Two-Photon Widths of the $\chi_{cJ}$ States of Charmonium

K. M. Ecklund, 1 W. Love, 2 V. Savinov, 2 A. Lopez, 3 H. Mendez, 3 J. Ramirez, 3 J. Y. Ge, 4 D. H. Miller, 4 I. P. J. Shipsey, 4 B. Xin, 4 G. S. Adams, 5 M. Anderson, 5 J. P. Cummings, 5 I. Danko, 5 D. Hu, 5 B. Moziak, 5 J. Napolitano, 5 Q. He, 6 J. Insler, 6 H. Muramatsu, 6 C. S. Park, 6 E. H. Thorndike, 6 F. Yang, 6 M. Artuso, 7 S. Blusk, 7 S. Khalil, 7 J. Li, 7 R. Mountain, 7 S. Nisar, 7 K. Randrianarivony, 7 N. Sultana, 7 T. Skwarnicki, 7 S. Stone, 7 J. C. Wang, 7 L. M. Zhang, 7 G. Bonvicini, 8 D. Cinabro, 8 M. Dubrovin, 8 A. Lincoln, 8 P. Naik, 9 J. Rademacker, 9 D. M. Asner, 10 K. W. Edwards, 10 J. Reed, 10 R. A. Briere, 11 T. Ferguson, 11 G. Titashvili, 11 H. Vogel, 11 M. E. Watkins, 11 J. L. Rosner, 12 J. P. Alexander, 13 D. G. Cassel, 13 J. E. Duboscq, 13 R. Ehrlich, 13 L. Fields, 13 R. S. Galik, 13 L. Gibbons, 13 R. Gray, 13 S. W. Gray, 13 D. L. Hartill, 13 D. Hertz, 13 J. M. Hunt, 13 J. Kandaswamy, 13 D. L. Kreinick, 13 V. E. Kuznetsov, 13 J. Ledoux, 13 H. Mahlke-Krüger, 13 D. Mohapatra, 13 P. U. E. Onyisi, 13 J. R. Patterson, 13 D. Peterson, 13 D. Riley, 13 A. Ryd, 13 A. J. Sadoff, 13 X. Shi, 13 S. Stroiney, 13 W. M. Sun, 13 T. Wilksen, 13 S. B. Athar, 14 R. Patel, 14 J. Yelton, 14 P. Rubin, 15 B. I. Eisenstein, 16 I. Karliner, 16 S. Mehrabyan, 16 N. Lowrey, 16 M. Selen, 16 E. J. White, 16 J. Wiss, 16 R. E. Mitchell, 17 M. R. Shepherd, 17 D. Besson, 18 T. K. Peclar, 19 D. Cronin-Hennessy, 20 K. Y. Gao, 20 J. Hietala, 20 Y. Kubota, 20 T. Klein, 20 B. W. Lang, 20 R. Poling, 20 A. W. Scott, 20 P. Zweber, 20 S. Dobbs, 21 Z. Metreveli, 21 K. K. Seth, 21 A. Tomaradze, 21 J. Libby, 22 A. Powell, 22 and G. Wilkinson 22

(CLEO Collaboration)

1 State University of New York at Buffalo, Buffalo, New York 14260, USA
2 University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
3 University of Puerto Rico, Mayaguez, Puerto Rico 00681
4 Purdue University, West Lafayette, Indiana 47907, USA
5 Rensselaer Polytechnic Institute, Troy, New York 12180, USA
6 University of Rochester, Rochester, New York 14627, USA
7 Syracuse University, Syracuse, New York 13244, USA
8 Wayne State University, Detroit, Michigan 48202, USA
9 University of Bristol, Bristol BS8 1TL, UK
10 Carleton University, Ottawa, Ontario, Canada K1S 5B6
11 Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
12 Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
13 Cornell University, Ithaca, New York 14853, USA
14 University of Florida, Gainesville, Florida 32611, USA
15 George Mason University, Fairfax, Virginia 22030, USA
16 University of Illinois, Urbana-Champaign, Illinois 61801, USA
17 Indiana University, Bloomington, Indiana 47405, USA
18 University of Kansas, Lawrence, Kansas 66045, USA
19 Luther College, Decorah, Iowa 52101, USA
20 University of Minnesota, Minneapolis, Minnesota 55455, USA
21 Northwestern University, Evanston, Illinois 60208, USA
Abstract

