.5$ GeV. The 1986 data has an improved resolution of track parameters due to the TASSO high precision vertex detector (VXD). A general description of the TASSO detector and the vertex chamber can be found in [16–17] respectively. No requirement has been made on the detection of the scattered e^+ and/or e^- in the final state.

The most effective trigger for low multiplicity events required two track candidates in the central drift chamber (DC) found by a hardware pre-processor, containing hit information from the DC, the time-of-flight (TOF) counters, the central proportional chamber (CPC), and, for the second run period, the vertex detector (VXD). In addition the information on the z coordinates of tracks from the CPC-cathode readout was used in this trigger. Other triggers, requiring at least 4 charged tracks or 2 back-to-back tracks were also used. The trigger efficiency per track varied as a function of the track momentum component, p_t, transverse to the beam direction. For the first run period this efficiency reached a value of $\sim 95\%$ for $p_t > 0.29$ GeV/c, while for the second period it was $\sim 70\%$ for $p_t > 0.22$ GeV/c.

Candidate events for reaction (1) produced via two-photon collisions were selected by requiring two acceptable tracks as defined in [18] originating from the interaction point, plus two oppositely charged tracks, taken to be pions, with an effective mass within ± 0.05 GeV of the K_s^0 mass. Candidate events for reactions (2) and (3) were obtained by requiring exactly four acceptable tracks. The net charge of the four tracks in reactions (1–3) had to be zero and the event had to fulfil at least one of the above triggers. In order to suppress background from one-photon annihilation events, the sum of the measured charged particle momenta had to be less than 8 GeV/c. Beam-gas contamination became negligible by requiring $|z_v| < 8$ cm (z_v being the average coordinate along the beam axis of the event tracks), and rejecting events with protons identified by time-of-flight measurements, as described below. Two-photon events with undetected particles were suppressed by demanding the vector sum of the transverse momenta of the final state particles, $|\Sigma\, \mathbf{p}_t|$, to be smaller than 0.2 GeV/c.

In order to obtain a clean event sample for reaction (1), all events with track combinations within ± 0.05 GeV of the K_s^0 mass and with $\gamma\gamma$ CM energy, $W_{\gamma\gamma}$, bigger than 2.0 GeV were scanned, and bad events inconsistent with the final state of reaction (1) were removed. Here $W_{\gamma\gamma}$ is equal to the $K_s^0 K^\pm \pi^\mp$ effective mass (assuming the relevant particle mass assignments), provided no particles are missing in the final state. Particle identification was used as described below. The $\pi^+\pi^-$ effective mass distribution of all track combinations of this sample shows a K_s^0 signal on top of a large background. In order to obtain a cleaner K_s^0 sample and improve the accuracy of its measured parameters, a vertex fit [19] was performed on the pair of pions from the K_s^0 decay by requiring a point of intersection in 3 dimensions. The probability associated with this 1-constraint geometric vertex fit was required to be greater than 1%. In this fit VXD hits were used when available.

An efficient combination of cuts to enhance the K_s^0 content and reduce non-K_s^0 track combinations is to restrict the angle α between the K_s^0 momentum vector and the line of flight connecting the K_s^0 production and decay vertices to values smaller than 10°, and to demand a cut on the K_s^0 decay length of $d > 0.4$ cm. This choice of cuts is also supported by

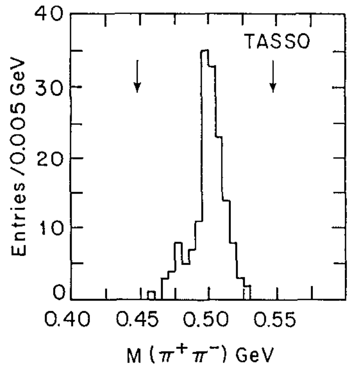

Fig. 1. $M(\pi^+\pi^-)$ distribution for the scanned event sample of reaction (1), with $W_{\gamma\gamma} > 2.0$ GeV/c, of track combinations within ± 0.05 GeV of the K_s^0 mass, as indicated by the arrows. A geometric vertex fit has been applied on the K_s^0 decay products with the additional cuts: $\alpha < 10°$, $d > 0.4$ cm and $|\Sigma\, p_t| < 0.2$ GeV/c (see text)

a Monte Carlo (MC) simulation that will be described later. The $M(\pi^+\pi^-)$ distribution after applying these cuts, shown in Fig. 1, yields a clean K_s^0 sample, with a width consistent with that of the Monte Carlo calculations.

