Evidence for the Charmless Annihilation Decay Mode $B_s^0 \to \pi^+\pi^-$

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(Received 1 November 2011; published 23 May 2012)

We search for annihilation decay modes of neutral b mesons into pairs of charmless charged hadrons with the upgraded Collider Detector at the Fermilab Tevatron. Using a data sample corresponding to 6 fb^{-1} of integrated luminosity, we obtain the first evidence for the $B_s^0 \to \pi^+\pi^-$ decay, with a significance of 3.7σ, and a measured branching ratio $\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.57 \pm 0.15(\mathrm{stat}) \pm 0.10(\mathrm{syst})) \times 10^{-6}$. A search for the $B^0 \to K^+K^-$ mode in the same sample yields a significance of 2.0σ, and a central value estimate $\mathcal{B}(B^0 \to K^+K^-) = (0.23 \pm 0.10(\mathrm{stat}) \pm 0.10(\mathrm{syst})) \times 10^{-6}$.

DOI: 10.1103/PhysRevLett.108.211803 PACS numbers: 13.25.Hw, 14.40.Nd

Our understanding of the dynamics of hadrons containing heavy quarks has made great progress in recent years. The development of effective theories has allowed increasingly accurate predictions for the partial decay widths of such hadrons. An ability to make accurate predictions for these processes is not only important in itself, but is a tool to uncover possible additional contributions due to interactions beyond the standard model. In spite of the general progress of the field, a specific class of decay amplitudes (annihilation topologies) has resisted attempts at quantitative prediction up to the present, and is often simply neglected in calculations. Predictions for these amplitudes vary greatly between approaches, and even within the same approach. Estimates based on the QCD factorization (QCDF) approach are affected by significant uncertainties, due to end-point singularities [1,2]. More recent perturbative QCD calculations (pQCD) provide more precise predictions, but they tend to be significantly larger than the predictions coming from QCDF [3,4]. No calculations are yet available within the soft collinear effective theory (SCET) [5]. The lack of knowledge of the size of annihilation-type amplitudes introduces irreducible uncertainties in the predictions for several decays of great interest in the search for new physics effects, such as $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ [6–9]. Experimental investigation of the issue is therefore very desirable, and has the potential to enable a significant advancement of the field. The $B_s^0 \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ decay modes are ideal for this investigation, because all quarks in the final state are different from those in the initial state, so they can be mediated solely by amplitudes with penguin-annihilation (PA) and W-exchange (E) topologies (see Fig. 1).

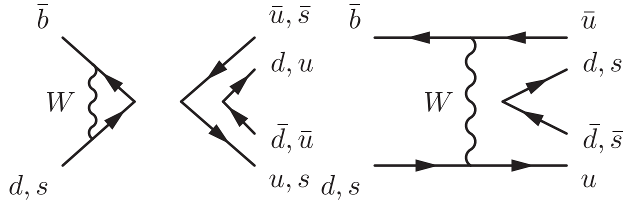

FIG. 1. PA (left panel) and E (right panel) diagrams contributing to $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ decays.

However, they have not yet been observed, the best upper limits at 90% CL being respectively 1.2×10^{-6} [10] and 0.41×10^{-6} [11]. A simultaneous measurement of branching fractions of both modes would be especially useful, as it would allow a better constraint on the strength of PA and E amplitudes [7].

In this Letter we report the results of a simultaneous search for the two decays $B_s^0 \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ [12], using data corresponding to 6 fb^{-1} integrated luminosity of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron.

The CDF II detector is described in detail in Ref. [13] with the detector subsystems relevant for this analysis discussed in Ref. [14]. The data are collected by a three-level online event-selection system (trigger). At level 1, tracks are reconstructed in the transverse plane [15]. 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, tracks are combined with silicon-tracking-detector hits and their impact parameter d (transverse distance of closest approach to the beam line) is determined with 45 μm resolution (including the beam spread) and required to be $0.1 < d < 1.0$ mm. A tighter opening-angle requirement, $20° < \Delta\phi < 135°$, is also applied. 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 traveled a distance $L_T > 200$ μm in the transverse plane. At level 3, a cluster of computers confirms the selection with a full event reconstruction.

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° of freedom) of the decay vertex of the B candidate. Requiring isolated candidates further 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 silicon-tracking detector in the z direction. We use the same final selection originally devised for the $B_s^0 \to K^-\pi^+$ search [10], whose simulation has proven to be nearly optimal also for detection of $B_s^0 \to \pi^+\pi^-$. This includes the following criteria: $I_B > 0.525$, $\chi^2 < 5$, $d >$ 120 μm, $d_B < 60$ μm, and $L_T > 350$ μm.

