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

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

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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 dynamical symmetry, allowing the cancellation of the unknown model parameters. An observable well suited for such studies is the direct CP asymmetry [2]

\[ A = \frac{\Gamma(b \rightarrow f) - \Gamma(\bar{b} \rightarrow \bar{f})}{\Gamma(b \rightarrow f) + \Gamma(\bar{b} \rightarrow \bar{f})}. \]

where \( \Gamma \) is the partial decay width of a generic \( b \)-hadron decay \( (b \rightarrow f) \) with non-CP-symmetric final state \( f \neq \bar{f} \). Recent examples of the interplay between different measurements include the significant difference observed between the measured direct CP asymmetries for \( B^0 \rightarrow K^-\pi^+ \) and \( B^0 \rightarrow K^-\pi^- \) decays to be \( A(B^0 \rightarrow K^-\pi^+) = +0.22 \pm 0.07 \) (stat) \( \pm 0.02 \) (syst) and \( A(B^0 \rightarrow K^-\pi^-) = -0.083 \pm 0.013 \) (stat) \( \pm 0.004 \) (syst), respectively, which are significantly different from zero and consistent with current world averages.

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
The current picture of charmless decays of $b$ hadrons. The $Λ_b^0 \to pK^-$ and $Λ_b^0 \to pπ^-$ 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 $B(Λ_b^0 \to pK^-)/B(Λ_b^0 \to pπ^-) = 0.66 \pm 0.14$(stat) ± 0.08(syst) significantly deviated from the predicted value of 2.6_{−1.4}^{+3.5} [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 $pp$ 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 $Λ_b^0 \to pK^-$ and $Λ_b^0 \to pπ^-$ which are unique. We also present final measurements on the meson decay modes $B_s^0 \to K^-π^+$ and $B^0 \to K^+π^-$. 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 Refs. [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 $Δφ < 135^\circ$. 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 $20^\circ < Δφ < 135^\circ$ is also applied. Each track pair is then used to form a $b$-hadron candidate ($H_b = B^0, B_s^0, Λ_b^0$) 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 off-line 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 1 d.o.f.) of the candidate decay vertex. We use

![FIG. 1 (color online). 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 the signal and background is overlaid on the data distribution.](image-url)
samples of $D^0$ two-body decays show residual effects on the $CP$-asymmetry measurements of the order of $10^{-4}$ [21]. The likelihood is defined as

\[ \mathcal{L} = \left( \frac{\nu^N}{N!} \right) e^{-\nu} \prod_{i=1}^{N} \mathcal{L}_i, \]

where $N$ is the total number of observed $H_b$ candidates, $\nu$ is the estimator of $N$ to be determined by the fit, and the likelihood for the $i$th event is

\[ \mathcal{L}_i = (1 - b) \sum_j f_p L_{j,p}^{\text{kin}} L_{j,p}^{\text{PID}} + b[f_p L_{p}^{\text{kin}} L_{p}^{\text{PID}} + (1 - f_p) L_{c}^{\text{kin}} L_{c}^{\text{PID}}], \]

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 $f_p$. $L_{j,p}^{\text{kin}}$ and $L_{j,p}^{\text{PID}}$ 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 $m_{\pi^+\pi^-}^2$, 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 $L_{j,p}^{\text{kin}}$ describe the kinematic distributions of the $m_{\pi^+\pi^-}^2$, $\beta$, and $p_{\text{tot}}$ variables for the physics signals and are obtained from Monte Carlo simulations. The corresponding distributions for the combinatorial background are extracted from data [23] and are included in the likelihood through the $L_{p}^{\text{kin}}$ term. The likelihood term $L_{j,p}^{\text{PID}}$ 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 with the full simulation of the detector. Effects of soft distributions assigned to each signal are modeled in detail in the vicinity of larger structures, the shapes of the mass background are extracted from data [23] and are included. The corresponding distributions for the combinatorial signals and are obtained from Monte Carlo simulations.

The $D^{+*} \rightarrow D^0 \pi^+$ 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 $D^{+*}$ to determine the flavor of the neutral $D$ meson. The response for protons and antiprotons is determined from a sample of $1.4 \times 10^6 \Lambda \rightarrow p\pi^-\pi^-$ 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 $\kappa$, defined as follows:

\[ \kappa = \frac{dE/dx - dE/dx(\pi)}{dE/dx(K) - dE/dx(\pi)}, \]

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 1.4$\sigma$, while the ionization rates of protons and kaons are quite similar. Thus, the separation between $K^+\pi^-\pi^-$ or $p\pi^-\pi^-$ final states and their charge conjugates is about 2.0$\sigma$ and 2.8$\sigma$ respectively, while that between $pK^-$ and $\bar{p}K^+$ is about 0.8$\sigma$. However, in the last case additional discrimination at the 2$\sigma$ level is provided by kinematic differences in $(m_{\pi^+\pi^-}^2, \beta)$ distributions [16,23]. The PID likelihood term, which is similar for physics signals and backgrounds, depends only on $\kappa$ and on its expectation value ($\overline{\kappa}$) (given a mass hypothesis) for the decay products. The physics signal model is described by the likelihood term $L_{j,p}^{\text{PID}}$, where the index $j$ uniquely identifies the final state. The background model is described by the two terms $L_{p}^{\text{PID}}$ and $L_{c}^{\text{PID}}$, 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 $\kappa_{\text{sum}} = \kappa_+ + \kappa_-$ and $\kappa_{\text{diff}} = \kappa_+ - \kappa_-$ as a function of $m_{\pi^+\pi^-}$, with fit projections overlaid, where $\kappa_+$ ($\kappa_-$) is the PID observable for positively (negatively) charged particles. The $\kappa_{\text{sum}}$ 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 $\kappa_{\text{diff}}$ distribution is expected to be uniformly zero, except in the presence of a charge asymmetry coupled with a different $dE/dx$
The sample of responses, but it is sensitive to the \( dE/dx \) meters and are extracted from control samples in data.