For further analysis we use the above cuts with K_s^0 candidates which are ± 0.025 GeV from the K_s^0 mass. Monte Carlo studies show that slow tracks which may have an appreciable amount of multiple scattering reduce the accuracy of the geometrical vertex fit. Therefore, both $\pi^\pm$ from the K_s^0 decay are required to have momentum bigger than 0.2 GeV/c.

Identification of charged particles in reactions (1–3) is partly achieved by using time-of-flight (TOF) measurements. The TASSO TOF system is described elsewhere [20]. For each particle type i ($i = \pi, K, p$) the probabilities $W_i = C \cdot \exp(-(\tau_m - \tau_i)^2/2\sigma^2)$ are calculated, where τ_m is the measured TOF, τ_i the expected TOF for hypothesis i, and σ is the resolution for the time measurement. C is a normalization factor such that $\Sigma W_i = 1$. A track is defined as an identified π if $W_\pi > 0.5\,(0.9)$ for the first (second) run period, and $0.2 < p_\pi < 1.0$ GeV/c; as an identified K if $W_K > 0.95\,(0.99)$ for the first (second) run period, $0.3 < p_K < 1.0$ GeV/c and $0.1 < M_{\mathrm{TOF}}^2 < 0.6$ GeV^2; and as an identified proton if $W_p > 0.95\,(0.99)$ for the first (second) run period, $0.4 < p_p < 1.4$ GeV/c and $M_{\mathrm{TOF}}^2 > 0.6$ GeV^2. The reason for the two sets of cuts is a slightly degraded TOF resolution for the second run period. A track is defined as consistent with being a $\pi(K; p)$ if it is *not* an identified K or p (π or p; π or K).

In the following analysis, π and K consistency will be required for the respective particles in reactions (1–3). For reaction (1), only one combination per event is given, and if both $K^\pm\pi^\mp$ combinations are consistent ones – each one is taken with a weight of 0.5. Events consistent with a $K_s^0 K_s^0$ final state are not considered as candidates for reaction (1). For reaction (3) $K^\pm$ identification is required, such that $W_{K^+} \cdot W_{K^-} > 0.3$. To reduce overlap with the final states with kaons, candidates for reaction (2) do not include events with any $\pi^+\pi^-$ combination in the K_s^0 mass region, or events which satisfy the requirement $W_{K^+} \cdot W_{K^-} > 0.3$ for reaction (3).

In order to derive the partial width $\Gamma_{\gamma\gamma}(\eta_c)$, Monte Carlo simulation programs have been used, with the full kinematics of the $\gamma\gamma$ system generated according to the flux of transverse photons, using the exact formula of [21]. The dependence on the photon four-momenta has been parametrized by the J/ψ-pole form factors, as in [6]. A ρ^0-pole dependence was also tried, and found to give similar results. The decay of the η_c into the various modes is generated according to phase space. All generated particles are passed through a detailed detector simulation program. The generated events are required to pass the same cuts imposed on the data.

The contamination of one-photon annihilation events leaking into the $\gamma\gamma \to K_s^0 K^\pm \pi^\mp$ event sample is found to be negligible by generating MC simulated events of the type $e^+e^- \to$ hadrons, passing them through the detector simulation and applying all the cuts of the analysis as described above.

3 Results

The M $(K_s^0 K^\pm \pi^\mp)$ distribution of reaction (1) candidates shows an enhancement in the η_c mass region, the precise significance of which depends on the form of background. A least-square fit of the experimental distribution to a Gaussian shape in the η_c region and a background shape of the form $\exp(aM + bM^2)$, where a and b are free parameters and M is the $K_s^0 K^\pm \pi^\mp$ effective mass, results in η_c mass and width values consistent with the accepted η_c mass [1] and with the experimental resolution of $\sigma = 63$ MeV as obtained from the MC simulation. The errors used in the fit are the Poisson errors of the experimental number of events in each bin. With $\sigma = 63$ MeV fixed, the fit yields $M(\eta_c) = 2974 \pm 26$ MeV and $10.6 \pm 3.8\,\eta_c$ events. The significance of the η_c signal, calculated from the difference of the chi-squared of the fits without and with the resonance, is 2.8 standard deviations.

