Observation of $B_s^0 \rightarrow D_s^{(*)} \pi^+$, $B_s^0 \rightarrow D_s^{(*)} \rho^+$ and $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ and Estimate of $\Delta \Gamma_{CP}$ at Belle

Sevda Esen
University of Cincinnati
E-mail: esens@mail.uc.edu

The large data sample being recorded with the Belle detector at the $\Upsilon(5S)$ energy provides a unique opportunity to study the less-well-known $B_s^0$ meson decays. Following our recent measurement of $B_s^0 \rightarrow D_s^- \pi^+$ in a sample of 23.6 fb$^{-1}$, we extend the analysis to include decays with photons in the final state. Using the same sample, we report the first observation of three other dominant exclusive $B_s^0$ decays, in the modes $B_s^0 \rightarrow D_s^- \pi^+$, $B_s^0 \rightarrow D_s^- \rho^+$ and $B_s^0 \rightarrow D_s^- \rho^+$. We measure their respective branching fractions and, using helicity-angle distributions, the longitudinal polarization fraction of the $B_s^0 \rightarrow D_s^{(*)-} \rho^+$ decay.

We also present a measurement of the branching fractions for the decays $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$. In the heavy quark limit, this branching fraction is directly related to the width difference between the $B_s$ CP-even and CP-odd eigenstates.
1. Introduction

Beginning in 2005, the Belle experiment running KEKB $e^+e^-$ collider [1] has recorded several data sets at the center-of-mass energy corresponding to the $\Upsilon(5S)$ resonance. Belle has used this data sets to measure several $B^0_s$ properties and branching fractions. A total of 120 fb$^{-1}$ at the $\Upsilon(5S)$ ($\sqrt{s} \approx 10.87$ GeV) has been recorded. The results presented here correspond to the first 23.6 fb$^{-1}$.

The total $e^+e^- \rightarrow b\bar{b}$ cross section at the $\Upsilon(5S)$ energy was measured to be $\sigma_{b\bar{b}} = (302 \pm 14)$ pb [2, 3], with the fraction $f_e = \sigma(e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)})/\sigma_{b\bar{b}} = (19.3 \pm 2.9)$% [4]. The dominant $B^0_s$ production mode is $e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$, with a fraction $f_{B_s^*}\bar{B}_s^* = (90.1^{+3.8}_{-4.0} \pm 0.2)$% of the b$\bar{b} \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$ events [5]. Thus for 23.6 fb$^{-1}$ the total number of $e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$ events is $(1.24 \pm 0.2) \times 10^6$.

All signal $B^0_s$ decays are fully reconstructed from final-state particles using two quantities: the beam-energy-constrained mass $M_{bc} = \sqrt{E^2_B - p^2_B}$, and the energy difference $\Delta E = E_B - E_\gamma$, where $p_B$ and $E_B$ are the reconstructed momentum and energy of the $B^0_s$ candidate, and $E_\gamma$ is the beam energy. These quantities are evaluated in the $e^+e^-$ center-of-mass frame. Although the $B_s^0$ always decays to $B_s^0\gamma$, the $\gamma$ is not reconstructed because of its extremely low momentum.

2. Observation of $B_s^0 \rightarrow D_s^+\pi^- + D_s^{(*)}-\rho^+$ Decays and Polarization Measurement of $B_s^0 \rightarrow D_s^+\rho^-$

Three CKM-favored decays with relatively large branching fractions, $B^0_s \rightarrow D_s^-\pi^+$ and $D_s^{(*)}-\rho^+$, have been observed recently by Belle [6]. Three $D_s^+$ decay modes are considered: $\phi(\rightarrow K^+K^-)\pi^+$, $K_S(\rightarrow \pi^+\pi^-)K^+$ and $K^{(*)0}(\rightarrow K^+\pi^-)K^+$. Since only four charged tracks and up to one $\pi^0$ are required, these final states have relatively large signals. The continuum events are removed using the ratio of the second to zeroth Fox-Wolfram moments [7]. This ratio differs for spherical $B$ events and jet-like continuum events.