Using a data sample of 24.5 million $\psi(2S)$ the reactions $\psi(2S) \rightarrow \gamma \chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma \gamma$ have been studied for the first time to determine the two-photon widths of the $\chi_{cJ}$ states of charmonium in their decay into two photons. The measured quantities are $B(\psi(2S) \rightarrow \gamma \chi_{c0}) \times B(\chi_{c0} \rightarrow \gamma \gamma) = (2.22 \pm 0.32 \pm 0.10) \times 10^{-5}$, and $B(\psi(2S) \rightarrow \gamma \chi_{c2}) \times B(\chi_{c2} \rightarrow \gamma \gamma) = (2.70 \pm 0.28 \pm 0.15) \times 10^{-5}$. Using values for $B(\psi(2S) \rightarrow \gamma \chi_{c0, c2})$ and $\Gamma(\chi_{c0, c2})$ from the literature the two-photon widths are derived to be $\Gamma_{\gamma \gamma}(\chi_{c0}) = (2.53 \pm 0.37 \pm 0.26) \text{ keV}$, $\Gamma_{\gamma \gamma}(\chi_{c2}) = (0.60 \pm 0.06 \pm 0.06) \text{ keV}$, and $R \equiv \Gamma_{\gamma \gamma}(\chi_{c2}) / \Gamma_{\gamma \gamma}(\chi_{c0}) = 0.237 \pm 0.043 \pm 0.034$. The importance of the measurement of $R$ is emphasized. For the forbidden transition, $\chi_{c1} \rightarrow \gamma \gamma$, an upper limit of $\Gamma_{\gamma \gamma}(\chi_{c1}) < 0.03 \text{ keV}$ is established.
Charmonium spectroscopy has provided some of the most detailed information about the quark-antiquark interaction in Quantum Chromodynamics (QCD). The most practical and convenient realization of QCD for onium spectroscopy is in terms of perturbative QCD (pQCD), modeled after Quantum Electrodynamics (QED). Two-photon decays of charmonium states $\chi_{cJ}(\mathbf{3}P_J)$ offer the closest parallel between QED and QCD, being completely analogous to the decays of the corresponding triplet states of positronium. Of course, the masses of the quarks and the wave functions of the $\chi_c$ states differ from those of positronium, but even these cancel out in the ratio of the two-photon decays, so that for both positronium and charmonium $R \equiv \Gamma(\mathbf{3}P_2 \to \gamma\gamma)/\Gamma(\mathbf{3}P_0 \to \gamma\gamma)=4/15\simeq 0.27$ [1]. The departure from this simple lowest order prediction can arise due to strong radiative corrections and relativistic effects, and the measurement of $R$ provides a unique insight into these effects. Two-photon decay of the spin one $\chi_{c1}$ state is forbidden by the Landau-Yang theorem [2].

There are numerous theoretical potential model predictions of $\Gamma_{\gamma\gamma}(\chi_{c0, c2})$ available in the literature, with some employing relativistic and/or radiative corrections. As shown in Table I, the predictions vary over a wide range. This underscores the importance of measuring these quantities with precision.

| Reference | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) | $\Gamma_{\gamma\gamma}(\chi_{c0})$ (eV) | $R$ |
|----------|------------------|------------------|----|
| Barbieri  | 930              | 3500              | 0.27 |
| Godfrey   | 459              | 1290              | 0.36 |
| Barnes    | 560              | 1560              | 0.36 |
| Bodwin    | 820±230          | 6700±2800         | 0.12±0.06 |
| Gupta     | 570              | 6380              | 0.09 |
| Münz      | 440±140          | 1390±160          | 0.32±0.16 |
| Huang     | 490±150          | 3720±1100         | 0.13±0.06 |
| Ebert     | 500              | 2900              | 0.17 |
| Schuler   | 280              | 2500              | 0.11 |

