

$B \rightarrow h^+h'^-$ modes at CDF

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We review CDF results and prospects on decays of B hadrons in two charged charmless hadrons.

I. INTRODUCTION

The rich production of all types of B hadrons at the Tevatron Collider at Fermilab allows studying charmless two-body decays both in known and new modes. Using a sample of $\int \mathcal{L} dt \simeq 1 \text{ fb}^{-1}$ of data, CDF performed a search for all possible modes of neutral bottom hadrons in two charged charmless hadrons (p , K or π) [1].

The CDFII detector is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors [2]. A silicon micro-strip detector (SVXII) and a cylindrical drift chamber (COT) immersed in a 1.4 T solenoidal magnetic field reconstruct charged particles within pseudorapidity $|\eta| < 1.0$, with a transverse momentum resolution $\sigma_{p_T}/p_T \simeq 0.15\% p_T/(\text{GeV}/c)$. This yields a mass resolution of $\simeq 22 \text{ MeV}/c^2$ for $B \rightarrow h^+h'^-$ decays, which is an important ingredient of this analysis. Particle identification information (PID) is obtained from the specific energy loss by ionization (dE/dx) of charged particles in the COT. This yields a nearly-constant separation of 1.4σ between pions and kaons of momenta $> 2 \text{ GeV}/c$. A three-level trigger system allows selecting events by requiring the presence of at least two tracks with large impact parameters relative to the beam axis.

II. DATA SAMPLE AND RECONSTRUCTION

B hadron candidates are initially selected by forming pairs of oppositely-charged tracks with $p_T > 2 \text{ GeV}/c$, transverse opening-angle $20^\circ < \Delta\phi < 135^\circ$, and $p_T(1) + p_T(2) > 5.5 \text{ GeV}/c$. In addition, both tracks are required to have a large transverse impact parameter d_0 relative to the $\bar{p}p$ interaction vertex ($100 \mu\text{m} < d_0 < 1 \text{ mm}$). The B candidate is required to point back to the primary vertex ($d_0(B) < 140 \mu\text{m}$), and to have travelled a transverse distance $L_{xy}(B) > 200 \mu\text{m}$.

Most of the above cuts are implemented at the trigger level. In the offline analysis, additional cuts are imposed on isolation I_B [3] and the quality of the fit (χ^2) to the 3D decay vertex of the B hadron candidate.

Final selection cuts are determined by an optimization procedure, based on minimizing the expected uncertainty of the physics observables to be measured. Two different sets of cuts are used, optimized respectively for best

resolution on $A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$ (loose cuts), and for best sensitivity [4] for the discovery of the yet unobserved $B_s^0 \rightarrow K^-\pi^+$ mode (tight cuts). The looser set of cuts is also used for measuring the decay rates of the largest-yields modes, while the tighter set is used for the other rare modes.

The invariant mass distribution of the candidates, with an arbitrary pion mass assignment to both tracks, shows a single large peak in the B mass range, formed by several overlapping modes (Fig. 1).

III. MEASUREMENT METHODOLOGY

The different modes are statistically separated and individually measured by means of an unbinned maximum-Likelihood fit, combining kinematics and PID. Kinematic information is summarized by three loosely correlated observables: (a) the mass $M_{\pi\pi}$ calculated with the pion mass assignment to both particles; (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 evaluating the mass of the B candidate for any mass assignment to the decay products. PID information is given by a dE/dx measurement for each track. The Likelihood for the i^{th} event is then:

$$\mathcal{L}_i = (1 - b) \sum_j f_j \mathcal{L}_j^{\text{kin}} \mathcal{L}_j^{\text{PID}} + b (f_A \mathcal{L}_A^{\text{kin}} \mathcal{L}_A^{\text{PID}} + (1 - f_A) \mathcal{L}_E^{\text{kin}} \mathcal{L}_E^{\text{PID}}) \quad (1)$$

where index ‘A(E)’ labels the physics (combinatorial) background-related quantities, and index j runs over the twelve possible $B \rightarrow h^+h'^-$ and $\Lambda_b^0 \rightarrow ph^-$ modes and conjugates having distinguishable final states (e.g. $B^0 \rightarrow K^+\pi^-$ and $\bar{B}^0 \rightarrow K^-\pi^+$ are distinct, while $B^0 \rightarrow \pi^+\pi^-$ and $\bar{B}^0 \rightarrow \pi^+\pi^-$ are treated as a single component). The f_j are the signal fractions to be determined by the fit, together with the background fraction parameters b and f_A .

