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Measurements of Direct CP-Violating Asymmetries in Charmless Decays of Bottom Baryons

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(Dated: December 9, 2014)

We report final 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 the complete $\sqrt{s} = 1.96$ TeV proton-antiproton collisions data set, corresponding to 9.3 fb^{-1} of integrated luminosity, we measure $\mathcal{A}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07$ (stat) $\pm\, 0.03$ (syst) and $\mathcal{A}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08$ (stat) $\pm\, 0.04$ (syst), compatible with no asymmetry. In addition we measure the *CP*–violating asymmetries in $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays to be $\mathcal{A}(B_s^0 \to K^-\pi^+) = +0.22 \pm 0.07$ (stat) $\pm\, 0.02$ (syst) and $\mathcal{A}(B^0 \to K^+\pi^-) = -0.083 \pm 0.013$ (stat) $\pm$ 0.004 (syst), respectively, which are significantly different from zero and consistent with current world averages.

PACS numbers: 14.20.Mr 14.40.Nd 11.30.Er

The experimentally established noninvariance of fundamental interactions under the combined symmetry transformations of charge conjugation and parity inversion (*CP* violation) is described within the standard model (SM) through the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1] by the presence of a single complex phase in the unitary three-generation quark-mixing matrix. All direct measurements of elementary particle phenomena to date support the CKM phase being the dominant source of *CP* violation observed in quark transitions. However, widely accepted theoretical arguments and cosmological observations suggest that the SM might be a lower-energy approximation of more generally valid theories which are likely to possess a different *CP* structure and therefore should manifest themselves as deviations from the CKM scheme.

The decays of b hadrons are highly relevant in this context, with nonleptonic final states being particularly interesting. They are sensitive to possible new contributions from internal *loop* amplitudes, which provide a sensitive probe into energies higher than those accessible by direct searches. Hadronic factors in the decay amplitudes make accurate SM predictions for individual decays difficult to obtain. Hence, the most useful information is obtained by combining multiple measurements of processes related by dynamical symmetries, allowing the cancellation of the unknown model parameters. An observable well suited for such studies is the *direct CP* asymmetry [2]

$$\mathcal{A} = \frac{\Gamma(b \to f) - \Gamma(\bar{b} \to \bar{f})}{\Gamma(b \to f) + \Gamma(\bar{b} \to \bar{f})}. \tag{1}$$

where Γ is the partial decay-width of a generic $b-$hadron decay ($b \to f$) with non-CP-symmetric final state $f \neq \bar{f}$. Recent examples of interplay between different measurements include the significant difference observed between the measured direct *CP* asymmetries for $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays [3], which prompted intense experimental and theoretical searches for an explanation, either by an enhanced color-suppressed SM *tree* contribution [4], or by non-SM physics in the electroweak penguin loop [5]. Similarly, the comparison of the direct *CP* asymmetries in $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays has been investigated as a nearly model-independent test for the presence of non-SM physics [6, 7], and has been experimentally performed only very recently [8].

While the properties of b mesons decays have been studied in detail and no deviation from the SM has yet been conclusively established, the decays of b baryons are still largely unexplored. An accurate experimental investigation of their *CP* asymmetries is useful to complete the current picture of charmless decays of b hadrons. The $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays proceed through the same weak transitions as the corresponding two-body charmless hadronic b–meson decays. The first measurements [9] of their branching fractions were not well described by predictions [10]. In particular, the measured ratio of branching fractions $\mathcal{B}(\Lambda_b^0 \to p\pi^-)/\mathcal{B}(\Lambda_b^0 \to pK^-) = 0.66 \pm 0.14$ (stat) $\pm\, 0.08$ (syst) significantly deviated from the predicted value of $2.6^{+2.0}_{-0.5}$ [11]. The discrepancy has been recently confirmed by an independent measurement from the LHCb Collaboration [12]. Since branching ratios are potentially sensitive to new physics contributions [13, 14], further investigation is clearly important [15]. The same calculations of Ref. [11] also predict CP asymmetries up to 30%, which were not testable by the previous measurements.

