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A Study of $B^{\pm} \to J/\psi\,\pi^{\pm}$ and $B^{\pm} \to J/\psi\,K^{\pm}$ Decays: Measurement of the Ratio of Branching Fractions and Search for Direct *CP*-Violating Charge Asymmetries

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We have studied the $B^{\pm} \to J/\psi\,\pi^{\pm}$ and $B^{\pm} \to J/\psi\,K^{\pm}$ decays using a 20.7 fb^{-1} data set collected with the *BABAR* detector. We observe a signal of 51 ± 10 $B^{\pm} \to J/\psi\,\pi^{\pm}$ events and determine the ratio $\mathcal{B}(B^{\pm} \to J/\psi\,\pi^{\pm})/\mathcal{B}(B^{\pm} \to J/\psi\,K^{\pm})$ to be $[3.91 \pm 0.78(stat.) \pm 0.19(syst.)]\%$. The *CP*-violating charge asymmetries for the $B^{\pm} \to J/\psi\,\pi^{\pm}$ and $B^{\pm} \to J/\psi\,K^{\pm}$ decays are determined to be $\mathcal{A}_{\pi} = 0.01 \pm 0.22(stat.) \pm 0.01(syst.)$ and $\mathcal{A}_{K} = 0.003 \pm 0.030(stat.) \pm 0.004(syst.)$.

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The decay $B^{\pm} \to J/\psi\,\pi^{\pm}$ is both Cabibbo-suppressed and color-suppressed. If the leading-order tree diagram is the dominant contribution, its branching fraction is expected to be about 5% of the Cabibbo-allowed mode $B^{\pm} \to J/\psi K^{\pm}$. A comparable prediction can be obtained with a simple model based on the factorization hypothesis [1]. Previous studies of this decay were performed by the CLEO [2] and CDF [3] collaborations. Significant interference terms between the suppressed tree and penguin amplitudes could produce a direct *CP*-violating charge asymmetry in the $B^{\pm} \to J/\psi \pi^{\pm}$ decays at the few percent level [4]. On the contrary, a negligible direct *CP*-violation is expected in the $B^{\pm} \to J/\psi K^{\pm}$ decays, because for $b \to c\bar{c}s$ transitions the Standard Model predicts that the leading- and higher-order diagrams are characterized by the same weak phase.

In this paper we present a measurement of the ratio of branching fractions $\mathcal{B}(B^{\pm} \to J/\psi \pi^{\pm})/\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})$ along with a search for direct *CP*-violation in these channels. The data were recorded at the $\Upsilon(4S)$ resonance in 1999-2000 with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center. The integrated luminosity is $20.7\,\mathrm{fb}^{-1}$, corresponding to 22.7 million $B\overline{B}$ pairs. We fully reconstruct $B^{\pm} \to J/\psi h^{\pm}$ decays, where $h^{\pm} = \pi^{\pm}, K^{\pm}$. Signal yields and charge asymmetries are determined from an unbinned maximum likelihood fit that exploits the kinematics of the decay to identify the $\pi^{\pm}$, $K^{\pm}$ and background components in the sample. This kinematic separation is sufficiently good so that no explicit particle identification is required on the charged hadron $h^{\pm}$, thereby simplifying the analysis. At the same time, particle identification can be used to perform a crosscheck of the measurement.

The *BABAR* detector is described in detail elsewhere [5]. 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 measurement of their momenta. The transverse momentum resolution is $\sigma_{p_t}/p_t = (0.13 \pm 0.01)\% \cdot p_t + (0.45 \pm 0.03)\%$, where p_t is measured in GeV/c. Electrons are detected in a CsI electromagnetic calorimeter (EMC), 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 a quartz bar radiator provides charged particle identification.

An electron candidate is selected according to the ratio of the energy detected in the EMC to track momentum, the cluster shape in the EMC, the energy loss in the DCH, and the DIRC Cherenkov angle, if available. A muon candidate is selected according to the difference between the expected and measured thickness of absorber traversed, the match of the hits in the IFR with the extrapolated track, the average and spread in the number of hits per IFR layer, and the energy detected in the EMC.

