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CP Violation in charmless B decays at CDF

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We present the CDF results on the branching fractions and time-integrated direct CP asymmetries for B^0, B_s^0 and Λ_b^0 decay modes into pairs of charmless charged hadrons (pions, kaons and protons). The data-set for these measurements corresponds to 1 fb^{-1} of $\bar{p}p$ collisions at a center of mass energy 1.96 TeV.

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1. Introduction

The interpretation of the CP violation mechanism is one of the most controversial aspects of the Standard Model. Many extensions of the 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 potential new physics effects. The large production cross section of b hadrons of all kinds at the Tevatron allows extending such measurements to B_s^0 and Λ_b^0 decays, which are important to supplement our understanding of B^0 and B^+ meson decays. The branching fraction of $B_s^0 \to K^-\pi^+$ decay mode provides information on the CKM angle γ [1] and the measurement of direct CP asymmetry could be a powerful model-independent test of the source of 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 $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays [3]. The $B_s^0 \to \pi^+\pi^-$ 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 amplitudes [6]. CP violating asymmetries in $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ decay modes may reach significant size $\mathscr{O}(10\%)$ in the Standard Model [7]. Measurements of asymmetries and branching fractions of these modes may favor or disfavor some specific extensions of the Standard Model [8]. Throughout this paper, C-conjugate modes are implied and branching fractions indicate CP-averages unless otherwise stated.

2. CDF II

The Collider Detector at Fermilab (CDF II) experiment is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors [9]. 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 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 (σ) is obtained in separating pions and kaons with momentum larger than 2 GeV/c. Consequently the separation between KK and $\pi\pi$, or $K^+\pi^-$ and $K^-\pi^+$ corresponds to about 2.1 σ.

3. Measurement of $B \to h^+h^{'-}$ decays

CDF analysed an integrated luminosity $\int \mathscr{L}dt \simeq 1$ 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 B candidates. The trigger required also a transverse opening angle $20^\circ < \Delta\phi < 135^\circ$ 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 (100 μm

$< d_0(1,2) < 1$ 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 $Ł_T > 200\ \mu$m. A sample of about 14,500 $B \to h^+h^{'-}$ decay modes (where $B = B^0, B_s^0$ or Λ_b^0 and $h = K$ or π) 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 statistical trials). 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 Λ_b^0 measurements, the additional requirement $p_T(B) > 6$ GeV/c was applied to allow easy comparison with other Λ_b^0 measurements at the Tevatron, that are only available above this threshold [11].

In the offline analysis the discriminating power of the B isolation and of the information provided by the 3D reconstruction capability of the CDF tracking were also used, allowing an improvement in the signal purity. Isolation is defined as $I(B) = p_{\rm T}(B)/[p_{\rm T}(B) + \sum_i p_{\rm T}(i)]$, in which the sum runs over every other track (not from the B hadron) within a cone of unit radius in the $\eta - \phi$ space around the B hadron flight direction. By requiring $I(B) > 0.5$, the background was reduced by a factor 4 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 2, with only a small efficiency loss on signal. The resulting $\pi\pi$-mass distributions (see Figure 1) show a clean signal of $B \to h^+h^{'-}$ decays. In spite of a good mass resolution ($\approx 22\,\text{MeV}/c^2$), the various $B \to h^+h^{'-}$ modes overlap into an unresolved mass peak with a width of about $\approx 35\,\text{MeV}/c^2$. In this condition, each mode is a background for the others: for example, the $B_s^0 \to K^-\pi^+$ signal is background of $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$.

