Hindawi
Advances in High Energy Physics
Volume 2019, Article ID 2567070, 5 pages
https://doi.org/10.1155/2019/2567070

Research Article

A Method for the Direct Absolute Measurement of J/ψ Decay with $\psi(3686)$ Data Set

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Received 9 November 2018; Accepted 12 December 2018; Published 17 January 2019

Guest Editor: Ling-Yun Dai

To take the full advantage of the $\psi(3686)$ data set collected at e^+e^- collider at $\tau-$charm energy region, a tag method is developed to directly measure the J/ψ meson decay branching fractions absolutely. The J/ψ meson decay can be measured with the J/ψ sample tagged by the two soft charged pions from the decay $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$. This method is illustrated by comparing the input and output branching fractions of $J/\psi \longrightarrow \gamma\eta$ with 106 million inclusive $\psi(3686)$ Monte Carlo samples. The consistent result confirms the validity of the tag method.

1. Introduction

The firstly discovered charmonium J/ψ [1, 2], $J^{PC} = 1^{--}$, is the lowest one among those which can be produced directly in e^+e^- annihilation. Many experiments [3–14] have been performed to study its production and decay properties. However, the summation of the measured J/ψ decay branching fraction is not more than 60% [15] without considering the interference between resonance and continuum amplitudes until now, which hampers the understanding of its properties. The precisely measured branching fractions of J/ψ decay not only provide information to understand the J/ψ properties, but also can test OZI (Okubo-Zweig-Iizuka) rule, flavor SU(3) symmetry, and perturbative QCD [16].

The J/ψ production and decay property are studied by using the data collected from e^+e^- collisions at the J/ψ resonance traditionally. At this energy, the events consist mostly of $e^+e^- \longrightarrow J/\psi$, $e^+e^- \longrightarrow l^+l^-$ (l represents e, μ), with small amounts of three-flavor continuum and other processes such as γV, where V represents vector meson. Due to some unavoidable influences, such as interference effect and undistinguishable backgrounds, some J/ψ decay channels can not be studied by using this kind of data sample. An energy scan experiment performed around the J/ψ resonance can solve the problem induced by interference effect, while it is not effective for the final states with undistinguishable backgrounds from other processes. Usually, a large data set will be taken at $\psi(3686)$ resonance for $\tau-$charm factory. Taking the Beijing Spectrometer III (BESIII) [17] at the Beijing Electron Positron Collider II (BEPCII) [17] as an example, a goal of 3.2 billion $\psi(3686)$ events is set to be taken before its closure. Considering the large branching fraction of $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$, $(34.67 \pm 0.30)\%$ [15], this sample can naturally be used to study the J/ψ decay.

In this paper, we propose a method to construct a J/ψ sample by tagging the J/ψ meson with the two soft charged pions from $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$(called tag method for convenient) in the $\psi(3686)$ data sample. The feasibility of the method is then verified by examining the input and output branching fractions of $J/\psi \longrightarrow \gamma\eta$ in the inclusive $\psi(3686)$ Monte Carlo (MC) sample.

2. BESIII Detector and Simulation

There are four subdetectors at BESIII detector, which has been described elsewhere [17]. From the inner to the outside is Main Drift Chamber (MDC), Time of Flight (TOF), Electromagnetic Calorimeter (EMC), and Muon Counter

(MUC). The information from four subdetectors is used to identify and select candidate particles. The Superconducting Magnet, between EMC and MUC, provides 1 T magnetic field.

The work is performed in the framework of the BESIII Offline Software System (BOSS) [18], the GAUDI [19] based, which contains five subprojects such as framework, simulation, calibration, reconstruction, and analysis tools. Monte Carlo (MC) simulations are used to optimize the event selection and background estimation. The simulation software, the GEANT4-based, includes the geometric and material description of the BESIII detector, the detector response, running conditions, and performance. The production of $\psi(3686)$ is simulated by the KKMC [20, 21] generator, while its decay is generated by EVTGEN [22, 23] for known decay channels with branching fractions being set to the PDG [15] values, and by LUNDCHARM [24, 25] for the remaining unknown decay. In this work, 106 million inclusive $\psi(3686)$ events generated by data production group of BESIII are used. In addition, 100 000 exclusive $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$ with $J/\psi \longrightarrow \gamma\eta$ and $\eta \longrightarrow \gamma\gamma$ events are generated with JPIPI generator [22, 23] for $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$ and phase space generator for $J/\psi \longrightarrow \gamma\eta$ and $\eta \longrightarrow \gamma\gamma$.