$J/\psi \to \mu^+\mu^-$ candidates are constructed from two identified muons with polar angle in the range $[0.3, 2.7]$ radians and with invariant mass $3.06 < M_{\mu^+\mu^-} < 3.14\,\mathrm{GeV}/c^2$. The absolute value of the cosine of the helicity angle of the J/ψ decay is required to be less than 0.9. $J/\psi \to e^+e^-$ candidates are constructed from two identified electrons with polar angle in the range $[0.41, 2.409]$ radians and with invariant mass $2.95 < M_{e^+e^-} < 3.14\,\mathrm{GeV}/c^2$. The absolute value of the cosine of the helicity angle is required to be less than 0.8.

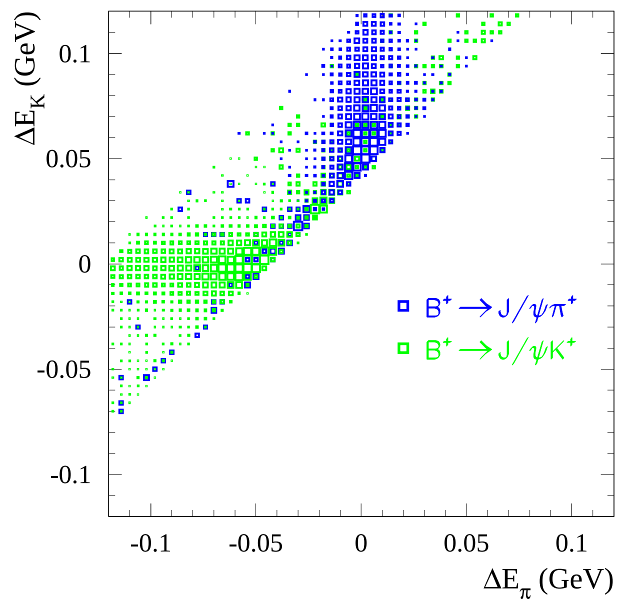

FIG. 1: Distribution of ΔE_K vs. ΔE_π for $B^{\pm} \to J/\psi K^{\pm}$ and $B^{\pm} \to J/\psi \pi^{\pm}$ events from Monte Carlo simulations.

$B^{\pm}$ candidates are formed from the combination of a reconstructed J/ψ, constrained to the world average mass [6], and a charged track $h^{\pm}$. A vertex constraint is applied to the reconstructed tracks before computing two kinematic quantities of the $B^{\pm}$ candidate used to discriminate signal from background. We define the beam energy-substituted mass m_{ES} as

$$m_{\mathrm{ES}} = \sqrt{[(s/2 + \mathbf{p_i} \cdot \mathbf{p_B})^2/E_i^2] - |\mathbf{p_B}|^2}\,, \qquad (1)$$

where $\sqrt{s}$ is the total energy of the e^+e^- system in the $\Upsilon(4S)$ rest frame, and $(E_i, \mathbf{p_i})$ 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. We define the kinematic variable ΔE_π (ΔE_K) as the difference between the reconstructed energy of the $B^{\pm}$ candidate and the beam energy in the $\Upsilon(4S)$ rest frame assuming $h^{\pm} = \pi^{\pm}(K^{\pm})$. We require $|\Delta E_\pi| < 120\,\mathrm{MeV}$, $|\Delta E_K| < 120\,\mathrm{MeV}$ and $m_{\mathrm{ES}} > 5.2\,\mathrm{GeV}/c^2$. Figure 1 shows the distribution for Monte Carlo simulations of $B^{\pm} \to J/\psi \pi^{\pm}$ and $B^{\pm} \to J/\psi K^{\pm}$ events in the $(\Delta E_\pi, \Delta E_K)$ plane.

