Measurements of Direct *CP* Violating Asymmetries in Charmless Decays of Strange Bottom Mesons and Bottom Baryons

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0031-9007/11/106(18)/181802(8)

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We report measurements of direct *CP*—violating asymmetries in charmless decays of neutral bottom hadrons to pairs of charged hadrons with the upgraded Collider Detector at the Fermilab Tevatron. Using a data sample corresponding to 1 fb^{-1} of integrated luminosity, we obtain the first measurements of direct *CP* violation in bottom strange mesons, $A_{CP}(B_s^0 \to K^- \pi^+) = +0.39 \pm 0.15(\mathrm{stat}) \pm 0.08(\mathrm{syst})$, and bottom baryons, $A_{CP}(\Lambda_b^0 \to p\pi^-) = +0.03 \pm 0.17(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ and $A_{CP}(\Lambda_b^0 \to pK^-) = +0.37 \pm 0.17(\mathrm{stat}) \pm 0.03(\mathrm{syst})$. In addition, we measure *CP* violation in $B^0 \to K^+\pi^-$ decays with 3.5σ significance, $A_{CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.023(\mathrm{stat}) \pm 0.009(\mathrm{syst})$, in agreement with the current world average. Measurements of branching fractions of $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays are also updated.

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Noninvariance of the fundamental interactions under the combined symmetry transformation of charge conjugation and parity inversion (*CP* violation) is an established experimental fact. The vast majority of experimental data are well described by the standard model (SM), and have supported the success of the Cabibbo-Kobayashi-Maskawa (CKM) [1] theory of quark-flavor dynamics. However, additional sources of *CP* violation are required to explain the matter—antimatter asymmetry of the Universe in standard big bang cosmology. This would have profound consequences on our understanding of fundamental interactions.

Violation of *CP* is *direct* if the partial decay-width (Γ) of a particle into a final state differs from the width of the corresponding antiparticle into the *CP*-conjugate final state. In recent times, the pattern of direct *CP* violation in charmless mesonic decays of *B* mesons has shown some unanticipated discrepancies from expectations. Under standard assumptions of isospin symmetry and smallness of contributions from higher-order processes, similar *CP* asymmetries are predicted for $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays [2,3]. However, experimental data show a significant discrepancy [4], which has prompted intense experimental and theoretical activity. Several simple extensions of the standard model could accommodate the discrepancy [5], but uncertainty on the contribution of higher-order SM amplitudes has prevented a firm conclusion [6]. The violation of *CP* symmetry in charmless modes remains, therefore, a very interesting subject of study. Rich samples of bottom-flavored hadrons of all types from the Tevatron offer the opportunity to explore new territory in the field of B_s^0 mesons and *b*-flavored baryons. Additional information coming from different decays yields further constraints on the possible explanations of previous findings, and may possibly reveal new deviations from expectations.

Specifically, measurements of direct *CP* violation in $B_s^0 \to K^-\pi^+$ decays have been proposed as a nearly model-independent test for the presence of non-SM physics [7,8]. The relationships between charged-current quark couplings in the SM predict a well-defined hierarchy between direct *CP* violation in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays, yielding a significant asymmetry for the latter, of about 40%. This large effect allows easier experimental investigation and any discrepancy may indicate contributions from non-SM amplitudes.

Supplementary information could come from *CP* violation in bottom baryons, an effect which has not been measured so far. Interest in charmless *b*—baryon decays is prompted by branching fractions recently observed being larger than expected [9–11]. Asymmetries up to about 10% are predicted for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays in the SM [10,12], and are accessible with current CDF event samples.

In this Letter we report the first measurement of direct *CP* violation in decays of bottom strange mesons and bottom baryons. We use 1 fb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Tevatron. The *CP*-violating asymmetries are measured in the recently established [11] $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ decays [13]. We also update our previous measurements [14] of asymmetry in the $B^0 \to K^+\pi^-$ decay, and branching fractions of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays.