For reference, the distribution of \( m_{\pi^0\pi^-} \) is shown by the dashed lower histogram. Dashed vertical lines indicate the position, from left to right, of the following signals: \( B^0 \to K^+\pi^- \), \( B^+_1 \to K^-\pi^+ \), \( \Lambda^0_b \to pK^- \), \( \Lambda^0_b \to p\pi^- \).

response of the final particles. It is insensitive to the \( \Lambda^0_b \to pK^- \) 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 Eq. (2) are reported in Table I together with the physical asymmetries, \( A(b \to f) \), derived as follows:

\[
\frac{\Gamma(b \to f) - \Gamma(\bar{b} \to \bar{f})}{\Gamma(b \to f) + \Gamma(\bar{b} \to \bar{f})} = \frac{N_{b\to f} - c_f N_{\bar{b}\to f}}{N_{b\to f} + c_f N_{\bar{b}\to f}},
\]

where \( c_f = e(f)/e(\bar{f}) \) 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.

The corrections for \( f = K^+\pi^- \) are extracted from a sample of \( 3 \times 10^7 \) \( D^+ \to K^+\pi^- \) decays collected without requiring the \( D^+ \to D^0\pi^+ \) decay chain \[21\]. By imposing the same off-line selection to the \( D^0 \) decays, we obtain \( K^+\pi^- \) 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 \[21\]. 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 \( N_{D^0\to K^-\pi^+}/N_{D^0\to K^+\pi^-} \) is measured by performing a simultaneous fit to the invariant \( K^-\pi^+ \) and \( K^+\pi^- \) mass distributions \[21\]. 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 \( A(D^0 \to K^-\pi^+) = (0.1 \pm 0.7)\% \) \[20\]. 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 \( \chi^2 \) 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 \( c_{p\pi^-}c_{K^-\pi^+} \) based on the assumption that the efficiency \( e(f) \) factorizes as the product of the single-particle efficiencies.

The dominant systematic uncertainties on \( A(\Lambda^0_b \to p\pi^-) \) and \( A(\Lambda^0_b \to pK^-) \) are due to the uncertainty on the model of the momentum distributions of the combinatorial background and the lack of knowledge on the \( \Lambda^0_b \) spin alignment. A polarized initial state would affect the distributions of the momentum-related variables used in the fit. A systematic uncertainty is ascribed by repeating the fit accounting for a nonvanishing polarization, by taking the difference with the central fit done in the hypothesis of no polarization. The dominant contribution to the systematic uncertainty on \( A(B^0 \to K^+\pi^-) \) 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 \( A(B^0 \to K^-\pi^+) \), 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, which 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 $\Lambda_b^0 \to p K^- \pi^+$ mode, implying a predicted difference $\mathcal{A}(\Lambda_b^0 \to p K^- \pi^+) - \mathcal{A}(\Lambda_b^0 \to p K^-) \approx -0.026$ between the two modes, to be compared to the measurement $0.16 \pm 0.12$. 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 $5\sigma$. The measured value is consistent with the latest results from asymmetric $e^+ e^-$ colliders \cite{Aaij:2012if} and LHCb \cite{Aaij:2013fba}. We also find a nonzero $\mathcal{A}(B^0 \to K^- \pi^+)$ with a significance of $3.0\sigma$, in good agreement with the recent LHCb measurement $\mathcal{A}(B^0 \to K^- \pi^+) = +0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$ \cite{Aaij:2013fba}, thus providing confirmation of their first observation of $CP$ violation in the $B^0$-meson system. The simultaneous measurement of $CP$ asymmetries in the $B^0$ and $B^0\bar{B}^0$ meson decays to $K^{\pm}\pi^\mp$ final states allows a quantitative test of the SM prediction $\mathcal{A}(B^0 \to K^- \pi^+) = +0.29 \pm 0.06$ \cite{Buchalla:2005cu}, consistent with our measurement at the 10\% level. This is obtained using the world average of the decay rates and lifetimes \cite{PDG2014} of the two decay modes, assuming the 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 $b$-hadron 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 $5\sigma$, and we find a nonzero $\mathcal{A}(B^0 \to K^- \pi^+)$ with a significance of $3.0\sigma$. Results on $b$-baryon decays $\mathcal{A}(\Lambda_b^0 \to p \pi^+) = +0.06 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$ and $\mathcal{A}(\Lambda_b^0 \to p K^-) = -0.10 \pm 0.08\,(\text{stat}) \pm 0.04\,(\text{syst})$ are unique measurements and are compatible with no asymmetry.

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[2] Throughout this Letter, C-conjugate modes are implied unless otherwise stated.

[19] CDF II uses a cylindrical coordinate system in which $\phi$ is the azimuthal angle, $r$ is the radius from the nominal beam line, and $z$ points in the proton beam direction, with the origin at the center of the detector. The transverse plane is the plane perpendicular to the $z$ axis.
[27] We use the relation $A(B^0 \to K^- \pi^+) = -A(B^0 \to K^+ \pi^-)$ from Ref. [6].