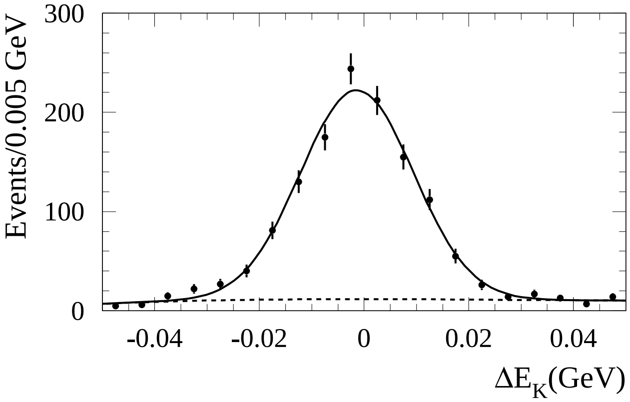

FIG. 2: The ΔE_K distribution and fit for the events in the data sample with $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$. The dashed curve represents the background contribution.

The selected sample contains 1074 $B^\pm \to J/\psi(\to \mu^+\mu^-)h^\pm$ and 1081 $B^\pm \to J/\psi(\to e^+e^-)h^\pm$ candidates. A fit to the ΔE_K distribution with the sum of a Gaussian and a polynomial function, modeling the $B^\pm \to J/\psi\,K^\pm$ signal and the background contribution, is shown in Fig. 2.

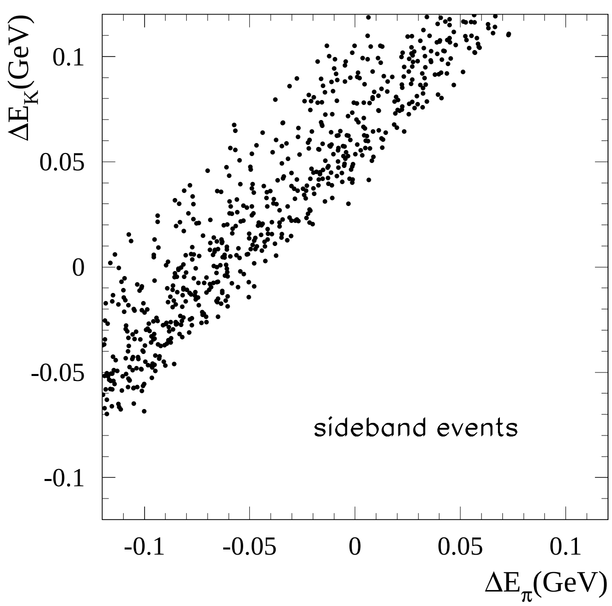

FIG. 3: Distribution of ΔE_K vs. ΔE_π for the events in the $m_{\rm ES}$ sideband of the data sample.

The background contaminating the sample is characterized with events in the data that are sufficiently far from the typical signal regions (sidebands of the data sample). We define $m_{\rm ES}$ sideband events by the requirement that $5.2 < m_{\rm ES} < M_B - 4\sigma(m_{\rm ES}) = 5.27\,{\rm GeV}/c^2$, where M_B is the world average $B^\pm$ mass [6] and $\sigma(m_{\rm ES})$ is the $m_{\rm ES}$ resolution; their distribution in the $(\Delta E_\pi, \Delta E_K)$ plane is shown in Fig. 3. We define ΔE_K and ΔE_π sideband events by the requirement that $120 > |\Delta E_K| > 4\sigma(\Delta E) = 42\,{\rm MeV}$ and $120 > |\Delta E_\pi| > 4\sigma(\Delta E) = 42\,{\rm MeV}$, where $\sigma(\Delta E)$ is the width of the fitted Gaussian in Fig. 2. The distribution in $m_{\rm ES}$ of the sideband events is modeled by an ARGUS function [7], with an additional Gaussian peak in the $m_{\rm ES}$ signal region for events from other $B \to J/\psi\,X$ decays. The number of background events in this peak has been estimated to be 10 ± 4 with detailed Monte Carlo simulation of inclusive charmonium decays. Figure 4 shows the $m_{\rm ES}$ distribution for the data sample, along with the fit.