The shape of the mass distribution of each single channel accounts for non-Gaussian tails, both from resolution and from emission of photons in the final state, which is simulated on the basis of analytical QED calculations [5]. The quality of this model was checked on a large sample ($\simeq 500\text{k}$) of $D^0 \rightarrow K^-\pi^+$ decays. The mass distribution

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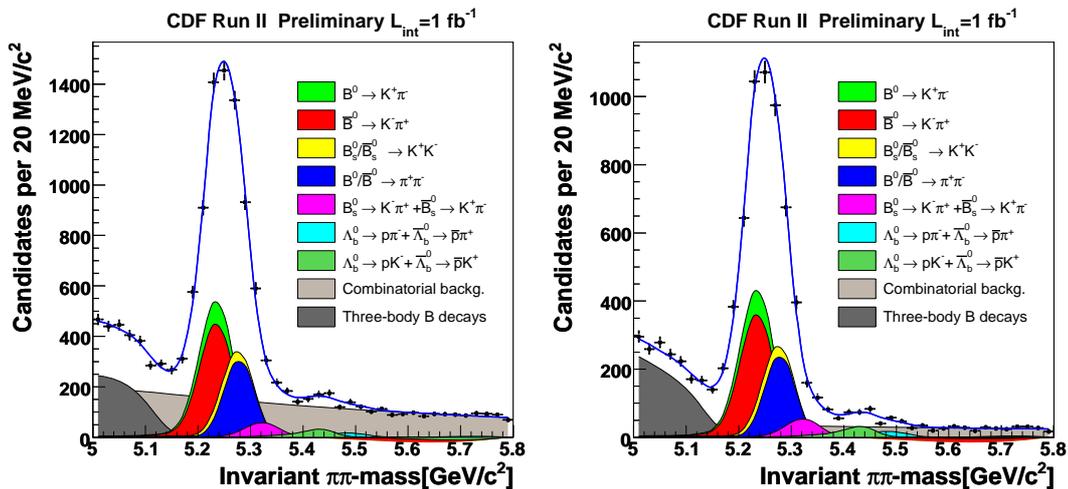


FIG. 1: Invariant mass distribution of $B_{(s)}^0 \rightarrow h^+ h'^-$ candidates passing the loose (left) or tight (right) selection cuts. The pion mass is assigned to both tracks. Cumulative projections of the likelihood fit for each mode are overlaid.

of the combinatorial background is fit to a smooth function, while the physics background is parameterized by an ‘Argus function’ [6] smeared with our mass resolution. Kinematical distributions for the signal are represented by analytical expressions, while for the combinatorial background are parameterized from the mass sidebands of data [7].

The dE/dx response of the detector to kaons and pions was calibrated from a sample of $1.5M D^{*+} \rightarrow D^0 \pi^+ \rightarrow [K^- \pi^+] \pi^+$ decays, where the D^0 decay products are identified by the charge of the D^{*+} pion. The PID term for the background allows for pion, kaon, proton, and electron components, which are free to vary independently in the fit. Background muons are indistinguishable from pions with the available dE/dx resolution and are therefore included as a part of the pion component.

To avoid the large uncertainties associated to production cross sections and reconstruction efficiency, branching fractions are measured relative to the $B^0 \rightarrow K^+ \pi^-$ mode, and then normalized to the world-average value of $\mathcal{B}(B^0 \rightarrow K^+ \pi^-)$ [8]. Upper limits [9] are quoted for modes in which no significant signal is observed.

To convert the raw signal fractions returned by the fit into relative branching fractions, corrections are applied for different efficiencies of trigger and offline selection requirements for different decay modes. Corrections related to decay kinematics are determined from the detector simulation, while others are measured on data using control samples. The dominant contributions to the systematic uncertainty come from: statistical uncertainty on isolation efficiency ratio (for B_s^0 modes); uncertainty on the dE/dx calibration and parameterization; and uncertainty on the combinatorial background model. Smaller systematic uncertainties are assigned for: trigger efficiencies; physics background shape and kinematics; B meson masses and lifetimes.