3. Introduction of the Method

Usually, the $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$ is used to study J/ψ decay experimentally by calculating the branching fraction of $J/\psi \longrightarrow f$ (f denotes the studied final states) with formula

$$\mathscr{B}(J/\psi \longrightarrow f) = \frac{N^{\text{obs}}}{\epsilon \times N^{\text{tot}}_{\psi(3686)} \times \mathscr{B}(\psi(3686) \longrightarrow J/\psi\pi^+\pi^-)}, \quad (1)$$

where $\mathscr{B}$, N^{obs}, ϵ, and $N^{\text{tot}}_{\psi(3686)}$ represent the branching fraction, the number of observed events, the detection efficiency for the whole process ($\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$) with $J/\psi \longrightarrow f$), and the total number of $\psi(3686)$ events. This is an indirect measurement, which replies on the input $\mathscr{B}(\psi(3686) \longrightarrow J/\psi\pi^+\pi^-)$. While an update measurement of $\mathscr{B}(\psi(3686) \longrightarrow J/\psi\pi^+\pi^-)$ is made, the $\mathscr{B}(J/\psi \longrightarrow f)$ should be updated accordingly.

To solve this problem, a tag method can be employed to determine the $\mathscr{B}(J/\psi \longrightarrow f)$, which is a direct measurement method. With the dominant $\psi(3686)$ decay channel, $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$, the J/ψ meson can be tagged with the two soft opposite charged pions. If the two pions are reconstructed correctly, there must be a J/ψ meson in the event, then the J/ψ decay can be studied. With this method, the branching fraction can be calculated directly by

$$\mathscr{B}(J/\psi \longrightarrow f) = \frac{N^{\text{obs}}}{\epsilon \times N^{\text{tag}}_{J/\psi}}, \quad (2)$$

where $N^{\text{tag}}_{J/\psi}$ is the number of tagged J/ψ mesons in $\psi(3686)$ sample and ϵ is the detection efficiency of $J/\psi \longrightarrow f$. In the following, we take the determination of $\mathscr{B}(J/\psi \longrightarrow \gamma\eta)$ as an example to illustrate and validate this method.

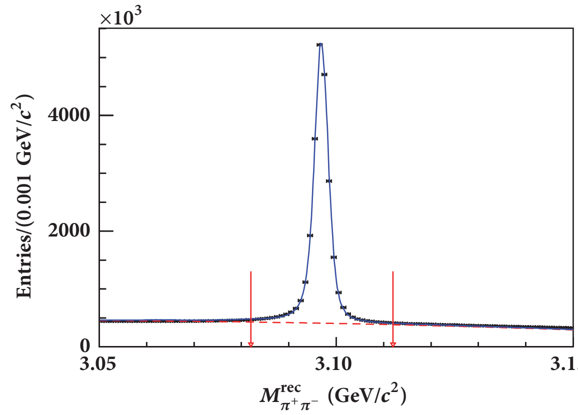

Figure 1: The $M^{\text{rec}}_{\pi^+\pi^-}$ spectra of candidate events from inclusive $\psi(3686)$ MC sample (the dots with error bars). The solid line shows the best fit to the spectra and the dashed line shows the background. The J/ψ signal region is shown between the two arrows.

4. General Track Selection

To be accepted as a good photon candidate, a neutral electromagnetic shower in the EMC must satisfy fiducial and shower-quality requirement. The good photon candidate showers reconstructed from the barrel EMC ($|\cos\theta| < 0.80$) must have a minimum energy of 25 MeV, while those in the end caps ($0.86 < |\cos\theta| < 0.92$) must have at least 50 MeV, where the energies deposited in nearby TOF counters are included. Showers in the region between the barrel and the end caps are poorly measured and excluded. To eliminate showers from charged particle, a photon candidate must be separated by at least 10° from any charged track. The time of EMC cluster (T_{EMC}) requirements is used to suppress electronic noise, which is $0 \leq T_{\text{EMC}} \leq 14$ (in unit of 50 ns).

Charged tracks in BESIII detector are reconstructed from MDC hits. Each charged track is required to satisfy $V_z < 10$ cm, $R_{xy} < 1$ cm and $|\cos\theta| < 0.93$, where V_z and R_{xy} are the closest approach to the beam axis in z direction and $x-y$ plane and θ is the polar angle.