Only one $B^0_s$ candidate is allowed per event. This candidate is chosen based on the intermediate-particle reconstructed masses. The $M_{bc}$ and $\Delta E$ distributions of the selected $B^0_s$ candidates are shown in Figure 1. For the $B_s^0 \rightarrow D_s^-\rho^+$ candidates, the helicity angles $\theta_{D_s^-}$ and $\theta_{\rho^+}$ are also reconstructed. These are defined as the angle between the $D_s^-$ or $\pi^+$ and the opposite direction of the $B_s^0$ in the $D_s^-$ or $\rho^+$ rest frame. The distributions of $\cos \theta_{D_s^-}$ and $\cos \theta_{\rho^+}$ are fitted to determine the longitudinal polarization fraction $f_\Sigma$ (see Table 1).

3. Observation of $B_s \rightarrow D_s^{(*)}-D_s^{(*)+}$ Decays and a Determination of the $\Delta\Gamma_s$

Decays of $B_s \rightarrow D_s^{(*)}-D_s^{(*)+}$ are interesting due to their large CP-even fraction. The pure CP-even $D_s^+\pi^-$ state and predominantly CP-even $D_s^0\pi^-$ states are Cabibbo-favored and expected to dominate the width difference of the $B_s^0 - \bar{B}_s^0$ system. In the heavy quark limit, assuming negligible CP violation, the relative width difference is $\Delta\Gamma_s^{CP}/\Gamma_s = 2\beta/(1 - \beta)$, where $\beta$ is the total branching fraction of $B_s \rightarrow D_s^{(*)}-D_s^{(*)+}$ decays [8].

For this study [9], $D_s^+$ candidates are reconstructed in six modes, $\phi\pi^+$, $K_SK^+$, $K_S^0K^{*+}, \phi\rho^+$, $K_S^{*+}K_S$ and $K^{*+}K^{*0}$. $B^0_s$ candidates are reconstructed from two oppositely charged $D_s^{(*)-}$ mesons. As the daughter photon of the $D_s^+$ has very low momentum, more than half of the events yield more than one $B^0_s$ candidate sharing the same $D_s^+$ pair. Only one candidate per event is selected.
Figure 1: Projections of $B^+_s\bar{B}^+_s$ signal region in $M_{bc}$ and $\Delta E$ for fits of $B^0 \to D_{s}^{*-} \pi^+$ (top-left), $D_{s}^{*-} \rho^+$ (bottom-left), and $D_{s}^{*-} \rho^+$ (top-right). The bottom-right figure shows the helicity distributions for $D_{s}^{*-} \rho^+$ mode. The solid-blue line represents the total fit, while the red-dashed(black-dotted) curve is the signal(background).

using a selection criteria based on $M_{D_s}$ and $M_{D_s} - M_{D_s}$ information. After rejecting continuum events using a Fisher discriminant based on a set of modified Fox-Wolfram moments [7, 10], the remaining background events are largely $B_{(s)} \to D_{s}^{(*)} X$ decays, where $X$ is an accidental particle combination with a reconstructed mass within the $D_s$ mass window. The $B^0 \to D_s^{*-} D_s^+$, $D_s^{*-} D_s^+$, and $D_s^{*-} D_s^{*+}$ modes are fitted simultaneously; the fit projections are shown in Figure 2.

Figure 2: $\Delta E$ (top) and $M_{bc}$ (bottom) distributions for $D_s^{*-} D_s^+$, $D_s^{*-} D_s^+$, and $D_s^{*-} D_s^{*+}$, from left to right respectively. The red-dashed curve represents correctly reconstructed signal events, the black curve is the total fit.

The signal yields, branching fractions, and resulting value of $\Delta \Gamma/\Gamma_{CP}$ are listed in Table 1. Various systematic uncertainties are studied, and the resulting systematic errors are listed after the statistical errors. The second systematic error is due to uncertainty of $f_s$ for $B^0 \to D_s^{*-} \pi^+$, $D_s^{(*)} \rho^+$ modes. For $B^0 \to D_s^{(*)} D_s^{(*)+}$ modes, it also includes uncertainties of $D_s$ branching fractions, $\sigma_{T(5S)}$, and $f_{B_s B_s}$. Our results are in good agreement with the theoretical predictions [11, 12] and existing measurements[13].

