Measurement of Branching Fractions in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ Decay

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Abstract

We report a measurement of the branching fractions in the $B^0 \to J/\psi \pi^+\pi^-$ decay based on a 140 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ energy with the Belle detector at the KEKB $e^+e^-$ collider. Charged pion pairs are found to arise mainly from $\rho^0$ and $f_2$ mesons; an upper limit for the non-resonant contribution is also set. The following branching fractions are obtained: $\mathcal{B}(B^0 \to J/\psi\rho^0) = (2.8 \pm 0.3 \pm 0.3) \times 10^{-5}$, $\mathcal{B}(B^0 \to J/\psi f_2) < 1.5 \times 10^{-5}$ (at 90% C.L.) and $\mathcal{B}(B^0 \to J/\psi(\pi^+\pi^-)_{\text{non-res.}}) < 1 \times 10^{-5}$ (at 90% C.L.).

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The decay $B^0 \to J/\psi \rho^0$, which is governed by the $b \to c \bar{c} d$ transition, can exhibit a $CP$-violating asymmetry. Since the tree diagram of this transition has the same weak phase as $b \to c \bar{c} s$, a measurement of indirect $CP$ violation in this decay provides an alternative estimate of $\sin 2\phi_1$. In contrast to the $b \to c \bar{c} s$ case, however, both tree and penguin amplitudes contribute to the $b \to c \bar{c} d$ transition in the same order of $\sin \theta_c$. Therefore, if penguin or other contributions are substantial, a precision measurement of the time-dependent $CP$ asymmetry in $b \to c \bar{c} d$ may reveal the values that differ from those for $b \to c \bar{c} s$. Thus, $B$ decays induced by the $b \to c \bar{c} d$ transition, such as $B^0 \to J/\psi \rho^0$, play an important role in probing non-tree diagram contributions.

Since the $\rho^0$ meson has a large width, it is necessary to study all the decays of the neutral $B$ meson that result in a $J/\psi \pi^+ \pi^-$ final state. In general, there are two possible contributions to the $B^0 \to J/\psi \pi^+ \pi^-$ mode. One is resonant, when a $\pi^+ \pi^-$ pair arises from some resonant state. The $B^0 \to J/\psi \rho^0$ decay mode is the largest in this class, although it is important to search for other resonant contributions. The other contribution is non-resonant, where a neutral $B$ meson decays directly into a $J/\psi$ and $\pi^+ \pi^-$ pair. For this process, the $CP$ eigenvalue is unknown; therefore, the evaluation of this contribution is important to control uncertainties when measuring $CP$ violation in $B^0 \to J/\psi \rho^0$ decays.

The first attempt to measure the branching fraction of $B^0 \to J/\psi \rho^0$ was made by the CLEO collaboration who set an upper limit $\mathcal{B}(B^0 \to J/\psi \rho^0) < 2.5 \times 10^{-4}$ at 90% C.L. using 2.39 fb$^{-1}$ of data [1]. Recently the BaBar collaboration reported their measurement of the branching fractions $\mathcal{B}(B^0 \to J/\psi \pi^+ \pi^-) = (4.6 \pm 0.7 \pm 0.6) \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi \rho^0) = (1.6 \pm 0.6 \pm 0.4) \times 10^{-5}$ based on a data sample of 52 fb$^{-1}$ [2]. In this paper, we report a measurement of the branching fractions of the neutral $B$ meson decays resulting in the $J/\psi \pi^+ \pi^-$ final state via $B^0 \to J/\psi \rho^0$ and $B^0 \to J/\psi f_2$ as well as an upper limit on the non-resonant $B^0 \to J/\psi \pi^+ \pi^-$ decay mode. These measurements are based on a 140 fb$^{-1}$ data sample, which contains 152 million $B \bar{B}$ pairs, collected with the Belle detector [3] at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [5] operating at the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer. Closest to the interaction point is a three-layer silicon vertex detector (SVD), followed by a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL). These subdetectors are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [4].

