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# Charmless $b$-hadrons decays at CDF

M. J. Morello (for the CDF collaboration)
*University and I.N.F.N. of Pisa, Building C, Polo Fibonacci, Largo B. Pontecorvo, 3 - 56127 Pisa, Italy*

We present CDF results on the branching fractions and time-integrated direct CP asymmetries for $B^0$, $B^0_s$ and $\Lambda^0_b$ decay modes into pairs of charmless charged hadrons (pions, kaons and protons). The data-set for these measurements amounts to 1 fb$^{-1}$ of $\bar{p}p$ collisions at a center of mass energy 1.96 TeV. We report on the first observation of the $B^0_s \to K^-\pi^+$, $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$ decay modes and on the measurement of their branching fractions and direct CP asymmetries.

## 1. INTRODUCTION

The interpretation of the CP violation mechanism is one of the most controversial aspects of the Standard Model. Many extensions of Standard Model predict that there are new sources of CP violation, beyond the single Kobayashi-Maskawa phase in the quark-mixing matrix (CKM). Considerations related to the observed baryon asymmetry of the Universe imply that such new sources should exist. The non-leptonic decays of $b$ hadrons into pairs of charmless charged hadrons are effective probes of the CKM matrix and sensitive to these potential new physics effects. The large production cross section of $b$ hadrons of all kinds at the Tevatron allows extending such measurements to $B^0_s$ and $\Lambda^0_b$ decays, which are important to supplement our understanding of $B^0$ meson decays.

The branching fraction of $B^0_s \to K^-\pi^+$ decay mode could be used to measure $\gamma$ [1] and the measurement of its direct CP asymmetry could be a powerful model-independent test of the source of direct CP asymmetry in the $B$ system [2]. This may provide useful information to solve the current discrepancy between the direct CP asymmetries observed in the neutral $B^0 \to K^+\pi^-$ decay mode and charged $B^+ \to K^+\pi^0$ decay mode [3]. The $B^0_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ decay modes proceed through annihilation and exchange topologies, which are currently poorly known and a source of significant uncertainty in many theoretical calculations [4, 5]. A measurement of both decay modes would allow a determination of the strength of these diagrams [6]. CP violating asymmetries in $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$ decay modes may reach significant size $\mathcal{O}(10\%)$ in the Standard Model [8]. Measurements of asymmetries and branching fractions of these modes would rule out (or allow) some extensions of the Standard Model [9].

Throughout this paper, C-conjugate modes are implied and branching fractions indicate CP-averages unless otherwise stated.

## 2. CDF II

CDF II is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors [7]. A silicon micro-strip detector (SVXII) and a cylindrical drift chamber (COT) situated in a 1.4 T solenoidal magnetic field reconstruct charged particles in the pseudo-rapidity range $|\eta| < 1.0$. The SVXII consists of five concentric layers of double-sided silicon detectors with radii between 2.5 and 10.6 cm, each providing a measurement with 15 $\mu$m resolution in the azimuthal ($\phi$) direction and 70 $\mu$m along the beam ($z$) direction. The COT has 96 measurement layers, between 40 and 137 cm in radius, organized into alternating axial and $\pm 2°$ stereo "super-layers". The transverse momentum resolution is $\sigma_{p_T}/p_T \simeq 0.15\%\, p_T/(\mathrm{GeV}/c)$ and the observed mass-widths are about 14 MeV/$c^2$ for $J/\psi \to \mu^+\mu^-$ decays, and about 9 MeV/$c^2$ for $D^0 \to K^-\pi^+$ decays. The specific energy loss by ionization (dE/dx) of charged particles in the COT is measured from the amount of charge collected by each wire. An average separation power of 1.5 Gaussian-equivalent standard deviation is obtained in separating pions and kaons with momentum larger than 2 GeV/$c$.

