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First evidence of $B_s^0 \to \pi^+\pi^-$ decay

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We search for new charmless decays of neutral b–mesons to pairs of charged hadrons with the upgraded Collider Detector at the Fermilab Tevatron. Using a data sample corresponding to 6 fb^{-1} of integrated luminosity, we report the first evidence of the $B_s^0 \to \pi^+\pi^-$ decay, with a significance of 3.7σ, and measure $\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.57 \pm 0.15\ (\text{stat}) \pm 0.10\ (\text{syst})) \times 10^{-6}$. No evidence is found for the decay $B^0 \to K^+K^-$ and we set a 90% confidence level interval $[0.05, 0.46] \times 10^{-6}$, corresponding to the central value $\mathcal{B}(B^0 \to K^+K^-) = (0.23 \pm 0.10\ (\text{stat}) \pm 0.10\ (\text{syst})) \times 10^{-6}$. Quoted branching fractions are measured using $\mathcal{B}(B^0 \to K^+\pi^-)$ as a reference.

Preliminary Results for 2011 Summer Conferences

I. INTRODUCTION

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 interaction dynamics. The quark-level transition $b \to u$ makes decay amplitudes sensitive to γ, the least known angle 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 $\Upsilon(4S)$ decays [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 phenomenological 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, the $B_s^0 \to \pi^+\pi^-$ is still missing. $B_s^0 \to K^+K^-$ and $B_s^0 \to K^-\pi^+$ has been observed to date [3–5]. 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 [10], which is currently poorly known and a source of significant uncertainty in many calculations [8]. The present search is sensitive to both modes.

In this document we report the results of a search for new rare decays of neutral bottom mesons into a pair of charged charmless mesons (K or π), performed in 6 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 evidence of the $B_s^0 \to \pi^+\pi^-$ mode and measure its relative branching fraction [11]. No evidence is found for the $B^0 \to K^+K^-$ decay, with 2σ level indication of a signal.

II. DETECTOR

CDF II is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors. The detector components relevant for this analysis are briefly outlined below; a more detailed description can be found in Ref. [12]. 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 $|\eta| < 1.0$ [13]. The SVX consists of six concentric layers 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 1.4σ separation between kaons and pions with momenta greater than 2 GeV$/c$.

III. SAMPLE AND SELECTION

The data were collected by a three-level trigger system, using a set of requirements specifically aimed at selecting two-pronged B decays. At level 1, COT tracks are reconstructed in the transverse plane by a hardware processor (XFT) [14]. Two opposite-charge particles are required, with reconstructed transverse momenta $p_{T1}, p_{T2} > 2$ 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) [15] combines XFT tracks with SVX hits to measure the impact parameter 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 requirement, $20° < \Delta\phi < 135°$, 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 impact parameter $d_B < 140$ μm and to have travelled a distance $L_T > 200$ 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 [16], 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 final selection, inherited from Ref. [4], was originally devised for the $B_s^0 \to K^-\pi^+$ search, but has proven to be optimal also for detection of the $B_s^0 \to \pi^+\pi^-$ and includes the following criteria: $I_B > 0.525$, $\chi^2 < 5$, $d > 120$ 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, 5]. A $B^0 \to K^+K^-$ signal would appear as an enhancement around 5.18 GeV/c^2, while a $B_s^0 \to \pi^+\pi^-$ signal would peak at the nominal B_s^0 mass of 5.3663 GeV/c^2, where other, more abundant modes, contribute [4]. Backgrounds include mis-reconstructed multi-body b–hadron decays (physics background) and random pairs of charged particles (combinatorial background).

IV. FIT OF COMPOSITION

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

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

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 $f_{\rm p}$.

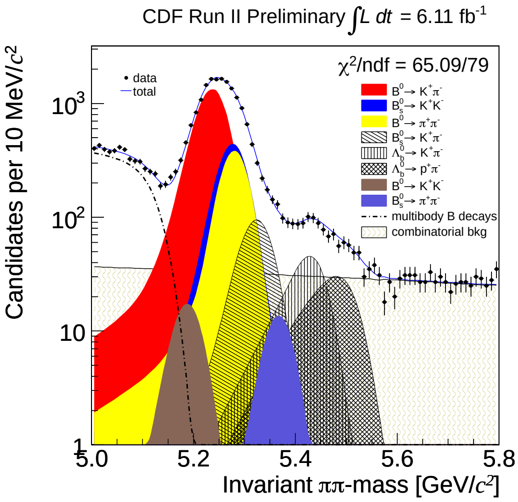

FIG. 1: Mass distribution of reconstructed candidates. The charged pion mass is assigned to both tracks. The total projection and projections of each signal and background component of the likelihood fit are overlaid on the data distribution. Signals and multi-body B background components are shown stacked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

