Updated Measurement of $B(B_s \to D_s^{(*)} \to \phi \pi^0)$ and Determination of $\Delta \Gamma_s$

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Using fully reconstructed $B_s$ mesons, we measure exclusive branching fractions for the decays $B_s \to D_s^{(*)} \to \phi \pi^0$. The results are $B(B_s^0 \to D_s^{(*)} \to \phi \pi^0) = (0.58^{+0.11}_{-0.09} \pm 0.13\%)$, $B(B_s^0 \to D_s^{(*)} \to \phi \pi^0) = (1.8 \pm 0.2 \pm 0.4\%)$, and $B(B_s^0 \to D_s^{(*)} \to \phi \pi^0) = (2.0 \pm 0.3 \pm 0.5\%)$; the sum is $B(B_s^0 \to D_s^{(*)} \to \phi \pi^0) = (4.3 \pm 0.4 \pm 1.0\%)$. Assuming these decay modes saturate decays to CP-even final states, the branching fraction determines the relative width difference between the $B_s$ CP-odd and CP-even eigenstates. Taking CP violation to be negligible small, we obtain $\Delta \Gamma_s / \Gamma_s = 0.090 \pm 0.009 \pm 0.022$ (syst.), where $\Gamma_s$ is the mean decay width. The results are based on a data sample collected with the Belle detector at the KEKB $e^+e^-$ collider running at the $\Upsilon(5S)$ resonance with an integrated luminosity of 121.4 fb$^{-1}$.

1. Introduction

An $e^+e^-$ collider running at a center-of-mass (CM) energy corresponding to the $\Upsilon(5S)$ resonance can produce significant amounts of $B_s^{(*)} \bar{B}_s^{(*)}$ pairs [1, 2]. The Belle detector [3] at the KEKB asymmetric-energy $e^+e^-$ collider [4] has collected a data sample corresponding to an integrated luminosity of 121.4 fb$^{-1}$ at the $\Upsilon(5S)$ resonance ($\sqrt{s} = 10.87$ GeV). This sample has allowed us to make the most precise measurement of the branching fractions of $B_s^0 \to D_s^{(*)} \to \phi \pi^0$ decays [5]. These Cabibbo-favored final states are expected to be predominantly CP-even [6] and dominate the difference in decay widths $\Delta \Gamma_s^CP$ between the two $B_s-\bar{B}_s$ CP eigenstates [6]. We report preliminary results of the updated branching fraction measurements, which replace our previous measurement based on 23.6 fb$^{-1}$ of data [7].

2. Event Selection

The Belle detector consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprising of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. For charged hadron identification, a likelihood ratio is formed based on a dE/dx measurement in the CDC and the response of the ACC and TOF. Only good quality charged tracks originating from near the $e^+e^-$ interaction point are accepted. For charged kaon tracks, this likelihood ratio is required to be $>0.60$; the tracks not satisfying this requirement are identified as pions. The kaon likelihood requirement is $\sim 90\%$ efficient and has a $\pi^\pm$ misidentification rate of $\sim 10\%$. With the exception of the tracks originating from $K_s^0$ decays, low-momentum charged tracks with $P < 100$ MeV/c are rejected. Neutral $K_s^0$ candidates are reconstructed from $\pi^+\pi^-$ pairs having an invariant mass within 10 MeV/c$^2$ of the nominal $K_s^0$ mass [8] and satisfying momentum-dependent requirements based on the decay vertex position [9].

Neutral $\pi^0$ candidates are reconstructed from $\gamma\gamma$ pairs having an invariant mass within 15 MeV/c$^2$ of the $\pi^0$ mass with each photon having a laboratory energy greater than 100 MeV. Neutral and charged $K^*$ candidates are reconstructed from a $K$ and $\pi^+$ having an invariant mass within 50 MeV/c$^2$ of $M_{K^*}$. Neutral $\phi$ candidates are reconstructed from $K^+K^-$ pairs having an invariant mass within 12 MeV/c$^2$ of $M_\phi$. Charged $\rho^+$ candidates are reconstructed from $\pi^+\pi^0$ pairs having an invariant mass within 100 MeV/c$^2$ of $M_{\rho^+}$.