In this Letter we report on measurements of direct CP violation in two-body charmless decays of bottom baryons and mesons performed using the full data set collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron, corresponding to 9.3 fb^{-1} of integrated luminosity from $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV. This is an update of a previous measurement based on a subsample of the present data [16] and provides significantly improved measurements of the baryonic decay modes $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ which are unique. We also present final measurements on the meson decay modes $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$.

The CDF II detector is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors. The detector subsystems relevant for this analysis are discussed in Ref. [17, 18]. Data are collected by a three-level on-line event-selection system (trigger). At level 1, charged-particle trajectories (tracks) are reconstructed in the plane transverse to the beam line [19]. Two oppositely-charged particles are required with reconstructed transverse momenta $p_{T1}, p_{T2} > 2$ GeV$/c$, a scalar sum $p_{T1} + p_{T2} > 5.5$ GeV$/c$, and an azimuthal opening angle $\Delta\phi < 135°$. At level 2, tracks are combined with silicon-tracking-detector measurement hits, and the impact parameter d (transverse distance of closest approach to the beam line) of each is determined with 45 μm resolution (including the beam spread) and is required to satisfy $0.1 < d < 1.0$ mm. A tighter opening-angle requirement, $20° < \Delta\phi < 135°$, is also applied. Each track pair is then used to form a b–hadron candidate ($H_b = B^0, B_s^0, \Lambda_b^0$) that is required to have an impact parameter $d_{H_b} < 140$ μm and to have traveled 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 two further observables: the isolation of the H_b candidate [9] and the quality of the three-dimensional fit (χ^2 with one degree of freedom) of the candidate decay vertex. We use the selection originally devised for the $B_s^0 \to K^-\pi^+$ search [9]. At most one H_b candidate per event is found, for which the invariant mass $m_{\pi^+\pi^-}$ is calculated using a charged-pion mass assignment for both decay products. The resulting mass distribution is shown in Fig. 1. It is 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 [16, 18] with backgrounds from misreconstructed multi-body b–hadron decays (physics background) and random pairs of charged particles (combinatorial background). Signals for the $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$ decays populate masses higher than the prominent narrow structure (5.33–5.55 GeV$/c^2$) [9]. The final data sample consists of 28 230 H_b candidates.

We use an extended unbinned maximum likelihood fit incorporating kinematic (kin) and particle-identification (PID) information, to disentangle the various contributions. From the fit we determine the fraction of events from each decay mode and the asymmetries, uncorrected for instrumental effects, $\tilde{\mathcal{A}} = [N_{b\to f} - N_{\bar{b}\to\bar{f}}]/[N_{b\to f} + N_{\bar{b}\to\bar{f}}]$, of the flavor-specific decays $B^0 \to K^+\pi^-$, $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$. For each channel, $N_{b\to f}(N_{\bar{b}\to\bar{f}})$ is the number of reconstructed decays of the hadron containing the $b(\bar{b})$ quark into the final state $f(\bar{f})$, where the flavor of the hadron is inferred from the charges of the final-state particles. In evaluating asymmetries we neglect any effect from CP violation in b–meson flavor mixing [21]. Production asymmetries also have negligible effects, as in $\bar{p}p$ collisions b and $\bar{b}$ quarks are produced in equal numbers and the symmetry in pseudorapidity of the CDF II detector, at level of 1%. This ensures equal acceptance down to a level of 10^{-3} even in the presence of possible forward-backward production asymmetries, constrained by CP conservation to change sign for opposite values of pseudorapidity. Detailed studies performed on large samples of D^0 two-body decays show residual effects on the CP-asymmetry measurements of the order of 10^{-4} [20] . The likelihood is defined as $\mathcal{L} = \frac{\nu^N}{N!} e^{-\nu} \prod_{i=1}^{N} \mathcal{L}_i$ where N is the total number of observed H_b candidates, ν is the estimator of N to be determined by the fit, and the likelihood for the ith event is