Most of the existing measurements of $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ are based on formation of $\chi_{cJ}$ in two-photon fusion. The only existing measurements based on the decay of $\chi_{cJ}$ into two photons are from the Fermilab E760/E835 experiments [12, 13, 14] with $\chi_{cJ}$ formation in $p\bar{p}$ annihilation. We report here results for $\Gamma_{\gamma\gamma}(\chi_{cJ})$ measured in the decay of $\chi_{cJ}$ into two photons. For these measurements we use the reactions

$$\psi(2S) \to \gamma_1 \chi_{cJ}, \; \chi_{cJ} \to \gamma_2 \gamma_3, \tag{1}$$

which have not been studied before. Since $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ are obtained from the same measurement, we also obtain $R$ with a good control of systematic errors. Few such simultaneous measurements have been reported in the literature.

A data sample of 24.5 million $\psi(2S)$ obtained in 48 pb$^{-1}$ $e^+e^-$ annihilations at the CESR electron-positron collider was used. The reaction products were detected and identified using the CLEO-c detector.

The CLEO-c detector [15], which has a cylindrical geometry, consists of a CsI electromagnetic calorimeter, an inner vertex drift chamber, a central drift chamber, and a ring-imaging
Cherenkov (RICH) detector, inside a superconducting solenoid magnet providing a 1.0 T magnetic field. For the present measurements the most important component of the detector is the CsI calorimeter which has an acceptance of 93% of 4π and photon energy resolutions of 2.2% at $E_γ=1$ GeV, and 5% at 100 MeV.

The event selection for the final state required three photon showers, each with $E_γ > 70$ MeV and angle $θ$ with respect $e^+$ beam direction with $|\cos θ| < 0.75$, and no charged particles. An energy-momentum conservation constrained 4C-fit was performed and events with $χ^2/d.o.f. < 6$ were accepted. To prevent overlap of the lowest energy photon $γ_1$ with the high energy photons $γ_{2,3}$, events were rejected if $\cos θ' > 0.98$, where $θ'$ is the laboratory angle between $γ_1$ and either $γ_2$ or $γ_3$.

Data were analyzed in two equivalent ways, by constructing the energy spectrum of $E(γ_1)$ and the invariant mass spectrum of $M(γ_2γ_3)$. Consistent results were obtained. Fig. 1 shows the $E(γ_1)$ spectrum. The enhancements due to the excitation of $χ_{c0}$ and $χ_{c2}$ over substantial backgrounds are clearly observed.

In order to analyze these spectra we need to determine the shapes of the background and the resonance peaks. For determining peak shapes and efficiencies fifty thousand signal Monte Carlo (MC) events were generated for $χ_{c0}$ and $χ_{c2}$ each, with masses and widths as given by PDG 07 [16]. The radiative transition $ψ(2S) → γ_1χ_{c0}$ is, of course, pure E1, and there is strong experimental evidence that the radiative transition $ψ(2S) → γ_1χ_{c2}$ is also almost pure E1 [17, 18]. Further, $γ_2γ_3$ in the decay $χ_{c2} → γ_2γ_3$ are expected to be produced with pure helicity two amplitudes [19]. With these assumptions the angular distributions are predicted to be [10]

$$χ_{c0} : \frac{dN}{d\cos Θ_1} = 1 + \cos^2 Θ_1, \quad (2)$$
$$χ_{c2} : \frac{d^3N}{(d\cos Θ_1) d\cos Θ_2 dφ_2} = 9 \sin^2 Θ_1 \sin^2 2Θ_2 
+ (1 + \cos^2 Θ_1)[(3 \cos^2 Θ_2 - 1)^2 + 9 \sin^4 Θ_2] 
+ 3 \sin 2Θ_1 \sin 2Θ_2[3 \cos^2 Θ_2 - 1 - 3 \sin^2 Θ_2] \cos φ_2 
+ 6 \sin^2 Θ_1 \sin^2 Θ_2(3 \cos^2 Θ_2 - 1) \cos 2φ_2, \quad (3)$$
$$χ_{c2} : \frac{dN}{d\cos Θ_1} = 1 - (1/13) \cos^2 Θ_1. \quad (4)$$