An alternative procedure to the use of the above mentioned K_s^0 mass and angle (α) cuts involves con-

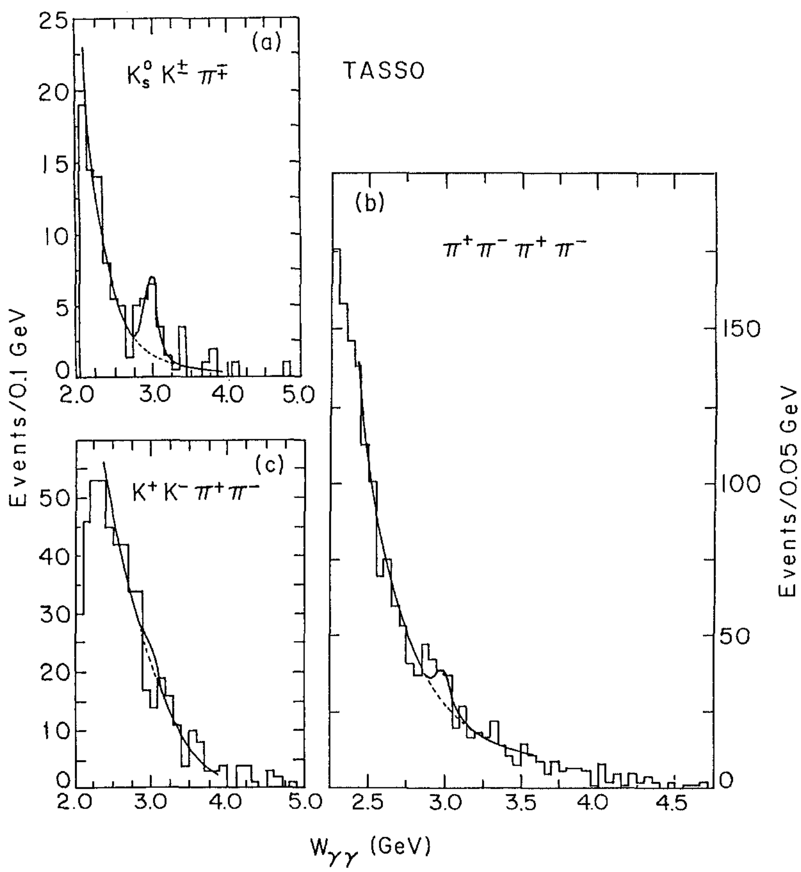

Fig. 2. a) $M(K_s^0 K^\pm \pi^\mp)$ distribution for reaction (1) after applying a kinematical $2C$ fit by requiring $M(\pi^+\pi^-) = M(K^0)$ and $\alpha = 0$, with a cut on the χ^2-probability of this fit bigger than 0.5%. The full curve is a result of a global fit of reactions (1–3) as described in the text and the dashed curve is the background contribution to the fit. **b)** $M(\pi^+\pi^-\pi^+\pi^-)$ distribution for reaction (2). The curves are as in a). **c)** $M(K^+K^-\pi^+\pi^-)$ distribution for reaction (3). The curves are as in a)

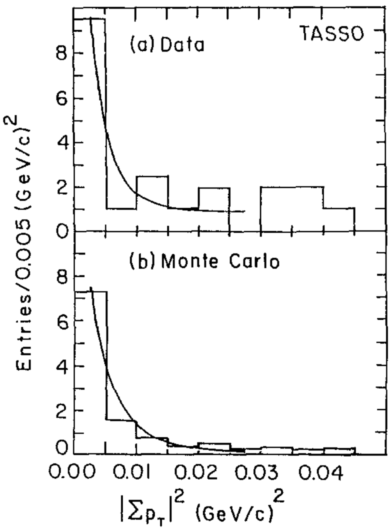

Fig. 3. a) $(\Sigma \mathbf{p}_t)^2$ distribution of data events of reaction (1) in the η_c mass region $(2.75 < M(K_s^0 K^\pm \pi^\mp) < 3.2$ GeV). The curve is a fit to the η_c MC shape of Fig. 3b plus a constant term. **b)** $(\Sigma \mathbf{p}_t)^2$ distribution of η_c Monte Carlo simulated events of reaction (1). The ordinate scale is in arbitrary units. The curve is a parametrization of the shape by an exponential distribution with a second order power

straining both quantities by a kinematical 2-constraint ($2C$) fit of $M(\pi^+\pi^-)$ to the K_s^0 mass, and of α to zero. Accepting only events with a χ^2-probability $P_{2C}(\chi^2)$ of this fit bigger than 0.5%, the resulting $M(K_s^0 K^\pm \pi^\mp)$ spectrum is shown in Fig. 2a. A fit similar to that above yields $M(\eta_c) = 2972 \pm 29$ MeV and $10.4 \pm 3.9\, \eta_c$ events (2.7 s.d.).

