An improved measurement of direct CP violation parameters in $B^{\pm} \to J/\psi K^{\pm}$ and $B^{\pm} \to J/\psi \pi^{\pm}$ decays

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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 10.4 fb^{-1} of proton-antiproton collisions collected by the D0 detector during Run II 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 $A^{J/\psi K} = [0.59 \pm 0.36]\%$, which is the most precise measurement to date, and $A^{J/\psi \pi} = [-4.2 \pm 4.8]\%$. Both measurements are consistent with standard model predictions. These measurements are combined with all previous measurements to form new world averages of $A^{J/\psi K}$ and $A^{J/\psi \pi}$.

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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, 2, 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

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

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

Previous measurements of $A^{J/\psi K}$ [6, 7, 8, 9, 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.

This Note presents a summary of the 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} which are described in detail in [13].

It is assumed that 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 [14, 15]. We measure the raw asymmetries

$$A_{\text{raw}}^{J/\psi K} = \frac{N_{J/\psi K^-} - N_{J/\psi K^+}}{N_{J/\psi K^-} + N_{J/\psi K^+}}, \tag{3}$$

$$A_{\text{raw}}^{J/\psi \pi} = \frac{N_{J/\psi \pi^-} - N_{J/\psi \pi^+}}{N_{J/\psi \pi^-} + N_{J/\psi \pi^+}}, \tag{4}$$

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)

$$A^{J/\psi K} = A_{\text{raw}}^{J/\psi K} + A_K, \tag{5}$$

$$A^{J/\psi \pi} = A_{\text{raw}}^{J/\psi \pi} + A_\pi, \tag{6}$$

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where A_K is the dominant correction and is the reconstruction asymmetry between positively and negatively charged kaons in the detector. The correction A_K is calculated using the measured kaon reconstruction asymmetry as described in [15]. 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 raw asymmetries are extracted by fitting the data sample using an unbinned maximum likelihood fit.

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. 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. 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. The resulting $J/\psi h^{\pm}$ polarity-weighted invariant mass distribution is shown in Fig. 1 (where $h^{\pm}$ is any charged hadron). The $B^{\pm} \to J/\psi K^{\pm}$ signal contains 105562 ± 370 (stat) events, and the $B^{\pm} \to J/\psi\pi^{\pm}$ signal contains 3110 ± 174 (stat) events.

The invariant mass distribution of the differences, $N(J/\psi h^-) - N(J/\psi h^+)$, are also shown in Fig. 1 with a resulting χ^2 of 58.5 for 61 degrees of freedom. The resulting raw asymmetries are extracted from the data are (including the effect of systematic uncertainties on the fitting procedure):

$$A_{\text{raw}}^{J/\psi K} = [-0.46 \pm 0.36 \,(\text{stat}) \pm 0.046 \,(\text{syst})] \,\%, \tag{7}$$

$$A_{\text{raw}}^{J/\psi\pi} = [-4.2 \pm 4.4 \,(\text{stat}) \pm 1.82 \,(\text{syst})] \,\%. \tag{8}$$

The raw asymmetry for $A^{J/\psi K}$ is corrected by

$$A_K = [1.046 \pm 0.043 \,(\text{syst})] \,\%. \tag{9}$$

Resulting in final asymmetries of

$$A^{J/\psi K} = [0.59 \pm 0.36 \,(\text{stat}) \pm 0.08 \,(\text{syst})] \,\%, \tag{10}$$

$$A^{J/\psi\pi} = [-4.2 \pm 4.4 \,(\text{stat}) \pm 1.8 \,(\text{syst})] \,\%. \tag{11}$$

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].

The D0 measurements of $A^{J/\psi K}$ and $A^{J/\psi\pi}$ can be combined with all other measurements to form updated world averages (Fig. 2). I use a simple weighted average, assuming that the measurements are fully independent. For $A^{J/\psi K}$ results from Belle [6, 8], BaBar [9] and Cleo [10]

