Recent Belle results from $\Upsilon(5S)$ sample

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The large data sample recorded with the Belle detector at the $\Upsilon(5S)$ energy provides a unique opportunity to study the poorly-known $B_s^0$ meson. Two analyses, performed with a data sample representing an integrated luminosity of 121 fb$^{-1}$, are presented: the measurement of the $B_s^0 \rightarrow J/\psi f_0(980)$ and $B_s^0 \rightarrow J/\psi f_0(1370)$ branching fractions, and the 5$\sigma$ observation of the decay $B_s^0 \rightarrow \Lambda_c^+ \pi^- \bar{\Lambda}$ which is the first observation of a baryonic $B_s^0$ decay. In addition, we present new results of a measurement of the CKM angle $\phi_1(\beta)$ with $B\pi$ tagged events.

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**Introduction**

The Belle experiment [1], located at the interaction point of the KEKB asymmetric-energy $e^+e^-$ collider, was designed for the study of $B$ mesons \(^1\) produced in $e^+e^-$ annihilation at a center-of-mass (CM) energy corresponding to the mass of the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.58$ GeV). However, a data sample of integrated luminosity $L_{\text{int}} = 121$ fb\(^{-1}\) has been recorded and analyzed at the energy of the $\Upsilon(5S)$ resonance ($\sqrt{s} \approx 10.87$ GeV), above the $\bar{B}^0\bar{B}^0$ threshold.

Apart from the $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ continuum events, the $e^+e^- \rightarrow b\bar{b}$ process can produce different kinds of final states involving a pair of non-strange $B$ mesons [2] ($B^+\bar{B}^-, B^+\bar{B}$, $B\bar{B}, B^*\bar{B}^*, B\bar{B}^*, B\bar{B}^\prime\pi, B\bar{B}\pi, B\bar{B}\pi\pi$ and $B\bar{B}\gamma$), a pair of $B^0_s$ mesons ($B^+_s\bar{B}^-_s$, $B^+_s\bar{B}^0_s$ and $B^0_s\bar{B}^0_s$), or final states involving a light bottomonium resonance below the open-beauty threshold [3]. The $B^+$ and $B^0_s$ mesons always decay by emission of a photon. 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 [4] and the fraction of $B^0_s$ events to be $f_s = \sigma(e^+e^- \rightarrow B^{(*)}_s\bar{B}^{(*)}_s) / \sigma_{b\bar{b}} = (19.3 \pm 2.9)$% [5]. The dominant $B^0_s$ production mode, $b\bar{b} \rightarrow B^+_s\bar{B}^-_s$, represents $f_{B^+_s\bar{B}^-_s} = (90.1^{+3.8}_{-4.0} \pm 0.2)$% of the $b\bar{b} \rightarrow B^{(*)}_s\bar{B}^{(*)}_s$ events, as measured with $B^0_s \rightarrow D^- \pi^+$ events [6].

$B^0_s$ candidates are fully reconstructed from the final-state particles. From the reconstructed four-momentum in the $e^+e^-$ center-of-mass, $(E^*_{B^0_s}, \mathbf{p}^*_{B^0_s})$, two observables are used to extract the signal yield: the energy difference $\Delta E = E^*_{B^0_s} - \sqrt{s}/2$ and the beam-constrained mass $M_{bc} = \sqrt{s}/4 - \mathbf{p}^2_{B^0_s}$. The corresponding branching fraction is then computed using the total efficiency (including sub-decay branching fractions) determined with Monte-Carlo (MC) simulations, $\sum \varepsilon B^0_s$, and the number of $B^0_s$ mesons produced via the $e^+e^- \rightarrow B^+_s\bar{B}^-_s$ process, $N_{B^0_s} = 2 \times L_{\text{int}} \times \sigma_{b\bar{b}} \times f_s \times f_{B^+_s\bar{B}^-_s}$.

### 1. Study of $\bar{B}^0_s \rightarrow \Lambda^+_c \pi^- \bar{\Lambda}$

The $\bar{B}^0_s \rightarrow \Lambda^+_c \pi^- \bar{\Lambda}$ decay is the counterpart if the already-observed $B^- \rightarrow \Lambda^+_c \pi^- \bar{\Lambda}$ decay. The study of $B^{(*)}$ baryonic decays is important as the latest observations [7] exhibit a baryon-antibaryon mass peak near the kinematic threshold and tend to have larger branching fractions than two-body decays.

We fully reconstruct the decay via $\Lambda^+_c \rightarrow pK^- \pi^+$ and $\bar{\Lambda} \rightarrow \bar{p} \pi^+$. After a fit of the two $\Lambda^{(*)}_c$ vertices, only $\bar{B}^0_s$ candidates for which the $\Lambda^+_c$ ($\bar{\Lambda}$) invariant mass lies within 100 MeV/c\(^2\) (4 MeV/c\(^2\)) of the PDG value [5] are retained. The continuum is rejected with requirements on second-to-zeroth Fox-Wolfram moment ratio [8], $R_2 < 0.5$, and the cosine of thrust angle, $\cos \theta_{th} < 0.85$.

