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Evidence for the Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{CP}/\Gamma_s$

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Evidence for the Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{CP}/\Gamma_s$

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We search for the semi-inclusive process $B_s^0 \to D_s^{(*)} D_s^{(*)}$ using 2.8 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the D0 detector operating at the Fermilab Tevatron Collider. We observe 26.6 ± 8.4 signal events with a significance above background of 3.2 standard deviations yielding a branching ratio of $\mathcal{B}(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$. Under certain theoretical assumptions, these double-charm final states saturate CP-even eigenstates in the B_s^0 decays resulting in a width difference of $\Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.})$.

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The phenomenon of CP violation is believed to be intimately tied to explaining the matter dominance in the present-day Universe [1]. CP violation is expected to occur in the evolution of neutral particles that can mix between different eigenbases. For the B_s^0 system, the flavor eigenstates can be decomposed into heavy (H) and light (L) states based on mass or into even and odd states based on CP. The width differences between these eigenstates are defined by $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Delta\Gamma_s^{CP} = \Gamma_s^{\text{even}} - \Gamma_s^{\text{odd}}$, respectively. These two quantities are connected with the possible presence of new physics (NP) by $\Delta\Gamma_s = \Delta\Gamma_s^{CP}\cos\phi_s$, where ϕ_s is the CP violating mixing phase which constrains models of NP.

In the standard model (SM) a mixing parameter Γ_{12}, determining the size of the width difference between CP eigenstates, stems from the decays into final states common to both B and $\bar{B}$. Since this quantity is dominated by Cabibbo-Kobayashi-Maskawa (CKM)-favored tree-level decays, it is practically insensitive to NP. Because of the hierarchy of the quark mixing matrix [2], the width difference is governed by the partial widths of B_s^0 decays into final CP eigenstates through the $b \to c\bar{c}s$ quark-level transition, such as $B_s^0 \to D_s^+ D_s^-$ or $B_s^0 \to J/\psi\phi$. Topologically, the former type of decay mode is a color-allowed spectator, while the latter type is suppressed by the effective color factor. Thus, the semi-inclusive decay modes $B_s^0 \to D_s^{(*)} D_s^{(*)}$, where $D_s^{(*)}$ denotes either $D_s^\pm$ or $D_s^{\pm *}$, are interesting because they give the largest contribution to the difference between the widths of the heavy and light states. The other decay modes are estimated to contribute less than 0.01 to the projected ~0.15 value of $\Delta\Gamma_s/\Gamma_s$ [3], where $\Gamma_s(= 1/\tau_s) \equiv (\Gamma_L + \Gamma_H)/2$.

In the Shifman-Voloshin (SV) limit [4], given by $m_b - 2m_c \to 0$ with $N_c \to \infty$ (where N_c is the number of colors), $\Delta\Gamma_s^{CP}$ is saturated by $\Gamma(B_s^0 \to D_s^{(*)} D_s^{(*)})$. Then the width difference can be related to the branching ratio of B_s^0 mesons to this inclusive double-charm final state by [5,6]

$$2\mathcal{B}(B_s \to D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP}\left[\frac{\frac{1}{1-2x_f} + \cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f} - \cos\phi_s}{2\Gamma_H}\right], \quad (1)$$

where x_f is the fraction of the CP-odd component of the decay $\Gamma_s^{\text{odd}}/\Gamma_s^{\text{even}} = x_f/(1 - x_f)$. Therefore, given the CP structure of the final state, $\Delta\Gamma_s^{CP}$ can be measured using the information from branching ratios without lifetime fits. The irreducible theoretical uncertainty of this approach stems from the omission of CKM-suppressed decays through the $b \to u\bar{u}s$ transition which is of order $2|V_{ub}V_{us}/V_{cb}V_{cs}| \sim 3\%$–$5\%$.

In this Letter, we report the first evidence for the decay $B_s^0 \to D_s^{(*)} D_s^{(*)}$. The study uses a data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of 2.8 fb^{-1} recorded by the D0 detector operating at the Fermilab Tevatron Collider during 2002–2007. This supersedes our previous study of the same final state based on 1.3 fb^{-1} [7]. A similar study based on events containing two ϕ mesons has been reported by the ALEPH Collaboration at the CERN LEP Collider [8].

This analysis considers the B_s^0 decay into two $D_s^{(*)}$ mesons. No attempt is made to identify the photon or π^0 emanating from the D_s^* decay. We search for one hadronic D_s decay to $\phi\pi$ and one semileptonic D_s decay to $\phi\mu\nu$, where both ϕ mesons decay to K^+K^-. The branching fraction is extracted by normalizing the $B_s^0 \to D_s^{(*)} D_s^{(*)}$ decay to the $B_s^0 \to D_s^{(*)}\mu\nu$ decay.