We reconstruct $D_s^+$ candidates using six final states: $\phi\pi^+$, $K_s^0 K^+$, $\overline{K}^0 K^+$, $\phi\rho^+$, $K_s^0 K^{*+}$, and $\overline{K}^0 K^{*+}$. The invariant mass windows used are 10 MeV/c$^2$ ($\sim 3\sigma$) for the three final states containing $K$ candidates, 20 MeV/c$^2$ (2.8$\sigma$) for $\phi\rho^+$, and 15 MeV/c$^2$ ($\sim 4\sigma$) for the remaining two modes. For the three vector-pseudoscalar final states, we require $|\cos \theta_{hel}| > 0.20$, where the helicity angle $\theta_{hel}$ is the angle between the momentum of the charged daughter of the vector particle and the direction opposite the $D_s$ momentum, in the rest frame of the vector particle.

We combine $D_s^+$ candidates with photon candidates to reconstruct $D_s^{(*)} \to D_s^+ \gamma$ decays, and we require that the mass difference $M_{D_s^{(*)} \gamma} - M_{D_s^+}$ be within 12.0 MeV/c$^2$ of the nominal value (143.8 MeV/c$^2$), where $D_s^+$ denotes the reconstructed $D_s^+$ candidate. This requirement (and that for the $D_s^{(*)}$ mass) is determined by optimizing a figure-of-merit $S/\sqrt{S+B}$, where $S$ is the expected signal based on Monte Carlo (MC) simulation and $B$ is the expected background as estimated from $D_s^+$ sideband data. We require that the photon energy in
the CM system be greater than 50 MeV, and that the energy deposited in the central 3 × 3 array of cells of the ECL cluster contain at least 85% of the energy deposited in the central 5 × 5 array of cells.

We select $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ decays using two quantities evaluated in the $e^+e^-$ CM frame: the beam-energy-constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$, and the energy difference $\Delta E = E_B - E_{\text{beam}}$, where $p_B$ and $E_B$ are the reconstructed momentum and energy of the $B_s^0$ candidate, and $E_{\text{beam}}$ is the beam energy. We determine our signal yields by fitting events in the region $5.25$ GeV$/c^2 < M_{bc} < 5.45$ GeV$/c^2$ and $-0.15$ GeV $< \Delta E < 0.10$ GeV. Within this region, the modes $\Upsilon(5S) \to B_s^0\bar{B}_s^0$, $B_s^0\bar{B}_s^0$ and $B_s^0\bar{B}_s^0$ are well-separated as the $\gamma$ from $B_s^0 \to B_s^0\gamma$ decay is not reconstructed. We expect only small amounts of signal in $B_s^0\bar{B}_s^0$ and $B_s^0\bar{B}_s^0$ and thus do not use these modes for the branching fraction measurement. In order to simplify the fit, we fix their relative ratios, which are difficult to calculate accurately from MC simulation. The fractions of CF-up events are taken from MC simulation. The fractions of CF-up events are taken from MC simulation. We use a single PDF for background which consists of $B_s^0\to D_s^{(*)+}D_s^{(*)-}$ and $B_s^0\to D_s^{(*)+}D_s^{(*)-}$ candidates reconstructed in an event, we select the candidate that minimizes the quantity

$$\chi^2 = \frac{1}{(2+N)} \left\{ \sum_{#D_s} \frac{\left( \bar{M}_{D_s} - M_{D_s} \right)^2}{\sigma_M} + \sum_{#D_s} \frac{(\Delta M - \Delta M)^2}{\sigma_{\Delta M}} \right\},$$

where $\Delta M = M_{D_s} - M_{D_s}$, the quantities $\bar{M}_{D_s}$ and $\Delta M$ are reconstructed, and the summations run over the two $D_s^{(*)}$ daughters and the possible $D_s^{(*)}$ daughters ($N = 0, 1, 2$) of a $B_s^0$ candidate. The mean mass $M_{D_s}$ and widths $\sigma_M$ and $\sigma_{\Delta M}$ are obtained from MC simulation and calibrated for any data-MC difference using a $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ sample in 563 fb$^{-1}$ of data at the $\Upsilon(4S)$ energy. Approximately half of the events have multiple candidates according to MC simulation, and this criterion selects the correct $B_s^0$ candidate 83%, 73%, and 69% of the time for $D_s^{(*)+}D_s^{(*)-}$, $D_s^{(*)+}D_s^{(*)-}$, and $D_s^{(*)+}D_s^{(*)-}$ final states, respectively.