(a) Mass distribution

(b) Difference distribution
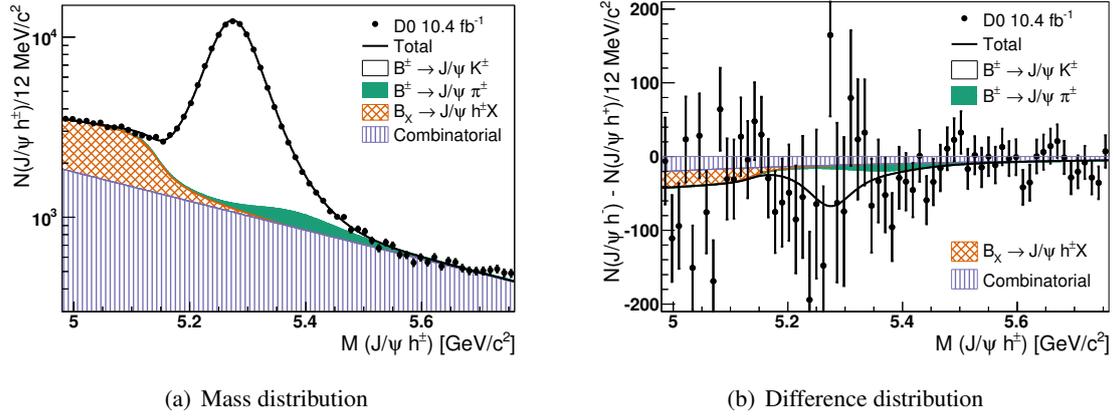
Figure 1: The polarity-weighted $J/\psi h^\pm$ invariant mass distribution, where the $h^\pm$ is assigned the charged kaon mass.

are combined with the D0 result. The resulting χ^2 for the three most precise measurements is 6.8, indicating that the measurements are not very consistent. The resulting error is then scaled by the square root of the χ^2 per degree of freedom, 1.8, giving

$$A^{J/\psi K}(\text{WA}) = (0.28 \pm 0.55)\%. \tag{12}$$

For $A^{J/\psi \pi}$ results from LHCb [12], BaBar [16] and Belle [17] are combined with the D0 result resulting in

$$A^{J/\psi K}(\text{WA}) = (-0.45 \pm 2.36)\%. \tag{13}$$

Both results are consistent with the standard model predictions.

(a) $A^{J/\psi K}$ combination
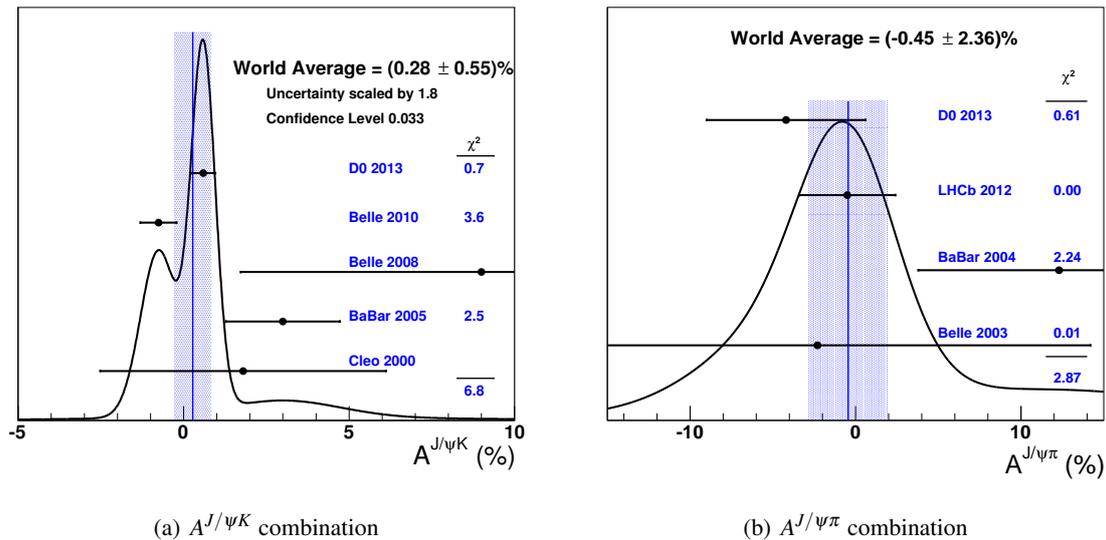
(b) $A^{J/\psi \pi}$ combination

Figure 2: Combination of all measurements of $A^{J/\psi K}$ and $A^{J/\psi \pi}$ made using the method used by the PDG [21] (see text).

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