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## *Study of $B \rightarrow D^{(*)} D_{s(J)}^{(*)}$ decays and measurement of $D_{s}^{-}$ and $D_{sJ}(2460)^{-}$ branching fractions*

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| <b>Citation</b>     | Aubert, B. et al. "Study of $B \rightarrow D^{(*)} D_{s(J)}^{(*)}$ Decays and Measurement of $D_{s}^{-}$ and $D_{sJ}(2460)^{-}$ Branching Fractions." Physical Review D 74.3 (2006). |
| <b>As Published</b> | <a href="http://dx.doi.org/10.1103/PhysRevD.74.031103">http://dx.doi.org/10.1103/PhysRevD.74.031103</a>  |
| <b>Publisher</b>    | American Physical Society  |
| <b>Version</b>      | Final published version  |
| <b>Citable link</b> | <a href="http://hdl.handle.net/1721.1/76279">http://hdl.handle.net/1721.1/76279</a>  |
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## Study of $B^\pm \rightarrow J/\psi\pi^\pm$ and $B^\pm \rightarrow J/\psi K^\pm$ Decays: Measurement of the Ratio of Branching Fractions and Search for Direct $CP$ Violation

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- (Received 23 January 2004; published 18 June 2004)

We study  $B^\pm \rightarrow J/\psi\pi^\pm$  and  $B^\pm \rightarrow J/\psi K^\pm$  decays in a sample of about  $89 \times 10^6 B\bar{B}$  pairs collected with the BABAR detector at the PEP-II asymmetric  $B$  factory at SLAC. We observe a signal of  $244 \pm 20 B^\pm \rightarrow J/\psi\pi^\pm$  events and determine the ratio  $\mathcal{B}(B^\pm \rightarrow J/\psi\pi^\pm)/\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$  to be

$[5.37 \pm 0.45(\text{stat}) \pm 0.11(\text{syst})]\%$ . The charge asymmetries for the  $B^\pm \rightarrow J/\psi\pi^\pm$  and  $B^\pm \rightarrow J/\psi K^\pm$  decays are determined to be  $\mathcal{A}_\pi = 0.123 \pm 0.085(\text{stat}) \pm 0.004(\text{syst})$  and  $\mathcal{A}_K = 0.030 \pm 0.015(\text{stat}) \pm 0.006(\text{syst})$ , respectively.

DOI: 10.1103/PhysRevLett.92.241802

PACS numbers: 13.25.Hw, 11.30.Er, 12.38.Qk

We present an analysis of  $B^\pm \rightarrow J/\psi\pi^\pm$  and  $B^\pm \rightarrow J/\psi K^\pm$  decays that measures the ratio of branching fractions and searches for direct  $CP$  violation. The Cabibbo-suppressed decay  $B^\pm \rightarrow J/\psi\pi^\pm$  proceeds via a  $b \rightarrow c\bar{c}d$  transition. It is expected to have a rate about 5% of that of the Cabibbo-allowed mode  $B^\pm \rightarrow J/\psi K^\pm$ . The standard model predicts that for  $b \rightarrow c\bar{c}s$  decays the tree and penguin contributions have a small relative weak phase and thus a small direct  $CP$  violation is expected in  $B^\pm \rightarrow J/\psi K^\pm$  decays. However, for  $b \rightarrow c\bar{c}d$ , the tree and penguin contributions have different phases and charge asymmetries as large as a few percent may occur [1,2]. In the absence of isospin violation, the  $CP$  asymmetry in  $B^\pm \rightarrow J/\psi K^\pm$  provides [3] a measurement of the ratio  $|\bar{A}/A|$ , where  $A$  ( $\bar{A}$ ) is the decay amplitude for the neutral mode  $B^0(\bar{B}^0) \rightarrow J/\psi K_S^0$ .

Previous studies of the  $B^\pm \rightarrow J/\psi\pi^\pm$  mode have been performed by the CLEO [4], the CDF [5], the BABAR [6], and the Belle [7] collaborations. The Particle Data Group (PDG) 2002 average [8] of the ratio of  $B^\pm \rightarrow J/\psi\pi^\pm$  and  $B^\pm \rightarrow J/\psi K^\pm$  branching fractions is  $(4.2 \pm 0.7)\%$ . A recent Belle result gives  $\mathcal{B}(B^\pm \rightarrow J/\psi\pi^\pm) = (3.8 \pm 0.6 \pm 0.3) \times 10^{-5}$ . The PDG 2002 averages of the charge asymmetries are  $\mathcal{A}_\pi = -0.01 \pm 0.13$  and  $\mathcal{A}_K = -0.007 \pm 0.019$  [see Eq. (3) for the definition of the sign of the asymmetry].