At most 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. 2, and is 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 [14,17], with backgrounds coming from misreconstructed multibody b-hadron decays (physics background) and random pairs of charged particles (combinatorial background). A $B^0 \to K^+K^-$ signal would appear in this distribution as an enhancement around 5.18 GeV/c^2, while a $B_s^0 \to \pi^+\pi^-$ signal is expected at the nominal B_s^0 mass of 5.3663 GeV/c^2, where other more abundant modes also contribute [10].

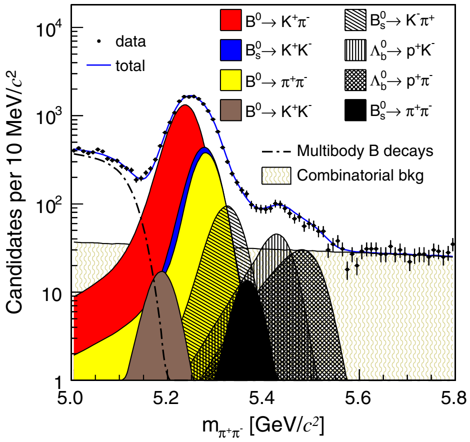

FIG. 2 (color online). Mass distribution of reconstructed candidates. The charged pion mass is assigned to both tracks. The sum of the fitted distributions and the individual components of signal and background are overlaid on the data distribution.

We used an extended unbinned likelihood fit, incorporating kinematic (kin) and particle-identification (PID) information, to determine the fraction of each individual mode in the sample. The likelihood is defined as

$$\mathcal{L} = \frac{\nu^N}{N!} e^{-\nu} \prod_{i=1}^{N} \mathcal{L}_i, \tag{1}$$

where N is the total number of observed candidates, ν is the estimator of N to be determined by the fit, and the likelihood for the ith event is

$$\mathcal{L}_i = (1 - b) \sum_j f_j \mathcal{L}_j^{\text{kin}} \mathcal{L}_j^{\text{PID}} + b(f_{\text{p}} \mathcal{L}_{\text{p}}^{\text{kin}} \mathcal{L}_{\text{p}}^{\text{PID}} + (1 - f_{\text{p}}) \mathcal{L}_{\text{c}}^{\text{kin}} \mathcal{L}_{\text{c}}^{\text{PID}}), \tag{2}$$

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}.

For each charged hadron pair, the kinematic information is summarized by three loosely correlated observables: the squared mass $m^2_{\pi^+\pi^-}$; the charged momentum asymmetry $\beta = (p_+ - p_-)/(p_+ + p_-)$, where p_+ (p_-) is the momentum of the positive (negative) particle; and the scalar sum of particle momenta $p_{\text{tot}} = p_+ + p_-$ [18]. The above variables allow evaluation of the squared invariant mass $m^2_{a^+b^-}$ of a candidate for any mass assignment of the positive and negative decay products (m_{a^+},m_{b^-}), using the equation

$$\begin{aligned} m^2_{a^+b^-} &= m^2_{\pi^+\pi^-} - m^2_{\pi^+} - m^2_{\pi^-} + m^2_{a^+} + m^2_{b^-} \\ &\quad + -2\sqrt{p_+^2 + m^2_{\pi^+}}\sqrt{p_-^2 + m^2_{\pi^-}} \\ &\quad + 2\sqrt{p_+^2 + m^2_{a^+}}\sqrt{p_-^2 + m^2_{b^-}}, \end{aligned} \tag{3}$$

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

The likelihood terms $\mathcal{L}_j^{\mathrm{kin}}$ describe the kinematic distributions of $m^2_{\pi^+\pi^-}$, β, and p_{tot} variables for the physics signals and are obtained from Monte Carlo simulations. The same distributions for the combinatorial background are instead extracted from real data [19], and are inserted into the likelihood through the $\mathcal{L}_{\mathrm{c}}^{\mathrm{kin}}$ term. In particular, the squared-mass distribution of the combinatorial background is parametrized by an exponential function. The slope is fixed in the fit to the value extracted from an enriched sample of two generic random tracks, containing events passing all requirements of final selections except for vertex quality, replaced by an antiselection cut $\chi^2 > 40$, which strongly rejects track pairs originating from a common vertex. The likelihood term $\mathcal{L}_{\mathrm{p}}^{\mathrm{kin}}$ describes the kinematic distributions of the background from partially reconstructed decays of generic B hadrons. The $m^2_{\pi^+\pi^-}$ distribution is, in this case, modeled by an ARGUS function [20] convoluted with a Gaussian resolution, while β and p_{tot} distributions are obtained from Monte Carlo simulation.

The fit has 28 free parameters. A detailed description of the fit and its parameters can be found in Refs. [19,21].