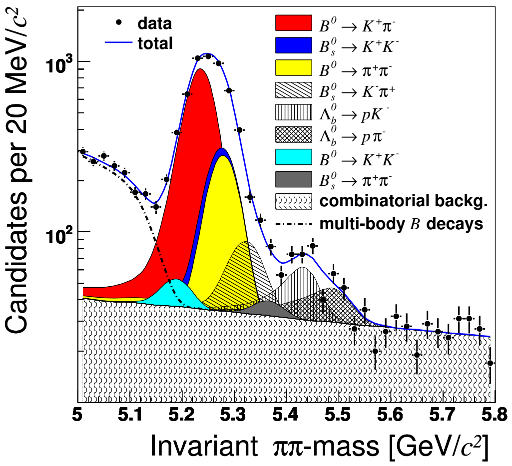

Figure 1: Invariant mass distribution of $B \to h^+h^{'-}$ candidates passing tight cuts selection, using a pion mass assumption for both decay products. Cumulative projections of the Likelihood fit for each mode are overlaid.

The resolution in invariant mass and in particle identification (dE/dx) is not sufficient for separating the individual $B \to h^+h^{'-}$ decay modes on an event-by-event basis, therefore a maximum Likelihood fit, incorporating kinematics and PID information, was performed. 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 $p_{\text{tot}} = p_1 + p_2$. 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

$$\begin{aligned} m_{12}^2 = m_{\pi\pi}^2 - 2m_\pi^2 + m_1^2 + m_2^2 + \\ -2\sqrt{p_1^2+m_\pi^2}\sqrt{p_2^2+m_\pi^2} + 2\sqrt{p_1^2+m_1^2}\sqrt{p_2^2+m_2^2}, \end{aligned} \tag{3.1}$$

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

From the signal fractions returned by the likelihood fit we calculate the signal yields. Significant signals are seen for $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, and $B^0_s \to K^+K^-$, previously observed by CDF [12]. Three new rare modes were observed for the first time $B^0_s \to K^-\pi^+$, $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$, with a significance respectively of 8.2, 6.0 and 11.5 σ [13] estimated using the Likelihood Ratio distribution (distributed with good approximation as a χ^2 distribution) on pseudo-experiments. No evidence was obtained for $B^0_s \to \pi^+\pi^-$ or $B^0 \to K^+K^-$ mode.

Table 1: Branching fractions results [13]. 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	$\mathcal{B}(10^{-6})$
$B^0_s \to K^-\pi^+$	$\frac{f_s}{f_d} \times \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.071 \pm 0.010 \pm 0.007$	$5.0 \pm 0.7 \pm 0.8$
$\Lambda^0_b \to pK^-$	$\frac{f_\Lambda}{f_d} \times \frac{\mathcal{B}(\Lambda^0_b \to pK^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.066 \pm 0.009 \pm 0.008$	$5.6 \pm 0.8 \pm 1.5$
$\Lambda^0_b \to p\pi^-$	$\frac{f_\Lambda}{f_d} \times \frac{\mathcal{B}(\Lambda^0_b \to p\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.042 \pm 0.007 \pm 0.006$	$3.5 \pm 0.6 \pm 0.9$
$B^0_s \to \pi^+\pi^-$	$\frac{f_s}{f_d} \times \frac{\mathcal{B}(B^0_s \to \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.007 \pm 0.004 \pm 0.005$	$0.49 \pm 0.28 \pm 0.36$ (< 1.2 @ 90% CL)
$B^0 \to K^+K^-$	$\frac{\mathcal{B}(B^0 \to K^+K^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.020 \pm 0.008 \pm 0.006$	$0.39 \pm 0.16 \pm 0.12$ (< 0.7 @ 90% CL)

Table 2: Branching fractions results [14]. 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 $f_s/f_d = 0.282 \pm 0.038$ [3]. The first quoted uncertainty is statistical, the second one is systematic.

Mode	Quantity	Measurement	$\mathcal{B}(10^{-6})$
$B^0 \to \pi^+\pi^-$	$\frac{\mathcal{B}(B^0 \to \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.259 \pm 0.017 \pm 0.016$	$5.02 \pm 0.33 \pm 0.35$
$B^0_s \to K^+K^-$	$\frac{f_s}{f_d} \times \frac{\mathcal{B}(B^0_s \to K^+K^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}$	$0.347 \pm 0.020 \pm 0.021$	$23.9 \pm 1.4 \pm 3.6$

Table 3: CP asymmetries results [13, 14]. The first quoted uncertainty is statistical, the second one is systematic.