Assuming, as in [2], that all the η_c events, within the $|\Sigma \mathbf{p}_t| < 0.2$ GeV/c cut, are exclusive $\gamma\gamma$ events with no missing particles, we obtain from reaction (1) a $\Gamma_{\gamma\gamma}(\eta_c)$ value similar to the PLUTO result [2]. The $(\Sigma \mathbf{p}_t)^2$ distribution of the events of Fig. 2a lying within the η_c mass region $(2.75 < M(K_s^0 K^\pm \pi^\mp) < 3.2$ GeV), is shown in Fig. 3a. In comparison, the same distribution of the MC generated η_c events, with the same cuts as for the data, is given in Fig. 3b. The data exhibits a higher $(\Sigma \mathbf{p}_t)^2$ tail compared with the MC events, indicating that part of the events in the η_c region may be non-exclusive events.

In order to subtract the non-exclusive contribution from the η_c signal, the shape of the non-exclusive part in the $(\Sigma \mathbf{p}_t)^2$ distribution of the data was described by a constant term. This assumption is consistent with the shape of the high $(\Sigma p_t)^2$ tail of the data and, for example, with the $(\Sigma p_t)^2$ distribution of MC generated events of the reaction $\gamma\gamma \to \eta_c \pi^0$, where the π^0 is ignored.

Using the full sample of events with no $|\Sigma \mathbf{p}_t|$ cut, the high $(\Sigma \mathbf{p}_t)^2$ part of the η_c mass region, $0.015 < (\Sigma \mathbf{p}_t)^2 < 0.25\,(\mathrm{GeV/c})^2$, was fitted to a constant shape, and extrapolated to the low $(\Sigma \mathbf{p}_t)^2$ part. A similar procedure was applied to the high $(\Sigma \mathbf{p}_t)^2$ part of control regions below $(2.4 < M(K_s^0 K^\pm \pi^\mp) < 2.65$ GeV) and above $(3.3 < M(K_s^0 K^\pm \pi^\mp) < 3.9$ GeV) the η_c mass region. Using the sample with the $2C$ fit, the fraction of the exclusive part inside the $|\Sigma \mathbf{p}_t| < 0.2$ GeV/c cut for all these mass regions falls within the range from 0.73 to 0.80. Assuming a smooth behavior of the non-η_c background in the three mass regions, this result is consistent with the exclusive fractions of real η_c events and of background events in the η_c region being about the same. Using the fraction 0.77 ± 0.09 of the η_c mass region, the number of exclusive η_c events is determined to be 8.0 ± 3.1. Similar results are obtained when this analysis is done on the sample with no kinematical fit, and/or with fixed η_c widths obtained from MC simulation with ρ^0 rather than the J/ψ-pole form factors. Similar results are also obtained by comparing the $(\Sigma \mathbf{p}_t)^2$ spectrum of the η_c MC shape (curve of Fig. 3b) with that of the data, fitted to the MC shape plus a constant term representing the non-exclusive contribution. The result of this fit is given by the curve of Fig. 3a.

The result of the above procedure was used to extract the $\gamma\gamma$ partial width of the η_c from reaction (1). We obtain $\Gamma_{\gamma\gamma}(\eta_c) \cdot B(\eta_c \to K\bar{K}\pi) = 1.06 \pm 0.41$ (stat.) ± 0.27 (syst.) keV. The systematic error includes 15% uncertainty due to the various fits as described above, and 20% from the acceptance and overall normalization, added in quadrature. Using [1] $B(\eta_c \to K\bar{K}\pi) = (5.4 \pm 1.8)\%$, and adding the branching ratio error quadratically to the systematic error, we obtain $\Gamma_{\gamma\gamma}(\eta_c) = 19.7 \pm 7.7 \pm 8.2$ keV.