Hadronic events are selected if they satisfy the following criteria: at least three reconstructed charged tracks; a total reconstructed ECL energy in the center of mass (cms) frame in the range between $0.1 \sqrt{s}$ and $0.8 \sqrt{s}$, where $\sqrt{s}$ is the total cms energy; an average ECL cluster energy below 1 GeV; at least one ECL shower in the region $-0.7 < \cos \theta < 0.9$ in the laboratory frame; a total visible energy, which is the sum of charged track momenta and total ECL energy, exceeding $0.2 \sqrt{s}$, and a reconstructed primary vertex that is consistent with the known interaction point. After imposing these requirements, the efficiency for selecting $B$-meson pairs that include a $J/\psi$ meson is estimated by Monte Carlo (MC) simulation to be 99%. To suppress continuum events, we require the event shape variable $R_2$ to be less than 0.5, where $R_2$ is the ratio of the second to the zeroth Fox-Wolfram moment [6].

The $B$ candidate selection is carried out using two observables in the rest frame of the
$\Upsilon(4S)$ (cms): the beam-energy constrained mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - (\sum \vec{p}_i)^2}$ and the energy difference $\Delta E \equiv \sum E_i - E_{\text{beam}}$, where $E_{\text{beam}} = \sqrt{s}/2$ is the cms beam energy, and $\vec{p}_i$ and $E_i$ are the cms three-momenta and energies of the B meson decay product candidates.

Candidate $J/\psi$ mesons are reconstructed via their decay into oppositely charged lepton pairs ($e^+e^-$ or $\mu^+\mu^-$). Leptons are selected from charged tracks satisfying a cut $|dz| < 5$ cm, where $dz$ is the track’s closest approach to the interaction point along the beam direction. For electron identification, the ratio between the charged track’s momentum and the associated shower energy ($E/p$) is the most powerful discriminant. Other information, including the CDC specific ionization, the distance between the ECL shower and the extrapolated track, and the shower shape is also used. Muons are identified by requiring an association between KLM hits and an extrapolated track. Both lepton tracks must be positively identified as such. In the $e^+e^-$ mode, ECL clusters that are within 50 mrad of the track’s initial momentum vector are included in the calculation of the invariant mass ($M_{ee(\gamma)}$), in order to include photons radiated by electrons/positrons. The invariant masses of $e^+e^-(\gamma)$ and $\mu^+\mu^-$ combinations are required to fall in the ranges $-0.15$ GeV/$c^2 < (M_{ee(\gamma)} - M_{J/\psi}) < +0.036$ GeV/$c^2$ and $-0.06$ GeV/$c^2 < (M_{\mu\mu} - M_{J/\psi}) < +0.036$ GeV/$c^2$, respectively. Here $M_{J/\psi}$ denotes the world average of the $J/\psi$ mass $[8]$. We perform a vertex fit to the lepton pair candidate. Then a mass constrained fit is applied to improve the $\Delta E$ and $M_{bc}$ resolutions of the selected $B$ meson candidates.

Information from the ACC, TOF and CDC is combined into a likelihood ratio for kaon/pion separation; we then impose a cut to reject kaons. The efficiency for pions is more than 85% while the kaon fake rate is 10%. Charged pion candidates are also rejected if they are positively identified as leptons. Using pion candidates with $|dz| < 5$ cm, $\pi^+\pi^-$ pairs are formed. We apply a vertex fit to $\pi^+\pi^-$ pairs and require the distance between the reconstructed vertices of the $J/\psi$ and the $\pi^+\pi^-$ pair to be less than 3 mm in order to suppress $B^0 \rightarrow J/\psi K_S^0, K_S^0 \rightarrow \pi^+\pi^-$ events and backgrounds due to accidentally formed pion pairs.

$J/\psi$ candidates and $\pi^+\pi^-$ pairs are combined to select $B$ candidates. The distribution of the candidates in $\Delta E$ and $M_{bc}$ is shown in Fig. [1]. The signal box to select candidate events is defined as $5.270$ GeV/$c^2 < M_{bc} < 5.290$ GeV/$c^2$ and $-0.04$ GeV $< \Delta E < 0.04$ GeV. Using a MC data set of $B^0 \rightarrow J/\psi\pi^+\pi^-$ decays distributed uniformly in phase space, the detection efficiency is estimated to be 27.8%, where a difference of the pion identification in efficiency between MC and data is taken into account: the MC efficiency is 2.8% higher per pion track than in data. After applying all selection criteria, there are 537 candidates remaining in the signal box.