The analysis reported in this paper is an update of the BABAR analysis in Ref. [6] and is based on a larger data set with improvements in data reconstruction. The data were recorded at the  $Y(4S)$  resonance with the BABAR detector [9] at the PEP-II storage ring at the Stanford Linear Accelerator Center. The integrated luminosity is  $81.9 \text{ fb}^{-1}$ , corresponding to  $89 \times 10^6 \text{ } B\bar{B}$  pairs.

At the BABAR detector, a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), in a 1.5-T solenoidal magnetic field, provide detection of charged particles and the measurement of their momenta. Electrons are detected in a CsI electromagnetic calorimeter, while muons are identified in the magnetic flux return system (IFR), which is instrumented with multiple layers of resistive plate chambers. A ring-imaging Cherenkov detector (DIRC) with quartz radiators provides charged-particle identification.

We fully reconstruct  $B^\pm \rightarrow J/\psi h^\pm$  decays, where  $h^\pm = \pi^\pm$  or  $K^\pm$ , from the combination of a  $J/\psi$  candidate and a charged track  $h^\pm$ . The  $J/\psi$  candidate is reconstructed via a  $J/\psi \rightarrow e^+e^-$  or  $J/\psi \rightarrow \mu^+\mu^-$  decay and is constrained to the nominal  $J/\psi$  mass [8]. The

electron candidates are combined with reconstructed photons in the calorimeter to recover some of the energy lost through bremsstrahlung. Details of the  $J/\psi$  reconstruction are given in Ref. [10]. Depending on the final state of the charmonium meson, the  $B^\pm$  candidates are divided into two categories,  $B_{ee}$  or  $B_{\mu\mu}$ . The distribution in the angle  $\theta_\ell$  in the  $J/\psi$  rest frame between one of the daughter leptons  $\ell$  of the  $J/\psi$  and the line of flight of the recoiling  $h^\pm$  is different for signal and background. The background peaks for  $|\cos\theta_\ell|$  near one while the signal follows a  $\sin^2\theta_\ell$  distribution. We require  $|\cos\theta_\ell| < 0.8$  for  $B_{ee}$  candidates and  $|\cos\theta_\mu| < 0.9$  for  $B_{\mu\mu}$  candidates.

Signal yields and charge asymmetries are determined by an unbinned maximum likelihood fit to the data. A vertex constraint is applied to the reconstructed tracks before computing the kinematic quantities of the  $B^\pm$  candidate. The beam energy-substituted mass  $m_{\text{ES}}$  is defined as

$$m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p} \cdot \mathbf{p}_B)^2/E^2 - |\mathbf{p}_B|^2}, \quad (1)$$

where  $\sqrt{s}$  is the total energy of the  $e^+e^-$  system in the  $Y(4S)$  rest frame, and  $(E, \mathbf{p})$  and  $(E_B, \mathbf{p}_B)$  are the four-momenta of the  $e^+e^-$  system and the reconstructed  $B$  candidate, both in the laboratory frame. The kinematic variable  $\Delta E_\pi$  ( $\Delta E_K$ ) is defined as the difference between the reconstructed energy of the  $B^\pm$  candidate and the beam energy in the  $Y(4S)$  rest frame assuming  $h^\pm = \pi^\pm$  ( $K^\pm$ ). Signal candidates for  $B^\pm \rightarrow J/\psi\pi^\pm$  ( $B^\pm \rightarrow J/\psi K^\pm$ ) peak in  $m_{\text{ES}}$  at the  $B^\pm$  meson mass and peak in  $\Delta E_\pi$  ( $\Delta E_K$ ) at 0. Candidates are required to satisfy loose requirements on these variables:  $|\Delta E_\pi| < 120 \text{ MeV}$ ,  $|\Delta E_K| < 120 \text{ MeV}$ , and  $m_{\text{ES}} > 5.2 \text{ GeV}/c^2$ . The kinematic separation is sufficiently good (see Fig. 3) so that no explicit particle identification is required on the charged hadron  $h^\pm$ , thereby simplifying the analysis.

The selected sample contains 3801  $B_{\mu\mu}$  and 4053  $B_{ee}$  candidates. Figure 1(a) shows the  $m_{\text{ES}}$  distribution in data fitted to the sum of a Gaussian and an empirical phase-space function (Argus function [11]) describing the signal and background components, respectively. Figure 1(b) shows the  $\Delta E_K$  distribution for data candidates with  $m_{\text{ES}} > 5.27 \text{ GeV}/c^2$  fitted to the sum of a double Gaussian and a polynomial function, describing the dominant  $B^\pm \rightarrow J/\psi K^\pm$  signal and the background contribution, respectively.

