Measurement of direct CP violation parameters in B^{±}→J/ψK^{±} and B^{±}→J/ψπ^{±} decays with 10.4 fb^{-1} of Tevatron data

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We present a measurement of the direct CP-violating charge asymmetry in $B^{\pm}$ mesons decaying to $J/\psi K^{\pm}$ and $J/\psi\pi^{\pm}$ where J/ψ decays to $\mu^+\mu^-$, using the full Run II data set of 10.4 fb^{-1} of proton-antiproton collisions collected using the D0 detector at the Fermilab Tevatron Collider. A difference in the yield of B^- and B^+ mesons in these decays is found by fitting to the difference between their reconstructed invariant mass distributions resulting in asymmetries of $A^{J/\psi K} = [0.59 \pm 0.37]\,\%$, which is the most precise measurement to date, and $A^{J/\psi\pi} = [-4.2 \pm 4.5]\,\%$. Both measurements are consistent with standard model predictions.

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Currently all measurements of CP violation, either in decay, mixing, or in the interference between the two, have been consistent with the presence of a single phase in the CKM matrix. The standard model predicts that for $b \to sc\bar{c}$ decays, the tree and penguin contributions have the same weak phase, and thus no direct CP violation is expected in the decays of $B^{\pm}$ mesons to $J/\psi K^{\pm}$. Estimates of the effect of penguin loops [1] show that there could be a small amount of direct CP violation of up to $\mathcal{O}(0.3\%)$. A measurement of a relatively large charge asymmetry would indicate the existence of physics beyond the standard model [1–3]. In the transition $b \to dc\bar{c}$, the tree and penguin contributions have different phases, and there may be measurable levels of CP violation in the decay $B^{\pm} \to J/\psi\pi^{\pm}$ [4, 5].

The CP-violating charge asymmetry in the decays $B^{\pm} \to J/\psi K^{\pm}$ and $B^{\pm} \to J/\psi\pi^{\pm}$ are defined as

$$A^{J/\psi K} = \frac{\Gamma\left(B^- \to J/\psi K^-\right) - \Gamma\left(B^+ \to J/\psi K^+\right)}{\Gamma\left(B^- \to J/\psi K^-\right) + \Gamma\left(B^+ \to J/\psi K^+\right)}, \quad (1)$$

$$A^{J/\psi\pi} = \frac{\Gamma\left(B^- \to J/\psi\pi^-\right) - \Gamma\left(B^+ \to J/\psi\pi^+\right)}{\Gamma\left(B^- \to J/\psi\pi^-\right) + \Gamma\left(B^+ \to J/\psi\pi^+\right)}. \quad (2)$$

Previous measurements of $A^{J/\psi K}$ [6–10] have been averaged by the Particle Data Group with the result $A^{J/\psi K} = [0.1 \pm 0.7]\,\%$ [11]. The most precise measurement of $A^{J/\psi K}$ was made by the Belle collaboration [6], with a total uncertainty of 0.54%. The most precise measurement of $A^{J/\psi\pi}$ was made by the LHCb collaboration [12], with a total uncertainty of 2.9%. The LHCb measurement is actually a measurement of the difference, $A^{J/\psi\pi} - A^{J/\psi K}$, and assumes that $A^{J/\psi K}$ is zero. The previous measurement made by the D0 Collaboration [7] has a total uncertainty of 0.68% for $A^{J/\psi K}$ and 8.5% for $A^{J/\psi\pi}$ using a data sample of 2.8 fb^{-1} of proton-antiproton collisions.

This Letter presents substantially improved measurements of $A^{J/\psi K}$ and $A^{J/\psi\pi}$ using the full Tevatron Run II data sample with an integrated luminosity of 10.4 fb^{-1}. We assume there is no production asymmetry between B^+ and B^- mesons in proton-antiproton collisions. An advantage of these decay modes into $J/\psi X^{\pm}$ is that no assumptions on the CP symmetry of subsequent charm decays need to be made.