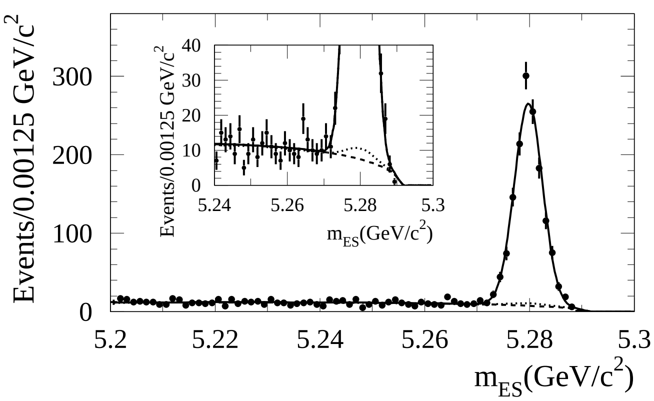

FIG. 4: The $m_{\rm ES}$ distribution and fit for the events in the data sample. The ARGUS (dashed curve) and peaking (dotted curve) components of the background are also displayed.

Our fit to the data sample is based on maximizing the following extended likelihood function:

$$L = {\rm e}^{-\sum_i N_i} \prod_{j=1}^{M} \sum_i P_i(\Delta E_\pi^j, p^j, {m_{\rm ES}}^j) N_i\,, \qquad (2)$$

where j is the index of the event, i is the index of the hypothesis ($i = \pi, K, bkd$), N_i are the yields for the $B^\pm \to J/\psi\,\pi^\pm$, $B^\pm \to J/\psi\,K^\pm$, and background events in the sample, and M is the total number of events. The observables ΔE_π, the momentum p of the final-state charged hadron computed in the laboratory frame, and $m_{\rm ES}$ are used as arguments of the probability density functions (PDF) P_i. The PDFs are mainly determined from data with limited input from simulation.

It is useful to define the new variables $D = \Delta E_K - \Delta E_\pi = \gamma\left(\sqrt{p^2+m_K^2} - \sqrt{p^2+m_\pi^2}\right)$, where γ is the Lorentz boost from the laboratory frame to the $\Upsilon(4S)$ rest frame, and $S = \Delta E_K + \Delta E_\pi = 2\Delta E_\pi + D$. These variables have the property that $(\Delta E_\pi, D)$ in the pion hypothesis, $(\Delta E_K, D)$ in the kaon hypothesis, and (S, D) in the background hypothesis are uncorrelated at the

1% level. Therefore, with appropriate transformations of variables, each $P_i(\Delta E_\pi, p, m_{\rm ES})$ can be written as a product of one-dimensional PDFs:

$$P_\pi(\Delta E_\pi, p, m_{\rm ES}) = f_\pi(\Delta E_\pi) g_\pi(D) h_\pi(m_{\rm ES}), \quad (3)$$
$$P_K(\Delta E_\pi, p, m_{\rm ES}) = f_K(\Delta E_K) g_K(D) h_K(m_{\rm ES}), \quad (4)$$
$$P_{bkd}(\Delta E_\pi, p, m_{\rm ES}) = f_{bkd}(S) g_{bkd}(D) h_{bkd}(m_{\rm ES}). \quad (5)$$

The $f_\pi(\Delta E_\pi)$, $f_K(\Delta E_K)$, $h_\pi(m_{\rm ES})$, and $h_K(m_{\rm ES})$ components are the ΔE and $m_{\rm ES}$ resolution functions for the signals. The mean values and the Gaussian widths are allowed to float as 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 ΔE and $m_{\rm ES}$ description in Monte Carlo simulations.

The f_{bkd} component is represented by a phenomenological function with eight fixed parameters, all estimated from the distribution of S for the events in the $m_{\rm ES}$ sideband (Fig. 5).

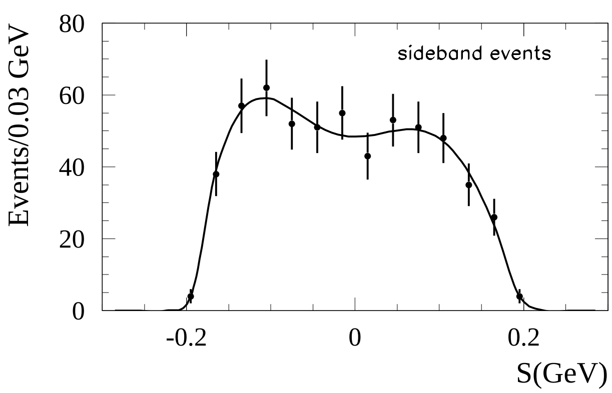

FIG. 5: The S distribution and fit for the events in the $m_{\rm ES}$ sideband of the data sample.