The CDF II detector is described in detail in Ref. [15] with the detector subsystems relevant for this analysis discussed in Ref. [14]. The data are collected by a three-level trigger system. At level 1, tracks are reconstructed in the transverse plane. Two opposite-charge particles are required, with reconstructed transverse momenta p_{T1}, $p_{T2} > 2$ GeV/c, the scalar sum $p_{T1} + p_{T2} > 5.5$ GeV/c, and an azimuthal opening angle $\Delta\phi < 135°$ [16]. At level 2, tracks are combined with silicon hits and their impact parameter d (transverse distance of closest approach to the beam line) is determined with 45 μm resolution (including the beam spread) and required to be $0.1 < d < 1.0$ mm. A tighter opening-angle requirement, $20° < \Delta\phi < 135°$, is also applied. Each track pair is then used to form a B candidate, which is required to have an impact parameter $d_B < 140$ μm and to have travelled a distance $L_T > 200$ μm in the transverse plane. At level 3, a cluster of computers confirms the selection with a full event reconstruction.

The offline selection is based on a more accurate determination of the same quantities used in the trigger, with the addition of requirements on two other observables: the isolation (I_B) of the B candidate [17], and the quality of the three-dimensional fit (χ^2 with 1 d.o.f.) of the decay vertex of the B candidate [11]. Asymmetries in the rarer $B_s^0 \to K^-\pi^+$ and Λ_b^0 decays are measured using the selection in Ref. [11]. For the measurement of the $B^0 \to K^+\pi^-$ asymmetry, instead, the selection is optimized by minimizing the expected variance of the measurement, evaluated by performing the full analysis on a set of simulated samples obtained with varied selection criteria [18]. This procedure yields the final selection: $I_B > 0.5$, $\chi^2 < 7$, $d > 100$ μm, $d_B < 80$ μm, and $L_T > 300$ μm. Only one B candidate per event is found after this selection, and a mass ($m_{\pi\pi}$) is assigned to each, using a nominal charged-pion mass assignment for both decay products. The resulting mass distribution is shown in Fig. 1. A large peak is visible, dominated by the overlapping contributions of the $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, and $B_s^0 \to K^+K^-$ decays [14]. Signals for $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$ modes populate masses higher than the main peak (5.33–5.55 GeV/c^2) [11]. Backgrounds include misreconstructed multibody *b*—hadron decays (physics

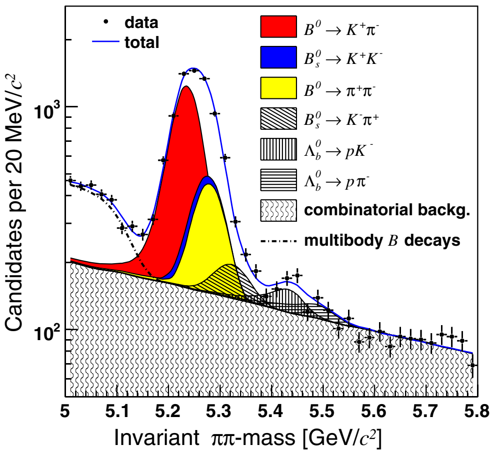

FIG. 1 (color online). Mass distribution of the 13 502 reconstructed candidates. The charged-pion mass is assigned to both tracks. The total projection and projections of each signal and background component of the likelihood fit are overlaid on the data distribution. Signals and multibody B backgrounds are shown stacked on the combinatorial background component.

background) and random pairs of particles (combinatorial background).

We incorporate kinematic and particle identification information in an unbinned likelihood fit [11,14] to determine the fraction of each mode and the charge asymmetries, uncorrected for instrumental effects, $\tilde{A}_{CP} = [N_{b\to f} - N_{\bar{b}\to\bar{f}}]/[N_{b\to f} + N_{\bar{b}\to\bar{f}}]$ of the flavor-specific decays $B^0 \to K^+\pi^-$, $B_s^0 \to K^-\pi^+$, and $\Lambda_b^0 \to p\pi^-$, pK^-. For each channel, $N_{b\to f}$ ($N_{\bar{b}\to\bar{f}}$) is the reconstructed number of decays of hadrons containing the b ($\bar{b}$) quark into the final state f ($\bar{f}$). The decay flavor is inferred from the charges of final state particles assuming equal numbers of b and $\bar{b}$ quarks at production (dominated by the strong interaction). Any effect from CP violation in b–meson flavor mixing is assumed negligible [19].