These updated measurements of $A^{J/\psi K}$ and $A^{J/\psi\pi}$ make use of the methods for extracting asymmetries used in the analyses of the time-integrated flavor-specific semileptonic charge asymmetry in the decays of neutral B mesons [13, 14]. We measure the raw asymmetries

$$A_{\rm raw}^{J/\psi K} = \frac{N_{J/\psi K^-} - N_{J/\psi K^+}}{N_{J/\psi K^-} + N_{J/\psi K^+}}, \quad (3)$$

$$A_{\rm raw}^{J/\psi\pi} = \frac{N_{J/\psi\pi^-} - N_{J/\psi\pi^+}}{N_{J/\psi\pi^-} + N_{J/\psi\pi^+}}, \quad (4)$$

where $N_{J/\psi K^-}$ ($N_{J/\psi K^+}$) is the number of reconstructed $B^- \to J/\psi K^-$ ($B^+ \to J/\psi K^+$) decays, and $N_{J/\psi\pi^-}$ ($N_{J/\psi\pi^+}$) is the number of reconstructed $B^- \to J/\psi\pi^-$ ($B^+ \to J/\psi\pi^+$) decays. The charge asymmetry in $B^{\pm}$ decays is then given by (neglecting any terms second-order or higher in the asymmetry)

$$A^{J/\psi K} = A_{\rm raw}^{J/\psi K} + A_K, \quad (5)$$

$$A^{J/\psi\pi} = A_{\rm raw}^{J/\psi\pi} + A_\pi, \quad (6)$$

where A_K is the dominant correction and is the reconstruction asymmetry between positively, $\epsilon(K^+)$, and negatively, $\epsilon(K^-)$, charged kaons in the detector [15]:

$$A_K = \frac{\epsilon(K^+) - \epsilon(K^-)}{\epsilon(K^+) + \epsilon(K^-)}. \quad (7)$$

The correction A_K is calculated using the measured kaon reconstruction asymmetry as described below [14]. As discussed later, data collected using regular reversals of magnet polarities results in no significant residual track reconstruction asymmetries, and hence, no correction for tracking asymmetries or pion reconstruction asymmetries need to be applied, hence $A_\pi = 0$.

The D0 detector has a central tracking system, consisting of a silicon microstrip tracker and the central fiber tracker, both located within a 2 T superconducting solenoidal magnet [15, 16]. A muon system, covering $|\eta| < 2$ [17], consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers after the toroids [18].

The polarities of the toroidal and solenoidal magnetic fields are reversed on average every two weeks so that the four solenoid-toroid polarity combinations are exposed to approximately the same integrated luminosity. This allows for a cancelation of first-order effects related to instrumental asymmetries. To ensure optimal cancelation of the uncertainties, the events are weighted according to the number of $J/\psi h^\pm$ decays for each data sample corresponding to a different configuration of the magnets' polarities (polarity-weighting). The weighting is based on the number of events that pass the selection criteria and the likelihood selection (described below) and that are in the $J/\psi h^\pm$ invariant mass range used to fit the data.

The data are collected with a suite of single and dimuon triggers. The selection and reconstruction of $J/\psi h^\pm$ events where $h^\pm$ is any stable charged hadron and $J/\psi \to \mu^+\mu^-$ requires three tracks with at least two hits in both the silicon microstrip tracker and the central fiber tracker. The muon selection requires a transverse momentum $p_T > 1.5$ GeV/c with respect to the beam axis. One of the reconstructed muons is required to have hits in at least two layers of the muon system with segments reconstructed both inside and outside the toroid. The second muon is required to have hits in at least the first layer of the muon system. The muon track segment has to be matched to a particle found in the central tracking system. The dimuon system must have a reconstructed invariant mass between 2.80 and 3.35 GeV/c^2 consistent with the J/ψ mass, 3.097 GeV/c^2 [11].

An additional charged particle with $p_T > 0.7$ GeV/c is selected. Since the D0 detector is unable to distinguish between $K^\pm$ and $\pi^\pm$, and since the $J\psi K^\pm$ process is dominant, this particle is assigned the charged kaon mass and is required to be consistent with coming from the same three-dimensional vertex as the two muons, with the χ^2 of the vertex fit being less than 16 for 3 degrees of freedom. The displacement of this vertex from the primary proton-antiproton interaction point is required to exceed 3 standard deviations for the resolution of the vertex position in the plane perpendicular to the beam direction.