The h_{bkd} component is represented by the sum of an ARGUS and a Gaussian function, with parameters estimated from the distribution of $m_{\rm ES}$ for the events in the ΔE_K and ΔE_π sidebands.

The g components are each represented by a phenomenological function with seven fixed parameters. The parameters are estimated with Monte Carlo simulations for the π and K hypotheses, and with events in the $m_{\rm ES}$ sideband for the background case. A comparison of the D distributions in the three hypotheses shows that this variable, introduced by our procedure for factorizing PDFs, provides little discriminating power.

From the maximum likelihood fit to the selected sample we obtain $N_\pi = 52 \pm 10$, $N_K = 1284 \pm 37$, and $N_{bkd} = 819 \pm 31$. The correlation coefficient between N_π and N_K is -0.04. The confidence level of the fit, defined as the probability to obtain a maximum value of the likelihood smaller than the observed value, is 54%, estimated by Monte Carlo techniques. The statistical significance of the $B^\pm \to J/\psi\,\pi^\pm$ signal, evaluated from the change in the maximum value of $\ln L$ when we constrain $N_\pi = 0$, is 7.0σ.

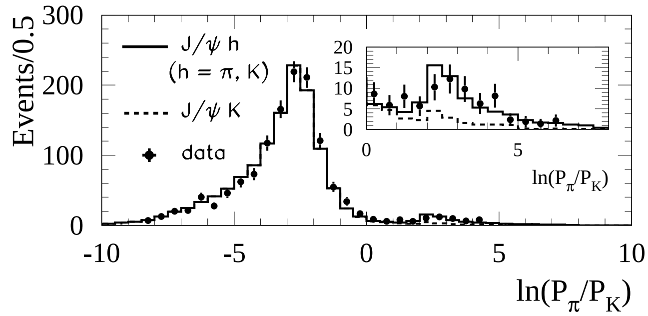

FIG. 6: The $\ln(P_\pi/P_K)$ distribution for events in the data sample (after the subtraction of the background component in each bin) and from Monte Carlo simulations of $B^\pm \to J/\psi\,\pi^\pm(K^\pm)$ events; the distributions are normalized to the yields extracted from the maximum likelihood fit.

The distribution of $\ln(P_\pi/P_K)$ for the sample, after subtraction of the background component in each bin, is shown in Fig. 6. The background distribution is normalized to the number of background events from the fit. The distribution of $\ln(P_\pi/P_K)$ for simulated signal samples, normalized to the yields extracted from the likelihood fit, is also shown. The distribution in ΔE_π for the events in the data sample with $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ is shown in Fig. 7, along with the likelihood fit result.

Possible biases in the fitting procedure were investigated by performing the fit on simulated samples of known composition and of the same size as the data. The differences, Δ_π and Δ_K, between the extracted and the input values are consistent with 0. However we correct the yields for the observed deviations $\Delta_\pi = 1.1 \pm 2.2$ and $\Delta_K = -11.3 \pm 8.8$. The corrected yields are 51 ± 10 and 1296 ± 38 for $J/\psi\,\pi^\pm$ and $J/\psi\,K^\pm$, respectively.

The use of particle identification for the charged hadron $h^\pm$ has been investigated by adding to the likelihood, as an additional argument, the Cherenkov angle θ_C measured in the DIRC for this track. The PDFs for the variable θ_C are determined from data and parameterized as Gaussian functions, with mean values and widths that depend on the momentum of the track. A fit with a modified likelihood function is performed with the subsample of events where the particle identification information is available. The ratio of branching fractions is determined separately for the $J/\psi(\mu^+\mu^-)h^\pm$ and $J/\psi(e^+e^-)h^\pm$ samples. A detailed comparison, reported in Table I, shows that the addition of particle identification does not significantly change the statistical precision of the results, which are consistent to within 1.6σ.

