Study of $X(3915)^{J/\psi}$ in two-photon collisions

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Study of $X(3915) \to J/\psi \phi$ in two-photon collisions


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(BABAR Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3INFN Sezione di Bari, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6Rohr Universitat Bochum, Institut fur Experimentalphysik 1, D-44780 Bochum, Germany
7University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
8Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
9Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
10University of California at Irvine, Irvine, California 92697, USA
11University of California at Riverside, Riverside, California 92521, USA
12University of California at Santa Barbara, Santa Barbara, California 93106, USA
13University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
14California Institute of Technology, Pasadena, California 91125, USA
15University of Cincinnati, Cincinnati, Ohio 45221, USA
16University of Colorado, Boulder, Colorado 80309, USA
17Colorado State University, Fort Collins, Colorado 80523, USA
18Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
19Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
20Laboratoire Leprince-Ringuet, Ecole Polytchnique, CNRS/IN2P3, F-91128 Palaiseau, France
21University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
22INFN Sezione di Ferrara, I-44100 Ferrara, Italy
23INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
24INFN Sezione di Genova, I-16146 Genova, Italy
25Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India
26Harvard University, Cambridge, Massachusetts 02138, USA
27Harvey Mudd College, Claremont, California 91711, USA
28Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
29Humboldt-Universität zu Berlin, Institut für Physik, Newtonstrasse 15, D-12489 Berlin, Germany
30Imperial College London, London, SW7 2AZ, United Kingdom
31University of Iowa, Iowa City, Iowa 52242, USA
32Iowa State University, Ames, Iowa 50011-3160, USA
33Johns Hopkins University, Baltimore, Maryland 21218, USA
34Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 Orsay Cedex, France
35Lawrence Livermore National Laboratory, Livermore, California 94550, USA
36University of Liverpool, Liverpool L69 7ZE, United Kingdom
37Queen Mary, University of London, London, E1 4NS, United Kingdom
38University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
39University of Louisville, Louisville, Kentucky 40292, USA
40Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
41University of Manchester, Manchester M13 9PL, United Kingdom
42University of Maryland, College Park, Maryland 20742, USA
43University of Massachusetts, Amherst, Massachusetts 01003, USA
44Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
45McGill University, Montréal, Québec, Canada H3A 2T8
46INFN Sezione di Milano, I-20133 Milano, Italy
47Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
48University of Mississippi, University, Mississippi 38677, USA
49Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
50NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, Netherlands
We study the process $\gamma\gamma \rightarrow J/\psi\omega$ using a data sample of 519.2 fb$^{-1}$ recorded by the BABAR detector at SLAC at the PEP-II asymmetric-energy $e^+e^-$ collider at center-of-mass energies near the $Y(nS)$ ($n = 2, 3, 4$) resonances. We confirm the existence of the charmoniumlike resonance $X(3915)$ decaying to $J/\psi\omega$ with a significance of 7.6 standard deviations, including systematic uncertainties, and measure its mass ($3919.4 \pm 2.2 \pm 1.6$) MeV/$c^2$ and width ($13 \pm 6 \pm 3$) MeV, where the first uncertainty is statistical and the second systematic. A spin-parity analysis supports the assignment $J^P = 0^+$ and therefore the identification of the signal as due to the $X(3915)$ resonance. In this hypothesis we determine the product between the two-photon width and the final state branching fraction to be $(52 \pm 10 \pm 3)$ eV.