IV. RESULTS

A. Rare Modes

The search for rare modes is performed using the ‘tight’ selection. The fit allows for the presence of any component of the form $B \rightarrow h^+ h'^-$ or $\Lambda_b^0 \rightarrow p h^-$ where $h, h' = K$ or π , with the yield as a free parameter. Final results are reported in Table I, where f_d and f_s indicate the production fractions respectively of B^0 and B_s^0 from fragmentation of a b quark in $\bar{p}p$ collisions.

The results provide the first observation of the $B_s^0 \rightarrow K^- \pi^+$ mode, with a significance of 8.2σ , which includes systematic uncertainties and is evaluated from Monte Carlo samples of background without signal. The branching fraction of this mode is significantly sensitive to the value of angle γ ; however, predictions obtained from different methods differ. Our measurement $\mathcal{B}(B_s^0 \rightarrow K^- \pi^+) = (5.0 \pm 0.75 \pm 1.0) \times 10^{-6}$ is in agreement with the prediction in [10], but is lower than most other predictions [11–13].

No evidence is found for modes $B_s^0 \rightarrow \pi^+ \pi^-$ or $B^0 \rightarrow K^+ K^-$, in agreement with expectations of significantly smaller branching fractions. The measurement $\mathcal{B}(B^0 \rightarrow K^+ K^-) = (0.39 \pm 0.16 \pm 0.12) \times 10^{-6}$ has the same precision of the other current measurements from $\Upsilon(4S)$ experiments [8], although the upper limit is weaker due to the observed positive central value. The $B_s^0 \rightarrow \pi^+ \pi^-$ upper limit is improved with respect to the previous best limit, obtained from the analysis of a subsample of the present data [14]. The sensitivity to both $B^0 \rightarrow K^+ K^-$ and $B_s^0 \rightarrow \pi^+ \pi^-$ is now close to the upper end of theoretically expected range [11, 13, 15, 16], and it will be interesting to see the results from the larger samples being accumulated. These modes proceed only through annihilation and exchange diagrams, which are

currently poorly known and a source of significant uncertainty in many theoretical calculations. Measuring of constraining both these channels is particularly useful since the physics parameters governing the strength of penguin-annihilation can be extracted from their ratio [17].

In the same sample, we also get to observe charmless decays of a B baryon for the first time: $\Lambda_b^0 \rightarrow p\pi^-$ (6σ) and $\Lambda_b^0 \rightarrow pK^-$ (11.5σ). We measure the ratio of branching fractions of these modes as $\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^-)/\mathcal{B}(\Lambda_b^0 \rightarrow pK^-) = 0.66 \pm 0.14 \pm 0.08$, in good agreement with the expected range $[0.60, 0.62]$ from [18]. Work is in progress towards a measurement of individual branching fractions and CP asymmetries, that are expected to be non-negligible and are sensitive to possible SUSY contributions [19].

B. CP asymmetries

We can measure from our data the CP asymmetries of both B^0 and B_s^0 decays in the self-tagging final state $K^\pm\pi^\mp$. The asymmetry of the B_s^0 mode is measured with the tight selection used in previous section, while the looser selection is used for the B^0 mode.

The raw asymmetries returned by the fitting procedure need to be corrected for possible detector and procedural biases. This has been done by measuring the asymmetry in a sample of 1M prompt $D^0 \rightarrow K^-\pi^+$ decays, reconstructed and selected with the same computer code used for analysis of the $B \rightarrow h^+h^-$ sample and similar selection criteria. Given the smallness of the CP asymmetry expected in the $D^0 \rightarrow K^-\pi^+$ mode ($\ll 1\%$), the experimentally measured asymmetry provides a good determination of the measurement bias, including asymmetries in the dE/dx response or other possible unanticipated effects. The observed effect ($0.6 \pm 0.14\%$) is in good agreement with the expected K^+/K^- asymmetry due to the different probability of interaction with the detector material.

