Measurement of the leptonic decay width of J/ψ using initial state radiation postprint

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Abstract

Using a data set of 2.93 fb−1 taken at a center-of-mass energy of s√ = 3.773 GeV with the BESIII detector at the BEPCII collider, we measure the process e+e−→J/ → + − and determine the product of the branching fraction and the electronic width B Γee=(333.4±2.5stat±4.4sys)~eV. Using the earlier-published BESIII result for B = (5.973 ± 0.007stat ± 0.037sys)%, we derive the J/ electronic width Γee~= (5.58 ± 0.05stat ± 0.08sys) keV.

Full Text

Preamble

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Abstract

Using a data set of 2.93 fb^{1} taken at a center-of-mass energy of $\sqrt{s}$ = 3.773 GeV with the BESIII detector at the BEPCII collider, we measure the process e e → J/ → and determine the product of the branching fraction and the electronic width B · Γee = (333.4 ± 2.5_stat ± 4.4_sys) eV. Using the earlier-published BESIII result for B = (5.973 ± 0.007_stat ± 0.037_sys)%, we derive the J/ electronic width Γee = (5.58 ± 0.05_stat ± 0.08_sys) keV.

Keywords: J/ resonance, electronic width, initial state radiation, BESIII

Introduction

The electronic width of the J/ resonance, Γee Γee(J/), has been measured by BaBar [1] and CLEO-c [2] employing the technique of Initial State Radiation (ISR), in which one of the beam particles radiates a photon, making the invariant mass range below the center-of-mass energy of the e e collider accessible. In this paper, we study the process e e → with invariant masses m between 2.8 and 3.4 GeV/c^2, which covers the charmonium resonance J/ . The cross section J/ (e e → J/ →) is proportional to Γee · B , where B B(J/ →) is the branching fraction of the muonic decay of the J/ resonance. With the precise measurement of B from BESIII [3], we have the opportunity to obtain Γee with high precision.

The differential cross section of J/ can be expressed in terms of the center-of-mass energy squared s as:

$$\frac{d\sigma_{J/\psi\gamma}}{dm^2_{\mu\mu}} = W(s, m^2_{\mu\mu}) \cdot BW(m^2_{\mu\mu}), \tag{1}$$

where W(s, m^2) is the radiator function describing the probability that one of the beam particles emits an ISR photon [4], and BW(m^2) is the Breit-Wigner function. W(s, m^2) is taken from the phokhara event generator with an estimated accuracy of 0.5% [5]. The Breit-Wigner function is:

$$BW(m^2_{\mu\mu}) = \frac{12\pi B_{\mu\mu} \cdot \Gamma_{ee}\Gamma_{tot}}{(m^2_{\mu\mu} - M^2_{J/\psi})^2 + M^2_{J/\psi}\Gamma^2_{tot}} \tag{2}$$

in which Γtot and MJ/ are the J/ full width and mass. Both values are taken from the world averages [6].

The cross section J/ over a specified m range can be expressed using:

$$\sigma_{J/\psi\gamma}(s) = \frac{N_{J/\psi}}{\epsilon \cdot L} = \Gamma_{ee} \cdot B_{\mu\mu} \cdot I(s), \tag{3}$$

where NJ/ is the number of signal events within the mass range after background subtraction, is the selection efficiency obtained from Monte Carlo (MC) simulation, L is the integrated luminosity of the data set, and I(s) is the integral:

$$I(s) \equiv \int_{m_{min}}^{m_{max}} W(s, m_{\mu\mu}^2) b(m_{\mu\mu}^2) dm_{\mu\mu}^2, \tag{4}$$

in which b(m^2) BW(m^2)/Γee ·B . A mass range between mmin = 2.8 GeV/c^2 and mmax = 3.4 GeV/c^2 is chosen in which NJ/ is determined.