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I. INTRODUCTION

In the last several years many new charmoniumlike states have been observed in the mass region between 3.7 and 5.0 GeV/$c^2$, above the $D\bar{D}$ threshold, with properties that disfavor their interpretation as conventional charmonium mesons [1–5]. The $X(3915)$ resonance, decaying to the $J/\psi\omega$ final state, was first observed by the Belle Collaboration in two-photon collisions [6]. Another resonance, dubbed $Y(3940)$, has been observed in the $B \rightarrow J/\psi\omega K$ process [4,5,7]. The mass measurement for the $Y(3940)$ [4,5,7] is consistent with that of the $X(3915)$ [6].
Thus, the same particle, with a mass of about 3915 MeV/c², may have been observed in two distinct production processes. The Z(3930) resonance has been discovered in the \( \gamma \gamma \rightarrow D \bar{D} \) process [2,3]. Its interpretation as the \( \chi_{c2}(2P) \), the first radial excitation of the \( ^3P_2 \) charmonium ground state, is commonly accepted [8]. Interpretation of the \( X(3915) \) as the \( \chi_{c0}(2P) \) [9] or \( \chi_{c2}(2P) \) state [10] has been suggested. The latter implies that the \( X(3915) \) and \( Z(3930) \) are the same particle, observed in different decay modes. However, the product of the two-photon width times the decay branching fraction \( \mathcal{B} \) for the \( X(3915) \) reported by Belle [6] is unexpectedly large compared to other excited \( c \bar{c} \) states [8]. Interpretation of the \( X(3915) \) in the framework of molecular models has also been proposed [11].

Despite the many measurements available [8], the nature of the \( X(3872) \) state, which was first observed by Belle [12], is still unclear [13]. The observation of its decay into \( \gamma J/\psi \) [14] ensures that this particle has positive parity. The spin analysis performed by CDF on the decay \( X(3872) \rightarrow J/\psi \pi^+ \pi^- \) concludes that only \( J^P = 1^+ \) and \( J^P = 2^- \) are consistent with data [15]. Similarly, a recent spin analysis performed by Belle [16] concludes that \( J^P = 1^+ \) describes the data as does \( J^P = 2^- \) with one free parameter. An analysis of the \( \pi^+ \pi^- \pi^0 \) mass distribution in the \( X(3872) \rightarrow J/\psi \omega \) decay performed by BABAR favors the spin-parity assignment \( J^P = 2^- \) [7], but a \( J^P = 1^+ \) spin assignment is not ruled out. If \( J^P = 2^- \), the production of the \( X(3872) \) in two-photon collisions would be allowed.

In this paper we search for the \( X(3915) \) and \( X(3872) \) resonances in the two-photon process \( e^+ e^- \rightarrow e^+ e^- \gamma \gamma \rightarrow e^+ e^- J/\psi \omega \), where \( J/\psi \rightarrow \ell^+ \ell^- \) (\( \ell = e \) or \( \mu \)) and \( \omega \rightarrow \pi^+ \pi^- \pi^0 \). Two-photon events where the interacting photons are not quasi-real are strongly suppressed in this analysis by the selection criteria described below. This implies that the allowed \( J^{PC} \) values of any produced resonances are \( 0^{++}, 2^{++}, 4^{++}, \ldots ; 3^{++}, 5^{++}, \ldots \) [17]. Angular momentum conservation, parity conservation, and charge conjugation invariance then imply that these quantum numbers also apply to the final state.

This paper is organized as follows. In Sec. II we give a brief description of the BABAR detector. Section III is devoted to the event reconstruction and data selection. In Sec. IV we present the study of the \( J/\psi \omega \) system while in Sec. V we perform an angular analysis of \( X(3915) \). The study of systematic uncertainties is described in Sec. VI. In Sec. VII we summarize the results.

### II. THE BABAR DETECTOR

The results presented here are based on data collected with the BABAR detector at the PEP-II asymmetric-energy \( e^+ e^- \) collider located at the SLAC National Accelerator Laboratory and correspond to an integrated luminosity of 519.2 fb\(^{-1}\) recorded at center-of-mass energies near the \( Y(nS) \ (n = 2, 3, 4) \) resonances. The BABAR detector is described in detail elsewhere [18]. Charged particles are detected, and their momenta are measured, by a five-layer double-sided microstrip detector and a 40-layer drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified in a CsI(Tl) crystal electromagnetic calorimeter. Charged-particle identification is provided by the specific energy loss in the tracking devices and by an internally reflecting, ring-imaging Cherenkov detector. Muons and neutral \( K^0_L \) mesons are detected in the instrumented flux return of the magnet. Monte Carlo (MC) simulated events [19], with sample sizes more than 10 times larger than the corresponding data samples, are used to evaluate the signal efficiency and determine background features. Two-photon events are simulated using the GamGam MC generator [3].
and ω candidates to a common vertex. The π⁰ mass is constrained to its nominal value [8] in this fit. Charged particles are required to originate from the interaction region. We require the vertex fit probability of the charmonium candidate to be larger than 0.1%.

