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Study of direct CP violation in $B^\pm \rightarrow J/\psi K^\pm(\pi^\pm)$ decays

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We present a search for direct CP violation in $B^\pm \rightarrow J/\psi K^\pm(\pi^\pm)$ decays. The event sample is selected from 2.8 fb^{-1} of $p\bar{p}$ collisions recorded by D0 experiment in Run II of the Fermilab Tevatron Collider. The charge asymmetry $A_{CP}(B^+ \rightarrow J/\psi K^+) = +0.0075 \pm 0.0061(\text{stat.}) \pm 0.0027(\text{syst.})$ is obtained using a sample of approximately 40 thousand $B^\pm \rightarrow J/\psi K^\pm$ decays. The achieved precision is of the same level as the expected deviation predicted by some extensions of the standard model. We also measured the charge asymmetry $A_{CP}(B^+ \rightarrow J/\psi \pi^+) = -0.09 \pm 0.08(\text{stat.}) \pm 0.03(\text{syst.})$.

This Letter presents a study of the charge asymmetry in the decay $B^\pm \rightarrow J/\psi K^\pm(\pi^\pm)$, which is defined as

$$A_{CP}(B^+ \rightarrow J/\psi K^+(\pi^+)) = \frac{N(B^- \rightarrow J/\psi K^-(\pi^-)) - N(B^+ \rightarrow J/\psi K^+(\pi^+))}{N(B^- \rightarrow J/\psi K^-(\pi^-)) + N(B^+ \rightarrow J/\psi K^+(\pi^+))}.$$

A non-zero value of $A_{CP}(B^+ \rightarrow J/\psi K^+(\pi^+))$ corresponds to direct CP violation in this decay. In the $b \rightarrow s\bar{c}$ transition (charge conjugate states are assumed throughout), the tree-level and $b \rightarrow s$ penguin amplitudes have a small relative weak phase, $\arg[-V_{cs}V_{cb}^*/V_{ts}V_{tb}^*]$. Therefore, the standard model (SM) predicts a small $A_{CP}(B^+ \rightarrow J/\psi K^+) \sim 0.003$ [1]. Thus, the measurement of $A_{CP}(B^+ \rightarrow J/\psi K^+)$ is an important way of constraining those new physics models which predict an enhanced value of this asymmetry, up to 0.01 or higher [1]. Most cited are the models with an extra $U(1)'$ gauge boson responsible for the flavor-changing coupling between b and s quarks [2] and the Two-Higgs Doublet Model (2HDM), which introduces an extra coupling to the charged Higgs boson [3].

In $b \rightarrow d\bar{c}$ transitions, on the contrary, the relative phase between the tree-level and $b \rightarrow d$ penguin diagram, $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, is expected to be significant so that direct CP-violation may be of the order of one percent [4, 5]. Decays governed by $b \rightarrow d\bar{c}$ transition have already been explored. Recently the Belle collaboration reported large direct CP violation in $B^0 \rightarrow D^+D^-$ decays, $\mathcal{A}_{D^+D^-} = +0.91 \pm 0.23 \pm 0.06$ [6], much in excess of the SM expectation. However, this result was not confirmed by the BABAR collaboration, which measured $\mathcal{C}_{D^+D^-} = -\mathcal{A}_{D^+D^-} = +0.11 \pm 0.22 \pm 0.07$ [7]. Here, we report a complementary measurement of the direct CP violation asymmetry in the $b \rightarrow d\bar{c}$ transition using the decay $B^+ \rightarrow J/\psi\pi^+$.

The D0 detector is described in detail elsewhere [8]. The detector components most important for this analysis are the central tracking and muon system. The D0 central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. The muon system is located outside the calorimeters and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers behind the toroids [9]. The polarities of the solenoid and toroid are reversed regularly during data taking, so that the four solenoid-toroid polarity combinations are exposed to approximately the same integrated luminosity. The reversal of magnet polarities is essential to reduce the detector-related systematics in asymmetry measurements and is fully exploited in this study.