A binned maximum likelihood fit is performed to the distribution of the two pion invariant mass ($M_{\pi^+\pi^-}$) of the selected events to determine various contributions to $B^0 \rightarrow J/\psi\pi^+\pi^-$ events. Five types of events are considered: (i) $B^0 \rightarrow J/\psi\rho^0$; (ii) $B^0 \rightarrow J/\psi f_2$; (iii) $B^0 \rightarrow J/\psi\pi^+\pi^-$ (non-resonant signal); (iv) $B^0 \rightarrow J/\psi K_S^0 (K_S^0 \rightarrow \pi^+\pi^-)$; (v) background. A probability density function (PDF) is constructed for each of these five cases. The $B^0 \rightarrow J/\psi K_S^0$ mode is not considered as a signal while determining the branching fractions for the decay modes contributing to $B^0 \rightarrow J/\psi\pi^+\pi^-$. The PDF used to model the $B^0 \rightarrow J/\psi\rho^0$ mode is a relativistic $P$-wave Breit-Wigner function $[3]$:

$$F_\rho(M_{\pi^+\pi^-}) = \frac{M_{\pi^+\pi^-}\Gamma(M_{\pi^+\pi^-})B^{2L_{\text{off}}+1}}{(M_\rho^2 - M_{\pi^+\pi^-}^2)^2 + M_\rho^2\Gamma(M_{\pi^+\pi^-})^2}$$

(1)
where

$$\Gamma(M_{\pi^+\pi^-}) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2l+1} \frac{M_{\rho}}{M_{\pi^+\pi^-}(1 + R^2 q_0^2)(1 + R^2 q^2)}.$$  \hspace{1cm} (2)$$

Here, \(q(M_{\pi^+\pi^-})\) is the pion momentum in the di-pion rest frame, with \(q_0 = q(M_{\rho})\); \(P\) is the \(J/\psi\) momentum in the \(B^0\) rest frame; \(l = 1\) is the \(\rho^0\) meson’s spin; \(M_{\rho} = 775.8\) MeV/c\(^2\) and \(\Gamma_0 = 146.4\) MeV/c\(^2\). Also, \(L_{\text{eff}}\) is the effective orbital angular momentum between the \(J/\psi\) and the \(\rho^0\), which can take any value between 0 and 2, and \(R\) is the Blatt-Weisskopf barrier-factor radius. The fit is performed with \(L_{\text{eff}}\) and \(R\) equal to 1 and 0.5 fm, respectively.

The PDF for the \(B^0 \rightarrow J/\psi f_2\) mode is a relativistic \(D\)-wave Breit-Wigner function that is obtained by replacing the appropriate parameters in the PDF for \(B^0 \rightarrow J/\psi \rho^0\): \(l = 2\), \(M_{f_2} = 1.285\) GeV/c\(^2\) and \(\Gamma_0 = 184.3\) MeV/c\(^2\).

The PDF used to model the \(B^0 \rightarrow J/\psi K_S^0\) mode is a single Gaussian function with the mass and width fixed to the values obtained by fitting a \(K_S^0 \rightarrow \pi^+\pi^-\) invariant mass distribution in \(B^0 \rightarrow J/\psi K_S^0\) MC events.

The PDF for the \(B^0 \rightarrow J/\psi\pi^+\pi^-\) non-resonant signal is a parameterized \(M_{\pi^+\pi^-}\) distribution of the \(B^0 \rightarrow J/\psi\pi^+\pi^-\) phase space decay model.

The \(\Delta E\) distribution is used to determine the PDF for the background \(M_{\pi^+\pi^-}\) shape. According to the MC study, background modes do not give a peak in the \(\Delta E\) distribution.
Therefore, we estimate background by fitting the $\Delta E$ distribution with a first order polynomial (for background) and a Gaussian (for signals and $K^0_S, B^0 \to J/\psi \pi^+\pi^-$ final state). In order to estimate the background as a function of $M_{\pi^+\pi^-}$, we subdivide the candidate event sample in 0.2 GeV/$c^2$ $M_{\pi^+\pi^-}$ bins from 0.25 GeV/$c^2$ to 2.25 GeV/$c^2$. Then a fit to the $\Delta E$ distribution in each $M_{\pi^+\pi^-}$ bin is performed. One of the major background sources here is the $B^0 \to J/\psi K^{*0}, K^{*0} \to K^+\pi^-$ decay, when a charged kaon is misidentified as a pion. Because of the difference between the kaon and pion masses, this background mainly populates a region around $\Delta E \approx -0.1$ GeV. By choosing the region of $-0.05 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ for our fits we avoid this contribution. The signal width and mean value are fixed according to signal MC expectations. Fig. 2 shows the results of the fits.