Background arises mainly from random combinations of particles from e⁺e⁻ annihilation, other two-photon collisions, and initial-state radiation (ISR) processes. We discriminate against J/ψπ⁺π⁻π⁰ events produced via ISR by requiring $M_{\text{mis}}^2 \equiv (p_{\text{e}^+e^-} - p_{\text{rec}})^2 > 2 \text{(GeV/c)}^2$, where $p_{\text{e}^+e^-} - p_{\text{rec}}$ is the four-momentum of the initial state (J/ψω final state). We define $p_T$ as the transverse momentum, in the $e^+e^-$ rest frame, of the J/ψω candidate with respect to the beam axis. Well-reconstructed two-photon events are expected to have a low transverse momentum $p_T$ and a small amount of electromagnetic calorimeter energy $E_{\text{extr}}$, i.e., energy not associated with the final state particles. We require $p_T < 0.2 \text{ GeV/c}$ and $E_{\text{extr}} < 0.3 \text{ GeV}$. Events originating from residual ISR $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ decays may create fake structures in the J/ψω mass spectrum. We therefore remove events in the mass window $3.675 < m(J/\psi\pi^+\pi^-) < 3.700 \text{ GeV/c}^2$, where $m(J/\psi\pi^+\pi^-) = m(\ell^+\ell^-\pi^+\pi^-) - m(\ell^+\ell^-) + m(J/\psi)^{\text{PDG}}$ and $m(J/\psi)^{\text{PDG}}$ is the nominal J/ψ mass [8].

The J/ψω signal region is defined as the intersection of the J/ψ and ω signal regions defined above. In about 10% of the events we find more than one candidate, and we select the one having the lowest $p_T$ value. We obtain 95 events in the J/ψω signal region.

FIG. 1 (color online). The $p_T$ distribution of selected candidates (solid points). The solid histogram represents the result of a fit to the sum of the simulated signal (dashed line) and background (dotted line) contributions.

IV. STUDY OF THE J/ψω SYSTEM

Figure 1 shows the $p_T$ distribution for the selected candidates, obtained by applying the above requirements with the exception of that on $p_T$. The distribution is fitted with the signal $p_T$ shape obtained from MC simulation plus a combinatorial background component, modeled using a second-order polynomial function with free parameters. The number of events from combinatorial background in the $p_T < 0.2 \text{ GeV/c}$ region is $4 \pm 3$.

Figure 2 shows the distribution in the $m(\ell^+\ell^-)$-plane of events that satisfy the selection criteria, except for the J/ψ and ω mass selections. The figure also shows the definitions of signal and background regions, indicated by the tiles labeled 1–9. The signal regions correspond to tile 5. Figures 3(a) and 3(b) show $m(\ell^+\ell^-)$ and $m(\pi^+\pi^-\pi^0)$ for events in the J/ψ signal regions, respectively. As a consistency check, we assign an ω-Dalitz-plot weight [7] to events in the J/ψω signal region. The procedure makes use of the ω decay angular distribution. The helicity angle $\theta$ is the angle between the π⁺ and π⁰ directions in the π⁺π⁻ reference frame. The cosθ distribution is proportional to $\sin^2\theta$, and the ω signal is projected by giving the ith event weight...
$w_i = \frac{1}{2}(1 - 3\cos^2 \theta_i)$. The sum of the $\omega$-Dalitz-plot weights is consistent with the number of events in the $J/\psi \omega$ signal region, thus consistent with the hypothesis that most of the observed events do indeed arise from true $\omega \to \pi^+\pi^-\pi^0$ decays.