The decay chain $B^+ \rightarrow J/\psi K^+(\pi^+)$ with $J/\psi \rightarrow \mu^+\mu^-$ is selected for this analysis from 2.8 fb⁻¹ recorded

by D0. Each muon is required to be identified by the muon system, to have an associated track in the central tracking system with at least two measurements in the SMT, and a transverse momentum $p_T^\mu > 1.5$ GeV/ c with respect to the beam axis. At least one of the two muons is required to have matching track segments both inside and outside the toroidal magnet. The di-muon system must have a reconstructed invariant mass between 2.80 GeV/ c^2 and 3.35 GeV/ c^2 . An additional charged particle with $p_T > 0.5$ GeV/ c , total momentum above 0.7 GeV/ c , and at least two measurements in the SMT, is selected. This particle is assigned the kaon mass and is required to have a common vertex with the two muons, with the χ^2 of the vertex fit being less than 16 for three degrees of freedom. The displacement of this vertex from the primary interaction point is required to exceed three standard deviations in the plane perpendicular to the beam direction. The primary vertex of the $p\bar{p}$ interaction is determined for each event using the method described in Ref. [10]. The average position of the beam-collision point is included as a constraint.

From each set of three particles fulfilling these requirements, a B^+ candidate is constructed. The momenta of the muons are corrected using the J/ψ mass constraint. To further improve the B^+ selection, a likelihood ratio method [11] is applied. The variables chosen for this analysis include the lower transverse momentum of the two muons, the χ^2 of the B^+ decay vertex fit, the B^+ decay length divided by its uncertainty, the significance S_B of the B^+ track impact parameter, the transverse momentum of the kaon, and the significance S_K of the kaon track impact parameter. For any track i , the significance is defined as $S_i = \sqrt{[\epsilon_T/\sigma(\epsilon_T)]^2 + [\epsilon_L/\sigma(\epsilon_L)]^2}$, where ϵ_T (ϵ_L) is the projection of the track impact parameter on the plane perpendicular to the beam direction (along the beam direction), and $\sigma(\epsilon_T)$ [$\sigma(\epsilon_L)$] is its uncertainty. The track of each B^+ is fitted assuming that it passes through the reconstructed vertex and is directed along the reconstructed B^+ momentum. Finally, the mass of the reconstructed B^+ candidate is constrained to the window $4.98 < m(J/\psi K) < 5.76$ GeV/ c^2 .

The resulting invariant mass distribution of the $J/\psi K$ system is shown in Fig. 1 with the result of an unbinned likelihood fit to the sum of contributions from $B \rightarrow J/\psi K$, $B \rightarrow J/\psi\pi$, and $B \rightarrow J/\psi K^*$ decays, as well as combinatorial background (BKG). The mass distribution of the $J/\psi K$ system from the $B \rightarrow J/\psi K$ hypothesis is parameterized by a Gaussian function with the width depending on the momentum of the K candidate. The mass distribution of the $J/\psi\pi$ system from the $B \rightarrow J/\psi\pi$ hypothesis is parameterized by a Gaussian function with the same width. It is then transformed into the distribution of the $J/\psi K$ system by assigning

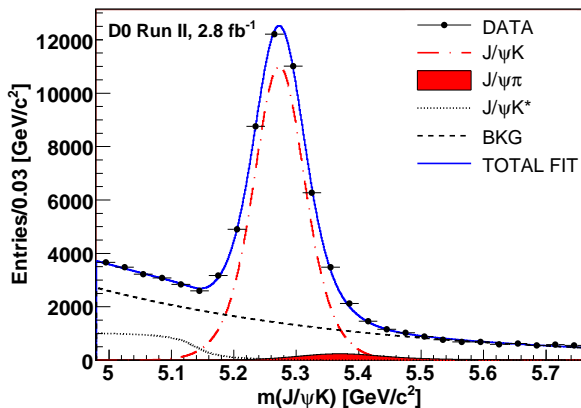


FIG. 1: The $J/\psi K$ invariant mass distribution together with the result from the unbinned likelihood fit (the unsplit sample).

the kaon mass to the pion. The decay $B \rightarrow J/\psi K^*$ with $K^* \rightarrow K\pi$, where the pion is not reconstructed, produces a broad $J/\psi K$ mass distribution with the threshold near $m(B) - m(\pi)$. It is parameterized using the Monte Carlo simulation. The combinatorial background is described by an exponential function. The $J/\psi K$, $J/\psi\pi$, and $J/\psi K^*$ contributions depend on the kaon momentum. The Monte Carlo simulation shows that this dependence can be modeled by the same polynomial function with different scaling factors for $J/\psi K$, $J/\psi\pi$, and $J/\psi K^*$ signals. The coefficients of the polynomial are determined from the fit. The $B \rightarrow J/\psi K$ signal contains $40,222 \pm 242(\text{stat.})$ events, while the $B \rightarrow J/\psi\pi$ signal contains $1,578 \pm 119(\text{stat.})$ events.