A search for an η_c signal in reactions (2) and (3) was performed in a similar manner to the above analysis of reaction (1). In order to improve the momentum resolution for charged particles, the average beam position was used as a constraint in the track reconstruction [22]. In Fig. 2b–c, the $M(\pi^+\pi^-\pi^+\pi^-)$ and $M(K^+K^-\pi^+\pi^-)$ distributions are shown respectively. An enhancement is seen in reaction (2) at a mass close to the η_c nominal value.

In order to extract a $\gamma\gamma$ partial width of the η_c from the 4π channel, possible reflections from reactions (1) and (3) due to $\pi - K$ misidentification were considered by taking a linear mixture of MC events of η_c decaying into $K_s^0 K^\pm \pi^\mp$, $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$ with fractions given by the known branching ratios [1]. When these MC events were analysed as 4π events, passing the same cuts imposed on the data, the overall contribution of the $K^+K^-\pi^+\pi^-$ final state to the 4π mass spectrum was 11%, peaking at ~ 2.73 GeV and extending to 2.85 GeV. The contribution of the $K_s^0 K^\pm \pi^\mp$ final state was found to be negligible. Analysing this mixture of events in terms of the $K_S^0 K^\pm \pi^\mp$ final state, the contributions of the 4π and $K^+K^-\pi^+\pi^-$ MC events were also negligible, presumably due to the stringent cuts imposed on reaction (1).

The data of Fig. 2b were thus fitted to a background shape of an exponential with a second order power as defined above, plus an η_c shape obtained by the above linear mixture of MC η_c events. The fit yielded $41 \pm 15\,\eta_c$ events, with a significance of 2.7 s.d. for the η_c signal.

Using the same procedure as described for reaction (1) to subtract the non-exclusive part of the η_c signal yields a similar fraction of exclusive events inside the $|\Sigma\, \mathbf{p}_t| < 0.2$ GeV/c cut. The result obtained for the η_c partial width to $\gamma\gamma$ is $\Gamma_{\gamma\gamma}(\eta_c) = 26.2 \pm 10.2 \pm 11.3$ keV. The systematic error includes an uncertainty of 35% in the η_c branching ratios [1]. The result is similar to the one obtained for reaction (1).

It has been claimed [23] from a study of J/ψ radiative decays that the $\pi^+\pi^-\pi^+\pi^-$ decay of the η_c is dominated by the $\rho^0\rho^0$ channel. There is however a contradictory result from a similar experiment [24]. Our small statistics and large background preclude a detailed study of this issue.

No η_c enhancement is observed in reaction (3) (Fig. 2c). A similar fitting procedure as described above yields $0 \pm 8.3\,\eta_c$ events, which corresponds to $\Gamma_{\gamma\gamma}(\eta_c) = 0 \pm 23$ keV. The error does not include the uncertainty in the η_c branching ratios or systematic uncertainties.

Our best estimate for the partial width of the η_c to two photons is obtained by performing a global one-parameter fit of reactions (1–3), including reflections. This reactions are the only known 4-prong final states with branching ratios and detection efficiencies which could yield detectable η_c signals in our data sample for all reasonable $\Gamma_{\gamma\gamma}(\eta_c)$ values.

The background of each distribution was parametrized by an exponential with a second order power, as defined above, using the data points outside the η_c region. The η_c was parametrized by the linear mixture of MC events, with branching fractions fixed at the PDG values [1], as described above. A simultaneous fit of the three distributions to the sum of the background shapes plus the η_c shapes, where the free parameter is the relative fraction between the background and η_c shapes, is shown by the full curves in Fig. 2, where the dashed curves are the background contributions. The fit yielded a 3.5 s.d. η_c signal of 49 ± 14 events. Various reasonable background shapes have been attempted. All of them yielded similar results with a significance ranging between about 3–4 s.d. After applying the non-exclusive subtraction as described above, we obtain $\Gamma_{\gamma\gamma}(\eta_c) = 19.9 \pm 6.1\,(\text{stat.}) \pm 8.6\,(\text{syst.})$ keV. As before, the uncertainties in the background shape and the branching ratios are included in the systematic error. Considering our result in terms of an upper limit, we obtain $\Gamma_{\gamma\gamma}(\eta_c) < 36$ keV (95% C.L. including the systematic error).

More data in $\gamma\gamma$ experiments and better η_c branching ratios are needed to obtain an accurate measurement of the $\gamma\gamma$ partial width of the η_c meson, in order to be able to make a critical comparison with the large range of predictions of the various theoretical models.

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