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. Momentum dependence and non-Gaussian resolution tails are accounted for by a full simulation of the detector, while the effects of soft photon radiation in the final state are simulated by PHOTOS [22]. This resolution model was accurately checked against the observed shape of the $3.2 \times 10^6 D^0 \to K^-\pi^+$ and $140 \times 10^3 D^0 \to \pi^+\pi^-$ signals in a sample of $D^{*+} \to D^0\pi^+$ decays, collected with a similar trigger selection. As a result, the systematic uncertainty related to the signal mass shapes is negligible with respect to other 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 $167\,000 \Lambda \to p\pi^-$ decays, where the kinematic properties and the momentum threshold of the trigger allow unambiguous identification of the decay products [21]. PID information is summarized by a single observable κ, defined as:

$$\kappa \equiv \frac{d\mathrm{E}/dx - d\mathrm{E}/dx(\pi)}{d\mathrm{E}/dx(K) - d\mathrm{E}/dx(\pi)}, \tag{4}$$

where $dE/dx(\pi)$ and $dE/dx(K)$ are the expected dE/dx depositions for those particle assignments [18]. The average values of κ expected for pions and kaons are by construction 0 and 1. Statistical separation between kaons and pions is about 1.4σ, while the ionization rates of protons and kaons are quite similar in the momentum range of interest. The PID likelihood term, which is similar for physics signals and backgrounds, depends only on κ and on its expectation value $\langle\kappa\rangle$ (given a mass hypothesis) of the decay products. In particular the physics signals model is described by the likelihood term $\mathcal{L}_j^{\mathrm{PID}}$, where the index j uniquely identifies the final state, while the background model is described by the two terms $\mathcal{L}_{\mathrm{p}}^{\mathrm{PID}}$ and $\mathcal{L}_{\mathrm{c}}^{\mathrm{PID}}$, respectively, for the physics and combinatorial background, that account for all possible pairs that can be formed combining only pions and kaons. In fact muons are indistinguishable from pions with the available dE/dx resolution, and are therefore included within the nominal pion component. For similar reasons, the small proton component in the background has been included within the nominal kaon component. Thus the physics background model allows for independent, charge-averaged contributions of pions and kaons, whose fractions are determined by the fit; while the combinatorial background model, instead, allows for more contributions, since independent fractions of positively and negatively charged pions and kaons are determined by the fit.

The signal fractions returned by the fit are in agreement with those obtained in the previous iteration of this analysis [10]. The yields for the $B_s^0 \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ modes, obtained from those fractions, are shown in Table I. The significance is evaluated as the ratio of the yield observed in data to its total uncertainty (statistical and systematic uncertainties added in quadrature), where the statistical uncertainty is 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 than the purely statistical estimate obtained from $\sqrt{-2\Delta\ln(\mathcal{L})}$.

We obtain a 3.7σ significant signal for the $B_s^0 \to \pi^+\pi^-$ mode, and we observe an excess at the 2.0σ level for the $B^0 \to K^+K^-$ mode. As a check on the method, Fig. 3 shows relative likelihood distributions for these modes, which are in good agreement with our model [18].

As a further check an alternate fit was performed, using kinematic information only. Removal of dE/dx information leads to results in agreement with the main fit, but with

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

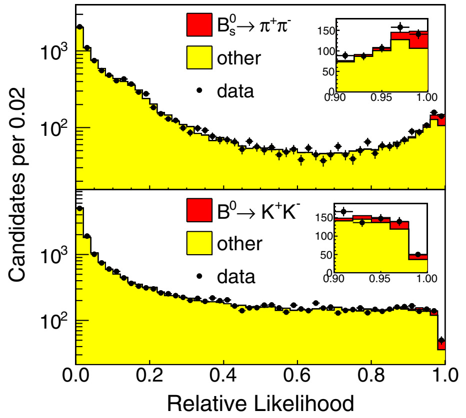

FIG. 3 (color online). Distribution of the relative signal likelihood, $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{\text{other}})$, in the region $5.25 < m_{\pi^+\pi^-} < 5.50$ GeV$/c^2$ for $B_s^0 \to \pi^+\pi^-$ and $5.10 < m_{\pi^+\pi^-} < 5.35$ GeV$/c^2$ for $B^0 \to K^+K^-$. For each event, $\mathcal{L}_S$ is the likelihood for the $B_s^0 \to \pi^+\pi^-$ (top panel) and $B^0 \to K^+K^-$ (bottom panel) 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. Zoom of the region of interest is shown in the inset.

a loss in resolution of a factor 2 for $B_s^0 \to \pi^+\pi^-$ and 3 for $B^0 \to K^+K^-$, confirming the importance of this information.