To measure the charge asymmetry A between the $J/\psi K^-(\pi^-)$ and $J/\psi K^+(\pi^+)$ final states, both physics and detector effects contributing to the possible imbalance of events with positive and negative kaons must be taken into account. One physics source of asymmetry is direct CP violation in the $B^+ \rightarrow J/\psi K^+(\pi^+)$ decay. In addition, forward-backward charge asymmetry of events produced in the proton-antiproton collisions can also be present. Detector effects can give rise to an artificial asymmetry if, for example, the reconstruction efficiencies of positive and negative particles are different. However, a positive particle produces the same track as a negative particle in the detector with reversed magnet polarity. Therefore, essentially all detector effects can be canceled by regularly reversing the magnet polarity.

Following the method applied in Ref. [12, 13], the event sample of Fig. 1 is divided into eight subsamples corresponding to all possible combinations of the solenoid polarity $\beta = \pm 1$, the sign of the pseudorapidity of the $J/\psi K$ system $\gamma = \pm 1$, and the sign of the kaon candidate charge $q = \pm 1$. In each subsample, the number $n_q^{\beta\gamma}$ of the events in the contributing channels, $J/\psi K$, $J/\psi\pi$

and $J/\psi K^*$, is obtained from the unbinned likelihood fit to the mass distribution $m(J/\psi K)$ using the same likelihood function as for the whole sample. All parameters of the fits apart from the fractions of the $J/\psi K$ signal, the $J/\psi\pi$ signal, and the $J/\psi K^*$ signal, are fixed to the values determined from the fit to the whole sample.

The number of events in the $J/\psi K$ and $J/\psi\pi$ channels for each $\beta\gamma q$ subsample are used to disentangle the physics asymmetries and the detector effects. The $n_q^{\beta\gamma}$ can be expressed through the physics and the detector asymmetries as follows [12]:

$$n_q^{\beta\gamma} = \frac{1}{4} N \epsilon^\beta (1 + qA)(1 + q\gamma A_{fb})(1 + \gamma A_{det}) \times (1 + q\beta\gamma A_{q\beta\gamma})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma}). \quad (1)$$

Here N is the total number of signal events; ϵ^β is the fraction of integrated luminosity with solenoid polarity β ($\epsilon^+ + \epsilon^- = 1$); A is the charge asymmetry to be measured; A_{fb} accounts for possible forward-backward asymmetric B meson production; A_{det} is the detector asymmetry for kaons emitted in the forward and backward direction; $A_{q\beta\gamma}$ accounts for the change in acceptance of kaons of different sign bent by the solenoid in different directions; $A_{q\beta}$ is the detector asymmetry, which accounts for the change in the kaon reconstruction efficiency when the solenoid polarity is reversed; $A_{\beta\gamma}$ accounts for any detector-related forward-backward asymmetries that remain after the solenoid polarity flip. We apply a χ^2 fit of Eq. 1 to the number of events in all subsamples and extract all asymmetries and the total number of events in the $J/\psi K$ and $J/\psi\pi$ channels together with the fraction of events with positive solenoid polarity ϵ^+ , which is constrained to be the same for both channels. Results are presented in Table I. The charge asymmetry between $B^- \rightarrow J/\psi K^-$ and $B^+ \rightarrow J/\psi K^+$ is measured to be $A(J/\psi K) = -0.0070 \pm 0.0060$, and the charge asymmetry between $B^- \rightarrow J/\psi\pi^-$ and $B^+ \rightarrow J/\psi\pi^+$ is found to be $A(J/\psi\pi) = -0.09 \pm 0.08$. The detector asymmetries are all consistent with zero, since the acceptance of the charged particles of different sign inside the solenoid is the same. However, we measure these asymmetries directly and do not rely on assumptions. The forward-backward asymmetry is also consistent with zero, as expected in the SM.