D0 is a general purpose detector [9] consisting of a central tracking system, uranium/liquid-argon calorimeters, and an iron toroid muon spectrometer. The central tracking system allows charged particles to be reconstructed. This system is composed of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT) embedded in a 2 T solenoidal magnetic field. Muons are identified and reconstructed with a magnetic spectrometer located outside of the calorimeter. The spectrometer contains magnetized iron toroids and three superlayers of proportional drift tubes along with scintillation trigger counters. Information from the muon and tracking systems is used to form muon triggers. For the events used by this analysis, the muon from the semileptonic D_s decay satisfies the inclusive single-muon triggers.

Muons are identified by requiring segments reconstructed in at least two out of the three superlayers in the muon system and associated with a trajectory reconstructed with hits in both the SMT and the CFT. We select muon candidates with transverse momentum $p_T > 2.0$ GeV/c and total momentum $p > 3.0$ GeV/c.

ϕ mesons are formed from two opposite sign charged particles with $p_T > 0.7$ GeV/c in the event assuming a kaon mass hypothesis. We require at least one kaon to have an impact parameter clearly separated from the $p\bar{p}$ interaction point (primary vertex) with at a minimum 4 standard deviations significance. The two-kaon systems

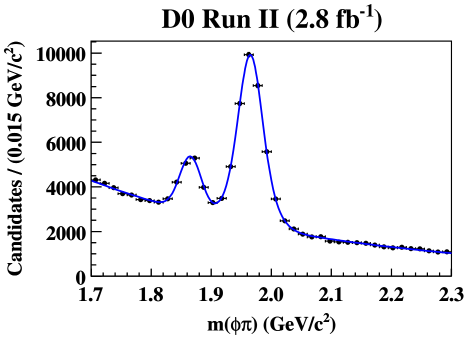

FIG. 1 (color online). Invariant mass distribution of the $\phi\pi$ system for the $B_s^0 \to D_s^{(*)}\mu\nu$ sample. The two peaks correspond to the $D^\pm$ candidates (lower masses) and D_s candidates (higher masses).

satisfying $p_T(KK) > 2.0$ GeV$/c$ and $1.010 < m(KK) < 1.030$ GeV$/c^2$ are selected as ϕ candidates.

The hadronic D_s meson is reconstructed by combining the ϕ candidate with a third track with $p_T > 0.5$ GeV$/c$ which is assigned the pion mass. The pion is required to have charge opposite to that of the muon. The three particles must form a well reconstructed vertex displaced from the primary vertex [10]. We require the cosine of the angle between the D_s momentum and the direction from the primary vertex to the D_s vertex to be greater than 0.9. For the signal decay chain of a pseudoscalar to a vector plus pseudoscalar, followed by the decay of the vector to two pseudoscalars, $\cos\theta_\phi$ is distributed quadratically, where θ_ϕ is the decay angle of a kaon in the ϕ rest frame with respect to the direction of the D_s meson, and hence a constraint $|\cos\theta_\phi| > 0.3$ is imposed.

The $B_s^0 \to D_s^{(*)}\mu\nu$ decay vertex is reconstructed based on the momentum and direction of the reconstructed hadronic D_s candidate and its intersection with the track of an oppositely charged muon. This vertex is required to be located between the primary vertex and the D_s vertex, whereby the individual B_s and D_s vertex displacements are consistent with a $p\bar{p} \to B_s \to D_s$ decay chain. The invariant mass of the B_s^0 candidate is required to be less than 5.2 GeV$/c^2$. We require the daughter particles of the B_s^0 meson to be well isolated from other tracks. Background is further suppressed using a likelihood ratio technique [11] that combines information from the invariant masses and momenta of the reconstructed particles, vertex quality, and the ϕ helicity angle.

The $\phi\pi$ invariant mass distribution for $B_s^0 \to D_s^{(*)}\mu\nu$ candidates is shown in Fig. 1. Maxima corresponding to the $D_s \to \phi\pi$ decay and the $D^\pm \to \phi\pi$ decay are clearly observed. The D_s signal originates from ~90% semileptonic B_s^0 decays and ~10% decays of the type $B \to D_sD$ followed by semileptonic D decay. These fractions are determined from Monte Carlo (MC) simulation using the known or estimated branching fractions from the Particle Data Group (PDG) [12] or EVTGEN [13]. Approximately 2% of the events are due to direct charm production $p\bar{p} \to DD$, determined by using full simulation and reconstruction of DD^* candidates. The overall sample composition is verified using studies of the B lifetime and mixing parameters [14,15].

