Observation of New Charmless Decays of Bottom Hadrons

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We search for new charmless decays of neutral b–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 report the first observation of the $B_s^0 \to K^-\pi^+$ decay, with a significance of 8.2σ, and measure $\mathcal{B}(B_s^0 \to K^-\pi^+) = (5.0 \pm 0.7 \text{ (stat)} \pm 0.8 \text{ (syst)}) \times 10^{-6}$. We also report the first observation of charmless b–baryon decays in the channels $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ with significances of 6.0σ and 11.5σ respectively, and we measure $\mathcal{B}(\Lambda_b^0 \to p\pi^-) = (3.5 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)}) \times 10^{-6}$ and $\mathcal{B}(\Lambda_b^0 \to pK^-) = (5.6 \pm 0.8 \text{ (stat)} \pm 1.5 \text{ (syst)}) \times 10^{-6}$. No evidence is found for the decays $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$, and we set an improved upper limit $\mathcal{B}(B_s^0 \to \pi^+\pi^-) < 1.2 \times 10^{-6}$ at the 90% confidence level. All quoted branching fractions are measured using $\mathcal{B}(B^0 \to K^+\pi^-)$ as a reference.

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Two-body non-leptonic charmless decays of b–hadrons are among the most widely studied processes in flavor physics. The variety of open channels involving similar final states provides crucial experimental information to improve the accuracy of effective models of strong inter- action dynamics. The quark-level transition $b \to u$ makes decay amplitudes sensitive to γ, the least known an- gle of the quark-mixing (Cabibbo-Kobayashi-Maskawa, CKM) matrix. Significant contributions from higher- order ('penguin') transitions provide sensitivity to the possible presence of new physics in internal loops, if the observed decay rates are inconsistent with expectations.

Rich experimental data are currently available for B^+ and B^0 mesons, produced in large quantities in $\Upsilon(4S)$ de- cays [1], while much less is experimentally known about the charmless decay modes of the B_s^0, which are expected to exhibit an equally rich phenomenology. Information from B_s^0 decays is needed to better constrain the phe- nomenological models of hadronic amplitudes in heavy flavor decays. This would lead to increased precision in comparing data to predictions, allowing extraction of CKM parameters from non-tree-level amplitudes [2] and greater sensitivity to new physics contributions.

Of the possible B_s^0 decay modes into pairs of charmless pseudoscalar mesons, only the $B_s^0 \to K^+K^-$ has been observed to date [3]. The $B_s^0 \to K^-\pi^+$ is of particular interest, because its branching fraction is sensitive to the CKM angle γ [4] and the current experimental bound [3] is lower than most predictions [5, 6, 7].

A measurement of the branching fraction of the $B_s^0 \to \pi^+\pi^-$ mode, along with the $B^0 \to K^+K^-$ mode, would allow a determination of the strength of penguin- annihilation amplitudes [8], which is currently poorly known and a source of significant uncertainty in many calculations [6]. The present search is sensitive to both modes. Two–body charmless decays are also expected

from bottom baryons. The modes $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ are predicted to have measurable branching fractions, of order 10^{-6} [9], and, in addition to the inter- est in their observation, must be considered as a possible background to the rare B_s^0 and B^0 modes being investi- gated.

In this Letter we report the results of a search for rare decays of neutral bottom hadrons into a pair of charged charmless hadrons (p, K or π), performed in 1 fb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. We report the first observation of modes $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to pK^-$, and $\Lambda_b^0 \to p\pi^-$, and measure their relative branching fractions [10].

CDF II is a multipurpose magnetic spectrometer sur- rounded by calorimeters and muon detectors. The detec- tor components relevant for this analysis are briefly out- lined below; a more detailed description can be found in Ref. [11]. A silicon microstrip vertex detector (SVX) and a cylindrical drift chamber (COT) immersed in a 1.4 T axial magnetic field allow reconstruction of charged– particle trajectories (tracks) in the pseudorapidity range $|\eta| < 1.0$ [12]. The SVX consists of six concentric lay- ers of double-sided silicon sensors with radii between 2.5 and 22 cm, each providing a measurement with up to 15 (70) μm resolution in the ϕ (z) direction. The COT has 96 measurement layers, between 40 and 137 cm in radius, organized into alternating axial and $\pm 2°$ stereo superlayers. The transverse momentum resolution is $\sigma_{p_T}/p_T^2 \sim 0.15\%/(\text{GeV}/c)$, corresponding to a typical mass resolution of 22 MeV/c^2 for our signals. The specific ionization energy loss (dE/dx) of charged particles in the COT can be measured from the collected charge, which is logarithmically encoded in the output pulse width of each wire, and provides 1.5σ separation between kaons and pions with momenta greater than 2 GeV/c.