The whole kinematic information is summarized by three loosely correlated observables [11]: the mass $m_{\pi\pi}$; the signed momentum imbalance $\alpha = (1 - p_1/p_2) \times q_1$, where p_1 (p_2) is the lower (higher) of the particle momenta, and q_1 is the sign of the charge of the particle of momentum p_1; and the scalar sum of particle momenta $p_{\text{tot}} = p_1 + p_2$. Particle identification relies on measurement of the specific ionization (dE/dx) in the drift chamber. For charged kaons and pions the dE/dx response was calibrated with a sample of 1.5×10^6 $D^{*+} \to D^0\pi^+$ decays, using the charge of the pion from D^{*+} decay to identify the products of the Cabibbo—favored D^0 decay. For protons we used 124 000 $\Lambda \to p\pi^-$ decays, where the kinematics and the momentum threshold of the trigger allow unambiguous identification of the decay products [18,20]. Identification information for each particle is summarized by a single observable in our fit (“kaonness”), defined as $\kappa = (dE/dx - dE/dx_\pi)/(dE/dx_K - dE/dx_\pi)$, where dE/dx is the observed response, and $dE/dx_{\pi(K)}$ is the average responses expected for pions (kaons). The separation between $K^+\pi^-$ or $p\pi^-$ final states and their charge—conjugates is in excess of 2.1σ (Fig. 2). Although a lower dE/dx separation is available between pK^- and $\bar{p}K^+$, due to similar ionization rates of protons and kaons, sufficient discrimination is achieved from their greater kinematics differences. The background model allows for independent contributions of positively and negatively charged pions, kaons, protons, and electrons, whose fractions are determined by the fit. Muons are indistinguishable from pions with the available 10% fractional dE/dx resolution and are therefore incorporated into the pion component.

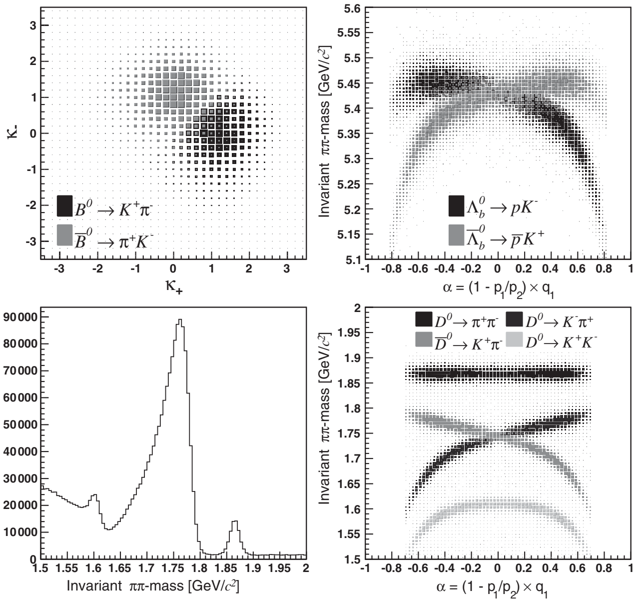

FIG. 2. Joint kaonness distribution for the positive (abscissa) and negative (ordinate) final state particles in $B^0 \to K^+\pi^-$ decays as determined from the calibration data of charm decays (top left). Dipion mass as a function of α for simulated $\Lambda_b^0 \to pK^-$ decays (top right). Mass of $D^0 \to h^+h'^-$ candidates with pion assignment to both final state particles (bottom left). Same quantity as a function of α for simulated $D^0 \to h^+h'^-$ decays (bottom right).