## 3. MEASUREMENTS OF $H_b^0 \to h^+h^{'-}$ DECAYS

The Collider Detector at Fermilab (CDF) experiment analysed an integrated luminosity $\int \mathcal{L}dt \simeq 1$ fb$^{-1}$ sample of pairs of oppositely-charged particles with $p_T > 2$ GeV/$c$ and $p_T(1) + p_T(2) > 5.5$ GeV/$c$, used to form hadron candidates. The trigger required also a transverse opening angle $20° < \Delta\phi < 135°$ between the two tracks, to reject background from particle pairs within the same jet and from back-to-back jets. In addition, both charged particles were required to originate from a displaced vertex with a large impact parameter $d_0$ ($100\ \mu$m $< d_0(1,2) < 1$ mm), while the $b$-hadrons candidate was required to be produced in the primary $\bar{p}p$ interaction ($d_0 < 140\ \mu$m) and to have travelled a transverse distance $L_T > 200\ \mu$m. A sample of about 14,500 $H_b^0 \to h^+h^{'-}$ decay modes (where $H_b^0 = B^0, B_s^0$ or $\Lambda_b^0$ and $h = K$ or $\pi$) was reconstructed after the off-line confirmation of trigger requirements. In the offline analysis, an unbiased optimization procedure determined a tightened selection on track-pairs fit to a common decay vertex. The selection cuts were chosen minimizing directly the expected uncertainty of the physics observables to be measured (through several "pseudo-experiments"). Just two different sets of cuts were used in the analysis, respectively optimized to measure the CP asymmetry $A_{\rm CP}(B^0 \to K^+\pi^-)$ (loose cuts) and to improve the sensitivity for discovery and limit setting [10] of the not yet observed $B_s^0 \to K^-\pi^+$ mode (tight cuts). For the $\Lambda_b^0$ measurements, the additional requirement $p_T(H_b^0) > 6$ GeV/$c$ was applied to allow easy comparison with other $\Lambda_b^0$ measurements at the Tevatron, that are only available above this threshold [11].

In addition to tightening the trigger cuts, in the offline analysis the discriminating power of the $H_b^0$ isolation and of the information provided by the 3D reconstruction capability of the CDF tracking were used, allowing a great improvement in the signal purity. Isolation is defined as $I(H_b^0) = p_{\rm T}(H_b^0)/[p_{\rm T}(H_b^0) + \sum_i p_{\rm T}(i)]$, in which the sum runs over every other track (not from the $H_b^0$ hadron) within a cone of unit radius in the $\eta - \phi$ space around the $H_b^0$ hadron flight direction. By requiring $I(H_b^0) > 0.5$, the background was reduced by a factor four while keeping almost 80% of signal. The 3D silicon tracking allowed multiple vertices to be resolved along the beam direction and the rejection of fake tracks, reducing the background by a factor of two, with only a small efficiency loss on signal. The resulting $\pi\pi$-mass distributions (see Figure. 1) show a clean signal of $H_b^0 \to h^+h^{'-}$ decays. In spite of a good mass resolution ($\approx 22\,\text{MeV}/c^2$), the various $H_b^0 \to h^+h^{'-}$ modes overlap into an unresolved mass peak.

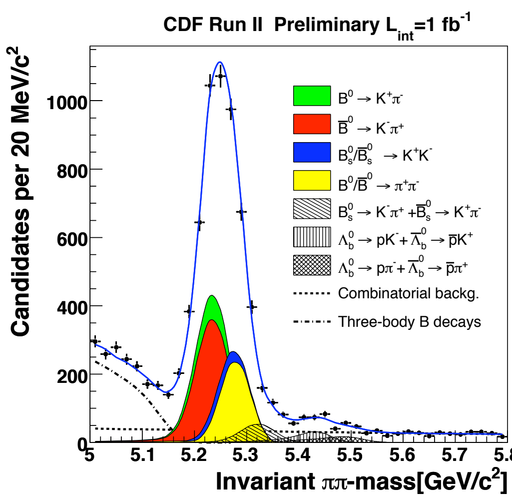


Figure 1: Invariant mass distribution of $H_b^0 \to h^+h^{'-}$ candidates passing tight cuts selection, using a pion mass assumption for both decay products. Cumulative projections of the likelihood fit for each mode are overlaid.

The resolution in invariant mass and in particle identification (dE/dx) is not sufficient for separating the individual $H_b^0 \to h^+h^{'-}$ decay modes on an event-by-event basis, therefore a maximum likelihood fit was performed. This combines kinematic and particle identification information to statistically determine both the contribution of each mode, and the relative contributions to the CP asymmetries.