$$\begin{aligned} \mathcal{L}_i &= (1-b)\sum_j f_j \mathcal{L}_j^{\text{kin}} \mathcal{L}_j^{\text{PID}} \\ &\quad + b\left[f_{\text{p}} \mathcal{L}_{\text{p}}^{\text{kin}} \mathcal{L}_{\text{p}}^{\text{PID}} + (1-f_{\text{p}})\mathcal{L}_{\text{c}}^{\text{kin}} \mathcal{L}_{\text{c}}^{\text{PID}}\right], \end{aligned} \quad (2)$$

where the index j runs over all signal decay modes, and the index 'p' ('c') labels the physics (combinatorial) background term. The f_j are signal fractions to be determined by the fit, together with the background fraction parameters b and f_{p}. $\mathcal{L}_{j,\text{p,c}}^{\text{kin}}$ and $\mathcal{L}_{j,\text{p,c}}^{\text{PID}}$ are respectively the likelihood terms incorporating the kinematic and PID information for signal decay modes and backgrounds, defined in more detail later.

For each charged-hadron pair, the kinematic information is summarized by three loosely correlated observables: the squared mass $m^2_{\pi^+\pi^-}$; the charged momentum asymmetry $\beta = (p_+ - p_-)/(p_+ + p_-)$, where p_+ (p_-) is the magnitude of the momentum of the positive (negative) particle; and the scalar sum of particle momenta $p_{\text{tot}} = p_+ + p_-$. These variables allow evaluation of the squared invariant mass of a candidate for any mass assignment of the positively- and negatively-charged decay products [22].

The likelihood terms $\mathcal{L}_j^{\text{kin}}$ describe the kinematic distributions of the $m^2_{\pi^+\pi^-}$, β, and p_{tot} variables for the physics signals and are obtained from Monte Carlo sim-

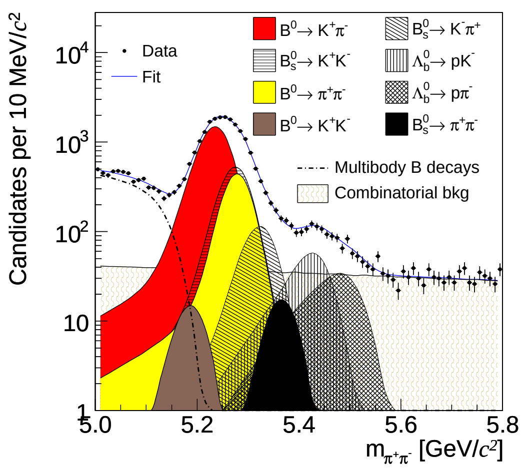

FIG. 1: Mass distribution of reconstructed candidates, where the charged pion mass is assigned to both tracks. The sum of the fitted distributions and the individual components (C-conjugate decay modes are also implied) of signal and background are overlaid on the data distribution.

ulations. The corresponding distributions for the combinatorial background are extracted from data [23] and are included in the likelihood through the $\mathcal{L}_{\rm c}^{\rm kin}$ term. The likelihood term $\mathcal{L}_{\rm p}^{\rm kin}$ describes the kinematic distributions of the background from partially reconstructed decays of generic b hadrons [22, 23].

To ensure the reliability of the search for small signals in the vicinity of larger structures, the shapes of the mass distributions assigned to each signal are modeled in detail with the full simulation of the detector. Effects of soft photon radiation in the final state are simulated by PHOTOS [24]. The mass resolution model is tuned to the observed shape of the 3.8×10^6 $D^0 \to K^-\pi^+$ and 1.7×10^5 $D^0 \to \pi^+\pi^-$ candidates in a sample of $D^{*+} \to D^0\pi^+$ decays, collected with a similar trigger selection. The accuracy of the procedure is checked by comparing the observed mass line-shape of 9×10^5 $\Upsilon(1S) \to \mu^+\mu^-$ decays to that predicted by the tuned simulation. A good agreement is obtained when a global scale factor to the mass resolution of 1.017 is applied to the model. Based on this result, we conservatively assign a 2% systematic uncertainty to the mass line-shape model.