The background (bkg) from continuum and generic  $B\bar{B}$  decays is characterized using events that are outside the

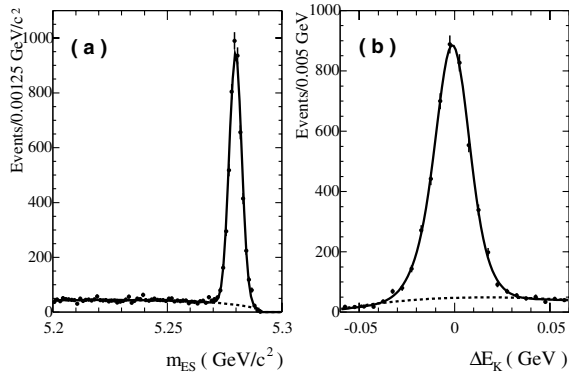


FIG. 1. (a) The  $m_{ES}$  distribution for the  $B^\pm$  candidates in data. A fit to the sum of a Gaussian and an empirical threshold function (dashed curve) is superimposed. The fitted resolution is approximately  $2.5 \text{ MeV}/c^2$ . (b) The  $\Delta E_K$  distribution for the  $B^\pm$  candidates in data with  $m_{ES} > 5.27 \text{ GeV}/c^2$ . A fit to the sum of a double Gaussian and a 3rd order polynomial function (dashed curve) is superimposed. The fitted resolution is approximately  $10.5 \text{ MeV}$ .

signal regions (sidebands of the data sample). Candidates in the  $m_{ES}$  sideband are defined by the requirement  $5.20 < m_{ES} < 5.27 \text{ GeV}/c^2$ , where the upper limit is approximately 4 times the experimental resolution below the  $B$  mass. Candidates in the  $\Delta E_K$  and  $\Delta E_\pi$  sidebands are defined by the requirement  $42 < |\Delta E_K| < 120 \text{ MeV}$  and  $42 < |\Delta E_\pi| < 120 \text{ MeV}$ , where the lower limit is approximately 4 times the  $\Delta E$  resolution obtained from the fit shown in Fig. 1(b).

We maximize the following extended likelihood function:

$$L = e^{-\sum_i N_i} \prod_{j=1}^M \sum_i P_i(\Delta E_\pi^j, p_h^j, m_{ES}^j) c_i(q^j) N_i,$$

where  $j$  is the index of the event,  $i$  is the index of the hypothesis ( $i = \pi, K, \text{bkg}$ ),  $N_i$  is the yield for each hypothesis, and  $M$  is the total number of events in the sample. The arguments of the probability density functions (PDFs)  $P_i$  are the kinematic observables  $(\Delta E_\pi, p_h, m_{ES})$ , where  $p_h$  is the  $h^\pm$  momentum in the laboratory frame. We use different PDFs for  $B_{ee}$  and  $B_{\mu\mu}$  candidates, while we assume the same PDFs for  $B^+$  and  $B^-$  candidates.

The factor  $c_i(q)$  is the fraction of candidates with charge  $q$  in hypothesis  $i$ :

$$c_i(q) = \begin{cases} 1/2(1 - \mathcal{A}_i), & \text{if } q = +1, \\ 1/2(1 + \mathcal{A}_i), & \text{if } q = -1, \end{cases} \quad (2)$$

where  $\mathcal{A}_i$  is the charge asymmetry:

$$\mathcal{A}_i = \frac{N_i^- - N_i^+}{N_i^- + N_i^+}. \quad (3)$$

The yields  $N_i$  and the asymmetries  $\mathcal{A}_i$  are free parameters in the likelihood fit.

Since the measured variables  $\Delta E_\pi$  and  $p_h$  are correlated, we define a new set of variables:

$$D = \Delta E_K - \Delta E_\pi = \gamma(\sqrt{p_h^2 + m_K^2} - \sqrt{p_h^2 + m_\pi^2}),$$

$$\Sigma = (\Delta E_K + \Delta E_\pi)/(D - a),$$

$$\Pi = D(D/2 - a),$$

where  $\gamma$  is the Lorentz boost from the laboratory frame to the  $\Upsilon(4S)$  rest frame and  $a = 240 \text{ MeV}$  is twice the maximum  $|\Delta E_\pi|$  or  $|\Delta E_K|$  value for the data sample. These variables have the property that  $(\Delta E_\pi, D)$  in the pion hypothesis,  $(\Delta E_K, D)$  in the kaon hypothesis, and  $(\Sigma, \Pi)$  in the background hypothesis are correlated at less than the few percent level. Therefore each  $P_i$  can be written as a product of one-dimensional PDFs:

$$P_\pi(\Delta E_\pi, p_h, m_{ES}) = f_\pi(\Delta E_\pi)g_\pi(D)h_\pi(m_{ES}),$$

$$P_K(\Delta E_\pi, p_h, m_{ES}) = f_K(\Delta E_K)g_K(D)h_K(m_{ES}),$$

$$P_{\text{bkg}}(\Delta E_\pi, p_h, m_{ES}) = f_{\text{bkg}}(\Sigma)g_{\text{bkg}}(\Pi)h_{\text{bkg}}(m_{ES}).$$

The  $f_\pi$  and  $f_K$  components are represented by double Gaussians, while  $h_\pi$  and  $h_K$  are described by single Gaussians. The parameters of  $f_\pi$  and  $h_\pi$  are constrained to be equal to the parameters of  $f_K$  and  $h_K$ , respectively. They are free parameters in the likelihood fit and are extracted together with the yields. This strategy reduces the systematic error due to possible inaccuracies of the Monte Carlo (MC) simulation in describing the  $\Delta E$  and  $m_{ES}$  distributions.

The  $g_\pi$  and  $g_K$  components are each represented by a phenomenological function with seven fixed parameters estimated from the MC simulation. They follow an exponential shape with Gaussian edges.

The  $f_{\text{bkg}}$  component is represented by a linear phenomenological function with fixed parameters estimated from the distribution of  $\Sigma$  for events in the  $m_{ES}$  sideband [Fig. 2(a)].

The  $g_{\text{bkg}}$  component is represented by a phenomenological function with 12 fixed parameters, all estimated from the distribution of  $\Pi$  for events in the  $m_{ES}$  sideband [Fig. 2(b)].

The  $h_{\text{bkg}}$  component is represented by the sum of an Argus function and a Gaussian function, with fixed parameters. The shape parameters are estimated from the distribution of  $m_{ES}$  for events in both the  $\Delta E_K$  and  $\Delta E_\pi$  sidebands. The small number of background events peaking in the  $m_{ES}$  signal region is due to candidates reconstructed from other  $B \rightarrow J/\psi X$  decays. From detailed MC simulations of inclusive charmonium decays we

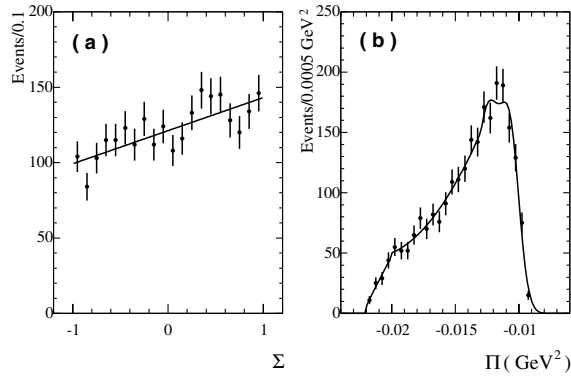


FIG. 2. The distribution of (a)  $\Sigma$  and (b)  $\Pi$  for events in the  $m_{ES}$  sideband in data. The curve corresponds to the projection of the best fit.

determine  $40 \pm 7$  peaking background events in our sample.

The yields determined with the unbinned maximum likelihood fit to the data sample are reported in Table I. The correlation coefficient between  $N_\pi$  and  $N_K$  is  $-0.02$ . The probability to obtain a maximum value of the likelihood smaller than the observed value is 50%, estimated by MC techniques. Figure 3 shows the distributions of  $\Delta E_\pi$  for the events in the data, compared with the distributions obtained by generating events with a parametric MC simulation based on the PDFs used in the fit.

Possible biases in the likelihood estimates were investigated by performing the fit on simulated samples of known composition and of the same size as the data. The samples were generated with parametric MC simulations based on the PDFs used in the fit. There is no evidence of bias in the fitted asymmetries, while a less than 1% deviation in the fitted yields from the nominal values is present. After correcting the yields for the observed bias, we obtain  $N_\pi = 244 \pm 20$ ,  $N_K = 4548 \pm 70$ , and a ratio of branching fractions of  $(5.37 \pm 0.45)\%$  with an absolute systematic error of 0.11%. The dominant source of systematic error is the fixed parameters of the PDFs, primarily the PDFs that describe the background. Other sources of systematic uncertainty, such as differences in the reconstruction efficiencies for  $J/\psi\pi^\pm$  and  $J/\psi K^\pm$  events and inaccuracies in the description of the tails of the  $\Delta E$  resolution function, are found to be negligible.