To improve the mass resolution, we define the reconstructed $J/\psi \omega$ mass as $m(J/\psi \omega) = m(\ell^+\ell^-\pi^+\pi^-\pi^0) - m(\ell^+\ell^-) + m(J/\psi)_{PDG}$. The non-$J/\psi \omega$ background is estimated from the $J/\psi$ and $\omega$ sidebands defined in Fig. 2. The $\omega$ sidebands are defined as [0.55, 0.59] and [1.00, 1.04] GeV/$c^2$. The $J/\psi$ sidebands are defined as [2.805, 2.900] and [3.170, 3.265] GeV/$c^2$ for the $e^+e^-$ channel and [2.970, 3.015] and [3.170, 3.215] GeV/$c^2$ for the $\mu^+\mu^-$ channel. With these definitions, each sideband size is half of the signal size. The $m(J/\psi \omega)$ spectrum of this background in the $J/\psi \omega$ signal region is obtained by $B(5) = B(2) + B(4) + B(6) + B(8) - (B(1) + B(3) + B(7) + B(9))$, where $B(i)$ is the $m(J/\psi \omega)$ spectrum in the $i$th region shown in Fig. 2. The estimated background from this method is $5 \pm 3$ in good agreement with the estimate from the fit to the $p_T$ distribution. The residual background from $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ decay is estimated by using the values of the integrated luminosity, MC efficiencies, the cross section for $\psi(2S)$ production in ISR events [20], and the nominal branching fractions for the relevant $\psi(2S)$ and $J/\psi$ decays [8]. The expected number of background events from such process is smaller than 0.9 at 90% confidence level (C.L.).

The detection efficiency depends on $m(J/\psi \omega)$ and $\theta^*_\ell$, where $\theta^*_\ell$ is the angle between the direction of the positively charged lepton from $J/\psi$ decay ($\ell^+$) and the beam axis in the $J/\psi \omega$ rest frame. Since we select events in which the $e^+$ and $e^-$ beam particles are scattered at small angles, the two-photon axis is approximately the same as the beam axis. Therefore we use the beam axis to determine $\theta^*_\ell$.

We parameterize the efficiency dependence with a two-dimensional [$m(J/\psi \omega)$, $\theta^*_\ell$] histogram. We label MC events where the reconstructed decay particles are successfully matched to the generated ones as truth-matched events. The detection efficiency in each histogram bin is defined as the ratio between the number of truth-matched MC events that satisfy the selection criteria and the number of MC events that were generated for that bin.

The $m(J/\psi \omega)$ spectrum is shown in Fig. 4, where each event is weighted to account for detector efficiency, which is almost uniform as a function of the $J/\psi \omega$ mass. The event weight is equal to $w_i / e_i(m(J/\psi \omega), \theta^*_\ell)$, where $e_i(m(J/\psi \omega), \theta^*_\ell)$ is the $m(J/\psi \omega)$- and $\theta^*_\ell$-dependent efficiency value and $\bar{e}$ is a common scaling factor that ensures all the weights are $O(1)$, since weights far from 1 can cause the estimate of the statistical uncertainty to be incorrect [21]. We observe a prominent peak near 3915 MeV/$c^2$ over a small background. No evident structure is observed around 3872 MeV/$c^2$.

We perform an extended unbinned maximum-likelihood fit to the efficiency-corrected $m(J/\psi \omega)$ spectrum to extract the resonance yield and parameters. In the likelihood function $L$ there are two components: one for the $X(3915)$ signal and one for the nonresonant (NR) $J/\psi \omega$ contribution. The probability density function (PDF) for the signal component is defined by the convolution of an $S$-wave relativistic Breit-Wigner distribution with a detector-resolution function. The NR contribution is taken to be proportional to $P_{bg}(m) = p^*(m) \times \exp[-\delta p^*(m)]$, where $p^*(m)$ is the $J/\psi$ momentum in the rest frame of a $J/\psi \omega$ system with an invariant mass $m$, $\delta$ is a fit parameter, and $m = m(J/\psi \omega)$. The signal and NR yields, the $X(3915)$ mass and width, and $\delta$ are free parameters in the fit.