The background from $e^+e^-\to q\bar{q}$ ($q = u, d, s, c$) continuum events is rejected using a Fisher discriminant based on a set of modified Fox-Wolfram moments [10]. This discriminant distinguishes jet-like $q\bar{q}$ events from more spherical $B_s^0\bar{B}_s^0$ events, and is used to calculate a likelihood $L_s(L_{q\bar{q}})$ for an event assuming the event is signal ($q\bar{q}$ background). We require the ratio $R = L_s/(L_s + L_{q\bar{q}})$ to be $> 0.20$. This selection is 93% efficient for signal and removes > 62% of $q\bar{q}$ background. The majority of the background consists of $\Upsilon(5S) \to B_s^0\bar{B}_s^0\to D_s^{(*)+}X$; $\Upsilon(5S) \to BBX$ (where $b\bar{b}$ hadronizes into $B^0$, $\bar{B}_s^0$, or $B^\pm$); and $B_s^0 \to D_{sJ}(2317)D_{sJ}(2600)D_{sJ}(2460)$, $B_s^0 \to D_s^{(*)+}(2460)D_s^{(*)-}$, and $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ final states. The last three processes peak at negative values of $\Delta E$, and their yields are expected to be very small assuming their branching fractions are similar to analogous $B_s^0\to D_{sJ}D_{sJ}$ decays.

Signal yields are measured using a two-dimensional extended unbinned maximum-likelihood fit to the $M_{bc}-\Delta E$ distributions. For each signal decay, we include probability density functions (PDFs) for signal and background. We use a single PDF for background which consists of $q\bar{q}$, $B_s^0\to D_{sJ}(2317)D_{sJ}(2600)$, and $\Upsilon(5S) \to BBX$ events. The background PDF is constructed using an ARGUS function [11] for $M_{bc}$ and a second-order Chebyshev polynomial for $\Delta E$. The two parameters of the Chebyshev function are taken from the data in which one of the $D_s$ “candidates” is required to be within the mass sideband. The signal PDFs have three components: correctly reconstructed (CR) decays; “wrong combination” (WC) decays in which a non-signal track or photon is included in place of a true signal track or photon; and “cross-feed” (CF) decays in which a $D_s^{(*)+}D_s^{(*)-}$ or $D_s^{(*)+}D_s^{(*)-}$ is reconstructed as a $D_s^{(*)+}D_s^{(*)-}$ or $D_s^{(*)+}D_s^{(*)-}$, respectively, or else a $D_s^{(*)+}D_s^{(*)-}$ or $D_s^{(*)+}D_s^{(*)-}$ is reconstructed as a $D_s^{(*)+}D_s^{(*)-}$ or $D_s^{(*)+}D_s^{(*)-}$. For these CF candidates $\Delta E$ is shifted by 100-150 MeV, but $M_{bc}$ remains almost unchanged. When the $B_s^0$ is not fully reconstructed, e.g. due to losing the $\gamma$ from $D_s^{(*)+}D_s^{(*)-}$ or $D_s^{(*)+}D_s^{(*)-}$ (CF-down), a negative shift in $\Delta E$ is observed. Conversely, in the case where the signal decay has gained a photon (CF-up), $\Delta E$ is typically shifted higher. The PDF for CR events is modeled with a Gaussian for $M_{bc}$ and a double Gaussian with common mean for $\Delta E$. CR and WC events have more complicated distributions. All signal shape parameters are taken from MC and calibrated using $B_s^0 \to D_s^{(*)+}\pi^+$ and $B_s^0 \to D_s^{(*)+}D^-\pi^0$ decays. The fractions of WC and CF events are taken from MC simulation. The fractions of CF-up events are difficult to calculate accurately from MC simulation as not all $B_s^0$ partial widths are measured; thus they are allowed to vary in the fit. As the CF-down fractions are fixed, the three distributions ($D_s^{(*)+}D_s^{(*)-}$, $D_s^{(*)+}D_s^{(*)-}$, and $D_s^{(*)+}D_s^{(*)-}$) are fitted simultaneously [12]. The CF fractions are listed in Table I.