TABLE I. Uncorrected yields  $N_i$  and uncorrected charge asymmetries  $\mathcal{A}_i$  from the fit to the data sample.

| $i$   | $N_i$         | $\mathcal{A}_i$   |
|-------|---------------|-------------------|
| $\pi$ | $242 \pm 20$  | $0.117 \pm 0.084$ |
| $K$   | $4538 \pm 70$ | $0.028 \pm 0.015$ |
| $bg$  | $3074 \pm 60$ | $0.019 \pm 0.020$ |

The sample that is used to determine the charge asymmetries is defined by imposing as a further requirement that the charged track  $h^\pm$  has a polar angle in the range  $[0.41, 2.54]$  radians, includes at least 12 DCH hits, has a momentum in the transverse plane  $p_t > 100$  MeV/c, and points back to the nominal interaction point within 1.5 cm in the transverse plane and within 3 cm along the longitudinal direction. For these tracks the difference in tracking efficiency between positively and negatively charged tracks—primarily pions—has been studied in hadronic events by comparing independently the SVT and DCH tracking systems.

The selected sample contains 3902  $B^- \rightarrow J/\psi h^-$  and 3696  $B^+ \rightarrow J/\psi h^+$  candidates. From the likelihood fit we obtain the charge asymmetries reported in Table I. The correlation coefficient between  $\mathcal{A}_\pi$  and  $\mathcal{A}_K$  is  $-0.003$ . Using MC techniques we estimate that the probability to obtain a fitted asymmetry  $\mathcal{A}_K$  greater or equal to the one observed, in the hypothesis of zero asymmetry, is 6.7%.

We correct the fitted asymmetries for the small observed difference in tracking efficiency between positively and negatively charged tracks, obtaining  $\mathcal{A}_\pi = 0.123 \pm 0.085$  and  $\mathcal{A}_K = 0.030 \pm 0.015$ . The uncertainty on the corrections contributes 0.004 and 0.005 to the systematic error on  $\mathcal{A}_\pi$  and  $\mathcal{A}_K$ , respectively. The asymmetry induced by the different probability of  $K^+$  and  $K^-$  interactions in the detector material before the DCH is estimated to be  $-0.004$ . This value is conservatively assumed to be a contribution to the systematic uncertainty. The uncertainty in the fixed parameters of the PDFs, determined by fits to simulated or nonsignal data sets, contributes 0.001 to the systematic errors on both  $\mathcal{A}_\pi$  and  $\mathcal{A}_K$ .

Summing in quadrature statistical and systematic errors, we obtain a 90% C.L. interval of  $[-0.017, 0.263]$  for  $\mathcal{A}_\pi$  and  $[0.003, 0.057]$  for  $\mathcal{A}_K$ .

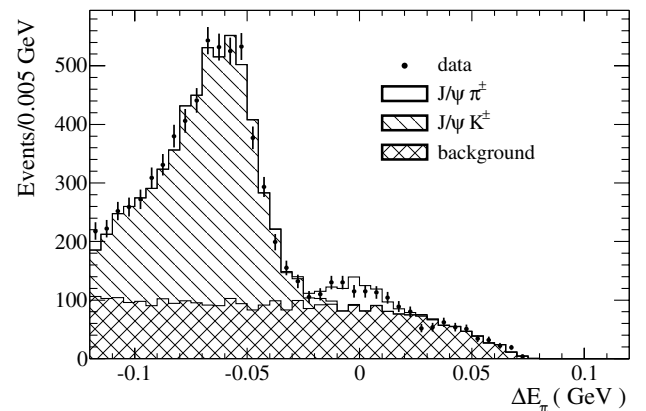


FIG. 3. The  $\Delta E_\pi$  distribution in data (points) compared with the distribution obtained from a simulated experiment (histogram). The distributions for each simulated component in the sample, normalized to the fitted event yields, are also displayed.

In conclusion we measure the ratio of branching fractions

$$\frac{\mathcal{B}(B^\pm \rightarrow J/\psi \pi^\pm)}{\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)} = [5.37 \pm 0.45(\text{stat}) \pm 0.11(\text{syst})]\%,$$

which is consistent with theoretical expectations and with previous measurements. We also determine the charge asymmetries

$$\mathcal{A}_\pi = 0.123 \pm 0.085(\text{stat}) \pm 0.004(\text{syst}),$$

$$\mathcal{A}_K = 0.030 \pm 0.015(\text{stat}) \pm 0.006(\text{syst}).$$

Our results are consistent with previous measurements but with significant improvement in the precision.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from

the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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