Particle identification is achieved by means of the energy deposition measurements (dE/dx) from the drift chamber. The $D^{*+} \to D^0\pi^+$ sample is also used to calibrate the dE/dx response to positively and negatively charged kaons and pions, using the charge of the pion from the $D^{*\pm}$ decay to determine the flavour of the neutral D meson. The response for protons and antiprotons is determined from a sample of 1.4×10^6 $\Lambda \to p\pi^-$ decays, where the kinematic properties and the momentum threshold of the trigger allow unambiguous identification of the decay products [23]. The PID information is summarized by a single observable κ, defined as follows:

$$\kappa \equiv \frac{dE/dx - dE/dx(\pi)}{dE/dx(K) - dE/dx(\pi)}, \tag{3}$$

in which $dE/dx(\pi)$ and $dE/dx(K)$ are the average expected specific ionizations given the particle momentum for the pion and kaon mass hypothesis, respectively. The statistical separation between kaons and pions with momentum larger than 2 GeV/c is about 1.4σ, while the ionization rates of protons and kaons are quite similar. Thus, the separation between $K^+\pi^-$ or $p\pi^-$ final states and their charge-conjugates is about 2.0σ and 2.8σ respectively, while that between pK^- and $\bar{p}K^+$ is about 0.8σ. However, in the last case additional discrimination at the 2σ level is provided by kinematic differences in $(m^2_{\pi^+\pi^-}, \beta)$ distributions [16, 23]. The PID likelihood term, which is similar for physics signals and backgrounds, depends only on κ and on its expectation value $\langle\kappa\rangle$ (given a mass hypothesis) for the decay products. The physics signal model is described by the likelihood term $\mathcal{L}_j^{\rm PID}$, where the index j uniquely identifies the final state. The background model is described by the two terms $\mathcal{L}_{\rm p}^{\rm PID}$ and $\mathcal{L}_{\rm c}^{\rm PID}$, respectively, for the physics and combinatorial background, that account for all possible pairs that can be formed combining only charged pions and kaons. With the available dE/dx resolution, muons are indistinguishable from pions with the available dE/dx resolution and are therefore included in the pion component. Similarly, the small proton component in the background is included in the kaon component. Thus, the combinatorial background model allows for independent positively and negatively charged contributions of pions and kaons, whose fractions are determined by the fit, while the physics background model, where charge asymmetries are negligible, only allows for charge-averaged contributions.

To check the goodness of the fit with regard to the PID observables, Fig. 2 shows the distributions of the average value of $\kappa_{\rm sum} = \kappa_+ + \kappa_-$ and $\kappa_{\rm dif} = \kappa_+ - \kappa_-$ as a function of $m_{\pi^+\pi^-}$, with fit projections overlaid, where $\kappa_+(\kappa_-)$ is the PID observable for positively(negatively) charged particles. The $\kappa_{\rm sum}$ distribution is sensitive to the identity of final-state particles, and reveals the presence of baryons as a narrow structure, where the mass distribution lacks prominent features. Conversely, the $\kappa_{\rm dif}$ distribution is expected to be uniformly zero, except in the presence of a charge asymmetry coupled with a different dE/dx response of the final particles. It is insensitive to the $\Lambda_b^0 \to pK^-$ signal due to the similarity of proton and kaon dE/dx responses, but it is sensitive to the CP asymmetries of the other decay modes, and indeed it displays a deviation corresponding to each of the other three decay modes object of this study. The signal yields from the likelihood fit of Equation (2) are reported in Table I together with the physical asymmetries, $\mathcal{A}(b \to f)$, derived as follows:

$$\frac{\Gamma(b \to f) - \Gamma(\bar{b} \to \bar{f})}{\Gamma(b \to f) + \Gamma(\bar{b} \to \bar{f})} = \frac{N_{b\to f} - c_f N_{\bar{b}\to\bar{f}}}{N_{b\to f} + c_f N_{\bar{b}\to\bar{f}}}, \quad (4)$$

where $c_f = \varepsilon(f)/\varepsilon(\bar{f})$ is the ratio between the efficiencies for triggering and reconstructing the final states f and $\bar{f}$. The c_f factors correct for detector-induced charge asymmetries and are extracted from control samples in data. Simulation is used only to account for differences between the kinematic distributions of $H_b \to h^+h'^-$ decays and control signals.