5. Reconstruction of Tag Side

The two charged tracks in the tag side are required to satisfy $|\vec{p}| < 0.45$ GeV/c and $\cos\theta_{+-} < 0.95$, where $\vec{p}$ is the momentum of the candidate track and θ_{+-} is the angle between positive and negative charged tracks. The candidate tracks are assumed to be pions. The recoil mass of $\pi^+\pi^-$, $M^{\text{rec}}_{\pi^+\pi^-}$, is calculated by

$$M^{\text{rec}}_{\pi^+\pi^-} = \sqrt{(p_{\text{tot}} - p_{\pi^+} - p_{\pi^-})^2}, \quad (3)$$

where p_{tot}, p_{π^+}, and p_{π^-} are the four momenta of e^+e^-, π^+, and π^-. To reject the obvious background events, we only keep the events satisfying $3.03 < M^{\text{rec}}_{\pi^+\pi^-} < 3.17$ GeV/c^2. The $M^{\text{rec}}_{\pi^+\pi^-}$ spectra of candidate events are shown in Figure 1, which shows a clear J/ψ peak over a smooth background.

We fit the distribution of $M^{\text{rec}}_{\pi^+\pi^-}$ with the signal shape obtained from exclusive decay of $\psi(3686) \longrightarrow$

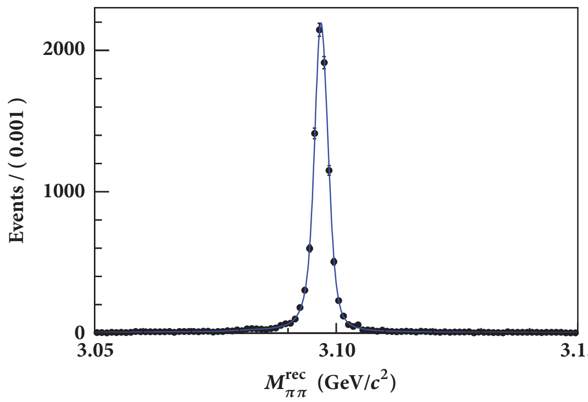

FIGURE 2: The $M^{rec}_{\pi^+\pi^-}$ spectra of the signal events from pure $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \mu^+\mu^-$ sample (the dots with error bars) and the signal shape (the solid blue line).

$J/\psi\pi^+\pi^-, J/\psi \longrightarrow \mu^+\mu^-$, which is shown in Figure 2, and a polynomial background. In Figure 2, the dots with error bar show the distribution of $M^{rec}_{\pi^+\pi^-}$ from pure $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \mu^+\mu^-$ MC events, and the solid line shows the extracted shape. Fitting the $M^{rec}_{\pi^+\pi^-}$ spectra of candidate events from 106 million inclusive $\psi(3686)$ MC samples with maximum likelihood method, the number of tagged J/ψ mesons can be obtained. The fitting results are shown in Figure 1, where the dots with error bar represent the numbers of events, the solid curve shows the total fitting result, and the dashed line shows the background. The fitting results given $(2.2515 \pm 0.0005) \times 10^7$ tagged J/ψ mesons. Considering the input $\mathcal{B}(\psi(3686) \longrightarrow J/\psi\pi^+\pi^-) = 32.6\%$, the tag efficiency is 65.2%.

To study the J/ψ decay in the recoil side, the $M^{rec}_{\pi^+\pi^-}$ is required to be located in J/ψ signal region, which is defined as from 3.082 to 3.112 GeV/c^2 according to the resolution of $M^{rec}_{\pi^+\pi^-}$ from the fitting. Integrating the signal distribution in the signal region, we obtain $(2.1120 \pm 0.0005) \times 10^7 J/\psi$ mesons.

6. Analysis of the J/ψ Decay

We choose the channel $J/\psi \longrightarrow \gamma\eta$ to study the validation of this method. The η meson is reconstructed with $\eta \longrightarrow \gamma\gamma$ and therefore there are three photons in the final states, one energetic radiative photon (denote by γ_1) and other two relative soft photons (denote by γ_2 and γ_3). Exactly three photons are required in each candidate event. For the energetic radiative photon, the deposited energy in EMC is required to be greater than 1.0 GeV in J/ψ rest frame. For the other two photons, the invariant mass of them ($M_{\gamma_2\gamma_3}$) is required to satisfy $0.45 < M_{\gamma_2\gamma_3} < 0.65$ GeV/c^2. To exclude the background from $\psi(3686) \longrightarrow \gamma\eta', \eta' \longrightarrow \eta\pi^+\pi^-$, the invariant mass of $\gamma_2\gamma_3$ and two soft pions ($M_{\gamma_2\gamma_3\pi^+\pi^-}$) is required to be greater than 1.0 GeV/c^2. A four-momentum constraint kinematic fit is performed to the candidate tracks and the χ^2 of the kinematic fit is required to be less than 40. The survived events are treated as $J/\psi \longrightarrow \gamma\eta$ candidates.