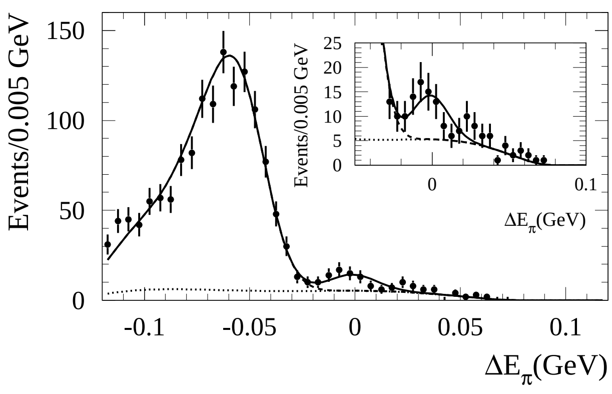

FIG. 7: The ΔE_π distribution for events with $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ compared with the fit result (solid curve). The dotted curve represents the fitted contribution from the background alone, while the dashed curve represents the fitted contributions from the sum of background and $J/\psi K^\pm$ components. The PDFs of the ΔE_π variable in the $J/\psi K^\pm$ and background hypotheses have been obtained with a numerical integration of the P_i PDFs: $p_K(\Delta E_\pi) = \int f_K(x) g_K(x - \Delta E_\pi)\,{\rm d}x$, $p_{bkd}(\Delta E_\pi) = \int f_{bkd}(x + \Delta E_\pi) g_{bkd}(x - \Delta E_\pi)\,{\rm d}x$.

Based on the fitted event yields, we find the ratio of branching fractions to be

$$\frac{\mathcal{B}(B^\pm \to J/\psi\,\pi^\pm)}{\mathcal{B}(B^\pm \to J/\psi\,K^\pm)} = [3.91 \pm 0.78(stat.) \pm 0.19(syst.)]\%.$$

The dominant systematic error (0.17%) comes from the uncertainty in the correction factors, Δ_π and Δ_K, due to the limited statistics of the simulated samples. The uncertainty in the fixed parameters of the PDFs, determined by fits to simulated or non-signal data sets, affects several aspects of the likelihood fit: the characterization of the S and D distributions; the characterization of the $m_{\rm ES}$ distribution for the background (including the fraction of peaking background events); and the fraction of signal events in the tails of the ΔE distribution. This uncertainty contributes 0.07% to the systematic error. Contributions due to any possible difference in the reconstruction efficiencies for $J/\psi\,\pi^\pm$ and $J/\psi\,K^\pm$ events are found to be negligible, as are uncertainties due to inaccuracies in the description of the tails of the ΔE resolution function.

Our determination of the ratio of branching fractions is consistent with the expectation reported in [1] and with previous measurements [2, 3], but has a substantially lower uncertainty than the world average value of $(5.1 \pm 1.4)\%$ [6].

To study direct *CP*-violation in these channels, we modify the likelihood function in Eq. 2 as follows:

$$L' = {\rm e}^{-\sum_i N_i} \prod_{j=1}^{M} \sum_i P'_i(\Delta E^j_\pi, p^j, {m_{\rm ES}}^j, q^j) N_i\,, \qquad (6)$$

where q is the charge of $h^\pm$. We factorize the PDFs as

$$P'_i(\Delta E_\pi, p, m_{\rm ES}, q) = P_i(\Delta E_\pi, p, m_{\rm ES}) c_i(q)\,, \qquad (7)$$

where $c_i(q)$ is the probability for the final state charged hadron, in a certain hypothesis, to have charge q. The c_i can be written in terms of the *CP*-violating charge asymmetries $\mathcal{A}_i$ as

$$c_i(q) = \frac{1}{2}[(1 - \mathcal{A}_i) f^+(q) + (1 + \mathcal{A}_i) f^-(q)]\,, \qquad (8)$$

where

$$\mathcal{A}_i = \frac{N_i^- - N_i^+}{N_i^- + N_i^+}\,, \qquad (9)$$

$$f^+(q) = \begin{cases} 1 & \text{if } q = +1 \\ 0 & \text{if } q = -1\,, \end{cases} \qquad (10)$$

$$f^-(q) = \begin{cases} 0 & \text{if } q = +1 \\ 1 & \text{if } q = -1\,. \end{cases} \qquad (11)$$

The asymmetry observables $\mathcal{A}_i$ are allowed to float as free parameters in the likelihood fit and are extracted together with the yields.