In addition to the detector effects, the charge asymmetry $A(B \rightarrow J/\psi K)$ is affected by the difference in the interaction cross-section of K^+ and K^- with the detector material [14], which is due to the fact that the reaction $K^- N \rightarrow Y\pi$ (where Y are hyperons Λ , Σ etc.) has no $K^+ N$ analog. The difference in the interaction cross section results in a lower reconstruction efficiency of K^- and a visible kaon charge asymmetry A_K between K^- and K^+ candidates, which shifts the $A(J/\psi K)$ asymmetry. The kaon asymmetry is measured directly in data by comparing the exclusive decay $c \rightarrow D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow \mu^+\nu_\mu K^-$ and its charge conjugate. It is expected

TABLE I: Physics and detector asymmetries for $J/\psi K$ and $J/\psi\pi$ channels. ϵ^+ is constrained to be the same for both channels.

	$J/\psi K$	$J/\psi\pi$
N	$40,217 \pm 243$	$1,577 \pm 118$
ϵ^+	0.5060 ± 0.0030	
A	-0.0070 ± 0.0060	-0.09 ± 0.08
A_{fb}	0.0013 ± 0.0060	0.04 ± 0.09
A_{det}	-0.0033 ± 0.0060	0.21 ± 0.08
$A_{q\beta\gamma}$	-0.0050 ± 0.0060	-0.02 ± 0.09
$A_{q\beta}$	0.0001 ± 0.0060	-0.19 ± 0.08
$A_{\beta\gamma}$	-0.0030 ± 0.0060	0.05 ± 0.08

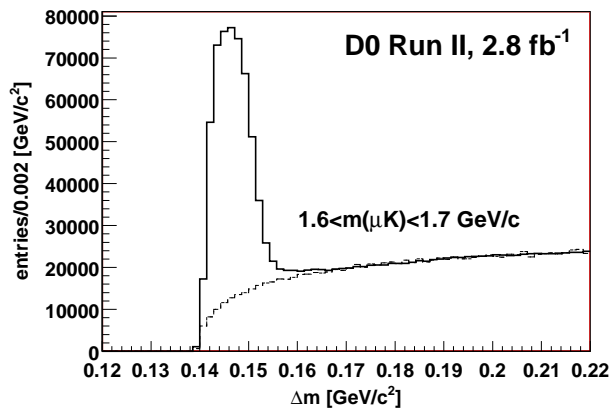


FIG. 2: The Δm distribution (solid line) for $1.6 < m(\mu K) < 1.7 \text{ GeV}/c^2$. The background distribution of events with wrong charge correlation of a muon and a kaon (dashed line) is also shown. The background normalization is required to give the same number of events with right and wrong charge correlation for $0.19 < \Delta m < 0.22 \text{ GeV}/c^2$.

from theory that there is no CP violation in the semileptonic D^0 decays [15]. The possible CP-violating effects in $B \rightarrow D^{*\pm} X$ decays are estimated to give a negligible contribution. Therefore, the observed asymmetry is only due to kaon reconstruction. The decay of D^* produces a clear peak in the mass difference, $\Delta m = m(\mu K \pi) - m(\mu K)$. Its width depends on the mass $m(\mu K)$. An example of the Δm distribution for $1.6 < m(\mu K) < 1.7 \text{ GeV}/c^2$ is shown in Fig. 2. The combinatorial background under the peak is determined using events where all three particles (muon, kaon, and pion) have the same charge, and its normalization is obtained using events with large values of Δm outside the D^* peak. The number of $D^* \rightarrow D^0 \pi$ decays is determined by subtracting the normalized number of background events from the number of signal events in the mass band corresponding to the D^* peak. The width of this band is varied depending on the mass of the μK system to ensure maximal signal significance.