The $B^\pm$ selection is further improved using a likelihood ratio method taken directly from Refs. [19–22] that combines a number of variables to discriminate between signal and background: the smaller of the transverse momenta of the two muons; the χ^2 of the B decay vertex; the $B^\pm$ decay length divided by its uncertainty; the significance, S_B, of the reconstructed $B^\pm$ meson impact parameter; the transverse momentum of the $h^\pm$; and the significance, S_K, of the $h^\pm$ impact parameter.

For any particle i, the significance S_i 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 impact parameter on the plane perpendicular to (along) the beam direction, and $\sigma(\epsilon_T)$ [$\sigma(\epsilon_L)$] is its uncertainty. The trajectory of each $B^\pm$ is formed assuming that it passes through the reconstructed $B^\pm$ vertex and is directed along the reconstructed $B^\pm$ momentum.

The final requirement on the likelihood ratio variable is chosen to minimize the statistical uncertainty on $A_{\rm raw}^{J/\psi K}$. The measurement of $A_{\rm raw}^{J/\psi\pi}$ makes use of a different selection on the likelihood ratio that minimizes the statistical uncertainty of $A_{\rm raw}^{J/\psi\pi}$. The asymmetry results extracted with both of these likelihood selections are consistent. No event has more than one possible track and J/ψ mass combination that passes all of the selection criteria.

From each set of three particles fulfilling these requirements, a $J/\psi h^\pm$ candidate is constructed. The momenta of the muons are corrected by constraining the J/ψ mass to the world average [11].

The number of signal candidates are extracted from the $J/\psi h^\pm$ mass distribution using an unbinned maximum likelihood fit over a mass range of $4.98 < M(J/\psi h^\pm) < 5.76$ GeV/c^2 as shown in Fig. 1. The dominant peak consists of the overlap of the $B^\pm \to J/\psi K^\pm$ and the $B^\pm \to J/\psi\pi^\pm$ (where the $\pi^\pm$ is mis-identified as a $K^\pm$) components. The mis-identified $B^\pm \to J/\psi\pi^\pm$ decay mode appears as a small peak shifted to a slightly higher mass than the $B^\pm$. The $B^\pm \to J/\psi K^\pm$ signal peak is modeled by two Gaussian functions constrained to have the same mean but, with different widths and normalizations to model the detector's mass resolution, $G_K(m)$. Taking account the D0 momentum scale, the mean is found to be consistent with the PDG average of the $B^\pm$ meson mass. To obtain a good fit to the data, the widths have a linear dependence on the kaon energy. We assume that the mass distribution of the $B^\pm \to J/\psi\pi^\pm$ is identical to that of $B^\pm \to J/\psi K^\pm$, if the correct hadron mass is assigned. To model the $J/\psi\pi^\pm$ mass distribution, $G_\pi(m)$, the $J/\psi\pi^\pm$ signal peak is transformed by assigning the pion track the charged kaon mass. Partially reconstructed decays such as $B_x \to J/\psi h^\pm X$ where $h^\pm$ is any stable charged hadron and X is additional charged or neutral particles (e.g., the decay $B^\pm \to J/\psi K^{*\pm}$) can be empirically modeled with a threshold function that extends to the $B^\pm$ mass and is based on Monte Carlo simulations [20]: $T(m) = \arctan\left[p_1(mc^2 - p_2)\right] + p_3$, where p_i are fit parameters. In the default fit only the normalization of $T(m)$ is allowed to vary and the other parameters are fixed to the values obtained from simulation. The combinatorial background is described by an exponential function, $E(m)$, with a slope that depends on the kaon energy. The fractions of the $J/\psi K$, $J/\psi\pi$, and partially reconstructed decays depend on the $h^\pm$ momentum. Empirical studies of the data show that this dependence can be modeled by the same polynomial function with different scaling factors for the $J/\psi K$, $J/\psi\pi$, and partially reconstructed fractions. The coefficients of the polynomial and the scaling factors are determined from the fit.

The likelihood function is defined to simultaneously fit the raw asymmetries, $A_{\rm raw}^{J/\psi K(\pi)}$, the asymmetry of the partially reconstructed decays, A_T, and the asymmetry in the combinatorial background, A_E:

$$\mathcal{L} = \left(1 - q_h A_{\rm raw}^{J/\psi K}\right) G_K(m) + \left(1 - q_h A_{\rm raw}^{J/\psi\pi}\right) G_\pi(m) + \left(1 - q_h A_T\right) T(m) + \left(1 - q_h A_E\right) E(m), \tag{8}$$

where q_h is the charge of the hadron.