### 2.1. Results

We measure the signal yields for $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ decays using $7.1 \pm 1.3$ million $B_s^0\bar{B}_s^0$ pairs with a $B_s^0\bar{B}_s^0$ fraction $f_{B_s^0\bar{B}_s^0} = (87.0 \pm 1.7)$% [13]. The fit results are listed in Table I and projections of the fit are shown.
The efficiencies ±ε of B_Y^B spectator decay yield. The likelihood function by a Gaussian having a width equal to the total systematic error obtained for the signal is set to the fitted value, respectively. We include systematic uncertainty in the significance by smearing the L where ε_0.15 −0.1 −0.05 0 0.05 0.1
5.25 5.3 5.35 5.4 5.45

Table I: Fractional distribution of the signal reconstruction types from MC simulation of B_s^0 decay modes.

| B_s^0 Mode | RC       | WC       | CF I                      | CF II                      |
|------------|----------|----------|---------------------------|---------------------------|
| D_s^0 D_s^- | 76.1     | 6.0 fixed | 17.1 (→ D_s^± D_s^-)      | 0.8 (→ D_s^± D_s^-)       |
| D_s^± D_s^± | 44.4     | 38.5 fixed | 8.2 (→ D_s^± D_s^-) fixed | 8.9 (→ D_s^± D_s^-)       |
| D_s^0 D_s^- | 31.8     | 37.6 fixed | 2.0 (→ D_s^± D_s^-) fixed | 28.6 (→ D_s^± D_s^-) fixed |

in Fig. 1. The branching fraction for channel i is calculated as \( B_i = Y_i / (\varepsilon^{i}_{MC} \cdot N_{B_s^{0}B_s^{+}} \cdot f_{B_s^{+}B_s^{0}} \cdot 2) \), where \( Y_i \) is the fitted CR yield, and \( \varepsilon^{i}_{MC} \) is the MC efficiency with intermediate branching fractions [8] included. The efficiencies \( \varepsilon^{i}_{MC} \) include small correction factors to account for differences between MC and data for kaon identification.

The systematic errors are listed in Table III. The error due to PDF shapes is evaluated by varying shape parameters by ±1σ. The systematic error for the fixed WC and CF-down fractions is evaluated by repeating the fit with each fixed fraction varied by ±20%. The uncertainties due to \( K^\pm \) identification and tracking are ∼1%(momentum-dependent) and 0.35% per track respectively. As the longitudinal polarization fraction \( f_L \) of \( B_s^0 \rightarrow D_s^+ D_s^- \) is not measured yet, we assume \( f_L \) to be the world average (WA) value for the analogous spectator decay \( B_d^0 \rightarrow D_s^+ D_s^- : 0.52 ± 0.05 \) [8]. The related systematic error is taken as the change in \( B \) when \( f_L \) is varied by twice the error on the WA value. Significant uncertainties arise from \( D_s^+ \) branching fractions and the fraction of \( Y(5S) \) decays producing \( B_s \) mesons, which are external factors that are expected to be measured more precisely in the future. The statistical significance given in Table II is calculated as \( \sqrt{-2 \ln(L_0/L_{\text{max}})} \), where \( L_0 \) and \( L_{\text{max}} \) are the values of the likelihood function when the signal yield \( Y_s \) is fixed to zero and when it is set to the fitted value, respectively. We include systematic uncertainty in the significance by smearing the likelihood function by a Gaussian having a width equal to the total systematic error obtained for the signal yield.

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Figure 1: \( M_{bc} \) and \( \Delta E \) projections of the fit result. The columns correspond to \( B_s^0 \rightarrow D_s^+ D_s^- \) (right), \( B_s^0 \rightarrow D_s^0 D_s^0 \) (middle), and \( B_s^0 \rightarrow D_s^0 D_s^- \) (left). The red dashed curves show RC+WC signal, the blue-purple solid curves show CF, the grey solid curve shows background, and the black solid curves show the total.
Table II: Signal yield (Y), efficiency including intermediate branching fractions (ε), branching fraction (B), and signal significance (S) including systematic uncertainty. The first errors listed are statistical, and the second are systematic.

| Mode           | Y (events) | ε (×10⁻⁴) | B (%) | S |
|----------------|------------|------------|-------|---|
| D⁺ s D⁻ s      | 33.1⁺⁵⁻⁵.⁴ | 4.72       | 0.58⁻⁰.⁰₉ ±0.13 | 11.5 |
| D⁺⁺ s D⁺⁺ s    | 44.5⁺⁵⁻⁵.⁵ | 2.08       | 1.8 ± 0.2 ±0.4 | 10.1 |
| D⁺⁺ s D⁻⁻ s    | 24.4⁺⁴⁻³.⁸  | 1.01       | 2.0 ± 0.3 ±0.5 | 7.8  |
| Sum            | 102.0⁺⁹⁻⁸.⁸ | 4.3 ± 0.4 ±1.0 |      |     |