The kinematic information is summarized by three loosely correlated observables: (a) the square mass $m^2_{\pi\pi}$; (b) the charged momentum asymmetry $\beta = (p_+ - p_-)/(p_+ + p_-)$, where p_+ (p_-) is the momentum of the positive(negative) particle; (c) the scalar sum of particle momenta $p_{tot} = p_1 + p_2$. The above variables allow evaluation of the square invariant mass m^2_{12} of a candidate for any mass assignment of the decay products (m_1,m_2), using the equation

$$\begin{aligned} m^2_{12} = m^2_{\pi\pi} - 2m^2_\pi + m^2_1 + m^2_2 + \\ -2\sqrt{p_1^2+m_\pi^2}\sqrt{p_2^2+m_\pi^2} + 2\sqrt{p_1^2+m_1^2}\sqrt{p_2^2+m_2^2}, \qquad (2)\end{aligned}$$

where $p_+ = p_{tot}\frac{1+\beta}{2}$, $p_- = \frac{1-\beta}{2}$.

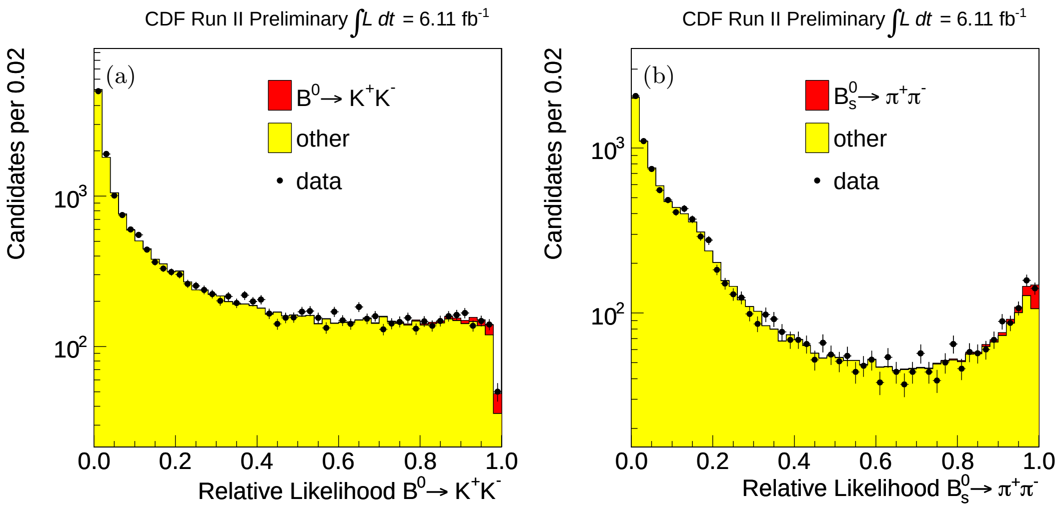

FIG. 2: Distribution of the relative signal likelihood, $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{\rm other})$, in the region $5.10 < m_{\pi\pi} < 5.35$ GeV/c^2 for the $B^0 \to K^+K^-$ and $5.25 < m_{\pi\pi} < 5.50$ GeV/c^2 for the $B_s^0 \to \pi^+\pi^-$. For each event, $\mathcal{L}_S$ is the likelihood for the $B_s^0 \to \pi^+\pi^-$ (a) and $B^0 \to K^+K^-$ (b) signal hypotheses, and $\mathcal{L}_{\rm other}$ 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.

We used data to obtain the kinematic distributions of combinatorial background [18] and simulation for physics backgrounds. The square mass distribution of the combinatorial background is parameterized by an exponential function. The slope is fixed in the fit and it has been extracted from an enriched sample of two generic random tracks, containing events that pass the final selections except for the requirement on the vertex quality, which is inverted to $\chi^2 > 40$. The physics background is modeled by an ARGUS function [19] convoluted with a Gaussian resolution function. The parameters of the ARGUS function are free to vary in the fit. 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. The momentum dependence and non–Gaussian tails of resolution are included from a full simulation of the detector, while the effects of soft photon radiation in the final state is based on PHOTOS package [20]. This resolution model was checked against the observed shape of the 3.2×10^6 $D^0 \to K^-\pi^+$ and 140×10^3 $D^0 \to \pi^+\pi^-$ signals in a sample of $D^{*+} \to D^0\pi^+$ decays, collected with a similar trigger selection. 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 167,000 $\Lambda \to p\pi^-$ decays, where the kinematics and the momentum threshold of the trigger allow unambiguous identification of the decay products [17]. The separation between kaons and pions is about 1.4σ (2.0σ for a pair of particles) while the ionization rates of protons and kaons is quite similar. The combinatorial background model allows for independent contributions of positively and negatively charged pions and kaons, whose fractions are determined by the fit. Protons are incorporated into the kaon component because of the low background level. Electrons contribution has been neglected. Muons are indistinguishable from pions with the available 10% fractional dE/dx resolution and are therefore incorporated into the pion component. The physics background model, instead, allows for independent charge averaged contributions of pions and kaons, whose fractions are determined by the fit.