The detector charge asymmetries are disentangled from the kaon asymmetry using the same detector model

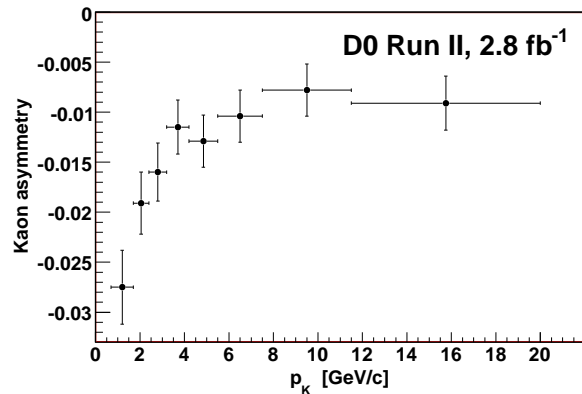


FIG. 3: Dependence of the kaon asymmetry on the kaon momentum p_K in eight bins of approximately equal statistics. Errors are statistical.

of Eq. 1. To account for the momentum dependence of the kaon cross-section [14], the kaon asymmetry is measured in different bins of kaon momentum p_K , as shown in Fig. 3. The obtained asymmetry is convoluted with the kaon momentum distribution in the $B \rightarrow J/\psi K$ decay and the resulting kaon asymmetry in the $B \rightarrow J/\psi K$ decay is found to be $A_K = -0.0145 \pm 0.0010$. Taking into account this value, we obtain $A_{CP}(B^+ \rightarrow J/\psi K^+) = A(J/\psi K) - A_K = +0.0075 \pm 0.0061(\text{stat.})$

The systematic uncertainty of $A_{CP}(B^+ \rightarrow J/\psi K^+)$ is estimated as follows. The systematic uncertainty from the unbinned fit of the invariant mass distribution of the $J/\psi K$ system is estimated by varying the parameters fixed during the unbinned fitting in the $\beta\gamma q$ subsamples by $\pm 1\sigma$, and is found to be 0.0002. The systematic uncertainty from the choice of the fitting range is found to be 0.0004. The shape of the $J/\psi K^*$ contribution to the likelihood function is parameterized using the Monte Carlo simulation, and therefore produces an uncertainty in the number of signal events. We repeat the fit with different models of $J/\psi K^*$ contribution, including a model without any such contribution. The maximal deviation in the resulting asymmetry is found to be 0.0025, which is taken as the systematic uncertainty from this source. To measure the kaon asymmetry in the detector, we subtract the combinatorial background under the D^* peak (see Fig. 2, dashed line). To estimate the uncertainty from the background definition, we required the muon and the pion to have different charges and repeated the measurement of the kaon asymmetry. The resulting deviation in $A_{CP}(B^+ \rightarrow J/\psi K^+)$ is found to be 0.0008. Also, the sample used to measure the kaon asymmetry contains a contribution of D^0 semileptonic decays without a charged kaon in the final state. They are taken into account assuming the same selection efficiency as the dominant $D^0 \rightarrow \mu\nu K$ decay. To find the impact of this assumption on the final result, we repeated the mea-

surement of the kaon asymmetry assuming a zero reconstruction efficiency for additional D^0 decay modes. The resulting deviation in $A_{CP}(B^+ \rightarrow J/\psi K^+)$ is 0.0005. Combining all contributions in quadrature, we estimate the total systematic uncertainty on $A_{CP}(B^+ \rightarrow J/\psi K^+)$ to be 0.0027, which is dominated by the uncertainty from the mass distribution model.

The systematic uncertainty of $A_{CP}(B^+ \rightarrow J/\psi \pi^+)$ is estimated similarly to that of $A_{CP}(B^+ \rightarrow J/\psi K^+)$. The only sizable contributions are: 0.01 from the variation of the fitting range, and 0.02 from the mass model. The total systematic uncertainty is 0.03.

In conclusion, the direct CP violating asymmetry in the $B^+ \rightarrow J/\psi K^+$ decay is measured to be $A_{CP}(B^+ \rightarrow J/\psi K^+) = +0.0075 \pm 0.0061(\text{stat.}) \pm 0.0027(\text{syst.})$, which is consistent with the world average, $A_{CP}(B^+ \rightarrow J/\psi K^+) = +0.015 \pm 0.017$ [14], but has a factor of two improvement in precision, thus providing the most stringent bounds for new models predicting large values of $A_{CP}(B^+ \rightarrow J/\psi K^+)$. The direct CP violating asymmetry in the $B^+ \rightarrow J/\psi \pi^+$ decay is measured to be $A_{CP}(B^+ \rightarrow J/\psi \pi^+) = -0.09 \pm 0.08(\text{stat.}) \pm 0.03(\text{syst.})$. Our result agrees with the previous measurements of this asymmetry [14] and has a competitive precision.

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