The signal yields from the fit (Table I) are corrected for different detection efficiencies to determine the physical asymmetries, $A_{CP}(b \to f)$, defined as

$$\frac{\mathcal{B}(b \to f) - \mathcal{B}(\bar{b} \to \bar{f})}{\mathcal{B}(b \to f) + \mathcal{B}(\bar{b} \to \bar{f})} = \frac{N_{b\to f} - c_f N_{\bar{b}\to\bar{f}}}{N_{b\to f} + c_f N_{\bar{b}\to\bar{f}}}, \quad (1)$$

where $c_f = \varepsilon(f)/\varepsilon(\bar{f})$ is the ratio between the efficiencies for triggering and reconstructing the final state f with respect to the state $\bar{f}$. The c_f factors correct for

TABLE I. Raw signal yields determined by the fit and final results. The first uncertainty is statistical, the second is systematic. Absolute branching fractions are derived by normalizing to the known value $\mathcal{B}(B^0 \to K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$, and assuming the average value at high energy for the production fraction $f_s/f_d = 0.282 \pm 0.038$ [19].

Mode	$N_{b\to f}$	$N_{\bar{b}\to\bar{f}}$	$A_{CP}(b \to f)$ (%)		Relative $\mathcal{B}$	Absolute $\mathcal{B}(10^{-6})$
$B^0 \to K^+\pi^-$	1836 ± 61	2209 ± 64	$-8.6 \pm 2.3 \pm 0.9$		⋯	⋯
$B_s^0 \to K^-\pi^+$	160 ± 26	70 ± 22	$+39 \pm 15 \pm 8$		⋯	⋯
$\Lambda_b^0 \to pK^-$	80 ± 14	36 ± 11	$+37 \pm 17 \pm 3$		⋯	⋯
$\Lambda_b^0 \to p\pi^-$	40 ± 10	38 ± 9	$+3 \pm 17 \pm 5$		⋯	⋯
$B^0 \to \pi^+\pi^-$	1121 ± 63		⋯	$\frac{\mathcal{B}(B^0\to\pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$= 0.259 \pm 0.017 \pm 0.016$	$5.02 \pm 0.33 \pm 0.35$
$B_s^0 \to K^+K^-$	1307 ± 64		⋯	$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to K^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$= 0.347 \pm 0.020 \pm 0.021$	$23.9 \pm 1.4 \pm 3.6$

detector-induced charge asymmetries, and are extracted from control samples in data. Simulation is only used to account for small differences between the kinematics of $B \to h^+ h'^-$ decays and control signals. The corrections for $f = K^+\pi^-$ are extracted from a sample of about 700 000 $D^0 \to K^-\pi^+$ decays, reconstructed in the same data set. By imposing the same offline selection to the D^0 decays we obtain $K^\mp \pi^\pm$ final states in a similar kinematic region as our signals (see Fig. 2). We assume that $K^+\pi^-$ and $K^-\pi^+$ final states from charm decays are produced in equal numbers at the Tevatron, because production is dominated by the strong interaction and, compared to the detector effects to be corrected, the possible CP—violating asymmetry in $D^0 \to K^-\pi^+$ decays is tiny ($< 10^{-3}$) as predicted by the SM [21] and confirmed by current experimental determinations [22]. We also checked that possible asymmetries in D^0 meson yields induced by CP violation in $B \to DX$ decays are small and can be neglected [18]. Therefore, any asymmetry between observed numbers of reconstructed $K^-\pi^+$ and $K^+\pi^-$ charm decays can be ascribed to detector-induced effects and used to extract the desired correction factors. The ratio $N_{\bar{D}^0 \to K^+\pi^-}/N_{D^0 \to K^-\pi^+}$ is measured with the same fit used for the signal. The dE/dx information is not used because kinematics alone is sufficient to provide an excellent separation in charm decays, as shown in Fig. 2. We checked separately that dE/dx information does not introduce additional charge asymmetries [18]. We find $c_{K^-\pi^+} = 0.9871 \pm 0.0027$, which is consistent and more precise than a previous estimate based on simulation [23]. For the $\Lambda_b^0 \to p\pi^-$ asymmetry, the factor $c_{p\pi^-} = 1.0145 \pm 0.0075$ is extracted using a similar strategy applied to a control sample of $\Lambda \to p\pi^-$ decays [20]. This factor is dominated by the different interaction probability of protons and antiprotons with detector material. In the measurement of CP violation in $\Lambda_b^0 \to pK^-$ decays, instrumental charge-asymmetries induced in both kaons and protons are relevant. The c_{pK^-} factor is extracted by combining the previous ones and assuming the trigger and reconstruction efficiency for two particles factorizes as the product of the single-particle efficiencies. Corrections are also applied for the branching ratio measurements. These corrections do not exceed 7% and account for differences in trigger and reconstruction efficiency between channels due to different lifetimes and kinematics (from simulation), and isolation properties (from control samples of fully reconstructed $B^0 \to J/\psi K^*(892)^0$ and $B_s^0 \to J/\psi \phi$ decays).