We impose additional requirements on the charged track $h^\pm$ in the events to be used in the fit, selecting only those tracks for which the tracking efficiency has been accurately measured from data. Tracks are required to have a polar angle in the range $[0.41, 2.54]$ radians, to include at least 12 DCH hits, to have $p_t > 100\,{\rm MeV}/c$, and to point back to the nominal interaction point within 1.5 cm in the vertical plane and within 3 cm along the longitudinal direction. The selected sample contains 982 $B^- \to J/\psi\,h^-$ and 970 $B^+ \to J/\psi\,h^+$ candidates.

From the maximum likelihood fit to the data sample we obtain $\mathcal{A}_\pi = 0.01 \pm 0.22$, $\mathcal{A}_K = -0.001 \pm 0.030$, $\mathcal{A}_{bkd} = 0.018 \pm 0.039$. The correlation coefficient between $\mathcal{A}_\pi$ and $\mathcal{A}_K$ is -0.03.

The uncertainty in the fixed parameters of the PDFs, determined by fits to simulated or non-signal data sets, contributes 0.0056 and 0.0002 to the systematic error on

TABLE I: Measurements of $\mathcal{B}(B^\pm \to J/\psi\,\pi^\pm)/\mathcal{B}(B^\pm \to J/\psi\,K^\pm)$ obtained with the original (fit 1) and a modified likelihood function (fit 2) that includes particle identification for $h^\pm$. The error on the difference Δ between the two measurements is estimated as $\sigma_\Delta = \sqrt{|\sigma_1^2 - \sigma_2^2|}$.

sample	fit 1	fit 2	Δ/σ_Δ
$J/\psi\,(\mu^+\mu^-)h^\pm$	$(4.2 \pm 1.0)\%$	$(4.7 \pm 1.1)\%$	1.1
$J/\psi\,(e^+e^-)h^\pm$	$(3.5 \pm 1.2)\%$	$(4.1 \pm 1.3)\%$	1.2

$\mathcal{A}_\pi$ and $\mathcal{A}_K$, respectively. The difference in tracking efficiency between positively and negatively charged tracks – primarily pions – has been studied in hadronic events by comparing the independent SVT and DCH tracking systems. The corrections to the asymmetries $\mathcal{A}_\pi$ and $\mathcal{A}_K$ are negligible. The uncertainty on the corrections contributes 0.0026 and 0.0020 to the systematic error on $\mathcal{A}_\pi$ and $\mathcal{A}_K$, respectively. The fake asymmetry due to the different probability of interaction of K^+ and K^- in the detector material before the DCH is estimated to be -0.0039. We correct $\mathcal{A}_K$ for this quantity and conservatively assume a contribution of 0.0039 to the systematic uncertainty. This represents the dominant systematic error on $\mathcal{A}_K$. A more careful evaluation of the materials and of K^+/K^- cross-section differences will make it possible to substantially reduce this contribution.

We determine the *CP*-violating charge asymmetries to be

$$\begin{aligned}\mathcal{A}_\pi &= 0.01 \pm 0.22(stat.) \pm 0.01(syst.)\,,\\ \mathcal{A}_K &= 0.003 \pm 0.030(stat.) \pm 0.004(syst.)\,.\end{aligned}$$

These results are consistent with Standard Model expectations and with the measurement reported in [8].

As a crosscheck, $\mathcal{A}_K$ has been determined also with a simple analysis based on the counting of $B^\pm \to J/\psi\, K^\pm$ signal events in the $m_{\rm ES}$ peak. The result is compatible with the likelihood fit analysis: $A_K = 0.005 \pm 0.030(stat.) \pm 0.004(syst.)$.

We observe no evidence for *CP*-violation in $B^\pm \to J/\psi\, \pi^\pm$ or $B^\pm \to J/\psi\, K^\pm$ decays. These results are statistically limited and can be expected to improve with additional data.

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