For the second ϕ candidate, we search for an additional pair of oppositely charged particles in the event imposing the same criteria as for the first ϕ meson. The two kaon tracks are combined with the muon track to produce a common vertex for the semileptonic D_s candidate. We require the D_s candidate to originate from a common vertex to the hadronic D_s candidate to complete the $B_s^0 \to D_s^{(*)}D_s^{(*)}$ decay. This approach is justified since the average transverse decay length of the D_s meson relative to the B_s^0 meson decay vertex is ~1.0 mm with an uncertainty of ~0.6 mm. By applying the same selection criteria as in the normalization $B_s^0 \to D_s^{(*)}\mu\nu$ decay sample, many detector related systematic effects cancel. The total invariant mass is required to lie between 4.30 and 5.20 GeV$/c^2$.

Correlated production of this double-charm decay, where both D_s mesons originate from the same parent B_s^0 meson, is then determined by examining the two-dimensional distribution of $m(\phi\pi)$ from hadronic D_s candidates versus $m(KK)$ from semileptonic candidates. We perform a maximum likelihood fit to this distribution with four components: The correlated D_sD_s component is modeled as the product of signal terms in both dimensions, the uncorrelated components are modeled as the product of the signal term in one dimension and the background term in the other dimension, and the background correlation is modeled as the combination of the background terms in both dimensions. Signal and background models are expected to be identical with those for the $B_s^0 \to D_s^{(*)}\mu\nu$ sample, from which the parameters of the signal models are determined. Projections of the two-dimensional likelihood fit onto both axes are displayed in Fig. 2. The fit returns a yield of 31.0 ± 9.4 correlated events.

Three possible sources of background are considered in the correlated sample. Direct charm production from $p\bar{p}$ is

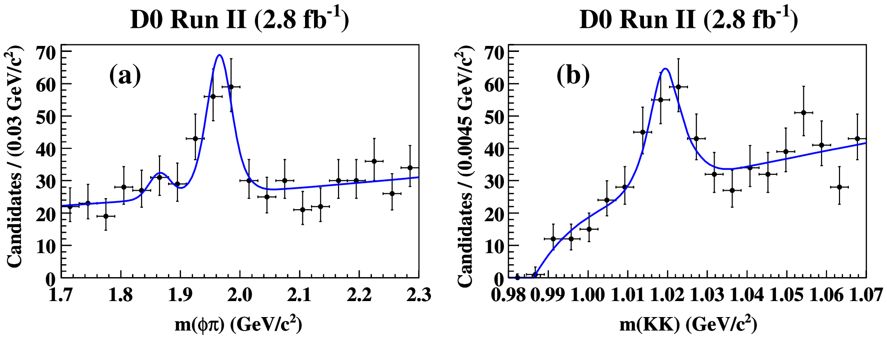

FIG. 2 (color online). Projections of the two-dimensional maximum likelihood fit onto invariant mass spectra of the (a) $\phi\pi$ system from hadronic D_s decays and (b) KK system from semileptonic D_s decays. The peaks in both distributions are explored to search for the correlation between the two systems.

estimated based on the fraction of prompt charm measured directly in the inclusive $D_s^{(*)}\mu\nu$ sample [$(10.3 \pm 2.5)\%$] along with the decay fraction of the second charm quark to a D_s meson and the reconstruction efficiency for this decay. Because of a shorter decay length of the charm decay, the lifetime requirement reduces its contribution significantly leading to an estimate of $(1.9 \pm 0.5)\%$.

The second background source arises from the semileptonic $B_s^0 \to D_s^{(*)}\phi\mu\nu$ decay. This can be extracted by studying the $m(\phi\mu)$ spectrum. In this variable, $B_s^0 \to D_s^{(*)}D_s^{(*)}$ events tend towards lower values, while $B_s^0 \to D_s^{(*)}\phi\mu\nu$ events tend towards higher values.

The third source consists of $B^{\pm,0} \to D_s^{(*)}D_s^{(*)}KX$ events. This background can be extracted by studying the visible mass of all reconstructed daughter particles $m(D_s\phi\mu)$. The mass tends to have higher values for $B_s^0 \to D_s^{(*)}D_s^{(*)}$ than for $B^{\pm,0} \to D_s^{(*)}D_s^{(*)}KX$.

These backgrounds are estimated with MC samples by repeating the fit in three separate regions chosen so that mainly one source contributes to each region in the $m(\phi\mu) - m(D_s\phi\mu)$ plane. The separate components, the signal and the two latter backgrounds, are then extracted based on the expected distribution over the three regions of the three components. We find a signal yield of 26.6 ± 8.4 events originating from the $B_s^0 \to D_s^{(*)}D_s^{(*)}$ process after subtracting the correlated background events.

The signal is normalized to the total $B_s^0 \to D_s^{(*)}\mu\nu$ yield taking into account the composition of the sample as discussed earlier. The reconstruction efficiency ratio between the two samples is estimated from MC calculations to be 0.082 ± 0.015. This small value results from the softer muon momentum spectrum in charm decays as compared to bottom decays. The systematic uncertainty in the ratio contains uncertainties from the modeling of the B_s^0 momentum spectrum, the decay form factors and sample composition, and the trigger and reconstruction efficiencies. Our efficiency model is verified by comparing the expected and measured D_s yield and the relative $B_s^0 \to D_s^{(*)}D_s^{(*)}$ to $B_s^0 \to D_s^{(*)}\mu\nu$ yields as a function of muon p_T.

