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-violating charge asymmetries

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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-violating charge asymmetries

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 Collider Detector at Fermilab (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 $b \to c\bar{c}e\bar{s}$ 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 $B(B^\pm \to J/\psi\pi^\pm)/B(B^\pm \to J/\psi K^\pm)$ along with a search for direct CP violation in these channels. The data were recorded at the $Y(4S)$ 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 fb$^{-1}$, corresponding to 22.7 million $B\bar{B}$ 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 cross-check of the
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 \( \text{GeV}/c \). 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.

The BABAR detector is described in detail elsewhere [5].

V. THE DATA ANALYSIS

The background contaminating the sample is characterized. A fit to the data sample with \( m_{ES} > 5.27 \text{ GeV}/c^2 \). The dashed curve represents the background contribution.

FIG. 1. Distribution of \( \Delta E_K \) vs \( \Delta E_\pi \) for \( B^\pm \rightarrow J/\psi K^\pm \) and \( B^\pm \rightarrow J/\psi \pi^\pm \) events from Monte Carlo simulations.

FIG. 2. The \( \Delta E_K \) distribution and fit for the events in the data sample with \( m_{ES} > 5.27 \text{ GeV}/c^2 \). The dashed curve represents the background contribution.
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 \( B^\pm \rightarrow J/\psi \pi^\pm \), \( B^\pm \rightarrow J/\psi K^\pm \), and background events in the sample, and \( M \) is the total number of events. The observables \( \Delta E_\pi \), the momentum \( p \) of the final-state charged hadron computed in the laboratory frame, and \( m_{ES} \) 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 \( D = \Delta E_K - \Delta E_\pi = \gamma(\sqrt{p^2 + m_K^2} - \sqrt{p^2 + m_\pi^2}) \), where \( \gamma \) is the Lorentz boost from the laboratory frame to the \( Y(4S) \) 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 \( P_i(\Delta E_\pi, p, m_{ES}) \) can be written as a product of one-dimensional PDFs:

\[
P_\pi(\Delta E_\pi, p, m_{ES}) = f_\pi(\Delta E_\pi) g_\pi(D) h_\pi(m_{ES}),
\]

\[
P_K(\Delta E_K, p, m_{ES}) = f_K(\Delta E_K) g_K(D) h_K(m_{ES}),
\]

\[
P_{bkd}(\Delta E_\pi, p, m_{ES}) = f_{bkd}(S) g_{bkd}(D) h_{bkd}(m_{ES}).
\]

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 \( m_{ES} \) sideband (Fig. 5).

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 \( N_\pi \) 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 \( B^\pm \rightarrow J/\psi \pi^\pm \) signal, evaluated from the change in the maximum value of \( \ln L \) when we constrain \( N_\pi = 0 \), is 7.0\( \sigma \).

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 \( \Delta E_\pi \) for the events in the data sample with \( m_{ES}>5.27 \) 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, \( \Delta_\pi \) and \( \Delta_K \), between the extracted and the input values are con-
consistent with 0. However, we correct the yields for the observed deviations $\Delta_p = 1.1 \pm 2.2$ and $\Delta_k = -11.3 \pm 8.8$. The corrected yields are $51 \pm 10$ and $1296 \pm 38$ 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 $\theta_c$ measured in the DIRC for this track. The PDFs for the variable $\theta_c$ are determined from data and parametrized 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 1, shows that the addition of particle identification does not significantly change the statistical precision of the results, which are consistent to within 1.6$\sigma$.

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

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

The dominant systematic error (0.17%) comes from the uncertainty in the correction factors, $\Delta_p$ and $\Delta_k$, due to the limited statistics of the simulated samples. The uncertainty in the fixed parameters of the PDFs, determined by fits to simulated or nonsignal data sets, affects several aspects of the likelihood fit: the characterization of the $S$ and $D$ distributions, the characterization of the $m_{ES}$ distribution for the background (including the fraction of peaking background events), and the fraction of signal events in the tails of the $\Delta E$ 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 $\Delta E$ 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:

$$L' = e^{-\sum N_i \prod_{j=1}^{M} P'_i(\Delta E_\pi, p^j, m_{ES}, q^i) N_i},$$

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

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

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 $A_i$, as

$$c_i(q) = \frac{1}{2}[(1 - A_i) f^+(q) + (1 + A_i) f^-(q)],$$

where

$$A_i = \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-},$$

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

and

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

TABLE 1. Measurements of $B(B^\pm \rightarrow J/\psi \pi^\pm)$ 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 $\Delta$ between the two measurements is estimated as $\sigma_\Delta = \sqrt{\sigma_1^2 + \sigma_2^2}$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fit 1</th>
<th>Fit 2</th>
<th>$\Delta / \sigma_\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi(\mu^+ \mu^-)h^\pm$</td>
<td>$(4.2 \pm 1.0)%$</td>
<td>$(4.7 \pm 1.1)%$</td>
<td>1.1</td>
</tr>
<tr>
<td>$J/\psi(e^+ e^-)h^\pm$</td>
<td>$(3.5 \pm 1.2)%$</td>
<td>$(4.1 \pm 1.3)%$</td>
<td>1.2</td>
</tr>
</tbody>
</table>

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 $B^\pm \rightarrow J/\psi \pi^\pm(K^\pm)$ events; the distributions are normalized to the yields extracted from the maximum likelihood fit.

FIG. 7. The $\Delta E_\pi$ distribution for events with $m_{ES} > 5.27\text{ GeV}/c^2$ 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 $\Delta E_\pi$ variable in the $J/\psi K^\pm$ and background hypotheses have been obtained with a numerical integration of the $P_i$ PDFs:

$$p_k(\Delta E_\pi) = \int_{-\Delta E_\pi}^{\Delta E_\pi} f_{k \pi}(x) g_k(x - \Delta E_\pi) dx,$$

$$p_{h_{kl}}(\Delta E_\pi) = \int_{-\Delta E_\pi}^{\Delta E_\pi} f_{h_{kl}}(x) g_{h_{kl}}(x - \Delta E_\pi) dx.$$
mated to be $-0.0039$. We correct $A_K$ for this quantity and conservatively assume a contribution of 0.0039 to the systematic uncertainty. This represents the dominant systematic error on $A_K$. 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

$$A_\pi = 0.01 \pm 0.22 \text{(stat)} \pm 0.01 \text{(syst)},$$

$$A_K = 0.003 \pm 0.030 \text{(stat)} \pm 0.004 \text{(syst)}.$$

These results are consistent with standard model expectations and with the measurement reported in [8].

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

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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