Three separate fits were performed: one on the sample selected with loose cuts, one on the sample selected with tight cuts and one on the sample selected with tight cuts plus the requirement $p_T(H_b^0) > 6$ GeV/$c$. Significant signals are seen for $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, and $B_s^0 \to K^+K^-$, previously observed by CDF [12]. Three new rare modes were observed for the first time $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$, with a significance respectively of 8.2, 6.0 and 11.5 Gaussian-equivalent standard deviation estimated using a $p$-value distribution on pseudo-experiments. No evidence was obtained for $B_s^0 \to \pi^+\pi^-$or $B^0 \to K^+K^-$ mode.

Table I: Branching fractions results. Absolute branching fractions are normalized to the the world–average values $\mathcal{B}(B^0 \to K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$ and $f_s/f_d = 0.276 \pm 0.034$ and $f_\Lambda/f_d = 0.230 \pm 0.052$ [3]. The first quoted uncertainty is statistical, the second one is systematic.

| Mode | Quantity | Measurement | $\mathcal{B}(10^{-6})$ |
|---|---|---|---|
| $B^0 \to \pi^+\pi^-$ | $\frac{\mathcal{B}(B^0\to\pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.259 ± 0.017 ± 0.016 | 5.02 ± 0.33 ± 0.35 |
| $B_s^0 \to K^+K^-$ | $\frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0\to K^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.324 ± 0.019 ± 0.041 | 24.4 ± 1.4 ± 3.5 |
| $B_s^0 \to K^-\pi^+$ | $\frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0\to K^-\pi^+)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.071 ± 0.010 ± 0.007 | 5.0 ± 0.7 ± 0.8 |
| $\Lambda_b^0 \to pK^-$ | $\frac{f_\Lambda}{f_d} \times \frac{\mathcal{B}(\Lambda_b^0\to pK^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.066 ± 0.009 ± 0.008 | 5.6 ± 0.8 ± 1.5 |
| $\Lambda_b^0 \to p\pi^-$ | $\frac{f_\Lambda}{f_d} \times \frac{\mathcal{B}(\Lambda_b^0\to p\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.042 ± 0.007 ± 0.006 | 3.5 ± 0.6 ± 0.9 |
| $B_s^0 \to \pi^+\pi^-$ | $\frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0\to\pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.007 ± 0.004 ± 0.005 | 0.49 ± 0.28 ± 0.36 (< 1.2 @ 90% CL) |
| $B^0 \to K^+K^-$ | $\frac{\mathcal{B}(B^0\to K^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$ | 0.020 ± 0.008 ± 0.006 | 0.39 ± 0.16 ± 0.12 (< 0.7 @ 90% CL) |

Table II: CP asymmetries results. The first quoted uncertainty is statistical, the second one is systematic.

| Quantity | Measurement |
|---|---|
| $\frac{\mathcal{B}(\overline{B}^0\to K^-\pi^+)-\mathcal{B}(B^0\to K^+\pi^-)}{\mathcal{B}(\overline{B}^0\to K^-\pi^+)+\mathcal{B}(B^0\to K^+\pi^-)}$ | -0.086 ± 0.023 ± 0.009 |
| $\frac{\mathcal{B}(\overline{B}_s^0\to K^+\pi^-)-\mathcal{B}(B_s^0\to K^-\pi^+)}{\mathcal{B}(\overline{B}_s^0\to K^+\pi^-)+\mathcal{B}(B_s^0\to K^-\pi^+)}$ | 0.39 ± 0.15 ± 0.08 |
| $\frac{\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}K^+)-\mathcal{B}(\Lambda_b^0\to pK^-)}{\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}K^+)+\mathcal{B}(\Lambda_b^0\to pK^-)}$ | -0.37 ± 0.17 ± 0.03 |
| $\frac{\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}\pi^+)-\mathcal{B}(\Lambda_b^0\to p\pi^-)}{\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}\pi^+)+\mathcal{B}(\Lambda_b^0\to p\pi^-)}$ | -0.03 ± 0.17 ± 0.05 |
| $\frac{f_d}{f_s} \times \frac{\Gamma(\overline{B}^0\to K^-\pi^+)-\Gamma(B^0\to K^+\pi^-)}{\Gamma(\overline{B}_s^0\to K^+\pi^-)-\Gamma(B_s^0\to K^-\pi^+)}$ | -3.00 ± 1.50 ± 0.22 |