The above equations do not take into account interference effects of the resonant production via J/ and the non-resonant e e → QED production. At lowest order in the fine structure constant , these can be included by replacing BW(m^2) with [7]:

$$BW'(m_{\mu\mu}^2) = \left|1 - \zeta(m_{\mu\mu}^2)\right|^2 BW(m_{\mu\mu}^2), \tag{5}$$

where

$$\zeta(m_{\mu\mu}^2) = \frac{i\sqrt{B_{\mu\mu} \cdot \Gamma_{ee}\Gamma_{tot}} M_{J/\psi}}{m_{\mu\mu}^2 - M_{J/\psi}^2 - iM_{J/\psi}\Gamma_{tot}} \tag{6}$$

and b(m^2) by b' (m^2) BW' (m^2)/Γee ·B . The interference is non-symmetrical around the peak: destructive below and constructive above. The radiator function gives a larger weight to lower photon energies, corresponding to higher di-muon invariant masses. This changes the m^2 shape around the peak asymmetrically. Replacing b(m^2) by b' (m^2) in formula (4) and using the world average [6] for Γee ·B enhances I(s) by about 2.2%. The function b' (m^2) depends on Γee ·B ; hence, an iterative procedure is used for its extraction.

Detector and Data

We use e e collision data collected at the Beijing Spectrometer III (BESIII) experiment. The BESIII detector [8] is located at the double-ring e e Beijing Electron Positron Collider (BEPCII). The cylindrical BESIII detector covers 93% of the full solid angle and consists of the following detector systems: (1) A

Multilayer Drift Chamber (MDC) filled with a helium-based gas, composed of 43 layers, providing a spatial resolution of 135 m and a momentum resolution of 0.5% for charged tracks at 1 GeV/c in a magnetic field of 1 T. (2) A Time-of-Flight system (TOF), composed of 176 plastic scintillator counters in the barrel part and 96 counters in the endcaps. The time resolution is 80 ps in the barrel and 110 ps in the endcaps, providing 2 K/ separation for momenta up to 1 GeV/c. (3) A CsI(Tl) Electro-Magnetic Calorimeter (EMC), with an energy resolution of 2.5% in the barrel and 5% in the endcaps at an energy of 1 GeV. (4) A Muon Chamber (MUC) consisting of nine barrel and eight endcap resistive plate chamber layers with a 2 cm position resolution.

We analyze 2.93 fb ^{1} [9] of data taken at $\sqrt{s} = 3.773$ GeV, which were collected in two separate runs in 2010 and 2011. A Geant4-based [13, 14] Monte Carlo (MC) simulation is used to determine efficiencies and study backgrounds. To simulate the ISR process e e $\rightarrow$, we use the phokhara event generator [5, 10], which includes ISR and final state radiation (FSR) corrections up to next-to-leading order (NLO). Hadronic ISR production is also simulated with phokhara. Bhabha scattering is simulated using the babayaga 3.5 event generator [11]. Continuum MC is produced with the kkmc generator [12].

Event Selection

We require the presence of at least two charged tracks in the MDC with net charge zero. The points of closest approach from the interaction point (IP) for these two tracks must be within a cylinder of 1 cm radius in the transverse direction and ±10 cm along the beam axis. In case of three-track events, we choose the track pair with net charge zero that is closest to the IP. The polar angle of the tracks must be within the fiducial volume of the MDC, 0.4 rad < < - 0.4 rad, where is measured with respect to the beam axis. We require the transverse momentum pt to be greater than 300 MeV/c for each track.

To enhance statistics and suppress non-ISR background, we investigate untagged ISR events, where the ISR photon is emitted under a small angle with respect to the beam axis. This is a new approach compared to BaBar and CLEO-c, both of which used tagged ISR photons. The ISR photon cannot be detected within the angular acceptance of the EMC. A one-constraint (1C) kinematic fit is performed under the hypothesis e e $\rightarrow$, using as input the two selected charged track candidates as well as the four-momentum of the initial e e system. The constraint is a missing massless particle, and the fit imposes overall energy and momentum balance. The ^{2} C value returned by the fit is required to be smaller than 10. In addition, the predicted missing photon angle with respect to the beam axis, , must be smaller than 0.3 radians or greater than - 0.3 radians in the lab frame.

Radiative Bhabha scattering e e ( ) has a cross section up to three orders of magnitude larger than the signal cross section, so electron tracks must be suppressed. An electron particle identification (PID) algorithm is used for this purpose, employing information from the MDC, TOF, and EMC [15]. The probabilities for the track being a muon P( ) or an electron P(e) are calculated, and P( ) > P(e) is required for both charged tracks, which leads to an electron suppression of more than 96%. To further suppress hadronic background, an Artificial Neural Network (ANN) built on the TMVA package [16] is used. The ANN is described in detail in Ref. [9]. Both charged tracks are required to have a classifier output value yANN smaller than 0.3 to be treated as muons, leading to a signal loss of less than 30% and a background rejection of more than 99%.