Quantity	Measurement
$\frac{\mathscr{B}(\overline{B}^0 \to K^-\pi^+) - \mathscr{B}(B^0 \to K^+\pi^-)}{\mathscr{B}(\overline{B}^0 \to K^-\pi^+) + \mathscr{B}(B^0 \to K^+\pi^-)}$	-0.086 ± 0.023 ± 0.009
$\frac{\mathscr{B}(\overline{B}_s^0 \to K^+\pi^-) - \mathscr{B}(B_s^0 \to K^-\pi^+)}{\mathscr{B}(\overline{B}_s^0 \to K^+\pi^-) + \mathscr{B}(B_s^0 \to K^-\pi^+)}$	0.39 ± 0.15 ± 0.08
$\frac{\mathscr{B}(\overline{\Lambda}_b^0 \to \overline{p}K^+) - \mathscr{B}(\Lambda_b^0 \to pK^-)}{\mathscr{B}(\overline{\Lambda}_b^0 \to \overline{p}K^+) + \mathscr{B}(\Lambda_b^0 \to pK^-)}$	-0.37 ± 0.17 ± 0.03
$\frac{\mathscr{B}(\overline{\Lambda}_b^0 \to \overline{p}\pi^+) - \mathscr{B}(\Lambda_b^0 \to p\pi^-)}{\mathscr{B}(\overline{\Lambda}_b^0 \to \overline{p}\pi^+) + \mathscr{B}(\Lambda_b^0 \to p\pi^-)}$	-0.03 ± 0.17 ± 0.05

The relative branching fractions are listed in tables 1 and 2, while the CP asymmetries are listed in Table 3, where f_d, f_s and f_Λ indicate the production fractions respectively of B^0, B_s^0 and Λ_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 1 and 2, obtained by normalizing the data to the world average of $\mathscr{B}(B^0 \to K^+\pi^-)$ [3].

The branching fraction of the observed mode $B_s^0 \to K^-\pi^+$ is in agreement with the theoretical expectation [15], which is lower than the previous predictions [4, 16]. This mode offers a unique opportunity to probe the direct CP violation in the B_s^0 meson 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 σ), although it is also compatible with zero [14]. In Ref. [1] and [2] a 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.

Under the assumption of equal lifetimes for B^0 and B_s^0, using external inputs [3], it is also possible to quote the following interesting quantity $R = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B_s^0 \to K^-\pi^+) - \Gamma(\overline{B}_s^0 \to K^+\pi^-)} = 0.85 \pm 0.42(\text{stat}) \pm 0.13(\text{syst})$, which is in agreement with the Standard Model expectation of unity. Assuming this relationship true (equal to unity), and using the measured value of the $\mathscr{B}(B_s^0 \to K^-\pi^+)$, the world–average for the direct CP violating asymmetry in the $B^0 \to K^+\pi^-$ decay mode [3], the $\mathscr{B}(B^0 \to K^+\pi^-)$ [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 (≈ 0.40) which is in agreement with the CDF measurement and provide additional support to the validity of the analysis.

The branching fraction of $B_s^0 \to K^+K^-$ decay mode is in agreement with the theoretical expectation [17, 18] 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 Λ_b^0 sector are in agreement with Standard Model expectations. The absolute branching fractions exclude $\mathscr{O}(10^{-4})$ values indicated for R-parity violating Minimal Supersymmetric extensions of the Standard Model [8]. The measurements of the direct CP violating asymmetries in the b-baryon decays, presented here, are the first such measurements. 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.

4. Outlook

With full Run II samples (10 fb^{-1} by year 2011) the CDF collaboration expects a measurement of the direct CP violating asymmetry in the $B^0 \to K^+\pi^-$ mode with an uncertainty at 1% level; significantly improved measurement of 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 Λ_b^0 charmless decays; and improved limits, or even evidence, 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.

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