The data were collected by a three-level trigger sys- tem, using a set of requirements specifically aimed at se- lecting two-pronged B decays. At level 1, COT tracks are reconstructed in the transverse plane by a hard- ware processor (XFT) [13]. Two opposite-charge par- ticles are required, with reconstructed transverse mo- menta $p_{T1}, p_{T2} > 2$ GeV/c, the scalar sum $p_{T1} + p_{T2} > 5.5$ GeV/c, and an azimuthal opening-angle $\Delta\phi < 135°$. At level 2, the silicon vertex trigger (SVT) [14] combines XFT tracks with SVX hits to measure the impact pa- rameter d (distance of closest approach to the beam line) of each track with 45 μm resolution. The requirement of two tracks with $0.1 < d < 1.0$ mm reduces the light quark background by two orders of magnitude while preserving about half of the signal. A tighter opening-angle require- ment, $20° < \Delta\phi < 135°$, preferentially selects two–body B decays over multi–body decays with 97% efficiency and further reduces background. Each track pair is then used to form a B candidate, which is required to have an im- pact parameter $d_B < 140$ μm and to have travelled a dis-

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tance $L_T > 200$ μm in the transverse plane. At level 3, an array of computers confirms the selection with a full event reconstruction. The overall acceptance of the trigger selection is $\approx 2\%$ for b–hadrons with $p_T > 4$ GeV/c and $|\eta| < 1$.

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 (I_B) of the B candidate [15], and the quality of the three-dimensional fit (χ^2 with 1 d.o.f.) of the decay vertex of the B candidate. Requiring a large value of I_B reduces the background from light-quark jets, and a low χ^2 reduces the background from decays of different long-lived particles within the event, owing to the good resolution of the SVX detector in the z direction. The selection is optimized for detection of the $B_s^0 \to K^-\pi^+$ mode. Maximal sensitivity for both discovery and limit setting is achieved with a single choice of selection requirements [16] by minimizing the variance of the estimate of the branching fraction in the absence of signal [17]. The variance is evaluated by performing the full measurement procedure on simulated samples containing background and all signals from the known modes, but no $B_s^0 \to K^-\pi^+$ signal. The background fraction for each selection is determined from data by extrapolating the mass sidebands of the signal, and the signal yield is predicted by a detailed detector simulation. This procedure yields the final selection: $I_B > 0.525$, $\chi^2 < 5$, $d > 120$ μm, $d_B < 60$ μm, and $L_T > 350$ μm.

No more than one B candidate per event is found after this selection, and a mass ($m_{\pi\pi}$) is assigned to each, using a 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 $B_s^0 \to K^+K^-$ modes [3]. A $B^0 \to K^+K^-$ signal would appear as an enhancement around 5.18 GeV/c^2, while signals for the other modes of this search are expected at masses higher than the main peak (5.33–5.55 GeV/c^2). Backgrounds include mis-reconstructed multibody b–hadron decays (physics background) and random pairs of charged particles (combinatorial background).

We used an unbinned likelihood fit, incorporating kinematic (kin) and particle identification (PID) information, to determine the fraction of each individual mode in our sample. The likelihood for the ith event is

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

where the index j runs over all signal modes, and the index 'p' ('c') labels the physics (combinatorial) background terms. The f_j are the signal fractions to be determined by the fit, together with the background fraction parameters b and f_{p}.
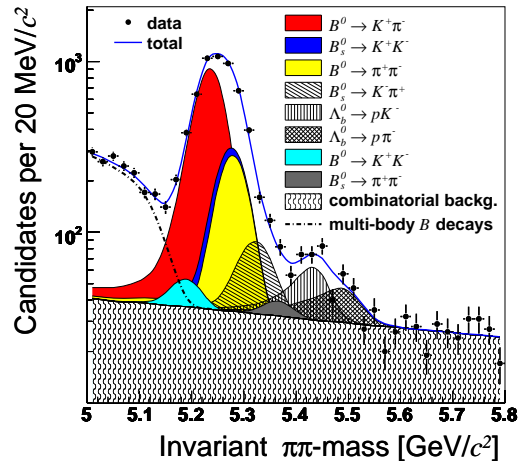