We use truth-matched MC events to determine the signal PDF detector-resolution function. The signal detector-resolution PDF is described by the sum of two Gaussian shapes for the $X(3915)$ and the sum of a Gaussian plus a Crystal Ball function [22] for the $X(3872)$. The parameters of the resolution functions are determined from fits to truth-matched MC events. The widths of the Gaussian core components are 5.7 and 4.5 MeV, respectively, for $X(3915)$ and $X(3872)$. No significant difference in the resolution function parameters is observed for the different $J/\psi$ decay modes. The parameters of the resolution functions are fixed to their MC values in the maximum-likelihood fit.

The fitted distribution from the maximum-likelihood fit to the efficiency-corrected $m(J/\psi \omega)$ spectrum is shown in Fig. 4. We observe $59 \pm 10$ signal events; the measured $X(3915)$ mass and width are $(3919.4 \pm 2.2)$ MeV/$c^2$ and $(13 \pm 6)$ MeV, respectively, where the uncertainties are statistical only. We add an $X(3872)$ component, modeled as a $P$-wave relativistic Breit-Wigner with mass
3872 MeV/c² and width 2 MeV [8], convoluted with the detector-resolution function. No significant change in the result is observed with the addition of this component, whose yield is estimated to be 1 ± 4 events. An excess of events over the fitted NR is observed at \( m(J/\psi\omega) \sim 4025 \text{ MeV/c}^2 \). If we add a resonant component in the likelihood function to fit this excess, modeled as a Gaussian having free parameters, we obtain a signal yield of 5 ± 3 events.

**V. Angular Analysis of the X(3915)**

We first attempt to discriminate between \( J^P = 0^- \) and \( J^P = 2^+ \) by using the Rosner [23] predictions. In addition to the previously defined \( \theta^*_n \) we consider the following two angles: \( \theta^*_\ell \) defined as the angle between the normal to the decay plane of the \( \omega(n) \) and the two-photon axis, and \( \theta_{in} \) defined as the angle between the lepton \( \ell^+ \) from \( J/\psi \) decay and the \( \omega \) decay normal (see Fig. 5). To obtain the normal to the \( \omega \) decay plane we boost the two pions from the \( \omega \) decay into the \( \omega \) rest frame and obtain \( \hat{n} \) by the cross product vector of the two charged pions. A projection of the efficiency values over \( \cos \theta^*_\ell \) in the X(3915) signal region is shown in Fig. 6(a). The projections of the efficiency over the angles \( \theta^*_n \) and \( \theta_{in} \) are shown in Figs. 6(b) and 6(c). The efficiency distributions are not uniform and are parameterized by fifth-order polynomials. The \( \cos \theta^*_\ell \), \( \cos \theta^*_n \), and \( \cos \theta_{in} \) distributions are sensitive to the spin parity of the resonance. We assume that for \( J^P = 2^+ \) the dominant amplitude has helicity 2. This is in agreement with previous charmonium measurements [24–26] and theoretical predictions [27,28]. The expected functional forms under this hypothesis are summarized in Table I. Figures 7(a)–7(c) show the efficiency-corrected \( \cos \theta^*_\ell \), \( \cos \theta^*_n \), and \( \cos \theta_{in} \) distributions for events in the X(3915) signal region, defined by \( 3890 < m(J/\psi\omega) < 3950 \text{ MeV/c}^2 \). Since the background is small, we assume that all the events come from X(3915) decay. The distributions for data are compared with the expected curves for \( J^P = 0^- \) and \( J^P = 2^+ \). The resulting \( \chi^2 \) for each distribution is reported in Table I. In all cases the \( J^P = 0^- \) expectations describe the data better than the \( J^P = 2^+ \) ones and this is particularly true for the \( \cos \theta^*_n \) distribution. In the latter case \( \chi^2 \) probabilities for \( J^P = 0^- \) and \( J^P = 2^+ \) are, respectively, 64.7% and \( 9.6 \times 10^{-9}\% \). We conclude that the data largely prefer \( J^P = 0^- \) over \( J^P = 2^+ \).