Background beyond the radiative processes is studied with MC simulations. Table 1 lists the number of events remaining after all previously described requirements in the mass range between 2.8 and 3.4 GeV/c^2. About 4.8 × 10 events are found in the data within this range. The background fraction is smaller than 0.04% for each of the 150 m^2 mass bins, and we subtract it from the data bin by bin.

Table 1: Total number of non-muon background events between 2.8 m 3.4 GeV/c^2 obtained with MC samples, normalized to the luminosity of the data set.

Final state	Background events
e e ( )	negligible
	8.4 ± 2.9
	3.3 ± 1.8
	0.3 ± 0.6
	negligible
K K	1.7 ± 1.3
K K	negligible
continuum	negligible
(3770) → D D	1.7 ± 1.3
(3770) → D D	negligible
(3770) → non-DD	negligible
J/ → non-	11.2 ± 3.4
Total	**11.8 ± 3.5**

Signal Extraction

The selection efficiency is determined based on signal MC events, obtained as the ratio of the measured number of events after all selection requirements to all generated ones. The true MC sample of J/ decays, which does not contain detector reconstruction, is used here with the full range, applying efficiency corrections on a track-by-track basis for muon tracking reconstruction, electron-PID, and ANN efficiency. These corrections have been derived in Ref. [9]. We find to be (32.04 ± 0.09)%, where the error is due to the size of the signal MC sample.

The number of J/ events NJ/ is determined from a binned maximum likelihood fit to data. The fit function f(x) used is:

$$f(x) = N_{J/\psi}[M(x) \otimes G(x)] + (N_{total} - N_{J/\psi})p(x), \tag{7}$$

where M(x) describes the shape of the MC-simulated J/ peak. We extract the shape from an MC simulation of J/ production using a certain Γee ·B value as input, together with QED production (including interference effects) as simulated with the phokhara event generator. The histogram M(x) is then obtained by subtracting a pure QED MC sample. It is shown in Fig. 1 [Figure 1: see original paper], using the world average [6] for Γee ·B as input. To account for differences in mass resolution between data and MC simulation, M(x) is convoluted (denoted by the operator) with a Gaussian distribution G(x) with mean x̄ and width , whose parameters are determined by the fit to data. To describe the non-resonant QED production in the fit, a fourth-order polynomial is used: p(x) = Σ a_i x^i. Ntotal is the constant number of data events between 2.8 and 3.4 GeV/c^2. Free parameters in the fit are NJ/ , x̄, , and the coefficients a_i (i = 1,···,4). Hence, NJ/ can be obtained directly by the fit. The fit result is shown in Fig. 2 [Figure 2: see original paper]; we find x̄ = (2.6 ± 0.1) MeV/c^2, = (10.5 ± 0.2) MeV/c^2, and ^{2}/ndf = 149.8/143.

Systematic Uncertainties

Equation (3) is used to determine Γee ·B in an iterative process. In each iteration, we simulate the histogram M(x) and calculate I(s) (including interference corrections) using a Γee ·B input value, and extract the Γee ·B output with Eq. (3). This result is used as input for the next iteration. We choose the PDG value [6] as the starting value. The results of each iteration are summarized in Table 3 . After three iterations the result becomes stable within four decimal places, which corresponds to the experimental uncertainty. As the final value we obtain:

$$\Gamma_{ee} \cdot B_{\mu\mu} = (333.4 \pm 2.5_{stat} \pm 4.4_{sys})\ \text{eV},$$

where the first error is the statistical uncertainty from the fit procedure, and the second error is the systematic uncertainty.

Table 3: Results of the single iteration steps. As start value the PDG 2014 one is used. The errors are the statistical ones.

Iteration	Γee ·B input value [eV]	Γee ·B output value [eV]
Start	PDG value [6]	333.9 ± 2.5
Step 1	result of step 1	333.3 ± 2.5
Step 2	result of step 2	333.4 ± 2.5
Step 3	result of step 3	333.4 ± 2.5

Iteration	Γee · B input value [eV]	Γee · B output value [eV]

All systematic uncertainties are summarized in Table 2 . They are summed up in quadrature to be 1.3% and are derived as follows:

1. **Integral I(s):** The difference in I(s) when enhancing or decreasing the value of Γee · B within five standard deviations of the error claimed by Ref. [6] is smaller than 0.2%. This deviation is considered as the systematic uncertainty of accommodating the interference effects in I(s).
2. **Background subtraction:** A conservative uncertainty of 100% is assumed for the MC samples. Hence, the systematic uncertainty due to background subtraction is smaller than 0.04% per bin and can therefore be neglected.
3. **Efficiency :** The data-MC efficiency corrections have been studied in Ref. [9]. The corresponding systematic uncertainties are listed in Table 2 and are found to be smaller than 0.5% in each case.
4. **Kinematic fit requirements:** To estimate the uncertainty introduced by the requirements on and ^{2} C, the resolution differences between data and MC simulation in these variables are obtained. For , we find the resolution difference to be (66 ± 3) × 10 radians by comparing an ISR photon tagged clean sample from both data and MC simulation. For ^{2} C, we determine the efficiency of the requirement ^{2} C $<$ 10 in data and MC simulation. We vary this requirement in data such that the efficiencies in data and MC simulation are the same. The difference from the actually used requirement is taken as resolution difference, which we find to be (1.1 ± 0.1) units in ^{2} C. To achieve a better description of , both variables are smeared in the signal MC sample with a Gaussian with mean zero and width corresponding to the resolution difference. To estimate the contribution to the systematic uncertainty, these variables are also varied by ±1 standard deviation, and the difference in is taken as the systematic uncertainty, which is found to be less than 0.5% for ^{2} C and negligible for .
5. **Fit range:** The chosen mass range between 2.8 and 3.4 GeV/c^2 is varied within 0.1 GeV/c^2 using the final value of Γee · B after the iteration procedure. The difference in Γee · B is smaller than 0.3% and is used as a systematic uncertainty.
6. **Luminosity:** The luminosity has been measured in Refs. [17, 9] with an uncertainty of 0.5%.
7. **Radiator function:** The radiator function is extracted from the phokhara event generator [10] and has an uncertainty of 0.5%.

8. **Angular acceptance:** The angular acceptance of the charged tracks is studied by varying this requirement by more than three standard deviations of the angular resolution and examining the corresponding difference in the final result. An uncertainty of less than 0.1% is found.

Table 2: Summary of the systematic uncertainties.

Source	Uncertainty
Background subtraction	negligible
Muon tracking efficiency	0.5%
Muon ANN efficiency	0.3%
Muon e-PID efficiency	0.1%
1C kinematic fit	0.5%
Angular acceptance	0.1%
Luminosity	0.5%
Radiator function	0.5%
Parametrizing the interference	0.2%
Variation of fit range	0.3%
Total	**1.3%**

Results

Using the BESIII measurement of B = (5.973 ± 0.007_stat ± 0.037_sys)% from Ref. [3], our measurement yields:

$$\Gamma_{ee} = (5.58 \pm 0.05_{stat} \pm 0.08_{sys})\ \text{keV}.$$

Our measurement of Γee · B is consistent with the results from BaBar [1] and CLEO-c [2]. The measured value for Γee is more precise, as summarized in Table 4 .

Table 4: Results of the BaBar [1] and CLEO-c [2] measurements compared to this work.

Measurement	Γee · B [eV]	Used B value [%]	Γee [keV]
BaBar	330.1 ± 7.7_stat ± 7.3_sys	5.88 ± 0.10 [18]	5.61 ± 0.20
CLEO-c	338.4 ± 5.8_stat ± 7.1_sys	5.953 ± 0.056_stat ± 0.042_sys [19]	5.68 ± 0.11_stat ± 0.13_sys
This work	333.4 ± 2.5_stat ± 4.4_sys	5.973 ± 0.007_stat ± 0.037_sys [3]	5.58 ± 0.05_stat ± 0.08_sys

Conclusion

In summary, we have used the ISR process e e → J/ → to measure Γee · B = (333.4 ± 2.5_stat ± 4.4_sys) eV with a total relative uncertainty of 1.5%. Combined with the BESIII measurement of B , we obtain Γee = (5.58 ± 0.05_stat ± 0.08_sys) keV with a relative precision of 1.7%.

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Figure 1: MC histogram from the phokhara generator after full detector simulation used for the fit. The value of $\Gamma ee \cdot B$ used for generation is the one from Ref. [6].

Figure 2: Fit to the data using the final value of $\Gamma ee \cdot B$ from Table 3 in the MC histogram for the fit.

Note: Figure translations are in progress. See original paper for figures.