FIG. 1: Mass distribution of reconstructed candidates. The charged pion mass is assigned to both tracks. The total projection and projections of each signal and background component of the likelihood fit are overlaid on the data distribution. Signals and multi-body B background components are shown stacked on the combinatorial background component.

The kinematic information is summarized by three loosely correlated observables: (a) the mass $m_{\pi\pi}$; (b) the signed momentum imbalance $\alpha = (1-p_1/p_2)q_1$, 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; (c) the scalar sum of particle momenta $p_{tot} = p_1+p_2$. The above variables allow evaluation of the invariant mass m_{12} of a candidate for any mass assignment of the decay products (m_1,m_2), using the equation

$$\begin{aligned}
m_{12}^2 &= m_{\pi\pi}^2 - 2m_\pi^2 + m_1^2 + m_2^2 + \\
-2\sqrt{p_1^2 + m_\pi^2}&\sqrt{p_2^2 + m_\pi^2} + 2\sqrt{p_1^2 + m_1^2}\sqrt{p_2^2 + m_2^2}, \quad (2)
\end{aligned}$$

where $p_1 = \frac{1-|\alpha|}{2-|\alpha|}p_{tot}$, $p_2 = \frac{1}{2-|\alpha|}p_{tot}$.

We used the mass sidebands in data ($m_{\pi\pi} \in [5.00, 5.12] \cup [5.6, 6.2]$ GeV/c^2) to obtain the kinematic distributions of backgrounds [17]. The mass distribution of the combinatorial background is parameterized by an exponential function, while the physics background is modeled by an ARGUS function [18] convoluted with a Gaussian resolution function. In order to ensure the reliability of the search for small signals in the vicinity of larger peaks, the shapes of the mass distributions assigned to each signal have been modeled in detail. We have included the momentum dependence and non–Gaussian tails of resolution from a full simulation of the detector, and the effects of soft photon radiation in the final state, based on recent QED calculations [19]. This resolution model was checked against the observed shape of the $D^0 \to K^-\pi^+$ signal in a sample of 1.5×10^6 $D^{*+} \to D^0\pi^+$ decays, collected with a similar trigger selection. The observed discrepancies are below the 10^{-3}
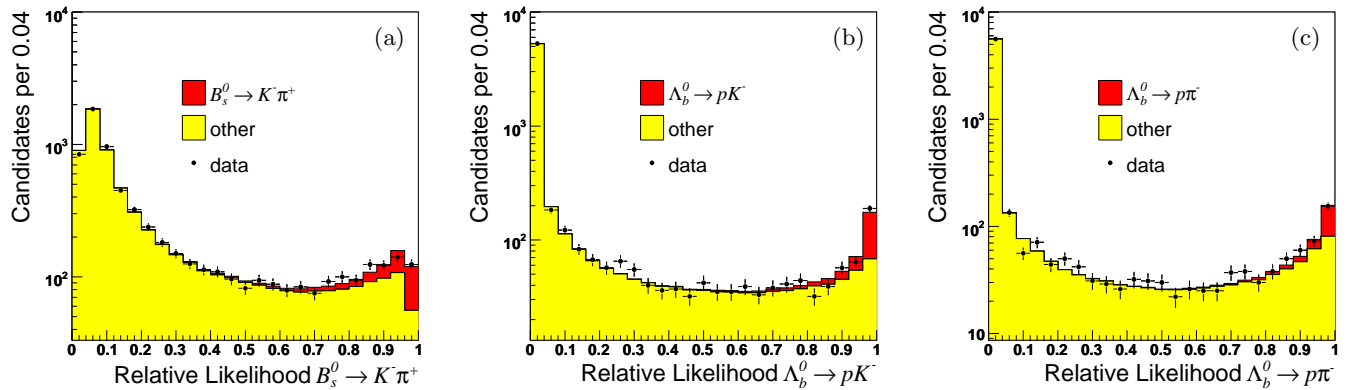
FIG. 2: Distribution of the relative signal likelihood, $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{\text{other}})$, in the region $5.1 < m_{\pi\pi} < 5.6$ GeV/c^2. For each event, $\mathcal{L}_S$ is the likelihood for the $B_s^0 \to K^-\pi^+$ (a), $\Lambda_b^0 \to pK^-$ (b), or $\Lambda_b^0 \to p\pi^-$ (c) signal hypotheses, and $\mathcal{L}_{\text{other}}$ is the likelihood for everything but the chosen signal, i.e. the weighted combination of all other components according to their measured fractions. Points with error bars show the distributions of data and histograms show the distributions predicted from the measured fractions.