The raw asymmetries are extracted by fitting the resulting data sample using the unbinned maximum likelihood fit described above. The resulting $J/\psi h^\pm$ polarity-weighted invariant mass distribution is shown in Fig. 1. The $B^\pm \to J/\psi K^\pm$ signal contains $105562 \pm 370\,({\rm stat})$ events, and the $B^\pm \to J/\psi\pi^\pm$ signal contains $3110 \pm 174\,({\rm stat})$ events.

The quality of the fit is estimated by projecting the resulting unbinned likelihood fit onto the $J/\psi K^\pm$ invariant mass distribution (65 bins in total). A χ^2 is then calculated with a value of 76.2 for 47 degrees of freedom (the number of bins less the number of fit parameters excluding the asymmetry parameters).

The invariant mass distribution of the differences, $N(J/\psi h^-) - N(J/\psi h^+)$, is shown in Fig. 2 with a resulting χ^2 of 58.5 for 61 degrees of freedom. The resulting raw asymmetries are extracted from the data are:

$$A_{\rm raw}^{J/\psi K} = [-0.46 \pm 0.36\,({\rm stat})]\,\%, \tag{9}$$

$$A_{\rm raw}^{J/\psi\pi} = [-4.2 \pm 4.4\,({\rm stat})]\,\%. \tag{10}$$

The background asymmetries are also determined: $A_T = [-1.3 \pm 1.0\,({\rm stat})]\,\%$ and $A_E = [-1.1 \pm 0.6\,({\rm stat})]\,\%$.

The systematic uncertainties in the fitting method are evaluated by varying the fitting procedure. For each of the following variations the systematic uncertainty is assigned to be half the maximum variation in the central

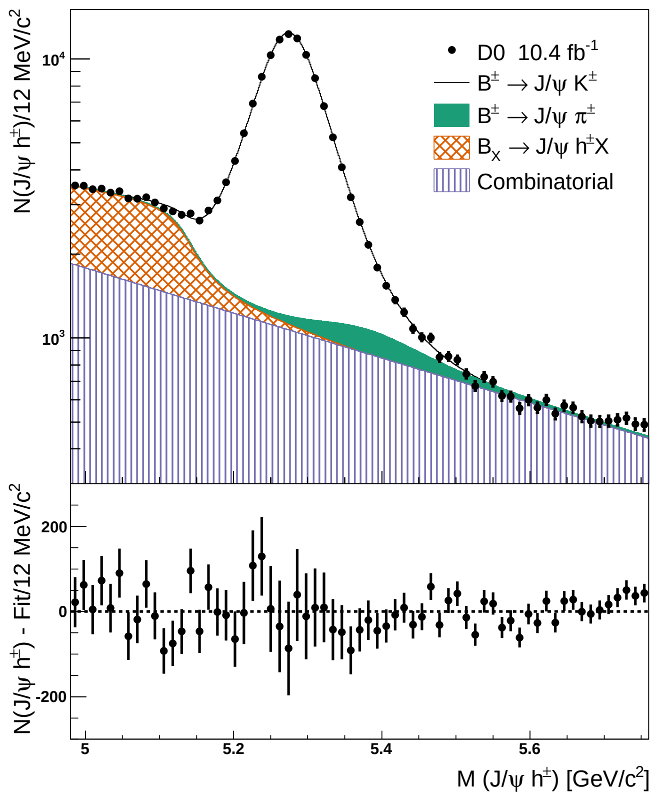

FIG. 1. The polarity-weighted $J/\psi h^\pm$ invariant mass distribution, where the $h^\pm$ is assigned the charged kaon mass, after selecting on the likelihood-ratio function optimized for $A_{\rm raw}^{J/\psi K}$. The bottom panel shows the fit residuals (the error bars represent the statistical uncertainty). Fit described in the text.