Here $Θ_1$ is the angle between $γ_1$ and the $e^+$ beam direction in the $ψ(2S)$ frame, and $Θ_2$ and $φ_2$ are the polar and azimuthal angles of the $γ_2γ_3$ axis in the rest frame of $χ_{c0,c2}$. These angular distributions were assumed in the MC simulations.

The energy resolutions determined by the MC simulations were $σ(E_{γ1})=(8.2±0.1)$ MeV for $χ_{c0}$ and $σ(E_{γ1})=(6.3±0.1)$ MeV for $χ_{c2}$. The overall efficiencies determined from these MC samples were $ε(χ_{c0})=(39.1±0.5)\%$ and $ε(χ_{c2})=(50.7±0.7)\%$. The difference between $ε(χ_{c0})$ and $ε(χ_{c2})$ arises primarily from the $cos Θ_1$ distributions (Eqs. (2) and (4)).

Because the background in our spectrum is large, it is important to determine its shape accurately. For this purpose the distributions of $E(γ_1)$ were examined in the 21 pb$^{-1}$ of off-$ψ(2S)$ data taken at $\sqrt{s}=3671$ MeV, as well as the 280 pb$^{-1}$ of large statistics $ψ(3770)$ data taken at $\sqrt{s}=3772$ MeV. As shown in Fig. 2, it is found that the off-$ψ(2S)$ data are in excellent agreement with the high statistics $ψ(3770)$ data, in which transitions to either $χ_{c0}$ or $χ_{c2}$ resonances were expected to yield ≤2 events [20]. The $E(γ_1)$ distribution for the $ψ(3770)$ data was fitted with a polynomial, and used as the shape of the background in the $ψ(2S)$ data shown in Fig. 1.

The final fit to the $E(γ_1)$ spectrum obtained with fixed $χ_{c0}$ and $χ_{c2}$ masses and intrinsic widths [16] is shown in Fig. 1. The $χ^2/d.o.f. = 41/61$ for the fit. It was found that
Various possible sources of systematic errors in our results were investigated. The number of \( \psi(2S) \) produced is determined using the background-subtracted and efficiency-corrected yield of hadronic events following the procedure described in detail in [21]. The background is estimated using the off-\( \psi(2S) \) data. The efficiency is estimated by a MC simulation of generic \( \psi(2S) \) decays. The systematic uncertainty is determined by varying the hadronic event selection and online trigger criteria by large amounts in both data and MC. It is

\[
\begin{align*}
N(\chi_{c0}) &= 212 \pm 31, \\
N(\chi_{c2}) &= 335 \pm 35.
\end{align*}
\]

The product branching ratios were determined as

\[
\frac{N(\chi_{cJ})}{\epsilon(\chi_{cJ}) \times N(\psi(2S))} \times \left[ \frac{B(\psi(2S) \to \gamma \chi_{cJ}) \times B(\chi_{cJ} \to \gamma \gamma)}{\epsilon(\chi_{cJ}) \times N(\psi(2S))} \right]
\]

with the results

\[
\begin{align*}
B(\psi(2S) \to \gamma \chi_{c0}) \times B(\chi_{c0} \to \gamma \gamma) &= (2.22 \pm 0.32\text{ (stat)}) \times 10^{-5}, \\
B(\psi(2S) \to \gamma \chi_{c2}) \times B(\chi_{c2} \to \gamma \gamma) &= (2.70 \pm 0.28\text{ (stat)}) \times 10^{-5}. 
\end{align*}
\]  