Table III: Systematic errors (%). Those listed in the top section affect the signal yield and thus the signal significance.

| Source                        | D⁺⁺ s D⁻⁻ s | D⁺ s D⁻ s | D⁺⁺ s D⁺⁺ s |
|-------------------------------|-------------|-----------|-------------|
|                               | +σ          | −σ        | +σ          | −σ          | +σ          | −σ          |
| Signal PDF Shape              | 2.7         | 2.2       | 2.2         | 2.4         | 5.1         | 3.8         |
| Background PDF Shape          | 1.5         | 1.2       | 1.3         | 1.4         | 2.9         | 2.2         |
| WC + CF fraction              | 0.7         | 0.6       | 4.6         | 4.5         | 6.2         | 6.2         |
| R requirement (q̅q̅ suppression) | 3.1         | 0.0       | 0.0         | 2.7         | 0.0         | 2.1         |
| Best candidate selection      | 5.5         | 0.0       | 1.5         | 0.0         | 1.5         | 0.0         |
| K± Identification            | 7.0         | 7.0       | 7.0         | 7.0         | 7.0         | 7.0         |
| Ks Reconstruction            | 1.1         | 1.1       | 1.1         | 1.1         | 1.1         | 1.1         |
| π⁰ Reconstruction            | 1.1         | 1.1       | 1.1         | 1.1         | 1.1         | 1.1         |
| Tracking                      | 2.2         | 2.2       | 2.2         | 2.2         | 2.2         | 2.2         |
| Polarization                  | 0.1         | 0.1       | 0.8         | 0.7         | 0.5         | 1.0         |
| MC statistics for ε          | 0.2         | 0.2       | 0.4         | 0.4         | 0.5         | 0.5         |
| D⁺⁺ s Branching Fractions    | 8.6         | 8.6       | 8.6         | 8.6         | 8.7         | 8.7         |
| N_B²(B⁺⁻)                    | 18.3        |           |             |             |             |             |
| f_{B²}                       | 2.0         |           |             |             |             |             |
| Total                         | 22.7        | 21.8      | 22.6        | 22.8        | 24.6        | 24.3        |

In the heavy quark limit with (m_b - 2m_s) → 0 and N_c → ∞, the dominant contribution to the decay width comes from B_s⁰ → D⁺⁺ s D⁺⁺ s decays [6, 14]. Assuming negligible CP violation, the branching fraction is related to ∆Γ_s as ∆Γ_s/Γ_s = 2B/(1 - B). Inserting the total B from Table II gives

$$\Delta\Gamma_s = 0.090 \pm 0.009 \pm 0.022,$$

(2)

where the first error is statistical and the second is systematic. This result is in good agreement with the current WA [6] and is consistent with theory [15]. There is a theoretical uncertainty arising mainly from the CP-odd component in B⁰ → D⁺⁺ s D⁺⁺ s and the unknown contribution of 3-body final states.

If a CP-violating phase φ_s is allowed, the above relation becomes

$$4B(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}) = \frac{\Delta\Gamma_s^{CP}}{\cos\phi_s} \left[ \frac{1 + \cos\phi_s}{1 + \Delta\Gamma_s^{CP}} + \frac{1 - \cos\phi_s}{1 - \Delta\Gamma_s^{CP}} \right],$$

(3)

where \(\phi_s = \text{Arg}(M_{12}/\Gamma_{12})\) [16]. Fig. 2 plots ∆Γ_s as a function of φ_s for our measurement.

In summary, we have measured the branching fractions for B_s⁰ → D⁺⁺ s D⁺⁺ s using e⁺e⁻ data taken at the Υ(5S) resonance. Our results constitute the first observation of B⁰ → D⁺⁺ s D⁺⁺ s (8σ significance). Using the
total measured branching fraction $B(B^0_s \to D^{(*)+}D^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$ and assuming no CP violation, we determine the relative $B_s\bar{B}_s$ decay width difference to be $\Delta \Gamma_s/\Gamma_s = 0.090 \pm 0.009 \pm 0.022$.

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