The dominant contributions to the systematic uncertainties on the asymmetry measurements come from the uncertainty on the dE/dx calibration and parameterization, the uncertainty on the combinatorial background model, and the uncertainty on b-hadron masses. Smaller contributions are assigned for the uncertainty on the global mass scale and the c_f corrections. The uncertainty on the dE/dx model dominates also the systematic uncertainty for the branching ratio measurements, for which the mass scale (in the $B^0 \to \pi^+\pi^-$ case) and the uncertainty on the difference in isolation efficiency between B^0 and B_s^0 mesons ($B_s^0 \to K^+K^-$) also play a role. The results are reported in Table I. We report 3.5σ evidence of CP violation in $B^0 \to K^+\pi^-$ decays. The observed asymmetry is consistent, and of comparable accuracy, with current results from asymmetric e^+e^- colliders [4]. It is also consistent with the result in Ref. [4] and supersedes it. The $B_s^0 \to K^-\pi^+$ result is the first measurement of direct CP violation in bottom strange mesons. It differs by 2.3σ from zero and it is consistent with recent theoretical predictions [3,24]. It allows the first experimental verification of the model-independent test proposed in Ref. [8]. Under the assumption of equal B^0 and B_s^0 lifetimes, using the measurement of the $B_s^0 \to K^-\pi^+$ branching ratio [19] and known values for the branching ratio and CP—violating asymmetry in $B^0 \to K^+\pi^-$ decays, and the b—quark fragmentation probabilities [19], we obtain $R = [\Gamma(B^0 \to K^+\pi^-) - \Gamma(\bar{B}^0 \to K^-\pi^+)]/[\Gamma(\bar{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)] = 0.85 \pm 0.42(\text{stat}) \pm 0.13(\text{syst})$, which is consistent with the standard prediction, $R^{\text{SM}} = 1$ [8]. The first measurement of CP violation in bottom baryons is also reported. The observed asymmetry in the $\Lambda_b^0 \to pK^-$ decay is 2.1σ from zero. The $\Lambda_b^0 \to p\pi^-$ result is consistent with zero. However, the limited experimental precision does not allow a conclusive discrimination between the standard model prediction (8%) and much suppressed values ($\approx 0.3\%$) expected in R-parity violating supersymmetric scenarios [12].

Table I includes also improved measurements of $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ CP-averaged branching fractions, using the $B^0 \to K^+\pi^-$ channel as a reference. Results are consistent with previous CDF measurements [14] and supersede them. The $B_s^0 \to K^+K^-$ result is the most precise to date and consistent with recent theoretical predictions [3,24–26]. Theory uncertainties, which are significantly larger than the experimental ones, prevent sensible discrimination between models. The present measurement of $\mathcal{B}(B^0 \to \pi^+\pi^-)$ agrees with measurements at e^+e^- colliders [27] with comparable accuracy. The dominant systematic uncertainties are limited by the finite size of control samples and should decrease in future extensions of the measurements.

In conclusion, we have measured CP-violating asymmetries in charmless B^0, B_s^0, and Λ_b^0 decays into pairs of charged hadrons reconstructed in CDF data. We report the first measurement of direct CP violation in bottom strange mesons, the first measurement of CP violation in bottom baryons, evidence for CP violation in $B^0 \to K^+\pi^-$ decays, and updated measurements of the $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ branching fractions.

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