level, and their effect on the present measurement is negligible in comparison with other systematic uncertainties. The $D^{*+} \to D^0\pi^+$ sample was also used to calibrate the dE/dx response of the drift chamber to kaons and pions, using the charge of the D^{*+} pion to identify the D^0 decay products. The dE/dx response of protons was determined from a sample of about $124{,}000$ $\Lambda^0 \to p\pi^-$ decays. The model of the background allows for pion, kaon, proton, and electron components, 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.

From the signal fractions returned by the likelihood fit we calculate the signal yields shown in Table I. The significance of each signal is evaluated as the ratio of the yield observed in data, and its total uncertainty (statistical and systematic) as determined from a simulation where the size of that signal is set to zero. This evaluation assumes a Gaussian distribution of yield estimates, supported by the results obtained from repeated fits to simulated samples. This procedure yields a more accurate measure of significance with respect to the purely statistical estimate obtained from $\sqrt{-2\Delta\ln(\mathcal{L})}$. We obtain significant signals for the $B_s^0 \to K^-\pi^+$ mode (8.2σ), and for the $\Lambda_b^0 \to p\pi^-$ (6.0σ) and $\Lambda_b^0 \to pK^-$ (11.5σ) modes. Figure 2 shows relative likelihood distributions for these modes. No evidence is found for the modes $B_s^0 \to \pi^+\pi^-$ or $B^0 \to K^+K^-$, in agreement with expectations of significantly smaller branching fractions.

To avoid large uncertainties associated with production cross sections and absolute reconstruction efficiency, we measure all branching fractions relative to the $B^0 \to K^+\pi^-$ mode. Frequentist upper limits [22] at the 90% C.L. are quoted for the unseen modes. For the measurement of Λ_b^0 branching fractions, the additional re-

TABLE I: Yields and significances of rare mode signals. The first quoted uncertainty is statistical, the second is systematic.

Mode	N_s	Significance
$B_s^0 \to K^-\pi^+$	$230 \pm 34 \pm 16$	8.2σ
$B_s^0 \to \pi^+\pi^-$	$26 \pm 16 \pm 14$	$< 3\sigma$
$B^0 \to K^+K^-$	$61 \pm 25 \pm 35$	$< 3\sigma$
$\Lambda_b^0 \to pK^-$	$156 \pm 20 \pm 11$	11.5σ
$\Lambda_b^0 \to p\pi^-$	$110 \pm 18 \pm 16$	6.0σ

quirement $p_T(\Lambda_b^0) > 6$ GeV/c was applied to allow easy comparison with other Λ_b^0 measurements at the Tevatron, which are only available above this threshold [20, 23]. This additional requirement lowers the Λ_b^0 yields by about 20%. The raw fractions returned by the fit were corrected for the differences in selection efficiencies between different modes, which range from 8% to 40% for the measurements of b–mesons and Λ_b^0 branching fractions, respectively. These corrections were determined from detailed detector simulation, with the following exceptions that were measured from data: the momentum-averaged relative isolation efficiency between B_s^0 and B^0, 1.00 ± 0.03, has been determined from fully-reconstructed samples of $B_s^0 \to J/\psi\phi$, and $B^0 \to J/\psi K^{*0}$ decays [17]; the difference in efficiency for triggering on kaons and pions due to the different specific ionization in the COT (a $\approx 5\%$ effect) was measured from a sample of $D^+ \to K^-\pi^+\pi^+$ decays triggered on two tracks, using the unbiased third track [24]. Possible differences in efficiency of the isolation requirement between B^0 and Λ_b^0, and in the trigger efficiency between kaons and protons, were taken into account in the systematic uncertainties.