A two-dimensional binned fit on $M_{bc}$ and $\Delta E$ leads to a first 5.0$\sigma$-significant (including systematic effects) observation of 24 $\pm$ 7 events (Fig. 1). This is the first observation of a $B^0_s$ baryonic decay. The measured branching fraction,

$$\mathcal{B}(\bar{B}^0_s \rightarrow \Lambda^+_c \pi^- \bar{\Lambda}) = (4.8 \pm 1.4(\text{stat.}) \pm 0.9(\text{syst.}) \pm 1.3(\Lambda^+_c)) \times 10^{-4},$$

where the uncertainty due to the $\Lambda^+_c$ branching fraction is quoted separately, is compatible with that of $B^- \rightarrow \Lambda^+_c \pi^- \bar{\Lambda}$ [5].

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\(^1\)The notation “$B$” refers either to a $B^0$ or a $B^+$. Moreover, charge-conjugated states are implied everywhere.
2. Study of $B_s^0 \to J/\psi f_0$

$B_s^0$ decays to CP eigenstates are important for CP-violation measurements [9]. The $B_s^0 \to J/\psi f_0$ mode is especially interesting for the hadron-collider experiments because it can be reconstructed from charged tracks only.

The $J/\psi$ candidates are formed with oppositely-charged electron or muon pairs, while $f_0$ candidates are formed with $\pi^+ \pi^-$ pairs. A mass and vertex constrained fit is then applied to the $J/\psi$ candidates. If more than one candidate per event satisfies all the selection criteria, the one with the $M_{bc}$ value the closest to the expected signal mean is selected. The main background is the continuum, which is reduced by requiring $R_2 < 0.4$. The $B_s^0 \to J/\psi f_0$ signal is fitted using the energy difference, $\Delta E$, and the $f_0$ mass, $M_{\pi^+ \pi^-}$, distributions. Two $f_0$ resonances, $f_0(980)$ and $f_0(1370)$, are included in the fit.

We obtain a 8.4σ observation of $63^{+16}_{-10} B_s^0 \to J/\psi f_0(980)$ events and the first evidence for $B_s^0 \to J/\psi f_0(1370)$ with $19^{+8}_{-5}$ events [10]. We extract the branching fractions $\mathcal{B}(B_s^0 \to J/\psi f_0(980)) = 1.16^{+0.33}_{-0.19}$ (stat.) $\pm 0.15$ (syst.) $\pm 0.06$ $(N(B_s^0)) \times 10^{-4}$ and $\mathcal{B}(B_s^0 \to J/\psi f_0(1370)) = 0.08^{+0.03}_{-0.02}$ $(N(B_s^0)) \times 10^{-4}$, which are in agreement with other hadron-collider experiments [11].

3. Measurement of $\sin 2\phi_1$ with $B\pi$ tagging

Because the $\Upsilon(5S)$ mass is above the $B^+ \bar{B}^0 \pi^+$ threshold, a significant number of $\Upsilon(5S) \to B^+ \bar{B}^0 \pi^+ \pi^-$ events are present in the data sample [2]. The sign of the pion indicates whether the event contains a $B^{(*)0}$ $(e^+ e^- \to B^{(*)0} \bar{B}^{(*)-} \pi^+)$ or a $\bar{B}^{(*)0}$ $(e^+ e^- \to \bar{B}^{(*)0} B^{(*)+} \pi^-)$. With $B^0$ decaying to a CP eigenstate, the asymmetry, $A_{B\pi} = (N(B\pi^-) - N(B\bar{\pi}^+))/(N(B\pi^-) + N(B\bar{\pi}^+))$, the CKM angle $\phi_1$ can be determined via the relation [12]: $\sin 2\phi_1 = -\eta_{CP} A_{B\pi}(1 + x^2)/x$, where $x = \Delta m/\Gamma$.

From a clean sample of $75.9^{+9.5}_{-9.0}$ fully reconstructed $B^0 \to J/\psi(\to l^+ l^-) K_S^0(l^+ \pi^-)$ events, we simultaneously fit the missing masses of the $B^0 \pi^-$ and $B^0 \pi^+$ candidates by adding a charged
Figure 2: \( B^0 \pi^+ \) (left) and \( B^0 \pi^- \) (right) missing mass distributions for selected \( B^0 \to J/\psi K^0_S \) candidates (data points) together with the fit result (solid curve) and its background component (dashed curve).

The fit involves three signal components for the \( B^* \bar{B}^* \pi \), \( B^* \bar{B} \pi (+c.c.) \) and \( B B \pi \) classes of events. A total signal of \( 21.5 \pm 6.8 \) \( B^0 \pi^\pm \) events is obtained together with the asymmetry \( A_{BBS} = 0.28 \pm 0.28(\text{stat.}) \). While this analysis clearly suffers from lack of statistics, it nevertheless demonstrates that \( \phi_1 \) can be measured by this alternative method.

Conclusion

We presented new results on \( B^0_s \) decays obtained from 121 fb\(^{-1} \) of \( \Upsilon(5S) \) data recorded by the Belle detector. While modes with large statistics can provide precise measurements of branching fractions and \( B_s^{(\mp)} \) properties, first observations of several \( CP \)-eigenstate \( B^0_s \) decays are a confirmation of the large potential of our 120fb\(^{-1} \) \( e^+e^- \to \Upsilon(5S) \) data sample and advocate an ambitious \( B^0_s \) program at super-\( B \) factories.

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