\[5\]
found that while the MC determined efficiency changes from 65% to 91% the efficiency-corrected yield changes by no more than 2%, which we include as a systematic error. The neutral trigger efficiency is uncertain by 0.2%. The uncertainty in our MC determination of absolute efficiency for three-photon detection was estimated as $3 \times 0.4\% = 1.2\% \ [22]$. The systematic error due to the simulation of the event selection criteria ($\chi^2$/d.o.f. distribution for 4C fit, acceptance variation, and shower overlap cut) was determined by varying the cuts. Similarly, systematic uncertainties due to our choice of the background and signal shapes were estimated by using a free parameter polynomial background shape and a free parameter Crystal Ball line shape $[21]$ convoluted with appropriate Breit-Wigner resonance shapes for the peaks. The extreme changes in the resonance yields obtained with these changes were taken as measures of systematic errors. We have assumed pure helicity two decay of $\chi_c^0$. In a relativistic calculation Barnes $[5]$ predicts the helicity zero component to be only 0.5%. To be very conservative, we have determined the change in our result for $\chi_c^2$ by including a helicity zero component of 8%, which is the experimental upper limit established by CELLO $[23]$ for the two photon decay of the $2^{++}$ light quark state $a_2(1320)$.

All individual systematic errors are listed in Table II. The sums of the systematic errors, added in quadrature are $\pm 4.5\%$ for $\chi_c^0$ and $\pm 5.7\%$ for $\chi_c^2$.

| Source of Systematic Uncertainty | $\chi_c^0$ | $\chi_c^2$ |
|---------------------------------|--------|--------|
| Number of $\psi(2S)^*$          | 2.0%   | 2.0%   |
| Neutral Trigger Efficiency*     | 0.2%   | 0.2%   |
| Photon Detection Efficiency *   | 1.2%   | 1.2%   |
| Event Selection Simulation      | 2.0%   | 2.0%   |
| Resonance Fitting               | 3.3%   | 4.6%   |
| Helicity 2 Angular Distribution | -      | 1.3%   |
| Sum in quadrature               | 4.5%   | 5.7%   |

Our final results for the measured quantities, $B(\psi(2S) \rightarrow \gamma \chi_{c0,c2}) \times B(\chi_{c0,c2} \rightarrow \gamma \gamma)$ are presented in Table III. We use the PDG 07 average results,

$$B(\psi(2S) \rightarrow \gamma \chi_{c0}) = (9.2 \pm 0.4) \times 10^{-2},$$
$$\Gamma(\chi_{c0}) = (10.5 \pm 0.9) \text{ MeV},$$
$$B(\psi(2S) \rightarrow \gamma \chi_{c2}) = (8.8 \pm 0.5) \times 10^{-2},$$
$$\Gamma(\chi_{c2}) = (1.95 \pm 0.13) \text{ MeV},$$

(6)

to derive $B(\chi_{c0,c2} \rightarrow \gamma \gamma)$, $\Gamma_{\gamma \gamma}(\chi_{c0,c2})$, and $R$. These are also listed in Table III.

By requiring an additional resonance in the spectrum of Fig. 1 corresponding to $\chi_c(3P_1)$, whose two-photon decay is forbidden by the Landau-Yang theorem [2], we obtain the 90% confidence limit $B(\chi_c \rightarrow \gamma \gamma) < 3.5 \times 10^{-5}$ which is nearly two orders of magnitude lower than the present limit quoted in PDG 07 $[16]$. It corresponds to the 90% confidence limit $\Gamma_{\gamma \gamma}(\chi_c) < 0.03$ keV.