The signal yields, branching fractions, and resulting value of $\Delta \Gamma/\Gamma_{CP}$ are listed in Table 1. Various systematic uncertainties are studied, and the resulting systematic errors are listed after the statistical errors. The second systematic error is due to uncertainty of $f_s$ for $B^0 \to D_s^{*-} \pi^+$, $D_s^{(*)} \rho^+$ modes. For $B^0 \to D_s^{(*)} D_s^{(*)+}$ modes, it also includes uncertainties of $D_s$ branching fractions, $\sigma_{T(5S)}$, and $f_{B_s B_s}$. Our results are in good agreement with the theoretical predictions [11, 12] and existing measurements[13].
Table 1: Summary of the results. Signal yields in the $B_s^0\bar{B}_s^0$ production mode, $N_{B_s^0\bar{B}_s^0}$; significances, S (including systematics); total signal efficiencies, $\epsilon$ (including all sub-decay branching fractions); and branching fractions, $\mathcal{B}$. The first error is statistical, while the latter two are systematic and arise from internal and external sources. The significance $S=\sqrt{-2\ln(L_0/L_{\max})}$, where $L_0$($L_{\max}$) are likelihood values when the signal yield is fixed to zero (floated).

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{B_s^0\bar{B}_s^0}$</th>
<th>S</th>
<th>$\epsilon$</th>
<th>$\mathcal{B}$ (%)</th>
<th>World Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to D_s^-\pi^+$</td>
<td>$53.4^{+10.3}_{-9.4}$</td>
<td>7.1</td>
<td>$9.13 \times 10^{-2}$</td>
<td>$0.24^{+0.05}_{-0.04}$ $0.03 \pm 0.04$</td>
<td>1st Measurement</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^-\rho^+$</td>
<td>$92.2^{+14.2}_{-13.2}$</td>
<td>8.2</td>
<td>$4.40 \times 10^{-2}$</td>
<td>$0.85^{+0.13}_{-0.12}$ $0.11 \pm 0.13$</td>
<td>1st Measurement</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^-\bar{\rho}^+$</td>
<td>$77.8^{+14.5}_{-13.4}$</td>
<td>7.4</td>
<td>$2.67 \times 10^{-2}$</td>
<td>$1.19^{+0.22}_{-0.20}$ $0.17 \pm 0.18$</td>
<td>1st Measurement</td>
</tr>
<tr>
<td>$f_1(B_s^0 \to D_s^-\rho^+)$</td>
<td>$1.05^{+0.08+0.03}_{-0.10-0.04}$</td>
<td></td>
<td></td>
<td></td>
<td>1st Measurement</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^+\pi^-$</td>
<td>$8.5^{+3.2+2.6}_{-2.6}$</td>
<td>6.2</td>
<td>$3.31 \times 10^{-4}$</td>
<td>$1.03^{+0.39}_{-0.32+0.13}$ $0.13 \pm 0.21$</td>
<td>(1.04 $\pm 0.35$)</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^+\pi^-$</td>
<td>$9.2^{+2.8+2.4}_{-2.4}$</td>
<td>6.6</td>
<td>$1.35 \times 10^{-4}$</td>
<td>$2.75^{+0.83}_{-0.71}$ $0.40 \pm 0.56$</td>
<td>1st Observation</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^+\pi^-$</td>
<td>$4.9^{+1.9+1.7}_{-1.7}$</td>
<td>3.1</td>
<td>$0.643 \times 10^{-4}$</td>
<td>$3.08^{+1.22}_{-1.04+0.57}$ $0.63 \pm 0.31$</td>
<td>1st Evidence</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^+\pi^-$</td>
<td>$22.6^{+4.7+3.4}_{-3.4}$</td>
<td>6.85</td>
<td>$1.53 \times 10^{-4}$</td>
<td>$6.85^{+1.53}_{-1.30}+1.40$ $1.11 \pm 1.40$</td>
<td>(4.0 $\pm 1.5$)</td>
</tr>
<tr>
<td>$\Delta \Gamma_s/\Delta \Gamma$</td>
<td>$0.147^{+0.036+0.042}_{-0.030-0.041}$</td>
<td></td>
<td></td>
<td></td>
<td>0.080 $\pm 0.030$</td>
</tr>
</tbody>
</table>

4. Conclusion

We presented recent branching fraction measurements of $B_s^0$ decays obtained from 23.6 fb$^{-1}$ of $\Upsilon(5S)$ data recorded by the Belle experiment. Also, the longitudinal polarization fraction is measured for the $B_s^0 \to D_s^-\rho^+$ mode and $\Delta \Gamma_s^{CP}/\Gamma_s$ is estimated using $D_s^{(*)-}\bar{D}_s^{(*)+}$ modes.

References