The result $A_{\text{CP}}(B^0 \rightarrow K^+\pi^-) = -0.086 \pm 0.023 \pm 0.009$ is in agreement with the world-average [8], and is the second most precise measurement. The updated world average $A_{\text{CP}}^{\text{ave.}}(B^0 \rightarrow K^+\pi^-) = -0.095 \pm 0.013$ has a significance of 7σ (previously 6σ). Comparison of this average with the asymmetry in the similar mode of the B^+ , shows a deviation of 4.8σ (previously 4.6σ). While it has been argued in the past that the asymmetries in these two modes should be equal in the standard model due to isospin symmetry, this is not anymore considered a reliable test [21–23]. Conversely, it has been argued [20, 24] that a much more robust test of the Standard Model origin of the asymmetry of the $B^0 \rightarrow K^+\pi^-$ mode is the comparison with the corresponding asymmetry in the $B_s^0 \rightarrow K^-\pi^+$ mode, where the final state is identical, thus canceling possible effects of final state interactions. The predicted equality of rate differences $\Gamma(\overline{B}^0 \rightarrow K^-\pi^+) - \Gamma(B^0 \rightarrow K^+\pi^-) = \Gamma(B_s^0 \rightarrow K^-\pi^+) - \Gamma(\overline{B}_s^0 \rightarrow$

$K^+\pi^-)$ is very robust under the Standard Model, while it would be completely fortuitous under a New Physics scenario, because it is produced by interference of very different amplitudes in the two cases. In addition, the smallness of the $\mathcal{B}(B_s^0 \rightarrow K^-\pi^+)$ (Tab. I), makes the predicted asymmetry large ($\simeq 40\%$) and therefore experimentally more accessible. Using our tight set of cuts, we find $A_{\text{CP}}(B_s^0 \rightarrow K^-\pi^+) = 0.39 \pm 0.15 \pm 0.08$. This value favors the large CP asymmetry predicted by the Standard Model and has the correct sign, but is still compatible with zero (significance just above 2σ). By combining our measurement with the world-average for the B^0 we obtain $\frac{\Gamma(\overline{B}^0 \rightarrow K^-\pi^+) - \Gamma(B^0 \rightarrow K^+\pi^-)}{\Gamma(B_s^0 \rightarrow K^-\pi^+) - \Gamma(\overline{B}_s^0 \rightarrow K^+\pi^-)} = 0.84 \pm 0.42 \pm 0.15$, in agreement with the Standard Model expectation of 1.0. It will be very interesting to see if this agreement persists with more data. Given the large expected asymmetry, the SM asymmetry will be visible as a 3σ effect with 1.5 fb^{-1} of data, and a 5σ effect before reaching 4 fb^{-1} . A non observation of this asymmetry would indicate a non-SM source of CP violation.

C. Precision Branching Fractions

The sample selection for $A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$ also provides good measurements of the branching fractions of the ‘large yield’ modes $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$. We obtain $\mathcal{B}(B_s^0 \rightarrow K^+K^-) = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$, in agreement with current predictions [11, 23, 25, 26] and with the previous CDF measurement [14], although the lower central value now indicates a smaller U-spin breaking effect. Work is in progress to reduce the systematic uncertainty which dominates the resolution of the present preliminary results.

A substantial yield is also available in the $B^0 \rightarrow \pi^+\pi^-$ mode, allowing a measurement of the branching fraction: $\mathcal{B}(B^0 \rightarrow \pi^+\pi^-) = (5.10 \pm 0.33 \pm 0.36) \times 10^{-6}$. This has the same precision, and is in agreement with the current results from $\Upsilon(4S)$ [8].

V. PROSPECTS

CDF results based on 1 fb^{-1} are beginning to show the Tevatron potential for B physics. The sample on tape is now almost doubled, and the luminosity keeps increasing; the default plan is to collect 8 fb^{-1} by year 2009. Most of the systematic uncertainty in the measurements described above is determined by statistical uncertainties in the calibration samples, and is therefore expected that the precision will keep increasing with statistics. Highlights from the full runII samples will be: A_{CP} in $B^0 \rightarrow K^+\pi^-$ at 1% level; 5-sigma observation of direct A_{CP} in $B_s^0 \rightarrow K^-\pi^+$ (or alternatively the discovery of non-SM CP violation); first A_{CP} measurements in the Λ_b^0 ; and tight constraint, or even observation, of annihilation modes.