value. The mass range of the fit is modified so that the lower edge is varied from 4.95 to 5.01 GeV/c^2, and the upper edge from 5.73 to 5.79 GeV/c^2, in 10 MeV/c^2 steps. This results in an uncertainty in $A_{\rm raw}^{J/\psi K}$ of 0.022% and in $A_{\rm raw}^{J/\psi\pi}$ of 0.55% (labeled "Mass range" in Table I). The following modifications are made to the functions used to model the data. The mean of the Gaussian functions is allowed to depend linearly on the energy of the kaon. The $p_T(K)$-dependence of the width of the Gaussian function is modeled with a quadratic and a cubic polynomial. The parameters of the threshold function are allowed to float. The ratio of branching fractions for the decays $B^\pm \to J/\psi K^\pm$ and $B^\pm \to J/\psi\pi^\pm$ which are not constrained in the default fit are fixed to the current ratio from the Particle Data Group, 0.0482 [11], and the latest measurement by the LHCb experiment, 0.0381 [12]. This results in an uncertainty in $A_{\rm raw}^{J/\psi K}$ of 0.011% and in $A_{\rm raw}^{J/\psi\pi}$ of 0.69% (labelled "Fit function"). The effect of the event weighting is studied by varying the number of events for each magnet configuration by the statistical uncertainty ($\sqrt{N}$). This results in uncertainties of less than 0.0005% in $A^{J/\psi K}$ and 0.014% in $A^{J/\psi\pi}$, which

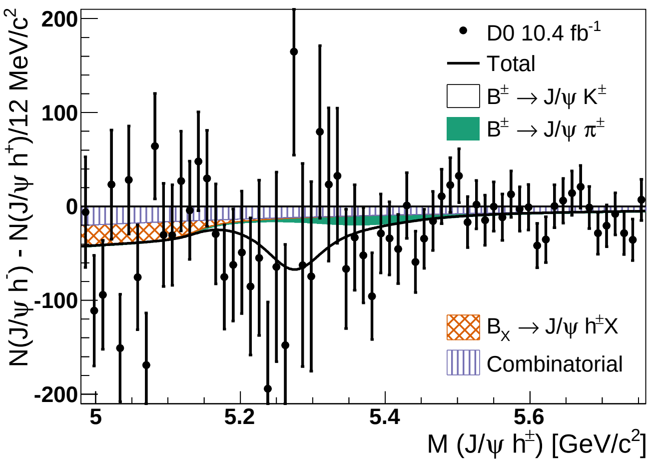

FIG. 2. The fit to the difference distribution for the data optimized for $A_{\rm raw}^{J/\psi K}$ (the fit is described in the text).

are small compared to the other uncertainties and is not included in the summary table.

The resulting systematic uncertainties are added in quadrature to obtain:

$$A_{\rm raw}^{J/\psi K} = [-0.46 \pm 0.36\,({\rm stat}) \pm 0.025\,({\rm syst})]\,\%, \quad (11)$$

$$A_{\rm raw}^{J/\psi \pi} = [-4.2 \pm 4.4\,({\rm stat}) \pm 0.88\,({\rm syst})]\,\%. \quad (12)$$

As a cross-check the following variations of the various asymmetry models are also examined. The asymmetries representing the threshold function and the combinatoric background are set to the same value, $A_T = A_E$. The asymmetry of the combinatoric background is set to zero, $A_E = 0$. The asymmetry of the threshold function is set to zero, $A_T = 0$. The asymmetries representing the threshold function and the combinatoric background are both set to zero, $A_E = A_T = 0$. When extracting $A_{\rm raw}^{J/\psi K}$, the asymmetry $A_{\rm raw}^{J/\psi \pi}$ is set equal to zero. When extracting $A_{\rm raw}^{J/\psi \pi}$, the asymmetry $A_{\rm raw}^{J/\psi K}$ is set equal to zero. This results in variations in $A_{\rm raw}^{J/\psi K}$ of 0.038% and in $A_{\rm raw}^{J/\psi \pi}$ of 1.59%. Given the statistical and systematic uncertainties, the observed variations are consistent with no significant biases.

To test the sensitivity of the fitting procedure, the charge of the charged hadron in the data is randomized to produce samples with no asymmetry, and 1000 trials are performed, each with the same statistics as the measurement. The central value of the asymmetry distribution, $(+0.008 \pm 0.011)\,\%$, is consistent with zero with a width of 0.37%, consistent with the statistical uncertainty found in data. These studies are repeated with introduced asymmetries of -1.0, -0.5 and 1.0%, each of which returns the expected asymmetries and statistical uncertainties with no significant bias.