TABLE 1: The background of $J/\psi \longrightarrow \gamma\eta, \eta \longrightarrow \gamma\gamma$. N denotes the number of events passed from each decay chain.

decay chain	N
$\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \gamma\eta', \eta' \longrightarrow \gamma\gamma$	51
$\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \gamma\pi^0$	20
$\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \gamma f_4, f_4 \longrightarrow \pi^0\pi^0$	7
$\psi(3686) \longrightarrow \gamma_{FSR}e^+e^-\gamma_{FSR}$	1
$\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \gamma\eta\pi^0, \eta \longrightarrow \gamma\gamma$	1
$\psi(3686) \longrightarrow J/\psi\pi^+\pi^-, J/\psi \longrightarrow \gamma f_2, f_2 \longrightarrow \pi^0\pi^0$	1
$\psi(3686) \longrightarrow \gamma\eta', \eta' \longrightarrow \pi^+\pi^-\eta, \eta \longrightarrow \gamma\gamma$	1
$\psi(3686) \longrightarrow \pi^+\pi^-\pi^0\eta, \eta \longrightarrow \gamma\gamma$	1
$\psi(3686) \longrightarrow \pi^0 h_1, h_1 \longrightarrow \rho^+\pi^-, \rho^+ \longrightarrow \pi^+\pi^0$	1
$\psi(3686) \longrightarrow \rho^+ a_0^-, \rho^+ \longrightarrow \pi^+\pi^0, a_0^- \longrightarrow \pi^-\eta, \eta \longrightarrow \gamma\gamma$	1

TABLE 2: The input and output results.

	input	output
N^{tag}		$(2.1120 \pm 0.0005) \times 10^7$
N^{obs}		3399 ± 60
ϵ		$(41.49 \pm 0.39)\%$
$\mathcal{B}(J/\psi \longrightarrow \gamma\eta)$	9.8×10^{-4}	$(9.9 \pm 0.2) \times 10^{-4}$

The $M_{\gamma_2\gamma_3}$ spectra are examined to determine the number of signal events.

There are backgrounds from other decay channels. The MC truth information is used to study the background. Table 1 shows the decay chain of background channels for $J/\psi \longrightarrow \gamma\eta, \eta \longrightarrow \gamma\gamma$, and the number of background events from each channel is listed in the last column. The $M_{\gamma_2\gamma_3}$ spectra of background events are shown in Figure 3, where the signal region is between two arrows. The figure shows that there is no peak background contribution to $J/\psi \longrightarrow \gamma\eta$; the $\gamma_2\gamma_3$ spectra from background events can be described with smooth function.

7. Results

The $M_{\gamma_2\gamma_3}$ distribution from signal MC sample is shown in Figure 4 in dots with error bar, and the solid curve in the figure shows the probability density function extracted from the shape. The $M_{\gamma_2\gamma_3}$ spectra for the candidate events from inclusive $\psi(3686)$ sample are shown in Figure 5. We fit the spectra with the shape of $M_{\gamma_2\gamma_3}$ from signal MC sample to describe the signal and 1st order Chebychev polynomial to describe the background. The fitting results are shown in Figure 5, where the dots with error bars represent the number of events, the solid curve shows the total fit results, and the dashed line shows the background. The detection efficiency ϵ can be determined with signal MC sample, which is listed in the Table 2. Inserting the numbers into (2), considering the input $\mathcal{B}(\eta \longrightarrow \gamma\gamma) = 0.3925$, we can calculate $\mathcal{B}(J/\psi \longrightarrow \gamma\eta)$,

$$\begin{aligned}\mathcal{B}(J/\psi \longrightarrow \gamma\eta) &= \frac{3399 \pm 60}{0.4149 \times 2.1120 \times 10^7 \times 0.3925} \\ &= (9.9 \pm 0.2) \times 10^{-4}\end{aligned} \tag{4}$$