TABLE I: CP-asymmetry results. The first quoted uncertainty is statistical; the second is systematic. $\mathcal{N}$ is the number of events determined by the fit for each decay mode.

Decay	$\mathcal{N}_{b\to f}$	$\mathcal{N}_{\bar{b}\to\bar{f}}$	$\mathcal{A}(b \to f)$
$B^0 \to K^+\pi^-$	5313 ± 109	6348 ± 117	−0.083 ± 0.013 ± 0.004
$B^0_s \to K^-\pi^+$	560 ± 51	354 ± 46	+0.22 ± 0.07 ± 0.02
$\Lambda^0_b \to p\pi^-$	242 ± 24	206 ± 23	+0.06 ± 0.07 ± 0.03
$\Lambda^0_b \to pK^-$	271 ± 30	324 ± 31	−0.10 ± 0.08 ± 0.04

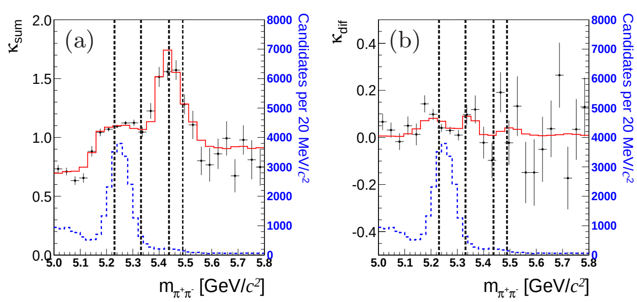

FIG. 2: Distribution of the average value of $\kappa_{\rm sum}$ (a) and $\kappa_{\rm dif}$ (b) as a function of $m_{\pi^+\pi^-}$. The fit function is overlaid. For reference, the distribution of $m_{\pi^+\pi^-}$ is shown by the dashed lower histogram. Dashed vertical lines indicate the position, from left to right, of the following signals: $B^0 \to K^+\pi^-$, $B^0_s \to K^-\pi^+$, $\Lambda^0_b \to pK^-$, $\Lambda^0_b \to p\pi^-$.

The corrections for $f = K^+\pi^-$ are extracted from a sample of 3×10^7 $D^0 \to K^-\pi^+$ decays collected without requiring the $D^{*+} \to D^0\pi^+$ decay chain [20]. By imposing the same offline selection to the D^0 decays, we obtain $K^\mp\pi^\pm$ final states in a similar kinematic regime to that of the H_b signals. We assume that $K^+\pi^-$ and $K^-\pi^+$ final states from charm decays are produced in equal numbers because their 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 [25]. We also check that possible asymmetries in D^0 meson yields induced by CP violation in $B \to DX$ decays are small and can be neglected [20]. Therefore, any asymmetry between observed numbers of reconstructed $K^-\pi^+$ and $K^+\pi^-$ charm decays is ascribed to detector-induced effects and used to extract the desired correction factor. The ratio $N_{\overline{D}^0\to K^+\pi^-}/N_{D^0\to K^-\pi^+}$ is measured by performing a simultaneous fit to the invariant $K^-\pi^+$ and $K^+\pi^-$ mass distributions [20]. We find a significant asymmetry $c_{K^+\pi^-} = 1/c_{K^-\pi^+} = 1.011 \pm 0.001$, consistent with expectation based on charge asymmetries of the interaction probability with detector material [26]. We also add a systematic uncertainty that allows for a possible nonvanishing CP violation, using the available experimental knowledge $\mathcal{A}(D^0 \to K^-\pi^+) = (0.1 \pm 0.7)\%$ [21]. For the $\Lambda^0_b \to p\pi^-$ asymmetry, the factor $c_{p\pi^-}$ is extracted from data using a similar strategy, where a simultaneous binned χ^2 fit to the $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ mass distributions is performed to estimate observed yields [23]. We average the obtained value with the same estimate based on simulation, taking half the difference as a systematic uncertainty. The final value is $c_{p\pi^-} = 1.03 \pm 0.02$ [23]. In the measurement of CP violation in $\Lambda^0_b \to pK^-$ decays, instrumental charge asymmetries induced from both kaon and proton interactions are relevant. The c_{pK^-} factor is determined by the product $c_{p\pi^-} \cdot c_{K^-\pi^+}$ based on the assumption that the efficiency $\varepsilon(f)$ factorizes as the product of the single-particle efficiencies.