The dominant contributions to the systematic uncertainty are the uncertainty on the combinatorial background model and the uncertainty on the dE/dx cali-

TABLE II: Measured relative branching fractions of rare modes. The ratio f_Λ/f_d is p_T–dependent [20], and is defined here as: $f_\Lambda/f_d = \sigma(p\bar{p} \to \Lambda_b^0 X; p_T > 6 \text{ GeV}/c, |\eta| < 1)/\sigma(p\bar{p} \to B^0 X; p_T > 6 \text{ GeV}/c, |\eta| < 1)$. Absolute branching fractions were derived by normalizing to the current world–average value $\mathcal{B}(B^0 \to K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$, and assuming the average values at high energy for the production fractions: $f_s/f_d = 0.276 \pm 0.034$, and $f_\Lambda/f_d = 0.230 \pm 0.052$ [21]. The first quoted uncertainty is statistical, the second is systematic.

Mode	Relative $\mathcal{B}$	Absolute $\mathcal{B}(10^{-6})$
$B_s^0 \to K^-\pi^+$	$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.071 \pm 0.010 \pm 0.007$	$5.0 \pm 0.7 \pm 0.8$
$B_s^0 \to \pi^+\pi^-$	$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to \pi^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.007 \pm 0.004 \pm 0.005$	$0.49 \pm 0.28 \pm 0.36$ (< 1.2 at 90% C.L.)
$B^0 \to K^+K^-$	$\frac{\mathcal{B}(B^0 \to K^-K^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.020 \pm 0.008 \pm 0.006$	$0.39 \pm 0.16 \pm 0.12$ (< 0.7 at 90% C.L.)
$\Lambda_b^0 \to pK^-$	$\frac{f_\Lambda}{f_d}\frac{\mathcal{B}(\Lambda_b^0 \to pK^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.066 \pm 0.009 \pm 0.008$	$5.6 \pm 0.8 \pm 1.5$
$\Lambda_b^0 \to p\pi^-$	$\frac{f_\Lambda}{f_d}\frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.042 \pm 0.007 \pm 0.006$	$3.5 \pm 0.6 \pm 0.9$

bration and parameterization. Other contributions come from trigger efficiencies, physics background shape and kinematics, b–hadron masses and lifetimes, and the possible polarization of Λ_b^0 decays.

The final results are listed in Table II. Absolute branching fractions are also quoted, by normalizing to world-average values of production fractions and $\mathcal{B}(B^0 \to K^+\pi^-)$ [1, 21]. The branching fraction measured for the $B_s^0 \to K^-\pi^+$ mode is consistent with the previous upper limit ($< 5.6 \times 10^{-6}$ at 90% C.L.), based on a subsample of the current data [3]. This agrees with the prediction in Ref. [25], but it is lower than most other predictions [5, 6, 26]. The $B_s^0 \to \pi^+\pi^-$ upper limit improves and supersedes the previous best limit [3]. The present measurement of $\mathcal{B}(B^0 \to K^+K^-)$ is in agreement with other existing measurements and has a similar resolution [21], but the resulting upper limit is weaker due to the observed central value. The sensitivity to both $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ is now close to the upper end of the theoretically expected range [5, 6, 7, 27]. We also report the first branching fraction measurements of charmless Λ_b decays. They are significantly lower than the previous upper limit of 2.3×10^{-5} [28], and in reasonable agreement with predictions [9], thus excluding the possibility of large ($O(10^2)$) enhancements from R-parity violating supersymmetric scenarios [29]. Their ratio can be determined directly from our data with greater accuracy than the individual values. For this purpose, the additional $p_T > 6$ GeV/c requirement is not necessary, and we can exploit the full sample size, obtaining $\mathcal{B}(\Lambda_b^0 \to p\pi^-)/\mathcal{B}(\Lambda_b^0 \to pK^-) = 0.66 \pm 0.14 \pm 0.08$, in good agreement with the predicted range 0.60–0.62 [9].

In summary, we have searched for rare charmless decay modes of neutral b–hadrons into pairs of charged hadrons in CDF data. We report the first observation of the modes $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$, and measure their relative branching fractions. We set upper limits on the unobserved modes $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$.

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