Our final results are compared to those of previous measurements in Table IV. As mentioned earlier, most of the results for $\Gamma_{\gamma \gamma}(\chi_{cJ})$ in Table IV are from measurements of the
The radiative correction factor for $\Gamma_{\gamma\gamma}(\chi_{cJ})$ (for $\alpha_s \simeq 0.32$ [16]) is nearly a factor of two, which strongly suggests possible problems with the radiative corrections. Unfortunately, a measurement of $\Gamma_{\gamma\gamma}(\chi_{cJ})$ alone cannot provide further insight into the problem because the charm quark mass $m_c$ and derivative of the wave function at origin $\Psi'(0)$ are not known. However, since both unknowns cancel in the ratio $\mathcal{R}$, a measurement of $\mathcal{R}$ can do so, as noted, for example, by Voloshin [33]. For $\alpha_s = 0.32$, the predicted value, which only depends on radiative corrections, is $\mathcal{R}_{th}=0.12$. Our experimental result, $\mathcal{R}_{exp}=0.24\pm0.06$, together with the other determinations of $\mathcal{R}$ in Table [IV] leads to the average $\langle \mathcal{R}_{exp} \rangle = 0.20\pm0.02$. This result provides experimental confirmation of the inadequacy of the present first-order radiative corrections, which have been often used to make theoretical predictions of $\Gamma_{\gamma\gamma}(\chi_{cJ})$ and experimental derivations of $\alpha_s$.

The above experimental results for $\mathcal{R}$ emphasize the need for calculations of radiative corrections to higher orders. Alternatively, as noted by Buchmüller [34], a different choice of the renormalization scheme and renormalization scale should be considered in order to arrive at a more convergent way of specifying the radiative corrections.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the A.P. Sloan Foundation, the National Science Foundation, the U.S. Department of Energy, the Natural Sciences and 

**TABLE III: Results of the present measurements.** First error is statistical, second is systematic, and third is due to the PDG parameters used. The common systematic errors have been removed in calculating $\mathcal{R}$. $B_1 \equiv B(\psi(2S) \to \gamma \chi_{c0, c2})$, $B_2 \equiv B(\chi_{c0, c2} \to \gamma \gamma)$, $\Gamma_{\gamma\gamma} \equiv \Gamma_{\gamma\gamma}(\chi_{c0, c2} \to \gamma \gamma)$.

| Quantity | $\chi_{c0}$ | $\chi_{c2}$ |
|----------|-------------|-------------|
| $B_1 \times B_2 \times 10^9$ | $2.22\pm0.32\pm0.10$ | $2.70\pm0.28\pm0.15$ |
| $B_2 \times 10^4$ | $2.41\pm0.35\pm0.11\pm0.10$ | $3.06\pm0.32\pm0.17\pm0.17$ |
| $\Gamma_{\gamma\gamma}$ (keV) | $2.53\pm0.37\pm0.11\pm0.24$ | $0.60\pm0.06\pm0.03\pm0.05$ |
| $\mathcal{R}$ | $0.237\pm0.043\text{(stat)}\pm0.015\text{(syst)}\pm0.031\text{(PDG)}$ |
results the errors in $R$

reevaluated by using the current PDG values for branching fr actions and total widths. For these
the error in the branching fractions and widths used. The res ults from the literature have been

∗ The first error is statistical. The second error is systemati c error combined in quadrature with

This measurement $B(\psi(2S) \rightarrow \gamma\chi_{cJ}) \times B_{\gamma\gamma}$ 2.53±0.37±0.26 0.60±0.06±0.06 0.24±0.04±0.03

Averages (weighted by total errors) 2.31±0.10±0.12 0.51±0.02±0.02 0.20±0.01±0.02

** The Belle publication gives only the product branching fractions $\Gamma_{\gamma\gamma} \times B(\chi_{c0,2} \rightarrow \text{hadrons})$. We have calculated $\Gamma_{\gamma\gamma}$ and $R$ by using the PDG 07 [16] values of branching fractions for the individual decays.

Engineering Research Council of Canada, and the U.K. Science and Technology Facilities Council.