The dominant systematic uncertainties on $\mathcal{A}(\Lambda^0_b \to p\pi^-)$ and $\mathcal{A}(\Lambda^0_b \to pK^-)$ are due to the uncertainty on the model of the momentum distributions of the combinatorial background and the lack of the knowledge on the Λ^0_b spin-alignment. A polarized initial state would affect the distributions of the momentum-related variables used in the fit. A systematic uncertainty is assessed by repeating the fit accounting for a nonvanishing polarization, by taking the difference with the the central fit done in the hypothesis of no polarization. The dominant contribution to the systematic uncertainty on $\mathcal{A}(B^0 \to K^+\pi^-)$ originates from the statistical uncertainty in the parameters used to model the correlated dE/dx response of the two decay products [23]. In the case of $\mathcal{A}(B^0_s \to K^-\pi^+)$, the systematic uncertainty mainly originates from three sources of similar importance: the uncertainty on the background and signal kinematic templates, the uncertainty on the dE/dx modeling discussed above, and the uncertainty on trigger efficiencies.

Table I reports the final results, that are consistent with and supersede the previous CDF results [16]. The asymmetries of the $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$ modes are now more precisely determined by a factor of 2.3 and 2.0, respectively. These are unique measurements. Both results are consistent with zero, excluding a large CP asymmetry in these decay modes, which was predicted by calculations [11] that yielded negative asymmetries for $\Lambda^0_b \to p\pi^-$ of approximately 30%, albeit with large uncertainties. The same calculation also predicts a vanishing asymmetry for the $\Lambda^0_b \to pK^-$, implying a predicted difference $\mathcal{A}(\Lambda_b^0 \to p\pi^-) - \mathcal{A}(\Lambda_b^0 \to pK^-) \approx -0.26$ between the two modes, to be compared to the measurement 0.16 ± 0.12. The uncertainty on the theory prediction is not known; it is a difference between two numbers with large uncertainties, but they are likely to be at least partially correlated. Evaluating this correlation would allow a more useful comparison with the experimental value.

We confirm the observation of $\mathcal{A}(B^0 \to K^+\pi^-)$ with a significance larger than 5σ. The measured value is consistent with the latest results from asymmetric e^+e^- colliders [3] and LHCb [8]. We also find a nonzero $\mathcal{A}(B_s^0 \to K^-\pi^+)$ with a significance of 3.0σ, in good agreement with the recent LHCb measurement $\mathcal{A}(B_s^0 \to K^-\pi^+) = +0.27 \pm 0.04$ (stat) ± 0.01 (syst) [8], thus providing confirmation of their first observation of CP violation in the B_s^0-meson system. The simultaneous measurement of CP asymmetries in the B^0 and B_s^0 meson decays to $K^\pm\pi^\mp$ final states allows a quantitative test of the SM-prediction $\mathcal{A}(B_s^0 \to K^-\pi^+) = +0.29 \pm 0.06$ [27], consistent with our measurement at the 10% level. This is obtained using the world average of the decay rates and lifetimes [21] of the two decay modes, assuming SM origin of the CP violation in these channels and U-spin symmetry.

In summary, we report the final CDF measurements of the CP asymmetries of charmless neutral b-hadrons decays into pairs of charged hadrons, using the complete Run II data sample. We confirm the observation of $\mathcal{A}(B^0 \to K^+\pi^-)$ with a significance larger than 5σ, and we find a nonzero $\mathcal{A}(B_s^0 \to K^-\pi^+)$ with a significance of 3.0σ. Results on $b-$baryon decays $\mathcal{A}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07$ (stat) ± 0.03 (syst) and $\mathcal{A}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08$ (stat) ± 0.04 (syst), are unique measurements and are compatible with no asymmetry.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, United Kingdom; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; the Australian Research Council (ARC); and the EU community Marie Curie Fellowship Contract No. 302103.

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