We fit the obtained background with a fourth order polynomial as a function of $M_{\pi^+\pi^-}$. Since this PDF is determined from data in a model independent way, we fix it in the fit.

In order to find the probability of the $B^0 \to J/\psi f_2$ and non-resonant $B^0 \to J/\psi \pi^+\pi^-$ decays, the fit is carried out in three different cases: (i) PDFs for $B^0 \to J/\psi \rho^0, B^0 \to J/\psi K_S$ and background are summed, (ii) the $B^0 \to J/\psi f_2$ contribution is additionally taken into account, and (iii) adding the non-resonant $B^0 \to J/\psi \pi^+\pi^-$ contribution to case (ii). The optimal likelihood values, $\mathcal{L}_i, \mathcal{L}_{ii}$ and $\mathcal{L}_{iii}$ for the cases (i), (ii) and (iii), respectively, are used to obtain a statistical significance: $-2 \ln \mathcal{L}_i = 42.4, -2 \ln \mathcal{L}_{ii} = 33.7$ and $-2 \ln \mathcal{L}_{iii} = 33.7$. By comparing cases (i) and (ii), a statistical significance of $B^0 \to J/\psi f_2$ is found to be 2.9$\sigma$. As shown in Fig. 3, which is the fit result in case (ii), the $M_{\pi^+\pi^-}$ spectrum is almost saturated by the $K_S, \rho^0$ and $f_2$ contributions, and the non-resonant $B^0 \to J/\psi \pi^+\pi^-$ signal is found to be small. As a result of the fit in case (ii), the signal yields are obtained to be $139.8 \pm 17.0$ for $B^0 \to J/\psi \rho^0$ and $27.6 \pm 11.0$ for $B^0 \to J/\psi f_2$. To get a conservative upper limit for the non-resonant $B^0 \to J/\psi \pi^+\pi^-$ contribution, the background PDF normalization is reduced by 1$\sigma$ and another fit to the $M_{\pi^+\pi^-}$ distribution is performed. The resulting yield is $15.1 \pm 20.1$ events. Taking systematic uncertainties listed in Table 1 and using the Feldman-Cousins approach [10], an upper limit is obtained to be $\mathcal{B}(B^0 \to J/\psi (\pi^+\pi^-)_{\text{non-res.}}) < 1 \times 10^{-5}$ at 90% C.L.

For the $B^0 \to J/\psi \rho^0$ and $B^0 \to J/\psi f_2$ modes, the following systematic uncertainties are taken into account: uncertainty of the track detection efficiency; background estimations; Breit-Wigner modeling; uncertainty of the relevant branching fractions; statistical uncertainties of the signal MC events; and uncertainty on the number of $B\bar{B}$ events.

The tracking efficiency is estimated by MC and the control samples of partially reconstructed $D^*$ mesons, and its uncertainty is estimated to be 1.2% per track. The lepton identification efficiency is obtained from the ratio between the yields of single and double-tagged $J/\psi$ mesons, and its uncertainty is found to be 1.9% per track. An uncertainty of high-momentum charged pion identification is estimated from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays to be 1.7% per pion pair. The normalization of the background PDF is changed by $\pm 1\sigma$ and a fit to $M_{\pi\pi}$ is performed again. Then the signal yield change is taken into account as a systematic error due to background estimation. An uncertainty due to $L_{\text{eff}}$ and $R$ in the Breit-Wigner PDFs is estimated by the fit that is carried out changing $L_{\text{eff}}$ over its allower range. Two different values of the Blatt-Weisskopf barrier-factor radius $R$ (0.5 and 1.0 fm) are also compared. The maximum variation of the signal yield of each mode is assigned as a systematic error. Using a large MC sample of $B^0 \to J/\psi \pi^+\pi^-$ phase space decays, the detection efficiency is obtained as a function of $M_{\pi^+\pi^-}$, and its product by the Breit-Wigner PDFs for $\rho^0$ and $f_2$ mesons is integrated. The resulting values are compared to the detection efficiency obtained as an average over the whole kinematical region, and
the difference is assigned as a systematic error due to the signal MC modeling.
All other investigated systematic uncertainties are small compared to those described above. We list all the estimated systematic uncertainties for each mode in Table I.