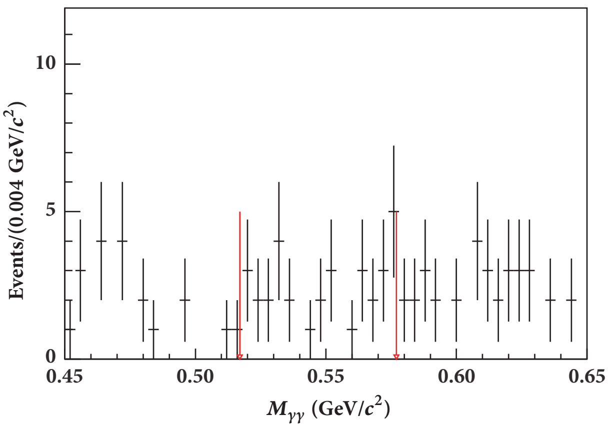

FIGURE 3: The $M_{\gamma_2\gamma_3}$ spectra of background events. The signal region of $M_{\gamma_2\gamma_3}$ is shown between the two arrows.

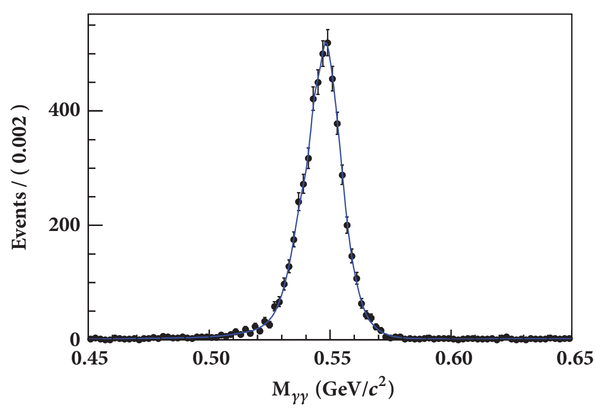

FIGURE 4: The $M_{\gamma_2\gamma_3}$ spectra of signal events from $J/\psi \longrightarrow \gamma\eta$ MC sample (dots with error bar) and the shape used to fit the $M_{\gamma_2\gamma_3}$ (solid blue line).

which is consistent with the input branching fraction 9.8×10^{-4}.

When considering the systematic uncertainty in the measurement of $J/\psi \longrightarrow \gamma\eta$, three sources, which are from the total number of $\psi(3686)$, the tracking efficiency of two soft pions, and the $\mathscr{B}(\psi(3686) \longrightarrow J/\psi\pi^+\pi^-)$, should be considered when the traditional method is used, but will not present in the tag method. The numbers for theses sources are 0.7% [26], 2.0% [27] in the BESIII experiment, and 0.9% [15], respectively. Therefore the total systematic uncertainty of the branching fraction measurement of this channel by using the tag method will be less than that of the traditional one.

8. Conclusion

In conclusion, we have developed a method to study the J/ψ decay with the $\psi(3686)$ data set. The two soft opposite charged pions from $\psi(3686) \longrightarrow J/\psi\pi^+\pi^-$ are used to tag the J/ψ meson. With the tagged J/ψ mesons from 106 million inclusive $\psi(3686)$ MC samples, the output branching fraction of $J/\psi \longrightarrow \gamma\eta$ is in good agreement with the input one, which gives a solid validation of this method. By employing this method, the J/ψ decay branching fractions can be precisely

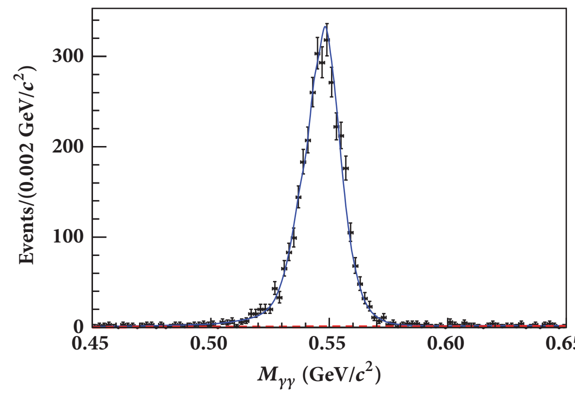

FIGURE 5: The $M_{\gamma_2\gamma_3}$ spectra of candidate events from 106 million inclusive $\psi(3686)$ MC samples (dots with error bar). The solid line shows the best fitting to the spectra and the dashed line shows the background.

measured absolutely with the large data set accumulated with BESIII and other detectors which will be run in charm energy region in the future [28] for the channels affected by interference effect or with undistinguishable background.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was partially supported by National Natural Science Foundation of China (Project Nos. 11575077 and 11475090), the Graduate Student Innovation Foundation (2018KYY033) and the Innovation Group of Nuclear and Particle Physics in USC.

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