V. FIT RESULTS

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 a significant signal for the $B_s^0 \to \pi^+\pi^-$ mode (3.7σ). No evidence is found for the $B^0 \to K^+K^-$ mode (2.0σ). Figure 2 shows relative likelihood distributions for these modes.

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. A frequentist interval [22] at the 90% C.L. is

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

Mode	N_s	Significance
$B^0 \to K^+K^-$	$120 \pm 49 \pm 42$	2.0σ
$B_s^0 \to \pi^+\pi^-$	$94 \pm 28 \pm 11$	3.7σ

TABLE II: Measured relative branching fractions of rare modes. 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: $f_s/f_d = 0.282 \pm 0.038$ [21]. The first quoted uncertainty is statistical, the second is systematic.

Mode	Relative $\mathcal{B}$	Absolute $\mathcal{B}$ (10^{-6})	Limit (10^{-6})
$B^0 \to K^+K^-$	$\frac{\mathcal{B}(B^0\to K^-K^+)}{\mathcal{B}(B^0\to K^+\pi^-)} = 0.012 \pm 0.005 \pm 0.005$	$0.23 \pm 0.10 \pm 0.10$	$[0.05, 0.46]$ at 90% C.L.
$B_s^0 \to \pi^+\pi^-$	$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to \pi^-\pi^+)}{\mathcal{B}(B^0\to K^+\pi^-)} = 0.008 \pm 0.002 \pm 0.001$	$0.57 \pm 0.15 \pm 0.10$	–

quoted for the seen $B^0 \to K^+K^-$ mode. The raw fractions returned by the fit were corrected for the differences in selection efficiencies between different modes, which do not exceed 10%. 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 samples of $D^0 \to h^+h'^-$ decays [18]. Corrections to the reconstruction efficiencies have been measured by comparing simulation and data. We fitted from data the raw yields of the $D^0 \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ decay modes. These have been corrected using the CDF simulation to extract the the relative braching fractions $\mathcal{B}(D^0 \to \pi^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ and $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(D^0 \to K^-\pi^+)$. The discrepancy between our estimates and the world averaged values from [21], has been ascribed to the different specific ionization in the COT and it has been used to correct reconstruction efficiencies for the $D^0 \to h^+h'^-$ decays and then for the $B \to h^+h'^-$ decays.

VI. SYSTEMATICS

The dominant contributions to the systematic uncertainty are the uncertainty on the dE/dx calibration and parameterization and the uncertainty on the combinatorial background model. An additional systematic uncertainty, of the order of 10% has been assessed because of a fit bias, found in the estimate of the relative fraction of the $B^0 \to K^+K^-$. Other contributions come from trigger efficiencies, physics background shape and kinematics, b–hadron masses and lifetimes.

VII. FINAL COMMENTS

The final results are listed in Table II. Absolute branching fractions are also quoted, by normalizing to world-average values of production fractions and $\mathcal{B}(B^0 \to K^+\pi^-)$ [21]. The branching fraction measured for the $B_s^0 \to \pi^+\pi^-$ mode is consistent with the previous upper limit ($< 1.2 \times 10^{-6}$ at 90% C.L.), based on a subsample of the current data [4]. This agrees with the prediction in Ref. [9] and in Ref. [24] within the pQCD approach. It is higher than most other predictions [7, 8, 23, 25]. The present measurement of $\mathcal{B}(B^0 \to K^+K^-)$ is the world's best measurement and supersedes the previous limit [3]. The central value is in agreement with other existing measurements [21], and with theoretical predictions [8, 26]

In summary, we have searched for new rare charmless decay modes of neutral b–mesons into pairs of charged mesons in CDF data. We report the first evidence of the $B_s^0 \to \pi^+\pi^-$ and measure its relative branching fraction. We set an 90% confidence interval for the unobserved mode $B^0 \to K^+K^-$.

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