The spin-0 hypothesis can be further tested by examining the \( \cos \theta_h \) distribution, where \( \theta_h \) is the angle formed by the \( J/\psi \) momentum in the \( J/\psi\omega \) rest frame with respect to

![FIG. 5 (color online). Diagram illustrating the reference frames involved in the definition of angular variables.](image)

![FIG. 6. The efficiency distributions in the X(3915) signal region 3890 < m(J/\psi\omega) < 3950 MeV/c² (solid points) as functions of (a) cosθ*, (b) cosθn, (c) cosθin, (d) cosθh, and (e) φ1. The curves show the results from the fits described in the text.](image)

**TABLE I. Functional shapes and \( \chi^2 \) for the different spin hypotheses. NDF = 9.**

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<th>Angle</th>
<th>( J^P = 0^- )</th>
<th>( J^P = 0^+ )</th>
<th>( J^P = 2^- )</th>
<th>( J^P = 2^+ )</th>
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<td>( \theta^*_\ell )</td>
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<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
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<tr>
<td>( \theta^*_n )</td>
<td>3.9</td>
<td>8.7</td>
<td>5.9</td>
<td>6.9</td>
</tr>
<tr>
<td>( \theta_{in} )</td>
<td>2.1</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>21.7</td>
<td>9.6</td>
<td>12.2</td>
<td>18.0</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>21.7</td>
<td>9.6</td>
<td>12.2</td>
<td>18.0</td>
</tr>
<tr>
<td>( \phi_1 )</td>
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<td>2 + cos(2 cosφ1)</td>
<td>2 - cos(2 cosφ1)</td>
<td>2 + cos(2 cosφ1)</td>
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the $J/\psi \omega$ direction in the laboratory frame. The efficiency distribution as a function of $\cos \theta_n$ is shown in Fig. 6(d), where it is parameterized by a third-order polynomial. The $\cos \theta_n$ distribution in the $X(3915)$ signal region, corrected for efficiency, is shown in Fig. 7(d) and is compared with the uniform distribution expected for the spin-0 hypothesis. The resulting $\chi^2$/NDF is 12.2/9 and we conclude that this test also supports the spin-0 assignment.

We attempt to discriminate between $J^P = 0^-$ and $J^P = 0^+$. For this purpose, we define the angles $\theta_n$, $\theta_1$, and $\phi_1$. To define these angles, we first boost all the 4-vectors into the $J/\psi \omega$ rest frame. We define $\theta_n$ to be the angle between the normal to the $\omega$ decay plane $\vec{n}$ and the $\omega$ direction in the $J/\psi \omega$ rest frame. The efficiency distribution as a function of $\cos \theta_n$ (not shown) is consistent with being uniform.

For $J/\psi$ decay, we first boost the $\ell^+$ to the $J/\psi$ rest frame. We define $\theta_1$ as the angle between the $\ell^+$ and the direction of the $J/\psi$ in the $J/\psi \omega$ rest frame. The efficiency distribution as a function of $\cos \theta_1$ (not shown) is consistent with being uniform.

Next we define a coordinate system as follows (see Fig. 5). For $\omega$ decay, we choose the $z$ axis along the $\omega$ momentum vector and represent the $\omega$ decay in terms of its decay plane normal $\vec{n}$. The cross product $\vec{z} \times \vec{n}$ gives the $y$-axis direction. Then we define the $x$-axis vector by $\vec{y} \times \vec{z}$. The $x-z$ plane, by construction, contains the $\omega$ decay plane normal.