[1] See, for example, V.A. Novikov et al., Phys. Rep. 41, 1 (1978).
[2] L. Landau, Phys. Abstracts A 52, 125 (1949); C.N. Yang, Phys. Rev. 77, 242 (1950).
[3] R. Barbieri, R. Gatto and R. Kögerler, Phys. Lett. B 60, 183 (1976).
[4] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985), as quoted in Ref. [7].
[5] T. Barnes, Proceedings of the IX International Workshop on Photon-Photon Collisions, edited
by D.O. Caldwell and H.P. Paar (World Scientific, Singapore, 1992), p. 263.
[6] G. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D 46, R1914 (1992).
[7] S.N. Gupta, J.M. Johnson and W.W. Repko, Phys. Rev. D 54, 2075 (1996).
[8] C.R. Münz, Nucl. Phys. A 609, 364 (1996).
[9] H.-W. Huang and K.-Ta Chao, Phys. Rev. D 54, 6850 (1996); errata Phys. Rev. D 56, 1821 (1997).
[10] D. Ebert, R.N. Faustov and V.O. Galkin, Mod. Phys. Lett. A 18, 601 (2003).
[11] G.A. Schuler, F.A. Berends and R. van Gulik, Nucl. Phys. B 523, 423 (1998).
[12] T.A. Armstrong et al. (E760 Collaboration), Phys. Rev. Lett. 70, 2988 (1993).
[13] M. Ambrogiani et al. (E835 Collaboration), Phys. Rev. D 62, 052002 (2000).
[14] M. Andreotti et al. (E835 Collaboration), Phys. Lett. B 584, 16 (2004).
[15] G. Viehhauser, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 146 (2001); D. Peterson et al., Nucl. Instrum. Methods Phys. Res., Sect A 478, 142 (2002).
[16] W.-M. Yao et al., Journal of Physics G 33, 1 (2006) and 2007 partial update for the 2008 edition available on the PDG WWW (URL: http://pdg.lbl.gov).
[17] M. Oreglia et al. (Crystal Ball Collaboration), Phys. Rev. D 25, 2259 (1982).
[18] M. Ambrogiani et al. (E835 Collaboration), Phys. Rev. D 65, 052002 (2002).
[19] P.K. Kabir and A.J.G. Hey, Phys. Rev. D 13, 3161 (1976).
[20] T.E. Coan et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 182002 (2006); R.A. Briere et al. (CLEO Collaboration), Phys. Rev. D 74, 031106 (2006).
[21] S.B. Athar et al. (CLEO Collaboration), Phys. Rev. D 70, 112002 (2004).
[22] N.E. Adam et al. (CLEO Collaboration), Phys. Rev. Lett. 94, 232002 (2005).
[23] H.J. Behrend et al. (CELOL Collaboration), Z. Phys. C 46, 583 (1990).
[24] K. Ackermott et al. (OPAL Collaboration), Phys. Lett. B 439, 197 (1998).
[25] M. Acciarri et al. (L3 Collaboration), Phys. Lett. B 453, 73 (1999).
[26] J. Dominick et al. (CLEO Collaboration), Phys. Rev. D 50, 4265 (1994).
[27] B. Eisenstein et al. (CLEO Collaboration), Phys. Rev. Lett. 87, 061801 (2001).
[28] S. Dobbs et al. (CLEO Collaboration), Phys. Rev. D 73, 071101 (2006).
[29] K. Abe et al. (Belle Collaboration), Phys. Lett. B 540, 33 (2002).
[30] W.T. Chen et al. (Belle Collaboration), Phys. Lett. B 651, 15 (2007).
[31] S. Uehara et al. (Belle Collaboration), Eur. Phys. J. C 53, 1 (2008).
[32] R. Barbieri et al., Phys. Lett. B 95, 93 (1980); Nucl. Phys. B 192, 61 (1981). For a review see W. Kwong et al., Phys. Rev. D 37, 3210 (1988).
[33] M.B. Voloshin, arXiv:hep-ph/0711.4556.
[34] W. Buchmüller, in “Quarkonia”, in Current Physics Sources and Comments”, vol. 9, North Holland Publishers, 1992.