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 limit [23] at the 90% C.L. is quoted for the $B^0 \to K^+K^-$ mode. The raw fractions returned by the fit are corrected for the differences in selection efficiencies among different modes, which do not exceed 10%. These corrections are determined from detailed detector simulation, with only two exceptions that are measured from data: the momentum-averaged relative isolation efficiency between B_s^0 and B^0, and the difference in efficiency for triggering on kaons and pions due to the different specific ionization in the drift chamber. The former is determined as 1.00 ± 0.03 from fully-reconstructed samples of $B_s^0 \to J/\psi\phi$, and $B^0 \to J/\psi K^{*0}$ decays [21]. The latter is determined from samples of D^0 mesons decaying into pairs of charged hadrons [19]. We measure the relative branching 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 numbers of events are extracted from the available samples of tagged $D^0 \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ decays, fitting the invariant $D^*\pi$ mass spectrum [19], while reconstruction efficiencies are determined from the same simulation used for the measurements described in this Letter. Comparison of these numbers with world measurement averages [24] allows us to extract the correction needed to compensate for the different efficiency of the tracking trigger for kaons and pions. The final corrections applied to our result do not exceed 5% and are independent of particle momentum.

The dominant contribution to the systematic uncertainty on both branching fractions is due to the dE/dx model, which derives from the statistical uncertainty on the 48 parameters used for the analytical description of the correlated dE/dx response of the two decay products [21]. This uncertainty is evaluated by repeating the likelihood fit 200 times with different sets of those parameters, randomly extracted from a multidimensional sphere, centered on the central value of the parametrization, with a radius corresponding to 1σ of statistical uncertainty. The correlations between the parameters are neglected because their total effect, known from Ref. [25], where they have been accounted for in detail, brings a reduction of the final systematic uncertainty because most correlations are negative. The dE/dx-induced systematic uncertainty on each observable is then obtained as the standard deviation of the distribution of that observable, over the ensemble of likelihood fits performed with different sets of parameters. This approach is adequate for our purposes since the statistical uncertainty is greater than or of the same order of the systematic uncertainty.

The second dominant contribution to the systematic uncertainty for $B_s^0 \to \pi^+\pi^-$ comes from the uncertainty on the relative efficiency correction, while for $B^0 \to K^+K^-$ it comes from the uncertainty in the background model, which includes a sizeable component of partially reconstructed decays with poorly known branching fractions. The latter systematic uncertainty is conservatively assessed by performing extreme variations of the assumed relative contributions of the various modes in the simulation; the resulting uncertainty is still a factor of 2 lower than the uncertainty associated to the dE/dx model.

Other contributions come from trigger efficiencies, b-hadron masses, b-hadron lifetimes and $\Delta\Gamma_s/\Gamma_s$, and transverse momentum distribution of the Λ_b^0 baryon. A further systematic uncertainty of the order of 10% is

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: $f_s/f_d = 0.282 \pm 0.038$ [24]. 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.
$B_s^0 \to \pi^+\pi^-$	$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to \pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)} = 0.008 \pm 0.002 \pm 0.001$	$0.57 \pm 0.15 \pm 0.10$	-

included for the $B^0 \to K^+K^-$ mode to account for a small bias of the fitting procedure observed in simulated samples.

The final results are listed in Table II. Absolute branching fractions are also quoted, by normalizing to world-average values of production fractions and $\mathcal{B}(B^0 \to K^+\pi^-)$ [24]. The branching fraction measured for the $B_s^0 \to \pi^+\pi^-$ mode is consistent with and supersedes the previous upper limit ($< 1.2 \times 10^{-6}$ at 90% C.L.), based on a subsample of the current data [10]. It is in agreement with predictions obtained with the pQCD approach [3,4], but it is higher than most other theoretical predictions [1,2,26]. The central value for $\mathcal{B}(B^0 \to K^+K^-)$ is the most precise determination of this quantity to date, and is in agreement with previous experimental results [11,27] and theoretical predictions [1,2]. It supersedes the previous CDF limit [10], based on a subsample of the current data. The present measurements represent a significant step in reducing a source of uncertainty in many theoretical predictions for charmless B-decays. The results favor a large annihilation scenario, which is somewhat unexpected for instance in QCDF [28].

In summary, we have searched in CDF data for as-yet-unmeasured charmless decay modes of neutral b mesons into pairs of charged mesons. We report an updated upper limit for the $B^0 \to K^+K^-$ mode and the first evidence for the $B_s^0 \to \pi^+\pi^-$ mode and a measurement of its branching fraction.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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[16] Isolation is defined as $I_B = p_T(B)/[p_T(B) + \sum_i p_{Ti}]$, where $p_T(B)$ is the transverse momentum of the B candidate, and the sum runs over all other tracks within a cone of radius 1, in η-ϕ space around the B flight-direction.

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