We now specify the $J/\psi$ decay coordinate system in terms of the unit vectors defined for $\omega$ decay. We define $\vec{z}^\prime = -\vec{z}$, $\vec{x}^\prime = -\vec{x}$, and $\vec{y}^\prime = \vec{y}$ so that $\vec{y}^\prime$ is along the normal to the plane containing the normal to the decay plane of the $\omega$. Next we define the $J/\psi$ decay plane normal $\vec{n}^\prime$ as the cross product of the $\ell^+$ in the $J/\psi$ rest frame and the $\vec{z}^\prime$ vector. By construction, $\vec{n}^\prime$ is in the $x^\prime - y^\prime$ plane. Then we compute the angle $\phi_1$ as the angle between the $J/\psi$ and $\omega$ decay plane normals.

The efficiency distribution as a function of $\phi_1$ is shown in Fig. 6(e) and is fitted using the function $f(\phi_1) = 1 - c \cdot \cos 2\phi_1$, where $c$ is a free parameter.

It can be shown that the full angular distribution for $J^P = 0^-$ can be written as

$$dN/d\cos \theta_n d\cos \theta_1 d\phi_1 = \frac{9N}{64\pi} \sin^2 \theta_n [1 + \cos^2 \theta_1 + \sin^2 \theta_1 \cos 2\phi_1].$$

For $J^P = 0^+$, assuming no $D$ wave, the normalized angular distribution is given by

$$dN/d\cos \theta_n d\cos \theta_1 d\phi_1 = \frac{3N}{32\pi} [2 \sin^2 \theta_n \cos^2 \theta_1 + \sin^2 \theta_n \cdot (1 + \cos^2 \theta_1 - \sin^2 \theta_1 \cos 2\phi_1) + \sin^2 \theta_1 \cos 2\phi_1 \sin 2\theta_n].$$

Equations (1) and (2), when projected onto the different angles, give the functional expectations shown in Table I and presented in Fig. 8. The resulting $\chi^2$ for all the distributions are summarized in Table I. In all cases the $J^P = 0^+$ hypothesis gives a smaller $\chi^2$ than the $J^P = 0^-$ hypothesis and this is particularly true for the $\cos \theta_n$ distribution. In the latter case $\chi^2$ probabilities for $J^P = 0^+$ and $J^P = 0^-$ are 6.1% and $4.8 \times 10^{-11}$%, respectively. We conclude that the $J^P = 0^+$ assignment is largely preferred over the $J^P = 0^-$ assignment.

We observe no correlation between any angles considered in this analysis except for $\phi_1$ which is strongly correlated with $\theta_n$.

VI. SYSTEMATIC UNCERTAINTIES

Several sources contribute to systematic uncertainties on the resonance yields and parameters. Systematic uncertainties due to the functional forms chosen for the PDF
parametrizations and fixed parameters in the fit are estimated to be the sum in quadrature of the changes observed when repeating the fit varying the fixed parameters by ±1 standard deviation (σ). Since the X(3915) spin assignment is unknown, we repeat the fit by parameterizing the X(3915) signal as the convolution of a P-wave relativistic Breit-Wigner with the detector-resolution function. The changes in the fit results are taken as the systematic uncertainty. We examine the dependence of the fit results on the fit range, varying the boundary of the fit from the nominal fit range, and the branching fractions used in the calculation is estimated with simulated data [29]. The K⁺K⁻π⁺π⁻π0 ISR-enriched control sample [29]. The K⁺K⁻π⁺π⁻π0 final state has the same number of charged and neutral particles as J/ψ. The observed difference in mass is (−1.1 ± 0.8) MeV/c². We take the sum in quadrature of this shift with its uncertainty as a systematic uncertainty. Previous studies show that MC events have a better mass resolution than data [29]. The effect of possible differences between data and MC in the m(J/ψω) resolution is estimated by increasing the width of the resolution function core component by 20%. The uncertainty due to the use of efficiency weights to correct the m(J/ψω) spectrum is estimated with simulated experiments. In each experiment, we randomly modify the efficiency weight according to its statistical uncertainty. We then fit the resulting mass spectra and plot the resulting yields and resonance parameters. The resulting spreads give the systematic uncertainties on these quantities. We find that the fit bias on the yield is negligible.