TABLE I: Results from the loose (top) and tight (bottom) selections. Absolute branching fractions are normalized to the the world-average values $\mathcal{B}(B^0 \rightarrow K^+\pi^-) = (19.7 \pm 0.6) \times 10^{-6}$ and $f_s = (10.4 \pm 1.4)\%$ and $f_d = (39.8 \pm 1.0)\%$ [8]. The first quoted uncertainty is statistical, the second is systematic. Limits are at 90% CL.

mode	N_s	Quantity	Measurement	$\mathcal{B}(10^{-6})$
$B^0 \rightarrow K^+\pi^-$	4045 ± 84	A_{CP}	$-0.086 \pm 0.023 \pm 0.009$	
$B^0 \rightarrow \pi^+\pi^-$	1121 ± 63	$\frac{\mathcal{B}(B^0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)}$	$0.259 \pm 0.017 \pm 0.016$	$5.10 \pm 0.33 \pm 0.36$
$B_s^0 \rightarrow K^+K^-$	1307 ± 64	$\frac{f_s \mathcal{B}(B_s^0 \rightarrow K^+K^-)}{f_d \mathcal{B}(B^0 \rightarrow K^+\pi^-)}$	$0.324 \pm 0.019 \pm 0.041$	$24.4 \pm 1.4 \pm 4.6$
$B_s^0 \rightarrow K^-\pi^+$	$230 \pm 34 \pm 16$	$\frac{f_s \mathcal{B}(B_s^0 \rightarrow K^-\pi^+)}{f_d \mathcal{B}(B^0 \rightarrow K^+\pi^-)}$	$0.066 \pm 0.010 \pm 0.010$	$5.0 \pm 0.75 \pm 1.0$
$B_s^0 \rightarrow \pi^+\pi^-$	$26 \pm 16 \pm 14$	A_{CP}	$0.39 \pm 0.15 \pm 0.08$	
$B_s^0 \rightarrow \pi^+\pi^-$	$26 \pm 16 \pm 14$	$\frac{f_s \mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-)}{f_d \mathcal{B}(B^0 \rightarrow K^+\pi^-)}$	$0.007 \pm 0.004 \pm 0.005$	$0.53 \pm 0.31 \pm 0.40 (< 1.36)$
$B^0 \rightarrow K^+K^-$	$61 \pm 25 \pm 35$	$\frac{\mathcal{B}(B^0 \rightarrow K^+K^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)}$	$0.020 \pm 0.008 \pm 0.006$	$0.39 \pm 0.16 \pm 0.12 (< 0.7)$
$\Lambda_b^0 \rightarrow pK^-$	$156 \pm 20 \pm 11$	$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow pK^-)}$	$0.66 \pm 0.14 \pm 0.08$	
$\Lambda_b^0 \rightarrow p\pi^-$	$110 \pm 18 \pm 16$			

In addition to the above, time-dependent measurements will be performed. Resolutions on time-dependent CP asymmetries can be predicted from the yields, flavor tagger performance (ϵD^2), and effective S/B. Tagger performance was optimized to $\epsilon D^2 = 5.3\%$ for the B_s^0 mixing analysis; we assume a performance $\epsilon D^2 = 4\%$ can be obtained for the B^0 with similar methods. For the other parameters we assume the values of current analysis with no further improvements.

The CP asymmetries in the $B^0 \rightarrow \pi^+\pi^-$ mode can be measured with a resolution $\sigma_{ACP} = 0.15$ with 6 fb^{-1} , which will offer an interesting additional measurement of

similar precision to the currently available results from $\Upsilon(4S)$, that still show a disagreement.

The performance in the measurement of CP asymmetry in the $B_s^0 \rightarrow K^+K^-$ mode depends on the assumed effective S/B ($\simeq 1$, depending on the selection), and proper-time resolution (between 70 and 100 fs^{-1}). A resolution in the range [0.15, 0.3] is expected for both direct and mixing A_{CP} from a sample of 6 fb^{-1} . These asymmetries are related in the SM to the B^0 asymmetries and angle γ via U-spin [23, 27], and are sensitive to possible SUSY effects [26]. In addition, it is possible to measure the B_s^0 lifetime in a CP eigenstate, see [28] for details.

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