The relative branching fractions are listed in Table I while the CP asymmetries are listed in Table II, where $f_d$, $f_s$ and $f_\Lambda$ indicate the production fractions respectively of $B^0$, $B_s^0$ and $\Lambda_b^0$ from fragmentation of a $b$ quark in $\bar{p}p$ collisions. An upper limit is also quoted for modes in which no significant signal is observed. Absolute results are also listed in Table I, they are obtained by normalizing the data to the world–average of $\mathcal{B}(B^0 \to K^+\pi^-)$ [3].

The branching fraction of the newly observed mode $B_s^0 \to K^-\pi^+$ is in agreement with the latest theoretical expectation [13], which is lower than the previous predictions [4, 14]. This mode offers an unique opportunity to probe the direct CP violation in the $B_s^0$ mesons system. For the first time, the direct CP asymmetry in the $B_s^0 \to K^-\pi^+$ decay mode was measured and its central value favors a large CP violation (different from 0 at 2.3 Gaussian-equivalent standard deviation), although it is also compatible with zero. In Ref. [2] a robust test of the Standard Model or a probe of new physics is suggested by the comparison of the direct CP asymmetries in $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays. Using the external input for $f_s/f_d = 0.276 \pm 0.034$ [3] it is also possible to quote the following interesting quantity $\frac{\Gamma(\overline{B}^0\to K^-\pi^+)-\Gamma(B^0\to K^+\pi^-)}{\Gamma(B_s^0\to K^-\pi^+)-\Gamma(\overline{B}_s^0\to K^+\pi^-)} = 0.83 \pm 0.41 \pm 0.12$, which is in agreement with the Standard Model expectation of unity. Assuming this relationship true (equal to unity), and using the external inputs for the $\mathcal{B}(B_s^0 \to K^-\pi^+)$, the world–average for the direct CP violating asymmetry in the $B^0 \to K^+\pi^-$ decay mode [3], the $\mathcal{B}(B^0 \to K^+\pi^-)$ [3], it is possible to estimate the expected value for the direct CP violating asymmetry in the $B_s^0 \to K^-\pi^+$ decay mode ($\approx 0.40$) which is in agreement with the CDF measurement presented here.

The branching fraction of $B_s^0 \to K^+K^-$ decay mode is in agreement with the latest theoretical expectation [15, 16] and with the previous CDF measurement [12].

The results on the $B^0$ sector are in agreement with world–average values [3]. The direct CP violating asymmetry in the $B^0 \to K^+\pi^-$ is competitive with the current $B$-Factories measurements [3].

The results on the $\Lambda_b^0$ sector are in agreement with Standard Model expectations. The absolute branching fractions exclude $\mathcal{O}(10^{-4})$ values indicated for $R$-parity violating Minimal Supersymmetric extensions of the Standard Model [9]. The measurements of the direct CP violating asymmetries in the $b$-baryon decays, presented here, are the first such measurements in this sector. The statistical uncertainty dominates the resolution and prevents a statement on the presence of asymmetry, whose measured value deviates from 0 at 2.1 Gaussian-equivalent standard deviation level in the $\Lambda_b^0 \to pK^-$ decay mode and is fully consistent with 0 in the $\Lambda_b^0 \to p\pi^-$ decay mode.

With full Run II samples ($5-6$ fb$^{-1}$ by year 2010) CDF collaboration expects a measurement of the direct CP violating asymmetry in the $B^0 \to K^+\pi^-$ mode with a statistical plus systematic uncertainty at 1% level; observation of the direct CP violating asymmetry in the $B_s^0 \to K^-\pi^+$ mode (or alternatively the possible indication of non-SM sources of CP violation); more precise measurements of direct CP violating asymmetries in the $\Lambda_b^0$ charmless decays; and improved limits, or even observation, of annihilation modes $B_s^0 \to \pi^+\pi^-$ and $B^0 \to K^+K^-$. In addition to the above, time-dependent measurements will be performed for $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decay [17]. See [18–21] for more details.

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