Using all of the above inputs, the branching ratio is measured as

$$\mathcal{B}(B_s^0 \to D_s^{(*)}D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.008(\text{exp.syst.}) \pm 0.007(\text{ext.}),$$

where the "ext." uncertainty arises from the external input branching ratios taken from the PDG [12]. This uncertainty contributes $\sim 45\%$ to the total systematic uncertainty (exp.syst. $\oplus$ ext.), which leaves room for further improvements in the result. The experimental systematic uncertainty accounts for the rest of the total systematic uncertainty, containing a 37% component from the reconstruction efficiency ratio, 11% from the background estimation, and 4% from the fitting procedure. All other uncertainties are $\leq 1\%$.

The probability that the total background would fluctuate to the measured event yield or higher is evaluated to be 1.2×10^{-3} through pseudoexperiments including systematic uncertainties. This corresponds to a significance of 3.2 standard deviations.

Information on the mixing-induced *CP* asymmetry in the B_s^0 system can be extracted from the branching fraction measurement through Eq. (1). Since the *CP* structure of the decay is presently not accessible in either theory or experiment, several scenarios for different x_f values can be considered. In the heavy quark hypothesis [3] along with the SV limit, the *CP*-odd component of the decay vanishes, leaving the inclusive final state to be *CP*-even, i.e., $x_f = 0$, with a theoretical uncertainty of $\sim 5\%$ [16]. This scenario is illustrated in Fig. 3, presenting the constraint in the $\Delta\Gamma_s - \phi_s$ plane from this measurement assuming the relation $\Delta\Gamma_s = \Delta\Gamma_s^{CP}\cos\phi_s$. Confidence-level (C.L.) contours from the flavor-tagged decay $B_s^0 \to J/\psi\phi$ at D0 [17] are superimposed. We take the mean lifetime of B_s^0 meson from Ref. [12].

Furthermore, within the SM framework, the mass eigenstates coincide with the *CP* eigenstates, and the expression used in the previous studies [7,8] is recovered. Our measurement gives

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \simeq \frac{2\mathcal{B}(B_s^0 \to D_s^{(*)}D_s^{(*)})}{1 - \mathcal{B}(B_s^0 \to D_s^{(*)}D_s^{(*)})} = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.}).$$

This result is consistent with the SM prediction [18] as well

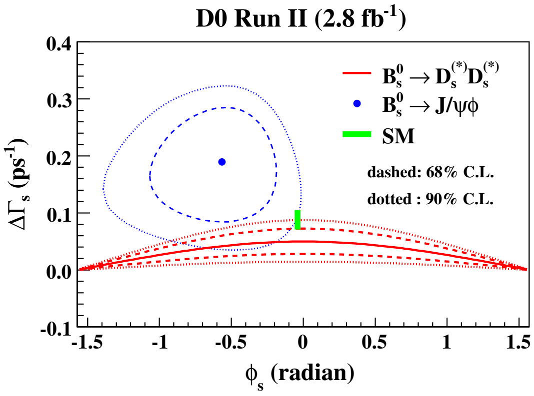

FIG. 3 (color online). Constraints in the $\Delta\Gamma_s - \phi_s$ plane. The solid line represents our measurement under the theoretical assumptions stated in the text and with $x_f = 0$. Two pairs of lines are 68% (dashed) and 90% (dotted) C.L. intervals of $\Delta\Gamma_s$ for a given assumed value of ϕ_s. Contours from the $B_s^0 \to J/\psi\phi$ decay are the equivalent C.L. regions of ($\Delta\Gamma_s$, ϕ_s) when measuring simultaneously both parameters. No theoretical uncertainties are reflected in the plot. The SM prediction is represented by the thick vertical line.

as with the current world average value [16]. Therefore, if the *CP* structure of the final state can be disentangled and the theoretical errors can be controlled, this approach can provide a powerful constraint on mixing and *CP* violation in the B_s^0 system.

In summary, we performed a study of B_s^0 decays into the semi-inclusive double-charm final state using an integrated luminosity of 2.8 fb^{-1} at the D0 experiment. We see evidence of this process and measure the branching ratio as $\mathcal{B}(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$. Based on this measurement and under certain theoretical assumptions, mixing and *CP* violation information in the B_s^0 meson system are extracted. This is the first single measurement that demonstrates a nonzero width difference in the B_s^0 system at greater than 3σ significance. In particular, in the absence of NP, the fractional width difference is derived as $\Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(\mathrm{stat.}) \pm 0.022(\mathrm{syst.})$.

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