TABLE I: Systematic uncertainties for each decay mode. Note that the uncertainty of background estimation for non-resonant \(J/\psi\pi^+\pi^-\) is already taken into account to obtain a yield.

| Mode                     | \(J/\psi^0\) | \(J/\psi f_2\) | \(J/\psi^{(\pi^+\pi^-)}_{\text{non-res.}}\) |
|--------------------------|--------------|----------------|-----------------------------------------------|
| Track reconstruction     | \(\pm 4.8\ %\) | \(\pm 4.8\ %\) | \(\pm 4.8\ %\) |
| Lepton-ID                | \(\pm 3.8\ %\) | \(\pm 3.8\ %\) | \(\pm 3.8\ %\) |
| \(\pi^\pm\)ID           | \(\pm 1.7\ %\) | \(\pm 1.7\ %\) | \(\pm 1.7\ %\) |
| Background estimation    | \(\pm 5.1\ %\) | \(\pm 15.4\ %\) | - |
| Breit-Wigner modeling    | \(\pm 2.7\ %\) | \(\pm 10.9\ %\) | - |
| Signal MC modeling       | \(\pm 2.7\ %\) | \(\pm 2.4\ %\) | - |
| MC statistics            | \(\pm 0.7\ %\) | \(\pm 0.7\ %\) | \(\pm 0.7\ %\) |
| \(\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)\) | \(\pm 1.7\ %\) | \(\pm 1.7\ %\) | \(\pm 1.7\ %\) |
| \(\mathcal{B}(f_2 \rightarrow \pi^+\pi^-)\) | - | \(\pm 2.9\ %\) | - |
| The number of \(B\bar{B}\) | \(\pm 0.4\ %\) | \(\pm 0.4\ %\) | \(\pm 0.4\ %\) |
| Total                    | \(\pm 9.2\ %\) | \(\pm 20.3\ %\) | \(\pm 6.6\ %\) |

Based on a large sample of \(B\bar{B}\) pairs, we obtained the following preliminary branching fractions for \(B\) decays resulting in the \(J/\psi\pi^+\pi^-\) final state: \(\mathcal{B}(B^0 \rightarrow J/\psi^0) = (2.8\pm0.3\text{(stat.)}\pm0.3\text{(syst.)}) \times 10^{-5}\) and \(\mathcal{B}(B^0 \rightarrow J/\psi f_2) = (9.8\pm3.9\text{(stat.)}\pm2.0\text{(syst.)}) \times 10^{-6}\). Since a statistical significance for the latter is \(2.9\sigma\) only, we also set an upper limit \(\mathcal{B}(B^0 \rightarrow J/\psi f_2) < 1.5 \times 10^{-5}\) at the 90\% C.L.; we also find \(\mathcal{B}(B^0 \rightarrow J/\psi^0_{\text{non-res.}}) < 1 \times 10^{-5}\) at the 90\% C.L. The obtained value of \(\mathcal{B}(B^0 \rightarrow J/\psi f_2)\) is consistent with that of BaBar and is more precise.

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[1] Throughout this paper, the inclusion of the charge conjugate decay modes is implied unless otherwise stated.
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FIG. 2: The $\Delta E$ distribution for $B^0 \to J/\psi \pi^+ \pi^-$ candidates in data in different $M_{\pi^+\pi^-}$ regions with the requirement $5.270 \text{ GeV}/c^2 < M_{bc} < 5.290 \text{ GeV}/c^2$. In each plot the $M_{\pi^+\pi^-}$ range is 0.2 GeV/$c^2$: from (a) $0.25 \text{ GeV}/c^2 < M_{\pi^+\pi^-} < 0.45 \text{ GeV}/c^2$ to (j) $1.05 \text{ GeV}/c^2 < M_{\pi^+\pi^-} < 1.25 \text{ GeV}/c^2$ in the alphabetic order. The combinatorial background is estimated by fitting this distribution with a Gaussian for a signal (the solid curve) and a first order polynomial for background (the dashed line).
FIG. 3: The distribution of $M_{\pi^+\pi^-}$ for $B^0 \to J/\psi\pi^+\pi^-$ candidates in data. The solid line shows the fitted results by taking the $K_S^0$, $\rho^0$, $f_2$ and background contributions into account. The dashed line is background only.