The X(3915) signal significance is 7.6σ, calculated from −2 ln(L₀/Lₘₐₓ), where L₀ and L are the likelihoods of the fits with and without the resonant component, respectively. The difference in the number of degrees of freedom is taken into account. Systematic uncertainties are incorporated into the likelihood function by convolving it with a Gaussian with mean equal to zero and width equal to the systematic uncertainty on the yield.

The product between the two-photon coupling Γγγ and the resonance branching fraction B to the J/ψω final state is measured using 473.8 fb⁻¹ of data collected near the Y(4S) energy. The efficiency-weighted yields for the resonances, the integrated luminosity near the Y(4S) energy, and the branching fractions B(J/ψ → ℓ⁺ℓ⁻) = (5.94 ± 0.06)% [8] and B(ω → π⁺π⁻π⁰) = (89.2 ± 0.7)% [8] are used to obtain Γγγ × B using the GamGam generator. In this calculation, the X(3915) parameters are fixed to the values obtained from the fit.

The uncertainties on the weighted signal yield described above are taken into account in the Γγγ × B systematic error. Systematic uncertainties on the efficiency due to tracking (0.3% per track), π⁰ reconstruction (3.0%) and particle identification (0.1% per pion, 0.8% per lepton) are obtained from auxiliary studies. The uncertainty on the luminosity is 1.1%. The uncertainty on the nominal J/ψ and ω branching fractions used in the calculation is propagated in the Γγγ × B error. The GamGam calculation has an uncertainty of 3% [3].

Since no significant X(3872) signal is observed, we determine a Bayesian upper limit (UL) at 90% C.L. on Γγγ × B, assuming a uniform prior probability distribution. The upper limit for Γγγ × B is thus computed according to

$$\int_0^{UL} L(\Gamma_{\gamma\gamma} \times B) d(\Gamma_{\gamma\gamma} \times B) = 0.90,$$

where L(Γγγ × B) is the likelihood function for Γγγ × B.

For a J = 0 resonance, the resulting value of Γγγ[X(3915)] × B(X(3915) → J/ψω) is (52 ± 10 ± 3) eV where the first uncertainty is statistical and the second systematic. For completeness we also report the value for J = 2: (10.5 ± 1.9 ± 0.6) eV. For X(3872), we obtain Γγγ[X(3872)] × B(X(3872) → J/ψω) < 1.7 eV at 90% C.L., assuming J = 2.

VII. SUMMARY

In summary, we confirm the observation of the charmoniumlike resonance X(3915) in the γγ → J/ψω process, with a significance of 7.6σ, including systematic uncertainties. The measured mass and width are

$$m[X(3915)] = (3919.4 ± 2.2 ± 1.6) \text{ MeV}/c^2,$$

$$\Gamma[X(3915)] = (13 ± 6 ± 3) \text{ MeV},$$

where the first uncertainty is statistical and the second systematic. These measurements are consistent with those previously reported by Belle for the same process [6] and by BABAR [5] and Belle [4] for B → J/ψωK. A detailed angular analysis has been performed. We find that the data largely prefer Jₚ = 0⁺ over Jₚ = 2⁺. In this hypothesis, Jₚ = 0⁺ is largely preferred over Jₚ = 0⁻ and this would identify the signal as being due to the χc₀(2P) resonance. The mass of X(3915) is consistent with the result of the potential model, which predicts the mass of the first radial excitation χc₀ to be around 3916 MeV according to the Godfrey-Isgur relativized potential model [30]. The product Γγγ[X(3915)] × B[X(3915) → J/ψω] is also measured. The value for J = 0 (relatively large compared to charmonium model predictions) is consistent with that reported by Belle [6]. This product, also computed in this analysis for J = 2, is smaller than the corresponding value obtained by Belle. We have also searched for the γγ → X(3872) → J/ψω process, but no significant signal is found.
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