The residual detector tracking asymmetry has been studied in Ref. [13, 14, 23] using $K_S^0 \to \pi^+\pi^-$ and $K^{*\pm} \to K_S^0\pi^\pm$ decays. No significant residual track reconstruction asymmetries are found and no correction for tracking asymmetries need to be applied. The tracking asymmetry of charged pions has been studied using MC simulations of the detector. The asymmetry is found to be less than 0.05%, which is assigned as a systematic uncertainty (labeled $\Delta A_{\rm tracking}$).

The correction A_K (Eq. 7), is calculated using the measured kaon reconstruction asymmetry presented in Ref. [14]. Negative kaons can interact with matter to produce hyperons, while there is no equivalent interaction for positive kaons. As a result, the mean path length for positive kaons is larger, the reconstruction efficiency is higher, and the kaon asymmetry, A_K, is positive.

The kaon asymmetry is measured using a dedicated sample of $K^{*0}(\bar{K}^{*0}) \to K^+\pi^-(K^-\pi^+)$ decays, based on the technique described in Ref. [23]. The $K^+\pi^-$ and $K^-\pi^+$ signal yields are extracted by fitting the charge-specific $M(K^\pm\pi^\mp)$ distributions, and the asymmetry is determined by dividing the difference by the sum. The track selection criteria are the same as those required for the $J/\psi h^\pm$ signal.

As expected, an overall positive kaon asymmetry of approximately 1% is observed. A strong dependence on kaon momentum and the absolute value of the pseudorapidity is found, and hence the final kaon asymmetry correction to be applied in Eq. 5 is determined by the polarity-weighted average of $A_K[p(K), |\eta(K)|]$ over the $p(K)$ and $|\eta(K)|$ distributions in the signal events. A relative systematic uncertainty of 5% is assigned to each bin to account for possible variations in the yield when different models are used to fit the signal and backgrounds in the K^{*0} mass distribution. Following studies over a range of fit variations, a relative systematic uncertainty of 3% on the $J/\psi K^\pm$ yields is applied. The resulting kaon correction is found to be (the uncertainty is labeled ΔA_K in Table I):

$$A_K = [1.046 \pm 0.043\,({\rm syst})]\,\%. \quad (13)$$

The value of A_K is consistent with that presented in Ref. 7 taking into account the changes in the data selection and the resulting changes in the $p(K)$ and $|\eta(K)|$ distributions.

The final uncertainties are summarized in Table I where their combination assumes that they are uncorrelated. We obtain final asymmetries of

$$A^{J/\psi K} = [0.59 \pm 0.36\,({\rm stat}) \pm 0.07\,({\rm syst})]\,\%, \quad (14)$$

$$A^{J/\psi \pi} = [-4.2 \pm 4.4\,({\rm stat}) \pm 0.9\,({\rm syst})]\,\%. \quad (15)$$

This is the most precise measurement of $A^{J/\psi K}$ to date and is a reduction in uncertainty by approximately a factor of two from the previous D0 result [7].

Several consistency checks are performed by dividing the data into smaller samples using additional selections

TABLE I. The statistical and systematic uncertainties for extracting the asymmetries $A^{J/\psi K}$ and $A^{J/\psi\pi}$.

Type of uncertainty	$A^{J/\psi K}$ (%)	$A^{J/\psi\pi}$ (%)
Statistical	0.36	4.4
Mass range	0.022	0.55
Fit function	0.011	0.69
$\Delta A_{\text{tracking}}$	0.05	0.05
ΔA_K	0.043	n/a
Total systematic uncertainty	0.07	0.9
Total uncertainty	0.37	4.5

based on data-taking periods, magnet polarities, transverse momentum, and rapidity of the charged track representing the kaon. The resulting variations of $A^{J/\psi K}$ and $A^{J/\psi\pi}$ are statistically consistent with the results of Eqs. 14 and 15.

In summary, we have presented the most precise measurement to date of the charge asymmetry $A^{J/\psi K} = [0.59 \pm 0.36\,(\text{stat}) \pm 0.07\,(\text{syst})]\,\%$ using 10.4 fb^{-1} of data. In addition we have improved our measurement of $A^{J/\psi\pi} = [-4.2 \pm 4.4\,(\text{stat}) \pm 0.9\,(\text{syst})]\,\%$. Both measurements are in agreement with standard model predictions.

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